

Accidental composite dark matter in $SU(5)$ -GUT theories

SM as guiding principle

Standard Model

- Accidental global symmetries arise in IR
- Example: proton stability $U(1)_B$ baryon number

DM stability due to an accidental symmetry like baryons in SM

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Minimal Extension

 $\mathcal{G}_{\text{SM}}$

Standard Model

+

 $\mathcal{G}_{\text{DC}}$

Dark Color

- Accidental global symmetries arise in IR
- Example: proton stability $U(1)_B$ baryon number

DM stability due to an accidental symmetry like baryons in SM

- $\psi_{\text{dark}} \equiv (R_{\text{DC}}, R_{\text{SM}})$
- Vector-like fermions: anomaly cancellation + mass term

[Kilic, Okui, Sundrum 2010]

[Antipin, Redi, Strumia, Vigianni 2015]

[Mitrdate, Redi, Smirnov, Strumia 2017]

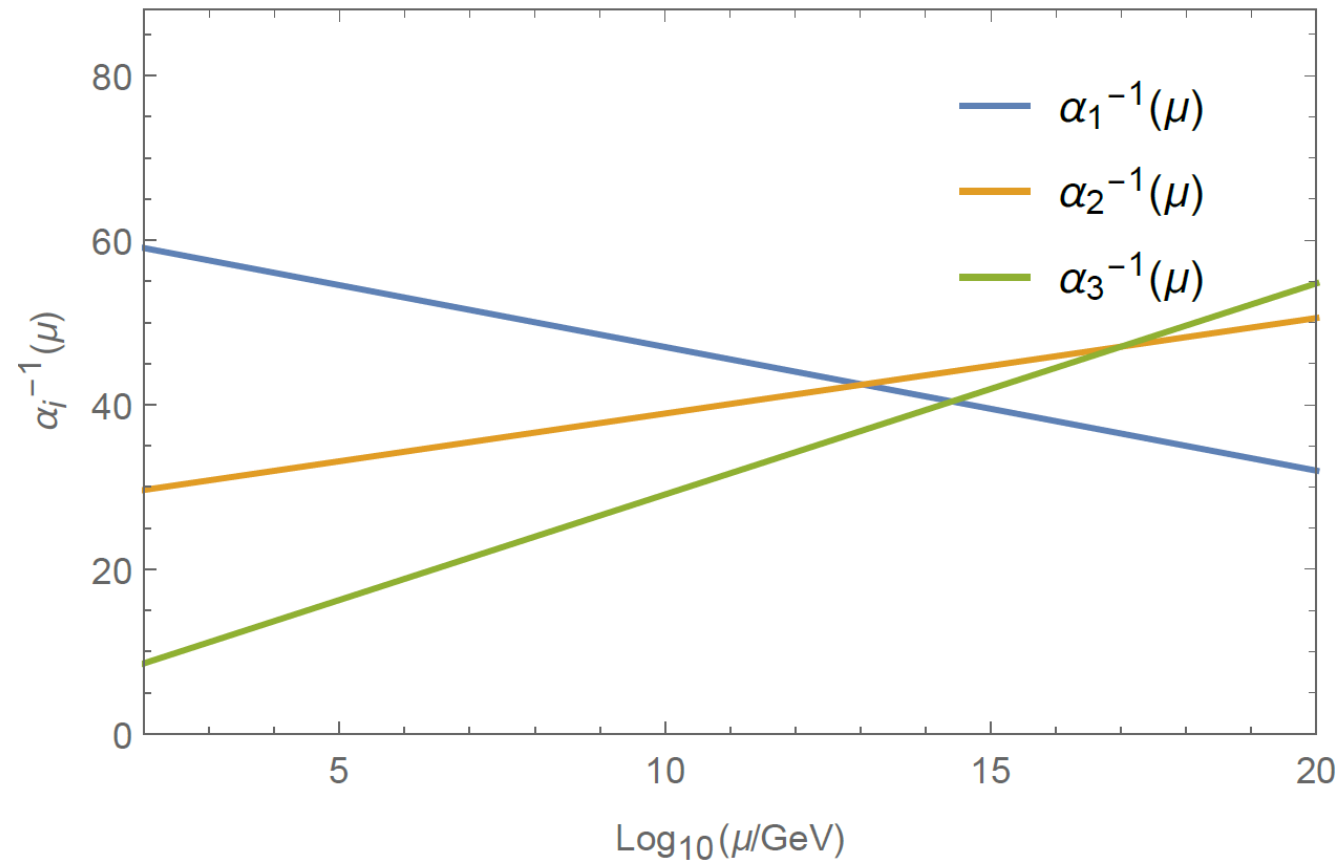
For chiral dark fermions, see for example:

[Contino, Podo, Revello 2020]

Coincidence or GUT?

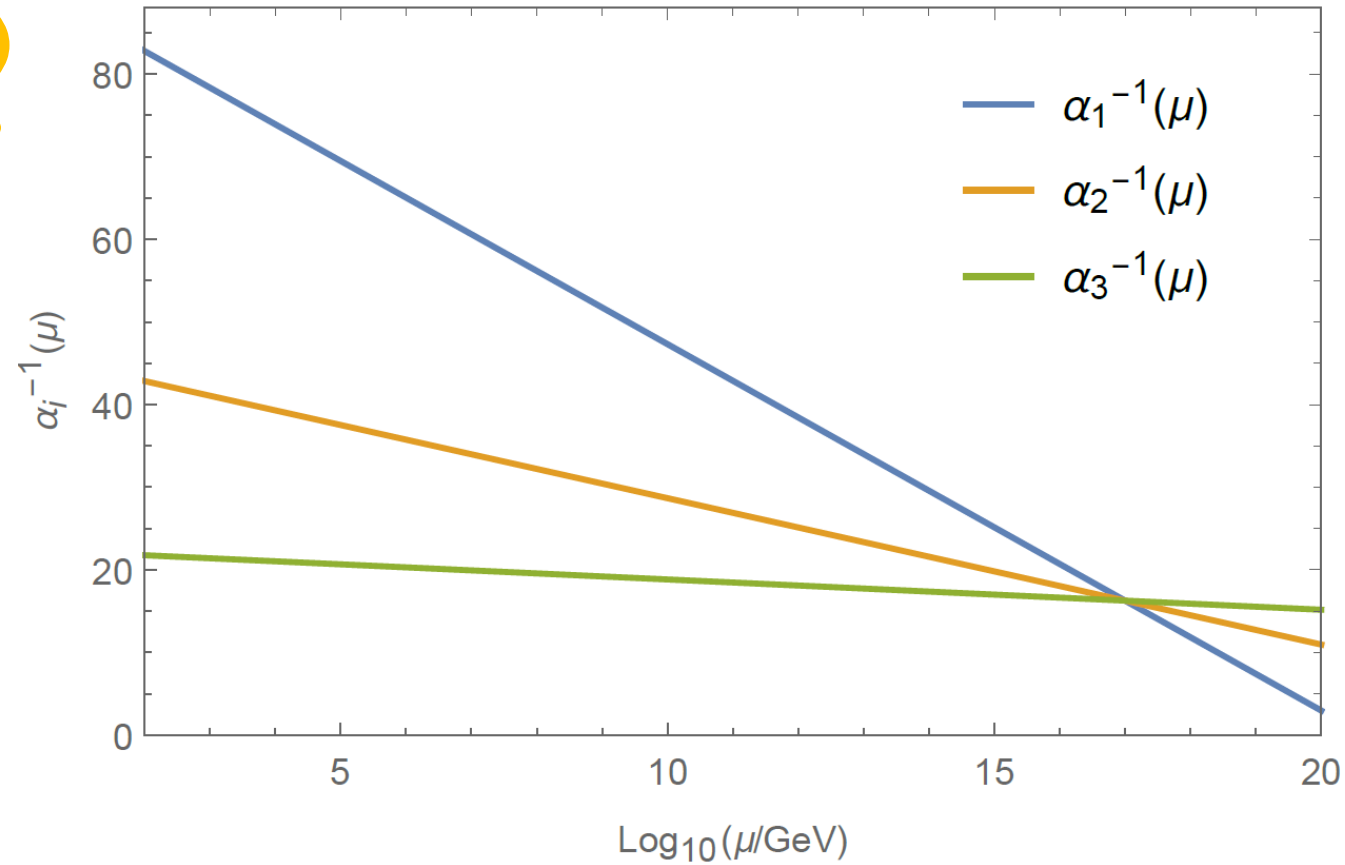
In the SM, $SU(3) \times SU(2) \times U(1)$ couplings seem to come very close at a scale $\sim 10^{14}$ GeV

SM only



Coincidence or GUT?

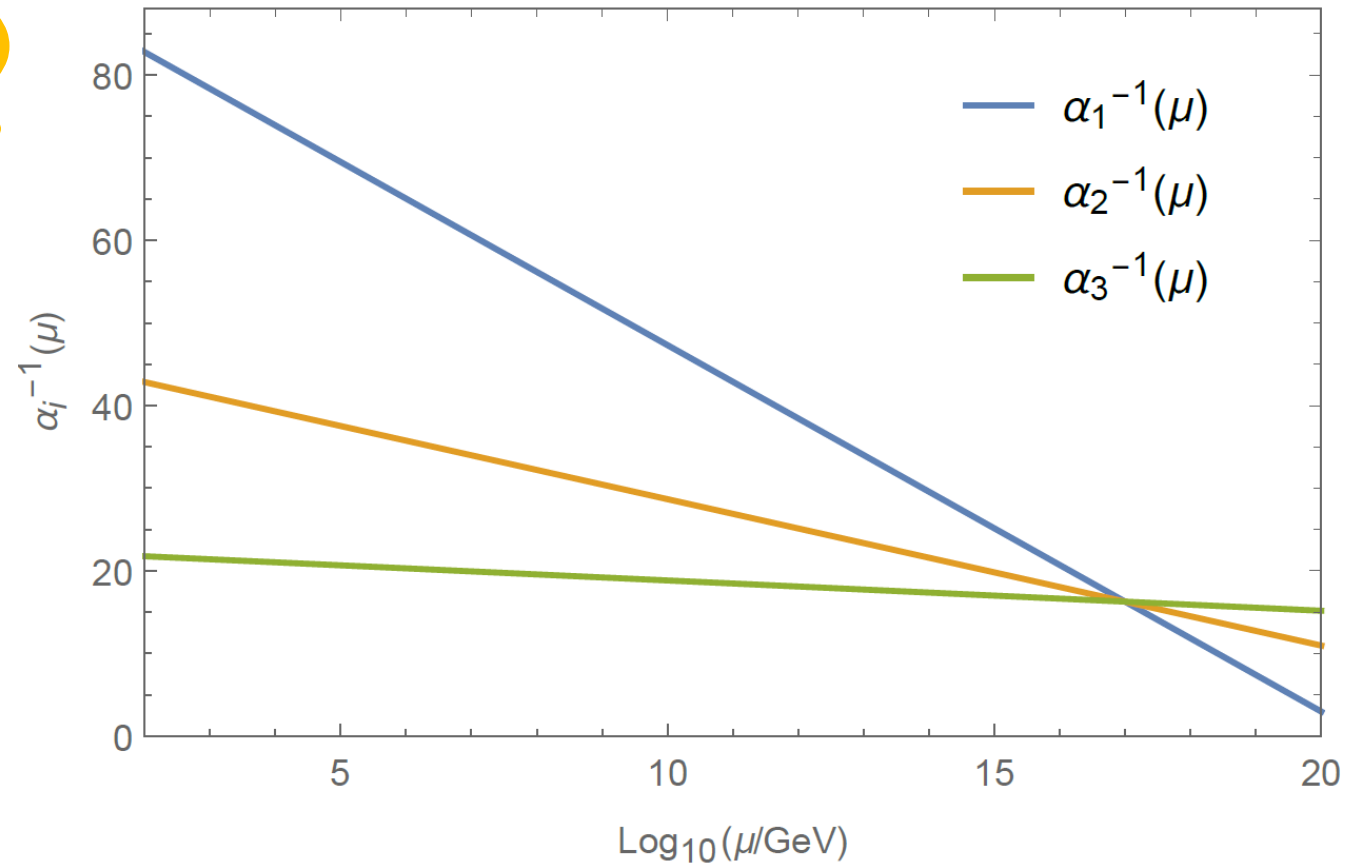
**SM + (some)
dark quarks**



Coincidence or GUT?

Could dark quarks give us both better unification and a stable composite DM candidate?

**SM + (some)
dark quarks**



Motivations?

[Antipin, Redi, Strumia, Vigiani 2015]

- $\psi_{\text{dark}} \in \mathcal{G}_{\text{SM}}$, embed in $SU(5)$

'light dark fermions' $m_\psi \lesssim \Lambda_{\text{DC}} \sim 100 \text{ TeV}$

Dark confinement scale

- Lightest dark baryons: DM candidate

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Bottaro, Contino, SV [In preparation]

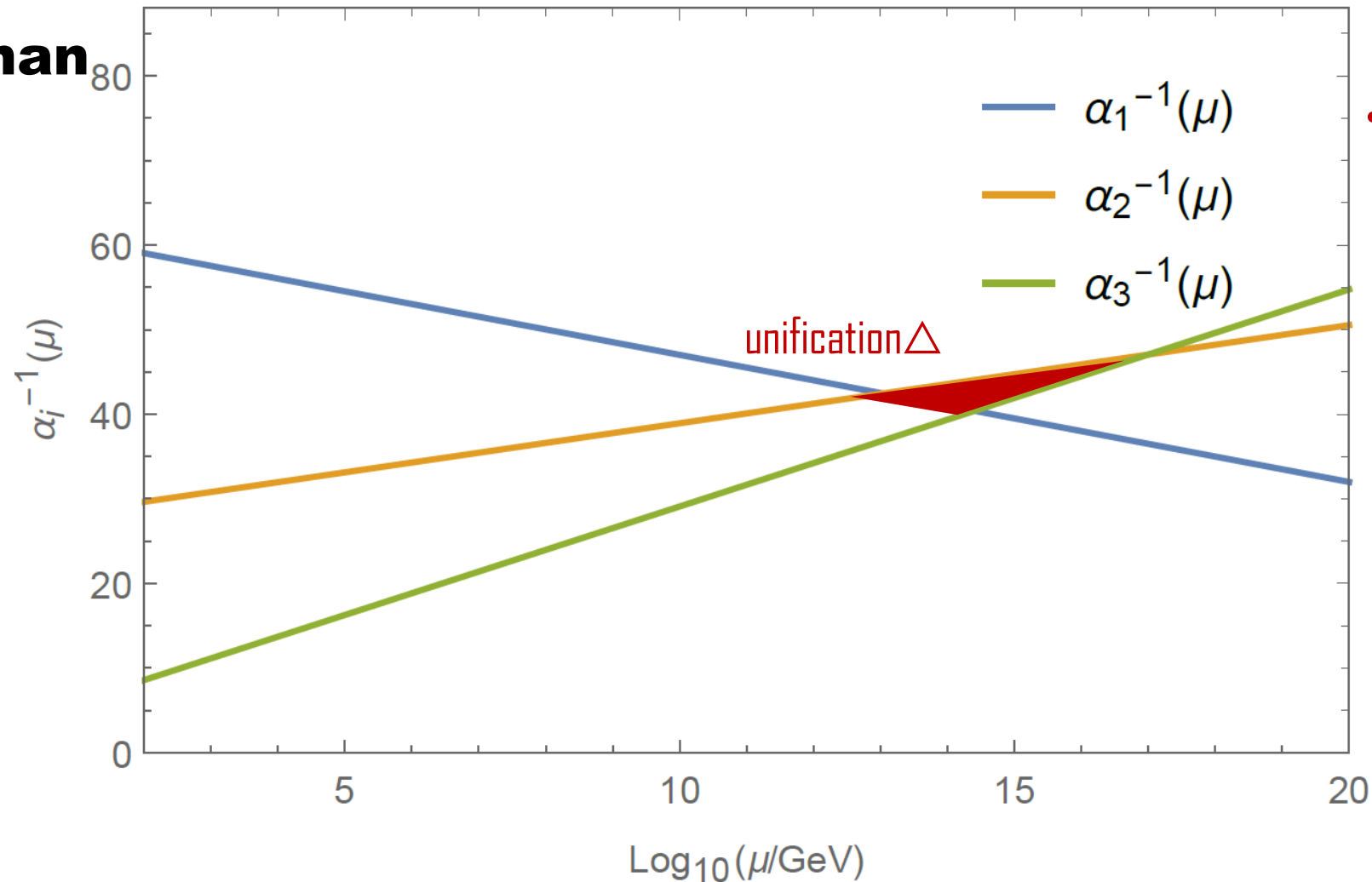
Can we find an $SU(5)$ GUT UV-completion to embed composite dark matter models giving accidentally stable DM?

Unification for millennials?

Bottaro, Contino, SV [In prep]

Optimistic and relaxed strategy for scanning for models...we do not want to exclude SM

**Better than
SM only**



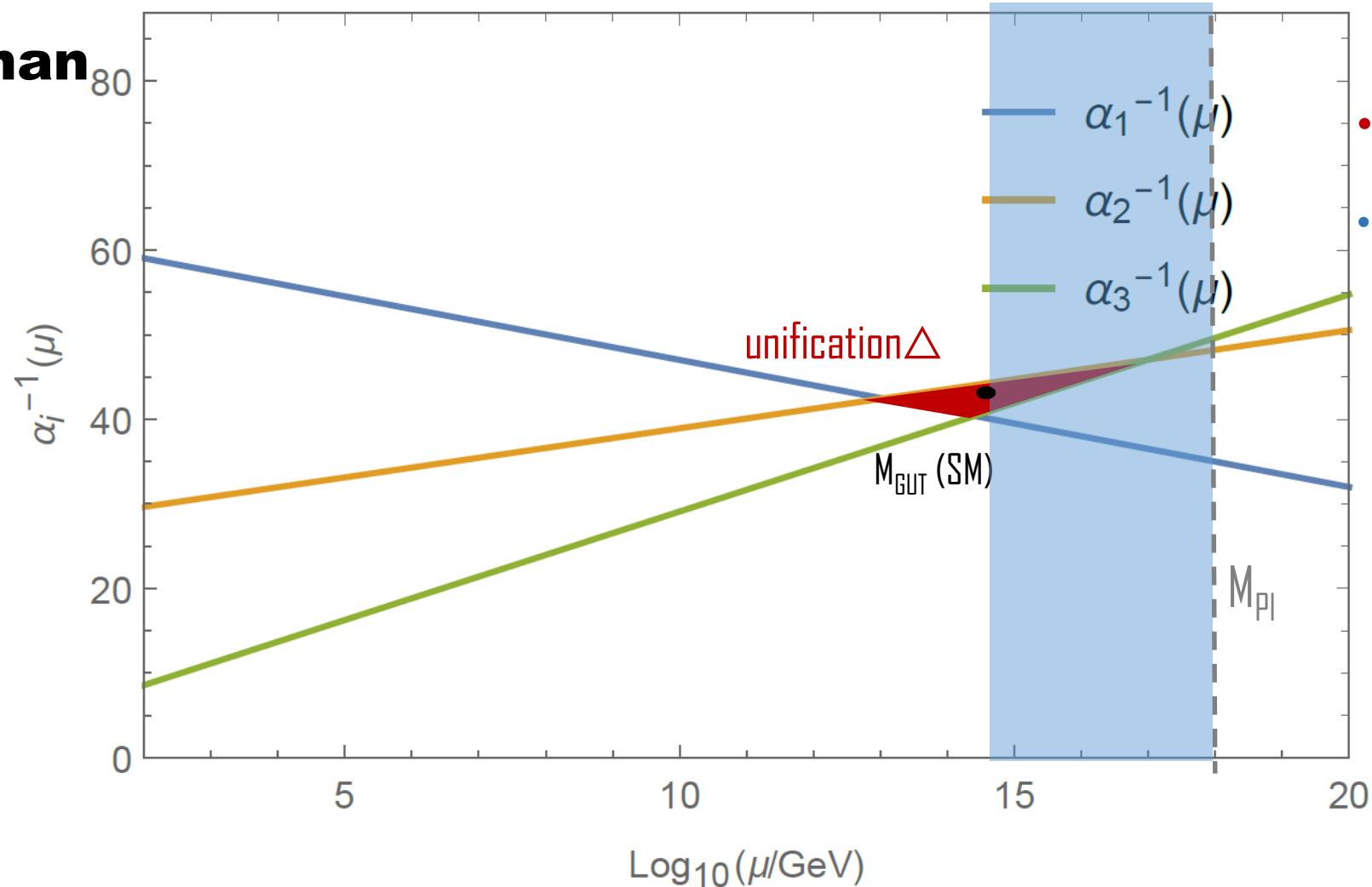
• $\text{Area}_{\Delta}(\text{SM+BSM}) \leq \text{Area}_{\Delta}(\text{SM})$

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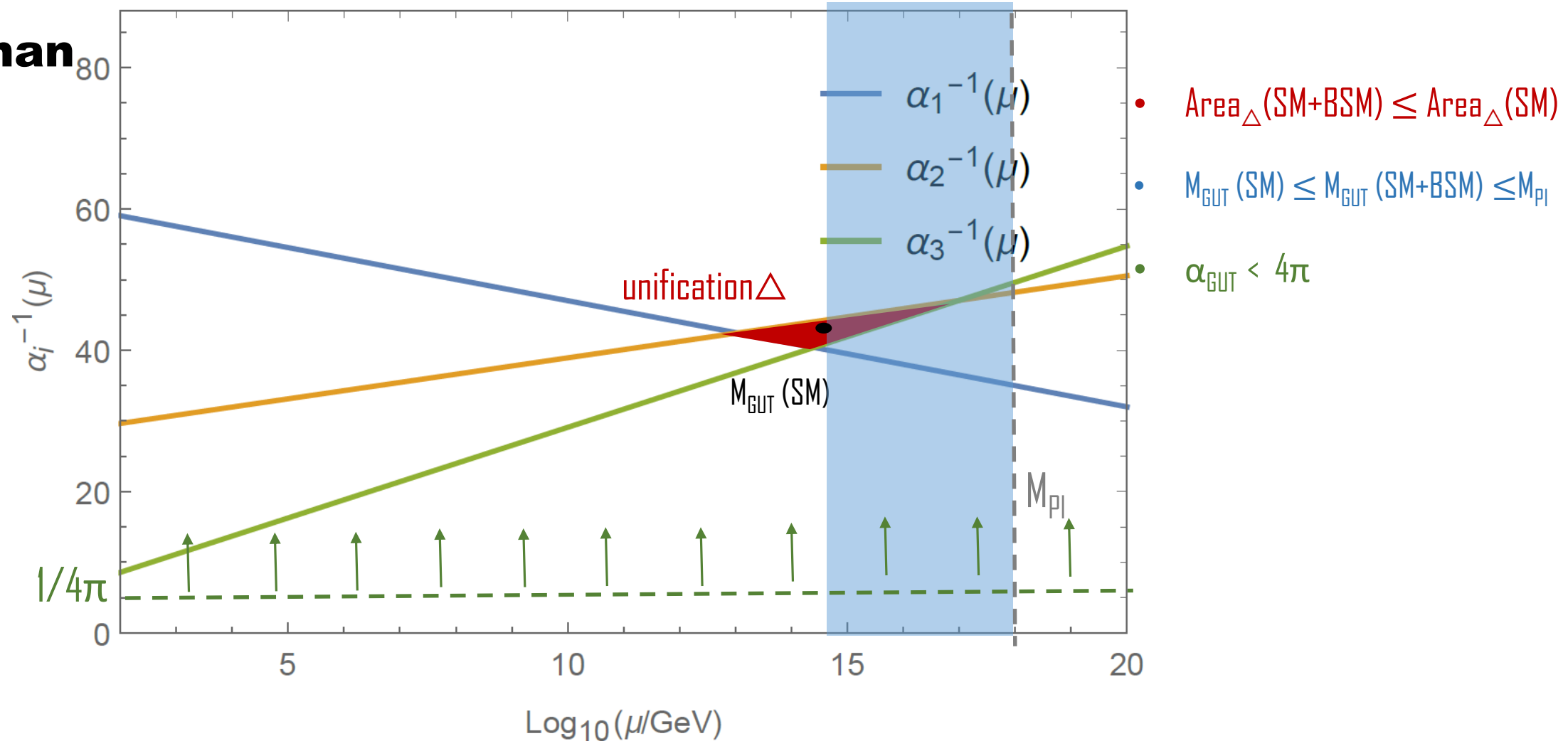
• $M_{\text{GUT}}(\text{SM}) \leq M_{\text{GUT}}(\text{SM}+\text{BSM}) \leq M_{\text{Pl}}$

Unification for millennials?

Bottaro, Contino, SV [In prep]

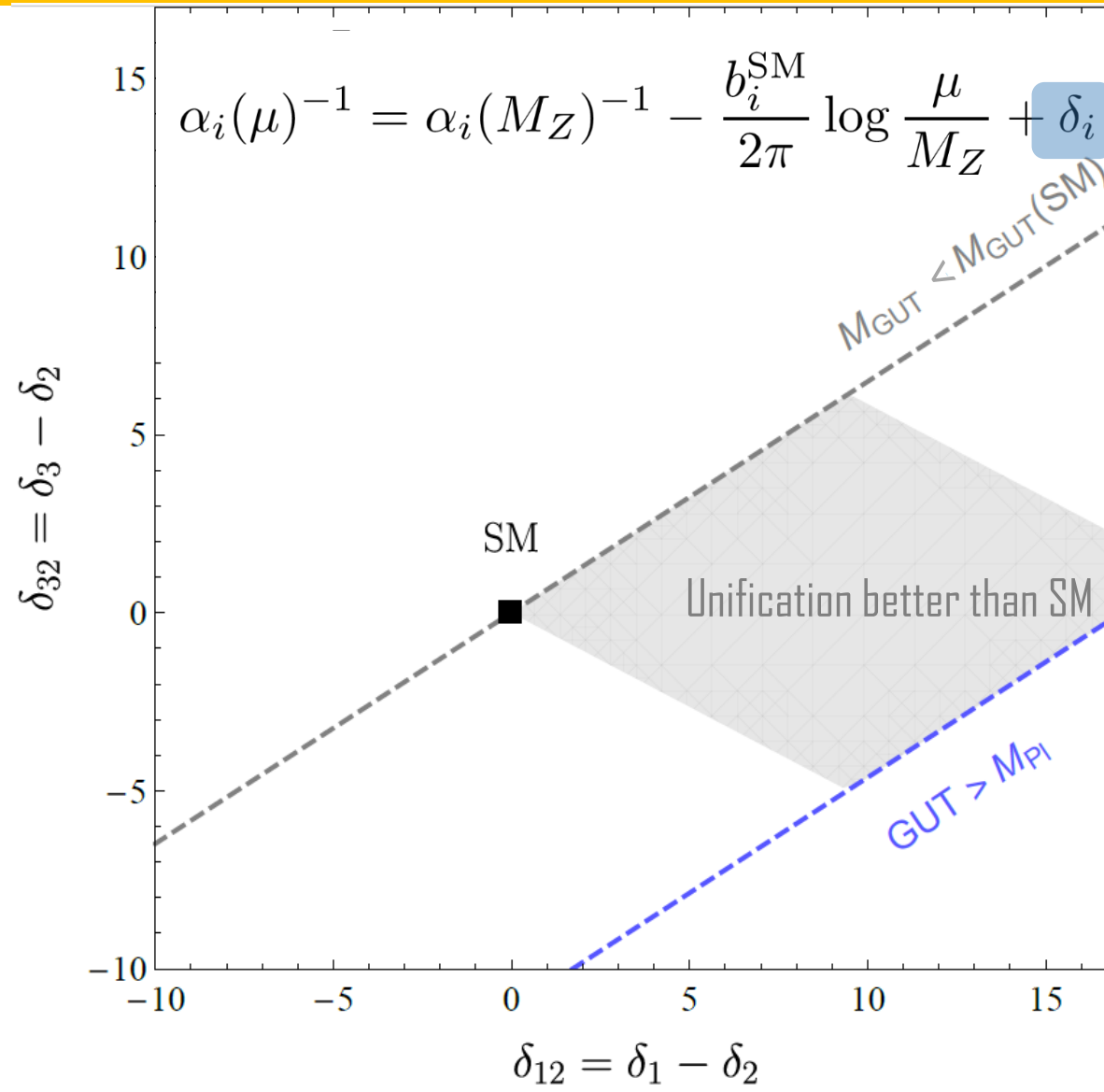
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Good models?

Bottaro, Contino, SV [In prep]

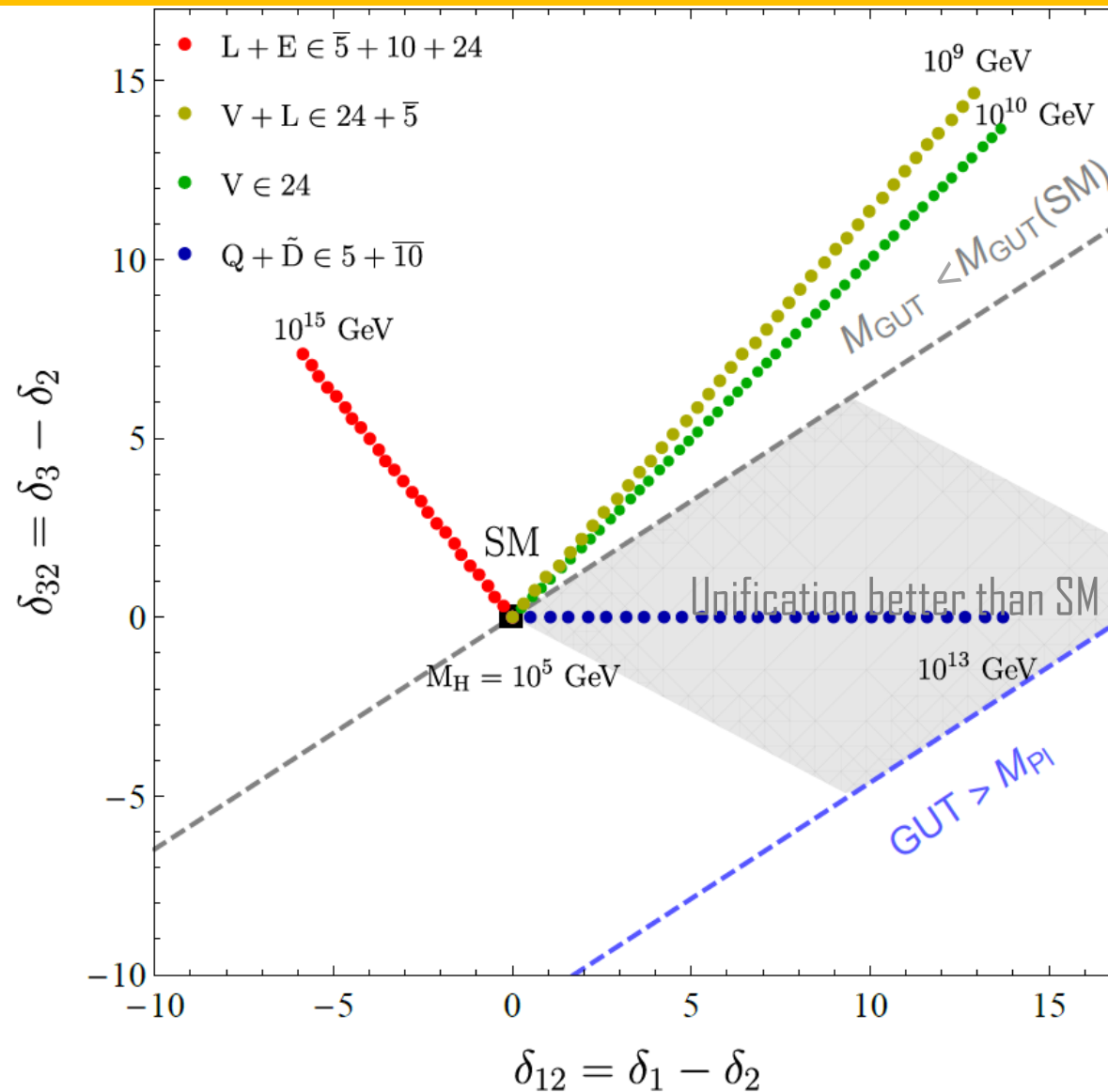


NP running
contribution to
SM couplings

Good models?

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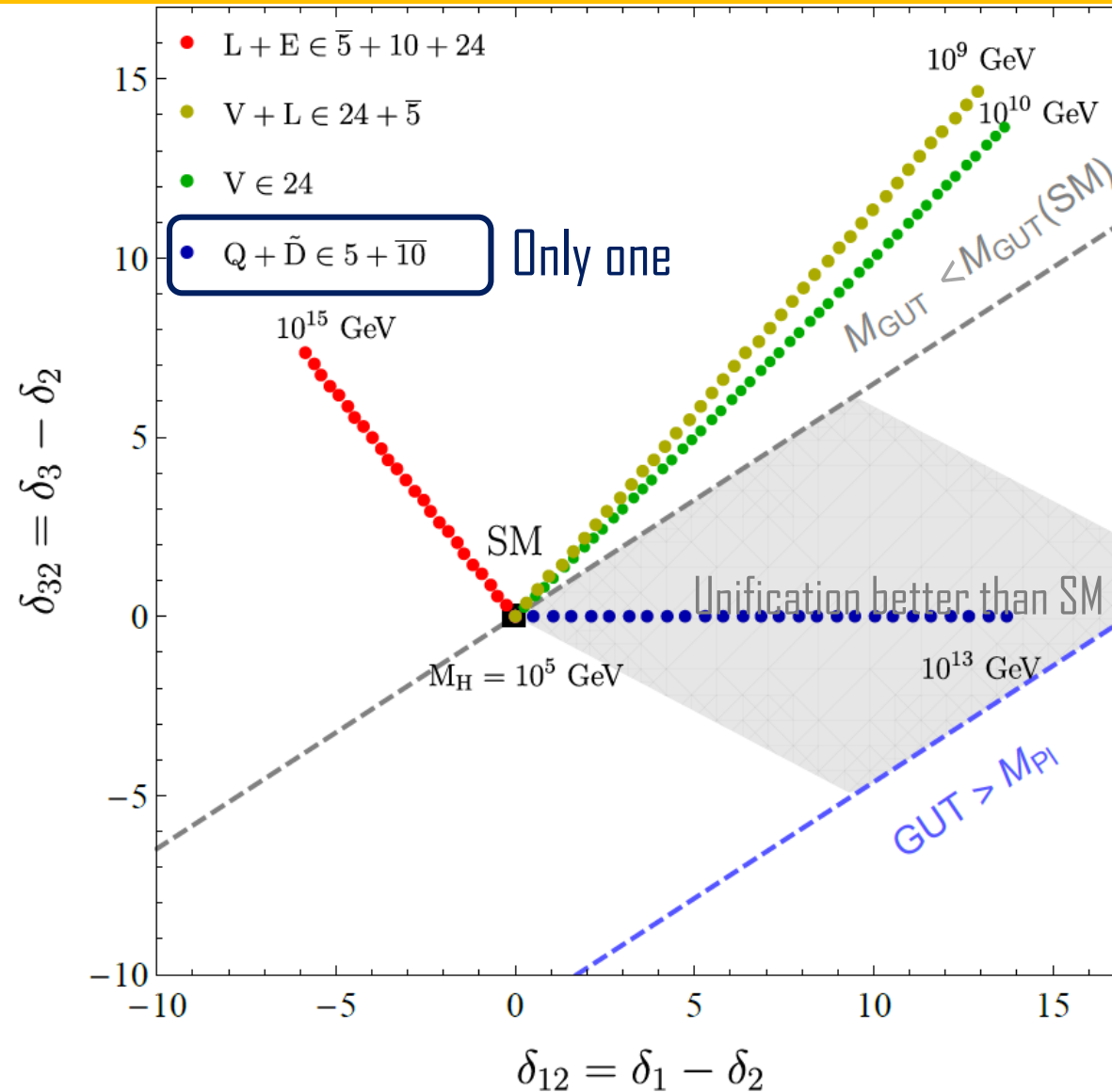
$SU(3)_{DC}$



Good models?

Bottaro, Contino, SV [In prep]

$SU(3)_{DC}$



More accidental symmetries?

Bottaro, Contino, SV [In prep]

$$SU(3)_{DC} \quad Q + \tilde{D} \quad 5 = \begin{bmatrix} \tilde{D} \\ \tilde{L} \end{bmatrix} \quad 10 = \begin{bmatrix} U & Q \\ & E \end{bmatrix} \quad \begin{aligned} H &= U, E, \tilde{L} \\ L &= Q, \tilde{D} \end{aligned}$$

M_{GUT}

Intermediate energy

$\Lambda_{DC} < M < M_{GUT}$

3 more species

$U, E, \tilde{L}$

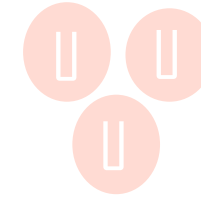
New accidental symmetries!

$U(1)_U$ U number

$U(1)_{DL}$ Dark lepton number

Broken at dim-6 level

e.g.



Dangerous stable states

Stable due to new accidental $U(1)_U$

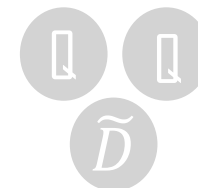
Low energy

$m \lesssim \Lambda_{DC} \sim 100 \text{ TeV}$

2 species

$Q, \tilde{D}$

$U(1)_{DB}$
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Baryonic DM

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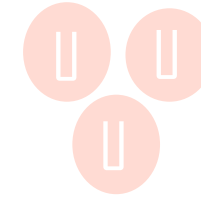
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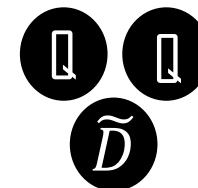
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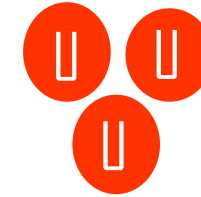
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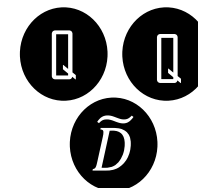
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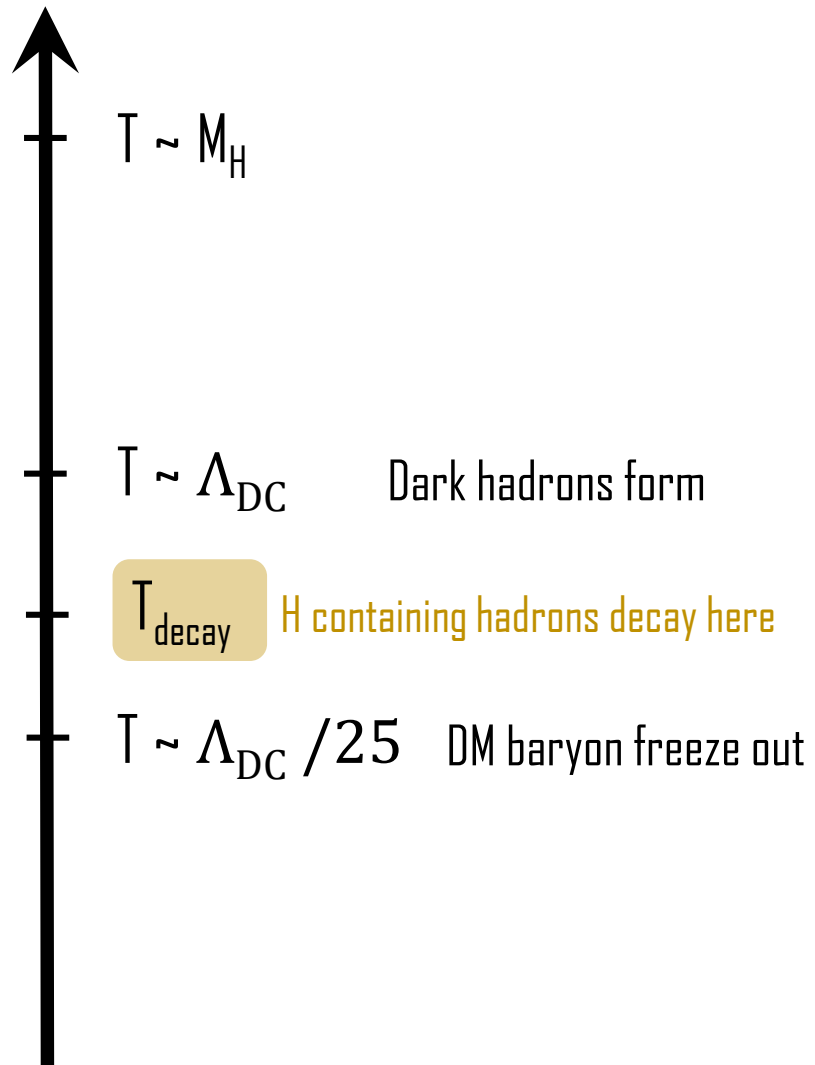


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Thermal history?

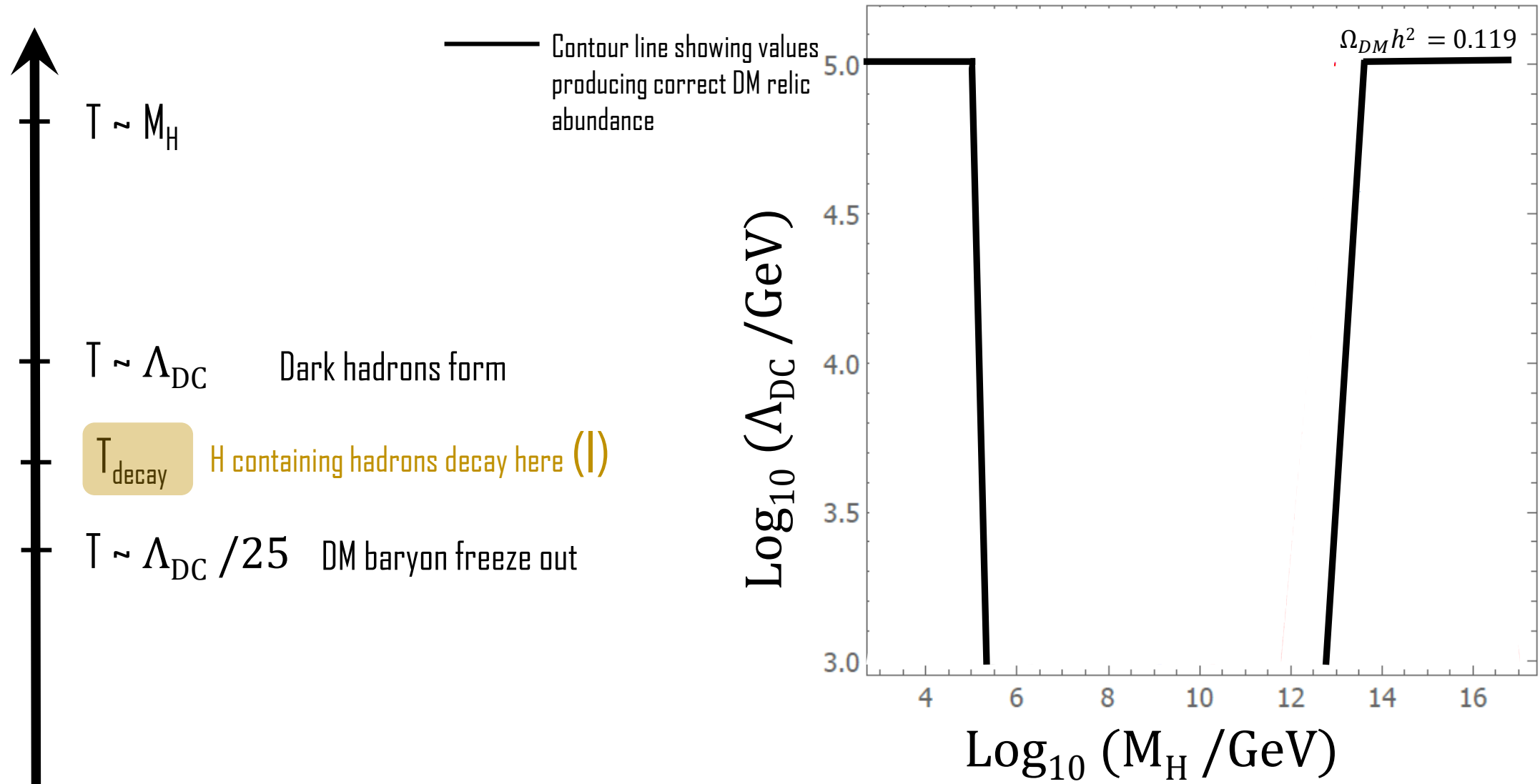
Bottaro, Contino, SV [In prep]



$$\tau_H \sim \left(\frac{g_{\text{GUT}}^4}{8\pi} \frac{M_H^5}{M_{\text{GUT}}^4} \right)^{-1}$$

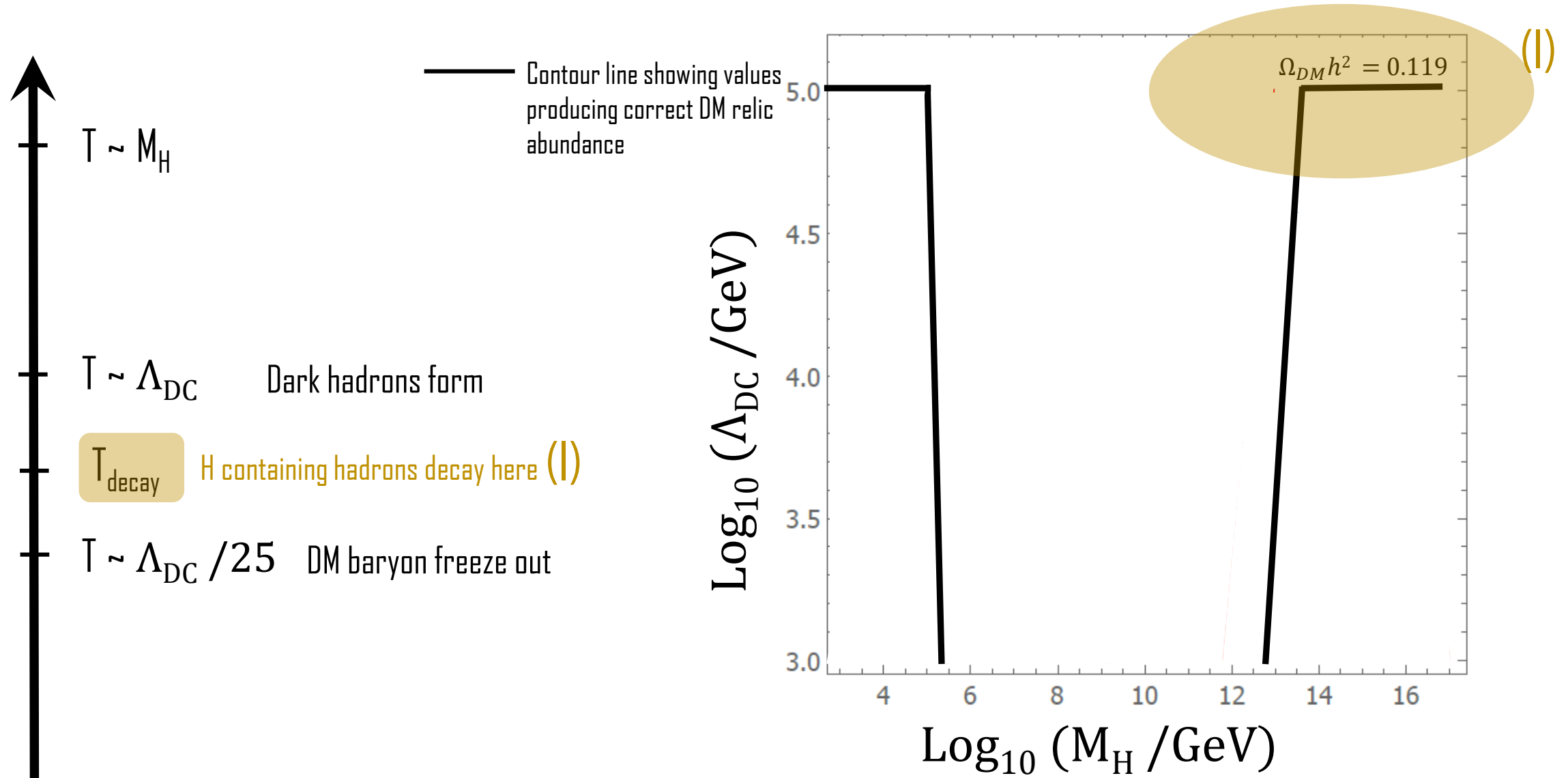
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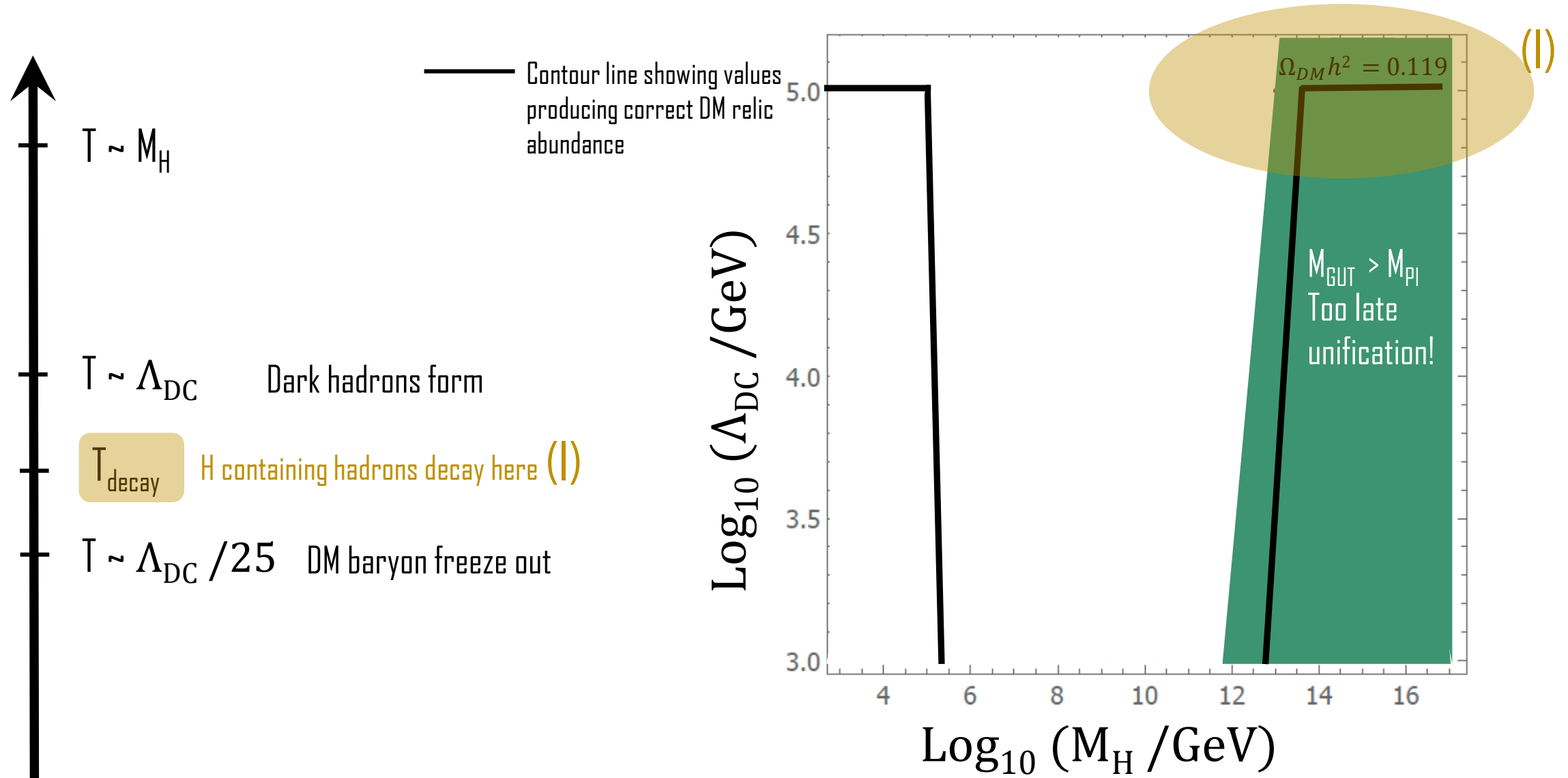
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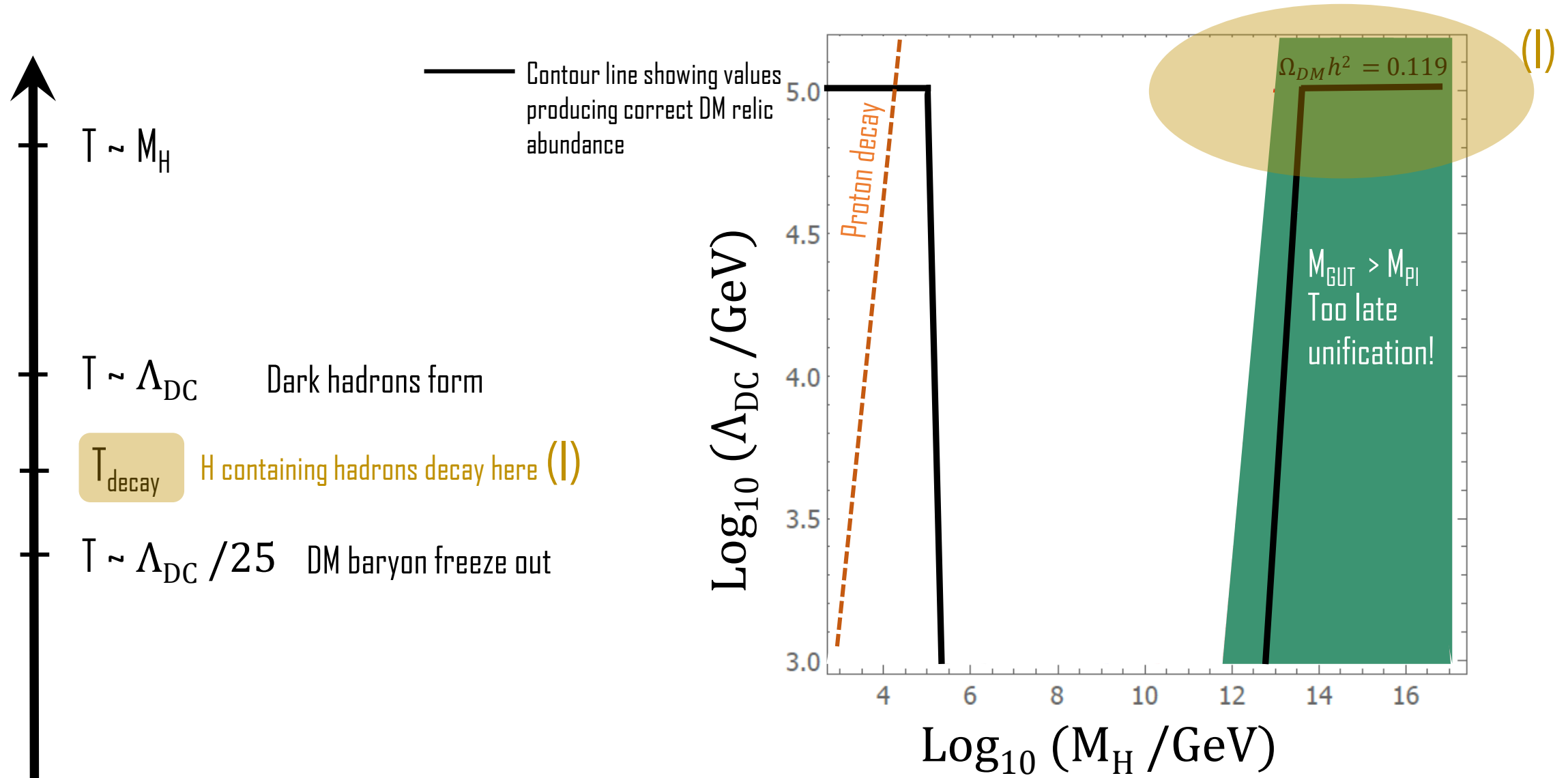
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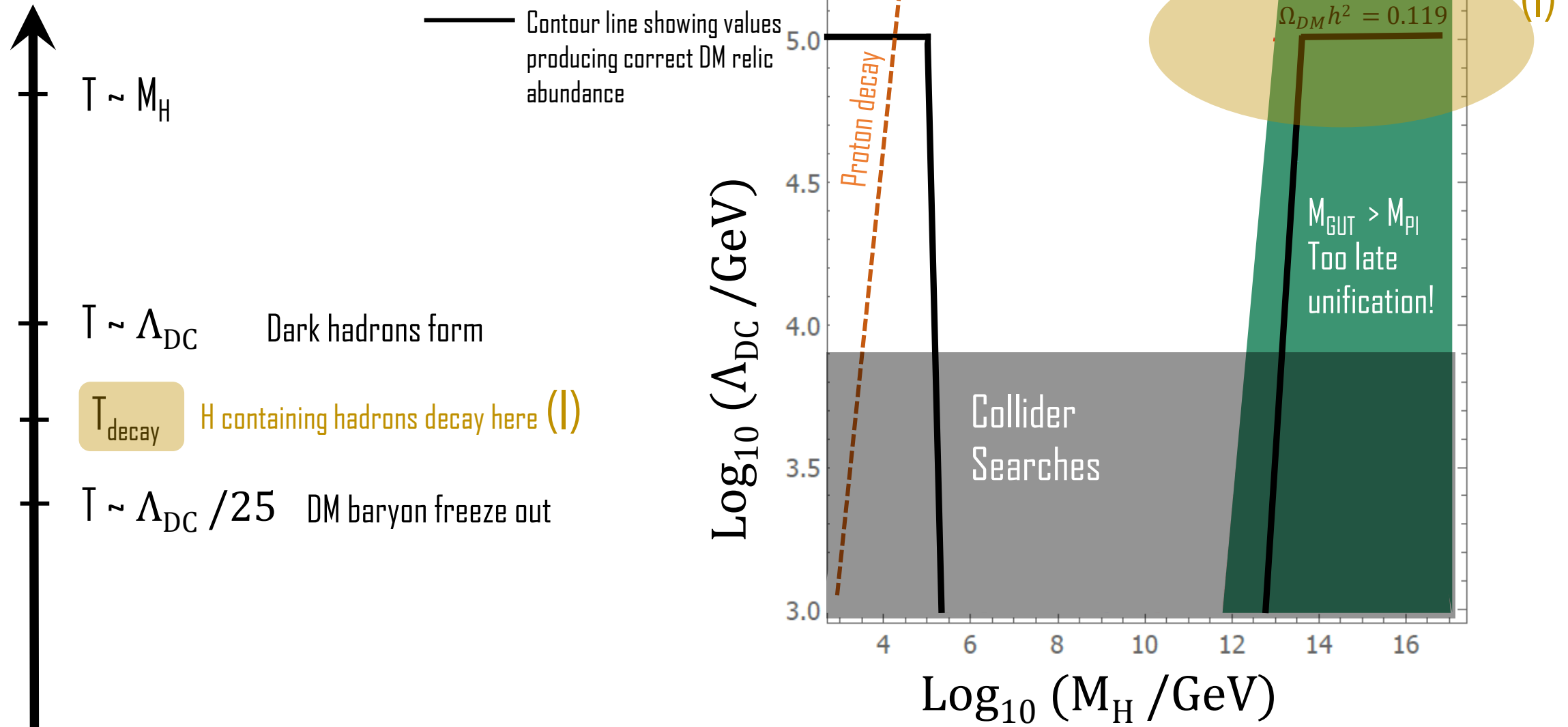
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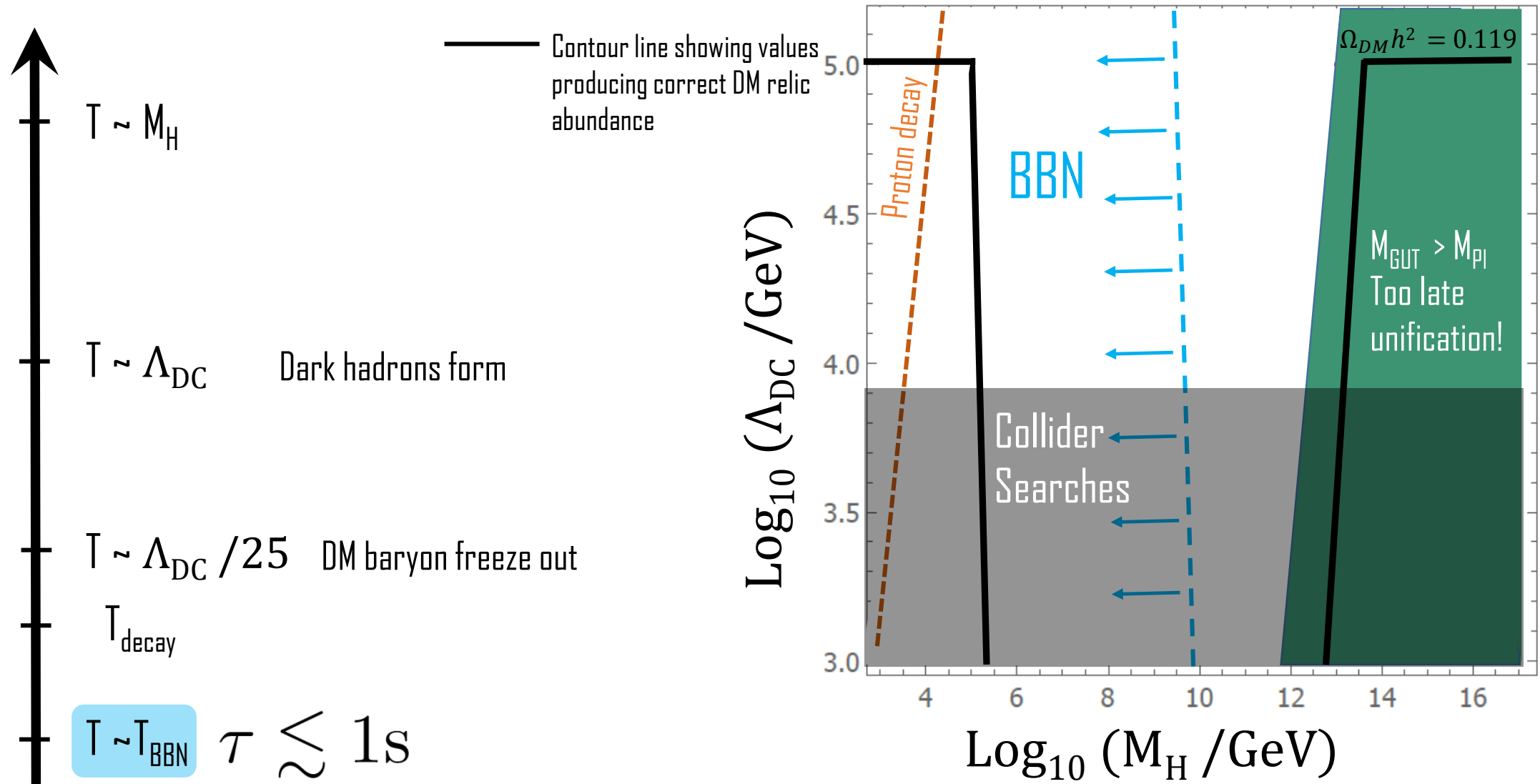
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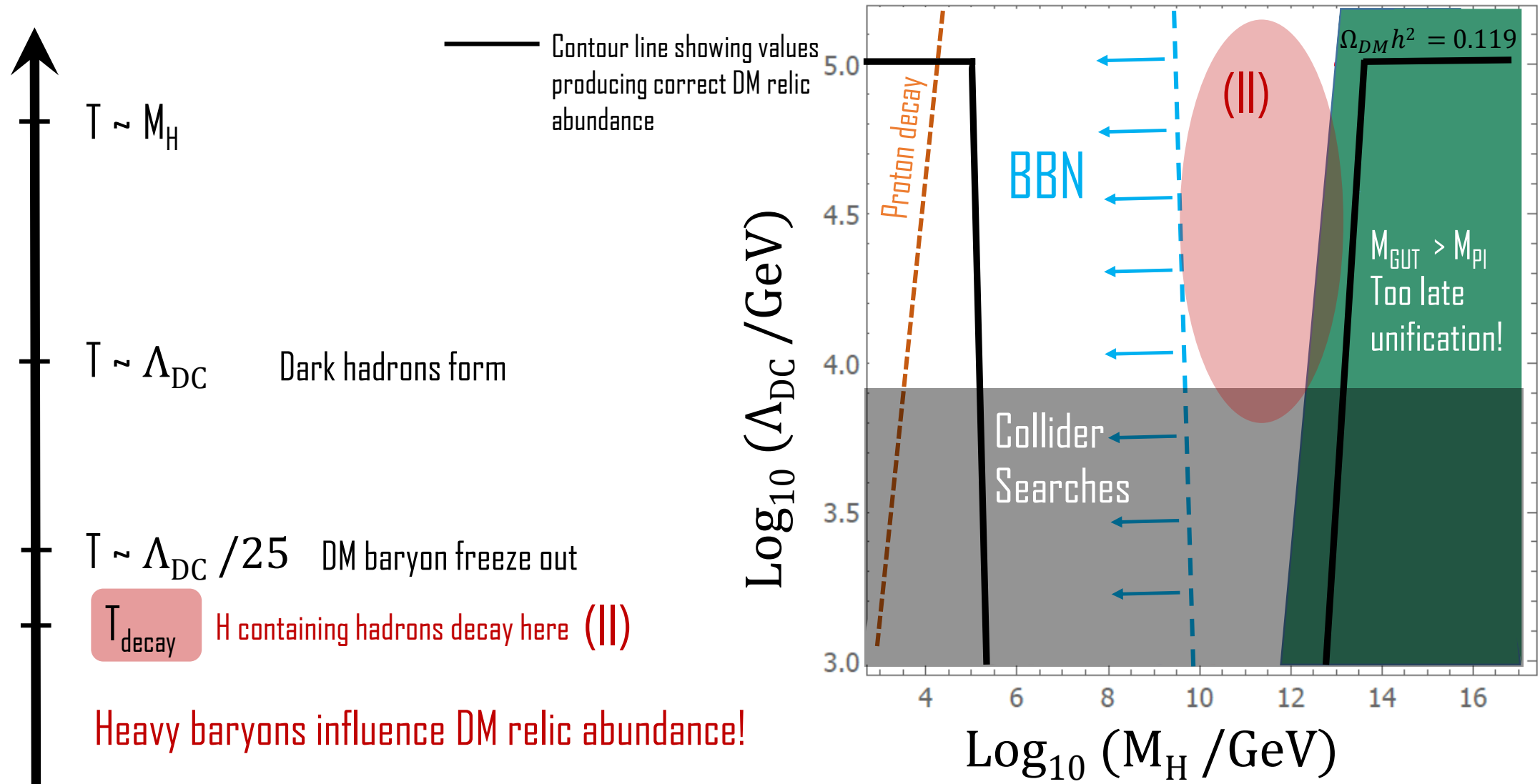
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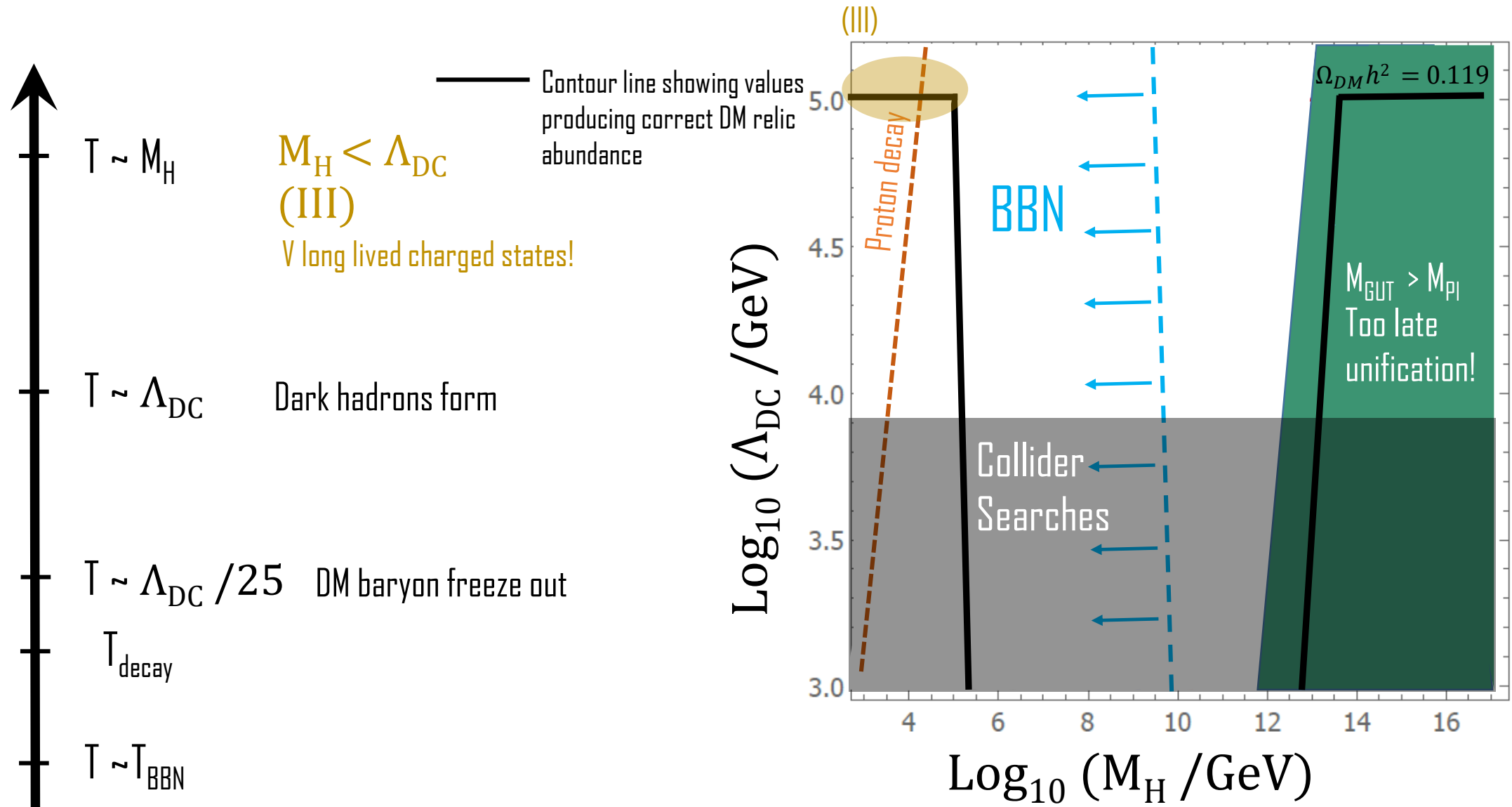
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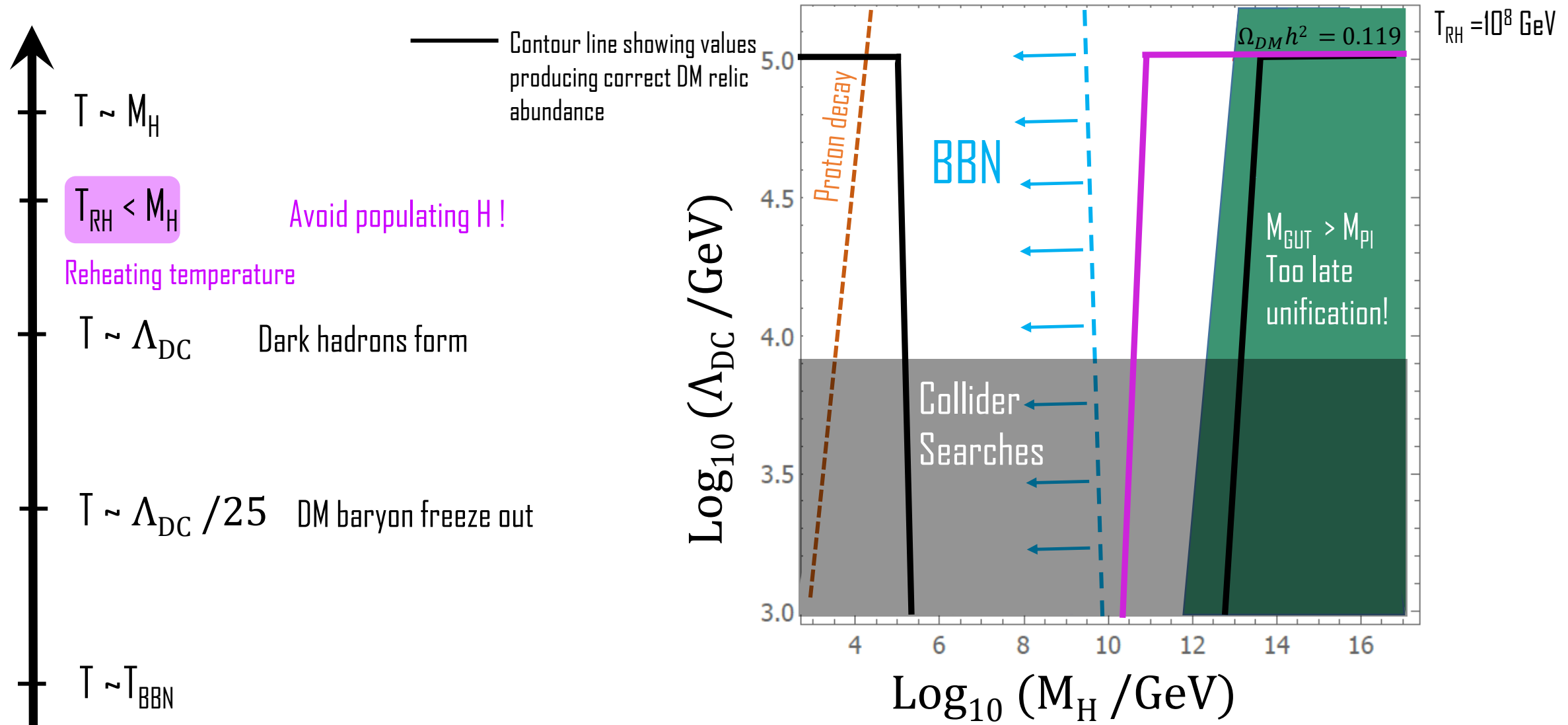
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Thermal history?

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Conclusion

- Not really many good models...
- Dark fermions cannot come in almost degenerate GUT multiplets.
- Cannot ignore role of GUT partners of dark quarks in the thermal history and phenomenology.
- To have good unification and evade BBN, we must not populate heavy states, $T_{RH} < M_H$

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Outlook

- Can we have natural hierarchy of various scales in the theory?

BACK-UP SLIDES

Can we produce a natural hierarchy?

Bottaro, Contino, SV [In prep]

$$Q + \tilde{D}$$

$$5 = \begin{bmatrix} \tilde{D} \\ \tilde{L} \end{bmatrix}$$

$$m_{\tilde{D}} \ll m_{\text{GUT}}$$

Protected by symmetry!

Hierarchy needed $m_{\tilde{D}} \ll m_{\tilde{L}} \ll m_{\text{GUT}}$

$$m_{\tilde{D}} \approx 10^5 \text{ GeV} \ll m_{\tilde{L}} \approx 10^{11} \text{ GeV}$$

$$\mathcal{L}_{\text{GUT}}^{\text{mass}} = -m_5 \bar{\psi}_5 \psi_5 + y_5 \bar{\psi}_5 \phi_{24} \psi_5$$

$$m_{\tilde{D}} = m_5 - \frac{2}{\sqrt{30}} y_5 v$$

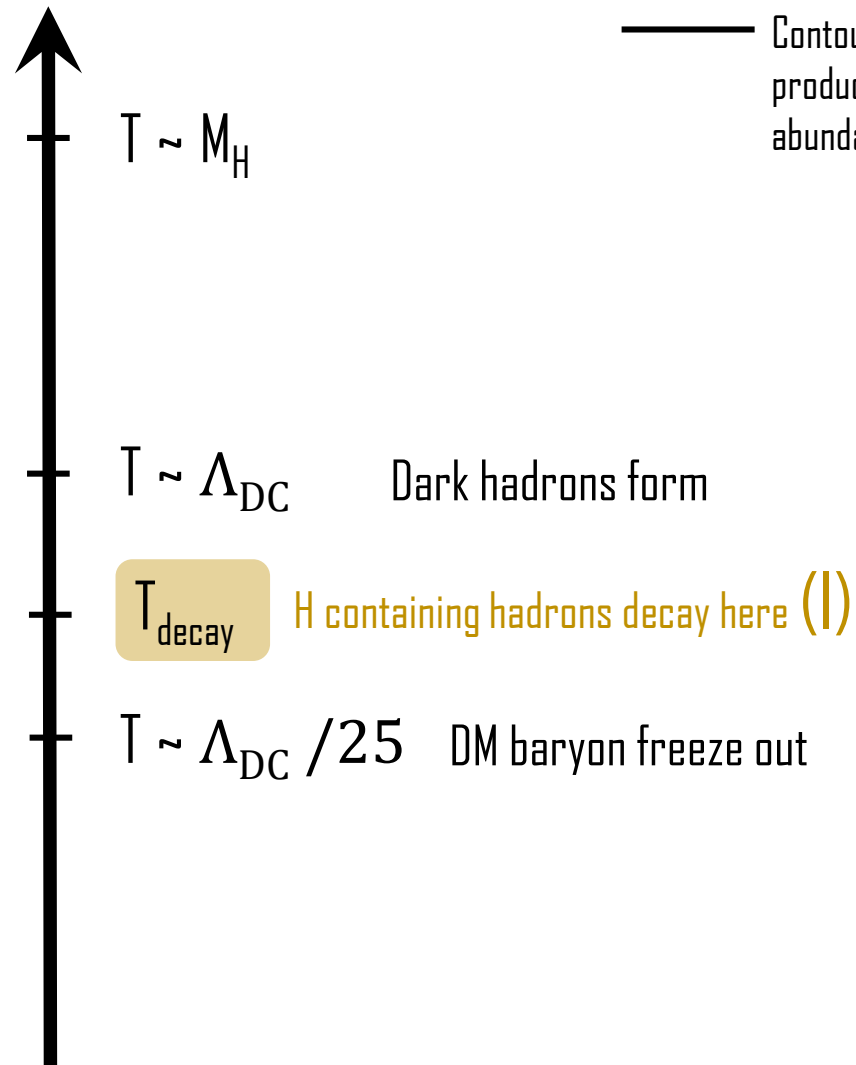
$$m_{\tilde{L}} = m_5 + \frac{3}{\sqrt{30}} y_5 v$$

$$\frac{m_5 \sqrt{30}}{y_5 v} = 2 + 5 \cdot 10^{-6}$$

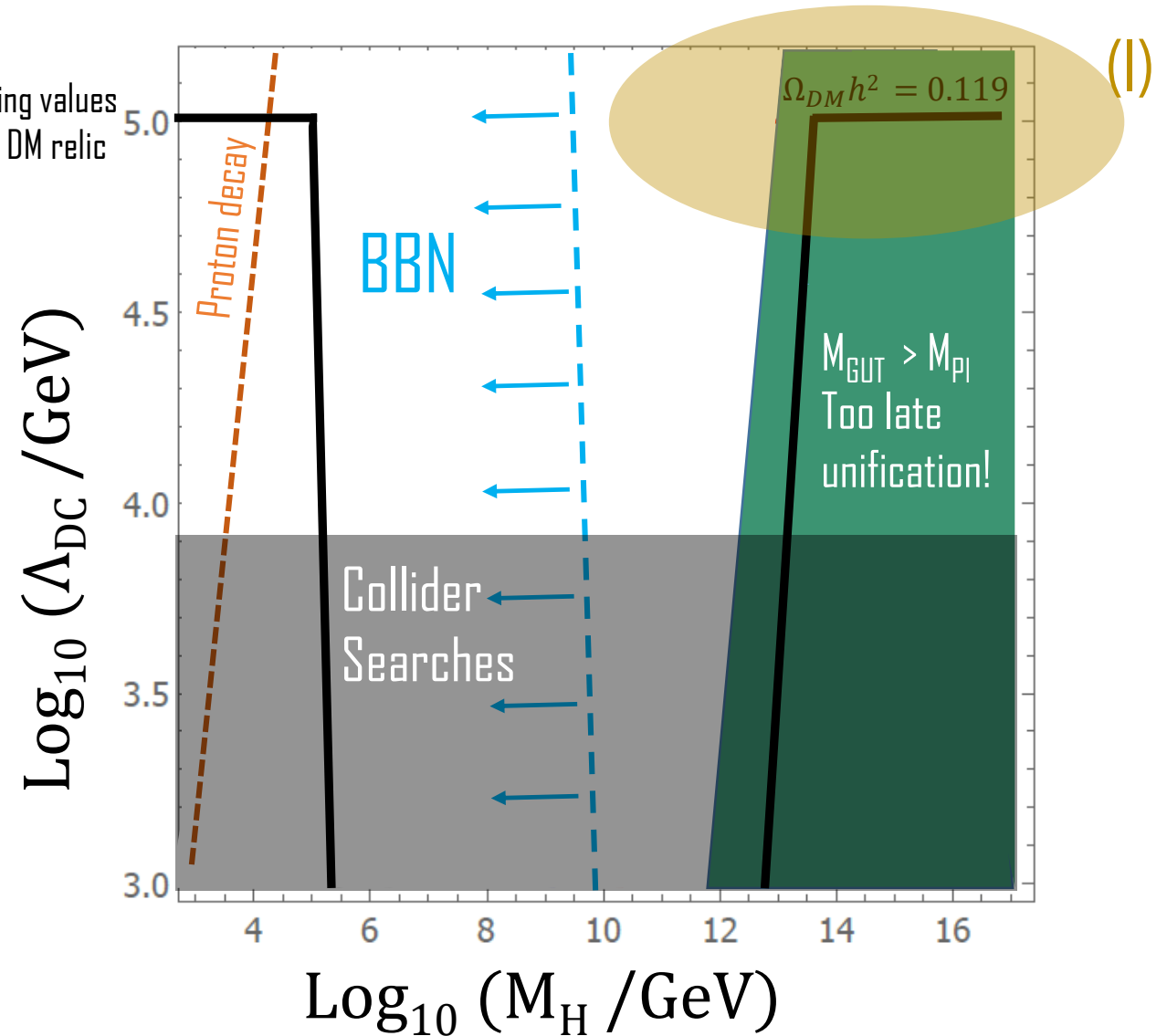
Tuning needed!

Thermal history?

Bottaro, Contino, SV [In prep]

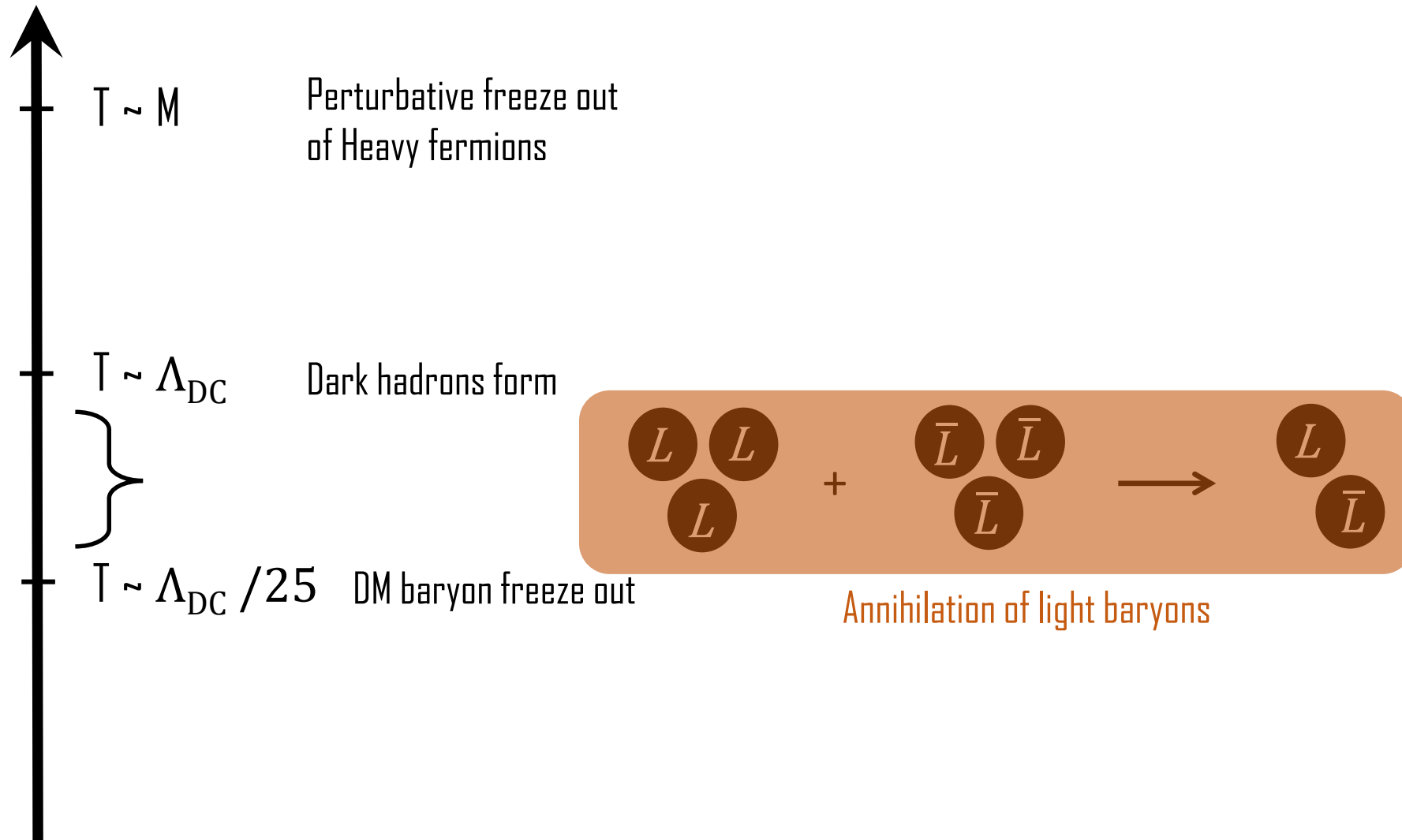


— Contour line showing values producing correct DM relic abundance



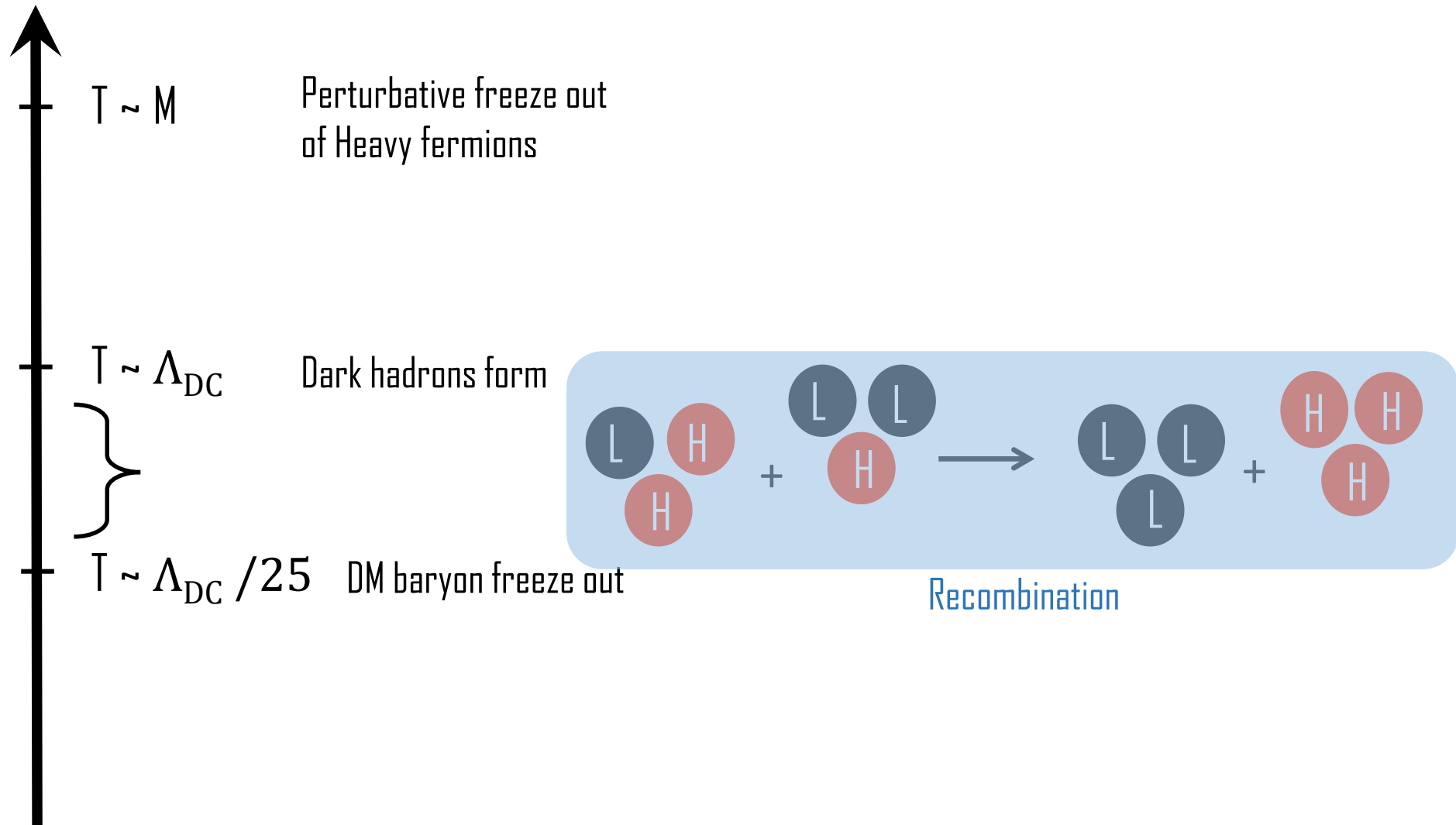
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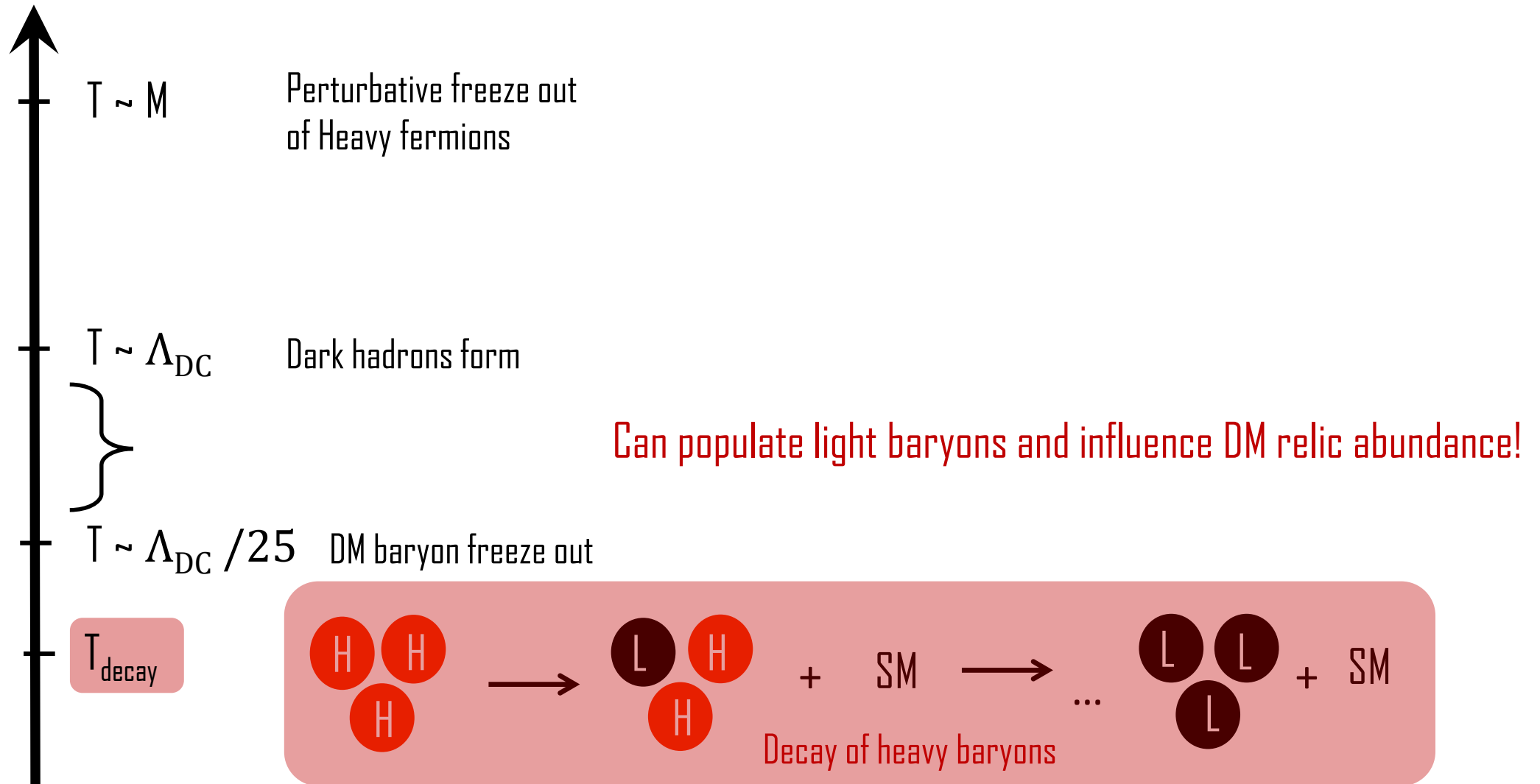
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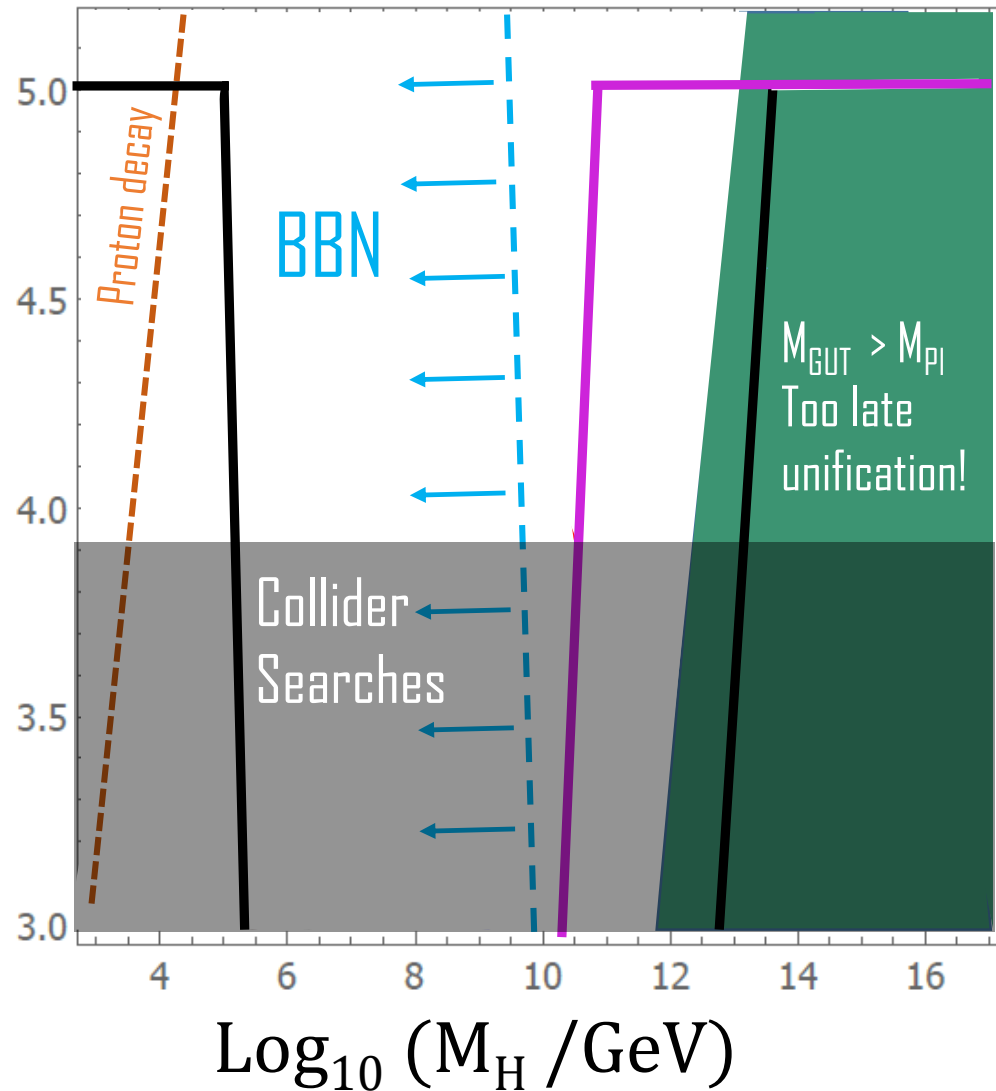


What do we find?

Bottaro, Contino, SV [In prep]

Light fermion mass
 $m = 1 \text{ TeV}$

$\text{Log}_{10} (\Lambda_{\text{DC}} / \text{GeV})$



— Contour line showing values
producing correct DM relic
abundance

— Reheating temp. $T_{\text{RH}} < M_{\text{H}}$

Can we produce a natural hierarchy?

Bottaro, Contino, SV [In prep]

$$Q + \tilde{D}$$

Hierarchy needed

$$m_{\tilde{D}} \ll m_{\tilde{L}}$$

$$5 = \begin{bmatrix} \tilde{D} \\ \tilde{L} \end{bmatrix}$$

$$\mathcal{L}_{\text{GUT}}^{\text{mass}} = -m_5 \bar{\psi}_5 \psi_5$$

$$\mathcal{L}_{\text{GUT}}^{\text{yuk}} = y_5 \bar{\psi}_5 \phi_{24} \psi_5$$

Tree level

After GUT $\rightarrow$ SM breaking

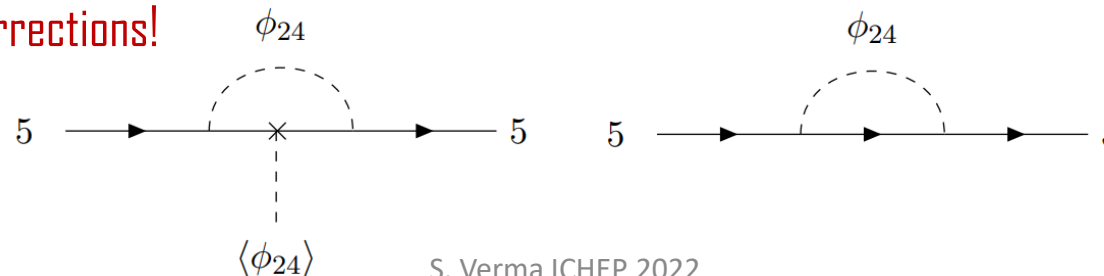
$$\langle \phi_{24} \rangle = \frac{1}{\sqrt{30}} v \text{ diag}(2, 2, 2, -3, -3)$$

$$\left. \begin{aligned} m_{\tilde{D}} &= m_5 - \frac{2}{\sqrt{30}} y_5 v \\ m_{\tilde{L}} &= m_5 + \frac{3}{\sqrt{30}} y_5 v \end{aligned} \right\} m_{\tilde{D}} \approx 10^5 \text{ GeV} \ll m_{\tilde{L}} \approx 10^{11} \text{ GeV}$$

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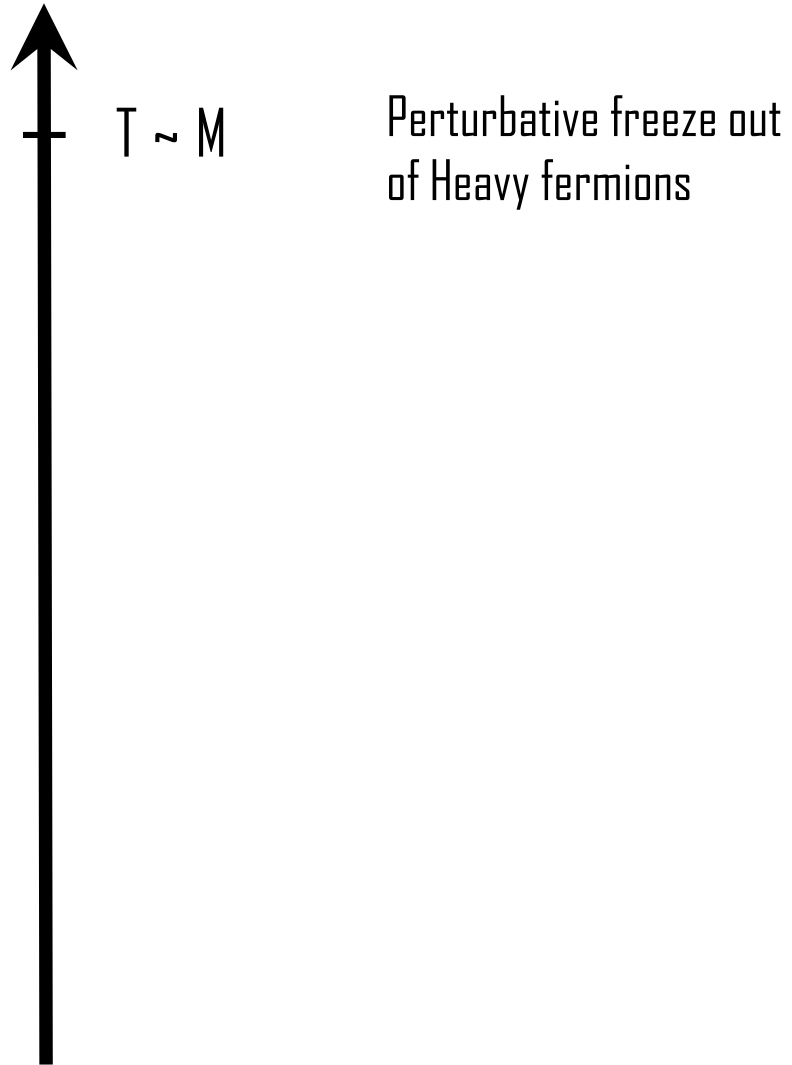
Tuning needed!

Tuning spoilt by such loop corrections!



Thermal history?

Bottaro, Contino, SV [In prep]



Benchmark GUT model?

Bottaro, Contino, SV [In prep]

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$$\mathfrak{5} = \begin{bmatrix} \tilde{D} \\ \tilde{L} \end{bmatrix}$$

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Low energy

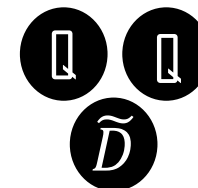
$$m \lesssim \Lambda_{\text{DC}} \sim 100 \text{ TeV}$$

$$Q, \tilde{D}$$

$$H\bar{Q}\tilde{D}$$

Breaks $\mathfrak{I}$ specie symmetry

$\mathfrak{U}(1)_{\text{DB}}$
dark baryon number



Baryonic DM

Stable due to $\mathfrak{U}(1)_{\text{DB}}$ dark baryon number!

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Intermediate energy

$$\Lambda_{\text{DC}} < M < M_{\text{GUT}}$$

3 more species

$$U, E, \tilde{L}$$

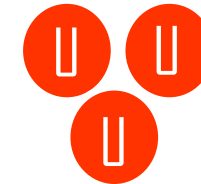
$$H^\dagger \bar{\tilde{L}} E$$

$$U(1)_U \text{ U number}$$

$$U(1)_{DL} \text{ Dark lepton number}$$

Broken at dim-6 level

e.g.



Dangerous stable states

Stable due to **new accidental** $U(1)_U$

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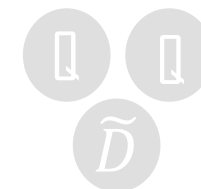
2 species

$$Q, \tilde{D}$$

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[Antipin, Redi, Strumia, Vigiani 2015]

- $\psi_{\text{dark}} \in \mathcal{G}_{\text{SM}}$, embed in $\text{SU}(5)$

'light dark fermions' $m_\psi \lesssim \Lambda_{\text{DC}}$

Dark confinement scale

Heavy dark fermions $m_\psi \gg \Lambda_{\text{DC}}$

See [Mitridate, Redi, Smirnov, Strumia 2017]

- $\mathcal{G}_{\text{DC}}$ unbroken by $\mathcal{G}_{\text{GUT}}$, dark quarks GUT multiplets.

Benchmark GUT model?

Bottaro, Contino, SV [In prep]

$$Q + \tilde{D}$$

$$5 = \begin{bmatrix} \tilde{D} \\ \tilde{L} \end{bmatrix}$$

$$10 = \begin{bmatrix} U & Q \\ & E \end{bmatrix}$$

$$\varphi_5 = \begin{bmatrix} H_3 \\ H \end{bmatrix}$$

$$5 + 10$$

Minimal GUT theory

UV theory
— M_{GUT}

2 GUT species

$$\psi_5, \psi_{10}$$

$$\bar{\psi}_5 \phi_5^\dagger \psi_{10}$$

Breaks 1 GUT species

3 more species

$$U, E, \tilde{L}$$

$$H^\dagger \tilde{L} E$$

Intermediate energy

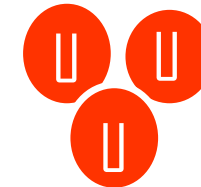
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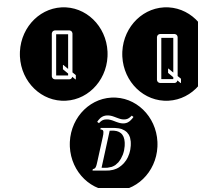
2 species

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$$H \bar{Q} \tilde{D}$$

Breaks 1 species symmetry

$$U(1)_{\text{DB}} \text{ dark baryon number}$$



Baryonic DM

Stable due to $U(1)_{\text{DB}}$ **dark baryon number!**

Motivations?

- Since $\psi_{\text{dark}} \in \mathcal{G}_{\text{SM}}$, embedding in $SU(5)$ gives another constraint
[Antipin, Redi, Strumia, Vigiani 2015]
- If dark group is unbroken by GUT group, dark quarks come as complete GUT multiplets.

Motivation I

Benchmark model gives "perfect" SM gauge coupling unification + accidentally stable proton-like DM

[Antipin, Redi, Strumia, Vigiani 2015]

e.g. $Q + \tilde{D}$

$$M_{\text{GUT}} \sim 10^{17} \text{ GeV}, \quad M_H \sim 10^{11} \text{ GeV}$$

S. Verma ICHEP 2022

Can we relax unification criteria and catch more models?

Bottaro, Contino, SV [In prep]

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[Antipin, Redi, Strumia, Vigiani 2015]
- If dark group is unbroken by GUT group, dark quarks come as complete GUT multiplets.

Motivation II

Benchmark model gives "perfect" SM gauge coupling unification + accidentally stable proton-like DM

Non DM bound states must decay fast: BBN

Can we make EFT pov explicit in the classification of models?

Motivations?

- Since $\psi_{\text{dark}} \in \mathcal{G}_{\text{SM}}$, embedding in $SU(5)$ gives another constraint
[Antipin, Redi, Strumia, Vigiani 2015]
- dark group is unbroken by GUT group, dark quarks come as complete GUT multiplets.

Motivation III $Q + \tilde{D}$

UV level

$$\mathcal{L}_{\text{GUT}}^{\text{mass}} = -m_5 \bar{\psi}_5 \psi_5$$

$$5 = \begin{bmatrix} \tilde{D} \\ \tilde{L} \end{bmatrix}$$

Intermediate mass scale

$$m_{\tilde{D}} \ll m_{\tilde{L}}$$

Low energy level

$$\mathcal{L}_{\text{IR}}^{\text{mass}} = -m_{\tilde{D}} \bar{\psi}_{\tilde{D}} \psi_{\tilde{D}}$$

Can we produce this hierarchy of scales naturally using GUT breaking terms?

Motivations?

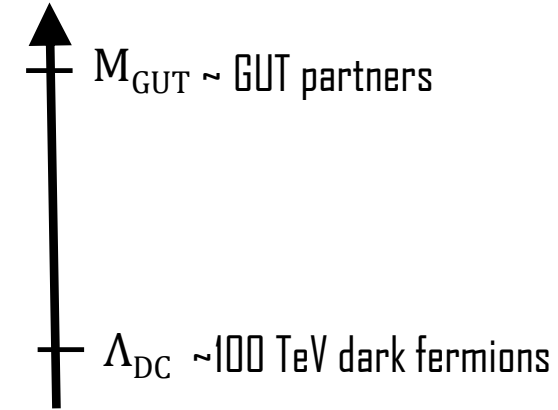
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'light dark fermions' $m_\psi \lesssim \Lambda_{\text{DC}}$

Dark confinement scale

- $\mathcal{G}_{\text{DC}}$ unbroken by $\mathcal{G}_{\text{GUT}}$, dark quarks $\mathcal{G}_{\text{GUT}}$ multiplets.



Motivations?

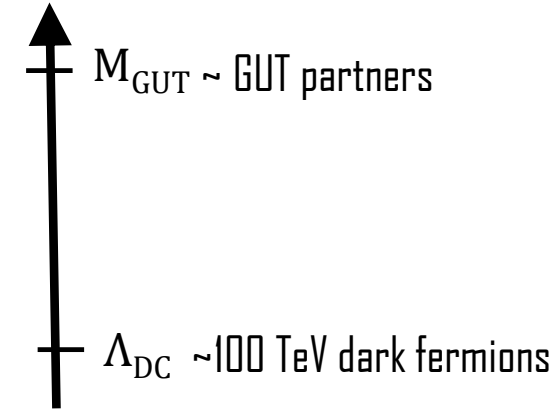
[Antipin, Redi, Strumia, Vigiani 2015]

- $\psi_{\text{dark}} \in \mathcal{G}_{\text{SM}}$, embed in $\text{SU}(5)$

'light dark fermions' $m_\psi \lesssim \Lambda_{\text{DC}}$

Dark confinement scale

- $\mathcal{G}_{\text{DC}}$ unbroken by $\mathcal{G}_{\text{GUT}}$, dark quarks GUT multiplets.



Bottaro, Contino, SV [In preparation]

Can we find an **SU(5) GUT UV-completion** to embed composite dark matter models giving accidentally stable DM?

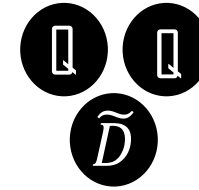
Benchmark GUT model?

$$Q + \tilde{D}$$

$$5 = \begin{bmatrix} \tilde{D} \\ \tilde{L} \end{bmatrix}$$

$$10 = \begin{bmatrix} U & Q \\ & E \end{bmatrix}$$

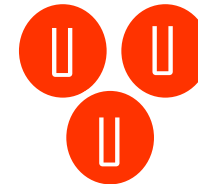
At $\Lambda_{\text{DC}} \sim 100 \text{ TeV}$



Baryonic DM

Stable due to $U(1)_{\text{DB}}$ dark baryon number!

- No Yukawa term with U consistent with $\mathcal{G}_{\text{SM}} \times \mathcal{G}_{\text{DC}}$
- Renormalisable GUT terms becomes

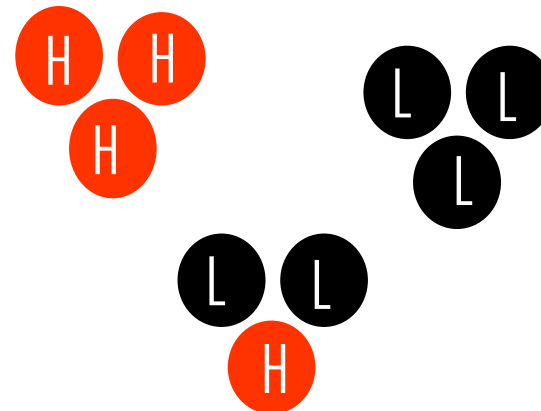
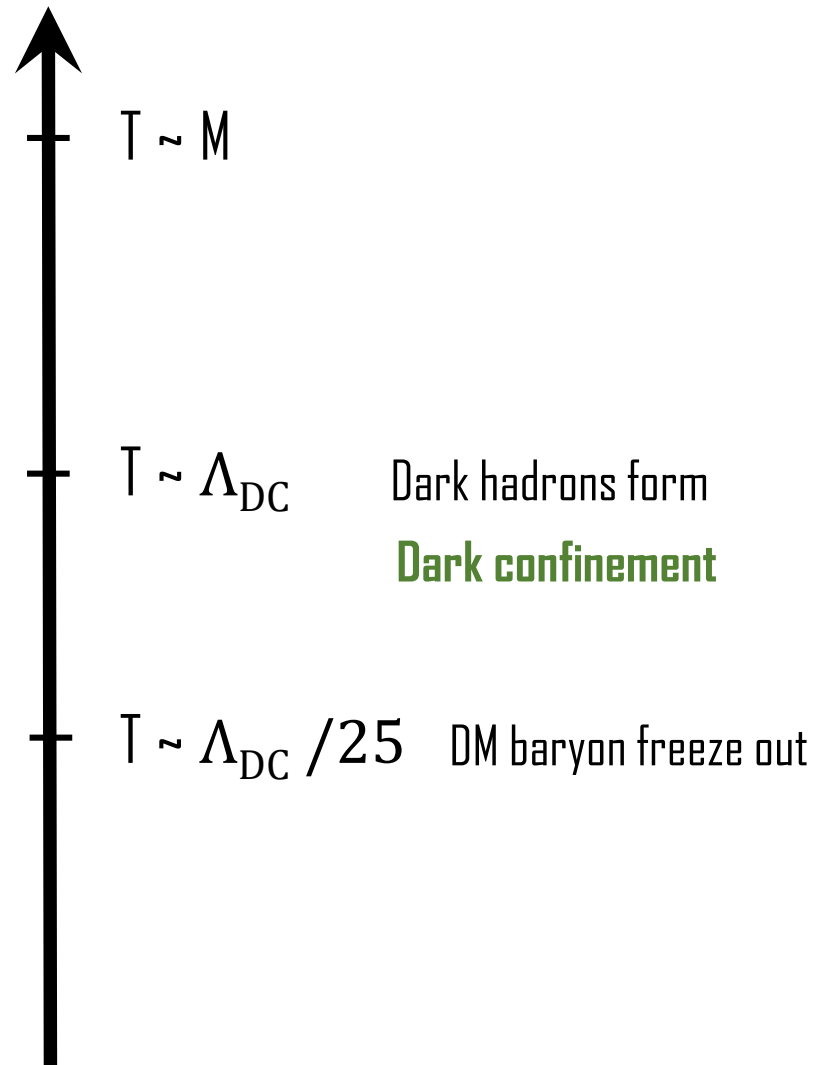


Dangerous stable states

Stable due to new accidental $U(1)_U$

Thermal history?

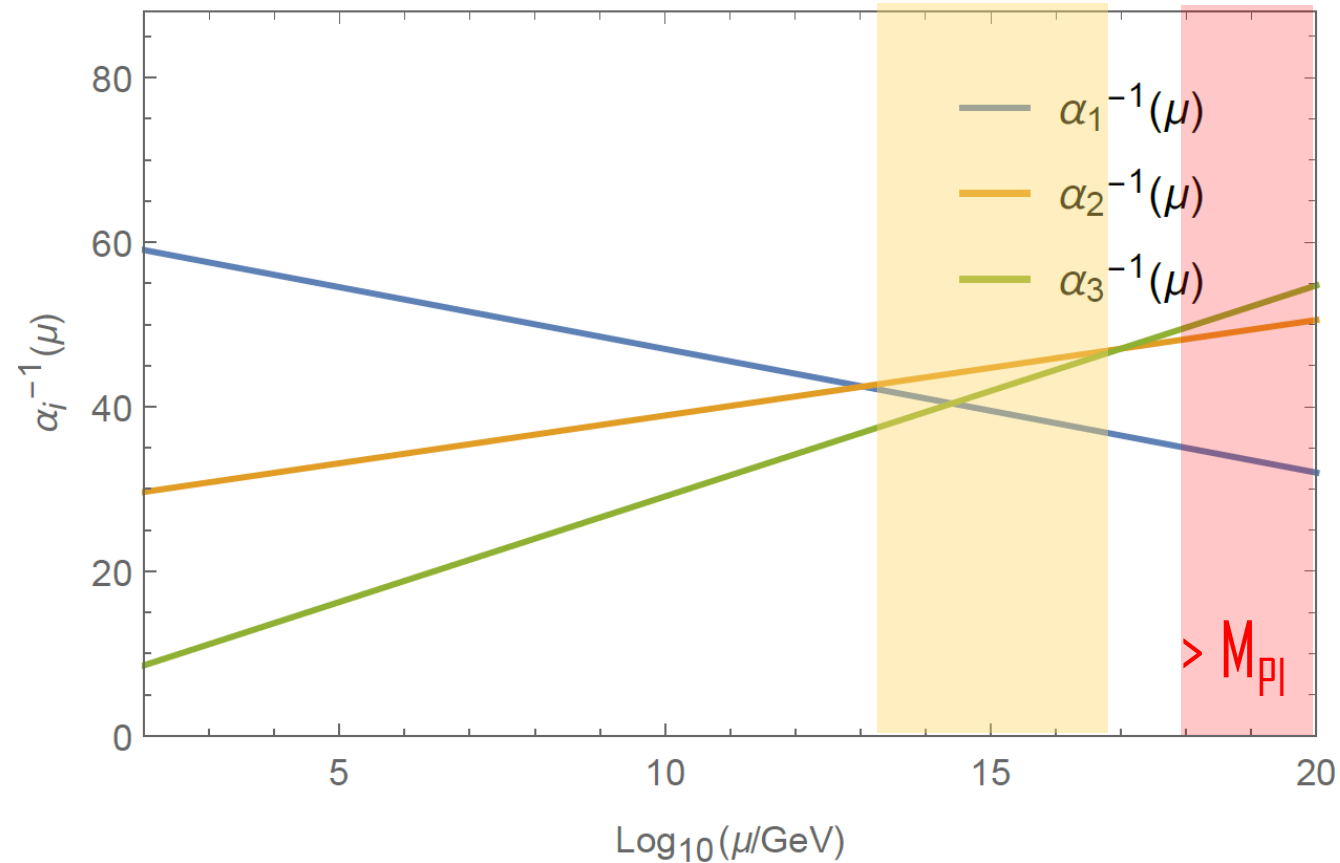
Bottaro, Contino, SV [In prep]



Coincidence or GUT?

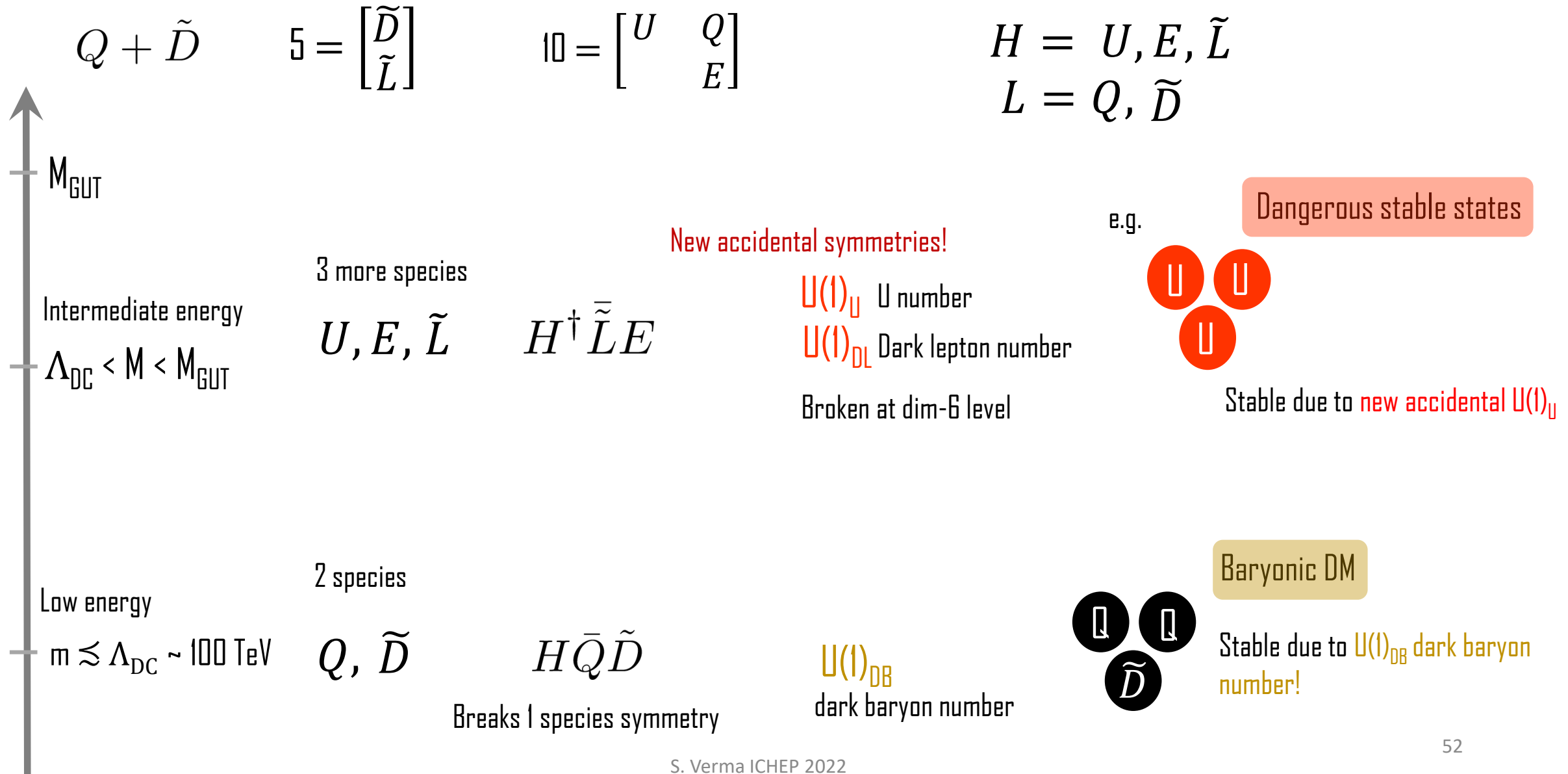
In the SM, $SU(3) \times SU(2) \times U(1)$ couplings seem to come very close at a scale $\sim 10^{14}$ GeV

SM only



Benchmark GUT model?

Bottaro, Contino, SV [In prep]



Thermal history?

Bottaro, Contino, SV [In prep]

