Hyper-stealth dark matter

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May 22, 2025

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

Outline

1. Motivation: composite dark matter

2. Composite dark matter: general properties

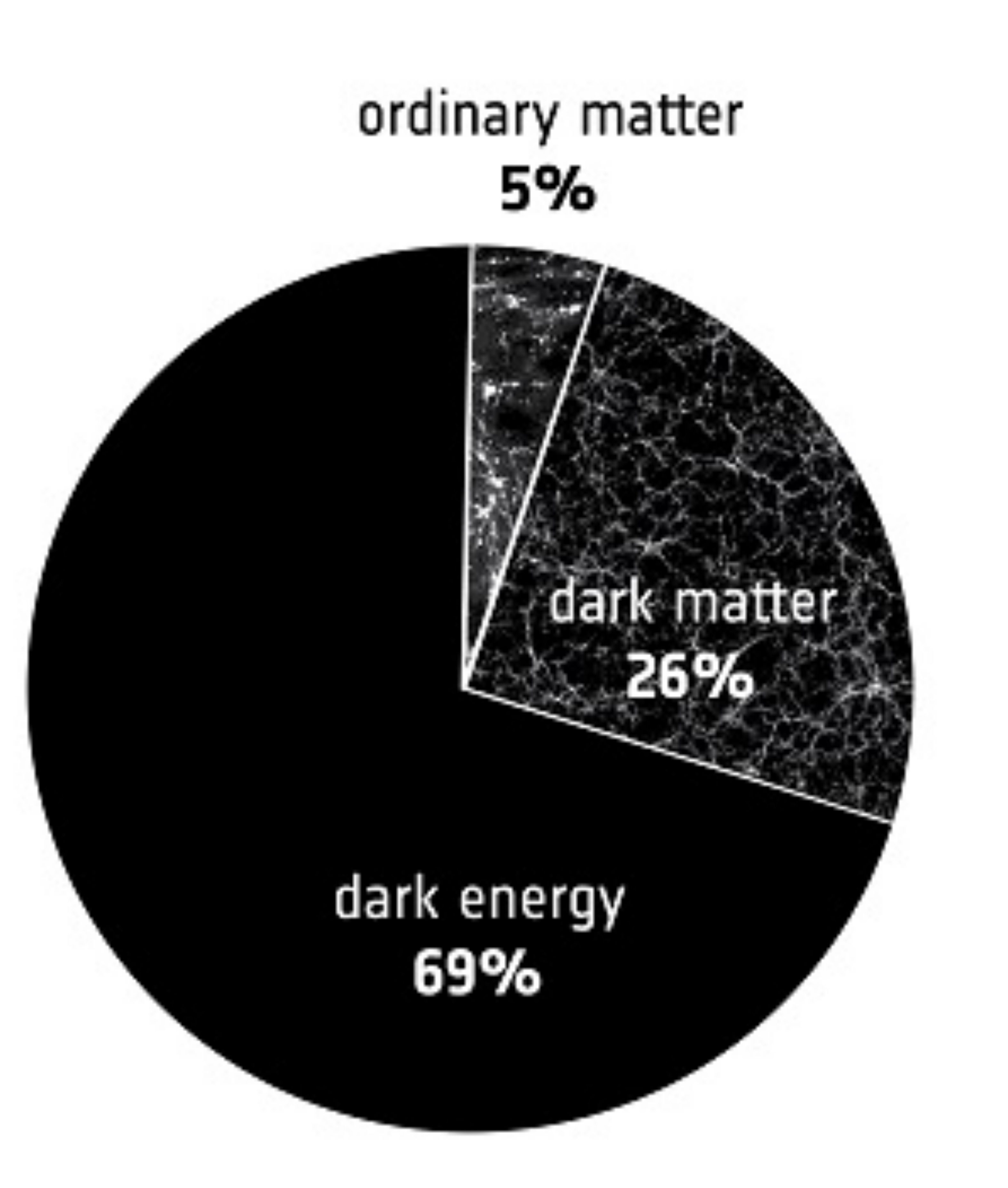
3. Hyper-stealth dark matter model

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:2412.14540

1. Motivation: composite dark matter

Cosmic coincidence

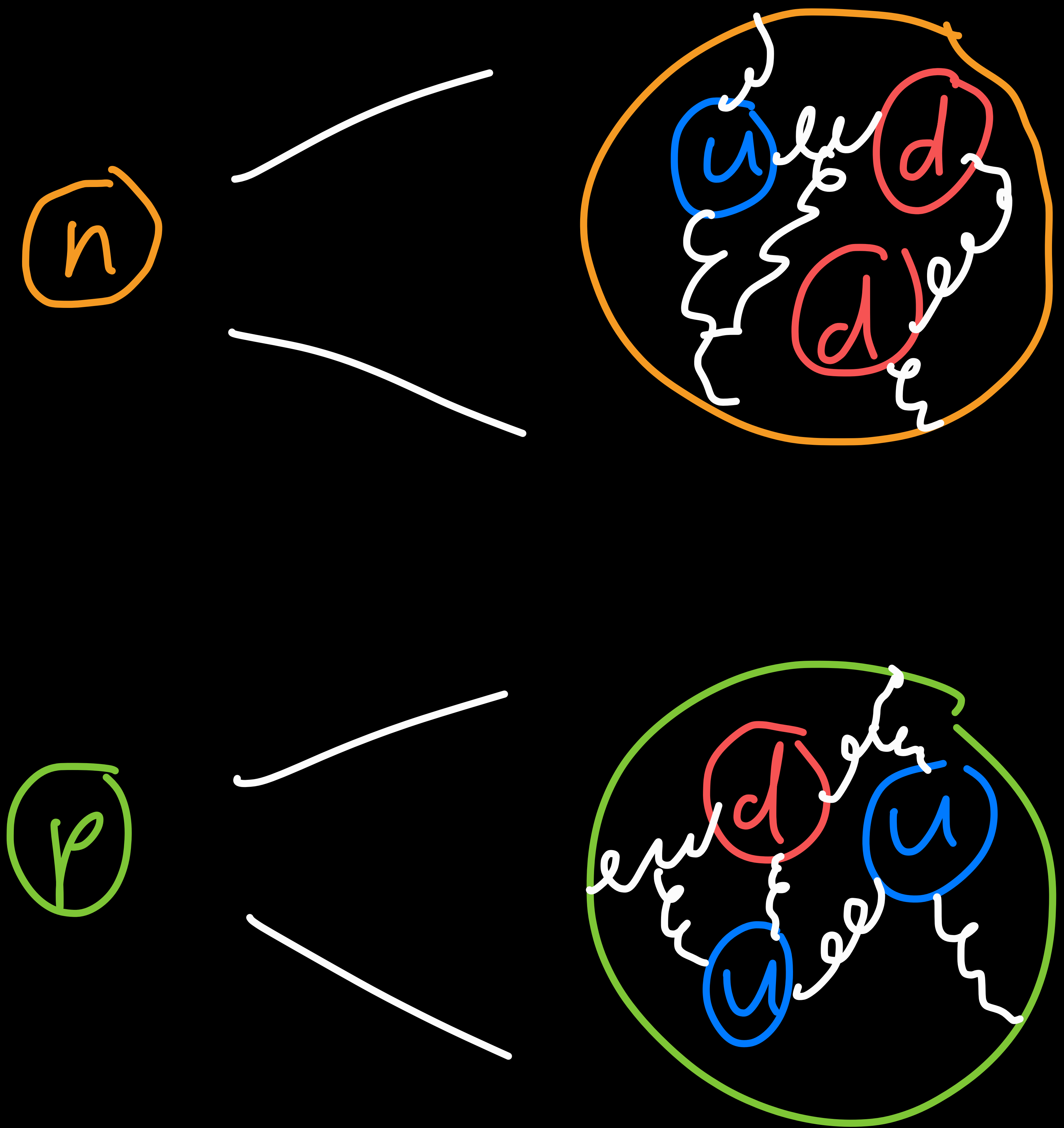


(image credit: ESA)

- 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.)

Invitation: the proton and neutron

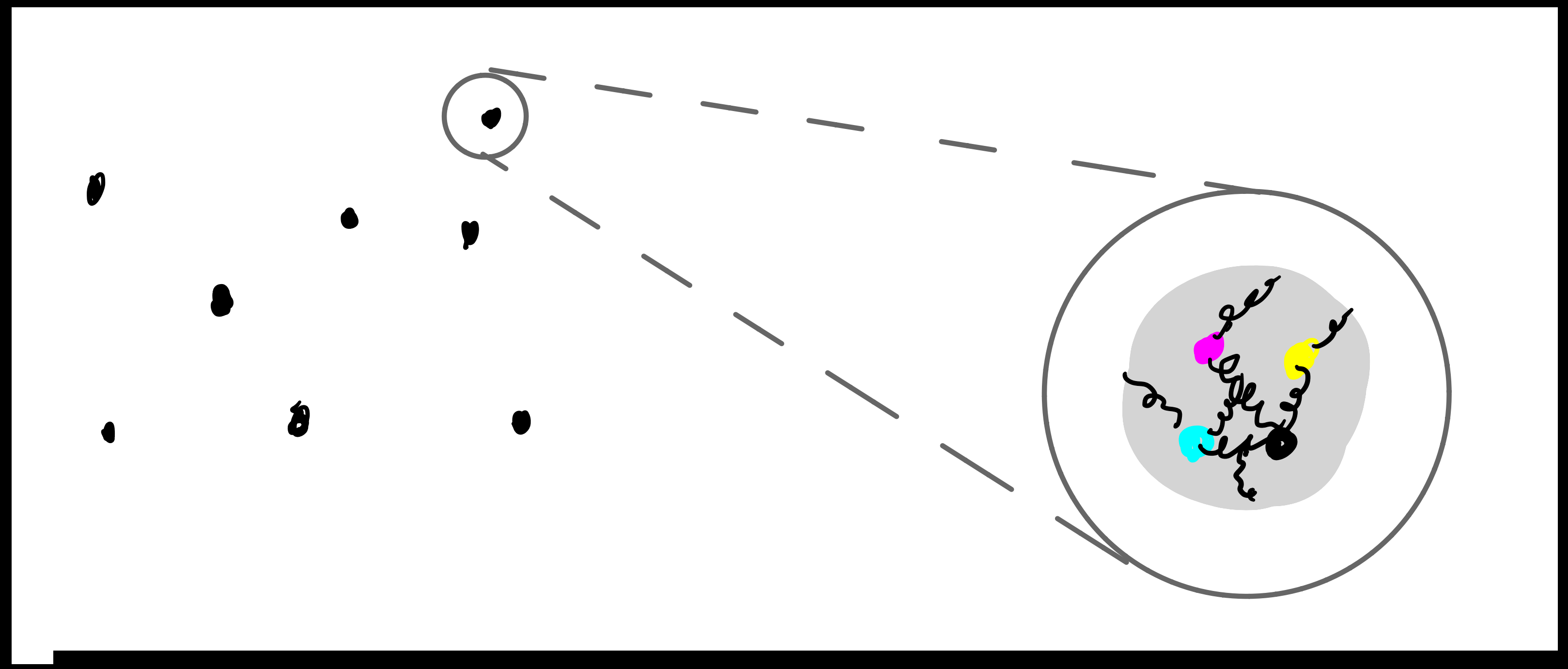
$u: Q = +\frac{2}{3}e$ $d: Q = -\frac{1}{3}e$



- 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

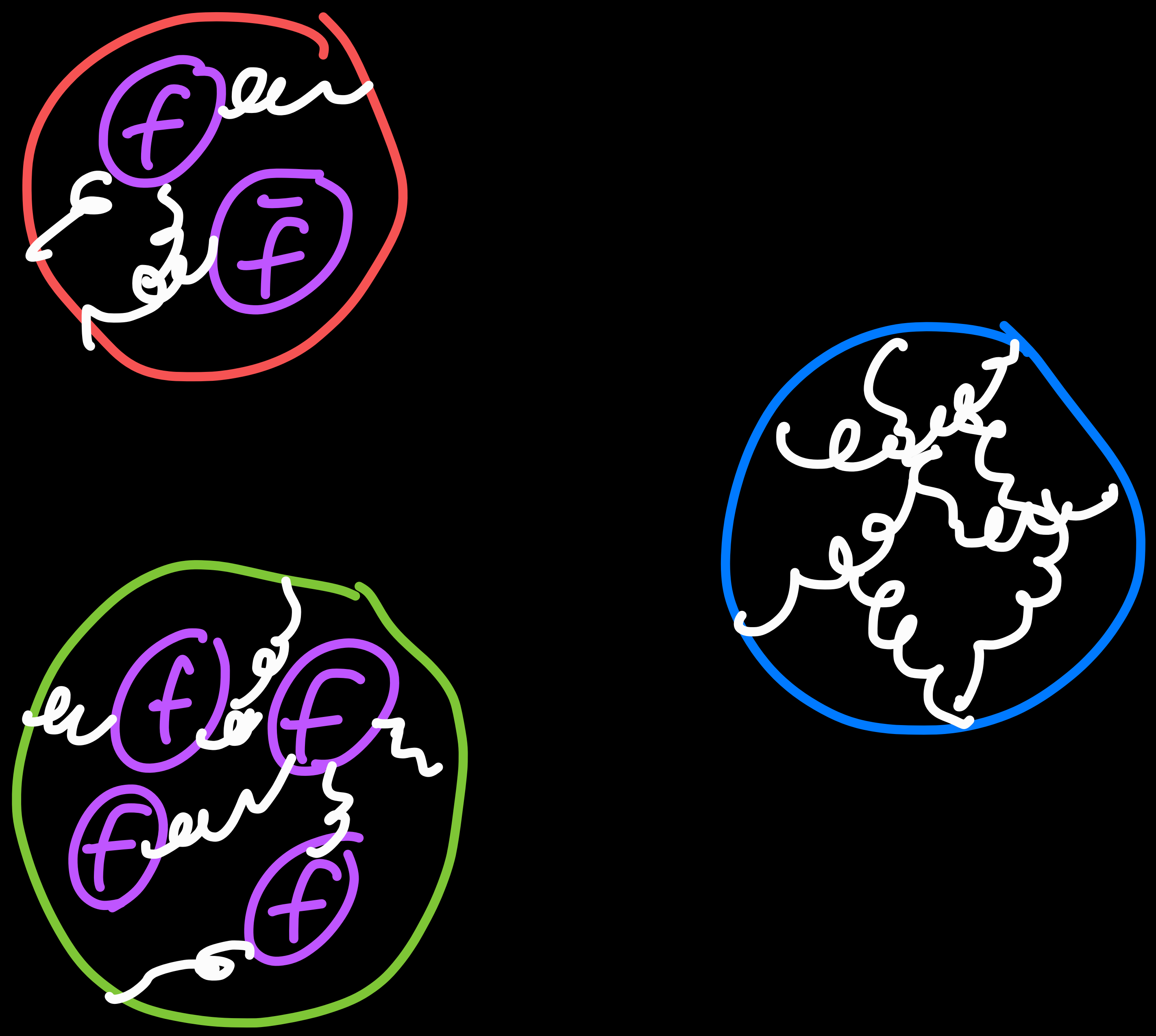


- Dark matter as a strongly-coupled composite bound state of some hidden sector.
- Weakly-bound composites, e.g. “dark atoms”, are possible and interesting too! But, I will focus mainly on strongly-bound composites.
- Well-motivated models with solutions to stability and cosmic coincidence;
- Distinctive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

2. Composite dark matter: general properties

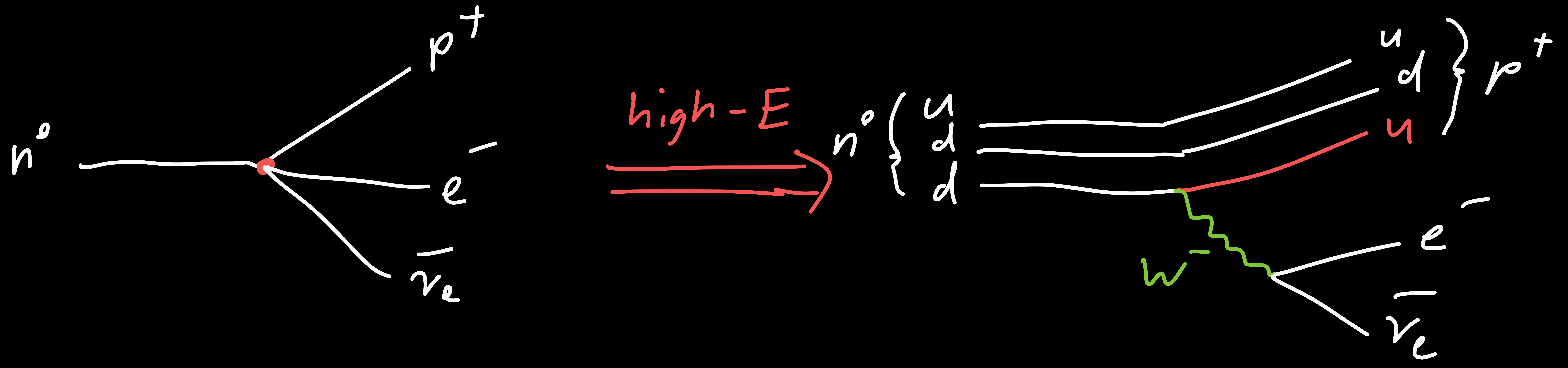
Types of cDM candidates

- 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 suppressed 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 ("integrating out"), new ones appear below the cutoff as well!

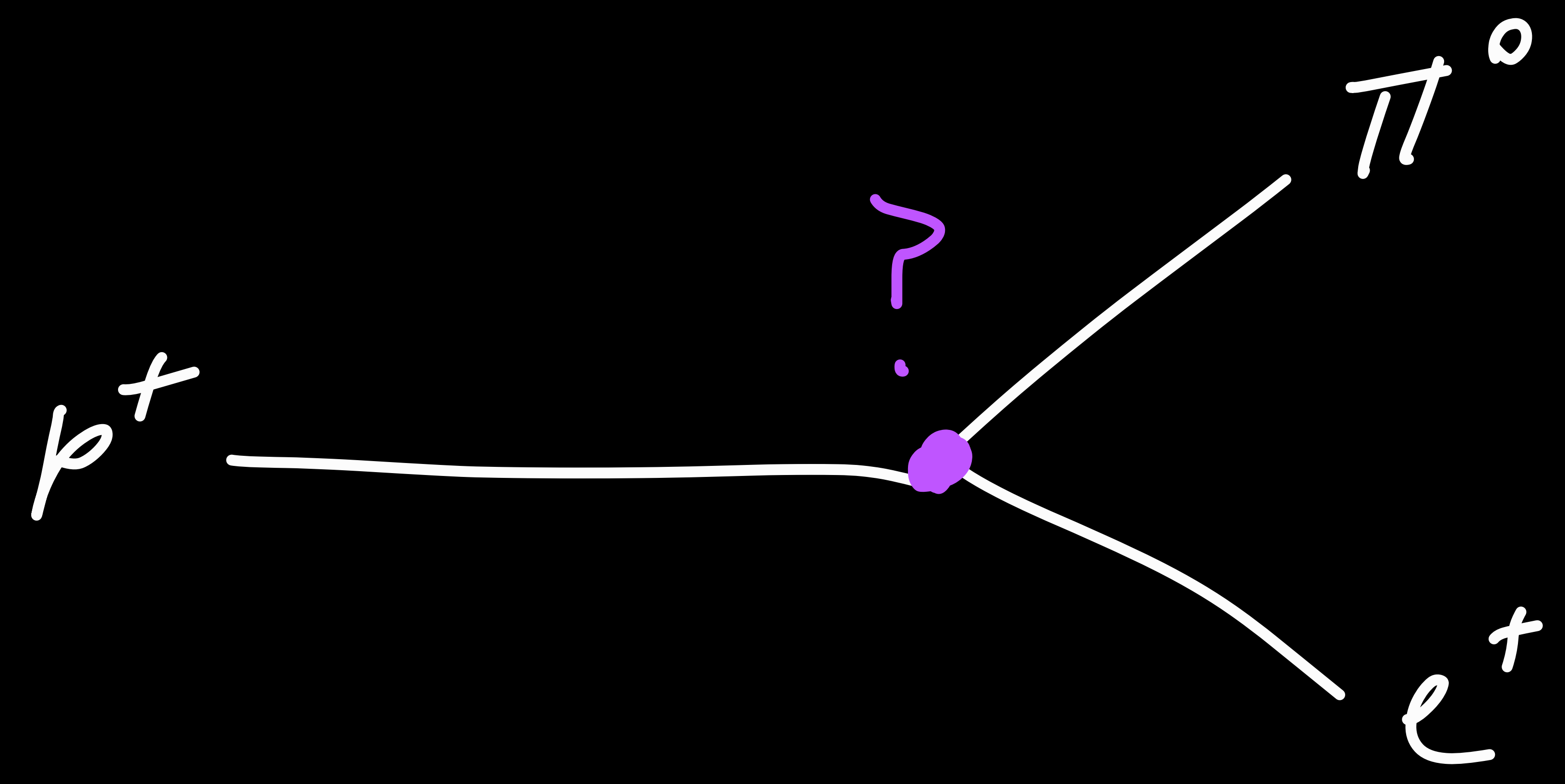


- This can lead to unexpected suppressions and "accidental" symmetries, compared to naive expectations in the low-energy theory of the composites.

Effective stability and accidental symmetry

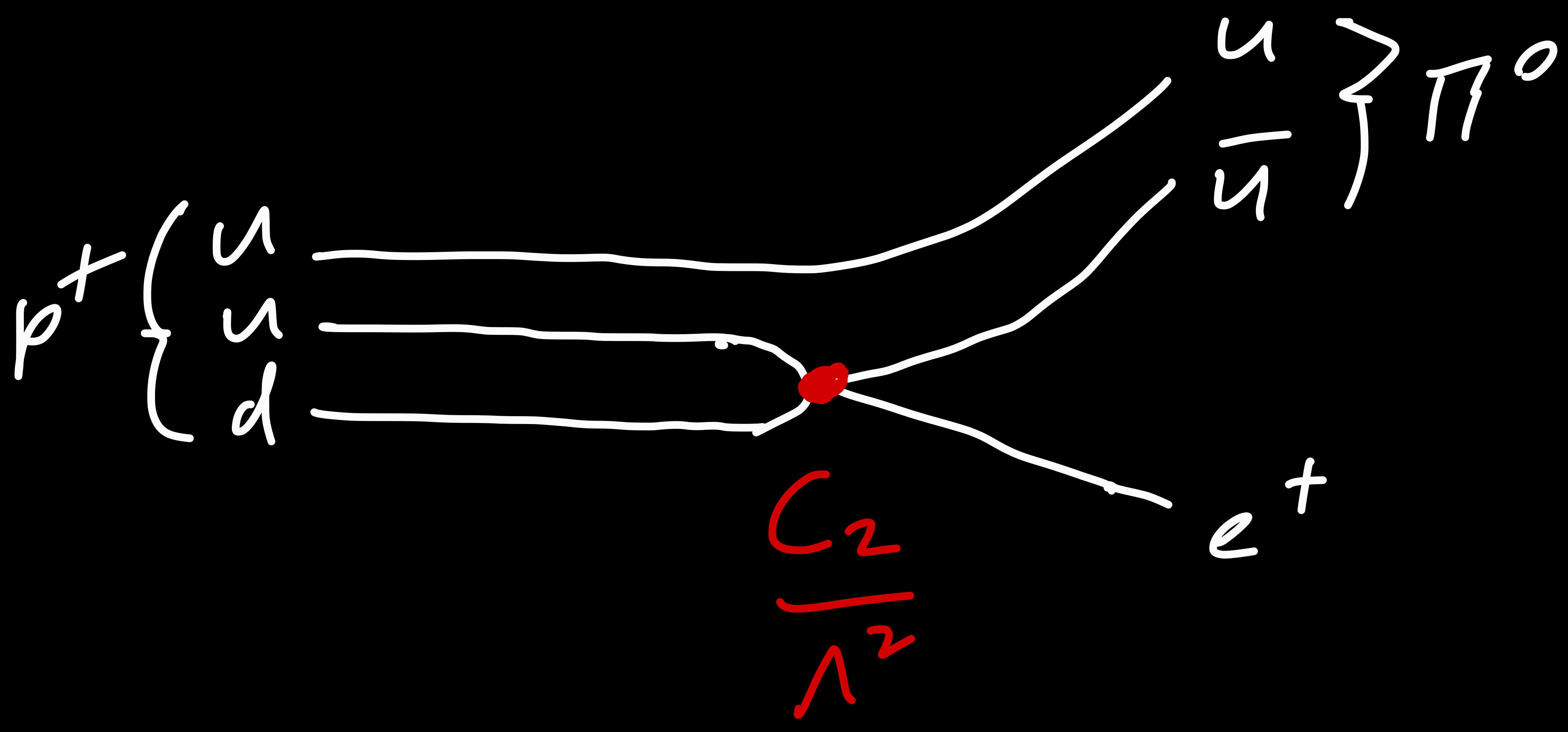
- Example: proton stability. Consider the process $p^+ \to e^+ \pi^0$. Could be mediated by an effective operator:

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



- 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!

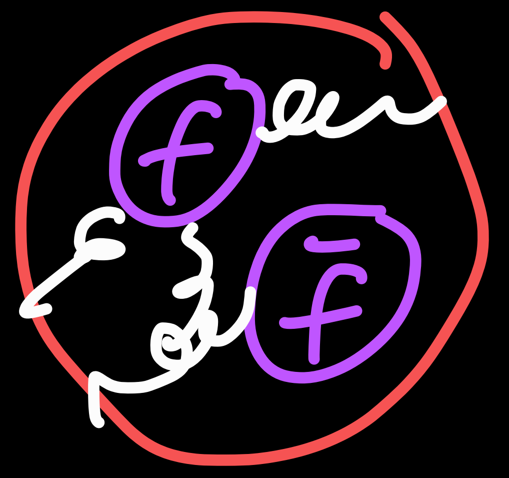
Stability of cDM candidates

- 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.

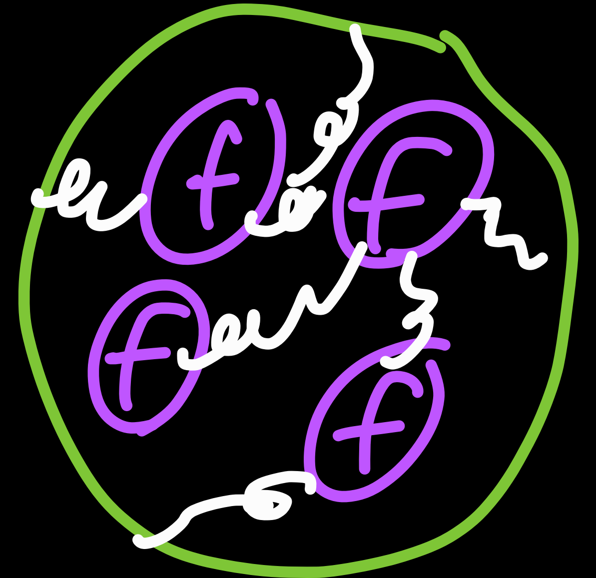
$$[\psi] = \frac{3}{2}; \quad [H] = 1; \quad [A_\mu] = [\partial_\mu] = 1 \Rightarrow [F_{\mu\nu}] = 2.$$



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

- 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!

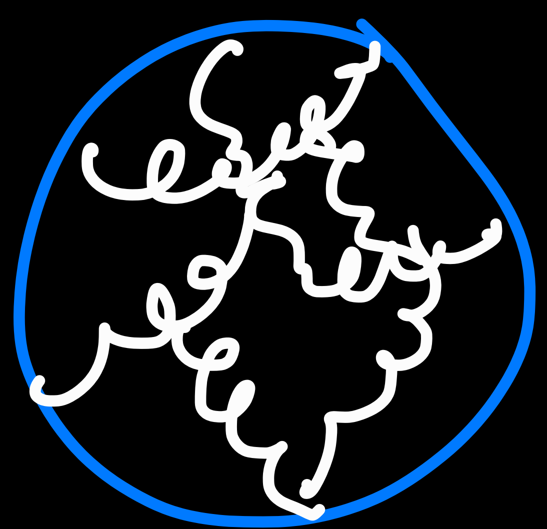
Stability of cDM candidates II



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

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

- 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:

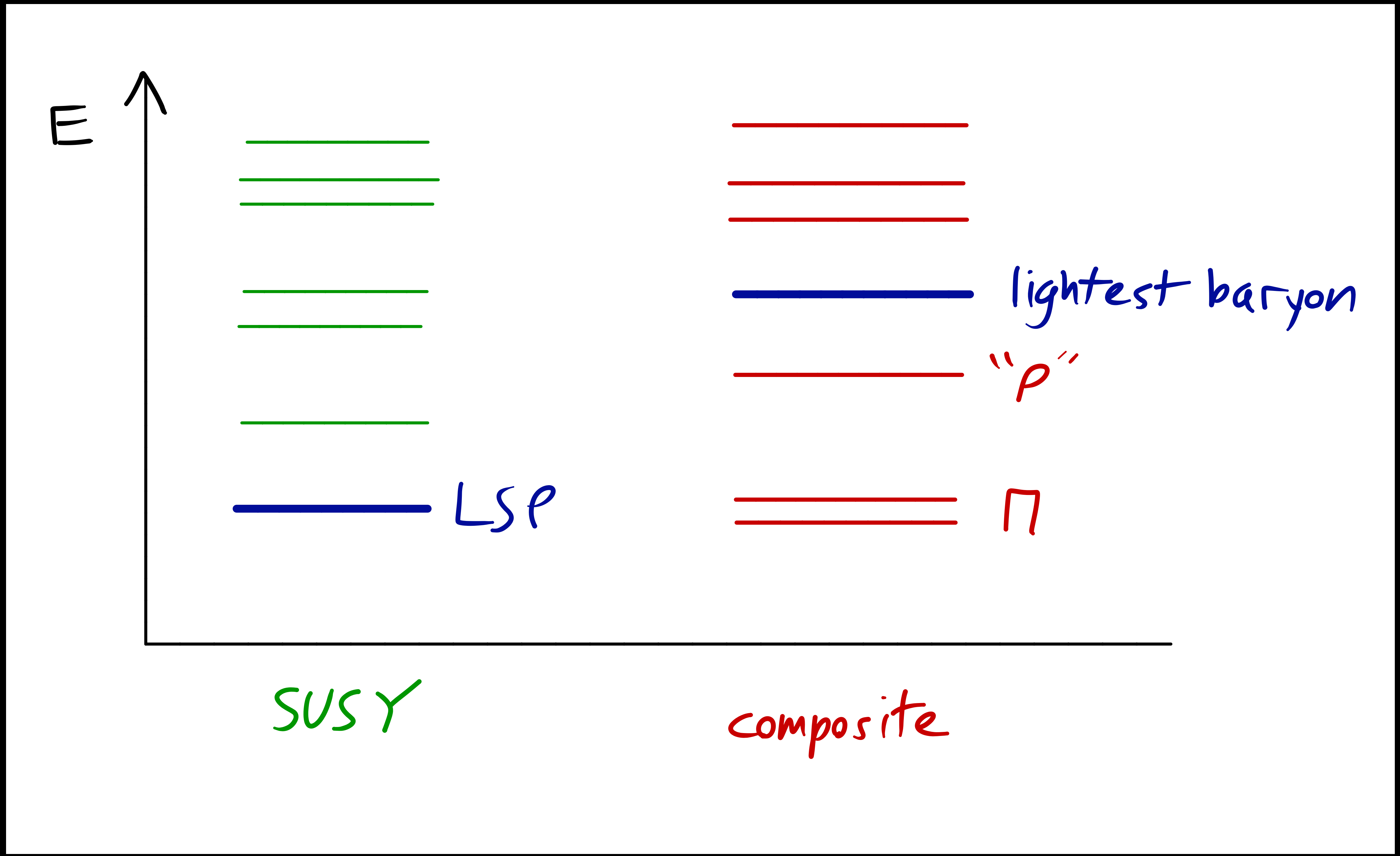
$$\frac{1}{\Lambda^2}G_{\mu\nu}G^{\mu\nu}H^\dagger H \qquad \frac{1}{\Lambda^4}\mathrm{Tr}[G_{\mu\nu}G^{\mu\nu}]\mathrm{Tr}[F_{\kappa\sigma}F^{\kappa\sigma}]$$

- Also easily stable; suppressed by ($\Lambda^2 M_h^2$) 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

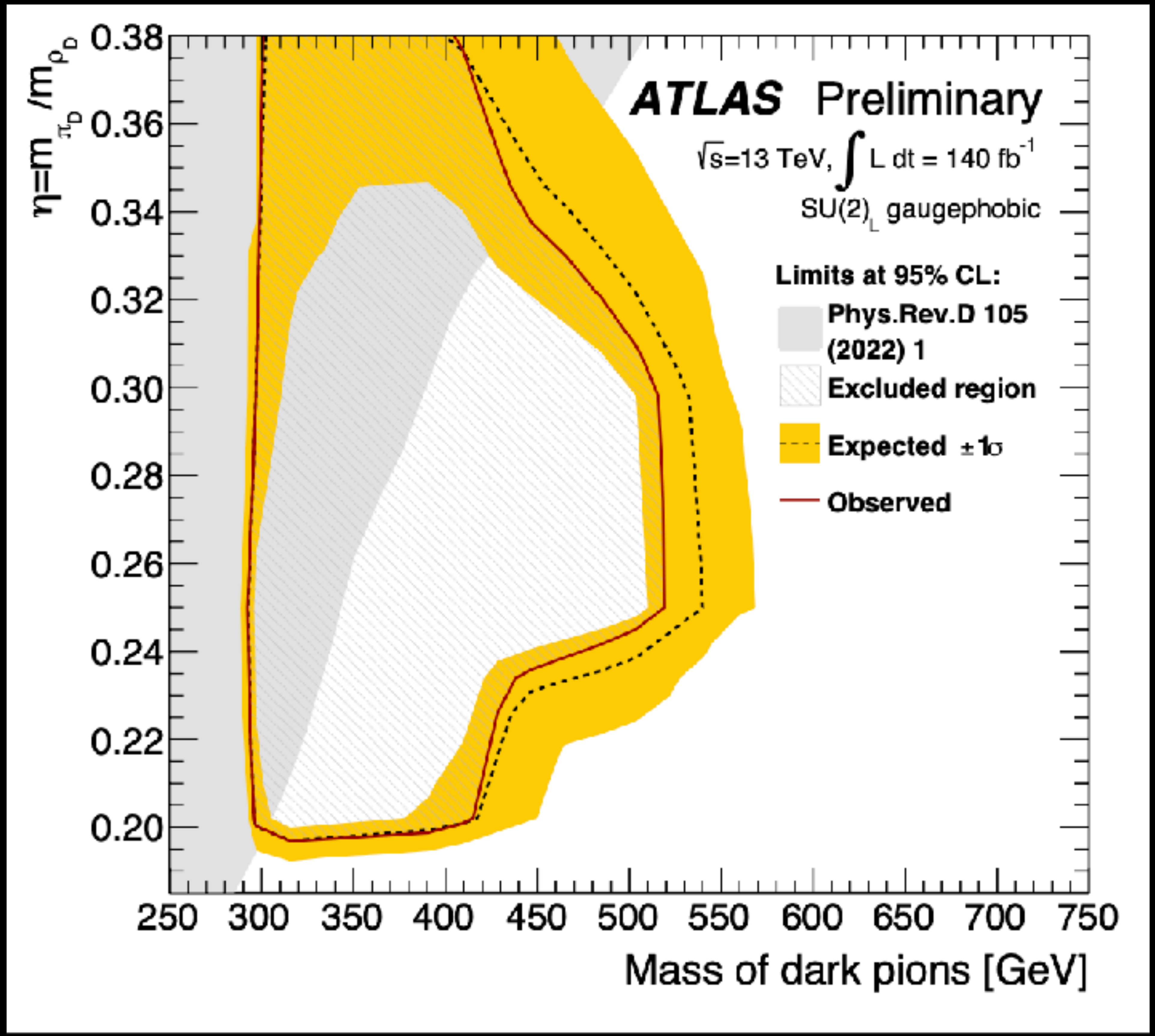
- In BSM scenarios, common for DM to be the *lightest* particle of some new sector to avoid decay, e.g. lightest supersymmetric partner in SUSY theories.

- 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!)

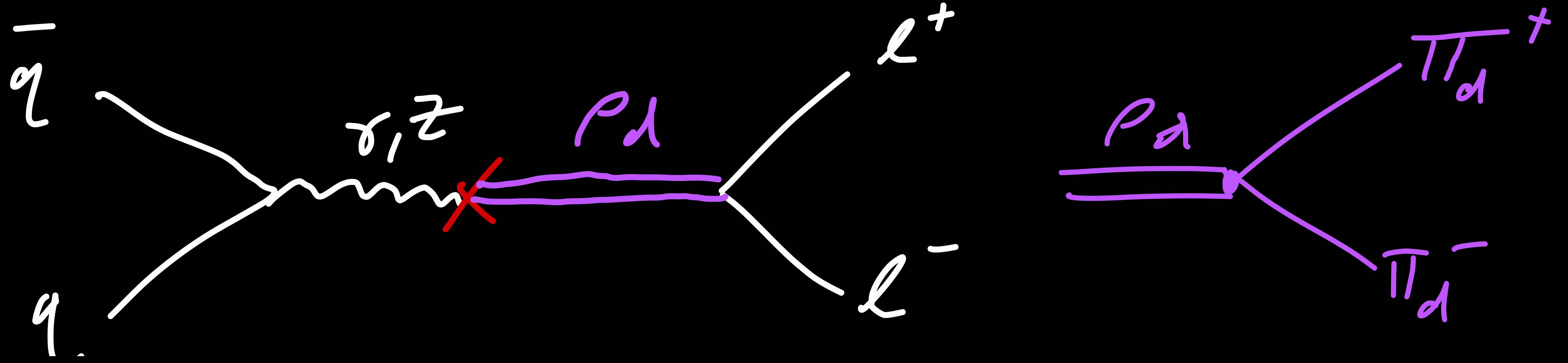


Bounds on charged dark mesons

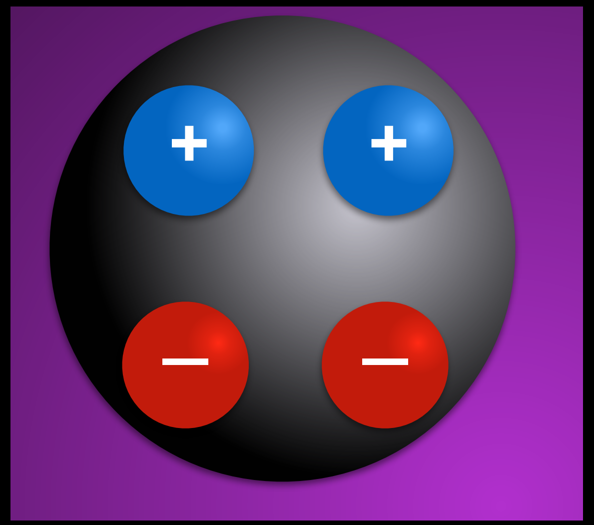
ATLAS experiment, ATLAS-CONF-2023-021



*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 $\pi_d > 100$ GeV (—> somewhat higher dark-baryon mass bound.)



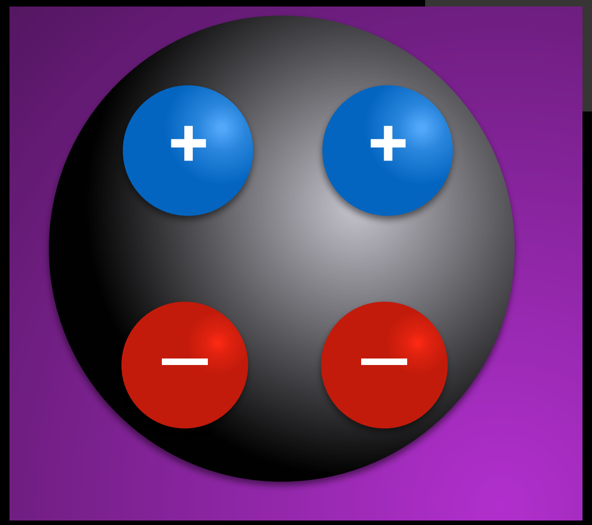
Example: “Stealth dark matter”

- 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	$\overline{\mathbf{N}}$	$(\mathbf{1}, -1/2)$	$-1/2$

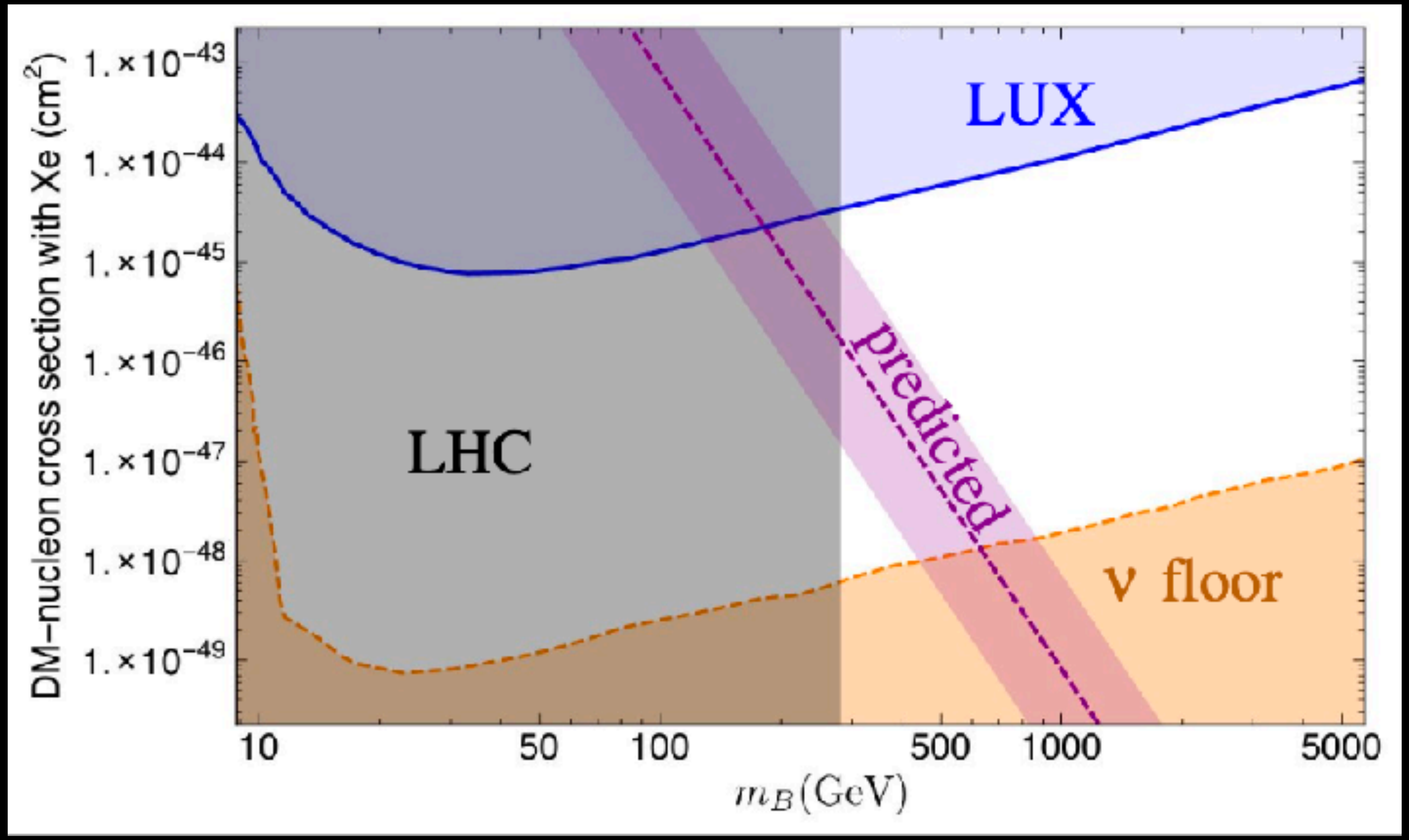
Stealth DM: Bounds on parameter space



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

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

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

- 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.)

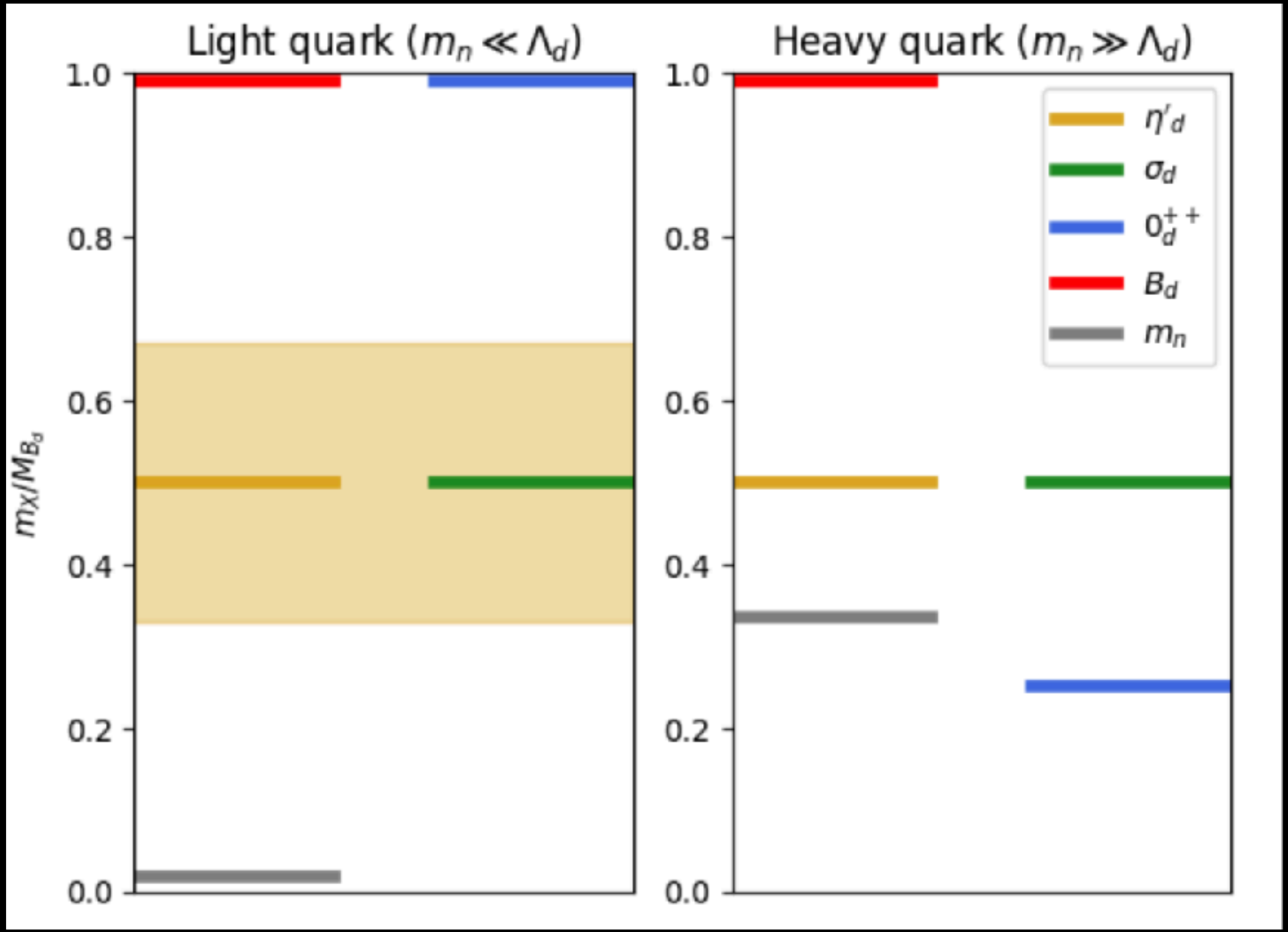
Spectrum and masses

- This is a "one-flavor" QCD-like dark sector, which has some highly distinctive features*:

- 1) <u>No light pions:</u> chiral symmetry $U(1)_L$ x $U(1)_R$ 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) <u>High-spin DM:</u> 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

- The hyper-stealth dark matter model is shown to the right. "Hyper stealth" since now all light states are SM singlet!

- **UV complete:** "equilibration sector" of more $SU(N_D)$-charged fermions, with electroweak interactions - heavy "lepton-like" doublet l_d. (Can also add singlet e_d to more closely match stealth DM, but not needed.)

- After EWSB, charge-neutral component of l_d can mix with n_d, giving rise to effective ops from above.

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

Matching

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

- Mass diagonalization gives two neutral fermions Ψ_n, Ψ_N (Q=0) and one charged Ψ_E (Q=-1).

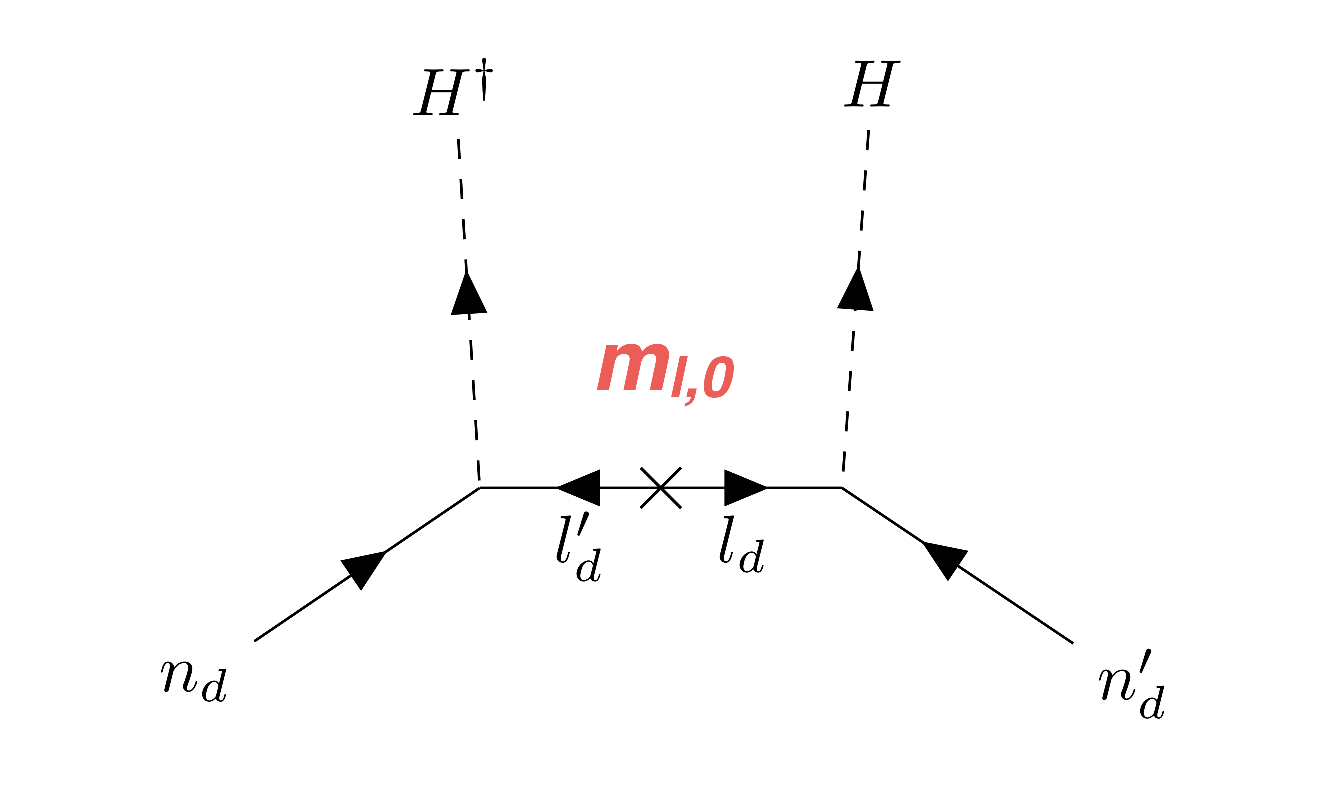
- Take **$m_{l,0} \sim m_{eq} >> m_{n,0}$**. Charged state and one neutral state are heavy; instead of full diagonalization and mixing, we can think of integrating out heavy fields to get our EFT.

- For example, Higgs diagram on the right leads to scalar coupling, identifying $\Lambda \sim m_{eq}$:

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

$$\mathcal{L} \supset -m_{n,0} n_d n'_d + m_{l,0} \epsilon_{ij} l^i_d l'^j_d + h.c.\,,$$

$$\mathcal{L} \supset y_{ln} \epsilon_{ij} l^i_d H^j n'_d - y'_{ln} l'^i_d H^\star_i n_d + h.c.\,.$$



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 yθ, extra enhancement.)
- The Yukawa splitting parameter ε is parity-violating; necessary to obtain the operator c_Z' that leads to η_d' decay.

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

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

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

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

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

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

4. HSDM constraints and phenomenology

Direct detection

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

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

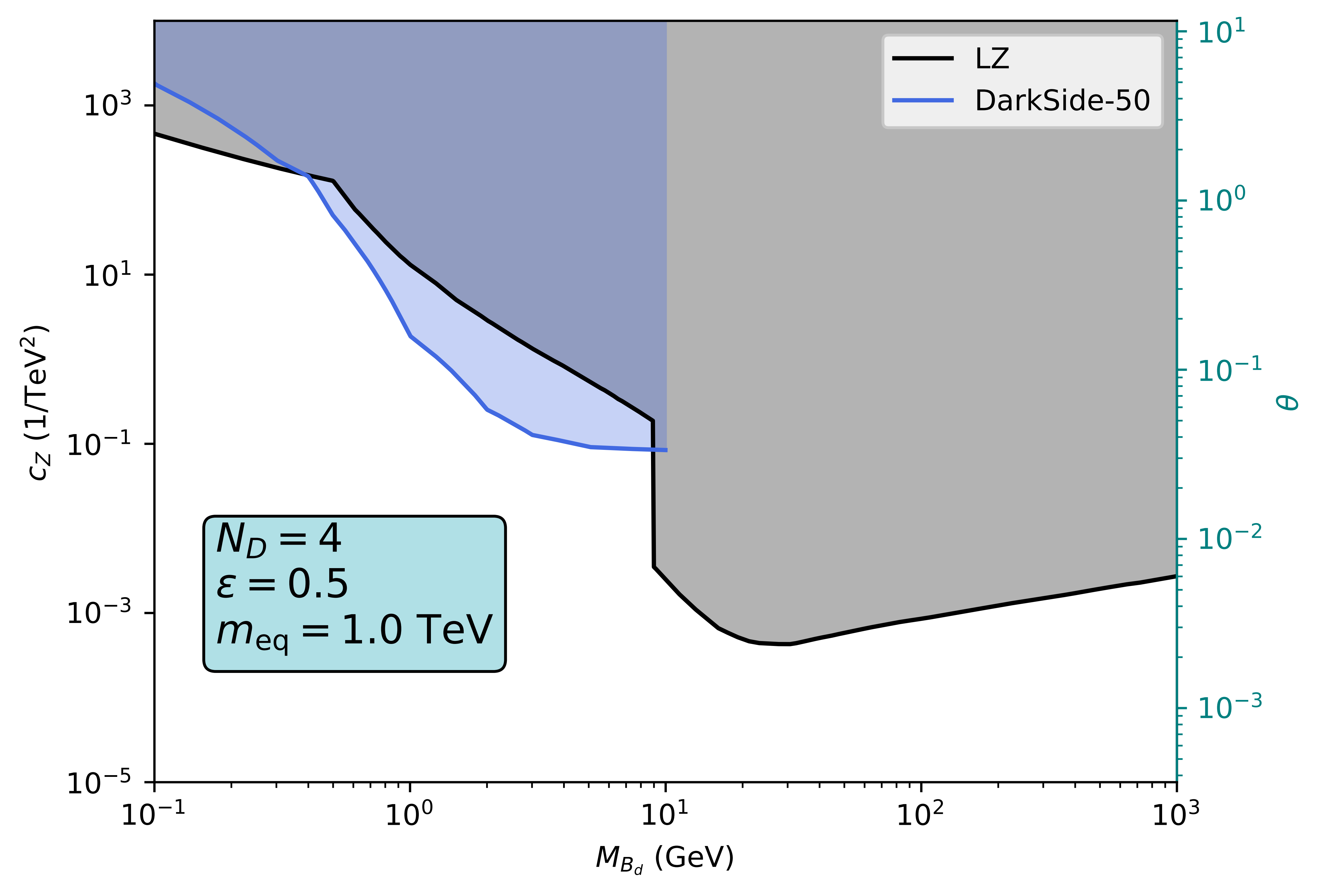
$$\sigma_{Z,n} \approx 10^{-37}\left(\frac{\mu_n}{1\ \mathrm{GeV}}\right)^2\theta^4\ \mathrm{cm}^2.$$

- 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.

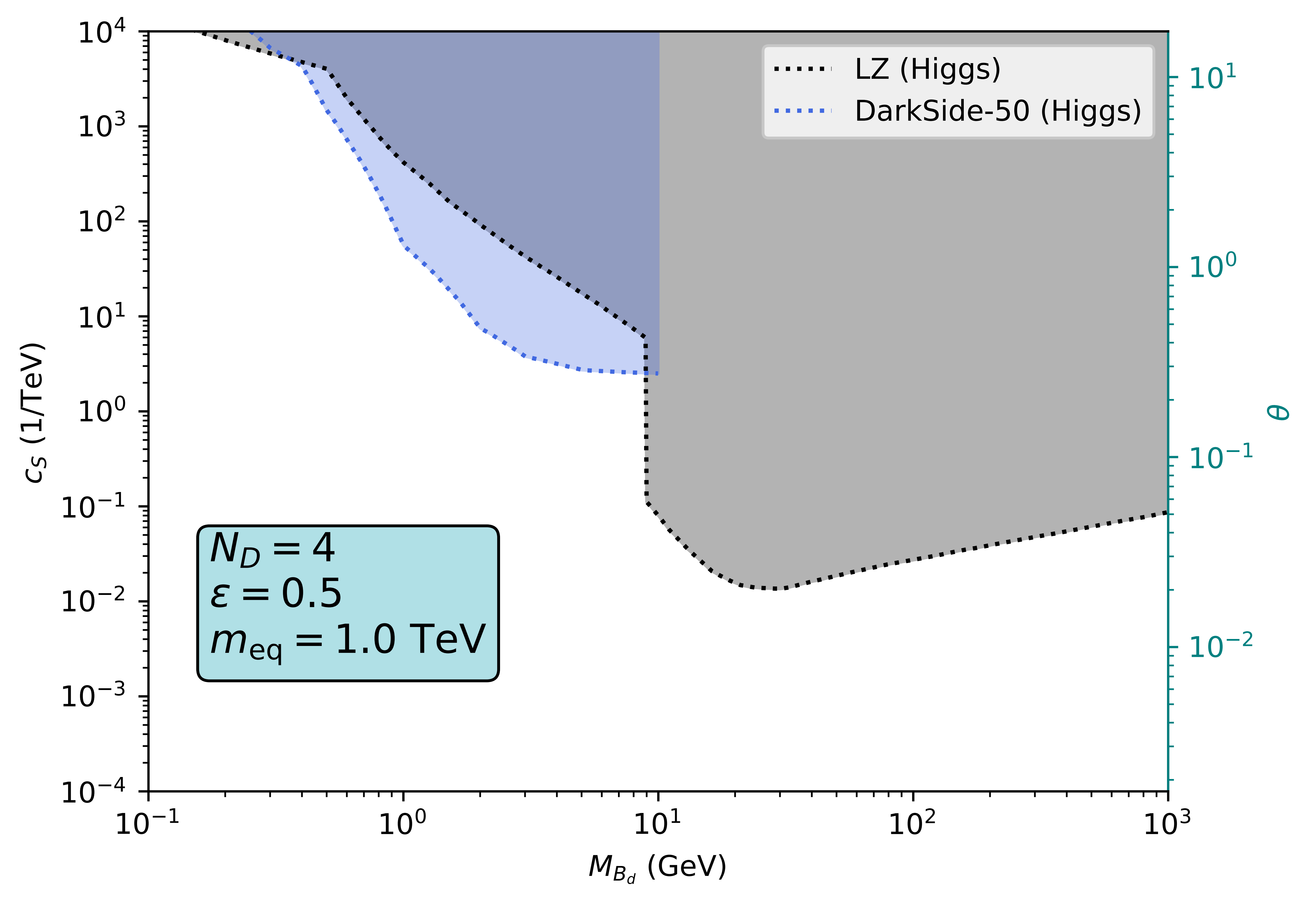
$$\sigma_{H,n}(B_d) = \frac{\mu_n^2}{\pi A^2}(Z\mathcal{M}_p + (A-Z)\mathcal{M}_n)^2, \quad \mathcal{M}_a = \frac{g_a g_{B_d,h}}{m_H^2},$$

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

(*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.

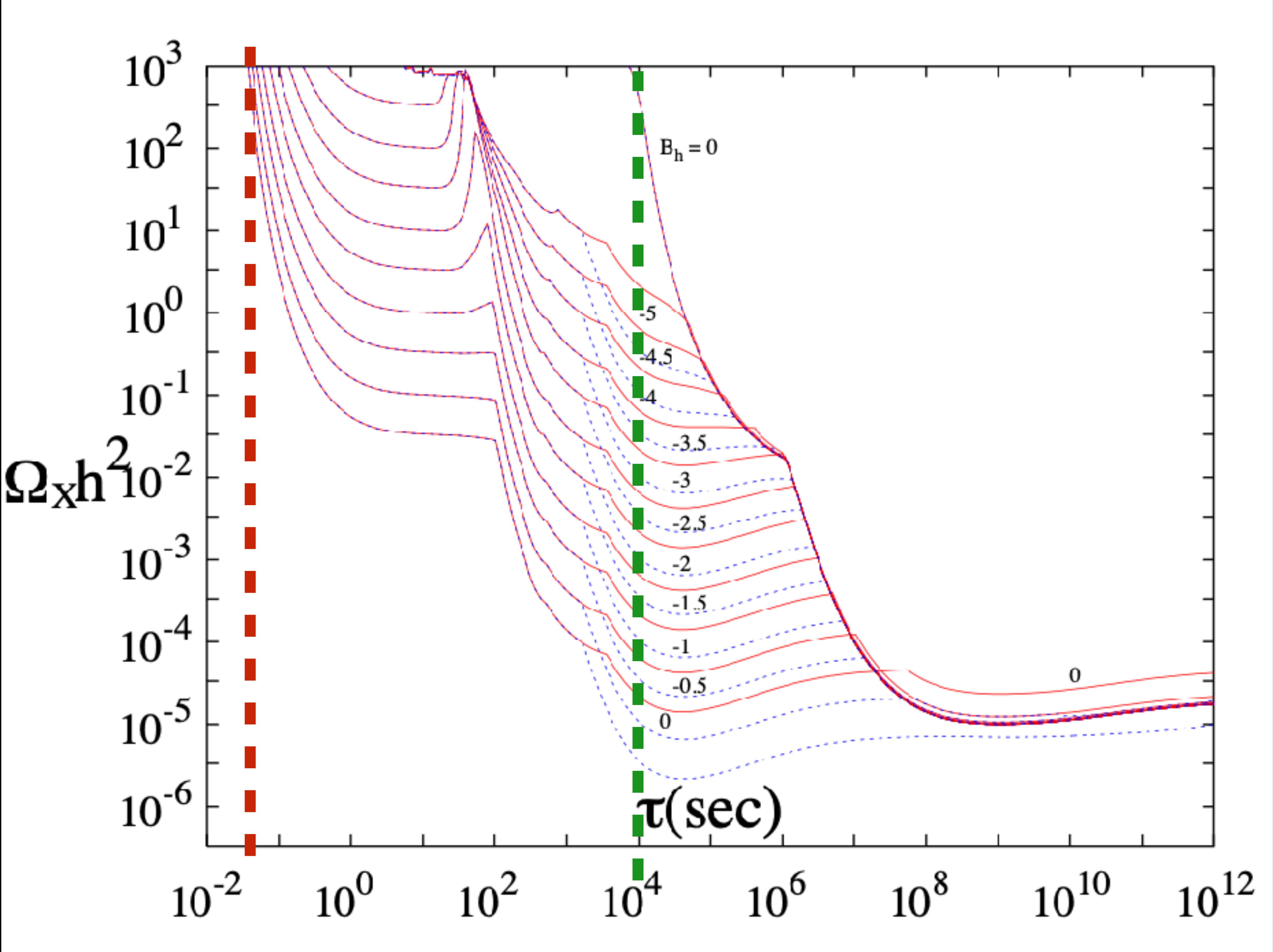


- Right: Higgs exchange bounds. In terms of HSDM completion (θ), they are always subleading. For the more general EFT, Higgs exchange constrains c_S vs. c_Z/c_Z'.

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.

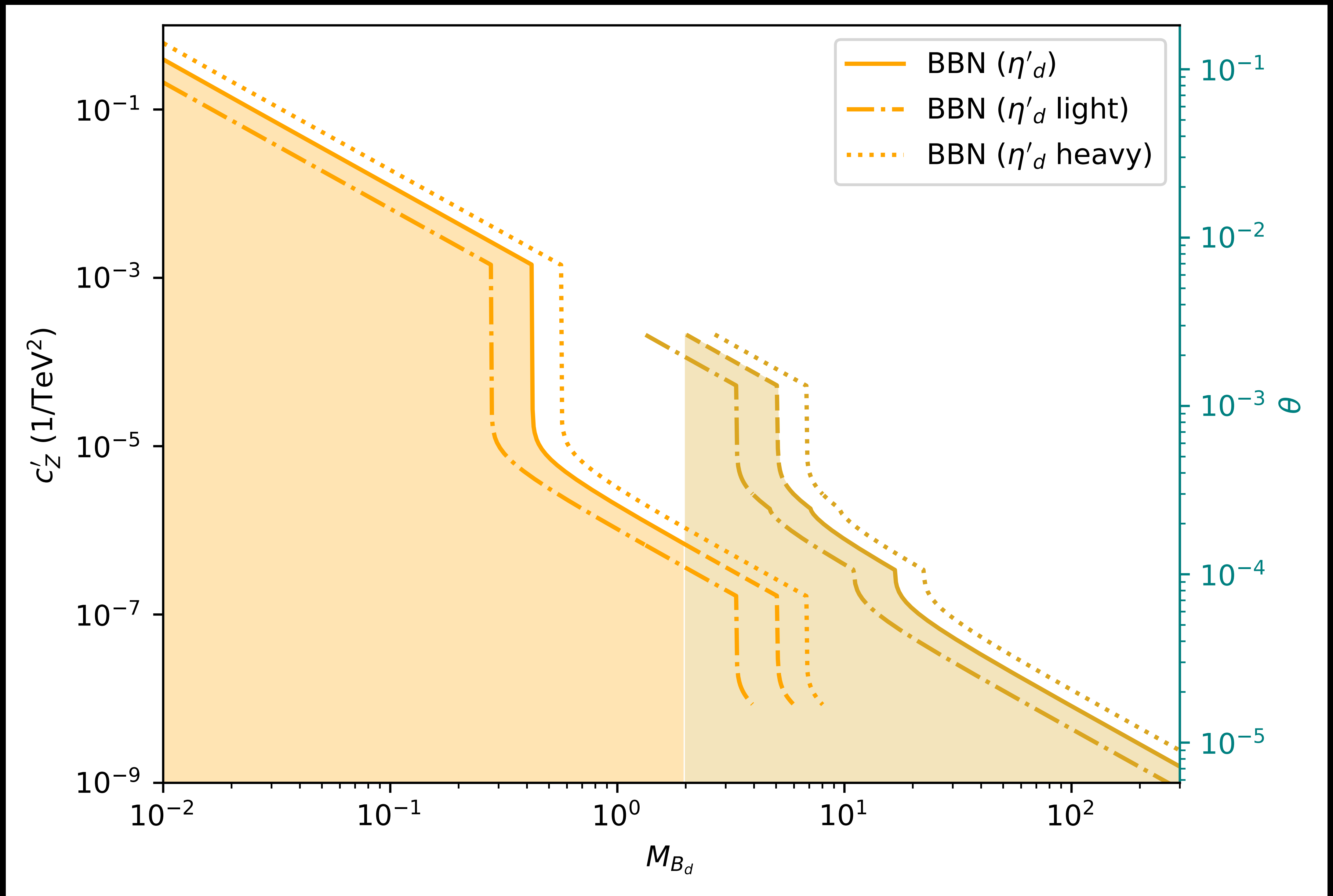


- Estimate η_d' decay by first matching on to low-energy effective theory (chiral Lagrangian):

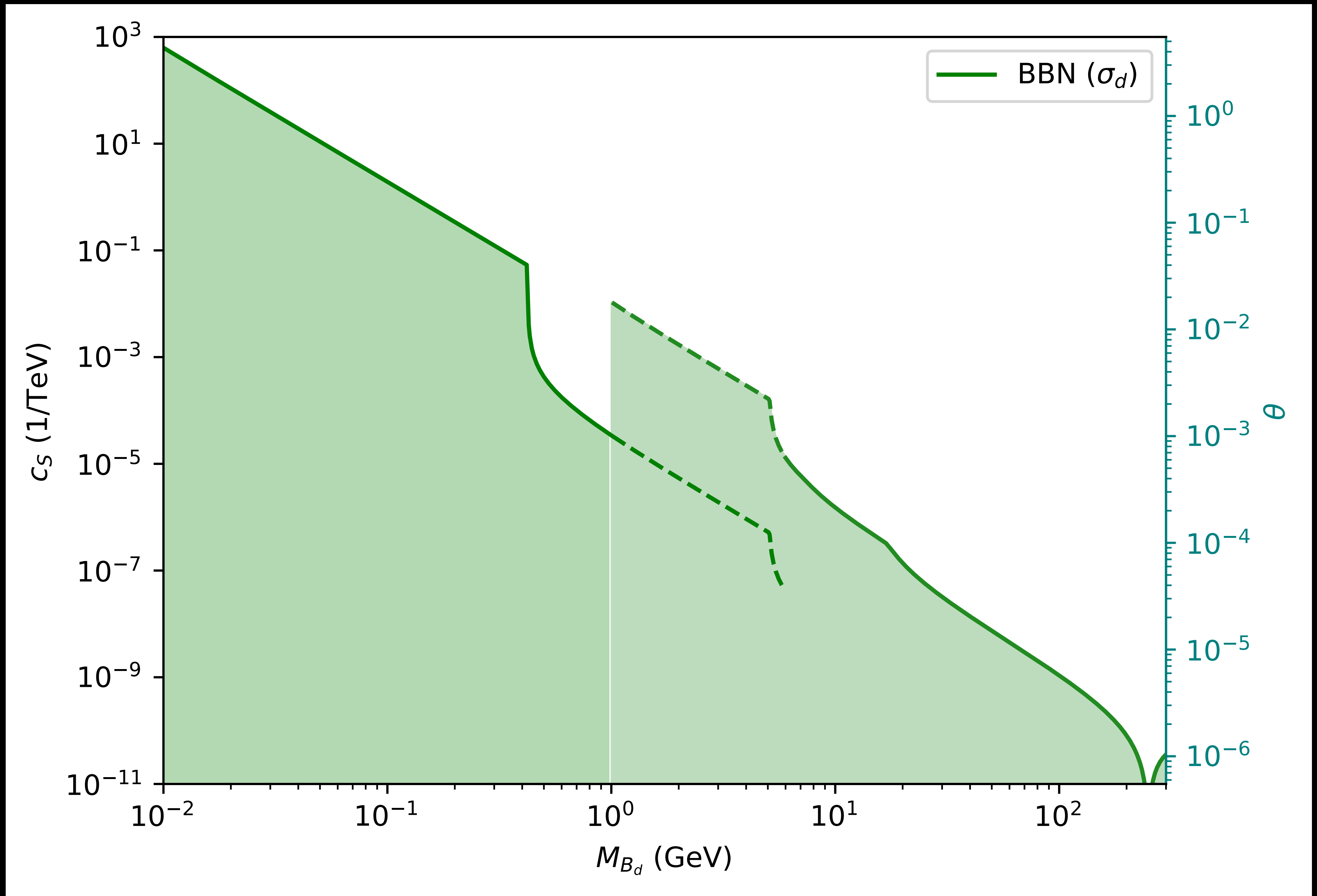
$$j_A^\mu = \bar{\Psi}_n \gamma^\mu \gamma^5 \Psi_n = -f_{\eta'} \partial^\mu \eta'_d$$

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

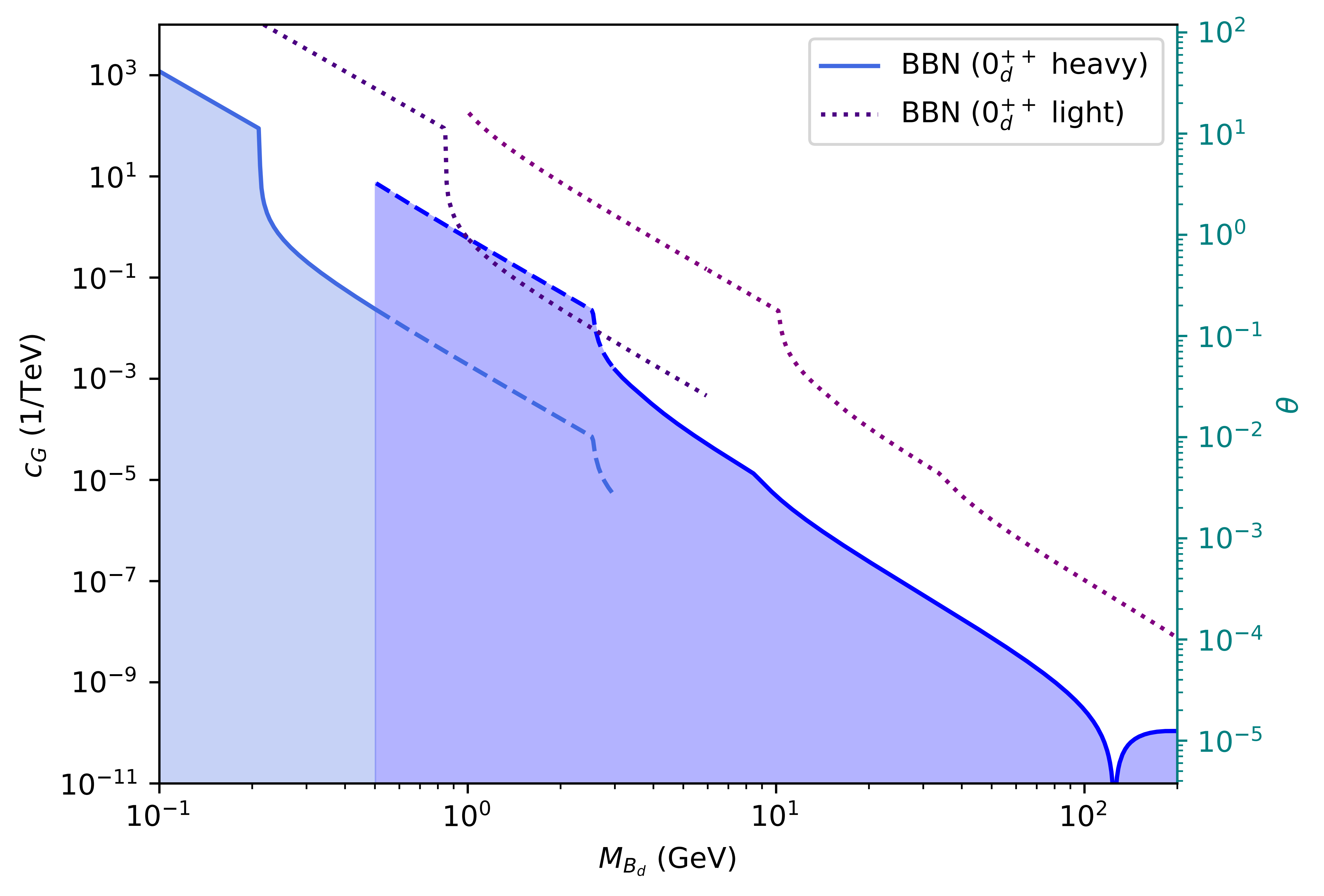
$$\mathcal{L}_{\eta'} \supset \frac{c'_Z}{\Lambda^2} f_{\eta'} \eta'_d \left(1 + \frac{h}{v}\right) \sum_f m_f \bar{f} i \gamma_5 f$$



- 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 η_d' varies over parameter space.

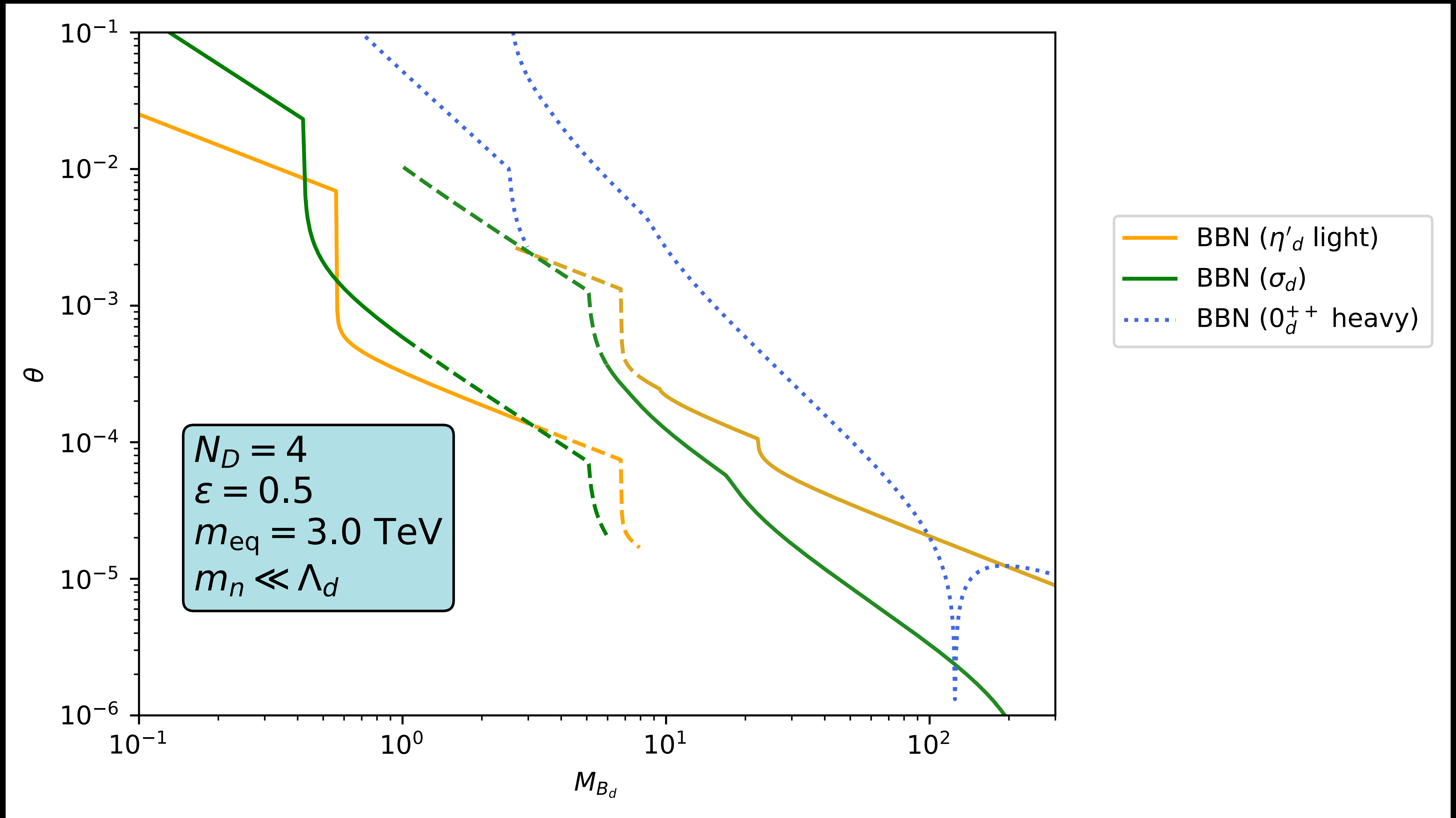


- Below: dark 0_d++ glueball decay through c_G operator (HH current coupling.) Estimated following details in arXiv:2310.13731*.
- Very strong bounds if the 0_d++ is light (heavy-quark case!) Also strong in light-quark case, but then mixing with σ_d meson accelerates decay.

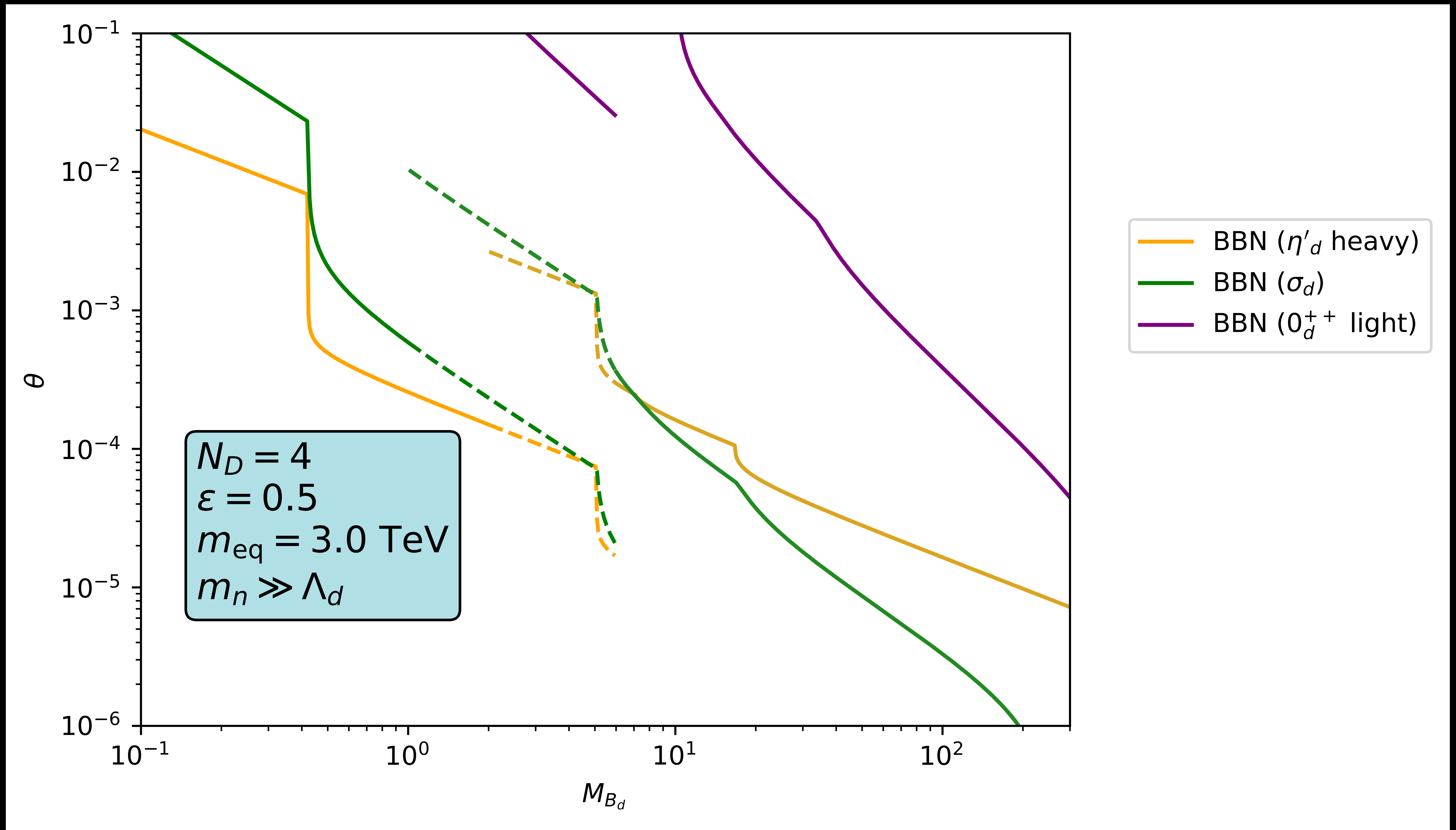


- Above: dark σ_d meson decay through c_S operator (HH current coupling again, but to fermions.)
- Estimated similar to 0_d++ case; decay width proportional to SM Higgs at different mass. Stronger bounds than η_d' in parts of parameter space!

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

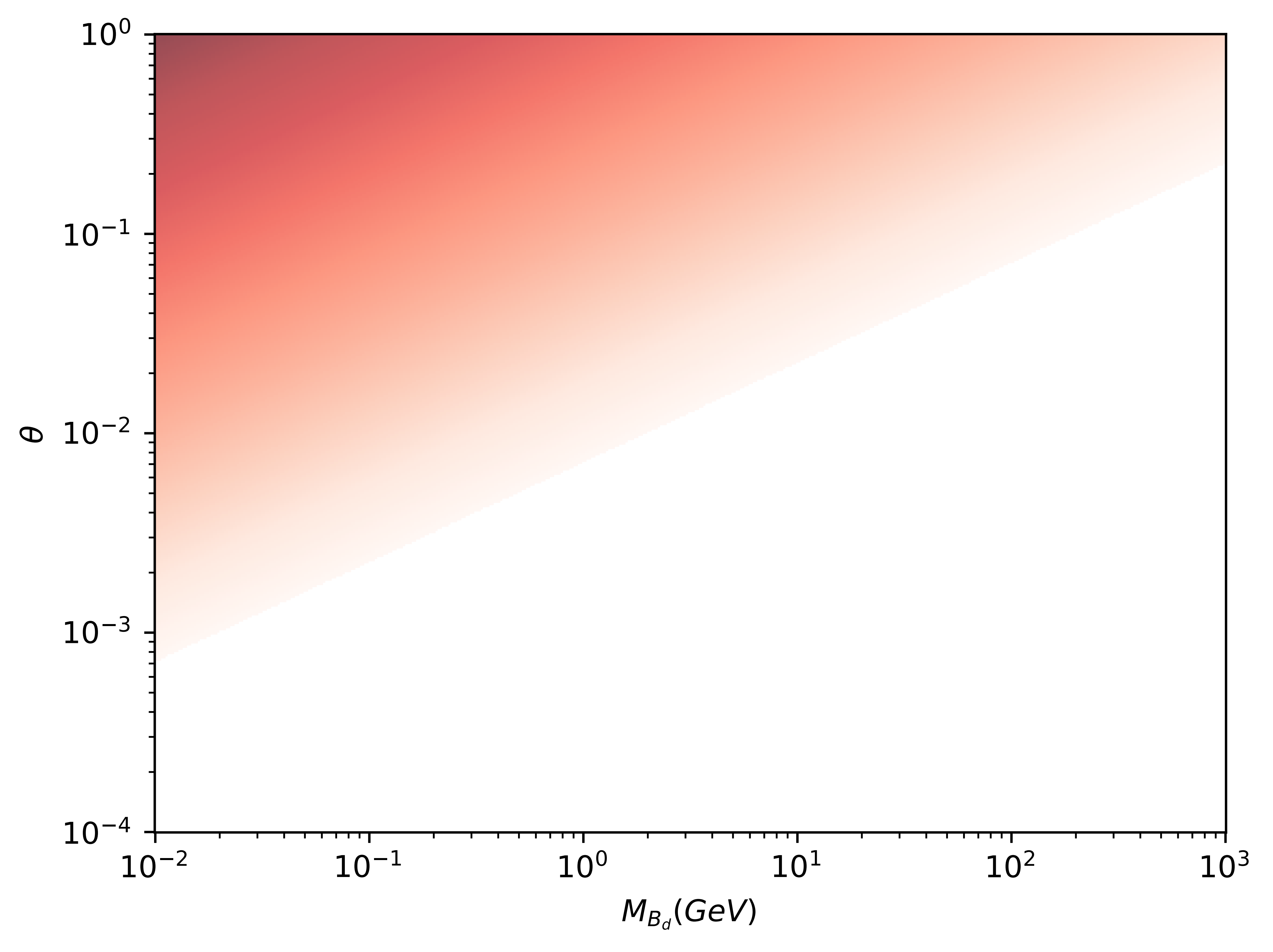


- Same results as above, now comparing various channels
- Light-quark case (left): strongest would-be bounds from glueball 0_d++, but expected to mix strongly with σ_d which reduces to σ_d bound.



- Heavy-quark case (right): 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

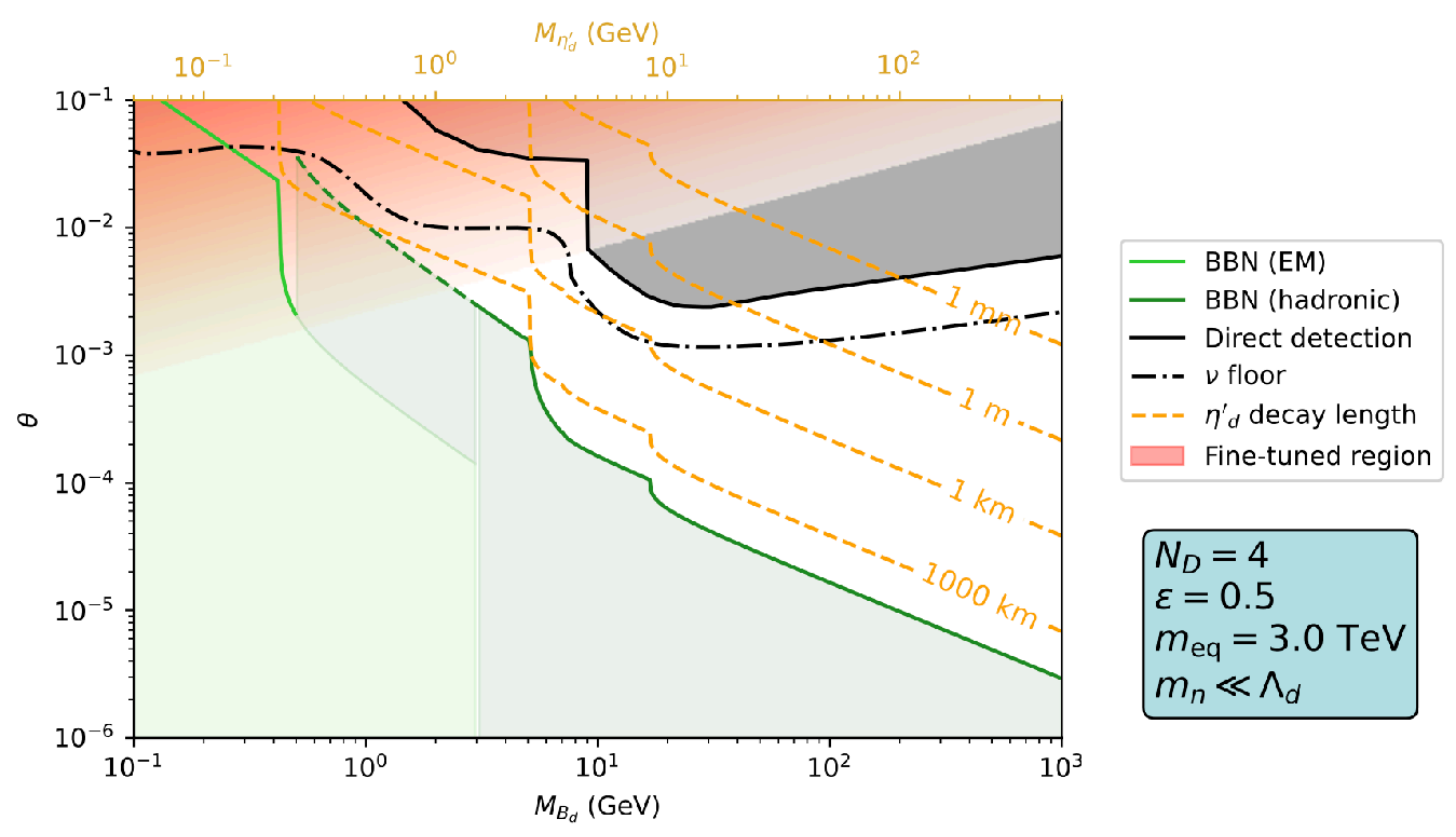
$$m_n \approx m_{n,0} - \frac{y_{ln} y'_{ln} v^2}{2\Lambda} = m_{n,0} - \theta^2 \Lambda$$

- Soft bound to avoid fine-tuning cancellation between vectorlike mass and EW-induced mass:

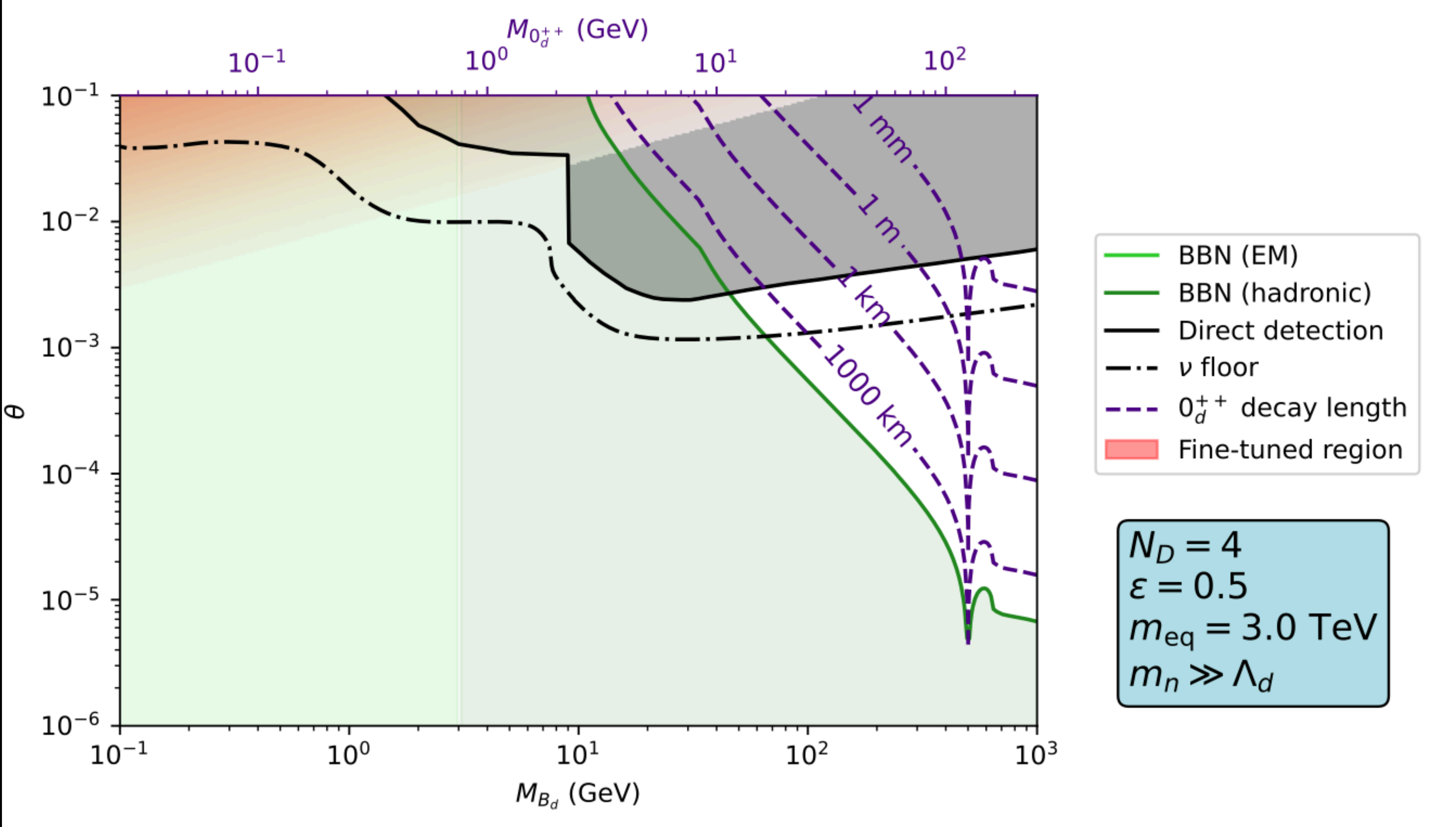
$$\theta^2 \Lambda \lesssim m_n$$

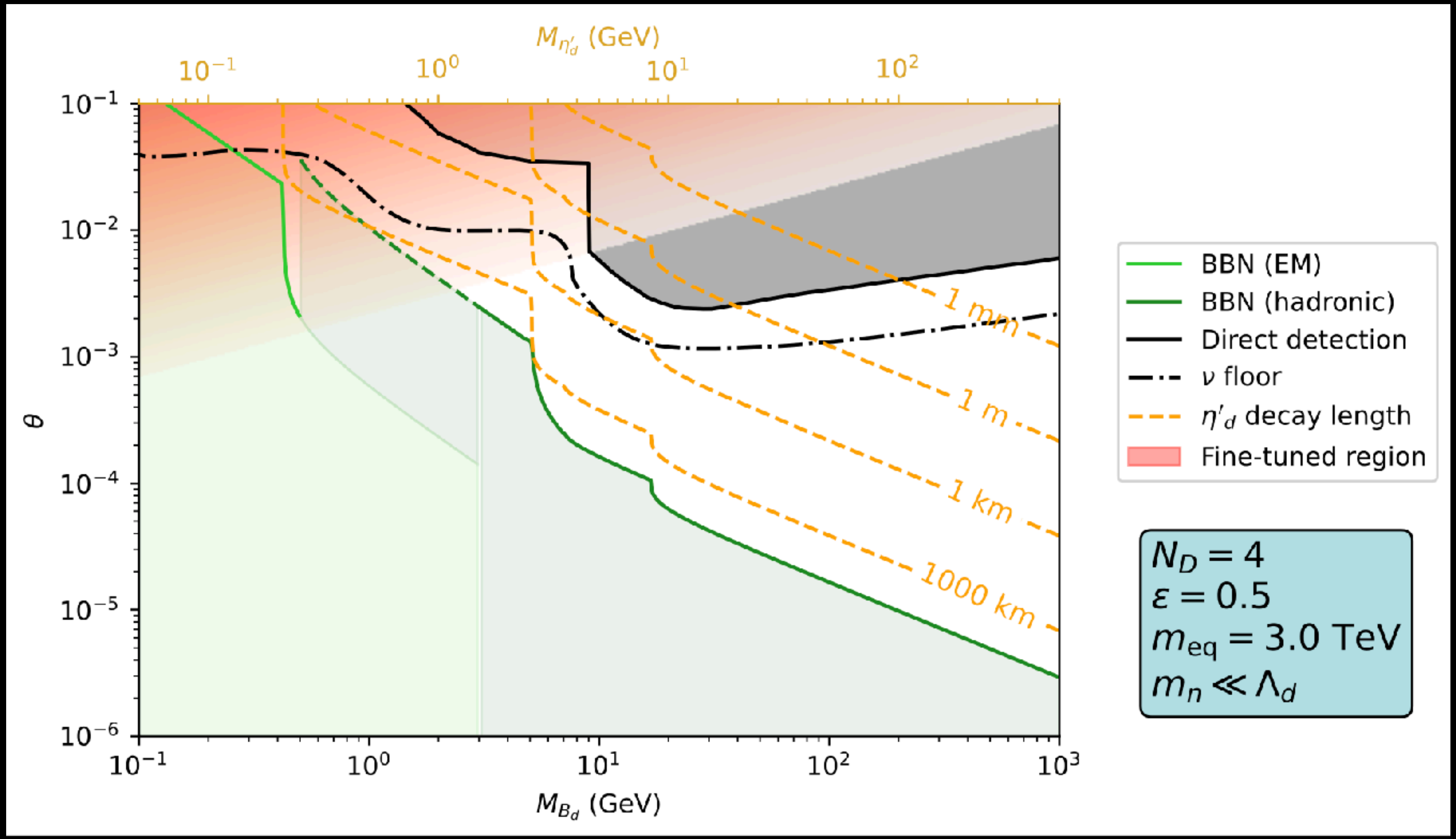
- Contribution to Higgs mass can also lead to fine-tuning if $\Lambda_d > v$, but negligible vs. other constraints.

Combined bounds



Combined bounds (HQ limit)

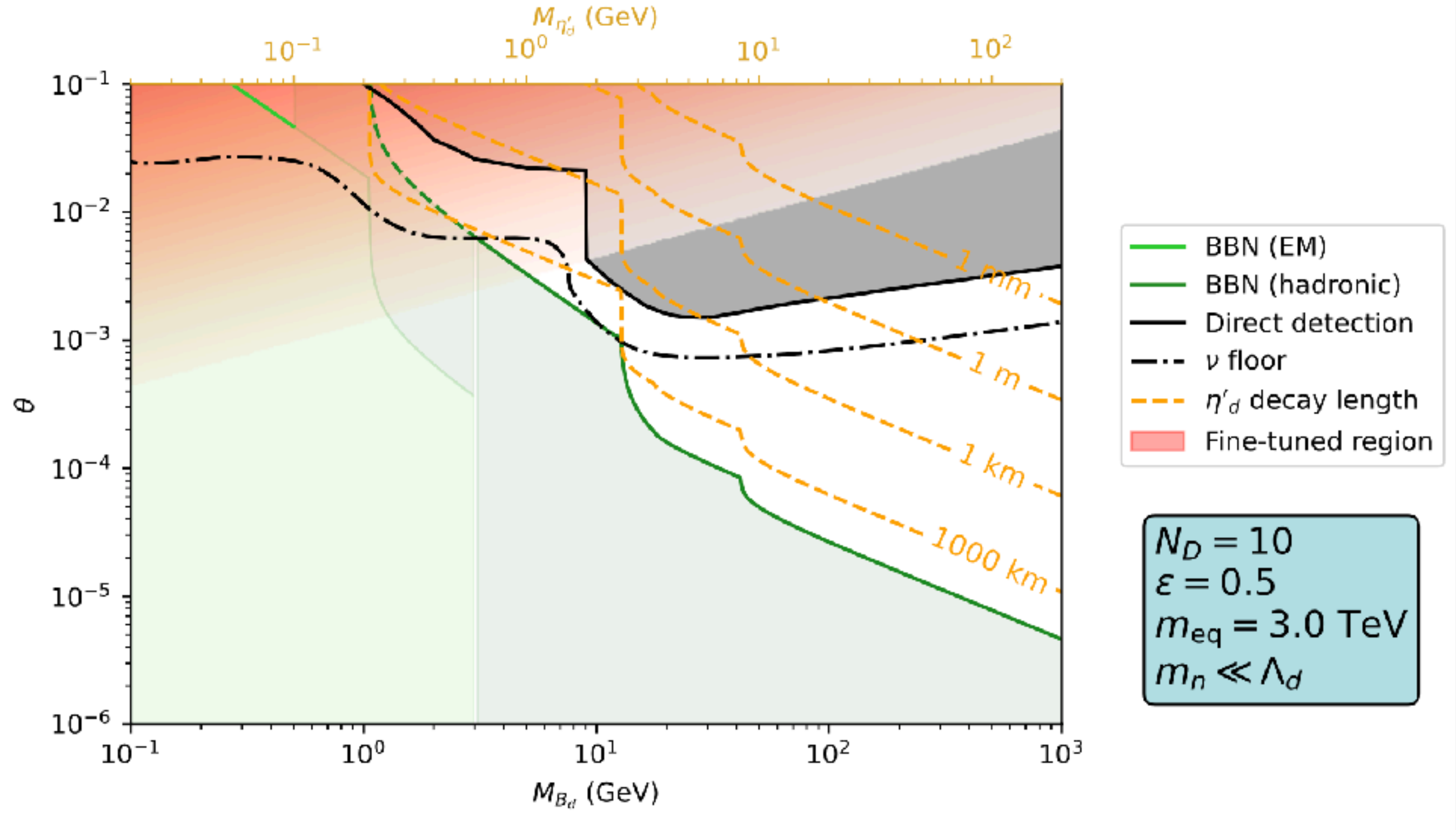


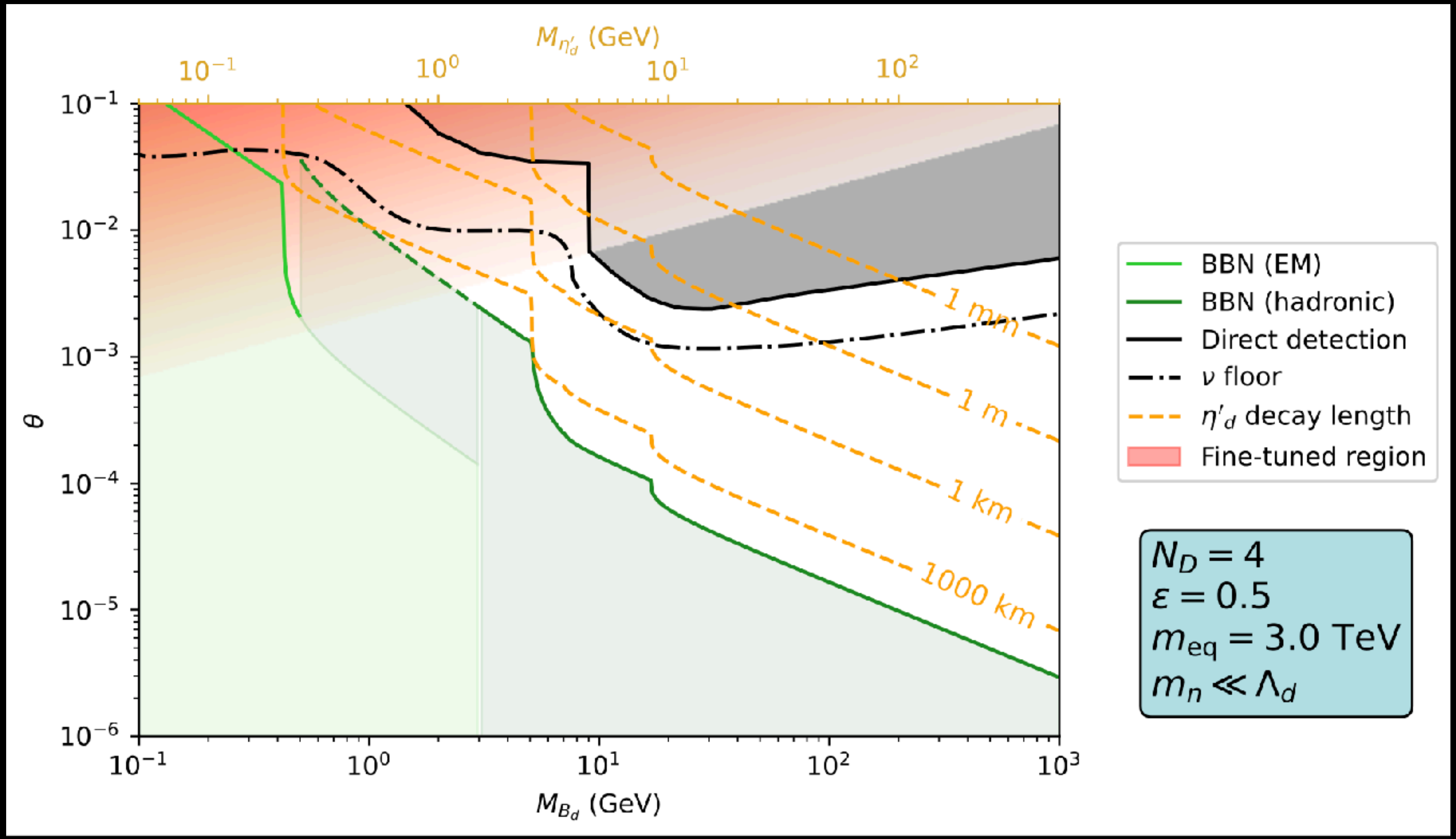


- Variation 1: increasing N_D strengthens both BBN (lighter η at given M_{Bd}) and direct detection ($\sigma_z \sim N_D^2$) bounds somewhat.

- Qualitatively, some parameter space remains open below $M_{Bd} \sim 10$ GeV.

N_D —> 10

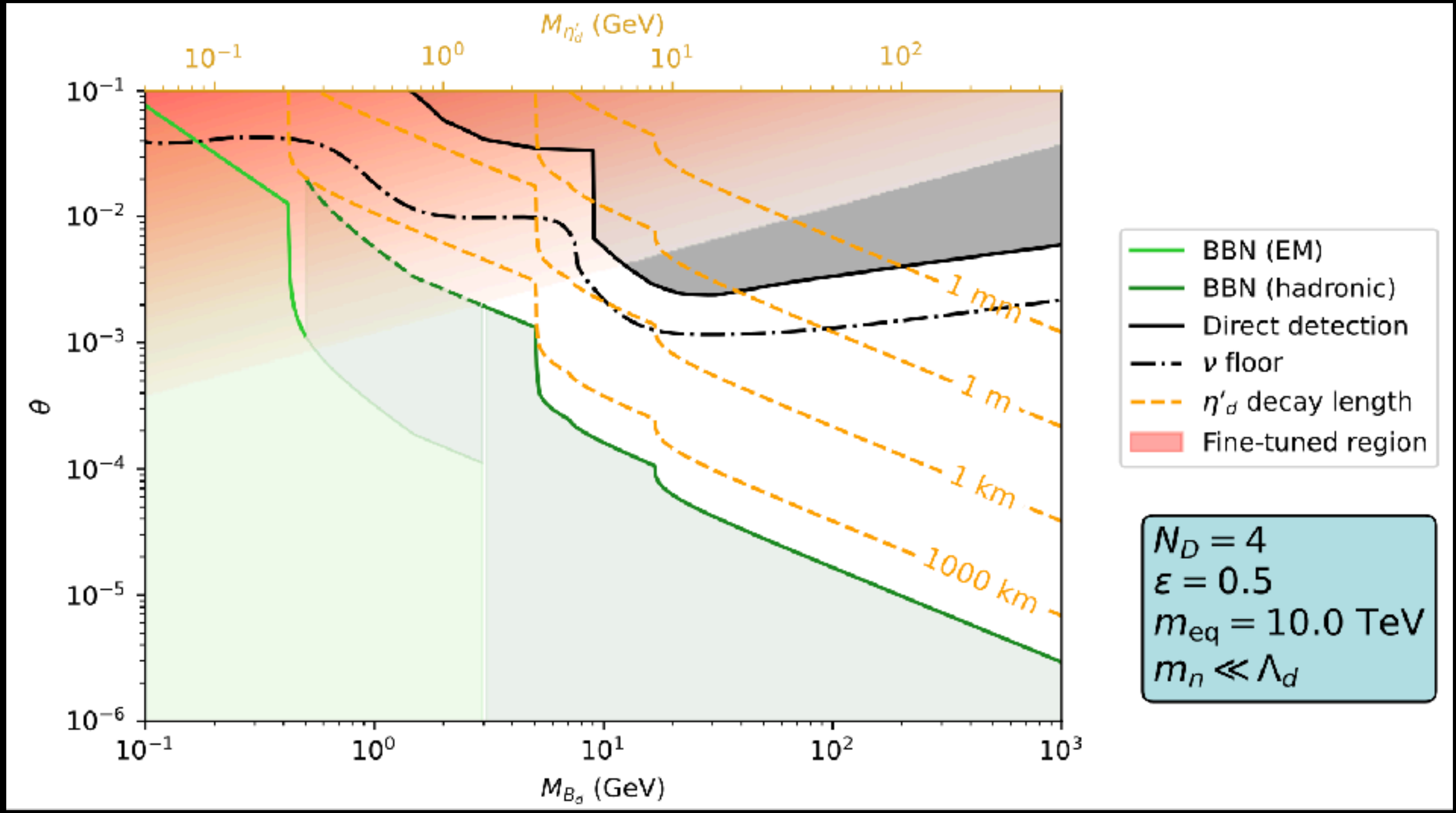




- Variation 2: increasing m_{eq} and reducing ε has no effect on direct detection, but strengthens BBN bounds by increasing η_d' lifetime.

- Again, qualitative effect on open parameter space is not too large.

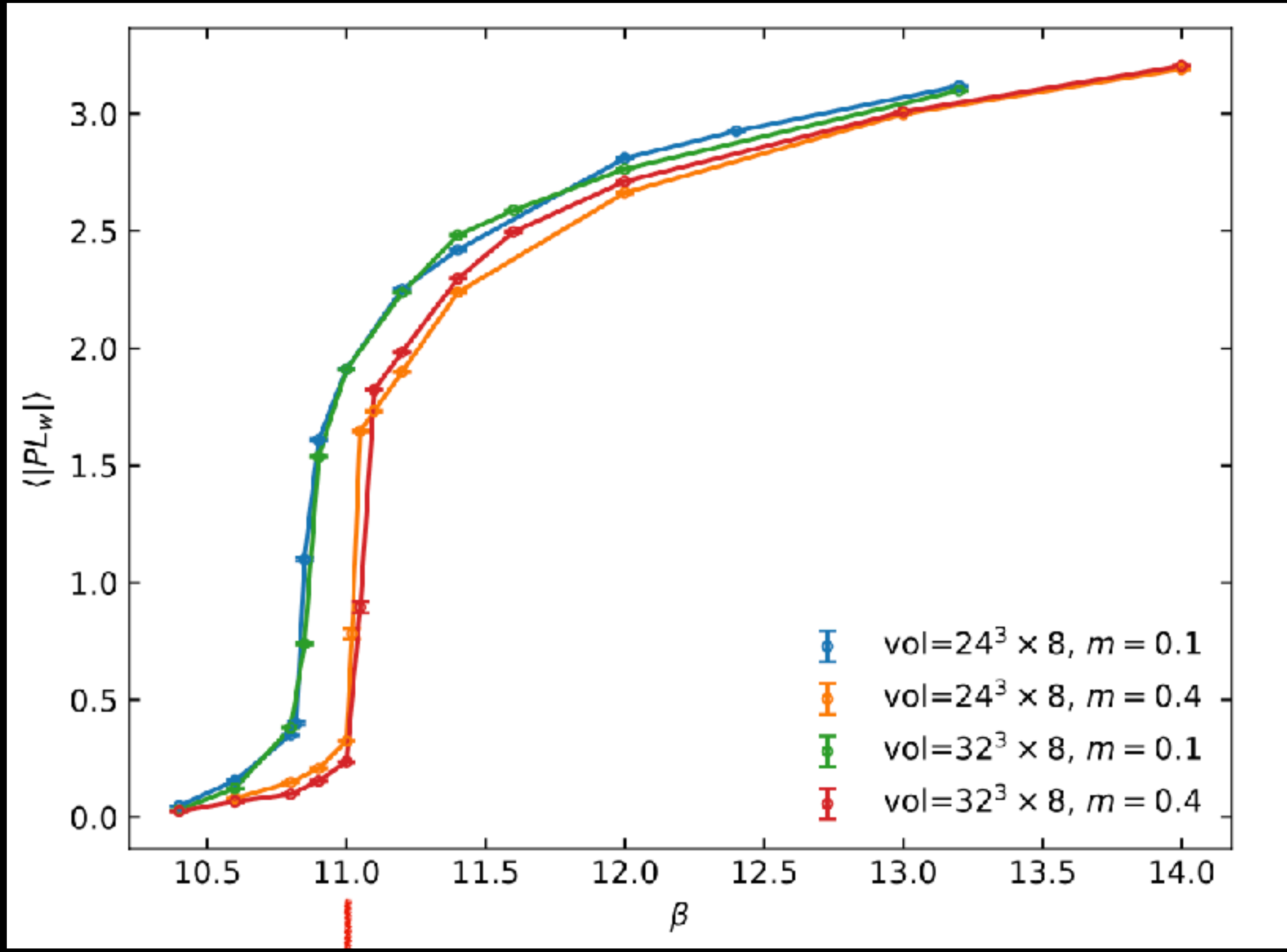
m_{eq} —> 5 TeV
ε —> 0.1



Other searches

- <u>Future directions?</u> 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. (<u>Right:</u> 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

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

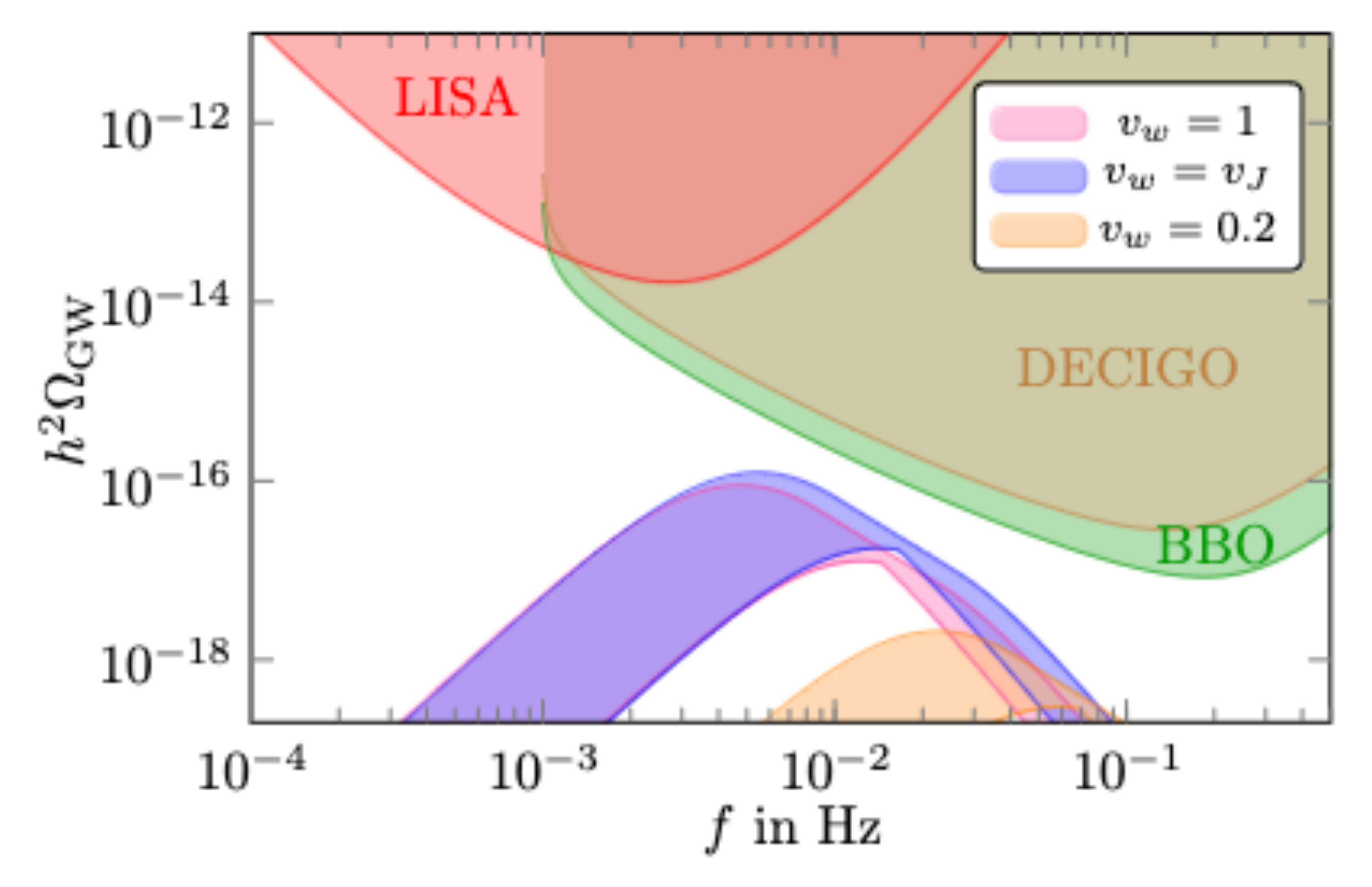
$$\Gamma_{0++,\text{tot}} \;=\; \frac{(2.3)^2}{9\pi^4} \left(\frac{N_D}{3}\right)^2 \theta^4 \frac{m_{0++}^6}{v^2(m_h^2 - m_{0++}^2)^2} \Gamma_{h,\text{tot}}^{\text{SM}}(m_{0++}^2)\,.$$

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

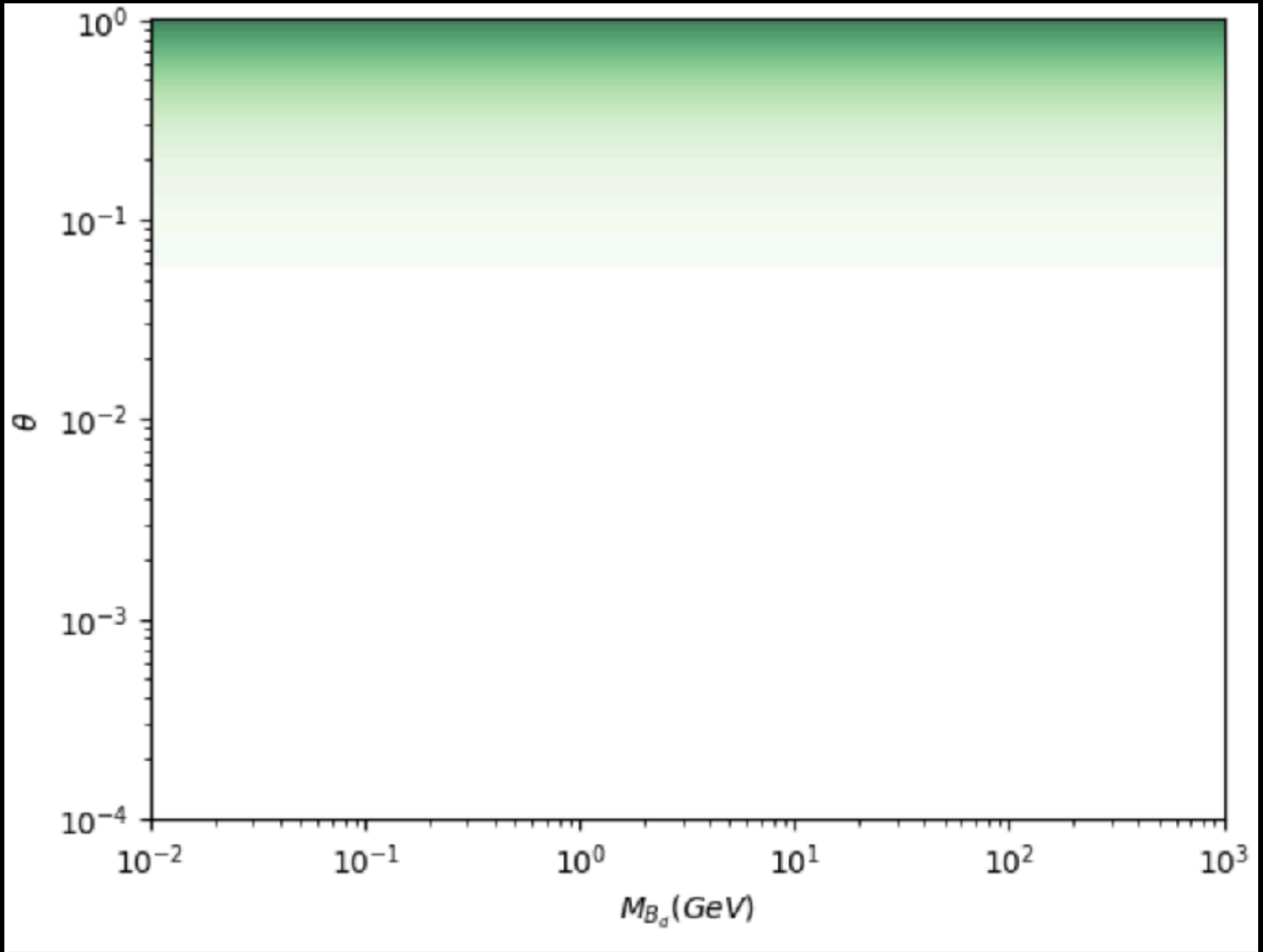
Primordial gravitational waves

- 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



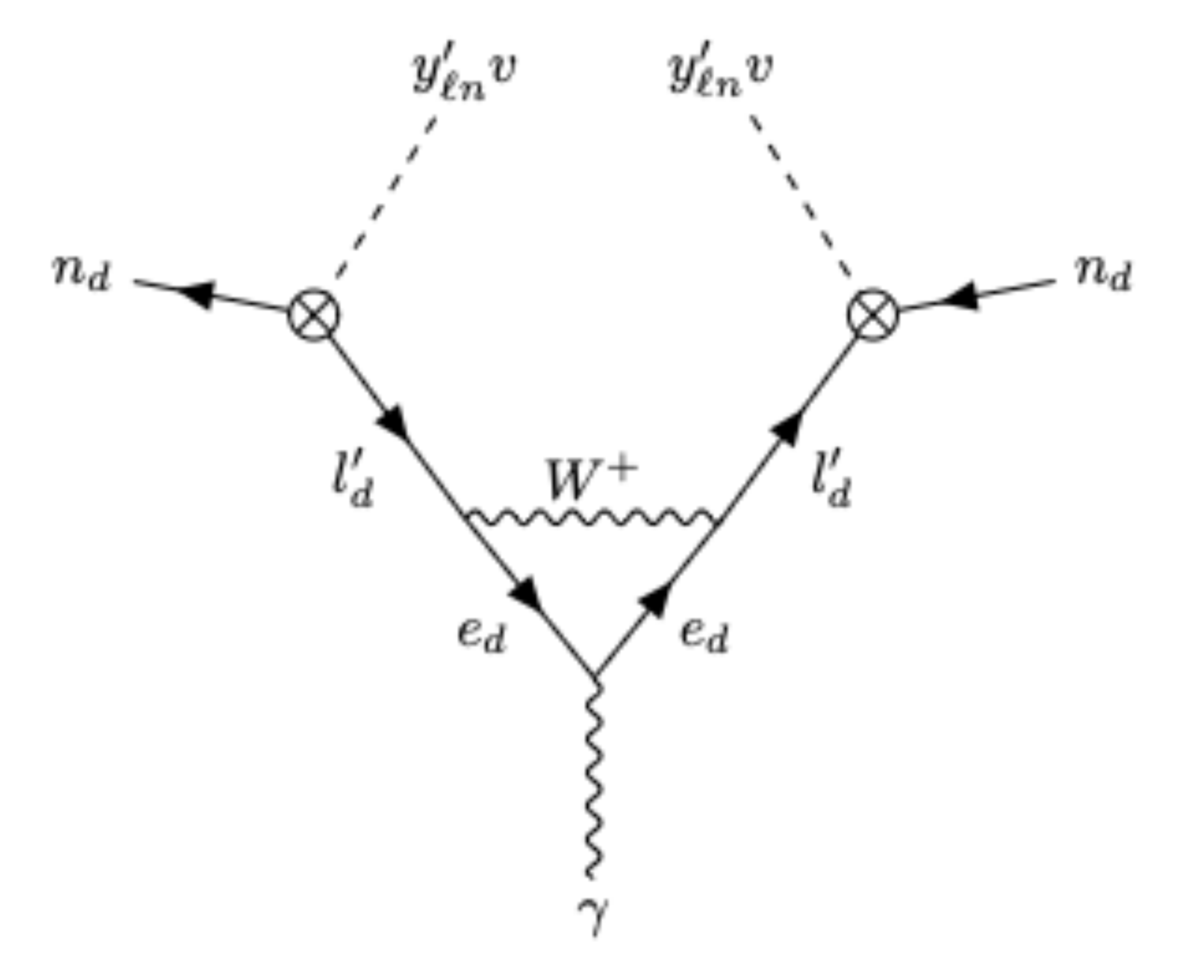
- Yukawas will become non-perturbatively strong if θ is too large; ε also matters.
- To avoid this, we require roughly θ < 0.1 and ε < 0.5.

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

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

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.



4-flavor HSDM variant

- Adding the singlet charged fermion e_d back in gives the model to the right.
- This version of HSDM can be viewed as a charge reassignment of stealth dark matter (also four flavors, this is “1+3” vs. “2+2”.)

	Field	$SU(N_D)$	$(SU(2)_L, Y)$	T_3	$U(1)_{\text{em}}$
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