

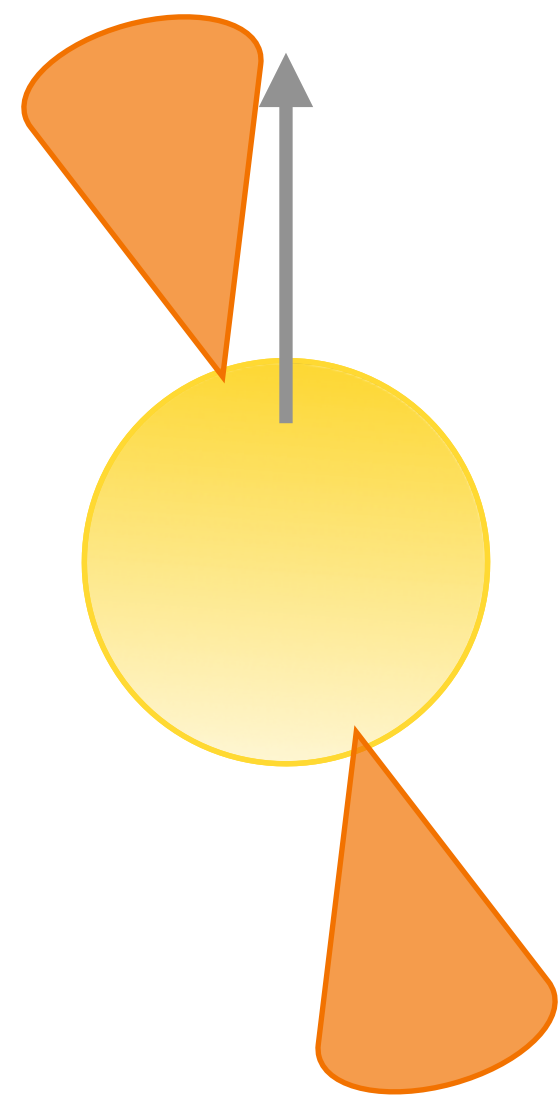
New Physics Explanations of PTA signal are incompatible with WIMPs Dark Matter

Yann Gouttenoire

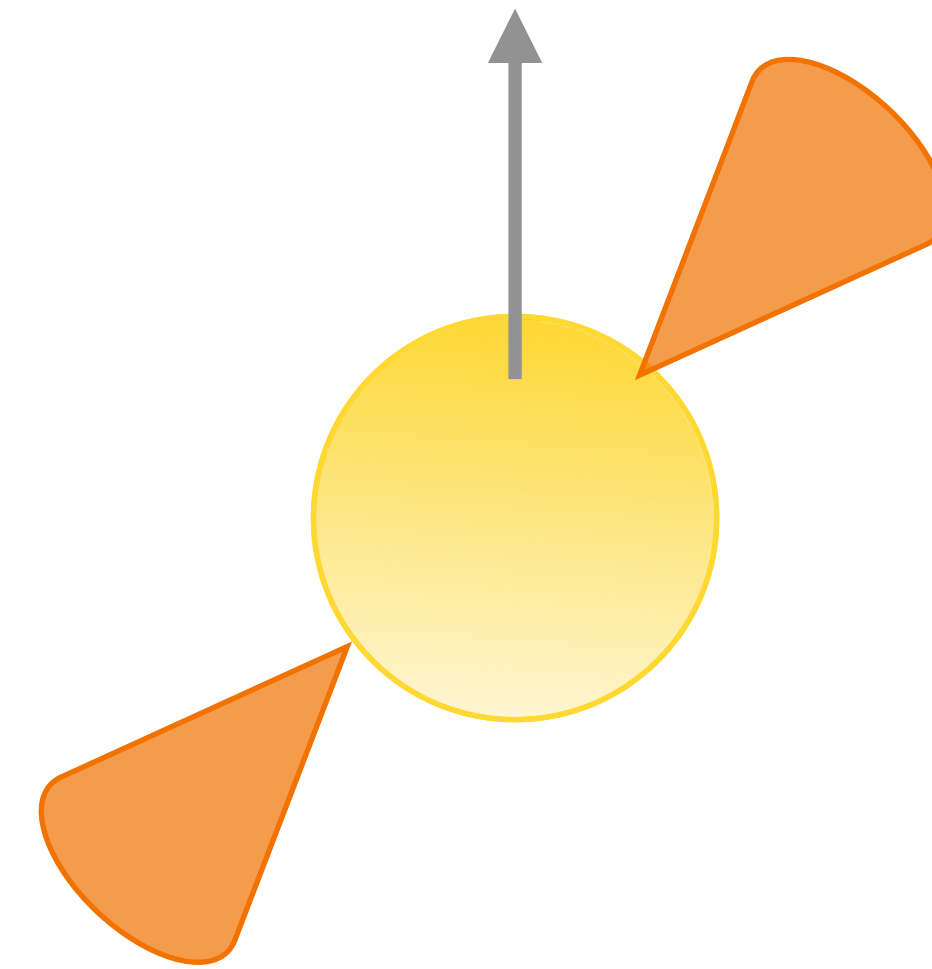
25th June 2025

GW from BSM 4 - Warsaw





Pulsar Timing Arrays (PTA)



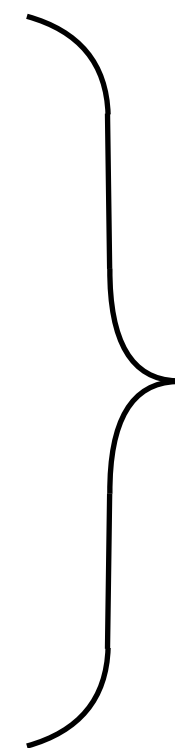
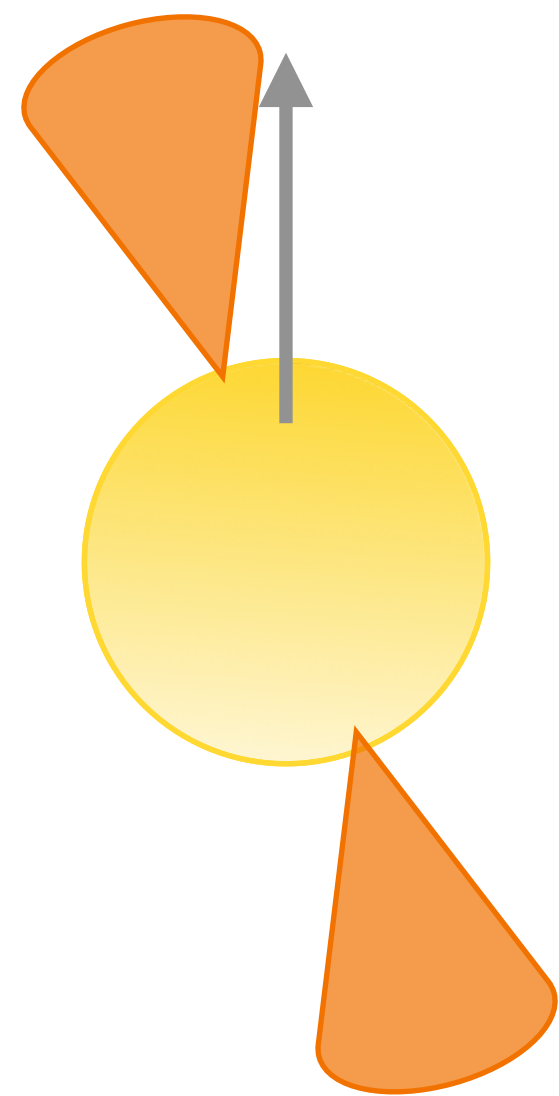
The New York Times

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NEW YORK, THURSDAY, JUNE 29, 2023

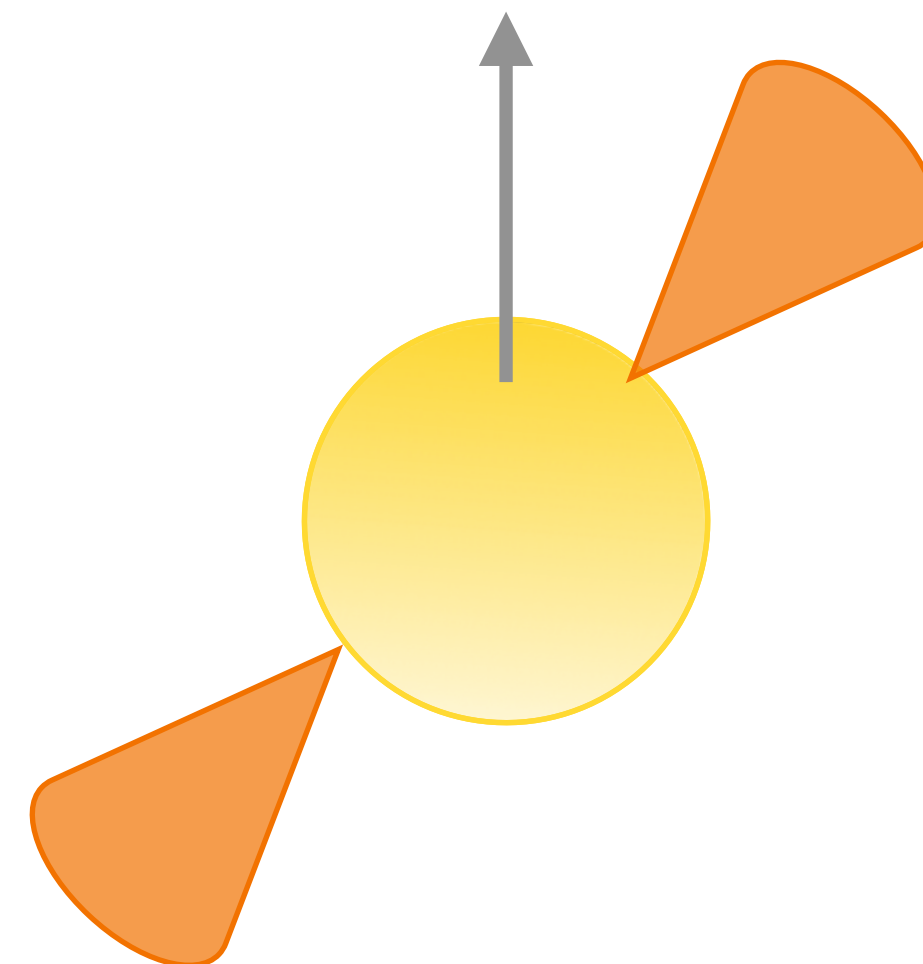
The Cosmos Is Thrumming With Gravitational Waves, Astronomers Find





Pulsar Timing Arrays (PTA)

$1 M_{\odot}$



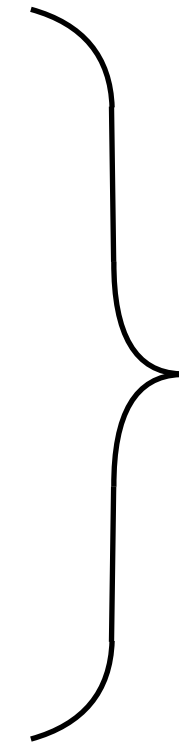
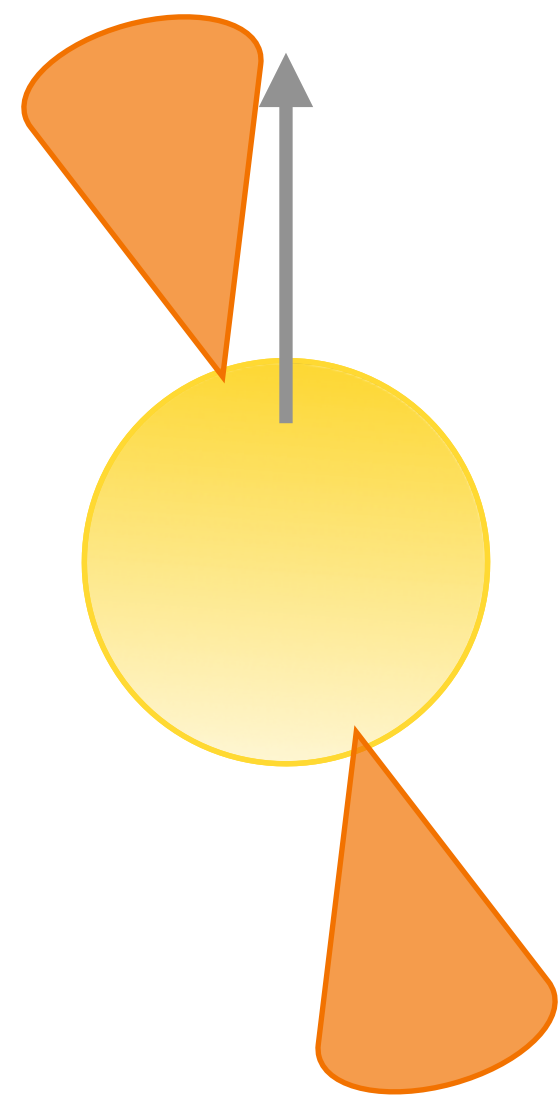
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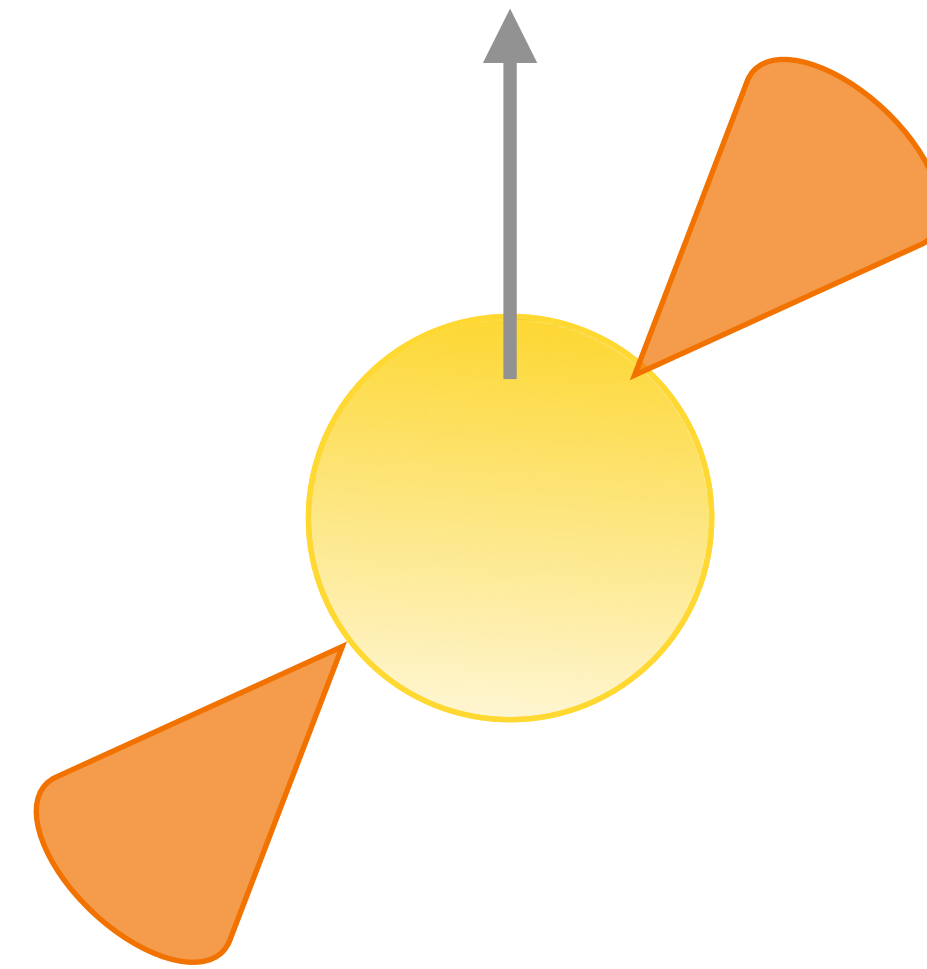




Pulsar Timing Arrays (PTA)

1 M_⊙

10 km



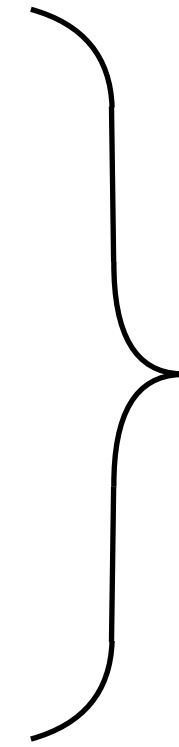
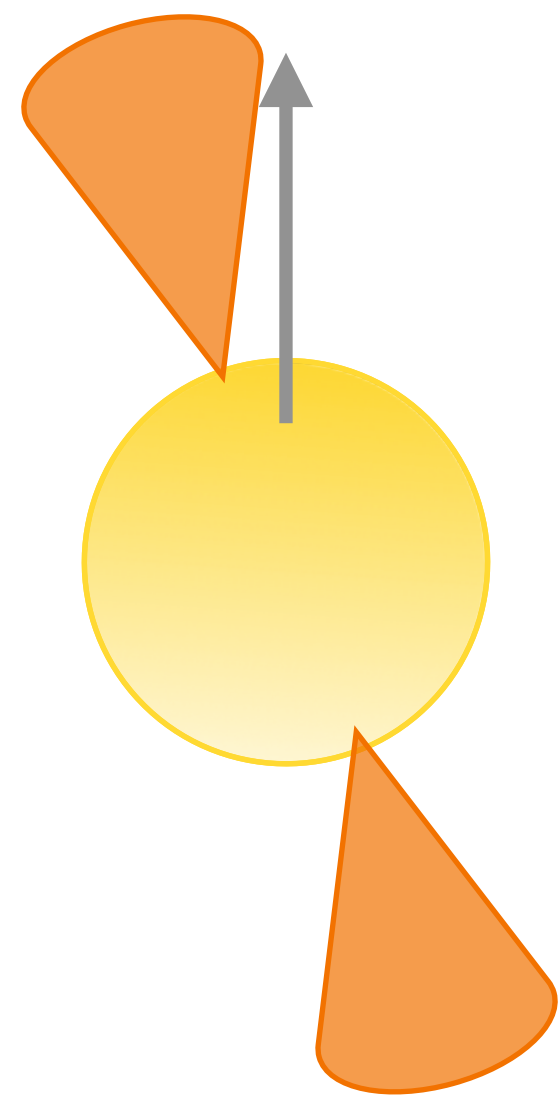
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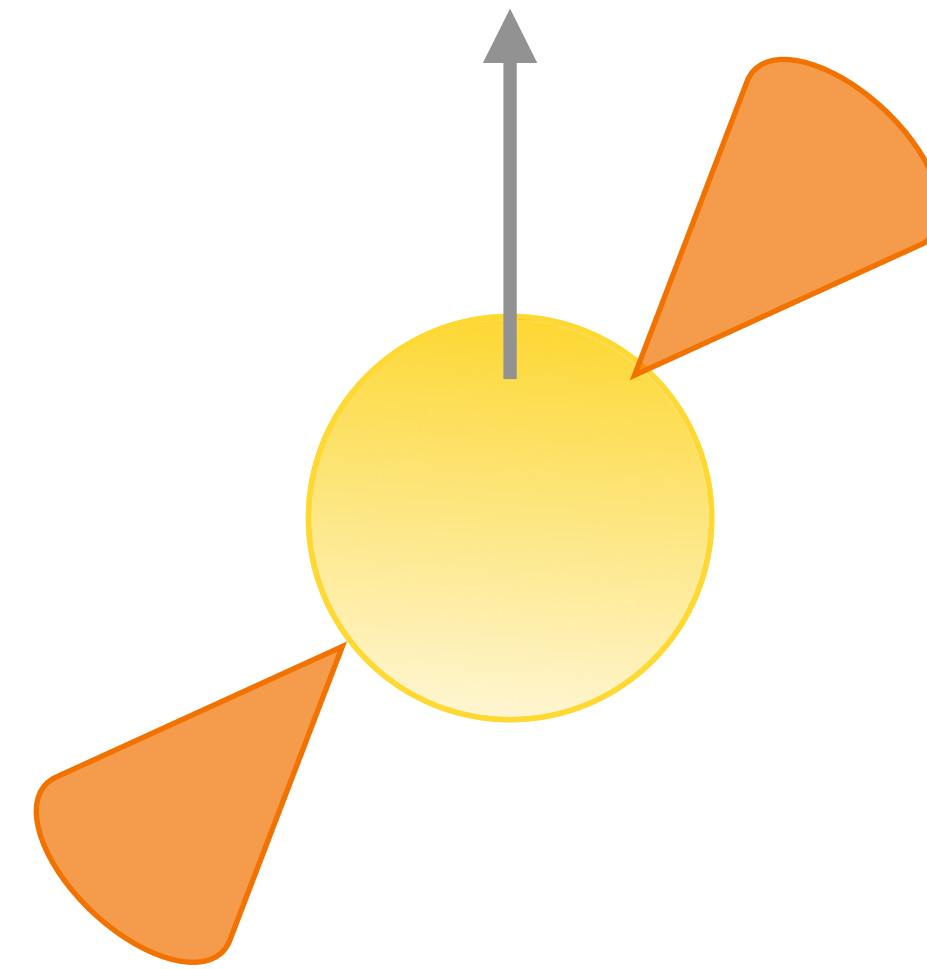


Pulsar Timing Arrays (PTA)

1 $M_{\odot}$

10 km

500 rotations/s



The New York Times

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The Cosmos Is Thrumming With Gravitational Waves, Astronomers Find



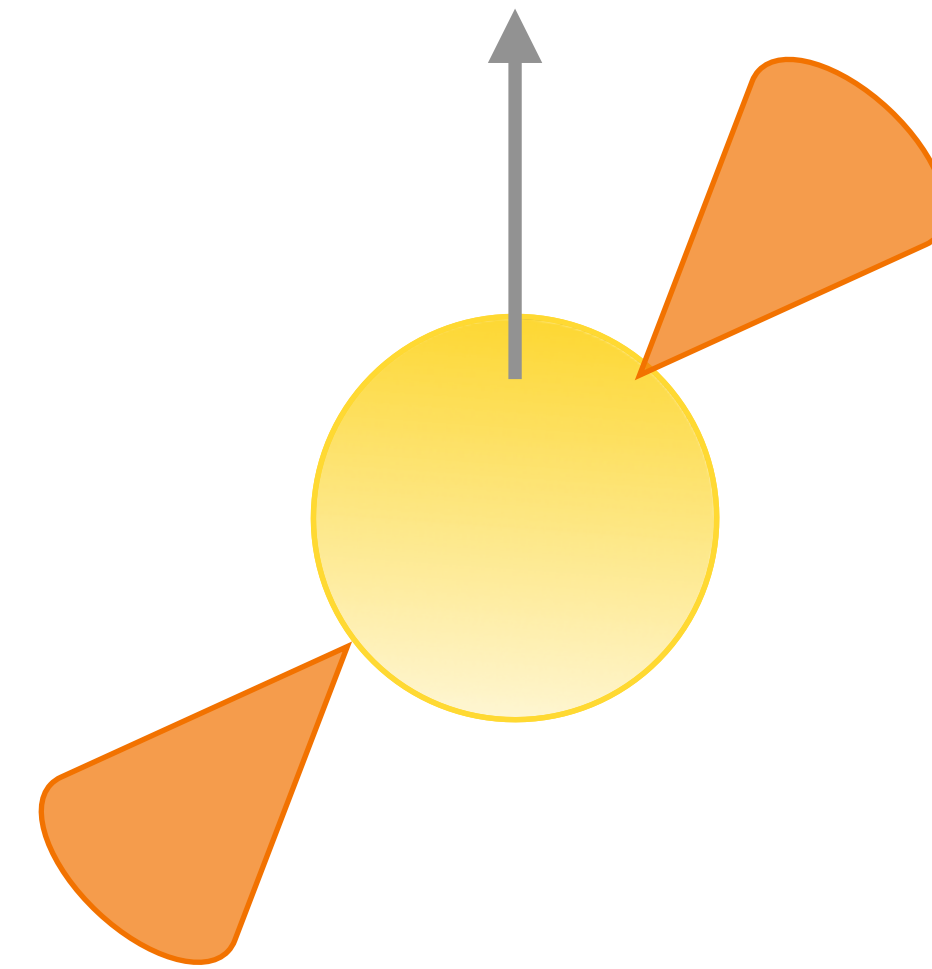
Pulsar Timing Arrays (PTA)

1 M_⊙

10 km

500 rotations/s

1 kpc



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The Cosmos Is Thrumming With Gravitational Waves, Astronomers Find



Pulsar Timing Arrays (PTA)

1 $M_{\odot}$

10 km

500 rotations/s

Pulses

Pulses

1 kpc



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***The Cosmos Is Thrumming With
Gravitational Waves, Astronomers
Find***



Pulsar Timing Arrays (PTA)

1 M_⊙

10 km

500 rotations/s

Pulses

Pulses

Gravitational
Waves

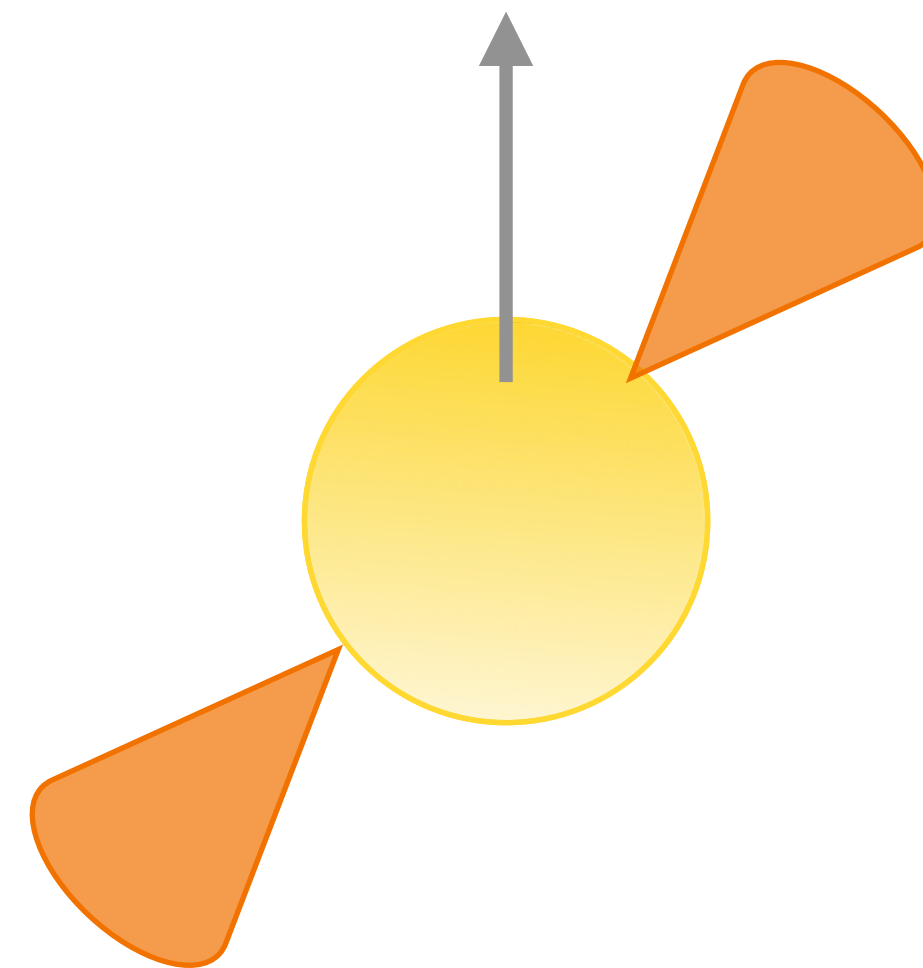
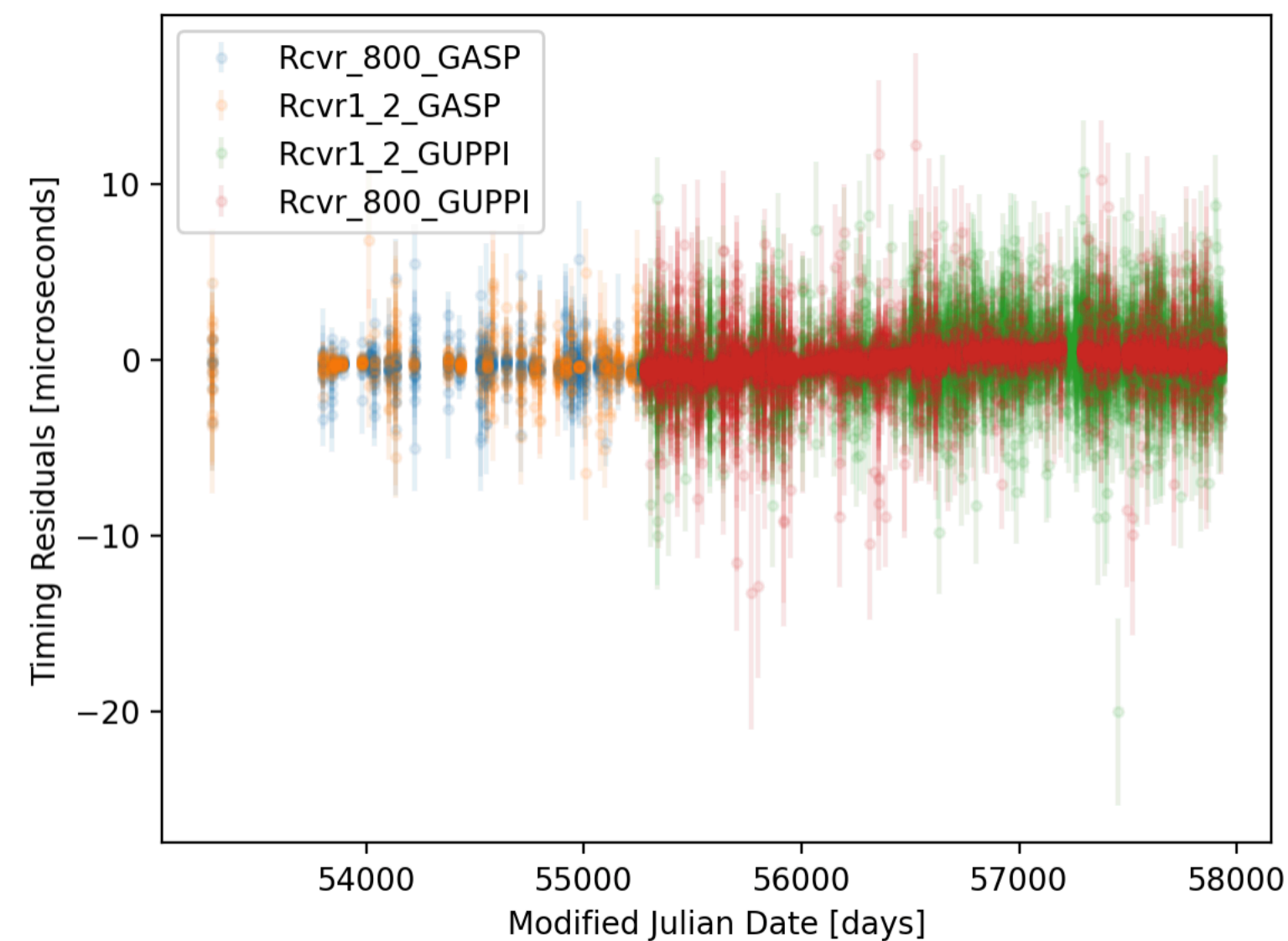
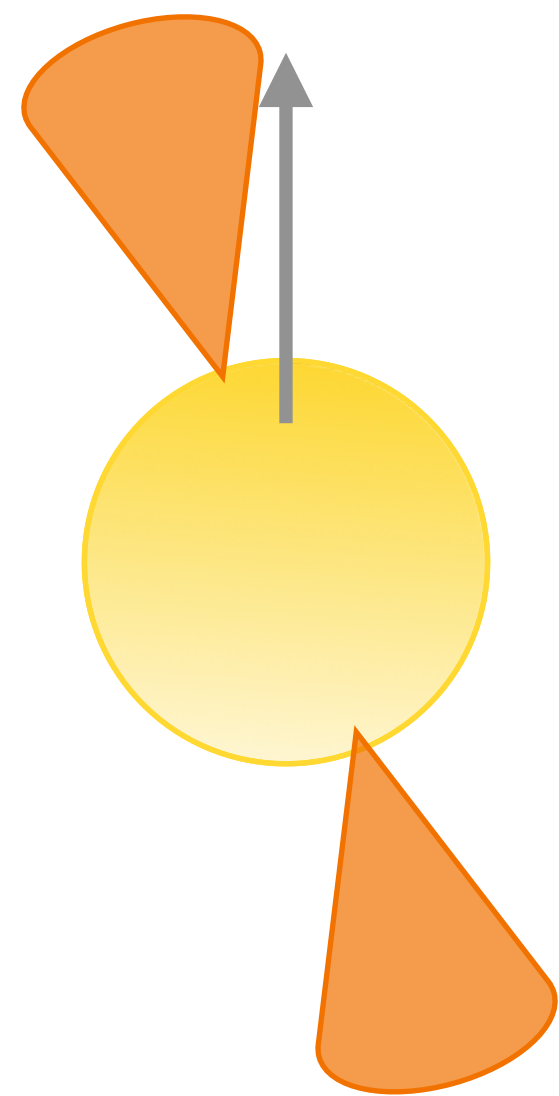
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*The Cosmos Is Thrumming With
Gravitational Waves, Astronomers
Find*





Pulses

Pulses

Gravitational
Waves



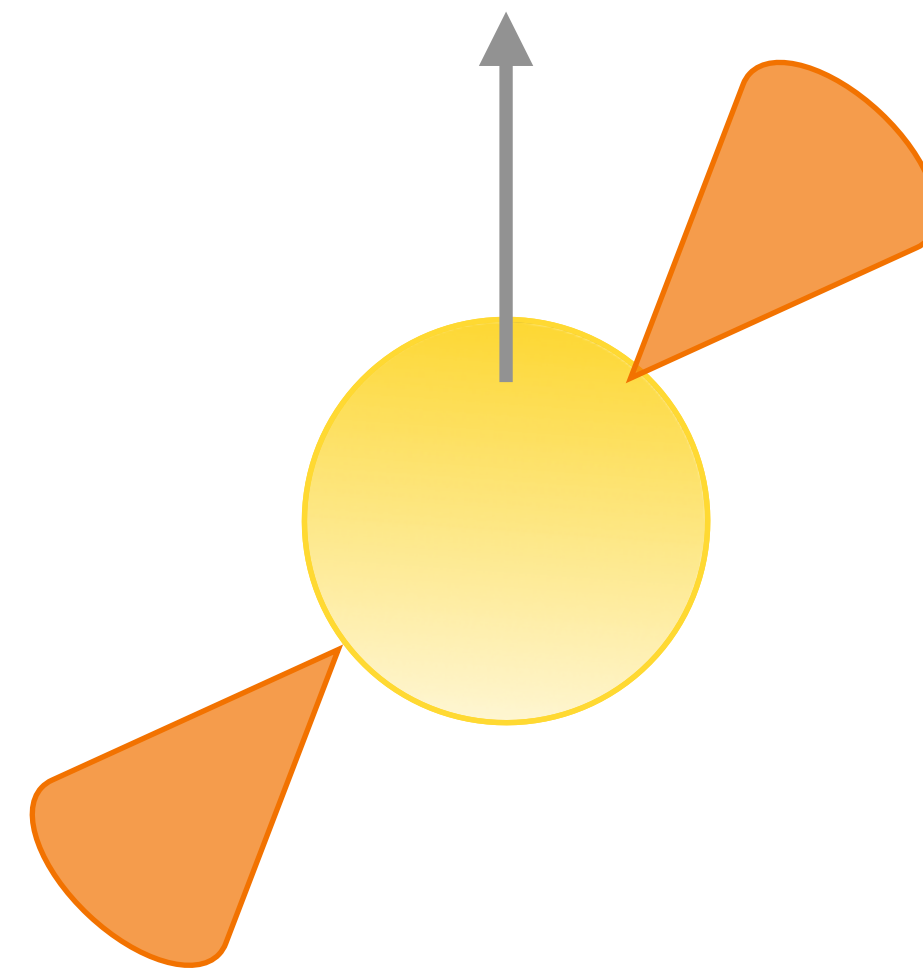
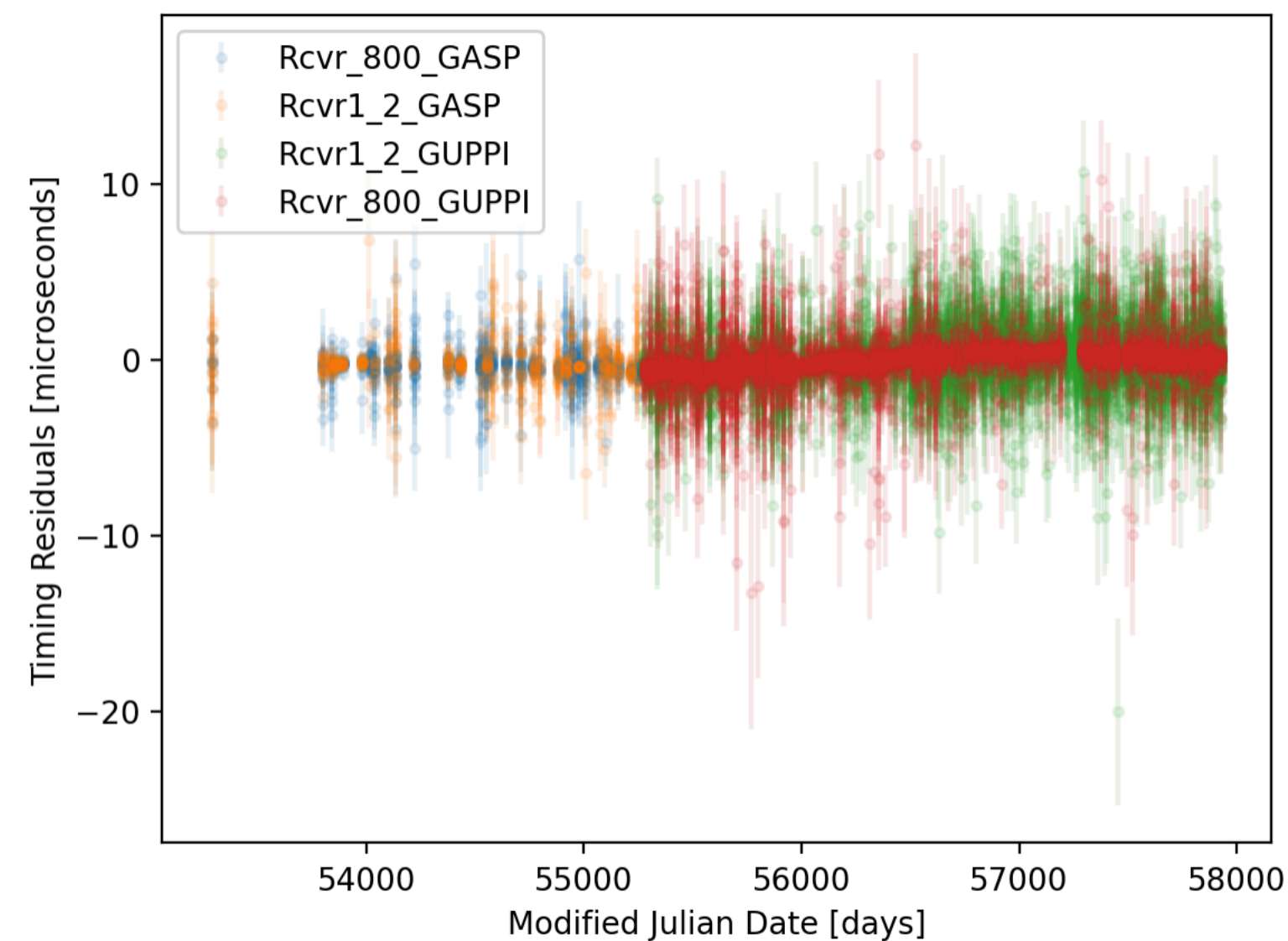
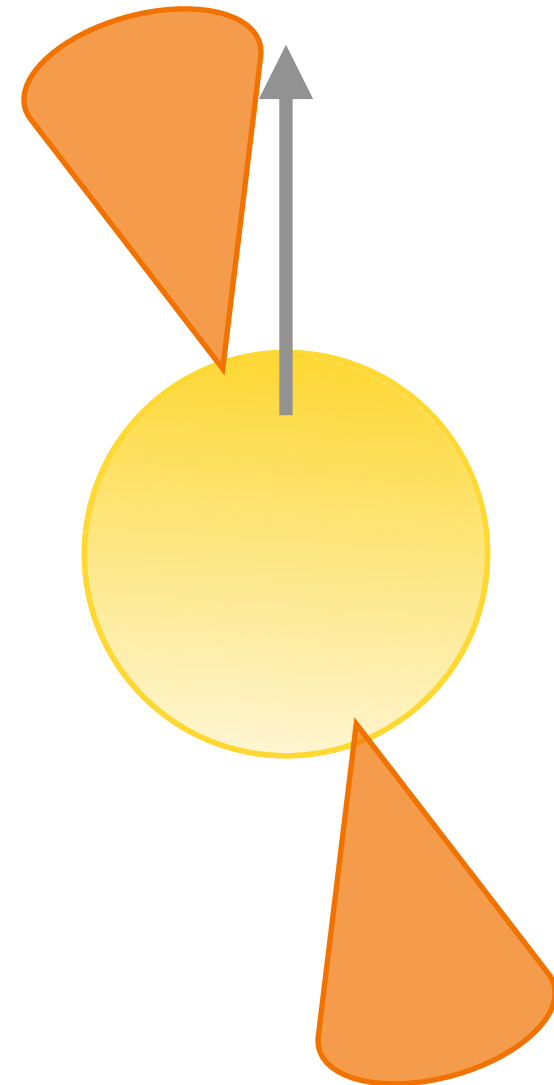
The New York Times

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***The Cosmos Is Thrumming With
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Find***

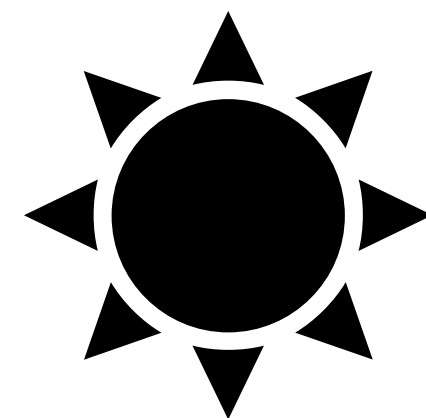
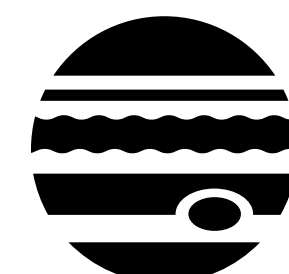
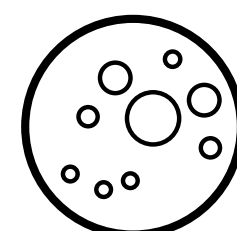




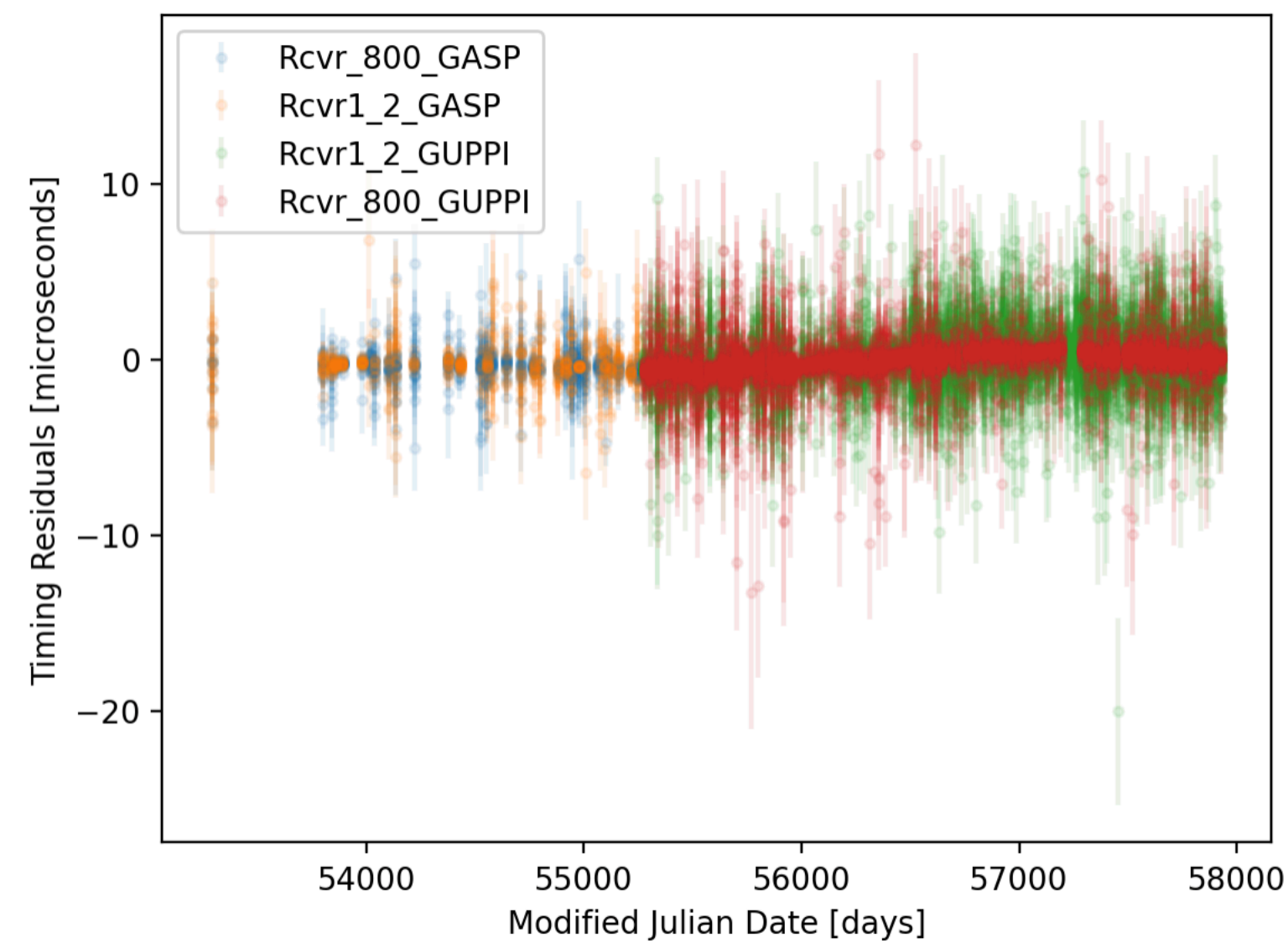
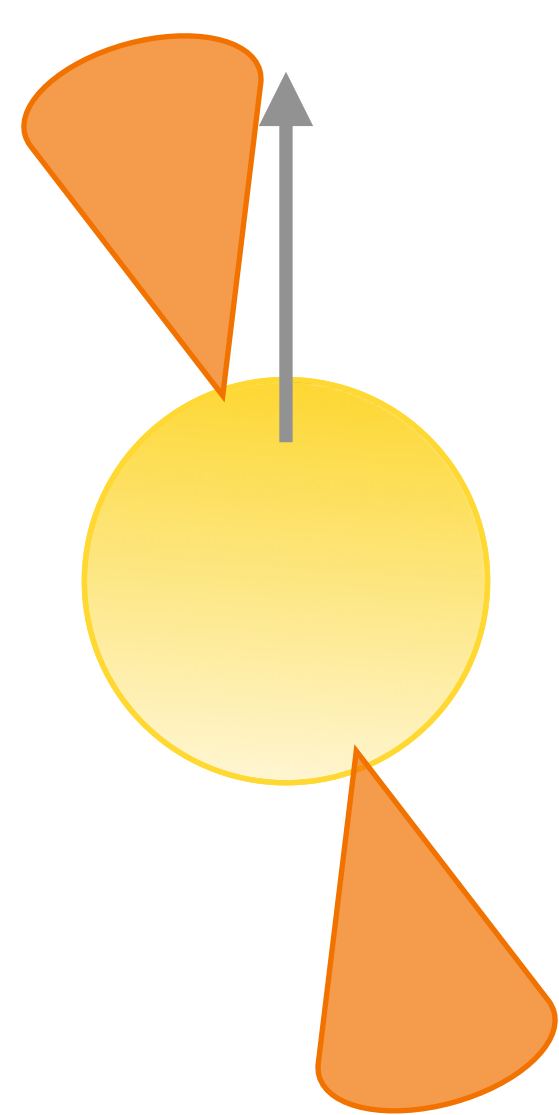
Pulses

Pulses

Gravitational
Waves

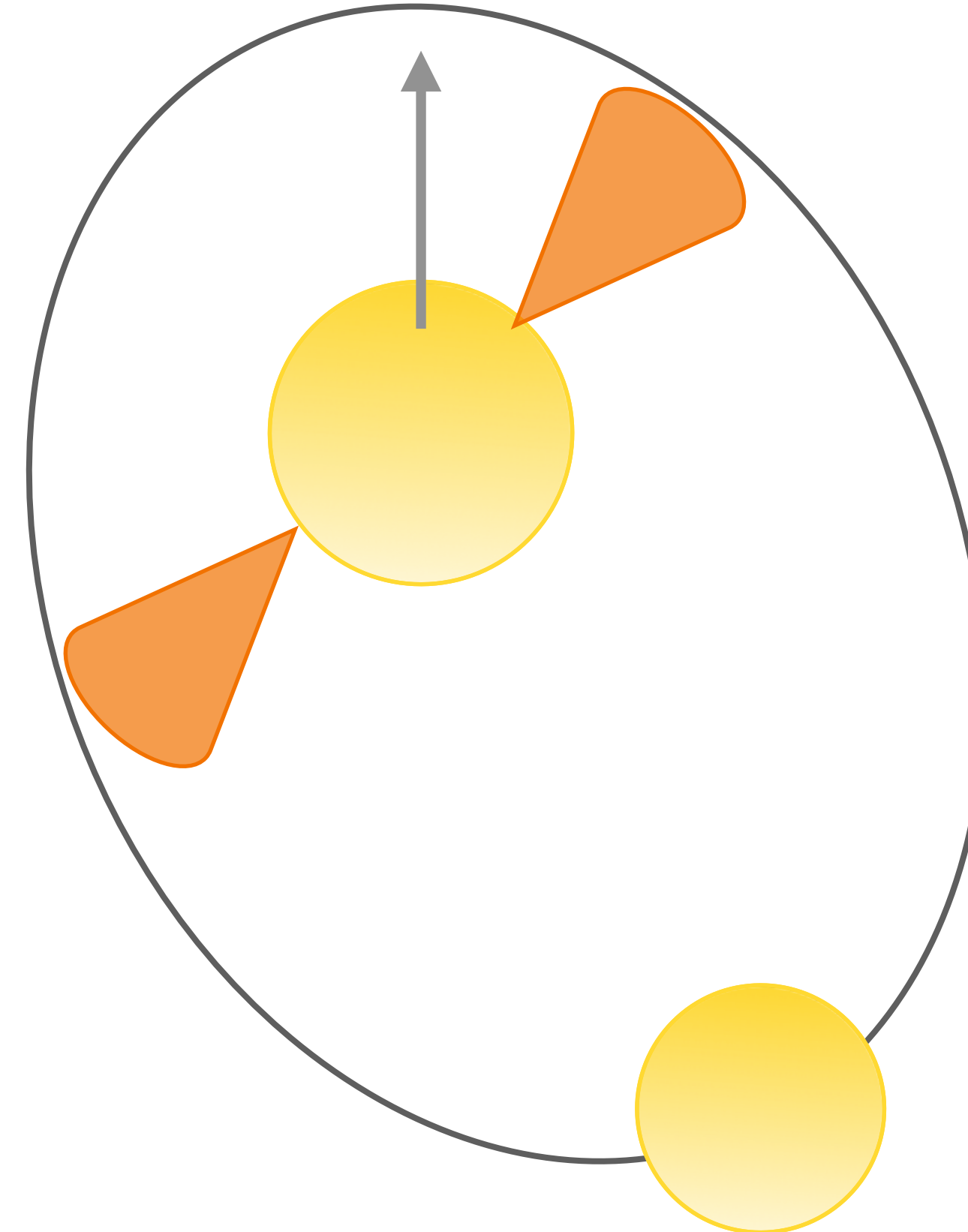


Solar system systematics



Pulses

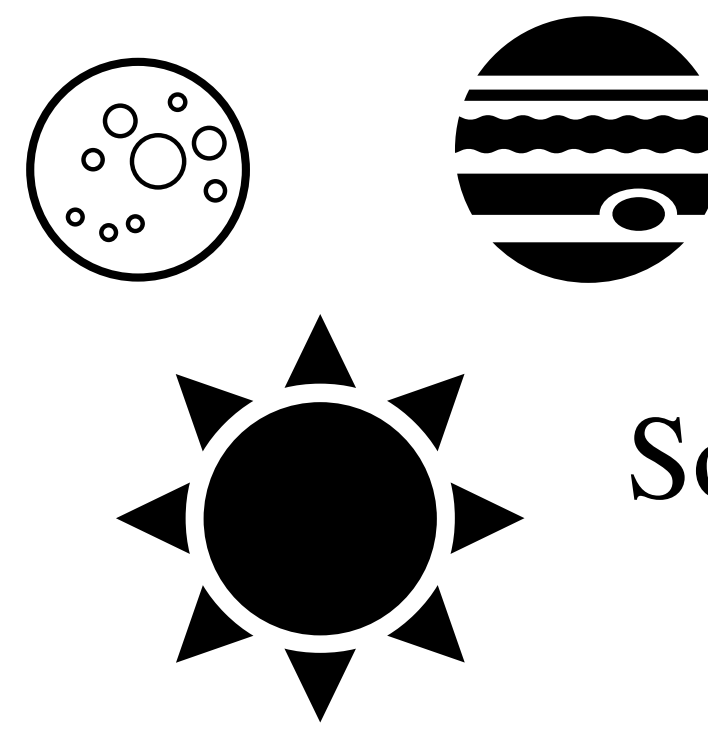
Pulses



Pulsar companion
systematics

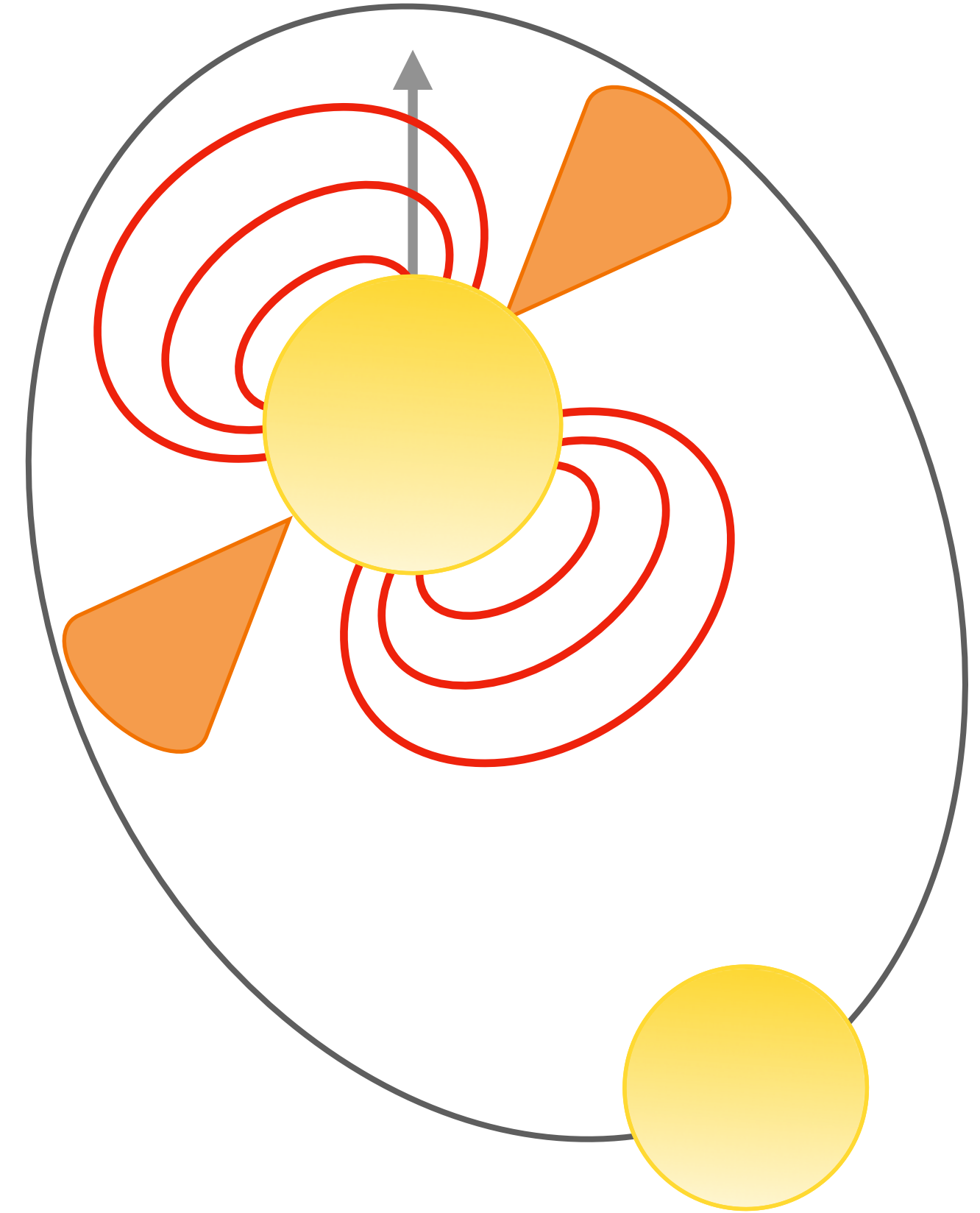


Gravitational
Waves



Solar system systematics

Pulsar red noise
(e . g . magnetosphere fluctuation)

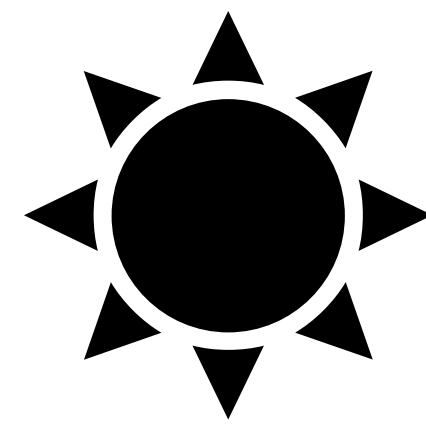
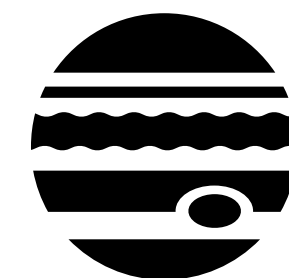
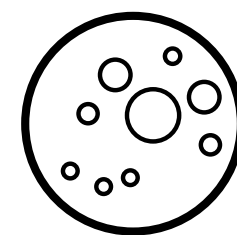


Pulsar companion
systematics

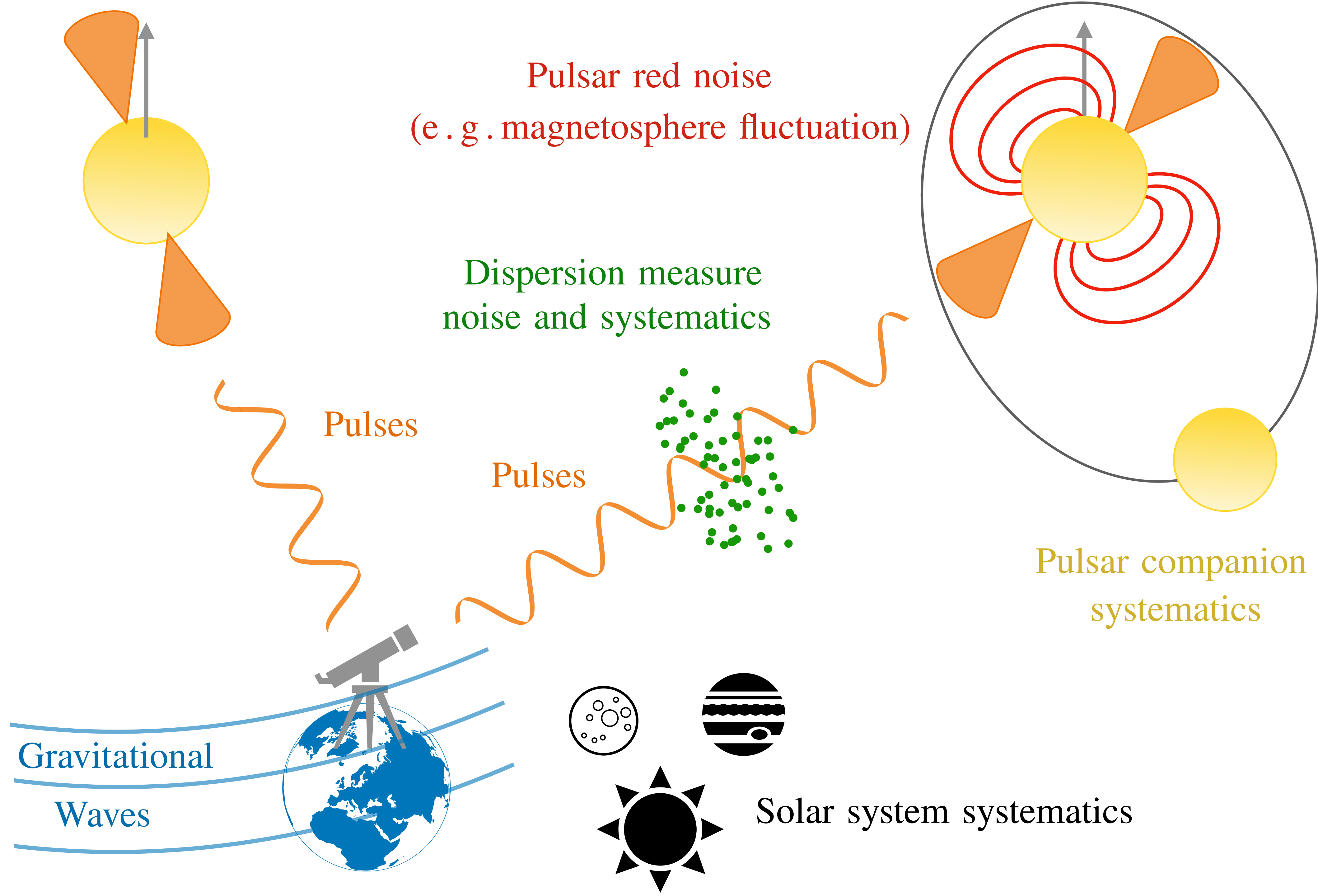
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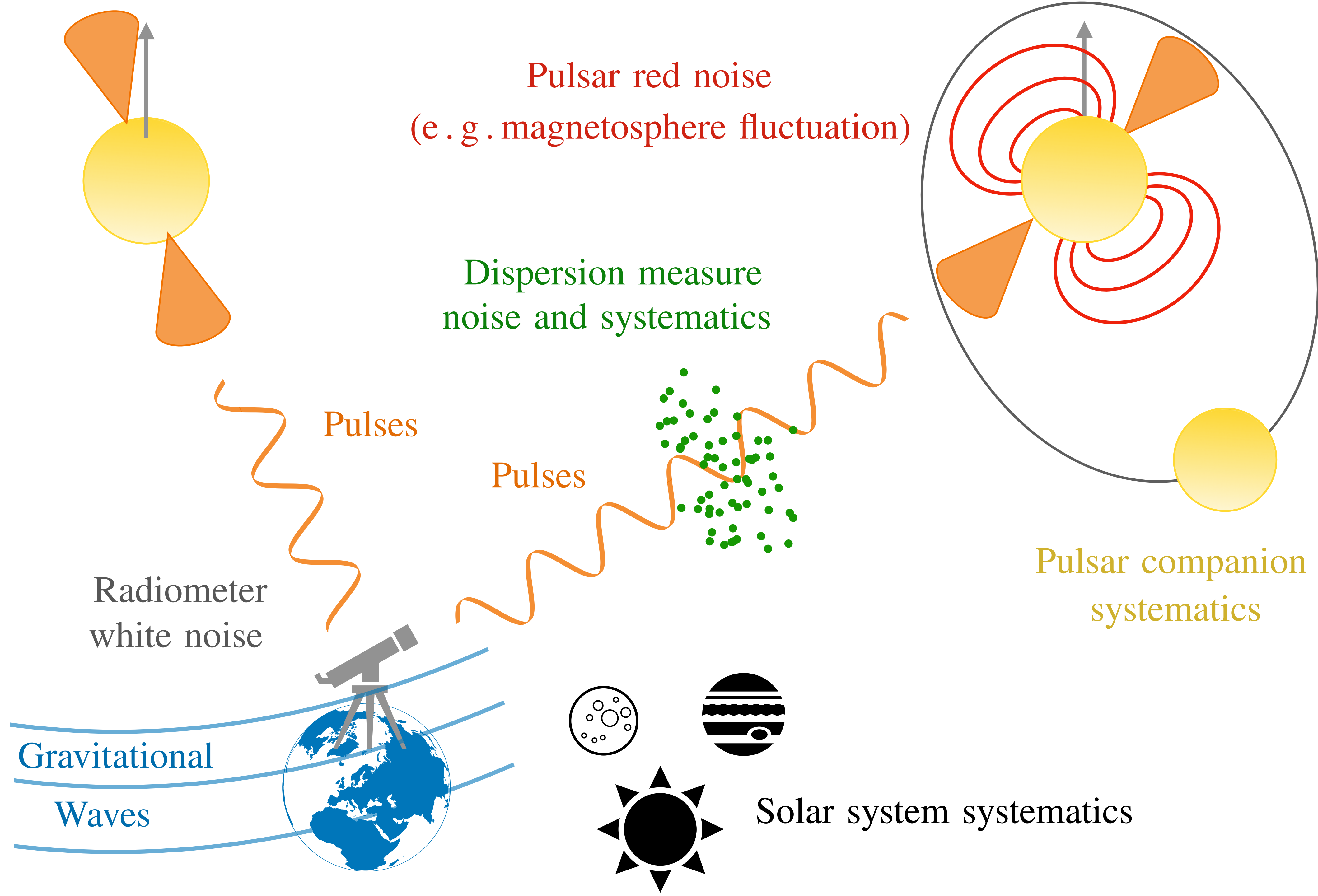
Pulses

Gravitational
Waves

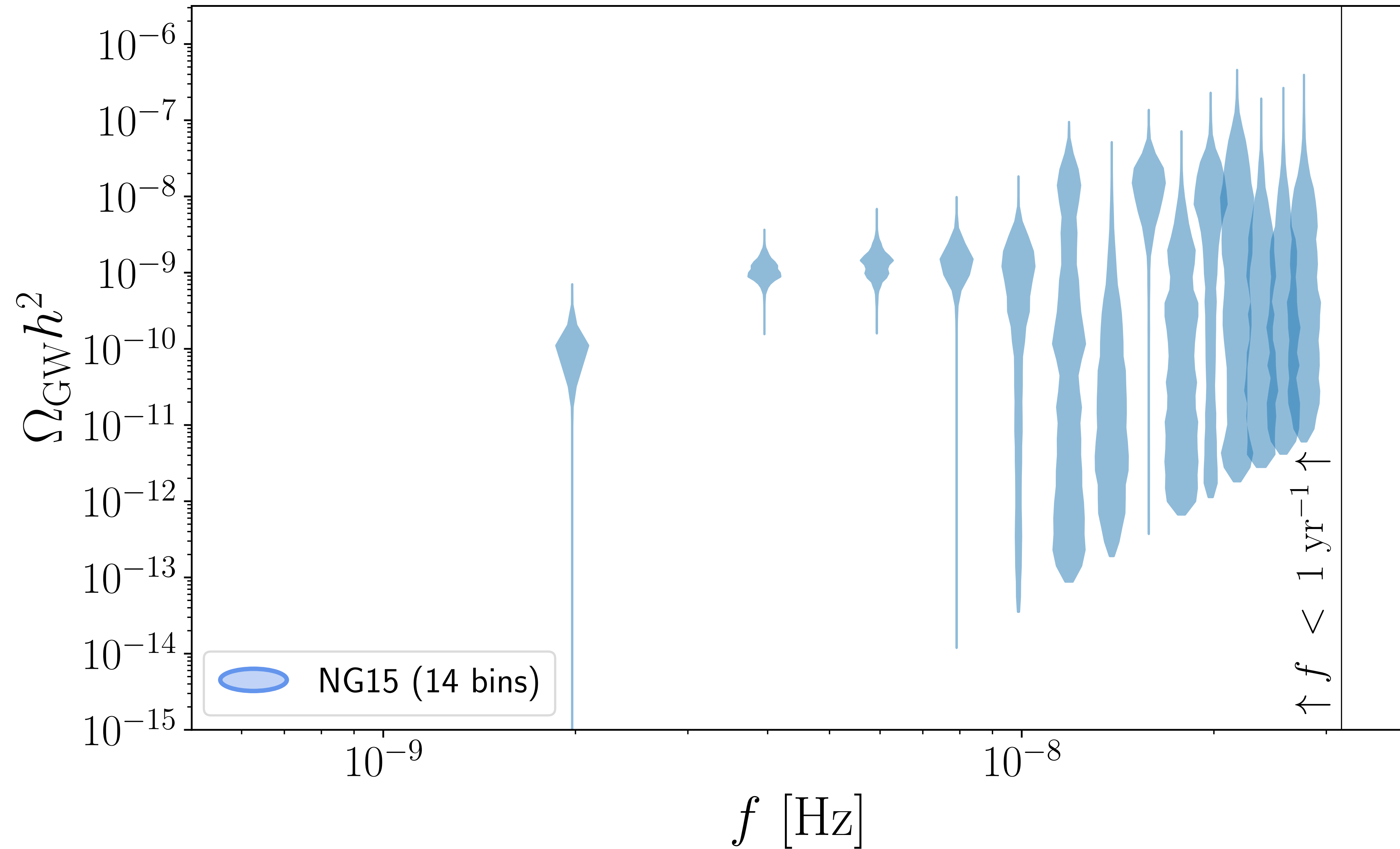


Solar system systematics

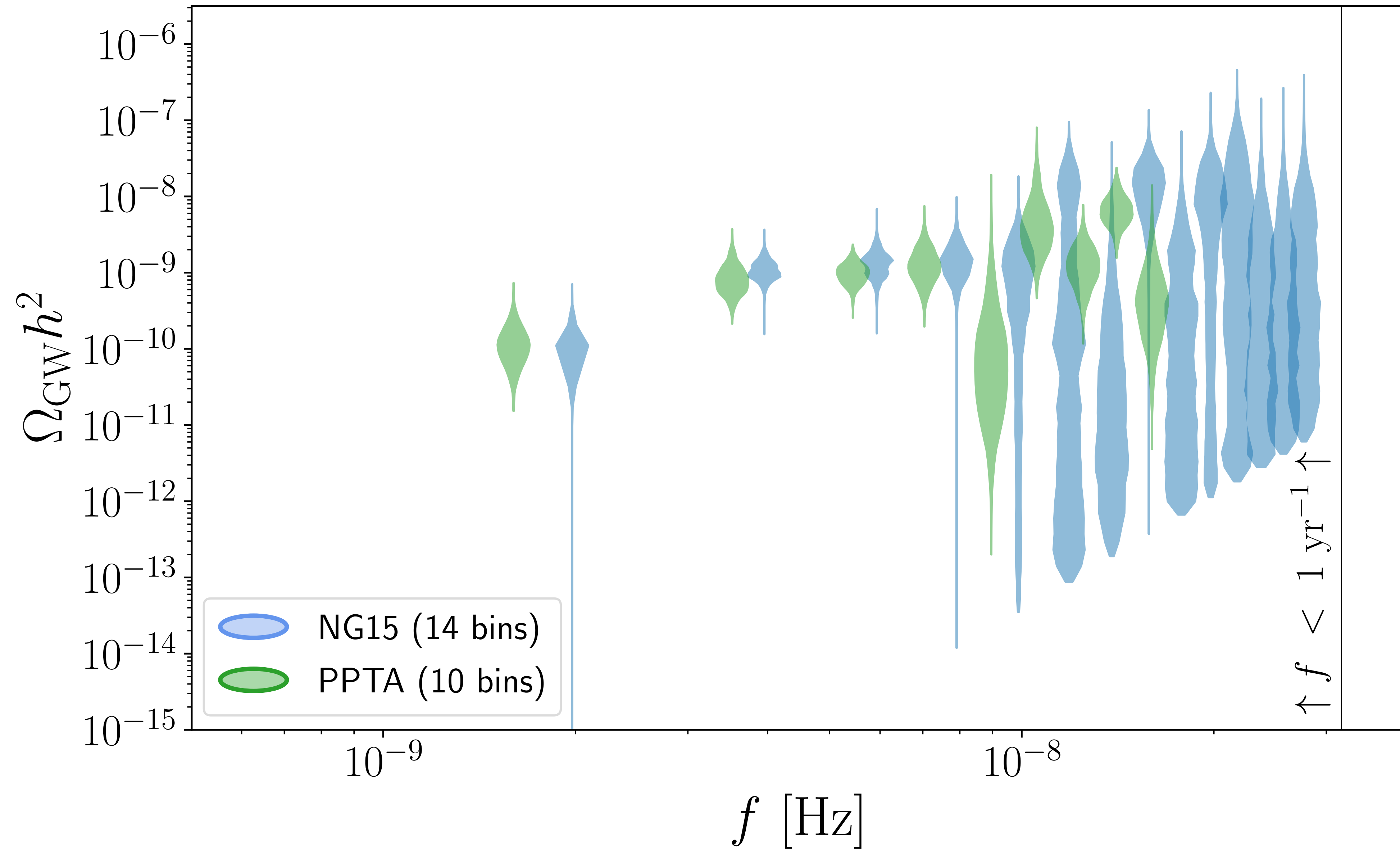




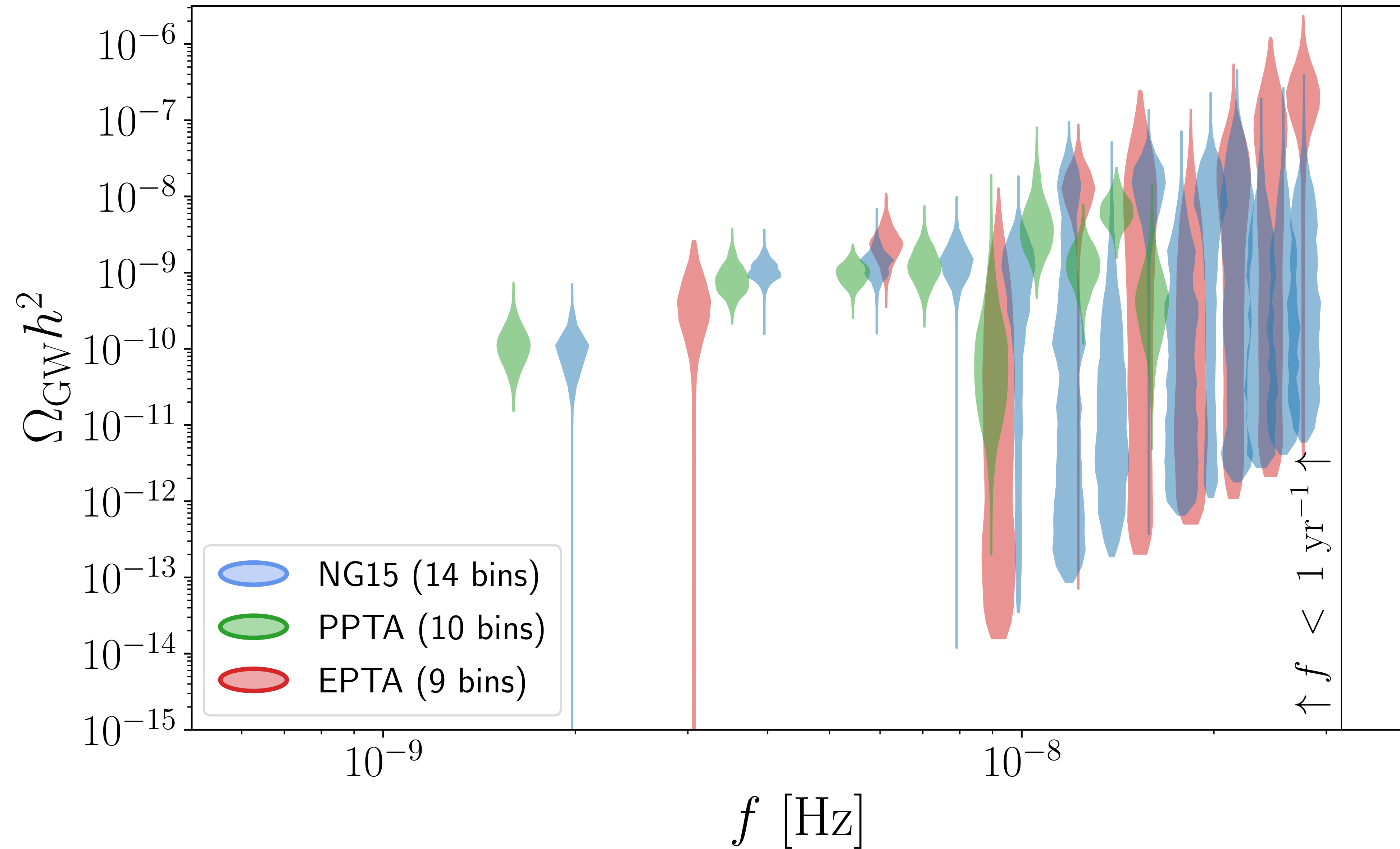
Discovery of the first stochastic GW background by Pulsar Timing Arrays (PTA)



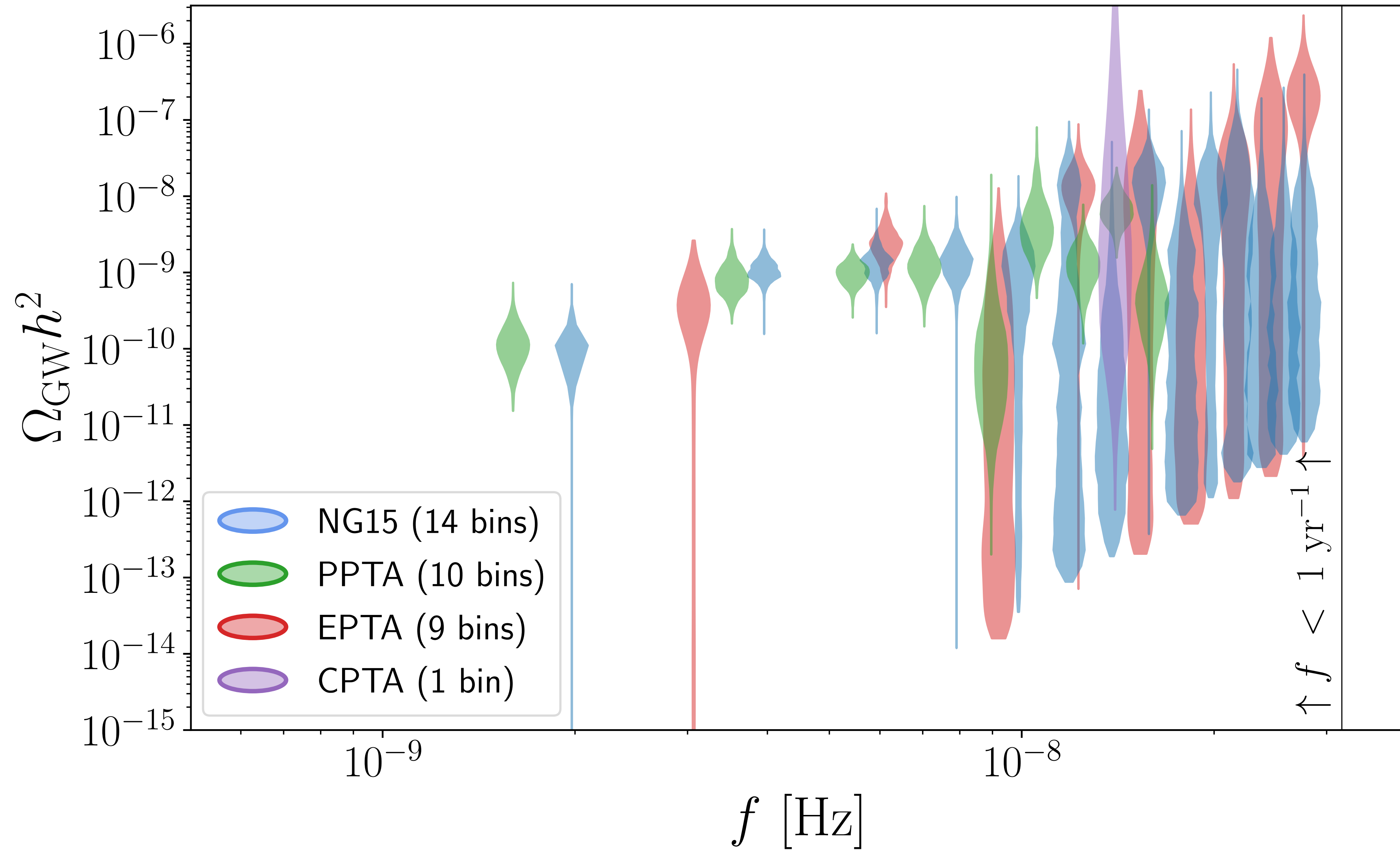
Discovery of the first stochastic GW background by Pulsar Timing Arrays (PTA)



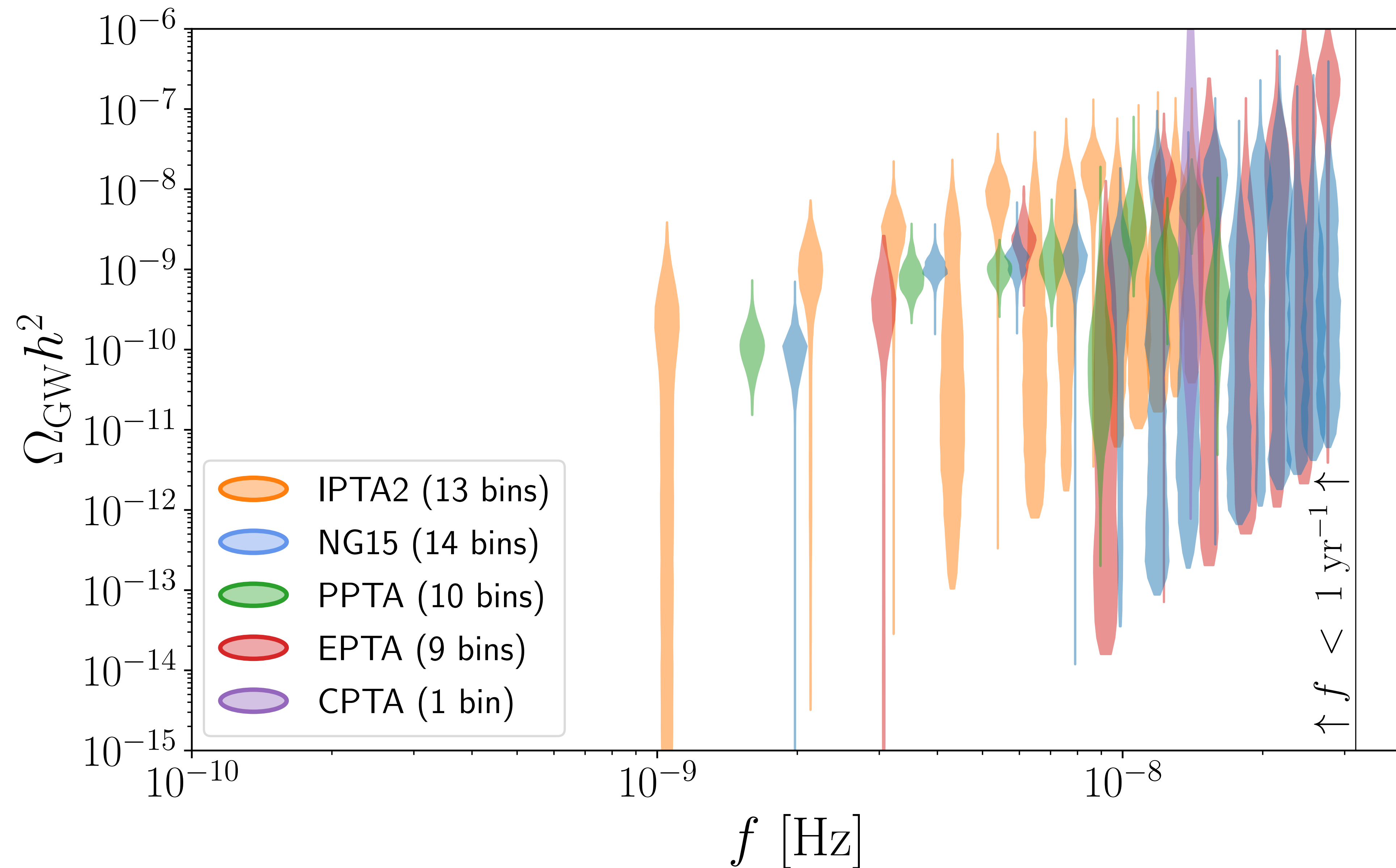
Discovery of the first stochastic GW background by Pulsar Timing Arrays (PTA)



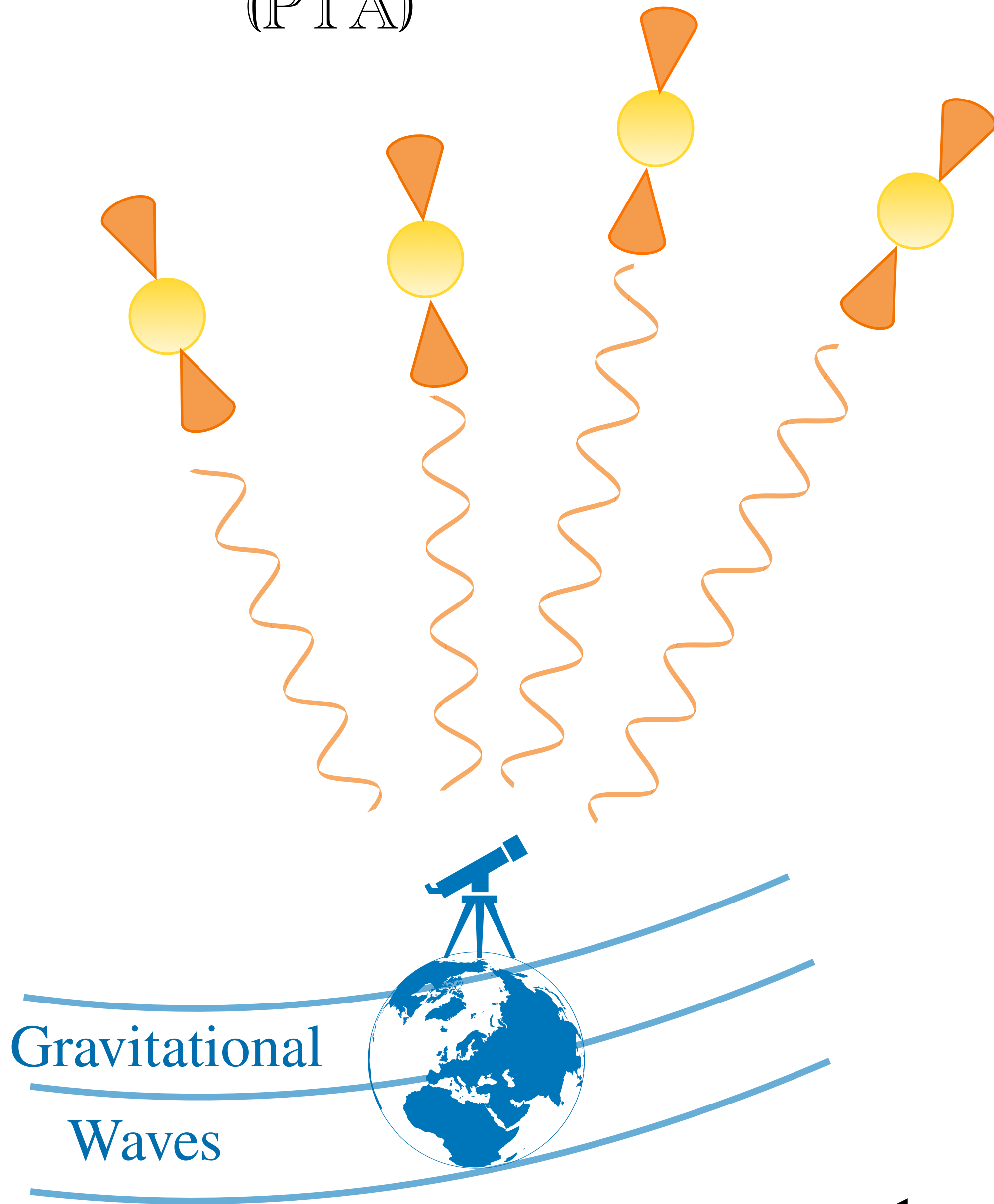
Discovery of the first stochastic GW background by Pulsar Timing Arrays (PTA)



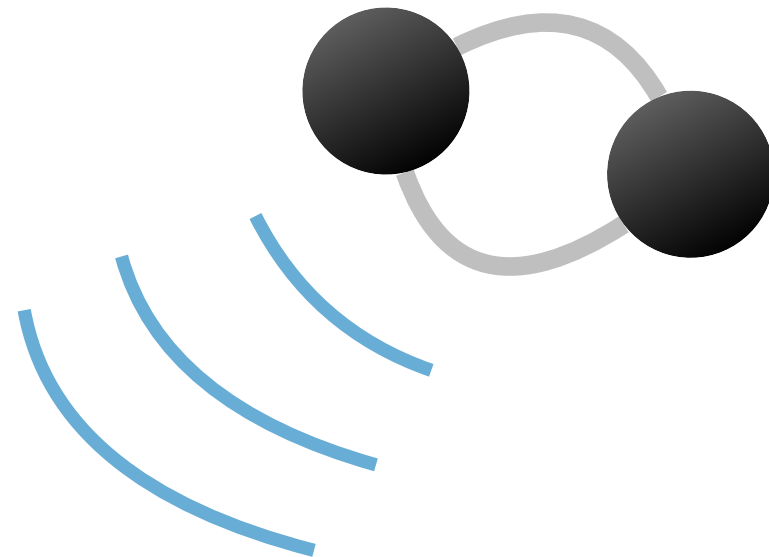
Discovery of the first stochastic GW background by Pulsar Timing Arrays (PTA)



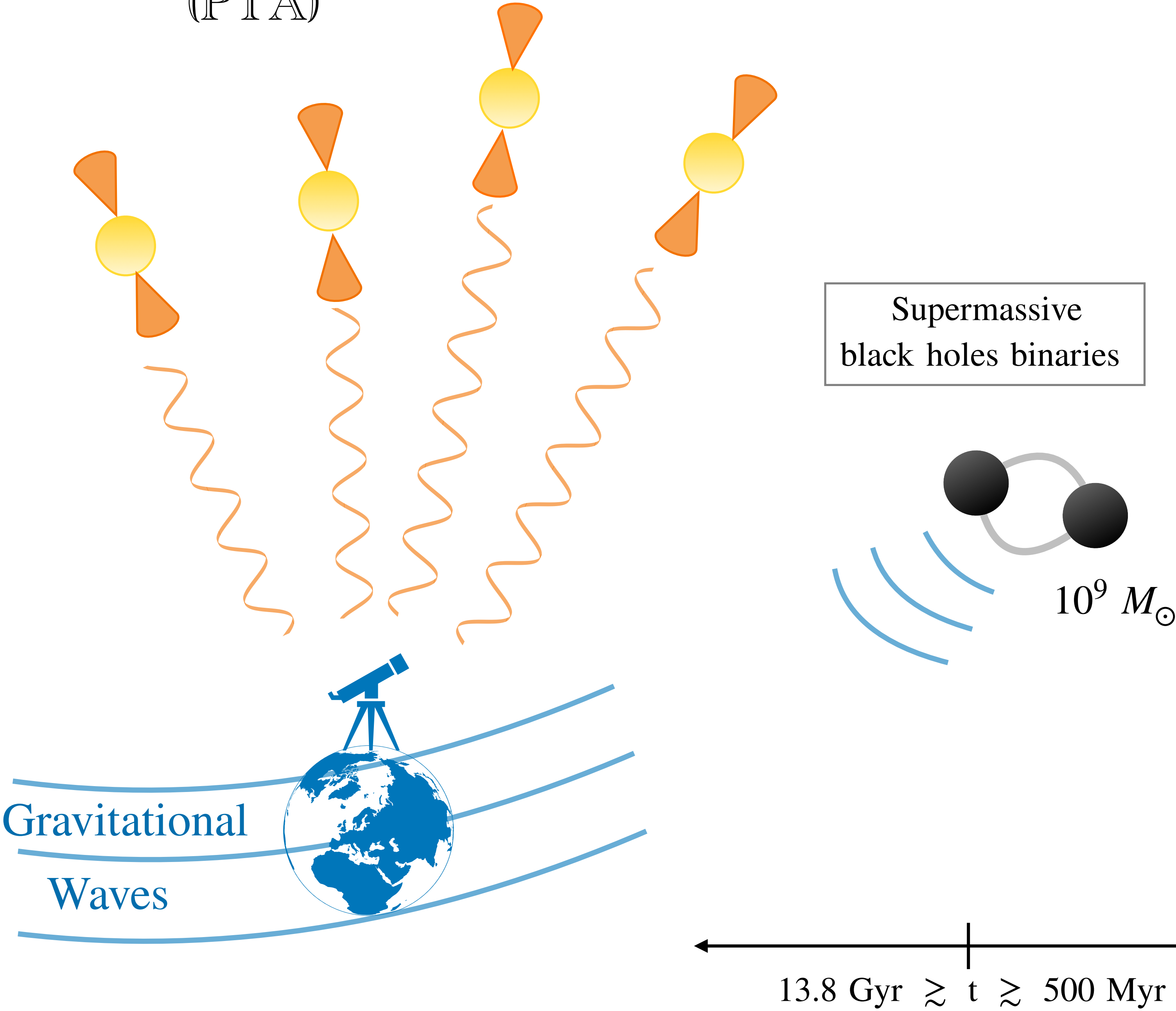
Pulsar Timing Arrays (PTA)



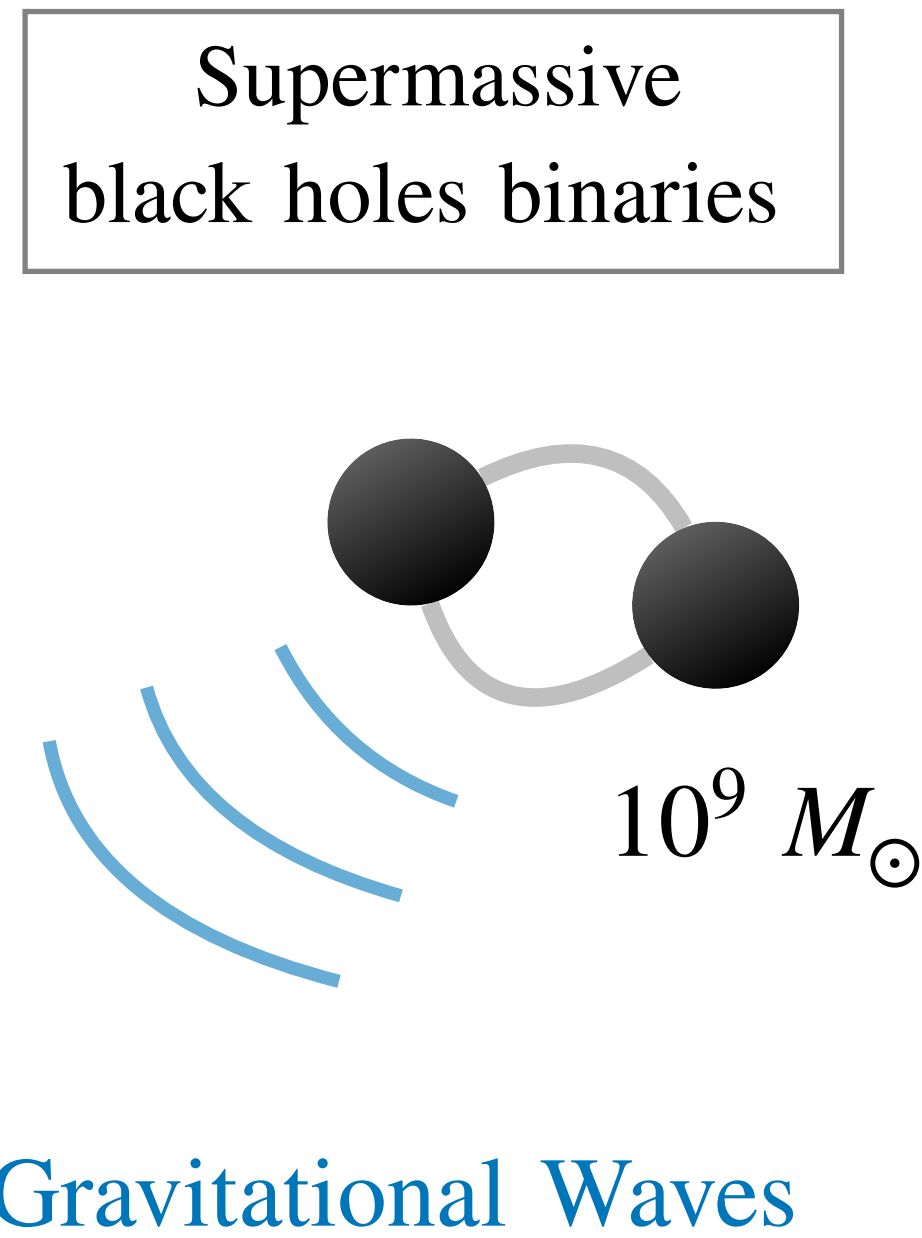
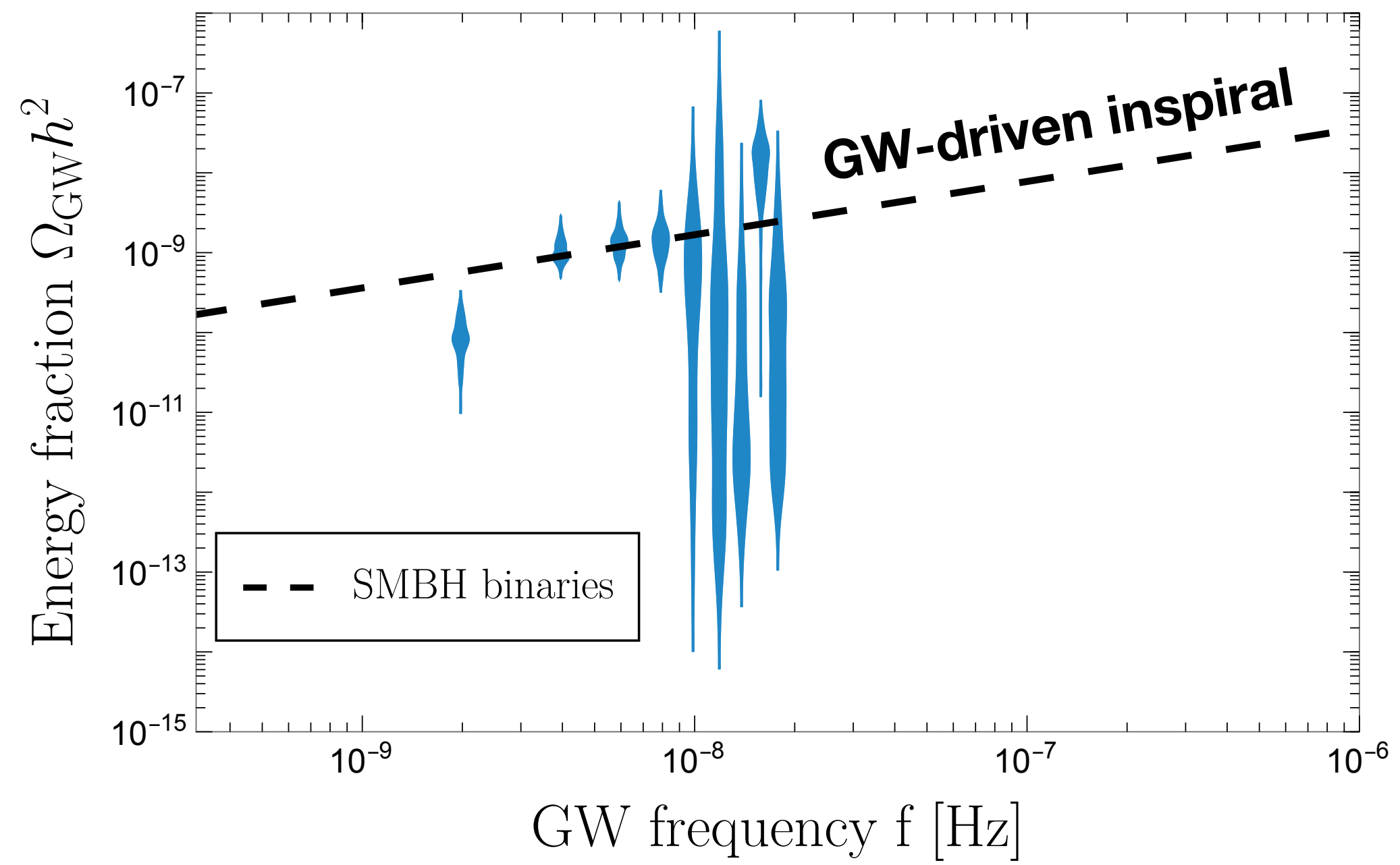
Supermassive
black holes binaries

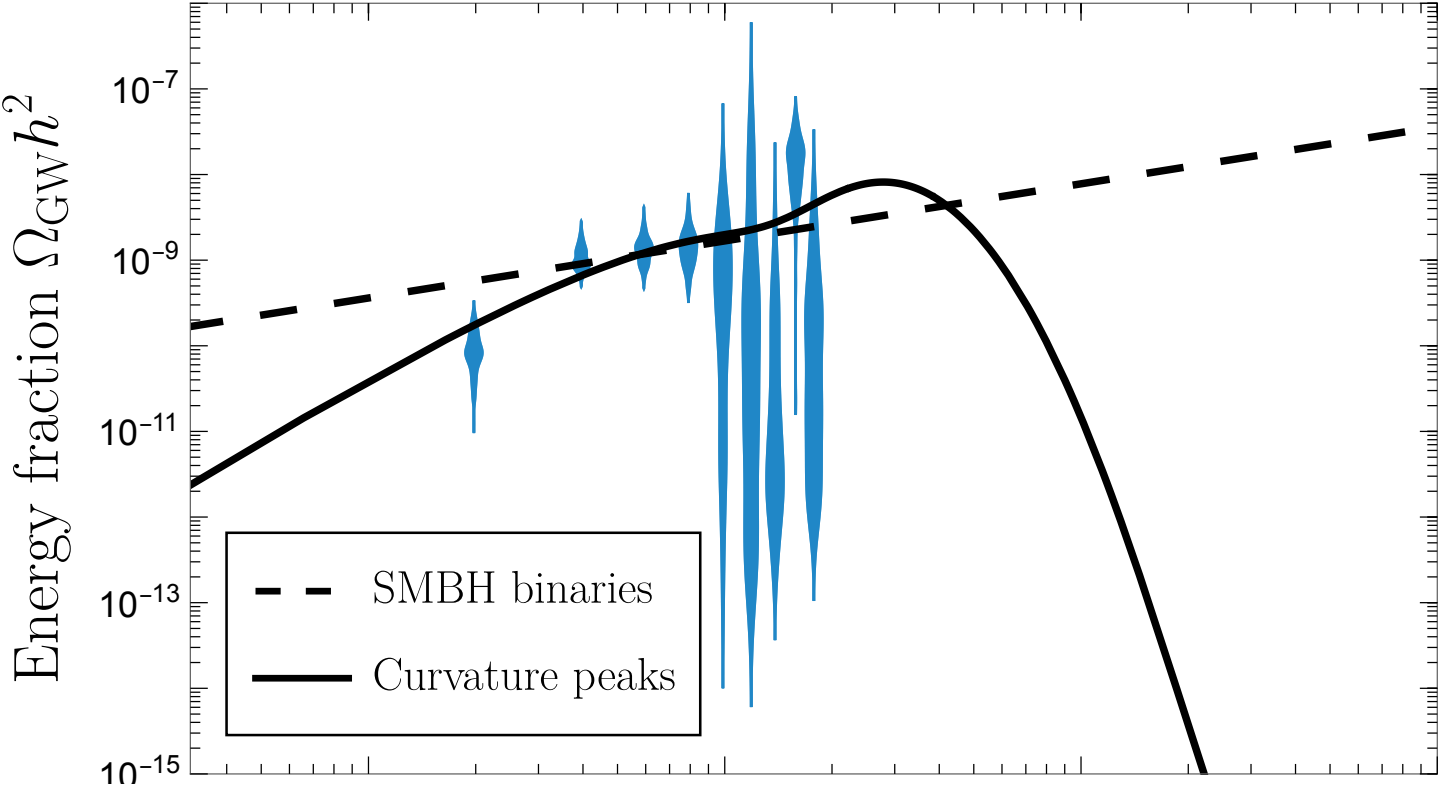


Pulsar Timing Arrays (PTA)



Pulsar Timing Arrays (PTA)



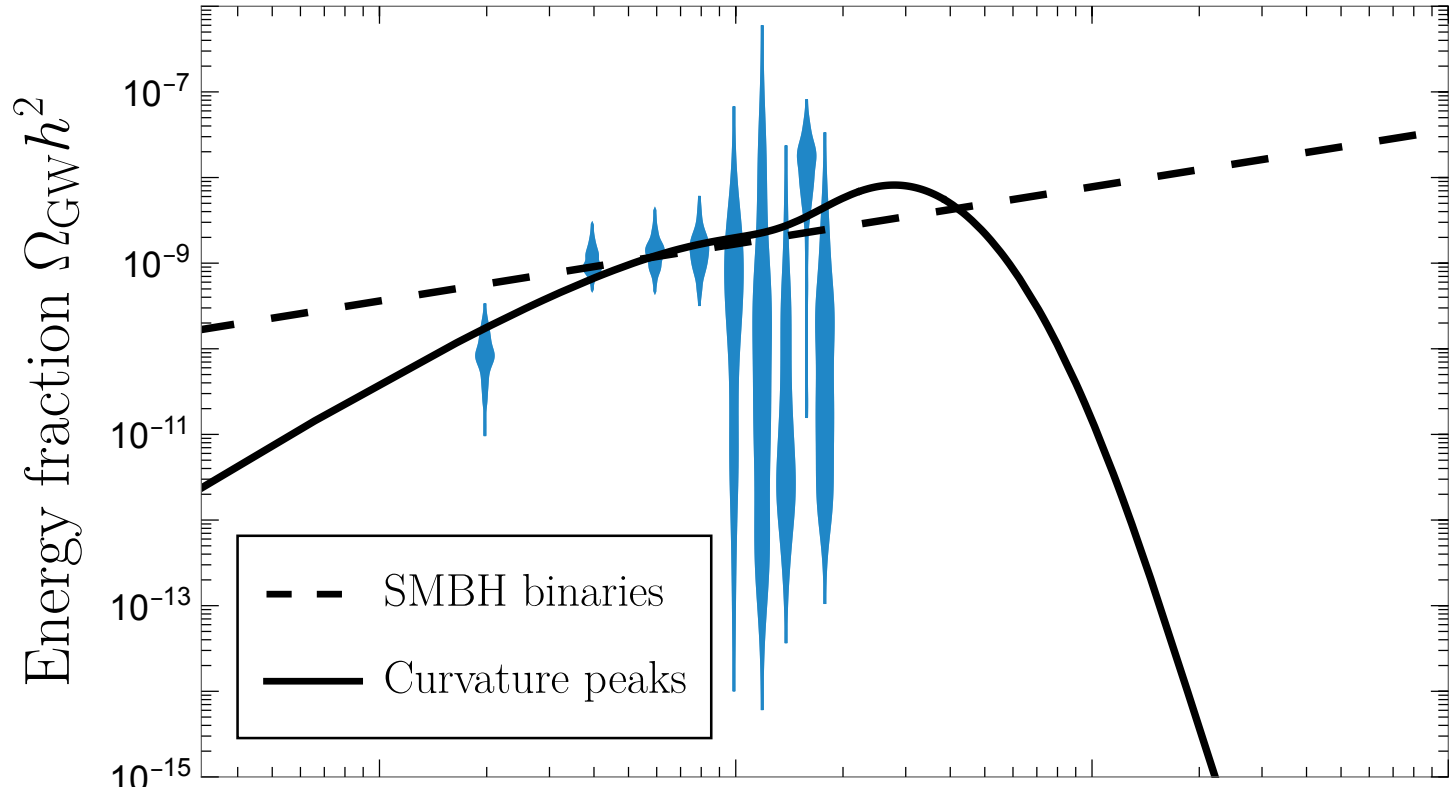


Curvature peaks

***Kohri, Terada (2009.11853)
Vaskonen, Veermäe (2009.07832),
Franciolini, Vaskonen, Vermae (2306.17143)
Cecchini, Franciolini, Pieroni (2503.10805)***

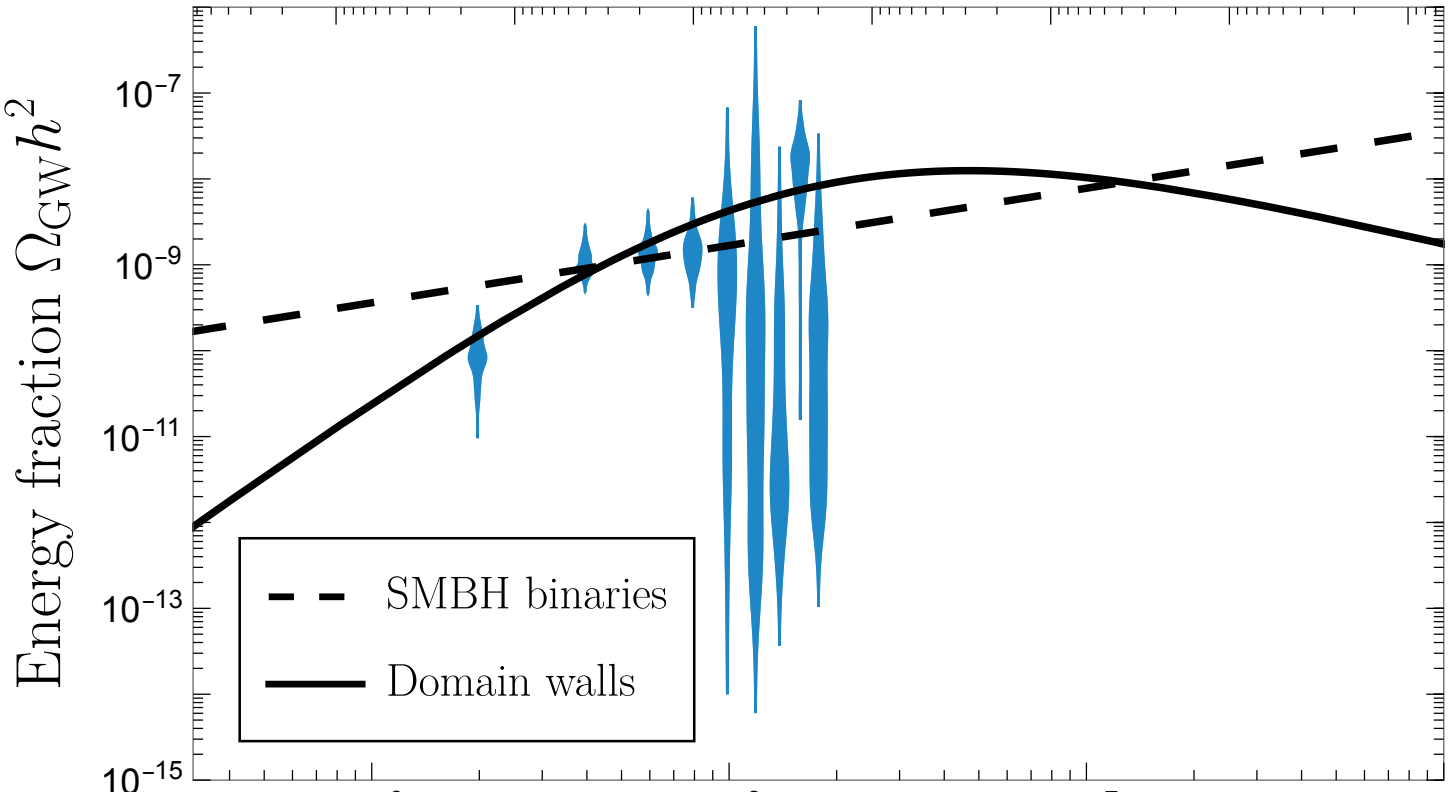
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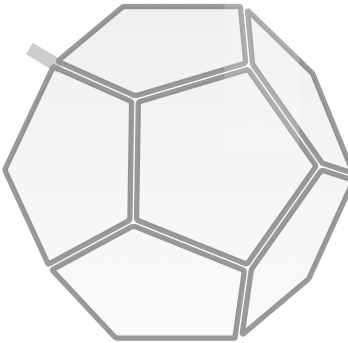
Curvature peaks

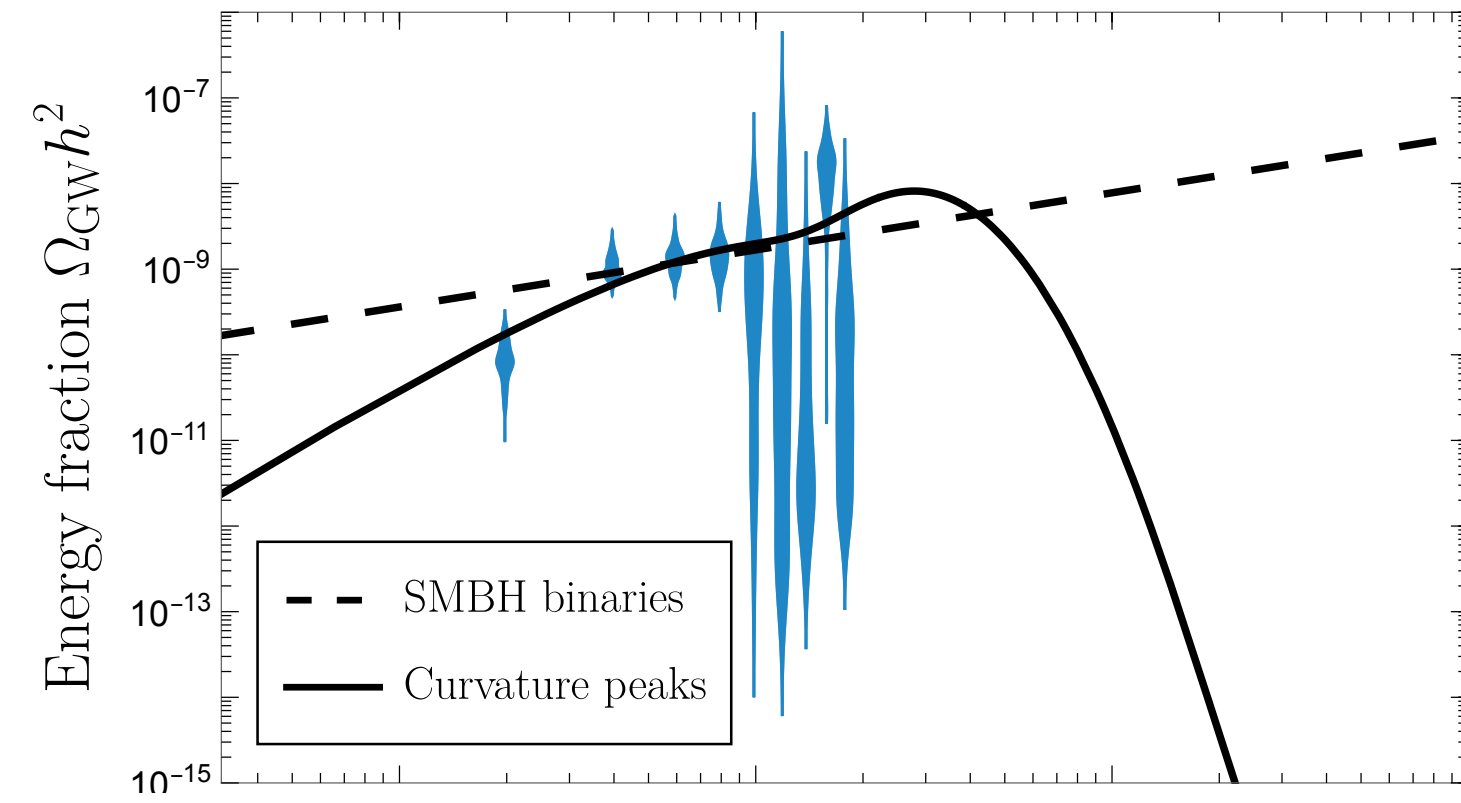
Kohri, Terada (2009.11853)
Vaskonen, Veermäe (2009.07832),
Franciolini, Vaskonen, Vermae (2306.17143)
Cecchini, Franciolini, Pieroni (2503.10805)
...



Domain wall networks

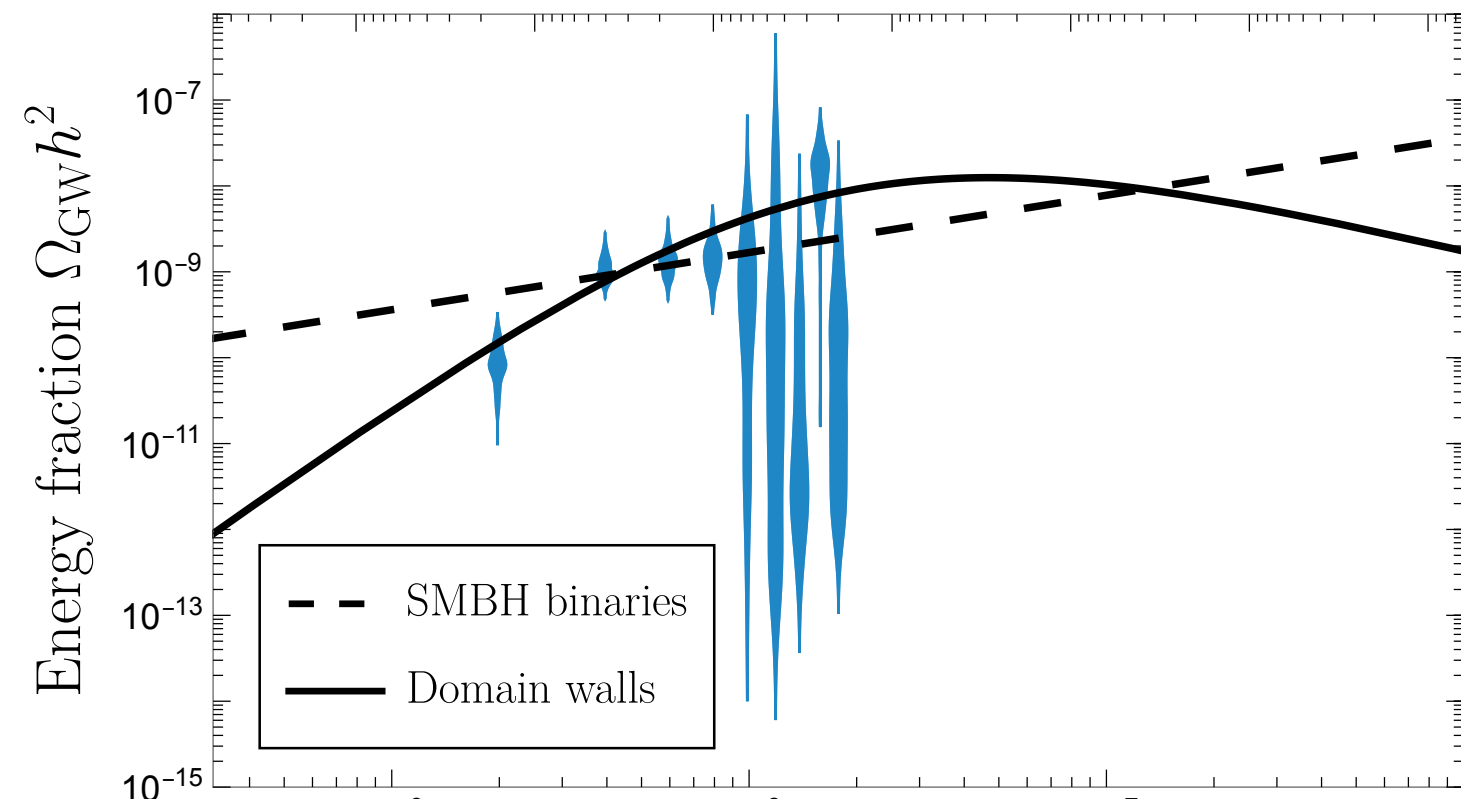
Ferreira, Notari, Pujolas, Rompineve (2204.04228)
Blasi, Mariotti, Rase, Sevrin (2306.17830)
...





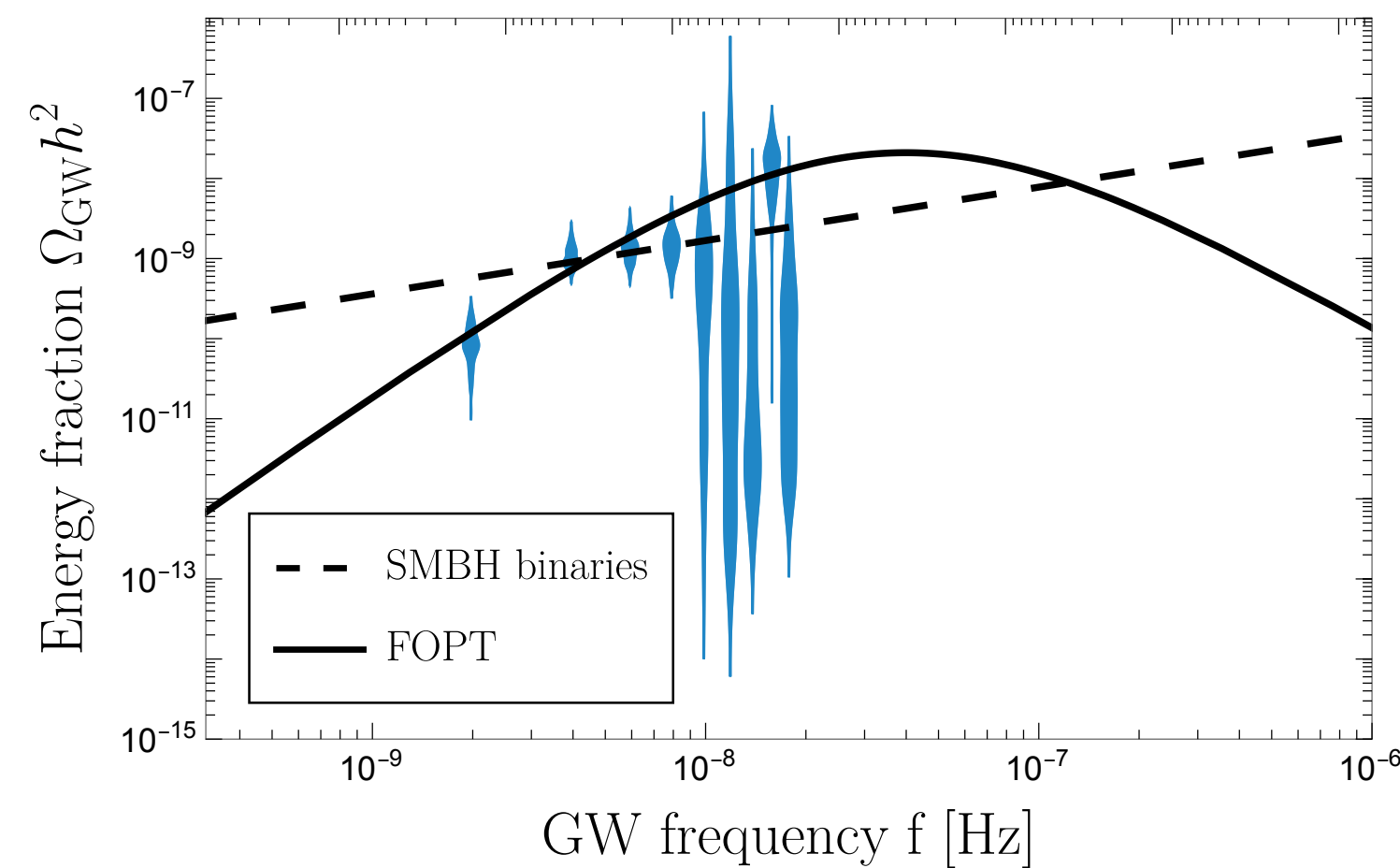
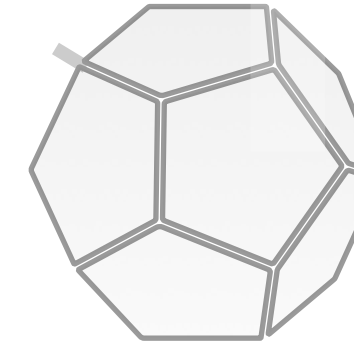
Curvature peaks

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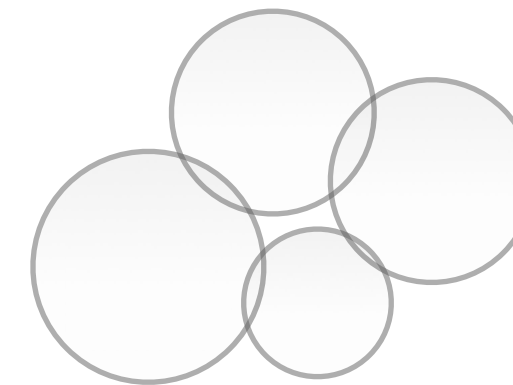
Domain wall networks

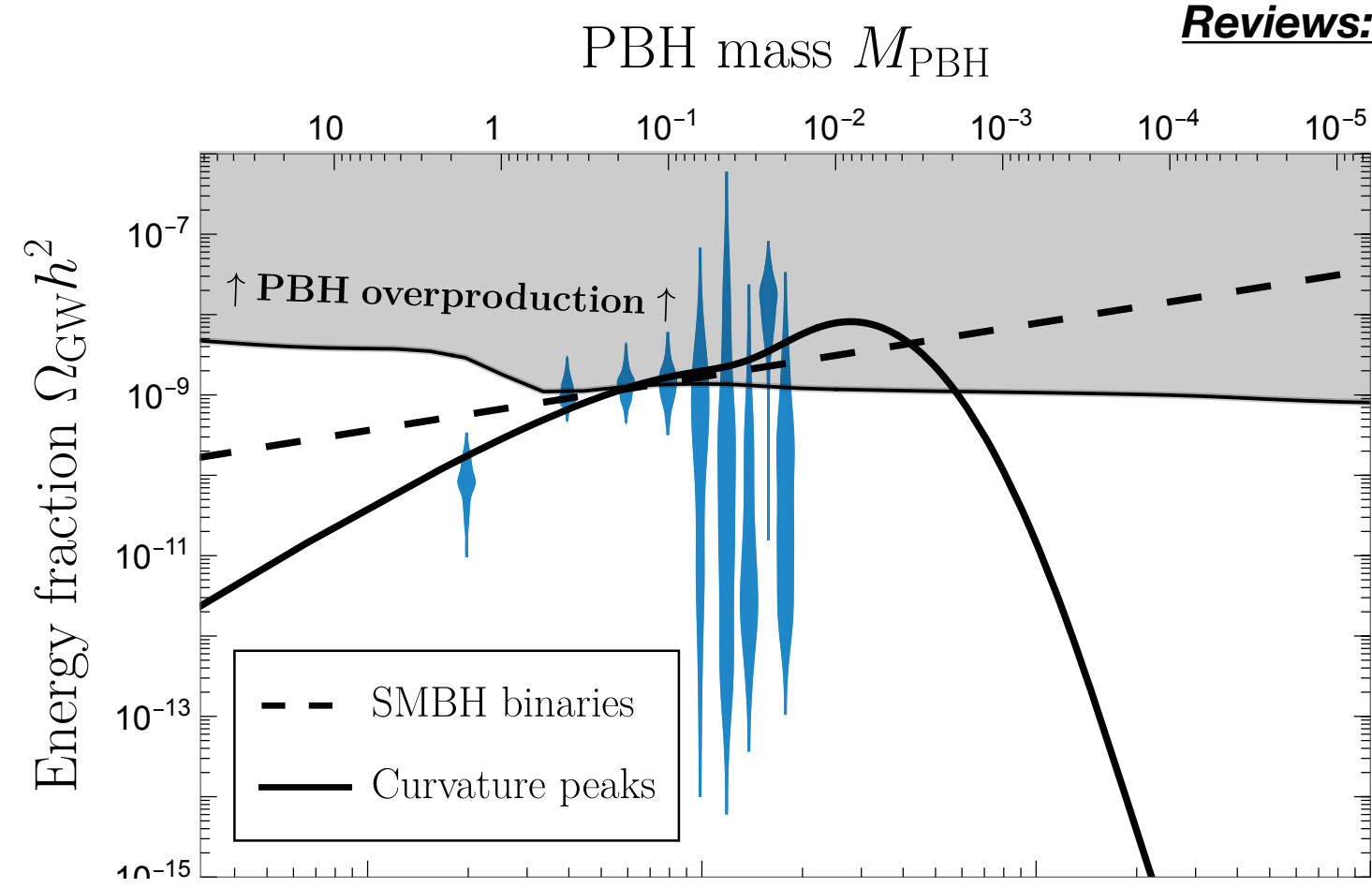
***Ferreira, Notari, Pujolas, Rompineve (2204.04228)
Blasi, Mariotti, Rase, Sevrin (2306.17830)
...***



First-order phase transitions

***Roper Pol et al. (2201.05630)
Ghoshal, White et al. (2307.02259)
YG (2307.04239)
Lewicki, Toczek, Vaskonen (2402.04158)
Hoefken Zink et al. (2501.15649)
...***





Reviews: *Madge, Morgante, Puchades-Ibáñez, Ramberg, Ratzinger, Schenk, Schwaller (2306.14856), Figueroa, Pieroni, Ricciardone, Simakachorn (2307.02399), Lewicki, Vaskonen et al (2308.08546)*

Curvature peaks

Overproduce PBH

Chen, Yuan, Huang (1910.12239)

Kohri, Terada (2009.11853)

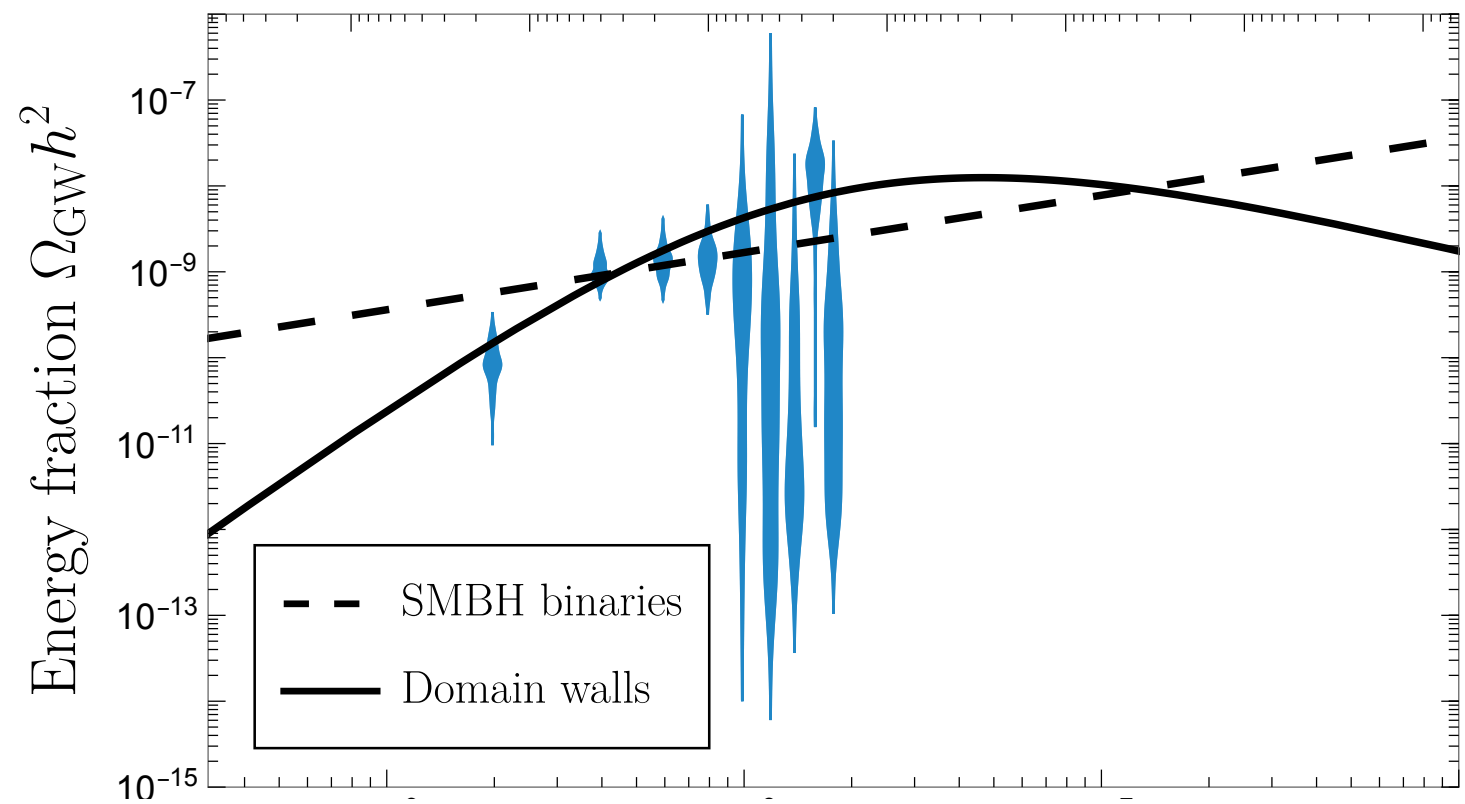
Inomata, Kawasaki, Mukaida, Yanagida (2011.01270)

Vaskonen, Veermäe (2009.07832),

De Luca, Franciolini, Riotto (2009.08268)

Except if negative non-Gaussianities

Franciolini, Vaskonen, Vermae (2306.17143)

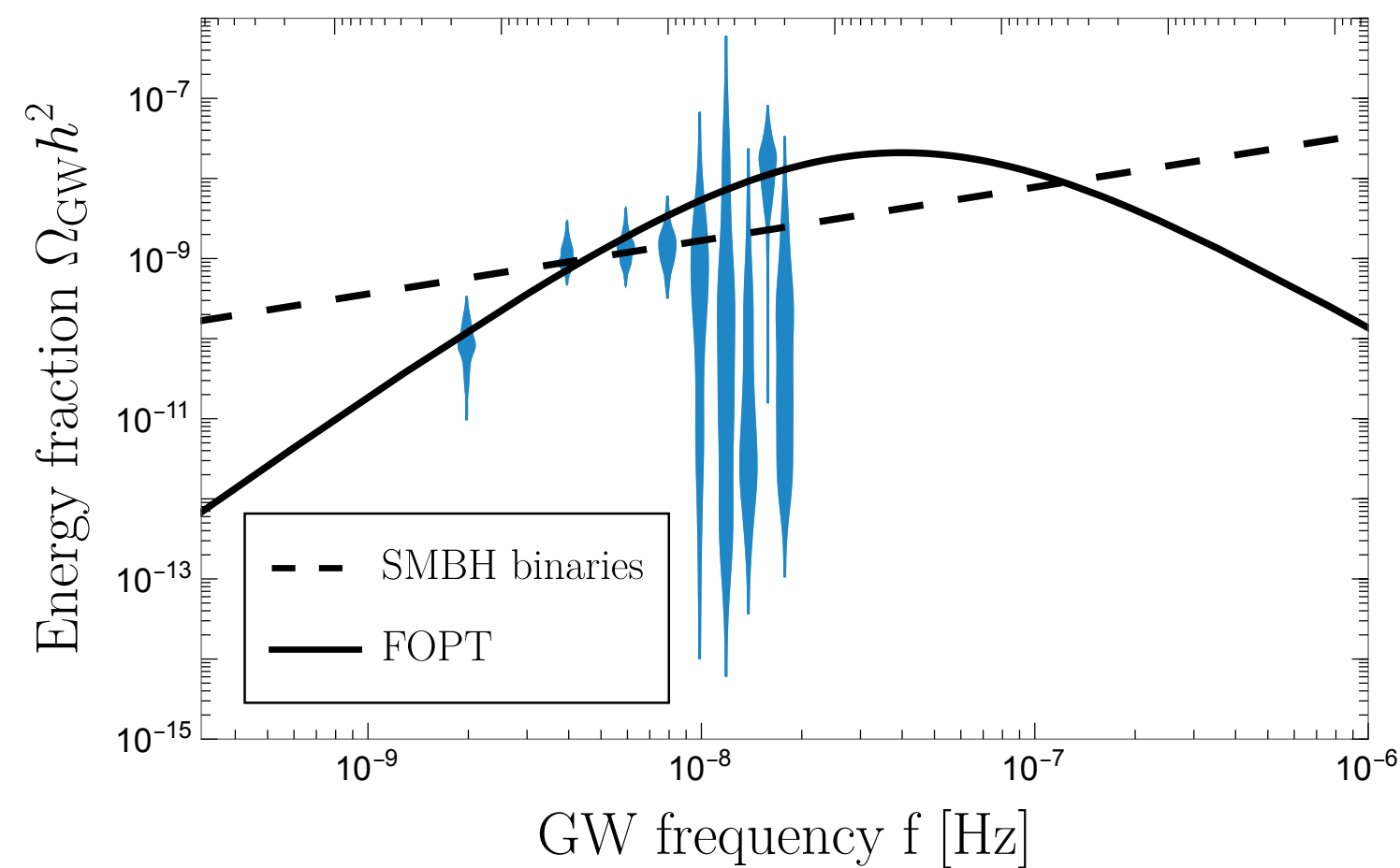
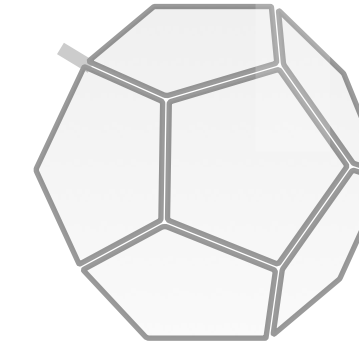


Domain wall networks

Ferreira, Notari, Pujolas, Rompineve (2204.04228)

Blasi, Mariotti, Rase, Sevrin (2306.17830)

...



First-order phase transitions

Roper Pol et al. (2201.05630)

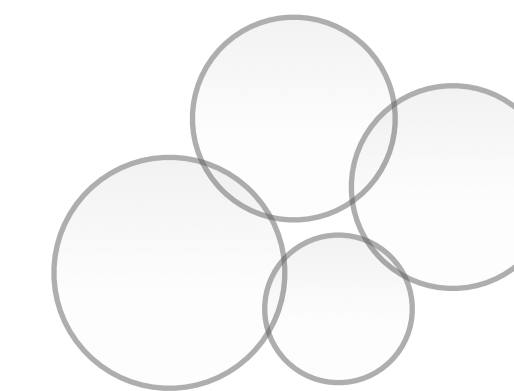
Ghoshal, White et al. (2307.02259)

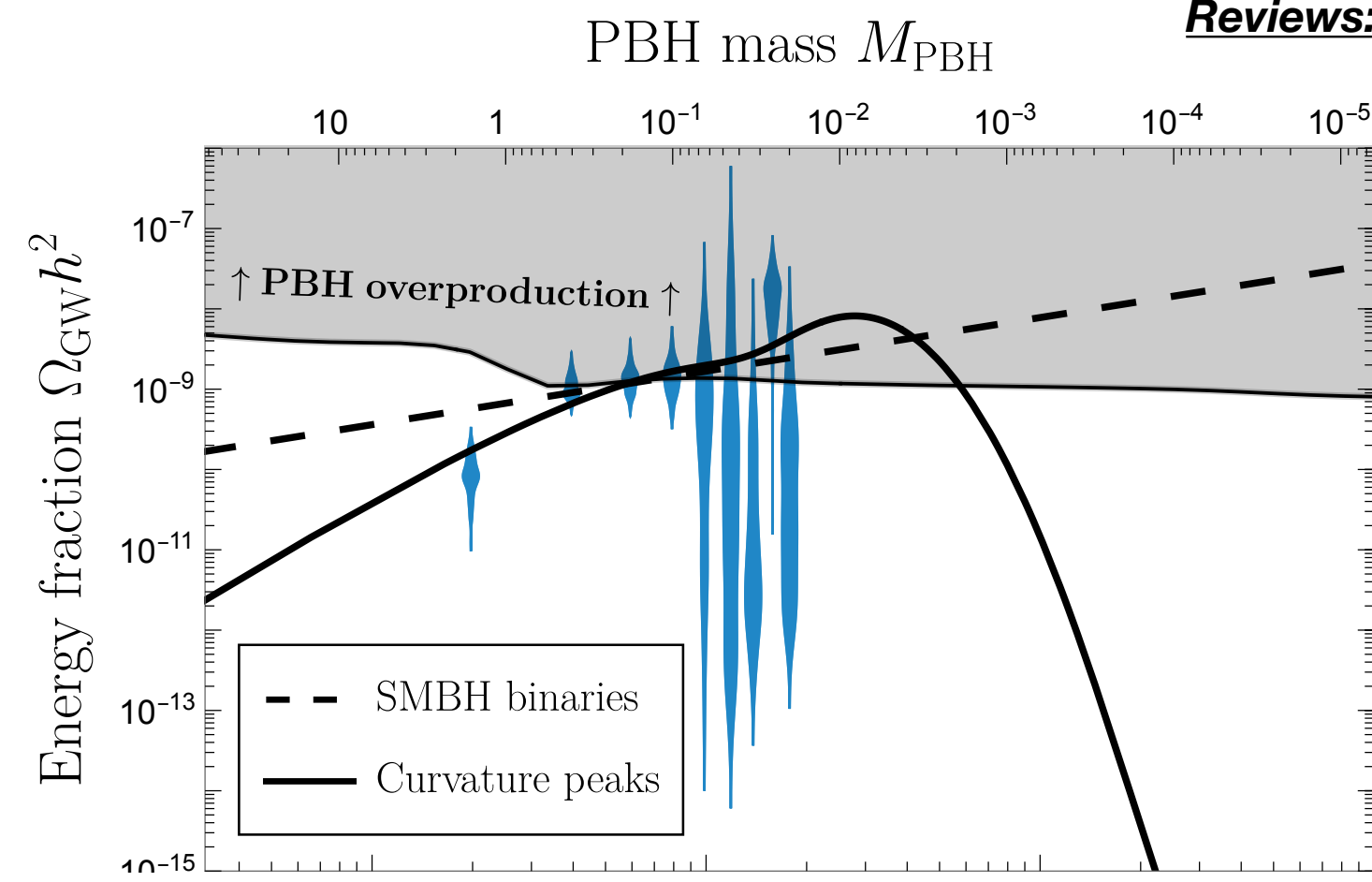
YG (2307.04239)

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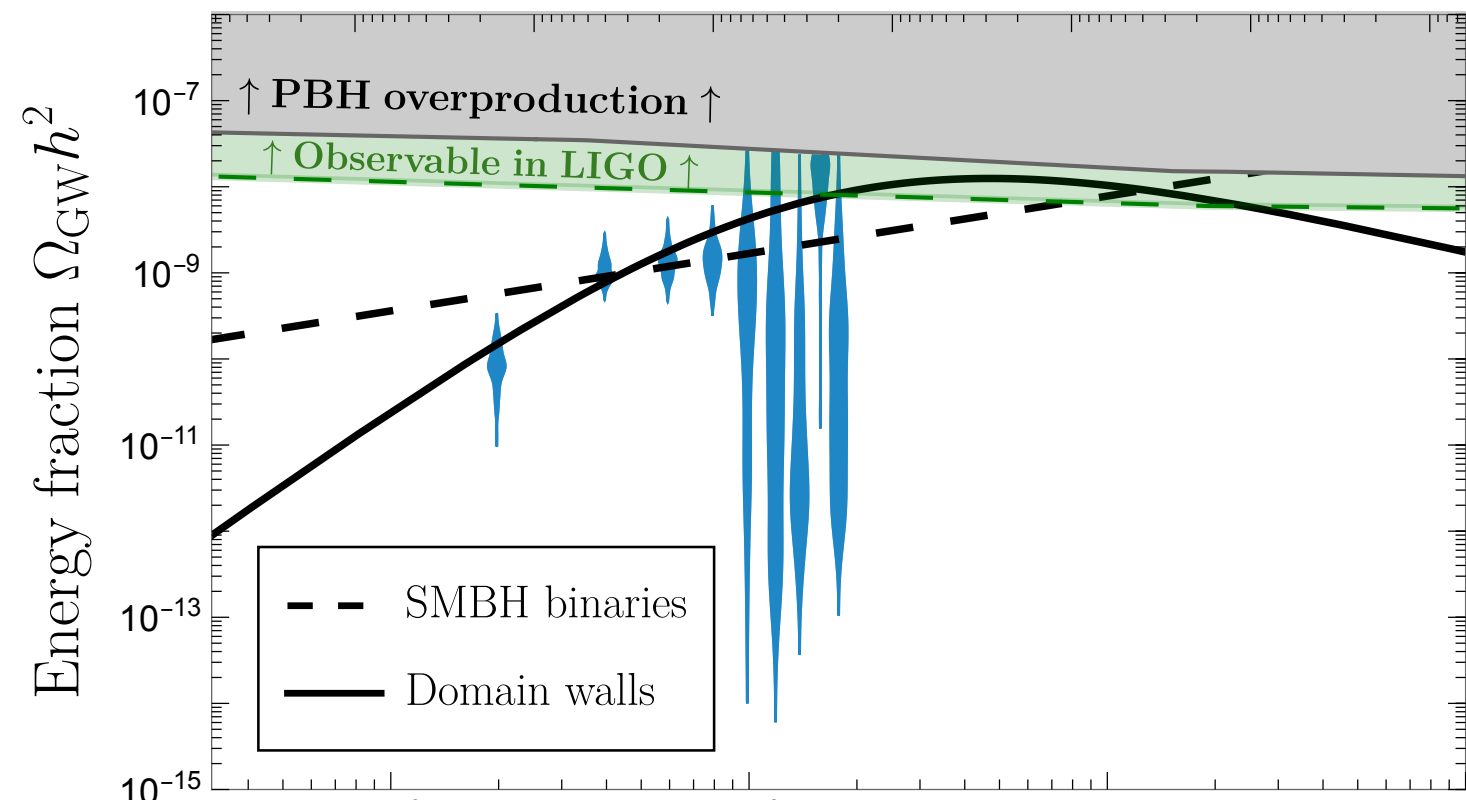
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Domain wall networks

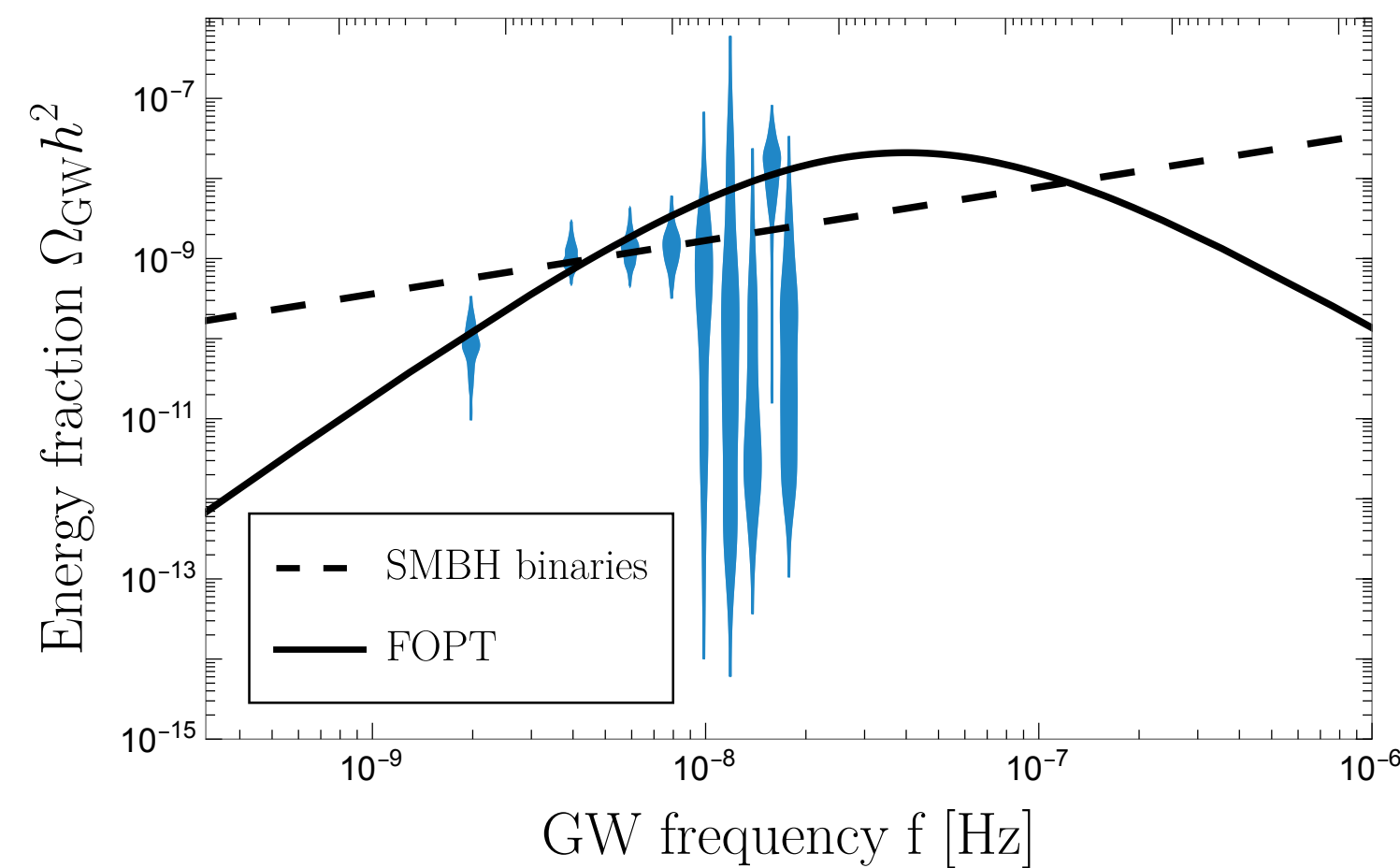
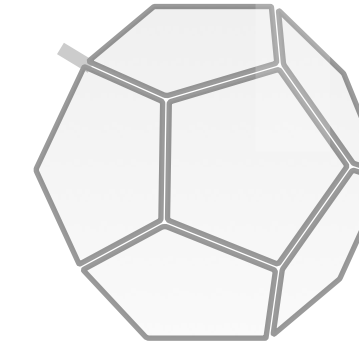
Ferreira, Notari, Pujolas, Rompineve (2204.04228)

Blasi, Mariotti, Rase, Sevrin (2306.17830)

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Produce sub-solar-mass PBH

YG, Vitagliano 2306.17841



First-order phase transitions

Roper Pol et al. (2201.05630)

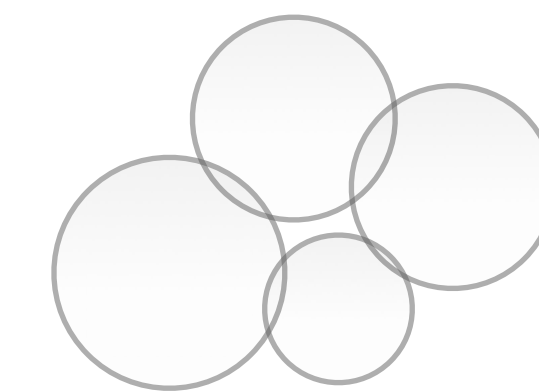
Ghoshal, White et al. (2307.02259)

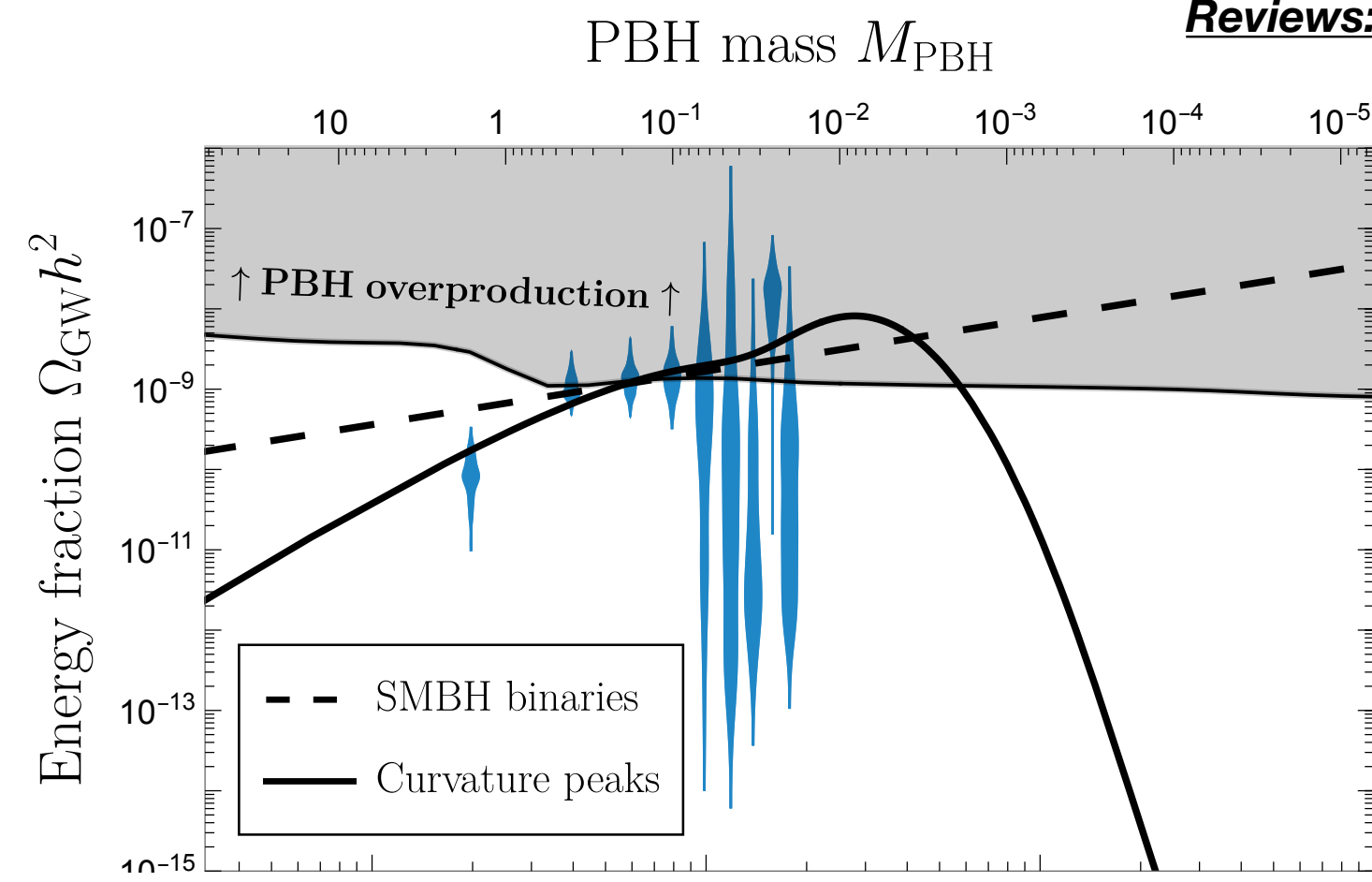
YG (2307.04239)

Lewicki, Toczek, Vaskonen (2402.04158)

Hoefken Zink et al. (2501.15649)

...





Curvature peaks

Overproduce PBH

Chen, Yuan, Huang (1910.12239)

Kohri, Terada (2009.11853)

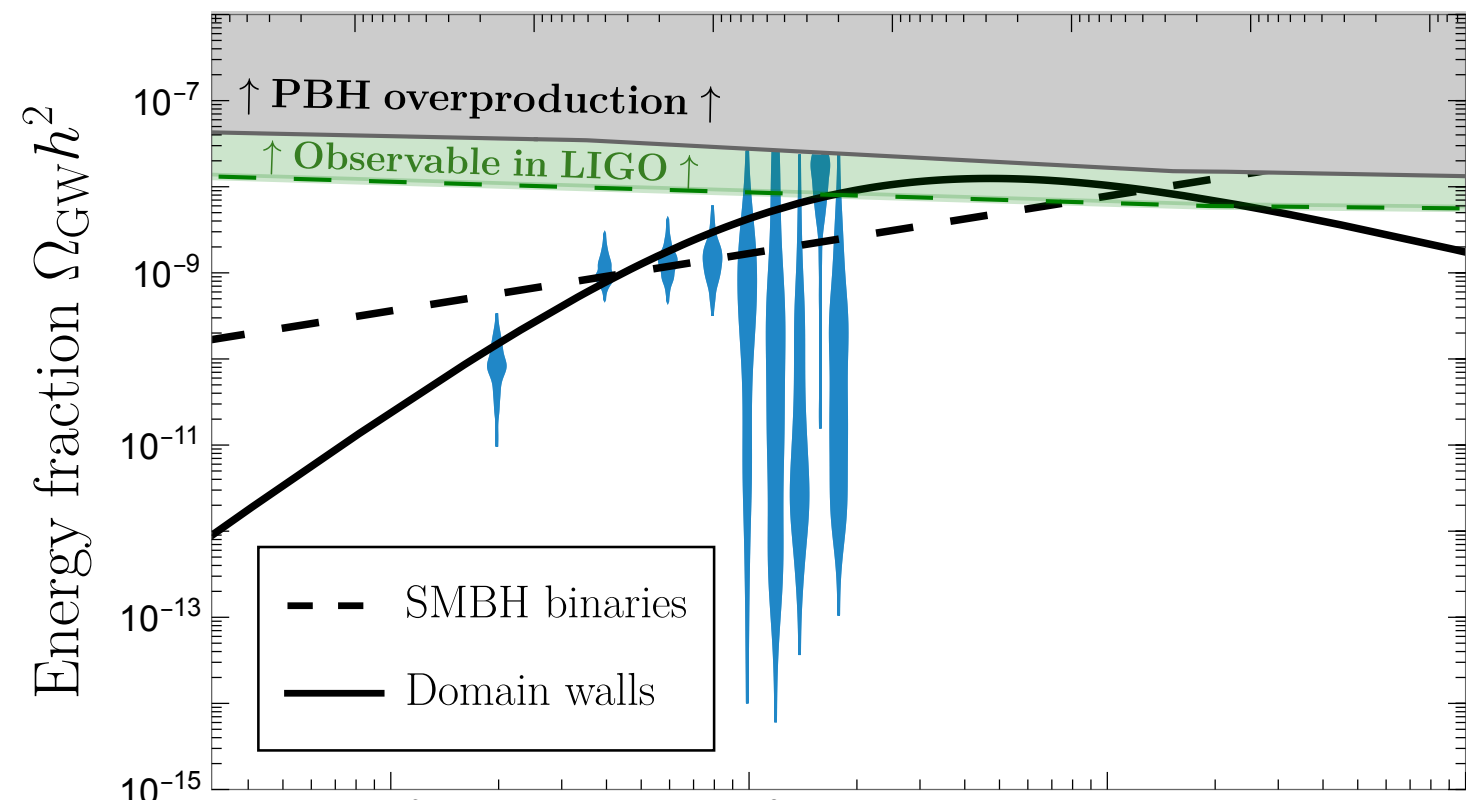
Inomata, Kawasaki, Mukaida, Yanagida (2011.01270)

Vaskonen, Veermae (2009.07832)

De Luca, Franciolini, Riotto (2009.08268)

Except if negative non-Gaussianities

Franciolini, Vaskonen, Vermae (2306.17143)



Domain wall networks

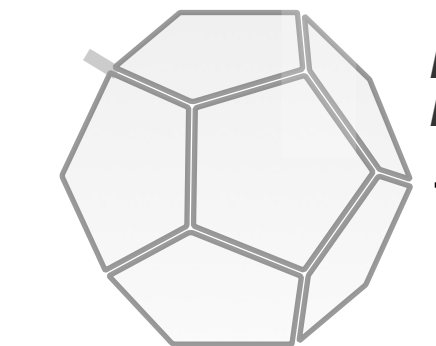
Ferreira, Notari, Pujolas, Rompineve (2204.04228)

Blasi, Mariotti, Rase, Sevrin (2306.17830)

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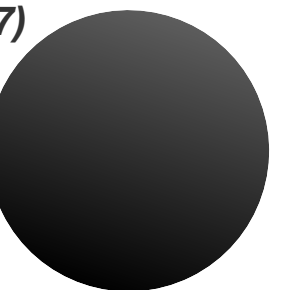
Produce sub-solar-mass PBH

YG, Vitagliano 2306.17841

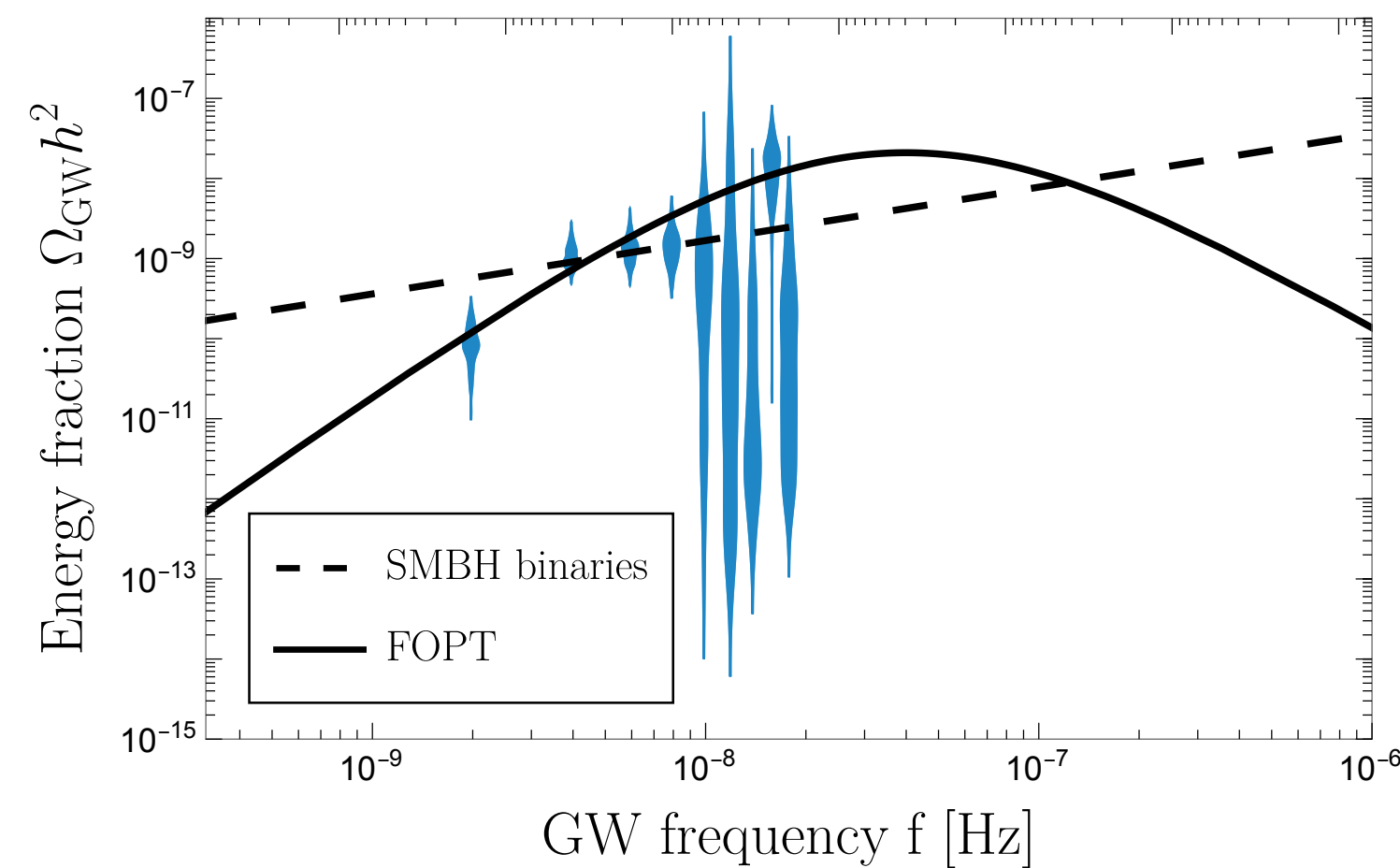


Ferrer, Masso, Panico, Pujolas, Rompineve (1807.01707)
Ferreira, Notari, Pujolas, Rompineve (2401.14331)

YG, Vitagliano, 2311.07670



PBH



First-order phase transitions

Roper Pol et al. (2201.05630)

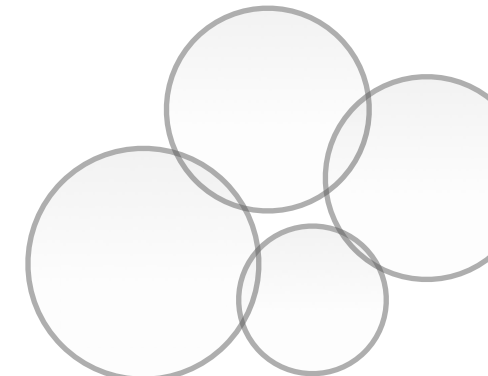
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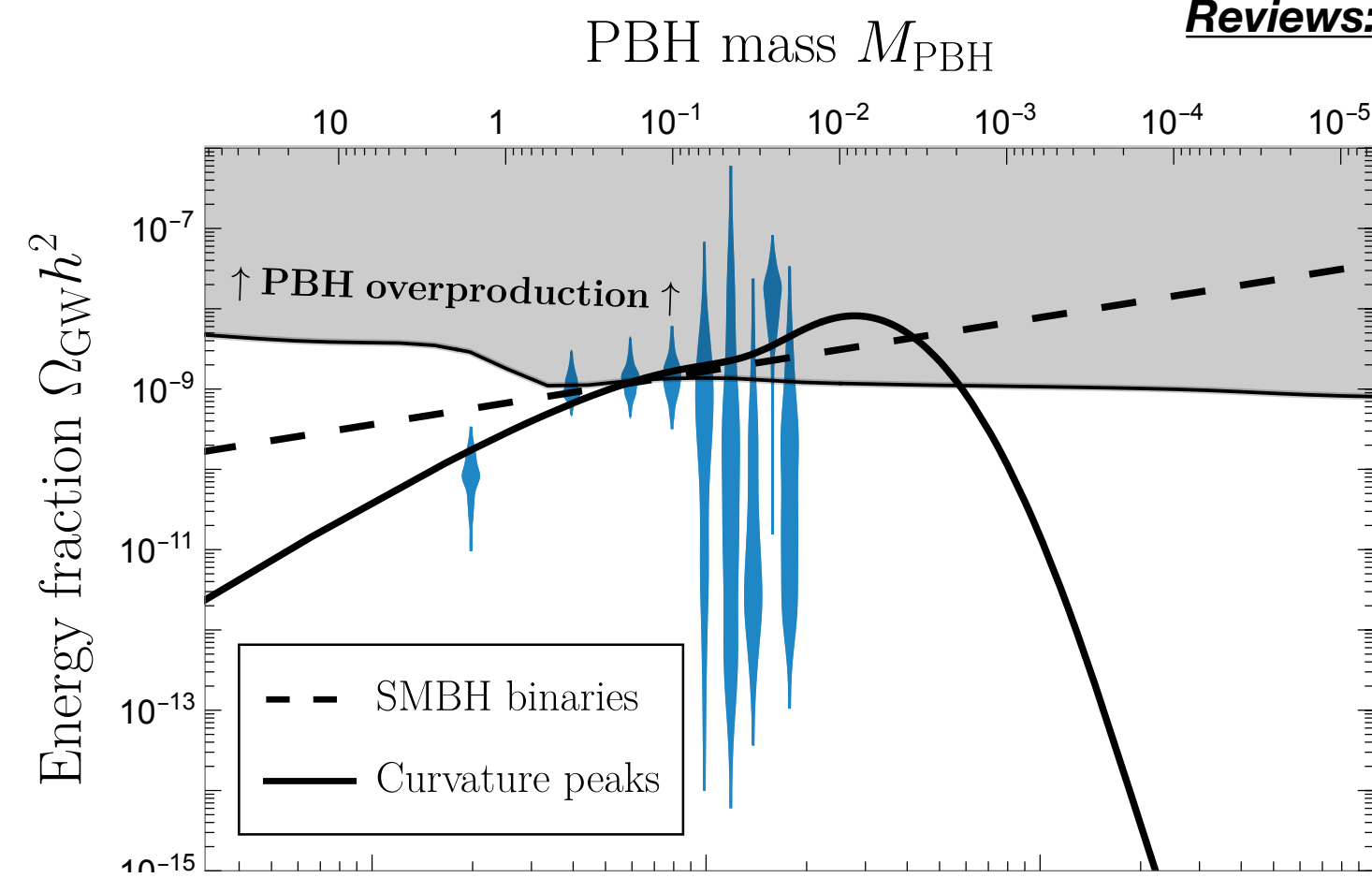
YG (2307.04239)

Lewicki, Toczek, Vaskonen (2402.04158)

Hoefken Zink et al. (2501.15649)

...





Curvature peaks

Overproduce PBH

Chen, Yuan, Huang (1910.12239)

Kohri, Terada (2009.11853)

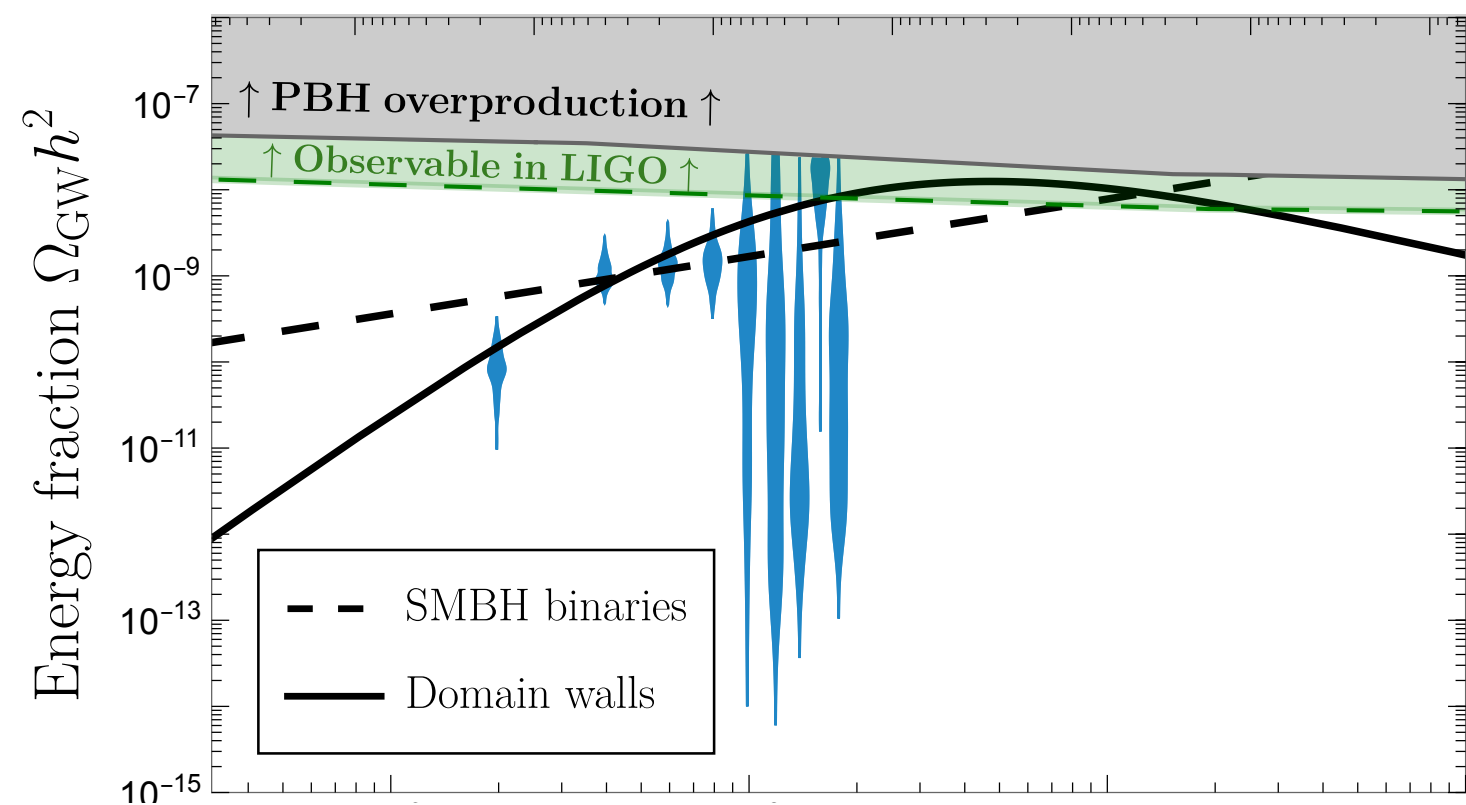
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Except if negative non-Gaussianities

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Domain wall networks

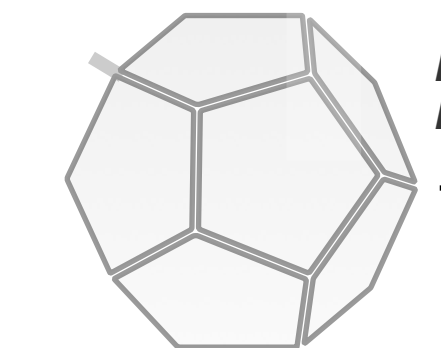
Ferreira, Notari, Pujolas, Rompineve (2204.04228)

Blasi, Mariotti, Rase, Sevrin (2306.17830)

...

Produce sub-solar-mass PBH

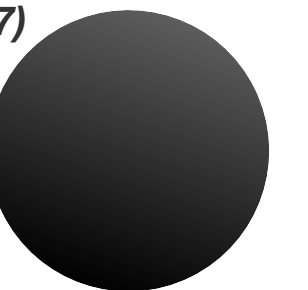
YG, Vitagliano 2306.17841



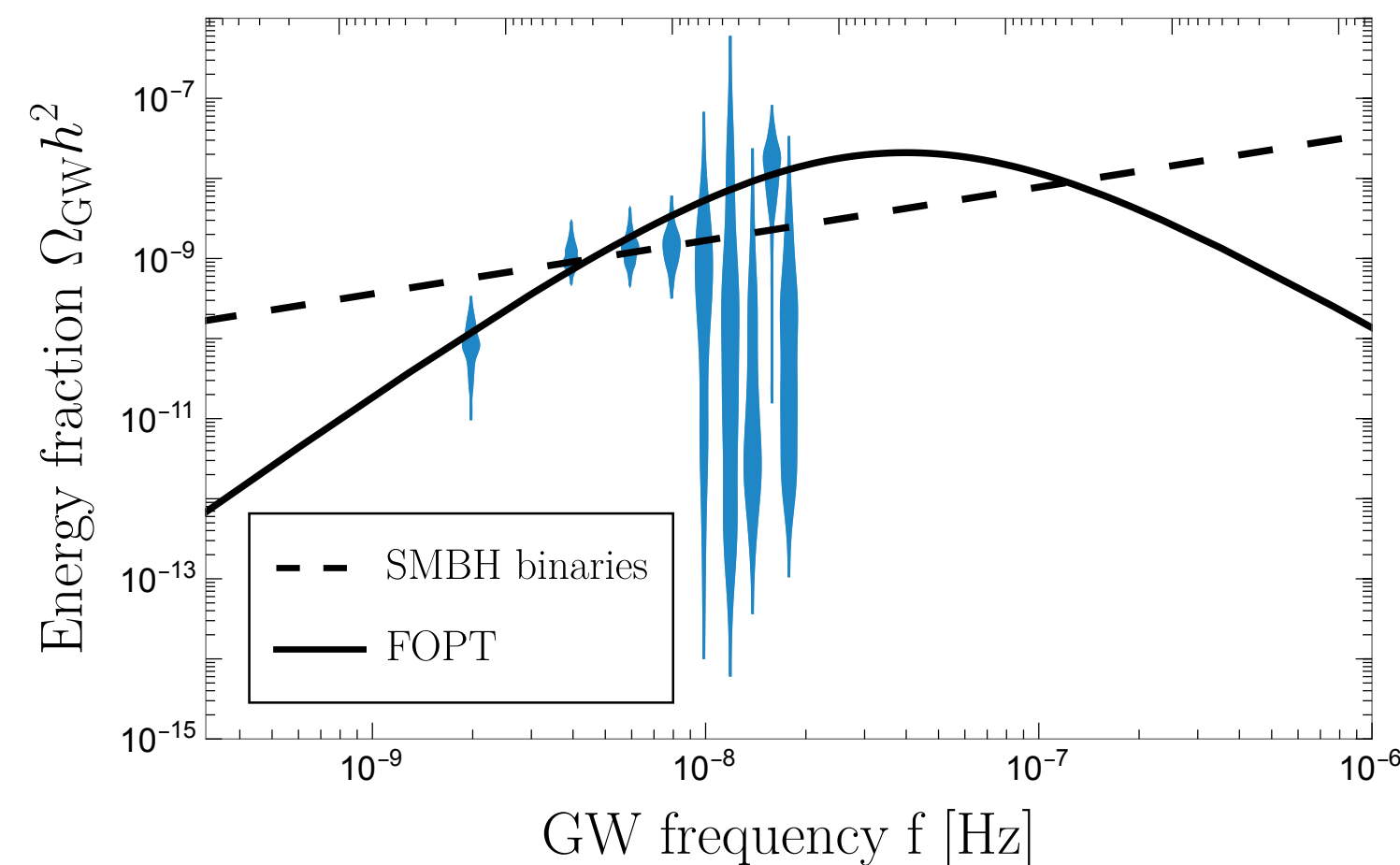
Ferrer, Masso, Panico, Pujolas, Rompineve (1807.01707)
Ferreira, Notari, Pujolas, Rompineve (2401.14331)

YG, Vitagliano, 2311.07670

**1) Solve DW trajectory
in full GR**



PBH



First-order phase transitions

Roper Pol et al. (2201.05630)

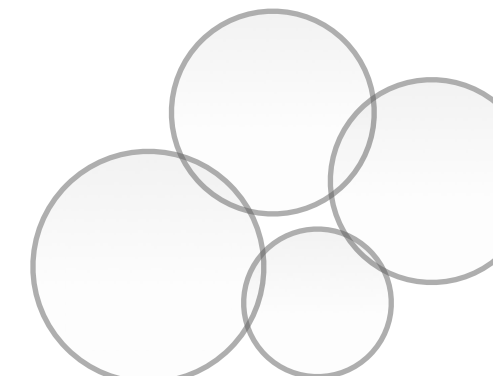
Ghoshal, White et al. (2307.02259)

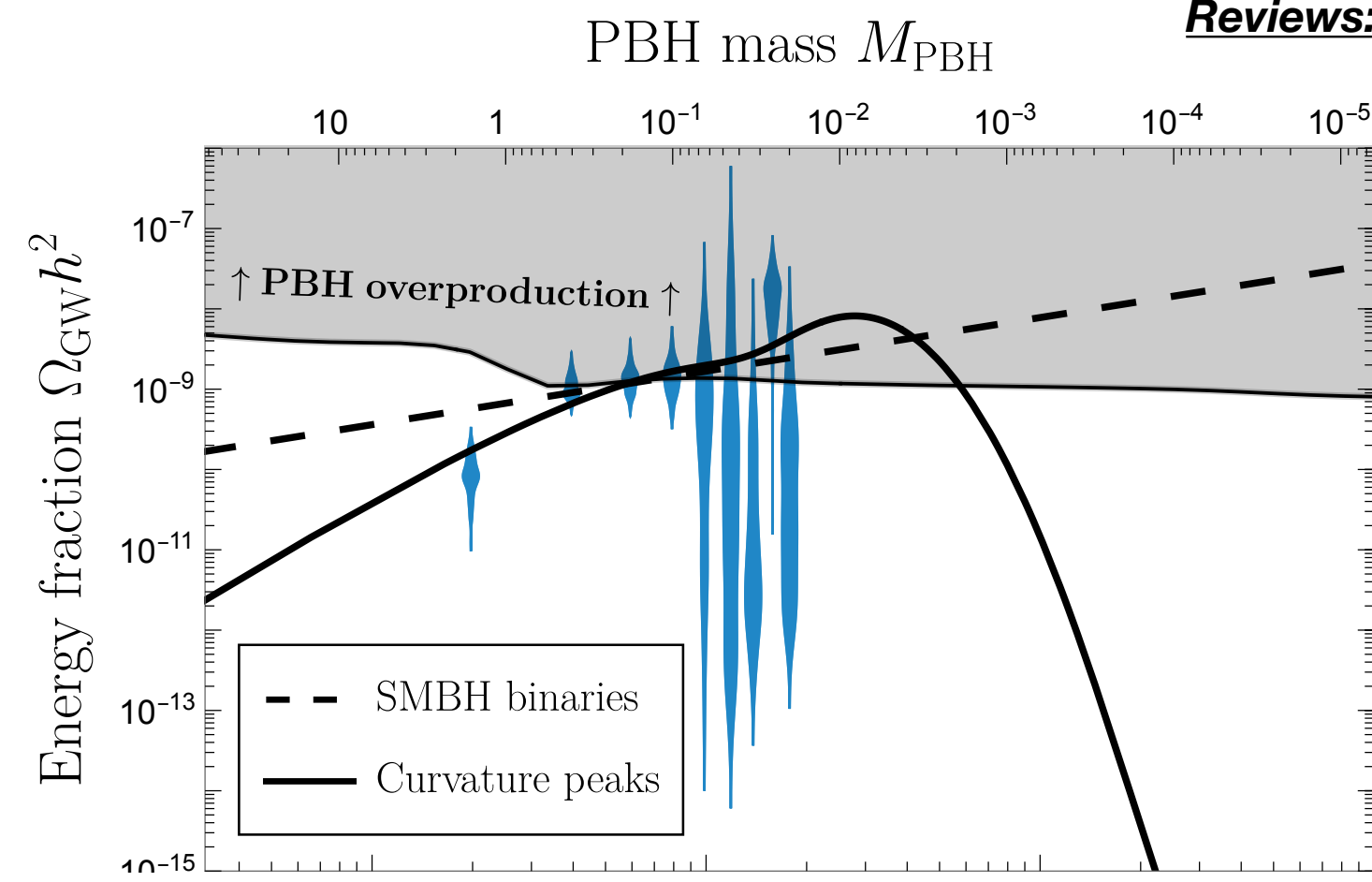
YG (2307.04239)

Lewicki, Toczek, Vaskonen (2402.04158)

Hoefken Zink et al. (2501.15649)

...





Curvature peaks

Overproduce PBH

Chen, Yuan, Huang (1910.12239)

Kohri, Terada (2009.11853)

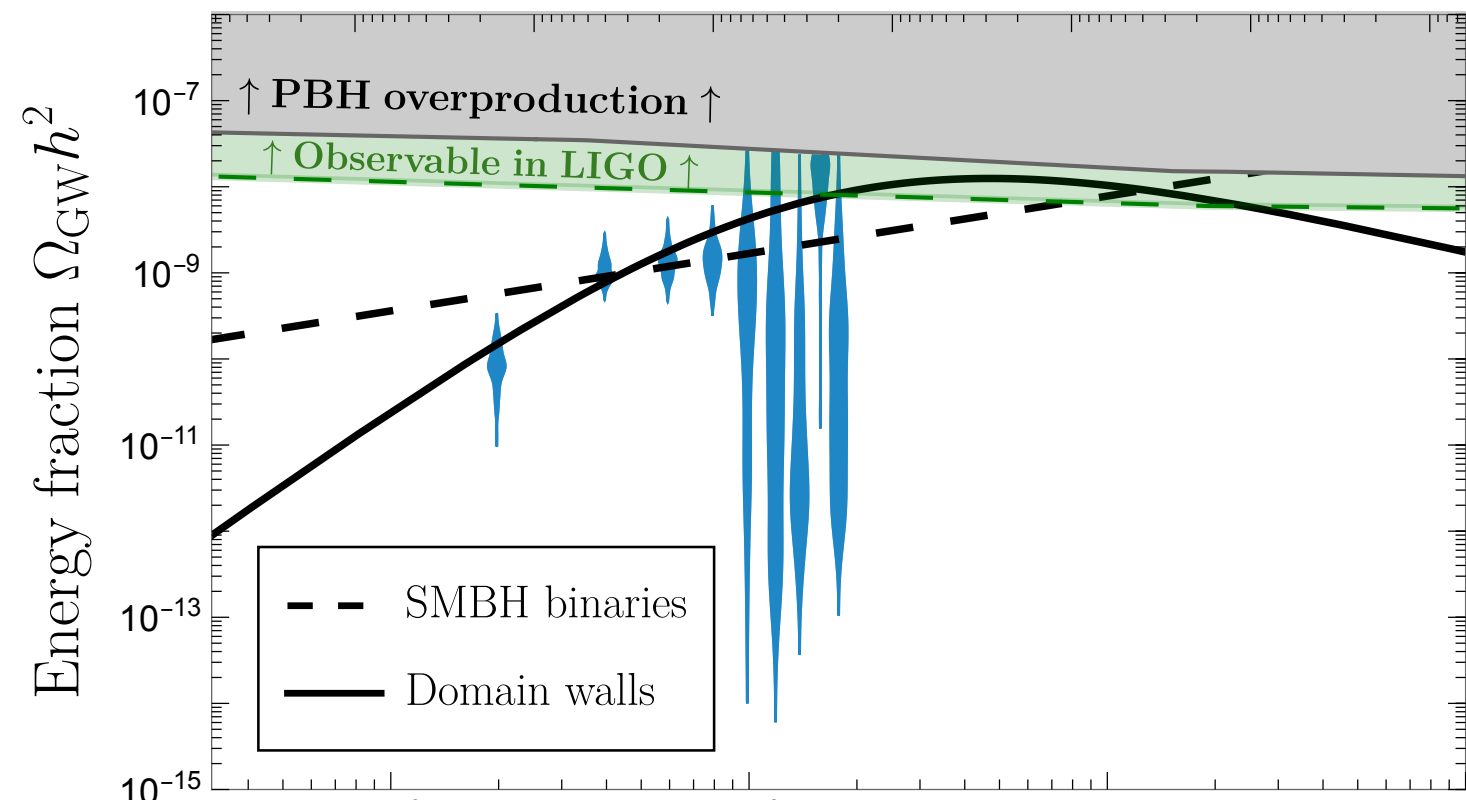
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Except if negative non-Gaussianities

Franciolini, Vaskonen, Vermae (2306.17143)



Domain wall networks

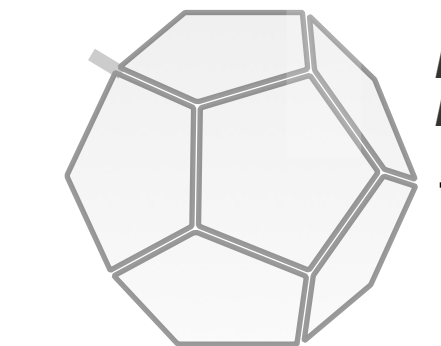
Ferreira, Notari, Pujolas, Rompineve (2204.04228)

Blasi, Mariotti, Rase, Sevrin (2306.17830)

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Produce sub-solar-mass PBH

YG, Vitagliano 2306.17841



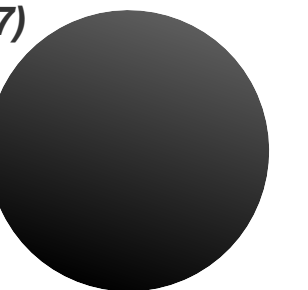
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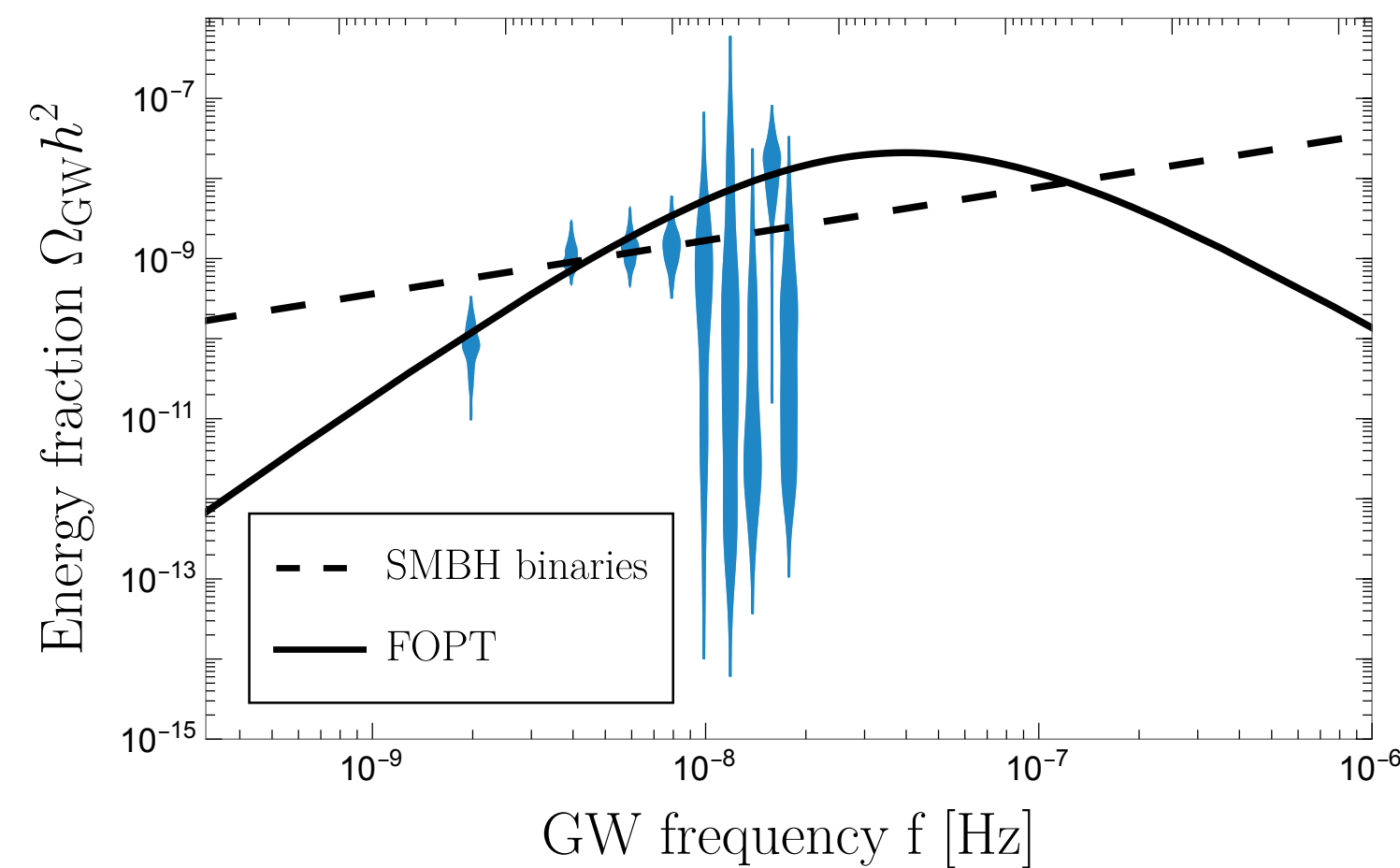
YG, Vitagliano, 2311.07670

**1) Solve DW trajectory
in full GR**

2) Percolation theory



PBH



First-order phase transitions

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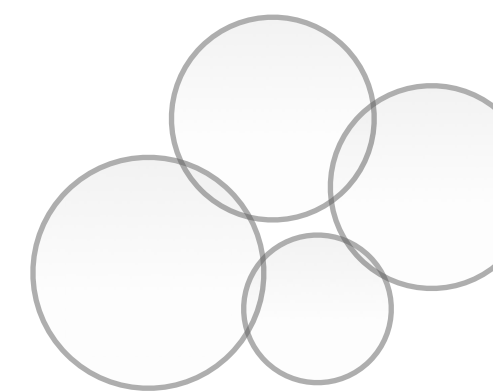
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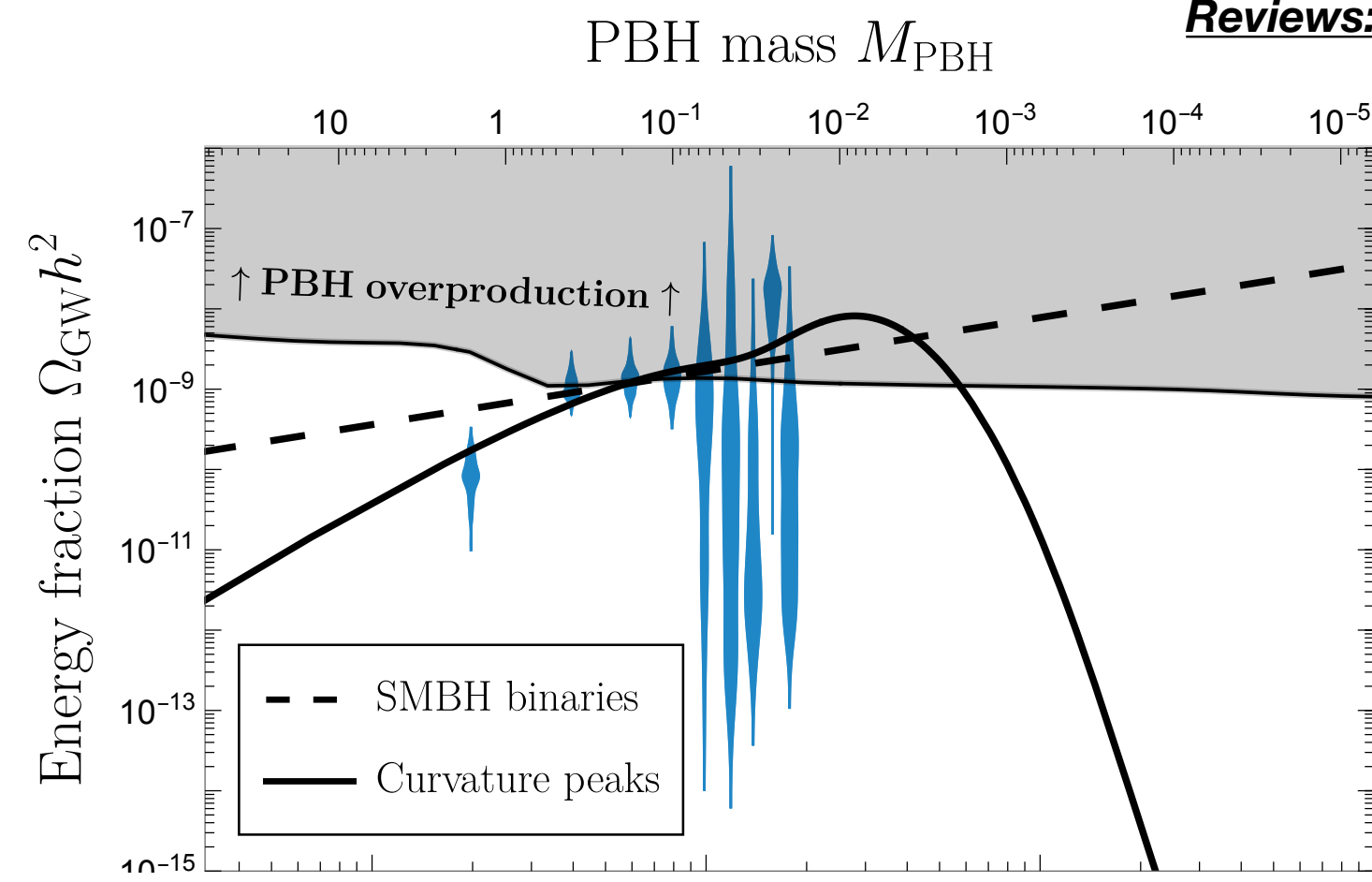
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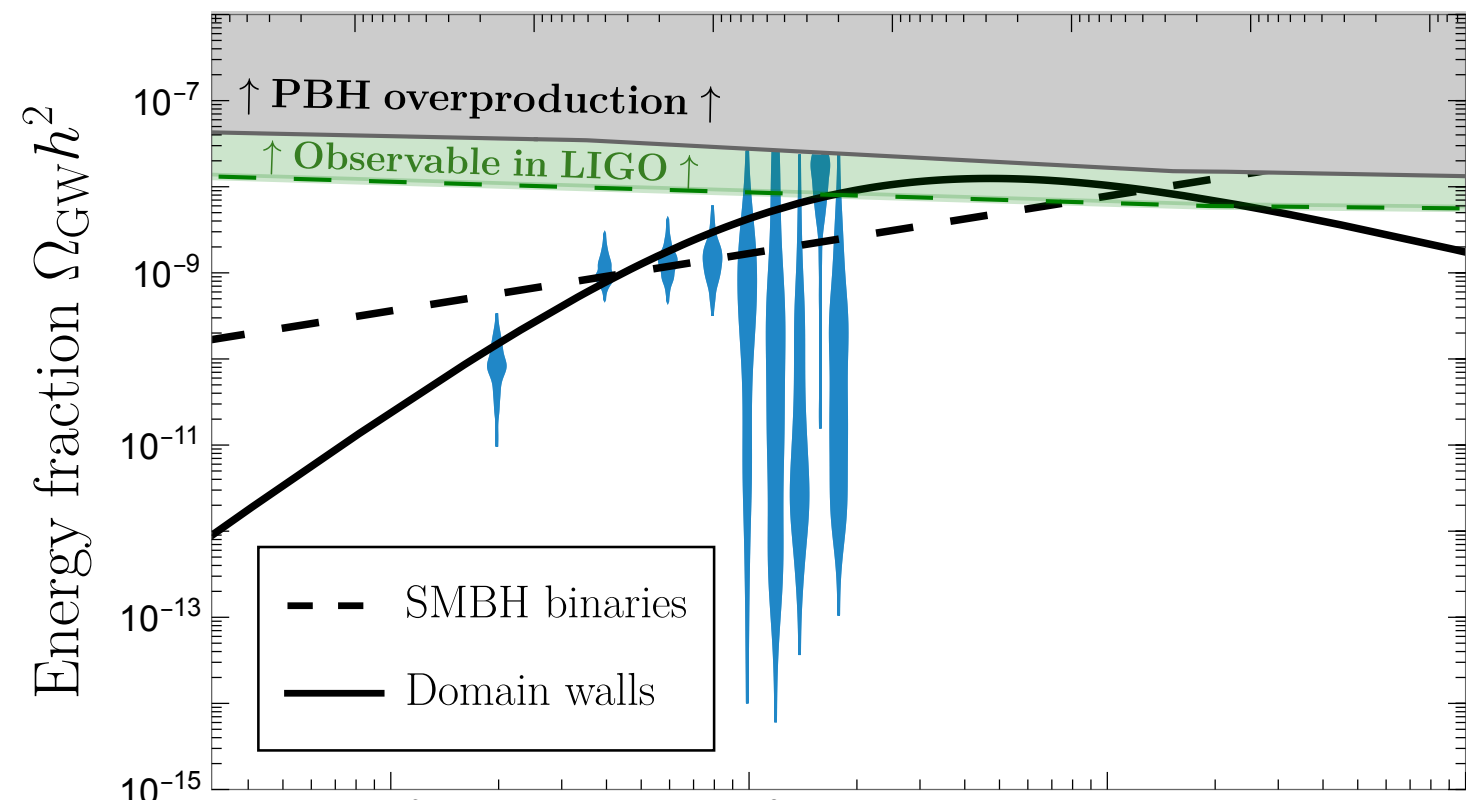
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Domain wall networks

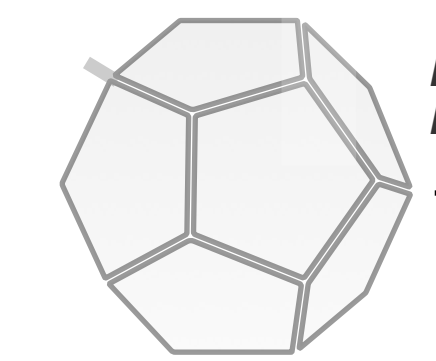
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Produce sub-solar-mass PBH

YG, Vitagliano 2306.17841



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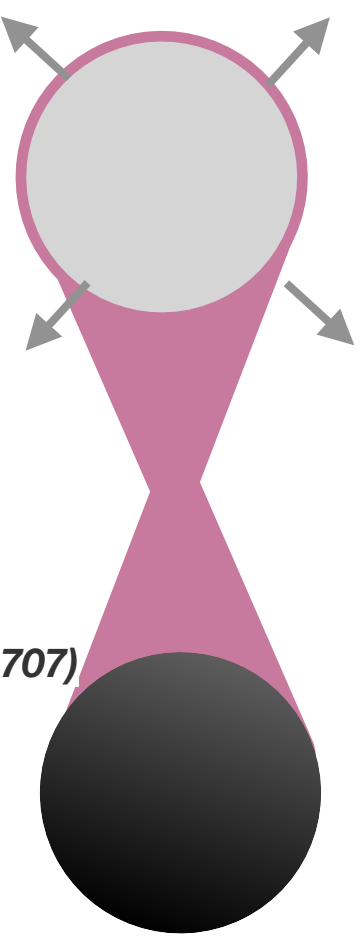
Ferreira, Notari, Pujolas, Rompineve (2401.14331)

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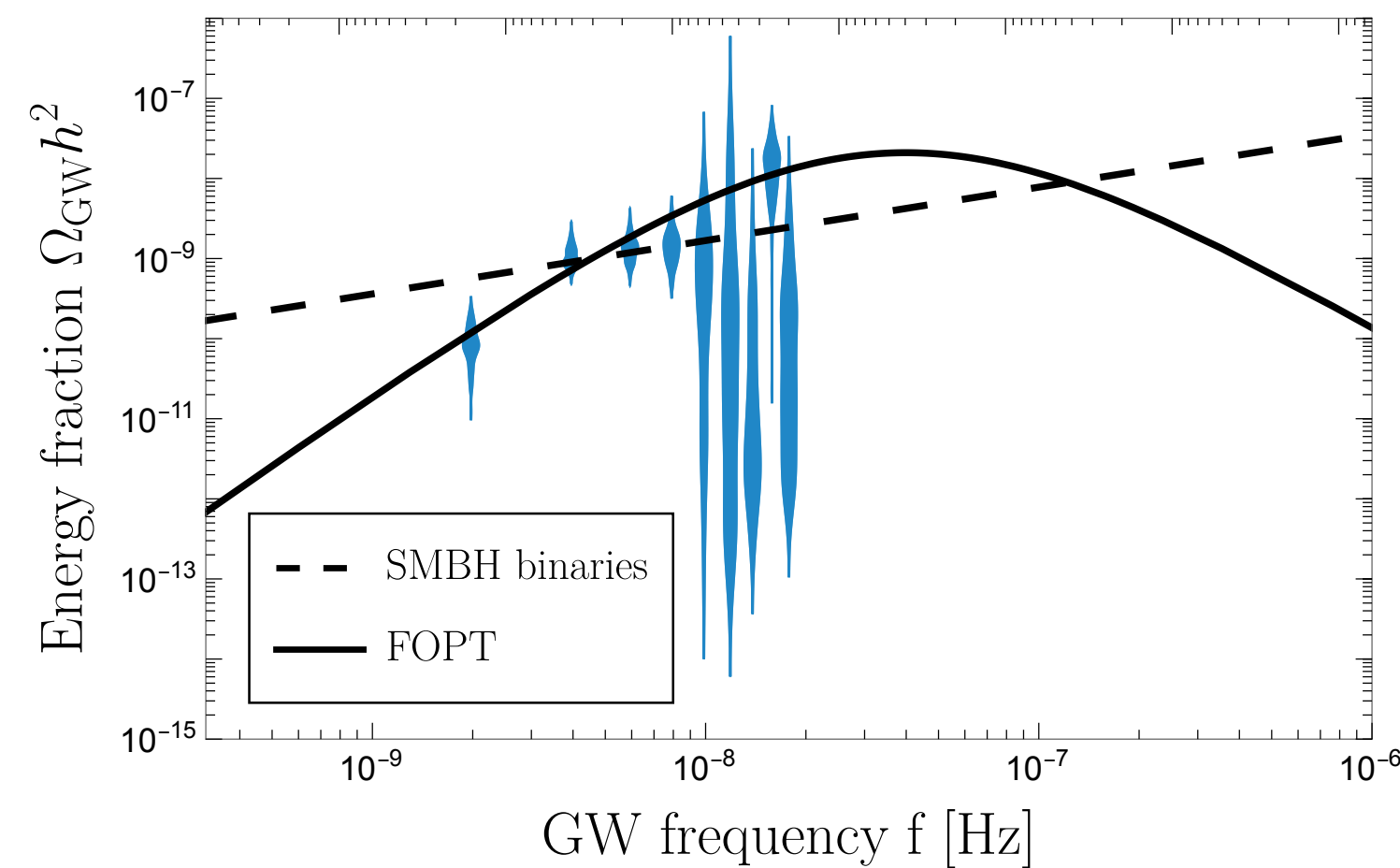
2) Percolation theory

Baby-universe

Wormhole



PBH



First-order phase transitions

Roper Pol et al. (2201.05630)

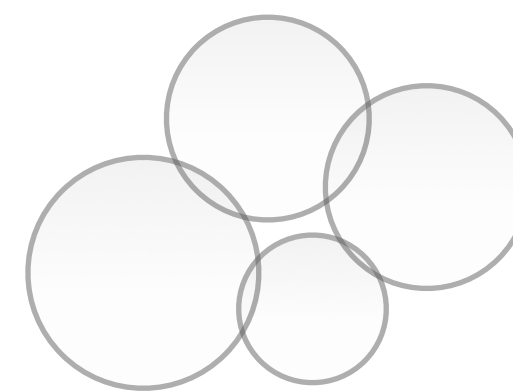
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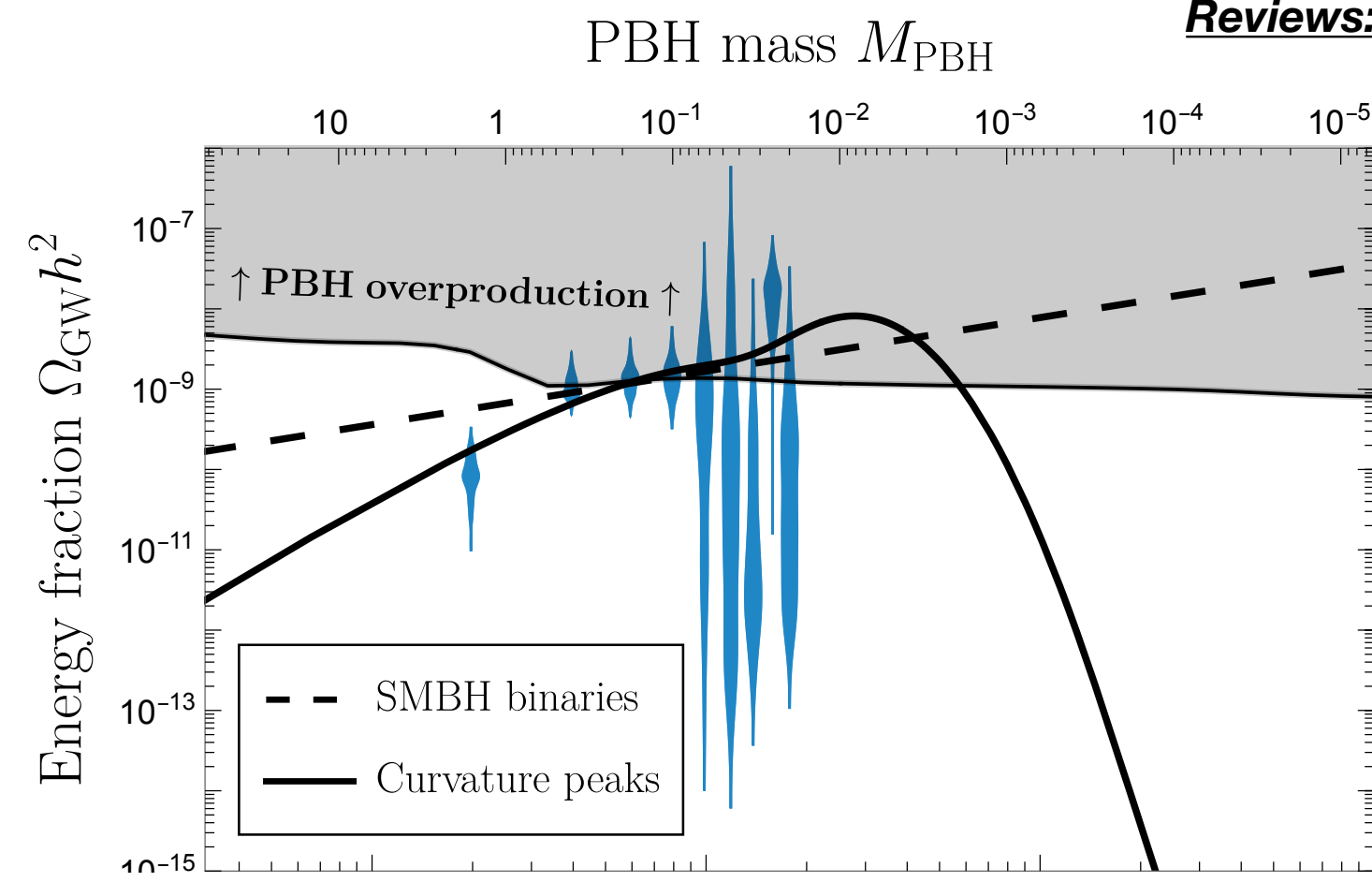
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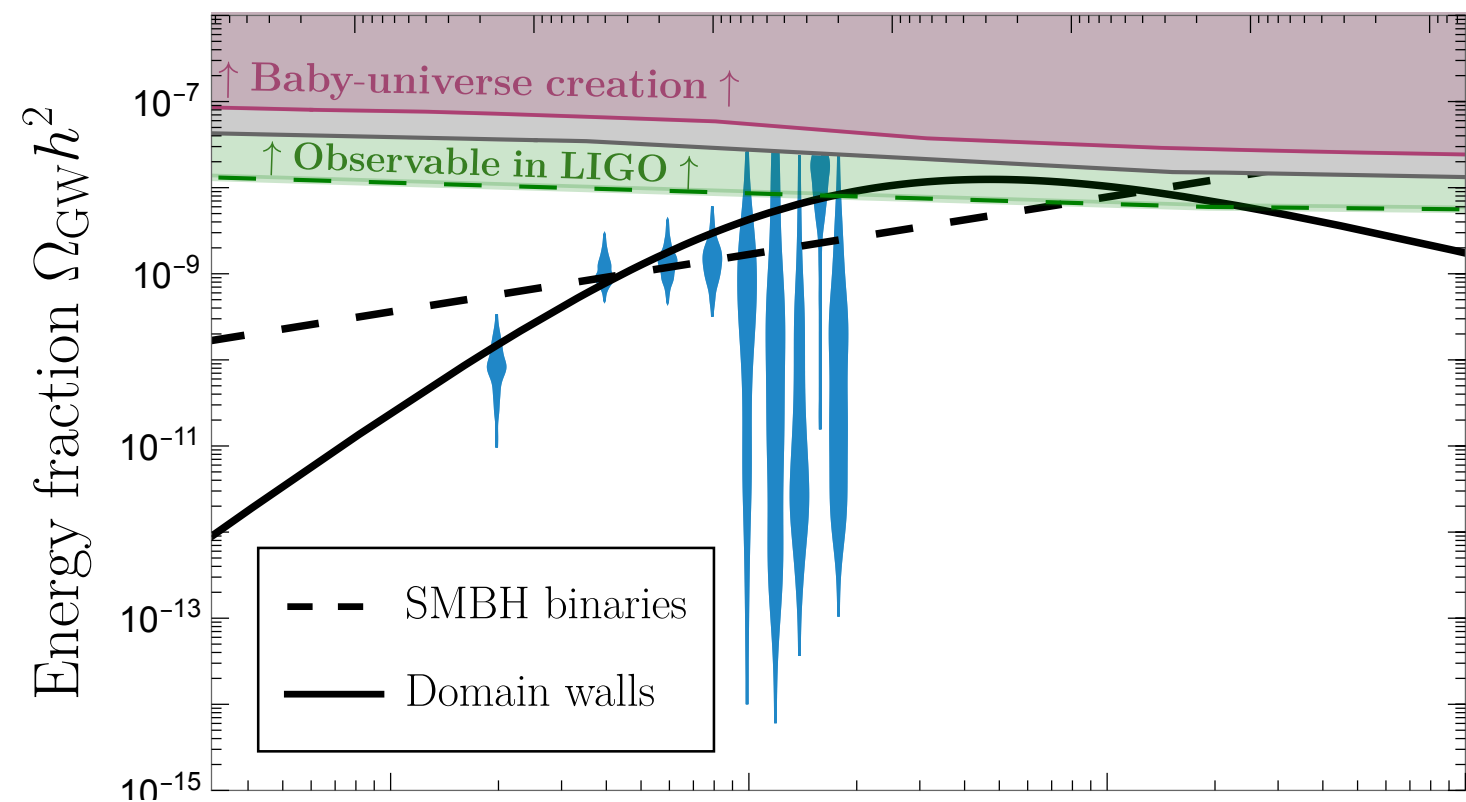
...





Curvature peaks

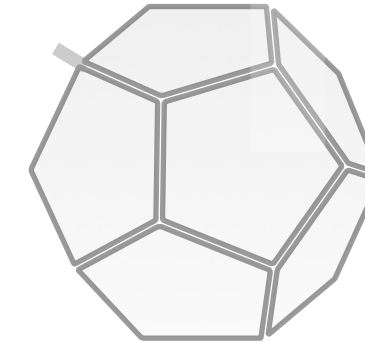
Overproduce PBH
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Franciolini, Vaskonen, Vermae (2306.17143)



Domain wall networks

Ferreira, Notari, Pujolas, Rompineve (2204.04228)
Blasi, Mariotti, Rase, Sevrin (2306.17830)
 ...

Produce sub-solar-mass PBH
YG, Vitagliano 2306.17841

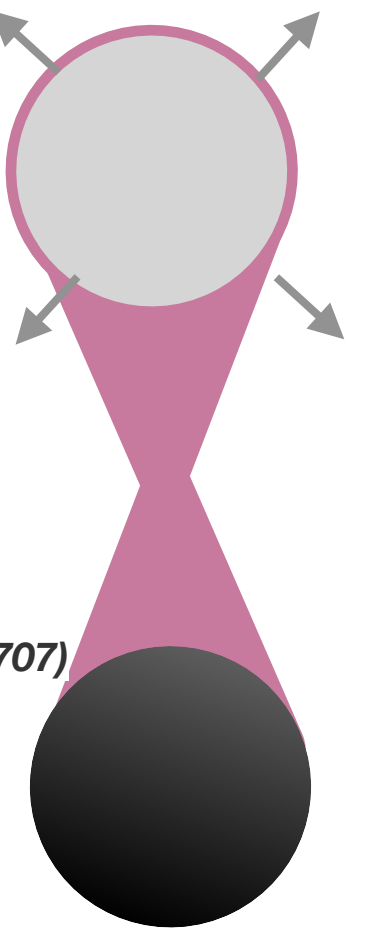


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Ferreira, Notari, Pujolas, Rompineve (2401.14331)

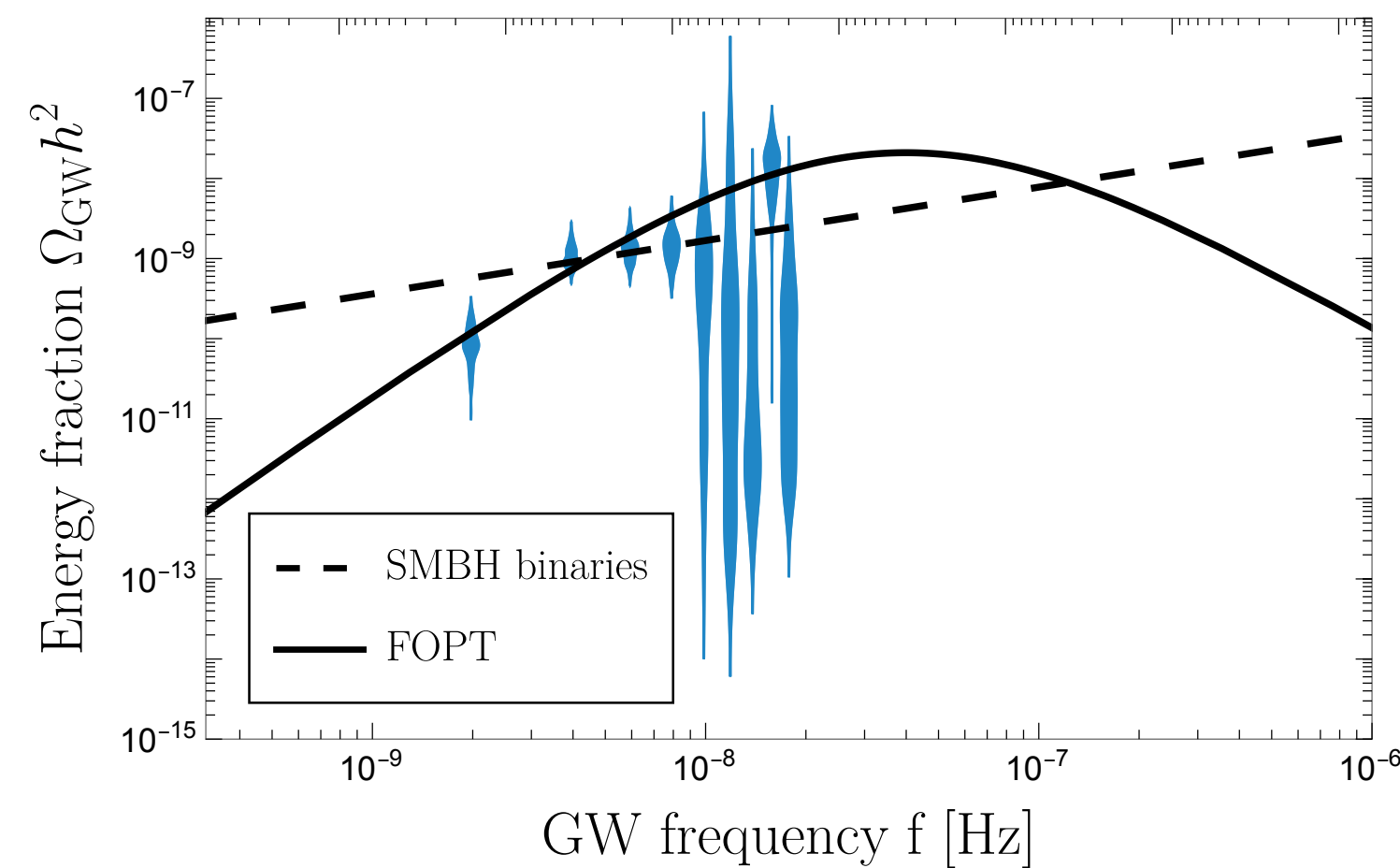
YG, Vitagliano, 2311.07670

**1) Solve DW trajectory
 in full GR**

2) Percolation theory

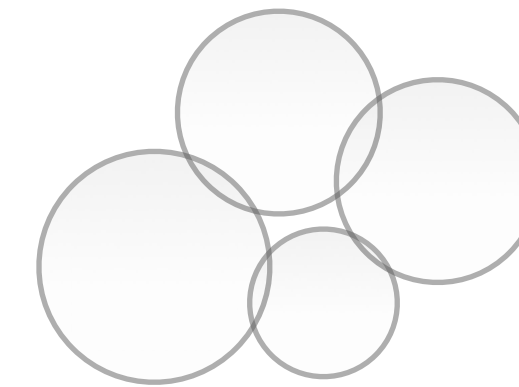


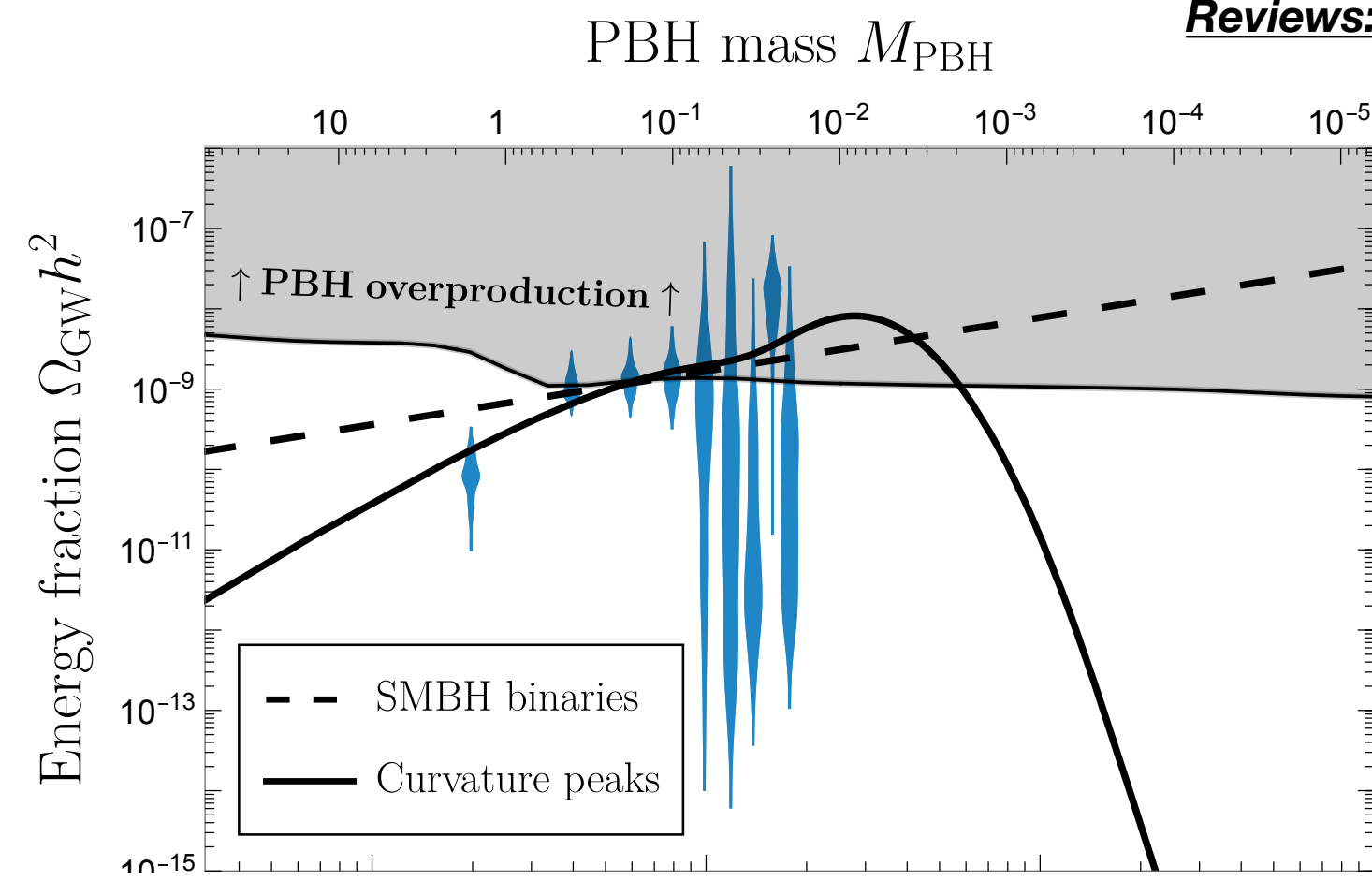
PBH



First-order phase transitions

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 ...





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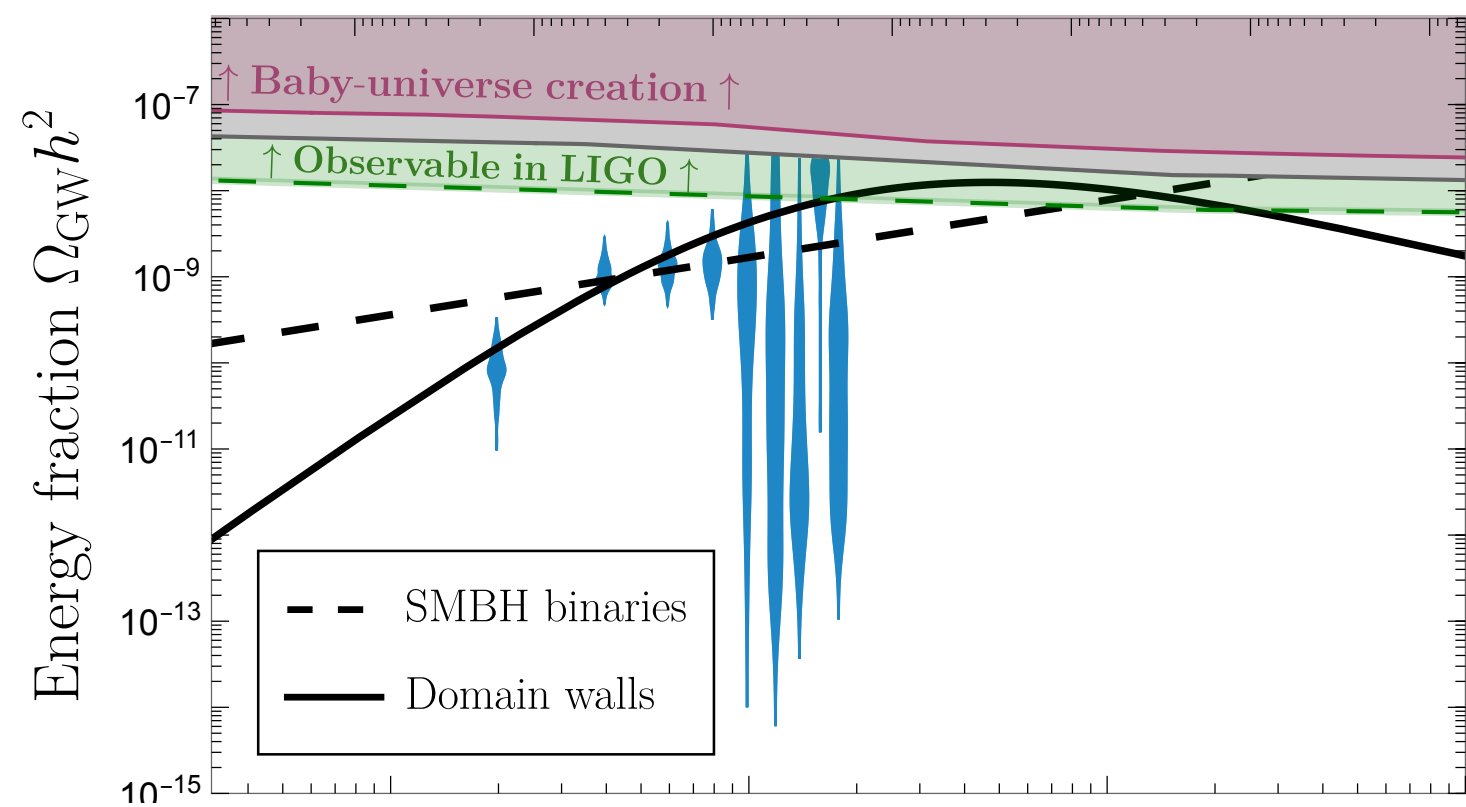
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Domain wall networks

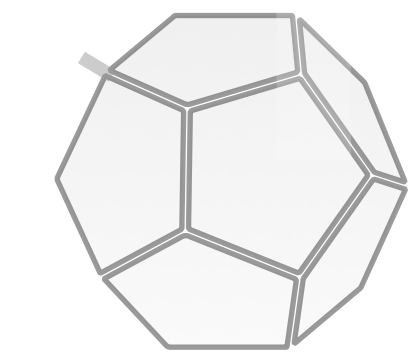
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...

Produce sub-solar-mass PBH

YG, Vitagliano 2306.17841

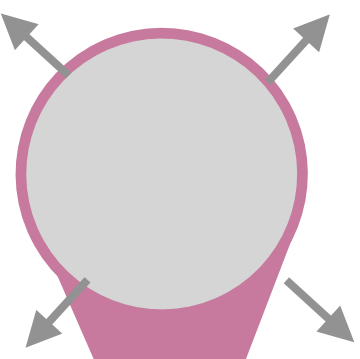


Ferrer, Masso, Panico, Pujolas, Rompineve (1807.01707)
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YG, Vitagliano, 2311.07670

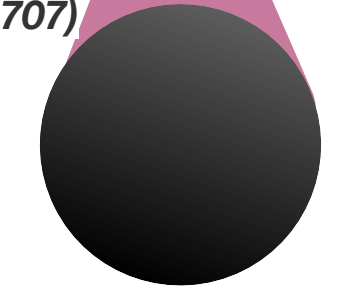
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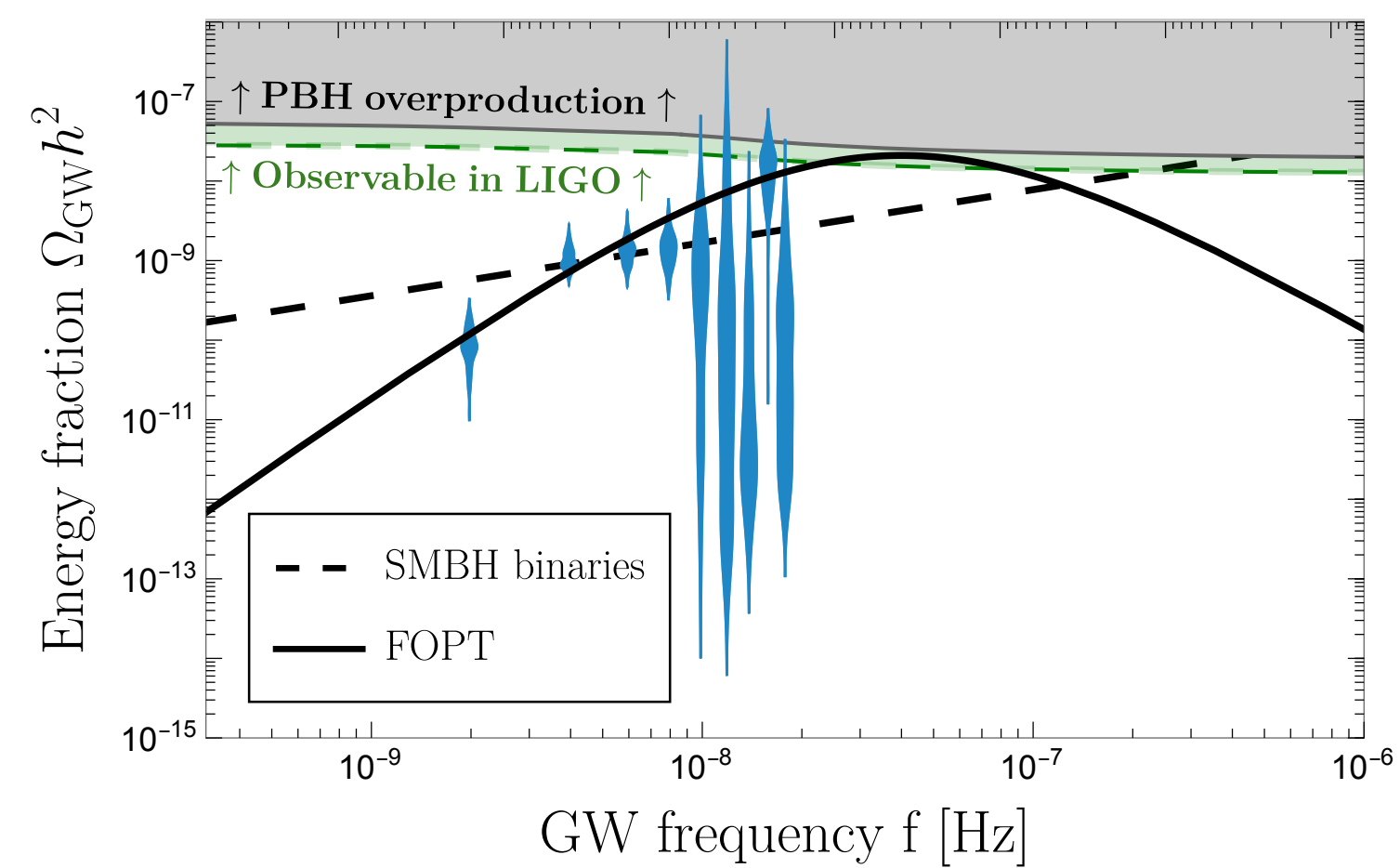


Baby-universe

Wormhole



PBH



First-order phase transitions

Roper Pol et al. (2201.05630)

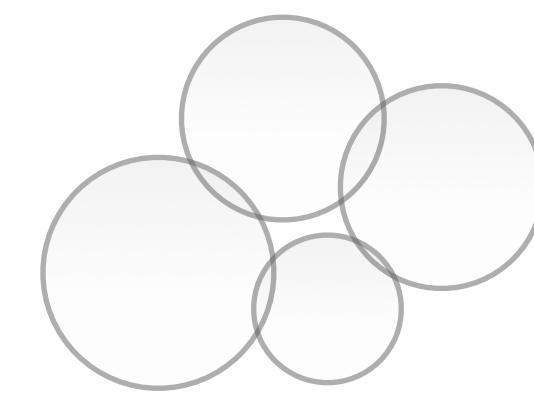
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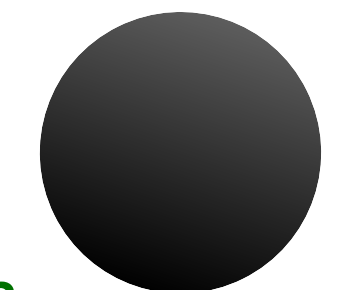
Lewicki, Toczek, Vaskonen (2402.04158)

Hoefken Zink et al. (2501.15649)

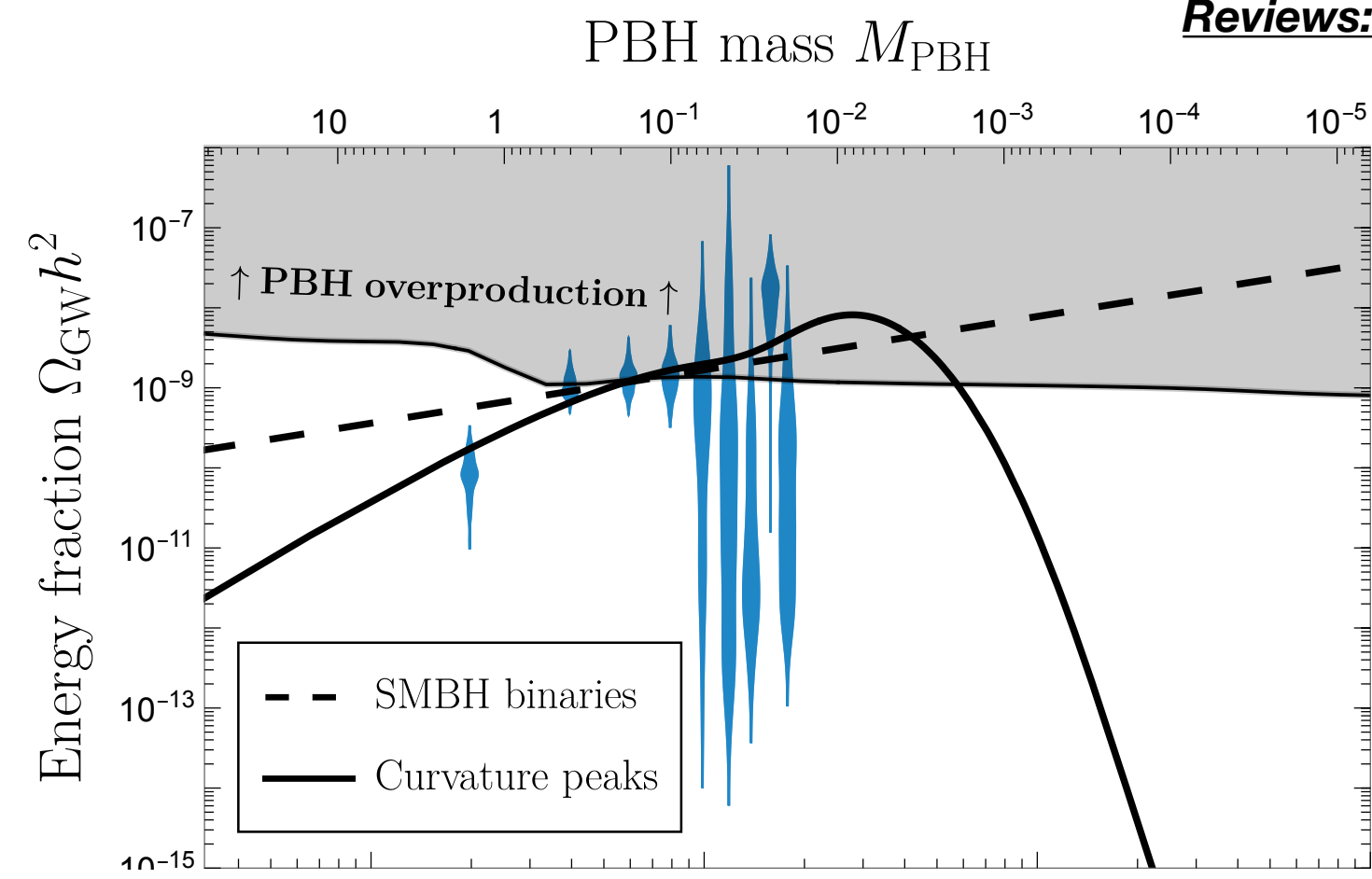
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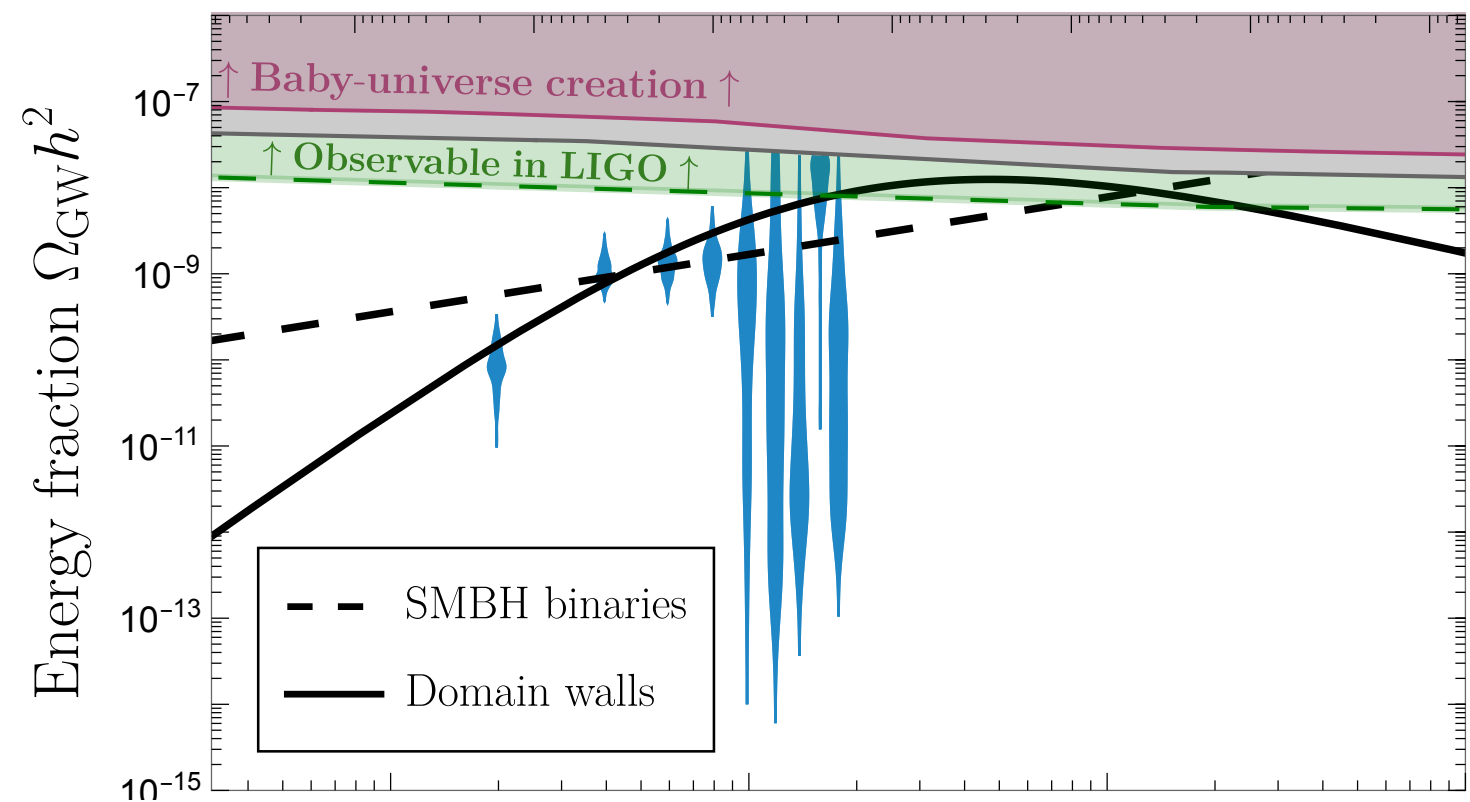
*Sasaki+ 1982, Bian+ 2021, Lu+ 2022,
 Lewicki, Toczek, Vaskonen 2023,
 YG&Volansky 2023, Baldes+ 2023,
 Lewicki, Toczek, Vaskonen 2024,*



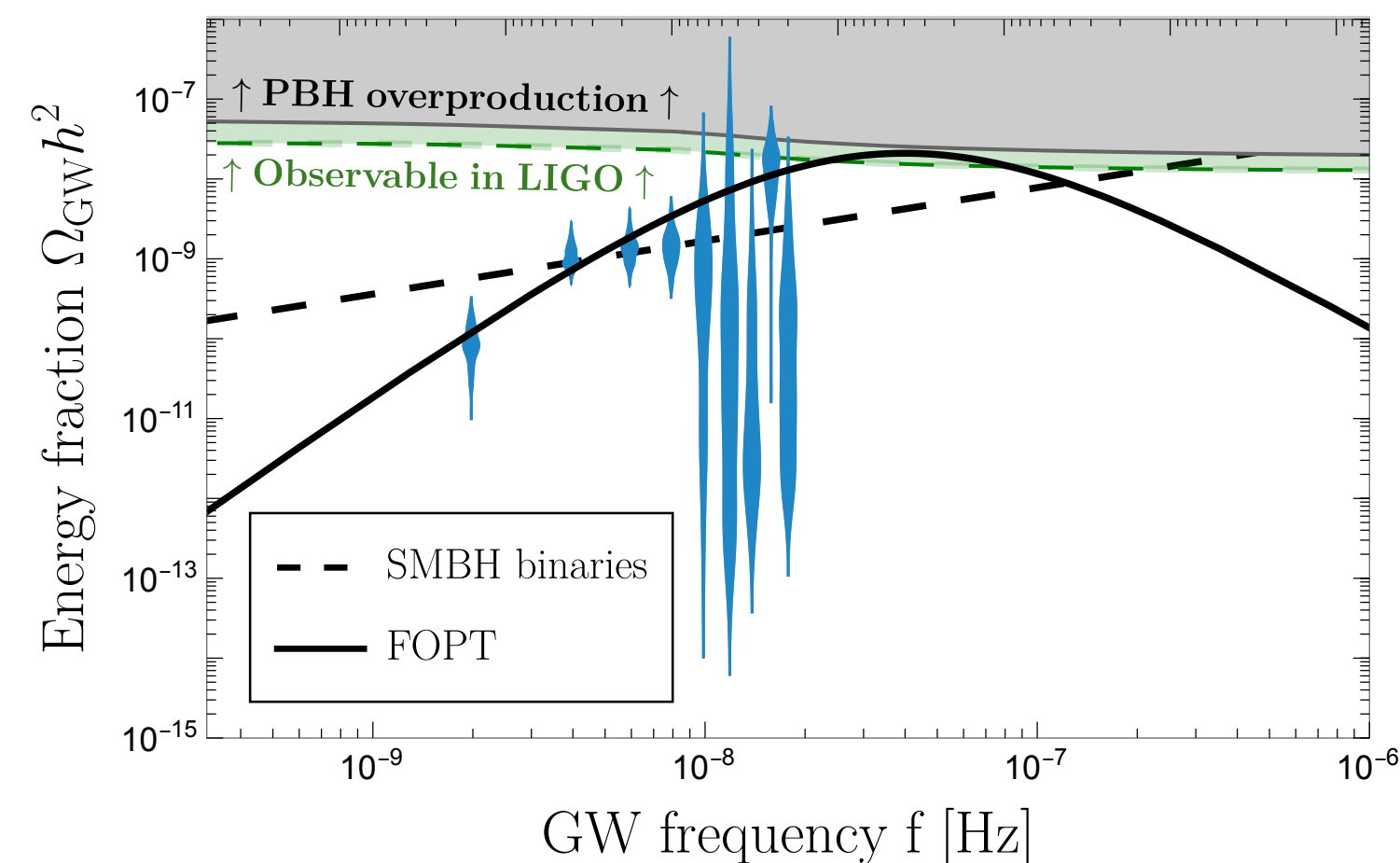
Reviews: *Madge, Morgante, Puchades-Ibáñez, Ramberg, Ratzinger, Schenk, Schwaller (2306.14856),
 Figueroa, Pieroni, Ricciardone, Simakachorn (2307.02399)
 Lewicki, Vaskonen et al (2308.08546)*



Curvature peaks
Overproduce PBH
Chen, Yuan, Huang (1910.12239)
Kohri, Terada (2009.11853)
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Domain wall networks
Ferreira, Notari, Pujolas, Rompineve (2204.04228)
Blasi, Mariotti, Rase, Sevrin (2306.17830)
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Produce sub-solar-mass PBH
YG, Vitagliano 2306.17841



First-order phase transitions
Roper Pol et al. (2201.05630)
Ghoshal, White et al. (2307.02259)
YG (2307.04239)
Lewicki, Toczek, Vaskonen (2402.04158)
Hoefken Zink et al. (2501.15649)
 ...

Motivate search
 in LIGO data

LIGO collab., “Search for sub-solar
 event in LIGO O1”, PRL 2018

LIGO collab., “Search for sub-solar
 event in LIGO O2”, PRL 2019

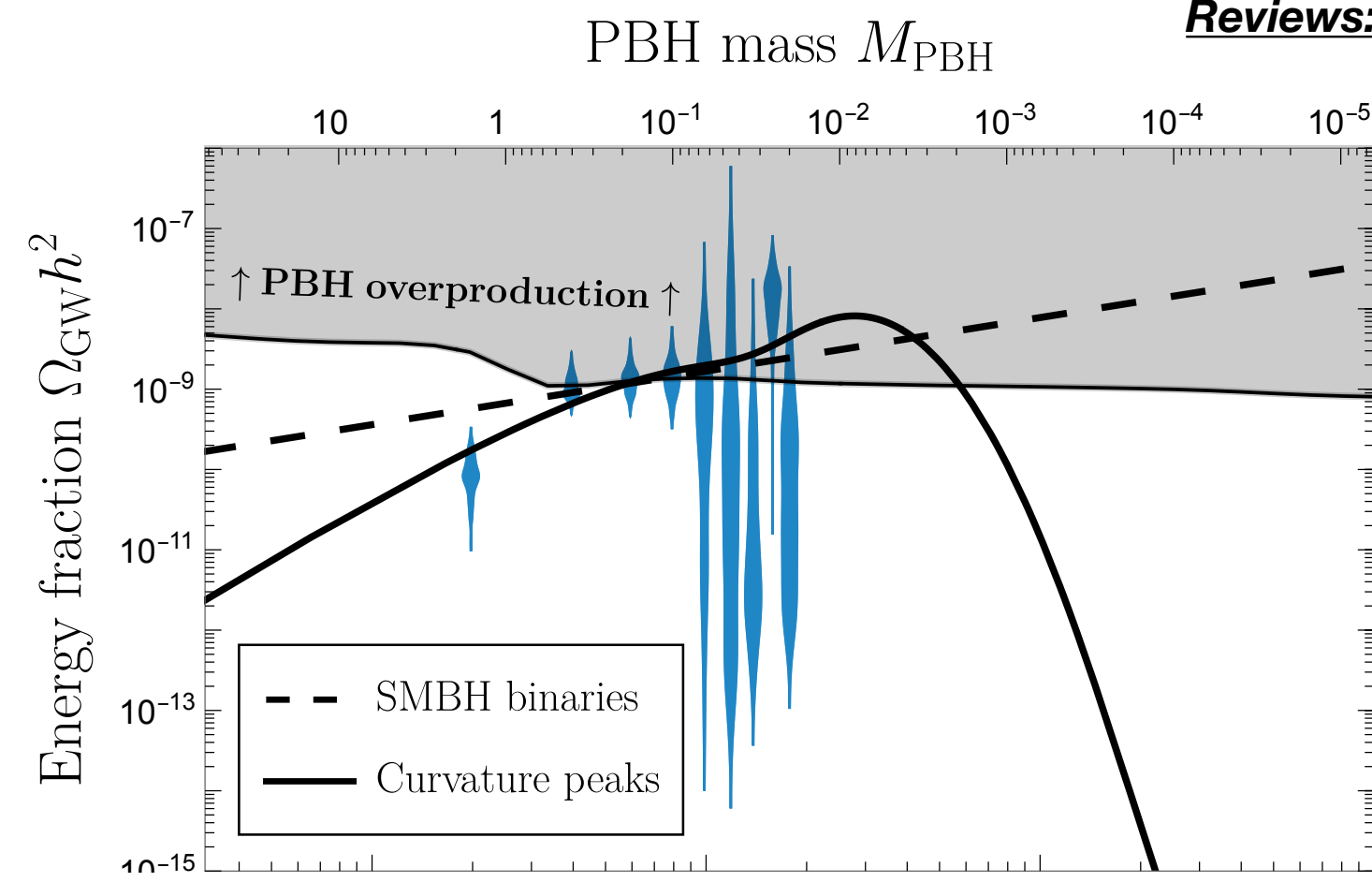
LIGO collab., “Search for sub-solar
 event in LIGO O3”, PRL 2022

⇒ one sub-solar candidate with 5yrs

false-alarm rate: $m = 0.27^{+0.12}_{-0.10}$

(Prunier+ 2311.16085)

Search in LIGO O4 on-going



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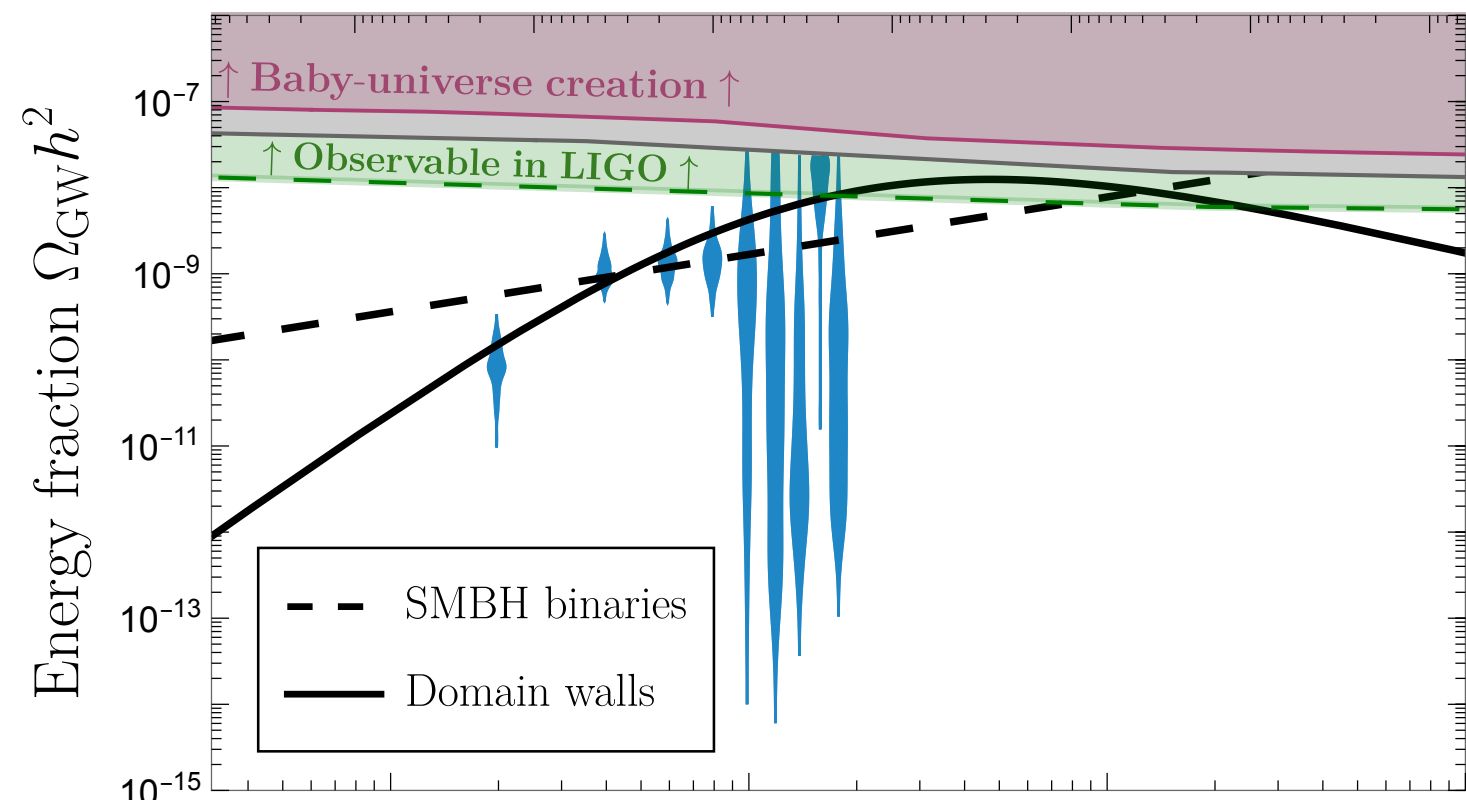
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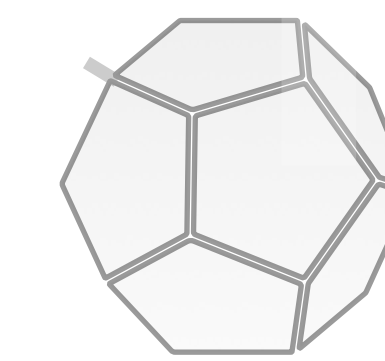
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Produce sub-solar-mass PBH

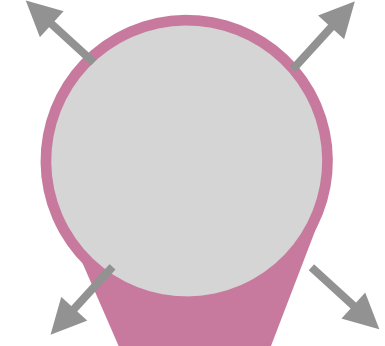
YG, Vitagliano 2306.17841



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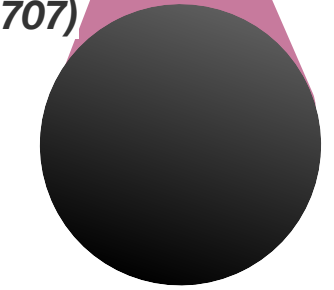
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- 1) Solve DW trajectory in full GR**
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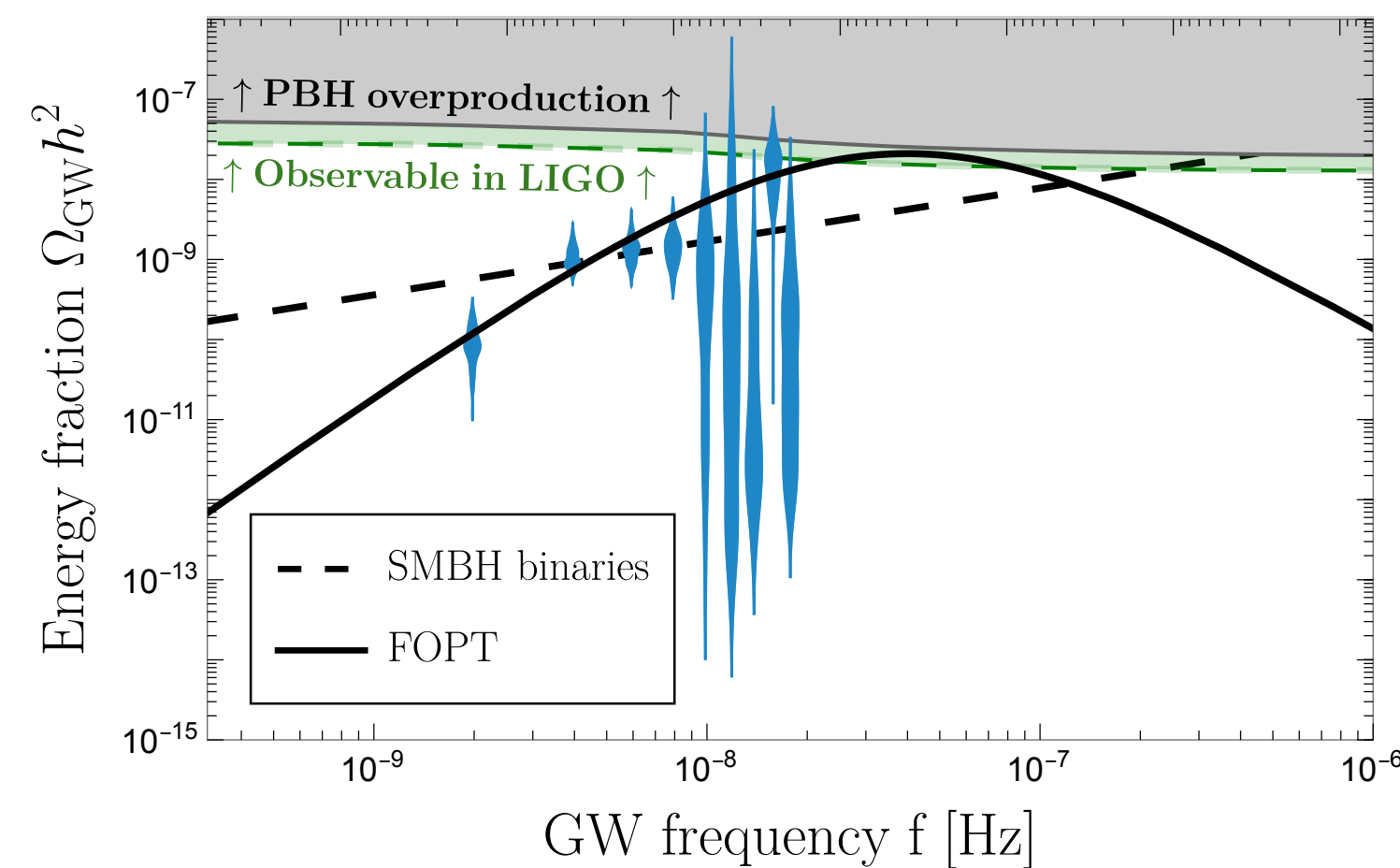


Baby-universe

Wormhole



PBH



First-order phase transitions

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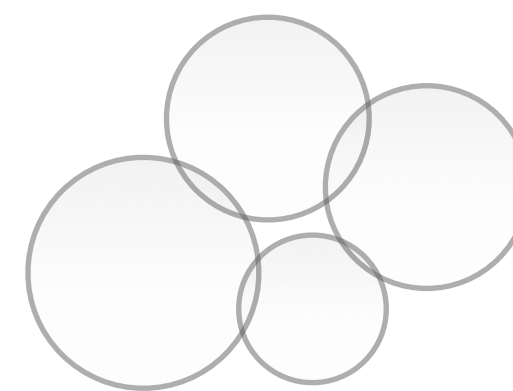
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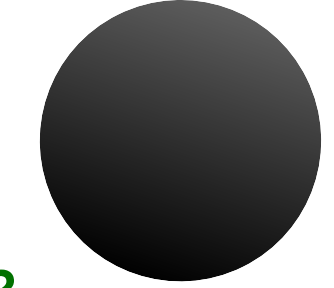
Lewicki, Toczec, Vaskonen (2402.04158)

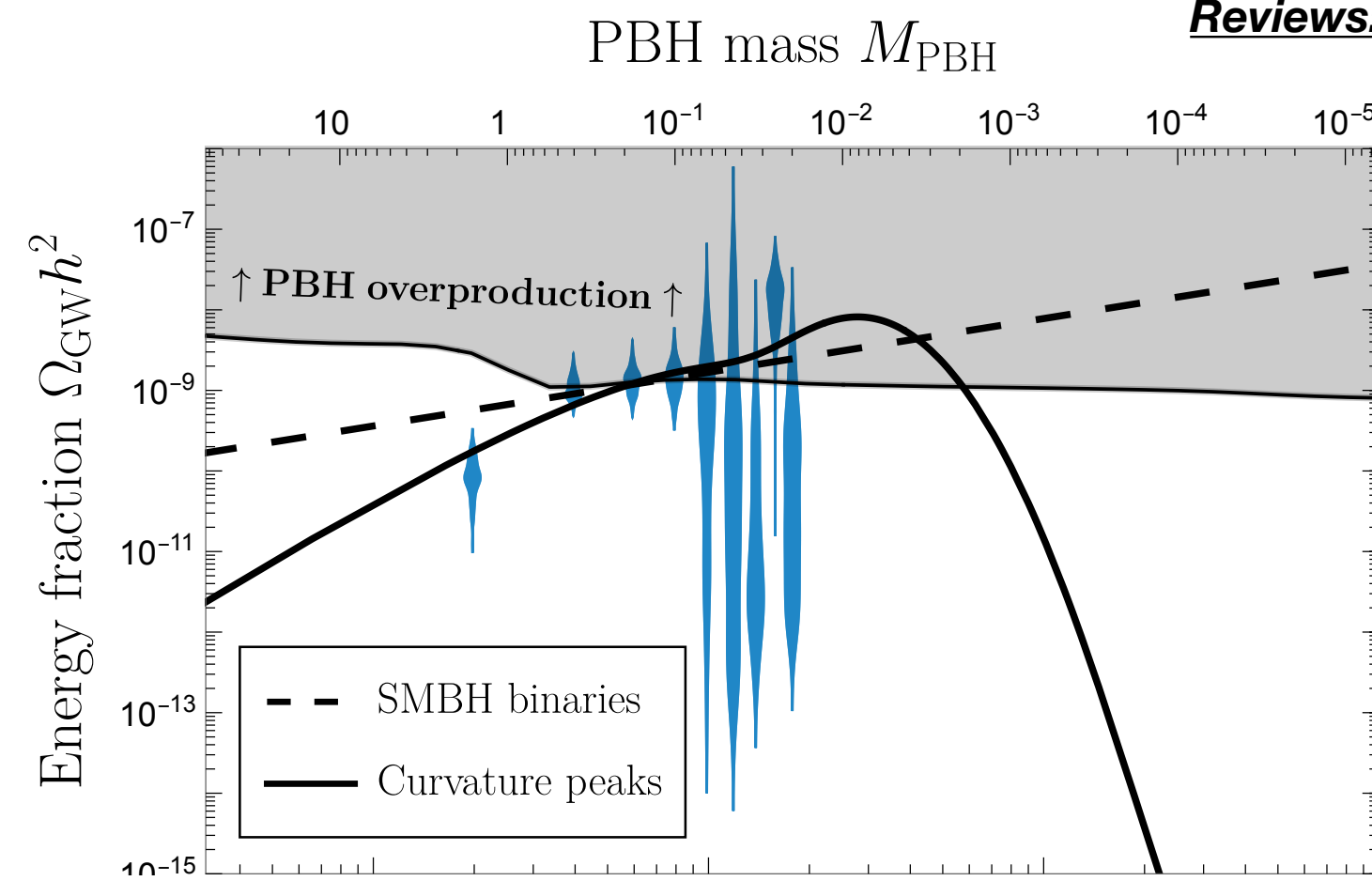
Hoefken Zink et al. (2501.15649)

...



*Sasaki+ 1982, Bian+ 2021, Lu+ 2022,
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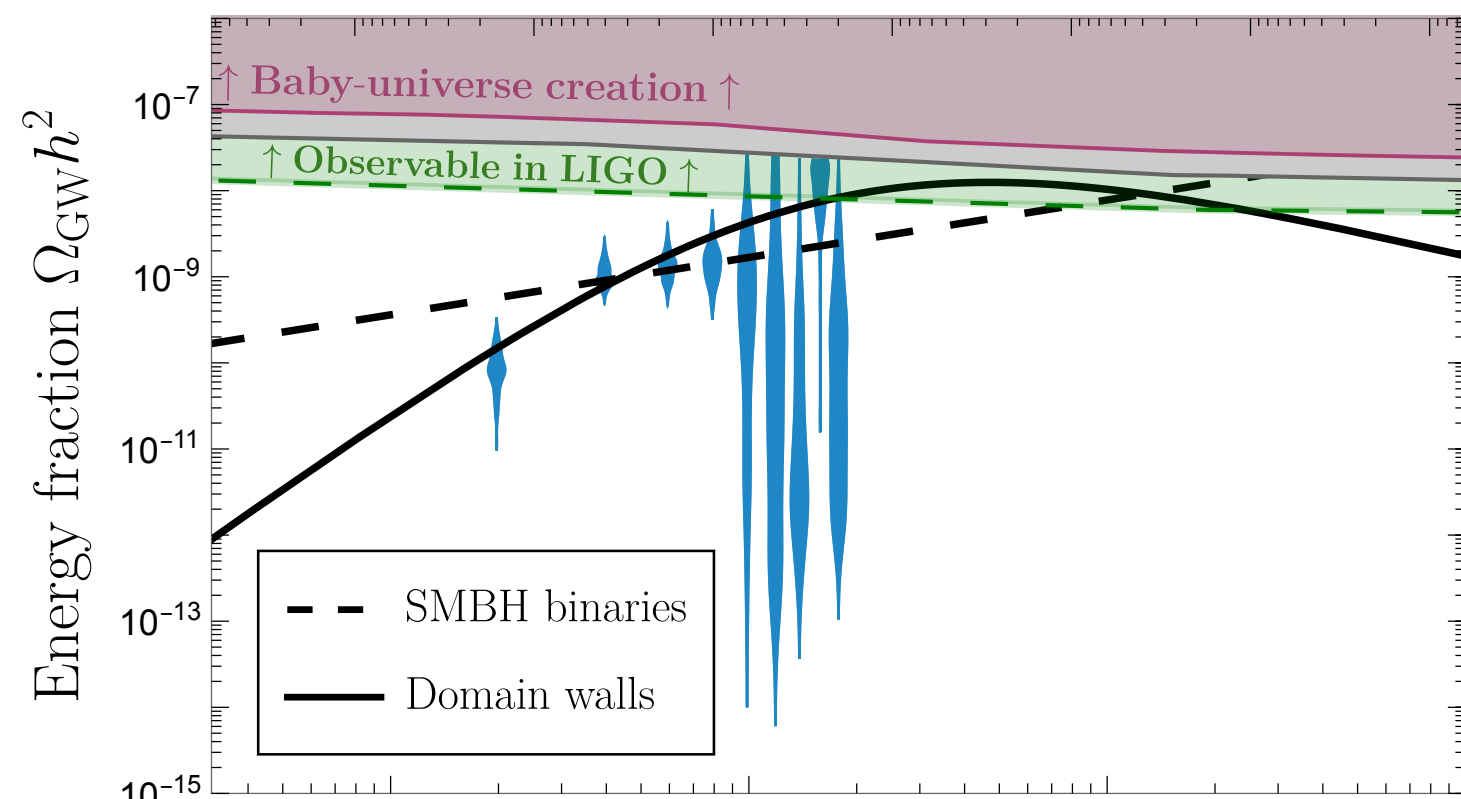
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Domain wall networks

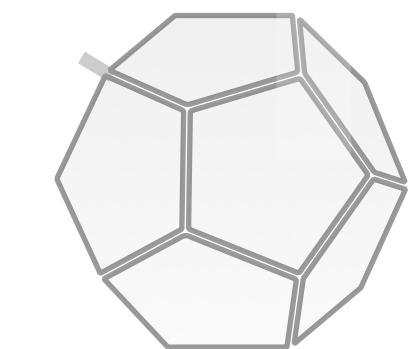
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Produce sub-solar-mass PBH

YG, Vitagliano 2306.17841

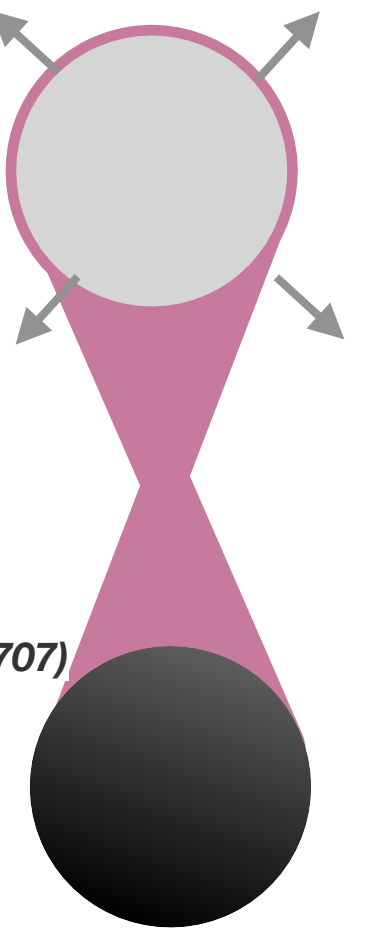


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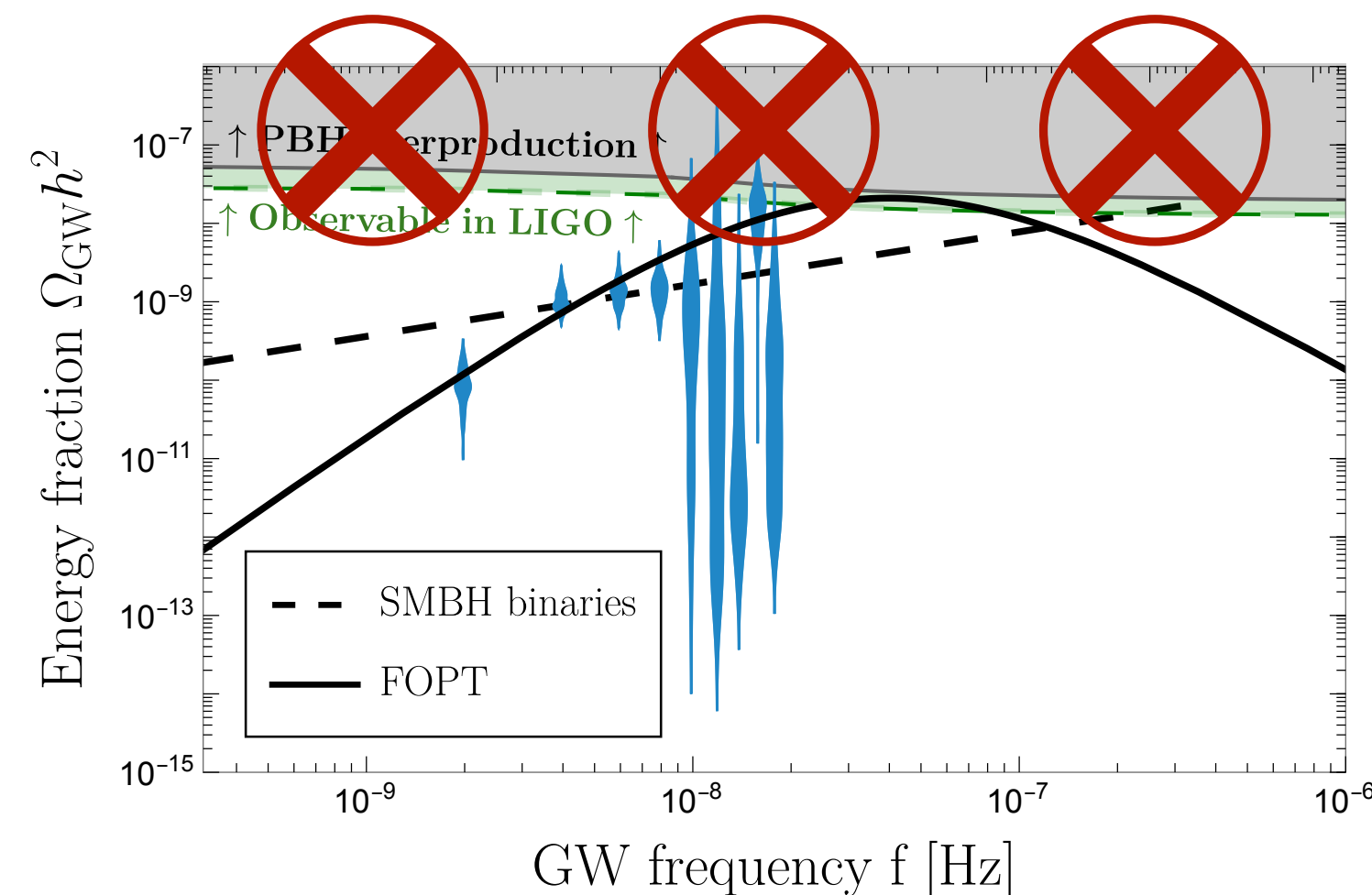
- 1) Solve DW trajectory in full GR**
- 2) Percolation theory**

Deng, Garriga, Vilenkin (1612.03753)

Wormhole



PBH



First-order phase transitions

Roper Pol et al. (2201.05630)

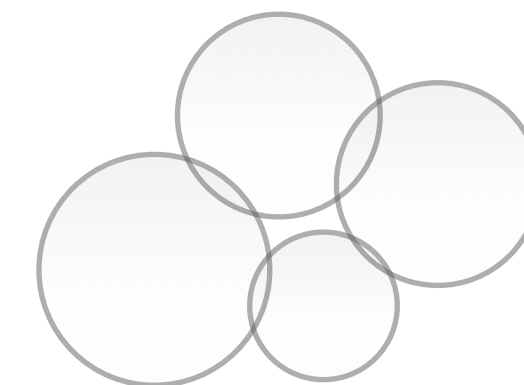
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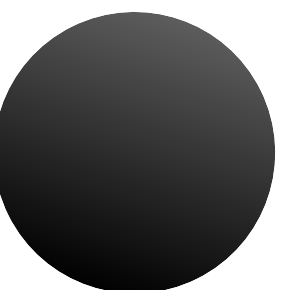
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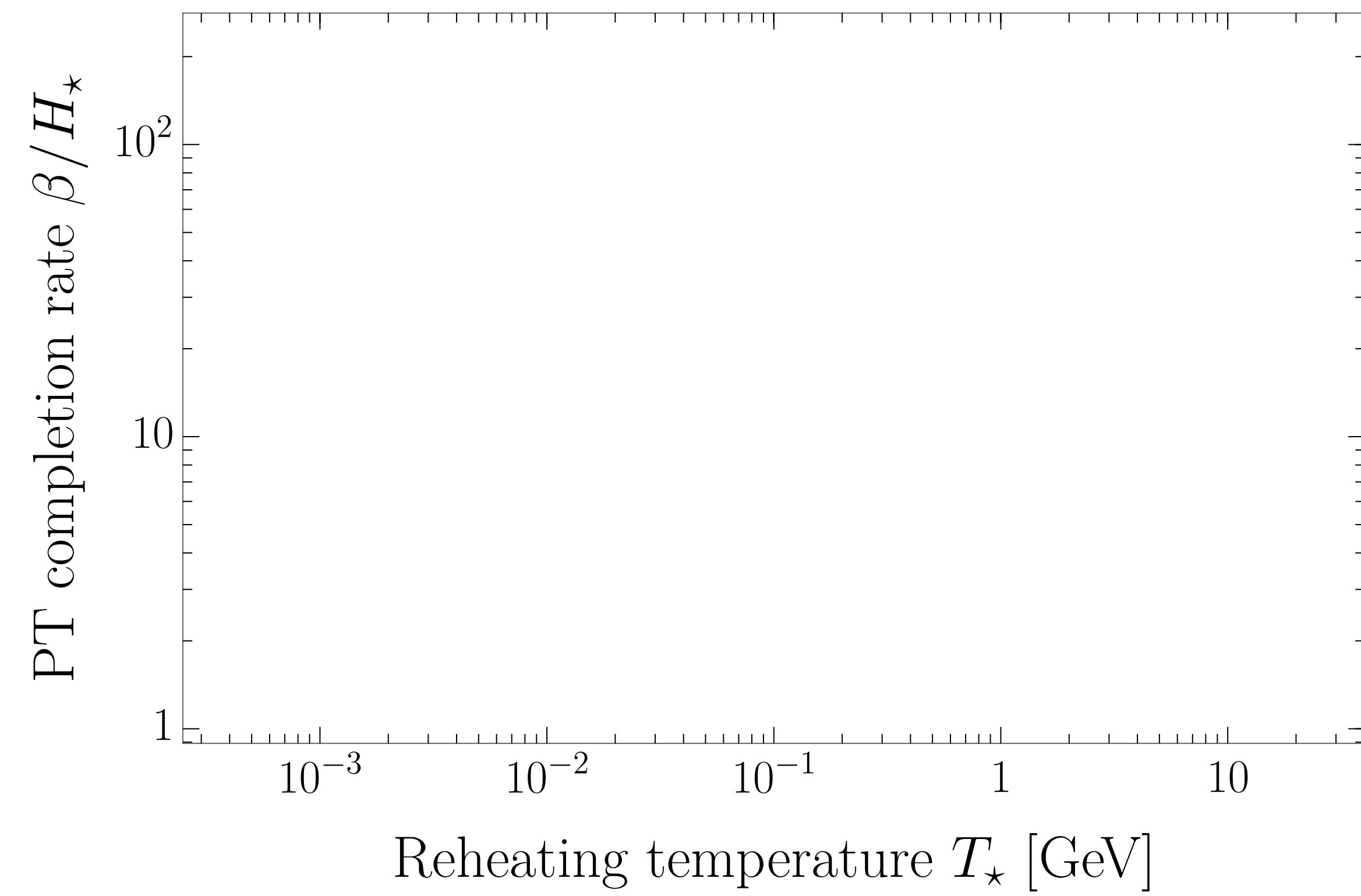
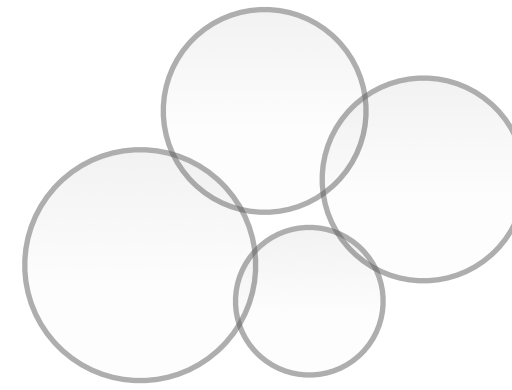
NEWS !

Franciolini, YG, Jinno, 2503.01962

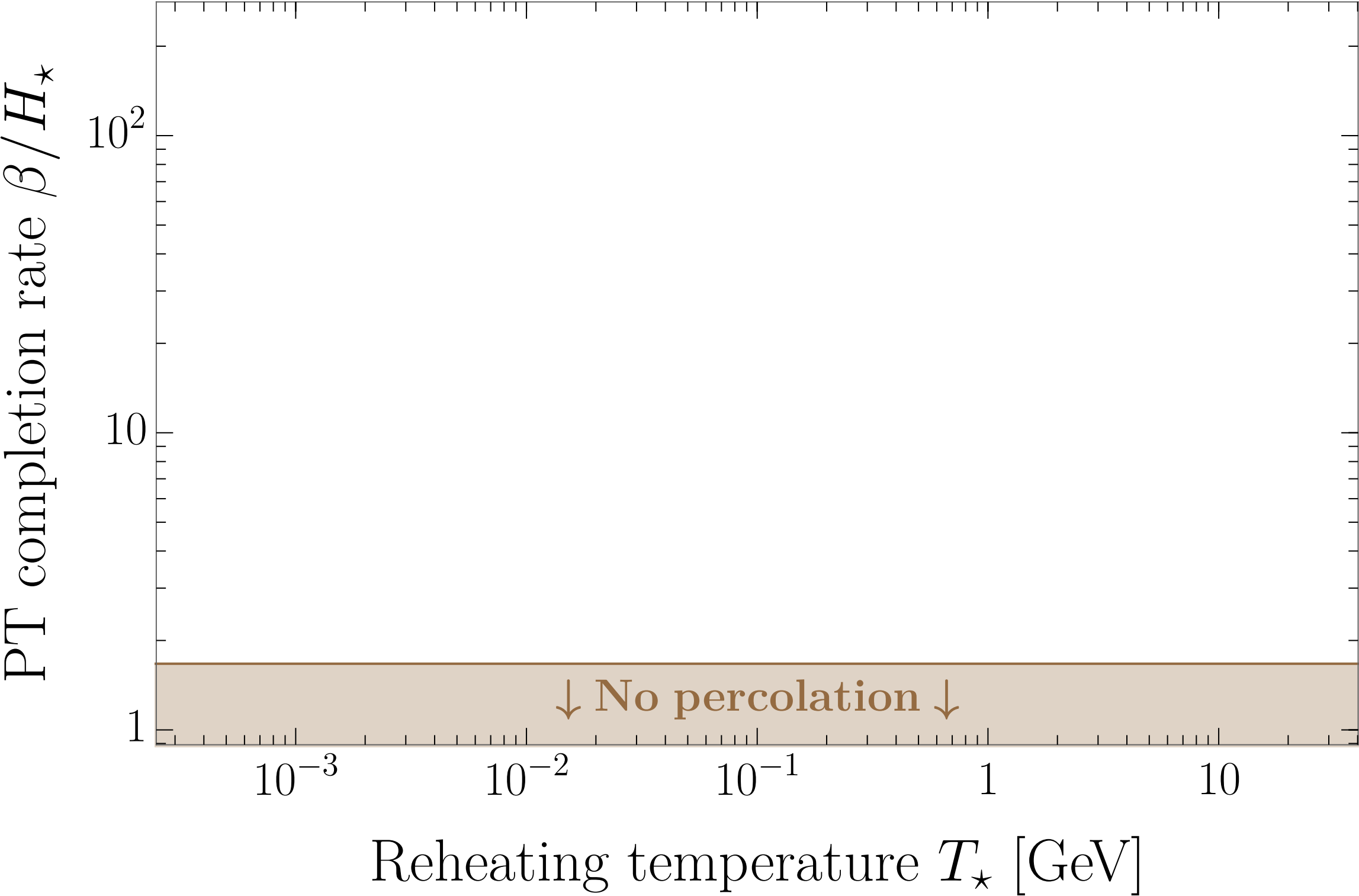
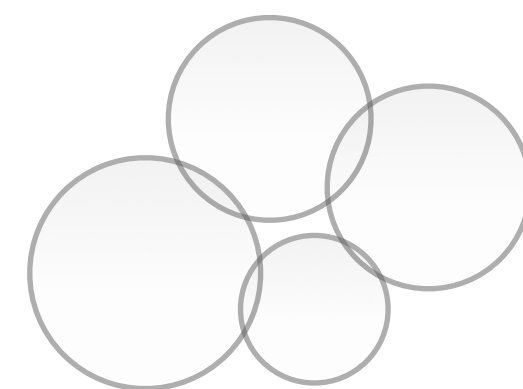
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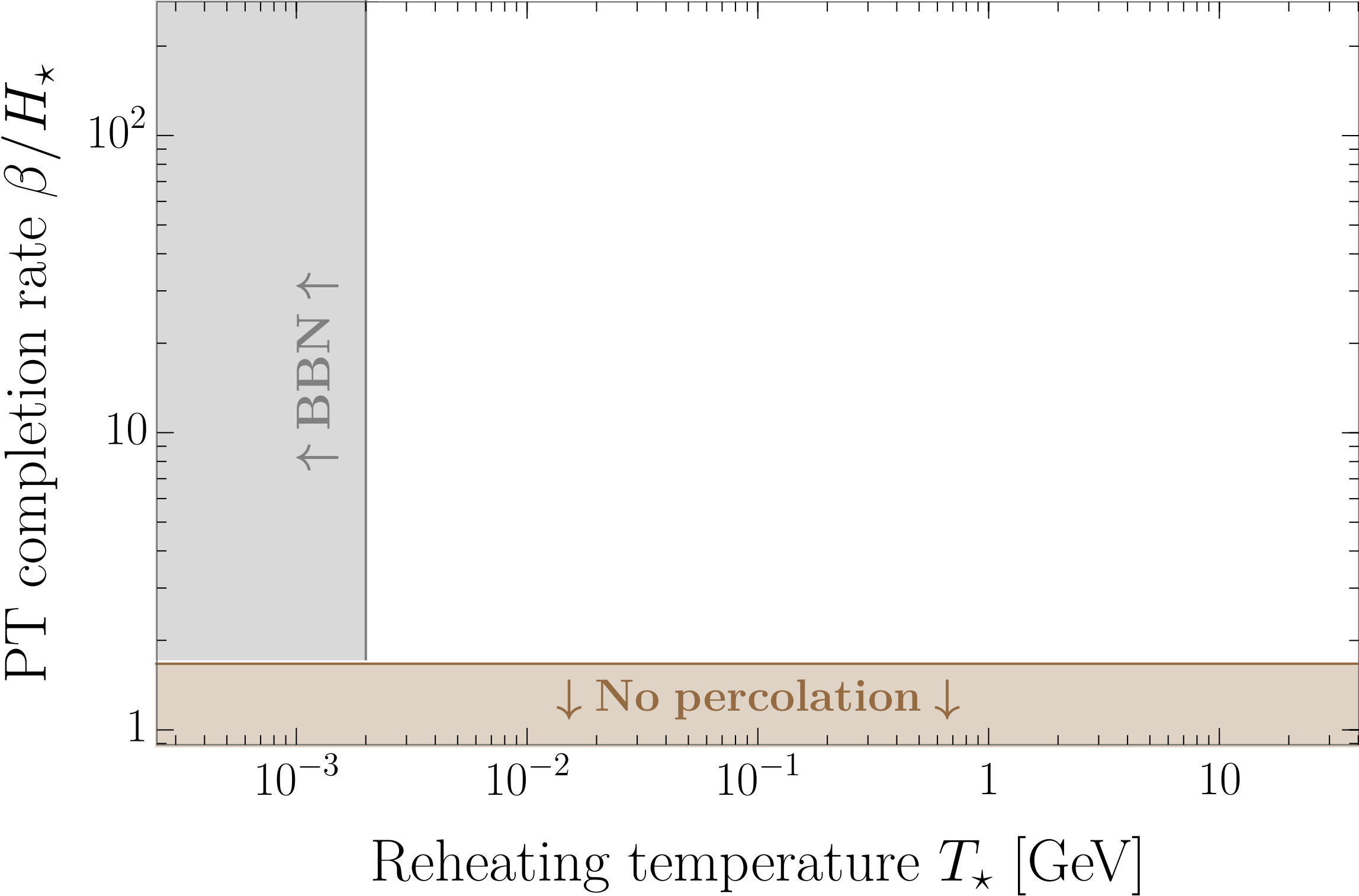
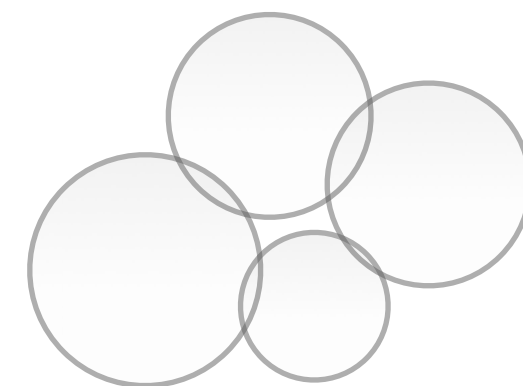
First-order
phase transition



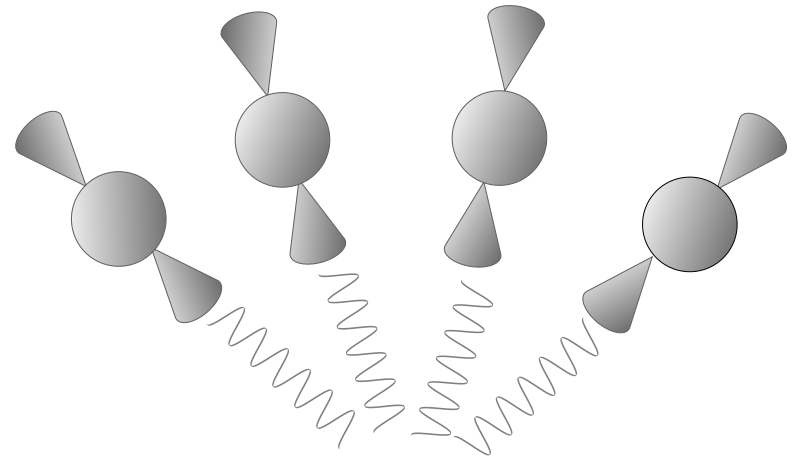
First-order
phase transition



First-order
phase transition



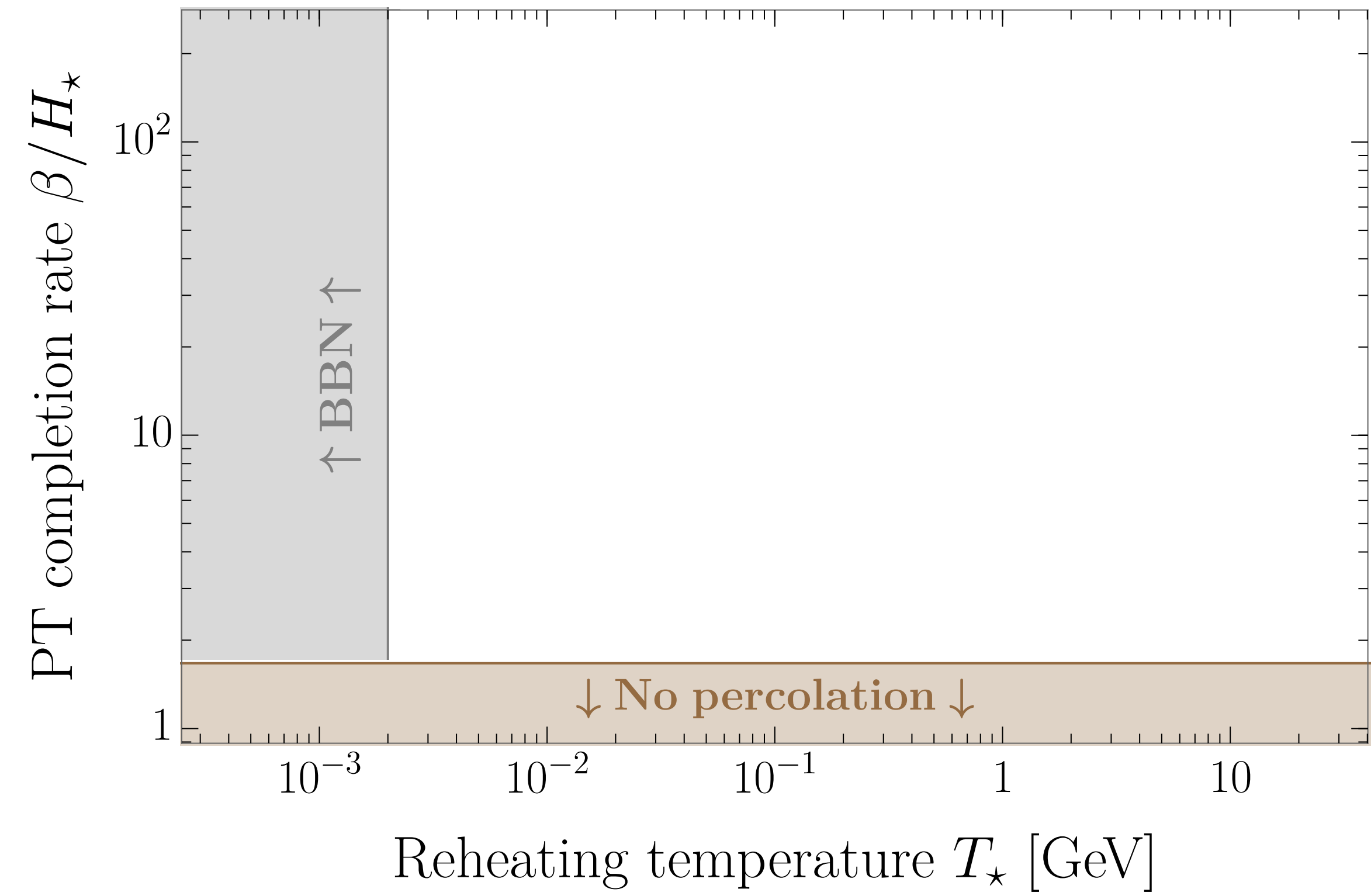
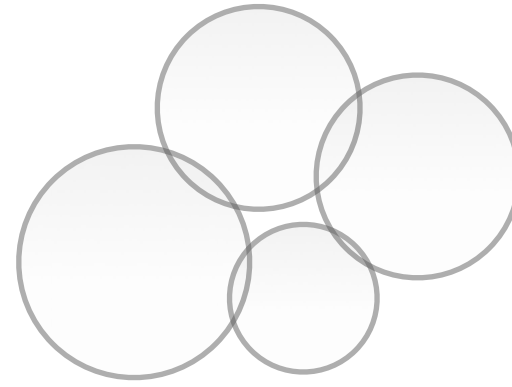
Pulsar Timing Arrays (PTA)



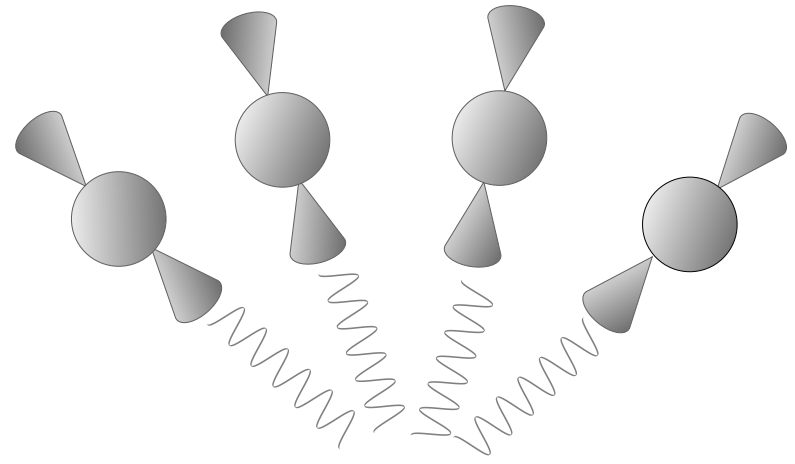
(GWs)
Gravitational
Waves



First-order phase transition



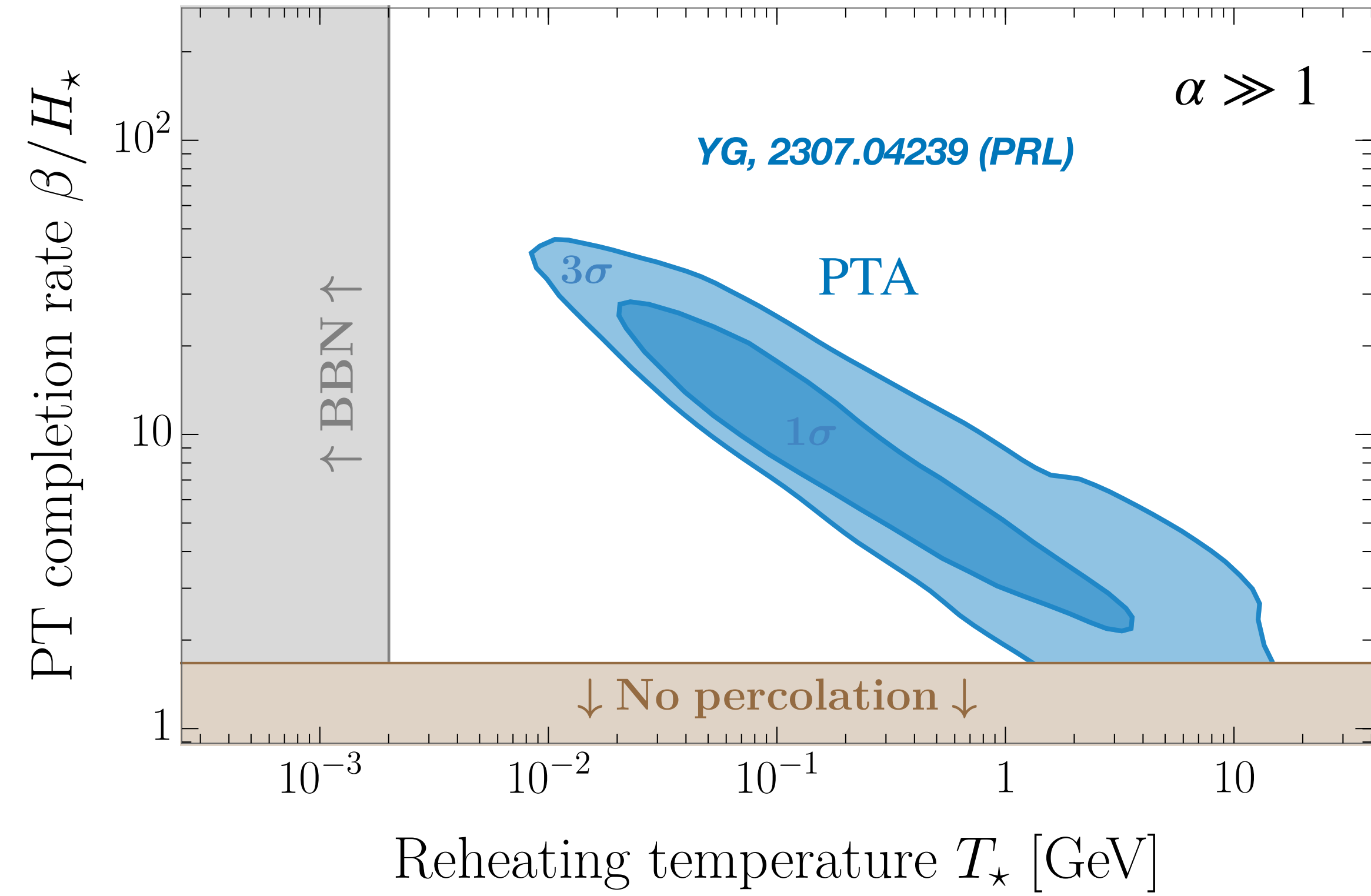
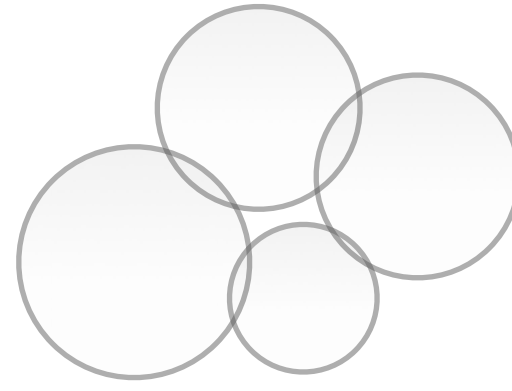
Pulsar Timing Arrays (PTA)



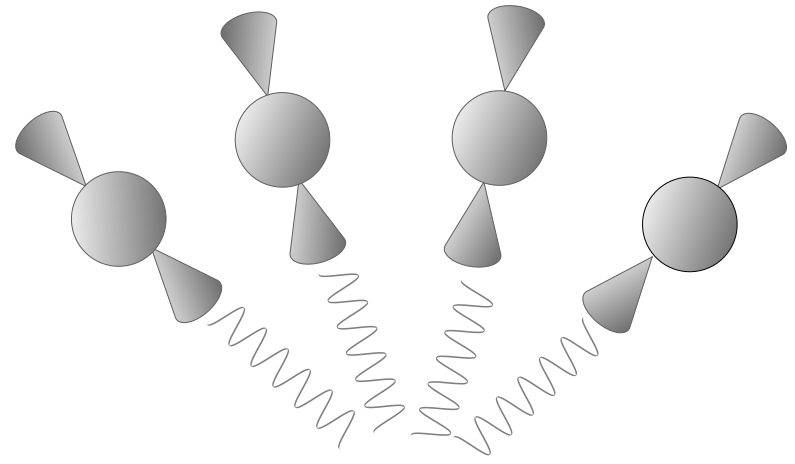
(GWs)
Gravitational
Waves



First-order phase transition



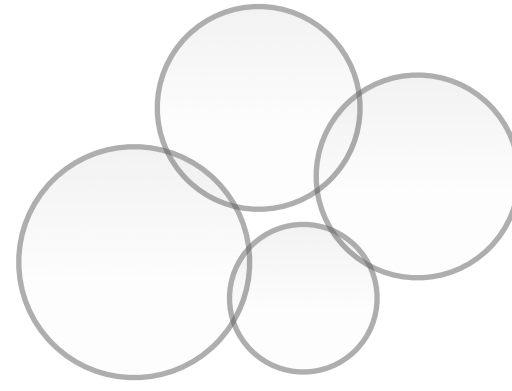
Pulsar Timing Arrays (PTA)



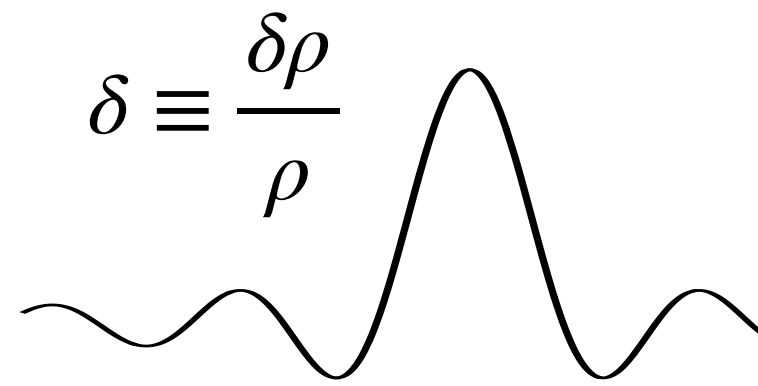
(GWs)
Gravitational
Waves



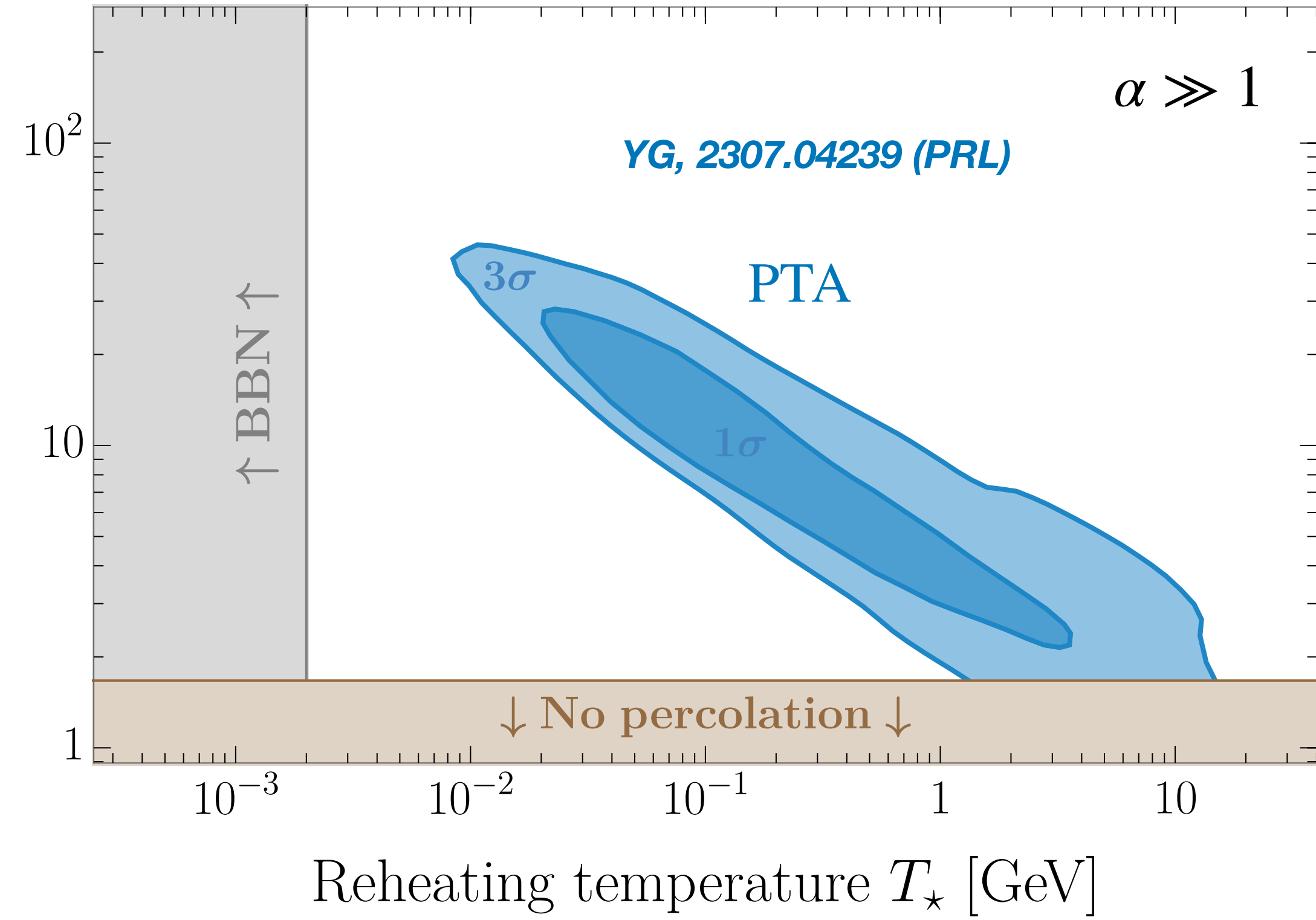
First-order phase transition



overdensities

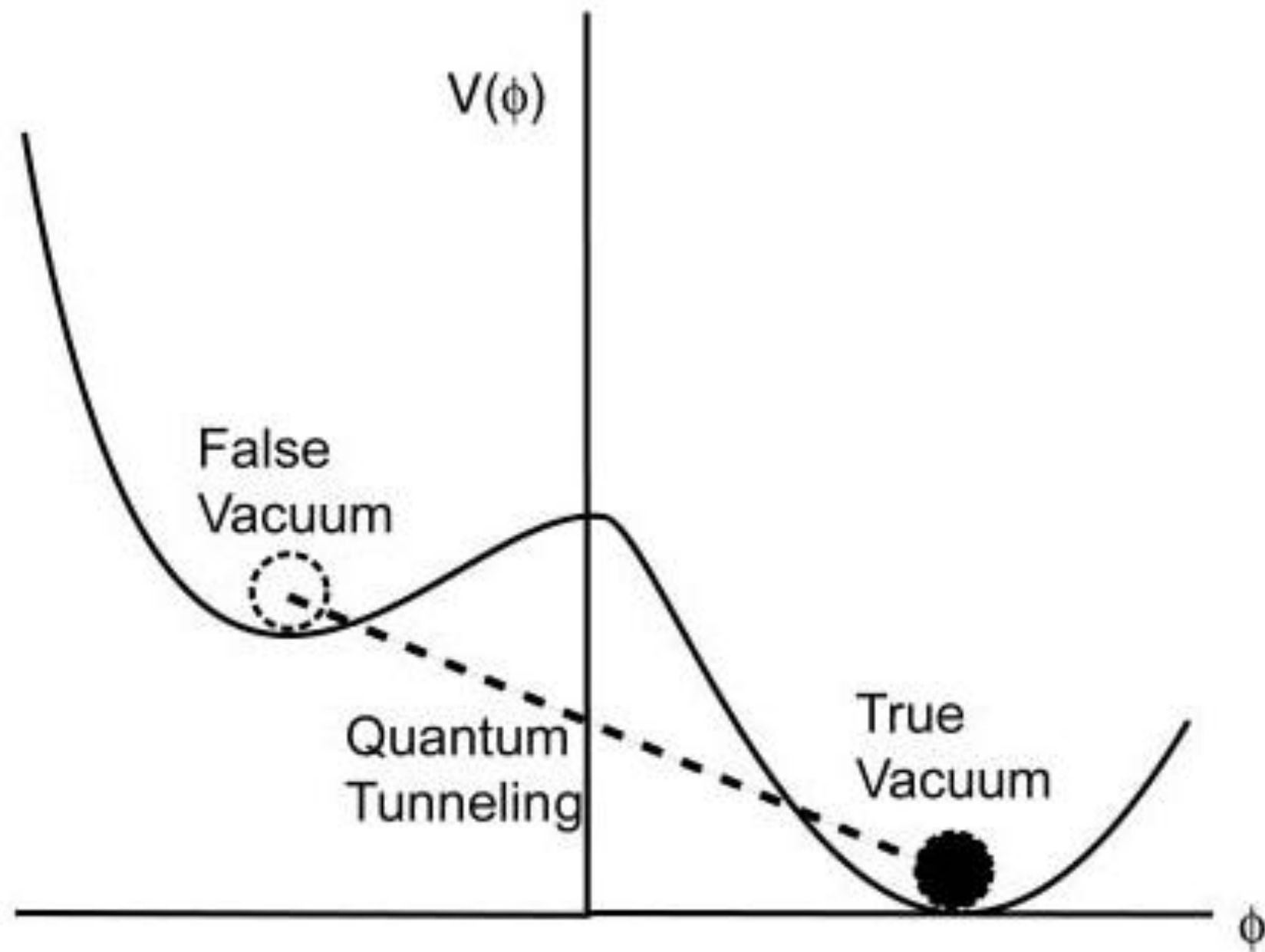


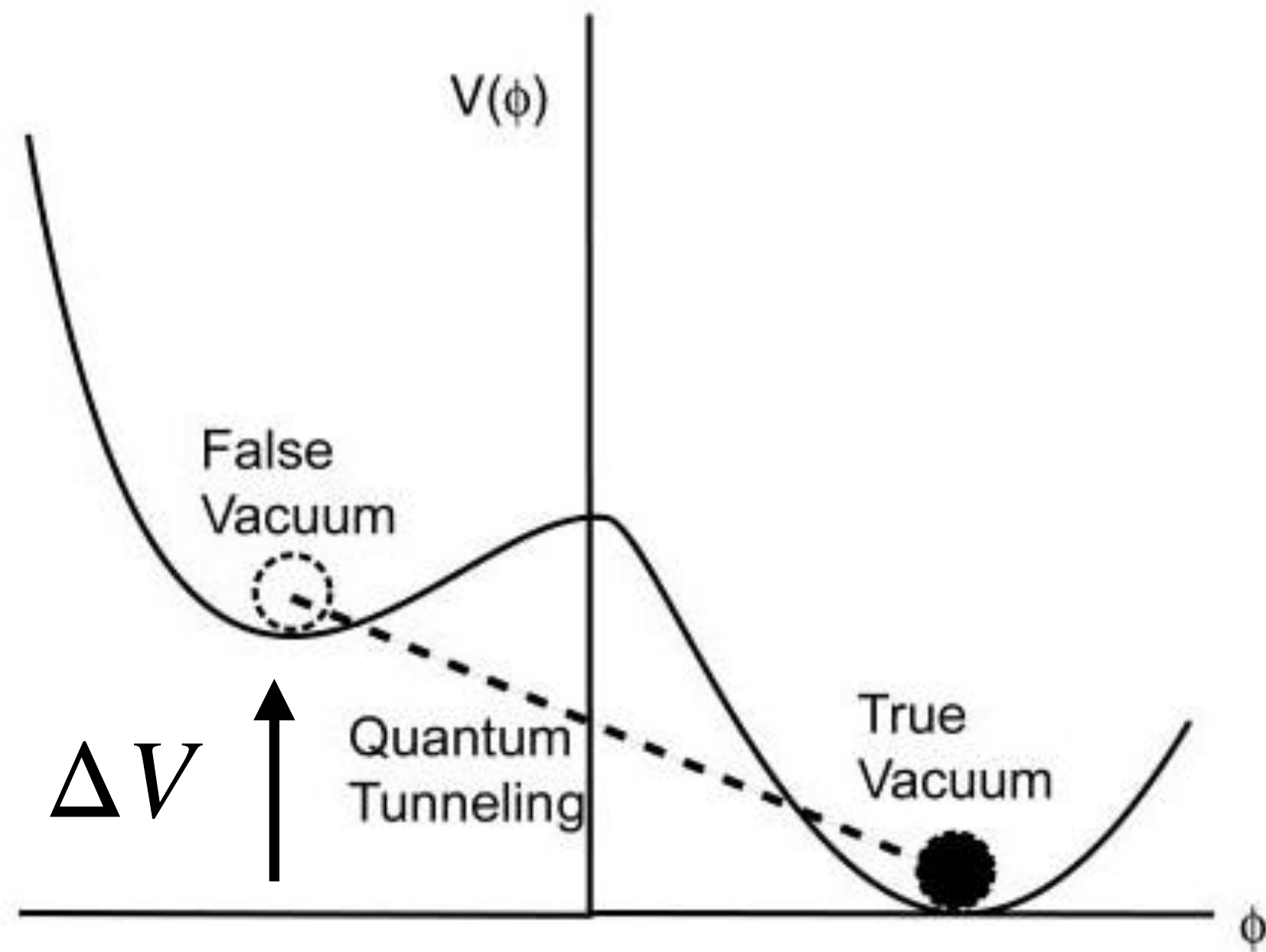
PT completion rate $\beta/H_\star$



PBHs from 1stOPT

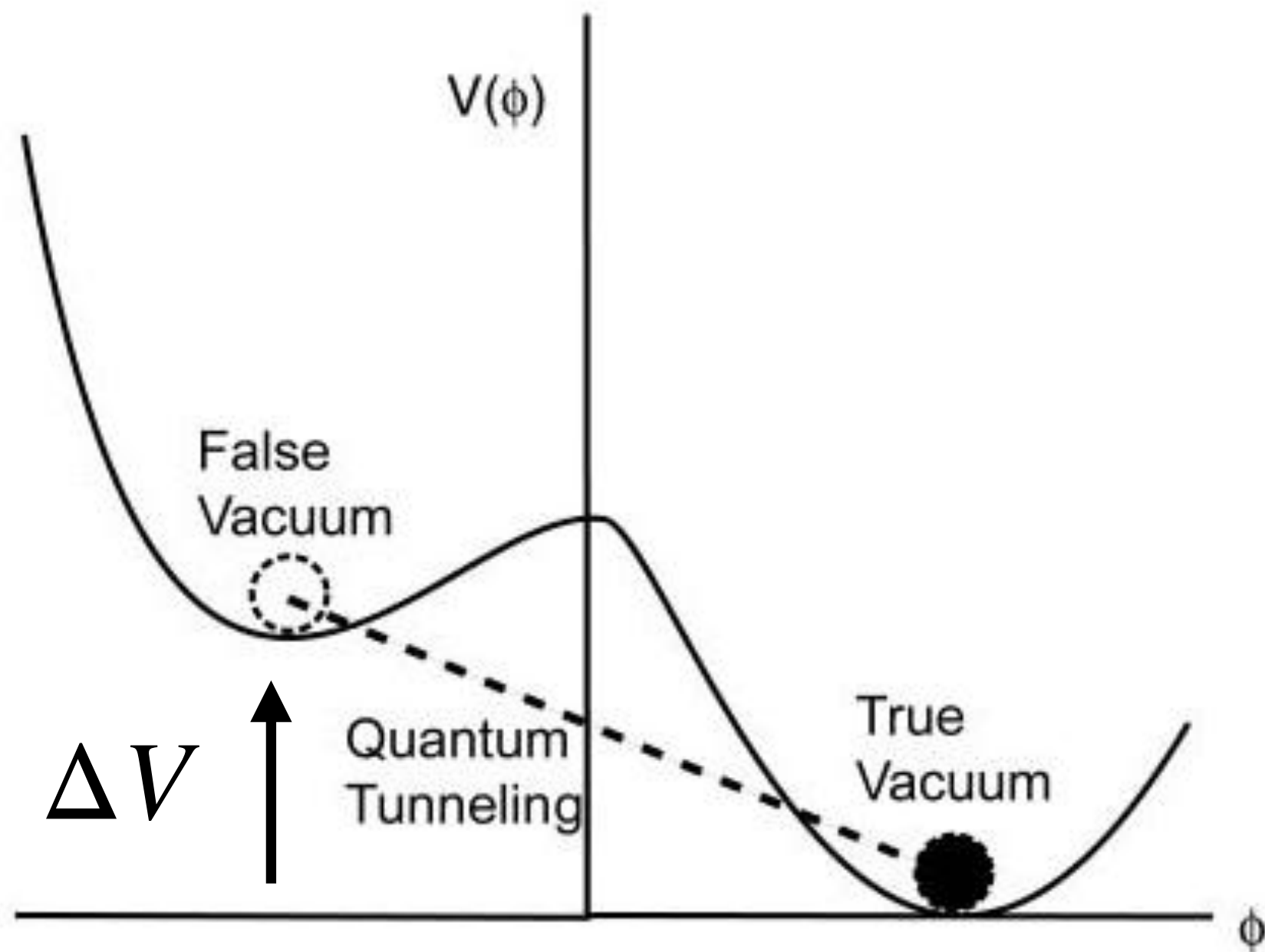
YG, Volansky 2305:04942





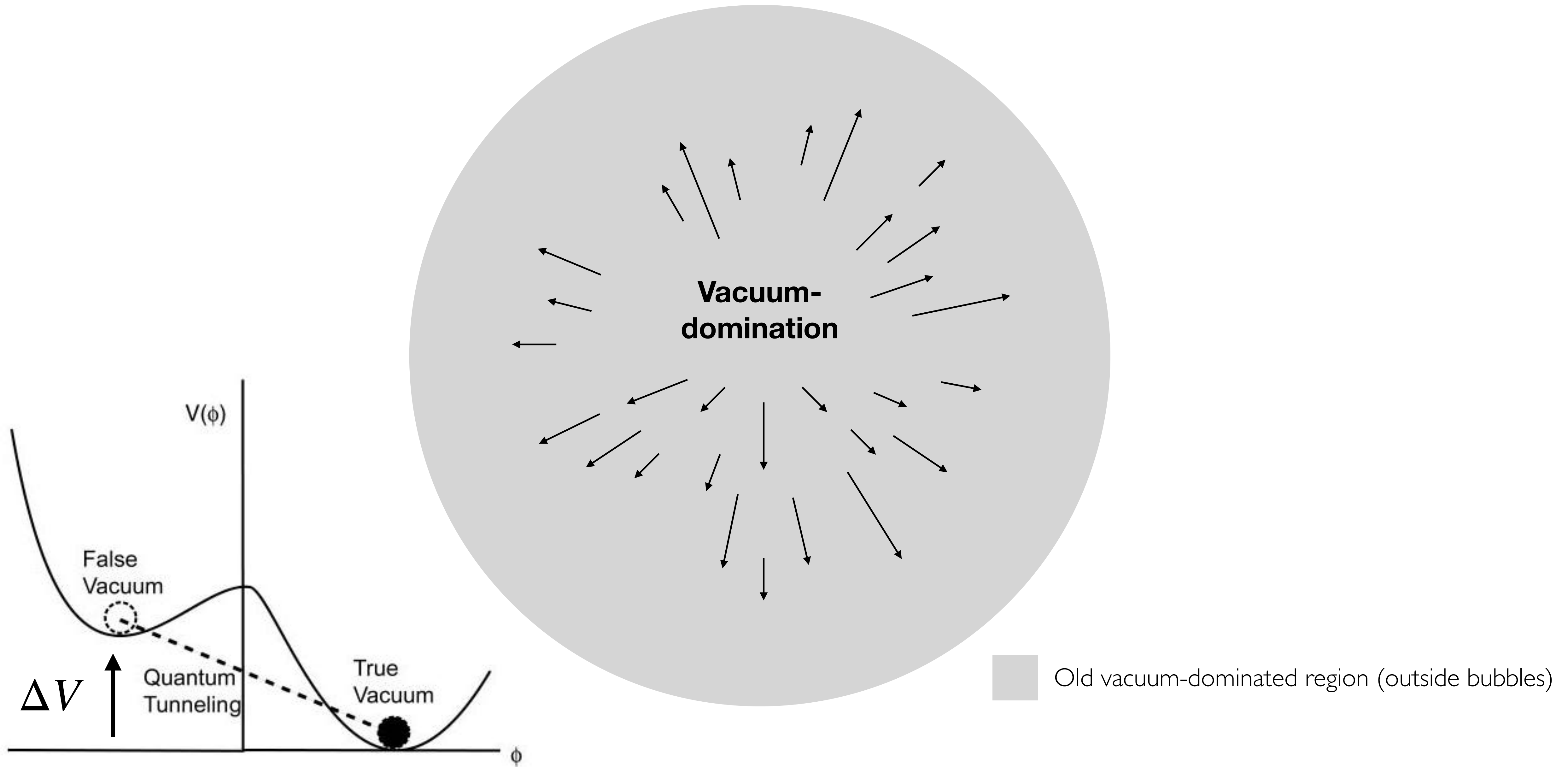
Strong 1st order PT:

$$\Delta V \gg \rho_{\text{rad}}$$



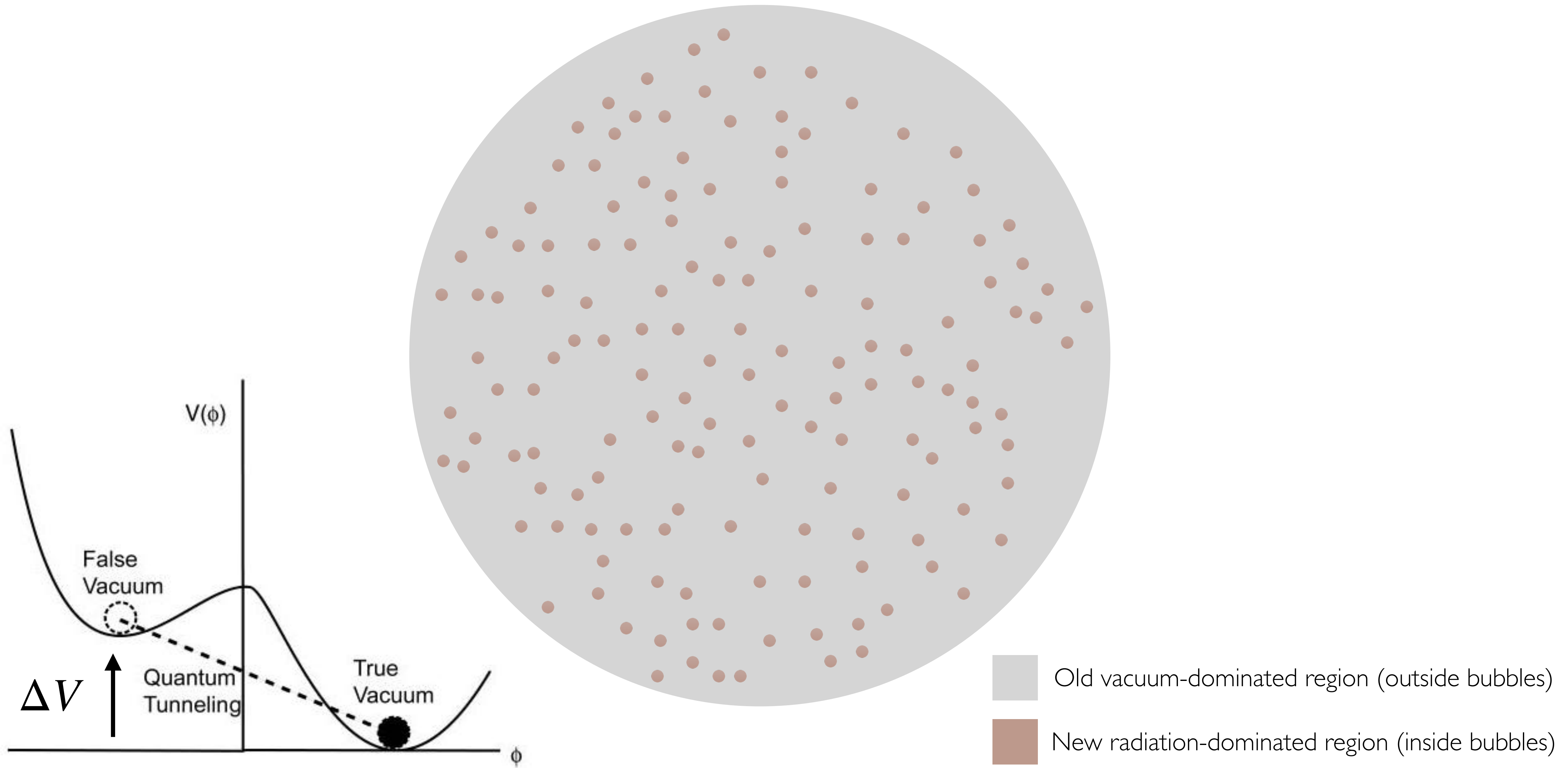
PBHs from 1stOPT

YG, Volansky 2305:04942



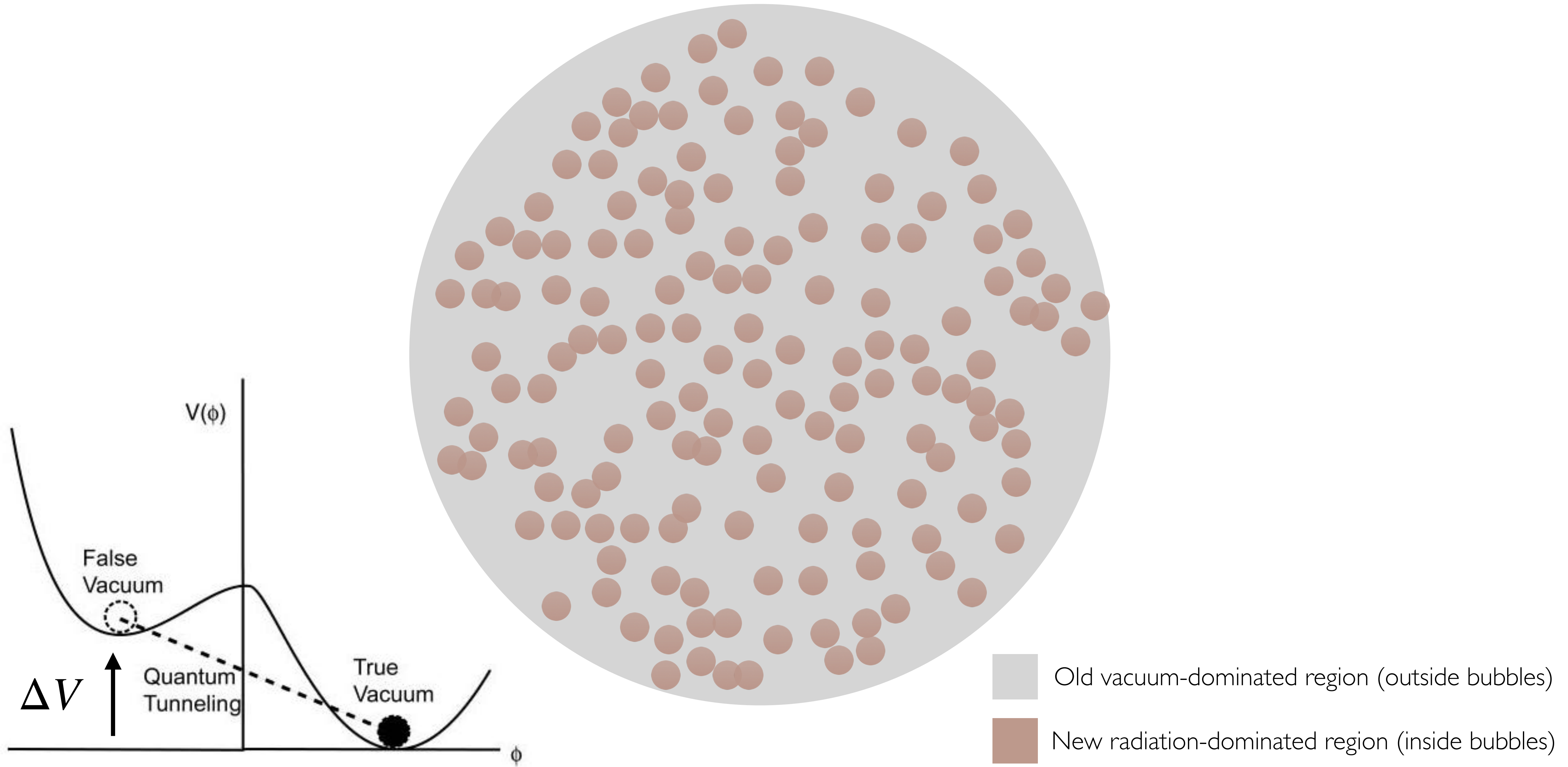
PBHs from 1stOPT

YG, Volansky 2305:04942



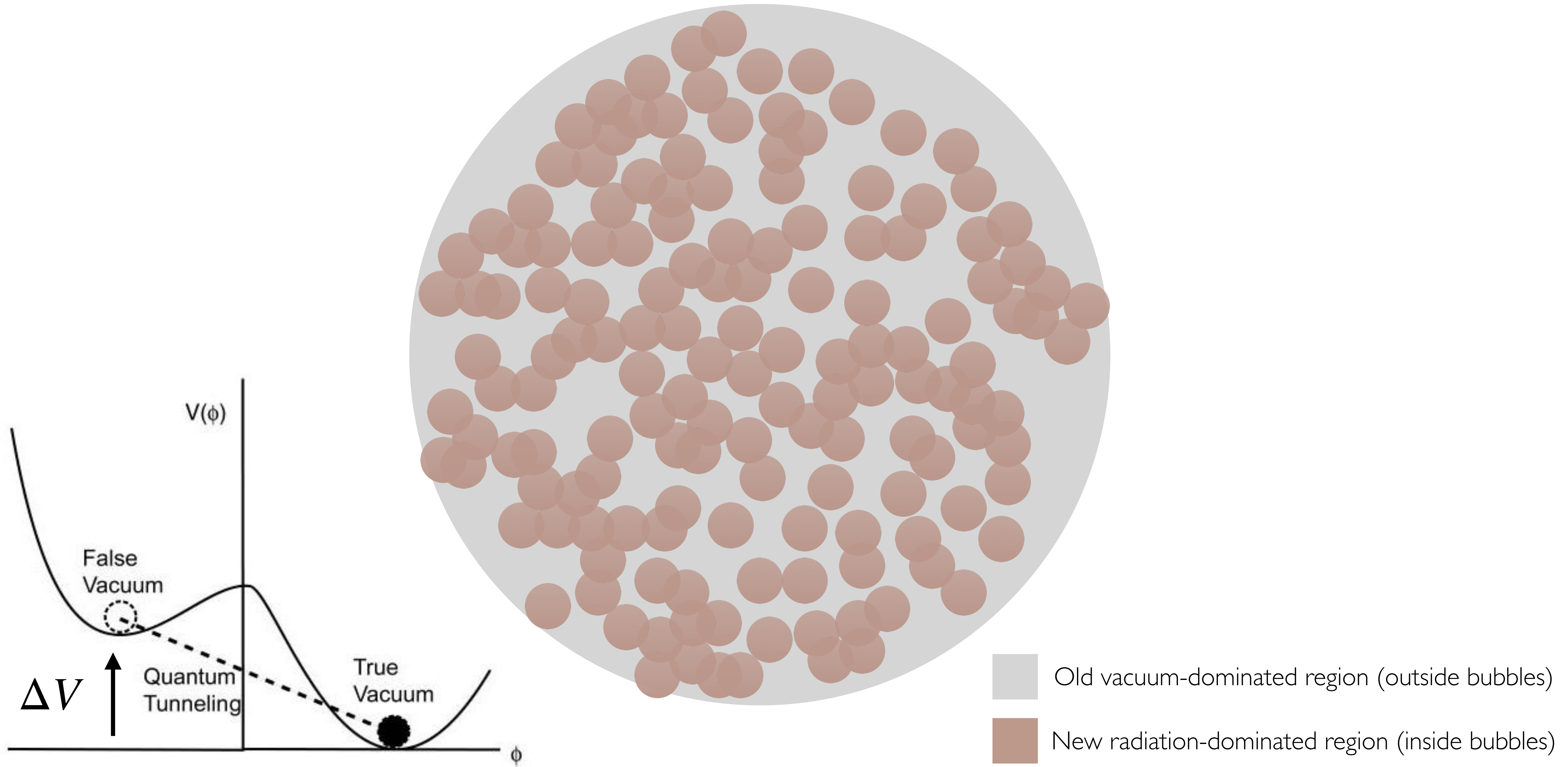
PBHs from 1stOPT

YG, Volansky 2305:04942



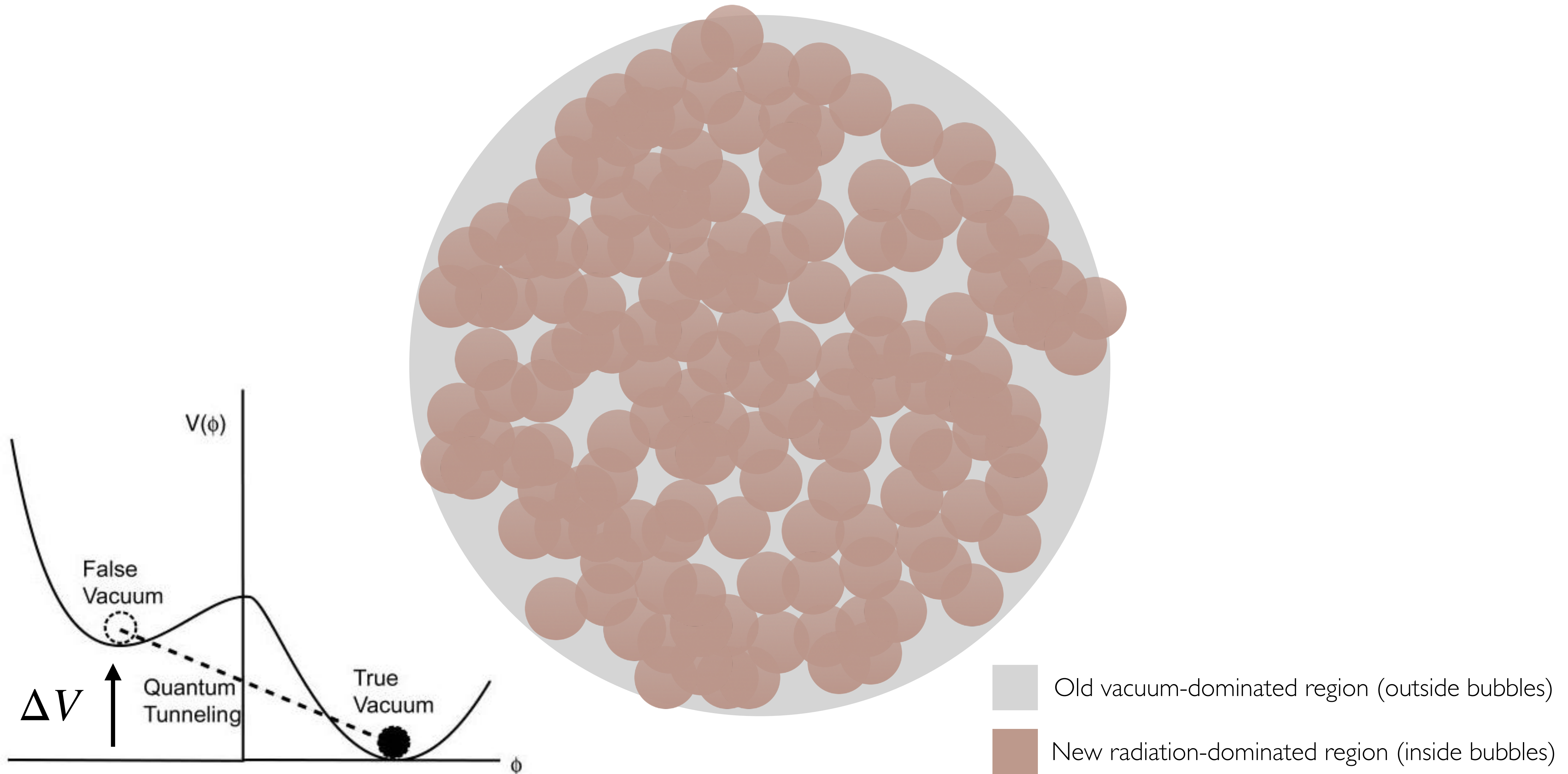
PBHs from 1stOPT

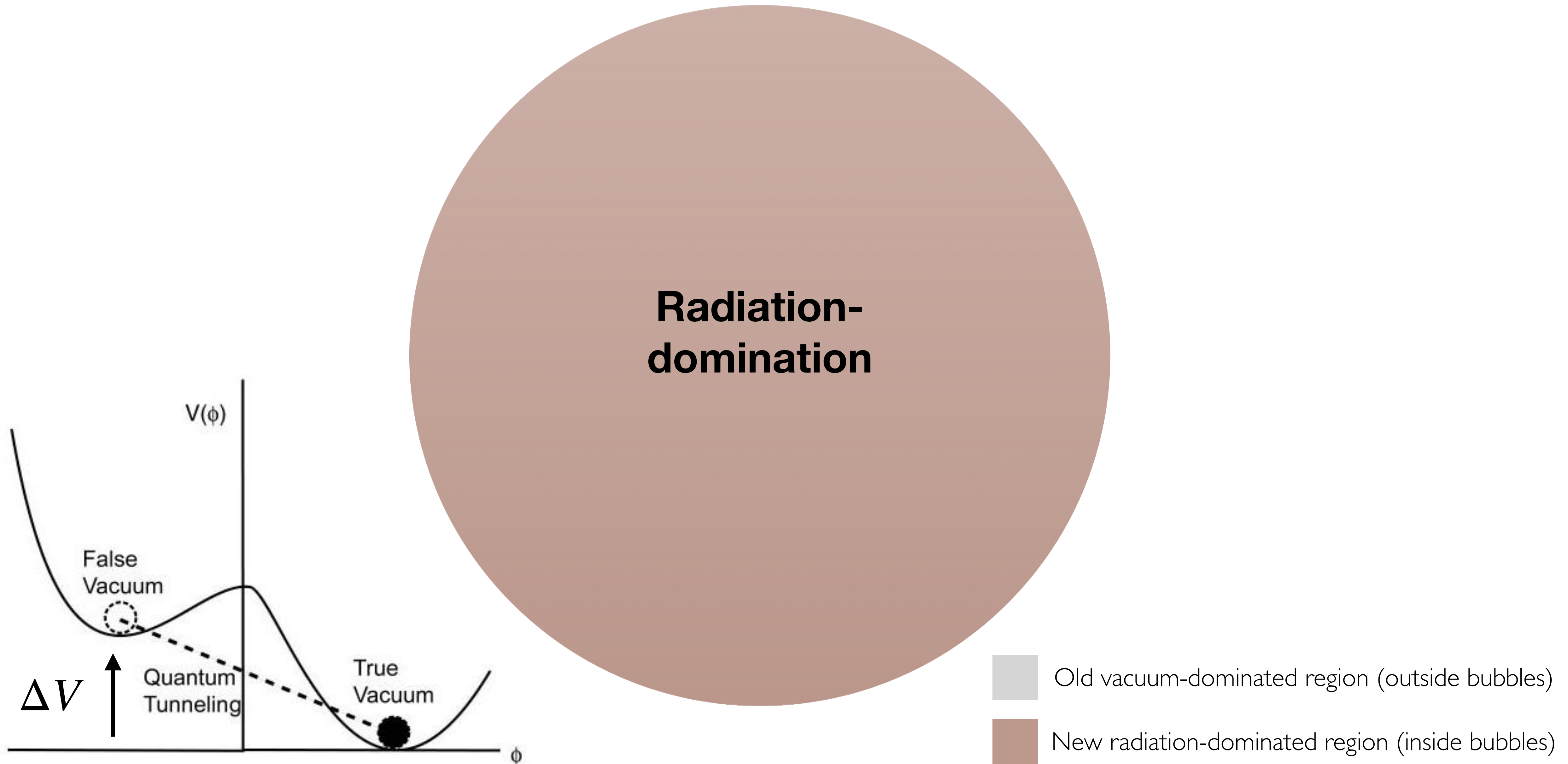
YG, Volansky 2305:04942



PBHs from 1stOPT

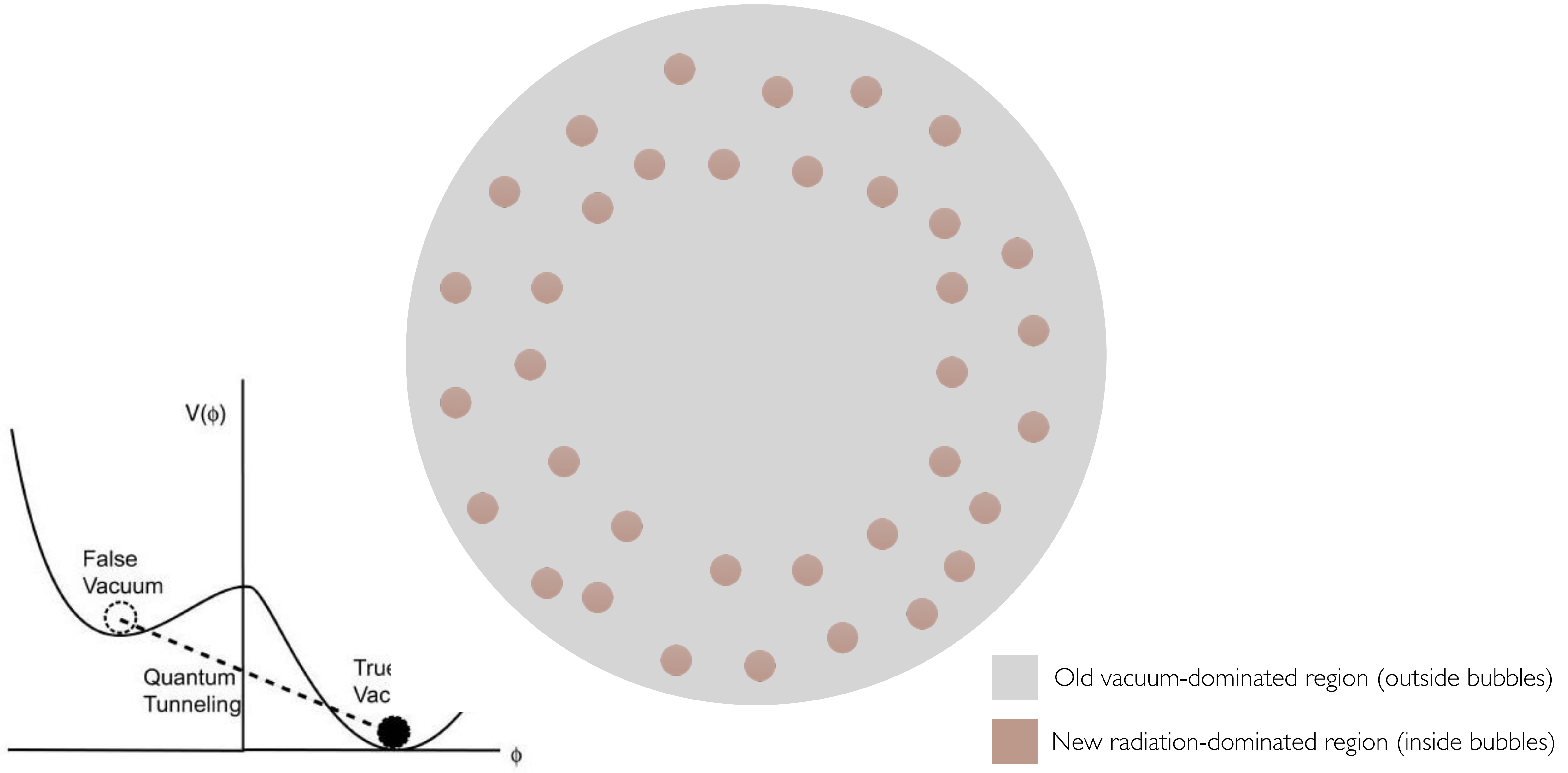
YG, Volansky 2305:04942





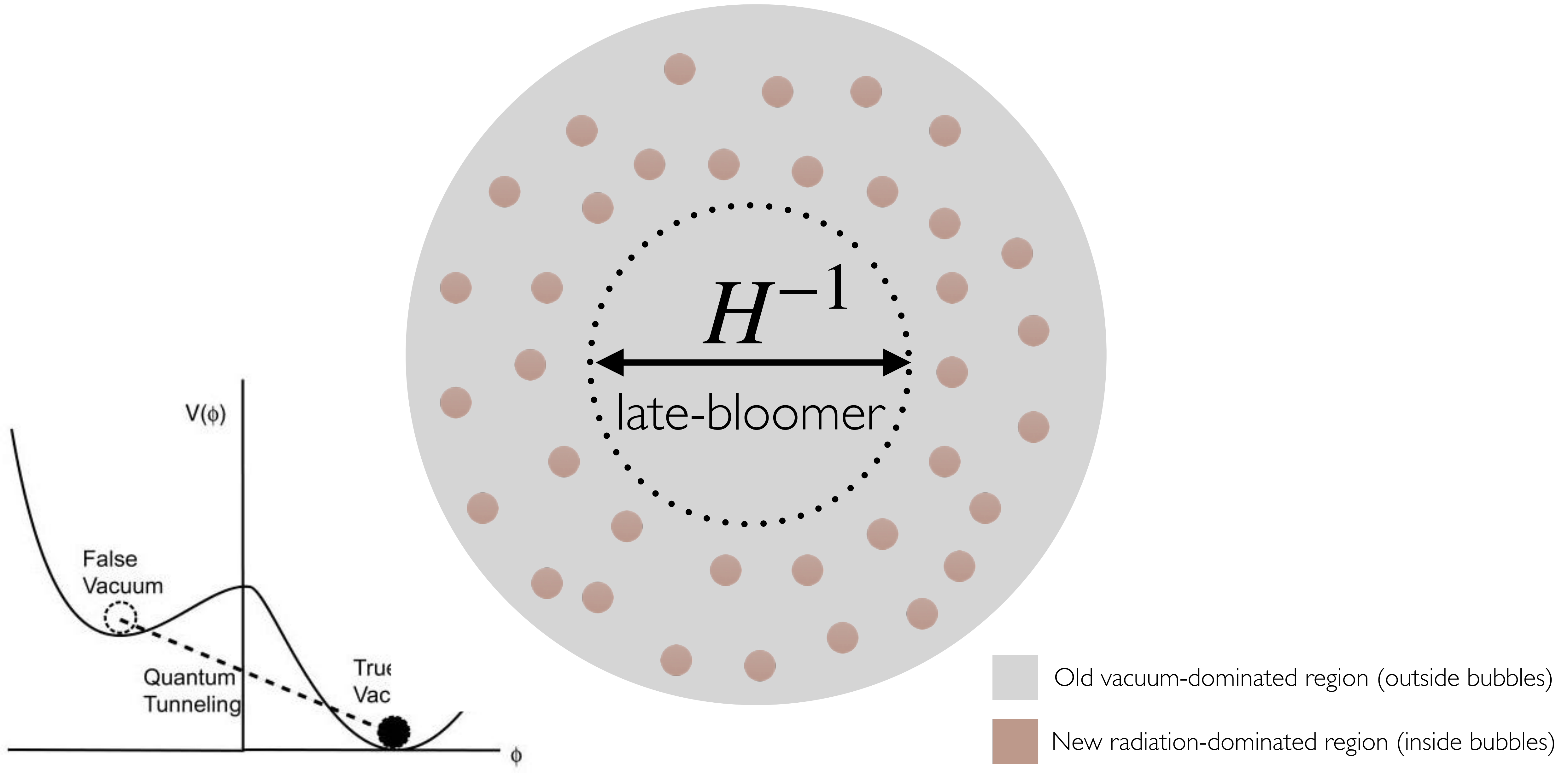
PBHs from 1stOPT

YG, Volansky 2305:04942



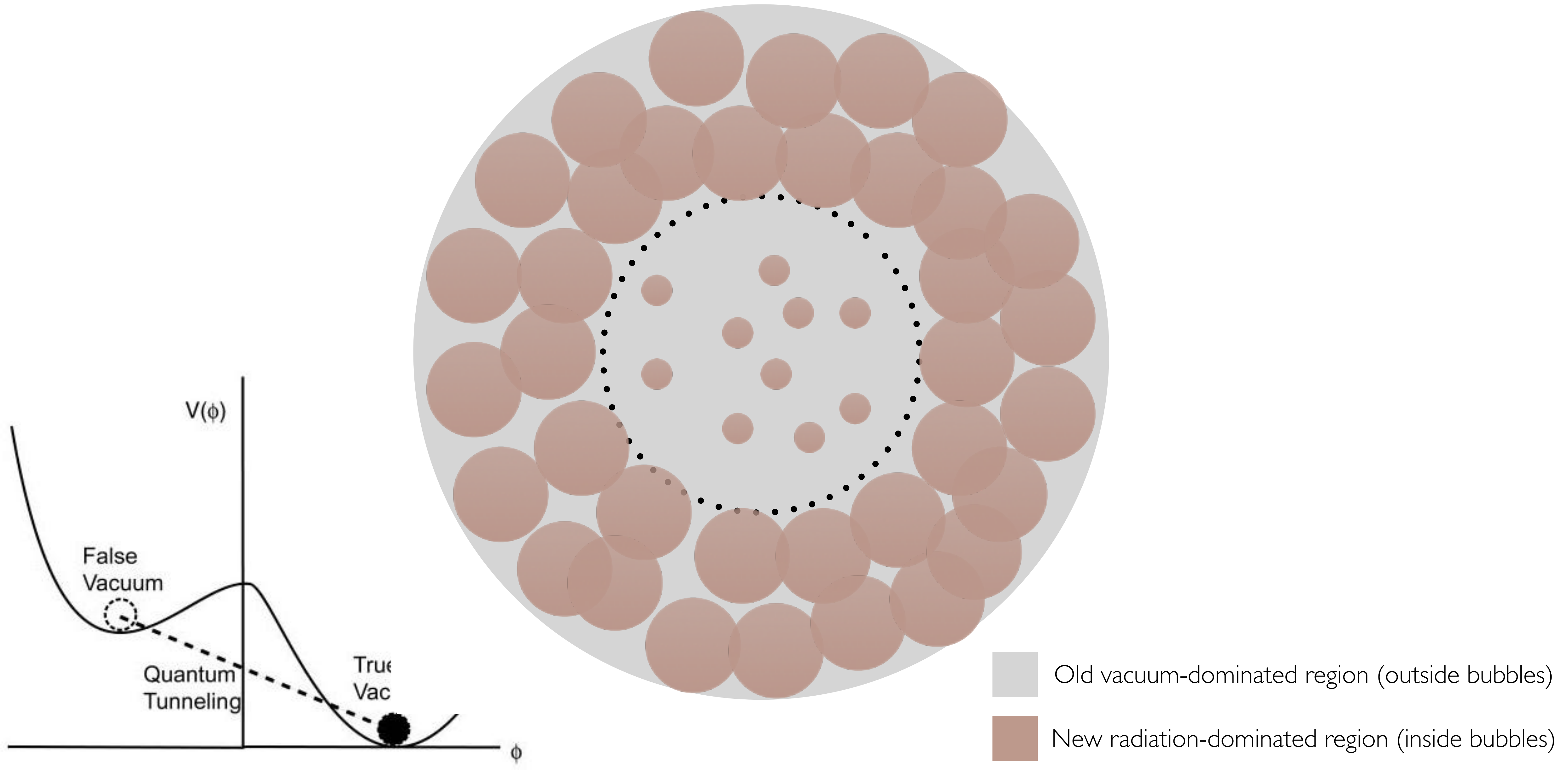
PBHs from 1stOPT

YG, Volansky 2305:04942



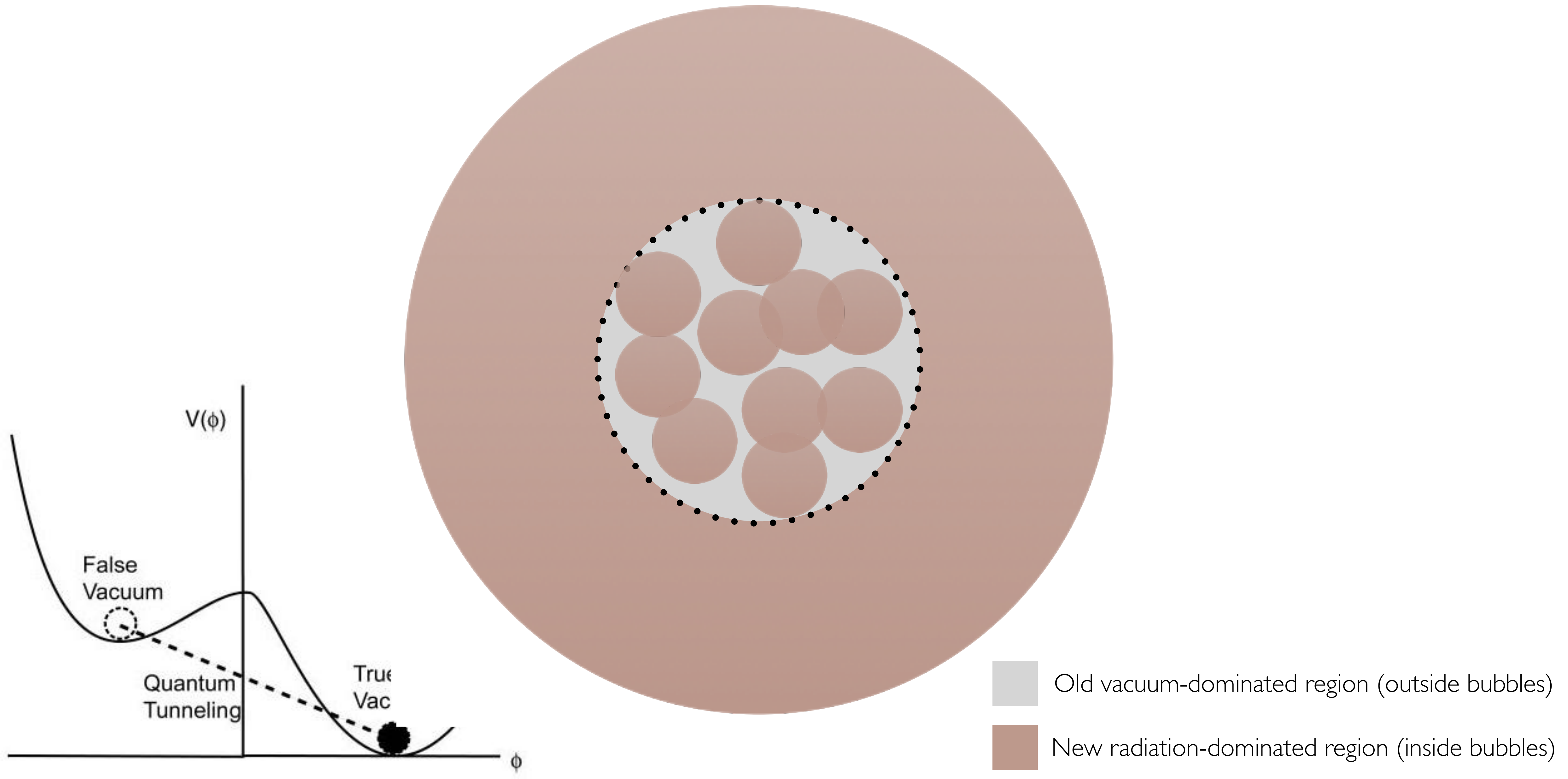
PBHs from 1stOPT

YG, Volansky 2305:04942



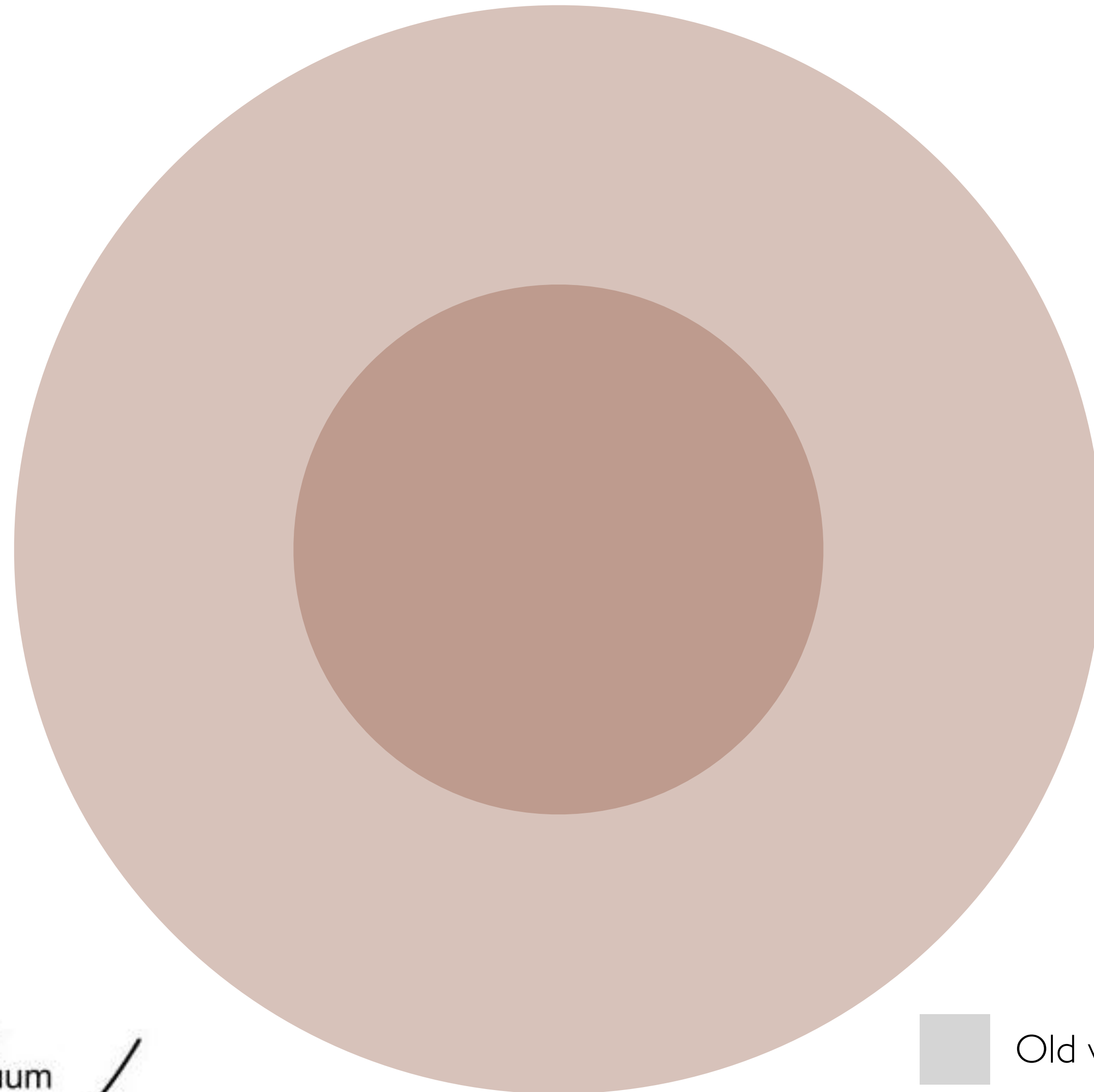
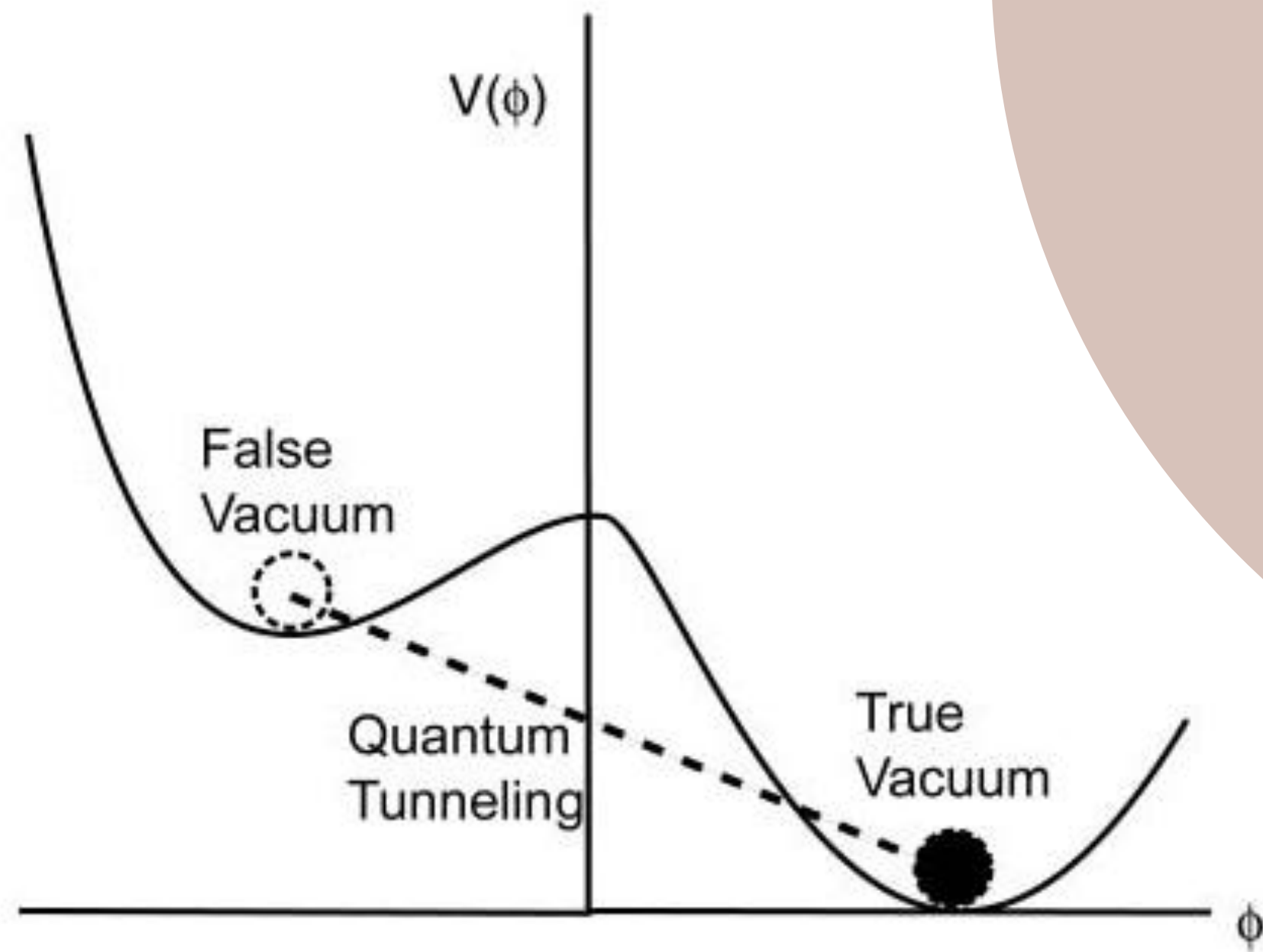
PBHs from 1stOPT

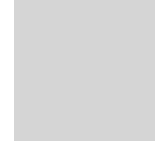
YG, Volansky 2305:04942



PBHs from 1stOPT

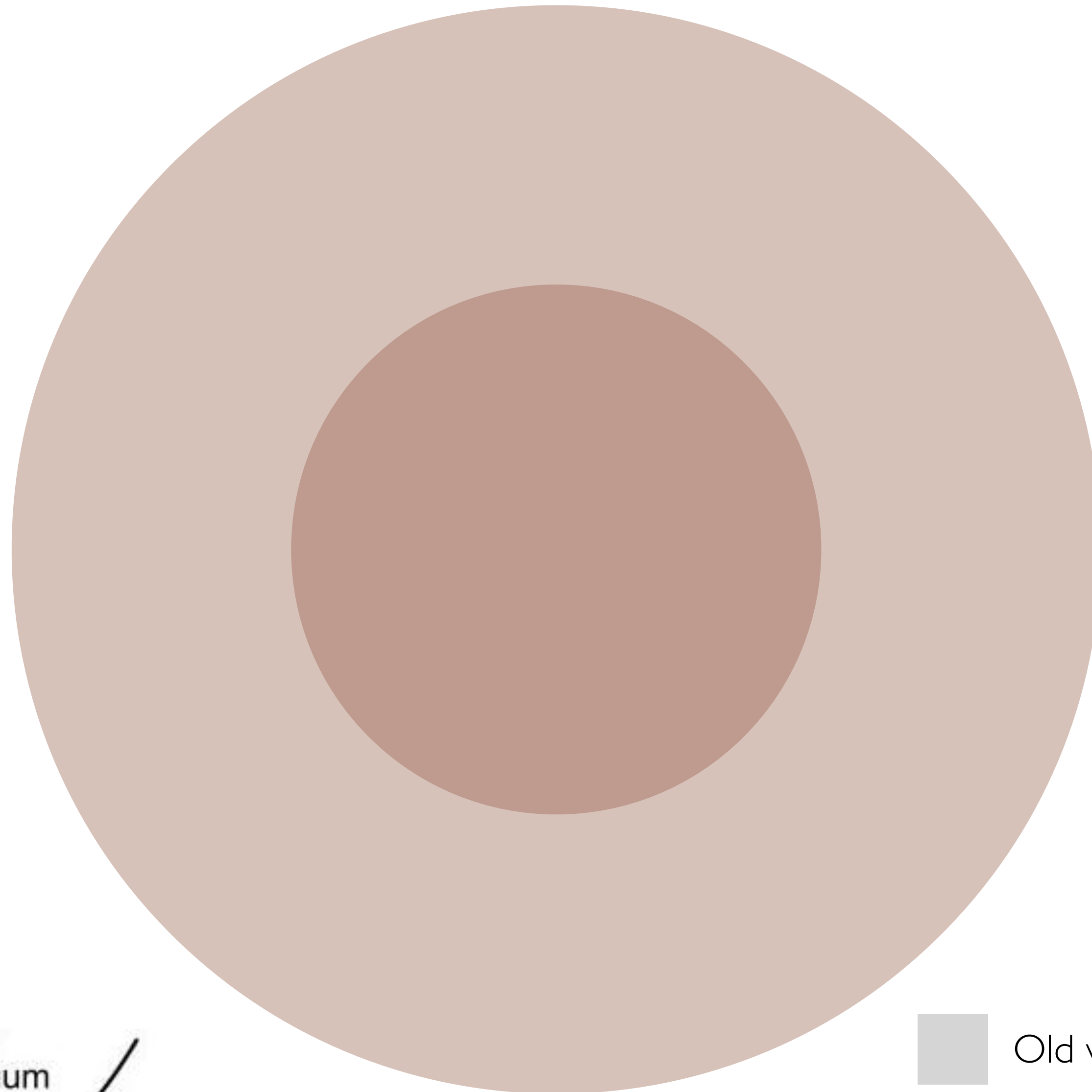
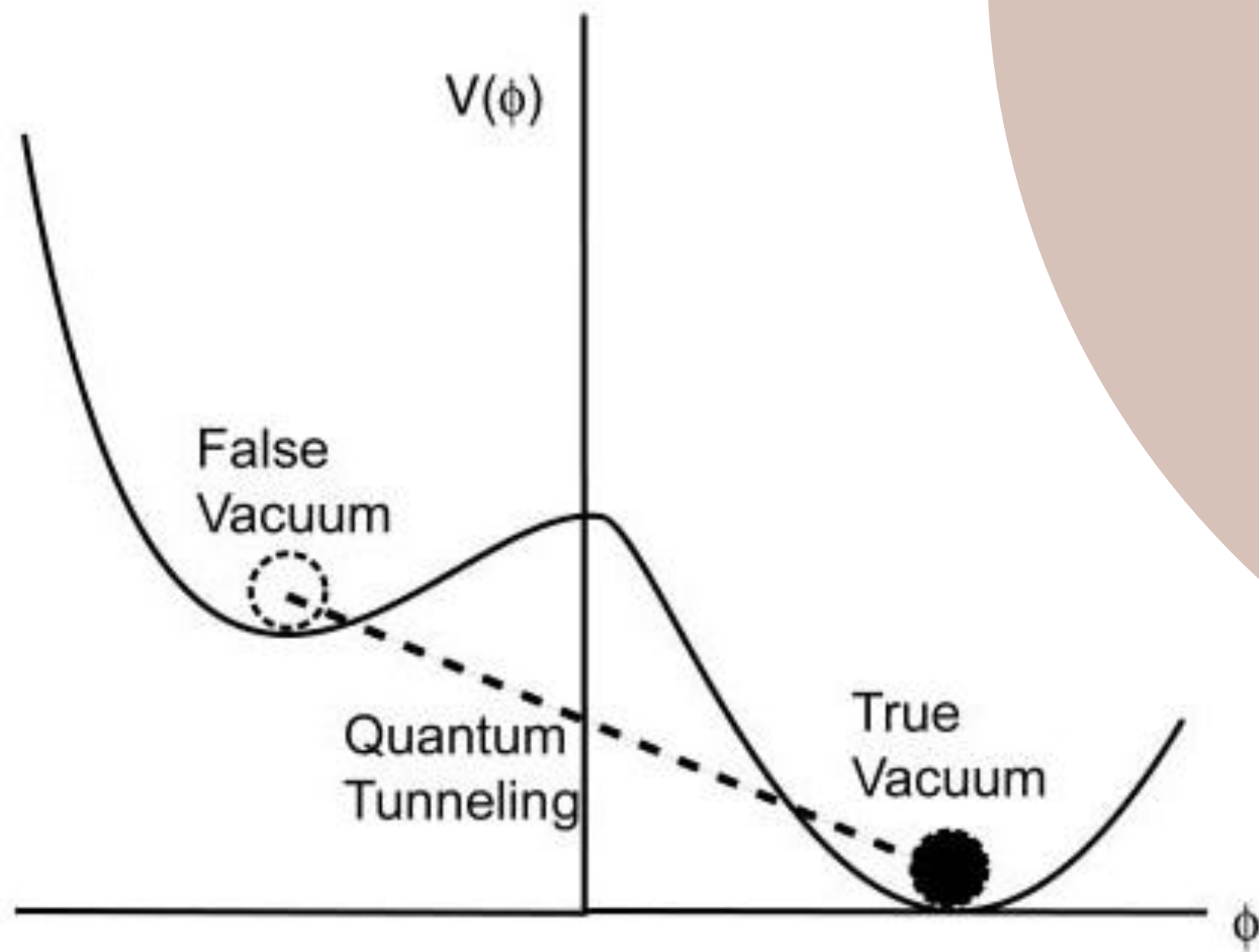
YG, Volansky 2305:04942



-  Old vacuum-dominated region (outside bubbles)
-  New radiation-dominated region (inside bubbles)

if

$$\delta\rho/\rho \gtrsim 0.50.$$



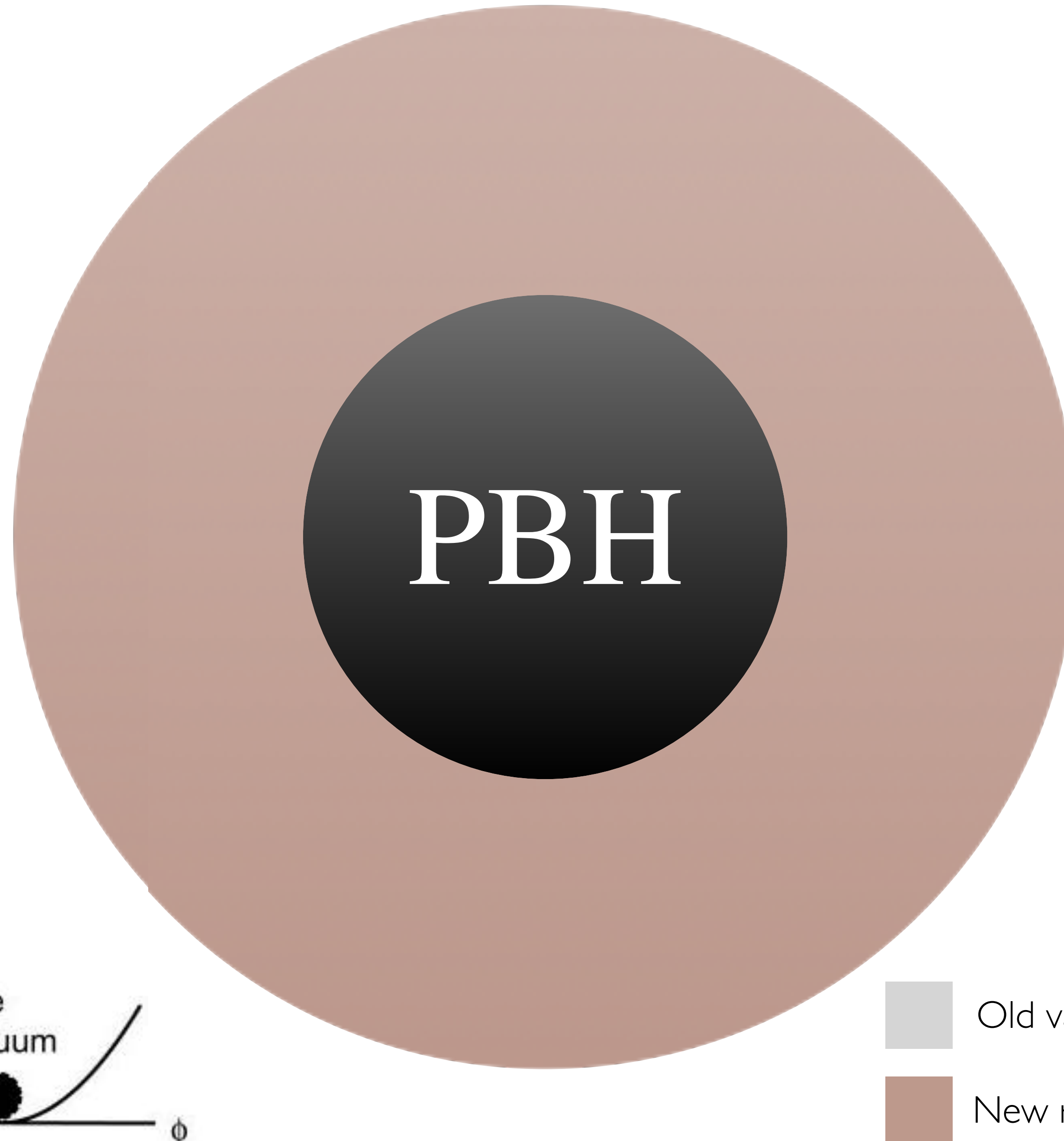
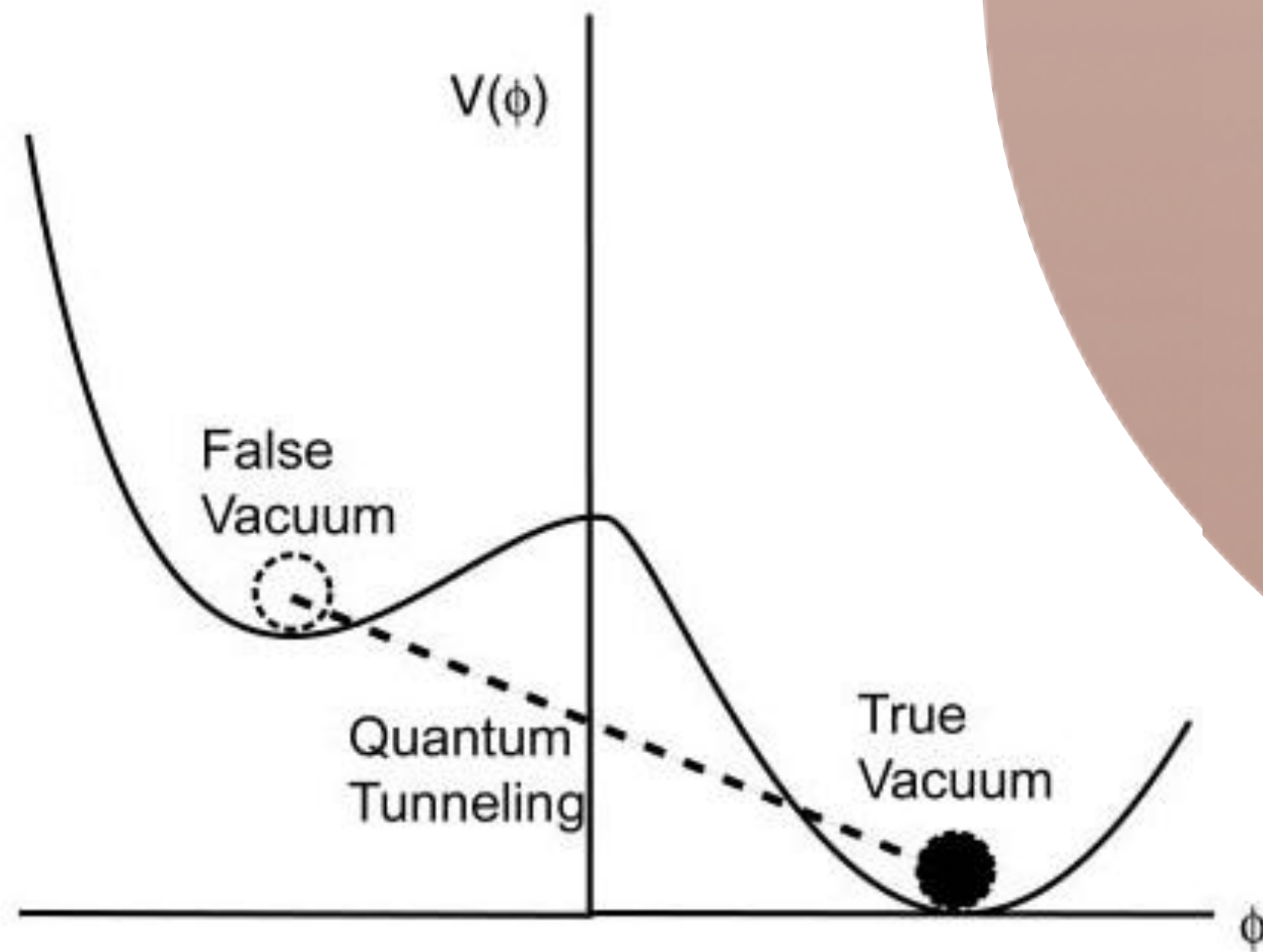
-  Old vacuum-dominated region (outside bubbles)
-  New radiation-dominated region (inside bubbles)

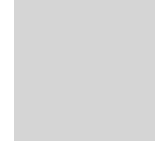
if

$$\delta\rho/\rho \gtrsim 0.50.$$

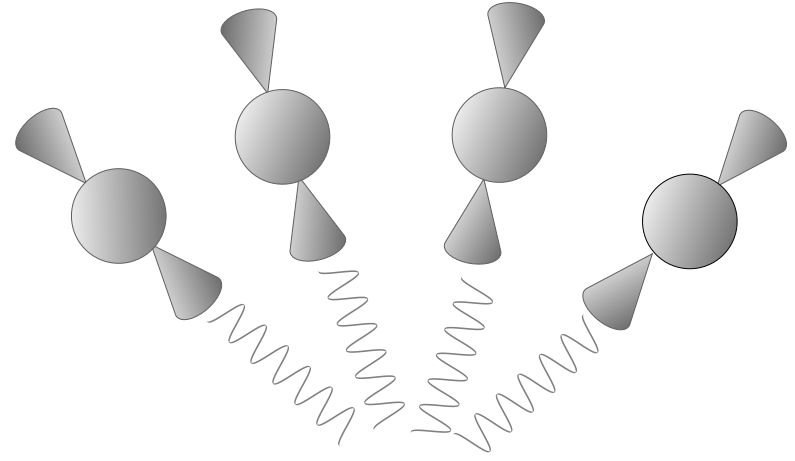
then

PBH



-  Old vacuum-dominated region (outside bubbles)
-  New radiation-dominated region (inside bubbles)

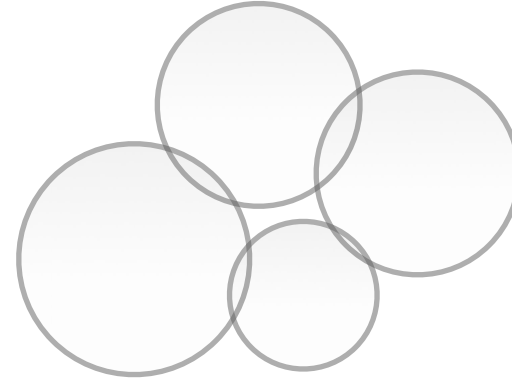
Pulsar Timing Arrays (PTA)



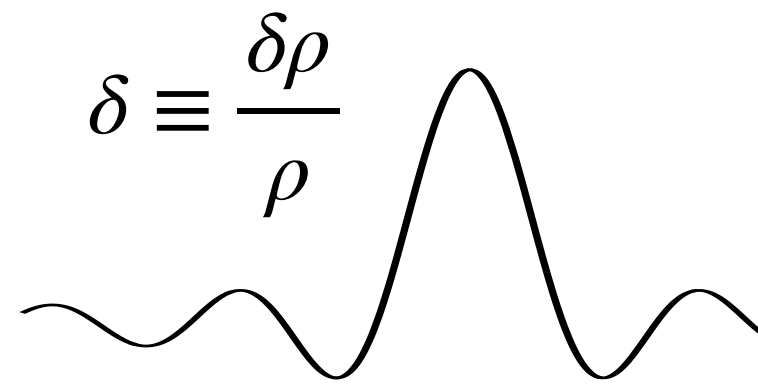
(GWs)
Gravitational
Waves



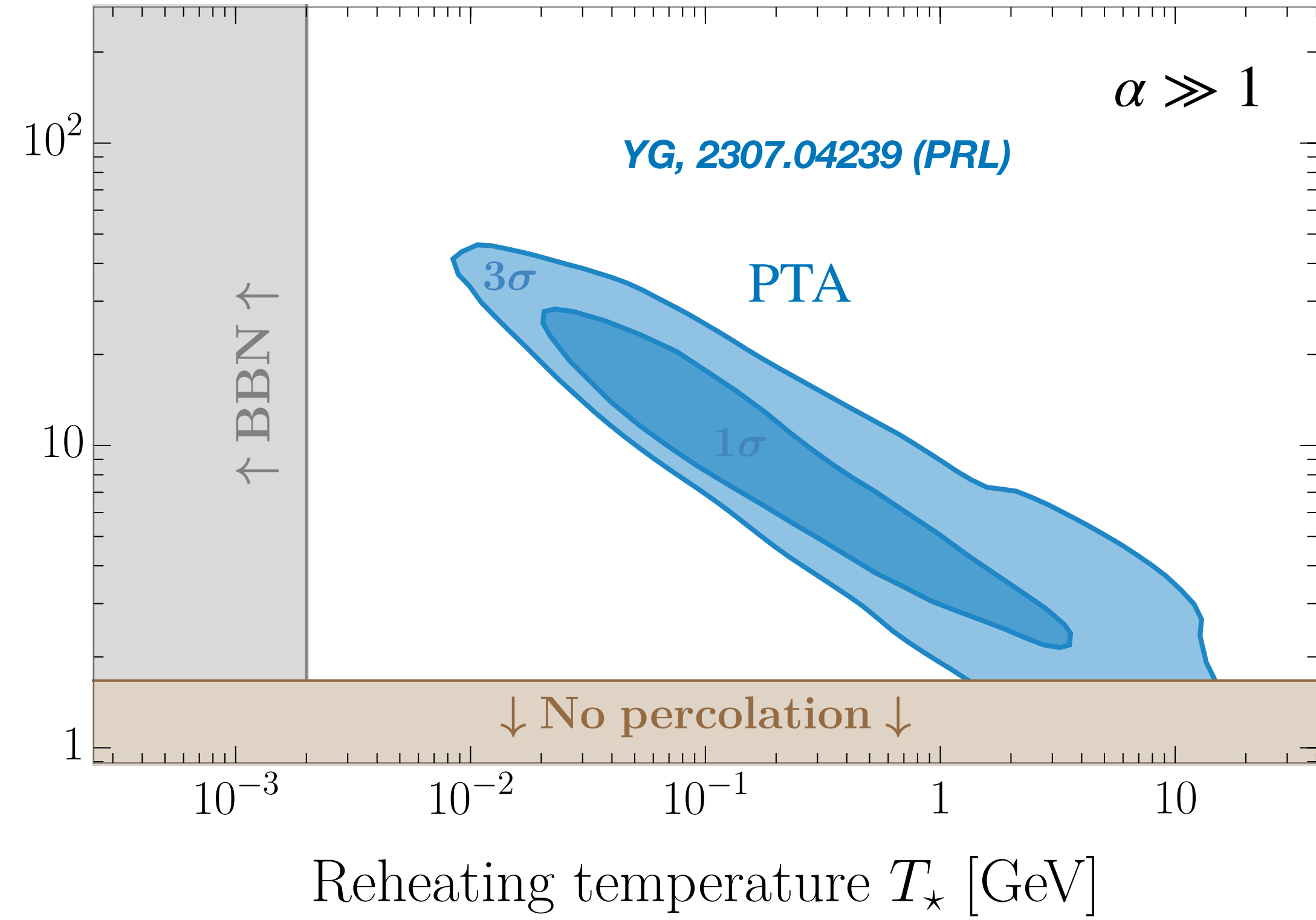
First-order phase transition



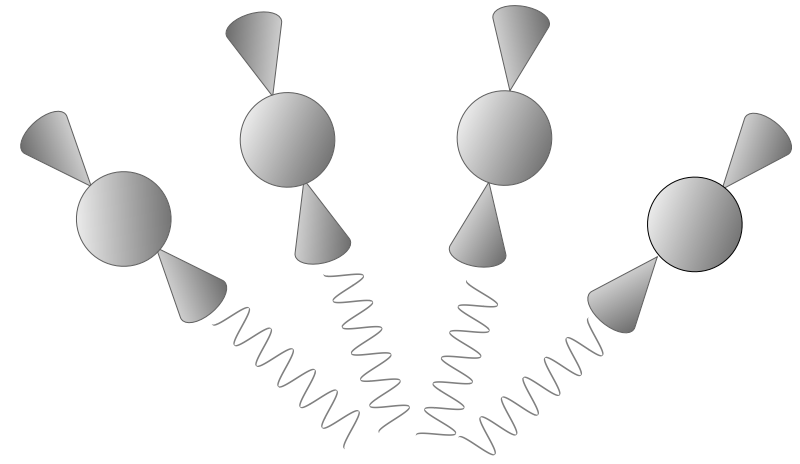
overdensities



PT completion rate $\beta/H_\star$



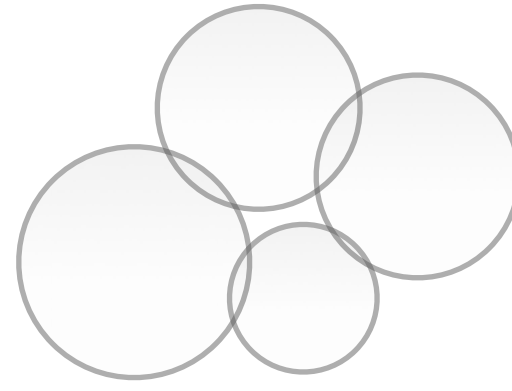
Pulsar Timing Arrays (PTA)



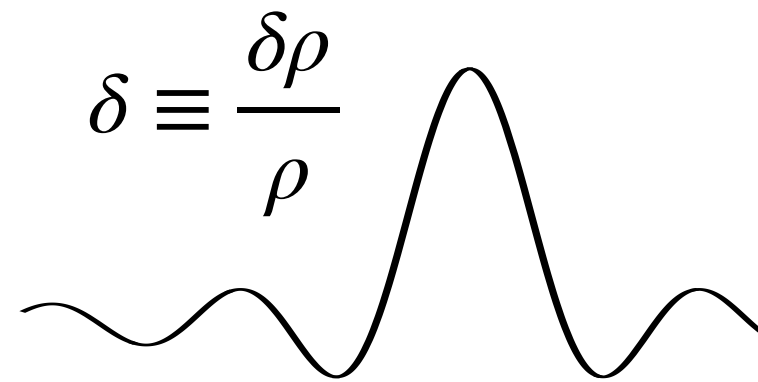
(GWs)
Gravitational
Waves



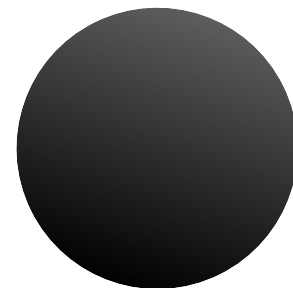
First-order phase transition



overdensities



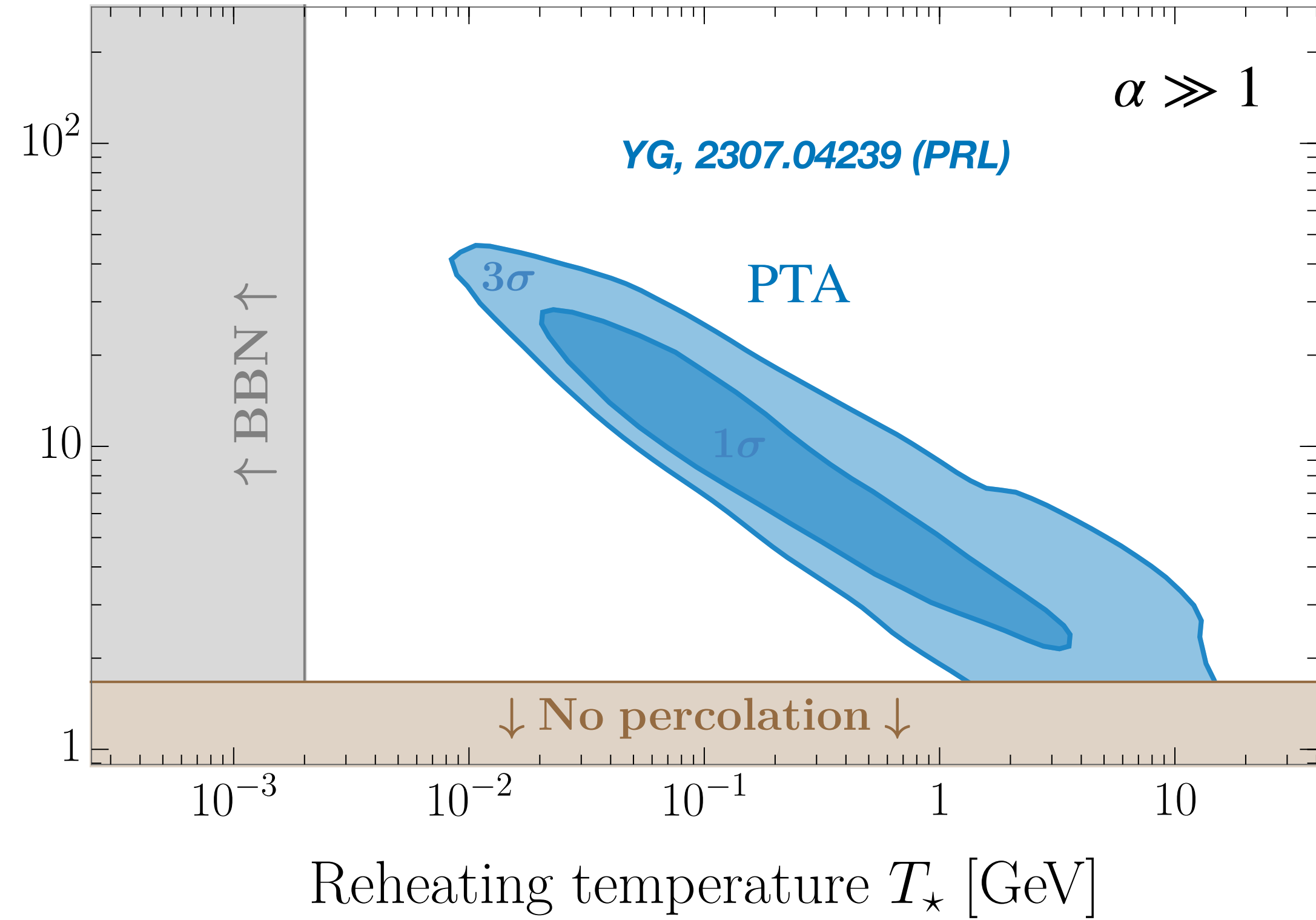
collapses if
 $\delta \gtrsim 0.5$



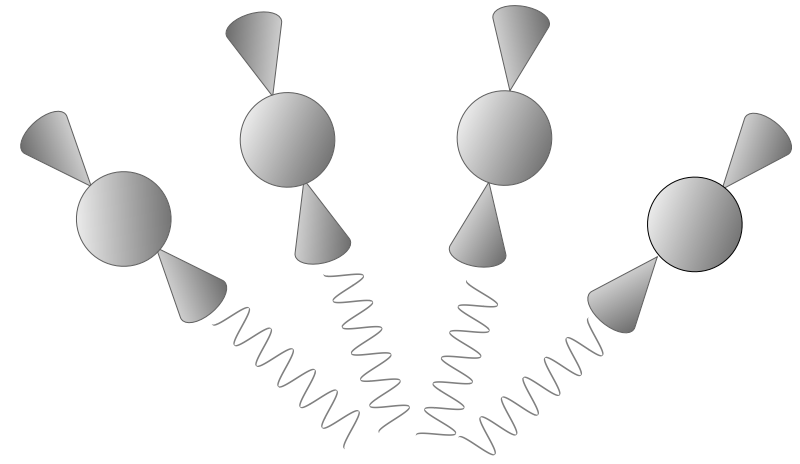
Primordial
Black Holes
(PBH)

*Bian+ 2021,
Lu+ 2022,
Lewicki+ 2023,
YG&Volansky 2023,
Baldes+ 2023,
Ellis+ 2023,
Lewicki+ PRL 2024,
.....*

PT completion rate $\beta/H_\star$



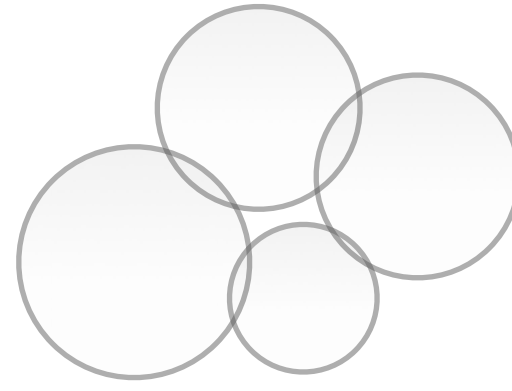
Pulsar Timing Arrays (PTA)



(GWs)
Gravitational
Waves



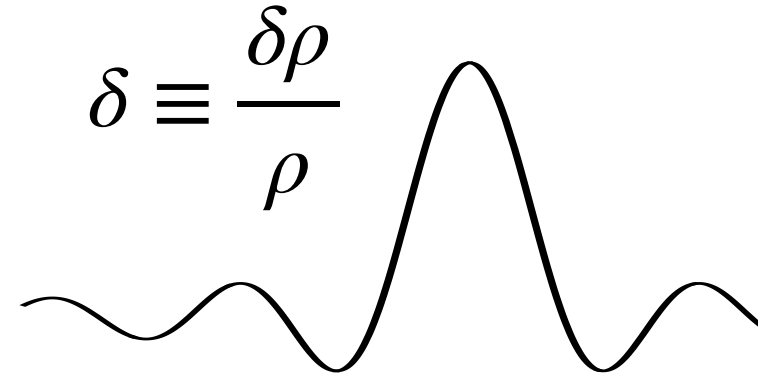
First-order phase transition



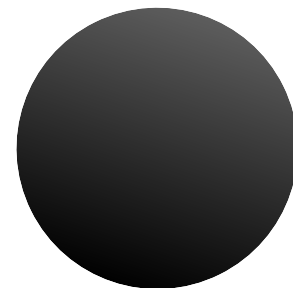
overdensities



$$\delta \equiv \frac{\delta\rho}{\rho}$$



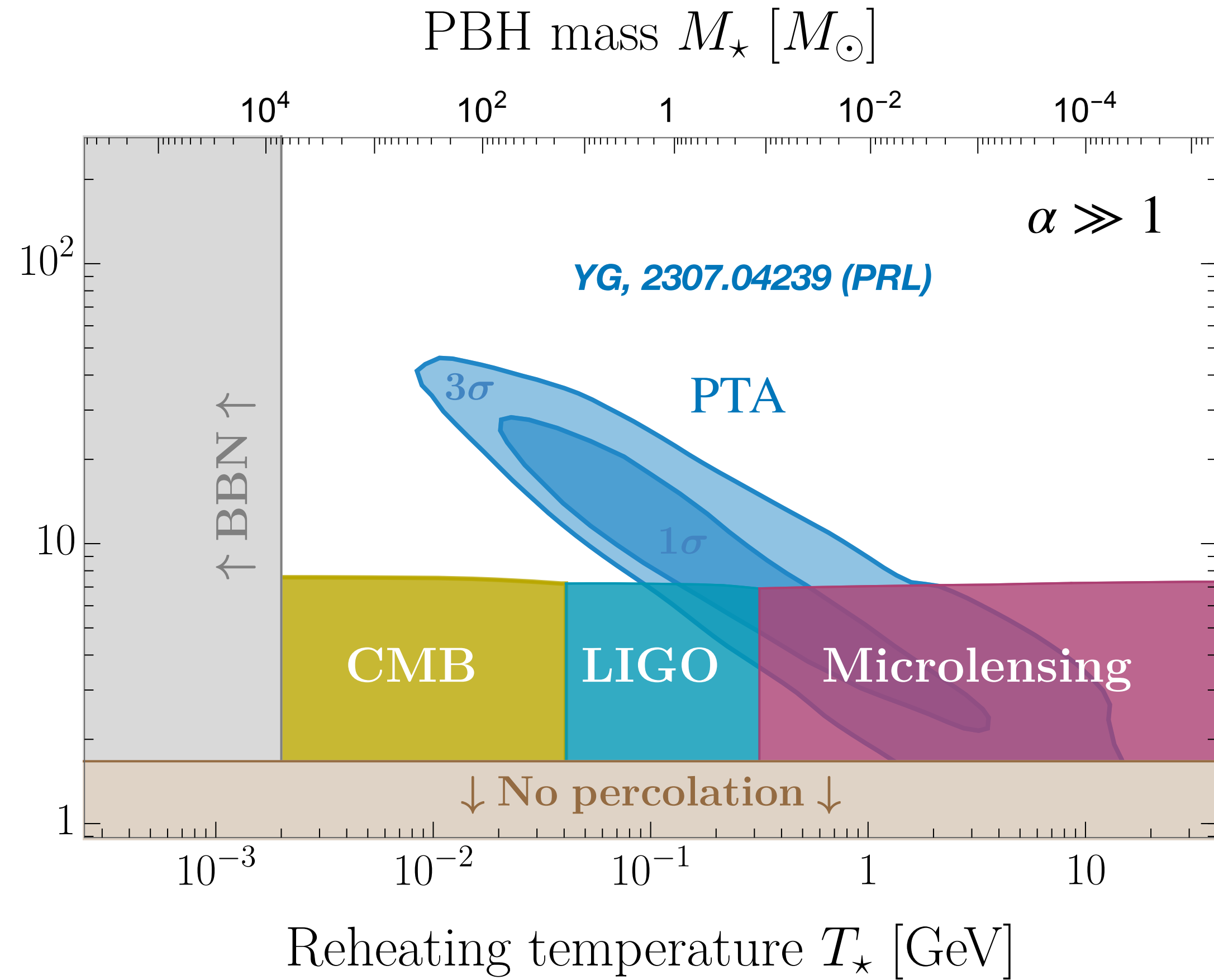
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 $\delta \gtrsim 0.5$



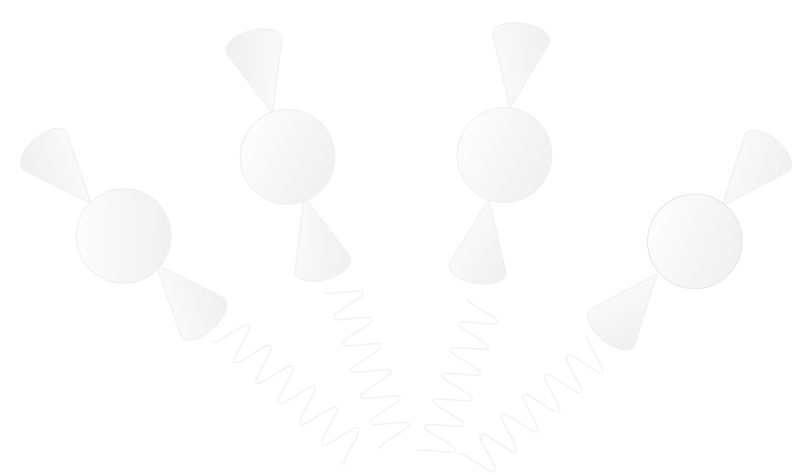
Primordial
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.....*

PT completion rate $\beta/H_\star$



Pulsar Timing Arrays
(PTA)



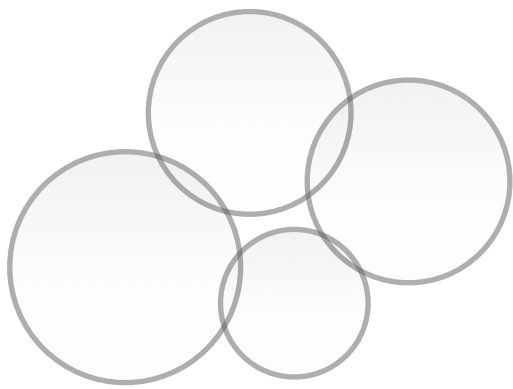
*Bian+ 2021, Lu+ 2022, Lewicki+ 2023,
YG&Volansky 2023, Baldes+ 2023, Lewicki+ PRL 2024,
.....*

$$\delta\dot{\rho} + 3H(\delta\rho + \delta p) = 0$$

(GWs)
Gravitational
Waves



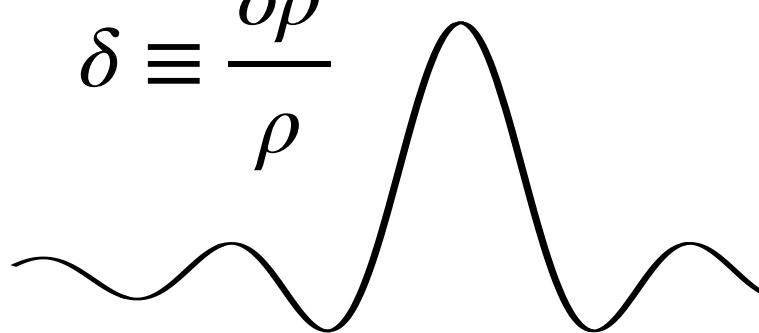
First-order
phase transition



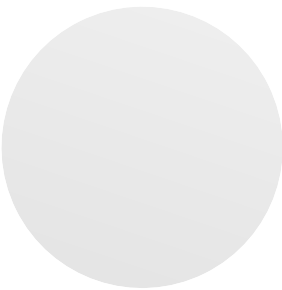
overdensities



$$\delta \equiv \frac{\delta\rho}{\rho}$$



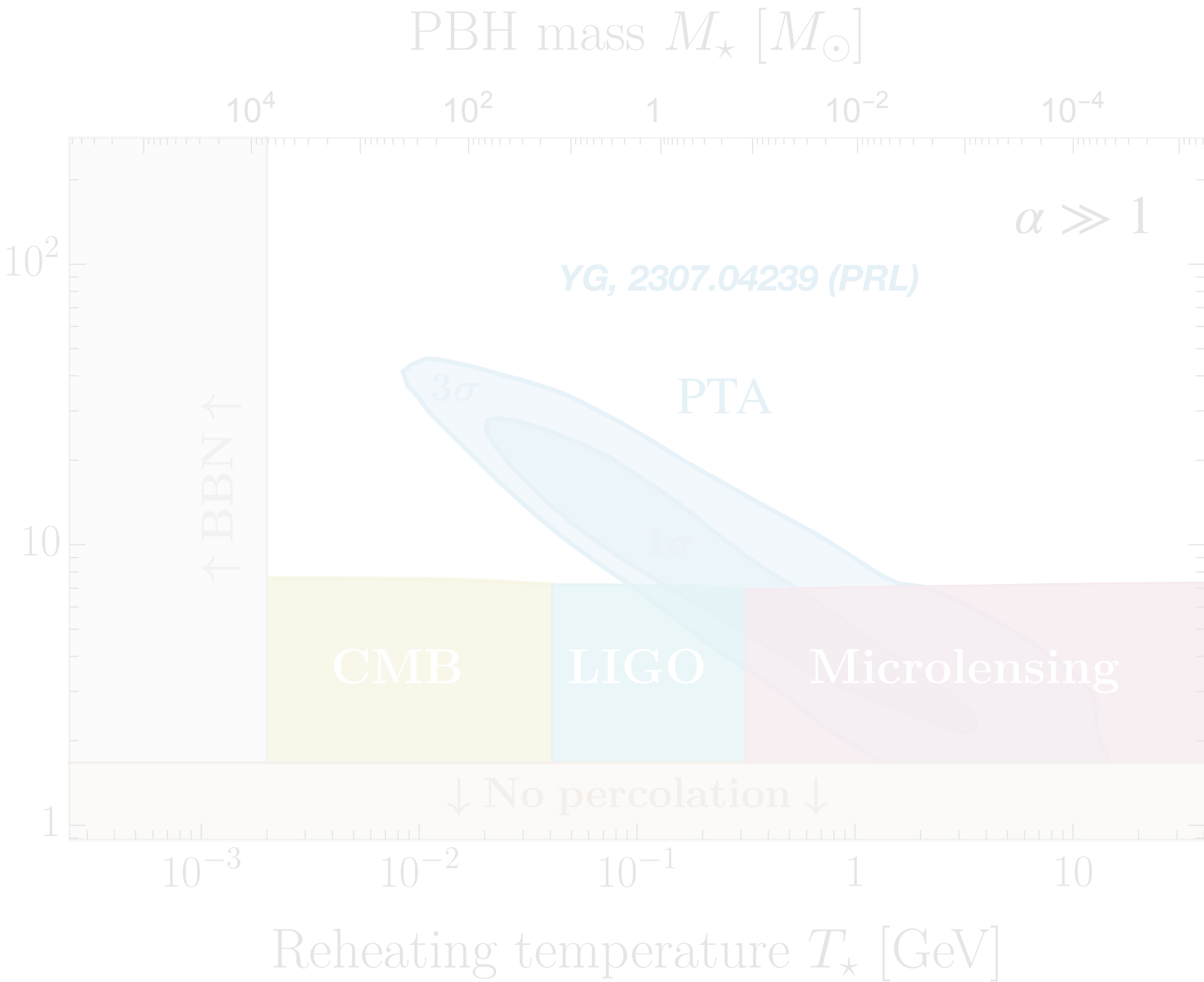
collapses if
 $\delta \gtrsim 0.5$



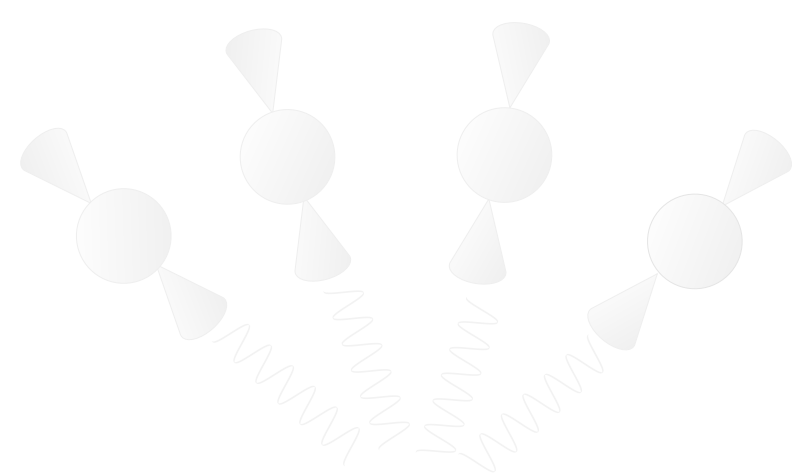
PBH

*Bian+ 2021,
Lu+ 2022,
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YG&Volansky 2023,
Baldes+ 2023,
Ellis+ 2023,
Lewicki+ PRL 2024,
.....*

PT completion rate $\beta/H_\star$



Pulsar Timing Arrays
(PTA)



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YG&Volansky 2023, Baldes+ 2023, Lewicki+ PRL 2024,
.....*

$$\delta\dot{\rho} + 3H(\delta\rho + \delta p) = 0$$

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

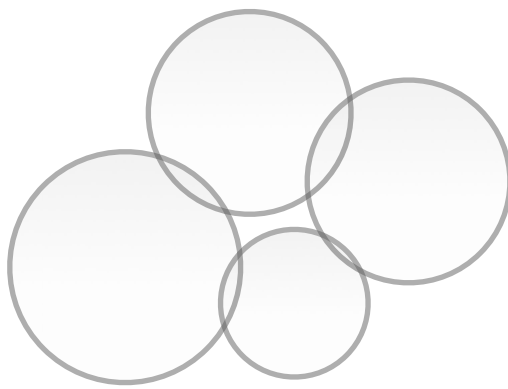
$$ds^2 = dt^2 - a^2 d\mathbf{x}^2$$

Homogeneously expanding universe

(GWs)
Gravitational
Waves

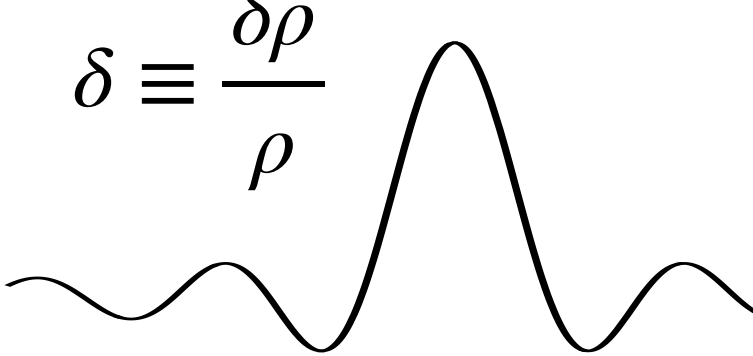


First-order
phase transition



overdensities

$$\delta \equiv \frac{\delta\rho}{\rho}$$



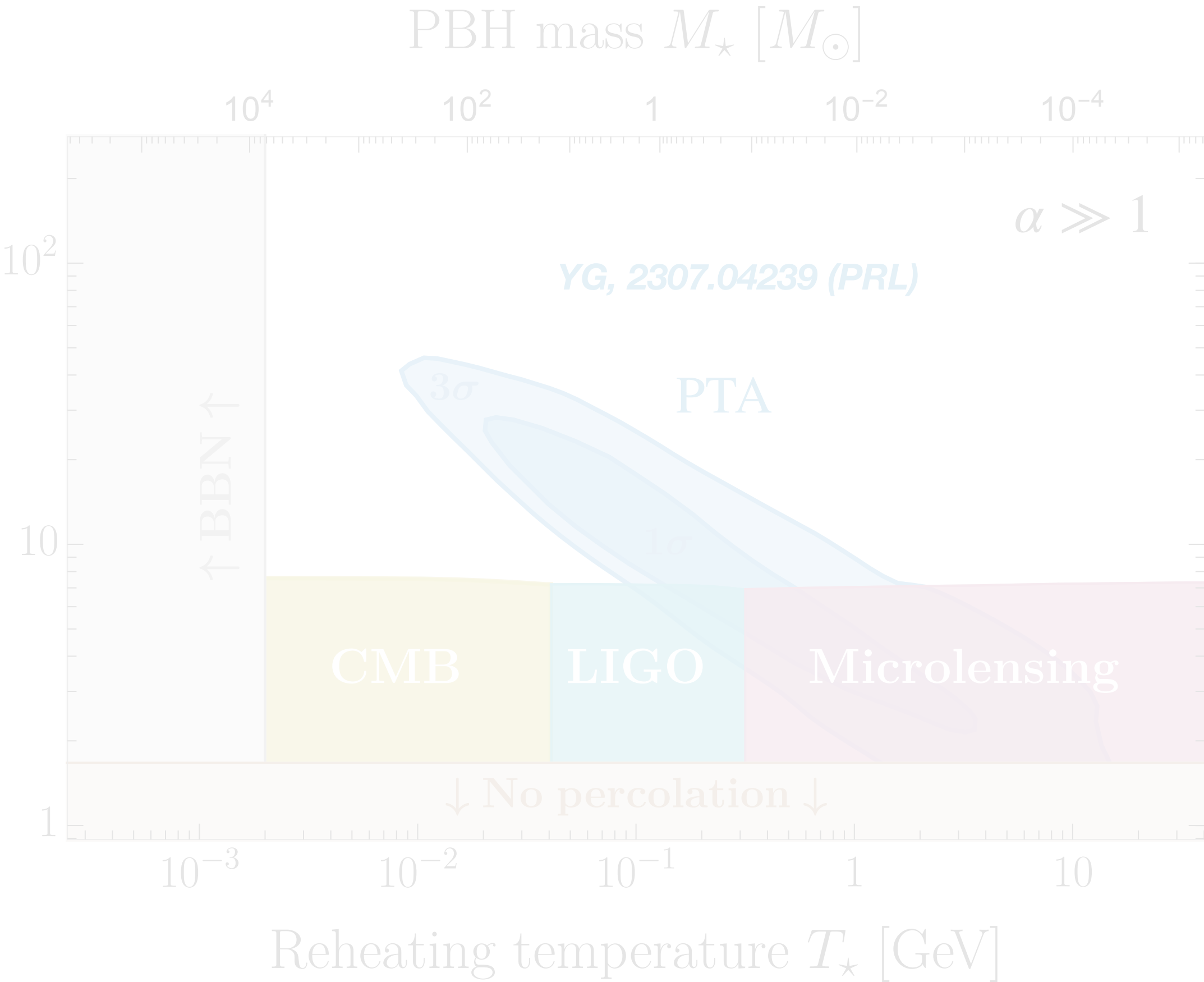
collapses if
 $\delta \gtrsim 0.5$



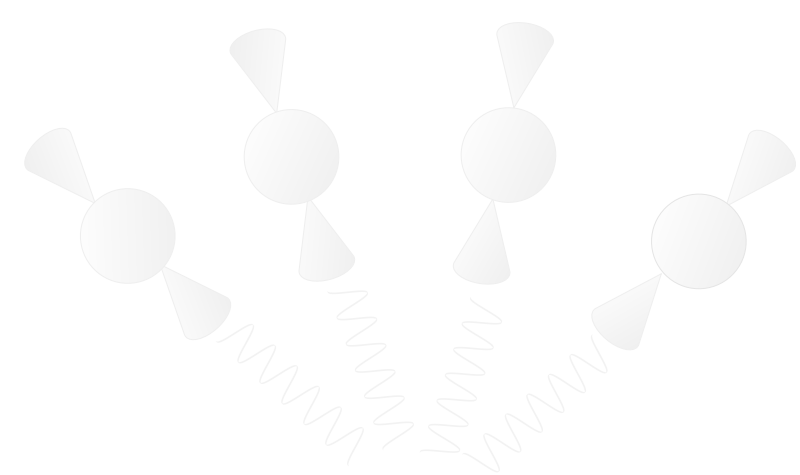
PBH

*Bian+ 2021,
Lu+ 2022,
Lewicki+ 2023,
YG&Volansky 2023,
Baldes+ 2023,
Ellis+ 2023,
Lewicki+ PRL 2024,
.....*

PT completion rate $\beta/H_\star$



Pulsar Timing Arrays
(PTA)



Bian+ 2021, Lu+ 2022, Lewicki+ 2023,
YG&Volansky 2023, Baldes+ 2023, Lewicki+ PRL 2024,
.....

$$\delta\dot{\rho} + 3H(\delta\rho + \delta p) = 0$$

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Scalar curvature

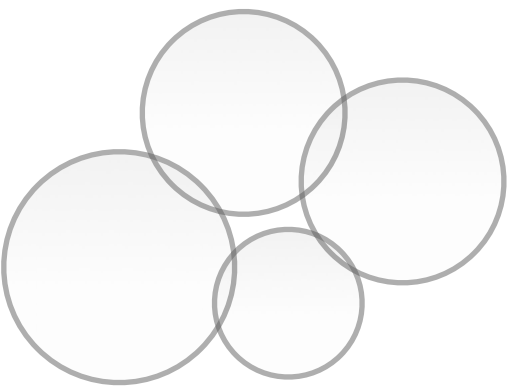
$$ds^2 = (1 + 2\Phi) dt^2 - a^2(1 - 2\Phi) d\mathbf{x}^2$$

inhomogeneously expanding universe

(GWs)
Gravitational
Waves

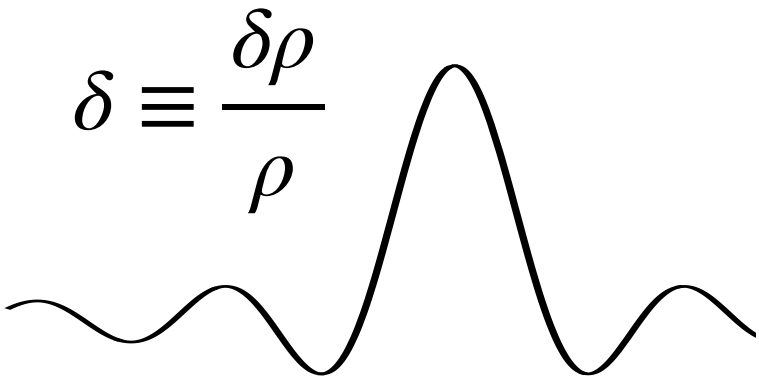


First-order
phase transition

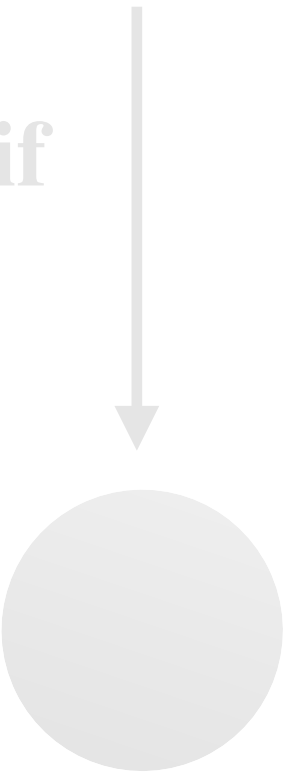


overdensities

$$\delta \equiv \frac{\delta\rho}{\rho}$$



collapses if
 $\delta \gtrsim 0.5$

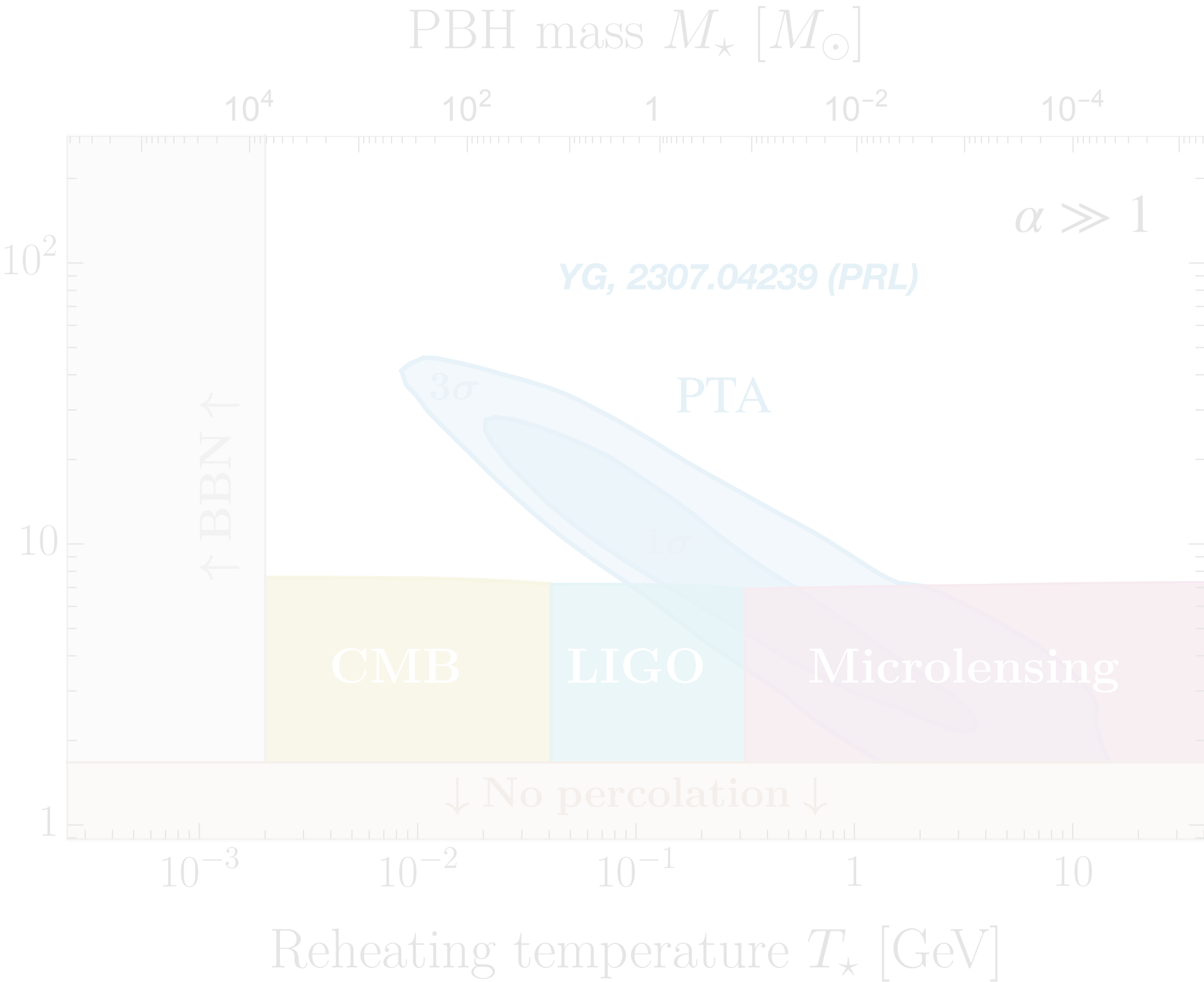


PBH

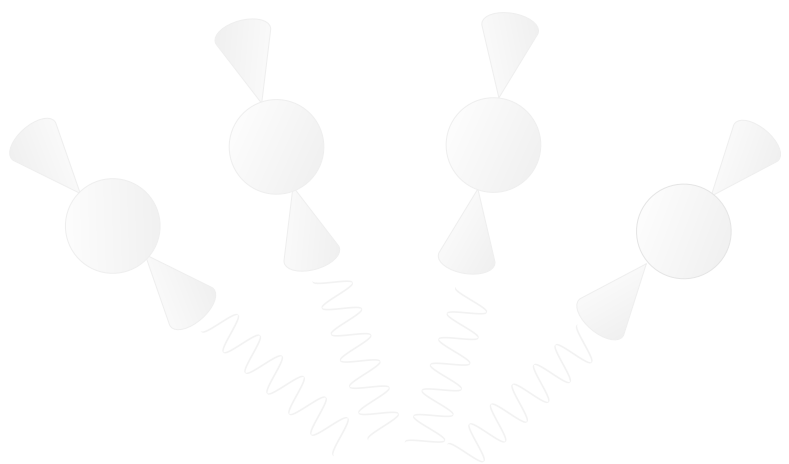
Bian+ 2021,
Lu+ 2022,
Lewicki+ 2023,
YG&Volansky 2023,
Baldes+ 2023,
Ellis+ 2023,
Lewicki+ PRL 2024,
.....

Franciolini, YG, Jinno, 2503.01962

PT completion rate $\beta/H_\star$



Pulsar Timing Arrays
(PTA)



Bian+ 2021, Lu+ 2022, Lewicki+ 2023,
YG&Volansky 2023, Baldes+ 2023, Lewicki+ PRL 2024,
.....

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$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Scalar curvature

$$\Phi = 0$$

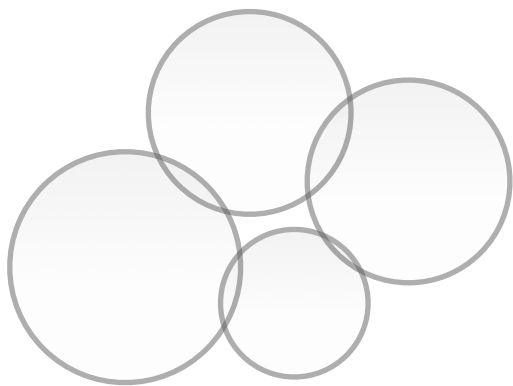
$$ds^2 = (1 + 2\Phi) dt^2 - a^2(1 - 2\Phi) d\mathbf{x}^2$$

INHOMOGENEOUSLY expanding universe

(GWs)
Gravitational
Waves

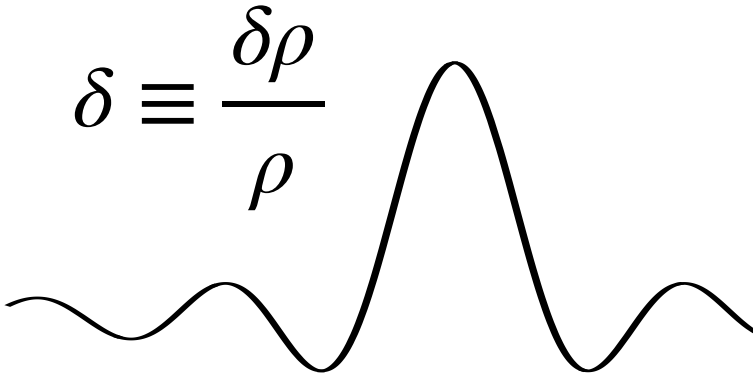


First-order
phase transition

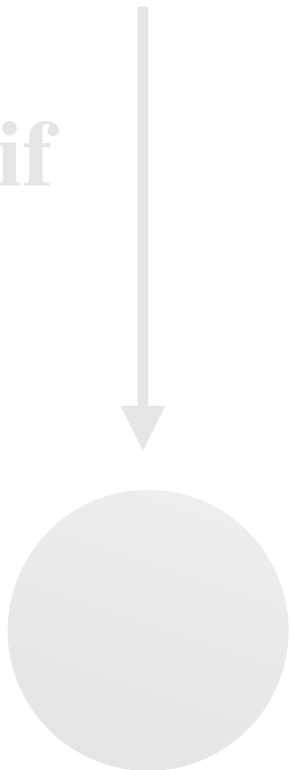


overdensities

$$\delta \equiv \frac{\delta\rho}{\rho}$$



collapses if
 $\delta \gtrsim 0.5$

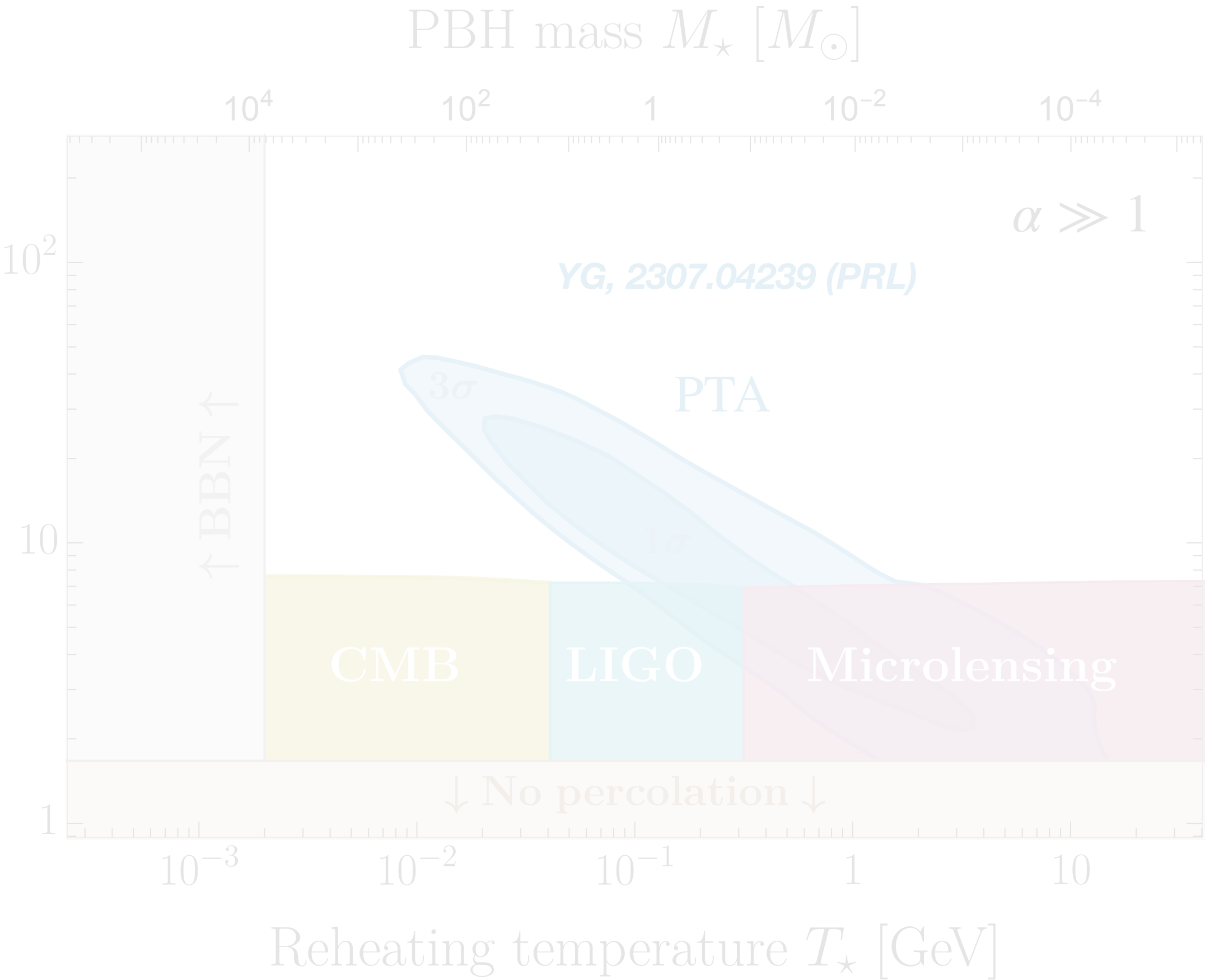


PBH

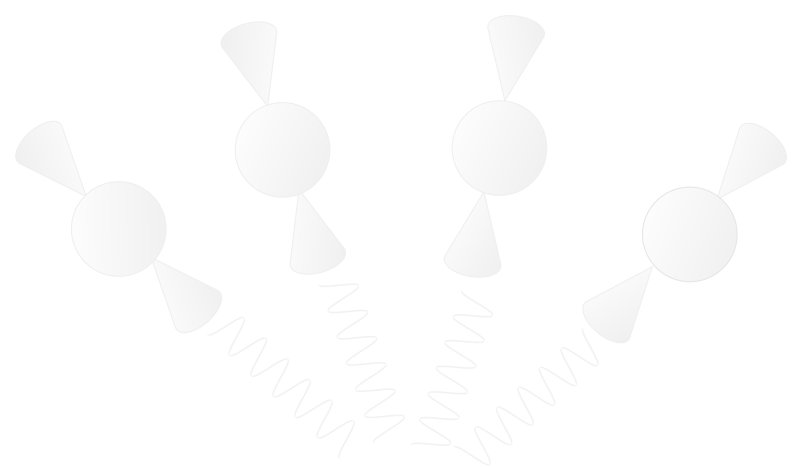
Bian+ 2021,
Lu+ 2022,
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Lewicki+ PRL 2024,
.....

Franciolini, YG, Jinno, 2503.01962

PT completion rate $\beta/H_\star$



Pulsar Timing Arrays
(PTA)



Bian+ 2021, Lu+ 2022, Lewicki+ 2023,
YG&Volansky 2023, Baldes+ 2023, Lewicki+ PRL 2024,
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Scalar curvature

Spatially-flat gauge

$$\Phi = 0$$

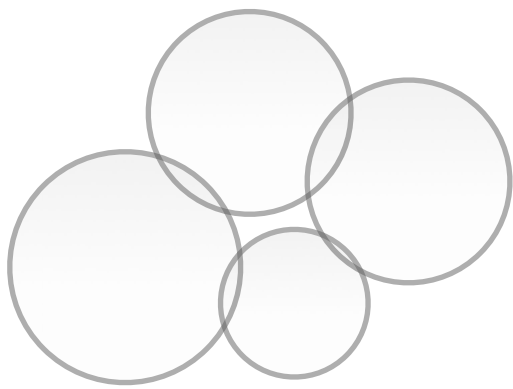
$$ds^2 = (1 + 2\Phi) dt^2 - a^2(1 - 2\Phi) d\mathbf{x}^2$$

INHOMOGENEOUSLY expanding universe

(GWs)
Gravitational
Waves

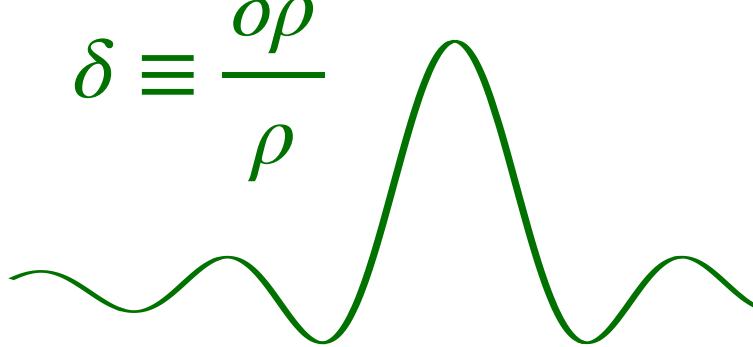


First-order
phase transition



overdensities

$$\delta \equiv \frac{\delta\rho}{\rho}$$



collapses if
 $\delta \gtrsim 0.5$

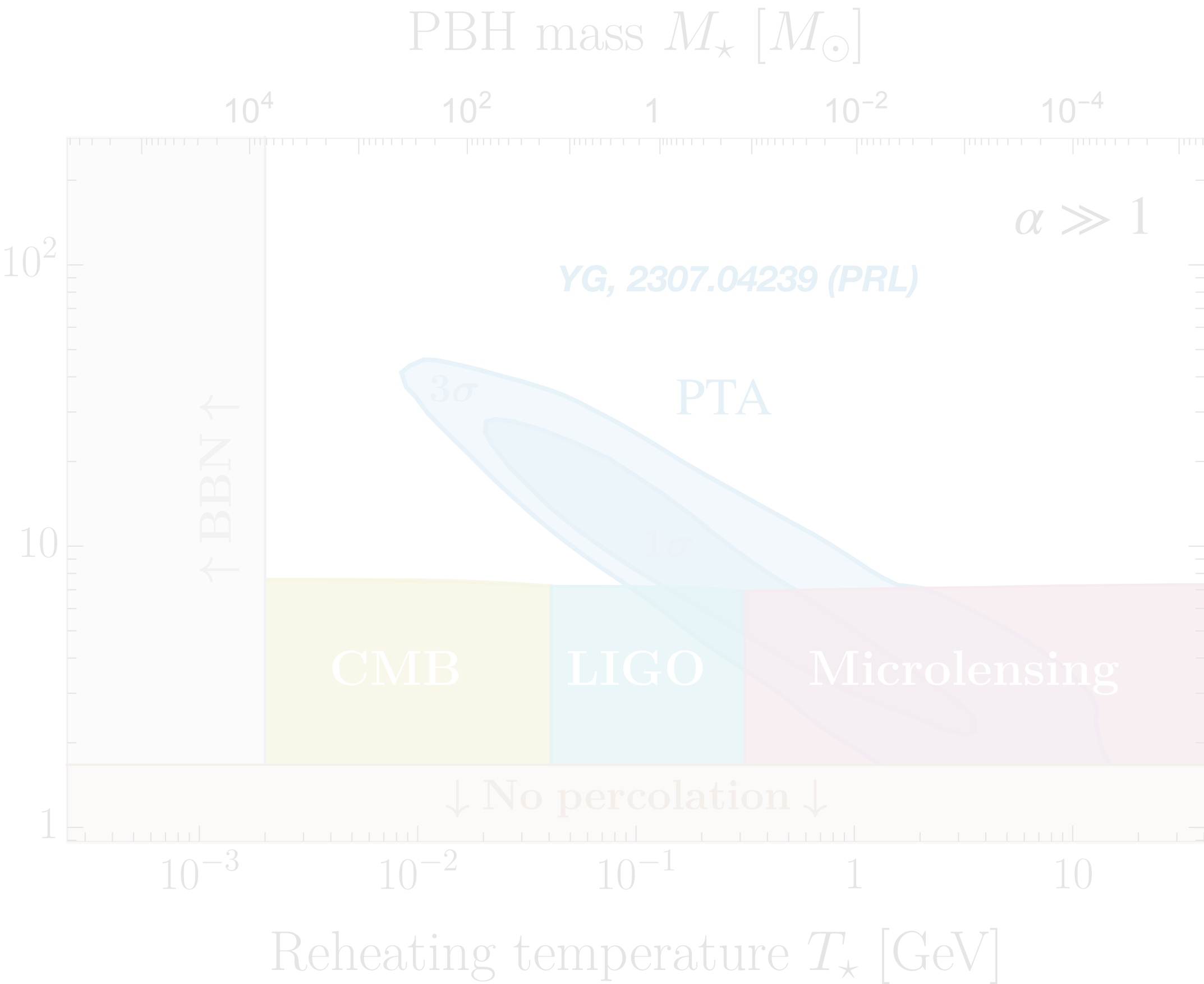


PBH

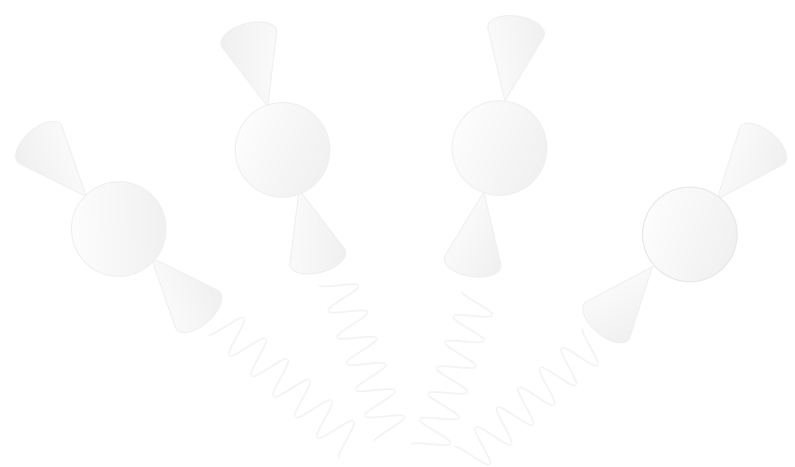
Bian+ 2021,
Lu+ 2022,
Lewicki+ 2023,
YG&Volansky 2023,
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Franciolini, YG, Jinno, 2503.01962

PT completion rate $\beta/H_\star$



Pulsar Timing Arrays
(PTA)



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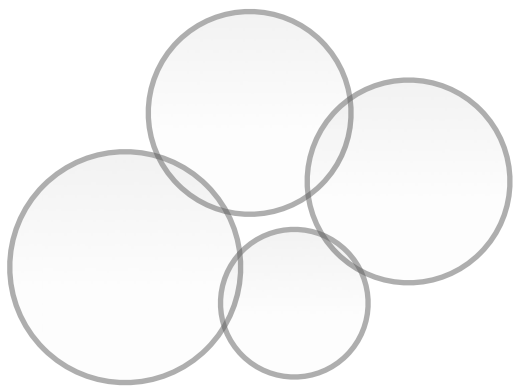
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INHOMOGENEOUSLY expanding universe

(GWs)
Gravitational
Waves

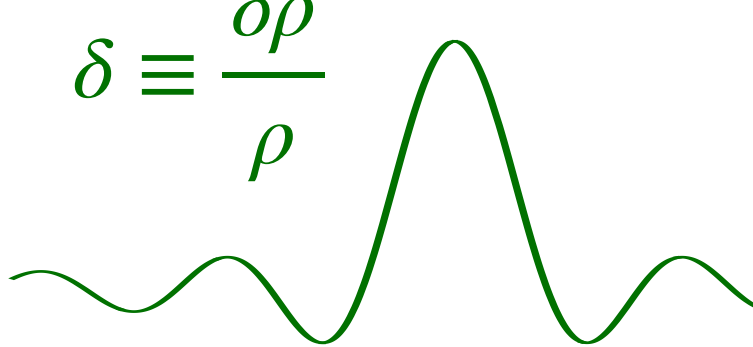


First-order
phase transition



overdensities

$$\delta \equiv \frac{\delta\rho}{\rho}$$



collapses if
 $\delta \gtrsim 0.5$

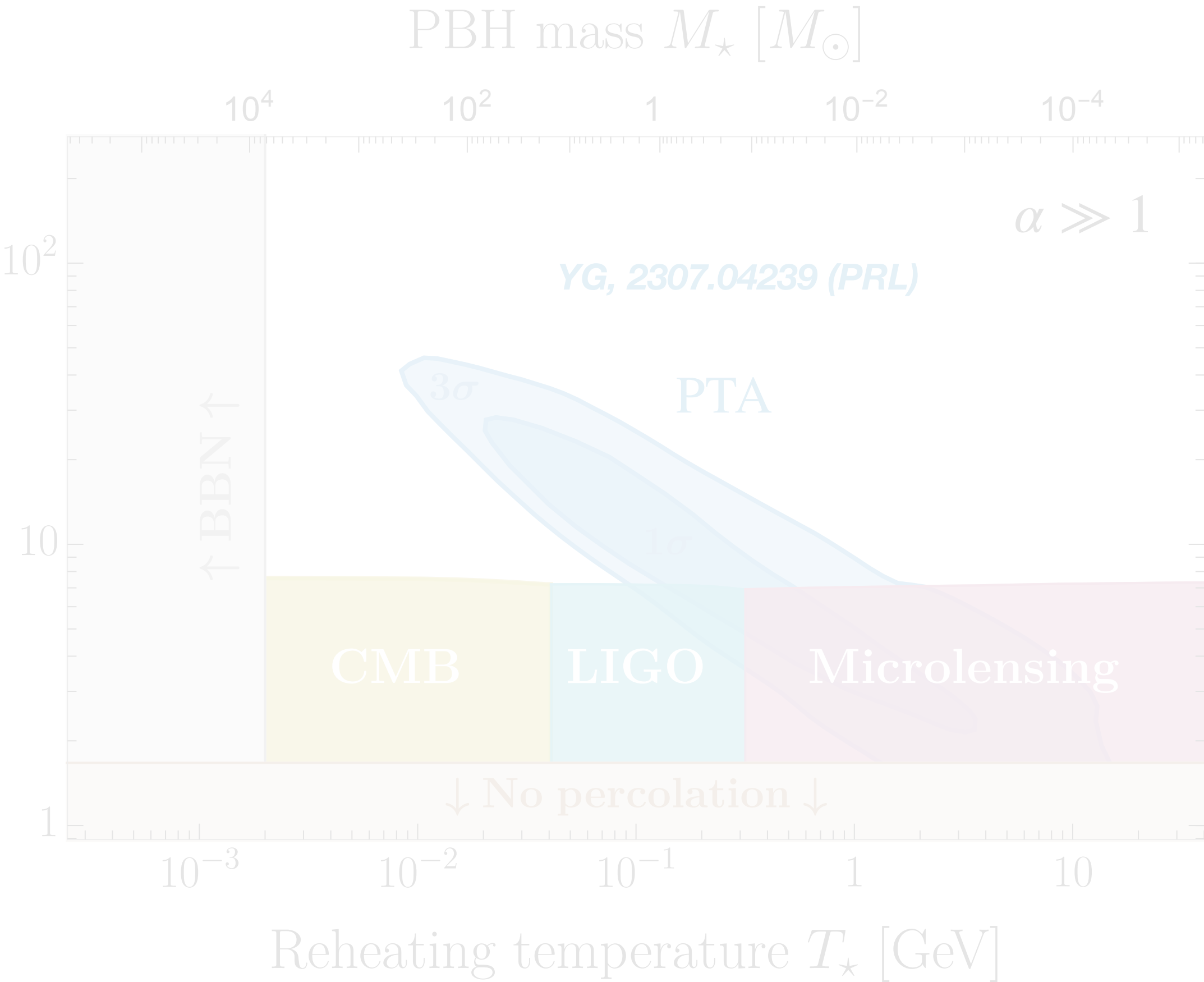


PBH

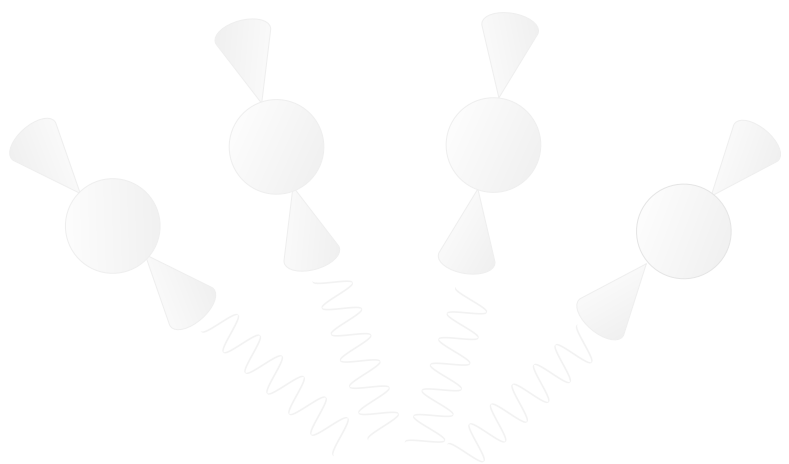
*Bian+ 2021,
Lu+ 2022,
Lewicki+ 2023,
YG&Volansky 2023,
Baldes+ 2023,
Ellis+ 2023,
Lewicki+ PRL 2024,
.....*

Franciolini, YG, Jinno, 2503.01962

PT completion rate $\beta/H_\star$



Pulsar Timing Arrays
(PTA)



Bian+ 2021, Lu+ 2022, Lewicki+ 2023,
YG&Volansky 2023, Baldes+ 2023, Lewicki+ PRL 2024,
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$$\delta\dot{\rho} + 3H(\delta\rho + \delta p) = 0$$

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Scalar curvature

Spatially-flat gauge

$$\Phi = 0$$

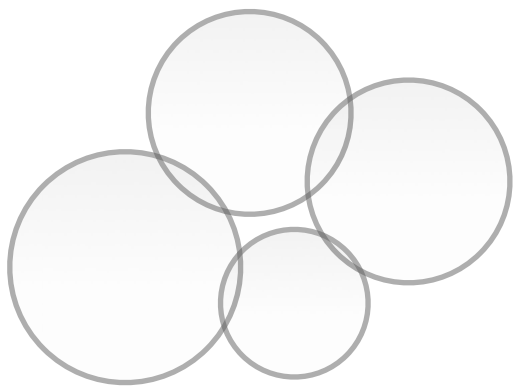
$$ds^2 = (1 + 2\Phi) dt^2 - a^2(1 - 2\Phi) d\mathbf{x}^2$$

Inhomogeneously expanding universe

(GWs)
Gravitational
Waves

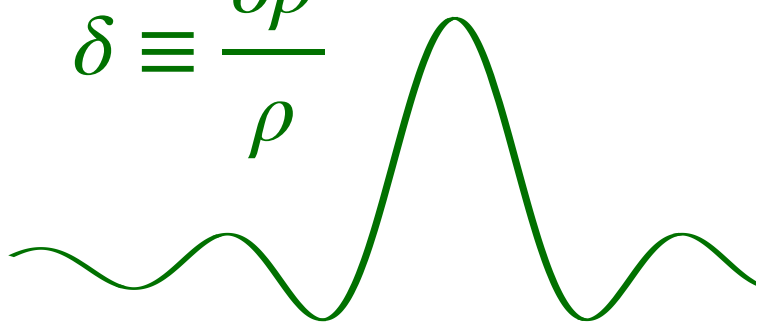


First-order
phase transition



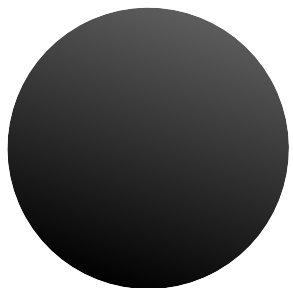
overdensities

$$\delta \equiv \frac{\delta\rho}{\rho}$$



collapses if

$$\delta \gtrsim 0.5$$

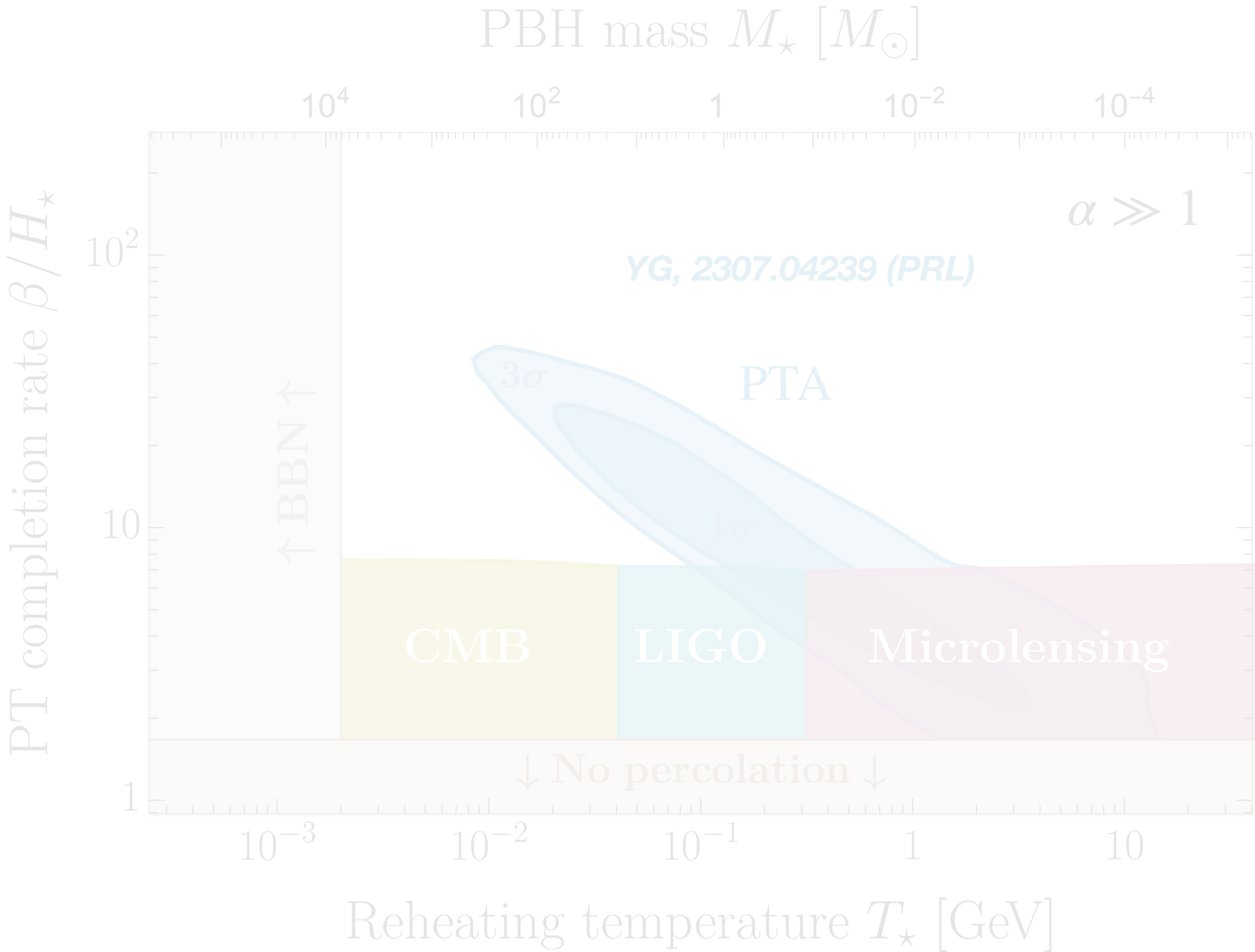


PBH

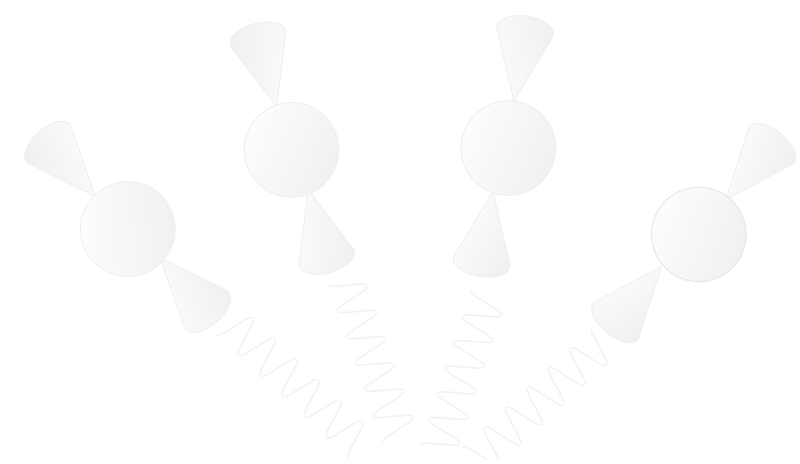
Musco 1809.02127
Escriva, Germani, Sheth 1907.13311

Comoving gauge

Franciolini, YG, Jinno, 2503.01962



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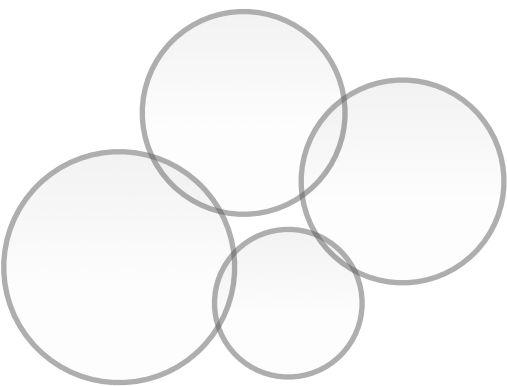
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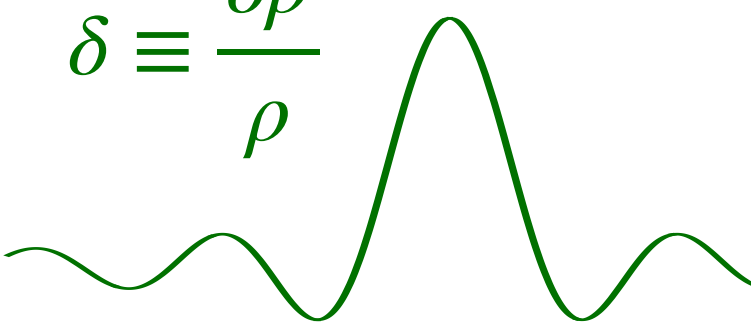


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phase transition



overdensities

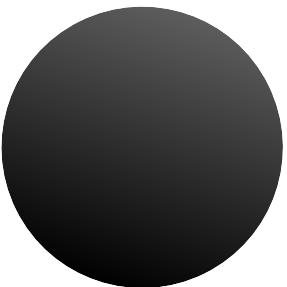
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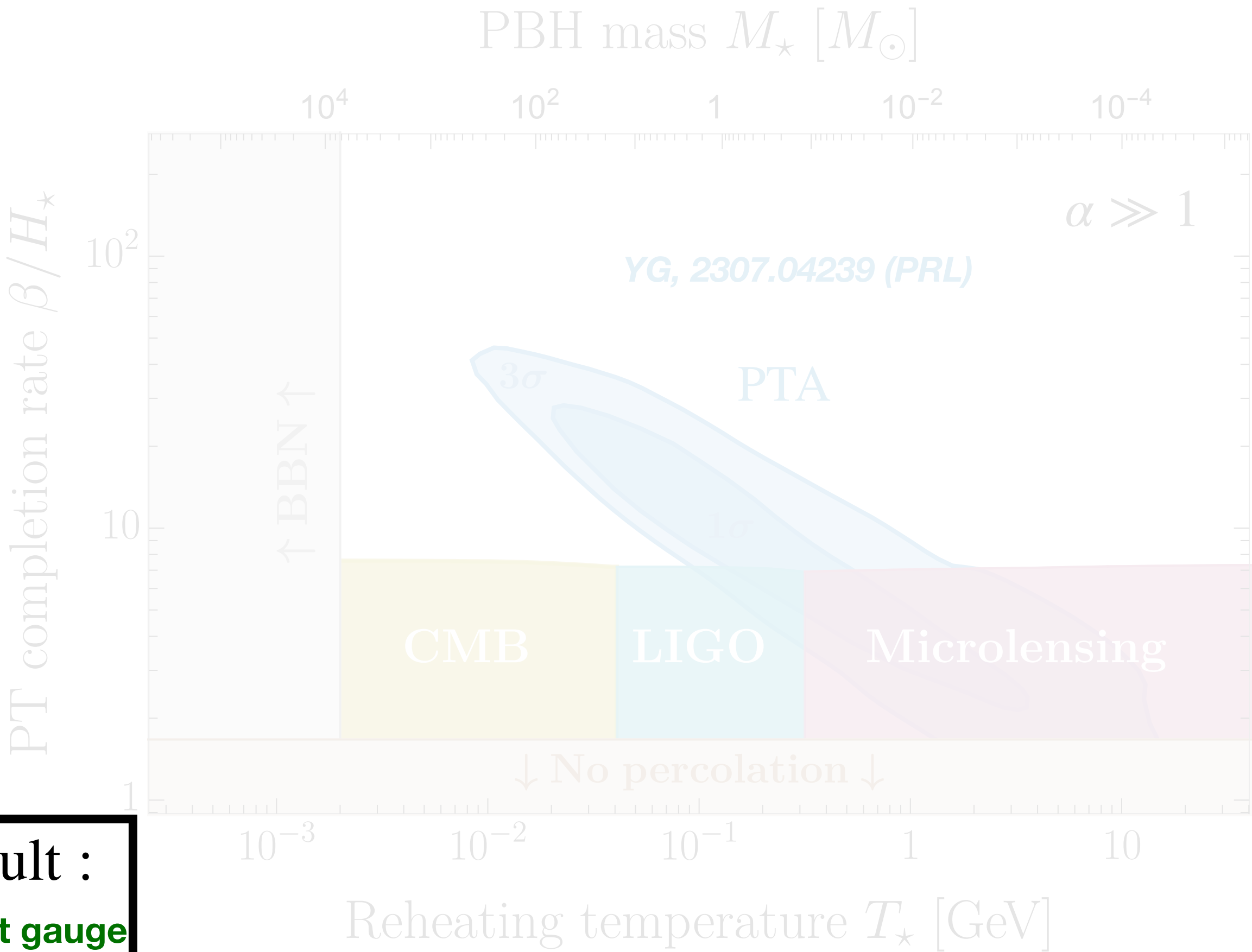
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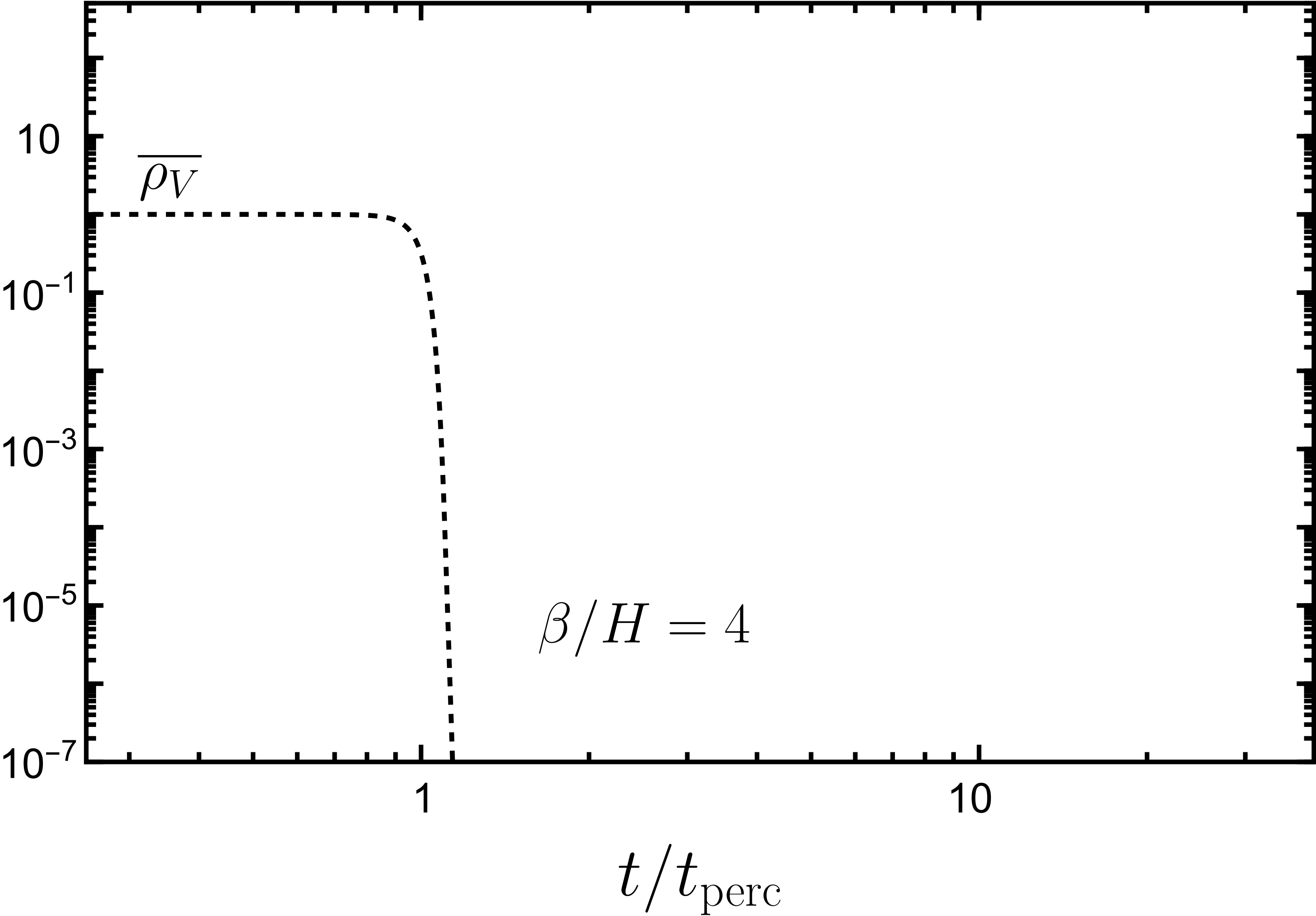


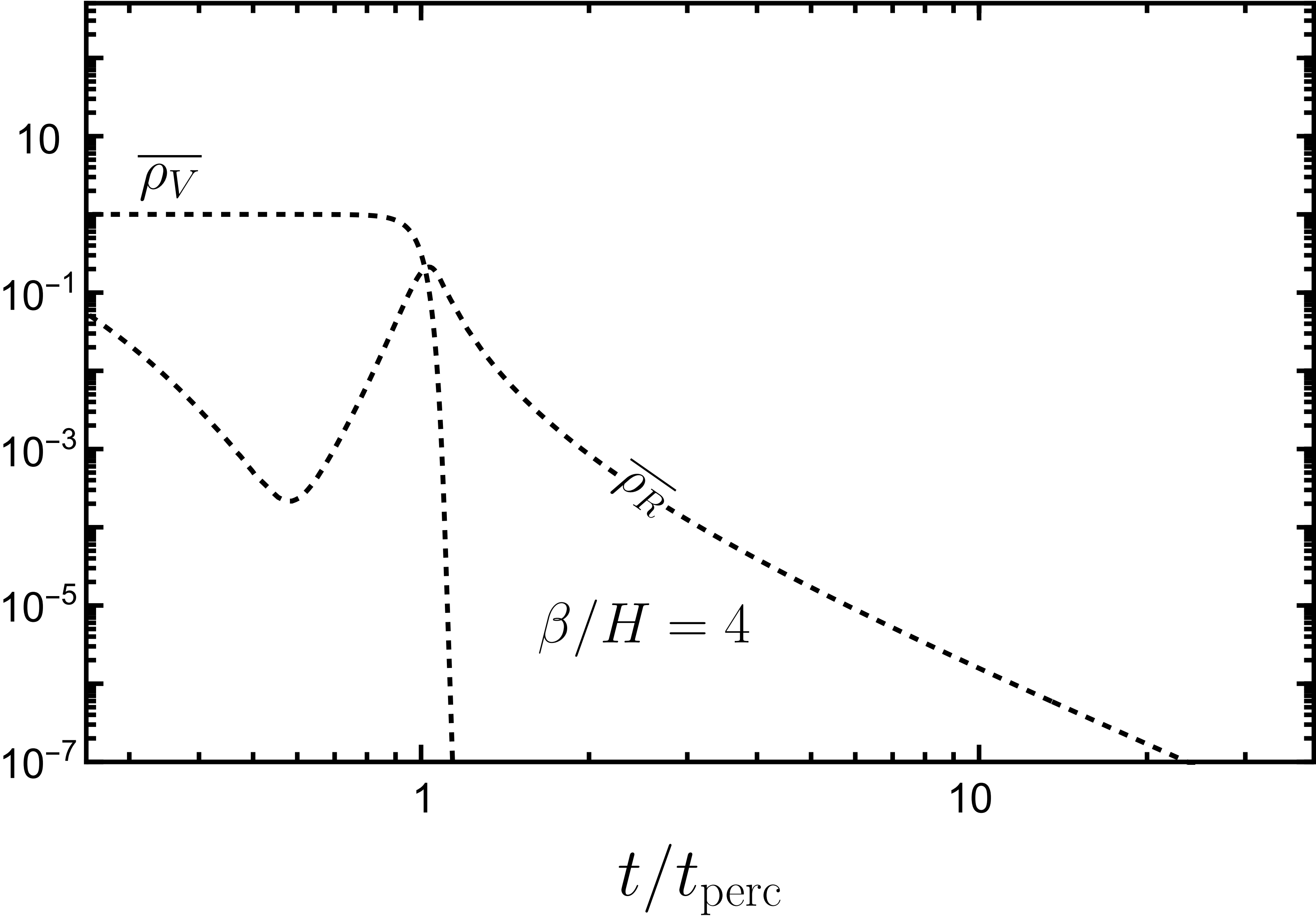
PBH

Key result :
Spatially-flat gauge
 $\delta \gtrsim 5$

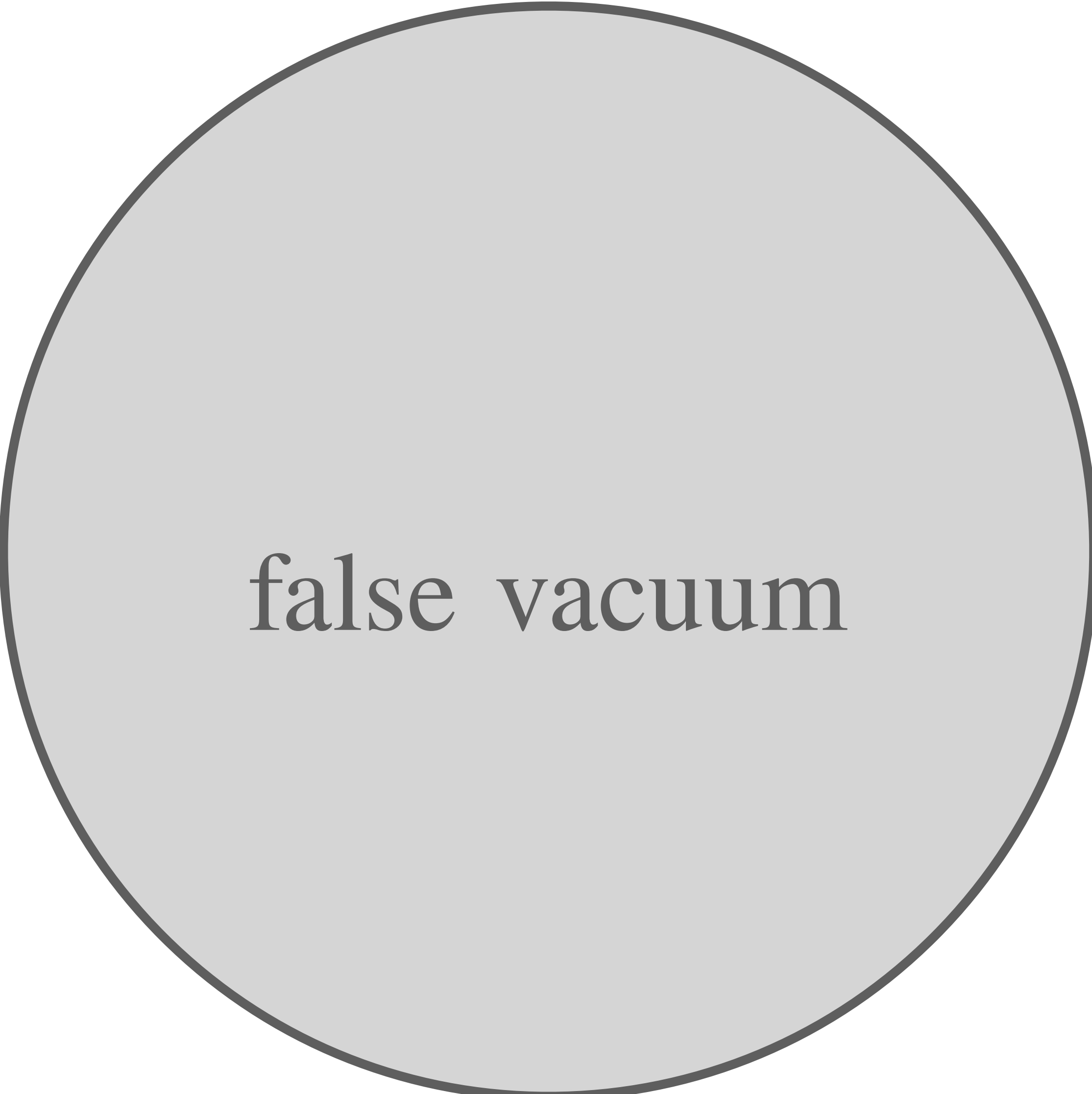
Franciolini, YG, Jinno, 2503.01962







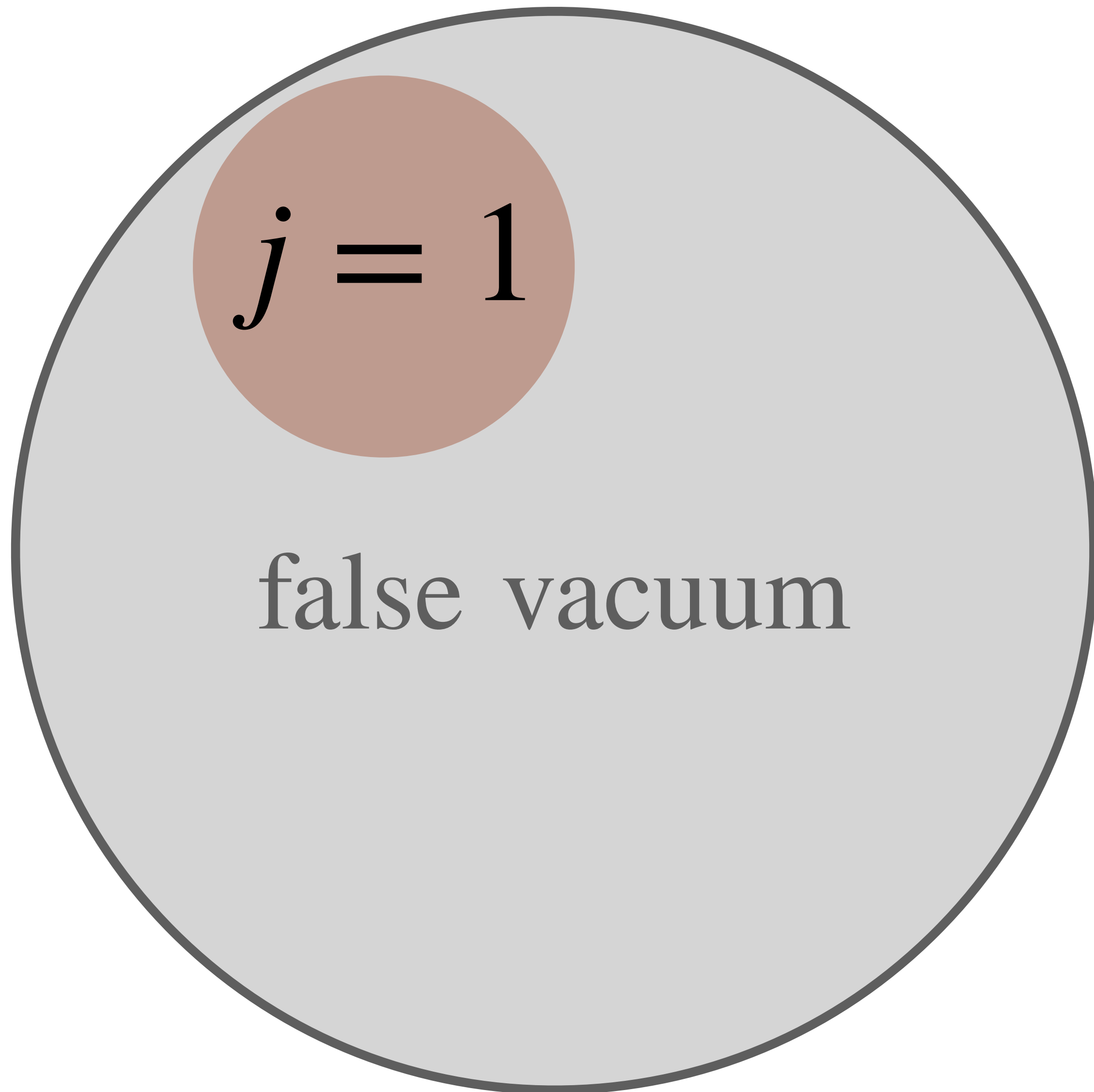
$$\rho_R'(t) + 4\mathcal{H}\rho_R(t) = -\rho_V'(t)$$



false vacuum

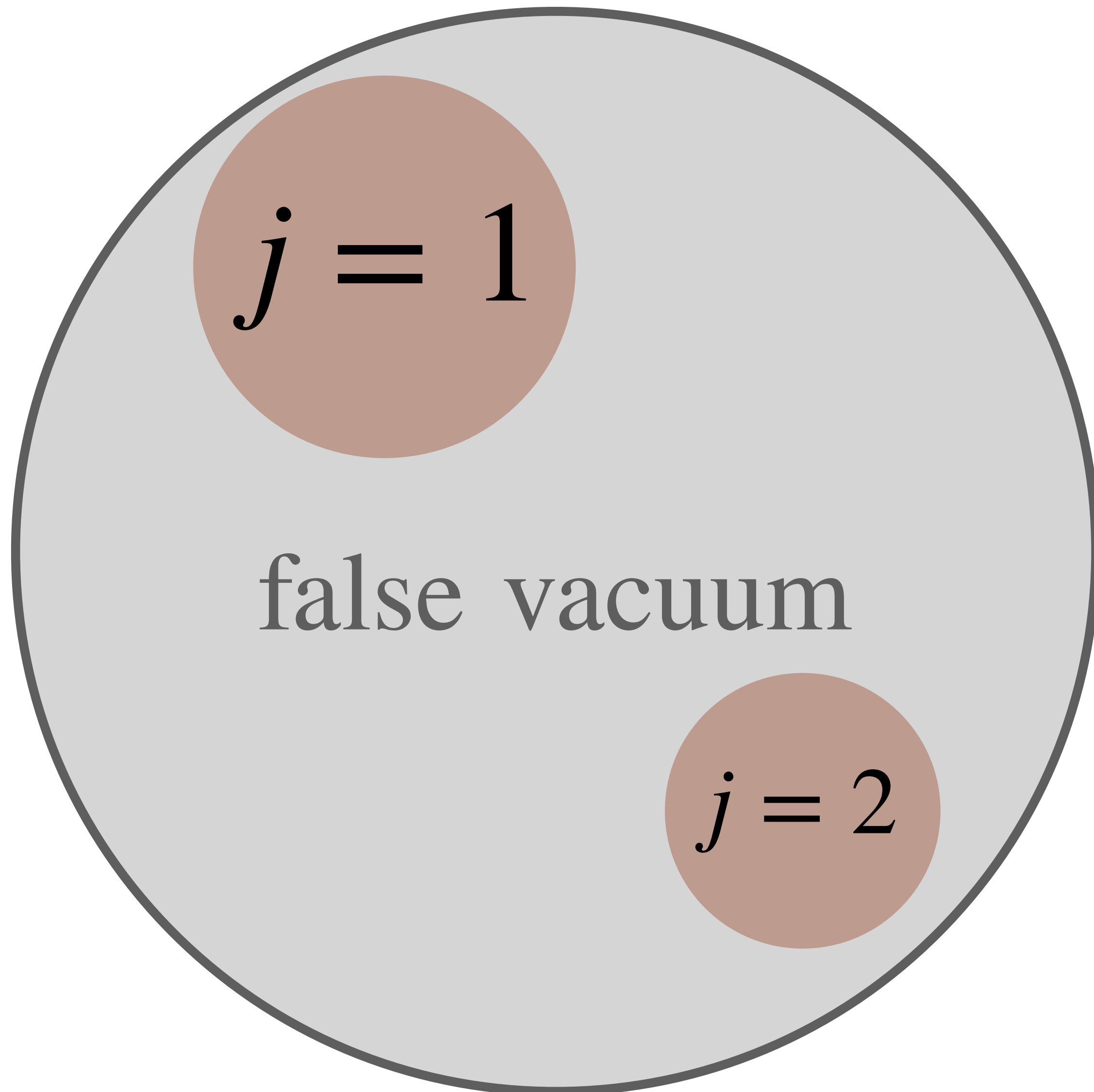
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$$\rho_R'(t) + 4\mathcal{H}\rho_R(t) = -\rho_V'(t)$$



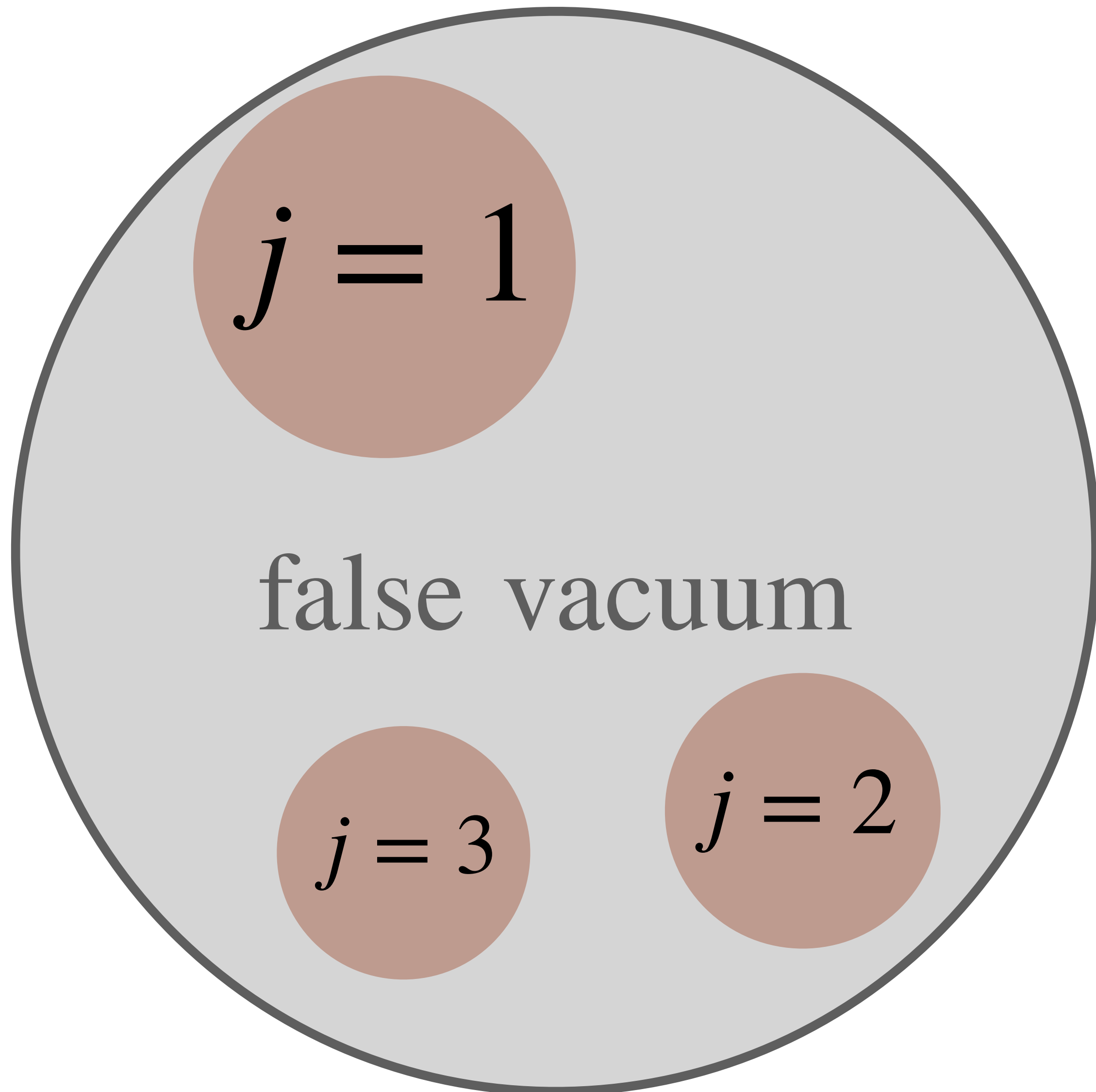
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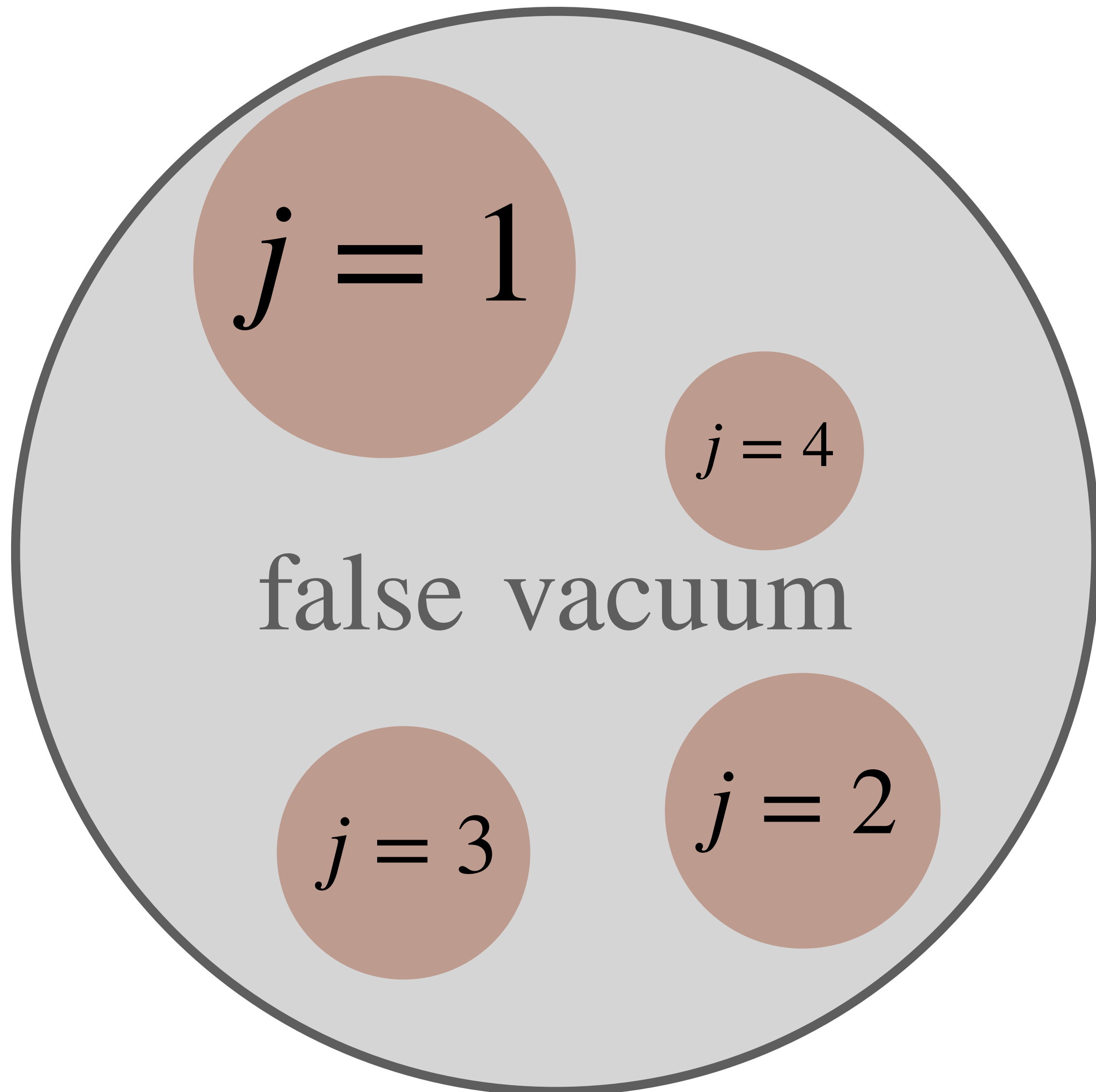
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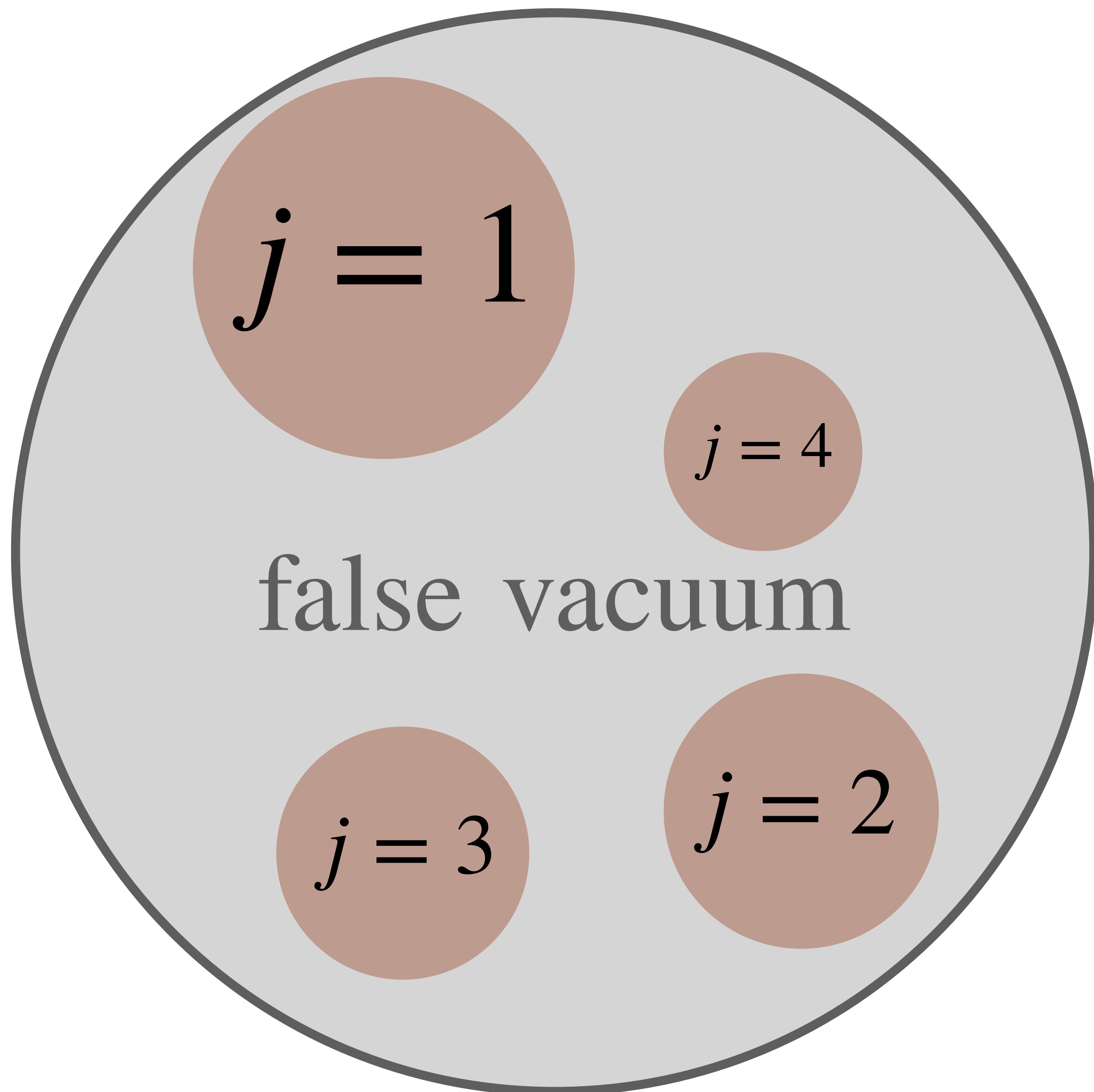
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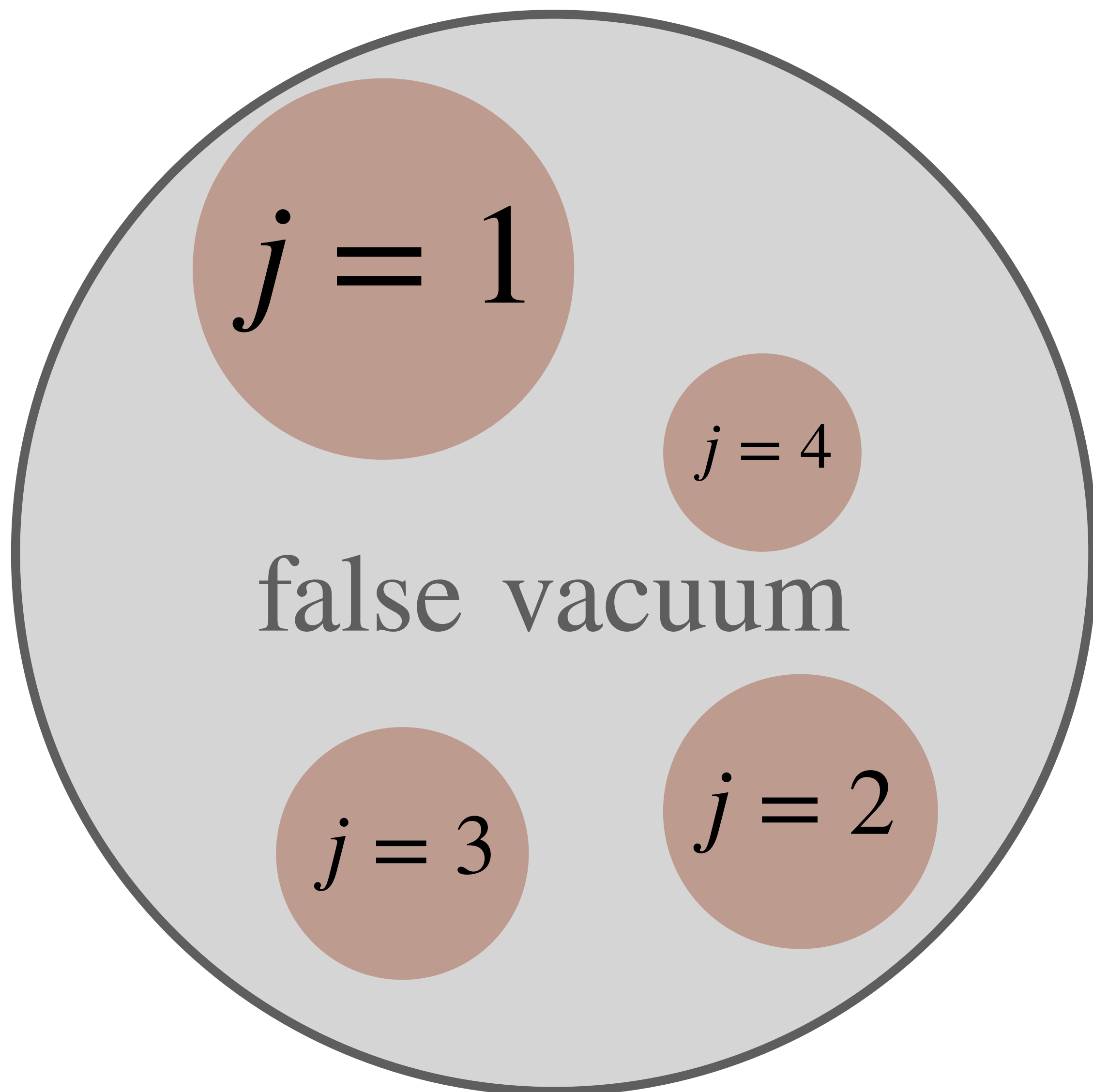
$$\rho_V = F_{\text{false}}$$

$$\rho_R'(t) + 4\mathcal{H}\rho_R(t) = -\rho_V'(t)$$



$$\rho_V = F_{\text{false}}(t_{j=1}, t_{j=2}, t_{j=3}, \dots t_{J_c})$$

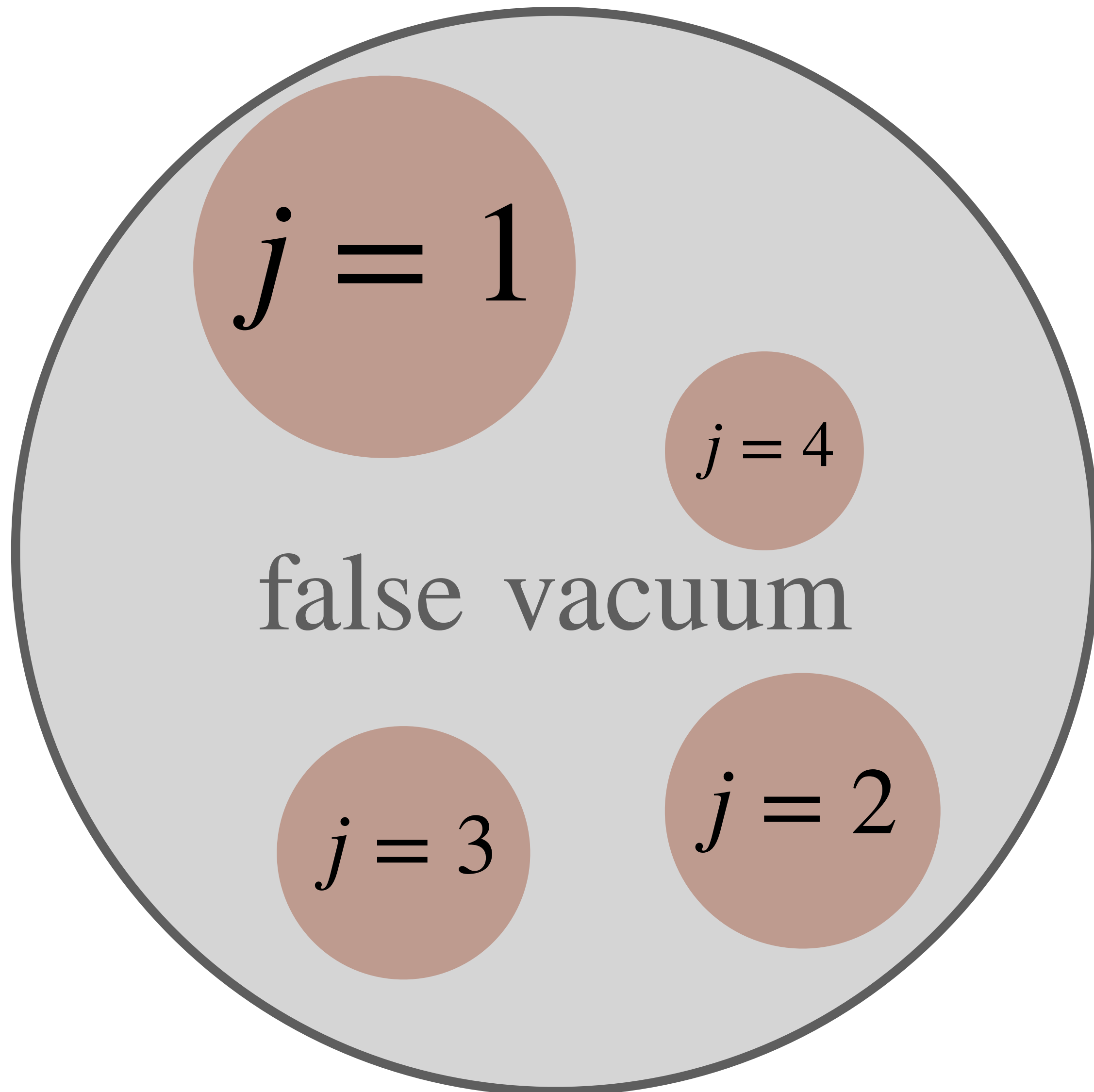
$$\rho_R'(t) + 4\mathcal{H}\rho_R(t) = -\rho_V'(t)$$



random variables

$$\rho_V(t) = F_{\text{false}}(\overbrace{t_{j=1}, t_{j=2}, t_{j=3}, \dots t_{J_c}}^{\text{random variables}})$$

$$\rho_R'(t) + 4\mathcal{H}\rho_R(t) = -\rho_V'(t)$$



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Sasaki+ 1982

Bian+, 2021

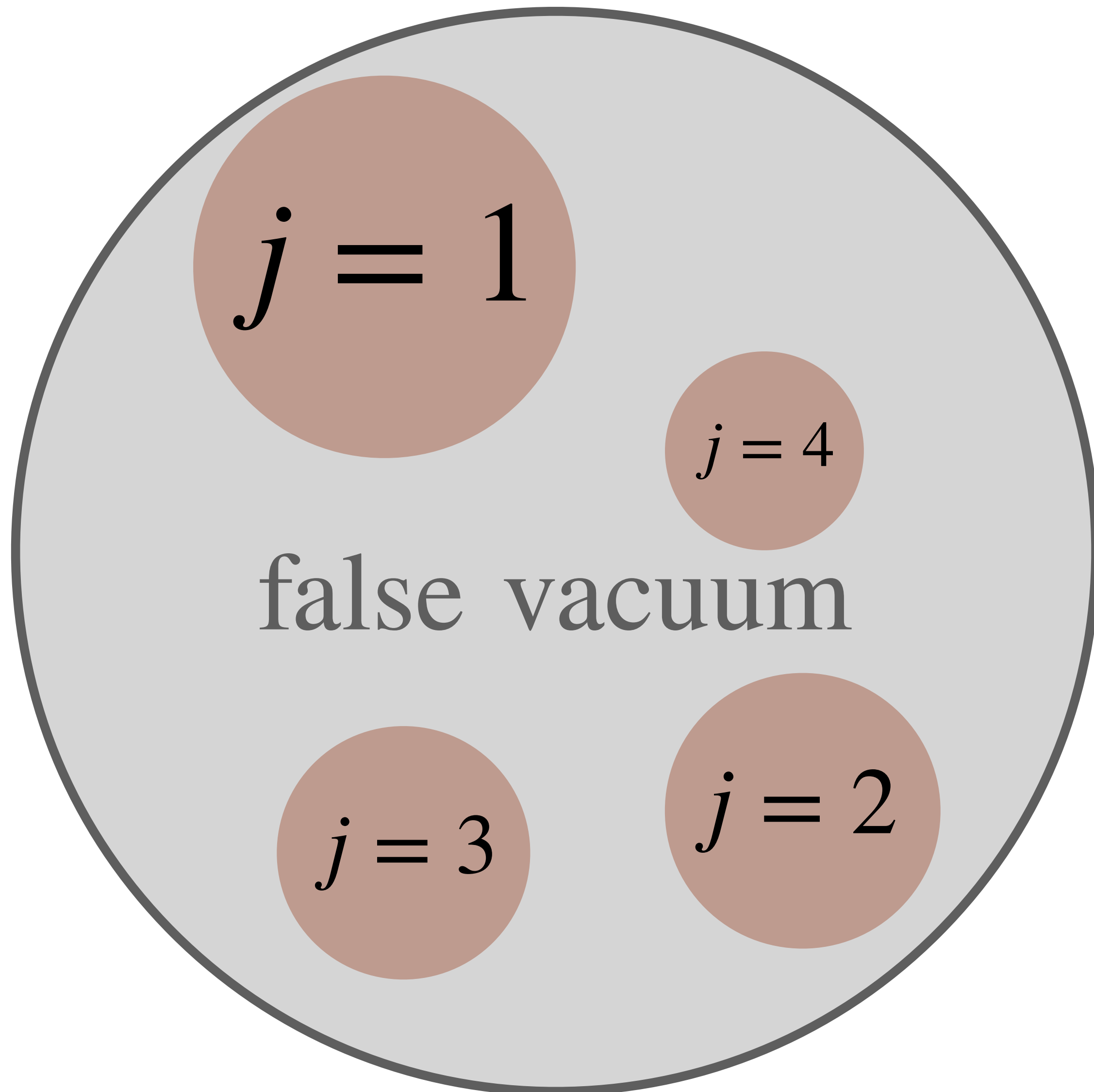
YG, Volansky 2305:04942

Baldes, Olea-Romacho, 2307.11639

YG, PRL, 2307.04239

YG, 2311.13640

$$\rho'_R(t) + 4\mathcal{H}\rho_R(t) = -\rho'_V(t)$$



random variables

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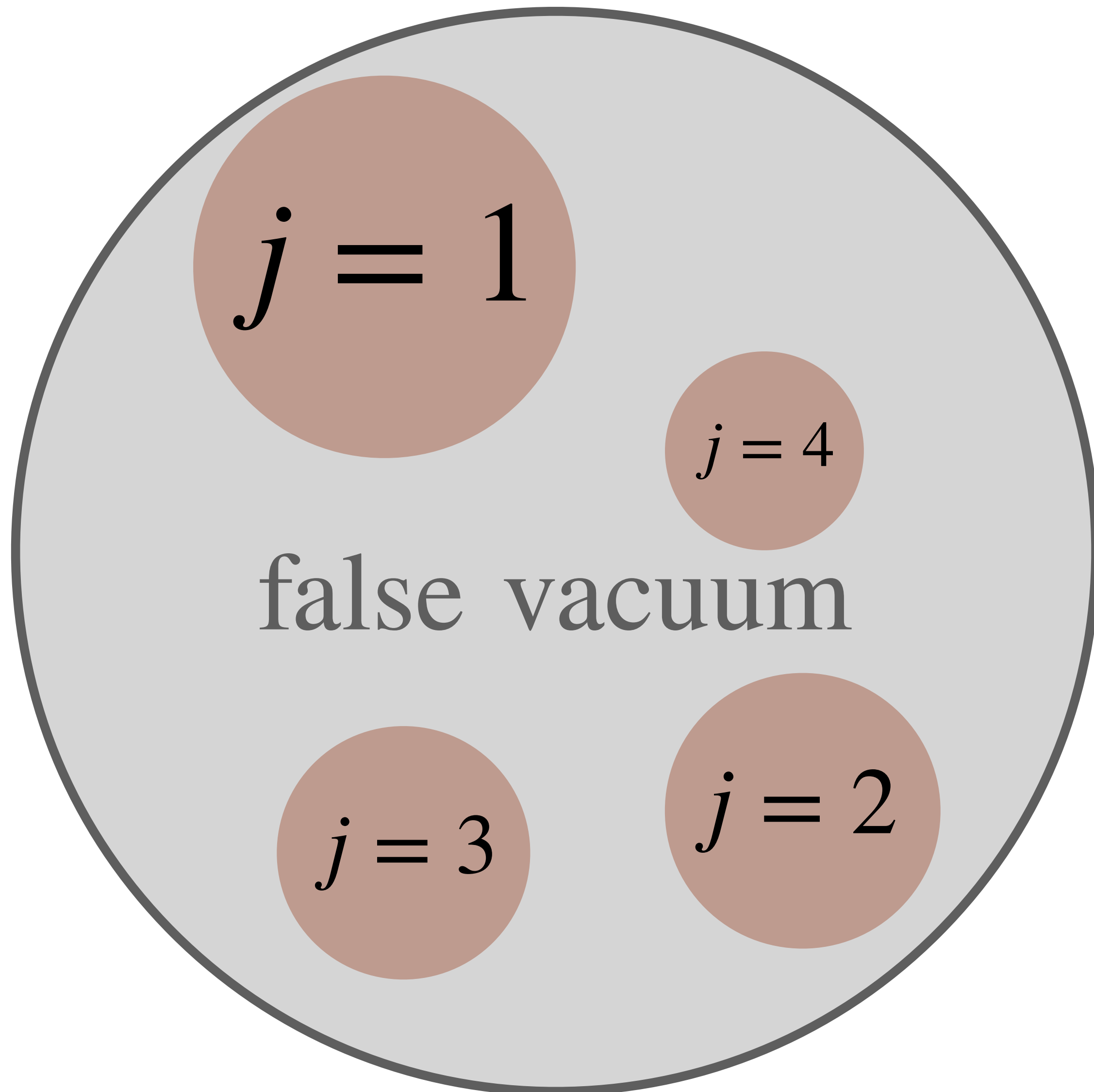
J_c arbitrary

Lewicki, Toczec, Vaskonen
PRL

2402.04158

c++ code: `deltaPT`

$$\delta\rho'_R(t) + 4\mathcal{H}\delta\rho_R(t) = -\delta\rho'_V(t)$$



random variables

$$\rho_V(t) = F_{\text{false}}(t_{j=1}, t_{j=2}, t_{j=3}, \dots t_{J_c})$$

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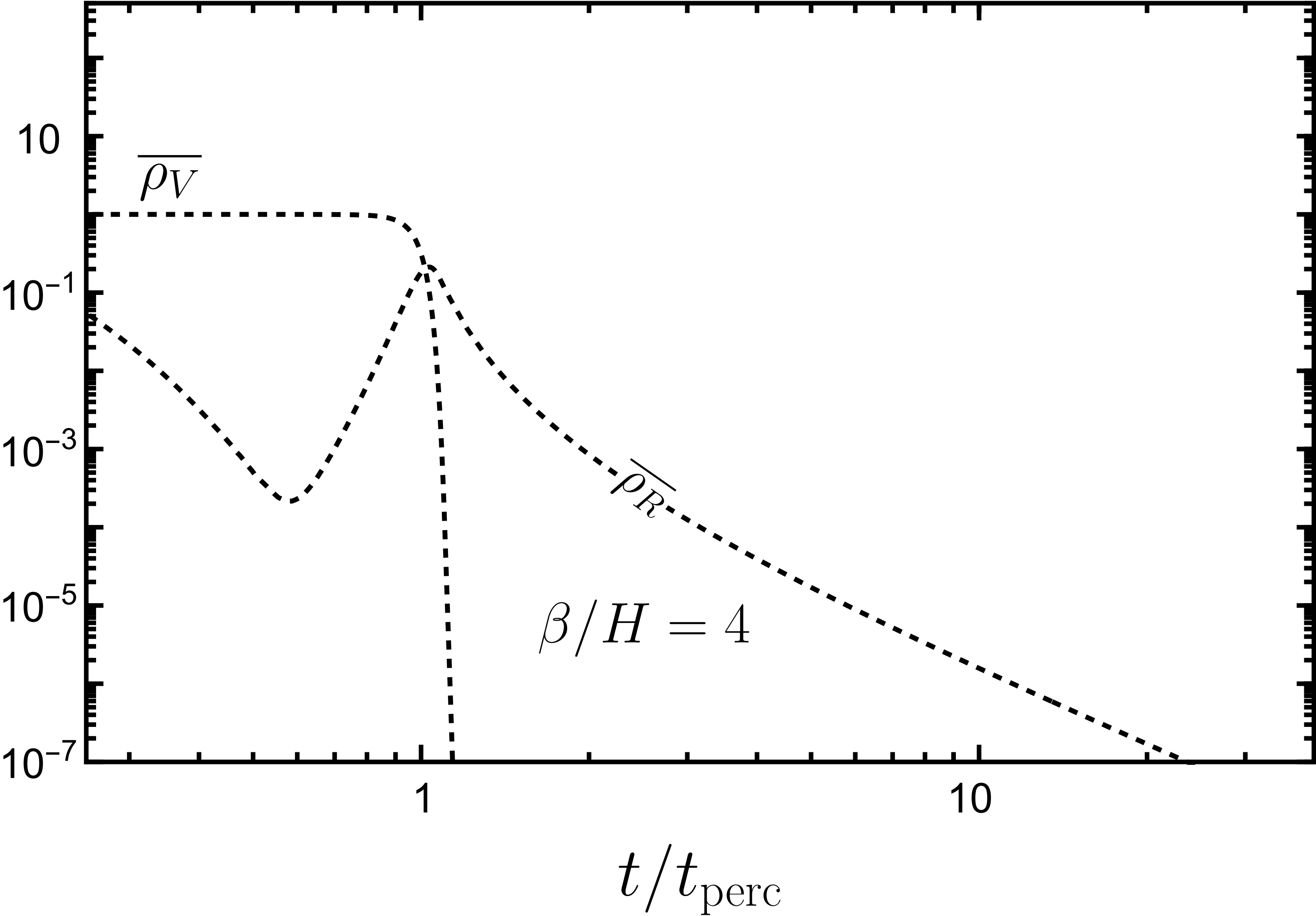
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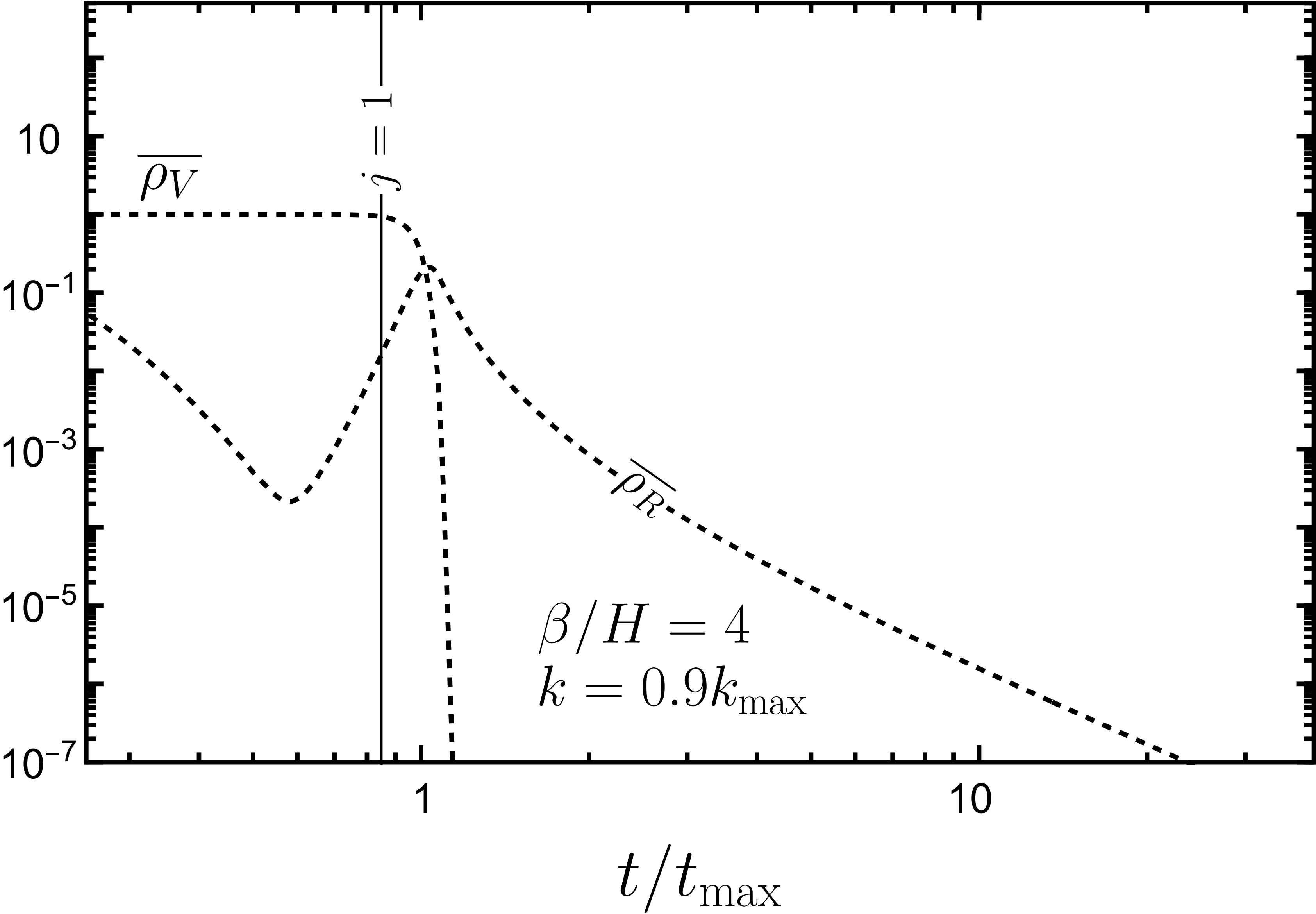
J_c arbitrary

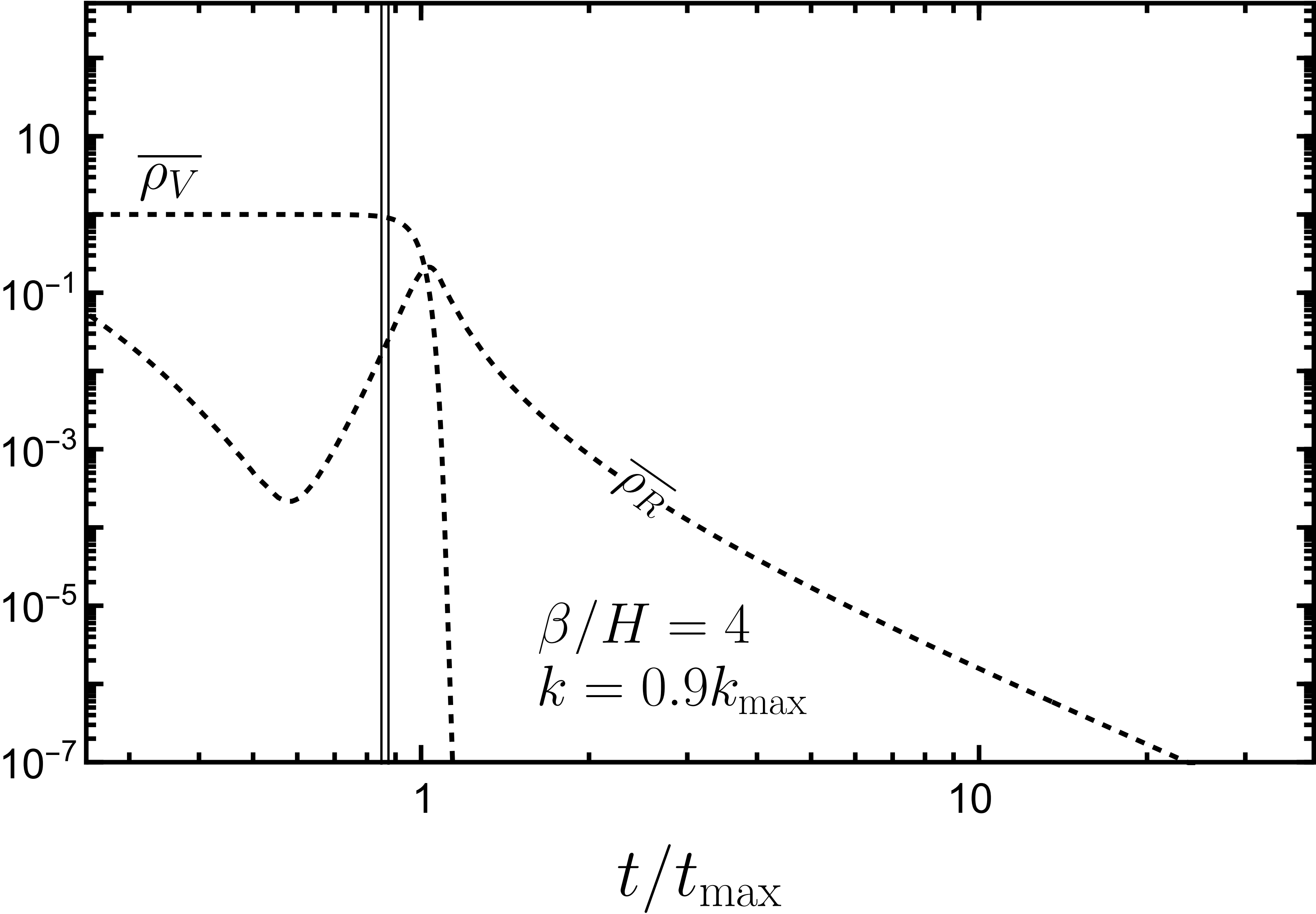
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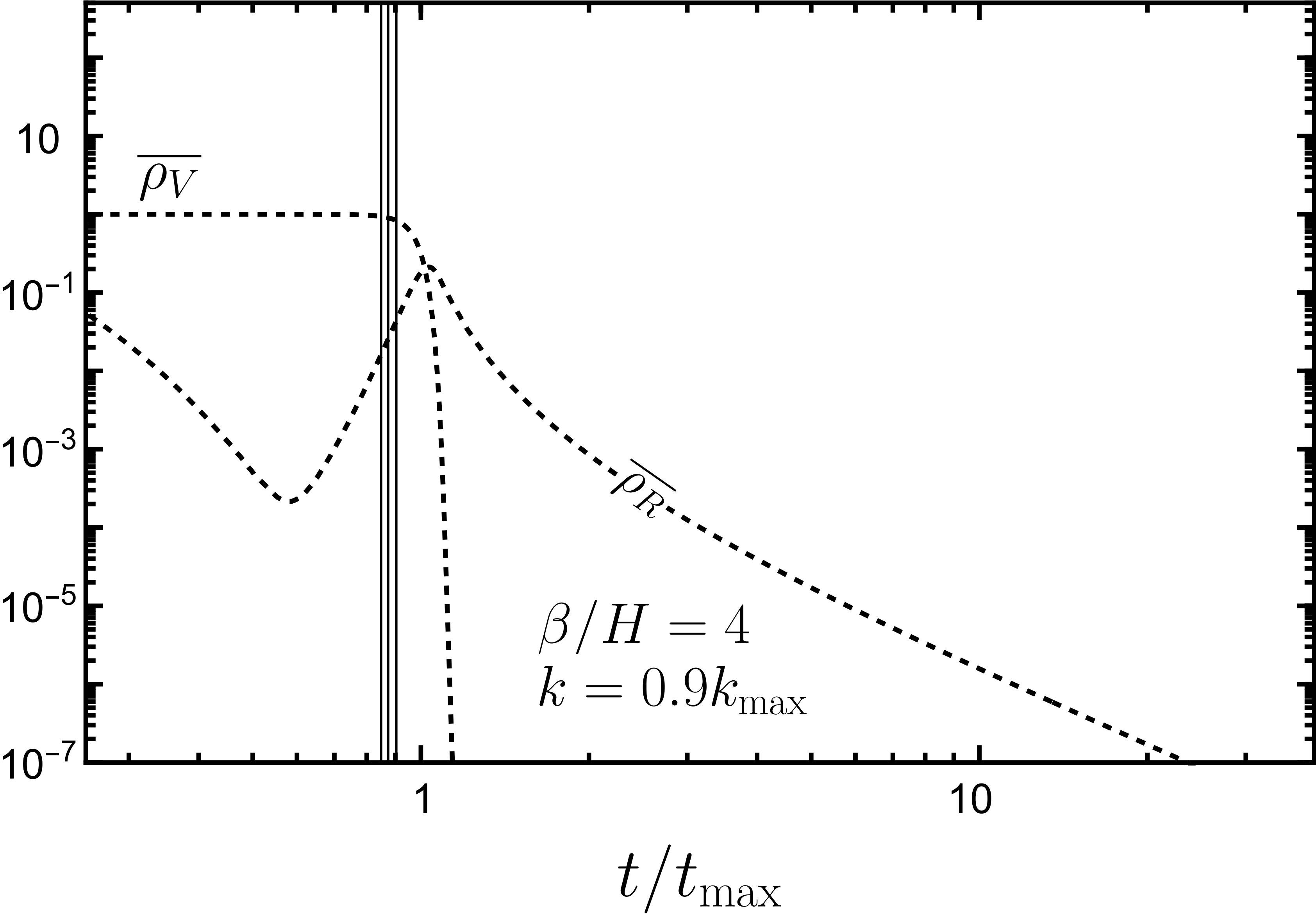
2402.04158

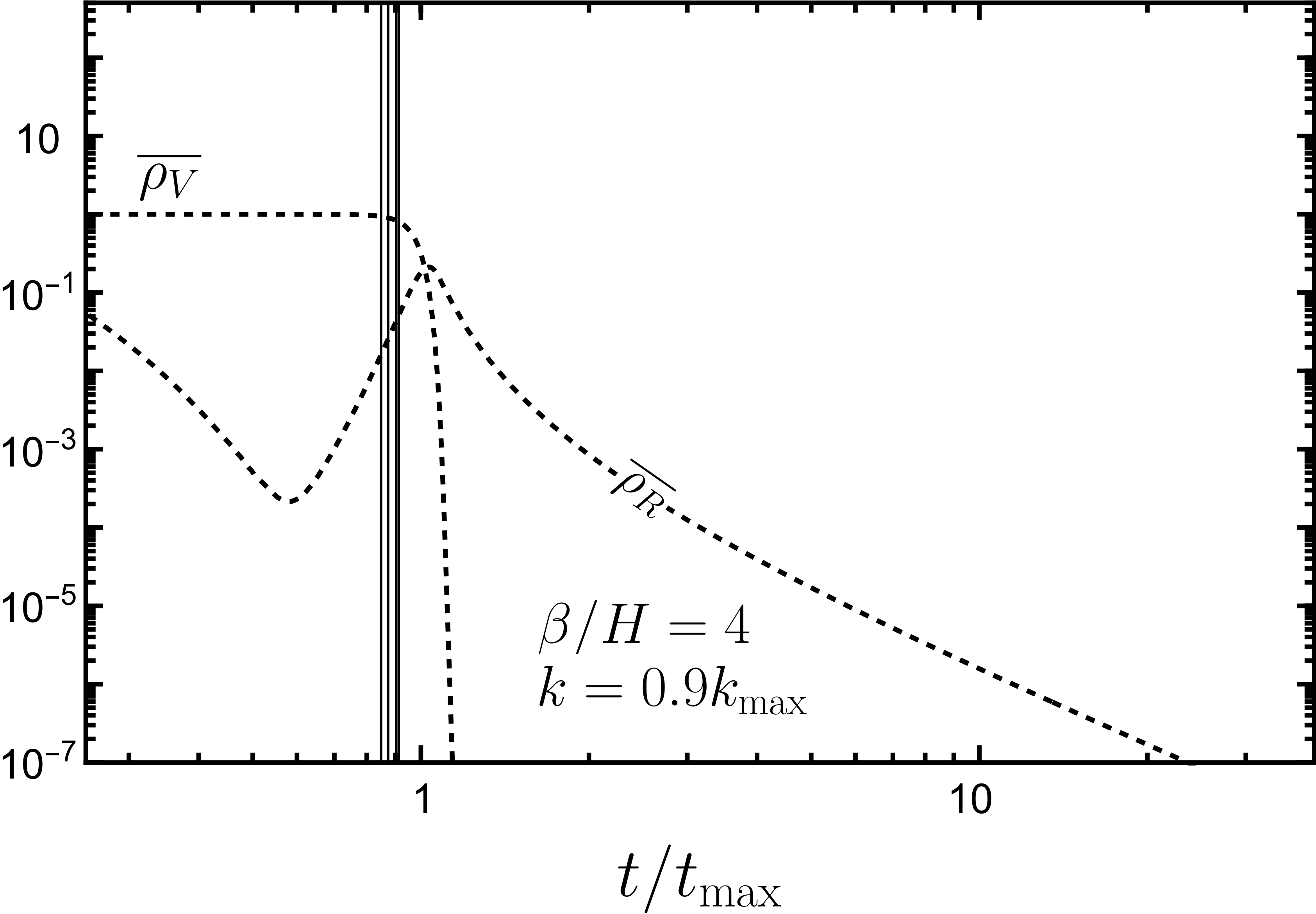
c++ code: *deltaPT*

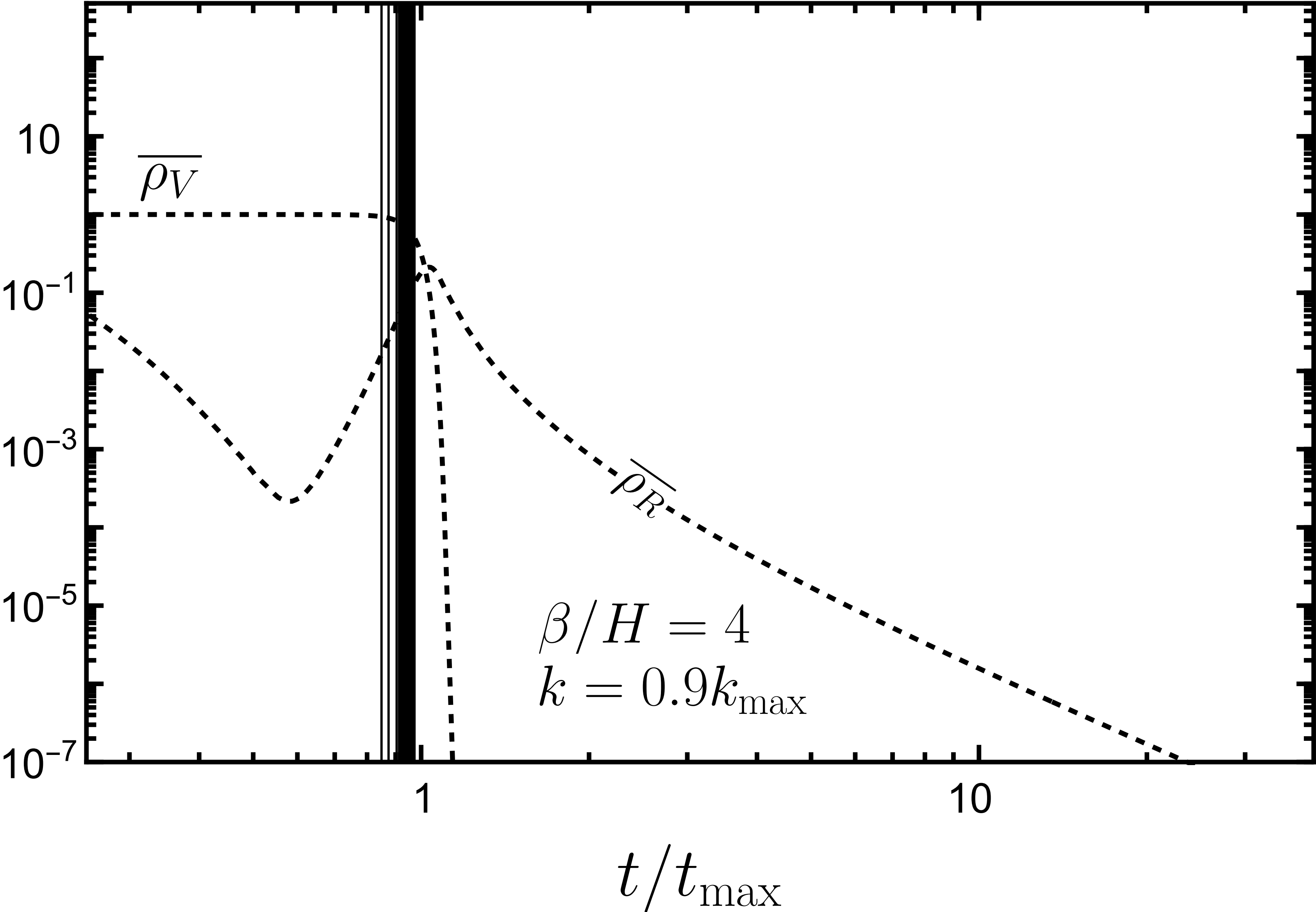


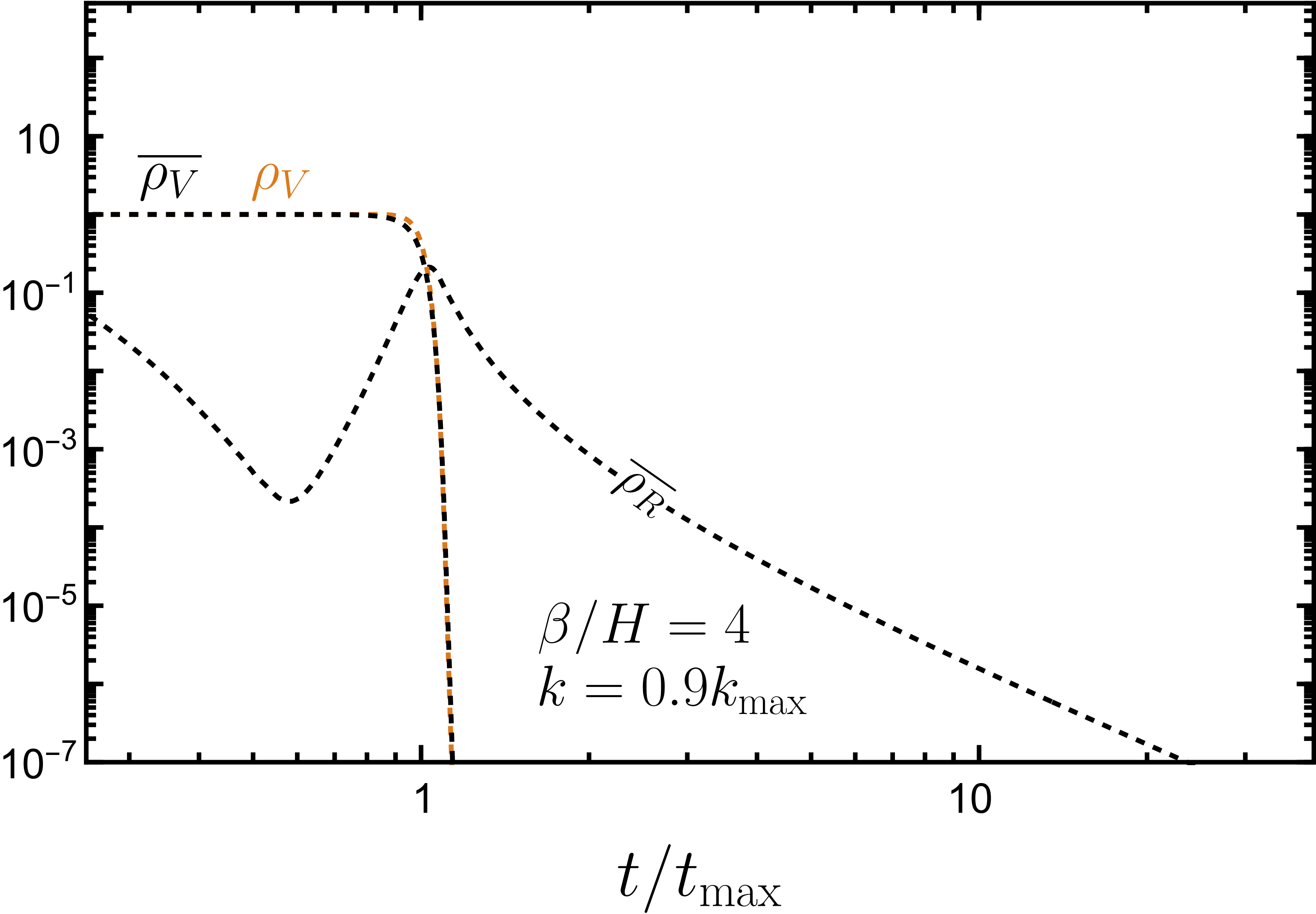


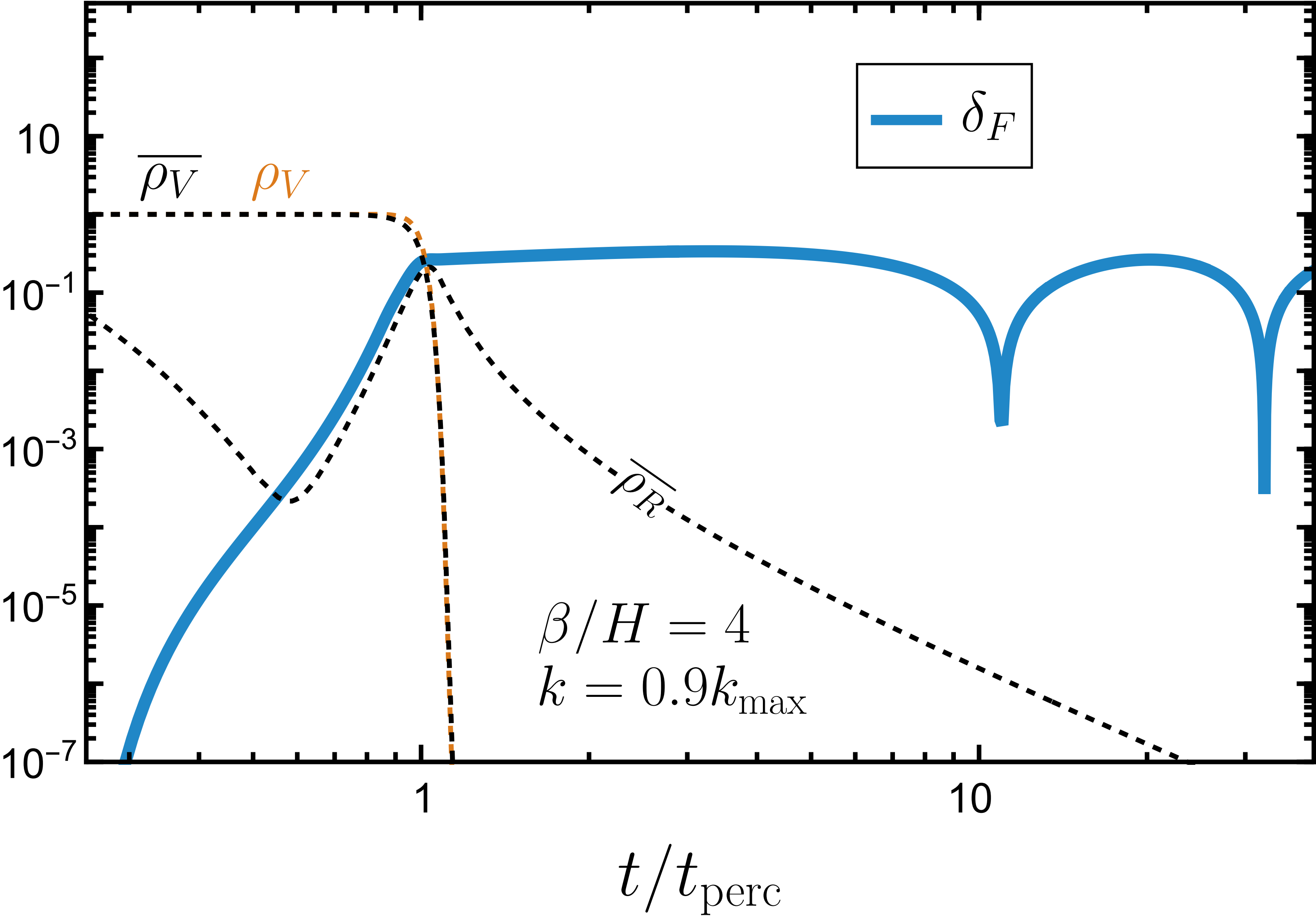


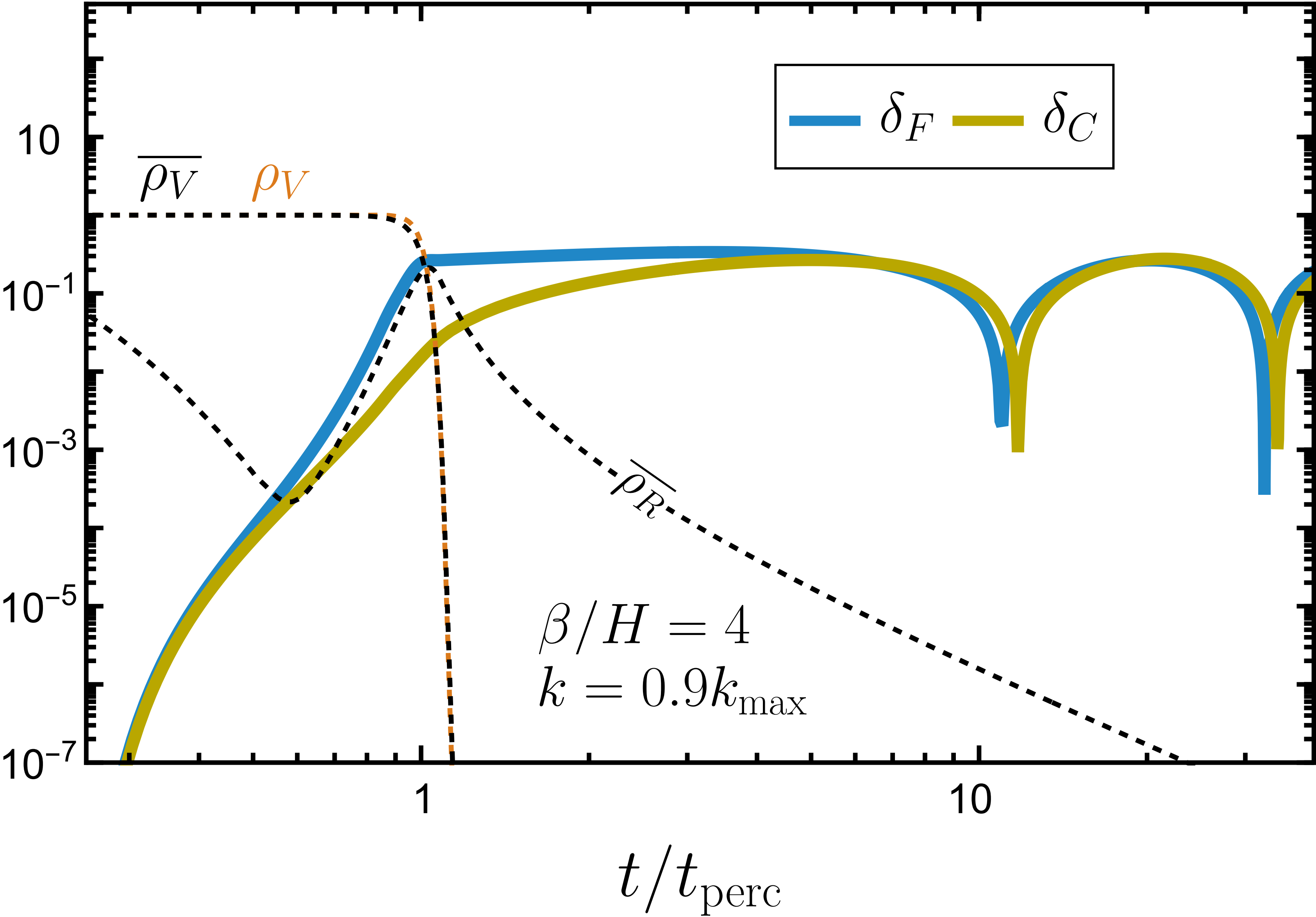




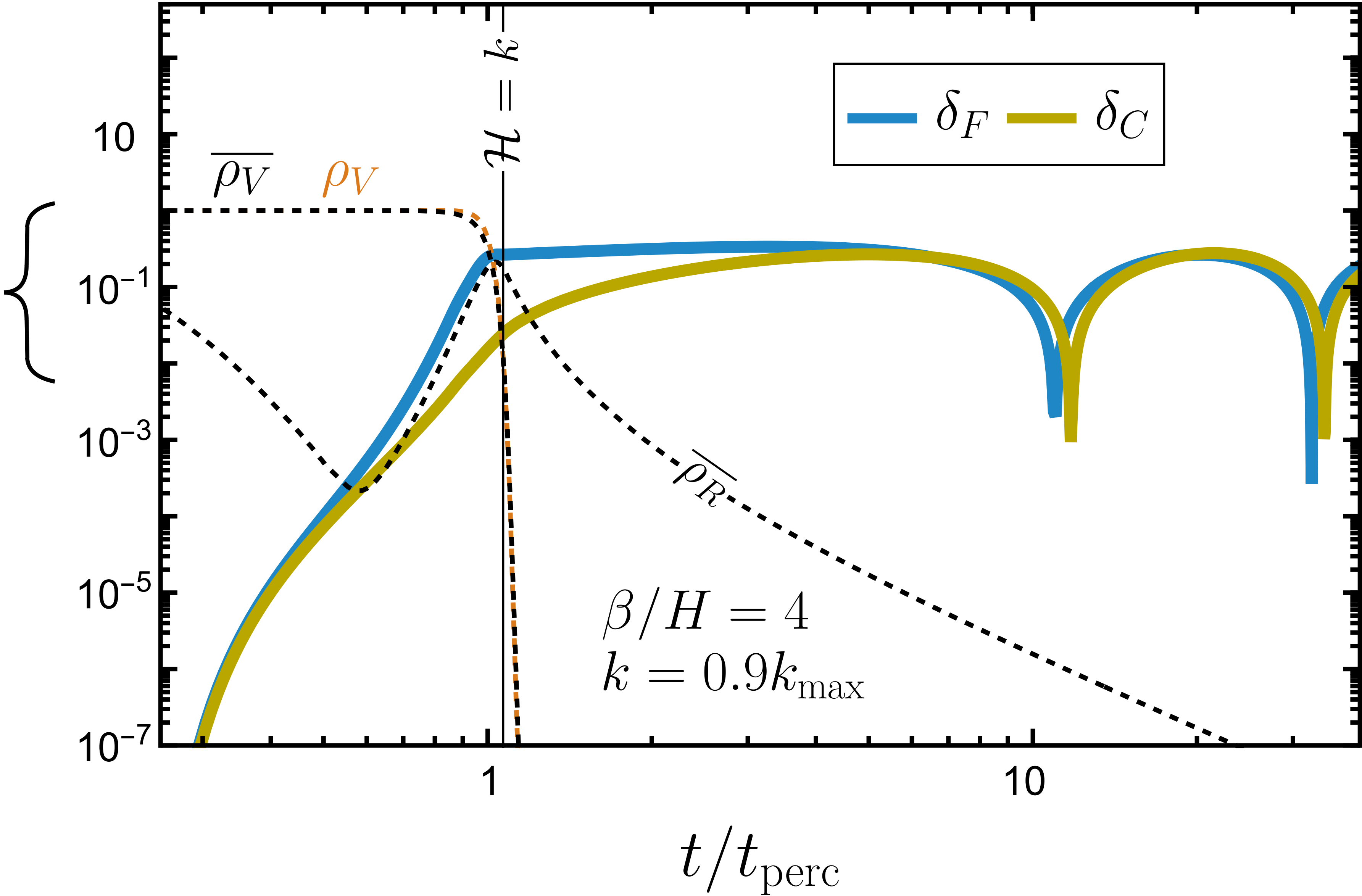




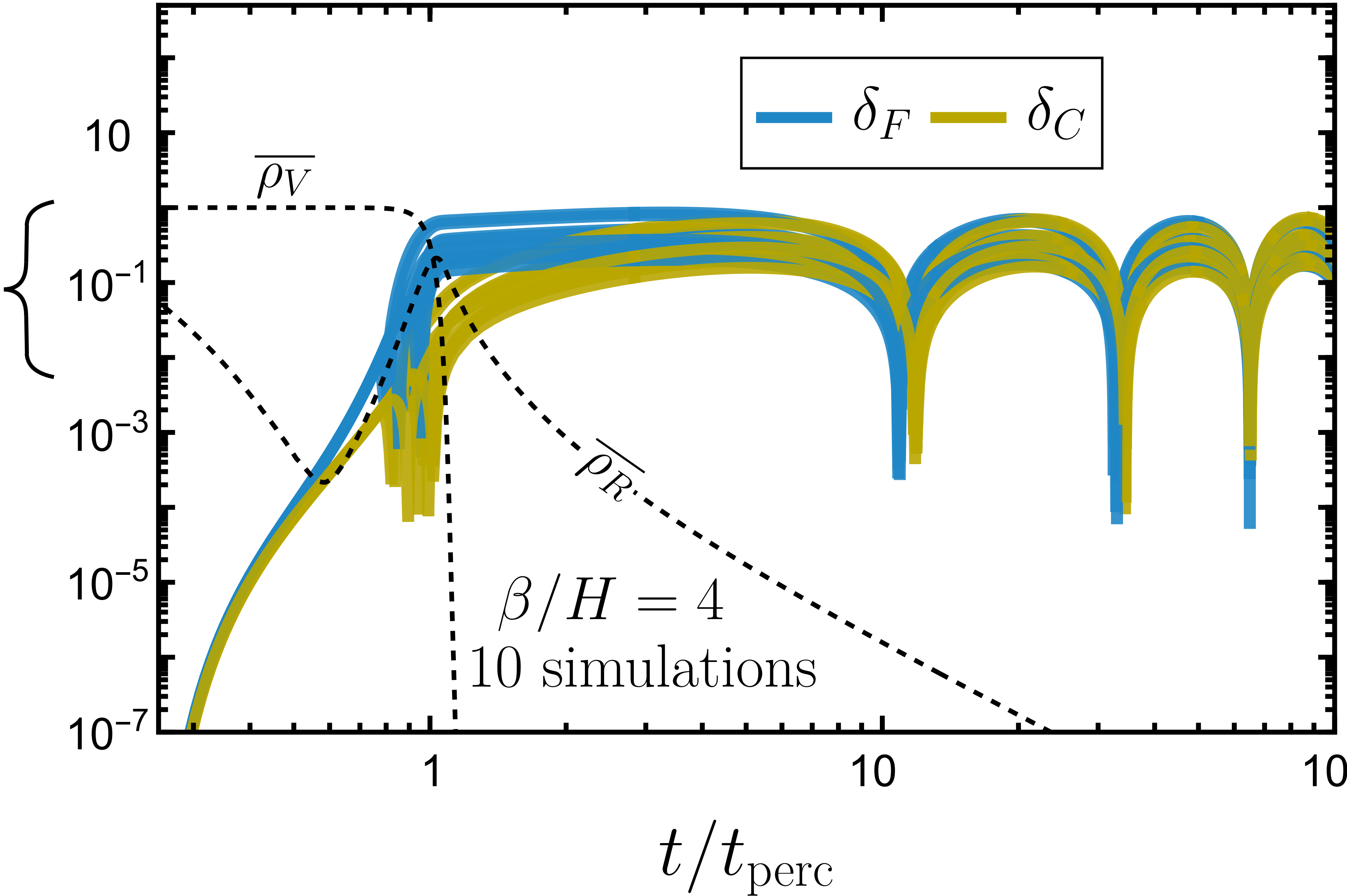




Key result 1
 $\delta^{(F)} \simeq 10 \delta^{(C)}$

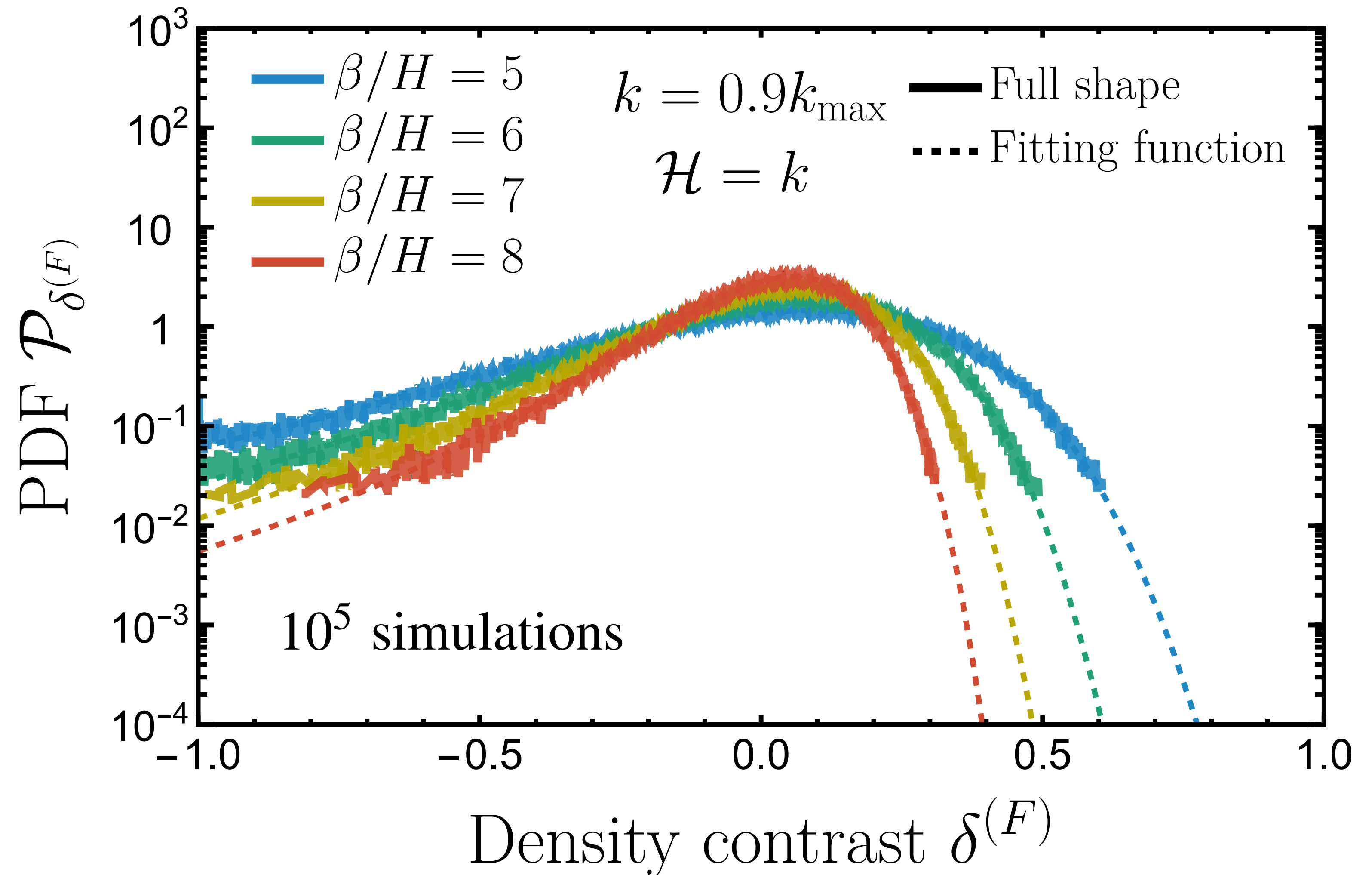


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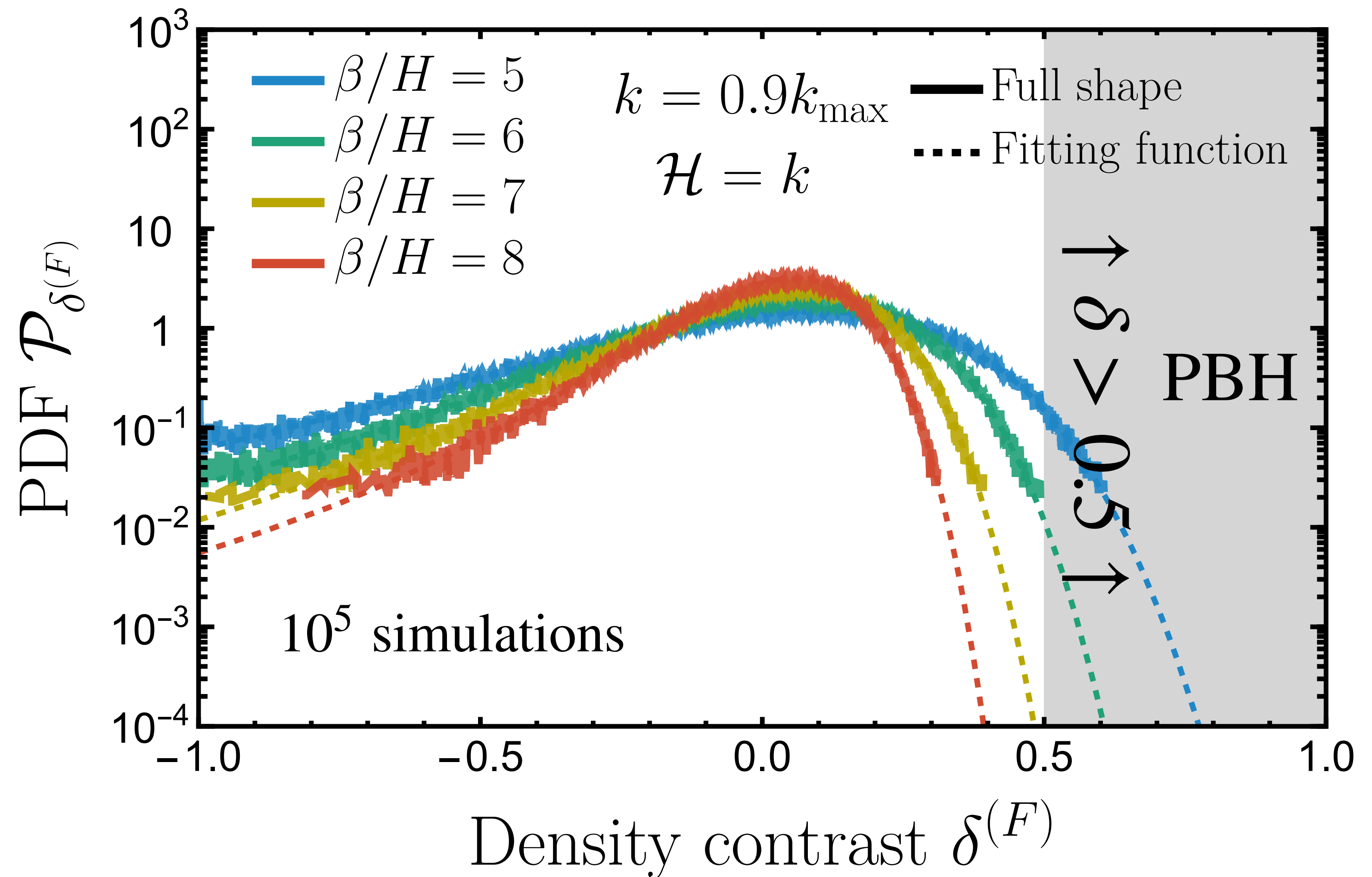
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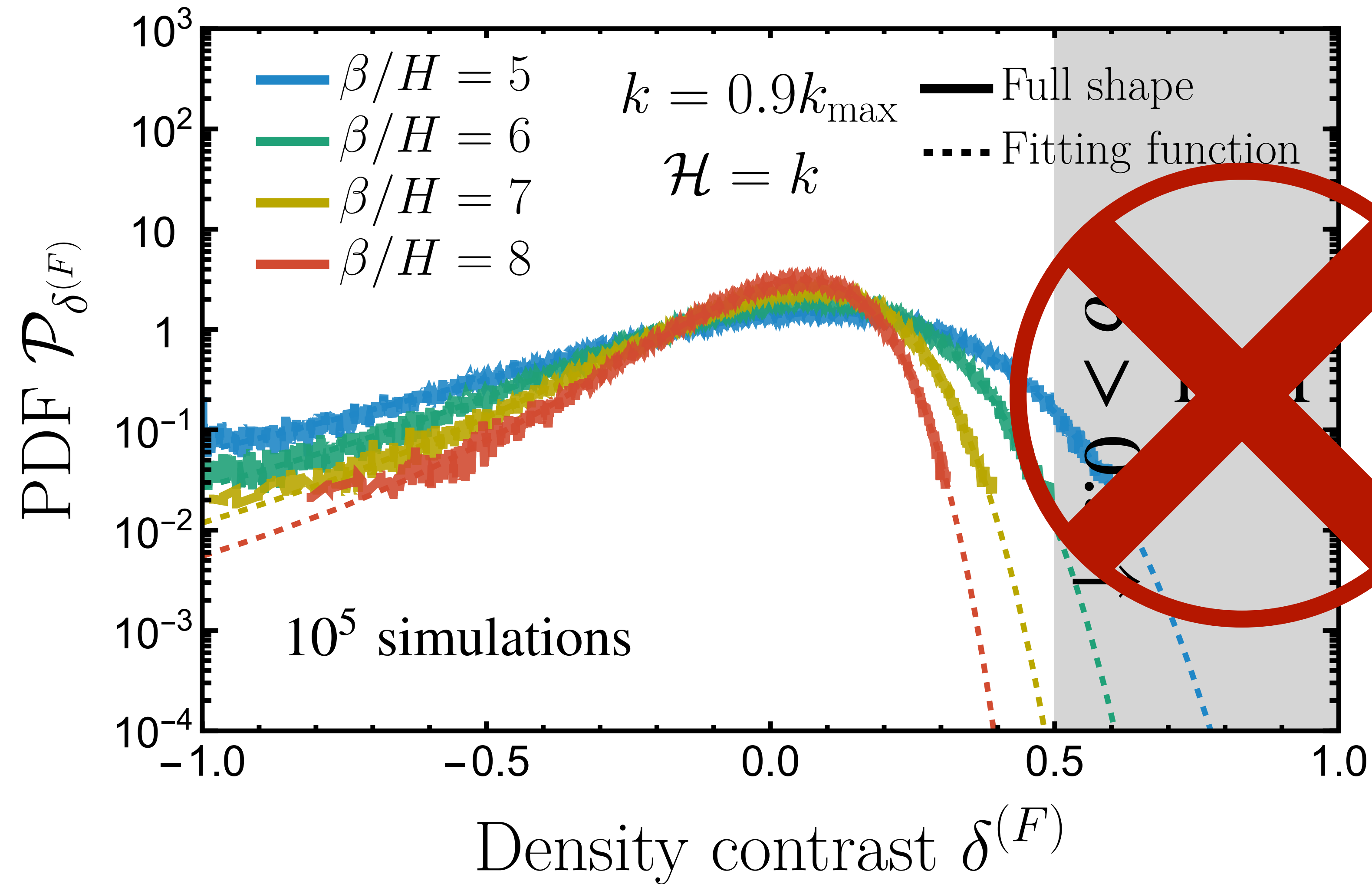
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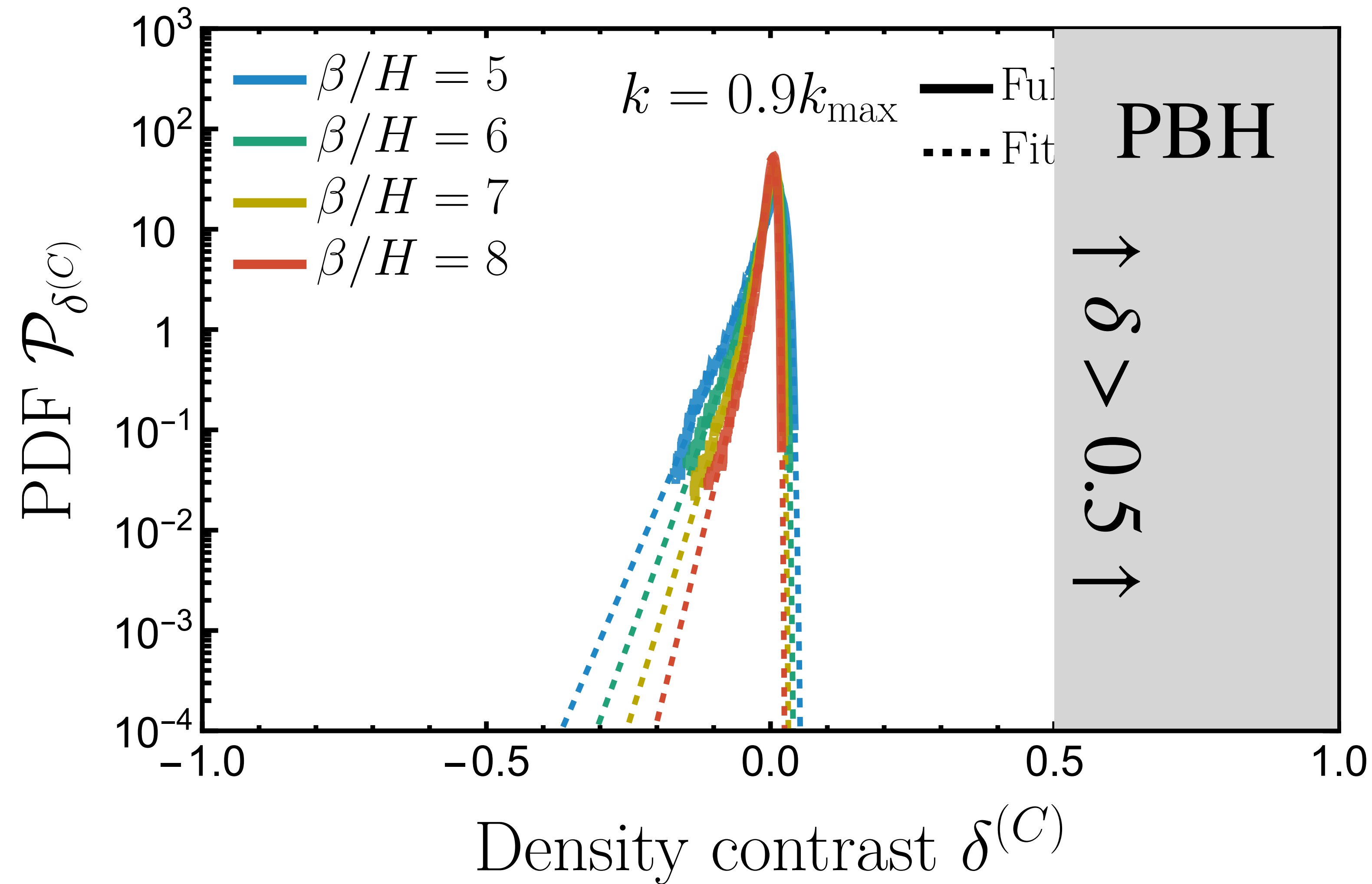
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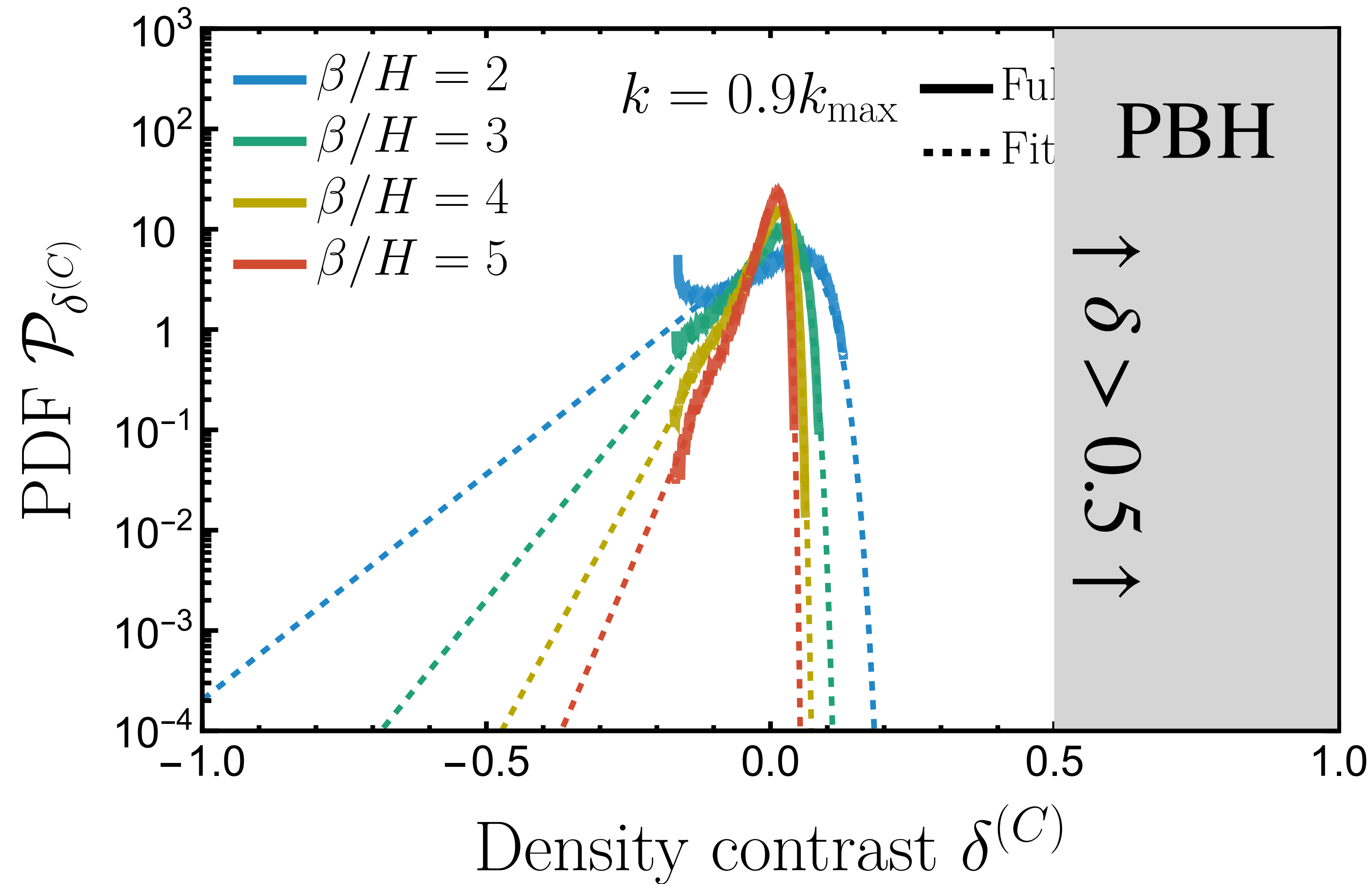
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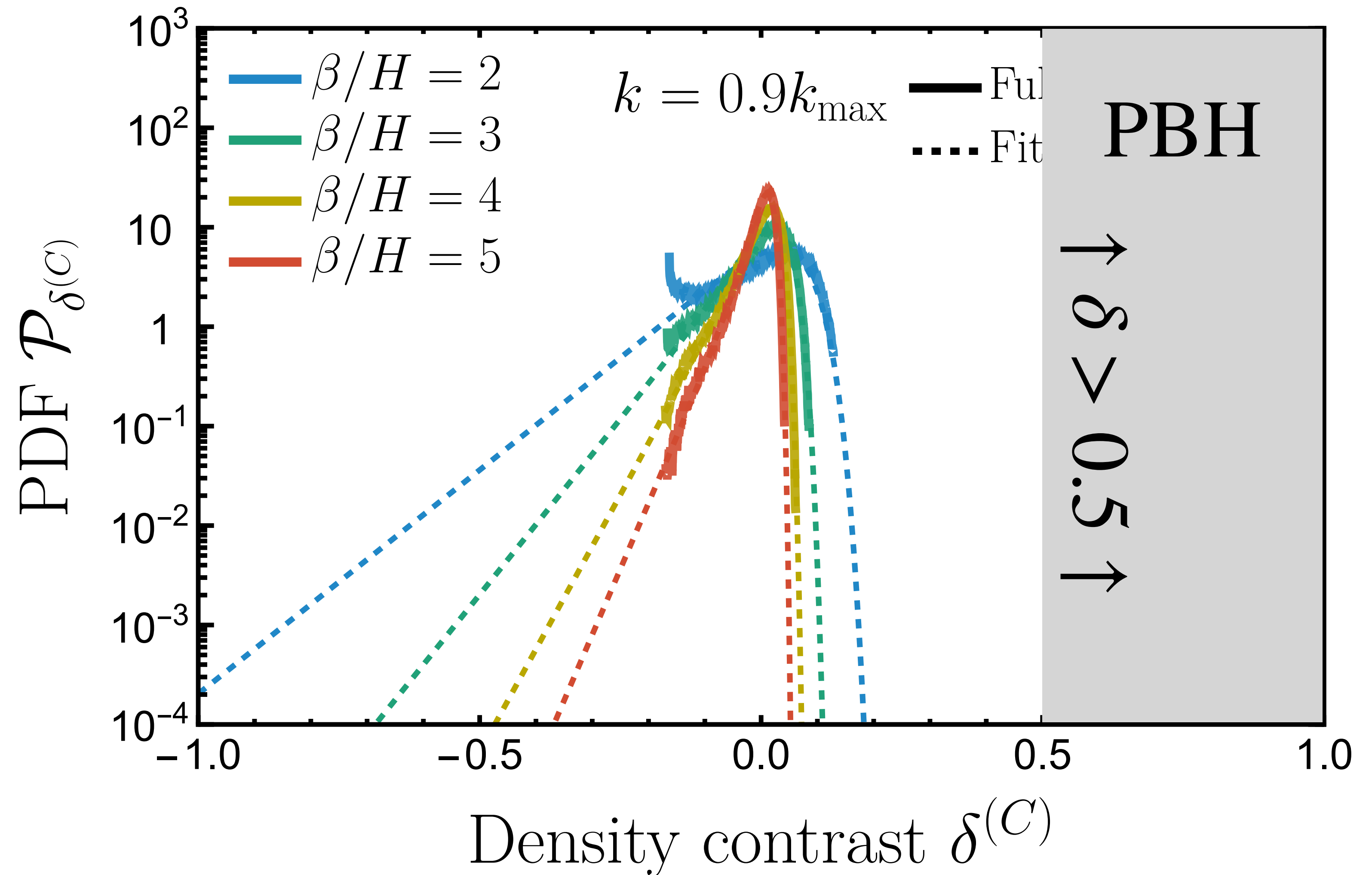
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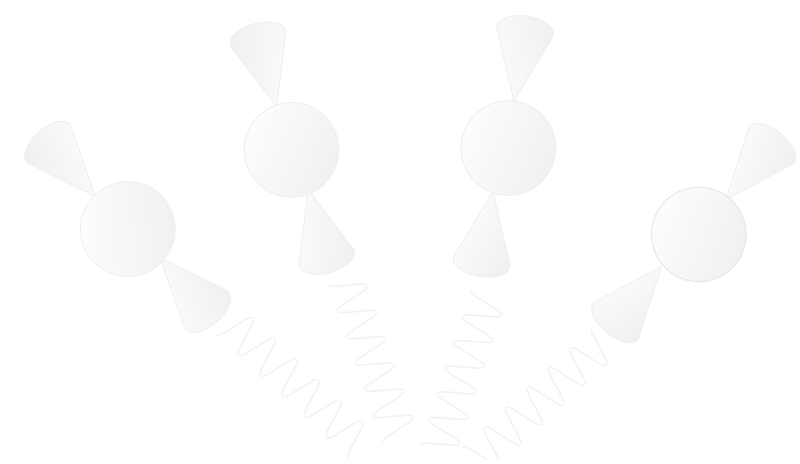


Key conclusion 1:

We find no PBH from FOPT



Pulsar Timing Arrays
(PTA)



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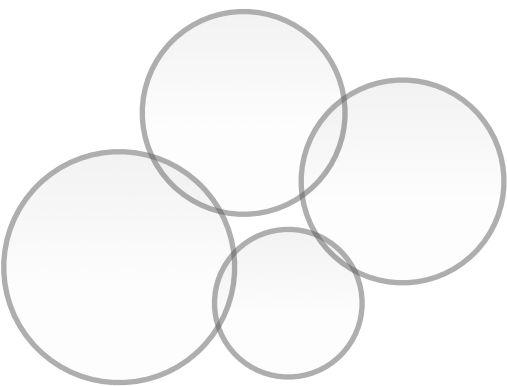
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Inhomogeneously expanding universe

(GWs)
Gravitational
Waves

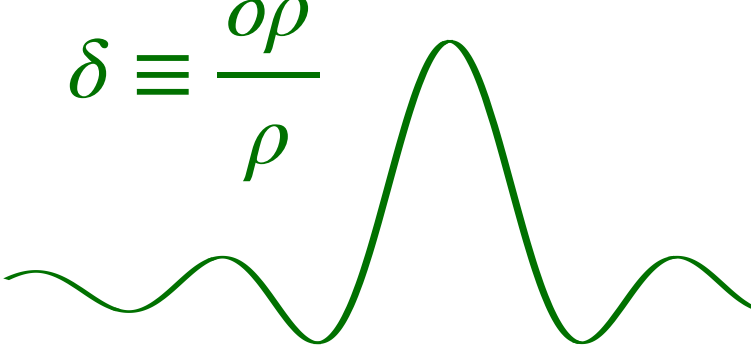


First-order
phase transition



overdensities

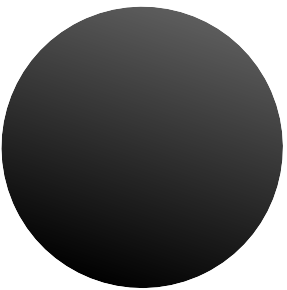
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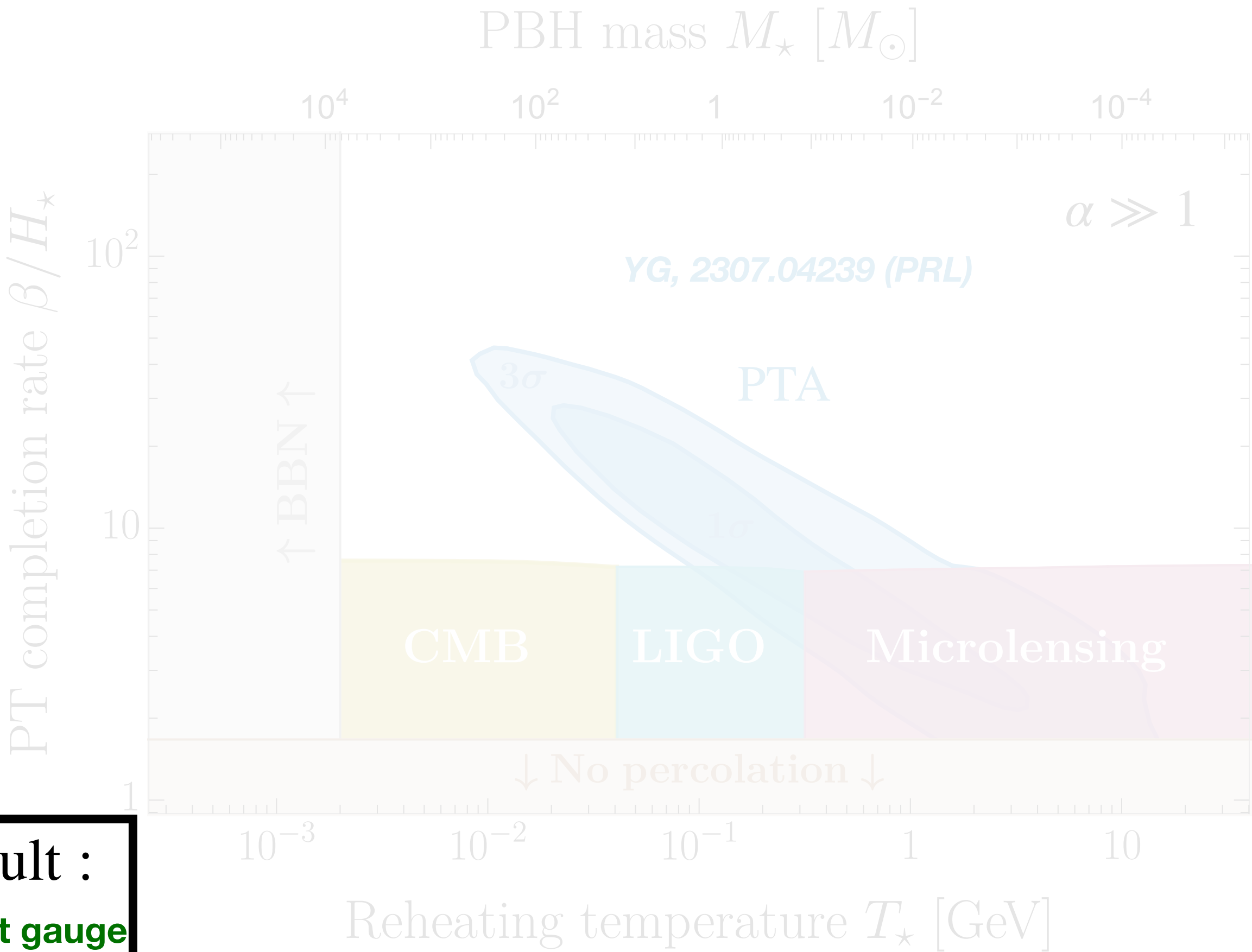
Musco 1809.02127
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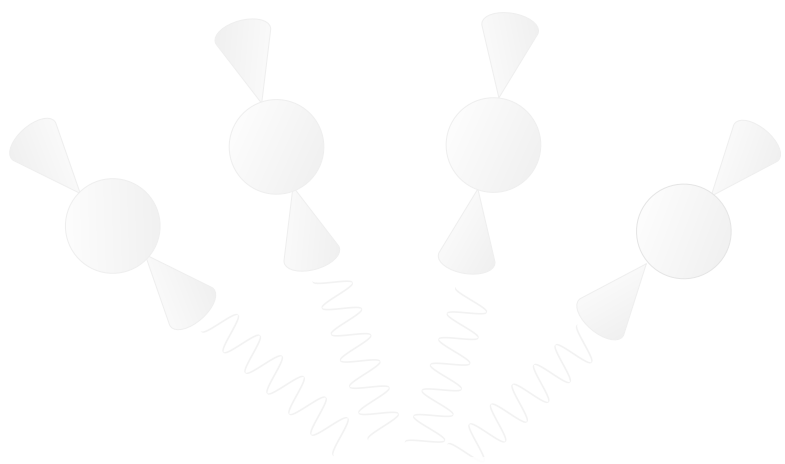
PBH

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Franciolini, YG, Jinno, 2503.01962



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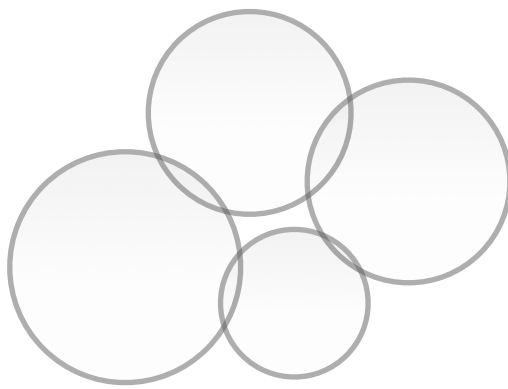
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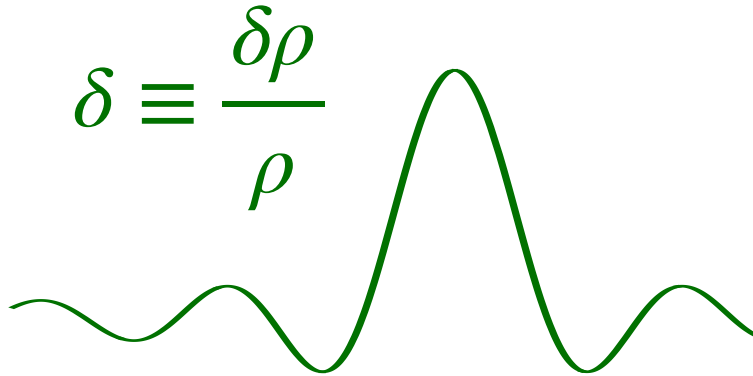


First-order
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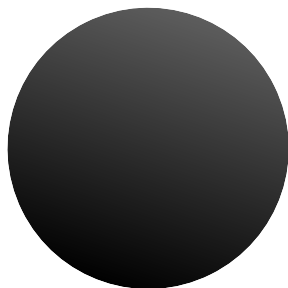
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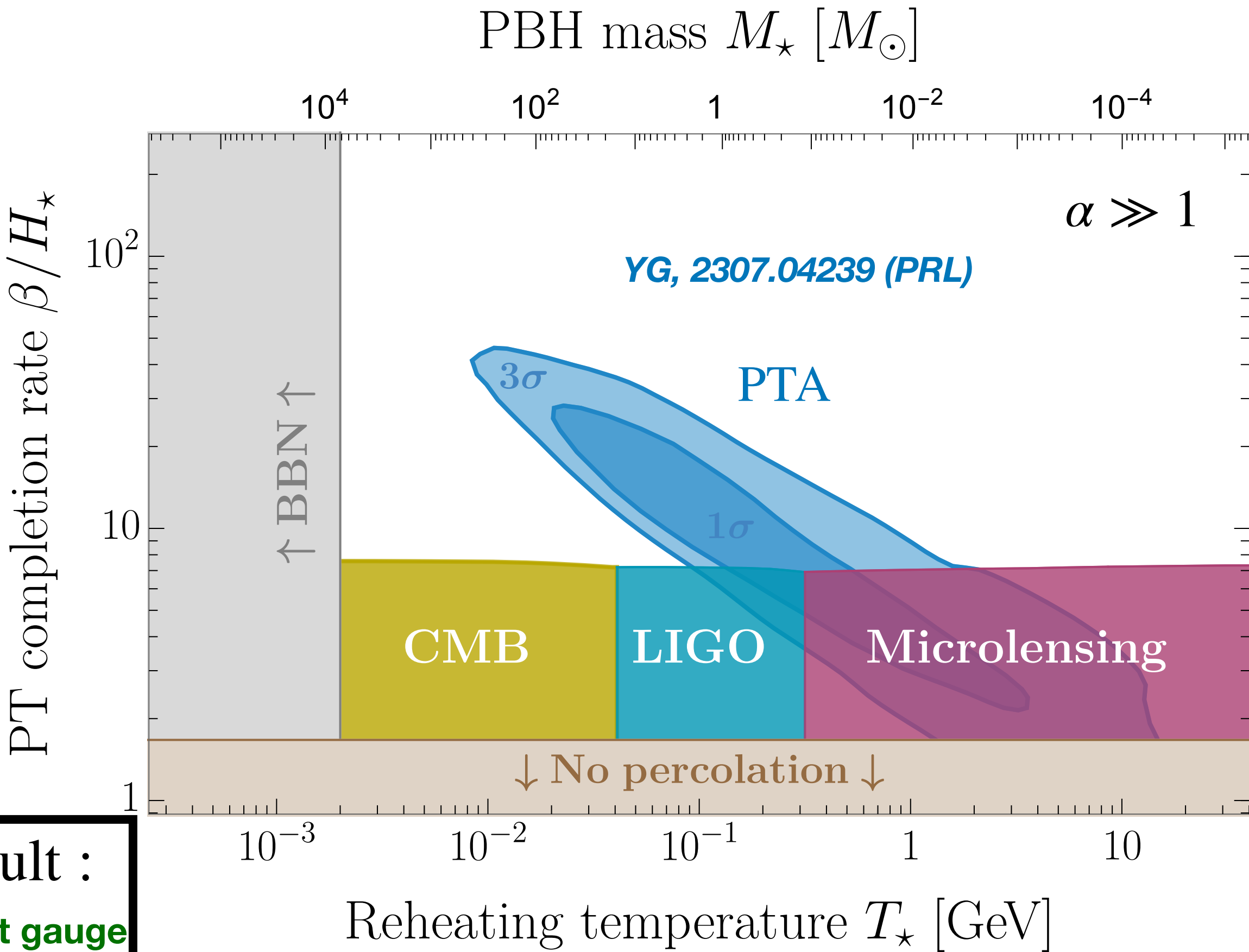
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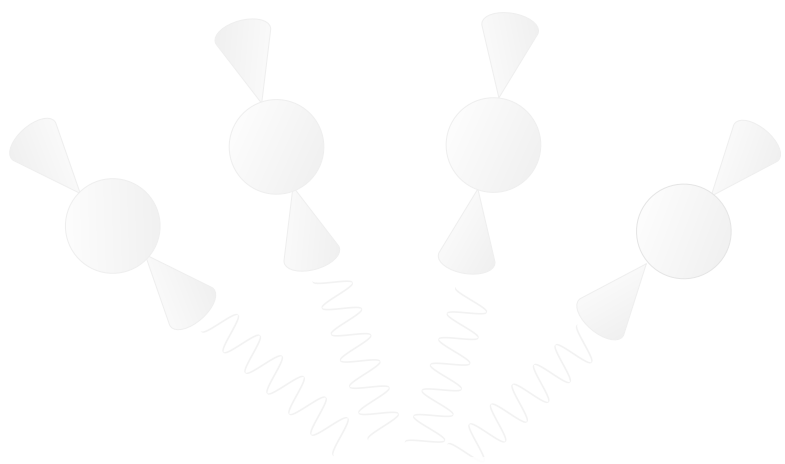
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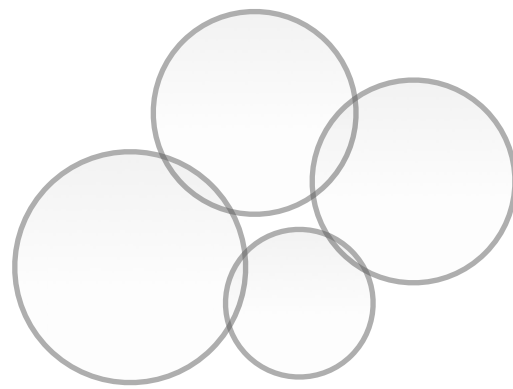
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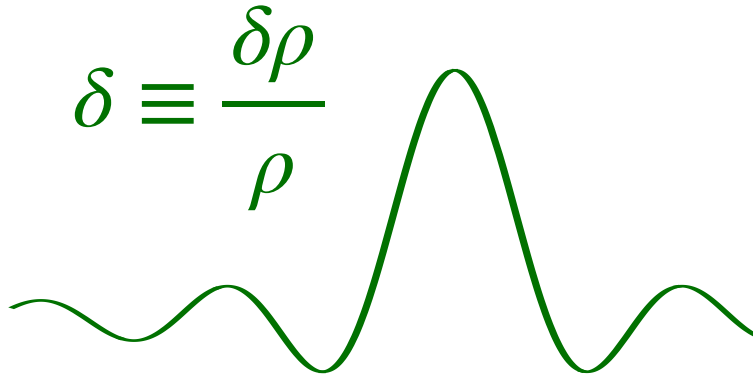
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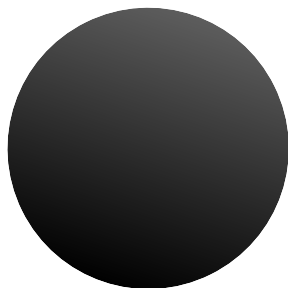
overdensities



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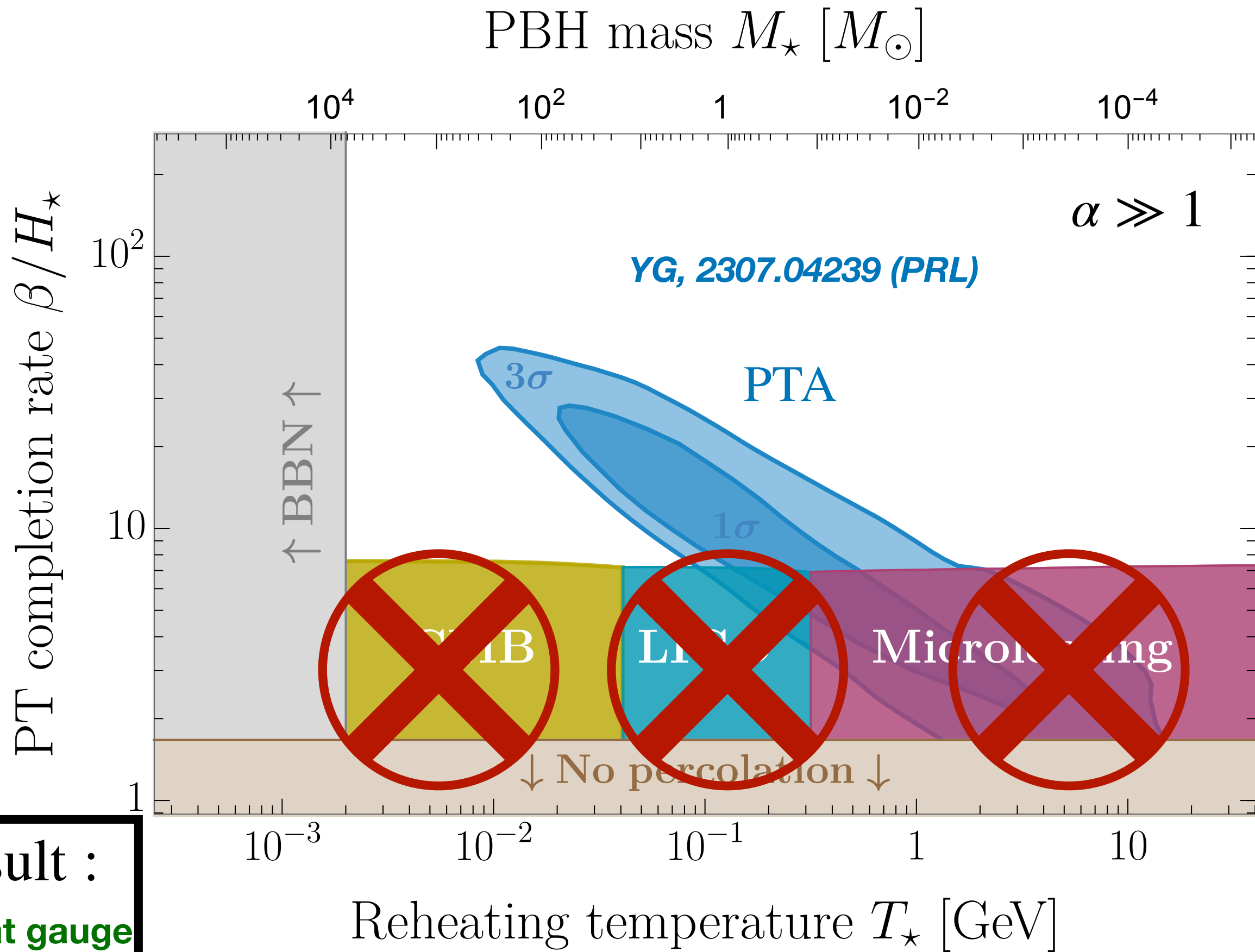


PBH

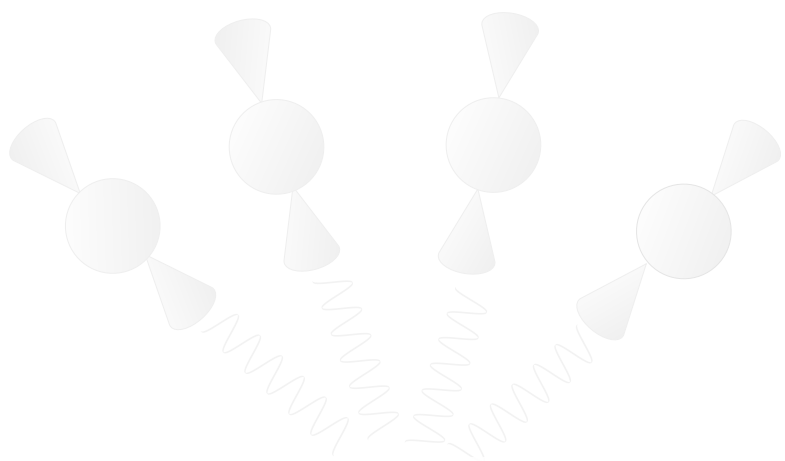
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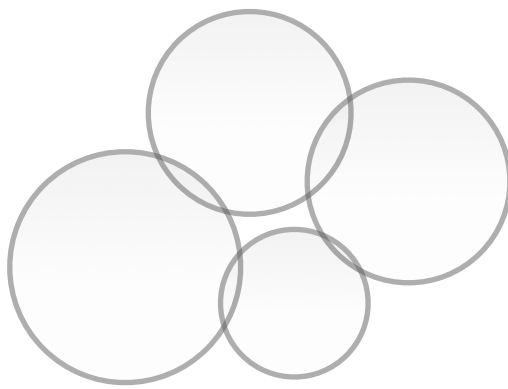
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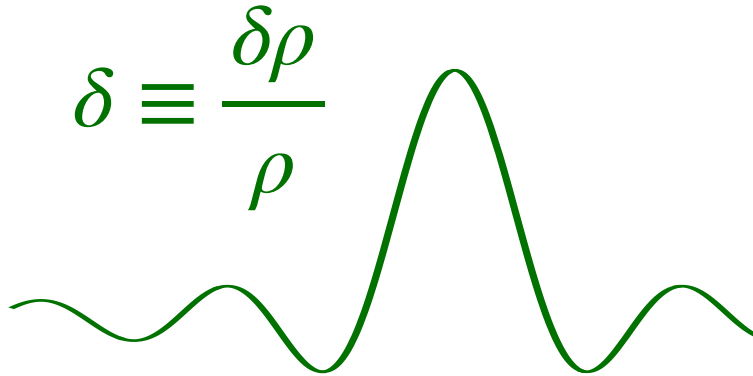
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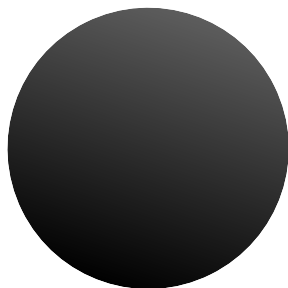


PT completion rate $\beta/H_\star$

collapses if

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Key result :
Spatially-flat gauge
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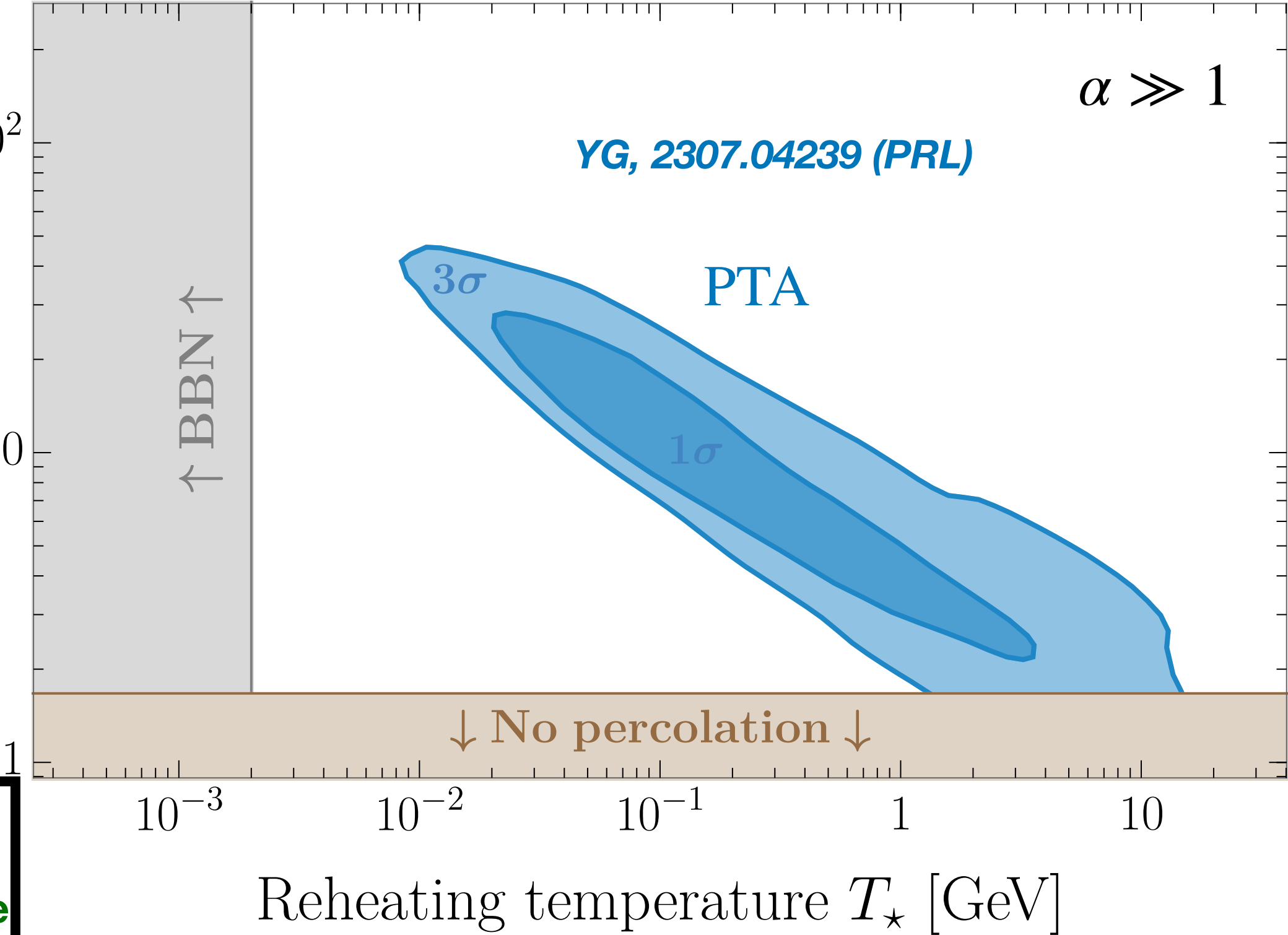


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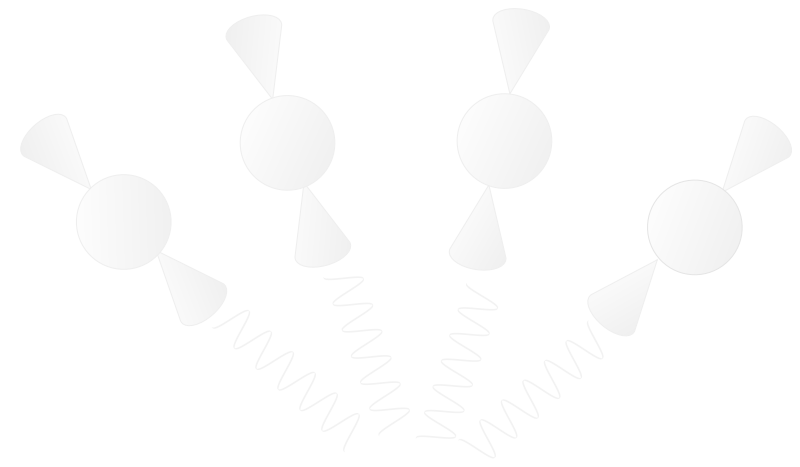
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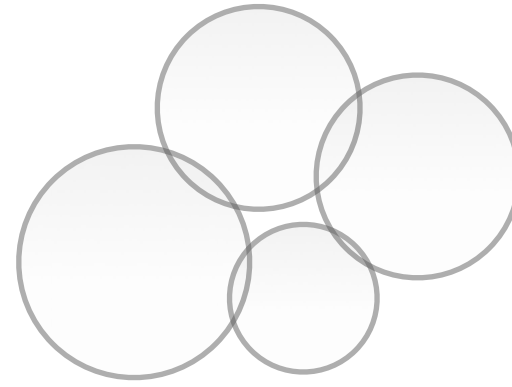
Pulsar Timing Arrays
(PTA)



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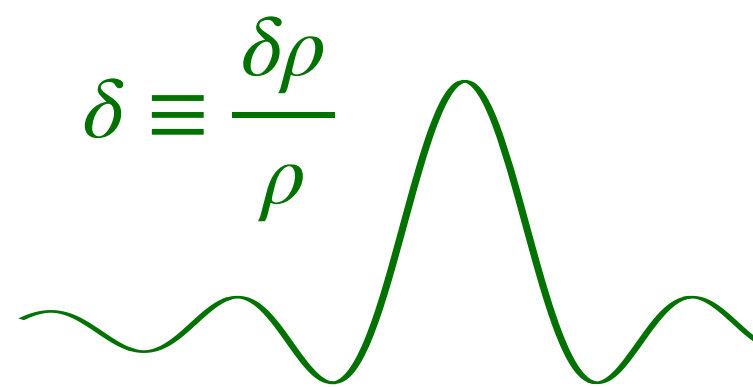
First-order
phase transition



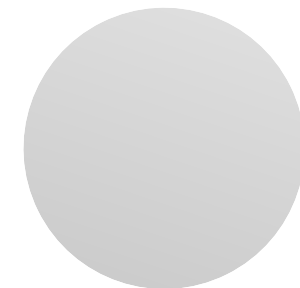
overdensities



$$\delta \equiv \frac{\delta\rho}{\rho}$$



$$\delta \gtrsim 5$$



PBH

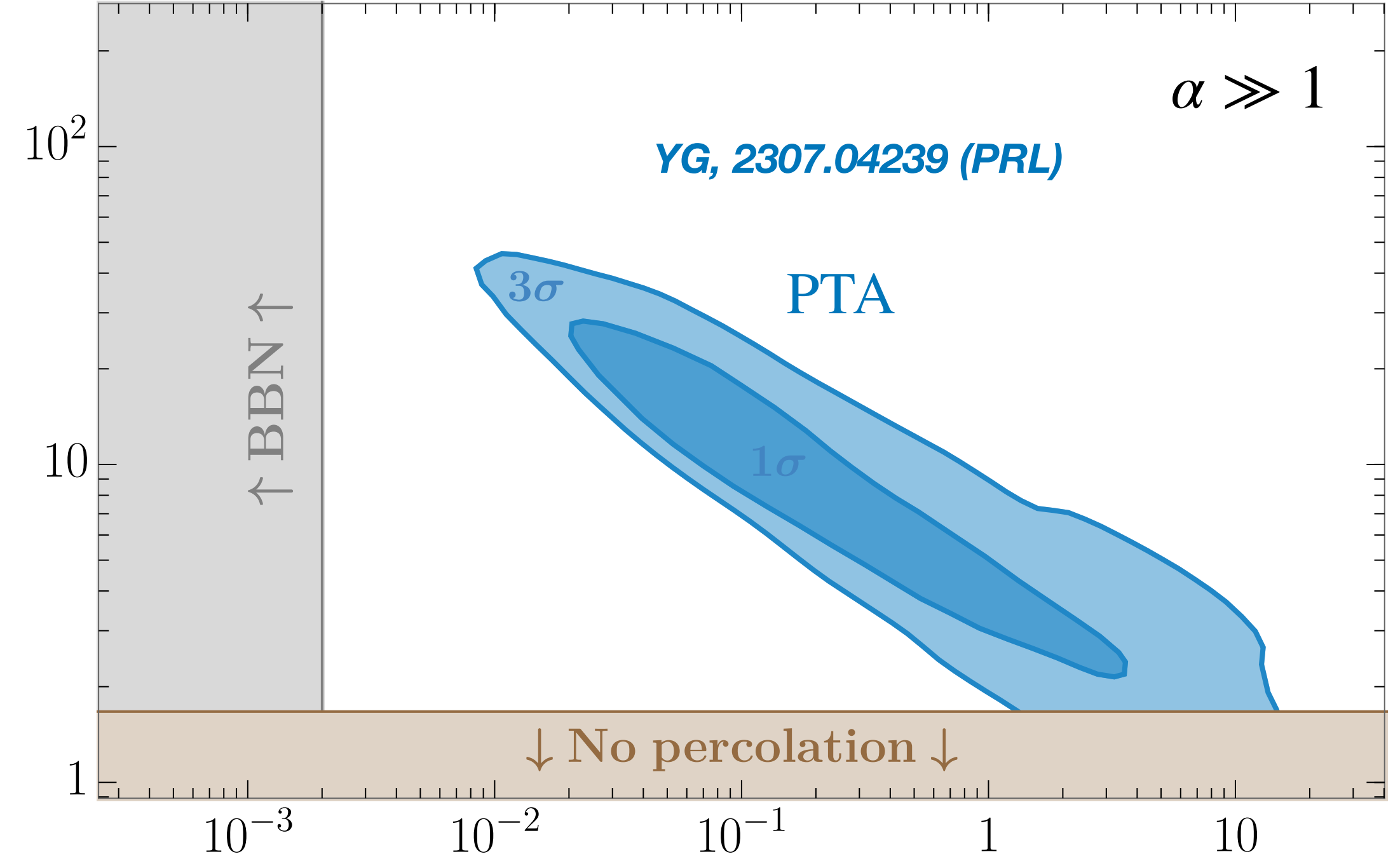
Curvature peaks $\mathcal{R}$

$$\mathcal{R} \simeq \frac{9}{4}\delta$$



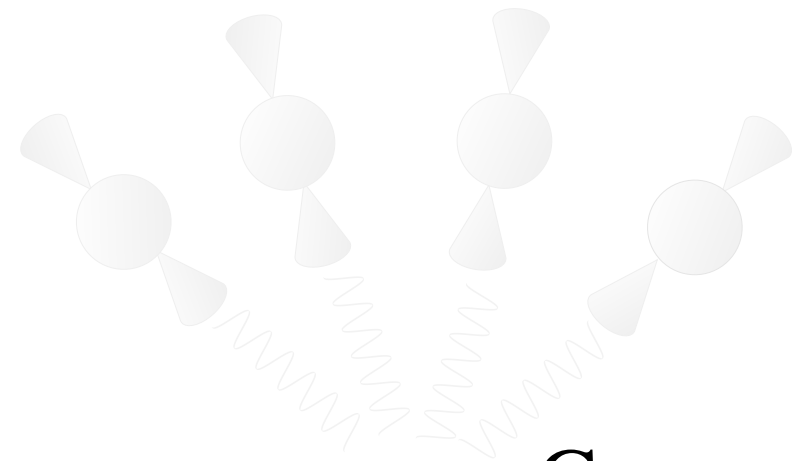
Franciolini, YG, Jinno, 2503.01962

PT completion rate $\beta/H_\star$



Reheating temperature $T_\star$ [GeV]

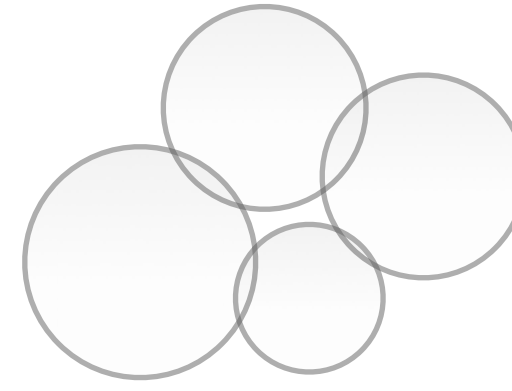
Pulsar Timing Arrays
(PTA)



(GWs)
Gravitational
Waves



First-order
phase transition



Gauge – invariant version of Φ



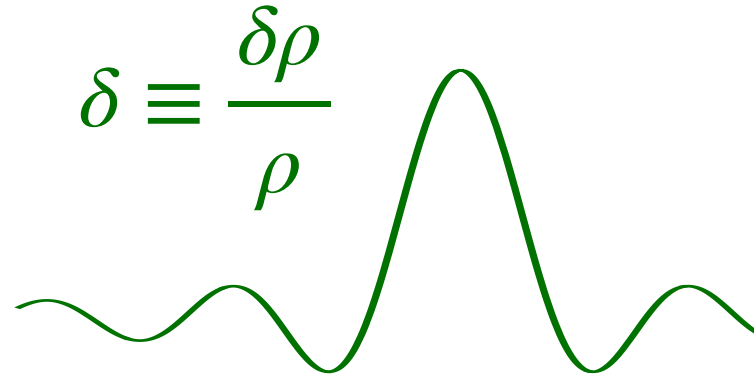
$$\mathcal{R} \simeq \frac{9}{4}\delta$$



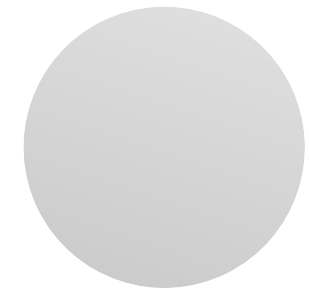
overdensities



$$\delta \equiv \frac{\delta\rho}{\rho}$$

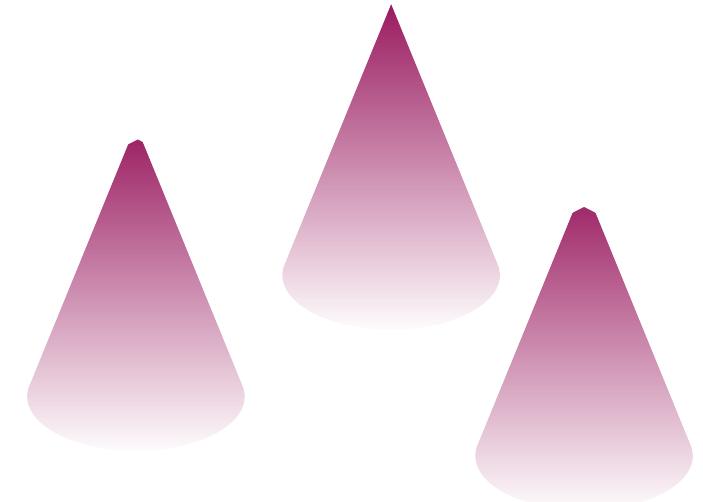


$$\delta \gtrsim 5$$

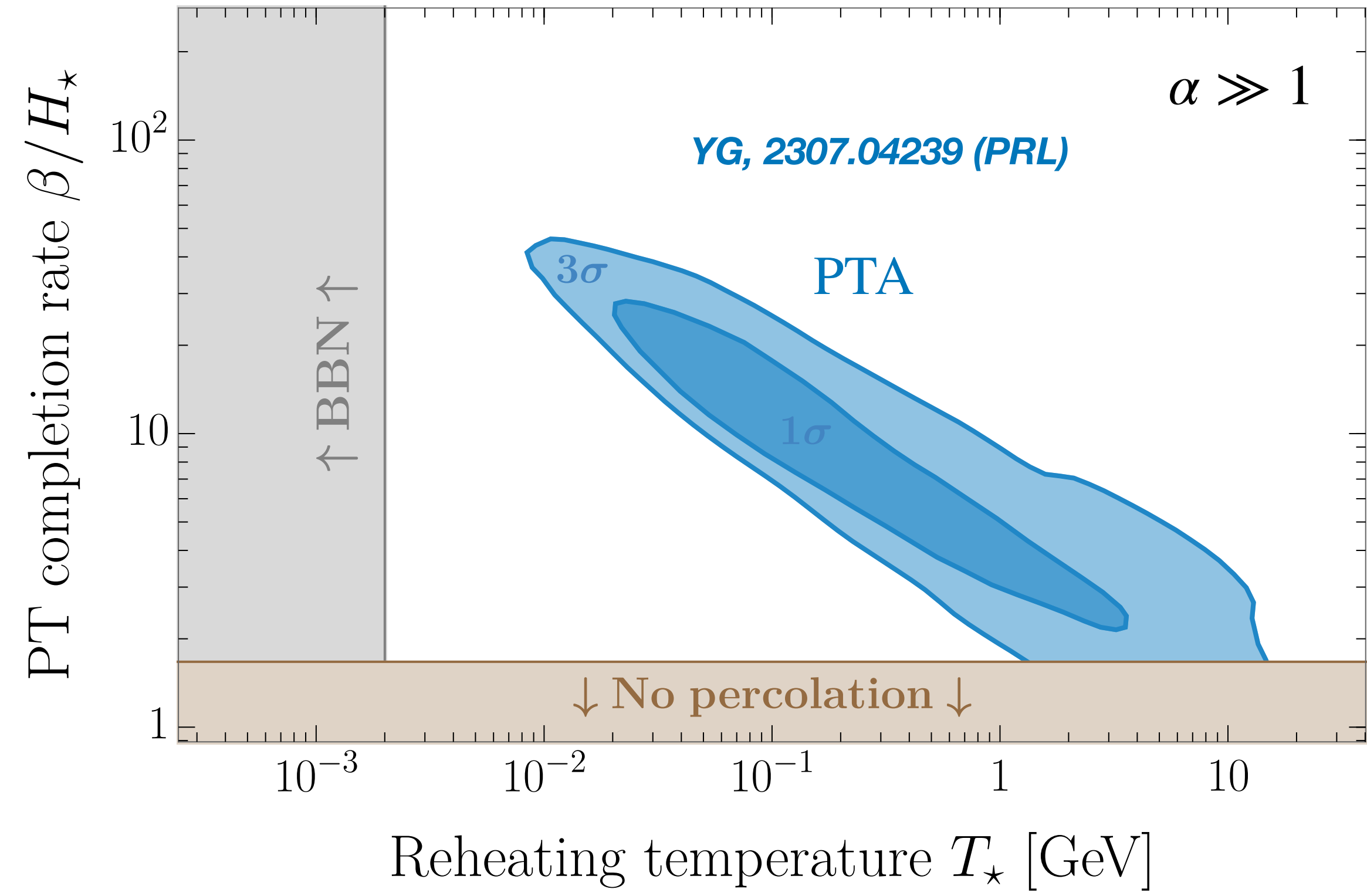


PBH

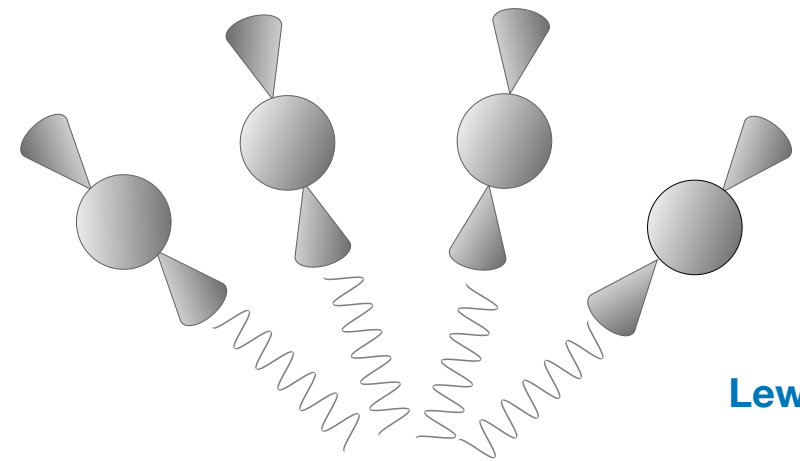
Curvature peaks $\mathcal{R}$



Franciolini, YG, Jinno, 2503.01962



PTA



Lewicki, Toczek, Vaskonen
(2402.04158)

Second – order GWs :

$$\Omega_{\text{GW}} \propto \mathcal{R}^4$$

$$\mathcal{R} \simeq \frac{9}{4}\delta$$

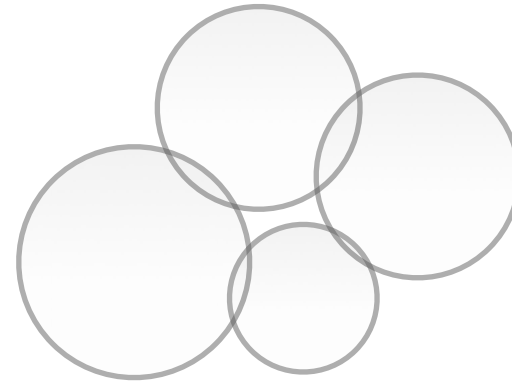
Curvature peaks $\mathcal{R}$



(GWs)
Gravitational
Waves



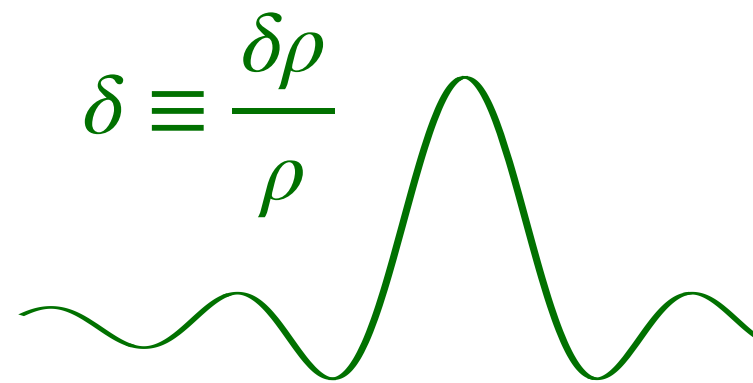
First-order
phase transition



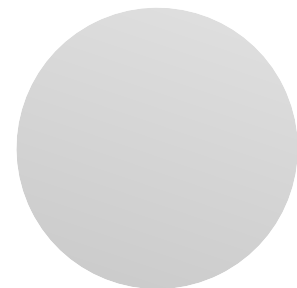
overdensities



$$\delta \equiv \frac{\delta\rho}{\rho}$$



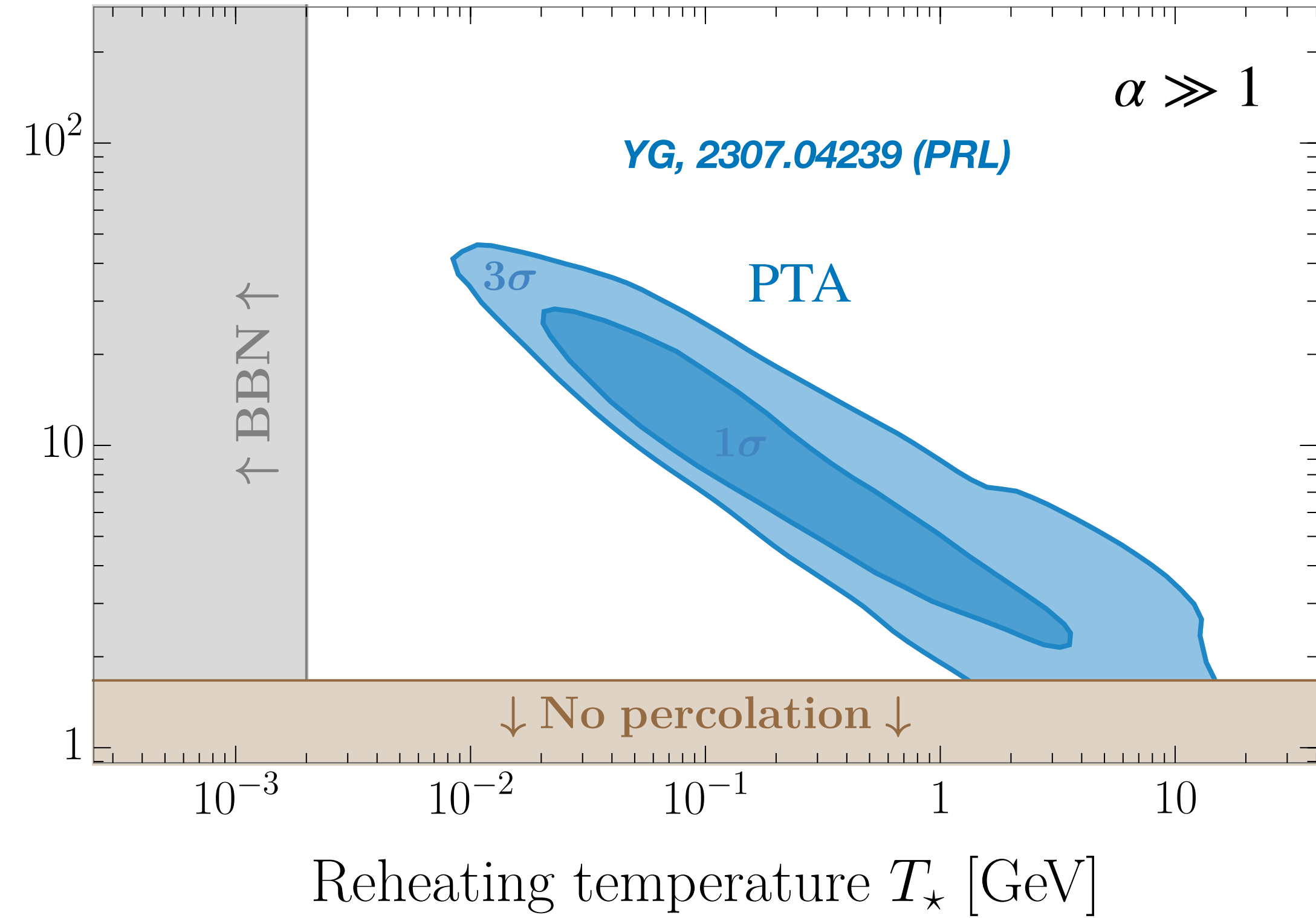
$$\delta \gtrsim 5$$



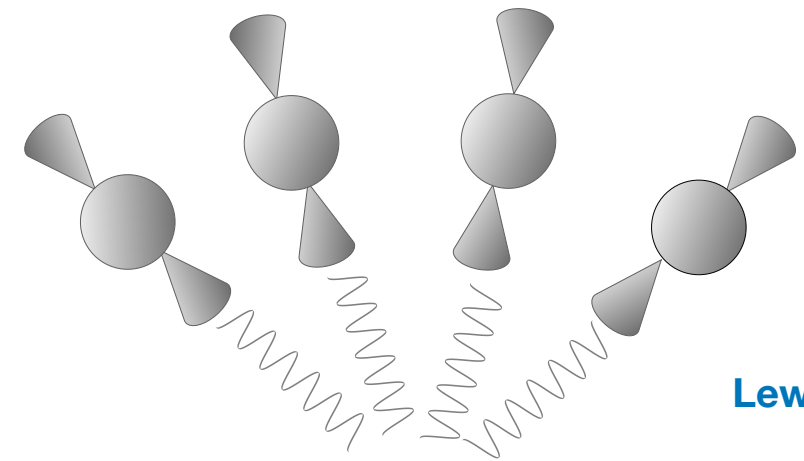
PBH

Franciolini, YG, Jinno, 2503.01962

PT completion rate $\beta/H_\star$



PTA



Lewicki, Toczek, Vaskonen
(2402.04158)

(GWs)
Gravitational
Waves

Second – order GWs :

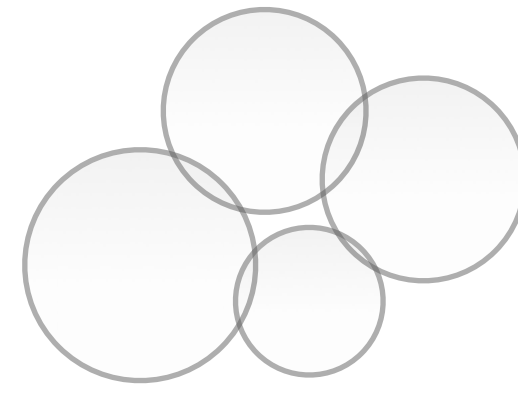
$$\Omega_{\text{GW}} \propto \mathcal{R}^4$$

Comoving gauge

$$\mathcal{R} \simeq \frac{9}{4}\delta$$

Curvature peaks $\mathcal{R}$

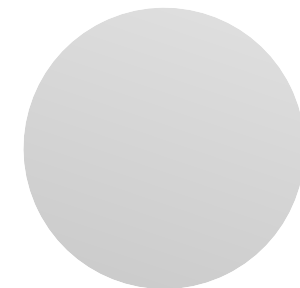
First-order
phase transition



overdensities

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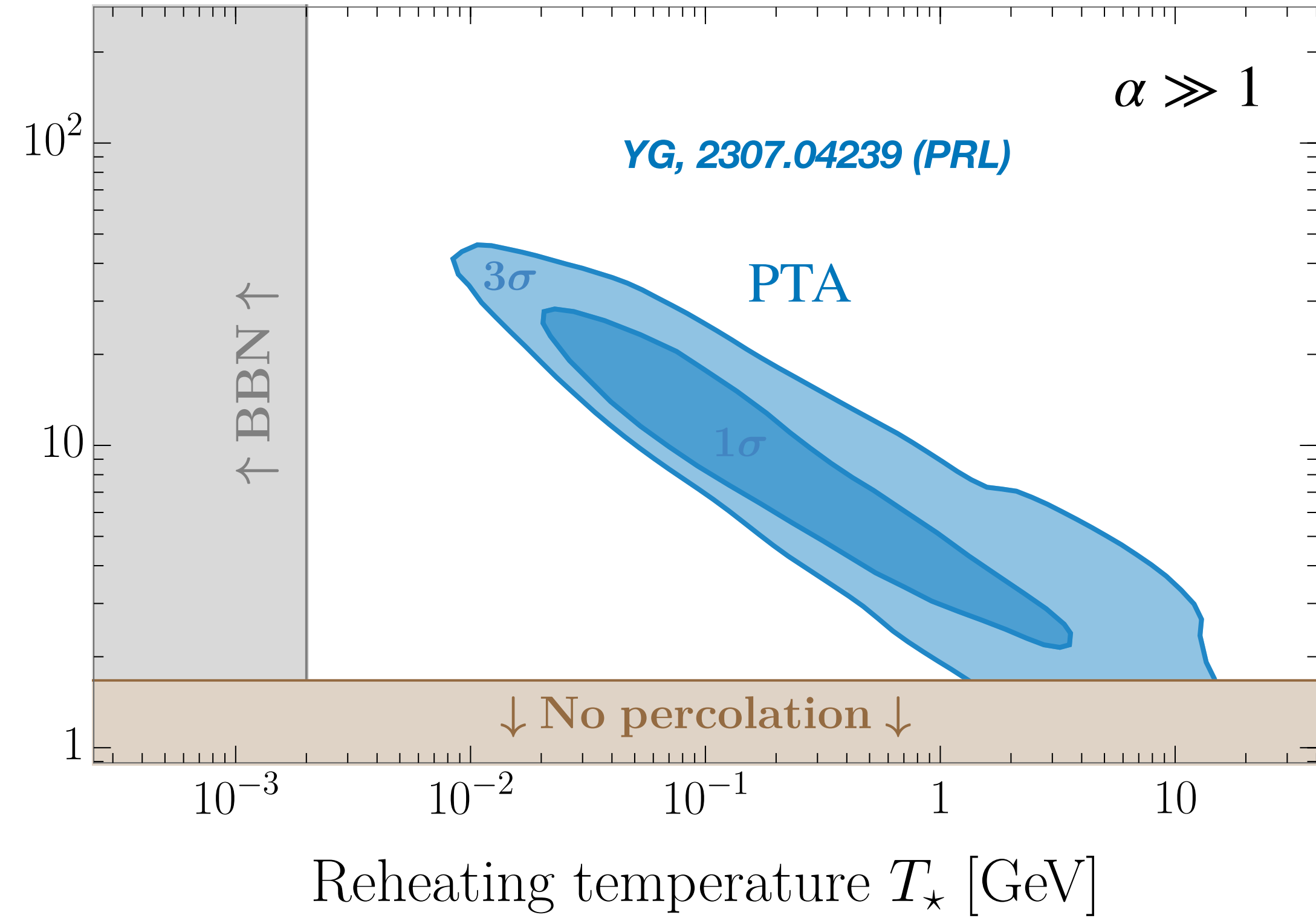
$$\delta \gtrsim 5$$

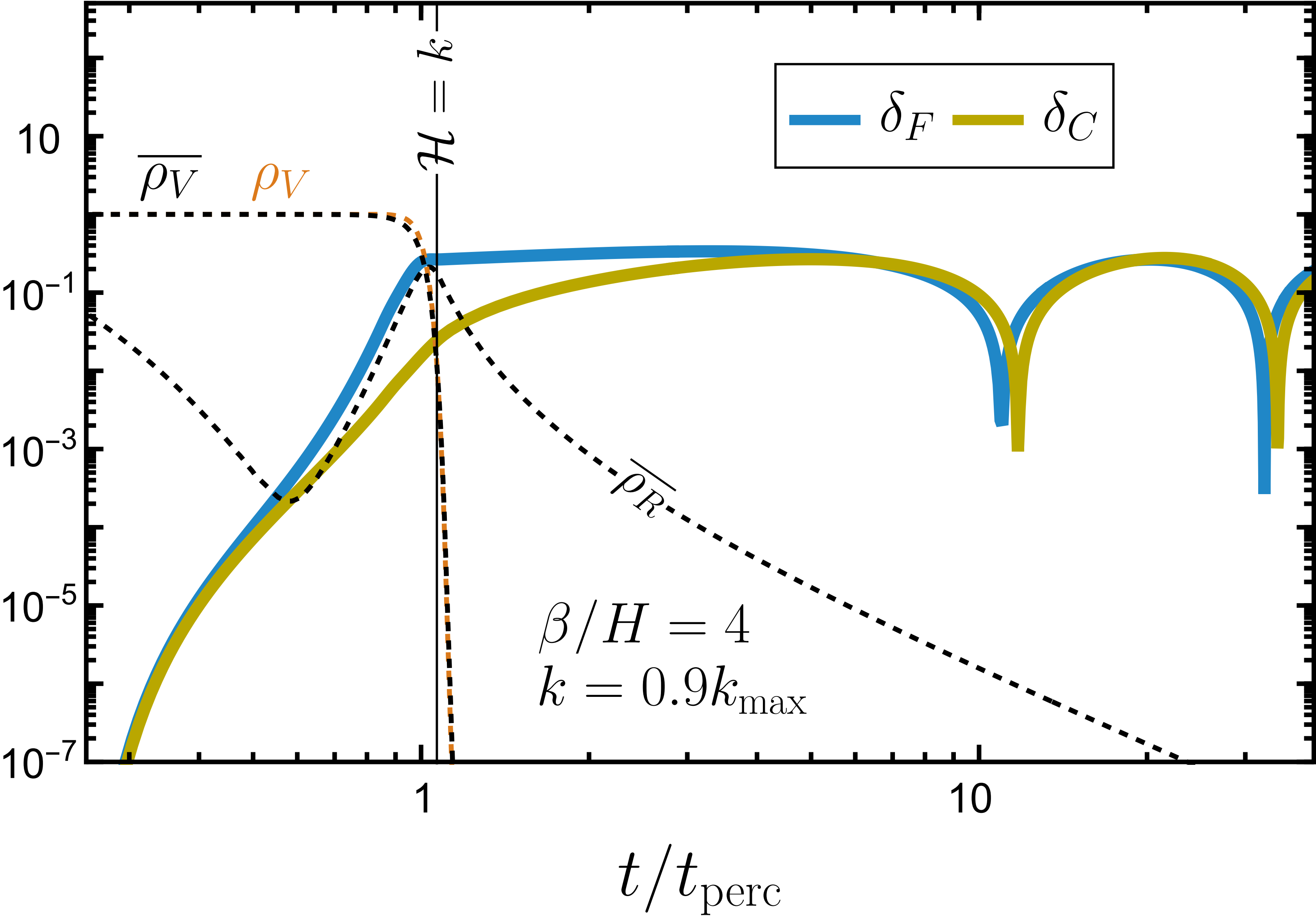


PBH

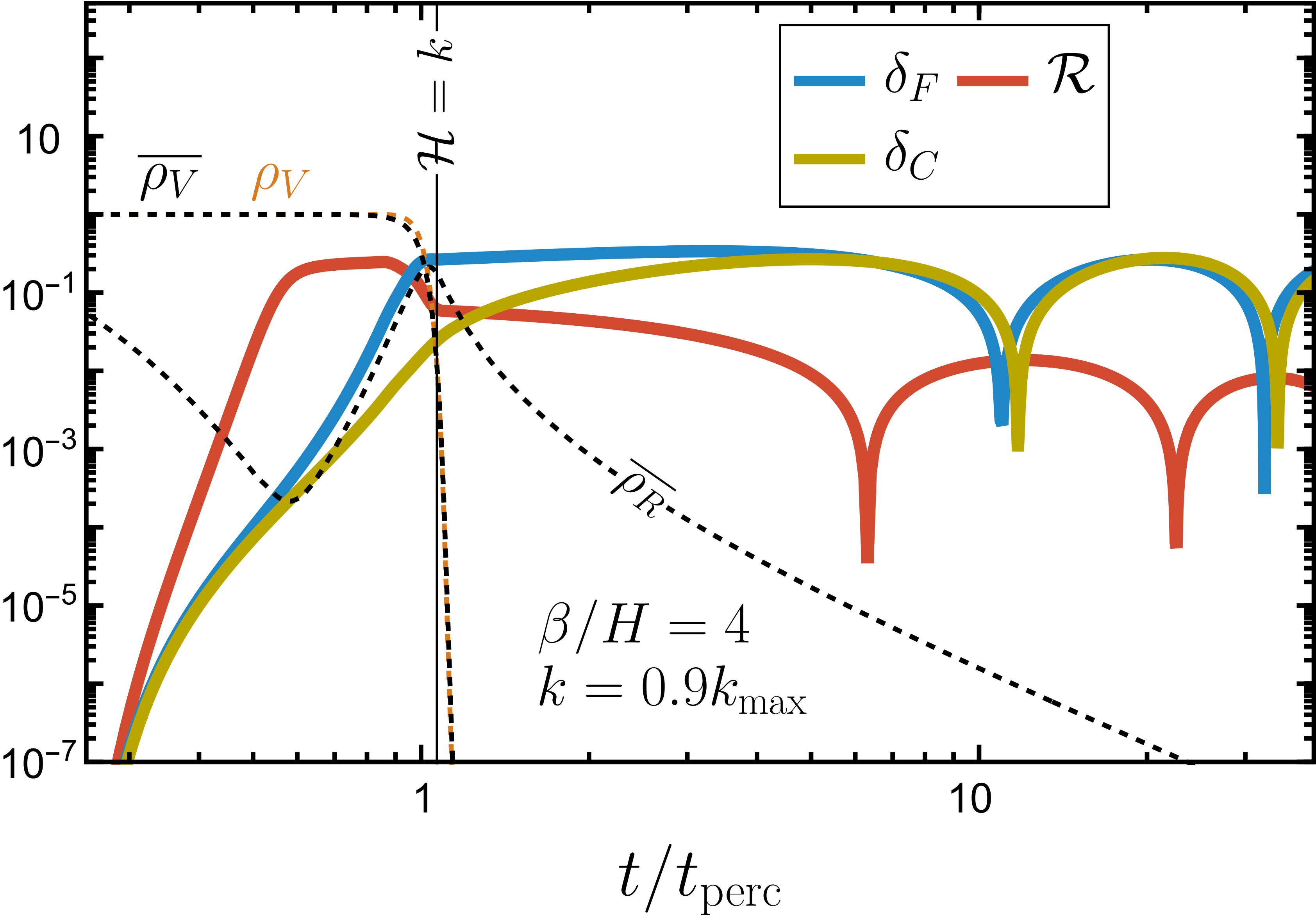
Franciolini, YG, Jinno, 2503.01962

PT completion rate $\beta/H_\star$



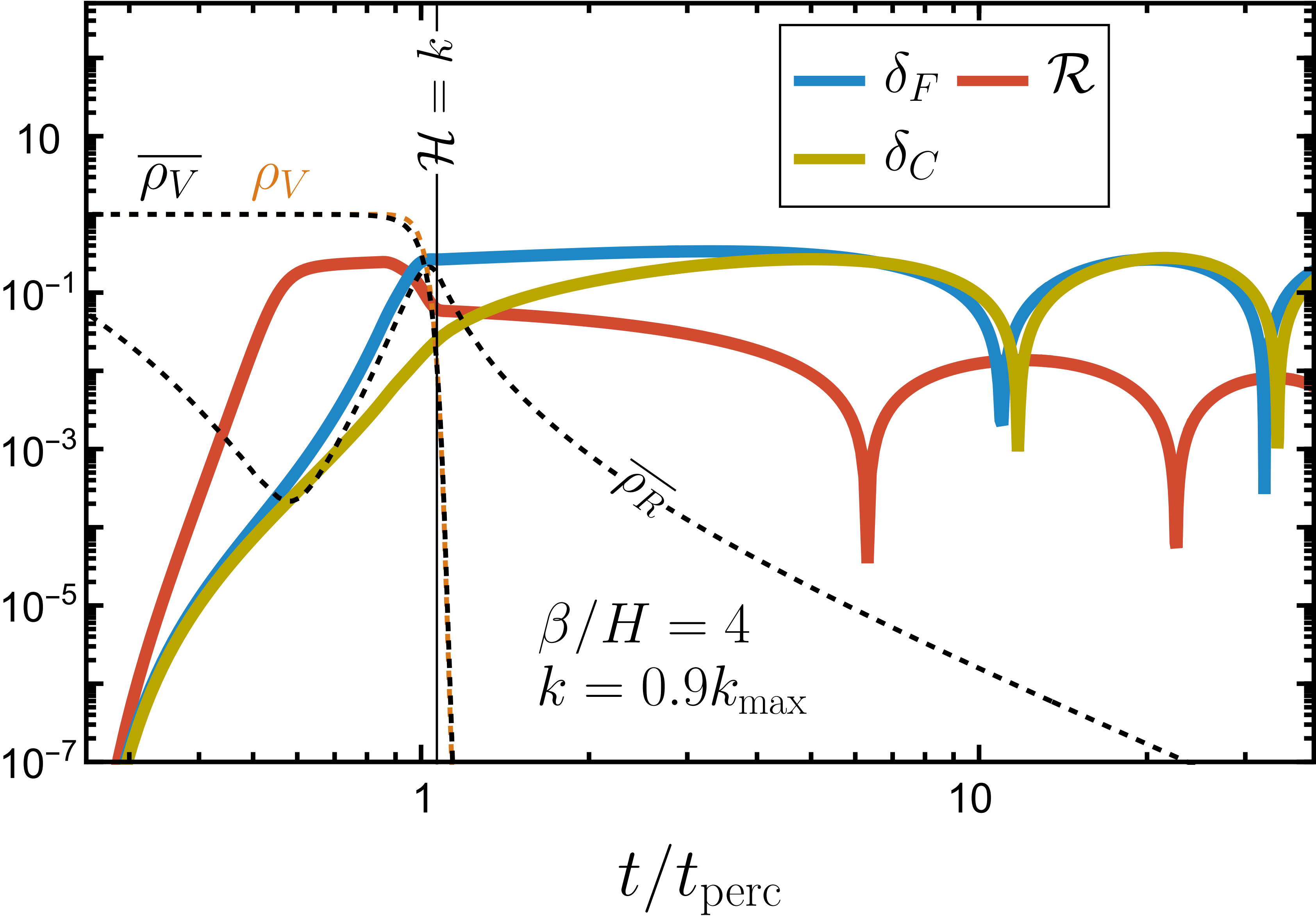


(with c++ code)



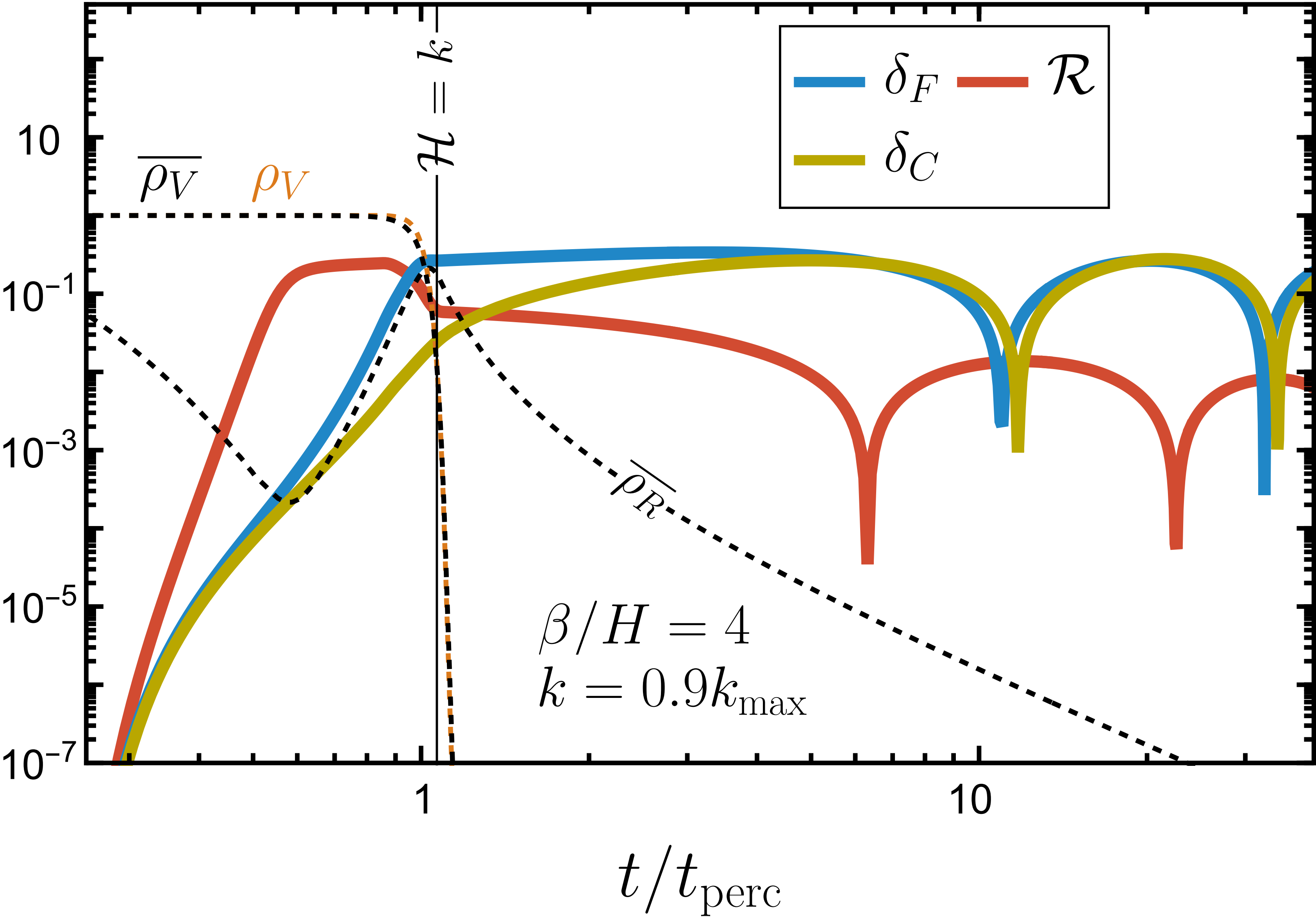
Key result 2

$$\mathcal{R} \simeq \frac{9}{4} \delta^{(C)}$$



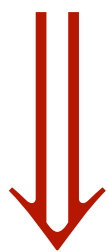
Key result 2

$$\mathcal{R} \simeq \frac{9}{4} \delta^{(C)} \simeq \frac{9}{40} \delta^{(F)}$$



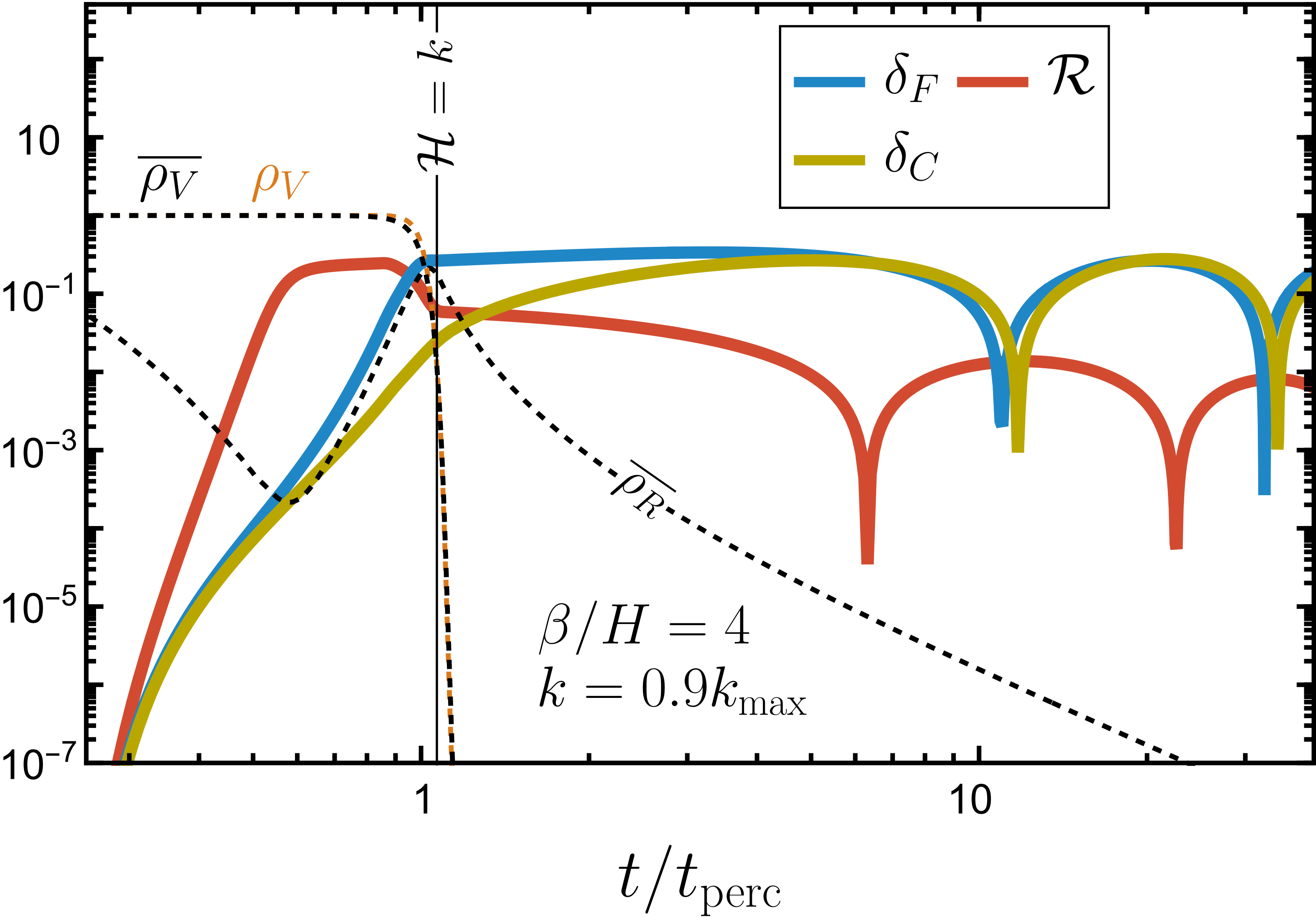
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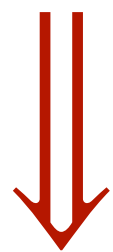
Key conclusion 2:

$$\Omega_{\text{GW}}^{\text{2nd}} \propto \mathcal{R}^4$$



Key result 2

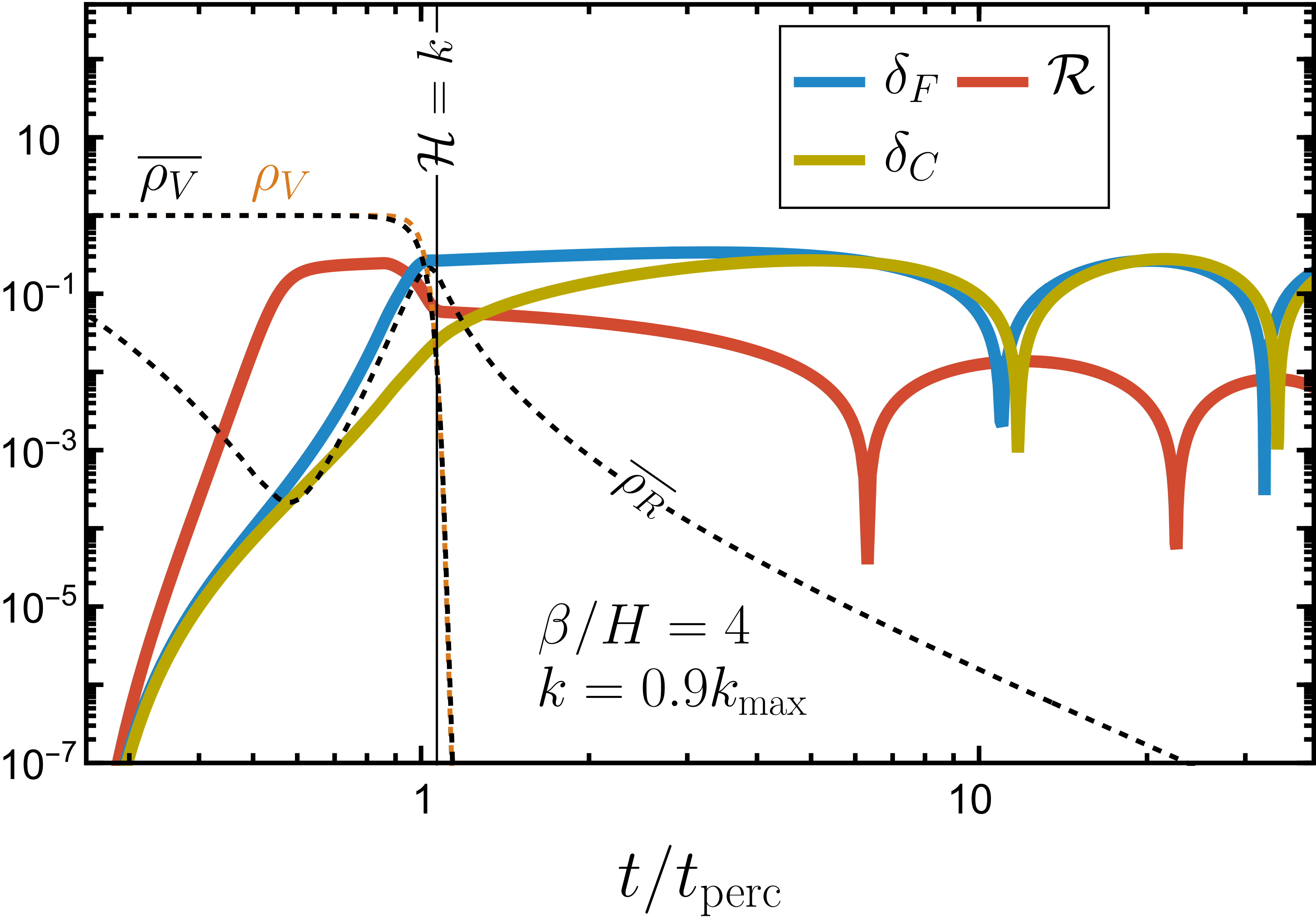
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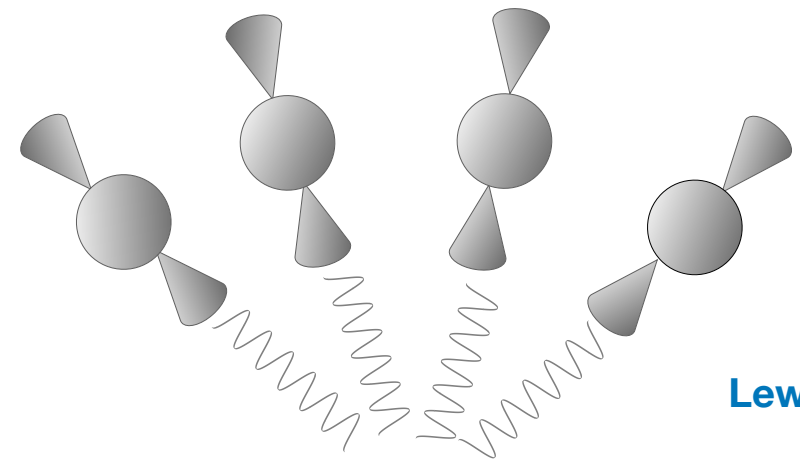
Key conclusion 2:

$$\Omega_{\text{GW}}^{\text{2nd}} \propto \mathcal{R}^4$$

$$\Omega_{\text{GW}}^{\text{2nd}} \rightarrow \Omega_{\text{GW}}^{\text{2nd}} / 10^4$$



PTA



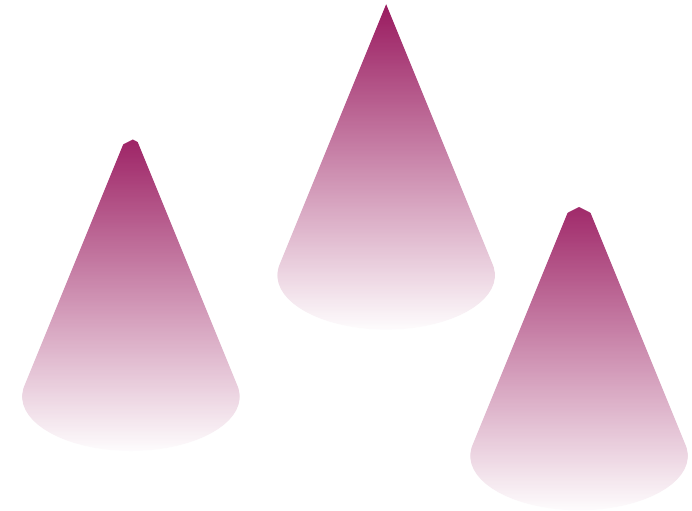
Lewicki, Toczek, Vaskonen
(2402.04158)

(GWs)
Gravitational
Waves



Second – order GWs :

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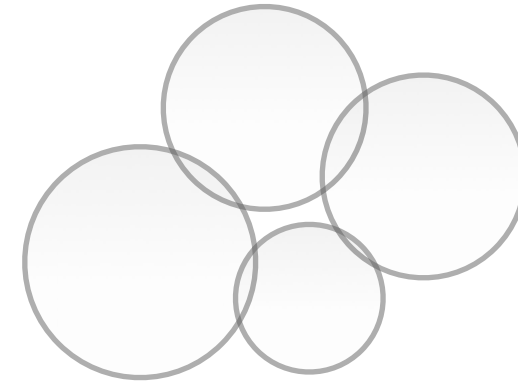


Curvature peaks $\mathcal{R}$

Comoving gauge

$$\mathcal{R} \simeq \frac{9}{4}\delta$$

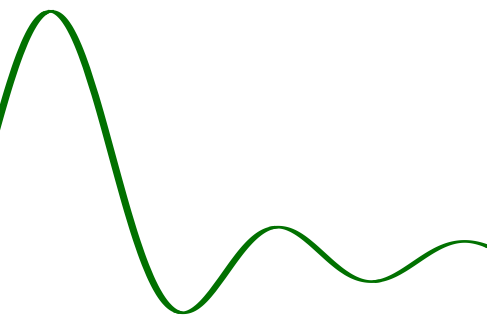
First-order
phase transition



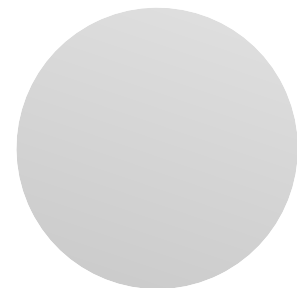
overdensities



$$\delta \equiv \frac{\delta\rho}{\rho}$$

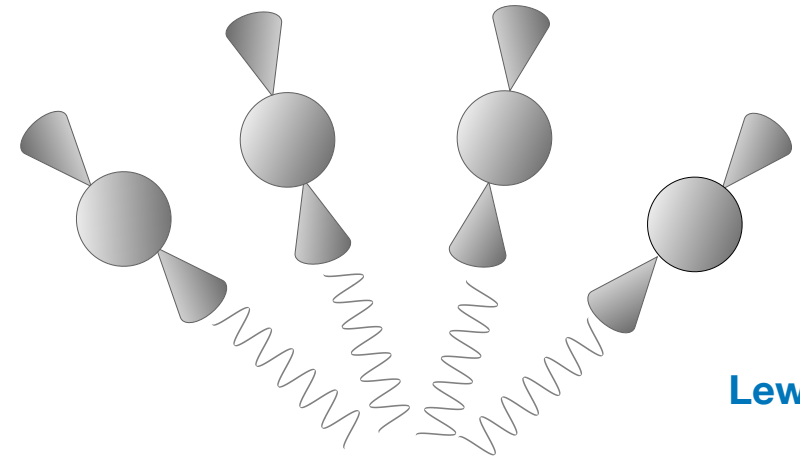


$$\delta \gtrsim 5$$



PBH

PTA



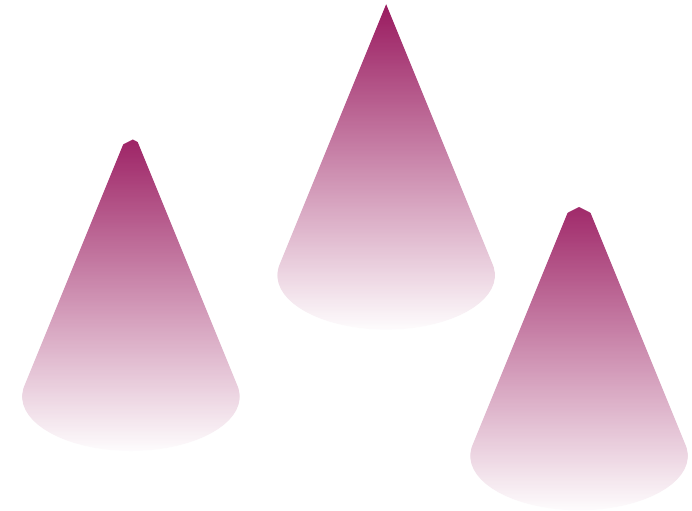
Lewicki, Toczek, Vaskonen
(2402.04158)

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Curvature peaks $\mathcal{R}$

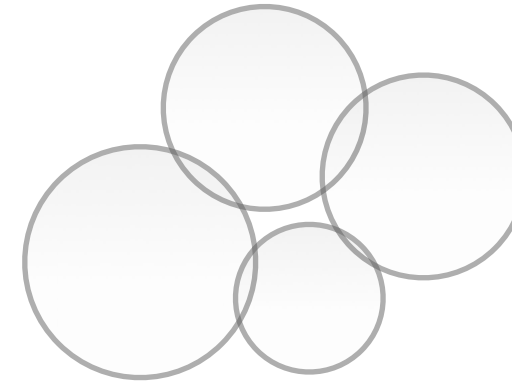
Comoving gauge

$$\mathcal{R} \simeq \frac{9}{4}\delta$$

Spatially-flat gauge

$$\mathcal{R} \simeq \frac{9}{40}\delta$$

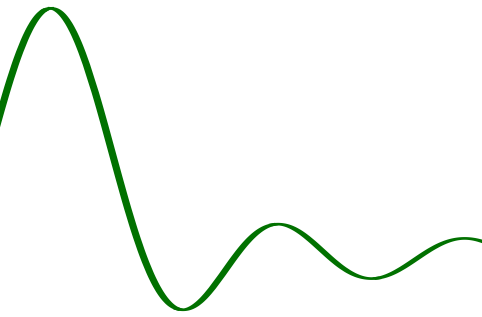
First-order
phase transition



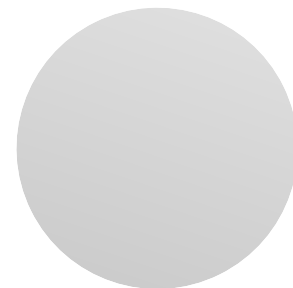
overdensities



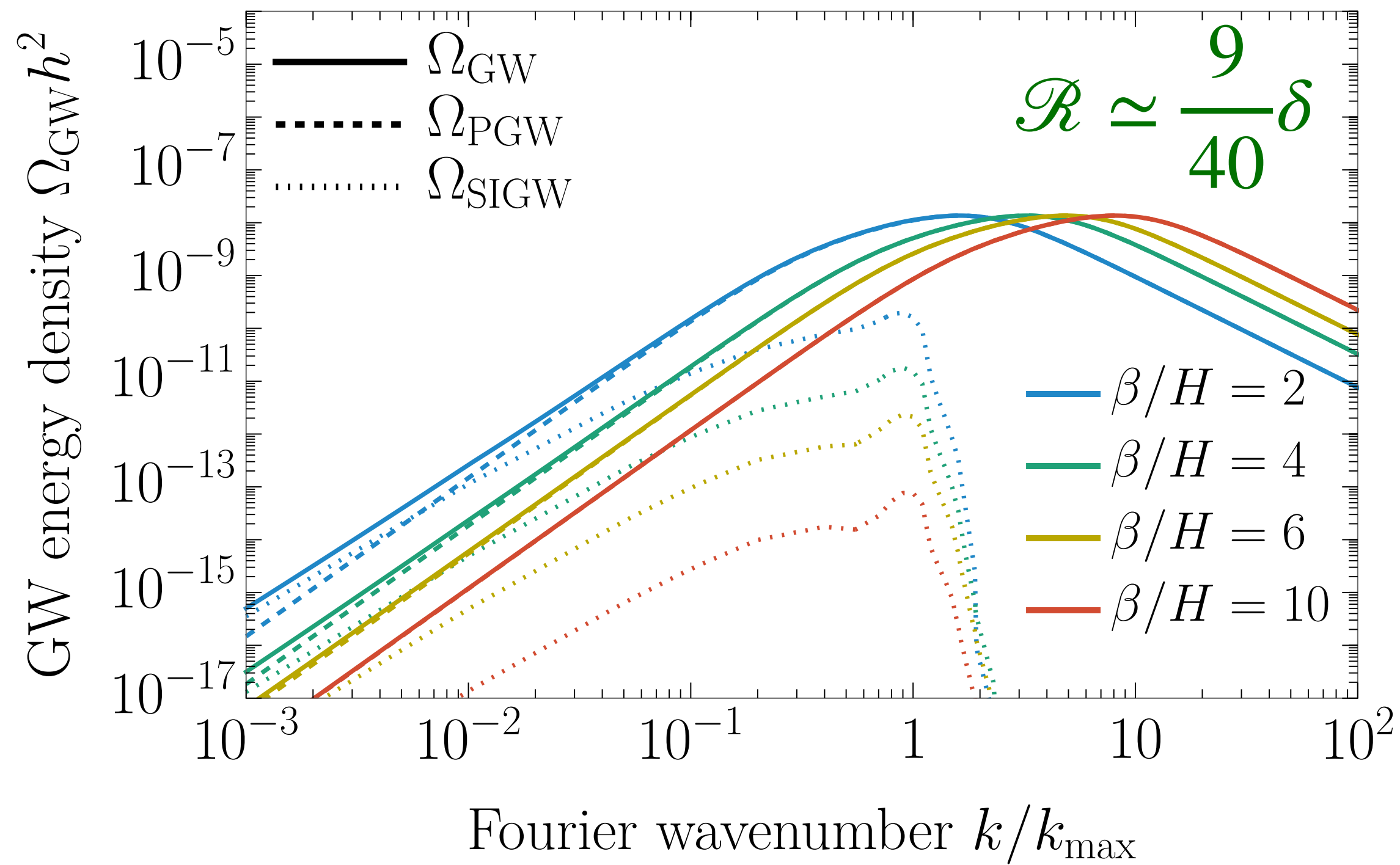
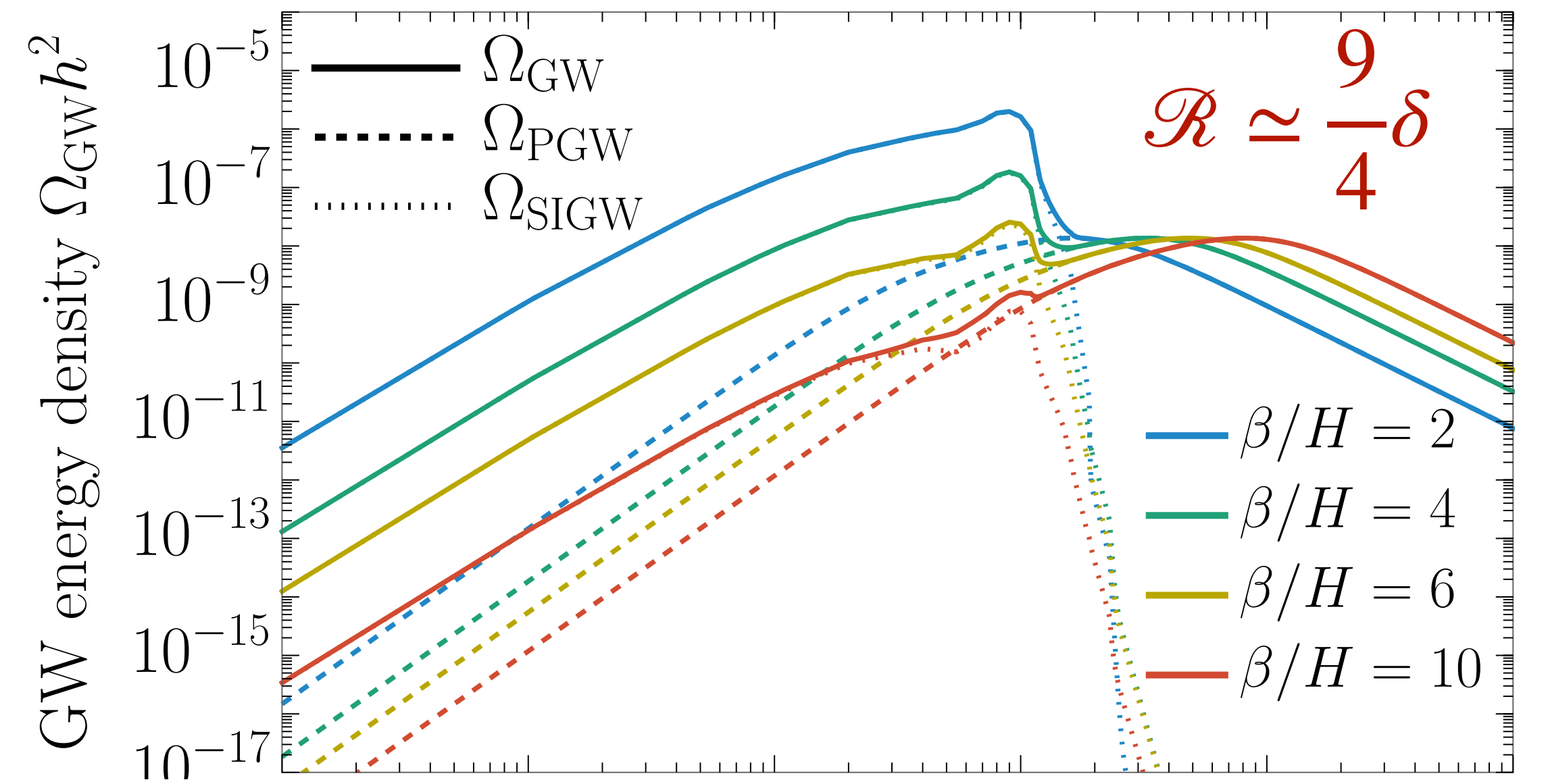
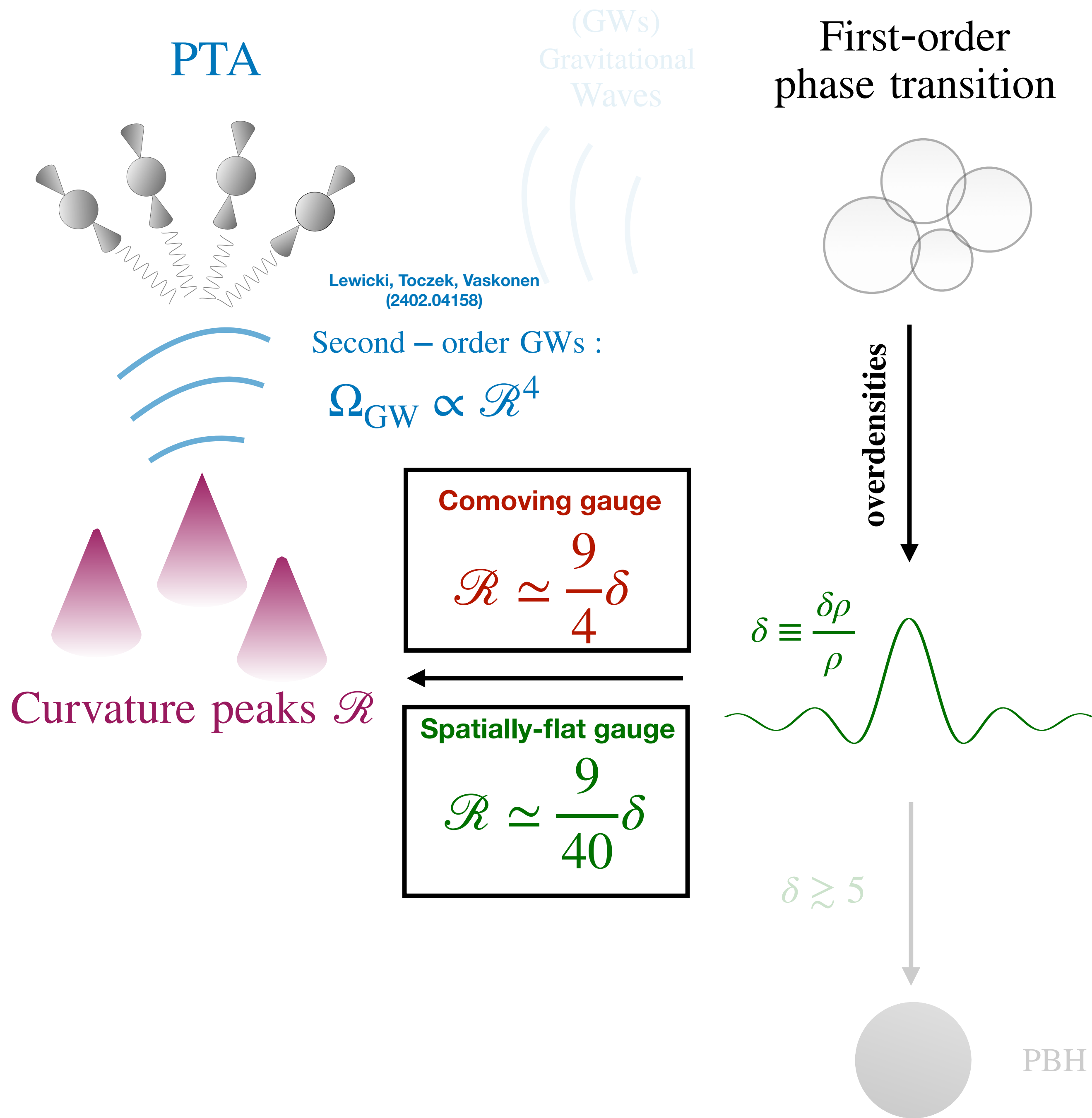
$$\delta \equiv \frac{\delta\rho}{\rho}$$

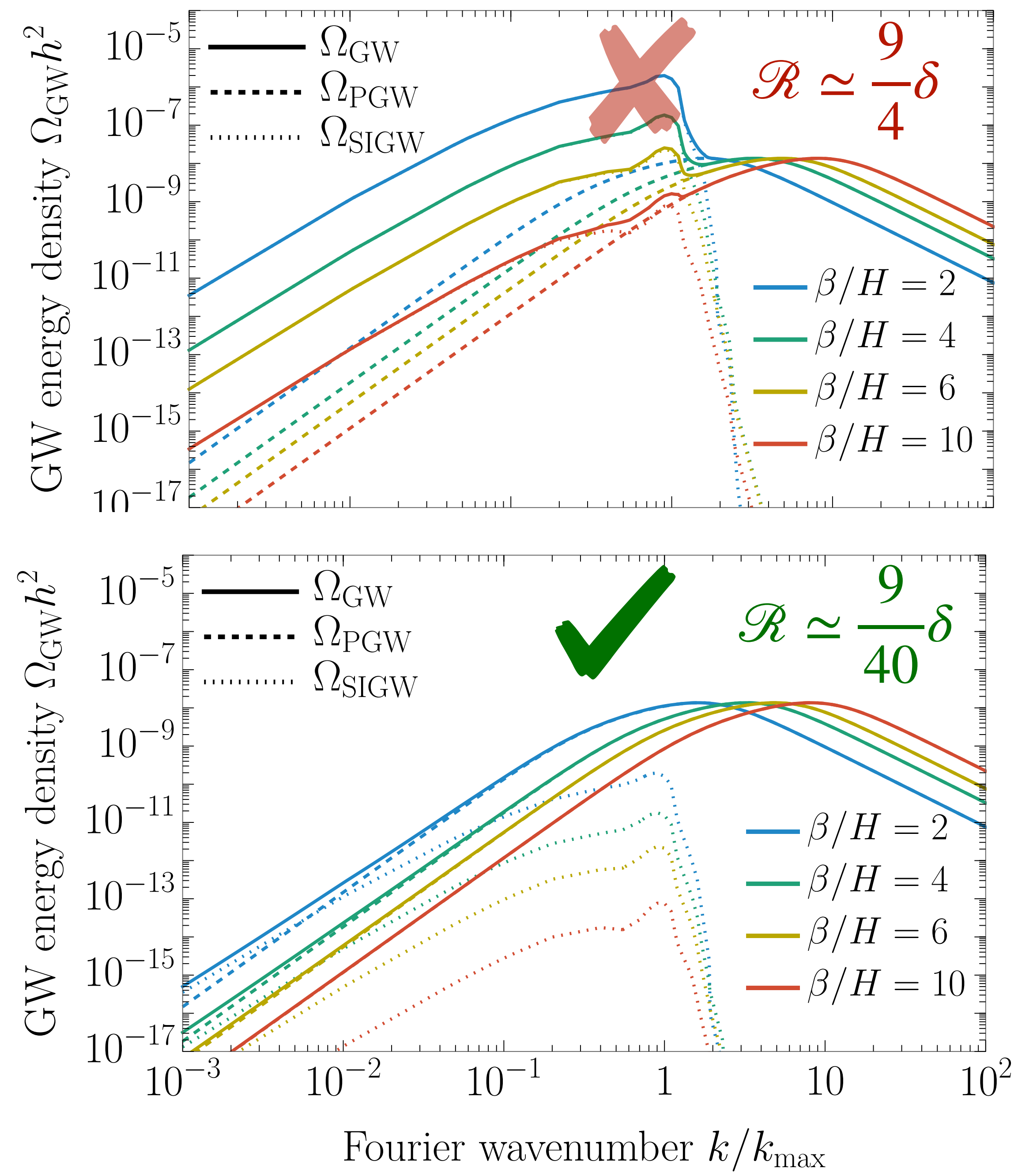
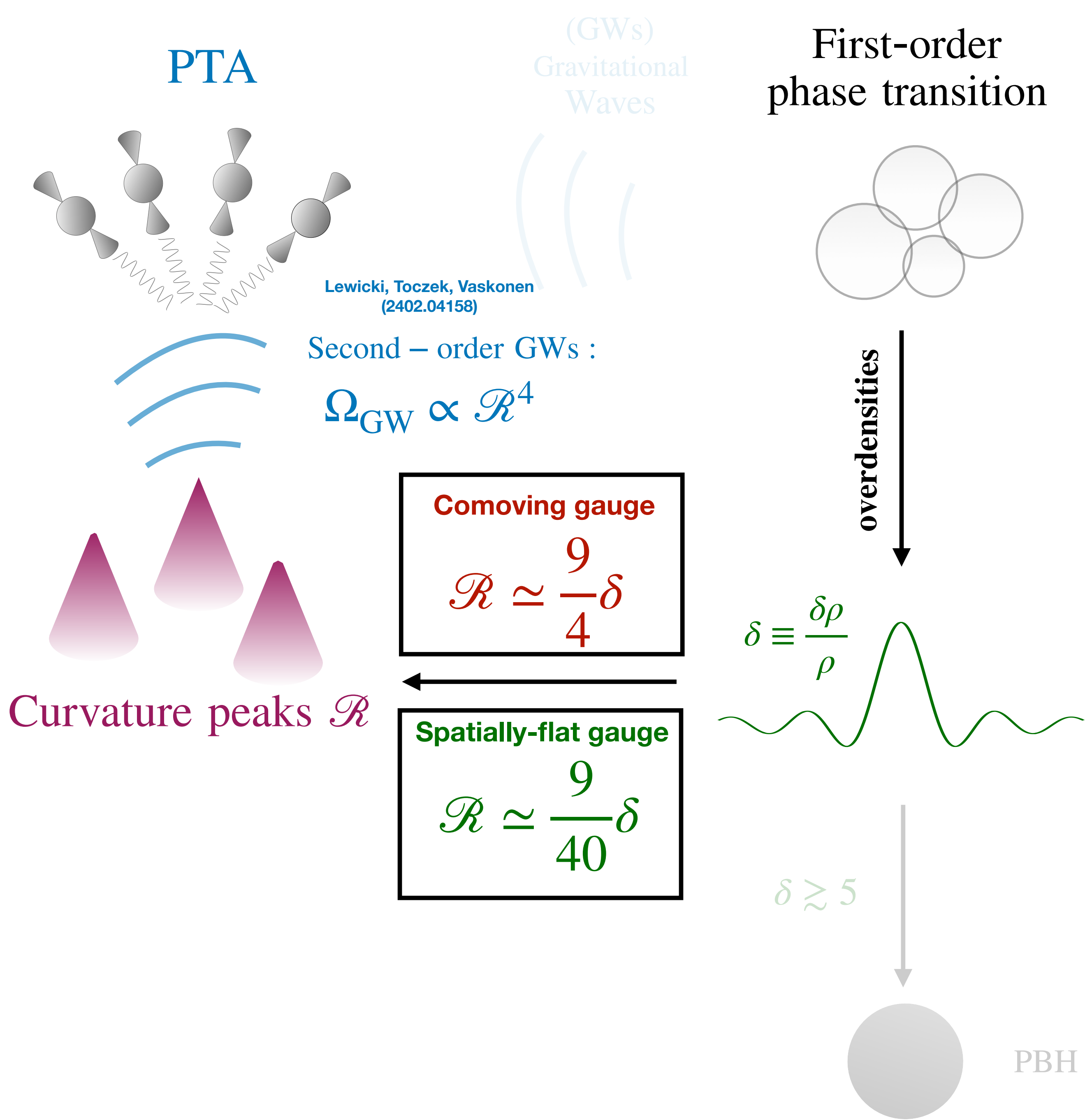


$$\delta \gtrsim 5$$

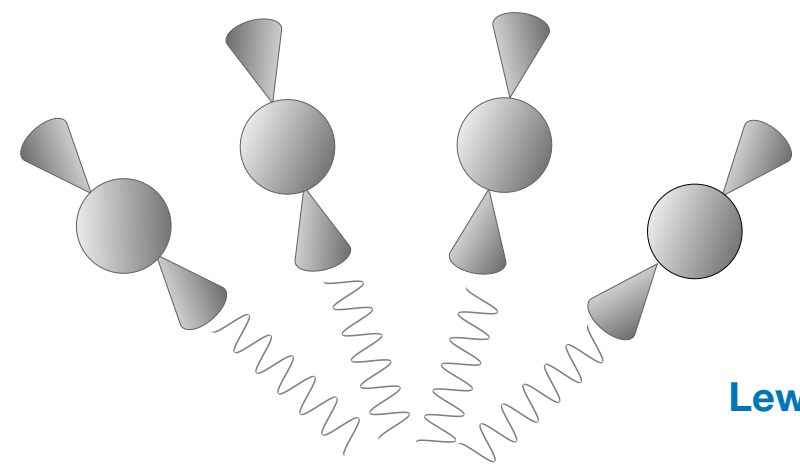


PBH





PTA

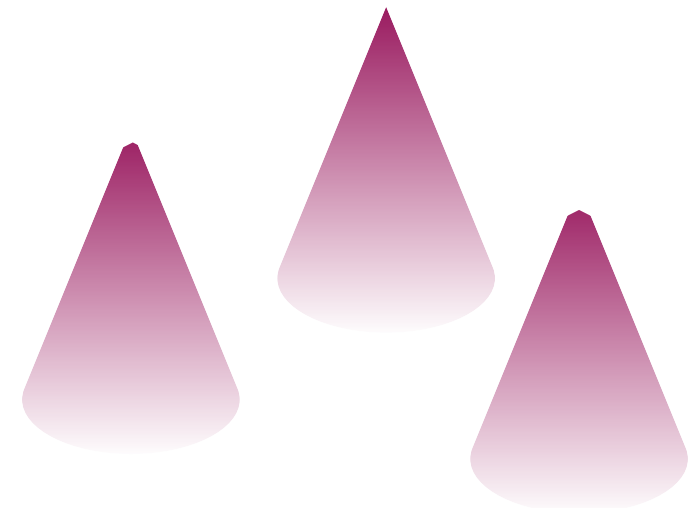


Lewicki, Toczek, Vaskonen
(2402.04158)

Second – order GWs :

$$\Omega_{\text{GW}} \propto \mathcal{R}^4$$

Curvature peaks $\mathcal{R}$



Comoving gauge

$$\mathcal{R} \simeq \frac{9}{4}\delta$$

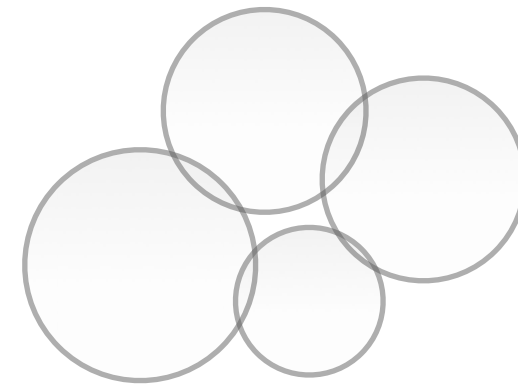
Spatially-flat gauge

$$\mathcal{R} \simeq \frac{9}{40}\delta$$

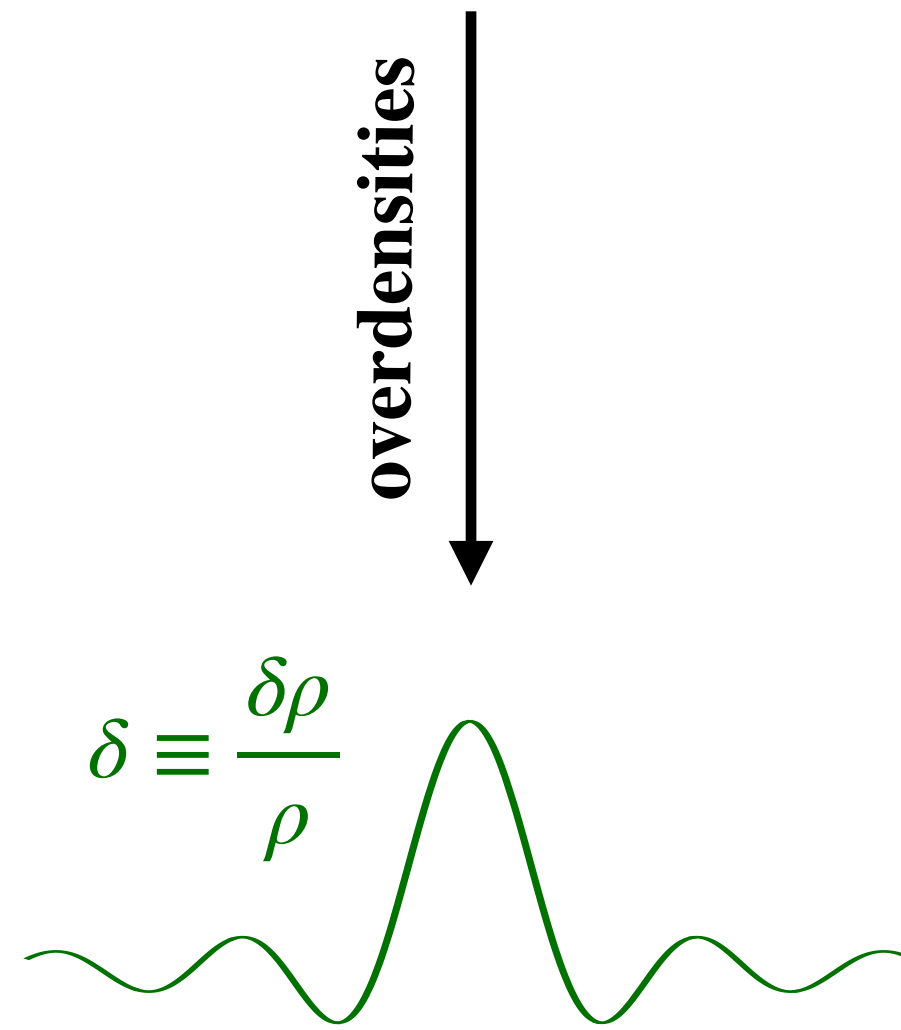
(GWs)
Gravitational
Waves



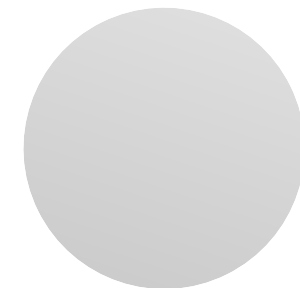
First-order
phase transition



overdensities

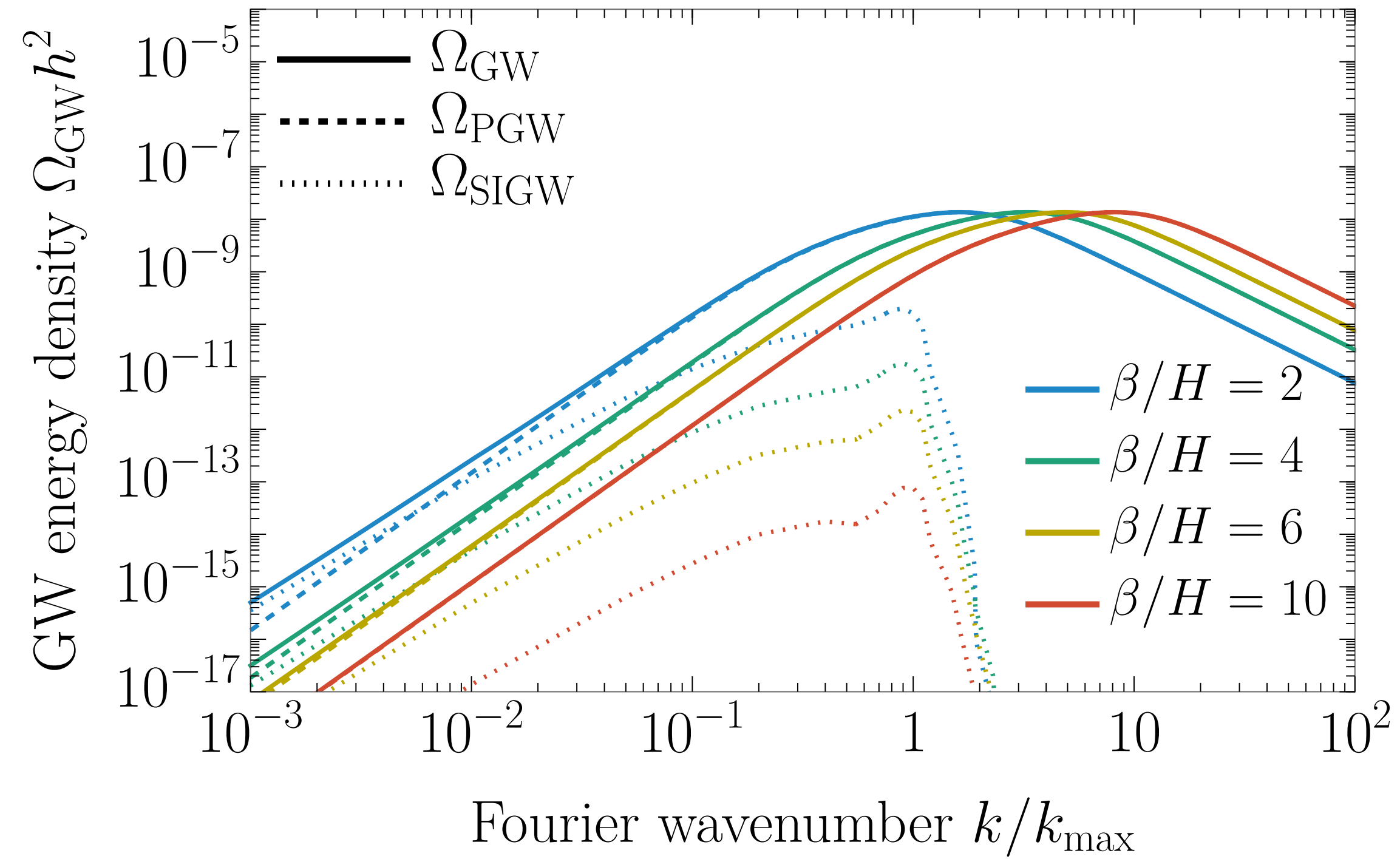


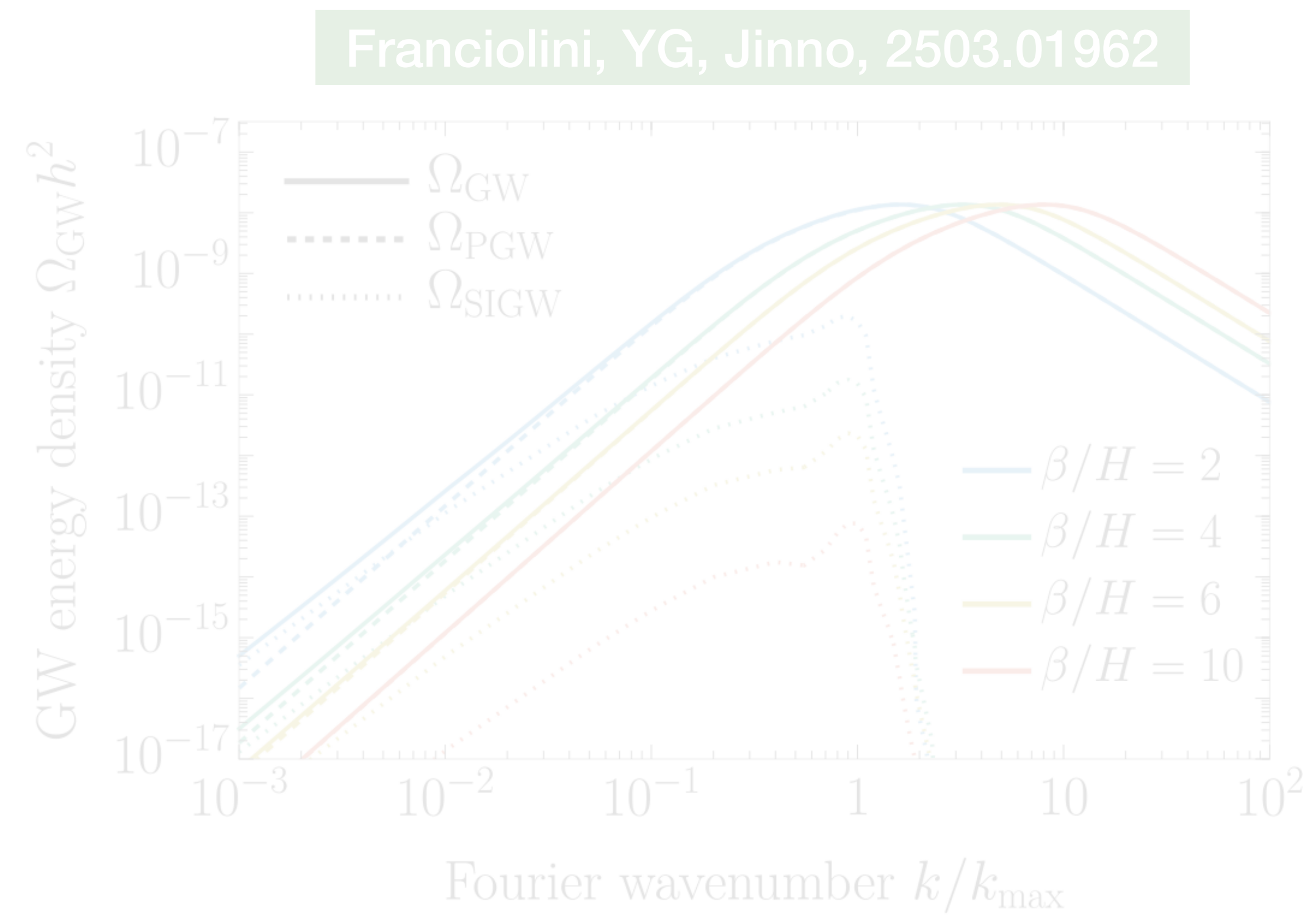
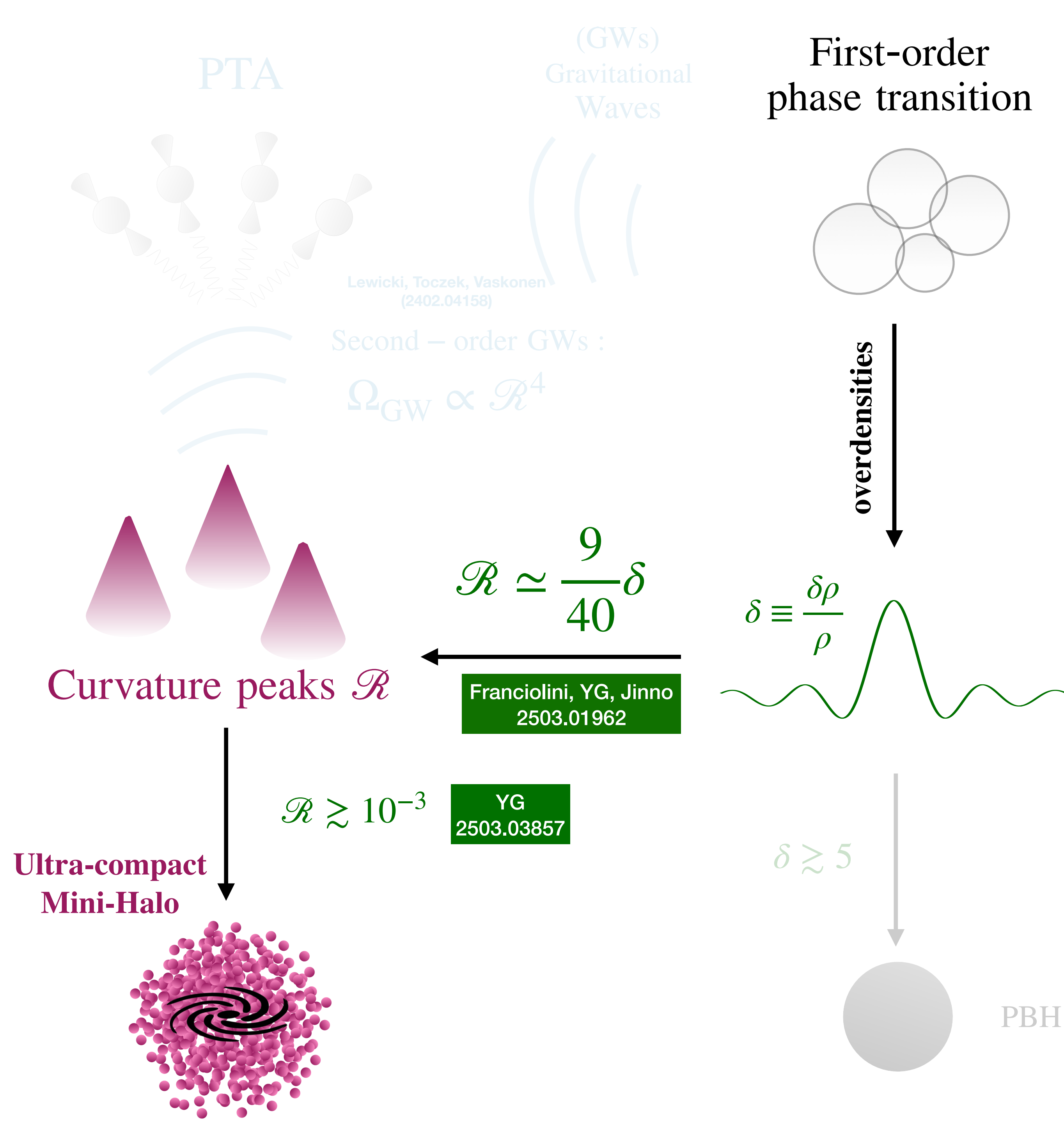
$\delta \gtrsim 5$

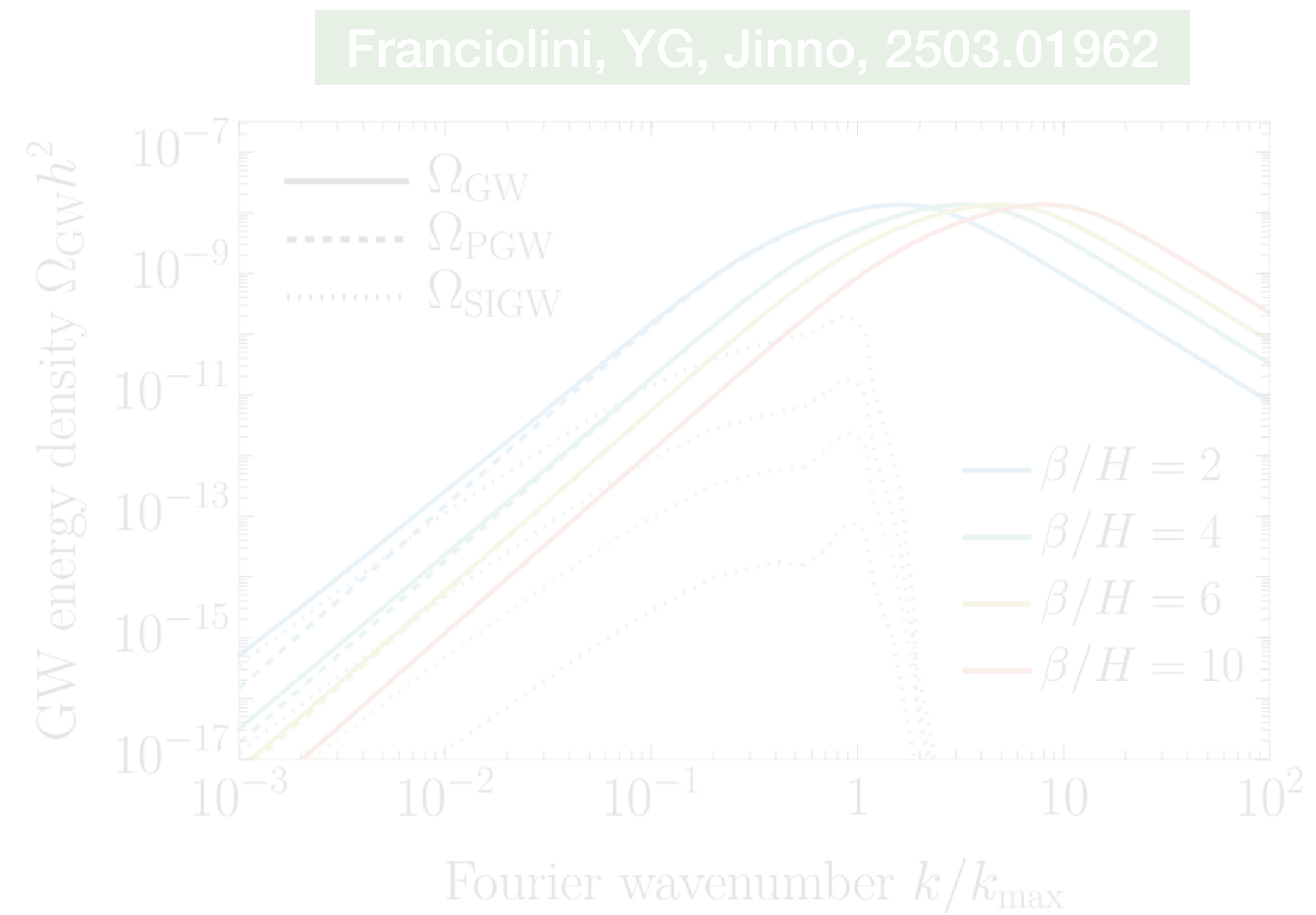
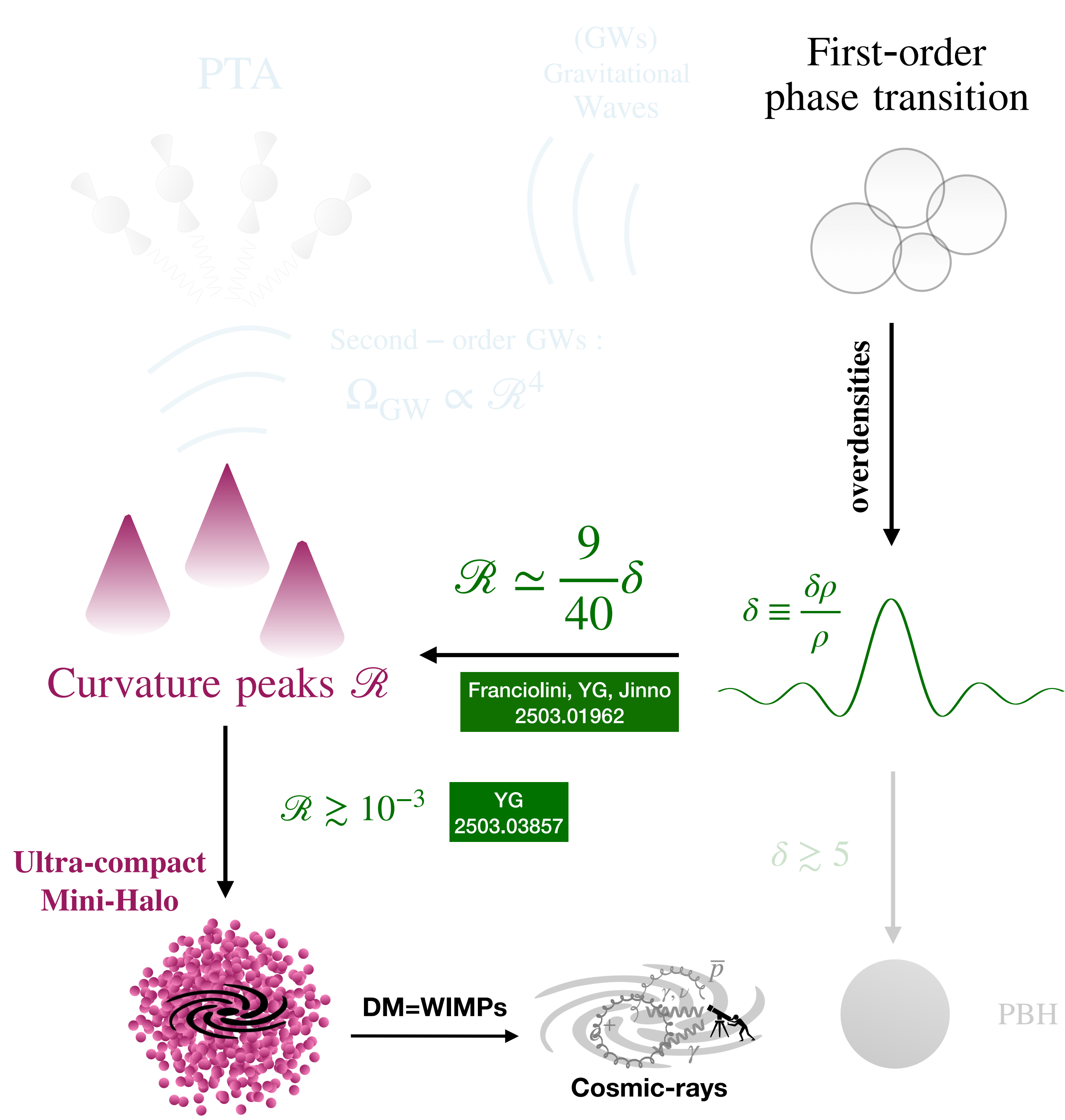


PBH

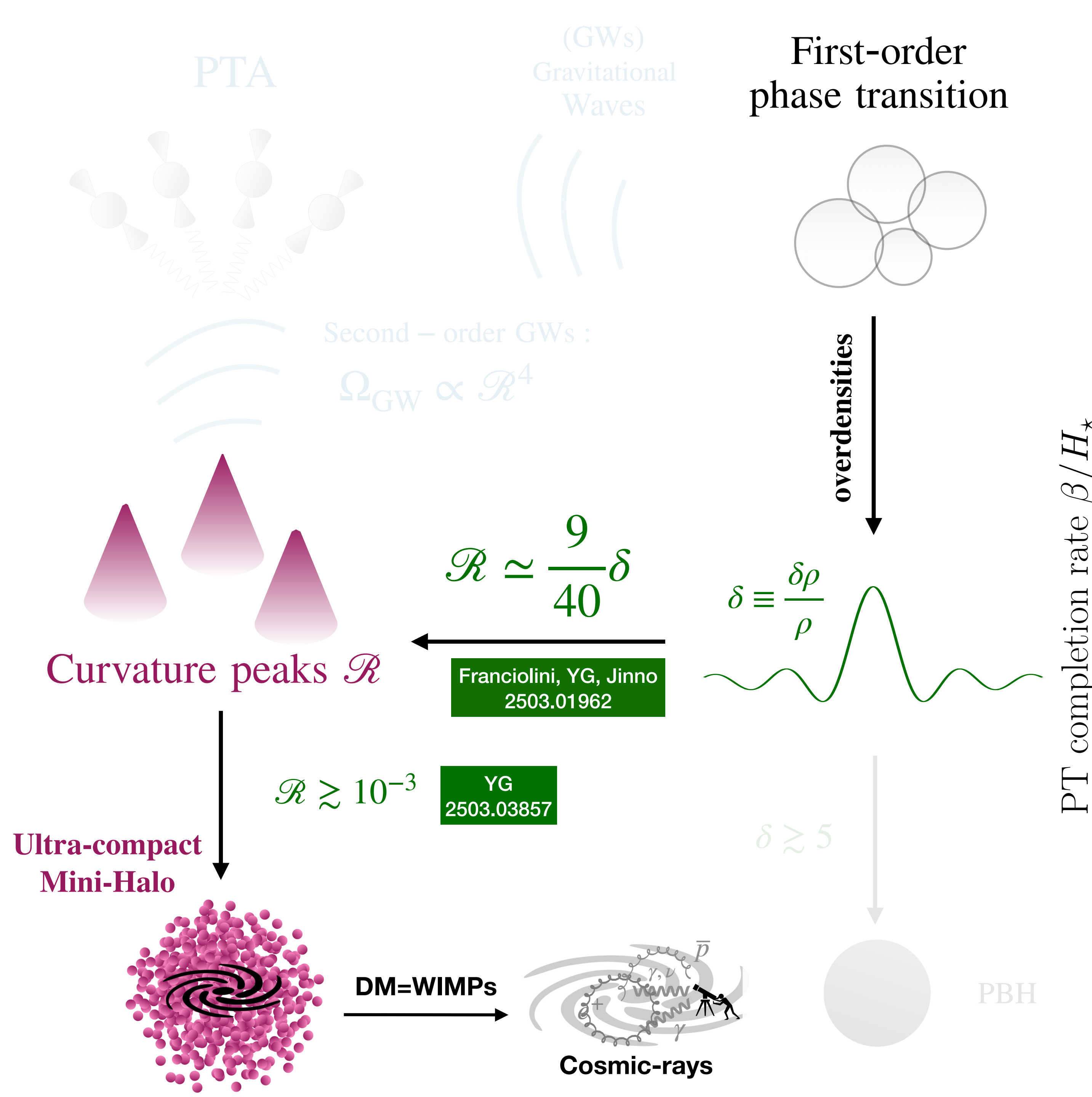
Franciolini, YG, Jinno, 2503.01962



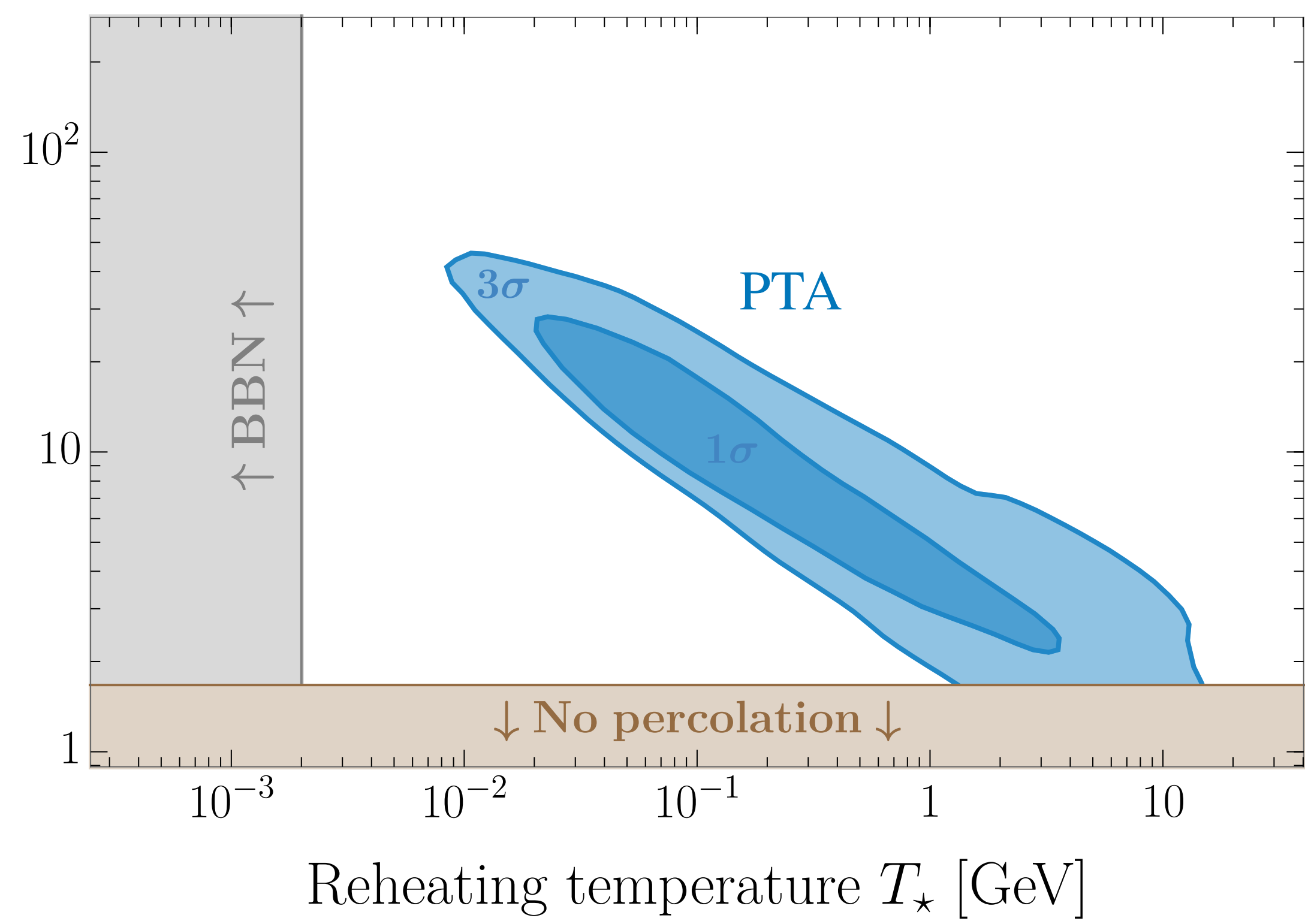




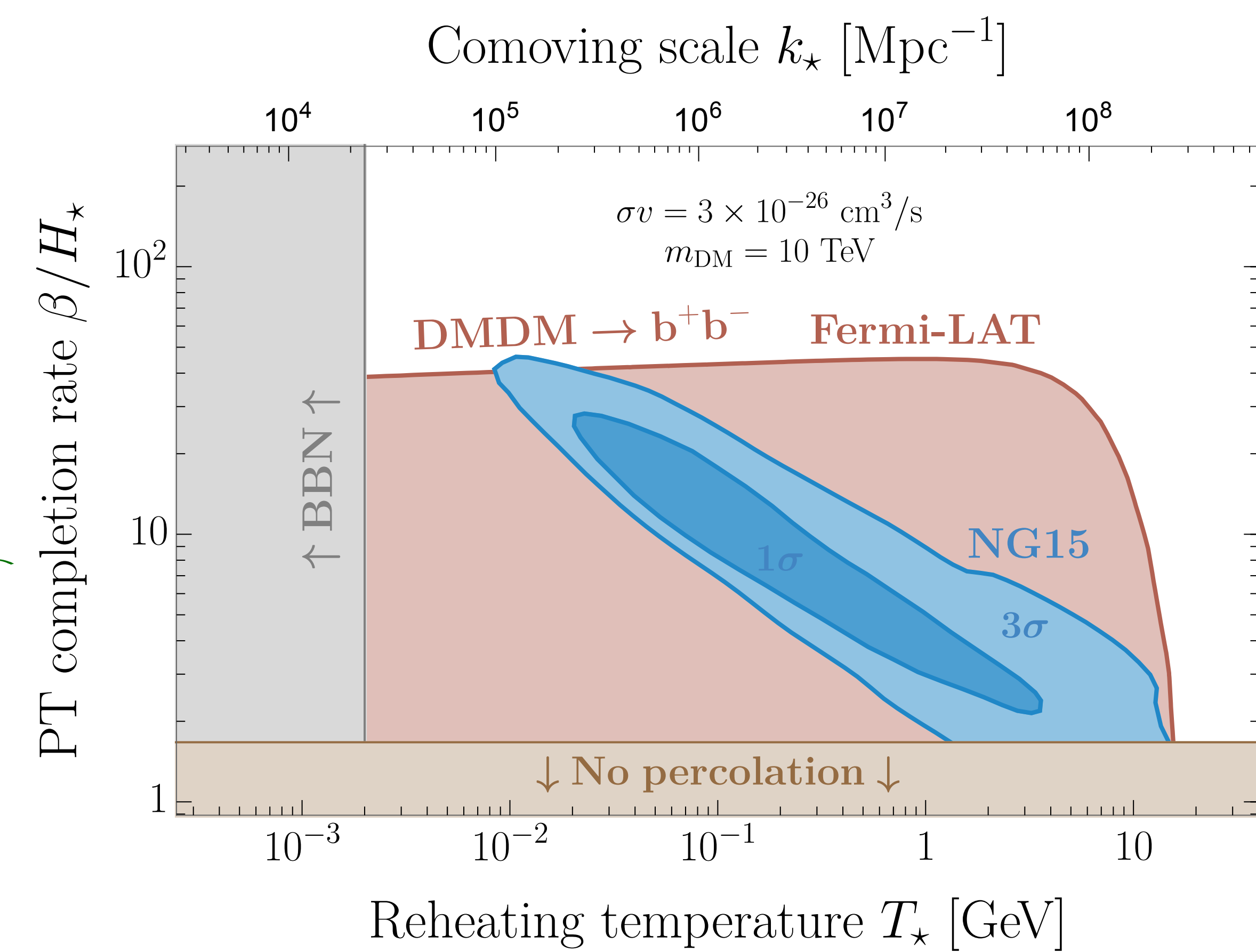
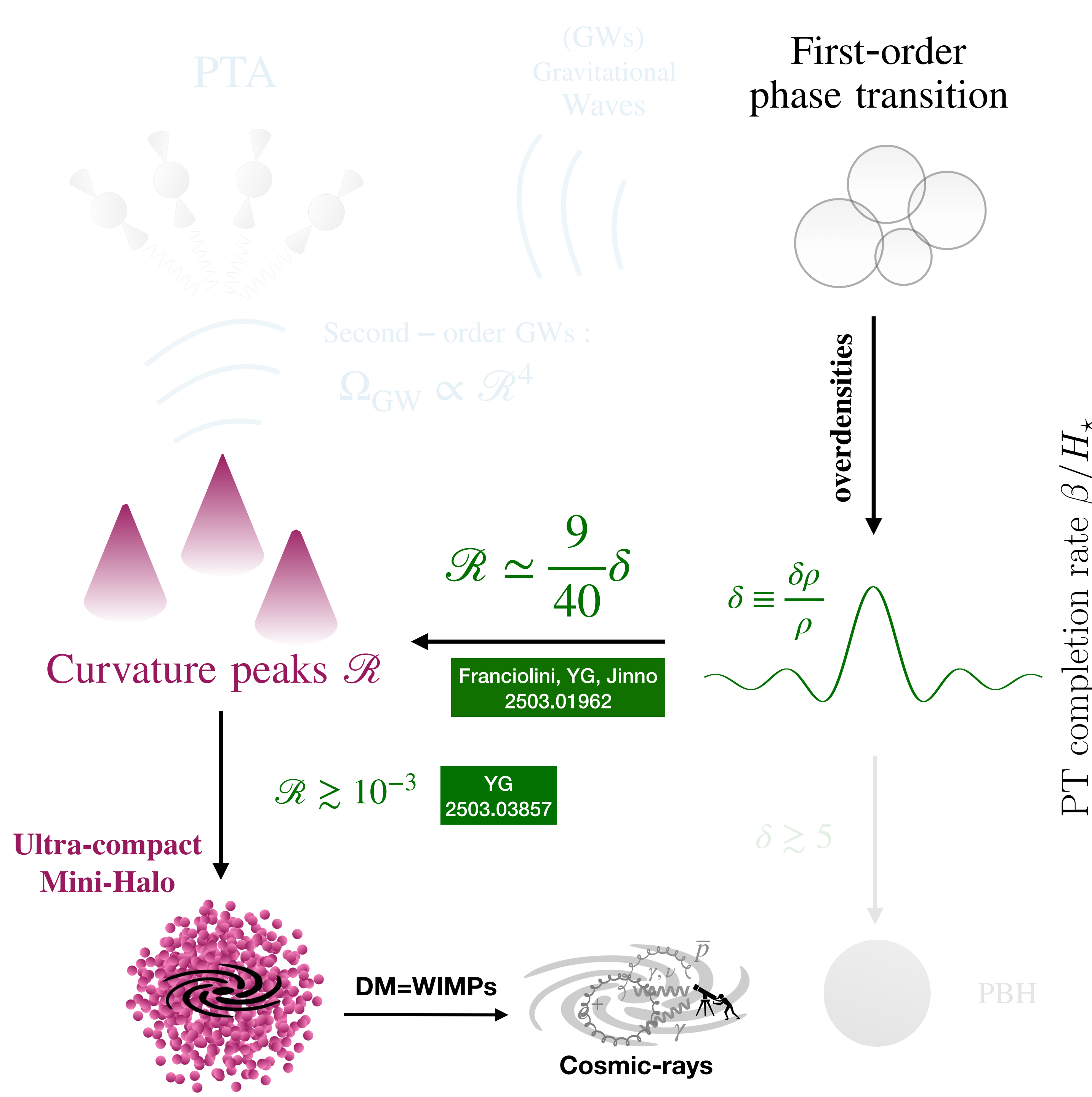
“New Physics Explanations of PTA signal are incompatible with WIMPs Dark Matter”



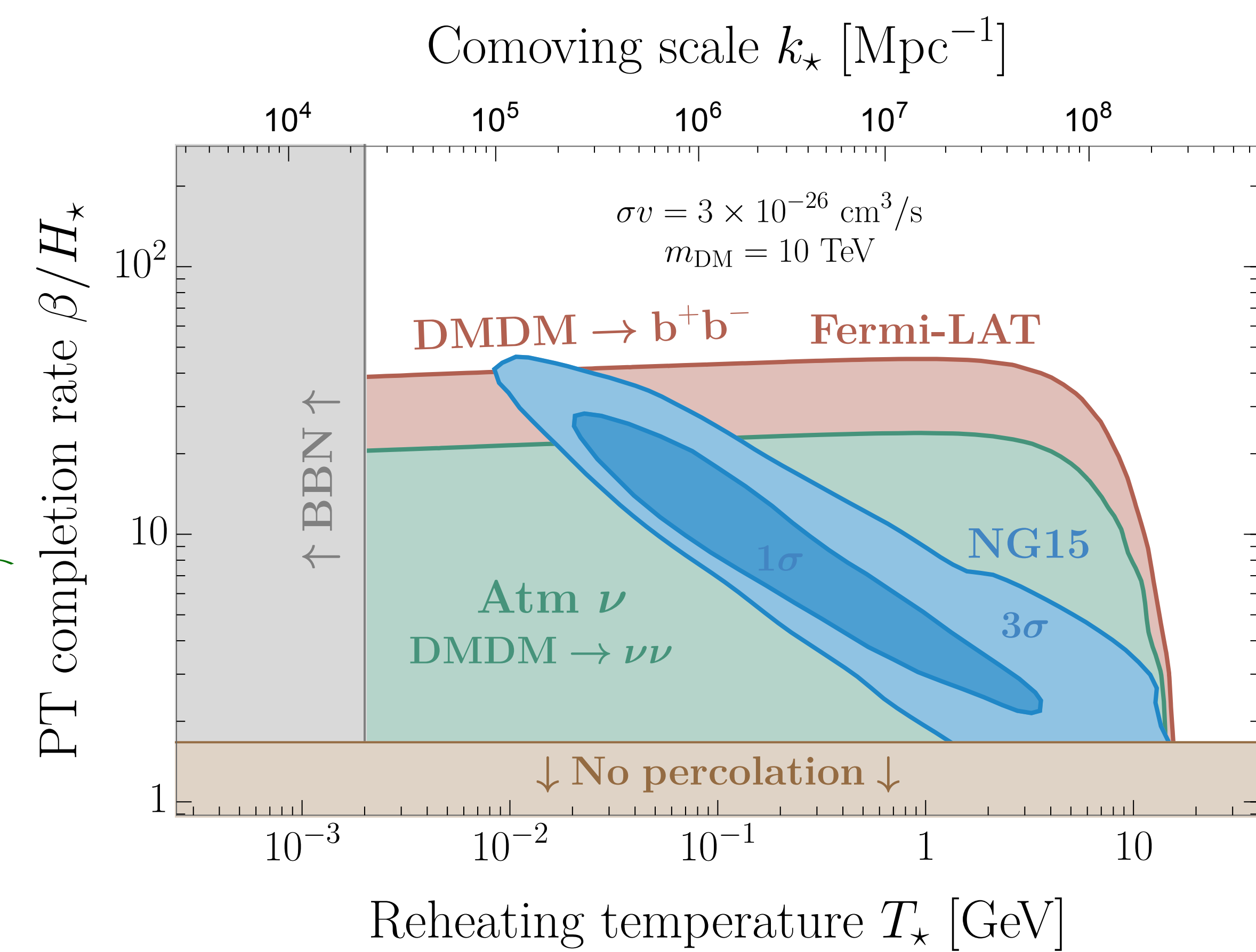
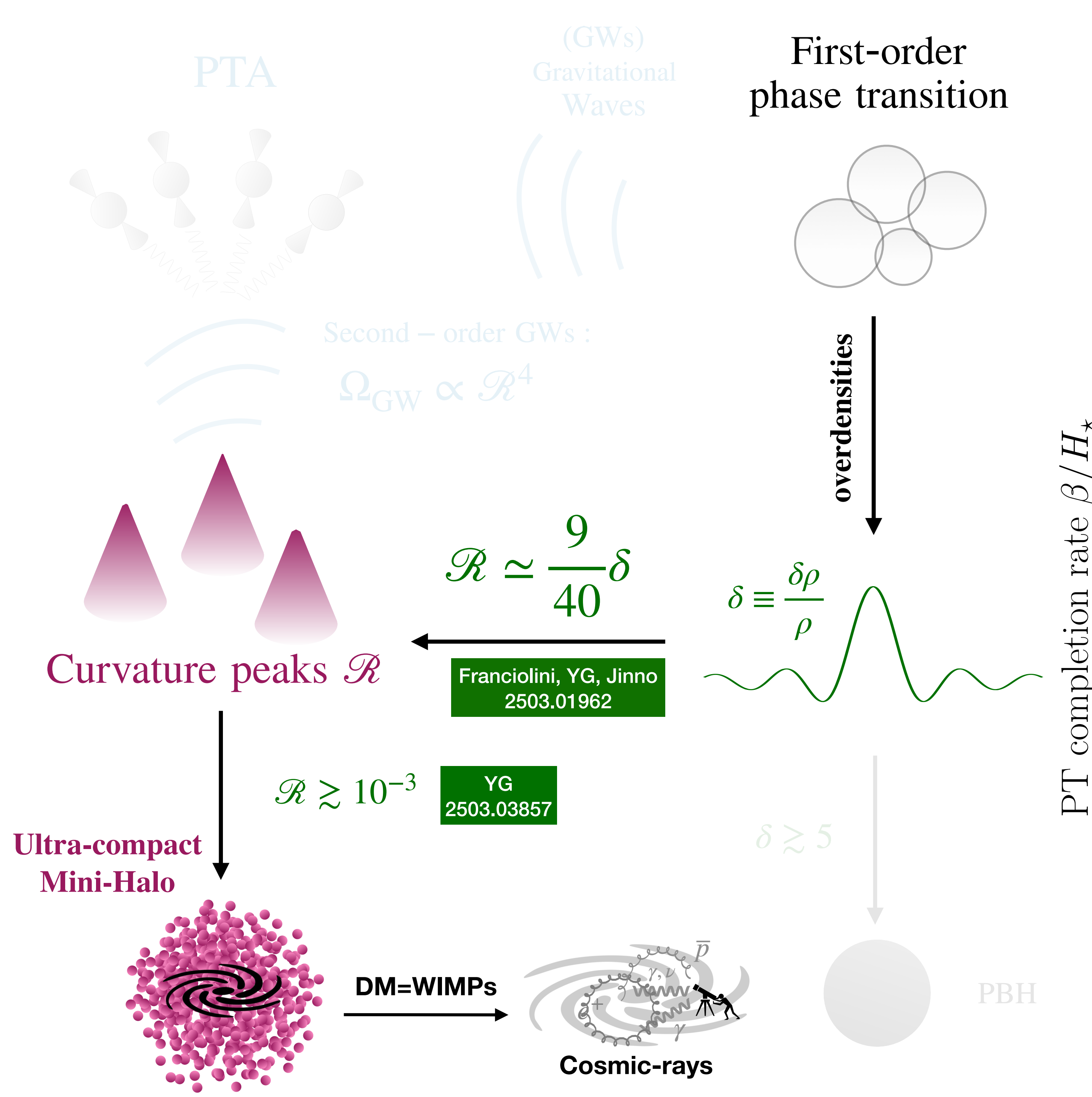
PT completion rate $\beta/H_\star$

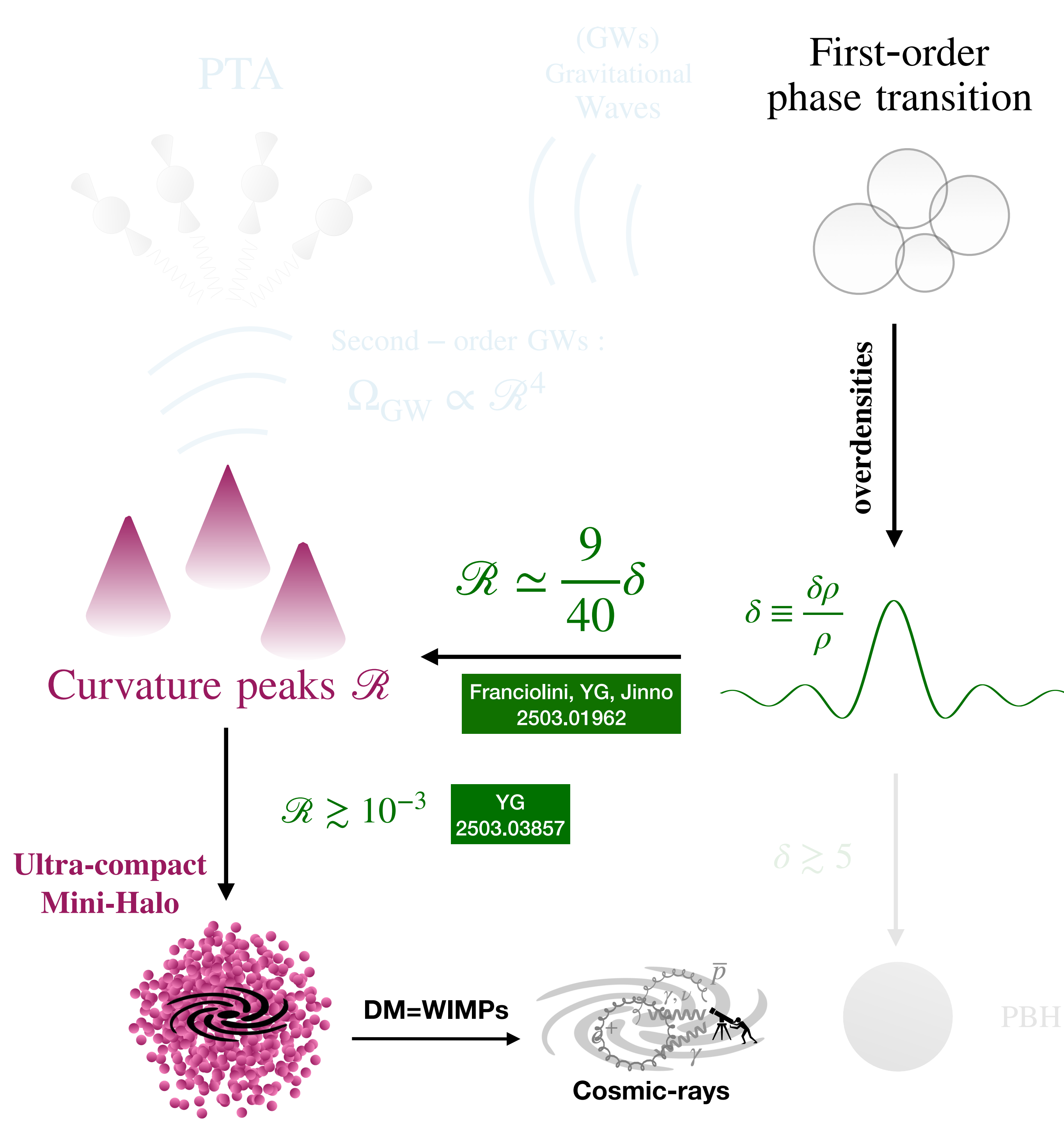


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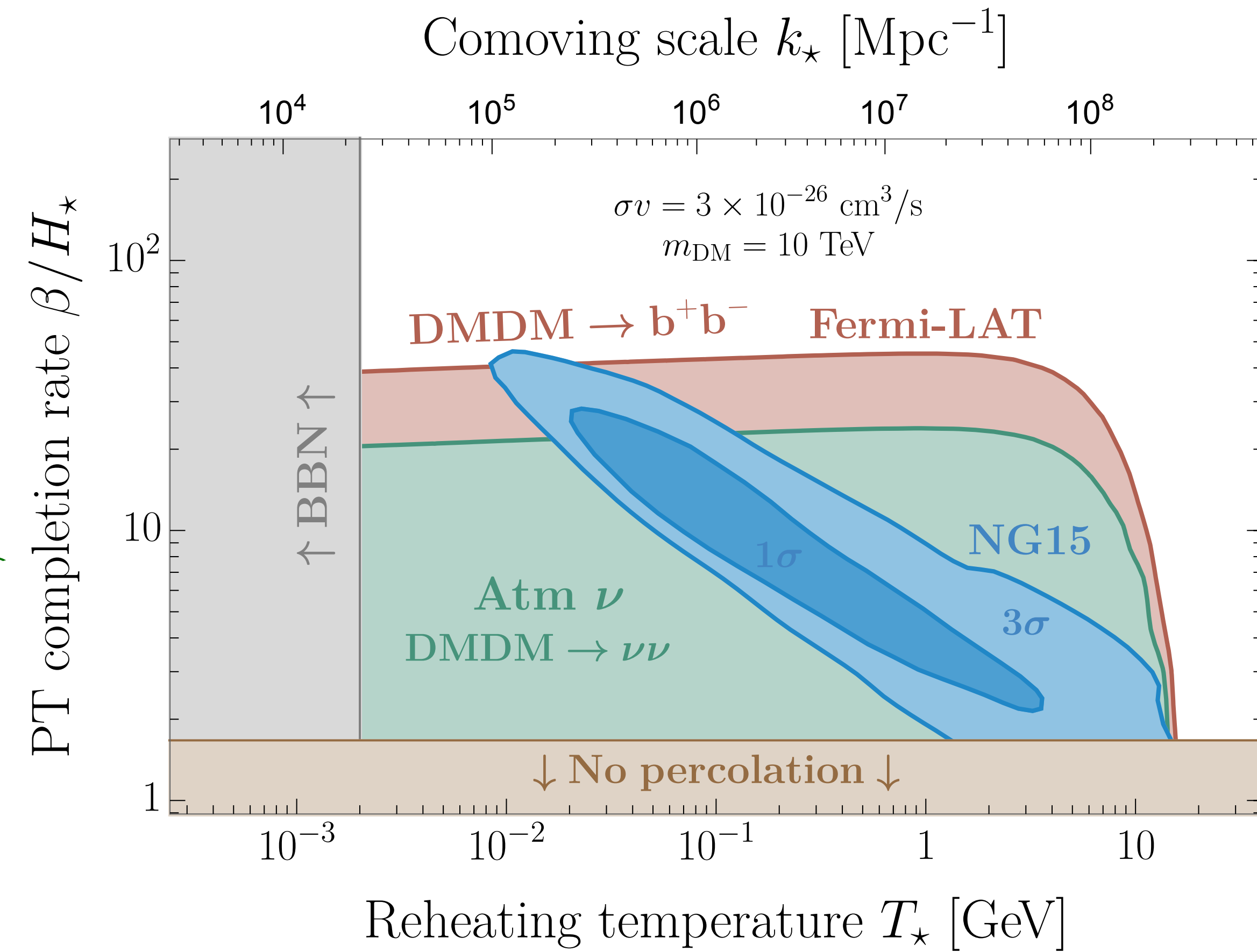


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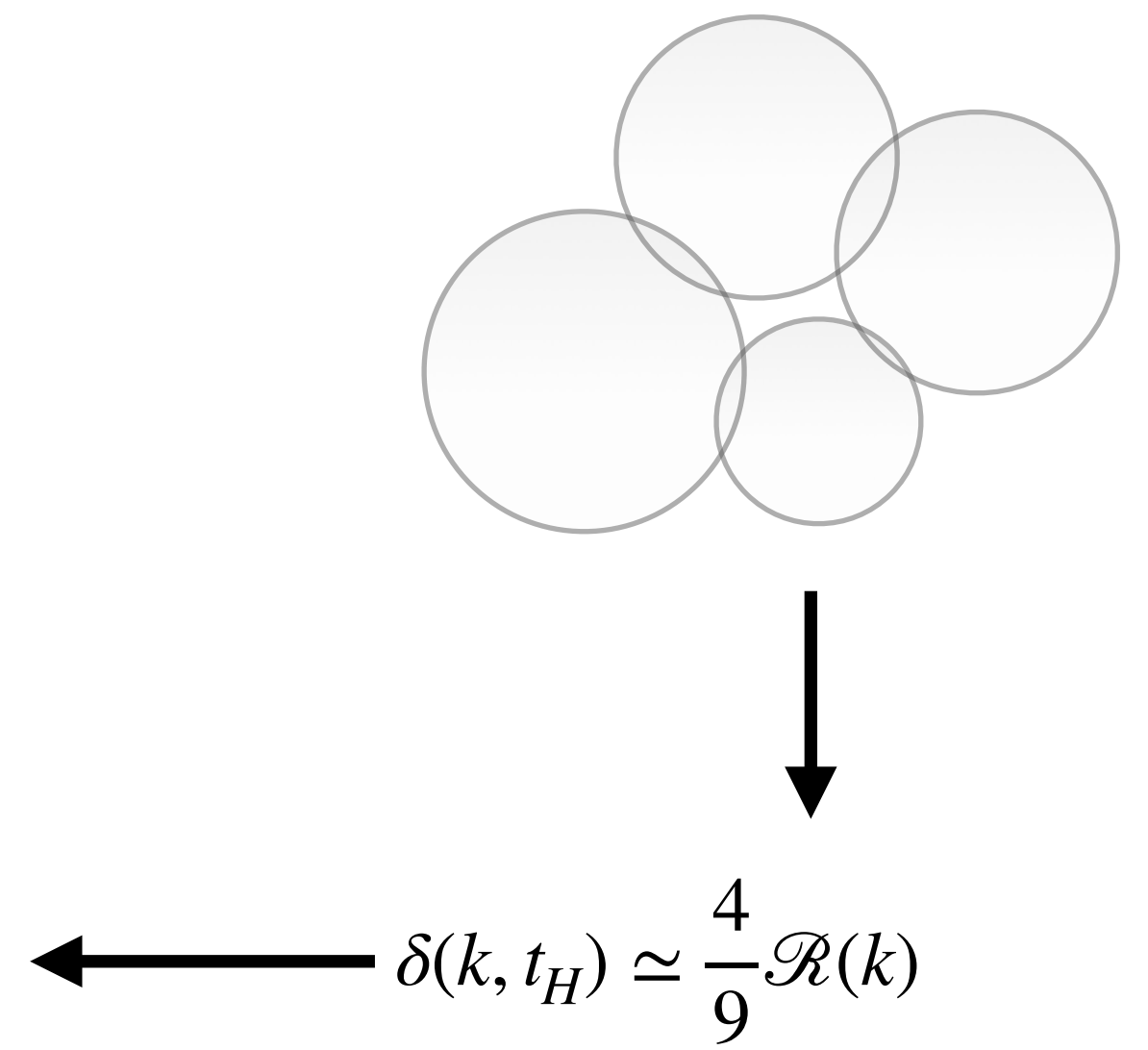
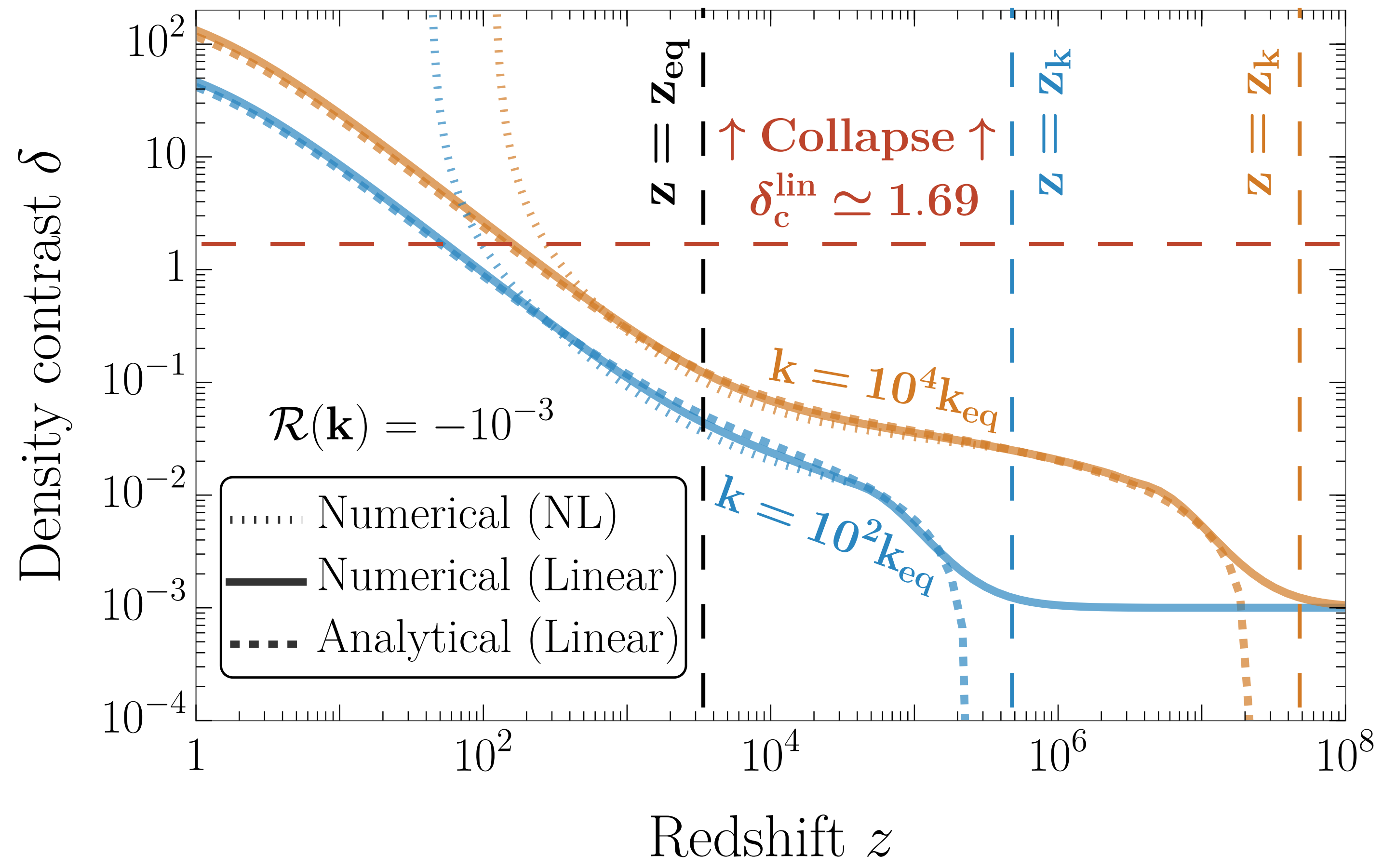


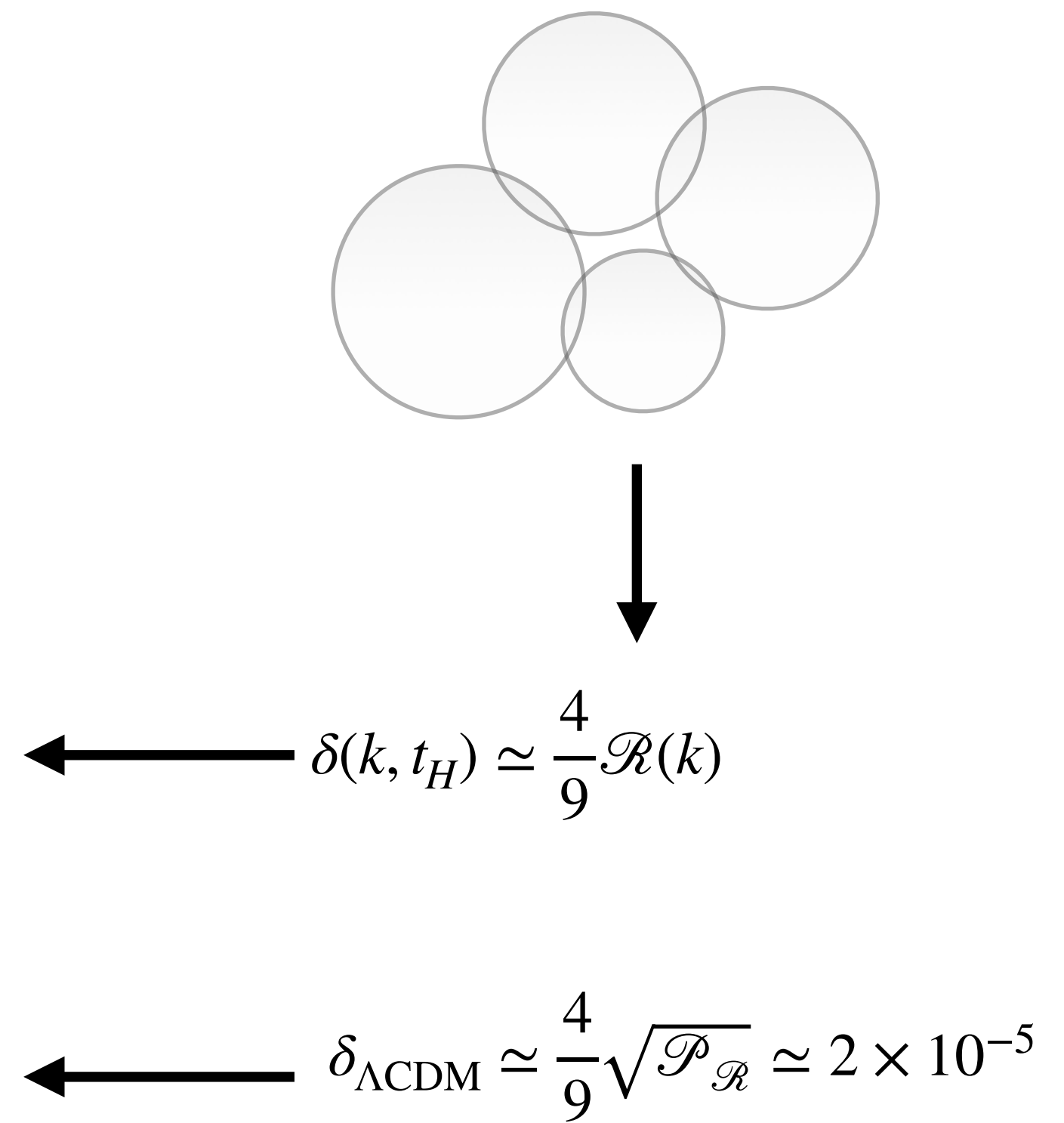
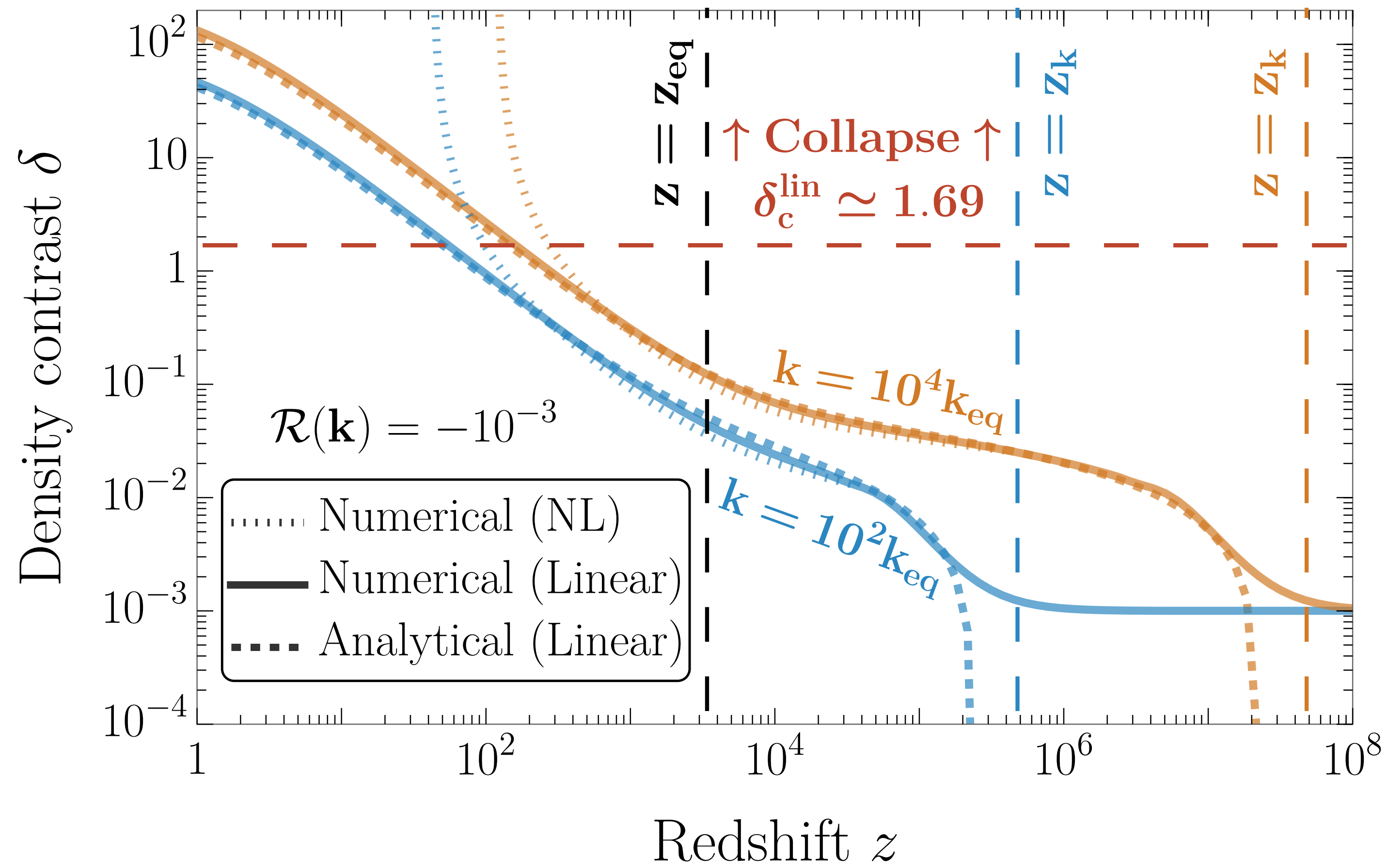


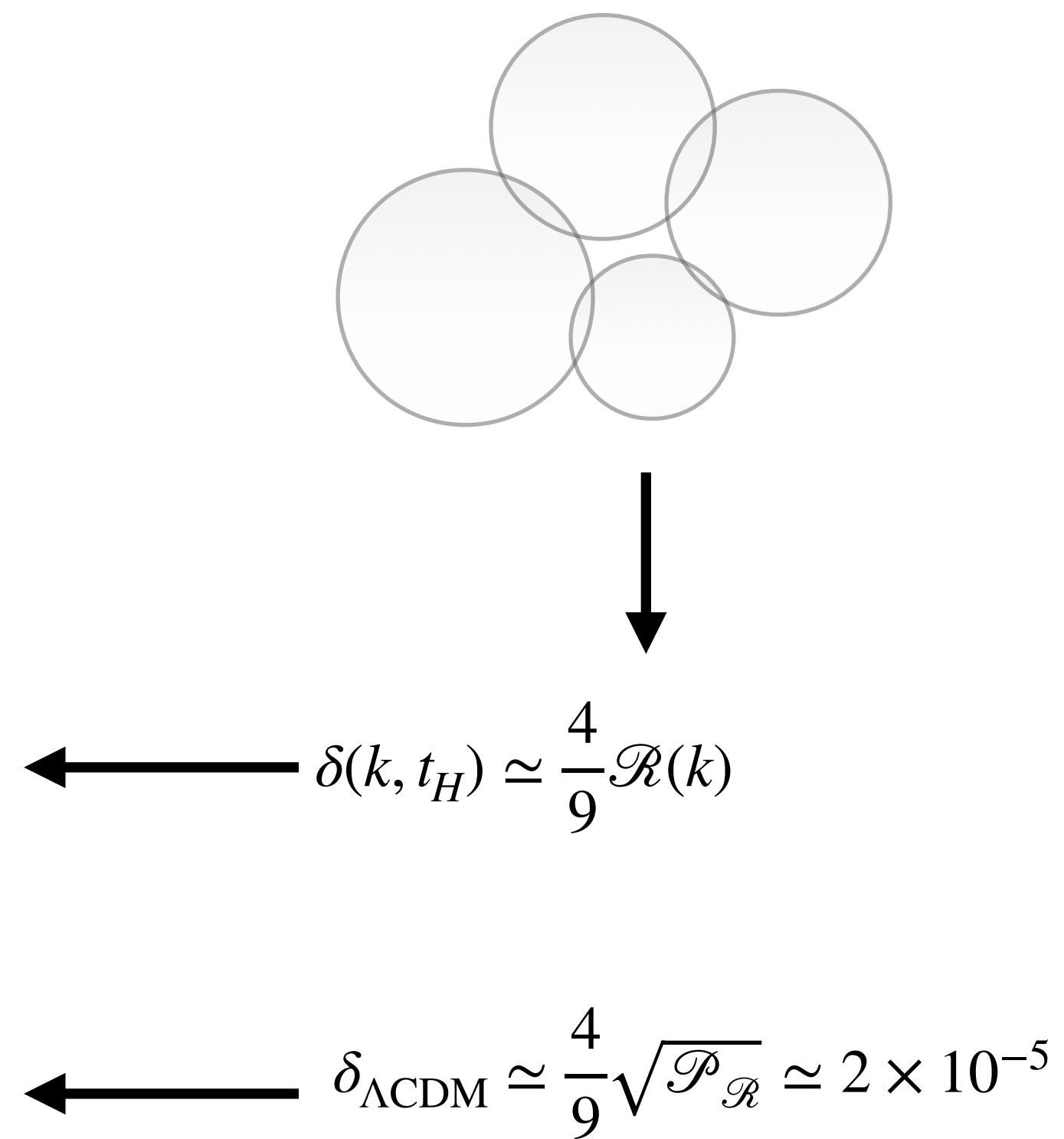
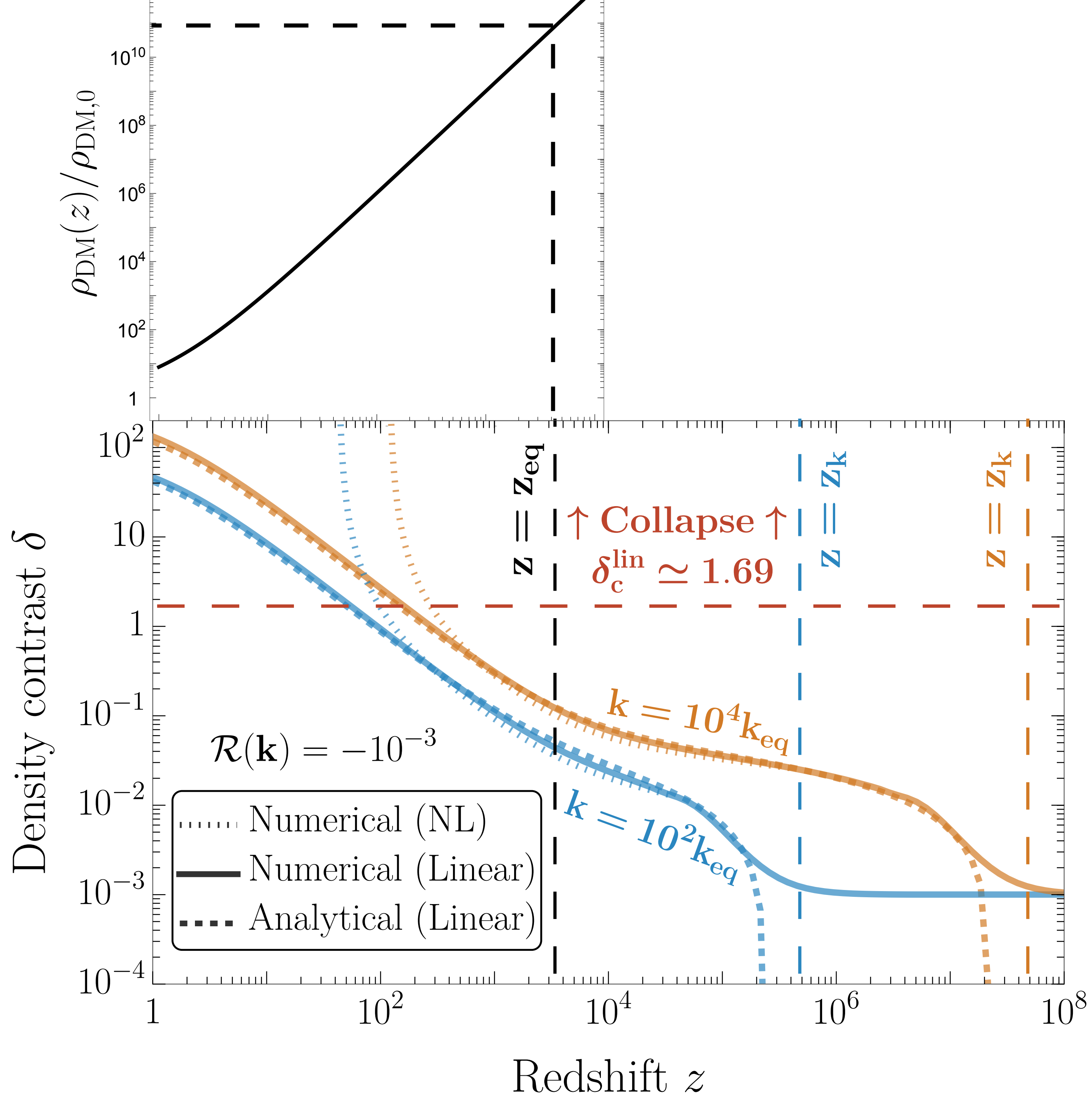
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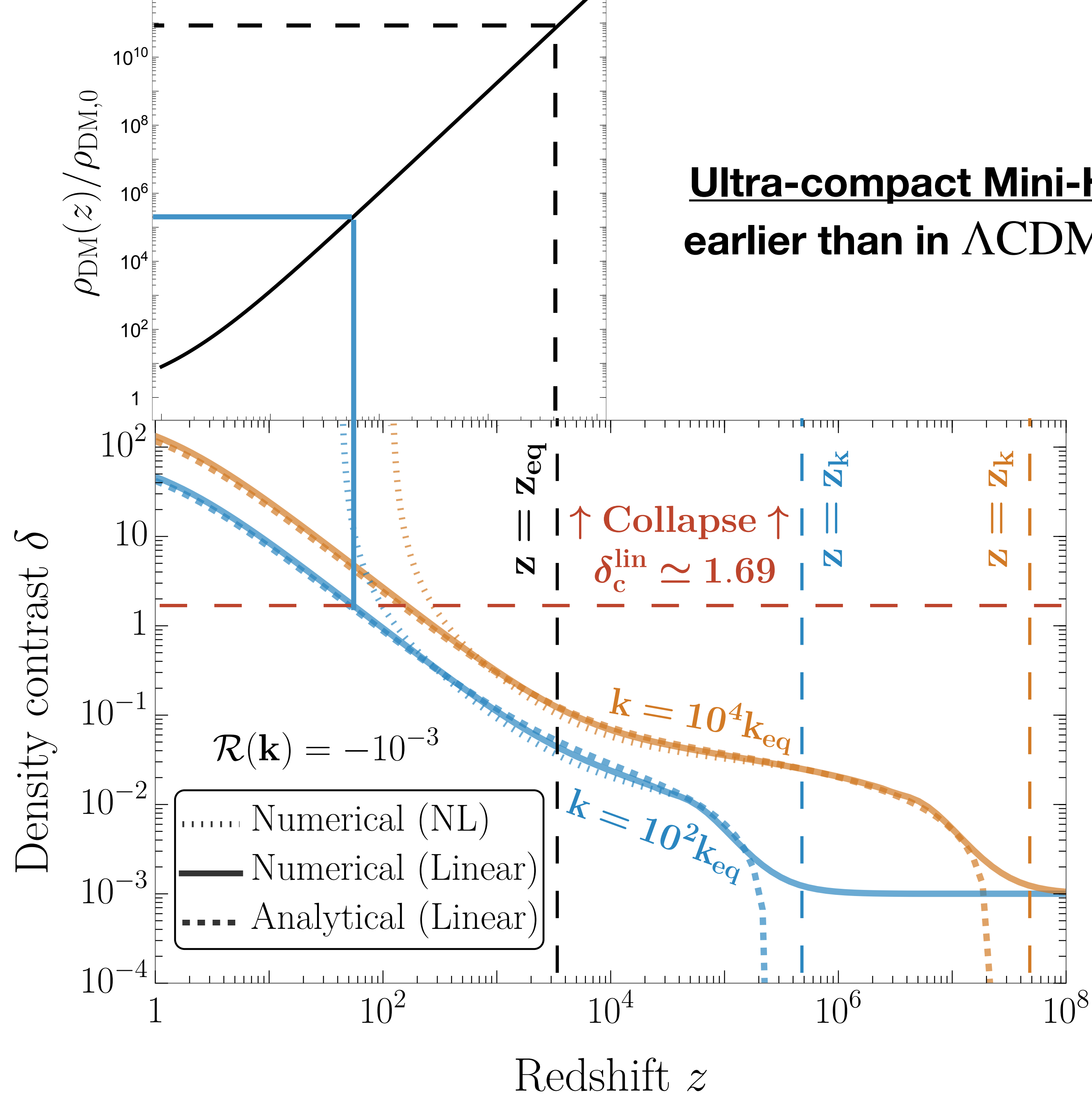


Same conclusion for : 1) Domain Wall Networks
2) Curvature Peaks from inflation

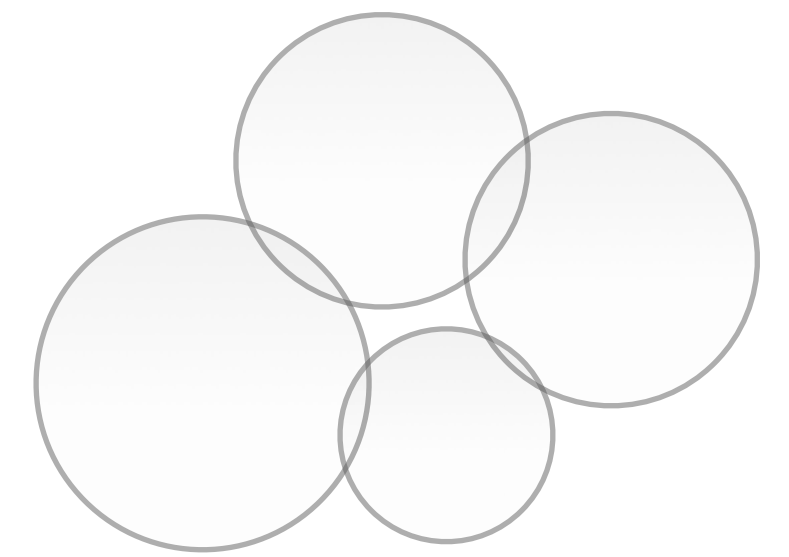






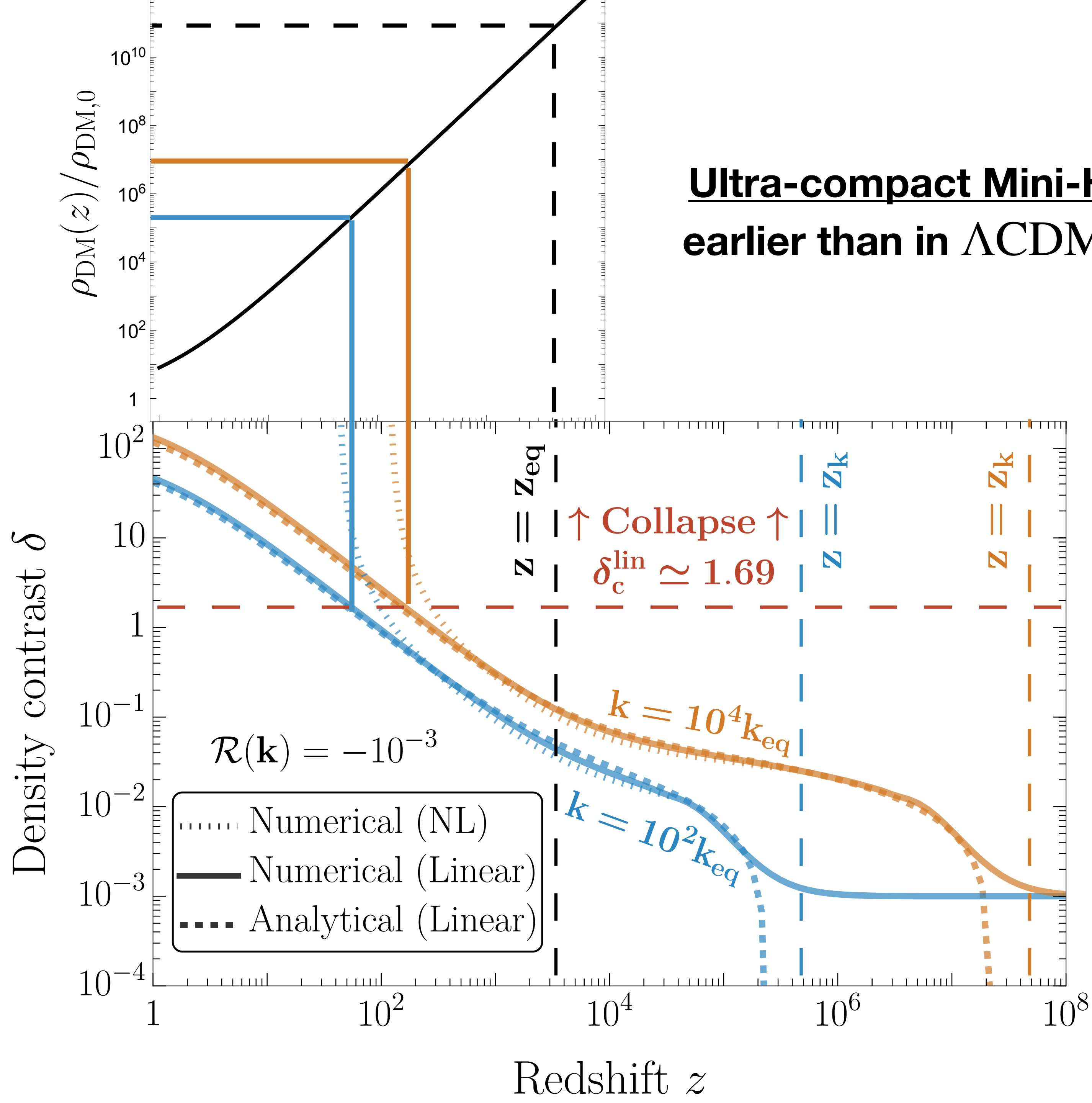


Ultra-compact Mini-Halo: DM halo that formed earlier than in Λ CDM and therefore are denser

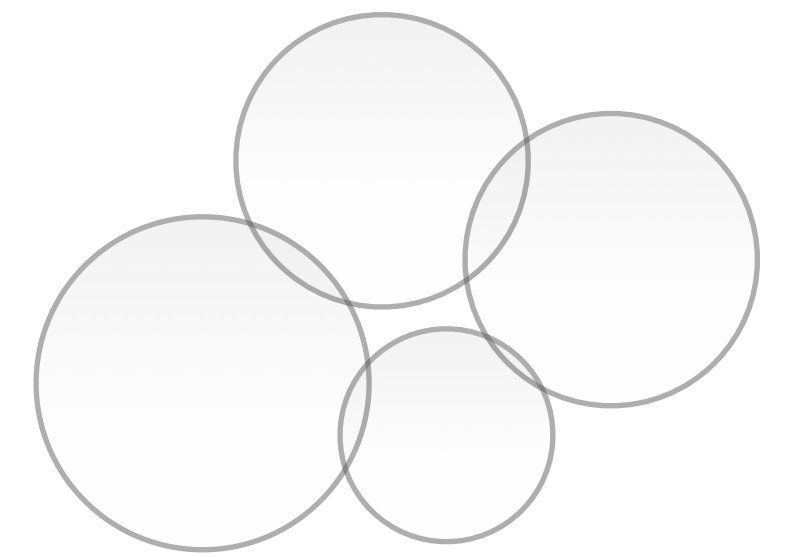


$$\delta(k, t_H) \simeq \frac{4}{9} \mathcal{R}(k)$$

$$\delta_{\Lambda\text{CDM}} \simeq \frac{4}{9} \sqrt{\mathcal{P}_{\mathcal{R}}} \simeq 2 \times 10^{-5}$$



Ultra-compact Mini-Halo: DM halo that formed earlier than in Λ CDM and therefore are denser

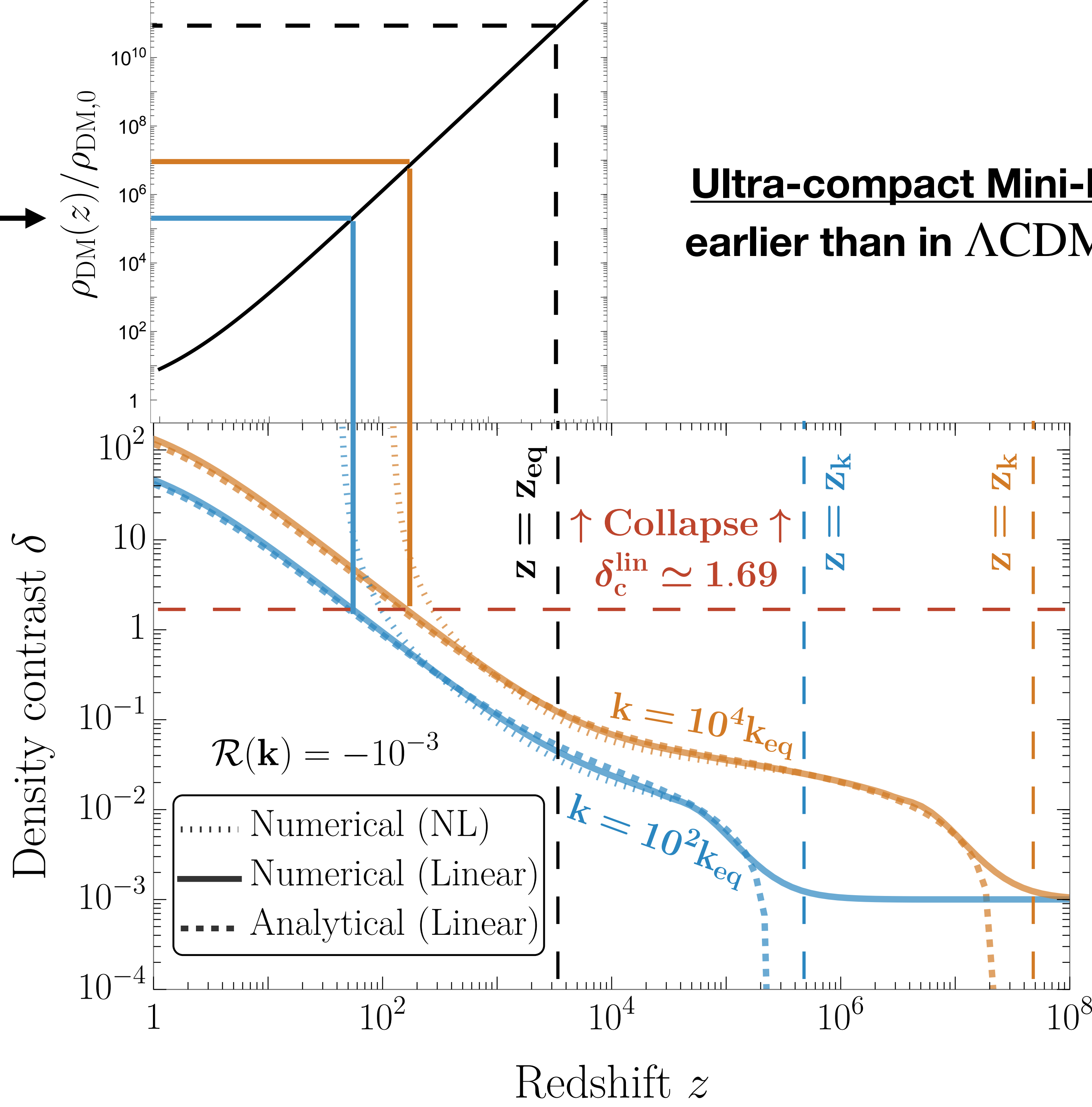


$$\delta(k, t_H) \simeq \frac{4}{9} \mathcal{R}(k)$$

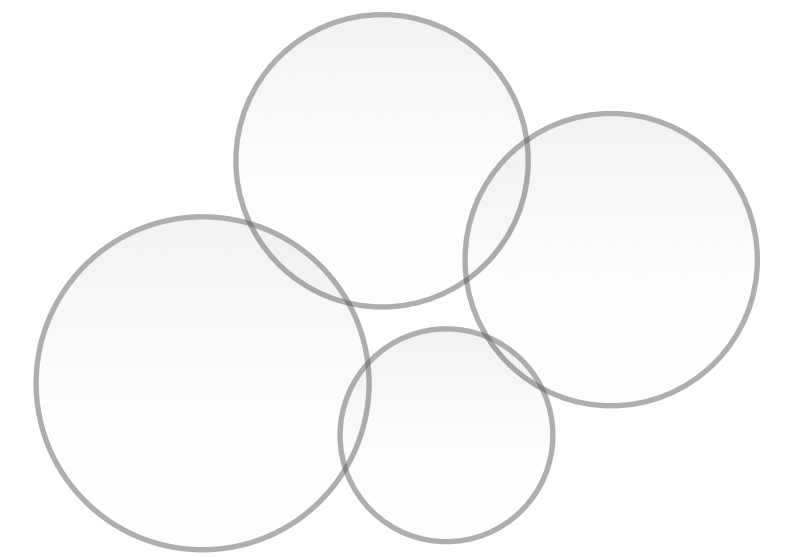
$$\delta_{\Lambda\text{CDM}} \simeq \frac{4}{9} \sqrt{\mathcal{P}_{\mathcal{R}}} \simeq 2 \times 10^{-5}$$

$$\rho_{\odot} \simeq 0.3 \text{ GeV/cm}^3$$

$$\simeq 2 \times 10^5 \rho_{\text{DM},0}$$



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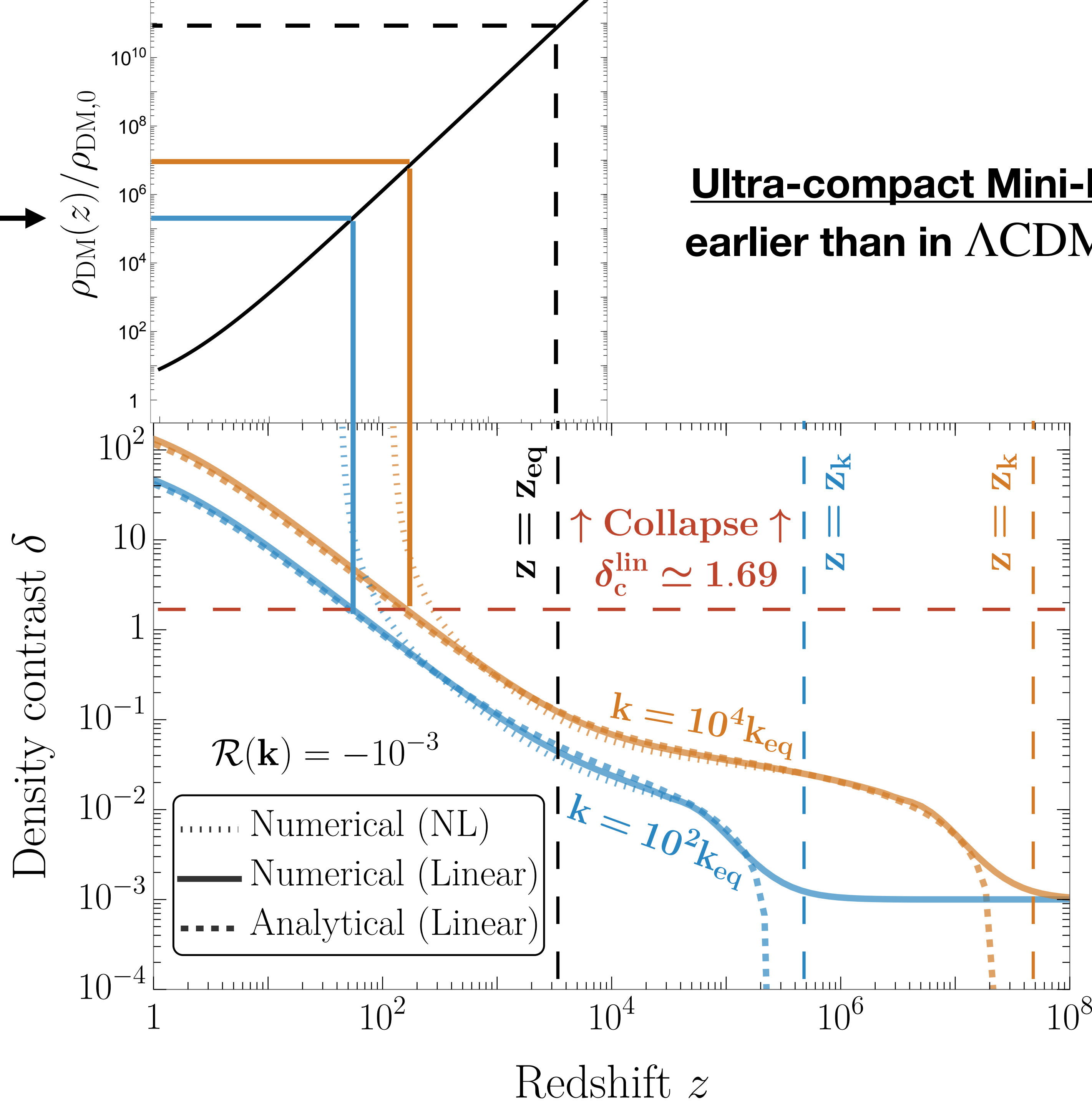


$$\delta(k, t_H) \simeq \frac{4}{9} \mathcal{R}(k)$$

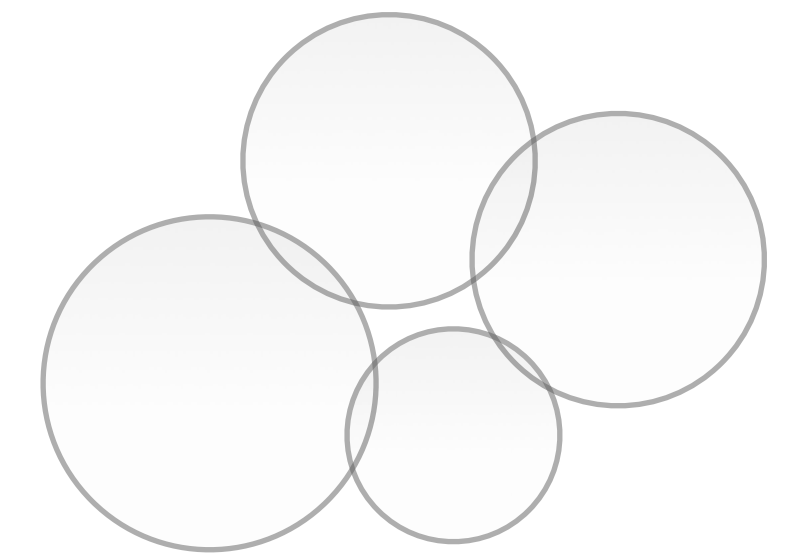
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$$\delta_{\Lambda\text{CDM}} \simeq \frac{4}{9} \sqrt{\mathcal{P}_{\mathcal{R}}} \simeq 2 \times 10^{-5}$$

“Number of DM pairs”

$$d\vec{r}^3 \frac{1}{2} \left(\frac{\rho_{\text{UCMH}}(\vec{r})}{m_{\text{DM}}} \right)^2$$

“Number of annihilation per second”

$$d\vec{r}^3 \frac{1}{2} \left(\frac{\rho_{\text{UCMH}}(\vec{r})}{m_{\text{DM}}} \right)^2 \sum_f \langle \sigma_f v \rangle$$

“Number of photon produced per second”

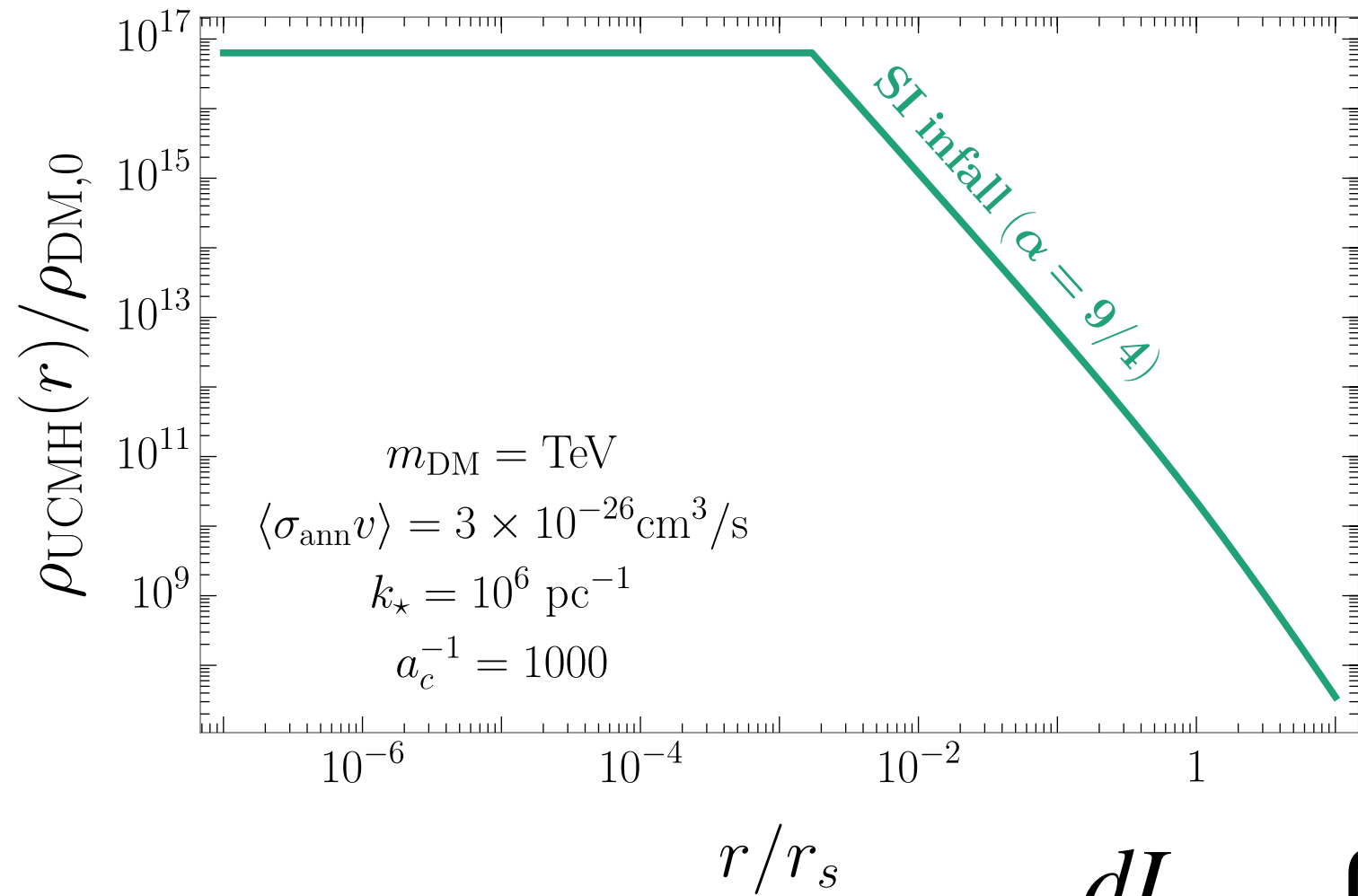
$$d\vec{r}^3 \frac{1}{2} \left(\frac{\rho_{\text{UCMH}}(\vec{r})}{m_{\text{DM}}} \right)^2 \sum_f \langle \sigma_f v \rangle \frac{dN_{f \rightarrow \gamma}}{dE}$$

“Number of photon produced per second per halo”

$$\frac{dL}{dE} = \int_0^R d\vec{r}^3 \frac{1}{2} \left(\frac{\rho_{\text{UCMH}}(\vec{r})}{m_{\text{DM}}} \right)^2 \sum_f \langle \sigma_f v \rangle \frac{dN_{f \rightarrow \gamma}}{dE}$$

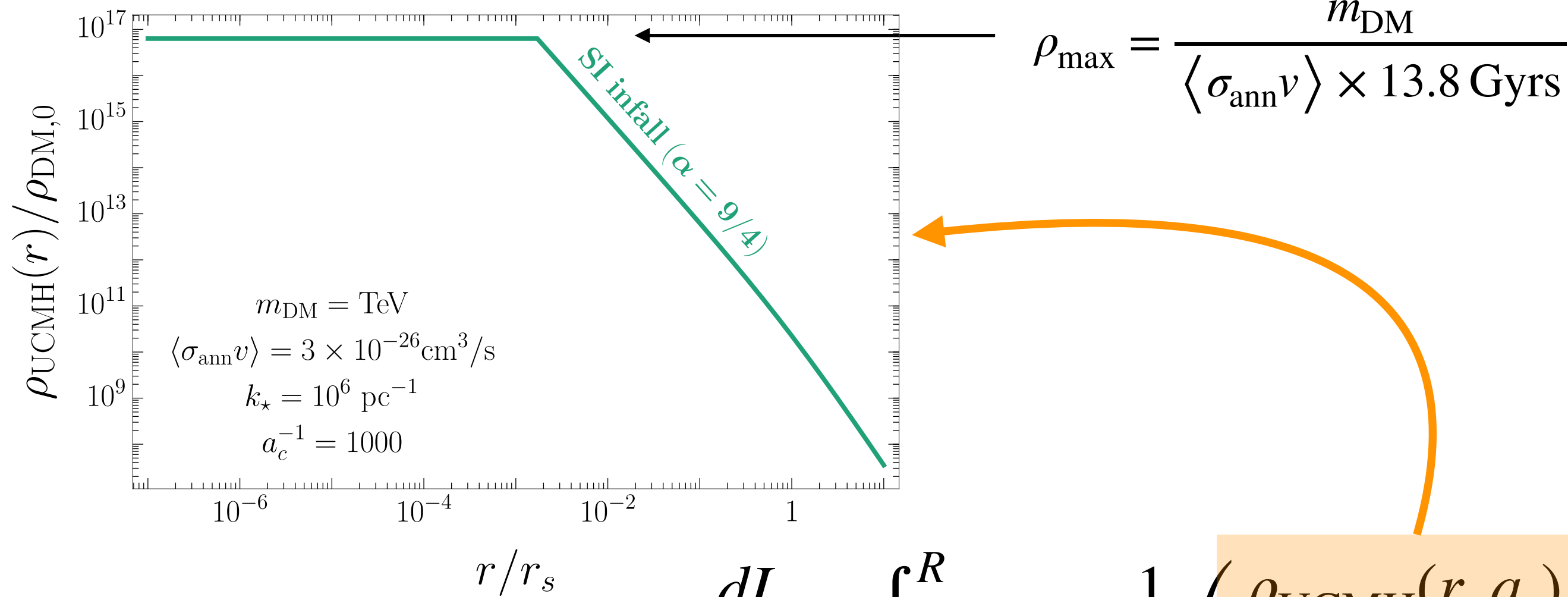
“Halo luminosity”

$$\frac{dL}{dE} = \int_0^R d\vec{r}^3 \frac{1}{2} \left(\frac{\rho_{\text{UCMH}}(\vec{r})}{m_{\text{DM}}} \right)^2 \sum_f \langle \sigma_f v \rangle \frac{dN_{f \rightarrow \gamma}}{dE}$$



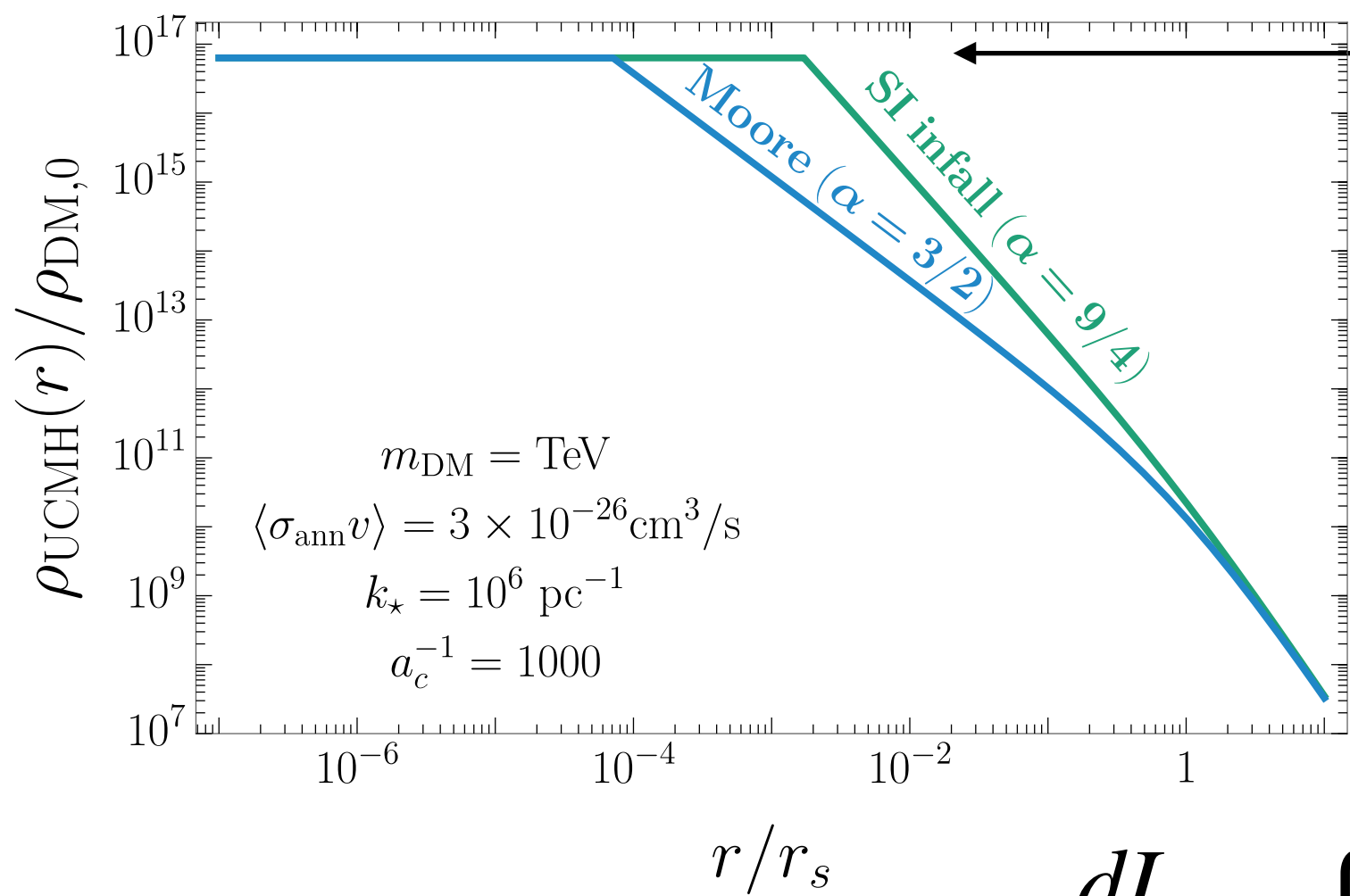
$$\frac{dL}{dE} = \int_0^R 4\pi r^2 dr \frac{1}{2} \left(\frac{\rho_{\text{UCMH}}(r, a_c)}{m_{\text{DM}}} \right)^2 \sum_f \langle \sigma_f v \rangle \frac{dN_{f \rightarrow \gamma}}{dE}$$

“Halo luminosity”



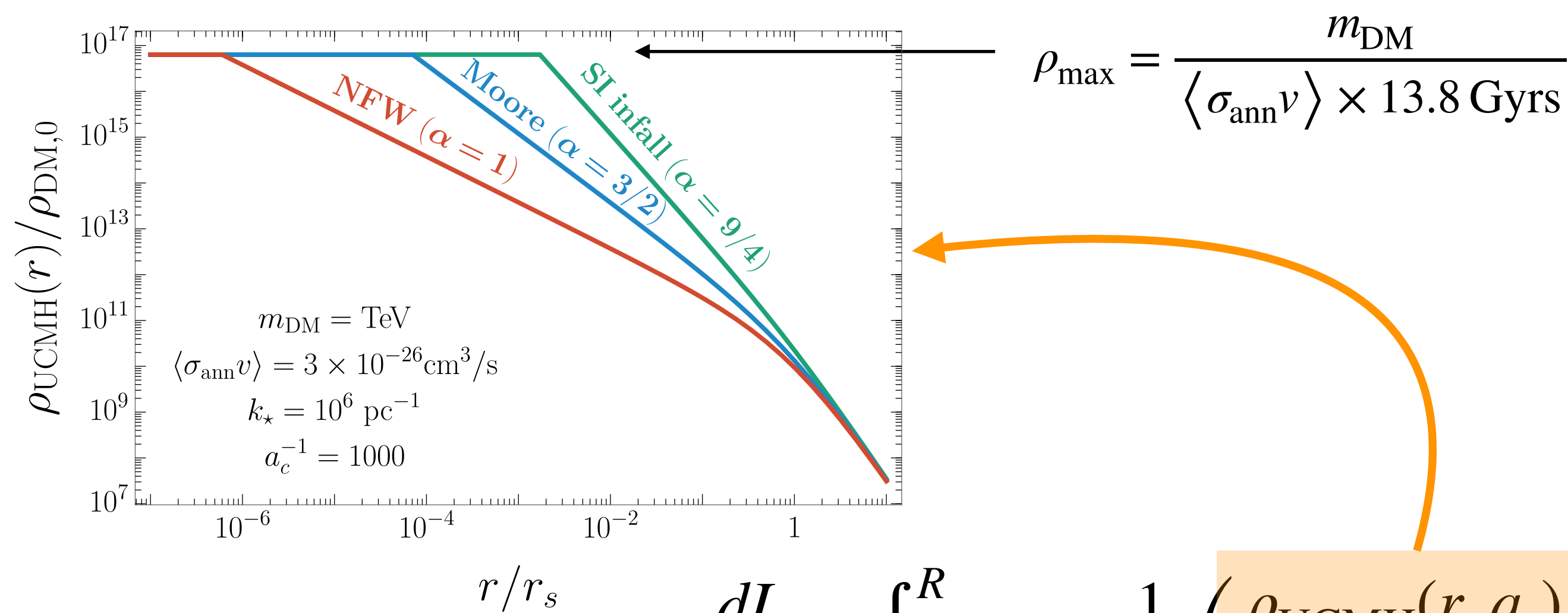
$$\frac{dL}{dE} = \int_0^R 4\pi r^2 dr \frac{1}{2} \left(\frac{\rho_{\text{UCMH}}(r, a_c)}{m_{\text{DM}}} \right)^2 \sum_f \langle \sigma_f v \rangle \frac{dN_{f \rightarrow \gamma}}{dE}$$

“Halo luminosity”



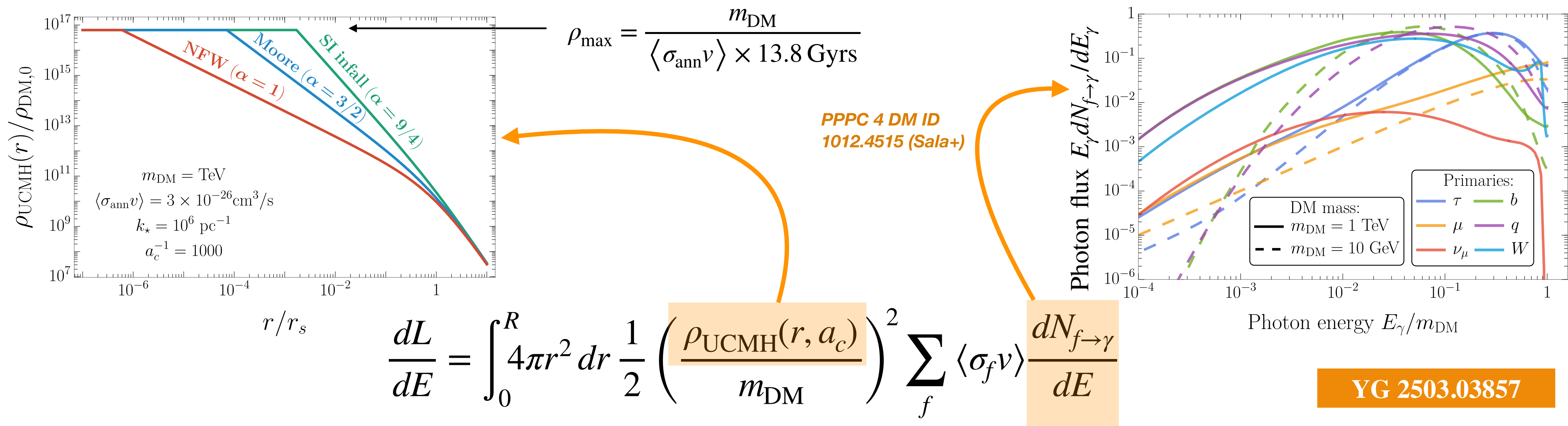
$$\frac{dL}{dE} = \int_0^R 4\pi r^2 dr \frac{1}{2} \left(\frac{\rho_{\text{UCMH}}(r, a_c)}{m_{\text{DM}}} \right)^2 \sum_f \langle \sigma_f v \rangle \frac{dN_{f \rightarrow \gamma}}{dE}$$

“Halo luminosity”

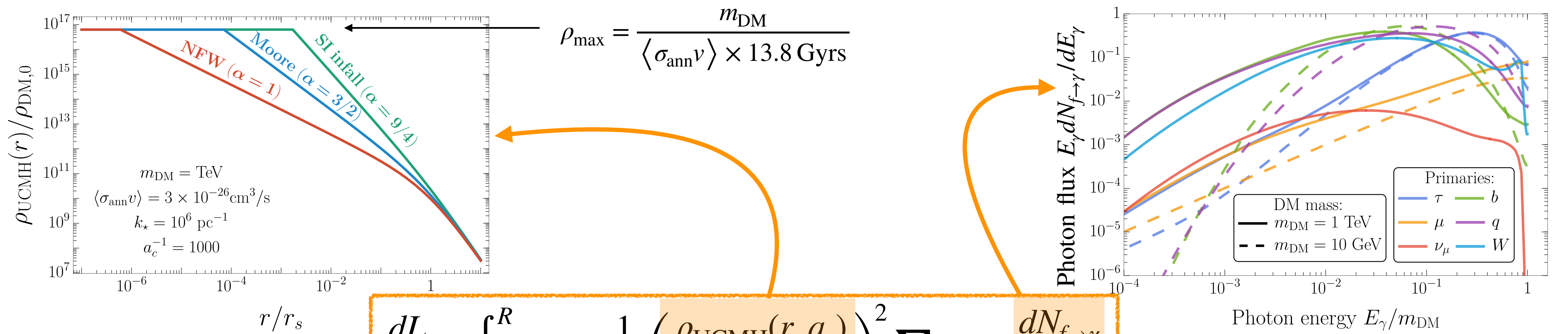


$$\frac{dL}{dE} = \int_0^R 4\pi r^2 dr \frac{1}{2} \left(\frac{\rho_{\text{UCMH}}(r, a_c)}{m_{\text{DM}}} \right)^2 \sum_f \langle \sigma_f v \rangle \frac{dN_{f \rightarrow \gamma}}{dE}$$

“Halo luminosity”



“Halo luminosity”

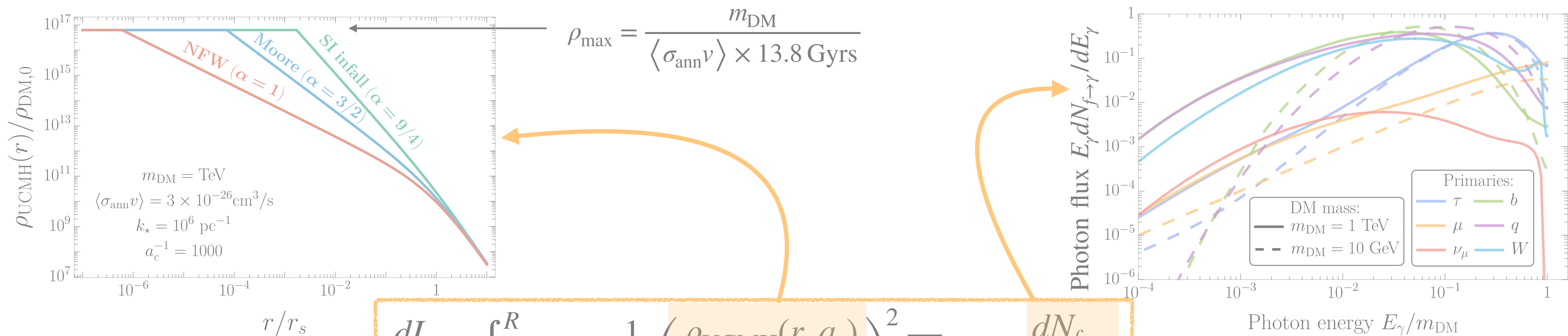


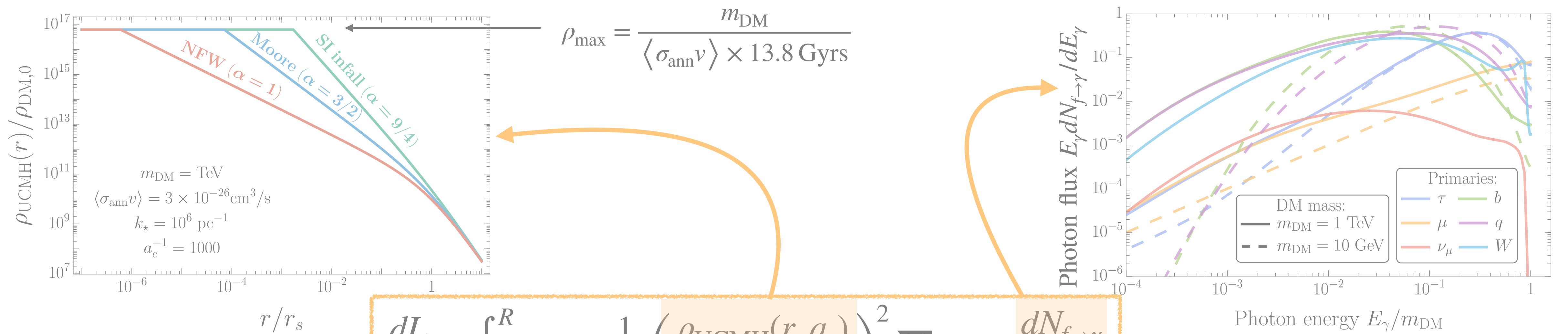
$$\rho_{\text{max}} = \frac{m_{\text{DM}}}{\langle \sigma_{\text{ann}} v \rangle \times 13.8 \text{ Gyrs}}$$

$$\frac{dL}{dE} = \int_0^R 4\pi r^2 dr \frac{1}{2} \left(\frac{\rho_{\text{UCMH}}(r, a_c)}{m_{\text{DM}}} \right)^2 \sum_f \langle \sigma_f v \rangle \frac{dN_{f \rightarrow \gamma}}{dE}$$

$$\frac{d^2 \mathcal{F}_\gamma(\theta)}{d\Omega dE} = \int_0^\infty \frac{ds}{4\pi} \frac{\rho_{\text{DM}}(s, \theta)}{\bar{\rho}_{\text{DM},0}} \times \int_0^\infty da_c \int_0^\infty \frac{dR}{R} \frac{dn}{da_c} \times \frac{dL[E, a_c, R]}{dE}$$

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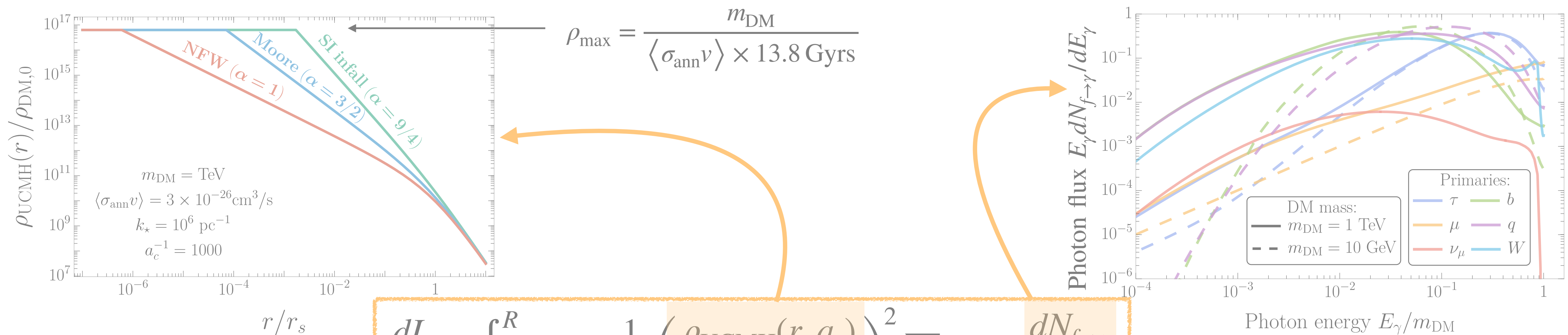


$$\frac{dL}{dE} = \int_0^R 4\pi r^2 dr \frac{1}{2} \left(\frac{\rho_{\text{UCMH}}(r, a_c)}{m_{\text{DM}}} \right)^2 \sum_f \langle\sigma_f v\rangle \frac{dN_{f \rightarrow \gamma}}{dE}$$

YG 2503.03857

$$\frac{d^2 \mathcal{F}_\gamma(\theta)}{d\Omega dE} = \int_0^\infty \frac{ds}{4\pi} \frac{\rho_{\text{DM}}(s, \theta)}{\bar{\rho}_{\text{DM},0}} \times \int_0^\infty da_c \int_0^\infty \frac{dR}{R} \frac{dn}{da_c} \times \frac{dL[(1+z_e)E, a_c, R]}{dE}$$

$$\rho_{\text{DM}}(s, \theta) = \rho_{\text{MW}} \left[\sqrt{s^2 + r_\odot^2 - 2r_\odot s \cos \theta} \right] + \frac{e^{-\tau(E, z_e)}}{(1+z_e)^3} \bar{\rho}_{\text{DM},0}$$



$$\frac{dL}{dE} = \int_0^R 4\pi r^2 dr \frac{1}{2} \left(\frac{\rho_{\text{UCMH}}(r, a_c)}{m_{\text{DM}}} \right)^2 \sum_f \langle\sigma_f v\rangle \frac{dN_{f \rightarrow \gamma}}{dE}$$

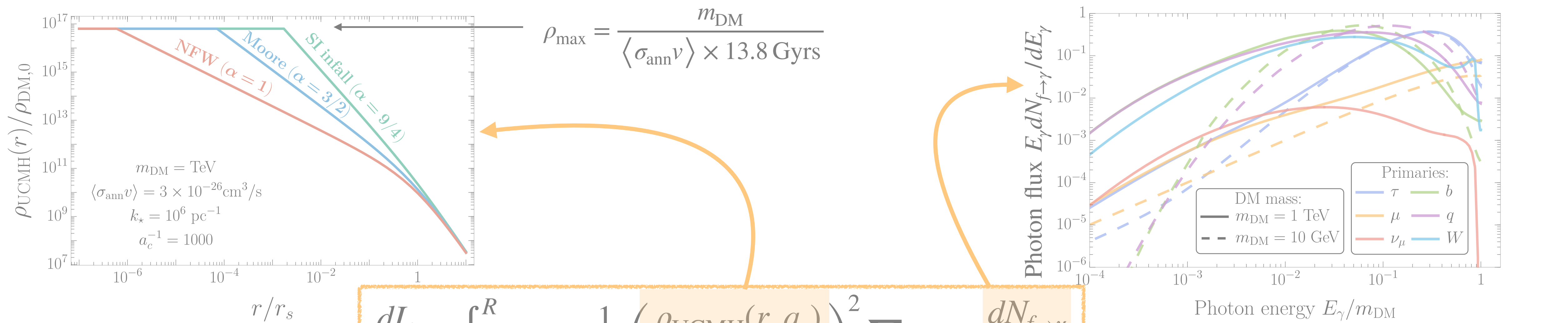
YG 2503.03857

$$\frac{d^2 \mathcal{F}_\gamma(\theta)}{d\Omega dE} = \int_0^\infty \frac{ds}{4\pi} \frac{\rho_{\text{DM}}(s, \theta)}{\bar{\rho}_{\text{DM},0}} \times \int_0^\infty da_c \int_0^\infty \frac{dR}{R} \frac{dn}{da_c} \times \frac{dL[(1+z_e)E, a_c, R]}{dE}$$

Press – Schechter theory

$$\frac{dn(R, a_c)}{da_c} \simeq R^{-3} \sqrt{\frac{2}{\pi}} \frac{\nu_c}{a_c} \exp\left(-\frac{\nu_c^2}{2}\right)$$

$$\rho_{\text{DM}}(s, \theta) = \rho_{\text{MW}} \left[\sqrt{s^2 + r_\odot^2 - 2r_\odot s \cos \theta} \right] + \frac{e^{-\tau(E, z_e)}}{(1+z_e)^3} \bar{\rho}_{\text{DM},0}$$

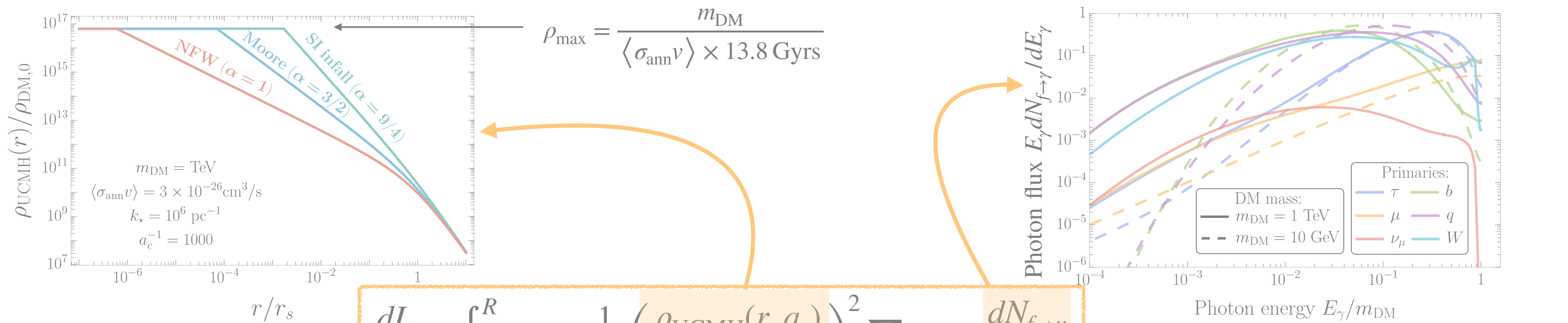


$$\frac{d^2 \mathcal{F}_{\gamma}(\theta)}{d\Omega dE} = \int_0^{\infty} \frac{ds}{4\pi} \frac{\rho_{\text{DM}}(s, \theta)}{\bar{\rho}_{\text{DM},0}} \times \int_0^{\infty} da_c \int_0^{\infty} \frac{dR}{R} \frac{dn}{da_c} \times \frac{dL[(1+z_e)E, a_c, R]}{dE}$$

Press – Schechter theory

$$\frac{dn(R, a_c)}{da_c} \simeq R^{-3} \sqrt{\frac{2}{\pi}} \frac{\nu_c}{a_c} \exp\left(-\frac{\nu_c^2}{2}\right) \quad \nu_c \equiv \frac{\delta_{\text{min}}(a_c)}{\sigma_0(R)}$$

$$\rho_{\text{DM}}(s, \theta) = \rho_{\text{MW}} \left[\sqrt{s^2 + r_{\odot}^2 - 2r_{\odot}s \cos \theta} \right] + \frac{e^{-\tau(E, z_e)}}{(1+z_e)^3} \bar{\rho}_{\text{DM},0}$$

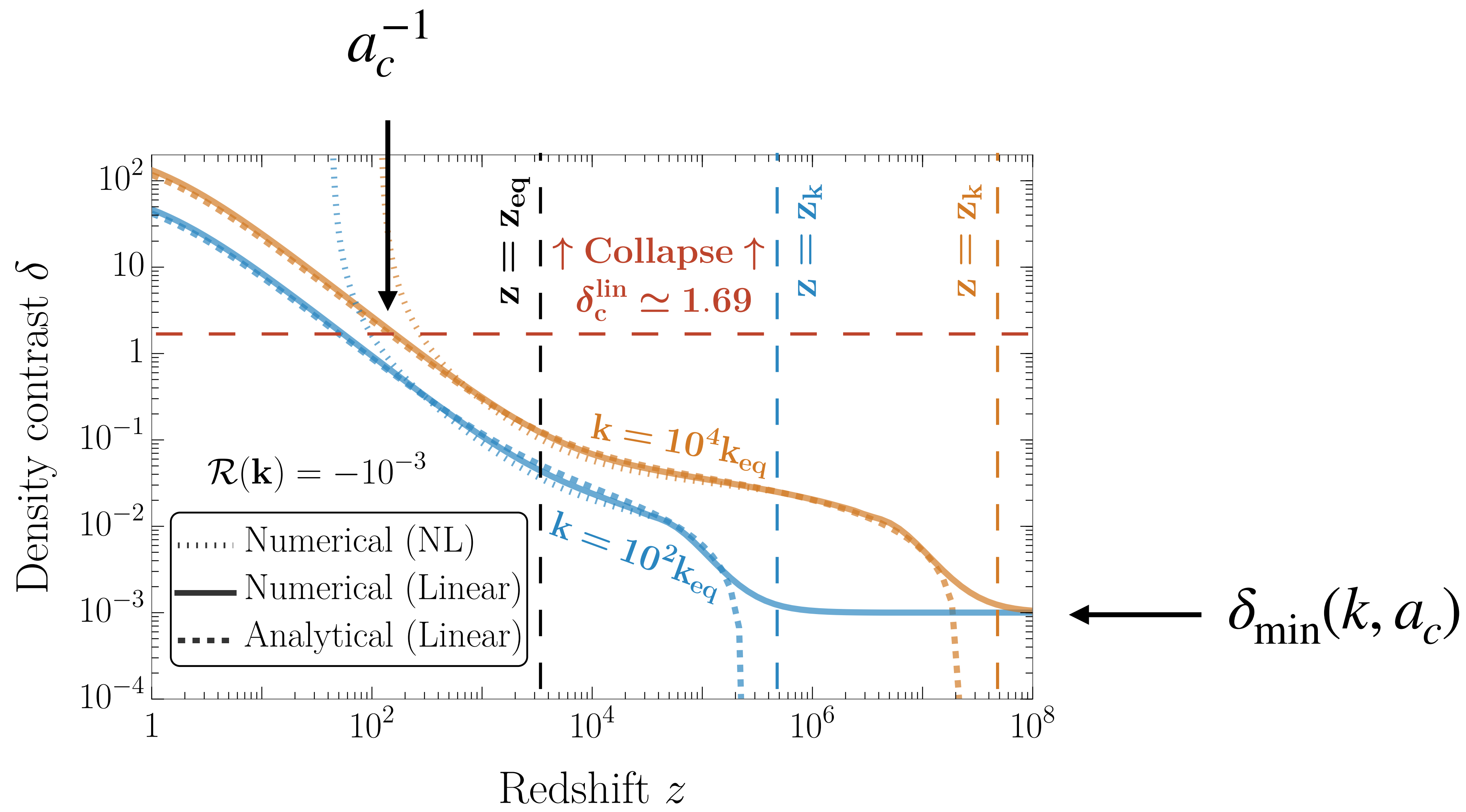


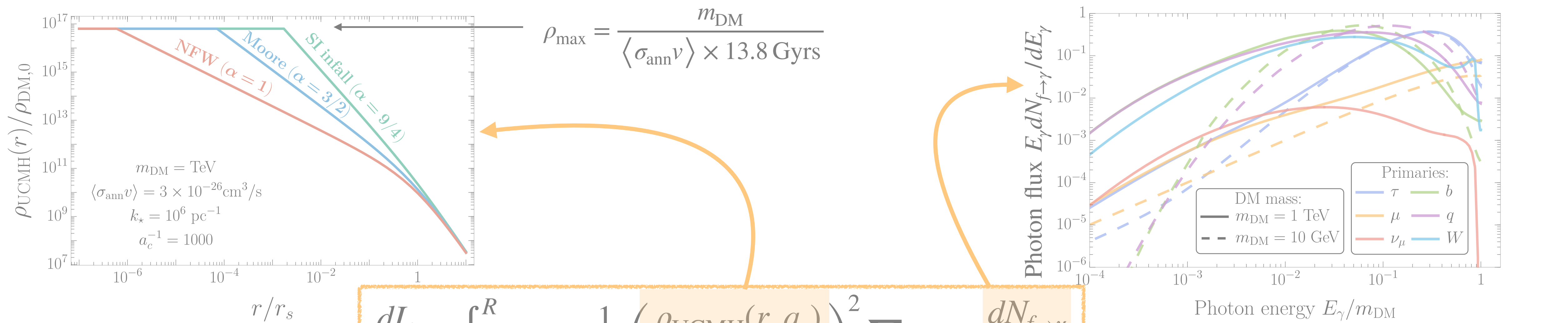
$$\frac{d^2 \mathcal{F}_{\gamma}(\theta)}{d\Omega dE} = \boxed{\int_0^{\infty} \frac{ds}{4\pi} \frac{\rho_{\text{DM}}(s, \theta)}{\bar{\rho}_{\text{DM},0}}} \times \boxed{\int_0^{\infty} da_c \int_0^{\infty} \frac{dR}{R} \frac{dn}{da_c}} \times \boxed{\frac{dL[(1+z_e)E, a_c, R]}{dE}}$$

Press – Schechter theory

$$\frac{dn(R, a_c)}{da_c} \simeq R^{-3} \sqrt{\frac{2}{\pi}} \frac{\nu_c}{a_c} \exp\left(-\frac{\nu_c^2}{2}\right) \quad \nu_c \equiv \frac{\delta_{\text{min}}(a_c)}{\sigma_0(R)} \quad \delta_{\text{min}} \simeq 10^{-4} \frac{a_c^{-1}}{100}$$

$$\rho_{\text{DM}}(s, \theta) = \rho_{\text{MW}} \left[\sqrt{s^2 + r_{\odot}^2 - 2r_{\odot}s \cos \theta} \right] + \frac{e^{-\tau(E, z_e)}}{(1+z_e)^3} \bar{\rho}_{\text{DM},0}$$





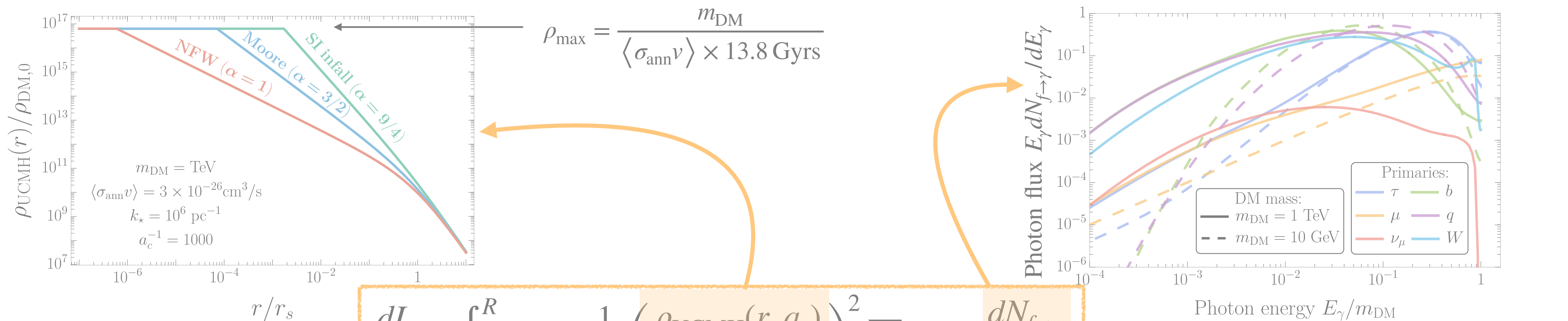
$$\frac{d^2 \mathcal{F}_{\gamma}(\theta)}{d\Omega dE} = \int_0^{\infty} \frac{ds}{4\pi} \frac{\rho_{\text{DM}}(s, \theta)}{\bar{\rho}_{\text{DM},0}} \times \int_0^{\infty} da_c \int_0^{\infty} \frac{dR}{R} \frac{dn}{da_c} \times \frac{dL[(1+z_e)E, a_c, R]}{dE}$$

Press – Schechter theory

$$\frac{dn(R, a_c)}{da_c} \simeq R^{-3} \sqrt{\frac{2}{\pi}} \frac{\nu_c}{a_c} \exp\left(-\frac{\nu_c^2}{2}\right) \quad \nu_c \equiv \frac{\delta_{\text{min}}(a_c)}{\sigma_0(R)} \quad \delta_{\text{min}} \simeq 10^{-4} \frac{a_c^{-1}}{100}$$

$$\sigma_0^2(R) = \frac{16}{81} \int_0^{\infty} \frac{dk}{k} \tilde{W}(k, R)^2 (kR)^4 T(k, R)^2 \mathcal{P}_{\mathcal{R}}(k, t_H)$$

$$\rho_{\text{DM}}(s, \theta) = \rho_{\text{MW}} \left[\sqrt{s^2 + r_{\odot}^2 - 2r_{\odot}s \cos \theta} \right] + \frac{e^{-\tau(E, z_e)}}{(1+z_e)^3} \bar{\rho}_{\text{DM},0}$$



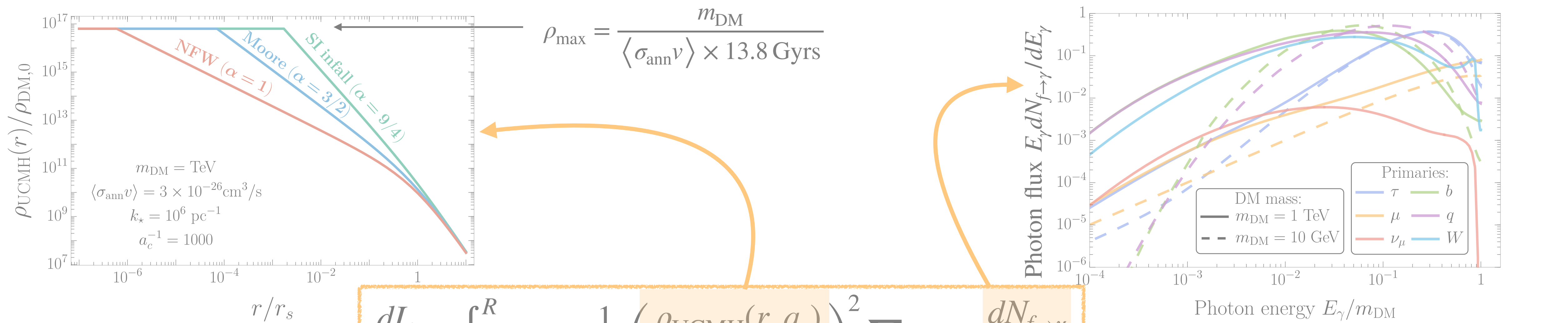
$$\frac{d^2 \mathcal{F}_{\gamma}(\theta)}{d\Omega dE} = \int_0^{\infty} \frac{ds}{4\pi} \frac{\rho_{\text{DM}}(s, \theta)}{\bar{\rho}_{\text{DM},0}} \times \int_0^{\infty} da_c \int_0^{\infty} \frac{dR}{R} \frac{dn}{da_c} \times \frac{dL[(1+z_e)E, a_c, R]}{dE}$$

Press – Schechter theory

$$\frac{dn(R, a_c)}{da_c} \simeq R^{-3} \sqrt{\frac{2}{\pi}} \frac{\nu_c}{a_c} \exp\left(-\frac{\nu_c^2}{2}\right) \quad \nu_c \equiv \frac{\delta_{\text{min}}(a_c)}{\sigma_0(R)} \quad \delta_{\text{min}} \simeq 10^{-4} \frac{a_c^{-1}}{100}$$

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$$\frac{d^2 \mathcal{F}_{\gamma}(\theta)}{d\Omega dE} = \boxed{\int_0^{\infty} \frac{ds}{4\pi} \frac{\rho_{\text{DM}}(s, \theta)}{\bar{\rho}_{\text{DM},0}}} \times \boxed{\int_0^{\infty} da_c \int_0^{\infty} \frac{dR}{R} \frac{dn}{da_c}} \times \boxed{\frac{dL[(1+z_e)E, a_c, R]}{dE}}$$

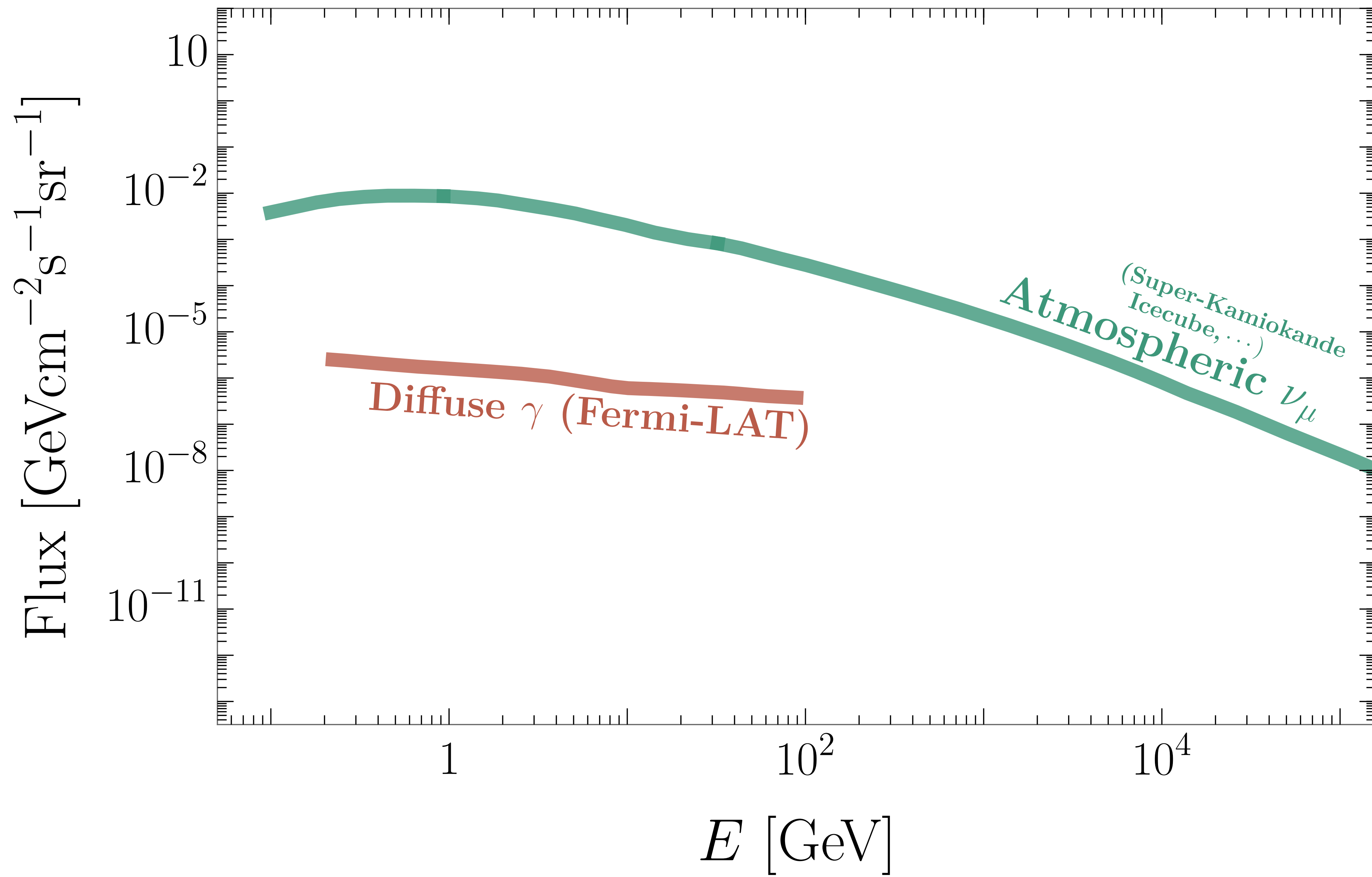
Press – Schechter theory

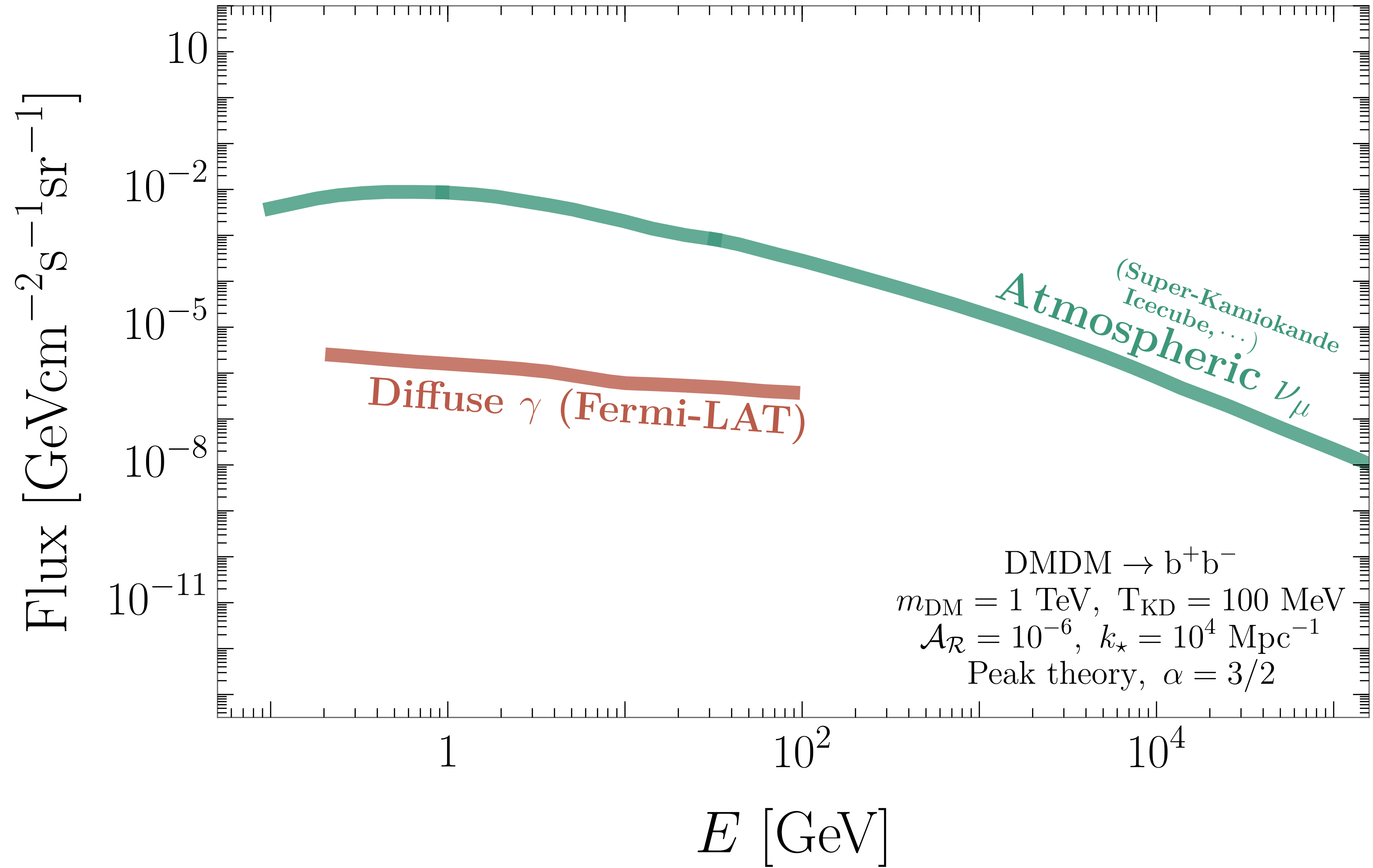
$$\frac{dn(R, a_c)}{da_c} \simeq R^{-3} \sqrt{\frac{2}{\pi}} \frac{\nu_c}{a_c} \exp\left(-\frac{\nu_c^2}{2}\right) \quad \nu_c \equiv \frac{\delta_{\min}(a_c)}{\sigma_0(R)} \quad \delta_{\min} \simeq 10^{-4} \frac{a_c^{-1}}{100}$$

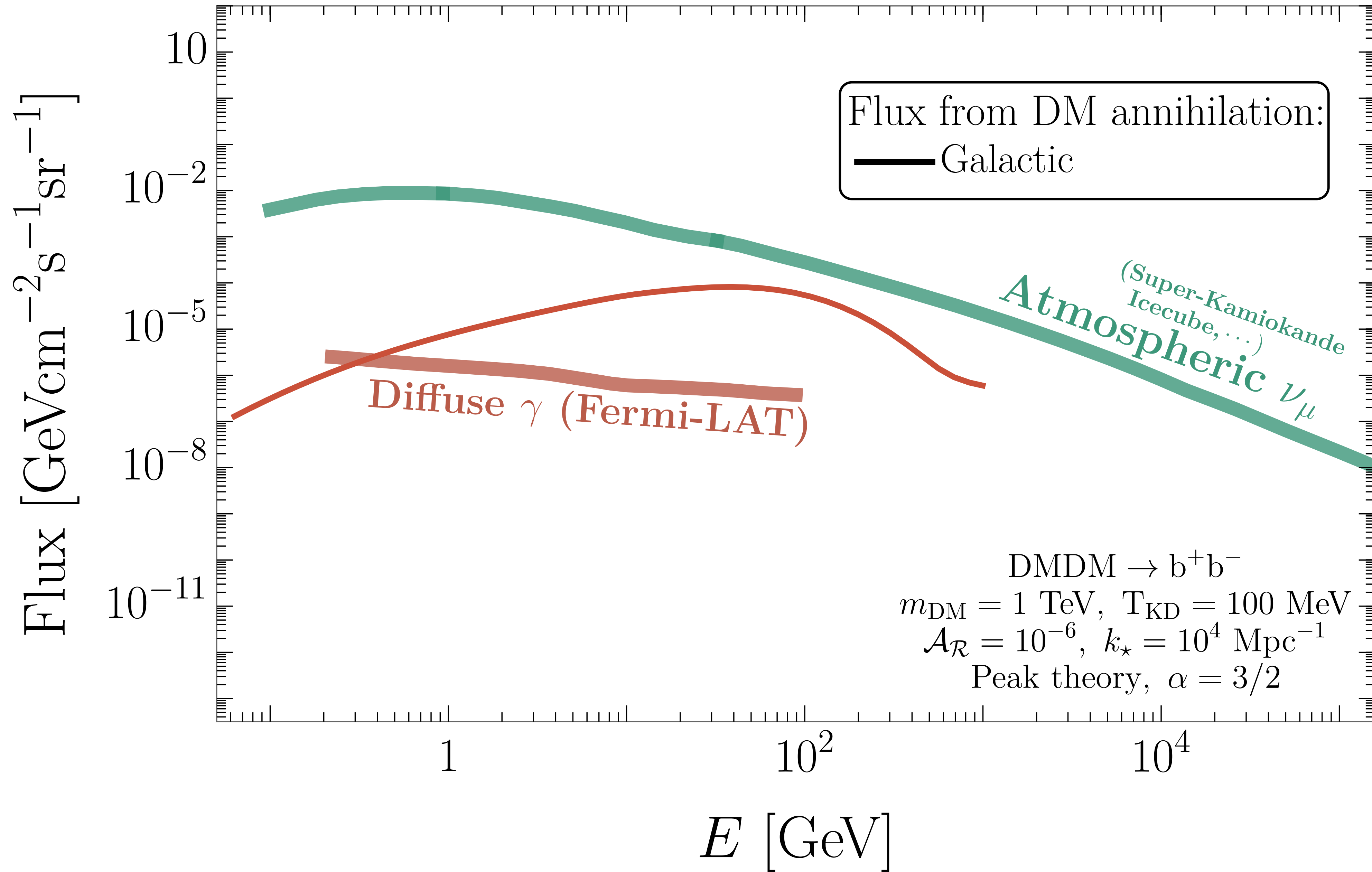
$$\sigma_0^2(R) = \frac{16}{81} \int_0^{\infty} \frac{dk}{k} \tilde{W}(k, R)^2 (kR)^4 T(k, R)^2 \mathcal{P}_{\mathcal{R}}(k, t_H)$$

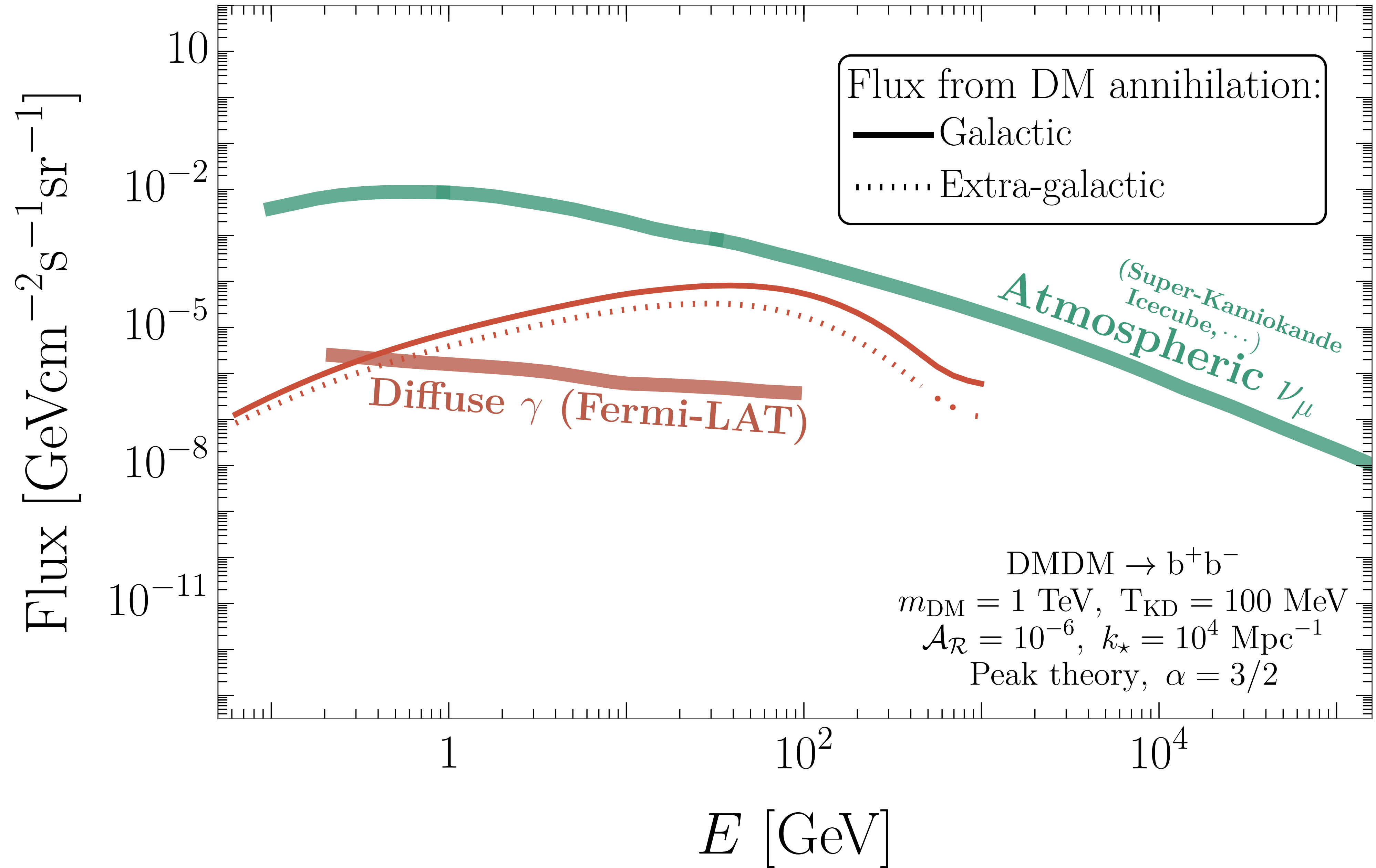
$$T(k, R) \rightarrow T(k, R) \times \exp\left[-\frac{1}{2} \left(\frac{k}{k_D}\right)^2\right] \quad k_D \simeq \frac{1.7 \times 10^8}{\text{Mpc}} \left(\frac{m_{\text{DM}}}{1 \text{ TeV}}\right)^{1/2} \left(\frac{T_{\text{KD}}}{30 \text{ MeV}}\right)^{1/2}$$

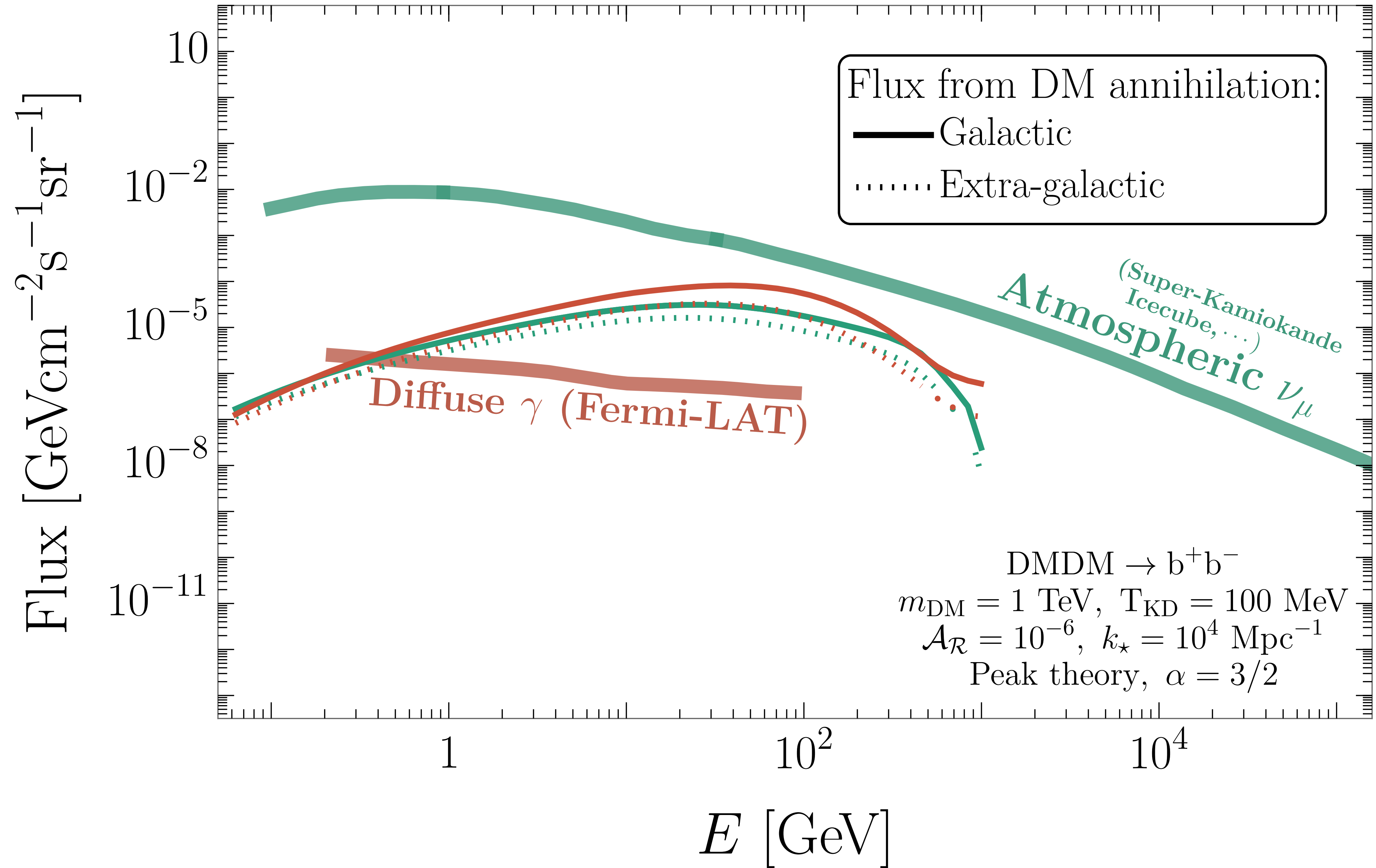
$$\rho_{\text{DM}}(s, \theta) = \rho_{\text{MW}} \left[\sqrt{s^2 + r_{\odot}^2 - 2r_{\odot}s \cos \theta} \right] + \frac{e^{-\tau(E, z_e)}}{(1+z_e)^3} \bar{\rho}_{\text{DM},0}$$







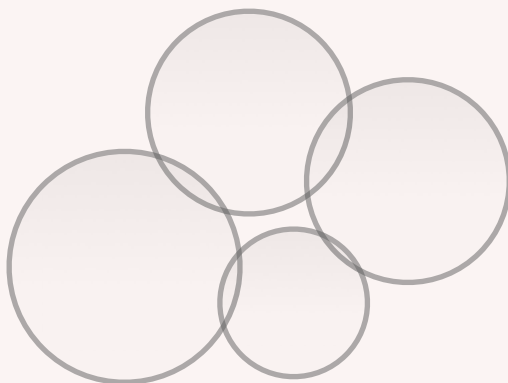




YG 2503.03857

**“New Physics Explanations of PTA
signal are incompatible with WIMPs
Dark Matter”**

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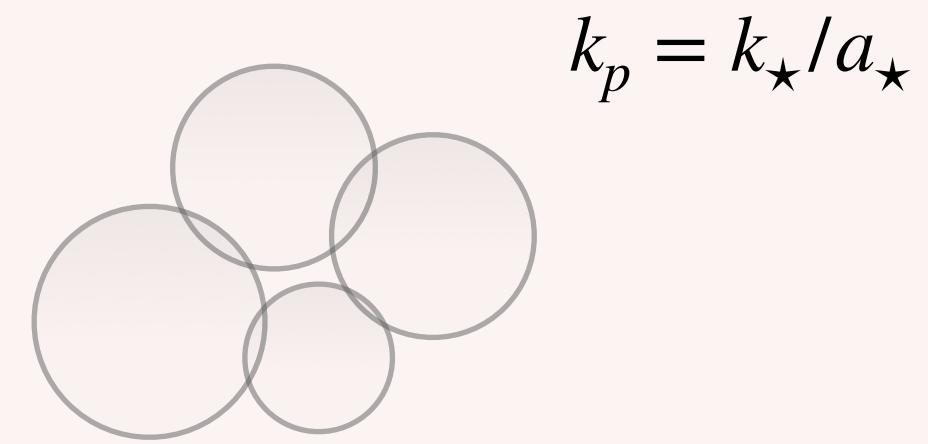


First-order Phase Transition

$$\mathcal{P}_{\mathcal{R}}(k) = \left(\frac{\alpha_{\star}}{1 + \alpha_{\star}}\right)^2 \left(\frac{H_{\star}}{\beta}\right)^2 \frac{a_1(k_p/\beta)^3}{\left(a_2 + (k_p/\beta)^2\right)^3}$$

Franciolini, YG, Jinno
2503.01962

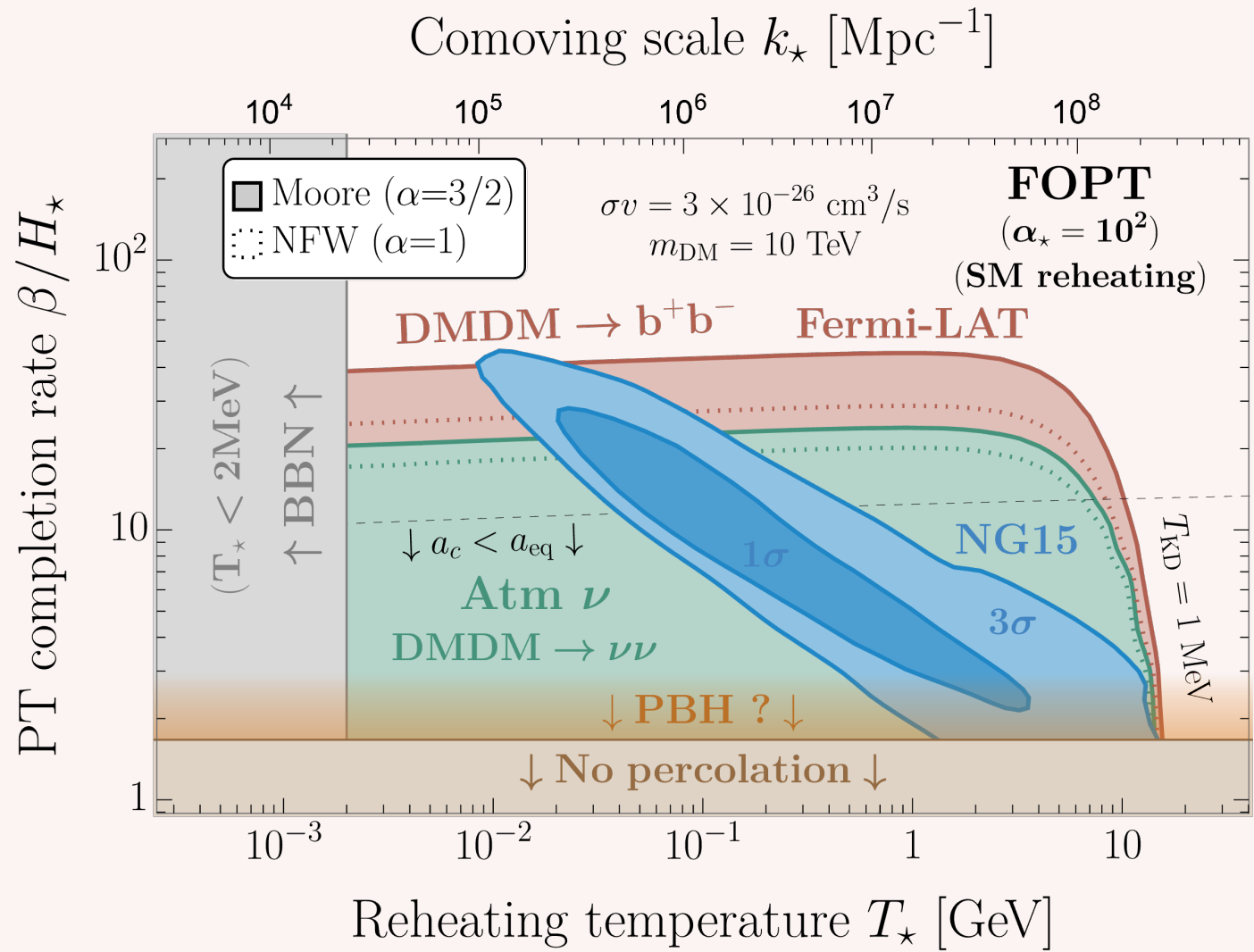
Elor, Jinno, Kumar,
McGehee, Tsai,
2311.16222 (PRL)



YG 2503.03857

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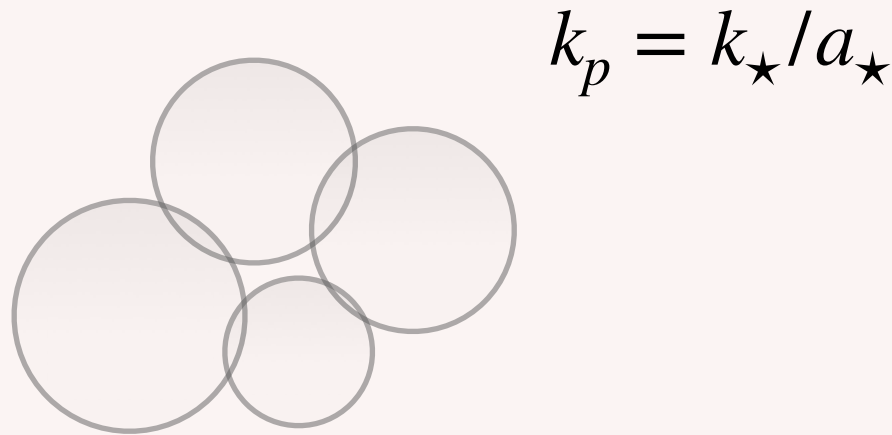
First-order Phase Transition



Franciolini, YG, Jinno
2503.01962

Elor, Jinno, Kumar,
McGehee, Tsai,
2311.16222 (PRL)

$$\mathcal{P}_{\mathcal{R}}(k) = \left(\frac{\alpha_\star}{1 + \alpha_\star}\right)^2 \left(\frac{H_\star}{\beta}\right)^2 \frac{a_1(k_p/\beta)^3}{\left(a_2 + (k_p/\beta)^2\right)^3}$$

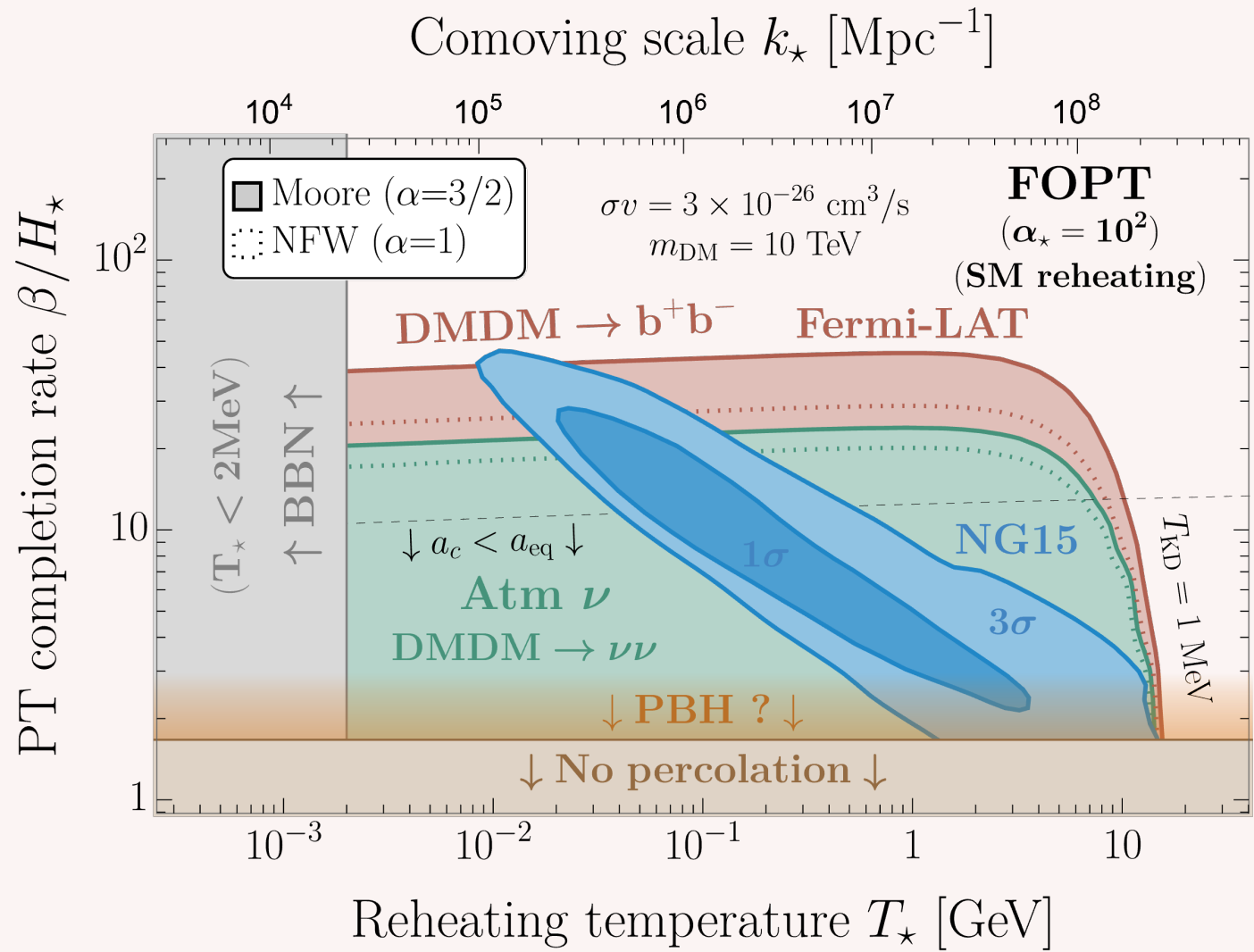


$$k_p = k_\star/a_\star$$

YG 2503.03857

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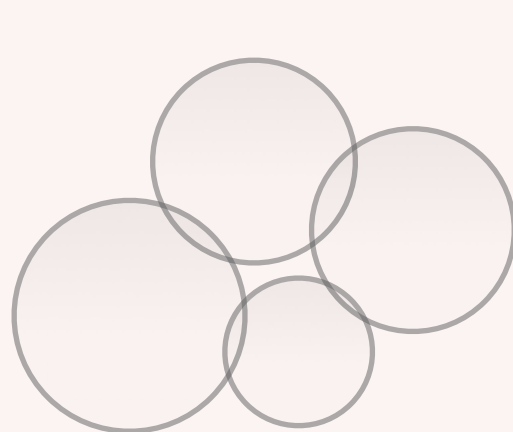
First-order Phase Transition



$$\mathcal{P}_{\mathcal{R}}(k) = \left(\frac{\alpha_{\star}}{1 + \alpha_{\star}}\right)^2 \left(\frac{H_{\star}}{\beta}\right)^2 \frac{a_1(k_p/\beta)^3}{\left(a_2 + (k_p/\beta)^2\right)^3}$$

Franciolini, YG, Jinno
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2311.16222 (PRL)



$$k_p = k_{\star}/a_{\star}$$

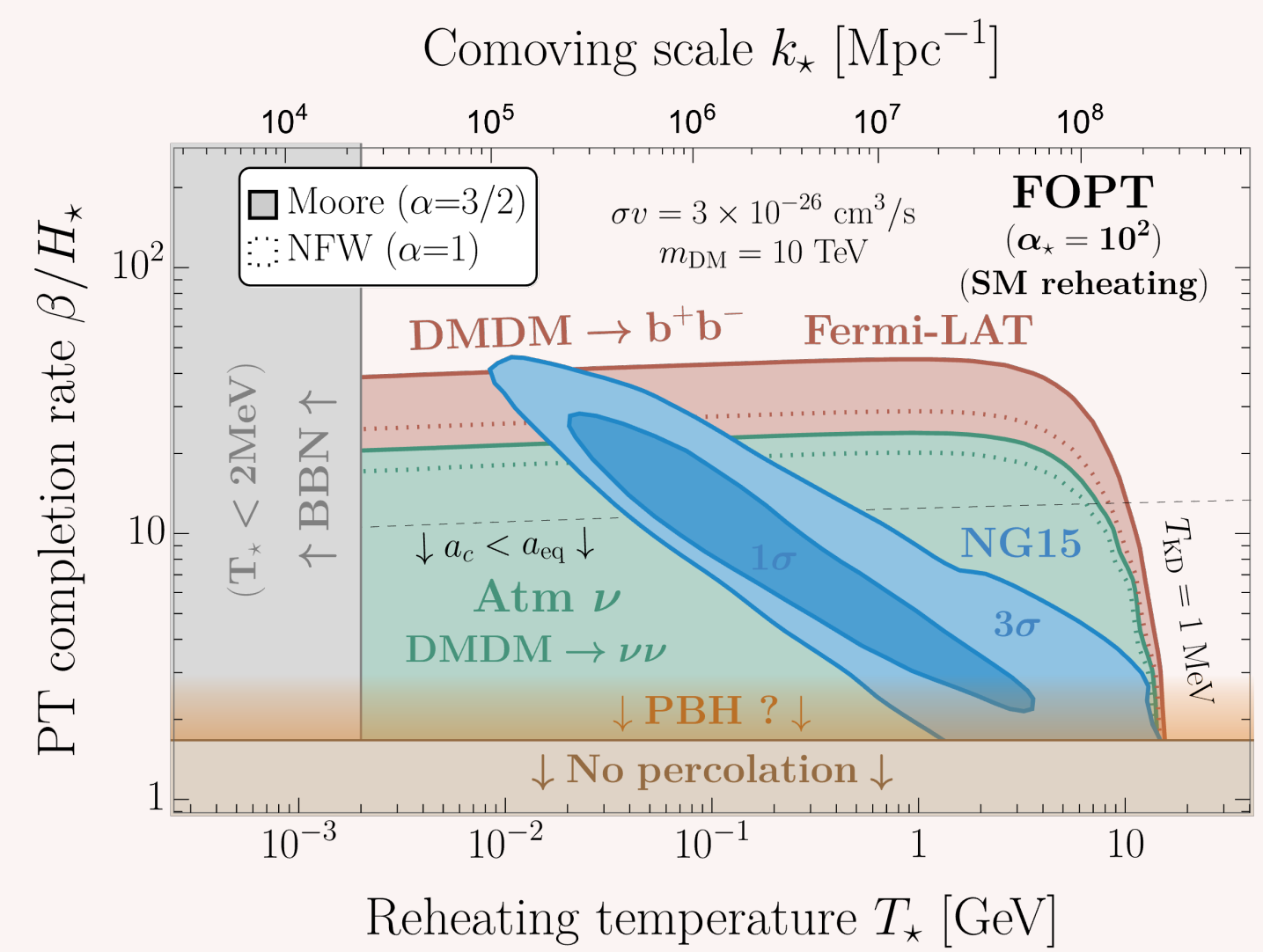
“New Physics Explanations of PTA
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Dark Matter”

Gaussian curvature peaks

$$\mathcal{P}_{\mathcal{R}}(k) = \frac{\mathcal{A}_{\mathcal{R}}}{\sqrt{2\pi}\Delta} \exp\left[-\frac{\log^2(k/k_{\star})}{2\Delta^2}\right]$$



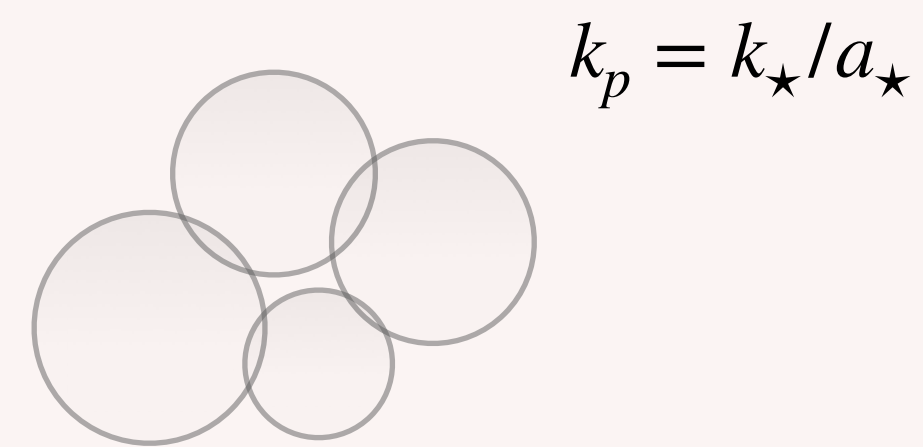
First-order Phase Transition



$$\mathcal{P}_{\mathcal{R}}(k) = \left(\frac{\alpha_{\star}}{1 + \alpha_{\star}} \right)^2 \left(\frac{H_{\star}}{\beta} \right)^2 \frac{a_1 (k_p / \beta)^3}{\left(a_2 + (k_p / \beta)^2 \right)^3}$$

Franciolini, YG, Jinno
2503.01962

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2311.16222 (PRL)

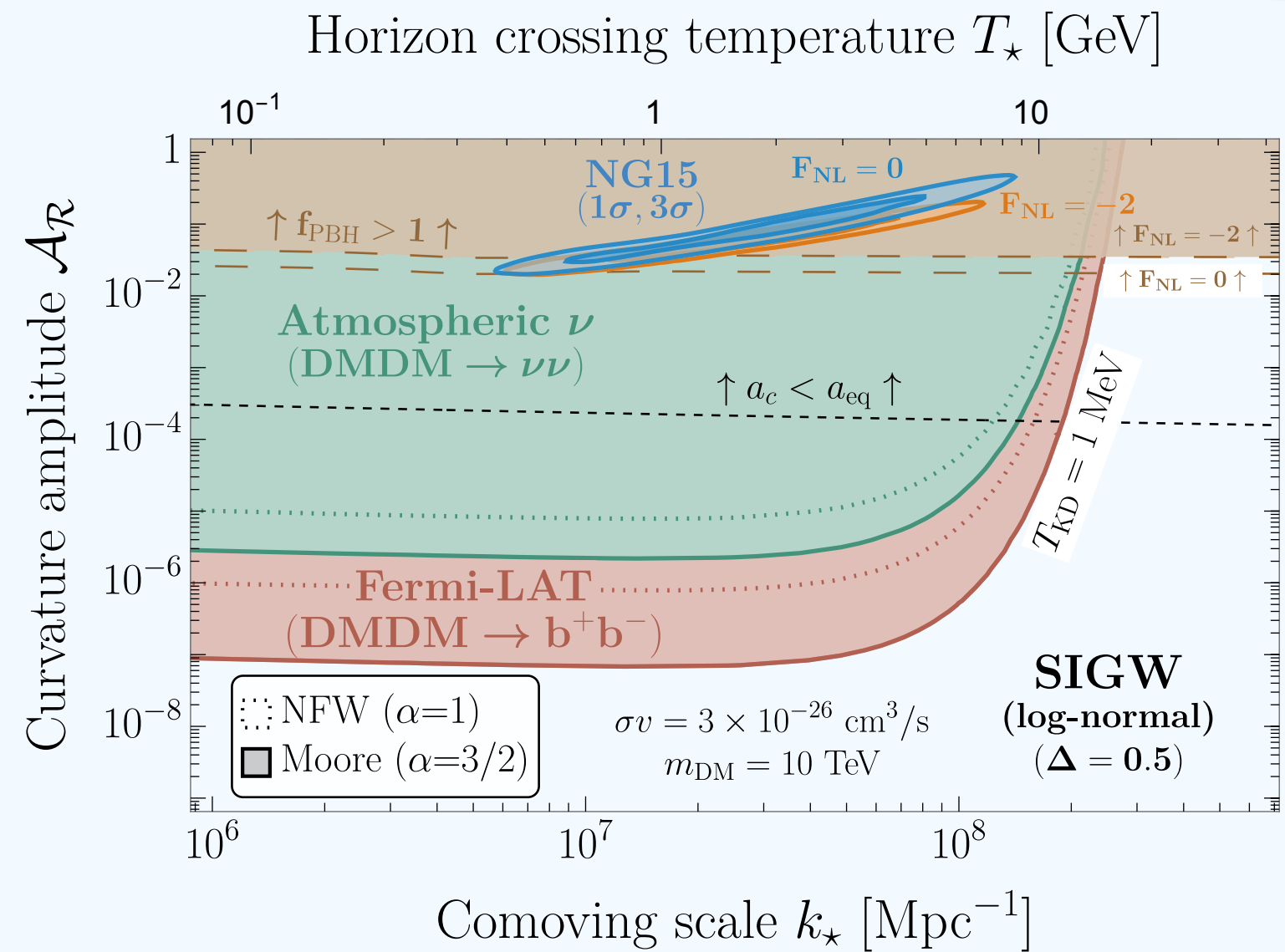


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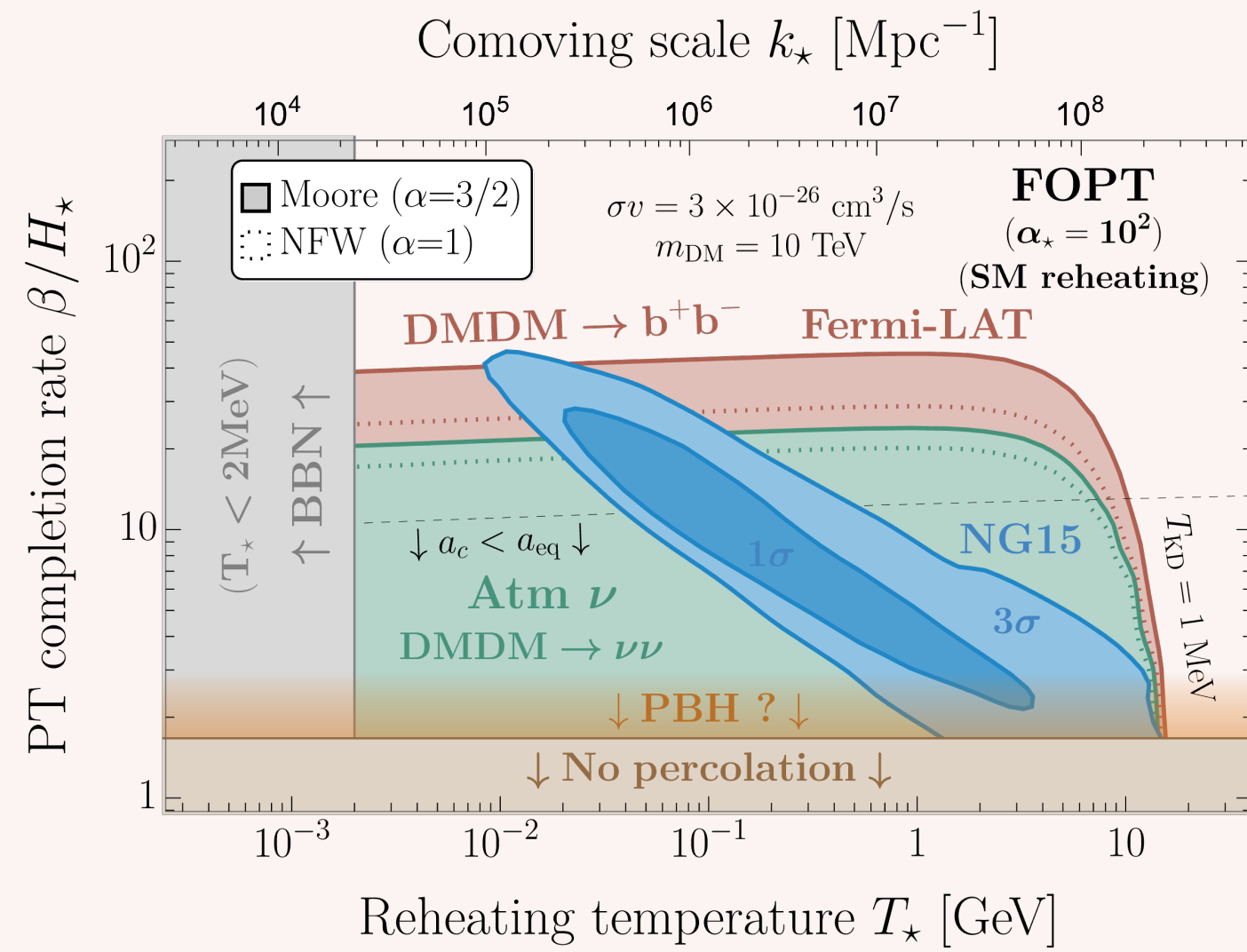
Gaussian curvature peaks

$$\mathcal{P}_{\mathcal{R}}(k) = \frac{\mathcal{A}_{\mathcal{R}}}{\sqrt{2\pi}\Delta} \exp \left[-\frac{\log^2(k/k_{\star})}{2\Delta^2} \right]$$



See also Nakama,
Suyama, Kohri,
Hiroshima (1712.08820)

First-order Phase Transition

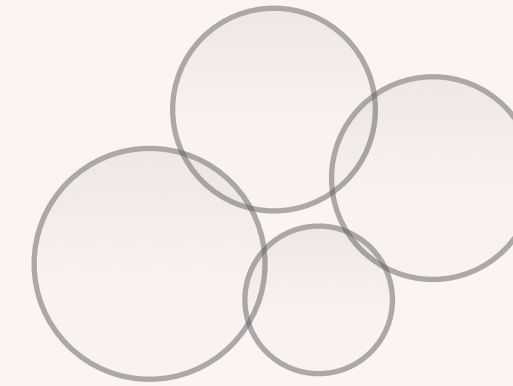


$$\mathcal{P}_{\mathcal{R}}(k) = \left(\frac{\alpha_{\star}}{1 + \alpha_{\star}} \right)^2 \left(\frac{H_{\star}}{\beta} \right)^2 \frac{a_1(k_p/\beta)^3}{\left(a_2 + (k_p/\beta)^2 \right)^3}$$

Franciolini, YG, Jinno
2503.01962

Elor, Jinno, Kumar,
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2311.16222 (PRL)

$$k_p = k_\star/a_\star$$



“New Physics Explanations of PTA signal are incompatible with WIMPs Dark Matter”

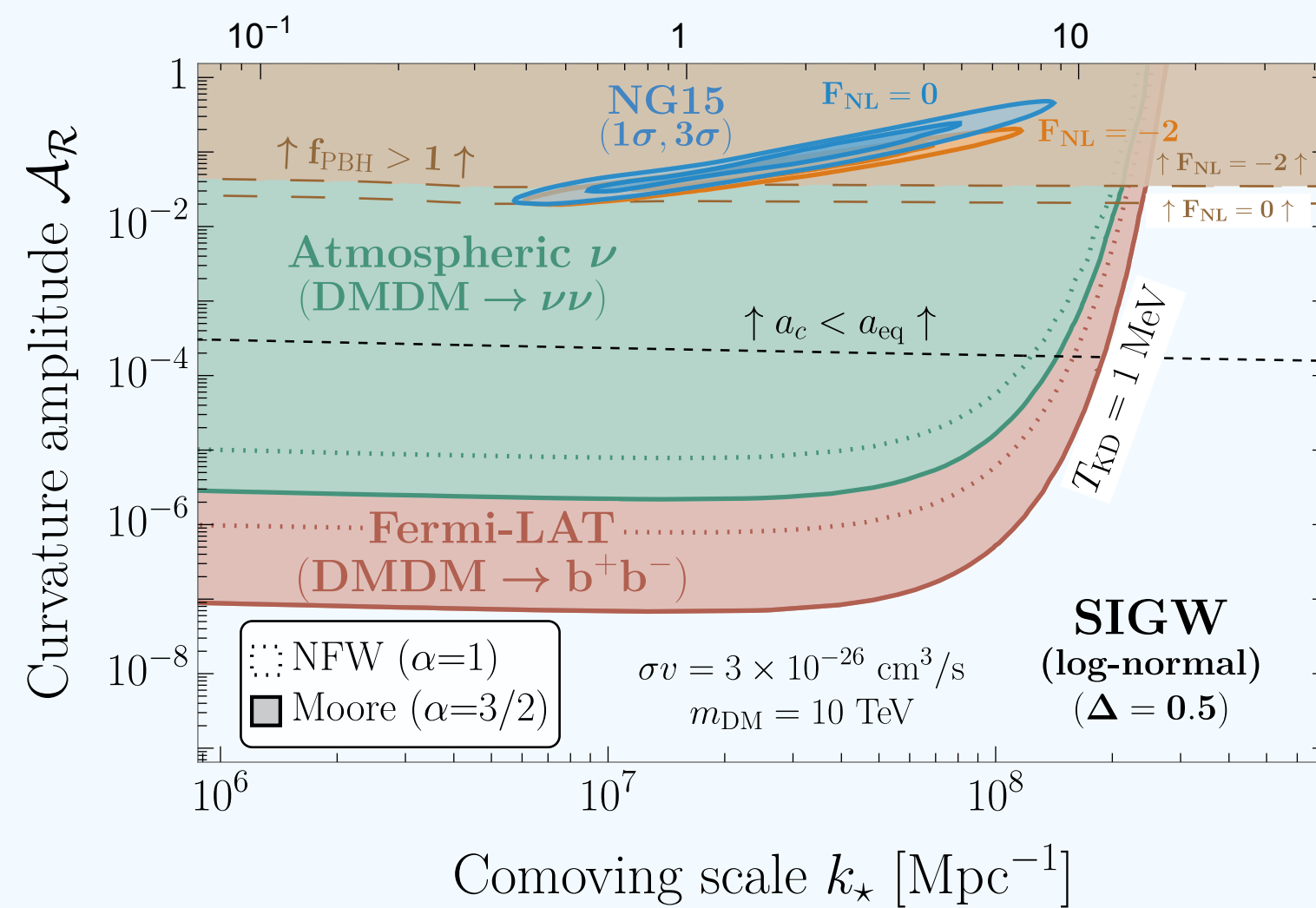
Domain Wall Networks

$$\mathcal{P}_{\mathcal{R}}(k) = \frac{\alpha_{\text{V}}^2}{2\pi} \frac{(k_p L_{\text{ann}})^3}{\left[4 + (k_p L_{\text{ann}})^2\right]^2}$$

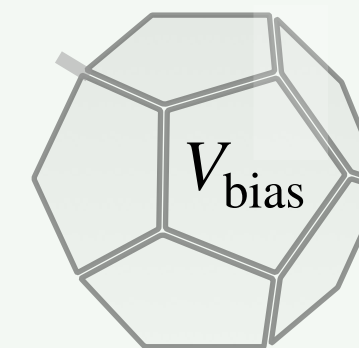
$$\alpha_V = V_{\text{bias}}/\rho_{\text{rad}} \Big|_{t=t_{\text{ann}}} \qquad L_{\text{ann}} \sim t_{\text{ann}}$$

Gaussian curvature peaks

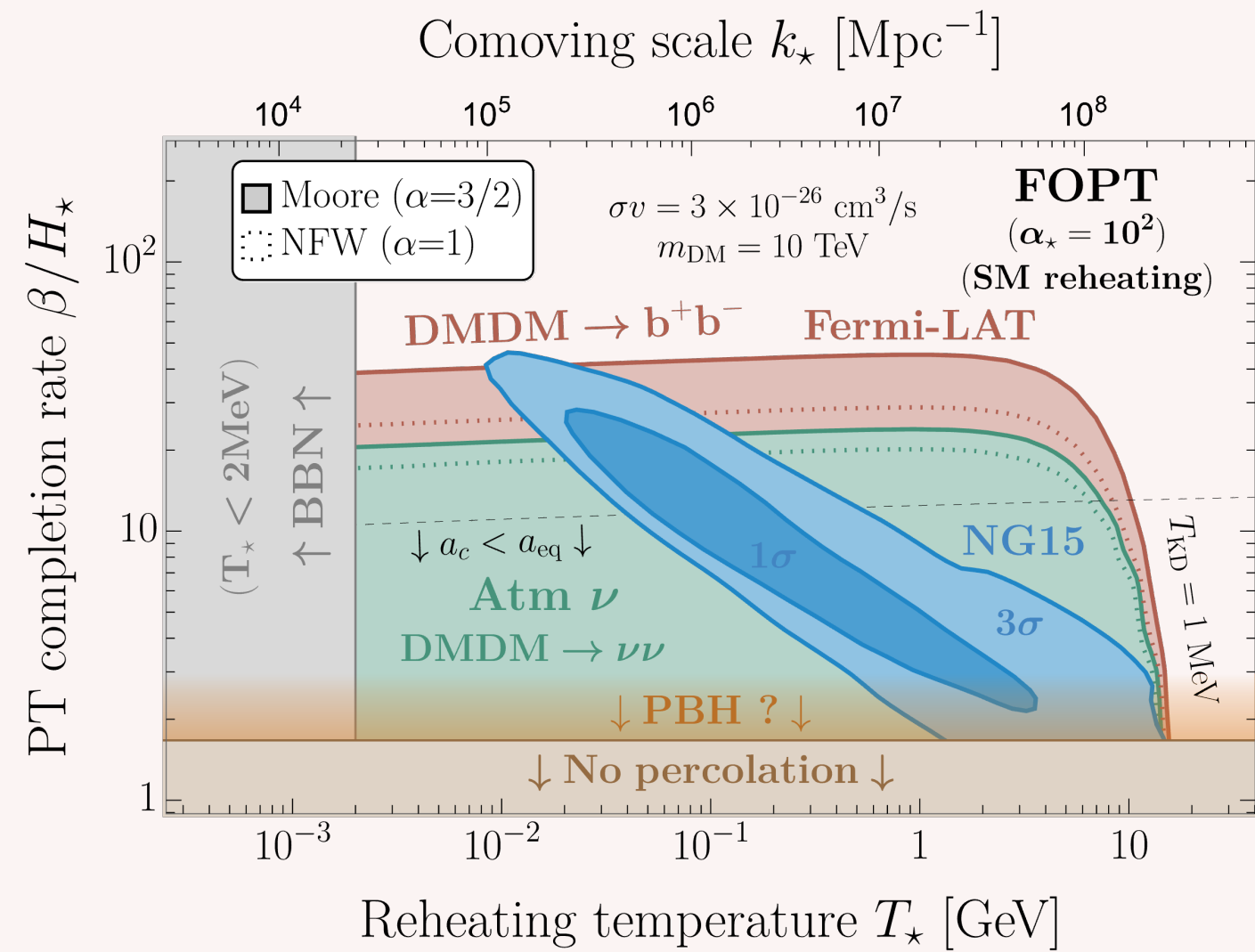
$$\mathcal{P}_{\mathcal{R}}(k) = \frac{\mathcal{A}_{\mathcal{R}}}{\sqrt{2\pi}\Delta} \exp\left[-\frac{\log^2(k/k_{\star})}{2\Delta^2}\right]$$

Horizon crossing temperature $T_\star$ [GeV]

**See also Nakama,
Suyama, Kohri,
Hiroshima (1712.08820)**



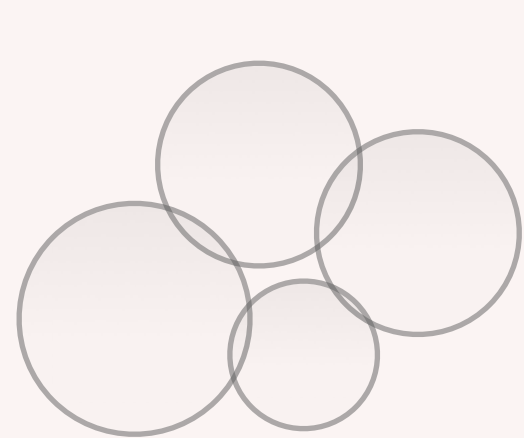
First-order Phase Transition



$$\mathcal{P}_{\mathcal{R}}(k) = \left(\frac{\alpha_\star}{1 + \alpha_\star}\right)^2 \left(\frac{H_\star}{\beta}\right)^2 \frac{a_1(k_p/\beta)^3}{\left(a_2 + (k_p/\beta)^2\right)^3}$$

Franciolini, YG, Jinno
2503.01962

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$$k_p = k_\star/a_\star$$

YG 2503.03857

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Domain Wall Networks

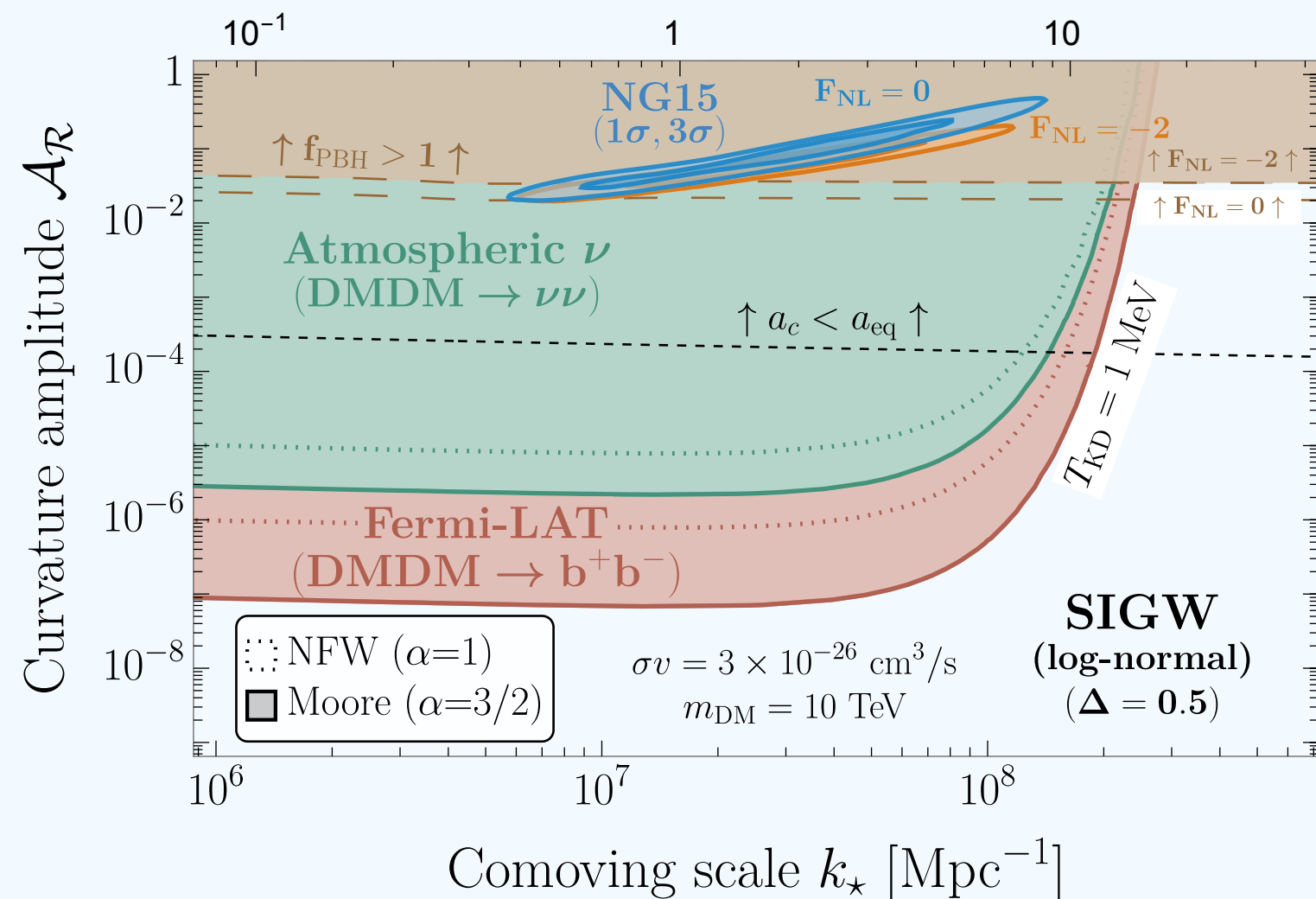
$$\mathcal{P}_{\mathcal{R}}(k) = \frac{\alpha_V^2}{2\pi} \frac{(k_p L_{\text{ann}})^3}{\left[4 + (k_p L_{\text{ann}})^2\right]^2}$$

$$\alpha_V = V_{\text{bias}}/\rho_{\text{rad}} \Big|_{t=t_{\text{ann}}} \quad L_{\text{ann}} \sim t_{\text{ann}}$$

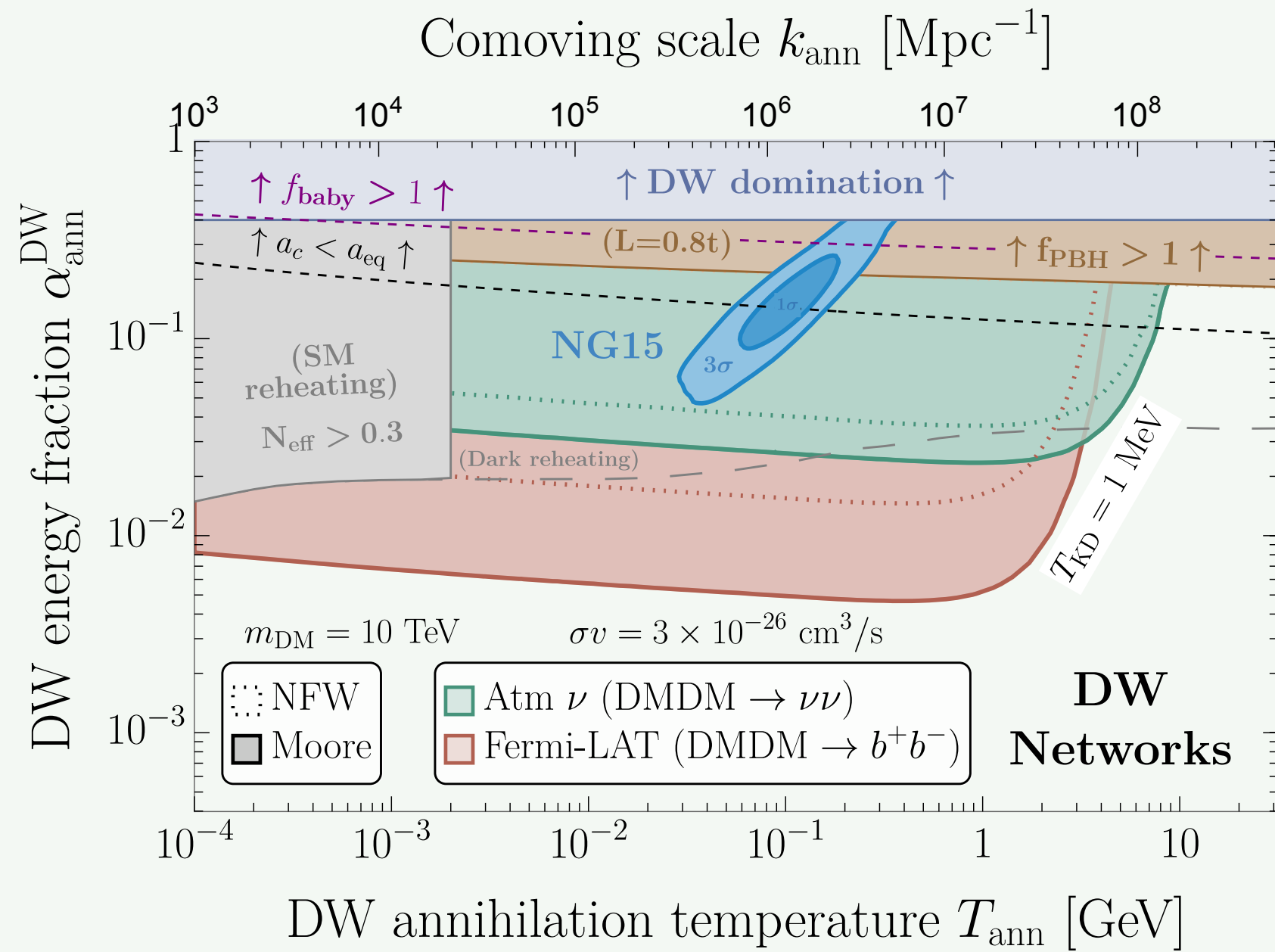
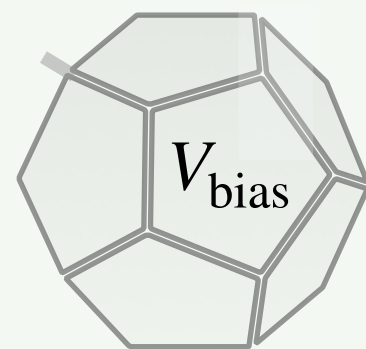
Gaussian curvature peaks

$$\mathcal{P}_{\mathcal{R}}(k) = \frac{\mathcal{A}_{\mathcal{R}}}{\sqrt{2\pi}\Delta} \exp\left[-\frac{\log^2(k/k_\star)}{2\Delta^2}\right]$$

Horizon crossing temperature $T_\star$ [GeV]

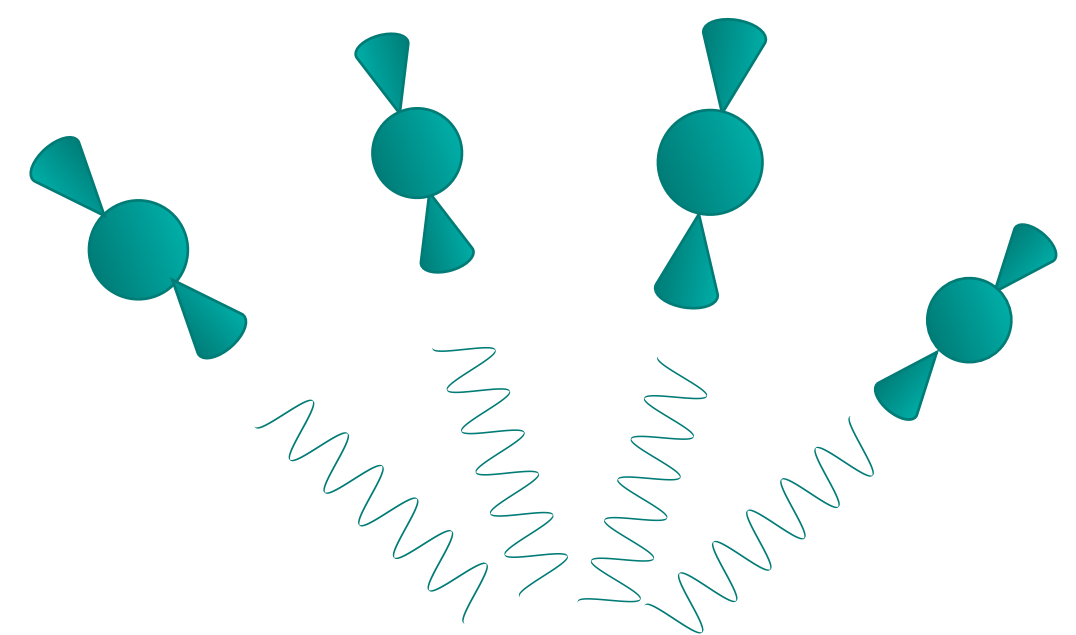


See also Nakama,
Suyama, Kohri,
Hiroshima (1712.08820)



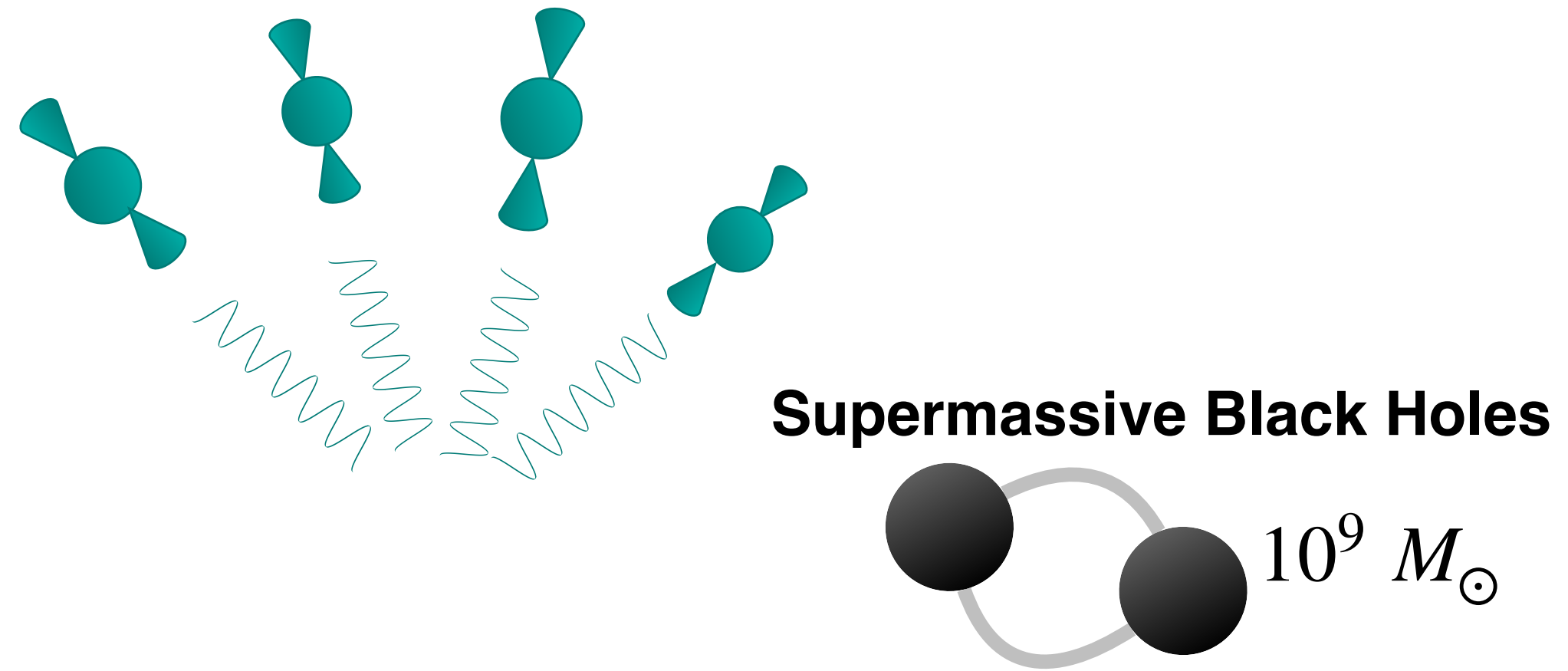
Conclusion

What is the PTA signal?



Conclusion

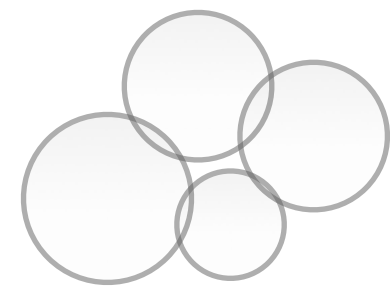
What is the PTA signal?



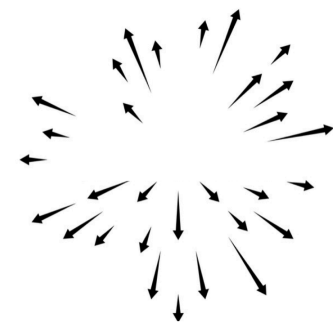
Conclusion

What is the PTA signal?

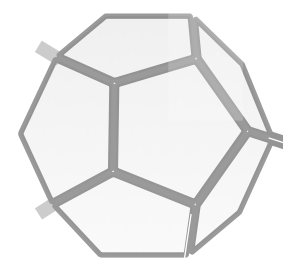
**First-order
Phase Transition**



Inflation



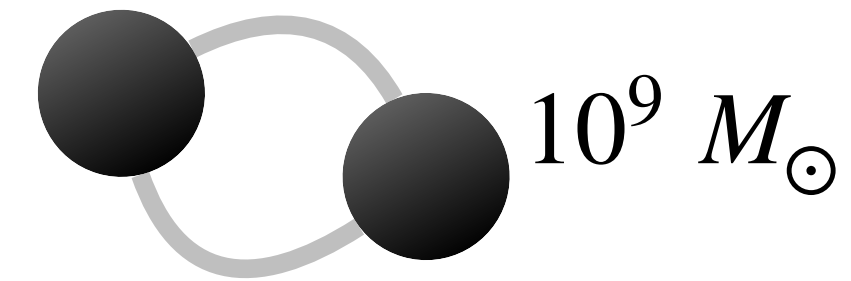
Domain walls



Cosmic strings



Supermassive Black Holes

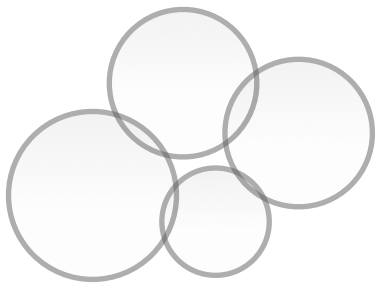


$10^9 M_{\odot}$

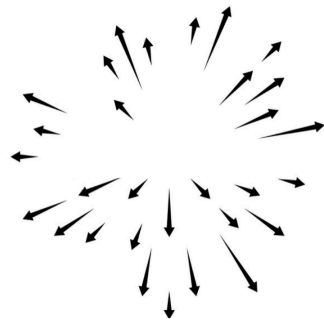
Conclusion

Search for new observables of
primordial sources of PTA signal

**First-order
Phase Transition**



Inflation



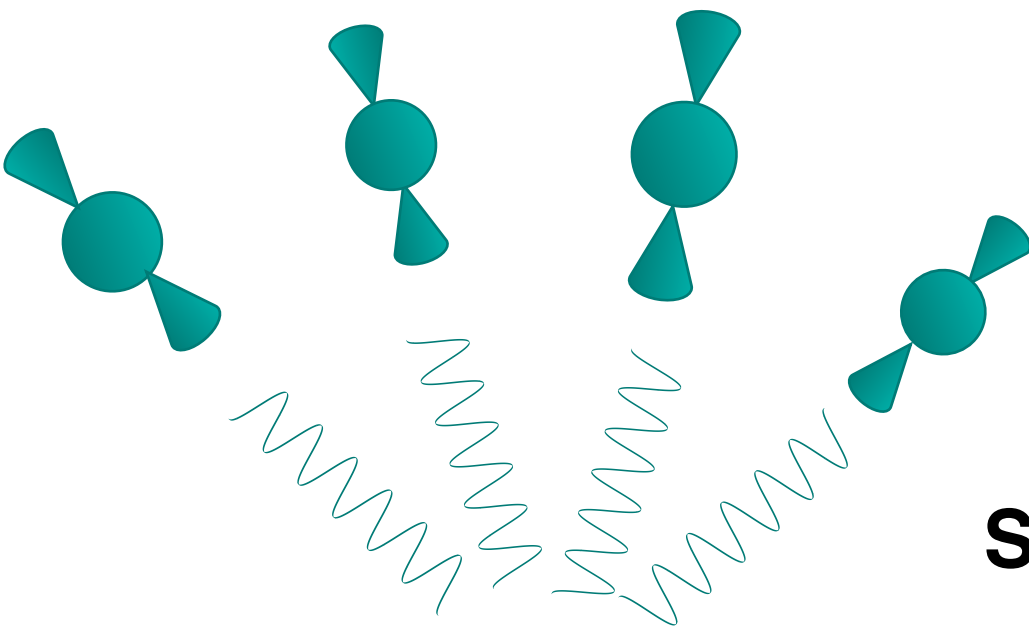
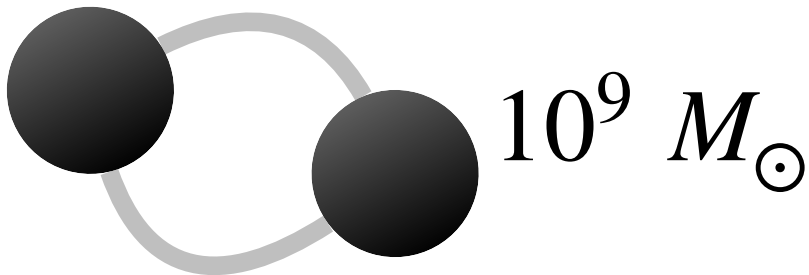
Domain walls



Cosmic strings

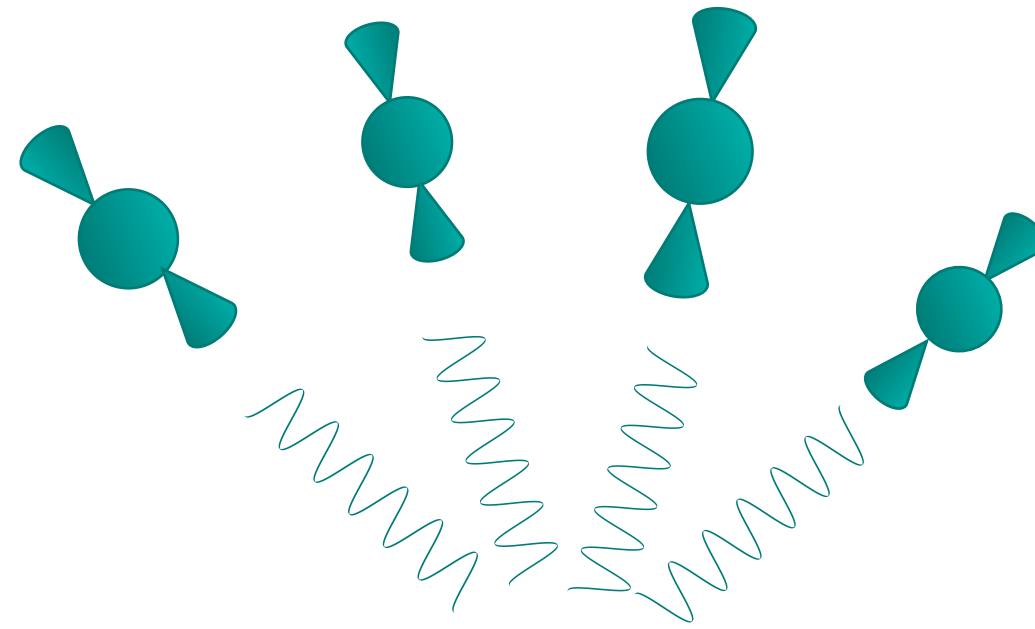


Supermassive Black Holes



Conclusion

Search for new observables of
primordial sources of PTA signal



Conclusion

Primordial Black Holes (PBHs)

Search for new observables of
primordial sources of PTA signal

Scalar curvature

Gravitational Waves (GWs)

“Space-time
perturbation Triangle”

Conclusion

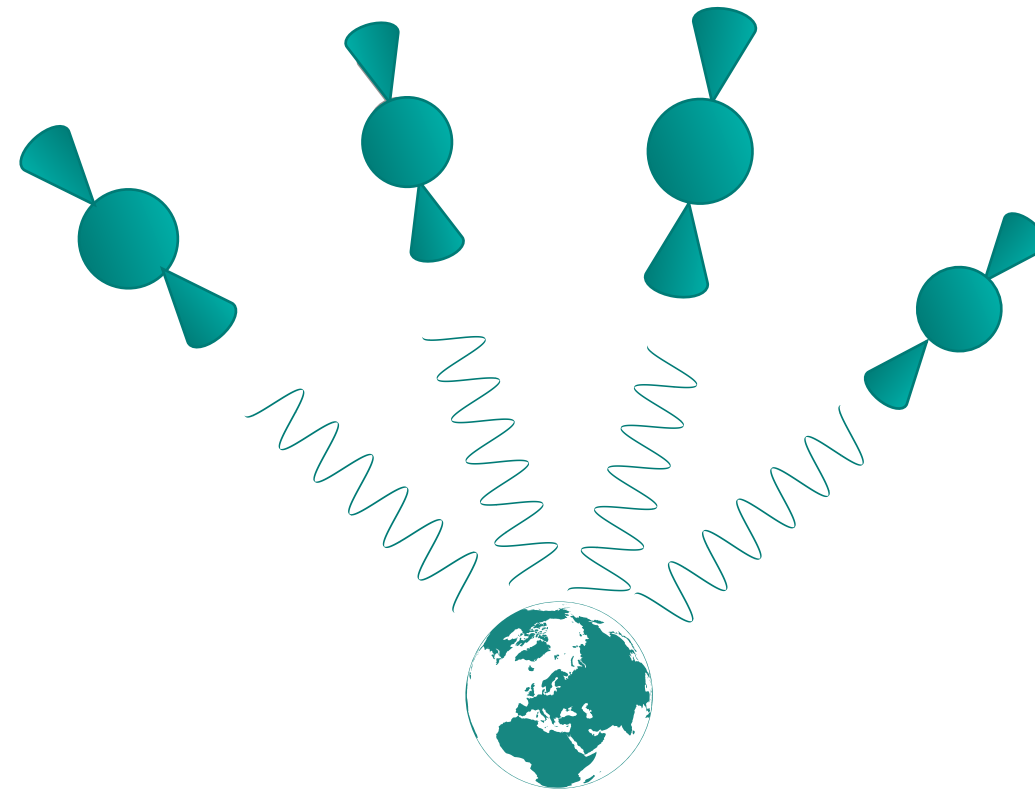
Primordial Black Holes (PBHs)

Motivate search in LIGO data

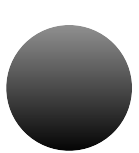
Search for new observables of
primordial sources of PTA signal

Scalar curvature

Gravitational Waves (GWs)



Conclusion

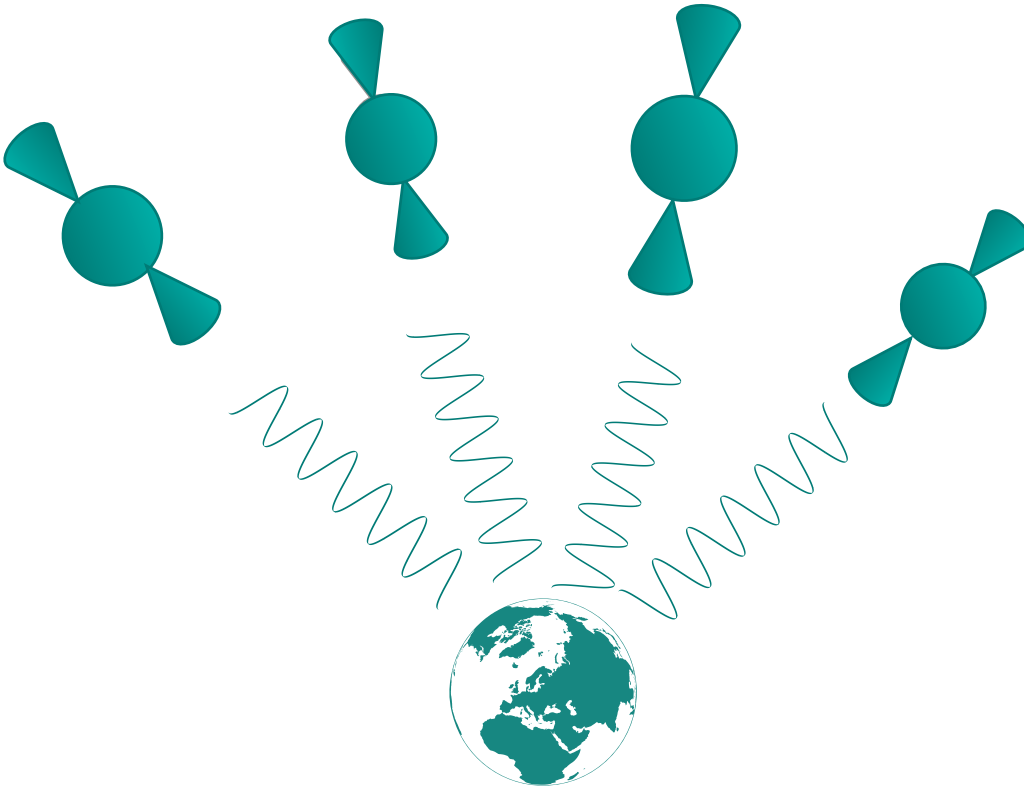


Primordial Black Holes (PBHs)

Search for new observables of
primordial sources of PTA signal

Motivate search in LIGO data
LIGO collab., “Sub-solar search”, PRL 2018
LIGO collab., “Sub-solar search”, PRL 2019
LIGO collab., “Sub-solar search”, PRL 2022

Scalar curvature



Gravitational Waves (GWs)

Conclusion



Primordial Black Holes (PBHs)

Search for new observables of
primordial sources of PTA signal

Motivate search in LIGO data

LIGO collab., “Sub-solar search”, PRL 2018

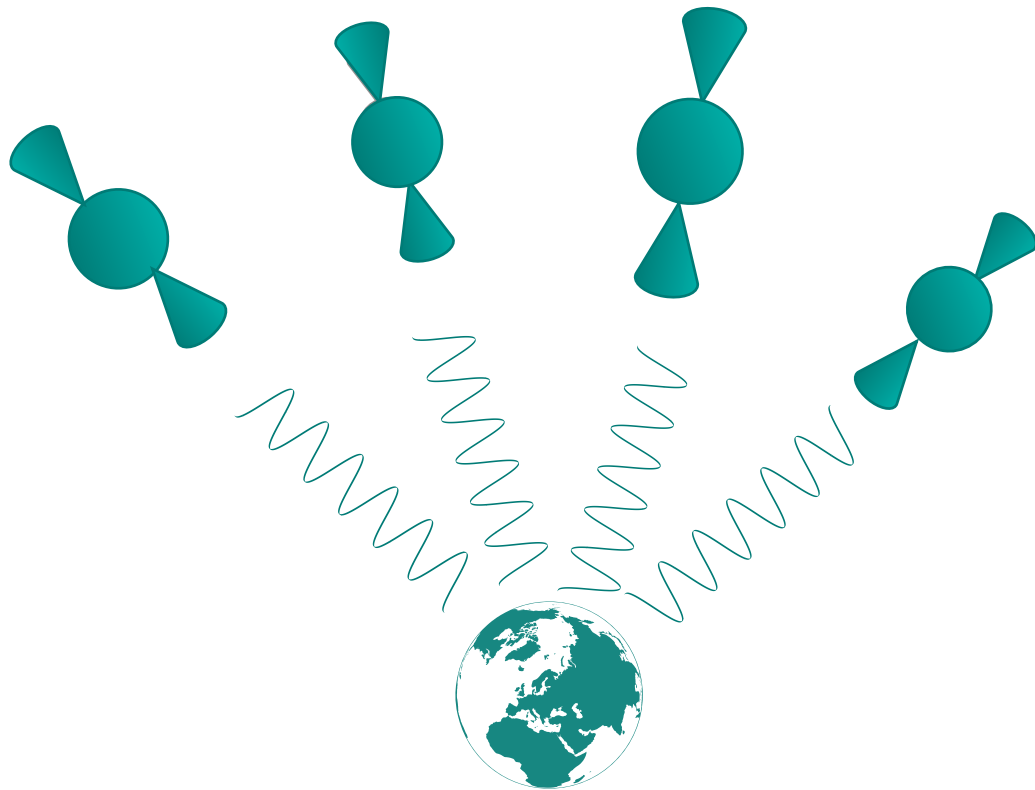
LIGO collab., “Sub-solar search”, PRL 2019

LIGO collab., “Sub-solar search”, PRL 2022

⇒ one sub-solar candidate at 3.7σ : $m = 0.27^{+0.12}_{-0.10}$


Scalar curvature

Gravitational Waves (GWs)



Conclusion



Primordial Black Holes (PBHs)

**Search for new observables of
primordial sources of PTA signal**

Motivate search in LIGO data

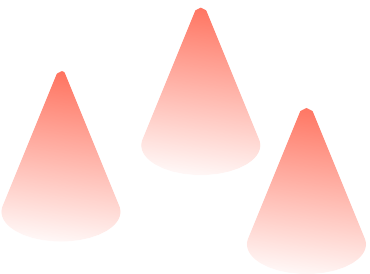
LIGO collab., “Sub-solar search”, PRL 2018

LIGO collab., “Sub-solar search”, PRL 2019

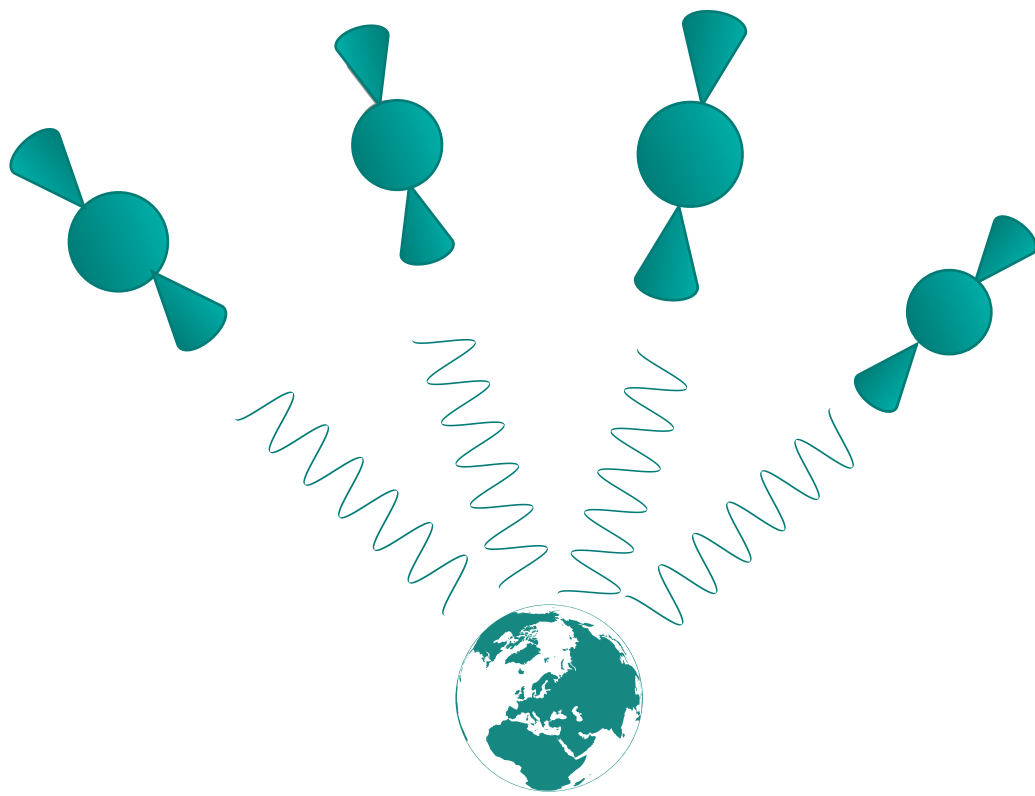
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⇒ one sub-solar candidate at 3.7σ : $m = 0.27^{+0.12}_{-0.10}$

Search in LIGO O4 on-going


Scalar curvature

Gravitational Waves (GWs)



Conclusion



Primordial Black Holes (PBHs)

Search for new observables of
primordial sources of PTA signal

Motivate search in LIGO data

LIGO collab., “Sub-solar search”, PRL 2018

LIGO collab., “Sub-solar search”, PRL 2019

LIGO collab., “Sub-solar search”, PRL 2022

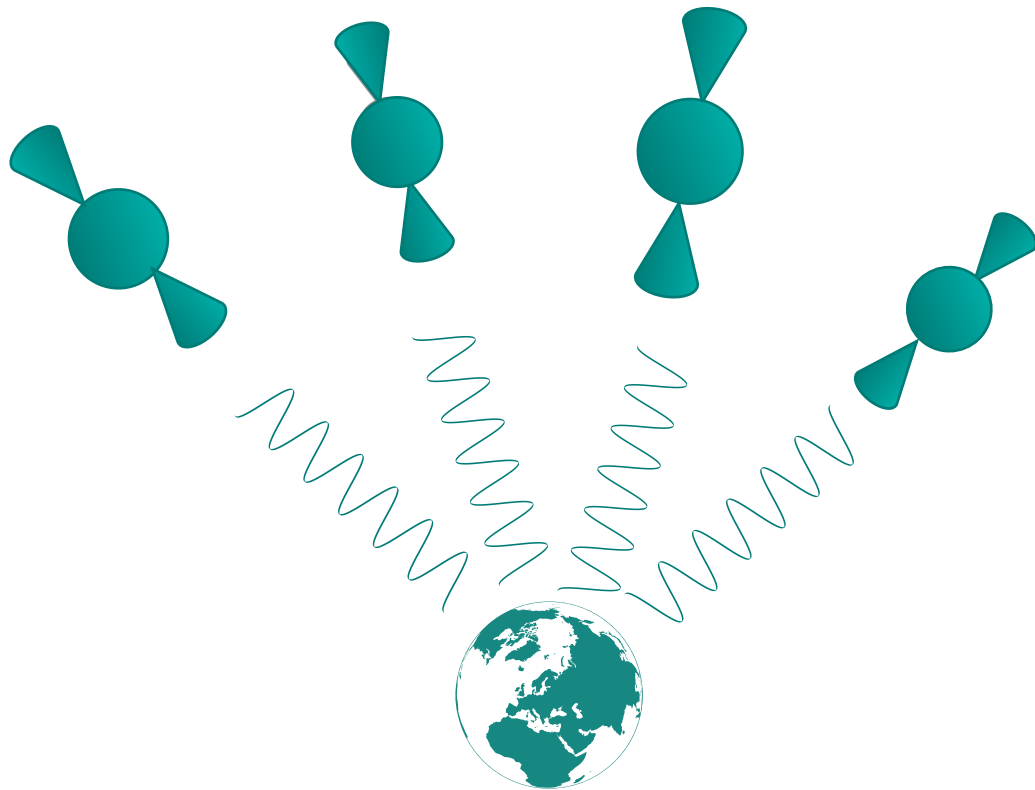
⇒ one sub-solar candidate at 3.7σ : $m = 0.27^{+0.12}_{-0.10}$

Search in LIGO O4 on-going

Scalar curvature

Ultra-Compact Mini-Halos

Gravitational Waves (GWs)



Conclusion

Primordial Black Holes (PBHs)

Search for new observables of
primordial sources of PTA signal

Motivate search in LIGO data

LIGO collab., "Sub-solar search", PRL 2018

LIGO collab., "Sub-solar search", PRL 2019

LIGO collab., "Sub-solar search", PRL 2022

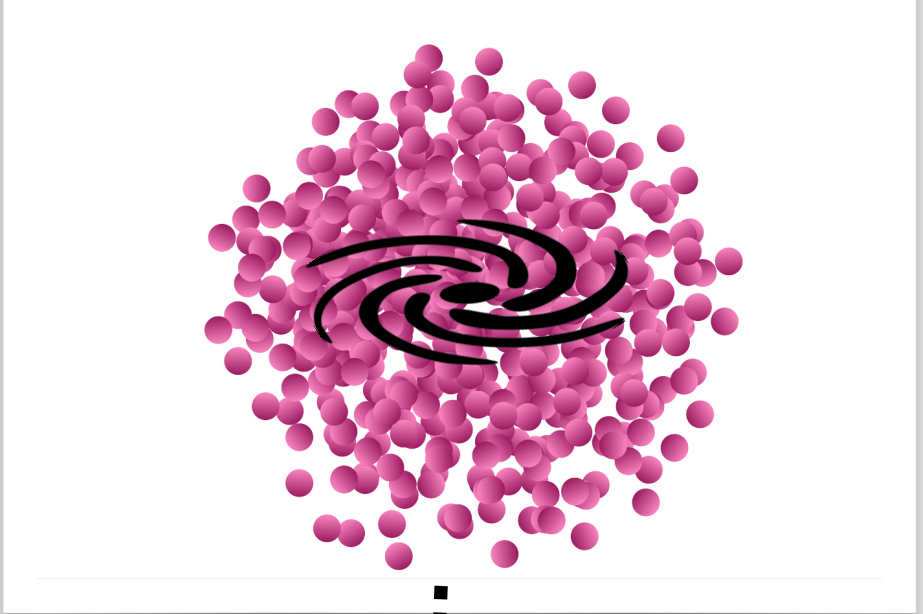
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Search in LIGO O4 on-going

Gravitational Waves (GWs)

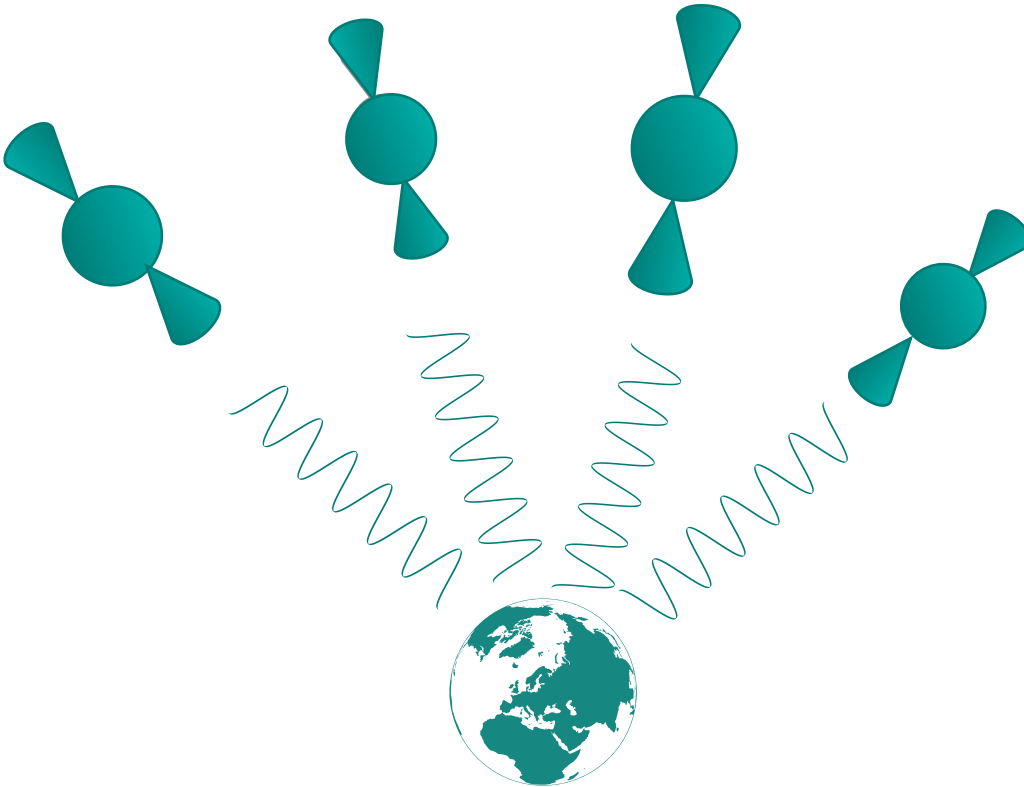
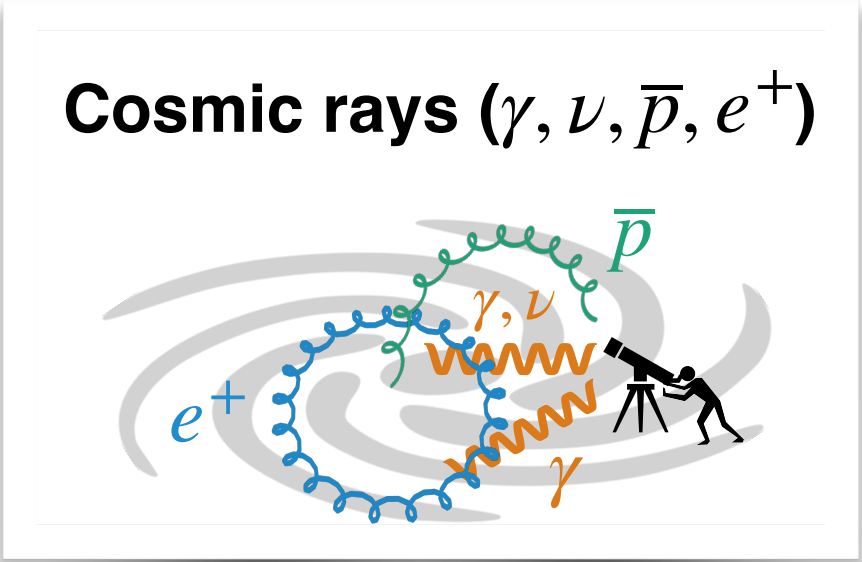
Scalar curvature

Ultra-Compact Mini-Halos



If DM=WIMPs

Cosmic rays ($\gamma, \nu, \bar{p}, e^+$)



Conclusion

Primordial Black Holes (PBHs)

Search for new observables of
primordial sources of PTA signal

Motivate search in LIGO data

LIGO collab., "Sub-solar search", PRL 2018

LIGO collab., "Sub-solar search", PRL 2019

LIGO collab., "Sub-solar search", PRL 2022

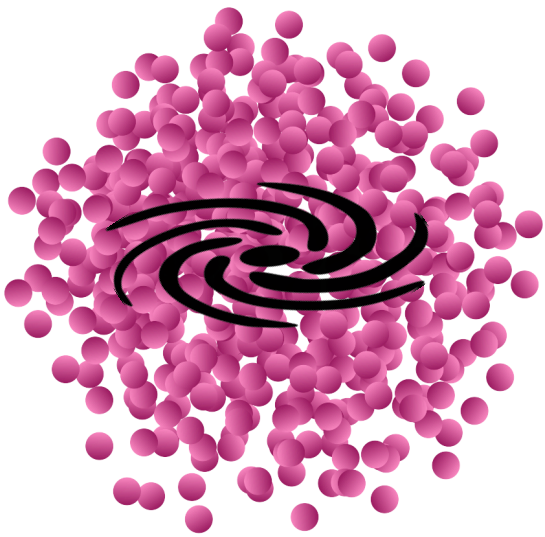
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Search in LIGO O4 on-going

Scalar curvature

Gravitational Waves (GWs)

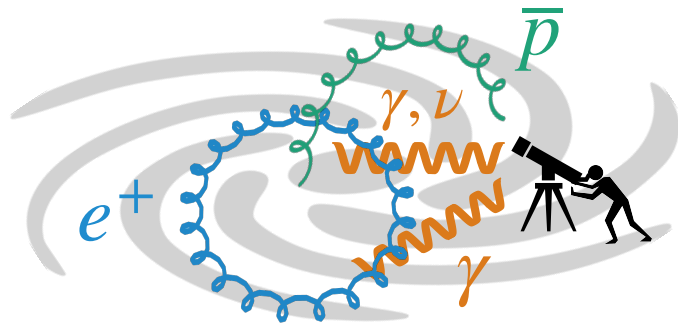
Ultra-Compact Mini-Halos



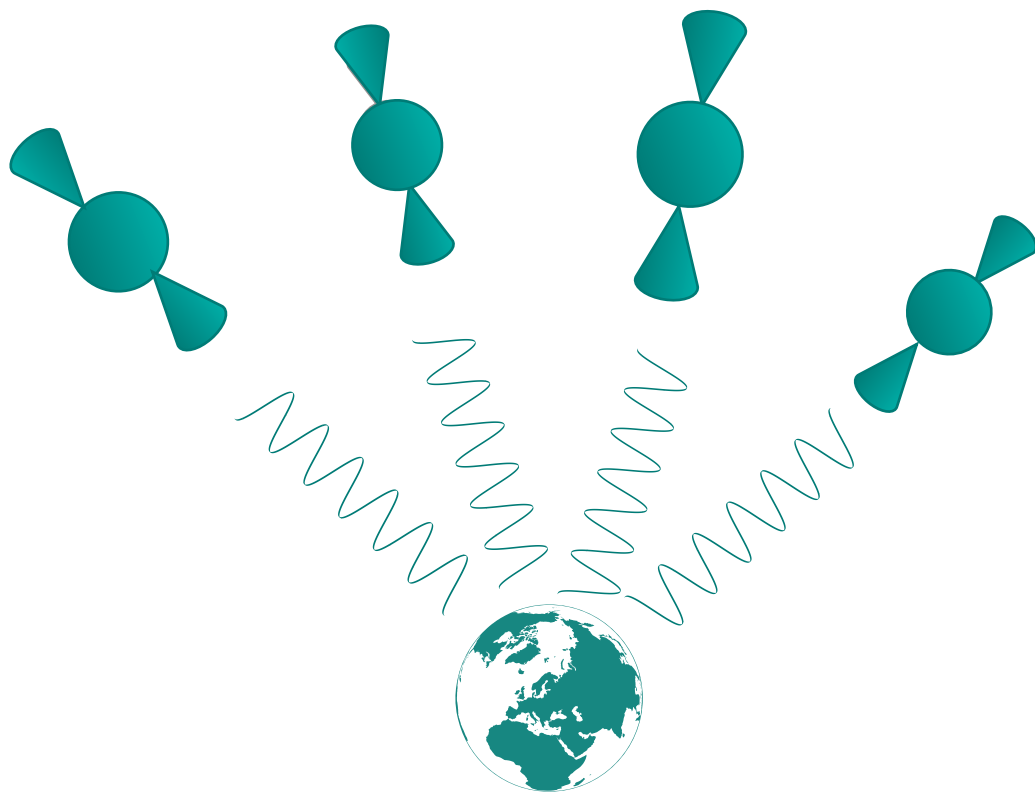
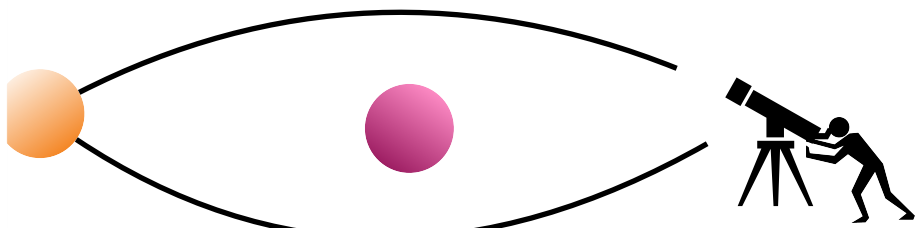
If DM=WIMPs

Future

Cosmic rays ($\gamma, \nu, \bar{p}, e^+$)



Gravitational Lensing



Conclusion

Primordial Black Holes (PBHs)

Search for new observables of
primordial sources of PTA signal

Motivate search in LIGO data

LIGO collab., "Sub-solar search", PRL 2018

LIGO collab., "Sub-solar search", PRL 2019

LIGO collab., "Sub-solar search", PRL 2022

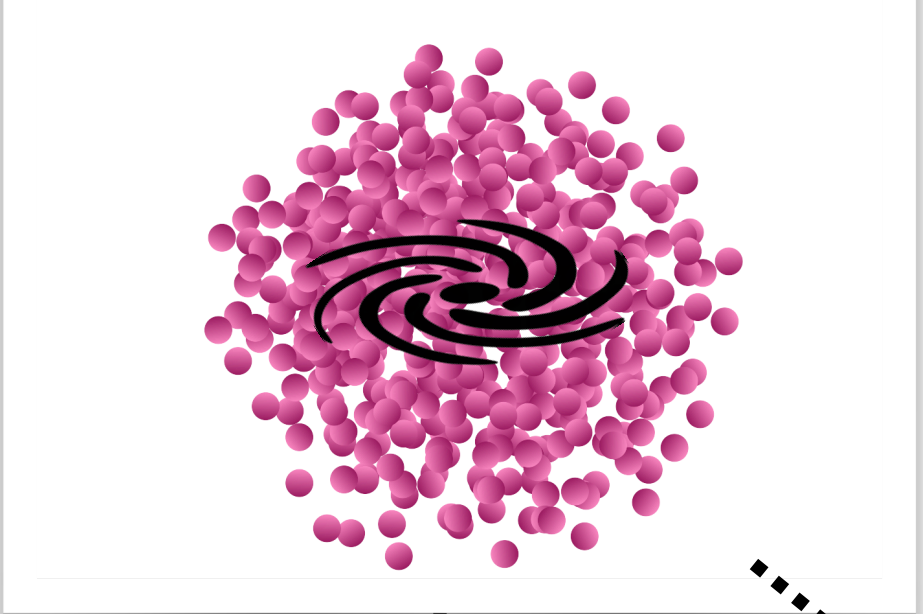
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Search in LIGO O4 on-going

Scalar curvature

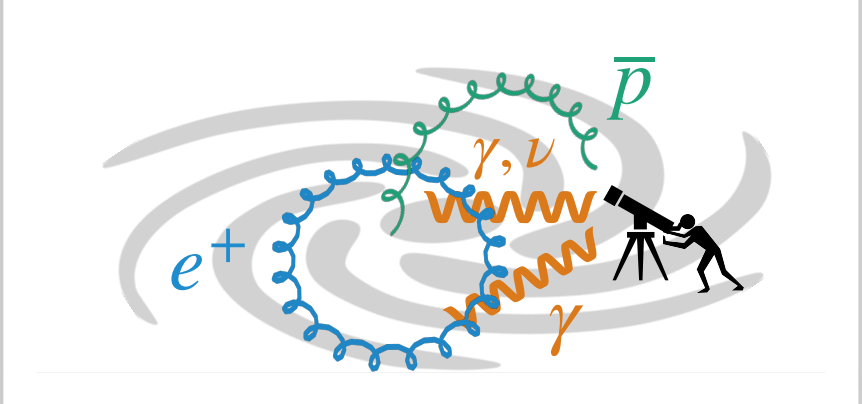
Gravitational Waves (GWs)

Ultra-Compact Mini-Halos

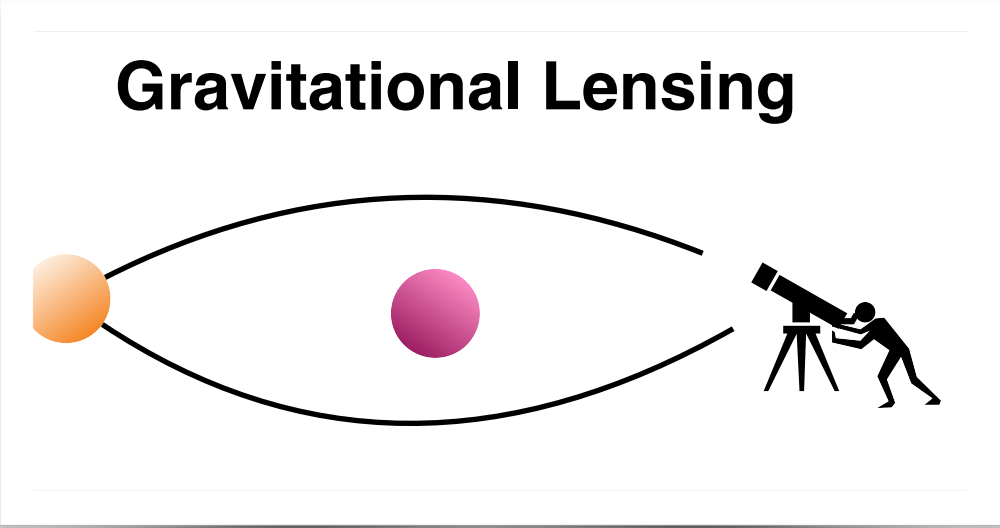


If DM=WIMPs

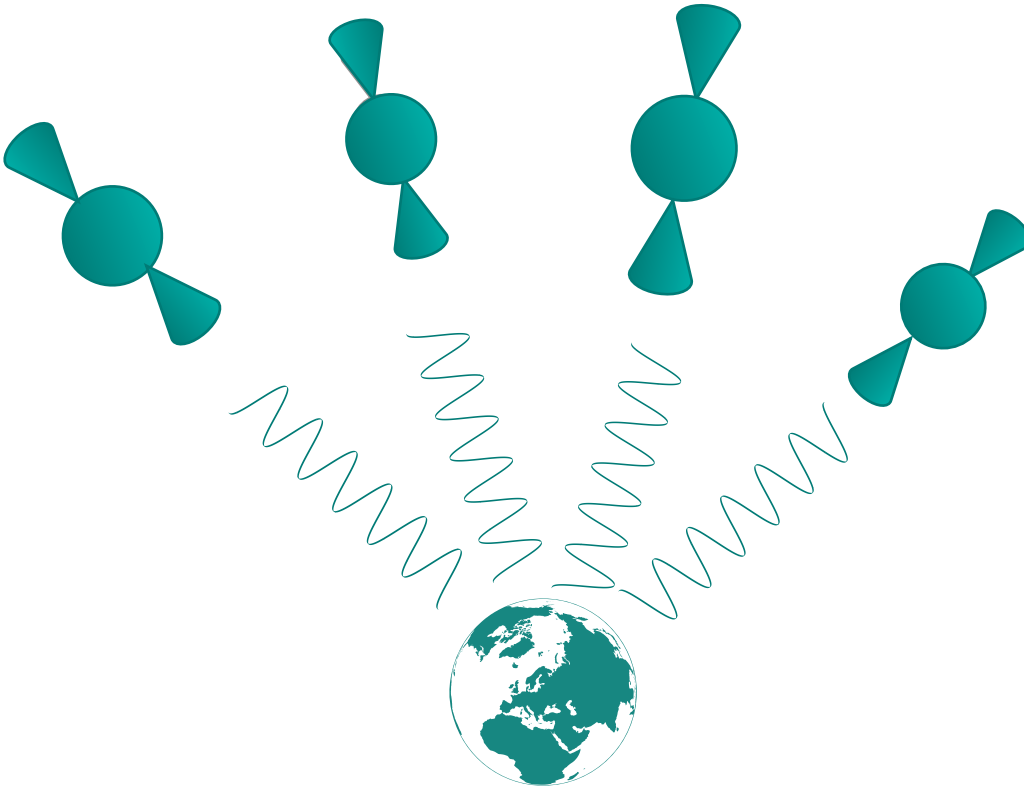
Cosmic rays ($\gamma, \nu, \bar{p}, e^+$)



Future



HSC microlensing
(in preparation)



Conclusion

Primordial Black Holes (PBHs)

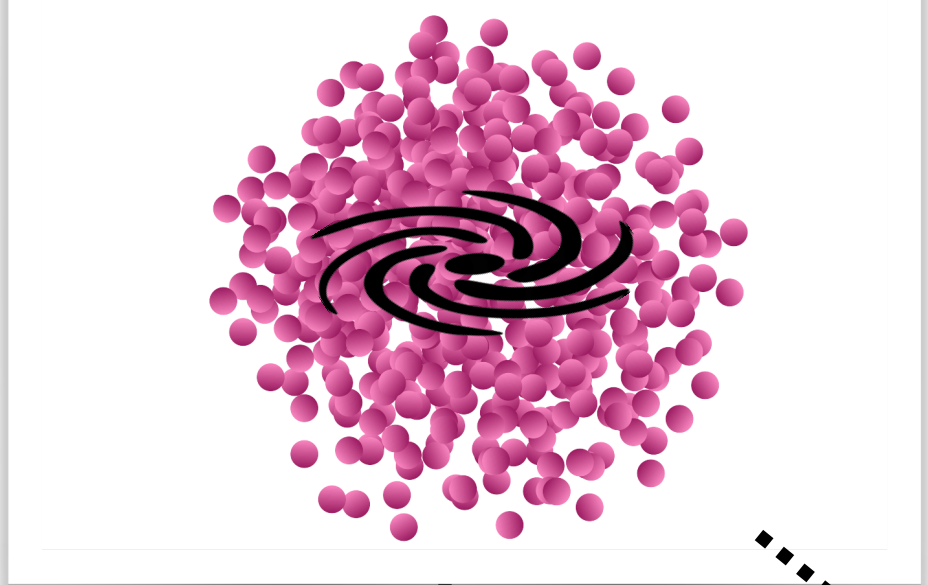
Search for new observables of
primordial sources of PTA signal

Motivate search in LIGO data
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⇒ one sub-solar candidate at 3.7σ : $m = 0.27^{+0.12}_{-0.10}$
Search in LIGO O4 on-going

Gravitational Waves (GWs)

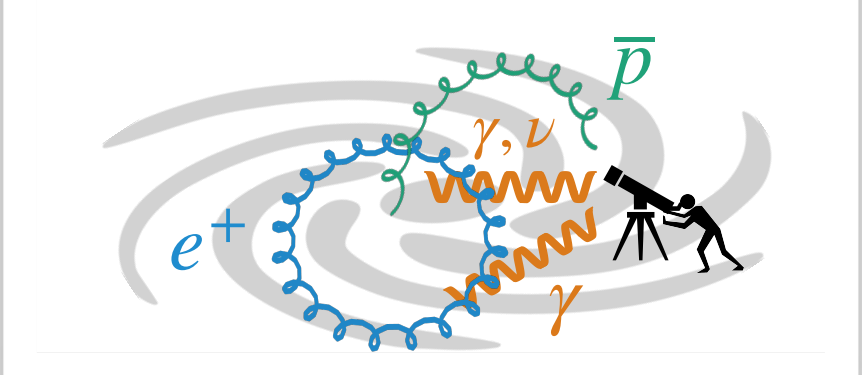
Scalar curvature

Ultra-Compact Mini-Halos

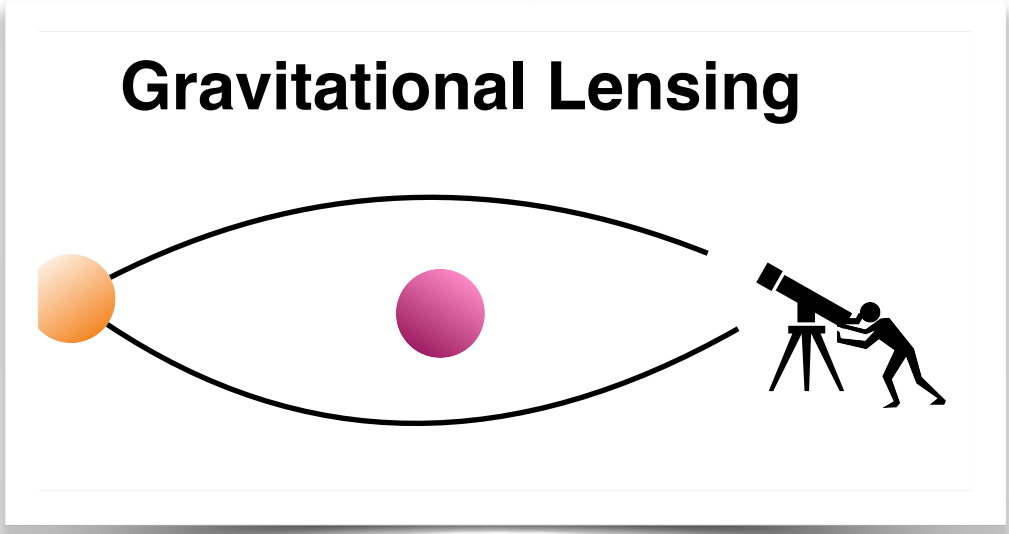


If DM=WIMPs

Cosmic rays ($\gamma, \nu, \bar{p}, e^+$)



Future



Gravitational Lensing

HSC microlensing
(in preparation)
Lensed Quasars
(in preparation)

Conclusion

Primordial Black Holes (PBHs)

Search for new observables of
primordial sources of PTA signal

Motivate search in LIGO data

LIGO collab., "Sub-solar search", PRL 2018

LIGO collab., "Sub-solar search", PRL 2019

LIGO collab., "Sub-solar search", PRL 2022

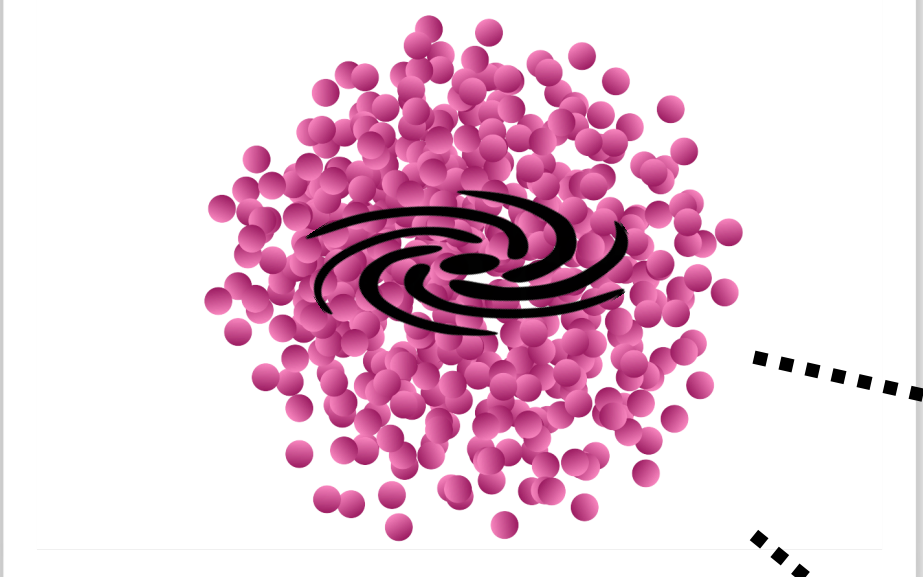
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Search in LIGO O4 on-going

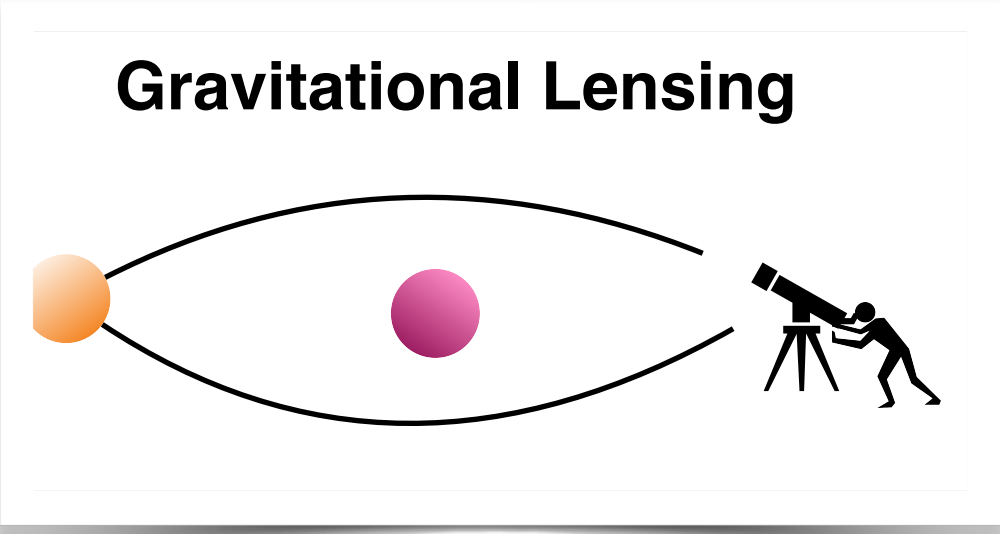
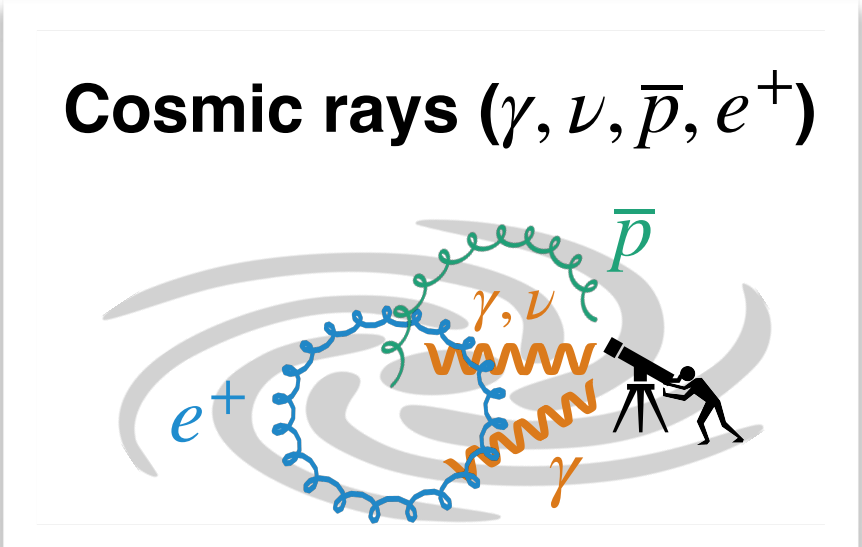
Gravitational Waves (GWs)

Scalar curvature

Ultra-Compact Mini-Halos

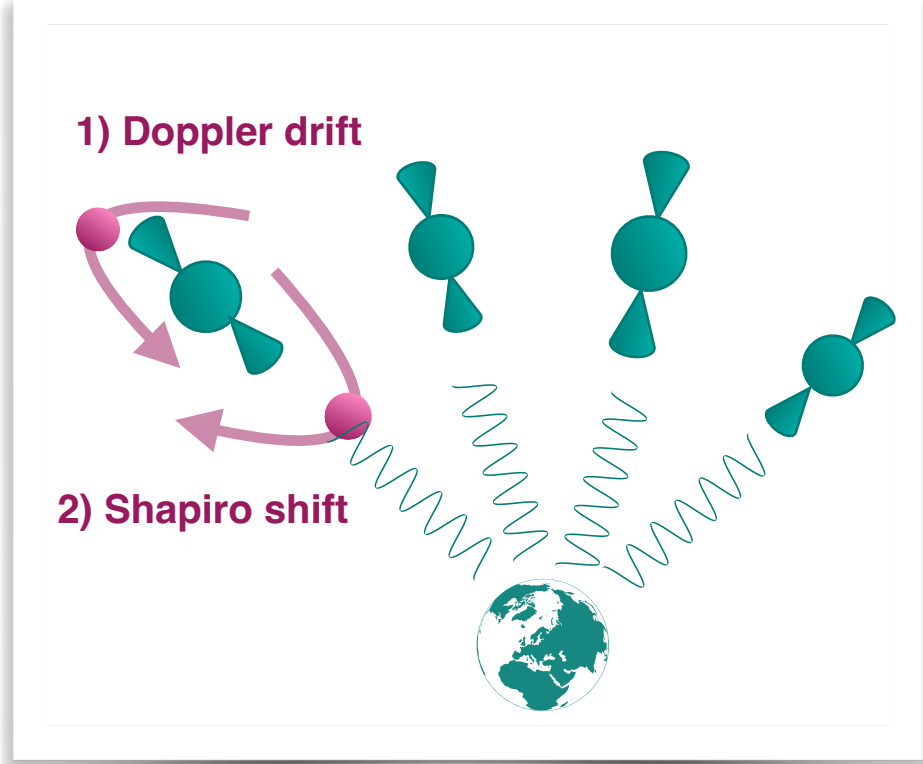


If DM=WIMPs



HSC microlensing
(in preparation)

Lensed Quasars
(in preparation)



Conclusion

Primordial Black Holes (PBHs)

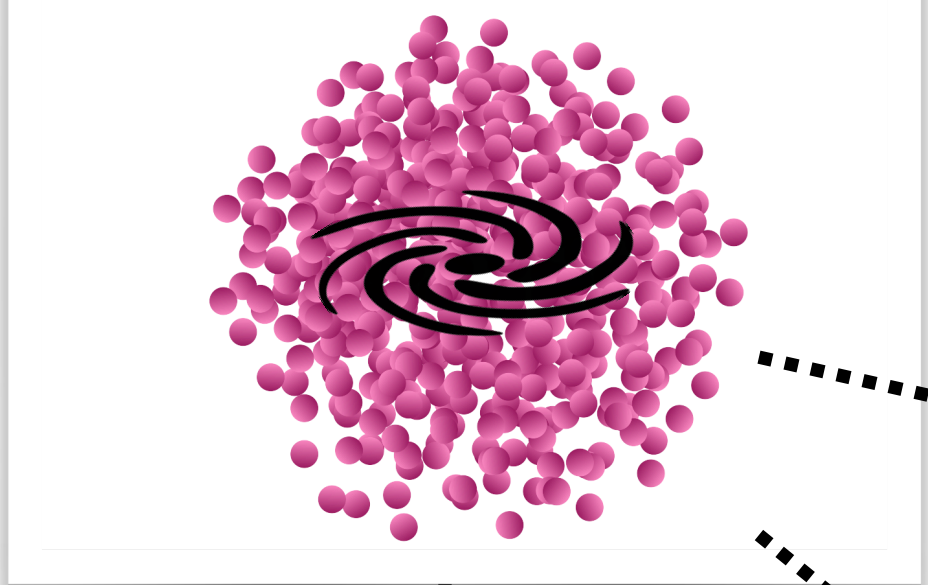
Search for new observables of
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Motivate search in LIGO data
LIGO collab., "Sub-solar search", PRL 2018
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Search in LIGO O4 on-going

Gravitational Waves (GWs)

Scalar curvature

Ultra-Compact Mini-Halos



If DM=WIMPs

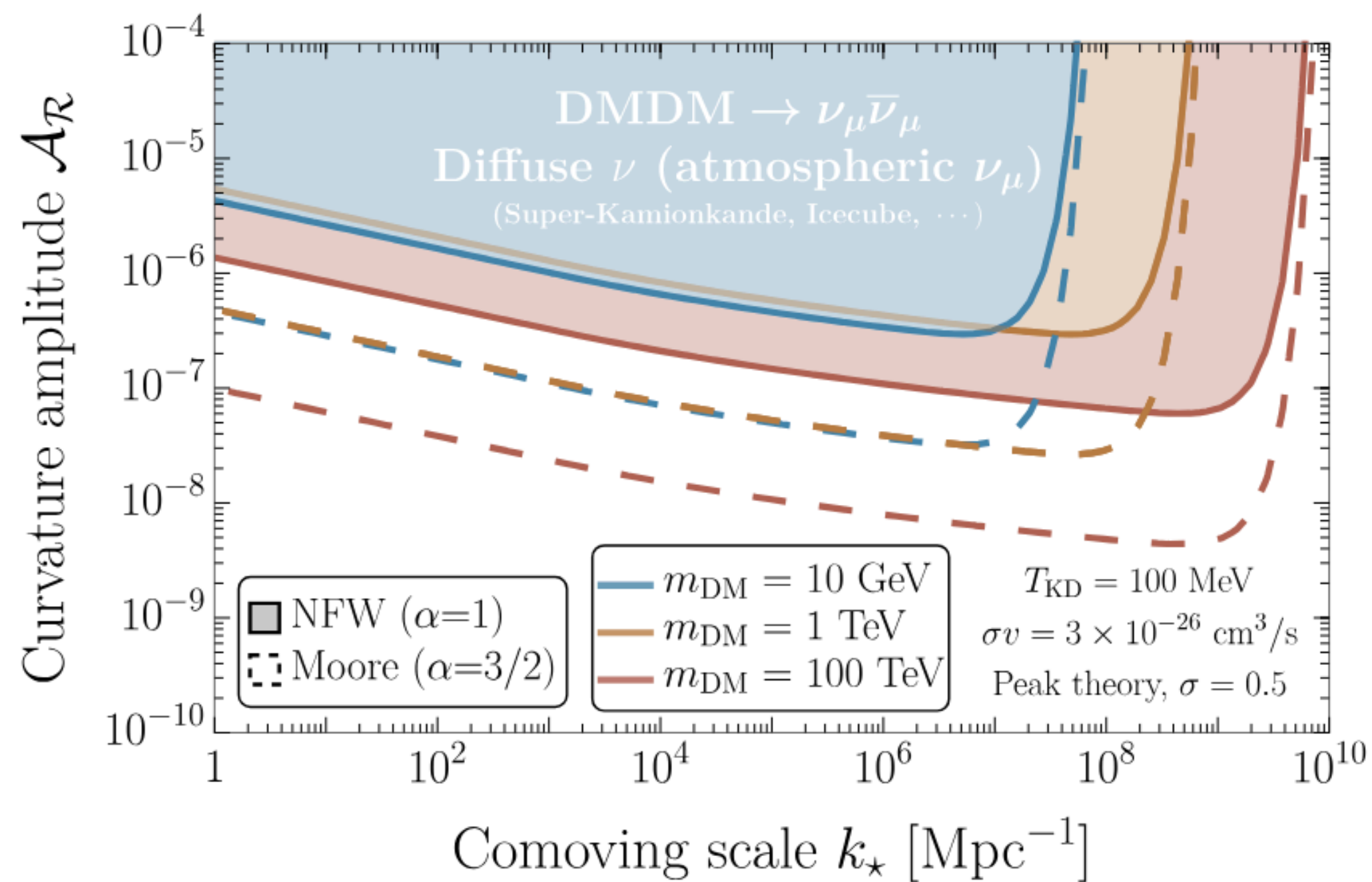
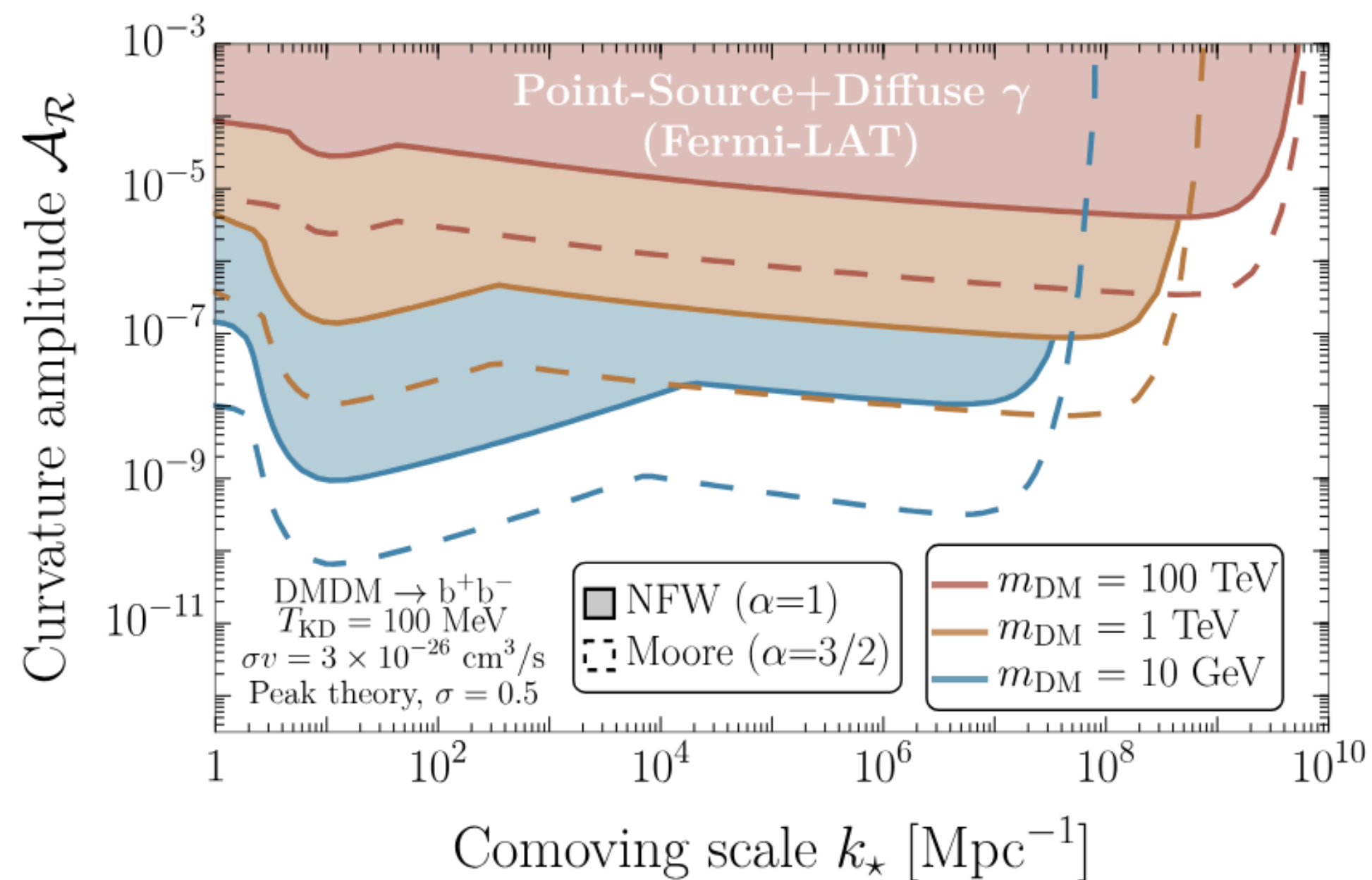
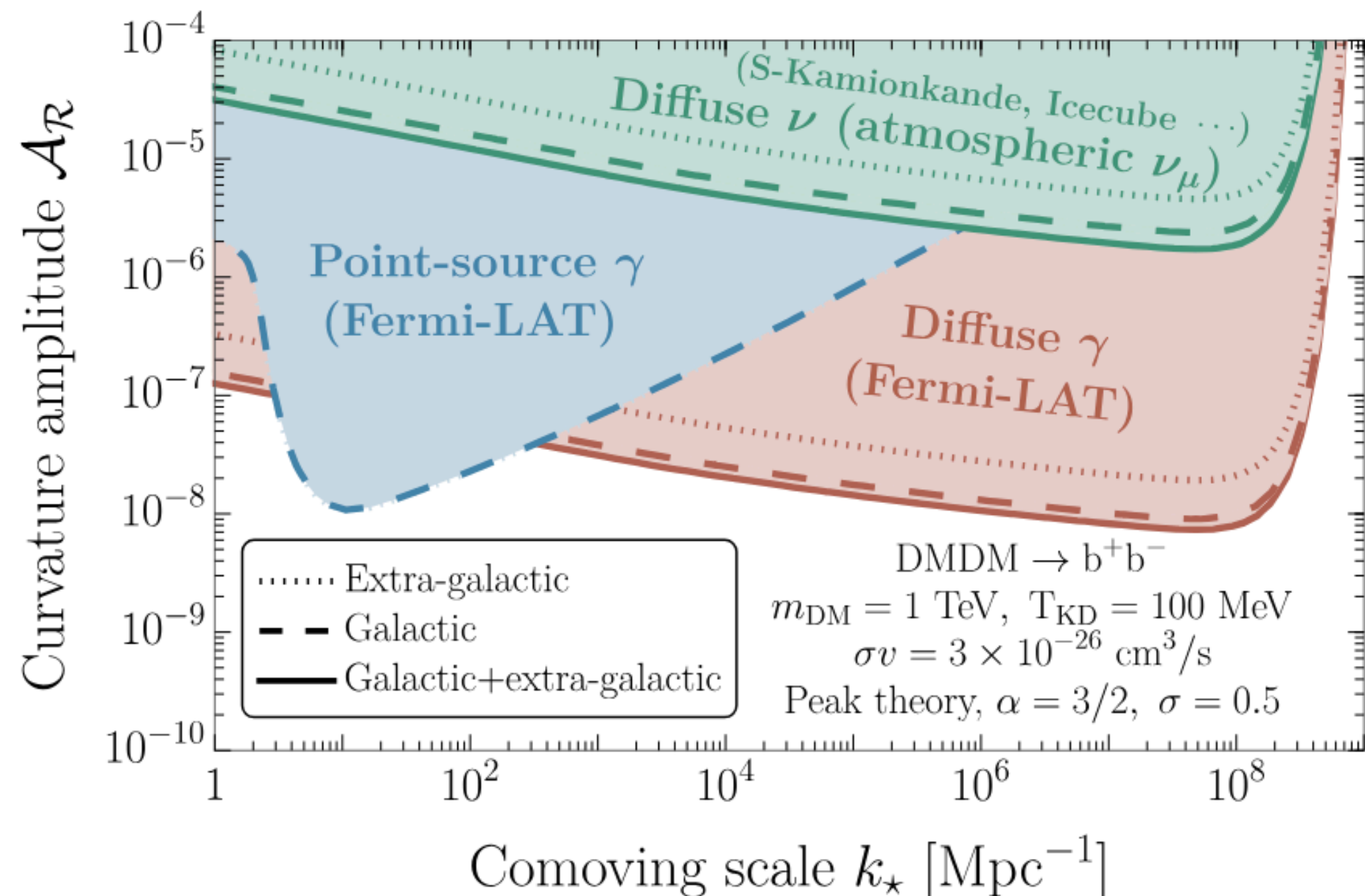
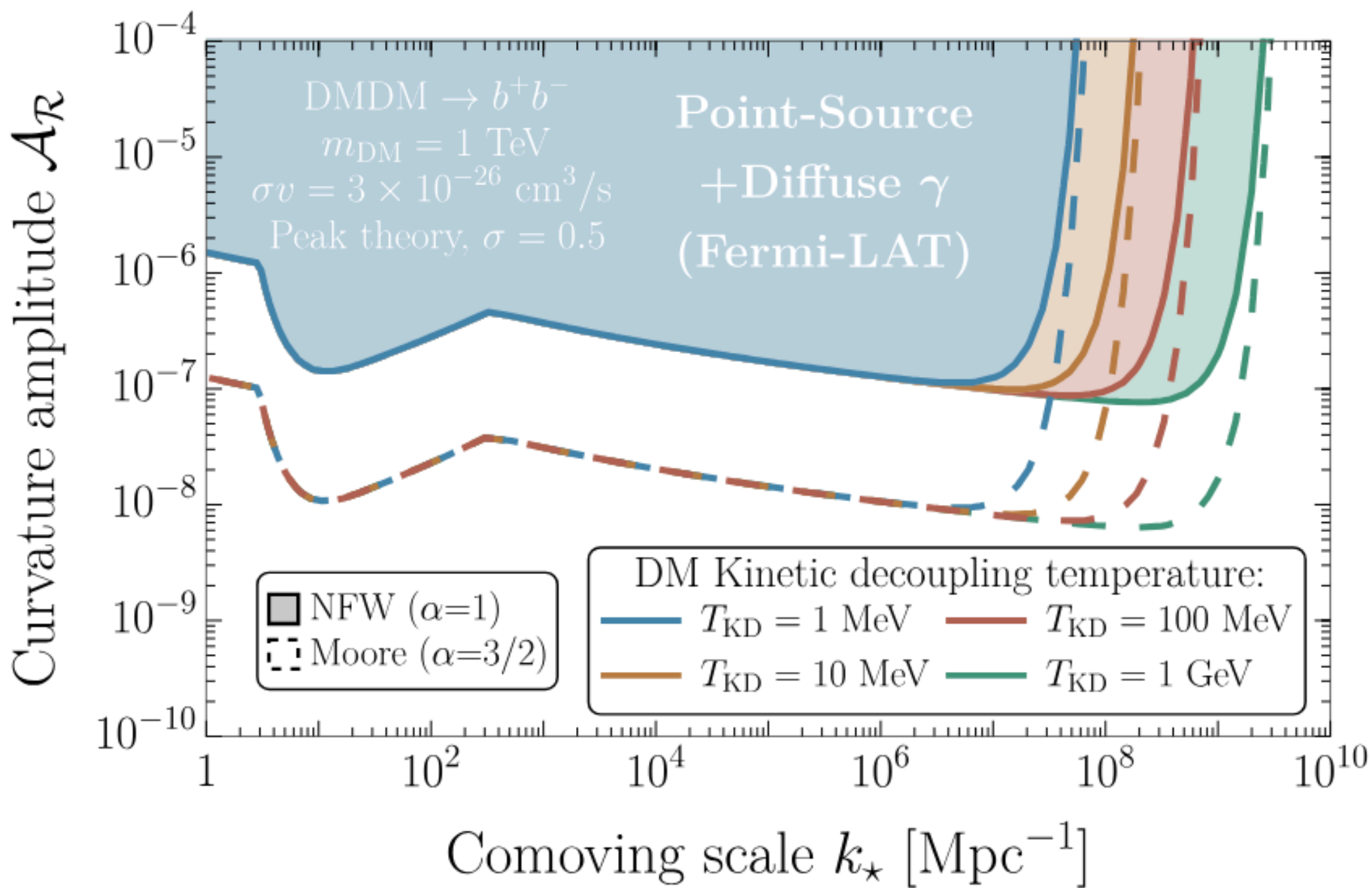
Cosmic rays ($\gamma, \nu, \bar{p}, e^+$)

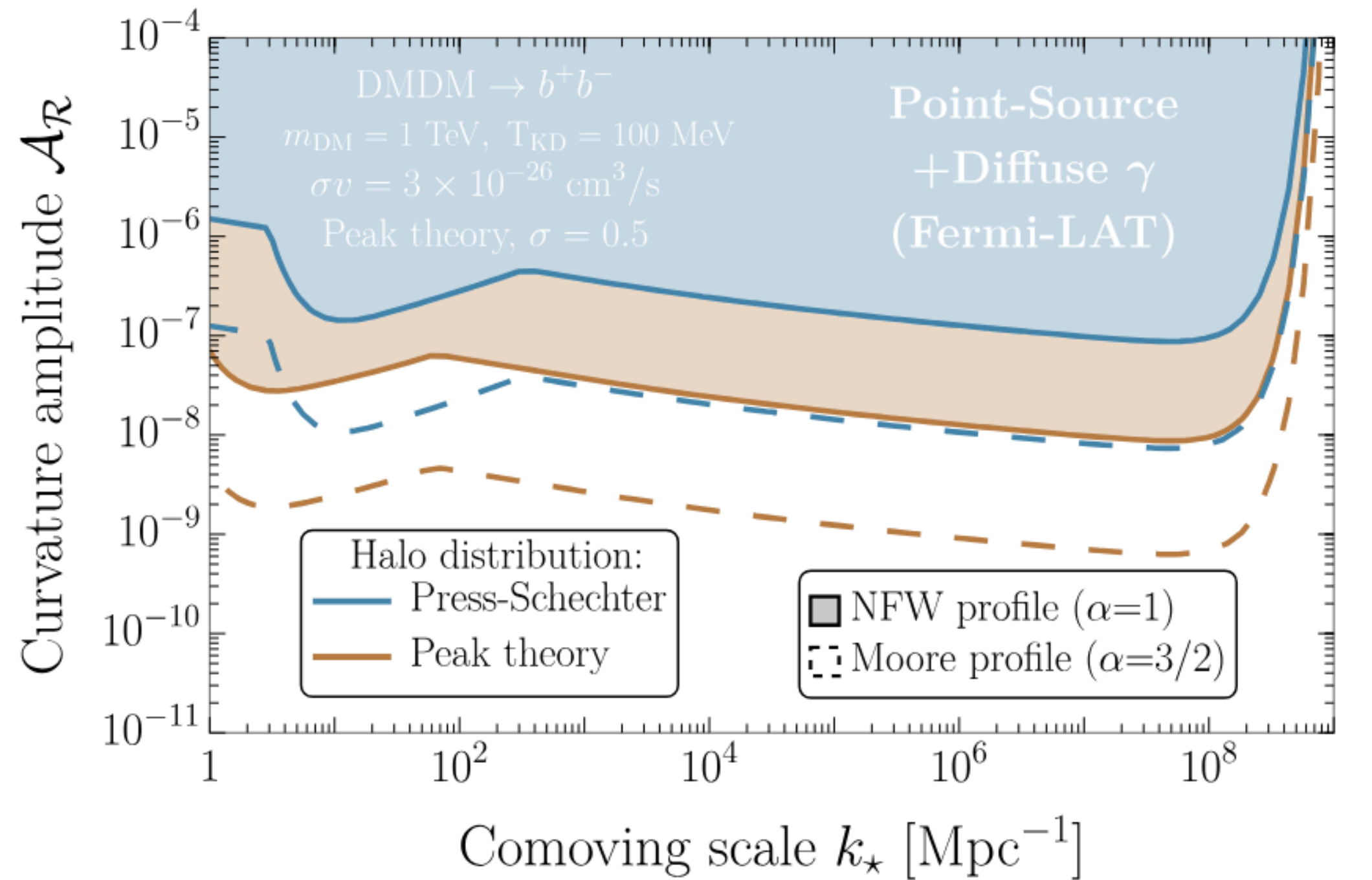
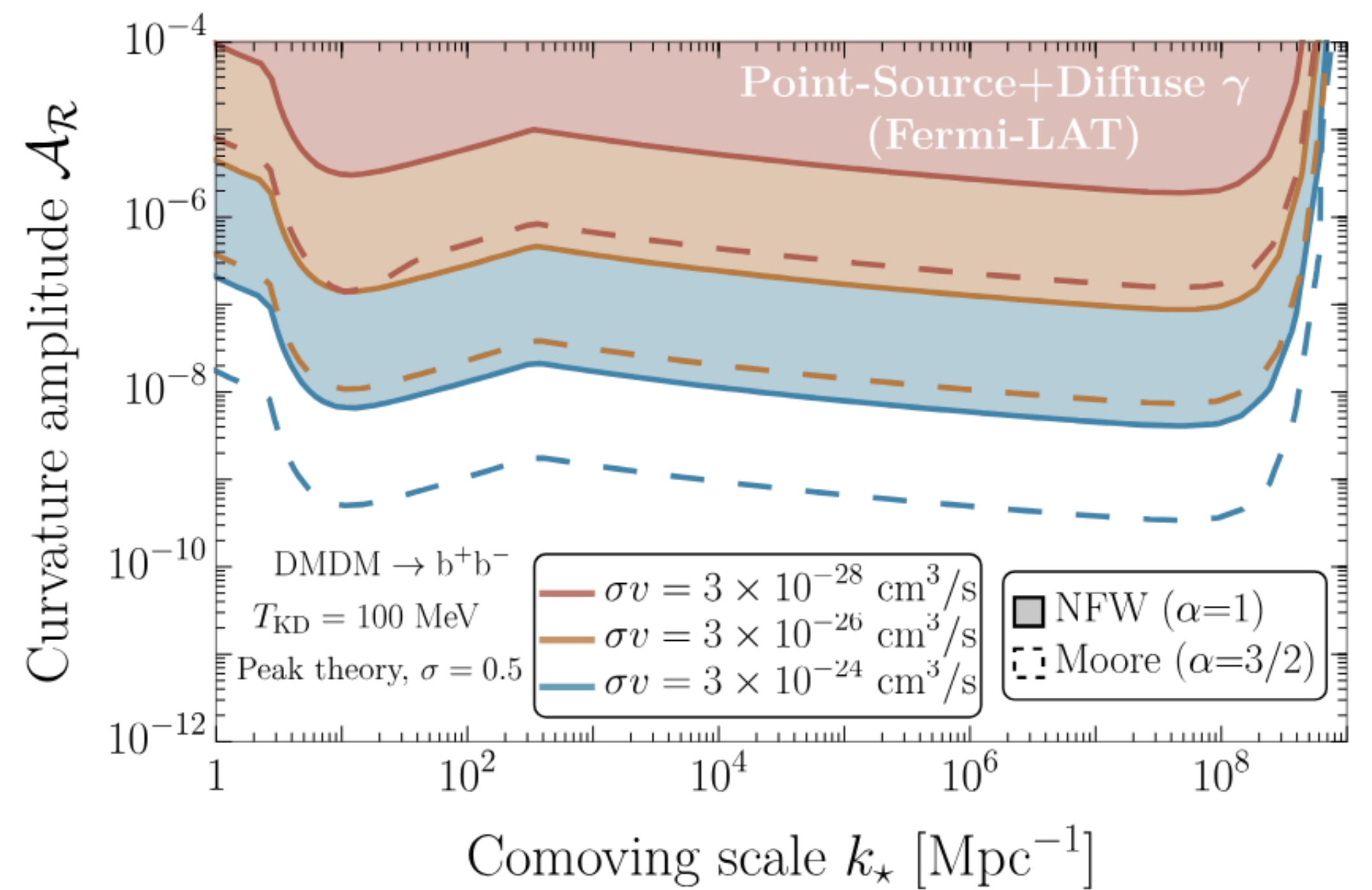
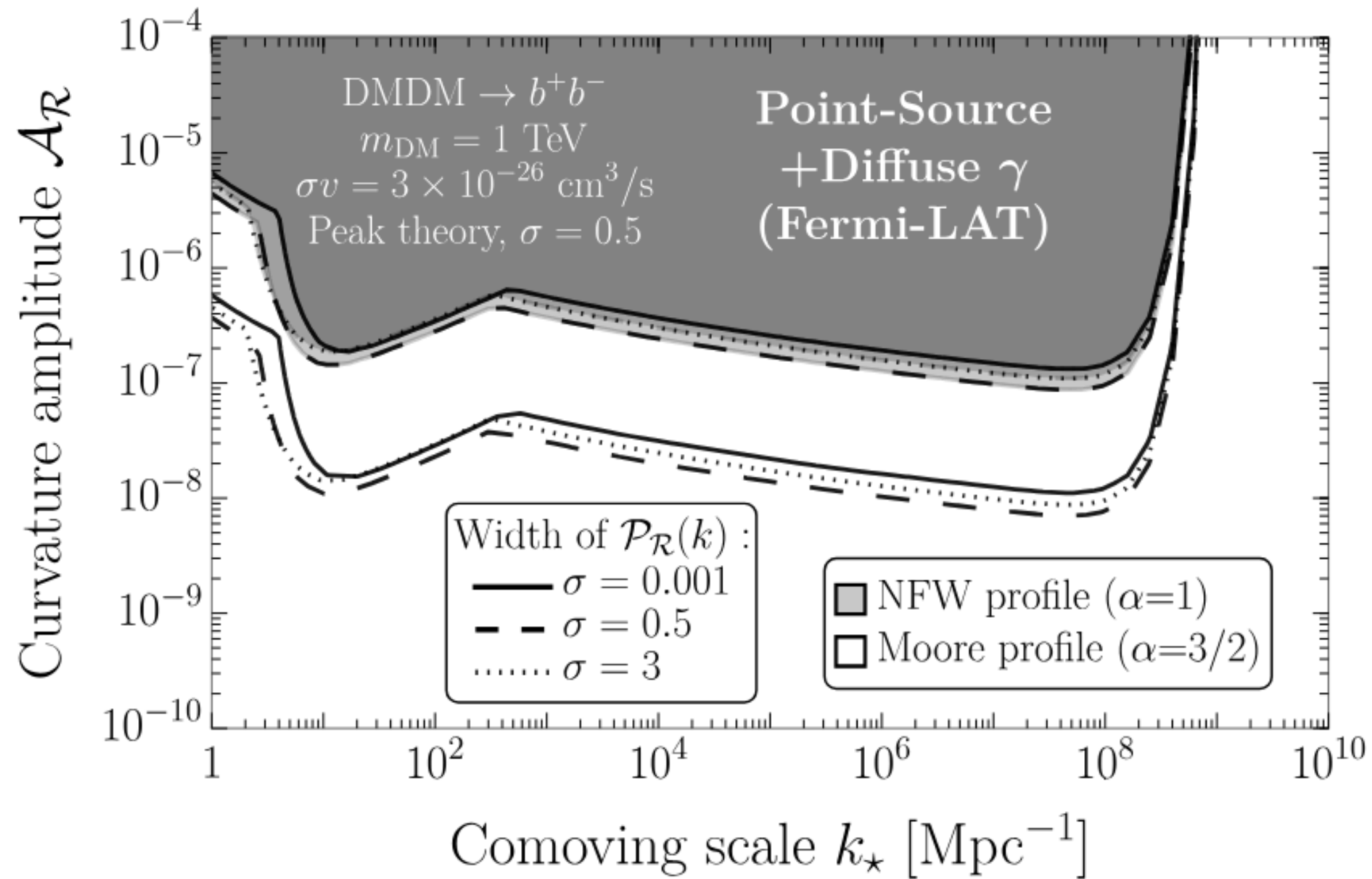
Gravitational Lensing

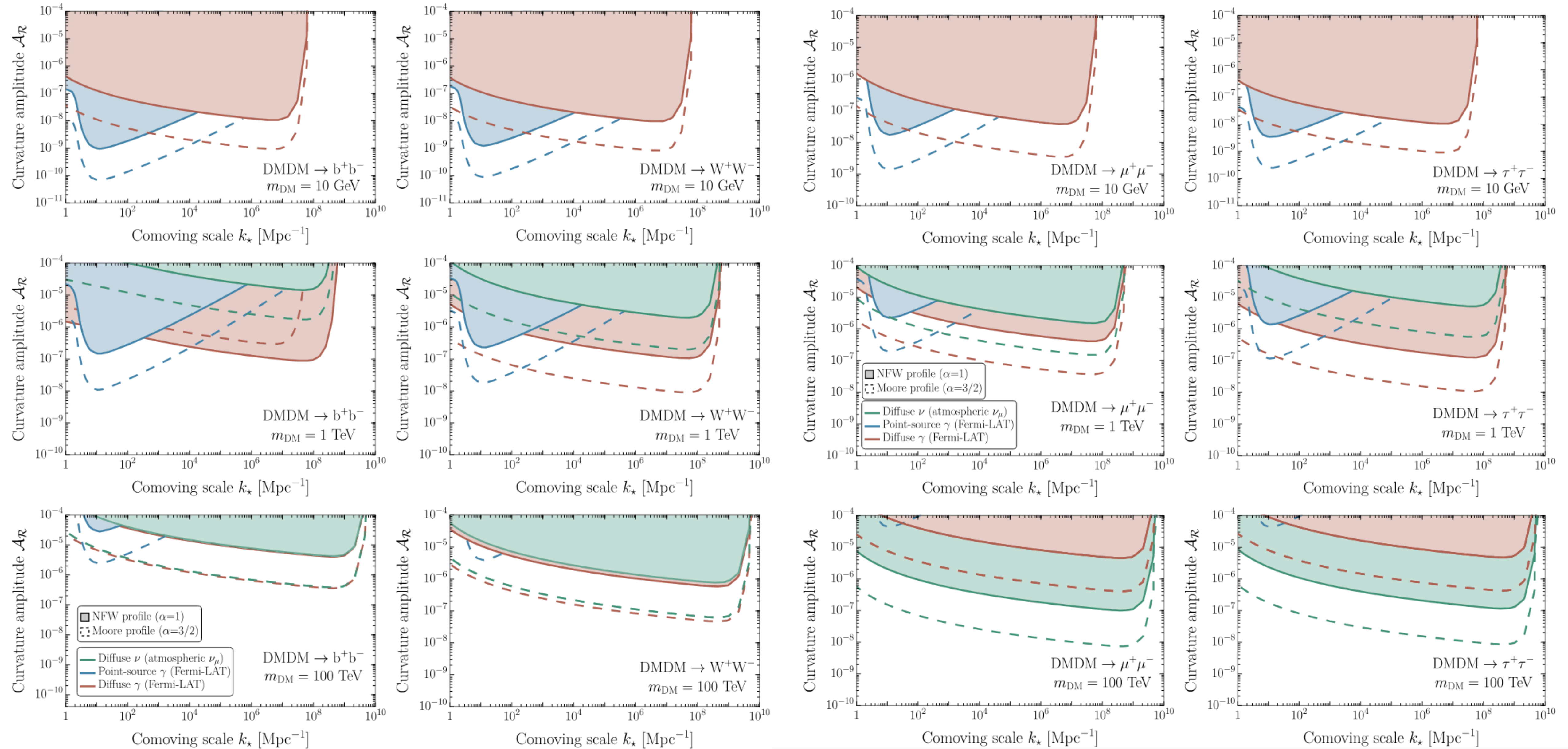
HSC microlensing
(in preparation)
Lensed Quasars
(in preparation)

1) Doppler drift
2) Shapiro shift

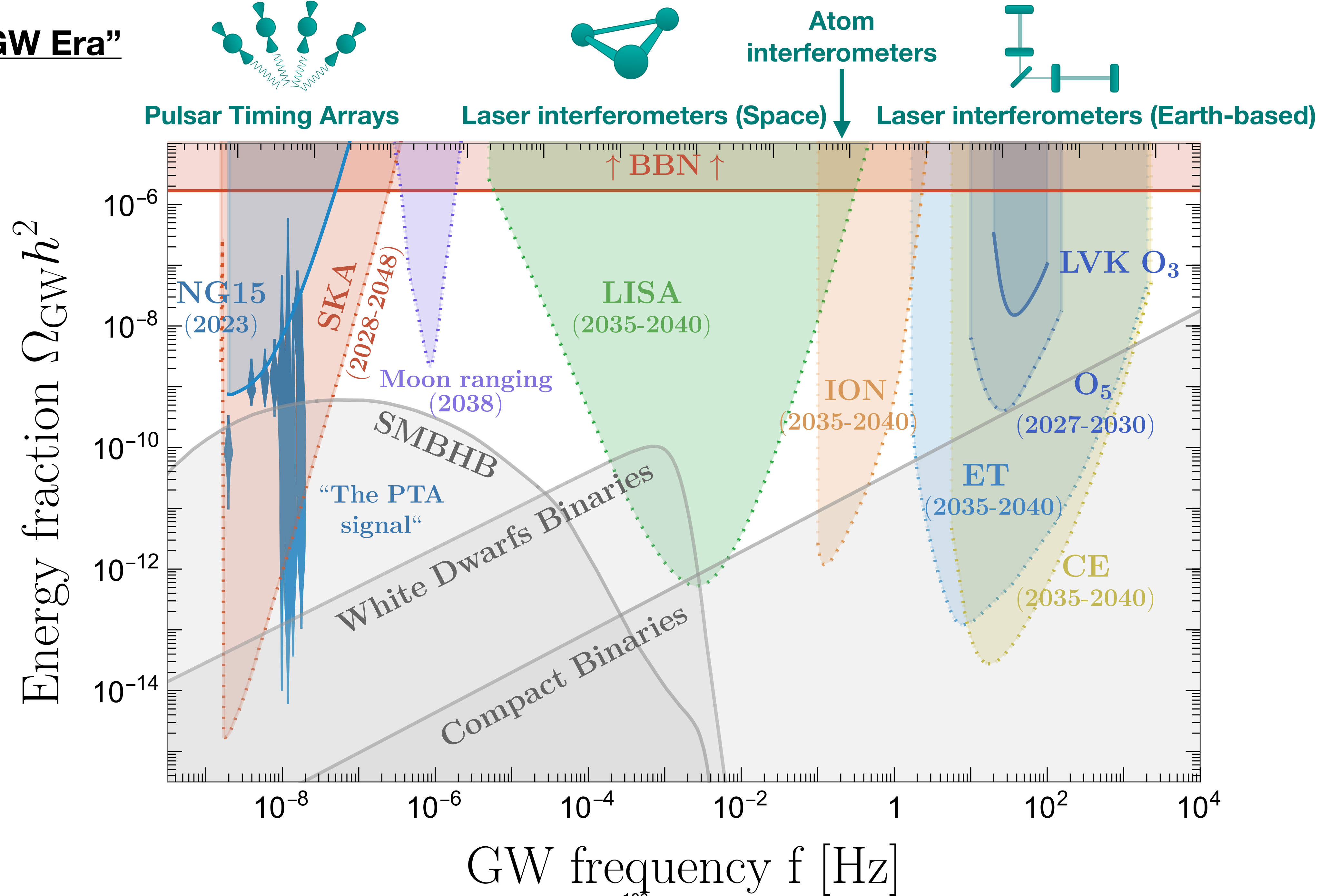
Thank you

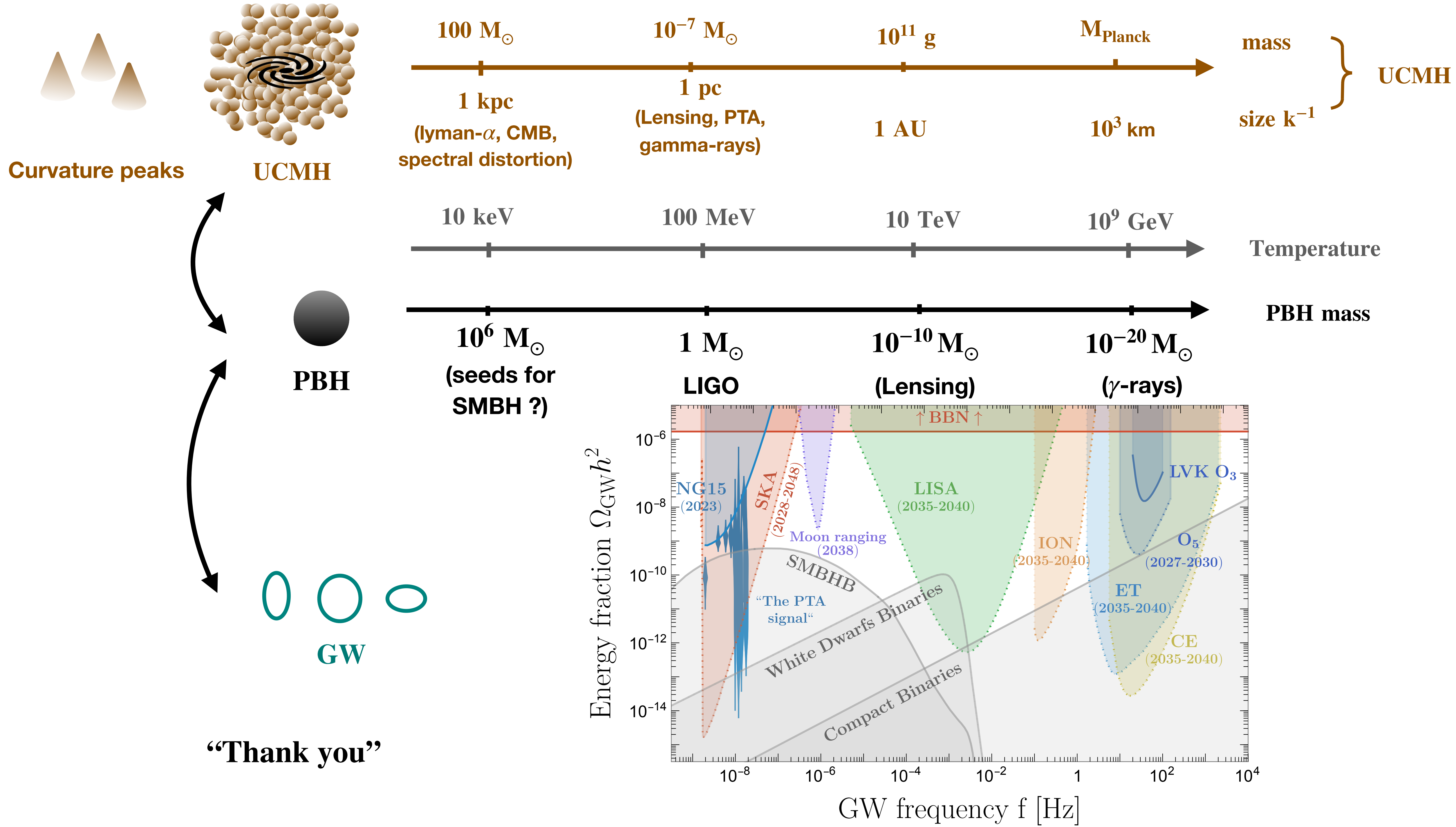


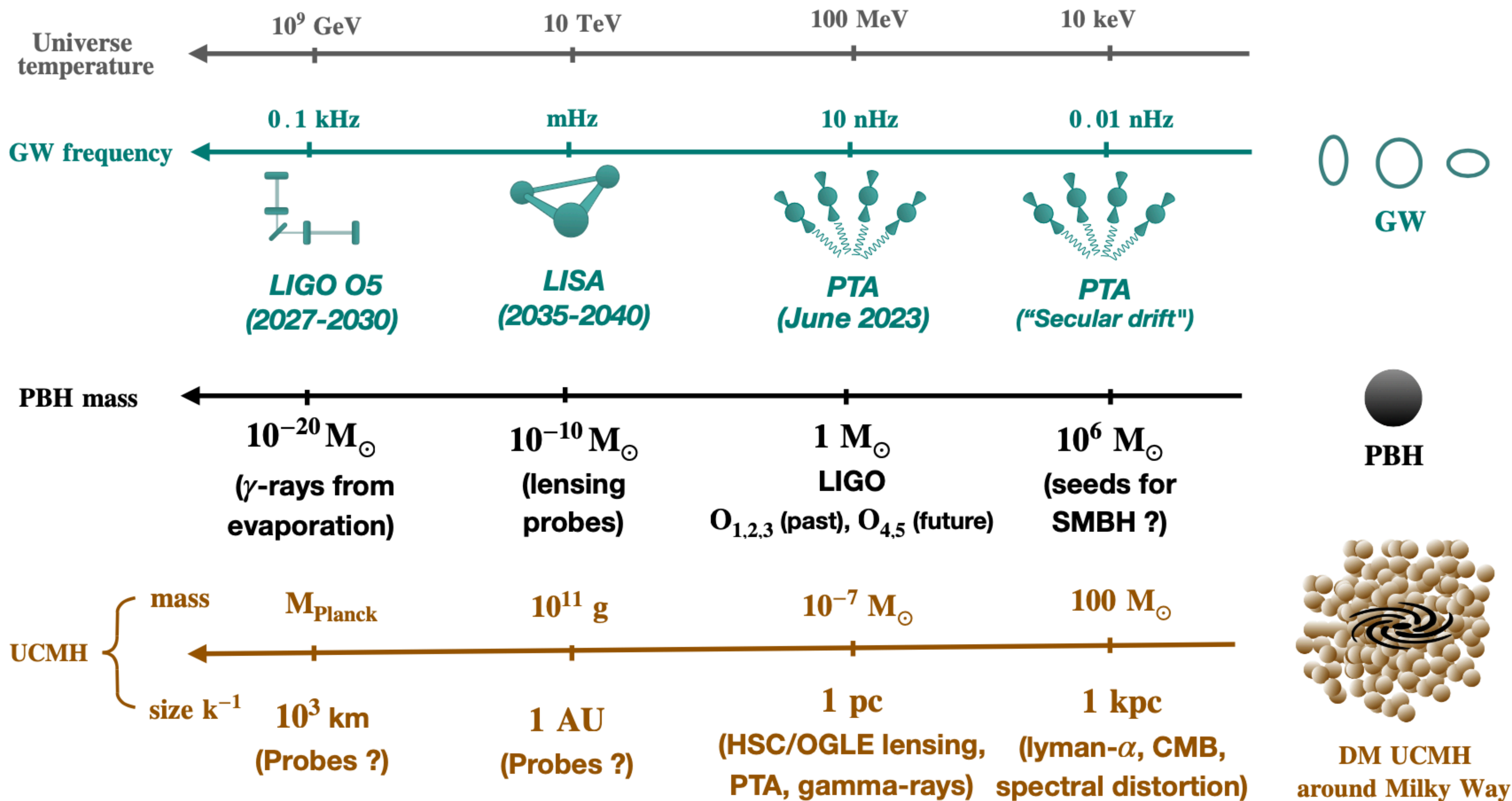


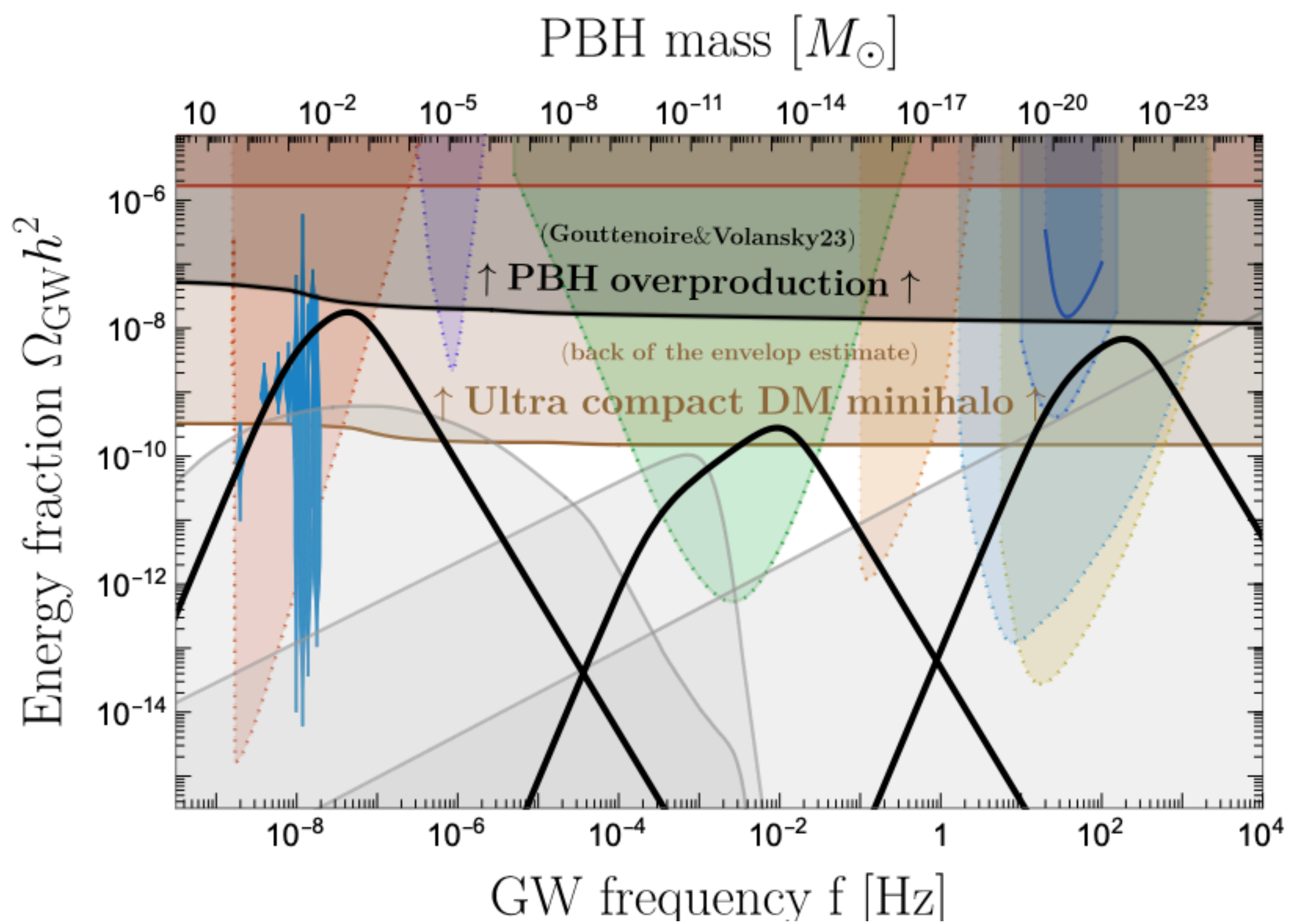


“The GW Era”









$$\delta\rho'_R + 4\mathcal{H}\delta\rho_R = -\delta\rho'_V \quad (\delta \equiv \delta\rho/\bar{\rho})$$

Sasaki+ 1982

Bian+, 2021

YG, Volansky 2305:04942

Baldes, Olea-Romacho, 2307.11639

YG, PRL, 2307.04239

YG, 2311.13640

$J_c = 1$ random bubble only

deltaPT

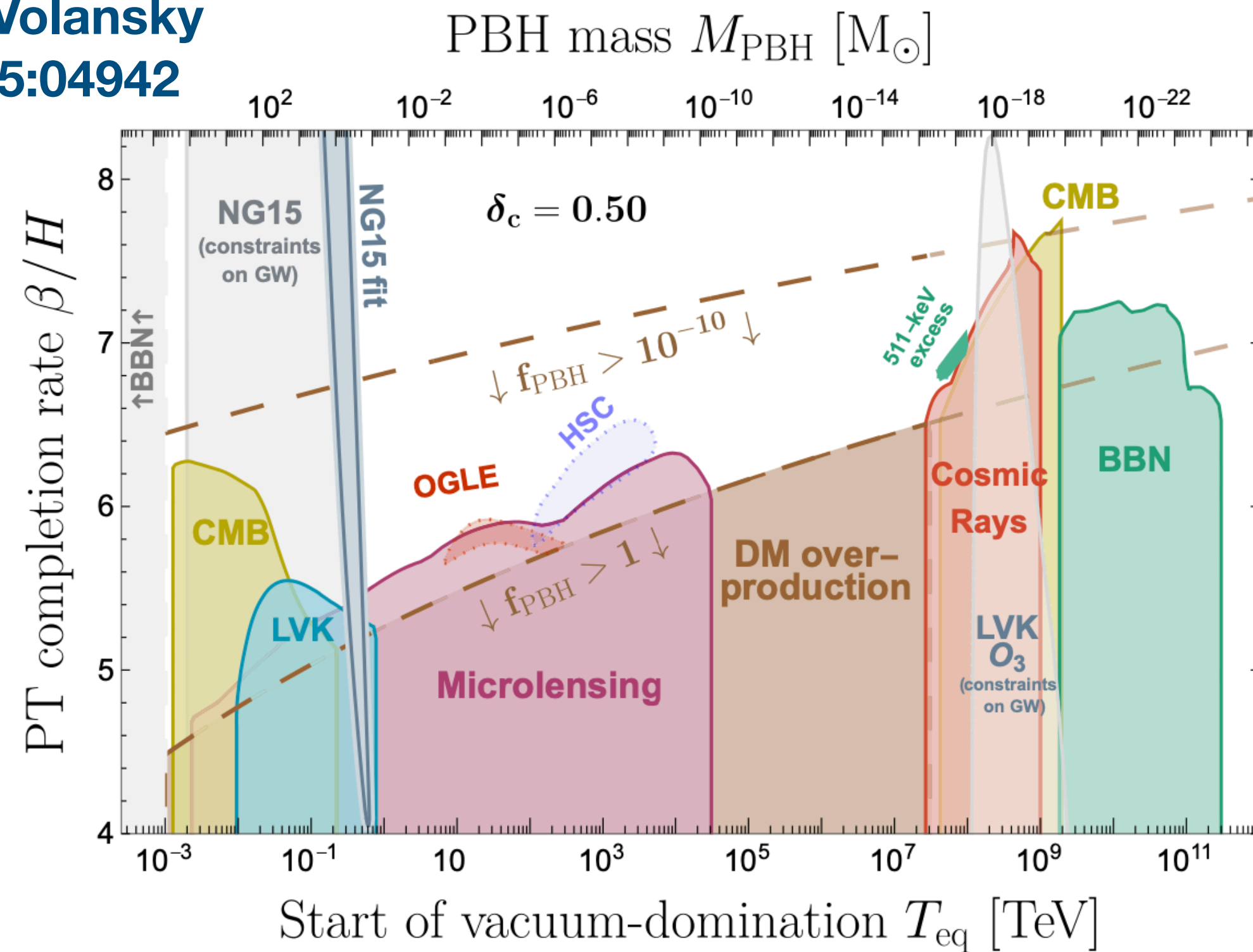
Lewicki, Toczek, Vaskonen

PRL

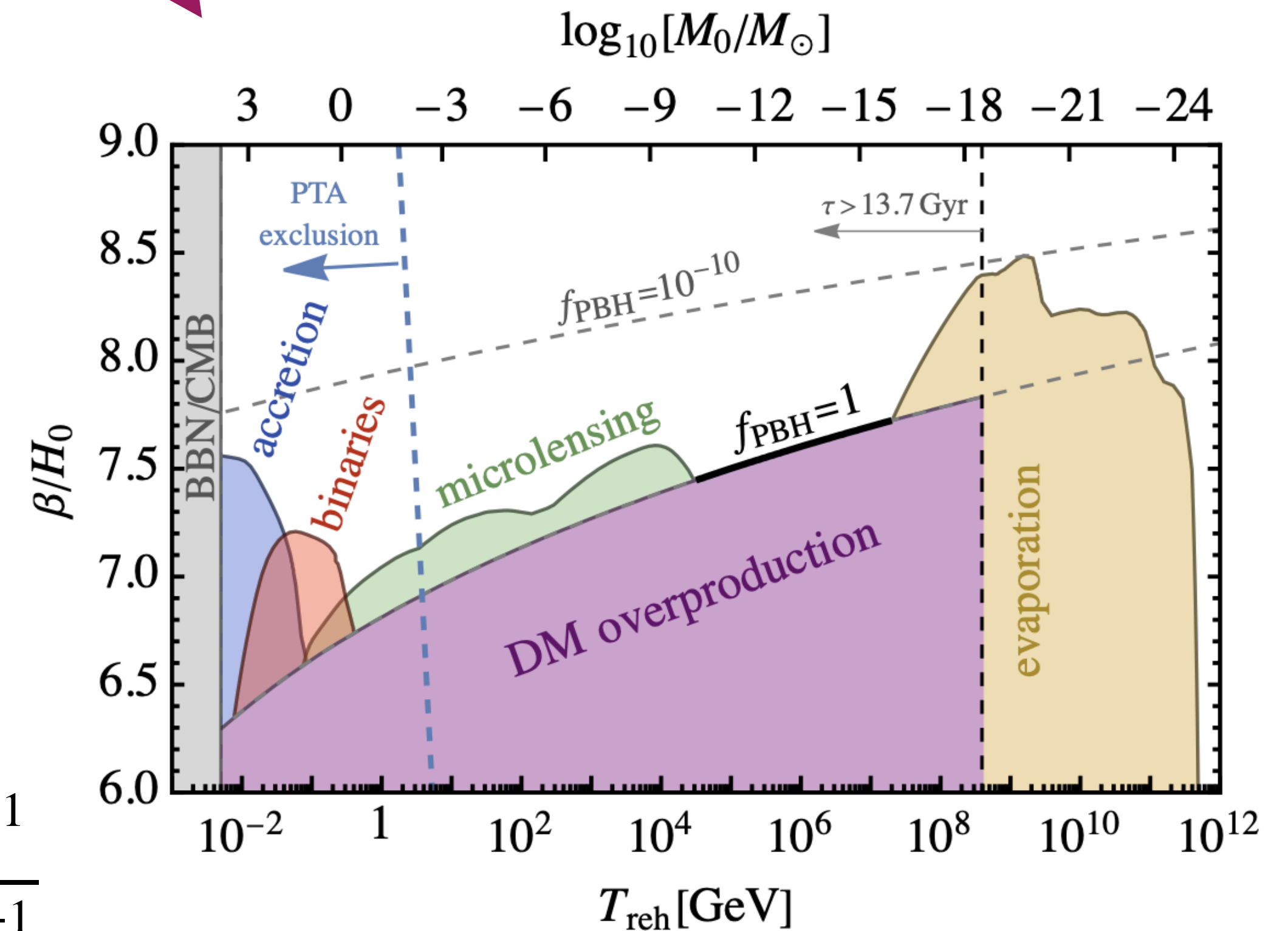
2402.04158

$J_c = 50$ random bubbles

YG, Volansky
2305:04942



Boiling time $\frac{\beta^{-1}}{H^{-1}}$



$$\delta\rho_R' + 4\mathcal{H}\delta\rho_R = -\delta\rho_V'$$

$$(\delta \equiv \delta\rho/\bar\rho)$$

Sasaki+ 1982

Bian+, 2021

YG, Volansky 2305:04942

Baldes, Olea-Romacho, 2307.11639

YG, PRL, 2307.04239

YG, 2311.13640

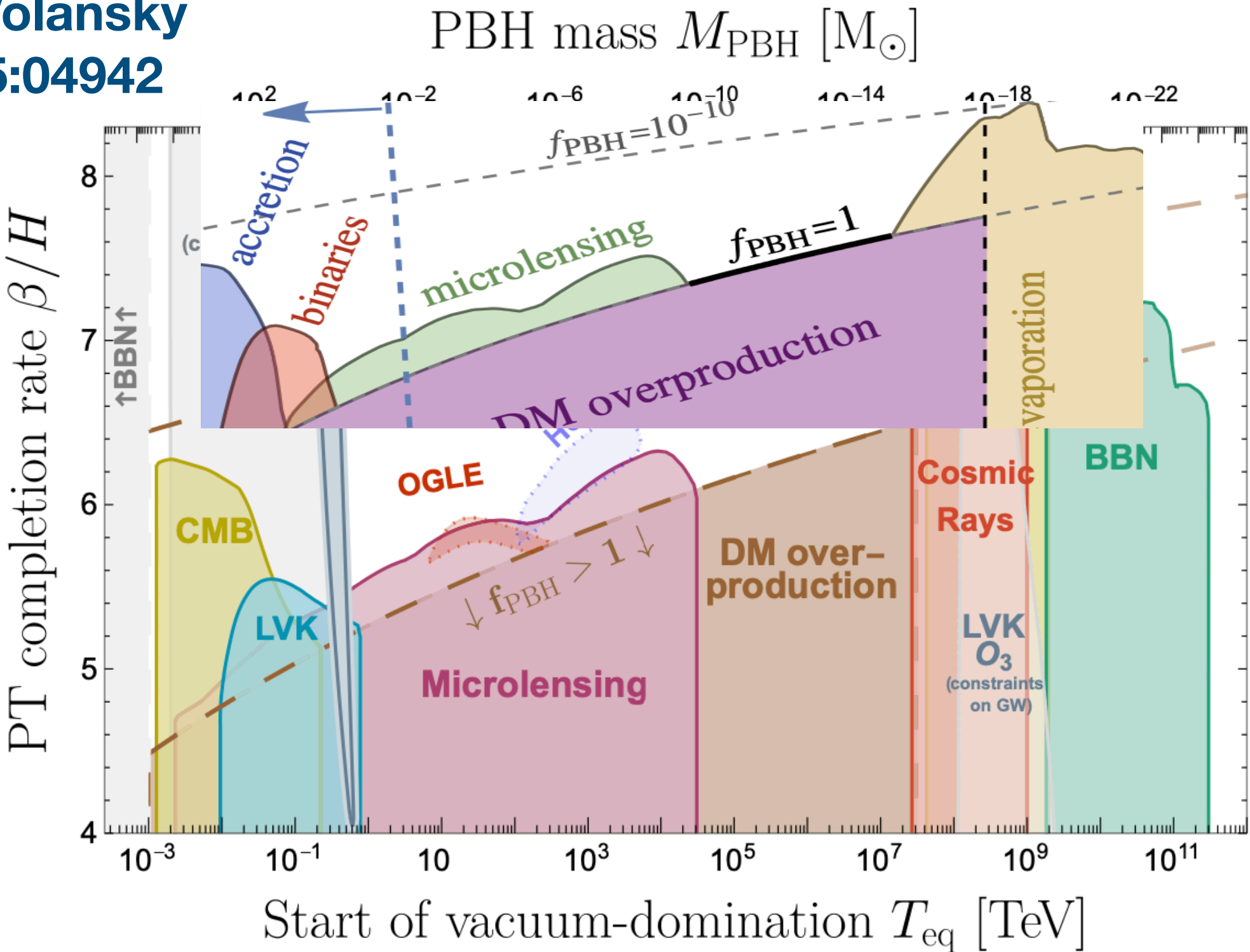
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deltaPT

Lewicki, Toczek, Vaskonen
PRL
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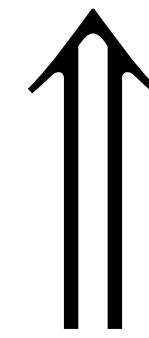
$J_c = 50$ random bubbles

YG, Volansky
2305:04942



Where does this come from ?

$$\delta\rho'_R + 4\mathcal{H}\delta\rho_R = -\delta\rho'_V \quad (\iff \bar{\rho}'_R + 4\mathcal{H}\bar{\rho}_R = -\bar{\rho}'_V)$$



Spatially-flat gauge

$$\Phi = 0$$

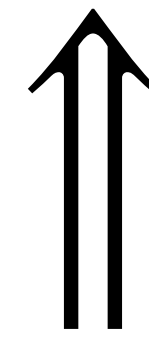
Einstein equation : $G_{\mu\nu} = T_{\mu\nu}$ $ds^2 = a^2[(1 + 2\Psi) d\eta^2 - (1 - 2\Phi) d\mathbf{x}^2]$

Perturbations

Friedmann background: $ds^2 = a^2[d\eta^2 - d\mathbf{x}^2]$

Where does this come from ?

$$\delta\rho'_R + 4\mathcal{H}\delta\rho_R = -\delta\rho'_V + 4\bar{\rho}_R\Phi$$



Newtonian gauge

$$\Phi = \Psi$$

Einstein equation : $G_{\mu\nu} = T_{\mu\nu}$

$$ds^2 = a^2[(1 + 2\Phi)d\eta^2 - (1 - 2\Phi)d\mathbf{x}^2]$$

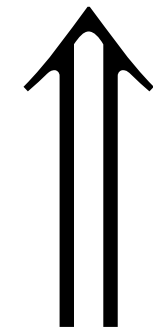
Perturbations



Friedmann background: $ds^2 = a^2[d\eta^2 - d\mathbf{x}^2]$

Where does this come from ?

$$\delta\rho'_R + 3\mathcal{H}(\delta\rho_R + \delta\rho_V) = -\delta\rho'_V$$

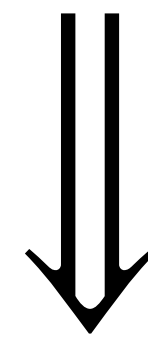


Comoving gauge

Choose B such that: $U_i = 0$

$$ds^2 = a^2 \left[(1 + 2\Phi - \mathcal{H}B - B') d\eta^2 - 2\partial_i B dx^i d\eta - (1 - 2\Phi - 2\mathcal{H}B) d\mathbf{x}^2 \right]$$

Poisson equation : $\Delta\Phi = -4\pi G\delta\rho \implies \mathcal{R}_{k=\mathcal{H}} \simeq \frac{9}{4}\delta$



$$\delta_{\text{th}} \simeq 0.5$$

