ACCIDENTAL DARK MATTER

Roberto Contino

Scuola Normale Superiore, Pisa

INFN, Pisa

Theory Colloquium - University of Torino and INFN, 11 December 2020

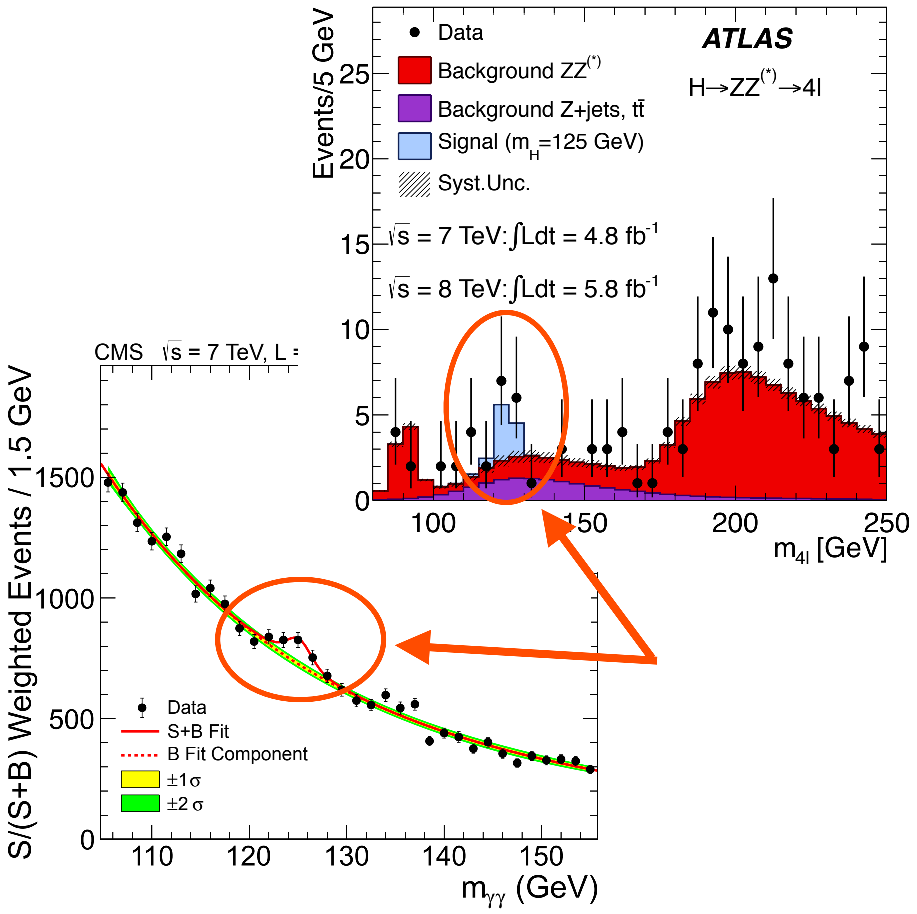
Plan of the talk

- Part I: Accidental (Emerging) Symmetries of the SM
- Part II: Accidental Dark Matter

Part I

Accidental (Emerging) Symmetries of the SM

Born on the 4th of July (2012)



With the discovery of the Higgs boson, we have for the first time a theory that describes all fundamental interactions (except gravity) and can be extrapolated to *extremely* high energies

$$m_W^2 W_\mu^+ W^{\mu -} + \frac{1}{2} Z_\mu Z^\mu \longrightarrow \frac{v^2}{4} \mathrm{Tr}\left[D_\mu \Sigma^\dagger D^\mu \Sigma \right]$$

$$\Sigma = \exp\left(\frac{i \chi^a \sigma^a}{v} \right)$$

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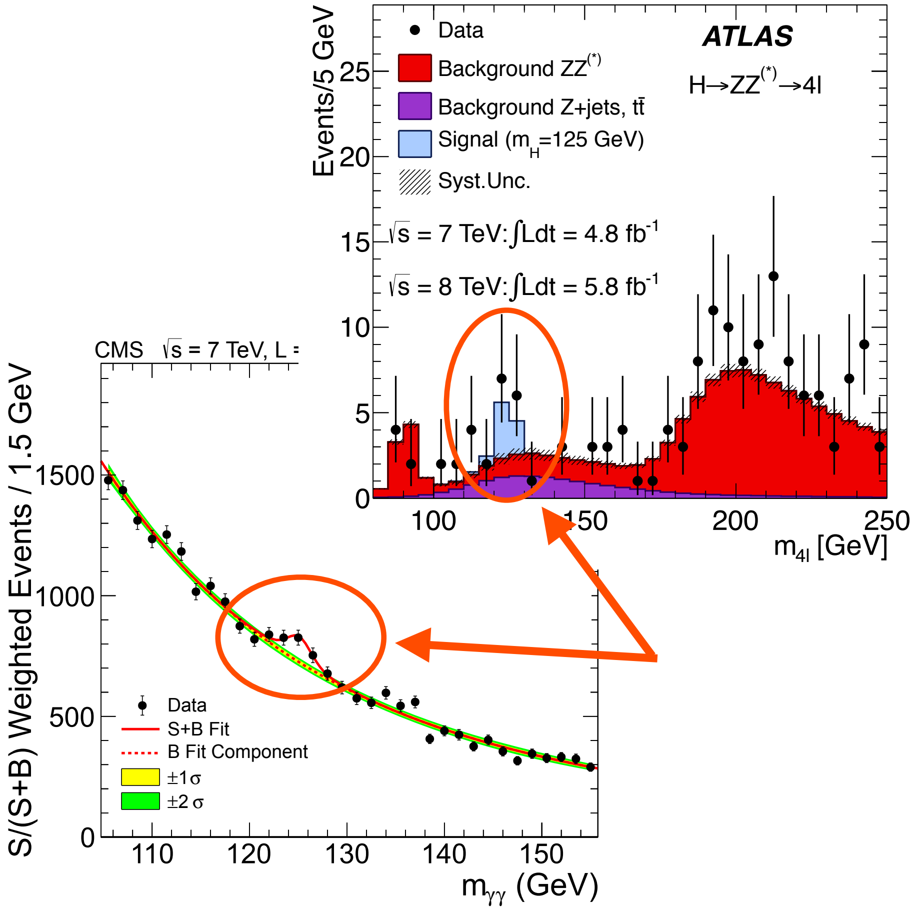

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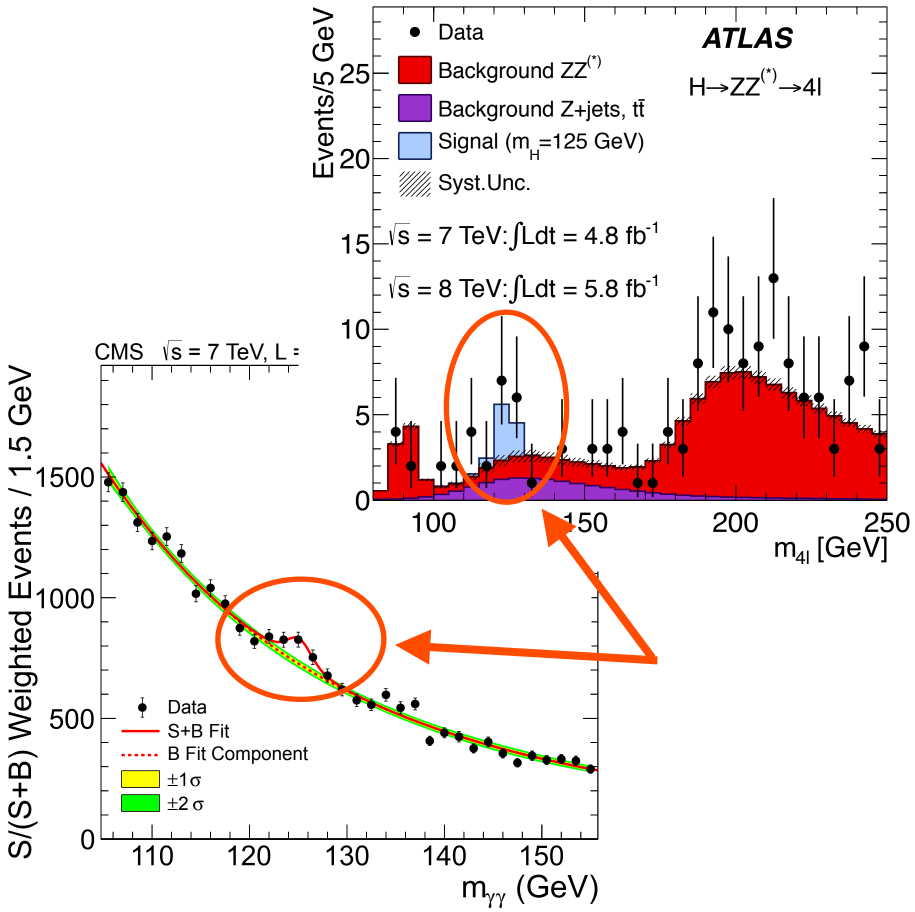

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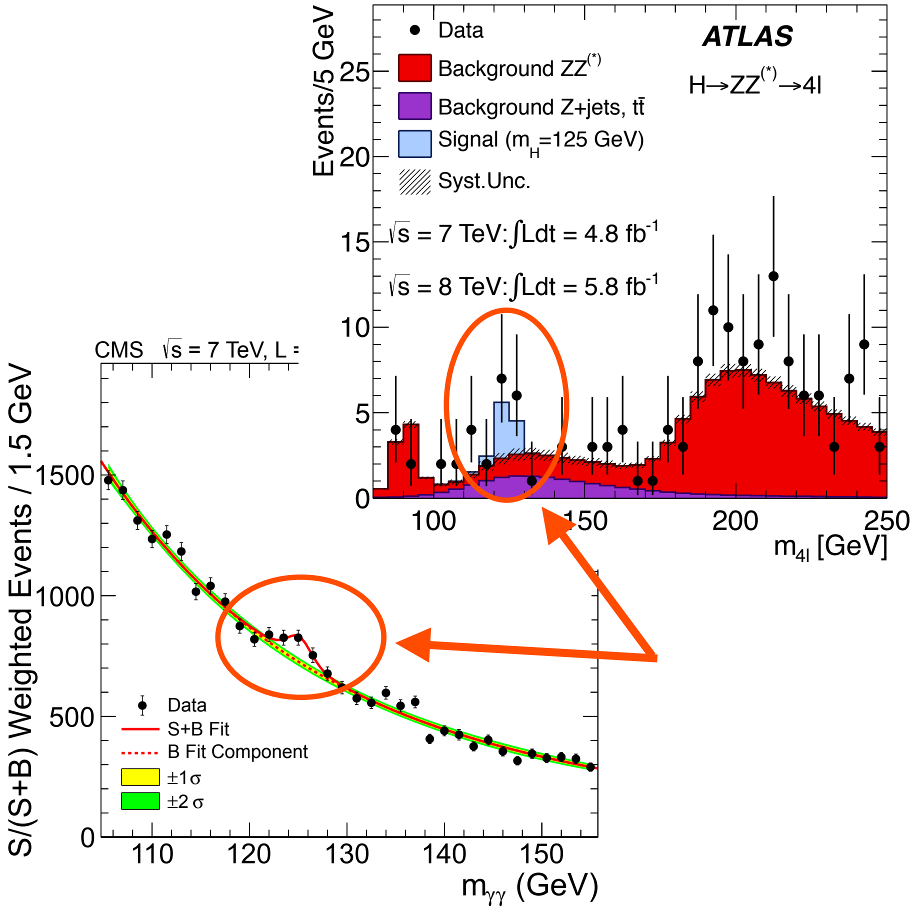

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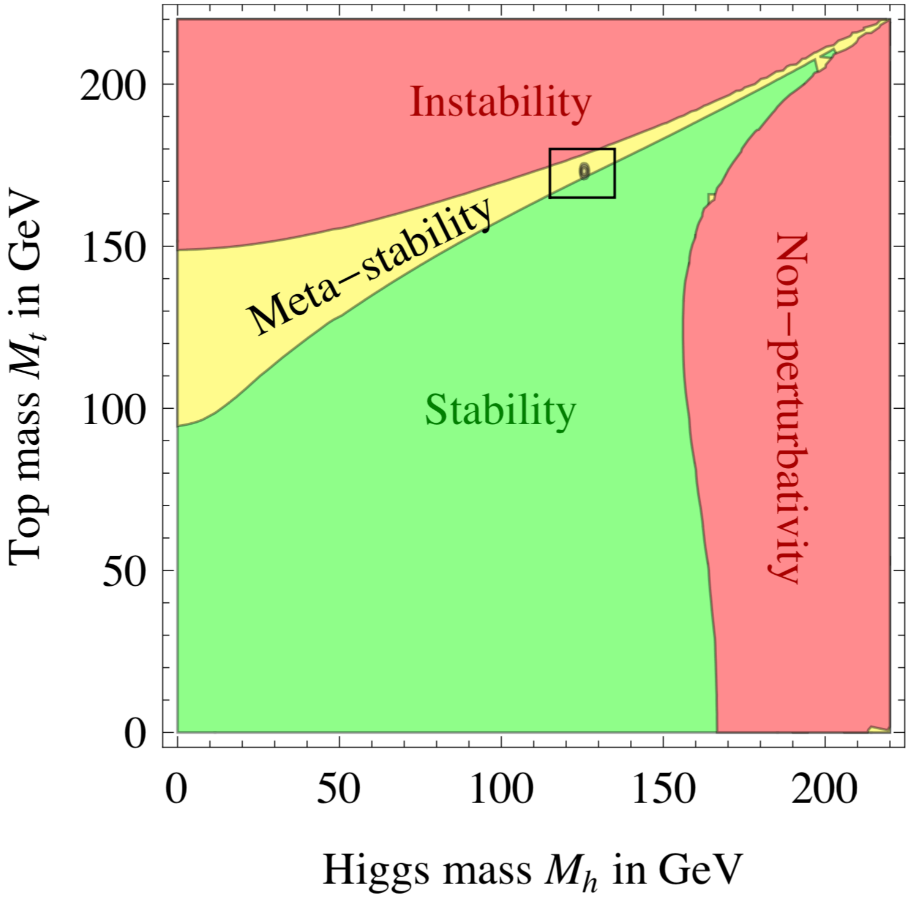
RENORMALIZABLE

The value of the Higgs mass makes the SM valid up to the Planck scale

$$\frac{d\lambda_4}{d\log E} = \frac{\beta_\lambda}{16\pi^2}\lambda_4^2 + \frac{\beta_t}{16\pi^2}y_t^4 = \beta(\lambda_4, y_t)$$

[From: Buttazzo et. al JHEP 12 (2013) 089]



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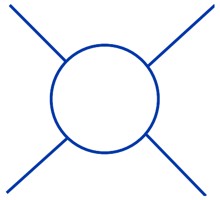

Here new physics needed to make our vacuum stable

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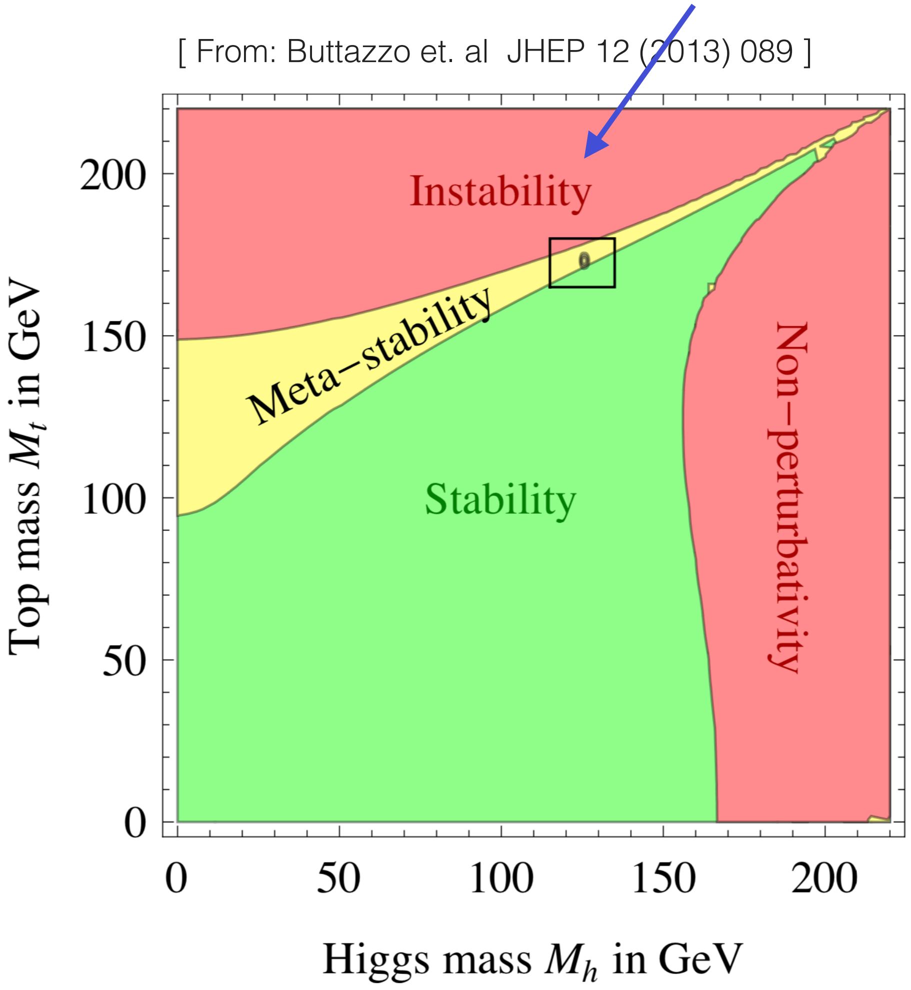

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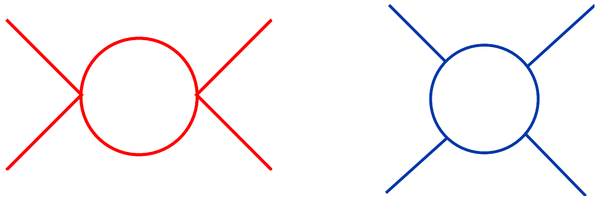

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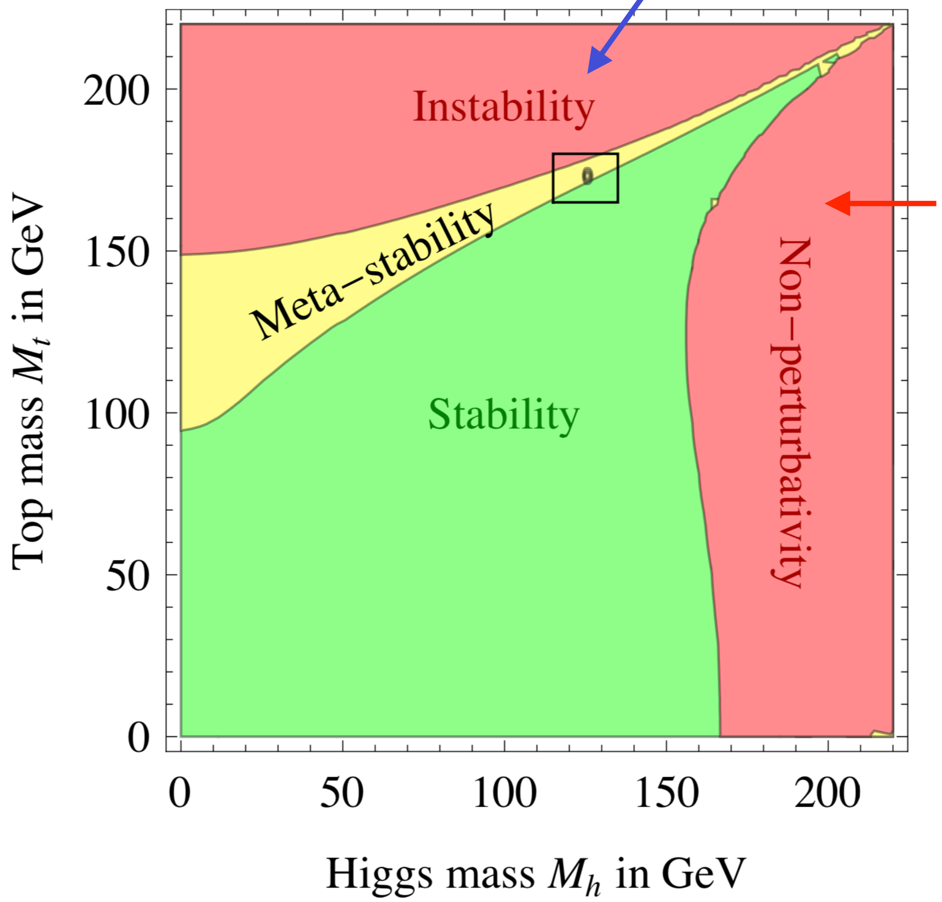

Here quartic coupling
hits a Landau pole
before the Planck scale

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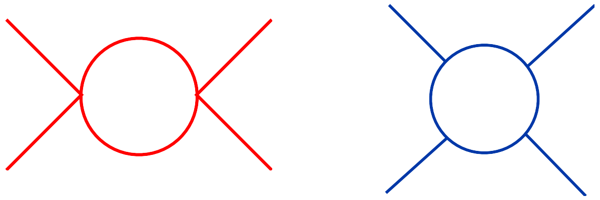

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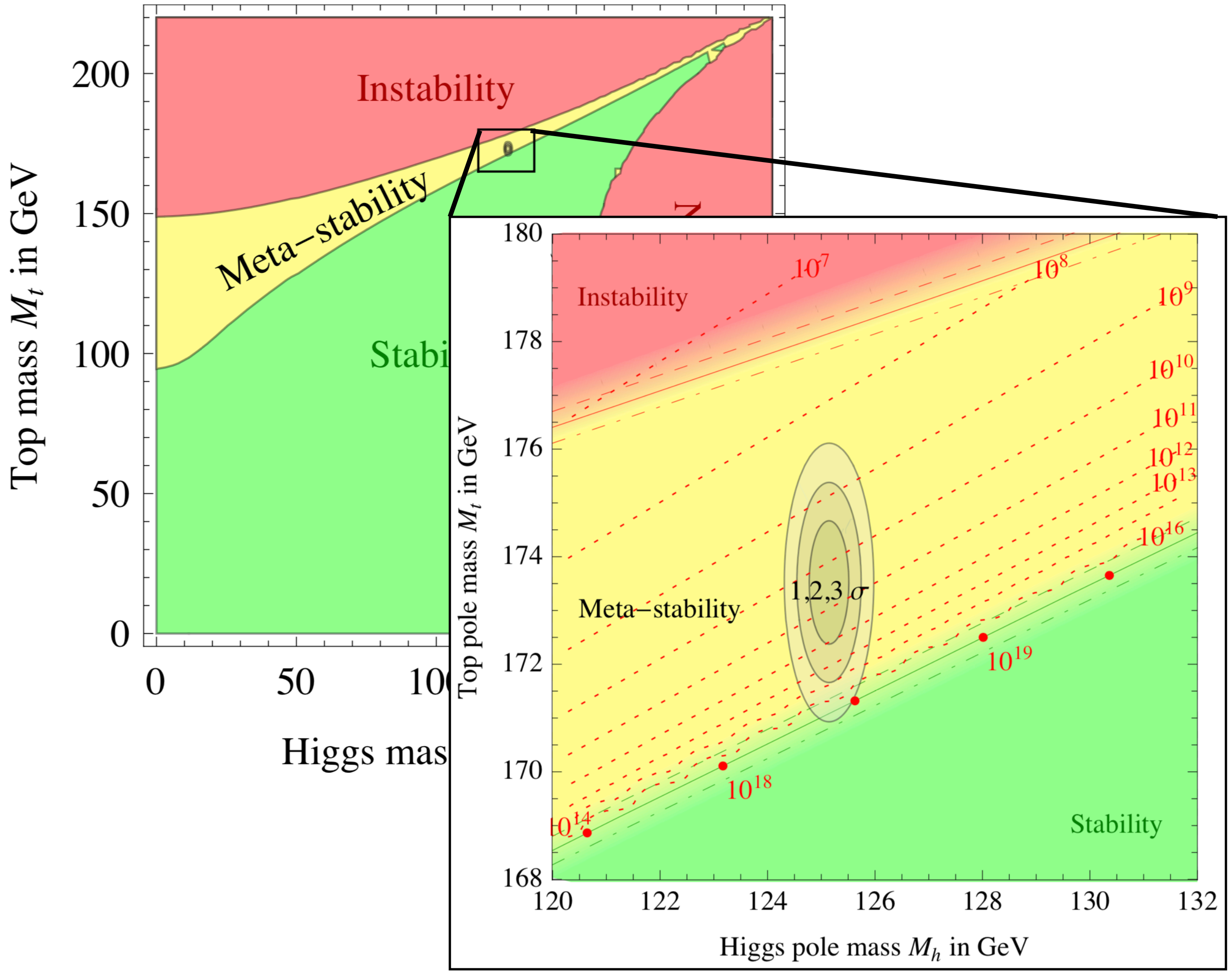

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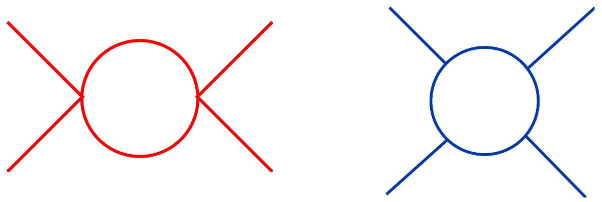
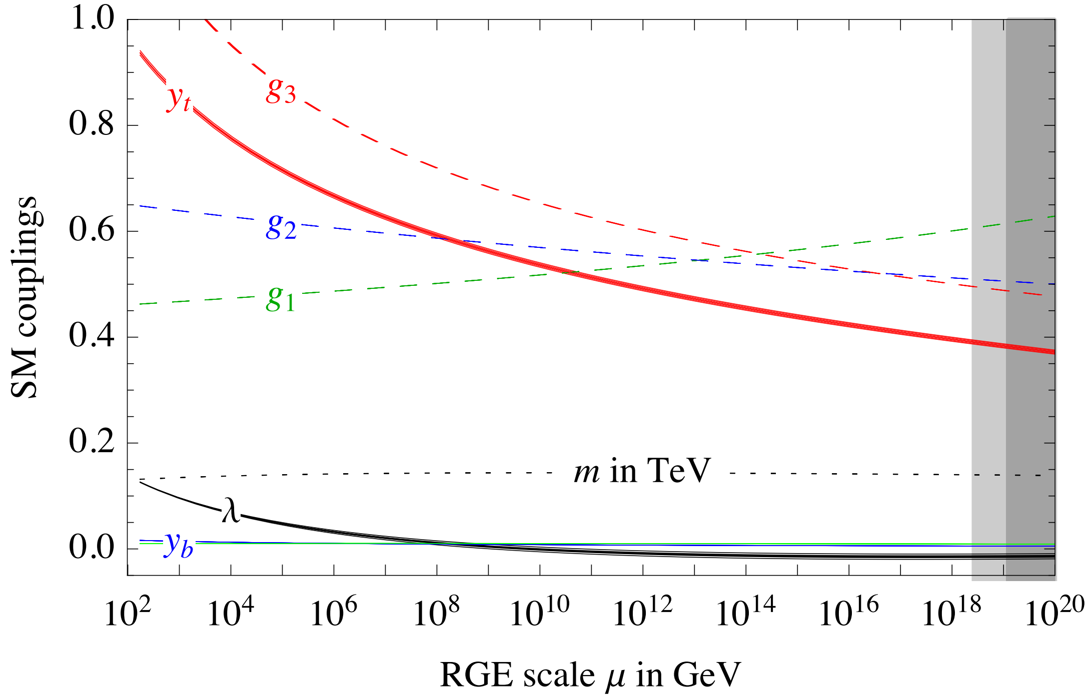


Can the theory be extrapolated at arbitrarily large energies ?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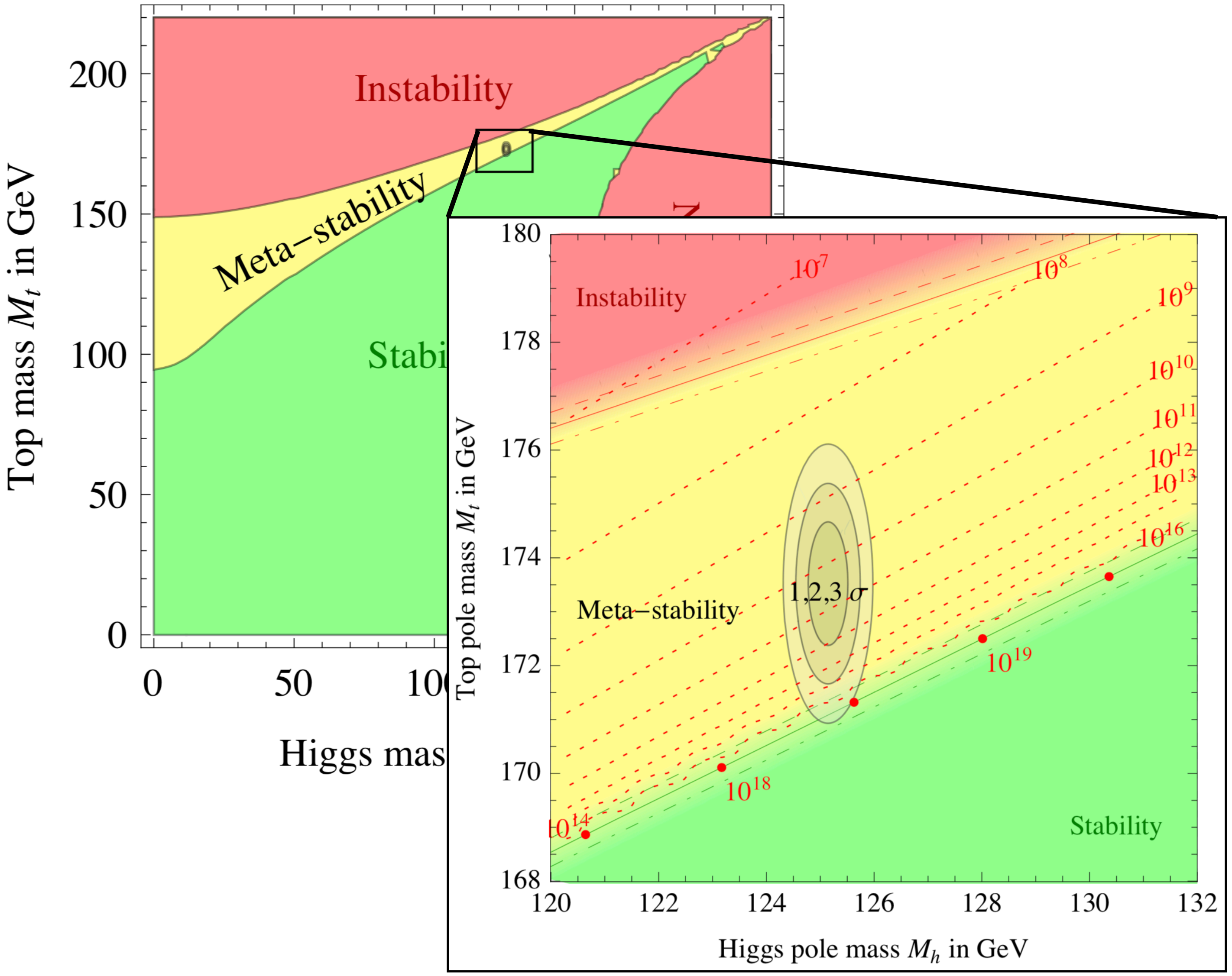

Both hypercharge and quartic coupling have Landau poles (*much*) above the Planck scale

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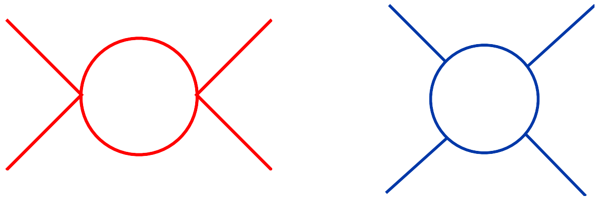

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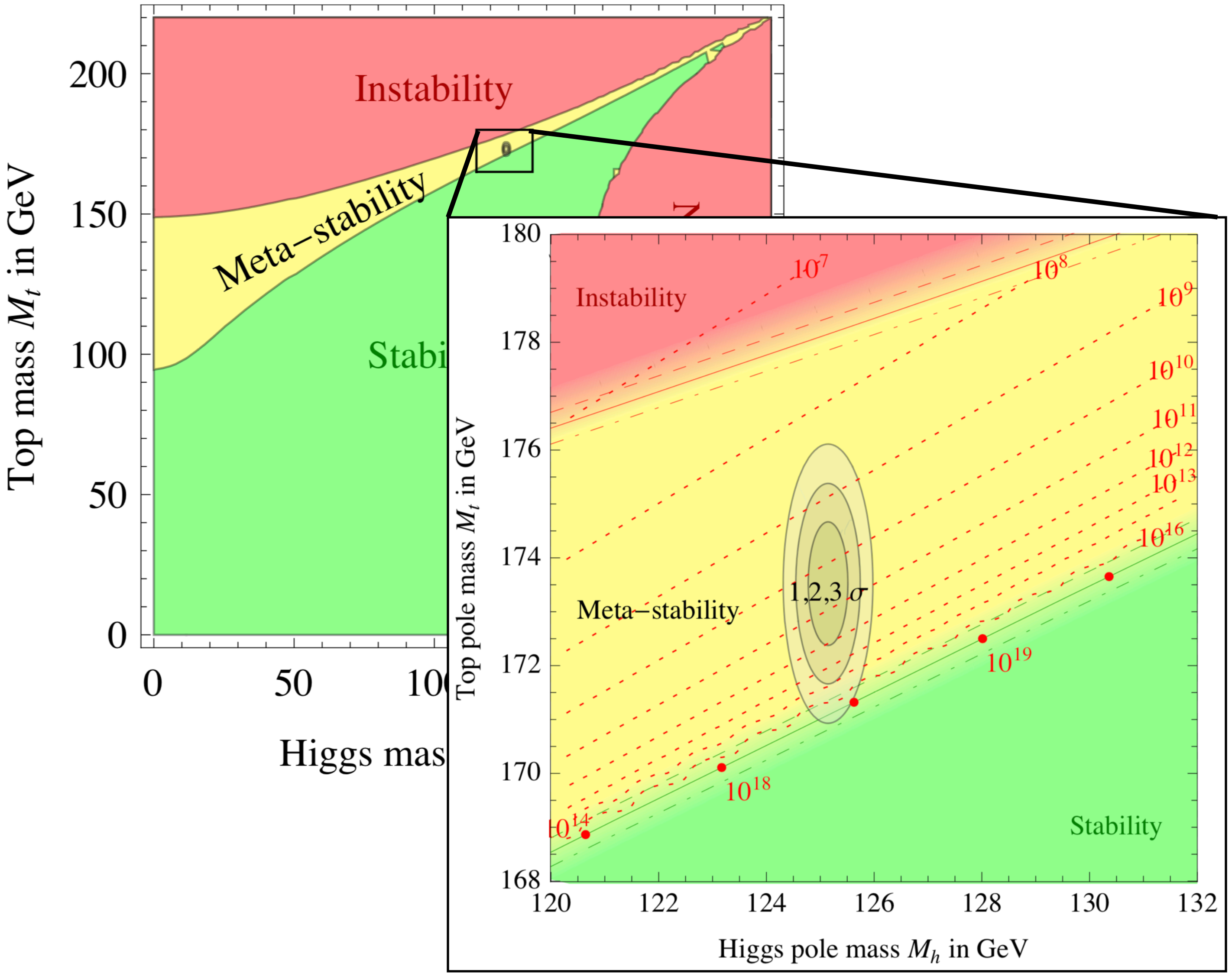

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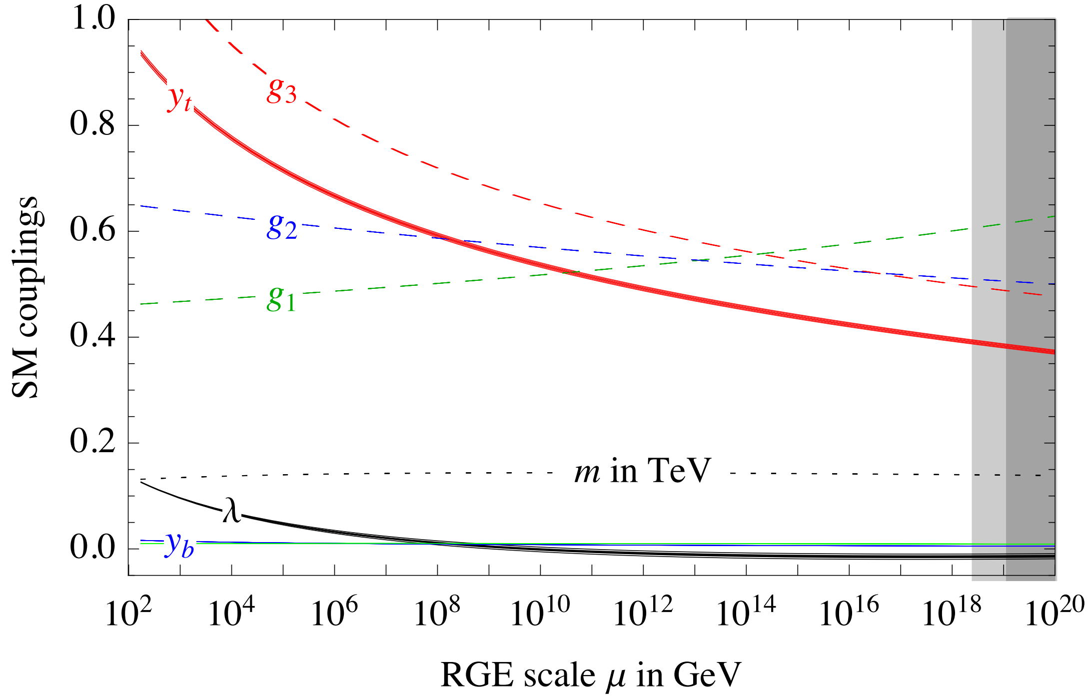

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The SM is an effective theory, not a Theory Of Everything

Emerging Features

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

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Almost all the observed features of the subatomic world are explained by the dim-4 SM Lagrangian

- Pattern of Flavor and CP violation (suppressed FCNC, suppressed CP, etc.)
- Approximate Custodial Symmetry $\quad \dfrac{m_W}{m_Z \cos\theta_W} \simeq 1 \qquad g_{hWW} = g_{hZZ}$
- No violation of B and L , Proton Stability

☞ Observed selection rules follow from (approximate) symmetries of $\mathcal{L}^{(4)}$

Emerging Features

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

Generic higher-dim operators destroy this picture

Exception:
neutrino masses and oscillations

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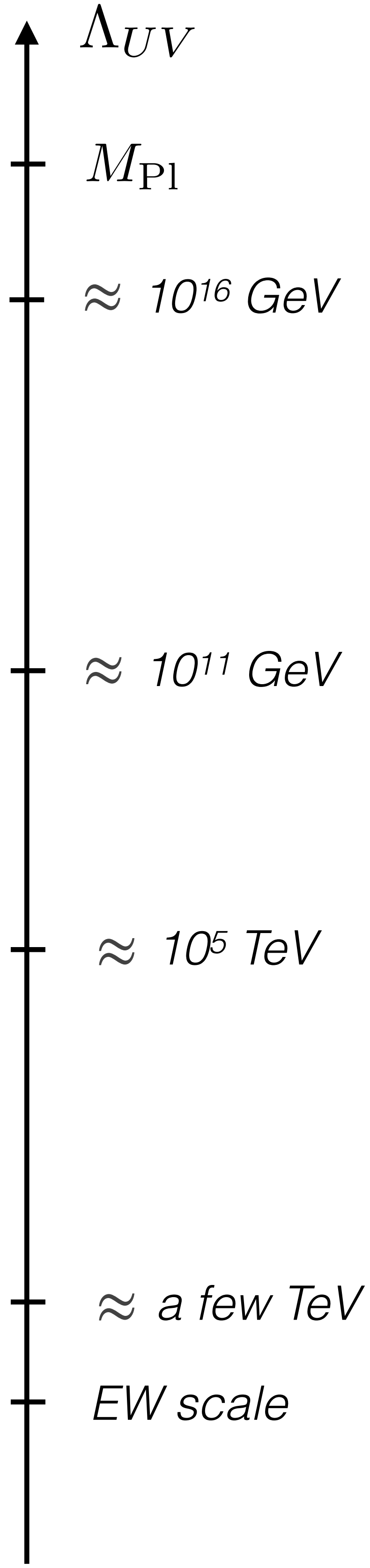


Λ_{UV}

$M_{\rm Pl}$

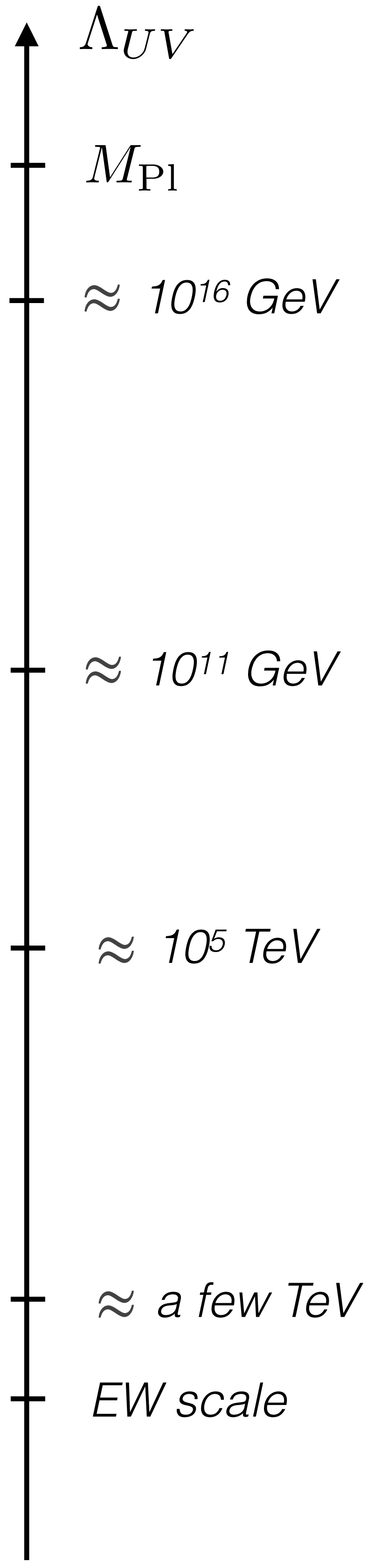
$\approx$ *10^{16} GeV*

$\approx$ *10^{11} GeV*

$\approx$ *10^{5} TeV*

$\approx$ *a few TeV*

EW scale



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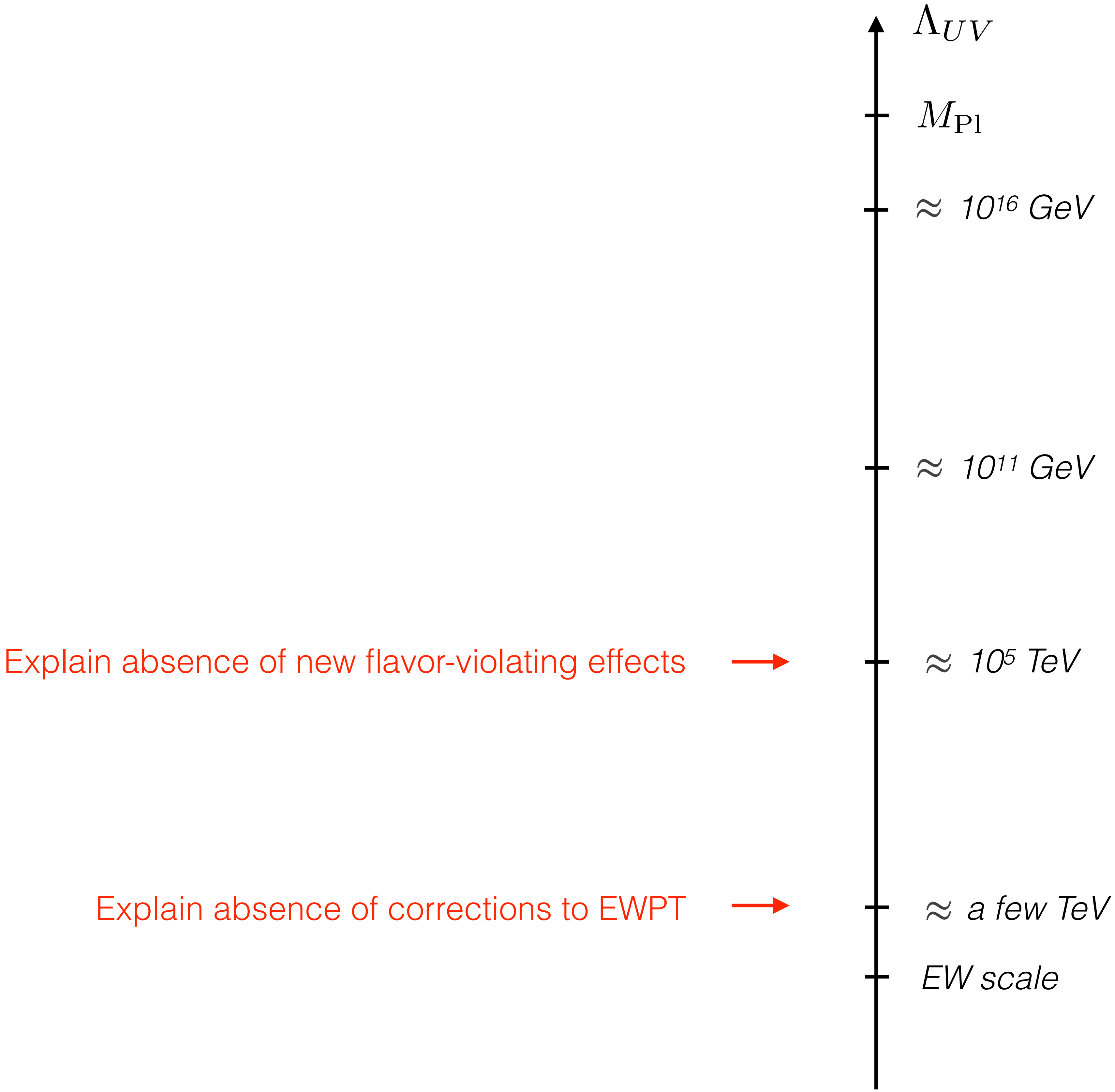

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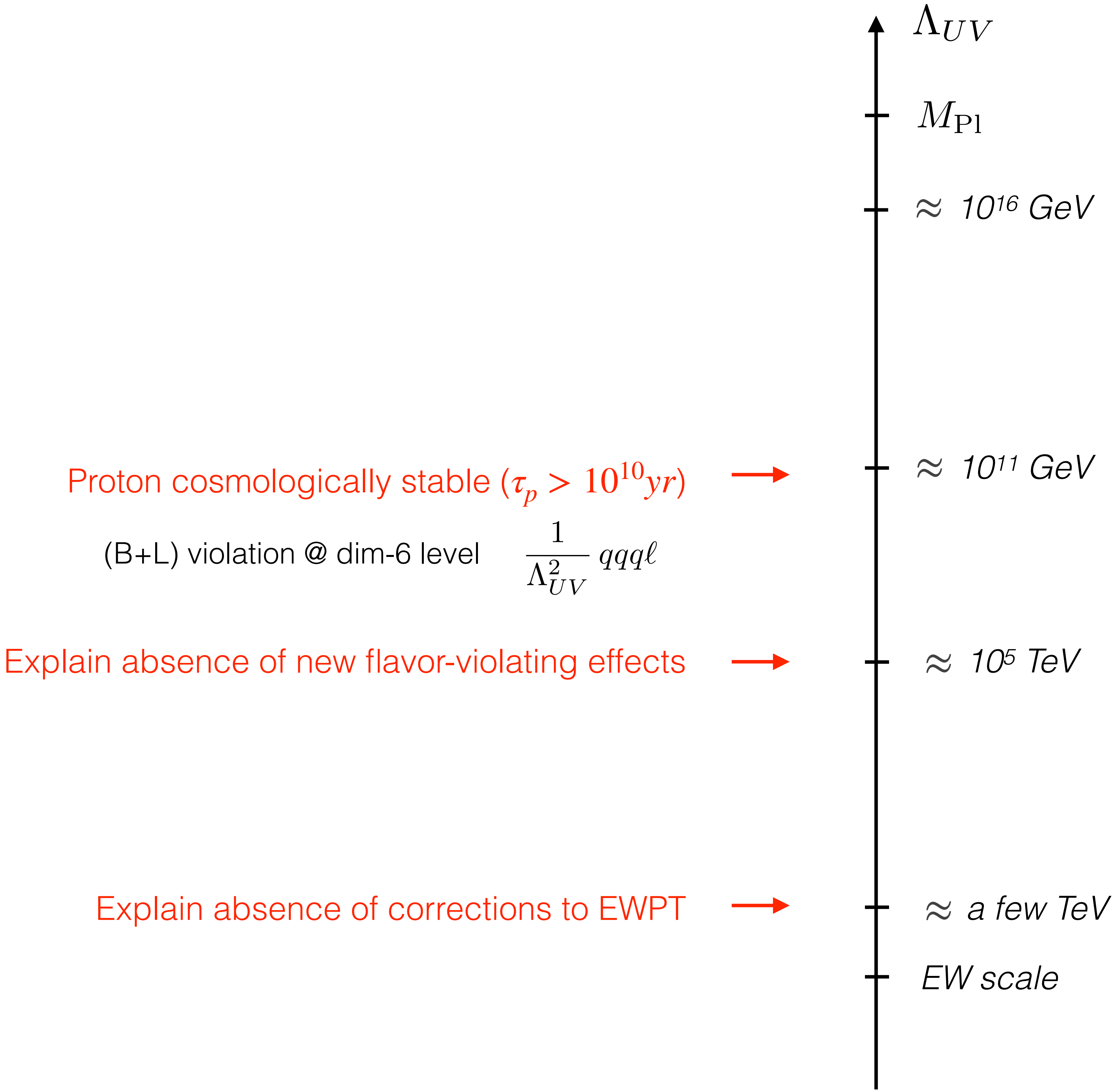

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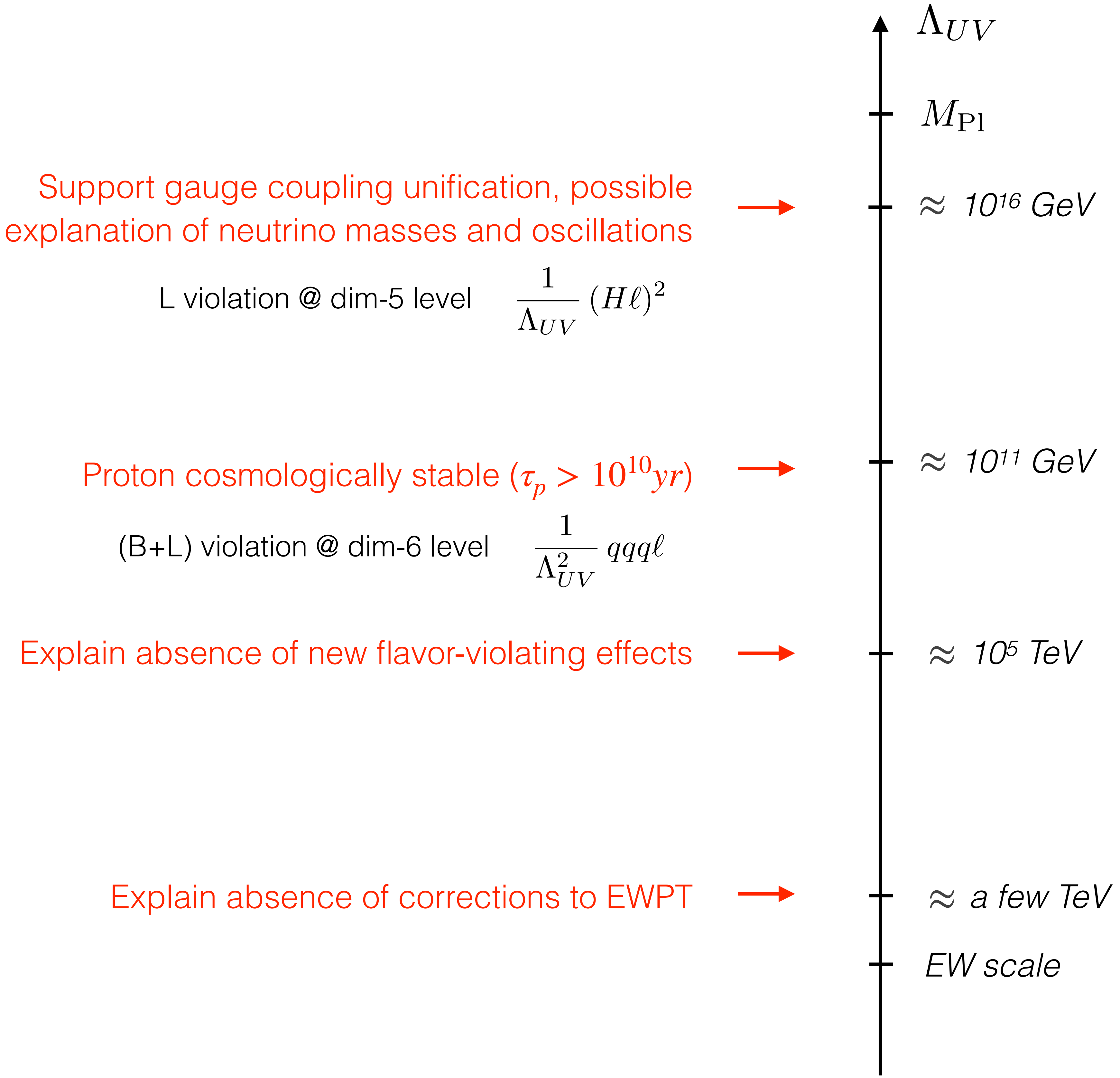

Λ_{UV}

M_{Pl}

Support gauge coupling unification, possible explanation of neutrino masses and oscillations → ≈ 10^{16} GeV

L violation @ dim-5 level $\frac{1}{\Lambda_{UV}}(H\ell)^2$

Proton cosmologically stable ($\tau_p > 10^{10} yr$) → ≈ 10^{11} GeV

(B+L) violation @ dim-6 level $\frac{1}{\Lambda^2_{UV}}qqq\ell$

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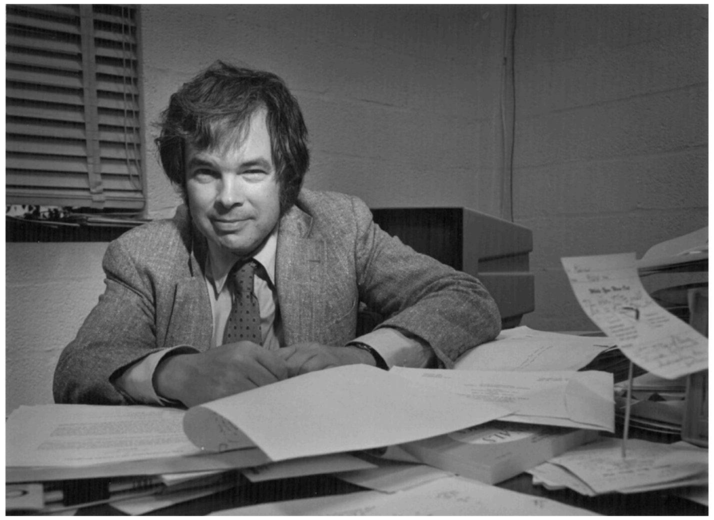
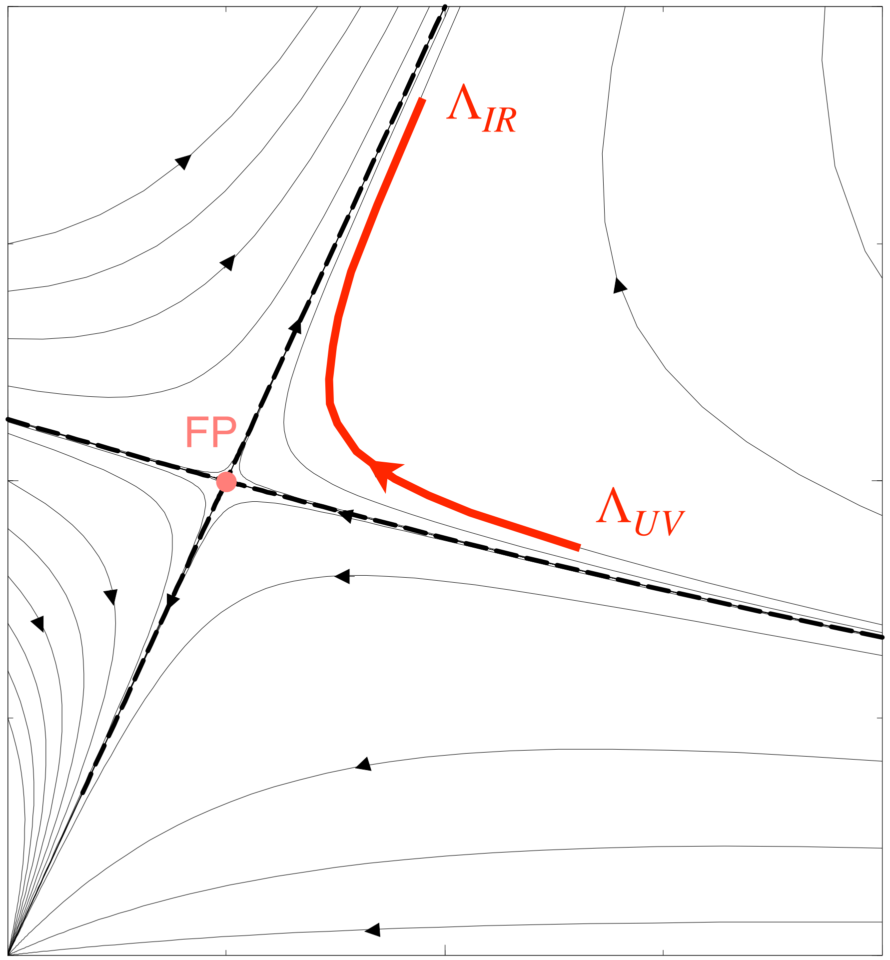
EW scale

- To have accidental symmetries one needs a large hierarchy, *not* necessarily a weakly-coupled theory

Wilson's viewpoint:





Large hierarchy =

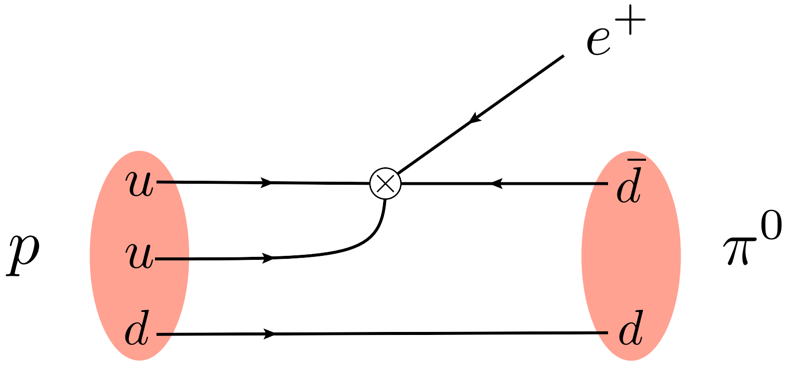
RG flow close to a Fixed Point, during which the theory is nearly self-similar (i.e. conformal)

- There exist several well know examples of strongly-coupled Fixed Points with enhanced symmetry in condensed matter systems

Proton Decay

In the SM the proton is *accidentally stable*, it can decay only 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: $\tau_P \gtrsim 10^{10}\text{yr} \Rightarrow \Lambda_{UV} \gtrsim 10^{10}\ \text{GeV}$

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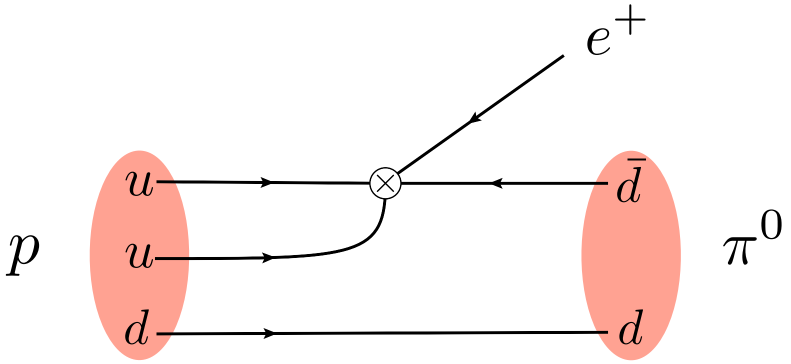

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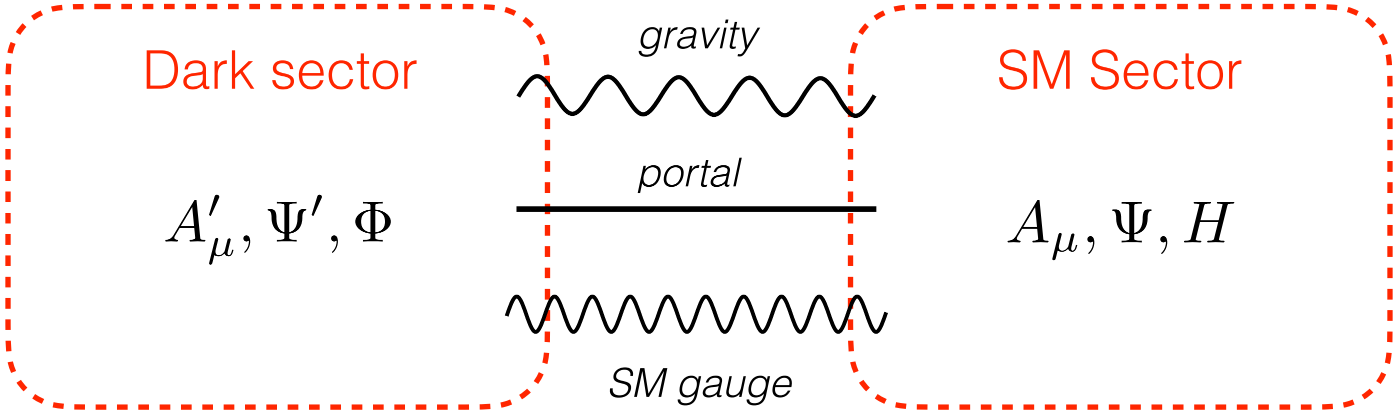
☞ Can Dark Matter be also stable due to some accidental symmetry ?

Part II

Accidental 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

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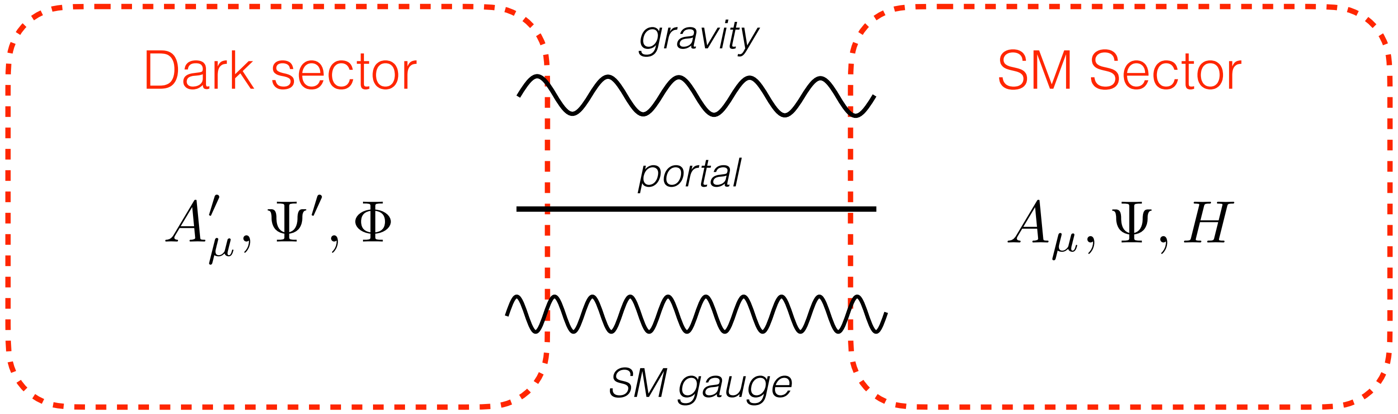

Dark sector

A'_μ, Ψ', Φ

gravity

portal

SM gauge

SM Sector

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

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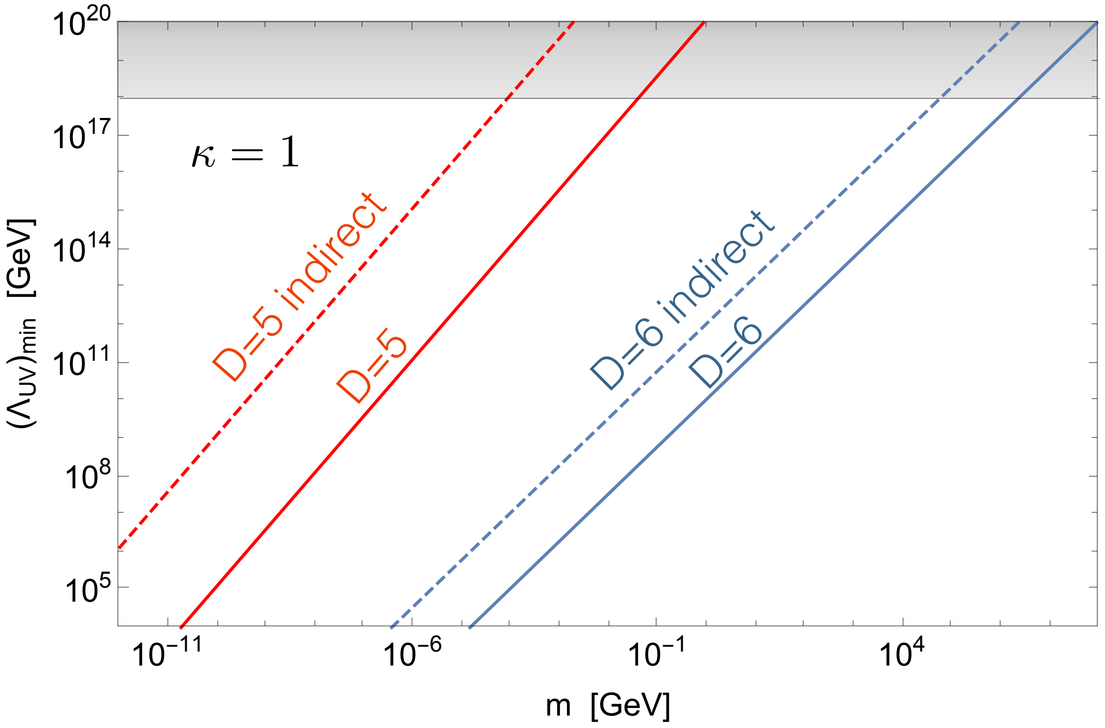

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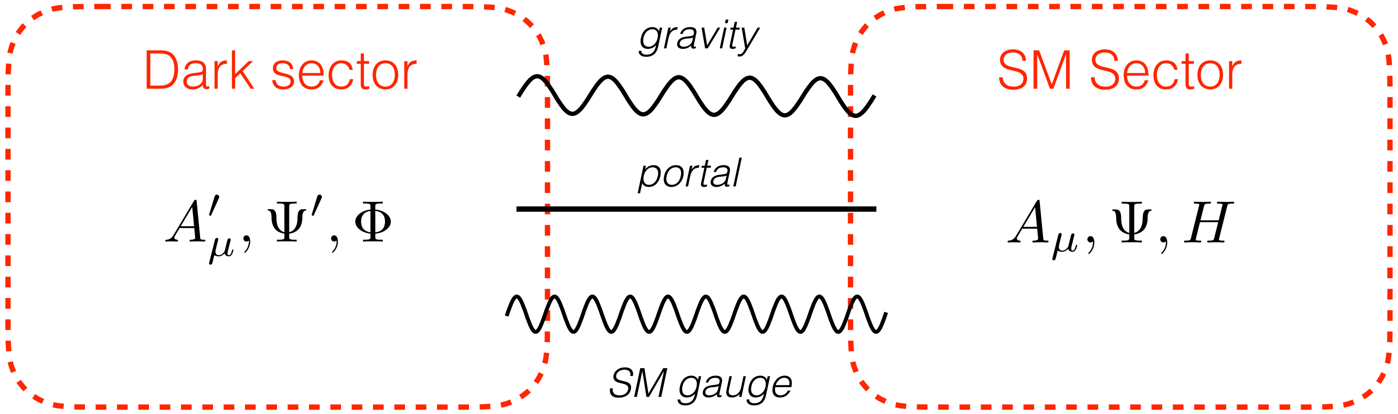

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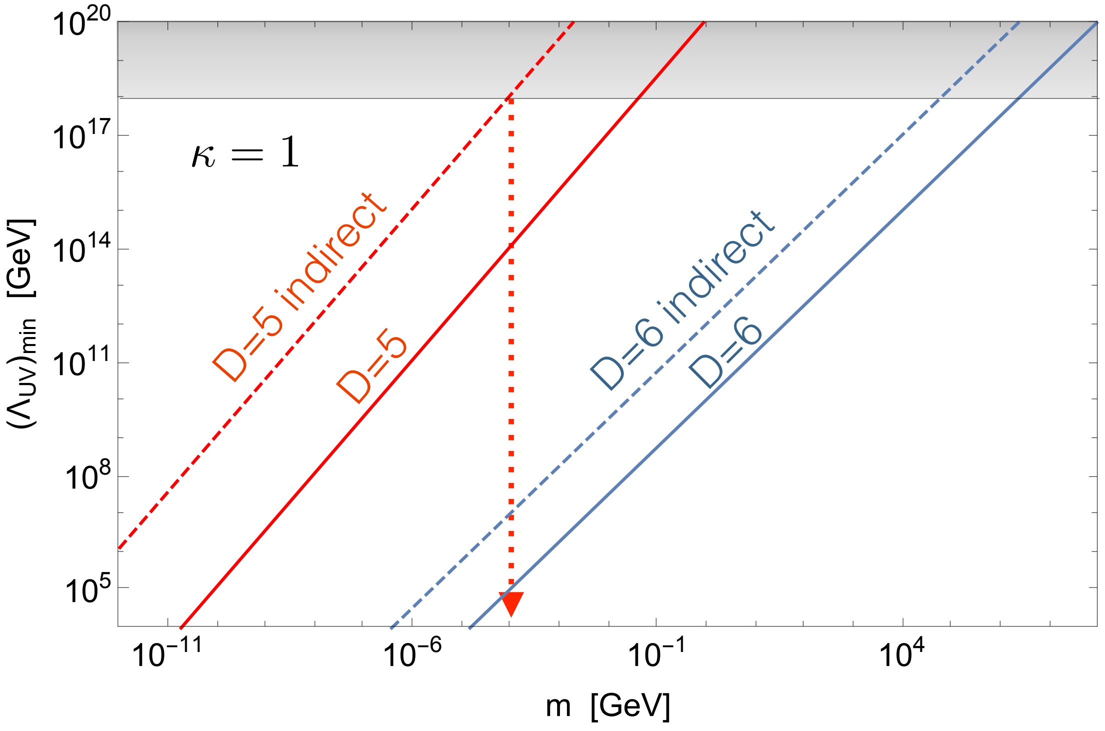

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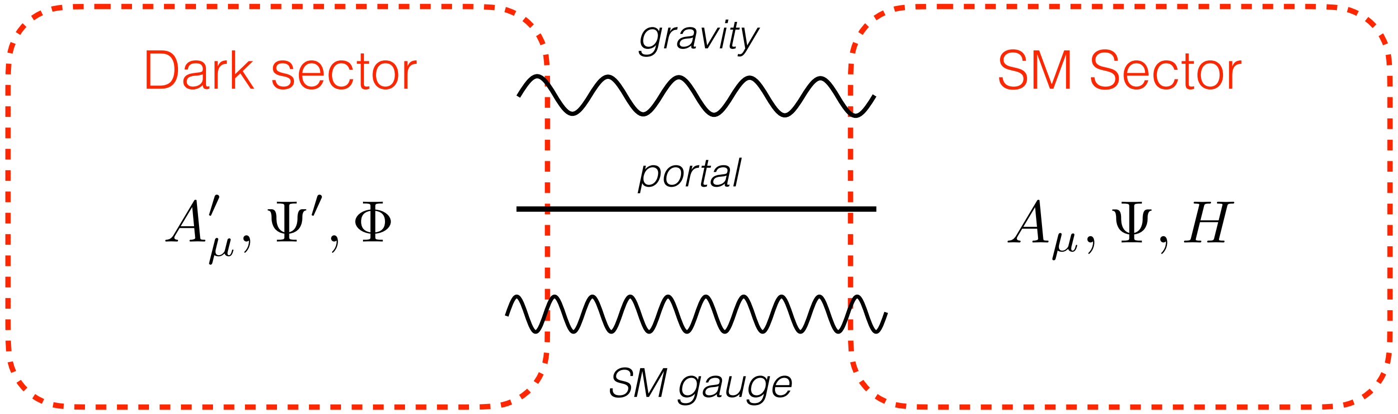

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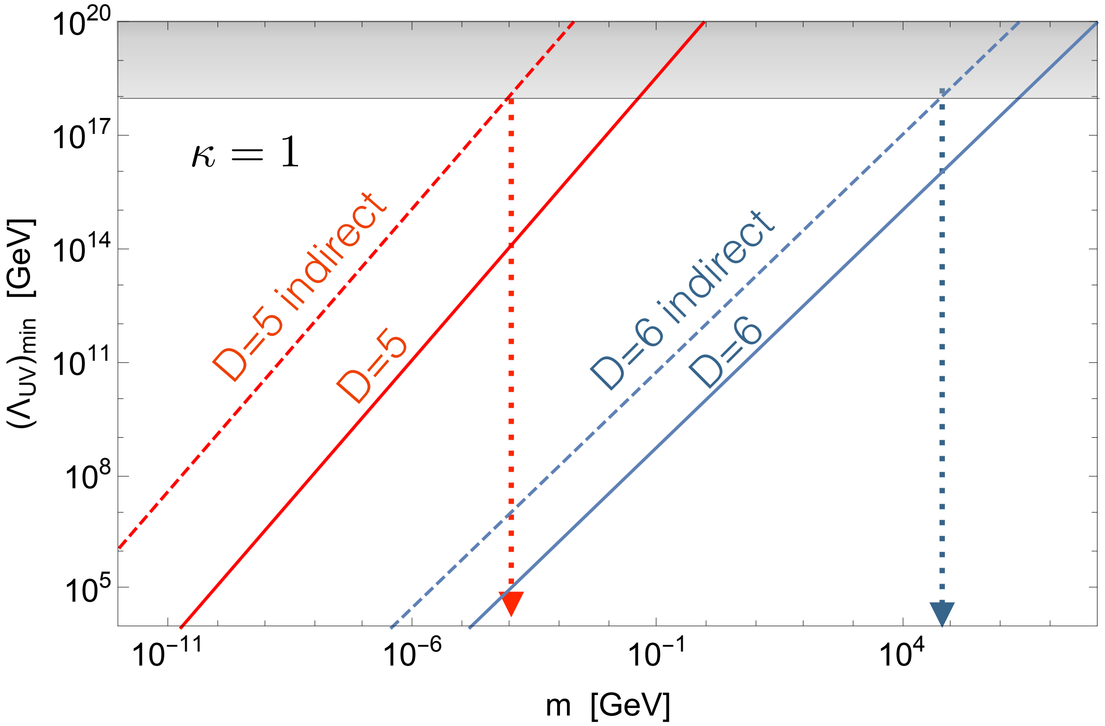

- Weakly-Coupled Dark Sector: Minimal Dark Matter

[Cirelli, Fornengo, Strumia NPB 753 (2006) 178]

Dark Sector = 1 Dirac fermion transforming as a 5-plet of $SU(2)_{EW}$ *with* $Y=0$

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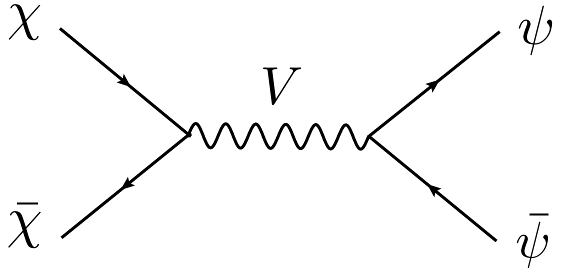
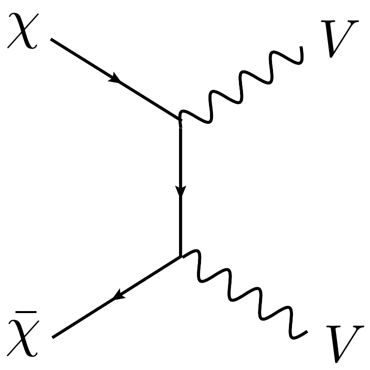
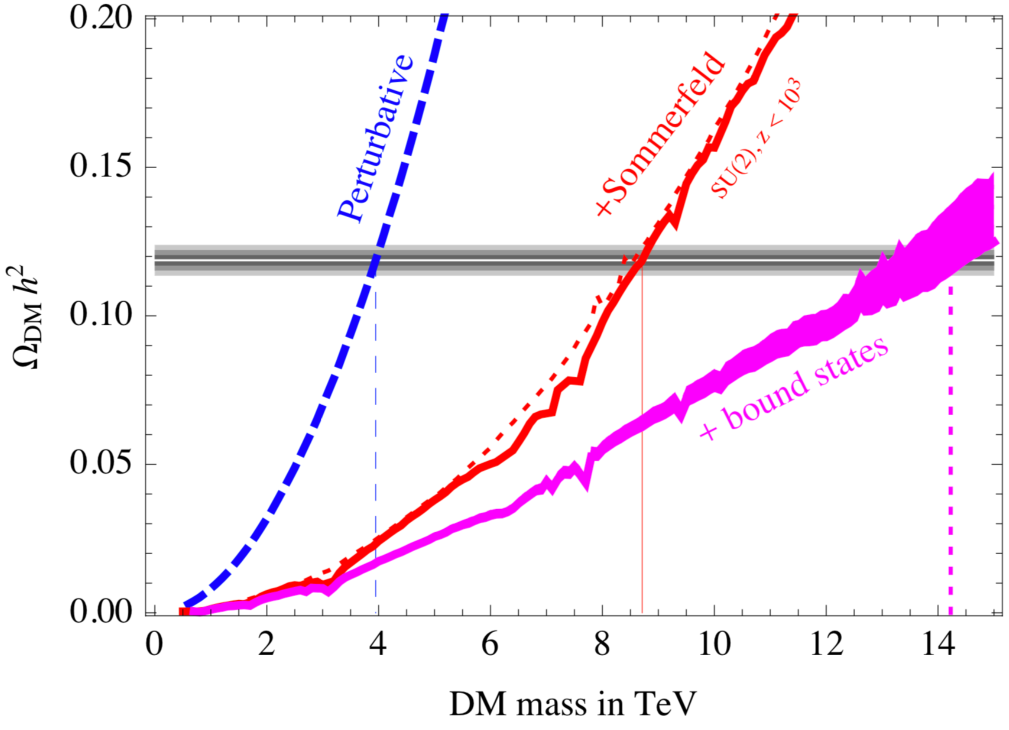




[From: Mitridate et. al JHEP 10 (2017) 210]

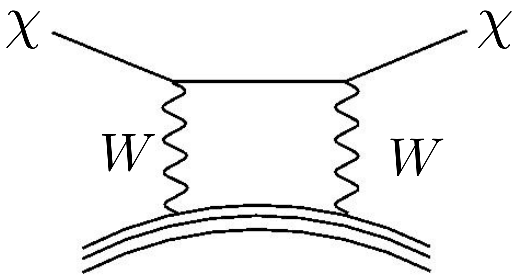


- Weakly-Coupled Dark Sector: Minimal Dark Matter

[Cirelli, Fornengo, Strumia NPB 753 (2006) 178]

Dark Sector = 1 Dirac fermion transforming as a 5-plet of SU(2)$_{EW}$ with Y=0

- Direct Detection



$$\sigma_{SI} \simeq 2 \times 10^{-46} \mathrm{cm}^2$$

Too small (close to neutrino floor)

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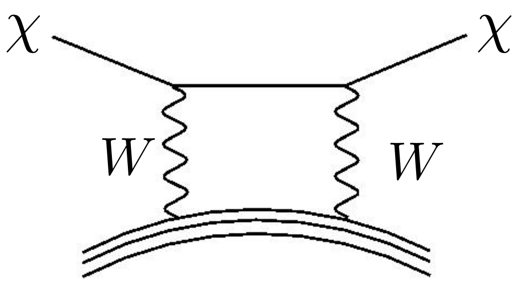


$$\sigma_{SI} \simeq 2 \times 10^{-46} \mathrm{cm}^2$$

Too small (close to neutrino floor)

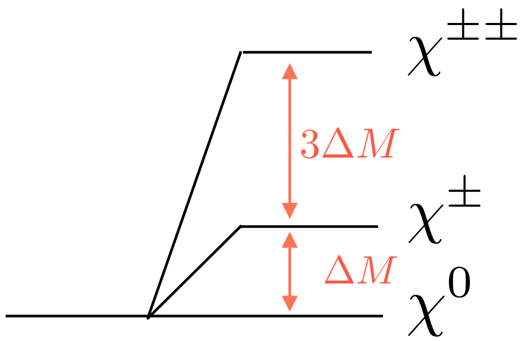
- Collider Searches

Disappearing tracks from inter-multiplet decays

$$\chi^{\pm} \to \pi^{\pm} \chi^{0}$$

soft and undetected

Mass splitting:



$$\Delta M = \alpha_2 M_W \sin^2 \frac{\theta_W}{2} = (166 \pm 1)\,\mathrm{MeV}$$

Unfortunately not within reach of FCC 100TeV for a thermal mass value $M \simeq 14\,\mathrm{TeV}$

- Strongly-Coupled Dark Sector: Vector-like Confining Gauge Theories

Dark Sector = Dark 'quarks' transforming as (R,r) of G_{DC} x G_{SM},
where G_{DC} is a confining dark color gauge group

$$\mathcal{L} = -\frac{1}{4g_{DC}^2}\mathcal{G}_{\mu\nu}^2 + \bar{Q}\,(i\not{D} - M)\,Q + y\,\bar{Q}HQ + h.c.$$

Q = Dirac (Majorana) if *(R,r)* is (pseudo)real

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Extremely reach phenomenology and several types of composite DM candidates

Type	Accidental Symmetry
Dark Baryons	$U(1)_{DB}$
Dark Mesons	Species number $U(1)_i$, G-parity
Gluequarks ($Q\mathcal{G}$ bound states in theories with adjoint dark quarks)	Z_2 dark parity

Example #1: Dark Baryon DM

[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

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

Accidental symmetry: dark baryon number

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

Example #2: Gluequark DM

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

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

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

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

DM candidate: (neutral component of) gluequark Vg = 3_0 of G_{SM}

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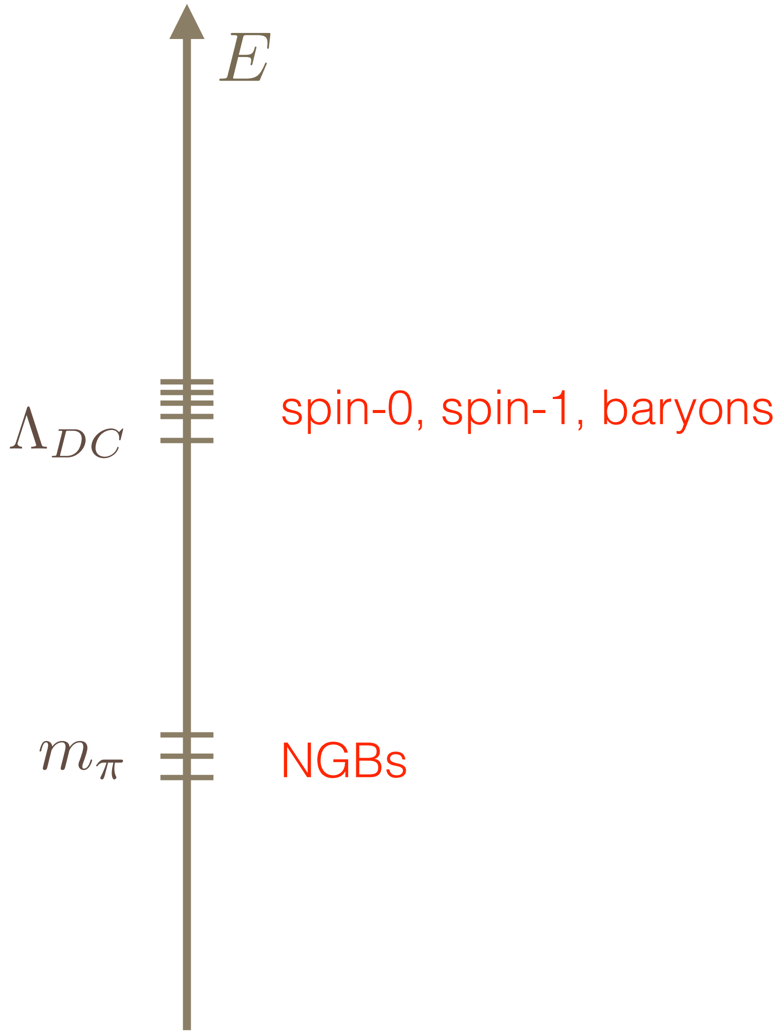
DM candidate: (neutral component of) gluequark Vg = 3_0 of G_{SM}

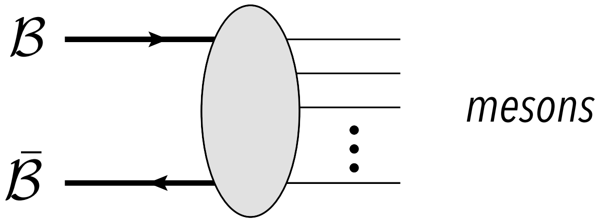
Two different regimes:

- Light dark quarks ($M < \Lambda_{DC}$)
- Heavy dark quarks ($M > \Lambda_{DC}$)

DM abundance: light quark regime ($M < \Lambda_{DC}$)



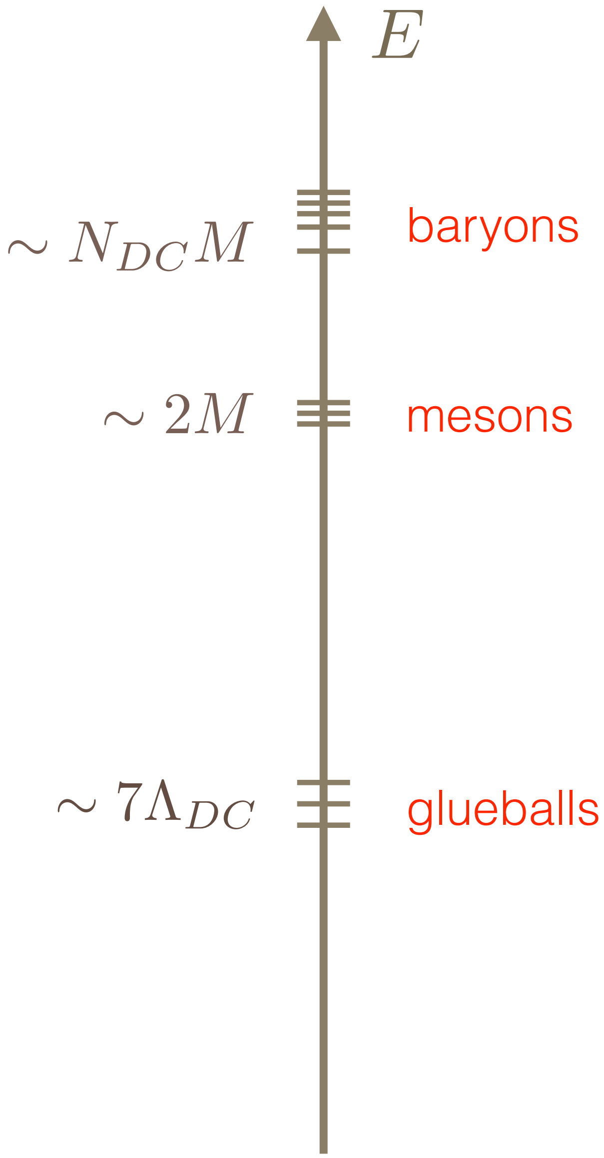
At $T \lesssim \Lambda_{DC}$ dark baryons undergo a thermal freeze out with non-perturbative annihilations into dark pions (which decay to SM)



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

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

DM abundance: heavy quark regime ($M > \Lambda_{DC}$)



[Mitridate, Redi, Smirnov, Strumia, JHEP 10 (2017) 210
R.C., Mitridate, Podo, Redi JHEP 1902 (2019) 187]

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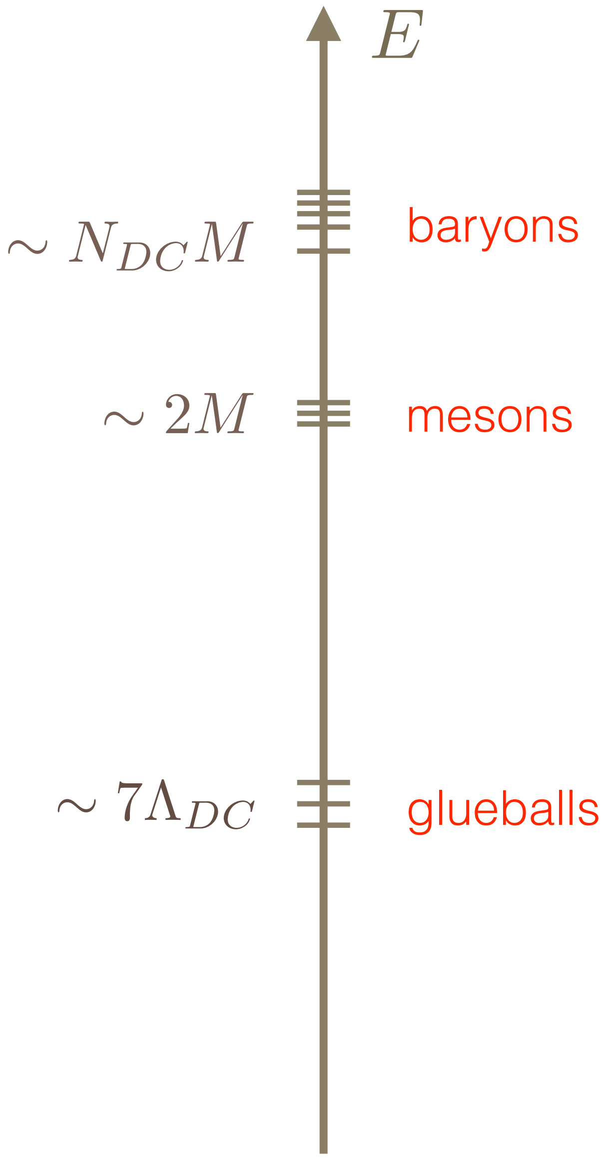
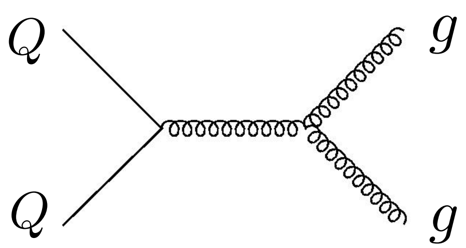


At $T \sim M$ dark quarks have a perturbative freeze out



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

[Mitridate, Redi, Smirnov, Strumia, JHEP 10 (2017) 210
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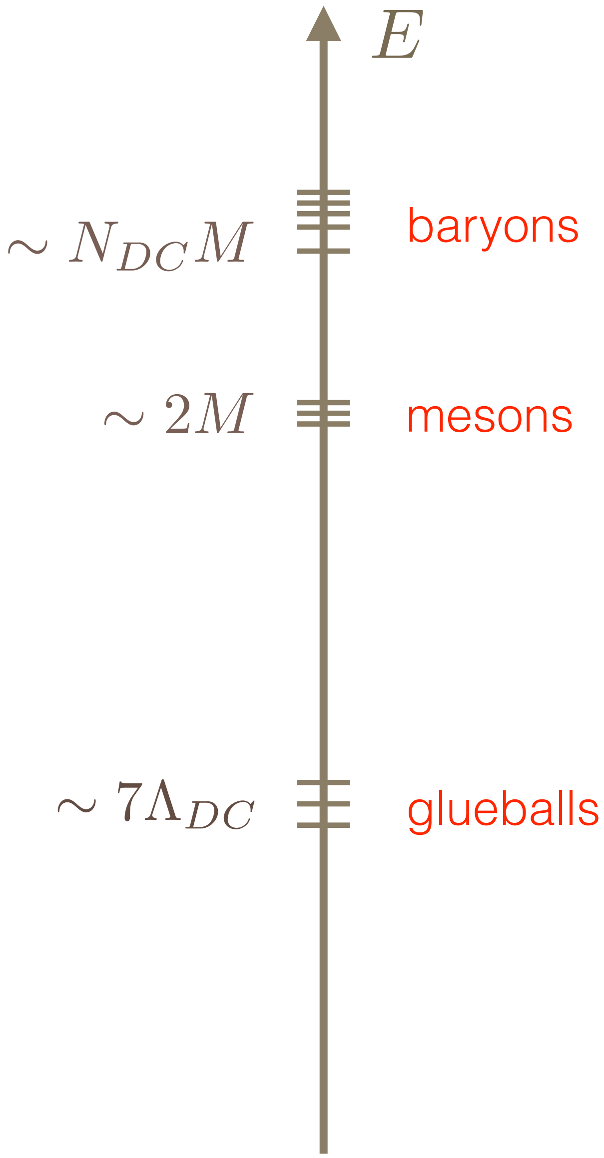

E

$\sim N_{DC} M$ baryons

$\sim 2M$ mesons

$\sim 7\Lambda_{DC}$ glueballs

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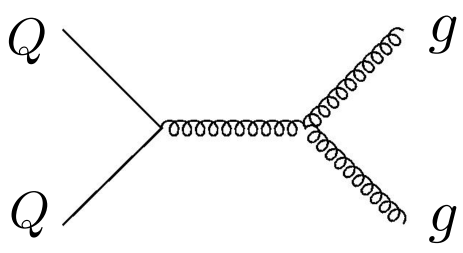

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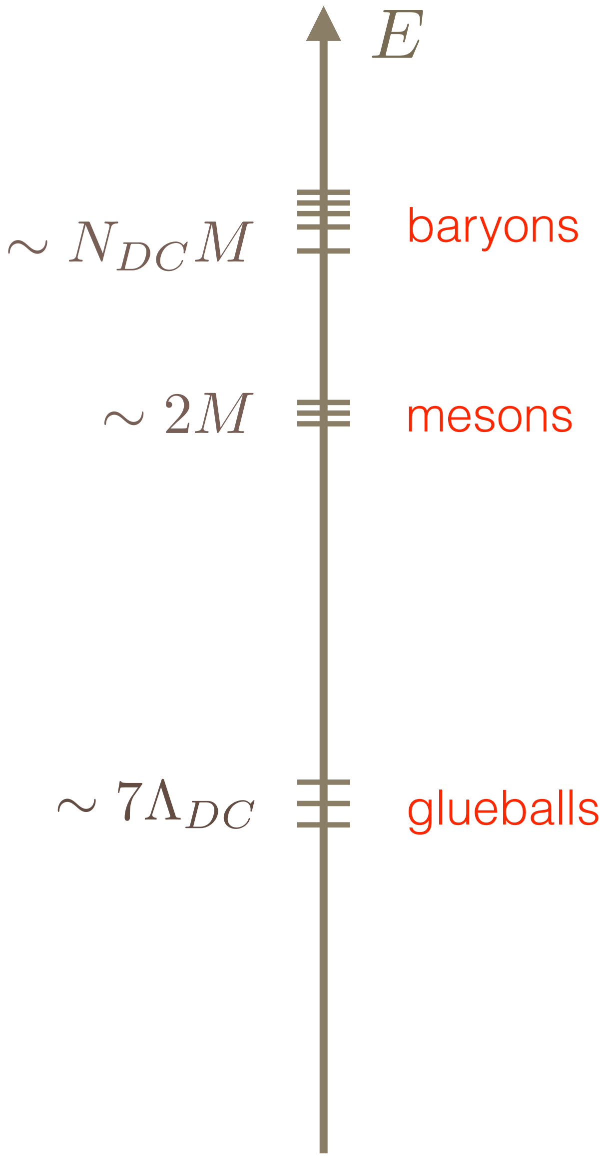
At $T \sim \Lambda_{DC}$ dark baryons undergo a new phase of non-perturbative annihilations

$$\mathcal{B} + \bar{\mathcal{B}} \to (Q\bar{Q})^* + (Q^{N_{DC}-1})(\bar{Q}^{N_{DC}-1})$$

$$\langle \sigma v \rangle \sim \alpha_{DC}\, r_B^2 \sim \frac{1}{\alpha_{DC}} \frac{1}{M^2}$$

[Mitridate, Redi, Smirnov, Strumia, JHEP 10 (2017) 210
R.C., Mitridate, Podo, Redi JHEP 1902 (2019) 187]

DM abundance: heavy quark regime ($M > \Lambda_{DC}$)



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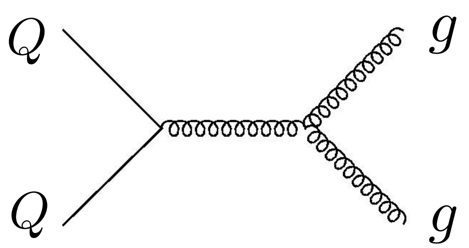

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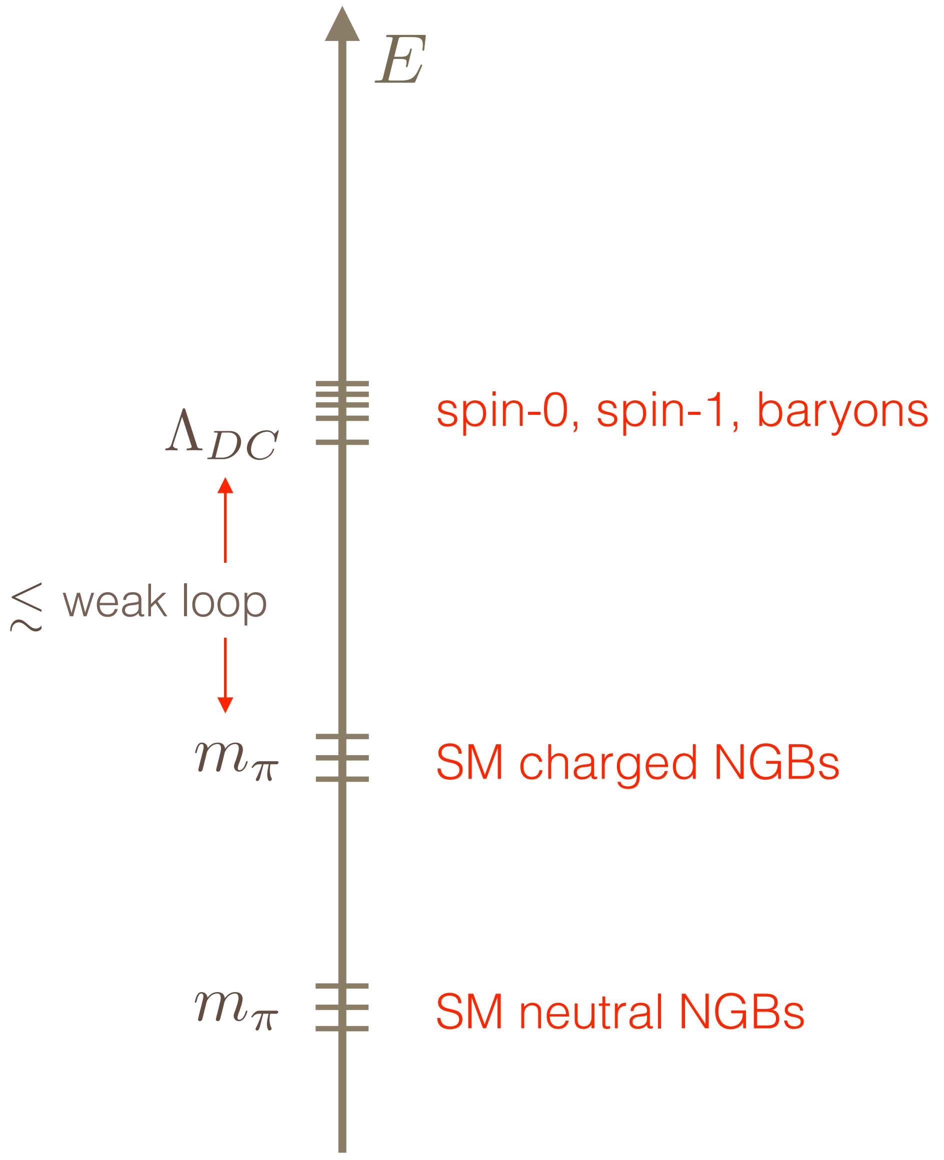
Late decay of the glueballs can lead to an era of early matter domination with modified scaling $a \propto T^{-8/3}$, and to a dilution of the DM abundance

[Mitridate, Redi, Smirnov, Strumia, JHEP 10 (2017) 210
R.C., Mitridate, Podo, Redi JHEP 1902 (2019) 187]

Phenomenology: light quark regime ($M < \Lambda_{DC}$)



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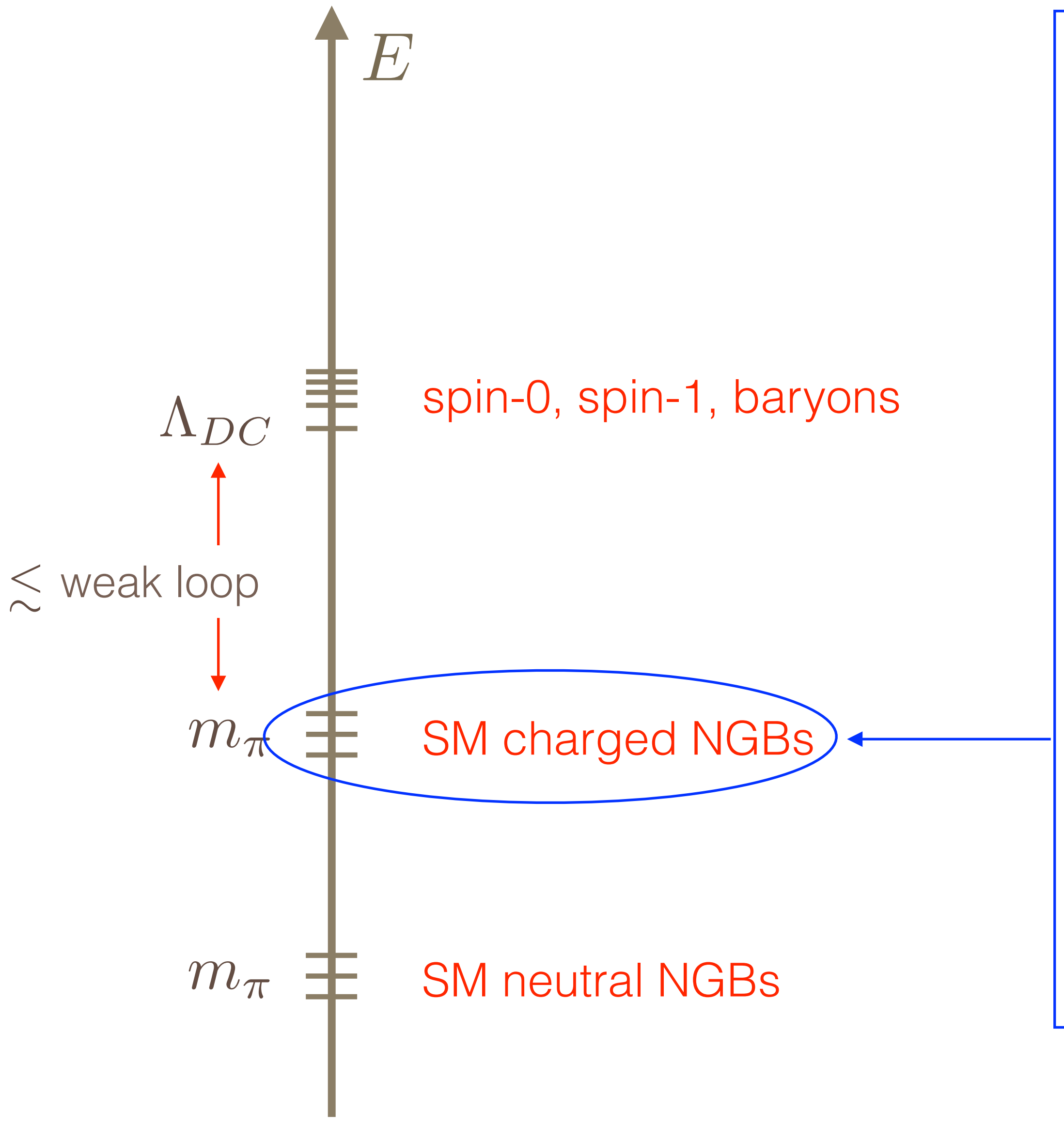


Dark pions charged under the SM

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

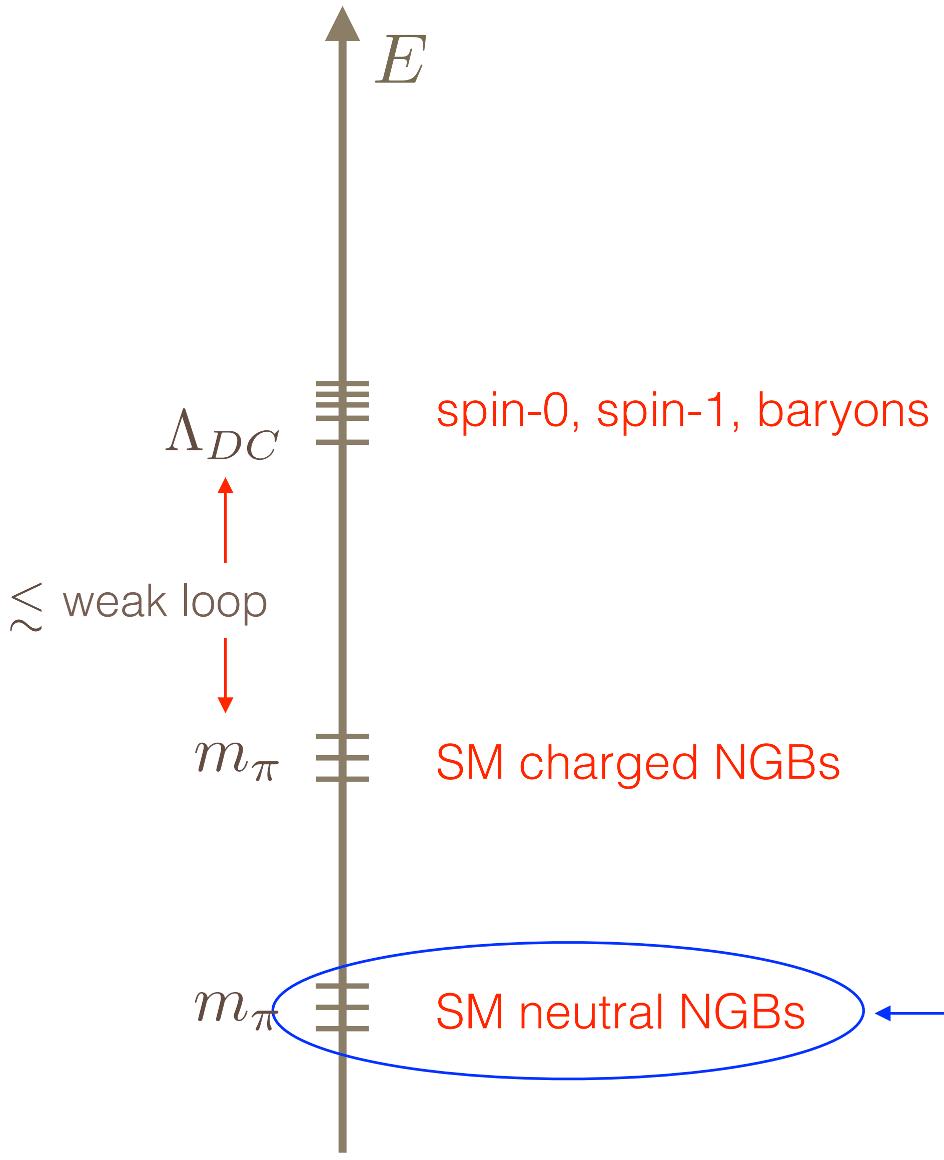
- pair produced via Drell-Yan

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

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

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

Phenomenology: light quark regime ($M < \Lambda_{DC}$)



E

Λ_{DC} spin-0, spin-1, baryons

$\lesssim$ weak loop

m_π SM charged NGBs

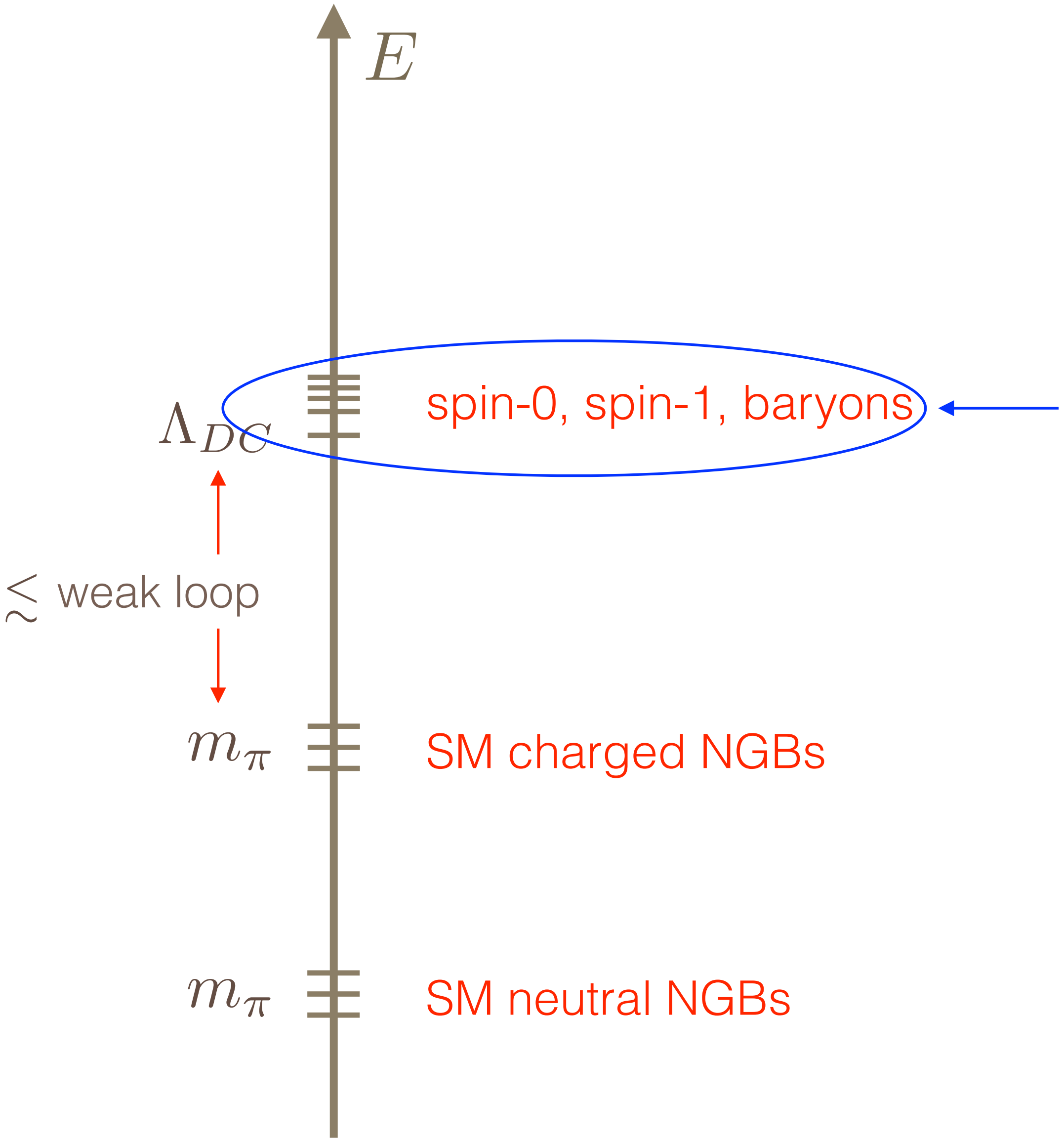
m_π SM neutral NGBs

Dark pions neutral under the SM

$$m_\pi^2 \sim m_\psi \Lambda_{DC}$$

- 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

Phenomenology: light quark regime ($M < \Lambda_{DC}$)



spin-1 resonances

- singly produced via Drell-Yan
- decay mostly to pairs of NGBs if kinematically allowed, decays to SM fermions parametrically suppressed

$$\Gamma(\rho \to \pi\pi) \sim \frac{g_\rho^2}{8\pi} m_\rho$$

$$\Gamma(\rho \to f\bar{f}) \sim \frac{1}{8\pi}\frac{g_{SM}^4}{g_\rho^2} m_\rho$$

- Benchmark: L+N vectorlike model

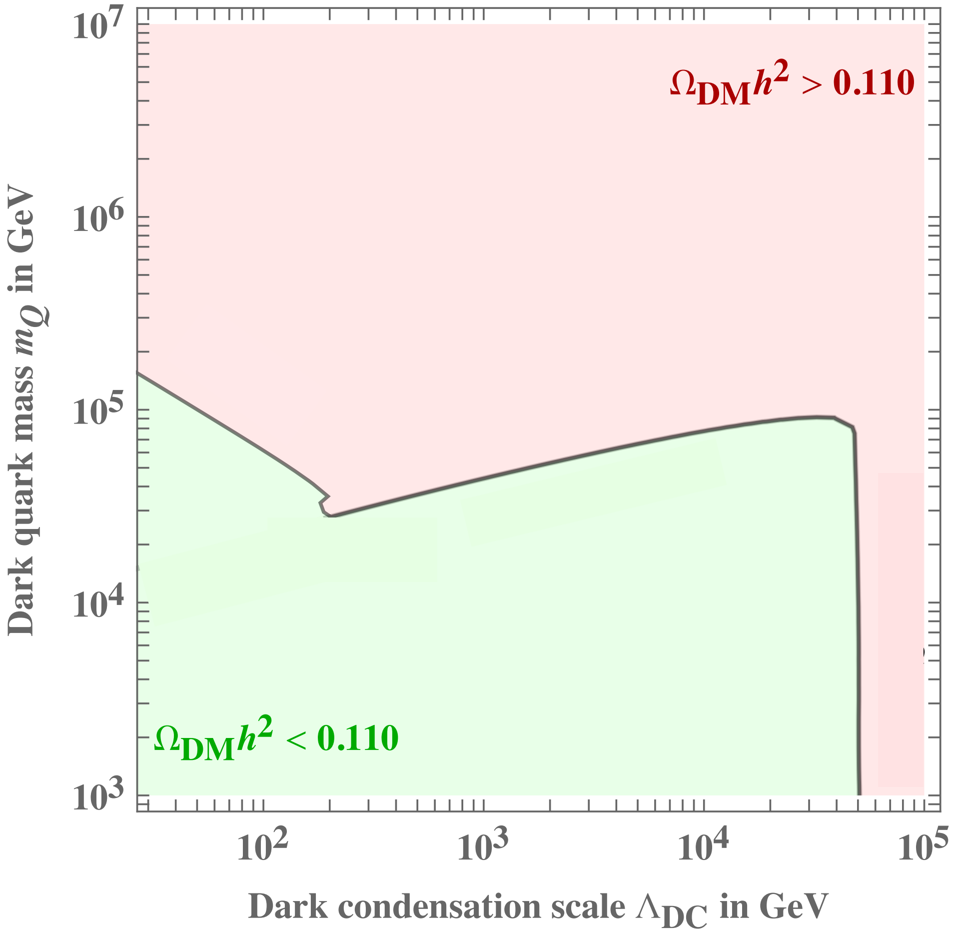
$$SU(3)_L \times SU(3)_R \to SU(3)_V$$

$$8 \text{ NGBs} = 1_0(\eta) \oplus 2_\pm(K) \oplus 3_0(\pi)$$

under $SU(2)_{EW} \times U(1)_Y$

$$\frac{g}{4\pi}\Lambda_{DC} \lesssim m_\pi < \Lambda_{DC}$$

[From: A. Mitridate, PhD thesis]



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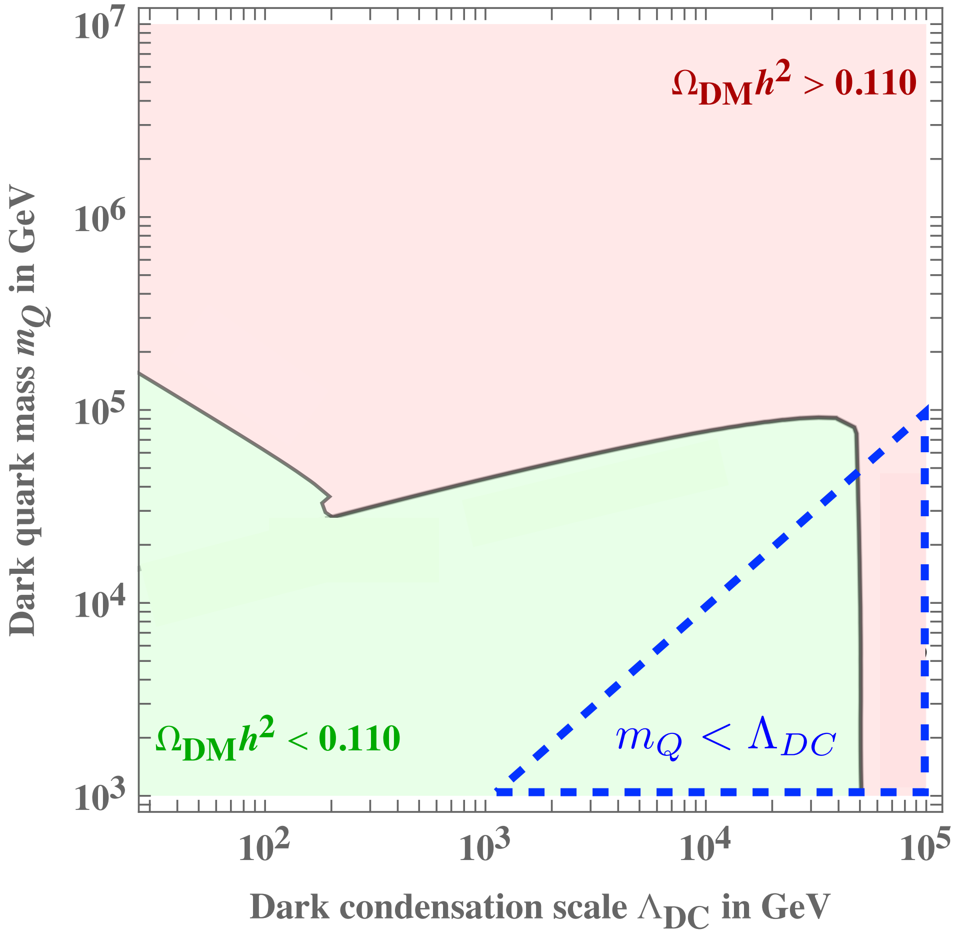

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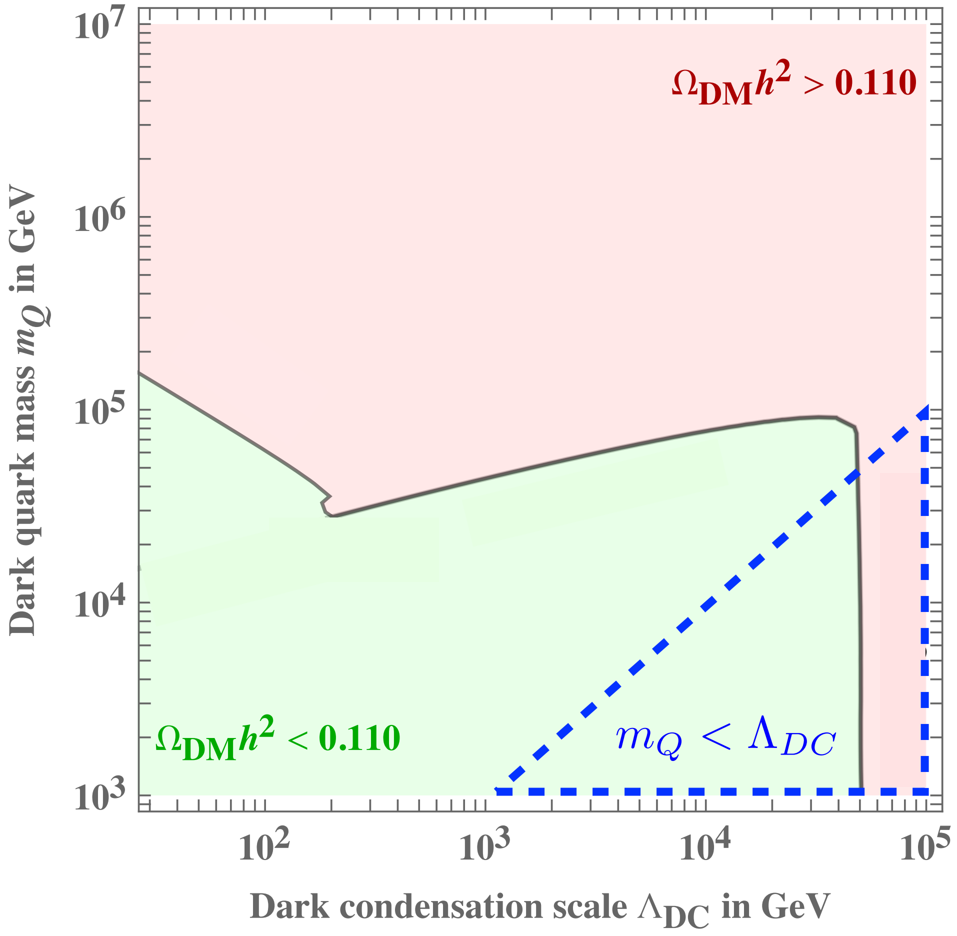
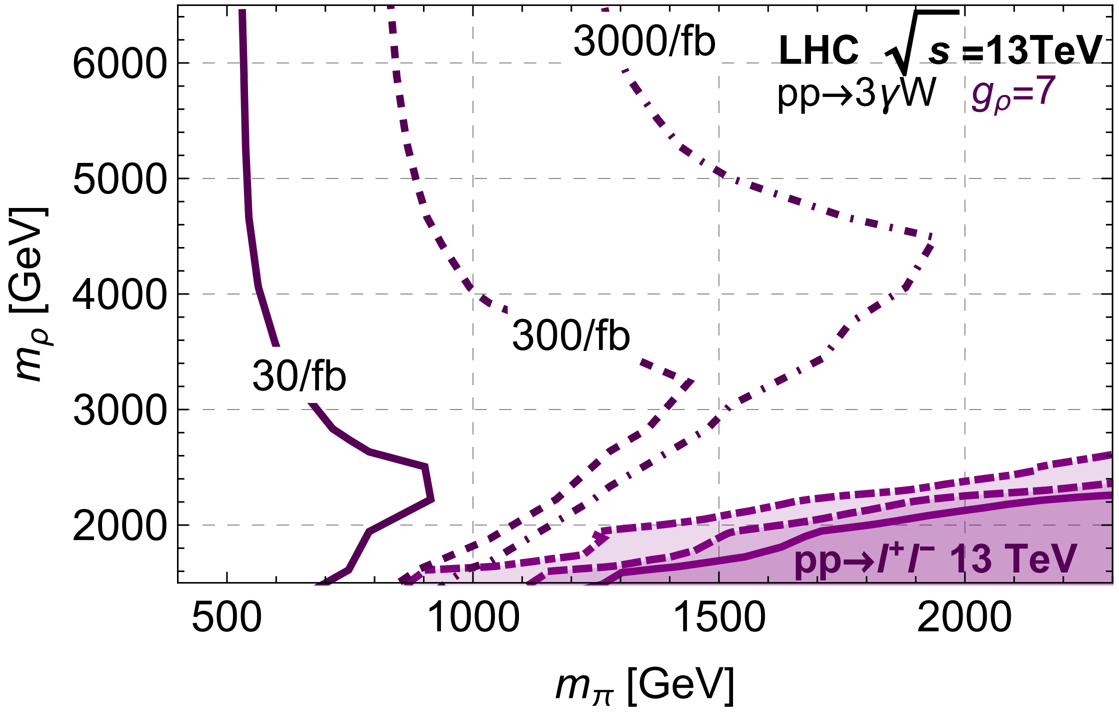


Reach on triplets at the LHC

[from: Barducci et al. JHEP 1808 (2018) 017]

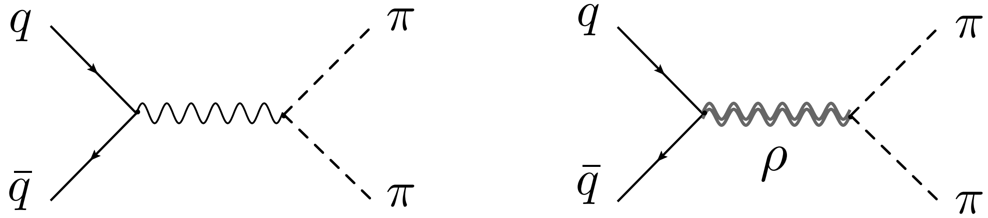
Estimated 95% exclusion from $3\gamma W$ final state



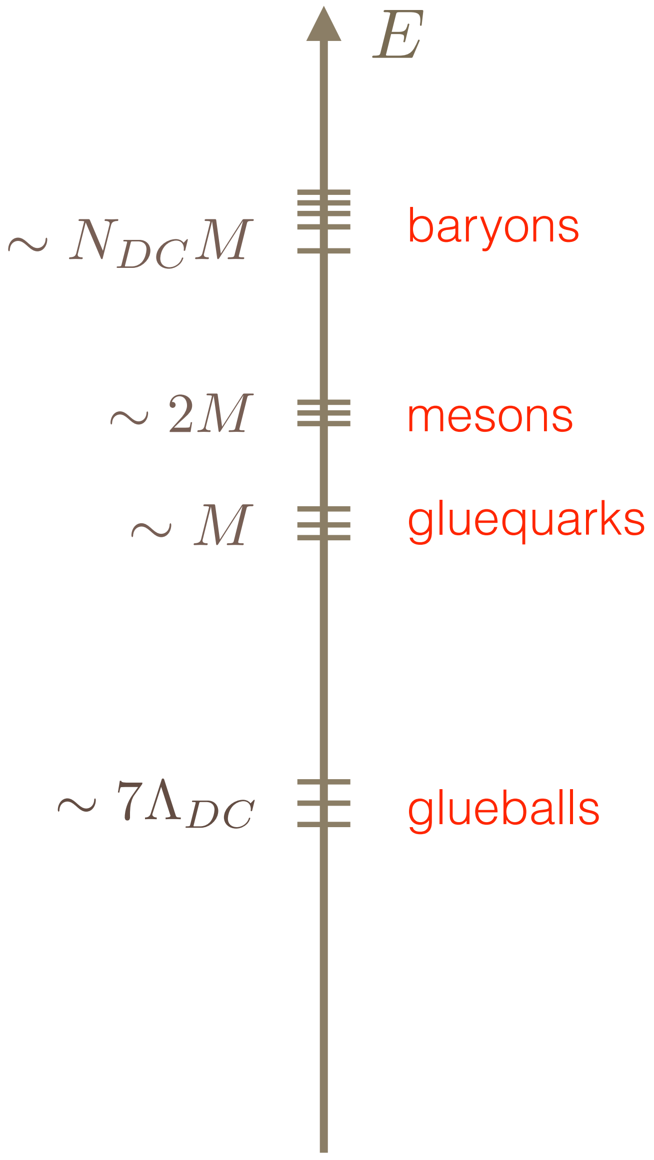
$$pp \to \pi^\pm \pi^0$$

↳ $\gamma\gamma$

↳ $W^\pm\gamma$



Phenomenology: Heavy quark regime ($M > \Lambda_{DC}$)



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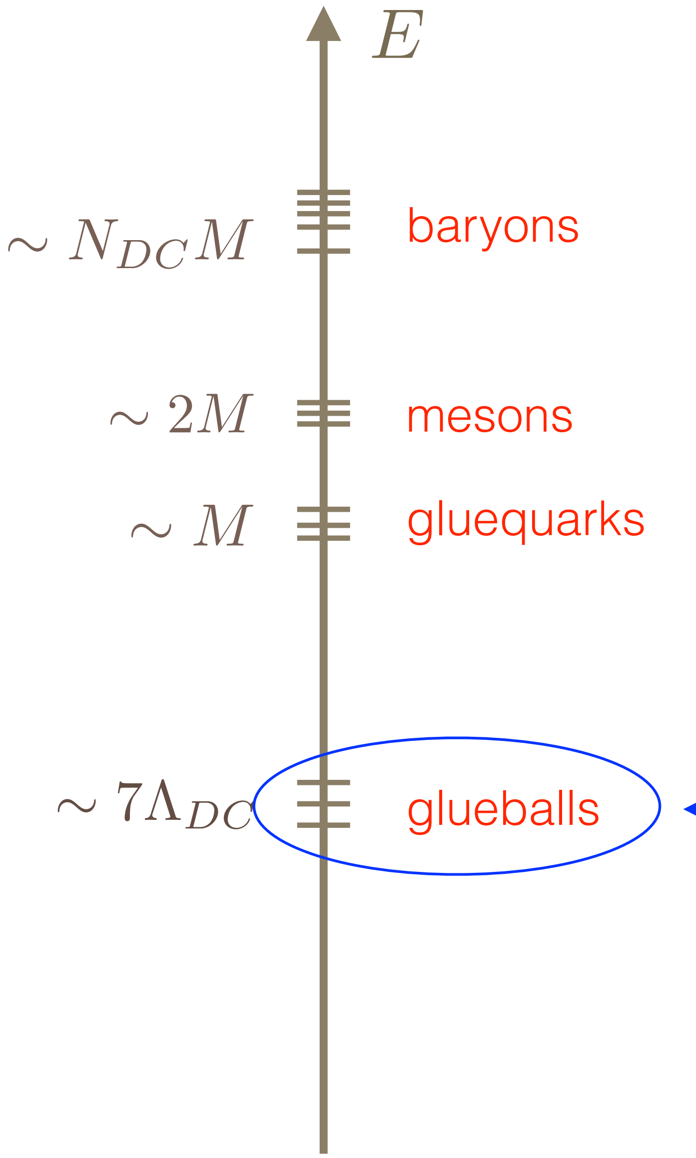
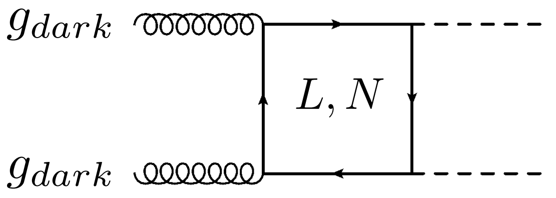


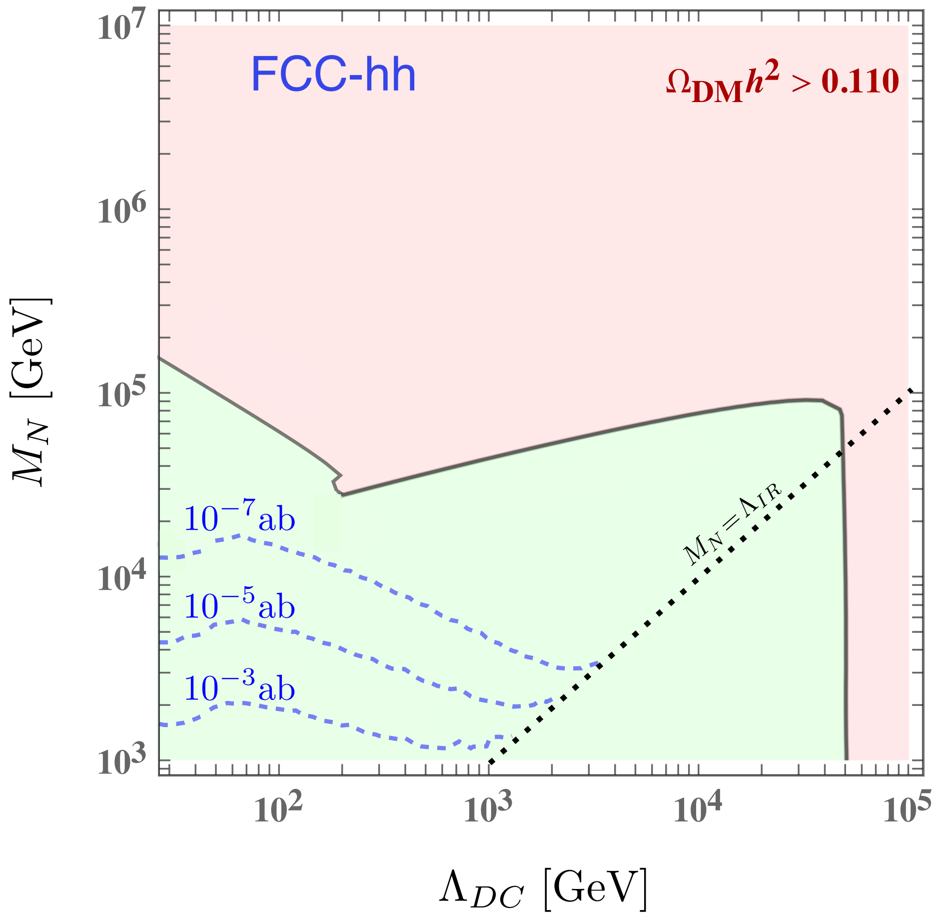
Glueballs couple to the SM only via loops of heavy fermions

Ex: in the L+N model



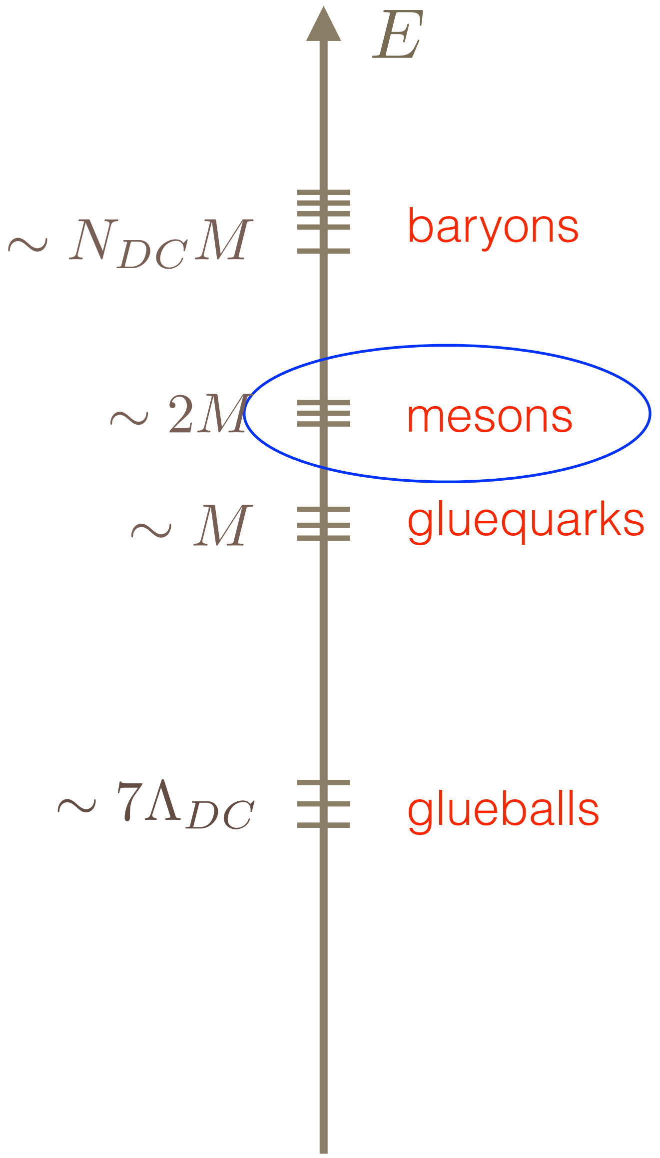
$$\rightarrow \frac{\alpha_{DC}}{4\pi}\frac{y^2}{M_L M_N} G^2_{\mu\nu} H^\dagger H$$

$$\Gamma[\Phi \to gg] \sim \frac{1}{8\pi}\left(\frac{\alpha_S}{4\pi}\right)^2 \frac{\alpha^2_{DC}(M_N)}{\alpha^2_{DC}(\Lambda_{DC})}\left(\frac{y^2}{16\pi^2}\right)^2 \frac{m^9_\Phi}{M^2_L M^2_N (m^2_h - m^2_\Phi)^2}$$



In blue:
isocurves of $\sigma(pp \to \Phi)$
for y=1, M_L/M_N=2

Phenomenology: Heavy quark regime ($M > \Lambda_{DC}$)

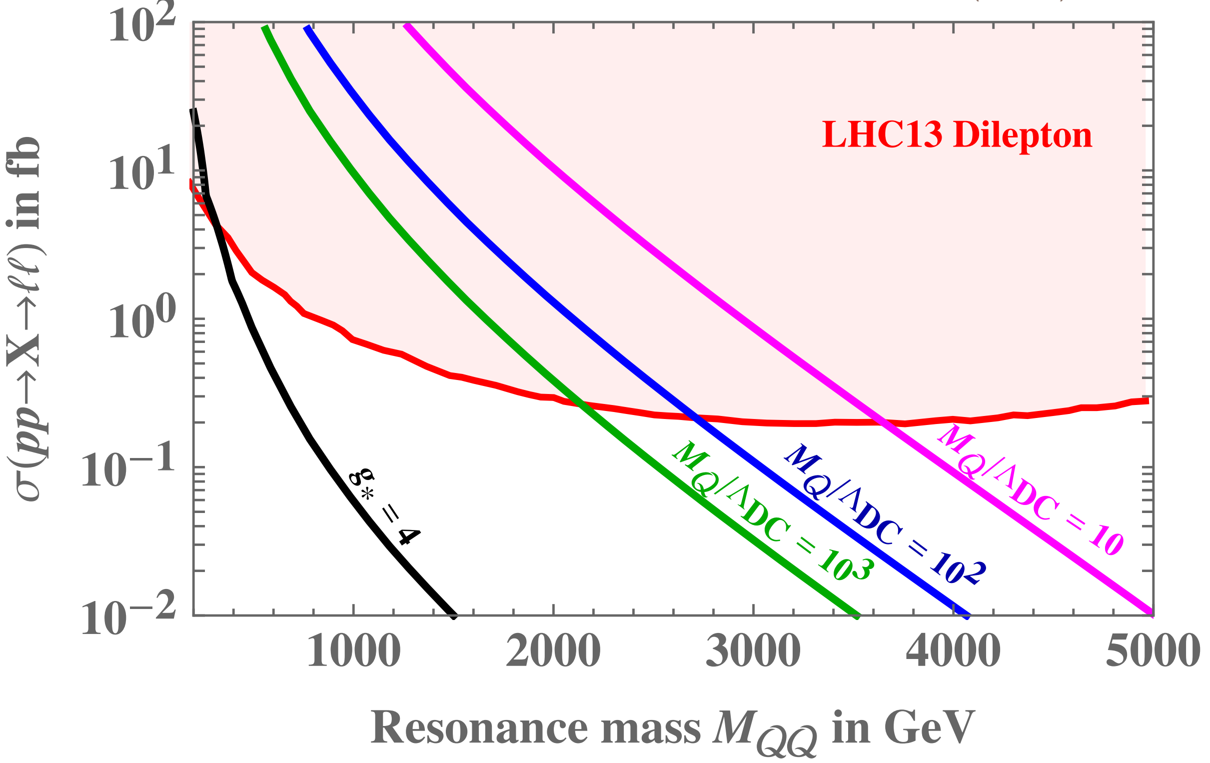


Heavy mesons are *perturbative* quarkonia bound states with calculable properties

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

Ex: in the V = adj model

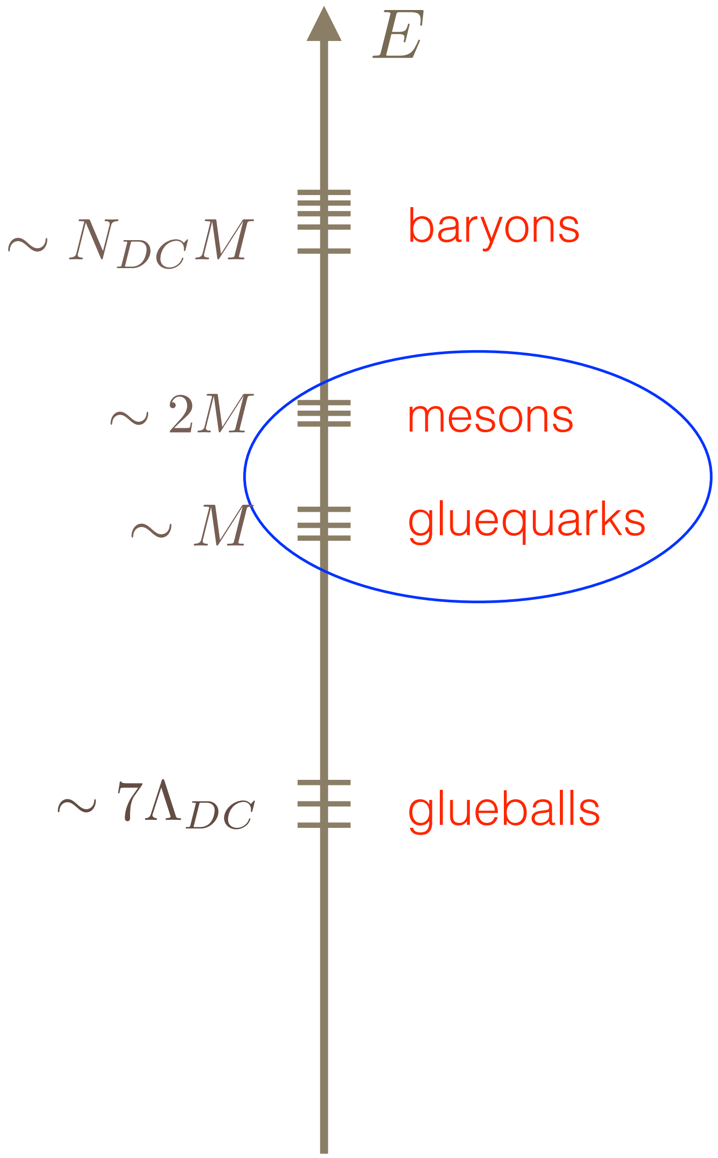
R.C., Mitridate, Podo, Redi JHEP 1902 (2019) 187



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

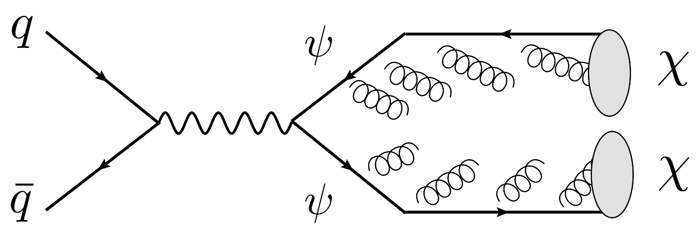
Naive exclusion at FCC-hh (20ab^{-1}): $M < 7 - 13\,\text{TeV}$

Phenomenology: Heavy quark regime ($M > \Lambda_{DC}$)



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

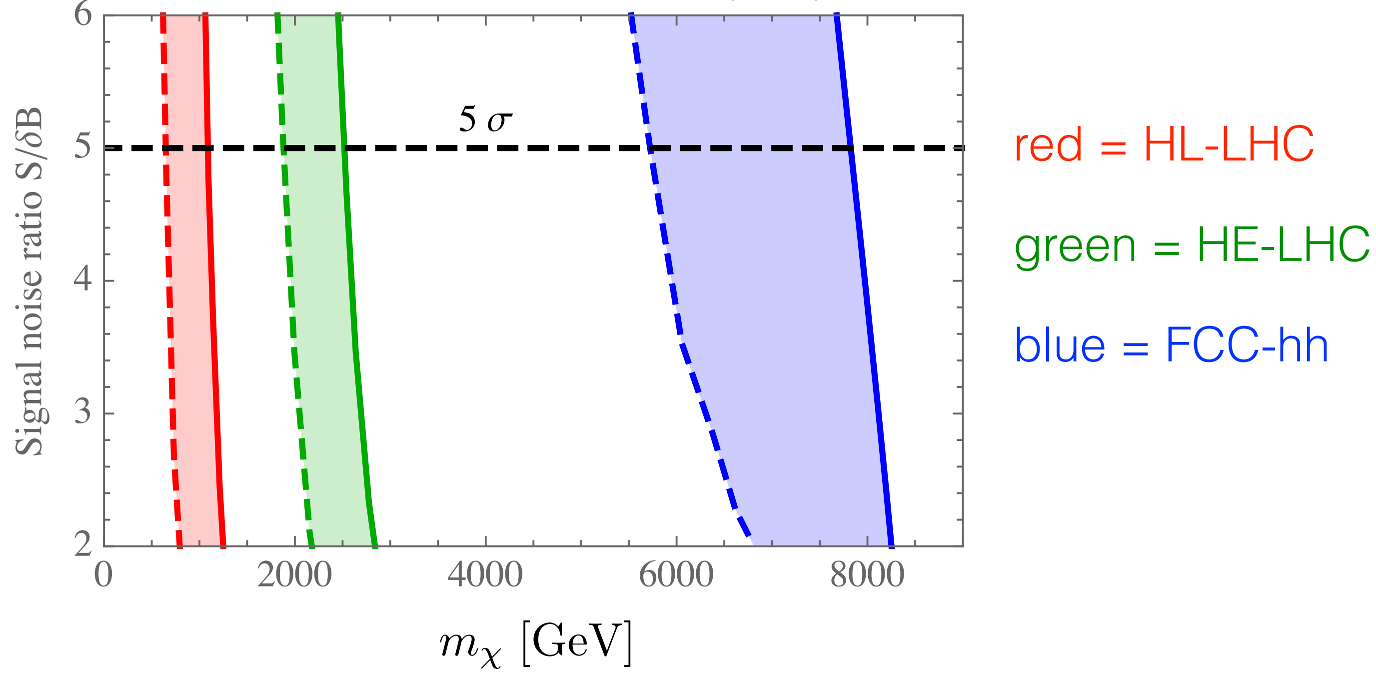
- Heavy quarks in the fundamental lead to string formation and exotic (quirk) signatures
- Heavy quarks in the adjoint instead hadronize into dark color-singlet gluequarks



Ex: in the V = adj model $m_{\chi^+} - m_{\chi^0} = 160\,\mathrm{MeV}$

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

recast from PRD 98 (2018) 035026



Dark Pions as Accidental DM

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

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

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In general, species numbers are broken by Yukawa couplings or D=5 operators:

$(\bar{Q}_1 Q_2)H$ if $(\bar{Q}_1 Q_2) = 2_{\pm\frac{1}{2}}$ of $SU(2)_{EW}$ x $U(1)_Y$

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

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☞ There is a way, however, to avoid such breaking.

	$SU(N_{DC})$	$SU(2)_{EW}$	$U(1)_{3V}$	$U(1)_V$
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

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

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

breaks species number U(1)3V

Global Symmetry breaking pattern:

$$SU(4)_L \times SU(4)_R \times U(1)_V \xrightarrow{\text{spont.}} SU(4)_V \times U(1)_V$$

$$\underset{\text{expl.}}{\hookrightarrow} SU(2)_{EW} \times U(1)_{3V} \times U(1)_V$$

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

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

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

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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

Now let's gauge an extra *chiral* U(1)$_D$:

[RC, Podo, Revello arXiv:2008.10607]

	$SU(N_{DC})$	$U(1)_D$	$SU(2)_{EW}$	$U(1)_{3V}$	$U(1)_V$
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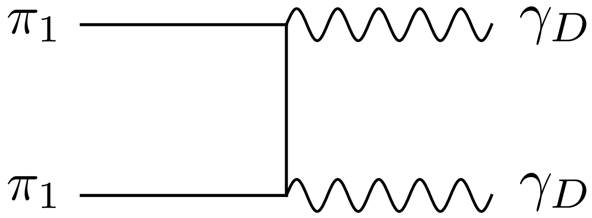
- $1_\pm$ and B are both thermal relics, DM abundance dominated by dark pion for small e_D



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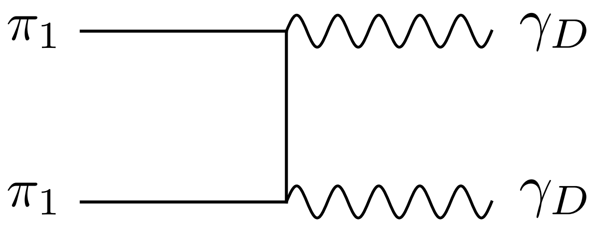

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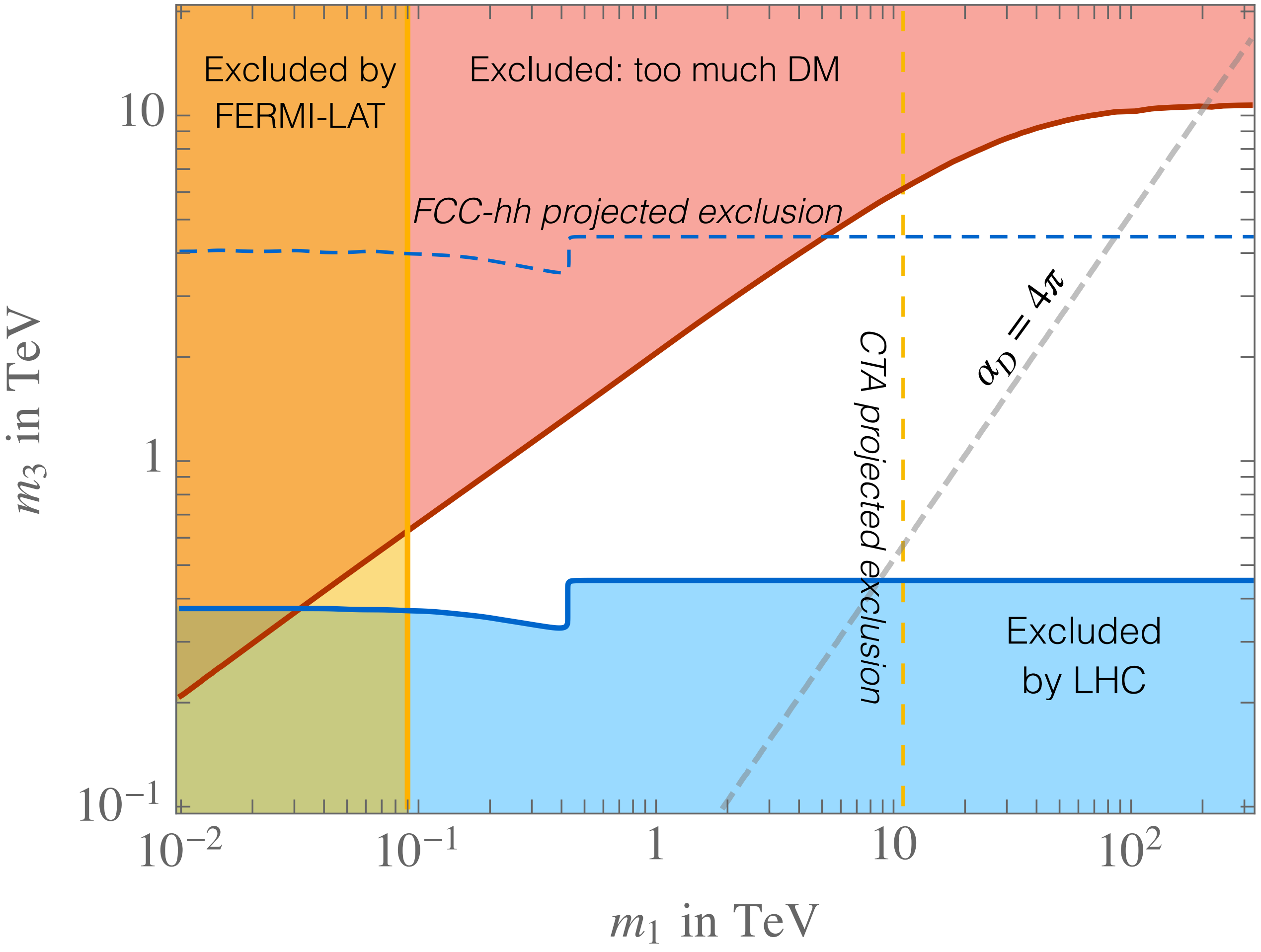
- Interesting correlation between collider searches and cosmological observations



Long-lived γ_D

$\varepsilon = 10^{-10}$

$a = 1/2, N_{DC} = 4$

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- Much work still needed (ex: models with non-thermal DM production)