

Freeze-In Composite Dark Matter

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In collaboration with:

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Particle Physics in the Early Universe @ Paris & Orsay, 18 Sept 2026

Motivation

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- In nature, there is one more stable particle: dark matter. *Dark matter may be like the “proton” of the dark sector*; a composite particle stabilised by an accidental symmetry.

Confining gauge theory; $SU(N_{\text{DC}}), SO(N_{\text{DC}})$

$$\mathcal{L}_{\text{DS}} = -\frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} + \bar{\psi}_i(\not{D} - m)\psi_i$$

accidental sym.

dark baryon number, G-parity, ...

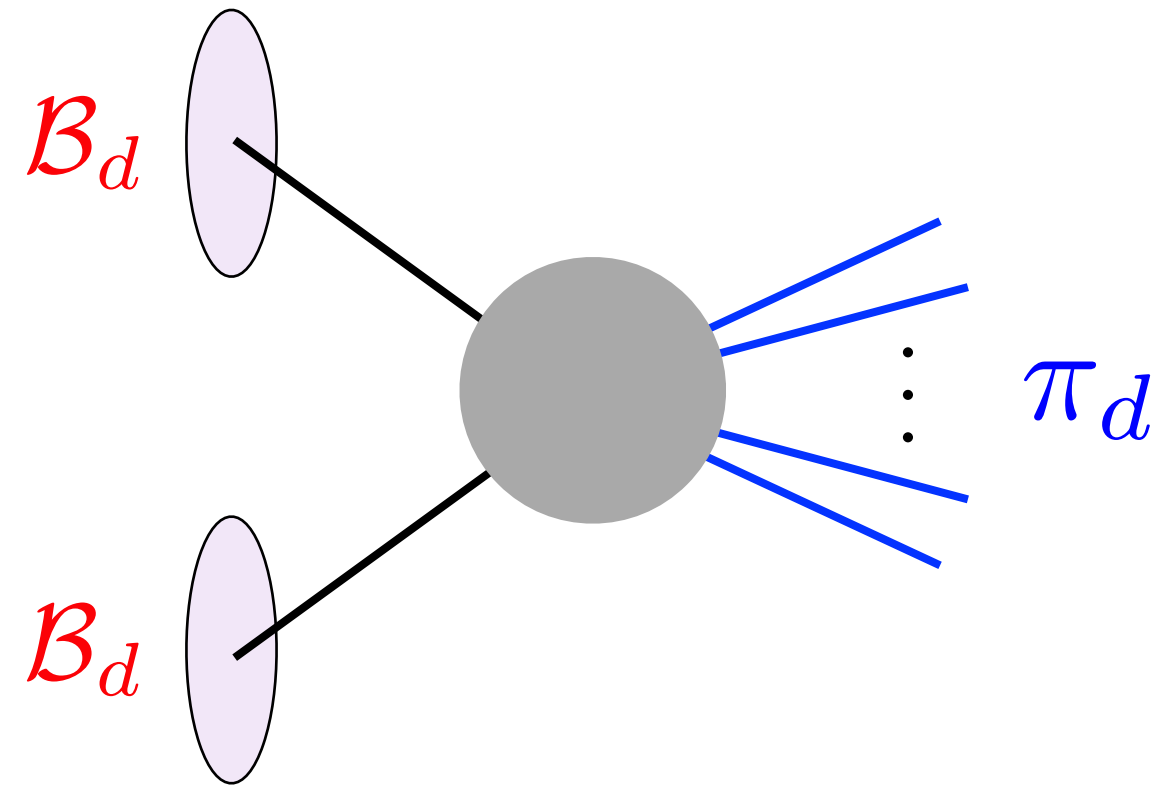
confinement
 $\xrightarrow{\Lambda_{\text{DC}}}$

$\mathcal{B}_d \equiv \equiv \equiv \}$ dark baryons, mesons

$\pi_d \equiv \equiv \equiv \}$ dark pions

dark matter candidate

- If dark baryons are **thermally produced** with the **geometric annihilation cross-section**, the dark baryon mass, $m_B \sim N_{\text{DC}} \Lambda_{\text{DC}}$, is expected to be ~ 100 TeV.



$$\sigma(\mathcal{B}_d \mathcal{B}_d \rightarrow \text{dark pions}) \sim \frac{1}{\Lambda_{\text{DC}}^2} \sim \frac{N_{\text{DC}}^2}{m_B^2}$$

$$\Omega_{\mathcal{B}} h^2 \simeq 0.12$$



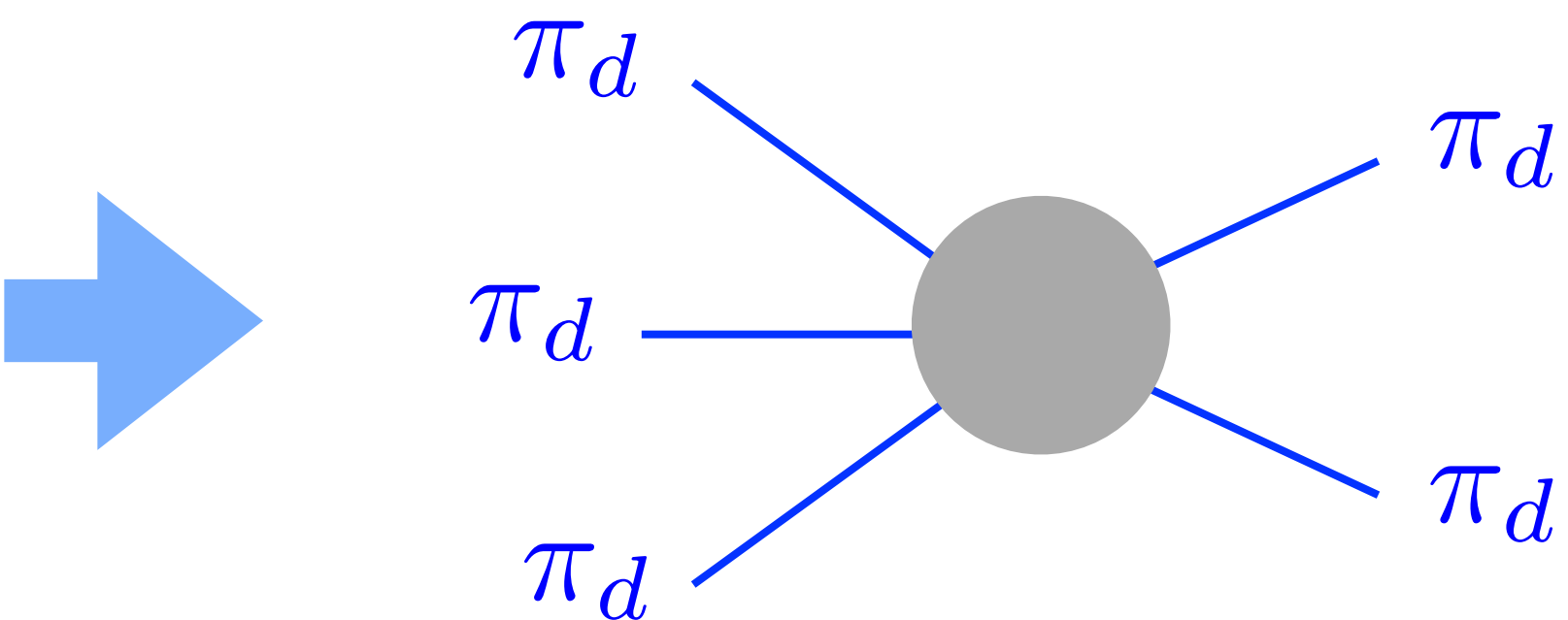
$$m_{\mathcal{B}} \sim 100 \text{ TeV}$$

Griest, Kamionkowski (1990), Antipin, Redi,
Strumia (+Vigiani) [1410.1817, 1503.08749],
Smirnov, Beacom [1904.11503]

- The **dark pions** can also be the dark matter.

In the **SIMPl**est model, the flavour symmetry breaking pattern is $G/H = SU(4)/Sp(4)$

There are 5 pNGBs and the **Wess-Zumino-Witten (WZW) term** is generated:

$$\mathcal{L}_{\text{WZW}} = \frac{2N_c}{15\pi^2 f_\pi^5} \epsilon^{\mu\nu\rho\sigma} \text{Tr} [\pi \partial_\mu \pi \partial_\nu \pi \partial_\rho \pi \partial_\sigma \pi]$$


- The freeze-out mechanism from the **3 → 2 annihilation** via the WZW term gives the correct relic abundance for

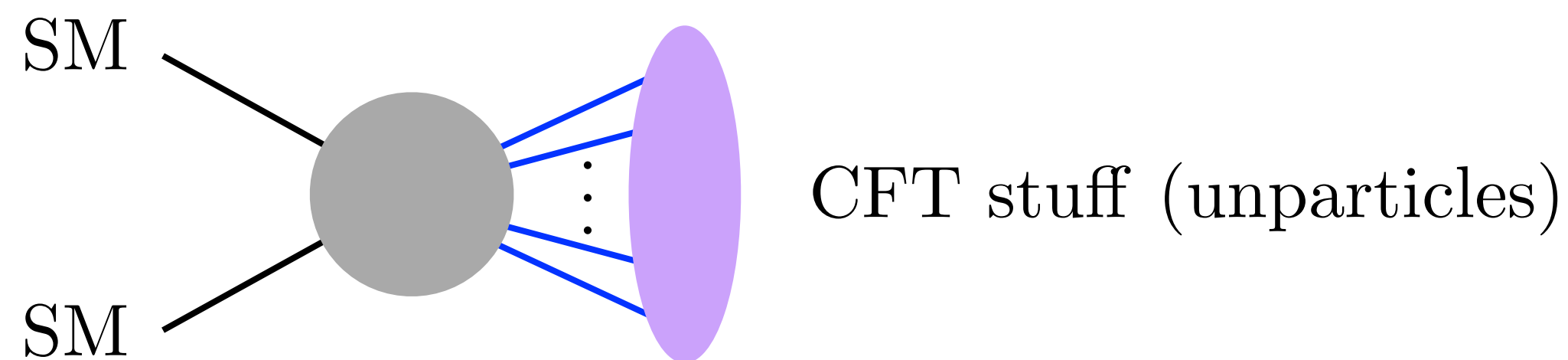
$$m_\pi \sim 300 \text{ MeV}$$

Hochberg, Kuflik, Murayama, Volansky, Wacker [1411.3727],
Hochberg, Kuflik, Murayama [1512.07917]

- Phenomenologically more interesting scenarios are those in which *the dark-visible interaction directly determines the final dark matter abundance*.
- One realisation of such scenarios is **Conformal Freeze-In (COFI)** :

$$\mathcal{L}_{\text{int}} = \frac{\lambda_{\text{CFT}}}{\Lambda_{\text{CFT}}^D} \mathcal{O}_{\text{SM}} \mathcal{O}_{\text{CFT}} \quad \mathcal{O}_{\text{SM}} = \{H^\dagger H, H Q^\dagger q\} \quad D = d_{\text{SM}} + d_{\text{CFT}} - 4$$

- Assuming the dark sector is in the **CFT phase** at the freeze-in period, the correct abundance is reached with the dark matter mass around keV–MeV



Hong, Kurup, Perelstein
[1910.10160] [2207.10093]

$$m_{\text{DM}} \sim \text{keV--MeV}$$

- The dimension of the CFT operator is highly constrained; $d_{\text{CFT}} \lesssim 2$ (Higgs portal).
The **UV completion** is rather **nontrivial**.

- We work on a similar model: **Composite DM** $\times$ **Freeze-In** via **Higgs portal**
- The model has **a concrete UV completion** and **no strongly coupled CFT phase**.

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Plan

- **UV Lagrangian, EFT below Λ_{DC}**
- **Dark Pion DM**
(incompatible with self-interaction bound)
- **Dark Baryon DM**

- At the cut-off Λ_U , the model is $L \otimes N$ with a **confining $SO(N_{\text{DC}})$ gauge theory** ($N_{\text{DC}} = 3$) :

Field	Spin	$SO(N_{\text{DC}})$	$SU(2)_L$	$U(1)_Y$	$SU(2)_f$	$\mathbb{Z}_2^d$
$\mathcal{G}_\mu$	1	adj.	1	0	1	+
L	$\frac{1}{2}$	fund.	2	$-\frac{1}{2}$	1	—
$\bar{L}$	$\frac{1}{2}$	fund.	2	$+\frac{1}{2}$	1	—
$N_i, i = 1, 2$	$\frac{1}{2}$	fund.	1	0	2	—

● **Accidental exact dark parity $\mathbb{Z}_2^d$**

● **Approximate $SU(2)_f, N_i \rightarrow U_{ij}N_j$**

Exact when $m_0, y_L, y_R \rightarrow 0$

$$\mathcal{L}_{\text{UV}} \supset -\frac{1}{2}m_0^{ij}N_iN_j - m_L \bar{L}\epsilon L - y_L^i H\epsilon L N_i - y_R^i H^\dagger \bar{L} N_i + \text{h.c.}$$

- The same model has been proposed and studied ([Mitridate, Redi, Smirnov, Strumia \[1707.05380\]](#), [Contino, Max, Mishra \[2012.08537\]](#)), while the freeze-in DM region hasn't been explored.

- We assume the hierarchy $m_L \gg \Lambda_{\text{DC}} \gg v_{\text{EW}}$.
- The **Higgs portal** operators are generated by integrating out $L, \bar{L}$.

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$\downarrow$ integrate out $L, \bar{L}$

$$\mathcal{L}_{\text{eff}} \supset \left[\frac{c_5^{ij}}{2m_L} H^\dagger H N_i N_j + \text{h.c.} \right] + \frac{c_6^{ij}}{2m_L^2} [H^\dagger i D_\mu H + \text{h.c.}] (N_i^\dagger \bar{\sigma}^\mu N_j)$$

$$c_5^{ij} = 2(y_L^i y_R^j + y_R^i y_L^j) \quad c_6^{ij} = y_L^{*i} y_L^j - y_R^{*i} y_R^j$$

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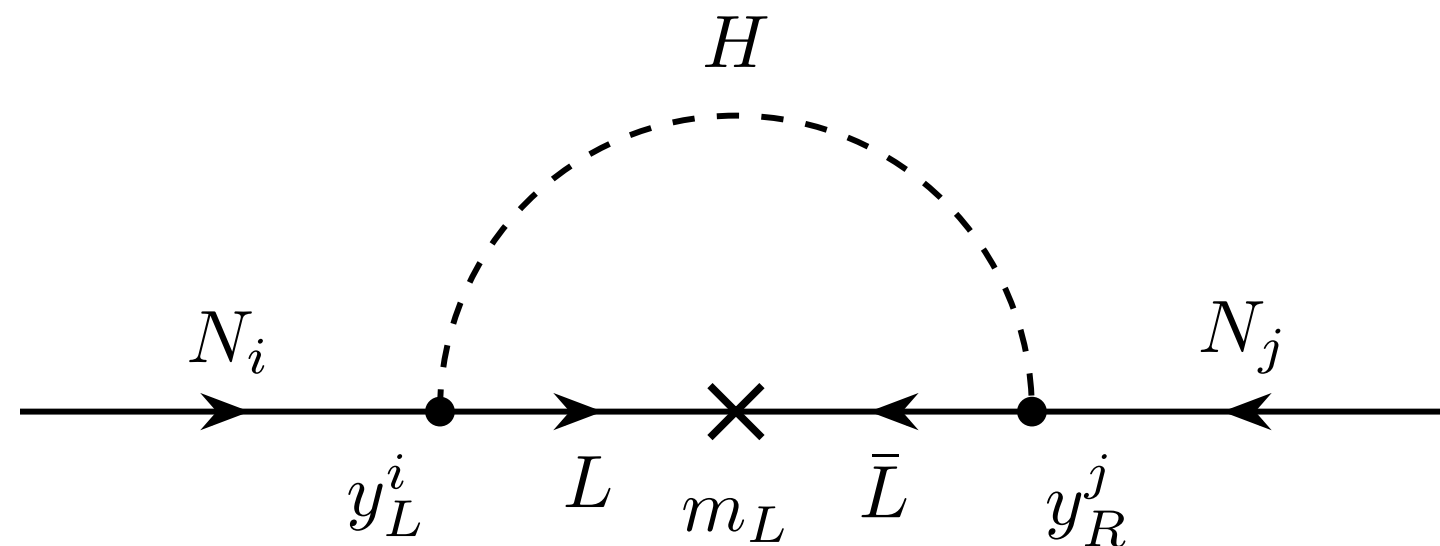
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- The m_L -enhanced 1-loop correction to m_0 is also generated.



$$\tilde{m}_N^{ij} = \bar{m}_0^{ij} + c_5^{ij} m_L x$$

$$x \equiv \frac{1}{16\pi^2} \ln \frac{\Lambda_{\text{UV}}^2}{m_L^2}$$

- Below Λ_{DC} , dark QCD $SO(N_{\text{DC}})$ confines and the Majorana condensate breaks the flavour symmetry.

$$\langle N_i N_j \rangle = V^3 \delta_{ij} \quad \Rightarrow \quad SU(2)_f \rightarrow SO(2)_f$$

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- T^2 preserved, while T^1, T^3 are broken $\Rightarrow$ **two pNGBs** π^1, π^3

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$$\mathcal{B}_d \equiv \equiv \equiv \left. \right\} \text{dark baryons, mesons} \quad \left\{ \begin{array}{l} m_B \simeq N_{\text{DC}} \Lambda_{\text{DC}} \\ \text{For odd } N_{\text{DC}}, \text{ dark baryons are } \mathbb{Z}_2^d \text{ odd} \\ \Rightarrow \text{the lightest dark baryon is stable} \end{array} \right.$$

$$\pi_d \equiv \equiv \equiv \left. \right\} \text{dark pions} \quad \left\{ \begin{array}{l} \text{Not protected by any symmetry (unstable)} \\ \Sigma \equiv \exp\left(i \frac{\pi^{\hat{a}} T^{\hat{a}}}{f_\pi}\right), \quad \hat{a} \in \{1, 3\}, \quad \Sigma \rightarrow U \Sigma U^T \end{array} \right.$$

- The leading chiral Lagrangian is

$$\Sigma \equiv \exp\left(i \frac{\pi^{\hat{a}} T^{\hat{a}}}{f_\pi}\right), \quad \hat{a} \in \{1, 3\},$$

$$\mathcal{L} \ni f_\pi^2 \text{Tr} [(\partial_\mu \Sigma)^\dagger (\partial^\mu \Sigma)]$$

$$c_6^{\hat{a}} \equiv \text{Tr}[c_6 T^{\hat{a}}]$$

$$c_6^{UB} \equiv \text{Tr}[c_6 T^2]$$

$$+ \underbrace{\left[\frac{V^3}{2} \text{Tr}[\tilde{M} \Sigma] + \text{h.c.} \right]}_{\text{D=5 portal}} - \underbrace{\frac{1}{m_L^2} [H^\dagger i D_\mu H + \text{h.c.}] [c_6^{\hat{a}} J_B^{\mu, \hat{a}} + c_6^{UB} J_{UB}^\mu]}_{\text{D=6 portal}}$$

D=5 portal

D=6 portal

$$\tilde{M}^{ij} = \tilde{m}_N^{ij} - \frac{c_5^{ij}}{m_L} H^\dagger H$$

$$J_B^{\mu, \hat{a}} = f_\pi \partial^\mu \pi^{\hat{a}} + \dots$$

$$J_{UB}^\mu = \pi^3 \partial^\mu \pi^1 - \pi^1 \partial^\mu \pi^3 + \dots$$

- Below v_{EW} , we expand around the Higgs vev.

$$\tilde{M}^{ij} = M^{ij} - \frac{c_5^{ij}}{2m_L} (2vh + h^2) \quad M^{ij} = m_0^{ij} + c_5^{ij} \left(x m_L - \frac{v^2}{m_L} \right), \quad x \equiv \frac{1}{16\pi^2} \ln \left(\frac{\Lambda_{UV}^2}{m_L^2} \right)$$

- The **dark pion mass** and the **Higgs-pNGB mixing** term are obtained as

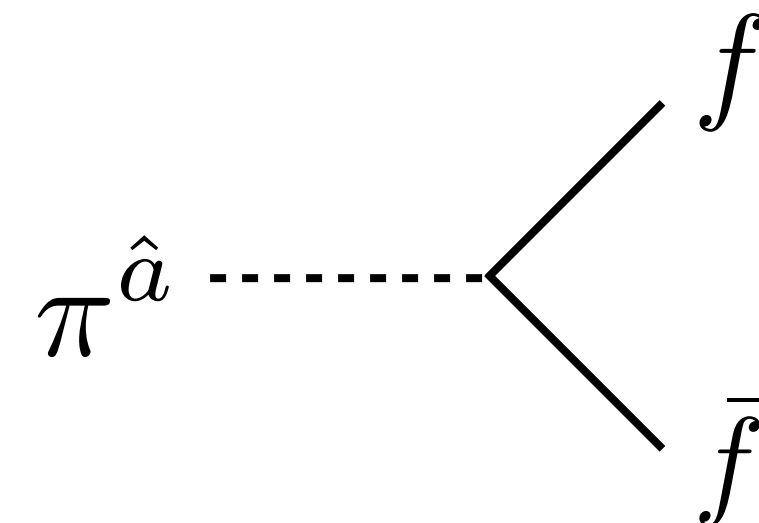
$$\mathcal{L}_5 = \frac{V^3}{2} \text{Tr}[\tilde{M}\Sigma] + \text{h.c.} \supset -\frac{1}{2}m_\pi^2 \pi^{\hat{a}} \pi^{\hat{a}} + \frac{2c_{5I}^{\hat{a}} v V^3}{f_\pi m_L} h \pi^{\hat{a}}$$

$$m_\pi^2 = \frac{V^3}{f_\pi^2} \text{Re Tr}[M]$$

$$c_{5I}^{\hat{a}} \equiv \text{Im Tr}(c_5 T^{\hat{a}})$$

- Through the Higgs-pNGB mixing, the **π - f - $\bar{f}$ vertex** is obtained as

$$\mathcal{L} \supset \frac{m_f}{v} s^{\hat{a}} \pi^{\hat{a}} \bar{\psi}_f \psi_f \quad s^{\hat{a}} \simeq \frac{c_{5I}^{\hat{a}} v V^3}{f_\pi m_L m_h^2}$$



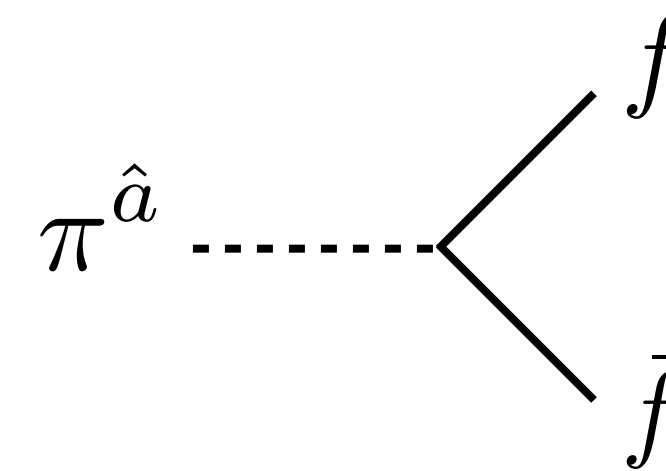
- The **Z-pNGB mixing** term appears from the D=6 portal term as

$$\mathcal{L}_6 = -\frac{f_\pi c_6^{\hat{a}}}{m_L^2} [H^\dagger i D_\mu H + \text{h.c.}] \partial^\mu \pi^{\hat{a}} \supset m_Z \xi^{\hat{a}} Z_\mu \partial^\mu \pi^{\hat{a}} \quad \xi^{\hat{a}} = \frac{c_6^{\hat{a}} f_\pi v}{m_L^2}$$

- We absorb this term by **redefining the would-be NGB field** as $\varphi_3 \rightarrow \varphi_3 - \xi^{\hat{a}} \pi^{\hat{a}}$

This gives the **axial π - f - $\bar{f}$ vertex** as

$$\mathcal{L} \ni \frac{m_f}{v} \xi^{\hat{a}} \pi^{\hat{a}} \bar{\psi}_f i \gamma_5 \psi_f$$

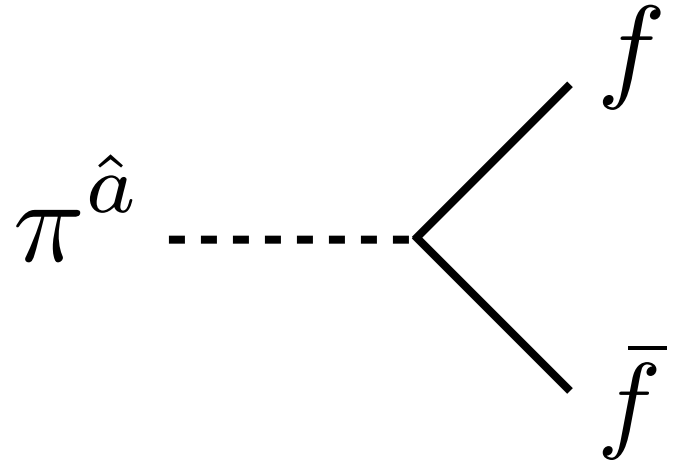


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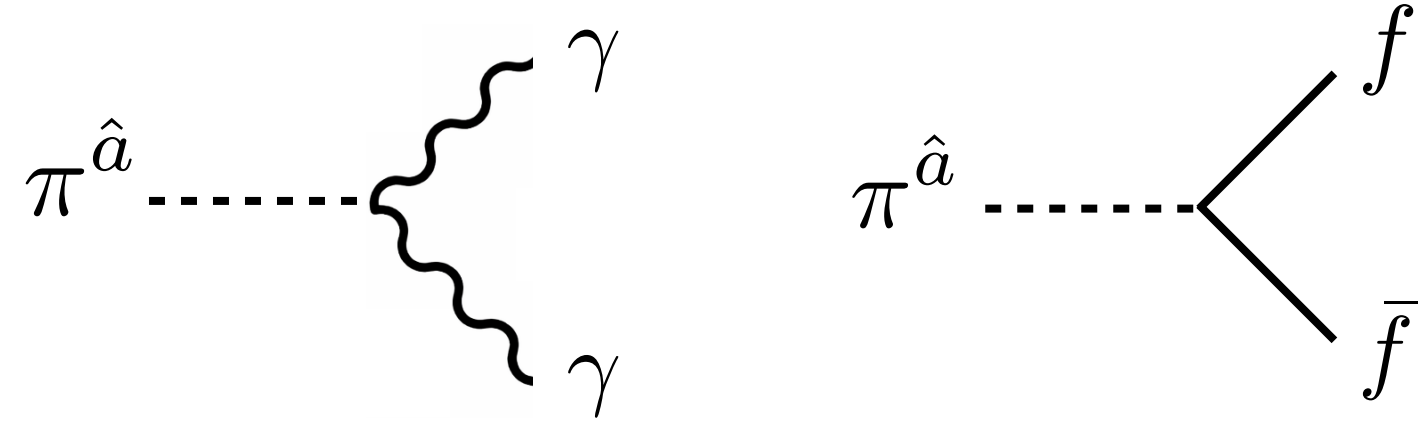
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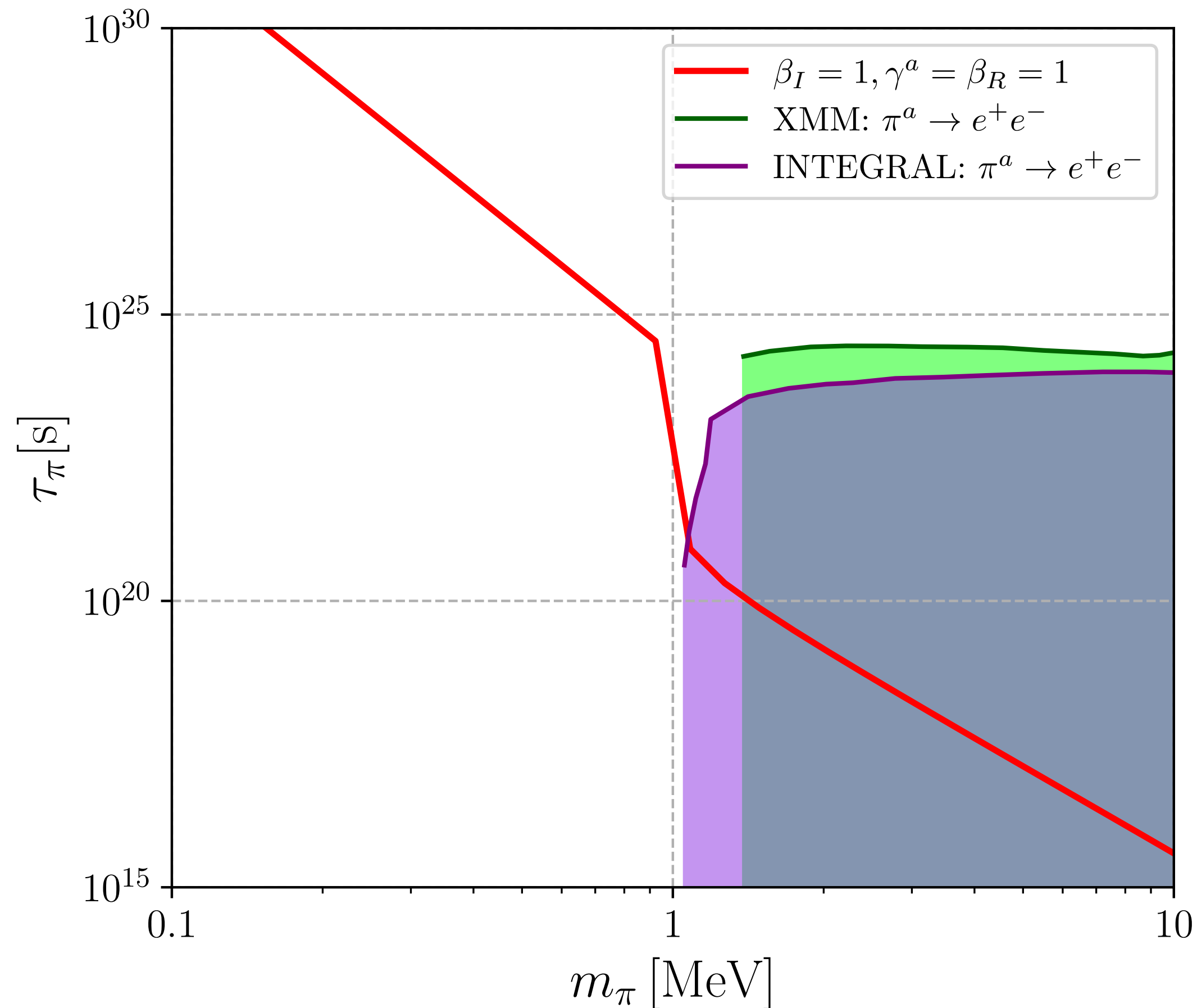
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- A natural expectation is $M = c_5 m_L x$. We define the **reference c_5 value** as

$$c_{5*} \equiv \frac{N_{\text{DC}} m_\pi^2}{x m_L m_B} \quad c_{5R} = \beta_R c_{5*}, \quad c_{5I}^{\hat{a}} = \beta_I^{\hat{a}} c_{5*}, \quad c_6^{\hat{a}} = \gamma^{\hat{a}} |\beta_R| c_{5*} \quad c_6^{UB} = \gamma^{UB} |\beta_R| c_{5*}$$



$$m_L = 5 \text{ TeV}, \quad m_B = 100 \text{ MeV}, \quad N_{\text{DC}} = 3$$



$$\Gamma_{f\bar{f}}^{\pi^{\hat{a}}} = N_c^f \frac{G_\mu m_f^2 \tilde{m}_\pi^{\hat{a}}}{4\sqrt{2} \pi} \beta_f [(\xi^{\hat{a}})^2 + (s^{\hat{a}})^2 \beta_f^2],$$

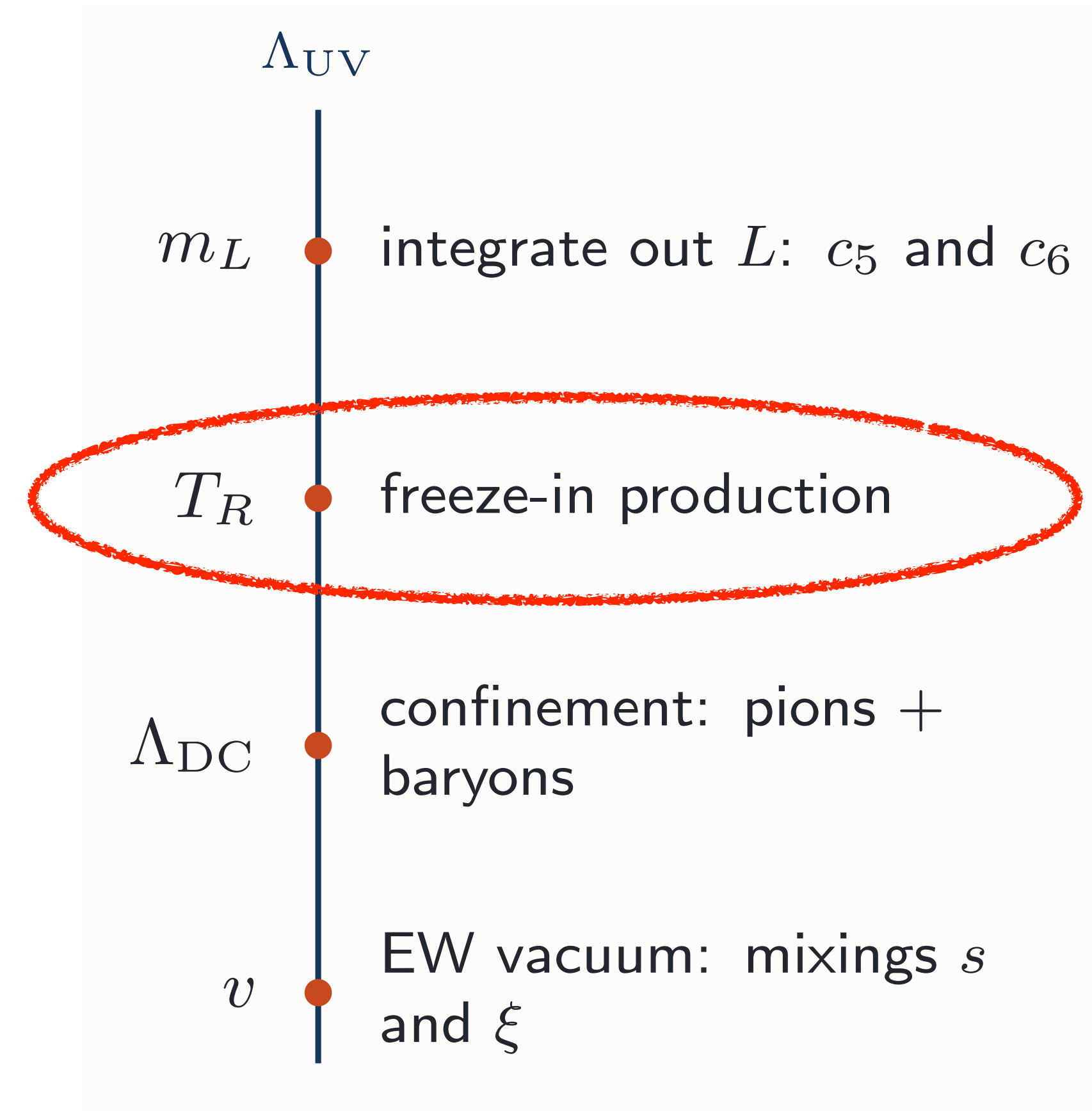
$$\Gamma_{\gamma\gamma}^{\pi^{\hat{a}}} = \frac{G_\mu \alpha^2 (\tilde{m}_\pi^{\hat{a}})^3}{128\sqrt{2} \pi^3} \left\{ (s^{\hat{a}})^2 \left| \sum_f N_c^f Q_f^2 A_{1/2}^H(\tau_f) + A_1(\tau_W) \right|^2 + (\xi^{\hat{a}})^2 \left| \sum_f N_c^f Q_f^2 A_{1/2}^A(\tau_f) \right|^2 \right\}$$

$$s^{\hat{a}} \simeq \beta_I^{\hat{a}} \frac{1}{4\pi\sqrt{N_{\text{DC}}}} \frac{v m_\pi^2 m_B}{x m_L^2 m_h^2} \quad \xi^{\hat{a}} = \gamma^{\hat{a}} |\beta_R| \frac{\sqrt{N_{\text{DC}}}}{4\pi} \frac{m_\pi^2 v}{x m_L^3}$$

Dark pion DM requires

$$m_\pi \lesssim 1 \text{ MeV}$$

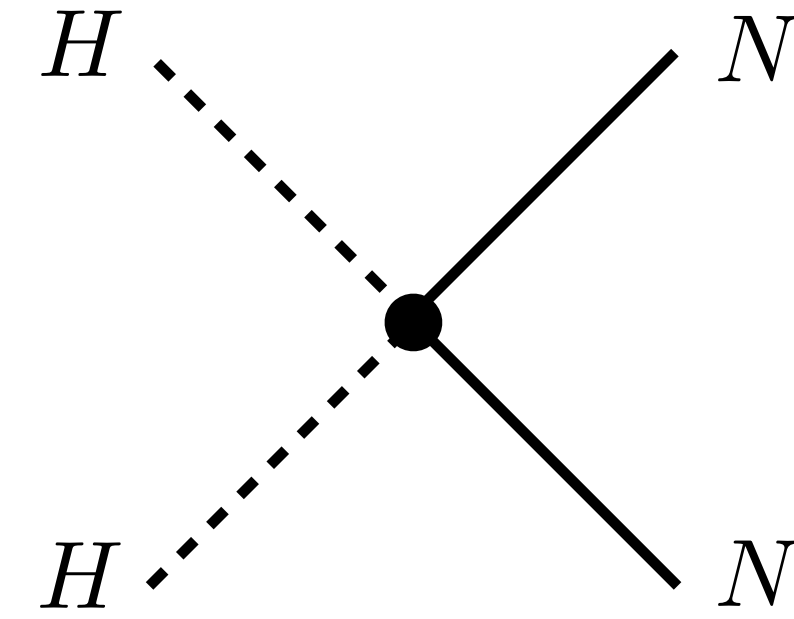
Freeze-In



- **Energy balance equation** ($NN \rightarrow HH$ neglected):

$$\dot{\rho}_{\text{DS}} + 4H\rho_{\text{DS}} = n_H^2 \langle \sigma(HH \rightarrow NN) E \rangle$$

$$\sim \frac{N_{\text{DC}} |c_5|^2}{8\pi m_L^2} T^7 \alpha_T$$

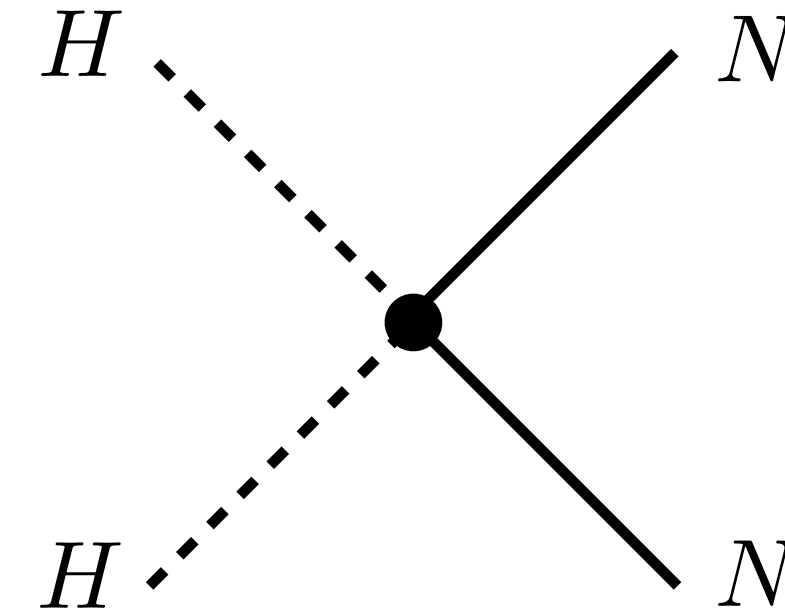


$$\sigma(HH \rightarrow NN) \sim \frac{N_{\text{DC}}}{8\pi m_L^2} \left(|c_5|^2 + \frac{|c_6|^2 E^2}{6m_L^2} \right)$$

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- Integrating $\dot{\rho}_{\text{DS}}$ from T_R to $T' < T_R$, one obtains

$$\rho_{\text{DS}}(T') \sim \frac{N_{\text{DC}}}{1.66[g_*(T_R)]^{3/2}} \frac{|c_5|^2 \alpha_R}{8\pi} \frac{M_{\text{Pl}} T_R}{m_L^2} g_*(T') F(T') T'^4$$

$$F(T') \equiv \left(1 - \left[\frac{g_*(T_R)}{g_*(T')} \right]^{3/2} \frac{T'}{T_R} \right)$$

$$n_H \sim T^3$$

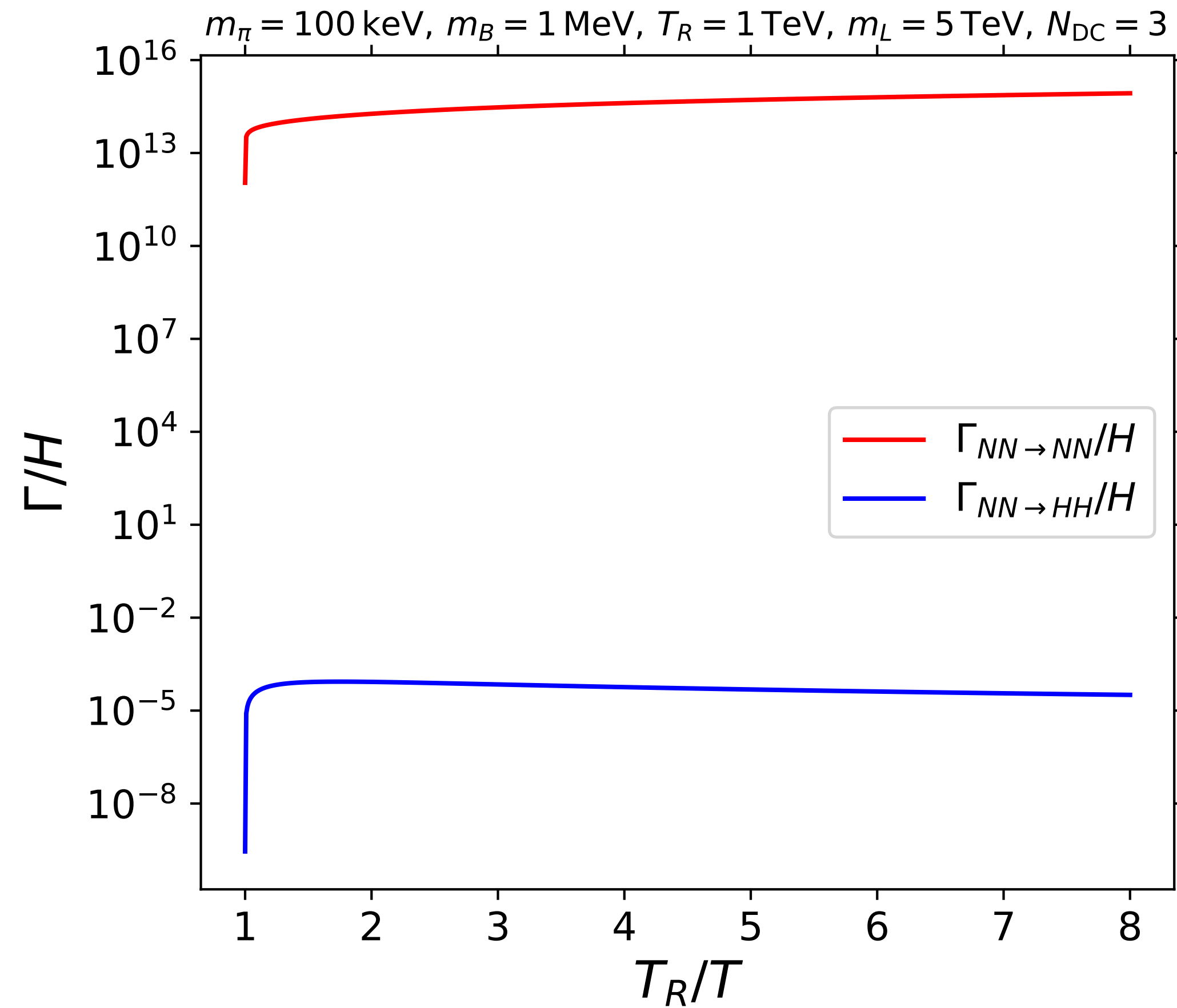
$$\alpha_T \equiv 1 + \frac{35}{6} \gamma^2 \frac{T^2}{m_L^2}$$

$$\alpha_R \equiv 1 + \frac{35}{18} \gamma^2 \frac{T_R^2}{m_L^2}$$

Freeze-In production is **UV dominated**

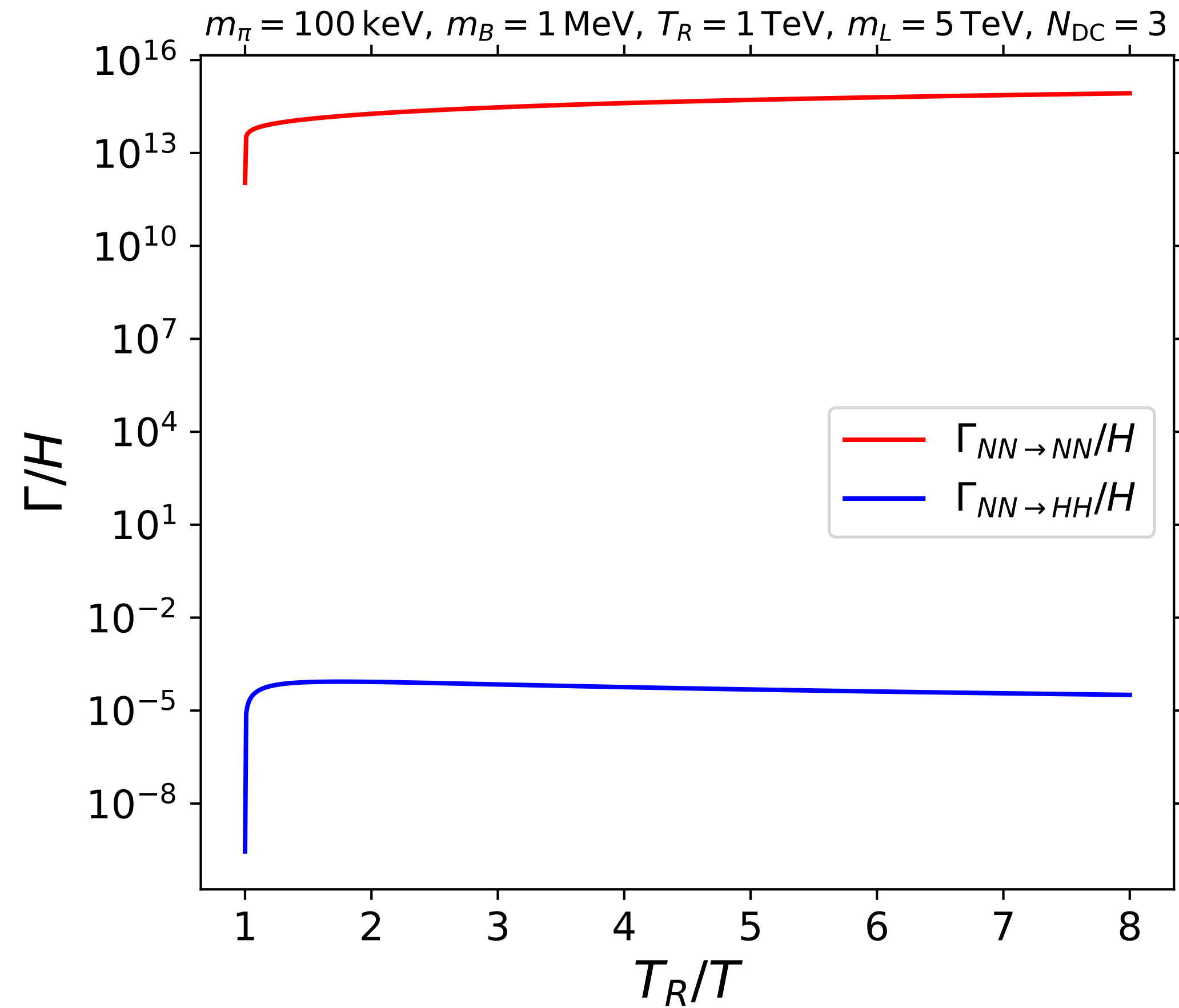
- $\Gamma_{NN \rightarrow NN}/H \gg 1$

$\Rightarrow$ The dark sector has its own temperature T_D



- $\Gamma_{NN \rightarrow HH}/H \ll 1$

$\Rightarrow$ backreaction is negligible



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$$\rho_{\text{DS}} = \frac{\pi^2}{30} g_{*DS} T_D^4$$

$$\Rightarrow T_D(T') \sim R(T') \cdot T'$$

$$R(T') \sim \left[\frac{30 N_{\text{DC}}}{1.66 \pi^2 [g_*(T_R)]^{3/2}} \frac{|c_5|^2 \alpha_R}{8\pi} \frac{M_{\text{Pl}} T_R}{m_L^2} \frac{g_*(T')}{g_{*DS}} F(T') \right]^{\frac{1}{4}}$$

$$\sim \left[\frac{30 N_{\text{DC}}}{1.66 \pi^2 [g_*(T_R)]^{3/2}} \frac{|c_5|^2 \alpha_R}{8\pi} \frac{M_{\text{Pl}} T_R}{m_L^2} \right]^{\frac{1}{4}} \equiv \tilde{R}$$

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Dark Pion DM

- Dark sector energy density by Freeze-In:

$$\rho_{\text{DS}}(T) \sim \frac{N_{\text{DC}}}{1.66[g_*(T_R)]^{3/2}} \frac{|c_5|^2 \alpha_R}{8\pi} \frac{M_{\text{Pl}} T_R}{m_L^2} g_*(T) T^4$$

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- Below T_π , the dark pions are non-relativistic and dilute as $\sim T^3$

$$\rho_\pi(T_0) \sim \rho_{\text{DS}}(T_\pi) \frac{g_*(T_0)T_0^3}{g_*(T_\pi)T_\pi^3}$$

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$$\rho_\pi(T_0) \sim \rho_{\text{DS}}(T_\pi) \frac{g_*(T_0) T_0^3}{g_*(T_\pi) T_\pi^3}$$

- The present-day relic abundance is estimated as

$$\begin{aligned} \Omega_\pi h^2 &= \frac{\rho_\pi(T_0)}{\rho_c} h^2 \sim 0.1 \cdot \left(\frac{\alpha_R}{1} \right)^{\frac{3}{4}} \left(\frac{N_{\text{DC}}}{3} \right)^{\frac{3}{4}} \left(\frac{m_\pi}{100 \text{ keV}} \right) \left(\frac{c_5}{5 \cdot 10^{-8}} \right)^{\frac{3}{2}} \left(\frac{T_R}{1 \text{ TeV}} \right)^{\frac{3}{4}} \left(\frac{5 \text{ TeV}}{m_L} \right)^{\frac{3}{2}} \\ &\sim 0.1 \cdot \left(\frac{\alpha_R}{1} \right)^{\frac{3}{4}} \left(\frac{\beta_R}{1} \right)^{\frac{3}{2}} \left(\frac{N_{\text{DC}}}{3} \right)^{\frac{9}{4}} \left(\frac{m_\pi}{100 \text{ keV}} \right)^4 \left(\frac{1 \text{ MeV}}{m_B} \right)^{\frac{3}{2}} \left(\frac{T_R}{1 \text{ TeV}} \right)^{\frac{3}{4}} \left(\frac{5 \text{ TeV}}{m_L} \right)^3 \end{aligned}$$

- Dark sector energy density by Freeze-In:

$$\tilde{R} \equiv \left[\frac{30 N_{\text{DC}}}{1.66 \pi^2 [g_*(T_R)]^{3/2}} \frac{|c_5|^2 \alpha_R}{8\pi} \frac{M_{\text{Pl}} T_R}{m_L^2} \right]^{\frac{1}{4}}$$

$$\rho_{\text{DS}}(T) \sim \frac{N_{\text{DC}}}{1.66 [g_*(T_R)]^{3/2}} \frac{|c_5|^2 \alpha_R}{8\pi} \frac{M_{\text{Pl}} T_R}{m_L^2} g_*(T) T^4$$

- It dilutes as $\sim T^4$, until $T_D(T_\pi) \sim m_\pi \Rightarrow T_\pi \sim \tilde{R}^{-1} m_\pi$

- Below T_π , the dark pions are non-relativistic and dilute as $\sim T^3$

dark baryons annihilate away

$$\rho_\pi(T_0) \sim \rho_{\text{DS}}(T_\pi) \frac{g_*(T_0) T_0^3}{g_*(T_\pi) T_\pi^3}$$

$$\Omega_{\mathcal{B}} h^2 \lesssim 10^{-20}$$

- The present-day relic abundance is estimated as

$$\begin{aligned} \Omega_\pi h^2 &= \frac{\rho_\pi(T_0)}{\rho_c} h^2 \sim 0.1 \cdot \left(\frac{\alpha_R}{1} \right)^{\frac{3}{4}} \left(\frac{N_{\text{DC}}}{3} \right)^{\frac{3}{4}} \left(\frac{m_\pi}{100 \text{ keV}} \right) \left(\frac{c_5}{5 \cdot 10^{-8}} \right)^{\frac{3}{2}} \left(\frac{T_R}{1 \text{ TeV}} \right)^{\frac{3}{4}} \left(\frac{5 \text{ TeV}}{m_L} \right)^{\frac{3}{2}} \\ &\sim 0.1 \cdot \left(\frac{\alpha_R}{1} \right)^{\frac{3}{4}} \left(\frac{\beta_R}{1} \right)^{\frac{3}{2}} \left(\frac{N_{\text{DC}}}{3} \right)^{\frac{9}{4}} \left(\frac{m_\pi}{100 \text{ keV}} \right)^4 \left(\frac{1 \text{ MeV}}{m_B} \right)^{\frac{3}{2}} \left(\frac{T_R}{1 \text{ TeV}} \right)^{\frac{3}{4}} \left(\frac{5 \text{ TeV}}{m_L} \right)^3 \end{aligned}$$

- The self-scattering cross-section of the dark pions is

$$\mathcal{M}(\pi\pi \rightarrow \pi\pi) \sim m_\pi^2 / f_\pi^2$$

$$\frac{\sigma_{\pi\pi}}{m_\pi} \sim \frac{m_\pi}{128\pi f_\pi^4} \sim 10^7 \text{ cm}^2/\text{g} \left(\frac{m_\pi}{100 \text{ keV}} \right) \left(\frac{N_{\text{DC}}}{3} \right)^2 \left(\frac{\text{MeV}}{m_B} \right)^4$$

- This is 7 orders of magnitude larger than the cluster / halo-shape bound

$$\frac{\sigma_\pi}{m_\pi} \lesssim 1 \text{ cm}^2/\text{g}$$

- Smaller m_π or larger m_B make the abundance too small

$\Rightarrow \Omega_\pi h^2 \sim 0.1$ is **incompatible** with the **self-interaction bound**

Dark Baryon DM

Dark Baryon DM

- The lightest dark baryon is stable thanks to the accidental dark parity.
- The lightest dark baryon mass $m_B \sim N_{\text{DC}} \Lambda_{\text{DC}}$ is independent of the portal coupling c_5 .
- A larger parameter space is available than for dark-pion DM.

strong



$$\Gamma_{NN \rightarrow HH} > H : \text{thermal}$$



Antipin, Redi, Strumia (+Vigiani)
[1410.1817, 1503.08749]

$$m_B \sim 100 \text{ TeV}$$

$$\Gamma_{\mathcal{B}_d \mathcal{B}_d \rightarrow \text{DS}} > H : \text{dark thermal}$$

$$\Gamma_{\mathcal{B}_d \mathcal{B}_d \rightarrow \text{DS}} < H : \text{dark non-thermal}$$

weak



$$\Gamma_{NN \rightarrow HH} \sim \frac{n_N |c_5|^2}{16\pi m_L^2}$$

$$\Gamma_{\mathcal{B}\mathcal{B} \rightarrow \pi s} \sim \frac{n_{\mathcal{B}}}{\Lambda_{\text{DC}}^2}$$

Dark thermal region $\Gamma_{\mathcal{B}_d \mathcal{B}_d \rightarrow \text{DS}} > H$

Dark density: $\rho_{\text{DS}}(T) \sim \frac{N_{\text{DC}}}{1.66[g_*(T_R)]^{3/2}} \frac{|c_5|^2 \alpha_R}{8\pi} \frac{M_{\text{Pl}} T_R}{m_L^2} g_*(T) T^4$

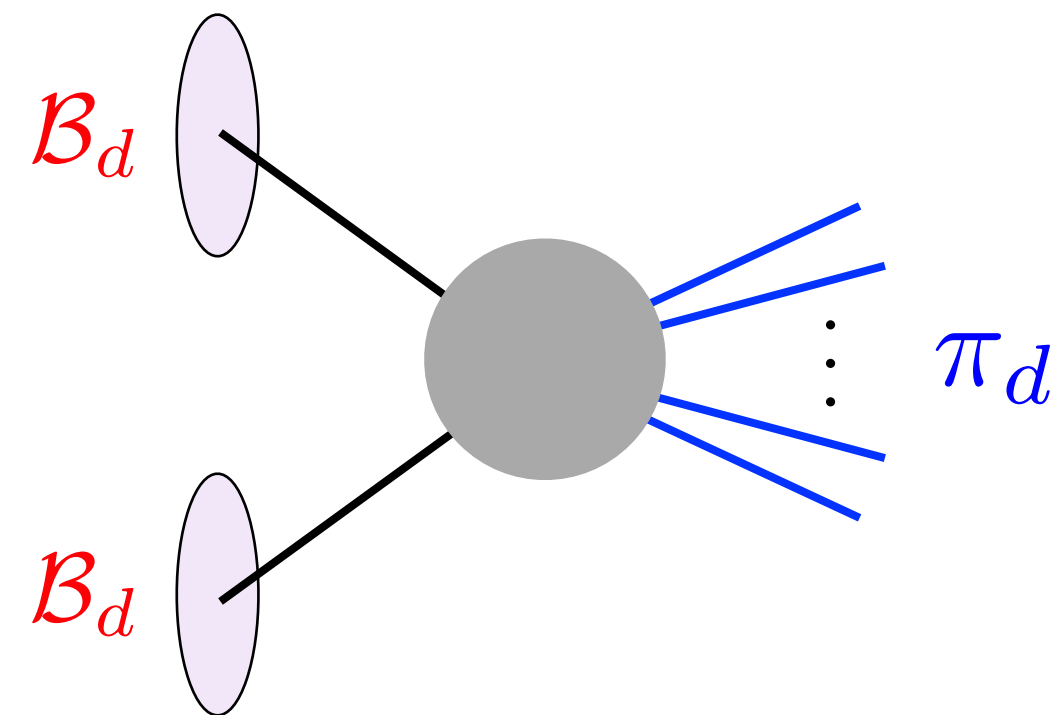
Dark temperature: $T_D \sim \tilde{R} T$ $\tilde{R} \equiv \left[\frac{30 N_{\text{DC}}}{1.66 \pi^2 [g_*(T_R)]^{3/2}} \frac{|c_5|^2 \alpha_R}{8\pi} \frac{M_{\text{Pl}} T_R}{m_L^2} \right]^{\frac{1}{4}}$

Dark thermal region $\Gamma_{\mathcal{B}_d \mathcal{B}_d \rightarrow \text{DS}} > H$

Dark density: $\rho_{\text{DS}}(T) \sim \frac{N_{\text{DC}}}{1.66[g_*(T_R)]^{3/2}} \frac{|c_5|^2 \alpha_R}{8\pi} \frac{M_{\text{Pl}} T_R}{m_L^2} g_*(T) T^4$

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● Around $x_{Df} = \frac{m_B}{T_D} \sim 20$, the **dark baryon freeze-out**:



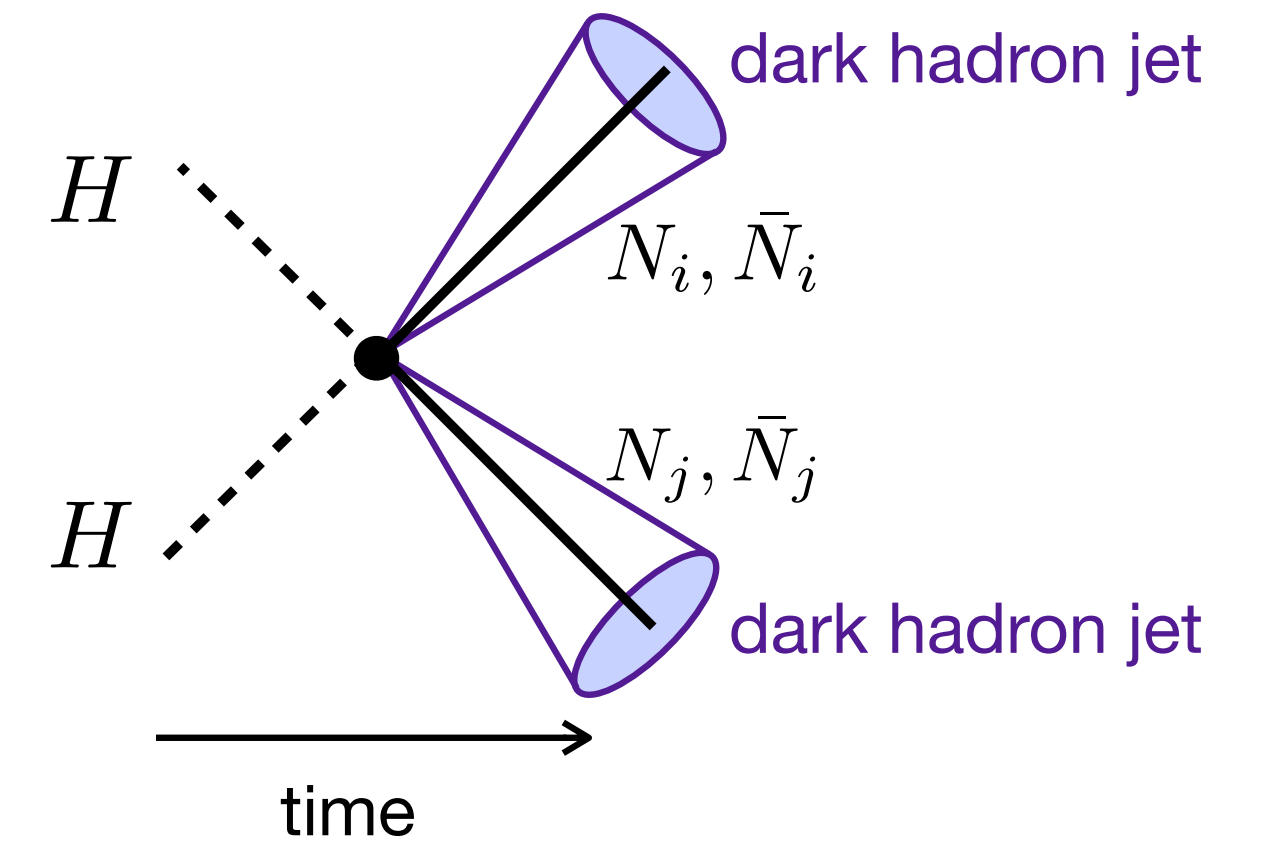
$$\Gamma_{\mathcal{B}\mathcal{B} \rightarrow \pi_s} \sim \frac{n_{\mathcal{B}}}{\Lambda_{\text{DC}}^2}$$

Dark non-thermal region

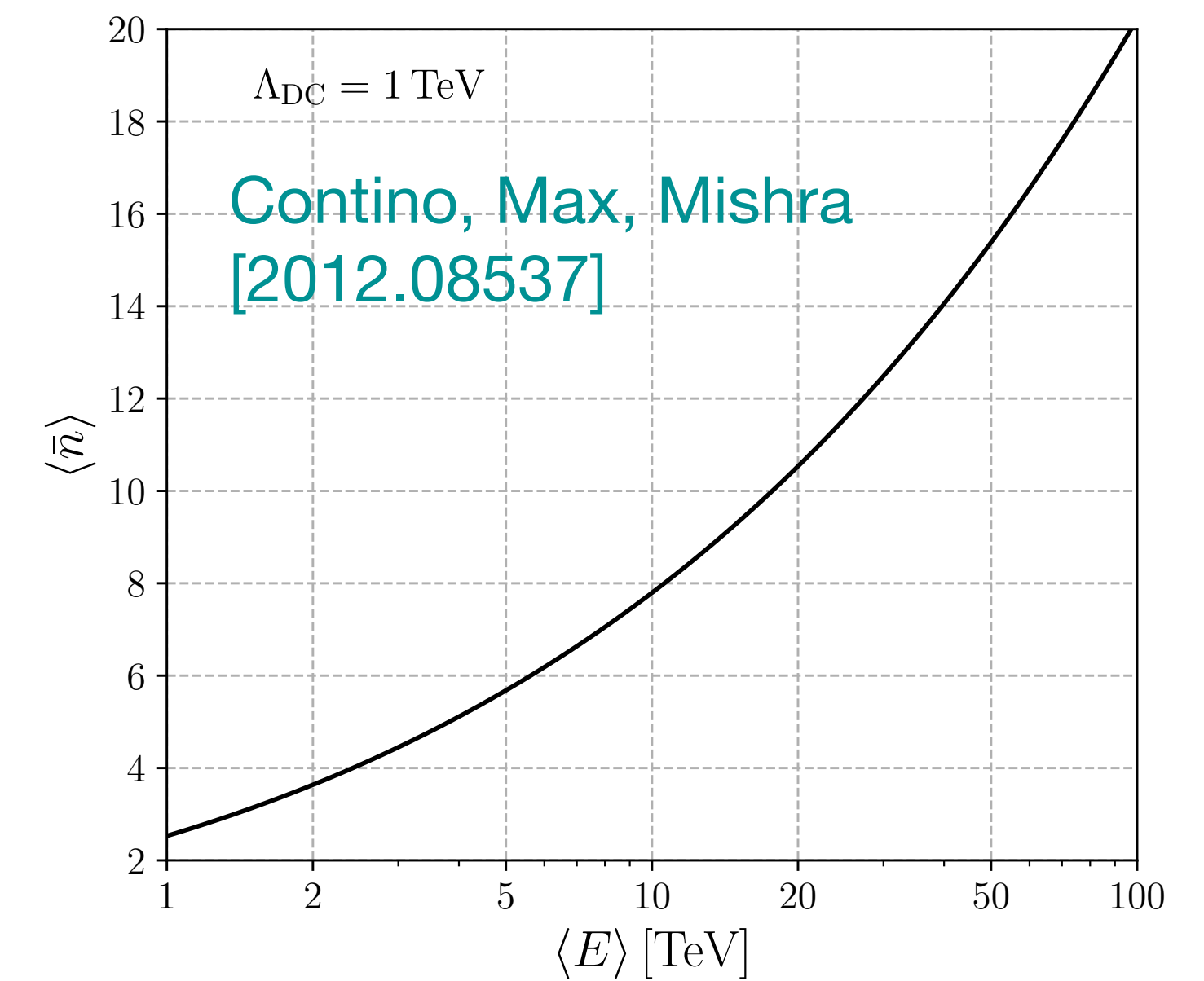
$$\Gamma_{\mathcal{B}_d \mathcal{B}_d \rightarrow \text{DS}} < H$$

- Boltzmann equation:

$$\begin{aligned} \dot{n} + 3Hn &\simeq \int d\Pi \langle \bar{n} \rangle |\mathcal{M}_{HH \rightarrow NN}|^2 f_H^2 \\ &\sim \frac{\langle \bar{n} \rangle_{T_R} N_{\text{DC}}}{16\pi^5 m_L^2} \left(|c_5|^2 + 24|c_6|^2 \frac{T^2}{m_L^2} \right) T^6 \end{aligned}$$



$\langle \bar{n} \rangle$: average # of dark hadrons per event



Dark non-thermal region $\Gamma_{\mathcal{B}_d \mathcal{B}_d \rightarrow \text{DS}} < H$

- Boltzmann equation:

$$\dot{n} + 3Hn \simeq \int d\Pi \langle \bar{n} \rangle |\mathcal{M}_{HH \rightarrow NN}|^2 f_H^2$$

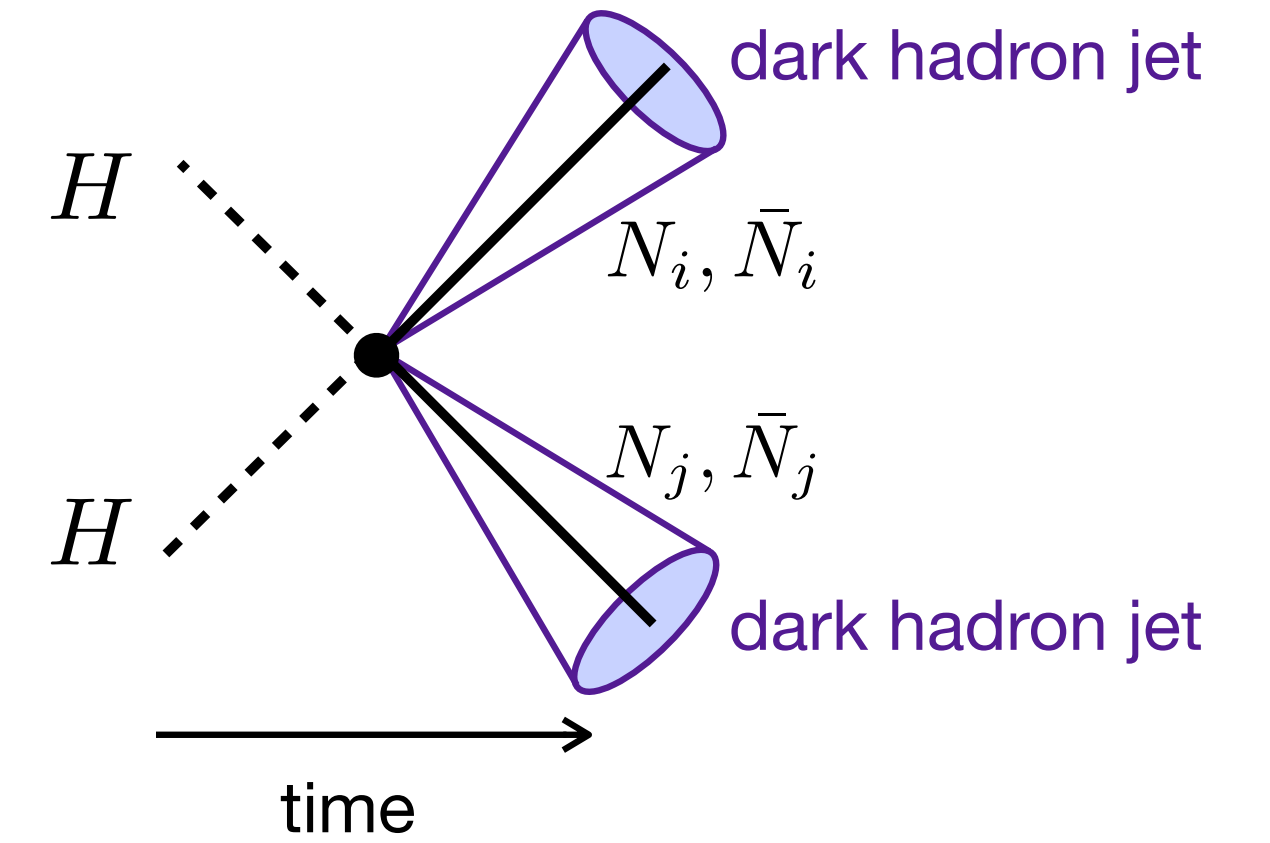
$$\sim \frac{\langle \bar{n} \rangle_{T_R} N_{\text{DC}}}{16\pi^5 m_L^2} \left(|c_5|^2 + 24|c_6|^2 \frac{T^2}{m_L^2} \right) T^6$$

- Integrating from T_R to 0 yields

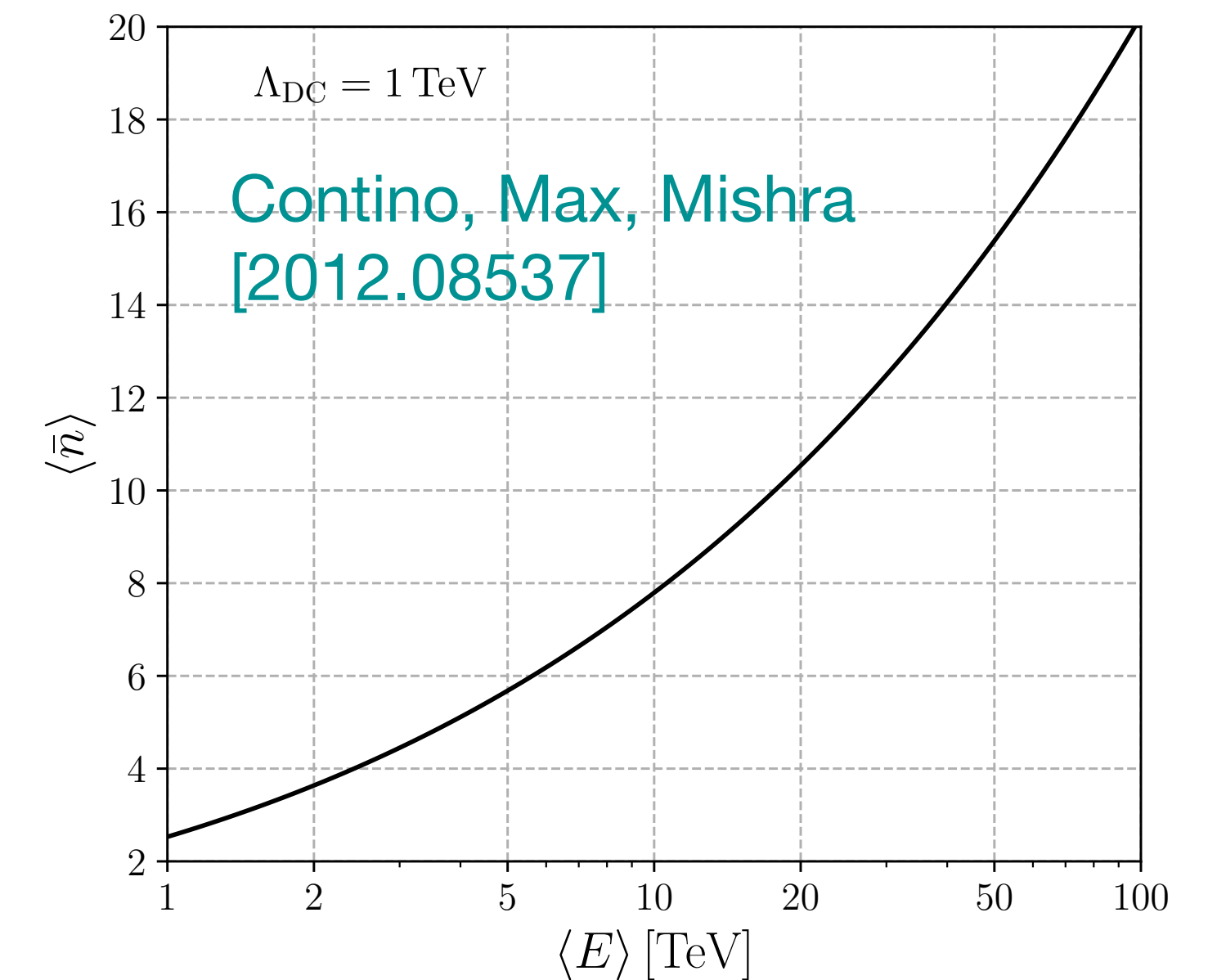
$$Y_{\mathcal{B}} = \frac{n}{S} \sim \frac{r_{\mathcal{B}} \cdot 180 N_{\text{DC}}^3 \alpha \beta_R^2}{1.66 \cdot (2\pi)^7 g_{*S} \sqrt{g_*} \cdot x^2} \frac{T_R M_{\text{Pl}} m_{\pi}^4}{m_B^2 m_L^4} \langle \bar{n} \rangle_{T_R}$$

$r_{\mathcal{B}} \sim 0.3$: fraction of dark baryons in a jet

$$\alpha \equiv 1 + \gamma^2 \cdot \frac{8T_R^2}{m_L^2}$$



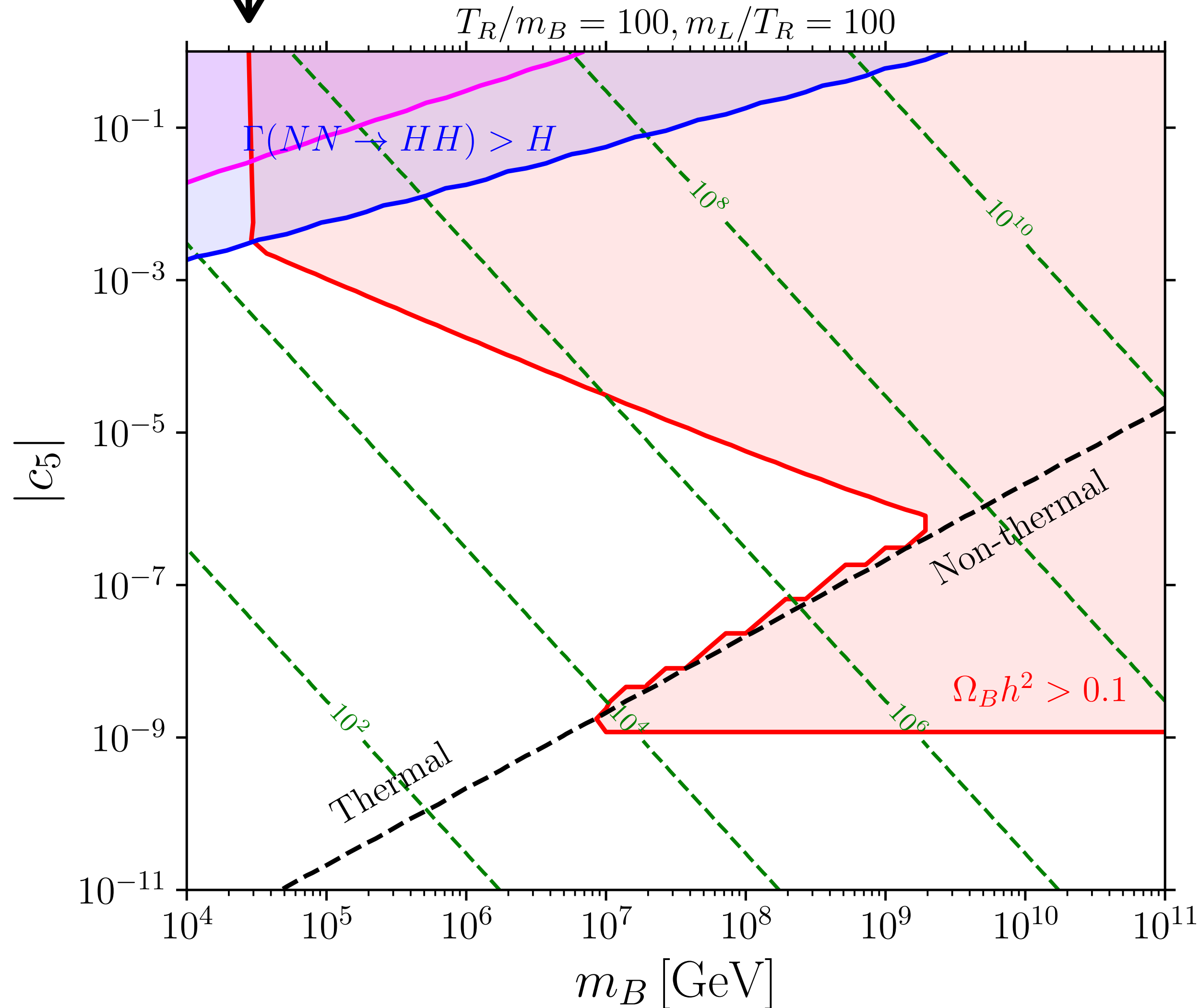
$\langle \bar{n} \rangle$: average # of dark hadrons per event



thermal freeze-out

$$m_B \sim 100 \text{ TeV}$$

Preliminary result



- $\Omega_B h^2 \simeq 0.12$
- $\Omega_B h^2 > 0.12$
- - - m_π
- $\Gamma(NN \rightarrow HH) > H$
- $\Gamma(\pi \rightarrow HH) > H$

Dark thermal:

$$10^5 \text{ GeV} \lesssim m_B \lesssim 10^9 \text{ GeV} \quad 10^{-6} \lesssim |c_5| \lesssim 10^{-3}$$

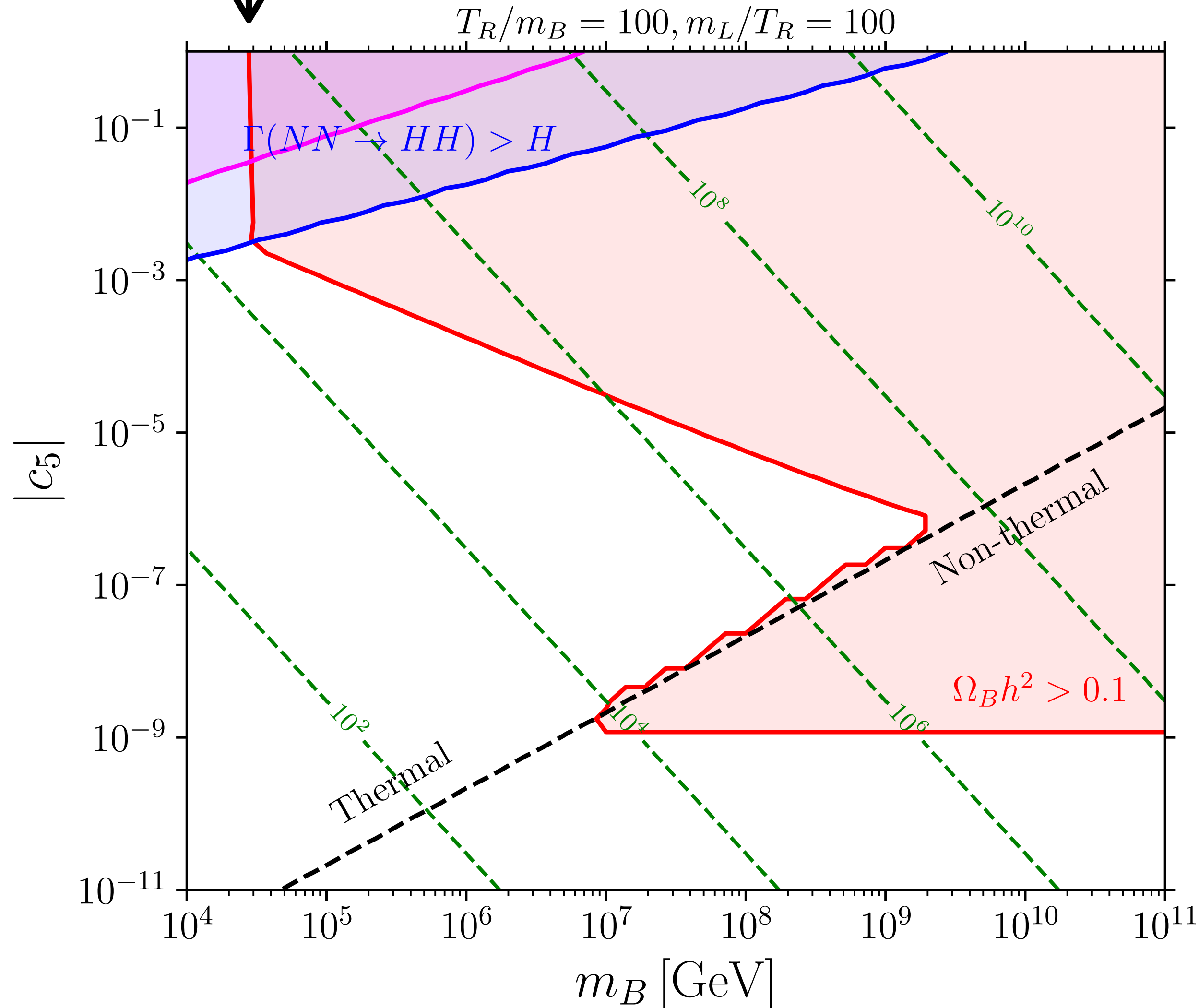
Dark non-thermal:

$$m_B \gtrsim 10^7 \text{ GeV} \quad |c_5| \sim 10^{-9}$$

thermal freeze-out

$$m_B \sim 100 \text{ TeV}$$

Preliminary result



- $\Omega_B h^2 \simeq 0.12$
- $\Omega_B h^2 > 0.12$
- - - m_π
- $\Gamma(NN \rightarrow HH) > H$
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Dark thermal:

$$10^5 \text{ GeV} \lesssim m_B \lesssim 10^9 \text{ GeV} \quad 10^{-6} \lesssim |c_5| \lesssim 10^{-3}$$

Dark non-thermal:

$$m_B \gtrsim 10^7 \text{ GeV} \quad |c_5| \sim 10^{-9}$$

The self-scattering bound is easily satisfied:

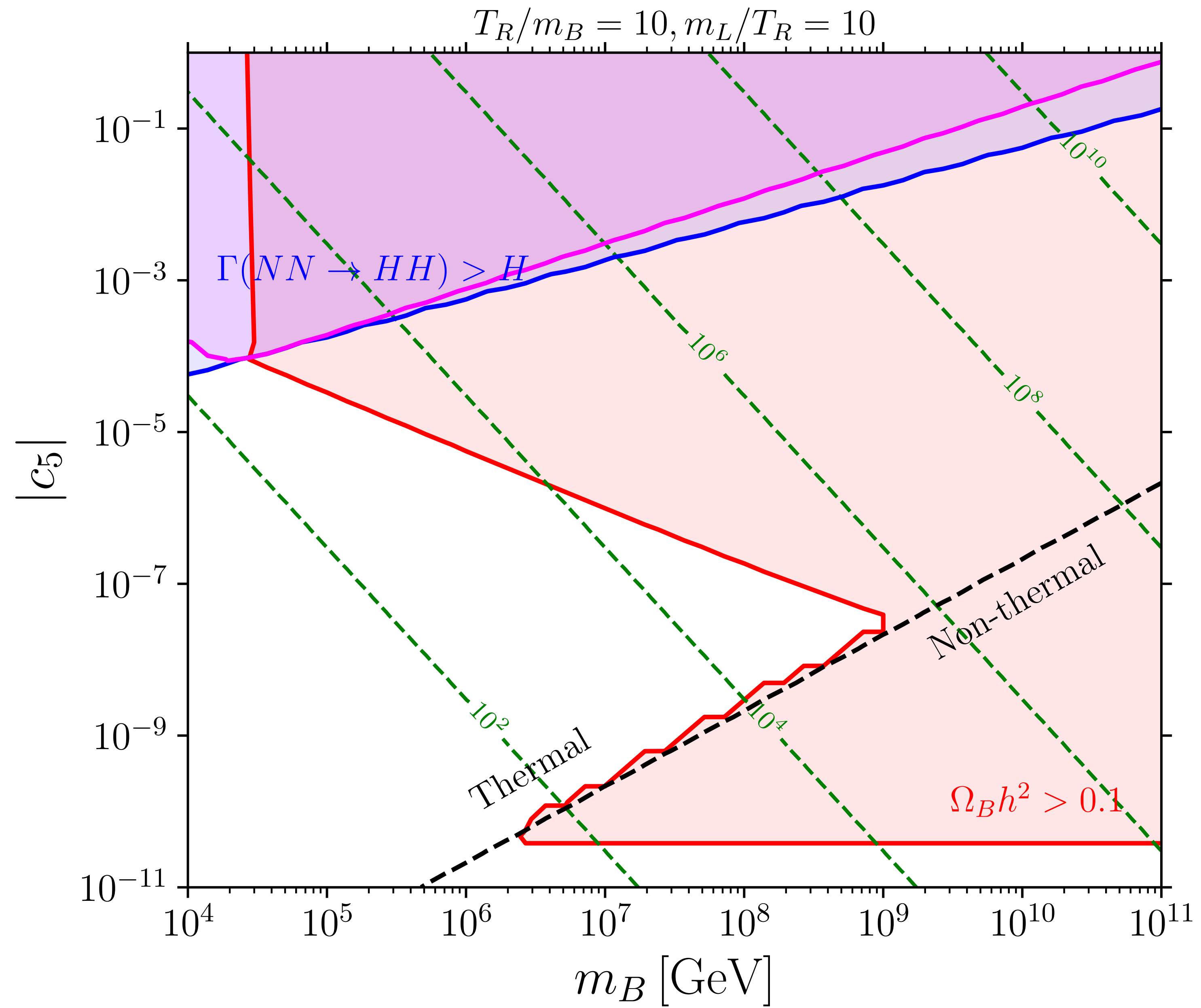
$$\frac{\sigma_{BB}}{m_B} \sim \frac{N_{\text{DC}}^2}{m_B^3} \sim 2 \times 10^{-15} \text{ cm}^2/\text{g} \left(\frac{10 \text{ TeV}}{m_B} \right)^3$$

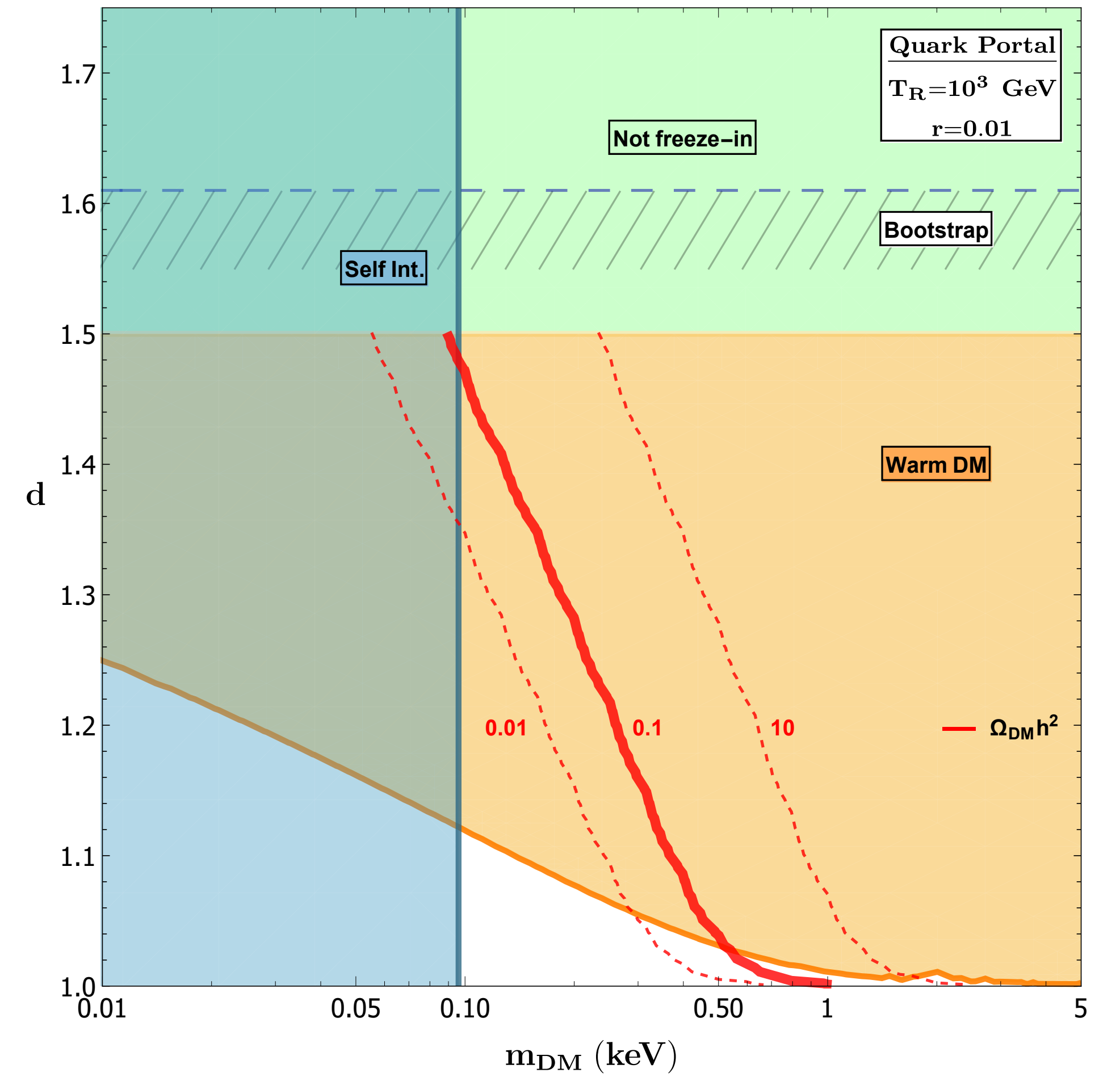
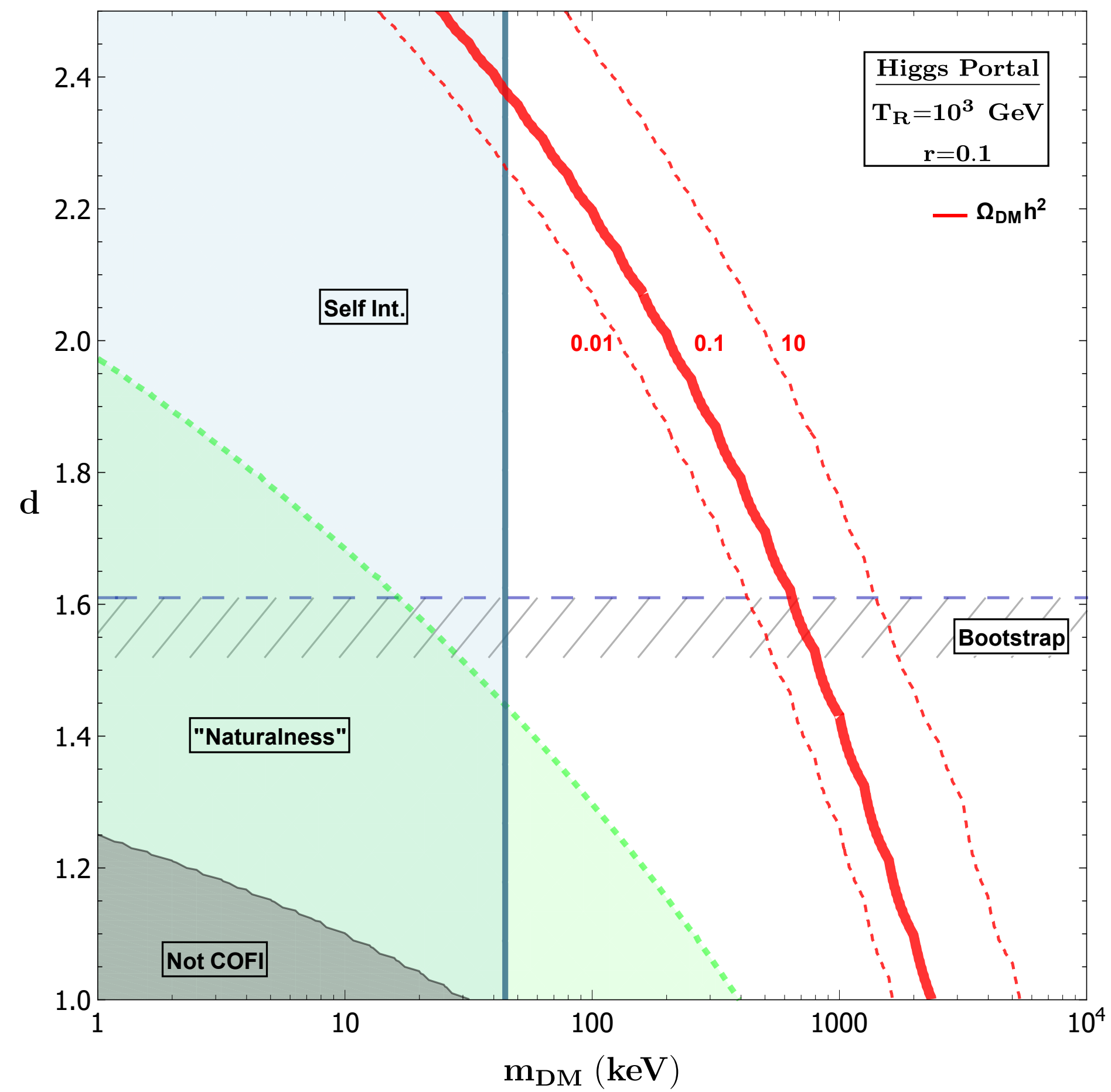
Conclusion

We studied **composite DM** × **freeze-in via the Higgs portal** in the $L \oplus N$ model
— a confining $SO(N_{DC})$ and **no WZW term, no CFT phase**.

	Dark pion π_d	Dark baryon $\mathcal{B}_d$
Production	UV freeze-in of dark quarks at $T \sim T_R$ via the $D = 5, 6$ Higgs portal	
Stability	none (decays via the portal)	accidental $\mathbb{Z}_2^d$
Relic set by	injected energy $\rightarrow$ redshifted pion gas	freeze-in yield / dark freeze-out
Mass for $\Omega h^2 \simeq 0.1$	$m_\pi \sim 100$ keV	$m_B \sim 10^5\text{--}10^9$ GeV and beyond
Indirect detection		$\mathcal{B}\mathcal{B} \rightarrow \pi s, \pi \rightarrow \gamma\gamma$ (CTAO?)
σ/m	$\sim 10^7 \text{ cm}^2/\text{g}$	$\sim 10^{-15} \text{ cm}^2/\text{g}$
Verdict	excluded	viable

Thank you for listening!





Hong, Kurup, Perelstein
[1910.10160] [2207.10093]

The loop functions

$$\begin{aligned} A_{1/2}^H(\tau) &= 2[\tau + (\tau - 1)f(\tau)] \tau^{-2}, \\ A_1^H(\tau) &= -[2\tau^2 + 3\tau + 3(2\tau - 1)f(\tau)] \tau^{-2}, \\ A_{1/2}^A(\tau) &= 2\tau^{-1}f(\tau), \end{aligned}$$

where $A_1 \equiv A_1^H$ is the W -boson contribution, and

$$f(\tau) = \begin{cases} \arcsin^2 \sqrt{\tau}, & \tau \leq 1, \\ -\frac{1}{4} \left[\log \frac{1 + \sqrt{1 - \tau^{-1}}}{1 - \sqrt{1 - \tau^{-1}}} - i\pi \right]^2, & \tau > 1, \end{cases}$$

evaluated at $\tau_i = (\tilde{m}_\pi^{\hat{a}})^2 / (4m_i^2)$ with $i = f, W$.