ACCIDENTAL DARK MATTER

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GGI Workshop on *Phase transitions in particle physics* - March 28-April 1, 2022

Plan of the talk

- Motivations: Accidental Symmetries of the SM
- Part I: Accidental Dark Matter
- Part II: Accidental Axion

Motivations

Accidental (Emerging) Symmetries of the SM

Accidental Symmetries in the SM

$$\mathcal{L} = \mathcal{L}^{(4)} + \sum_{n,i} \frac{c_{n,i}}{\Lambda_{UV}^n} O_i^{(4+n)}$$

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The renormalizable SM Lagrangian has accidental global symmetries that lead to distinctive selection rules

- Exact Baryon and individual Lepton numbers
- Approximate Custodial Symmetry $\quad \dfrac{m_W}{m_Z \cos\theta_W} \simeq 1 \qquad g_{hWW} = g_{hZZ}$
- Approximate Flavor Symmetry (→ suppressed FCNC, suppressed CP)

Accidental Symmetries in the SM

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Higher-dim operators are in fact *required* to explain neutrino masses and oscillations

L violation @ dim-5 level

$$\frac{1}{\Lambda_{UV}} (H\ell)^2$$

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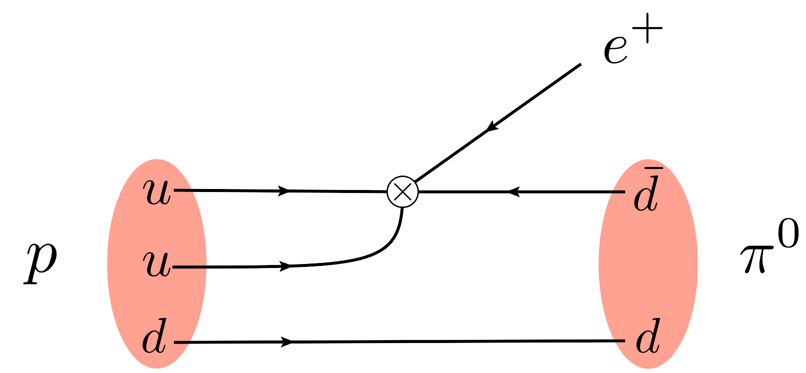
Proton decay can occur through *B*-violating dim-6 operators

$$O = \frac{\kappa}{\Lambda_{UV}^2}\,(uude) \quad \rightarrow \quad \tau_P = \frac{1}{\Gamma_P} \sim \left(\frac{\kappa^2}{8\pi}\frac{m_P^5}{\Lambda_{UV}^4}\right)^{-1}$$

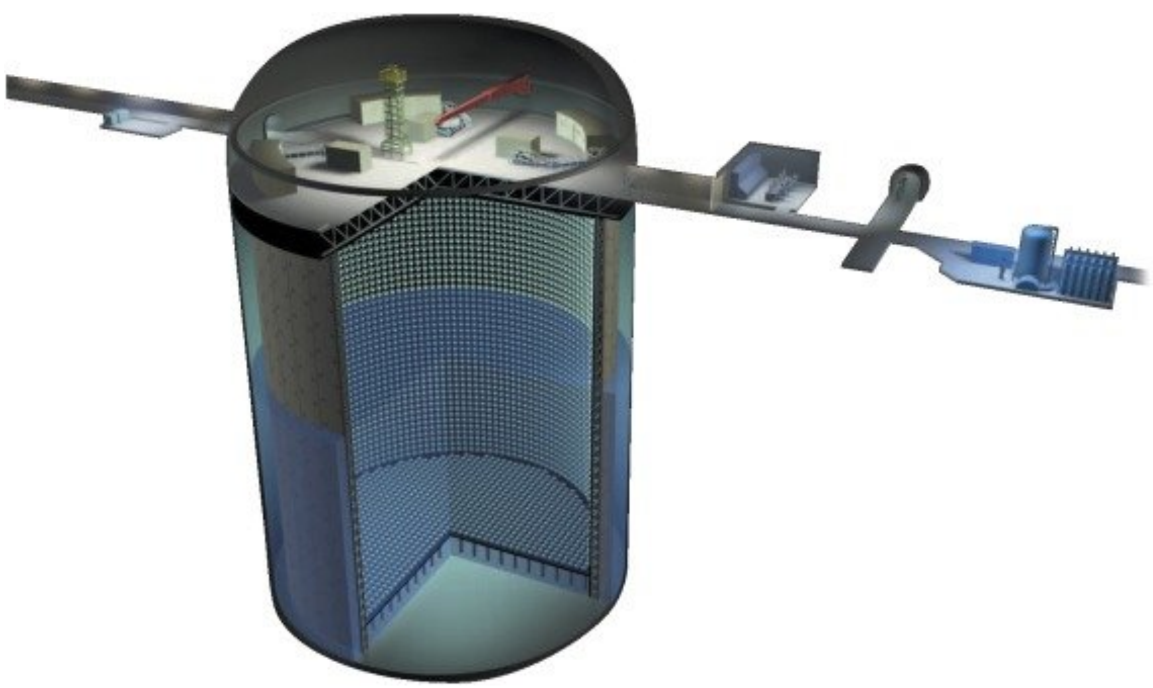


Cosmological stability:

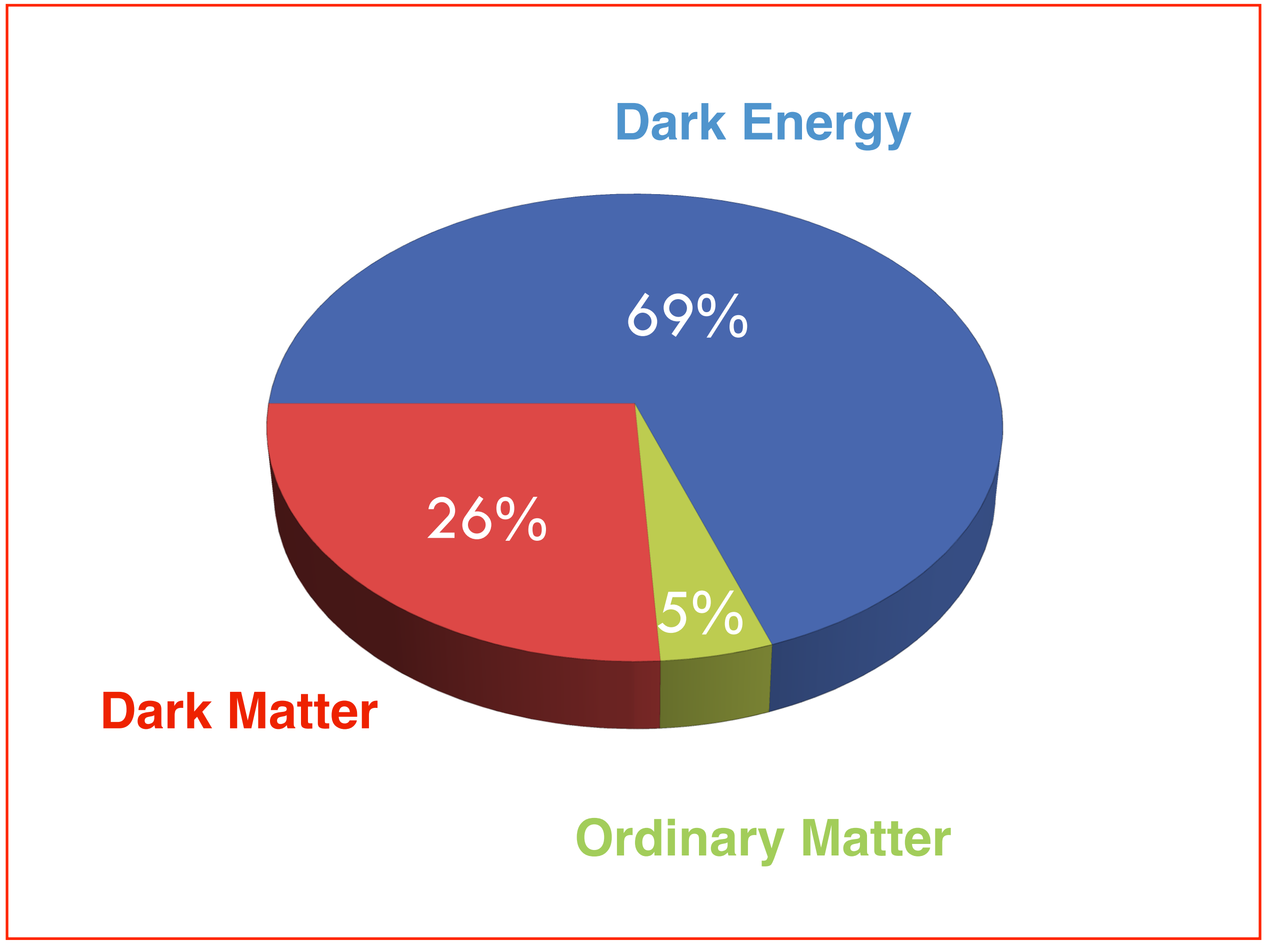
$\tau_P \gtrsim 10^{10}\mathrm{yr} \quad \Rightarrow \quad \Lambda_{UV} \gtrsim 10^{10}\,\mathrm{GeV}$

Bound from Super-Kamiokande (50k tons):

$\tau_P > 1.67 \times 10^{34}\mathrm{yr} \quad \Rightarrow \quad \Lambda_{UV} \gtrsim 10^{16}\,\mathrm{GeV}$



The Energy Budget of the Universe



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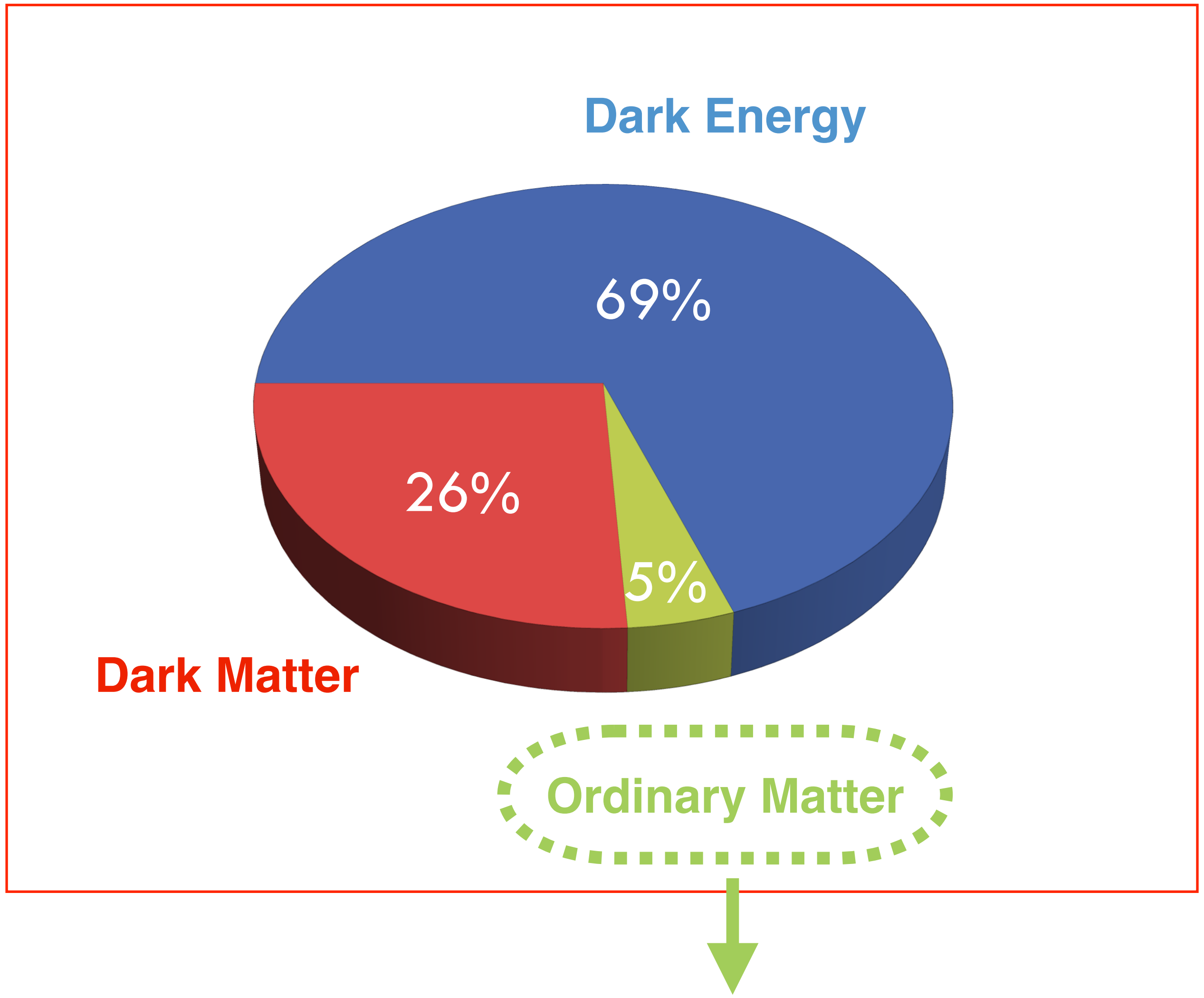

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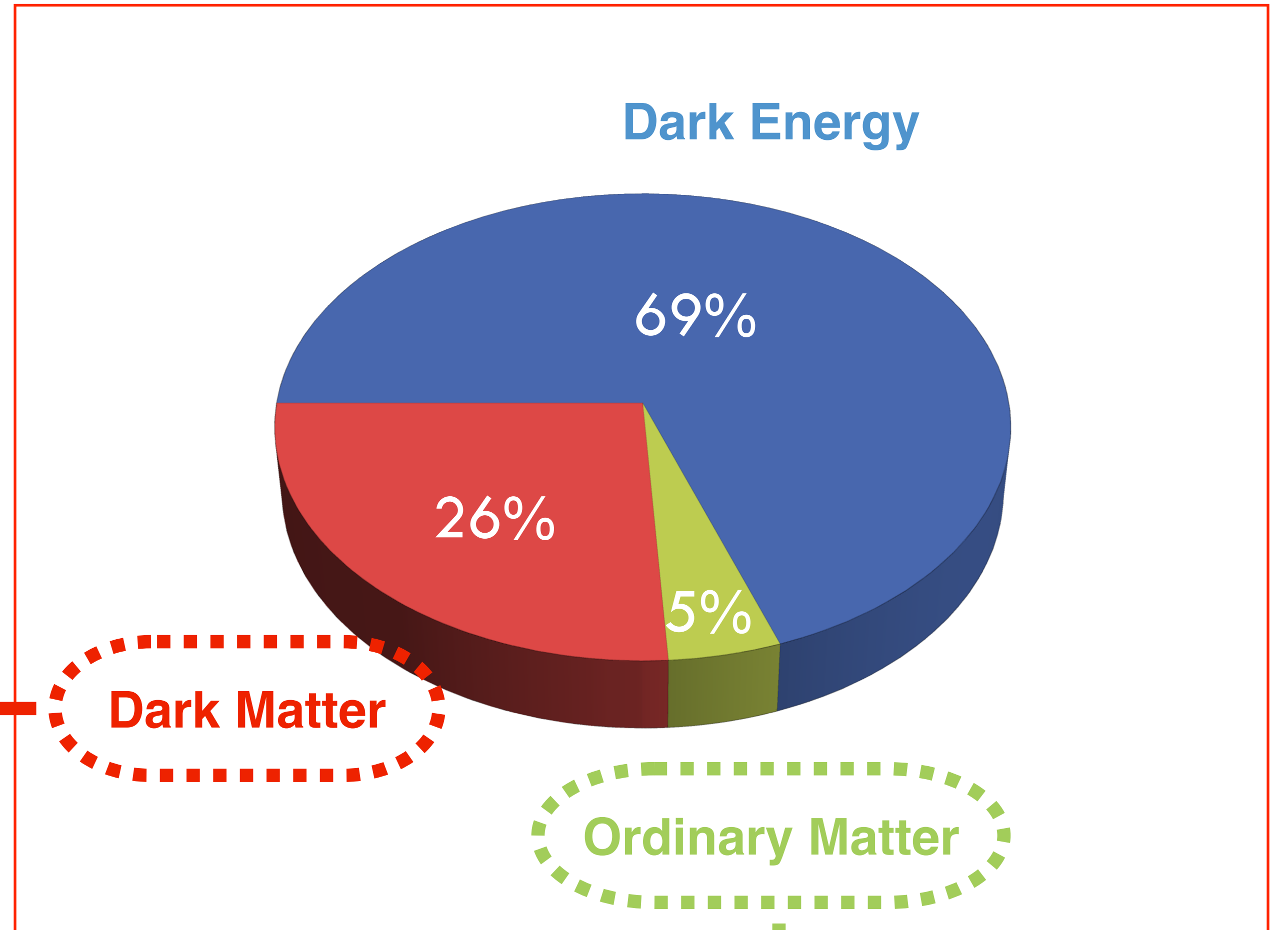


Can Dark Matter be stable due to its own accidental symmetry ?

It exists thanks to proton stability, ultimately due to accidental baryon number conservation

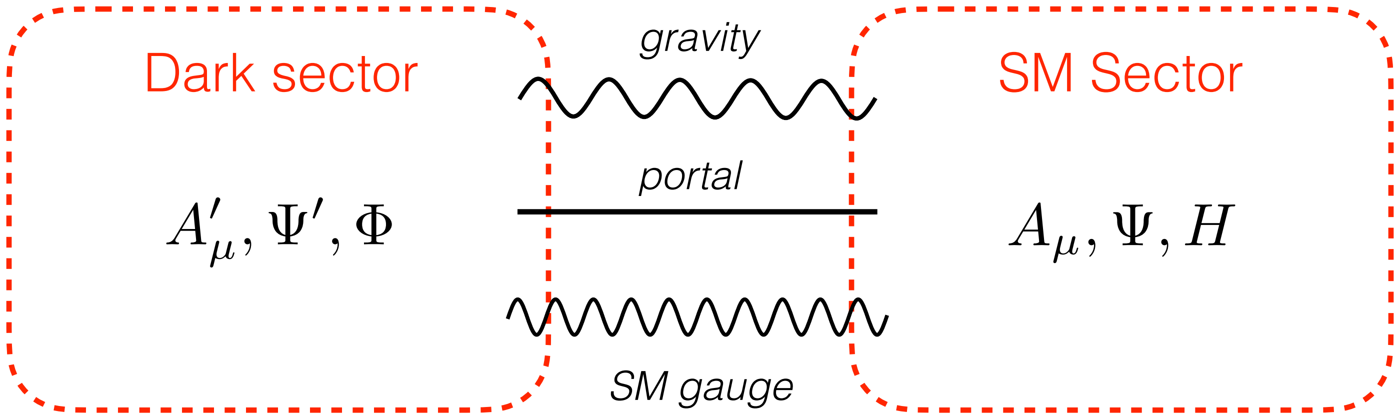
Accidental vs Exact Global Symmetries

- Accidental symmetries are only approximate, emerge at low energy and do not characterize the UV fundamental dynamics
- Exact global symmetries are believed to be incompatible with quantum gravity and black holes
- Accidental symmetries are thus more theoretically satisfactory than imposing ad-hoc exact symmetries in the theory

Part I

Accidental (Particle) Dark Matter

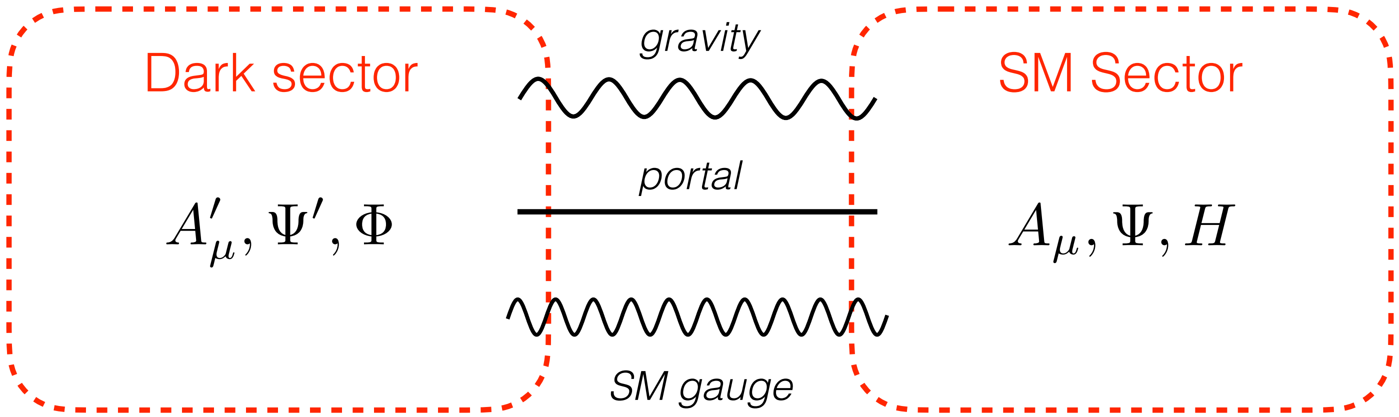
Extending the SM: Accidental Dark Matter



Postulate a new sector with new matter and/or new dynamics

Dark Sector must contain (at least) one DM candidate that is cosmologically stable due to one of its accidental symmetries

Extending the SM: Accidental Dark Matter



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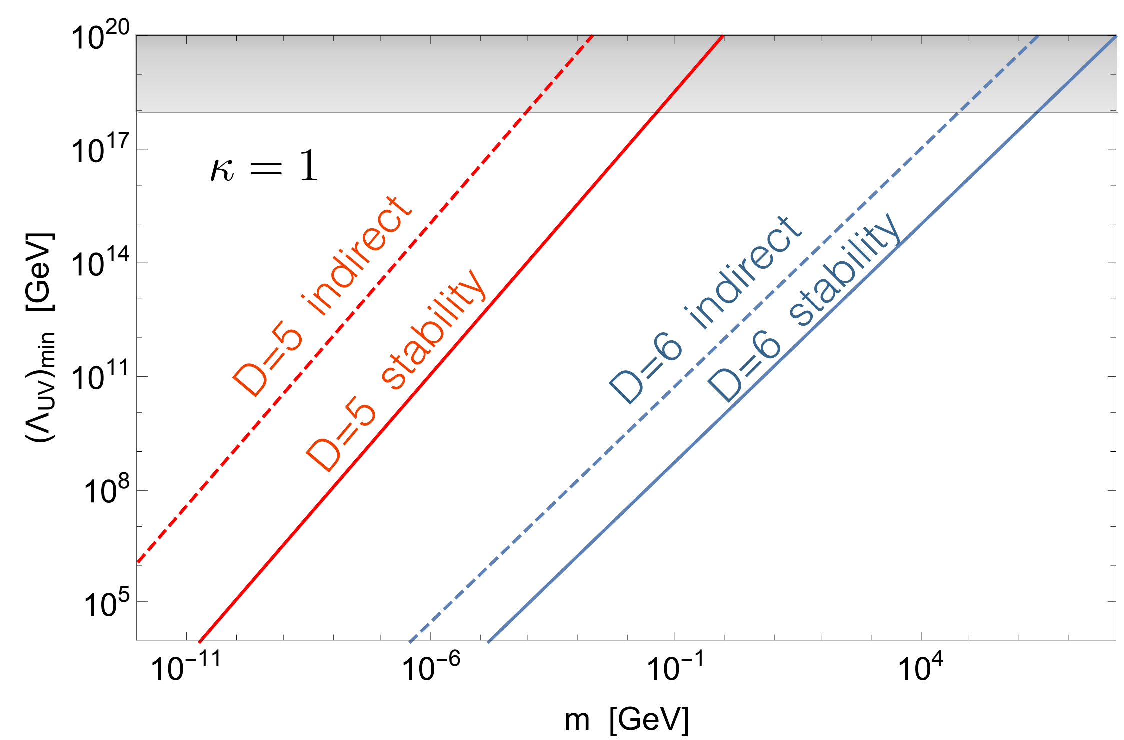
If symmetry broken by operator with dimension D: $\Gamma \sim \frac{\kappa^2}{8\pi} \frac{m^{2D-7}}{\Lambda_{UV}^{2D-8}}$

Cosmological stability: $\tau \gtrsim 10^{10}\,\mathrm{yr}$

Bounds from CMB, 21cm, DM indirect detection: $\tau \gtrsim 10^{18}\,\mathrm{yr}$



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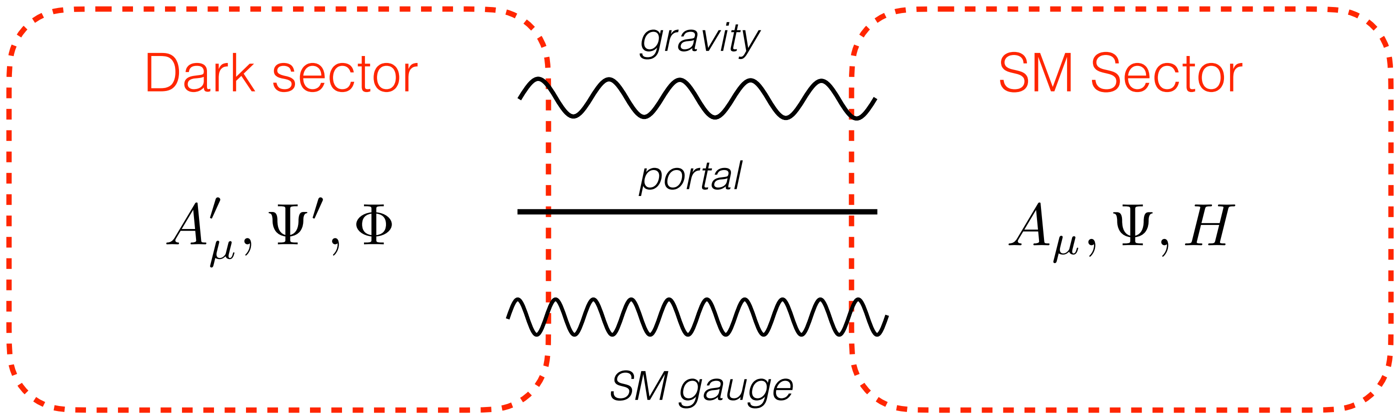

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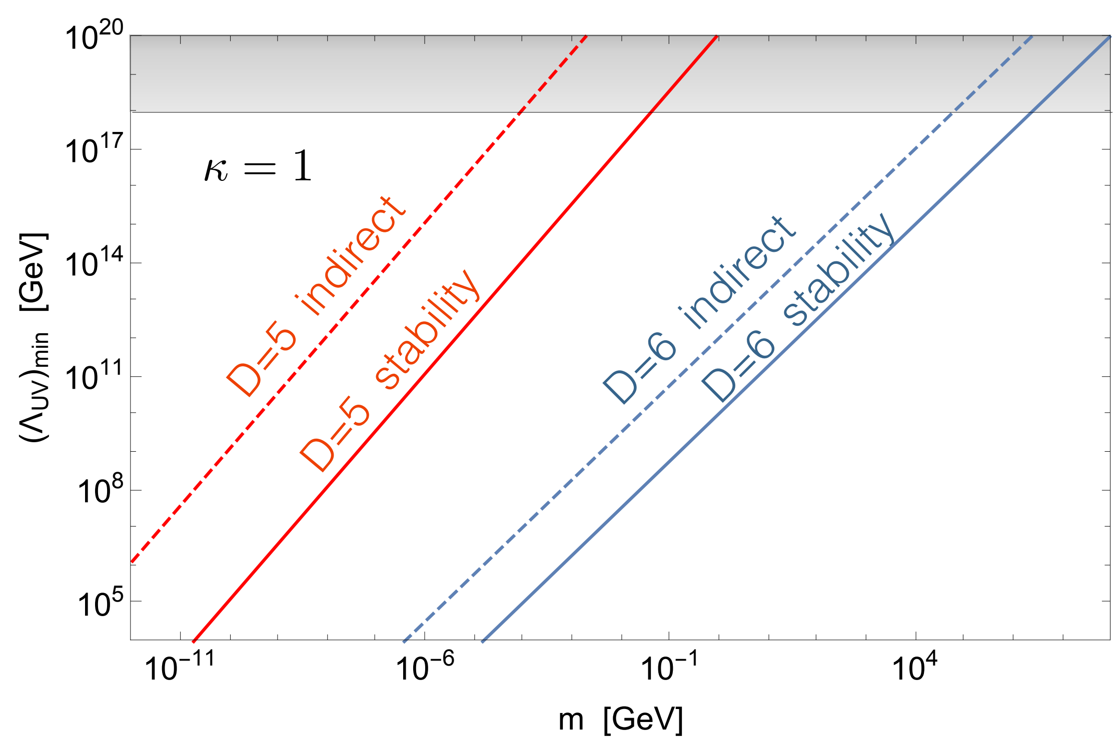

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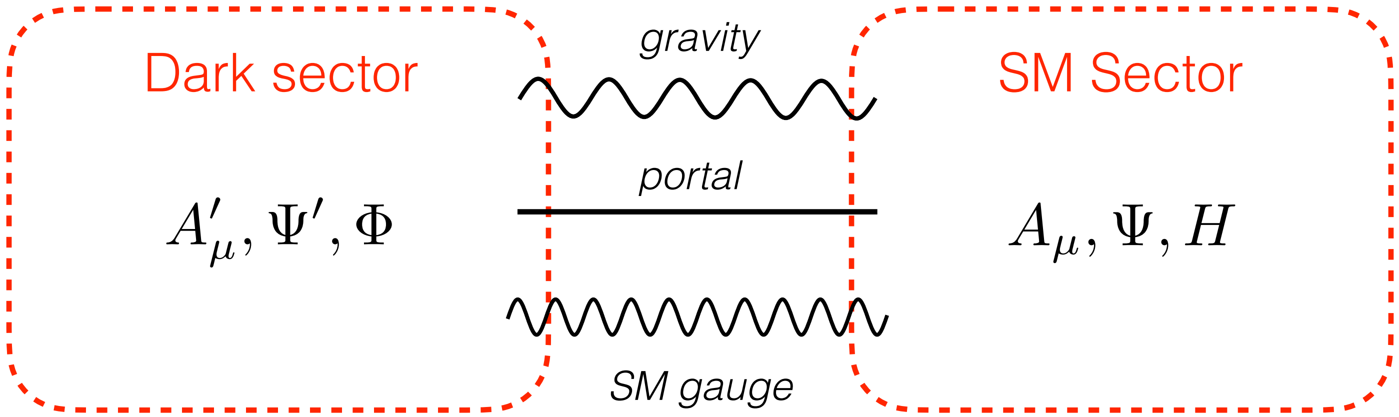

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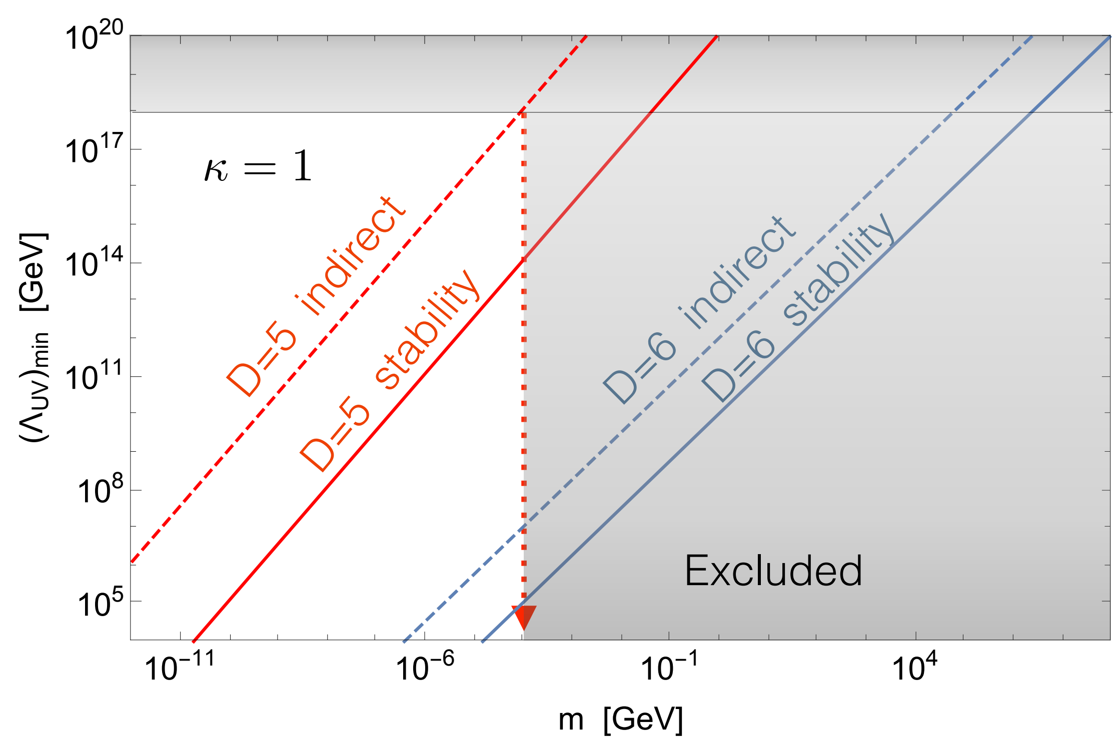

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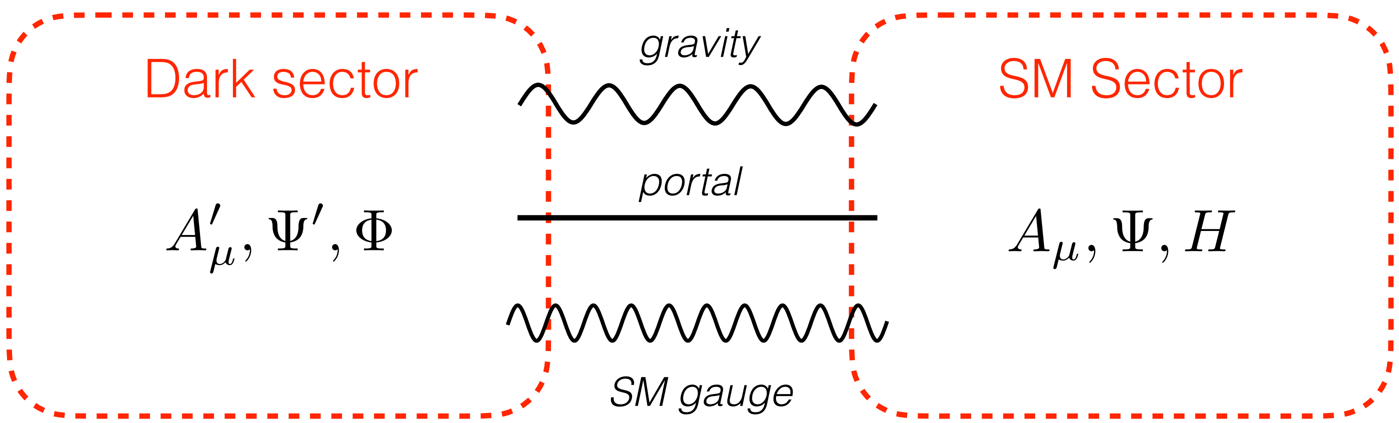

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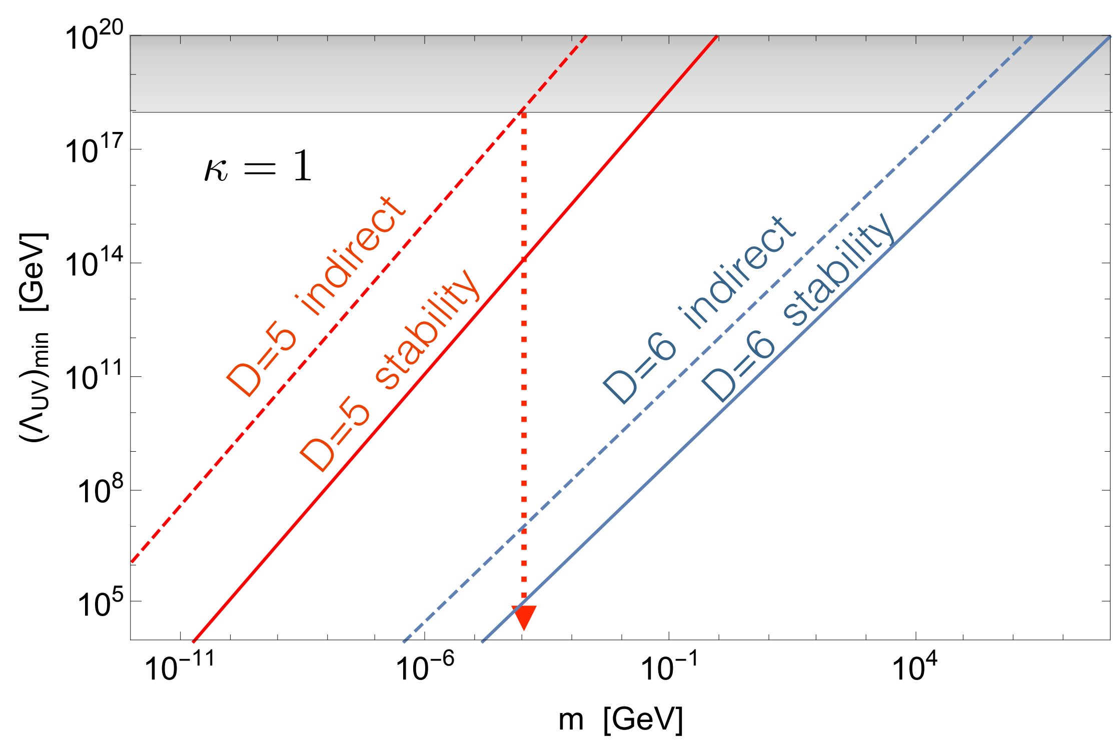

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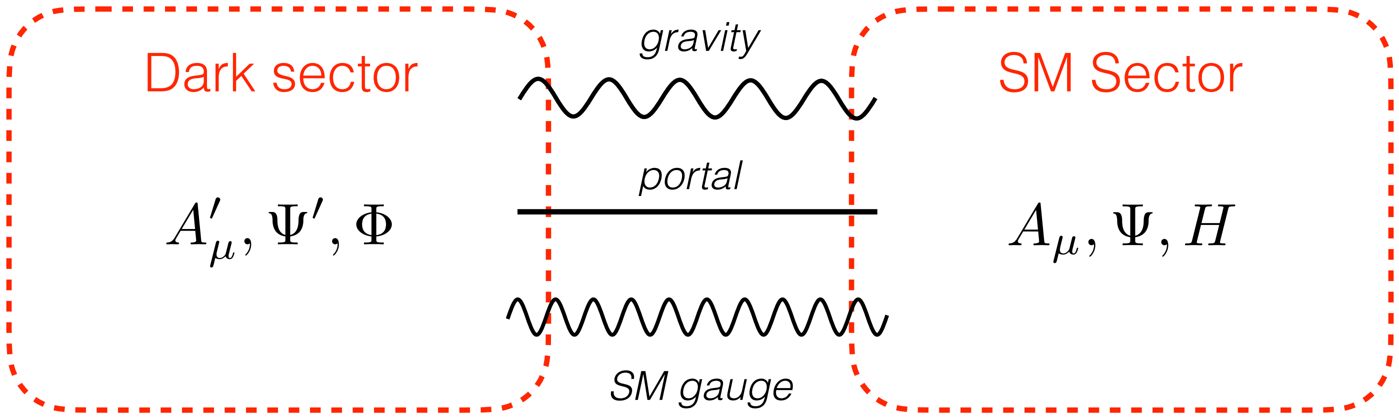

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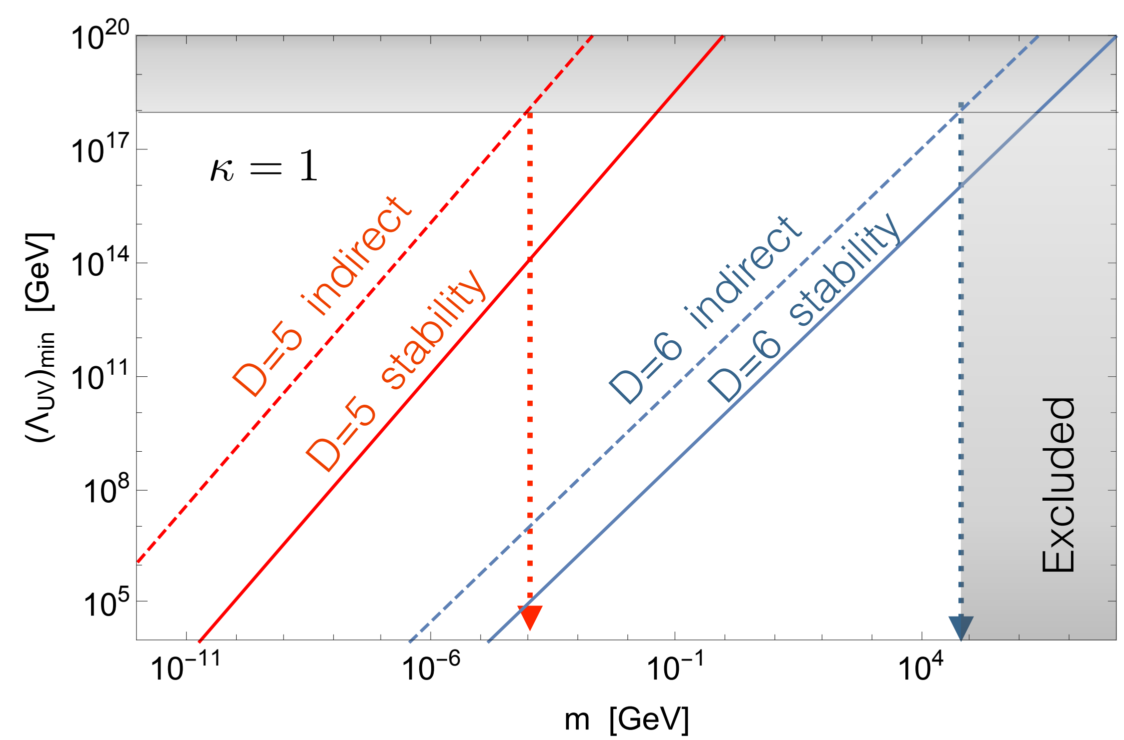

Overview of some of the most interesting accidental SM candidates

Weakly coupled dark sector

Type	Accidental Symmetry	
Minimal DM	$U(1)$ dark number	Cirelli, Fornengo, Strumia NPB 753 (2006) 178

Strongly coupled dark sector

Type	Accidental Symmetry
Dark Baryons	$U(1)_{DB}$ dark baryon number
Gluequarks	Z_2 dark parity
Dark Mesons	Species number $U(1)_i$ or G-parity
Axion	$U(1)_{PQ}$ Peccei-Quinn

Strongly-Coupled Dark Sector

See for ex: Kribs, Neil, Int. J. Mod. Phys. A31 (2016) 1643004
Antipin, Redi, Strumia, Vigiani JHEP 1507 (2015) 039
R.C., Mitridate, Podo, Redi JHEP 1902 (2019) 187

Dark Sector = *G_D gauge theory with dark 'quarks' transforming as (R,r) of $G_D \times G_{SM}$, and $G_{DC} \subset G_D$ a confining 'dark color' subgroup*

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- Below the dark confinement scale, the dark sector develops a complex spectrum of bound states, one (or more) of them is accidentally stable and plays the role of the DM candidate

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- I will assume that (at least some of) the dark quarks are charged under the SM gauge symmetry. This leads to experimental signatures testable at colliders as well as direct and indirect DM searches.

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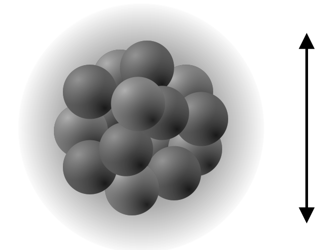
- To avoid exclusion from Electroweak Precision Tests, I will assume that the dark quark representations under G_{SM} are vector-like (i.e. dark dynamics does not break G_{SM})

- Dark Baryons



$\sim 1/\Lambda$

Example: [Antipin, Redi, Strumia, Vigiani JHEP 1507 (2015) 039]

	$SU(N_{DC})$	$SU(2)_{EW}$	$U(1)_Y$
L	$\square$	2	$-1/2$
N	$\square$	1	0
L^c	$\bar{\square}$	$\bar{2}$	$+1/2$
N^c	$\bar{\square}$	1	0

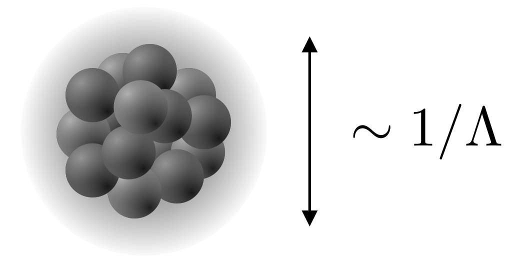
Vector-like

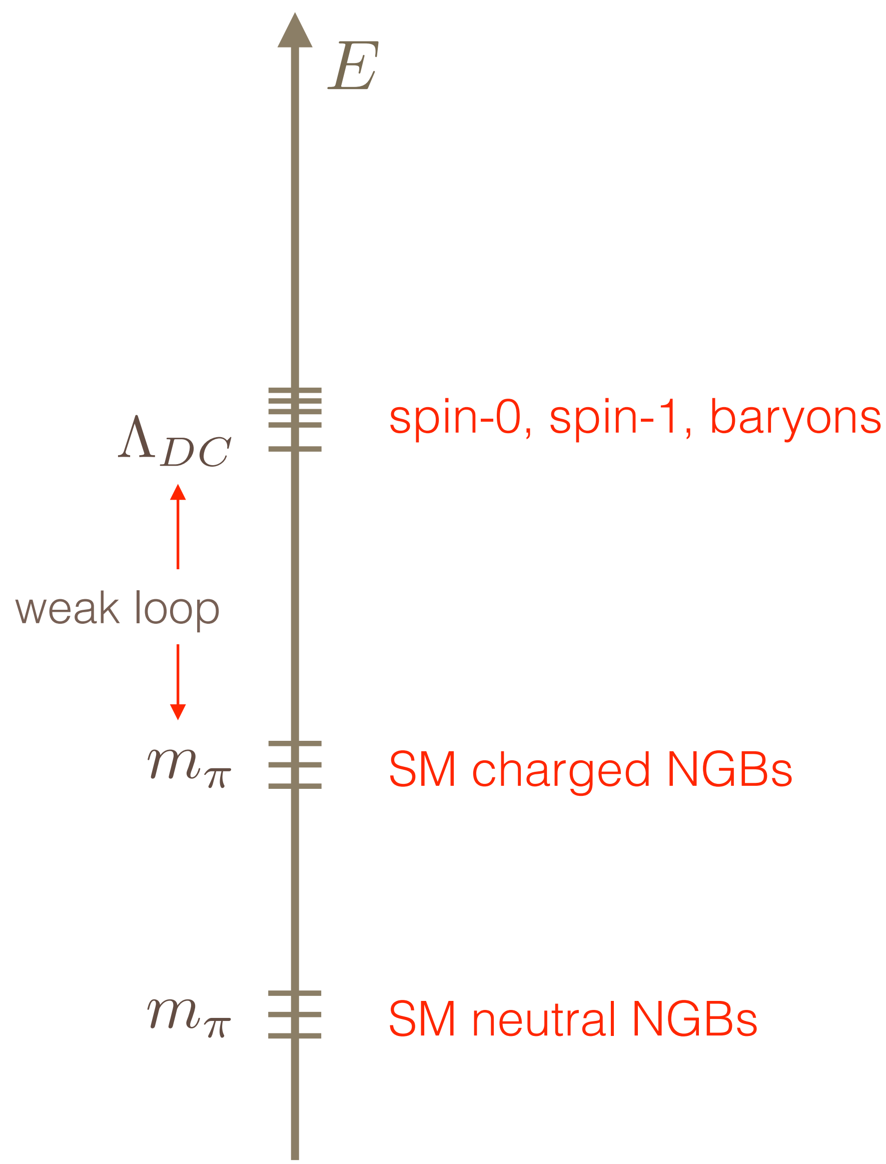
$$\mathcal{L} = -\frac{1}{4g_{DC}^2} G_{\mu\nu}^2 + \bar{L}(i\not{D} - M_L)L + \bar{N}(i\not{\partial} - M_N)N + y\bar{N}LH + h.c.$$

Accidental symmetry: U(1) dark baryon number

DM candidate: $\mathcal{B} \sim \underbrace{(N \ldots N)}_{N_{DC}}$ spin = $N_{DC}/2$, singlet of G_{SM}

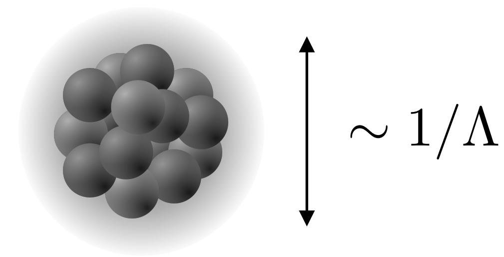
- Dark Baryons



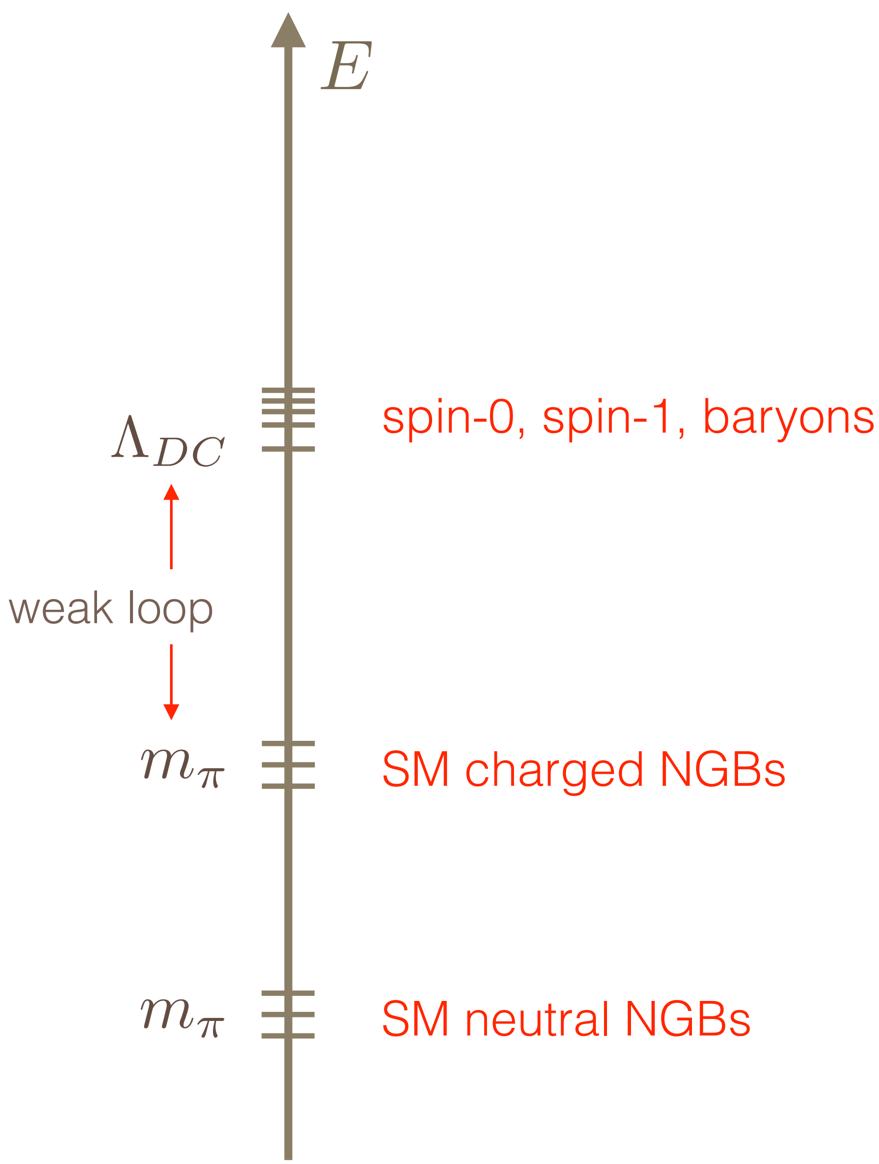


Energy cartoon for $m_\psi \lesssim \Lambda_{DC}$

- Dark Baryons



At $T \lesssim \Lambda_{DC}$ dark baryons undergo a thermal freeze out with non-perturbative annihilations into dark pions (which decay to SM)



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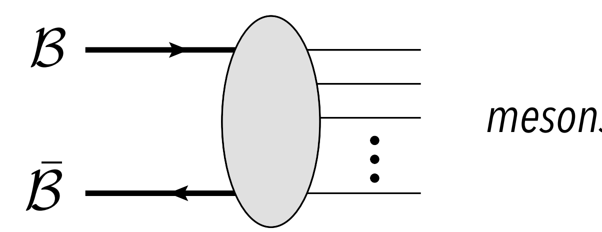

$$\langle \sigma_{B\bar{B}} v \rangle \sim \frac{\pi}{\Lambda_{DC}^2} \quad \Rightarrow \quad \boxed{\Lambda_{DC} \sim 100\,\mathrm{TeV}}$$

[K. Griest, M. Kamionkowski, PRL 64 (1990) 615
Antipin, Redi, Strumia, Vigiani JHEP 1507 (2015) 039]

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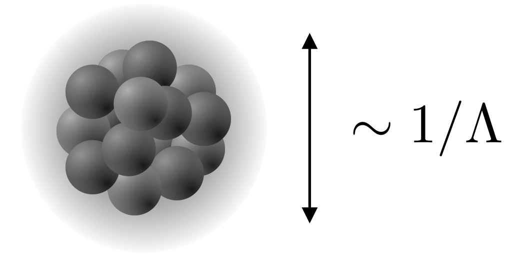

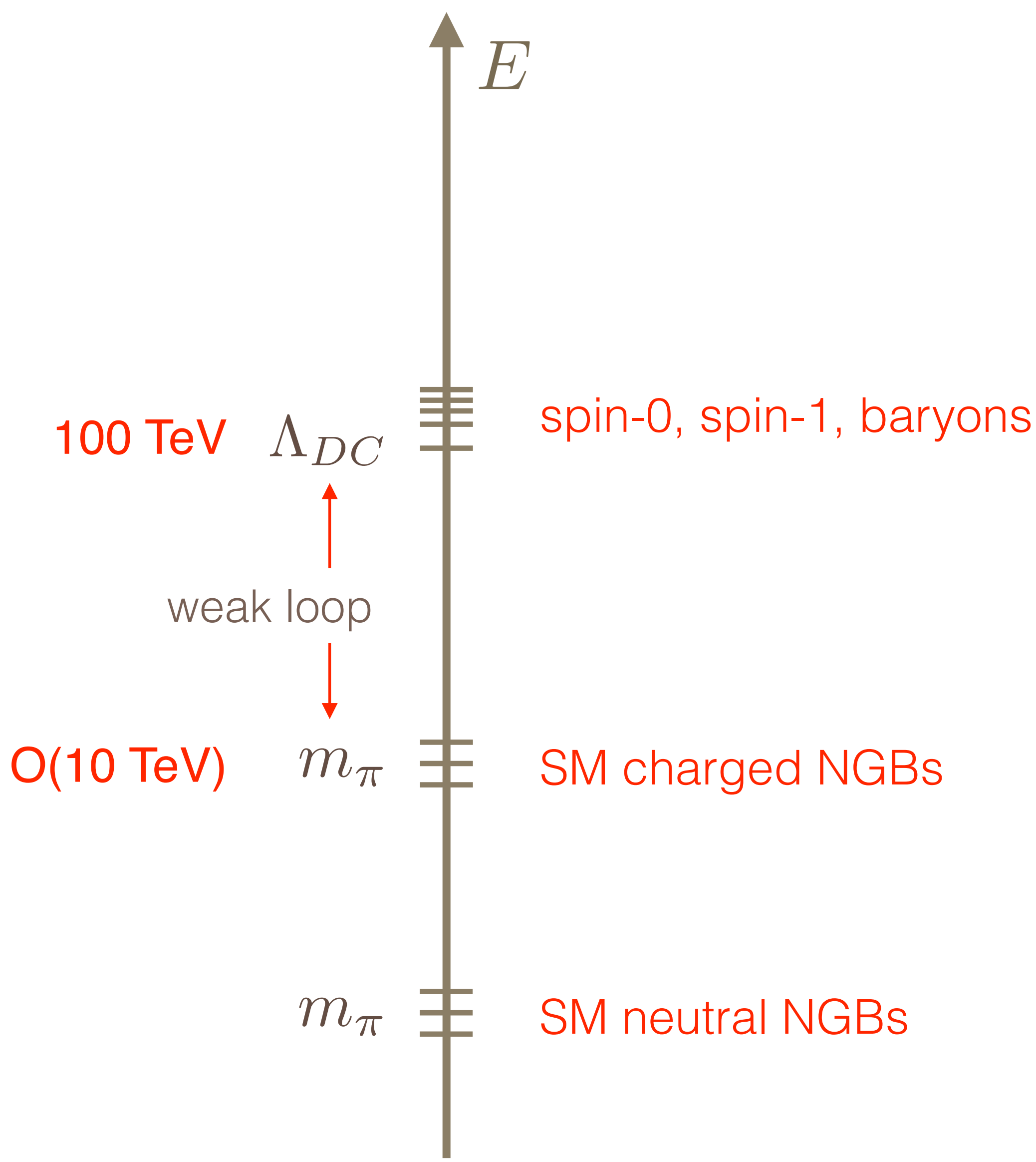

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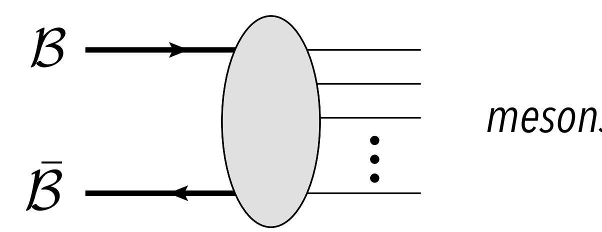

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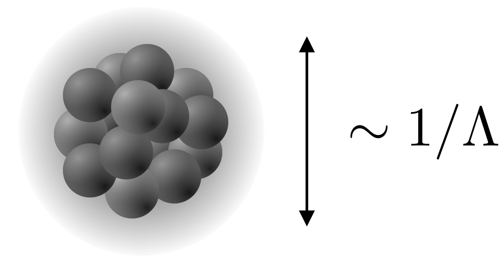

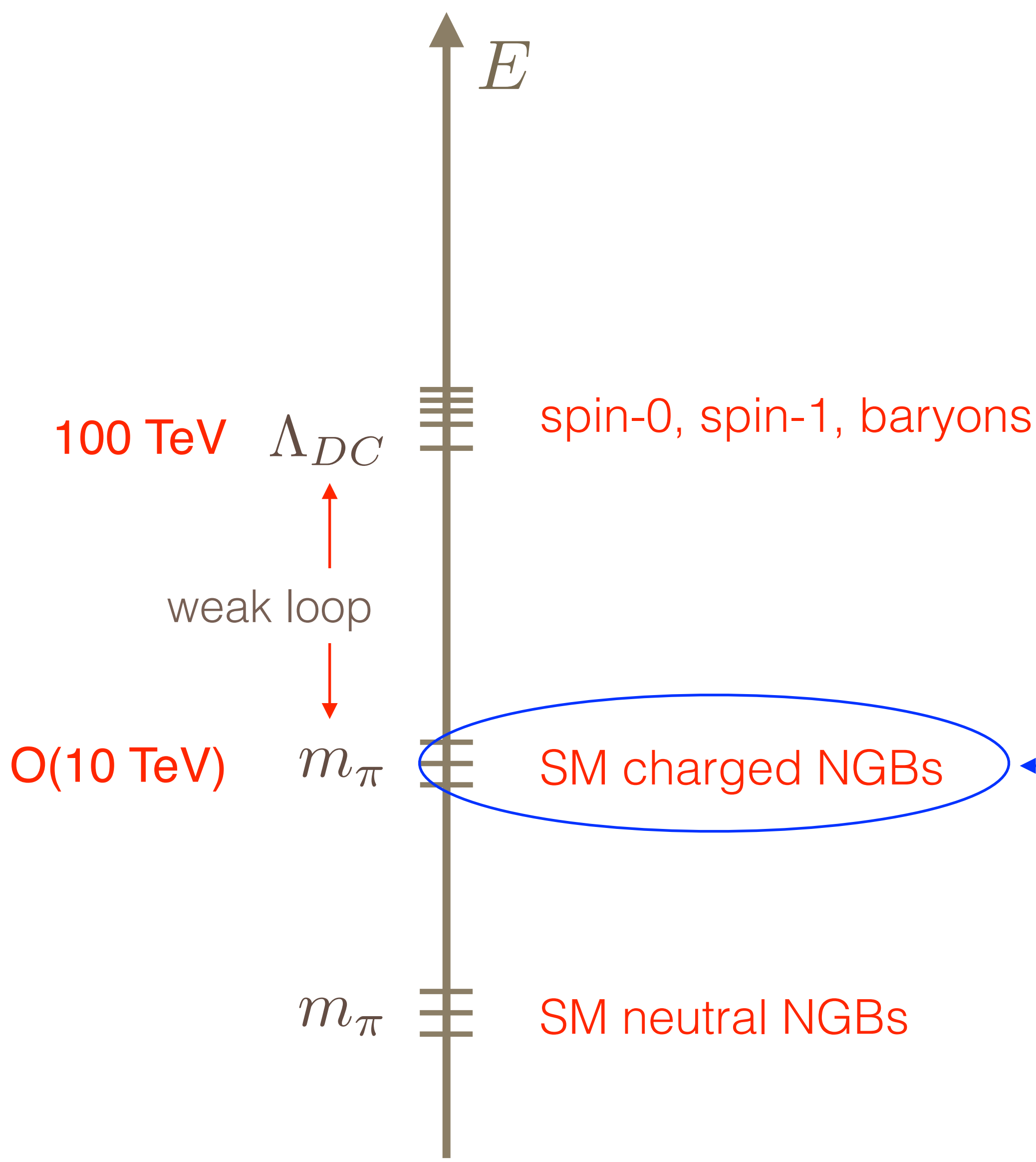

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$$m_\pi^2 \sim \frac{g^2}{16\pi^2}\Lambda_{DC}^2 + m_\psi \Lambda_{DC}$$

- pair produced via Drell-Yan

$$pp \to V \to \pi\pi \qquad (V = W, Z, \gamma)$$

- decay through anomalous/1-loop couplings or Yukawa couplings

$$\pi \to VV$$
$$\pi \to \pi' V \,/\, \pi' H \qquad (H = W_L, Z_L, h)$$

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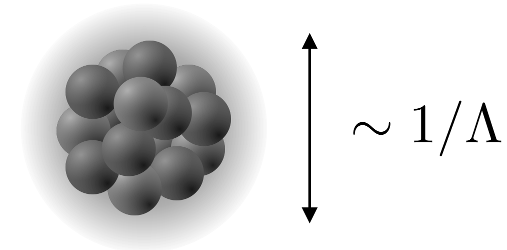

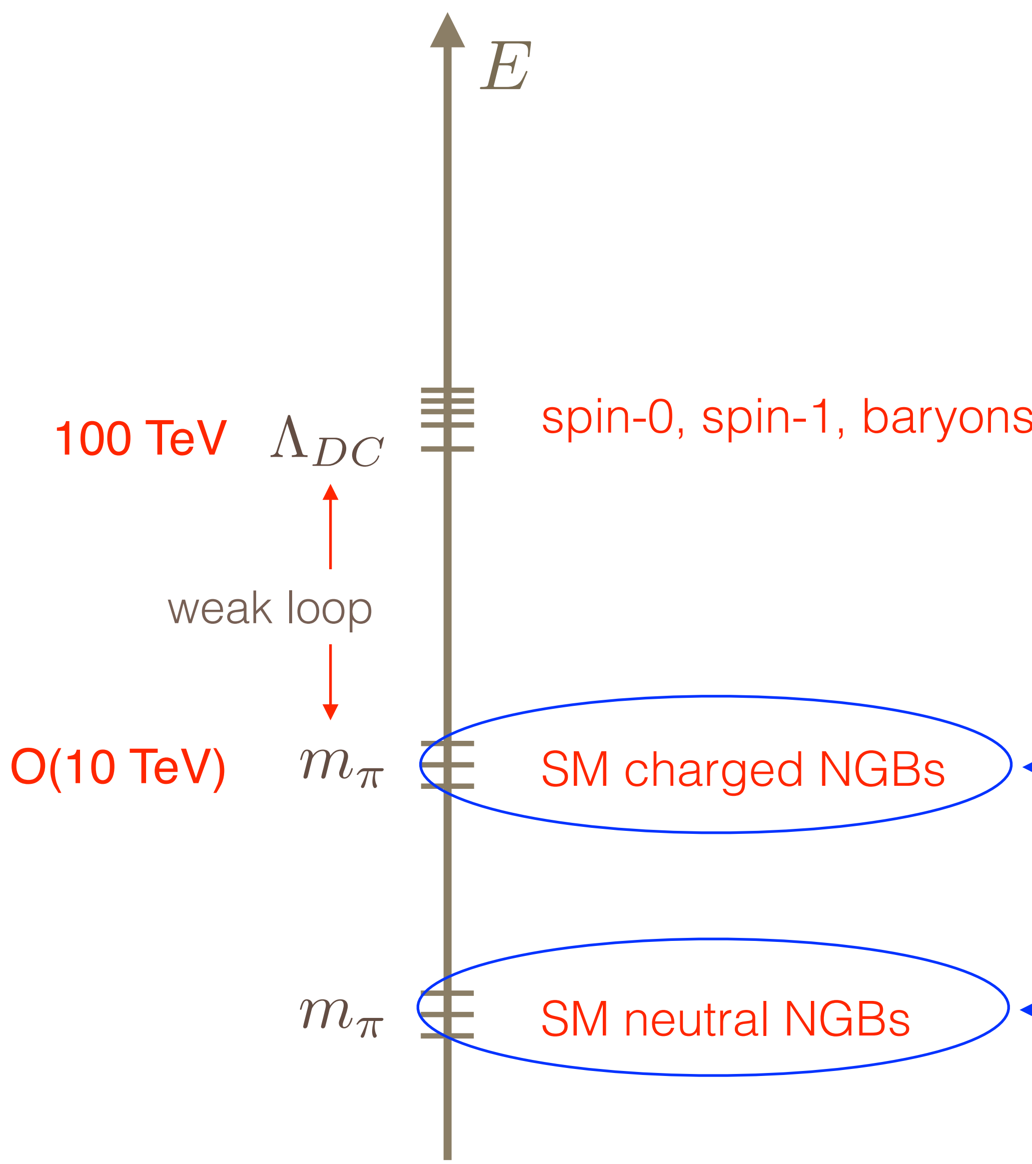

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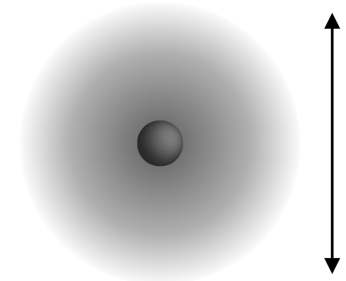
- singly produced via VBF, in association with a SM vector boson or from decays of heavier NGBs
- decay through anomalous couplings (to VV) or via higher-dim operators

- Gluequarks



$\sim 1/\Lambda_{DC}$

Example: [R.C., Mitridate, Podo, Redi JHEP 1902 (2019) 187]

	$SU(N_{DC})$	$SU(2)_{EW}$	$U(1)_Y$	
Q	adj	3	0	Real

$$\mathcal{L} = -\frac{1}{4g_{DC}^2} G_{\mu\nu}^2 + Q^\dagger i\bar{\sigma}^\mu D_\mu Q - \frac{M_Q}{2}(QQ + Q^\dagger Q^\dagger)$$

Accidental symmetry: dark parity ($Q \to -Q$)

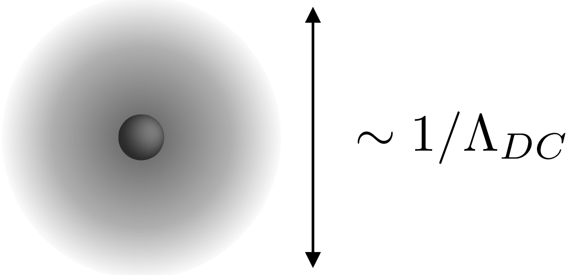
DM candidate: (EM neutral component of) gluequark

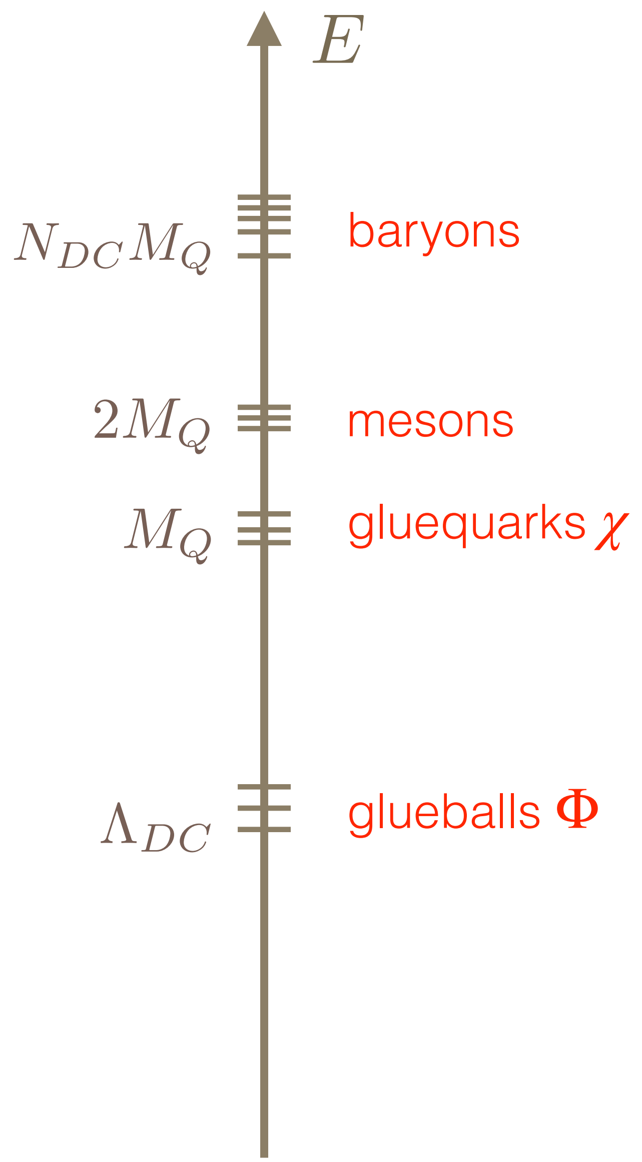
$\chi \sim Qg$ = 3_0 of G_{SM}

Lattice results for adjoint QCD

Nc/Nf	1	2	3	4	5	6
2	confining (SYM) Bergner et al. 1511.05097 1701.08992	conformal (?) Lucini et al. 1412.5994	conformal Bergner et al. 1712.04692	conformal Catterall et al. 1108.3794 Bergner et al. 1610.01576	conformal (perturbative)	AF lost
3				unclear DeGrand et al. 1307.2425	conformal (perturbative)	AF lost

- Gluequarks





- Gluequark mass computed on the lattice in the limit of heavy quark masses through simulations with adjoint static sources, see:

M. Foster, C. Michael PRD 59 (1999) 094509
G.S. Bali, A. Pineda Phys. Rev. D69 (2004) 094001

Energy cartoon for $M_Q > \Lambda_{DC}$

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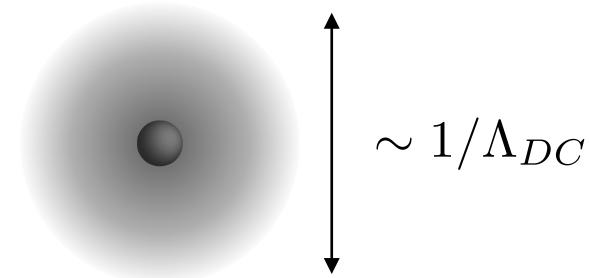

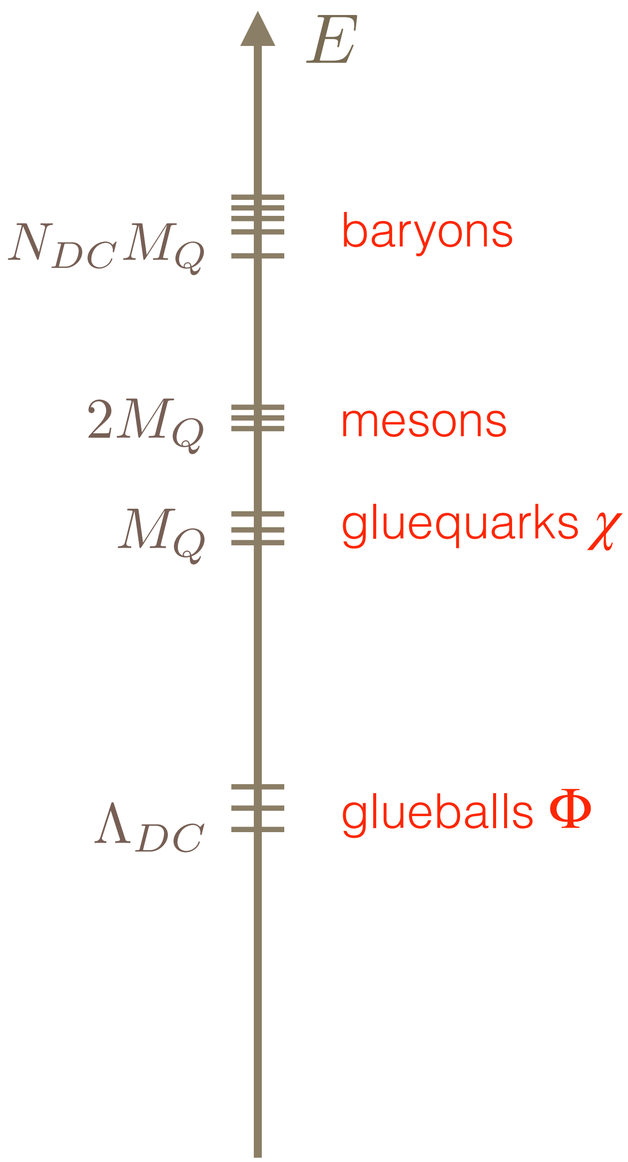

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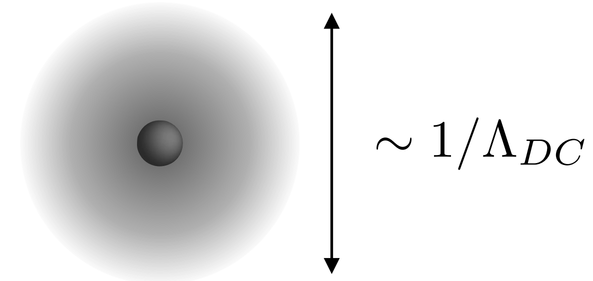
- Gluequarks are stable due to accidental dark parity

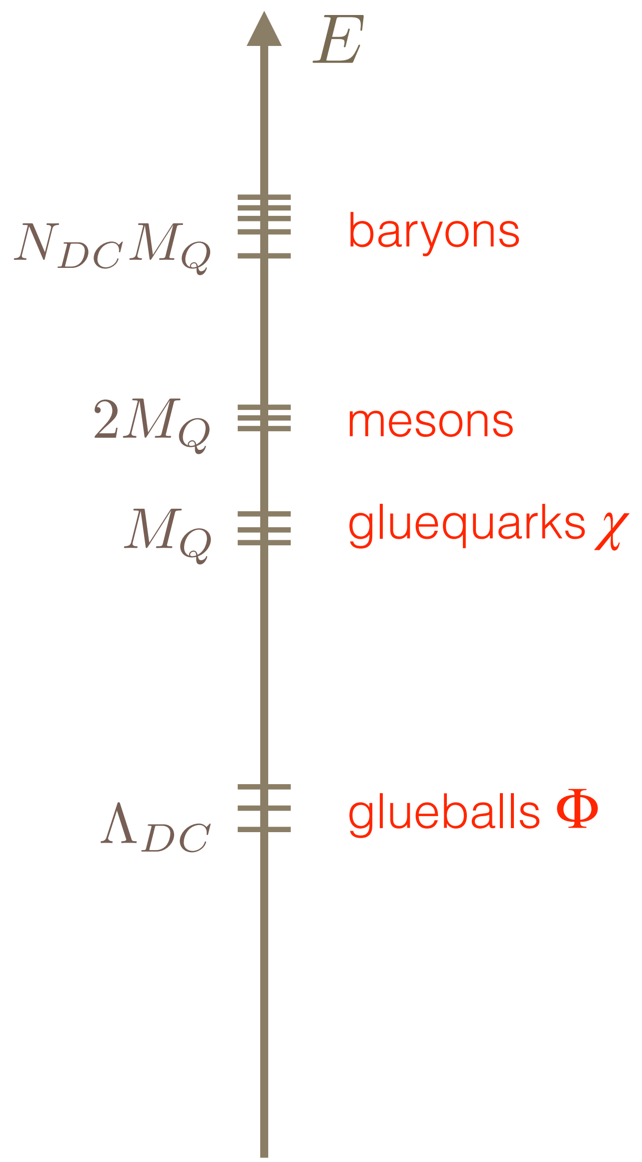
D=6 operators can induce gluequark decays

$$\Delta\mathcal{L} = \frac{g_{UV}^2}{\Lambda_{UV}^2}(H^{c\dagger}\sigma^i \ell)(G_{\mu\nu}\sigma^{\mu\nu}Q^i) + h.c.$$

$$\Gamma(\chi \to h\nu) \simeq \frac{g_{UV}^4}{4096\pi^3}\frac{M_Q^5}{\Lambda_{UV}^4} \simeq 10^{-28}\mathrm{s}^{-1} g_{UV}^4 \left(\frac{M_Q}{100\ \mathrm{TeV}}\right)^5 \left(\frac{10^{18}\ \mathrm{GeV}}{\Lambda_{UV}}\right)^4$$

- Gluequarks





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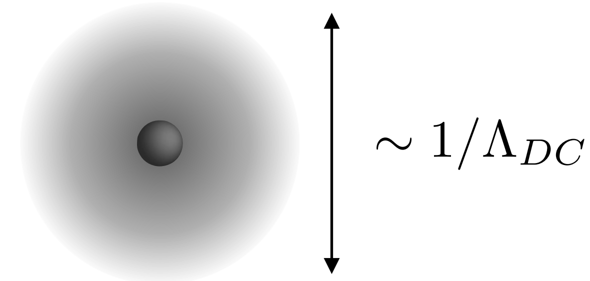
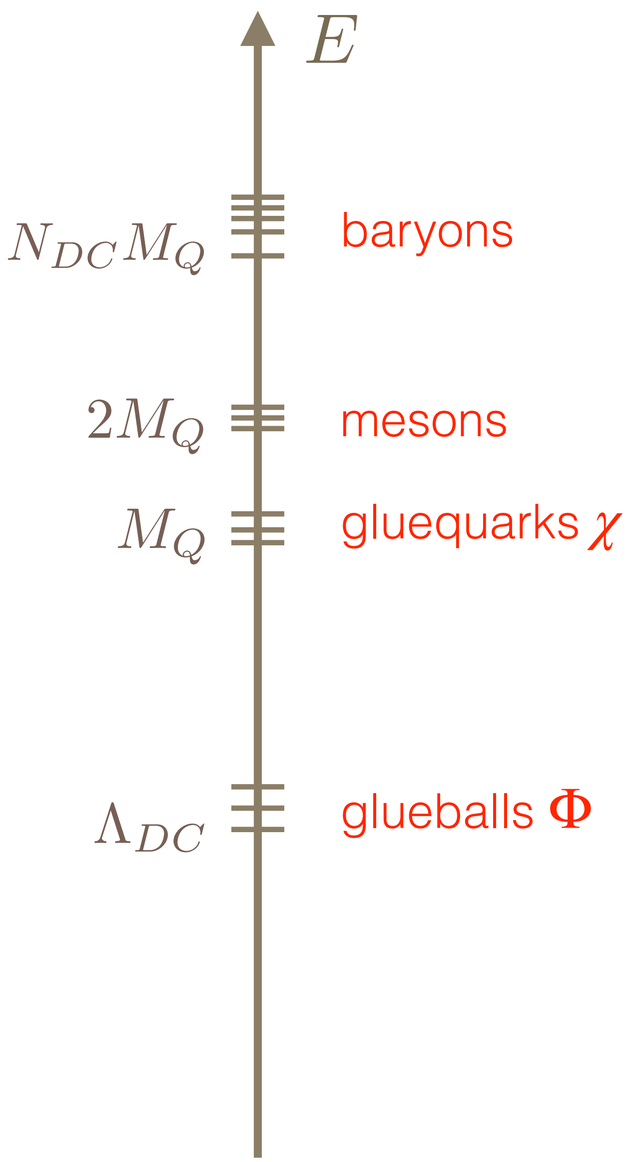
- For $M_Q > \Lambda_{DC}$ gluequarks are heavy and large

$$M_\chi \sim M_Q \qquad R_\chi \sim 1/\Lambda_{DC}$$

- Gluequarks



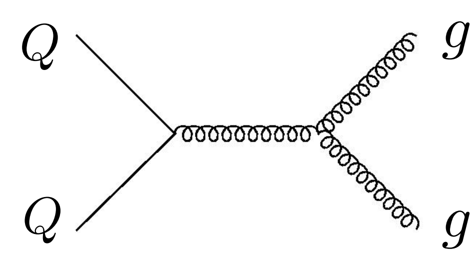


Energy cartoon for $M_Q > \Lambda_{DC}$

- For $M_Q > \Lambda_{DC}$ gluequarks are heavy and large

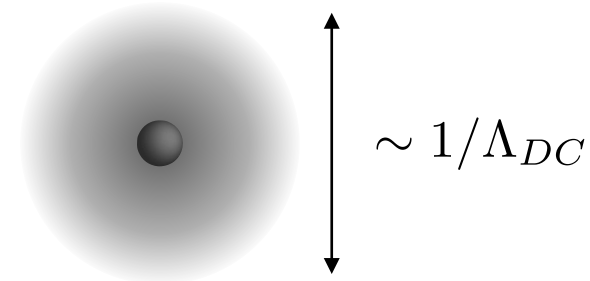
$$M_\chi \sim M_Q \qquad R_\chi \sim 1/\Lambda_{DC}$$

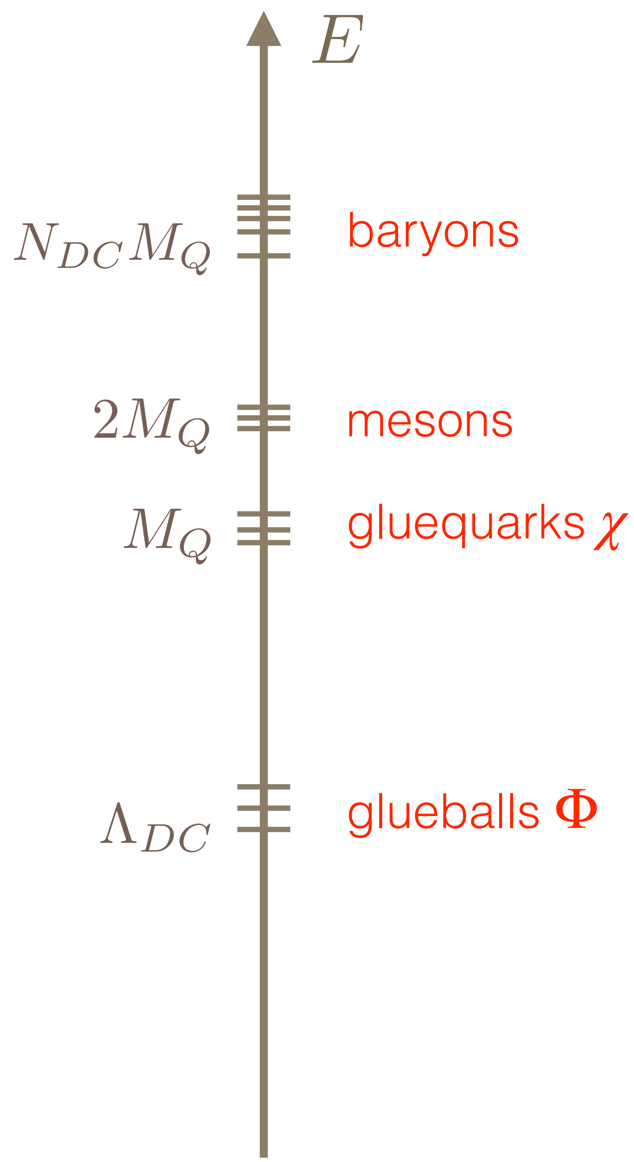
- At $T \sim M_Q$ dark quarks have a first perturbative freeze out



$$\langle \sigma v \rangle \sim \frac{\pi \alpha_{DC}^2}{M_Q^2}$$

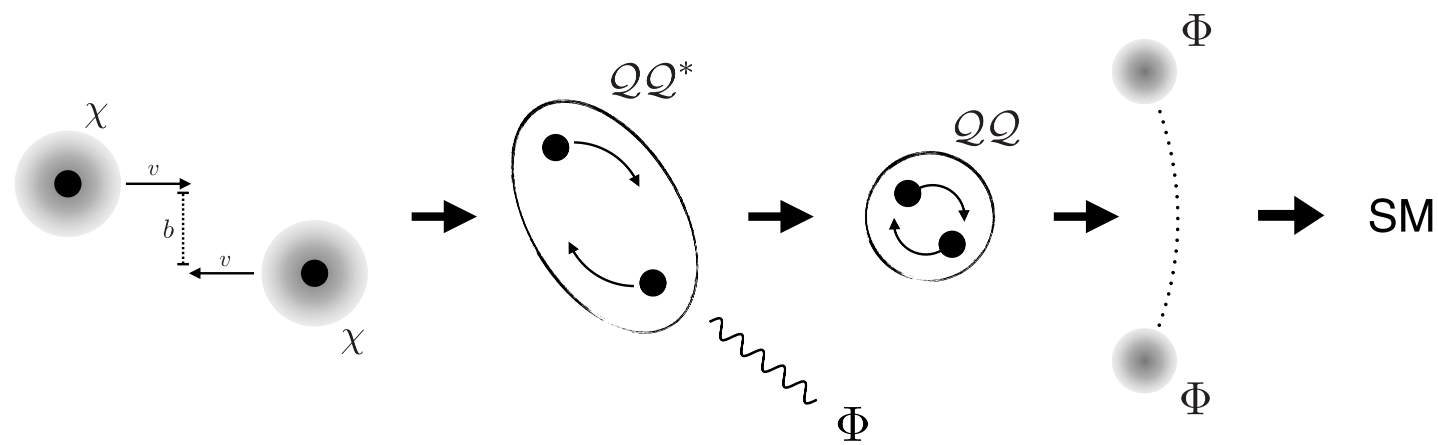
- Gluequarks





Energy cartoon for $M_Q > \Lambda_{DC}$

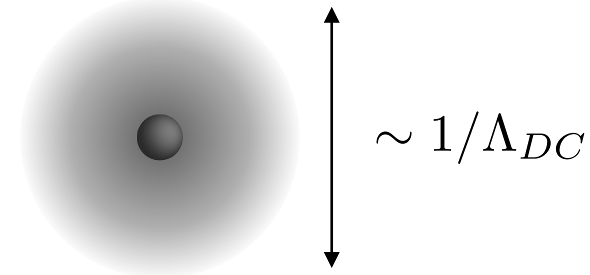
- At $T \lesssim \Lambda_{DC}$ gluequarks undergo a second freeze out through recombination processes into SM particles

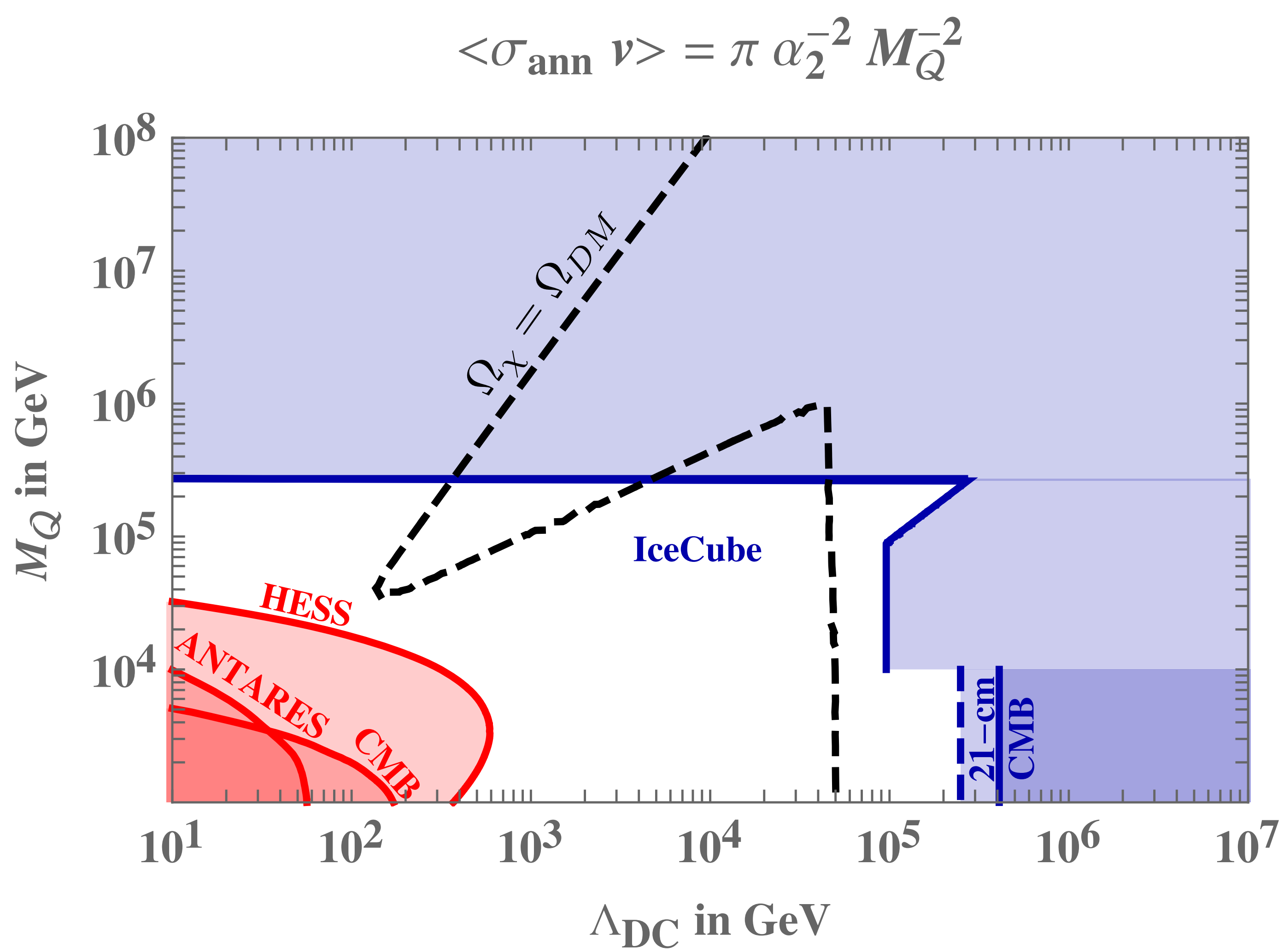


Cross section for gluequarks recombination is much larger than that for direct annihilation

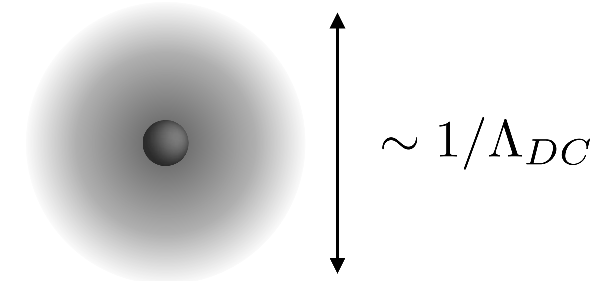
$$\sigma_{\chi\chi} \sim \frac{\pi}{\Lambda_{DC}^2} \qquad \text{(geometrical)}$$

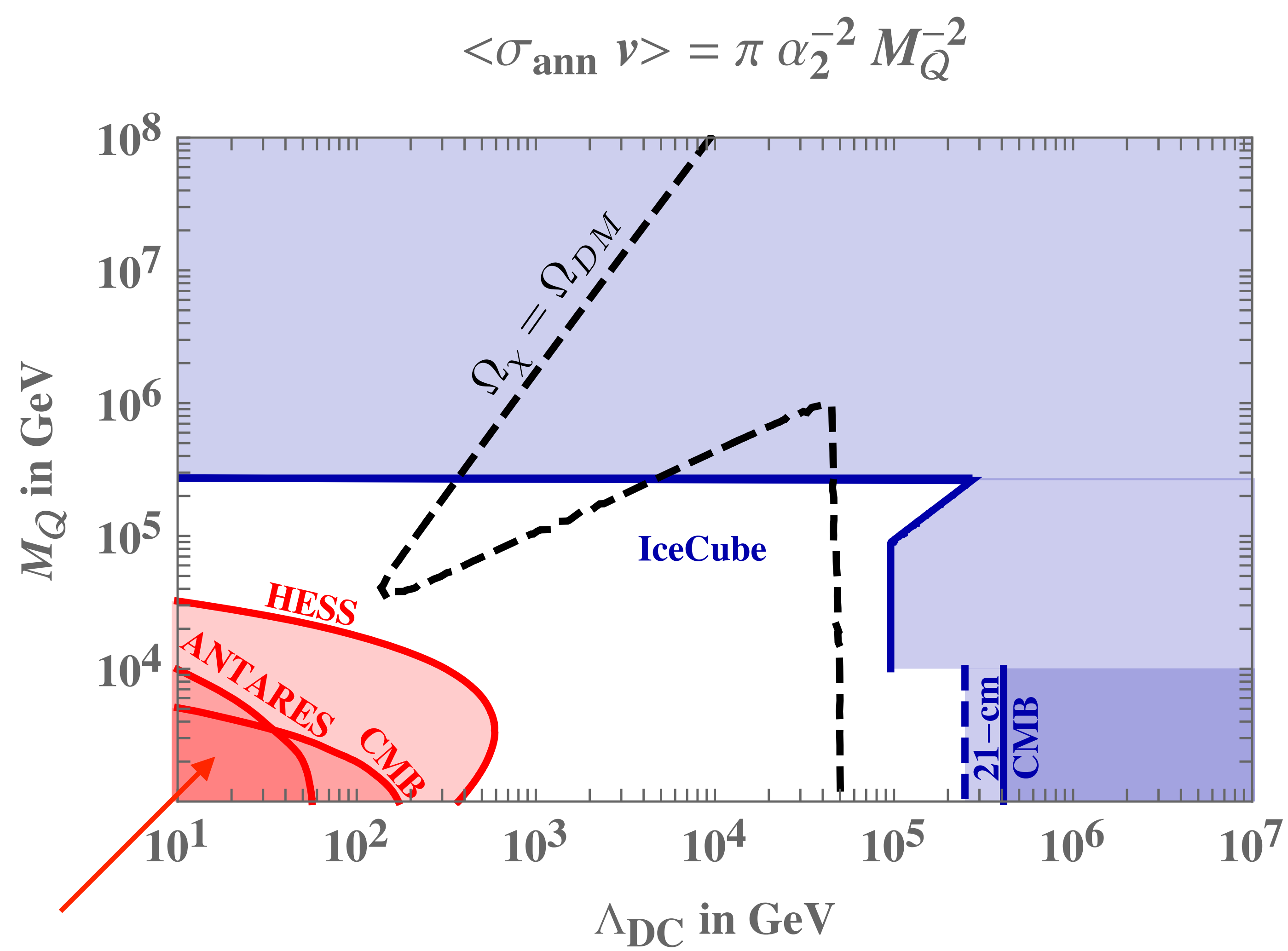
- Gluequarks


$\sim 1/\Lambda_{DC}$


$<\sigma_{\text{ann}}\, v> = \pi\, \alpha_2^{-2}\, M_Q^{-2}$
$\Omega_X = \Omega_{DM}$
IceCube
HESS
ANTARES
CMB
21–cm
CMB
M_Q in GeV
Λ_{DC} in GeV
10^4
10^5
10^6
10^7
10^8
10^1
10^2
10^3
10^4
10^5
10^6
10^7

- Gluequarks

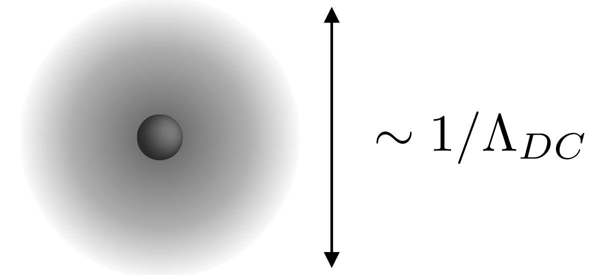




Exclusion from
gluequark annihilations

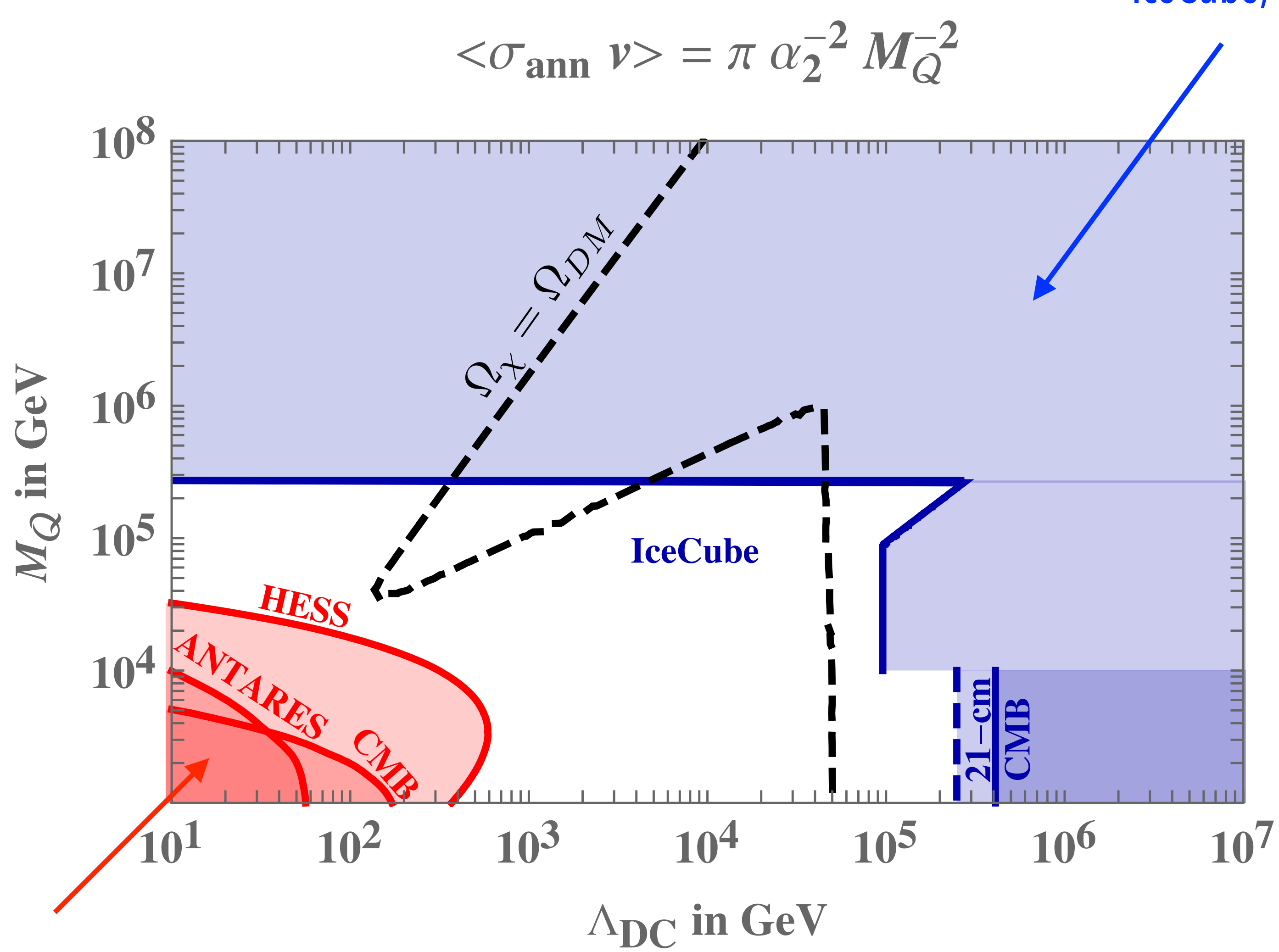
ANTARES, HESS, Fermi-IceCube, CMB

- Gluequarks



Exclusion from gluequark decay

IceCube, CMB, 21cm



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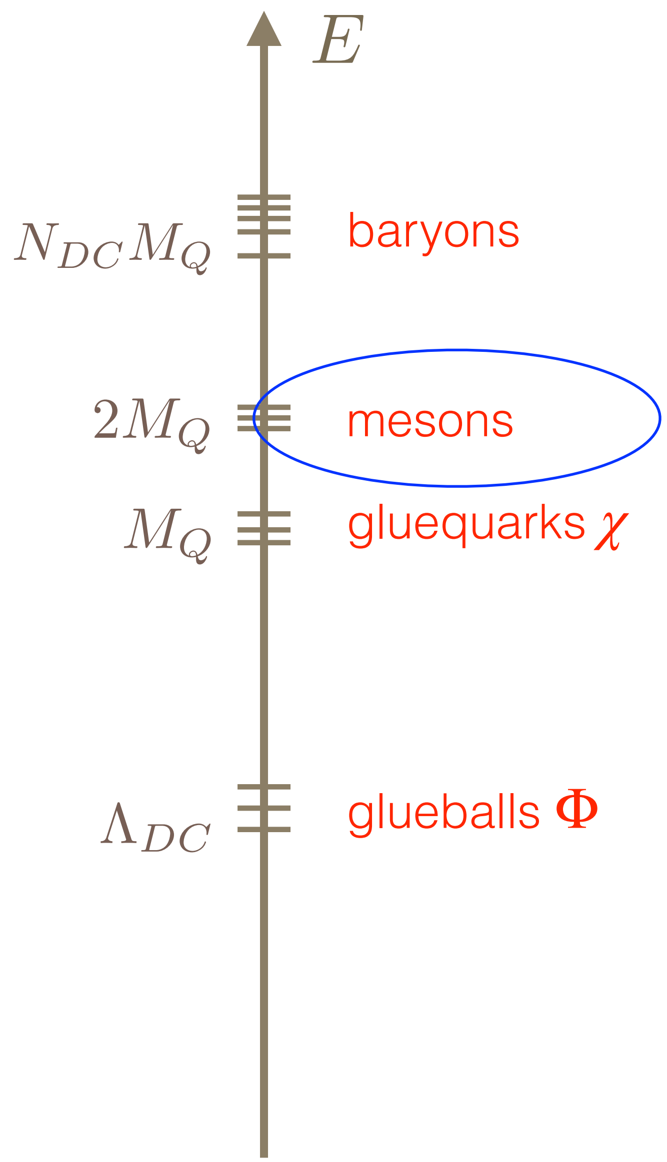
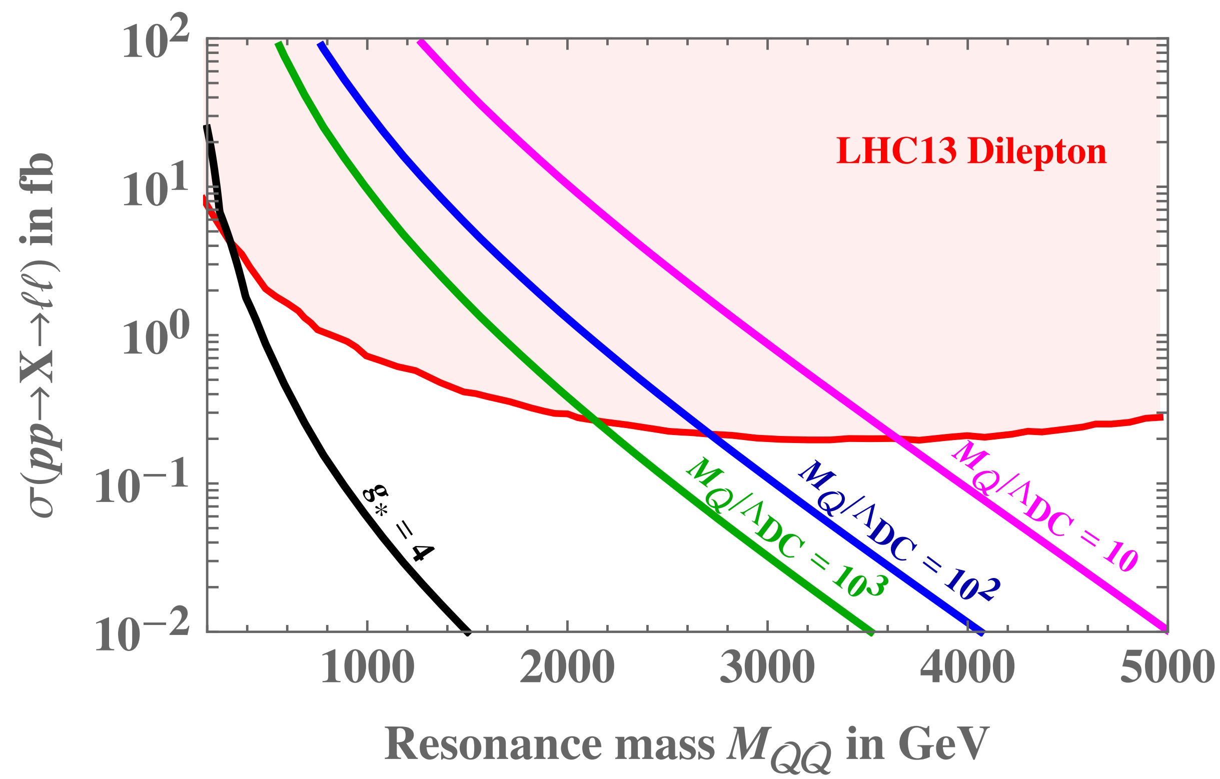


Energy cartoon for $M_Q > \Lambda_{DC}$

Heavy mesons are *perturbative* quarkonia bound states with calculable properties

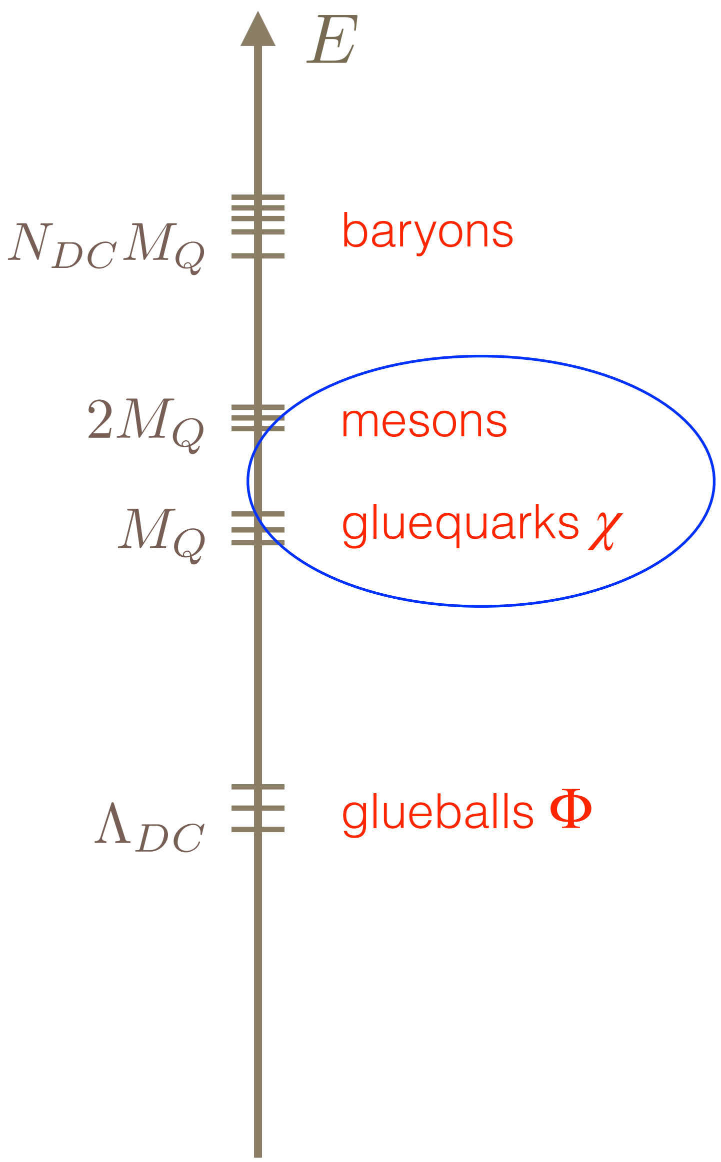
- Spin-1 mesons are singly produced via Drell-Yan and have a sizeable (~7%) BR into SM leptons



Dilepton searches at the LHC exclude $M_Q < 1.0 - 1.8\,\mathrm{TeV}$

Naive exclusion at FCC-hh (20ab[-1]): $M_Q < 7 - 13\,\mathrm{TeV}$

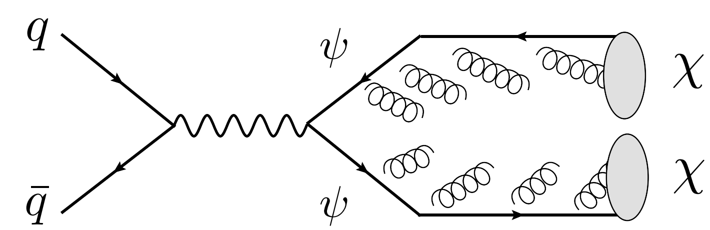
- Gluequarks



Energy cartoon for $M_Q > \Lambda_{DC}$

At $E > 2M$ one has open production of $\bar{\psi}\psi$

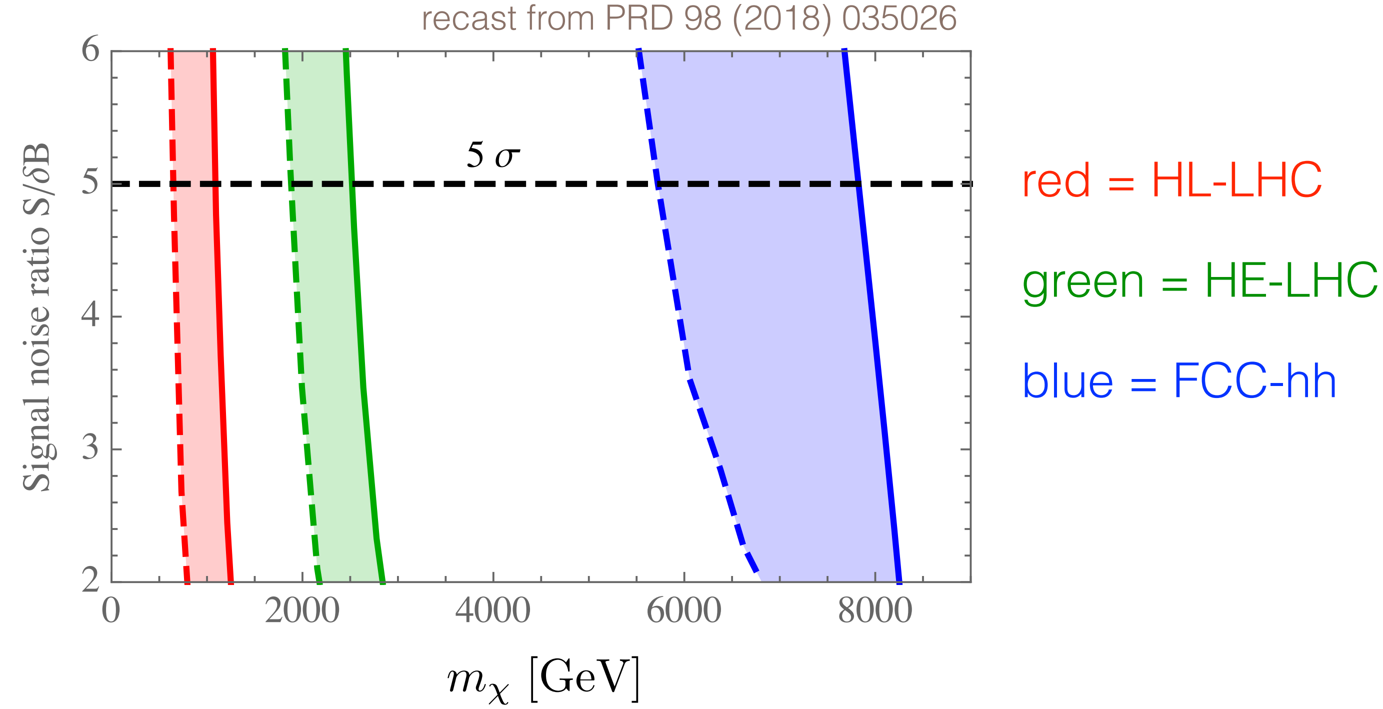
- Heavy quarks in the adjoint hadronize into dark color-singlet gluequarks



$$m_{\chi^+} - m_{\chi^0} = 160\,\mathrm{MeV}$$

χ^+ long-lived gives disappearing track ($\chi^+ \to \chi^0 + \pi^+$)

recast from PRD 98 (2018) 035026



- Dark Mesons

Dark mesons (pions) do not have dark baryon number but can be stable due to accidental species numbers

$$\pi \sim (\bar{Q}_1 Q_2) \qquad\qquad U(1): \begin{cases} Q_1 \to e^{-i\alpha}\, Q_1 \\ Q_2 \to e^{+i\alpha}\, Q_2 \end{cases}$$

Notice: viable DM candidates must be have zero hypercharge and zero EM charge (hence integer weak isospin)

In general, species numbers are broken by D=5 operators (in the basis where mass terms are flavor diagonal):

$(\bar{Q}_1 Q_2)(HH)$ if $(\bar{Q}_1 Q_2) = 1_0, 3_0$ of $SU(2)_{EW}$ x $U(1)_Y$

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☞ Dark pions naively less stable than dark baryons and not viable accidental DM candidates

Analogy: low-energy QCD with 2 flavors

	$SU(3)_c$	$U(1)_{EM}$	$U(1)_{3V}$	$U(1)_V$
u_L	$\square$	$+2/3$	$+1$	$+1/3$
d_L	$\square$	$-1/3$	-1	$+1/3$
u^c_R	$\bar{\square}$	$-2/3$	-1	$-1/3$
d^c_R	$\bar{\square}$	$+1/3$	$+1$	$-1/3$

$$\mathcal{L}_{mass} = m_u\, u_L u^c_R + m_d\, d_L d^c_R + h.c.$$

$$\mathcal{L}_{6D} \supset \bar{d}_L \gamma^\mu u_L \bar{\nu}_\ell \gamma_\mu \ell + h.c.$$ (from W exchange)

breaks species number U(1)$_{3V}$

Global Symmetry breaking pattern:

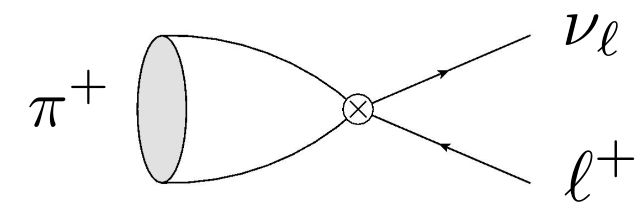
$$SU(2)_L \times SU(2)_R \times U(1)_V \xrightarrow{\text{spont.}} SU(2)_V \times U(1)_V$$

$$\hookrightarrow_{\text{expl.}} U(1)_{EM} \times U(1)_{3V}$$

accidental
species number

3 pseudo NGBs = $\pi^\pm$, π^0

$\pi^\pm$ decays through the
number species violating
D=6 operator (weak decay)



A Model of Accidental Meson DM

	$SU(N_{DC})$	$SU(2)_{EW}$	$U(1)_{3V}$	$U(1)_V$
ψ_1	$\square$	$\square$	$+1$	$+1$
ψ_2	$\square$	$\square$	-1	$+1$
χ_1	$\bar{\square}$	$\bar{\square}$	-1	-1
χ_2	$\bar{\square}$	$\bar{\square}$	$+1$	-1

$$\mathcal{L}_{mass} = M_1\psi_1\chi_1 + M_2\psi_2\chi_2 + h.c.$$

$$\mathcal{L}_{5D} \supset \psi_1\chi_2 H^\dagger H, \quad \psi_2\chi_1 H^\dagger H$$

break species number $U(1)_{3V}$

Global Symmetry breaking pattern:

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accidental

15 (pseudo) NGBs = $3_\pm$, 3_0, $3_0'$, $1_\pm$, 1_0

$$1_+ \sim (\psi_1\chi_2)$$

$$1_- \sim (\psi_2\chi_1)$$

$$1_0 \sim (\psi_1\chi_1 - \psi_2\chi_2)$$

All the NGBs decay through 5D operators

Mass terms and 5D operators can be forbidden by gauging the anomaly-free *chiral* U(1) subgroup

[R.C., Podo, Revello JHEP 02 (2021) 091]

	$SU(N_{DC})$	$U(1)_D$	$SU(2)_{EW}$	$U(1)_{3V}$	$U(1)_V$
ψ_1	$\square$	$+1$	$\square$	$+1$	$+1$
ψ_2	$\square$	-1	$\square$	-1	$+1$
χ_1	$\bar{\square}$	$-a$	$\bar{\square}$	-1	-1
χ_2	$\bar{\square}$	$+a$	$\bar{\square}$	$+1$	-1

For $a \neq 1$ the representations are *chiral*, no mass term or 5D operators allowed by gauge invariance

$$Q_D = T_{3L} + a\, T_{3R}$$

Free parameters:

dark dynamical scale: Λ_D

dark coupling: e_D

dark charge: a

hypercharge-dark photon mixing: ε

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stable → DM candidate

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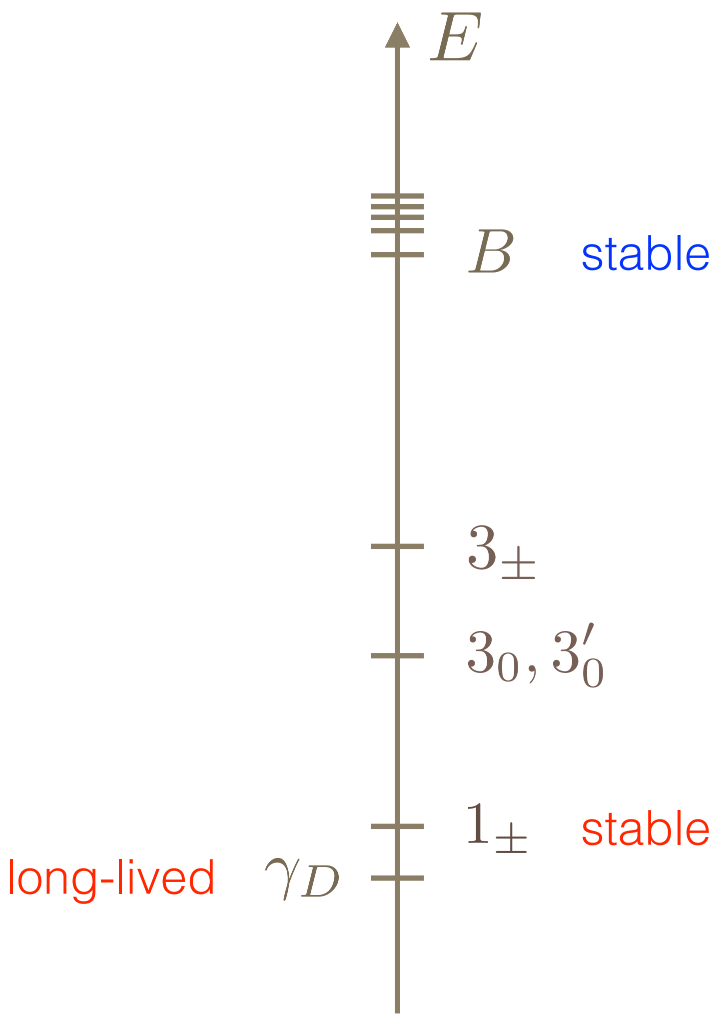
- Spectrum



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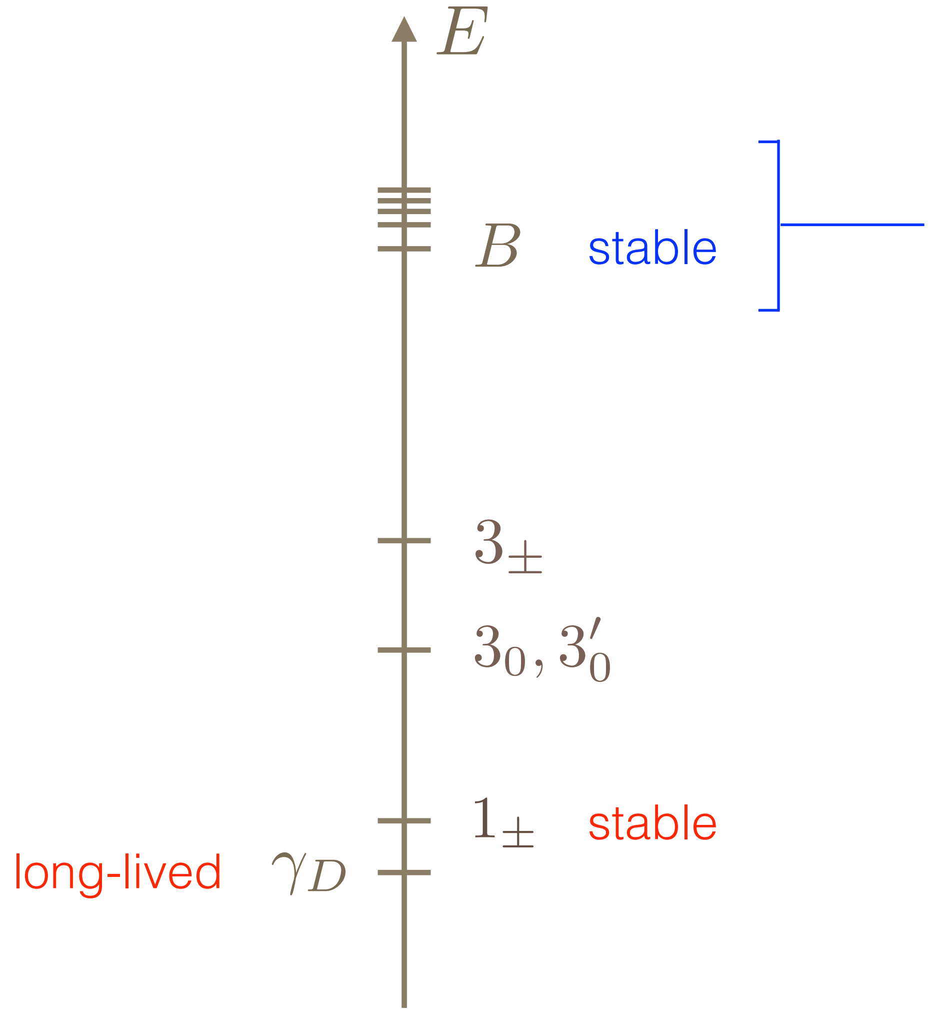

N_{DC} odd excluded because lightest baryon is charged under EM

Hence N_{DC}=4 or 6

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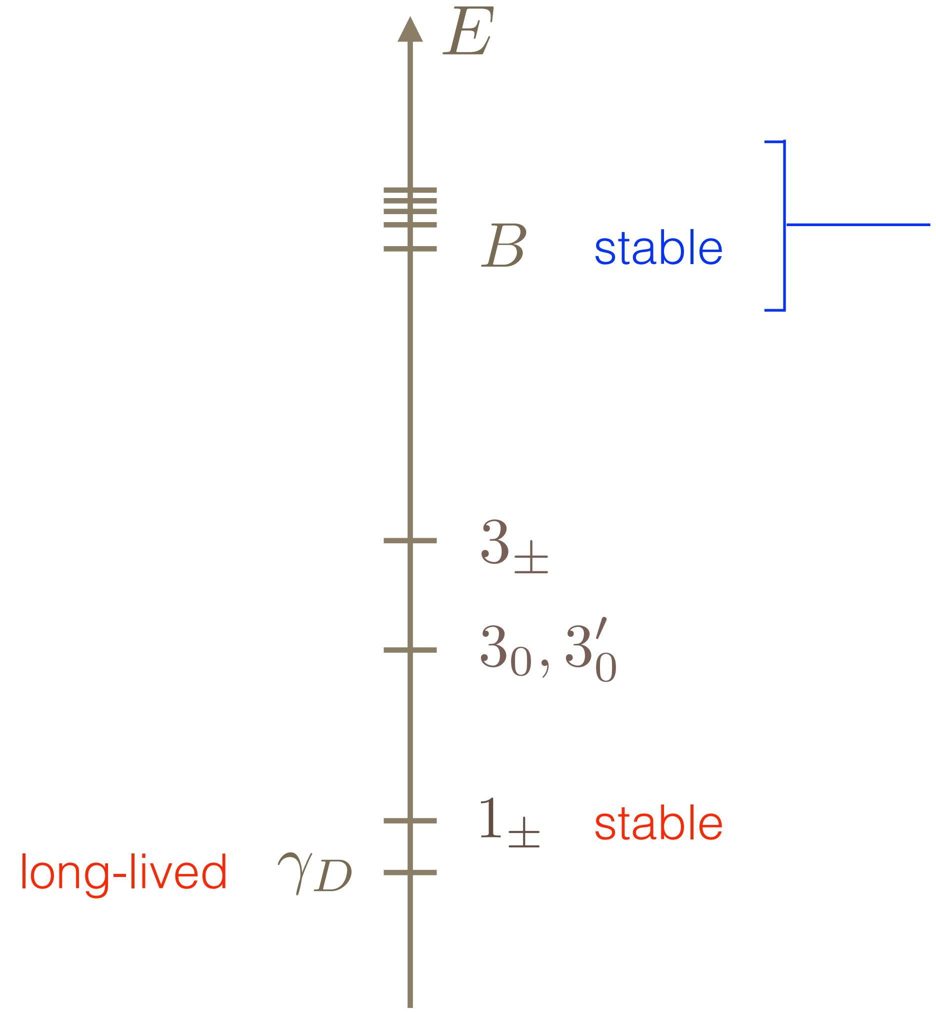

Heavy dark hadrons
(including lightest baryon)

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Pseudo NGBs
and Dark Photon

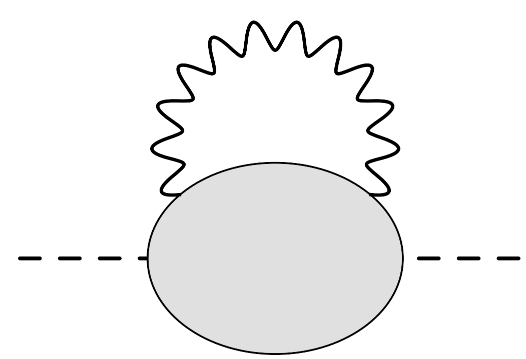
Acquire mass from weak gauging

$$m_1^2 = 24\ln(2)a\frac{e_D^2}{16\pi^2}m_\rho^2$$

$$m_3^2 = 12\ln(2)\frac{g^2}{16\pi^2}m_\rho^2$$

$$m_{3_\pm}^2 = \left(24\ln(2)\frac{e_D^2}{16\pi^2} + 12\ln(2)\frac{g^2}{16\pi^2}\right)m_\rho^2$$

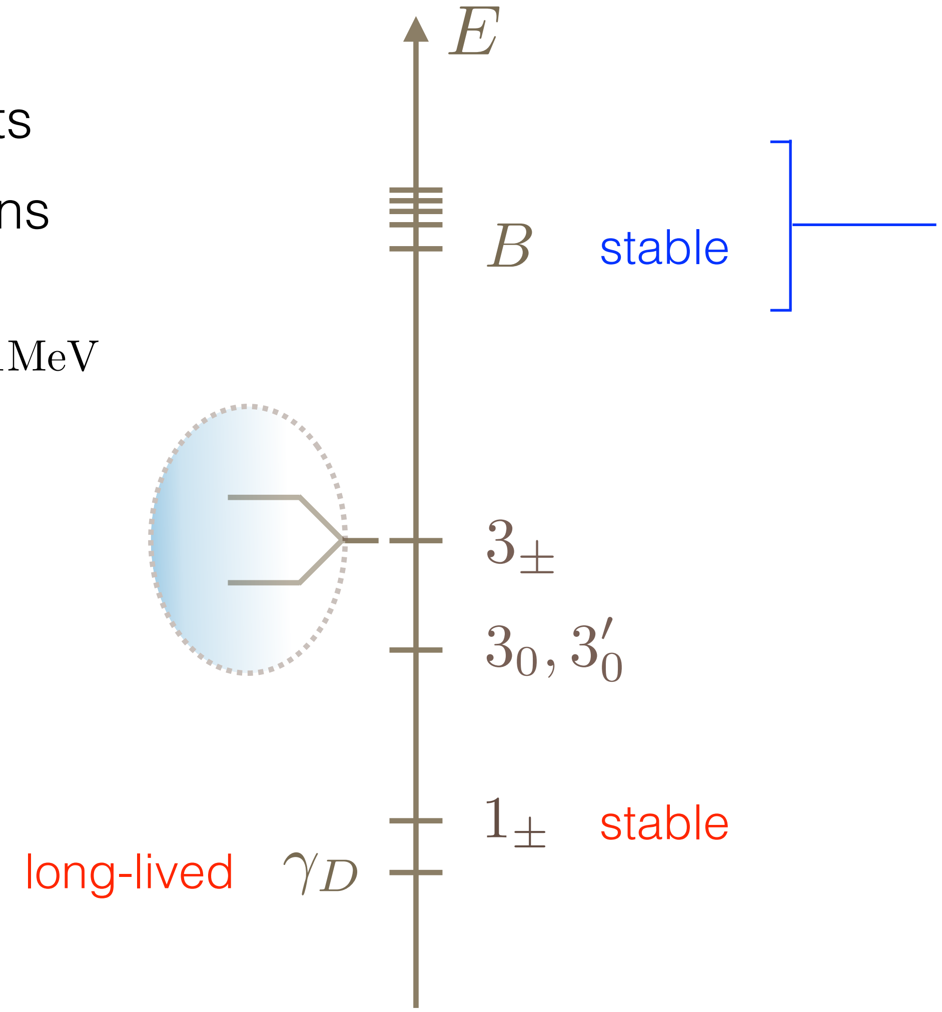
$$m_{\gamma_D}^2 = 2e_D^2(1-a)^2 f^2 \sim \frac{N_{DC}}{8\pi^2}e_D^2(1-a)^2 m_\rho^2$$



- Spectrum

Hyperfine splitting of triplets
at $O(g^4)$ from EW corrections

$$\Delta m|_{EW} = \frac{g}{4\pi} m_W \sin^2 \frac{\theta_W}{2} = 166 \pm 1\text{MeV}$$



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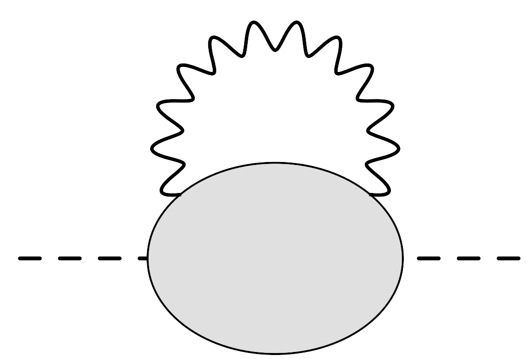

- Accidental stability

  - $U(1)_{3V}$ breaking operators

    d=6 (for $a=0$) $\psi_1\chi_2\psi_2\chi_2$

    d=7 (for $a=\pm 1/3, \pm 3$) $\chi_1^\dagger i\not{D}\chi_2\,\psi_1\chi_2$

    d>7 for other values of a

    Dark pions more stable than in vector-like theories

  - $U(1)_V$ breaking operators

    d=6 ($N_{DC}=4$) $\chi\chi\chi\chi\,,\ \psi\psi\psi\psi$

    d>6 for $N_{DC}\neq 4$

- Accidental stability

  - $U(1)_{3V}$ breaking operators

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    Dark pions more stable than in vector-like theories

  - $U(1)_V$ breaking operators

    d=6 ($N_{DC}=4$) $\chi\chi\chi\chi\,,\ \psi\psi\psi\psi$

    d>6 for $N_{DC}\neq 4$

- Accidental discrete symmetries

  - Dark Charge Conjugation

$$\mathcal{C}_D : \begin{cases} A_\mu^D \longrightarrow -A_\mu^D \\ \psi_1 \longleftrightarrow \psi_2 \\ \chi_1 \longleftrightarrow \chi_2 \end{cases}$$

Broken by kinetic mixing ε

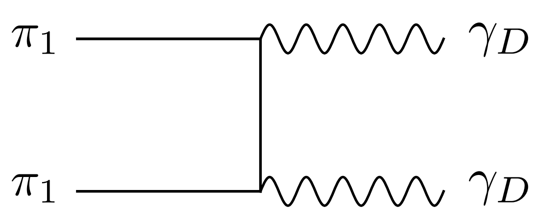
Small values of ε are technically natural (even though dark quarks have SM charges)

  - Dark G-Parity

$$\mathcal{G}_D : \begin{cases} \psi_i \longrightarrow e^{i\pi T_2}\chi_i \\ G_\mu^a\lambda_a \longrightarrow -G_\mu^a\lambda_a^* \end{cases}$$

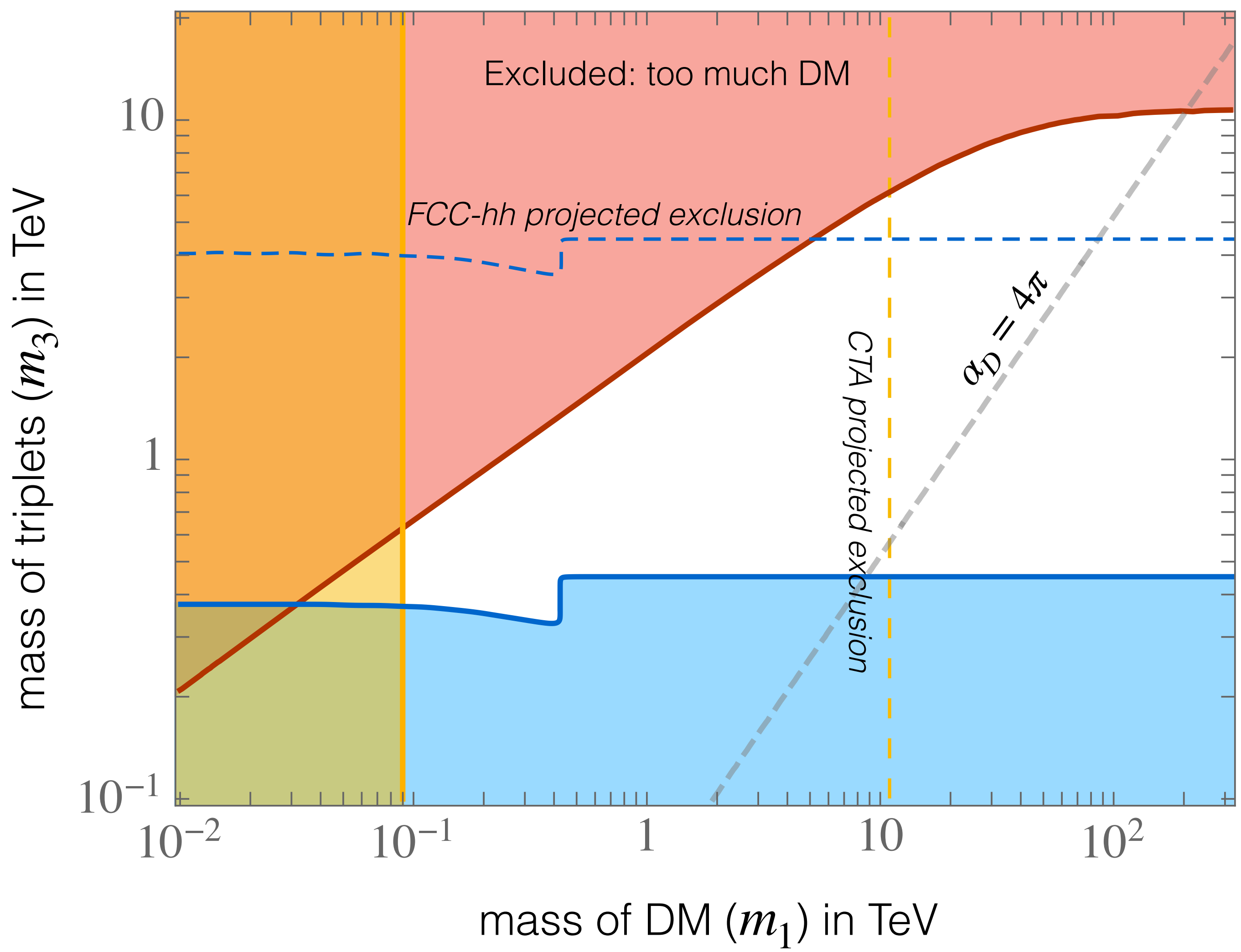
Broken by $U(1)_D$ gauging

- Dark pions ($1_\pm$) and dark baryons are both thermal relics, DM abundance dominated by dark pion for small e_D



$$\langle \sigma_{\pi\pi} v \rangle \sim \frac{e_D^4}{8\pi} \frac{1}{m_1^2} \sim e_D^2 \frac{\pi}{\Lambda^2}$$

- Interesting correlation between collider signatures and cosmological/astrophysical predictions



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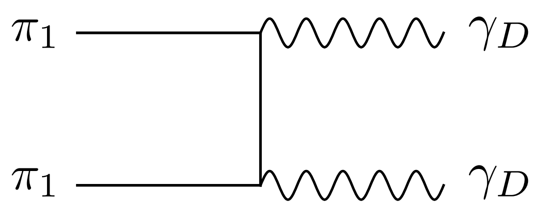

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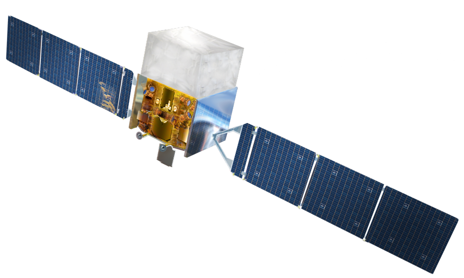
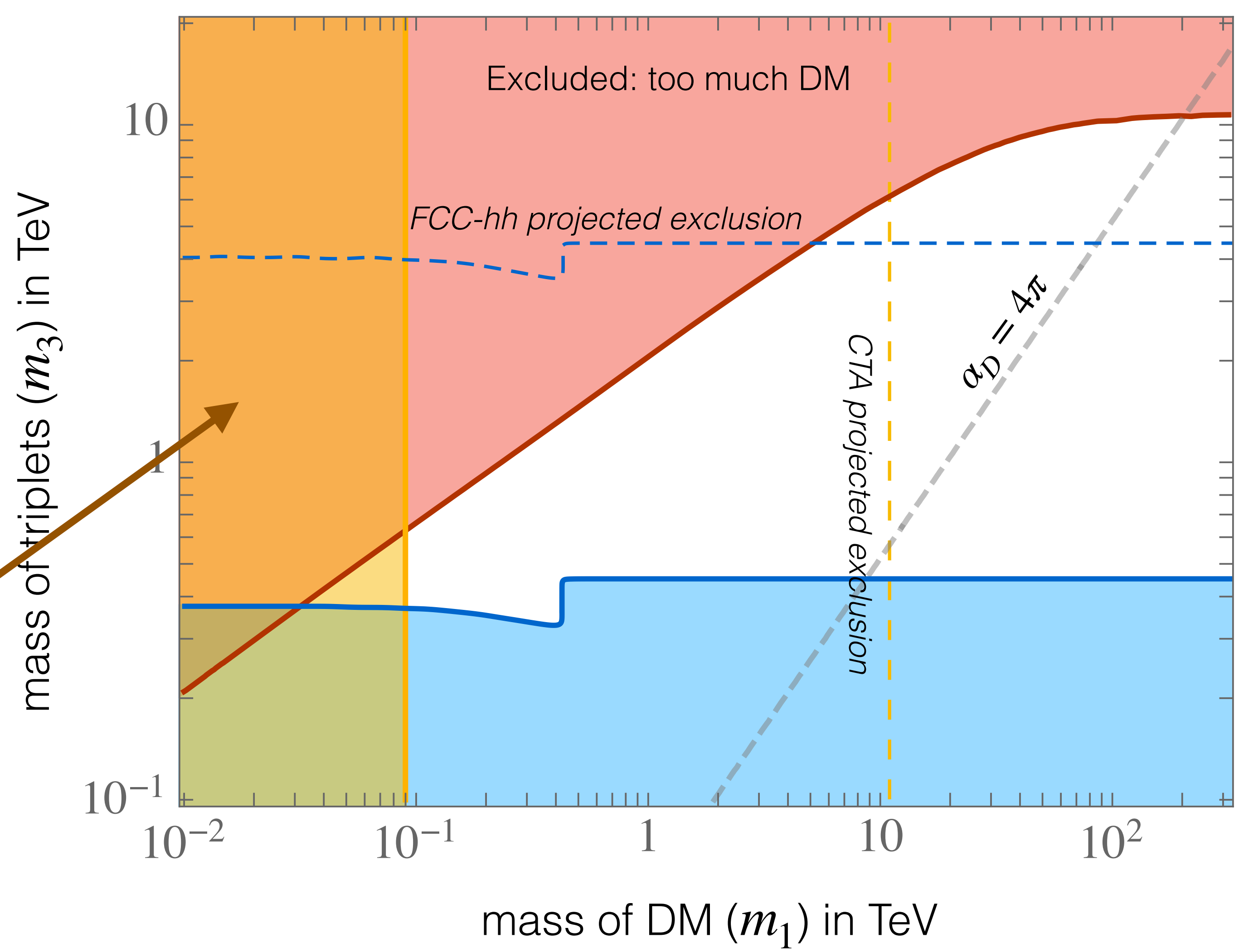


Excluded by FERMI-LAT

Dark pion annihilations produce galactic and extra galactic high-energy photons

- γ-rays from dwarf spheroidal galaxies



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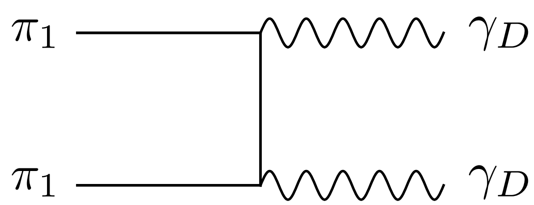

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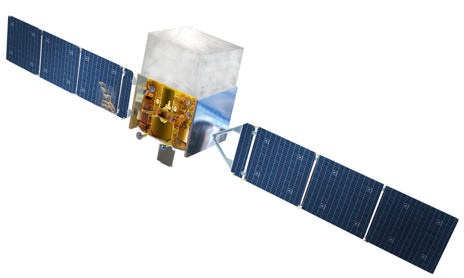

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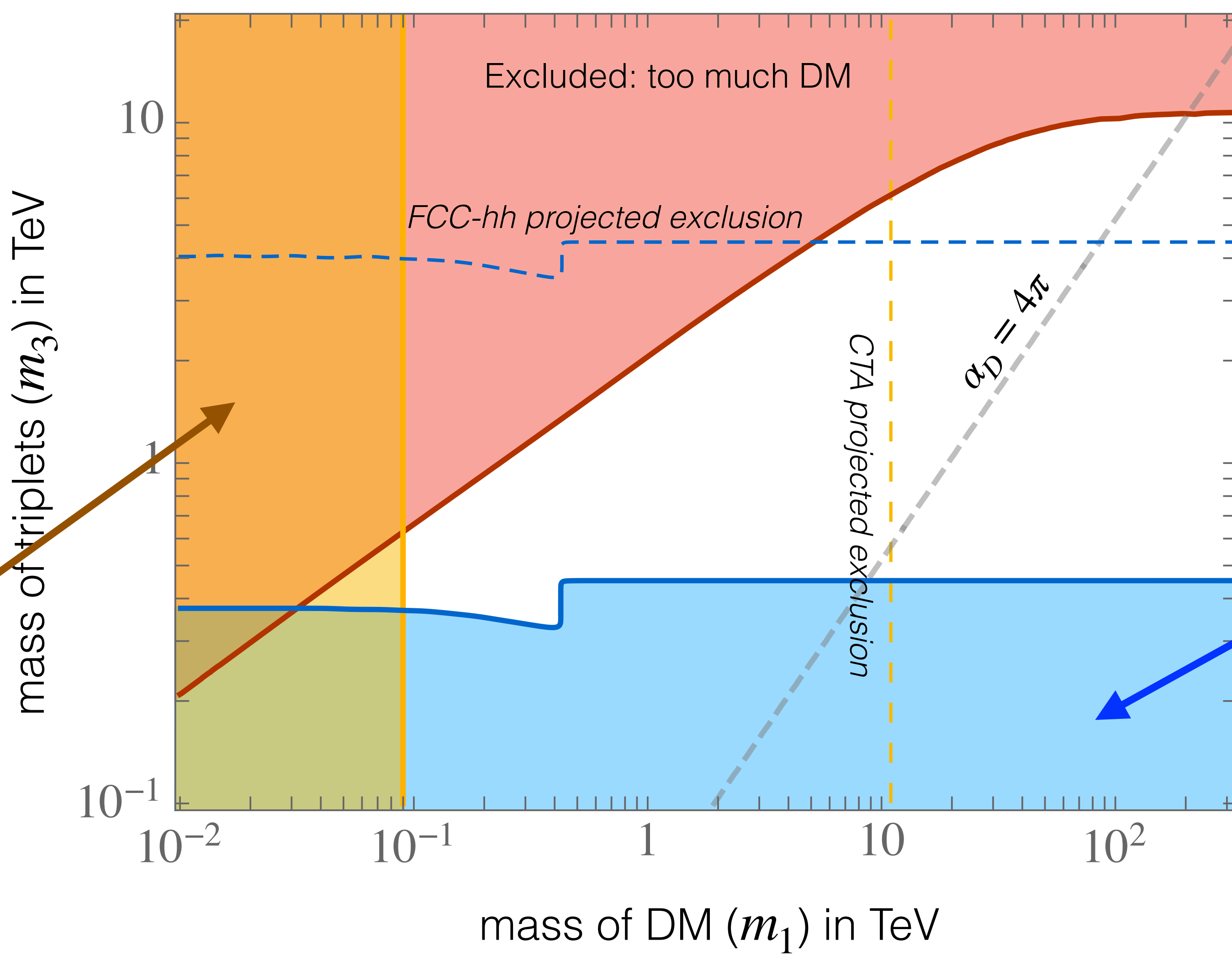

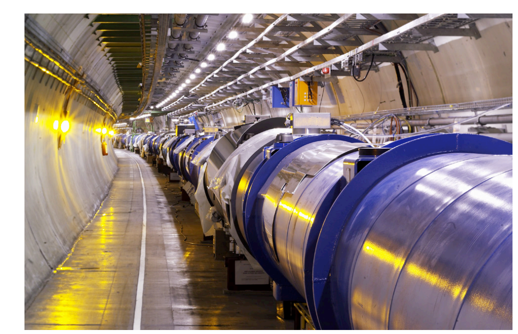

Excluded by LHC

Pair production of triplets

$pp \to \pi_3 \pi_3$

- leptons + missing E_T
- displaced vertices (long-lived γ_D)
- resonant decays (prompt γ_D)

Part II

Accidental Axion

Axion = pNGB of a spontaneously broken
U(1)$_{PQ}$ anomalous under SU(3) color

$$\mathcal{L} = \frac{\alpha_s}{8\pi}\left(\frac{a(x)}{f_a} - \theta\right) G_{\mu\nu}\tilde{G}^{\mu\nu} + \Delta\mathcal{L}_{\cancel{PQ}}$$

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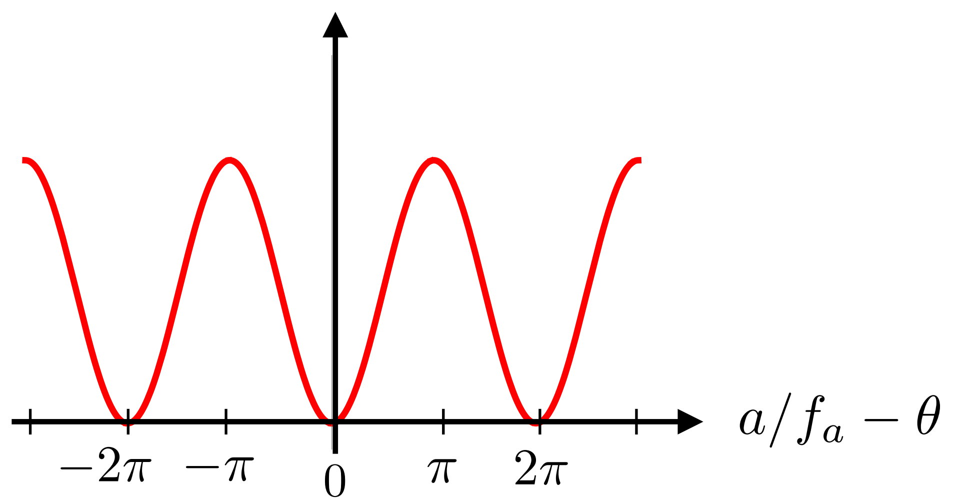

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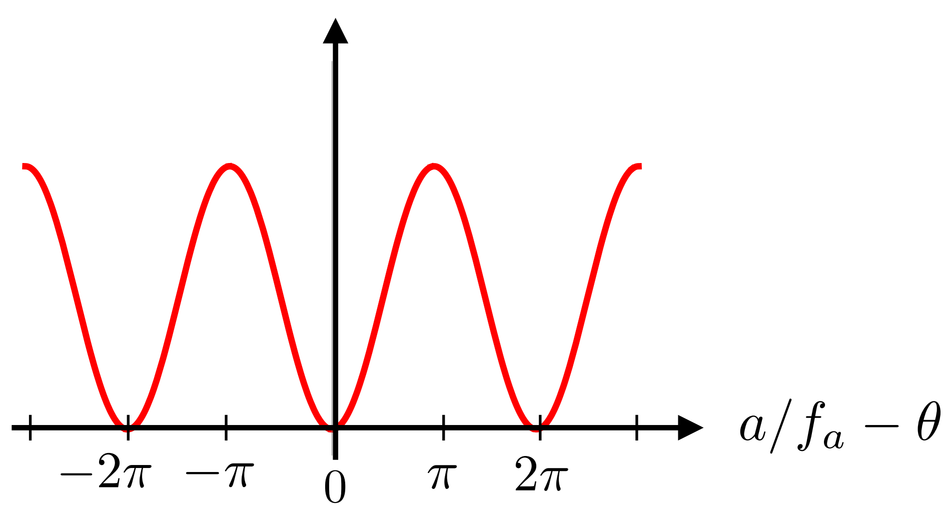

$$\Delta V(a/f_a) \lesssim 10^{-10}\, V_{QCD}$$

from neutron EDM bound

$$|\theta| \lesssim 10^{-10}$$

Q: Can the PQ symmetry be accidental ?

Randall PLB 284 (1992) 77
Redi, Sato JHEP 05 (2016) 104
Fukuda et al. PLB 771 (2017) 327
Lillard, Tait JHEP 11 (2017) 005; 11 (2018) 199
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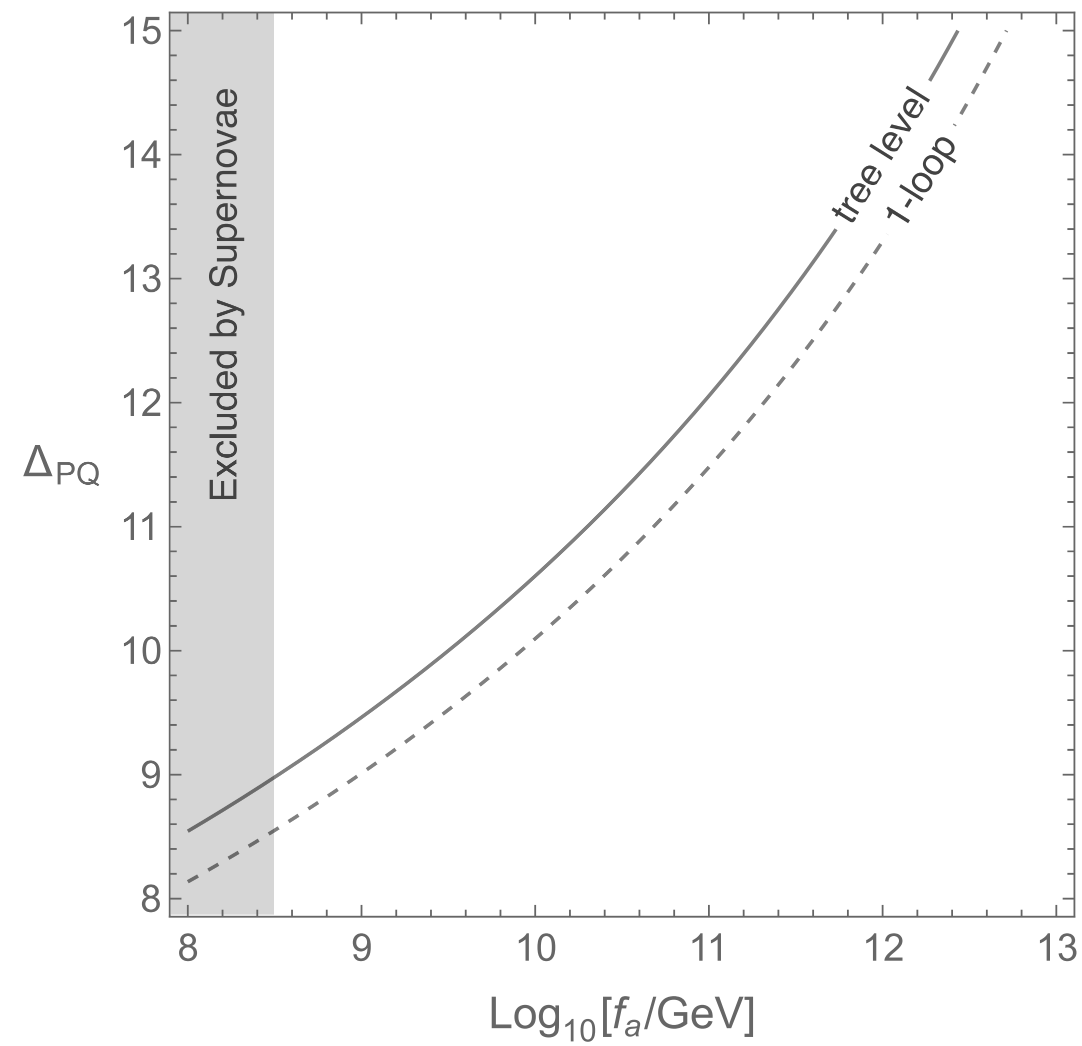
Vecchi Eur. Phys. J. C 81 (2021) 938

$$\Delta\mathcal{L}_{\cancel{PQ}} = \frac{g_{UV}^{2-n}}{M_{\mathrm{Pl}}^{3n-4}} \left(\bar{\psi}\psi\right)^n$$

$$\Downarrow$$

$$\Delta\theta \approx g_{UV}^{2-\frac{\Delta_{\cancel{PQ}}}{3}} \phi_{CP} \left(\frac{M_{\mathrm{Pl}}}{\Lambda_{QCD}}\right)^4 \left(\frac{f_a}{M_{\mathrm{Pl}}}\right)^{\Delta_{\cancel{PQ}}}$$



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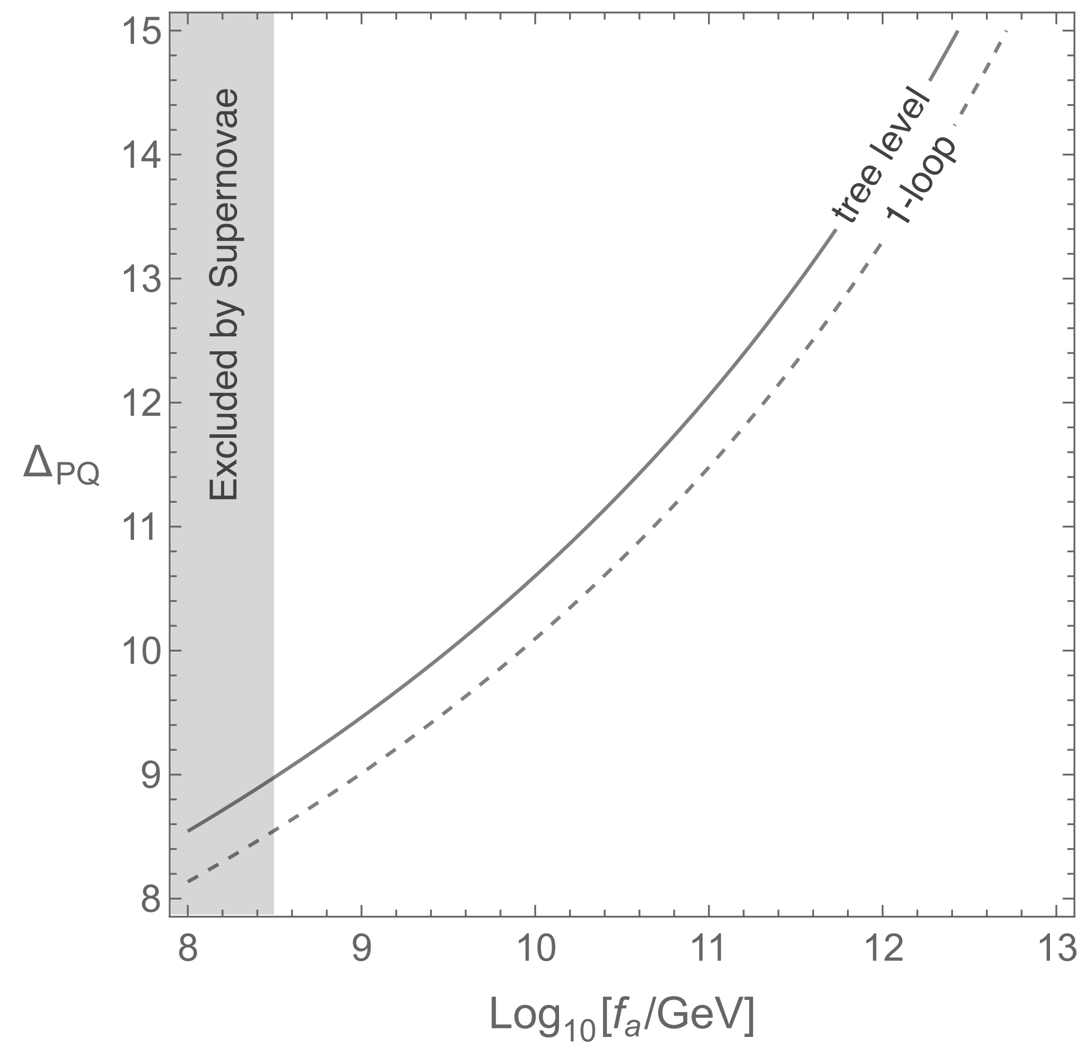

- Supernovae bounds are satisfied for $f_a \geq 4\cdot 10^8\,\mathrm{GeV}$, which requires $\Delta_{\cancel{PQ}} \gtrsim 9$

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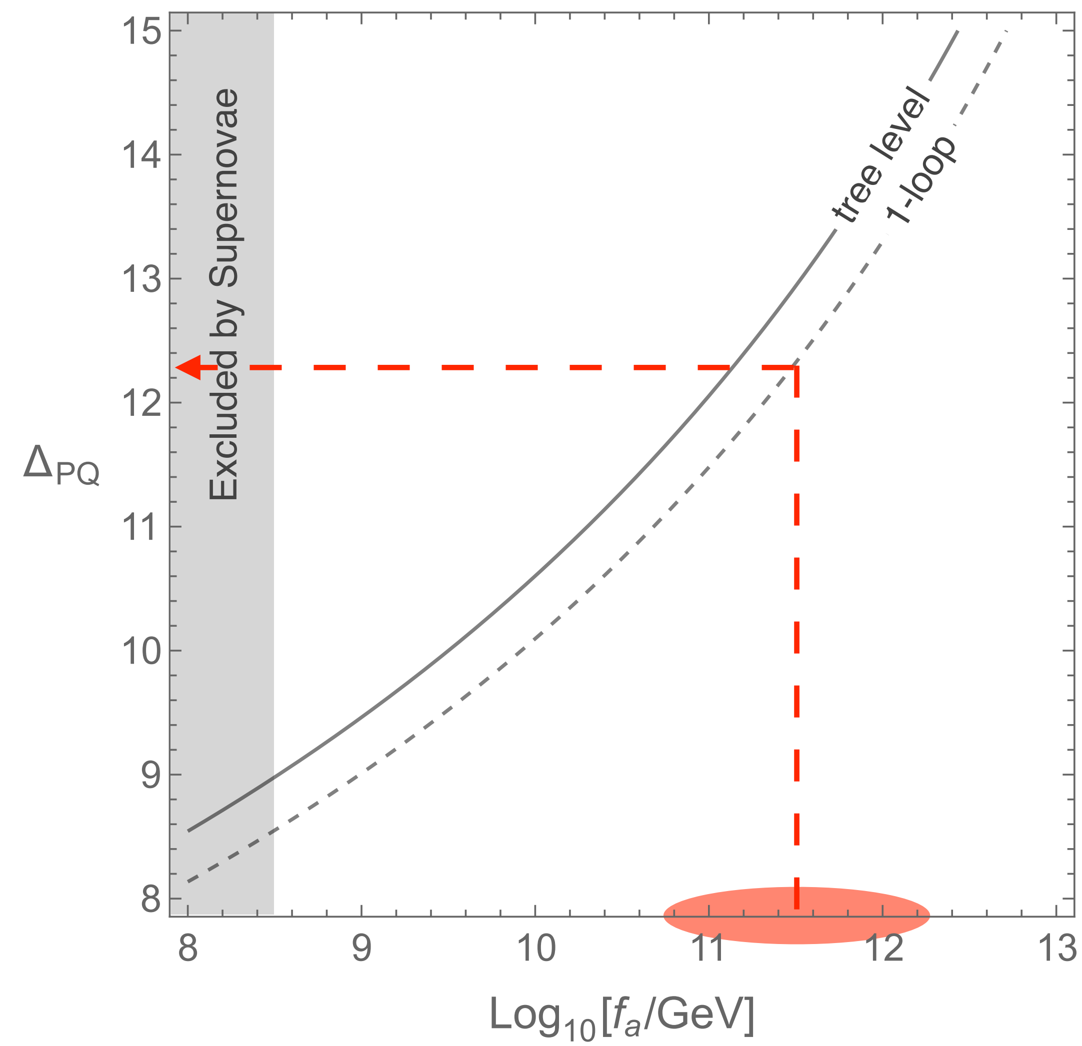

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  Axion Quality Problem

- Axion DM through misalignment requires $\Delta_{\cancel{PQ}} \gtrsim 12$

GUT Models of Composite Accidental Axion

[R.C., Podo, Revello arXiv:2112.09635]

Minimal models have 3 irreducible GUT representations:

	$\mathrm{SU}(N_{\mathrm{DC}})$	$\mathrm{U}(1)_{\mathrm{D}}$	$\mathrm{SU}(5)_{\mathrm{GUT}}$	$\mathrm{U}(1)_{\mathrm{PQ}}$
ψ_1	$\square$	p_1	r_1	α
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$\mathrm{U}(1)_{\mathrm{D}}$ chiral representations

Accidental global symmetry: $[\mathrm{U}(1)_{\mathrm{V}}]^3 \times \mathrm{U}(1)_{\mathrm{PQ}}$

1 SM-singlet NGB (axion) + 1 NGB eaten by dark photon

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$$\begin{cases} (p_1+q_1)T_1 + (p_2+q_2)T_2 + (p_3+q_3)T_3 = 0 \\ (p_1+q_1)d_1 + (p_2+q_2)d_2 + (p_3+q_3)d_3 = 0 \\ (p_1^3+q_1^3)d_1 + (p_2^3+q_2^3)d_2 + (p_3^3+q_3^3)d_3 = 0 \end{cases}$$

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Only 3+3 possible choices of irreps

r_1	r_2	r_3	$\Delta^{\max}_{\cancel{PQ}}$	N_{DC}	$f_a^{\min}$
$\mathbf{1}$	$\bar{\mathbf{5}}$	$\mathbf{10}$	12	$4, 5, \ldots, 11$	$4 \cdot 10^8$ GeV
$\mathbf{1}$	$\bar{\mathbf{5}}$	$\mathbf{15}$	15	$6, 7$	10^{11} GeV
$\mathbf{1}$	$\mathbf{10}$	$\mathbf{15}$	18	7	10^{12} GeV

Analysis of (1+$\bar{5}$+10) Models

- (1+$\bar{5}$+10) models can have f_a as low as $4 \times 10^8\,\mathrm{GeV}$
- Charge assignments exist which give $\Delta_{\cancel{PQ}} = 12$ ➡ robust solution to quality problem

Ex:

$$(p_1, p_2, p_3) = (-5, -6, +2) \qquad (q_1, q_2, q_3) = (+10, +3, -1)$$
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$$m_\varphi^2 \sim \frac{\alpha_{\rm GUT}}{4\pi}\frac{\Lambda_{\rm DC}^4}{M_{\rm GUT}^2}$$

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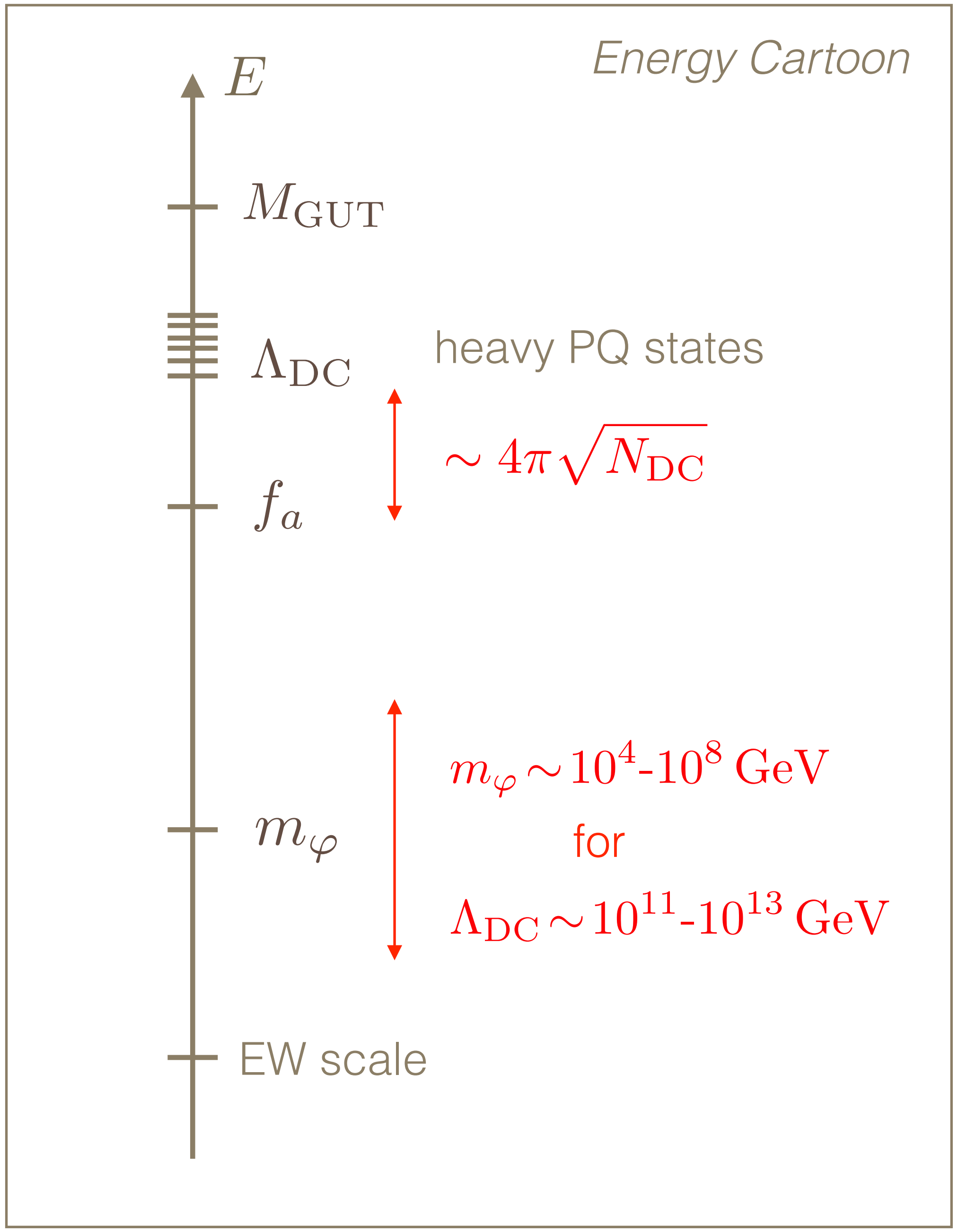

Conclusions/Outlook

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- Current models are interesting though not completely satisfactory, especially in their connection with SM gauge coupling unification.

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  Dark Baryon/Gluequark Models

  - *Spectrum (e.g. gluequark and glueball masses)*
  - *Dark baryon/Gluequark annihilation rate (for $M_Q < \Lambda_{DC}$)*
  - *Dark baryon/Gluequark recombination rate (for $M_Q > \Lambda_{DC}$)*
  - *Decay rates (e.g. of gluequark, for $M_Q < \Lambda_{DC}$, and glueballs, for $M_Q > \Lambda_{DC}$)*
  - *Chiral Symmetry Breaking in Gluequark theories (for $M_Q < \Lambda_{DC}$)*
  - *Cross section for DM self interaction*

  Dark Pion Chiral Models

  - *Spectrum (e.g. pseudo NGB, dark baryons)*
  - *Dark baryon annihilation rate*

  Accidental Axion Models

  - *Spectrum of PQ sector and ratio f_a/Λ_{DC}*
  - *Dimension of PQ-breaking operators in theories near a strongly-coupled IR fixed point*