Probing GUT with Accidentally Stable dark matter

Sonali Verma, ULB Brussels | PLANCK2025 Padova 27th May 2025

Based on arxiv: 2407.20591, + work [to appear] with Roberto Contino, Salvatore Bottaro

Artwork by Sandbox Studio, Chicago with Ana Kova

Coincidence or “compelling rationale”

[Snowmass 1310.8327]

guiding principle in BSM physics

Coincidence or "compelling rationale"

[Snowmass 1310.8327]

guiding principle in BSM physics

WIMP MIRACLE

$$\Omega_\chi \simeq 20 \left(\frac{T_{CMB}^3}{\rho_{crit}\, M_{Pl}} \right) \left(\frac{1}{\sigma} \right)$$

Coincidence or "compelling rationale"

[Snowmass 1310.8327]

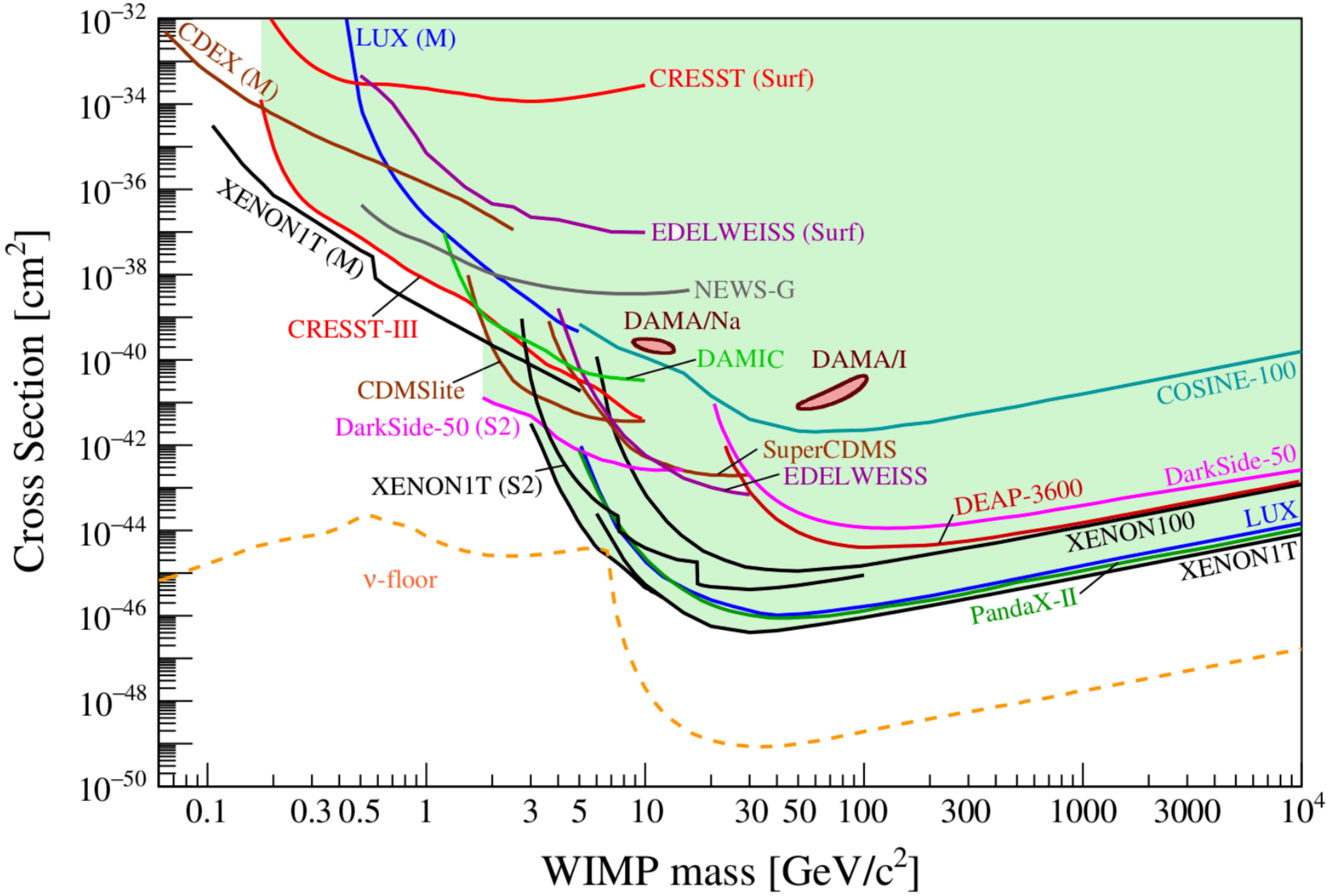
guiding principle in BSM physics

WIMP MIRACLE

$$\Omega_\chi \simeq 20 \left(\frac{T_{CMB}^3}{\rho_{crit}\ M_{Pl}} \right) \left(\frac{1}{\sigma} \right)$$

$$\left(\frac{\Omega_\chi}{0.2} \right) \simeq \left(\frac{10^{-8}\ \mathrm{GeV}^{-2}}{\sigma} \right)$$

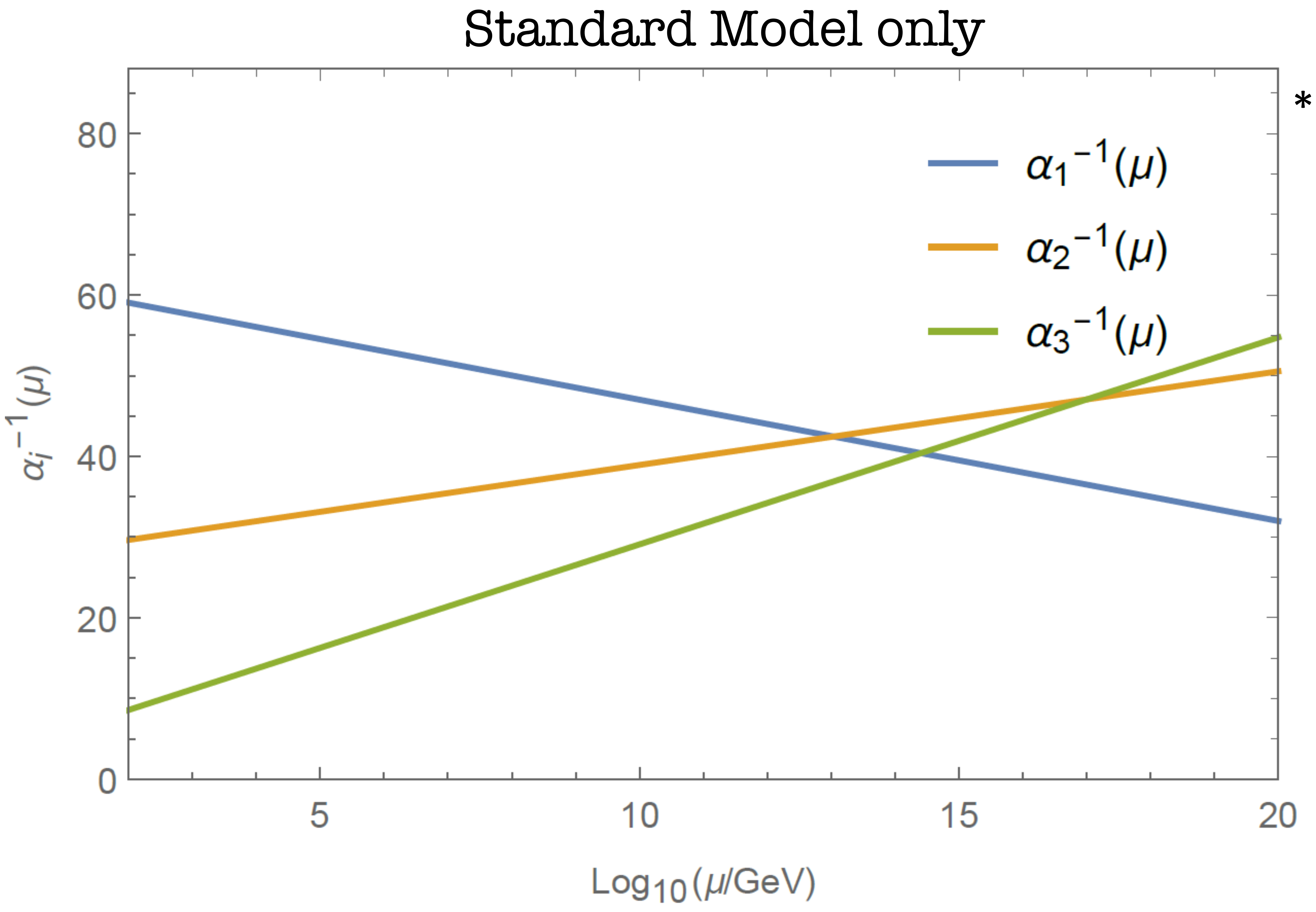
Coincidence or "compelling rationale"



Coincidence or "Grand unification"?

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

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

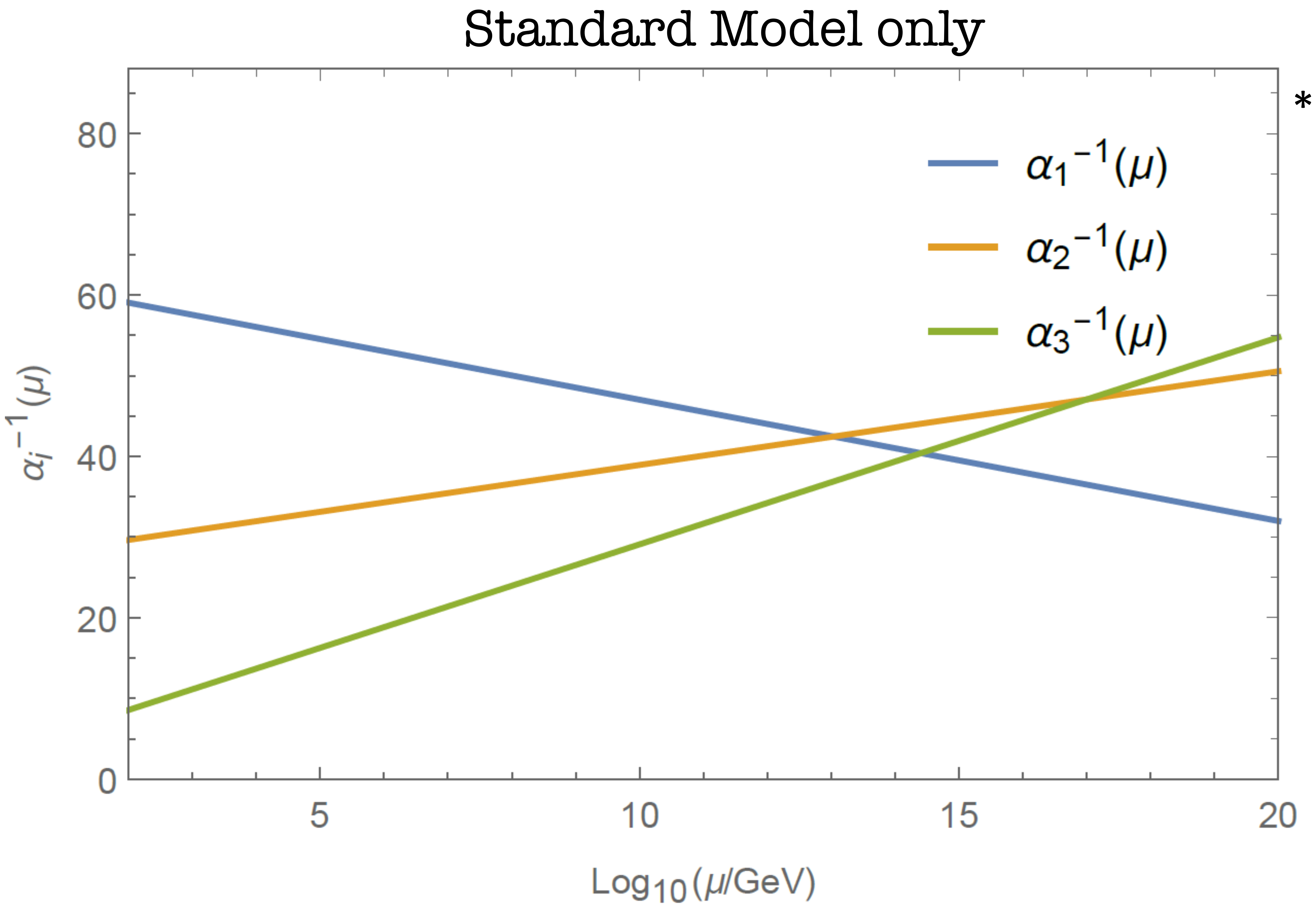


*$\alpha_1 = 5/3\ \alpha_Y$

Coincidence or "Grand unification"?

SU(5) Unification in SM?

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

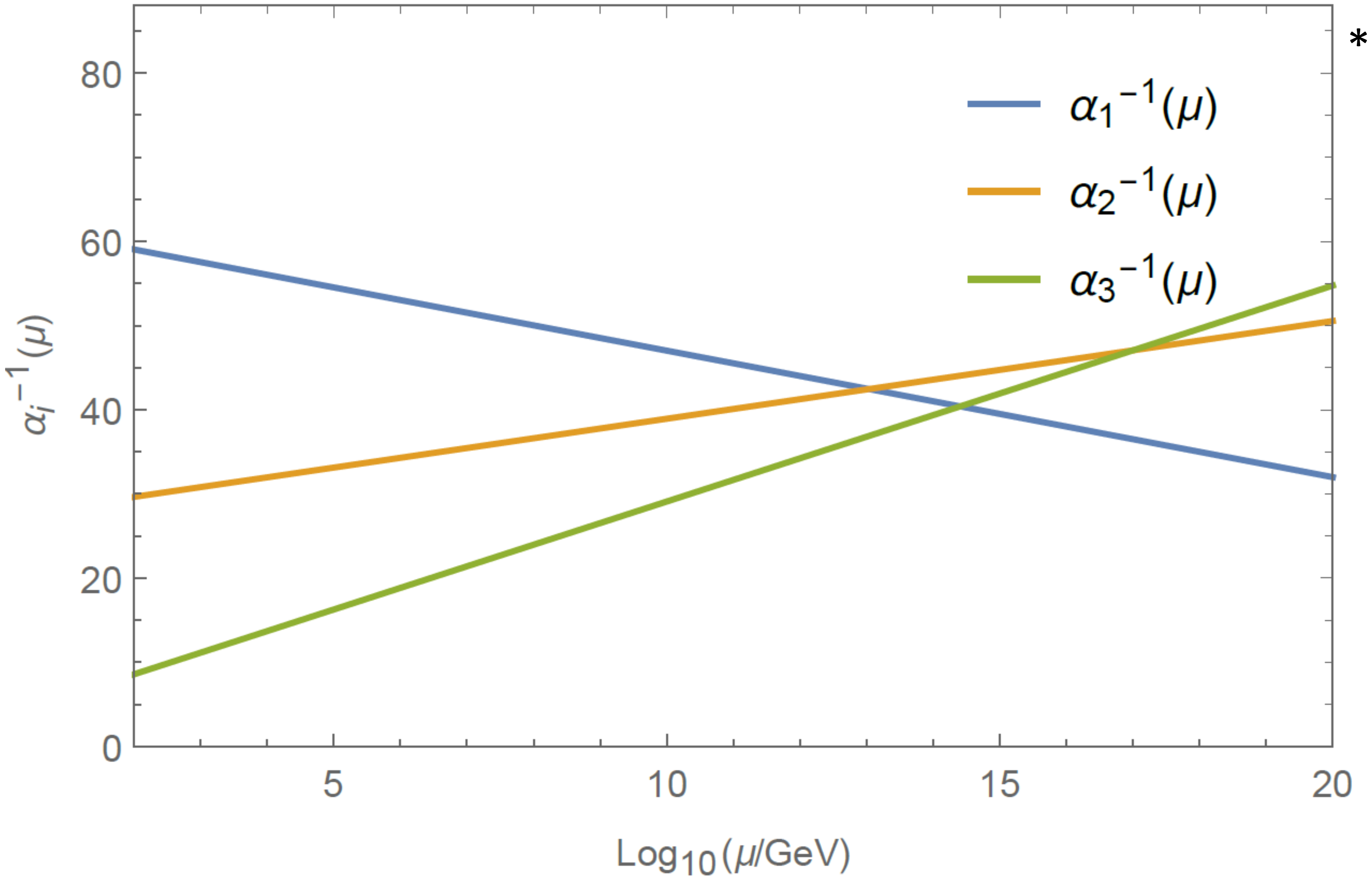


*$\alpha_1 = 5/3\ \alpha_Y$

unification as a guiding principle

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

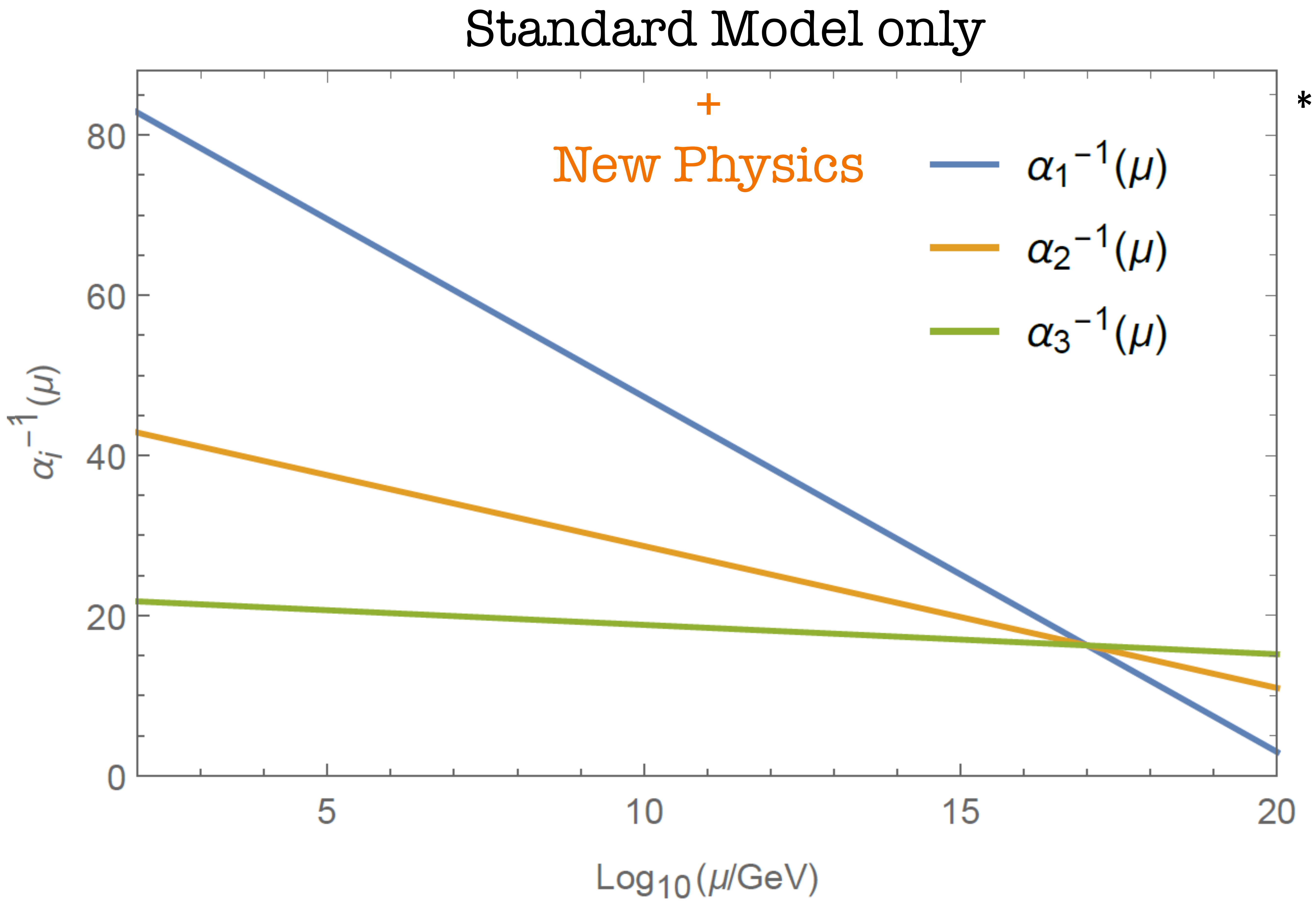
Standard Model only



*α_1 = 5/3 α_Y

unification as a guiding principle

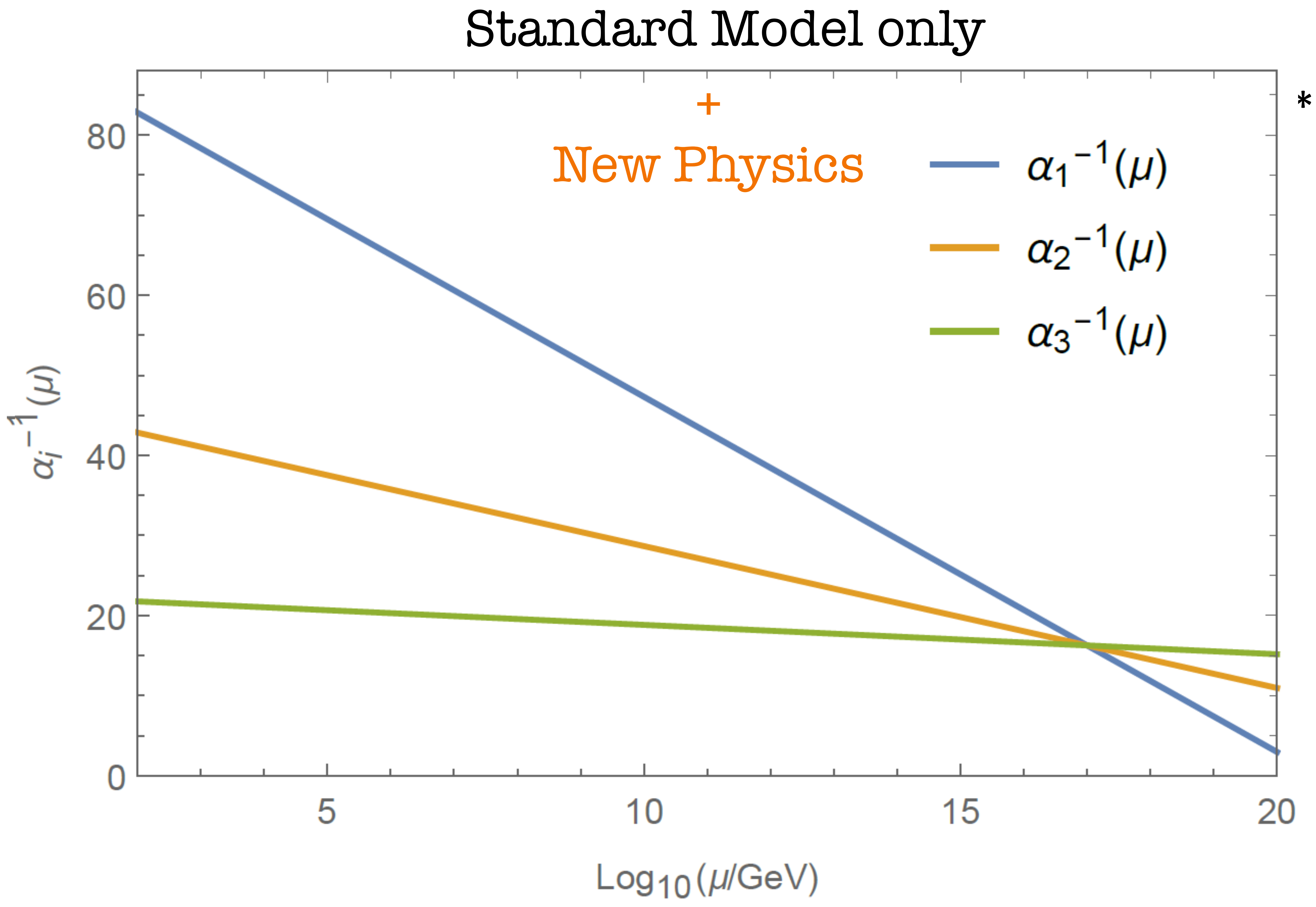
$$\alpha_i(\mu)^{-1} = -\alpha_i(M_Z)^{-1} - \frac{b_i^{SM}}{2\pi} \log \frac{\mu}{M_Z} + \boxed{\Delta_{NP}}$$



*$\alpha_1 = 5/3\ \alpha_Y$

[Ibe '09], [Aizawa, Ibe, Kaneta `16], [Mahbubani, Senatore`06], [Harigaya et. Al.`16], [Antipin et. al.`15], [Di Luzio, Tamarit, Ringwald '18], [Perez, Murgui, Plascencia '19], [Ernst, Ringwald, Tamarit '18] [Gherghetta, Murayama, Quilez '25]...

Can a dark sector give good unification and a dark matter?

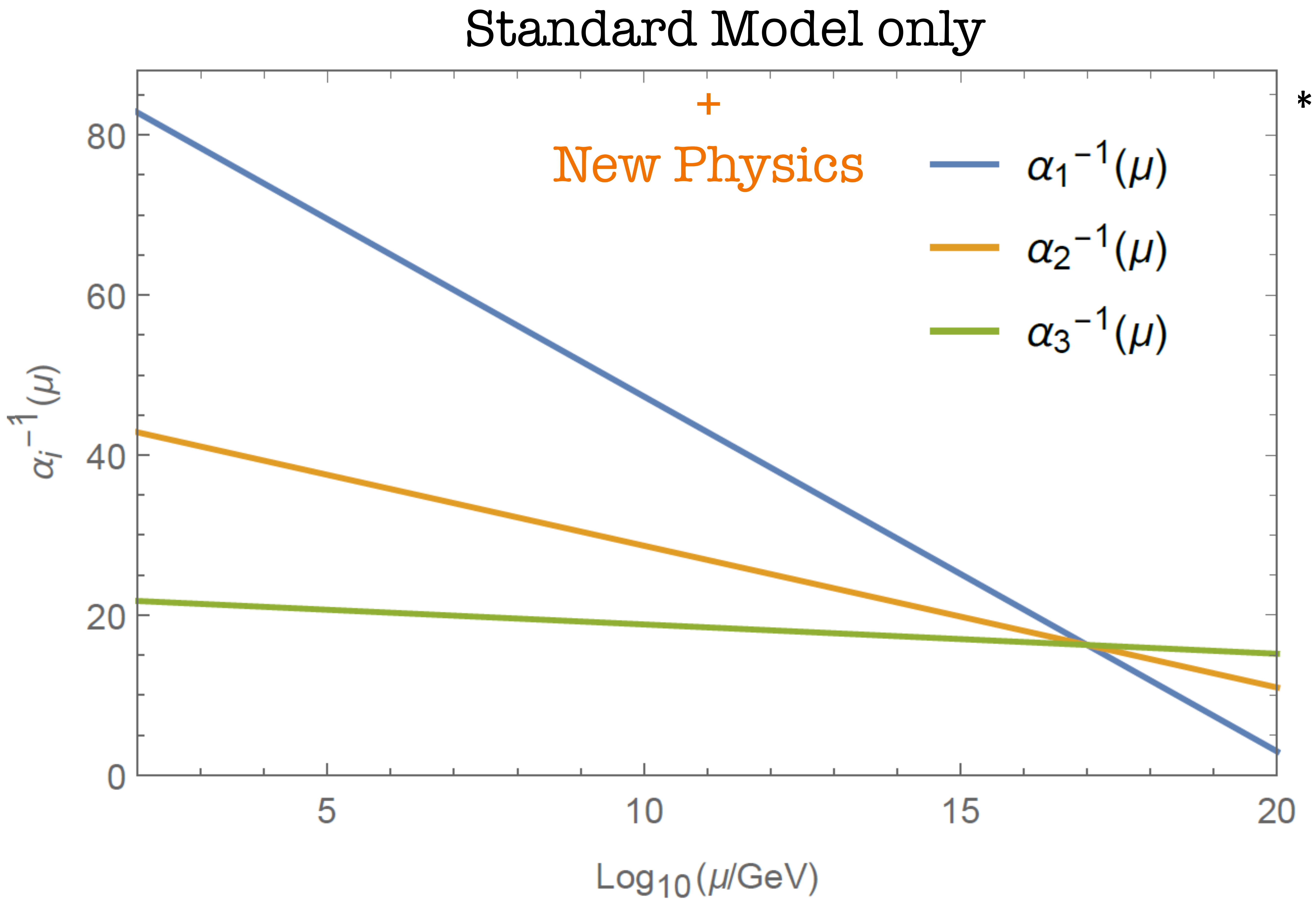


*$\alpha_1 = 5/3\ \alpha_Y$

[Bottaro, Contino, SV `24] Bottaro, Contino, SV [In prep] [Antipin et. al.`15]

accidentally stable

Can a dark sector give good unification and a dark matter?



*$\alpha_1 = 5/3\ \alpha_Y$

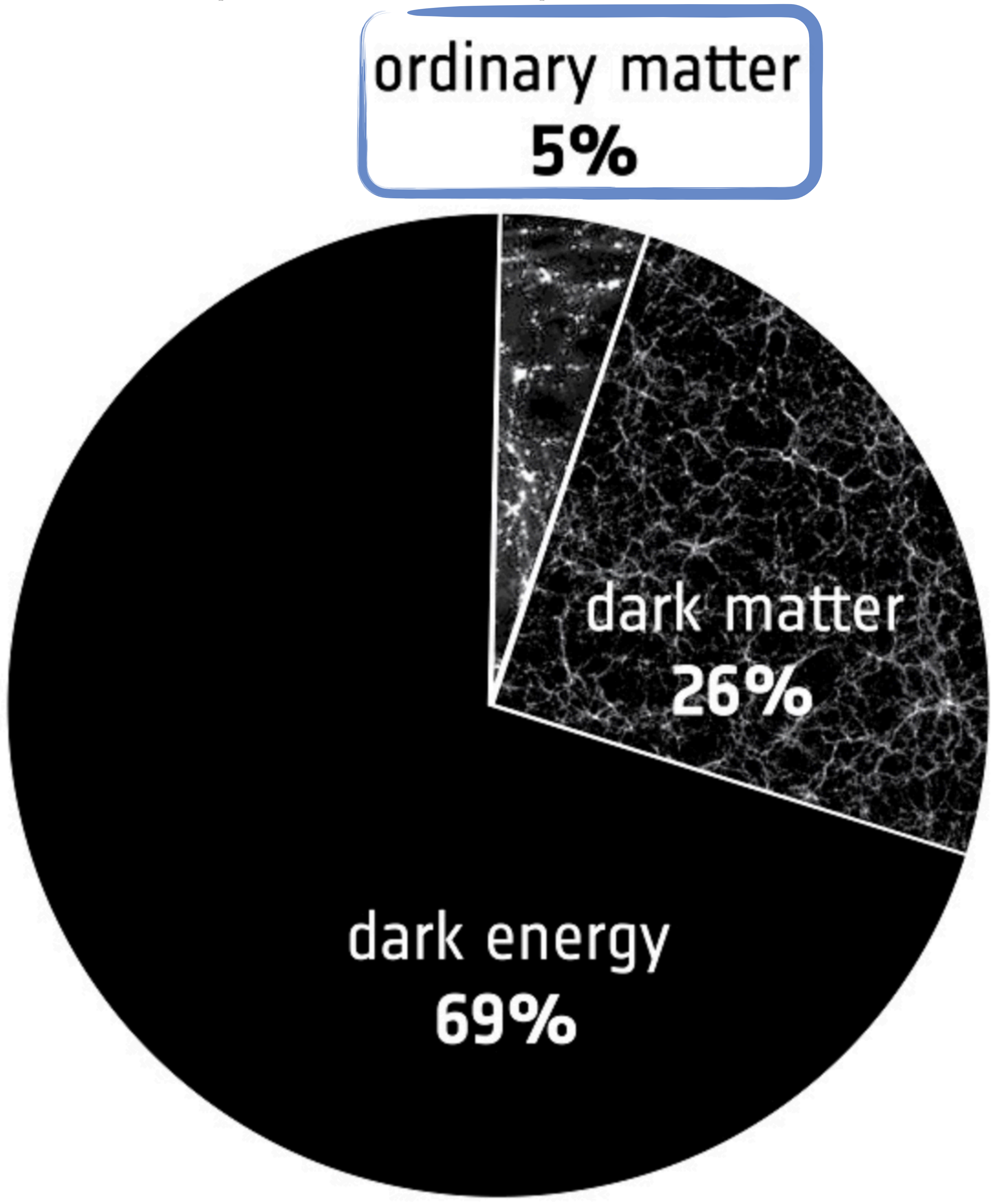
accidentally stable

dark matter?

accidentally stable

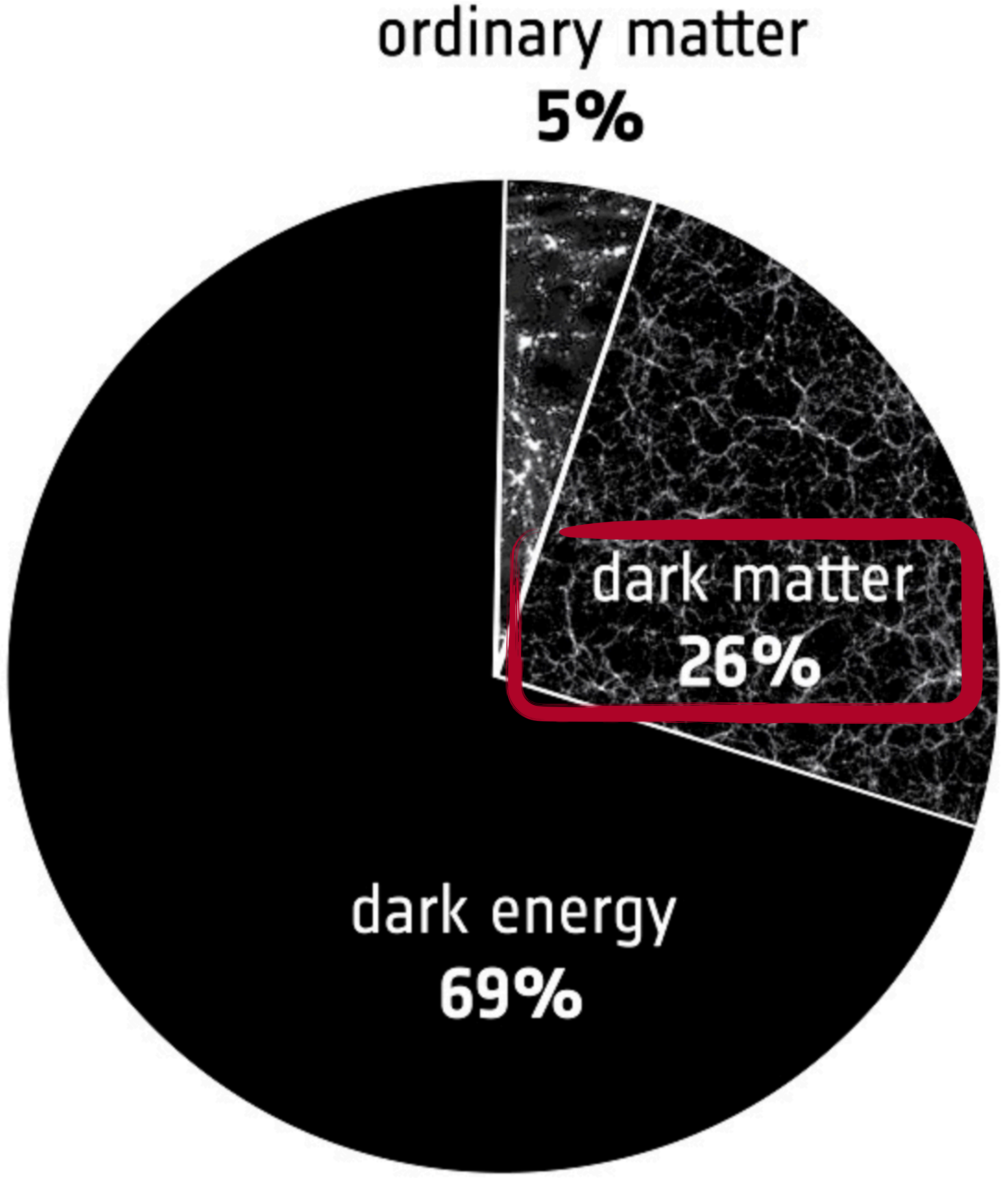
dark matter?

Visible Matter exists due to proton stability, ultimately due to accidental baryon number conservation

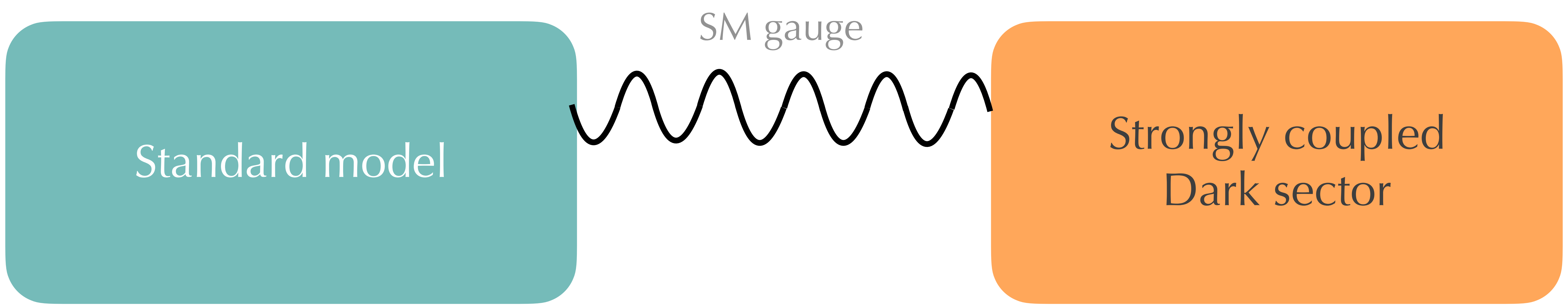


accidentally stable
dark matter?

Could the stability of dark matter be the result of accidental symmetry too?



$$\mathcal{G}_{\mathrm{SM}} \times \mathcal{G}_{\mathrm{DC}}$$

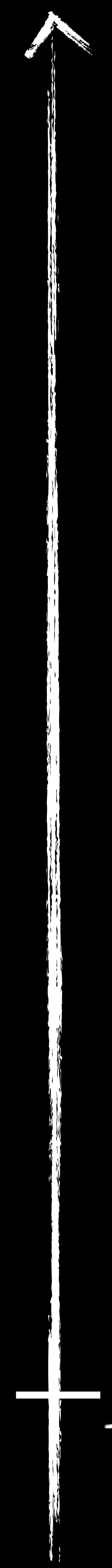


New sector with new matter and new gauge dynamics

Composite DM theories

[Bai, Schwaller '14], [Okun '80], [Kribs, Roy, Terning, Zurek ' 10], [Hambye, Tytgat '10], [Bai, Hill '10], [Frigerio, Pomarol, Riva, Urbano '12], [Buckley, Neil '13], [Antipin, Redi, Strumia, Vigiani `15], [Yamanaka, Fujibayashi, Gongyo, Iida '14], [Appelquist ' 15], [Carmona, Chala '15], [Soni, Zhang '16], [De Luca, Mitridate, Redi, Smirnov, Strumia '18], [Kribs, Martin, Tong '19],[Contino, Podo, Revello '21], [Dondi, Sannino, Smirnov '20]...

Model



M_Z

$$\mathcal{G}_{\mathrm{SM}} \equiv SU(3) \times SU(2) \times U(1)$$

$$\mathcal{Q}_r \equiv (\Box, R_{\mathrm{SM}})$$

$$SU(5)_{GUT} \times \mathcal{G}_{DC}$$

$SU(N)_{\mathrm{DC}}$ (or $SO(N)_{\mathrm{DC}}$)

$$\mathcal{G}_{SM} \times \boxed{\mathcal{G}_{DC}}$$

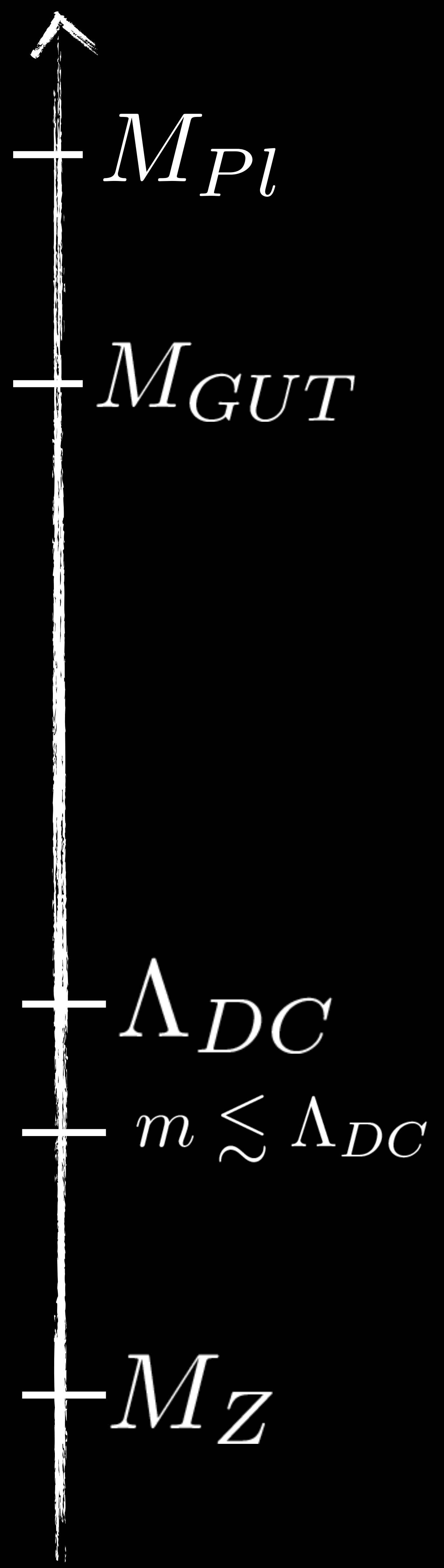
Dark Colour

$$\mathcal{G}_{\mathrm{SM}} \equiv SU(3) \times SU(2) \times U(1)$$

Dark Dirac fermions $\mathcal{Q}_r \equiv (\square, R_{\text{SM}})$

Vectorlike confinement

[Kilic, Okui, Sundrum '10]



$$SU(5)_{GUT} \times \mathcal{G}_{DC}$$

$$\mathcal{G}_{SM} \times \mathcal{G}_{DC}$$

$$\mathcal{G}_{\text{SM}} \equiv SU(3) \times SU(2) \times U(1)$$

Dark Dirac fermions $\boxed{\mathcal{Q}_r \equiv (\square, R_{\mathrm{SM}})}$

Vectorlike confinement
[Kilic, Okui, Sundrum '10]

M_{Pl}

M_{GUT}

Λ_{DC}

$m \lesssim \Lambda_{DC}$

M_Z

N_{DC} # dark colours

N_{DF} # dark flavours

$SU(5)_{GUT} \times \mathcal{G}_{DC}$

$$\mathcal{G}_{SM} \times \mathcal{G}_{DC}$$

$$\mathcal{G}_{\mathrm{SM}} \equiv SU(3) \times SU(2) \times U(1)$$

Dark Dirac fermions $\boxed{\mathcal{Q}_r \equiv (\Box, R_{\mathrm{SM}})}$

Vectorlike confinement

[Kilic, Okui, Sundrum '10]

M_{Pl}

$SU(5)_{GUT} \times \mathcal{G}_{DC}$

M_{GUT}

$\mathcal{G}_{SM} \times \mathcal{G}_{DC}$

Λ_{DC}

$\boxed{m \lesssim \Lambda_{DC}}$

Light dark fermions [Antipin et. al.`15]

$$\mathcal{G}_{\mathrm{SM}} \equiv SU(3) \times SU(2) \times U(1)$$

M_Z

$$\mathcal{Q}_r \equiv (\Box, R_{\text{SM}})$$

M_{Pl}

M_{GUT}

dark baryons

$$m_{\text{DB}} \sim N_{\text{DC}}\Lambda_{DC} + \frac{\alpha_{\text{SM}}}{4\pi}\Lambda_{\text{DC}}$$

Λ_{DC}

Large N limit [Witten '79]

$m \lesssim \Lambda_{DC}$

M_Z

$$SU(5)_{GUT} \times \mathcal{G}_{DC}$$

$$\mathcal{G}_{SM} \times \mathcal{G}_{DC}$$

$$\mathcal{G}_{\text{SM}} \equiv SU(3) \times SU(2) \times U(1)$$

$$\mathcal{Q}_r \equiv (\square, R_{\mathrm{SM}})$$

M_{Pl}

$$SU(5)_{GUT} \times \mathcal{G}_{DC}$$

M_{GUT}

$$\mathcal{G}_{SM} \times \mathcal{G}_{DC}$$

dark baryons

lightest baryon is SM neutral!

$$m_{\mathrm{DB}} \sim N_{\mathrm{DC}} \Lambda_{DC} + \frac{\alpha_{\mathrm{SM}}}{4\pi} \Lambda_{\mathrm{DC}}$$

Λ_{DC}

Large N limit [Witten '79]

$m \lesssim \Lambda_{DC}$

$$\mathcal{G}_{\mathrm{SM}} \equiv SU(3) \times SU(2) \times U(1)$$

M_Z

$$\mathcal{Q}_r \equiv (\Box, R_{\rm SM})$$

M_{Pl}

$SU(5)_{GUT} \times \mathcal{G}_{DC}$

M_{GUT}

Stabilized by dark baryon number

$$\mathcal{B} = (\mathcal{Q}\mathcal{Q}...\mathcal{Q})$$

dark mesons

$\mathcal{G}_{SM} \times \mathcal{G}_{DC}$

$$m_{\pi_D}^2 \sim a\, m\Lambda_{\rm DC} + \frac{\alpha_{\rm SM}}{4\pi}\Lambda_{\rm DC}^2$$

$$\mathcal{L}_{\rm dark} = -\frac{1}{4g_{\rm DC}^2}(\mathcal{G}_{\mu\nu}^A)^2 + \bar{\mathcal{Q}}_r(i\gamma^\mu D_\mu - m)\mathcal{Q}_r - y_{rs}\bar{\mathcal{Q}}_r H \mathcal{Q}_s$$

Λ_{DC}

$m \lesssim \Lambda_{DC}$

$$U(1)_{\rm DB} : \mathcal{Q}_{r,s} \to e^{i\theta}\mathcal{Q}_{r,s}$$

$$\mathcal{G}_{\rm SM} = SU(3) \times SU(2) \times U(1)$$

M_Z

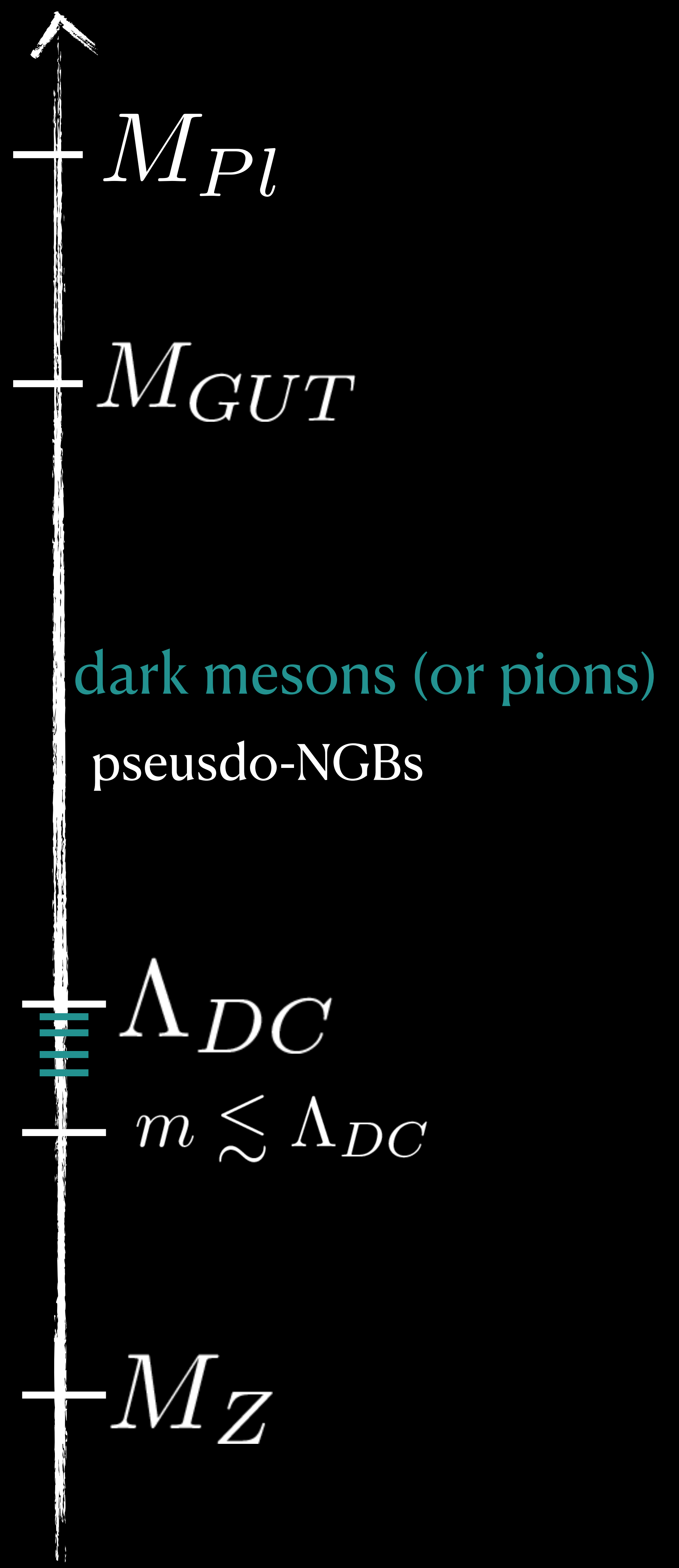
Stabilized by dark baryon number

$$\mathcal{B} = (\mathcal{Q}\mathcal{Q}...\mathcal{Q})$$

$$\mathcal{L}_{\rm dark} = -\frac{1}{4g_{\rm DC}^2}(\mathcal{G}^A_{\mu\nu})^2 + \bar{\mathcal{Q}}_r(i\gamma^\mu D_\mu - m)\mathcal{Q}_r - y_{rs}\bar{\mathcal{Q}}_r H \mathcal{Q}_s$$

$$U(1)_{\rm DB} : \mathcal{Q}_{r,s} \to e^{i\theta}\mathcal{Q}_{r,s}$$

$$\mathcal{Q}_r \equiv (\square, R_{\rm SM})$$

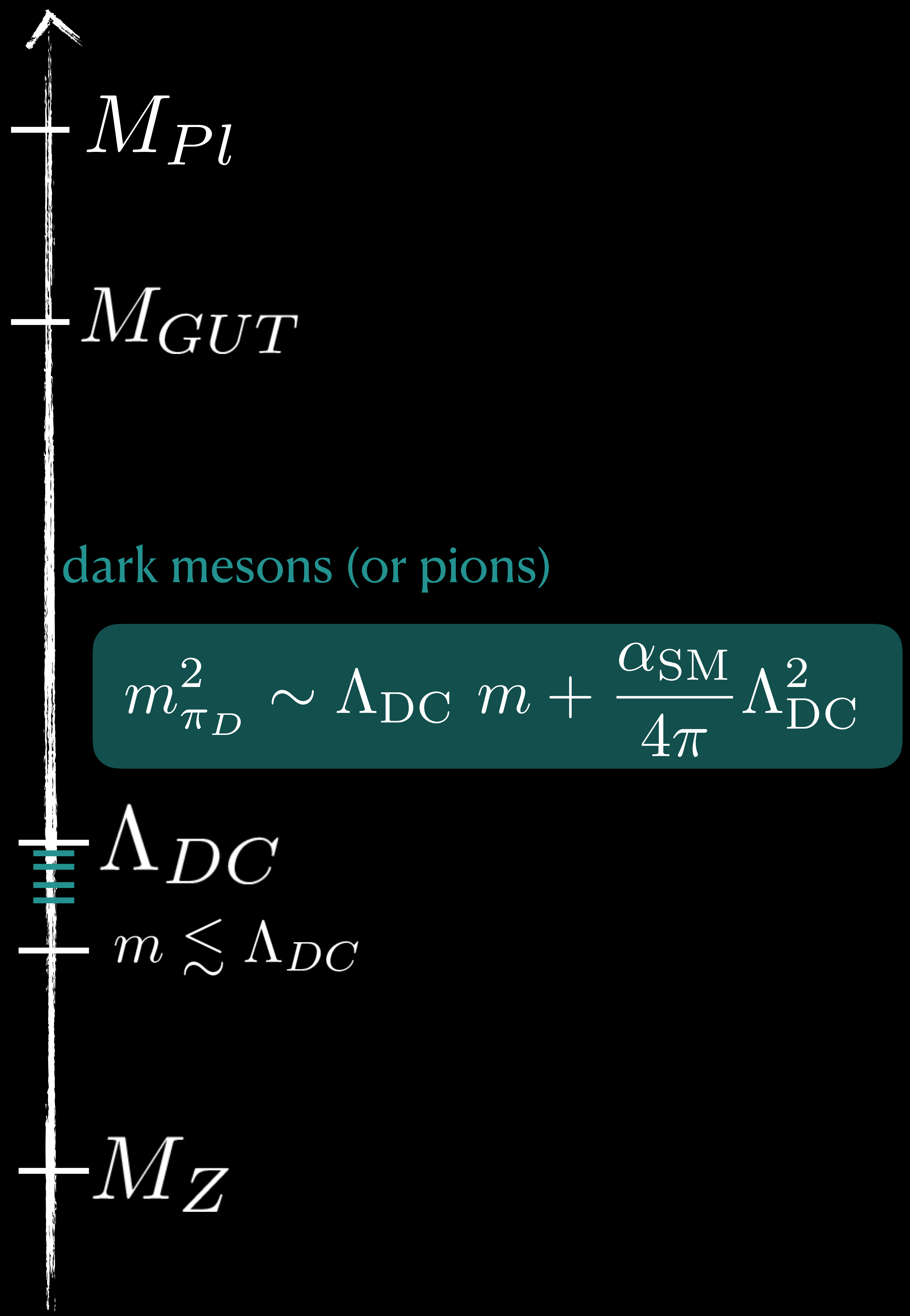


$$SU(5)_{GUT} \times \mathcal{G}_{DC}$$

$$\mathcal{G}_{SM} \times \mathcal{G}_{DC}$$

$$\mathcal{G}_{\rm SM} \equiv SU(3) \times SU(2) \times U(1)$$

$$\mathcal{Q}_r \equiv (\Box, R_{\mathrm{SM}})$$



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$$\mathcal{Q}_r \equiv (\Box, R_{\text{SM}})$$

$$SU(5)_{GUT} \times \mathcal{G}_{DC}$$

Stabilized by species number

$$\pi = \bar{\mathcal{Q}}_r \mathcal{Q}_s$$

$$\mathcal{G}_{SM} \times \mathcal{G}_{DC}$$

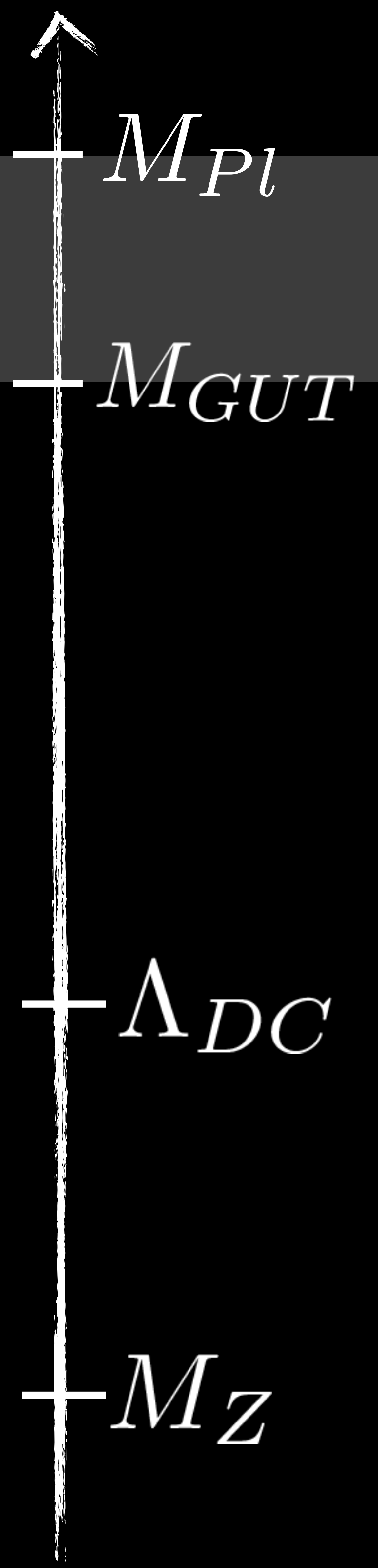
$$\mathcal{L}_{\text{dark}} = -\frac{1}{4g_{\text{DC}}^2}(\mathcal{G}^A_{\mu\nu})^2 + \bar{\mathcal{Q}}_r(i\gamma^\mu D_\mu - m)\mathcal{Q}_r - y_{rs}\bar{\mathcal{Q}}_r H \mathcal{Q}_s$$

Large N limit [Witten '79]

$$U(1)_{\text{Sp.}} : \mathcal{Q}_r \to e^{i\theta_r}\mathcal{Q}_r$$

$$\mathcal{Q}_s \to e^{i\theta_s}\mathcal{Q}_s$$

$$\mathcal{G}_{\text{SM}} \equiv SU(3) \times SU(2) \times U(1)$$



GUT breaking

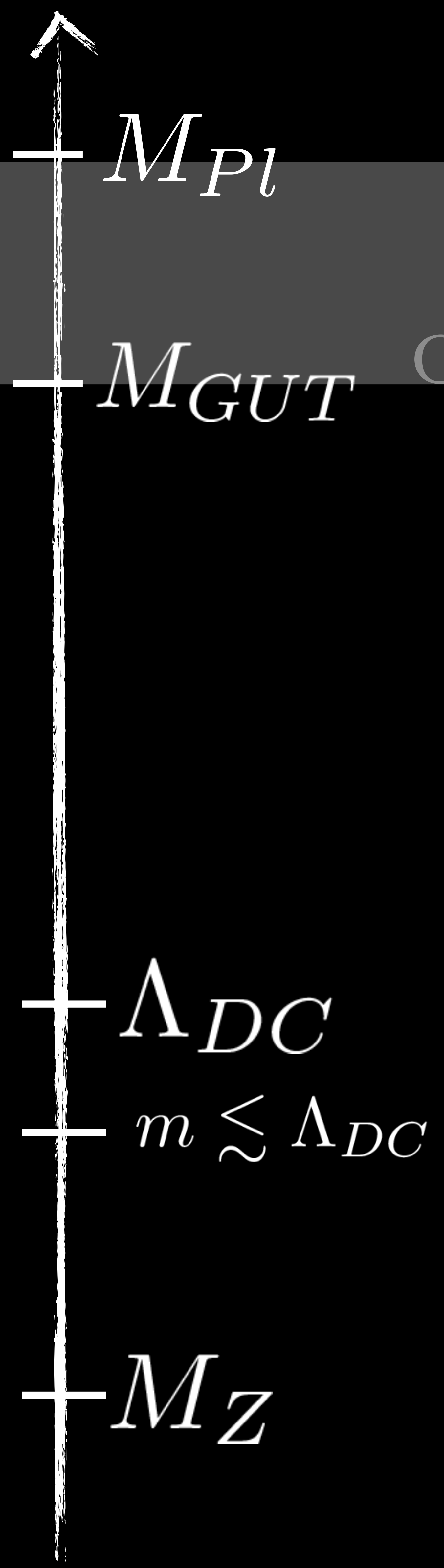
$$SU(5)_{GUT} \times \mathcal{G}_{DC}$$

$$\mathcal{G}_{SM} \times \mathcal{G}_{DC}$$

$$\mathcal{G}_{\text{SM}} \equiv SU(3) \times SU(2) \times U(1)$$

[Bottaro, Contino, SV `24]

$$\Psi \equiv (\square, R) \qquad R = 1, 5, 10, 15, 24$$



GUT breaking

$$SU(5)_{GUT} \times \mathcal{G}_{DC}$$

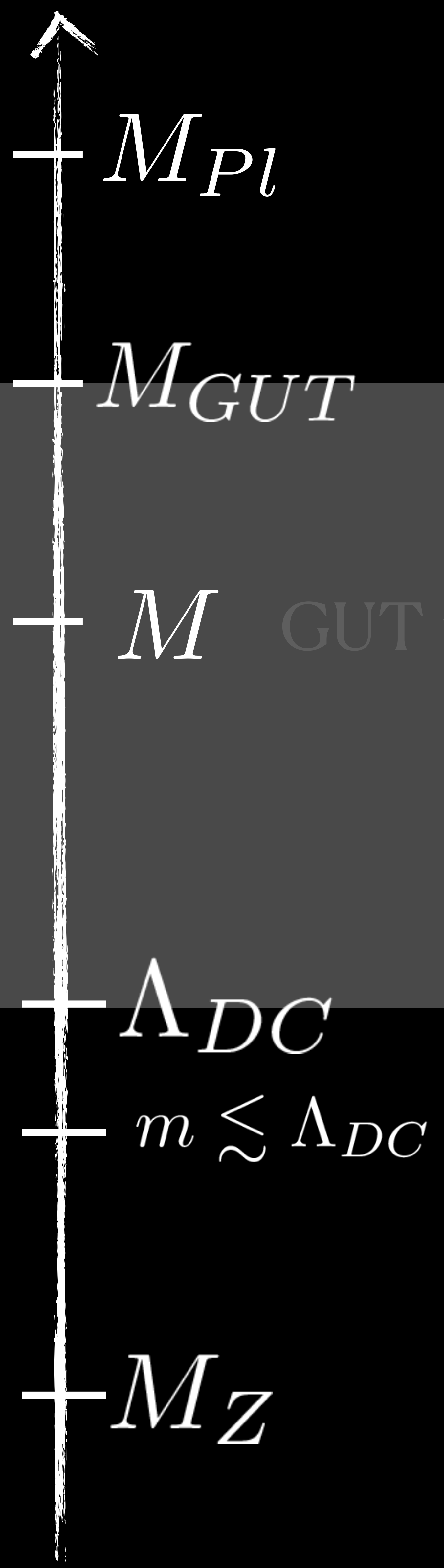
$$\mathcal{G}_{SM} \times \mathcal{G}_{DC}$$

$$\mathcal{G}_{\rm SM} \equiv SU(3) \times SU(2) \times U(1)$$

[Bottaro, Contino, SV `24]

$\sum_r \mathcal{Q}_r \equiv (\square, R\ \ )$ $R = 1, 5, 10, 15, 24$

Remaining GUT reps?



GUT partners?

$SU(5)_{GUT} \times \mathcal{G}_{DC}$

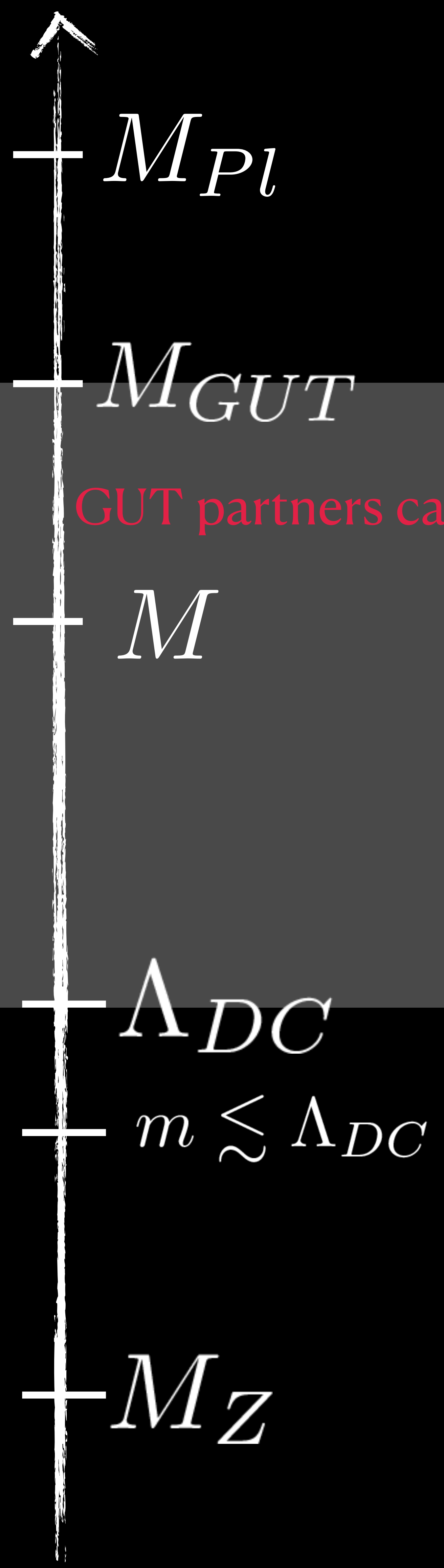
$\mathcal{G}_{SM} \times \mathcal{G}_{DC}$

$\mathcal{G}_{\rm SM} \equiv SU(3) \times SU(2) \times U(1)$

[Bottaro, Contino, SV `24]

$$\sum_r \mathcal{Q}_r \equiv (\square, R\quad)$$ $R = 1, 5, 10, 15, 24$

Remaining GUT reps?



$$SU(5)_{GUT} \times \mathcal{G}_{DC}$$

GUT partners can be long-lived due to accidental species number

$$\mathcal{G}_{SM} \times \mathcal{G}_{DC}$$

$$\mathcal{G}_{\rm SM} \equiv SU(3) \times SU(2) \times U(1)$$

[Bottaro, Contino, SV `24]

$$\sum_r \mathcal{Q}_r \equiv (\square, R \quad) \quad R = 1, 5, 10, 15, 24$$

Remaining GUT reps?

M_{Pl}

$SU(5)_{GUT} \times \mathcal{G}_{DC}$

M_{GUT}

GUT hadrons should decay before BBN (big bang nucleosysnthesis)!

$M \quad \tau \lesssim t_{\text{BBN}} \sim 1 \text{ s}$

$\mathcal{G}_{SM} \times \mathcal{G}_{DC}$

Λ_{DC}

$m \lesssim \Lambda_{DC}$

$\mathcal{G}_{\text{SM}} \equiv SU(3) \times SU(2) \times U(1)$

M_Z

[Bottaro, Contino, SV `24]

$$\sum_r \mathcal{Q}_r \equiv (\square, R \quad)$$ $R = 1, 5, 10, 15, 24$

Remaining GUT reps?

M_{Pl}

$SU(5)_{GUT} \times \mathcal{G}_{DC}$

M_{GUT}

Split spectrum allows GUT hadrons to decay before BBN!

M $\tau \lesssim t_{\rm BBN} \sim 1$ s

$\gg$

$\mathcal{G}_{SM} \times \mathcal{G}_{DC}$

Λ_{DC}

$m \lesssim \Lambda_{DC}$

$\mathcal{G}_{\rm SM} \equiv SU(3) \times SU(2) \times U(1)$

M_Z

[Bottaro, Contino, SV `24]

$$\sum_r \mathcal{Q}_r \equiv (\square, R \quad)$$ $R = 1, 5, 10, 15, 24$

Remaining GUT reps?

M_{Pl}

$$SU(5)_{GUT} \times \mathcal{G}_{DC}$$

M_{GUT}

Split spectrum also needed for better gauge coupling unification

M

$$\Delta_L = -b_i^L \log \frac{M}{\Lambda_{DC}}$$

$$\mathcal{G}_{SM} \times \mathcal{G}_{DC}$$

$\gg$

Λ_{DC}

$m \lesssim \Lambda_{DC}$

$$\mathcal{G}_{\rm SM} \equiv SU(3) \times SU(2) \times U(1)$$

M_Z

[Bottaro, Contino, SV `24]

$\sum_r \mathcal{Q}_r \equiv (\square, R \quad)$ $R = 1, 5, 10, 15, 24$

Remaining GUT reps?

M_{Pl}

$SU(5)_{GUT} \times \mathcal{G}_{DC}$

M_{GUT}

M GUT partners?

$\mathcal{G}_{SM} \times \mathcal{G}_{DC}$

Λ_{DC}

$m \lesssim \Lambda_{DC}$

Minimal (non-SUSY) SU(5) unification

$\Psi_{\text{SM}} = \bar{5} + 10$

$\phi_5 + \phi_{24}$

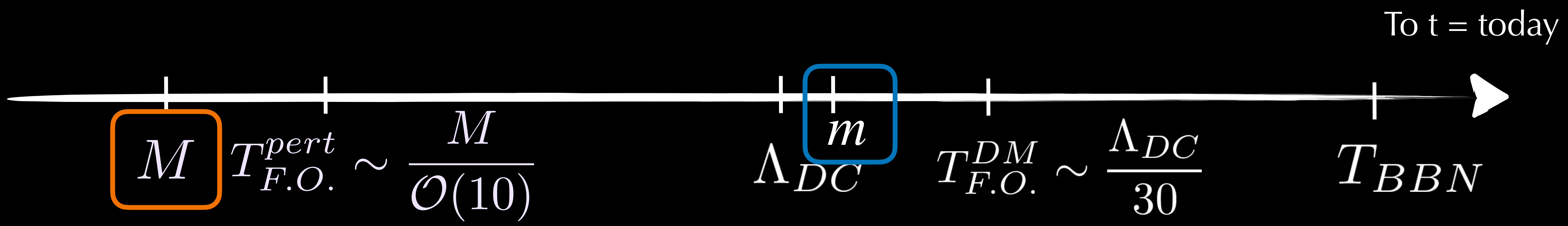
$\mathcal{G}_{\text{SM}} \equiv SU(3) \times SU(2) \times U(1)$

M_Z

Cosmology

To t = today

$$M \qquad T_{F.O.}^{pert} \sim \frac{M}{\mathcal{O}(10)} \qquad \Lambda_{DC} \qquad T_{F.O.}^{DM} \sim \frac{\Lambda_{DC}}{30} \qquad T_{BBN}$$



$\boxed{5 \oplus 10}$

Benchmark Model $SU(3)_{\mathrm{DC}}$

Dark matter

$QQ\tilde{D}$

$\Psi_{10} = Q + U + E$

$\Psi_5 = \tilde{D} + \tilde{L}$

$\boxed{Q \oplus \tilde{D}}$

Dark fermions (L)

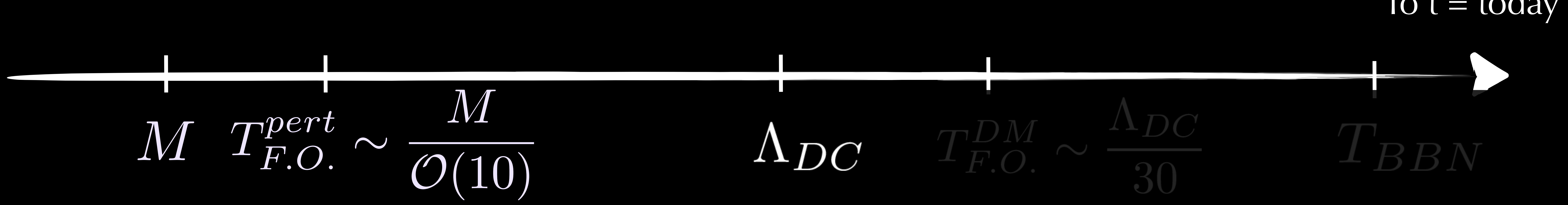
$m \lesssim \Lambda_{DC}$

Heavy fermions (H)

$M \gg \Lambda_{DC}$

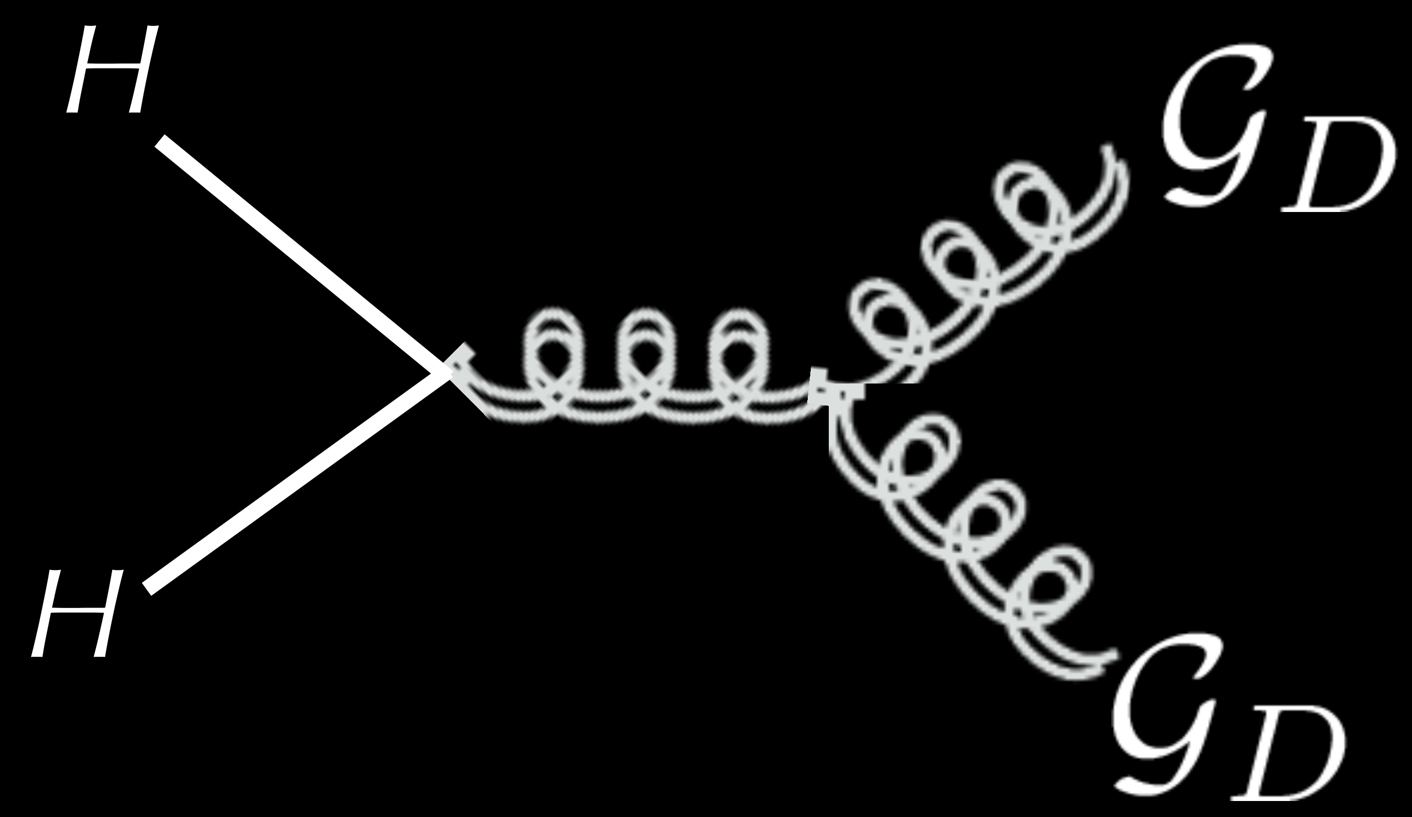
$\boxed{E \oplus U \oplus \tilde{L}}$

$Q = (3,2)_{1/6}$ $\tilde{D} = (\bar{3},1)_{1/3}$ $U = (3,1)_{2/3}$ $\tilde{E} = (1,1)_1$ $\tilde{L} = (1,2)_{1/2}$

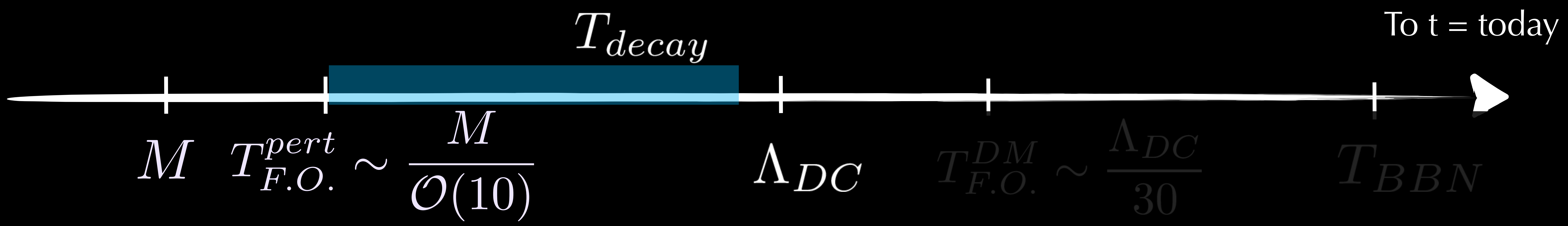


$$M \gg \Lambda_{\mathrm{DC}}, \alpha_{\mathrm{DC}}(M) < 1$$

Perturbative freeze-out (F.O.) of free GUT partners H

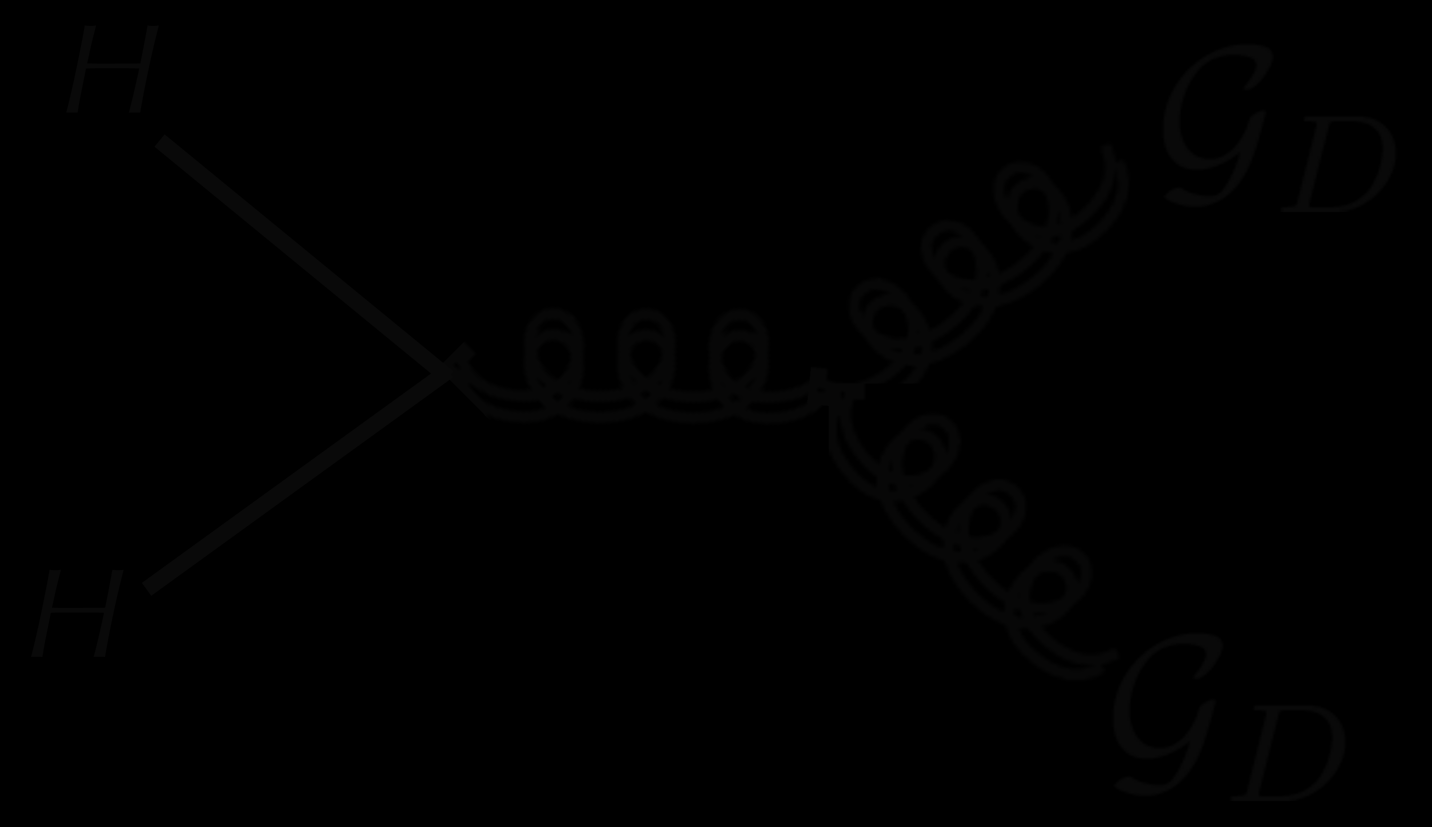


$$\langle \sigma v \rangle \sim \frac{\pi \alpha_{DC}^2(M_H)}{M_H^2}$$



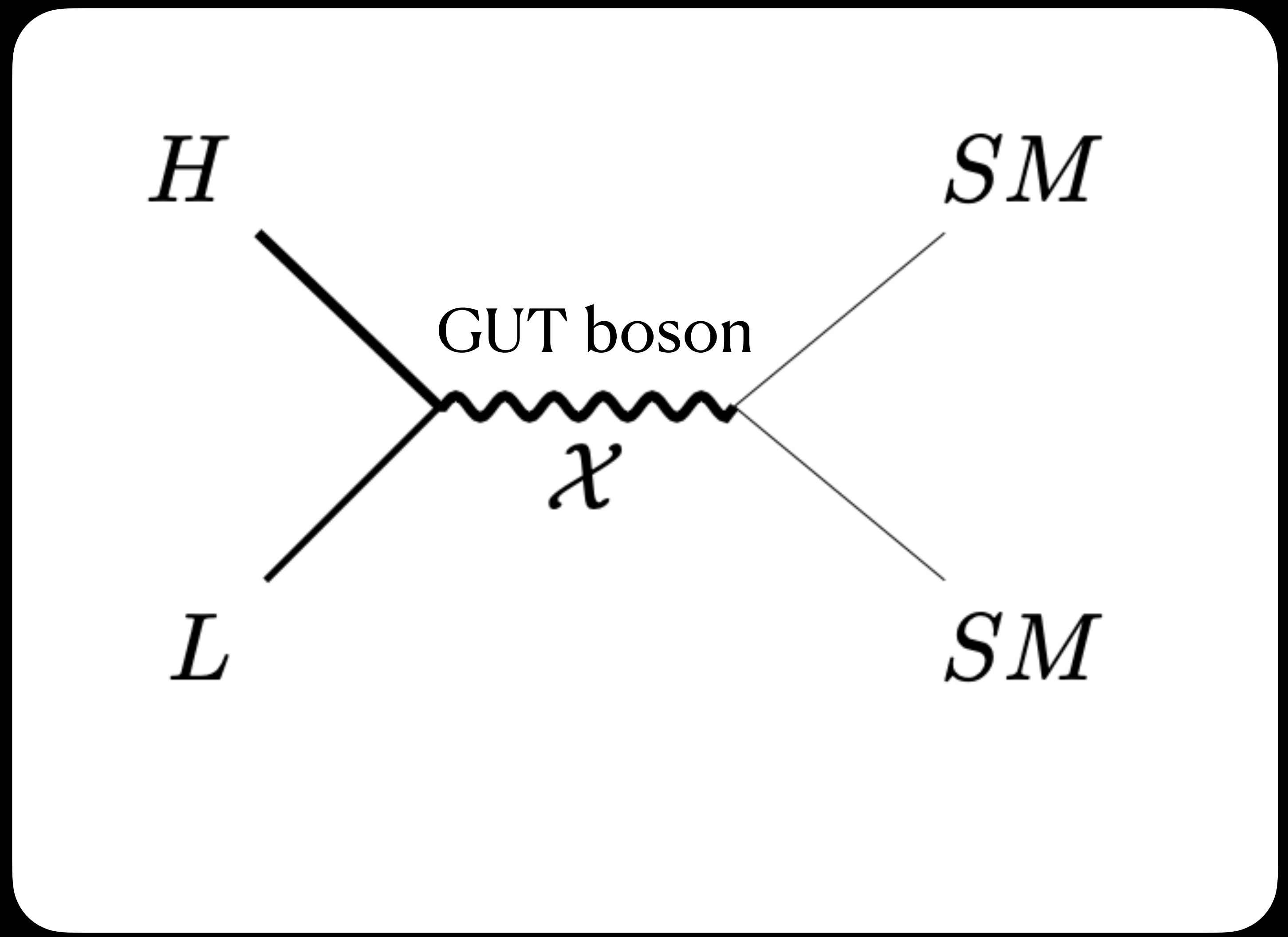
$M \gg \Lambda_{DC}, \alpha_{DC}(M) < 1$

Perturbative freeze-out (F.O.) of free GUT partners H



$$\langle \sigma v \rangle \sim \frac{\pi \alpha^2_{DC}(M_H)}{M_H^2}$$

GUT partner decay via D= 6 operators to SM and light dark fermions L



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

Bottaro, Contino, SV [In prep]

Dark Confinement

To t = today

M $\quad T_{F.O.}^{pert} \sim \frac{M}{\mathcal{O}(10)}$ $\quad \Lambda_{DC}$ $\quad m$ $\quad T_{F.O.}^{DM} \sim \frac{\Lambda_{DC}}{30}$ $\quad T_{BBN}$

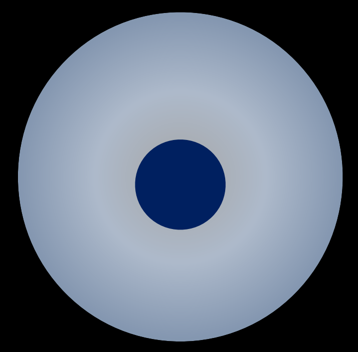
Light hadrons

$r \sim \Lambda_{DC}^{-1}$

$m_{DM} \sim \Lambda_{DC}$

Hybrid hadrons

$r \sim \Lambda_{DC}^{-1}$



$\bar{L}H, HLL$

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

[Kang, Luty, Nasri '08], [Jacoby, Nussinov '07],
[De Luca et. al. '19]

Bottaro, Contino, SV [In prep]

Dark Confinement

To t = today

M $\quad T_{F.O.}^{pert} \sim \frac{M}{\mathcal{O}(10)}$ $\quad \Lambda_{DC}$ $\quad m$ $\quad T_{F.O.}^{DM} \sim \frac{\Lambda_{DC}}{30}$ $\quad T_{BBN}$

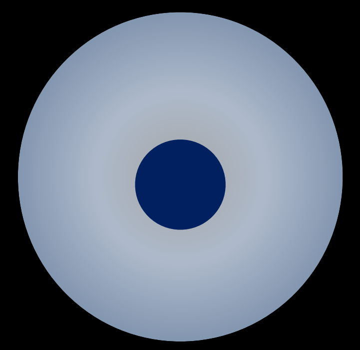
Light hadrons

$r \sim \Lambda_{DC}^{-1}$

$m_{DM} \sim \Lambda_{DC}$

Hybrid hadrons

$r \sim \Lambda_{DC}^{-1}$



$\bar{L}H, HLL$

$m \sim M_H + \boxed{\mathcal{O}(\Lambda_{DC})}$

Binding energy

[Bali, Pineda '03]

[Kang, Luty, Nasri '08], [Jacoby, Nussinov '07],
[De Luca et. al. '19]

Bottaro, Contino, SV [In prep]

Dark Confinement

To t = today

M $\quad T_{F.O.}^{pert} \sim \frac{M}{\mathcal{O}(10)}$ $\quad \Lambda_{DC}$ $\quad m$ $\quad T_{F.O.}^{DM} \sim \frac{\Lambda_{DC}}{30}$ $\quad T_{BBN}$

Light hadrons

$$r \sim \Lambda_{DC}^{-1}$$

$$m_{DM} \sim \Lambda_{DC}$$

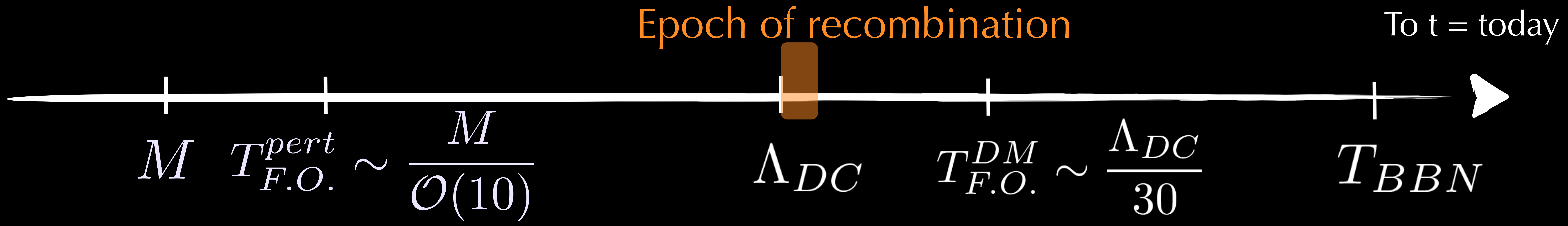
Hybrid hadrons

$$r \sim \Lambda_{DC}^{-1} \qquad \bar{L}H, HLL$$

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

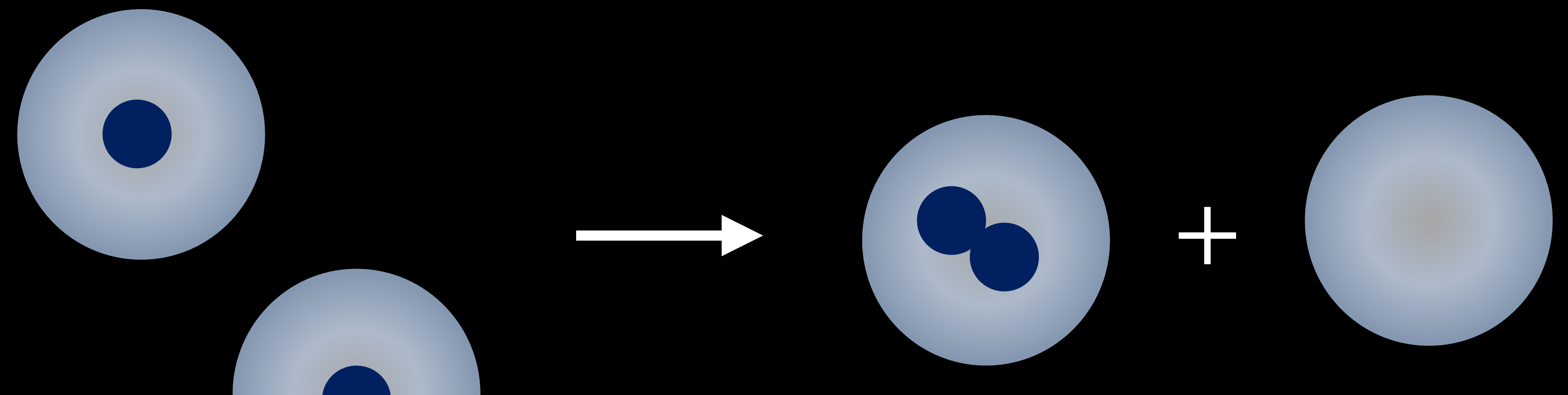
[Kang, Luty, Nasri '08], [Jacoby, Nussinov '07],
[De Luca et. al. '19]

Bottaro, Contino, SV [In prep]



Recombinations favouring creation of perturbative states with larger binding energy

$$HLL + HLL \to HHL^* + LLL$$



$$m \sim 2M_H + \boxed{\mathcal{O}(-\alpha_{DC}^2 M_H)}$$

Binding energy

[Kang, Luty, Nasri '08], [Jacoby, Nussinov '07],
[De Luca et. al. '19]

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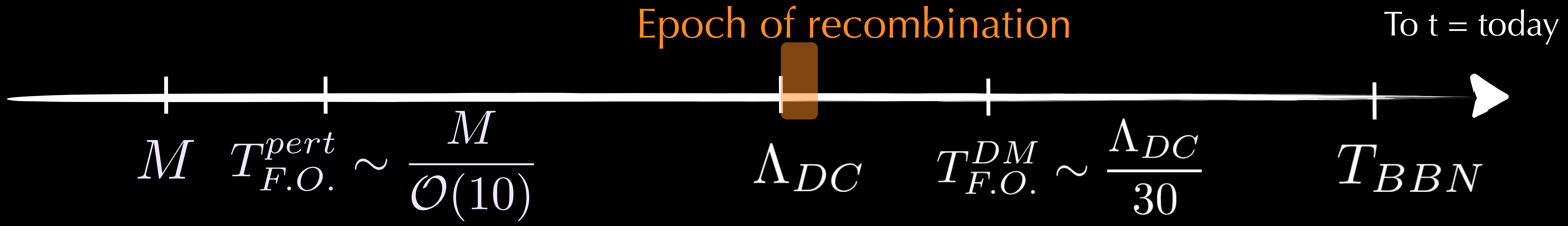

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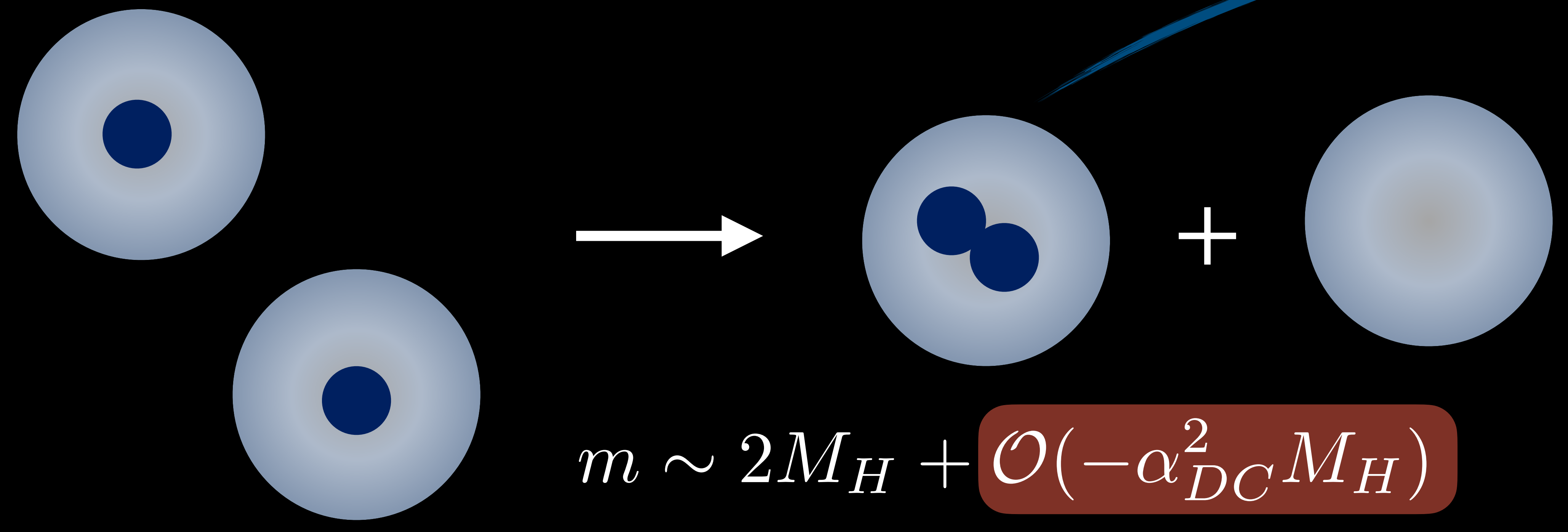


$$m \sim 2M_H + \mathcal{O}(-\alpha_{DC}^2 M_H)$$

Binding energy

[Einchten et. al. '74]

$$V_{HH}(r) \approx \frac{\alpha_{eff}}{r} + \sigma r$$

Cornell potential

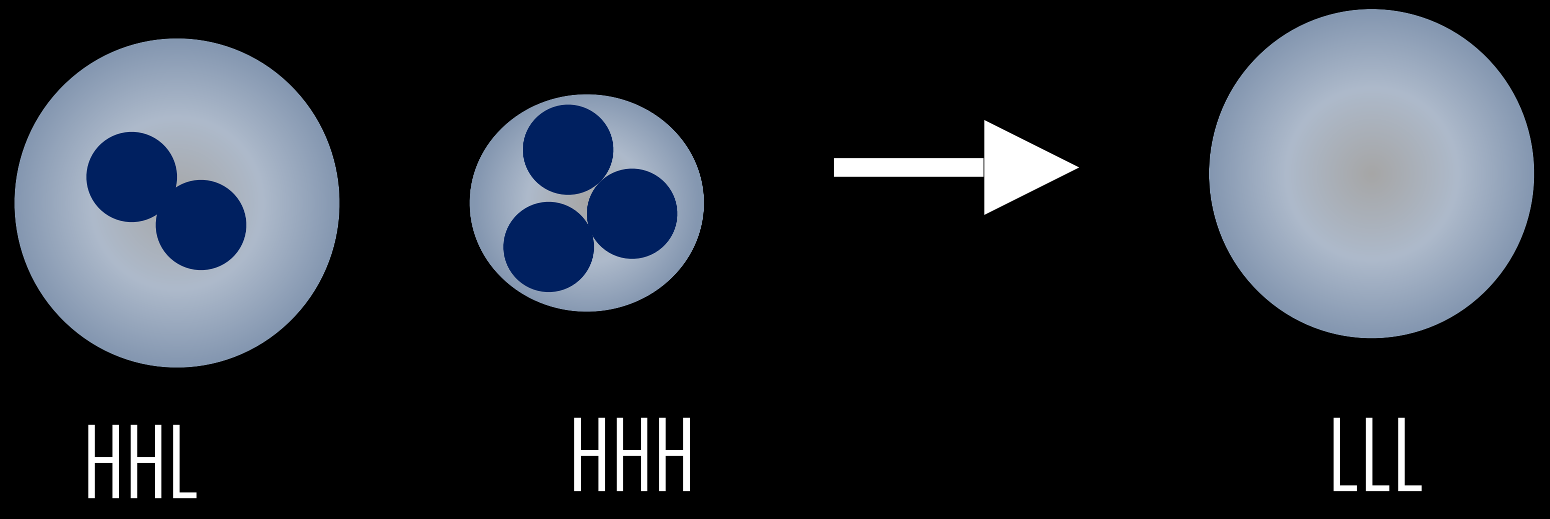
[Kang, Luty, Nasri '08], [Jacoby, Nussinov '07], [De Luca et. al. '19]

Temperature T $\leftarrow$

H Decay phase

T_{decay}

$M \quad T_{F.O.}^{pert} \sim \dfrac{M}{\mathcal{O}(10)} \quad \Lambda_{DC} \quad T_{F.O.}^{DM} \sim \dfrac{\Lambda_{DC}}{30} \quad T_{BBN}$



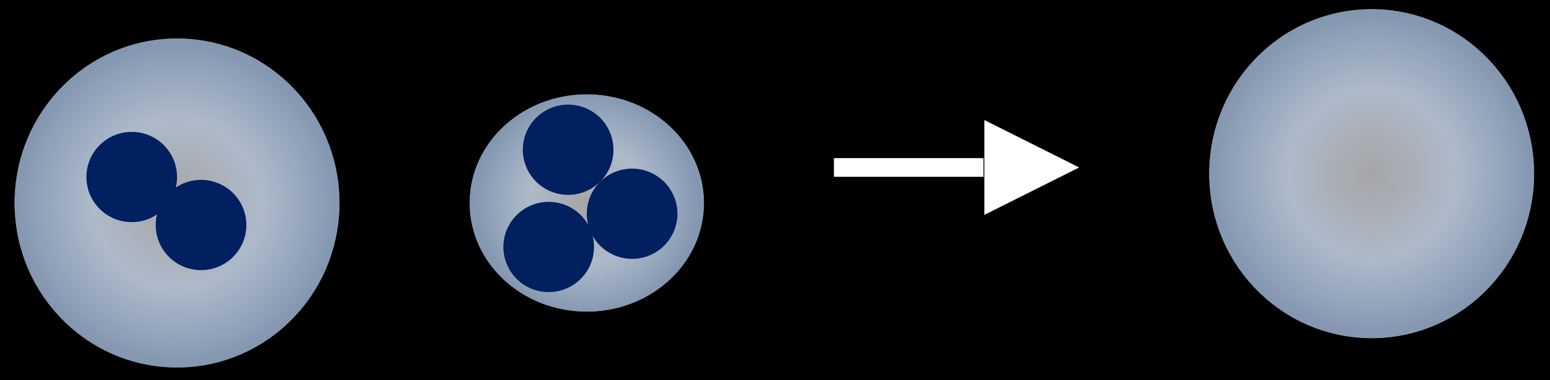
Non-Thermal contribution

$$\Omega_{\rm DM} = \frac{M_{\rm DM} T_0^3}{\rho_{crit}} \left(Y_{DM}^{F.O.} + f \cdot Y_H e^{-t_{F.O.}\Gamma_H} \right) \mathcal{F}$$

Bottaro, Contino, SV [To Appear]

Temperature T $\leftarrow$

M — $T_{F.O.}^{pert} \sim \dfrac{M}{\mathcal{O}(10)}$ — Λ_{DC} — H Decay phase — $T_{F.O.}^{DM} \sim \dfrac{\Lambda_{DC}}{30}$ — T_{decay} — T_{BBN}



$$\boxed{Y_H \sim \frac{x_{FO}^H}{M_{Pl}\, M\, \sigma_{HH}} \sim \frac{10\ M}{\pi\ M_{Pl}\ \alpha_{DC}^2}}$$

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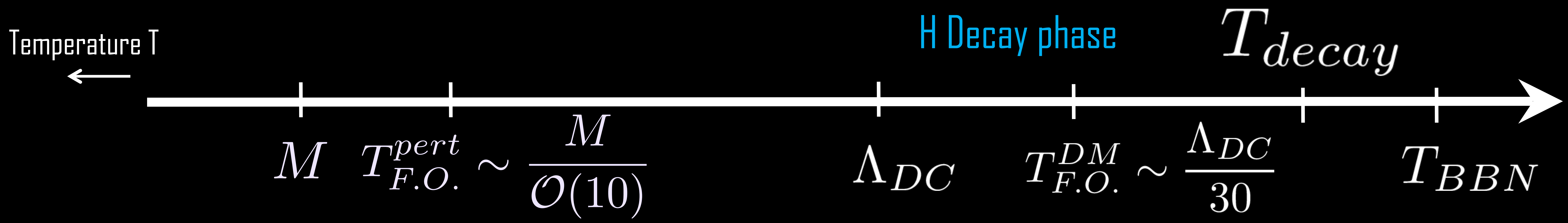
fraction of GUT partners in heavy baryons
after recombination

Bottaro, Contino, SV [To Appear]

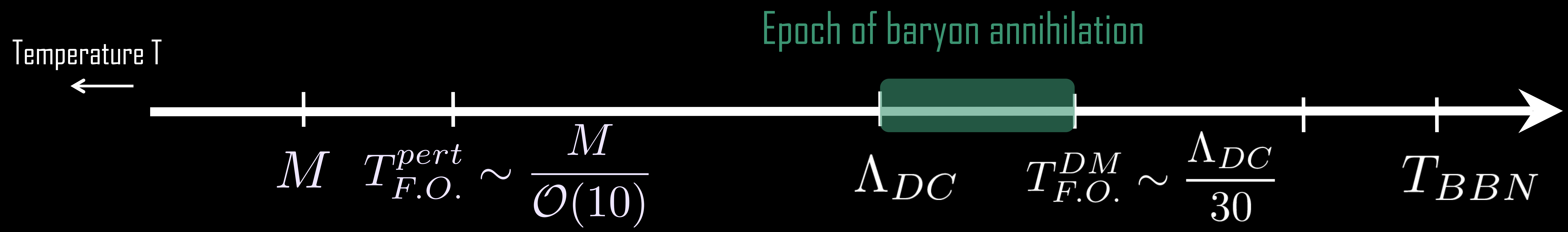


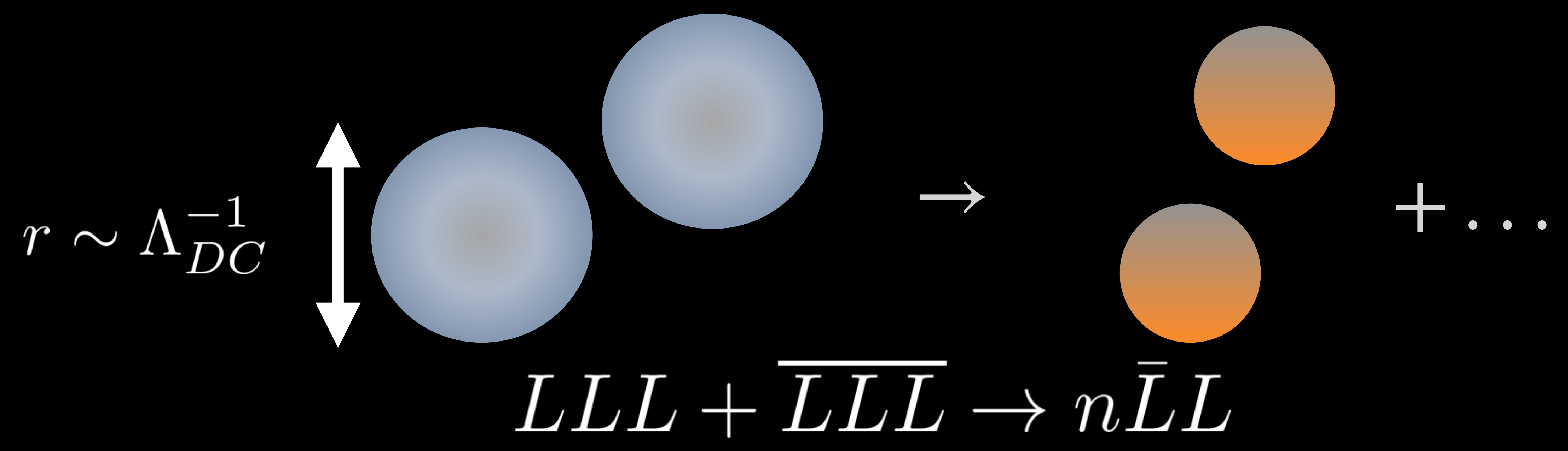
Thermal contribution from baryonic freeze-out

$$\Omega_{\mathrm{DM}} = \frac{M_{\mathrm{DM}} T_0^3}{\rho_{crit}} \left(Y_{DM}^{F.O.} + f \cdot Y_H e^{-t_{F.O.}\Gamma_H} \right) \mathcal{F}$$

[Antipin et. al. `15]

Bottaro, Contino, SV [To Appear]





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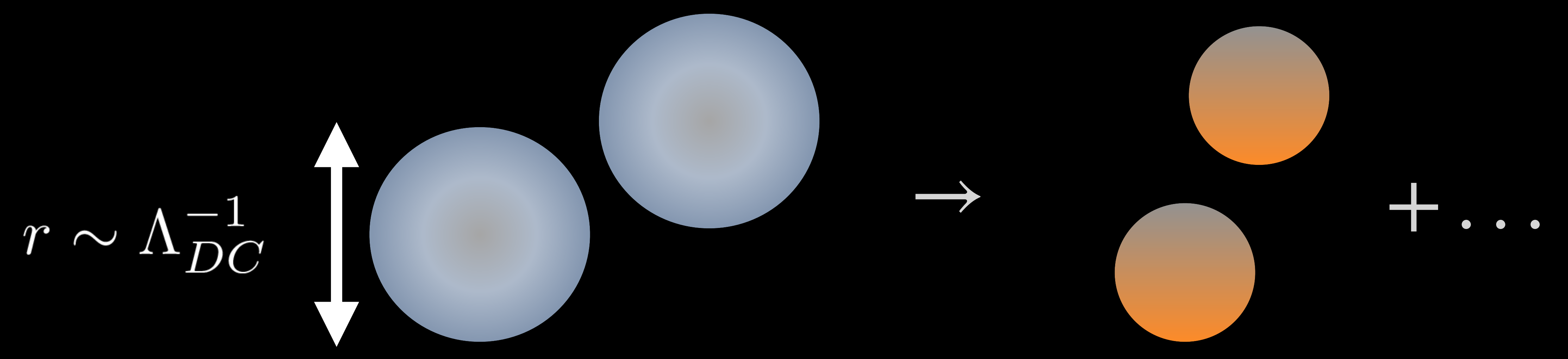
[Antipin et. al. `15]

Bottaro, Contino, SV [To Appear]

Temperature T $\longleftarrow$

Epoch of baryon annihilation

$M \quad T^{pert}_{F.O.} \sim \dfrac{M}{\mathcal{O}(10)} \quad \Lambda_{DC} \quad T^{DM}_{F.O.} \sim \dfrac{\Lambda_{DC}}{30} \quad T_{BBN}$



Analogy with $p-\bar{p}$ annihilation [Zenoni et. Al.]

$$\langle \sigma_{BB} v \rangle^{*} \sim \frac{\pi}{\Lambda_{\rm DC}^2}$$

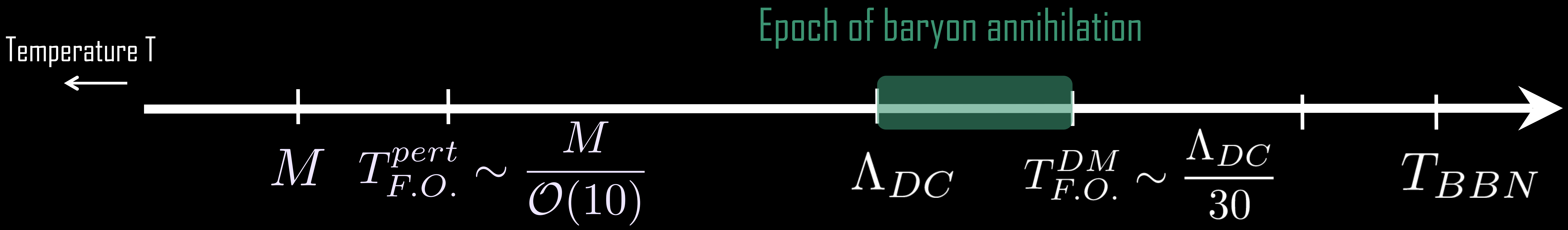
*suppressed as $e^{-\mathcal{O}(1)N}$ for large N [Witten '79]

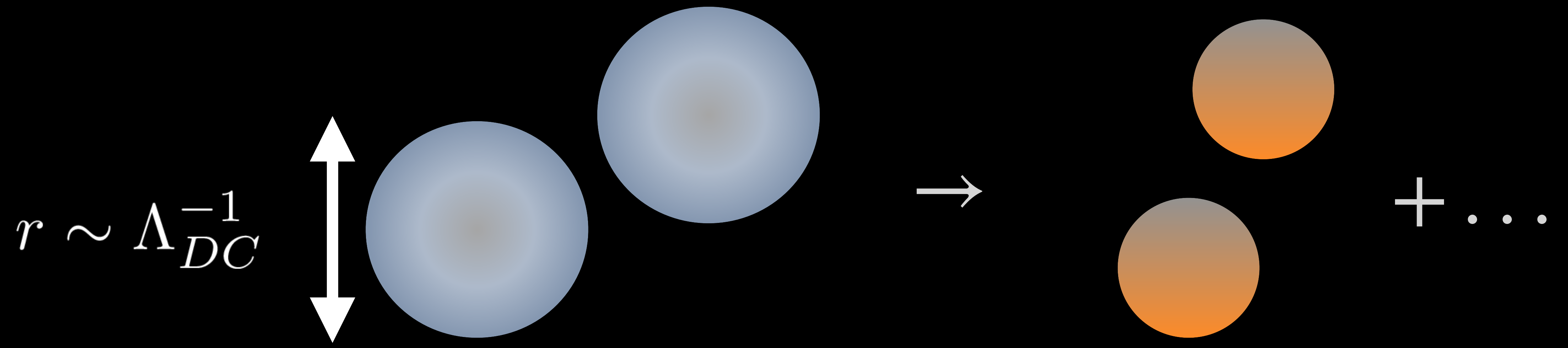
$$\Omega_{\rm DM} = \frac{M_{\rm DM} T_0^3}{\rho_{crit}} \left(\boxed{Y_{DM}^{F.O.}} + f \cdot Y_H e^{-t_{F.O.}\Gamma_H} \right) \mathcal{F}$$

$$\boxed{Y_{DM}^{F.O.} \sim \frac{x_{FO}^{DM}}{M_{Pl} \Lambda_{DC} \sigma_{BB}} \sim \frac{30 \Lambda_{DC}}{\pi M_{Pl}}}$$

[Antipin et. al. `15]

Bottaro, Contino, SV [To Appear]





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$\Omega_{\rm DM} h^2 \sim 0.12 \rightarrow \quad \Lambda_{\rm DC} \sim 50$ TeV

[Antipin et. al. `15]
Bottaro, Contino, SV [To Appear]

Constraints?

Contino, Bottaro, SV [To appear]

Observed DM density

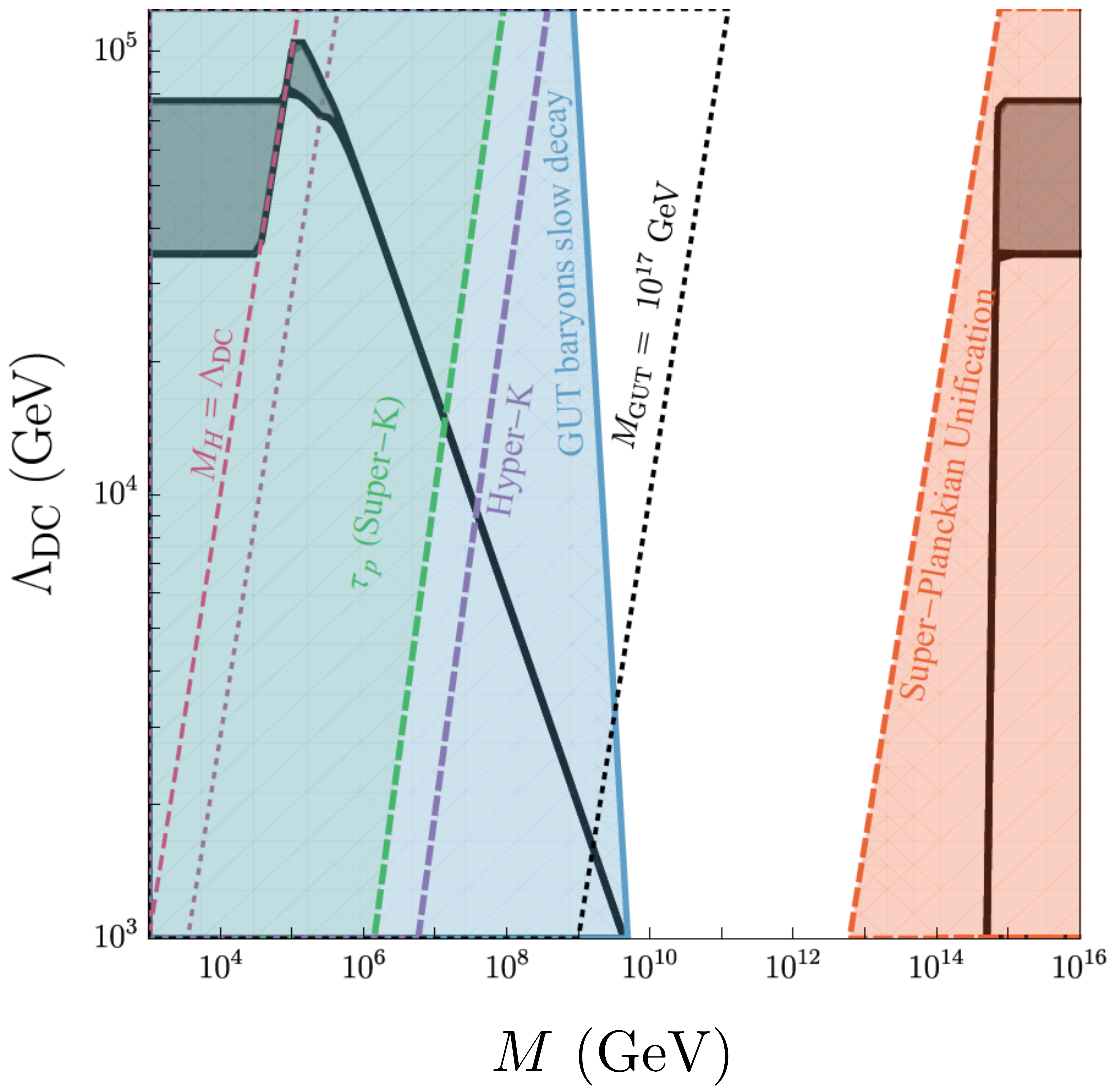
$\Omega_{DM}h^2 = 0.12$

Non-perturbative uncertainties

Proton lifetime

Late unification

Big Bang Nucleosynthesis



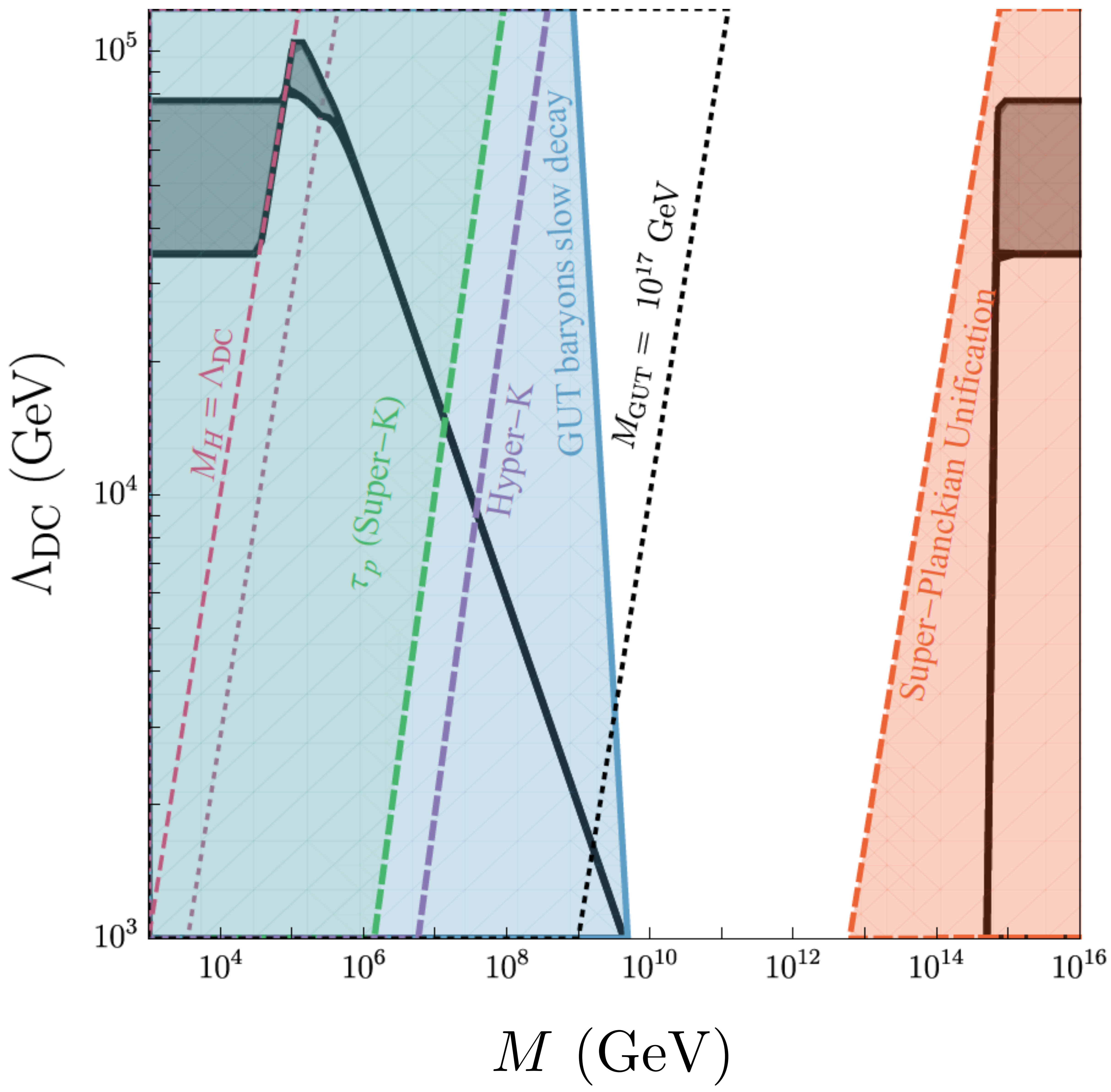
Benchmark Model

$Q + \tilde{D}$

GUT theory: 5 + 10

$SU(3)_{\rm DC}$

- $\Omega_{DM}h^2 = 0.12$
- Non-perturbative uncertainties
- Proton lifetime
- Late unification
- Big Bang Nucleosynthesis



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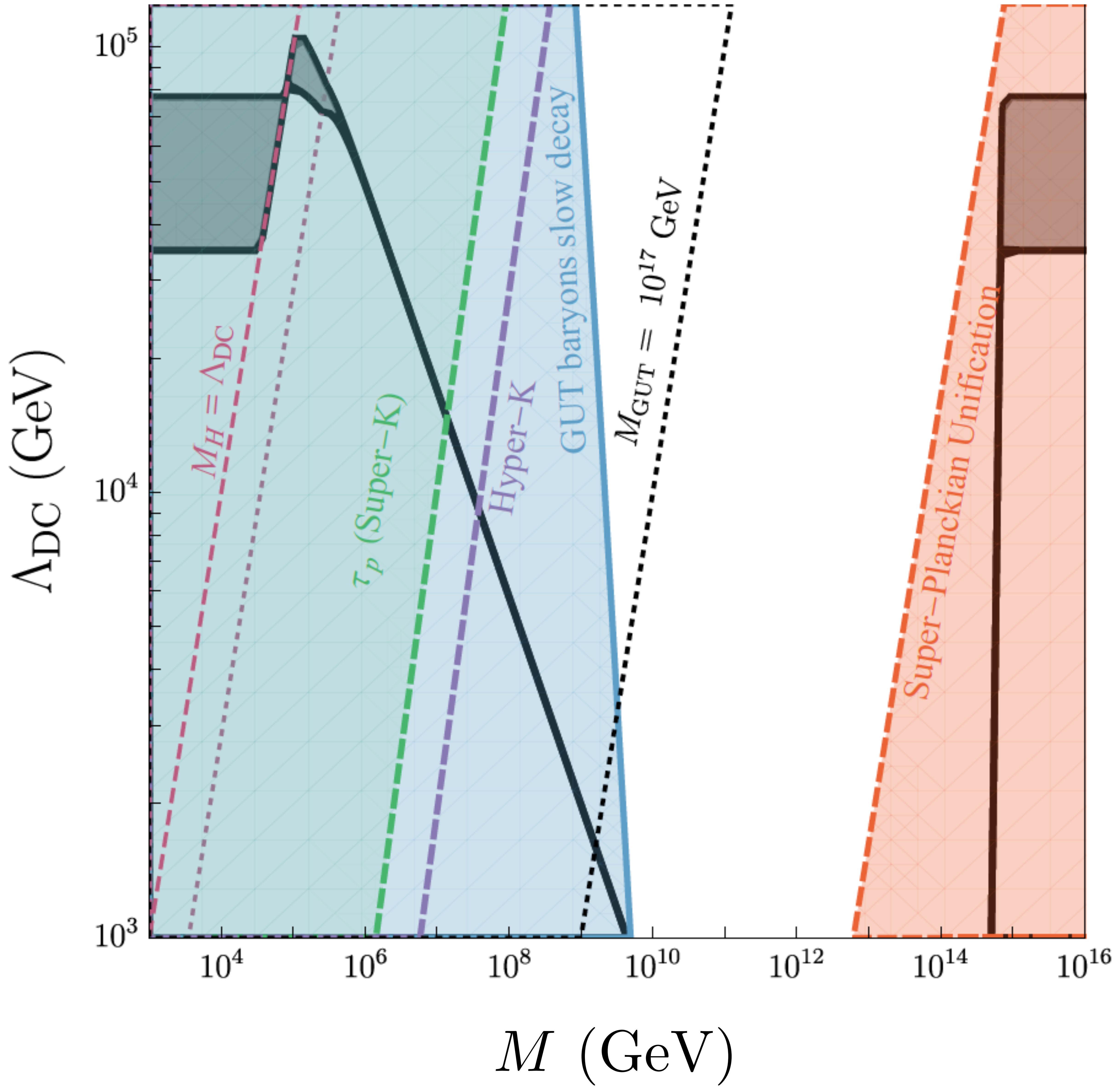

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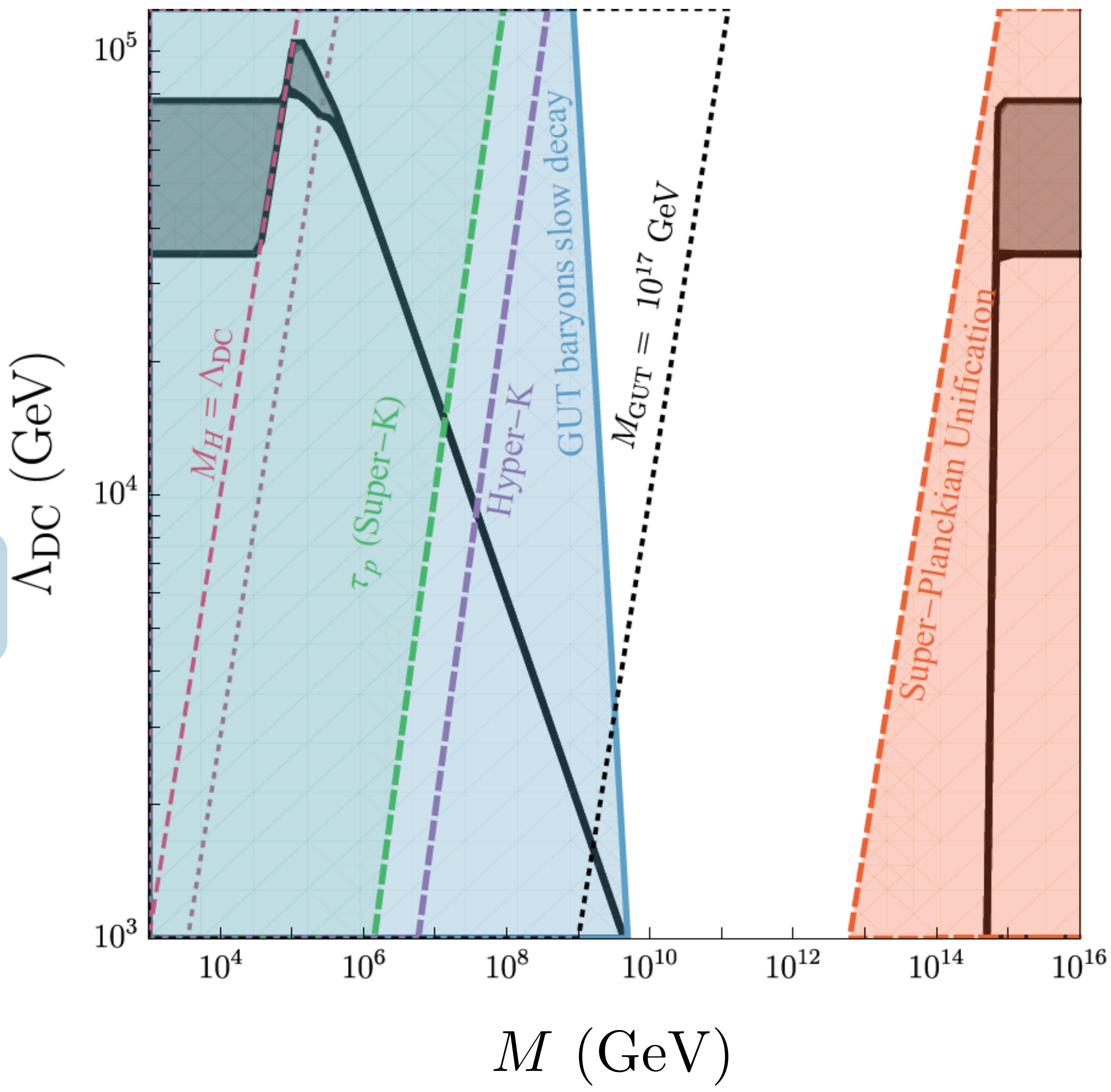

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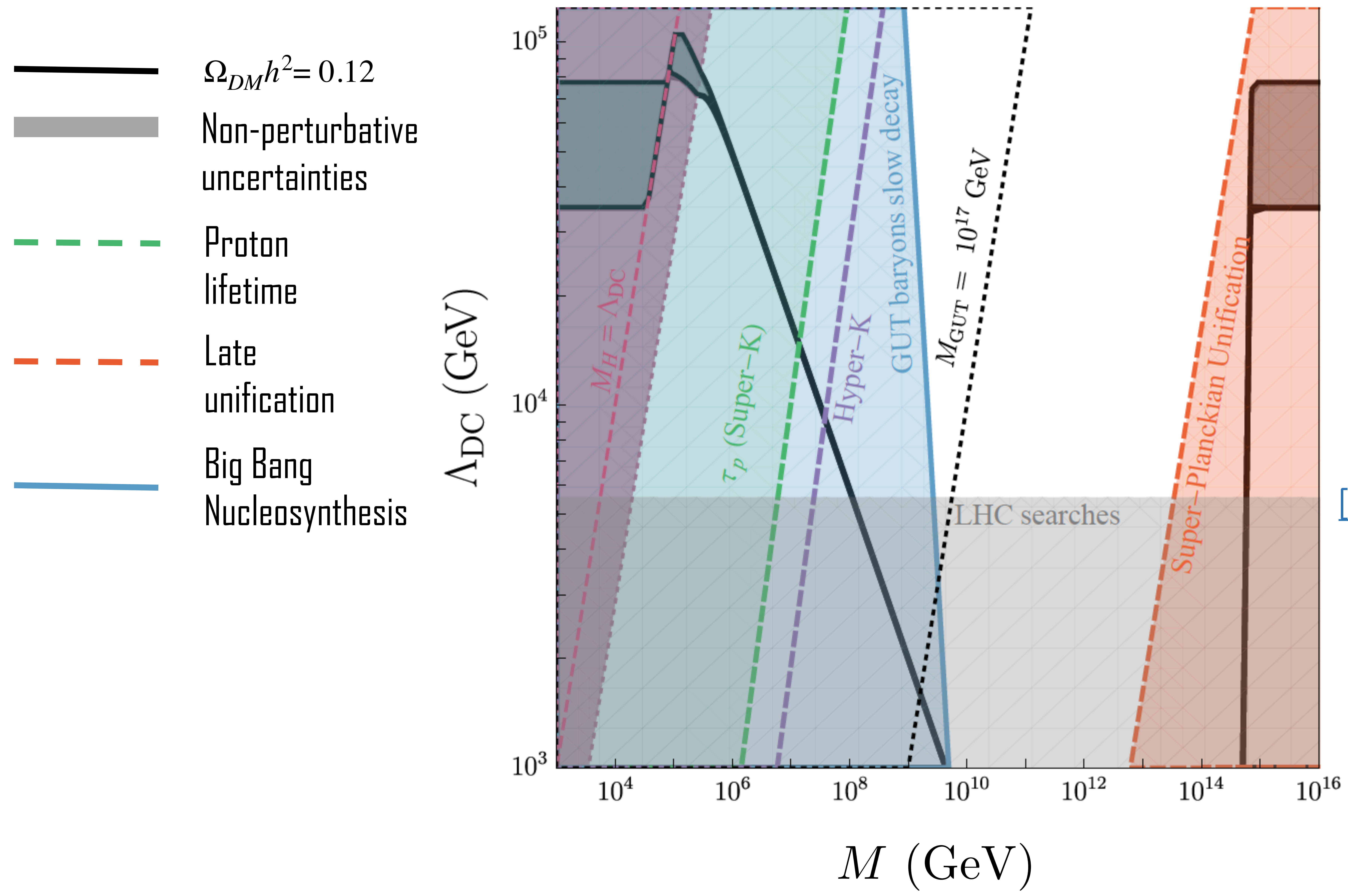

Benchmark Model

$$Q + \tilde{D}$$

GUT theory: 5 + 10

$$SU(3)_{\mathrm{DC}}$$

Mass of dark pions

$$m_{\pi_D} \lesssim 500 \text{ GeV}$$

[Barducci, De Curtis, Redi, Tesi '18]

Contino, Bottaro, SV [To appear]

GUT partners are overclosing the universe!

$\Omega_{DM}h^2 = 0.12$

Non-perturbative uncertainties

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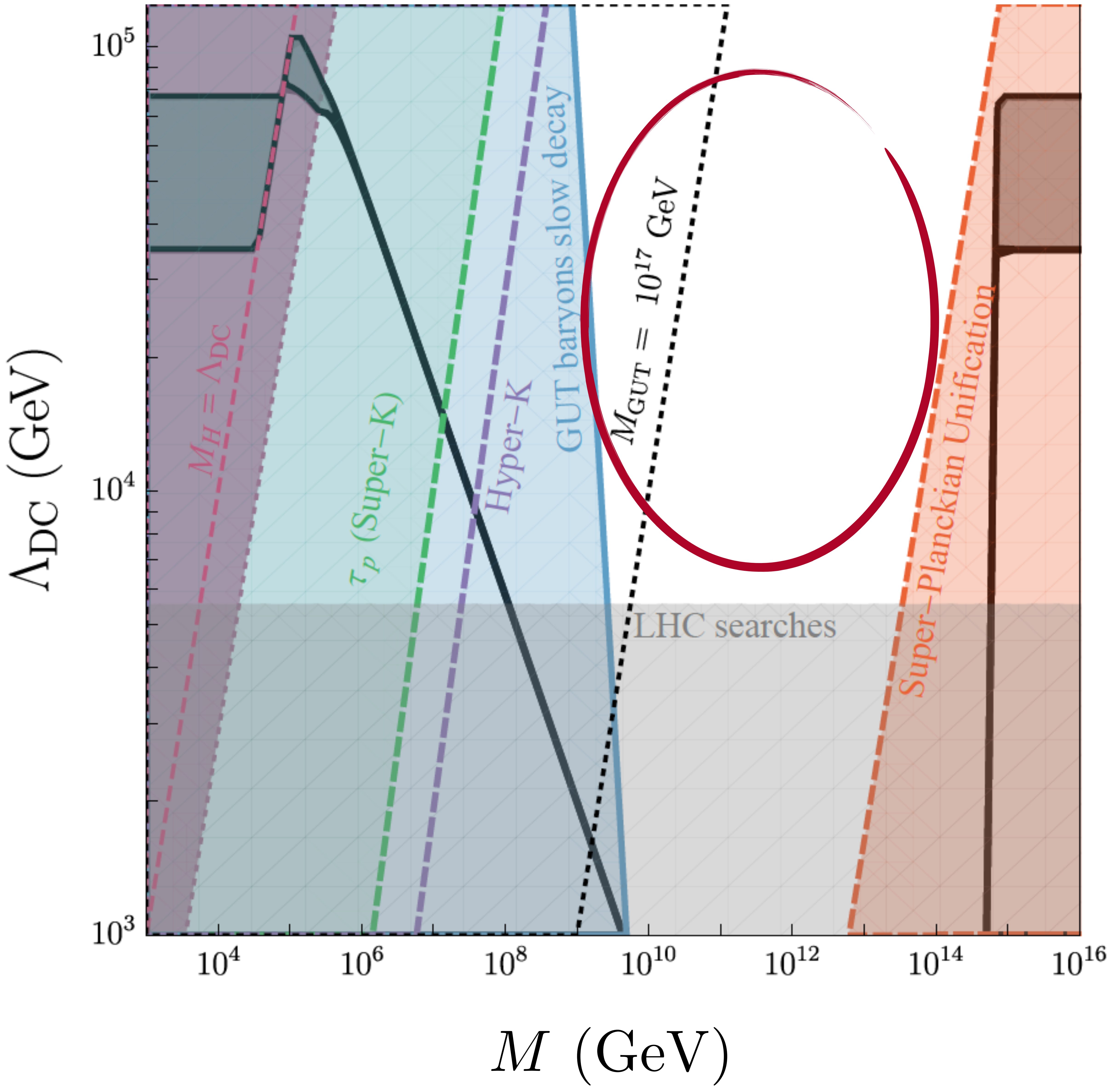

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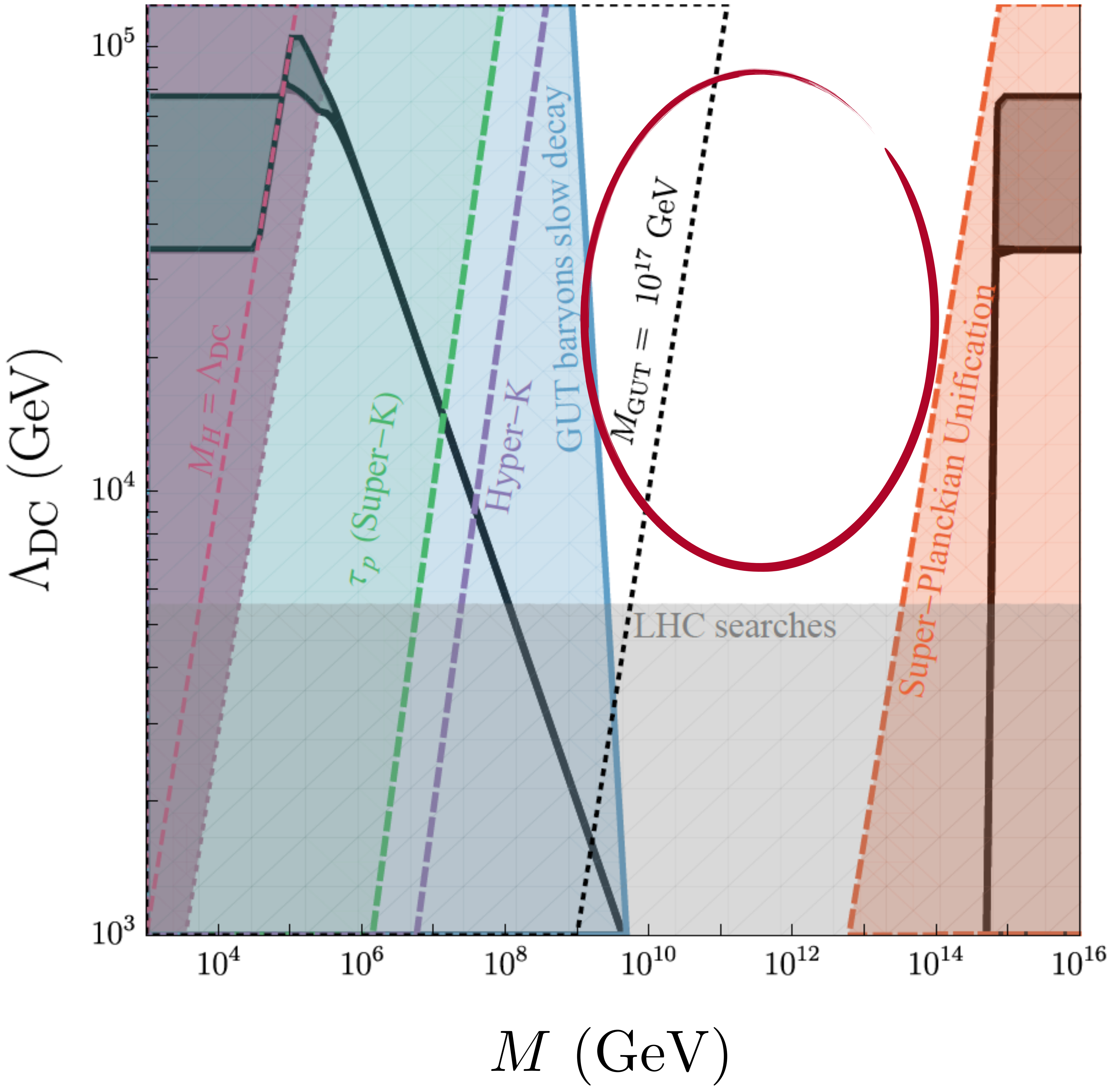

Benchmark Model

$$Q + \tilde{D}$$

GUT theory: 5 + 10

Way out? Dilute the GUT partner abundance with a low reheating Temperature

Vectorlike confining theories give attractive ideas for DM stability

Gauge coupling unification highly restrictive theory prior for composite DM

Role of GUT partners cannot be ignored when considering DM phenomenology

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Role of GUT partners cannot be ignored when considering DM phenomenology

Is there any hope to test these theories?

[Work in Progress]

Is there any hope to test these theories?

standard predictions

SM charged pions with $m \sim \mathcal{O}(\text{TeVs})$

Dark matter with $m \sim 100$ TeV

GUT partner fermions with mass allowed $M \sim 10^{10} - 10^{13}$ GeV

GUT gauge bosons with $m \sim M_{GUT} \sim 10^{17}$ GeV

GUT theory predictions

How can we experimentally probe these large scales?

Gravitational Waves?

Strong first order phase transition (FOPT) expected in benchmark model

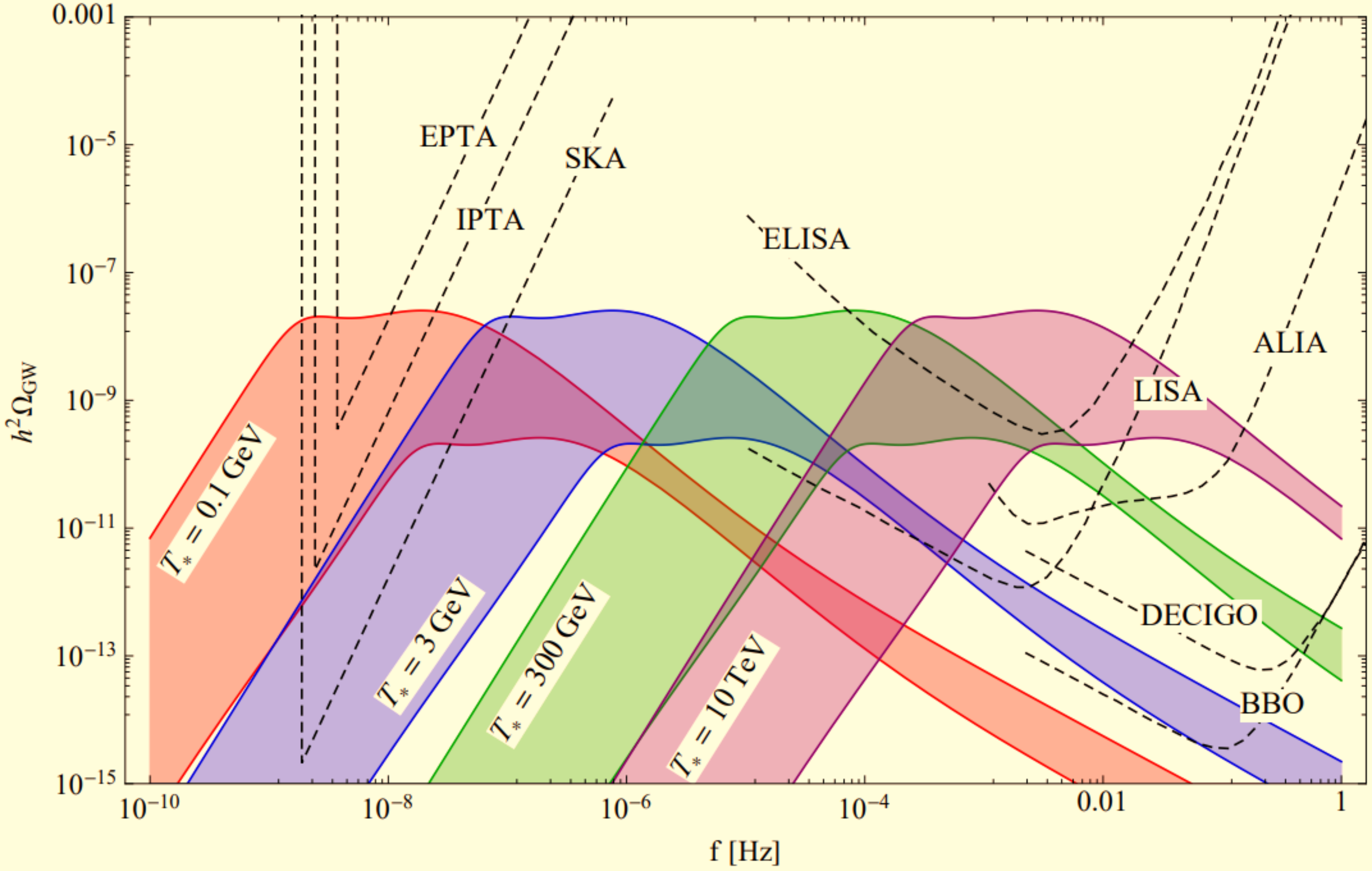
$$Q + \tilde{D}, \quad N_{\mathrm{DC}} = 3, \quad N_{\mathrm{DF}} = 9$$

[Pisarski, Wilczek '84]

$$T_\star \sim \Lambda_{\mathrm{DC}} \sim 100 \text{ TeV} \blacktriangleright f_{\mathrm{peak}} \sim \mathcal{O}(10^{-2}) \text{ Hz}$$

Gravit

[Schwaller '15]



czek '84]

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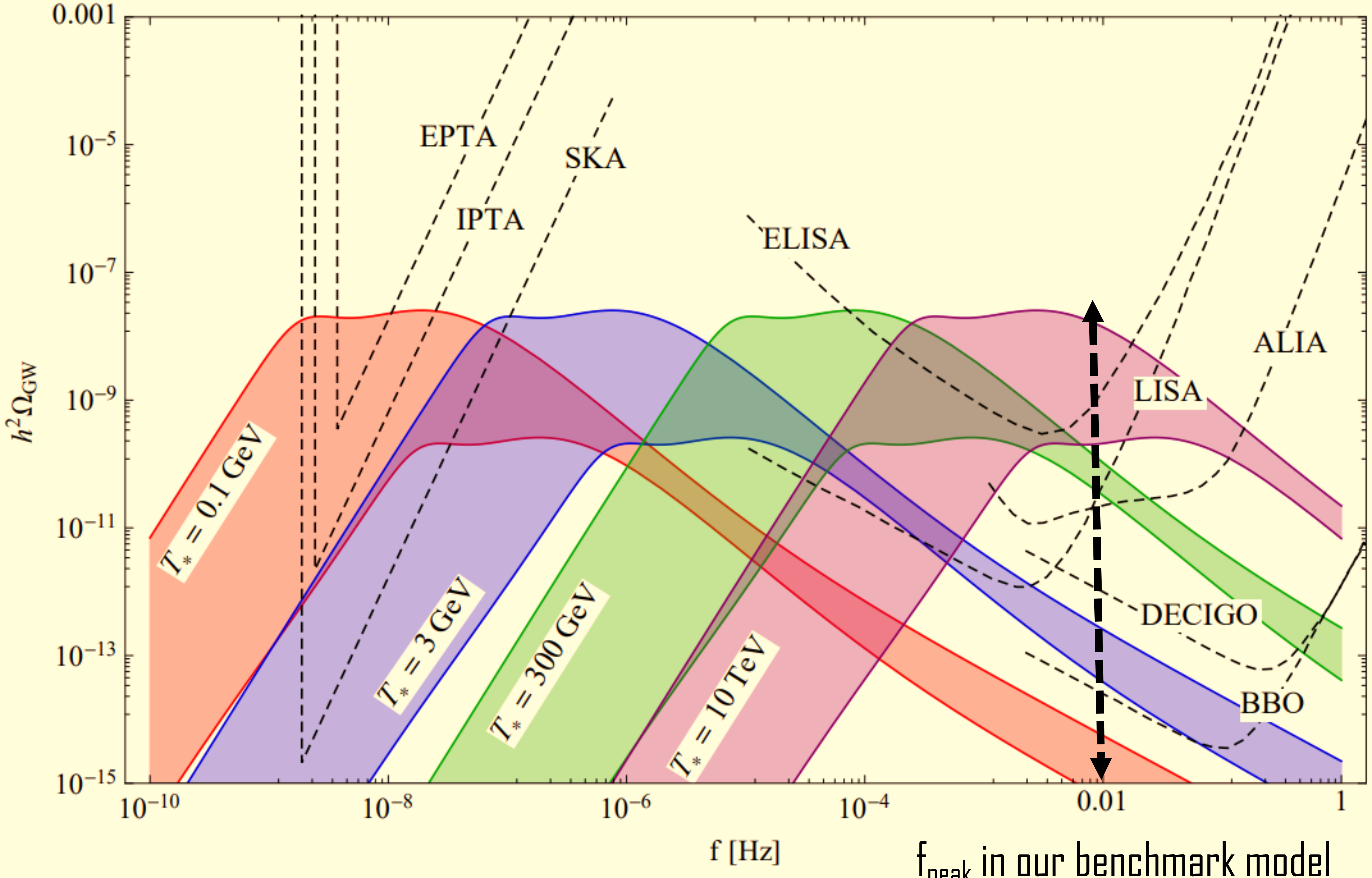

f_{peak} in our benchmark model

czek '84]

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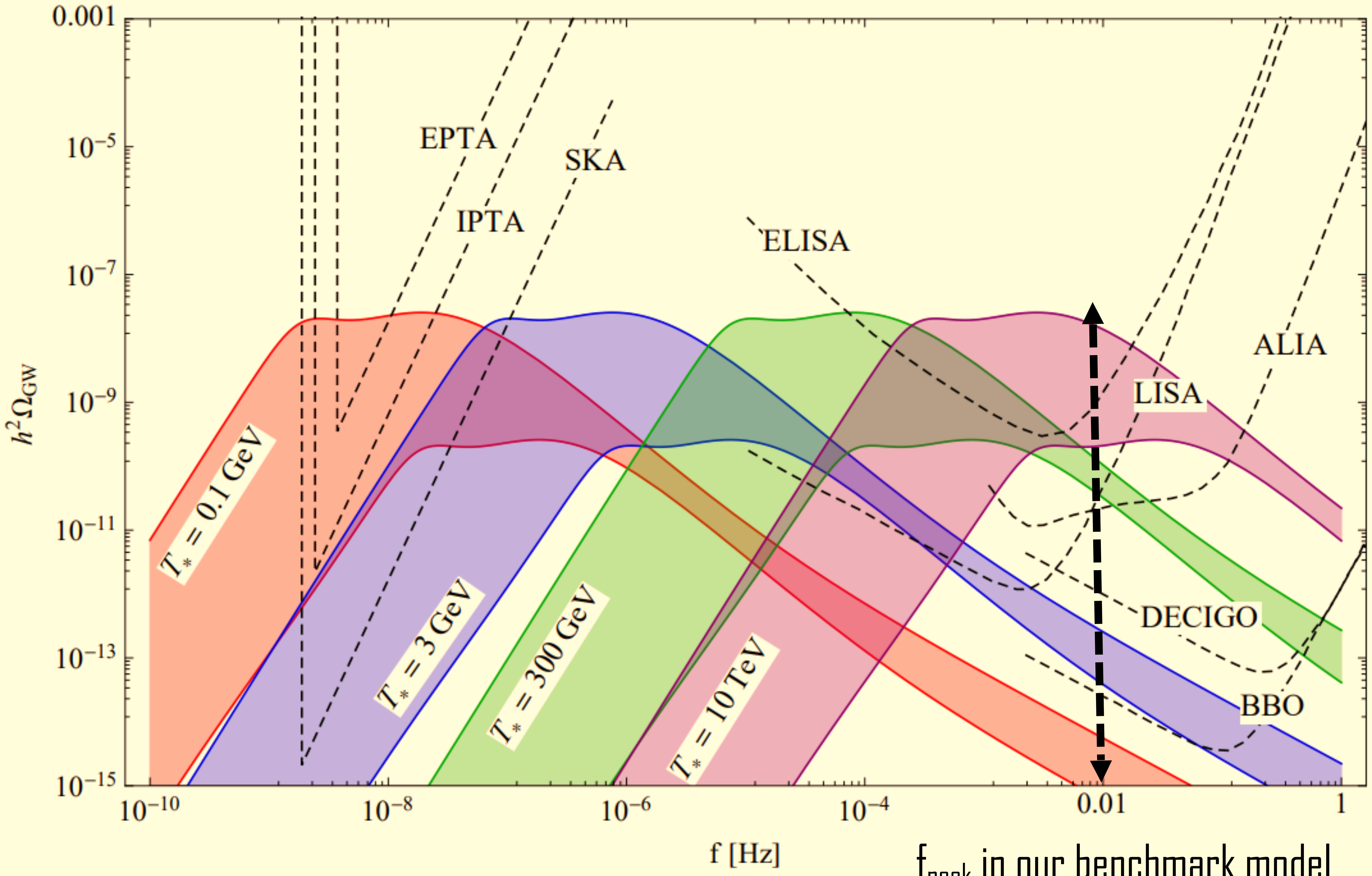


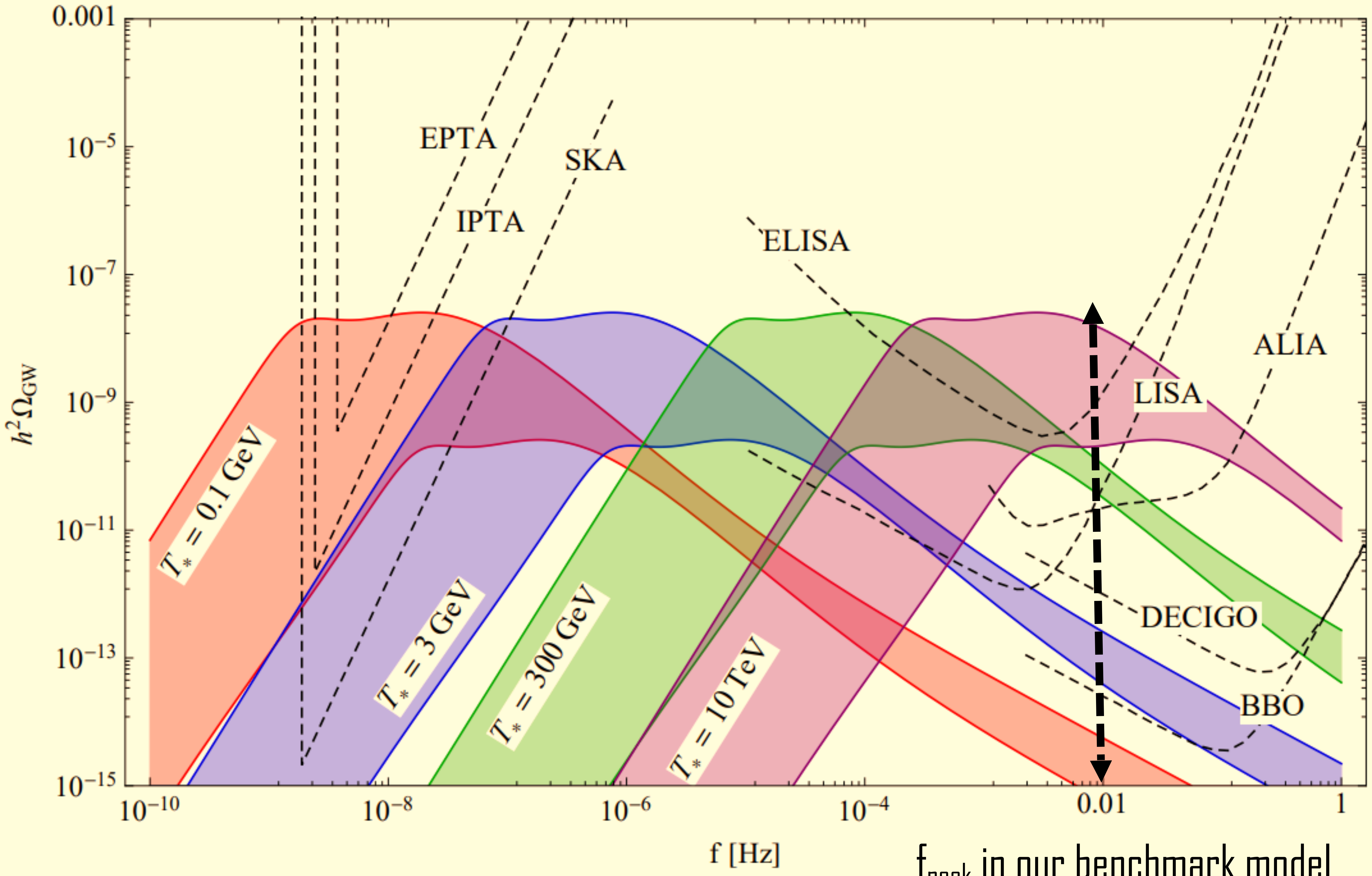
f_{peak} in our benchmark model

czek '84]

Only if GW are produced during radiation dominated era ~ M > 10^{13} GeV

Gravit

[Schwaller '15]



f_{peak} in our benchmark model

czek '84]

For M < 10^{13} GeV, GW are produced during matter dominated era with suppressed amplitude

DM Decay?

$$\mathcal{O}_6 \equiv QQQl_{SM}$$

Current stringest limits from Fermi-LAT $\tau_{\rm DM} \gtrsim 10^{28}\ \rm s$

Future experiments [CTA, SWGO etc.] will improve $\tau_{\rm DM} \gtrsim 10^{29}\ \rm s$

Credit: NASA's Goddard Space Flight Center/Chris Smith (USRA/GESTAR)

Symmetry breaking Os

dark species number is broken by $D \geq 5$ $\mathcal{O}s$

Example: $\mathcal{O}_5 = (\bar{\mathcal{Q}}_r \mathcal{Q}_s) HH$ $\quad (\bar{\mathcal{Q}}_r \mathcal{Q}_s) = 3_0$ or 1_0 under $SU(2)_{EW} \times U(1)_Y$

Dark mesons with $m_{\pi_D} \ll m_{EW}$ ruled out due to collider constraints on SM-charged dark sector

π_D

[Antipin et. al.`15] [Bottaro, Contino, SV `24]

For a via … ould satisfy

$$D = 5: \quad m_{\rm DM} \lesssim 1.5 \text{ MeV}$$

Radiative cooling of gas in Leo T [Wadekar, Wang '21]

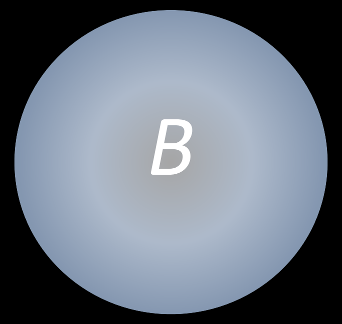
Symmetry breaking Os

For a via … ould satisfy

<u>dark baryon number</u> is broken by $D \geq 6$ $\mathcal{O}s$

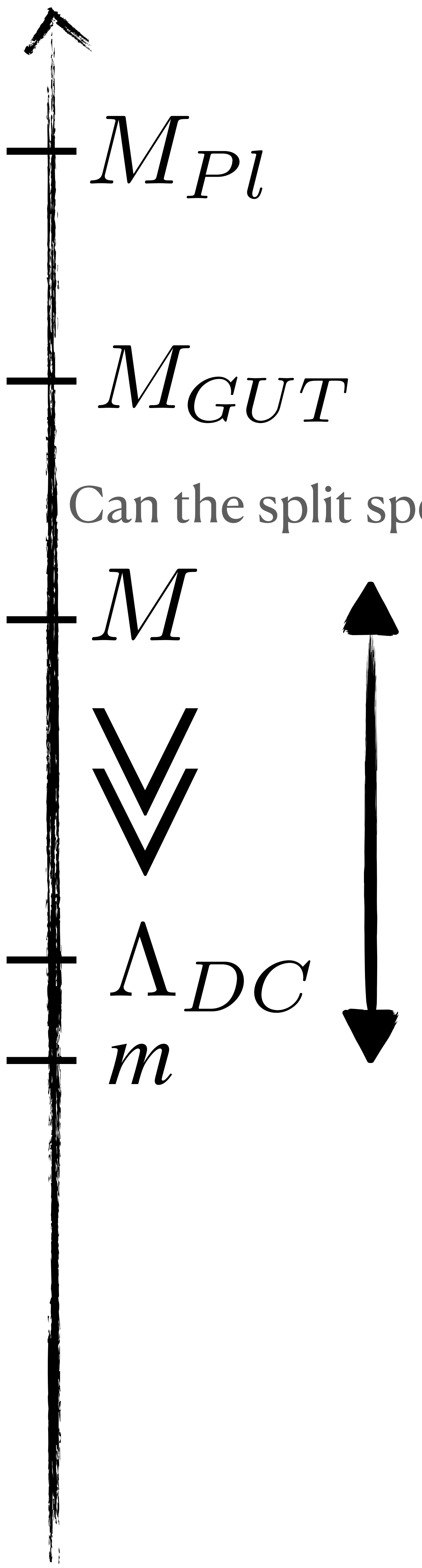
$$\mathcal{O}_6 \equiv QQQ\psi_{\rm SM}$$

lightest dark baryon with $m_{\rm DB} \sim 100$ TeV is viable



$$D = 6: \quad m_{\rm DM} \lesssim 100 \text{ TeV}$$

Fermi gamma-ray data [Cohen et. al. '16]



Can the split spectrum be natural?

$$Q + \tilde{D}$$

$$\Psi_5 = \tilde{D} + \tilde{L} \qquad \Psi_{10} = Q + U + E$$

$$\mathcal{L} \supset -m_5 \bar{\Psi}_5 \Psi_5 - m_{10} \bar{\Psi}_{10} \Psi_{10} - y_5 \bar{\Psi}_5 \phi_{24} \Psi_5 - y_{10} \bar{\Psi}_{10} \phi_{24} \Psi_{10}$$
$$- y_L \bar{\Psi}_5 P_L \phi_5^\dagger \Psi_{10} - y_R \bar{\Psi}_5 P_R \phi_5^\dagger \Psi_{10} + \text{h.c.}$$

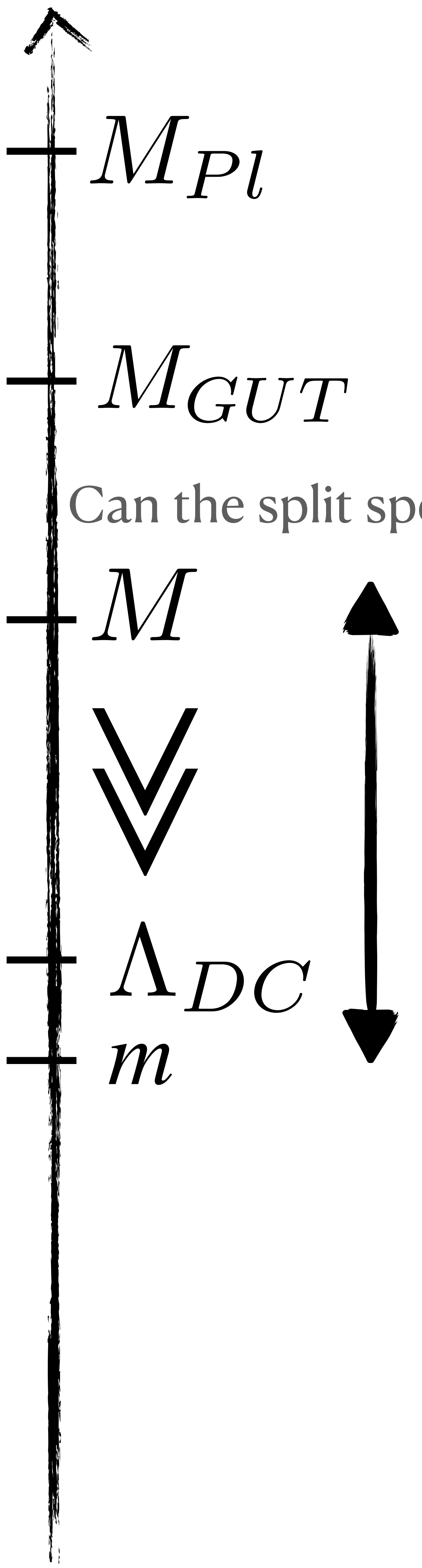
$$\langle \phi_{24} \rangle = \frac{v_{GUT}}{\sqrt{30}} \, \text{diag}(2,\ 2,\ 2,\ -3,\ -3)$$

$$m_{\tilde{D}} = m_5 + \frac{2}{\sqrt{30}} y_5 v_{\text{GUT}} \qquad m_U = m_{10} + \frac{2}{\sqrt{30}} y_{10} v_{\text{GUT}}$$

$$m_{\tilde{L}} = m_5 - \frac{3}{\sqrt{30}} y_5 v_{\text{GUT}} \qquad m_E = m_{10} - \frac{3}{\sqrt{30}} y_{10} v_{\text{GUT}}$$

$$m_Q = m_{10} - \frac{1}{2\sqrt{30}} y_{10} v_{\text{GUT}}$$

$m_Q, m_{\tilde{D}} \ll m_U, m_E, m_{\tilde{L}}$ obtained for $m_{5,10} \sim y_{5,10} v_{GUT} \sim M$ with two fine tunings



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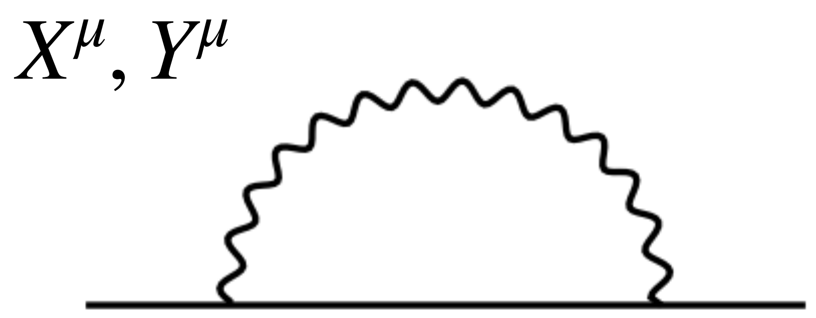
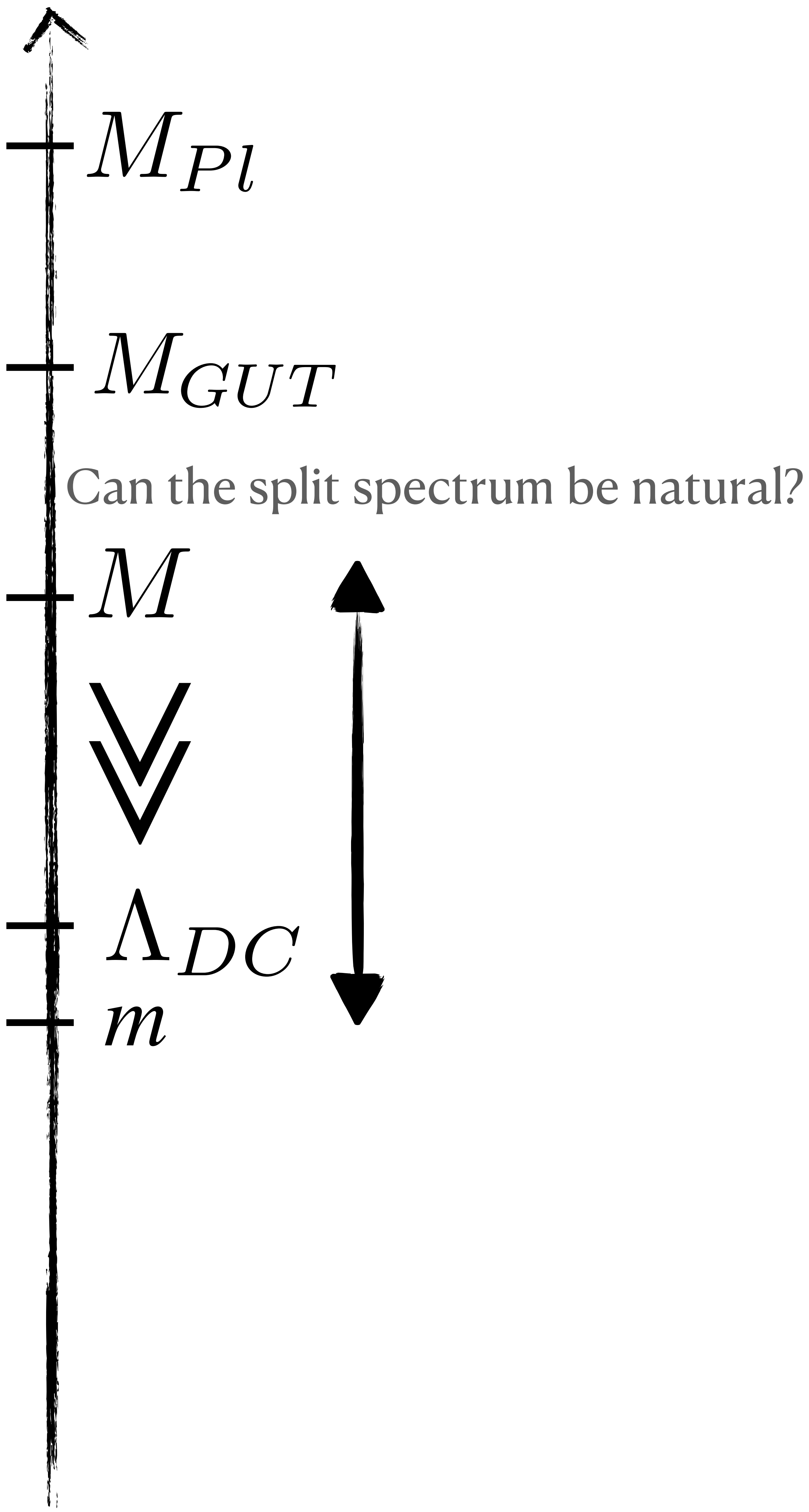
Is the tuning stable under radiative corrections?



$$\delta m_5 \sim \frac{\alpha_{GUT}}{4\pi} m_5$$

For $\delta m_5 < m,\ m_5 \sim \mathcal{O}(M)$
$m \ll M \ll (4\pi)m/\alpha_{GUT}$

mass hierarchy between light dark fermions and their GUT partners is not stable under radiative corrections



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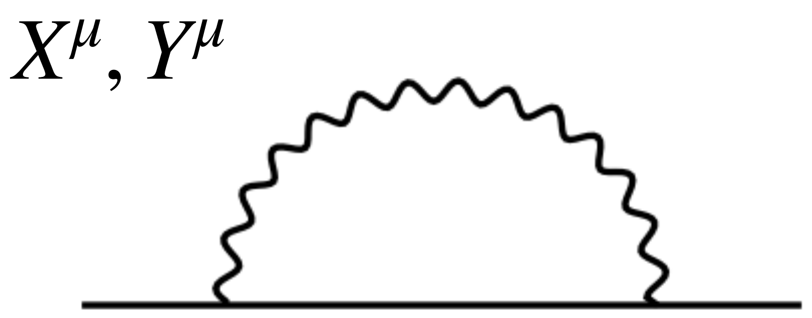

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For $\delta m_5 < m,\ m_5 \sim \mathcal{O}(M)$

$m \ll M \ll (4\pi) m / \alpha_{GUT}$

For $m \sim \Lambda_{DC} \sim 100$ TeV, $\alpha_{GUT} \sim 1/15 \rightarrow$ 10^5 GeV $\ll M \lesssim 2 \times 10^7$GeV

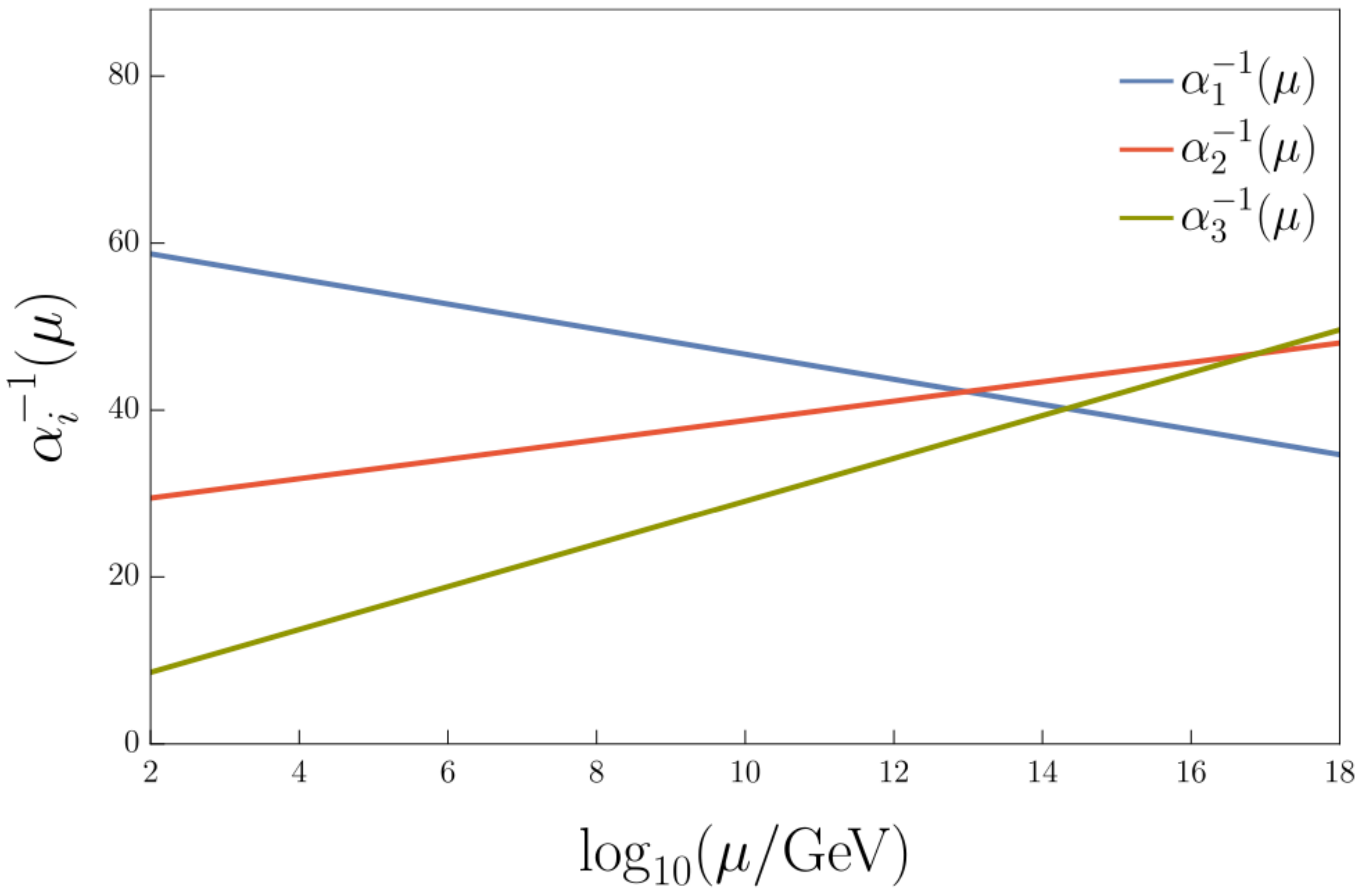
Tuning is stable here!

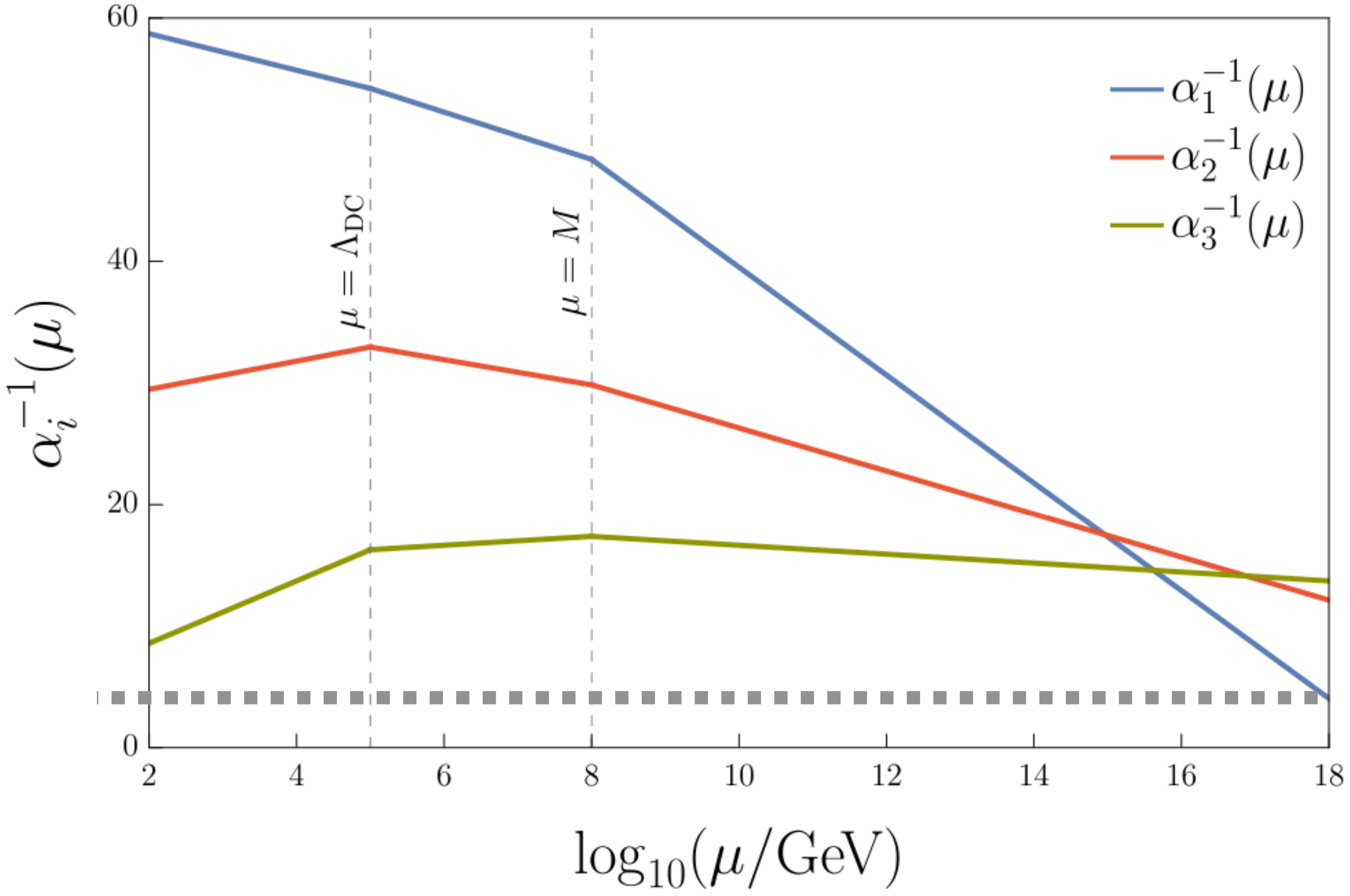
[Bottaro, Contino, SV `24]

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

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

$$\alpha_{\text{GUT}}(\text{BSM}) < 4\,\pi$$





$\mathcal{G}_{SM} \times SU(3)_{DC}$

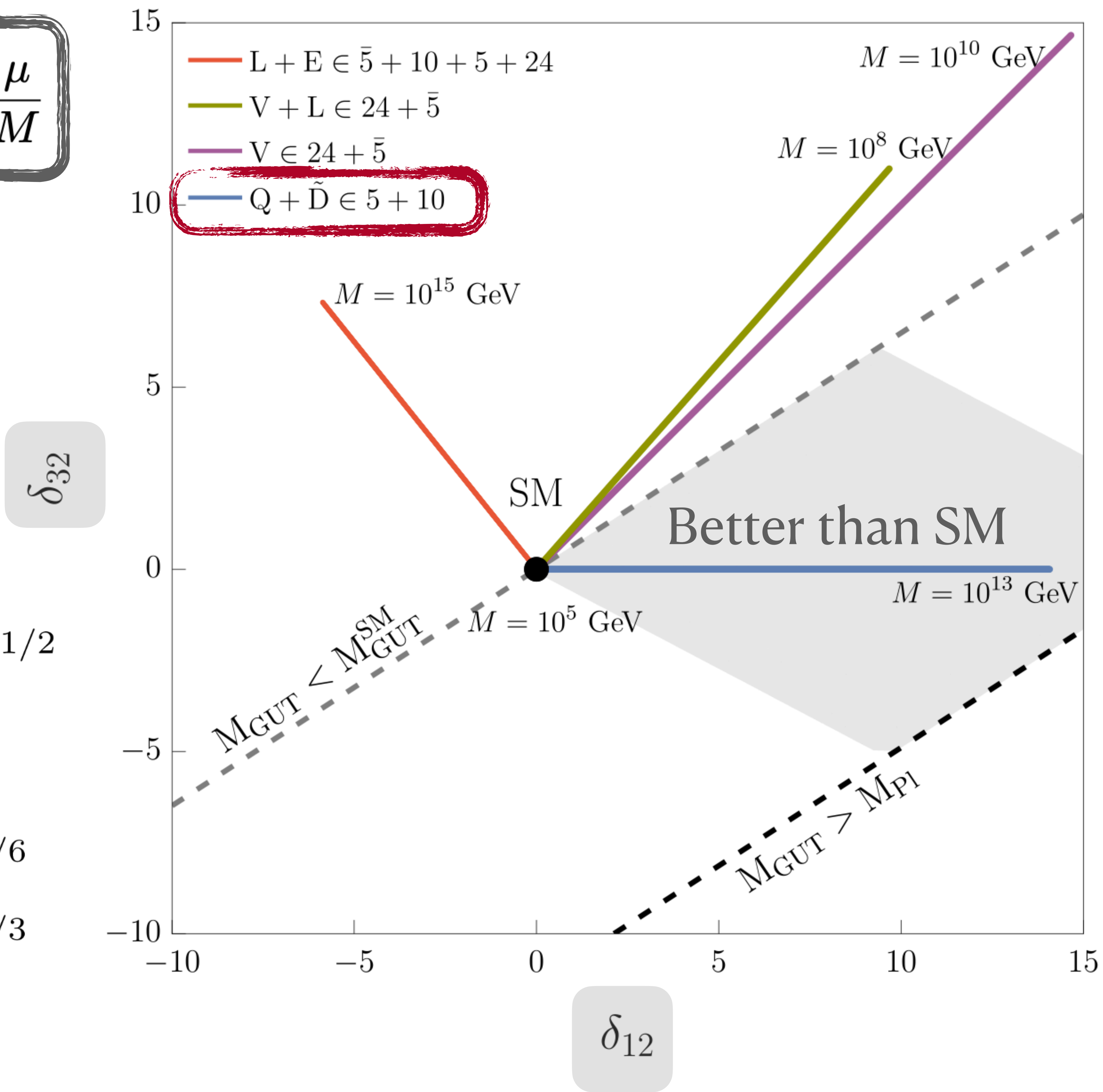
[Bottaro, Contino, SV `24]

$$\boxed{\frac{1}{\alpha_i(\mu)} = \frac{1}{\alpha_i(m_Z)} - \frac{\beta_i^{SM}}{2\pi}\log\frac{\mu}{m_Z} - \frac{\beta_i^{L}}{2\pi}\log\frac{M}{\Lambda_{DC}} - \frac{\beta^{SU(5)}}{2\pi}\log\frac{\mu}{M}}$$

$$\delta_{ij} = -\frac{\beta_i^L - \beta_j^L}{2\pi}\log\frac{M}{\Lambda_{\rm DC}}$$

Contribution from light dark fermions

$$L = (1,2)_{-1/2}$$
$$E = (1,1)_1$$
$$V = (1,3)_0$$
$$Q = (3,2)_{1/6}$$
$$\tilde{D} = (\bar{3},1)_{1/3}$$



NGB Production at Colliders