Displaced new physics at colliders and the pre-BBN universe

Università degli Studi di Padova

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Dark Universe Workshop — ICTP-SAIFR, October 23rd 2019

There are bounds and bounds...

Different bounds have different implications

and (hopefully soon!)

different signals will deliver different information

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Astro Searches

Actually search for dark matter

but

several uncertainties
(e.g., local density, velocity distribution, density profile, …)

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No overproduction within a given theoretical framework

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one needs to specify a cosmological history

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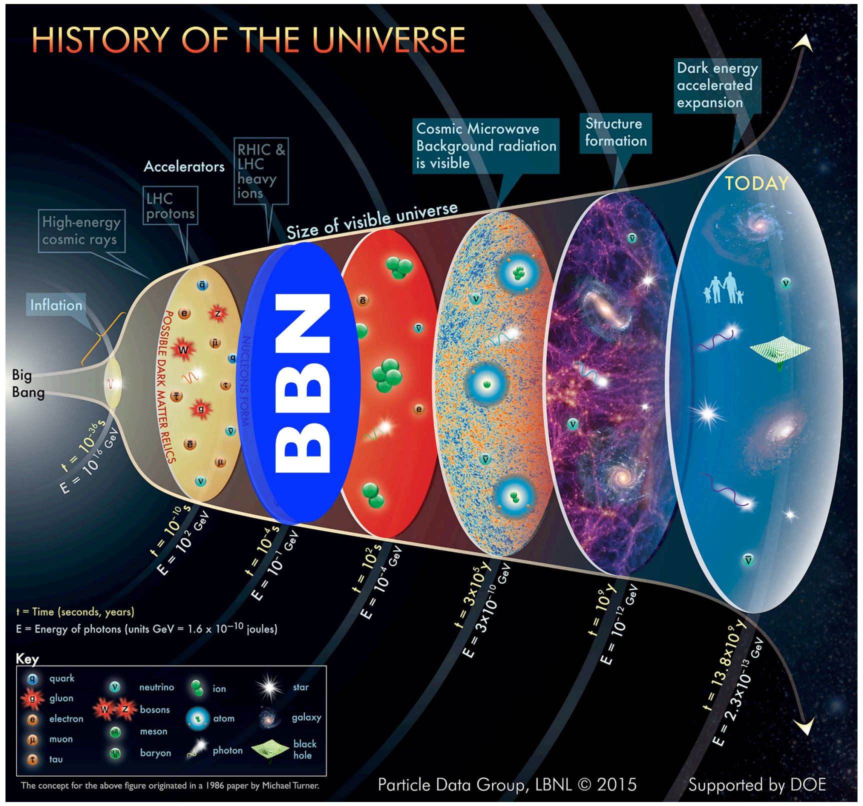

Can we learn about
the pre-BBN universe from
displaced events at colliders?

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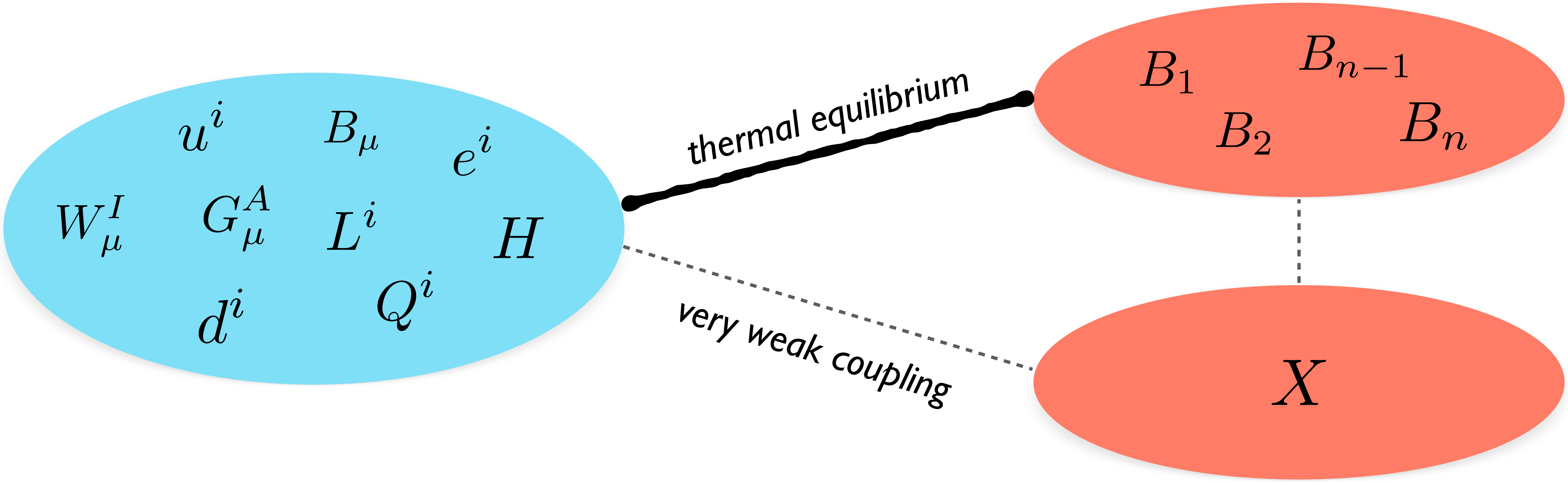
THIS TALK

FIMPs

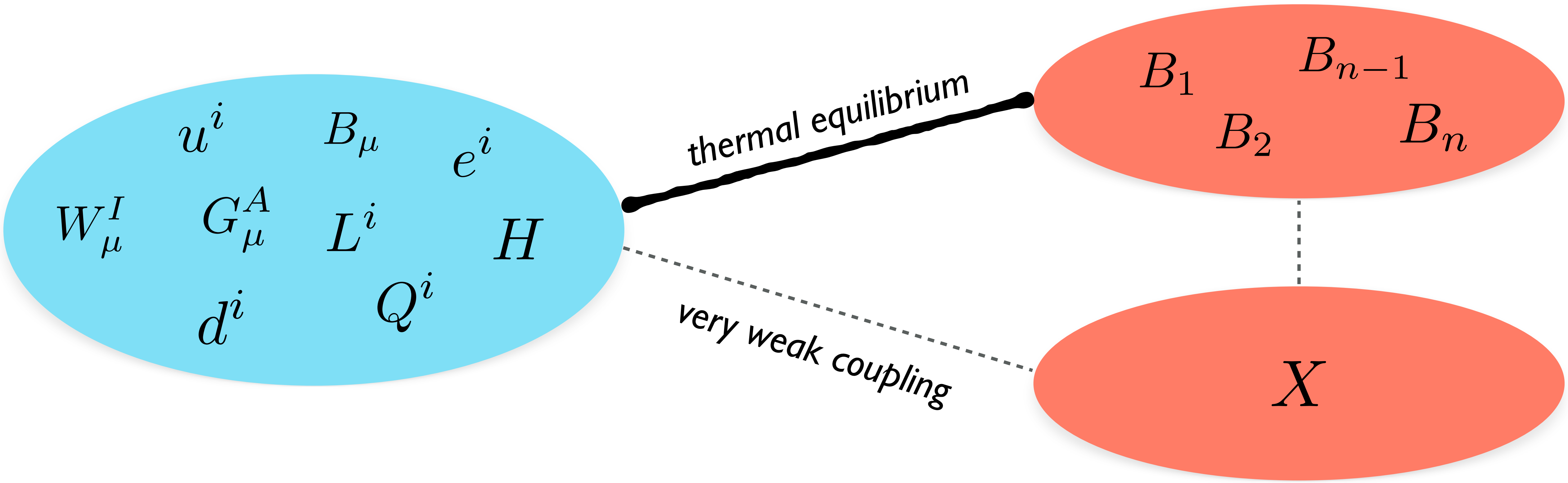


B_i and X odd under a Z_2 symmetry

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

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

FIMPs



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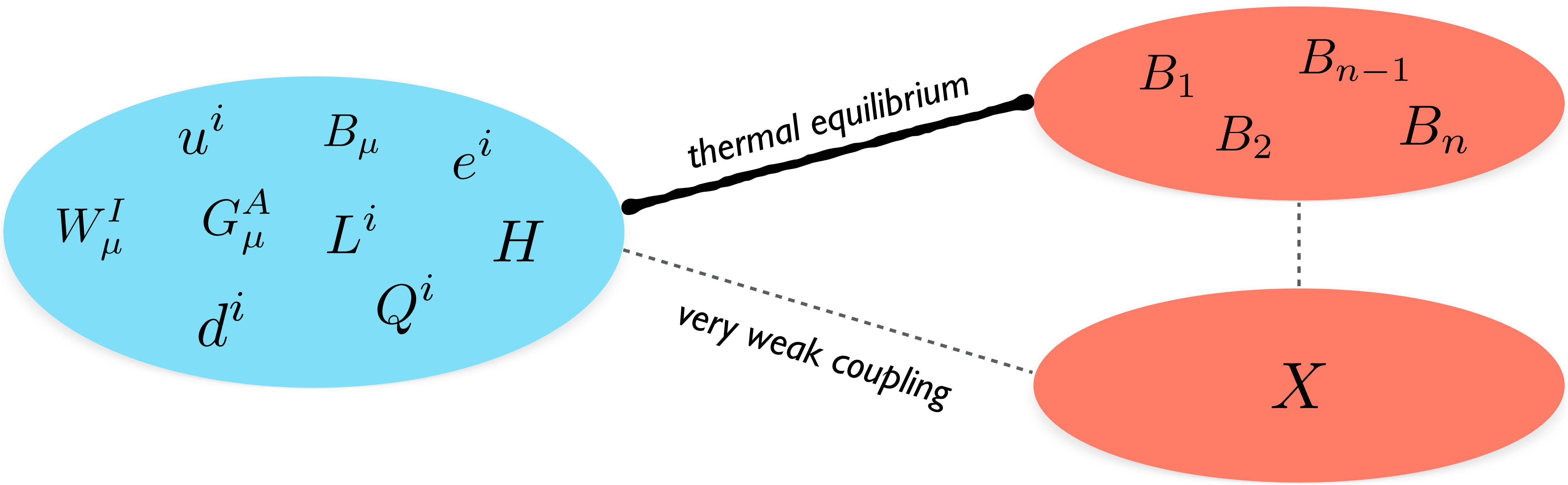
Nightmare for dark matter searches

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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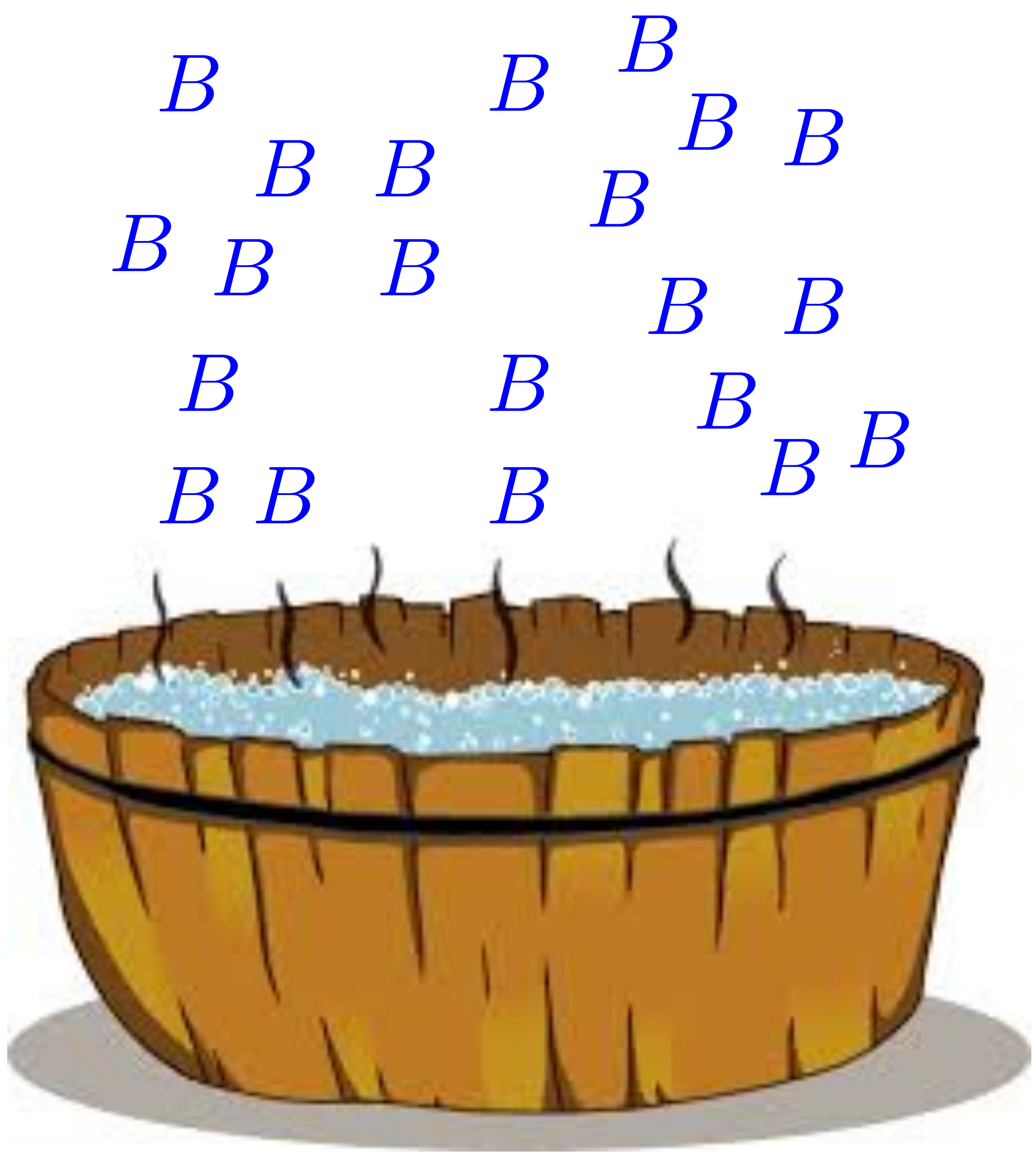
<u>T ≫ bath particles mass:</u>

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



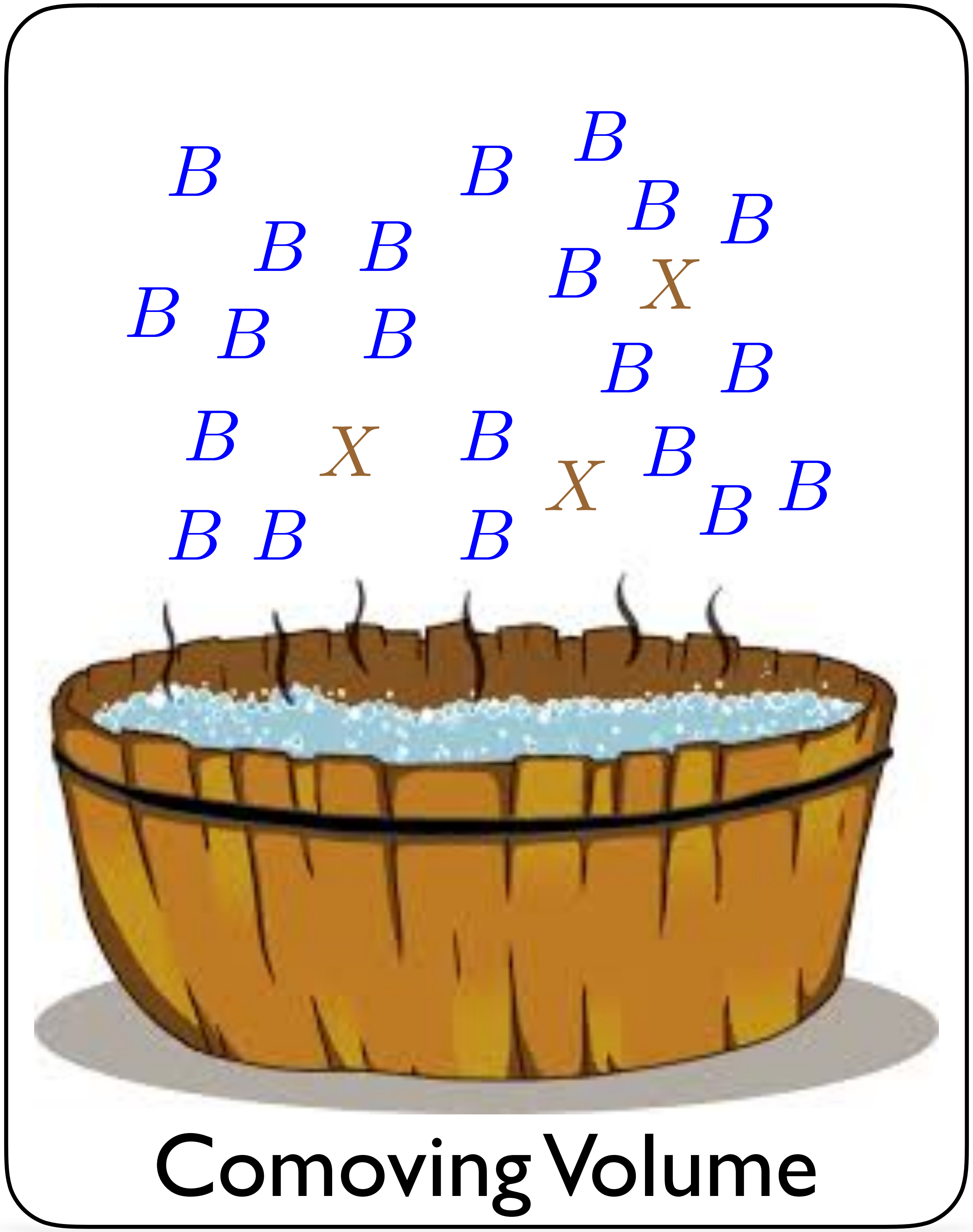
Comoving Volume

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 (<u>when</u> this happens is important)



Freeze-in via decays

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

Bath particles decays produce X particle that will never thermalize

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When does freeze-in happen in the early universe?

$$\frac{n_X}{s} = Y_X(T) \simeq \frac{m_B}{T}\Gamma_B\, t(T) \simeq \frac{m_B \Gamma_B M_{\rm Pl}}{T^3}$$

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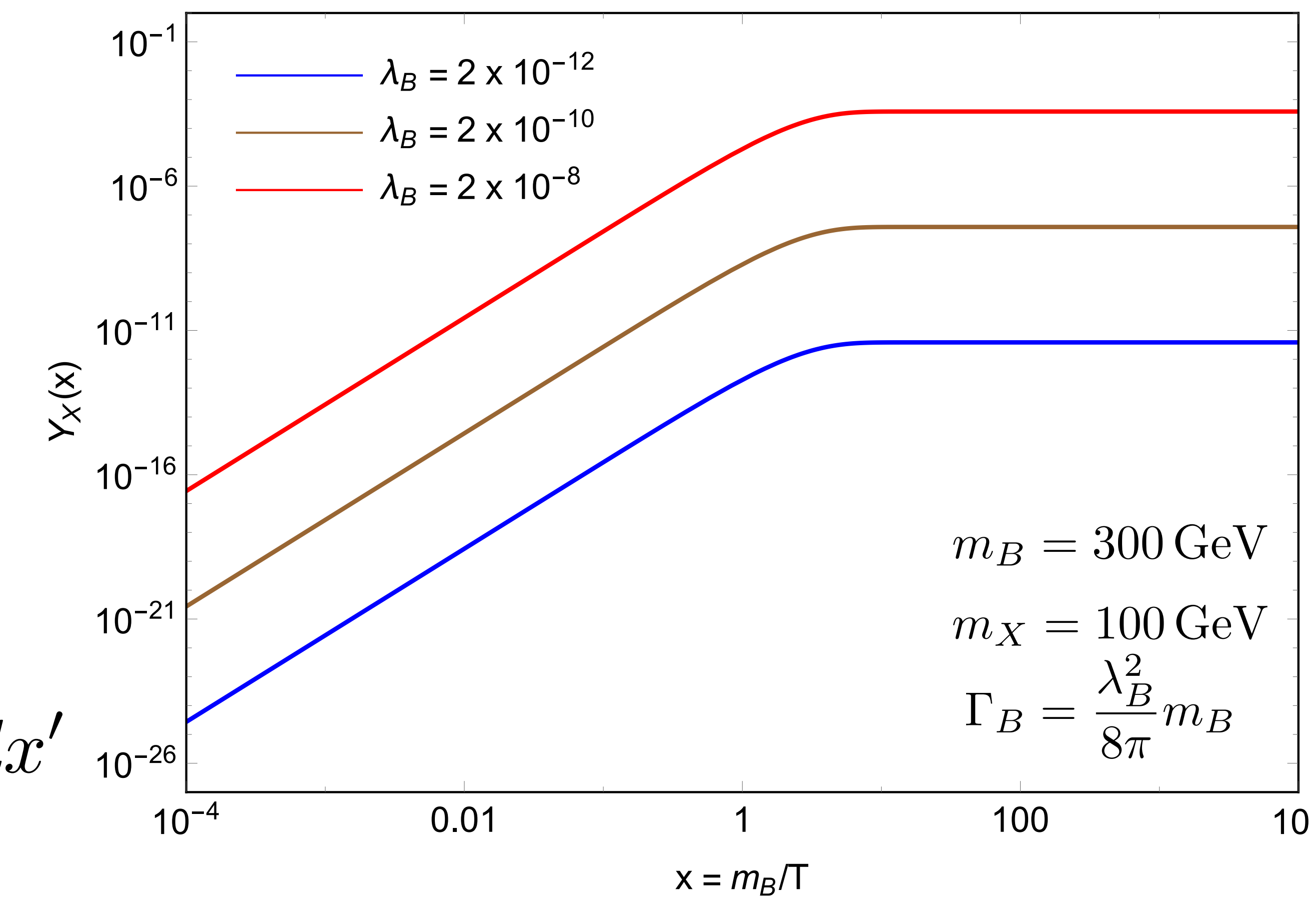
The production is more efficient at low temperatures
(good: we do not need to know the thermal history above!)
Valid as long as the temperature is above the B mass

"IR dominated"

Freeze-in via decays

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

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



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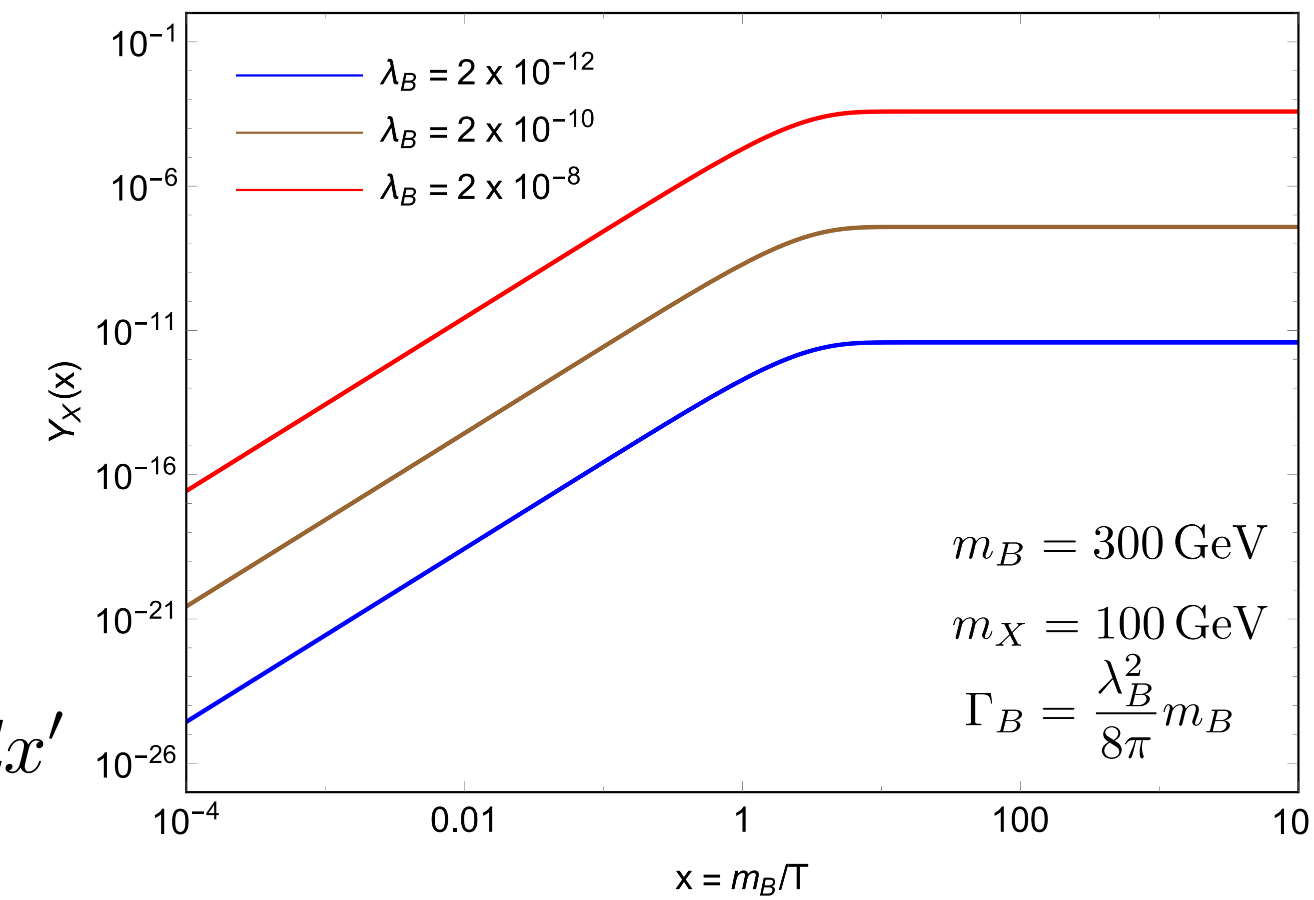

We can integrate starting from arbitrarily high temperature (IR domination)

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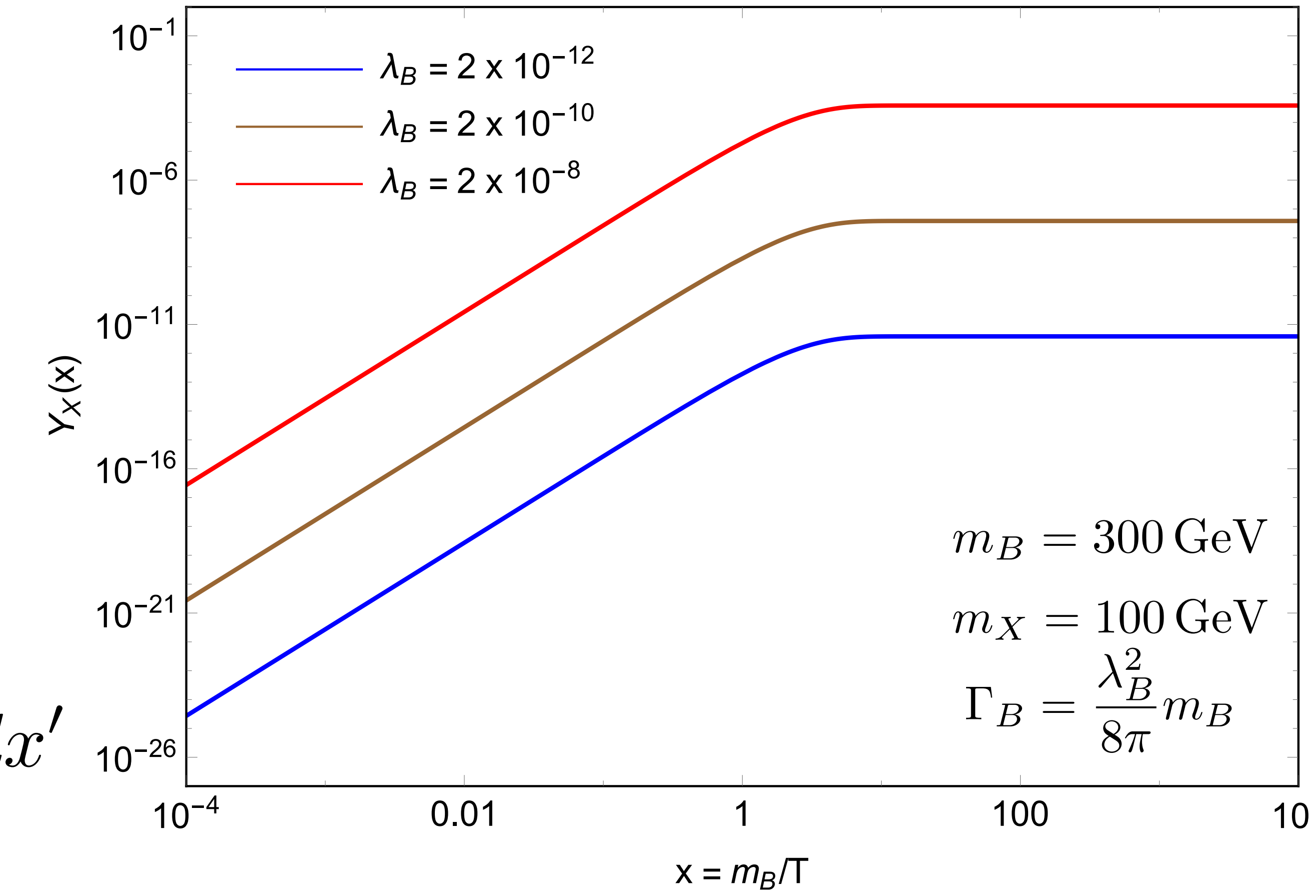

Cosmological history enters through the Hubble parameter

A collider signal of freeze-in?

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

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

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Parameters "constrained" by relic density

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

Decay length beyond the detector size, unless we consider very light X

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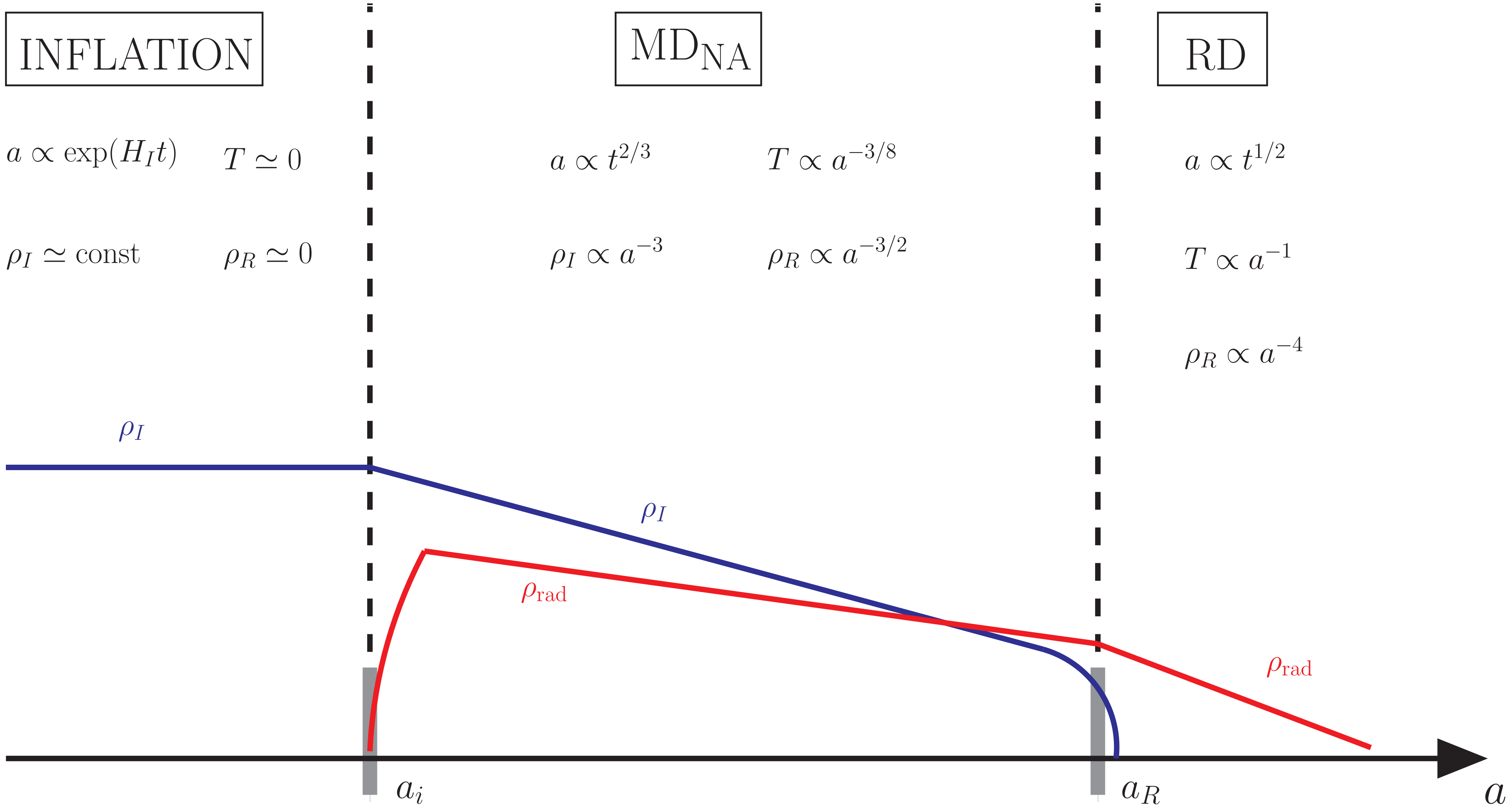
Displaced events at collider could give information about the dark matter mass and the cosmological history of our universe

Case 1: FI and Early MD



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

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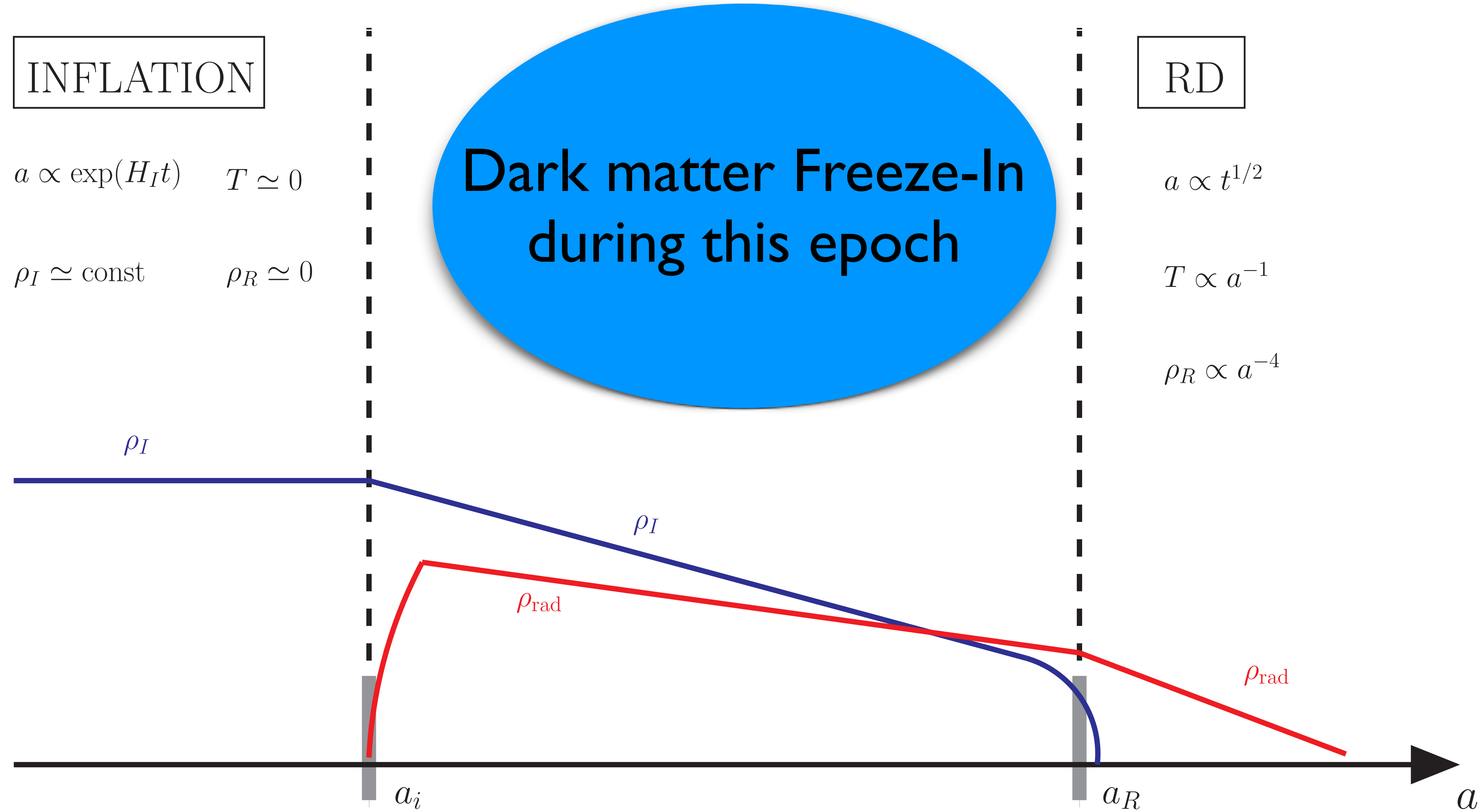

Decaying particle in the bath

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

Freeze-In density depends on the reheat temperature

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

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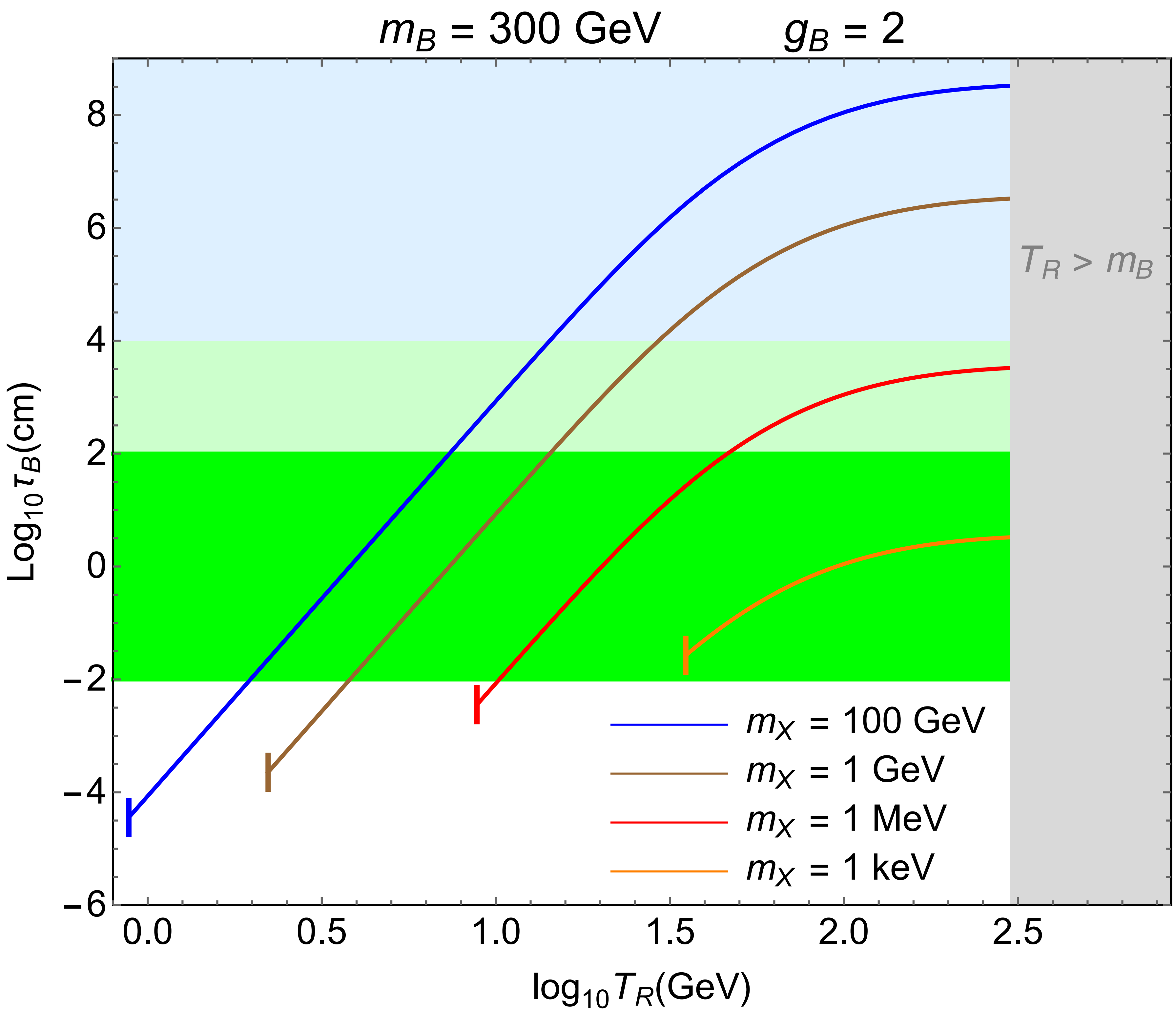

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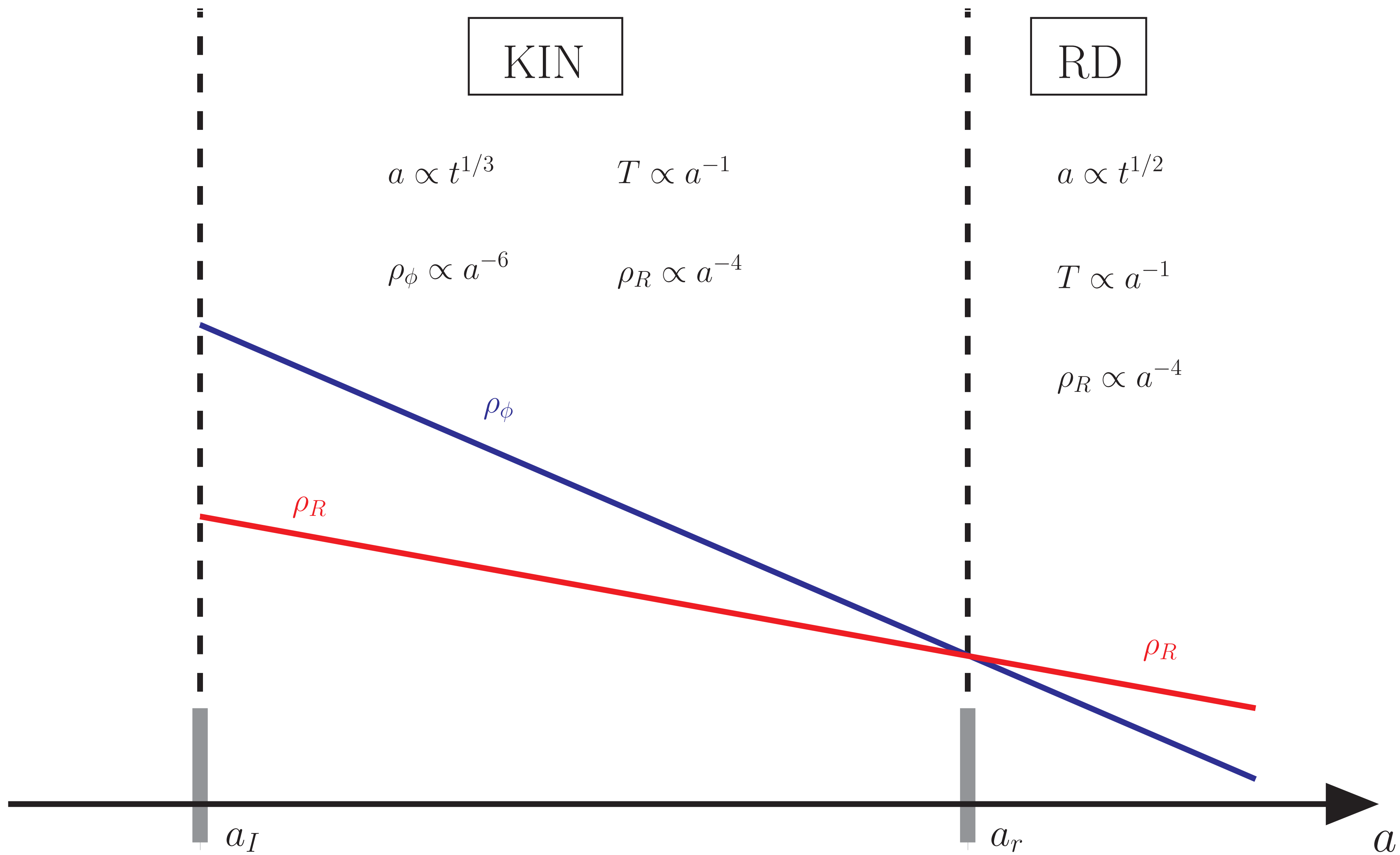
Case 2: FI and Kination



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

Kination phase: w = 1
(Kinetic ≫ Potential)

FD, Fernandez, Profumo, JCAP 1802 (2018)

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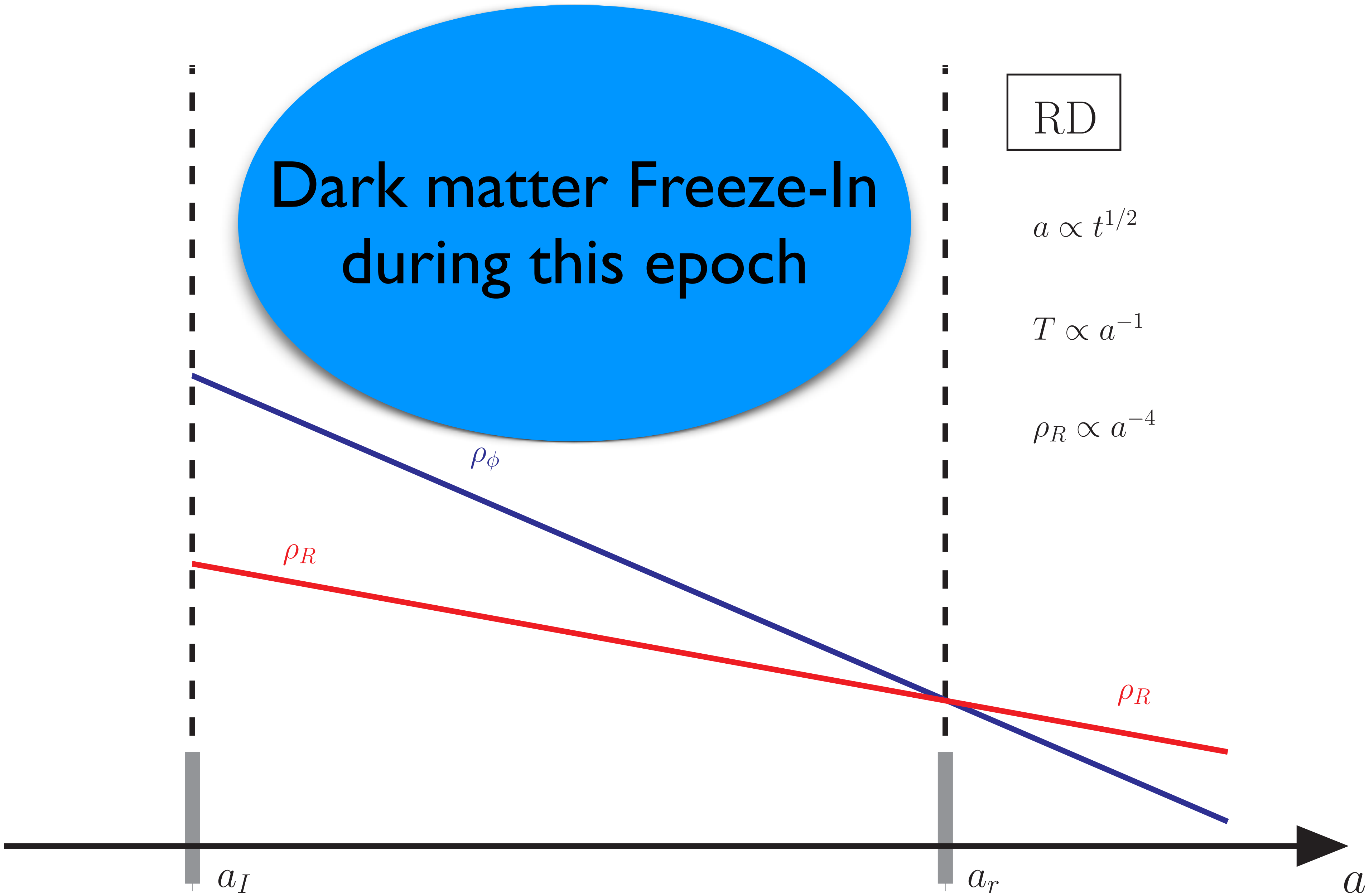

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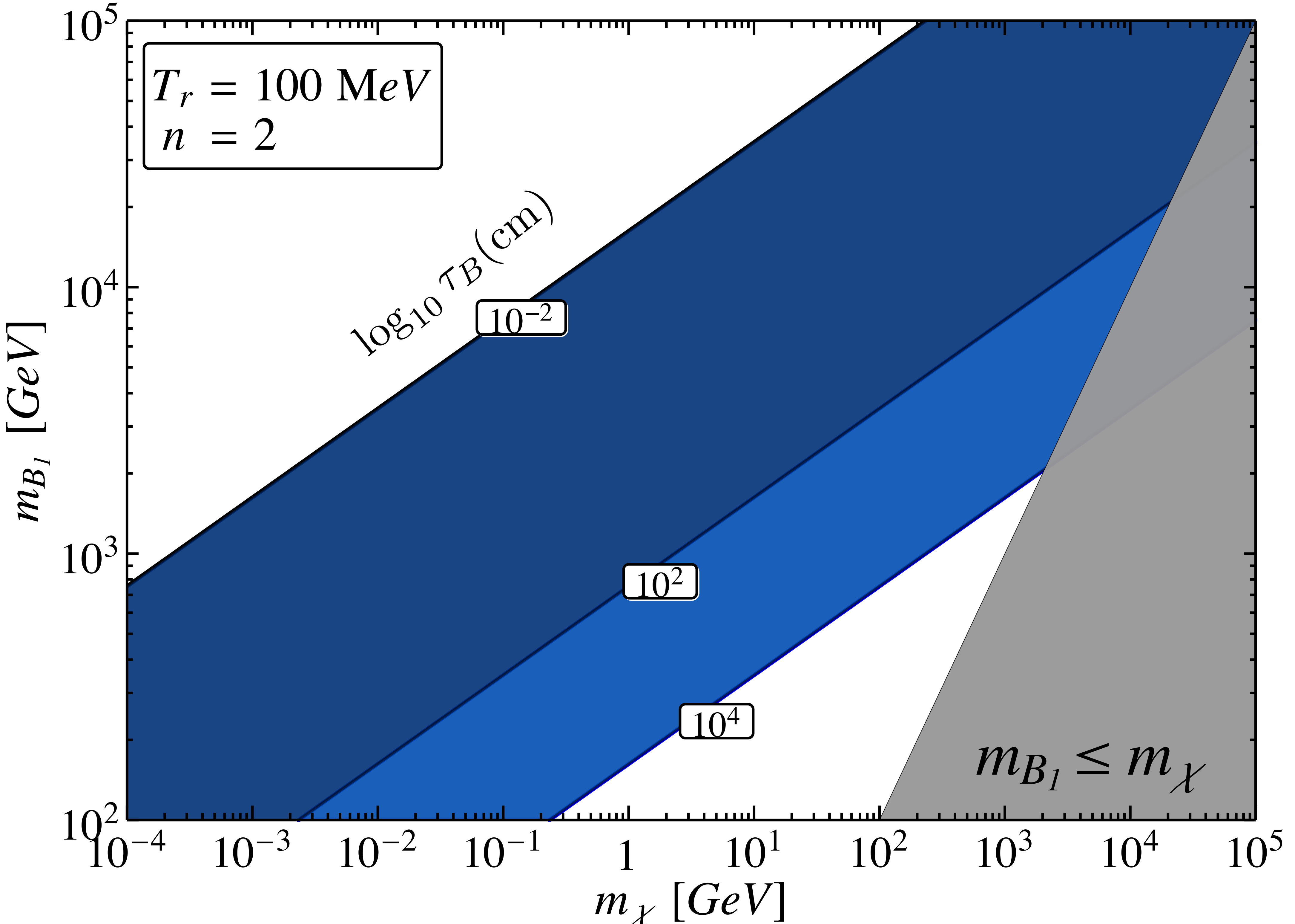

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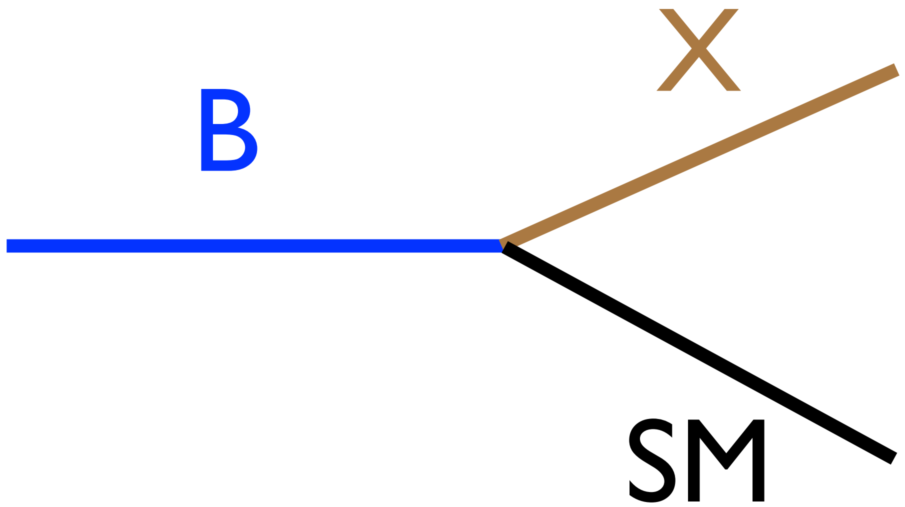
Renormalizable? It matters!



Very different cosmology if the operator mediating the decay is renormalizable or not

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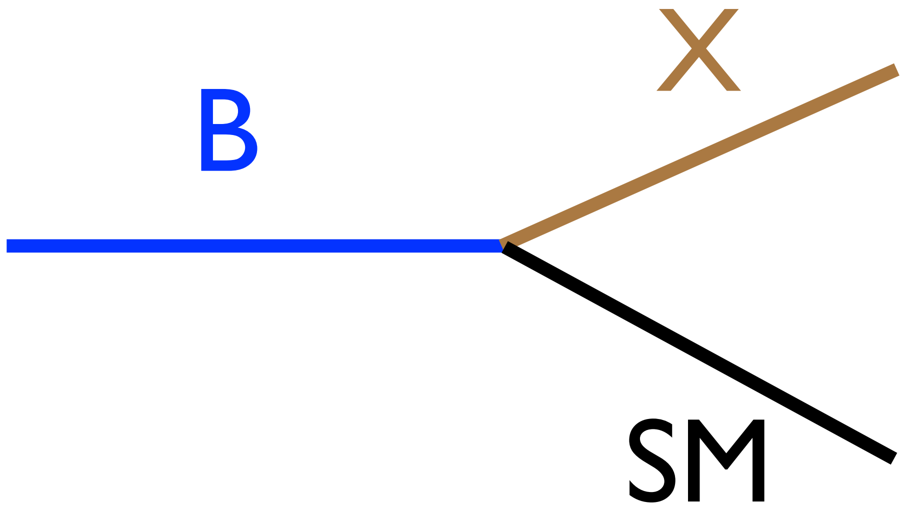

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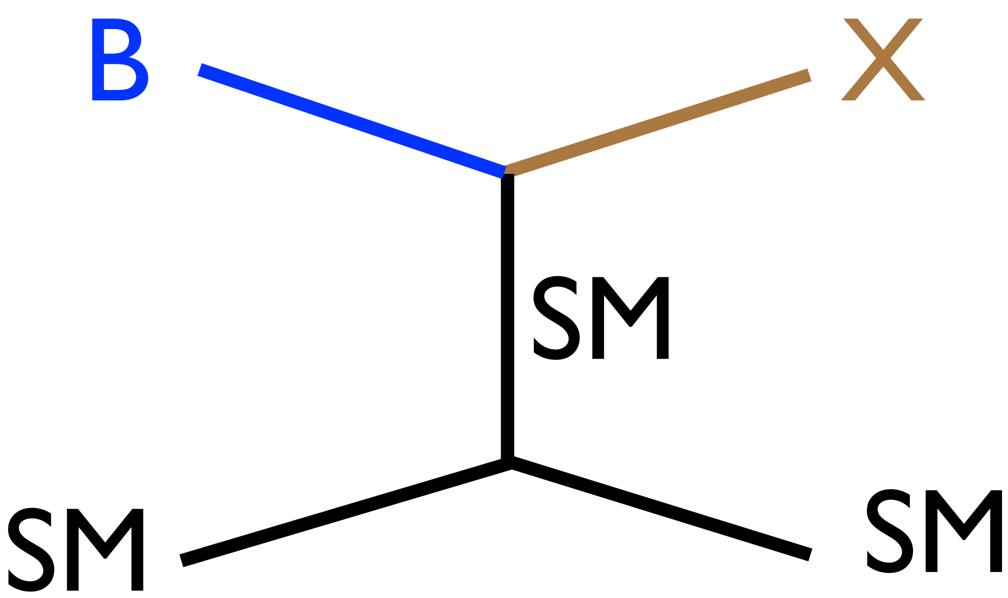

$$Y_X^{\text{scattering}}(T) \propto T^{2d-9}$$

Non-renormalizable: scattering is UV sensitive

(e.g., production dominated at the reheat temperature after inflation)

A motivated example

Hierarchy Problem

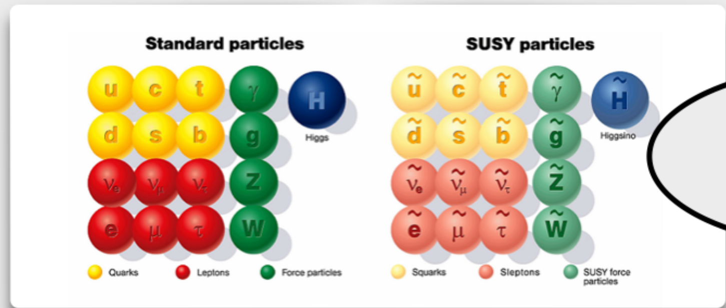

Image credit: DESY at Hamburg

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Strong CP Problem

Image credit: http://motls.blogspot.com

Gravitino and Axino in SUSY PQ theories

Co, FD, Hall, Phys.Rev. D94 (2016)
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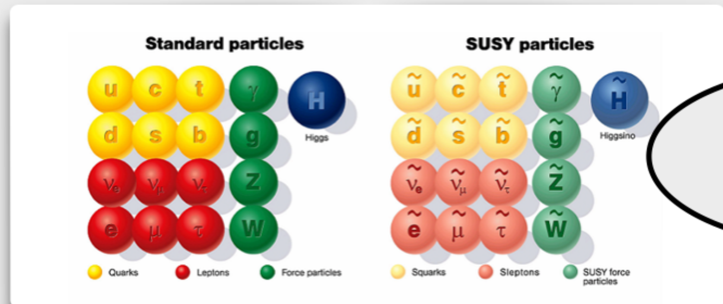

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Gravitino and Axino in SUSY PQ theories

$$W_{\rm DFSZ} \subset q_\mu \frac{\mu}{V_{PQ}} A\, H_u H_d$$

EWinos in thermal equilibrium decaying to axinos, production dominated at TeV scale (IR)

$$\widetilde{h^0} \to \tilde{a}\, h$$

$$\widetilde{h^0} \to \tilde{a}\, Z$$

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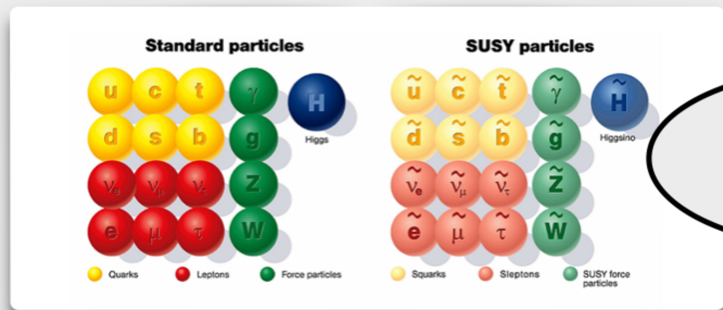

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Gravitino and Axino in SUSY PQ theories

A cosmological disaster from frozen-in LSP axinos?

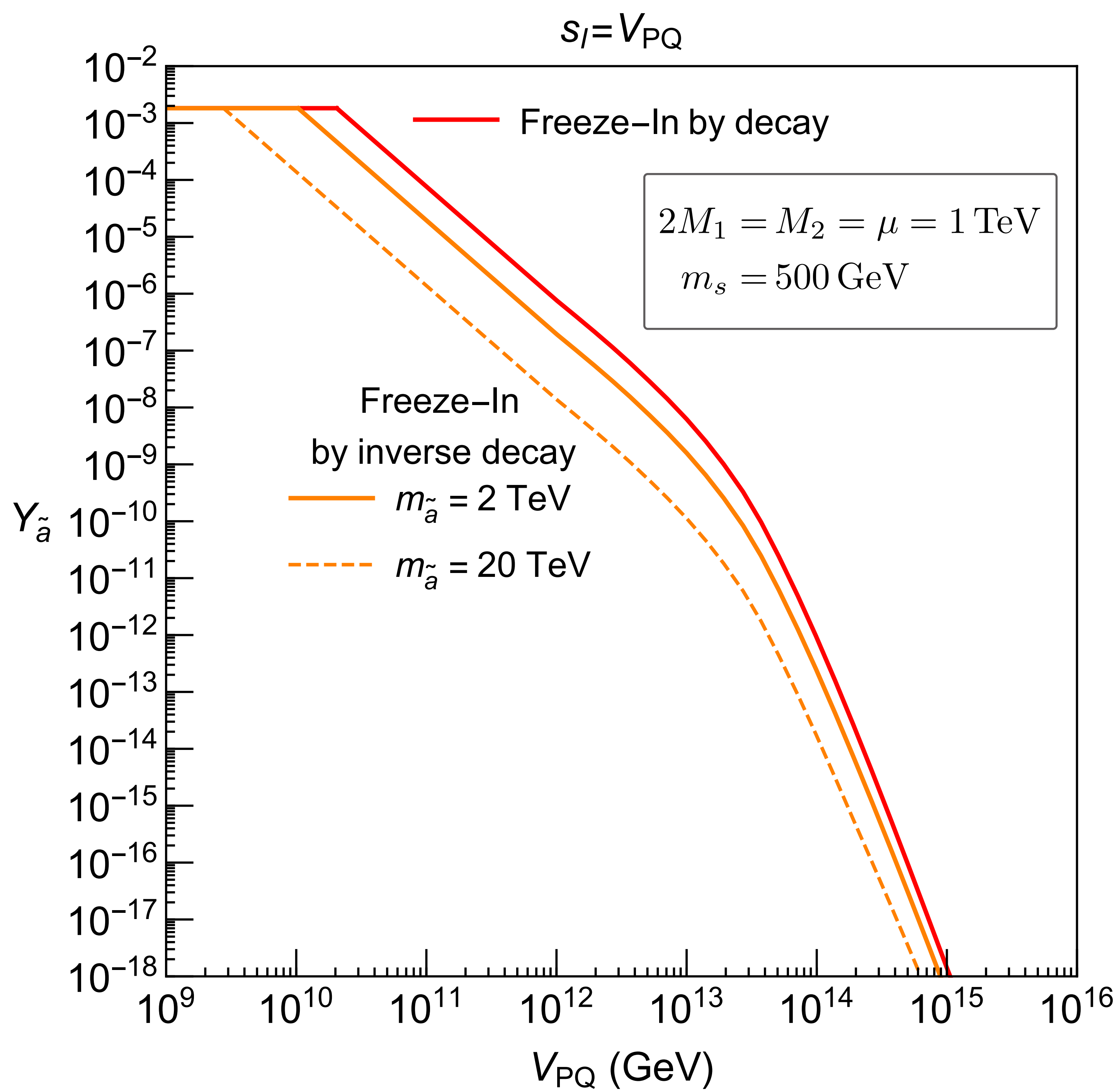
$$\frac{\rho_{\tilde{a}}(\mathrm{FI})}{\rho_{\mathrm{DM}}^{\mathrm{obs}}} \approx 4.5 \times 10^{8} \left(\frac{106.75}{g_*}\right)^{3/2} \left(\frac{m_{\tilde{a}}}{100\,\mathrm{GeV}}\right) \left(\frac{\mu}{300\,\mathrm{GeV}}\right) \left(\frac{10^{10}\,\mathrm{GeV}}{f}\right)^{2}$$

(cosmological problems also if the axino is not the LSP)

Co, FD, Hall, Phys.Rev. D94 (2016)
Co, FD, Hall, JHEP 1703 (2017)
Co, FD, Hall, Harigaya, JHEP 1707 (2017)

A motivated example

- Lightest observable SUSY particle (LOSP) highly diluted
- R-odd particles produced by processes with axino and gravitino in the final state
- Cold and/or warm dark matter
- No gravitino problem
- Axion dark radiation
- Imposing the dark matter relic density points toward displaced signals at colliders



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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	$(\mathbf{1},\mathbf{1})_{-1}$
$F_{\mu\nu}$	$G^A_{\mu\nu}$	$(\mathbf{8},\mathbf{1})_0$
	$W^I_{\mu\nu}$	$(\mathbf{1},\mathbf{3})_0$
	$B_{\mu\nu}$	$(\mathbf{1},\mathbf{1})_0$
H	H	$(\mathbf{1},\mathbf{2})_{+1/2}$

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

$A_{\rm SM}$	**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	$\overline{\Psi_B}\chi\,H$	$\mathcal{F}_{H\chi}$

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

Related work:

- Singlet-doublet model for standard cosmological history

Calibbi et al. , JHEP 1809 (2018) 037

- Scalar DM coupled to SM fermions with a fermion B particle and instantaneous reheating

Bélanger et al. , JHEP 1902 (2019) 186

See Genevieve Bélanger's Talk

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

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

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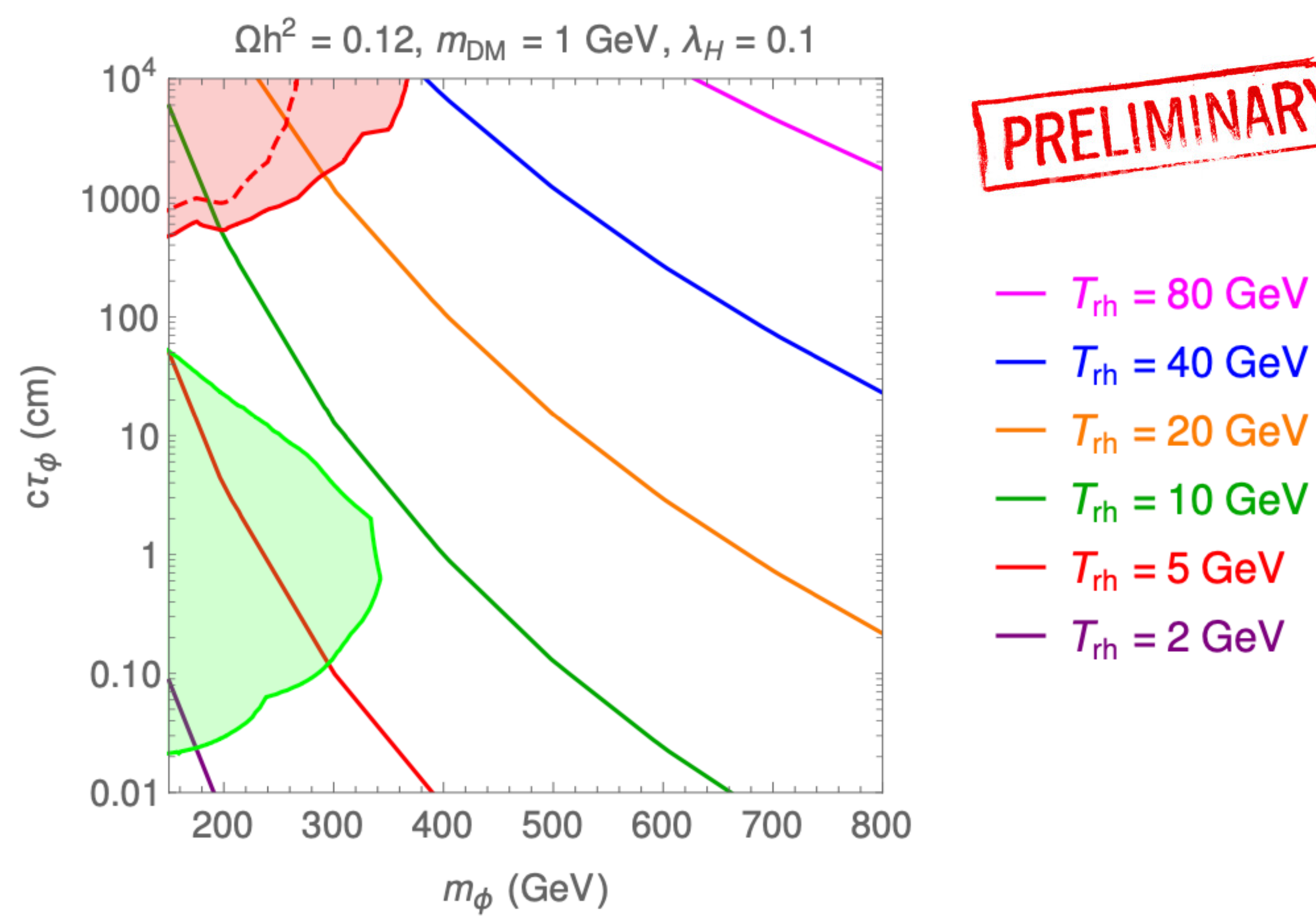
Heavy Stable Charged Particles

Displaced Leptons



PRELIMINARY

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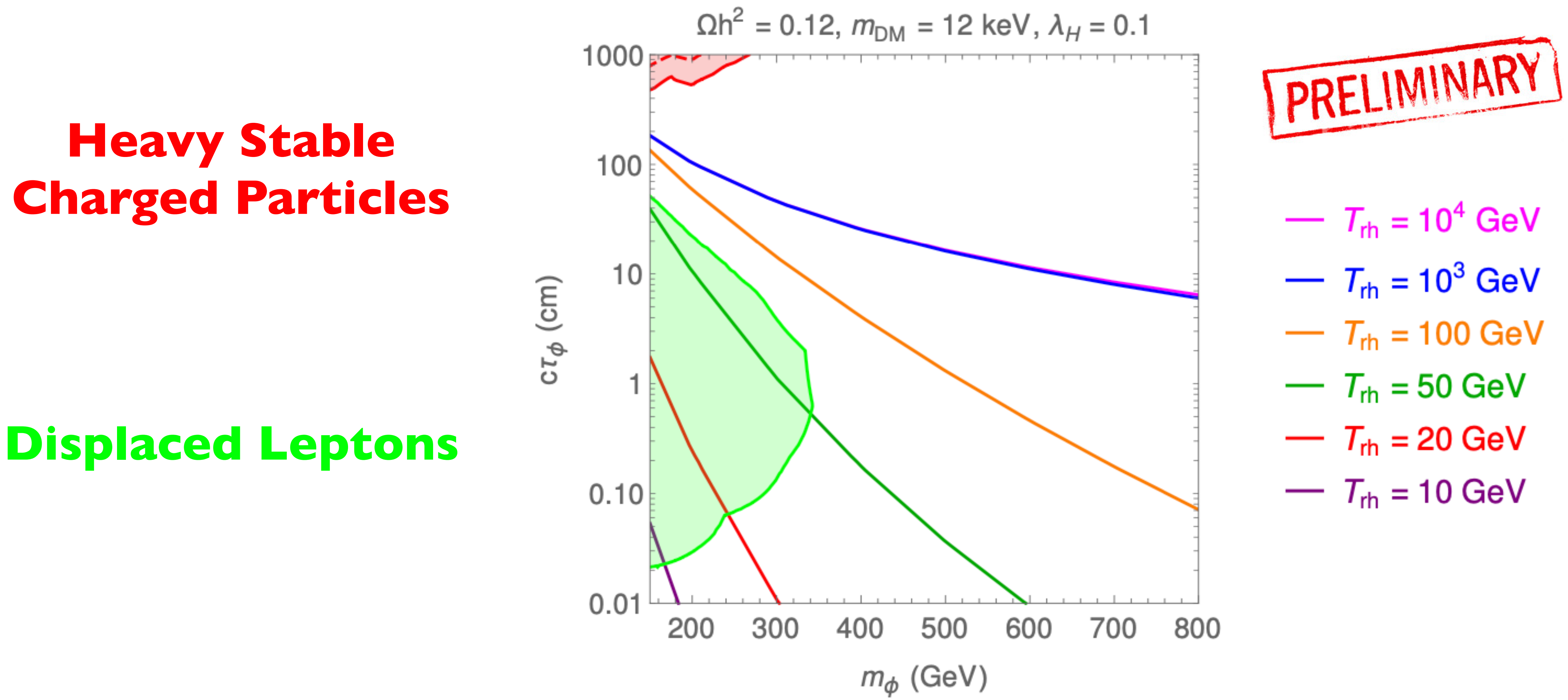
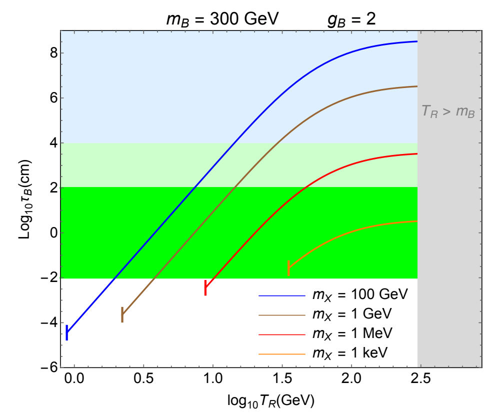
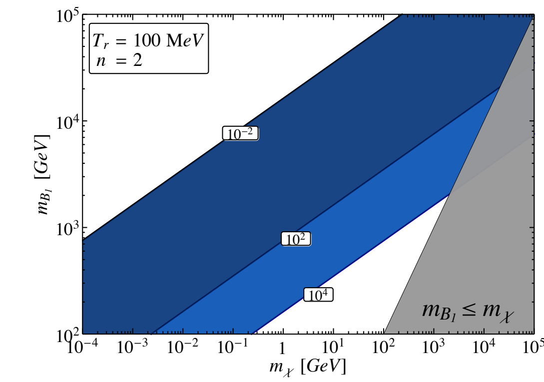


Outlook

- Freeze-in in modified cosmologies and displaced signatures





- A motivated example: DFSZ axino disaster and the saxion

$$\widetilde{h^0} \to \tilde{a}\, h$$
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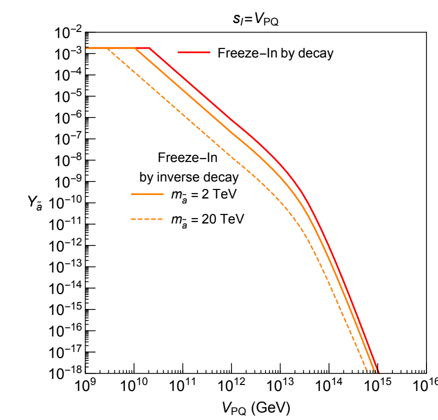
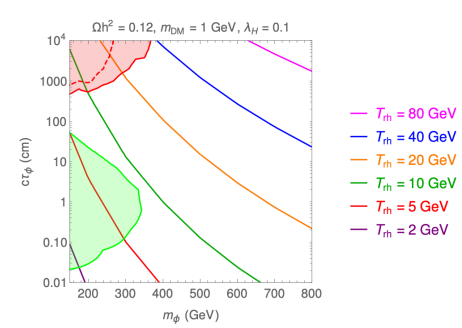
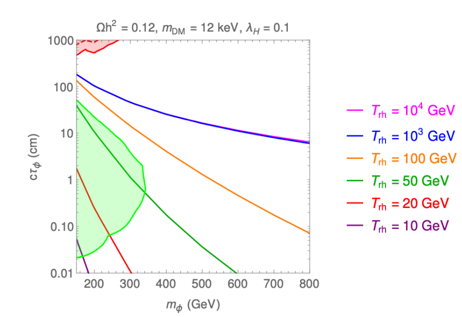


- Bottom-up classification





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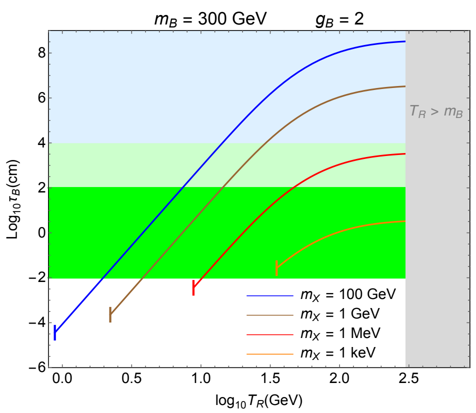

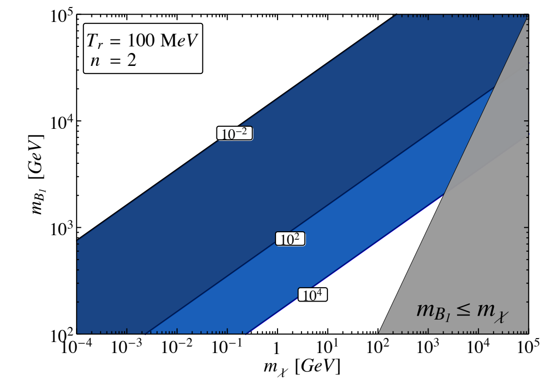

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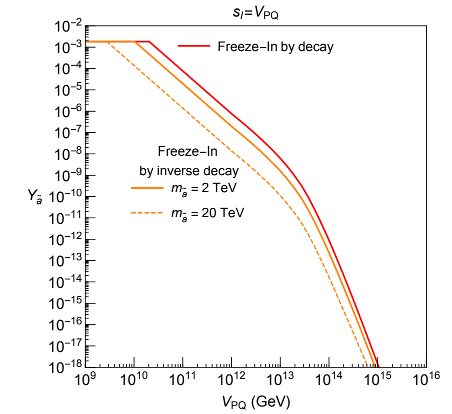

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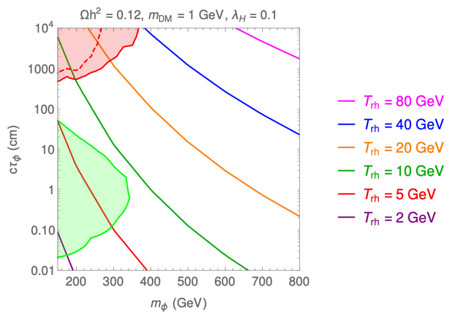

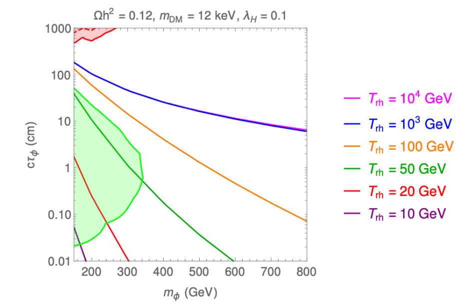

Obrigado