Realising DM and PTA detected signal via Dark Branes

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HR EXCELLENCE IN RESEARCH

*Based on arXiv: 2403.06276 (**Accepted to PRD**)*
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CONTENTS

Intro

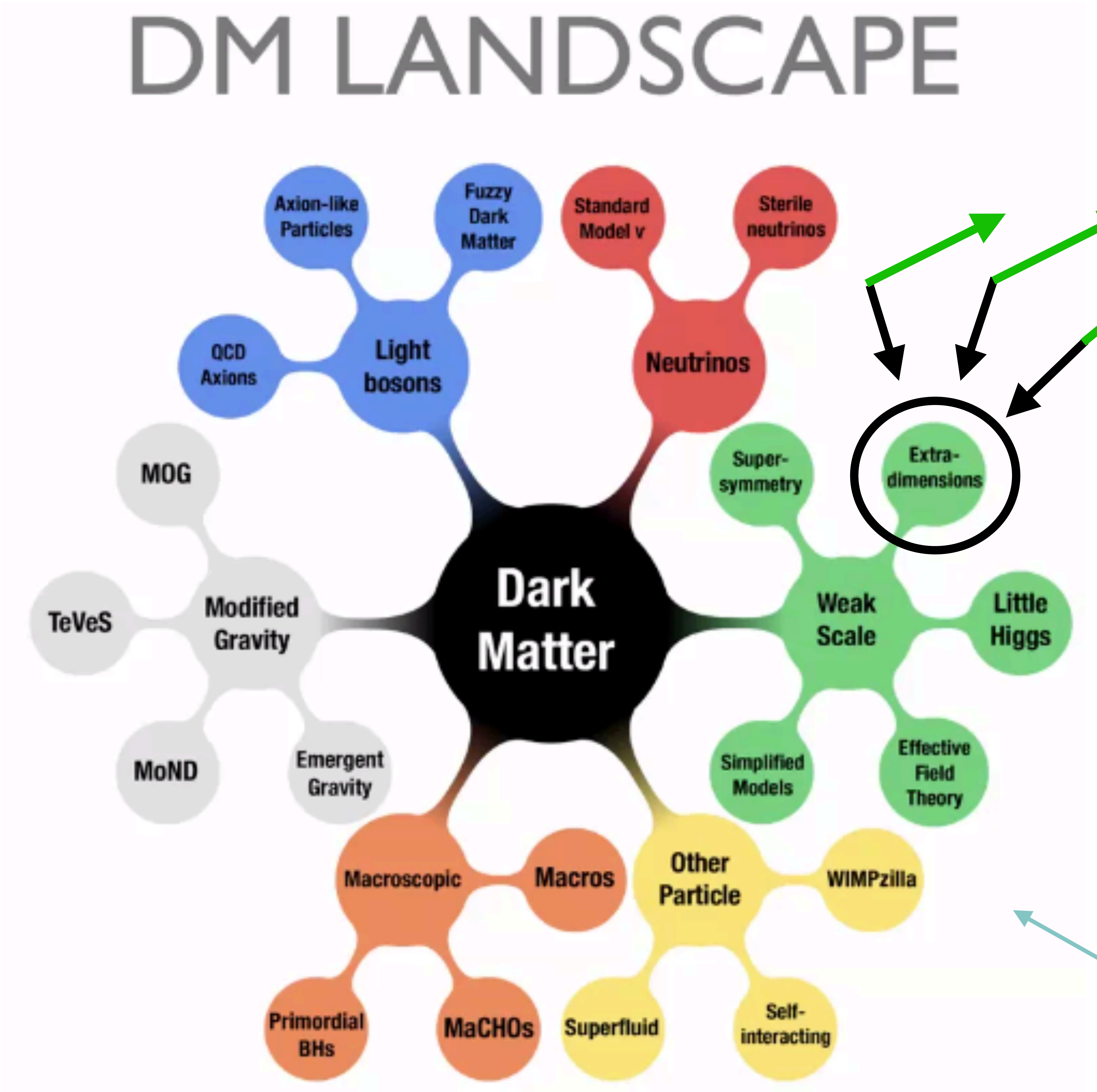
- Compelling evidence for the existence of Dark Matter (DM) on different astrophysical scales (galactic, clusters of galaxies, cosmological scale,…)

- ~ 84% of the matter in the Universe is DARK

- DM candidate: **stable** (compared to the current age of the Universe), (dominantly) **Non-relativistic**, **electrically neutral** and **colorless**. (Only?) **gravitational interactions**

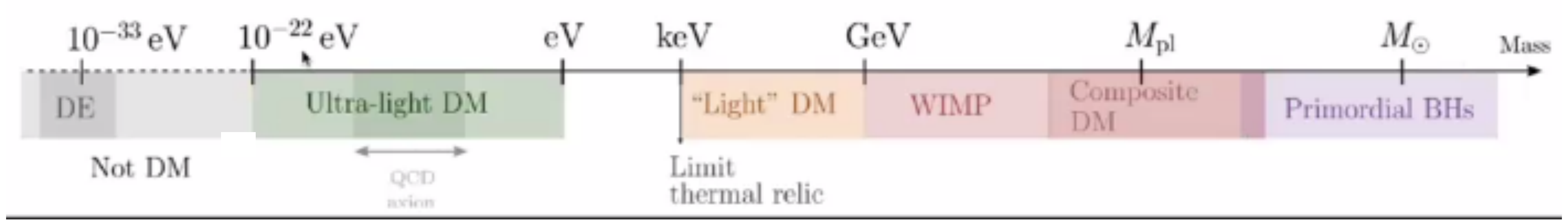
- Usual problem with DM candidates (e.g. WIMPs): **Conflict** between relic abundance and direct/indirect/accelerator searches because of **interactions with the SM**

Intro



Warped extra dimensional model with three 3-branes (extended Randall-Sundrum (RS) models)

80 orders of magnitude



Michele Redi talk

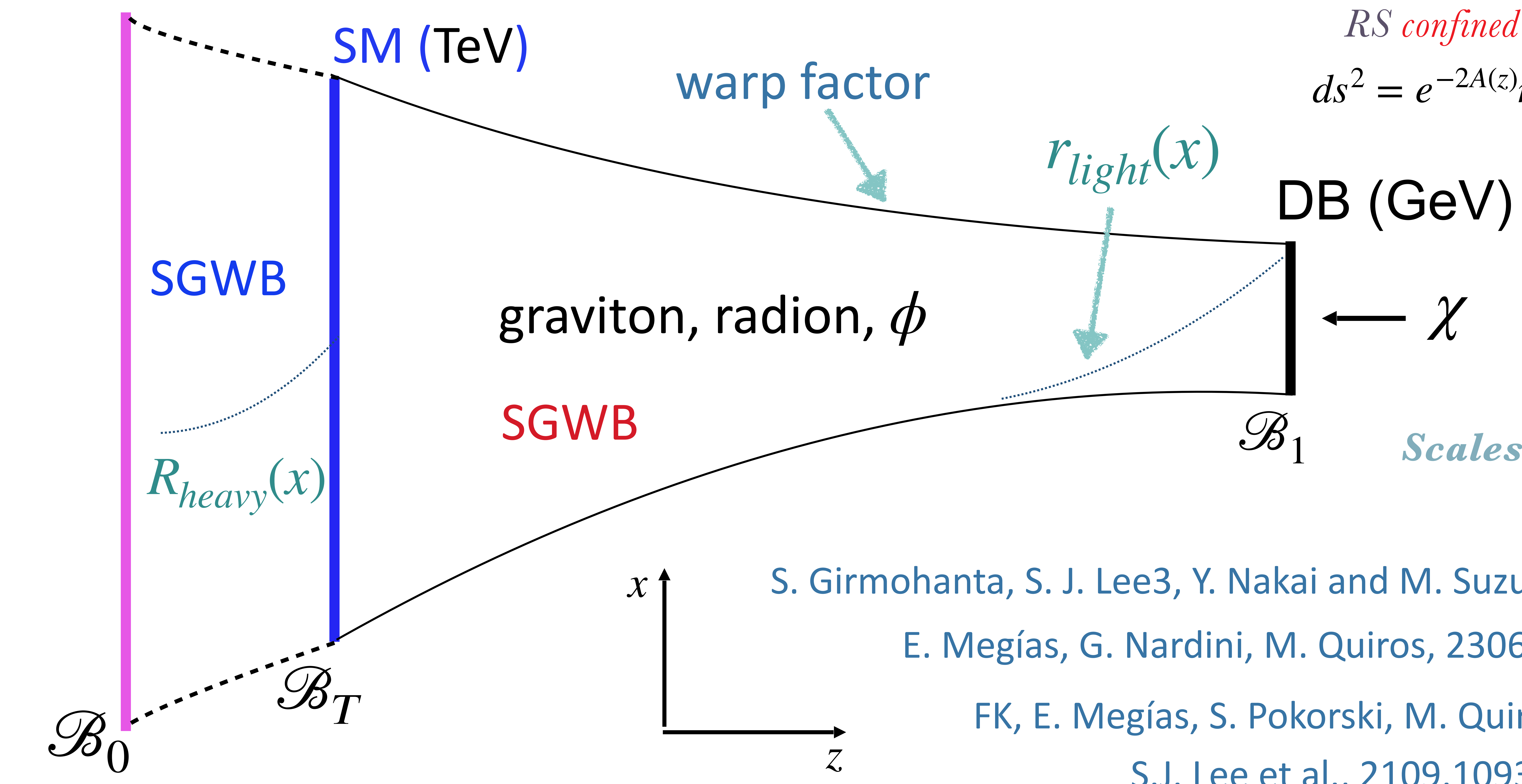
Bertone and Tait, Nature '18

The simplest 5D model

Occam's razor

RS confined phase (low T):

$$ds^2 = e^{-2A(z)}\eta_{\mu\nu}dx^\mu dx^\nu - dz^2$$



Scales denoted as $\tilde{\rho}$

S. Girmohanta, S. J. Lee3, 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

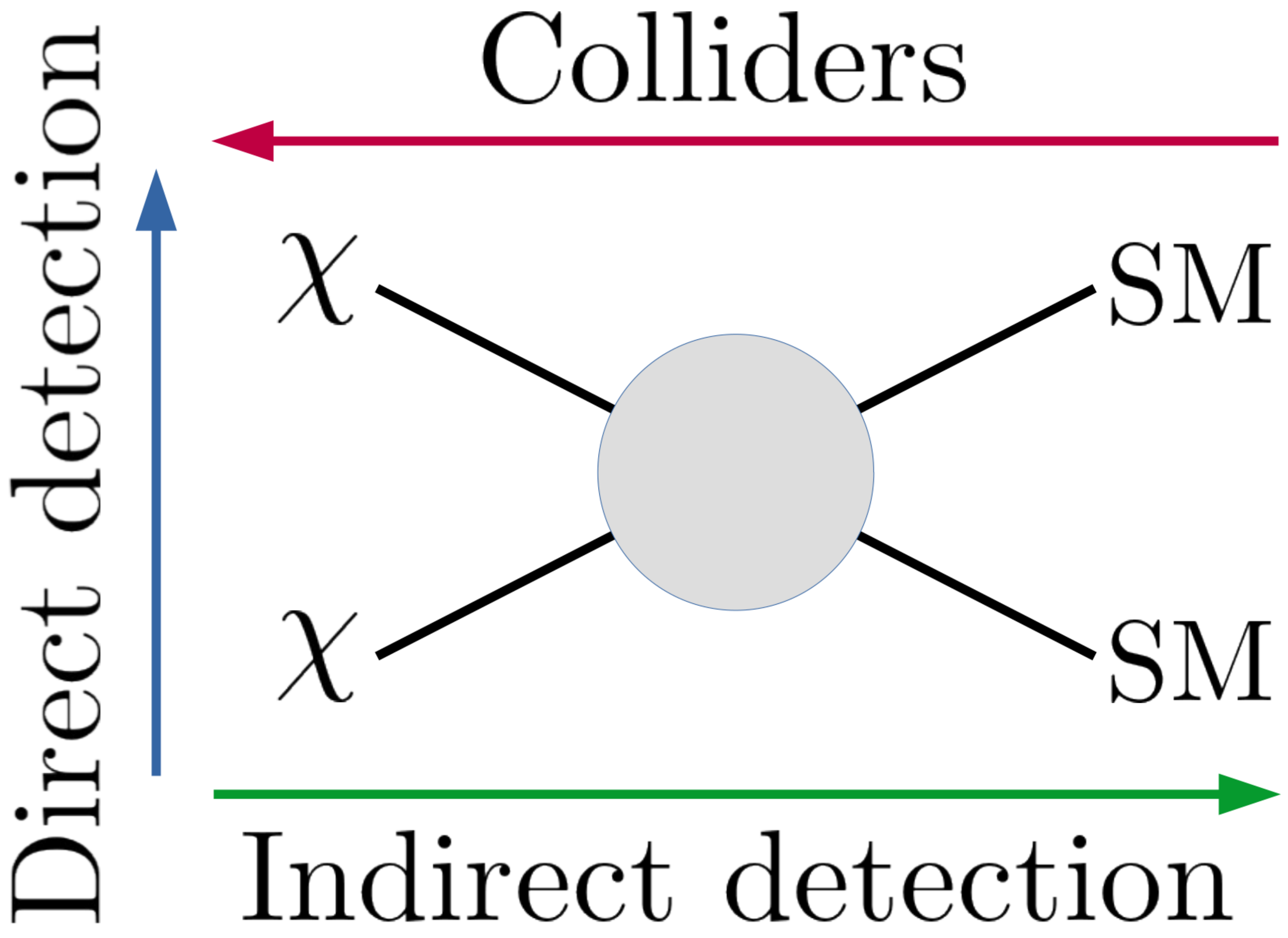
PTA's SGWB with three branes

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*

The simplest 5D model



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

<u>*Two branes models*</u>

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

<u>*Three branes models*</u>

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

Radion interactions

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

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

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

SM brane ↙ ↘ ***Dark brane***

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

↓

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

The setup

- The model has 3 free parameters:

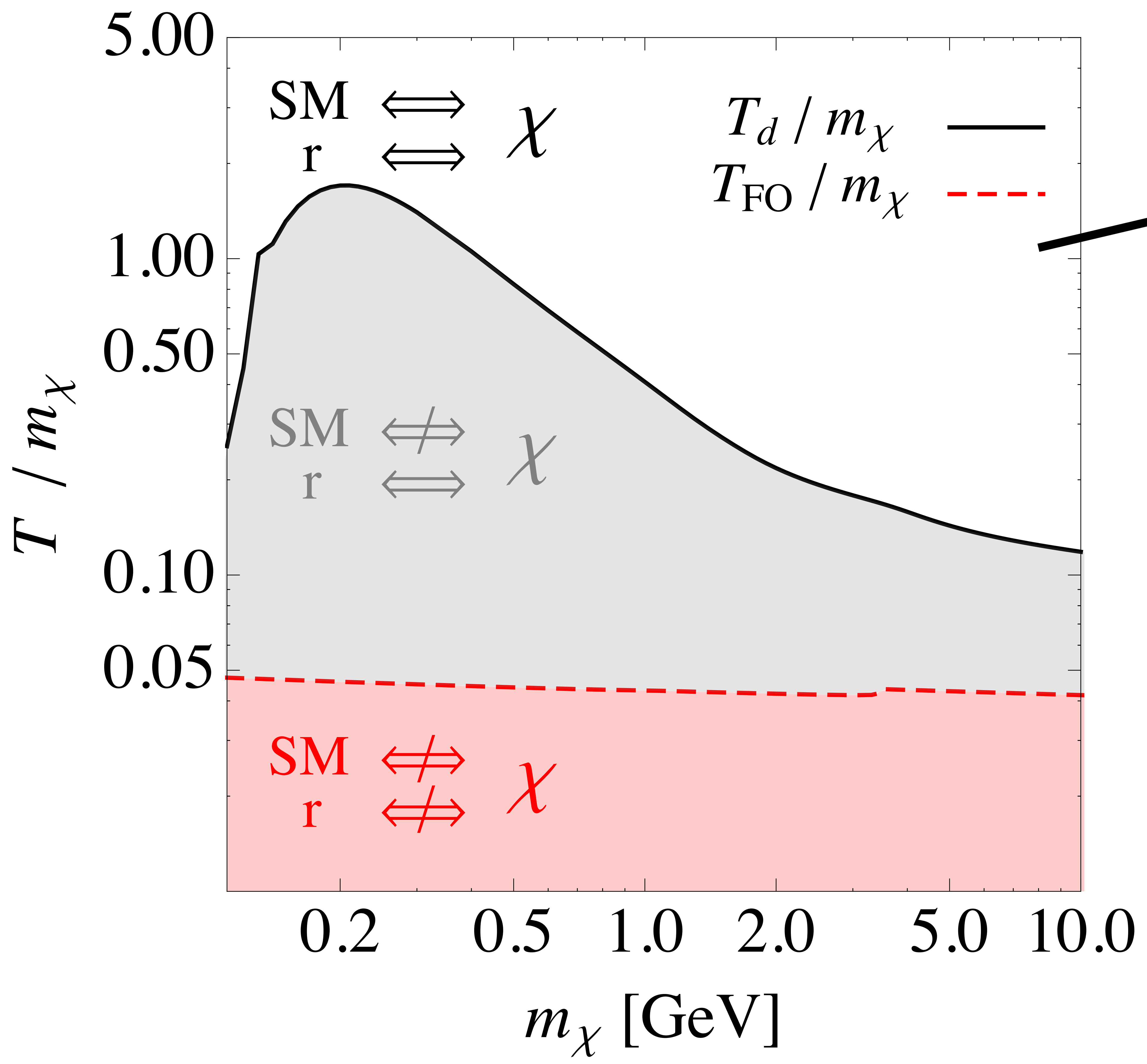
1. *The scale of the Dark Brane* $\tilde{\rho}_1 = \frac{M_{\rm pl}}{k}\rho_1$. *Its range to describe the PTA data is* $10\ \mathrm{MeV} \lesssim \tilde{\rho}_1 \lesssim 10\ \mathrm{GeV}$, *but in principle we also have considered a broader range*

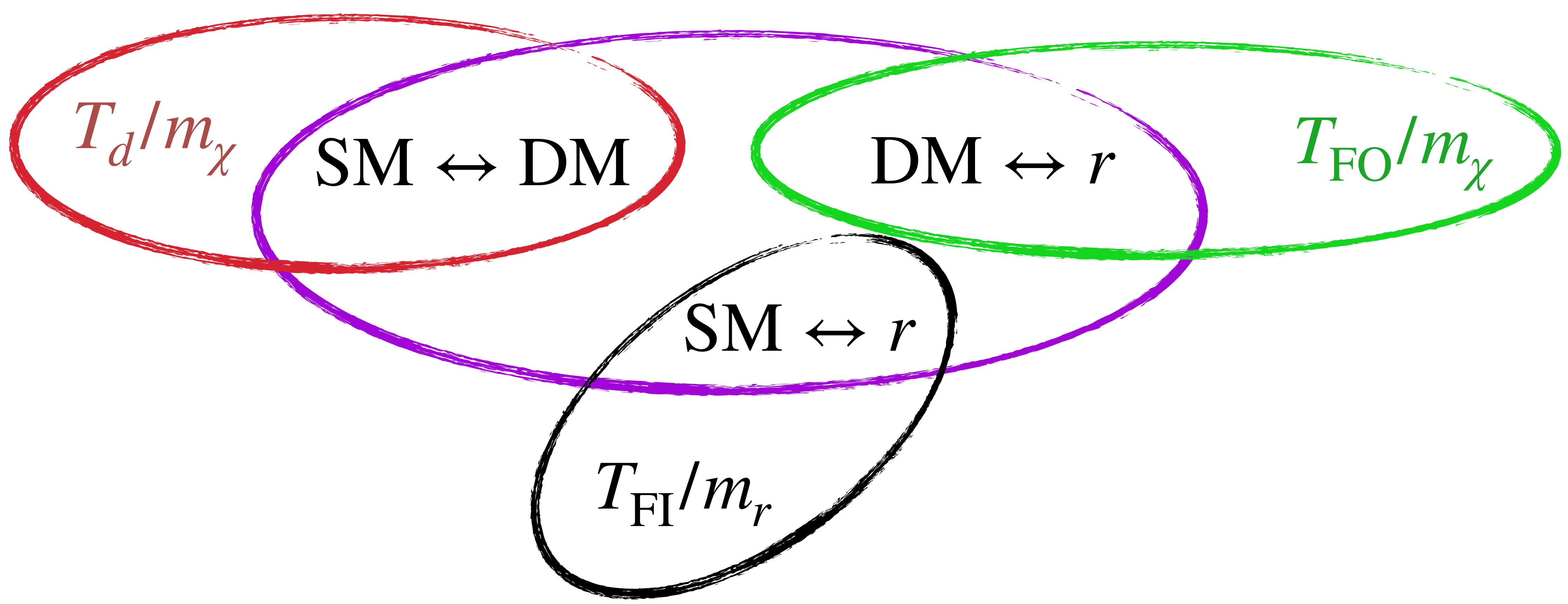
2. *The DM mass* m_χ. *We consider it in the range* $m_\chi < \tilde{\rho}_1$. *In this way the non-relativistic annihilation into gravitons KK modes* $\chi\bar{\chi} \to G_n G_n$ *cannot take place*

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* $r \to \chi\bar{\chi}$ *is closed and only the channel* $r \to \mathrm{SM} + \mathrm{SM}$ *is kinematically accessible*

- DM relic abundance **via annihilation into radions** whereas its detection signatures **via interactions with the SM**

Thermal history of SM+DM+radion





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

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

Relic density

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

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

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

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

Only radion mediation → $\chi+\bar\chi\to f+\bar f$

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

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

$$\sigma_f \lesssim 10^{-4}\,\frac{m_\chi^2}{\tilde\rho_T^4}$$

$\lesssim 10$ GeV, $\gtrsim 1$ TeV →

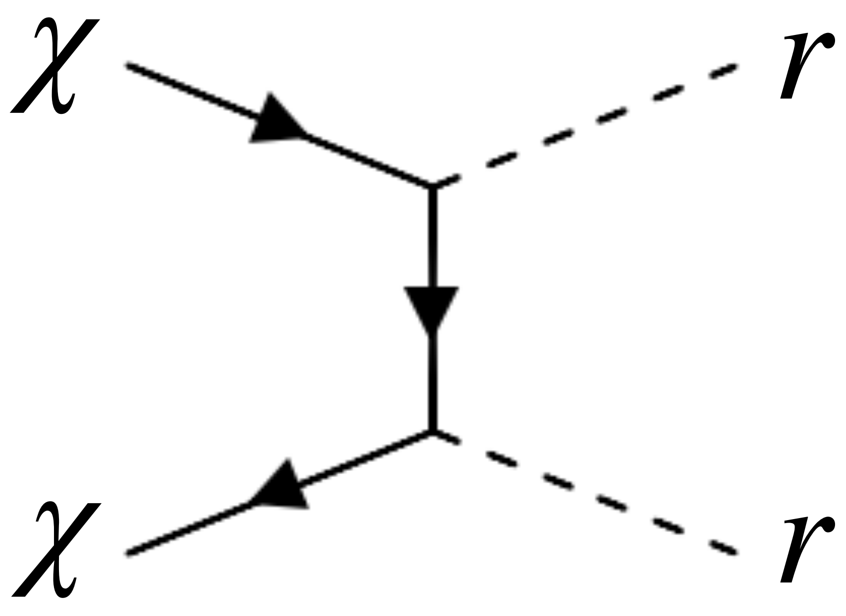
$$\sigma_f v \lesssim 10^{-14}\ {\rm GeV}^{-2}$$

$\sim \chi+\bar\chi\to g+g$

$\gg \chi+\bar\chi\to \gamma+\gamma$

Relic density

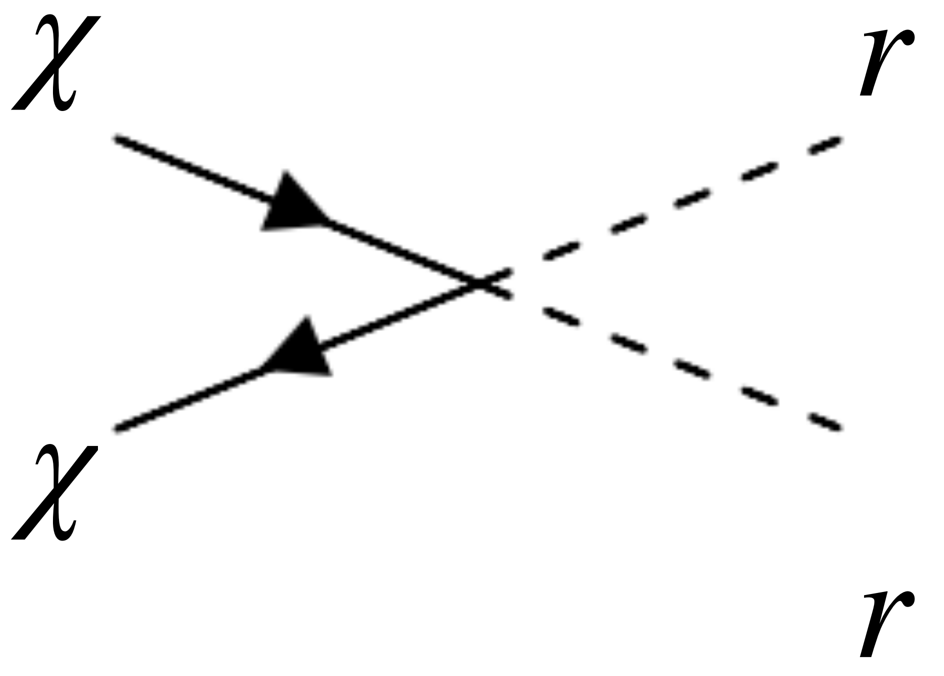
No DM relic density **but** freeze-out from SM → $m_\chi < 10$ GeV, $T_d < 1.2$ GeV



+
t-channel

But (again) DM + radion still in equilibrium

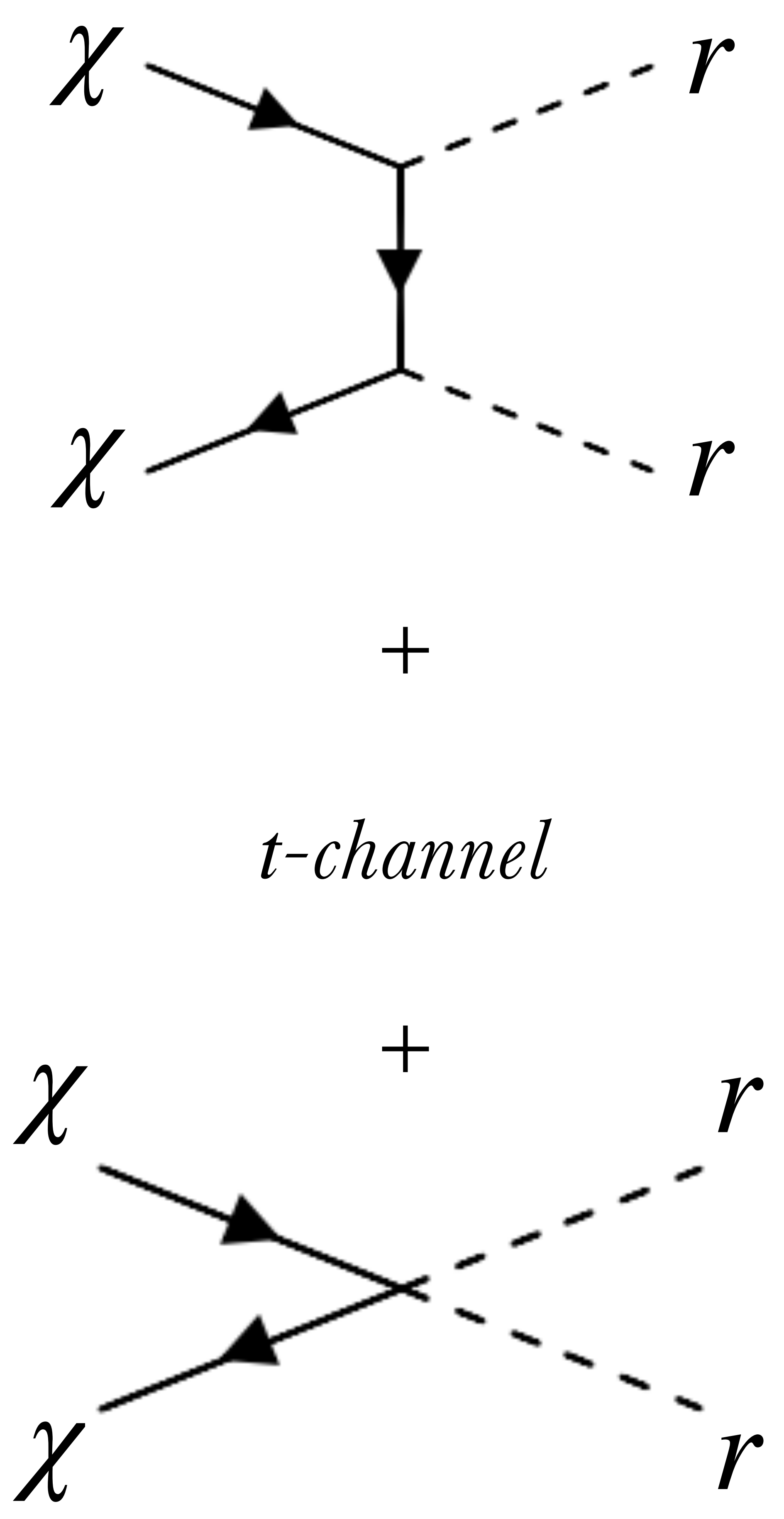
$$\chi(p) + \bar{\chi}(p') \to r(k) + r(k')$$

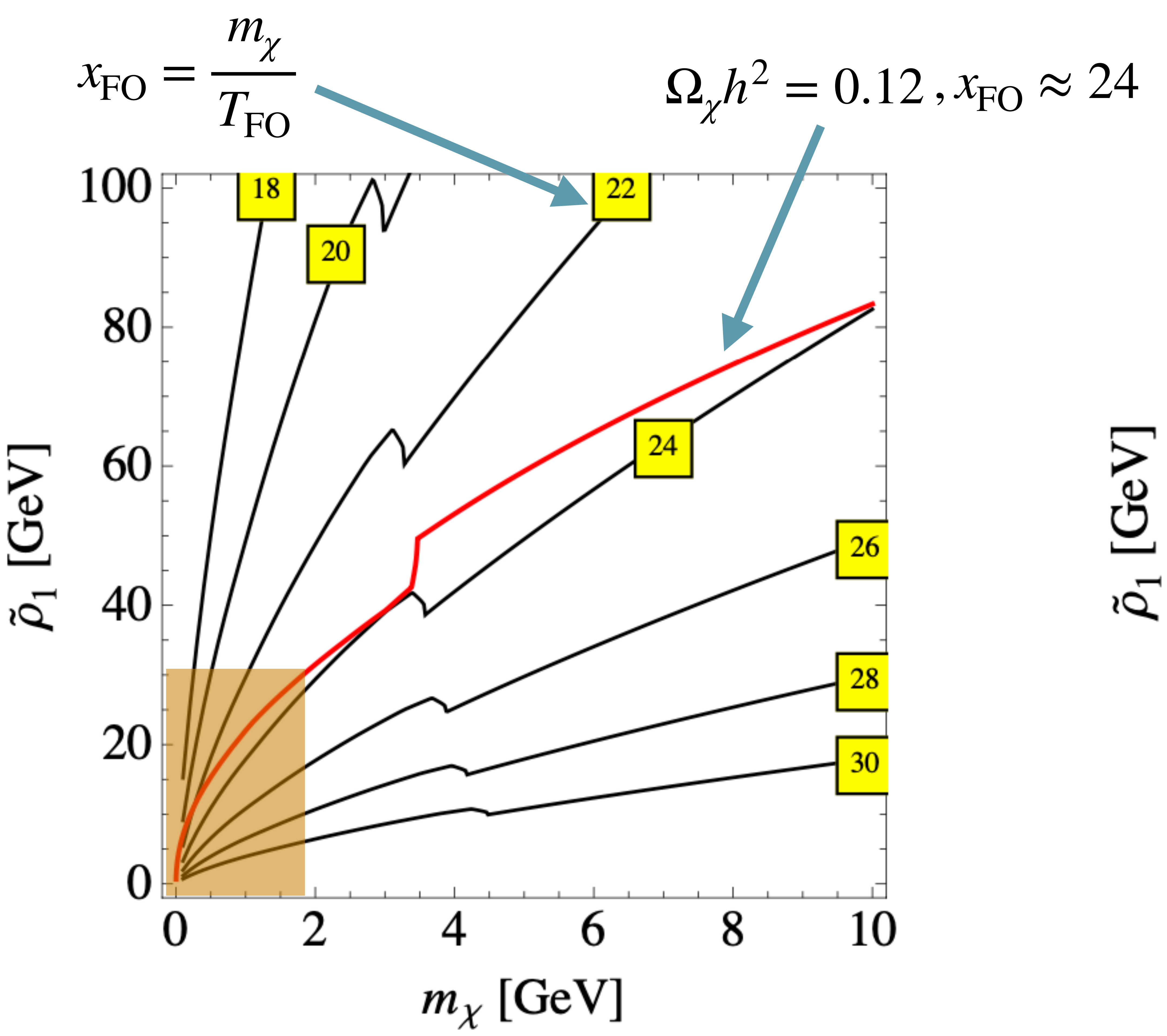


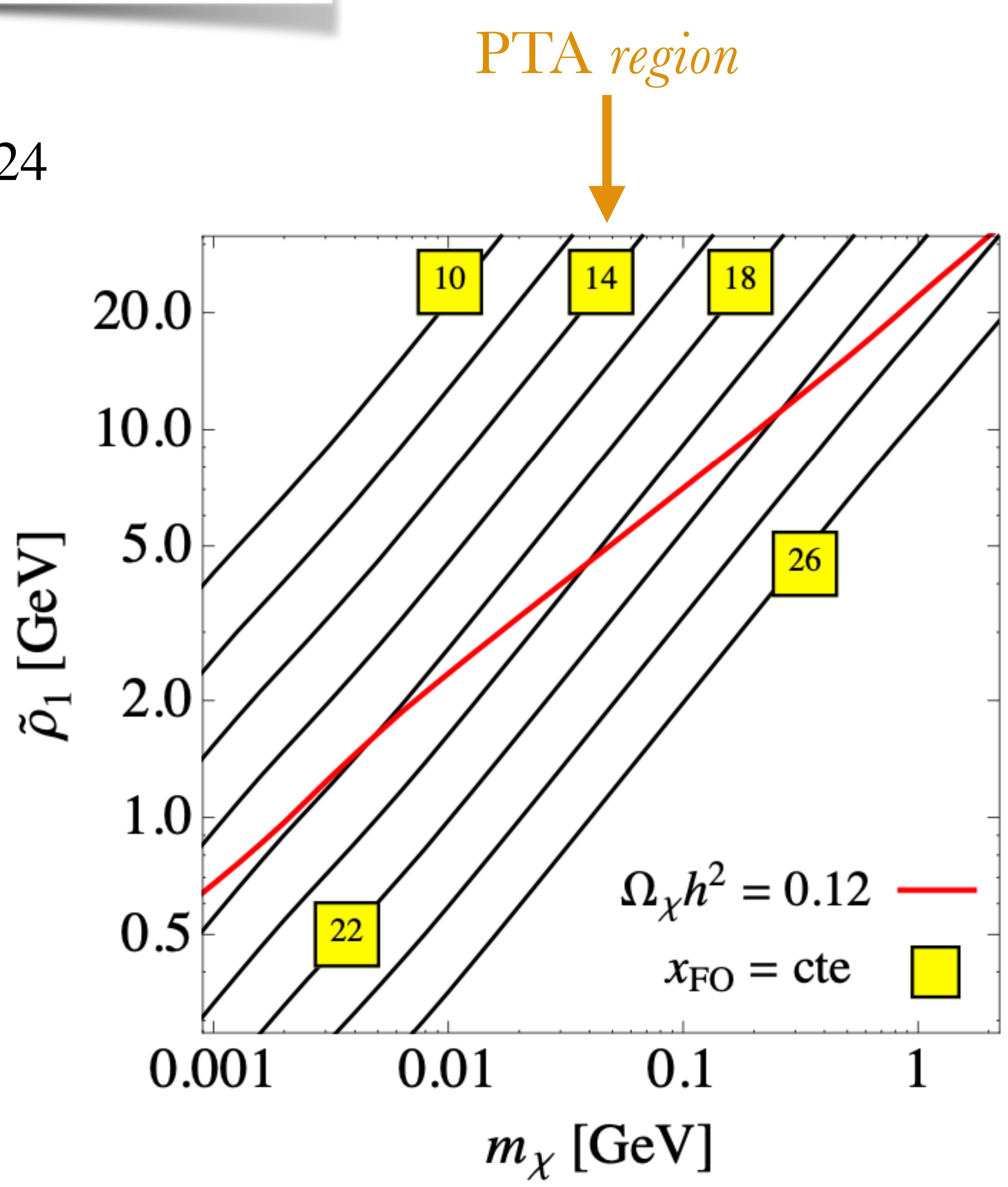
$$\sigma_r = \frac{1}{1152\pi}\frac{m_\chi^2}{\tilde{\rho}_1^4}\left[\frac{z^2(7-11z^2-z^4)}{(1-z^2)}\tanh^{-1}(\sqrt{1-z^2}) + \frac{169-121z^2-8z^4}{8(1-z^2)^{1/2}}\right] \quad \text{with} \quad z^2 = \frac{4m_\chi^2}{s}$$

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

Relic density







Direct detection

Scattering off nuclei $\mathcal{L}_{\rm eff} = b_r(\bar\chi\chi)(\bar Q Q)$ with $b_r = a_r m_\chi m_Q = \dfrac{m_\chi m_Q}{6 m_r^2 \tilde\rho_T^2}$

$Q = u, d, s$
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

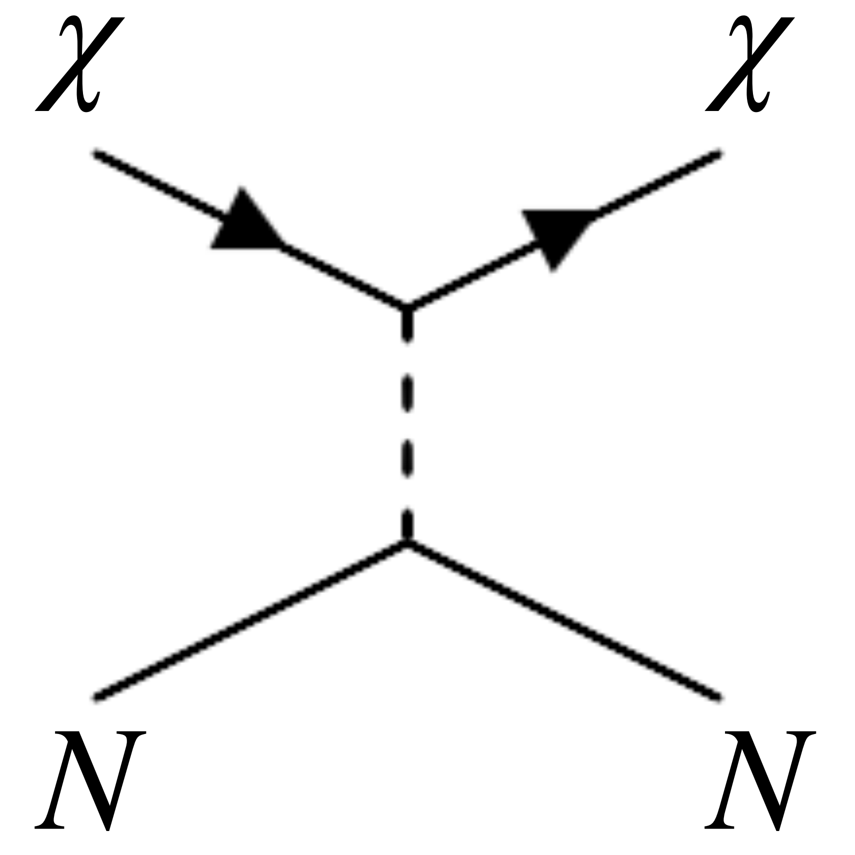
↓

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

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

$f_{T_s}^{(p)} = 0.037(7)$ 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 $\sigma_N = \dfrac{\mu_{N\chi}^2}{\pi} f_N^2$ with $f_N \sim 1/m_r^2$

The reduced DM-nucleon mass $\mu_{N\chi} = m_N m_\chi / (m_N + m_\chi)$

Direct detection

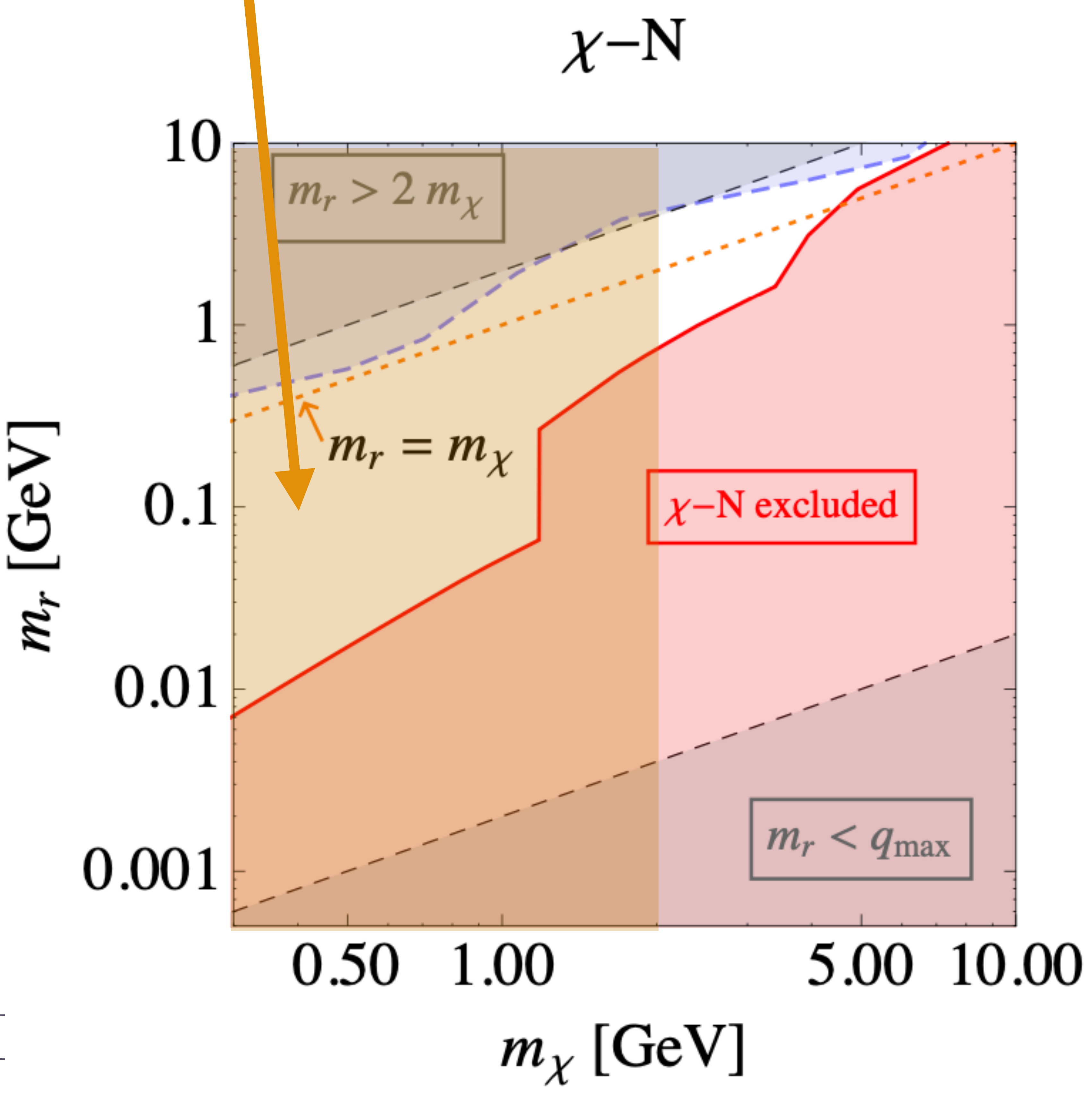
$3\ \text{GeV} \lesssim m_\chi \lesssim 10\ \text{GeV}$
XENON1T collab.
1907.12771, 1907.11485

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

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

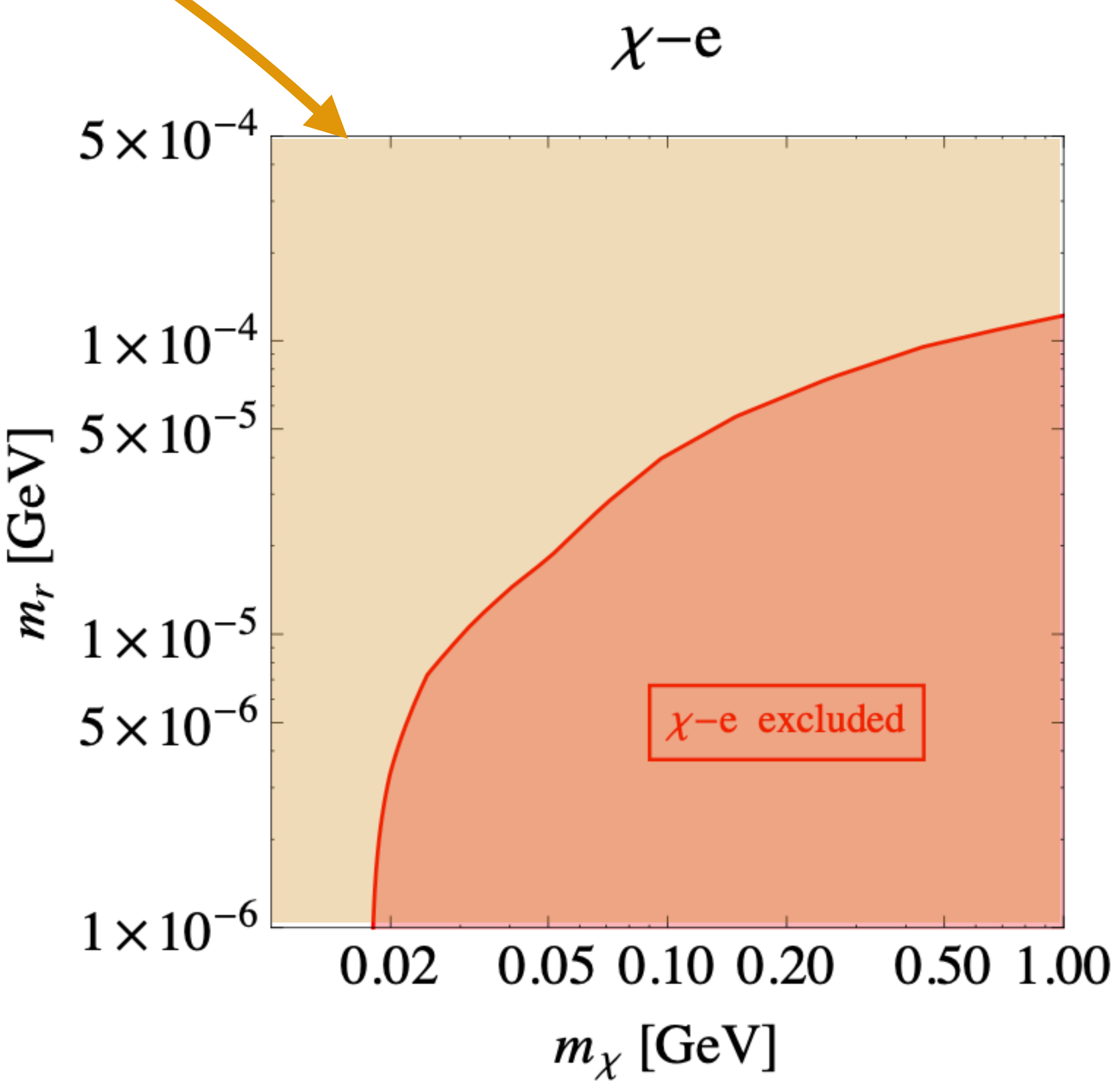
$1\ \text{MeV} \lesssim m_\chi \lesssim 1\ \text{GeV}$
XENON1T, DarkSide, SENSEI

PTA *region*



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

Sub-GeV Dark Matter



Accelerator searches

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

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

↓

$\Lambda \gtrsim 40$ GeV

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

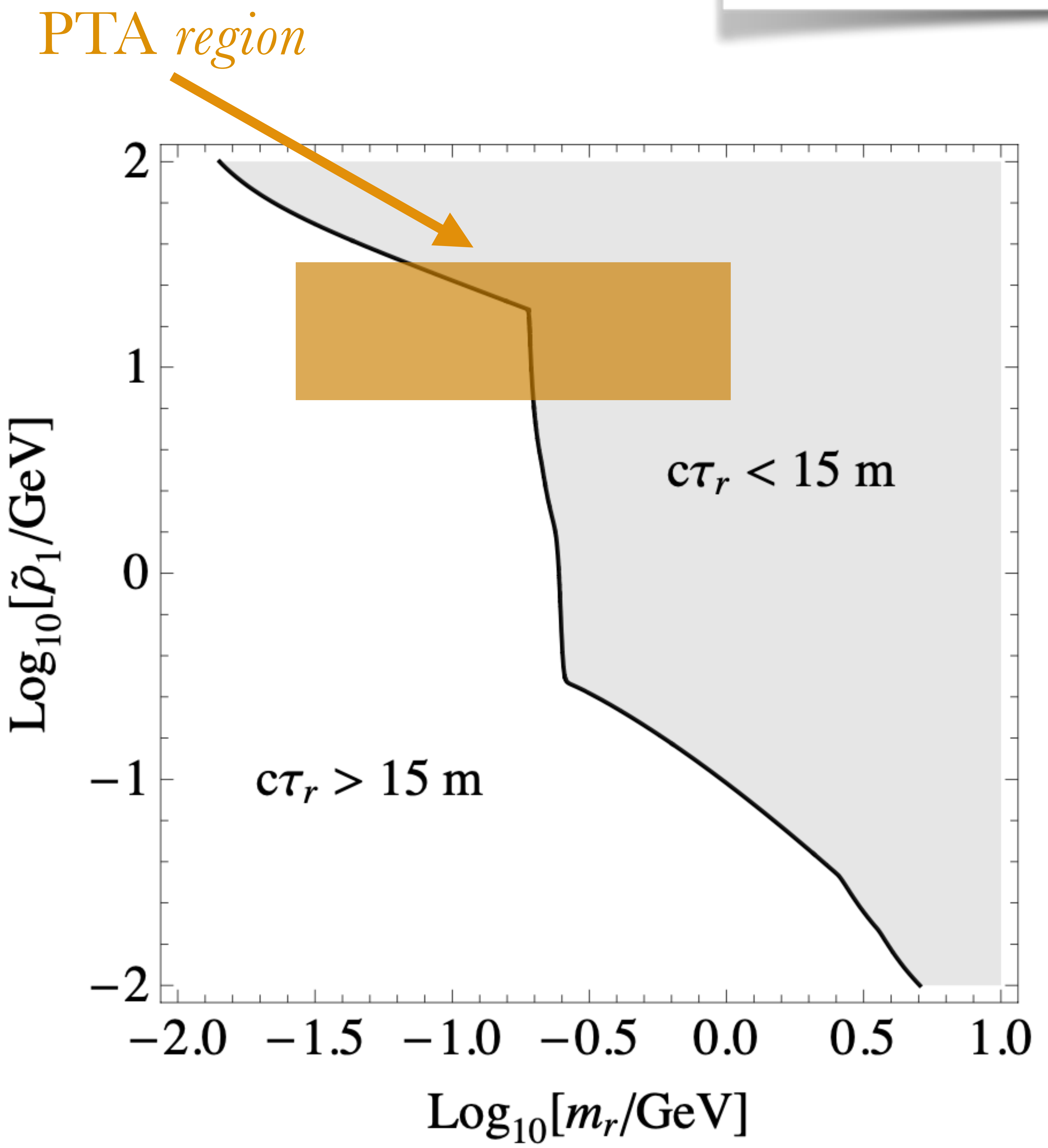
2) For $m_e \lesssim m_\chi \lesssim m_p$ fixed-target experiments NA64 (CERN SPS) and LDMX (SLAC) could probe **new boson** (radion) → $e^- Z \to e^- Z r$ → invisible decay inside NA64

↓

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

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

Accelerator searches



But for $m_r < 2m_\chi$ then $r \to \mathrm{SM} + \mathrm{SM}$ → **No** invisible decay and **no** bounds. Unless radion **decays outside** the detector

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

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

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

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

Indirect constraints

Bounds from **CMB**, **Cosmic Rays**, **Galactic Center**:
$\chi\bar{\chi} \to l^+l^-, q\bar{q}, \gamma\gamma$ **for** $0.1\ \text{GeV} \lesssim m_\chi \lesssim 10\ \text{GeV}$ → $\langle \sigma_\chi v \rangle \ll \langle \sigma_{\text{bound}} v \rangle \sim 10^{-27}\ \text{cm}^3/\text{s}$

Bounds from **BBN**

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

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

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

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

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

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

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

$T = T_{\text{FO}}$ → $\sigma \equiv \frac{T_{\text{FI}}}{T_{\text{FO}}} = \frac{24\gamma m_r}{m_\chi} \gg 1$ → $Y_r = Y_r^{\text{eq}}$

Before DM freezes-out

Indirect constraints

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

BBN not perturbed when $\tau_r \lesssim 10$ sec

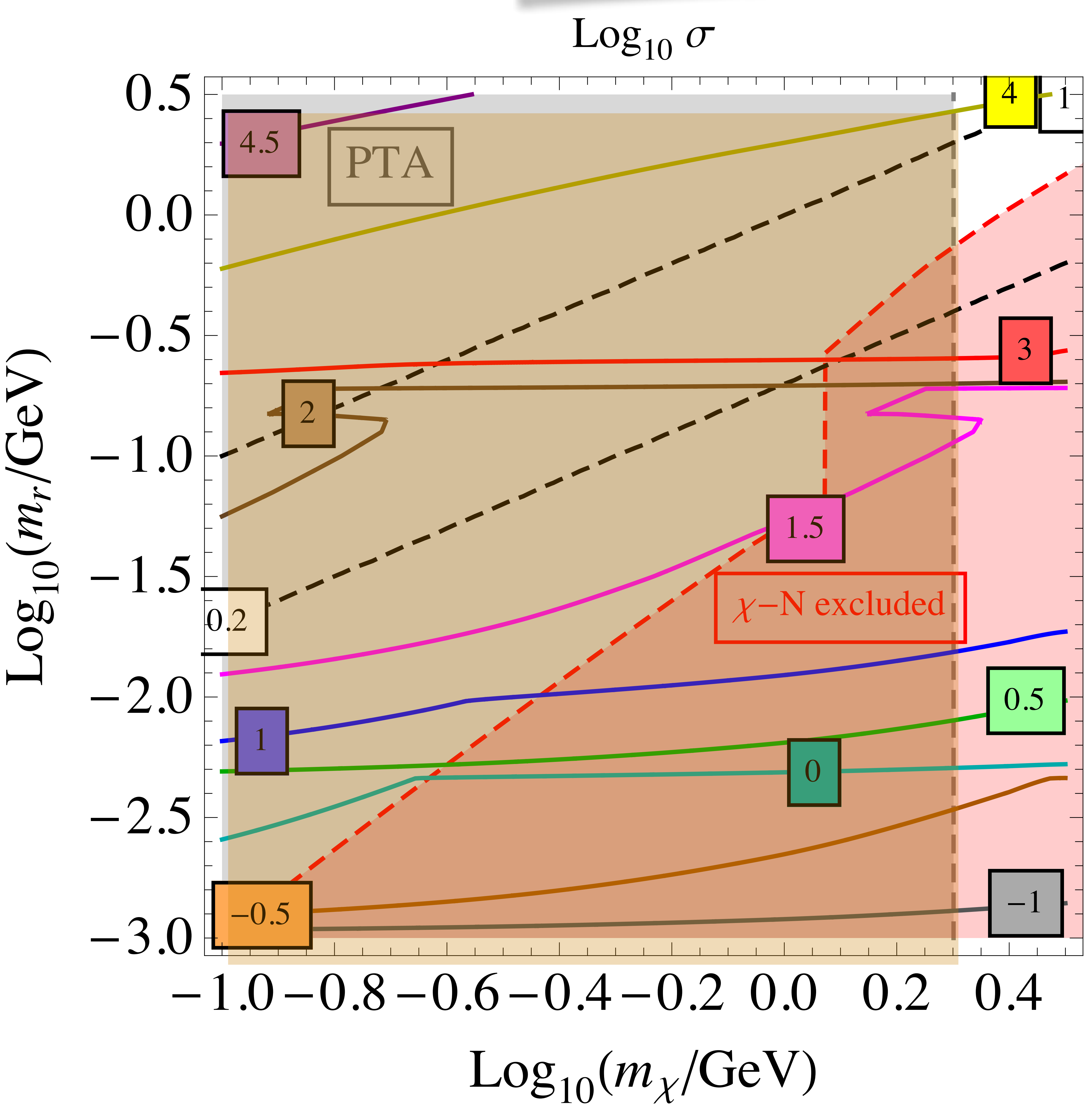
F. Abu-Ajamieh, J. S. Lee and J. Terning, JHEP 10 (2018) 050
M. Kawasaki, K. Kohri, T. Moroi and Y. Takaesu, Phys. Rev. D 97 (2018) 023502

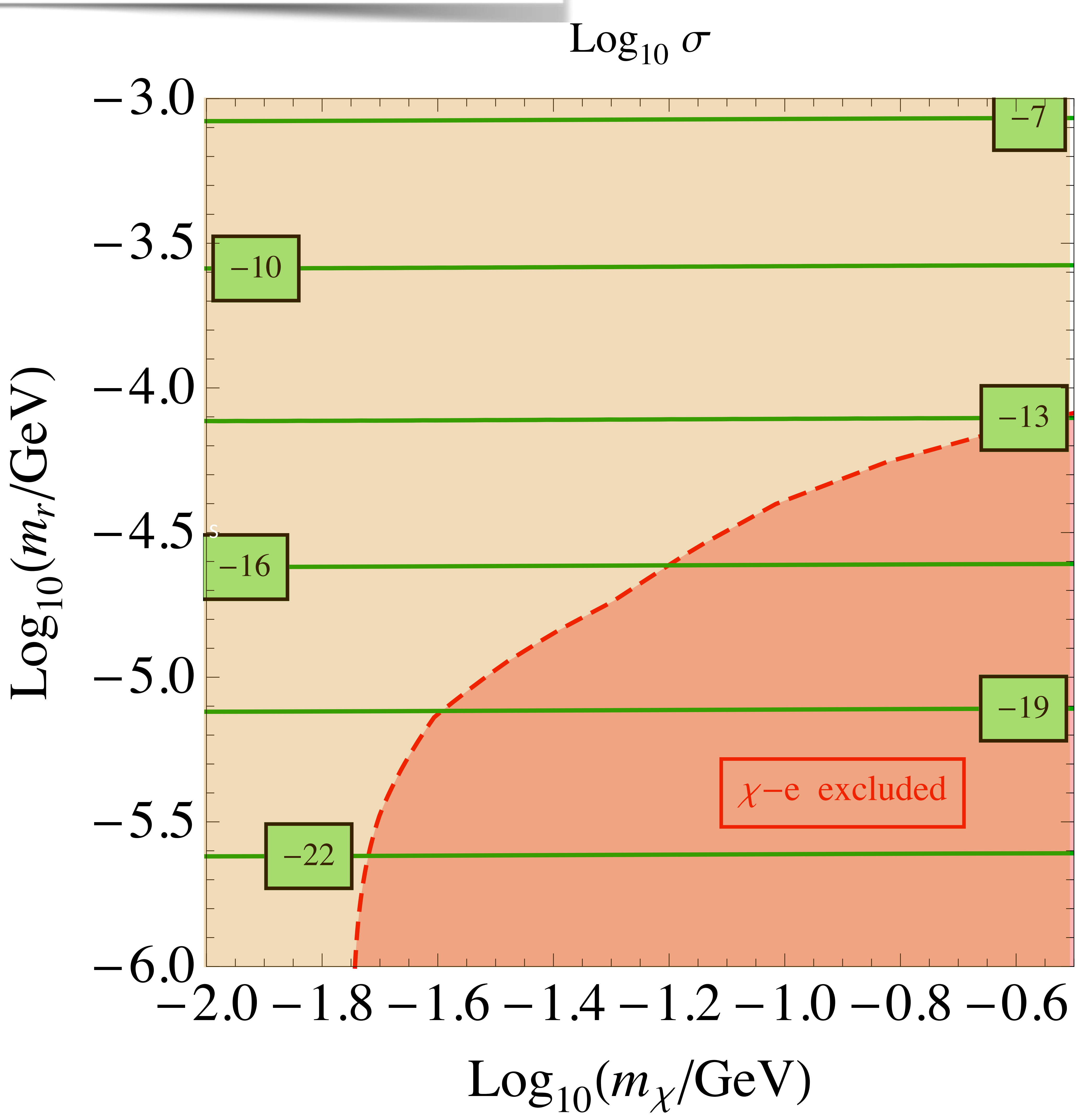
$$\tau_r \simeq 0.4\,\text{sec}\left(\frac{\tilde{\rho}_T}{\text{TeV}}\right)^4\left(\frac{\text{GeV}}{\tilde{\rho}_1}\right)^2\left(\frac{\text{MeV}}{m_r}\right)$$

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

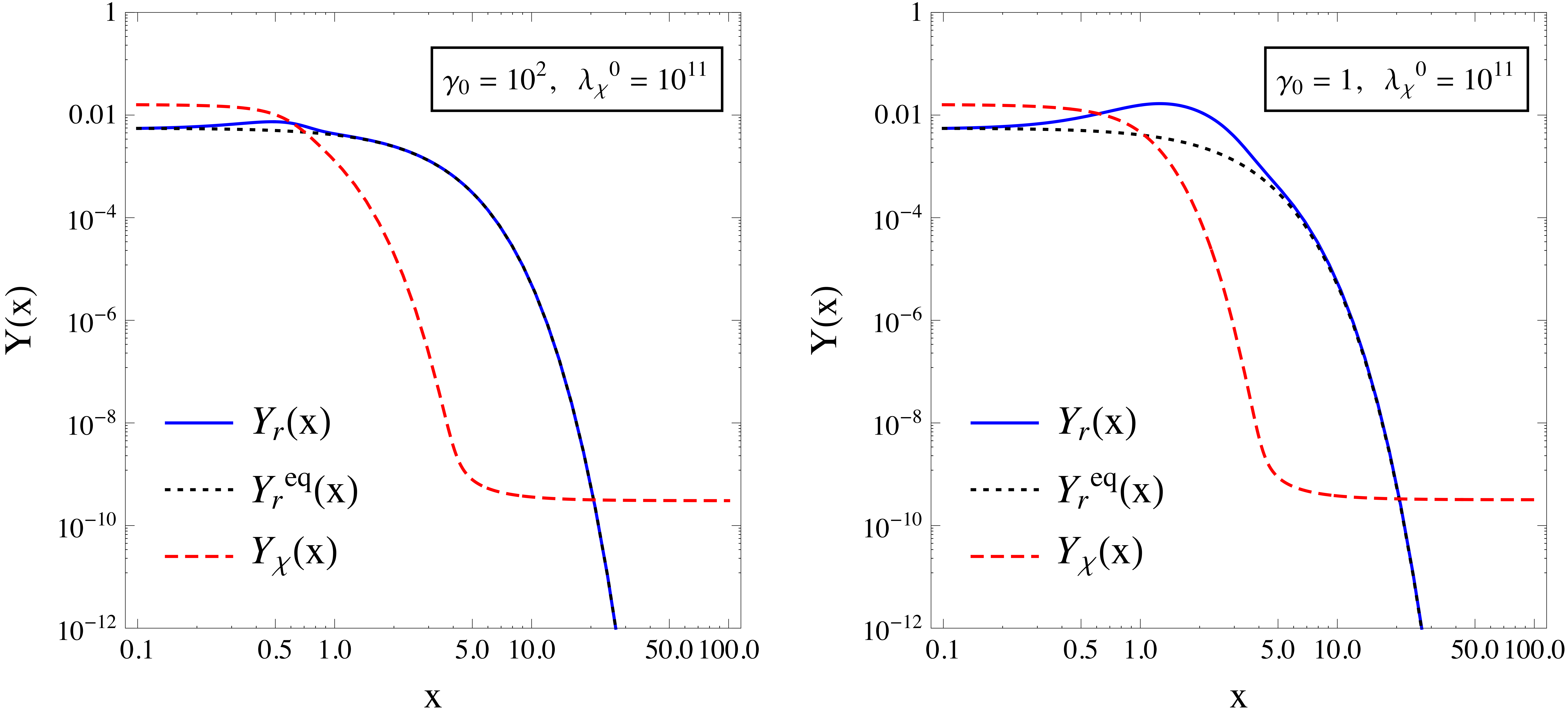
2a) Region $m_r < 2m_e$ ⟶ Dominant channel $r \to \gamma\gamma$ and $\sigma \sim m_r \ll 1$ ⟶ $T_{\text{FO}} \gg T_{\text{FI}}$ ⟶ $Y_r \ll Y_r^{\text{eq}}$, $\tau_r > 10$ sec, Excluded by **BBN**

Indirect constraints

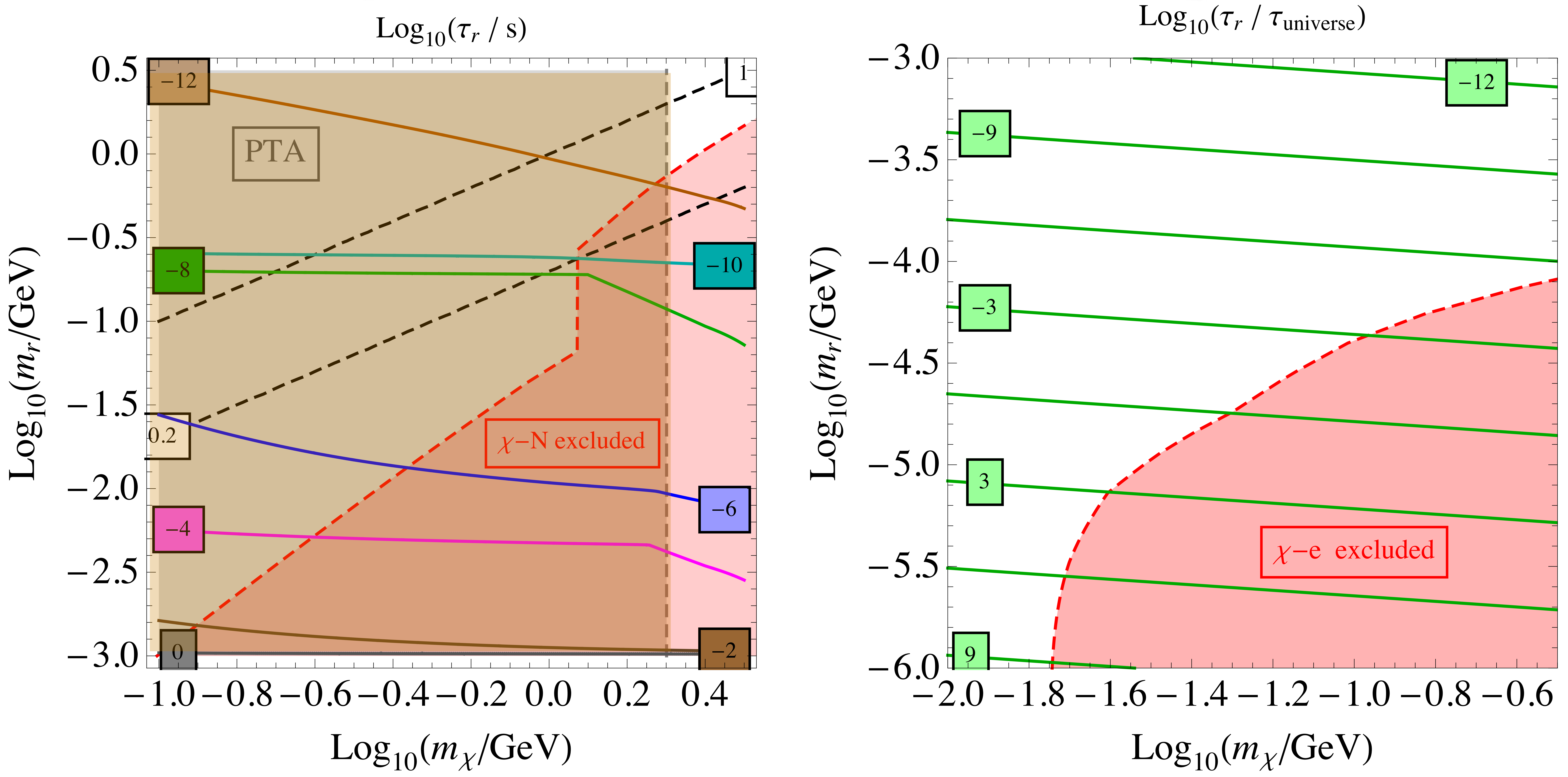




Indirect constraints



Indirect constraints



Indirect constraints

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

↓

For $\Delta_{N_{\text{eff}}}$ to be **safe** $\lesssim 0.07$ 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 $T_r(T_0) \approx 1.16$ **K** $< T_{\text{CMB}}$

Conclusions

- DM interacts **only** gravitationally via radions and massive KK gravitons. Strong annihilations into **radions** can trigger the **observed relic density** after the non-relativistic freeze-out

- Interactions of **radions** with the SM are **weak enough** to **evade constraints** from direct measurements, **but not so weak** as to also evade **the neutrino floor**, leaving a wide window for future experimental detection, mainly from nuclear recoil

- 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, in the future, **can be detected** in present fixed target experiments, as NA64 at the CERN SPS, and the future LDMX at SLAC

- Finally, assuming that the PTA experiments have found a **new physics scale** around the GeV ($\Lambda_{\text{PTA}} \sim$ GeV) scale, our proposal would suggest that the new scale can be **provided by the dark matter sector** in our universe

THANK YOU!!!