

The GUT way for Composite Dark Matter

Sonali Verma
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DarkCosmoGrav Conference

Work in progress
with Salvatore Bottaro,
Roberto Contino.

SCUOLA
NORMALE
SUPERIORE



Lesson I

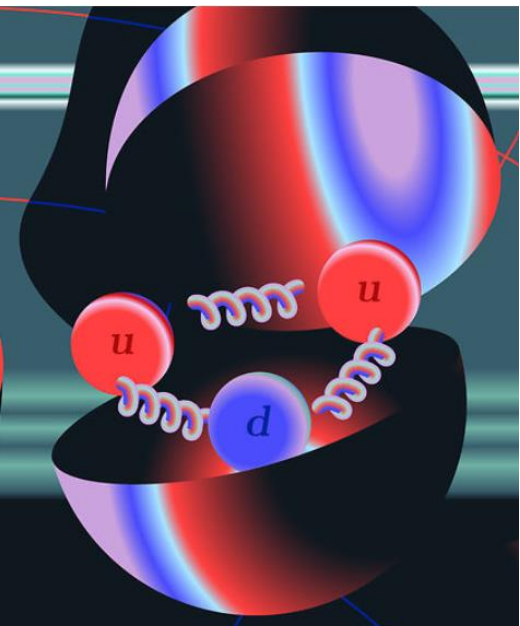
$$\mathcal{L}_{eff} = \mathcal{L}^{(4)} + \sum_{n,i} \frac{c_i^{(n)}}{\Lambda_{UV}^n} \mathcal{O}_i^{(4+n)}$$

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Low energy dynamics well explained by the renormalizable SM lagrangian

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Low energy dynamics well explained by the renormalizable SM lagrangian



Example:
proton stability

Feature of $\mathcal{L}^{(4)}$: (Approximate) Emergent Symmetries

$$\mathcal{L}_{eff} = \mathcal{L}^{(4)} + \sum_{n,i} \frac{c_i^{(n)}}{\Lambda_{UV}^n} \mathcal{O}_i^{(4+n)}$$

Higher-dimension operators break these...

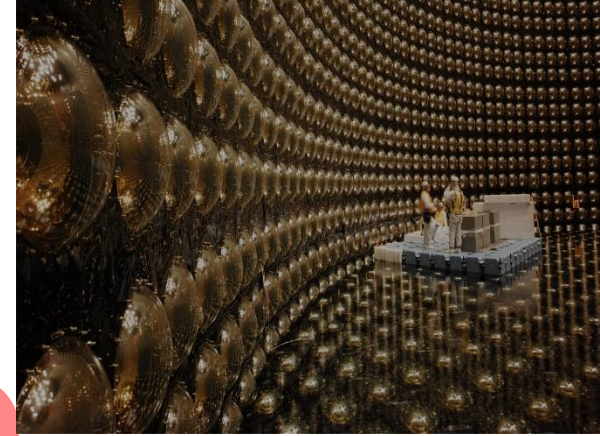
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Higher-dimension operators break these...

$$p^+ \rightarrow e^+ + \pi^0$$

Proton decay via
dim-6 operator

$$\mathcal{O} = \frac{c}{\Lambda_{UV}^2} uude$$



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Super Kamiokande lower limit

$$\tau_p > 1.6 \times 10^{34} \text{ yrs}$$

$$\mathcal{O} = \frac{c}{\Lambda_{UV}^2} u u d e$$

Proton lifetime

$$\tau_p \sim \left(\frac{c^2}{8\pi} \frac{m_p^5}{\Lambda_{UV}^4} \right)^{-1}$$

$$\Lambda_{UV} \gtrsim 10^{16} \text{ GeV}$$

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Lesson from SM: Proton stability arising due to accidental symmetries broken by higher dimension operators.

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Stable due to accidental symmetry!!

Could dark matter candidate be like the proton?

Extend Standard Model with new matter and/or new dark force

Standard Model

Dark Sector

Dark
matter?

See: Cirelli, Fornengo, Strumia (2006); Antipin, Redi, Strumia, Vigiani (2015); Kribs, Neil (review) (2015); Mitridate, Redi, Smirnov, Smirnov (2017); Contino, Mitridate, Podo, Redi (2019)...

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Weakly Coupled Dark Sector: Minimal Dark Matter [Cirelli, Fornengo, Strumia (2006)]

Strongly Coupled Dark Sector

Extend Standard Model with new matter and/or new dark force

\mathcal{G}_{SM}

Standard Model

\mathcal{G}_{DC} Dark colour

Dark Sector

Dark matter?

Strongly Coupled Dark Sector

$$\psi_{\text{DS}} \equiv (R_{\text{DC}}, R_{\text{SM}}) \oplus (\bar{R}_{\text{DC}}, \bar{R}_{\text{SM}})$$

Dirac dark fermions

Vector-like representations under
SM gauge group

See: Vectorlike confinement
[Kilic, Okui, Sundrum 2010]

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Dirac dark fermions

$$\mathcal{L}_{\text{DS}} = -\frac{1}{4g_{\text{DC}}^2} \mathcal{G}_{\mu\nu}^2 + \bar{\psi}(iD - m)\psi + y \bar{\psi}H\psi + h.c.$$

Vectorlike mass term

Vector-like representations under SM gauge group

See: Vectorlike confinement [Kilic, Okui, Sundrum 2010]

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\mathcal{G}_{SM}

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Dirac dark fermions

DM candidates:

- Dark baryons [Antipin, Redi, Strumia, Vigiani 2015]
- Dark Mesons [Mitridate, Redi, Smirnov, Strumia 2017]
- Gluequark DM [Contino, Mitridate, Podo, Redi 2019]

Vector-like representations under
SM gauge group

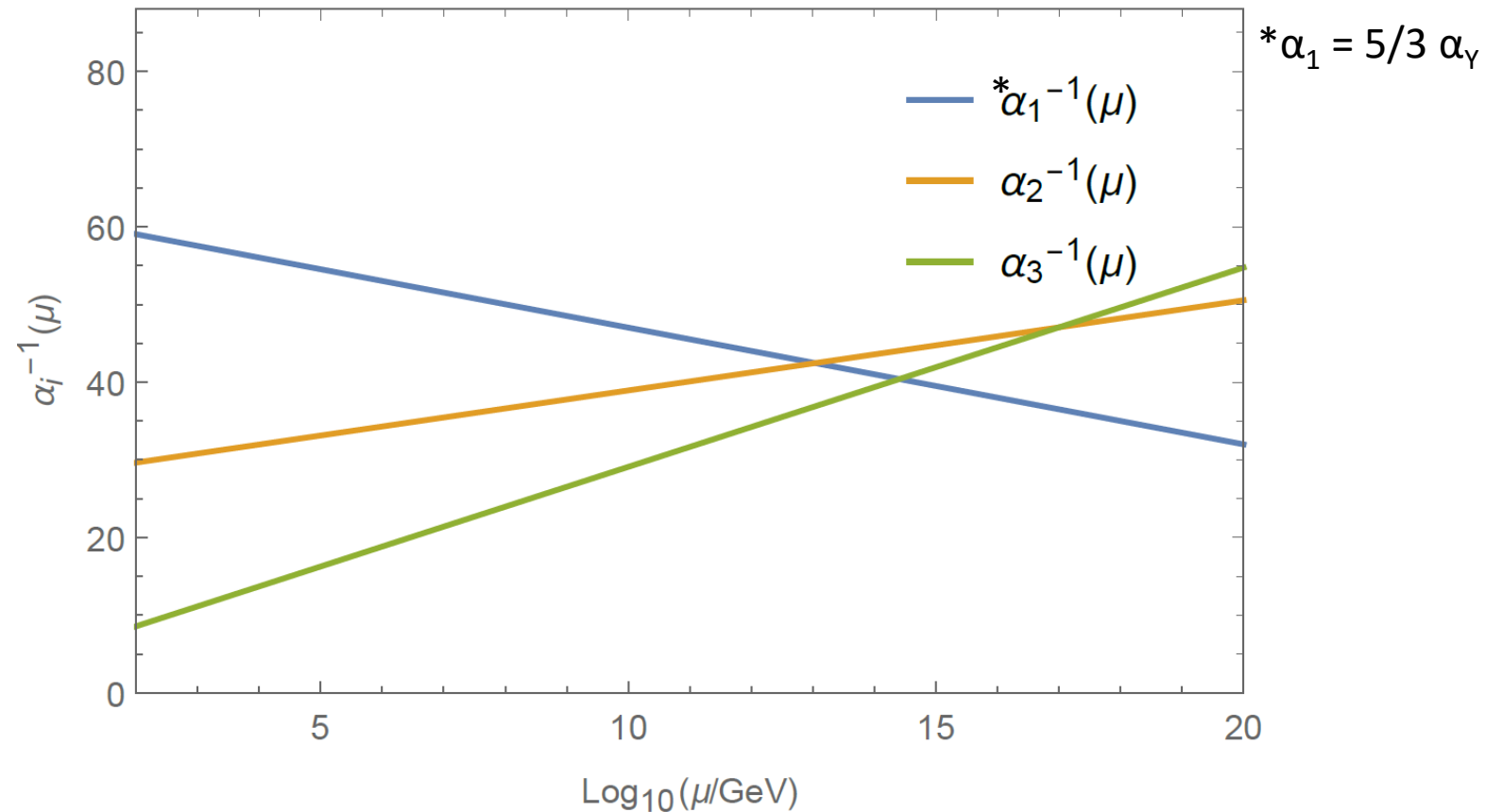
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[Kilic, Okui, Sundrum 2010]

Lesson II

Coincidence or GUT?

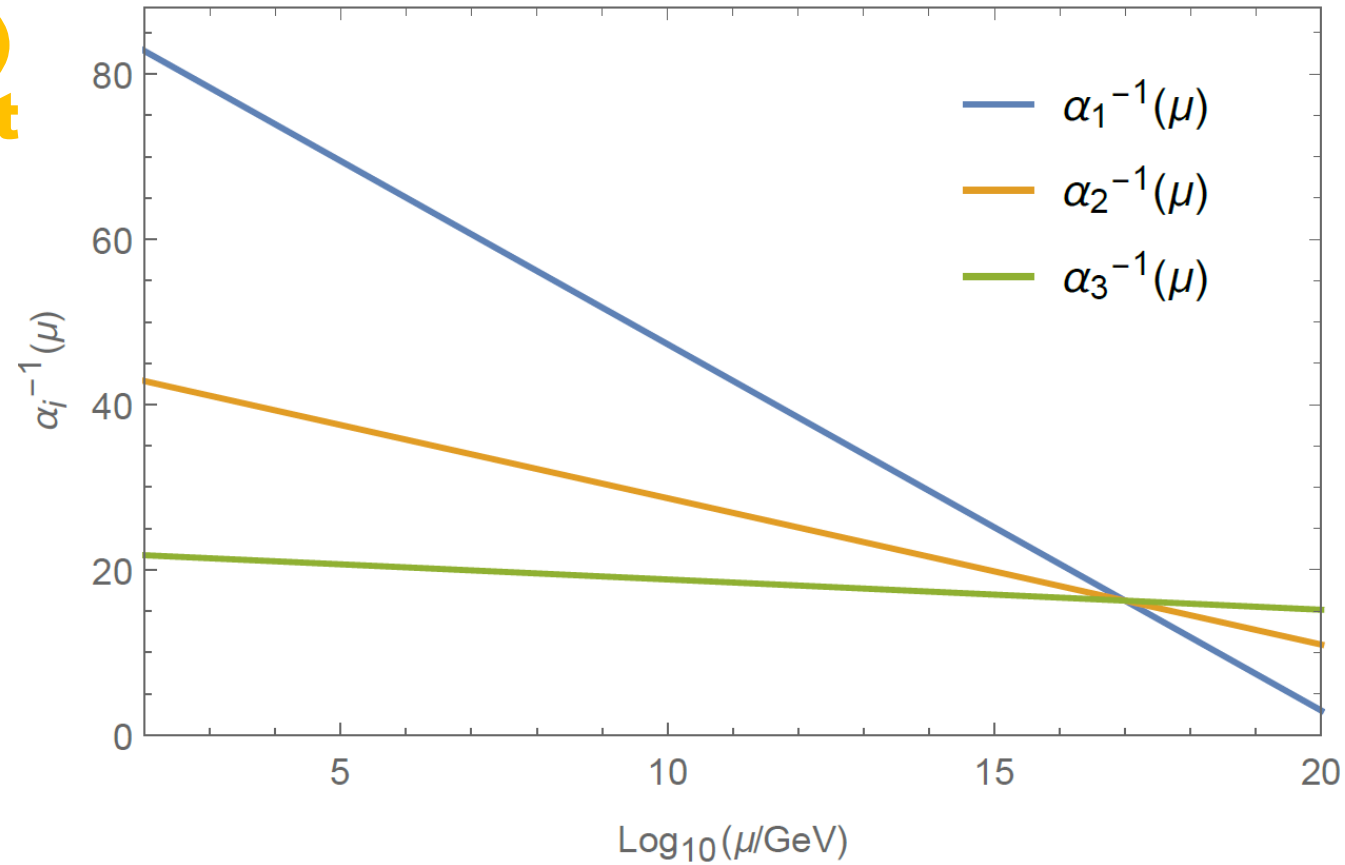
In the SM, $SU(3) \times SU(2) \times U(1)$ couplings seem to come very close at a scale $\sim 10^{14}$ GeV

SM content only



Coincidence or GUT?

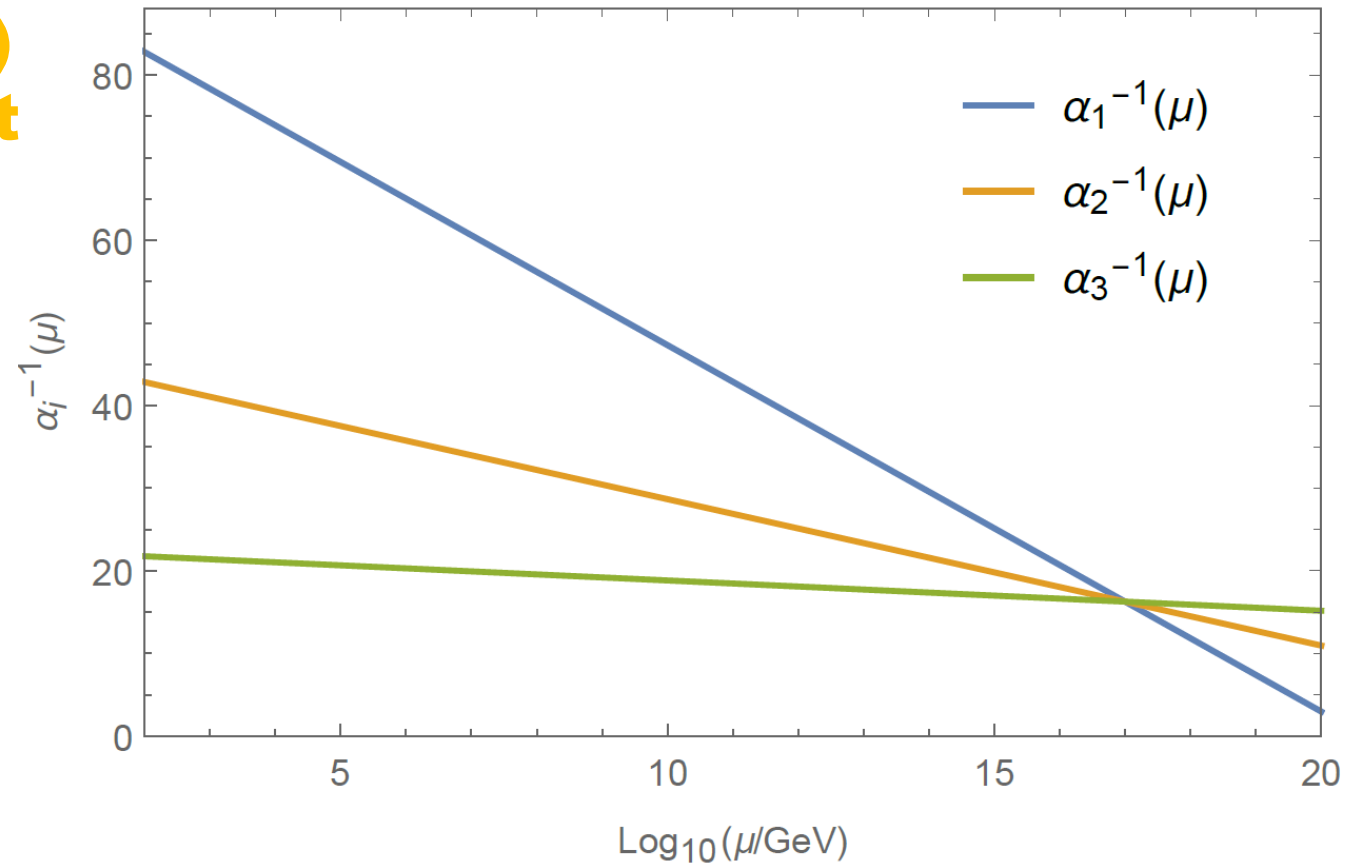
**SM + (some)
new content**



Coincidence or GUT?

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

**SM + (some)
new content**



This work

Bottaro, Contino, SV (In prep)

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

$\psi \equiv (N_{\text{DC}}, R_{\text{SM}})$, embed in SU(5) multiplets

See also [Antipin, Redi, Strumia, Vigiani 2015]

$m_\psi \lesssim \Lambda_{\text{DC}}$
Dark confinement scale
'light dark fermions regime'

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$$m_\psi \lesssim \Lambda_{\text{DC}} \sim 100 \text{ TeV}$$

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DM candidate: Lightest dark baryons

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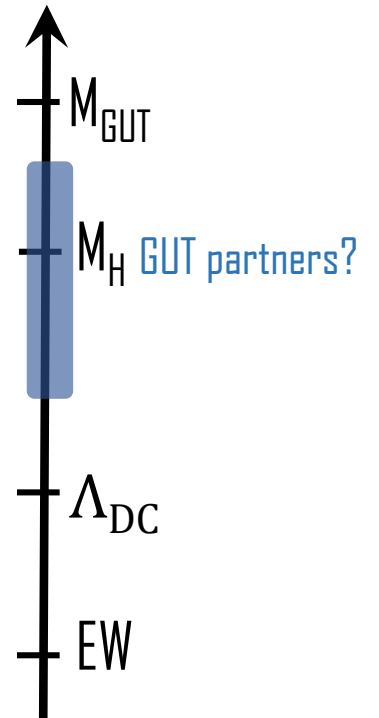
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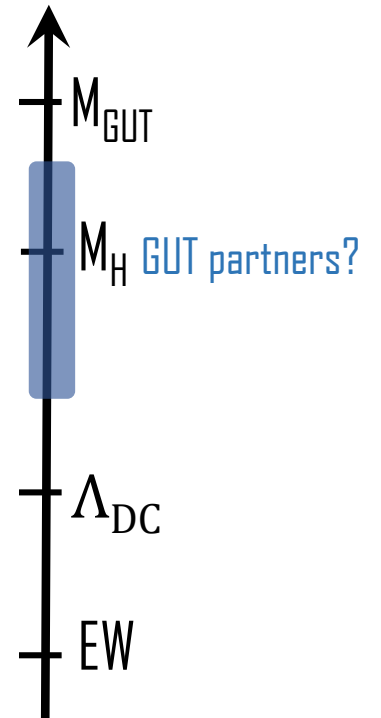
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Impact of GUT partners of dark fermions on phenomenology?



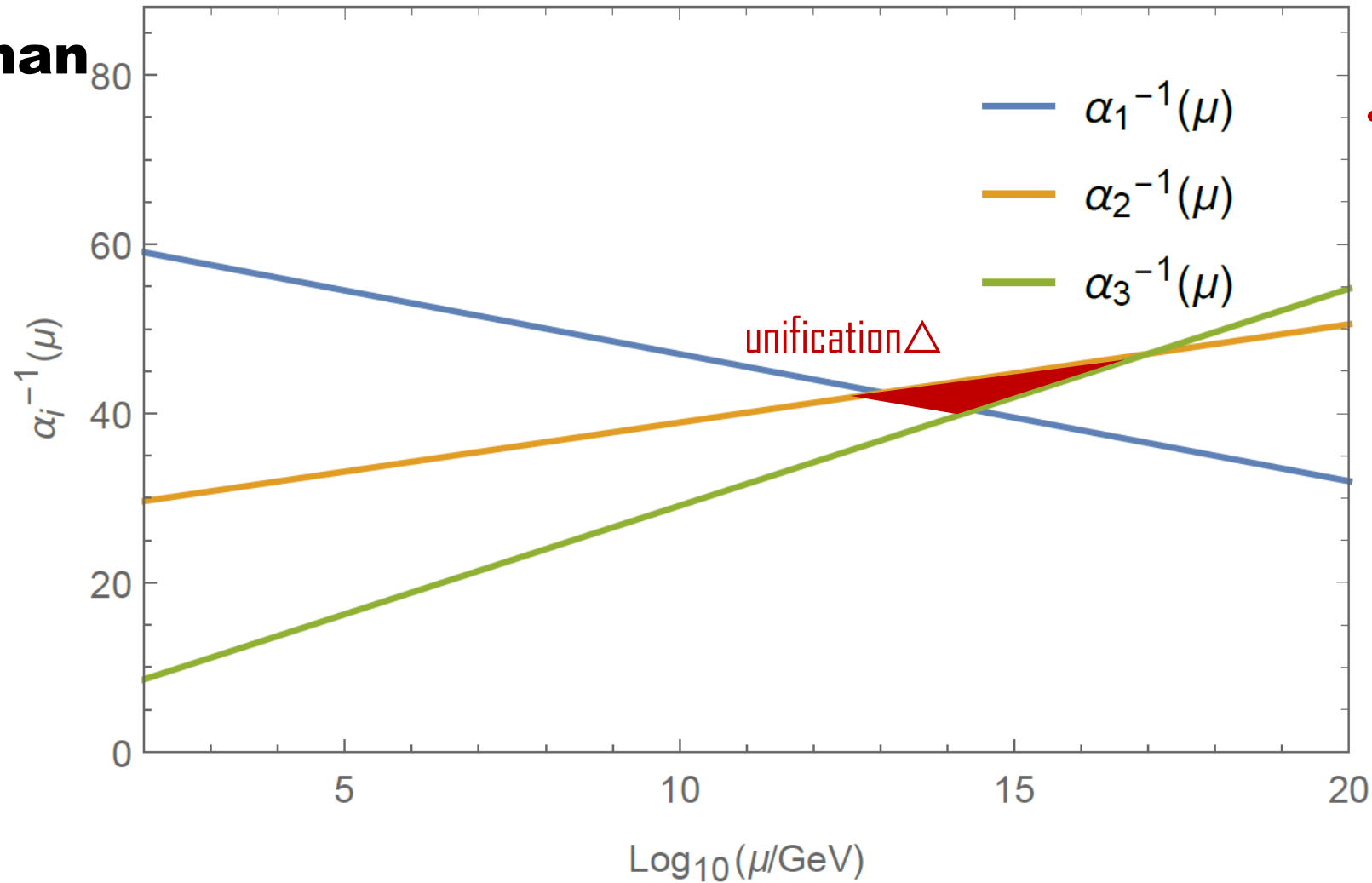
Unification for Millenials?

Unification Criterion?

Bottaro, Contino, SV [In prep]

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

Better than SM only



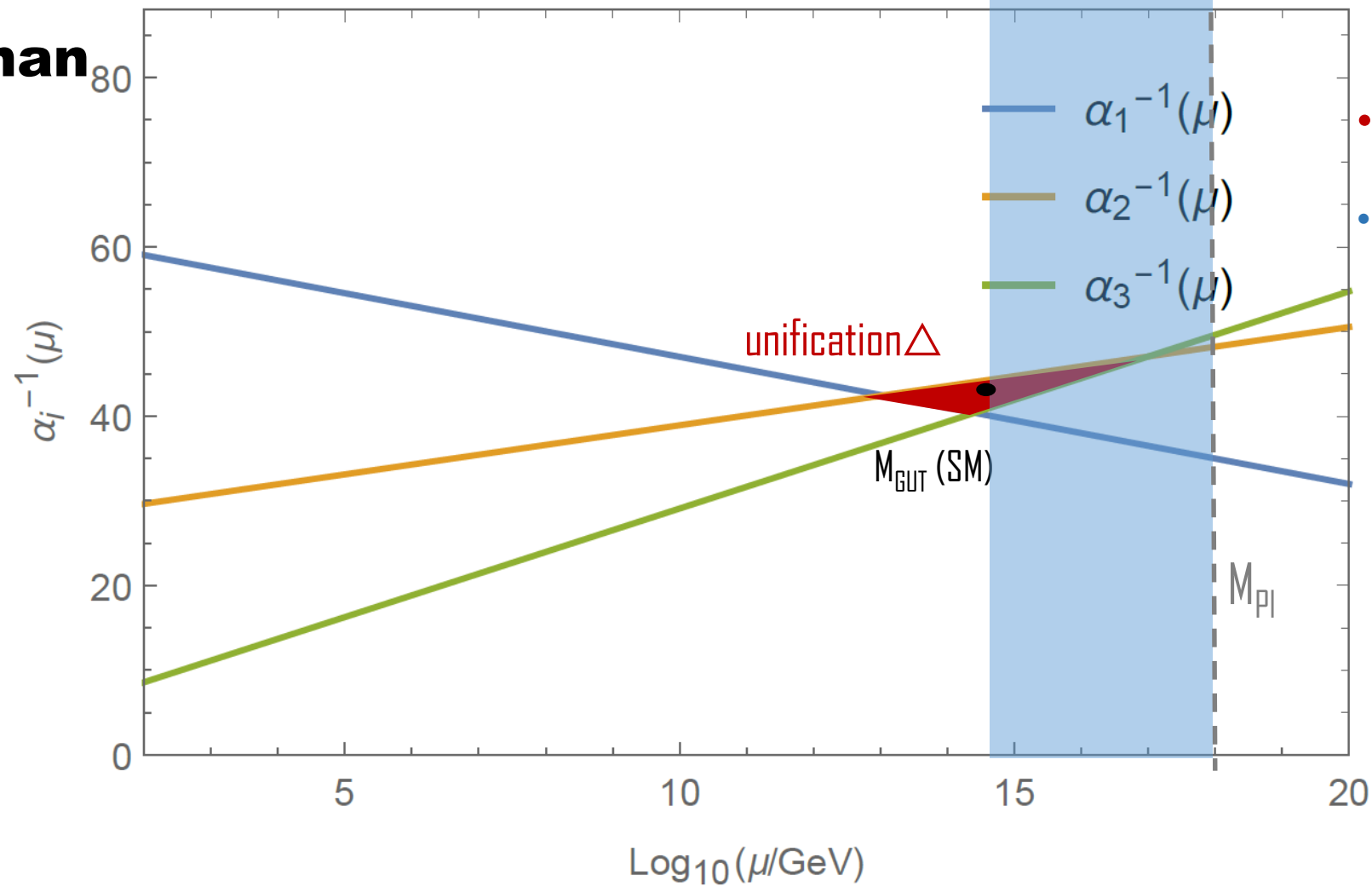
• $\text{Area}_{\triangle}(\text{SM+BSM}) \leq \text{Area}_{\triangle}(\text{SM})$

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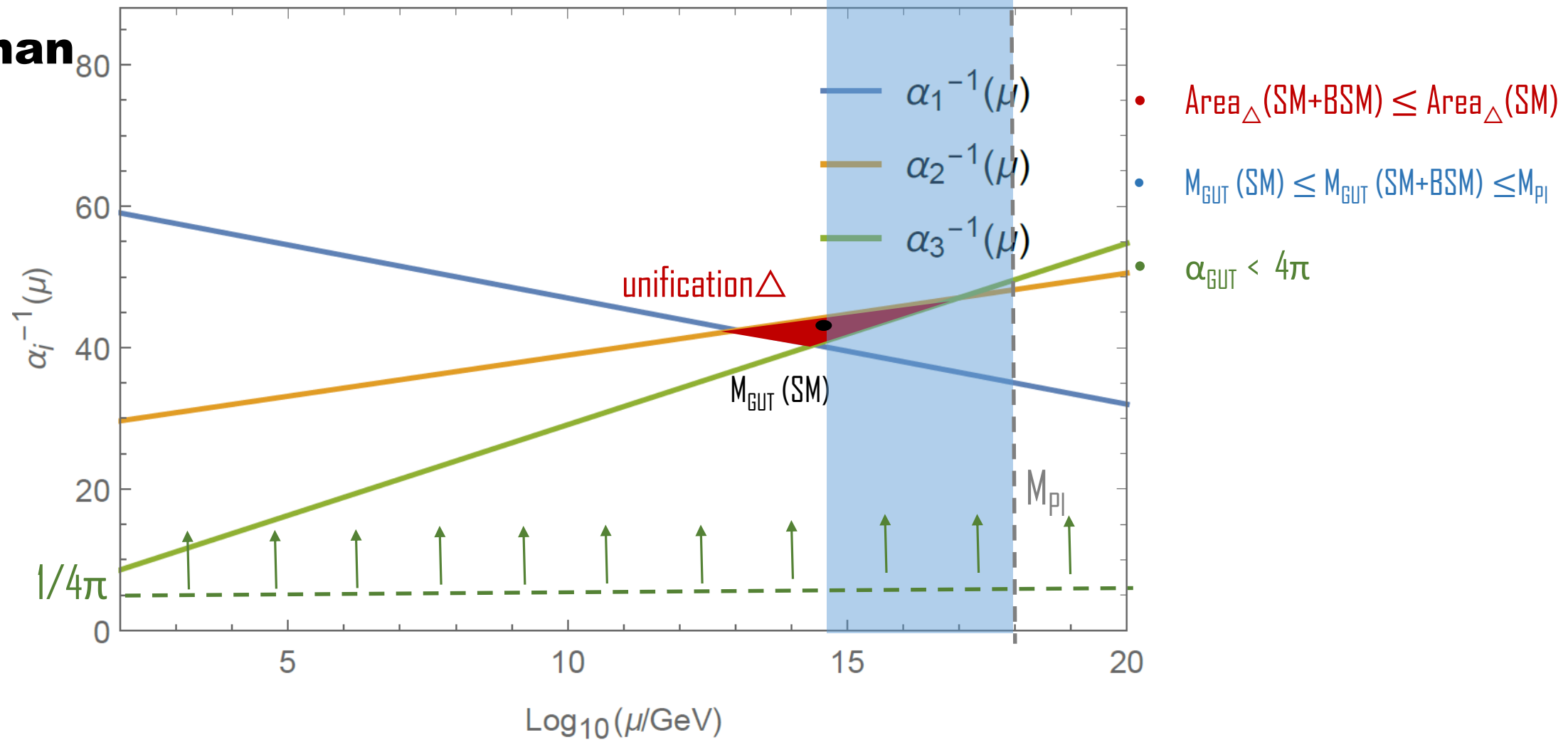
• $M_{\text{GUT}}(\text{SM}) \leq M_{\text{GUT}}(\text{SM}+\text{BSM}) \leq M_{\text{Pl}}$

Unification Criterion?

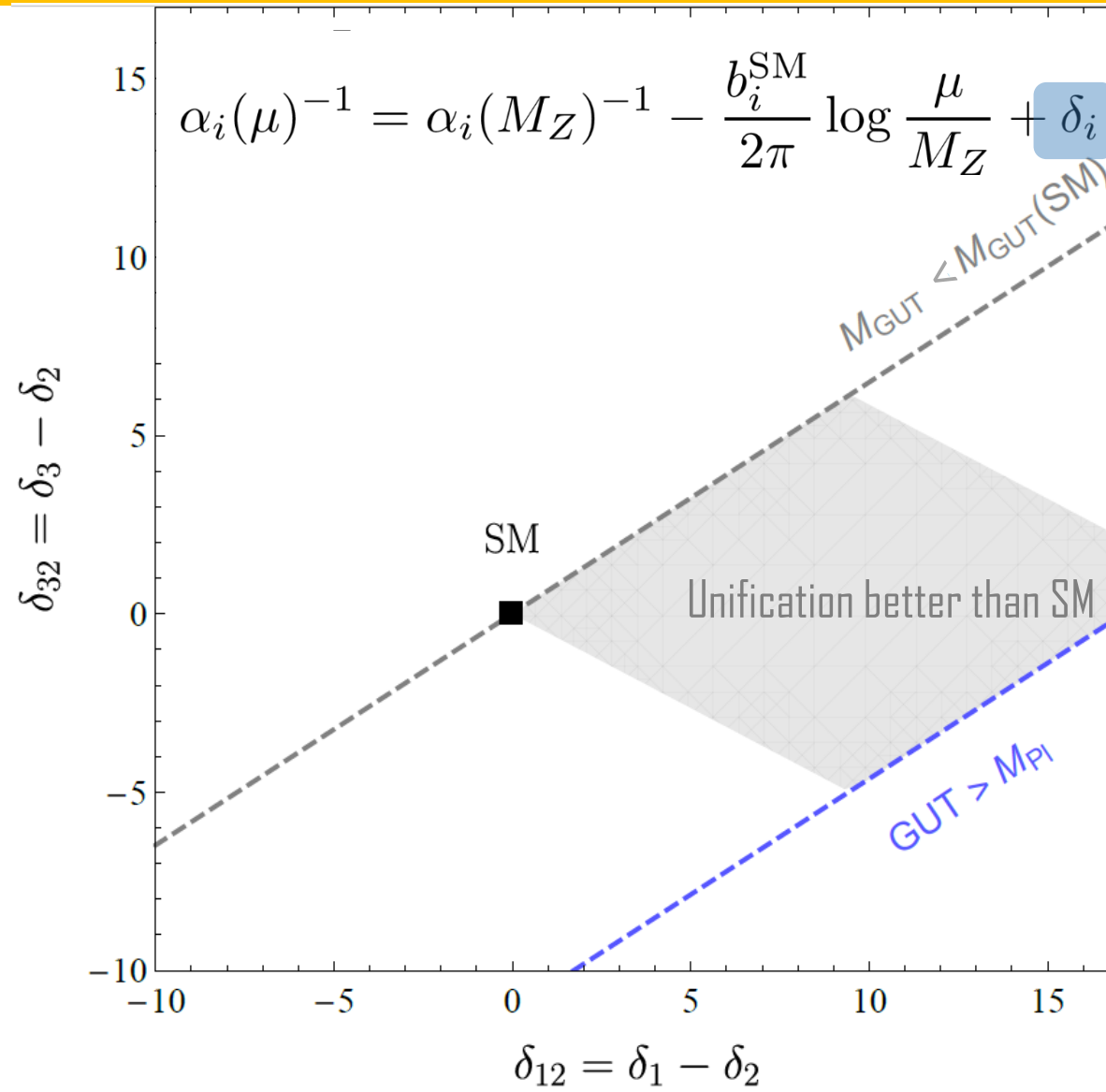
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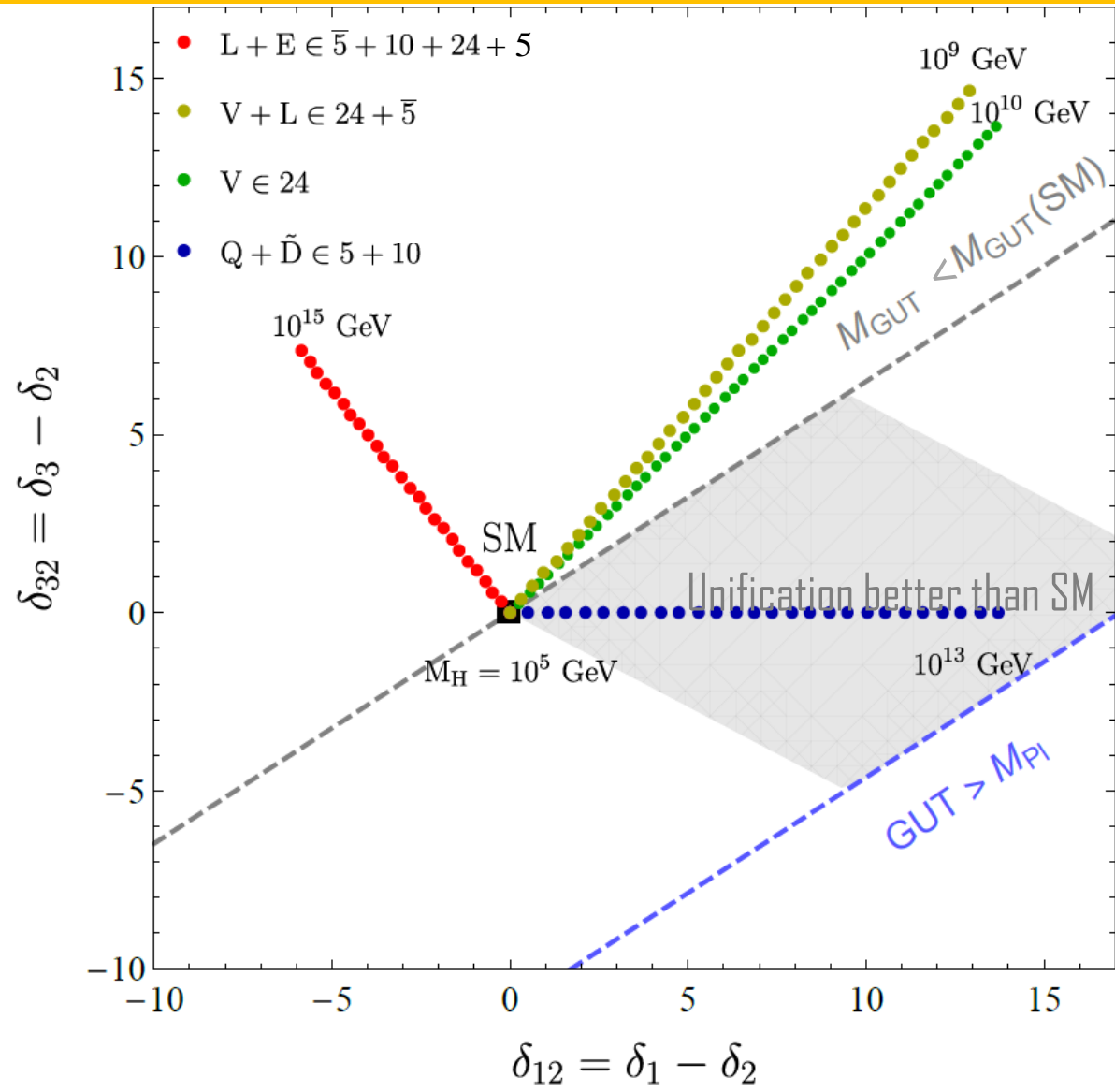
Good models?



NP running
contribution to
SM couplings

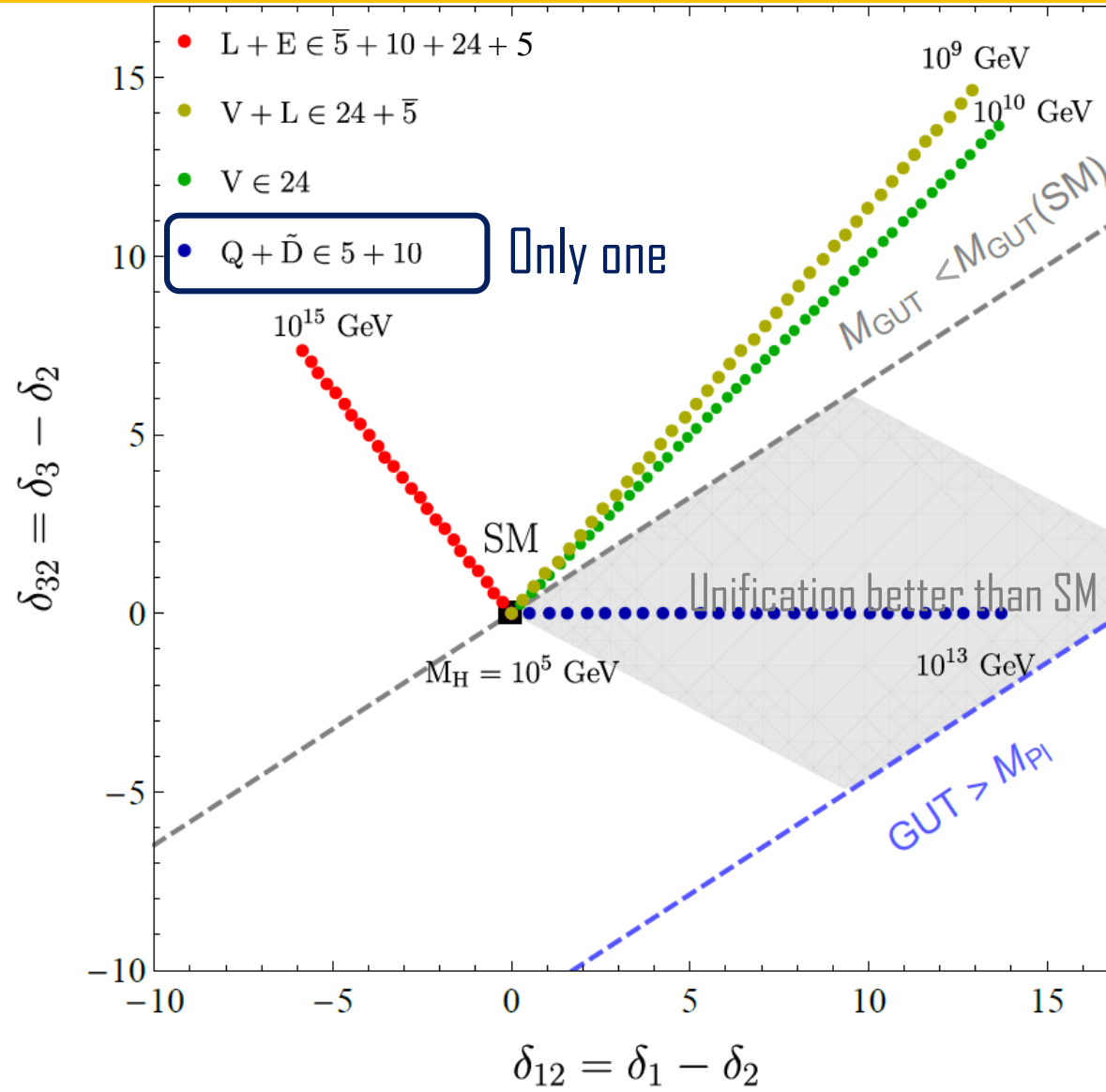
Good models?

$SU(3)_{DC}$



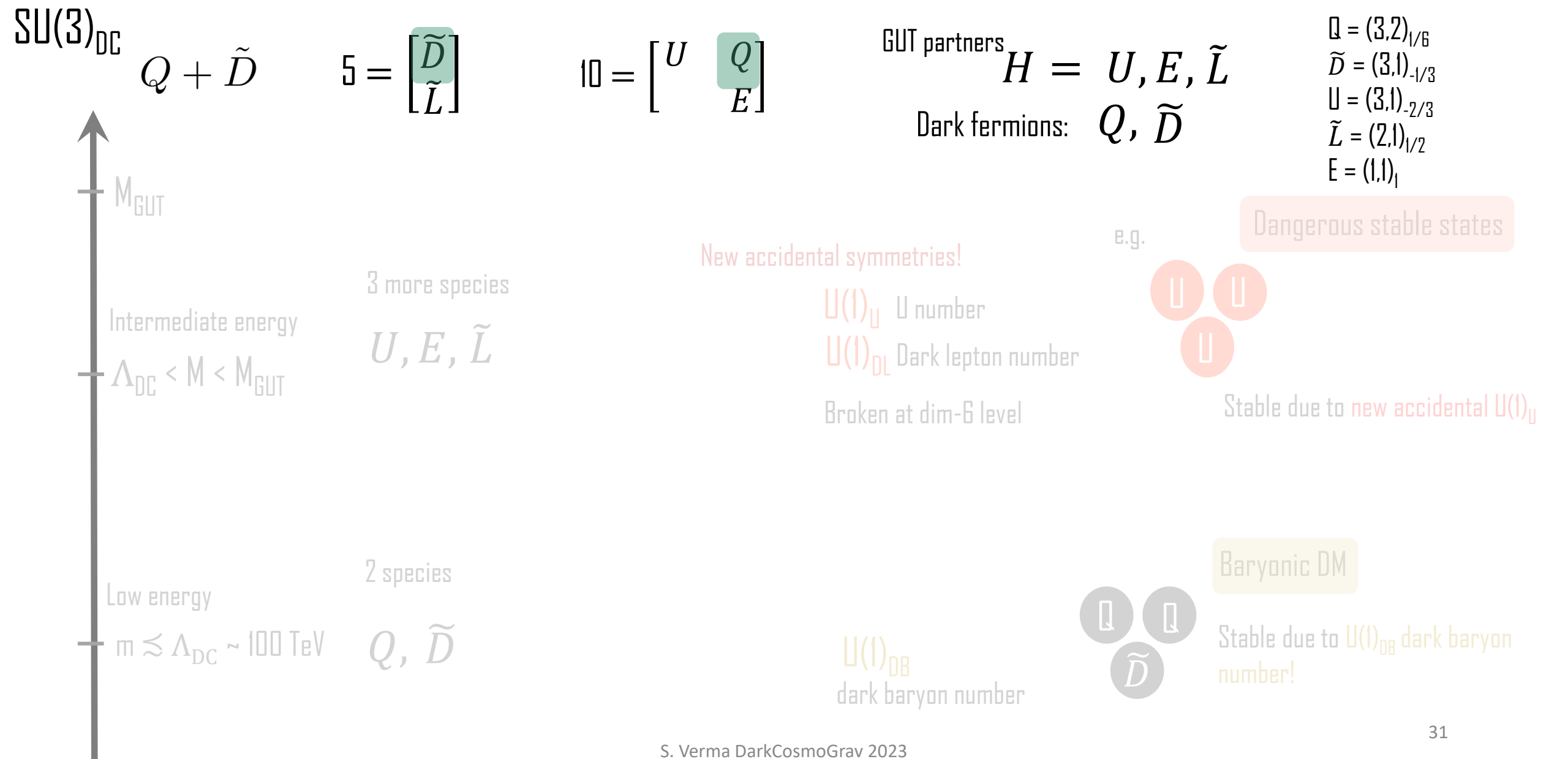
Good models?

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More accidental symmetries?

Bottaro, Contino, SV [In prep]



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Bottaro, Contino, SV [In prep]

$SU(3)_{DC}$

$Q + \tilde{D}$

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

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

GUT partners $H = U, E, \tilde{L}$

Dark fermions: Q, \tilde{D}



M_{GUT}

Intermediate energy

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

3 more species

U, E, \tilde{L}

Low energy

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

2 species

Q, \tilde{D}

New accidental symmetries!

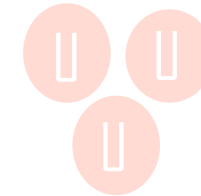
$U(1)_U$ U number

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

Broken at dim-6 level

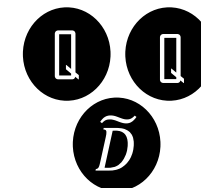
$U(1)_{DB}$
dark baryon number

e.g.



Dangerous stable states

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



Baryonic DM

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

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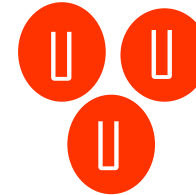
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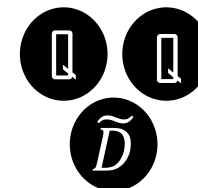
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Dangerous stable states

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

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

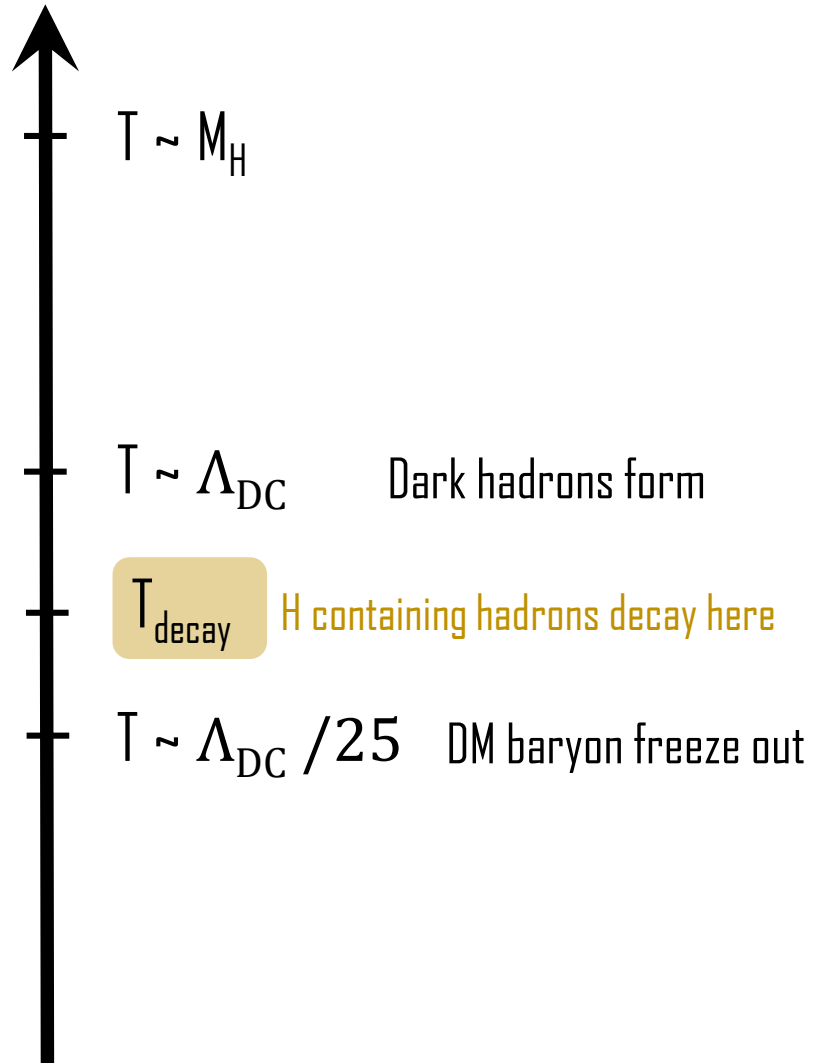


Baryonic DM

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

Thermal history?

Bottaro, Contino, SV [In prep]

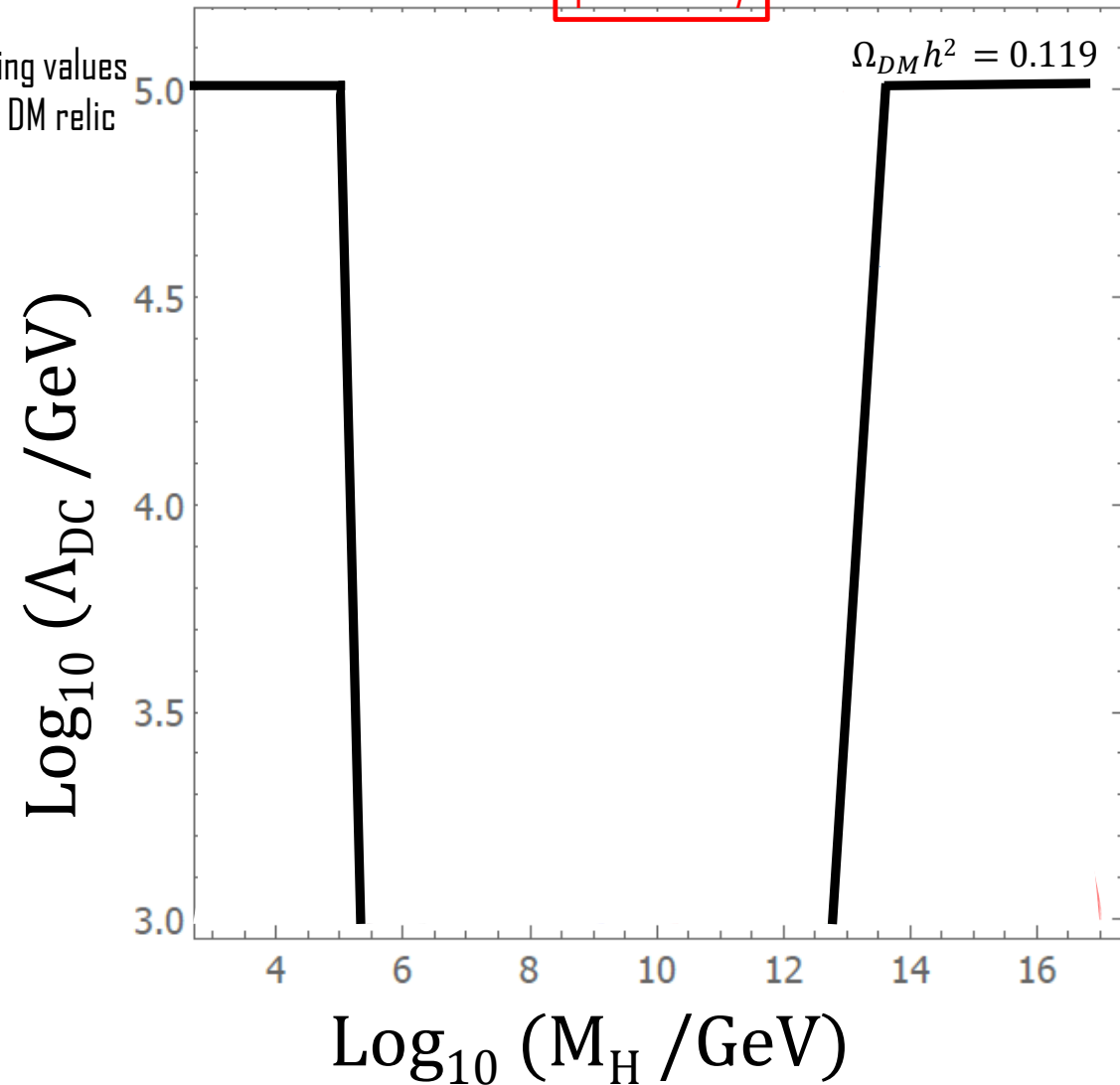
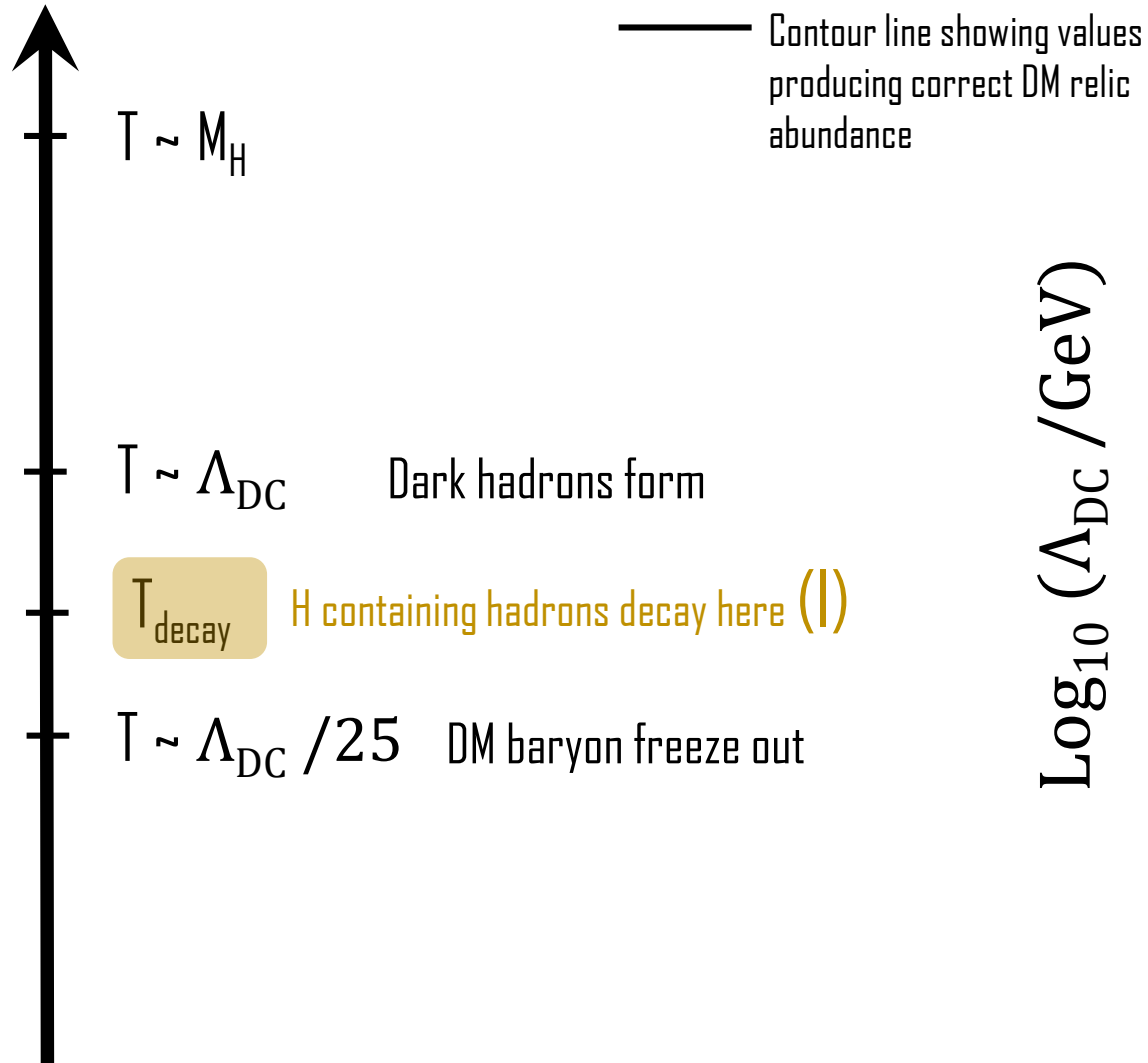


$$\tau_H \sim \left(\frac{g_{\text{GUT}}^4}{8\pi} \frac{M_H^5}{M_{\text{GUT}}^4} \right)^{-1}$$

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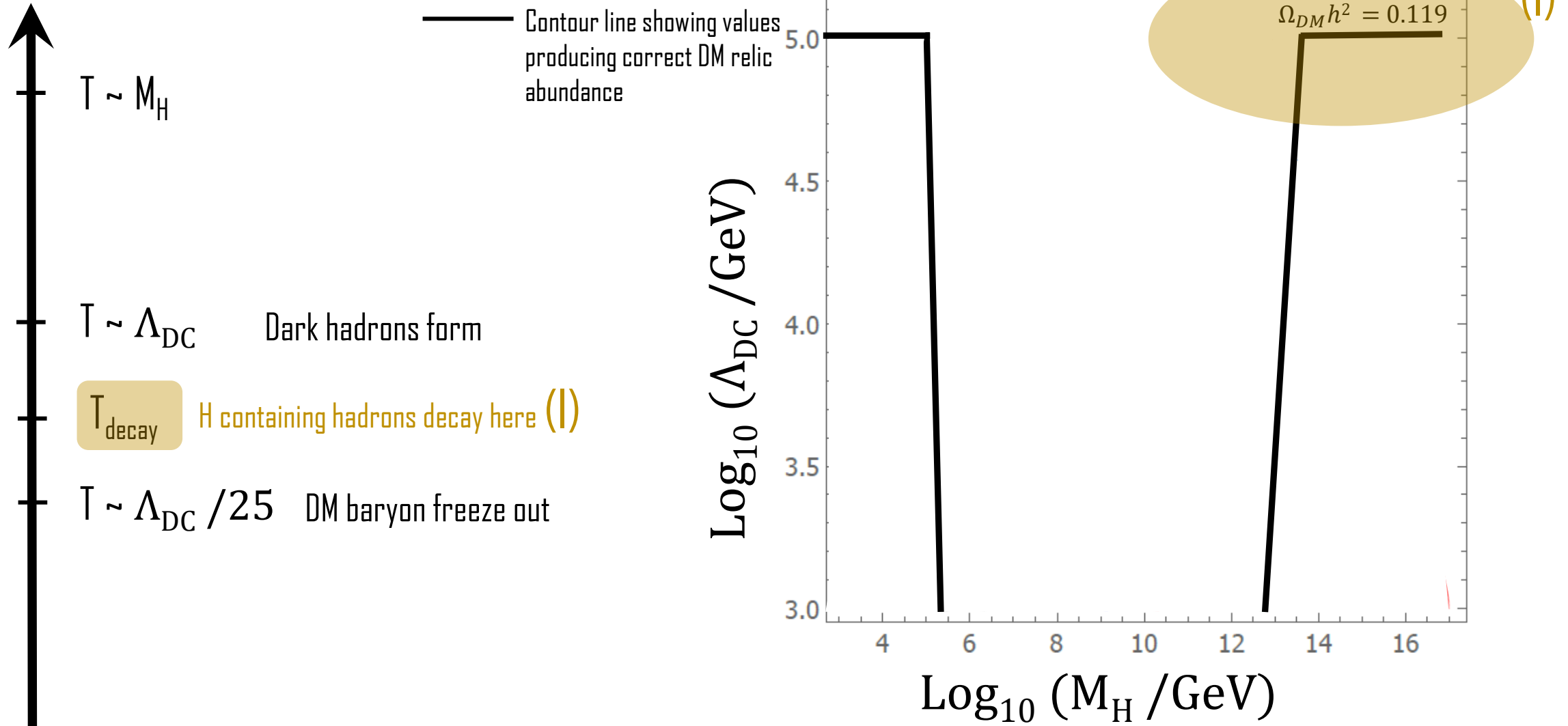
preliminary



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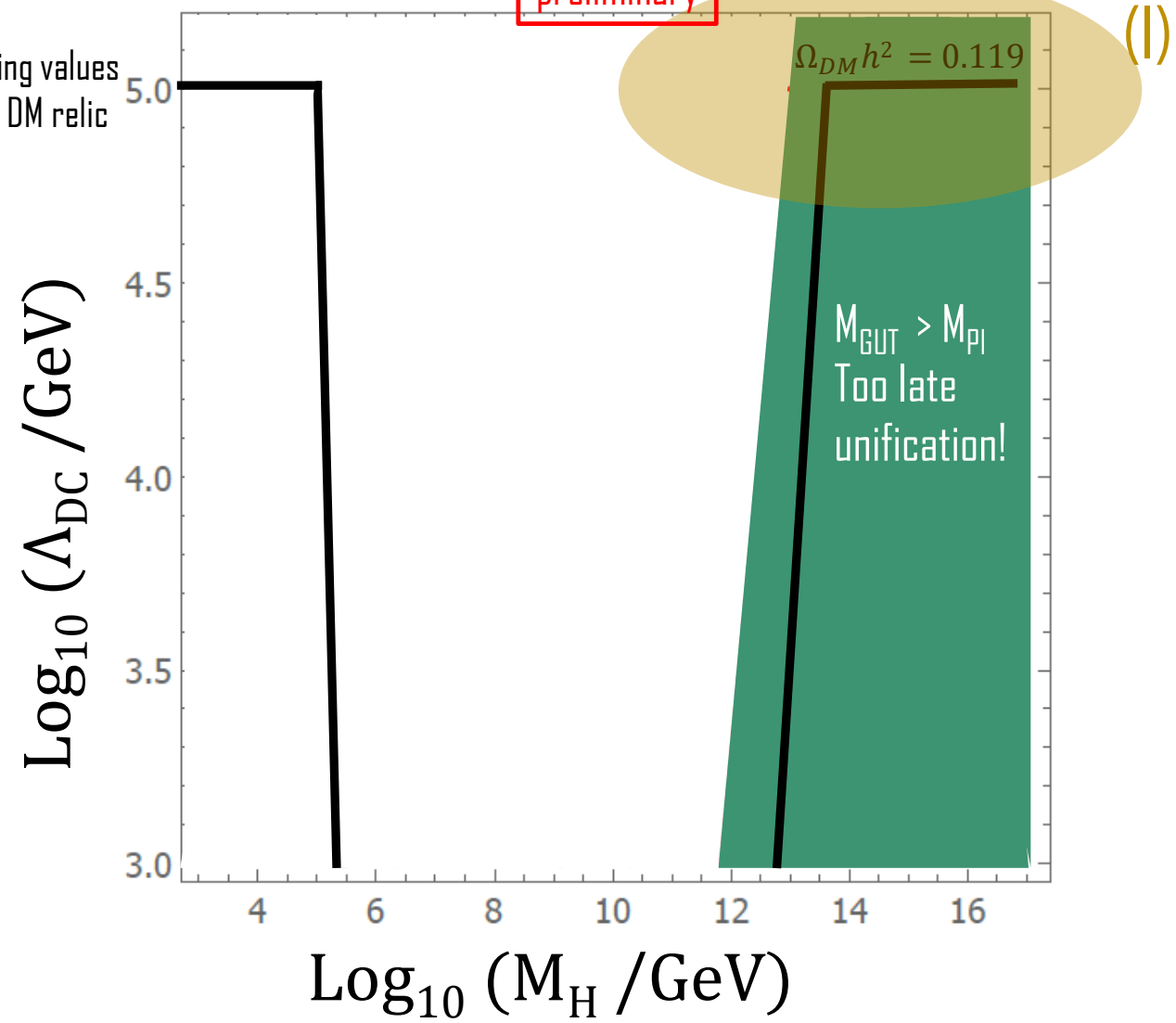
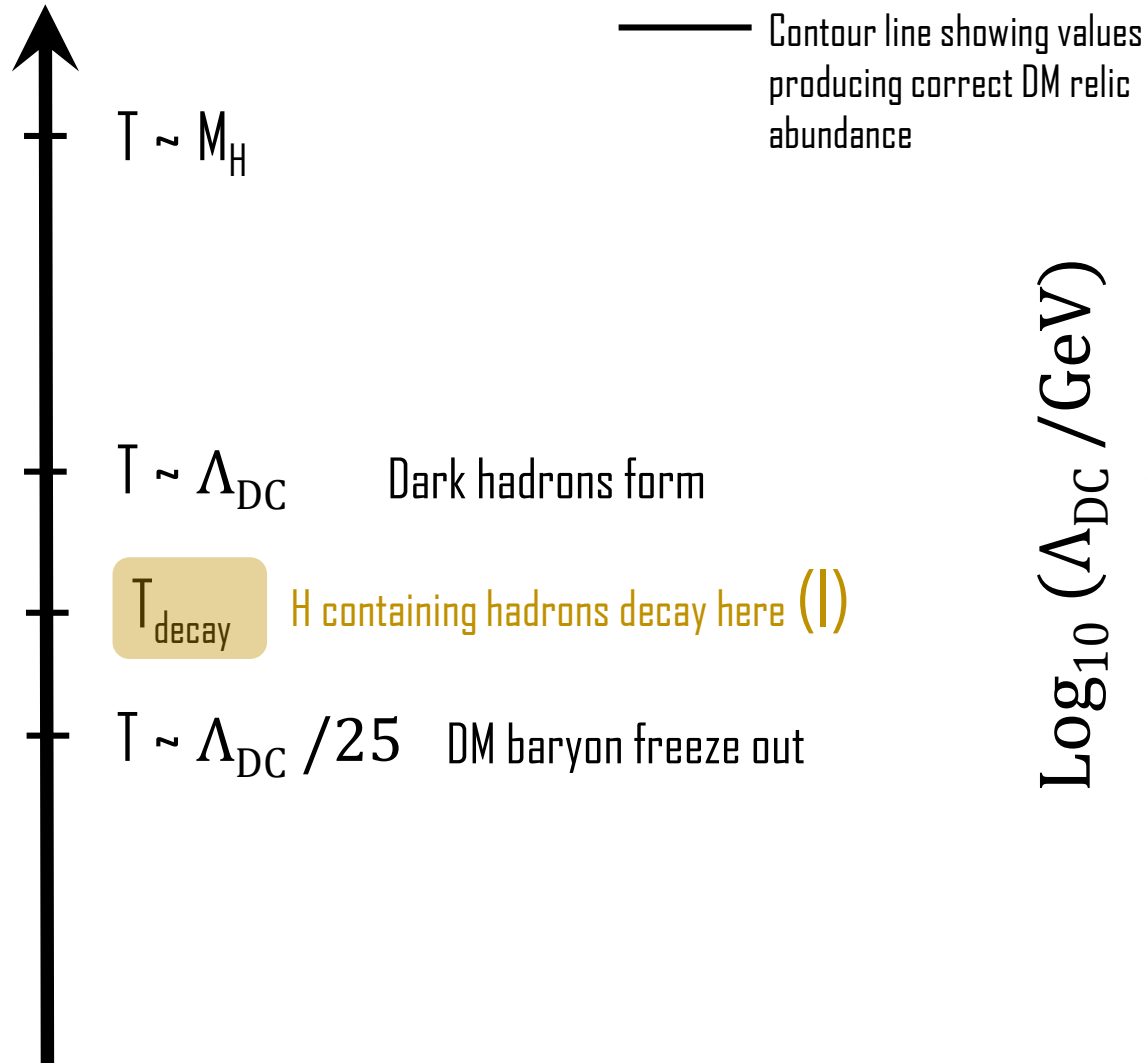
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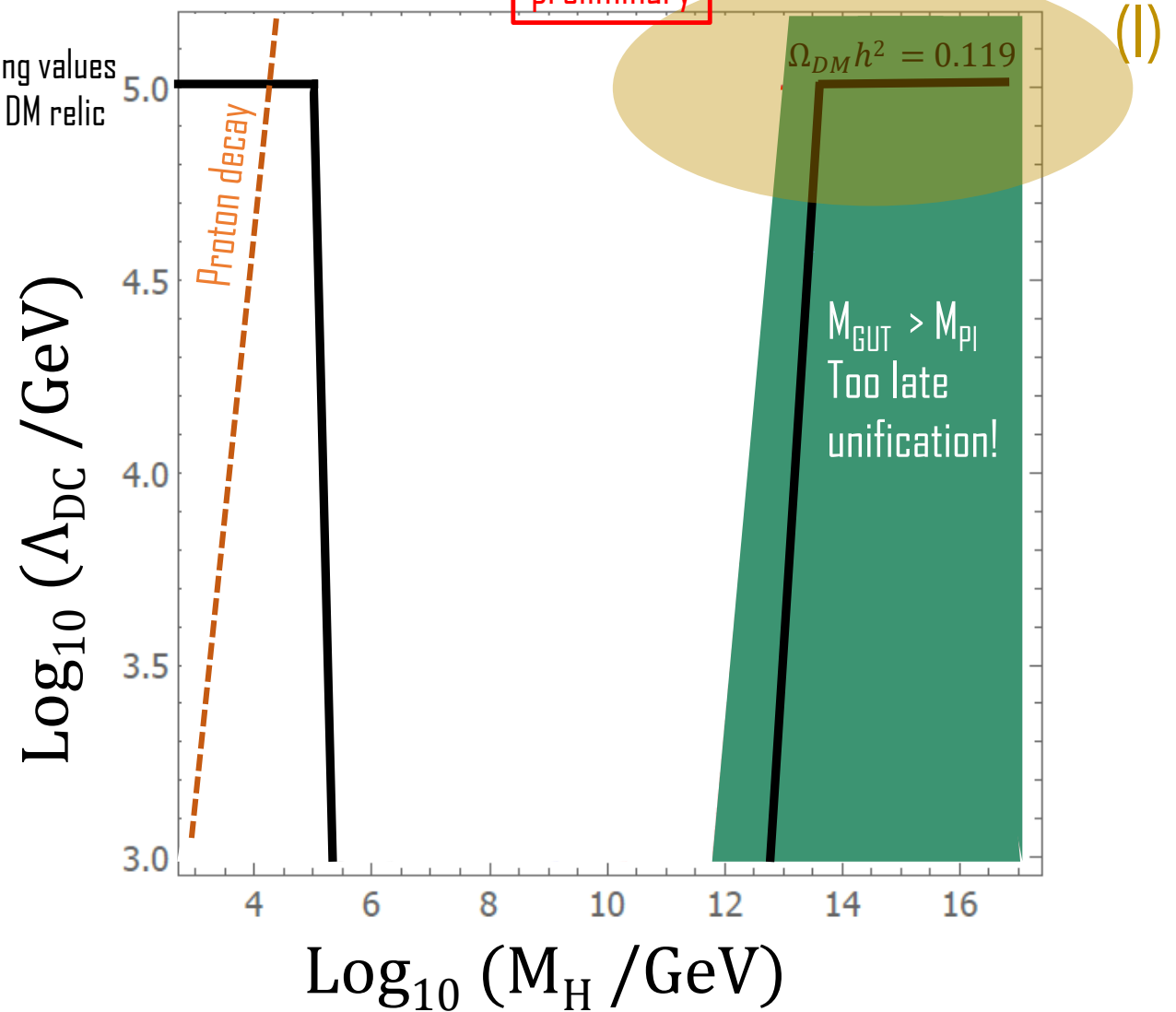
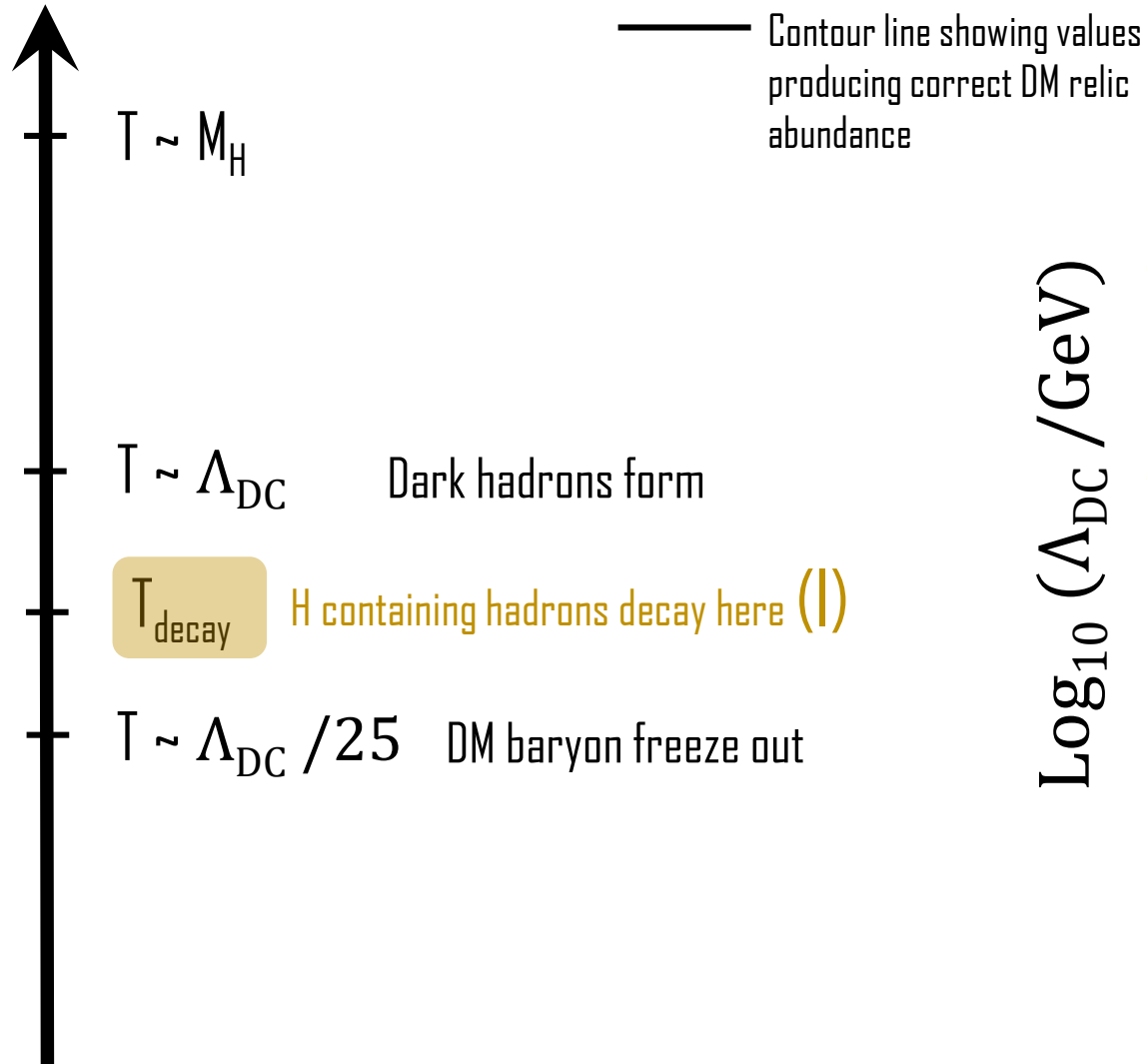
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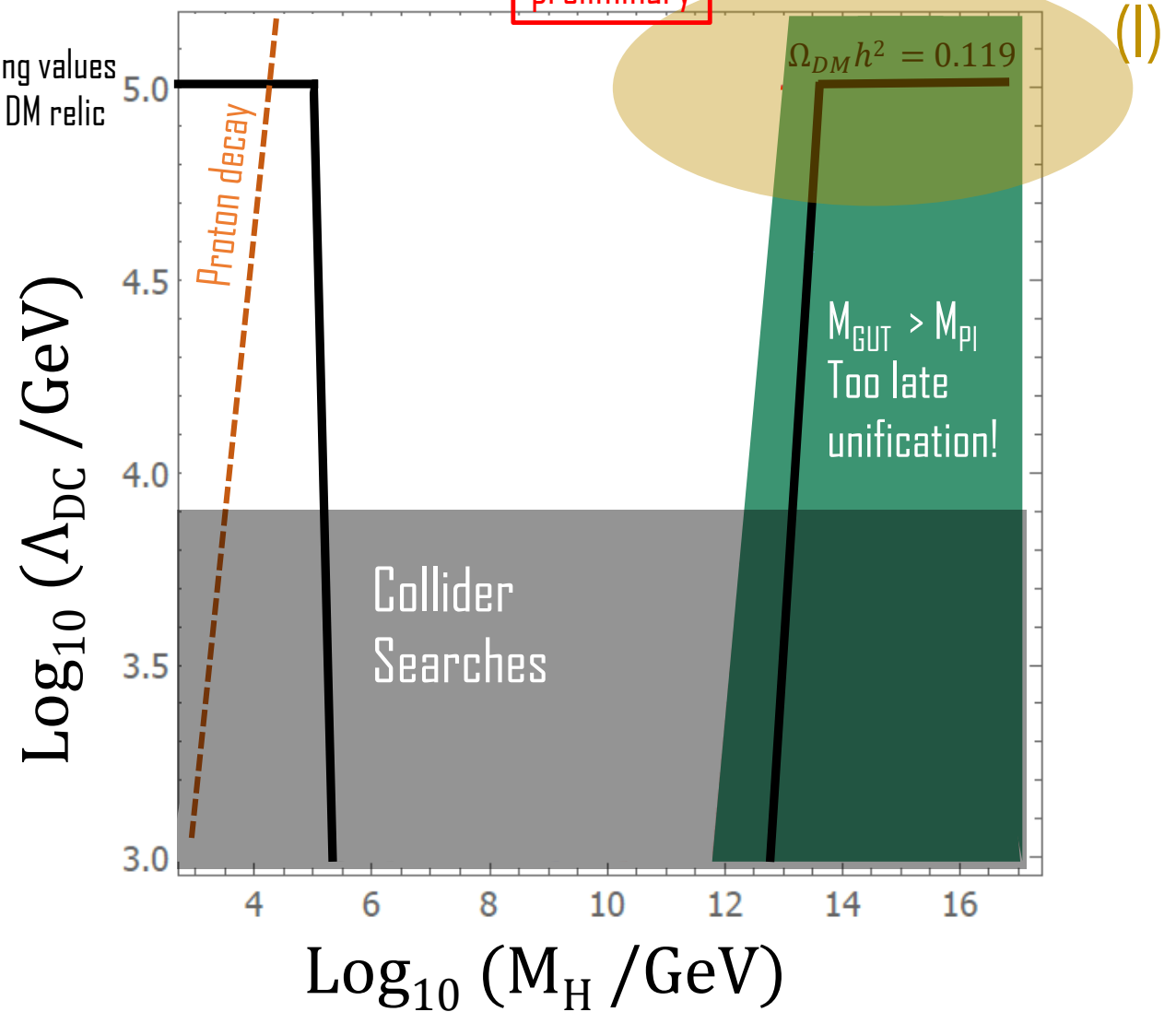
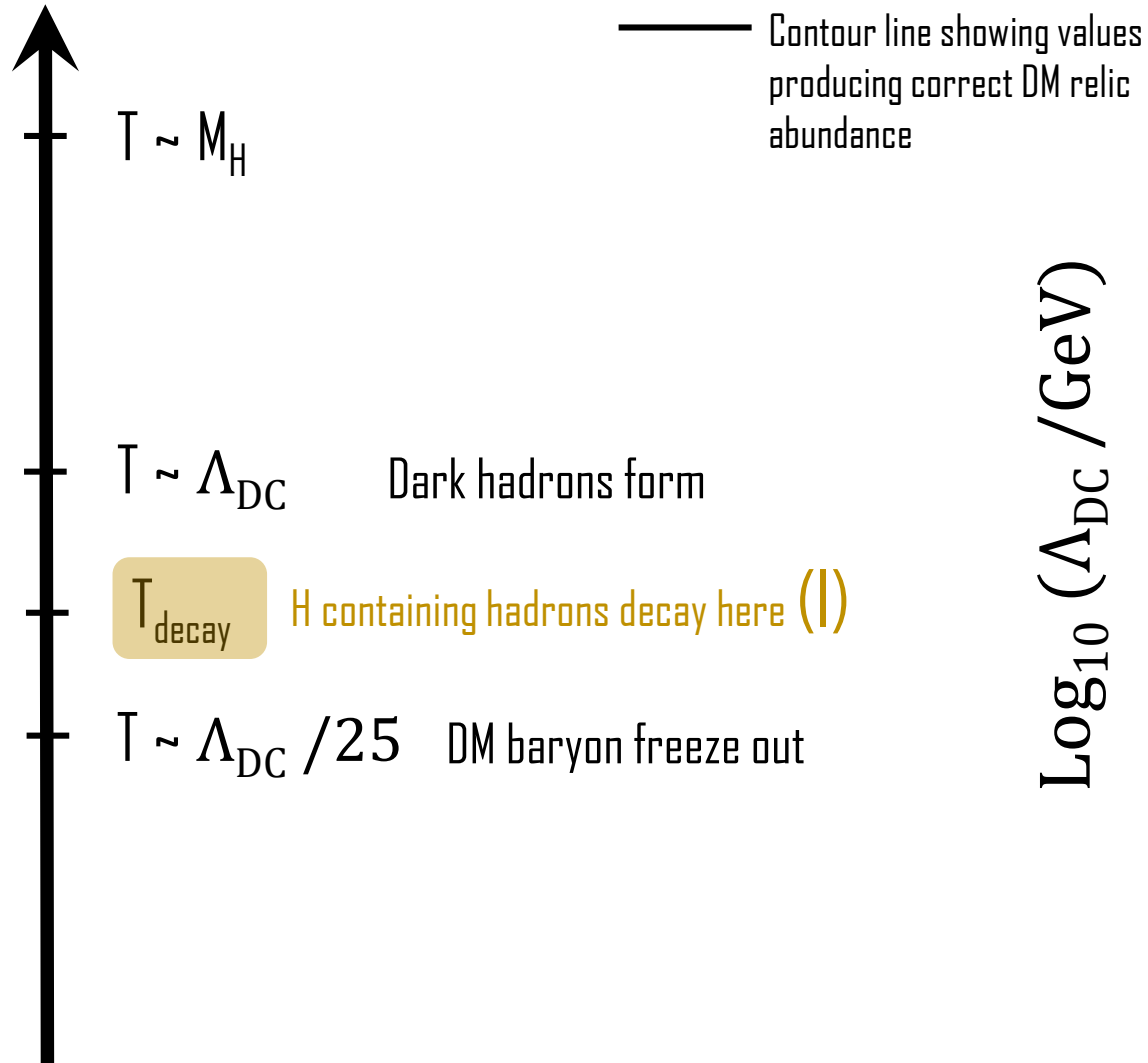
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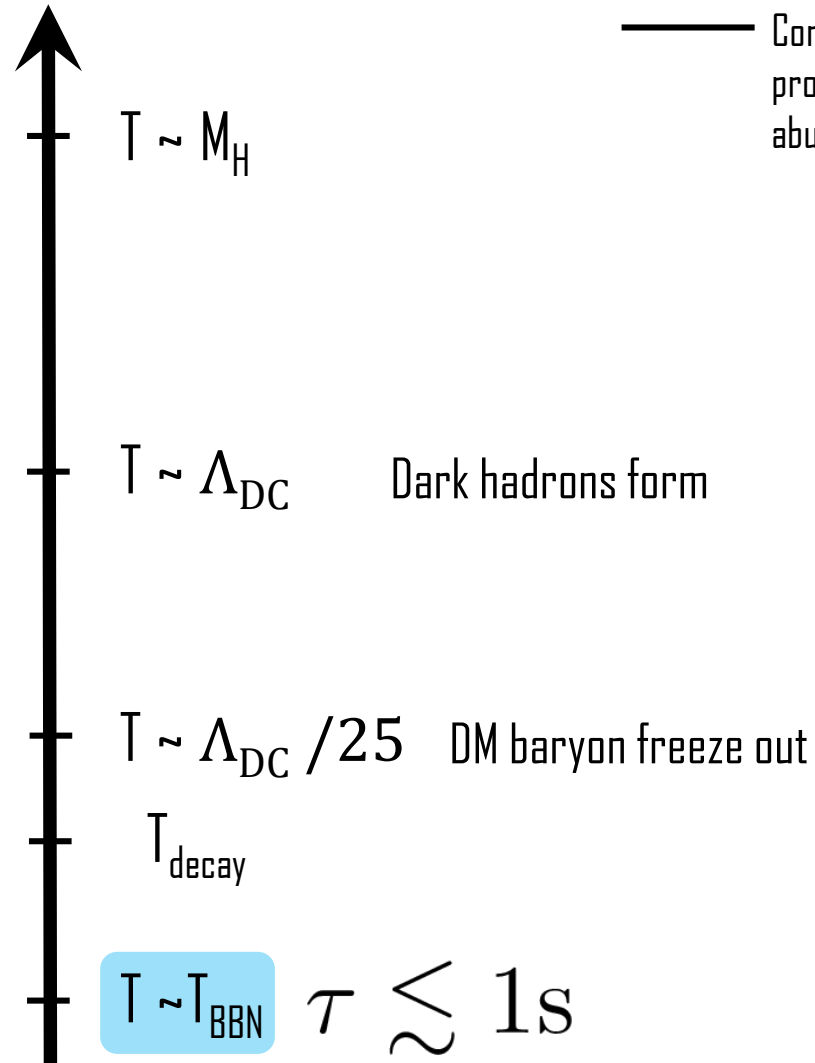
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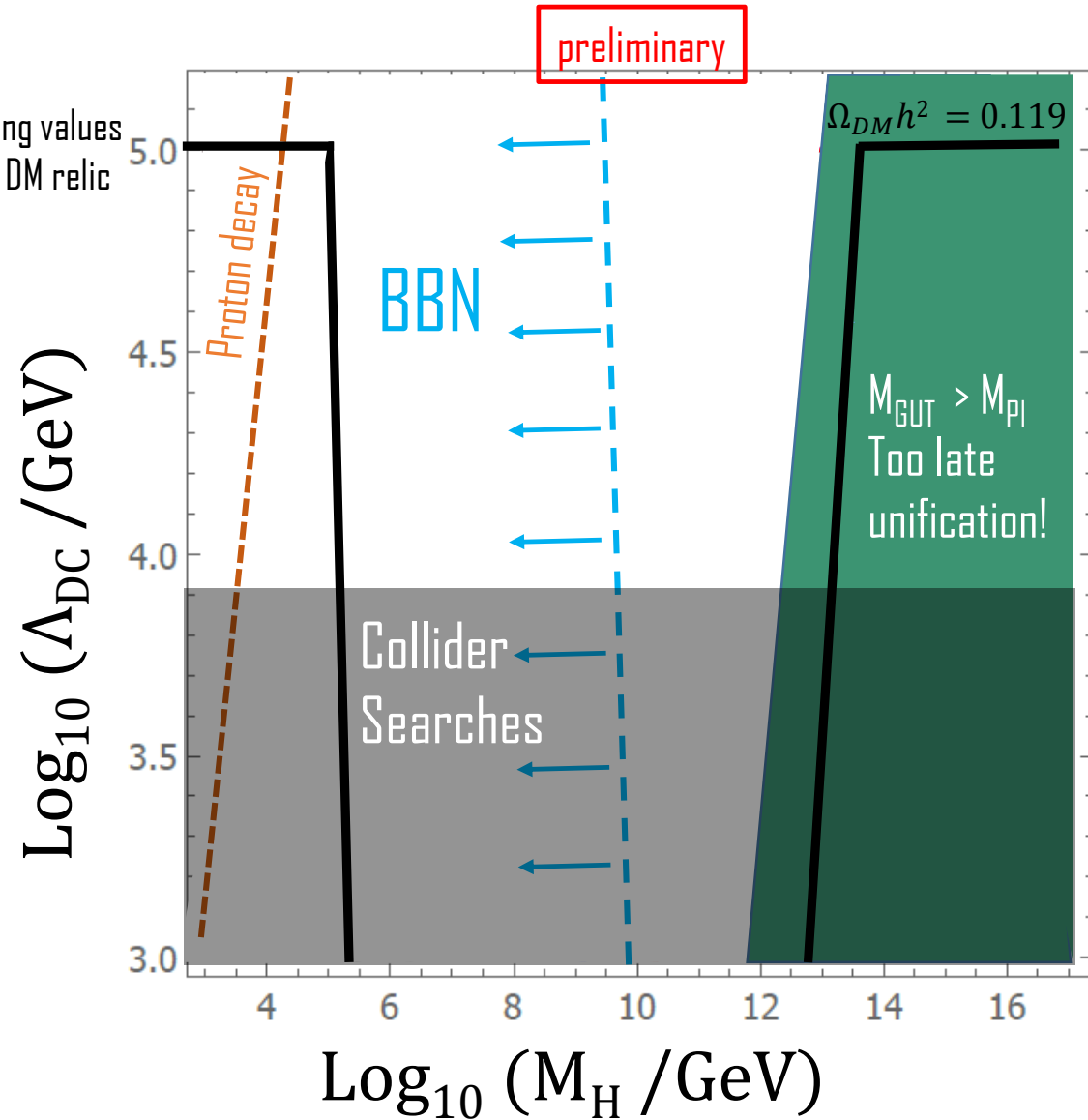


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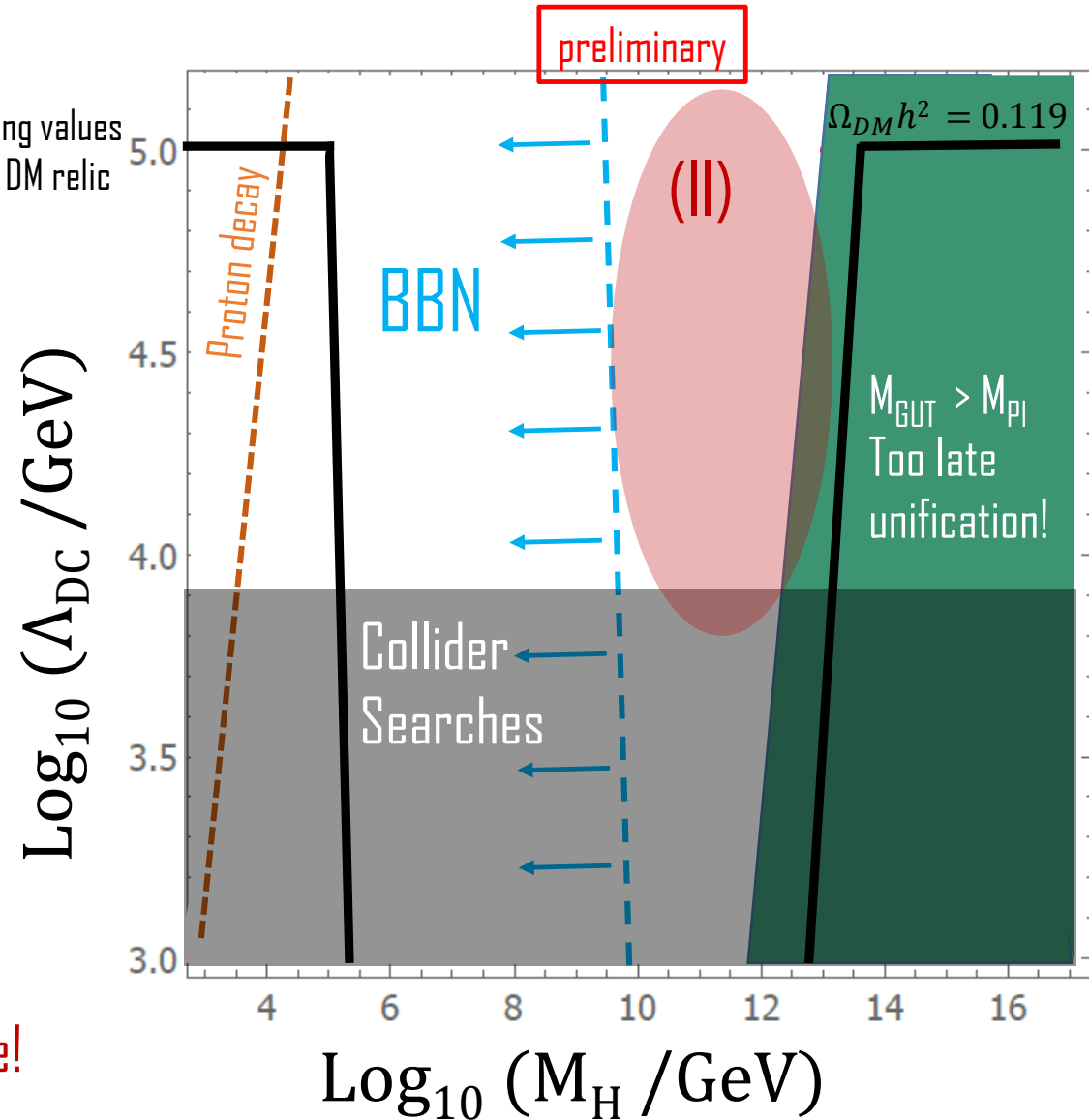
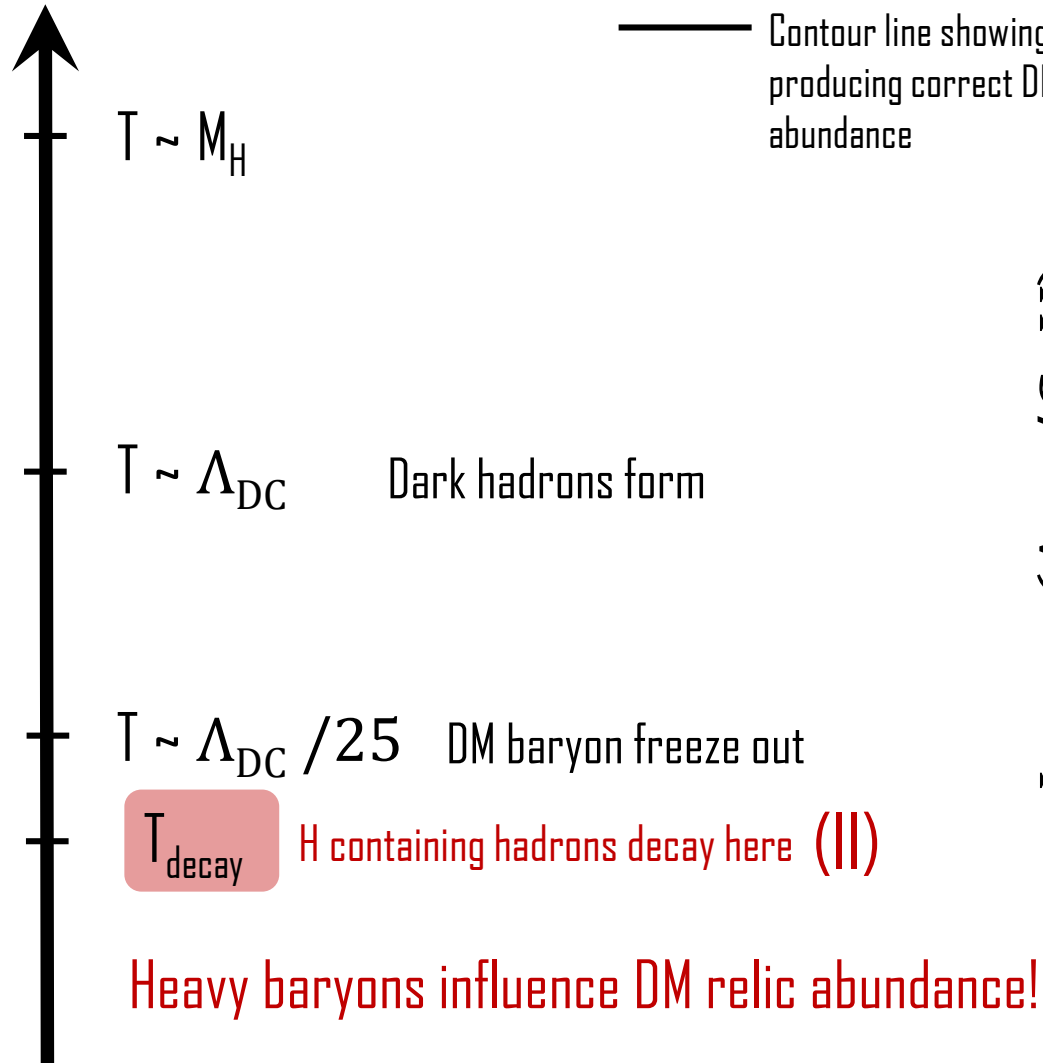


— Contour line showing values producing correct DM relic abundance

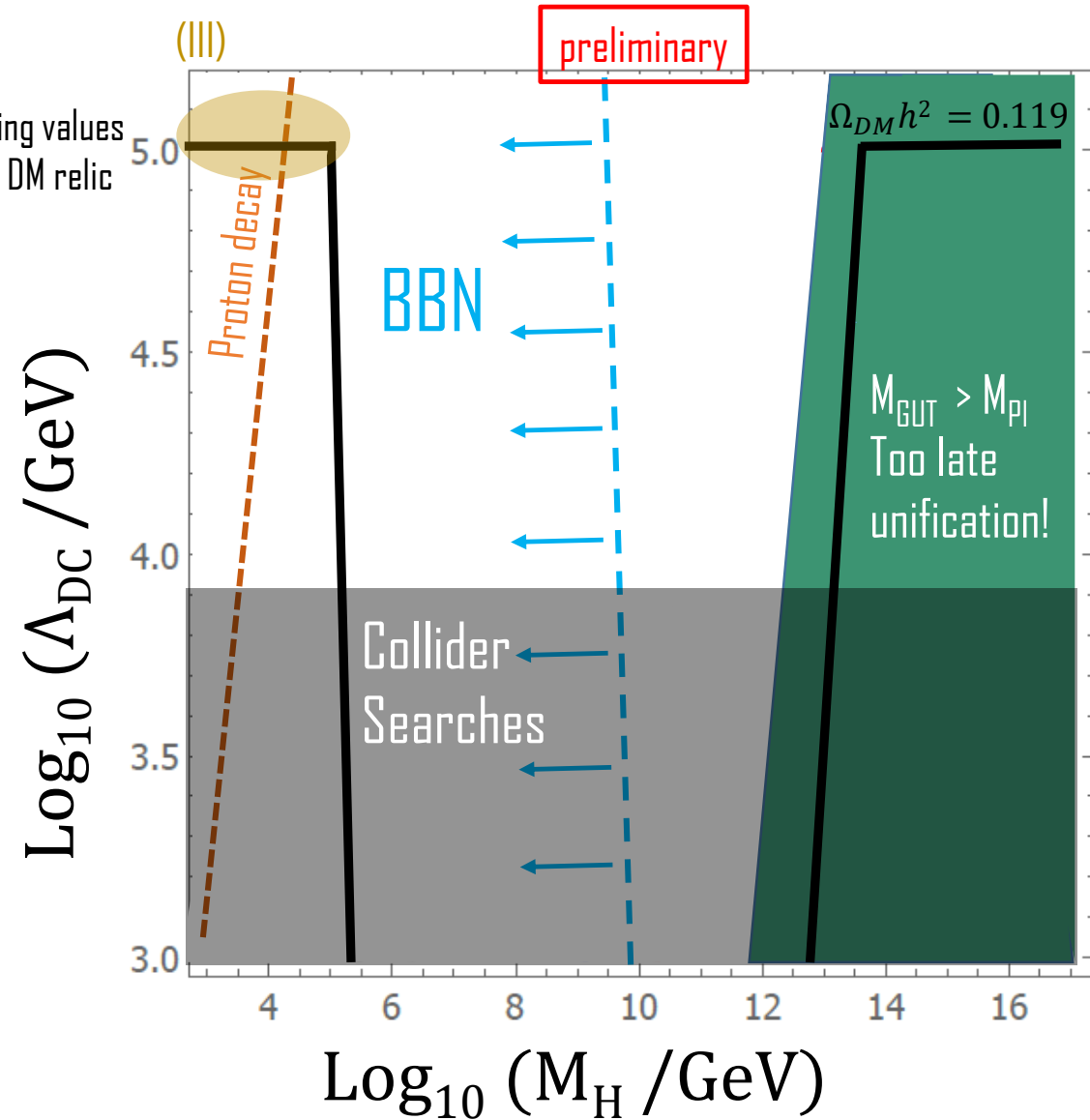
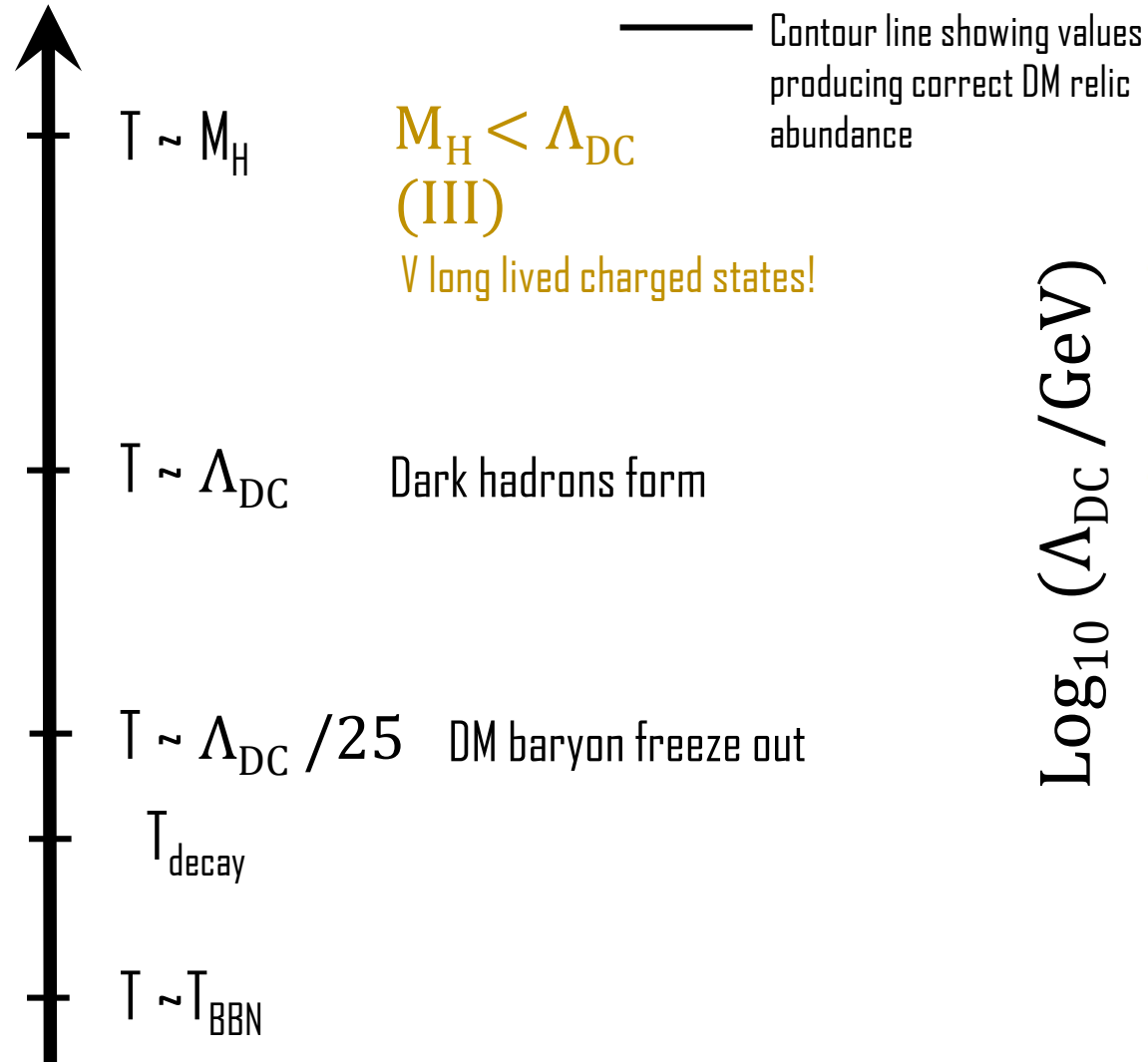


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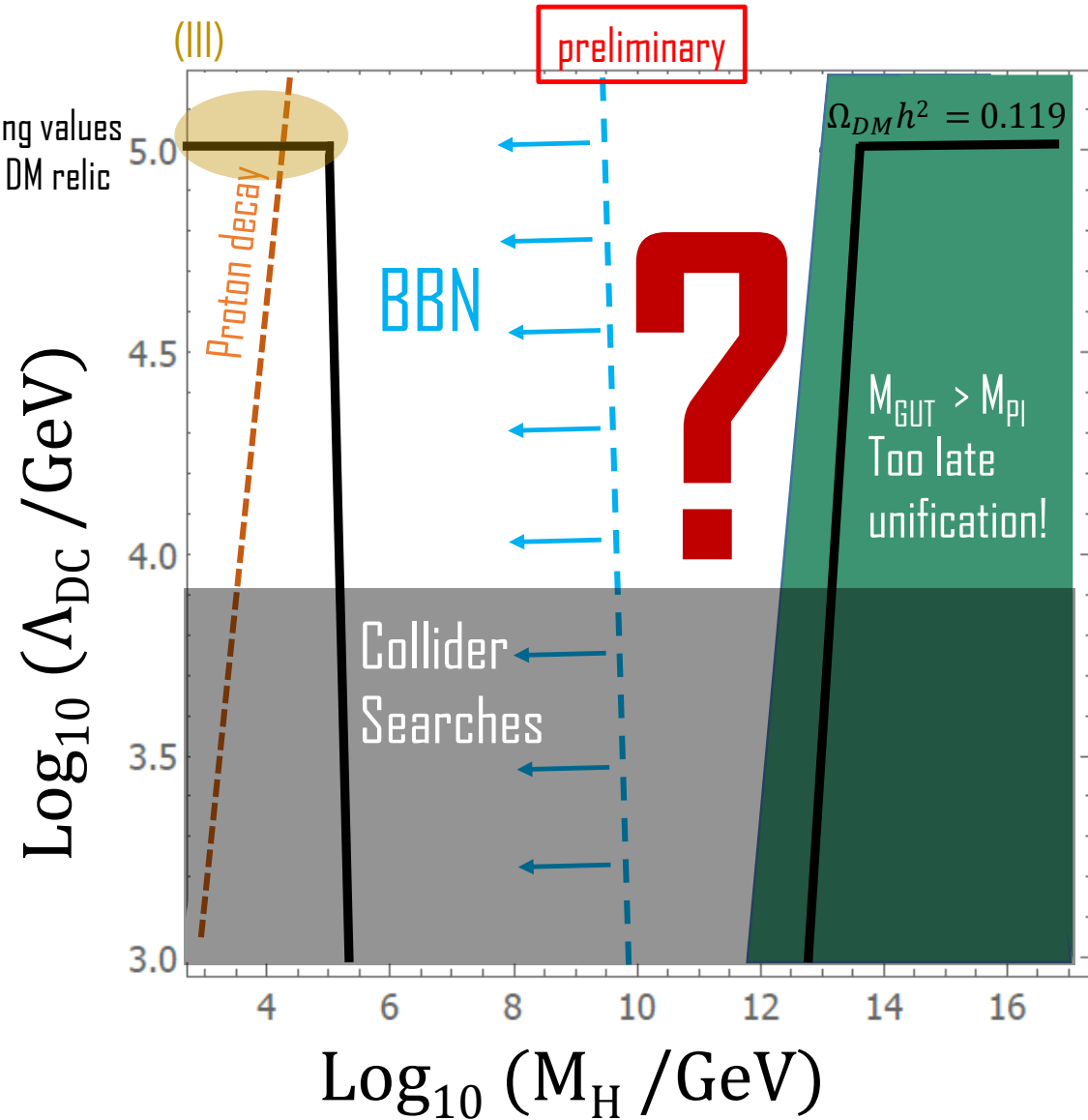
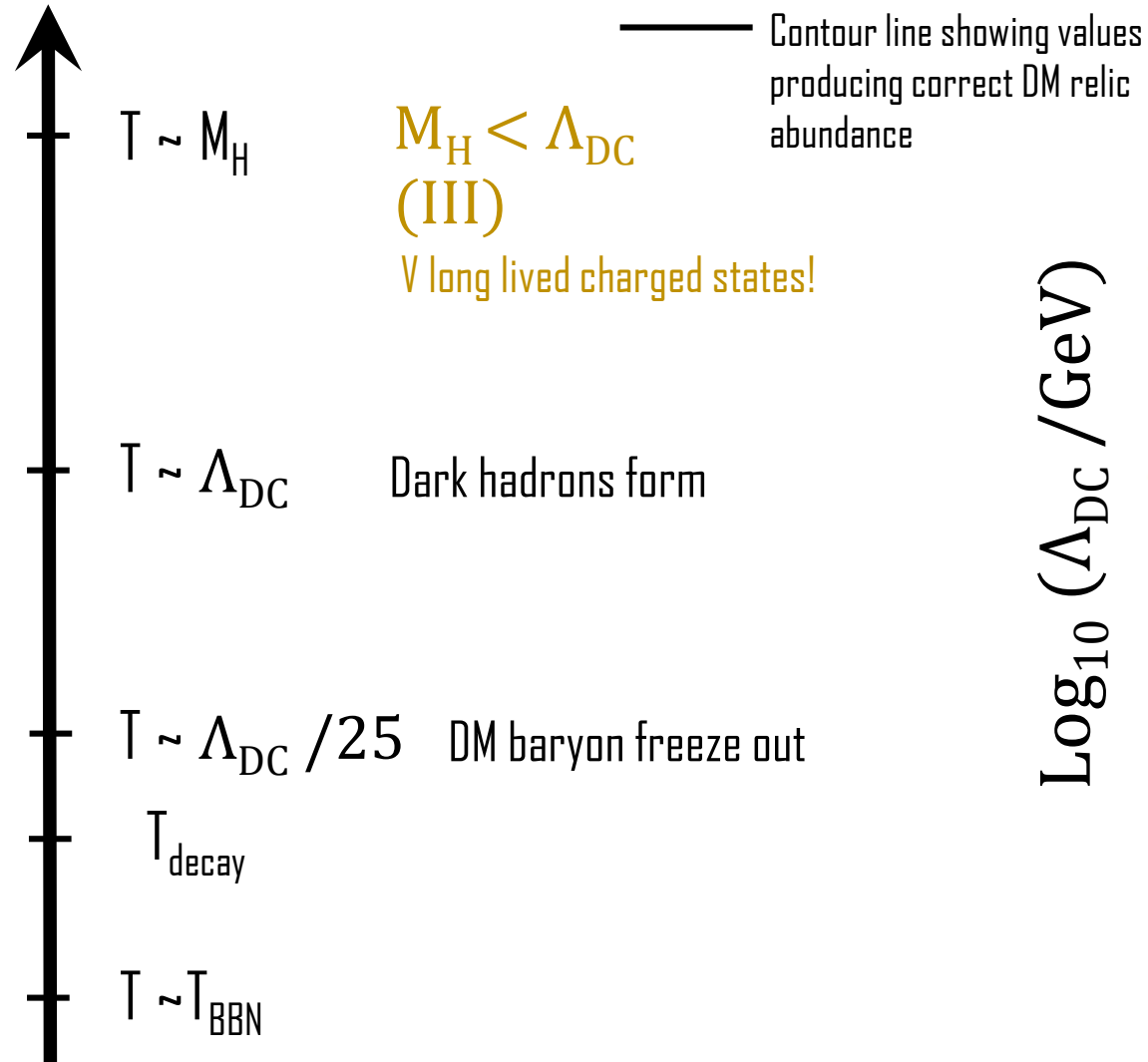


Thermal history?



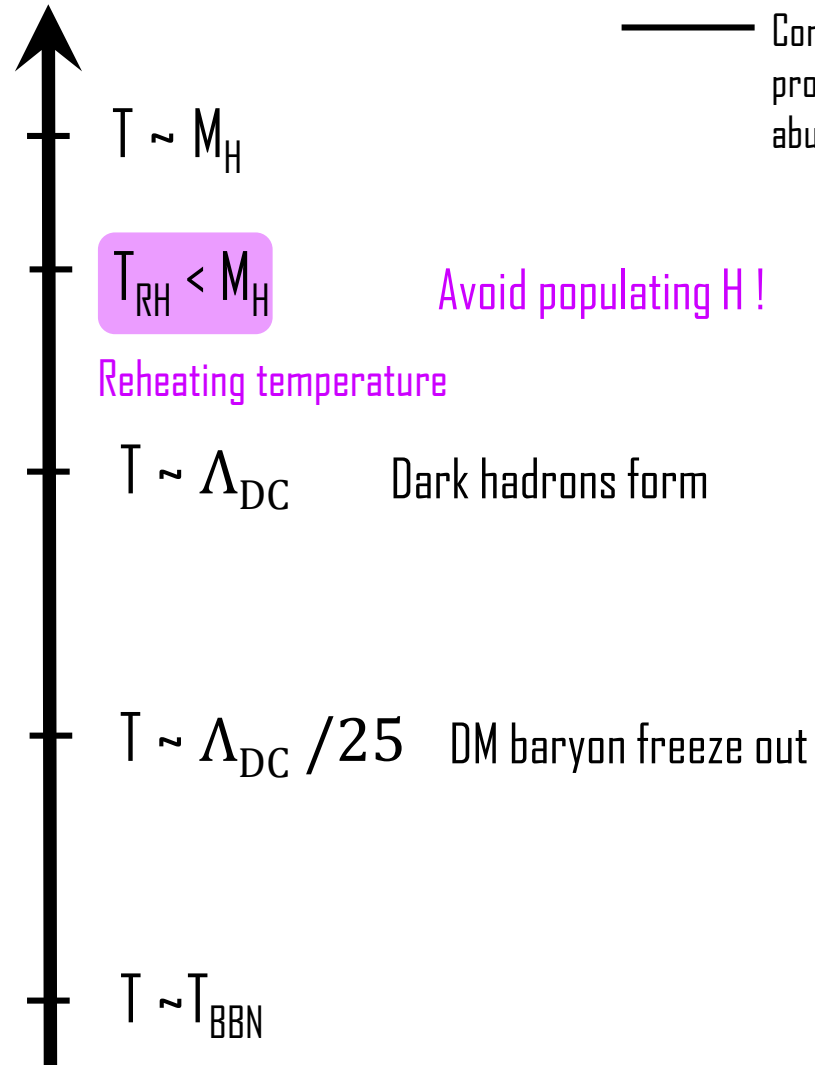
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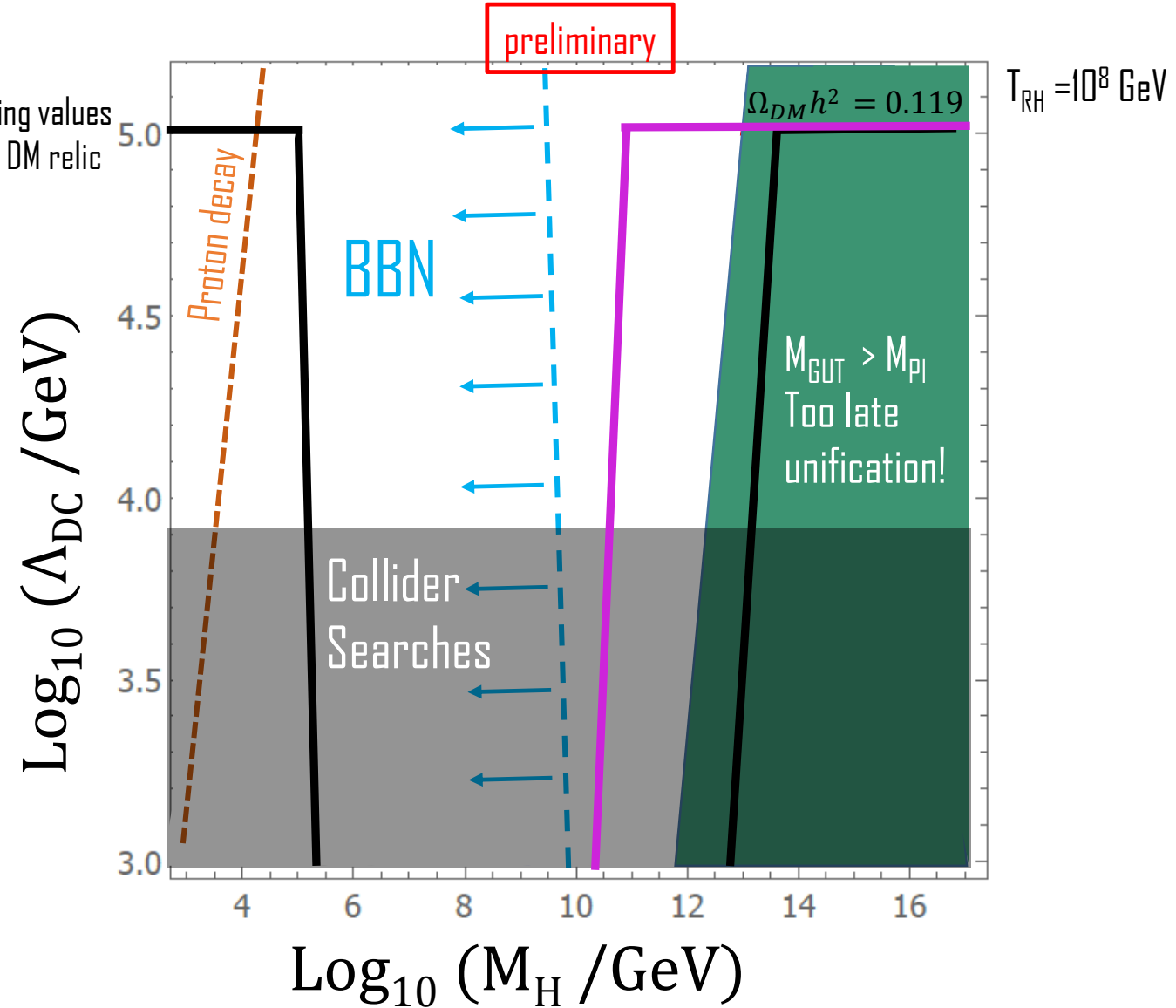


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Conclusion

- 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

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

SM as guiding principle

Standard Model

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DM stability due to an accidental symmetry like baryons in SM

Minimal Extension

 \mathcal{G}_{SM}

Standard Model

+

 \mathcal{G}_{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, Vigiani 2015]

[Mitridate, Redi, Smirnov, Strumia 2017]

For chiral dark fermions, see for example:

[Contino, Podo, Revello 2020]

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

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

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

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

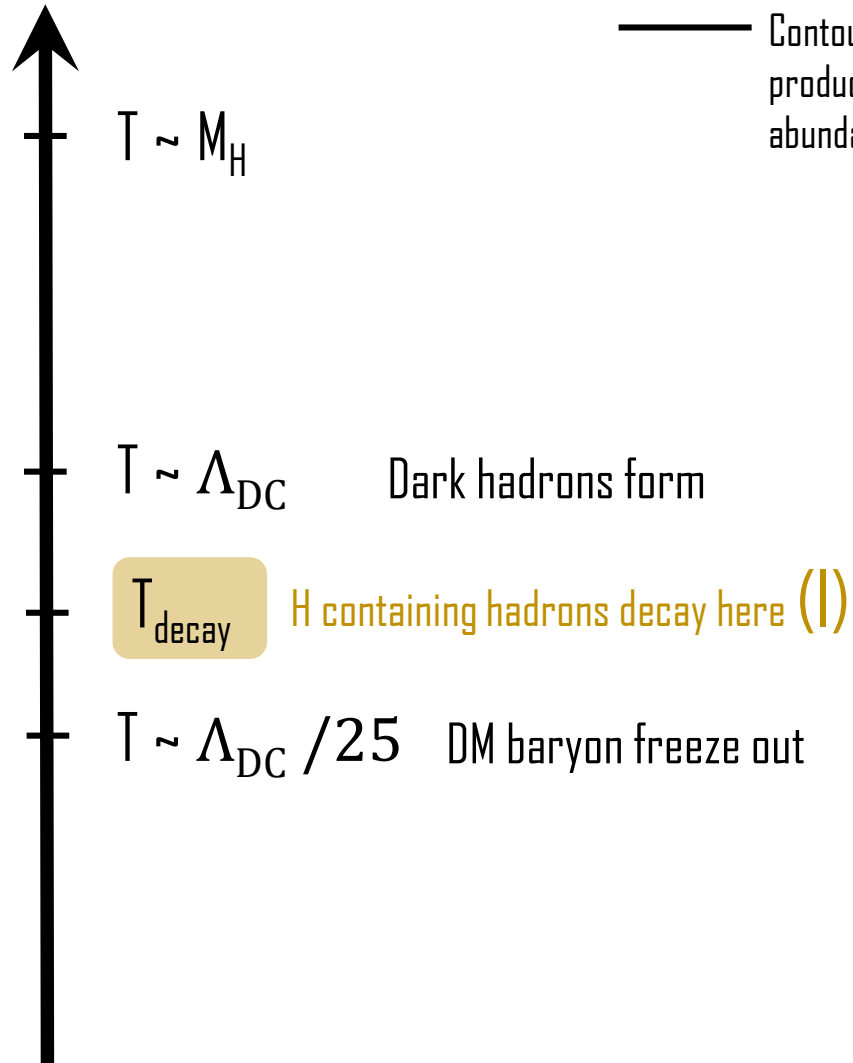
$$m_{\tilde{L}} = m_5 + \frac{3}{\sqrt{30}} y_5 v$$

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

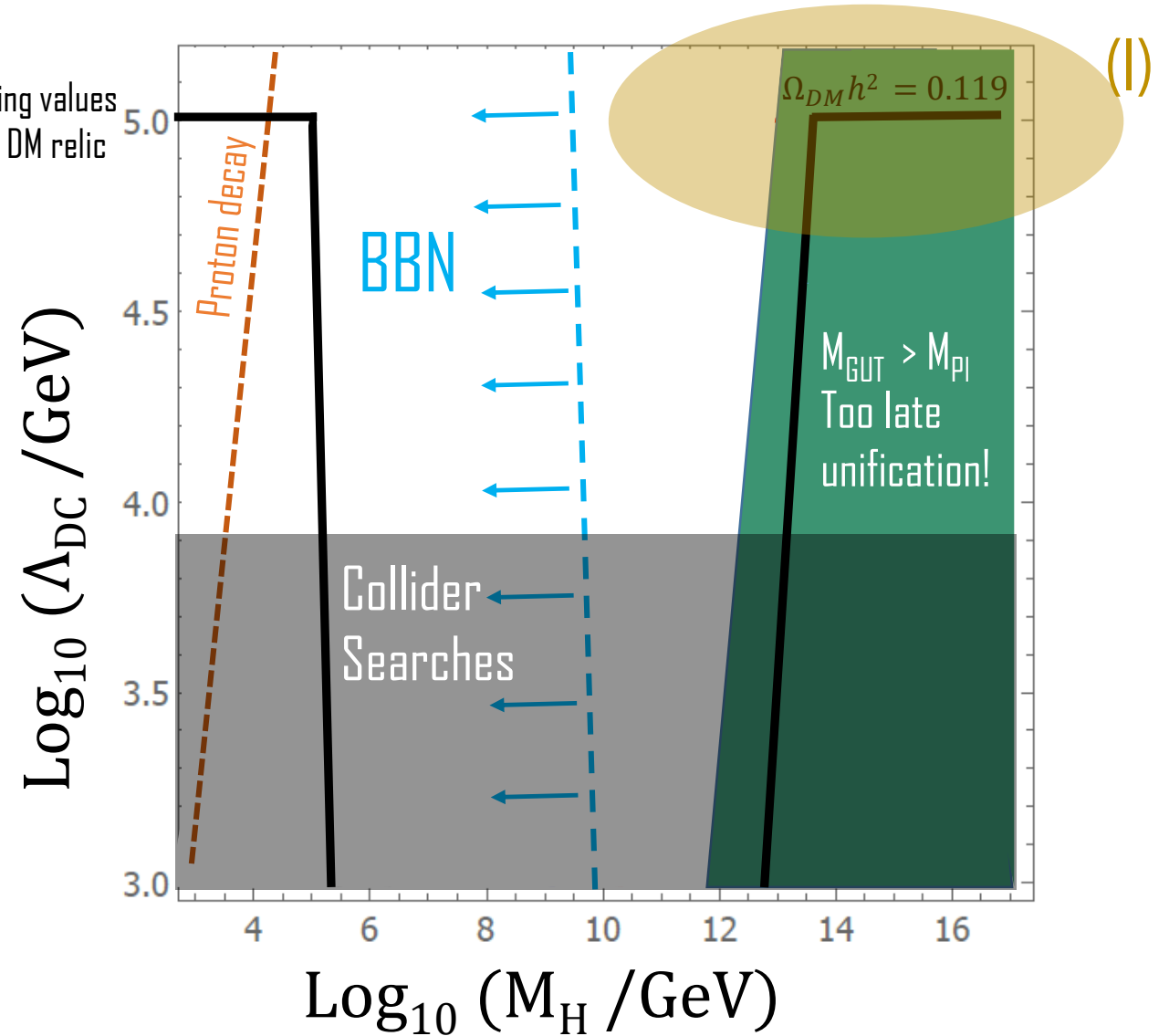
Tuning needed!

Thermal history?

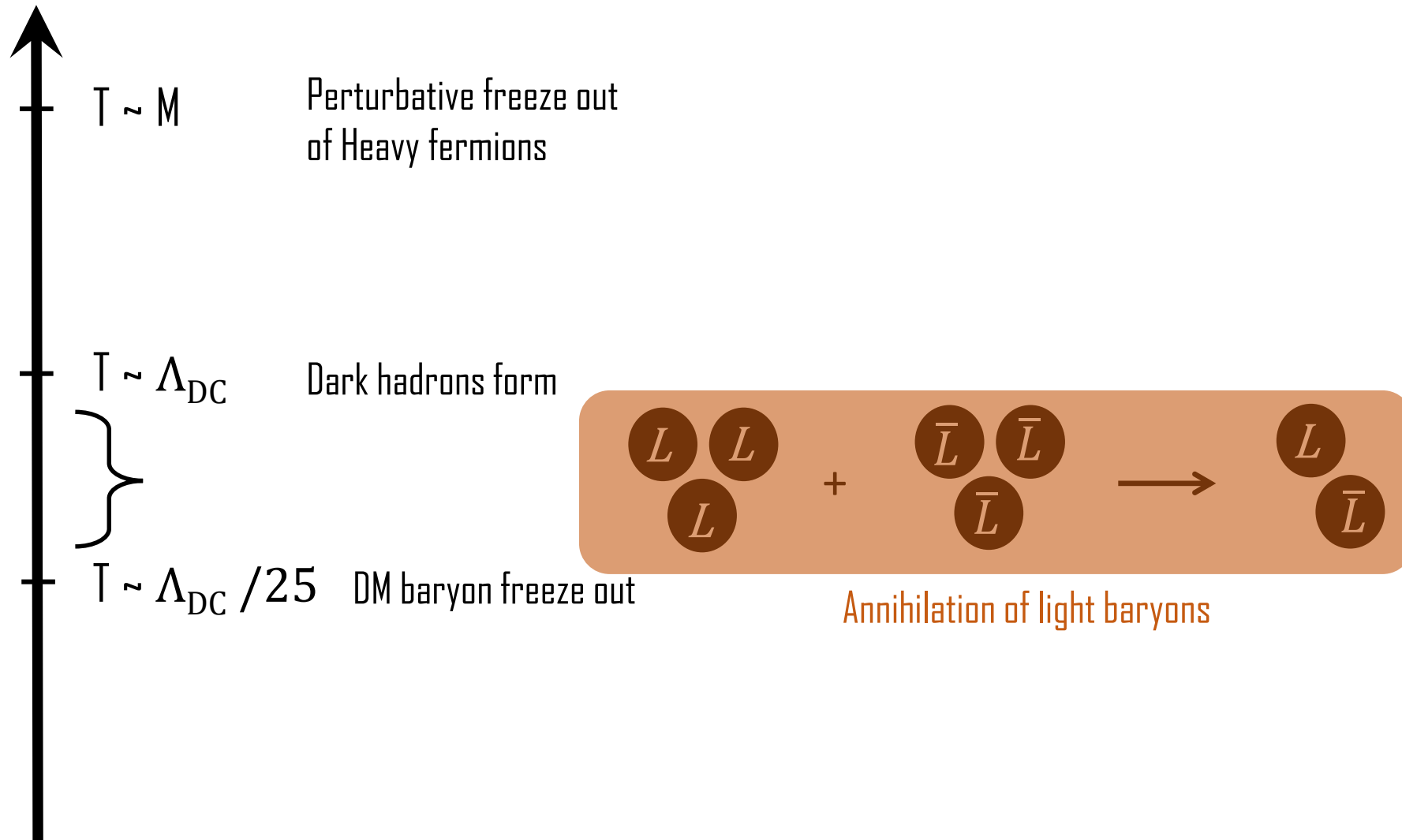
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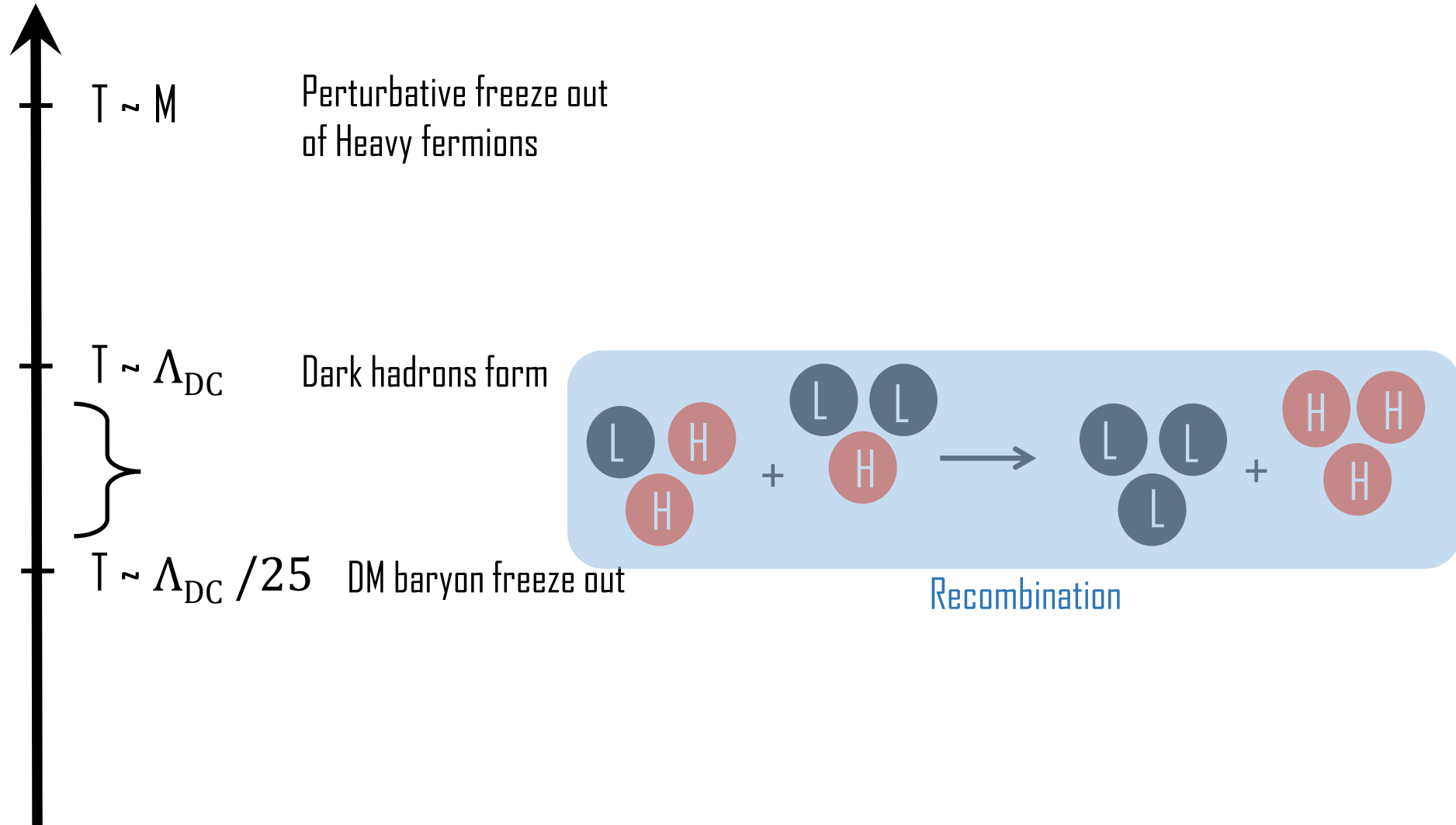
— Contour line showing values producing correct DM relic abundance



Thermal history?

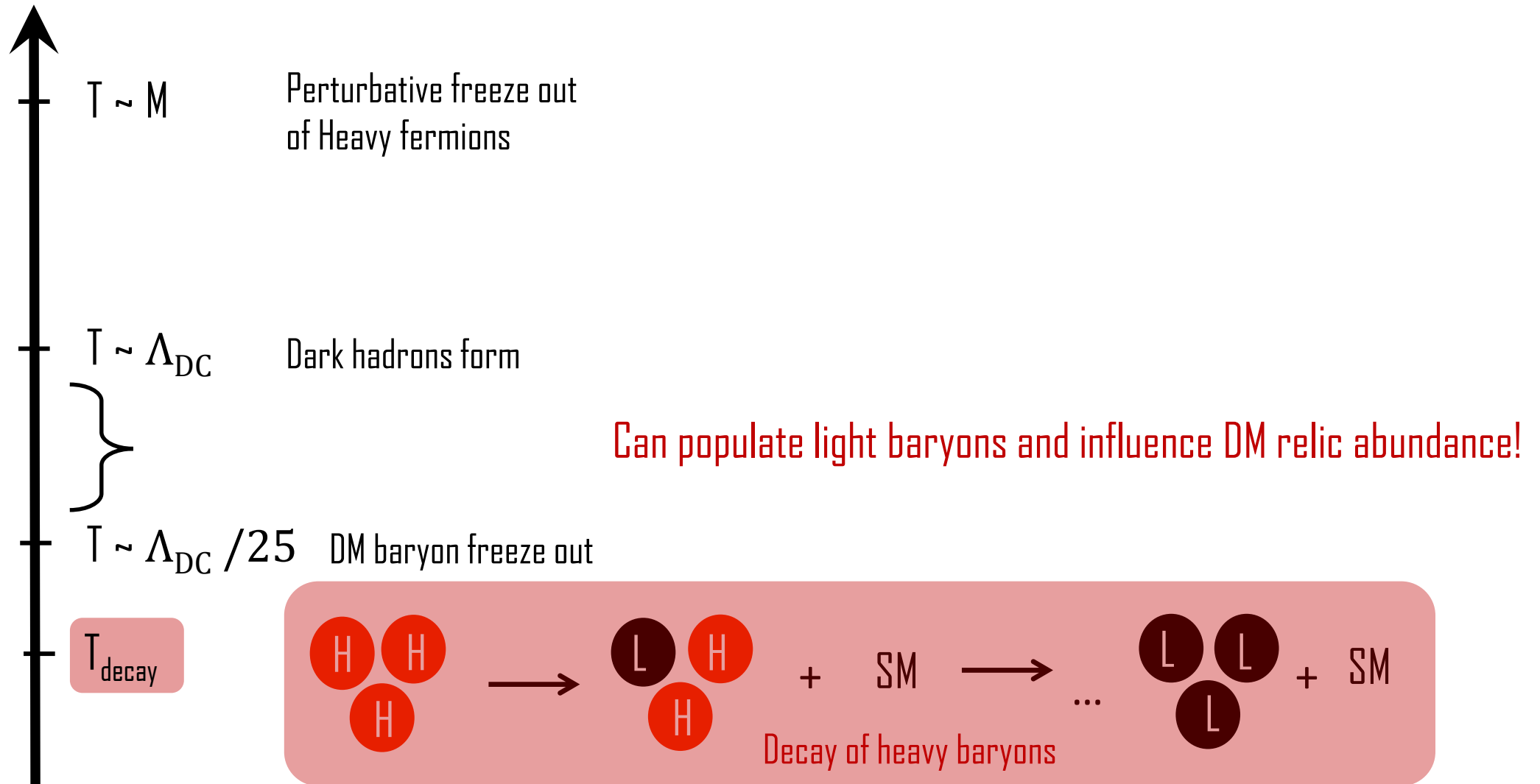


Thermal history?



Thermal history?

Bottaro, Contino, SV [In prep]

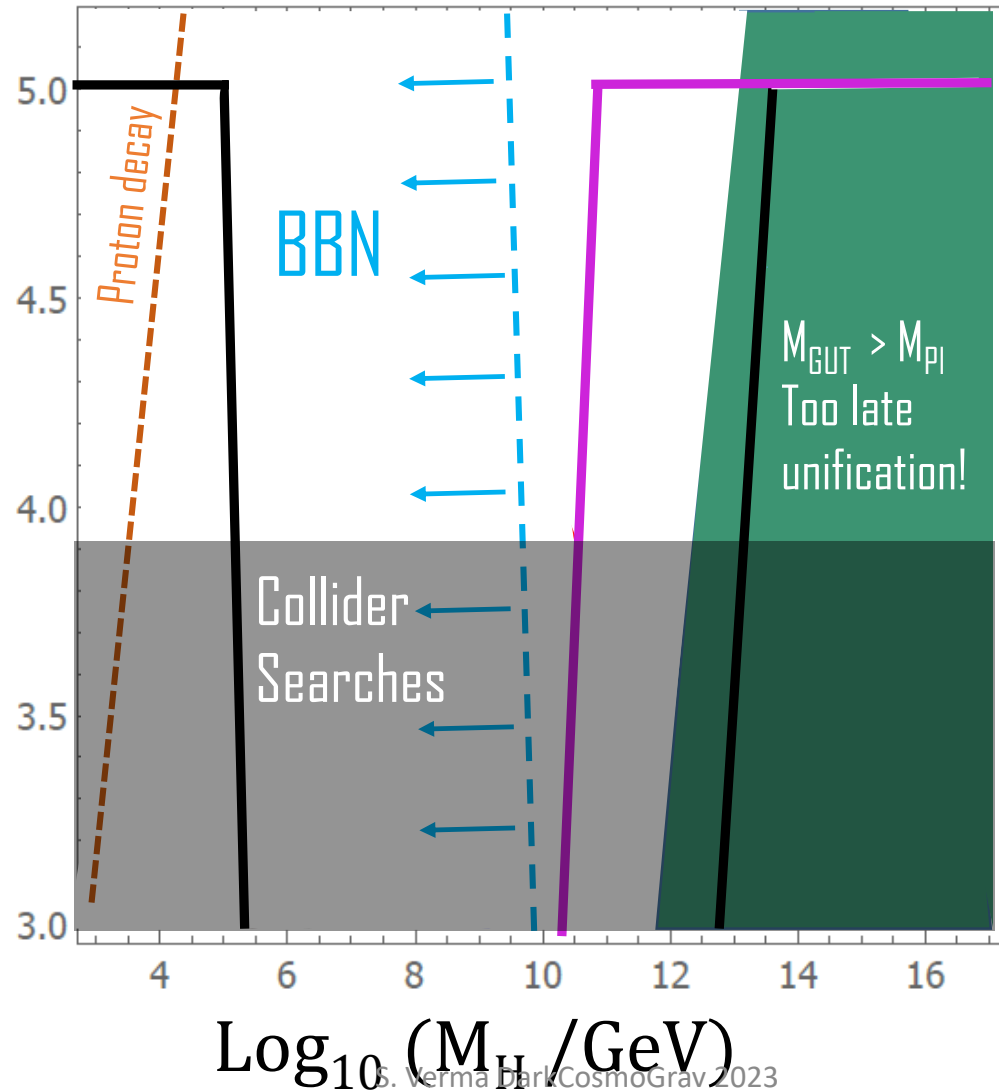


What do we find?

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. $T_{\text{RH}} < M_H$

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

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

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

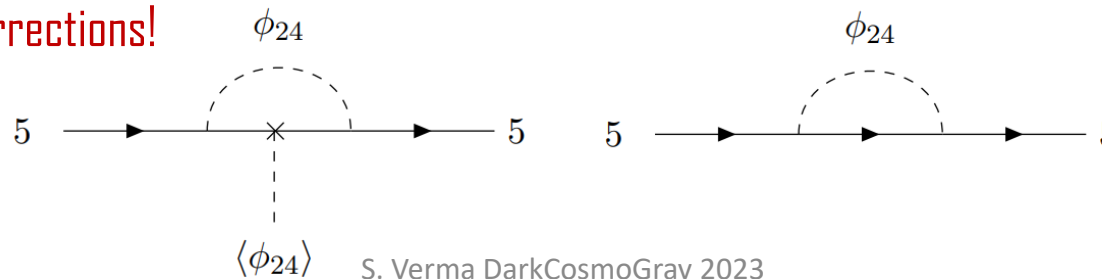
$$m_{\tilde{L}} = m_5 + \frac{3}{\sqrt{30}} y_5 v$$

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

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

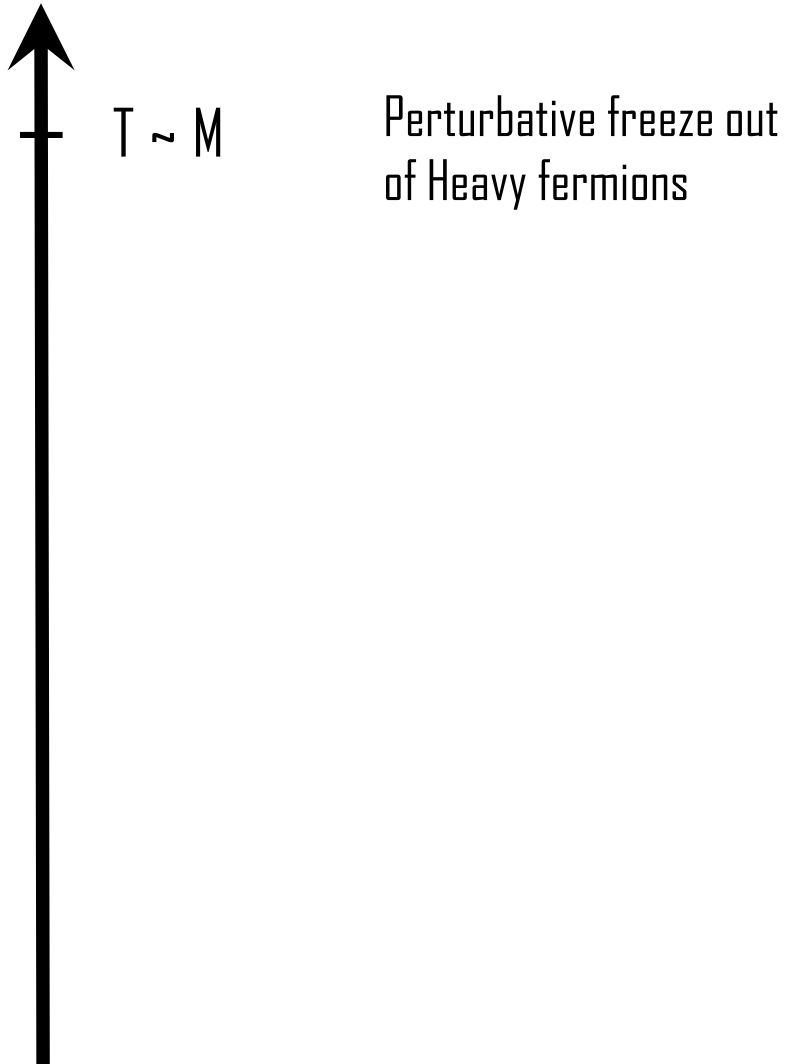
Tuning needed!

Tuning spoilt by such loop corrections!



Thermal history?

Bottaro, Contino, SV [In prep]



Benchmark GUT model?

Bottaro, Contino, SV [In prep]

$$Q + \tilde{D}$$

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

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



Low energy

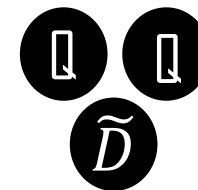
$$m \approx \Lambda_{\text{DC}} \sim 100 \text{ TeV}$$

$$Q, \tilde{D}$$

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

Breaks 1 specie symmetry

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



Baryonic DM

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

Benchmark GUT model?

$$Q + \tilde{D}$$

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

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



Intermediate energy

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

3 more species

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

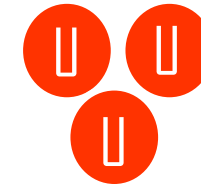
$$H^\dagger \tilde{\tilde{L}} E$$

$U(1)_U$ U number

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

Broken at dim-6 level

e.g.



Dangerous stable states

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

Low energy

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

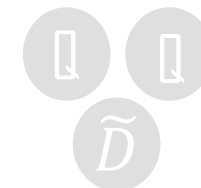
2 species

$$Q, \tilde{D}$$

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

Breaks 1 specie symmetry

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



Baryonic DM

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

Motivations?

[Antipin, Redi, Strumia, Vigianni 2015]

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

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

Dark confinement scale

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

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

See [Mitridate, Redi, Smirnov, Strumia 2017]

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

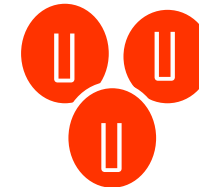
$$\Lambda_{\text{DC}} < M < M_{\text{GUT}}$$

$U(1)_U$ U number

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

Broken at dim-6 level

e.g.



Dangerous stable states

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

Low energy

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

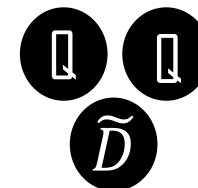
2 species

$$Q, \tilde{D}$$

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

Breaks 1 species symmetry

$U(1)_{\text{DB}}$
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 an another constraint
[Antipin, Redi, Strumia, Vigianni 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, Vigianni 2015]

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

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

S. Verma DarkCosmoGrav 2023

Can we relax unification criteria and catch more models?

Bottaro, Contino, SV [In prep]

Motivations?

- Since $\psi_{\text{dark}} \in \mathcal{G}_{\text{SM}}$, embedding in $SU(5)$ gives an another constraint
[Antipin, Redi, Strumia, Vigianni 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 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, Vigianni 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?

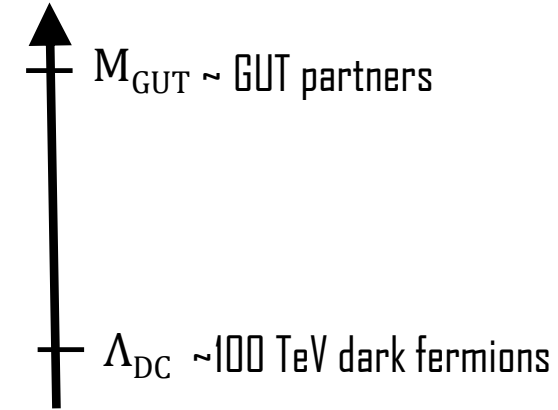
[Antipin, Redi, Strumia, Vigianni 2015]

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

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

Dark confinement scale

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



Motivations?

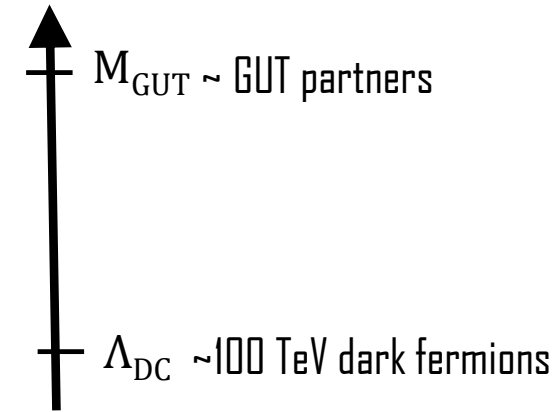
[Antipin, Redi, Strumia, Vigianni 2015]

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

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Dark confinement scale

- \mathcal{G}_{DC} unbroken by \mathcal{G}_{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?

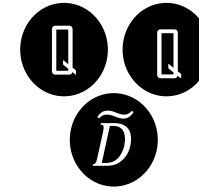
Benchmark GUT model?

$$Q + \tilde{D}$$

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

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

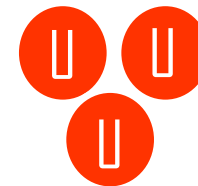
At $\Lambda_{\text{DC}} \sim 100 \text{ TeV}$



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

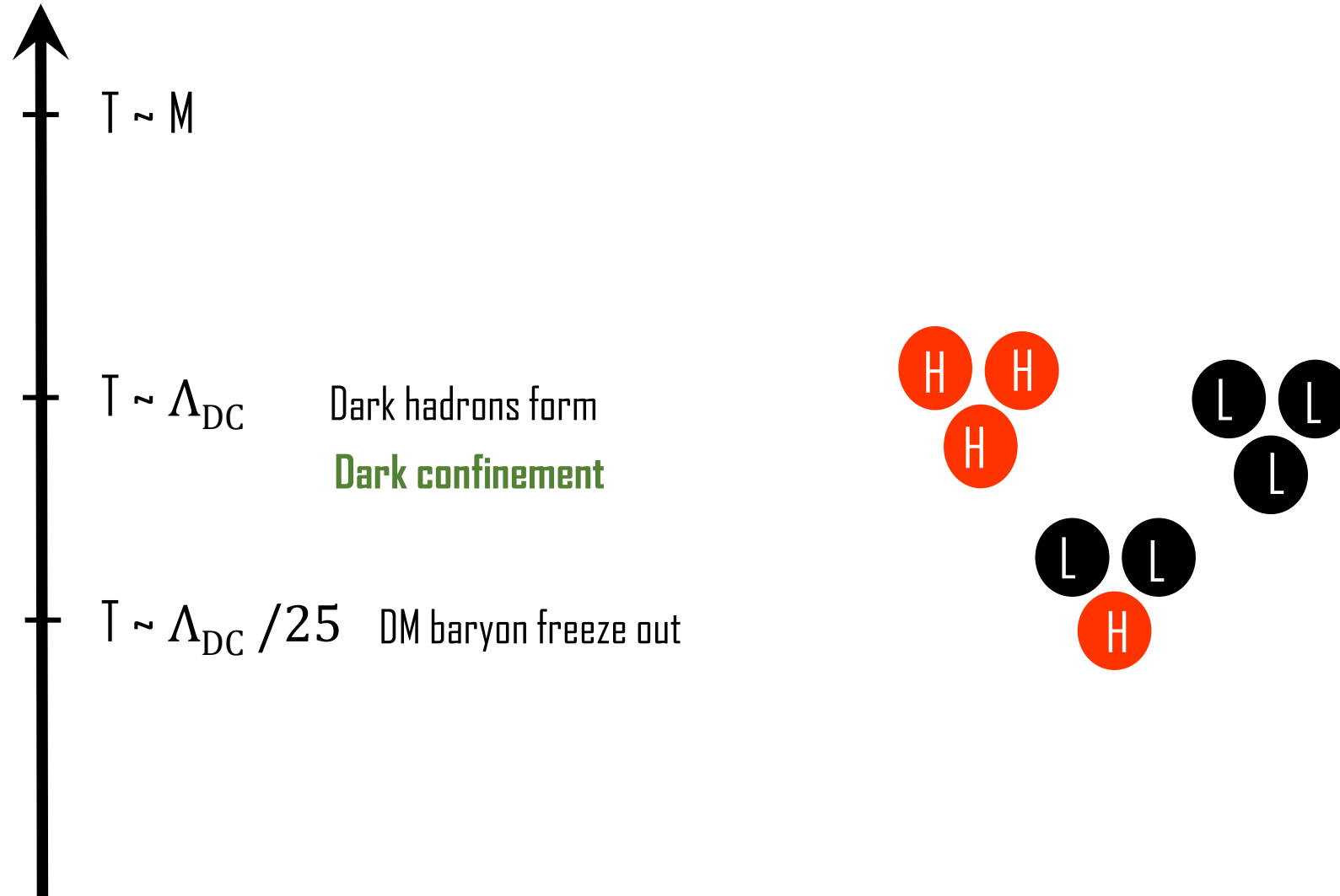


Dangerous stable states

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

Thermal history?

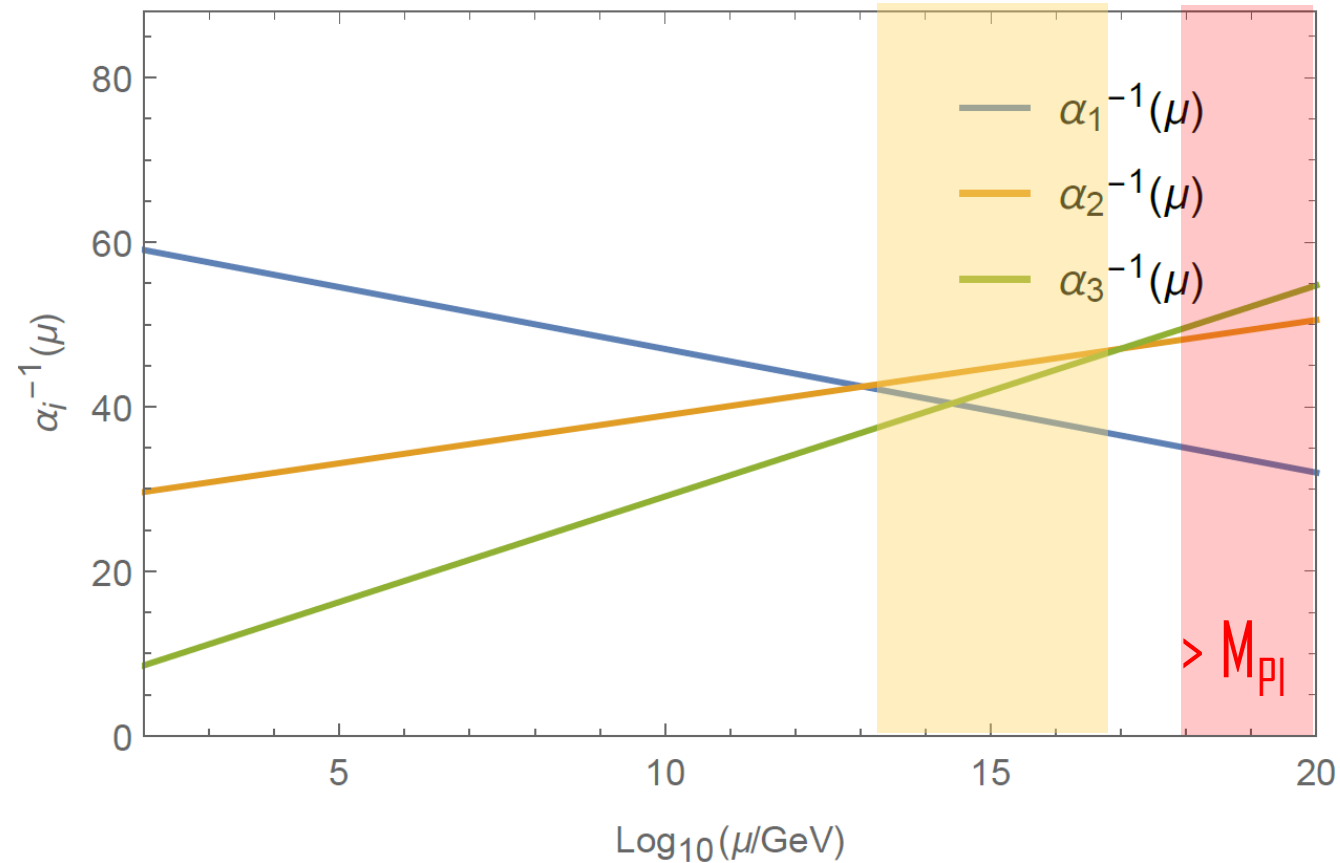
Bottaro, Contino, SV [In prep]



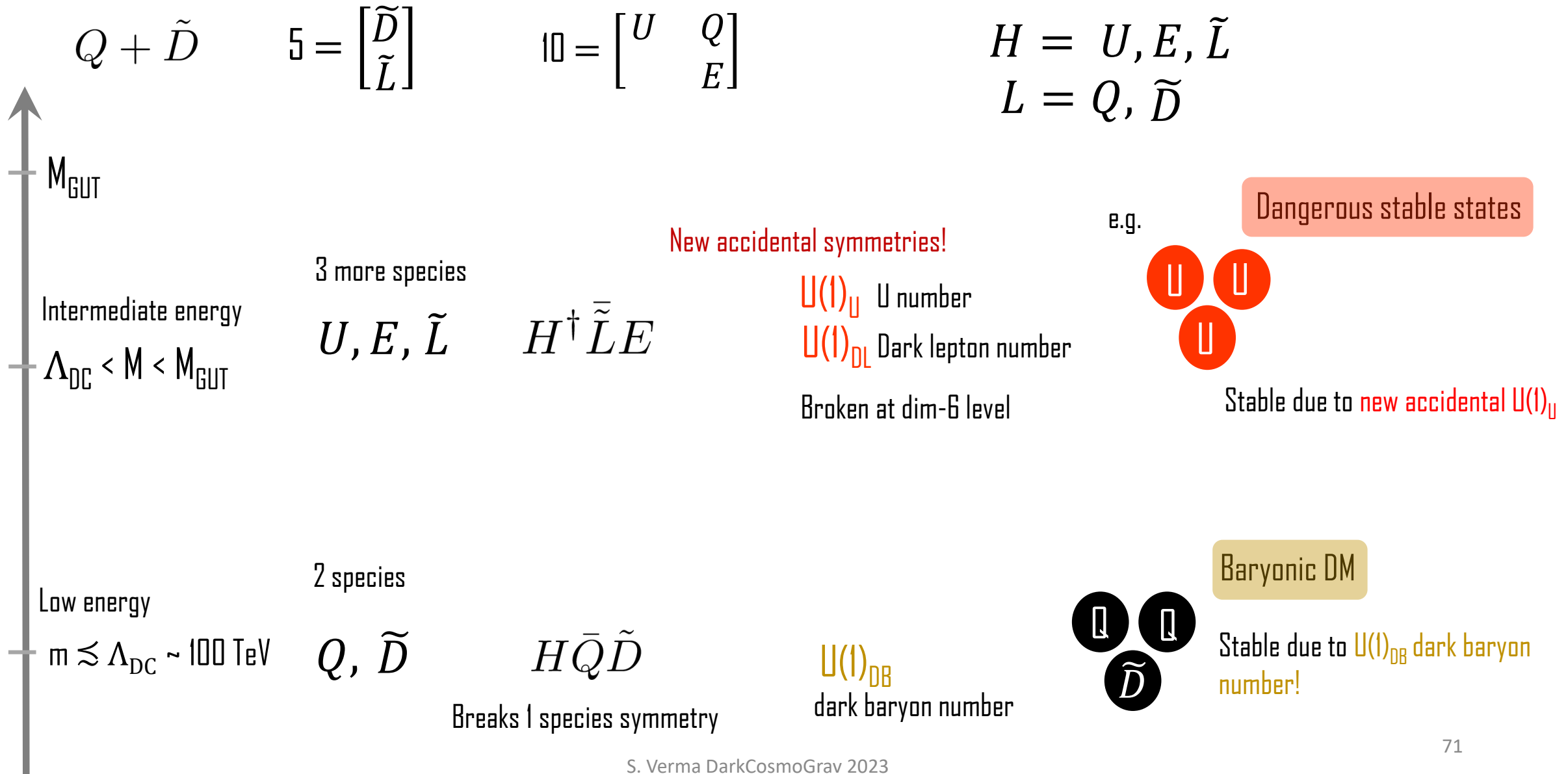
Coincidence or GUT?

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?



Thermal history?

Bottaro, Contino, SV [In prep]

