Sub-GeV Dark Matter and the pre-BBN Universe

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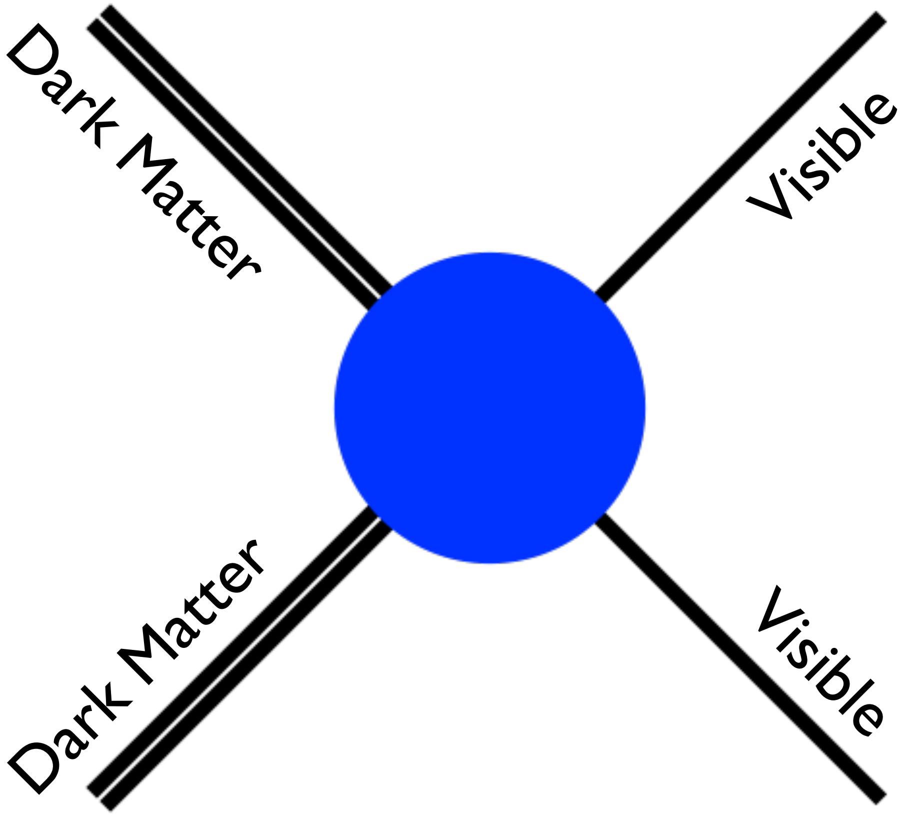
Light Dark Matter 2019 — Venice, November 20th 2019

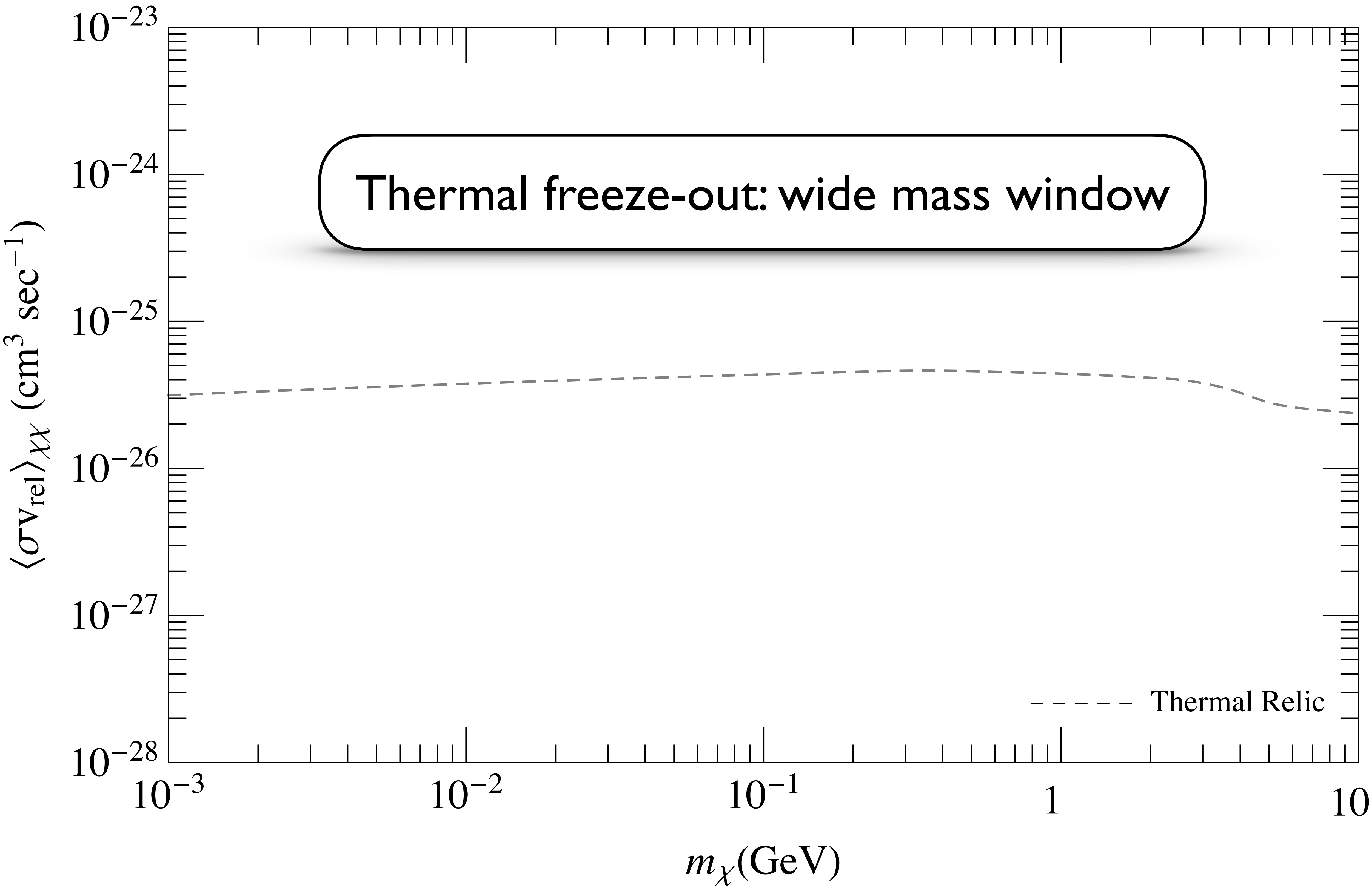
What mass for the dark matter?



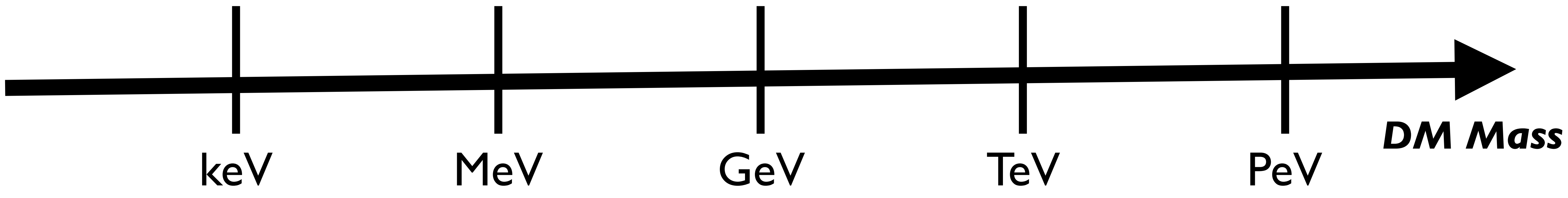
Relic density bounds annihilation rate at freeze-out

$$\langle \sigma v_{\rm rel} \rangle \simeq 3 \times 10^{-26}\,{\rm cm}^3{\rm s}^{-1}$$

What mass for the dark matter?



Bounds on the dark matter mass

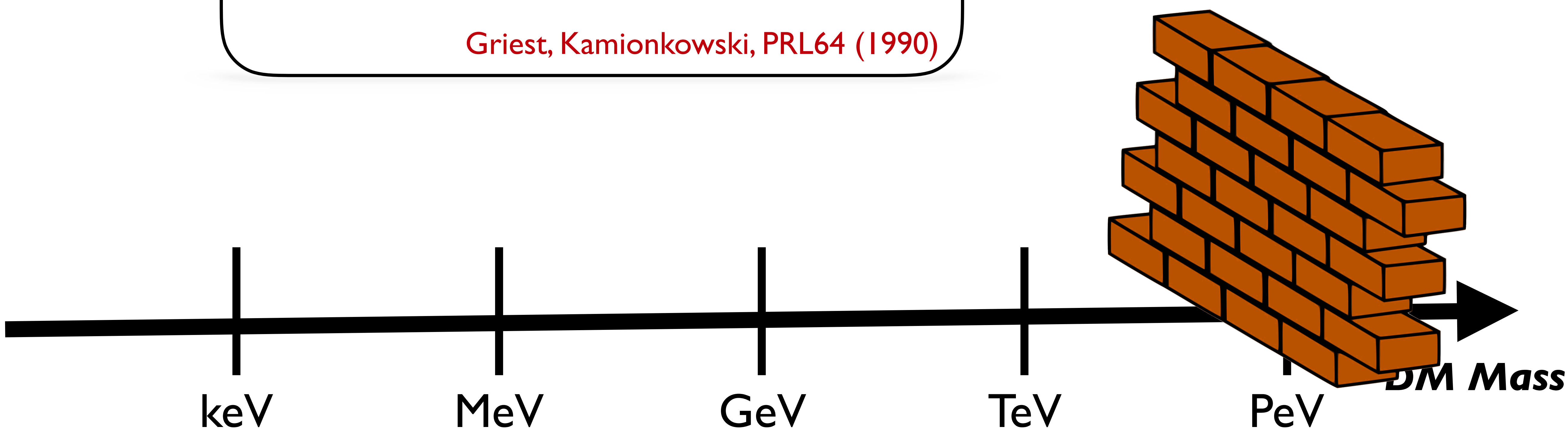


Bounds on the dark matter mass

Unitarity

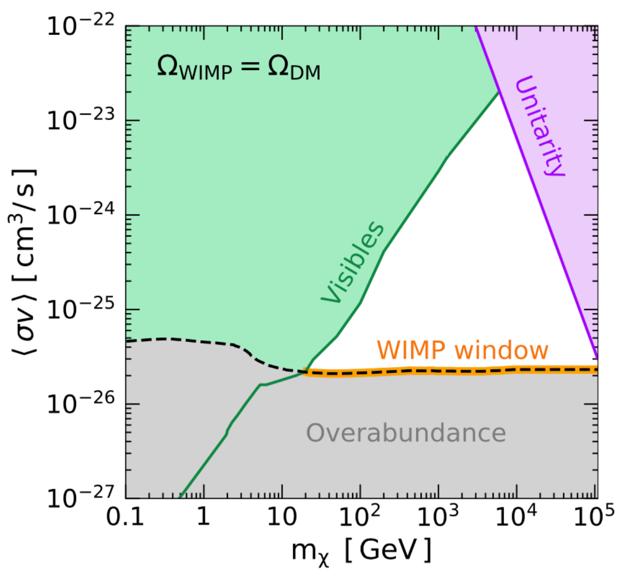
$$\sigma v \lesssim \frac{4\pi}{m_{\mathrm{DM}}^2 v}$$

Griest, Kamionkowski, PRL64 (1990)



Bounds on the dark matter mass

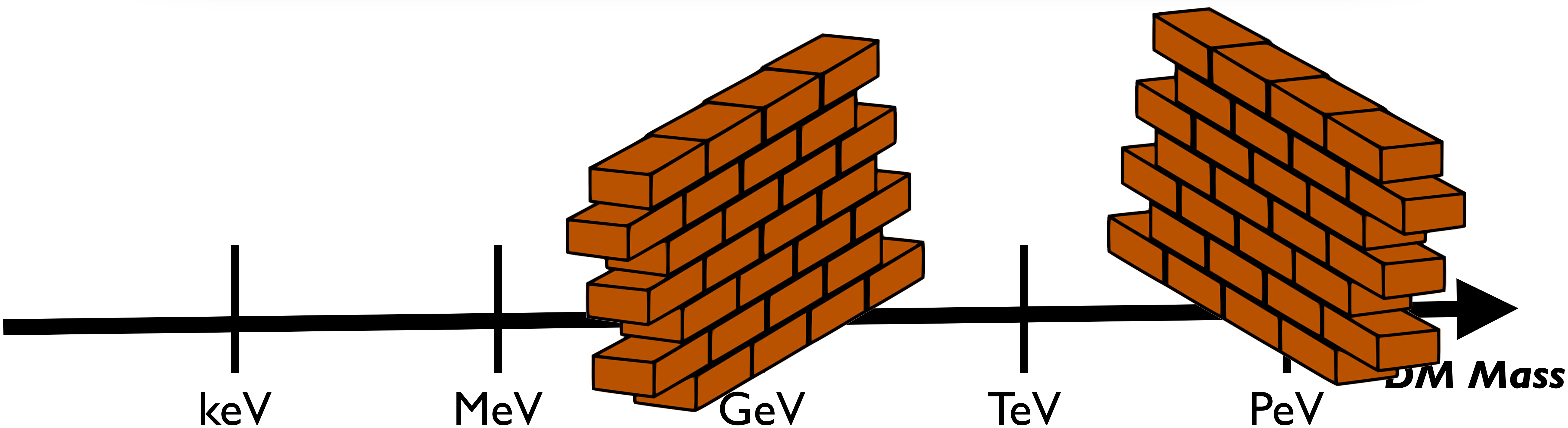
The WIMP Window



Dark matter with s-wave annihilation to visible states

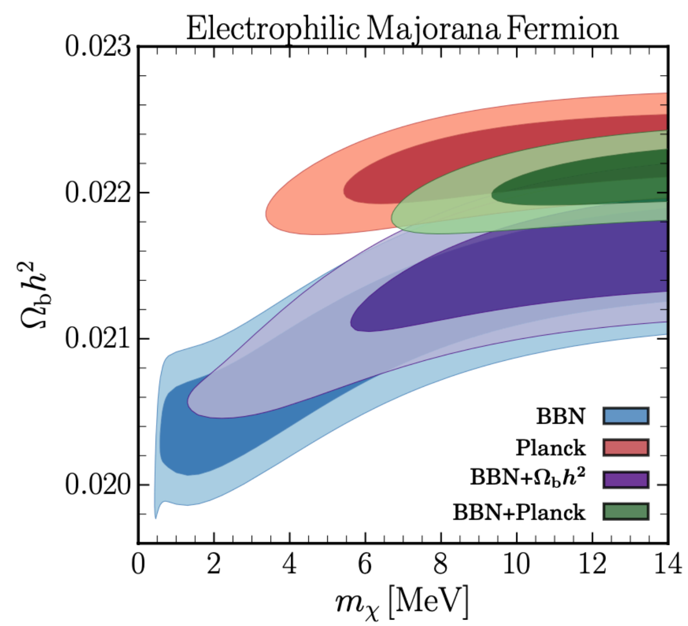
$$10\,\mathrm{GeV} \lesssim m_{\mathrm{WIMP}} \lesssim 100\,\mathrm{TeV}$$

Leane, Slatyer, Beacom, Ng, PR D98 (2018)



Bounds on the dark matter mass

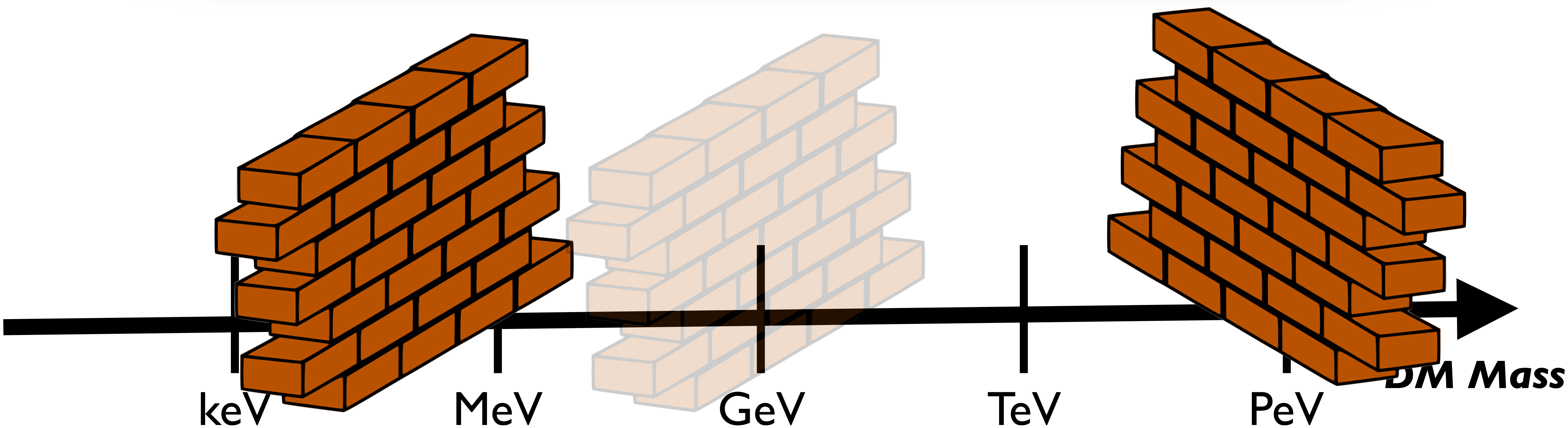
The BBN Wall



Thermal relics with mass below MeV spoil BBN and CMB

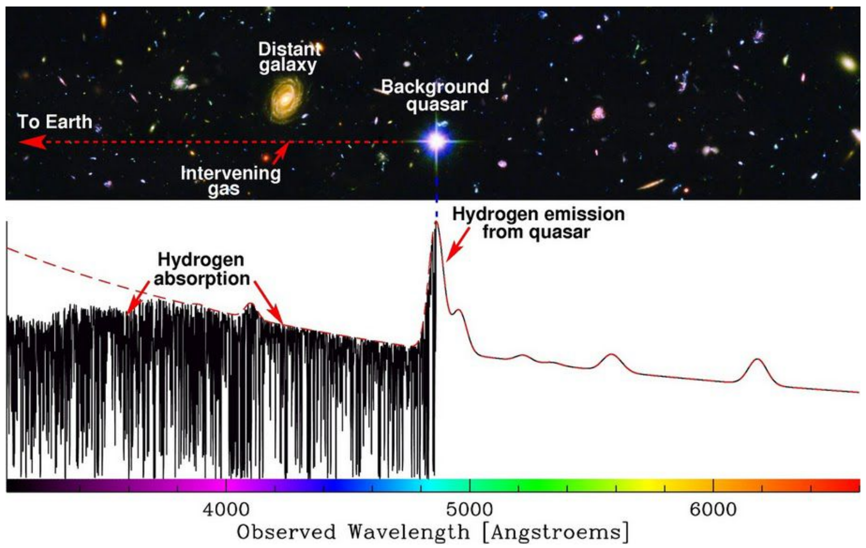
$$\mathrm{MeV} \lesssim m_{\mathrm{thermal}} \lesssim 100\ \mathrm{TeV}$$

Sabti, Alvey, Escudero, Fairbairn, Blas, arXiv:1910.01649



Bounds on the dark matter mass

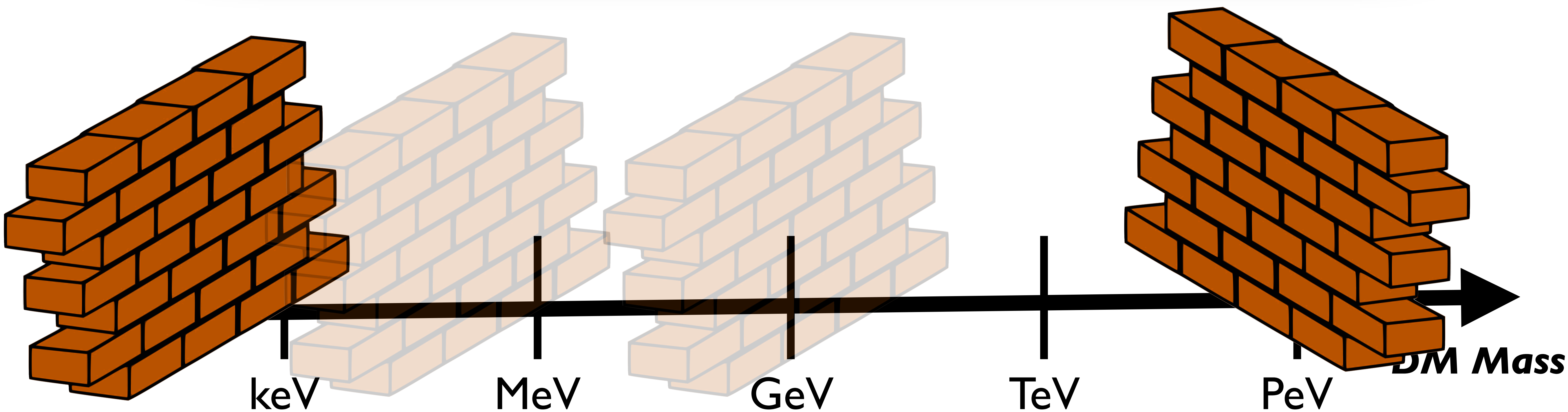
Cannot be "too hot"



Bounds on the dark matter free-streaming length

$$m_{\rm warm} \gtrsim \text{keV}$$

Viel, Becker, Bolton, Haehnelt, PRD88 (2013)

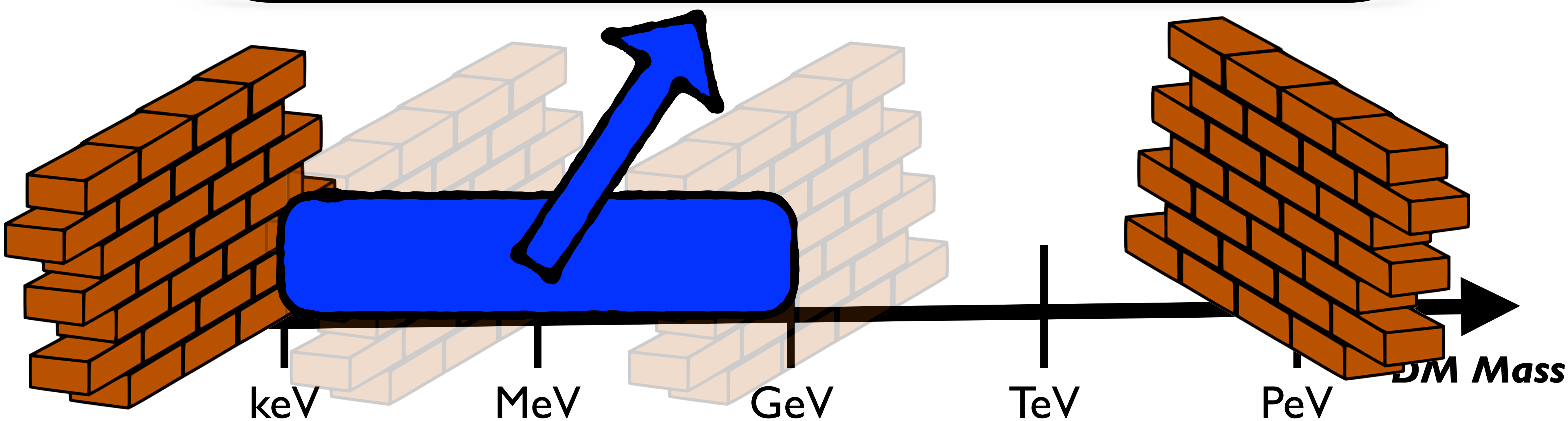


The sub-GeV mass window

Is it accessible?

Can we successfully produce sub-GeV dark matter in the early universe?

How do we test it today?

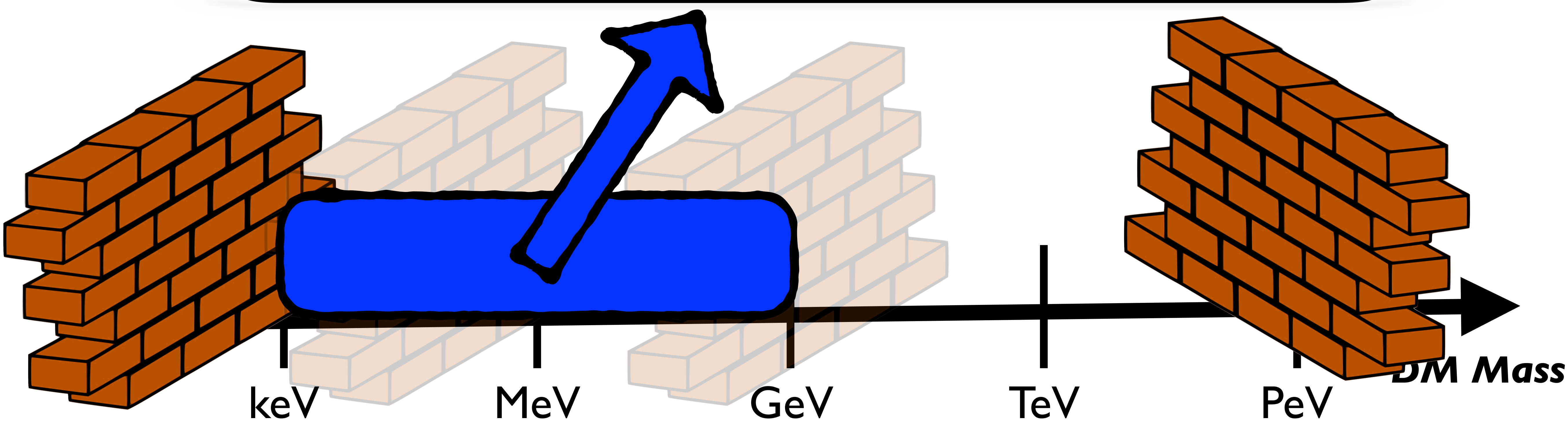


The sub-GeV mass window

Is it accessible?

Can we successfully produce sub-GeV dark matter in the early universe? **YES!**

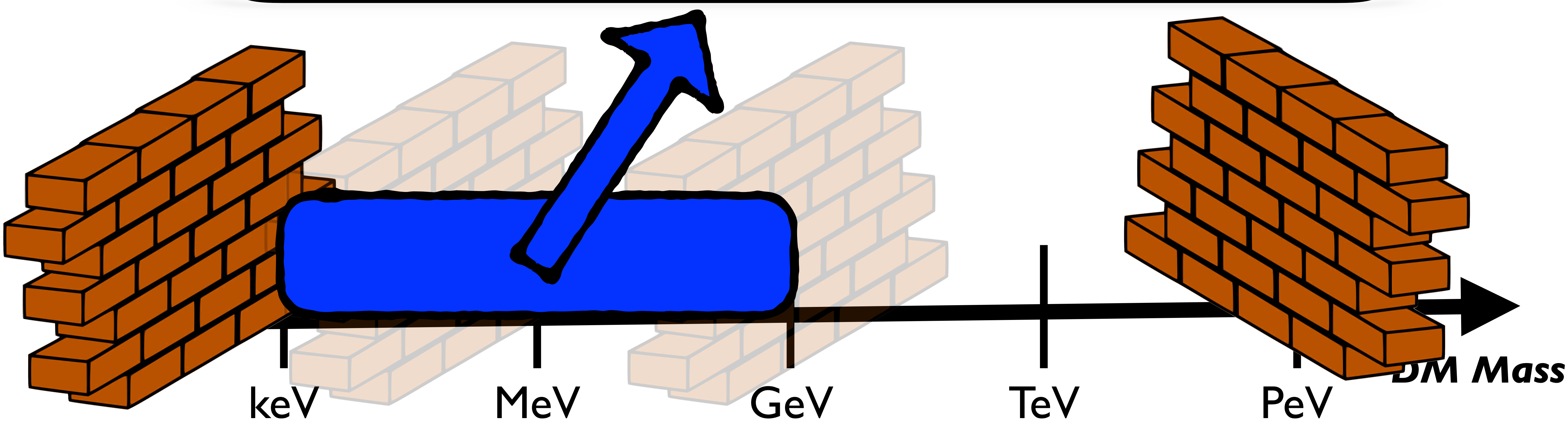
How do we test it today? **DEPENDS!**



The sub-GeV mass window

Requirements

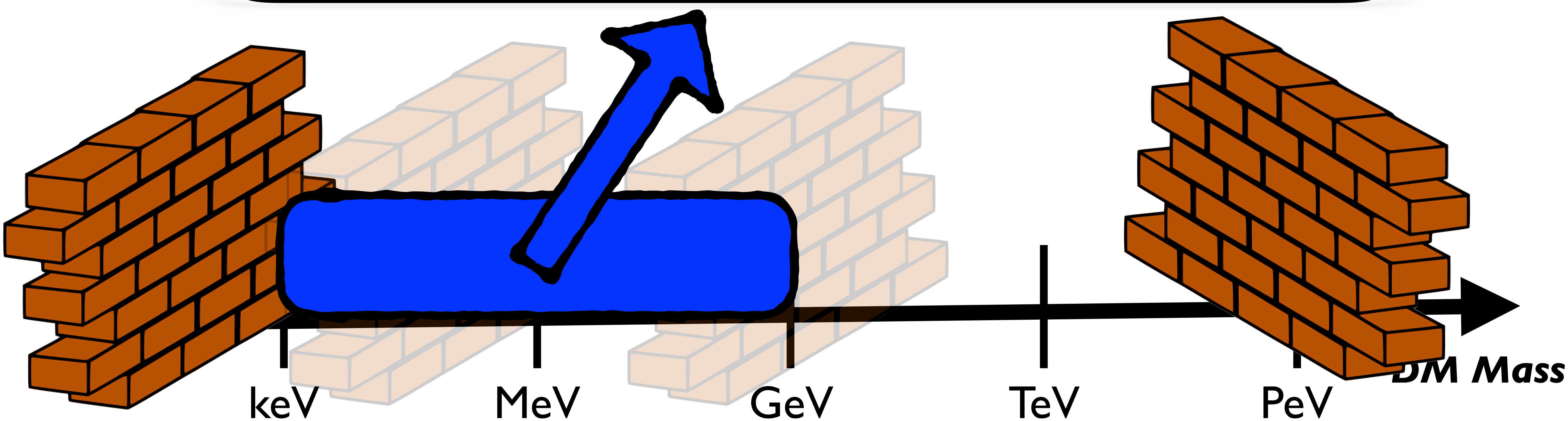
- It cannot annihilate via s-wave (GeV bound)
- It cannot be in thermal equilibrium at BBN (MeV bound)
- It has to talk to the visible sector (detectability)



The sub-GeV mass window

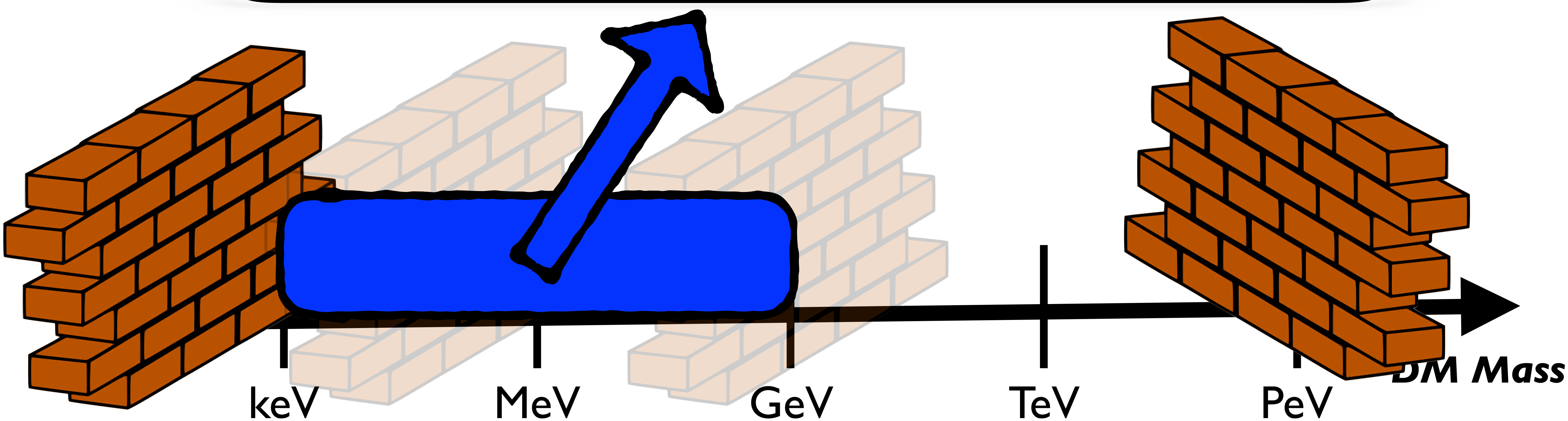
In this talk

- Framework for sub-GeV non-thermal dark matter
- How to test it today
- What we can learn about our universe

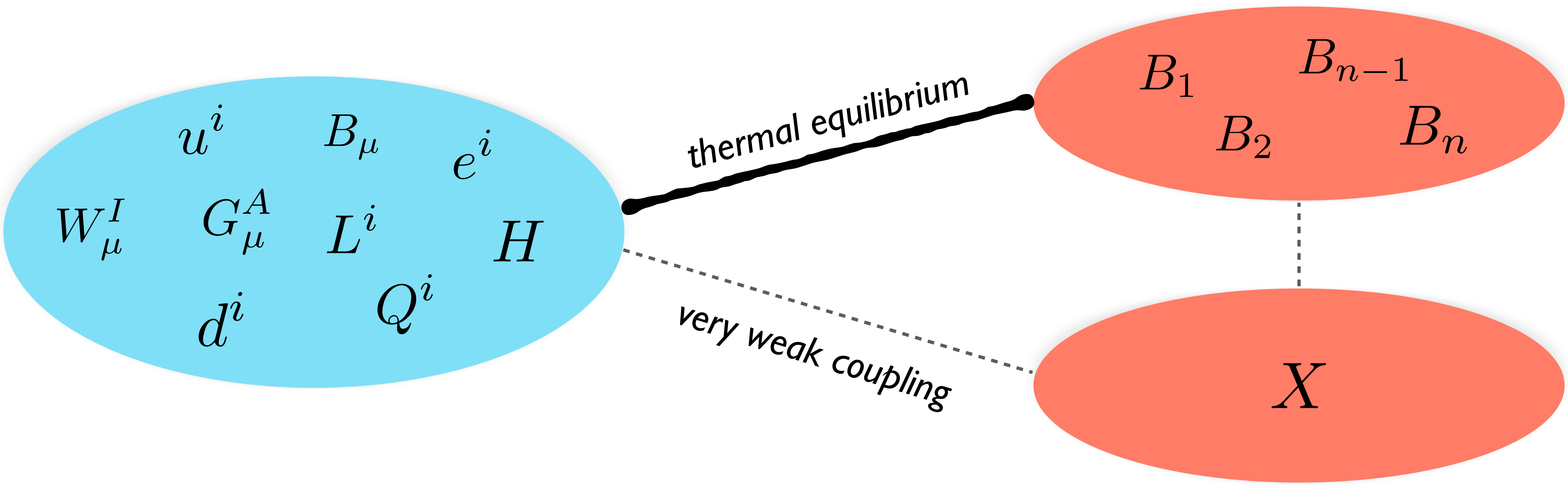


The sub-GeV mass window

Other scenarios discussed by *Berlin*, *D'Agnolo*, *Darmé*, *Kuflik* in this workshop



FIMPs

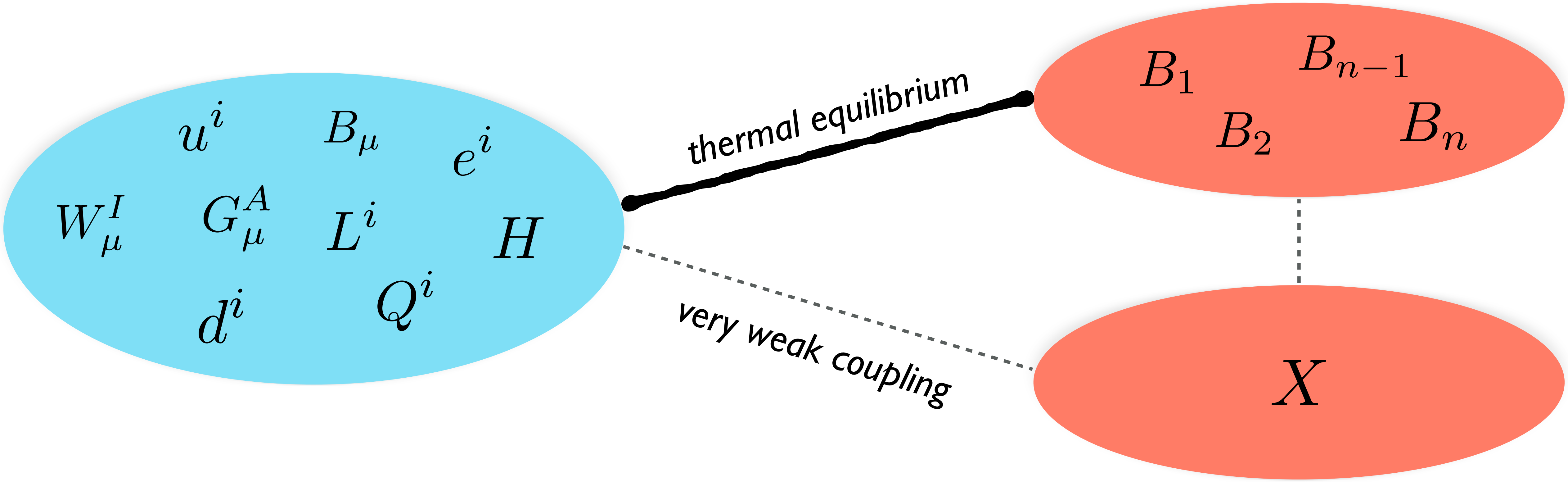


B_i and X odd under a Z_2 symmetry

For this talk: X is the lightest Z_2-odd particle

Hall, Jedamzik, March-Russell, West, JHEP 1003 (2010)

FIMPs



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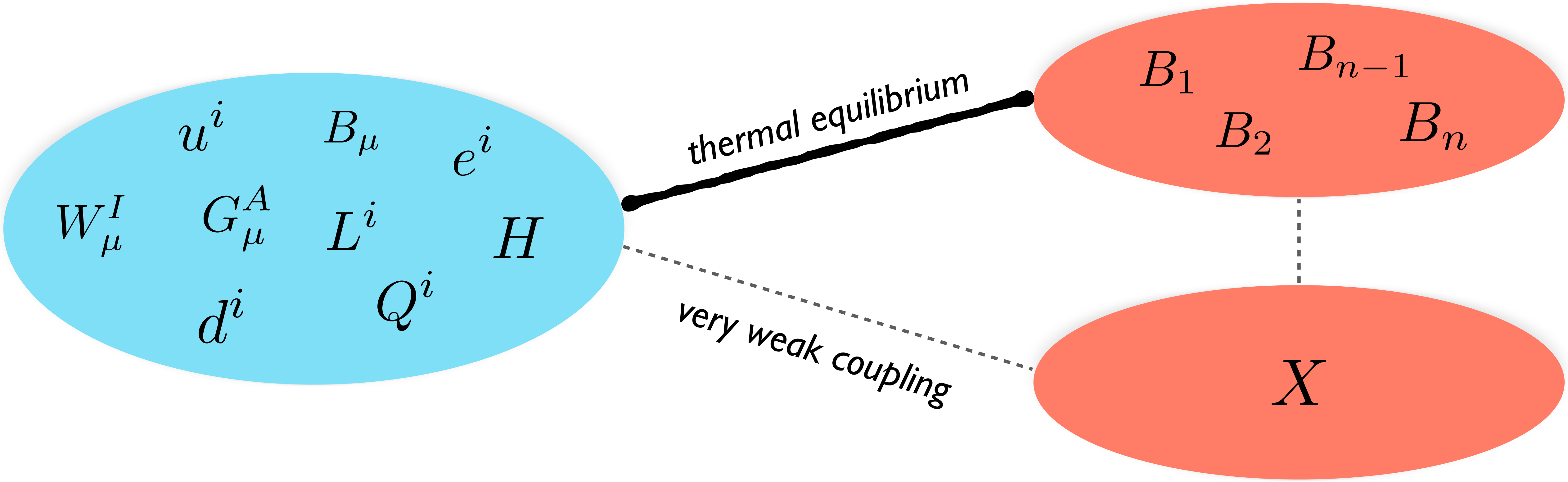
Nightmare for dark matter searches

Testable by direct detection in some exceptions (see, e.g., Hambye et al., PRD98 (2018))

FIMPs



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Production mechanism for FIMPs in the early universe?

Freeze-in

Bath particles collisions and/or decays dump X out of equilibrium

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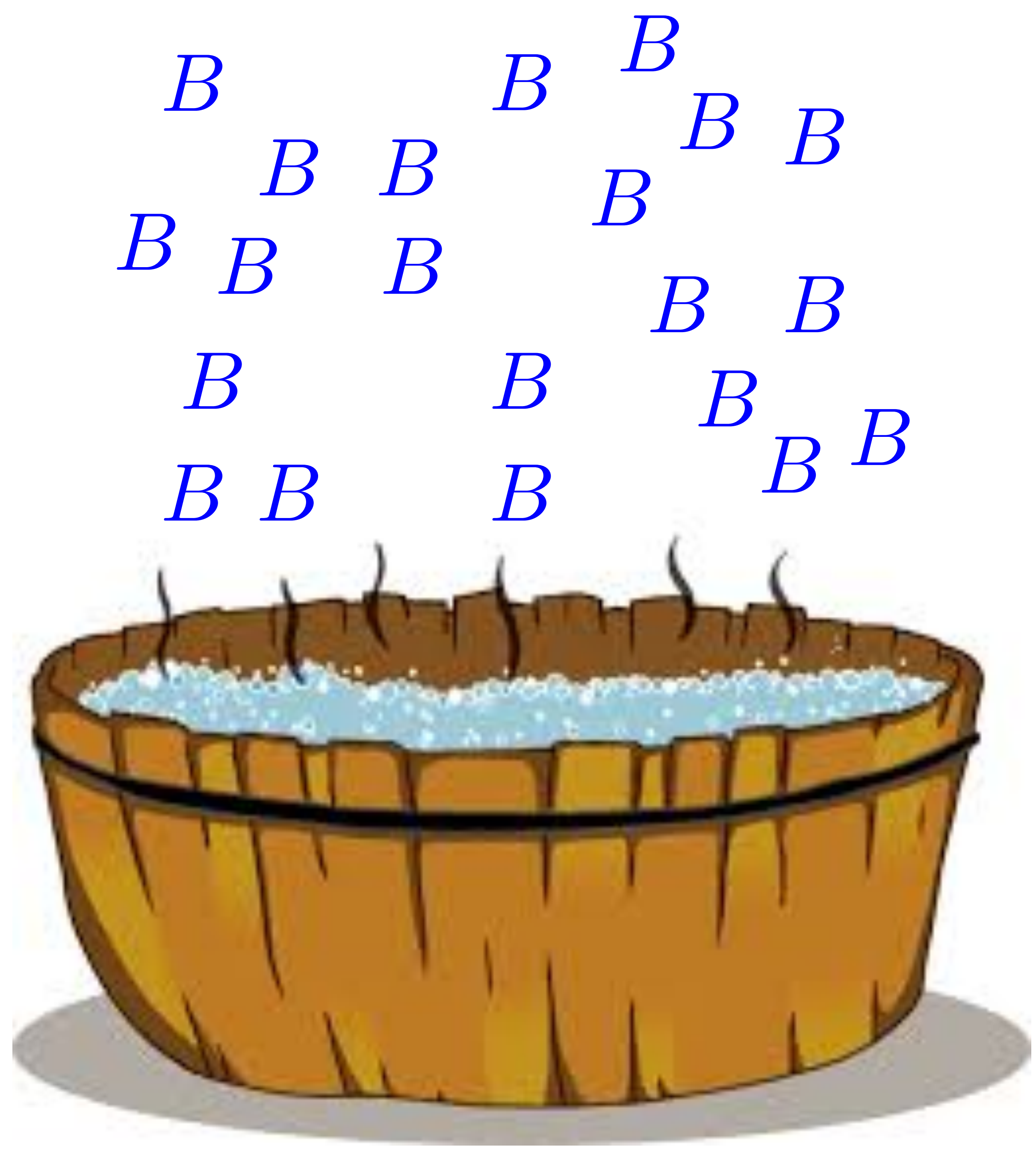
Bath particles collisions and/or decays dump X out of equilibrium

<u>T ≫ bath particles mass:</u>

after inflation, universe reheated without any dark matter particle in the bath (this is an assumption)



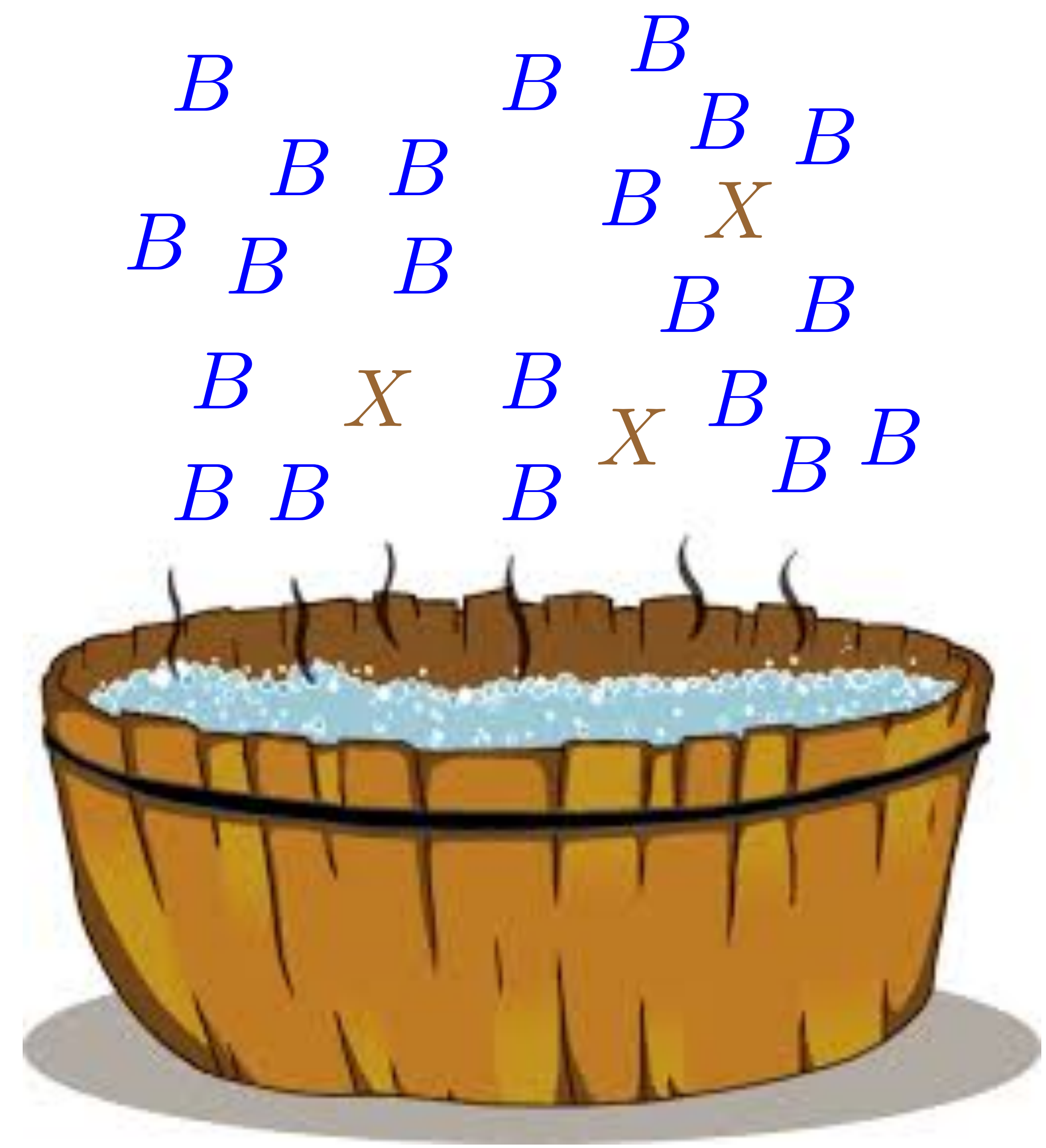
Comoving Volume

Freeze-in

Bath particles collisions and/or decays dump X out of equilibrium

<u>T ~ freeze-in epoch:</u>

dark matter particles
dumped in the primordial plasma
and then free-stream
until the present time



Comoving Volume

Freeze-in via decays

$$B \rightarrow \mathrm{SM} + X$$

Bath particles decays produce X particle that will never thermalize

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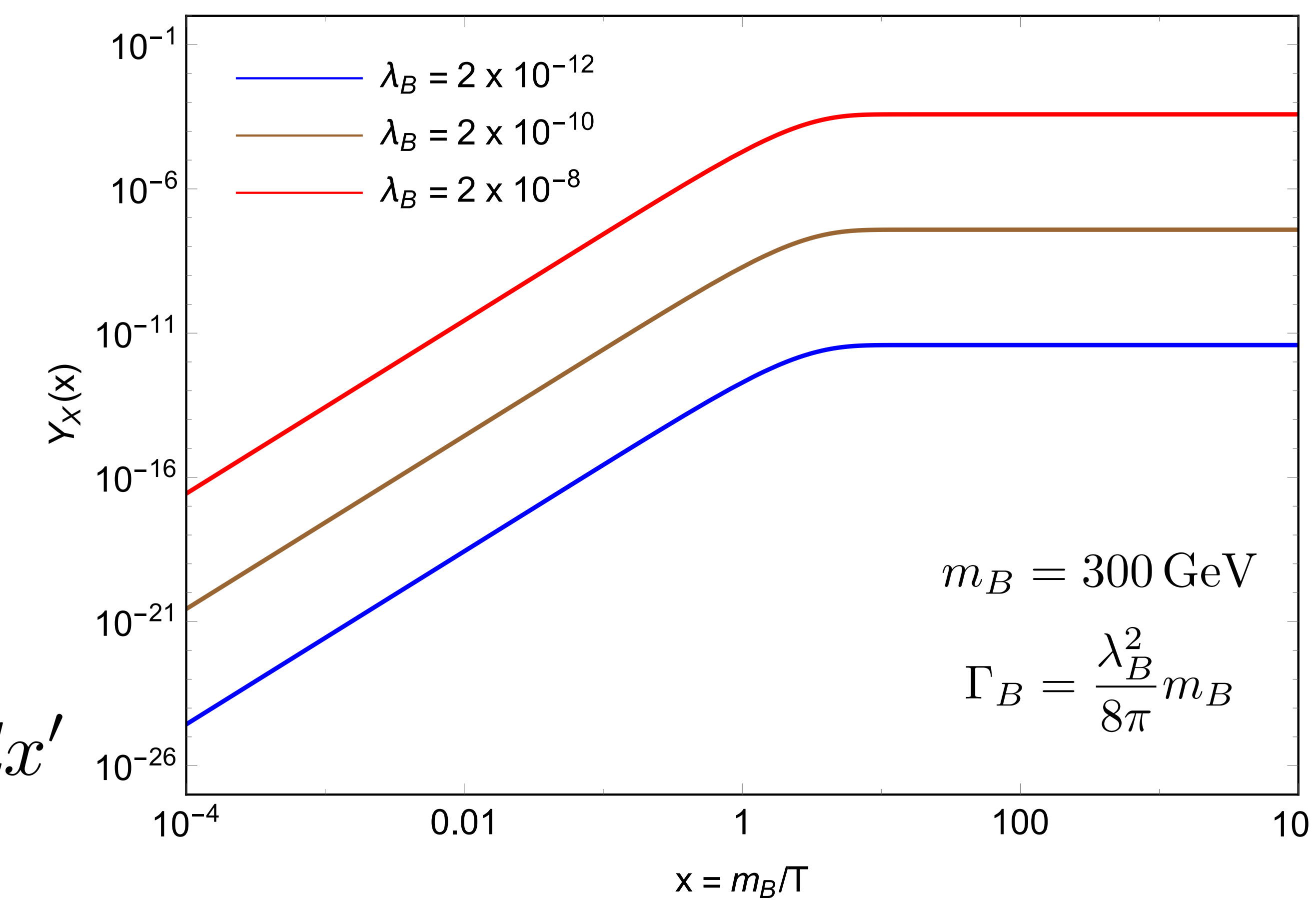
$$\frac{dn_X}{dt} = -3Hn_X + \Gamma_B n_B^{\mathrm{eq}} \frac{K_1[m_B/T]}{K_2[m_B/T]}$$

$$Y_X(x) = g_B \frac{45}{4\pi^4} \Gamma_B \int_0^x \frac{x' \, K_1[x']}{g_{*s}(x') H(x')} \, dx'$$



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A collider signal?

B's pair-produced at colliders, subsequent decays could be observed

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B's pair-produced at colliders, subsequent decays could be observed

Parameters "constrained" by relic density

$$\tau_B = \Gamma_B^{-1} \simeq 3.7 \times 10^8 \text{ cm} \left(\frac{m_X}{100 \text{ GeV}} \right) \left(\frac{300 \text{ GeV}}{m_B} \right)^2$$

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A collider signal?

Hopeless? B seems stable on the scale of experiments

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A collider signal?

Hopeless? B seems stable on the scale of experiments

CAVEAT: result valid for a standard cosmological history

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Freeze-in via decays

$$B \to \mathrm{SM} + X$$

Bath particles decays produce X particle that will never thermalize

A collider signal?

Displaced events at collider could give information about the dark matter mass and the cosmological history of our universe

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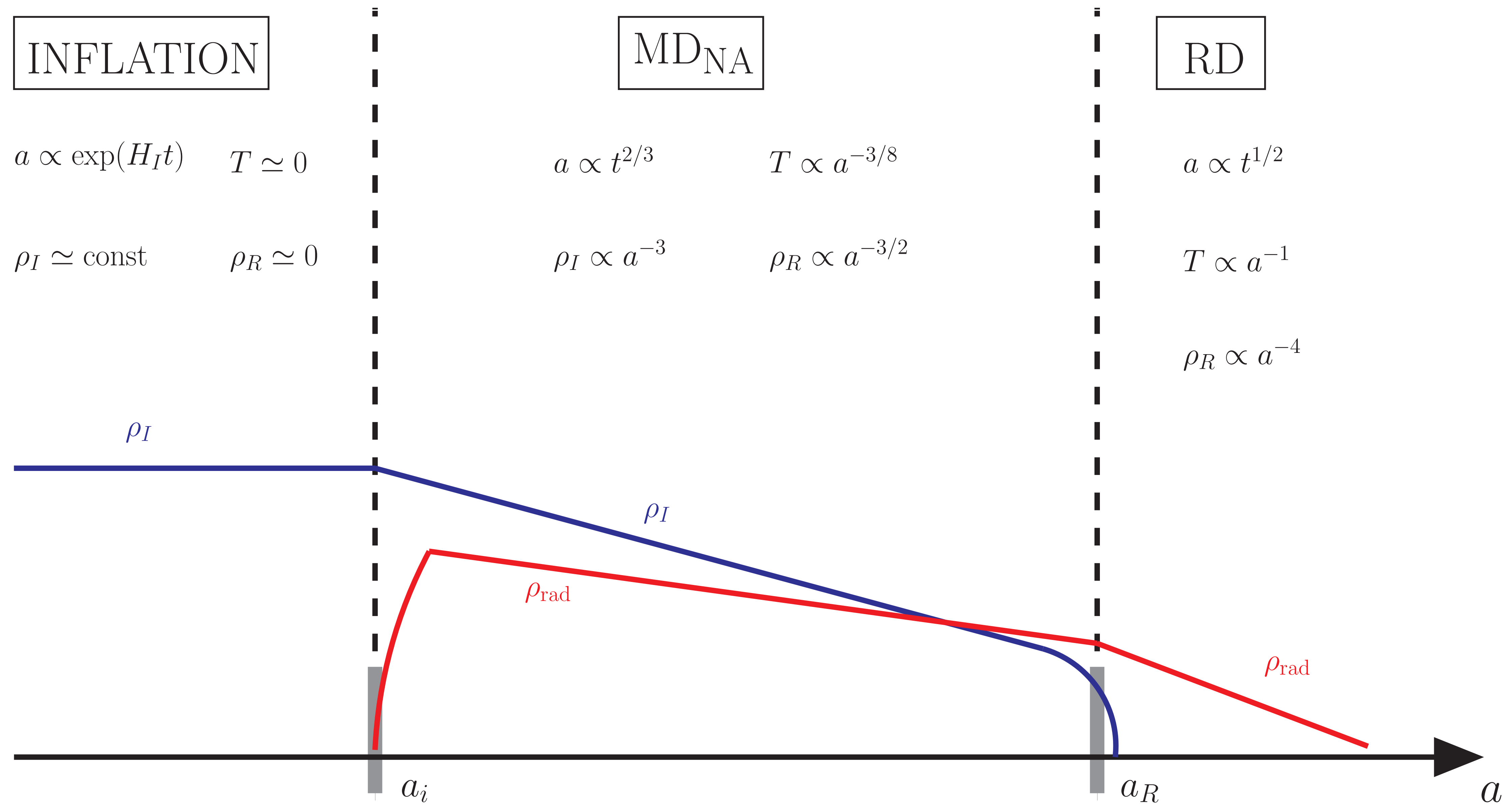
Case 1: FI and Early MD



Co, FD, Hall, Pappadopulo, JCAP 1512 (2015)

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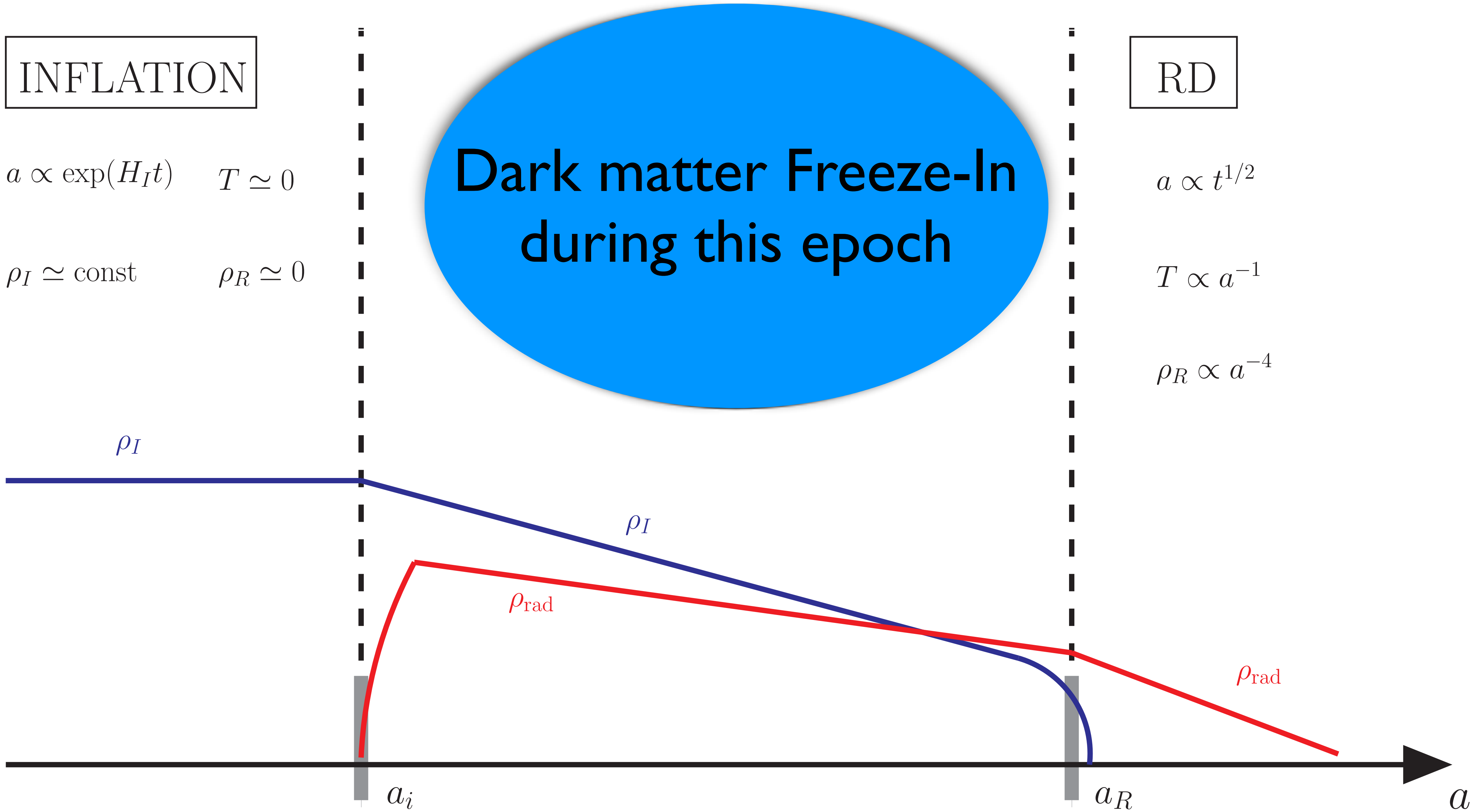

Decaying particle in the bath

$$T_{\max} \simeq (E_I T_R)^{1/2} \gtrsim m_B$$

Freeze-In density depends on the reheat temperature

Co, FD, Hall, Pappadopulo, JCAP 1512 (2015)

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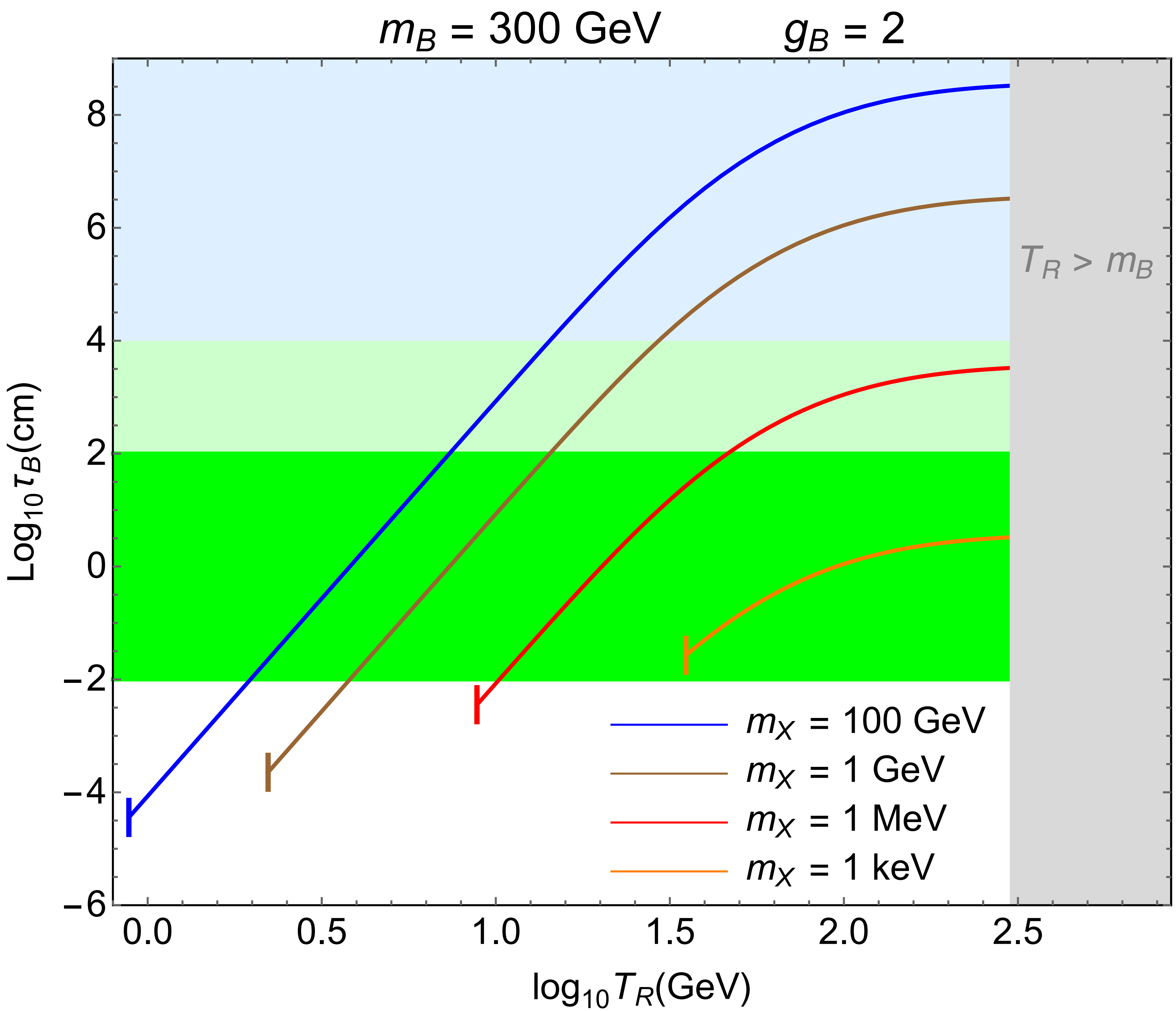

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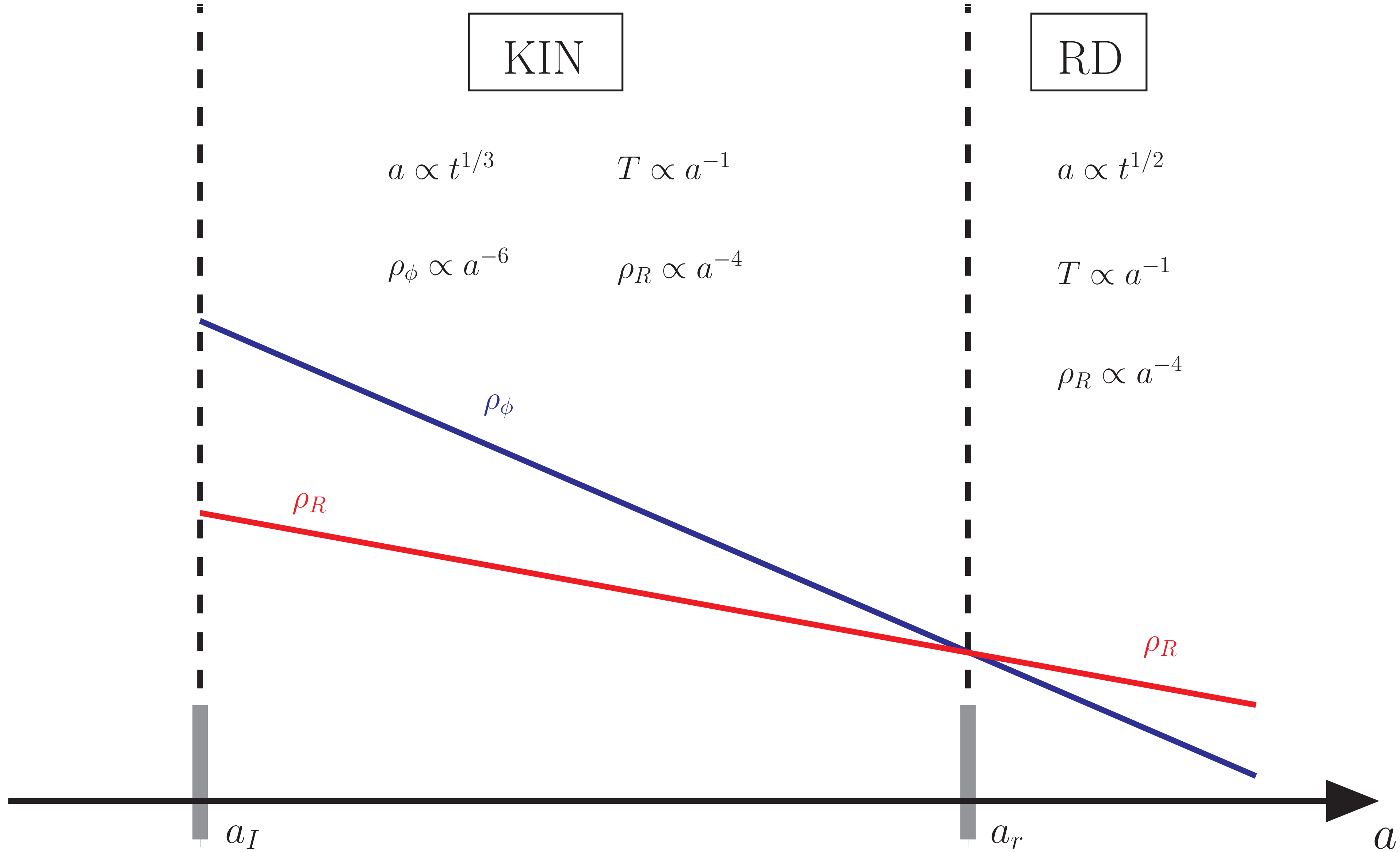
Case 2: FI and Kination



$$\frac{p}{\rho} = w = \frac{\frac{\dot{\phi}^2}{2} - V(\phi)}{\frac{\dot{\phi}^2}{2} + V(\phi)}$$

Kination phase: w = 1
(Kinetic ≫ Potential)

FD, Fernandez, Profumo, JCAP 1802 (2018)

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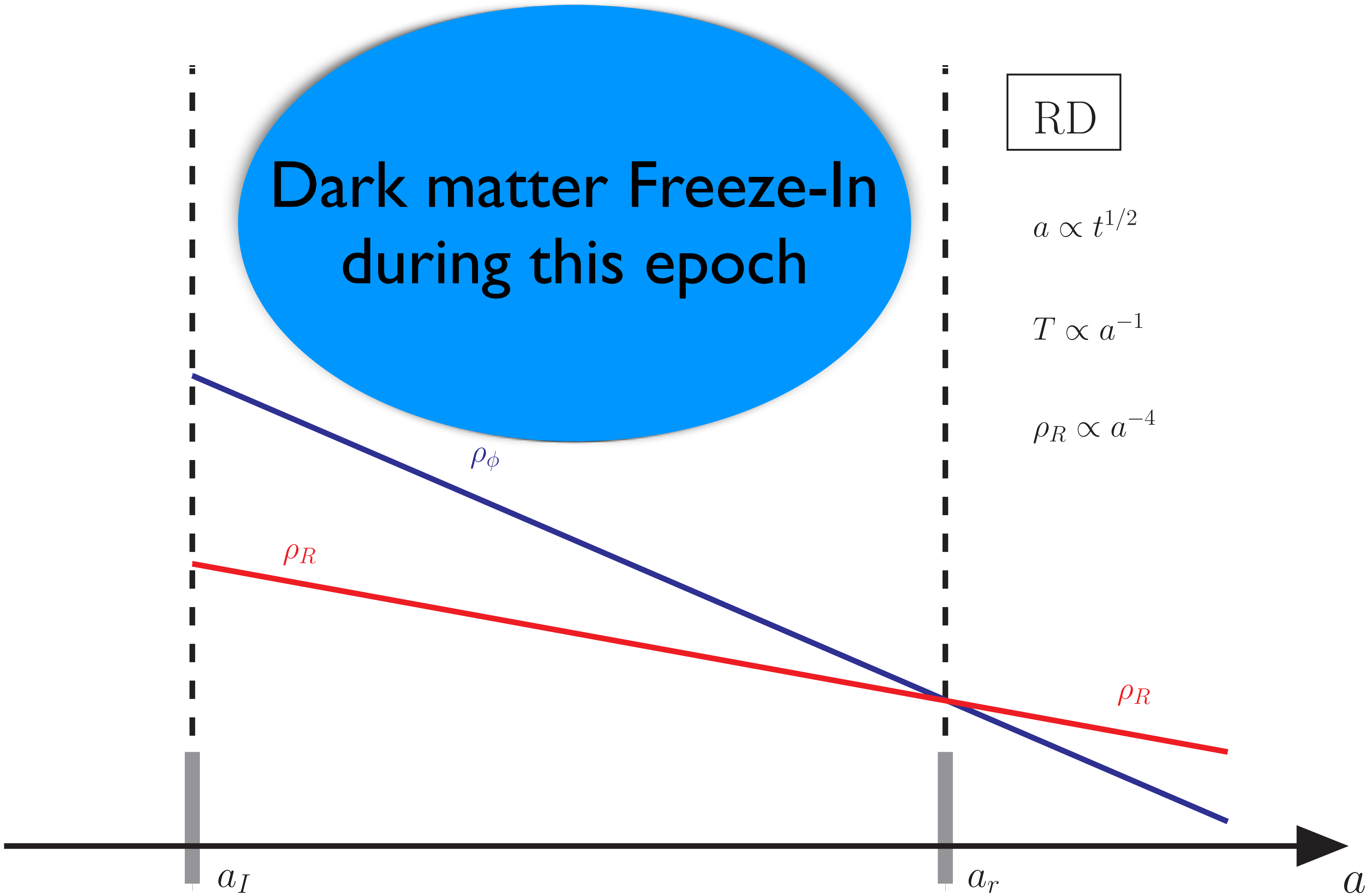

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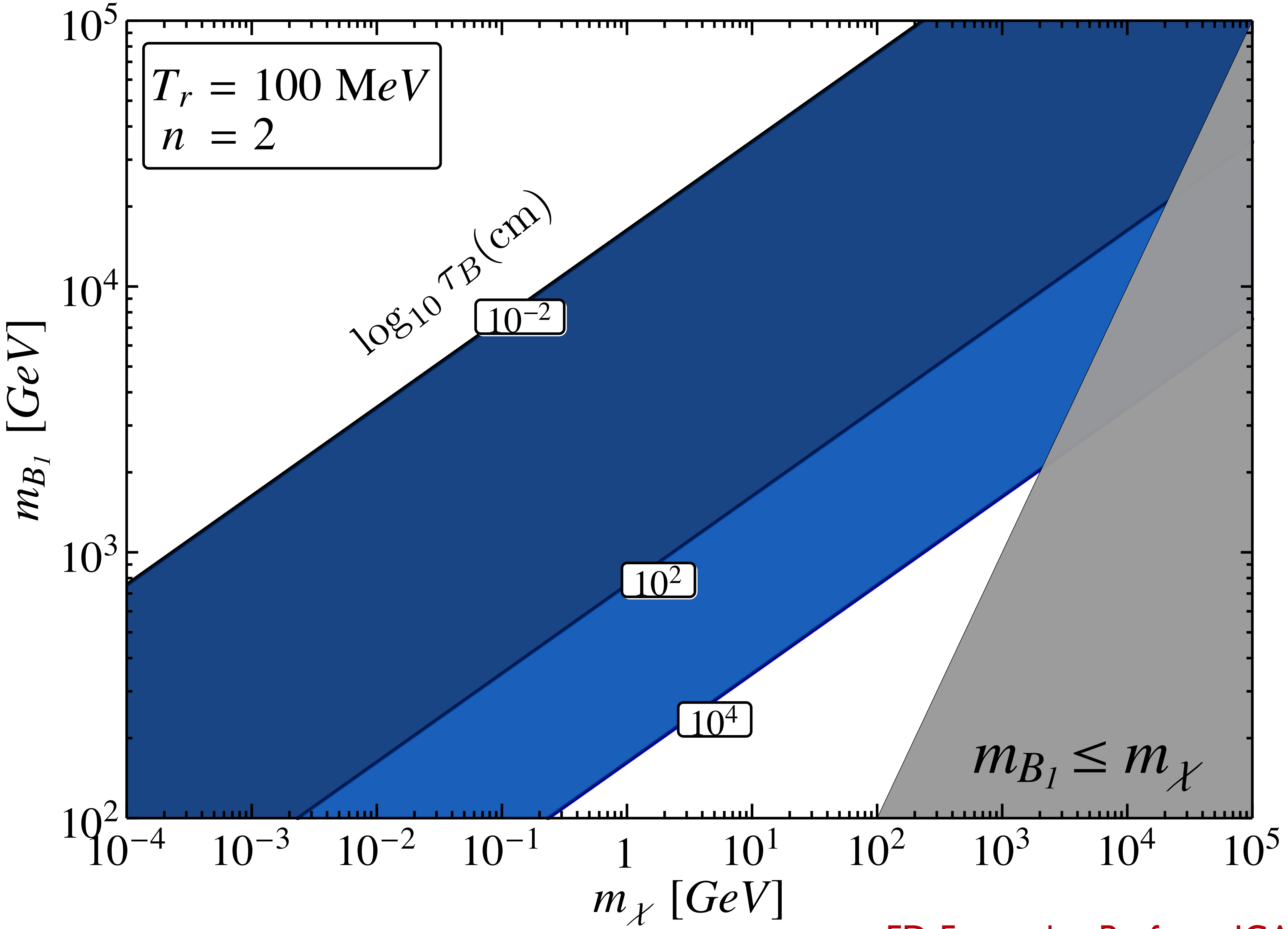

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A bottom-up approach

Classification of all possible operators mediating the decay

$$B \rightarrow \mathrm{SM} + X$$

Work in progress with Calibbi, Junius, Lopez-Honorez, Mariotti

A bottom-up approach

Classification of all possible operators mediating the decay

$$B \;\to\; \mathrm{SM} + X$$

For each choice of the SM particle, we know the quantum numbers of B (X must be a gauge singlet)

We consider:
spin 0 and 1/2 DM
spin 0, 1/2 and 1 for B

Class for $A_{\rm SM}$	**Field for** $A_{\rm SM}$	**Gauge Charges**
$\psi_{\rm SM}$	Q_L^i	$(\mathbf{3},\mathbf{2})_{+1/6}$
	u_R^i	$(\mathbf{3},\mathbf{1})_{+2/3}$
	d_R^i	$(\mathbf{3},\mathbf{1})_{-1/3}$
	E_L^i	$(\mathbf{1},\mathbf{2})_{-1/2}$
	d_R^i	$(\mathbf{1},\mathbf{1})_{-1}$
$F_{\mu\nu}$	$G_{\mu\nu}^A$	$(\mathbf{8},\mathbf{1})_0$
	$W_{\mu\nu}^I$	$(\mathbf{1},\mathbf{3})_0$
	$B_{\mu\nu}$	$(\mathbf{1},\mathbf{1})_0$
H	H	$(\mathbf{1},\mathbf{2})_{+1/2}$

Work in progress with Calibbi, Junius, Lopez-Honorez, Mariotti

A bottom-up approach

Classification of all possible operators mediating the decay

$$B \;\to\; \mathrm{SM} + X$$

$A_{\rm SM}$	**Spin** X	**Spin** B	**Interaction**	**Label**
$\psi_{\rm SM}$	0	1/2	$\overline{\psi_{\rm SM}}\Psi_B\,\phi$	$\mathcal{F}_{\psi_{\rm SM}\phi}$
	1/2	0	$\overline{\psi_{\rm SM}}\chi\,\Phi_B$	$\mathcal{S}_{\psi_{\rm SM}\chi}$
		1	$\overline{\psi_{\rm SM}}\Gamma^\mu\chi\,V_B^\mu$	$\mathcal{V}_{\psi_{\rm SM}\chi}$
$F_{\mu\nu}$	0	1	$V_B^{\mu\nu}F_{\mu\nu}\phi$	$\mathcal{V}_{F\phi}$
	1/2	1/2	$\overline{\psi_{\rm SM}}\sigma_{\mu\nu}\chi\,F^{\mu\nu}$	$\mathcal{F}_{F\chi}$
H	0	0	$\Phi_B^\dagger H\,\phi$	$\mathcal{S}_{H\phi}$
		1	$V_B^\mu(c_\phi H\partial_\mu\phi + c_H\phi D_\mu H)$	$\mathcal{V}_{H\phi}$
	1/2	1/2	$\overline{\Psi_B}\chi\,H$	$\mathcal{F}_{H\chi}$

Work in progress with Calibbi, Junius, Lopez-Honorez, Mariotti

A fermion DM example

Fermion dark matter with a scalar partner coupled to leptons

$$\bar{l}\,\chi\,\Phi_B$$

Also a Higgs portal operator allowed by all symmetries

$$\lambda_H H^\dagger H\,\Phi_B^\dagger \Phi_B$$

A fermion DM example

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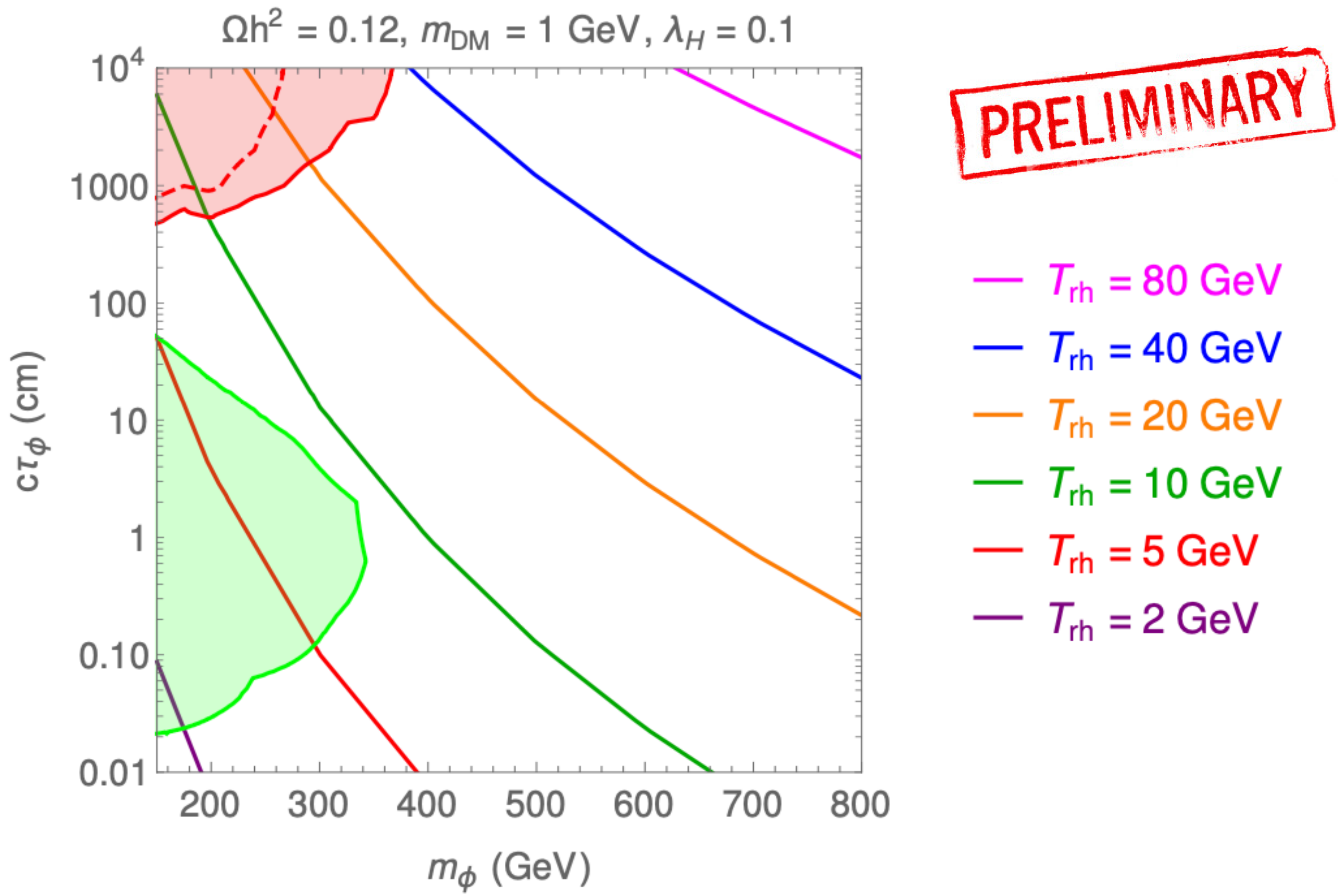
Heavy Stable Charged Particles

Displaced Leptons



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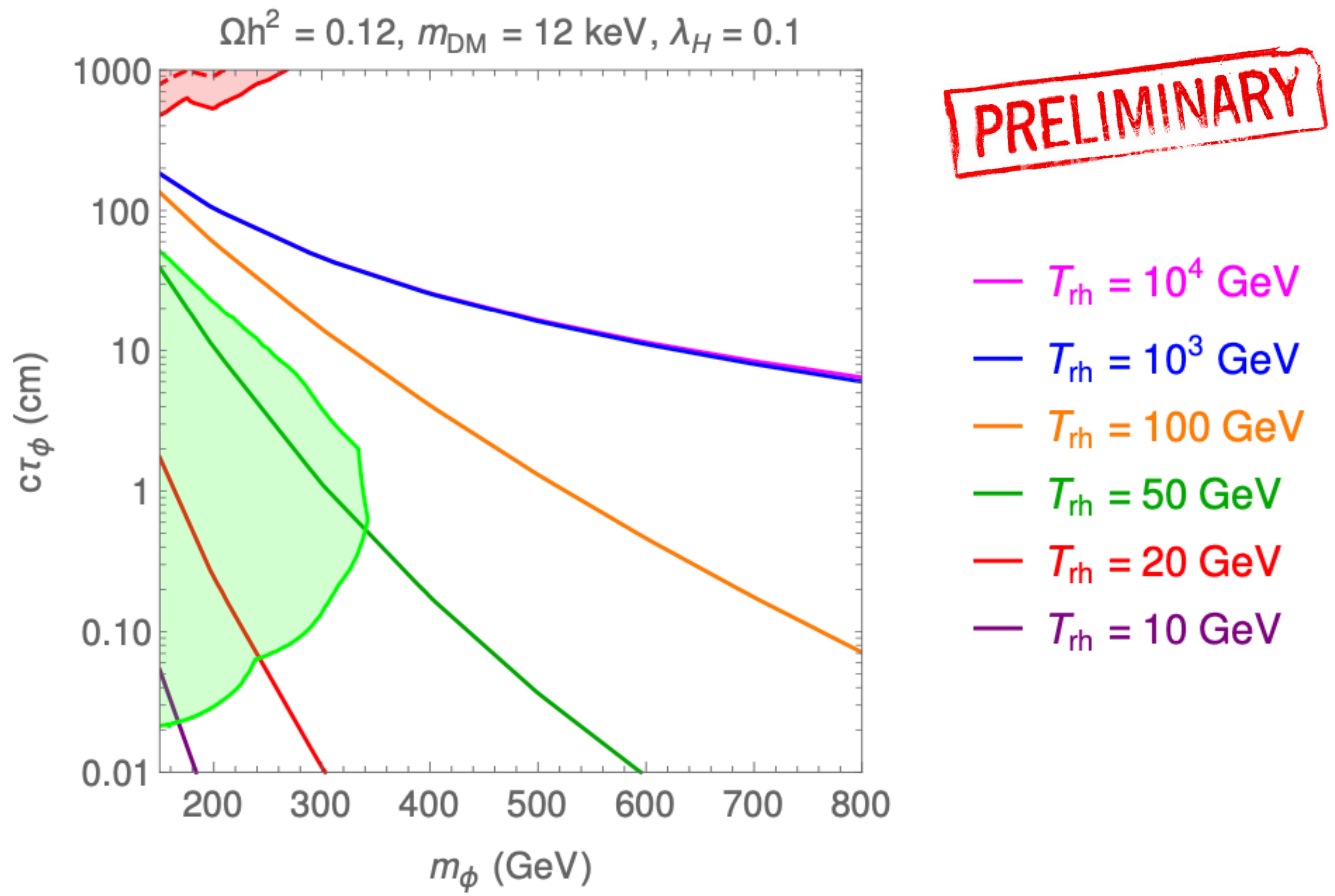
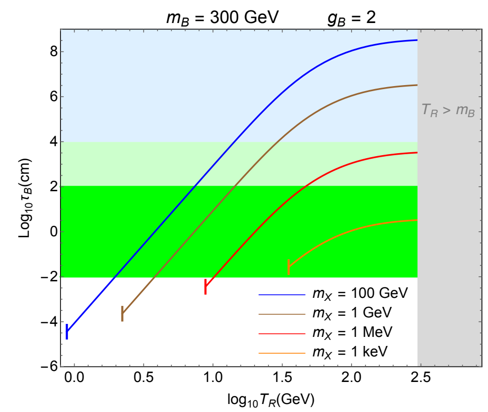
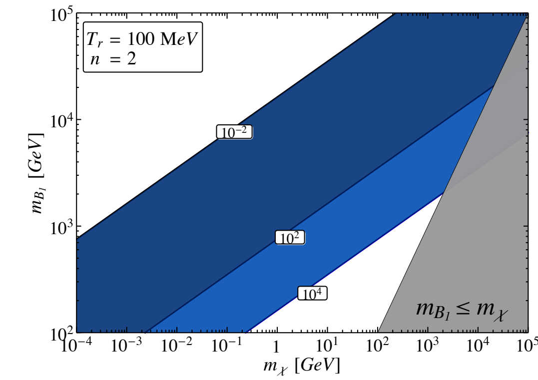


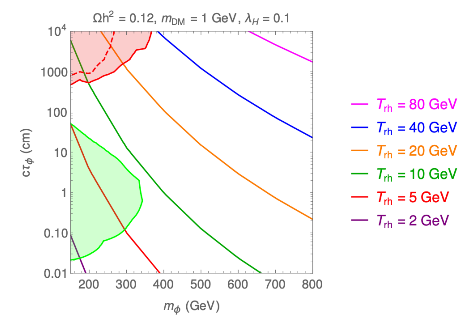
Outlook

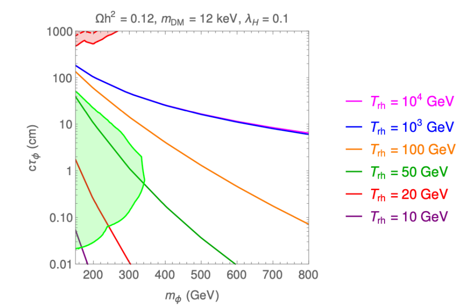
- Modified cosmologies and displaced signatures





- Bottom-up classification for displaced signatures @LHC





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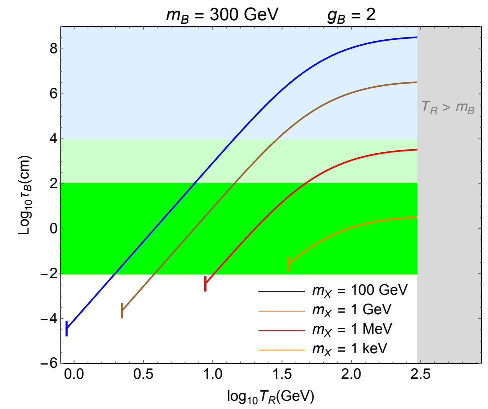

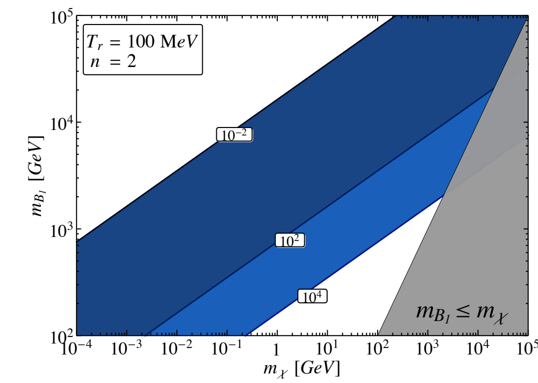

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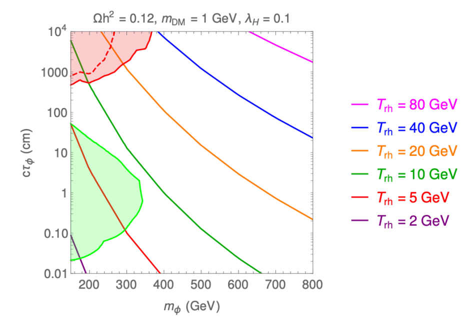
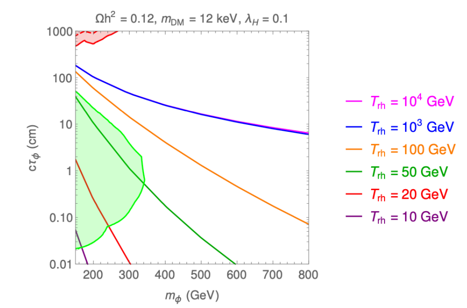
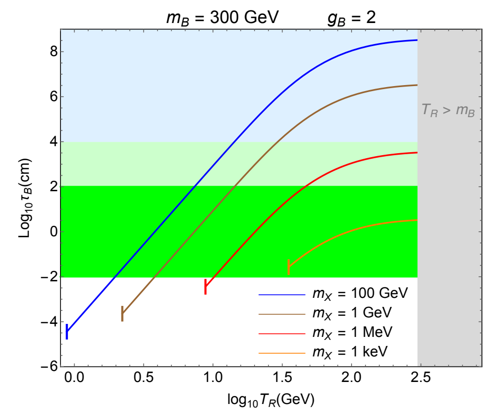


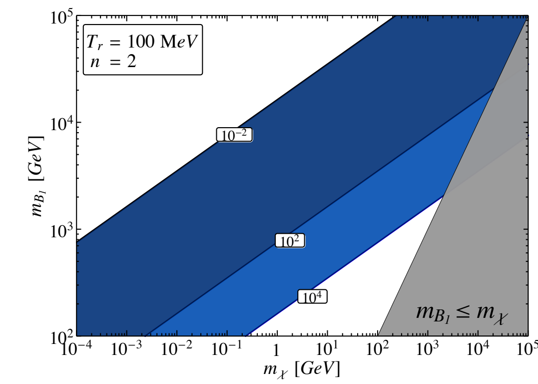


- Displaced signatures at low-energy accelerators and connection with cosmological histories?

Outlook

- Modified cosmologies and displaced signatures





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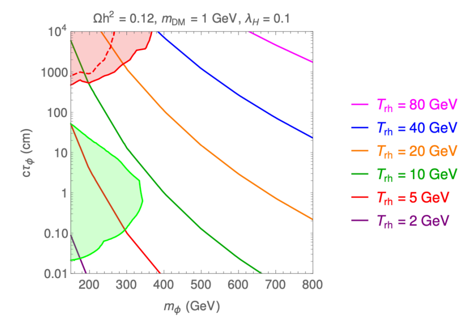

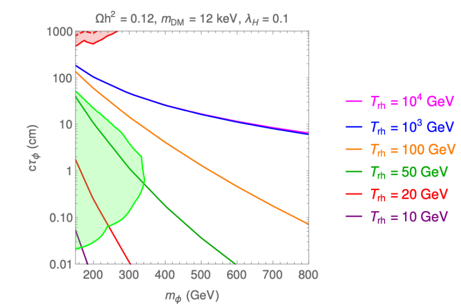

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Thank you