The (complicated) story of Primordial Black Holes production in cosmological Phase Transitions

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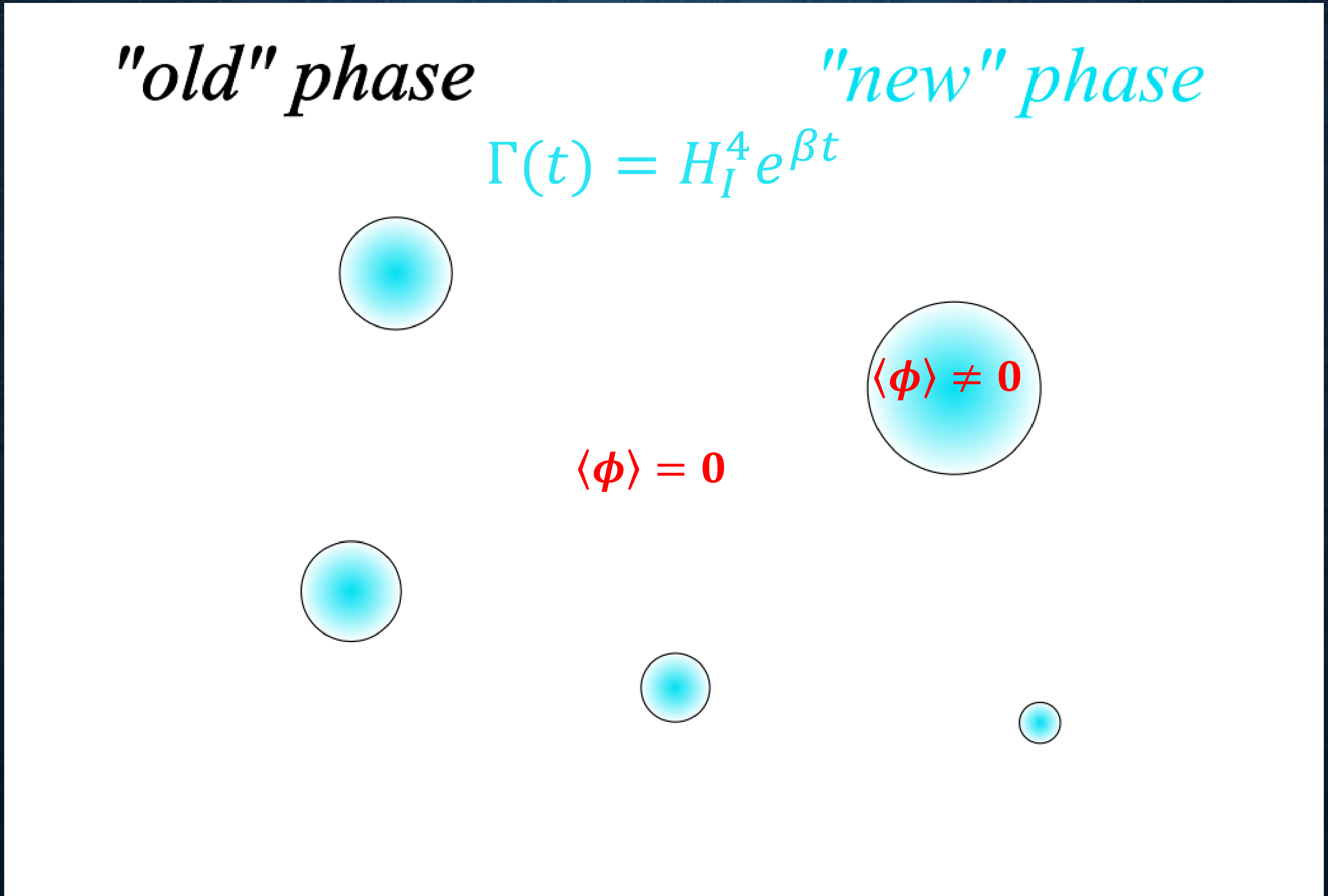
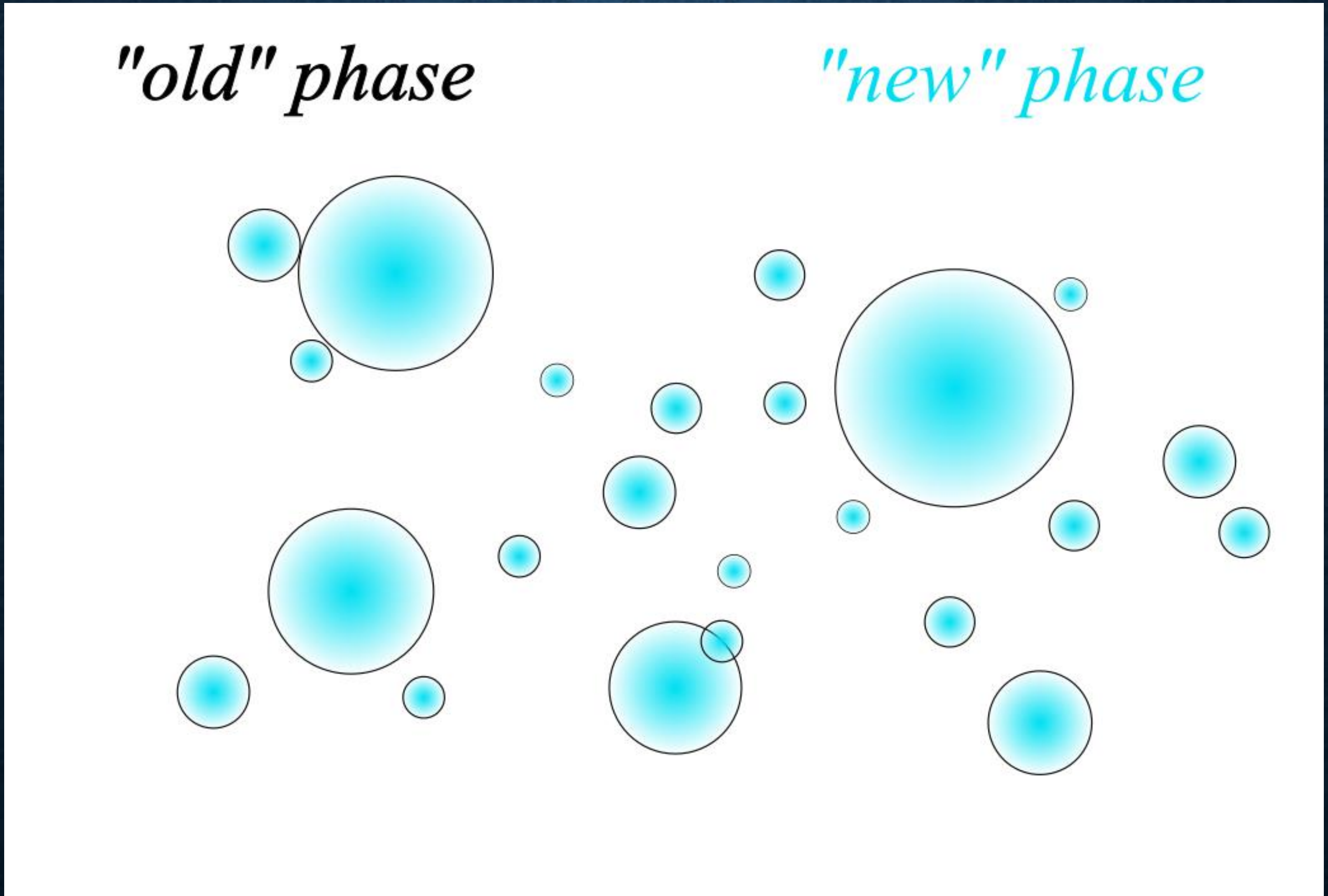
in collaboration with
Marek Lewicki and Ville Vaskonen

Part I – Bright prospects of PBHs

Why would we expect PBHs to form?

"old" phase


"old" phase
"new" phase
$\Gamma(t) = H_I^4 e^{\beta t}$
$\langle\phi\rangle \neq 0$
$\langle\phi\rangle = 0$


"old" phase
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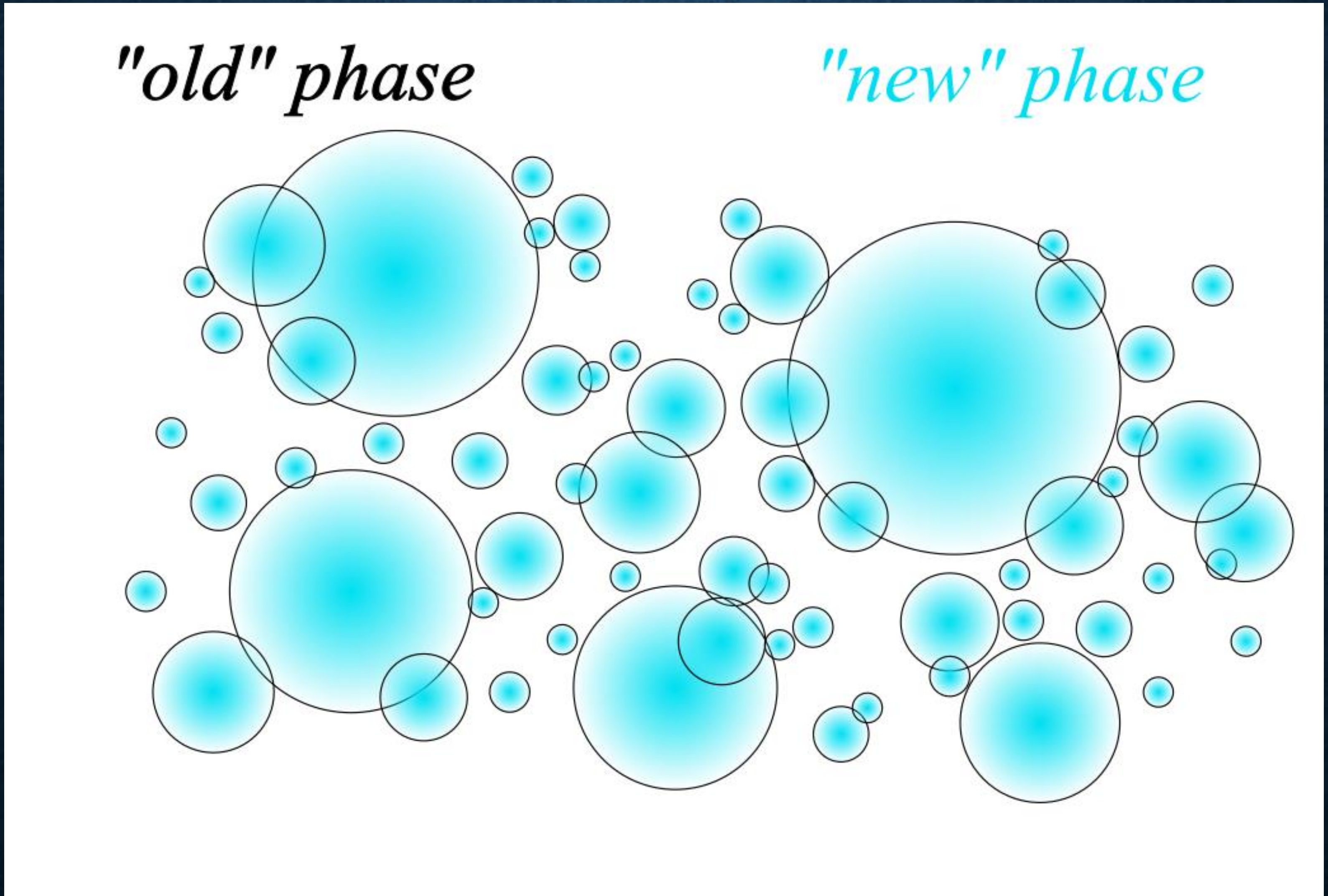
"old" phase
"new" phase

BLACK HOLE FORMATION

Statistical nature of bubble nucleation

↓

inhomogeneitites

Slow, supercooled transition

↓

period of thermal inflation

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Statistical nature of bubble nucleation

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Slow, supercooled transition

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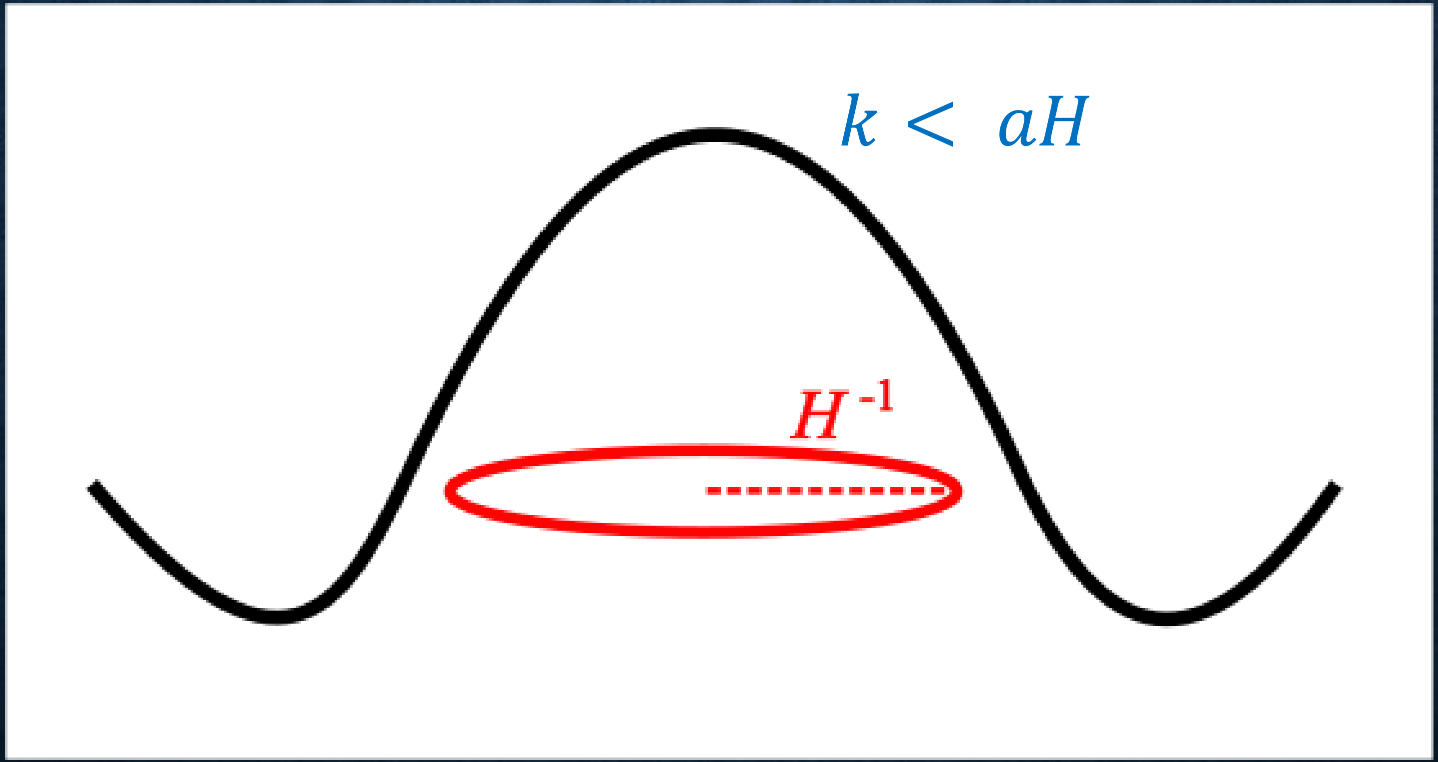
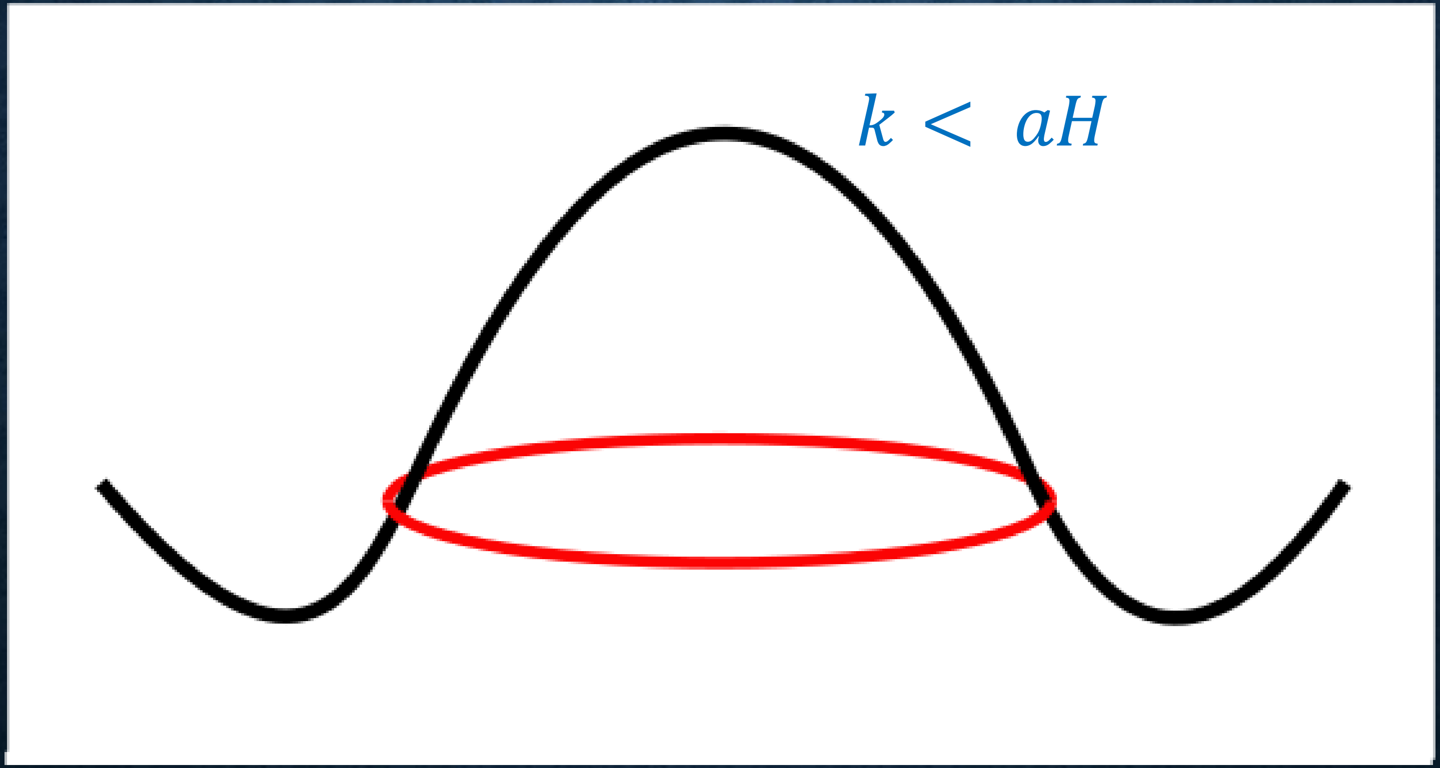
period of thermal inflation

$$\dot{\rho}_r + 4H\rho_r = -\dot{\rho}_v$$

Large fluctuations of energy density

$$\delta = \frac{\rho - \rho_b}{\rho_b}$$


$k < aH$
H^{-1}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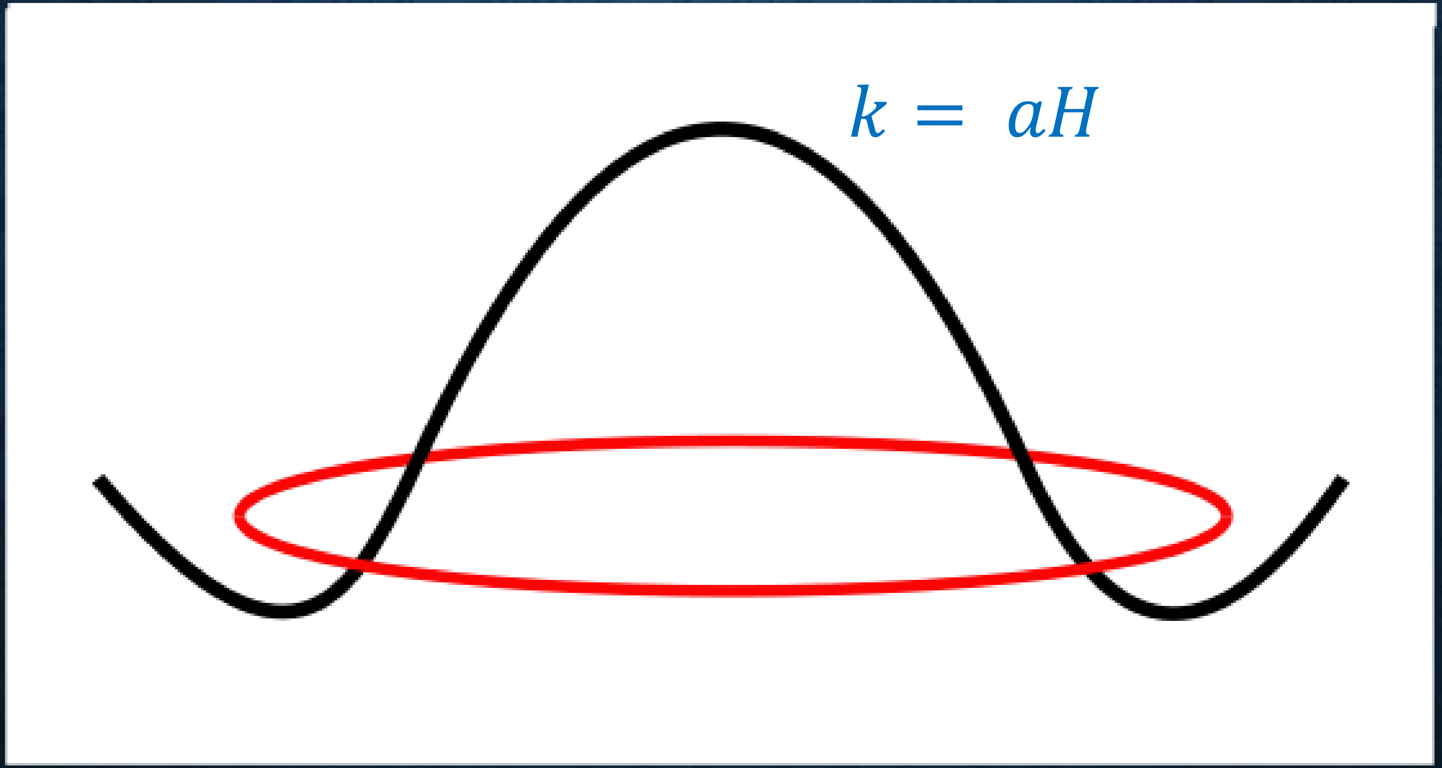
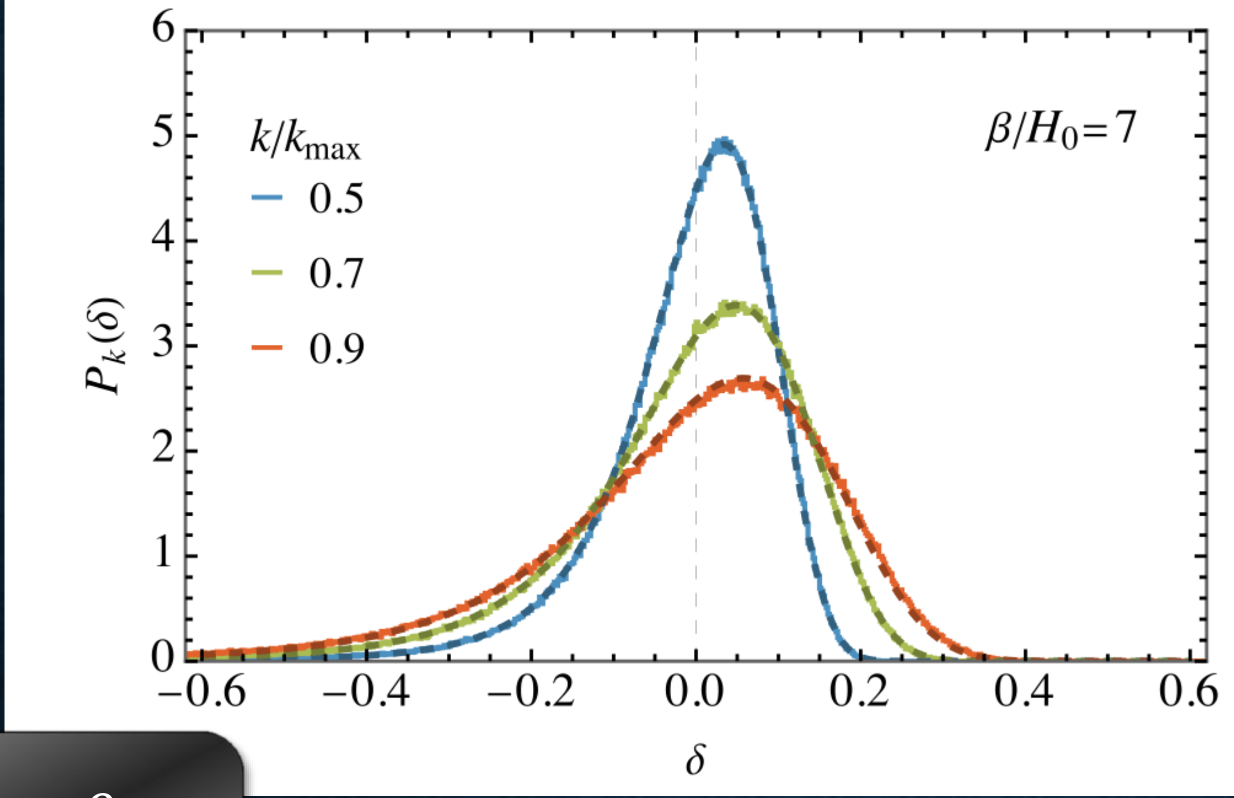

$k = aH$

BLACK HOLE FORMATION

Strategy:

perform the evolution of different-sized patches described by the wavenumber k

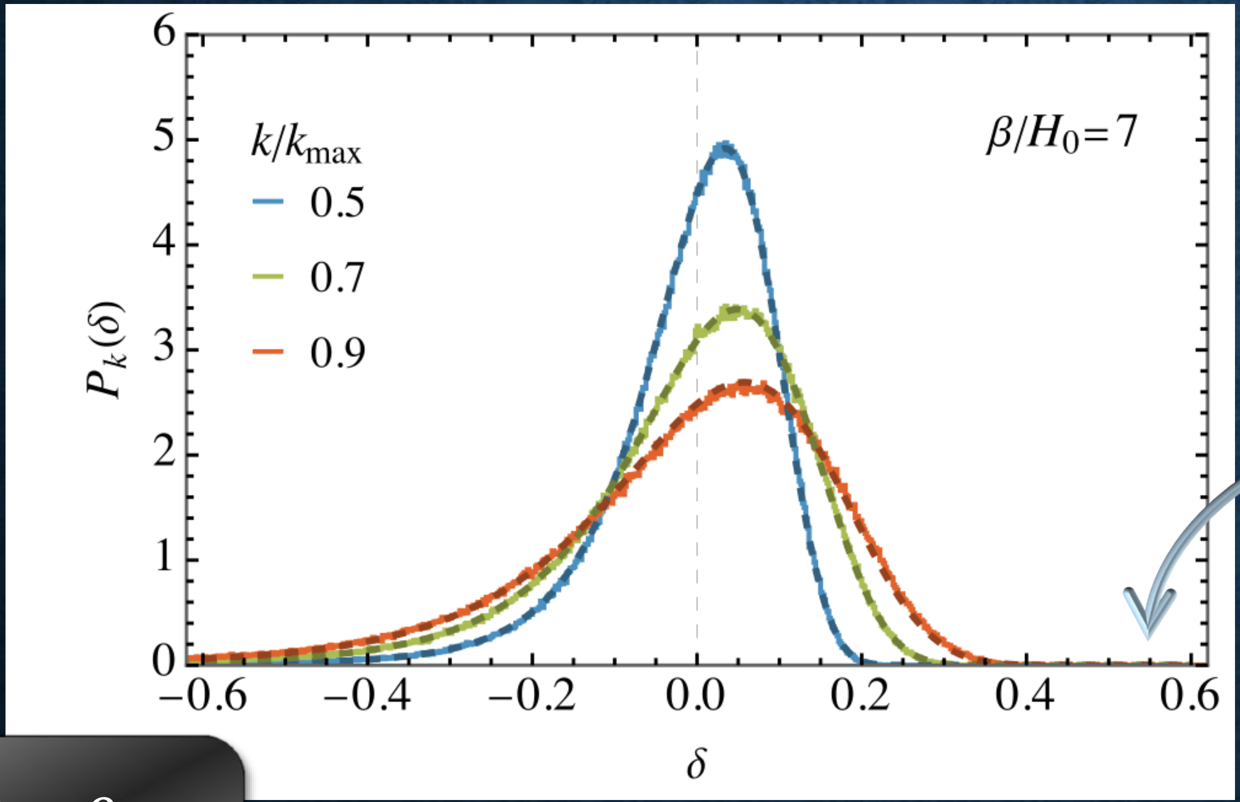
BLACK HOLE FORMATION



$$\Gamma(t) \approx H_I^4 e^{\beta t}$$

$$\delta = \frac{\rho - \rho_b}{\rho_b}$$

BLACK HOLE FORMATION



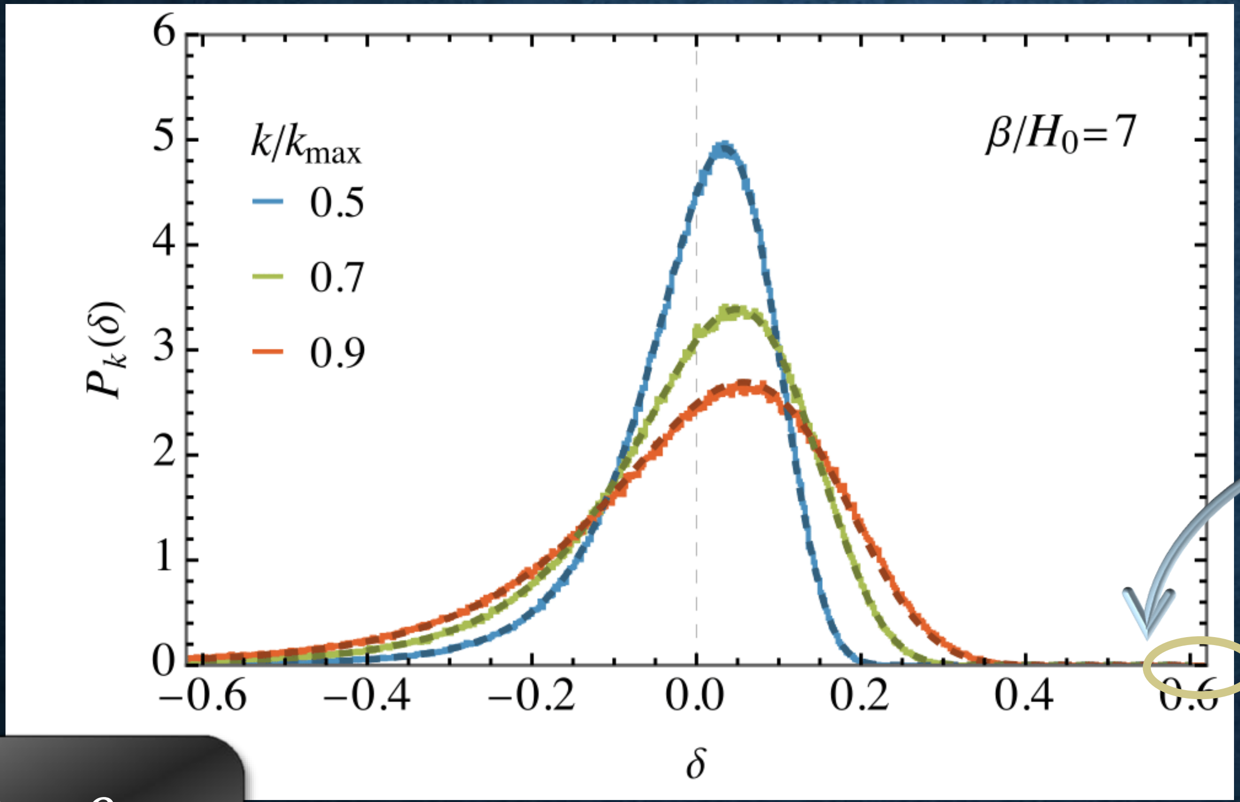
Critical scaling law

$$M(\delta) = \kappa M_k(\delta - \delta_c)^\gamma$$

$$\delta_c = 0.55$$

$$\delta = \frac{\rho - \rho_b}{\rho_b}$$

BLACK HOLE FORMATION



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PBH formation

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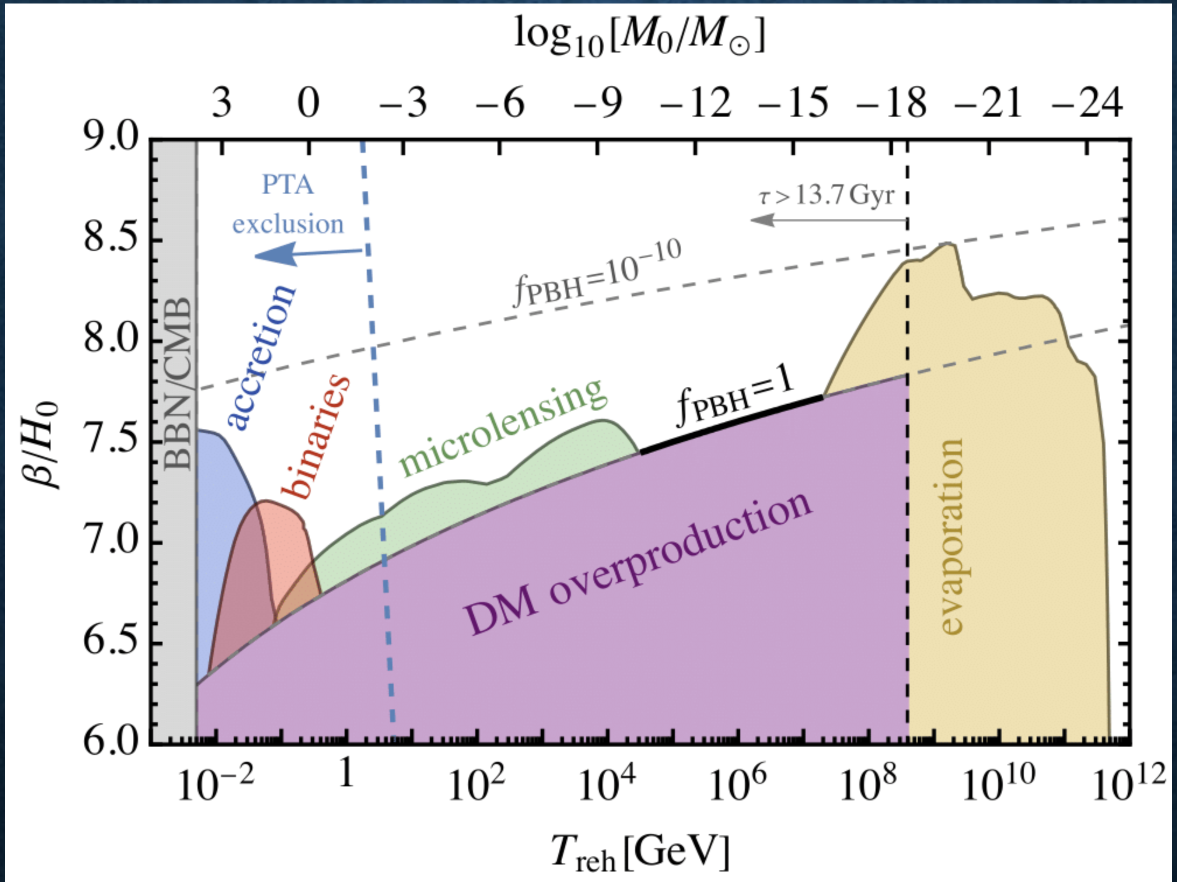
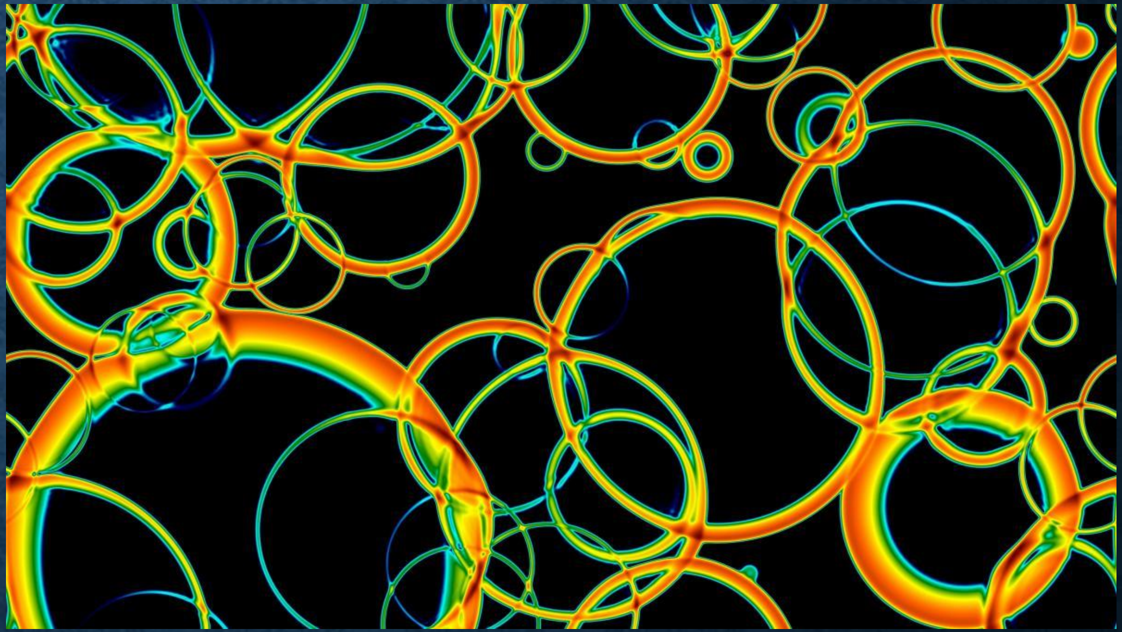


GRAVITATIONAL WAVES

During phase transition:

- bubble collisions
- sound waves in plasma



D. Weir, University of Helsinki

GRAVITATIONAL WAVES

During phase transition:

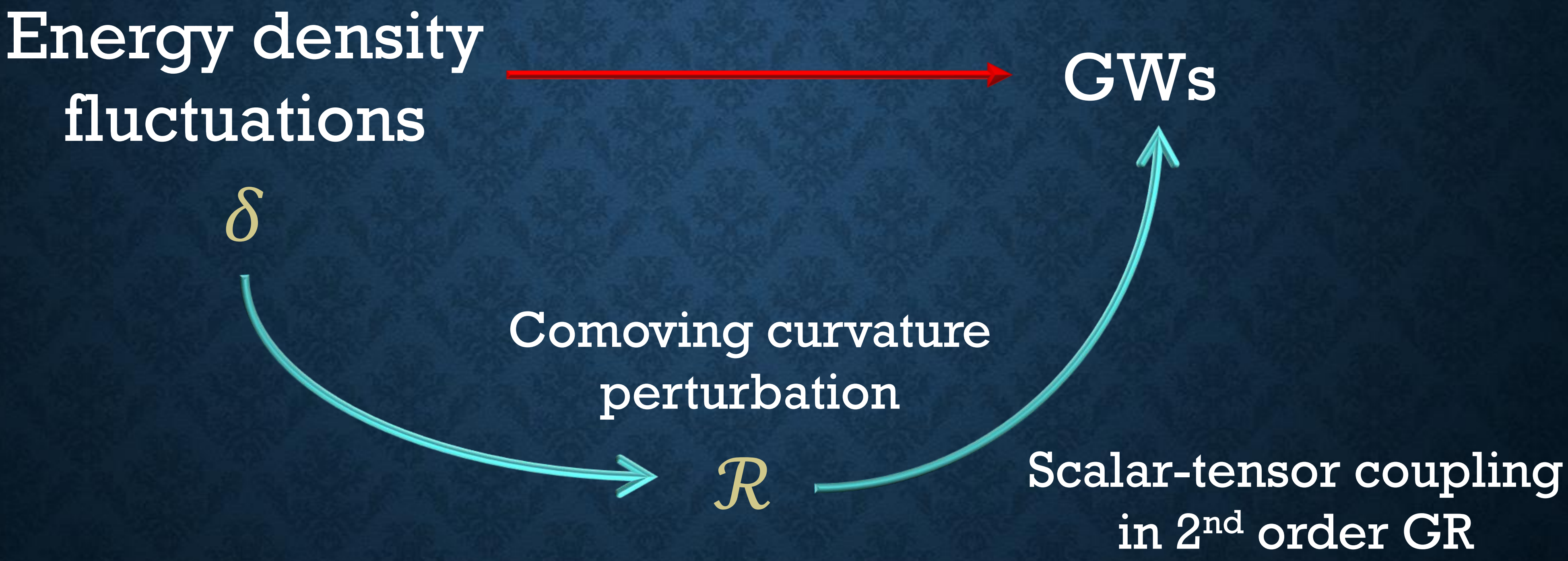
- bubble collisions
- sound waves in plasma

Second order effects?

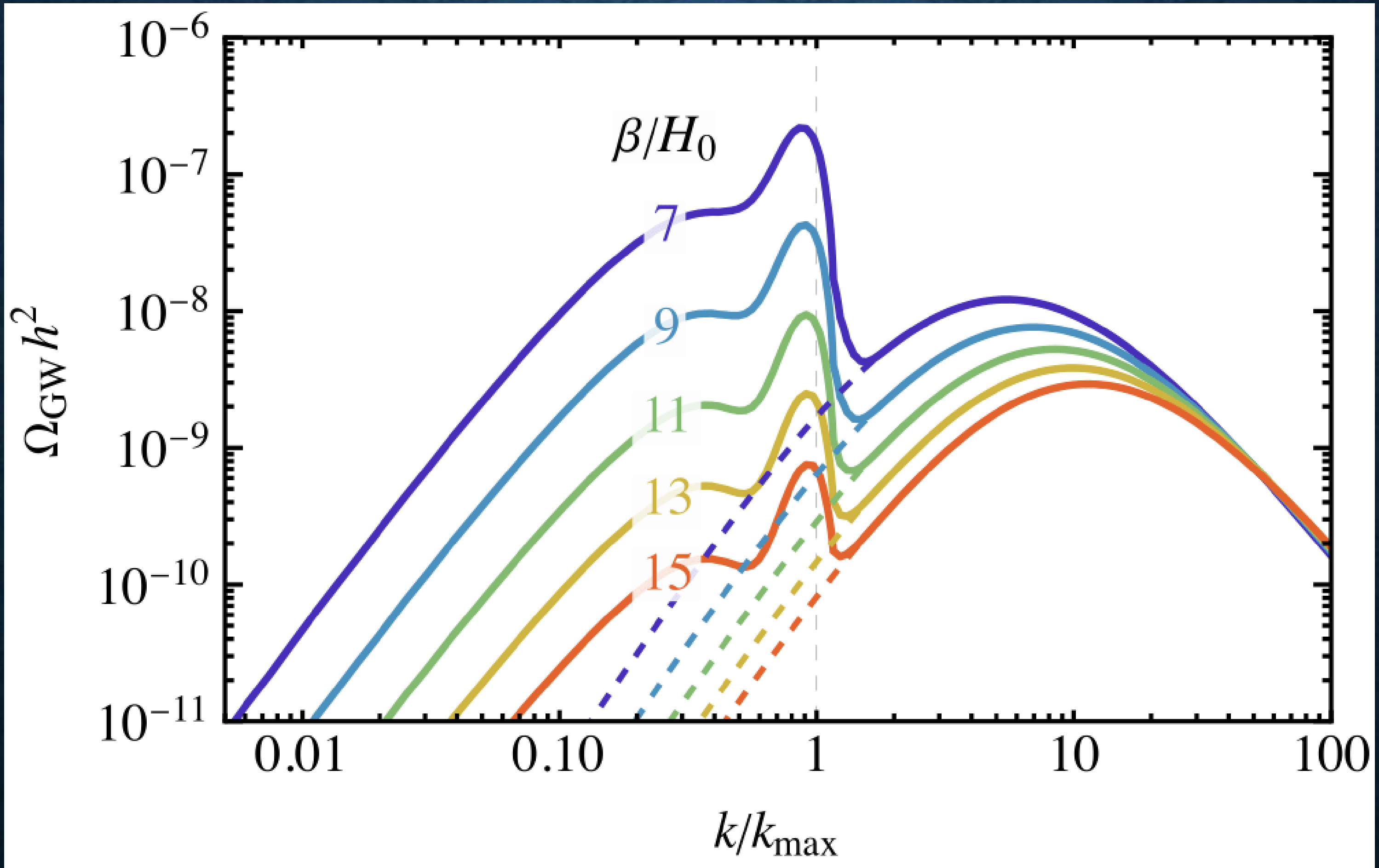
- scalar induced gravitational waves

Energy density fluctuations → GWs

SCALAR INDUCED GRAVITATIONAL WAVES



Gravitational Waves



Part II – The tragedy is revealed

Based on work by
G. Franciolini, Y. Gouttenoire and R. Jinno
[2503.01962]

THE TROUBLE BEHIND IT ALL

Discussing energy density fluctuations, we introduce

$$\rho_k = \bar{\rho} + \delta\rho_k$$

Background

Linear perturbation

THE TROUBLE BEHIND IT ALL

We are working with objects in linear regime of GR perturbation theory

!

THE TROUBLE BEHIND IT ALL

We are working with objects in linear regime of GR perturbation theory

!

We have to employ full linearized GR formalism!

LINEARIZED GENERAL RELATIVITY

Gauge dependence

Gauge invariant quantities

$\Phi_B, \Psi_B, \zeta, \mathcal{R}, \delta\rho_m$

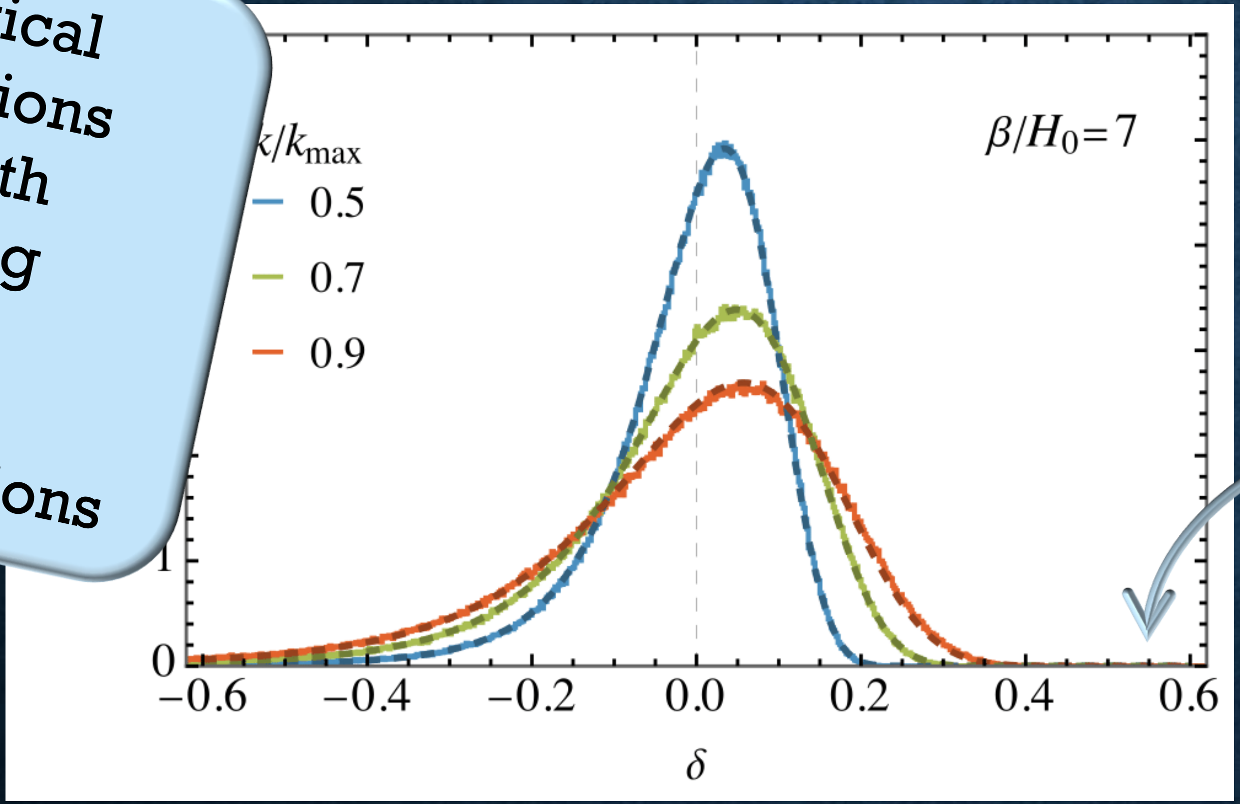
Gauge freedom

- longitudinal gauge
- comoving gauge

…

BLACK HOLE FORMATION

Numerical simulations work with comoving energy density perturbations



Critical scaling law

$$M\left(\delta^{(C)}\right) = \kappa M_k \left(\delta^{(C)} - \delta_c^{(C)}\right)^{\gamma}$$

$$\delta_c^{(C)} = 0.55$$

$$\delta^{(C)} = \frac{\rho^{(C)} - \rho_b}{\rho_b} = \frac{\delta\rho_m}{\rho_b}$$

STRATEGY

Solve the dynamics in different Hubble patches during the transition and find the distribution of $\delta^{(C)}$ working in the comoving gauge

OR

Compute the evolution in the gauge of your choice and translate the density contrast $\delta^{(*)}$ into $\delta^{(C)}$

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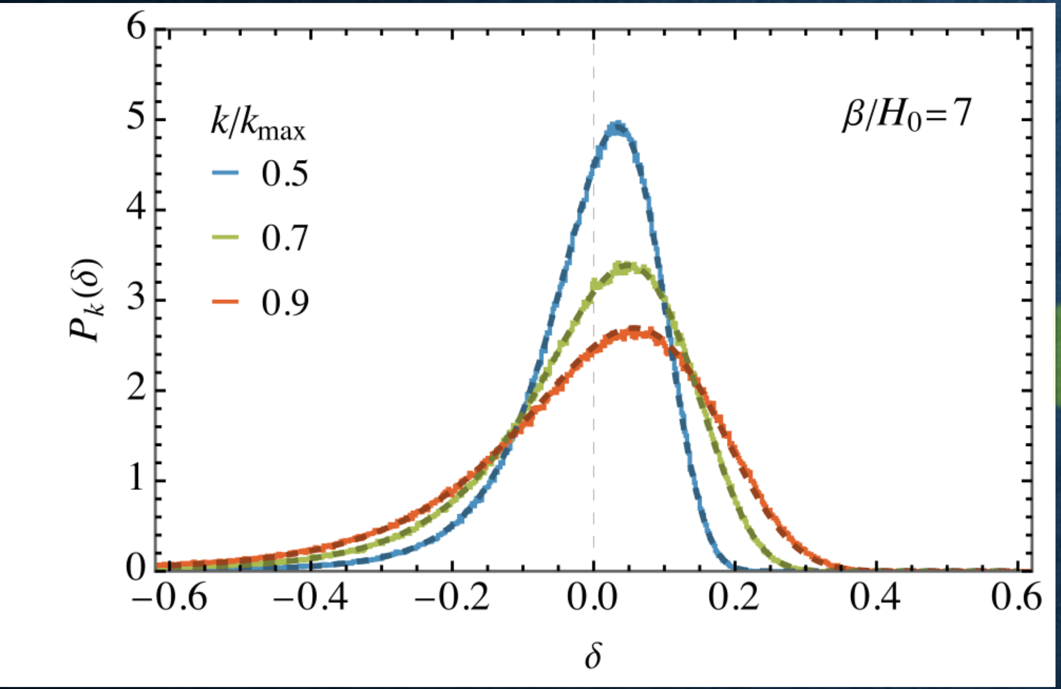
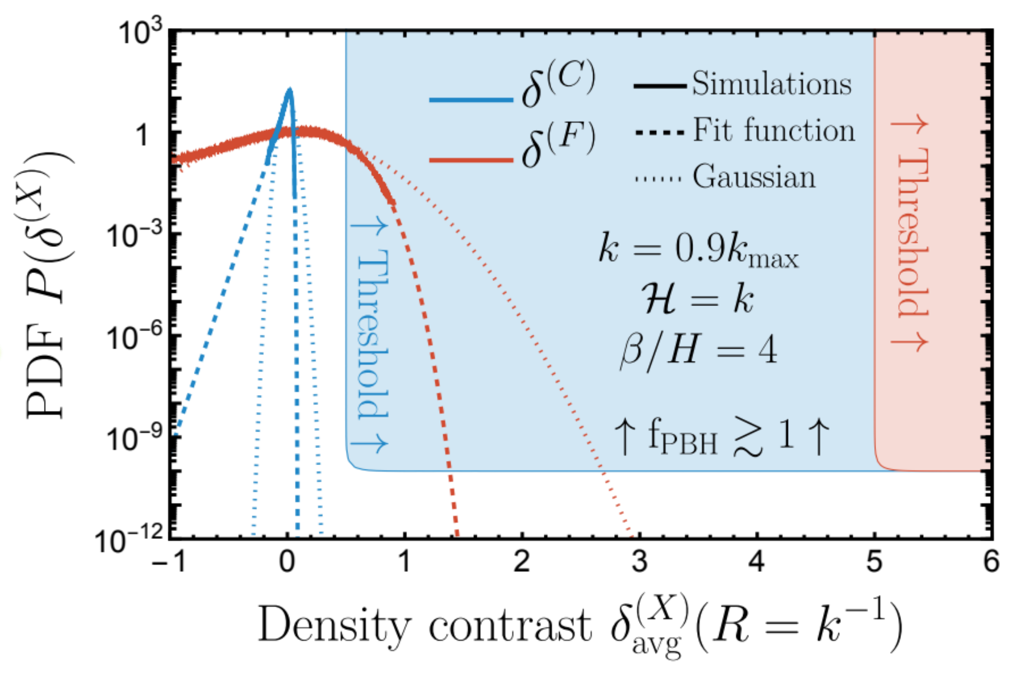
RESULTS





G. Franciolini, Y. Gouttenoire, R. Jinno, arXiv: 2503.01962

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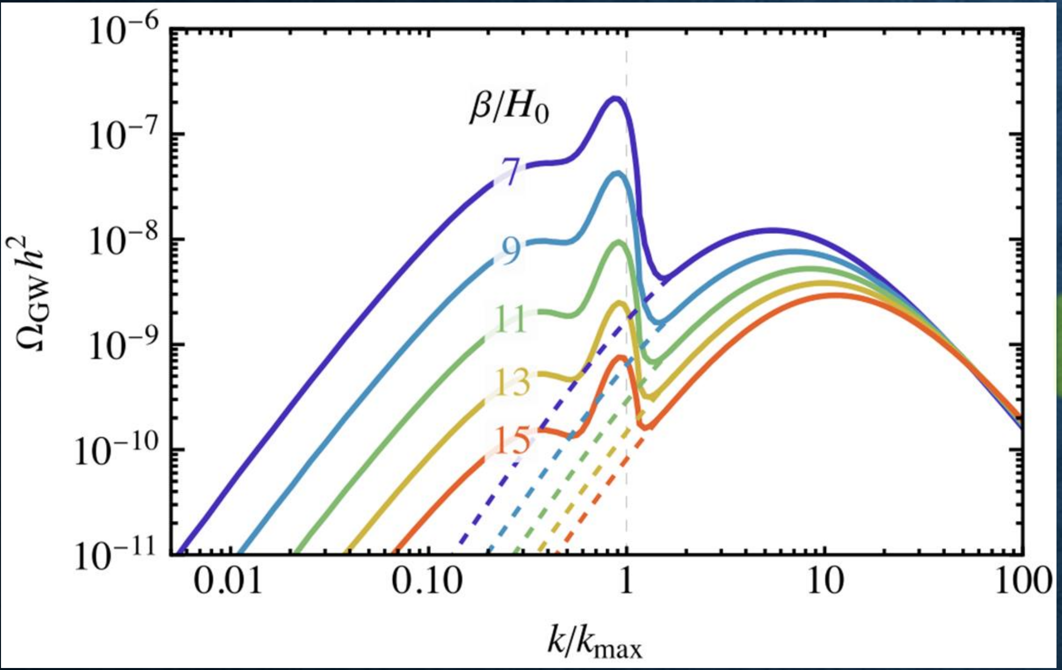

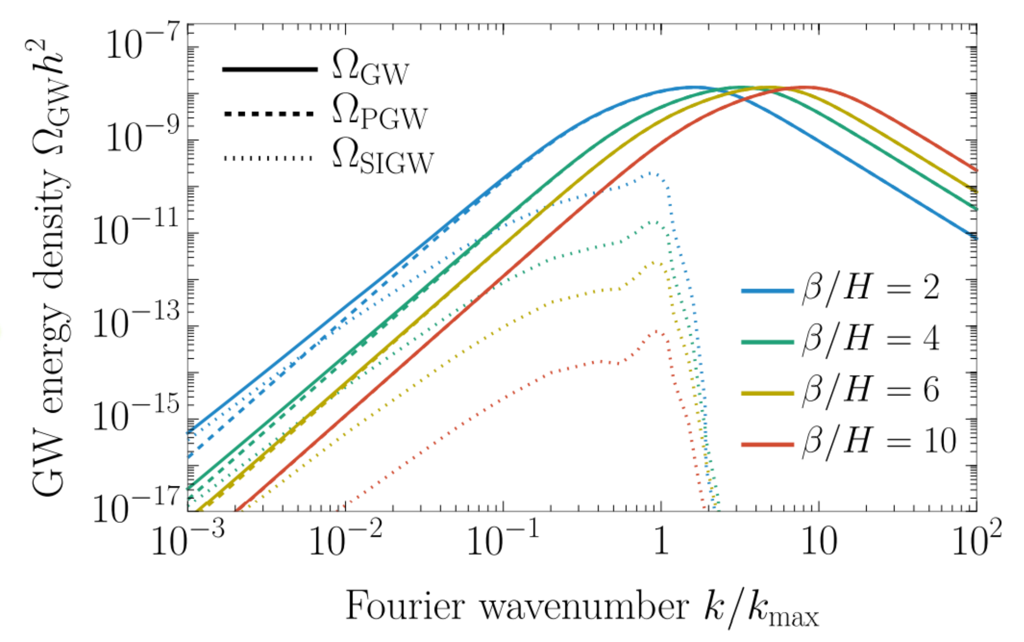

G. Franciolini, Y. Gouttenoire,
R. Jinno, arXiv: 2503.01962

CONCLUSIONS

No PBHs from first-order phase transitions

No visible secondary GW signals

IS THERE ANY HOPE?

- Expand the nucleation rate to 2nd order

$$\Gamma(t) \approx H_I^4 e^{\beta t - \gamma^2 t^2}$$

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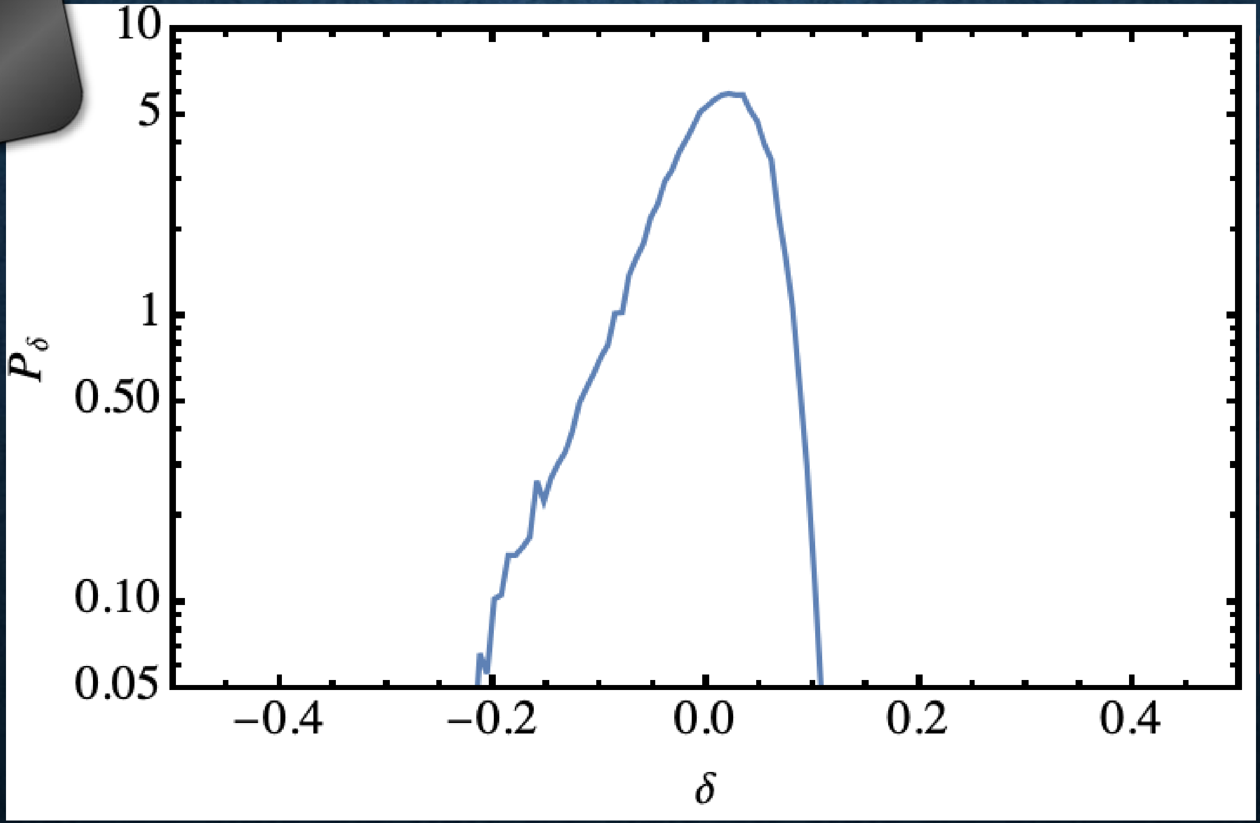
Does not help ☹

$\beta / H_I = 4$
$\gamma / \beta = 0.4$



PBH formation

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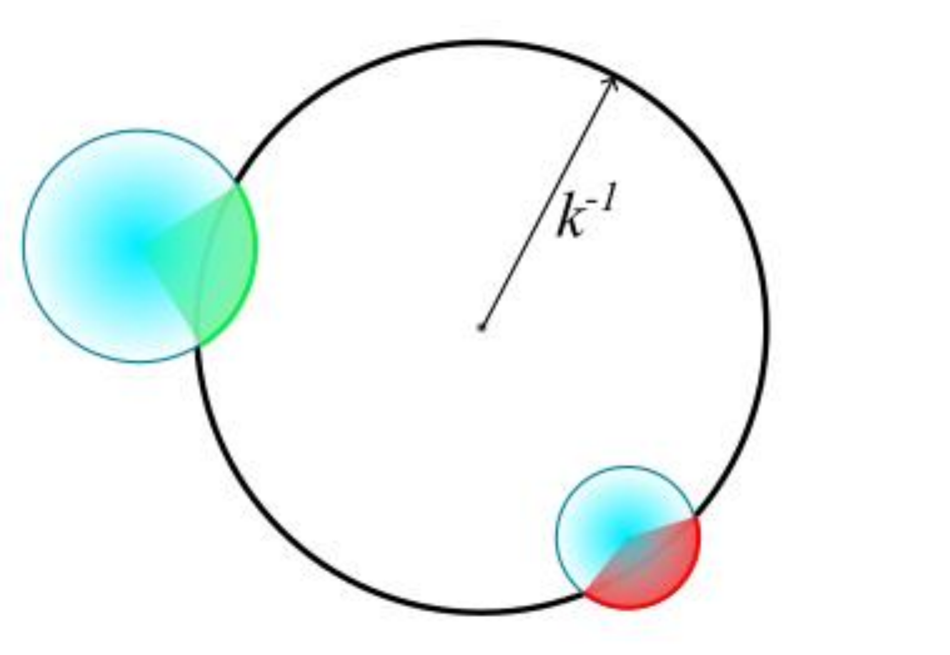

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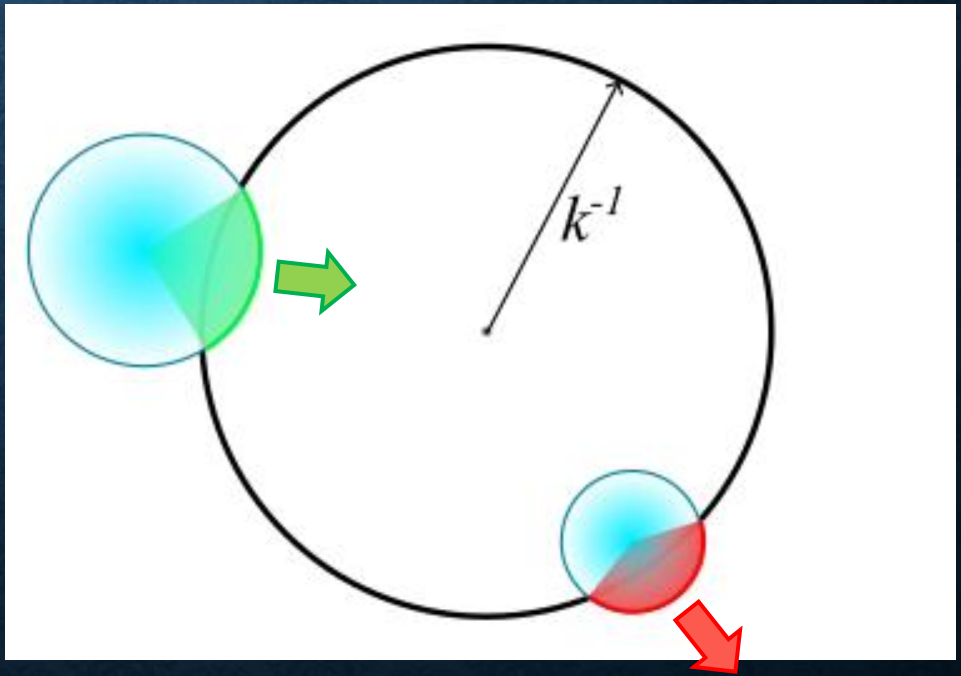

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Work in progress

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- Consider different EoS after the transition:

  Scalar field oscillation → early MD

  QCD phase transition

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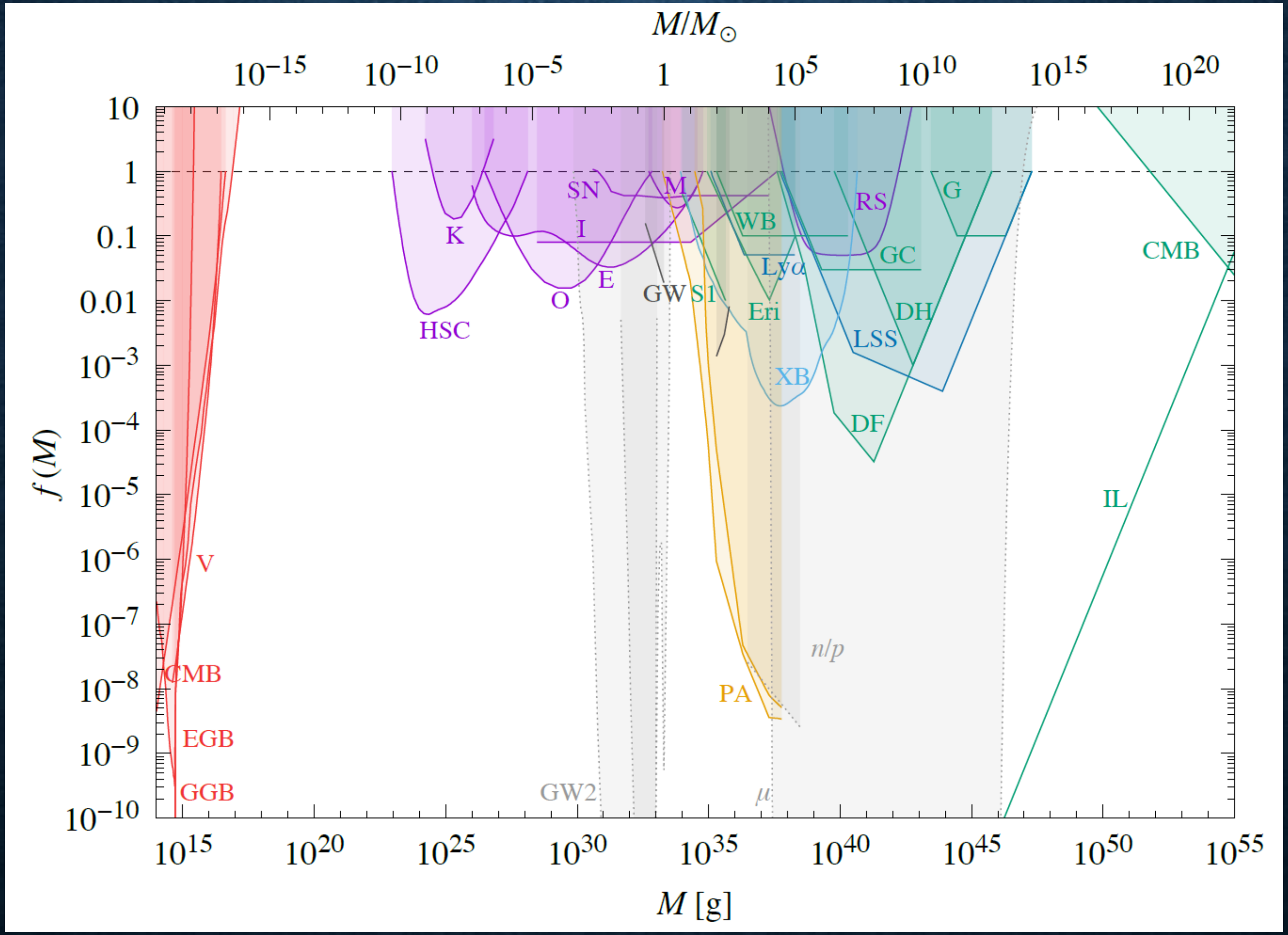
Distant (?) Future work

Thank you!

PBHs AS DARK MATTER CANDIDATES



B. Carr, K. Kohri, Y. Sendouda, J. Yokoyama, *Rept. Prog. Phys.* **84** (2021) 11, 116902

SUPERCOOLED PHASE TRANSITION

nucleation of true vacuum bubbles

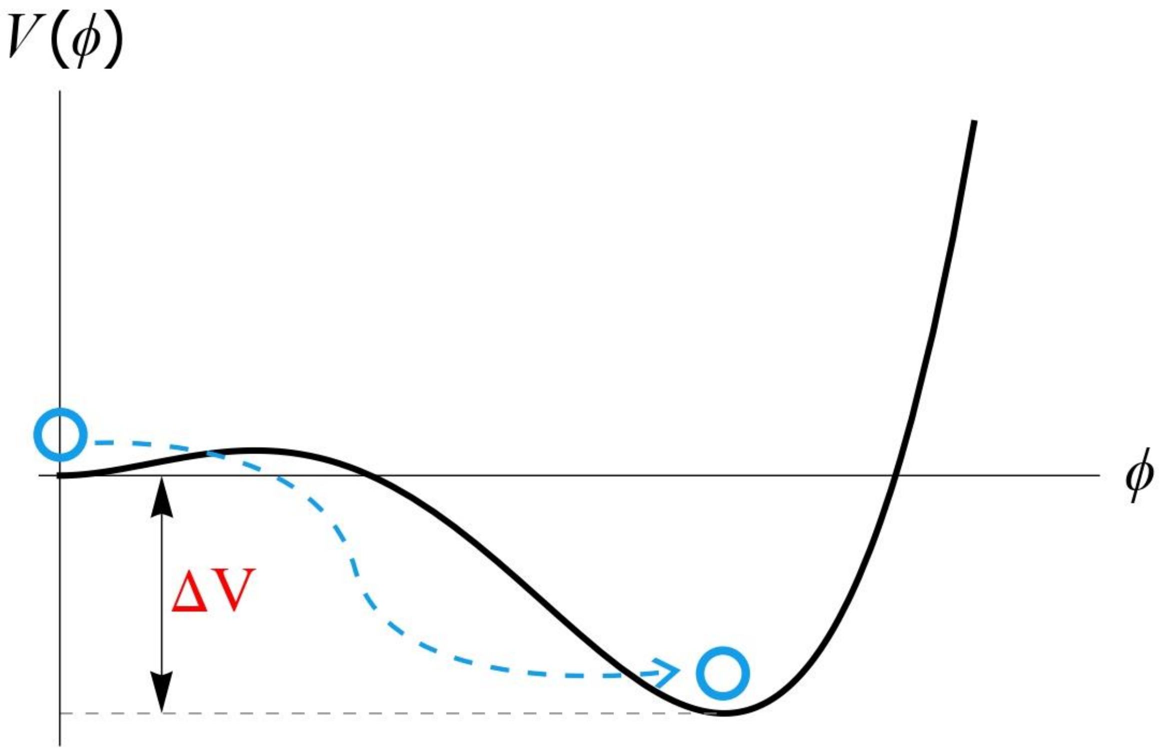
$$\Gamma(t) \approx H_I^4 e^{\beta t}$$

Transition strength

$$\alpha \approx \frac{\Delta V}{\rho_r} \gg 1$$

bubble wall velocity

$$v_w \approx 1$$



BLACK HOLE FORMATION

density distribution $P_k(\delta)$

fraction of total energy density collapsing to PBHs

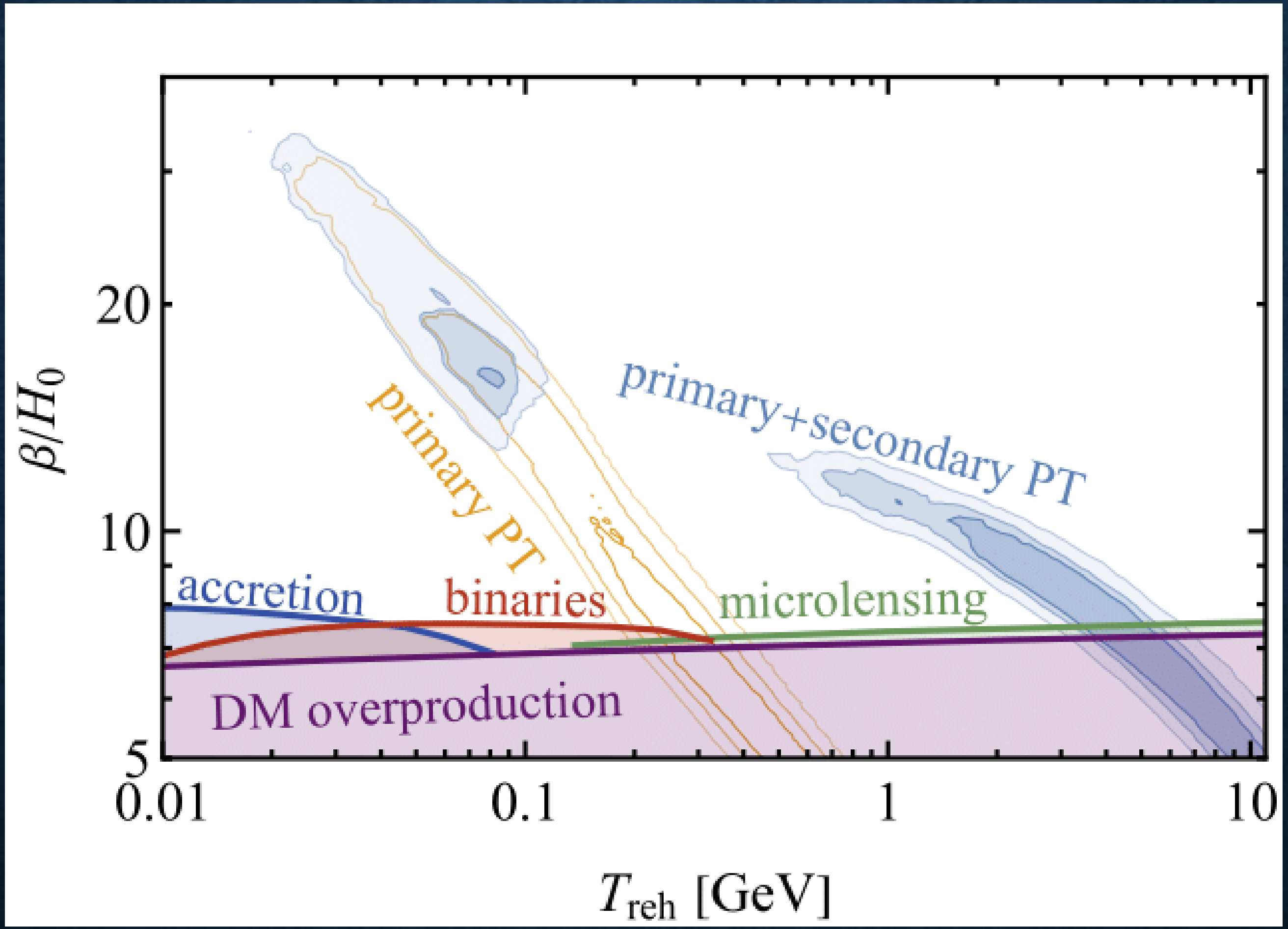
$$\beta_k(M) = \int_{\delta_c} \mathrm{d}\delta \, \frac{M}{M_k} P_k(\delta) \delta_D \left(\ln \frac{M}{M(\delta)} \right)$$

present PBH mass function

$$\psi(M) = \int \mathrm{d} \ln k \, \beta_k(M) \frac{\rho_r(T_k)}{\rho_c} \frac{s(T_0)}{s(T_k)}$$

PBH abundance $\Omega_{PBH} = \int \mathrm{d} \ln M \, \psi(M)$

GRAVITATIONAL WAVES



GRAVITATIONAL WAVES