Large-Nightmare Dark Matter

Logan A. Morrison, Stefano Profumo and
Dean Robinson

arXiv:2010.XXXX

UNIVERSITY OF CALIFORNIA SANTA CRUZ

SCIPP
SANTA CRUZ INSTITUTE FOR PARTICLE PHYSICS

Outline

- Theory Overview / Large-N estimates
- Thermally Decoupled Sectors
- Cosmic Evolution
- Results

The Dark SU(N) Theory

- We consider a SU(N) gauge theory with a single dark (effectively massless, $m_{\tilde{q}} \ll \Lambda$) "quark"

field	$\mathrm{U}(1)_{\mathrm{Y}}$	$\mathrm{SU}(2)_{\mathrm{L}}$	$\mathrm{SU}(3)_{\mathrm{c}}$	$\mathrm{SU}(N)_{\mathrm{dark}}$
$\tilde{q}_L$	0	$\mathbf{1}$	$\mathbf{1}$	$\boldsymbol{N}$
$\tilde{q}_R$	0	$\mathbf{1}$	$\mathbf{1}$	$\boldsymbol{N}$
$\tilde{q}_L^\dagger$	0	$\mathbf{1}$	$\mathbf{1}$	$\overline{\boldsymbol{N}}$
$\tilde{q}_R^\dagger$	0	$\mathbf{1}$	$\mathbf{1}$	$\overline{\boldsymbol{N}}$
$\tilde{g}$	0	$\mathbf{1}$	$\mathbf{1}$	$\boldsymbol{N}^2 - \mathbf{1}$

- We take $N \gg 1$

- We assume that the dark coupling constants scales like: $g_{\text{dark}} \sim 1/\sqrt{N}$

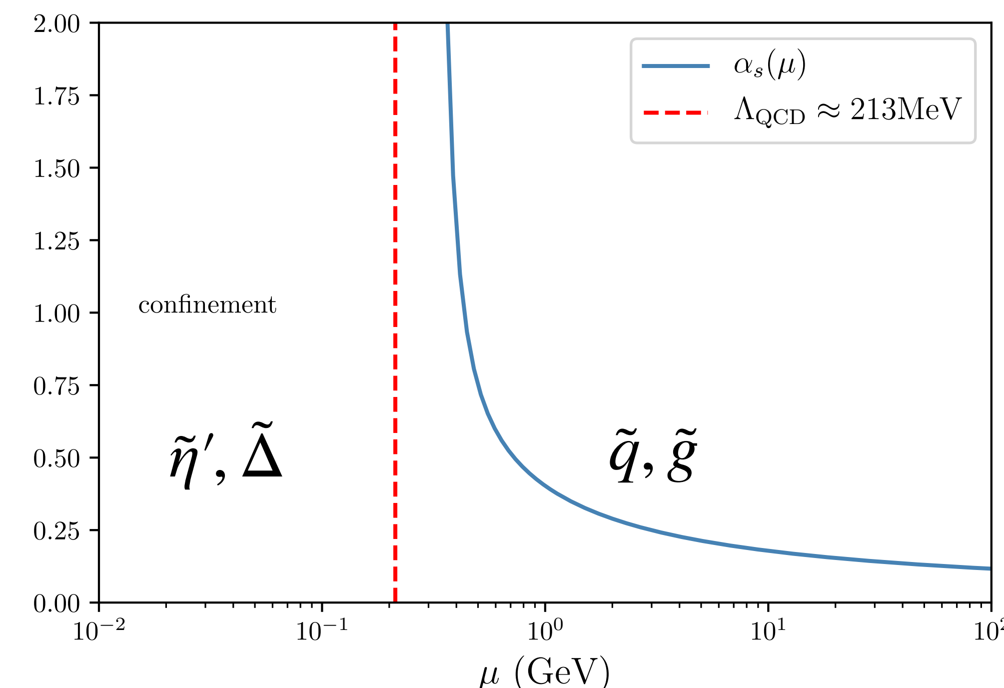
- This allows us to compute the scaling of physical observables with N

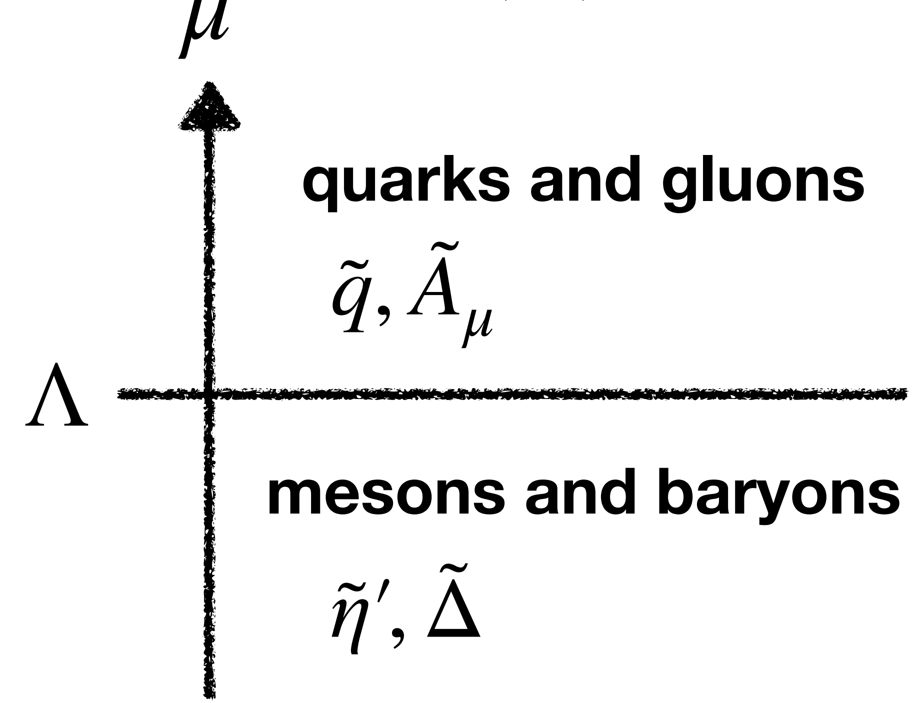
Confinement

- The β-function is:

$$\beta(\mu) = -\left(\frac{11}{3} - \frac{2}{3}\frac{1}{N}\right)\frac{\tilde{g}^3}{16\pi^2} + \mathcal{O}(\tilde{g}^5)$$

- At a scale Lambda, the theory will confine
- Below confinement, the relevant d.o.f. will be mesons and baryons
- Since we have a single quark, our asymptotic states are a $\tilde{\Delta}$-baryon and an $\tilde{\eta}'$-meson





Stable Asymptotic States

- $\bar{\eta}'$ is very light: pseudo-Goldstone with mass proportional to chiral anomaly
- Δ is very heavy: made up of N dark quarks

State	Mass	Lifetime	$U(1)_V$
$\bar{\eta}'$	$\sim \Lambda/\sqrt{N}$	stable	0
Δ	$\sim N\Lambda$	stable	N
ω_d	$\sim \Lambda$	$\sim N^2/\Lambda$	0
G_d	$\sim \mathrm{few} \times \Lambda$	$\sim N^2/\Lambda$	0

Interactions

- $\tilde{\eta}'$ interactions are described by $\mathscr{L}_{\text{ChPT}}$

$$\mathcal{L}_{\bar{\eta}'} = \frac{1}{2}\partial_\mu \bar{\eta}' \partial_\mu \bar{\eta}' + \frac{m_{\bar{\eta}'}^2}{2}\bar{\eta}'\bar{\eta}' + \sum_{k=1} \frac{\lambda_k}{n_k!}\left[\frac{16\pi^2}{\Lambda^4 N}\right]^k (\partial\bar{\eta}' \cdot \partial\bar{\eta}')^{k+1}$$

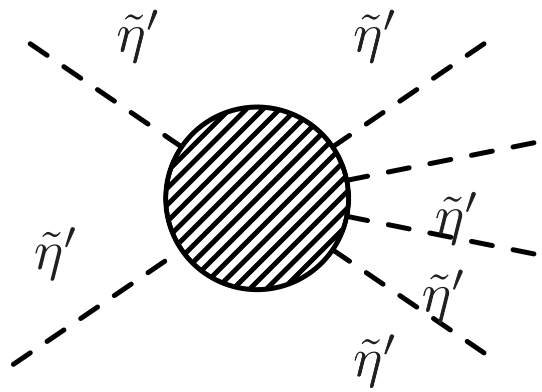
- $\Delta\bar{\Delta} \leftrightarrow \bar{\eta}'\bar{\eta}'$ exponentially suppressed (color matching)

$$A_{\bar{\eta}'\bar{\eta}' \to \Delta\bar{\Delta}} \sim e^{-cN}\,, \qquad c > 0$$

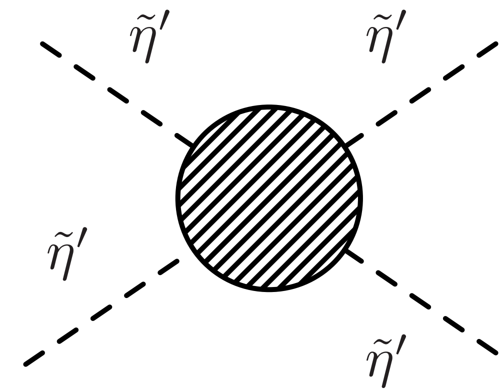
- $\Delta\Delta \to \Delta\Delta$ scattering from exchange of light meson

Number-changing

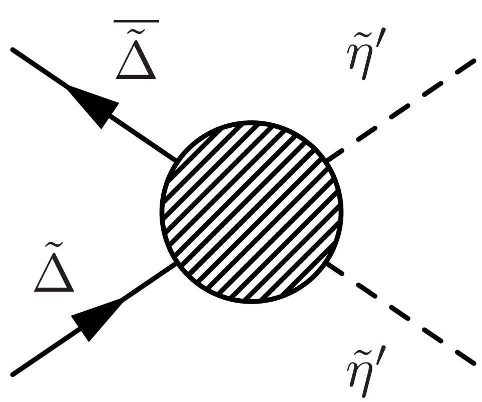
Self-interaction



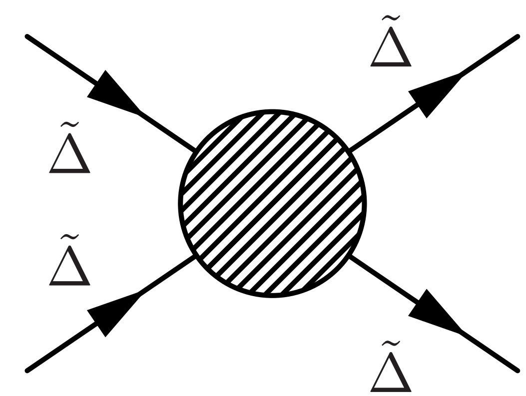
$$\sigma_{2\bar{\eta}'\to 4\bar{\eta}'}(s) \sim \frac{\pi^3 s^7}{48\Lambda^{16}N^4}\left|10\lambda_1^2+\lambda_2\right|^2$$



$$\sigma_{2\bar{\eta}'\to 2\bar{\eta}'}(s) \sim \frac{\pi^3 s^3|\lambda_1|^2}{4\Lambda^8 N^2}$$



$$\sigma_{\bar{\eta}'\bar{\eta}'\to\Delta\bar{\Delta}} \sim \frac{e^{-2cN}}{64\pi N^2\Lambda^2}$$



$$\sigma_{2\Delta\to 2\Delta} \sim \frac{4\pi^3}{\Lambda^2}$$

Thermally Decoupled Theory

- If a theory is thermally decoupled from the SM, it may have a different temperature

- Total entropy in dark and SM sectors will be conserved

- Ratios of entropy densities will be constant

$$\text{constant} = \frac{S_d}{S_{\rm SM}} = \frac{a^3 s_d}{a^3 s_{\rm SM}} = \frac{h_d(T_d)T_d^3}{h_{\rm SM}(T_{\rm SM})T_{\rm SM}^3}$$

- We can determine dark temperature a later times if we know ratio at early time

Thermally Decoupled Theory

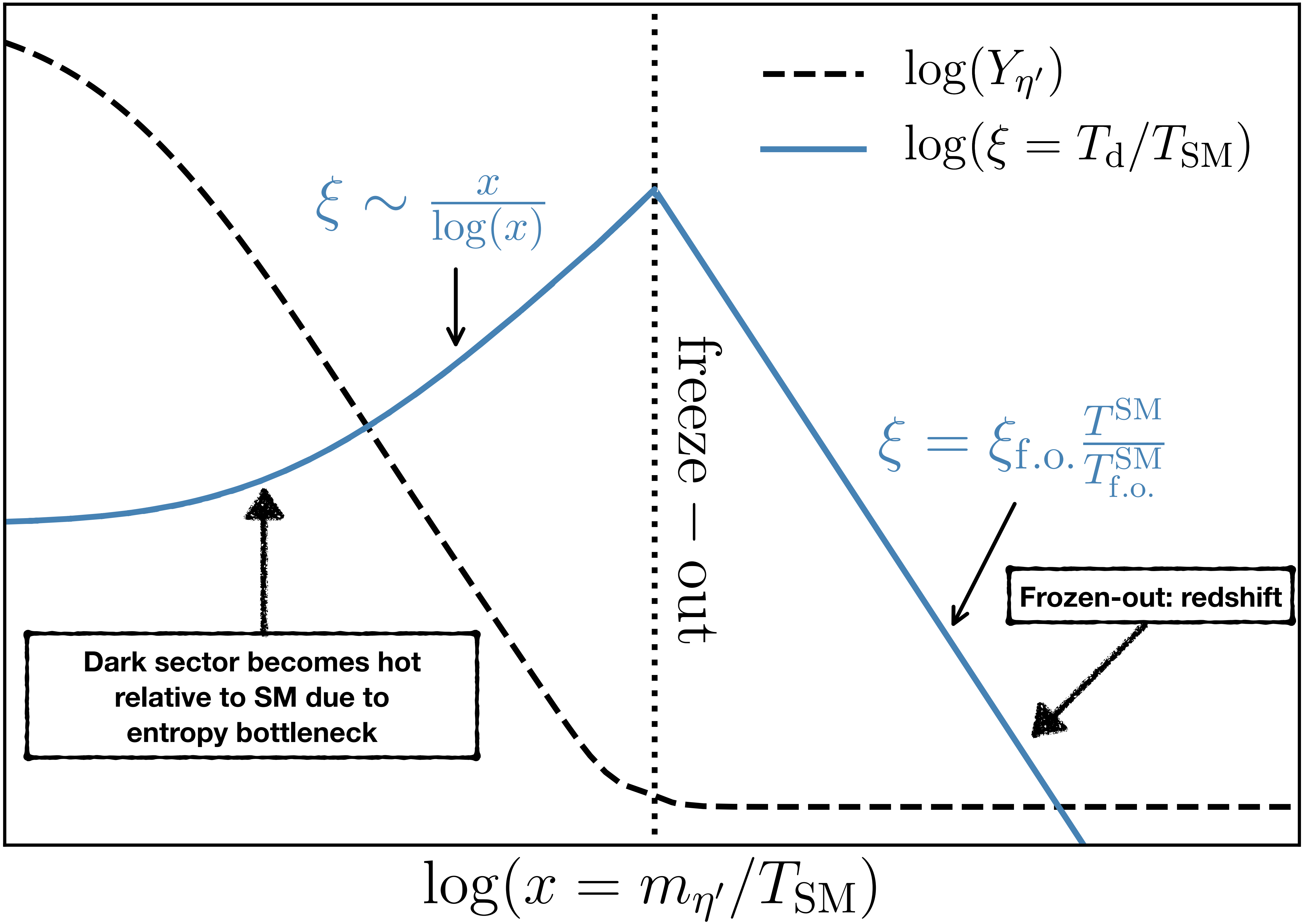
- If the temperature ratio is known at $T_{\rm SM}^{\infty}$, then:

$$\xi(T_{\rm SM}) \equiv \frac{T_d}{T_{\rm SM}} = \left(\frac{h_{\rm SM}(T_{\rm SM})}{h_{\rm SM}^{\infty}} \frac{h_d^{\infty}}{h_d(\xi T_{\rm SM})} \right)^{1/3} \xi^{\infty}$$

- For massive particles in thermal equilibrium

$$h(x = m/T) \sim x^3 K_3(x) \sim x^{5/2} e^{-x} \qquad (\text{as} \quad x \to \infty)$$

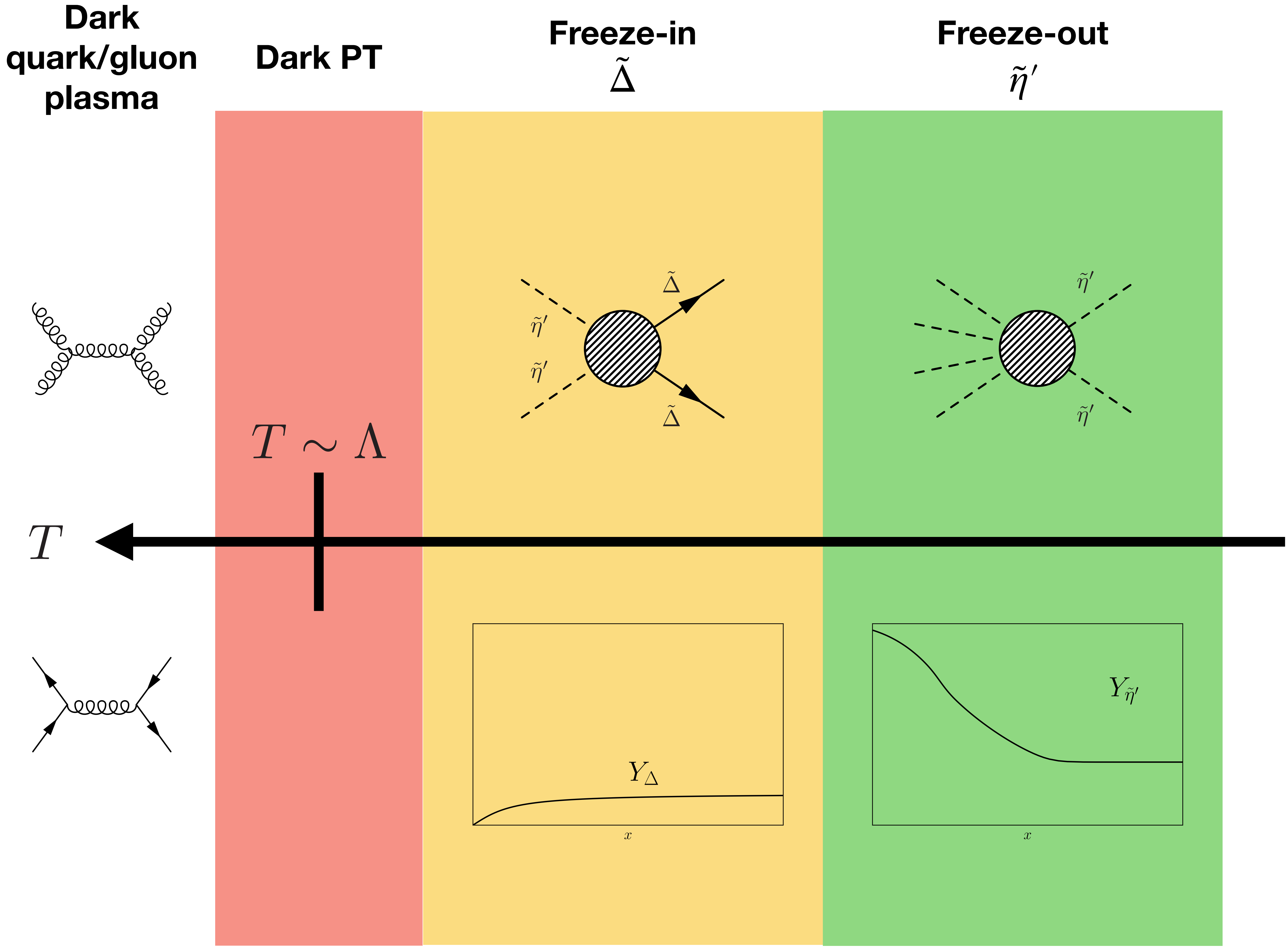
- As long as the dark sector is in thermal equilibrium, it will become exponentially hot relative to the SM



$\log(Y_{\eta'})$
$\log(\xi = T_{\rm d}/T_{\rm SM})$
$\xi \sim \frac{x}{\log(x)}$
freeze − out
$\xi = \xi_{\rm f.o.} \frac{T^{\rm SM}}{T^{\rm SM}_{\rm f.o.}}$
Frozen-out: redshift
Dark sector becomes hot relative to SM due to entropy bottleneck
$\log(x = m_{\eta'}/T_{\rm SM})$

Cosmic Evolution

- High temperature we have a dark quark/gluon plasma
- For temperatures below confinement dark quarks/gluon confine to eta-prime and deltas
- Initial number density of delta is suppressed
- $\tilde{\eta}'s$ change number via $4 \to 2$
- $\tilde{\Delta}$'s are produced via $\tilde{\eta}' + \tilde{\eta}' \to \tilde{\Delta} + \overline{\tilde{\Delta}}$



Dark quark/gluon plasma
Dark PT
Freeze-in $\tilde{\Delta}$
Freeze-out $\tilde{\eta}'$
$\tilde{\eta}'$
$\tilde{\Delta}$
$T \sim \Lambda$
T
Y_{Δ}
$Y_{\tilde{\eta}'}$
x

Experimental Handles

- Measurements from bullet cluster and shapes of halos put tight constraints on self interaction cross section: $\sigma_{\mathrm{SI}}/m_\chi < \mathrm{barn/GeV}$

- From measurements of CMB, we have constraints on effective number of neutrino species: $\Delta N_{\mathrm{eff}}^{\mathrm{CMB}} < 0.3$

- BBN additionally requires a small ΔN_{eff}

$$N_{\mathrm{eff}}^{\mathrm{CMB}} \sim 3.046 + \frac{4}{7}\left(\frac{11}{4}\right)^{4/3} g_d \xi^4 \qquad N_{\mathrm{eff}}^{\mathrm{BBN}} \sim 3 + \frac{4}{7} g_d \xi^4$$

Relic Density

- The eta relic density can be computed using entropy conservation and the instantaneous freeze-out approximation

Entropy Conservation $\rightarrow r_s = \dfrac{h_d}{h_{\rm SM}}\xi^3 \sim \dfrac{N^2}{100}\xi_\infty^3$

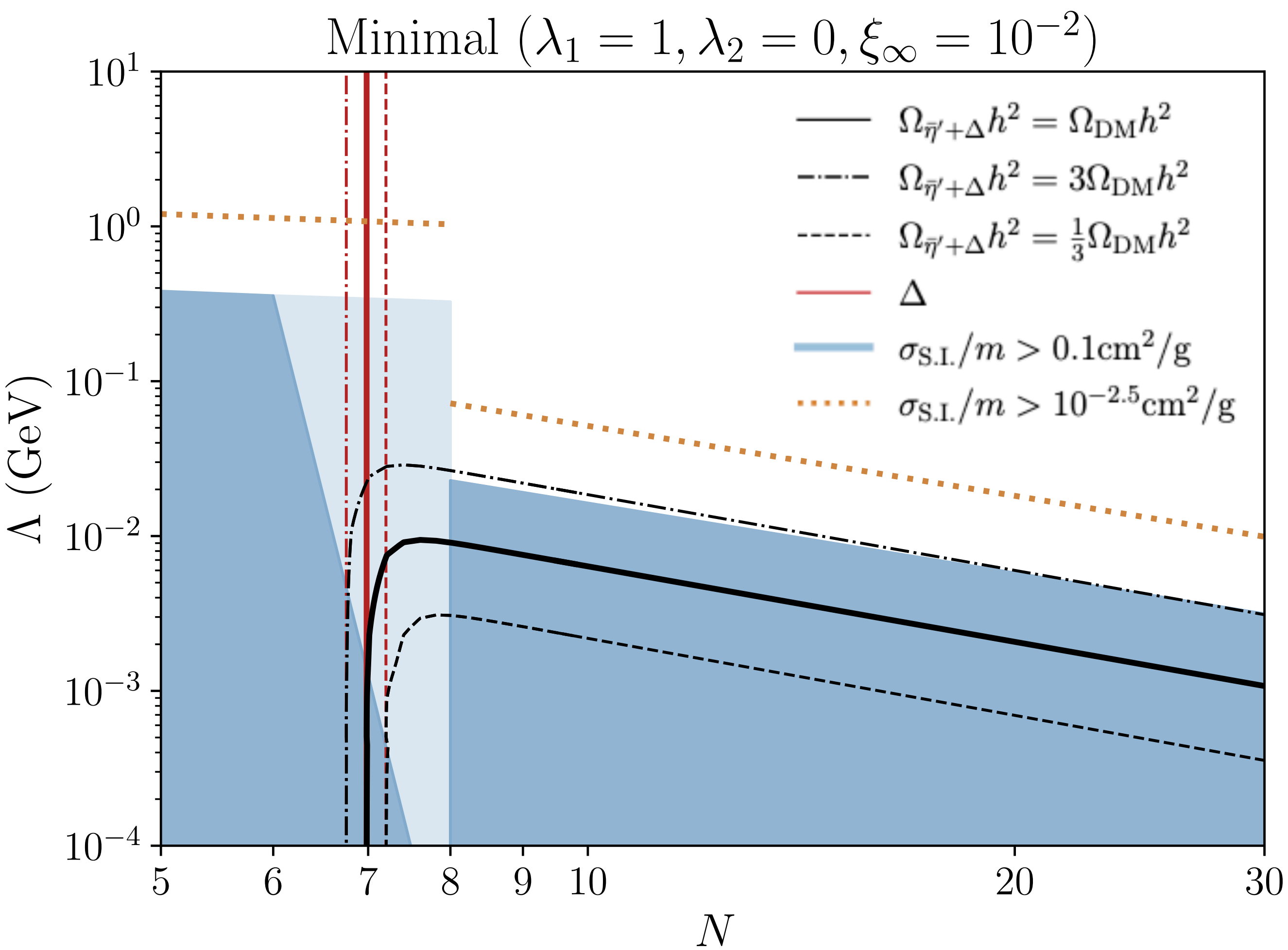
Instantaneous F.O. $\rightarrow Y_{\bar{\eta}',0} \sim Y_{\bar{\eta}',f} = \dfrac{n_{\bar{\eta}',f}}{s_{\rm SM}} = \dfrac{S_{d,f}}{s_{\rm SM,f}x_{d,f}} = \dfrac{r_s}{x_{d,f}}$

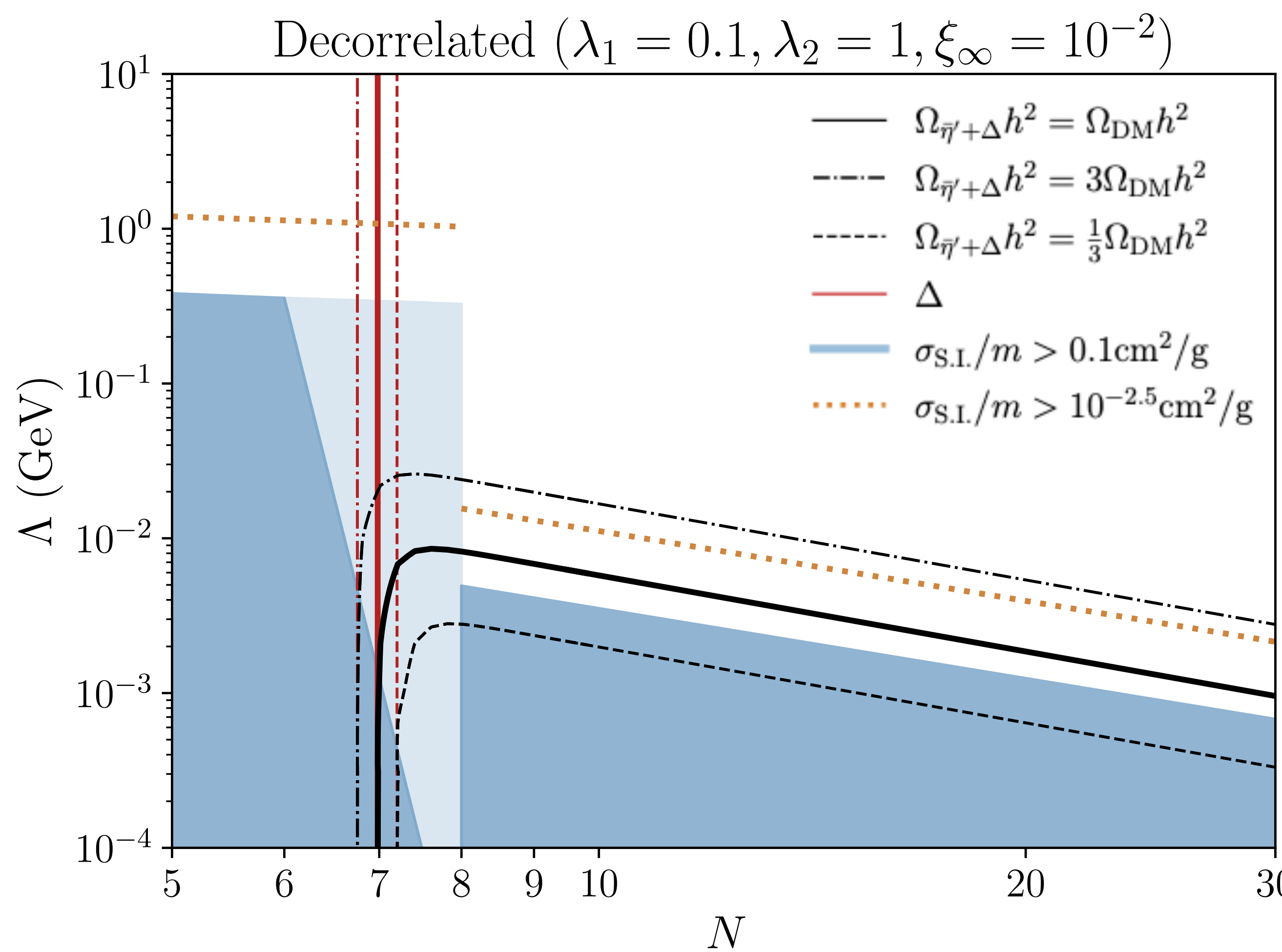
$$\implies \Omega_{\bar{\eta}'}h^2 \sim 0.12\left(\frac{10}{x_f+1}\right)\left(\frac{\xi_\infty}{10^{-2}}\right)^3\left(\frac{\Lambda}{20\mathrm{MeV}}\right)\left(\frac{N}{10}\right)^{3/2}$$

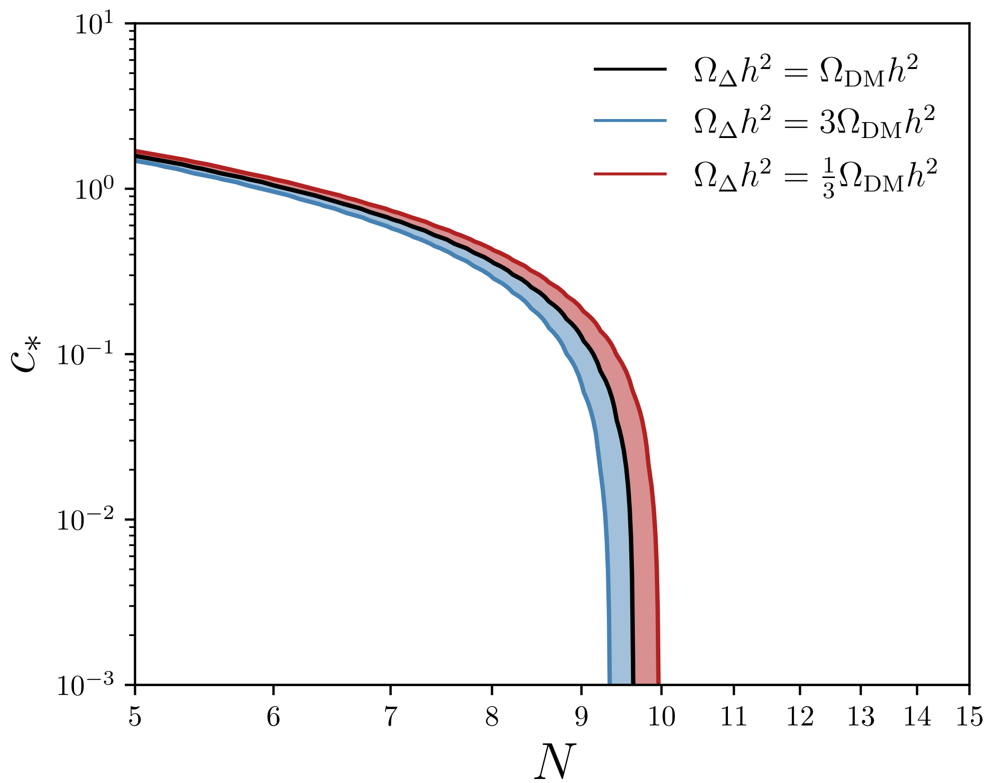
- Delta relic density comes from direct integration of Boltzmann equation

$$\Omega_\Delta h^2 \sim (\mathrm{const.})N^{3/2}e^{-2(c+1)N}$$

Results

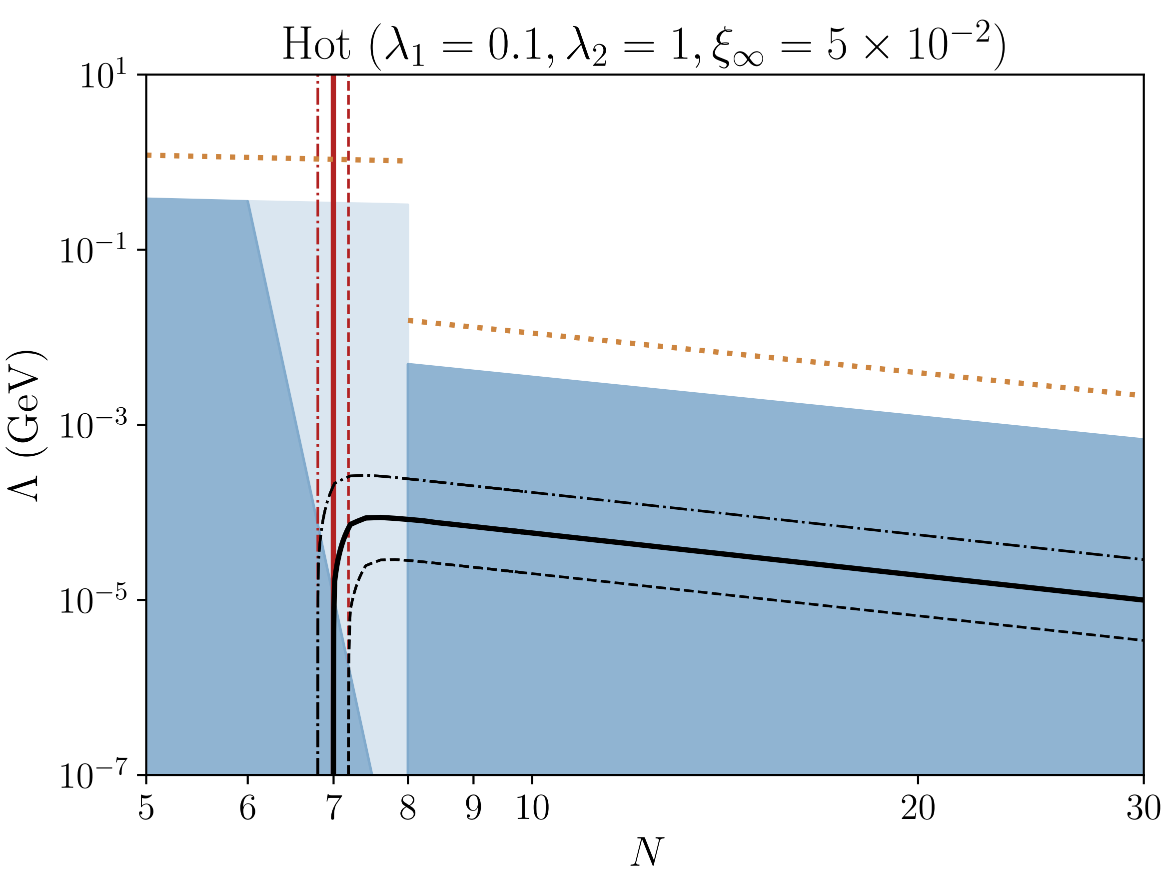

Minimal ($\lambda_1 = 1, \lambda_2 = 0, \xi_\infty = 10^{-2}$)
$\Omega_{\bar{\eta}'+\Delta}h^2 = \Omega_{\rm DM}h^2$
$\Omega_{\bar{\eta}'+\Delta}h^2 = 3\Omega_{\rm DM}h^2$
$\Omega_{\bar{\eta}'+\Delta}h^2 = \frac{1}{3}\Omega_{\rm DM}h^2$
Δ
$\sigma_{\rm S.I.}/m > 0.1{\rm cm}^2/{\rm g}$
$\sigma_{\rm S.I.}/m > 10^{-2.5}{\rm cm}^2/{\rm g}$
Λ (GeV)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
5 6 7 8 9 10 20 30
N

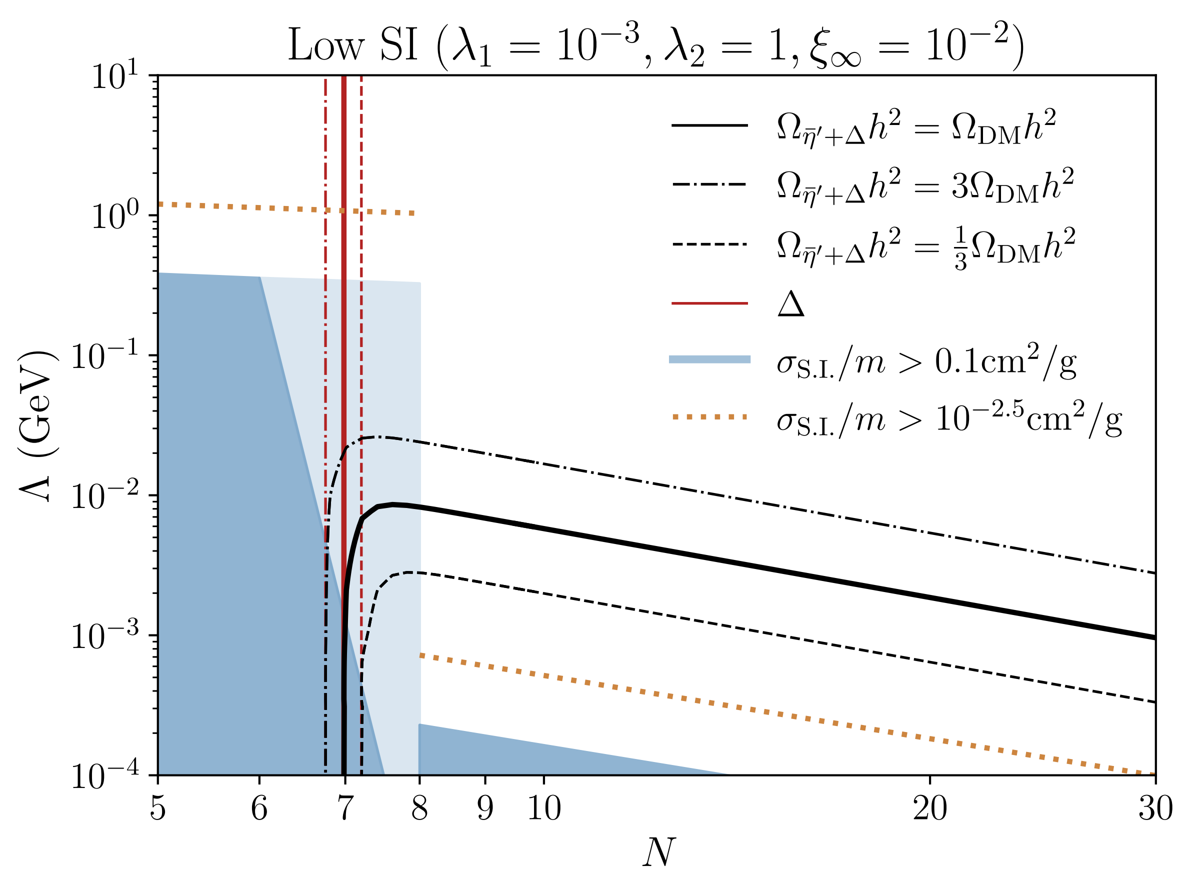

Decorrelated ($\lambda_1 = 0.1, \lambda_2 = 1, \xi_\infty = 10^{-2}$)
$\Omega_{\bar{\eta}'+\Delta}h^2 = \Omega_{\rm DM}h^2$
$\Omega_{\bar{\eta}'+\Delta}h^2 = 3\Omega_{\rm DM}h^2$
$\Omega_{\bar{\eta}'+\Delta}h^2 = \frac{1}{3}\Omega_{\rm DM}h^2$
Δ
$\sigma_{\rm S.I.}/m > 0.1{\rm cm}^2/{\rm g}$
$\sigma_{\rm S.I.}/m > 10^{-2.5}{\rm cm}^2/{\rm g}$
Λ (GeV)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
5 6 7 8 9 10 20 30
N



$$\Omega_\Delta h^2 \sim (\text{const.})\, N^{3/2} e^{-2(c+1)N}$$

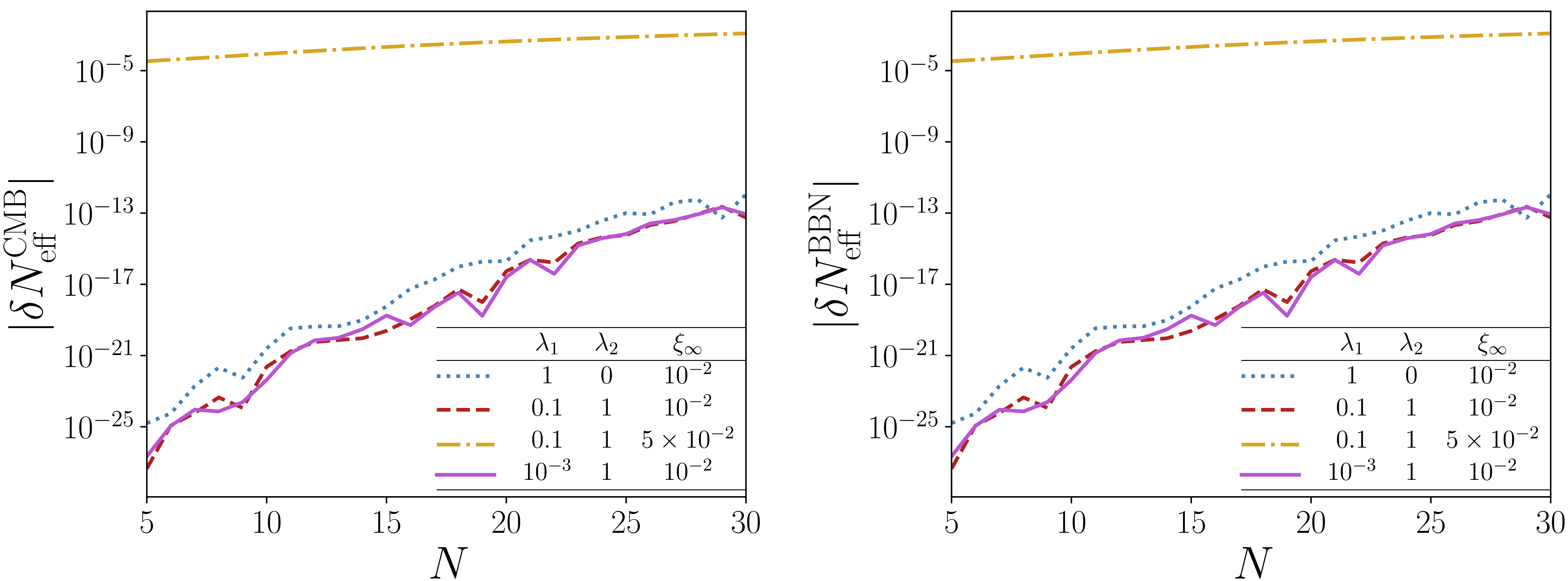
$$\Omega_{\bar{\eta}'} h^2 \sim 0.12 \left(\frac{10}{x_f+1}\right)\left(\frac{\xi_\infty}{10^{-2}}\right)^3 \left(\frac{\Lambda}{20\text{MeV}}\right)\left(\frac{N}{10}\right)^{3/2}$$





Summary

- η' - DM viable when $\bar{\eta}'\bar{\eta}' \to \bar{\eta}'\bar{\eta}'$ is small enough
- Temperature ratio of dark/SM must be small (smaller the better)
- Self-interaction constraints rule out Δ-DM when $\bar{\eta}'$ is stable
- Δ-DM viable when $\bar{\eta}'$ is unstable and $\Lambda \gtrsim 200\ \mathrm{MeV}$



$|\delta N_{\rm eff}^{\rm CMB}|$
$|\delta N_{\rm eff}^{\rm BBN}|$
10^{-5}
10^{-9}
10^{-13}
10^{-17}
10^{-21}
10^{-25}
5
10
15
20
25
30
N
λ_1 λ_2 ξ_∞
1 0 10^{-2}
0.1 1 10^{-2}
0.1 1 5×10^{-2}
10^{-3} 1 10^{-2}