Hyper-stealth dark matter

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(image credit: Invoke AI/Dreamshaper XL v2 Turbo)

Outline

1. Motivation: composite dark matter

2. Composite dark matter: general properties

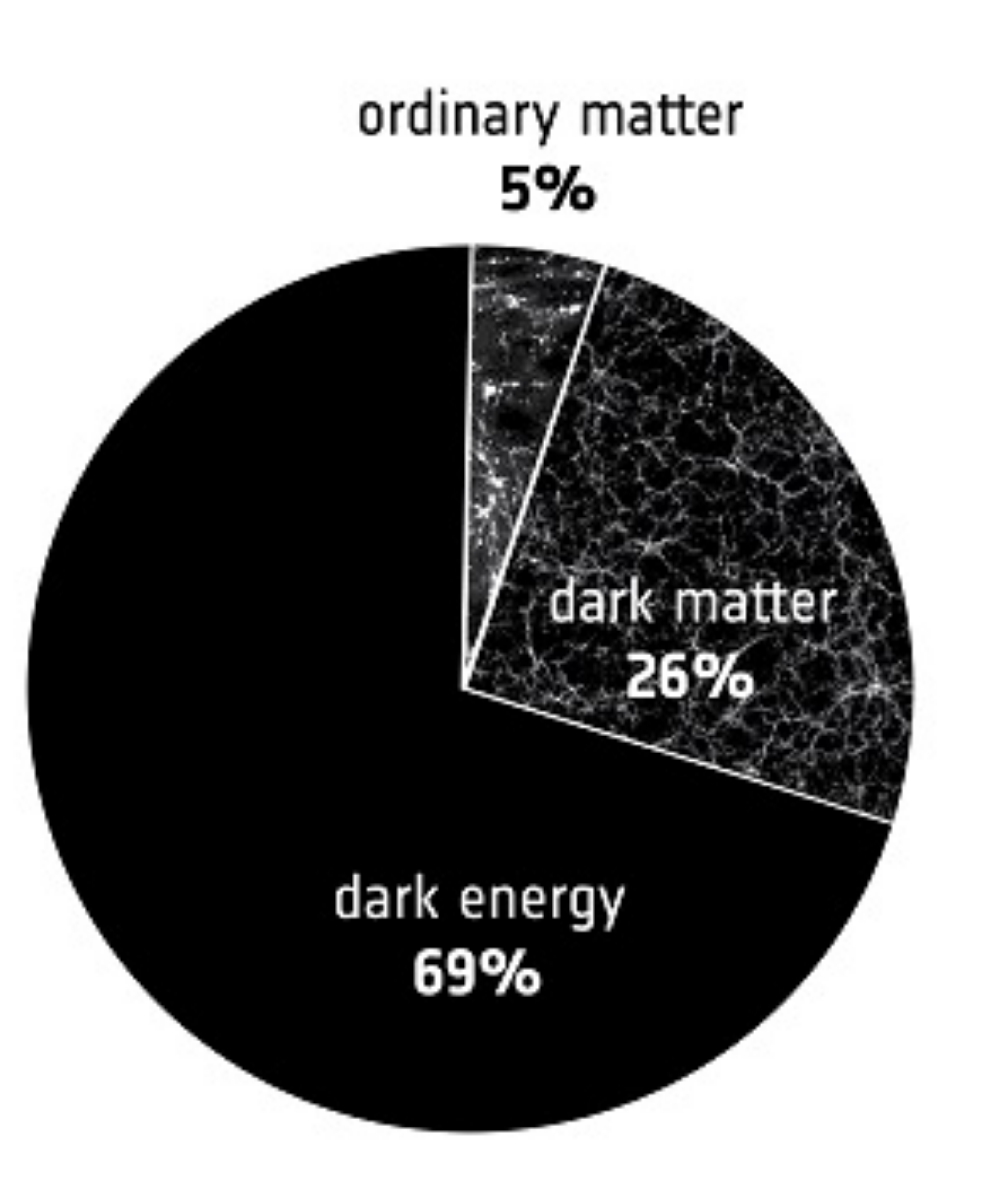
3. Hyper-stealth dark matter model

4. HSDM bounds and phenomenology

Composite DM reviews: G.D. Kribs and ETN, Int. J. Mod. Phys. A31 (2016) arXiv:1604.0462
J.M. Cline, Les Houches 2021 lectures, arXiv:2108.10314
"Stealth dark matter": T. Appelquist et al., PRD 92 (2015), arXiv:1503.04203
Hyper-stealth dark matter: G.T. Fleming, G.D. Kribs, ETN, D. Schaich, and P.M. Vranas, arXiv:2409.XXXXX

1. Motivation: composite dark matter

Cosmic coincidence



(image credit: ESA)

- We only have direct evidence of dark matter's gravitational effects. *What if it has no interactions with us, just gravity*?
- This hypothesis leads to the cosmic coincidence problem: why are DM and ordinary matter abundance not different by orders of magnitude?
- DM interaction with the Standard Model is motivated. But, must preserve key properties: cosmic stability and neutrality (i.e. still "dark" enough to avoid other constraints.)

Dark matter and primordial asymmetry

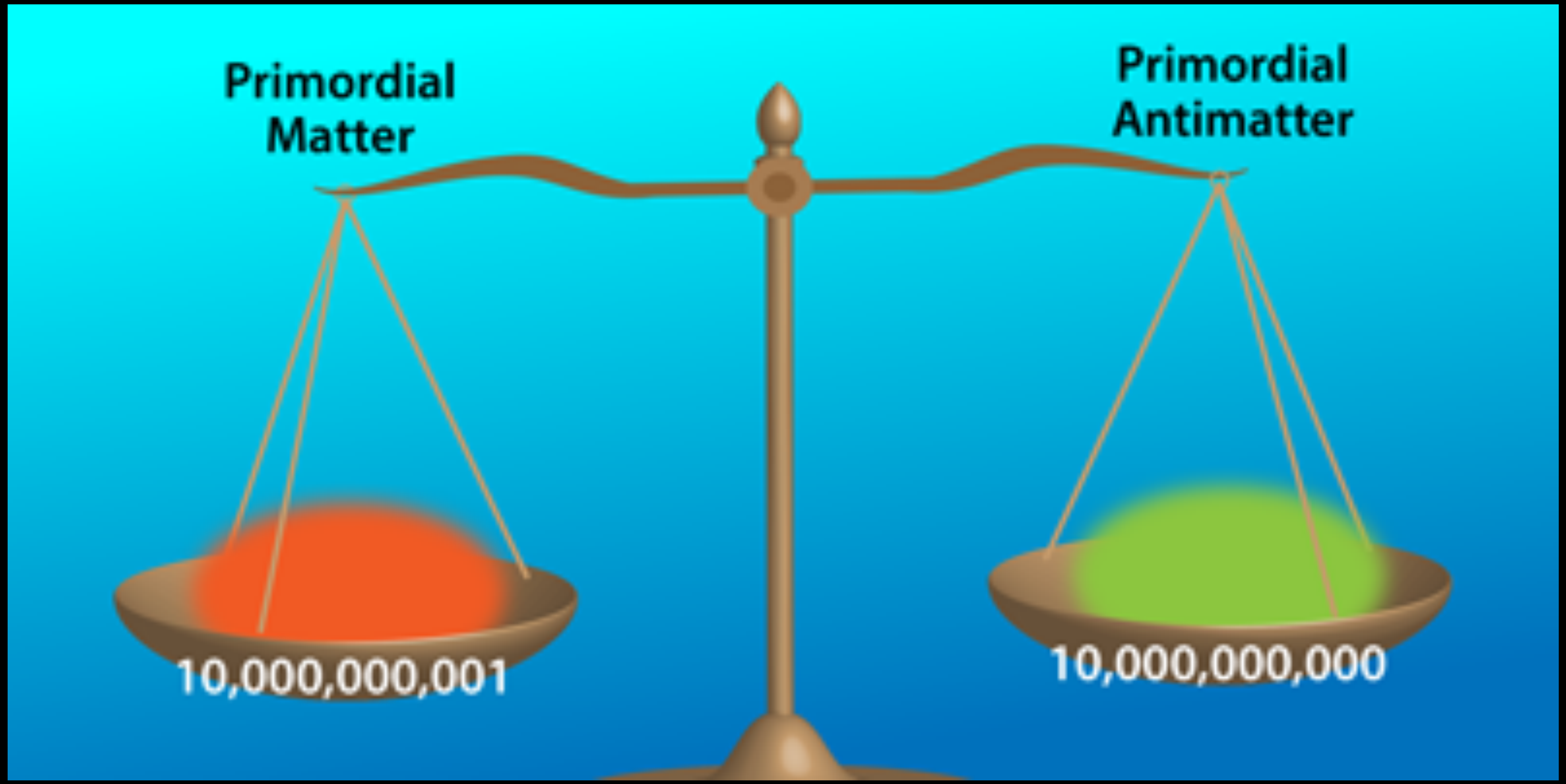
- Abundance of ordinary matter is set by *asymmetry*: slightly more matter than antimatter is produced, efficient annihilation in early universe.

- Primordial asymmetry in baryon number:

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$$

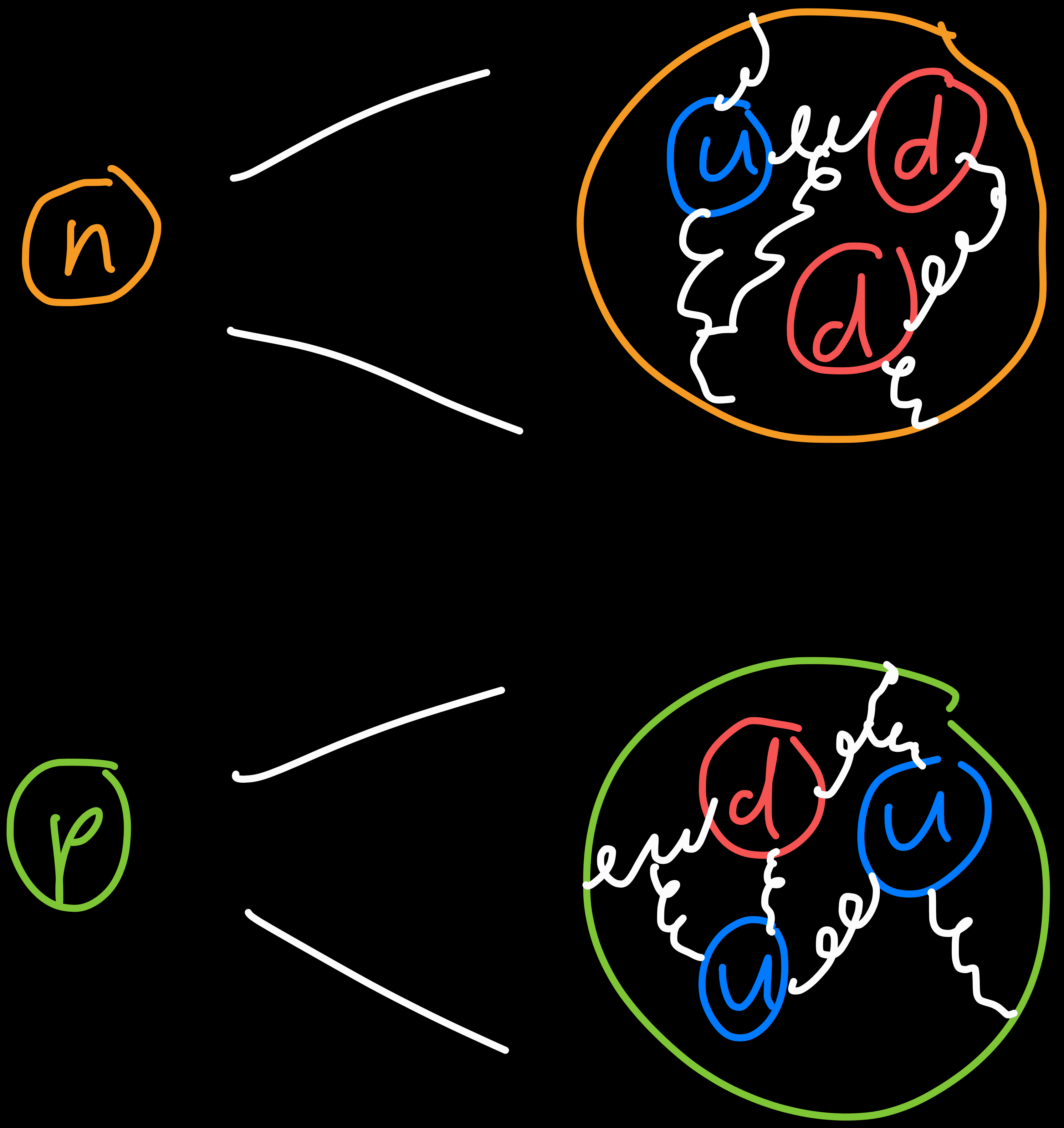
- If dark matter carries another symmetry number X, and there is DM/SM interaction, then we can naturally have $n_X \sim n_B$!

- Nice motivation for cosmic coincidence; requires $m_X \sim 5\ m_B \sim 5$ GeV in simplest case.



(image credit: APS/Alan Stonebraker)

Invitation: the proton and neutron

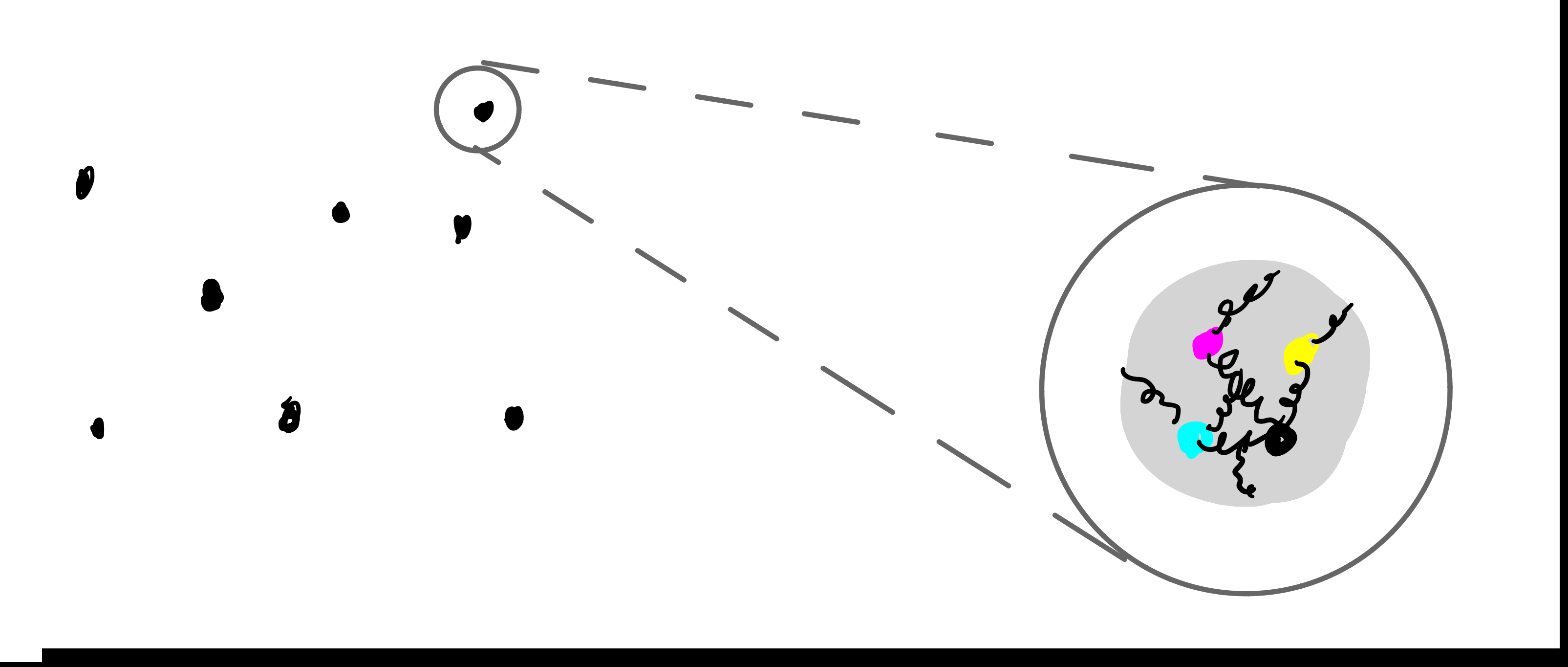


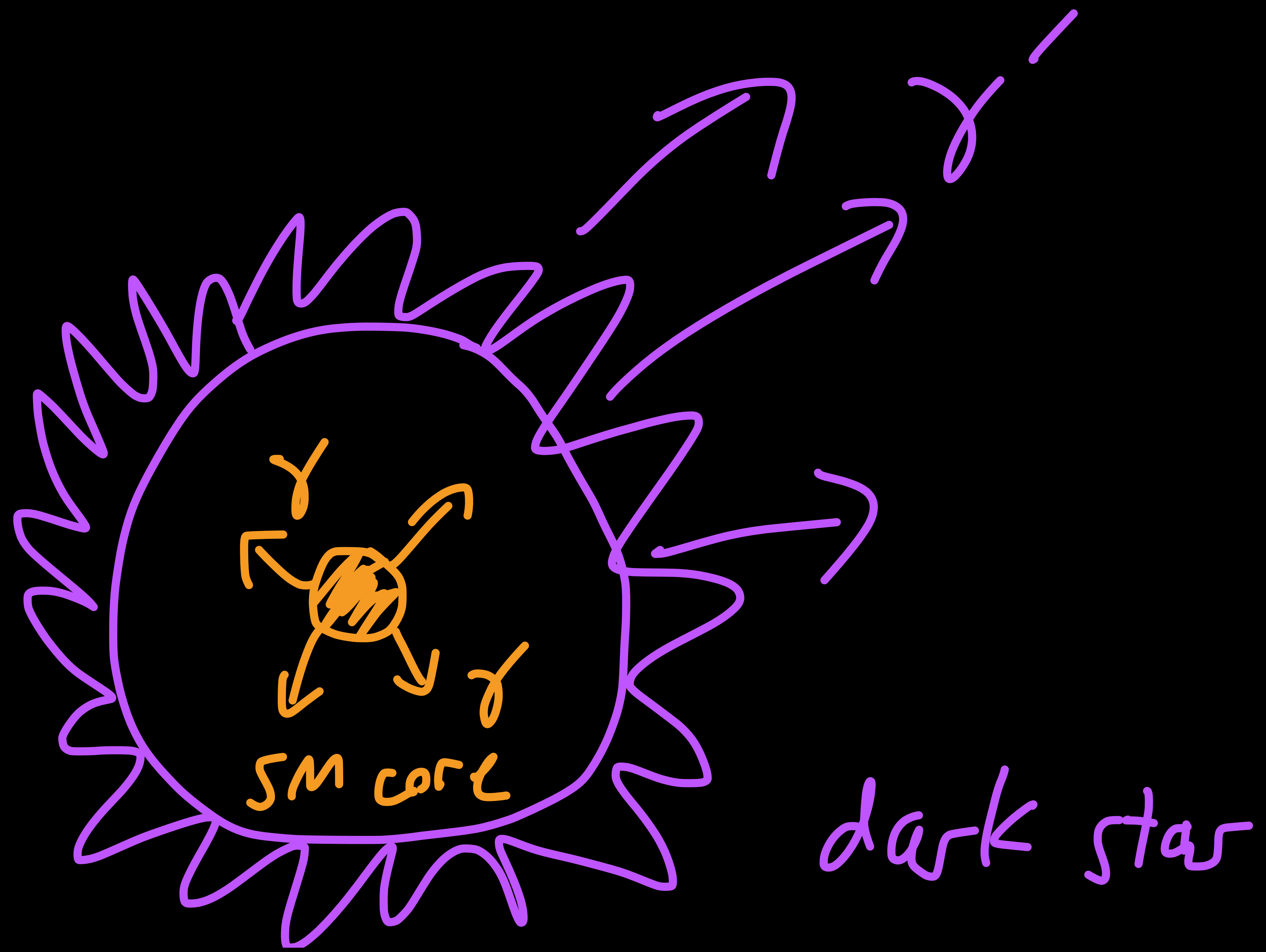
u: $Q = +\frac{2}{3}e$ d: $Q = -\frac{1}{3}e$

- Familiar composite states that make up our everyday world!
- Neutrons are neutral, even though the up/down quarks are charged. Neutrons do interact with light, but heavily suppressed!
- Protons are stable, due to “accidental symmetry”: proton decay ~ triple quark decay.
- A “dark neutron” that is neutral and stable seems like an ideal DM candidate!

(for more, see G.D. Kribs and ETN review, Int. J. Mod. Phys. A31, 2016)

Composite dark matter



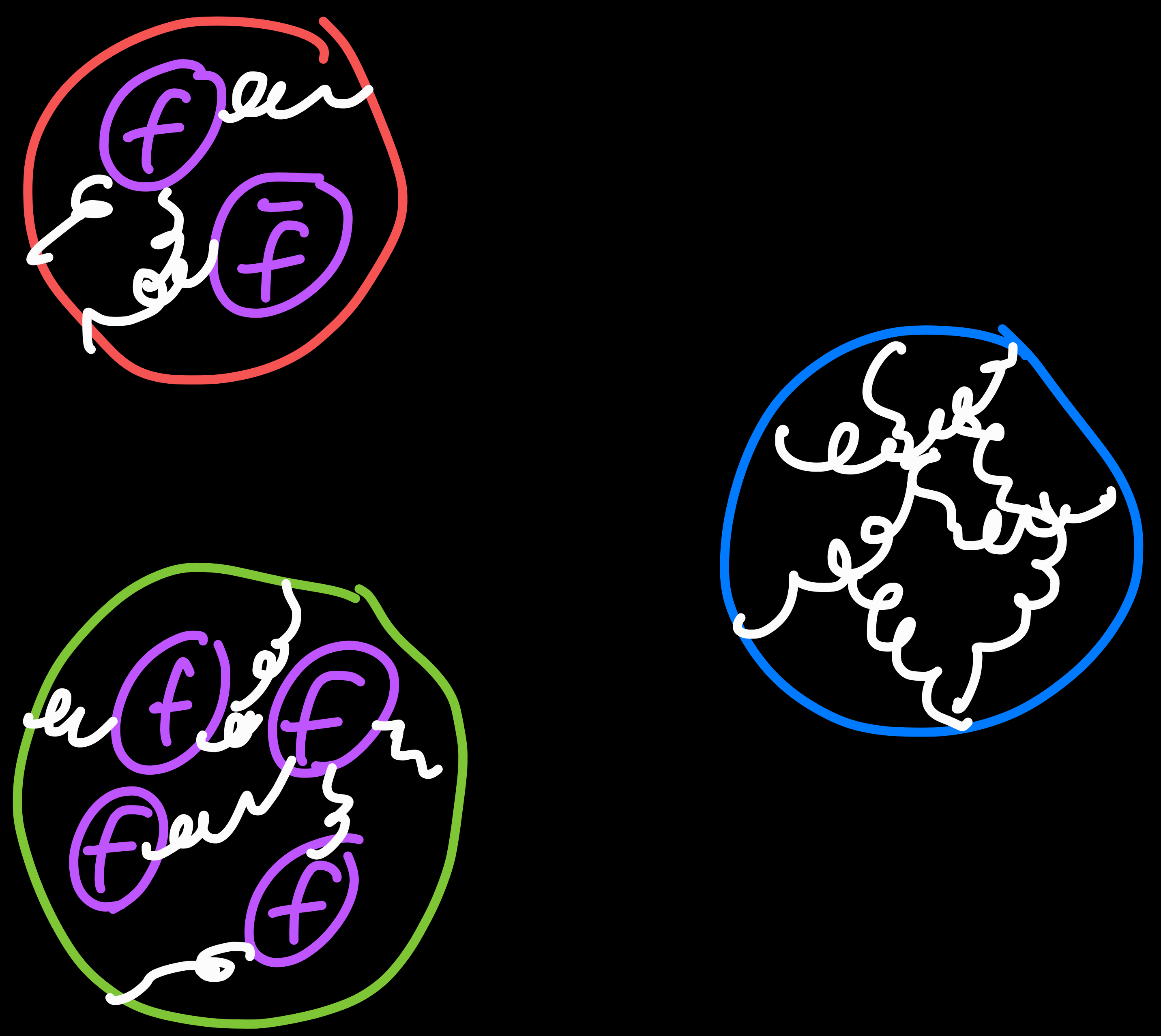


- Dark matter as a strongly-coupled composite bound state of some hidden sector.
- Weakly-bound composites, e.g. “dark atoms”, are possible and interesting too! But, I will focus mainly on strongly-bound composites.
- Well-motivated models with solutions to stability and cosmic coincidence;
- Distinctive experimental signatures, and exotic objects like large “dark nuclei” and even “dark stars”!

2. Composite dark matter: general properties

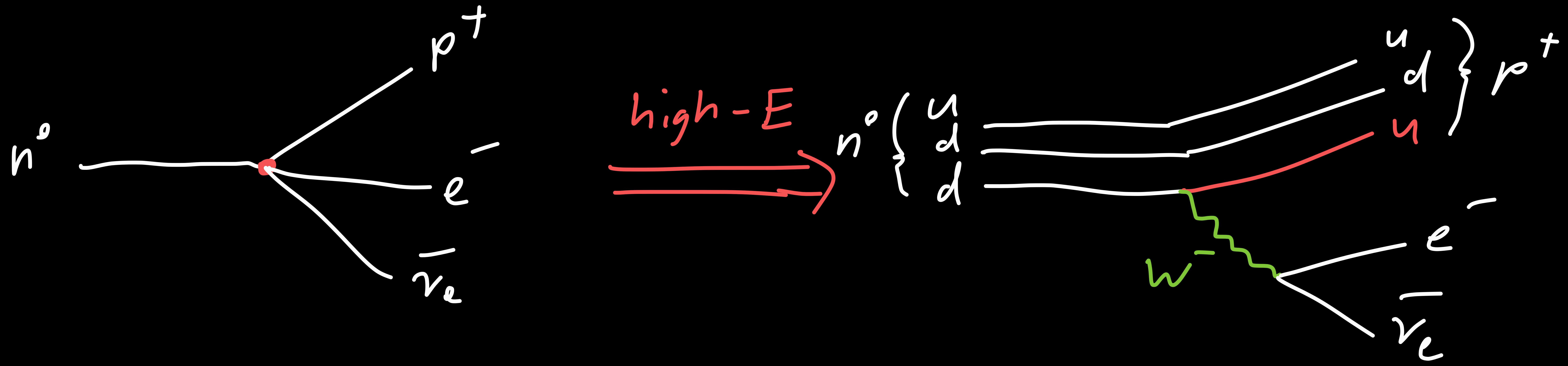
Types of cDM candidates

- Given a confining hidden gauge theory, what types of cDM candidates can arise?
- Roughly, three classes:
  - 1. Mesons ($\bar{f}f$)
  - 2. Baryons (fff…)
  - 3. Glueballs (no f's!)
- All have <u>suppressed</u> SM interactions, even if quarks are charged. (Glueballs are generally the *most* suppressed.)
- SM interactions are motivated, but they can also lead to *decay* - we must make sure the DM candidates remain stable enough!



Compositeness and EFT: "integrating in"

- Something unusual happens in composite theories: as we remove some particles from the theory at the confinement scale Λ_c, new ones appear below the cutoff as well!

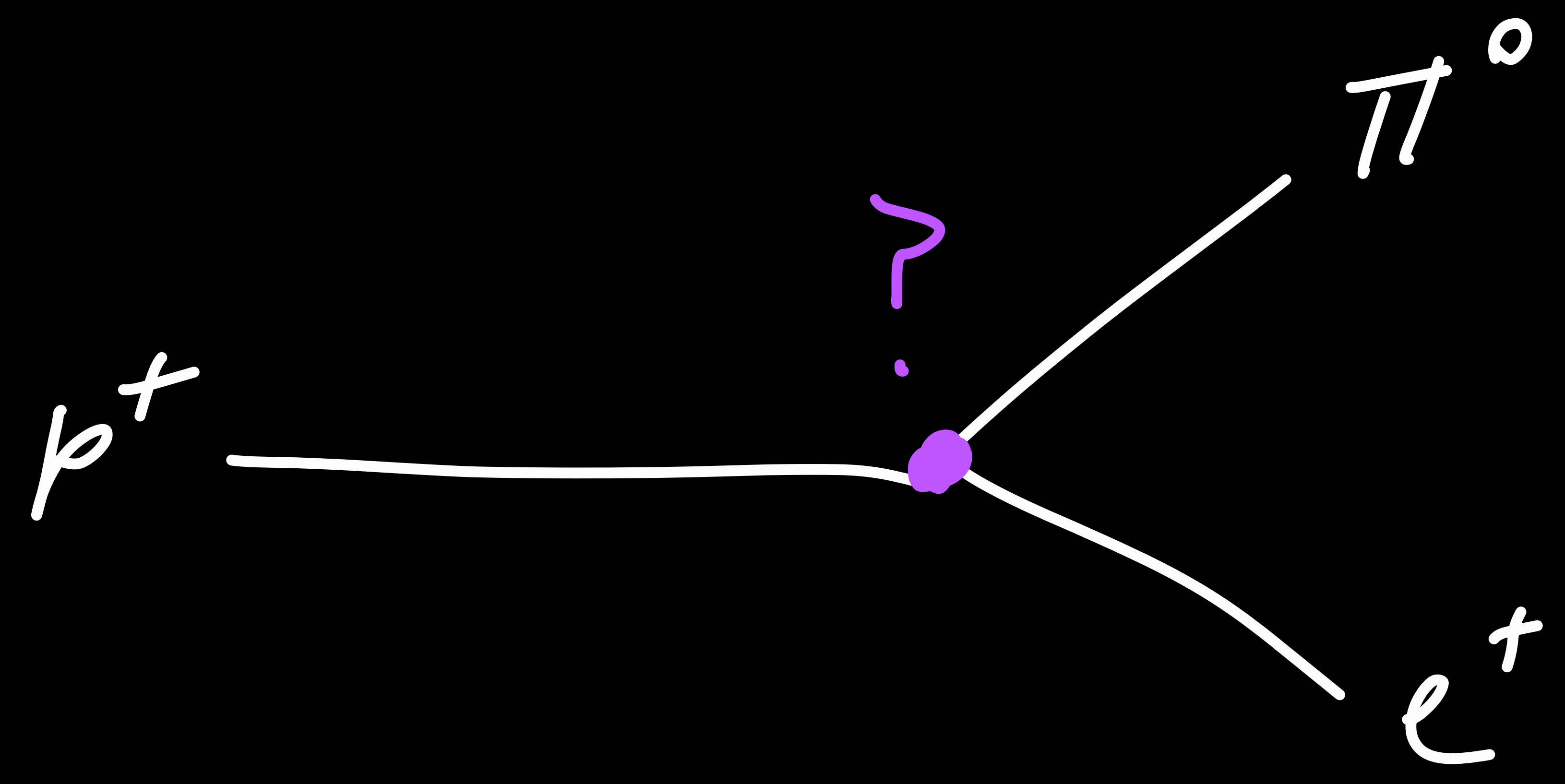


- This can lead to unexpected suppressions and "accidental" symmetries, compared to naive expectations in the low-energy theory of the composites.

Effective stability and accidental symmetry

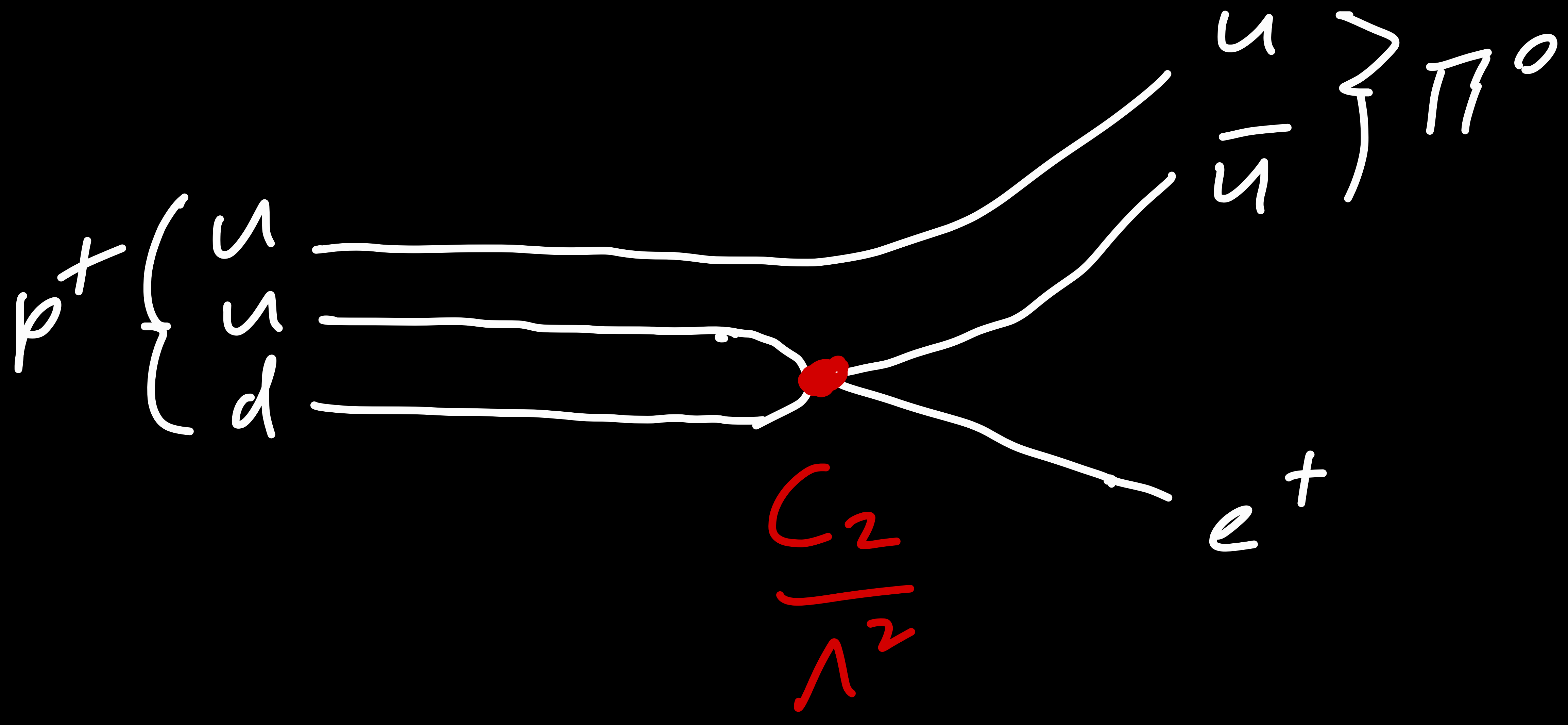
- Example: proton stability. Consider the process $p^+ \rightarrow e^+ \pi^0$. Could be mediated by an effective operator:

$$\mathcal{O}_{\mathrm{p-decay,naive}} = \frac{C_1}{\Lambda^0} \bar{p} e \pi$$



- But if Λ >> 1 GeV, the proton and pion are not fundamental! We need a quark-level operator. p+ ~ (uud) and π0 ~ (ūu), so

$$\mathcal{O}_{\mathrm{p-decay}} = \frac{C_2}{\Lambda^2} \bar{u}^c u \bar{d}^c e$$

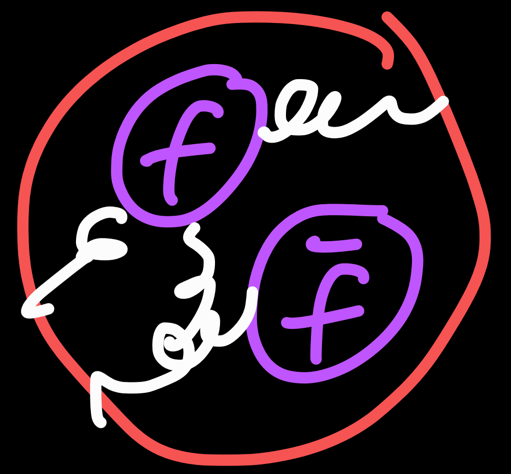


- "Accidental symmetry": proton decay (baryon-number violation) comes from only irrelevant operators. Consequence of compositeness!

Stability of cDM candidates

- In general, decay width $\Gamma = 1/\tau$ from a decay-mediating operator: $\mathcal{O} \sim \frac{1}{\Lambda^m} \Rightarrow \Gamma \sim \frac{M_{\rm DM}^{2m+1}}{\Lambda^{2m}}.$
  - Required lifetime is longer than the age of the universe, ~ 10^{17} s
    —> $\Gamma < 10^{-42}$ GeV. *(Bound can be orders of magnitude stronger from experiments, depending on decay final states.)*
  - **Dimensional analysis rules:** Each operator is a term in the Lagrangian, [L]=4. Count mass dimension of fields, add powers of Λ to get total [O]=4.

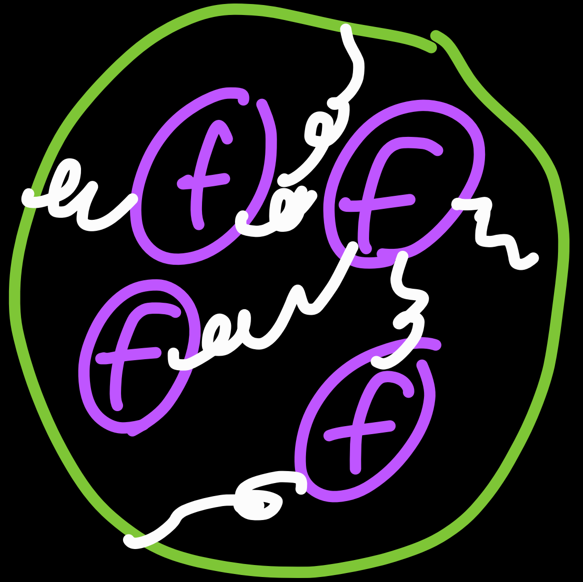
$$[\psi] = \frac{3}{2}; \quad [H] = 1; \quad [A_\mu] = [\partial_\mu] = 1 \Rightarrow [F_{\mu\nu}] = 2.$$



- Meson decay: $\frac{1}{\Lambda}\bar{\psi}\psi H^\dagger H$ $\qquad$ $\frac{1}{\Lambda}\bar{\psi}\sigma^{\mu\nu}\psi F_{\mu\nu}$

- With only one power of Λ ("dimension 5"), even setting $\Lambda = M_{pl} \sim 10^{19}$ GeV is not sufficient to guarantee DM cosmic stability!

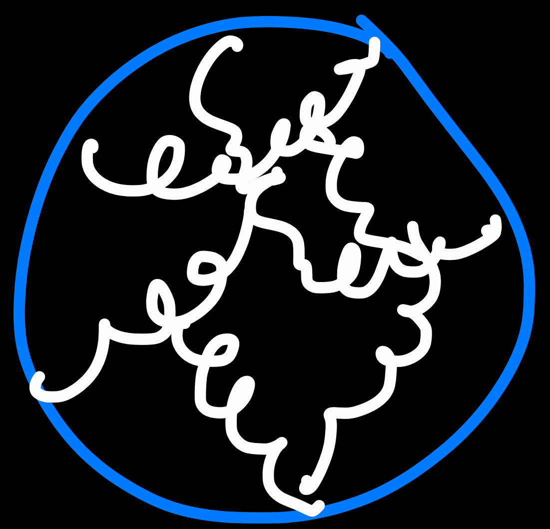
Stability of cDM candidates II



- Baryon decay: consider 3-body decay B_d —> π_d + X;

$$(\psi)^N \to (\bar{\psi}\psi)X \quad \Rightarrow \quad \frac{1}{\Lambda^{3N_c/2+d_X-4}}(\bar{\psi}\psi)^{N_c/2}X$$

- For $N_c > 2$, suppressed by at least $1/\Lambda^2$; enough for DM stability at Planck scale, better as Nc increases. Automatic stability for "dark baryon" cDM!



- Glueball decay:

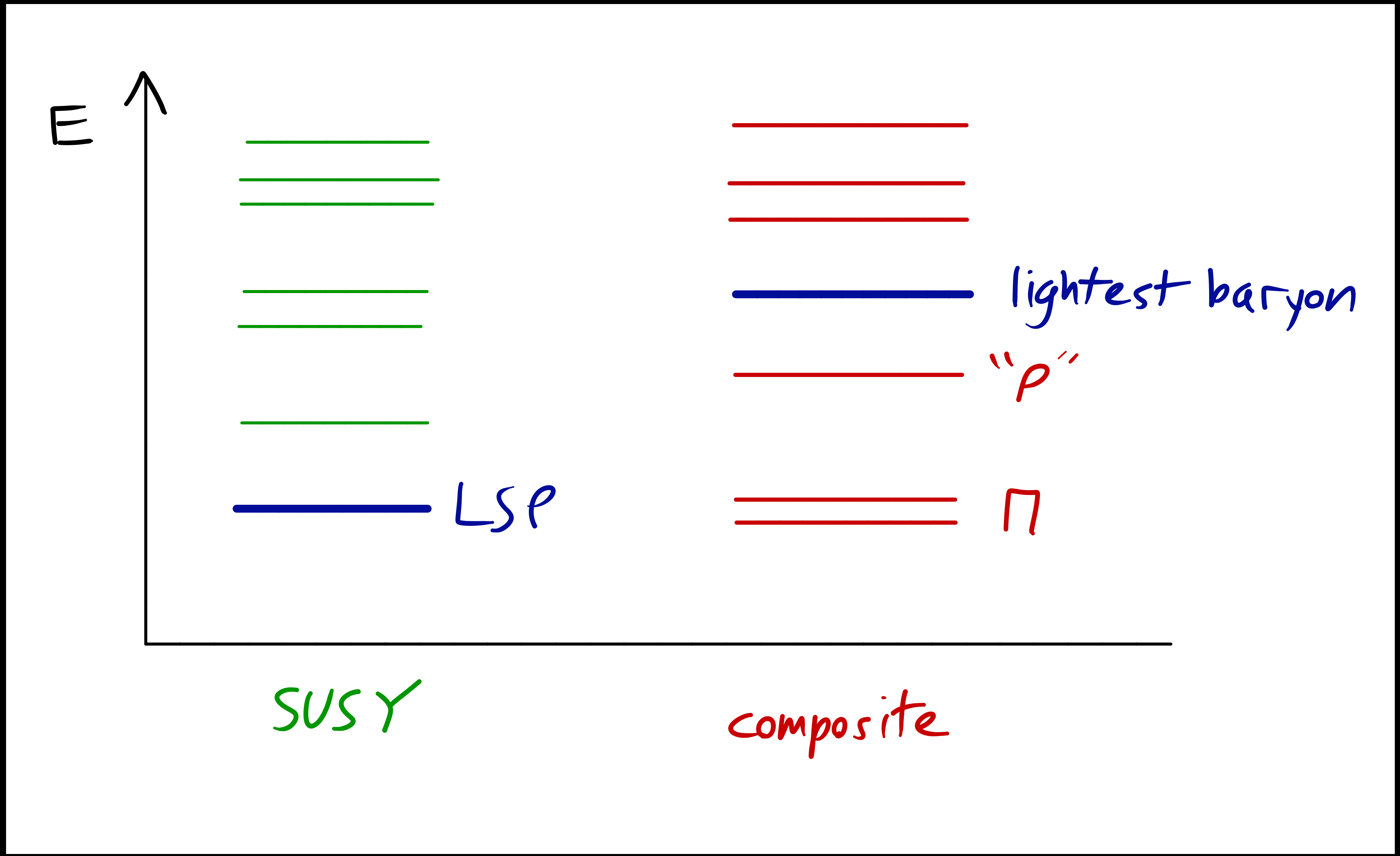
$$\frac{1}{\Lambda^2}G_{\mu\nu}G^{\mu\nu}H^\dagger H \qquad \frac{1}{\Lambda^4}\mathrm{Tr}[G_{\mu\nu}G^{\mu\nu}]\mathrm{Tr}[F_{\kappa\sigma}F^{\kappa\sigma}]$$

- Also easily stable; suppressed by (Λ^2 M_h^2) or Λ^4. However, *all interactions are similarly suppressed* - very hard to detect experimentally (and explaining cosmic coincidence may be more difficult.)

Composite DM spectrum

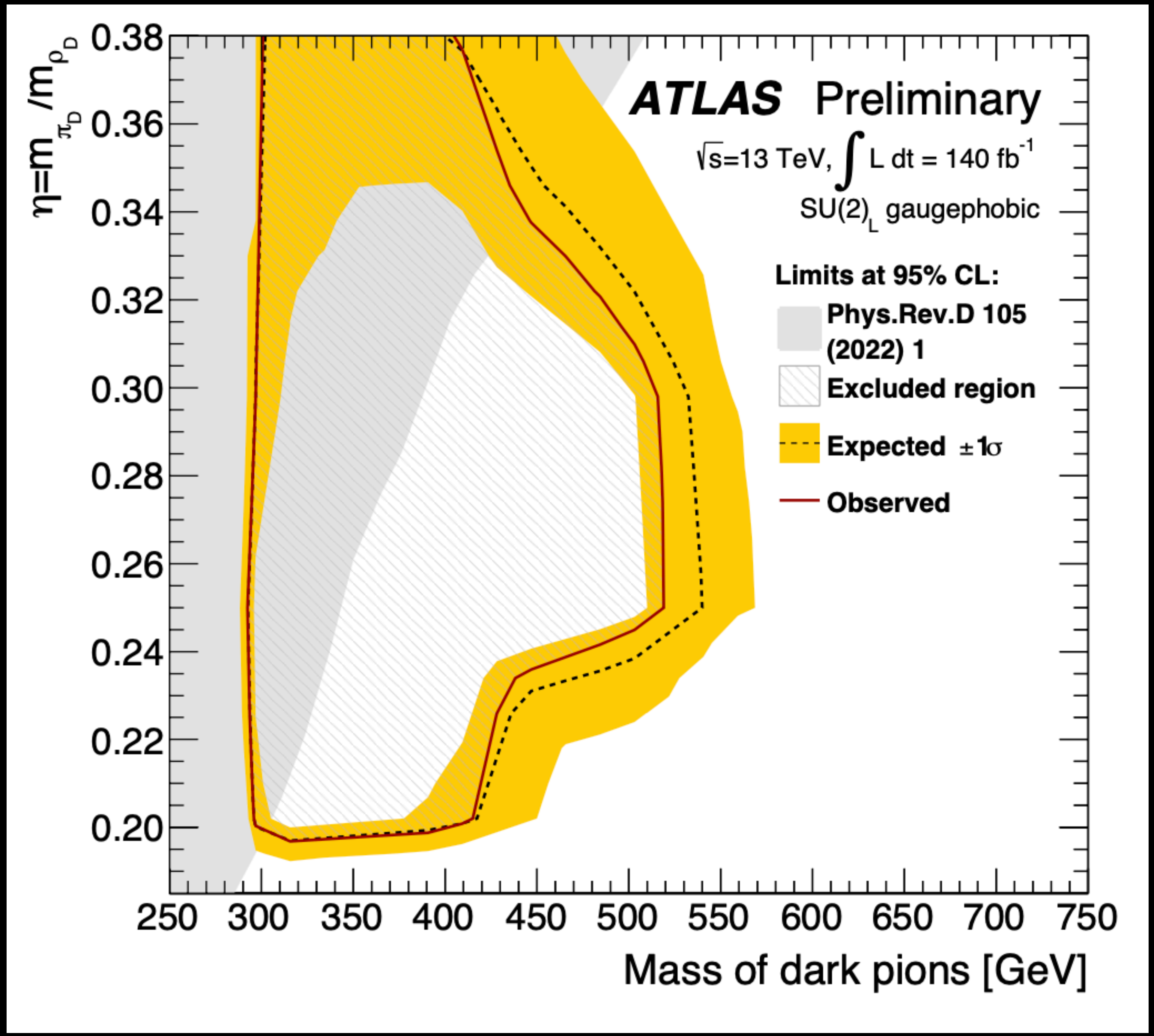
- In BSM scenarios, common for DM to be the *lightest* particle of some new sector to avoid decay, e.g. lightest supersymmetric partner in SUSY theories.

- For baryon-like cDM, stabilized by accidental symmetry; expect other lighter particles in the spectrum (especially at large N_D: baryons have N_D dark quarks, mesons have 2!)

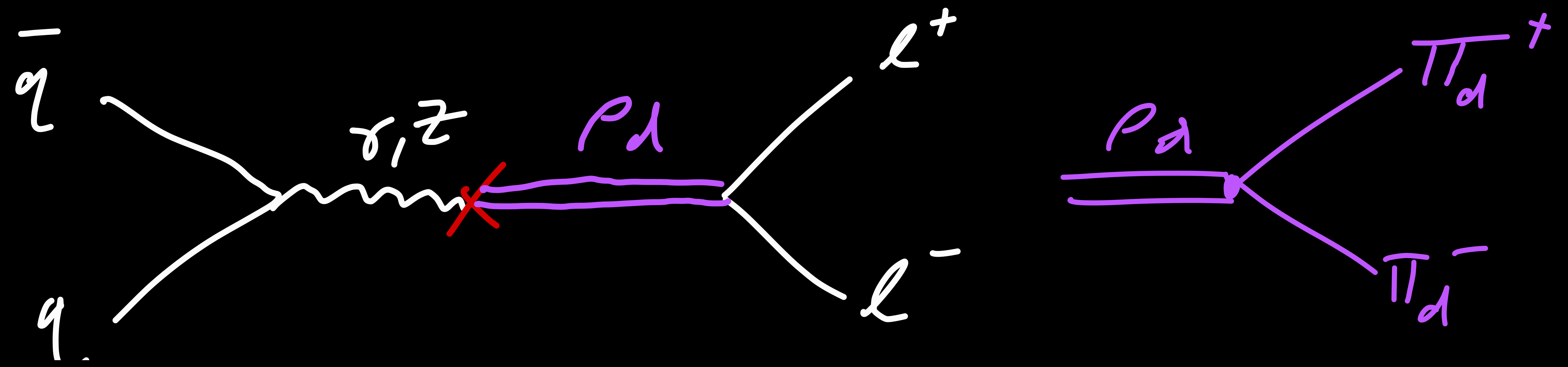


Bounds on charged dark mesons

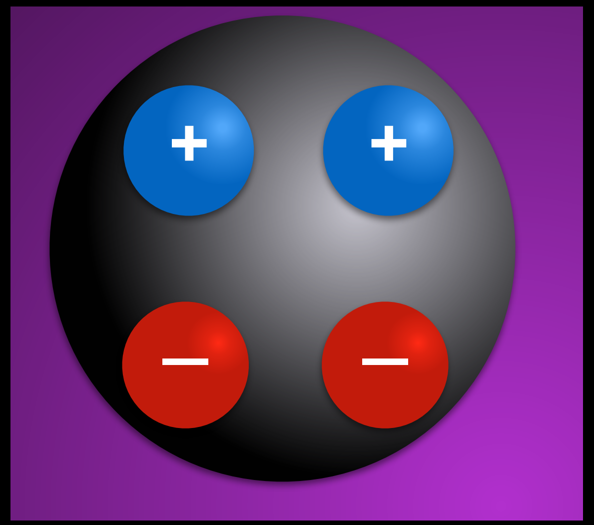
ATLAS experiment, ATLAS-CONF-2023-021



*see e.g. G.D. Kribs, A.O. Martin, B. Ostdiek and T. Tong, arXiv:1809.10184



- "*Everything not forbidden is compulsory*" - if DM is a neutral baryon w/ charged constituents, there will also be charged composites. From last slide, charged mesons are lightest and can give strong constraints.
- Search specifics and reach depend on details*, e.g. decay width of dark vector ρ_d into dark pions π_d. LHC searches have good reach to ~ 500 GeV in parts of parameter space.
- LEP-II direct production of charged π_d is very robust, and restricts charged π_d > 100 GeV (—> somewhat higher dark-baryon mass bound.)



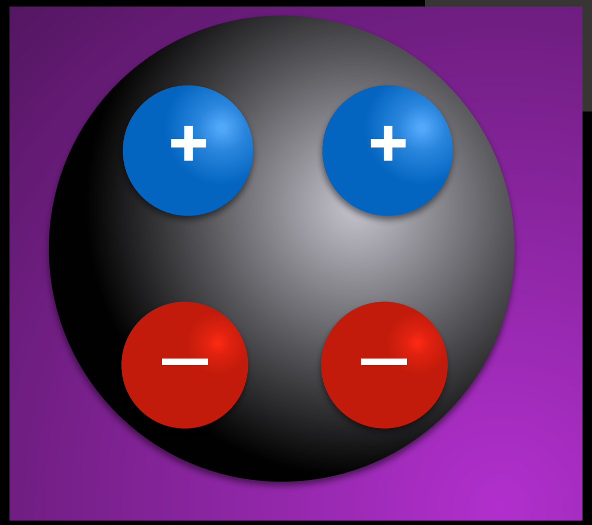
Example: "Stealth dark matter"

- Four dark fermions, in two pairs with equal and opposite electric charge Q=±1; one light pair (—> DM), one heavy pair. DM candidate is neutral with two +1, two -1 light dark fermions.
- Electroweak charges are also present, to mediate decay of other non-DM composite states.
- Field content to the right. Note $SU(2)_R$ custodial symmetry to suppress electroweak precision effects.

T. Appelquist et al (LSD Collab), 1503.04203

Field	$SU(N_D)$	$(SU(2)_L, Y)$	Q
$F_1 = \begin{pmatrix} F_1^u \\ F_1^d \end{pmatrix}$	$\mathbf{N}$	$(\mathbf{2}, 0)$	$\begin{pmatrix} +1/2 \\ -1/2 \end{pmatrix}$
$F_2 = \begin{pmatrix} F_2^u \\ F_2^d \end{pmatrix}$	$\overline{\mathbf{N}}$	$(\mathbf{2}, 0)$	$\begin{pmatrix} +1/2 \\ -1/2 \end{pmatrix}$
F_3^u	$\mathbf{N}$	$(\mathbf{1}, +1/2)$	$+1/2$
F_3^d	$\mathbf{N}$	$(\mathbf{1}, -1/2)$	$-1/2$
F_4^u	$\overline{\mathbf{N}}$	$(\mathbf{1}, +1/2)$	$+1/2$
F_4^d	$\overline{\mathbf{N}}$	$(\mathbf{1}, -1/2)$	$-1/2$

Stealth DM: Bounds on parameter space

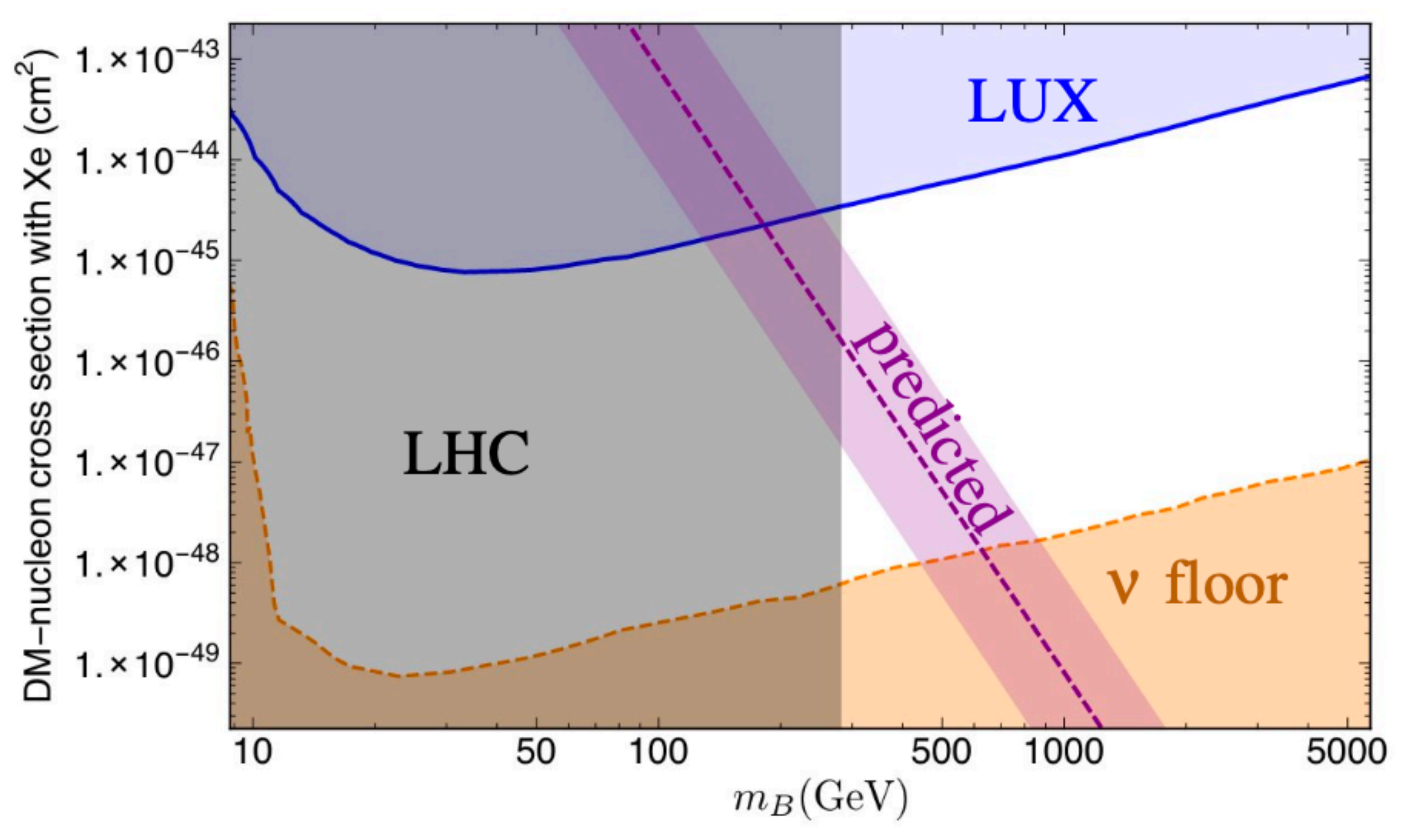


- Stealth DM has photon-mediated interactions with ordinary matter!
- "Form factor" (momentum-dependent) interactions, or think of in terms of effective ops suppressed by stealth confinement scale
- Discrete symmetries of stealth DM require only two-photon exchanges. Leading operator is the *EM polarizability*:

$$\mathcal{L} \supset \frac{1}{\Lambda^3} \bar{\chi}\chi F_{\mu\nu} F^{\mu\nu}$$

- Lattice calculation of the SU(4) baryon χ polarizability leads to bounds on the right from direct detection.

- Resulting dark matter direct-detection cross section shown below (Xe target.) At TeV scale, below the irreducible ν background.
- Even ignoring direct detection, charged particle bounds require mass > few hundred GeV! Few-GeV "asymmetry-motivated" region seems inaccessible…



J. Cline, 2108.10314; adapted from T. Appelquist et al (LSD Collab), 1503.04205

3. Hyper-stealth dark matter

Low-energy effective theory

Field	$\mathrm{SU}(N_D)$	$(SU(2)_L, Y)$	T_3	$\mathrm{U}(1)_{\mathrm{em}}$
ψ_n	$\mathbf{N}$	$(\mathbf{1}, 0)$	0	0
ψ'_n	$\overline{\mathbf{N}}$	$(\mathbf{1}, 0)$	0	0

$$\Psi_n \equiv \begin{pmatrix} \psi_n \\ (\psi'_n)^\dagger \end{pmatrix}$$

$$\begin{aligned} \mathcal{L} \supset\ & c_s \frac{\overline{\Psi}_n \Psi_n H^\dagger H}{\Lambda} + c_G \frac{\mathrm{Tr}[G_{\mu\nu} G^{\mu\nu}] H^\dagger H}{\Lambda^2} \\ & + c_Z \frac{\overline{\Psi}_n \gamma_\mu \Psi_n (H^\dagger i D^\mu H + \mathrm{h.c.})}{\Lambda^2} \\ & + c'_Z \frac{\overline{\Psi}_n \gamma_\mu \gamma^5 \Psi_n (H^\dagger i D^\mu H + \mathrm{h.c.})}{\Lambda^2} \end{aligned}$$

- Single light Dirac fermion Ψ_n, total SM singlet, plus $SU(N_D)$ gauge interaction. SU(4) as "default" case (as in stealth DM), but general here.
- Assume UV completion couples to electroweak. No direct coupling to QCD or SM fermions ($G_{\mu\nu}$ = $SU(N_D)$ field strength.)
- *Not* an exhaustive list of operators, but all pheno-relevant ops given UV model to be used.

Low-energy effective theory (II)

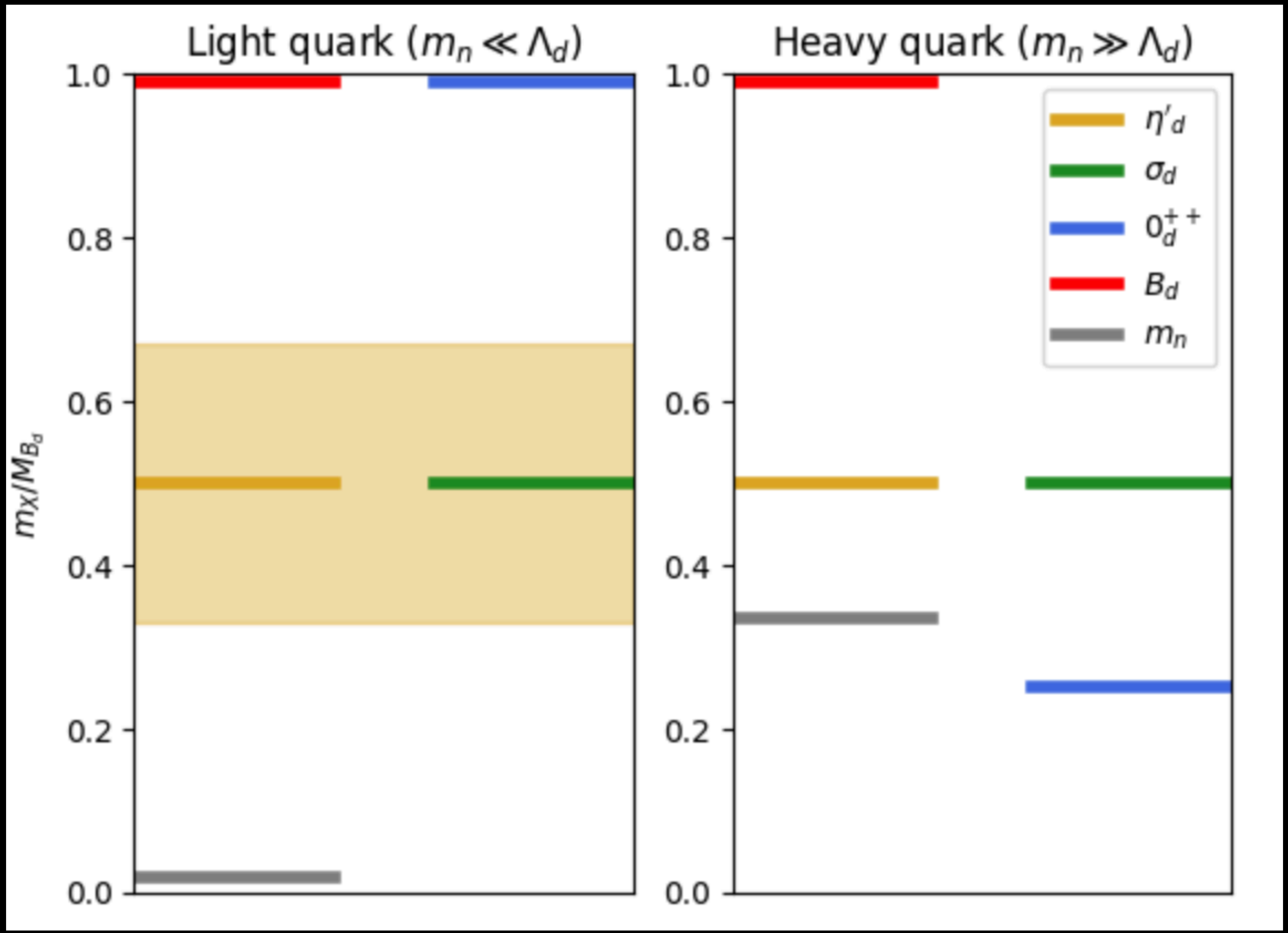
- Going through operators: c_S and c_G mediate scalar meson and glueball decays.
- c_Z gives dominant contribution to DM direct detection. (c_S and c_G also contribute, but generally subleading.)
- c_Z' mediates pseudoscalar meson decay; it is *parity violating* (opposite parity to the Higgs current.)

$$\mathcal{L} \supset c_s \frac{\overline{\Psi}_n \Psi_n H^\dagger H}{\Lambda} + c_G \frac{\mathrm{Tr}[G_{\mu\nu} G^{\mu\nu}] H^\dagger H}{\Lambda^2} + c_Z \frac{\overline{\Psi}_n \gamma_\mu \Psi_n (H^\dagger i D^\mu H + \mathrm{h.c.})}{\Lambda^2} + c_Z' \frac{\overline{\Psi}_n \gamma_\mu \gamma^5 \Psi_n (H^\dagger i D^\mu H + \mathrm{h.c.})}{\Lambda^2}$$

(*see also “Large N-ightmare DM”, L. Morrison, S. Profumo and D.J. Robinson, arXiv:2010.03586 - one-flavor theory, but no SM portal.)

Spectrum and masses

- This is a “one-flavor” QCD-like dark sector, which has some highly distinctive features*:
- 1) No light pions: chiral symmetry $U(1)_L \times U(1)_R$ is broken purely by anomaly. “Dark eta-prime” η_d is the lightest bound state, but not a pseudo-Goldstone boson so can’t be too light vs. dark baryon B_d.
- 2) High-spin DM: due to Fermi statistics, the dark baryon B_d ground state has spin $N_D/2$. (Pheno consequences of this seem to be pretty mild, but maybe there are interesting facets we haven’t thought of!)
- Aside from the η_d, other relevant bound states for pheno are the lightest scalar (CP-even) meson σ_d, and the lightest glueball 0^{++}_d.



- A mixture of lattice QCD results* and a bit of hand-waving results in the (rough) spectra given above. Large-N_D scaling formulas are used to extrapolate from $N_D=3$ (shown); baryon splits further from mesons as N_D increases.

- Key parameter to determine the spectrum is ratio m_n / Λ_D, dark quark mass vs. dark confinement scale. "Light-quark" scenario $m_n << \Lambda_D$ has compressed spectrum in 1-flavor case (no dark pions.) "Heavy-quark" scenario $m_n >> \Lambda_D$ results in very light glueballs, and will be more heavily constrained.

*T. DeGrand and ETN, arXiv:1910.08561

Hyper-stealth dark matter

- UV complete: add "equilibration sector" of more SU(N_D)-charged fermions, with electroweak interactions. Heavy "lepton-like" doublet l_d + singlet e_d.
- After EWSB, charge-neutral component of l_d can mix with n_d, giving rise to effective ops from above.
- This is the hyper-stealth dark matter model. Can be viewed as charge reassignment of stealth DM, with 1 light + 3 heavy vs. 2+2. "Hyper stealth" since now all light states are SM singlet!

	Field	$SU(N_D)$	$(SU(2)_L, Y)$	T_3	$U(1)_{em}$
dark matter sector	n_d	$\mathbf{N}$	$(\mathbf{1}, 0)$	0	0
	n'_d	$\overline{\mathbf{N}}$	$(\mathbf{1}, 0)$	0	0
dark equilibration sector	l_d	$\mathbf{N}$	$(\mathbf{2}, -\frac{1}{2})$	$\begin{pmatrix} +\frac{1}{2} \\ -\frac{1}{2} \end{pmatrix}$	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$
	l'_d	$\overline{\mathbf{N}}$	$(\mathbf{2}, +\frac{1}{2})$	$\begin{pmatrix} +\frac{1}{2} \\ -\frac{1}{2} \end{pmatrix}$	$\begin{pmatrix} +1 \\ 0 \end{pmatrix}$
	e_d	$\mathbf{N}$	$(\mathbf{1}, -1)$	0	-1
	e'_d	$\overline{\mathbf{N}}$	$(\mathbf{1}, +1)$	0	+1

Matching

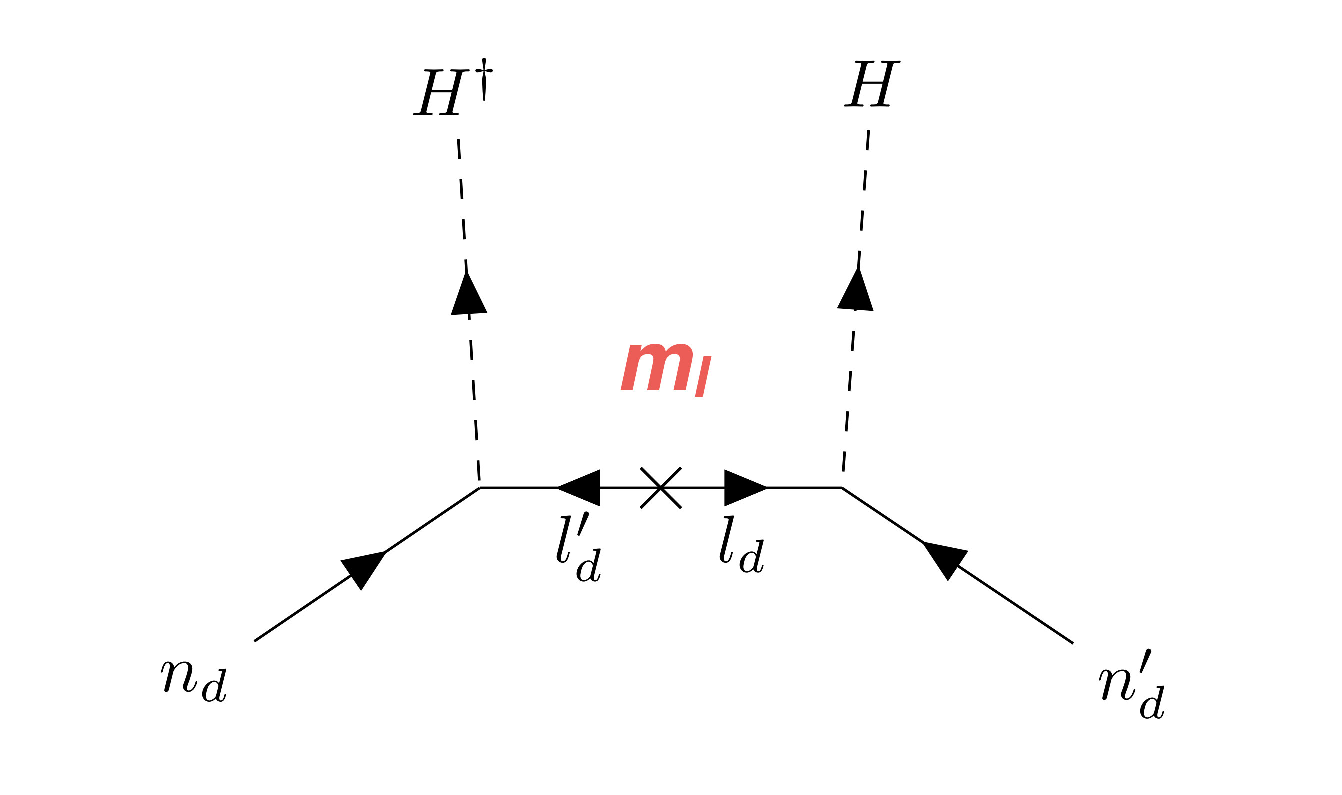
- Working in two-component notation: introduce vector-like masses for l_d, e_d, and "off-diagonal" Yukawa couplings including n_d.

$$\mathcal{L} \supset m_{l,0}\epsilon_{ij} l_d^i l_d'^j - m_{e,0} e_d e_d' + h.c.$$

- Mass diagonalization gives two neutral fermions Ψ_n, Ψ_N (Q=0) and two charged Ψ_{E1}, Ψ_{E2} (Q=-1).

$$\mathcal{L} \supset \quad y_{ln}\epsilon_{ij} l_d^i H^j n_d' + y_{le} l_d \cdot H^\dagger e_d' \\ - y_{le}' \epsilon_{ij} l_d'^i H^j e_d - y_{ln}' l_d' \cdot H^\dagger n_d + h.c.$$

- Take **$m_{l,0}$ and $m_{e,0}$ ~ m_{eq} >> $m_{n,0}$**. All charged states are heavy; instead of full diagonalization and mixing, we can think of integrating out heavy fields to get our EFT.



- For example, Higgs diagram on the right leads to scalar coupling, identifying Λ ~ m_{eq}:

$$c_s \frac{\overline{\Psi}_n \Psi_n H^\dagger H}{\Lambda} \longrightarrow c_s = -y_{ln} y_{ln}'$$

Matching summary

- Similar matching calculations give rise to the set of results to the right.
- Dimensionless parameter θ (light to heavy fermion mass scale, roughly) is the key small parameter; all couplings go as θ^2. (If you look closely, c_S really goes as $y\theta$, extra enhancement.)
- The Yukawa splitting parameter ε is parity-violating; necessary to obtain the operator c_Z' that leads to η_d' decay.

$$y_{ln} = y(1+\epsilon)$$
$$y'_{ln} = y(1-\epsilon)$$

$$\theta \equiv \frac{yv}{\sqrt{2}m_{\rm eq}}$$

$$\frac{c_Z}{\Lambda^2} = \frac{c_Z}{m_{\rm eq}^2} = \theta^2 \frac{2(1+\epsilon^2)}{\sqrt{g^2+g'^2}v^2} = \frac{\theta^2(1+\epsilon^2)}{2M_Z^2},$$

$$\frac{c'_Z}{\Lambda^2} = \frac{c'_Z}{m_{\rm eq}^2} = \frac{\epsilon^2\theta^2}{M_Z^2},$$

$$\frac{c_s}{\Lambda} = \frac{c_s}{m_{\rm eq}} = -\sqrt{2}\frac{\theta}{v}y = -2\frac{\theta^2}{v}\frac{m_{\rm eq}}{v}.$$

$$\frac{c_G v^2}{\Lambda^2} \simeq \frac{4\alpha_d}{3\pi}\theta^2$$

4. HSDM constraints and phenomenology

Direct detection

- Dominant direct-detection bound is from Z exchange ~ $\alpha^2 c_Z^2 \sim \alpha^2 \theta^4$:

$$\sigma_Z(B_d) = \frac{\mu^2 G_F^2}{2\pi}[(1-4\sin^2\theta_W)Z-(A-Z)]^2 \times N_D^2\theta^4(1+\epsilon^2)^2\frac{v^2}{4M_Z^2}.$$

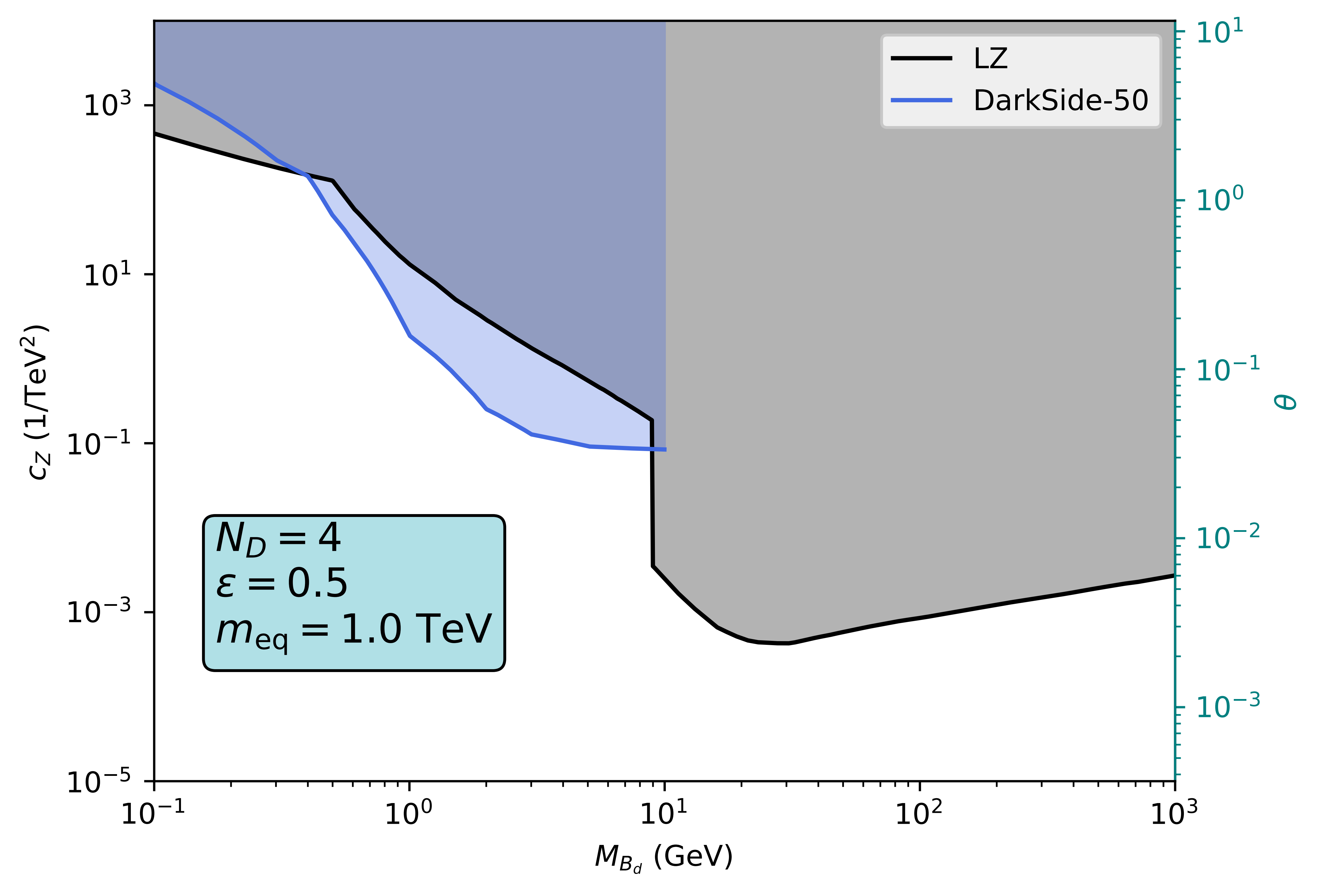
$$\sigma_{Z,n} \approx 10^{-37}\left(\frac{\mu_n}{1\text{ GeV}}\right)^2\theta^4\ \text{cm}^2.$$

- Higgs exchange also gives a direct detection cross-section. Modification of classic SVZ result* used to estimate cS, cG matrix elements of dark baryon in terms of θ.

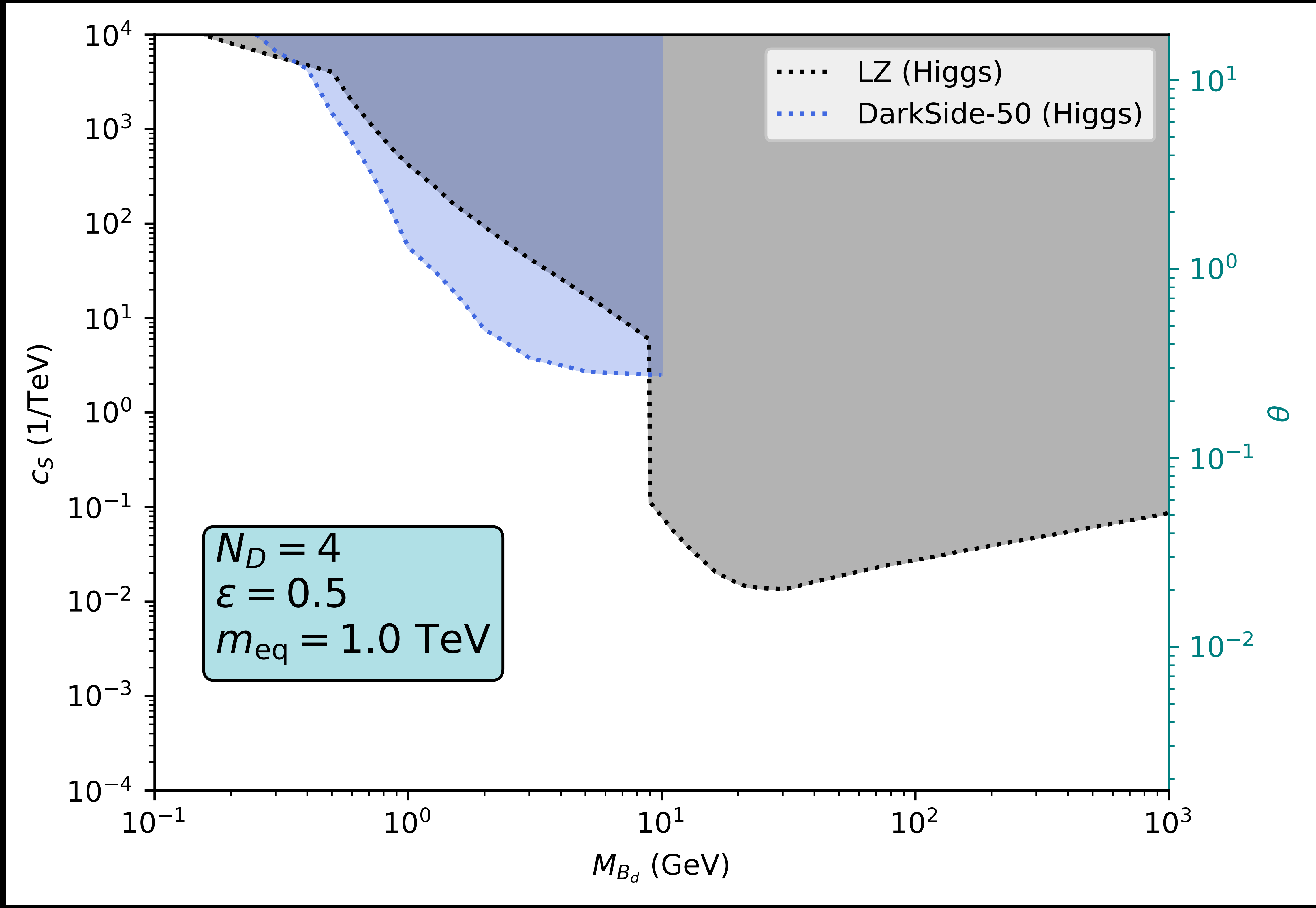
$$\sigma_{H,n}(B_d) = \frac{\mu_n^2}{\pi A^2}(Z\mathcal{M}_p+(A-Z)\mathcal{M}_n)^2, \quad \mathcal{M}_a = \frac{g_a g_{B_d,h}}{m_H^2},$$

$$\sigma_{H,n} \approx 5\times 10^{-39}\left(\frac{\mu_n}{1\text{ GeV}}\right)^2\theta^4\left[f_n^{(B_d)}\right]^2\ \text{cm}^2.$$

(*M.A. Shifman, A.I. Vainshtein, V.I. Zakharov, PLB 78, 443, 1978.)



- Left: Z-exchange bounds from LZ and DarkSide-50. Both bounds below 10 GeV use electron recoils + Migdal effect. (This region will be disfavored by other factors later on, anyway…)
- EFT bound shown vs. c_Z, but c_Z' also contributes.

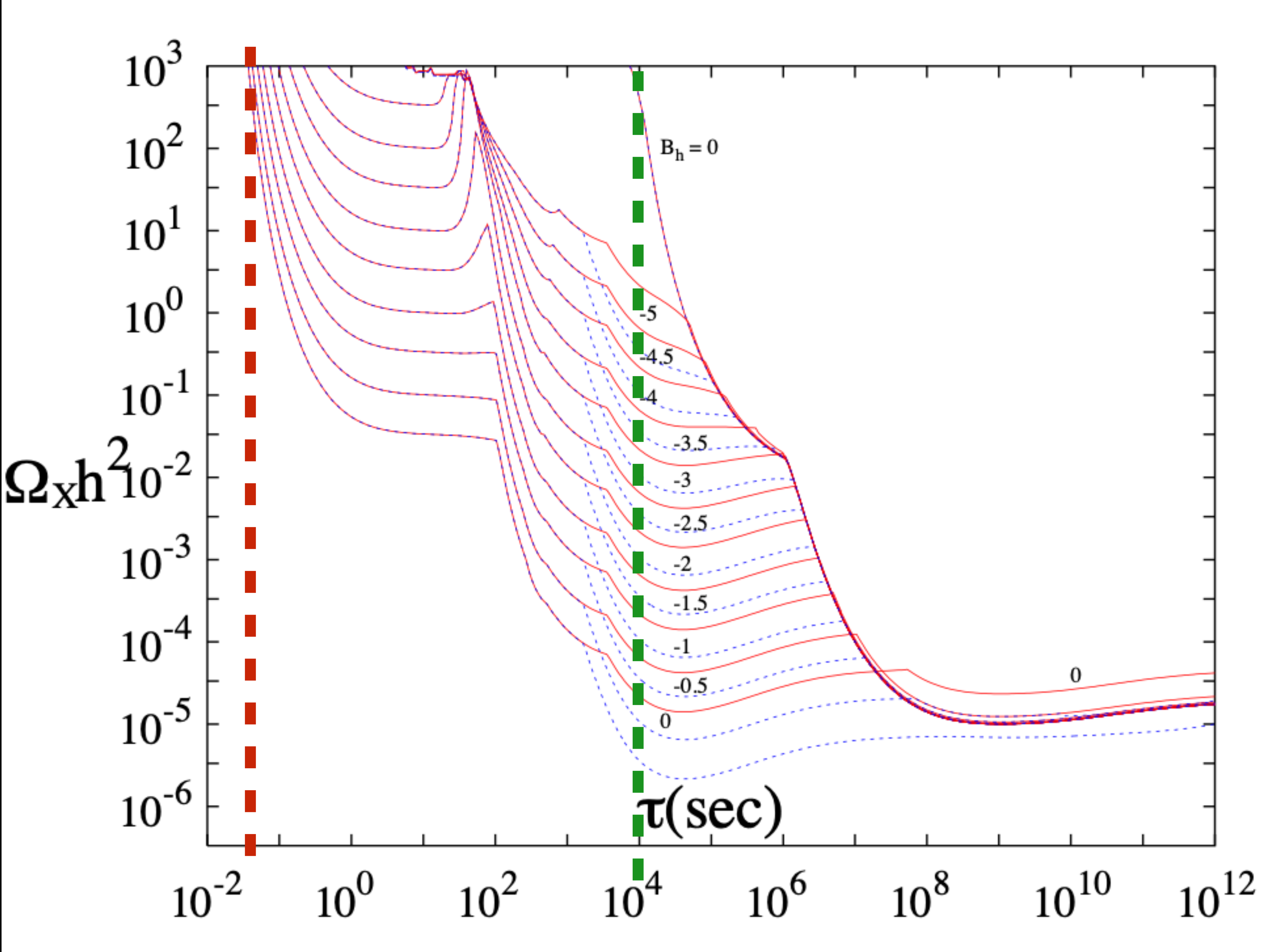


- Right: Higgs exchange bounds. In terms of HSDM completion (θ), they are always subleading. For the more general EFT, Higgs exchange constrains c_S vs. c_Z/c_Z'.

Big-bang nucleosynthesis (BBN)

(K. Jedamzik, PRD 74 103509 (2006), arXiv:hep-ph/0604251)

- Additional production of SM final states during BBN is heavily constrained; our dark mesons can have long-lived decays, leading to bounds.
- Order-of-magnitude estimates: 0.1s (B_h~1), 10^4 s (B_h~0)
- Computing production —> abundance of dark mesons is very difficult: we conservatively require they have lifetimes < 0.1s (10^4 s) so that they will decay away before BBN, regardless of abundance.

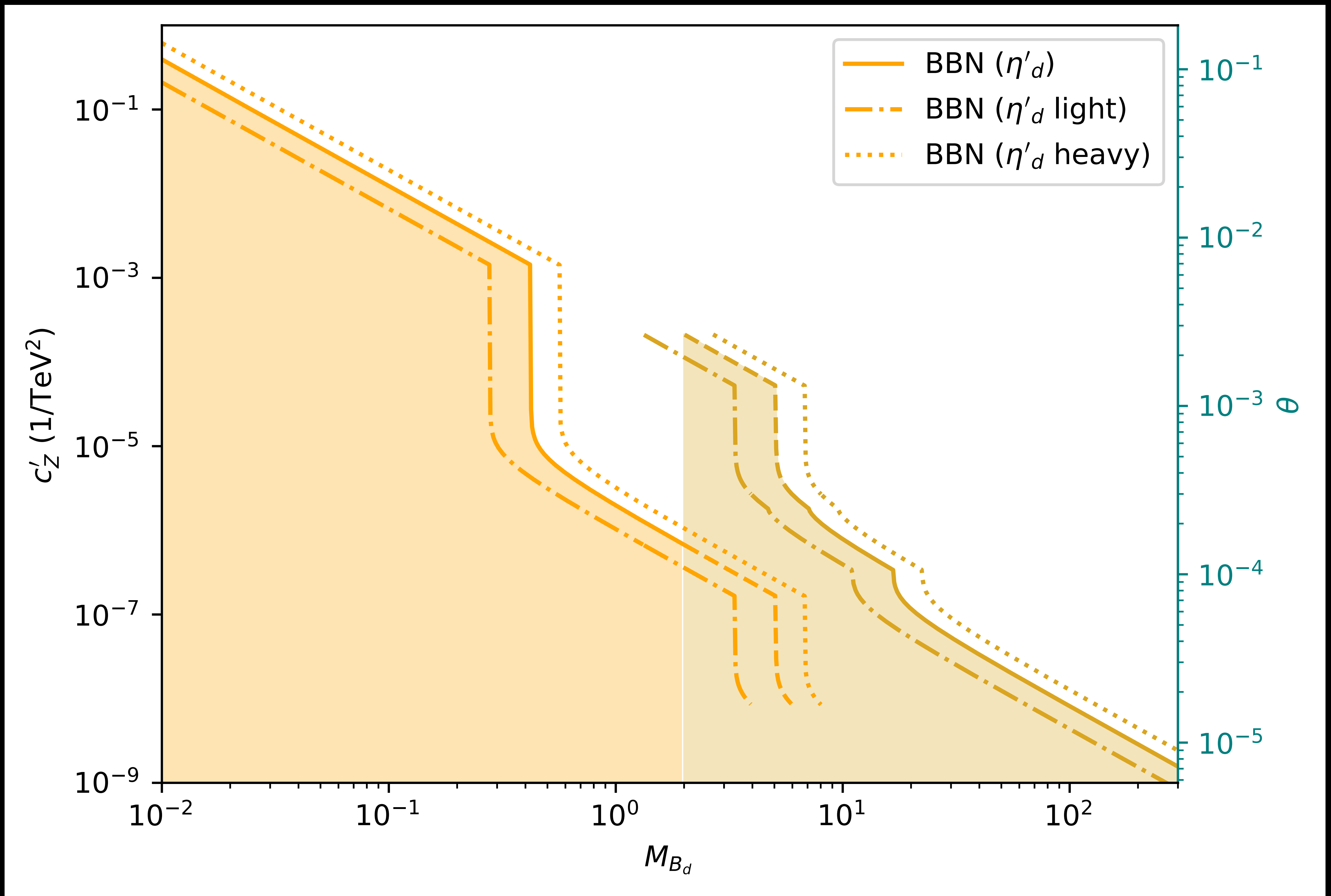


- Estimate ηd' decay by first matching on to low-energy effective theory (chiral Lagrangian):

$$j_A^\mu = \bar{\Psi}_n \gamma^\mu \gamma^5 \Psi_n = -f_{\eta'} \partial^\mu \eta'_d$$

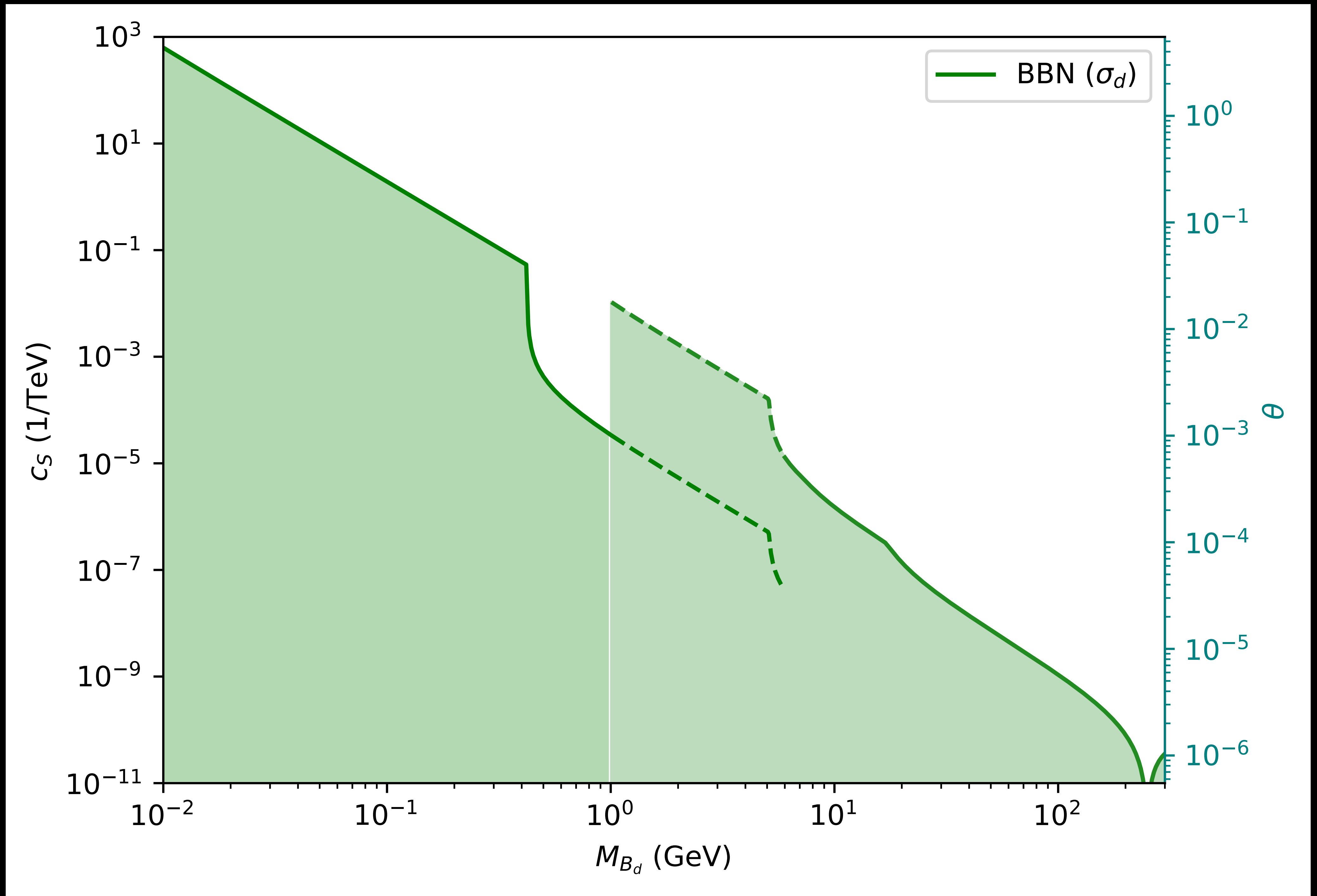
$$-\frac{c'_Z}{\Lambda^2} f_{\eta'} \partial_\mu \eta'_d (H^\dagger i D^\mu H + \text{h.c.}).$$

$$\mathcal{L}_{\eta'} \supset \frac{c'_Z}{\Lambda^2} f_{\eta'} \eta'_d \left(1 + \frac{h}{v}\right) \sum_f m_f \bar{f} i \gamma_5 f$$

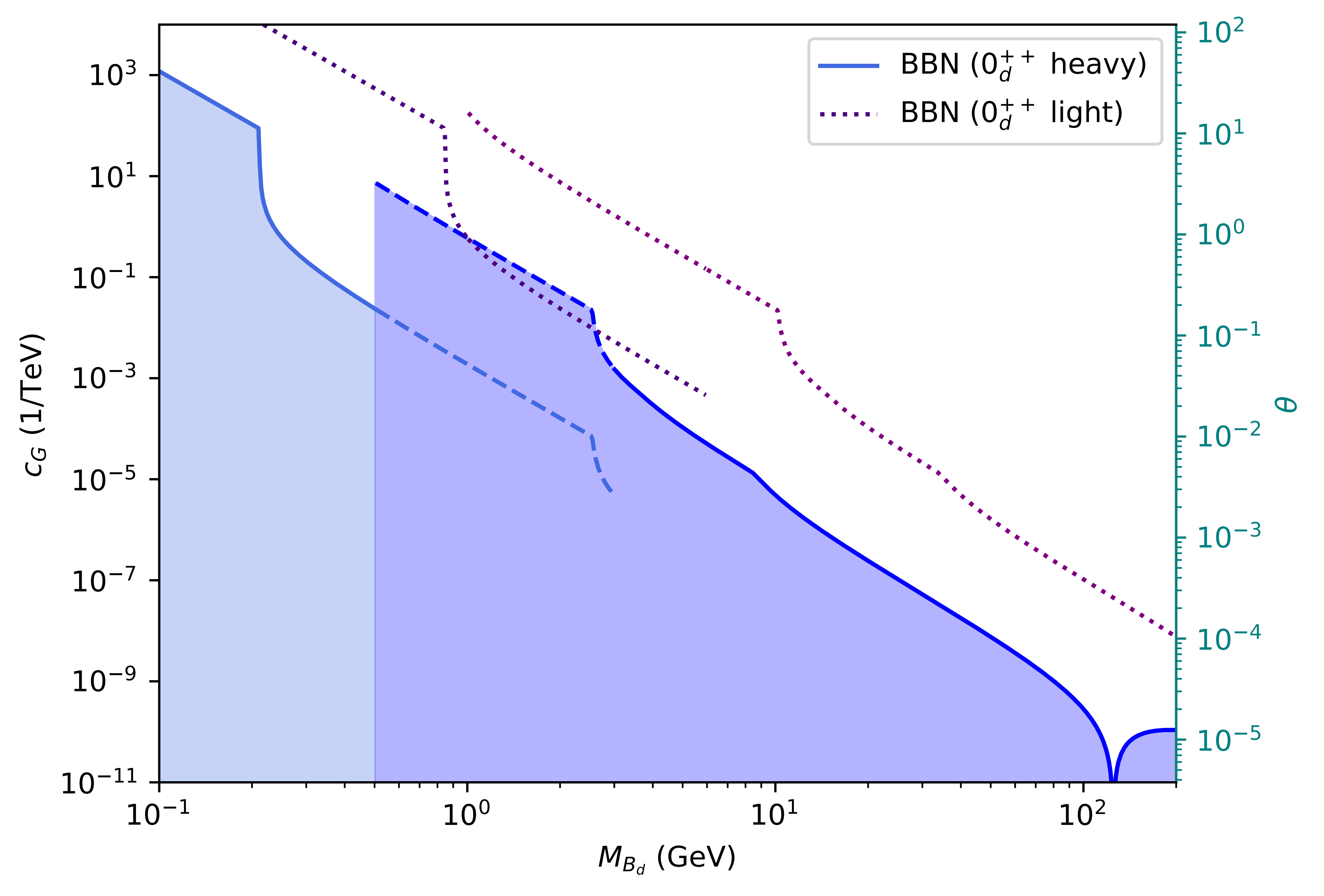


- Now looks like a standard axion-like particle (ALP) interaction; adopt formulas from literature to get decay width.

- BBN bounds shown above; three curves as mass of ηd' varies over parameter space.

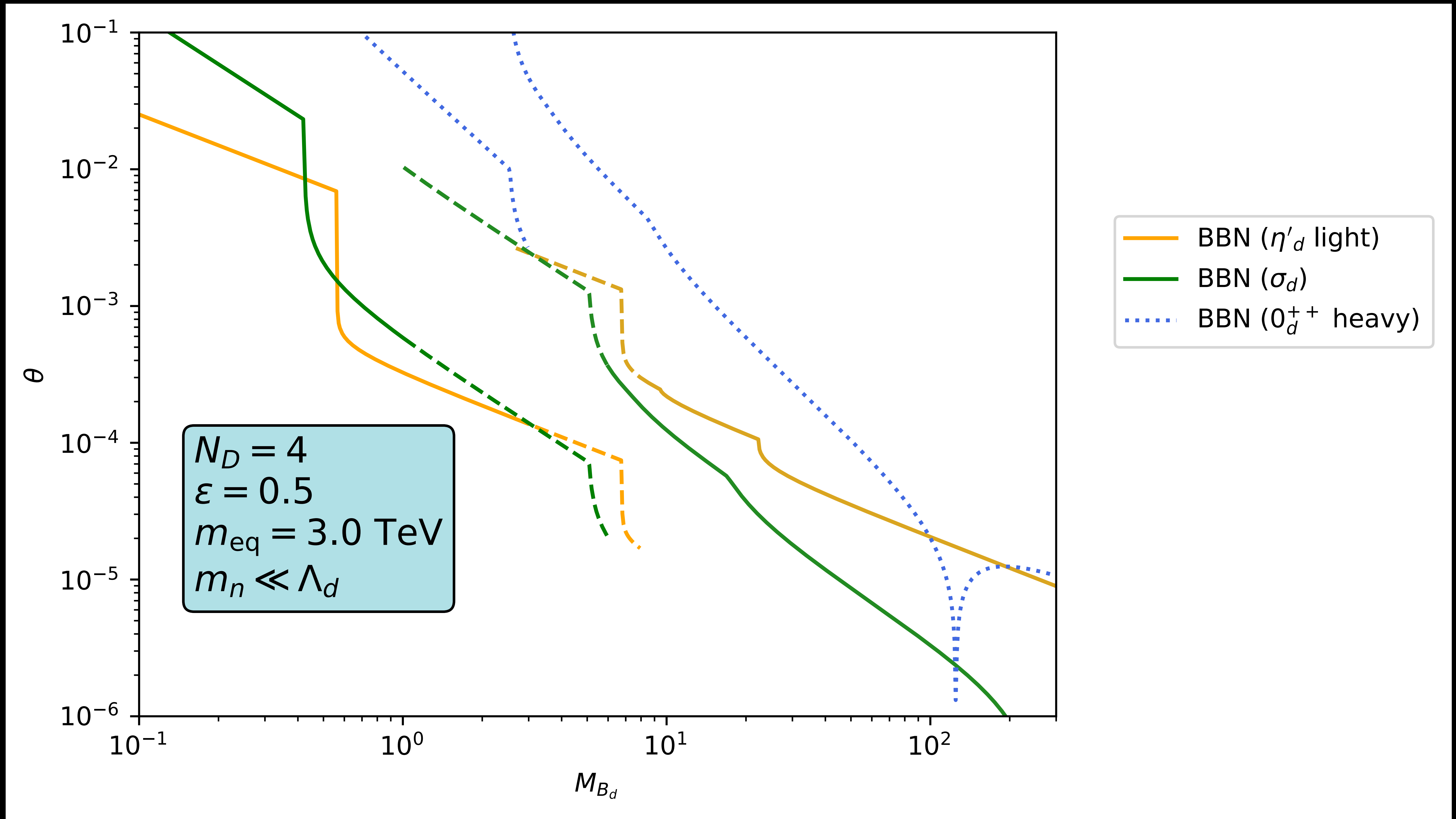


- Below: dark 0_d++ glueball decay through c_G operator (HH current coupling.) Estimated following details in arXiv:2310.13731*.
- Very strong bounds if the 0_d++ is light (heavy-quark case!) Also strong in light-quark case, but then mixing with σ_d meson accelerates decay.

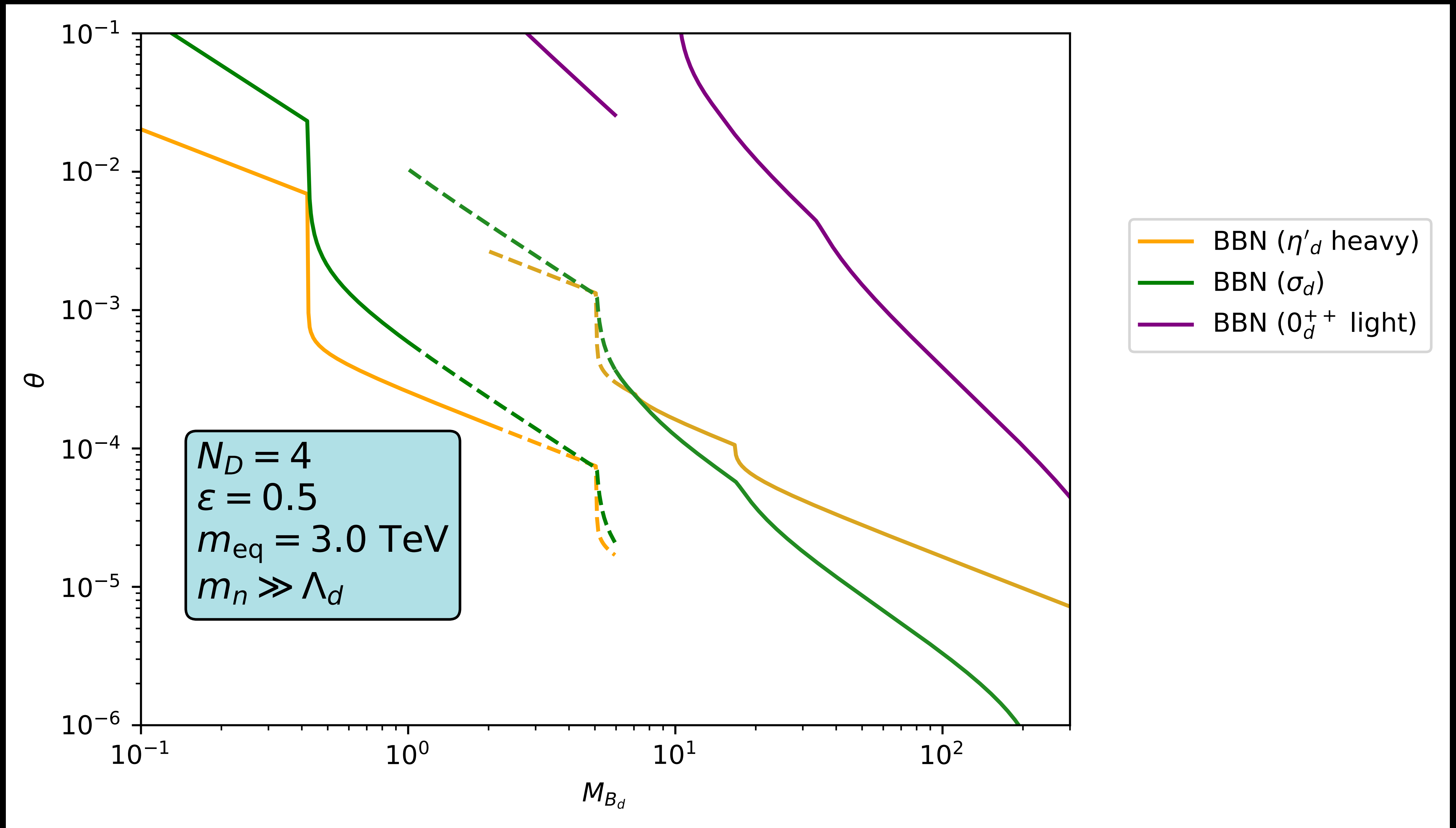


- Above: dark σ_d meson decay through c_S operator (HH current coupling again, but to fermions.)
- Estimated similar to 0_d++ case; decay width proportional to SM Higgs at different mass. Stronger bounds than η_d' in parts of parameter space!

(*A. Batz, T. Cohen, D. Curtin, C. Gemmell, and G.D. Kribs)

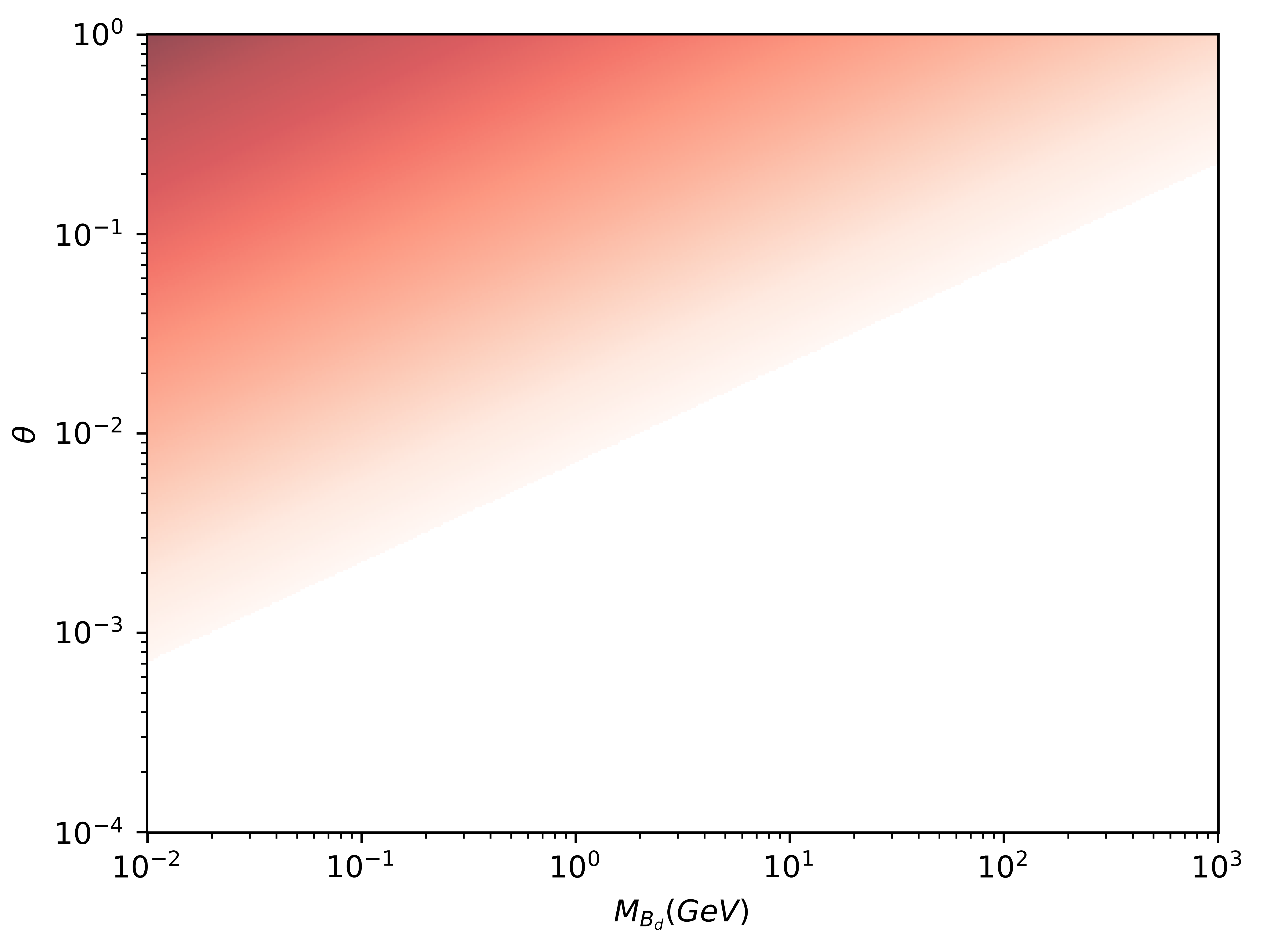


- Same results as above, now comparing various channels
- <u>Light-quark case (left):</u> strongest would-be bounds from glueball 0_d++, but expected to mix strongly with σ_d which reduces to σ_d bound.



- <u>Heavy-quark case (right):</u> 0_d++ is now much lighter, mixing suppressed; long lifetime leads to *much* stronger BBN bounds vs σ_d and η_d'.

Fine-tuning



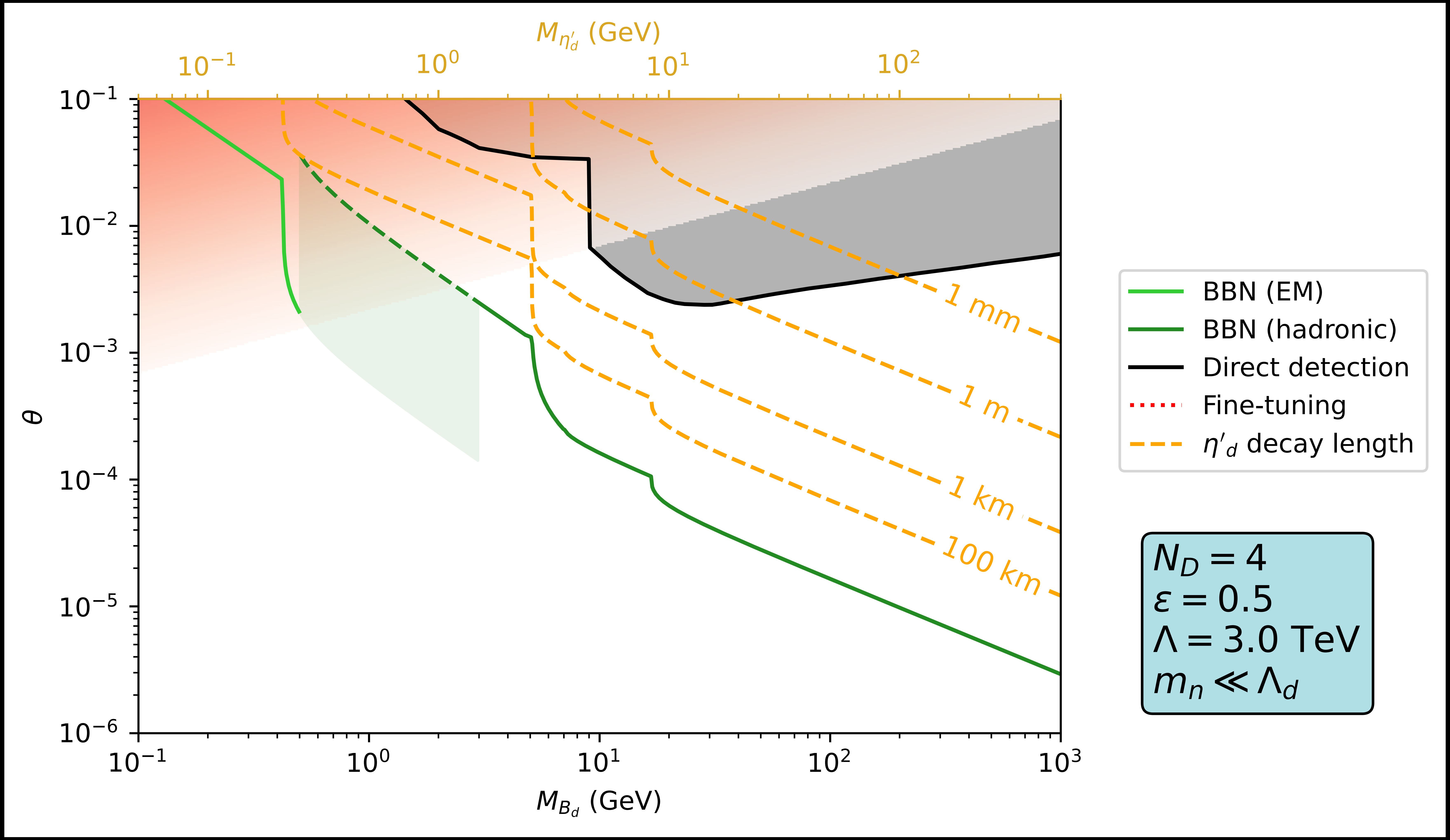
- Mass of the dark fermion Ψ_n gets contribution from Higgs mass

$$m_n \approx m_{n,0} - \frac{y_{ln} y'_{ln} v^2}{2\Lambda} = m_{n,0} - \theta^2 \Lambda$$

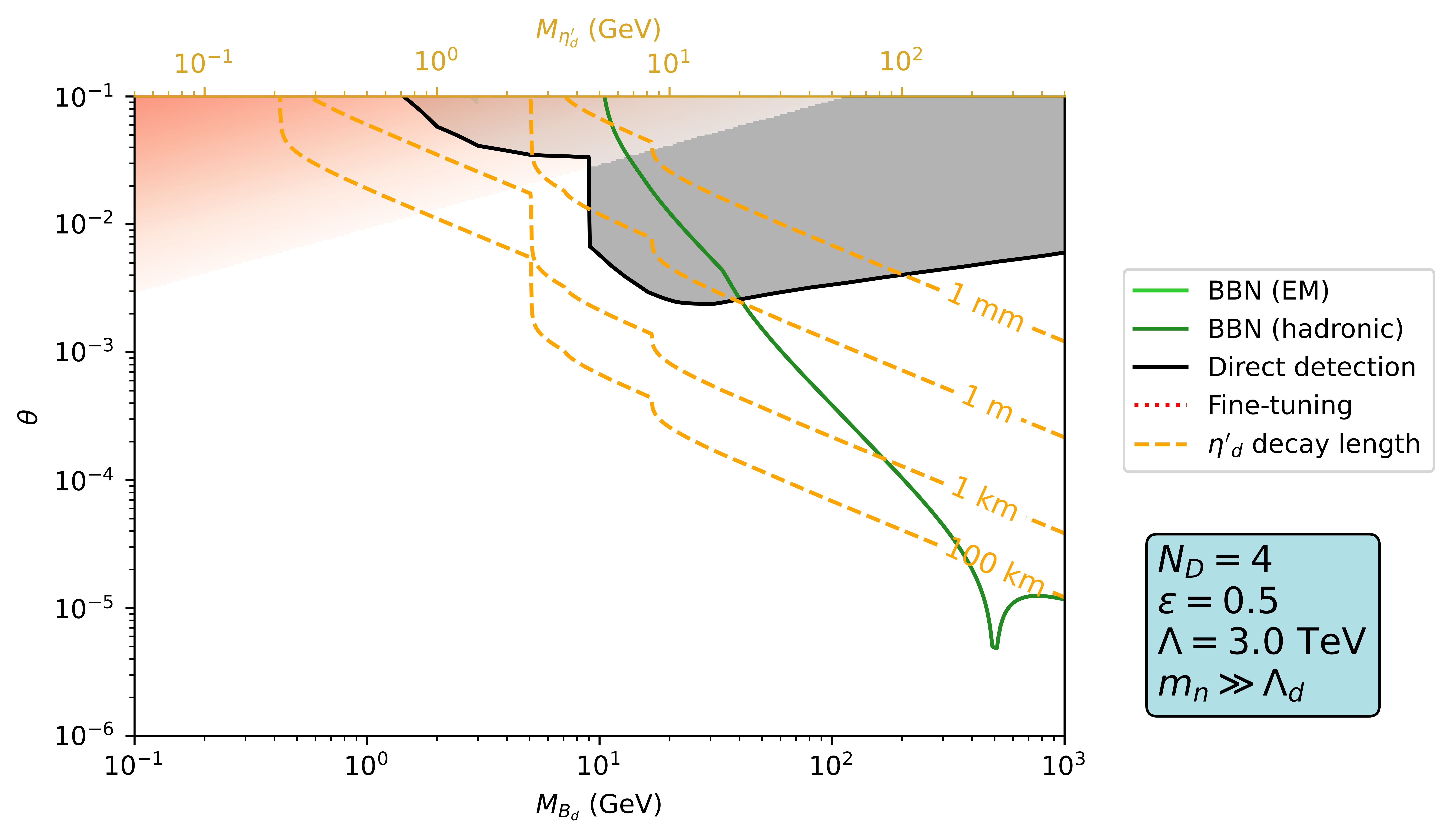
- Soft bound to avoid fine-tuning:

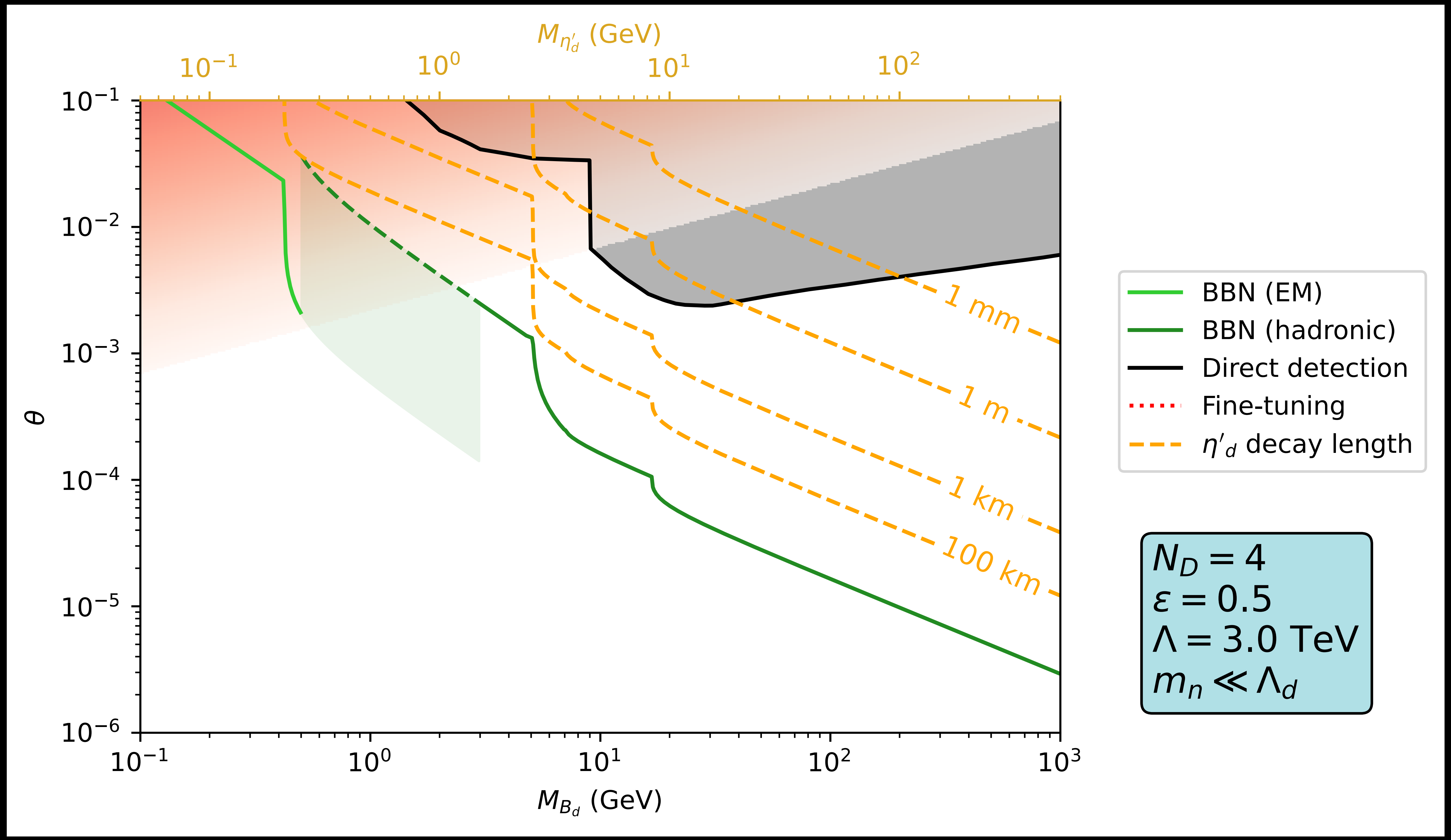
$$\theta^2 \Lambda \lesssim m_n$$

Combined bounds



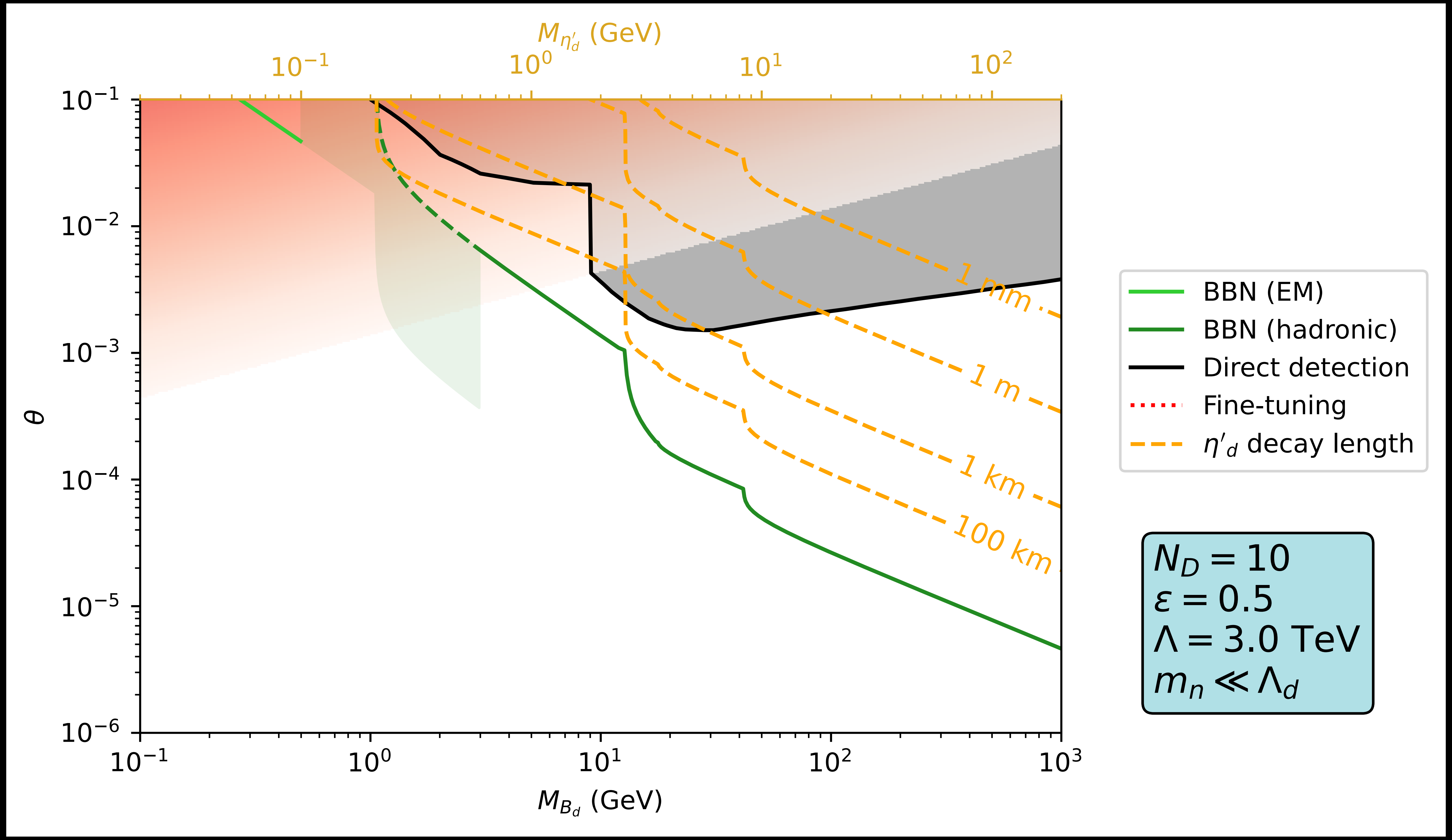
Combined bounds (HQ limit)

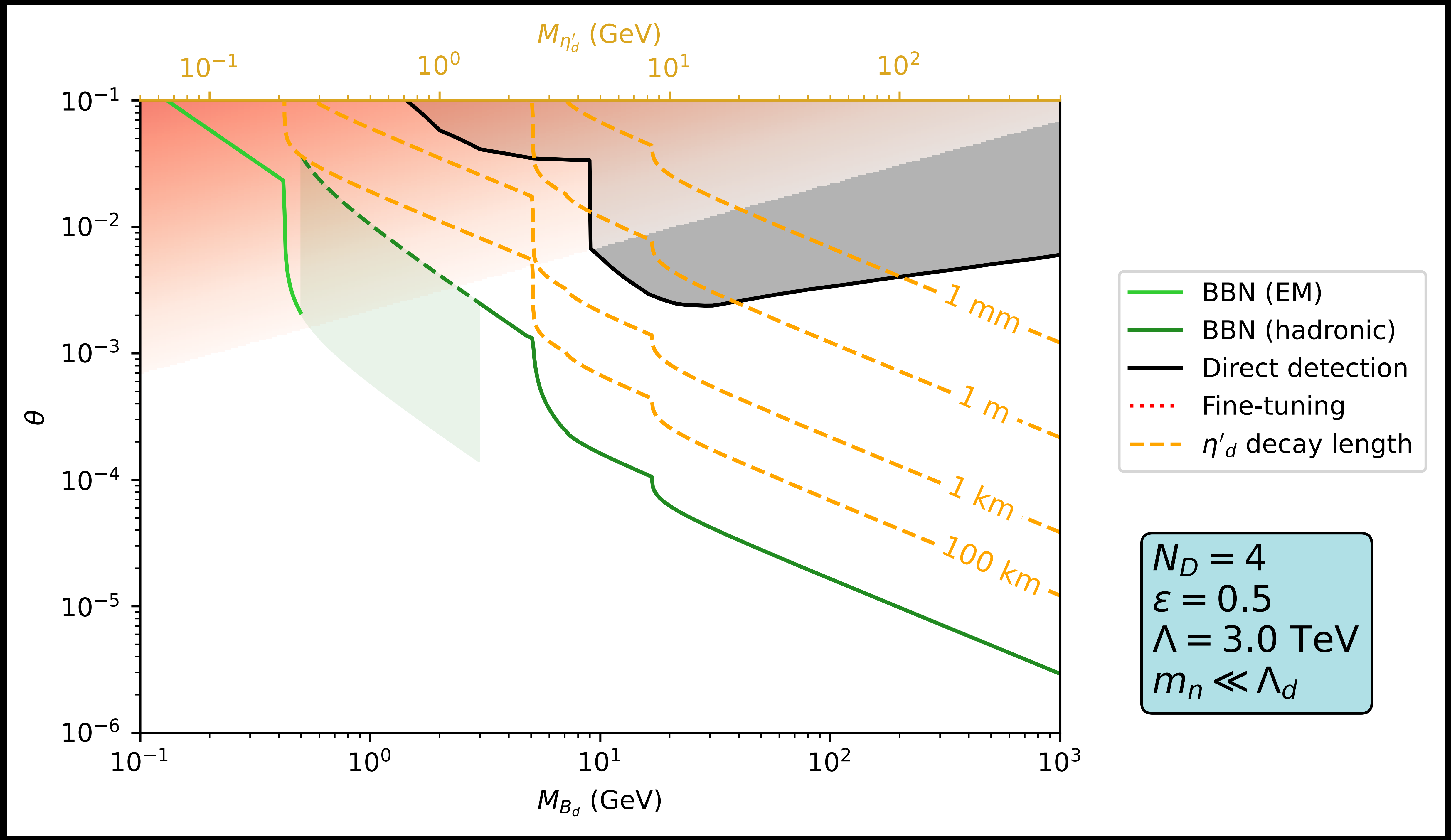




- <u>Variation 1:</u> increasing N_D strengthens both BBN (lighter η at given M_{Bd}) and direct detection ($\sigma_z \sim N_D^2$) bounds somewhat.
- Qualitatively, some parameter space remains open below $M_{Bd} \sim 10$ GeV.

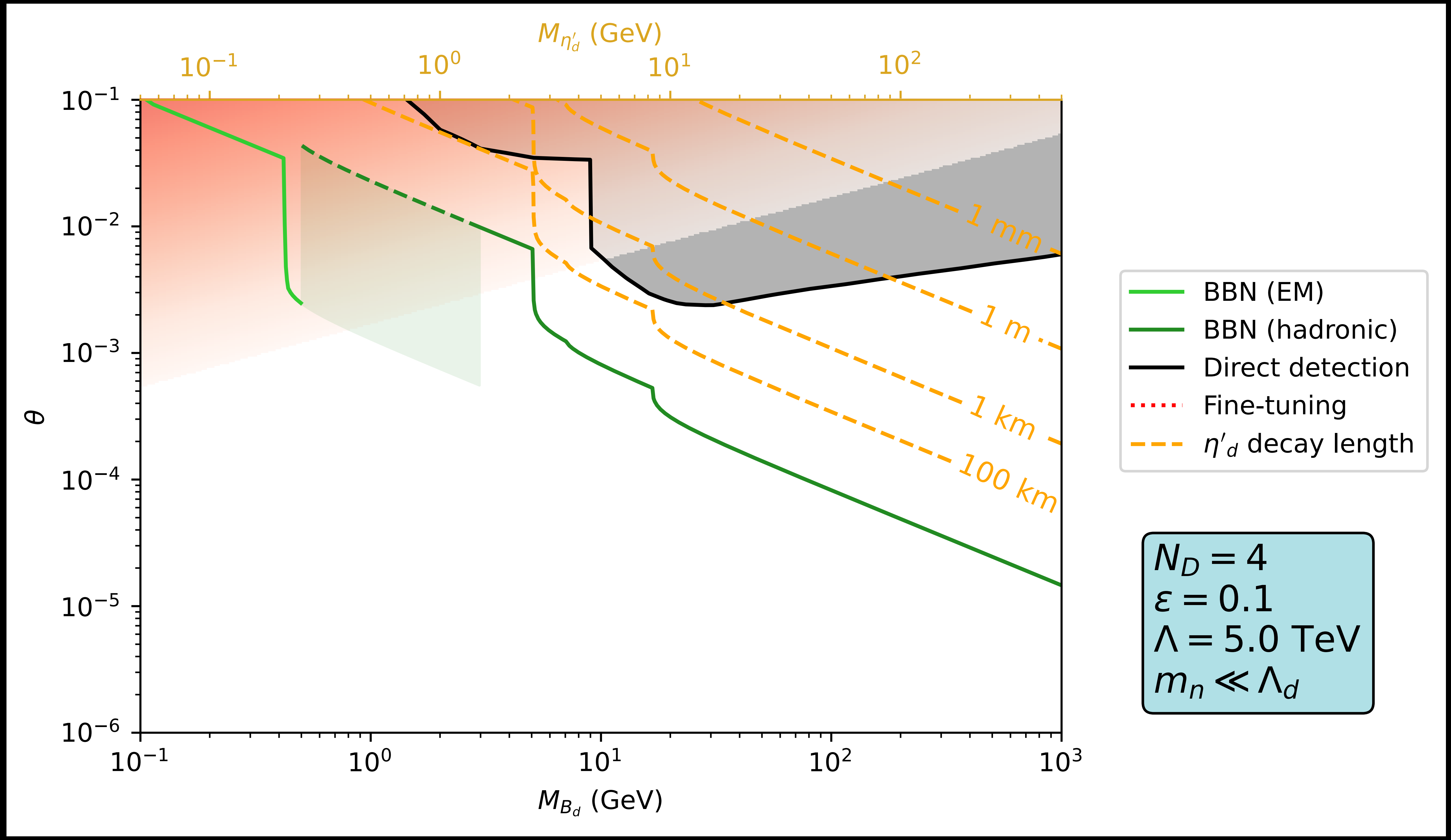
N_D —> 10





- Variation 2: increasing m_{eq} and reducing ε has no effect on direct detection, but strengthens BBN bounds by increasing ηd' lifetime.
- Again, qualitative effect on open parameter space is not too large.

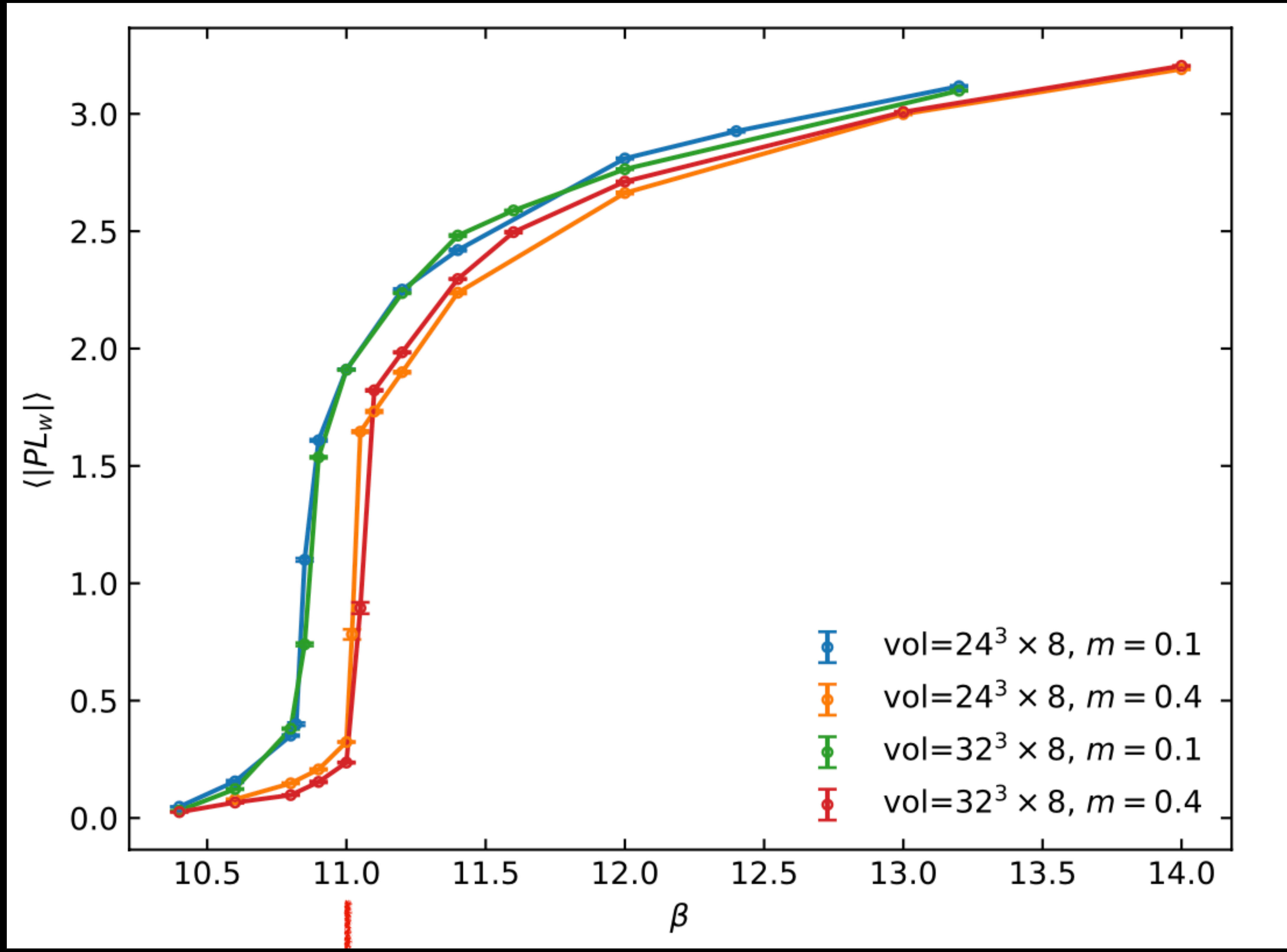
N_D —> 10



Other searches

- Future directions? Searches for long-lived dark mesons in colliders can cover lot of parameter space (see previous slides.)
- Self-interacting DM bounds should be looked at; one-flavor theory should be a bit less constrained than other composite DM (no light pions to mediate strong baryon-baryon interactions…)
- Primordial gravity waves! Requires first-order thermal phase transition in early universe; lattice calculations ongoing. (Right: preliminary results for SU(4), Nf=1 theory. Hints of first-order at heavy fermion mass!)
- In general, lattice calculations of spectroscopy and matrix elements in 1-flavor theory can help pin down the parameter space in more detail.

(LSD collaboration, plot from S. Park talk at Lattice 2024)



Summary

- Composite dark sectors give rise to naturally stable dark matter candidates, with SM interactions that can be strong in the early universe and very weak today.
- Dark baryon models w/SM interactions have nice properties, but difficult to realize below ~few hundred GeV due to collider bounds
- “Hyper-stealth DM” evades these bounds and gives viable dark-baryon DM around the few GeV scale!
- Further work is needed to understand how relic abundance is obtained; asymmetric case is particularly interesting here.
- This variant has long-lived dark mesons instead of charged mesons; potential for interesting collider bounds from displaced meson decay, more work needed here too.

Backup slides

Detailed decay-width formulas

$$\Gamma(\eta'_d \to f\bar{f}) = N_C^f \frac{M_{\eta'} m_f^2}{8\pi\Lambda^2} |c'_Z|^2 \frac{f_{\eta'}^2}{\Lambda^2} \sqrt{1 - \frac{4m_f^2}{m_{\eta'}^2}}$$
$$= \frac{N_C^f}{8\pi} M_{\eta'} \theta^4 \epsilon^4 \frac{m_f^2 f_{\eta'}^2}{M_Z^4} \sqrt{1 - \frac{4m_f^2}{M_{\eta'}^2}},$$

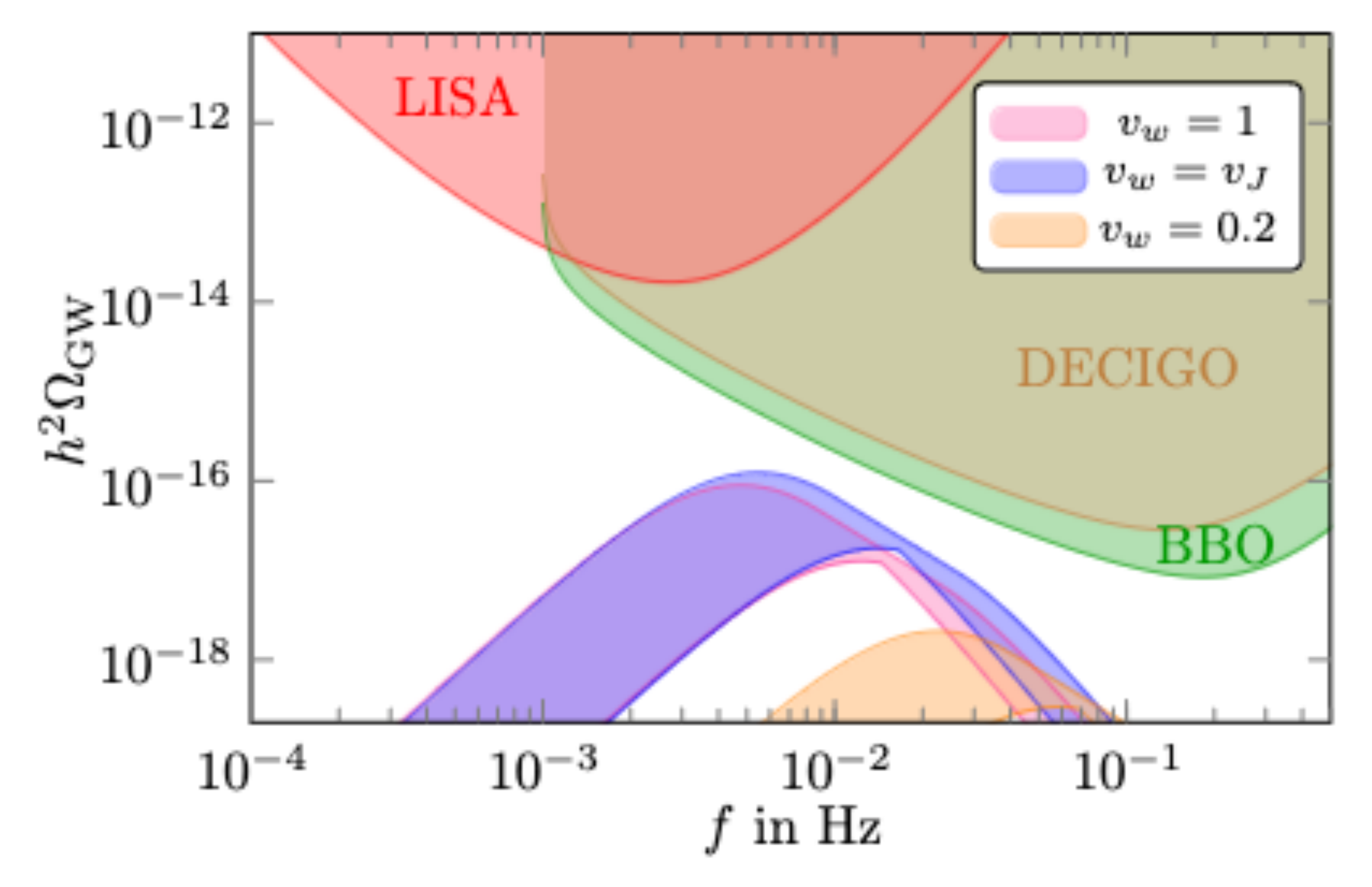
$$\Gamma_{0^{++},\text{tot}} = \frac{(2.3)^2}{9\pi^4} \left(\frac{N_D}{3}\right)^2 \theta^4 \frac{m_{0^{++}}^6}{v^2(m_h^2 - m_{0^{++}}^2)^2} \Gamma_{h,\text{tot}}^{\text{SM}}(m_{0^{++}}^2)\,.$$

$$\Gamma_{\sigma\to\xi\xi} = 4\,\theta^4 \left(\frac{m_{\text{eq}}}{v}\right)^2 \left(\frac{\mathbf{F}_\sigma}{m_h^2 - m_\sigma^2}\right)^2 \Gamma_{h\to\xi\xi}^{\text{SM}}(m_\sigma^2)\,,$$

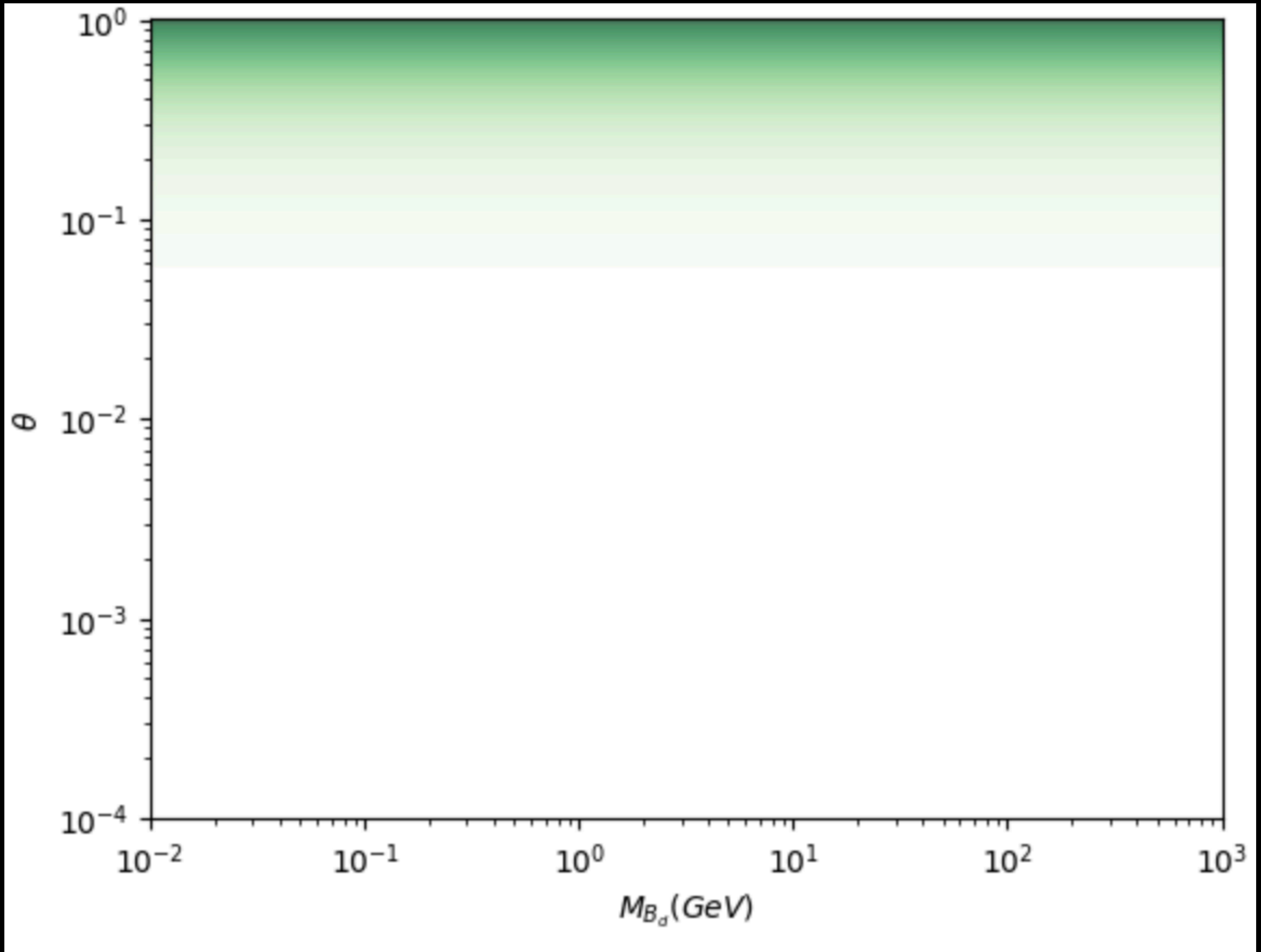
Primordial gravitational waves

- Lattice calculations have shown many QCD-like theories to have first-order thermal phase transitions.
- First-order transitions proceed by supercooling and nucleation of bubbles of the low-temperature phase.
- Bubble collisions (and subsequent hydrodynamics) gives rise to primordial gravitational waves (like the CMB) - highly distinctive signature of cDM models!
- *Right:* pure-gauge lattice calculations predict GW spectra - unfortunately, too weak to be seen by even future GW experiments.

(from W.-C. Huang, M. Reichert, F. Sannino and Z.-W. Wang, Phys. Rev. D 104, 035005 (2021))



Yukawa perturbativity



- Yukawas will become non-perturbatively strong if θ is too large; ε also matters.
- To avoid this, we require roughly θ < 0.1 and ε < 0.5.

$$\frac{y_{\text{large}}^2}{4\pi} \lesssim 0.5,$$

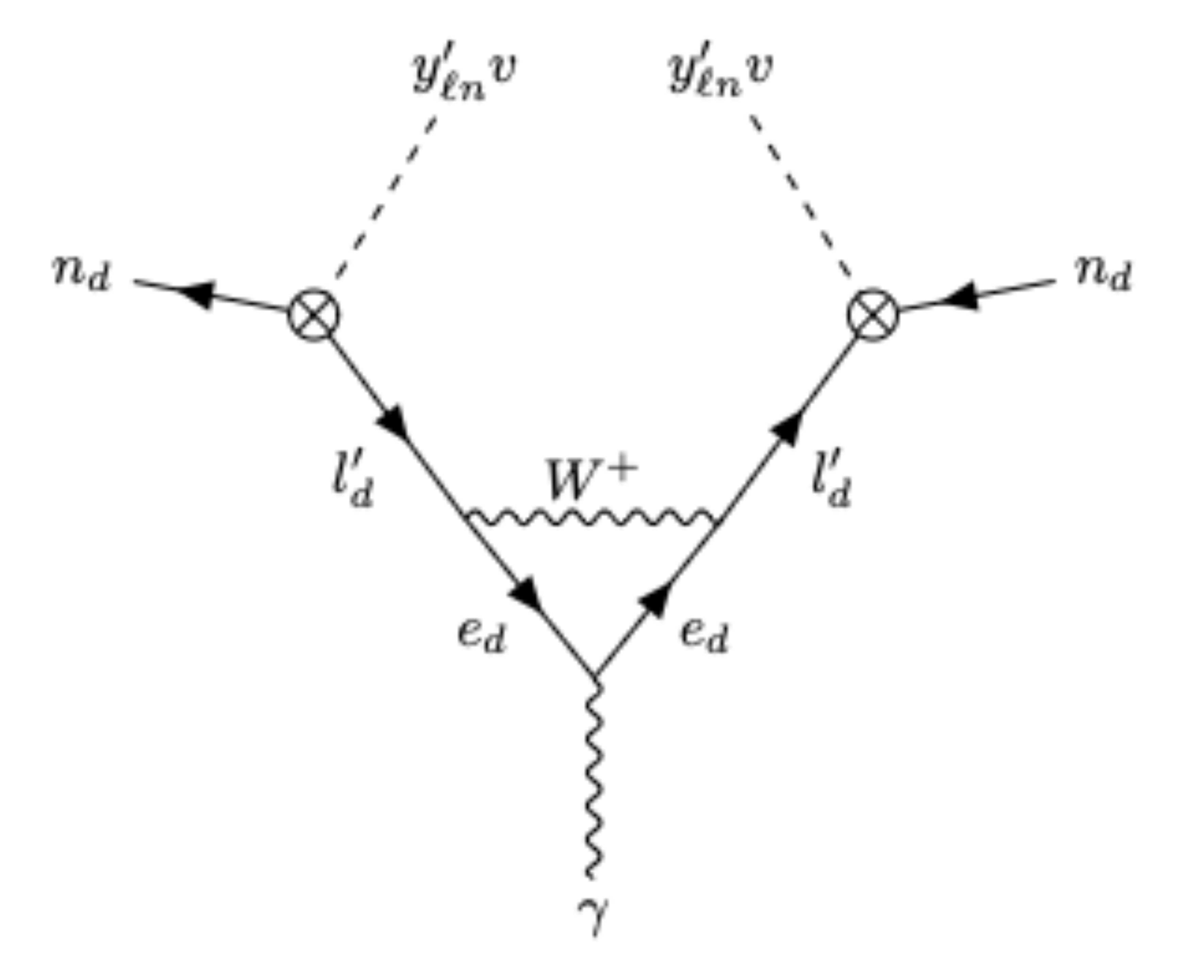
$$\begin{aligned} y_{ln} &= y(1+\epsilon) \\ y'_{ln} &= y(1-\epsilon) \end{aligned}$$

Magnetic moment?

- Magnetic moment *is* induced for neutral dark quarks by equilibration sector, e.g. diagram on the right

- This leads to a magnetic moment for the dark baryons Bd, but of order $\alpha\theta^2$.

- Direct-detection cross section ~ $\alpha^4\theta^4$, much more suppressed vs. Z exchange.

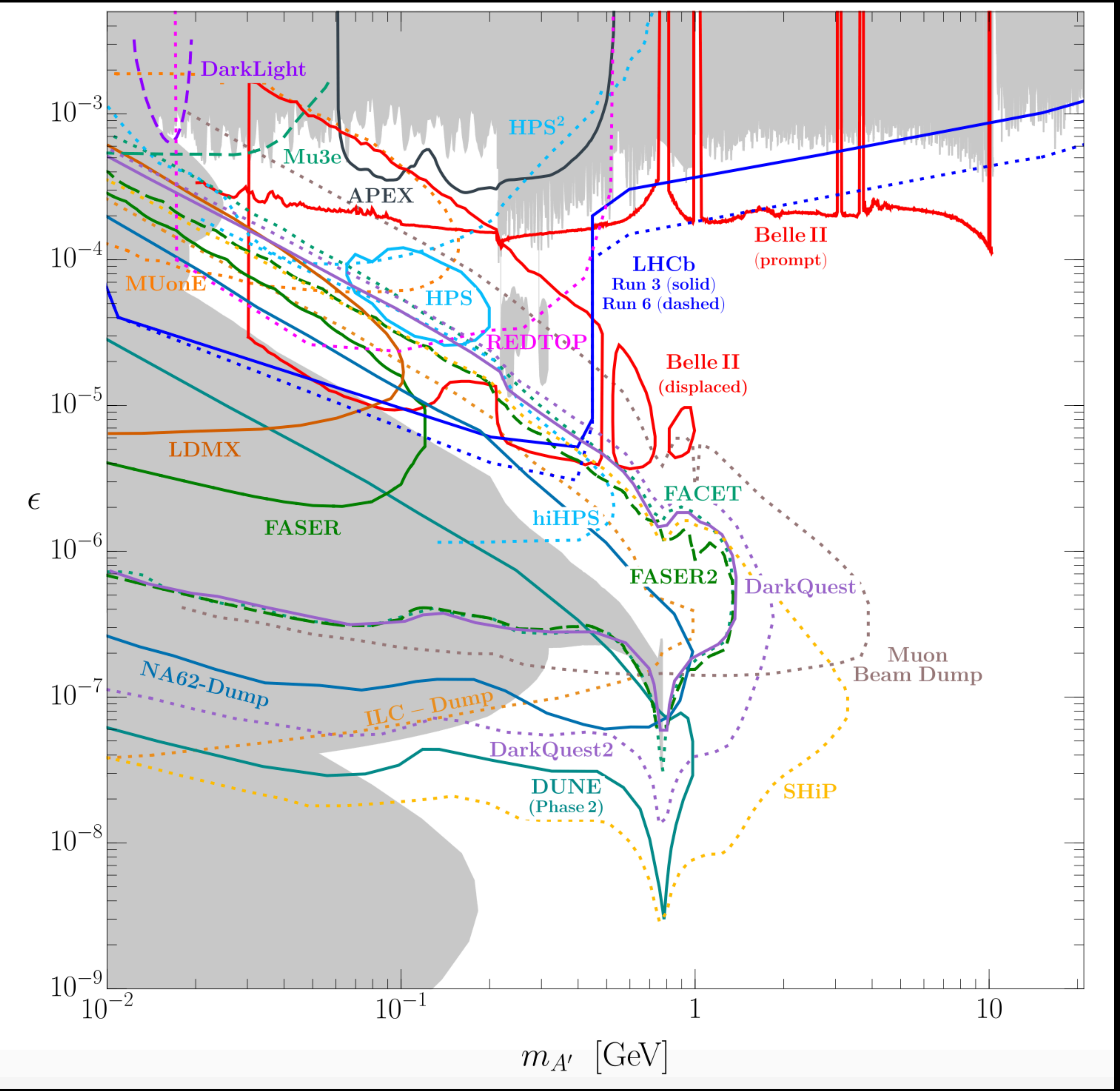


Other mirror-matter searches

See review: Batell, Low, ETN and Verhaaren, 2203.05531

Batell, Blinov, Hearty and McGehee, 2207.06905

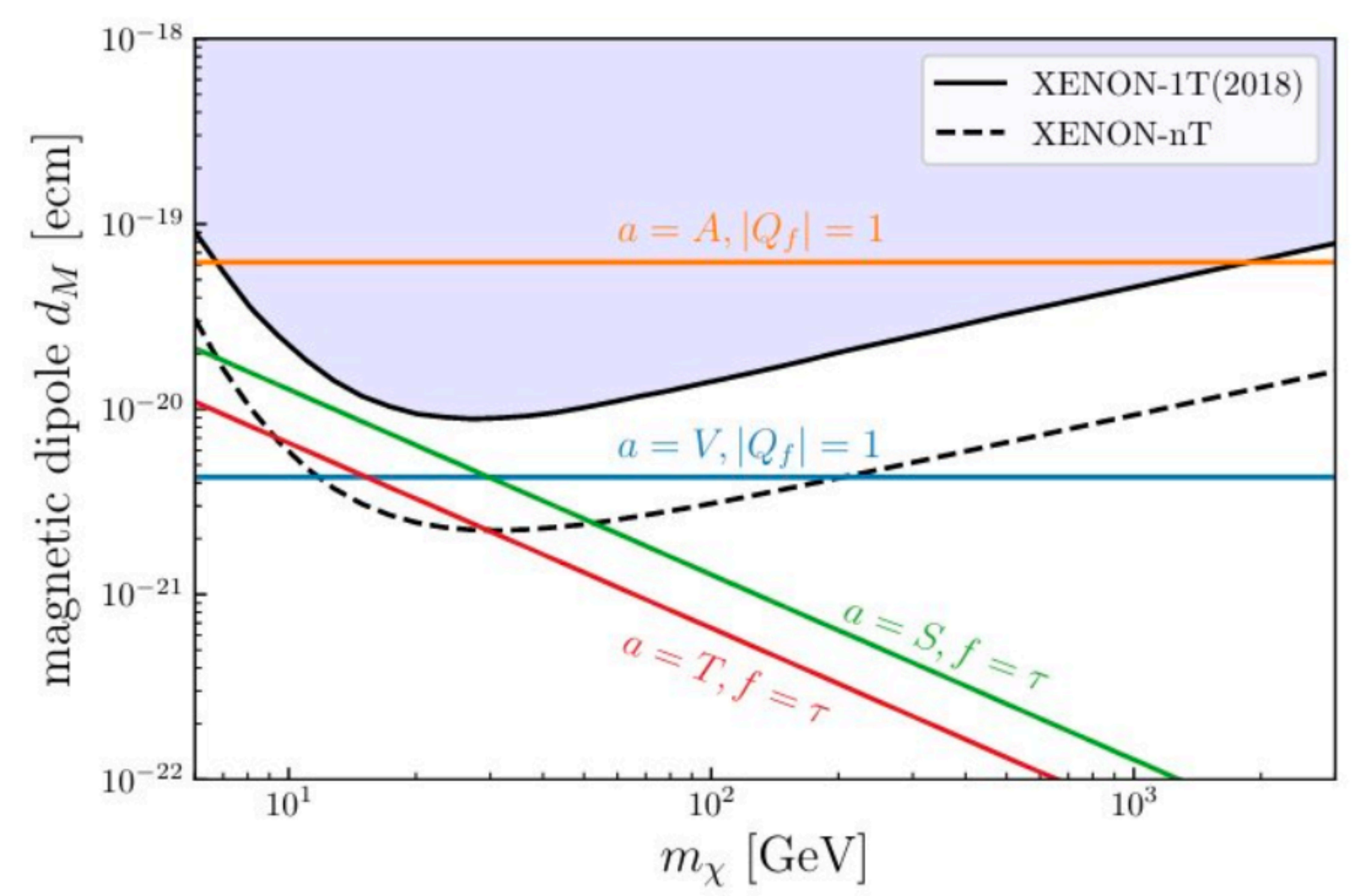
- Mirror matter is not coupled directly to SM forces, so direct collider production is very difficult
- Searches for exotic Higgs decays, modified couplings, or for the extended Higgs sector directly are more promising
- There can be other "portal" couplings probed directly at high-intensity experiments, e.g. the twin/dark photon (right) or twin Z.



Updated bounds on DM/photon scattering

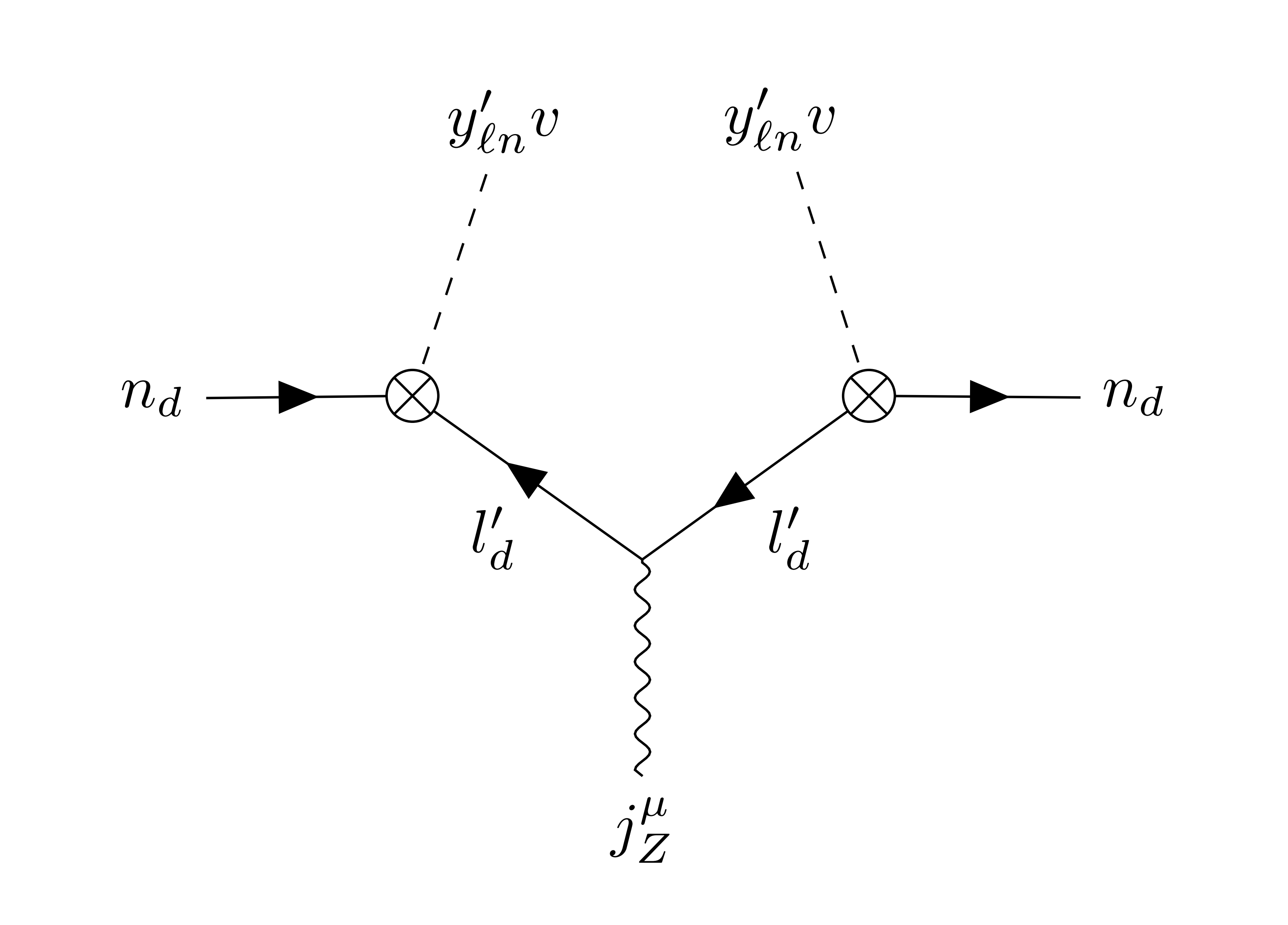
- Bound shown for XENON-1T and projection for nT.
- Conversion to bound on composite dark matter mass requires interpretation within a specific model.
- (Not sure about updates for charge-radius scattering…)

J.M. Cline, Les Houches lectures on composite DM/dark atoms, 2108.10314



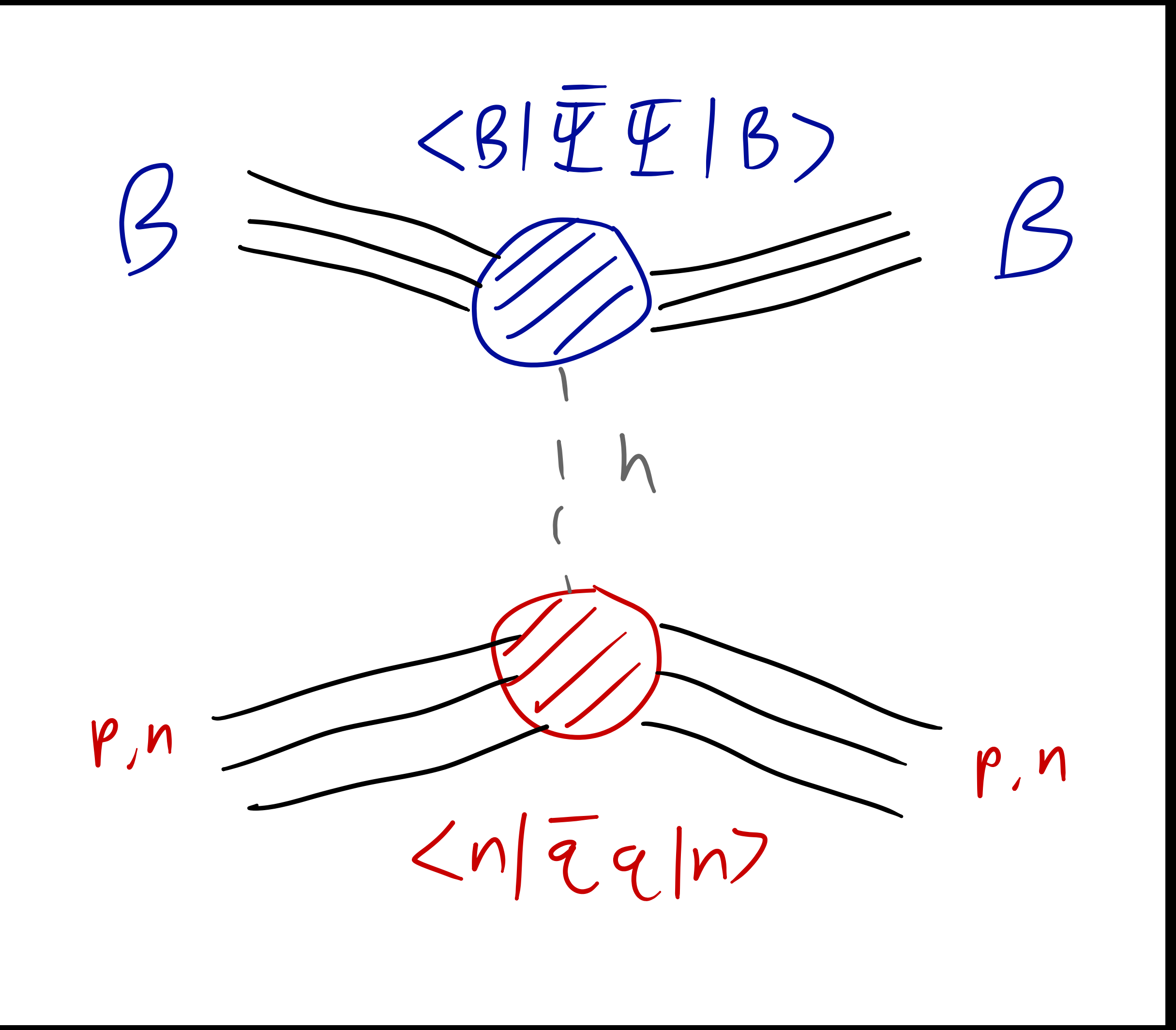
Matching, continued

- Matching for Z current shown to the left.
- P (not CP) violation is needed to give the c_Z' vertex that mediates η_d' decay; y != y' gives the desired result (C-conjugate diagram), leads to ε parameter.

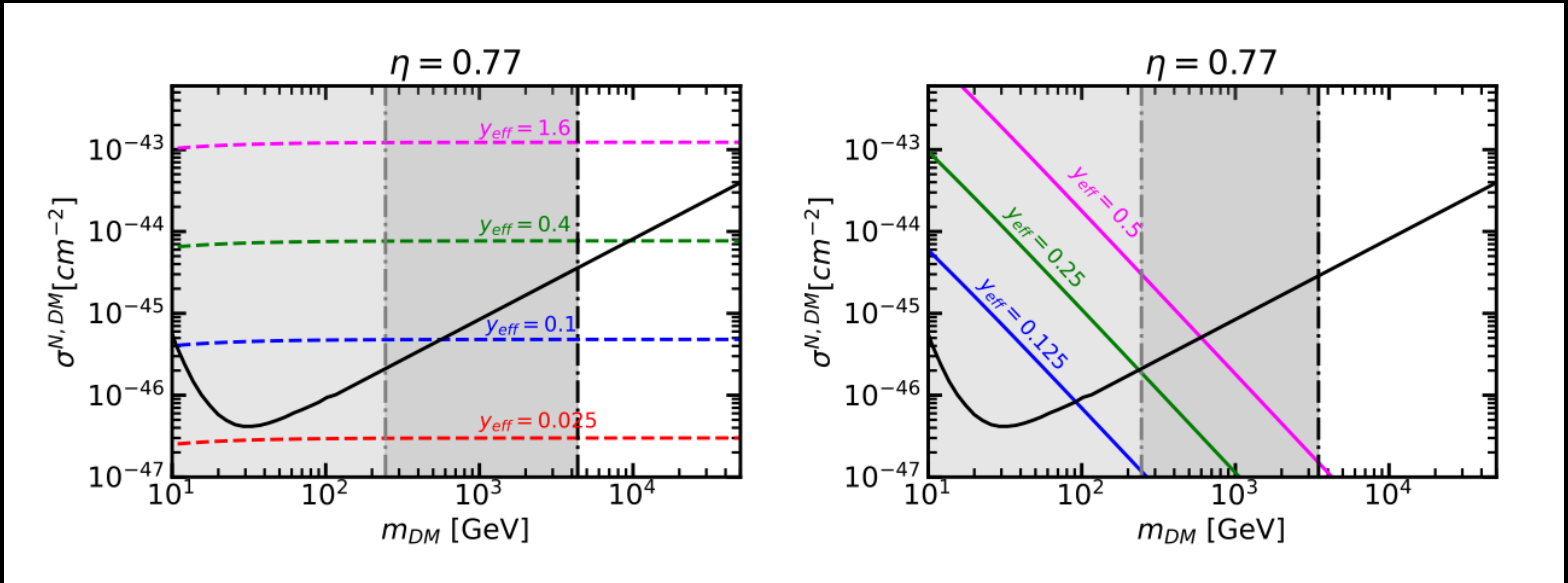


Direct detection: Higgs exchange

- Within stealth DM, a "Higgs portal" coupling is also possible, can give dominant direct-detection signal vs. polarizability.
- Can give fairly strong bounds from direct detection, e.g. Xenon1T below, depending on "effective Yukawa" yeff. Depends on "linear" vs. "quadratic" regime in stealth model.

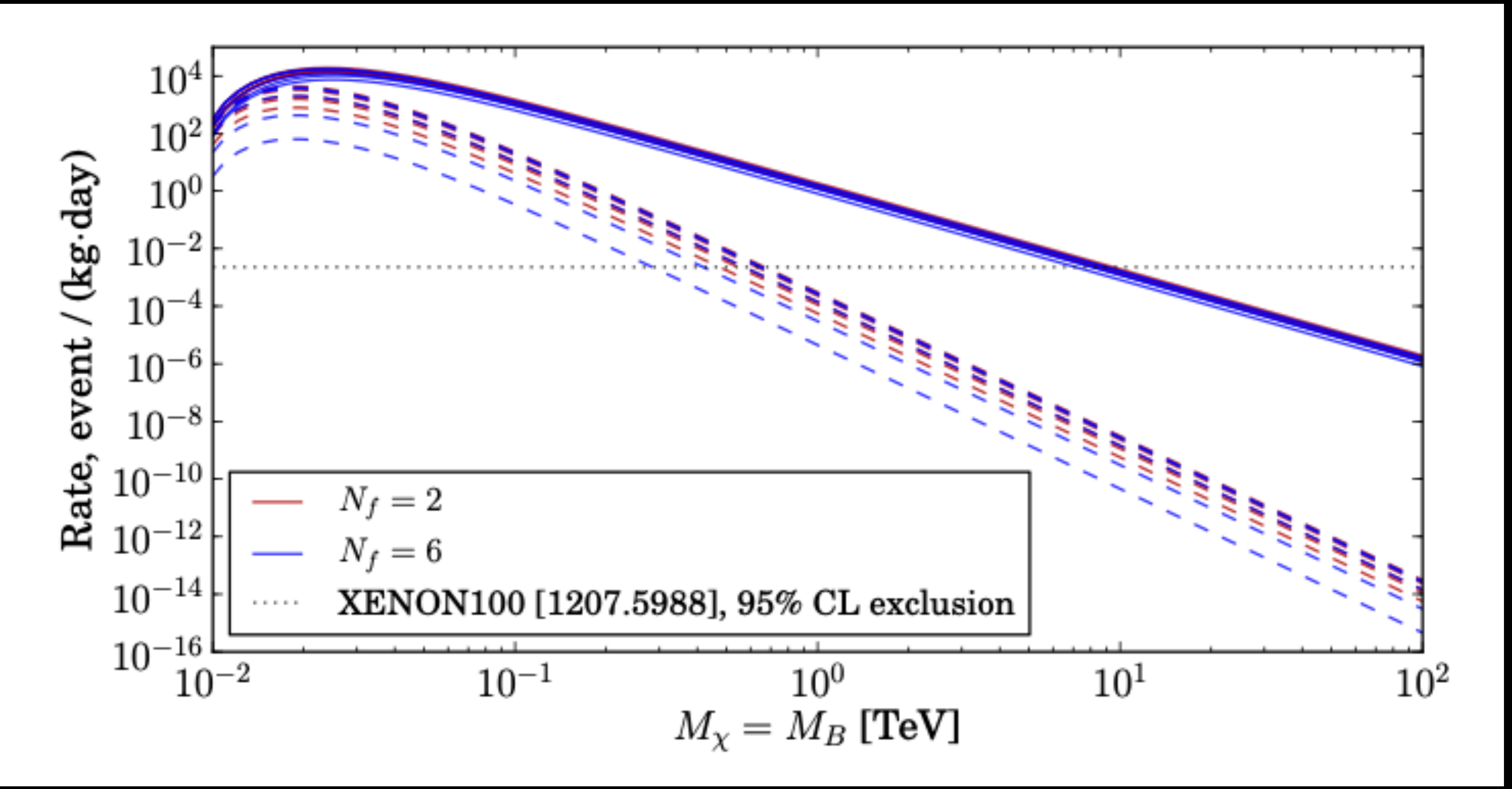


J.M. Butterworth et al, 2105.08494



Direct detection: photon exchange

T. Appelquist et al (LSD Collab), 1301.1693



- Bounds from magnetic moment (solid) and charge radius (dashed), right; TeV-scale bounds even from older experiment, likely even stronger if updated.
- In case of discovery, photon exchange with DM means distinctive patterns would occur in rates with different target materials!
- Polarizability not considered here, it's too small, except in theories where both of these operators vanish…(I'll come back to this.)

target	$\mu^2(J+1)/J$	Z^2/A^2	$Z^4/A^{8/3}$
Xe	1	1	1
Si	0.06681	1.472	0.2766
Ge	0.1130	1.152	0.6010
Na	12.68	1.357	0.1798

(G.D. Kribs and ETN, Int. J. Mod. Phys. A31, 2016)

Stealth DM: symmetries and interactions

$(F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu)$

$$\chi \sim (F_+ F_- F_+ F_-)$$

$$C: \quad \begin{array}{c} F_+ \leftrightarrow F_- \\ \chi \leftrightarrow \chi \\ A_\mu \leftrightarrow -A_\mu \end{array} \quad \text{(photon)}$$

- Accidental symmetry guarantees dark baryon χ stability, as usual, even from Planck-scale decays.
- Additional symmetry: the (bosonic) baryon is even under charge conjugation. Eliminates charge radius! (No mag moment - bosonic.)
- Symmetric structure of model also suppresses electroweak effects (e.g. S parameter.)

~~$\frac{1}{\Lambda^2}\chi^\dagger \chi v_\mu \partial^\mu F_{\mu\nu}$~~ $\qquad \frac{1}{\Lambda^3}\chi^\dagger \chi F_{\mu\nu} F^{\mu\nu}$

Stealth DM: How large is the polarizability?

- Polarizability is already $1/\Lambda^3$ suppressed, but dynamics of the composite sector are important too.
- With four dark fermions in a stealth baryon, "Pauli pairing" could occur. Polarization of two dipoles vs. uncorrelated charges would be further suppressed!
- Should see *massive* suppression of 4-color vs. 3-color polarizability if Pauli pairing occurs. Lattice calculation to answer!