

# *Realising DM and NANOGrav data via Dark Branes*

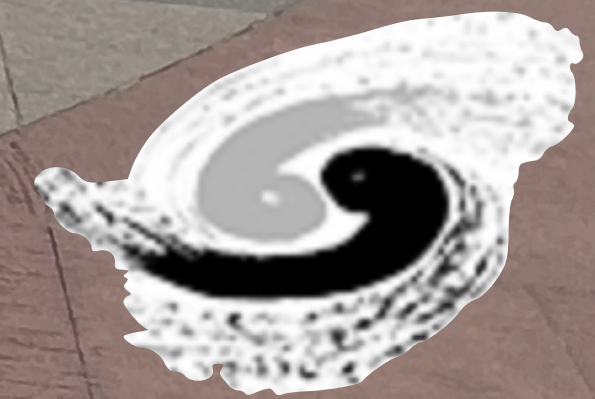
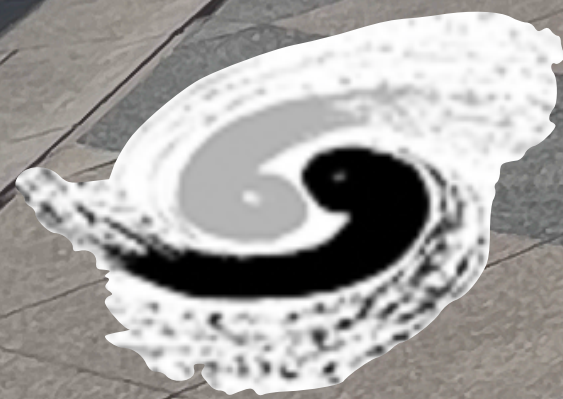
22/09/2025 @SCALARS 2025

Fotis Koutroulis  
Institute of High Energy Physics,  
China Center of Advanced Science and Technology

Based on *Phys. Rev. D* 110, 055015

In collaboration with:

*E. Megias, S. Pokorski, M. Quiros*





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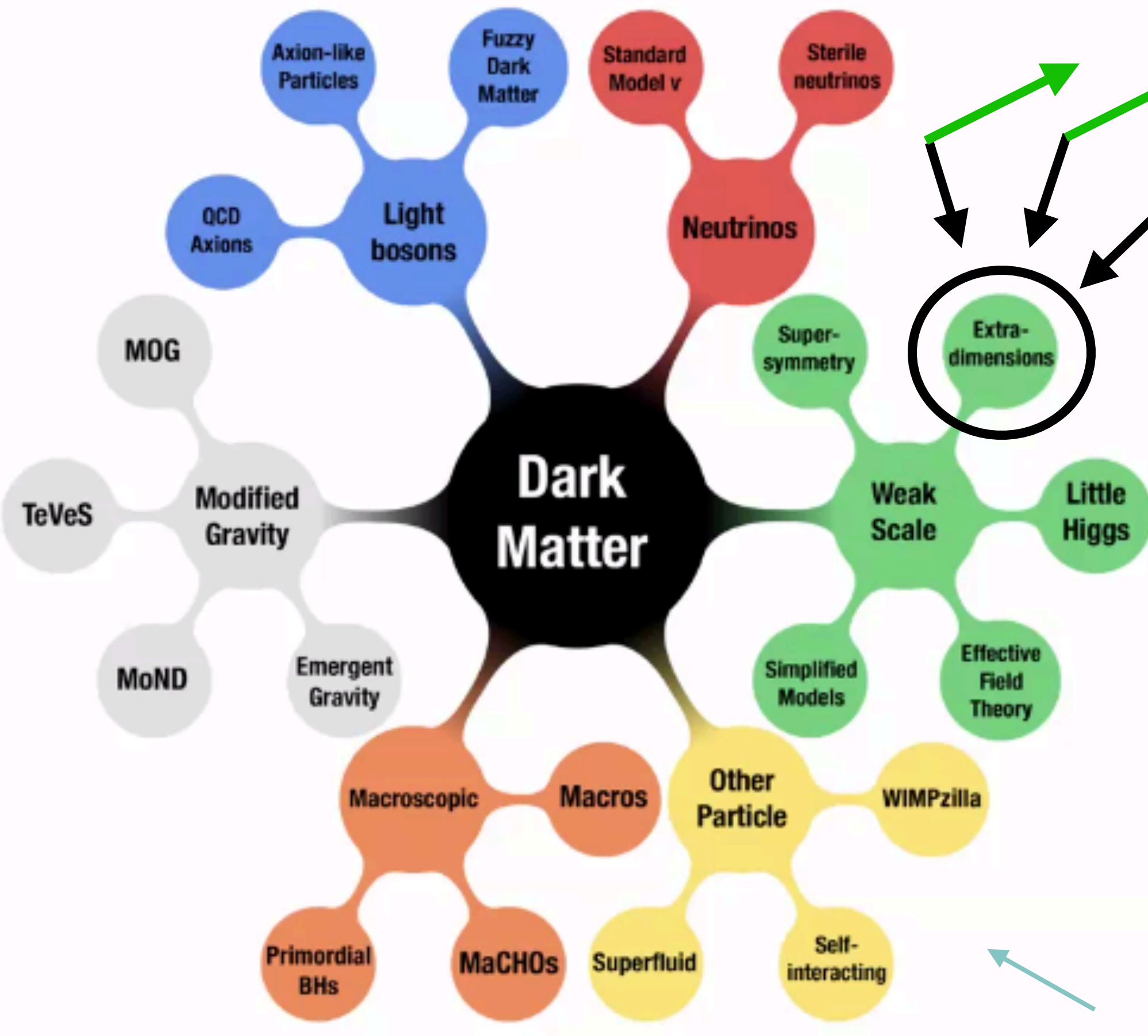


## Intro

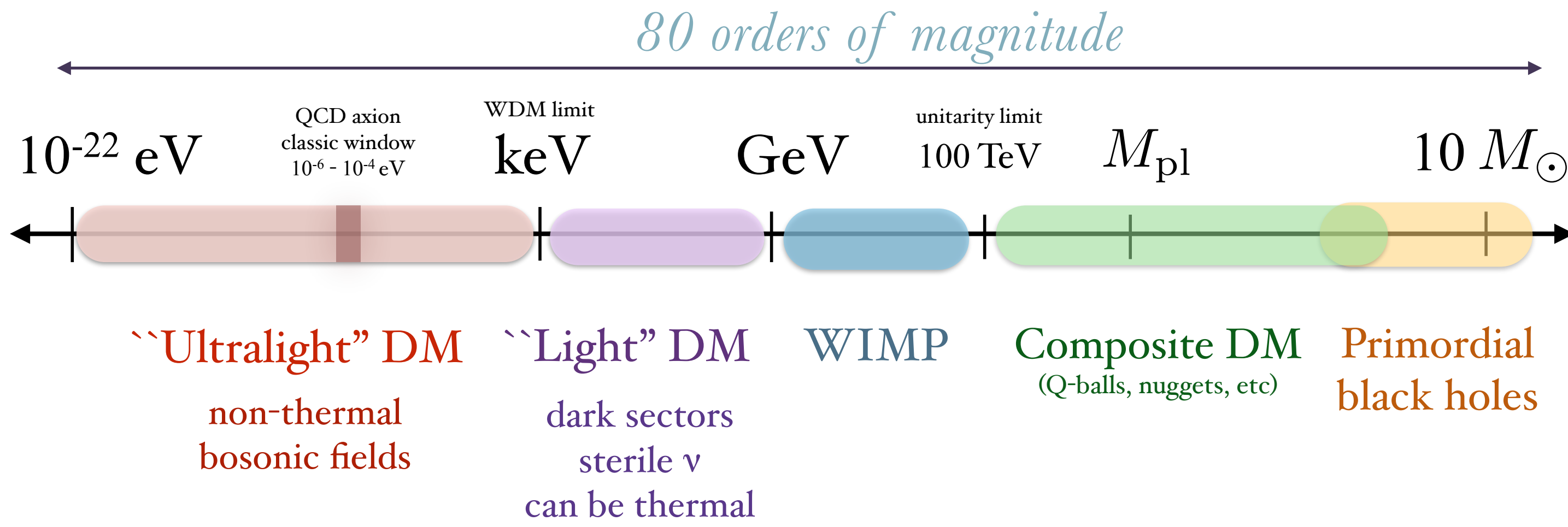
- Compelling evidence for the existence of Dark Matter (DM) on different astrophysical scales (galactic, clusters of galaxies, cosmological scale,...)
- $\sim 84\%$  of the matter in the Universe is DARK
- DM candidate: **stable** (lifetime must be long compared to cosmological timescales), (dominantly) **Non-relativistic**, **electrically neutral** and **colorless**. (Only?) **gravitational interactions**
- Usual problem with DM candidates (e.g. WIMPs): **Conflict** between relic abundance and direct/indirect/accelerator searches because of **interactions with the SM**



# DM LANDSCAPE



*Warped extra dimensional model with three 3-branes, an extended Randall-Sundrum (RS) model*



*Bertone and Tait, Nature '18*

*Tongyan Lin '19  
TASI lectures on DM*

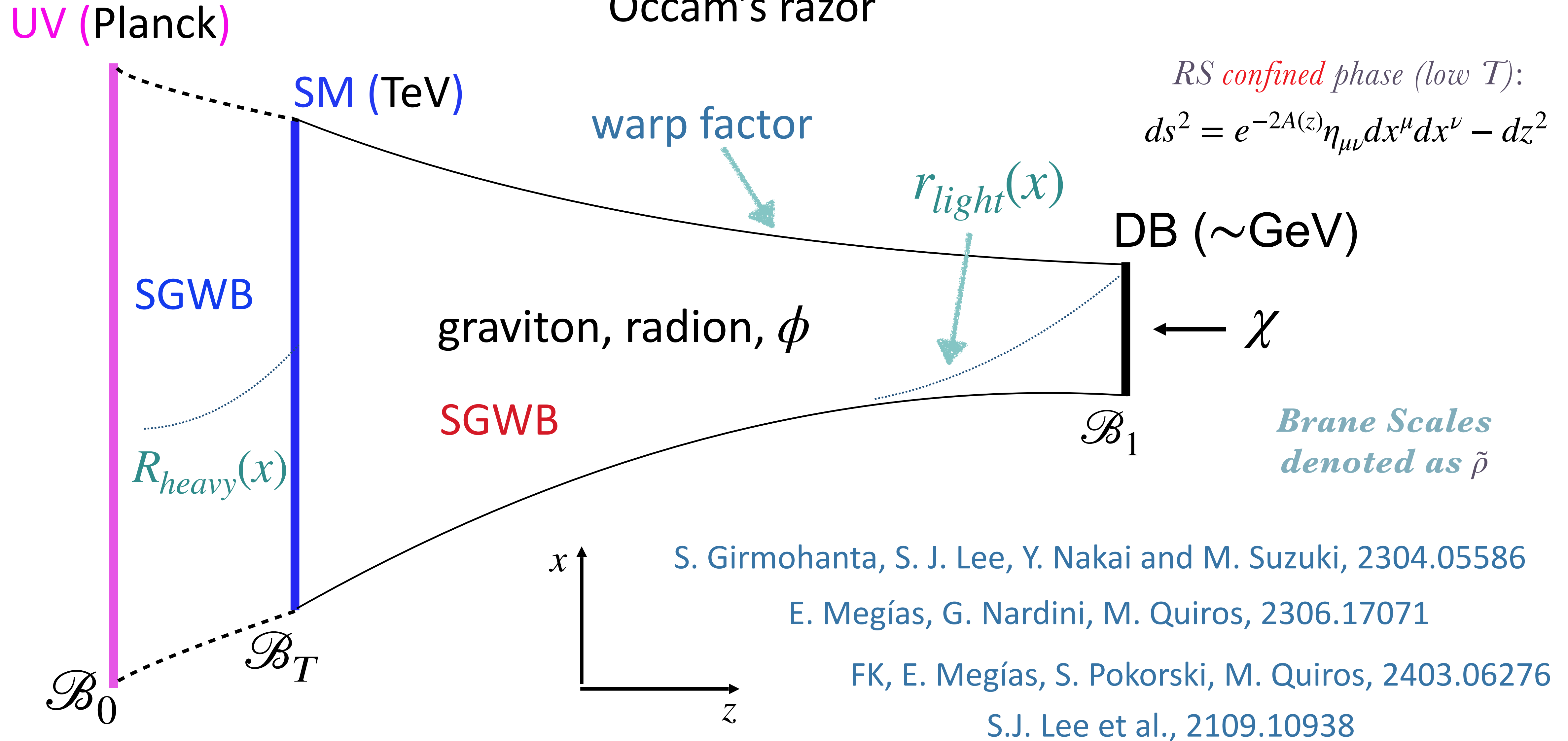


# **DARK MATTER (SECTOR) SETUP**



# The simplest 5D model

Occam's razor



S. Girmohanta, S. J. Lee, Y. Nakai and M. Suzuki, 2304.05586

E. Megías, G. Nardini, M. Quiros, 2306.17071

FK, E. Megías, S. Pokorski, M. Quiros, 2403.06276

S.J. Lee et al., 2109.10938



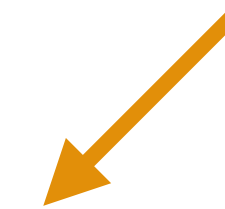
# PTA's SGWB with three branes

*See Mariano's talk  
on PBH*

*BH deconfined phase (high  $T$ ):*  $ds^2 = e^{-2A(z)}[h(z)dt^2 - d\vec{x}^2] - \frac{1}{h(z)}dz^2$

*RS confined phase (low  $T$ ):*  $ds^2 = e^{-2A(z)}\eta_{\mu\nu}dx^\mu dx^\nu - dz^2$

PTA region



Part I

Part II

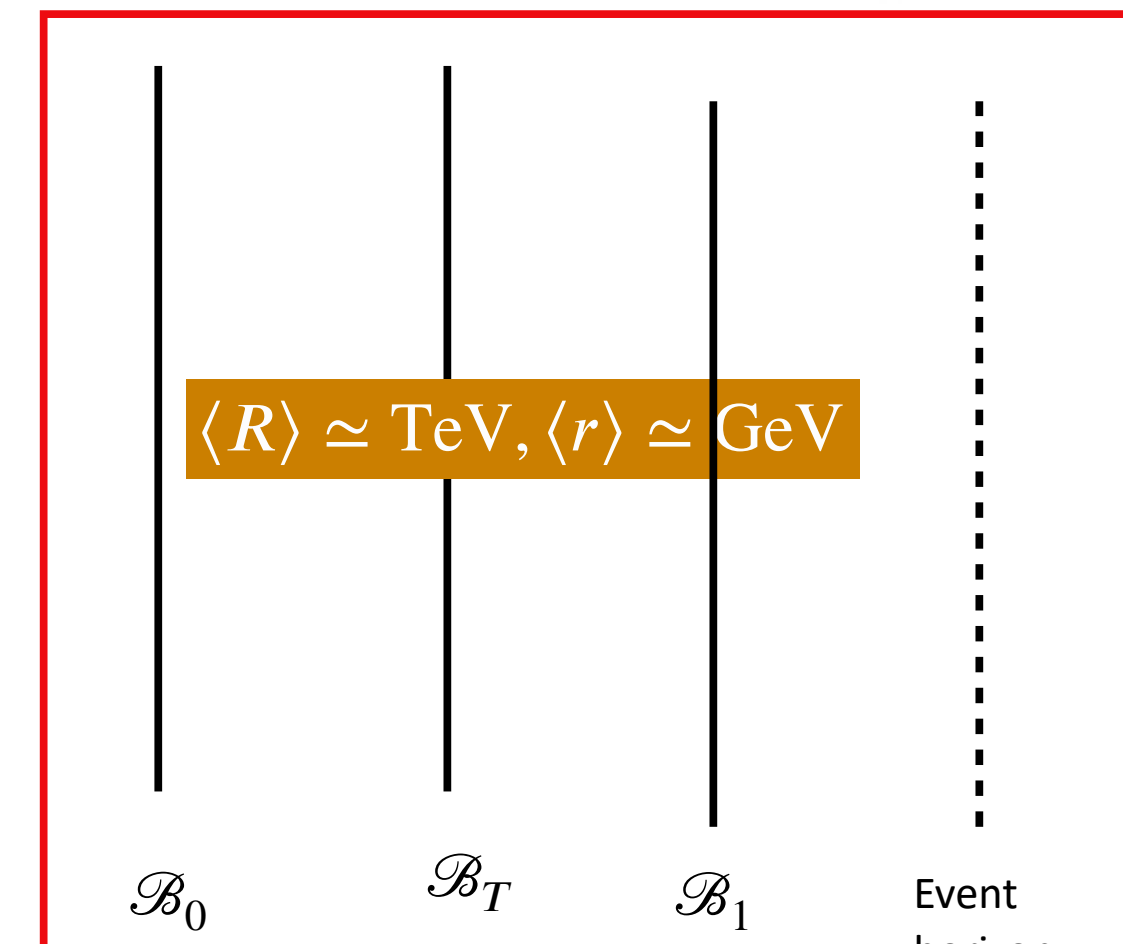
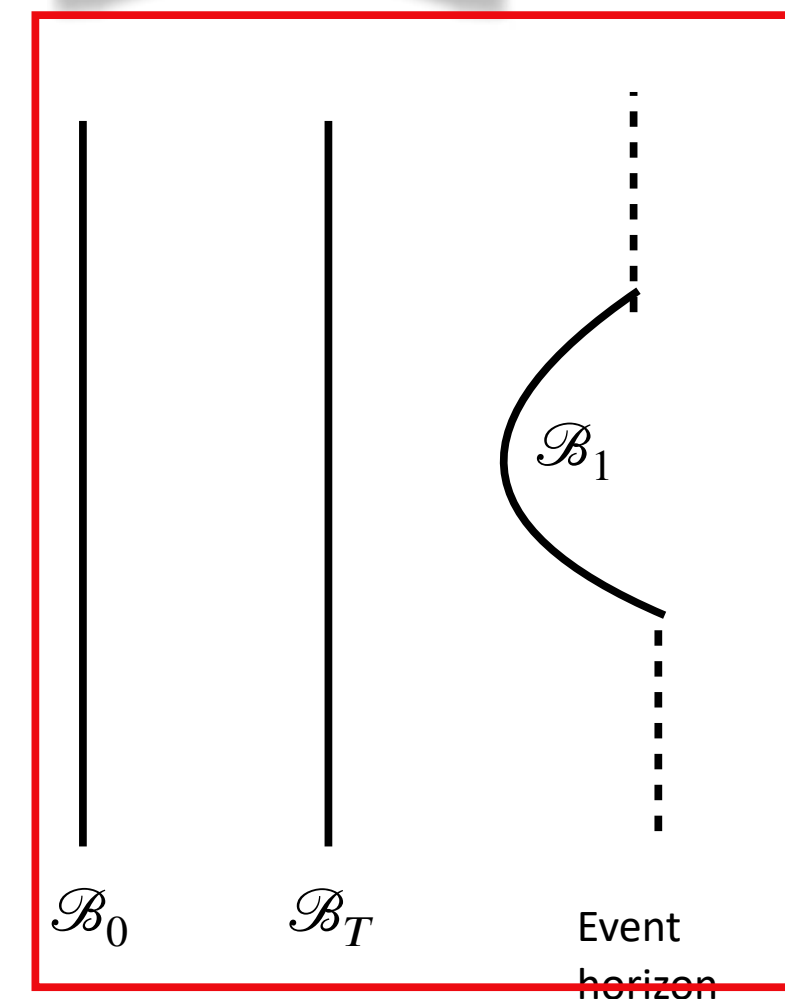
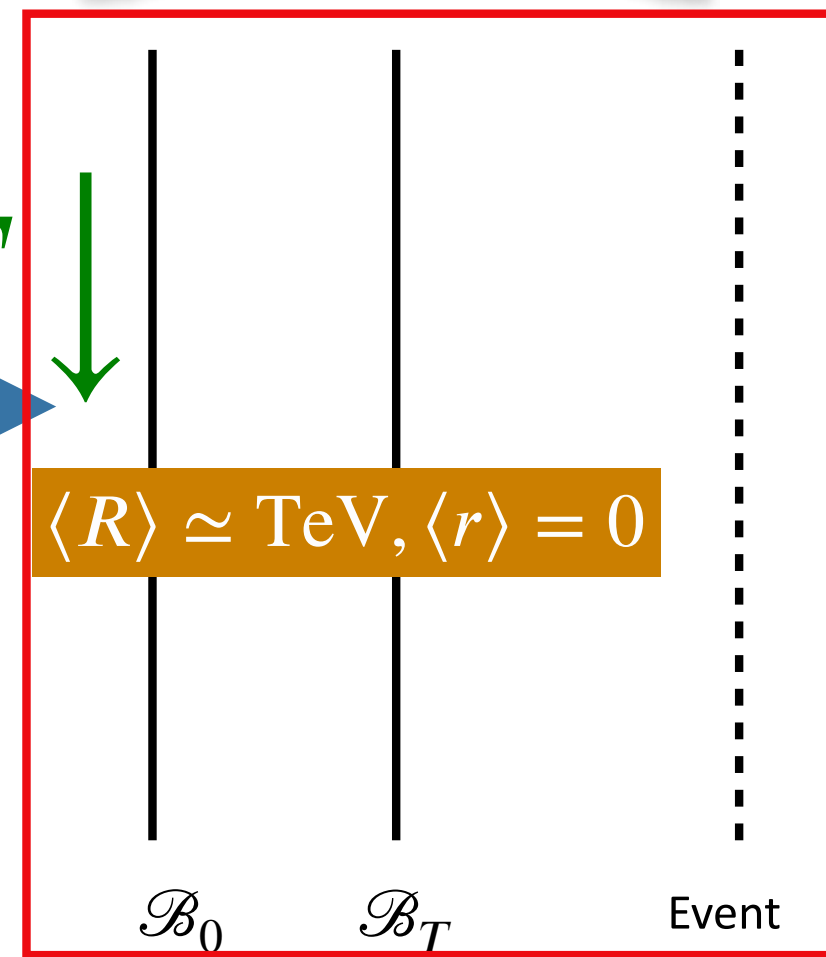
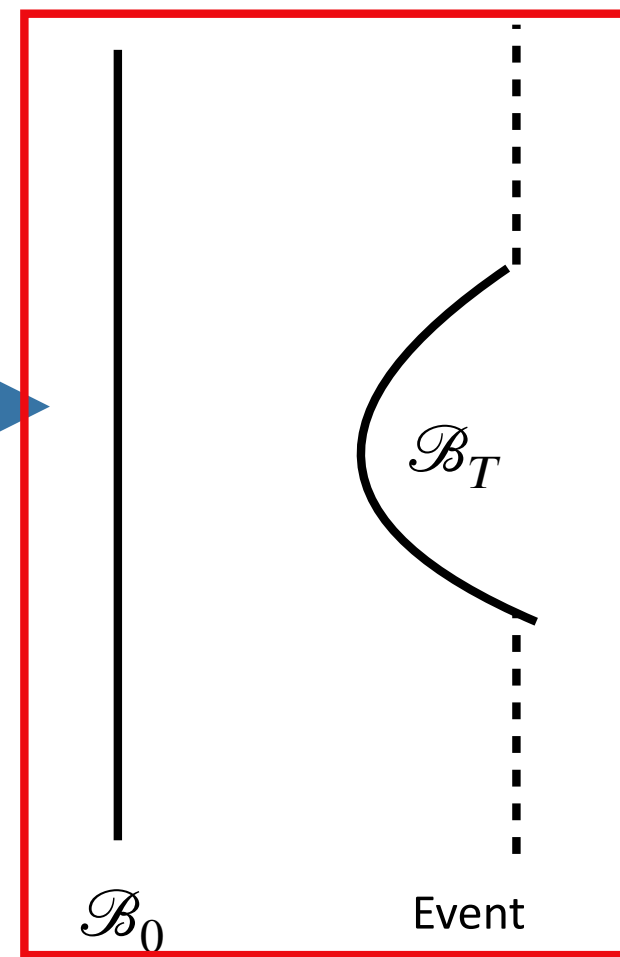
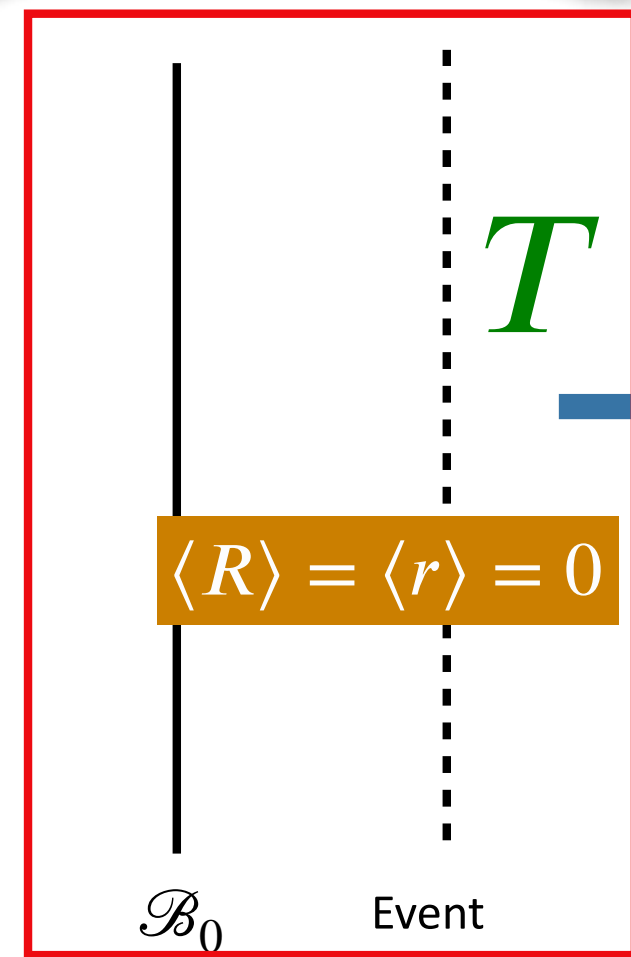
Symmetric phase

Intermediate phase transition

Partly confined phase

Final phase transition

Fully confined phase





## The message

- DM interacts **only “gravitationally”** via radions and massive KK gravitons
- DM relic abundance obtained via **annihilation into radions** whereas its detection signatures via **interactions with the SM**
- Assuming that the PTA experiments have found a **new physics scale** around the GeV ( $\Lambda_{\text{PTA}} \sim \text{GeV}$ ) scale, our proposal would suggest that the new scale can be **provided by the dark matter sector** in our Universe



## Other scenarios

### *Two branes models*

B. von Harling and K. L. McDonald, JHEP 08 (2012) 048

H. M. Lee, M. Park and V. Sanz, Eur. Phys. J. C 74 (2014) 2715

M. G. Folgado, A. Donini and N. Rius, JHEP 01 (2020) 161

A. de Giorgi and S. Vogl, JHEP 11 (2021) 036

A. de Giorgi and S. Vogl, JHEP 04 (2023) 032

### *Three branes models*

S. Ferrante, A. Ismail, S. J. Lee and Y. Lee, JHEP  
11 (2023) 186

Andrea Donini et al, arXiv: 2505.1360,  
2509.04580



## Radion interactions

$$ds^2 = e^{-2A(z)} \left[ e^{-2F(z,x)} \eta_{\mu\nu} dx^\mu dx^\nu + (1 + 2F(z,x))^2 dz^2 \right] \quad F(z,x) = \sum_{n=0}^{\infty} f^{(n)}(z) r^{(n)}(x)$$

$$\mathcal{L} = -c_r(z_b) r(x) T_b(x) \longrightarrow c_r(z_b) = \left( \frac{k}{M_{\text{Pl}}} \right) \frac{1}{\sqrt{6}} \frac{z_b^2}{z_1}$$

$$\frac{m_r}{\tilde{\rho}_1} = \frac{2}{\sqrt{3}} \bar{v}_1 u$$

**SM brane**

**Dark brane**

$$c_r(z_T) = \frac{\tilde{\rho}_1}{\sqrt{6} \tilde{\rho}_T^2}, \quad c_r(z_1) = \frac{1}{\sqrt{6} \tilde{\rho}_1}, \quad \text{and} \quad c_r(z_T) c_r(z_1) = \frac{1}{6 \tilde{\rho}_T^2}$$

$$\mathcal{L}_{\text{eff}} = a_r T_{\text{SM}} T_{\text{DS}}, \quad \text{where} \quad a_r = - \frac{c_r(z_T) c_r(z_1)}{q^2 - m_r^2}$$



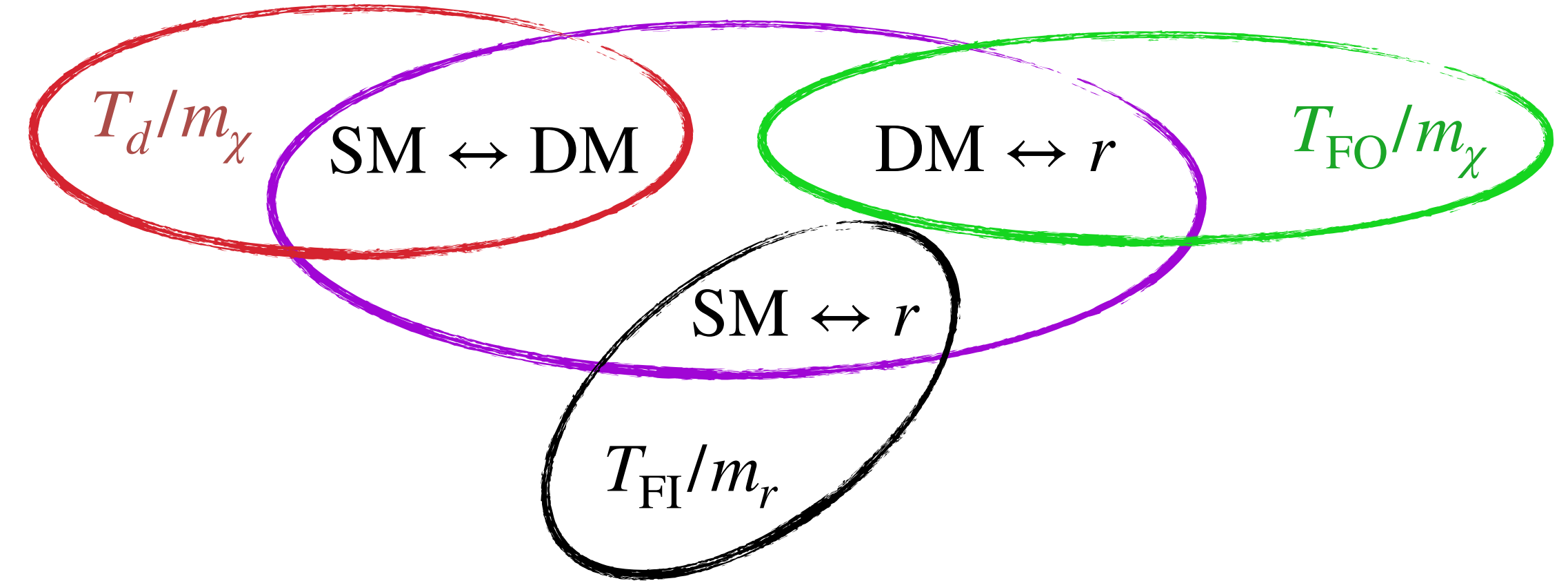
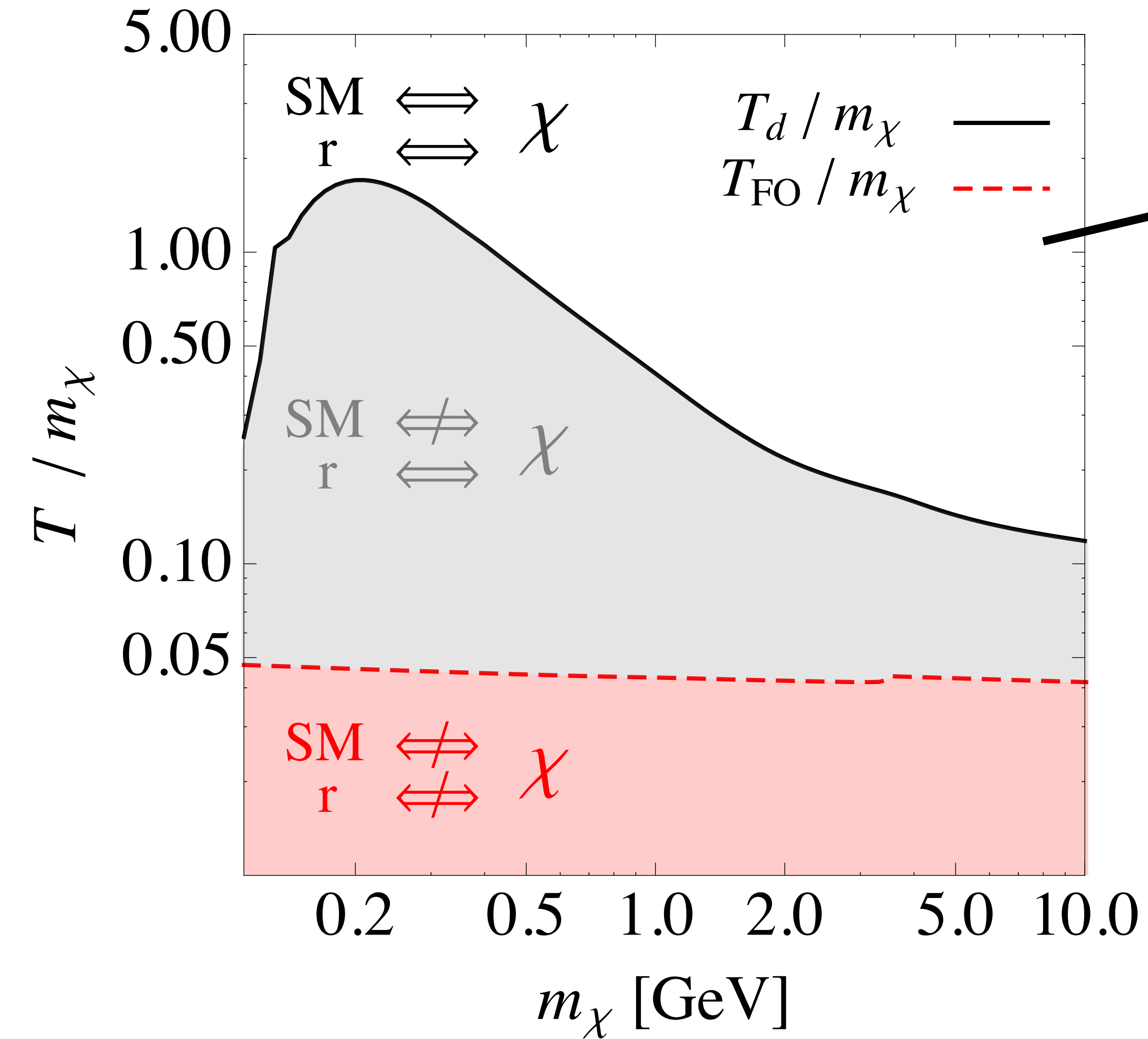
## The setup

- The model has 3 free parameters:

- 1.** *The scale of the Dark Brane  $\tilde{\rho}_1 = \frac{M_{\text{pl}}}{k} \rho_1$ . Its range to describe the PTA data is  $10 \text{ MeV} \lesssim \tilde{\rho}_1 \lesssim 10 \text{ GeV}$ , but in principle we also have considered a broader range*
- 2.** *The DM mass  $m_\chi$ . We consider it in the range  $m_\chi < \tilde{\rho}_1$ . In this way the non-relativistic annihilation into gravitons  $KK$  modes  $\chi\bar{\chi} \rightarrow G_n G_n$  cannot take place*
- 3.** *The radion mass  $m_r$ . We will assume that  $m_r < m_\chi$  and  $m_r \ll \tilde{\rho}_1$ . In this way the radion decay  $r \rightarrow \chi\bar{\chi}$  is closed and only the channel  $r \rightarrow \text{SM} + \text{SM}$  is kinematically accessible*



# Thermal history of SM+DM+radion



$$\frac{dn_r}{dt} + 3Hn_r = -\langle \Gamma_r \rangle [n_r - n_r^{\text{eq}}] - \langle \sigma_r v \rangle [n_r^2 - (n_r^{\text{eq}})^2] + \langle \sigma_\chi v \rangle \left[ n_\chi^2 - \left( \frac{n_\chi^{\text{eq}}}{n_r^{\text{eq}}} \right)^2 n_r^2 \right]$$

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma_\chi v \rangle \left[ n_\chi^2 - \left( \frac{n_\chi^{\text{eq}}}{n_r^{\text{eq}}} \right)^2 n_r^2 \right] - \langle \sigma_0 v \rangle [n_\chi^2 - (n_\chi^{\text{eq}})^2]$$

# RELIC DENSITY



# Relic density

$$\Omega_\chi h^2 \simeq 0.1 \frac{x_{\text{FO}}}{10} \sqrt{\frac{65}{g_*(T_{\text{FO}})}} \frac{\langle \sigma v \rangle_c}{\langle \sigma v \rangle}$$

$$\langle \sigma v \rangle n_\chi(T_{\text{FO}}) \simeq H(T_{\text{FO}})$$

$$x_{\text{FO}} = m_\chi / T_{\text{FO}} \gg 1$$

$$\langle \sigma v \rangle_c \sim 1.09 \times 10^{-9} \text{ GeV}^{-2}$$

**Only radion mediation**  $\longrightarrow$

$$\chi + \bar{\chi} \rightarrow f + \bar{f}$$

$$g_{r\chi\bar{\chi}} g_{rf\bar{f}} \simeq \frac{m_\chi m_f}{6\tilde{\rho}_T^2}$$

$$\sigma_f = (g_{r\chi\bar{\chi}} g_{rf\bar{f}})^2 \frac{1}{16\pi s} \left(1 - \frac{4m_\chi^2}{s}\right)^{1/2} \left(1 - \frac{4m_f^2}{s}\right)^{3/2}$$

$$\sigma_f \lesssim 10^{-4} \frac{m_\chi^2}{\tilde{\rho}_T^4}$$

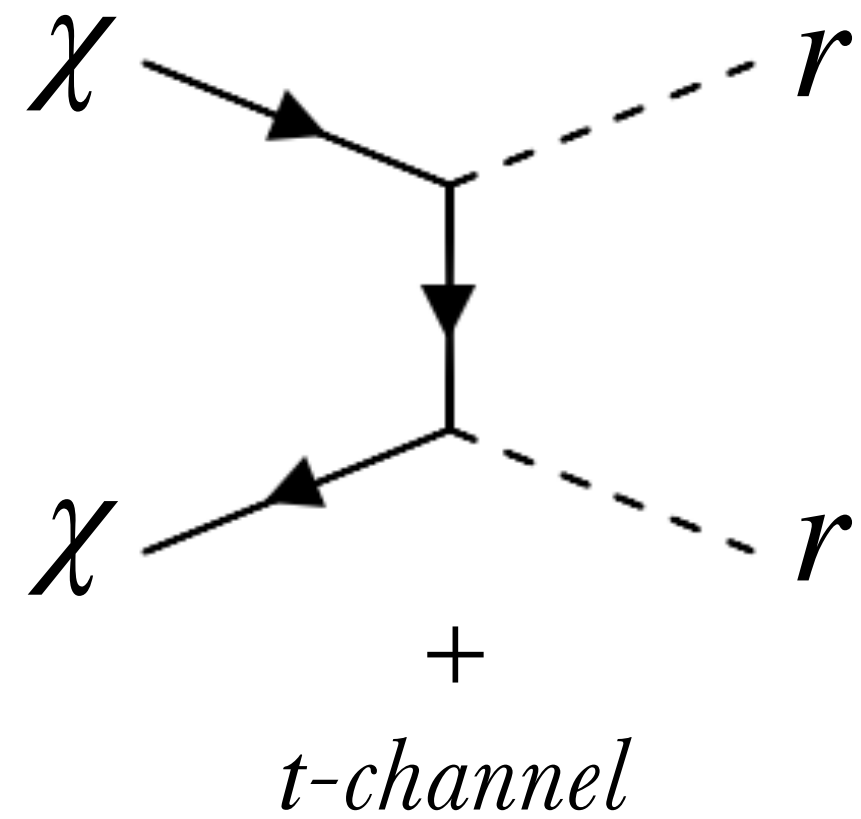
$$\begin{array}{l} \lesssim 10 \text{ GeV,} \\ \gtrsim 1 \text{ TeV} \end{array}$$

$$\sigma_f v \lesssim 10^{-14} \text{ GeV}^{-2}$$

$$\begin{array}{l} \sim \chi + \bar{\chi} \rightarrow g + g \\ \gg \chi + \bar{\chi} \rightarrow \gamma + \gamma \end{array}$$

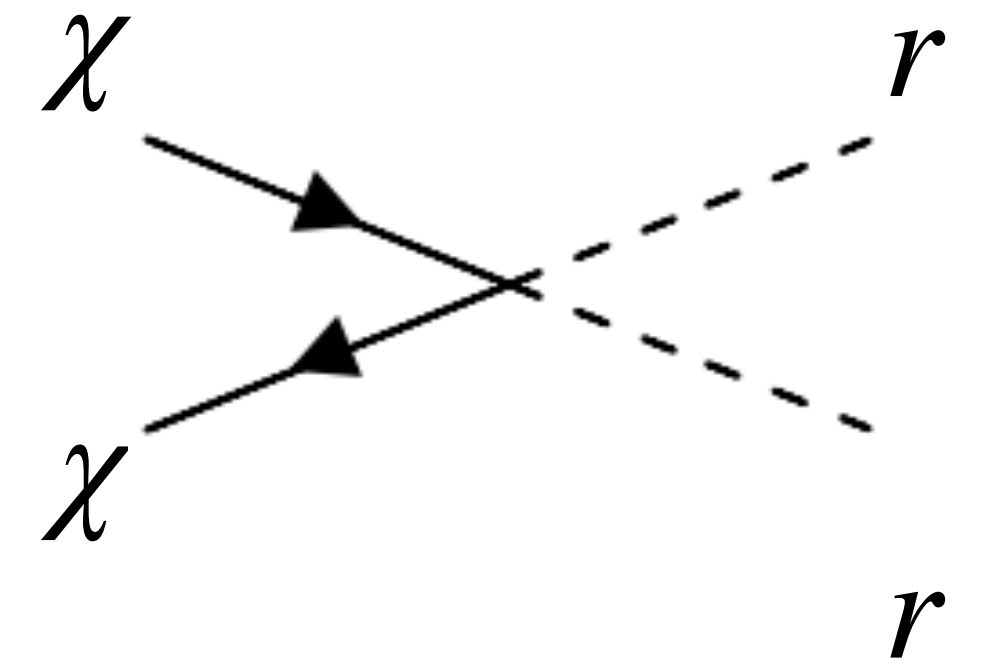
# Relic density

No DM relic density **but** freeze-out from SM  $\longrightarrow$   $m_\chi < 10$  GeV  
 $T_d < 1.2$  GeV



**But** (again) DM + radion still in equilibrium

$$\chi(p) + \bar{\chi}(p') \rightarrow r(k) + r(k')$$

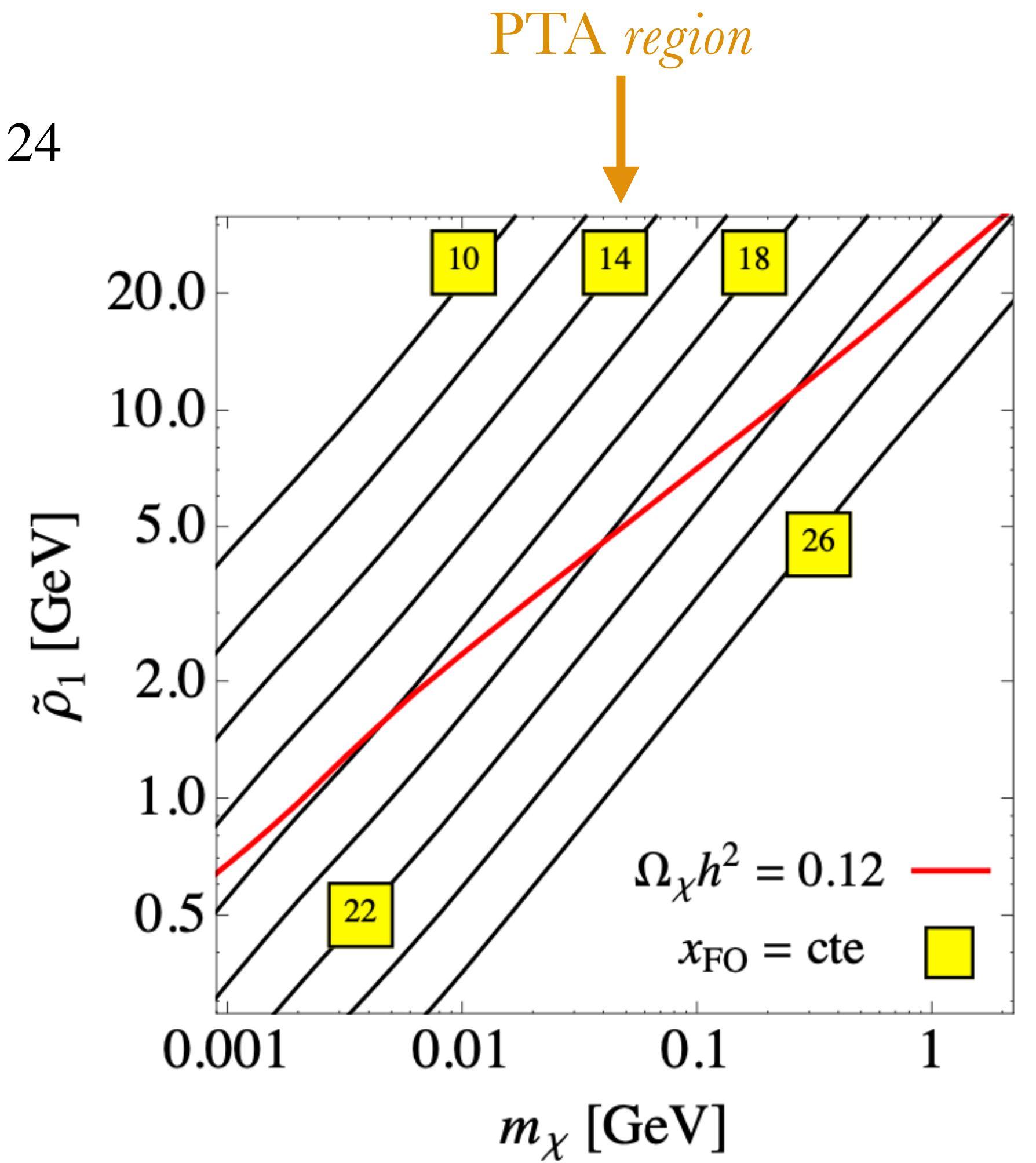
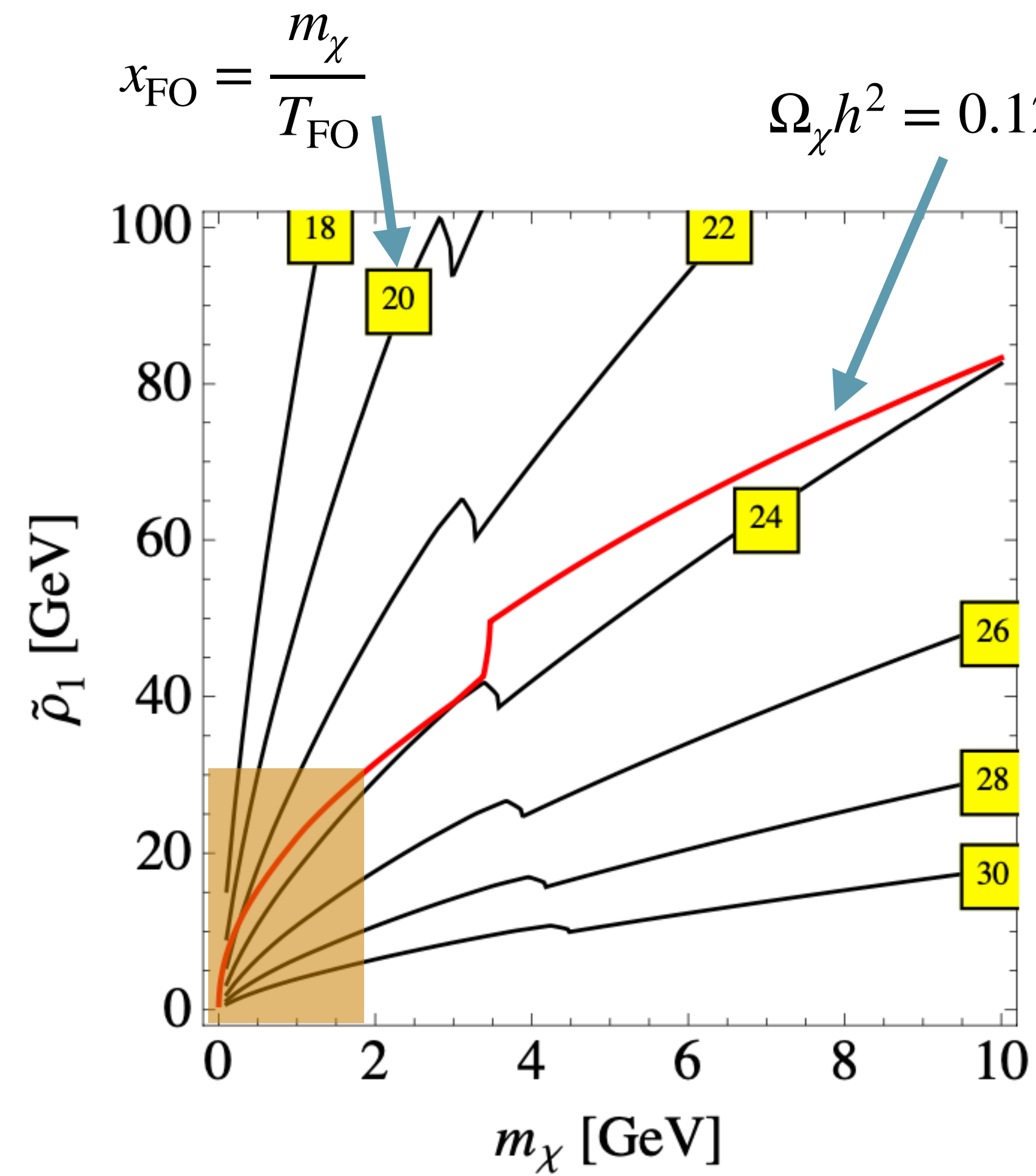
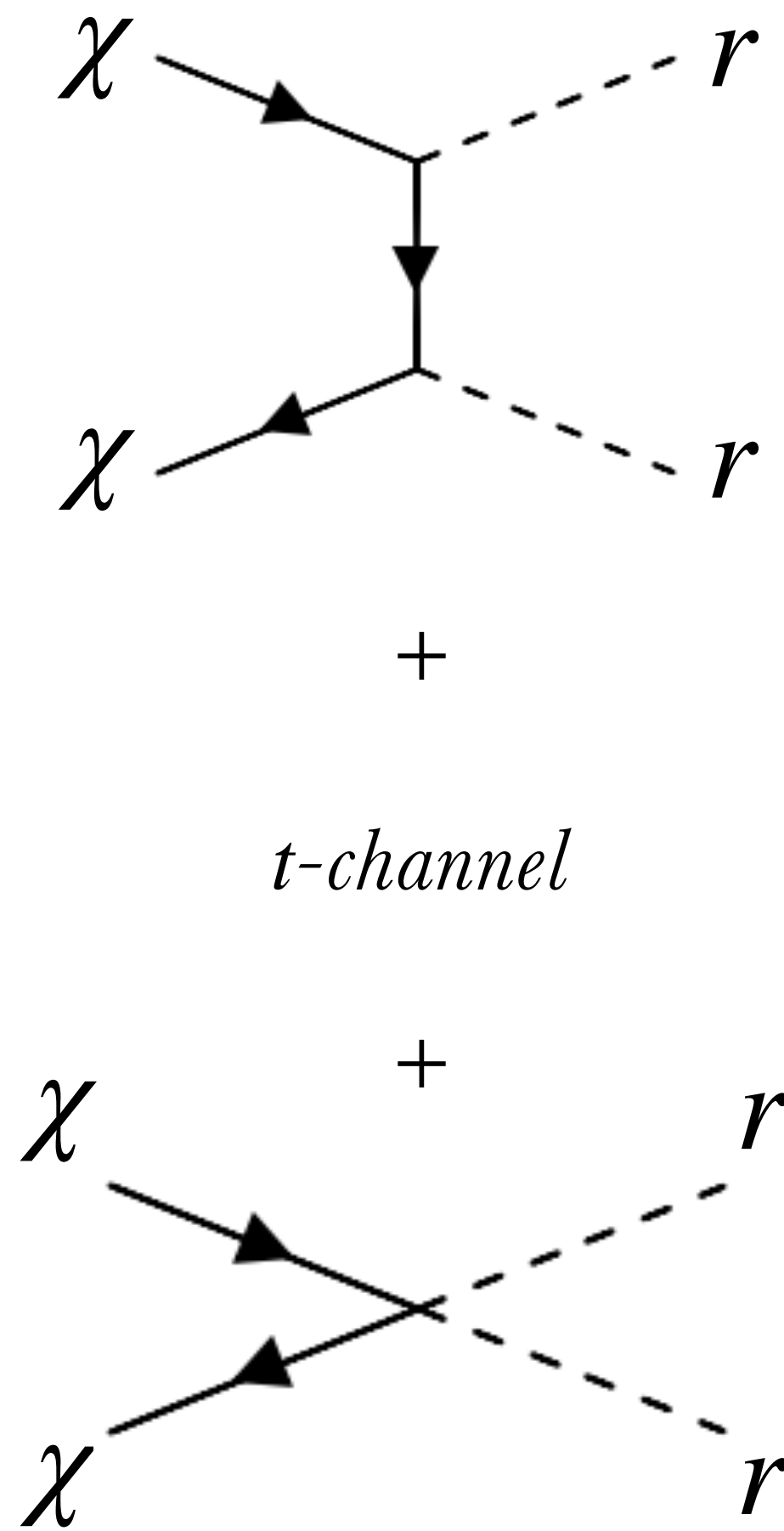


$$\sigma_r = \frac{1}{1152\pi} \frac{m_\chi^2}{\tilde{\rho}_1^4} \left[ \frac{z^2(7 - 11z^2 - z^4)}{(1 - z^2)} \tanh^{-1}(\sqrt{1 - z^2}) + \frac{169 - 121z^2 - 8z^4}{8(1 - z^2)^{1/2}} \right] \quad \text{with} \quad z^2 = \frac{4m_\chi^2}{s}$$

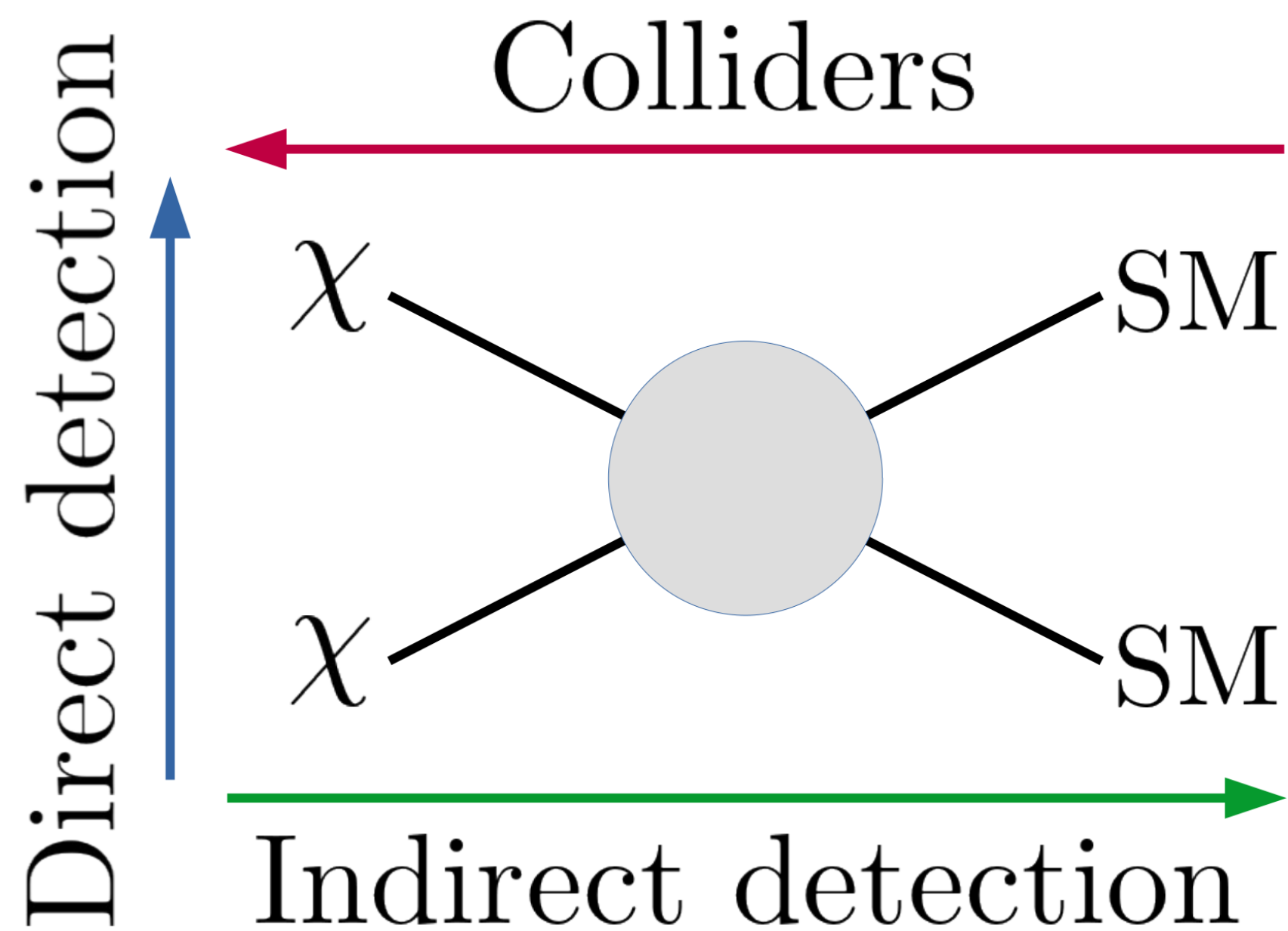
$$x_{\text{FO}} = m_\chi / T_{\text{FO}}$$



# Relic density



# OBSERVATIONAL CONSTRAINTS



*A. Arbey and F. Mahmoudi, **Dark matter and the early Universe: a review***

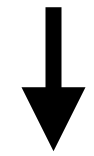


# Direct detection

**Scattering off nuclei**      $\mathcal{L}_{\text{eff}} = b_r (\bar{\chi}\chi)(\bar{Q}Q)$      with      $b_r = a_r m_\chi m_Q = \frac{m_\chi m_Q}{6m_r^2 \tilde{\rho}_T^2}$

$Q = u, d, s$

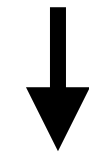
P. Agrawal, Z. Chacko, C. Kilic  
and R. K. Mishra, 1003.1912



$$\langle N | m_Q \bar{Q}Q | N \rangle = m_N f_{T_Q}^{(N)}$$

$Q = c, b, t$

J. Ellis, N. Nagata and K. A.  
Olive, Eur. Phys. J. C 78 (2018) 569

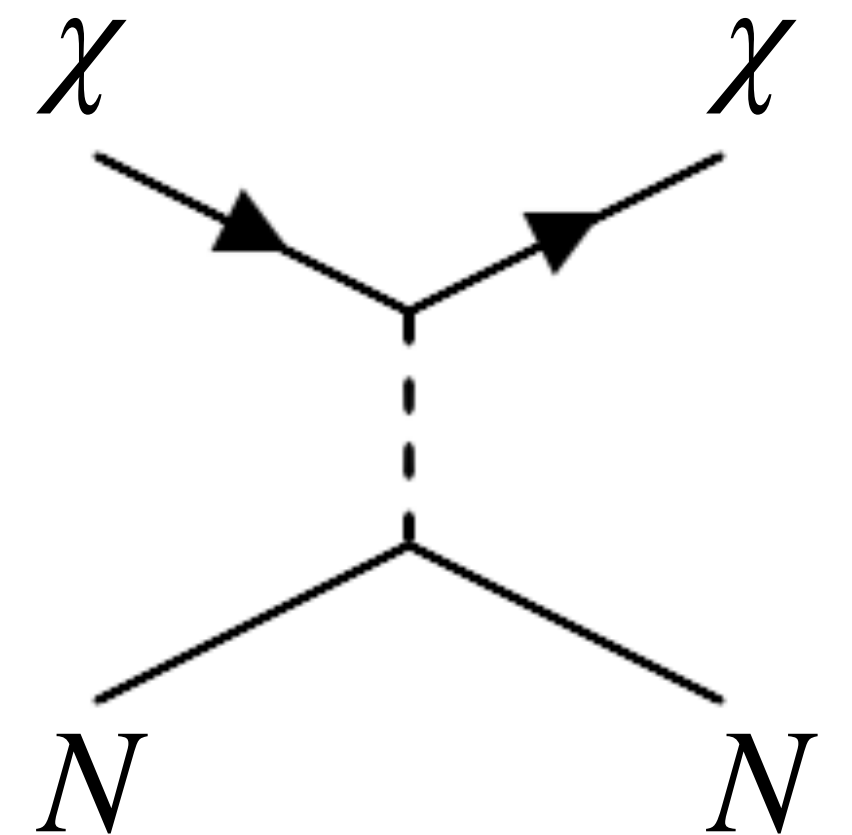


$$\langle N | m_Q \bar{Q}Q | N \rangle = \frac{2}{27} m_N \left( 1 - \sum_{Q=u,d,s} f_{T_Q}^{(N)} \right)$$

$$f_{T_u}^{(p)} = 0.018(5), f_{T_d}^{(p)} = 0.027(7)$$

$$f_{T_s}^{(p)} = 0.037(7) \text{ and } f_{T_u}^{(n)} = 0.013(3)$$

$$f_{T_d}^{(n)} = 0.040(10), f_{T_s}^{(n)} = 0.027(7)$$



**DM-nucleon spin-indep.  
total cross-section**

$$\sigma_N = \frac{\mu_{N\chi}^2}{\pi} f_N^2 \quad \text{with} \quad f_N \sim 1/m_r^2$$

**The reduced  
DM-nucleon mass**

$$\mu_{N\chi} = m_N m_\chi / (m_N + m_\chi)$$

# Direct detection

$3 \text{ GeV} \lesssim m_\chi \lesssim 10 \text{ GeV}$   
XENON1T collab.  
1907.12771, 1907.11485

$1 \text{ GeV} \lesssim m_\chi \lesssim 3 \text{ GeV}$   
DarkSide-50 collab.  
2207.11966

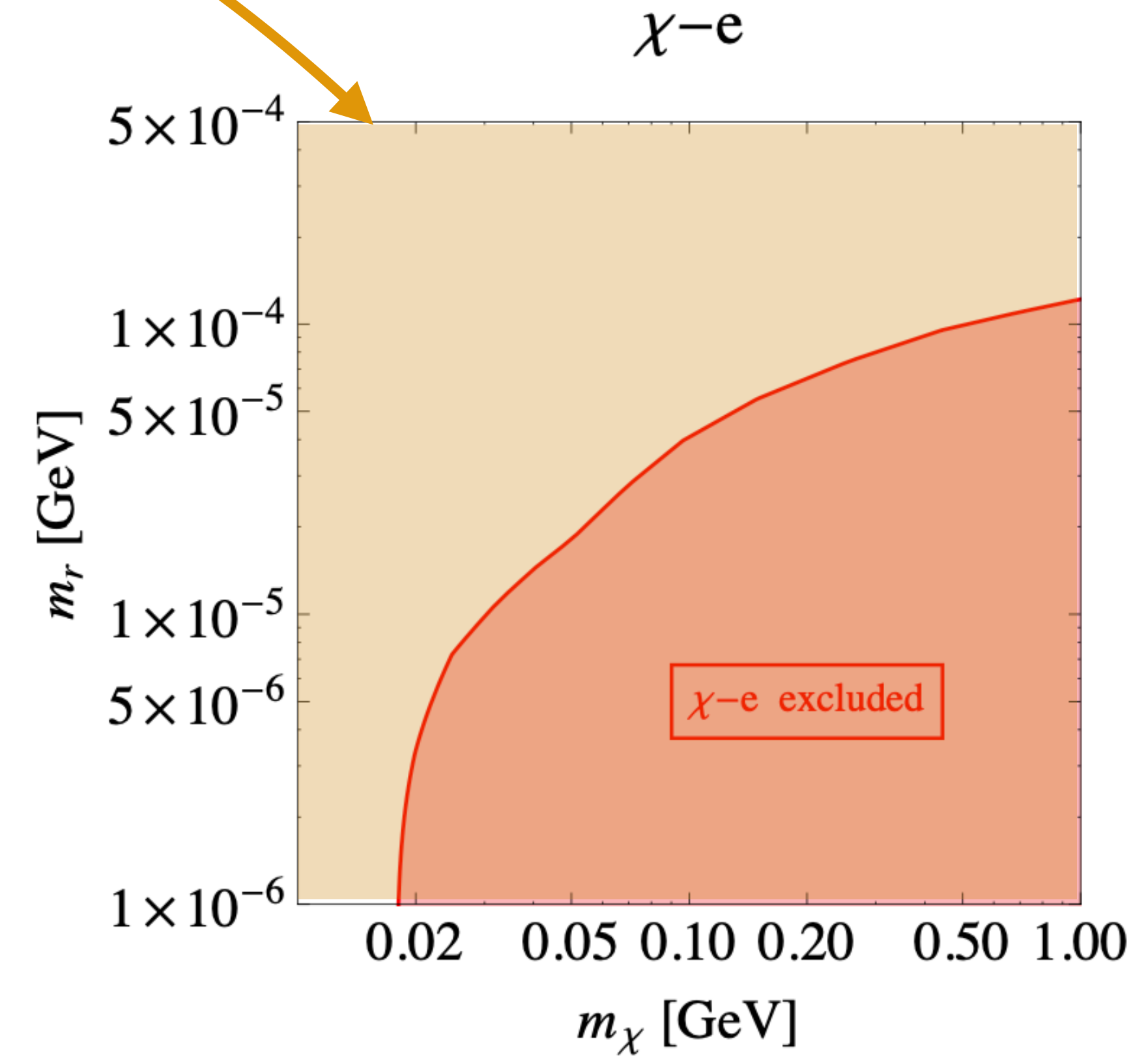
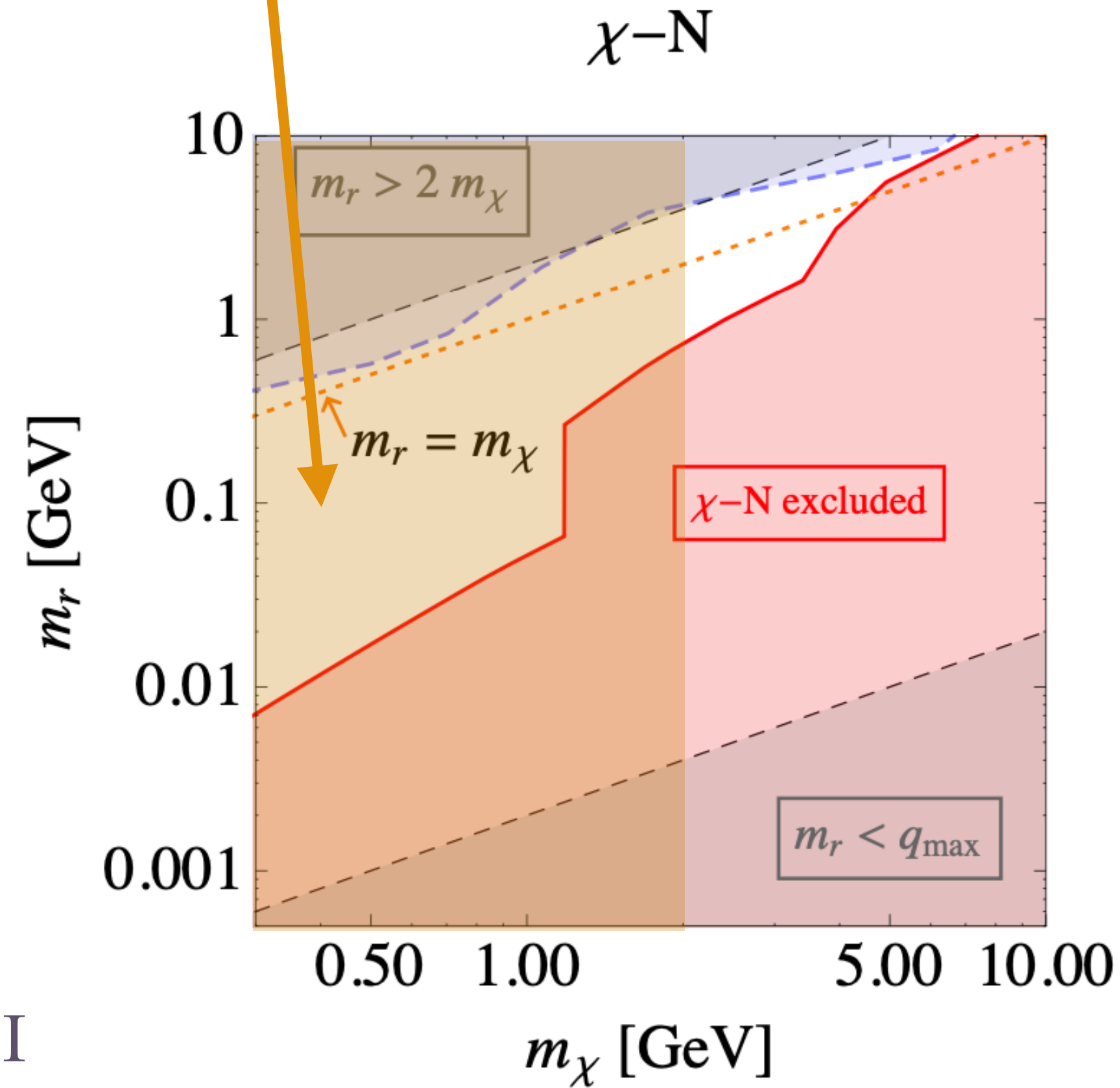
$0.5 \text{ GeV} \lesssim m_\chi \lesssim 1 \text{ GeV}$   
CREST collab.  
1904.00498

$1 \text{ MeV} \lesssim m_\chi \lesssim 1 \text{ GeV}$   
XENON1T, DarkSide, SENSEI

R. T. D'Agnolo and J. T.  
Ruderman, Phys. Rev.  
Lett. 115 (2015) 061301

Sub-GeV Dark Matter

PTA region





## Accelerator searches

1) DM searches at the LHC for our model:  
**missing energy events** and mono-Z/jets  
 ATLAS collab. 1211.6096, 1502.01518

$$\mathcal{L} = \frac{m_q}{\Lambda^3} (\bar{q}q)(\bar{\chi}\chi), \quad \text{where} \quad \Lambda = \left( \frac{6m_r^2 \tilde{\rho}_T^2}{m_\chi} \right)^{1/3}$$



$$\Lambda \gtrsim 40 \text{ GeV}$$



$$1 \text{ GeV} \lesssim m_\chi \lesssim 10 \text{ GeV}$$

$$m_r \gtrsim 10^{-1} \text{ GeV} \left( \frac{m_\chi}{1 \text{ GeV}} \right)$$

2) For  $m_e \lesssim m_\chi \lesssim m_p$  fixed-target experiments NA64  
 (CERN SPS) and future LDMX (SLAC)  
 could probe **new boson** (radion)

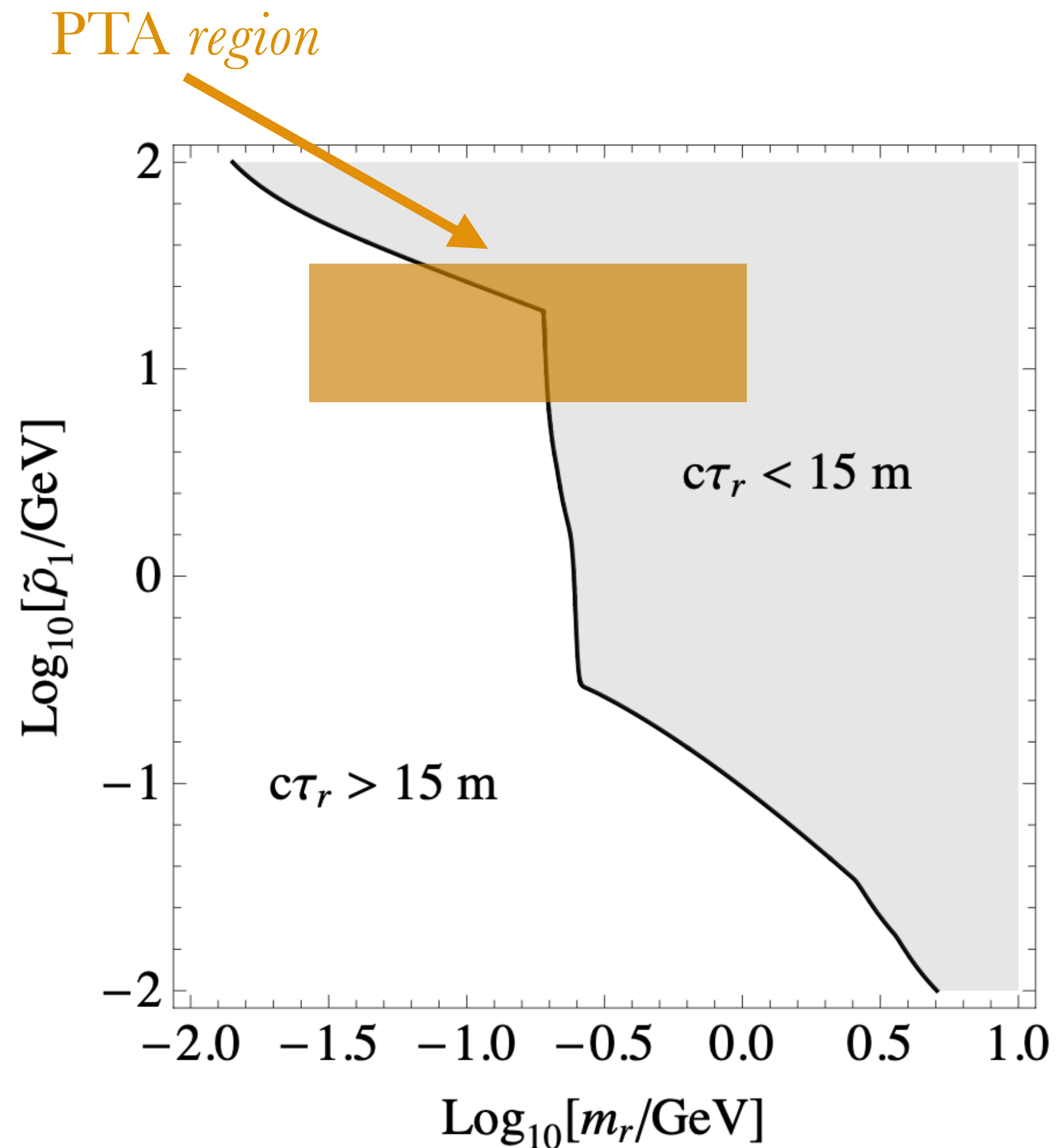
$$e^- Z \rightarrow e^- Z r \rightarrow \text{invisible decay inside NA64}$$



$$g_{ree} = \frac{m_e \tilde{\rho}_1}{\sqrt{6} \tilde{\rho}_T^2}$$

$$g_{ree} = 2 \times 10^{-10} \left( \frac{\tilde{\rho}_1}{1 \text{ GeV}} \right) < 2 \times 10^{-9}, \quad \text{for} \quad \tilde{\rho}_1 < 10 \text{ GeV}$$

# Accelerator searches



**But** for  $m_r < 2m_\chi$  then  
 $r \rightarrow \text{SM} + \text{SM}$

**No** invisible decay and **no**  
 bounds. Unless radion **decays**  
**outside** the detector

$$\Gamma_{r \rightarrow f\bar{f}} = N_c \frac{m_r \tilde{\rho}_1^2 m_f^2}{48\pi \tilde{\rho}_T^4} \left(1 - \frac{4m_f^2}{m_r^2}\right)^{3/2} \quad \Gamma_{r \rightarrow gg} = \frac{\alpha_3^2 b_{\text{QCD}}^2}{192\pi^3} \frac{m_r^3 \tilde{\rho}_1^2}{\tilde{\rho}_T^4}$$

$$\Gamma_{r \rightarrow \gamma\gamma} = \frac{\alpha_{\text{QED}}^2 b_{\text{QED}}^2}{1536\pi^3} \frac{m_r^3 \tilde{\rho}_1^2}{\tilde{\rho}_T^4}$$

$$\Gamma_r \simeq \sum_f \Gamma_{r \rightarrow f\bar{f}} + \Gamma_{r \rightarrow gg}$$

$$\tau_r = 1/\Gamma_r \quad c\tau_r > 15 \text{ m}$$



## Indirect constraints

Bounds from **CMB, Cosmic Rays, Galactic Center:**

$\chi\bar{\chi} \rightarrow l^+l^-, q\bar{q}, \gamma\gamma$  **for**  $0.1 \text{ GeV} \lesssim m_\chi \lesssim 10 \text{ GeV}$

$$\longrightarrow \langle \sigma_\chi v \rangle \ll \langle \sigma_{\text{bound}} v \rangle \sim 10^{-27} \text{ cm}^3/\text{s}$$

Bounds from **BBN**

$$\frac{dY_r}{dx} = -\gamma x [Y_r - Y_r^{\text{eq}}] + \frac{\lambda_\chi^0}{x^3} \left[ Y_\chi^2 - \left( \frac{Y_\chi^{\text{eq}}}{Y_r^{\text{eq}}} \right)^2 Y_r^2 \right]$$

$$\frac{dY_\chi}{dx} = -\frac{\lambda_\chi^0}{x^3} \left[ Y_\chi^2 - \left( \frac{Y_\chi^{\text{eq}}}{Y_r^{\text{eq}}} \right)^2 Y_r^2 \right]$$

$$\gamma \simeq \gamma_0 \frac{K_1(x)}{K_2(x)}, \quad \gamma_0 \equiv \frac{\Gamma_r}{H(m_r)},$$

$$\lambda_i = \frac{s(m_r) \langle \sigma_i v \rangle}{H(m_r)}, \quad (i = r, \chi, 0) \quad \lambda_\chi \equiv \lambda_\chi^0/x$$

$$Y_r = n_r/s \quad x = m_r/T$$

$$Y_r^{\text{eq}}(x) \simeq \frac{45}{4\pi^4} \frac{1}{g_*(x)} x^2 K_2(x)$$

$$\sigma(T) = \frac{T_{\text{FI}}}{T}$$

$$\sigma \equiv \frac{T_{\text{FI}}}{T_{\text{FO}}} = \frac{24\gamma m_r}{m_\chi} \gg 1$$

$T = T_{\text{FO}}$

$$\longrightarrow Y_r = Y_r^{\text{eq}}$$

**Before** DM freezes-out

## Indirect constraints

1) Region  $m_r > 2m_e$  and for  $m_r \gtrsim \text{few MeV} \rightarrow \sigma \gg 1$  and radion freezes-in **before** DM freezes-out

**BBN** not perturbed when

$$\tau_r \lesssim 10 \text{ sec}$$

F. Abu-Ajamieh, J. S. Lee and J. Terning,  
JHEP 10 (2018) 050

M. Kawasaki, K. Kohri, T. Moroi and Y.  
Takaesu, Phys. Rev. D 97 (2018) 023502

$$\tau_r \simeq 0.4 \text{ sec} \left( \frac{\tilde{\rho}_T}{\text{TeV}} \right)^4 \left( \frac{\text{GeV}}{\tilde{\rho}_1} \right)^2 \left( \frac{\text{MeV}}{m_r} \right)$$

Dominant channel  
 $r \rightarrow e^- e^+$

2) Region  $m_r < 2m_e \rightarrow$  Dominant channel  $r \rightarrow \gamma\gamma$  and  
 $\sigma \sim m_r \ll 1$

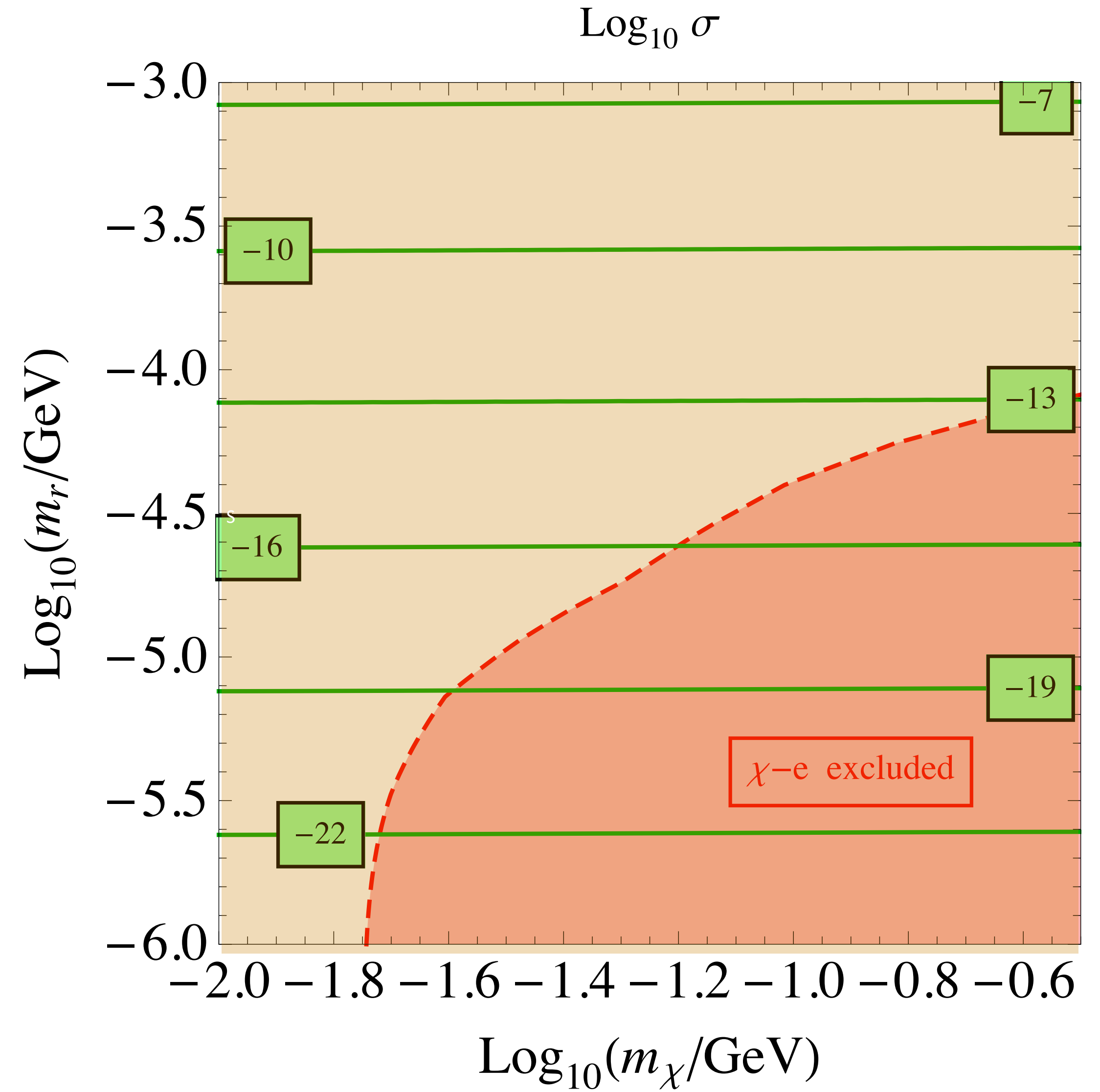
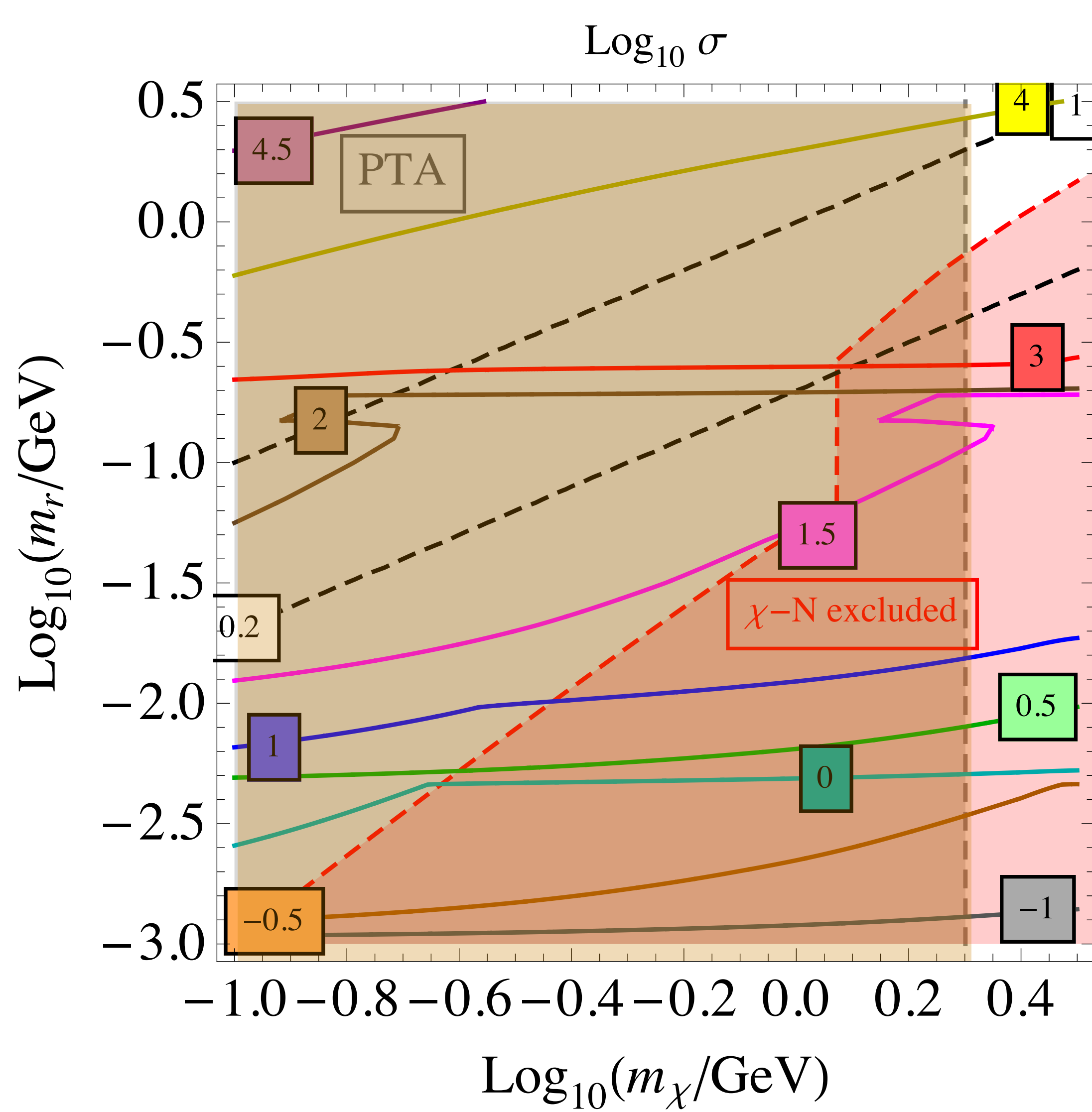
$$\rightarrow T_{\text{FO}} \gg T_{\text{FI}} \rightarrow$$

$$Y_r \ll Y_r^{\text{eq}}$$

$$\tau_r > 10 \text{ sec}$$

Excluded by **BBN**

# Indirect constraints





## Radion Cosmology

2a) Region  $10 \text{ keV} \lesssim m_r < 2m_e \longrightarrow T_{\text{FO}} \gg T_{\text{FI}} \longrightarrow$

$$Y_r \ll Y_r^{\text{eq}}$$

$$\tau_r > 10 \text{ sec}$$

Excluded by **BBN**

2b) For  $m_r \lesssim 10 \text{ keV}$  **light long-lived** radions exist with  $\tau_r > t_{\text{universe}}$



For  $\Delta_{N_{\text{eff}}}$  to be **safe**  $\lesssim 0.045$  radions should decouple from SM at  
 $T_0 \gtrsim \Lambda_{\text{QCD}}$



A **relic background** of radions from the time of their decoupling exists with temperature  $T_r(T_0) \approx 1.16 \text{ K} < T_{\text{CMB}}$

---

## Conclusions

- DM interacts **only** gravitationally (via radions) with the SM and its **relic density** and **detection constraints** processes are **decoupled**
- The scale provided by the DM sector could explain the nanoHz SGWB from the PTA experiments. The dark matter mass window,  $m_\chi \in [0.15 \text{ GeV}, 2 \text{ GeV}]$ , consistent with all direct and indirect constraints **will allow to sharply concentrate** the experimental searches
- A spinoff is the **prediction of a light radion** which **would be detected** in present fixed target experiments, as NA64 at the CERN SPS, and the future LDMX at SLAC
- Ongoing work: **Ultra-light** radion cosmology: **Dark Energy** and/or **Matter**, concrete **Inflationary** scenario in the multi-brane set up

THANK YOU!!!