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Dark QCD for Dark Matter

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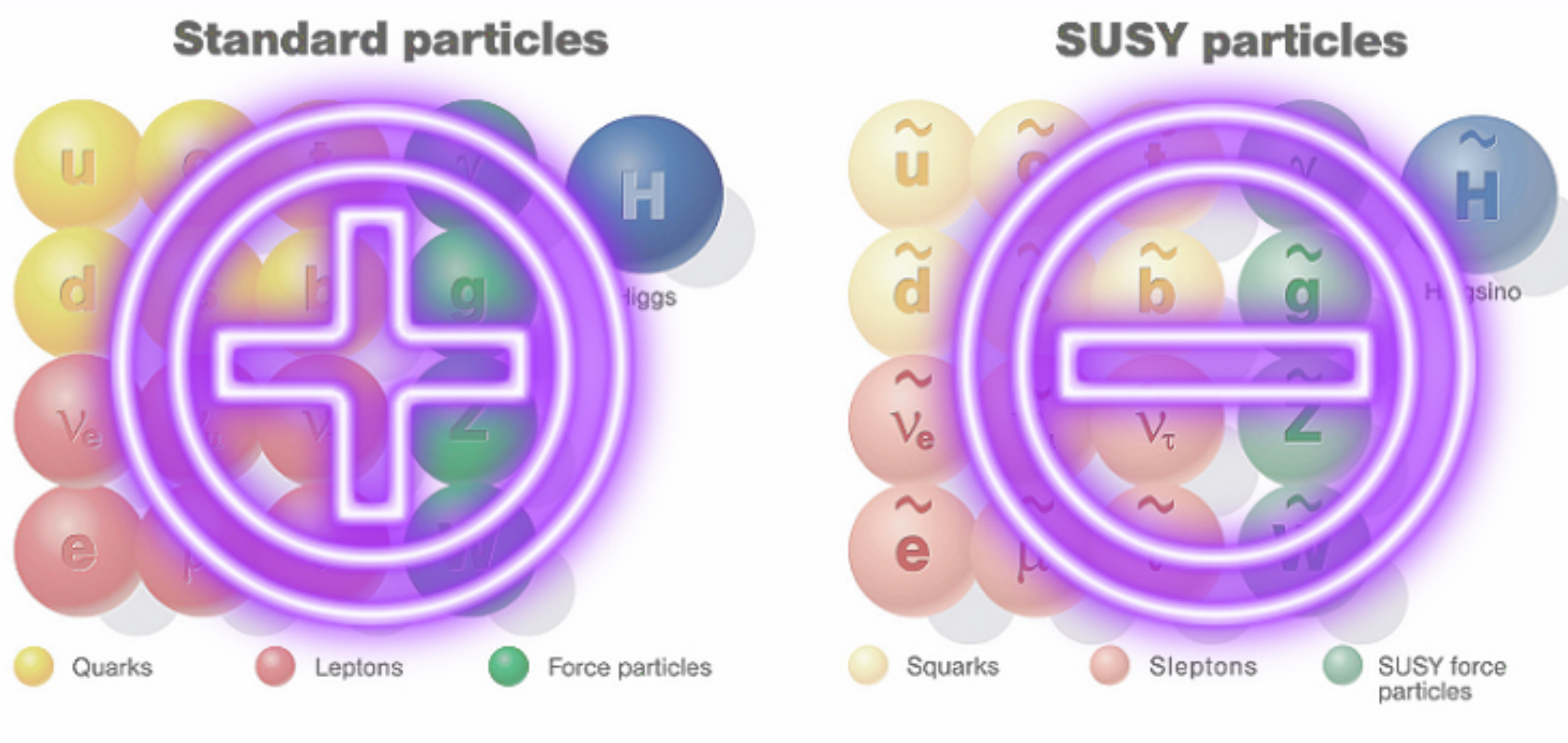
Based on 2011.10565 and 2105.03429

Quark confinement - August 5, 2021

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

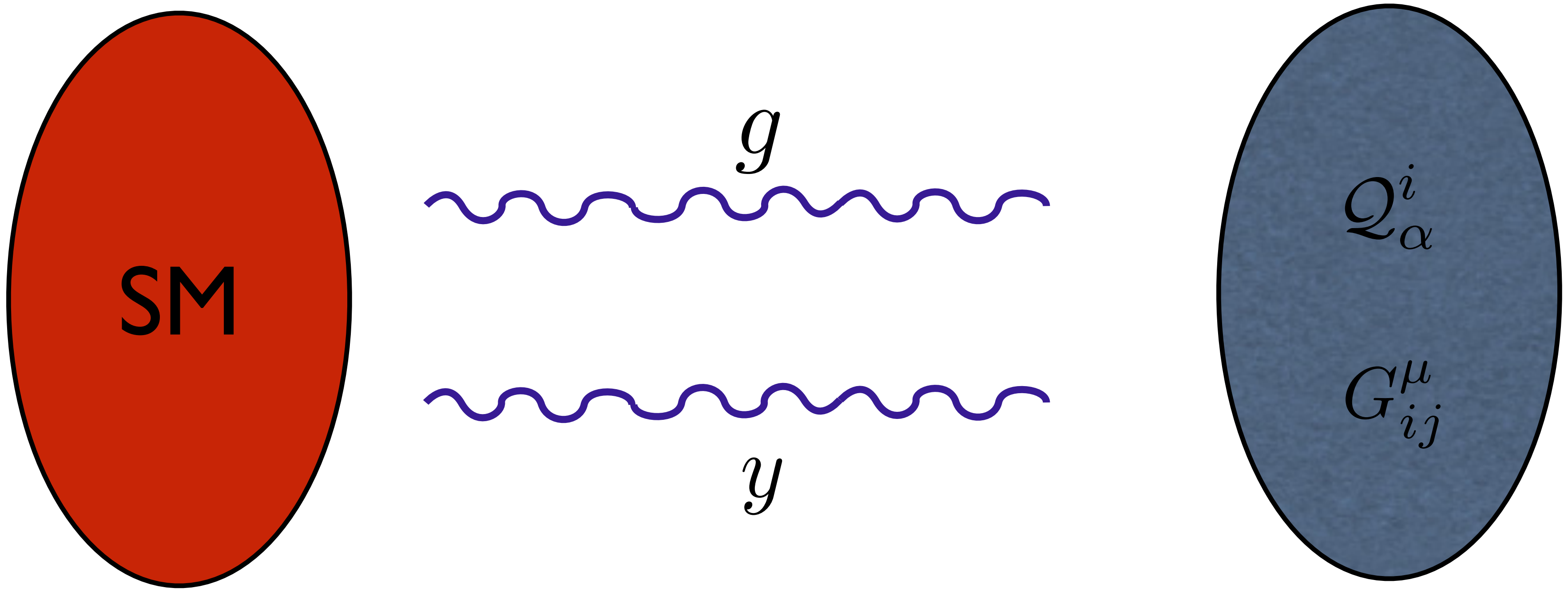
R-parity:



Can DM be accidentally stable as the proton?

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

Confining gauge theory with vector-like fermions



Composite DM with SM charges:

[Antipin, MR, Strumia Vigiani, 2015]
[Mitridate, MR, Smirnov, Strumia, 2017]

[Contino, Mitridate, Podo, MR, 2018]
[Neil, Kribs, 2016]

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

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

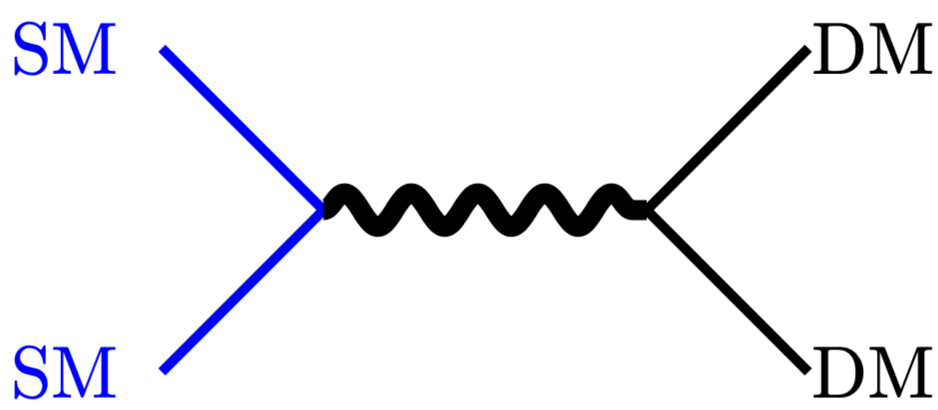
- Dark-Species number

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

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

Production

- Gravity: [Garny-Sandora-Sloth '15]



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

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

- Inflationary: [Kolb et al.]

Particles are produced in a time dependent background.
Negligible for gauge theories with fermions.

- Inflaton decay

Glueball DM

A very minimal scenario for DM is a decoupled 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 can decay 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.

Dark glueballs should never be in thermal contact with SM.

Gravitational production automatically produces a cold dark sector.

For $T_R > \Lambda$ 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:

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

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

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

- No thermalization:

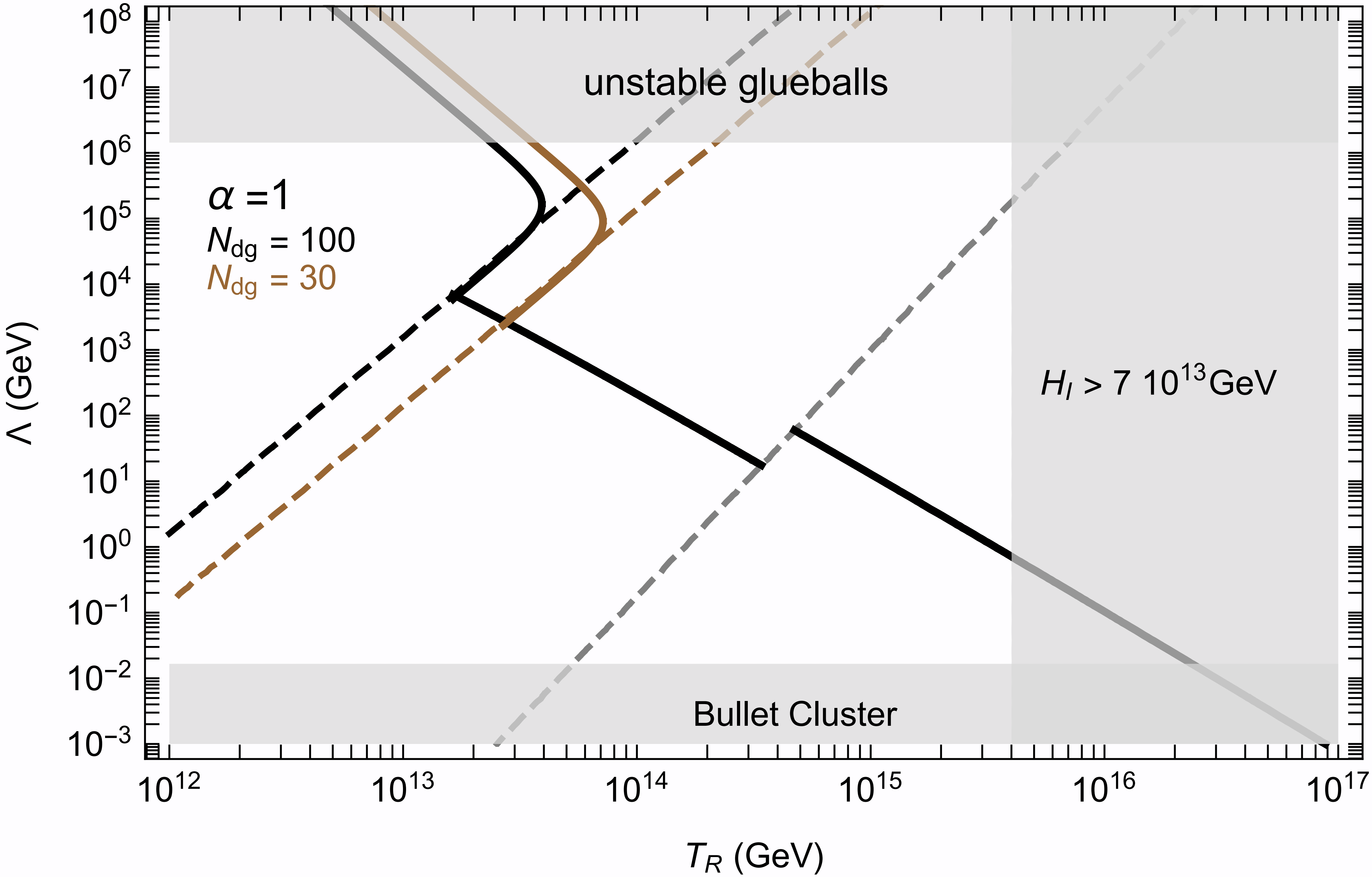
If interactions are weak the system does not thermalize in relativistic regime. Confinement takes place out of equilibrium at the visible temperature:

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

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:

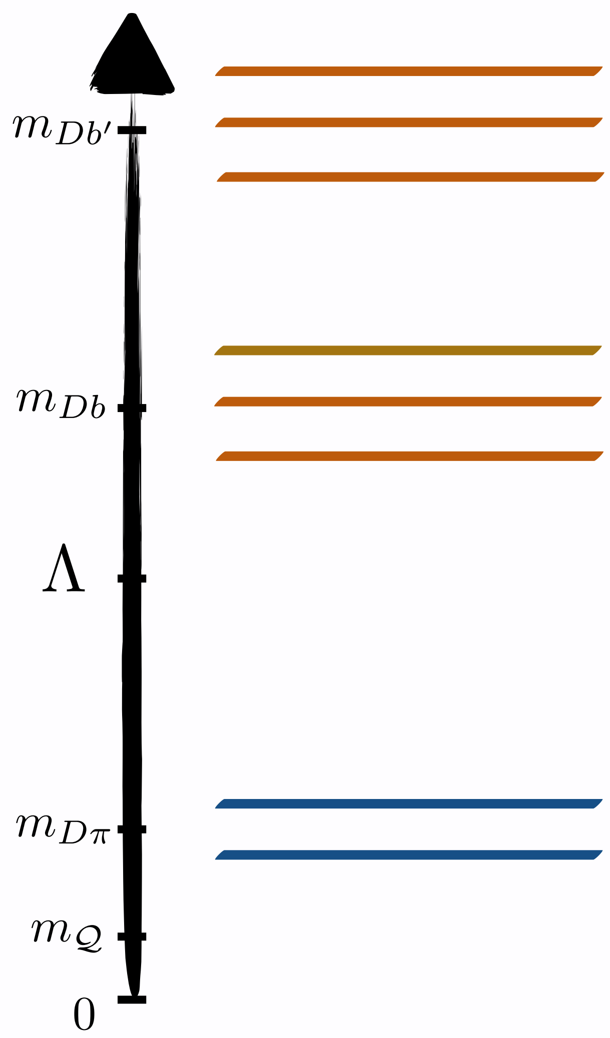
$$Y_{\rm DG}(T_\Lambda) = N_{\rm DG} Y_{\rm D}$$

Glueball Dark Matter



Hadronic DM

In theories with light quarks the spectrum is radically different:

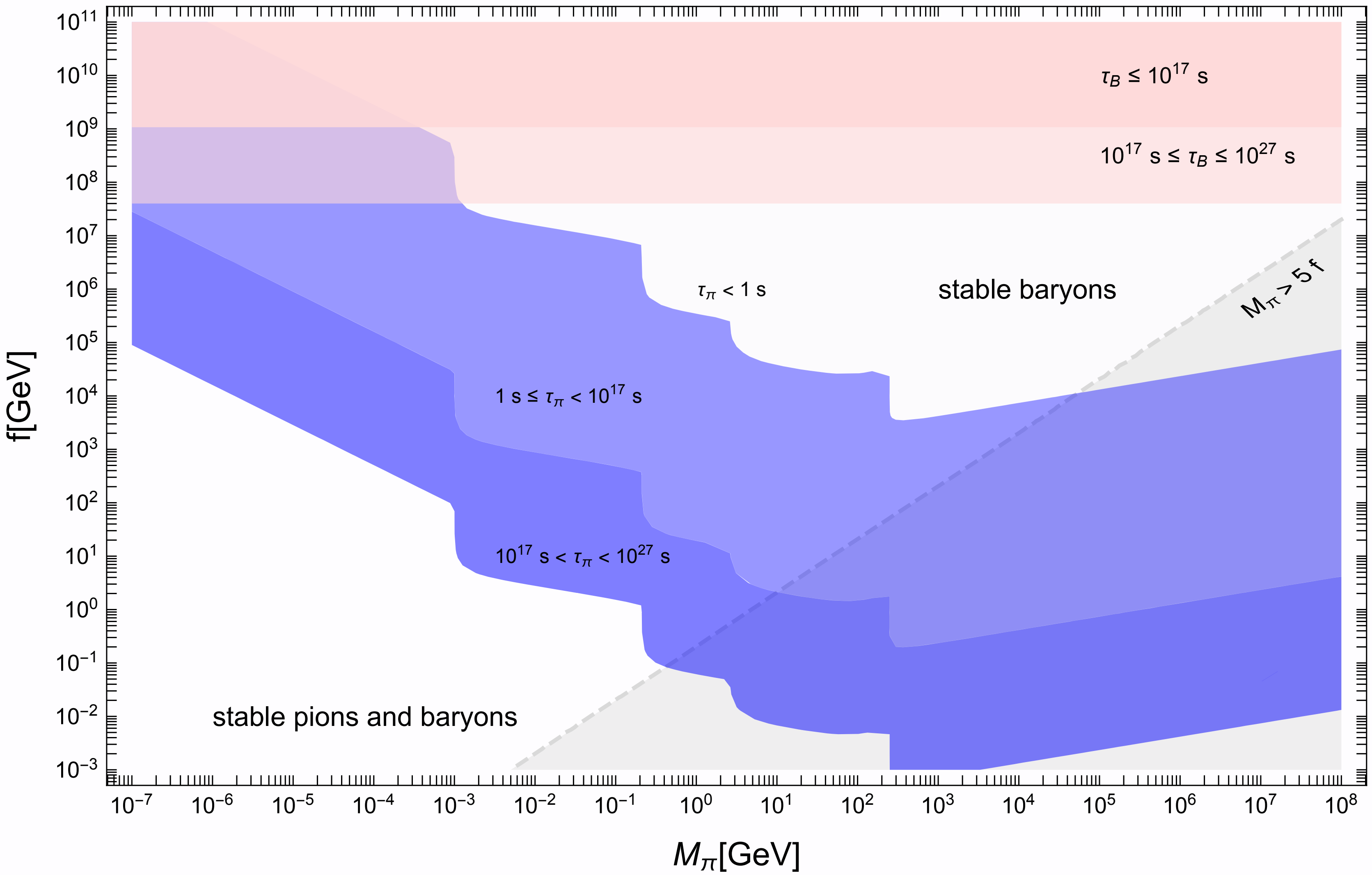


Lightest dark baryon and dark pions are DM candidates.

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 pions 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:

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

Pion DM is light.

The baryon abundance is determined by freeze-out:

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

The critical mass can be further increased by pion decays.
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:

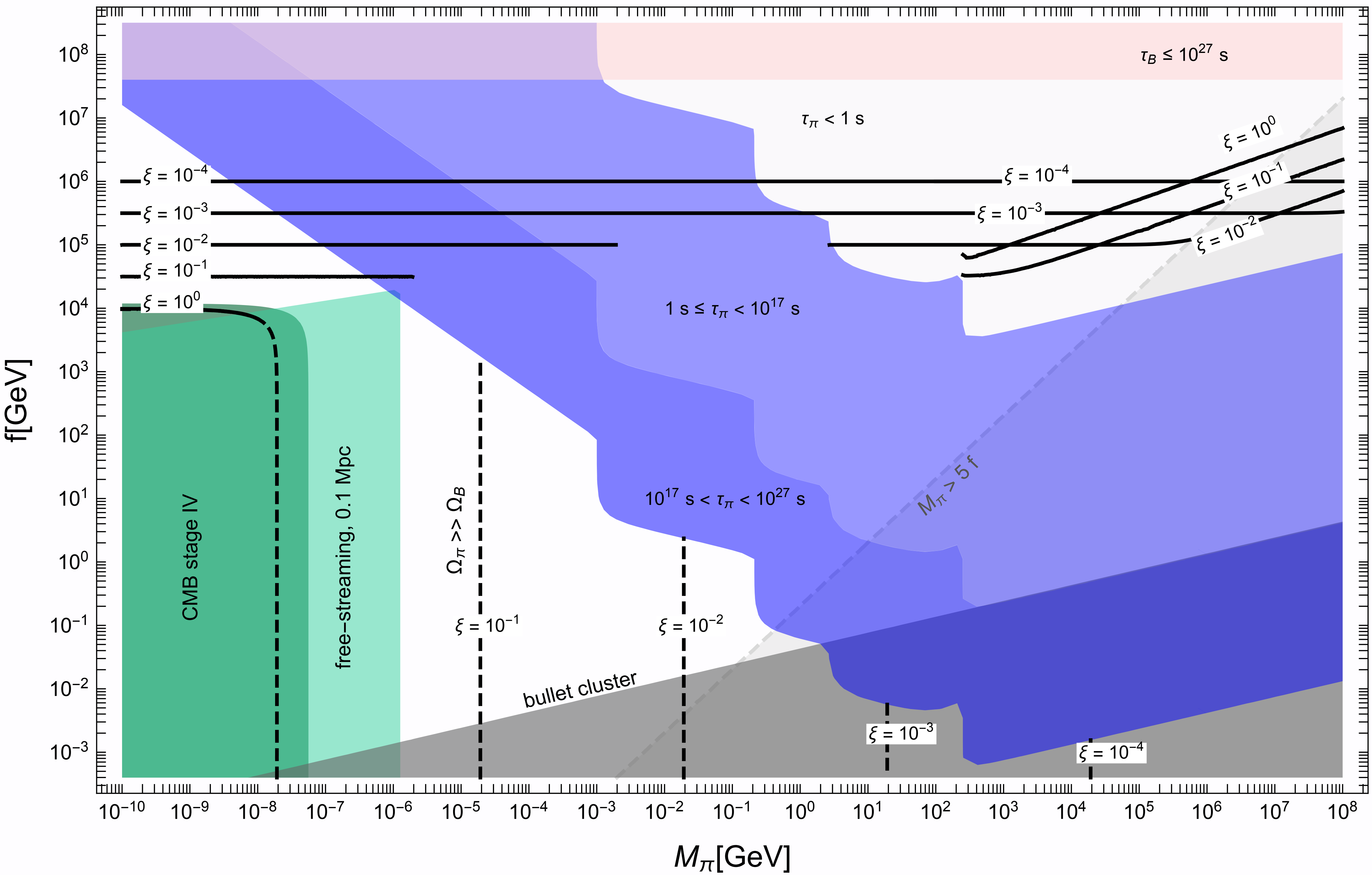
$$\lambda_{\rm FS} \approx 0.1\,{\rm Mpc} \left(\frac{T}{T_D}\right) \frac{\rm KeV}{M_\pi} \left(\frac{106.75}{g_*^s(T_\Lambda)}\right)^{\frac{1}{3}} \qquad\qquad \lambda_{\rm FS}^{\rm exp} \lesssim 0.06\,{\rm Mpc}$$

Massless pions contribute to radiation:

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

$T = T_D$ is excluded!

Pion and Baryon Dark Matter



SUMMARY

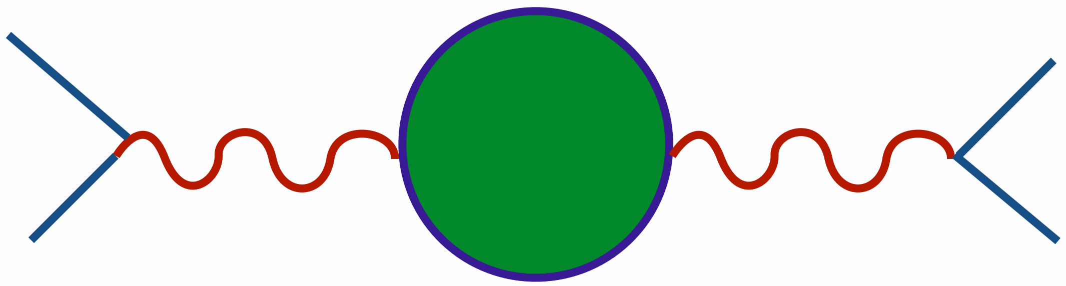
- Accidental stability of DM is most simply realized if it is charged under a new gauge interaction. If the dark sector is neutral it is minimally produced through gravitational interaction interaction leading to colder dark sectors.

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

- 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.

After Production

- No Interactions:

At production all rates are smaller than H and interactions are not important. This would lead to an abundance:

$$\frac{\Omega h^2}{0.12} = \frac{Y_D M}{0.4\,\mathrm{eV}} \approx \frac{c_D M}{2 \cdot 10^6\,\mathrm{GeV}} \left(\frac{T_R}{10^{15}\,\mathrm{GeV}}\right)^3$$

- Thermalization:

In relativistic regime $\Gamma \propto T$ while $\mathrm{H} \sim T^2/M_p$ so the system would thermalize at the visible temperature:

$$T^* \approx 5 \cdot 10^{-5} (c_D \alpha_{\mathrm{eff}}^3) \left(\frac{T_R}{M_p}\right)^3 M_p \approx 7 \times 10^3\,\mathrm{GeV} (c_D \alpha_{\mathrm{eff}}^3) \left(\frac{T_R}{10^{15}\,\mathrm{GeV}}\right)^3$$

Using conservation of energy:

$$\frac{T_D}{T} = \left(\frac{g_* r}{g_{\mathrm{D}}}\right)^{\frac{1}{4}} \approx 0.2 \left(\frac{c_D}{g_D}\right)^{\frac{1}{4}} \left(\frac{T_R}{M_p}\right)^{\frac{3}{4}}$$

Extremely cold dark sector!

In the process numerical abundance increases:

$$\frac{n_{th}}{n_D} \sim \left(\frac{M_p}{T_R}\right)^{\frac{3}{4}}$$

- Out of equilibrium dynamics:

If $\mathrm{T}^* < M$ the system does not thermalize.

Interactions can still change abundance.

This can lead to non standard phase transitions.