A GUT FRAMEWORK FOR ACCIDENTAL DARK MATTER

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Based on:
S. Bottaro, R.C., S. Verma, work in progress

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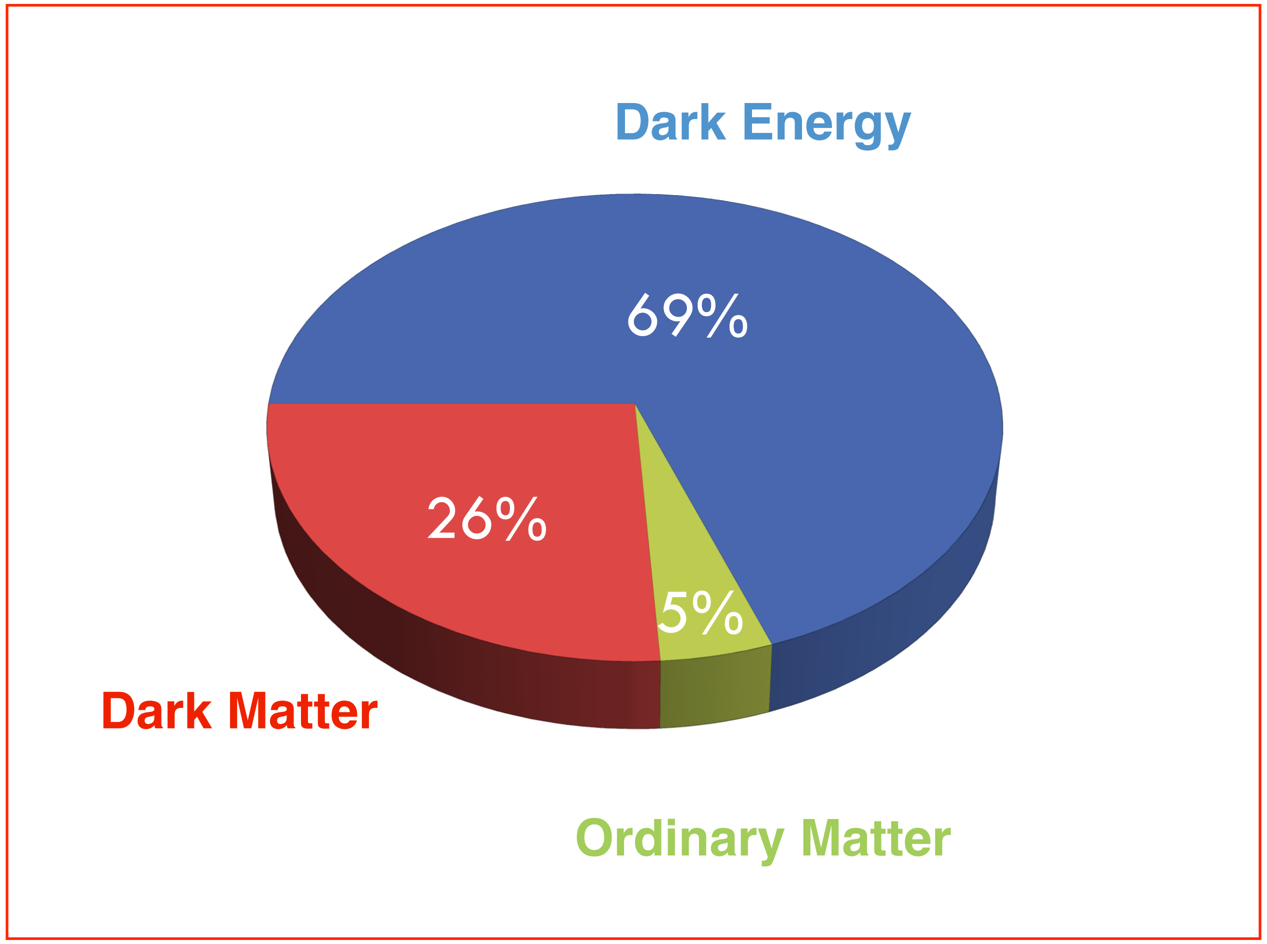
The Energy Budget of the Universe



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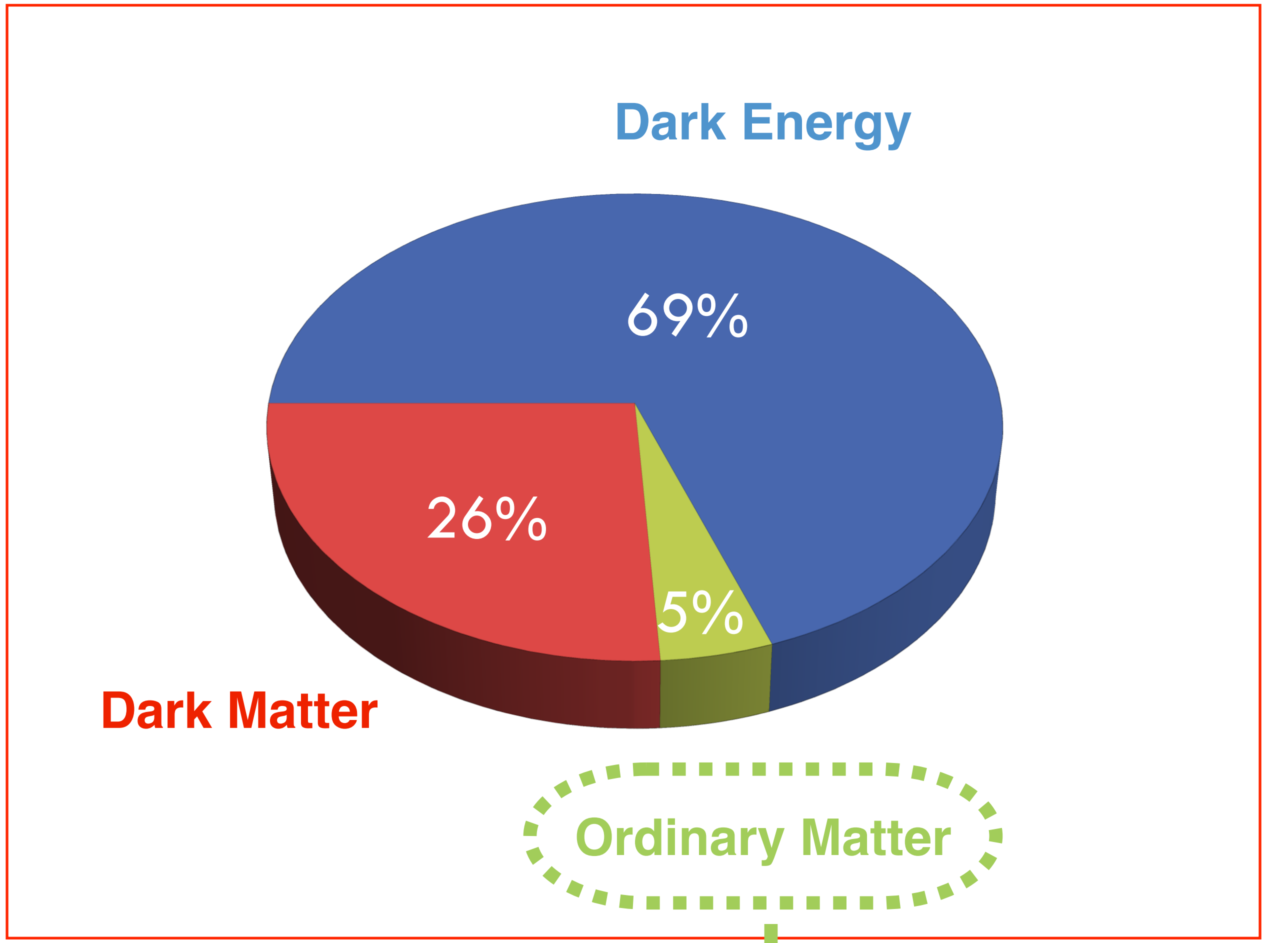

It exists thanks to proton stability, ultimately due to accidental baryon number conservation

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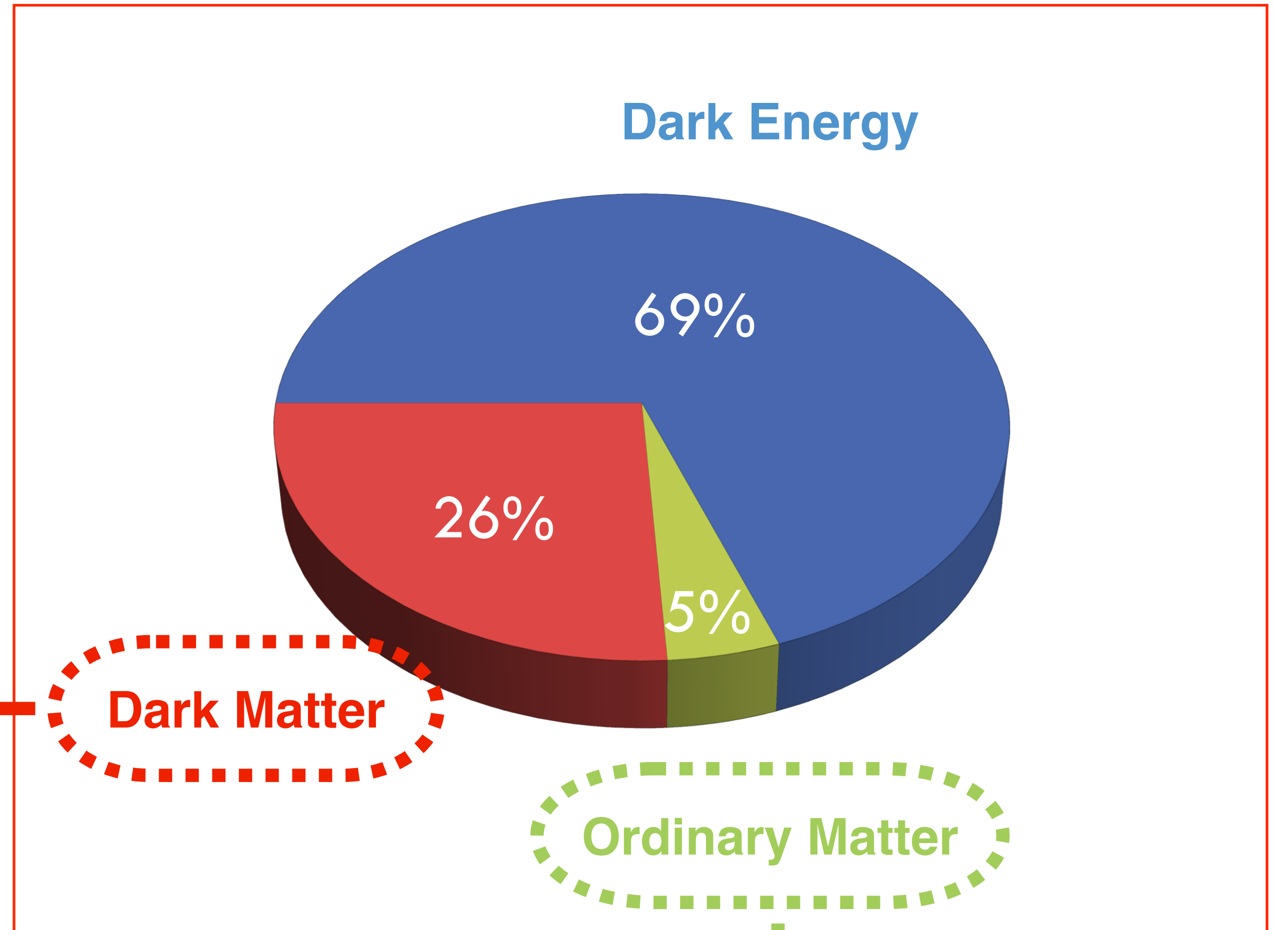


Can Dark Matter be stable due to its own accidental symmetry ?

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

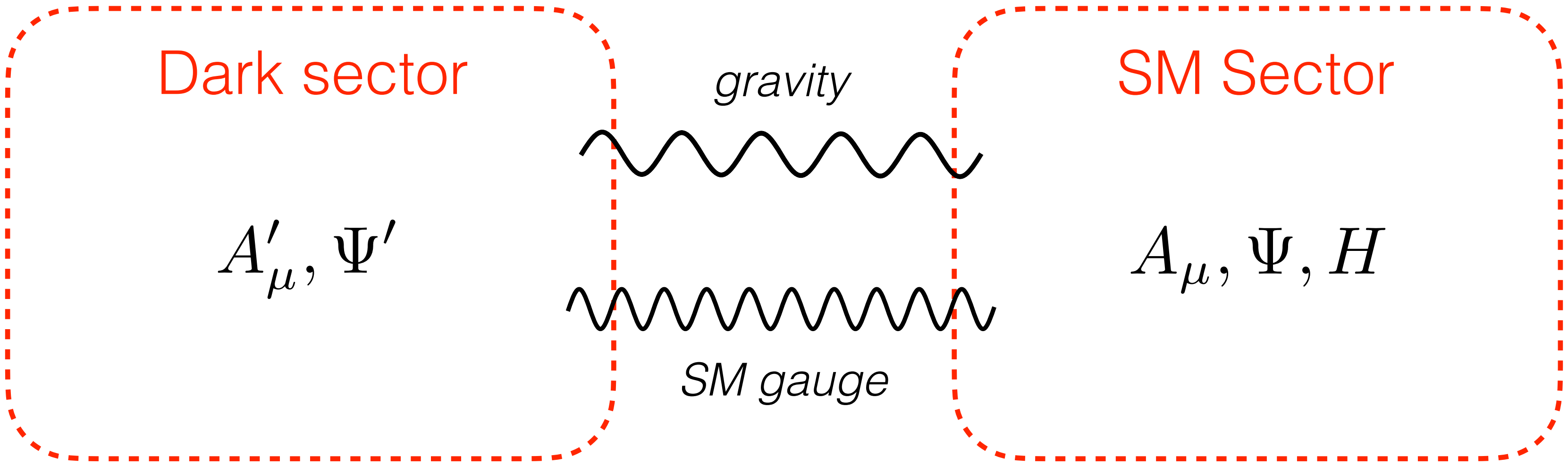
Accidental vs Exact Global Symmetries

- Accidental symmetries are only approximate, emerge at low energy (large separation of scales required!) 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

Models of Accidental Dark Matter



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

Requirement:

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

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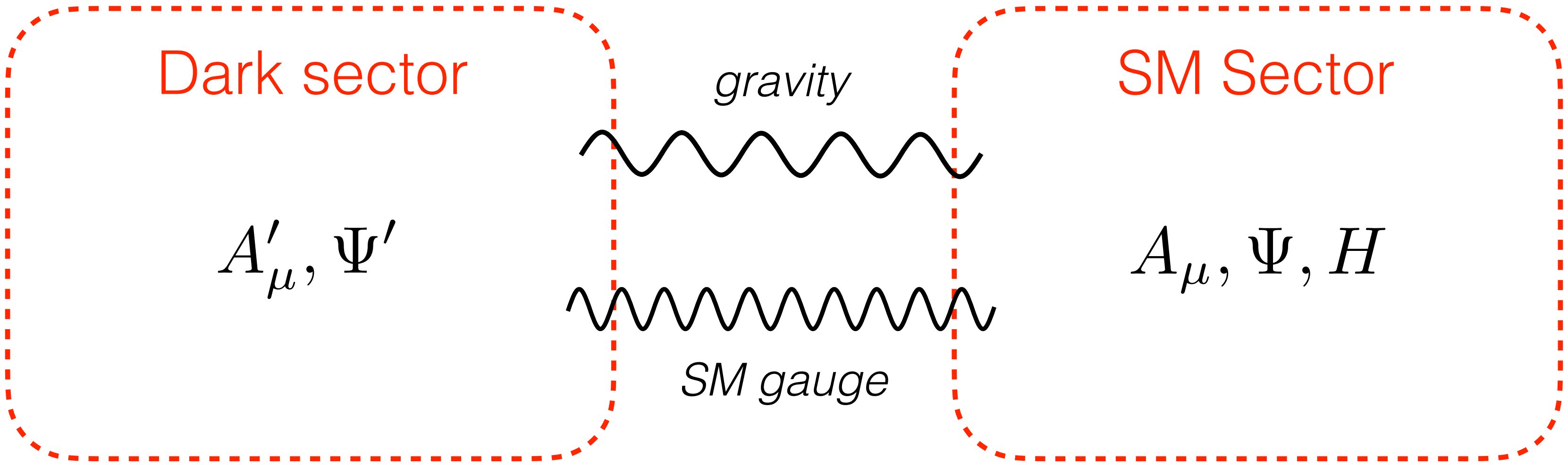

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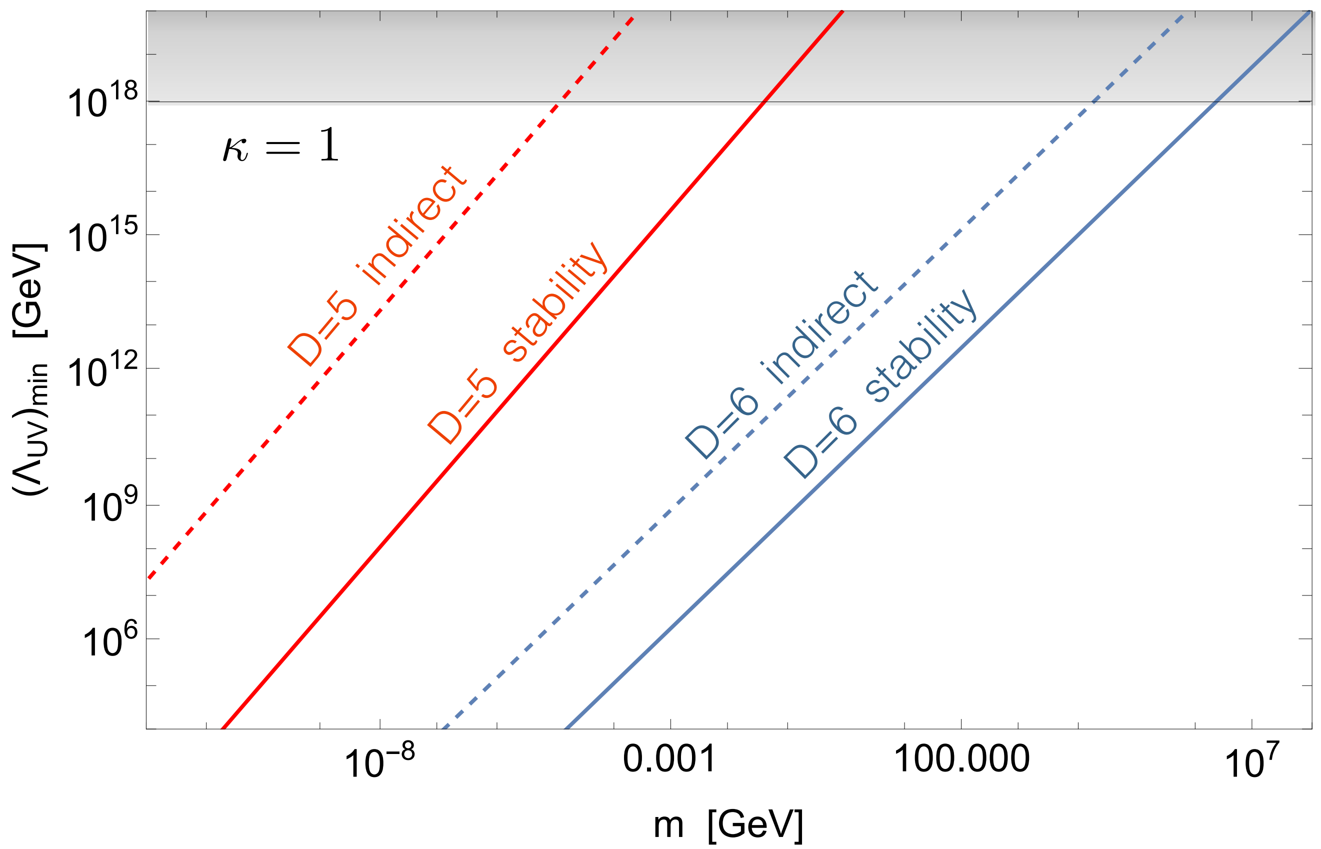
☞ Accidental symmetries easily obtained from strongly-coupled dark sectors

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: $\tau \gtrsim 10^{17}\mathrm{sec}$

Bounds from CMB, 21cm, DM indirect detection: $\tau \gtrsim 10^{28}\mathrm{sec}$



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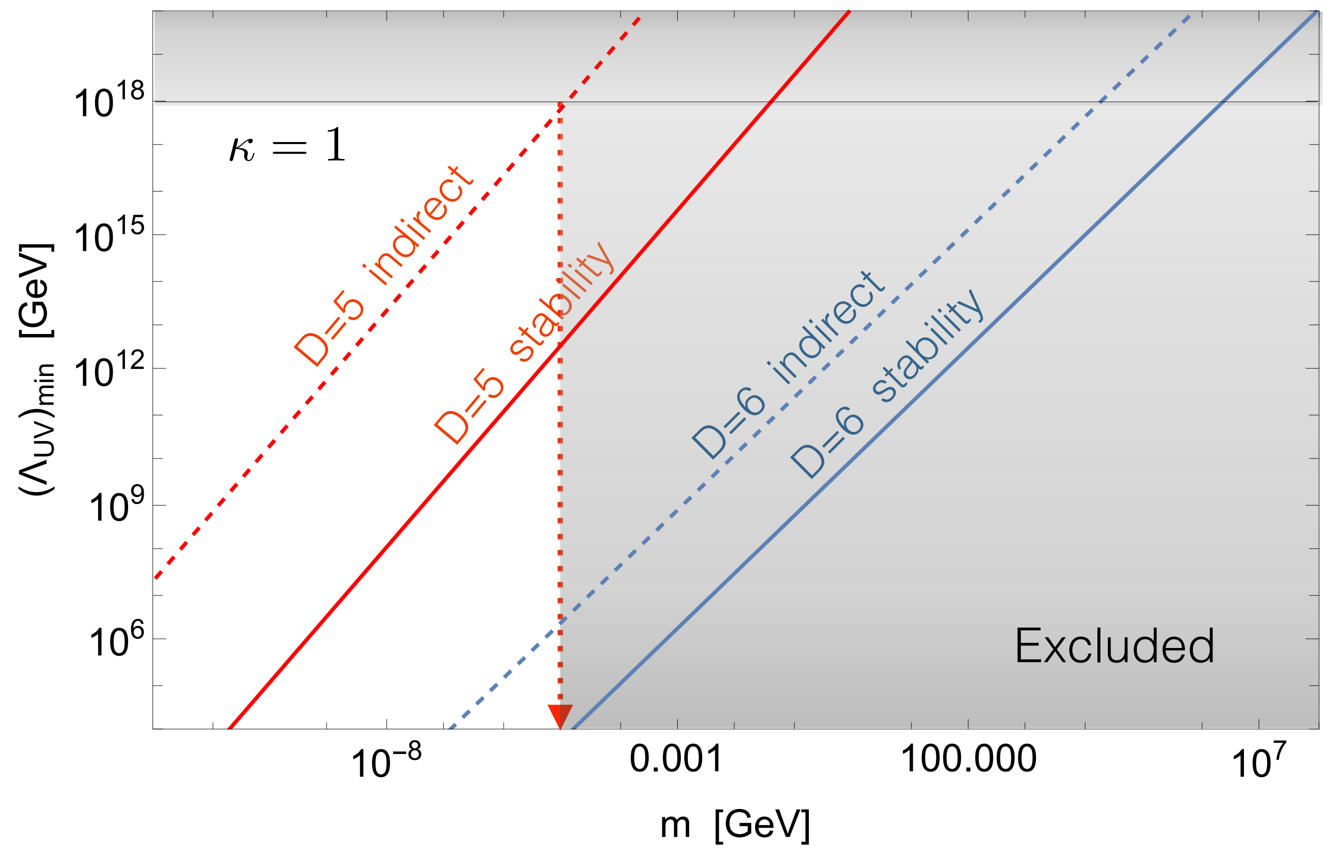

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  - too light for a SM-charged sector

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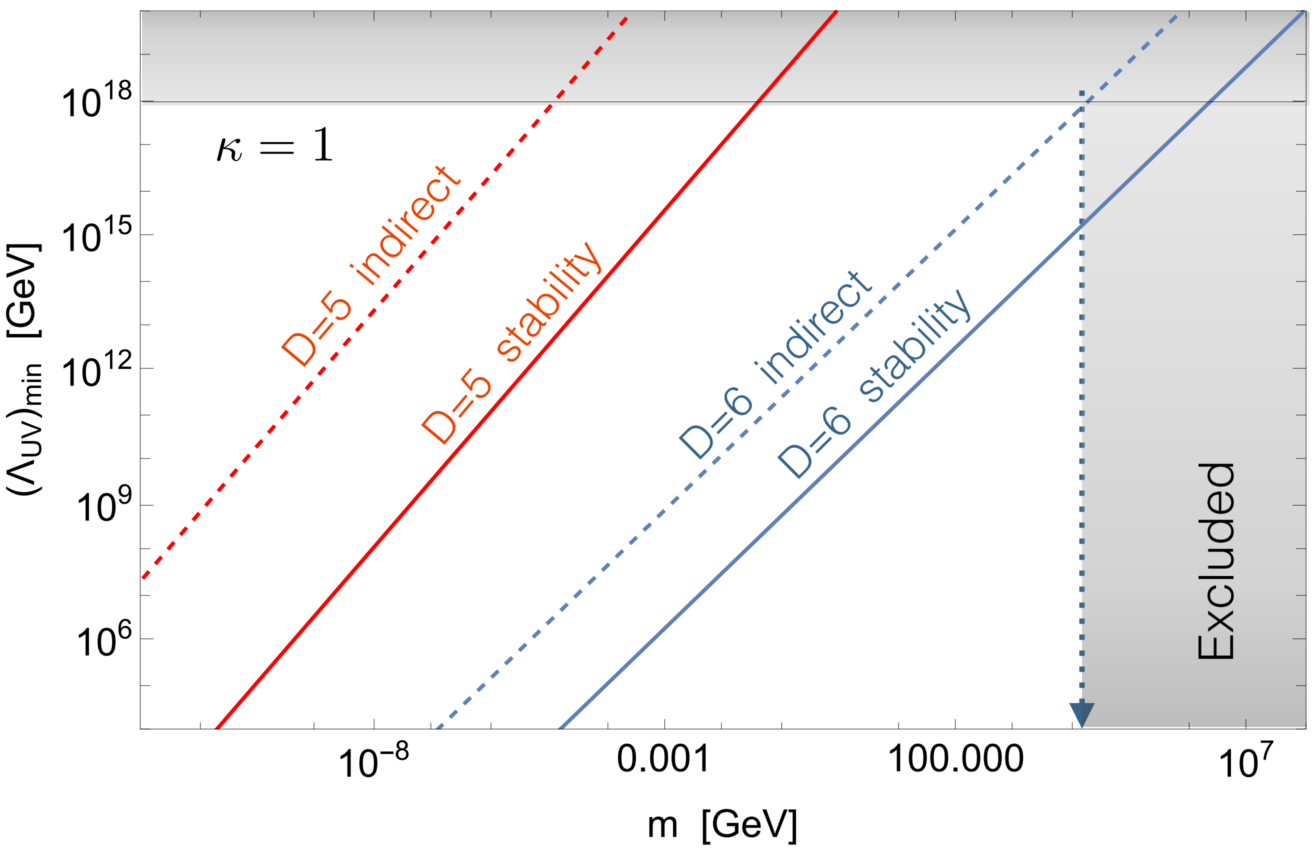

- D=5 requires $m_{DM} \lesssim 10\,\mathrm{keV}$
  - too light for a SM-charged sector
- D=6 requires $m_{DM} \lesssim 100\,\mathrm{TeV}$
  - sufficiently heavy for SM-charged sector to have escaped detection
  - DM with $m_{DM} \sim 50\,\mathrm{TeV}$ can be a thermal relic if strongly coupled

Dark Matter Sector: Vector-like Confining Gauge Theory

Kilic, Okui, Sundrum JHEP 1002 (2010) 018
Antipin, Redi, Strumia, Vigiani JHEP 1507 (2015) 039
Mitridate, Redi, Smirnov, Strumia, JHEP 10 (2017) 210

Gauge Group = G_{DC} x G_{SM} where G_{DC} = $SU(N)_{DC}$ or $SO(N)_{DC}$

Dark 'quarks' $\mathcal{Q}$ = ($\square$,*r*) *of* G_{DC} x G_{SM}, *Dirac/Majorana if* ($\square$,*r*) is complex/real

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

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- Accidental dark baryon number $U(1)_{DB}$, broken at $D \geq 6$

  Lightest dark baryon stable and good DM candidate $\mathcal{B} \sim (QQ \cdots Q)$

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- Accidental dark baryon number $U(1)_{DB}$, broken at $D \geq 6$

  Lightest dark baryon stable and good DM candidate $\mathcal{B} \sim (\mathcal{Q}\mathcal{Q}\cdots\mathcal{Q})$

- Accidental species numbers, broken at $D \geq 5$

  Long-lived mesons not good DM candidates, must decay before BBN $\pi \sim \bar{\mathcal{Q}}_i\mathcal{Q}_j$

Request: DM model must be embeddable into SU(5) GUT

$$\mathcal{L}_{DM} = -\frac{1}{4g_{\rm DC}^2}\mathcal{G}_{\mu\nu}^2 + \sum_i \bar{\mathcal{Q}}^i(i\not{D} - m_{\mathcal{Q}})\mathcal{Q}^j + y_{ij}^L \bar{\mathcal{Q}}^i H P_L \mathcal{Q}^j + y_{ij}^R \bar{\mathcal{Q}}^i H P_R \mathcal{Q}^j + \text{h.c.}$$

sum over SU(5) fragments

$\mathcal{Q}^i$	$SU(5)$	SM Quantum Numbers
N	1	$(1,1,0)$
$D \oplus L$	$\bar{5}$	$(\bar{3},1,1/3) \oplus (1,2,-1/2)$
$U \oplus E \oplus Q$	10	$(\bar{3},1,-2/3) \oplus (1,1,1) \oplus (3,2,1/6)$
$Q \oplus T \oplus S$	15	$(3,2,1/6) \oplus (1,3,1) \oplus (6,1,-2/3)$
$V \oplus G \oplus X \oplus N$	24	$(1,3,0) \oplus (8,1,0) \oplus (\bar{3},2,5/6) \oplus (1,1,0)$

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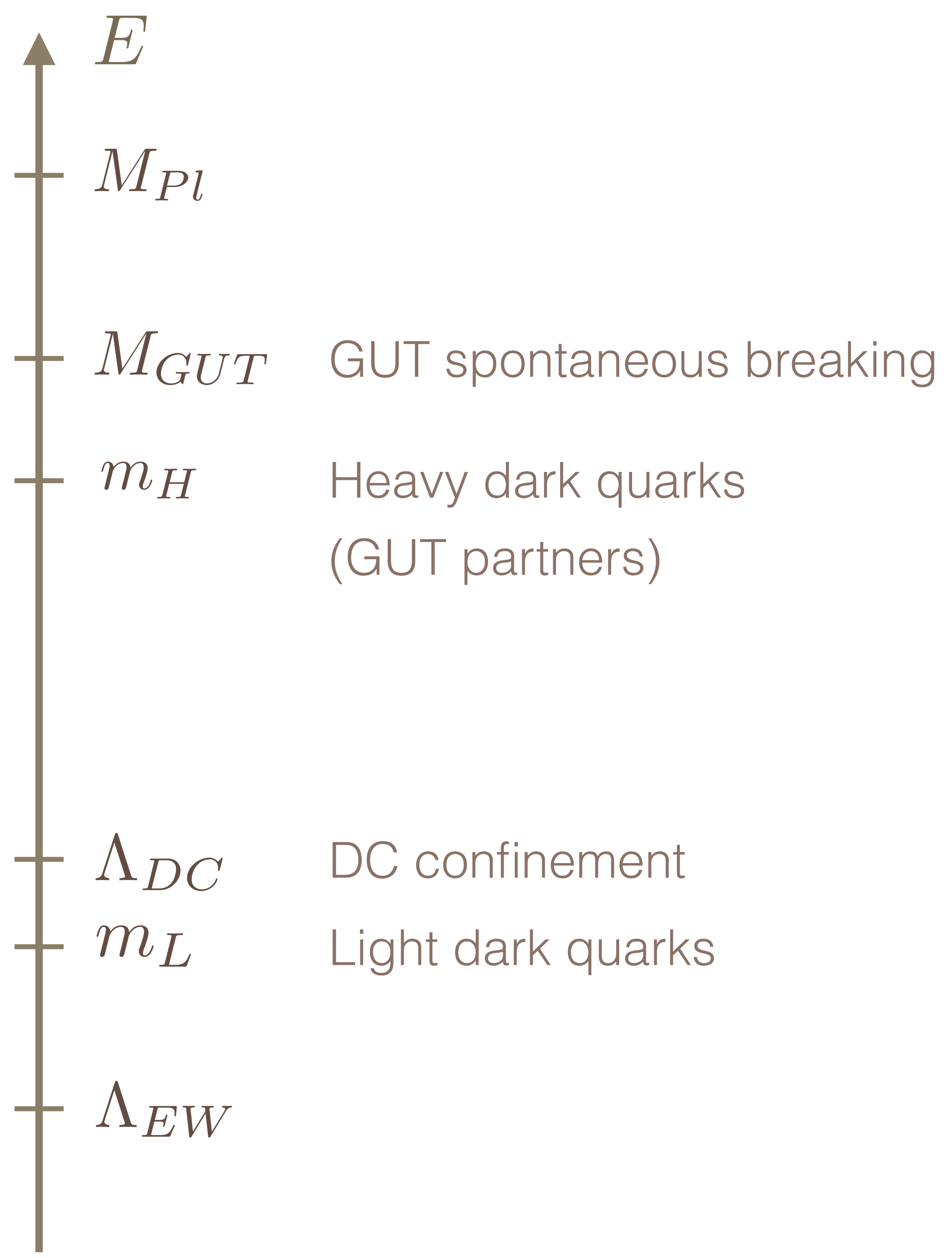
Example: $Q+\tilde{D}$ model with $G_{DC}=SU(3)_{DC}$

- 1 Yukawa: $\mathcal{L}_Y = \bar{Q}H\tilde{D} + h.c.$ No accidental species number
- DM candidate: $QQ\tilde{D}$

UV completing DM models into SU(5) GUT

Bottaro, R.C., Verma, work in progress



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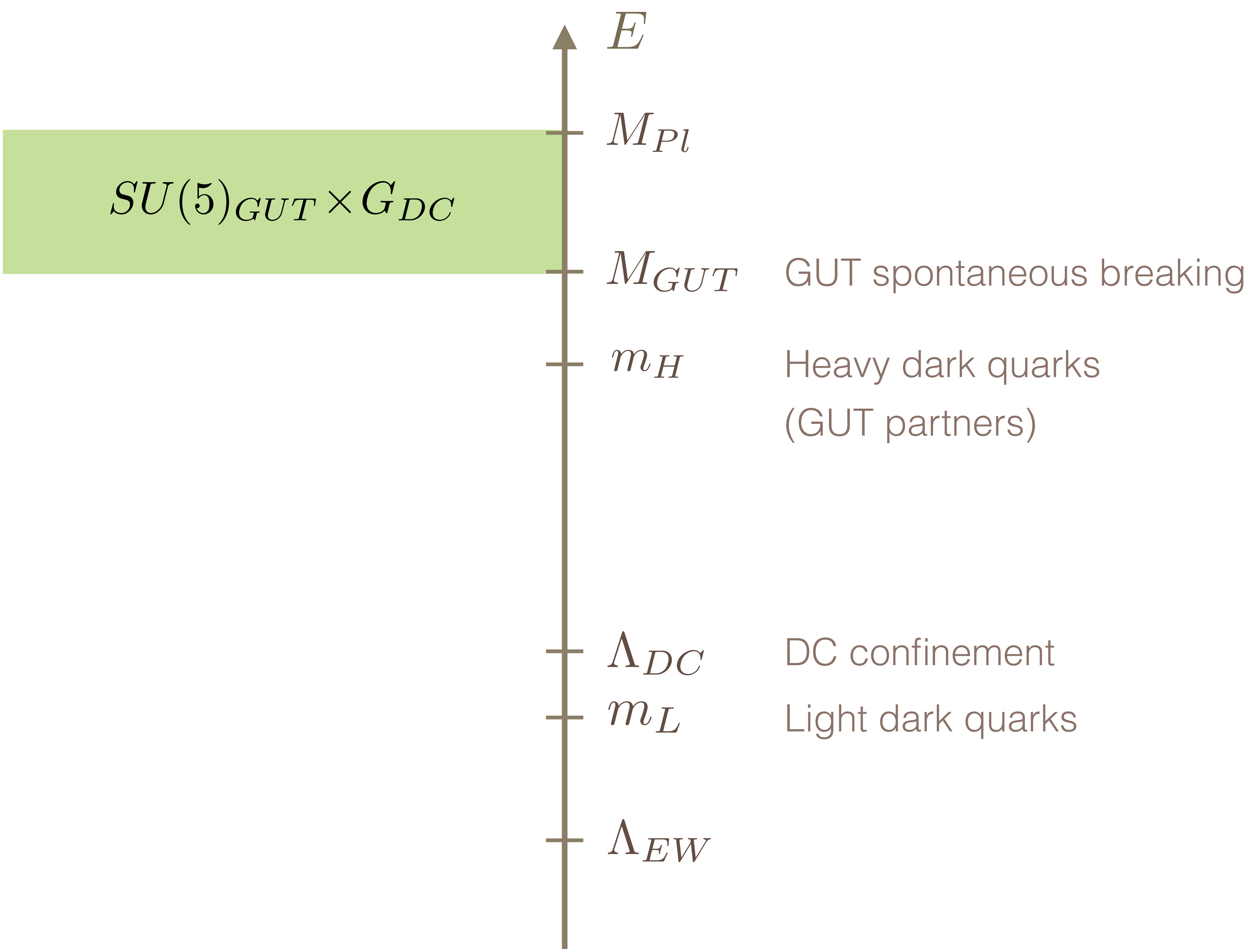

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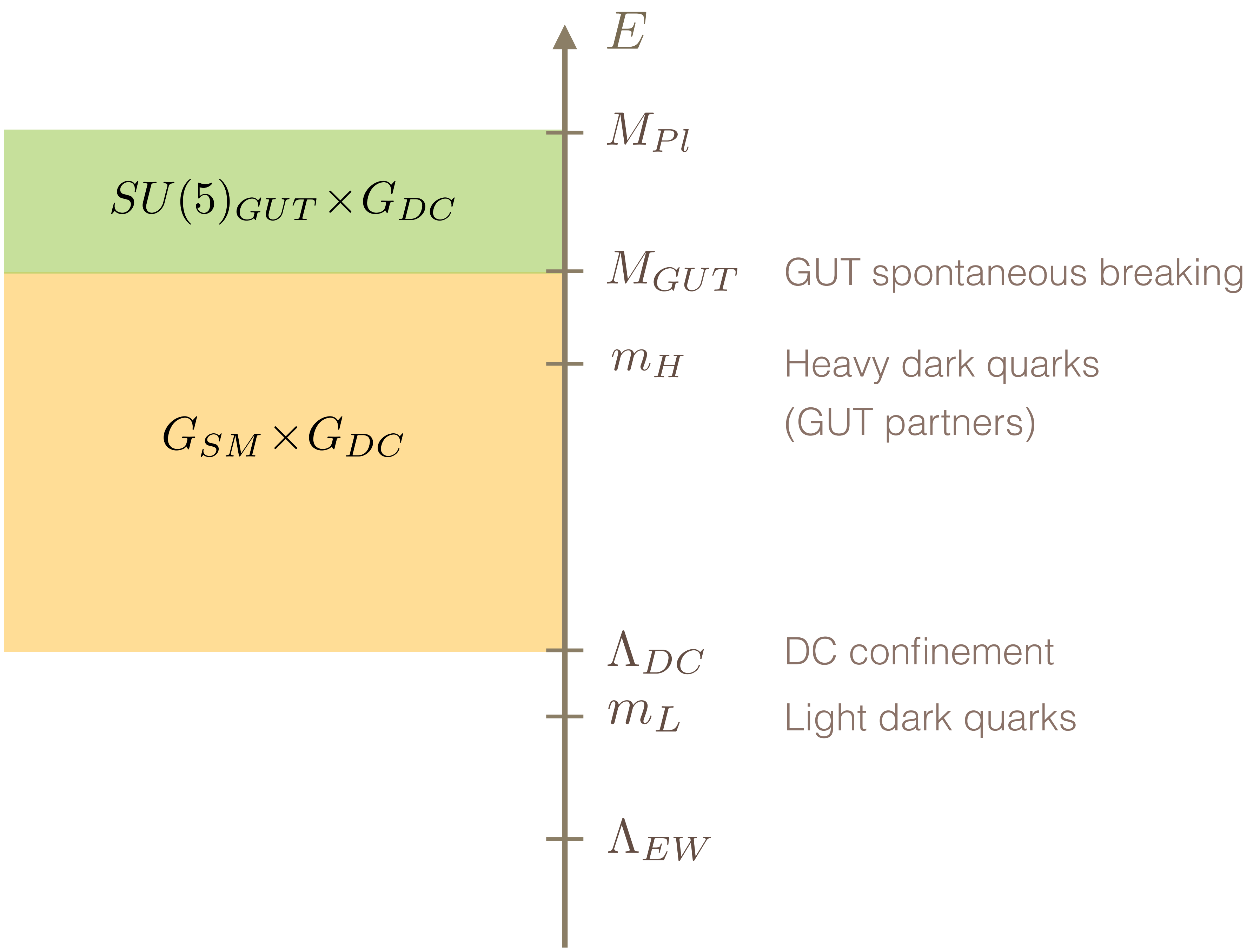

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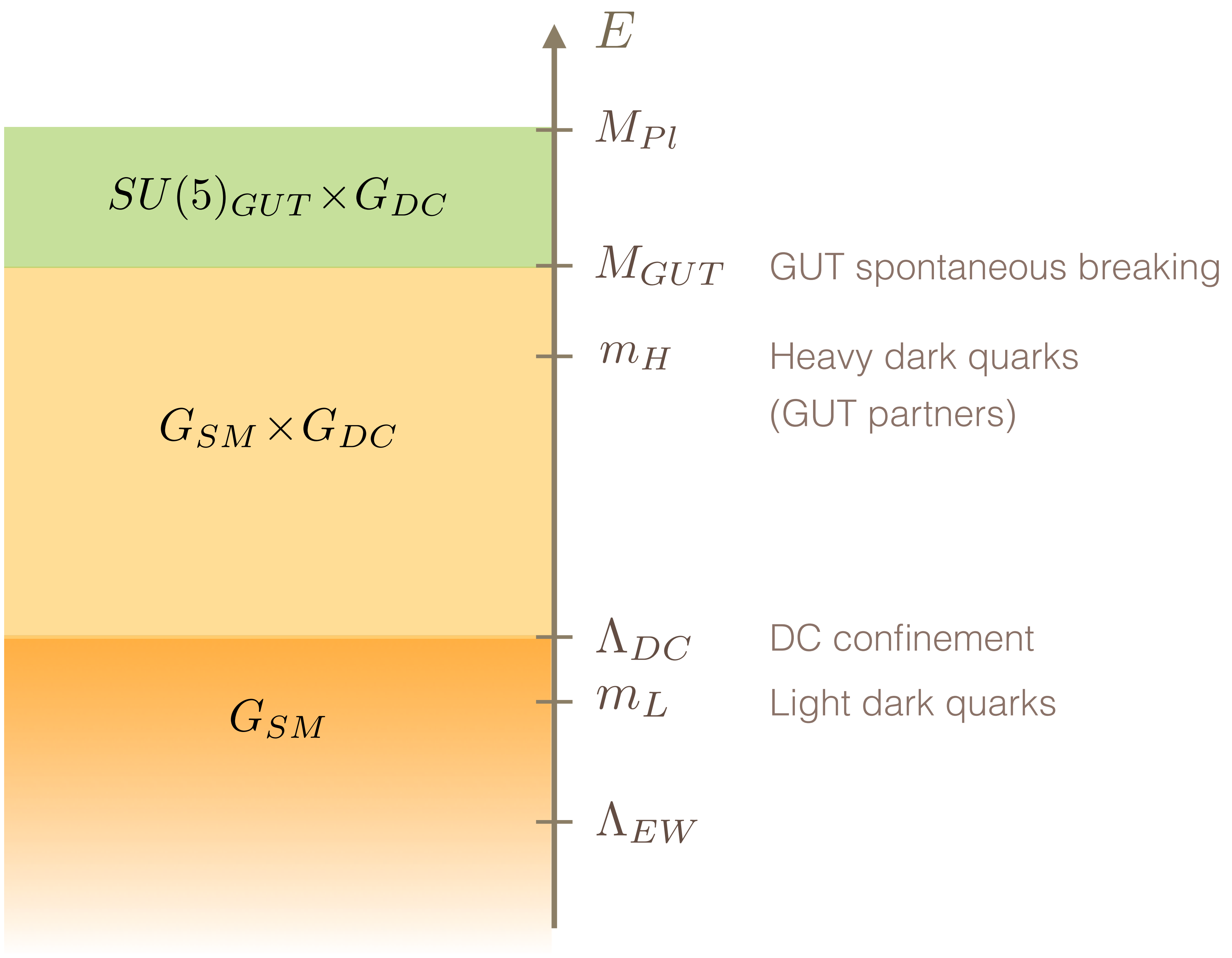

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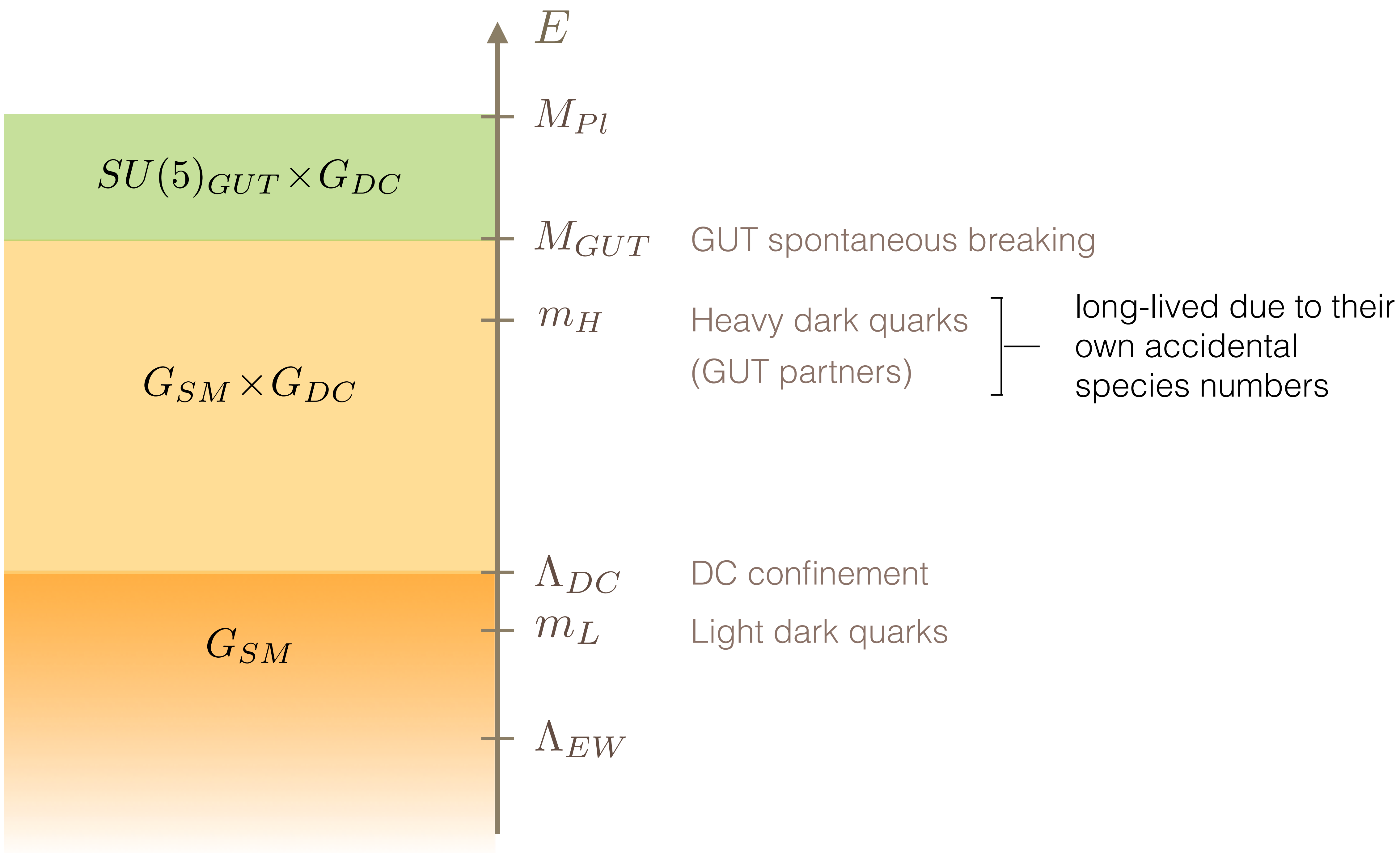

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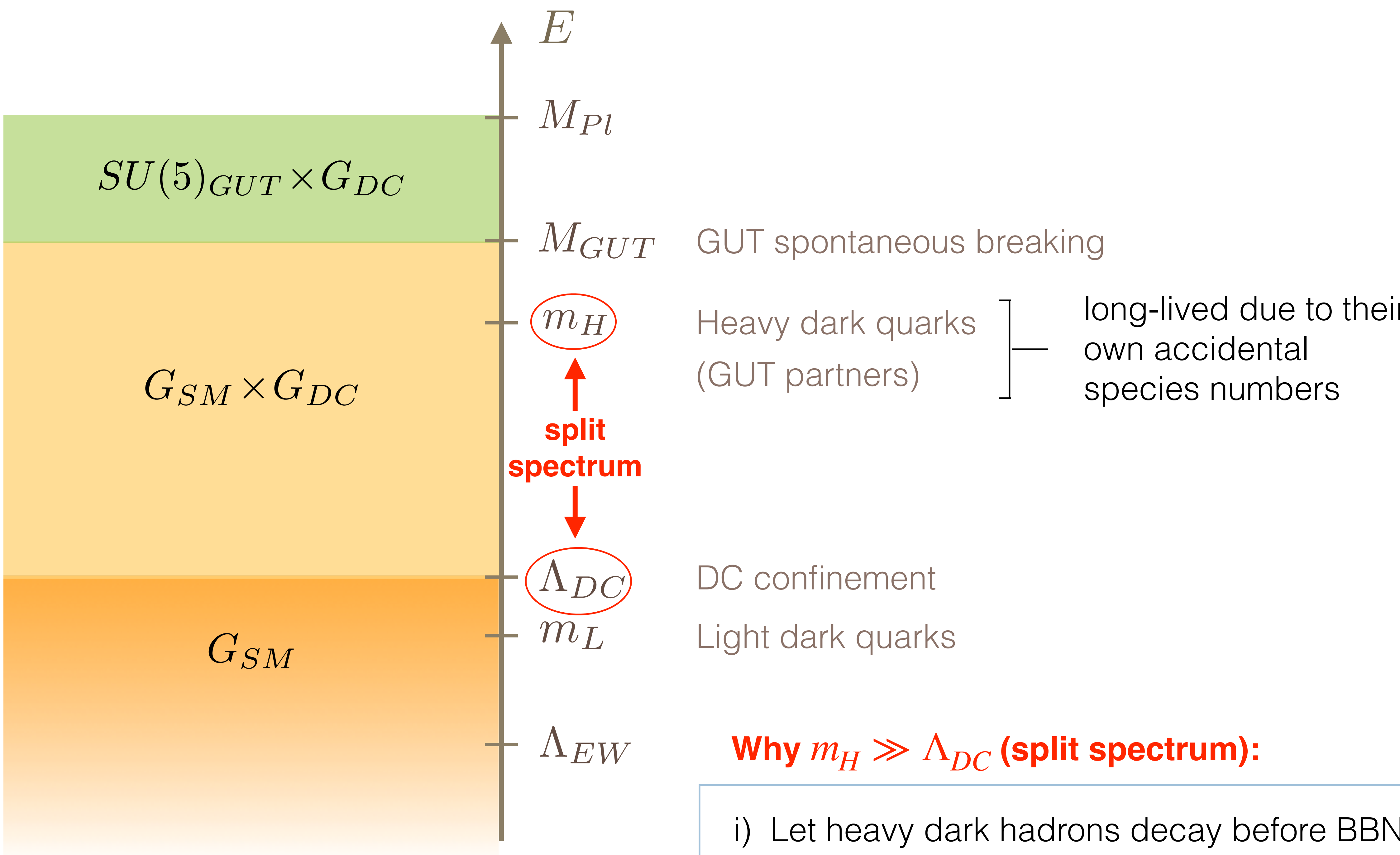


Why $m_H \gg \Lambda_{DC}$ (split spectrum):

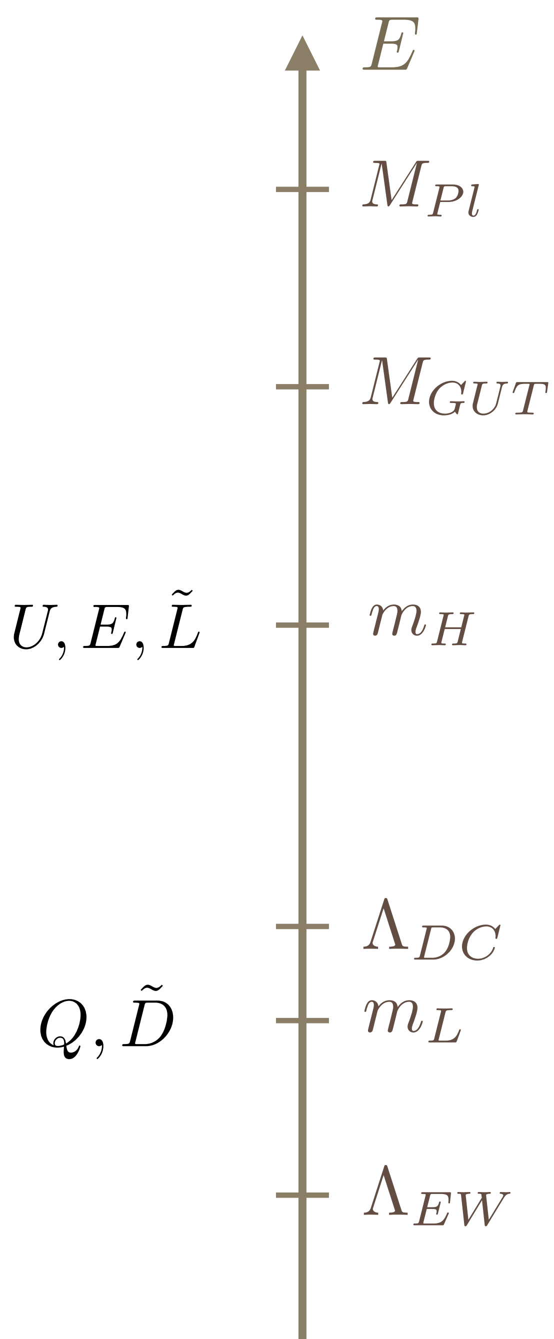
i) Let heavy dark hadrons decay before BBN

ii) Better unification

Mass Spectrum and Naturalness

Ex: $Q+\tilde{D}$ model from $5\oplus 10$ GUT theory

$$\psi_5 = \tilde{D}\oplus\tilde{L} \qquad \psi_{10} = Q\oplus U\oplus E$$



$$\mathcal{L} \supset -m_5\bar{\psi}_5\psi_5 - m_{10}\bar{\psi}_{10}\psi_{10} - y_5\,\bar{\psi}_5\Phi_{24}\psi_5 - y_{10}\,\bar{\psi}_{10}\Phi_{24}\psi_{10}$$
$$- y_L\,\bar{\psi}_5\phi_5^\dagger P_R\psi_{10} - y_R\,\bar{\psi}_5\phi_5^\dagger P_L\psi_{10} + h.c.$$

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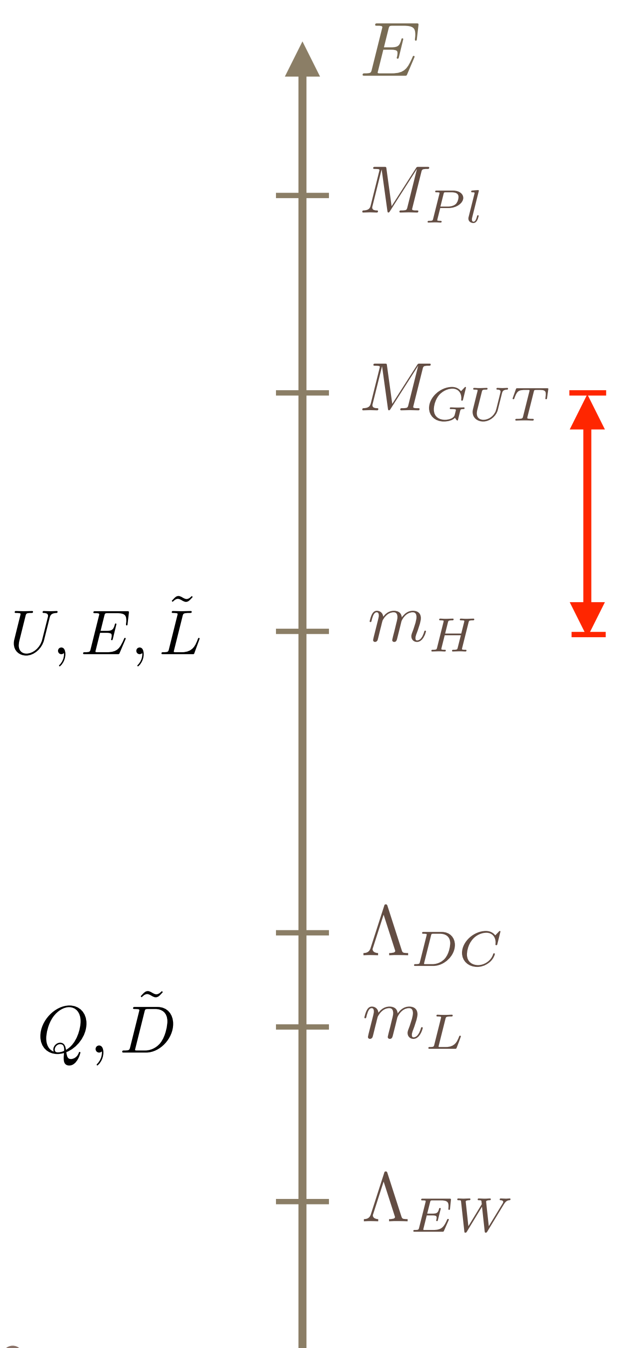

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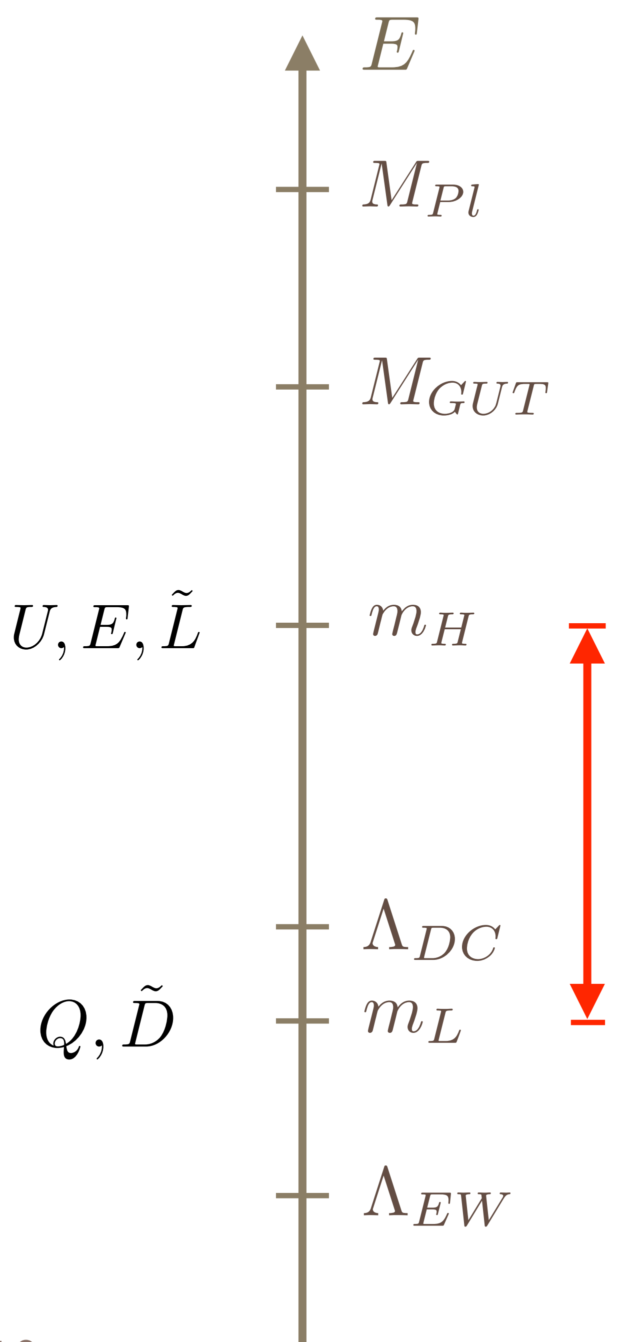
Hierarchy $m_{U,E,\tilde{L}} \ll M_{GUT}$ is technically natural for $y_5, y_{10} \ll 1$

$m_{5,10},\ y_{5,10}$ are the only spurions under $U(1)_L\times U(1)_R$:

$$U(1)_L : \begin{cases} \psi_{5L} \to e^{i\alpha}\,\psi_{5L} \\ \psi_{10R} \to e^{i\alpha}\,\psi_{10R} \end{cases} \qquad U(1)_R : \begin{cases} \psi_{5R} \to e^{i\beta}\,\psi_{5R} \\ \psi_{10L} \to e^{i\beta}\,\psi_{10L} \end{cases}$$

Mass Spectrum and Naturalness



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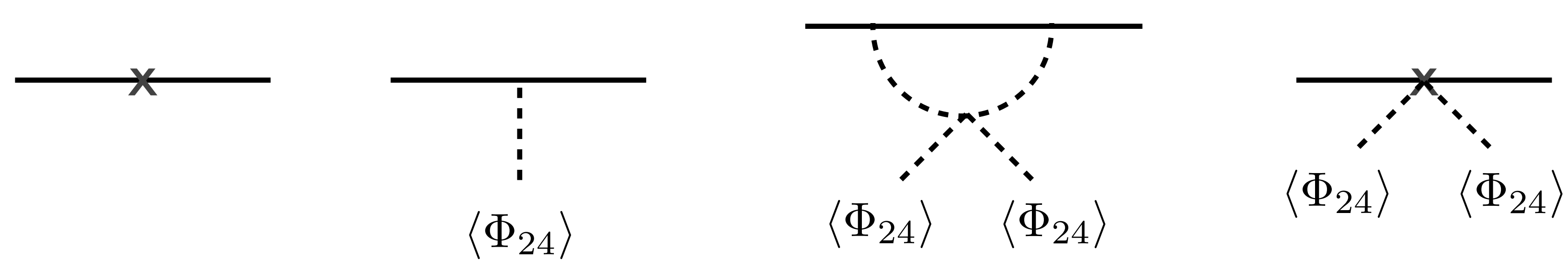
$$- y_L \, \bar{\psi}_5 \phi_5^\dagger P_R \psi_{10} - y_R \, \bar{\psi}_5 \phi_5^\dagger P_L \psi_{10} + h.c.$$

Hierarchy $m_{Q,\tilde{D}} \ll m_{U,E,\tilde{L}}$ requires *two* fine tunings

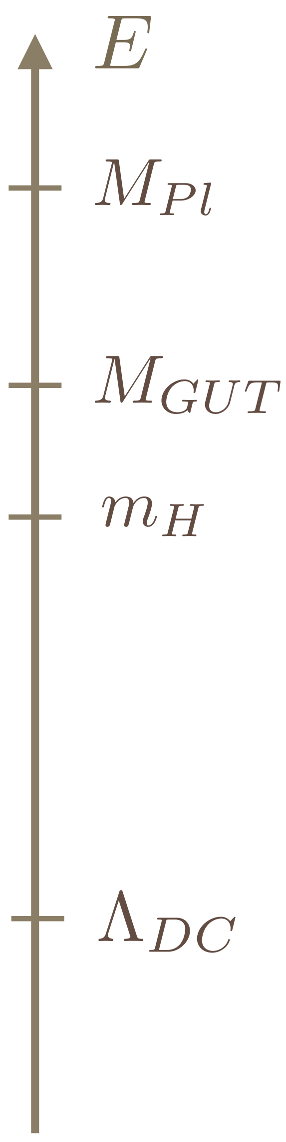
$$\bar{\psi}_5 \mathcal{M}_5 \psi_5 \qquad \mathcal{M}_5 = m_1 \, \mathbb{1} + m_{24} \, \langle \Phi_{24} \rangle$$

$$-\frac{2}{5} - \sqrt{\frac{6}{5}} \frac{m_1}{m_{24}} \simeq \frac{m_{\tilde{D}}}{m_{\tilde{L}}} \ll 1$$



Viable Species Number-Breaking Operators

- All long-lived mesons must decay before BBN $$\tau \sim \left(\frac{\kappa^2}{8\pi} \frac{m^{2D-7}}{\Lambda_{UV}^{2D-8}} \right)^{-1} < 1\,\mathrm{sec}$$



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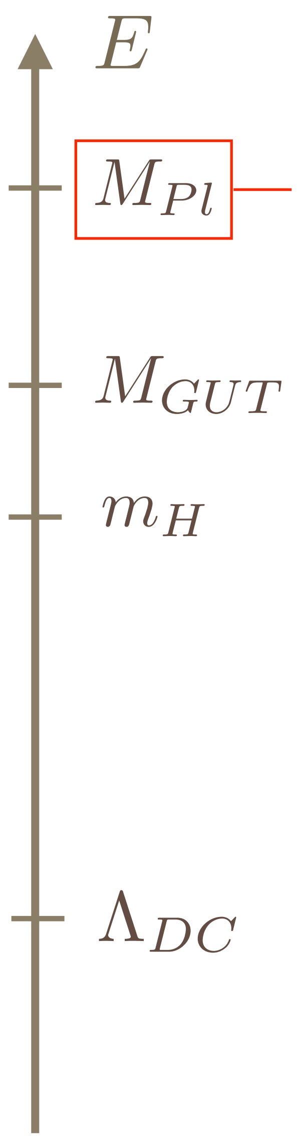

$D = 5$ operators generated at the Planck scale

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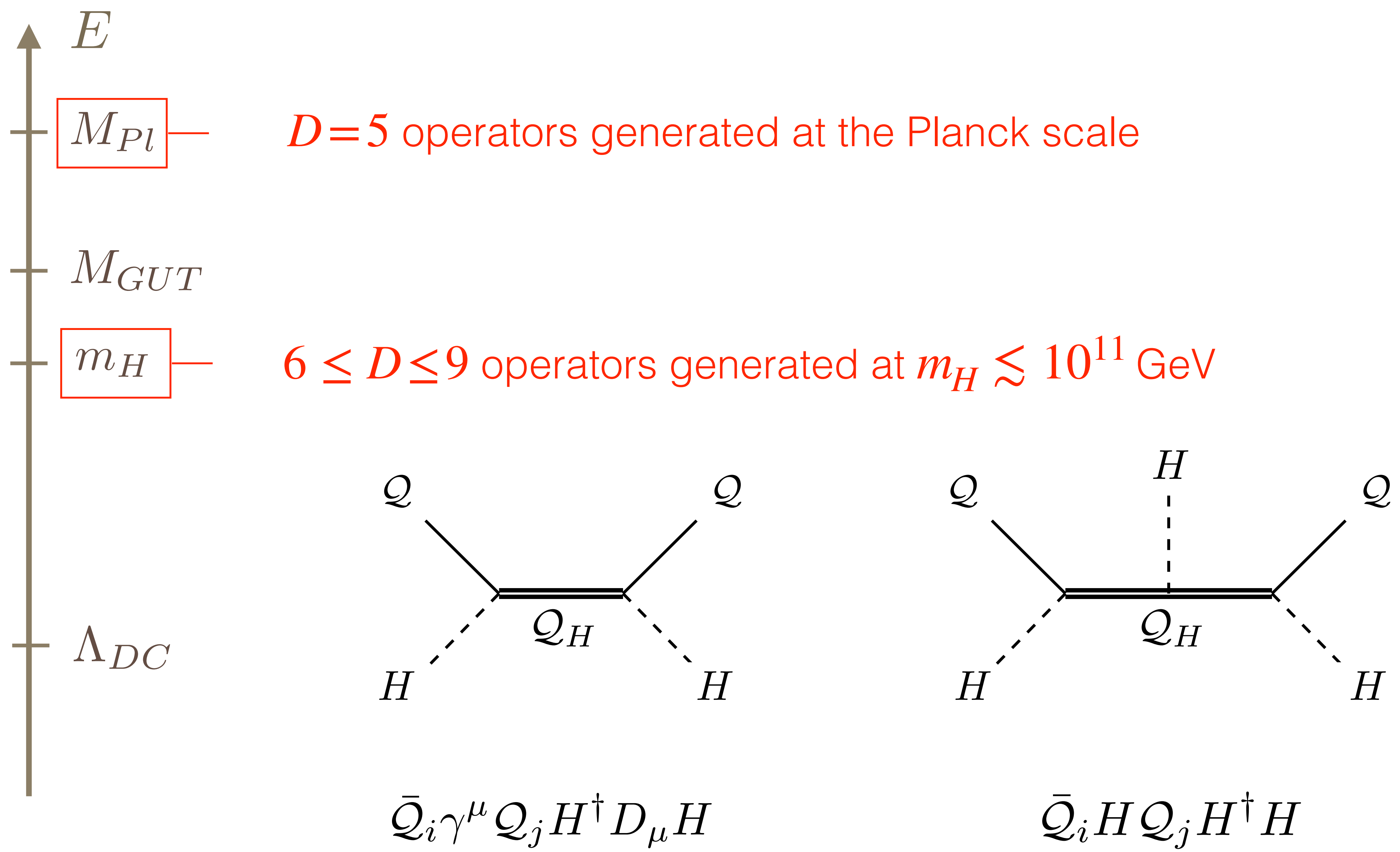


Minimal Parent Theories

- For each DM model one can identify one or more Minimal Parent Theories

Minimal Parent Theory = minimal GUT field content that reproduces the field content of the low-energy theory *and breaks all its accidental species numbers*.

Acceptable Minimal Parent Theories have

i) no accidental species numbers

OR ii) accidental species numbers broken at the D=5 level; the inherited species numbers of the low-energy theory must also be broken at the D=5 level

Minimal Parent Theories

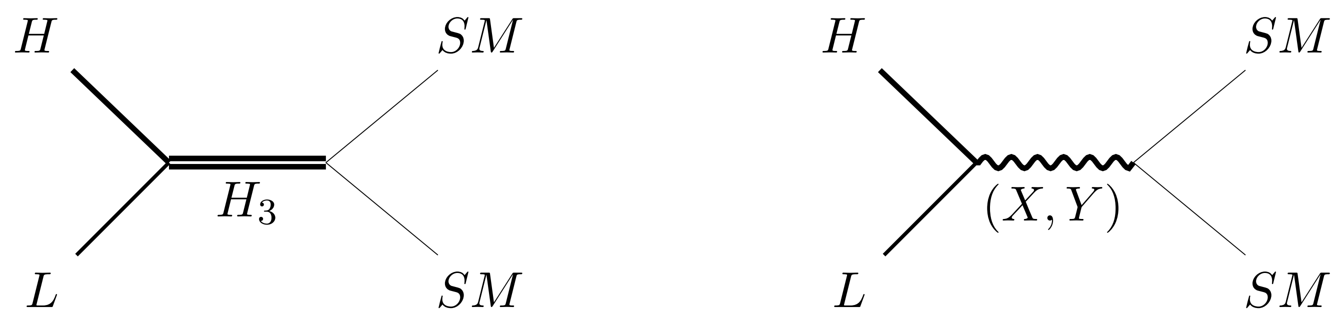
- Example: $Q \oplus \tilde{D} \to 10 \oplus 5$

  - GUT theory has 1 Yukawa $\mathcal{L}_Y = \bar{\psi}_{10}\phi_5^\dagger\psi_5 + h.c.$ hence no accidental species number

  - DM sector ($Q+\tilde{D}$) has 1 Yukawa $\mathcal{L}_Y = \bar{Q}H\tilde{D} + h.c.$ hence no accidental species number

  - Theory below MGUT has 3 more fields ($U+E+\tilde{L}$) and 1 more Yukawa $\mathcal{L}_Y \supset \bar{E}H\tilde{L}$

    Two accidental species numbers ($U(1)_{DL}, U(1)_U$), heavy hadrons are metastable and decay through D=6 operators generated at the GUT scale



Selecting Viable Theories

We select theories that satisfy the following criteria:

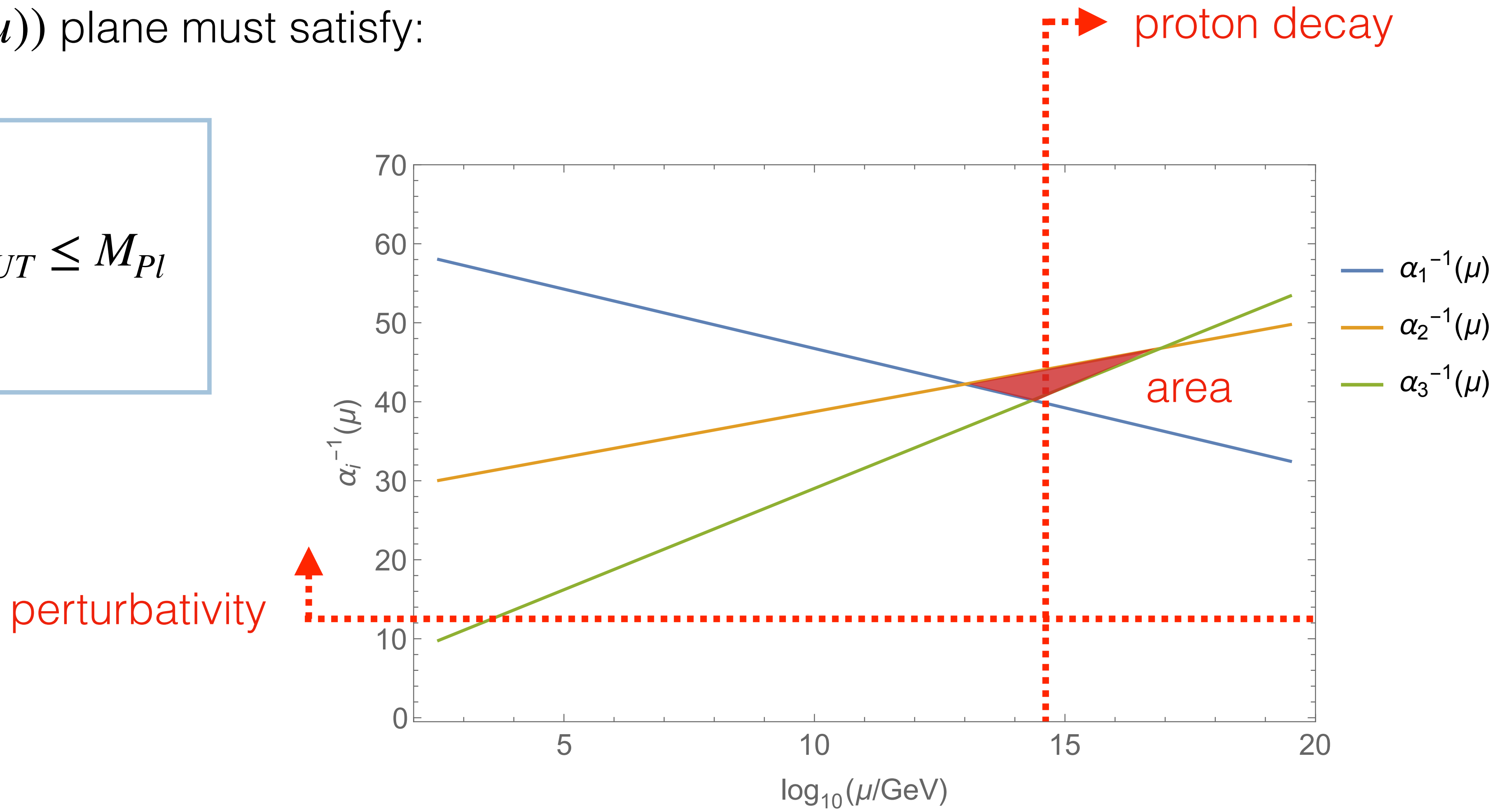
1. SU(N_{DC}) must confine
2. Light quark sector must contain a viable DM candidate
3. No Landau poles of $SU(5)_{GUT} \times SU(N_{DC})$ below M_{Pl}
4. Quality of unification as in the SM or better;

   Triangle in the $(\mu, \alpha^{-1}(\mu))$ plane must satisfy:

Area $\leq$ Area^{SM}

6.5×10^{14}GeV $\leq M_{GUT} \leq M_{Pl}$

$\alpha_{GUT} < 4\pi$



We find only two viable theories:

- $Q \oplus \tilde{D}$

  Minimal Parent theory: $10 \oplus 5$

  $7 \times 10^6 \text{GeV} < m_H < 5 \times 10^{14} \text{GeV}$

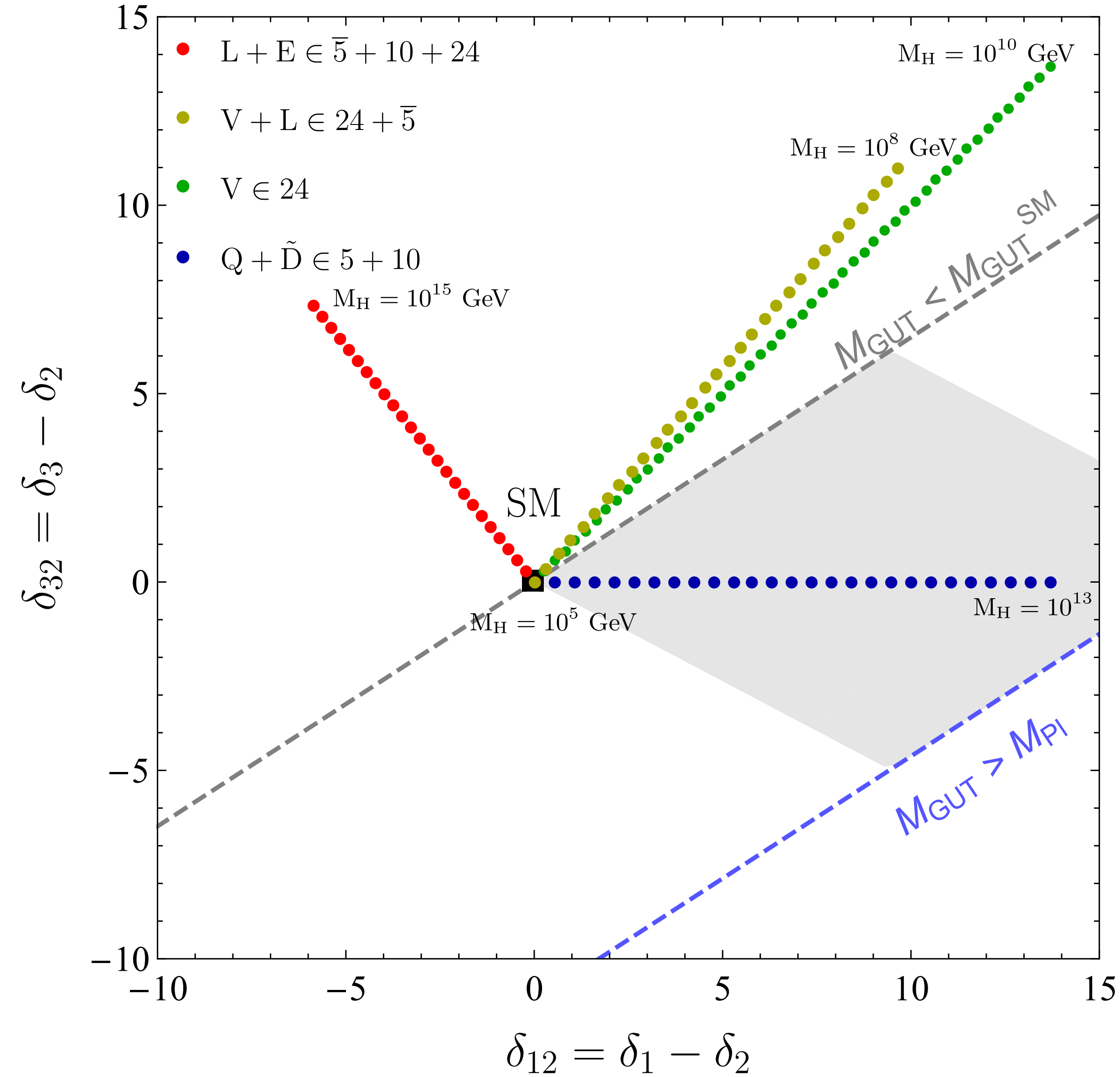
  Minimal Parent theory: $15 \oplus 5$

  $4 \times 10^{11} \text{GeV} < m_H < 5 \times 10^{14} \text{GeV}$

- N

  Minimal Parent theory: 24

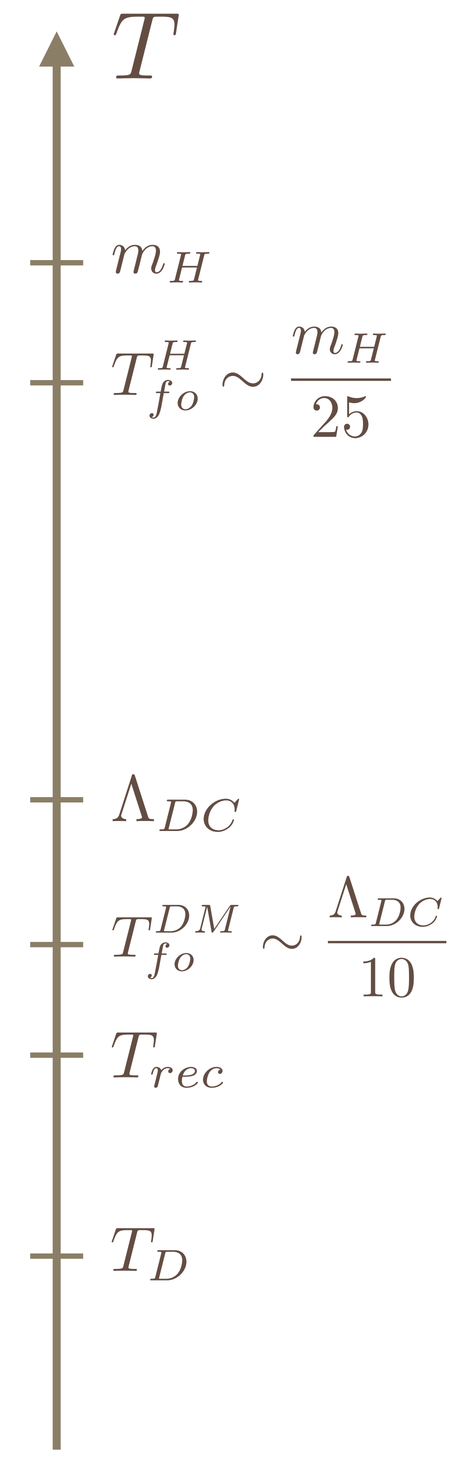
  $m_H > 10^9 \text{GeV}$



$$\alpha_i(\mu)^{-1} = \alpha_i(M_Z)^{-1} - \frac{b_i^{\text{SM}}}{2\pi} \log \frac{\mu}{M_Z} + \delta_i$$

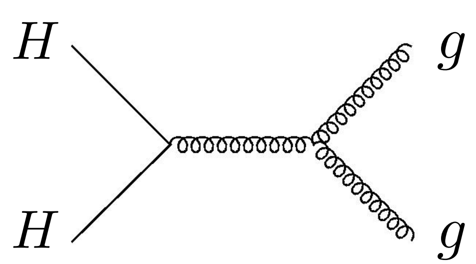
$$\delta_i = -\frac{\Delta\beta_i^L}{2\pi} \log \frac{\mu}{\Lambda_{DC}} - \frac{\Delta\beta^H}{2\pi} \log \frac{\mu}{m_H}$$

Thermal history of the dark color states

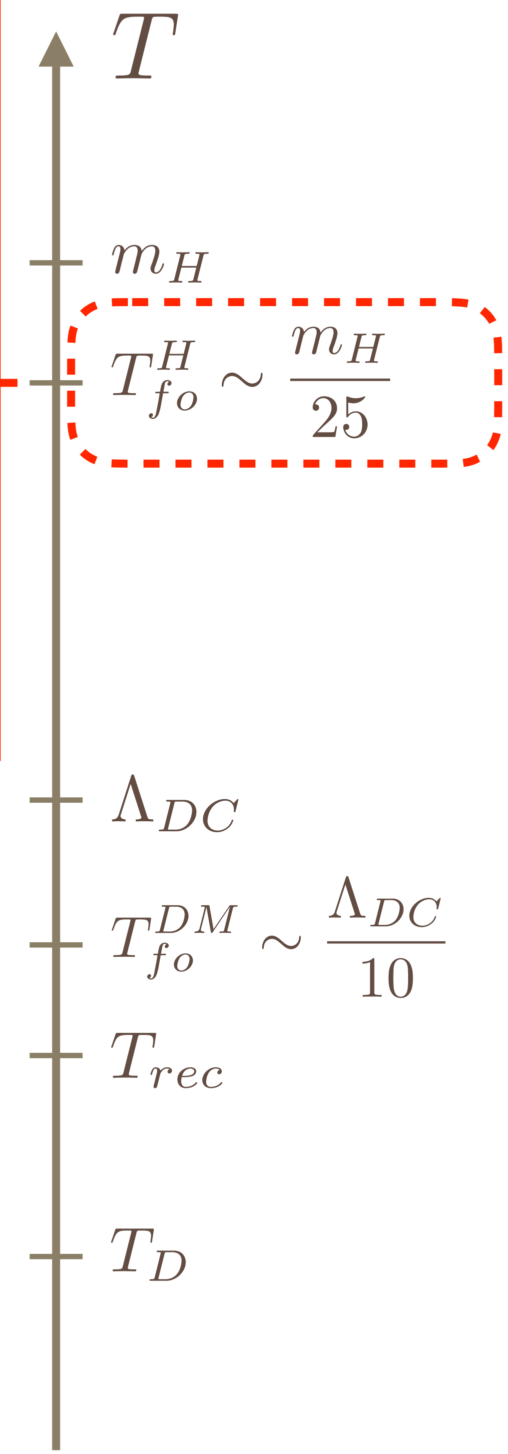


Thermal history of the dark color states

At $T \sim m_H/25$ heavy dark quarks undergo a first perturbative freeze out



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



perturbative freeze out of heavy dark quarks

Thermal history of the dark color states

At temperatures of order Λ_{DC} various types of dark color bound states are formed:

- Light hadrons

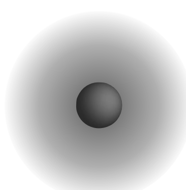
$LLL,\ L\bar{L}$

$r_0 \sim 1/\Lambda_{DC}$

$m \sim \Lambda_{DC}$

- Hybrid hadrons

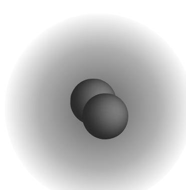
$HLL,\ H\bar{L}$ (type I)



$r_0 \sim 1/\Lambda_{DC}$

$m \sim m_H + O(\Lambda_{DC})$

HHL (type II)

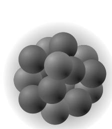


$r_0 \sim 1/\Lambda_{DC}$

$m \sim 2m_H + O\left(m_H \alpha_{DC}^2\right)$

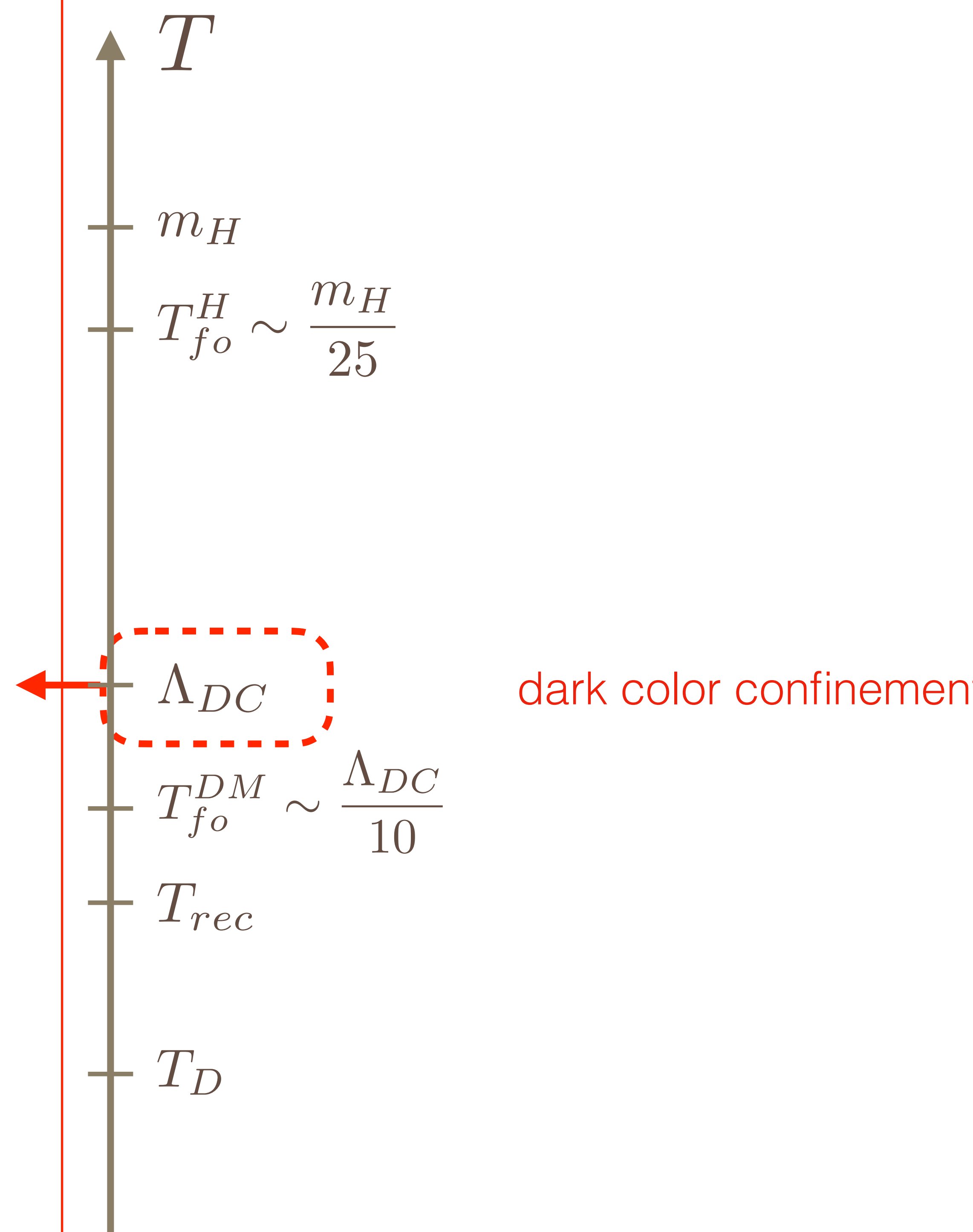
- Heavy (perturbative) hadrons

$HHH,\ \bar{H}H$ (type III)



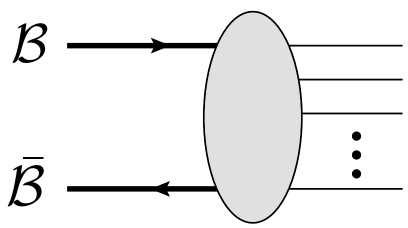
$r_0 \sim 1/(\alpha_{DC} m_H)$

$m \sim n\, m_H + O\left(m_H \alpha_{DC}^2\right)$



Thermal history of the dark color states

At $T \lesssim \Lambda_{DC}$ dark baryons have an epoch of annihilation into dark mesons with large non-perturbative cross section



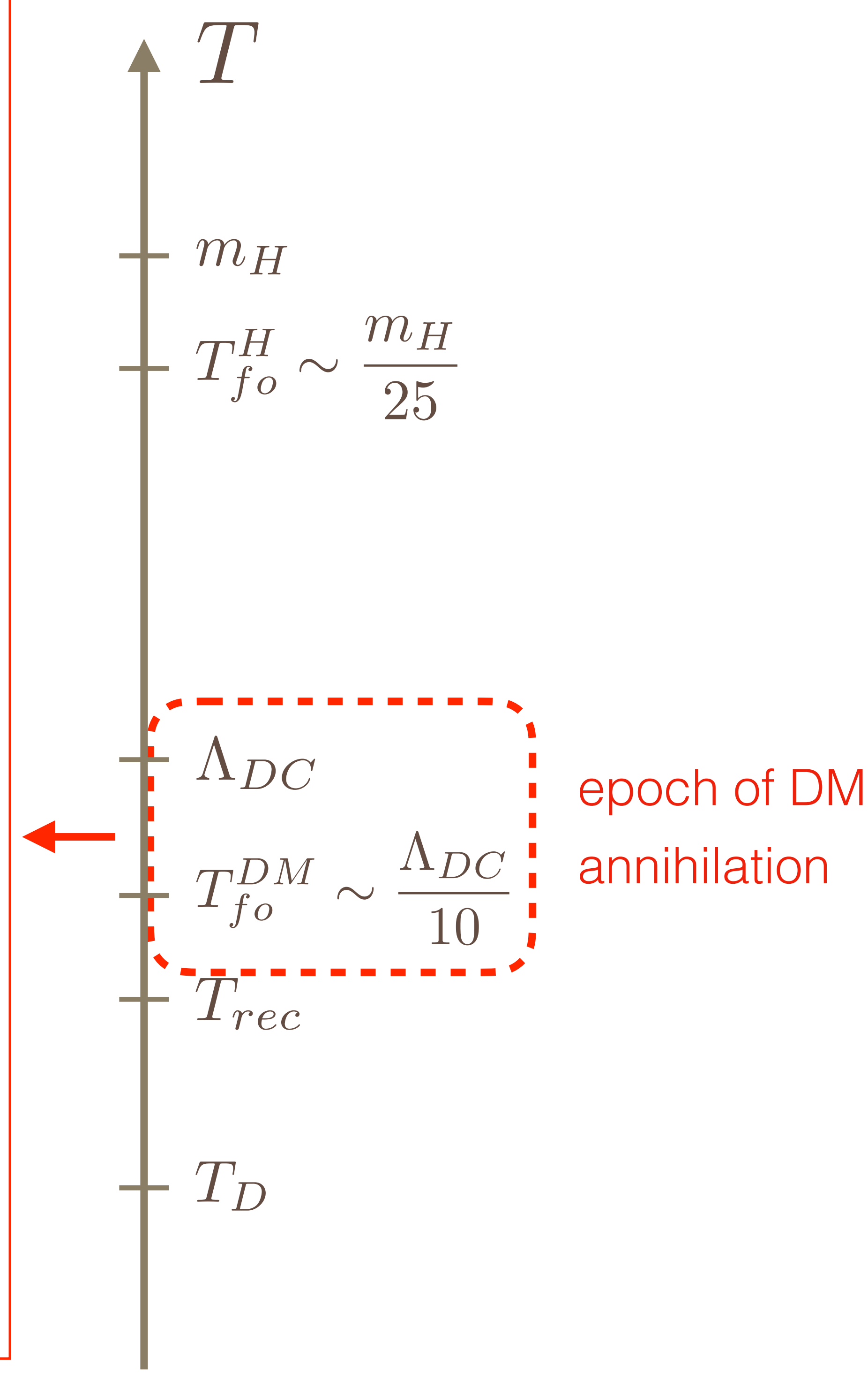
dark mesons

$$\langle \sigma_{B\bar{B}} v \rangle \sim \frac{\pi}{\Lambda_{DC}^2}$$

These reactions go out of equilibrium at temperatures $T \sim \Lambda_{DC}/10$ leaving a thermal abundance of DM

$$\Omega_{\mathcal{B}} \leq \Omega_{DM} \quad \Rightarrow \quad \Lambda_{DC} \lesssim 100\text{TeV}$$

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



Thermal history of the dark color states

For $T_{rec} \lesssim T \lesssim \Lambda_{DC}$ various reactions change the abundance of heavy hadrons:

- Recombination of Type-I hybrids

$$HLL + L\bar{L} \to H\bar{L} + LLL$$
$$HLL + \overline{LLL} \to H\bar{L} + n\, L\bar{L}$$

- Type-I + Type-I → Type-II

$$HLL + H\bar{L} \to (HHL)^* + n\, LL$$
$$HLL + \bar{H}L \to (H\bar{H})^* + LLL$$
$$HLL + HLL \to (HHL)^* + LLL$$
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- Type-II + Type-I → Type-III

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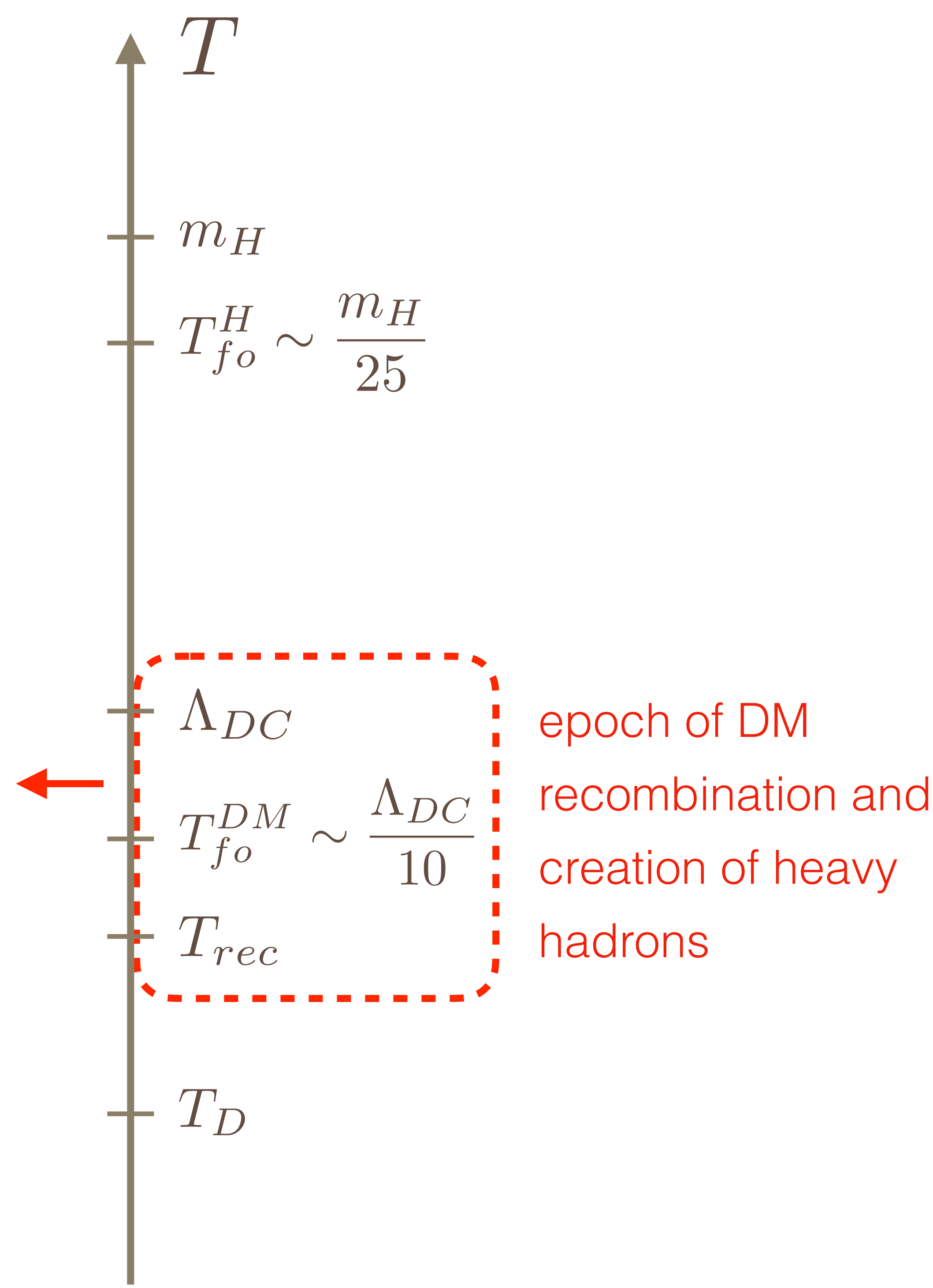
$$HHL + HLL \to (HHH)^* + LLL$$



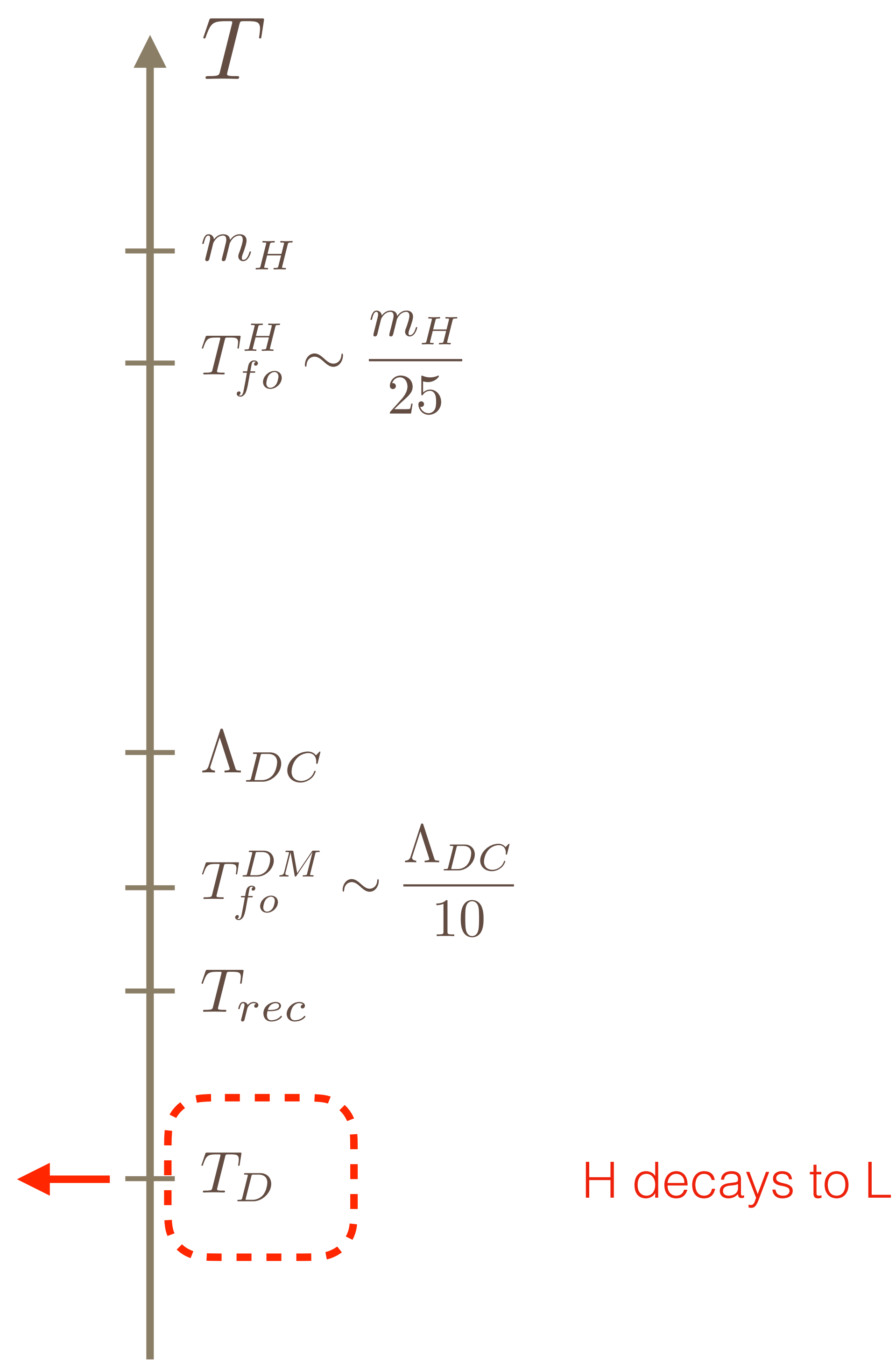
Thermal history of the dark color states

Heavy dark quarks H decay into L through D=6 operators generated at M_{GUT}

$$\Gamma_{H\to L} \sim \frac{g^4_{GUT}}{192\pi^3}\frac{m^5_H}{M^4_{GUT}}$$

- Decays occurring at $T_D > T^{DM}_{fo}$ do not affect the DM abundance
- Decays occurring after BBN are subject to strong constraints and excluded
- Decays occurring at $T_{BBN} < T_D < T^{DM}_{fo}$ give an extra non-thermal contribution to the DM abundance

$$Y_{DM} = Y^T_{DM} + e^{-t_{fo}/\tau_H}\cdot f_{\mathcal{B}}\cdot Y_H$$



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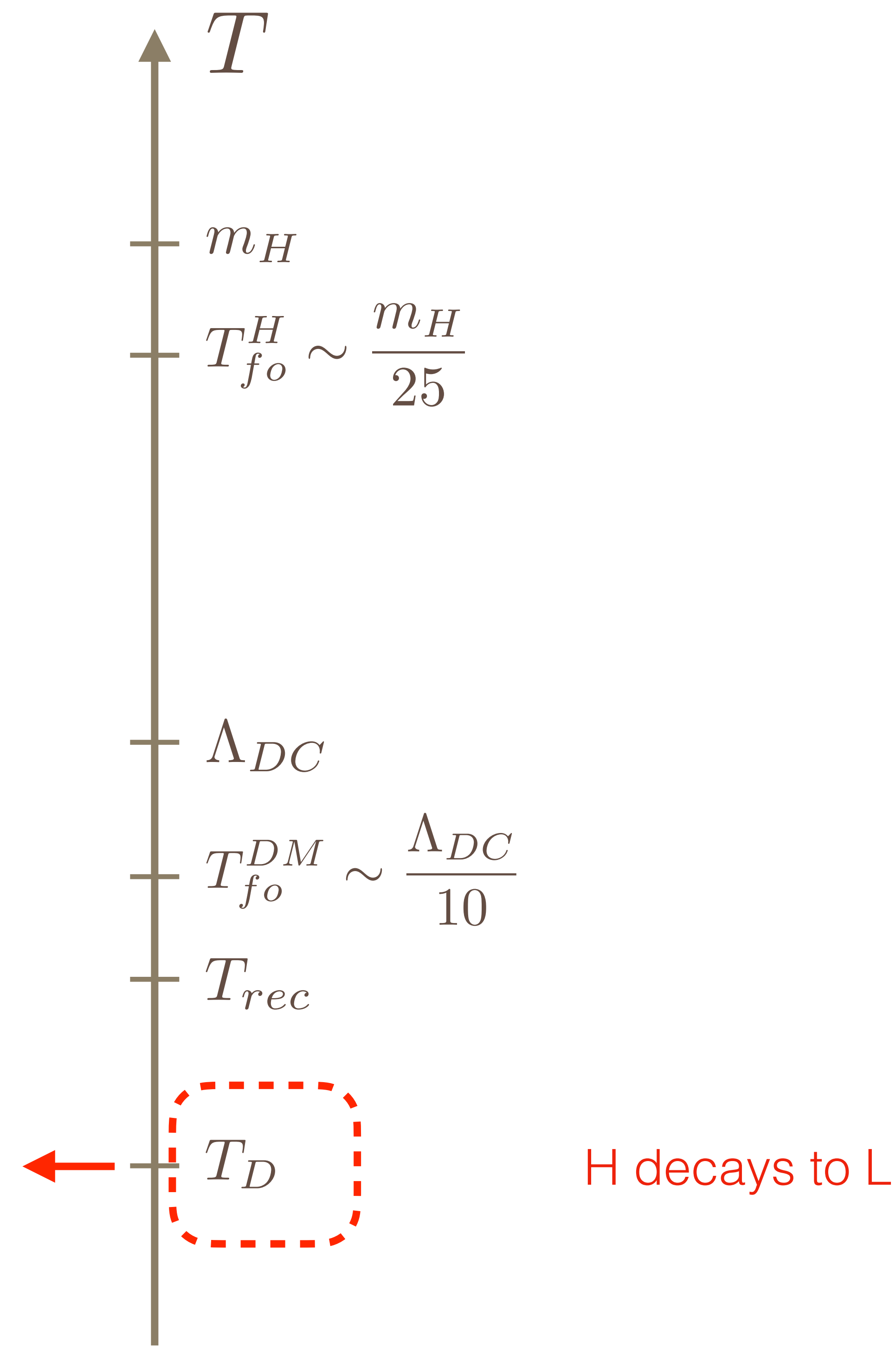
DM thermal aboundance



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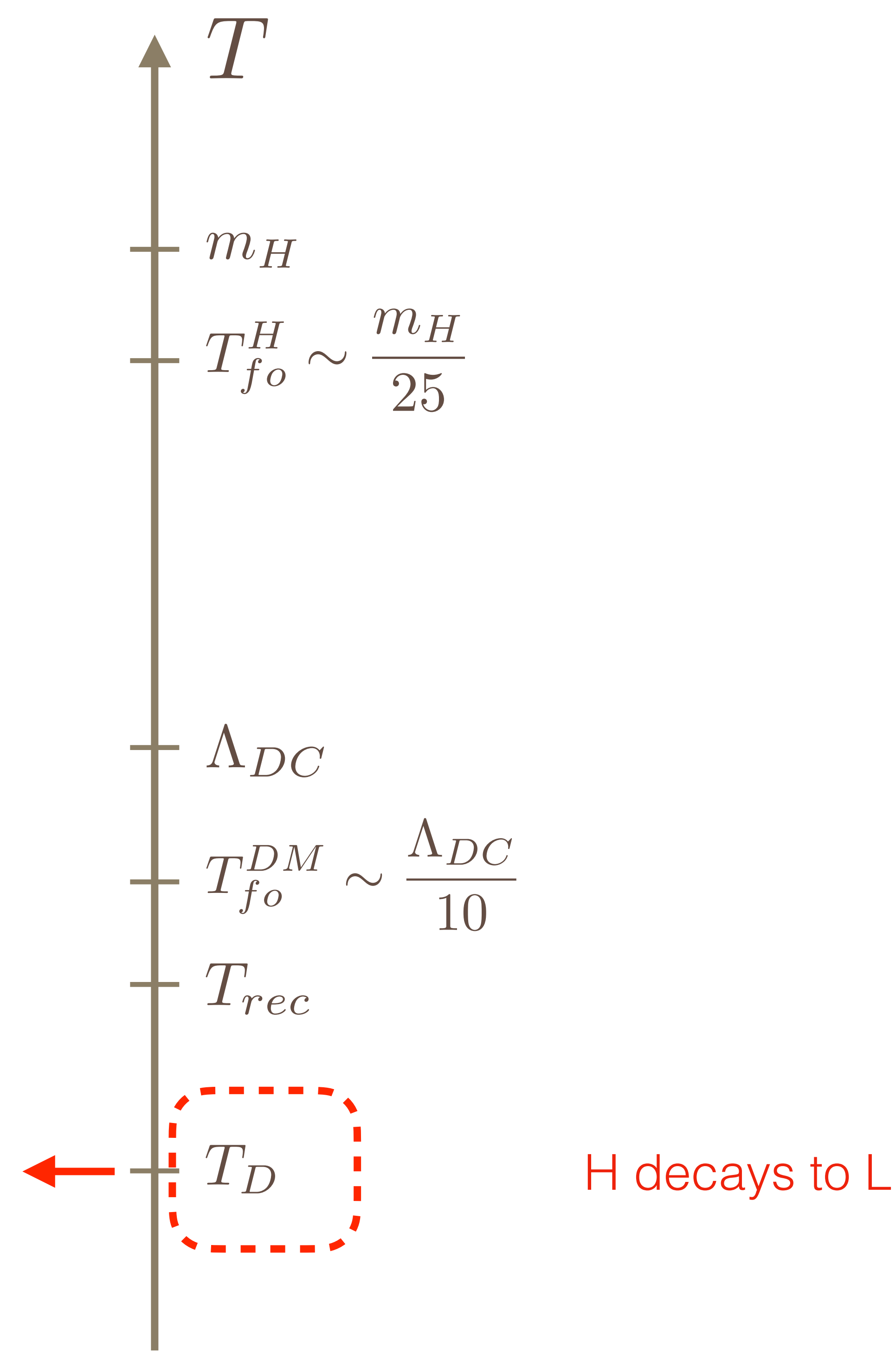
DM thermal aboundance

fraction of heavy baryons over all heavy hadrons at end of recombination



Non-thermal contribution to DM from recombination and decays of heavy hadrons can be much larger than the thermal one and overclose the Universe

$$Y_{DM} = Y_{DM}^{T} + e^{-t_{fo}/\tau_H} \cdot f_{\mathcal{B}} \cdot Y_H$$

$$Y_H \sim \frac{x_{fo}^H}{M_{Pl} m_H \sigma_H} \sim \frac{25\, m_H}{\pi M_{Pl} \alpha_{DC}^2}$$

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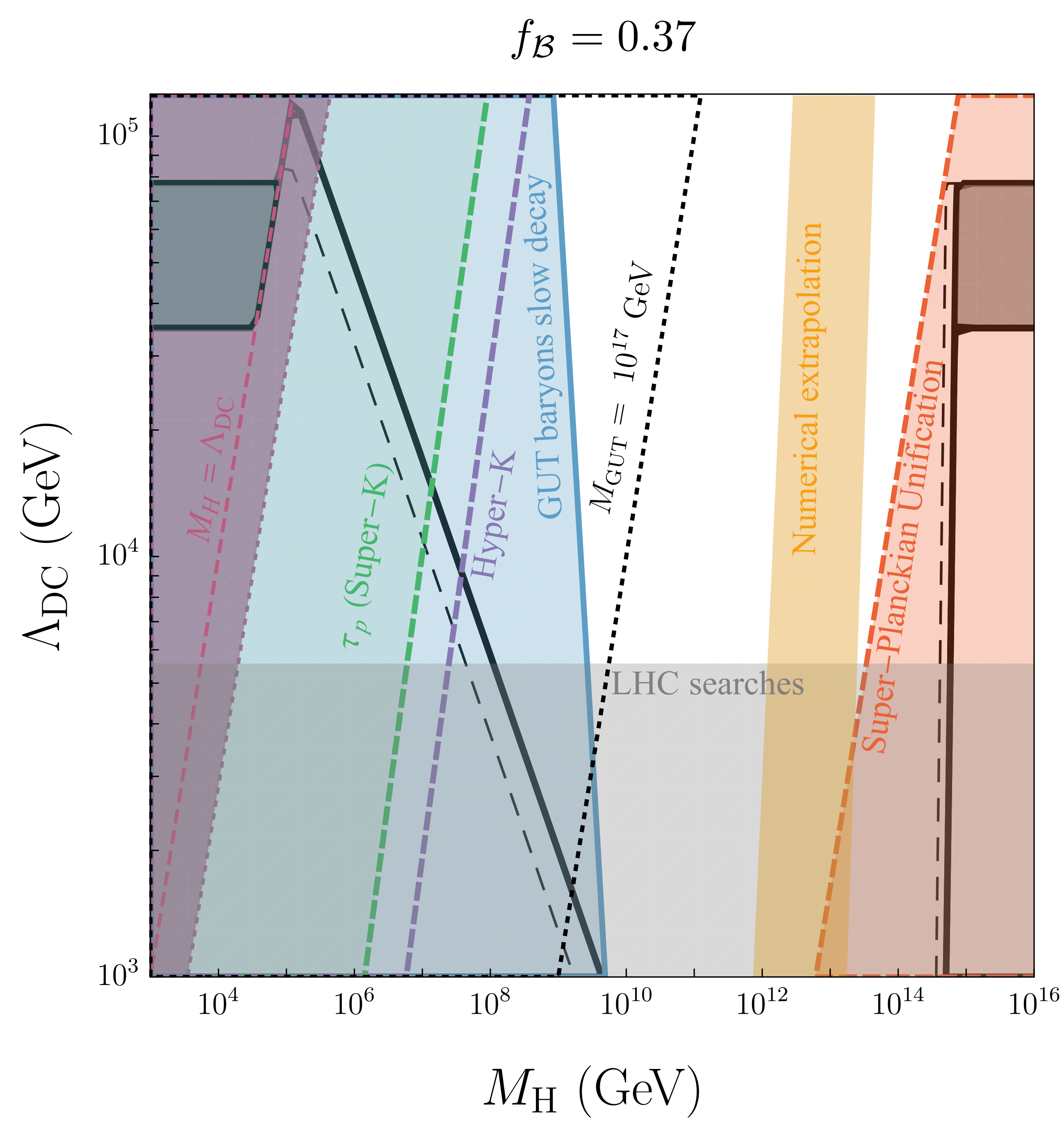

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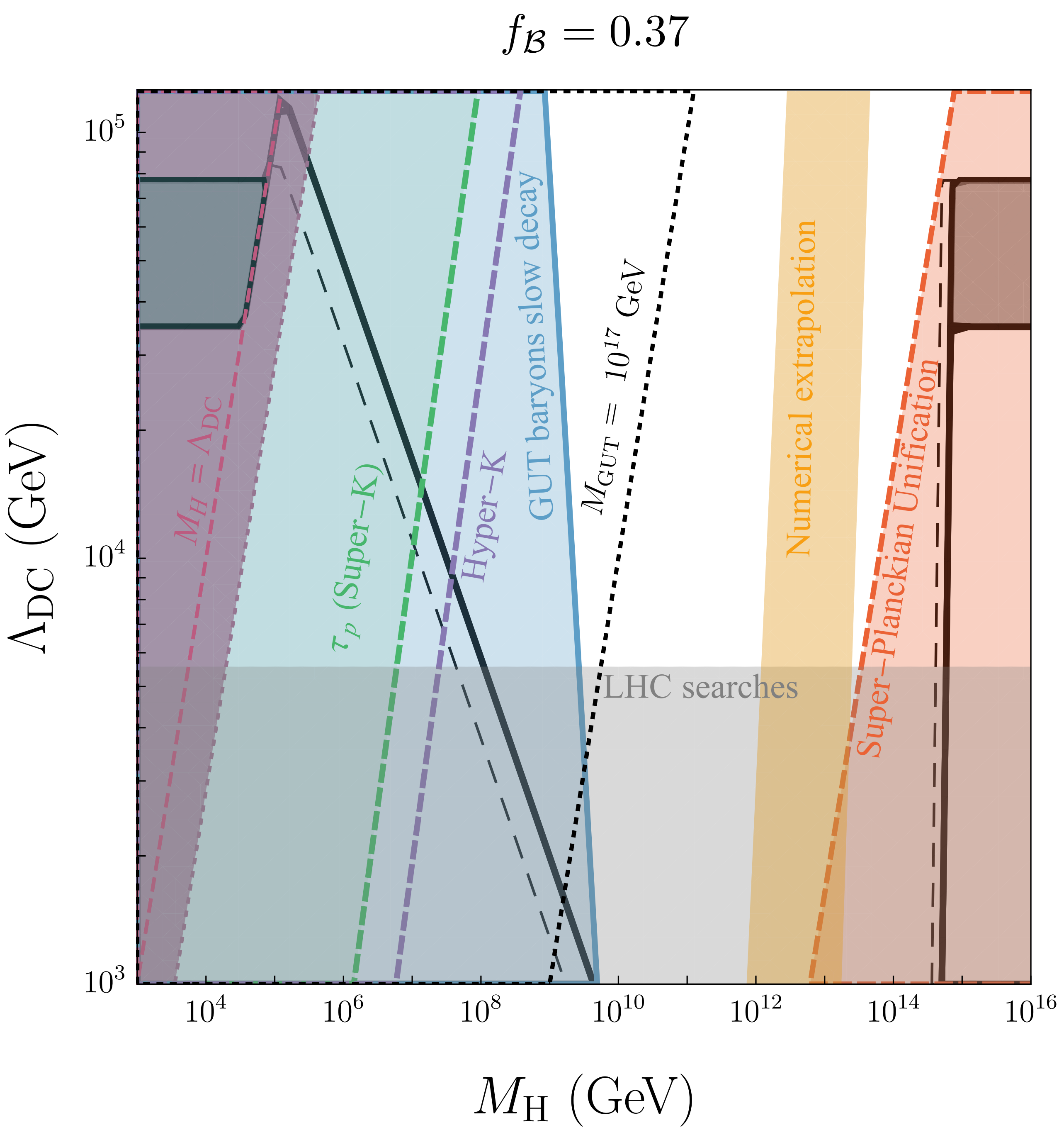

☞ **Moral**: model excluded unless reheating temperature is lower than m_H, so that sector of heavy dark quarks is not populated

Conclusions

- Accidental DM + SU(5) GUT realized by very few models, among which:
  - $SU(3)_{DC}, \quad \Psi = Q \oplus \tilde{D} \to 10 \oplus 5$ / $15 \oplus 5$
  - $SU(3)_{DC}, \quad \Psi = N \to 24$
  - $SU(3)_{DC}, \quad \Psi = L \oplus E \to \bar{5} \oplus 10 \oplus 5 \oplus 24$ (with split heavy quark spectrum)
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- Dark confinement scale $\Lambda_{DC} \simeq 100\,\mathrm{TeV}$ too large to produce dark hadrons at colliders. Potentially observable signals (indirect detection): i) DM decays via D=6 operators; ii) DM annihilations

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- Study the case in which the light dark quarks have mass larger than the dark dynamical scale, $m_L > \Lambda_{DC}$