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

SCUOLA NORMALE SUPERIORE

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Work in progress
with Salvatore Bottaro, Roberto Contino.

INFN
Istituto Nazionale di Fisica Nucleare

Artwork by Sandbox Studio, Chicago with Ana Kova

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

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

Standard Model

+

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

Dark Color

- Accidental global symmetries arise in IR
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DM stability due to an accidental symmetry like baryons in SM

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

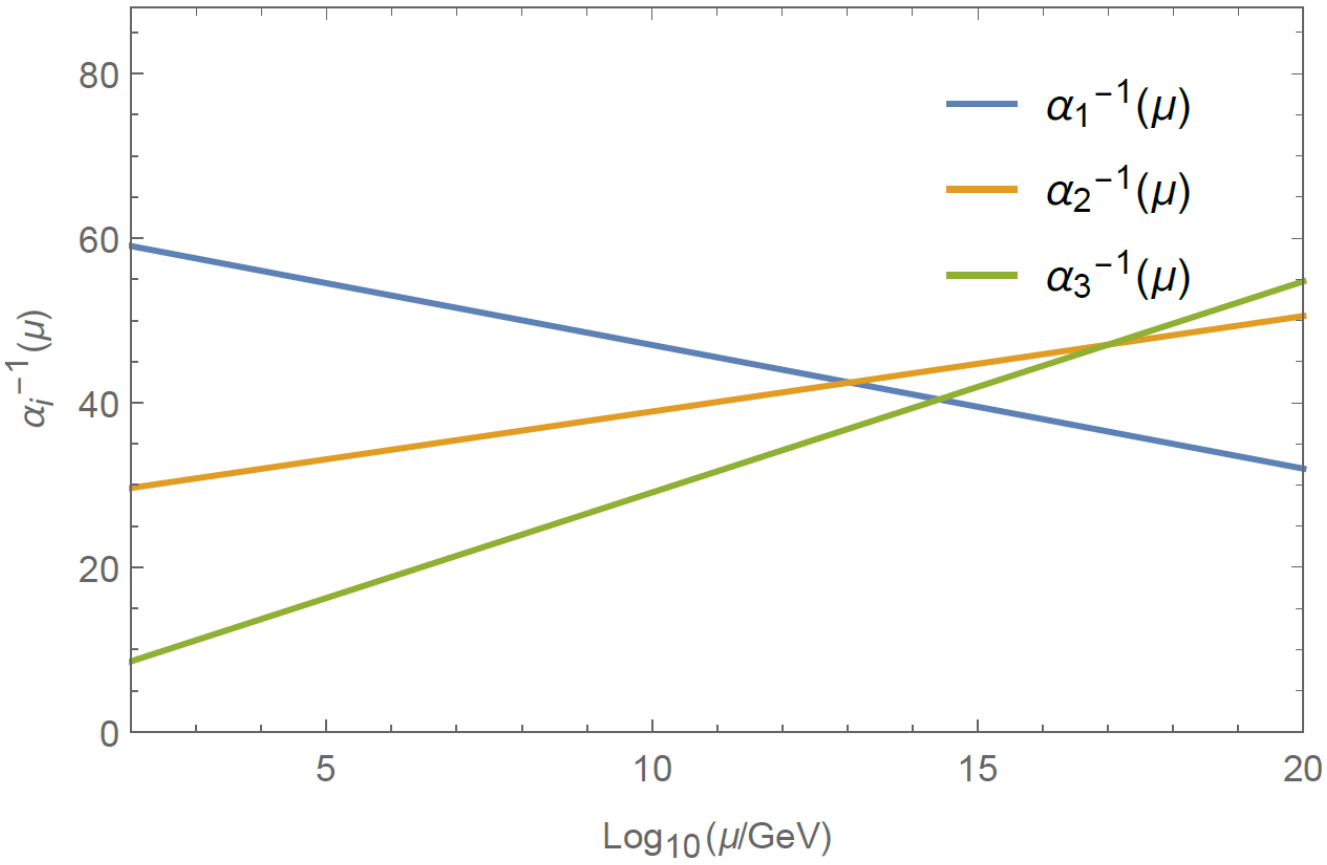
[Kilic, Okui, Sundrum 2010]
[Antipin, Redi, Strumia, Vigiani 2015]
[Mitridate, Redi, Smirnov, Strumia 2017]

For chiral dark fermions, see for example:
[Contino, Podo, Revello 2020]

Coincidence or GUT?

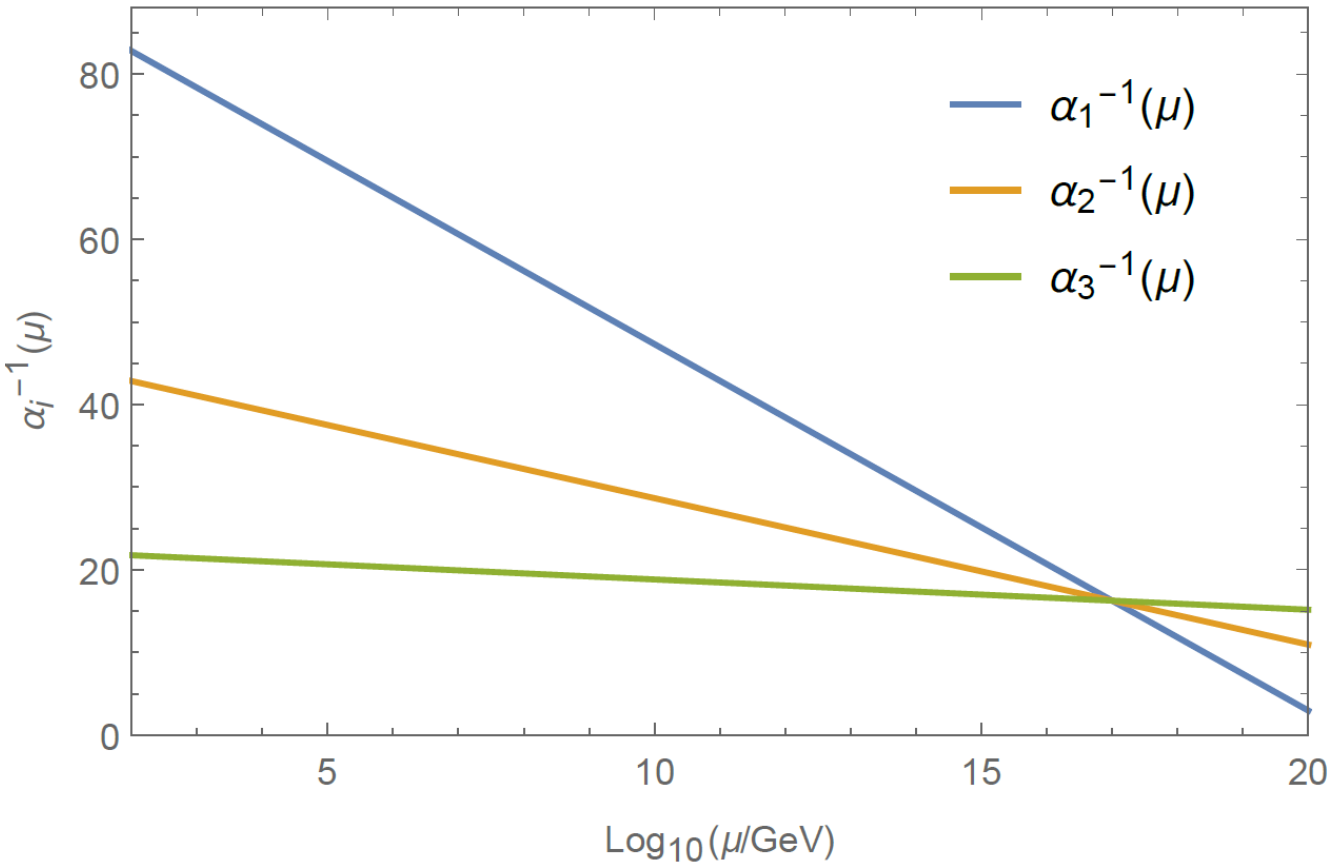
In the SM, SU(3) X SU(2) X U(1) couplings seem to come very close at a scale ~ 10^{14} GeV

SM only



Coincidence or GUT?

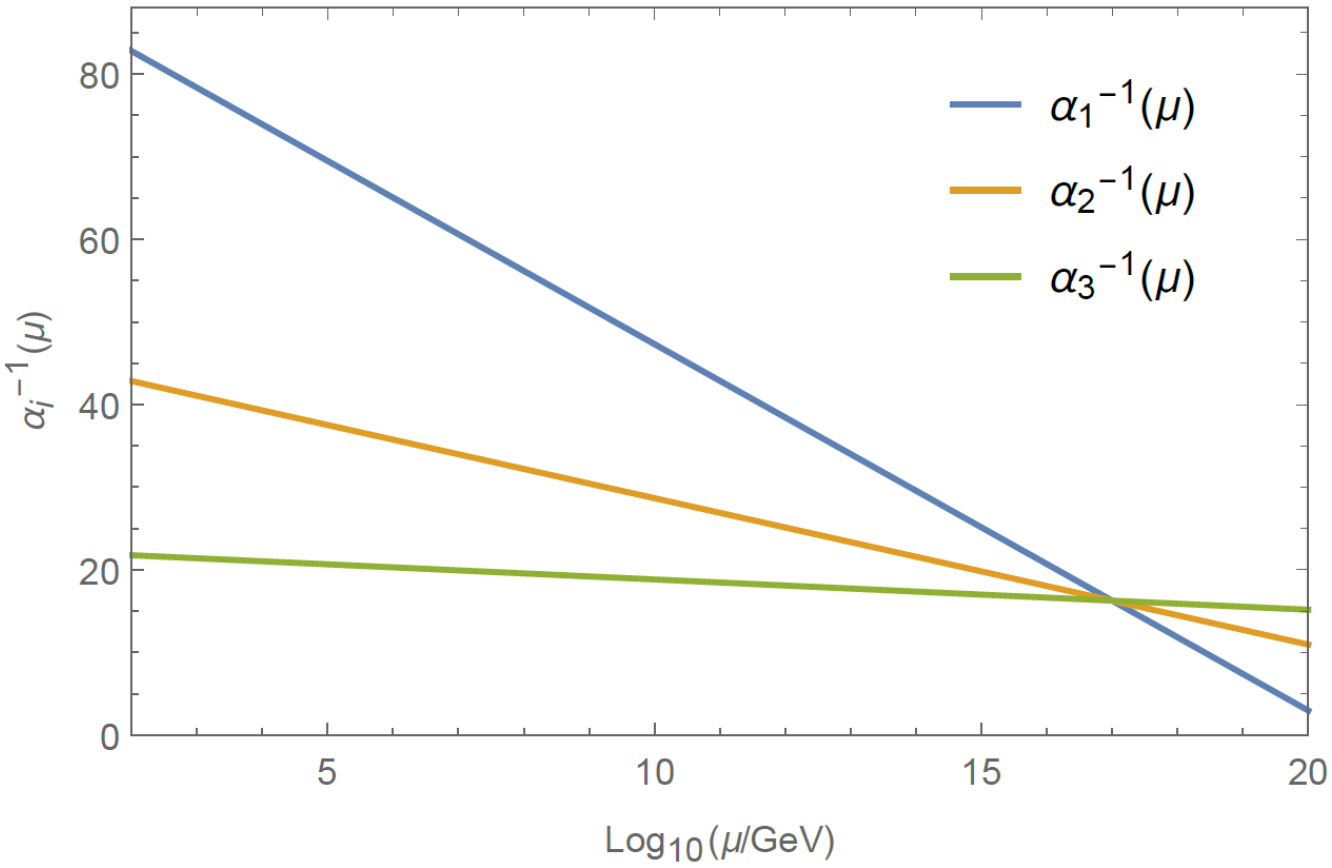
SM + (some) dark quarks



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]

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

'light dark fermions' $m_\psi \lesssim \Lambda_{\rm DC}$ ~ 100 TeV

Dark confinement scale

- Lightest dark baryons: DM candidate

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Bottaro, Contino, SV [In preparation]

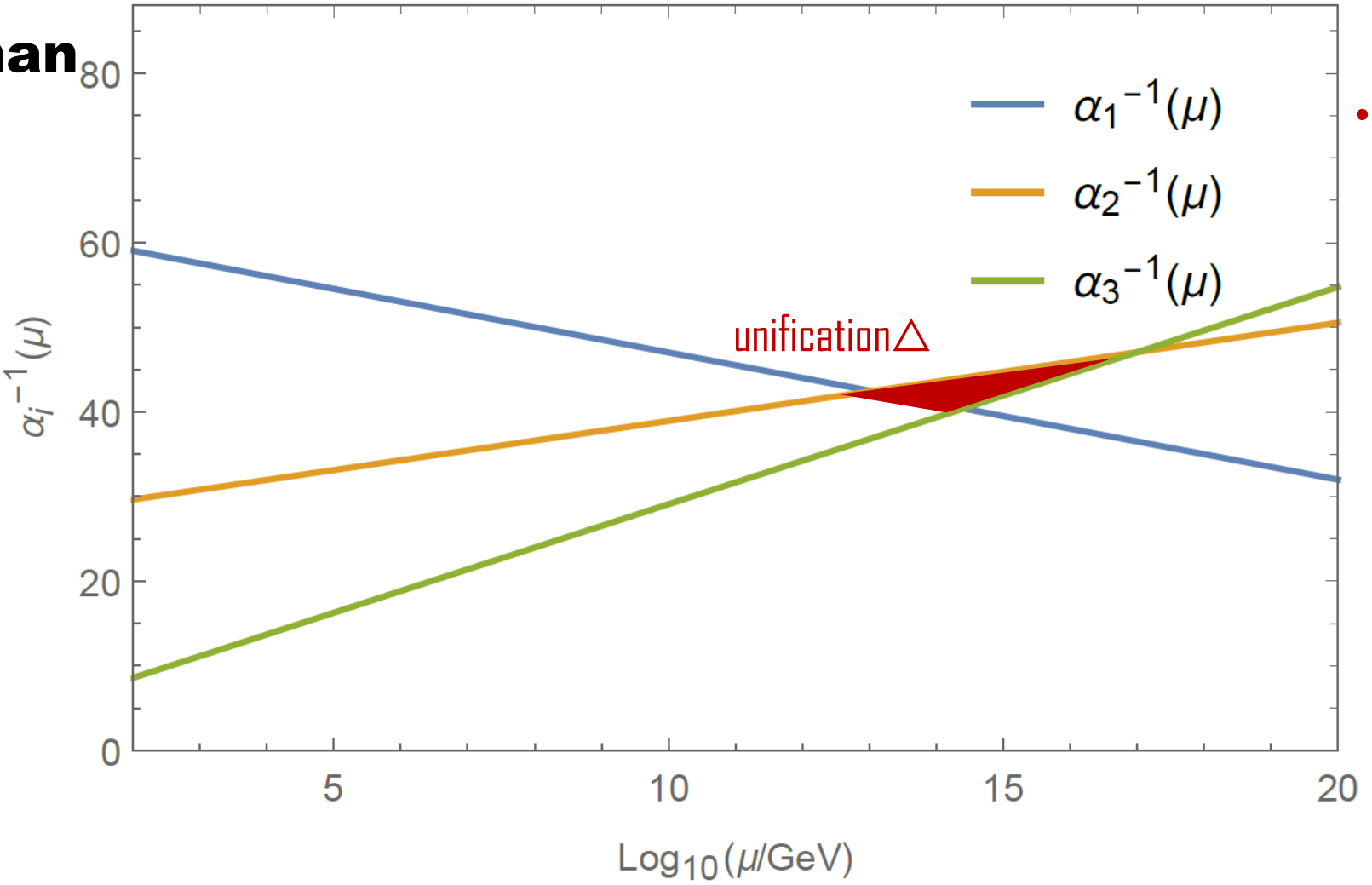
Can we find an SU(5) GUT UV-completion to embed composite dark matter models giving accidentally stable DM?

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



- $\mathrm{Area}_{\triangle}(\mathrm{SM+BSM}) \leq \mathrm{Area}_{\triangle}(\mathrm{SM})$

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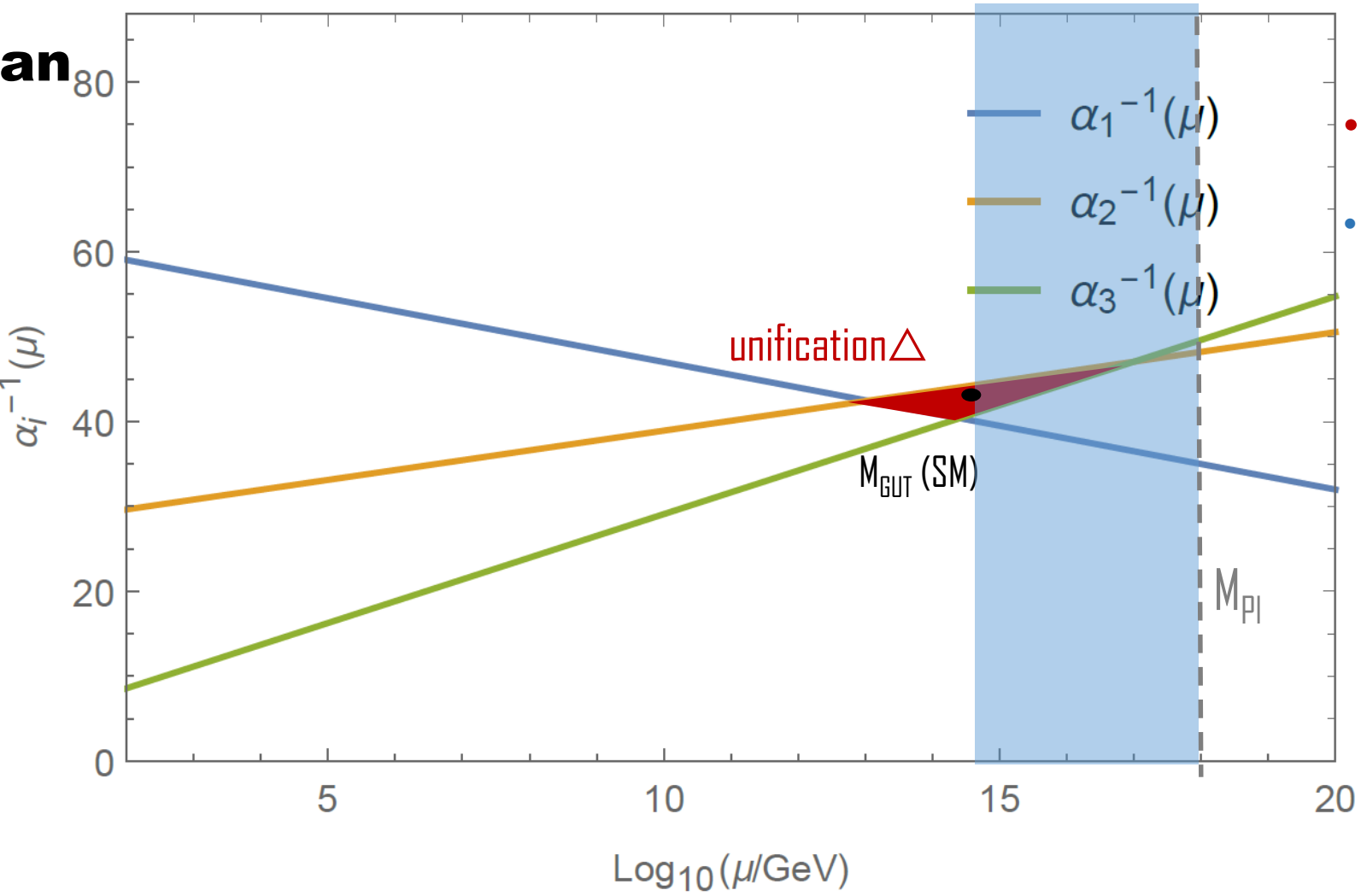

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- $M_{GUT}\,(\mathrm{SM}) \leq M_{GUT}\,(\mathrm{SM+BSM}) \leq M_{Pl}$

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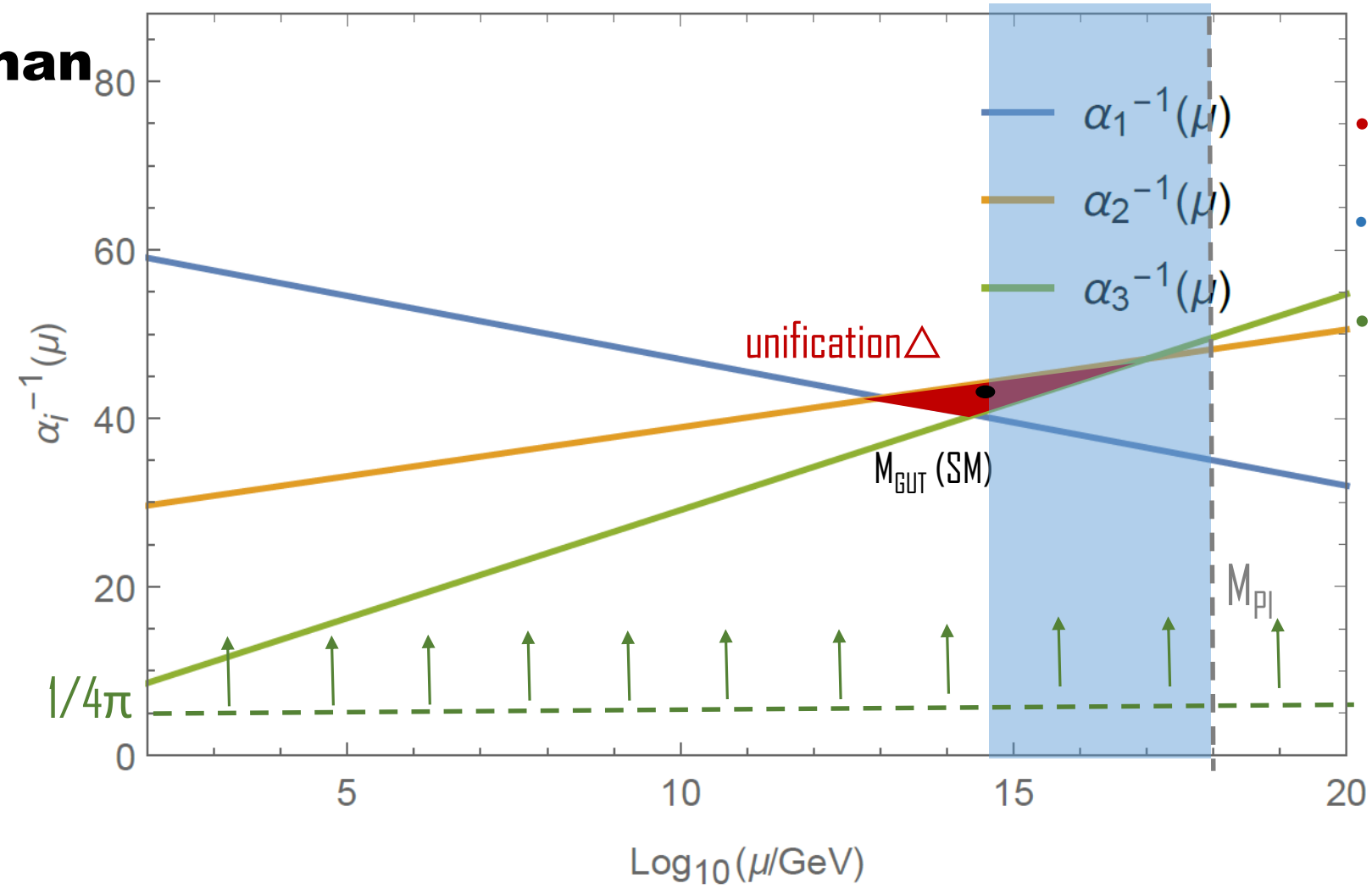

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- $M_{GUT}\,(\mathrm{SM}) \leq M_{GUT}\,(\mathrm{SM+BSM}) \leq M_{Pl}$
- $\alpha_{GUT} < 4\pi$

Good models?

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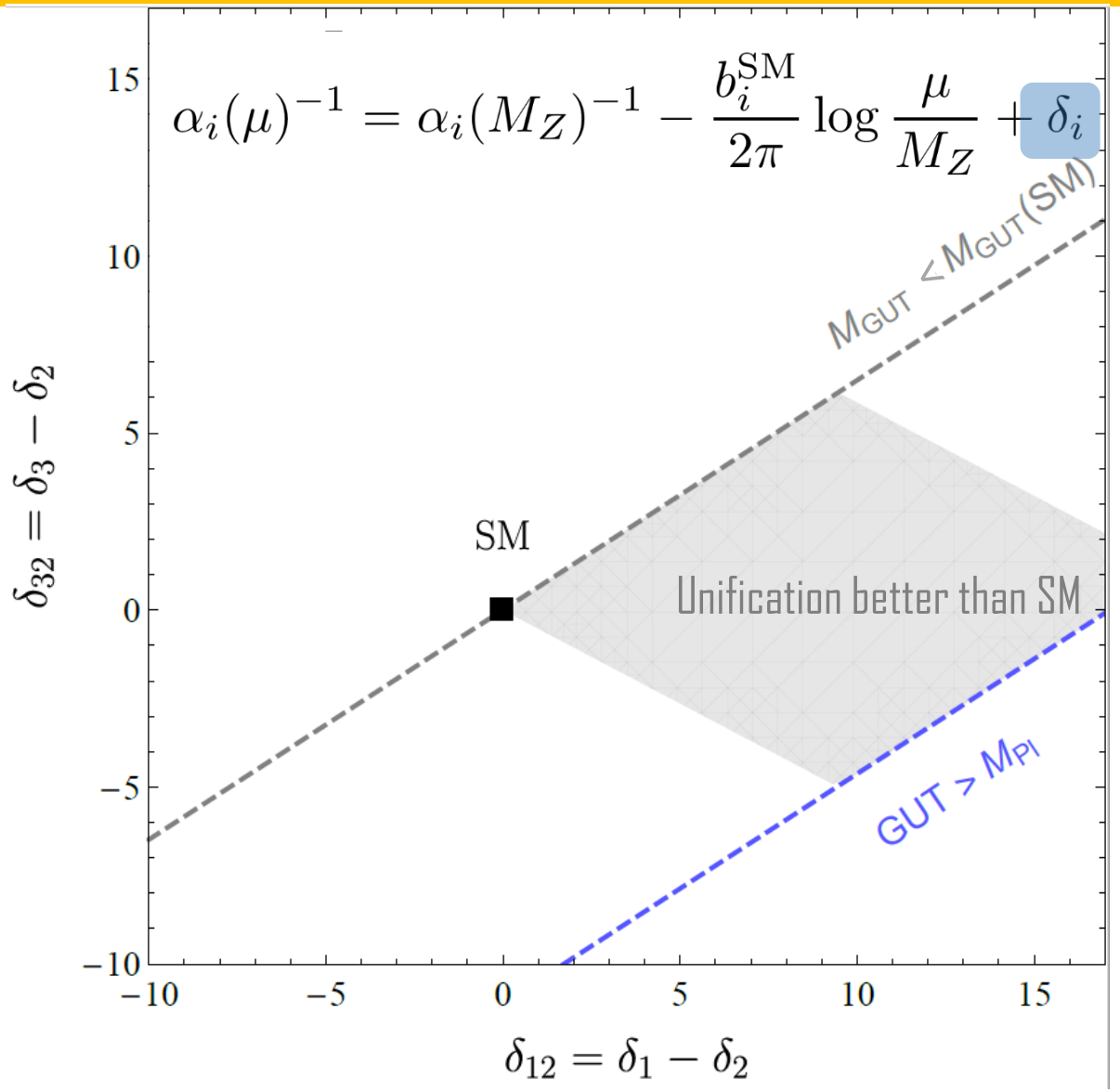

NP running contribution to SM couplings

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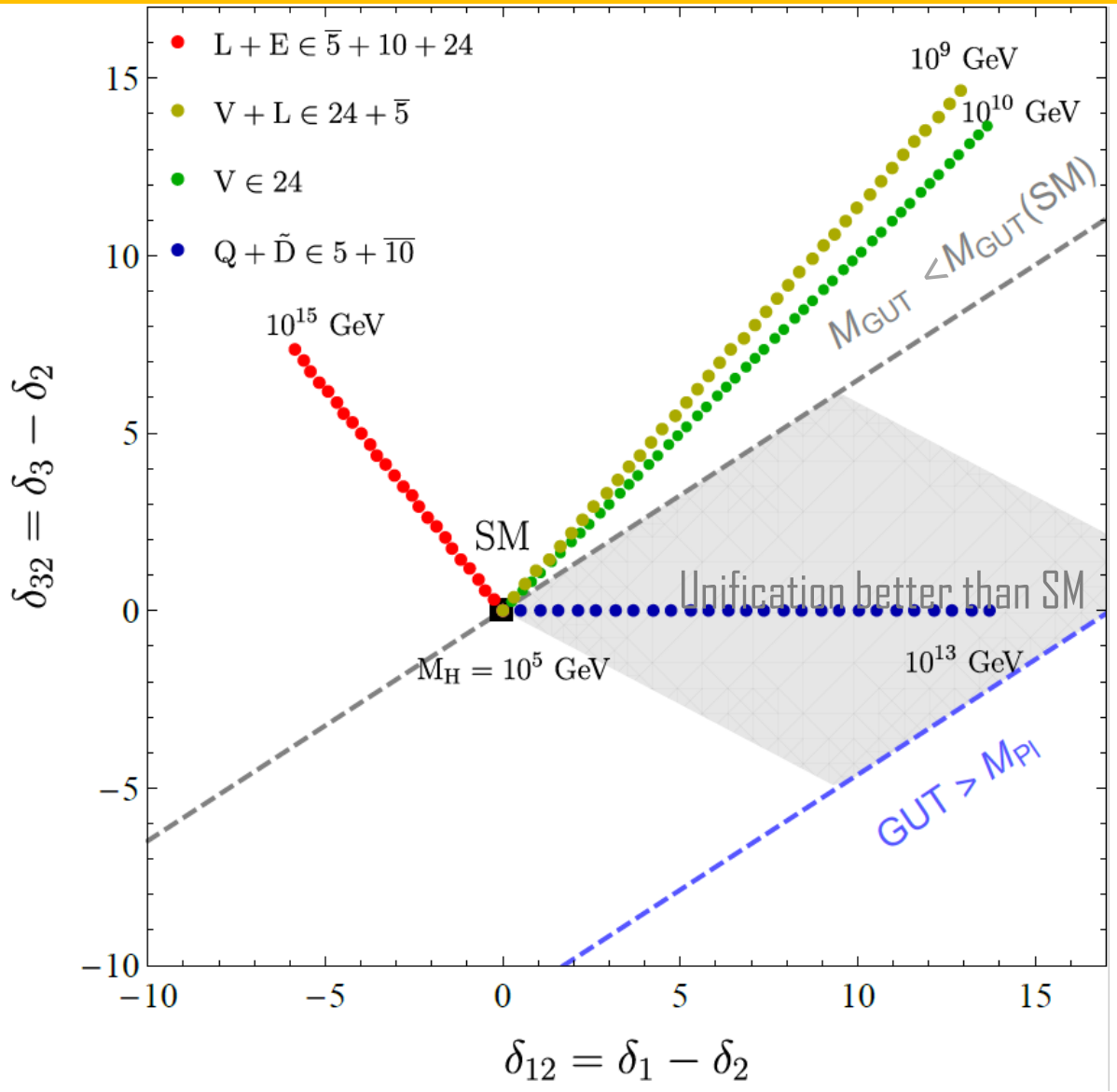

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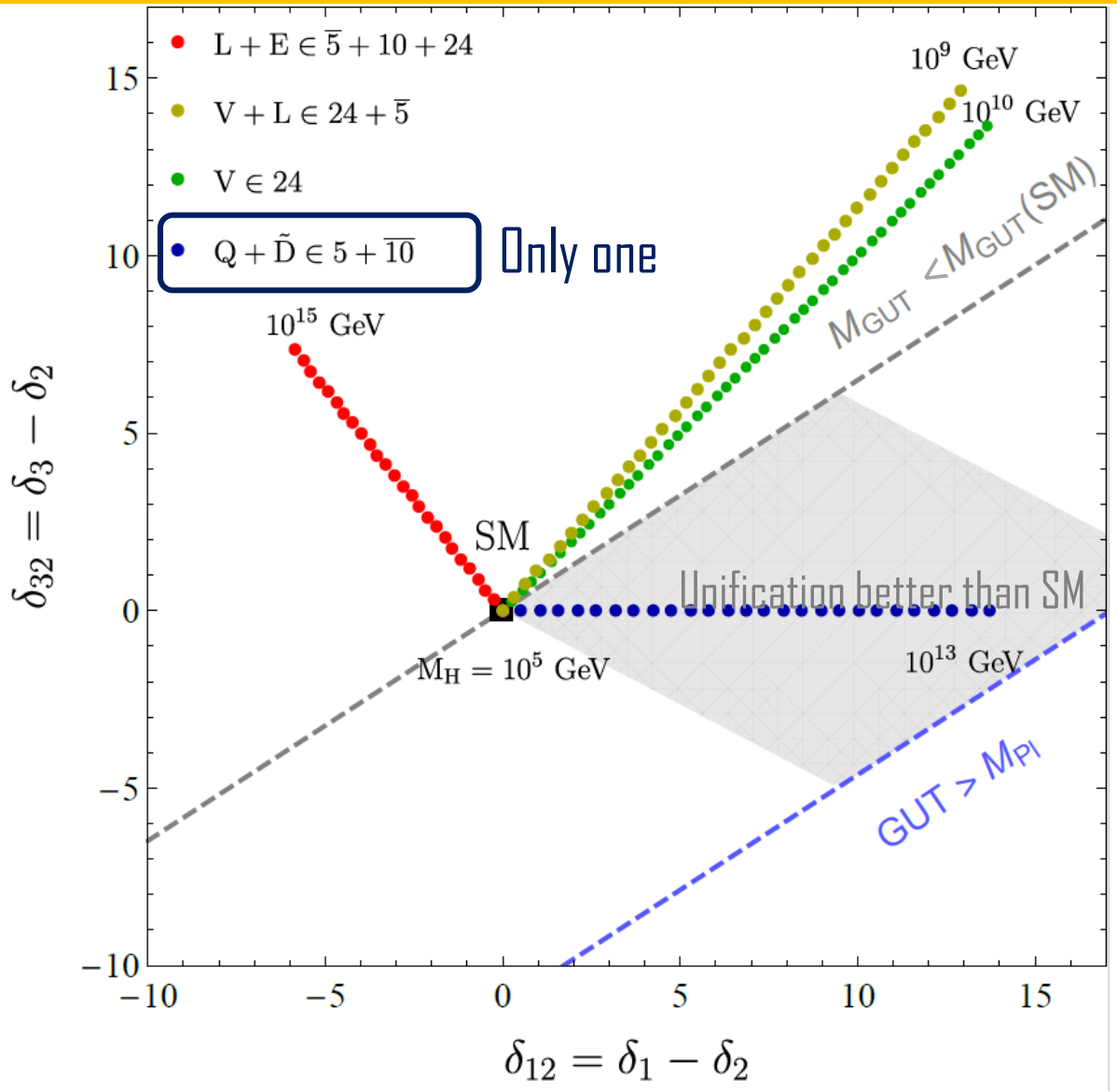

More accidental symmetries?

Bottaro, Contino, SV [In prep]

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

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

$L = Q, \tilde{D}$

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

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

2 species

$Q, \tilde{D}$

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Baryonic DM

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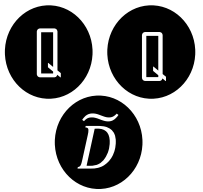

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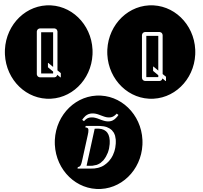

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Thermal history?

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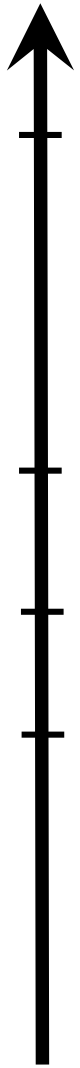

$T \sim M_H$

$T \sim \Lambda_{DC}$ Dark hadrons form

T_{decay} H containing hadrons decay here

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

$T \sim \Lambda_{DC}\,/25$ DM baryon freeze out

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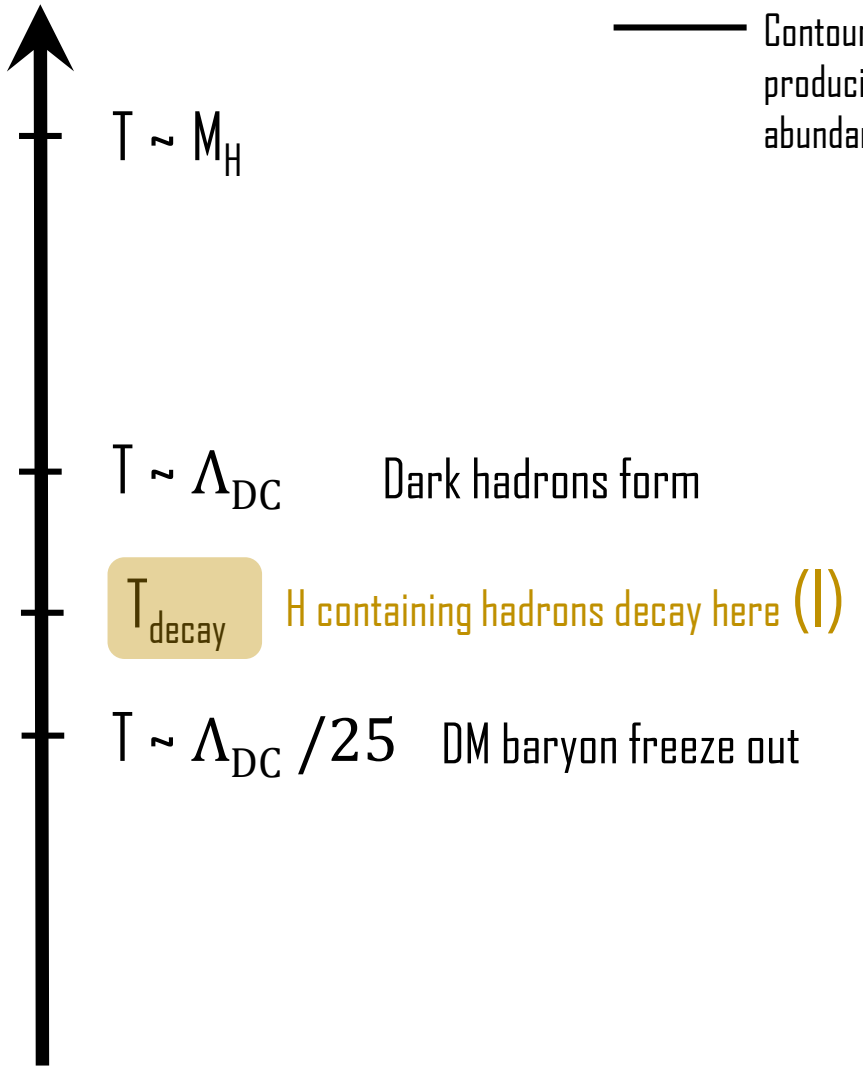
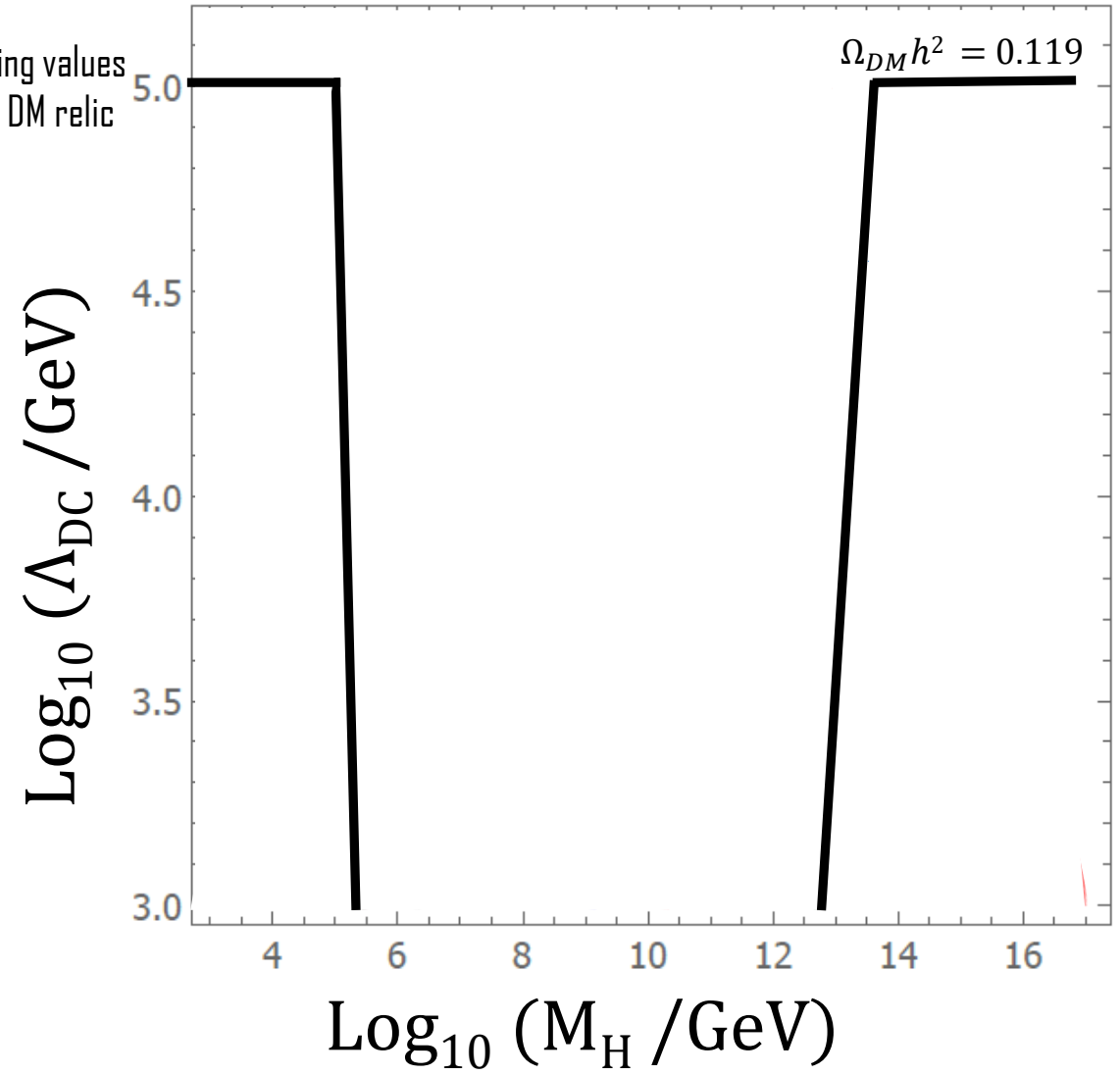


Contour line showing values producing correct DM relic abundance



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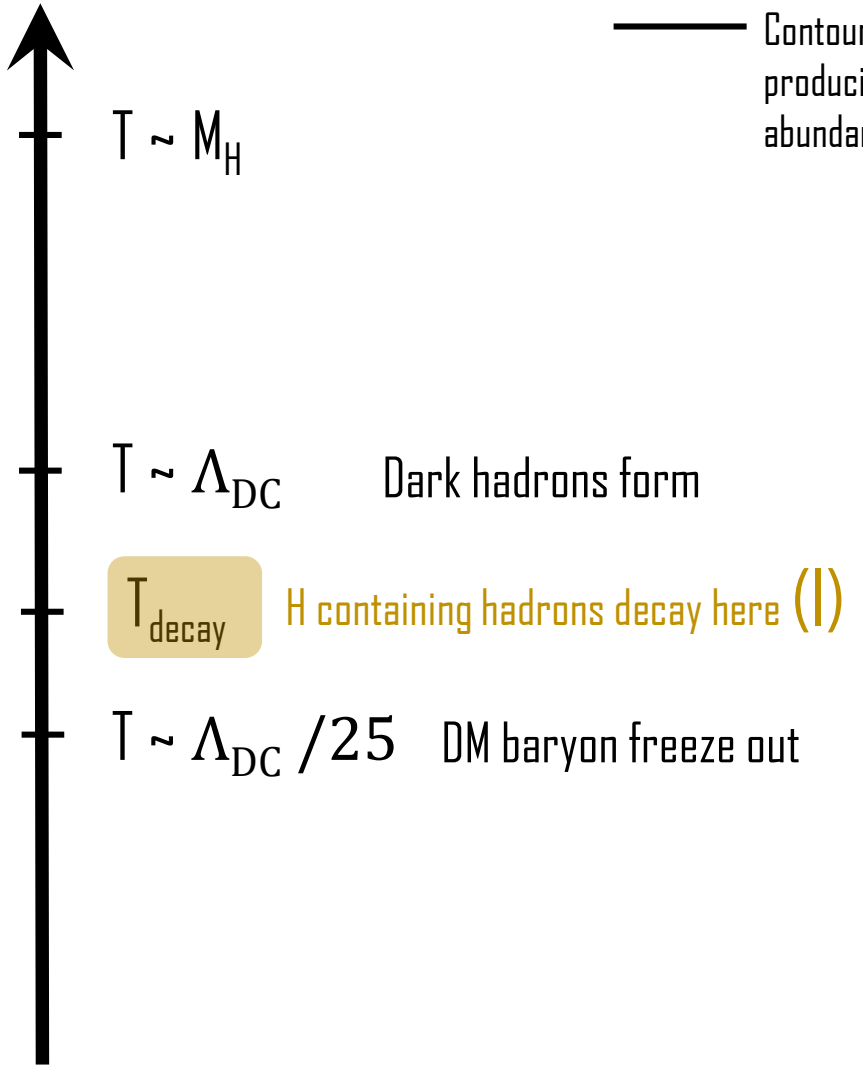

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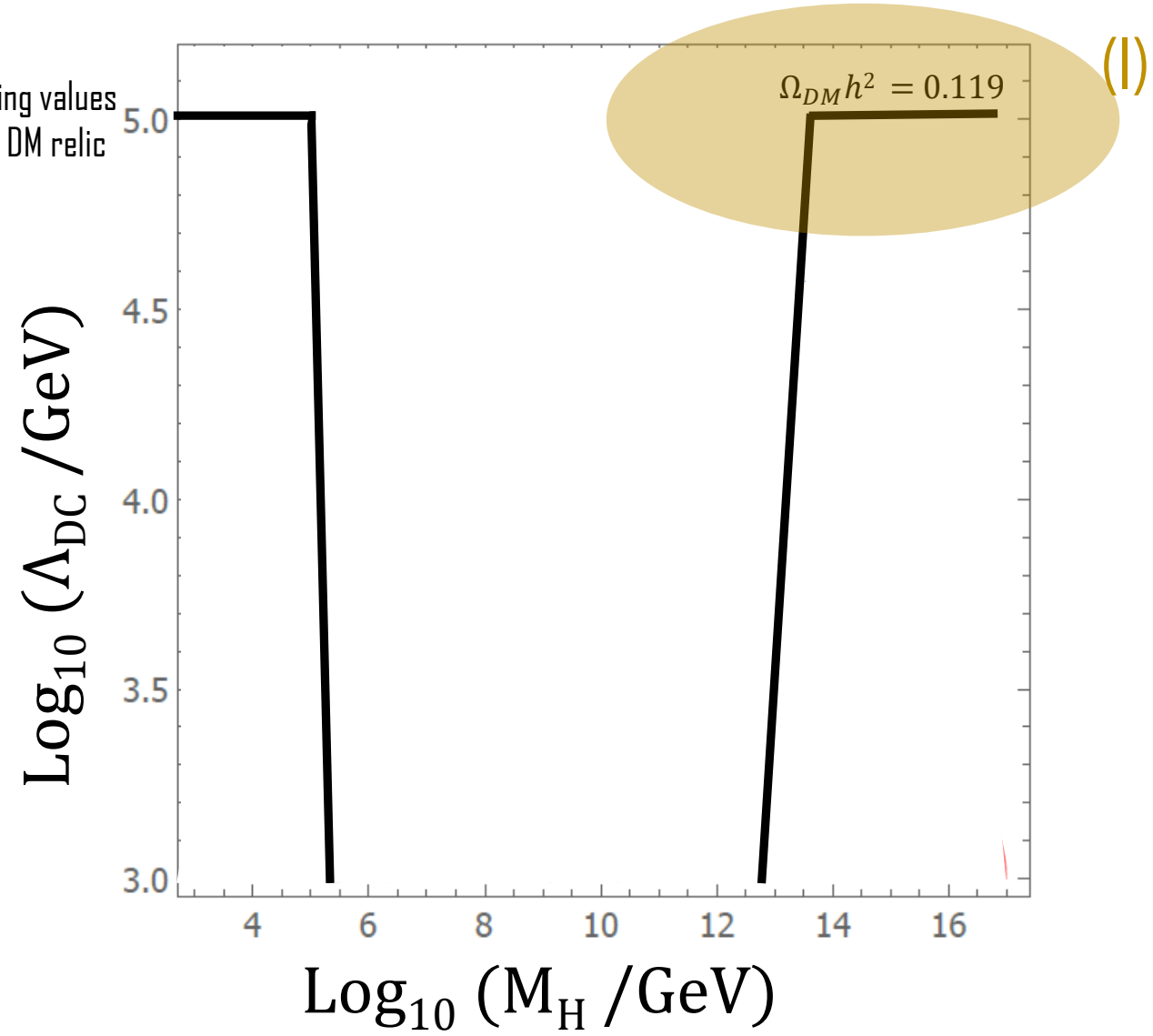

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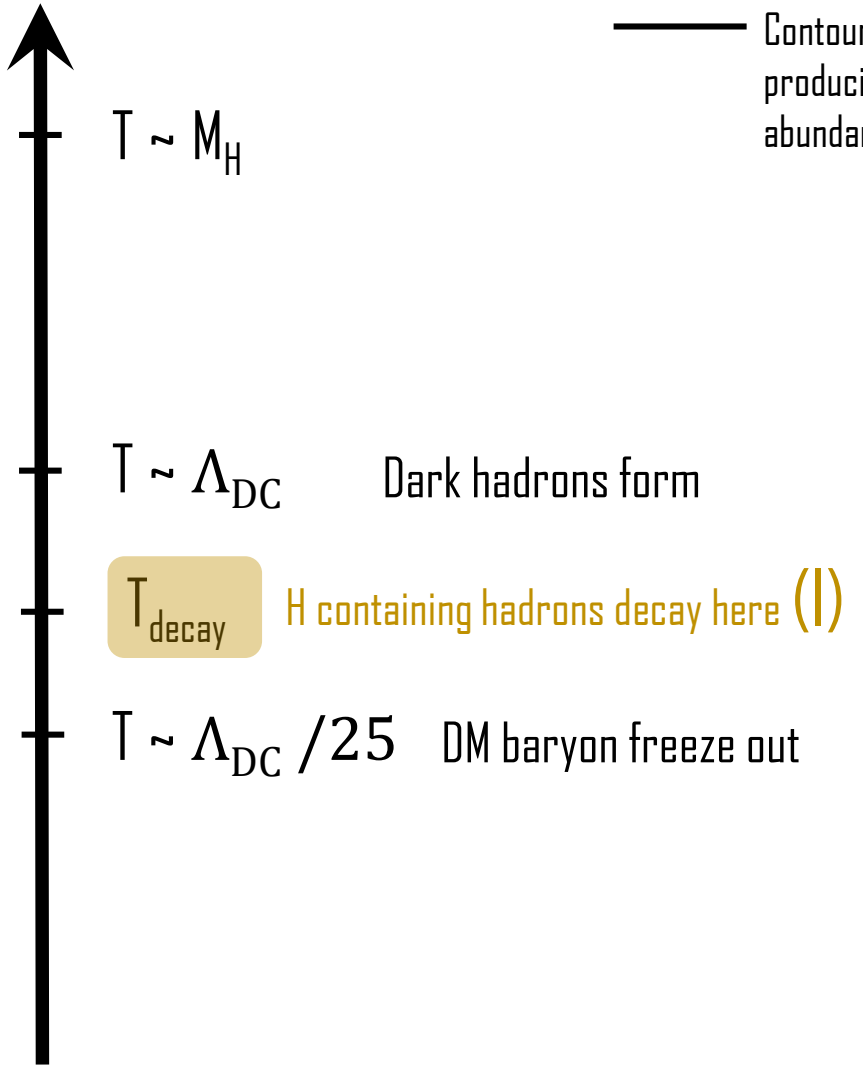

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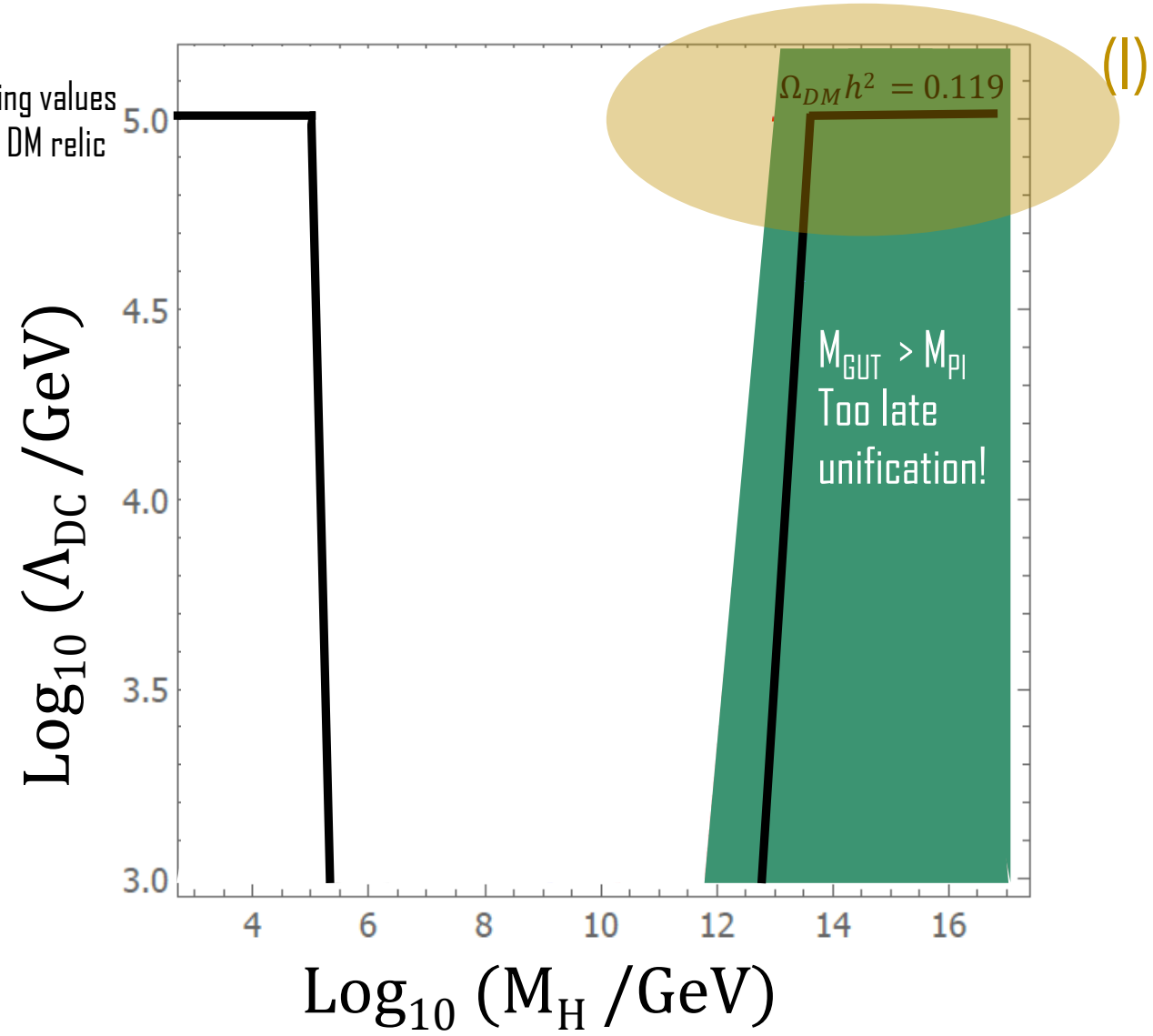

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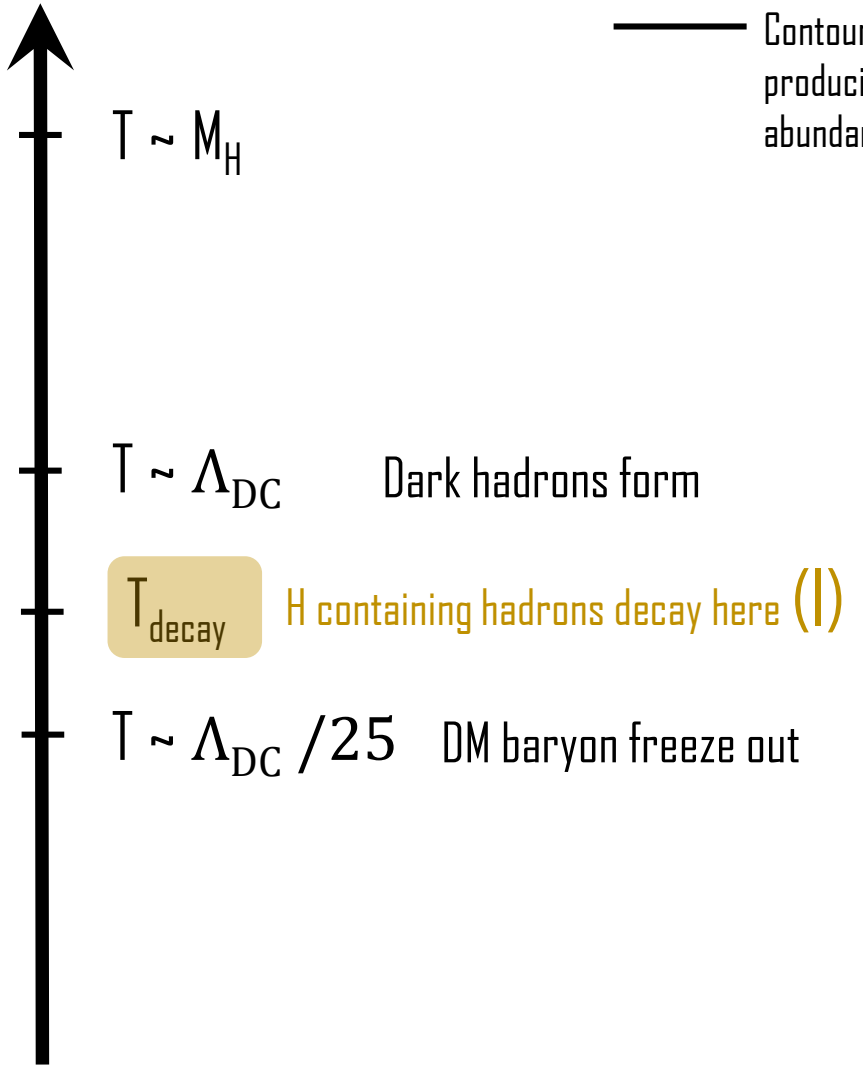

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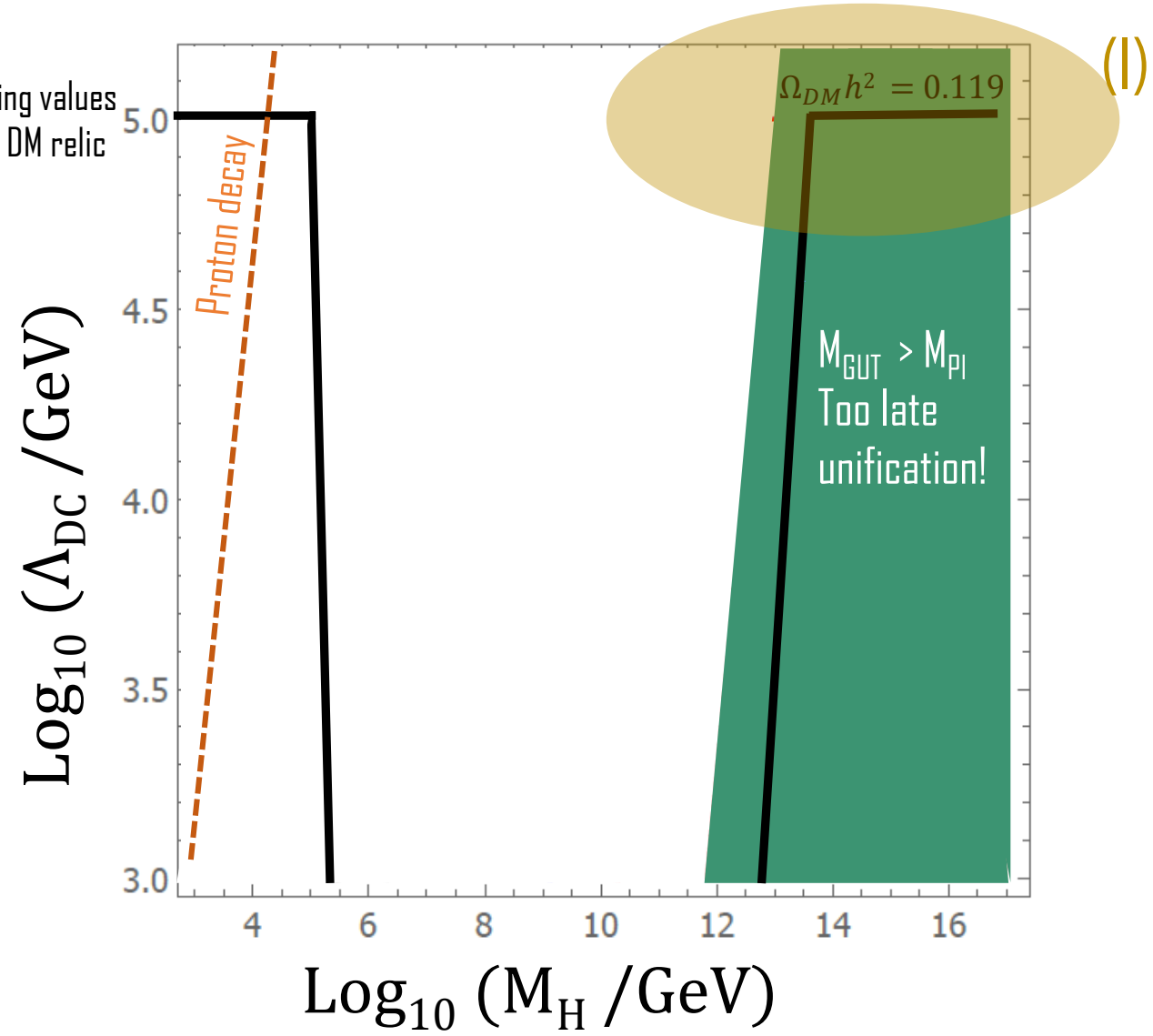

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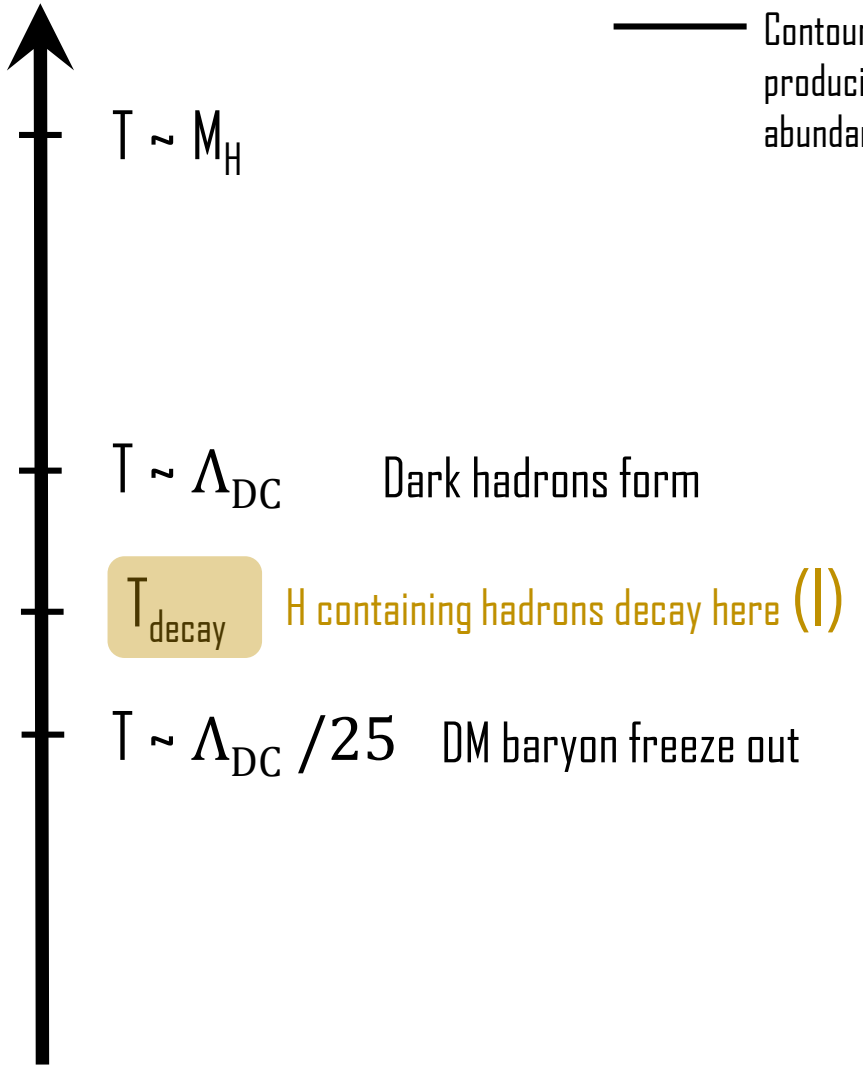

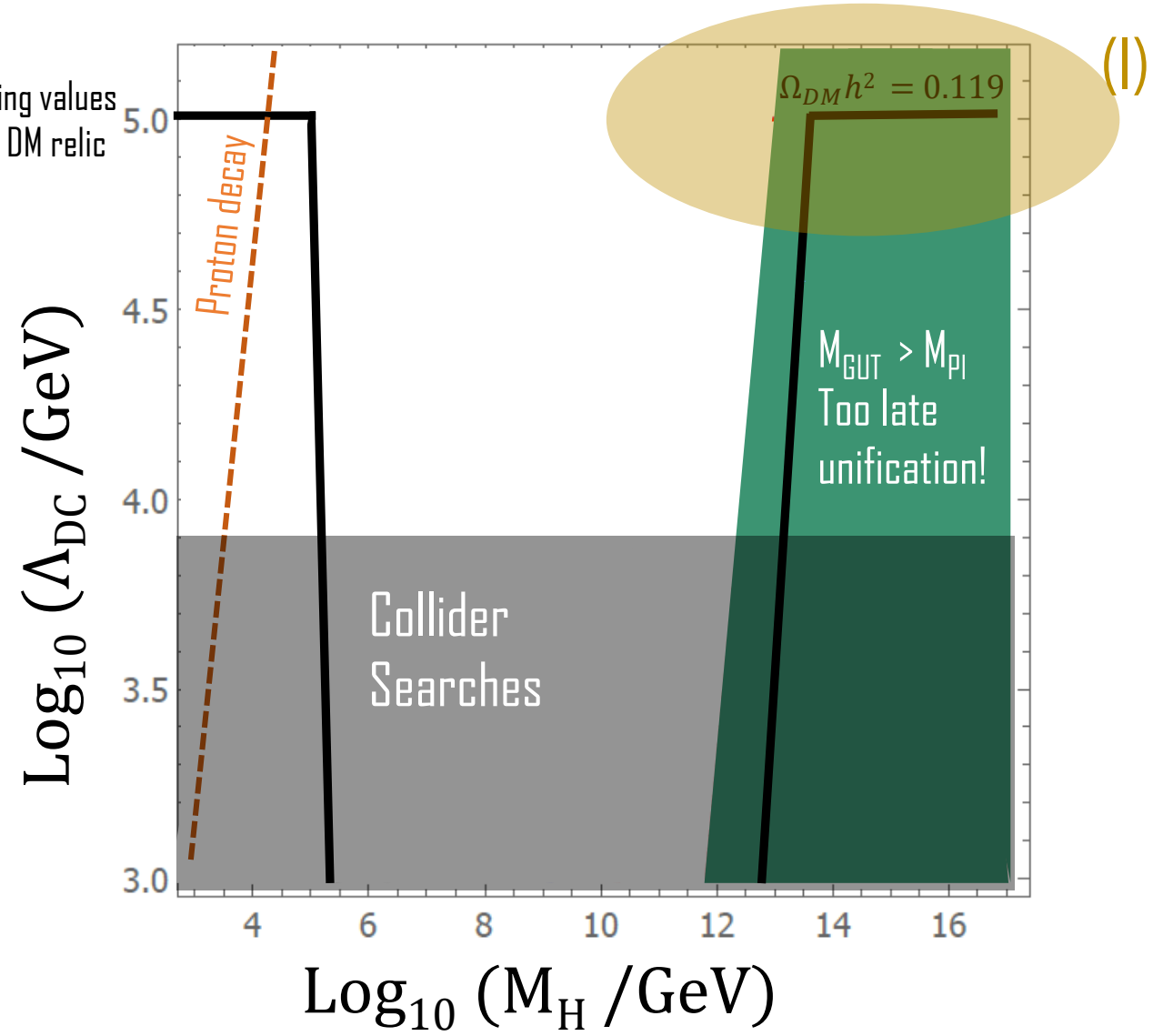

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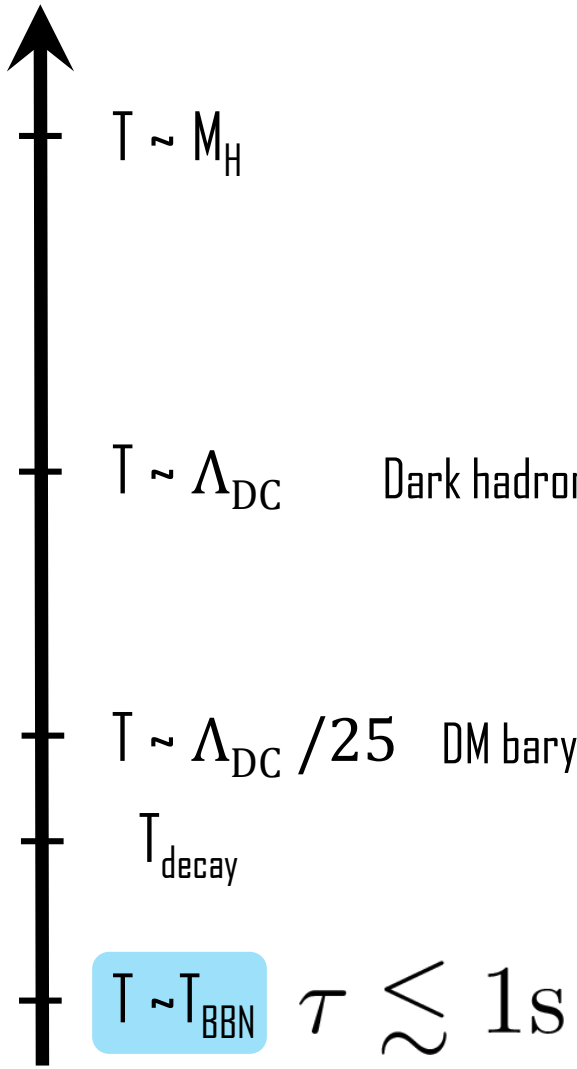

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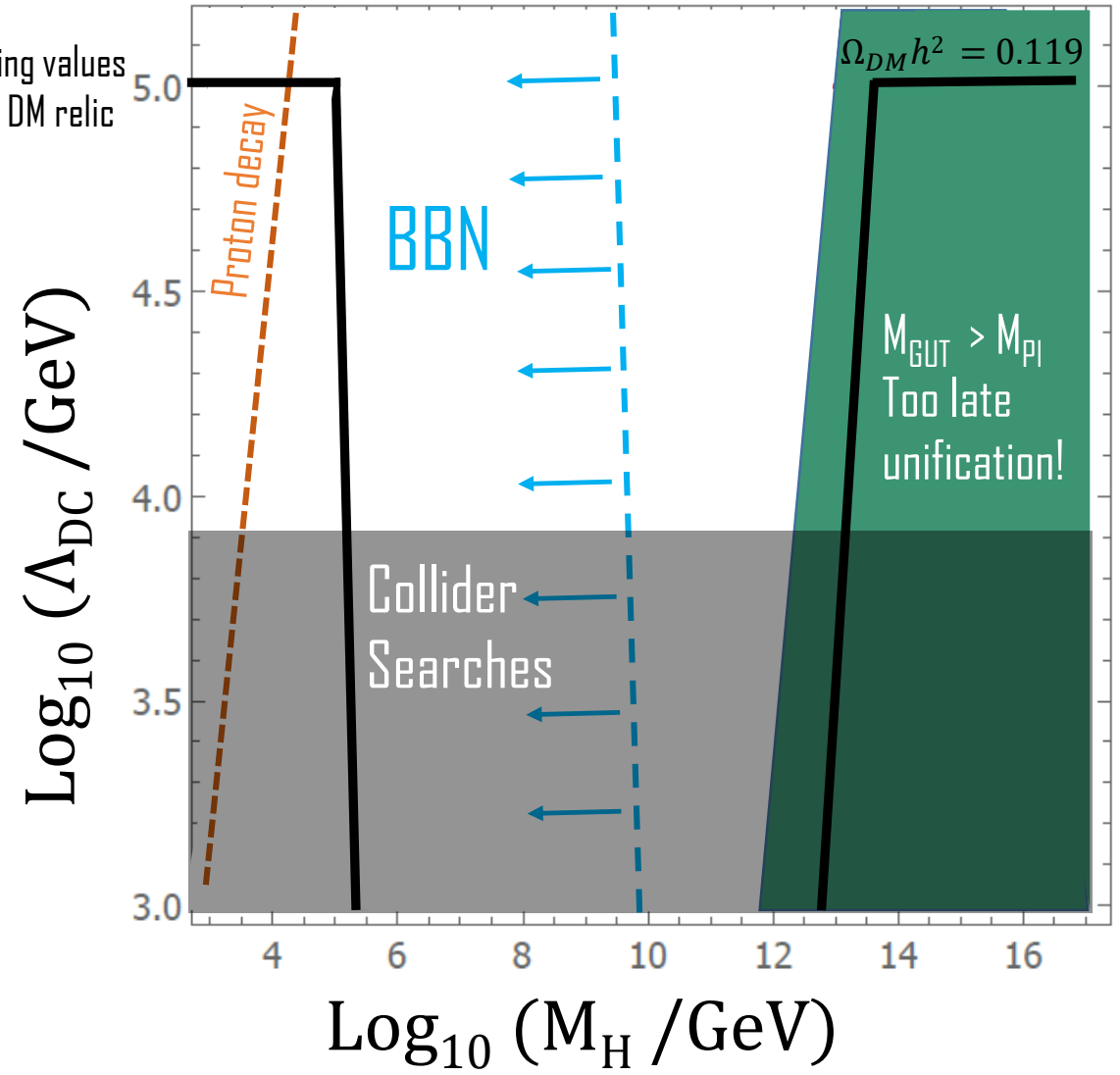

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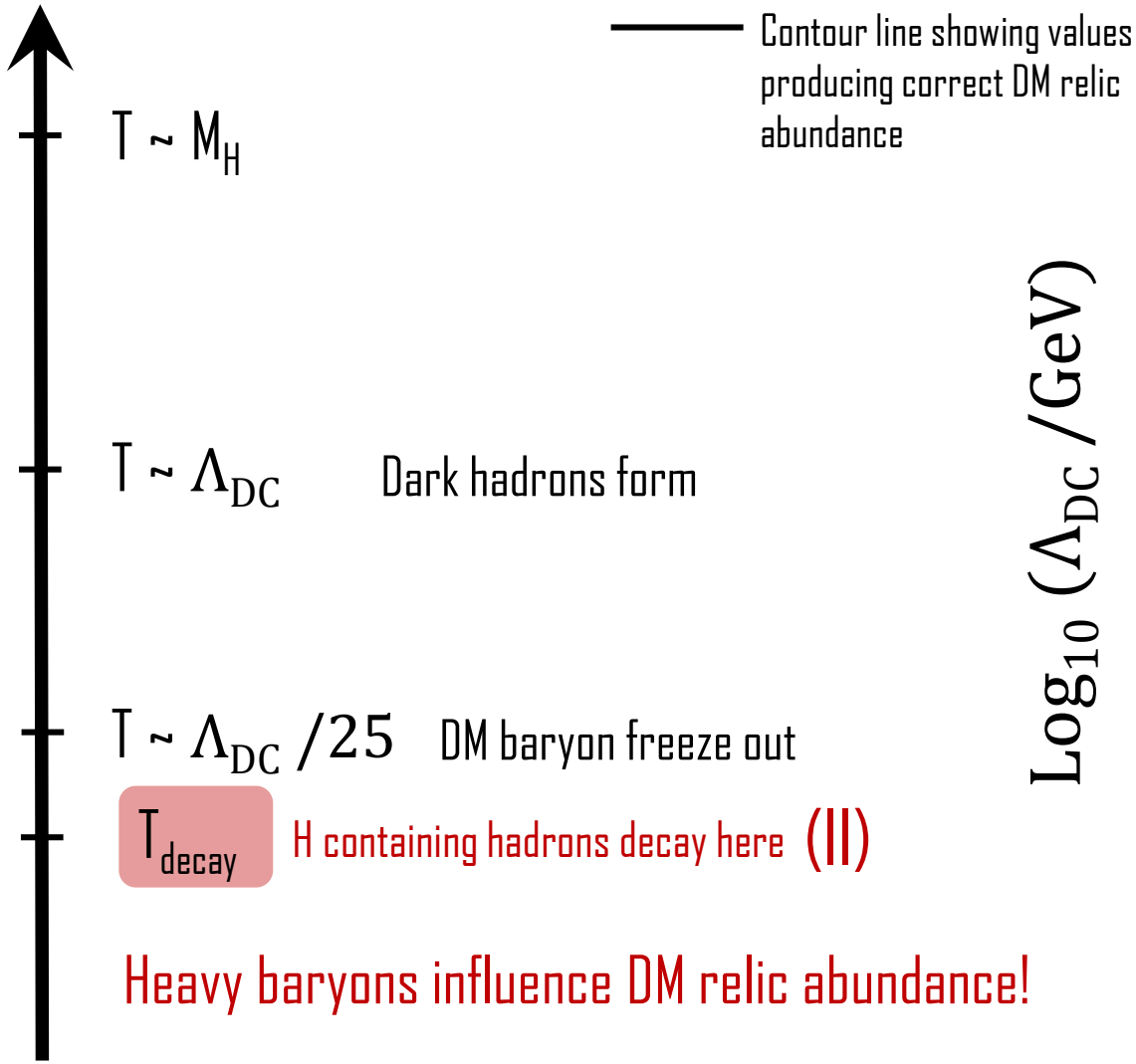

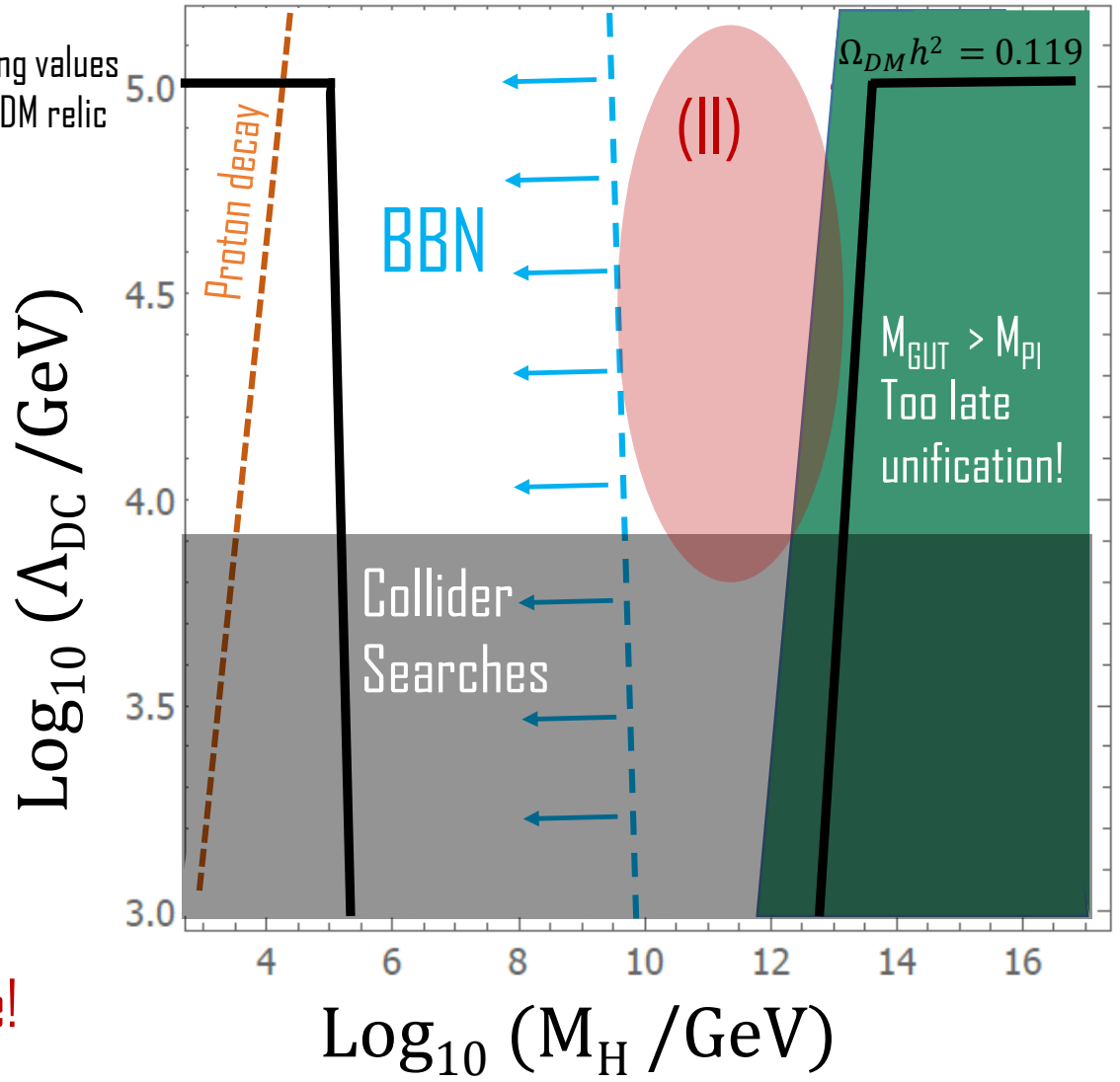

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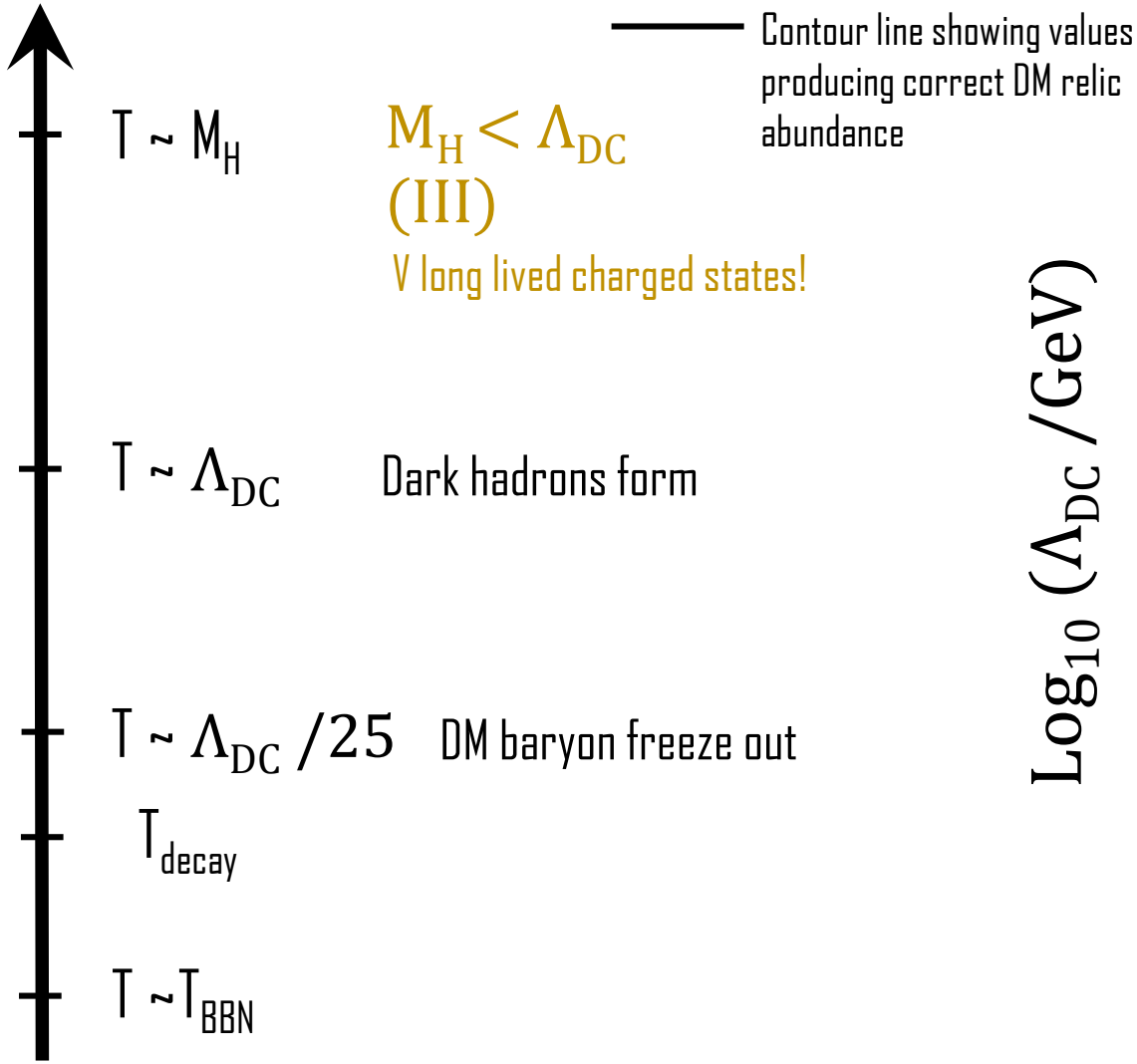

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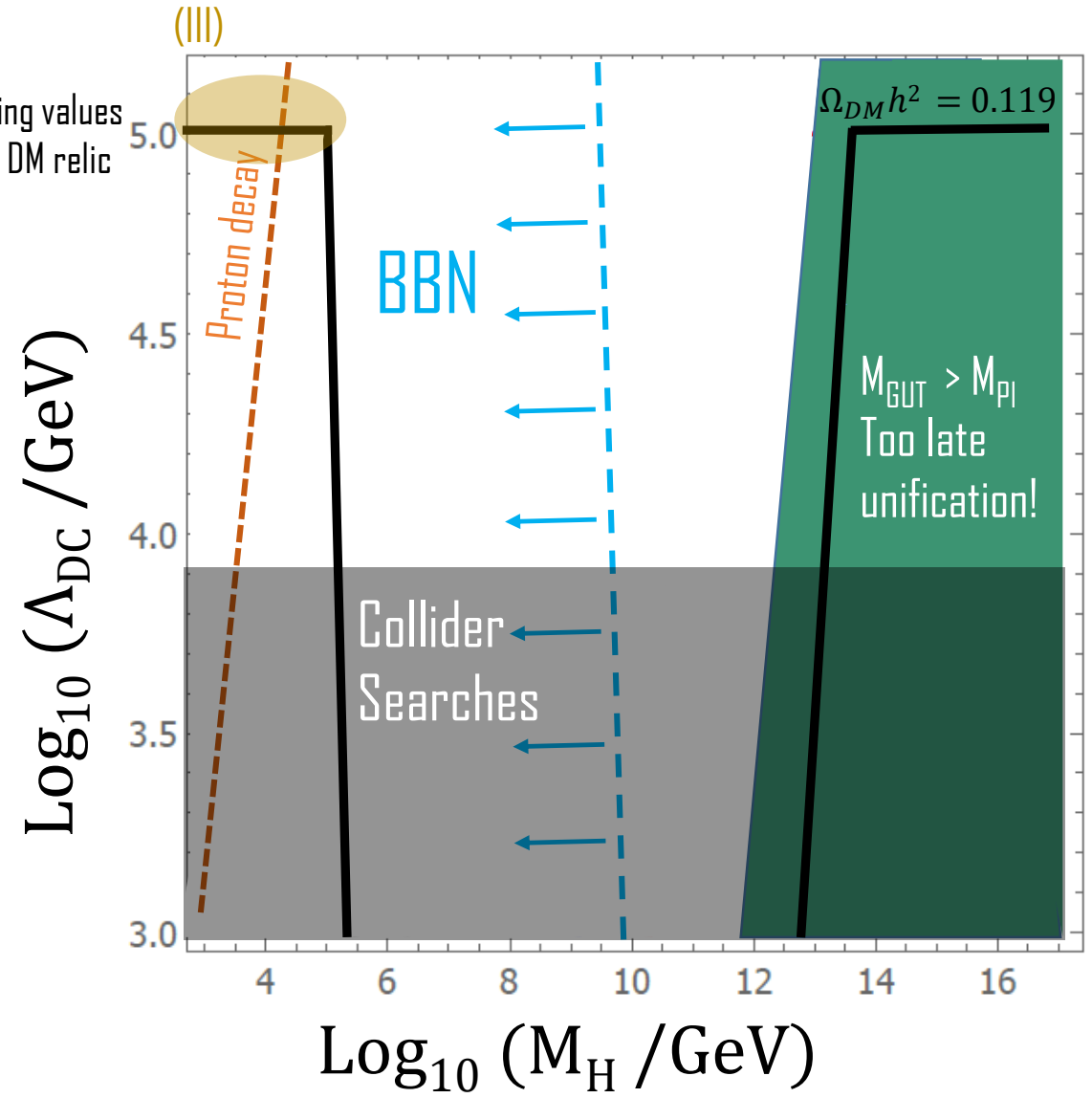

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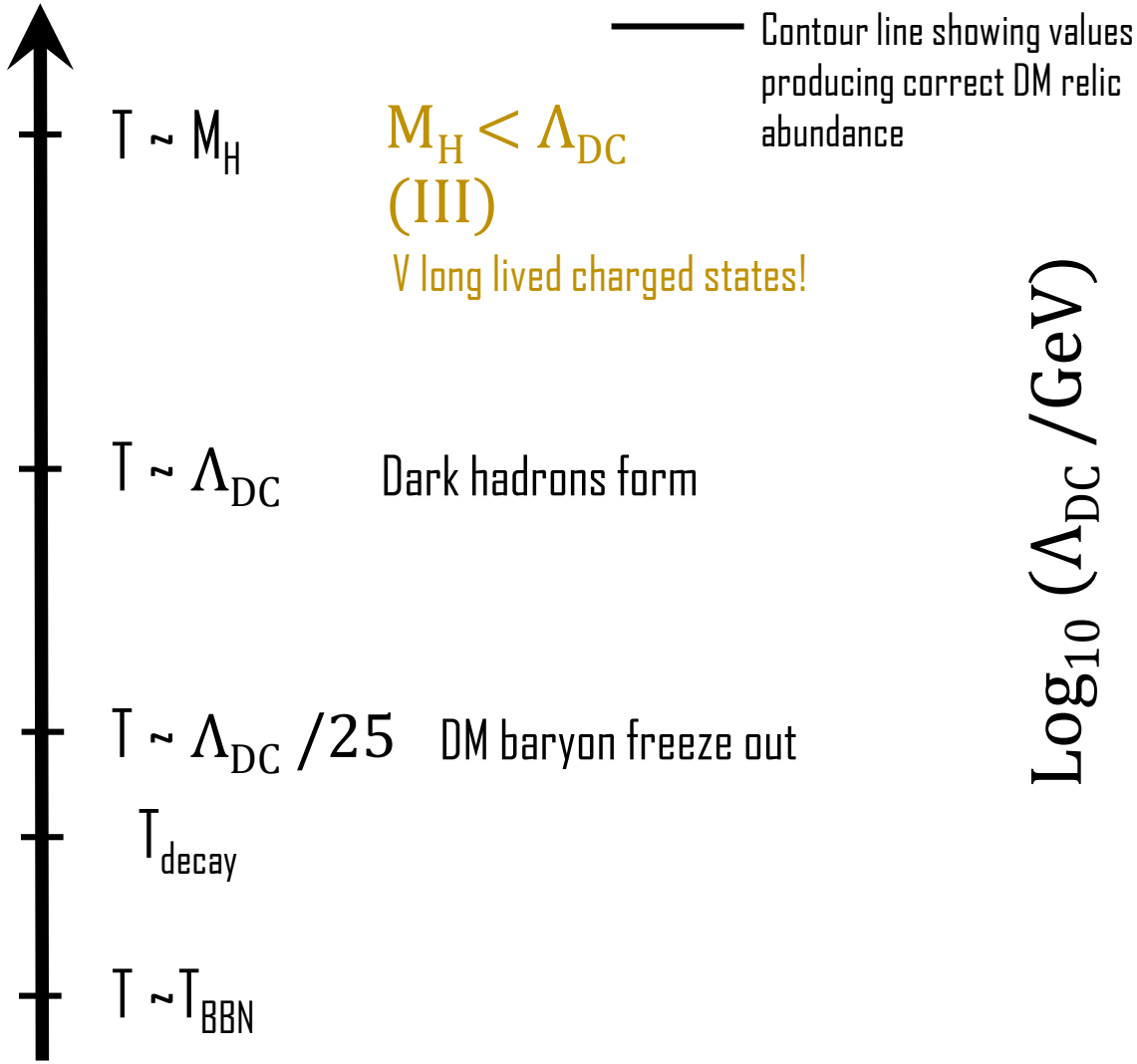

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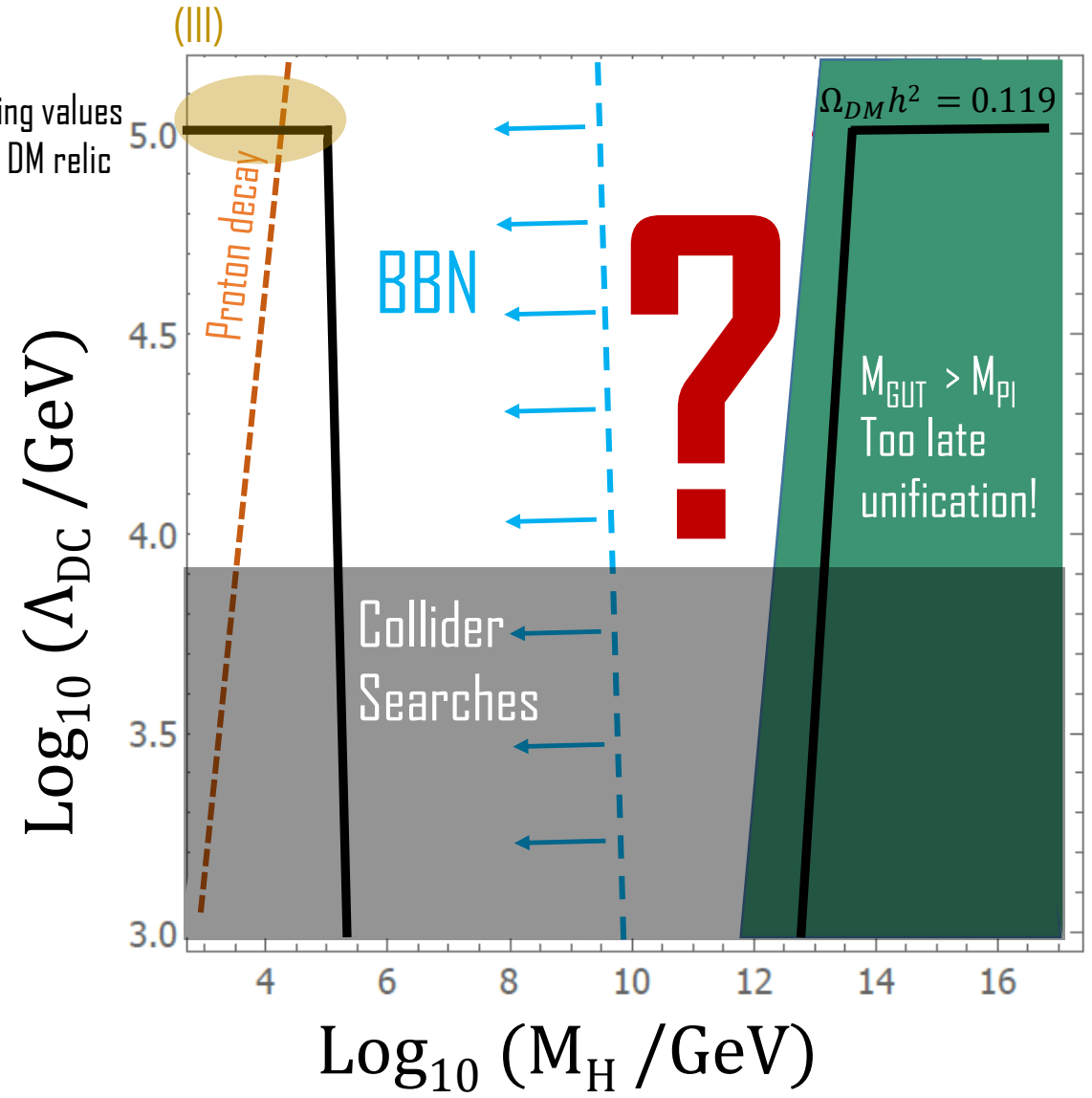

Thermal history?

Bottaro, Contino, SV [In prep]

$T \sim M_H$

$T_{RH} < M_H$ Avoid populating H !

Reheating temperature

$T \sim \Lambda_{DC}$ Dark hadrons form

$T \sim \Lambda_{DC}/25$ DM baryon freeze out

$T \sim T_{BBN}$

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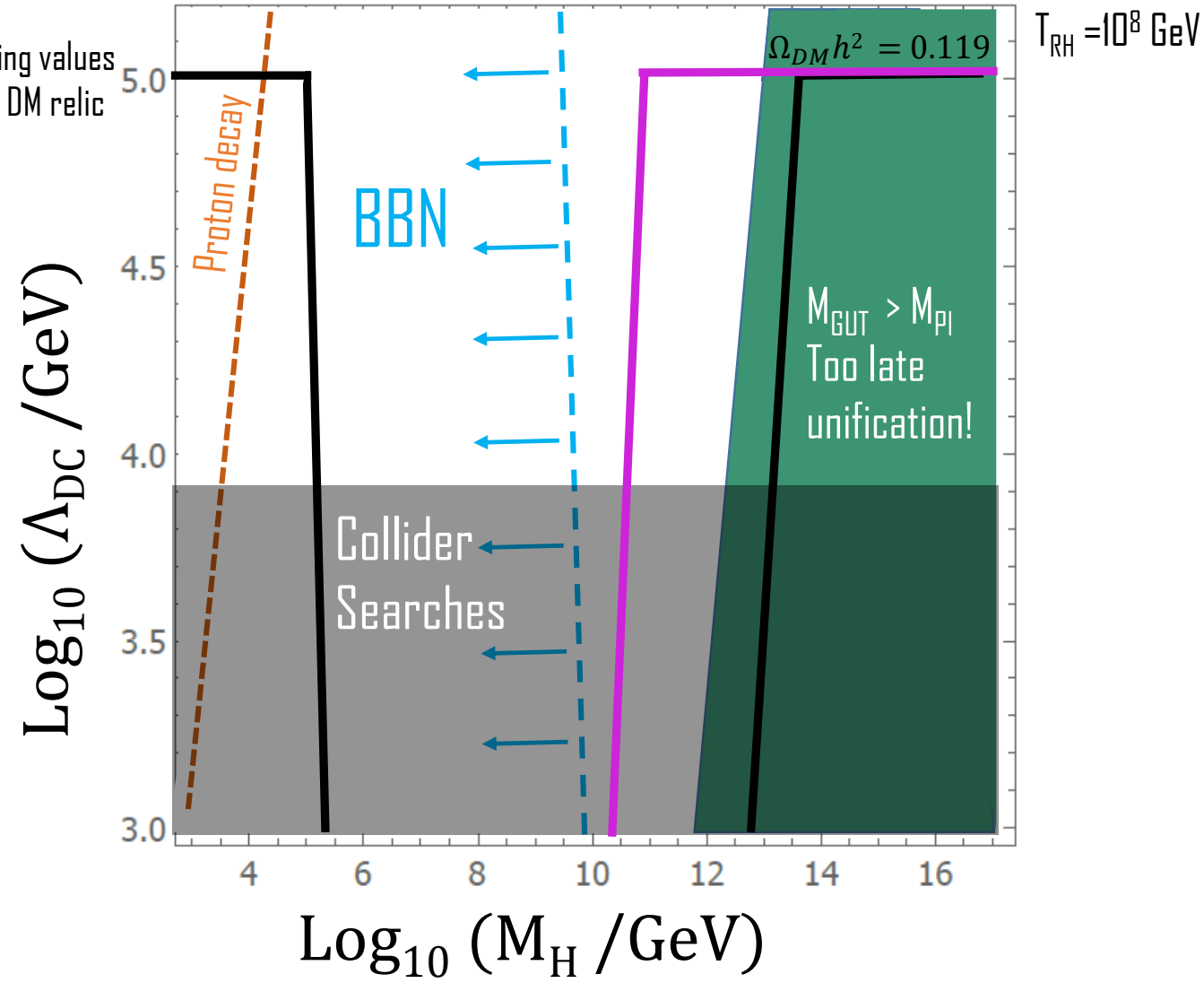

Conclusion

- 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]

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

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

Protected by symmetry!

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

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

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

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

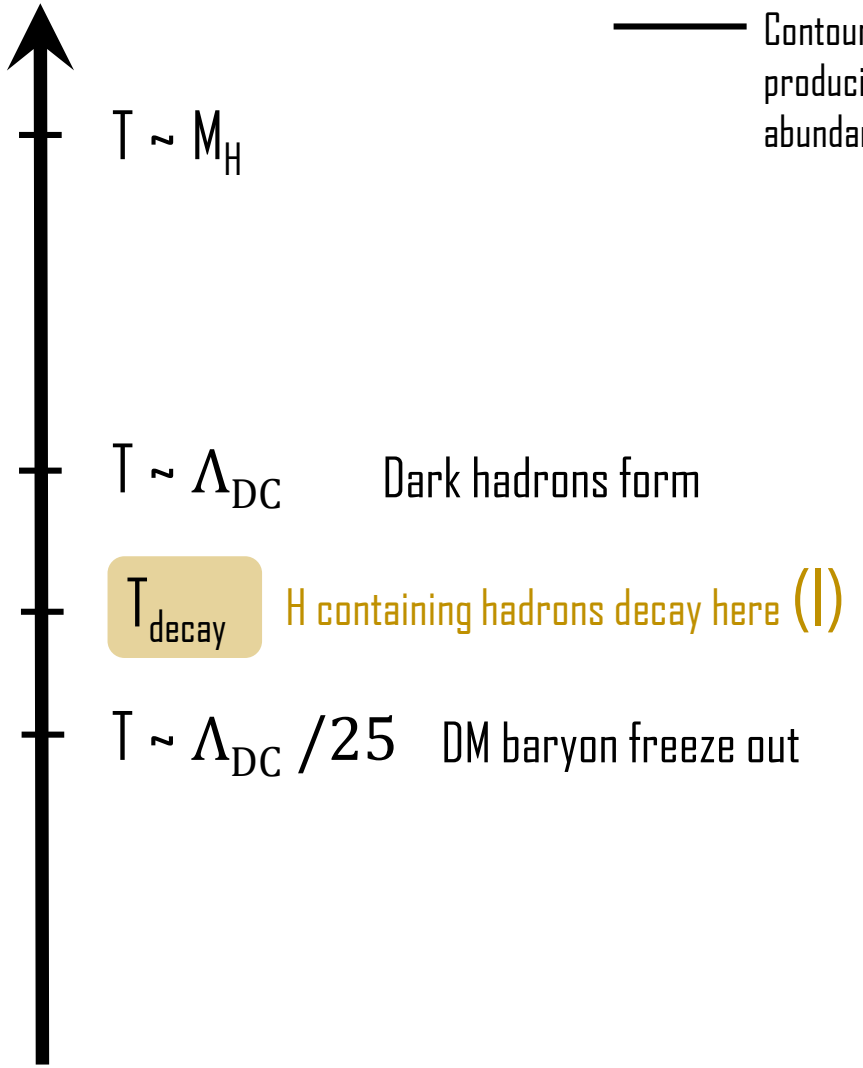
$$m_{\tilde{L}} = m_5 + \frac{3}{\sqrt{30}} y_5 v$$

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

Tuning needed!

Thermal history?

Bottaro, Contino, SV [In prep]



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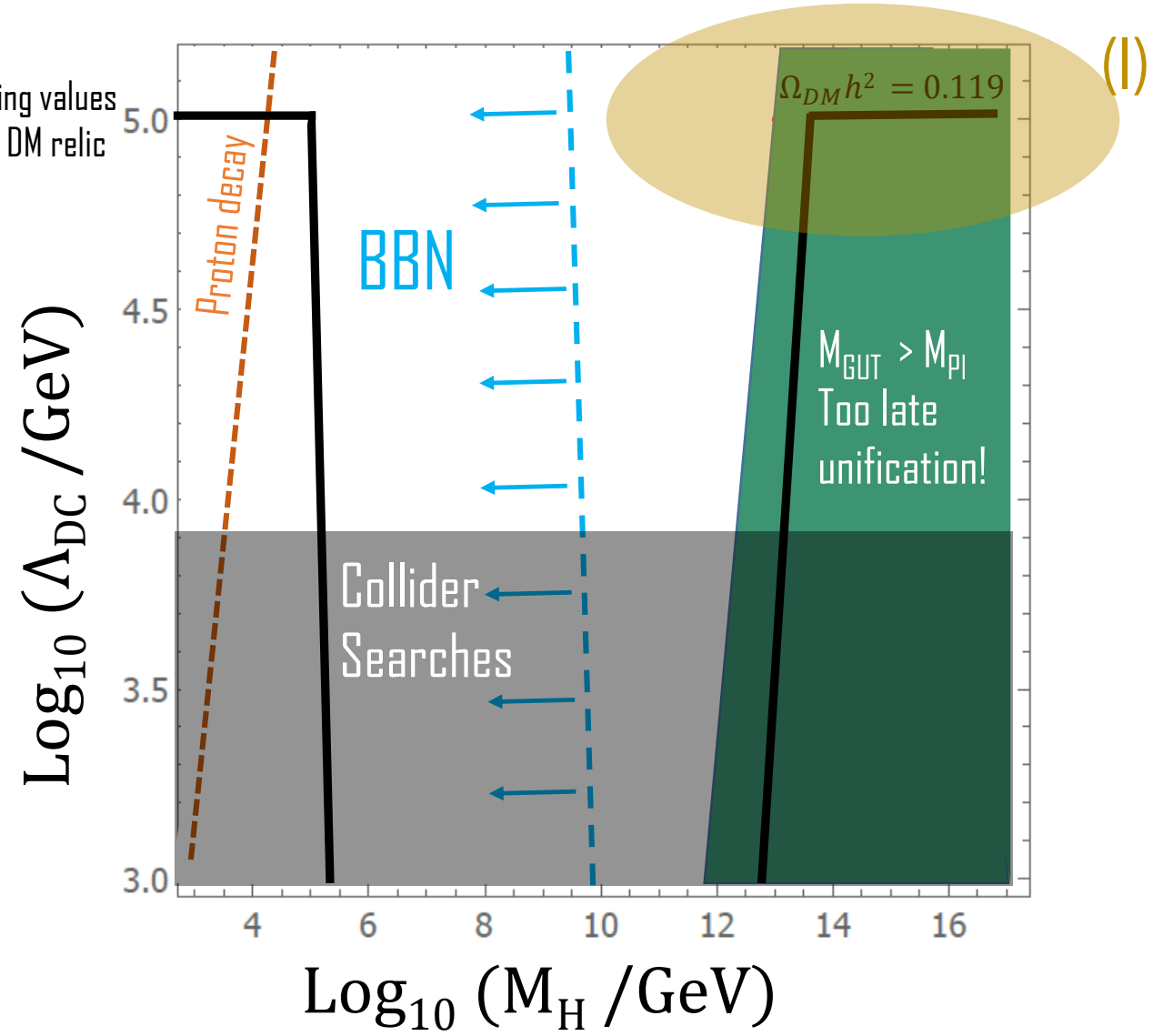

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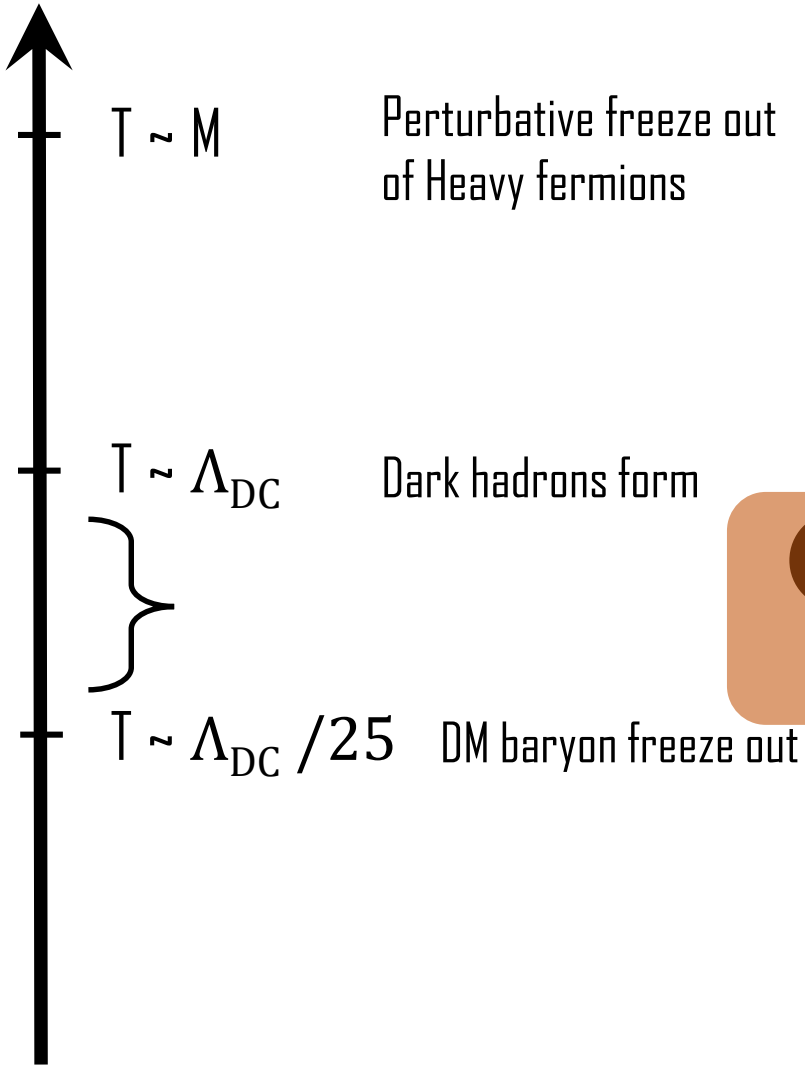
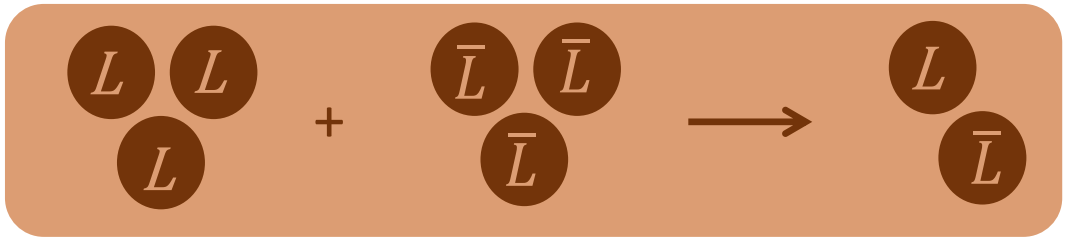
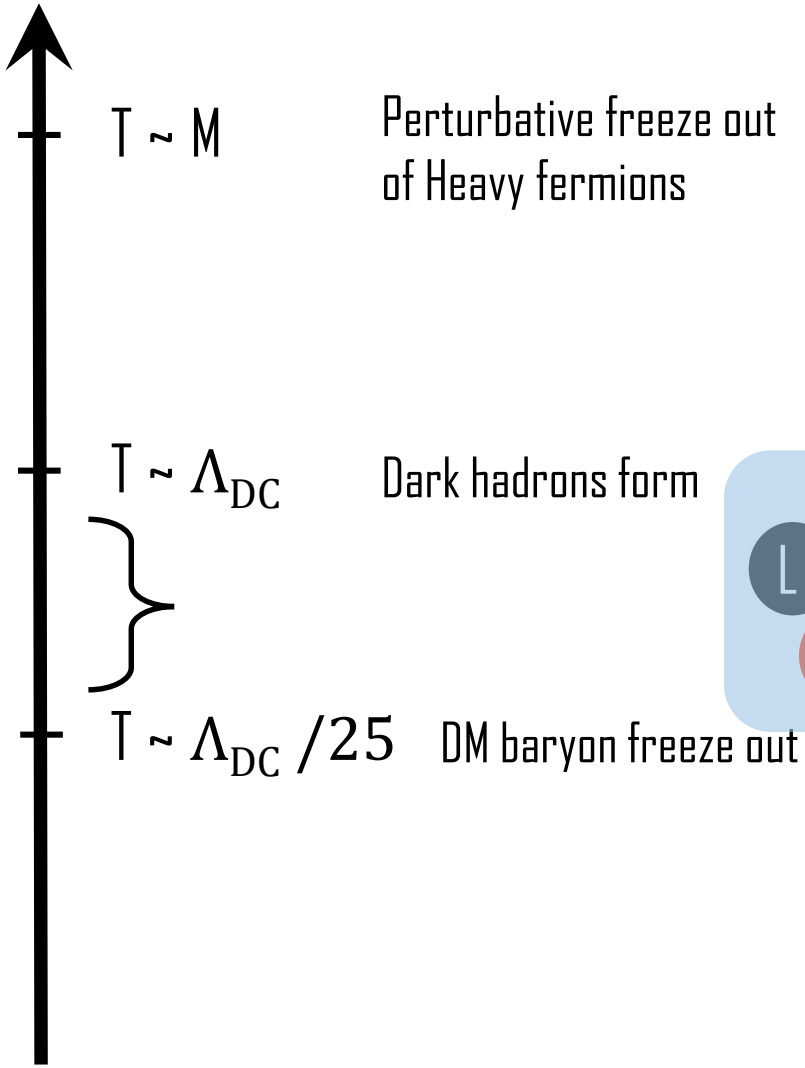


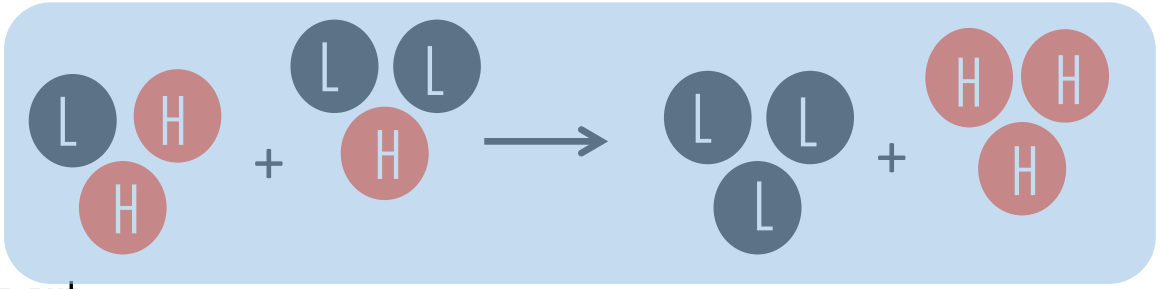


Annihilation of light baryons

Thermal history?

Bottaro, Contino, SV [In prep]





Recombination

Thermal history?

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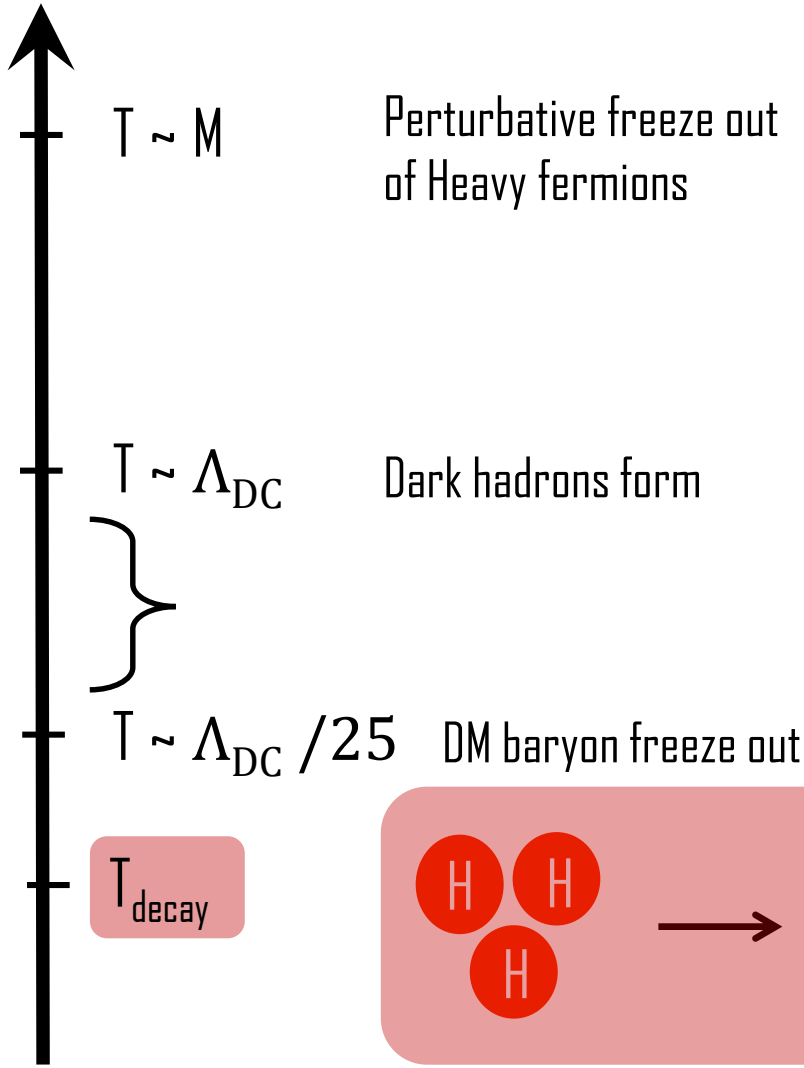
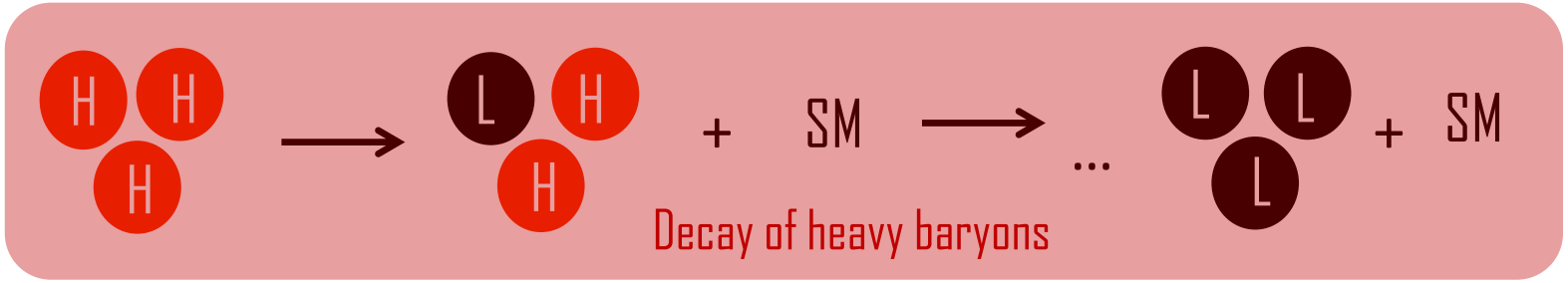


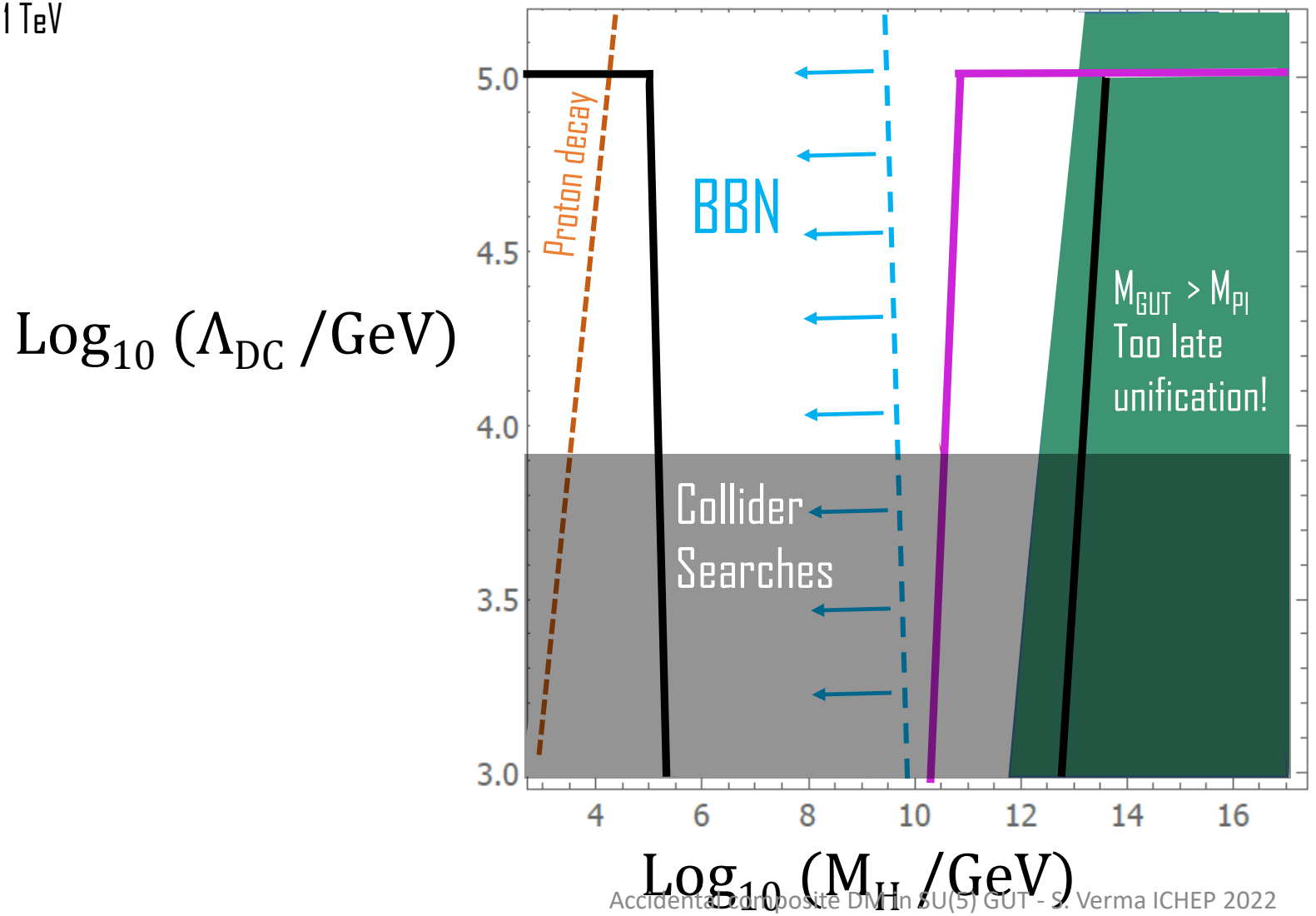
Can populate light baryons and influence DM relic abundance!



What do we find?

Bottaro, Contino, SV [In prep]

Light fermion mass
m = 1 TeV



Contour line showing values producing correct DM relic abundance

Reheating temp. $T_{RH} < M_H$

Can we produce a natural hierarchy?

Bottaro, Contino, SV [In prep]

$Q + \tilde{D}$ Hierarchy needed $m_{\tilde{D}} \ll m_{\tilde{L}}$

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

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

Tree level

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

After GUT → SM breaking

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

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

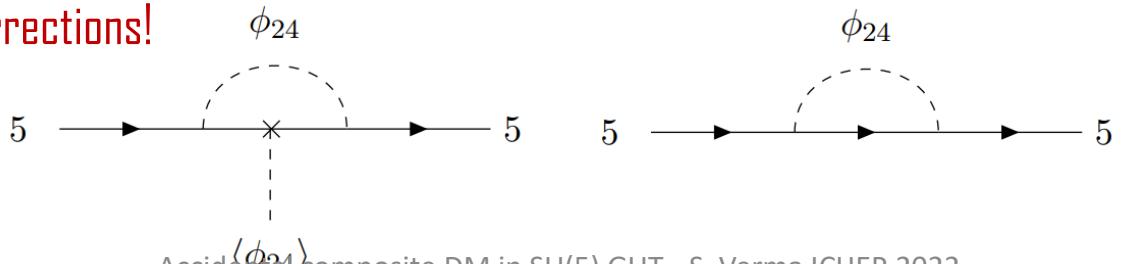
$$m_{\tilde{L}} = m_5 + \frac{3}{\sqrt{30}} y_5 v$$

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

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

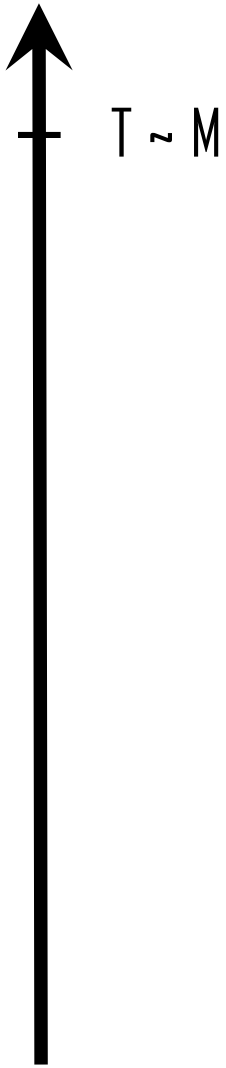
Tuning needed!

Tuning spoilt by such loop corrections!



Thermal history?

Bottaro, Contino, SV [In prep]



Perturbative freeze out
of Heavy fermions

Benchmark GUT model?

Bottaro, Contino, SV [In prep]

$Q + \tilde{D}$

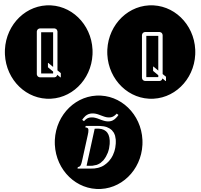
$$5 = \begin{bmatrix} \tilde{D} \\ \tilde{L} \end{bmatrix} \qquad 10 = \begin{bmatrix} U & Q \\ & E \end{bmatrix}$$

Low energy

$m \lesssim \Lambda_{DC} \sim 100$ TeV $\quad Q,\ \tilde{D}$ $\quad H\bar{Q}\tilde{D}$

Breaks 1 specie symmetry

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



Baryonic DM

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

Benchmark GUT model?

Bottaro, Contino, SV [In prep]

$Q + \tilde{D}$

$5 = \begin{bmatrix} \tilde{D} \\ \tilde{L} \end{bmatrix}$ $\quad 10 = \begin{bmatrix} U & Q \\ & E \end{bmatrix}$

Intermediate energy

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

3 more species

$U, E, \tilde{L}$ $\quad H^\dagger \bar{\tilde{L}} E$

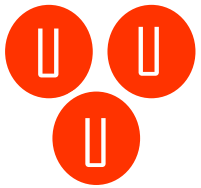
$U(1)_U$ U number

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

Broken at dim-6 level

e.g.

Dangerous stable states



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

Low energy

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

2 species

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

Breaks 1 specie symmetry

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

Baryonic DM

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

Motivations?

[Antipin, Redi, Strumia, Vigiani 2015]

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

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

Dark confinement scale

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

See [Mitridate, Redi, Smirnov, Strumia 2017]

- $\mathcal{G}_{\rm DC}$ unbroken by $\mathcal{G}_{\rm GUT}$, 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

ψ_5, ψ_{10} $\bar{\psi}_5 \phi_5^\dagger \psi_{10}$

Breaks 1 GUT species

Intermediate energy

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

3 more species

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

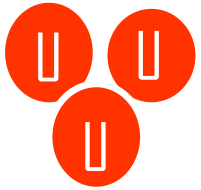
$U(1)_U$ U number

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

Broken at dim-6 level

e.g.

Dangerous stable states



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

Low energy

$m \lesssim \Lambda_{DC}$ ~ 100 TeV

2 species

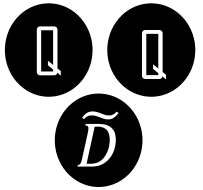
$Q, \tilde{D}$ $H \bar{Q} \tilde{D}$

Breaks 1 species symmetry

$U(1)_{DB}$

dark baryon number

Baryonic DM



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

Motivations?

- Since $\psi_{\rm dark} \in \mathcal{G}_{\rm SM}$, embedding in SU(5) gives an 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. $Q + \tilde{D}$

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

Can we relax unification criteria and catch more models?

Bottaro, Contino, SV [In prep]

Motivations?

- Since $\psi_{\rm dark} \in \mathcal{G}_{\rm SM}$, embedding in SU(5) gives an another constraint

[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 make EFT pov explicit in the classification of models?

Bottaro, Contino, SV [In prep]

Motivations?

- Since $\psi_{\rm dark} \in \mathcal{G}_{\rm SM}$, 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 $\mathcal{L}^{\rm mass}_{\rm GUT} = -m_5 \bar{\psi}_5 \psi_5$

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

Intermediate mass scale $m_{\tilde{D}} \ll m_{\tilde{L}}$

Low energy level $\mathcal{L}^{\rm mass}_{\rm IR} = -m_{\tilde{D}} \bar{\psi}_{\tilde{D}} \psi_{\tilde{D}}$

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

Bottaro, Contino, SV [In prep]

Motivations?

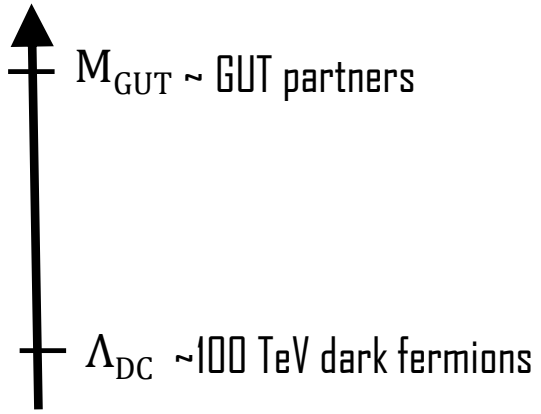
[Antipin, Redi, Strumia, Vigiani 2015]

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

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

Dark confinement scale

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



Motivations?

[Antipin, Redi, Strumia, Vigiani 2015]

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

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

Dark confinement scale

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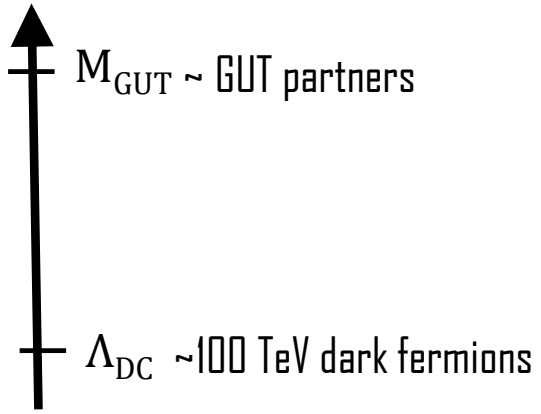


Bottaro, Contino, SV [In preparation]

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

Benchmark GUT model?

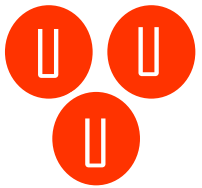
$Q + \tilde{D}$ $\qquad 5 = \begin{bmatrix} \tilde{D} \\ \tilde{L} \end{bmatrix}$ $\qquad 10 = \begin{bmatrix} U & Q \\ & E \end{bmatrix}$

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

At $\Lambda_{\rm DC}$ ~ 100 TeV

Baryonic DM

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

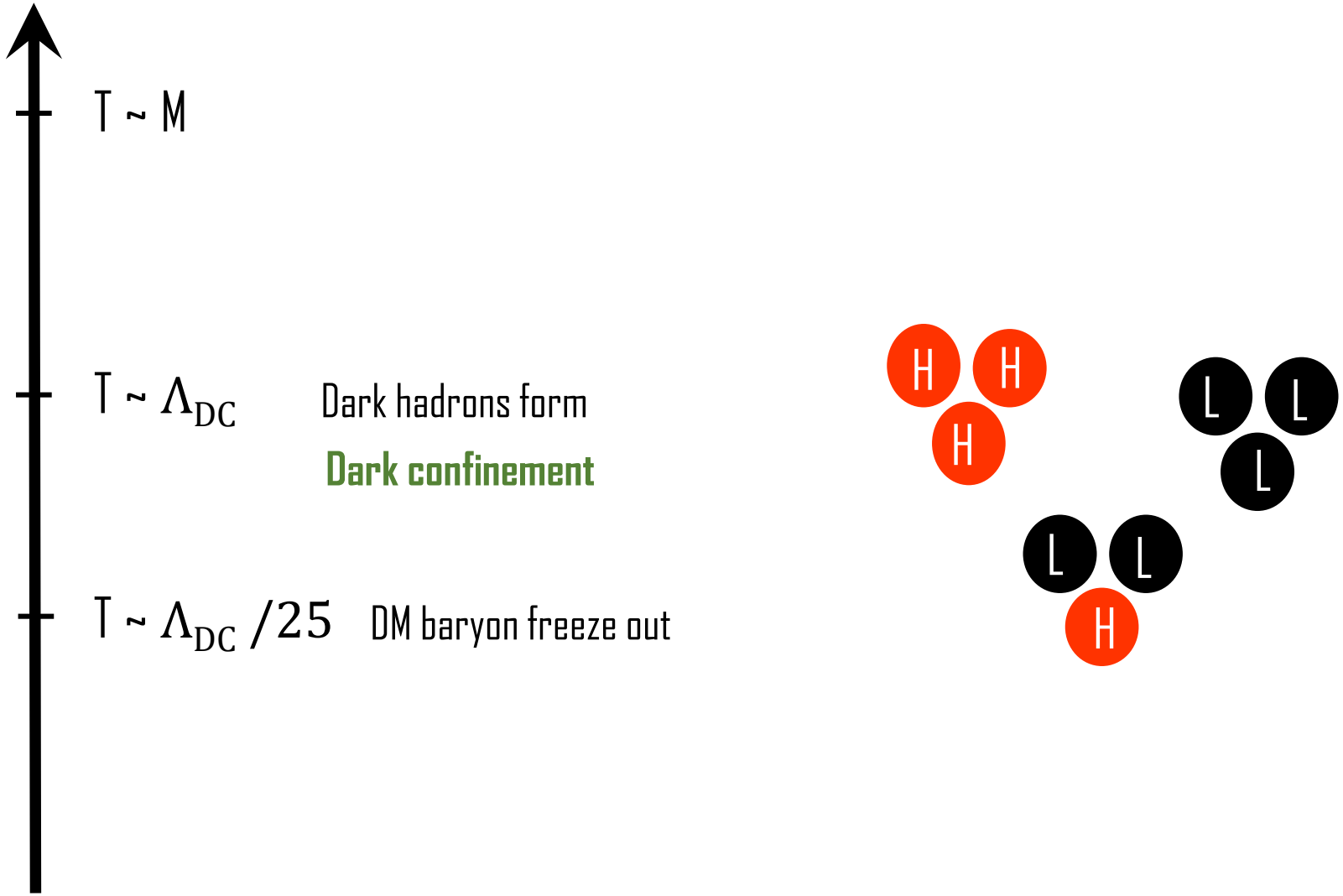


Dangerous stable states

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

Thermal history?

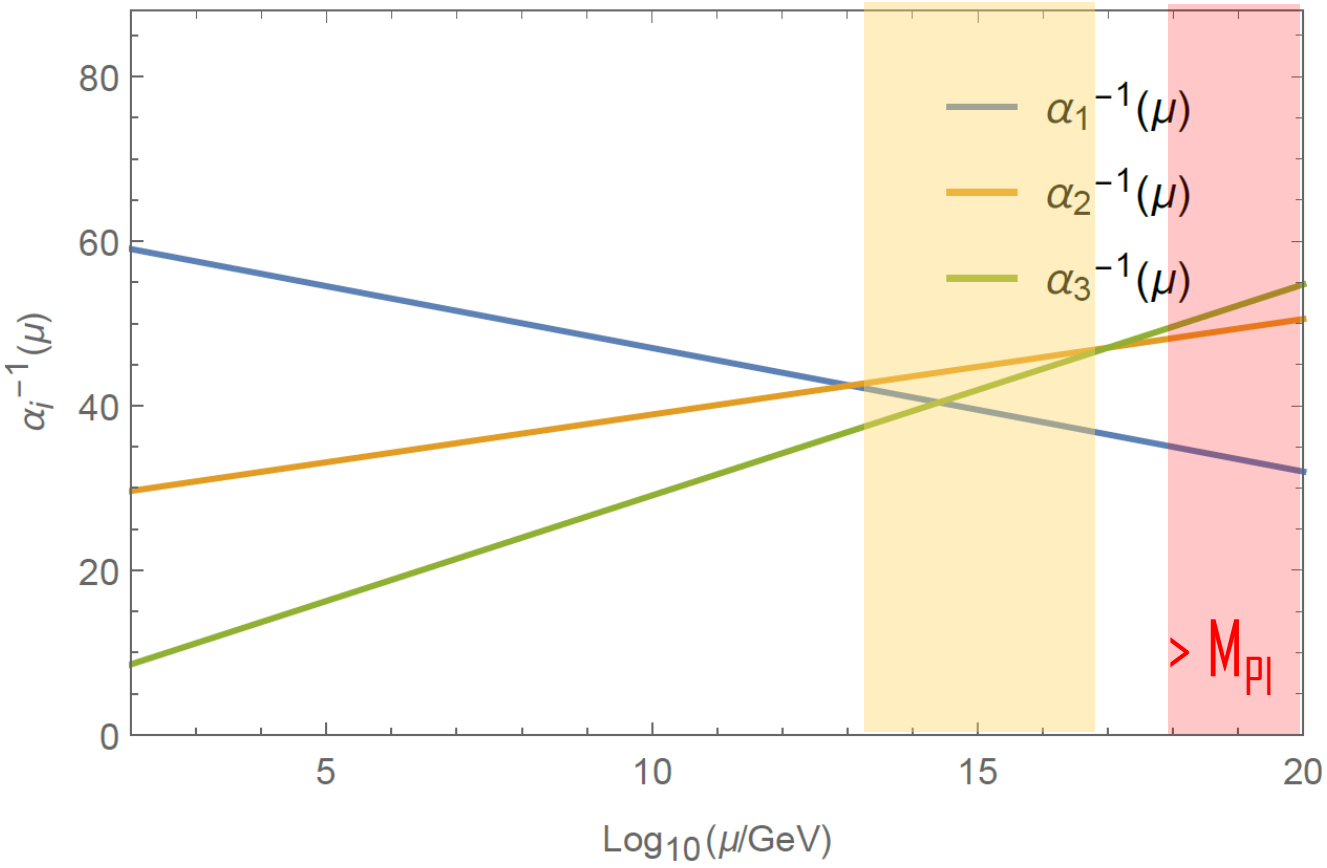
Bottaro, Contino, SV [In prep]



Coincidence or GUT?

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

SM only



Benchmark GUT model?

Bottaro, Contino, SV [In prep]

$Q + \tilde{D}$ $\quad 5 = \begin{bmatrix} \tilde{D} \\ \tilde{L} \end{bmatrix}$ $\quad 10 = \begin{bmatrix} U & Q \\ & E \end{bmatrix}$

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

$L = Q, \tilde{D}$

M_{GUT}

Intermediate energy

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

3 more species

$U, E, \tilde{L}$ $\quad H^\dagger \bar{\tilde{L}} E$

New accidental symmetries!

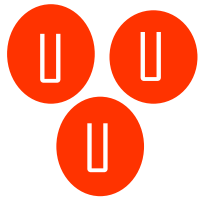
$U(1)_U$ U number

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

Broken at dim-6 level

Dangerous stable states

e.g.



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

Low energy

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

2 species

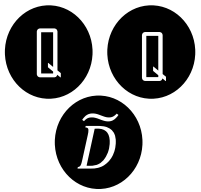
$Q, \tilde{D}$ $\quad H \bar{Q} \tilde{D}$

Breaks 1 species symmetry

$U(1)_{DB}$

dark baryon number

Baryonic DM



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

Thermal history?

Bottaro, Contino, SV [In prep]