Dark Matter from Dark Gauge Theories

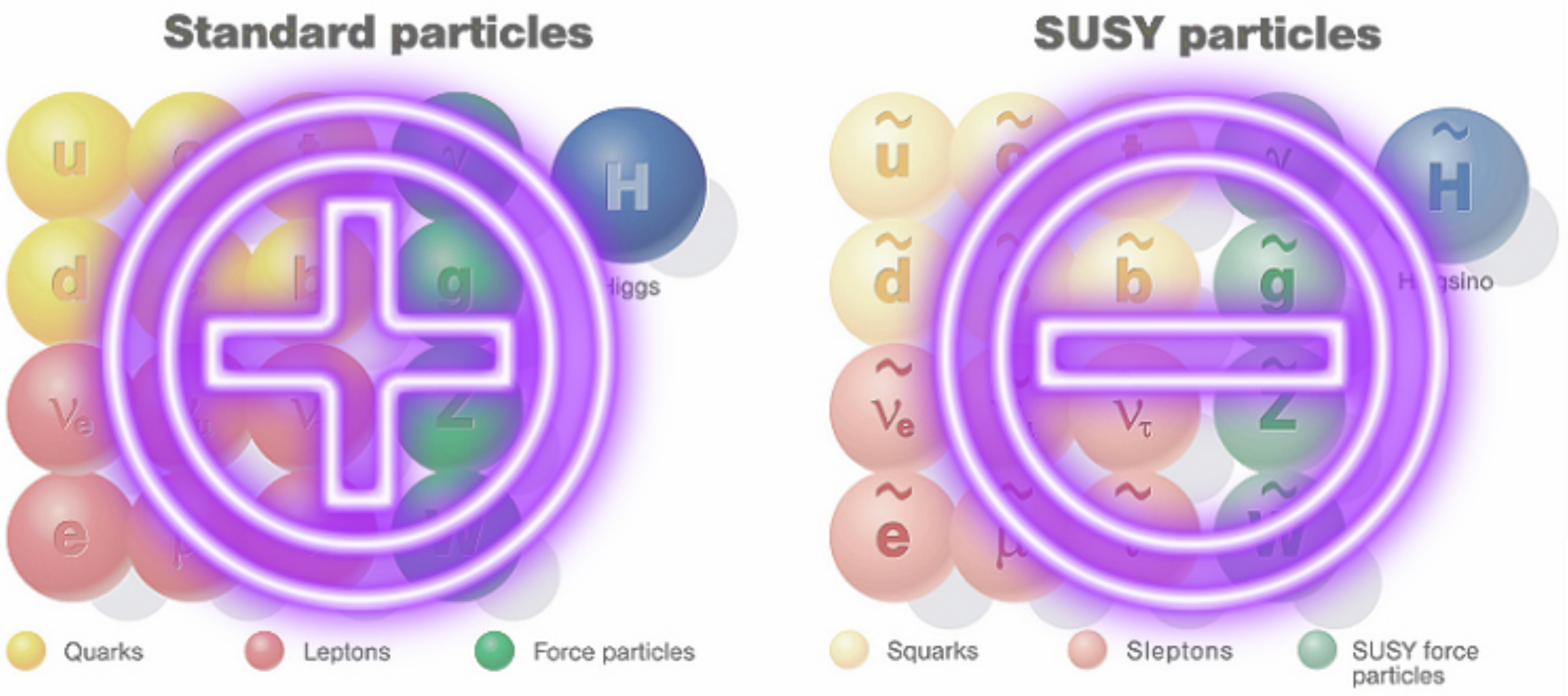
Based on 2011.10565 and 2105.03429

Michele Redi

Portoroz - 22 September 2021

Cosmological stability of DM is often obtained imposing ad hoc global symmetries. In supersymmetry:

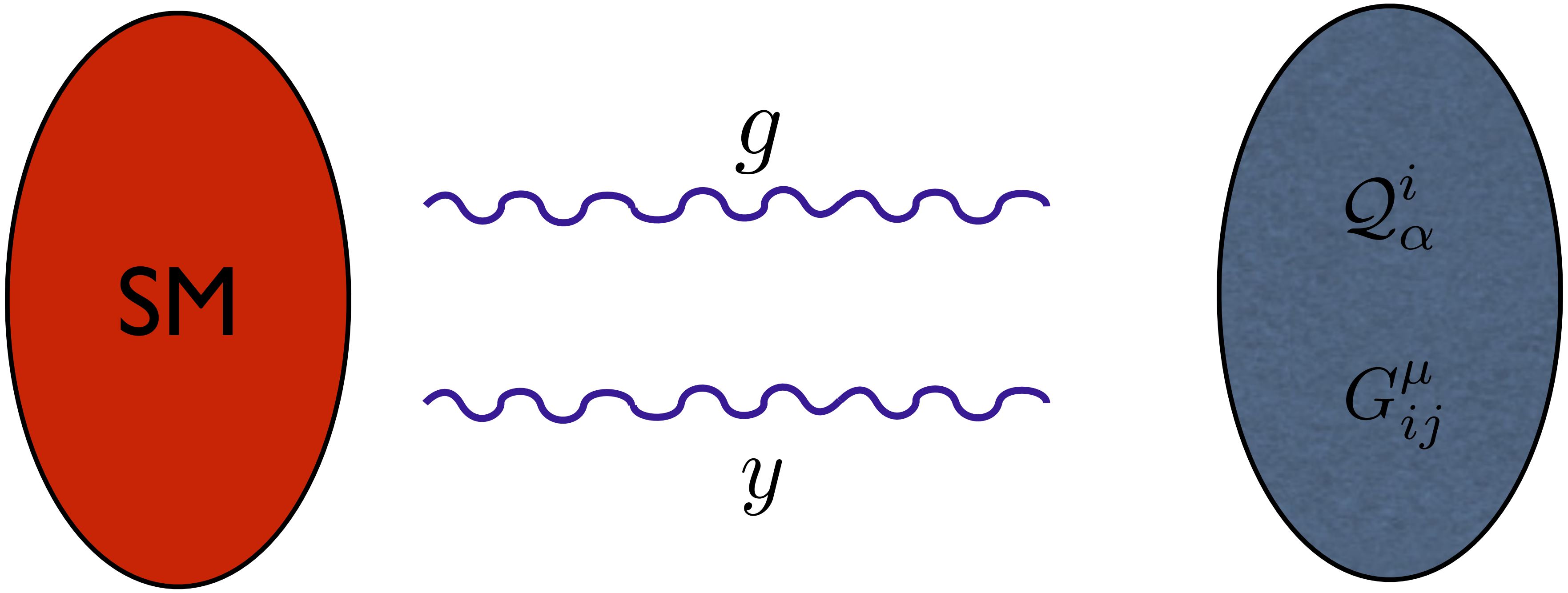
R-parity:



Can DM be accidentally stable as the proton?

New ``dark" gauge forces:
DM is an accidentally stable dark-hadron

Confining gauge theory with fermions



Composite DM with SM charges:

[Antipin, MR, Strumia Vigiani, '15]
[Mitridate, MR, Smirnov, Strumia, '17]

[Contino, Mitridate, Podo, MR, '18]
[Neil, Kribs, '16]

I will focus on dark sectors neutral under the SM:

$$\int d^4x \sqrt{-g}\, [\mathcal{L}_{\rm SM} - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu a} + \bar{\psi}_i \, (D - m_i)\, \psi_i + \sum \frac{O_{\rm SM} O_{\rm dark}}{M_p^{\#}}]$$

Accidental symmetries:

- Dark-Baryon number

$$\mathcal{Q}^i \to e^{i\alpha}\mathcal{Q}^i \qquad \longrightarrow \qquad B = \epsilon^{i_1 i_1 \dots i_n} Q_{i_1}^{\{\alpha_1} Q_{i_2}^{\alpha_2} \dots Q_{i_n}^{\alpha_n\}}$$

- Dark-Species number

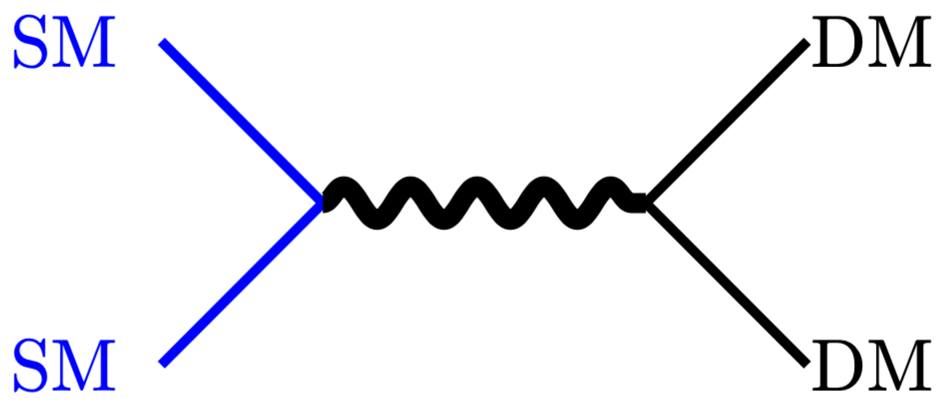
$$\mathcal{Q}^i \to e^{i\alpha_i}\mathcal{Q}^i \qquad \longrightarrow \qquad M = \bar{\mathcal{Q}}^i \mathcal{Q}^j$$

Lightest state of secluded sector is also accidentally stable due to individual energy-momentum conservation.

Production

- Gravity:

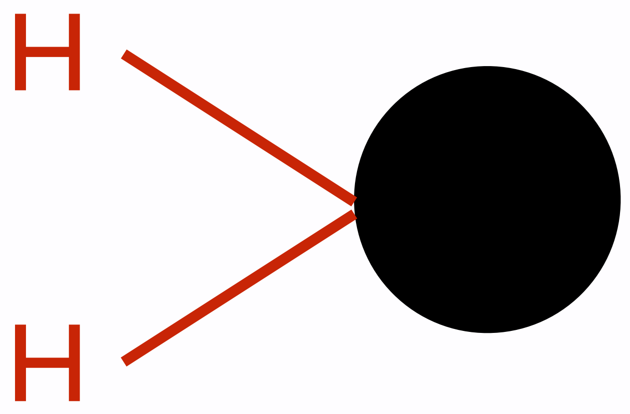
[Garny-Sandora-Sloth '15]



$$\mathcal{A} = \frac{1}{M_p^2 s}\left(T^{\rm SM}_{\mu\nu}T^{\rm DM}_{\alpha\beta}\eta^{\mu\alpha}\eta^{\nu\beta} - \frac{1}{2}T^{\rm SM}T^{\rm DM}\right)$$

$$\rho_D \approx 5\cdot 10^{-4}\, c_D \left(\frac{T_R}{M_p}\right)^3 T^4$$

[Redi, Tesi '21]



$$\rho_D \approx 10^{-4} a_D \left(\frac{T_R}{M_{Pl}}\right)^{2d-5} T^4$$

- Inflationary:

[Kolb et al.]

Particles are produced in a time dependent background.
Requires breaking of Weyl invariance:

$$T_\mu^\mu \neq 0$$

Negligible for gauge theories with fermions.

- Inflaton decay

$$\rho_D = \frac{g_D}{g_{SM}} \rho_{SM}$$

- Renormalizable int.

$$T_D = T$$

Glueball DM

A very minimal scenario for DM is a decoupled ``pure glue" gauge theory. Simplest example $\mathrm{SU}(3)$:

$$\frac{M_{\mathrm{DG}}}{\Lambda} \approx 5.5 \qquad\qquad \frac{L_h}{\Lambda^4} \approx 1.4$$

Lightest glueball is a CP even scalar that decays at least to gravitons:

$$\tau \sim \frac{M_p^4}{M_{\mathrm{DG}}^5} \sim 10^{19}\,\mathrm{s}\left(\frac{10^6\,\mathrm{GeV}}{M_{\mathrm{DG}}}\right)^5$$

This scenario requires $\mathrm{T}_D \ll T$ to avoid structure formation and self-interaction constraints.

Gravitational production automatically produces a cold dark sector.

For $\mathrm{T}_R > \Lambda$ free gluons are produced:

$$c_D = 16 \times 8$$

- Thermalization:

If gluons thermalize the temperature is determined by energy conservation:

$$\xi \equiv \frac{T_D}{T} \approx 0.4 \left(\frac{T_R}{M_p}\right)^{\frac{3}{4}}$$

When T_D drops below Λ glueballs form:

$$\frac{\rho^0_{\mathrm{DG}}}{s_0} \approx \left.\frac{\rho_{th}(T) + L_h}{s(T)}\right|_{T_n} \approx 0.01\Lambda \left(\frac{T_R}{M_p}\right)^{9/4}$$

$$\frac{\Omega_{\rm DG} h^2}{0.12} \approx \frac{M_{\rm DG}}{10\,{\rm GeV}} \left(\frac{T_R}{10^{15}\,{\rm GeV}}\right)^{9/4}$$

Glueballs can again thermalize giving rise to "cannibalism" through 3->2 processes.

- No thermalization:

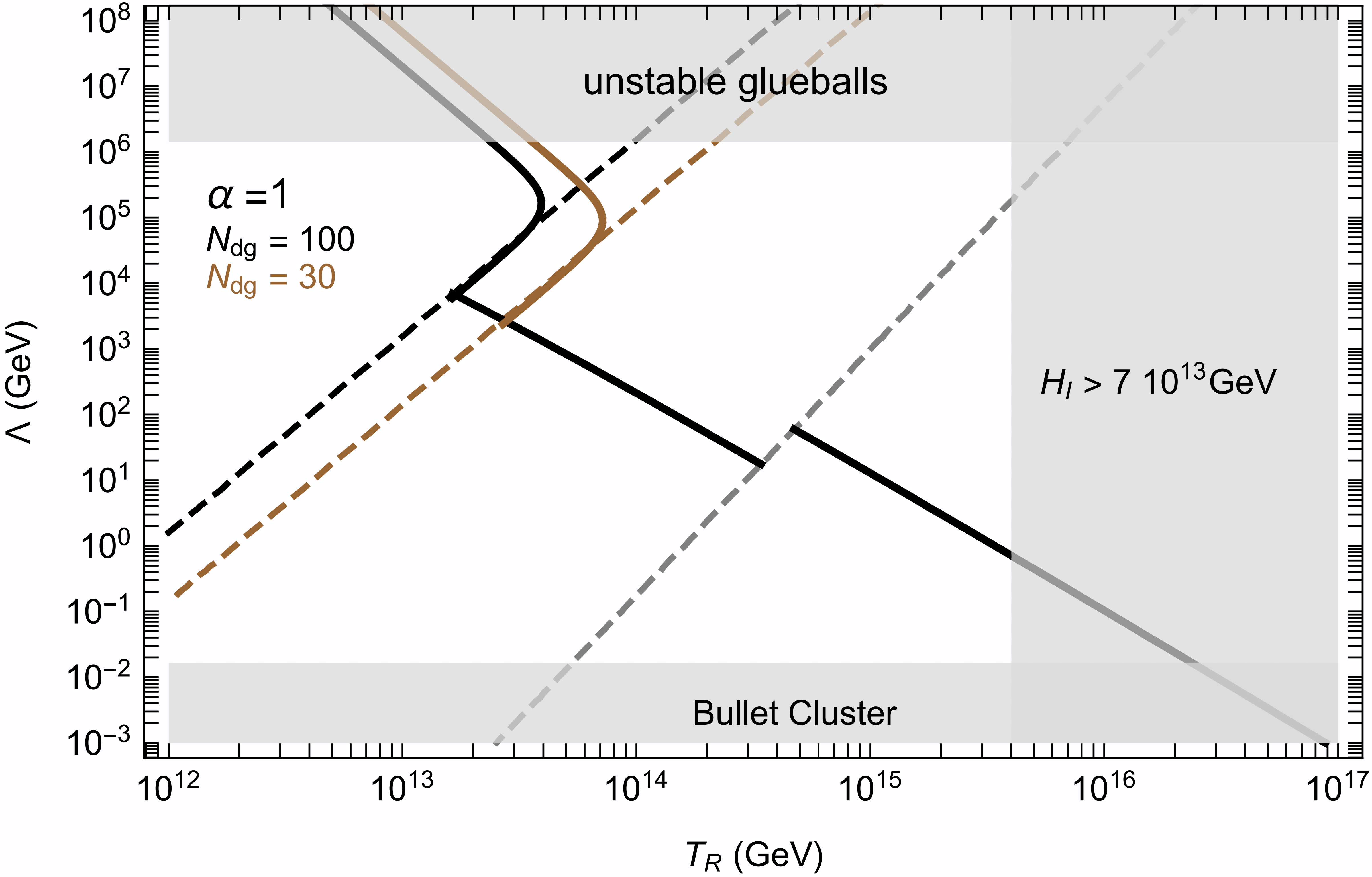
If interactions are weak the system does not thermalize in relativistic regime. Confinement takes place out of equilibrium at the visible temperature:

$$n_D(T_\Lambda) \sim \Lambda^3 \qquad \longrightarrow \qquad T_\Lambda \sim \Lambda \frac{M_p}{T_R}$$

T_Λ is also the gluon energy. This gives rise to a "cosmological collider" where each high energy gluon hadronize. This enhances the DM abundance:

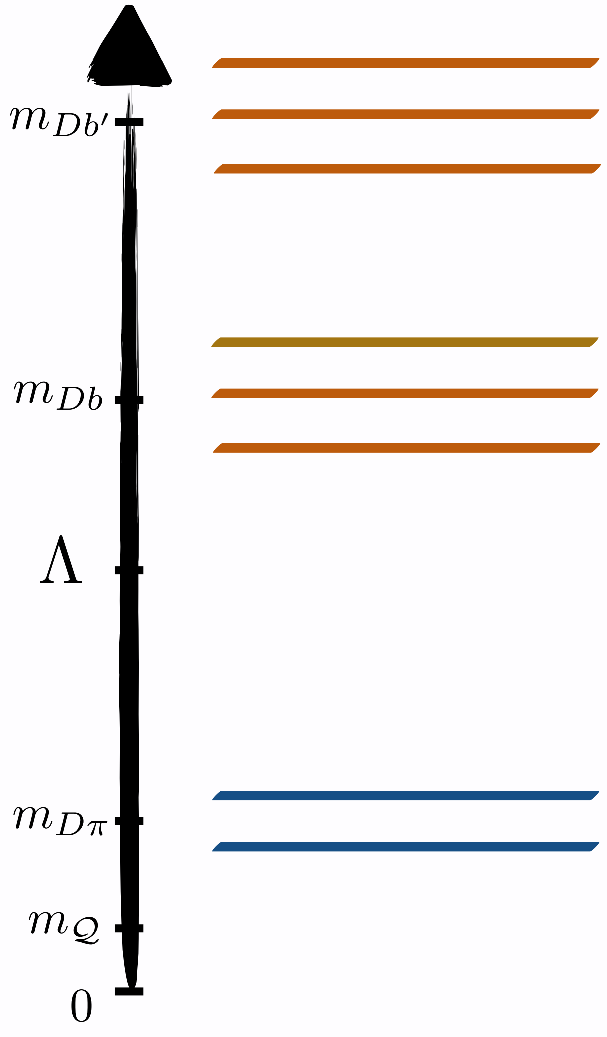
$$Y_{\rm DG}(T_\Lambda) = N_{\rm DG} Y_{\rm D}$$

Glueball Dark Matter



Hadronic DM

In theories with light quarks the spectrum is radically different:

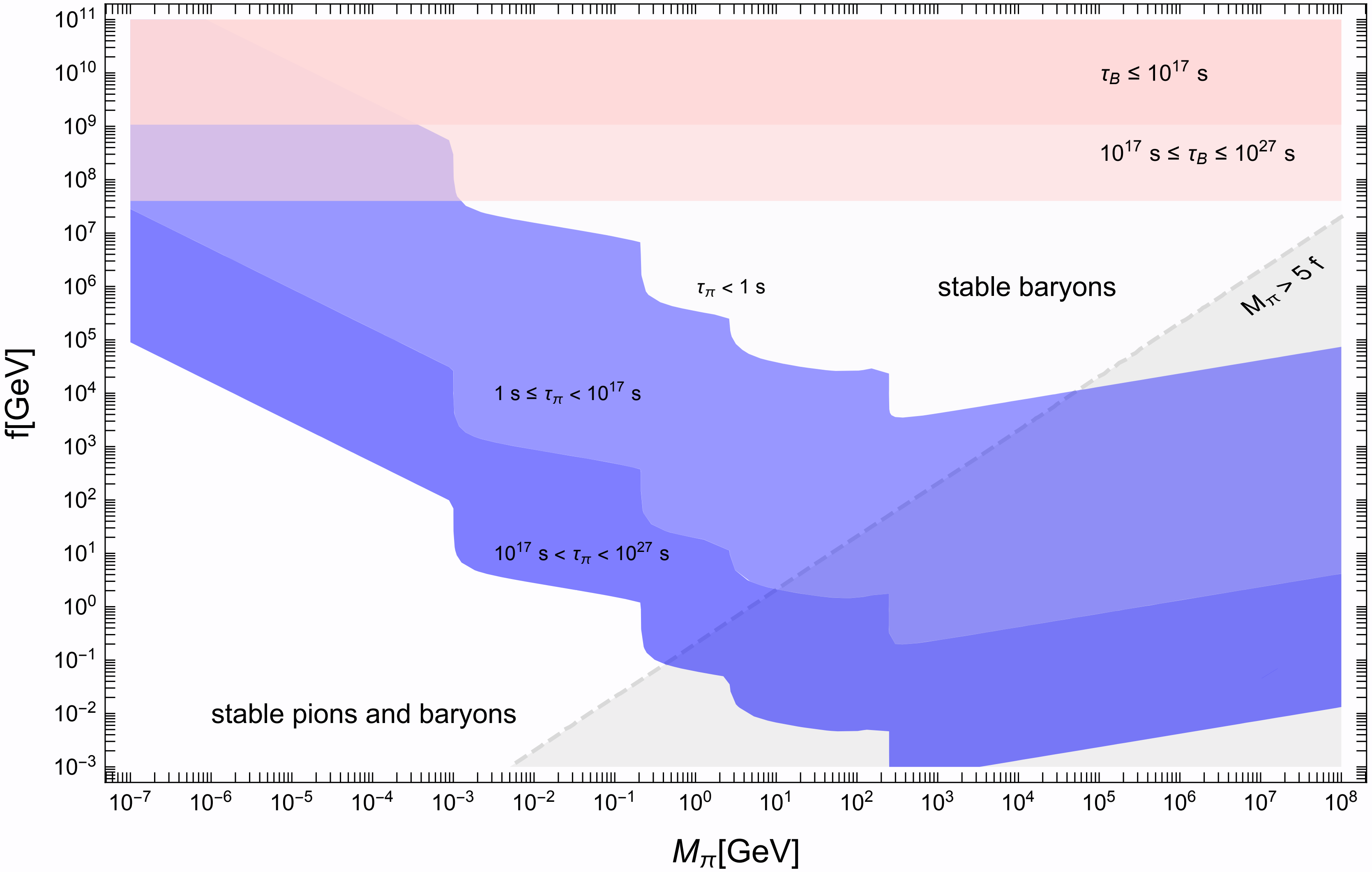


Lightest dark baryon and dark pions are DM candidates.

The leading interaction with SM is through the Higgs portal,

$$\frac{\kappa}{M_p}|H|^2\bar{\Psi}^i\Psi^j$$

This leads to more efficient production and faster decay of pion DM.



Warmer dark sector.

Pions are produced relativistically at the dark confinement phase transition. The dark sector energy density is converted into a thermal bath of pions:

$$\frac{\Omega_\pi h^2}{0.12} \approx N_F^2 \frac{M_\pi}{0.1\mathrm{KeV}} \left(\frac{T_D}{T}\right)^3$$

Pion DM is light.

The baryon abundance is determined by freeze-out:

$$\frac{\Omega_B h^2}{0.12} = \frac{T_D}{T} \left(\frac{M_B}{100\,\mathrm{TeV}}\right)^2$$

The critical mass is further increased pions decay.
Baryon DM is very heavy.

- Phenomenology:

DM self-interactions are constrained by bullet cluster:

$$\sigma_{\rm el}^{\pi} \overset{N_F\to 3}{=} \frac{77}{1536\,\pi}\frac{M_\pi^2}{f^4}\,. \qquad\qquad \frac{\sigma_{\rm el}^{\rm exp}}{M_{\rm DM}} < \frac{\rm g}{\rm cm^2}$$

Pion DM is warm leading to effects for structure formation:

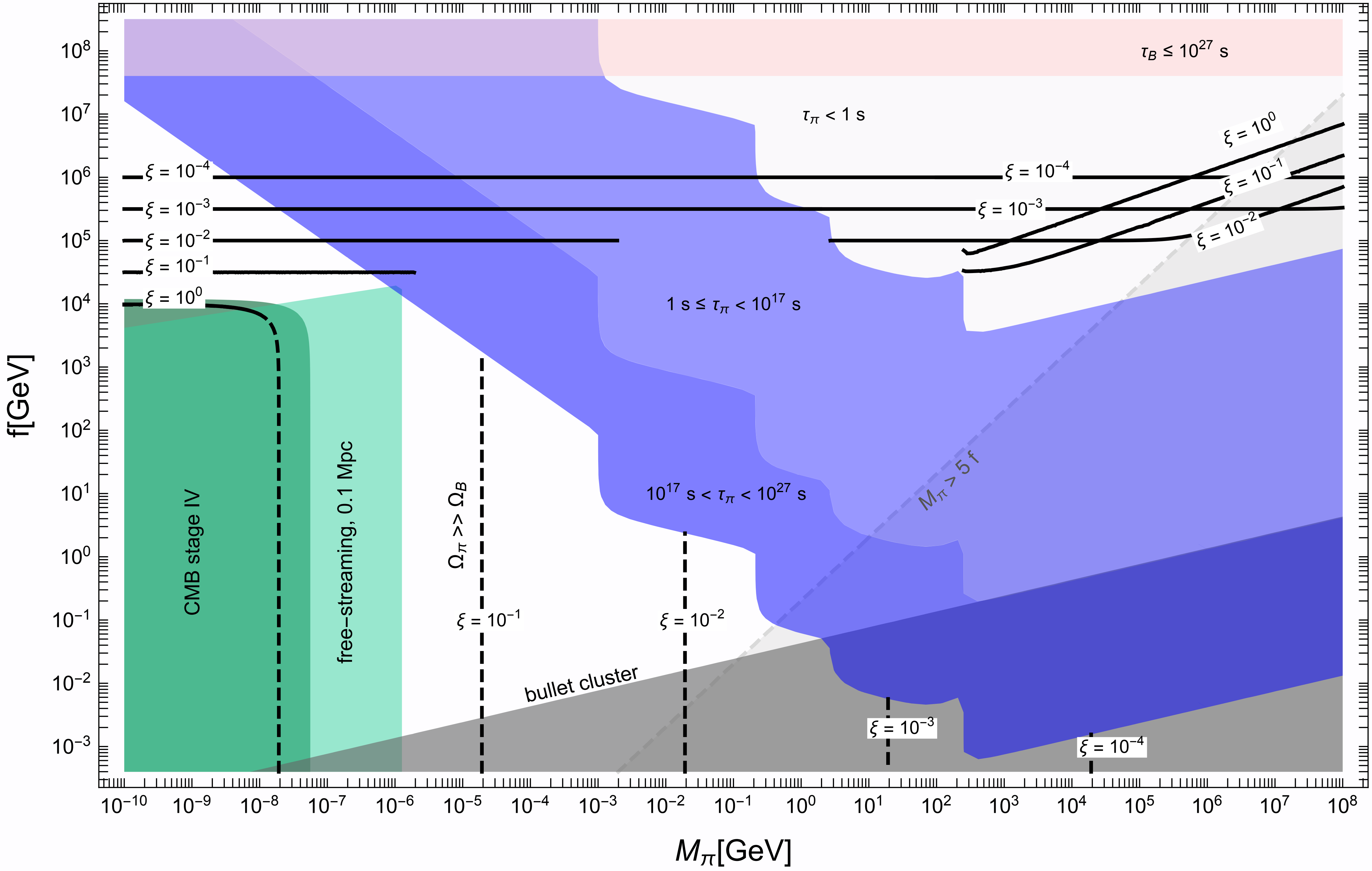
$$\lambda_{\rm FS} \approx 0.1\,{\rm Mpc}\left(\frac{T_D}{T}\right)\frac{\rm KeV}{M_\pi}\left(\frac{106.75}{g_*^s(T_\Lambda)}\right)^{\frac{1}{3}} \qquad\qquad \lambda_{\rm FS}^{\rm exp} \lesssim 0.06\,{\rm Mpc}$$

Massless pions contribute to radiation:

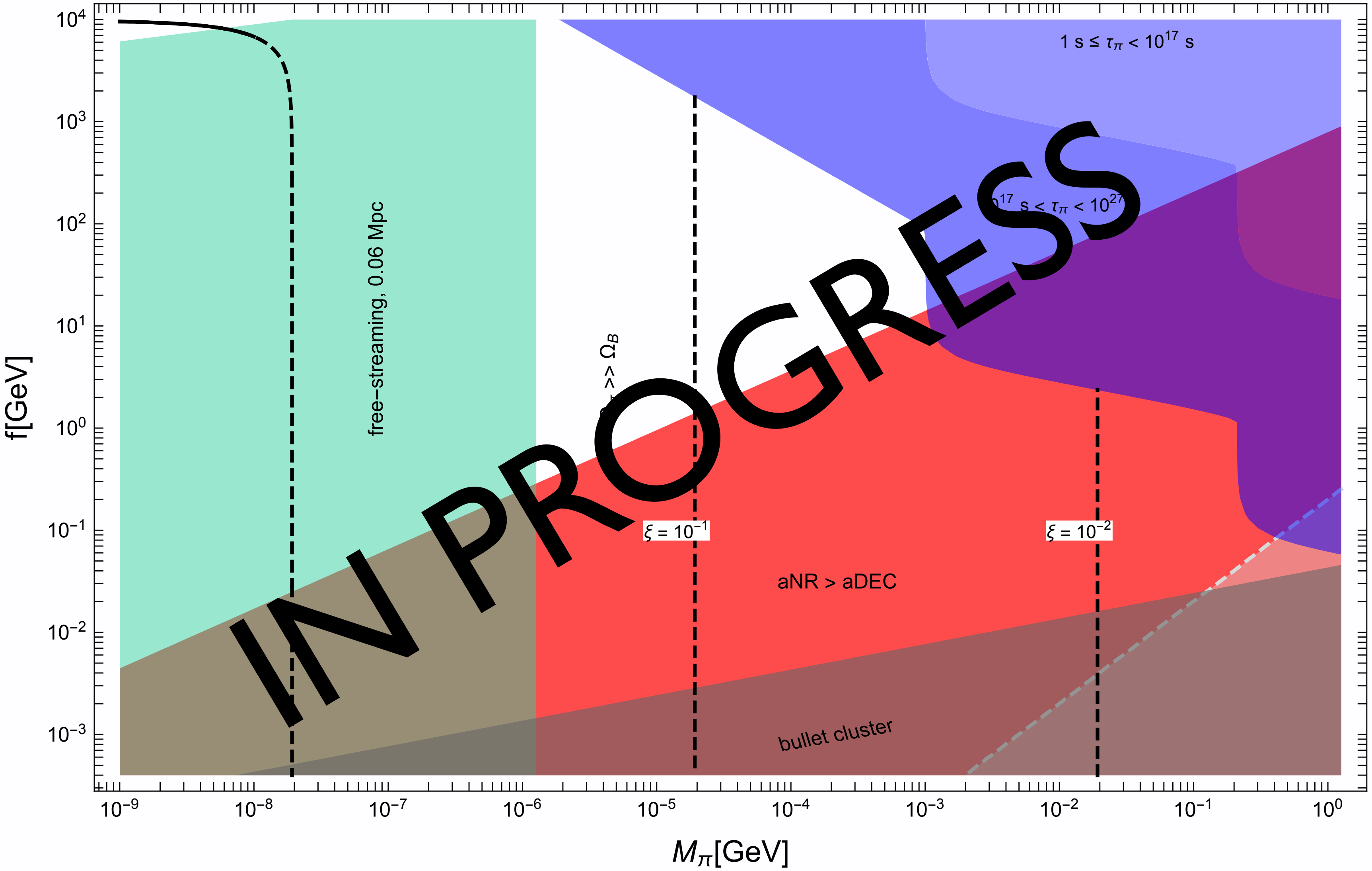
$$\Delta N_{\rm eff}\big|_{\rm CMB} = 0.027(N_F^2-1)\left(\frac{T_D}{T}\right)^4\,, \qquad\qquad \Delta N_{\rm eff}^{\rm exp} < 0.25$$

$T = T_D$ mostly excluded!

Pion and Baryon Dark Matter



For $f < KeV(M_\pi/KeV)^{7/12}$ (red region) DM remains self-coupled in NR regime:

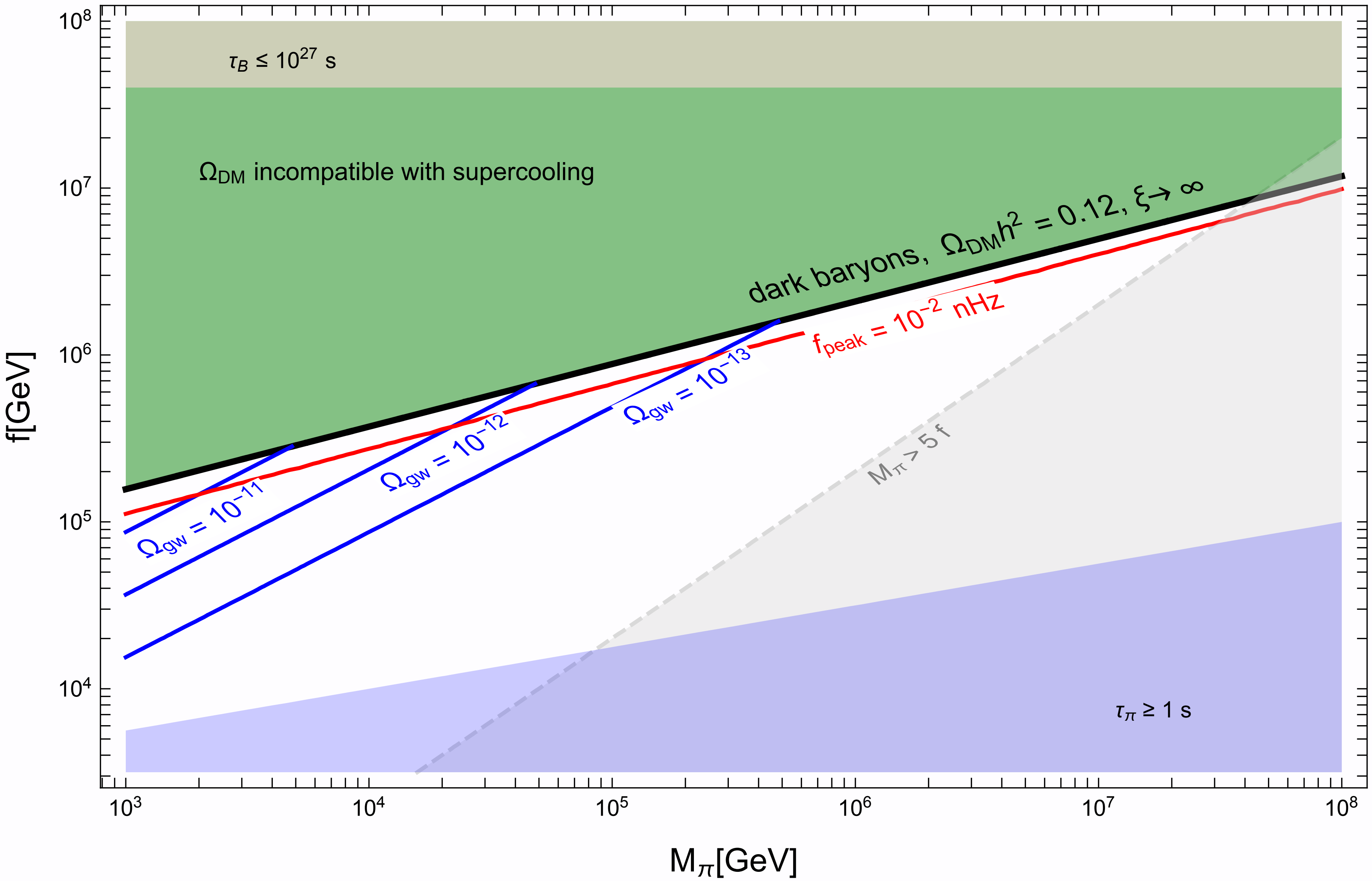


More detailed analysis of structure formation required.

Late pion decay can lead to early matter domination producing different DM halos than CDM.

[Baremboim, Blinov, Stebbins '21]

The dark sector can undergo a 1st order phase transition producing gravity waves.



Signal is typically too small in QCD-like theories.

Observable gravity waves require strong supercooling where the dark sector dominates the energy density and pions that decay rapidly after the phase transition.

SUMMARY

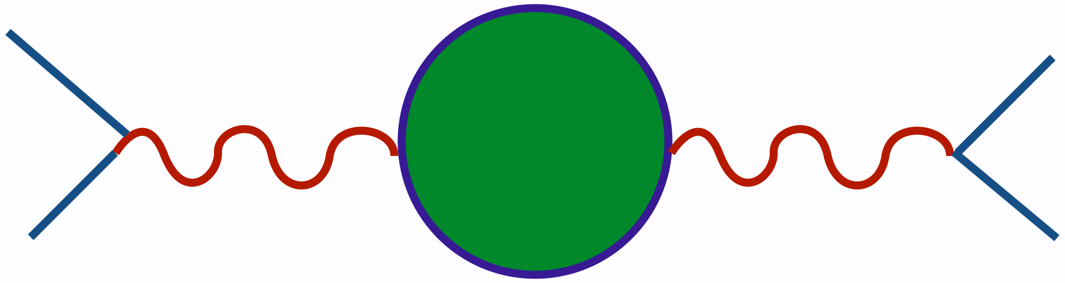
- Accidental stability of DM is automatically realized if DM is charged under a new gauge interaction. If the dark sector is neutral it is minimally produced through gravitational interactions leading to very cold dark sectors.

- Dark glueballs produced through gravitational freeze-in are excellent DM candidates. Depending on the confinement scale thermalisation or out of equilibrium phase transitions are realized. DM Mass can be as low as 100 MeV.

- In gauge theories with fermions the lightest pion and baryon are DM candidates. Dark baryons give rise to heavy DM while pions are warm DM candidates with interesting effects for structure formation, Neff and self-interactions.

Gravitational production:

$$\frac{dn_D}{dT} + 3Hn_D = \frac{\langle \sigma v \rangle}{HT}(n_D^2 - n_{\rm eq}^2) \qquad \frac{n_D(0)}{s(0)} = \int_0^{T_R} \frac{dT}{T} \frac{\langle \sigma v \rangle}{Hs(T)} n_{\rm eq}^2$$

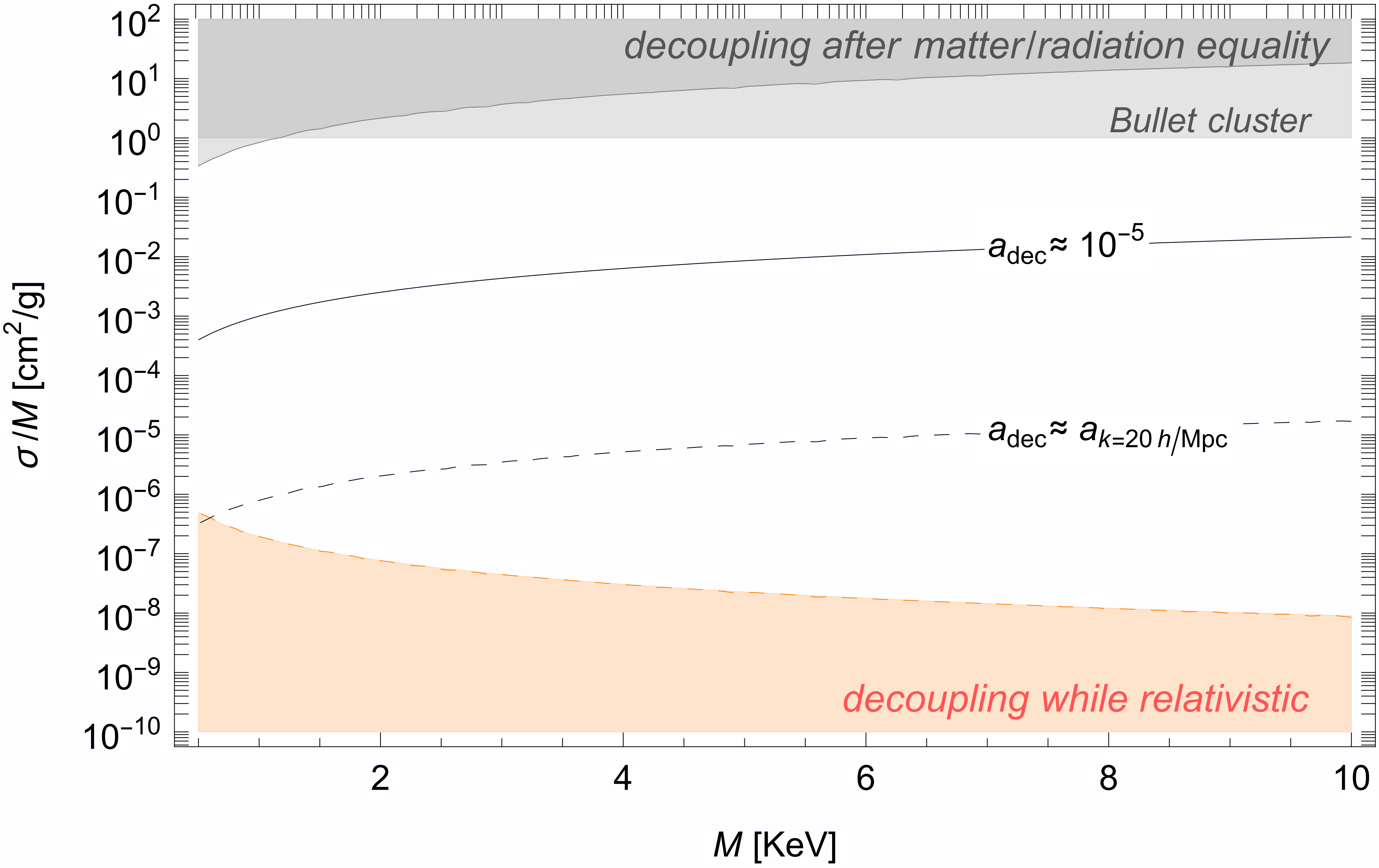


$$\mathcal{A} \sim T_{SM} \frac{1}{p^2} \langle T(p) T(-p) \rangle \frac{1}{p^2} T_{SM}$$

Integrating Boltzmann equations we obtain:

$$\frac{n_{\rm D}}{n_{\rm eq}} \approx 0.0014 \frac{c_D}{g_D} \left(\frac{T_R}{M_p} \right)^3 \qquad \rho_D \approx \frac{\pi^2}{30} g_{\rm D} T^4 \frac{n_{\rm D}}{n_{\rm eq}}$$

This is a very diluted plasma with typical energy equal to the SM and very small numerical abundance.


decoupling after matter/radiation equality
Bullet cluster
$a_{\rm dec} \approx 10^{-5}$
$a_{\rm dec} \approx a_{k=20\,h/\rm Mpc}$
decoupling while relativistic
σ/M [cm^2/g]
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
2
4
6
8
10
M [KeV]