Dark Matter from a Dark SU(N) Gauge Theory with a Single Quark Flavor

Logan A. Morrison, Stefano Profumo and Dean Robinson

arXiv:2005.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: $g_{\mathrm{dark}} \sim 1/\sqrt{N}$

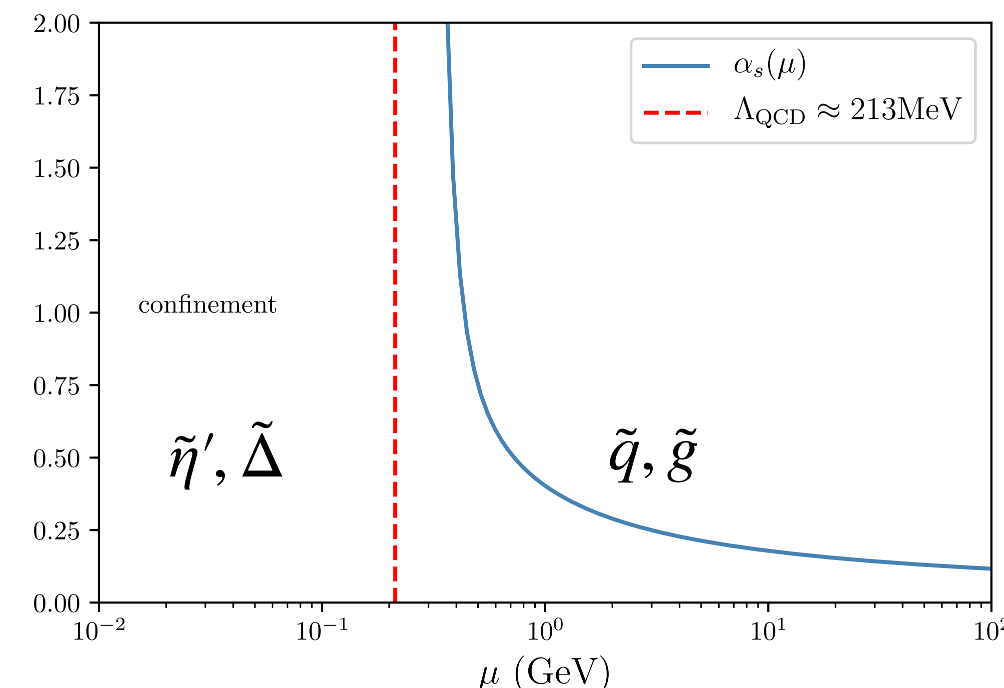
- This allows us to compute the scaling of physical observables with N

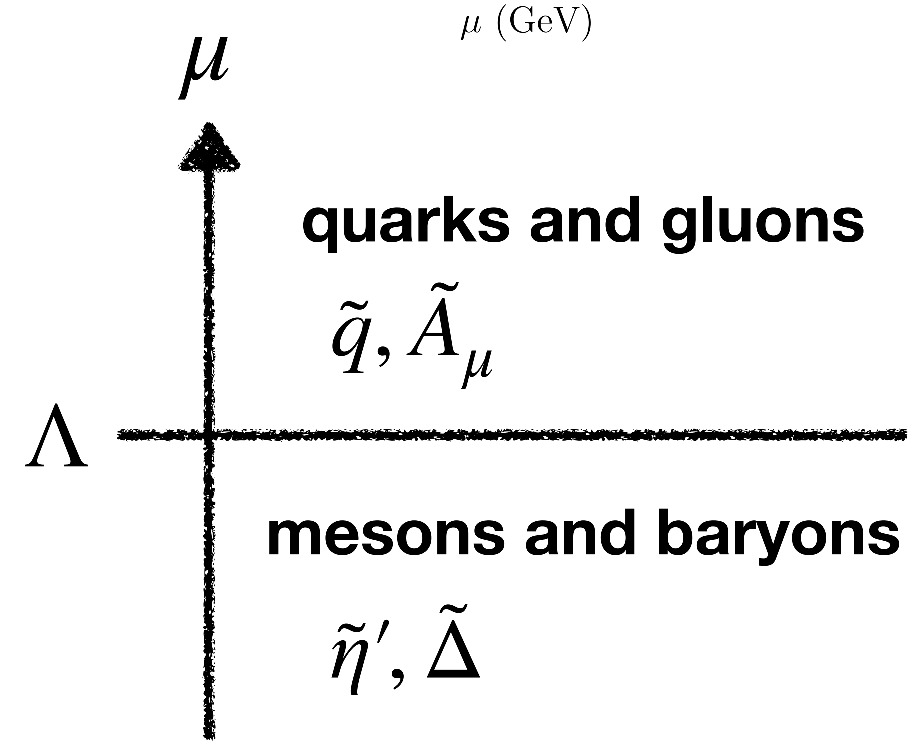
Confinement

- 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

- $\tilde{\eta}'$ is very light: pseudo-Goldstone with mass proportional to chiral anomaly

- $\tilde{\Delta}$ is very heavy: made up of N dark quarks

field	mass	spin
$\tilde{\eta}'$	$\sim \Lambda/\sqrt{N}$	0
$\tilde{\Delta}$	$\sim N\Lambda$	$N/2$

Interactions

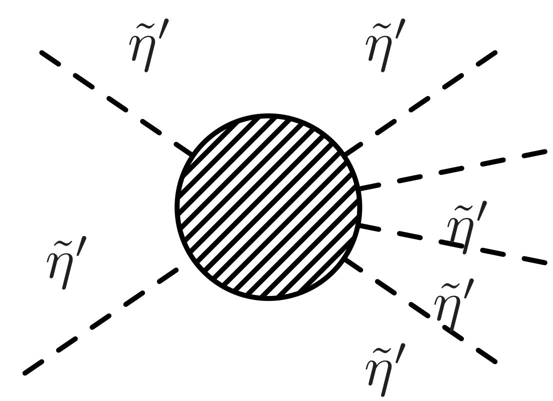
- $\tilde{\eta}'$ interactions are described by $\mathscr{L}_{\mathrm{ChPT}}$

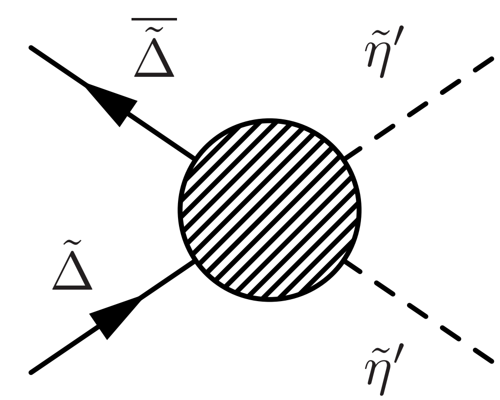
$$\mathcal{L}_{\mathrm{ChPT}} \supset L_1 \frac{f_{\eta'}^2}{\Lambda^2} \frac{(\partial_\mu \eta')^4}{f_{\eta'}^4} + L_2 \frac{f_{\eta'}^2}{\Lambda^2} \frac{(\partial_\mu \eta')^6}{f_{\eta'}^6} + \cdots$$

- Δ creation/annihilation exponentially suppressed (color matching)

- Δ scattering dominated by mediation of lightest scalar state

Number-changing

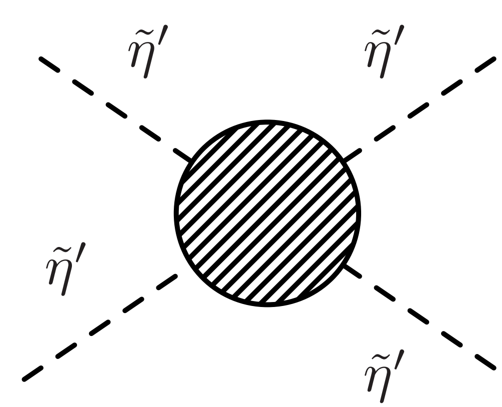


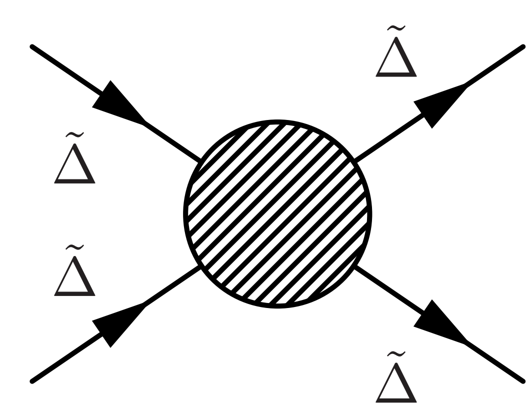


$$L_2 \frac{f_{\eta'}^2}{\Lambda^2} \frac{(\partial_\mu \tilde{\eta}')^6}{f_{\eta'}^6}$$

$$\mathcal{M} \sim e^{-cN}$$

Self-interaction





$$L_1 \frac{f_{\eta'}^2}{\Lambda^2} \frac{(\partial_\mu \tilde{\eta}')^4}{f_{\eta'}^4}$$

$$\sigma \sim \frac{m_\Delta^2}{m_\sigma^4}$$

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

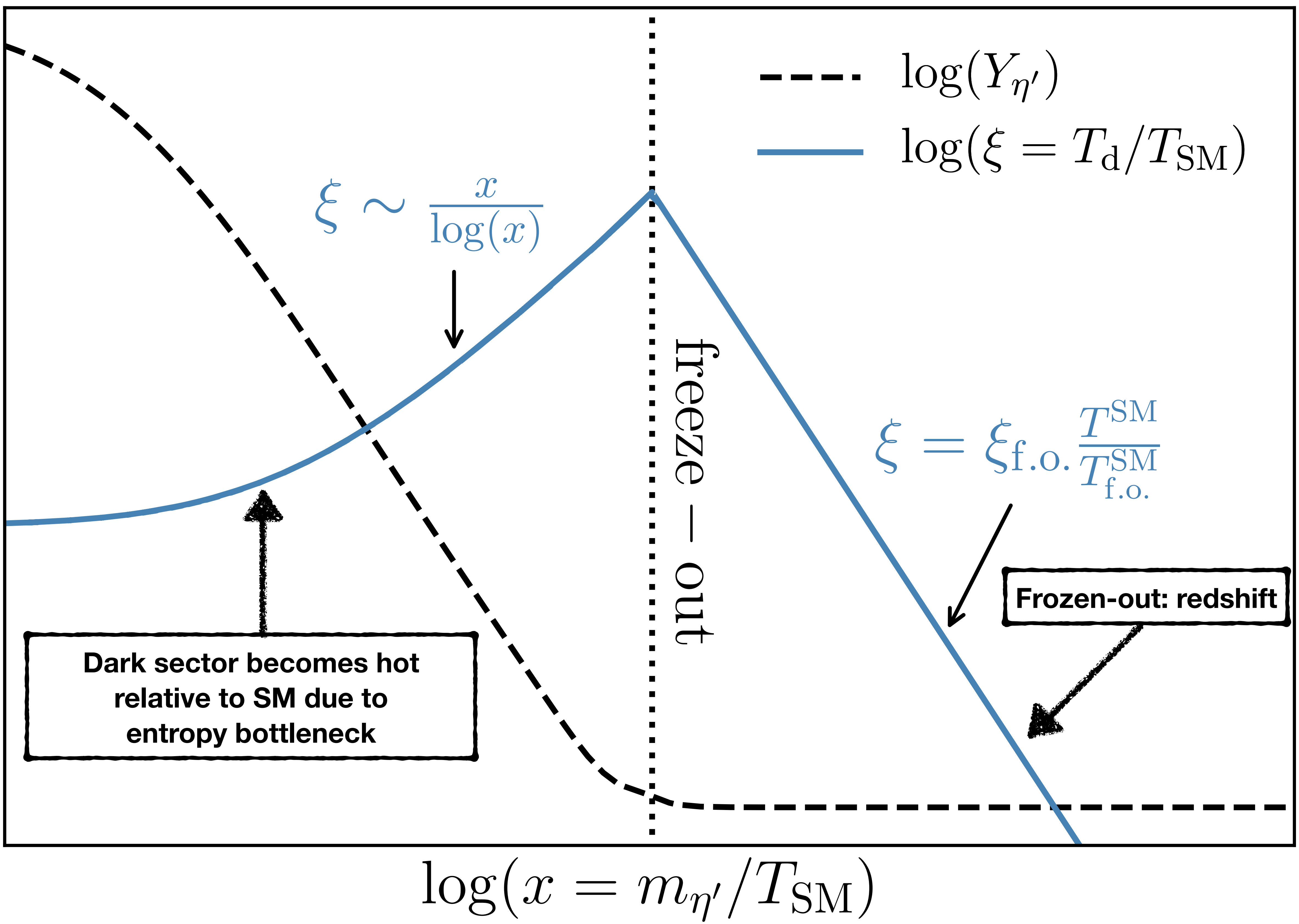
- If the temperature ratio is known at $T_{\rm SM}^{\infty}$, then:

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

- For massive particles in thermal equilibrium

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

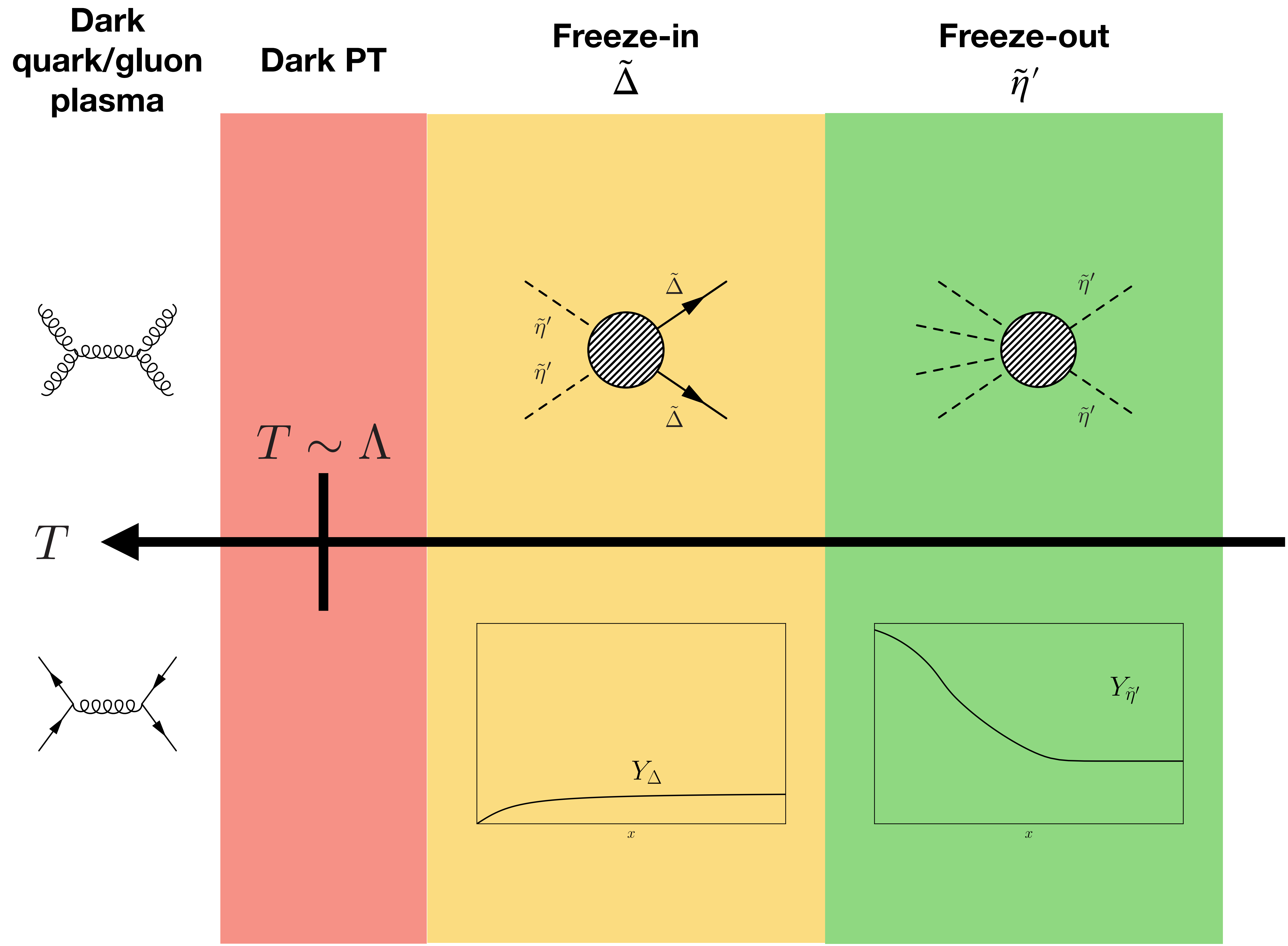
- As long as the dark sector is in thermal equilibrium, it will become exponentially hot relative to the SM



$\log(Y_{\eta'})$
$\log(\xi = T_{\rm d}/T_{\rm SM})$
$\xi \sim \frac{x}{\log(x)}$
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 $\tilde{\eta}' + \tilde{\eta}' \to \tilde{\Delta} + \overline{\tilde{\Delta}}$



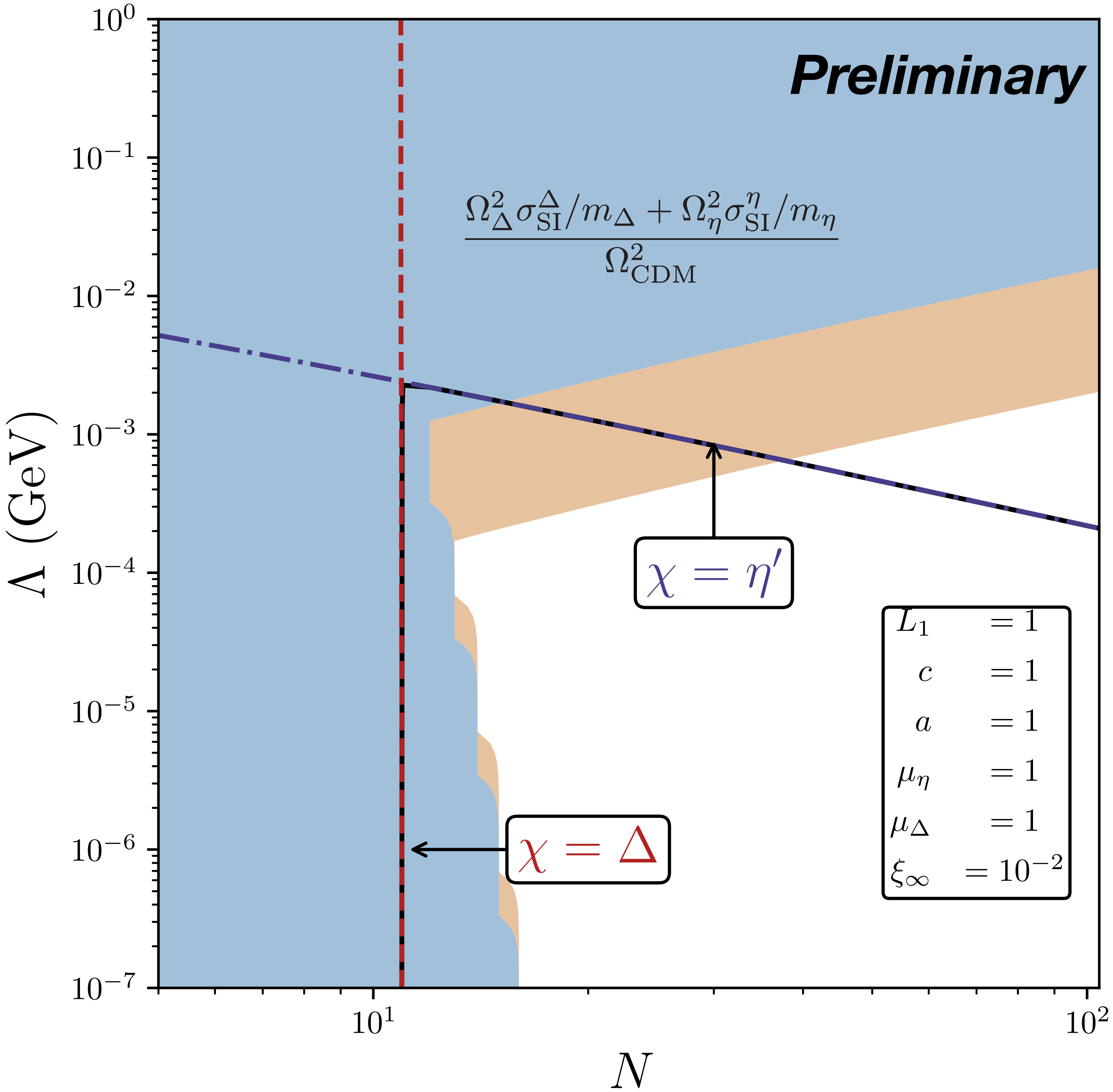
Dark quark/gluon plasma
Dark PT
Freeze-in $\tilde{\Delta}$
Freeze-out $\tilde{\eta}'$
$\tilde{\eta}'$
$\tilde{\eta}'$
$\tilde{\Delta}$
$\tilde{\Delta}$
$\tilde{\eta}'$
$\tilde{\eta}'$
$T \sim \Lambda$
T
Y_{Δ}
x
$Y_{\tilde{\eta}'}$
x

Experimental Handles

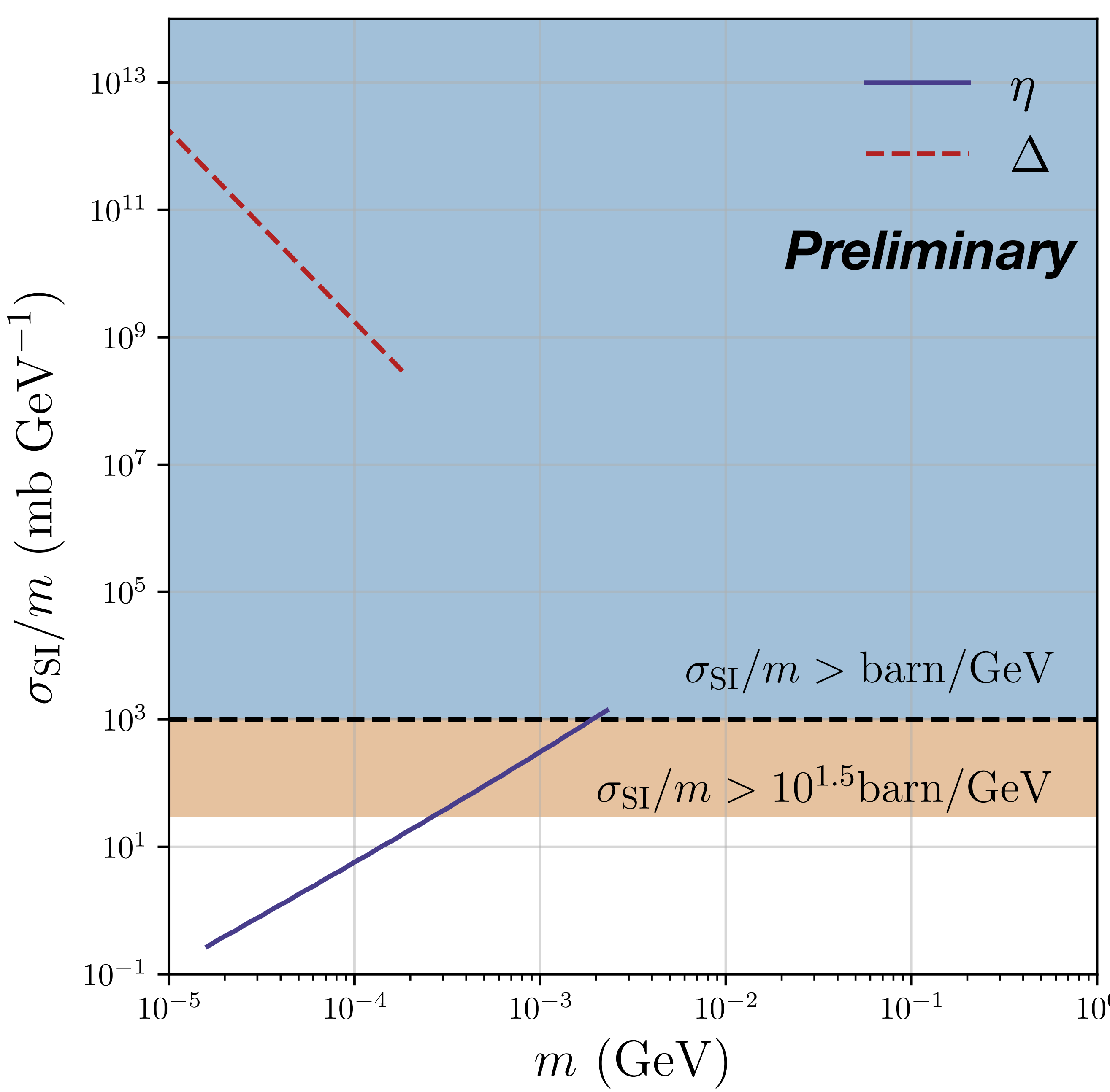
- Measurements from bullet cluster and shapes of halos put tight constraints on self interaction cross section: $\sigma_{\mathrm{SI}}/m_\chi < \mathrm{barn/GeV}$
- From measurements of CMB, we have constraints on effective number of neutrino species: $\Delta N_{\mathrm{eff}}^{\mathrm{CMB}} < 0.3$
- BBN additionally requires a small ΔN_{eff}

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

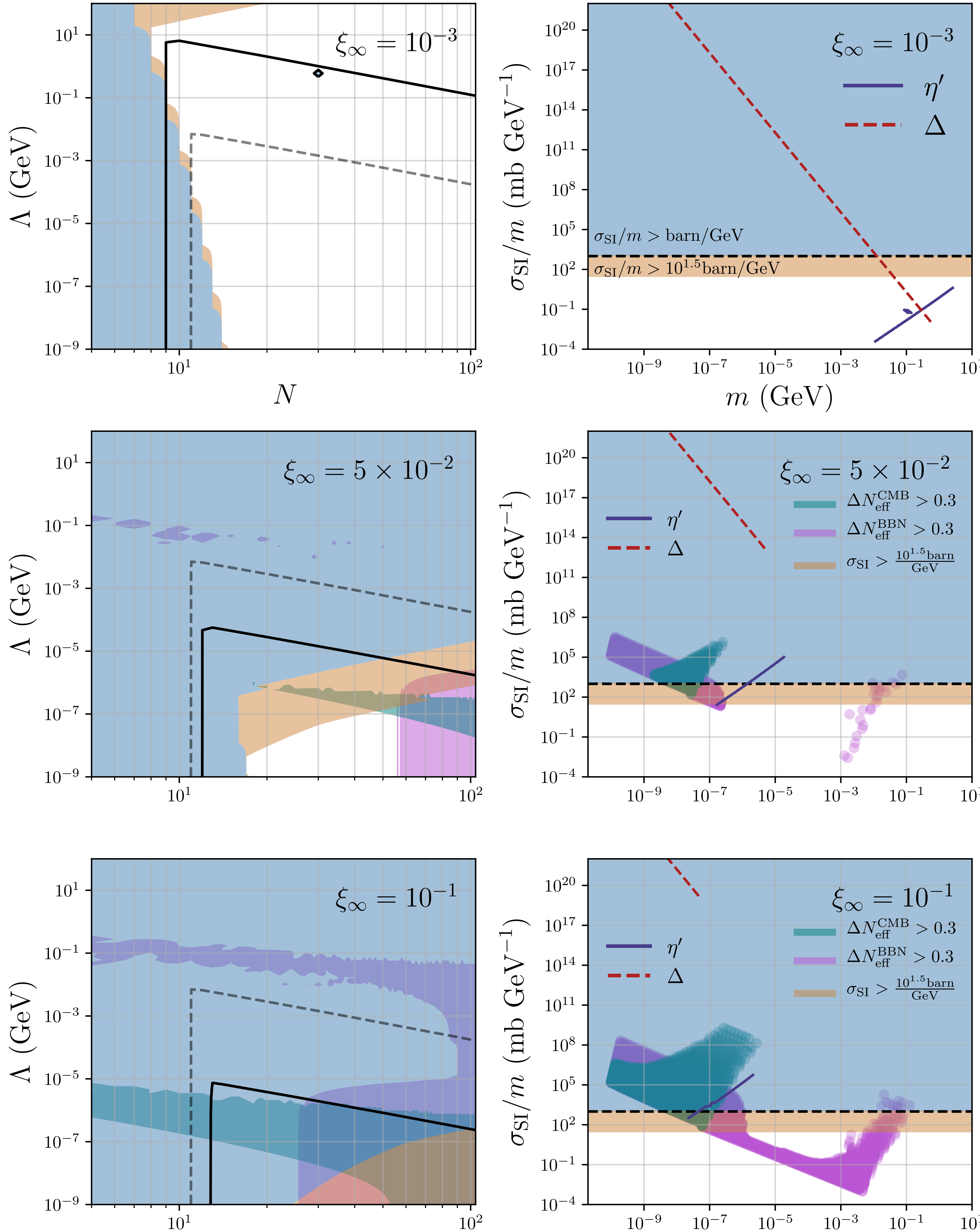
Results



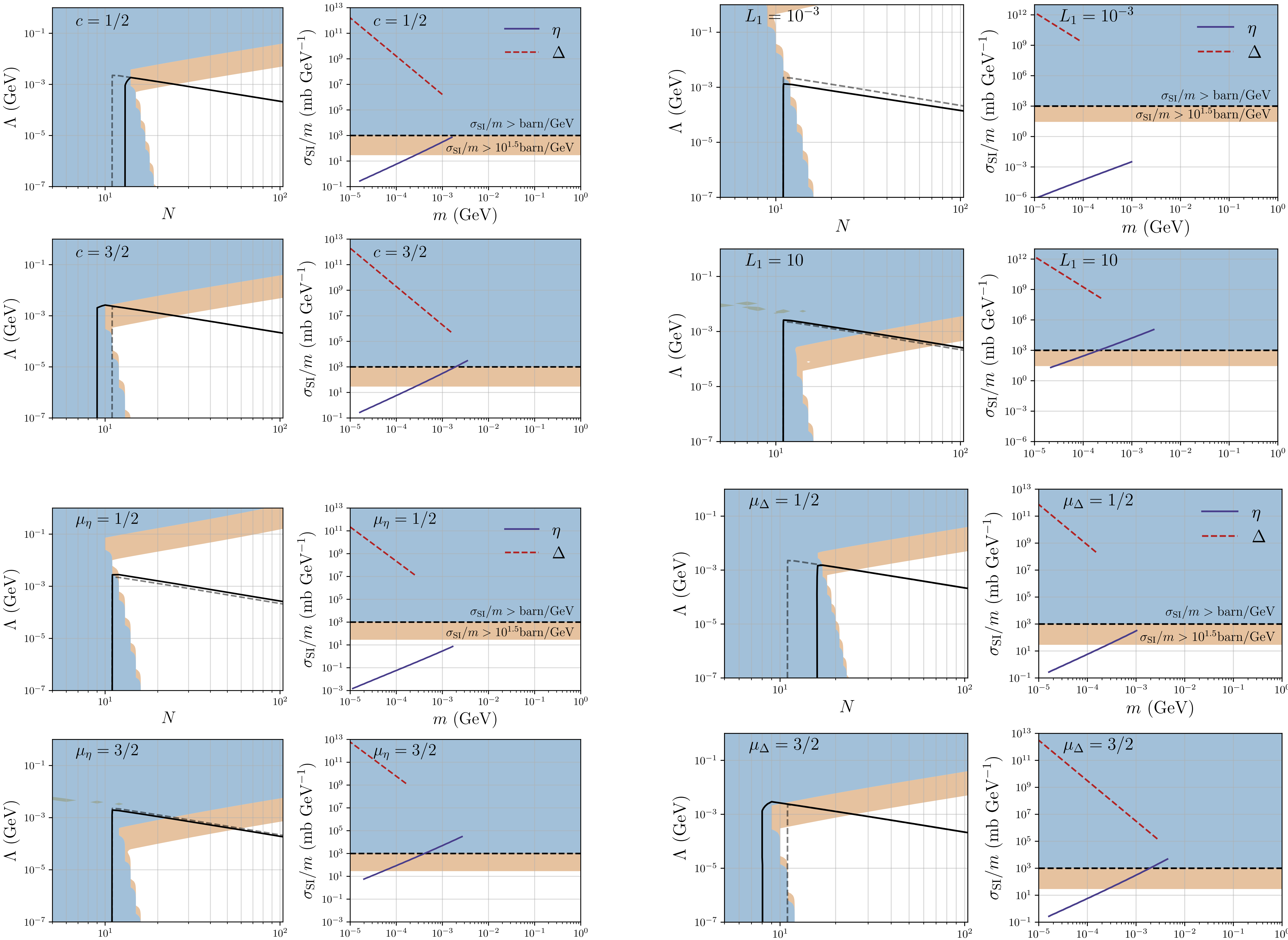
Preliminary
$\frac{\Omega_\Delta^2 \sigma_{SI}^\Delta / m_\Delta + \Omega_\eta^2 \sigma_{SI}^\eta / m_\eta}{\Omega_{CDM}^2}$
$\chi = \eta'$
$\chi = \Delta$
$L_1 = 1$
$c = 1$
$a = 1$
$\mu_\eta = 1$
$\mu_\Delta = 1$
$\xi_\infty = 10^{-2}$
Λ (GeV)
N



η
Δ
Preliminary
$\sigma_{SI}/m >$ barn/GeV
$\sigma_{SI}/m > 10^{1.5}$barn/GeV
σ_{SI}/m (mb GeV^{-1})
m (GeV)



$\xi_\infty = 10^{-3}$
Λ (GeV)
N
η'
Δ
$\sigma_{\rm SI}/m$ (mb GeV^{-1})
$\sigma_{\rm SI}/m >$ barn/GeV
$\sigma_{\rm SI}/m > 10^{1.5}$barn/GeV
m (GeV)
$\xi_\infty = 5 \times 10^{-2}$
$\Delta N_{\rm eff}^{\rm CMB} > 0.3$
$\Delta N_{\rm eff}^{\rm BBN} > 0.3$
$\sigma_{\rm SI} > \frac{10^{1.5}\rm barn}{\rm GeV}$
$\xi_\infty = 10^{-1}$



$c = 1/2$
Λ (GeV)
N
$\sigma_{\rm SI}/m$ (mb GeV^{-1})
m (GeV)
η
Δ
$\sigma_{\rm SI}/m >$ barn/GeV
$\sigma_{\rm SI}/m > 10^{1.5}$barn/GeV
$c = 3/2$
$\mu_\eta = 1/2$
$\mu_\eta = 3/2$
$L_1 = 10^{-3}$
$L_1 = 10$
$\mu_\Delta = 1/2$
$\mu_\Delta = 3/2$

Summary

- We can generically have η' - DM
- Temperature ratio of dark/SM must be small (smaller the better)
- Self-interaction constraints (mostly) rule out Δ-DM