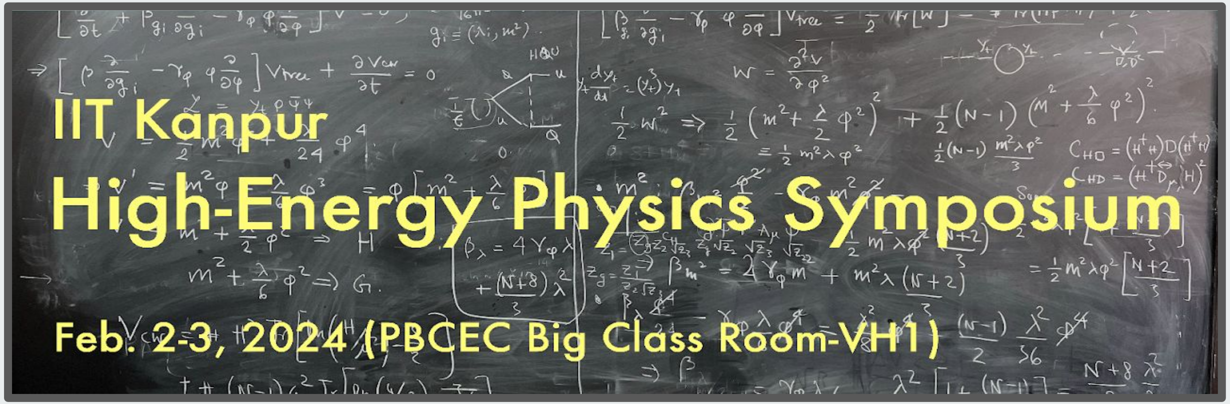
Unitarity Bound on Dark Matter in Low-temperature Reheating Scenarios

Based on

arXiv : 2311.01587 (Accepted In PRD)

In collaboration with Nicolás Bernal and Partha Konar



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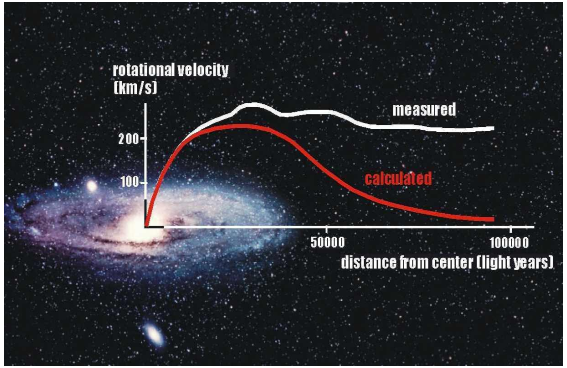
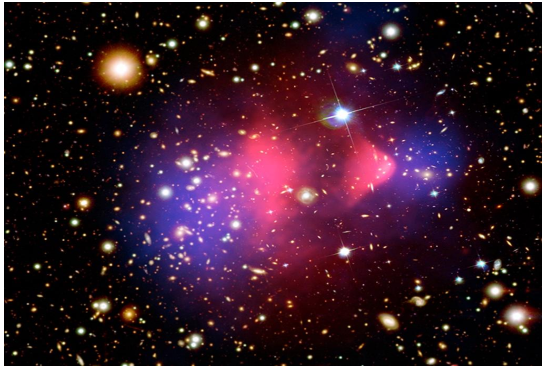
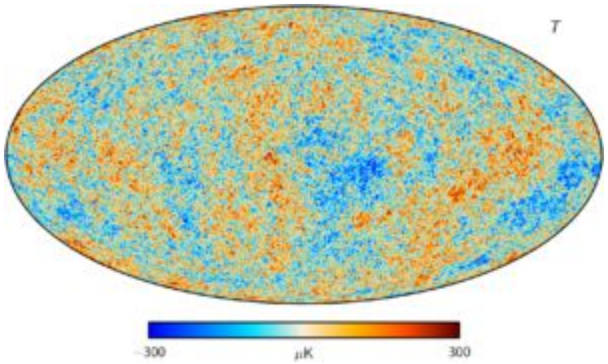
February 2, 2024

Evidences of dark matter at different scales







Properties inferred from observations

- ➢ Possess gravitational interaction
- ➢ Electrically neutral
- ➢ Collisionless
- ➢ 80 percent of matter (26 percent of total energy budget)
- ➢ Stable and relic density = 0.12

Freeze-out of thermal dark matter

Assumption: DM maintains thermal equilibrium with bath particles

- ***Steps to freeze-out (WIMP Picture)***

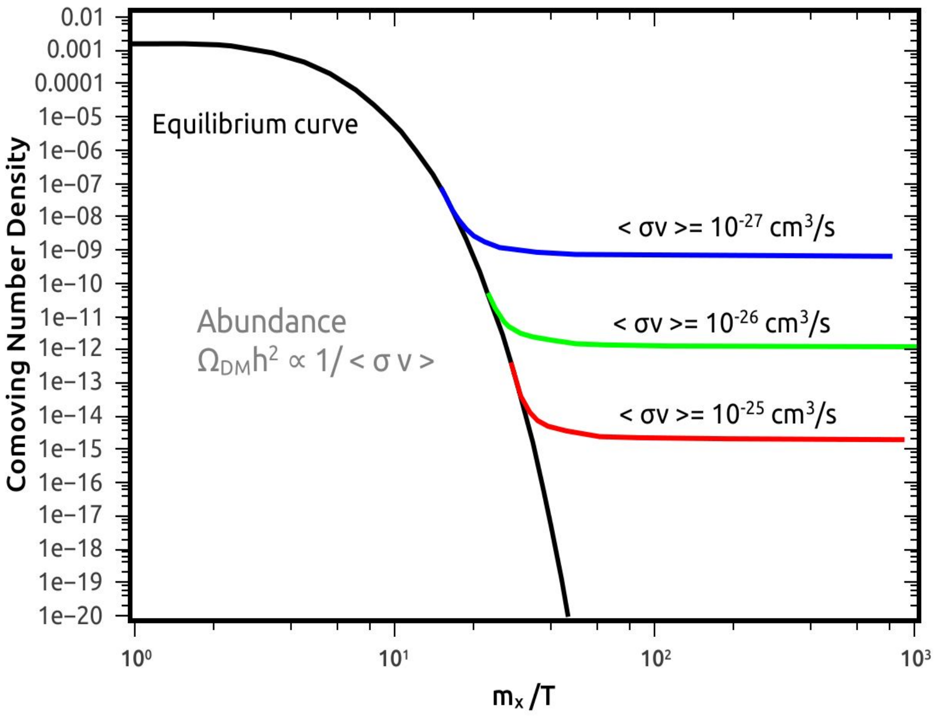
$$\mathrm{DM\,DM} \Leftrightarrow \mathrm{SM\,SM}$$

$$\mathrm{DM\,DM} \Rightarrow \mathrm{SM\,SM}$$

$$\mathrm{DM\,DM} \not\Rightarrow \mathrm{SM\,SM}$$

- ***Criterion for freeze-out***

$$\Gamma(= n_{\mathrm{DM}}\langle\sigma v\rangle) \simeq H$$



Required Cross-section to satisfy relic density

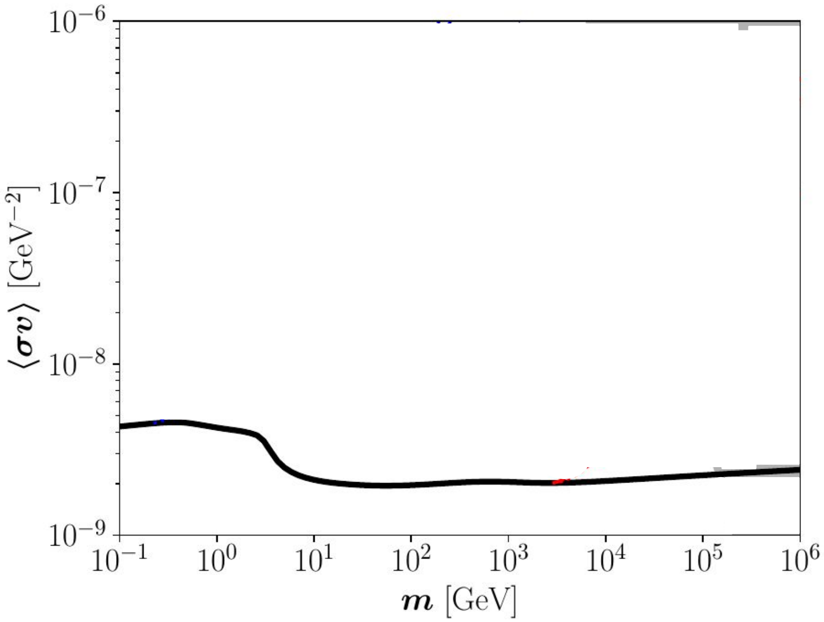
❖ ***Boltzmann equation***

$$\frac{dY}{dx} = -\frac{\langle \sigma v \rangle s}{x\,H}\left[Y^2 - Y_{\rm eq}^2\right]$$

❖ $Y = \frac{n}{s}, x = \frac{m}{T}$

❖ ***Relic density***

$$\Omega h^2 = 2.755 \times 10^8 \times m \times Y$$



Unitarity and Upper bound on dark matter mass

- *Unitarity puts an upper limit on the inelastic cross-section for 2 to 2 process*

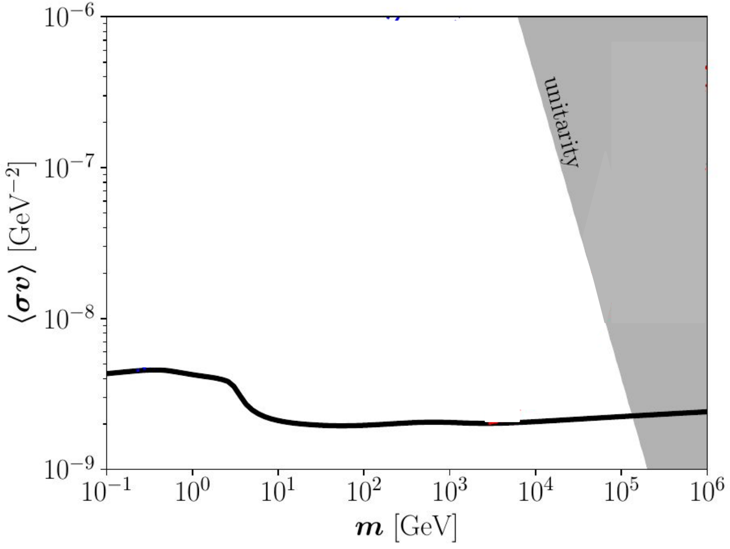
$$\langle \sigma_{2\to 2} v_{\rm rel} \rangle_{\rm max} = \sum_l \frac{4\sqrt{\pi}}{m^2}(2l+1)\sqrt{x}$$

- *Freeze-out point*

$$H(T_{\rm fo}) = n_{\rm eq}(T_{\rm fo})\langle \sigma v \rangle$$

- *Upper bound on DM mass*

$$\Longrightarrow m \simeq 140 \text{ TeV}$$

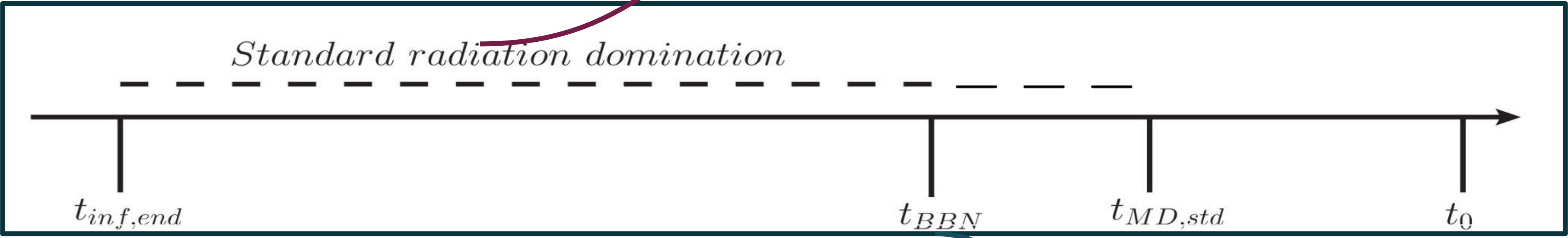


[Phys. Rev. Lett. 64, 615]

Standard picture of cosmology

- ***Standard cosmological picture***

No evidence of radiation domination



$T_{\rm BBN} \simeq 4\ \mathrm{MeV}$

- ***DM mass range*** $\sim\ (100\ \mathrm{GeV} - 10\ \mathrm{TeV})$

$x_{\rm fo}(= m/T_{\rm fo}) \sim (20 - 30)$ ⇒ $T_{\rm fo} \sim\ (4 - 400)\ \mathrm{GeV}$

- ***History is unknown when the freeze-out occurs***

Fast Expansion

- *Energy density of the early Universe is dominated by a species,* ϕ

$$\rho_\phi \propto a^{-(4+n)}$$

- *The modified Hubble rate,*

$$H(T) \simeq H_R(T) \times \begin{cases} \left(\frac{T}{T_{\rm rh}}\right)^{n/2} \text{ for } T \geq T_{\rm rh} \\ 1 \text{ for } T \leq T_{\rm rh} \end{cases}$$

where, $H_R(T) = \frac{\pi}{3}\sqrt{\frac{g_{\star s}(T)}{10}}\frac{T^2}{M_P}$

$$T_{\rm rh} : \rho_\phi(T_{\rm rh}) = \rho_R(T_{\rm rh})$$

- *BBN constraints,* $T_{\rm rh} \geq (15.4)^{1/n}\ \mathrm{MeV}$

[*JCAP* 05 (2017) 012]

Effect of fast expansion on freeze-out

Fast expansion makes difficult to maintain thermal equilibrium

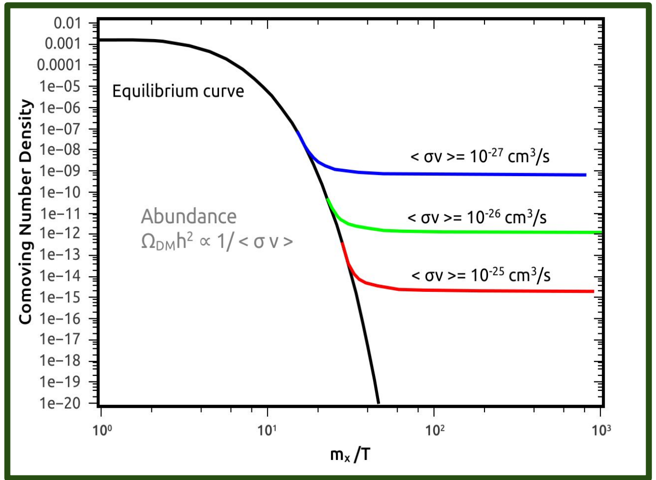
⇩

Early freeze-out occurs

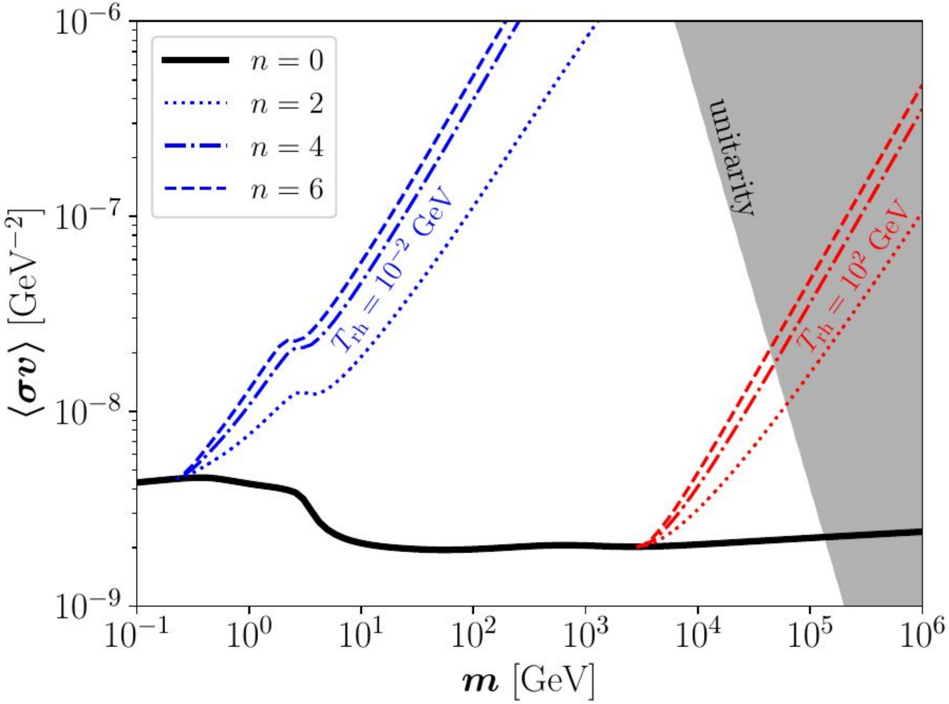
⇩

Provides large abundance of dark matter

- *Relic density,* $\Omega h^2 \propto mY$
- *Needs larger cross section to satisfy relic density*



Required Cross-section in Fast Expansion



Fast expansion provides more stringent bound

Late time reheating

- *Energy density of the early Universe is dominated by a species,* ϕ

$$\rho_\phi \propto a^{-3}$$

- *The Hubble rate,*

$$H(T) \simeq \begin{cases} H_R(T_{\rm rh})\left(\frac{T}{T_{\rm rh}}\right)^4 & \text{for } T \geq T_{\rm rh} \\ H_R(T) & \text{for } T \leq T_{\rm rh} \end{cases}$$

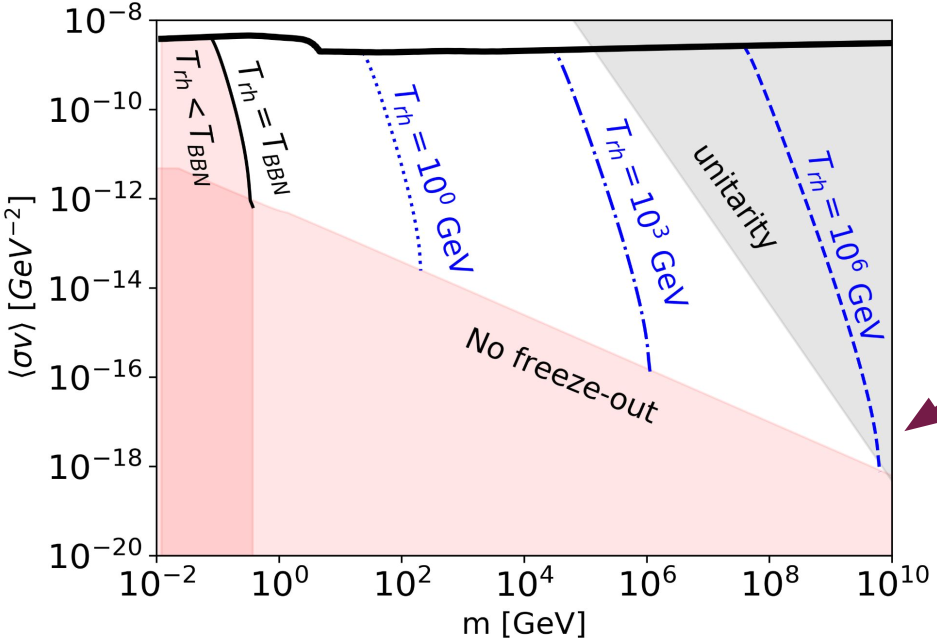
$$T_{\rm rh} : \rho_\phi(T_{\rm rh}) = \rho_R(T_{\rm rh})$$

- *BBN constraints,* $T_{\rm rh} \geq T_{\rm BBN}$

- *Late time reheating demands smaller cross-section due to entropy production*

[JCAP 12 (2022) 017]

Required Cross-section in Late time reheating



Late time reheating relaxes the bound

Summary and Conclusion

- ➢ Non-standard cosmology has a significant impact on the DM phenomenology
- ➢ Fast expansion demands larger cross-section which makes the Unitarity constraints more tighter
- ➢ Late time reheating demands smaller cross-section which relaxes the Unitarity bound
- ➢ Very smaller cross-section is disallowed by no freeze-out criterion

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- ➢ Non-standard cosmology has a significant impact on the DM phenomenology
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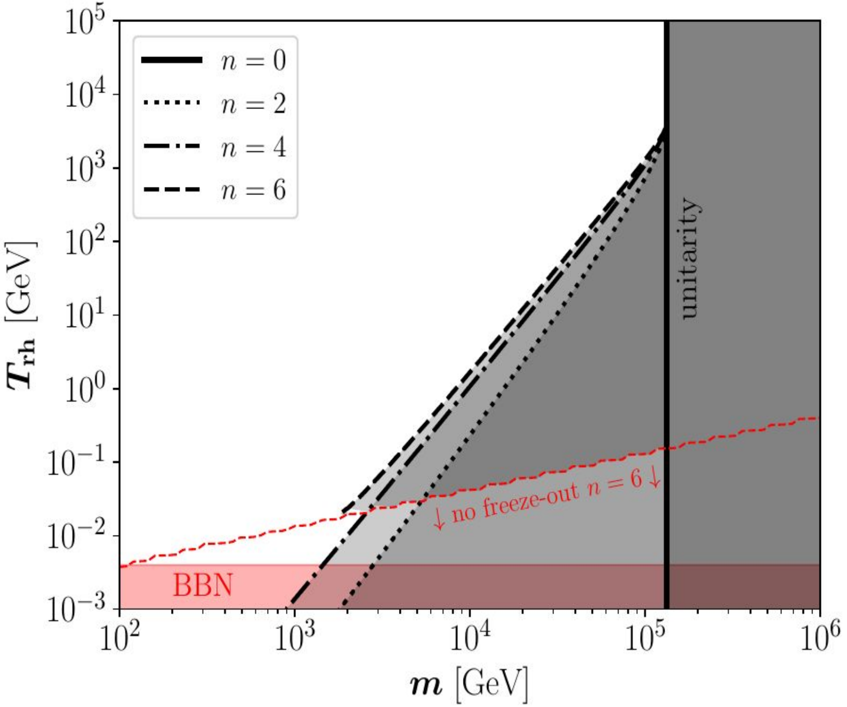
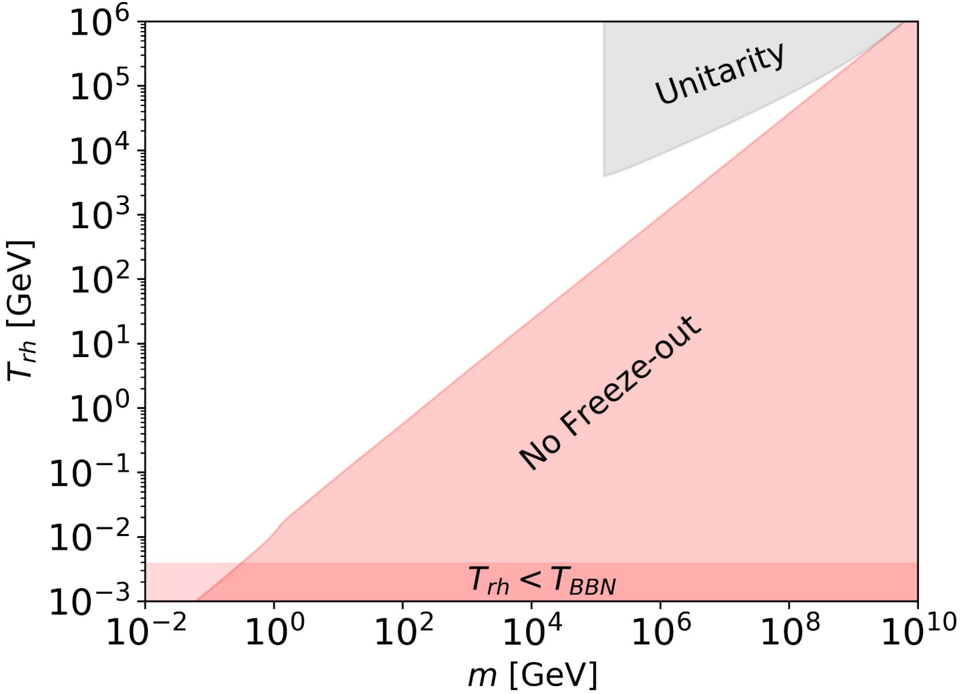
Thank You

BACK UP

Summary plot



Summary plot



Possibility of other number changing process other than 2 to 2

- *Generally, thermal dark matter involves 2 to 2 inelastic interaction*

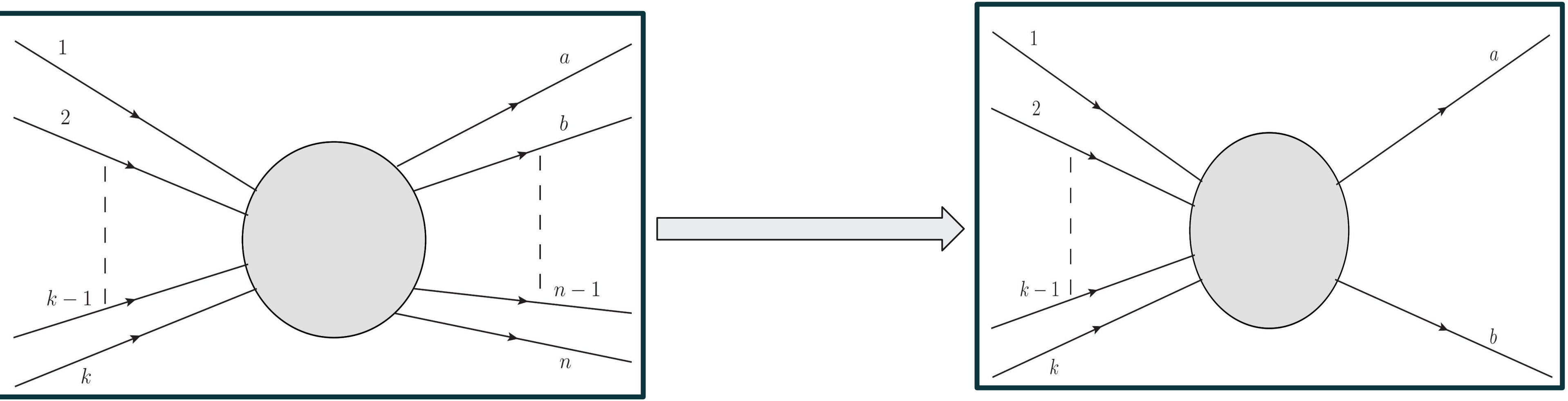
- *DM number changing process can solely occur in dark sector itself*

- *Dominating number changing process may involve 3 to 2 or 4 to 2 … interaction*

[Phys. Rev. Lett. 113, 171301 ; JHEP 10 (2017) 162]

- *Is it possible to obtain a Unitarity bound for any general process ?*

Consequence of S-matrix Unitarity for general process



- *Maximum cross-section allowed by Unitarity for 2 to k process*

$$\langle \sigma_{2\to k} v_{\rm rel}\rangle_{\max} = \sum_l (2l+1)\,\frac{4\sqrt{\pi}}{m^2}\sqrt{x}\,e^{-(k-2)x}$$

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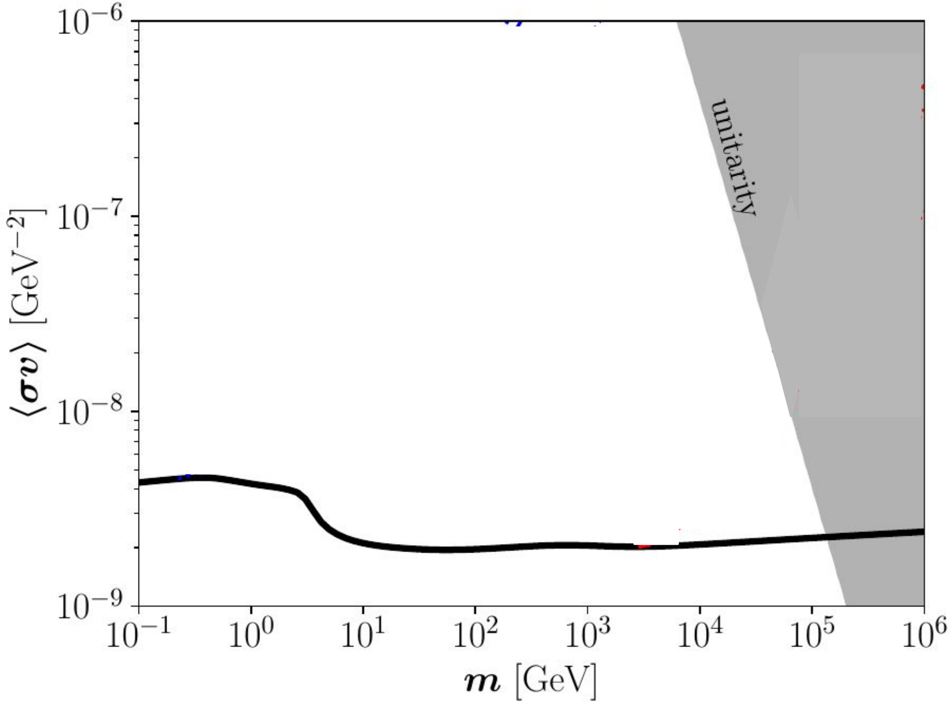
Boltzmann equation for general DM number changing process

- ***Boltzmann equation for k to 2 annihilation process***

$$\frac{dn}{dt} + 3Hn = -\left[n_1 n_2 \ldots . n_k \langle \sigma_{k\to 2} v_{\rm rel}^{k-1} \rangle - n_a n_b \langle \sigma_{2\to k} v_{\rm rel} \rangle\right]$$

- ***For any process in equilibrium***

$$n_1^{\rm eq} n_2^{\rm eq} \ldots . n_k^{\rm eq} \langle \sigma_{k\to 2} v_{\rm rel}^{r-1} \rangle = n_a^{\rm eq} n_b^{\rm eq} \langle \sigma_{2\to k} v_{\rm rel} \rangle$$



10^{-6}
10^{-7}
10^{-8}
10^{-9}
$\langle \sigma v \rangle$ [GeV^{-2}]
unitarity
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
m [GeV]

Maximum thermally averaged cross-section for k to 2 process

- *Thermally averaged cross-section for k to 2 process*

$$\langle \sigma_{k\to 2} v_{\rm rel}^{r-1} \rangle_{\rm max} = \sum_l (2l+1) \frac{2^{\frac{3k-2}{2}} (\pi x)^{\frac{3k-5}{2}}}{g^{k-2} m^{3k-4}}$$

- *The well-known result for s-wave 2 to 2 process*

$$\langle \sigma_{2\to 2} v_{\rm rel} \rangle_{\rm max,\ s\text{-}wave} = \frac{4\sqrt{\pi}}{m^2} \sqrt{x}$$

- *For 3 to 2 process*

$$\langle \sigma_{3\to 2} v_{\rm rel}^2 \rangle_{\rm max,\ s\text{-}wave} = \frac{8\sqrt{2}(\pi x)^2}{g m^5}$$