Reflections on the Matter-Dark matter Coincidence

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arXiv: 2401.12286

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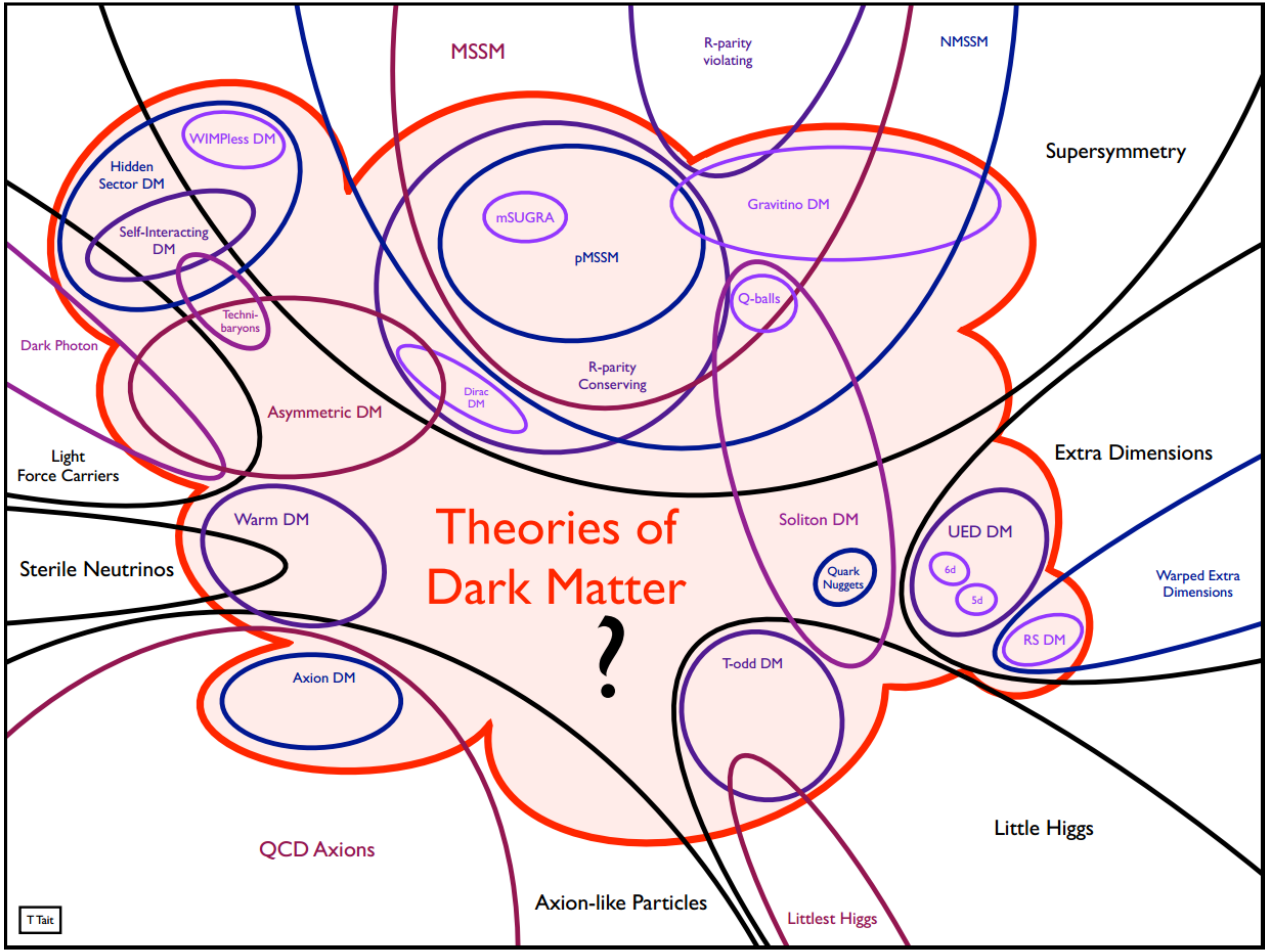
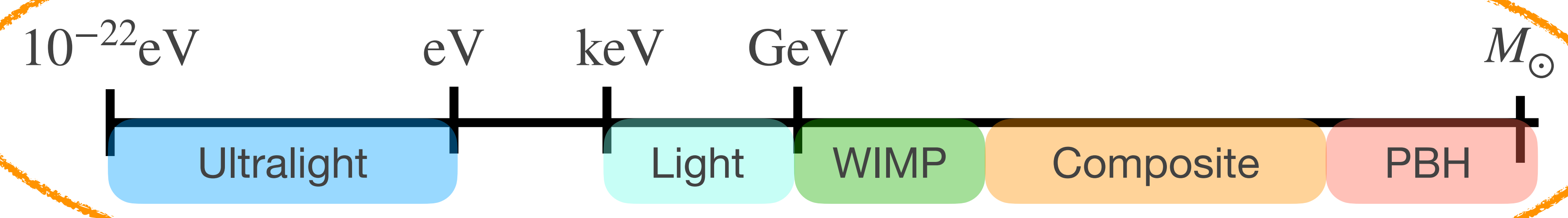

MSSM
R-parity
violating
NMSSM
Supersymmetry
WIMPless DM
Hidden
Sector DM
Self-Interacting
DM
Techni-
baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
Dark Photon
R-parity
Conserving
Dirac
DM
Asymmetric DM
Light
Force Carriers
Extra Dimensions
Warm DM
Theories of
Dark Matter
?
Soliton DM
UED DM
6d
5d
Quark
Nuggets
Warped Extra
Dimensions
RS DM
Sterile Neutrinos
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

An intriguing hint

$$\rho_{\rm dm} \approx 5\,\rho_{\rm b}$$

$$m_{\rm dm}\, n_{\rm dm} \approx 5\, m_b\, n_{\rm b}$$



Freeze-out, Freeze-in, misalignment,..

$$\Lambda_{\rm QCD} \sim M_{\rm UV} e^{-\frac{1}{\beta\,\alpha_s(M_{\rm UV})}}$$

$$\frac{n_b - n_{\bar{b}}}{s} \sim 10^{-10}$$

New $\not{C}\not{P}$ physics

Common origins

$$m_{\rm dm}\, n_{\rm dm} \approx 5\, m_b\, n_{\rm b}$$

Asymmetric DM

$$m_{\rm dm} \sim 5\,{\rm GeV}$$

Reasonable given weak scale

$$\Lambda_{\rm QCD} \sim M_{\rm UV} e^{-\frac{1}{\beta\,\alpha_s(M_{\rm UV})}}$$

NOT set by weak scale

Still need a robust mechanism that can relate $m_{\rm dm} \sim m_{\rm b}$

What is required for $m_{\rm dm} \sim m_{\rm b}$

$m_{\rm b}$ comes from confinement ($\Lambda_{\rm QCD}$) $\longrightarrow$ $m_{\rm dm}$ also comes from confinement ($\Lambda'_{\rm QCD}$).

$$\Lambda_{\rm QCD}^{\frac{11N_c}{3}-\frac{2N_L}{3}} = M_{\rm Pl}^{\frac{11N_c}{3}-\frac{2N_F}{3}}\, e^{-\frac{2\pi}{\alpha_s(M_{\rm Pl})}} \prod_{m_i>\Lambda_{\rm QCD}} m_i^{2/3}$$

$N_c\,,\, N_L\,,\, N_F\,,\, \alpha_s(M_{\rm Pl})$ in the exponent $\longrightarrow$ $\Delta\alpha_s/\alpha_s(M_{\rm Pl}) \lesssim 10\,\%$ and $(N_c\,,\, N_L\,,\, N_F)$ must be replicated to get $\Lambda'_{\rm QCD} \sim \Lambda_{\rm QCD}$ robustly.

If dark matter is so similar to the SM, why does it look so different?

SM is on a razor's edge

$m_n - m_p \sim 2\,\mathrm{MeV} \ll \Lambda_{\mathrm{QCD}}$ comes from the mass difference between the lightest up and down quarks.

If the lightest u and d Yukawas were slightly different from SM values such that protons were heavier than neutrons, the world could have looked very different.

In particular, if protons were 3 MeV heavier than neutrons, they would have decayed before BBN. Leftover neutrons in this world would have looked just like dark matter, and with the same abundance as baryons in our world!

A slightly imperfect replica of SM can produce dark matter in the form of dark neutrons!

In the paper

Premise:

→ There is a dark sector (DS) that is *approximately* $\mathbb{Z}_2$ symmetric with the SM which makes the visible sector (VS).

→ Dark matter is made of the asymmetric component of dark neutrons, which is generated by the same mechanism that generates asymmetry in baryons

We *reflect* on these models of dark matter with *reflection* symmetry.

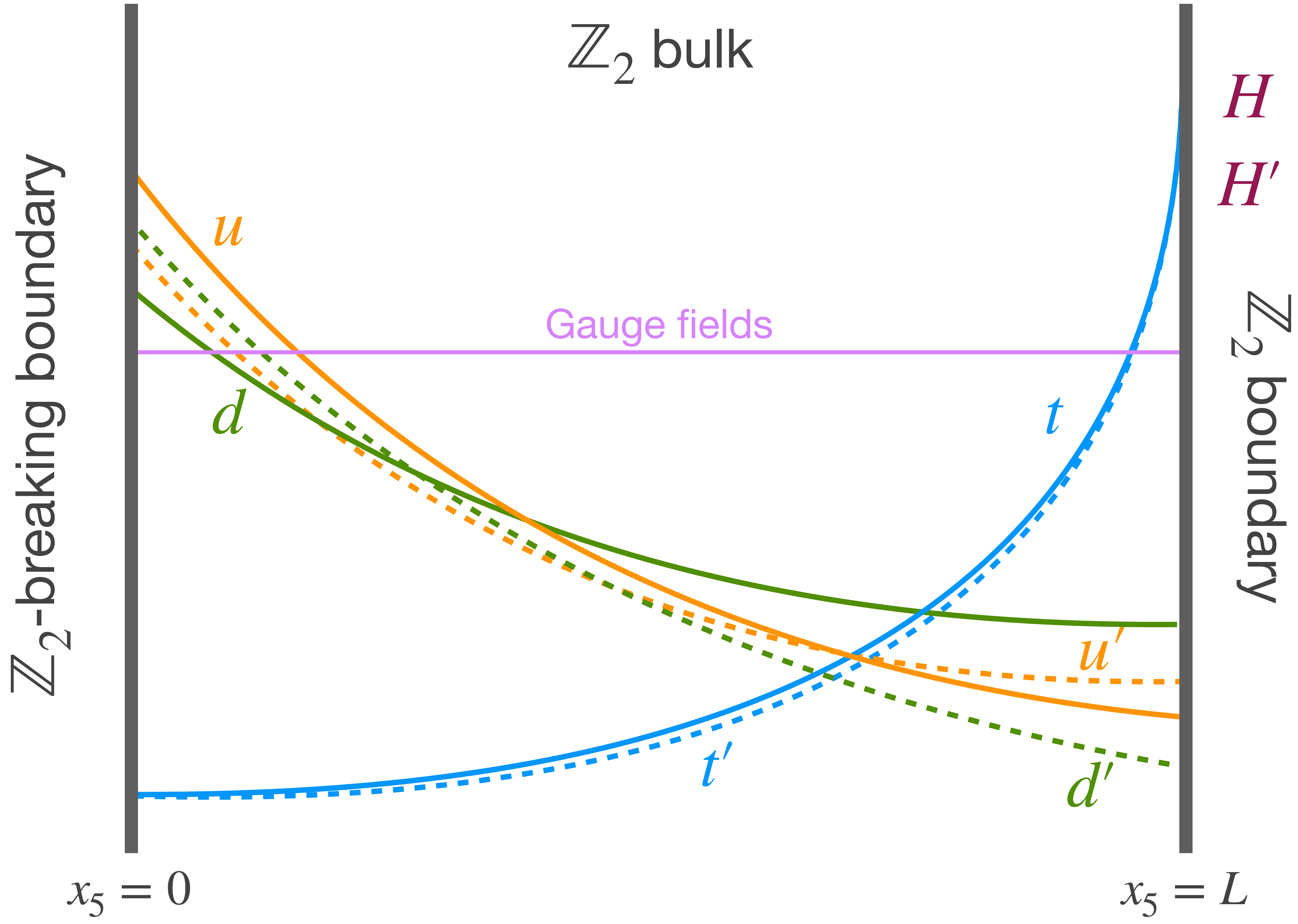
- A consistent scheme to break $\mathbb{Z}_2$?
- Compatible with cosmology without losing naturalness?

  → $\Delta N_{\rm eff}$

  → Avoiding dark atoms (heavily constrained by Bullet cluster)

A guiding principle for $\mathbb{Z}_2$ breaking

$\mathbb{Z}_2$ broken by $\mathcal{O}(1)$ for small u and d Yukawas, preserved for larger Yukawas like t, and $\Delta\alpha/\alpha \lesssim 10\,\%$



$$n_{\mathrm{dm}} \approx n_{\mathrm{b}}$$

(WIMP) Baryogenesis

Y. Cui, R. Sundrum 1212.2973

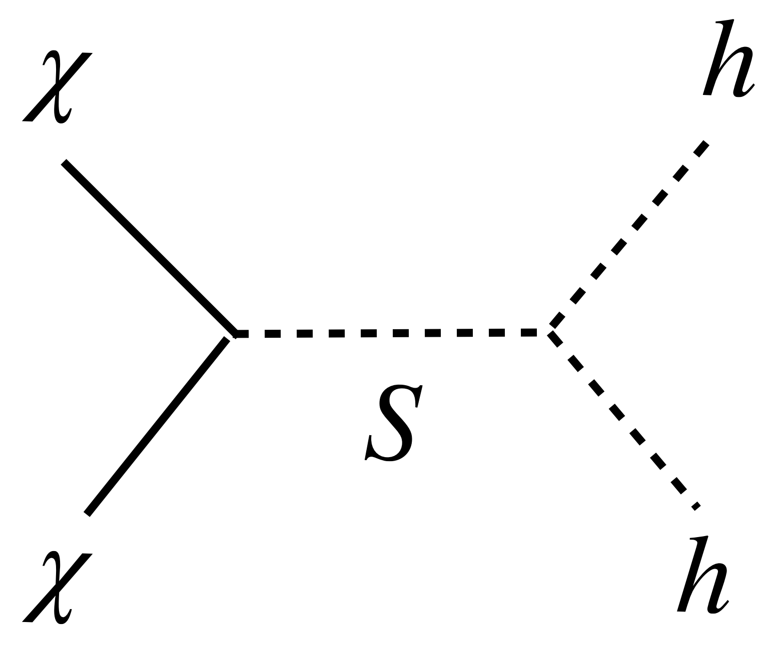
$Y_b \equiv n_b/s \sim 10^{-10}$ → close to the abundance from a WIMP ("miracle").

WIMP-like baryogenesis parent χ with mass $\sim$ (few) TeV with weak scale couplings.

Non-relativistic freeze-out of χ gives abundance in the ballpark of Y_b.

$$\mathscr{L} \supset \frac{1}{2}\alpha\chi^2 S + \beta_S S\,|H|^2 + \frac{1}{2}m_\chi\chi^2 + \frac{1}{2}m_S^2 S^2$$

Taking where $\alpha \sim 0.5$, $\beta_S \sim 100\,\text{GeV}$, $m_\chi \sim 3\,\text{TeV}$, $m_S \sim 10\,\text{TeV}$

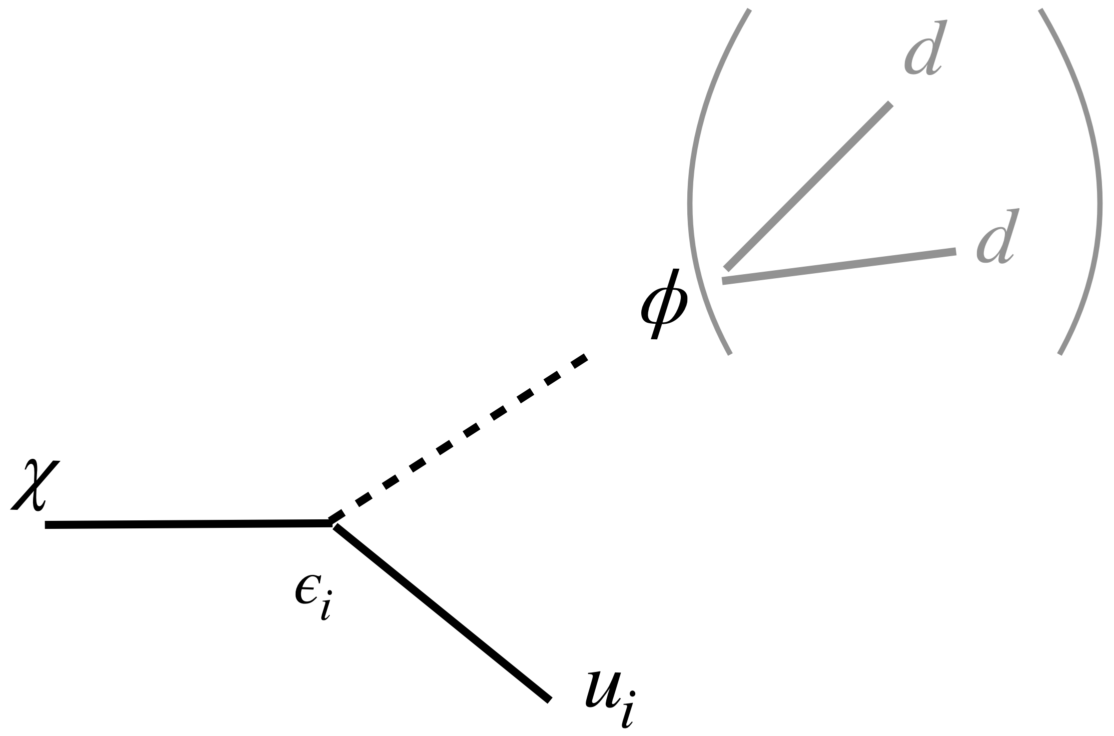


$$Y_\chi \approx 8 \times 10^{-8} \left(\sqrt{\frac{200}{g_{*\chi\text{fo}}^{\text{tot}}}}\right)\left(\frac{3\text{TeV}}{m_\chi}\right)\left(\frac{10^{-15}\text{GeV}^{-2}}{\langle\sigma v\rangle_{\chi h}}\right)\left(\frac{x_\text{fo}}{11}\right)$$

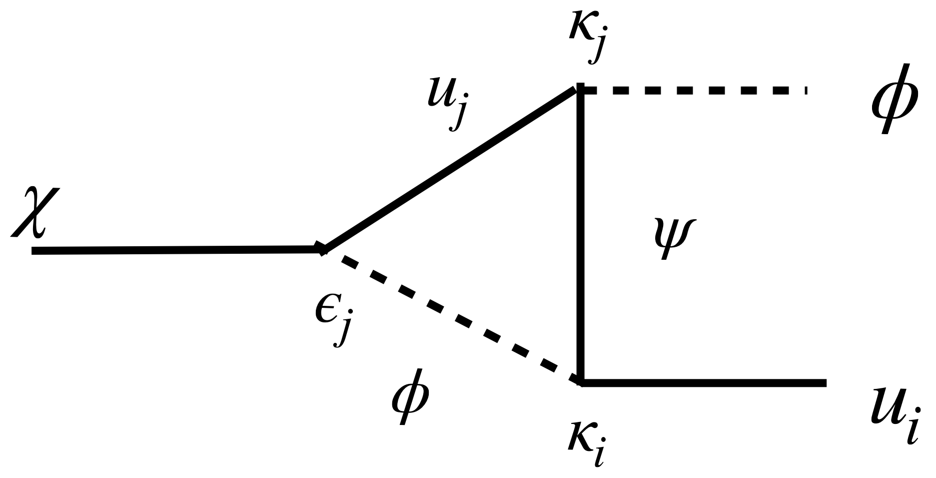
(WIMP) Baryogenesis

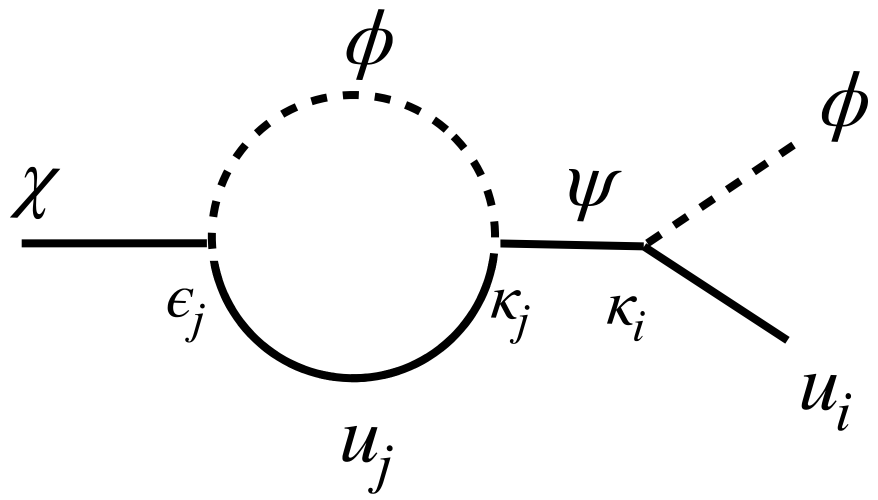
When χ decays, interference between tree-level and loop diagrams provide CP-violation necessary for the generation of baryons asymmetry (similar to leptogenesis)

$\mathscr{L} \supset \lambda_{ij}\phi d_i^{c\dagger} d_j^{c\dagger} + \epsilon_i \phi \chi u_i^c + \kappa_i \phi \psi u_i^c$ where κ_i, $\lambda_{ij} \sim \mathcal{O}(1)$, $10^{-14} < \epsilon_i < 10^{-7}$, $m_\chi \approx 3\,\mathrm{TeV}$, $m_\psi \approx 10\,\mathrm{TeV}$, $m_\phi \approx \mathrm{TeV} < m_\chi$



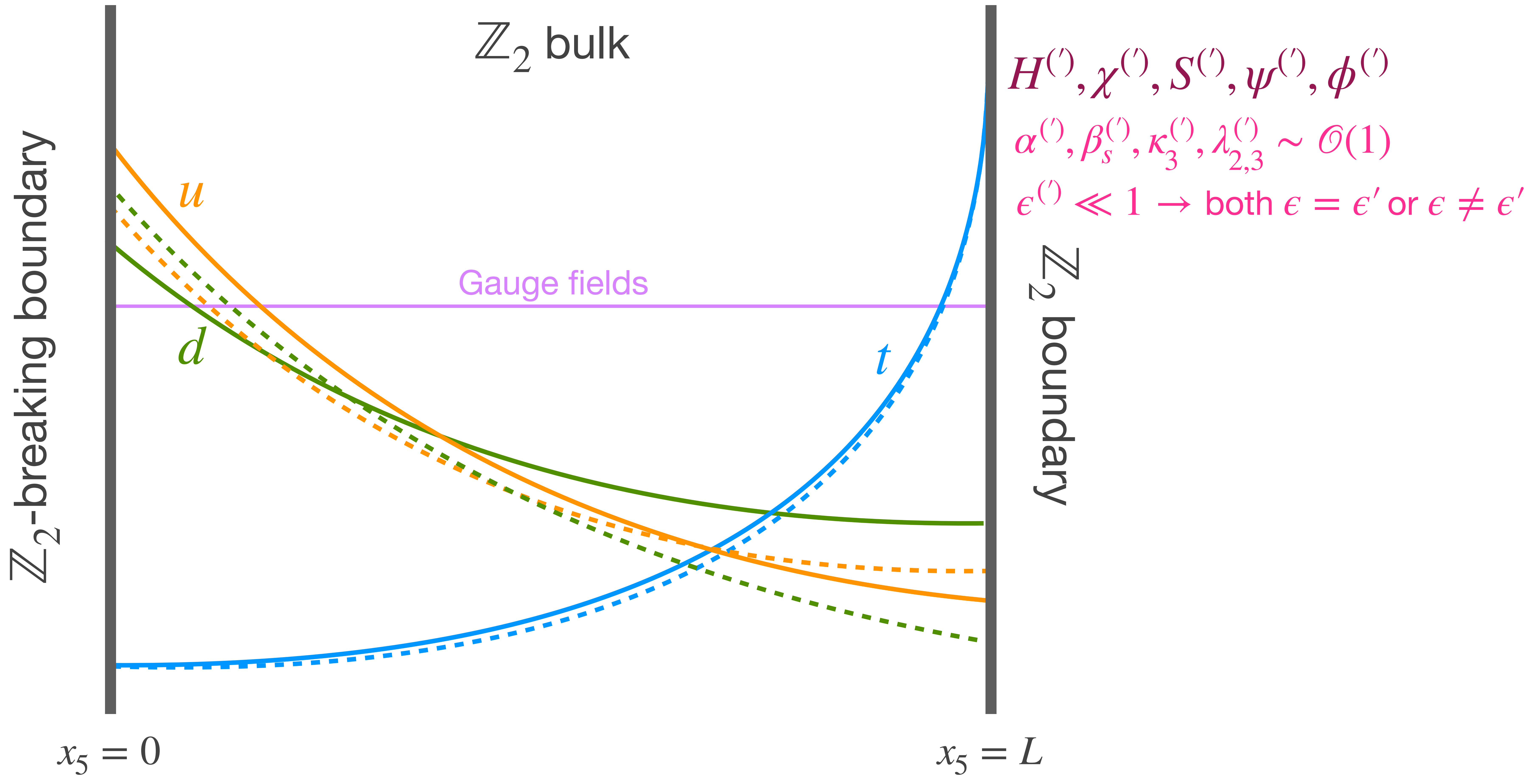
$$\epsilon_{\mathrm{CP}} \approx \frac{2}{8\pi} \frac{\mathrm{Im}\left(\left(\sum_i \epsilon_i \kappa_i^*\right)^2\right)}{\sum_i |\epsilon_i|^2} \frac{m_\chi}{m_\psi}$$





$$Y_b = \epsilon_{\mathrm{CP}} Y_\chi \sim 10^{-10}$$

We take this mechanism to be duplicated in the dark sector, which gives $Y_{\mathrm{dm}} \approx Y_{\mathrm{b}} \sim 10^{-10}$



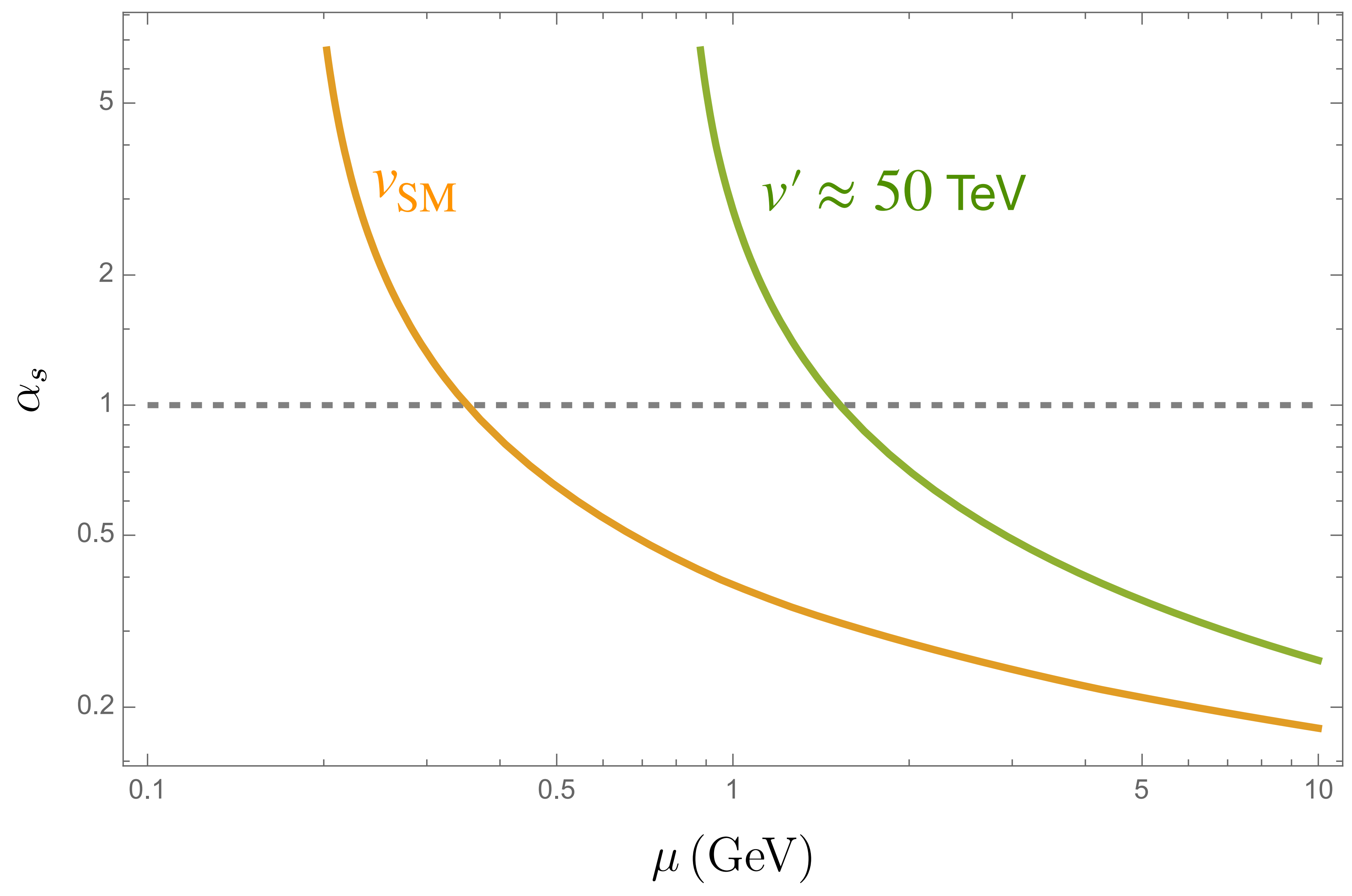
$\mathbb{Z}_2$ bulk
$\mathbb{Z}_2$-breaking boundary
$\mathbb{Z}_2$ boundary
$H^{(\prime)}, \chi^{(\prime)}, S^{(\prime)}, \psi^{(\prime)}, \phi^{(\prime)}$
$\alpha^{(\prime)}, \beta_s^{(\prime)}, \kappa_3^{(\prime)}, \lambda_{2,3}^{(\prime)} \sim \mathcal{O}(1)$
$\epsilon^{(\prime)} \ll 1 \rightarrow$ both $\epsilon = \epsilon'$ or $\epsilon \neq \epsilon'$
Gauge fields
u
d
t
$x_5 = 0$
$x_5 = L$

$$n_{\mathrm{dm}} \approx n_{\mathrm{b}} \rightarrow m_{\mathrm{dm}} \approx 5\, m_{\mathrm{b}}$$

Dark weak scale v'

If $\mathbb{Z}_2$ is broken, we would expect the most sensitive parameter of the SM to change, i.e., the weak scale v.

$$\Lambda_{\rm QCD}^{\frac{11N_c}{3}-\frac{2N_L}{3}} = M_{\rm Pl}^{\frac{11N_c}{3}-\frac{2N_F}{3}} e^{-2\pi/\alpha_s(M_{\rm Pl})} \prod_{m_i>\Lambda_{\rm QCD}} m_i^{2/3}$$



The hierarchy problem must be solved such that $v' \sim \mathcal{O}(10)$ TeV!

Other restrictions on ν': dark BBN

Dark BBN can change the nature of dark matter from dark neutrons to atomic dark matter.

Bullet cluster bound: $\frac{\sigma}{m_{\rm dm}} \lesssim 1 \frac{\rm cm^2}{g} \equiv \frac{1}{(100\,{\rm MeV})^3}$ with self-interacting DM $\lesssim 10\,\%$

A. Robertson, R. Massey, V. Eke: 1605.04307

To ensure that dark neutrons make dark matter, we have to avoid formation of dark atoms through dark BBN.

p' decay

p' must decay before the onset of dark Deuterium ($D' \equiv {}^2_1H'$) formation → constrains p' lifetime ($\tau_{p'}$)

1) $T'_{D'} \sim \dfrac{\mathrm{BE}_{D'}}{20}$

2) $\dfrac{\mathrm{BE}_D}{m_n} \propto \left(\dfrac{m_\pi}{m_n}\right)^2 \longrightarrow \mathrm{BE}_{D'} \approx \dfrac{(y'_u + y'_d)\,v'}{(y_u + y_d)\,v}\,\mathrm{BE}_D$ where $\mathrm{BE}_D \approx 2.2\,\mathrm{MeV}$

S. Beane et al: 1206.5219

3) $\dfrac{\tau_{p'}}{\tau_n} \approx \dfrac{G_F\,\Delta m^5_{n-p}}{G'_F\,\Delta m^5_{p'-n'}}$ where $\tau_n \approx 880\,\mathrm{s}$

$$0.015\,\left(\frac{v'}{1\ \mathrm{TeV}}\right)^4\left(\frac{30\ \mathrm{MeV}}{\Delta m'}\right)^5\left(\frac{T_{D'}}{1\ \mathrm{MeV}}\right)^2 \lesssim 1$$

Stability of dark di-neutron $(n' - n')$ state

If $(n' - n')$ state is stable, bigger nuclei of pure n' can form and grow to be very large due to the lack of electromagnetic repulsion.

However, as the dark nucleus grows, the Fermi energy from Pauli blocking increases, contributing negatively to the binding energy.

At some point, it will be energetically favorable for the n' inside a dark nucleus to decay to heavier p' to reduce Fermi energy, and transition to a mixed nucleus of n' and p'.

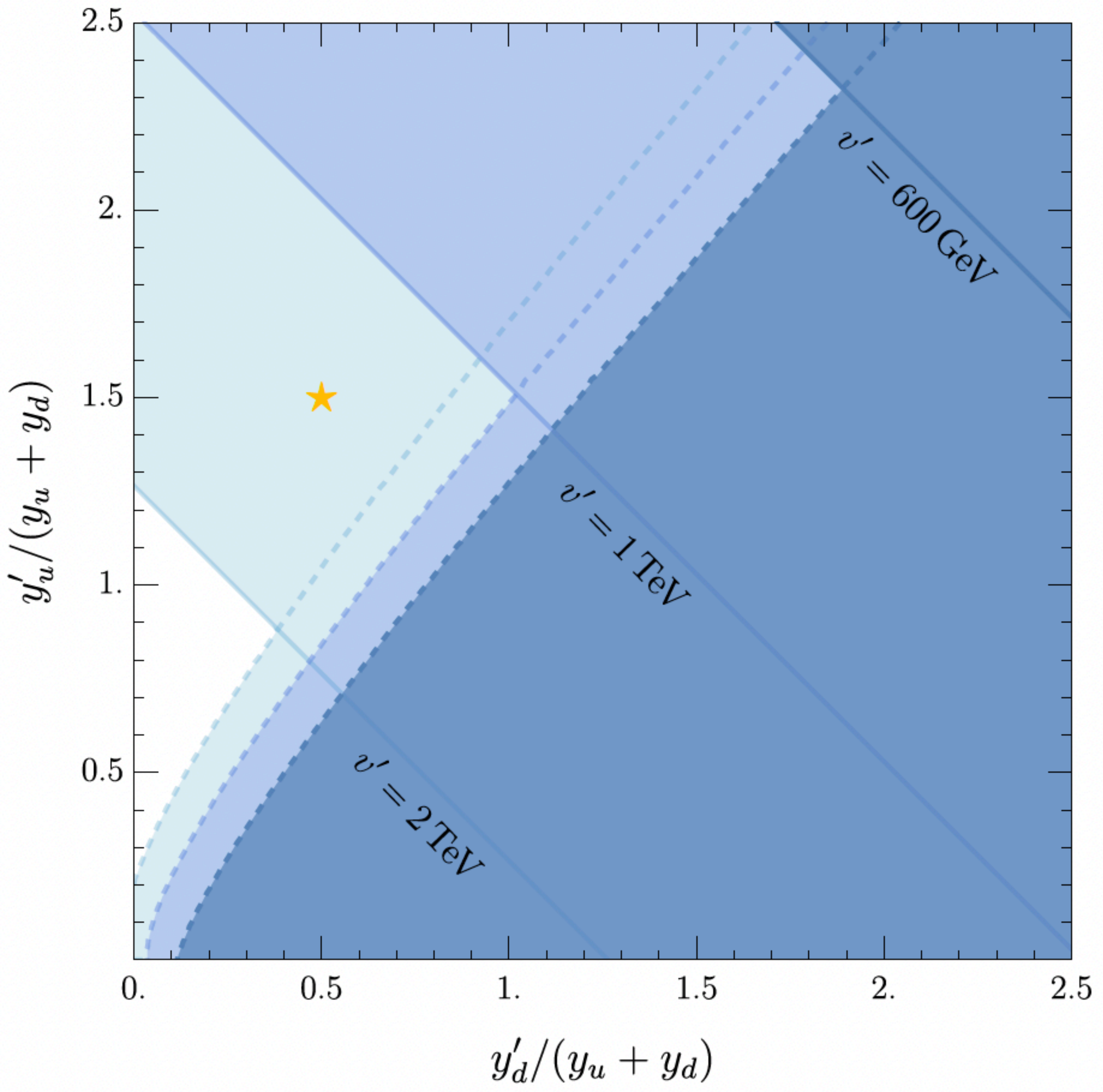
Example of β^+ decay in SM: ${}^{11}_{6}\mathrm{C} \to {}^{11}_{5}\mathrm{B} + e^+ + \nu_e \; (+1\,\mathrm{MeV})$

Lattice simulations show that $(n - n)$ state would have been stable if $m_\pi \gtrsim 300\,\mathrm{MeV}$. So the stability flip happens somewhere between $135\,\mathrm{MeV}$ and $300\,\mathrm{MeV}$.

T. Yamazaki, K. Ishikawa, Y. Kuramashi, A. Ukawa: 1502.04182

K. Orginos et al: 1508.07583

$$\frac{m_{\pi'}}{m_{n'}} < 0.2$$



$$v' < \text{(few) TeV} \longrightarrow \Lambda' \sim 1.5\Lambda$$

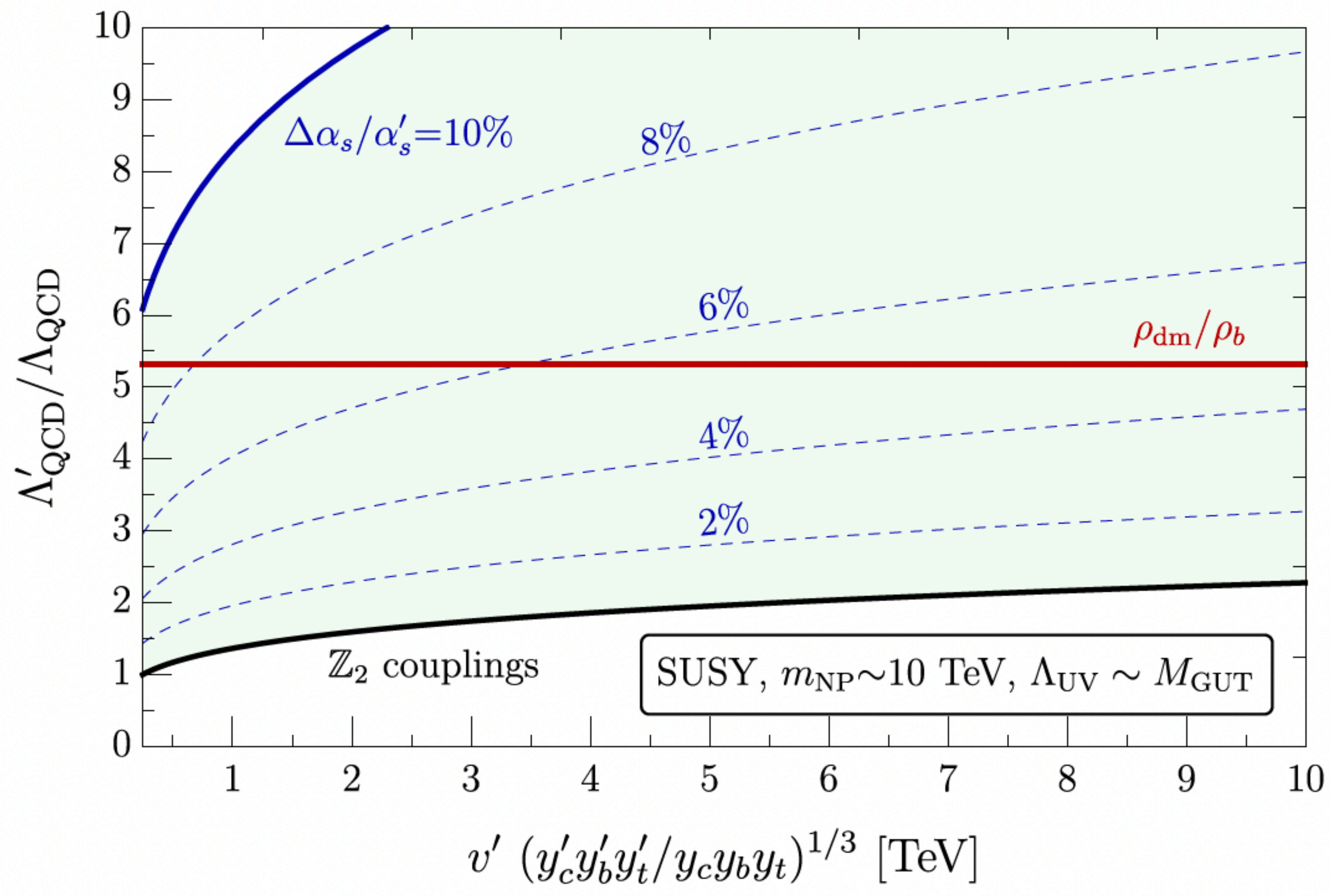
Additional contributions to the factor of 5

$\mathcal{O}(1)$ breaking of $\mathbb{Z}_2$ on the left boundary

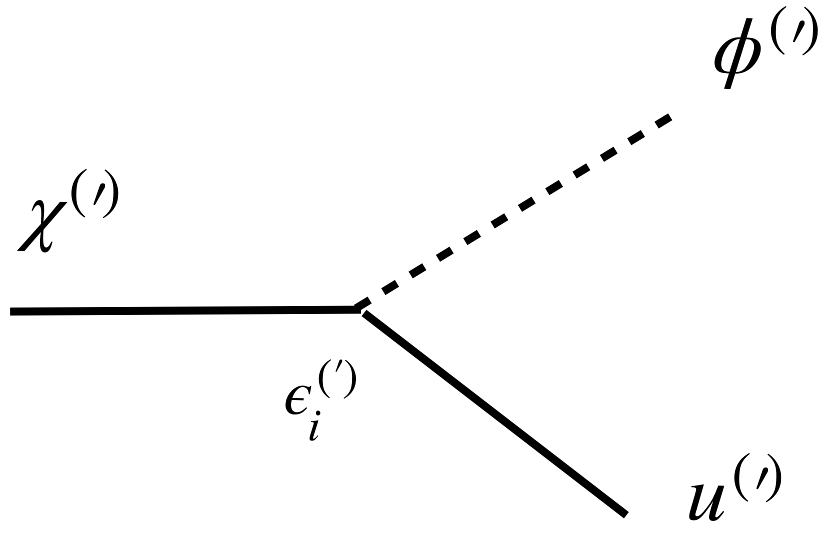
$$\frac{1}{\alpha_s^{(\prime)}} = \delta^{(\prime)}_{\text{boundary}} + \frac{L}{\alpha_{s,5}}$$

If $\frac{\alpha_{s,5}}{L} \lesssim \frac{1}{10}$ and boundary contributions break $\mathbb{Z}_2$ by $\mathcal{O}(1)$,

$$\frac{\Delta\alpha_s}{\alpha_s'} \sim 10\,\%$$



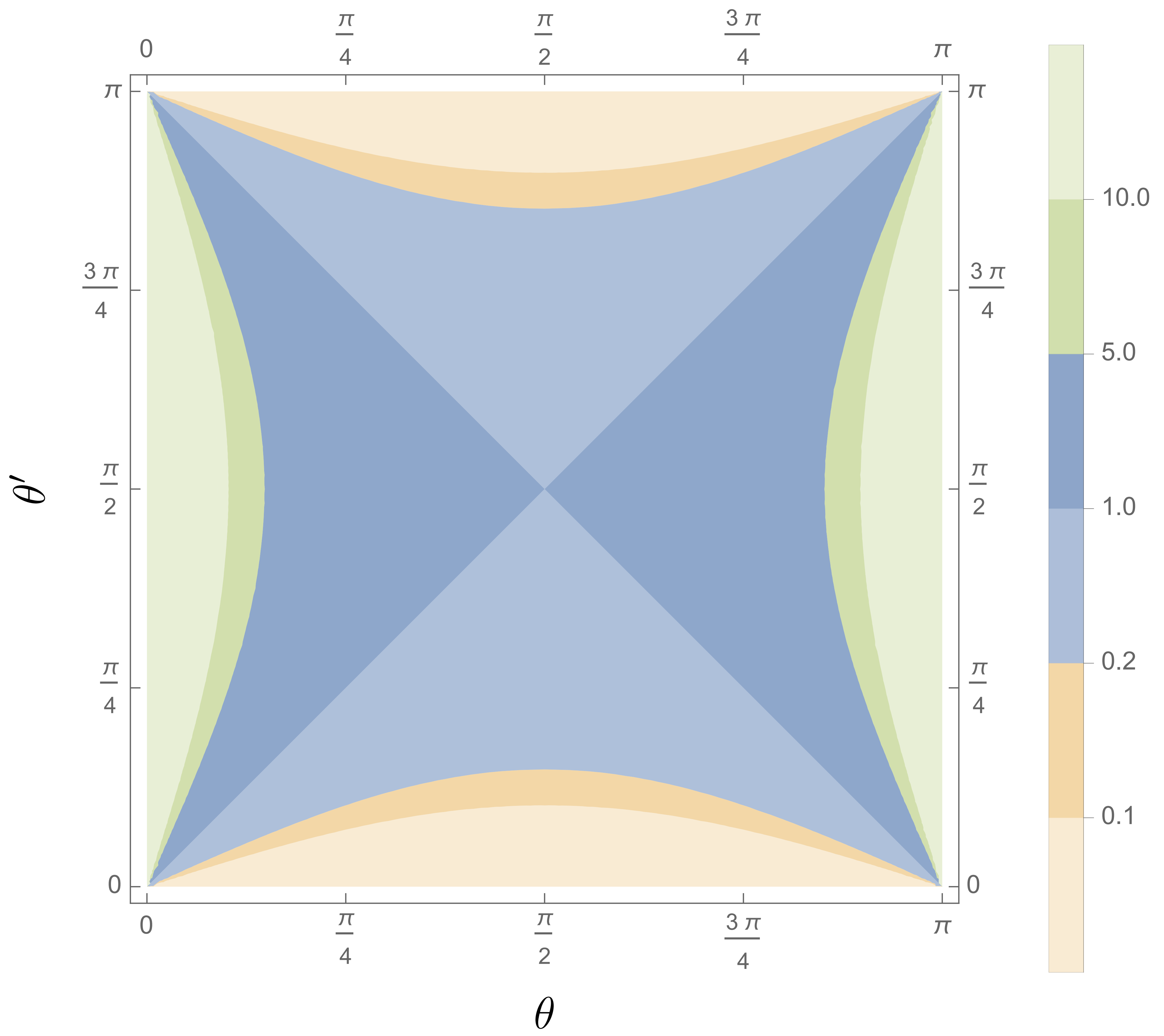
Additional contributions to the factor of 5



If $\epsilon \neq \epsilon' \longrightarrow \quad \epsilon_{\mathrm{CP}} \approx \frac{2}{8\pi} \frac{\mathrm{Im}\left(\left(\sum_i \epsilon_i \kappa_i^*\right)^2\right)}{\sum_i |\epsilon_i|^2} \frac{m_\chi}{m_\psi}$

$$\frac{n_{b'}}{n_b} \sim \frac{\sin(\theta')}{\sin(\theta)} \xrightarrow{\text{typically}} \mathcal{O}(1)!$$

P. Bittar, G. Burdman, and L. Kiriliuk: 2307.04662



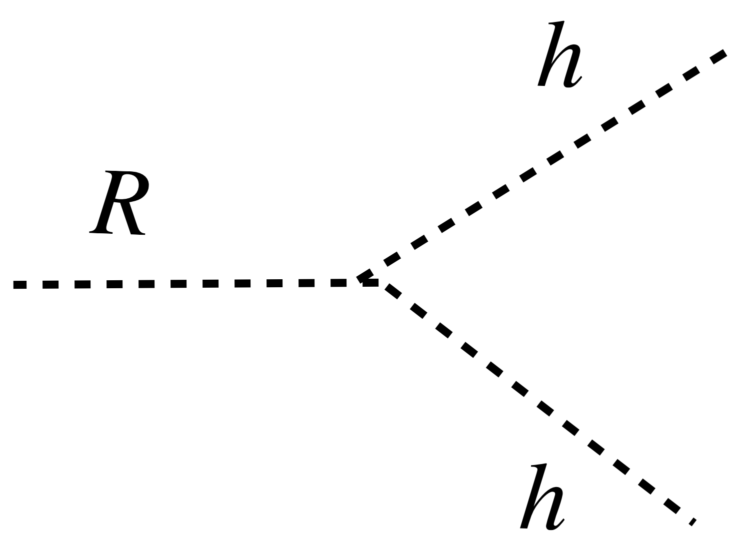
Where is all the extra stuff?

ΔN_{eff} constraints

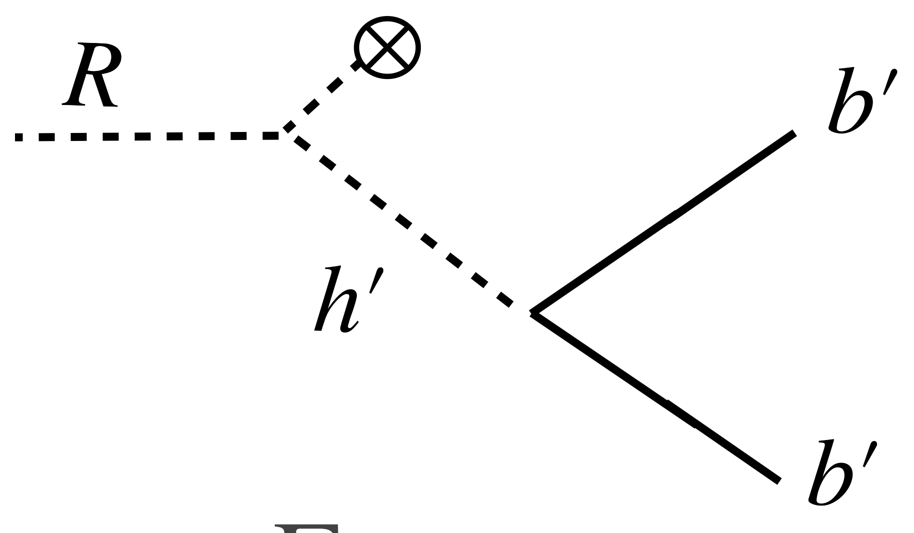
Despite thermal initial conditions, the dark sector can end up colder than the visible sector at later times if there is asymmetric reheating.

Consider a late decaying scalar R (reheaton) with $\mathscr{L} \supset \beta_R R\,|H|^2 + \beta'_R R\,|H'|^2 + \frac{1}{2} m_R^2 R^2$

Asymmetric reheating can occur purely through kinematic factors if $2m_{h'} > m_R > 2m_h$



Γ_{VS}



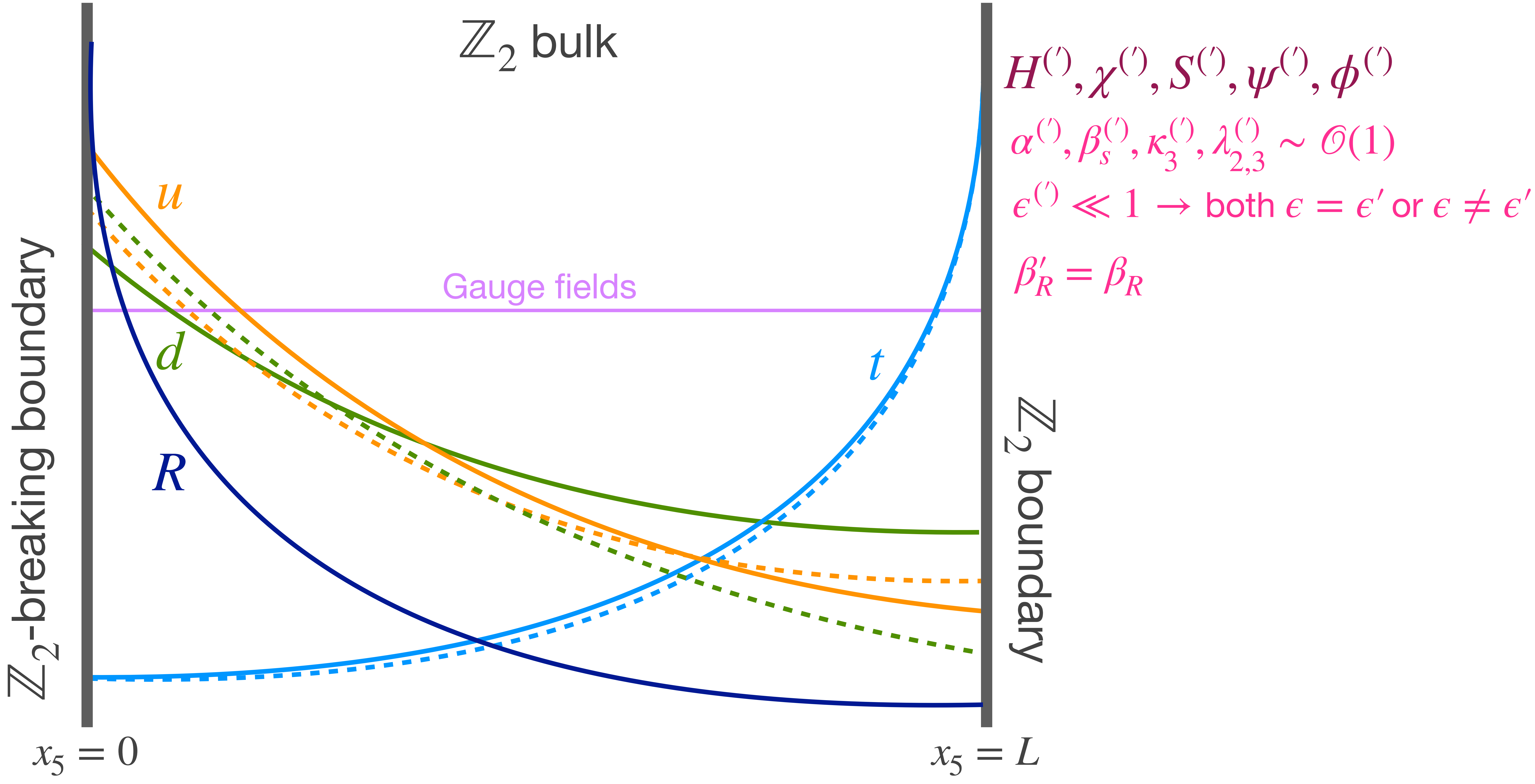
Γ_{DS}

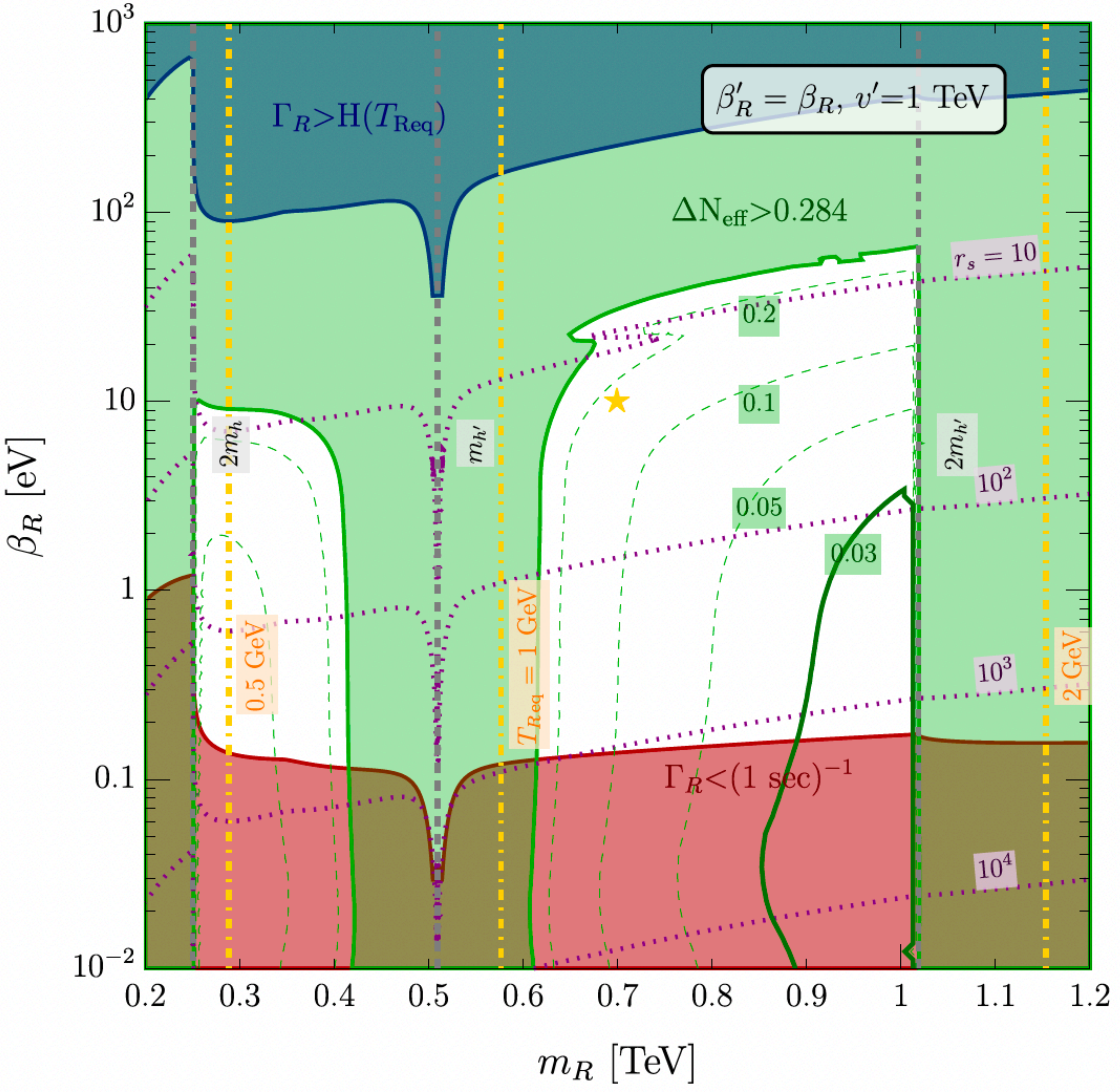
$$\frac{\Gamma_{\text{DS}}}{\Gamma_{\text{VS}}} \sim y_b'^2 \frac{m_R^2}{m_{h'}^2} \ll 1$$

N. Arkani-Hamed et al: 1607.06821

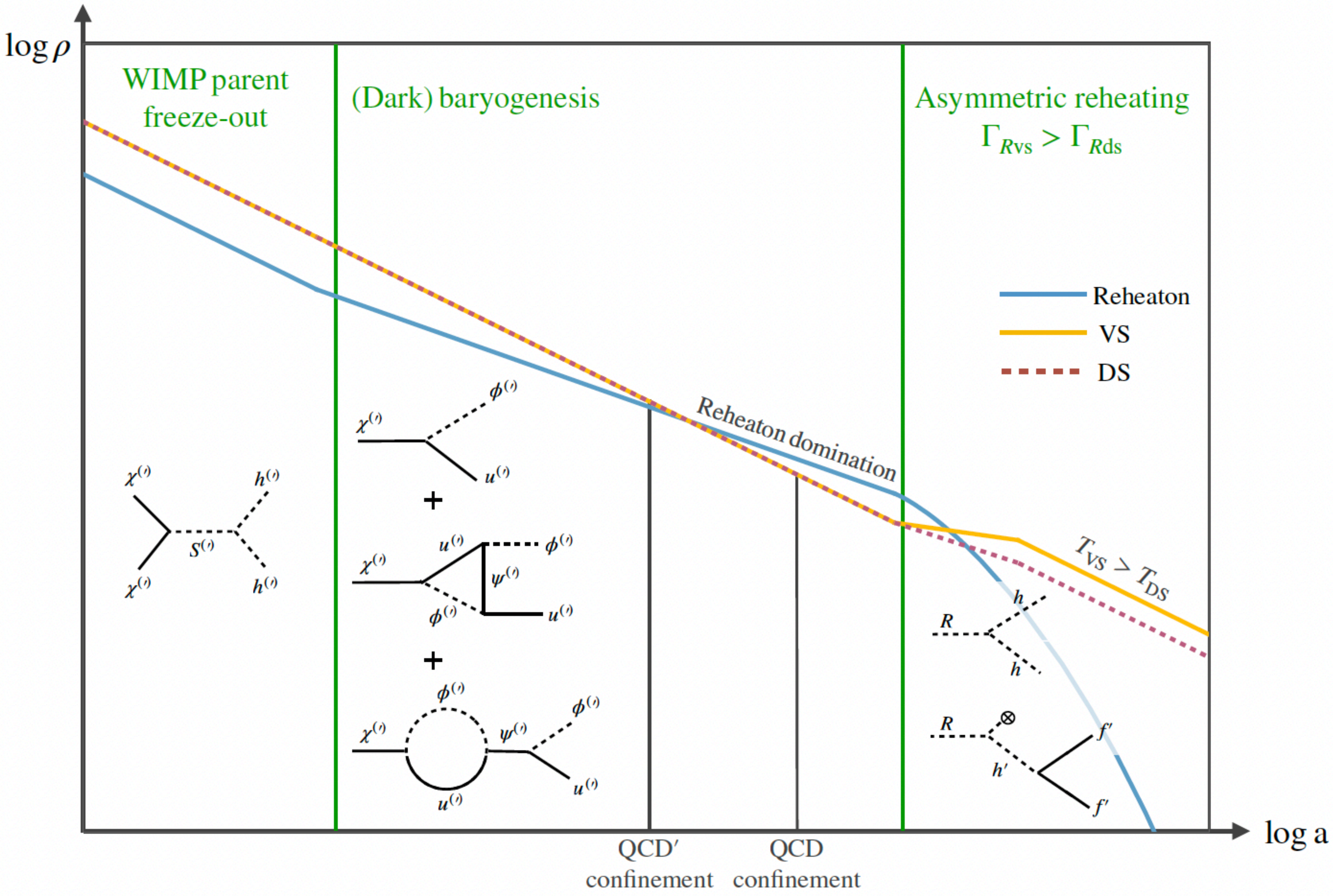
Z. Chacko, N. Craig, P. Fox, R. Harnik: 1611.07975

$\beta_R^{(\prime)}\,(\mathrm{TeV})^{-1} \ll 1$ to ensure late decay $\longrightarrow R$ is leaning towards the $\mathbb{Z}_2$-breaking boundary and therefore have a small overlap with the Higgses that are localized on the $\mathbb{Z}_2$ boundary. However, the reheaton is *common* to both sectors, ensuring $\beta_R' = \beta_R$.




$\beta'_R = \beta_R$, v'=1 TeV
Γ_R>H($T_{\rm Req}$)
$\Delta N_{\rm eff}$>0.284
$r_s = 10$
10^2
10^3
10^4
0.2
0.1
0.05
0.03
$2m_h$
$m_{h'}$
$2m_{h'}$
0.5 GeV
$T_{\rm Req}$ = 1 GeV
2 GeV
Γ_R<(1 sec)$^{-1}$
β_R [eV]
m_R [TeV]
10^3
10^2
10
1
0.1
10^{-2}
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2

Complete thermal history



Phenomenology

Consider a generic heavy mediator of mass M bridging the two sectors with a coupling g such that $\langle \sigma_{\rm portal} v \rangle \sim g^4 T^2/(64\pi M^4)$

Then requiring decoupling of the two sectors before reheaton decay gives a week constrain:

$$\frac{M}{g} \gtrsim 5 \text{ TeV} \left(\frac{75}{g_{*R\rm eq}}\right)^{1/8} \left(\frac{200}{g_{*sR\rm fo}^{\rm tot}}\right)^{3/4} \left(\frac{m_R}{700 \text{ GeV}}\right)^{3/4}$$

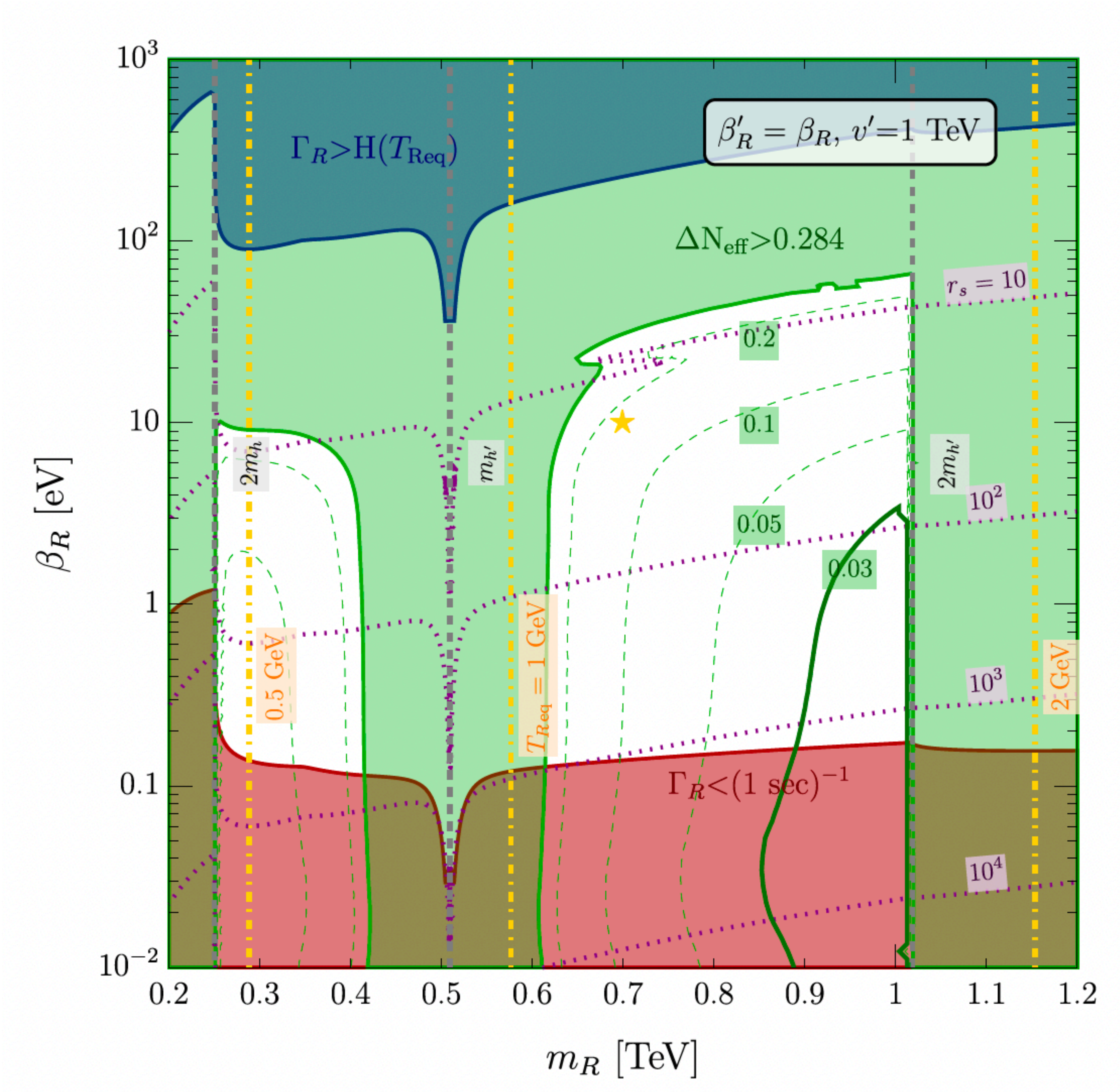
Higgs portal: $\lambda_{HH'} |H|^2 |H'|^2$

$$\lambda_{HH'} < 11 \left(\frac{g_{*\rm Req}}{75}\right)^{1/4} \left(\frac{g_{*sR\rm fo}^{\rm tot}}{200}\right)^{3/2} \left(\frac{700 \text{ GeV}}{m_R}\right)^{3/2} \left(\frac{v'}{1 \text{ TeV}}\right) \left(\frac{y_c}{y'_f}\right)$$

(for $c\bar{c} \to f'\bar{f}'$ scattering)

Phenomenology

Precision $N_{\rm eff}$ measurements with future experiments such as CMB-S4, CMB-HD, MegaMapper, etc



Final remarks

- Can this coincidence help us select baryogenesis mechanisms for a given DM model, and vice versa?
- Are there dynamical mechanism that can directly relate the two energy densities?
- More interesting phenomenology with dark BBN?

Thank you!