Superheavy Thermal Dark Matter

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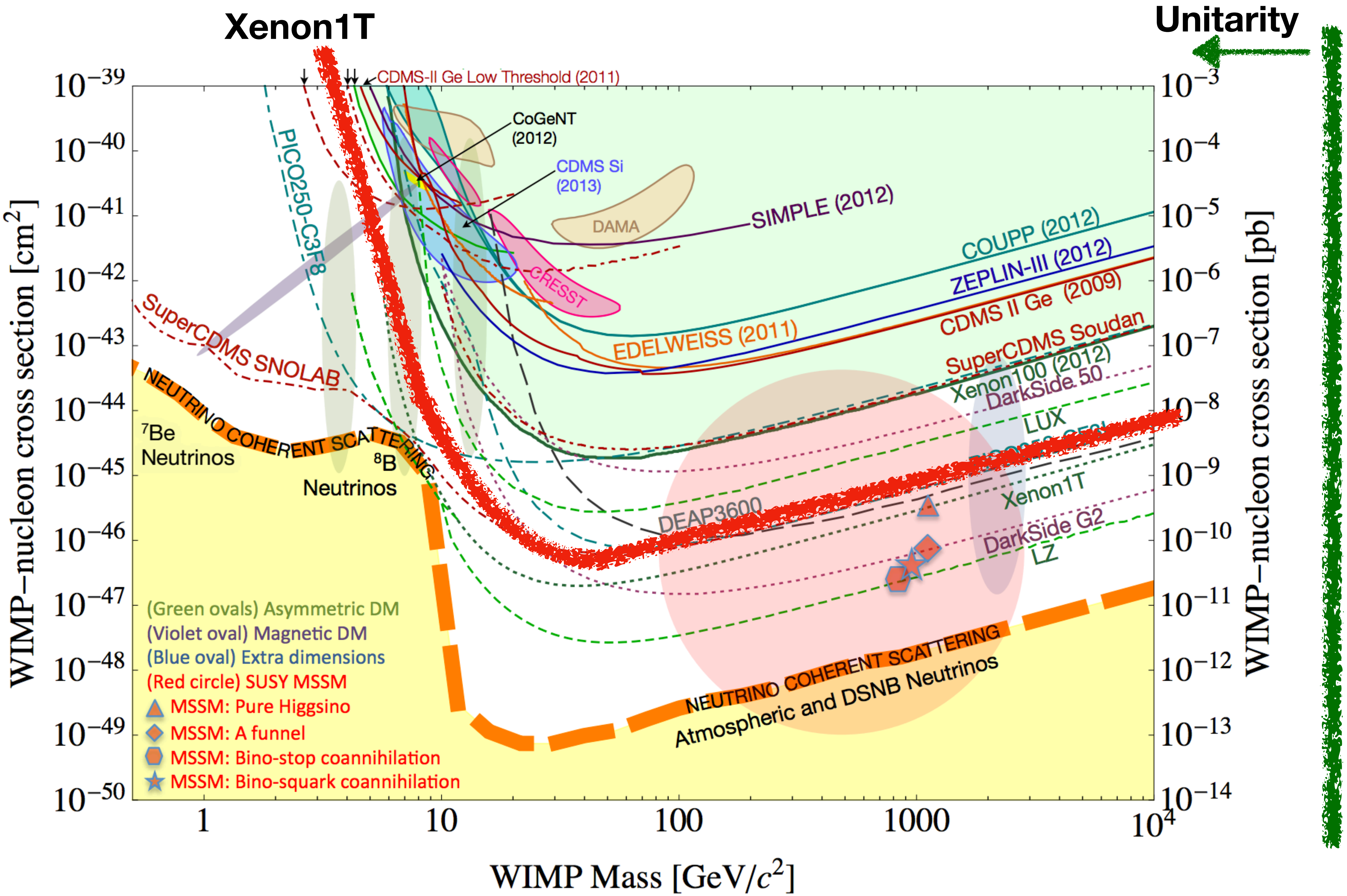
Work /w Joe Bramante [1701.05859]
& Saleh Hamdan [1710.03758]

Introduction



Superheavy Dark Matter

Superheavy implies well **above the unitarity limit** in range PeV — M_{pl}

aka **WIMPZillas**

- Gravitational production
  Chung, Crotty, Kolb, & Riotto [hep-ph/0104100]
- Inflationary preheating
  e.g. Kofman, Linde, & Starobinsky [hep-ph/9704452]
- Thermal inflation
  Hui & Stewart[hep-ph/9812345]
- Freeze-in production
  e.g. Higgs Portal: Kolb & Long [1708.04293]

Clean mechanism for Superheavy Dark Matter is **thermal freeze-out followed by dilution**

Cosmological Impact

After dark matter is frozen out its number does not change from interactions.

$$\Omega_{\rm DM} \propto m_{\rm DM} Y_{\rm DM} \propto m_{\rm DM} \frac{n_{\rm DM}}{n_\gamma}$$

However, **decaying particles** can heat SM bath, & **dilute $Y_{\rm DM}$** since $n_\gamma \propto T^3$.

$$\Omega_{\rm DM} \propto \zeta m_{\rm DM} Y_{\rm FO}$$

Randall, Scholtz & JU [1509.08477]
Berlin, Hooper & Krnjaic [1602.08490]
Bramante & JU [1701.05859]

Dilution factor ζ from temperature after decays $T_{\rm after}$ compared to without decays:

$$\zeta = \left(\frac{T_{\rm without}}{T_{\rm after}}\right)^3 \leq 1$$

Because of dilution, correct relic density for **weaker interactions with SM.**

Changes expectation for $m_{\rm DM}$ and σ_0 and **reduces tension with experiments**.

Cosmological Impact

Earliest cosmological evidence

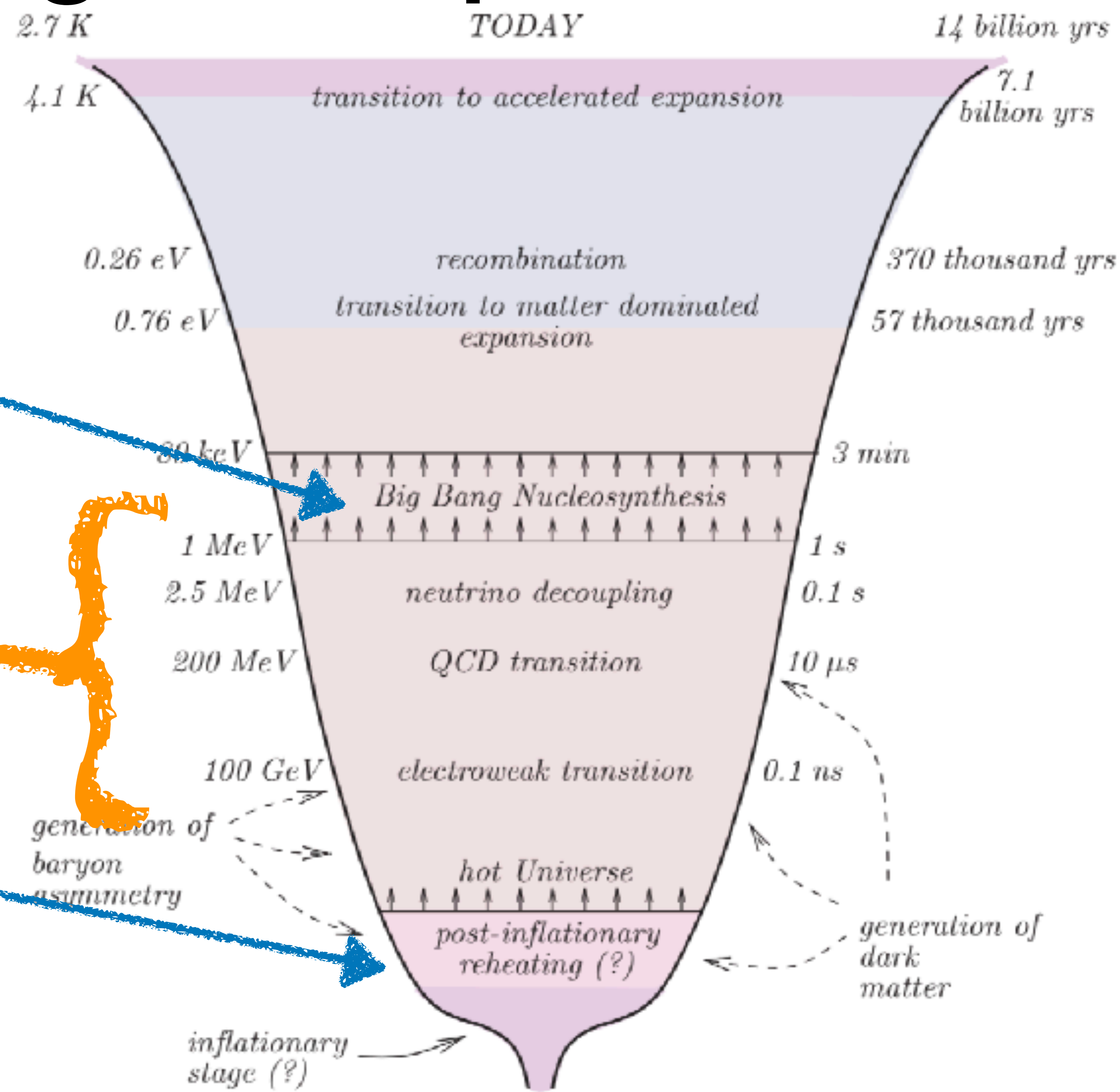
(know to be radiation dominated)

Non-Standard Model

cosmological events?

End of Inflation

(start of radiation domination?)



Dilution of Dark Matter

Dilution from a Decaying State

Add a state χ which becomes **matter-like** at T_{crit} — typically $T_{crit}=m_\chi$

Friedman equation for gives **evolution of energy** for $H(T_{\rm crit}) > H > \Gamma_\chi$

$$H^2 \simeq \frac{\pi^2}{90}\frac{g_\star T_{\rm crit}^4}{M_{\rm Pl}^2}\left[R_\chi\left(\frac{1}{\Delta a}\right)^3 + R_{\rm rad}\left(\frac{1}{\Delta a}\right)^4\right] \quad \textbf{with} \quad R_i \equiv \rho_i/(\rho_\chi+\rho_{\rm rad})\big|_{\rm crit}$$

The relative **energy density in χ grows** until it decays at:

$$\Delta a_\Gamma \equiv \frac{a(H=\Gamma_\chi)}{a(T_{\rm crit})} \simeq \left(\frac{\pi^2 g_\star T_{\rm crit}^4}{90 M_{\rm Pl}^2\Gamma_\chi^2}R_\chi\right)^{1/3}$$

If **χ is long lived**, it may evolves to dominate the energy density of Universe.

χ decay heats the bath to $T_{\rm RH}\simeq\sqrt{M_{\rm Pl}\Gamma_\chi}$ and **dilutes any frozen-out species**

$$\zeta = \left(\frac{T_{\rm without}}{T_{\rm after}}\right)^3 \simeq \left(\frac{R_{\rm rad}}{R_\chi}\Delta a_\Gamma^{-1}\right)^{3/4} \sim 10^{-10}\left(\frac{T_{\rm RH}}{10~{\rm MeV}}\right)\left(\frac{10^8~{\rm GeV}}{T_{\rm crit}}\right)$$

for $\quad R_{\rm rad}/R_\chi \simeq 1,$

Relic Density after Dilution

Consider "standard" dark matter **freeze-out followed by dilution**

$$\Omega_{\rm DM}^{\rm Relic} h^2 \simeq \zeta \times \left[10^9 \frac{\sqrt{g_\star}(n+1) x_{\rm FO}^{n+1}}{g_{\star \rm S} M_{\rm Pl} \sigma_n {\rm GeV}} \right]$$

For mediator and DM of similar mass, assuming s-wave annihilation, then

$$\sigma_0 \sim \alpha_{\rm DM}^2 / m_{\rm DM}^2$$

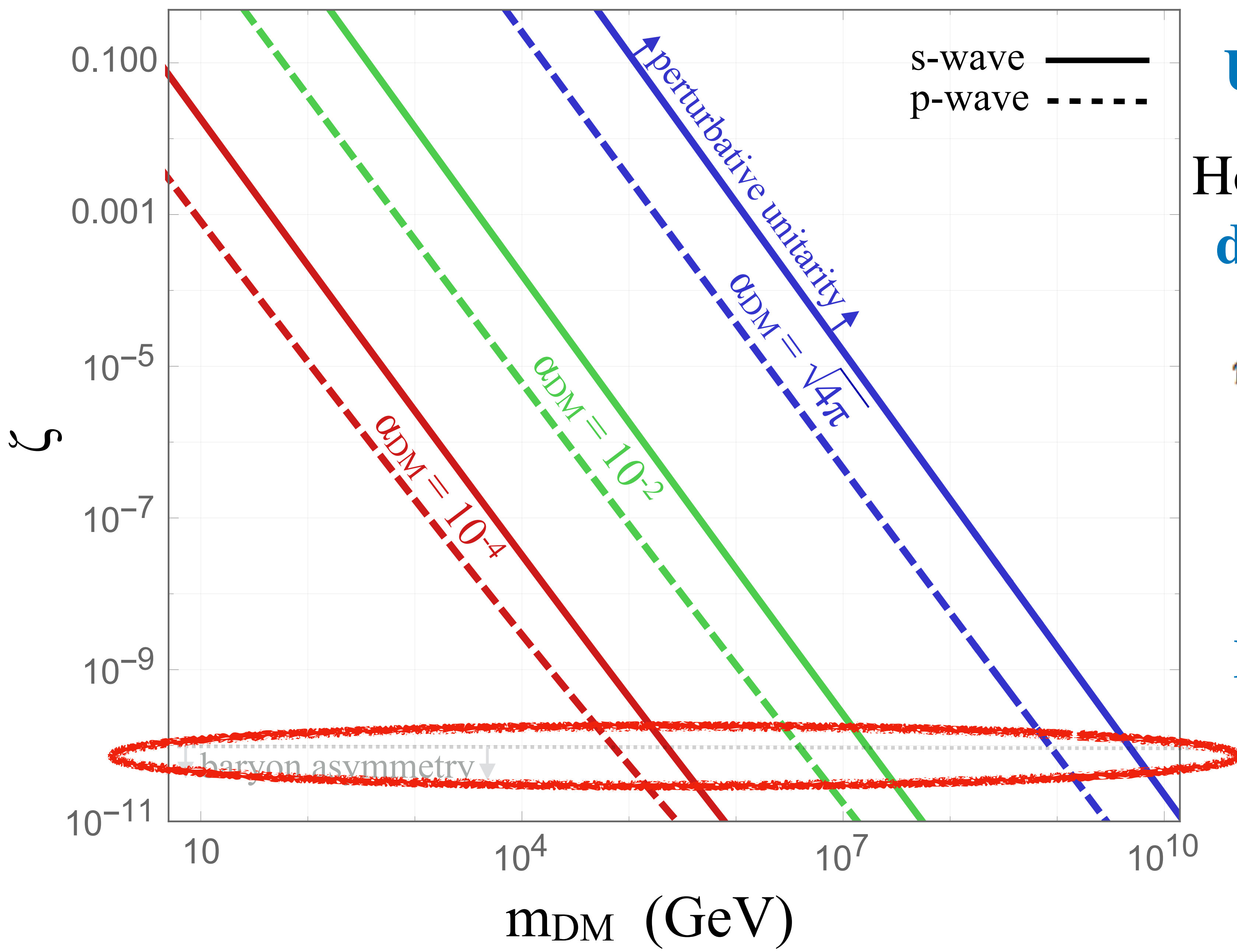
and **parametrically**

$$\Omega_{\rm DM}^{\rm Relic} h^2 \simeq 0.1 \left(\frac{m_{\rm DM}}{\rm PeV}\right)^2 \left(\frac{0.3}{\alpha_{\rm DM}}\right)^2 \left(\frac{\zeta}{10^{-5}}\right).$$

- Entropy injections permit correct relic density for **smaller couplings.**
- **Superheavy Dark Matter** arises readily for modest entropy injections.

Relic Density after Dilution

The dilution ζ needed to match the **relic density** for given $\sigma \sim \frac{\alpha_{\rm DM}^2}{m_{\rm DM}}$



Bramante & JU [1701.05859]

Unitarity bound relaxed…

However, entropy injection also **dilutes particle asymmetries**

$$\eta_B^{\rm final} = \eta_B^{\rm initial}\zeta$$
$$\simeq 10^{-10}\left(\frac{\eta_B^{\rm initial}}{10^{-5}}\right)\left(\frac{\zeta}{10^{-5}}\right)$$

Maximum dilution assuming high scale baryogenesis

Unitarity limit
relaxed to 10^{10} GeV

Parameter Space

To dilute dark matter via χ decay and avoid cosmological constraints:

a). Assume: Universe radiation dominated during freeze-out

b). Decay of χ prior to BBN

c). Decay of χ after dark matter freeze-out

The requirement can be expressed $T_{\rm crit} = m_\chi < T_{\rm FO}$ which bounds χ

$$m_\chi < 10^9\ \mathrm{GeV}\left(\frac{10}{x_{\rm FO}}\right)\left(\frac{m_{\rm DM}}{10^{10}\ \mathrm{GeV}}\right)$$

Freeze-out during **matter domination** possible, but changes calculation.

Parameter Space

To dilute dark matter via χ decay and avoid cosmological constraints:

a). Assume: Universe radiation dominated during freeze-out

b). Decay of χ prior to BBN

c). Decay of χ after dark matter freeze-out

The BBN constraint implies $T_{\rm RH} \simeq \sqrt{M_{\rm Pl}\Gamma_\chi}$ > 10 MeV .

Assuming $R_{\rm rad}/R_\chi \simeq 1$, and $\sigma_0 \sim \alpha_{\rm DM}^2/m_{\rm DM}^2$ BBN constraints imply

$$m_\chi \leq 10^{-8}\ {\rm GeV} \left(\frac{m_{\rm DM}}{\rm GeV}\right)^2 \left(\frac{1}{\alpha_{\rm DM}^2}\right)^2 \left(\frac{T_{\rm RH}}{10\ {\rm MeV}}\right)$$

Parameter Space

To dilute dark matter via χ decay and avoid cosmological constraints:

a). Assume: Universe radiation dominated during freeze-out

b). Decay of χ prior to BBN

c). Decay of χ after dark matter freeze-out

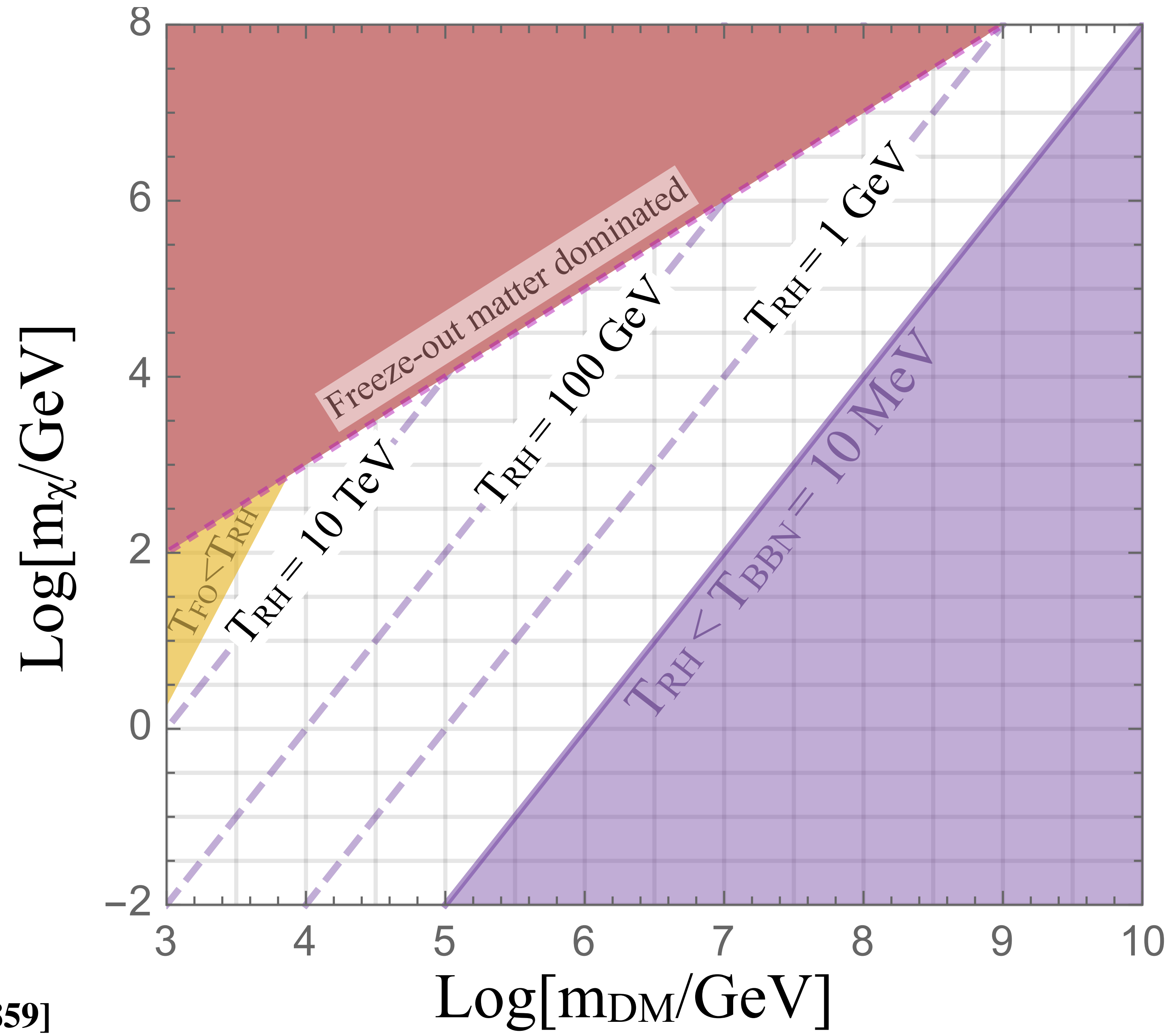
For dark matter to be **diluted rather than repopulated** require that energy injection occurs after dark matter freeze-out

This implies $T_{\rm FO} \gtrsim T_{\rm RH} \sim \sqrt{\Gamma_\chi M_{\rm Pl}}$, which constrains

$\Gamma_\chi \lesssim 10^{-8}\ {\rm GeV} \left(\frac{m_{\rm DM}}{1\ {\rm PeV}}\right)^2 \left(\frac{10}{x_{\rm FO}}\right)^2$ or equivalently $T_{\rm RH} \lesssim 10^5\ {\rm GeV} \left(\frac{m_{\rm DM}}{1\ {\rm PeV}}\right) \left(\frac{10}{x_{\rm FO}}\right)$

Parameter Space

Putting this together, the parameter space for $\sigma = 1/(m_{DM})^2$, and $R_\chi/R_{rad} = 1$



Bramante & JU [1701.05859]

Matter Dominated Freeze-out

Changes to the Expansion Rate

Notable, expansion rate H depends critically on cosmology:

$$H \propto \begin{cases} T^2 & \text{During radiation domination} \\ T^4 & \text{During particle decays (heating)} \\ T^{3/2} & \text{During matter domination} \end{cases}$$

Giudice, Kolb, and Riotto, PRD 64 (2001) 023508

Hamdan & JU [1710.03758]

Also: Kamionkowski & Turner PRD 42 (1990) 3310

Recall $T_{\rm FO}$ is defined $\Gamma(T_{\rm FO}) = H(T_{\rm FO})$, changing $T_{\rm FO}$ impacts final $Y_{\rm DM}$.

Matter Dominated Freeze-out

One can **emulate** the standard Boltzmann treatment

$$\dot{n}_X + 3Hn_X = -\langle\sigma v\rangle[n_X^2 - (n_X^{\rm eq})^2]$$

but with different form for H

$$H \simeq H_\star \left(\frac{g_*(T)}{g_*(T_\star)}\right)^{3/8}\left(\frac{T}{T_\star}\right)^{3/2}\left[(1-r)+r\left(\frac{T}{T_\star}\right)\right]^{1/2} \text{ for } r = \begin{cases} 1 & \text{RD} \\ 0 & \text{MD}\end{cases}$$

Where $T_\star$ is temperature χ becomes matter-like and $H_\star \equiv H(T_\star)$

Radiation dominated freeze-out

$$T_{\rm FO}^{\rm RD} \simeq \frac{m_{\rm DM}}{\ln\left[m_{\rm DM}M_{\rm Pl}\sigma_0\right]}$$

$$Y_{\rm FO}^{\rm RD} = 3\sqrt{\frac{5}{\pi}}\frac{\sqrt{g_\star}}{g_{\star S}}\frac{(n+1)x_F^{n+1}}{M_{\rm pl}m_{\rm DM}\sigma_0}$$

Scherrer and Turner, PRD 33 (1986) 1585

Matter dominated freeze-out

$$T_{\rm FO}^{\rm MD} \simeq \frac{m_{\rm DM}}{\ln\left[m_{\rm DM}^{3/2}M_{\rm Pl}\sigma_0/\sqrt{T_\star}\right]}$$

$$Y_{\rm FO}^{\rm MD} = 3\sqrt{\frac{5}{\pi}}\frac{\sqrt{g_*}}{g_{*S}}\frac{(n+3/2)x_F^{n+3/2}}{M_{\rm Pl}m_X\sigma_0\sqrt{x_\star}}\ .$$

Hamdan & JU [1710.03758]

Matter Dominated Freeze-out

$Y_{\rm DM}$ in matter dominated FO **different to radiation dominated** case.

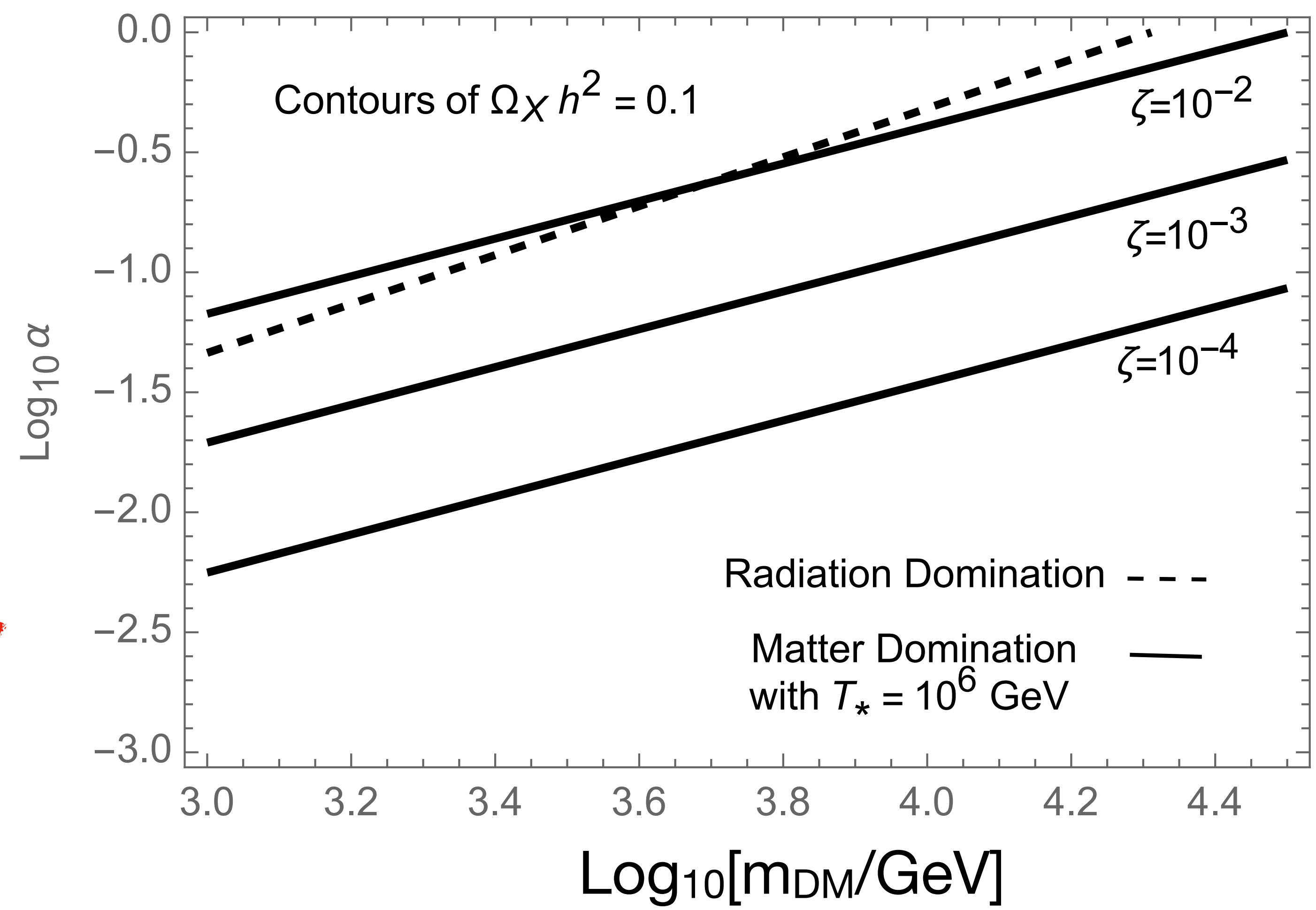
Radiation domination restored after freeze-out as **"matter" decays** to SM.

Required because **observations imply** radiation domination prior to current epoch.

This **leads to dilution ζ** of the dark matter abundance:

$$\Omega_{\rm DM} = \zeta \times \frac{s_0 m_X Y_{\rm FO}}{\rho_c}$$

More dilution implies smaller couplings



Hamdan & JU [1710.03758]

Again, **weakening search limits** compared to radiation dominated FO.

Matter Dominated Freeze-out

For DM freeze-out **during matter domination**,
whilst avoiding cosmological constraints:

a). Universe **matter dominated** during freeze-out

b). Decay of χ prior to **BBN**

c). Decay of χ after dark matter freeze-out

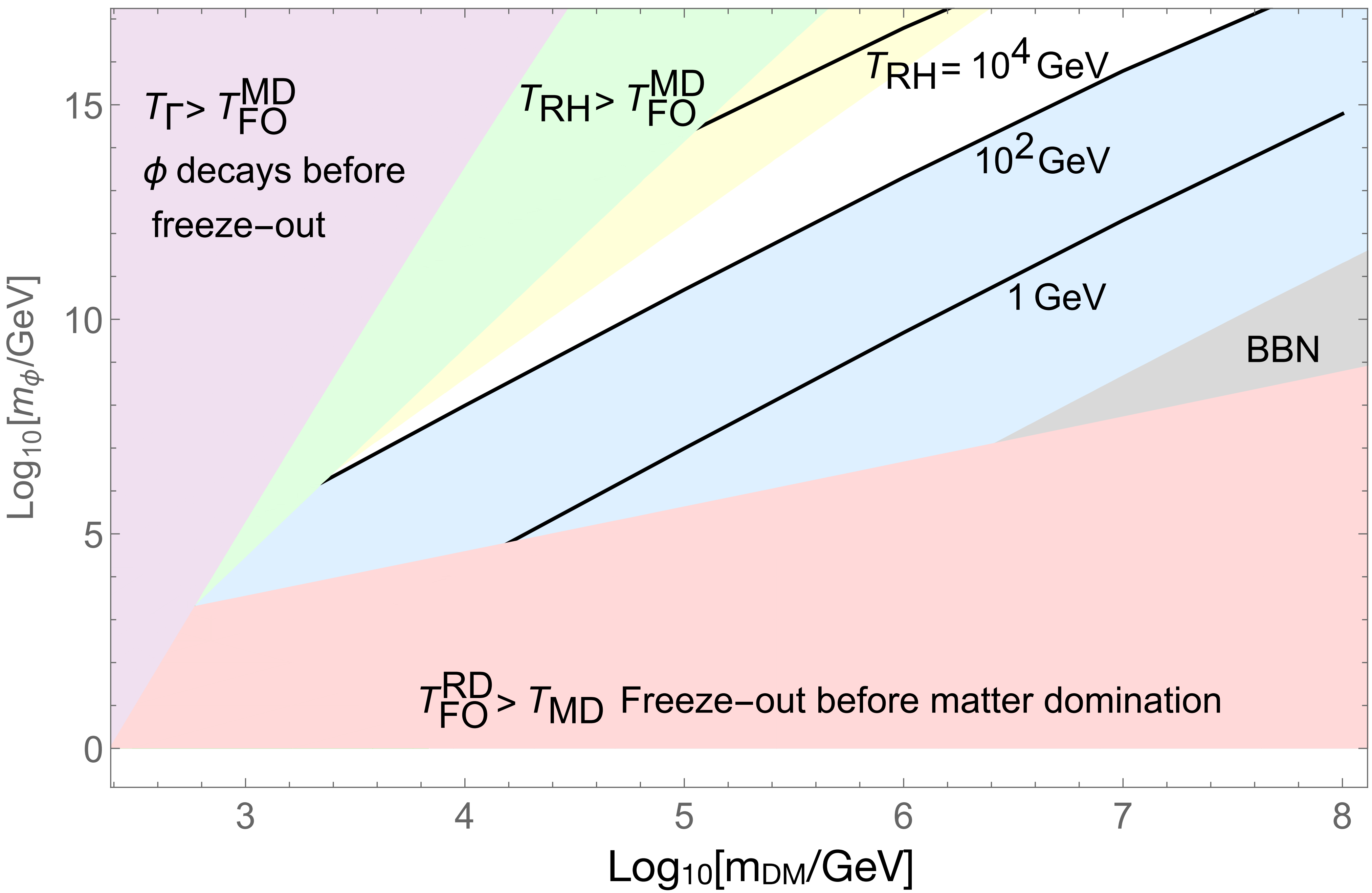
d). χ **decays negligible** during dark matter freeze-out

o.w./ similar to Giudice, Kolb, and Riotto, PRD 64 (2001) 023508

e). Decays of χ prior to **EWPT** (optional - model dependent)

MDFO Parameter space

Putting this together, the parameter space for $\sigma \sim \frac{\alpha_{\rm DM}^2}{m_{\rm DM}}$, $\alpha = 0.1$ and $T_\star \simeq m_\phi$



Hamdan & JU [1710.03758]

Superheavy Asymmetric DM

Asymmetric Dark Matter

Suppose dark matter carries a **conserved quantum number** analogous to B or L.

Dark matter could have **particle-antiparticle asymmetry**, similar to baryons.

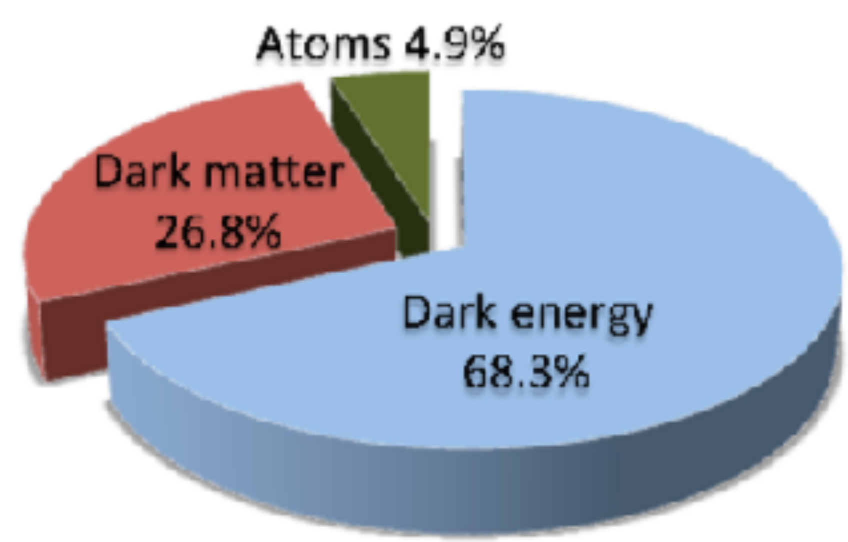
ADM: dark matter asymmetry $\eta_{\rm DM}$ can be **responsible for DM relic density**

Requires the abundance of **particle anti-particle pairs** $\Omega^{\rm FO}_{\rm Sym} \ll \Omega^{\rm FO}_{\rm Asym} \propto \eta_{\rm DM}$

ADM implies the relationship

$$\frac{\Omega^{\rm Relic}_{\rm DM}}{\Omega^{\rm Relic}_{B}} = \frac{m_{\rm DM}\ \eta^{\rm now}_{\rm DM}}{m_p\ \eta^{\rm now}_{B}} \approx 5.5$$

Classic models favour $m_{\rm DM}$ ~ 5 GeV



Superheavy Asymmetric Dark Matter

Superheavy ADM needs a much smaller asymmetry

$$\frac{\Omega_{\rm DM}^{\rm Relic}}{\Omega_{B}^{\rm Relic}} = \frac{m_{\rm DM}\ \eta_{\rm DM}^{\rm now}}{m_p\ \eta_B^{\rm now}} \simeq \left(\frac{m_{\rm DM}}{1\ {\rm PeV}}\right)\left(\frac{\eta_{\rm DM}^{\rm now}}{6\times 10^{-16}}\right)$$

For DM to be asymmetric the **symmetric component must annihilate.**

Thus a form of the **unitarity bound** remains for ADM.

Baldes & Petraki [1703.00478]

Heavy ADM possible via entropy injection: $\Omega_{\rm DM}^{\rm Relic} = \frac{s_0 m_{\rm DM}}{\rho_c}\zeta\left[Y_{\rm Sym}^{\rm FO} + \eta_{\rm DM}^{\rm FO}\right]$

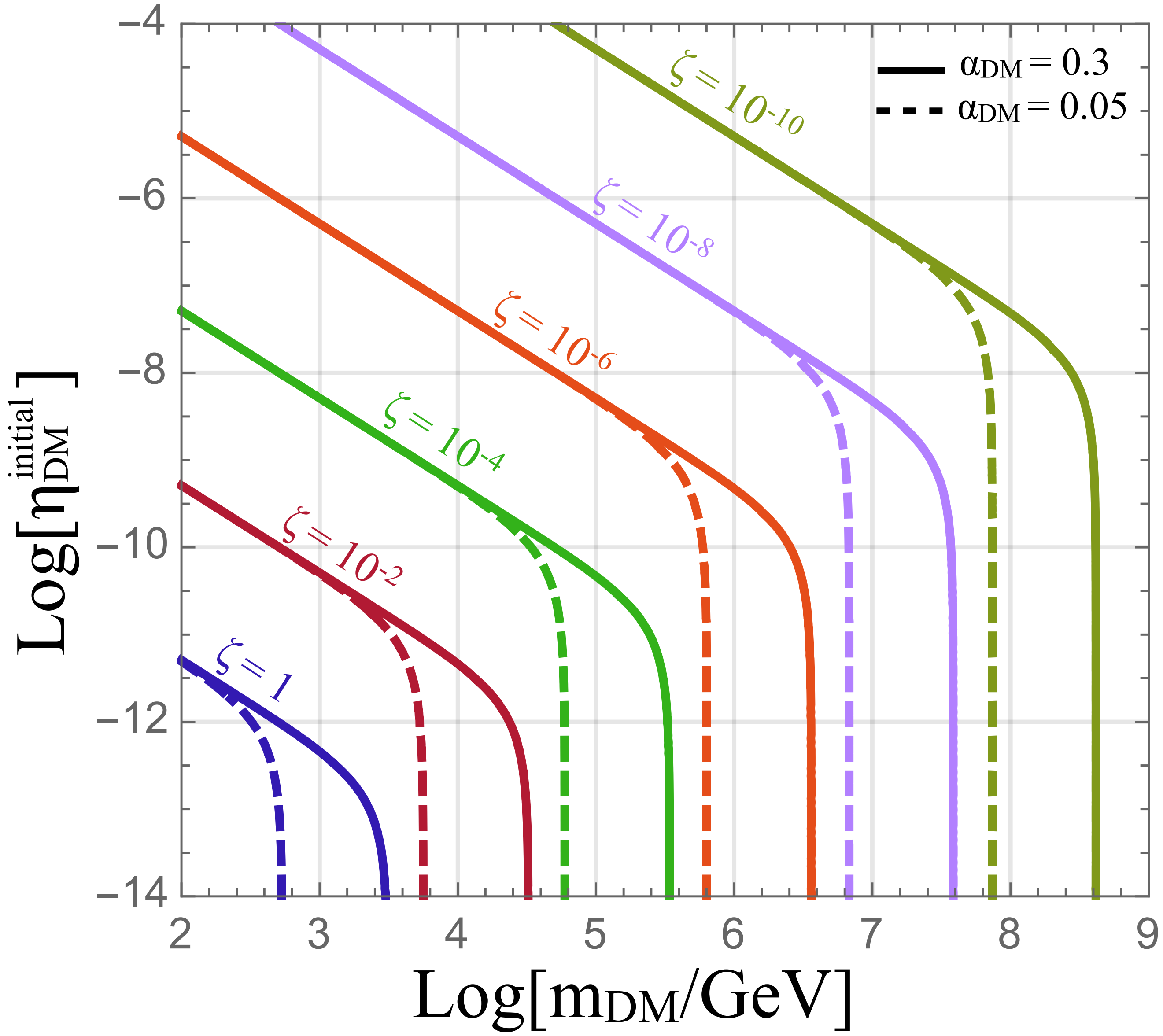
Now entropy injection **dilutes both asymmetries and frozen out species**

$$\Omega_{\rm DM}^{\rm Relic}h^2 \simeq 0.01\left(\frac{m_{\rm DM}}{\rm PeV}\right)^2\left(\frac{0.3}{\alpha_{\rm DM}}\right)^2\left(\frac{\zeta}{10^{-6}}\right) + 0.1\left(\frac{\eta_{\rm DM}^{\rm initial}}{5\times 10^{-10}}\right)\left(\frac{m_{\rm DM}}{\rm PeV}\right)\left(\frac{\zeta}{10^{-6}}\right)$$

For appropriate parameters relic abundance is correct and $\Omega_{\rm Sym}^{\rm relic} \ll \Omega_{\rm Asym}^{\rm relic}$

Dilution of DM Asymmetry

The dilution ζ needed to **match the relic density** for given $\sigma \sim \frac{\alpha_{\rm DM}^2}{m_{\rm DM}}$



Transition to vertical implies symmetric component becomes dominant.

Bramante & JU [1701.05859]

Conclusion

- Entropy injection is **simple extension** and can drastically alter expectations.
- Dilution permit correct relic density for **heavier DM** or **smaller couplings**.
- **High scale baryogenesis** implies maximum dilution & unitarity limit of 10^{10} GeV
- Superheavy dark matter can potentially give (spectacular) **signals**.

  e.g. Blasi, Dick, Kolb [astro-ph/0105232]
- Superheavy ADM impacts **neutron stars** & perhaps solve missing pulsar problem.
  - **See talk of Tim Linden.**
- Early periods of **matter domination** may also have observable implications.
  - **See talk of Adrienne Erickcek.**

Thank you.