Picture credit: NASA

PASCOS 2026, Sheffield, 23 June 2026

Cosmological signals of Dark Matter semi-annihilation

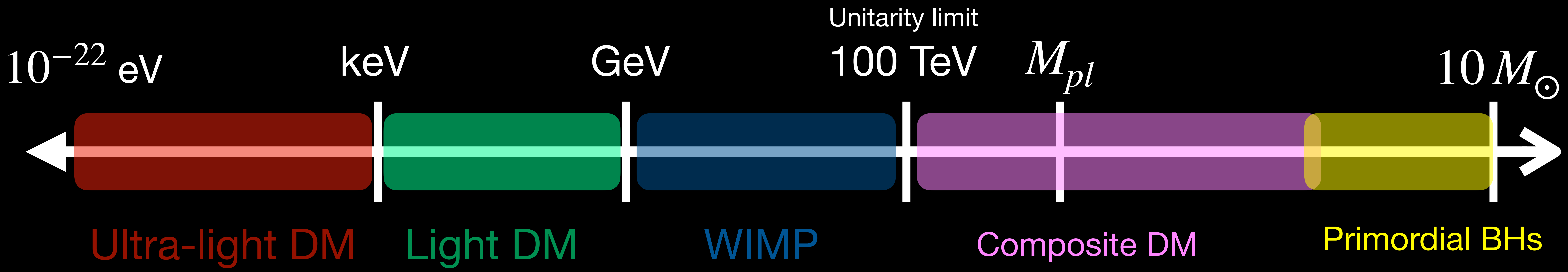
based on 2606.14495 with Boris Betancourt Kamenetskaia, Mathias Garny, Alejandro Ibarra, Merlin Reichard

Alessia Musumeci
Technical University of Munich

SFB 1258 Neutrinos Dark Matter Messengers

Mass Scale of Dark Matter

Not in correct scale
Reproduced from [Lin 1904.07915]



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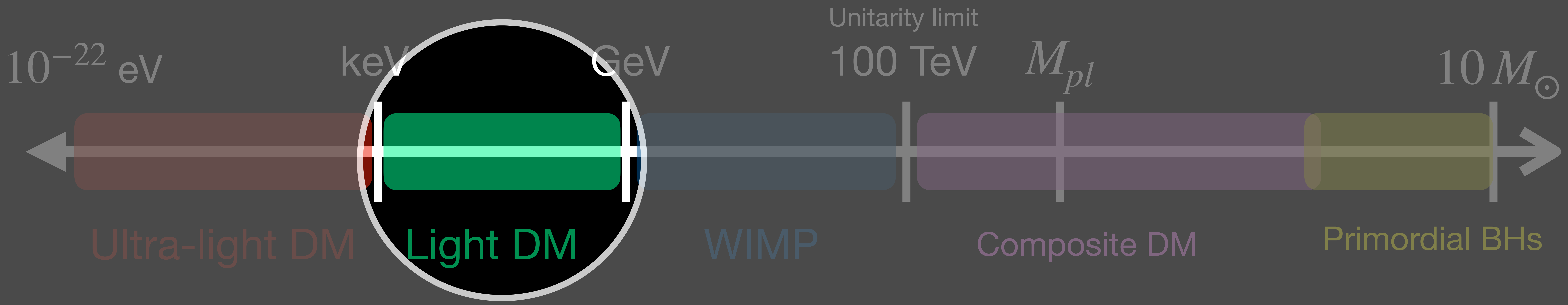

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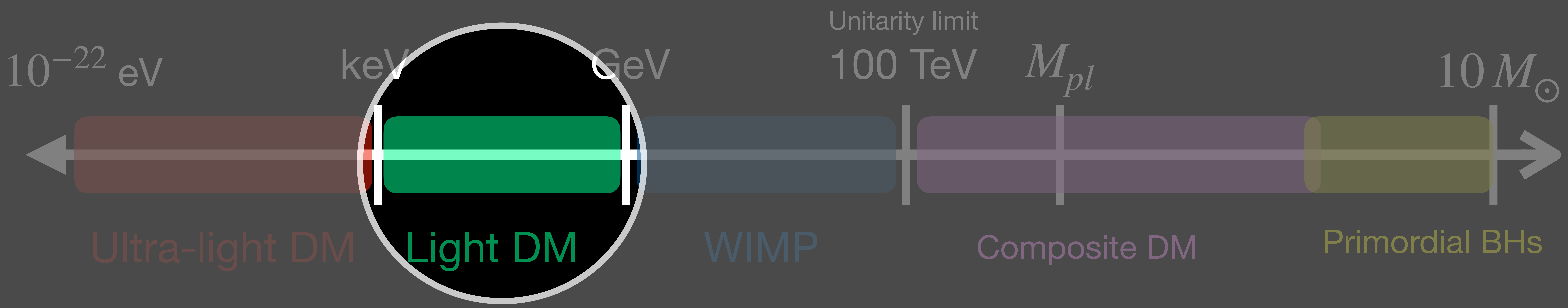

- New *frontier* for direct detection experiments
- Interesting connections with current anomalies and theoretical puzzles
- Thermal relic in different classes of models

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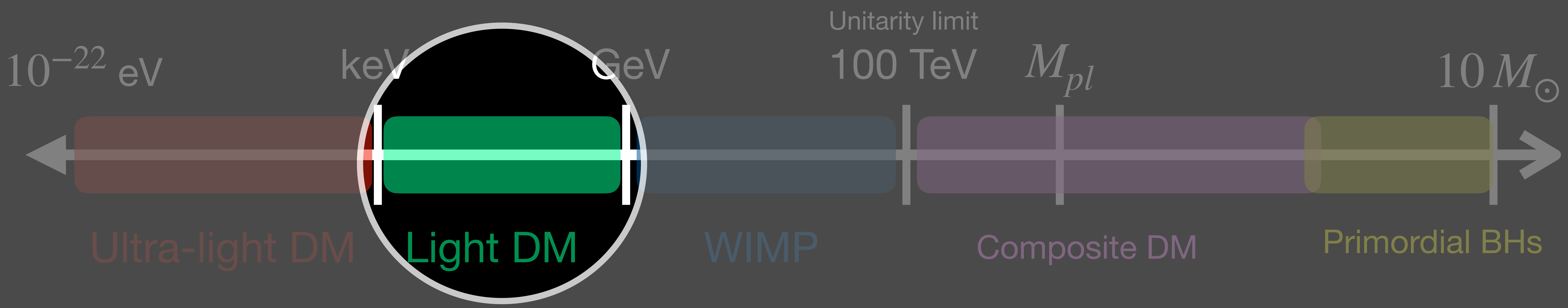

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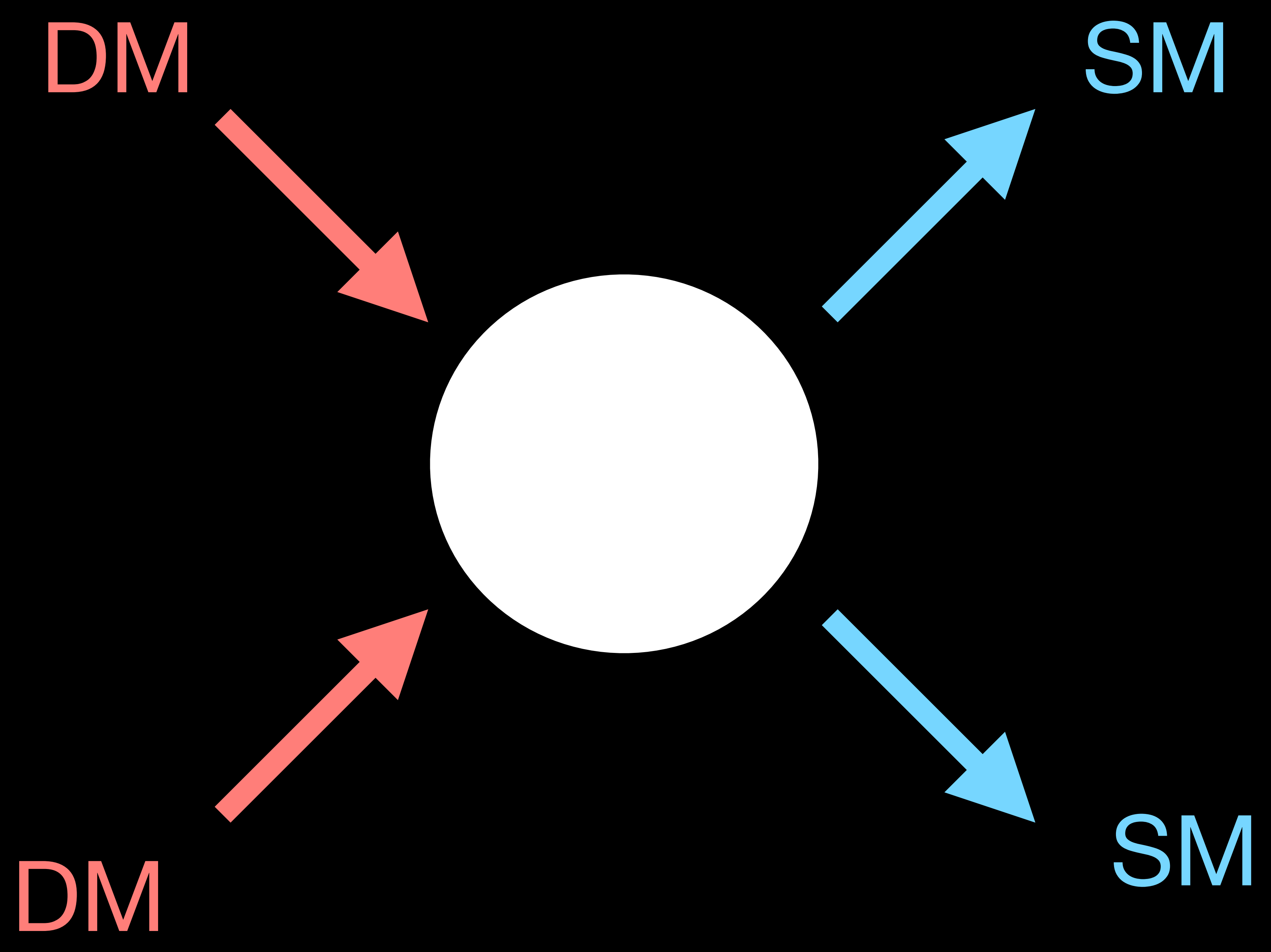
- Thermal relic in different classes of models

DM as a thermal relic

2→0 annihilation



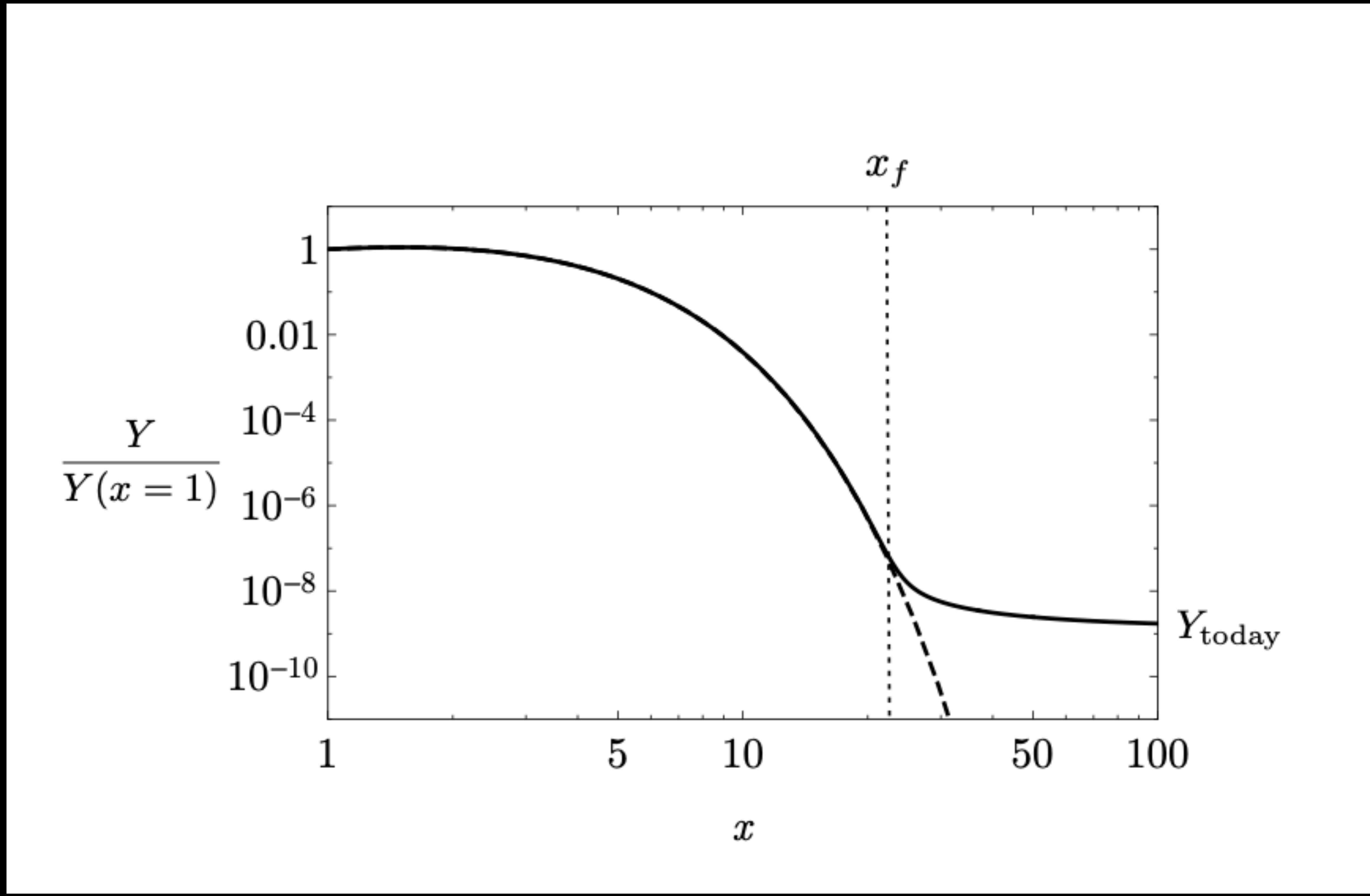
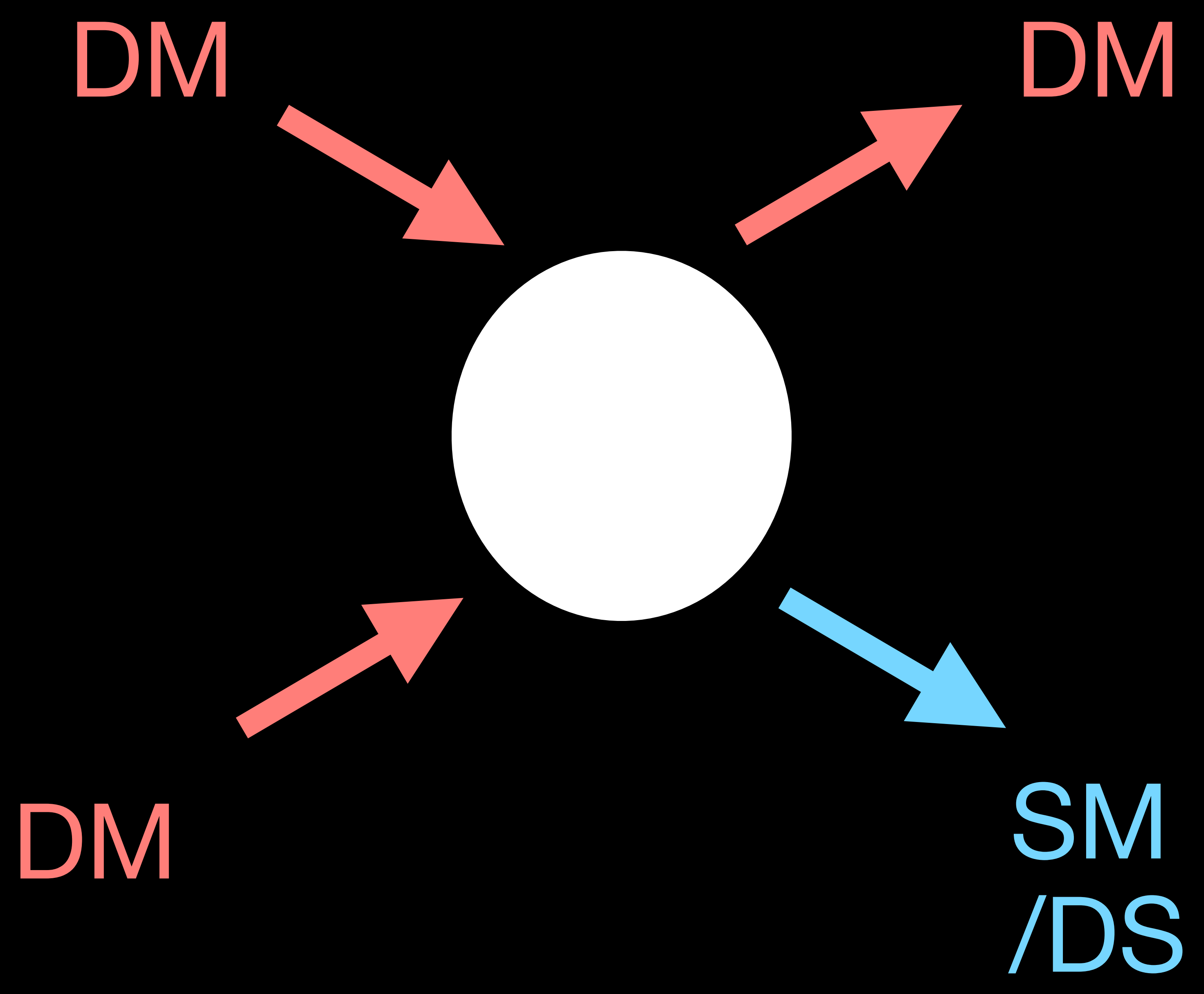


Figure from [Lisanti 1603.03797]

DM as a thermal relic

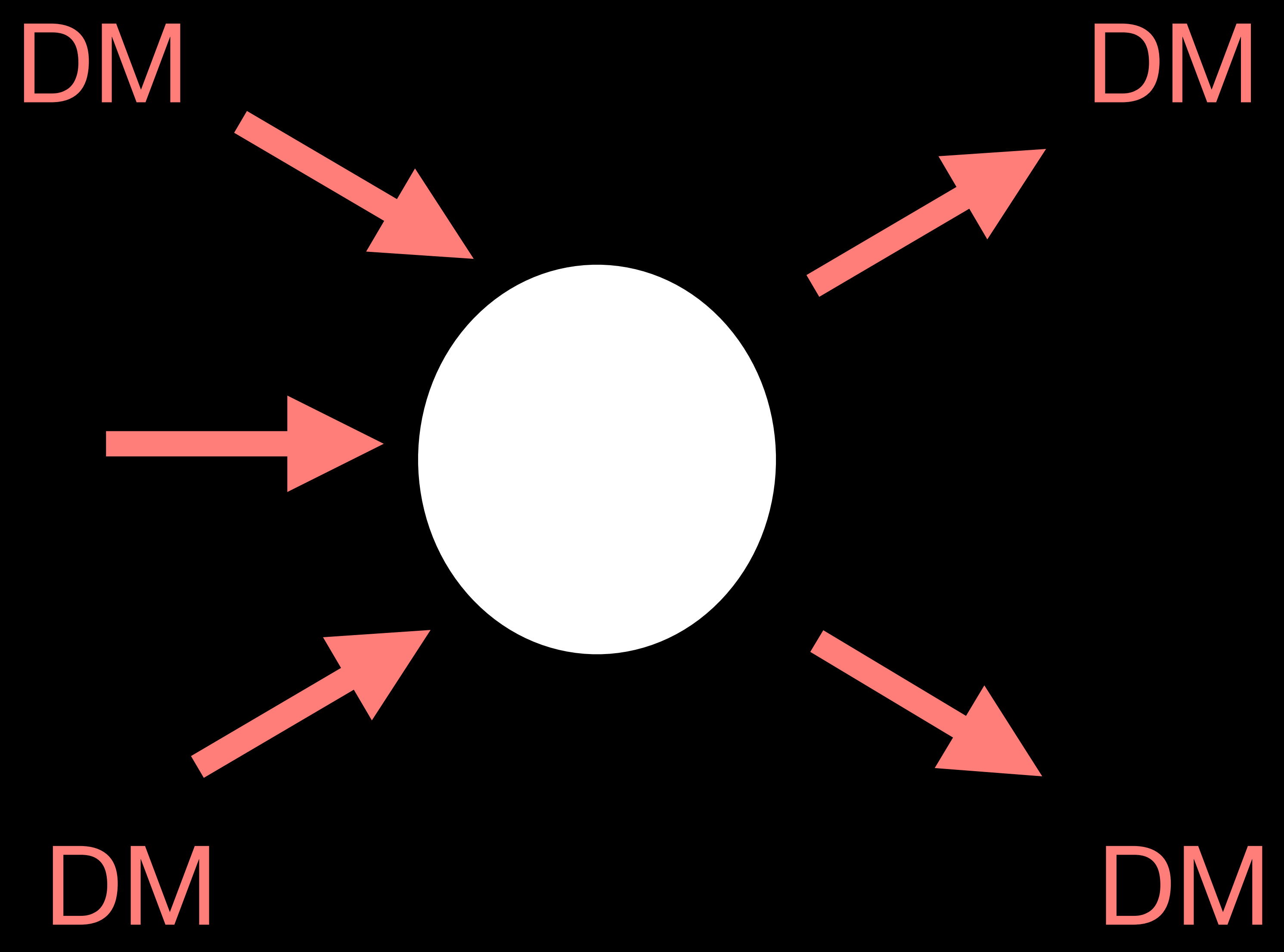
2→1 semi-annihilation

[e.g. Hambye 0811.0172; D'Eramo,Thaler 1003.5912]



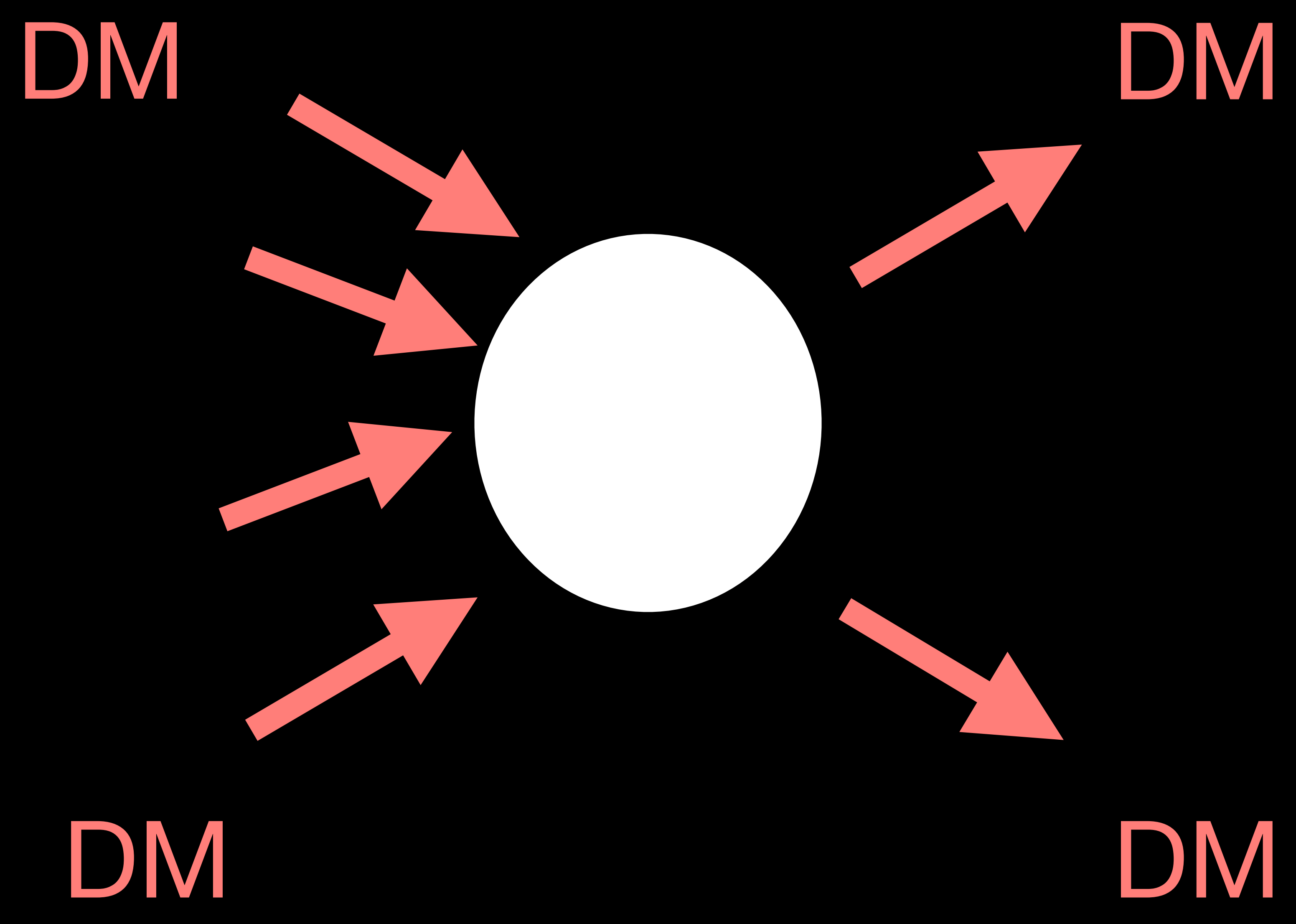
3→2 process

Hochberg et al 1402.5143



4→2 process

Hochberg et al 1402.5143



DM as a thermal relic

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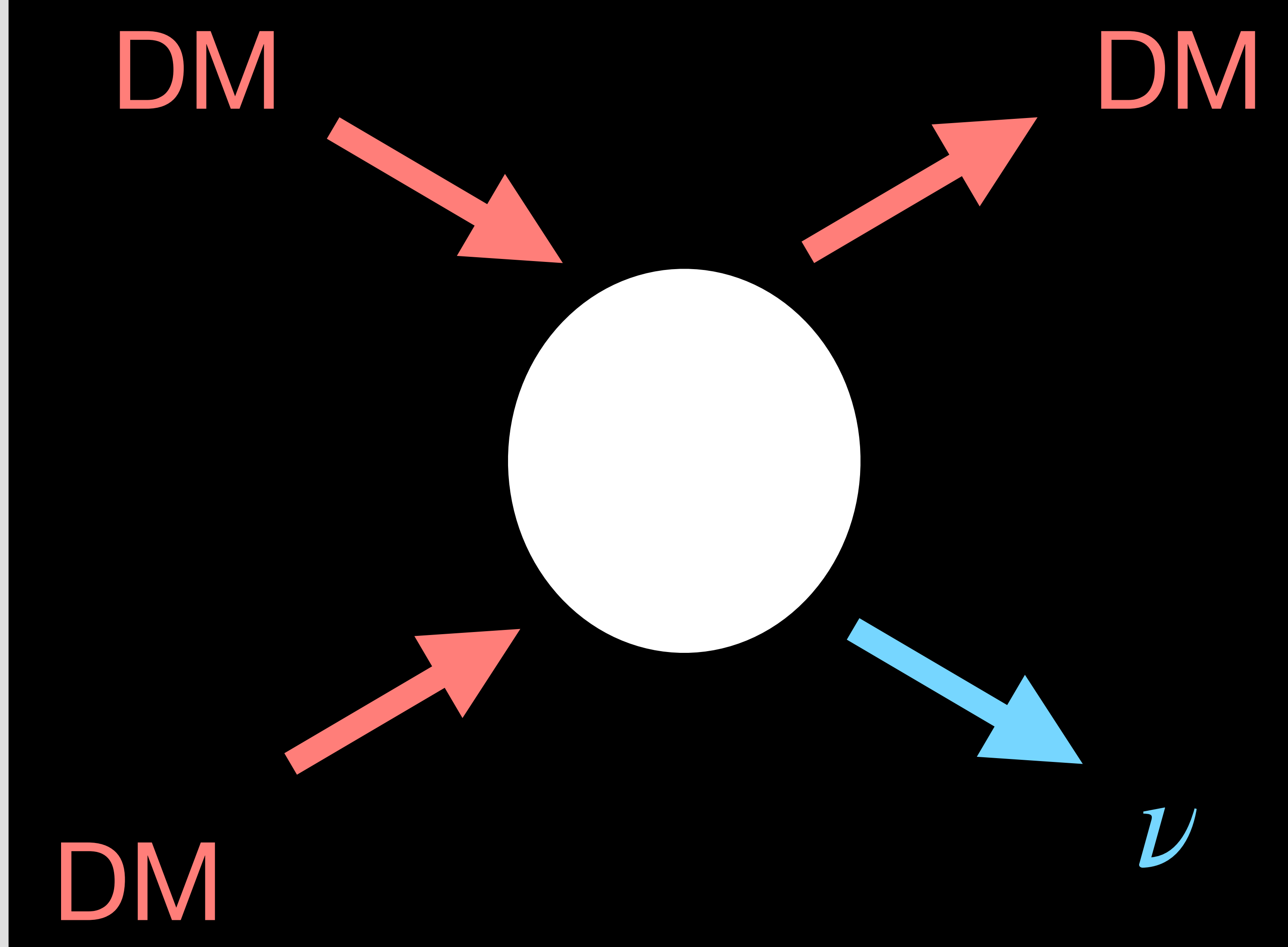
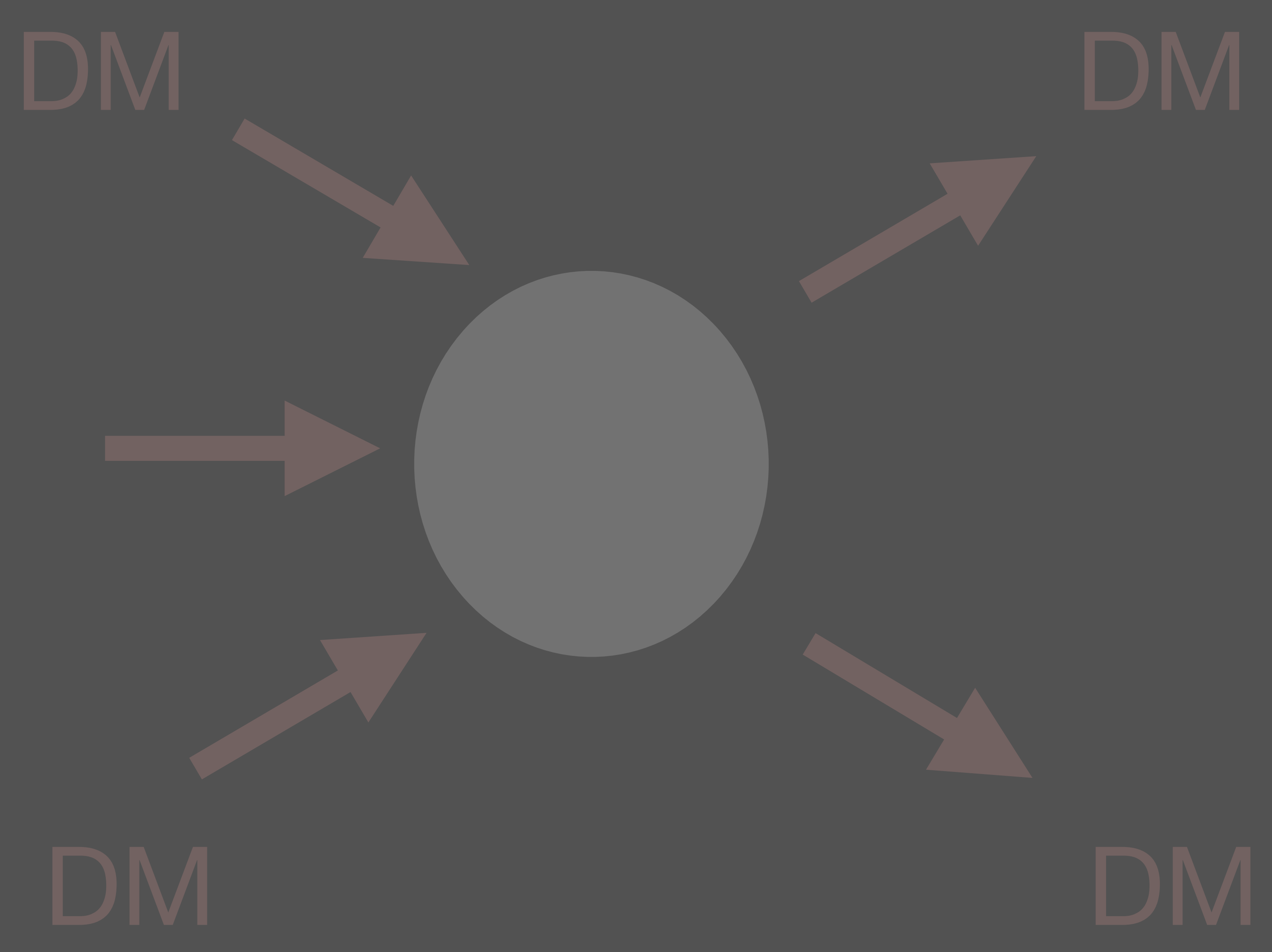


3→2 process

Hochberg et al 1402.5143

This work



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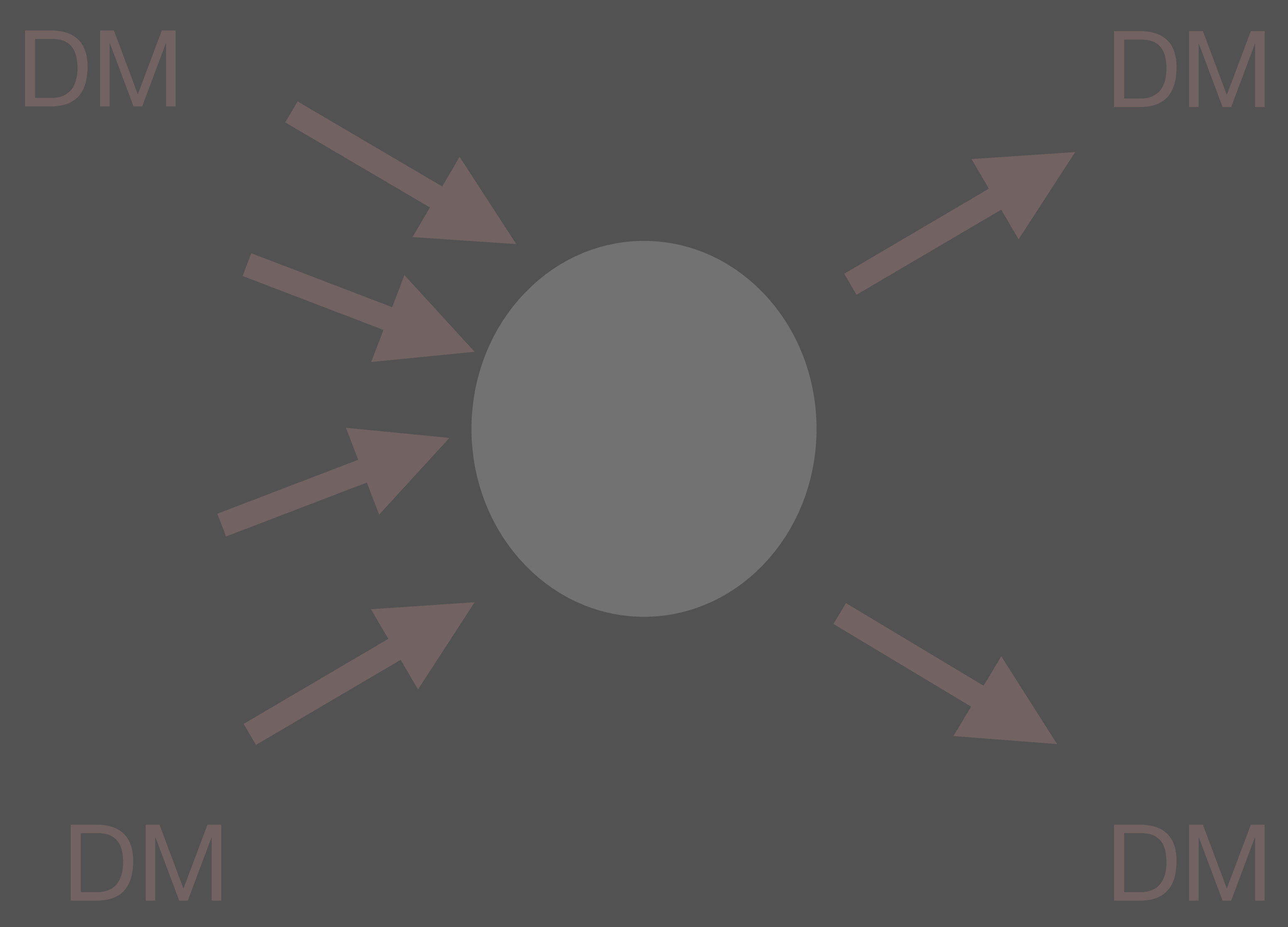
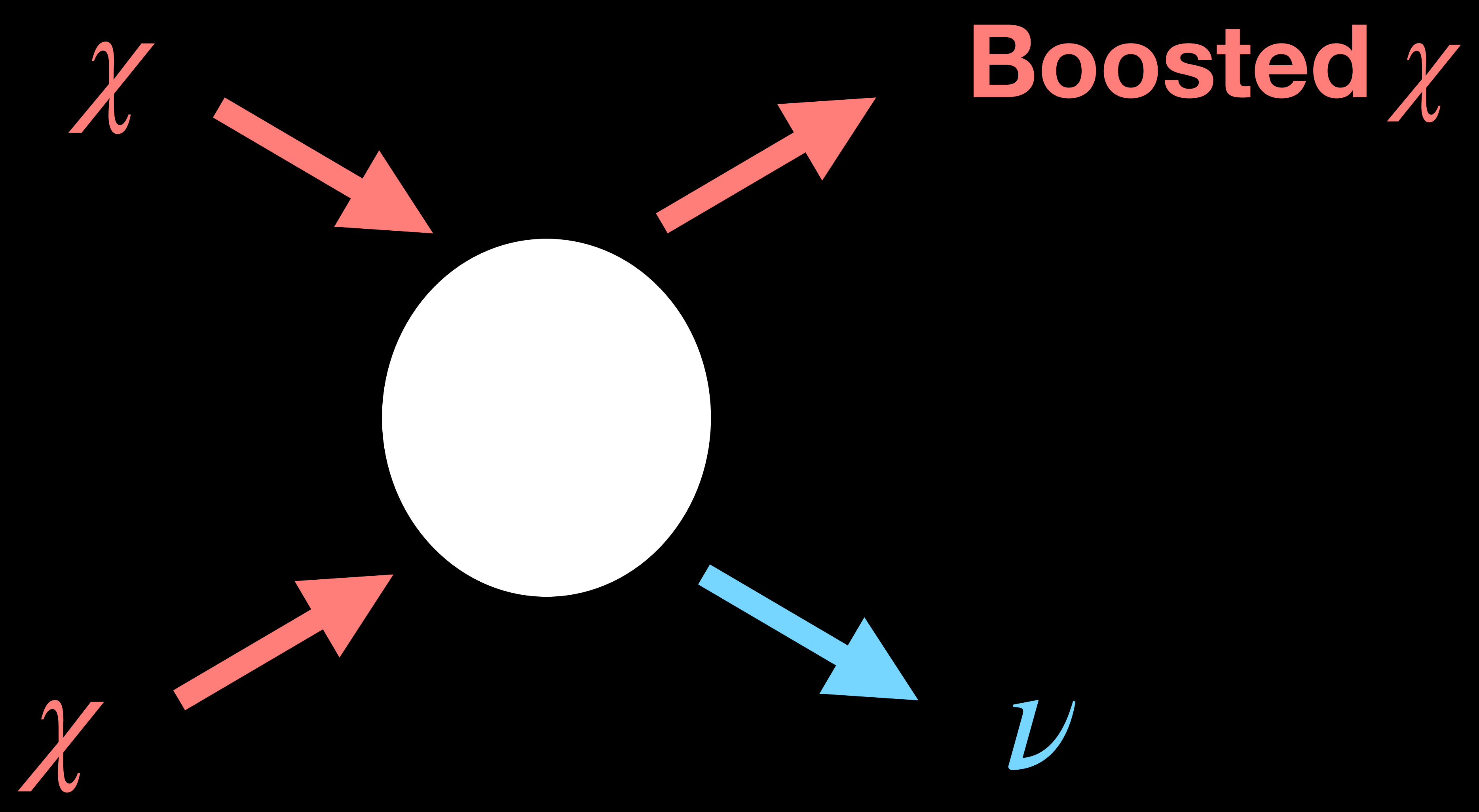


Boosted Dark Matter from semi-annihilation

The idea



Semi-annihilations provide a ***new* source of boosted dark matter!**

Simply by energy conservation:

$$T_\chi = \frac{m_\chi}{4} \qquad T_\nu = \frac{3m_\chi}{4}$$

Boosted Dark Matter from semi-annihilation

Signatures

So far, studied signatures of boosted DM (*BDM*) from semi-annihilation:

- Galactic Center [Betancourt Kamenetskaia, Fujiwara, Ibarra, Toma 2511.12117]
- Sun [Berger,Cui,Zhao 1410.2246; Toma 2109.05911; Aoki,Toma 2309.00395]
- DM spike [Betancourt Kamenetskaia, Fujiwara, Ibarra, Toma 2506.12642]
- …

New Target:
Dark matter halos at high redshift

Dark Matter halos

- In the paradigm of structure formation, we have the formation of cold DM halos, even at high redshift

- The cosmological boost factor $G(z)$ accounts for the enhancements to the DM (semi-)annihilation rate in the halos.

$$G(z) = \frac{1}{\Omega^2_{DM,0}\,\rho_{c,0}} \frac{1}{(1+z)^6} \int_{M_{min}}^{\infty} dM \, \frac{dn(M,z)}{dM} \int_0^{r_\Delta} dr \, 4\pi r^2 \, \rho_\chi^2(r)$$

Cosmological boost factor

- Contribution from a single halo of mass M

$$M = \Delta\,\rho_c(z)\,\frac{4\pi}{3}\,r_\Delta^3 \qquad (\Delta = 200)$$

Halo mass

$$\rho_{halo}(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2}$$

NFW profile

- Solve the integral analytically

$$\int_0^{r_\Delta} dr\; 4\pi r^2\,\rho_{halo}^2(r) = \tilde{g}(c_\Delta)\,\frac{M\,\Delta\,\rho_c(z)}{3}$$

$$\tilde{g}(c_\Delta) = \frac{c_\Delta^3\,[1 - (1 + c_\Delta)^{-3}]}{3[\ln(1 + c_\Delta) - c_\Delta(1 + c_\Delta)^{-1}]^2}$$

$$c_\Delta = \frac{r_\Delta}{r_s}$$

← Parametrization using $\sigma(M,z)$ from the fits from the MultiDark/BigBolshoi simulations [Prada et al. 1104.5130, or also found in Lopez-Honorez et al. 1303.5094]

Cosmological boost factor

- Halo mass function

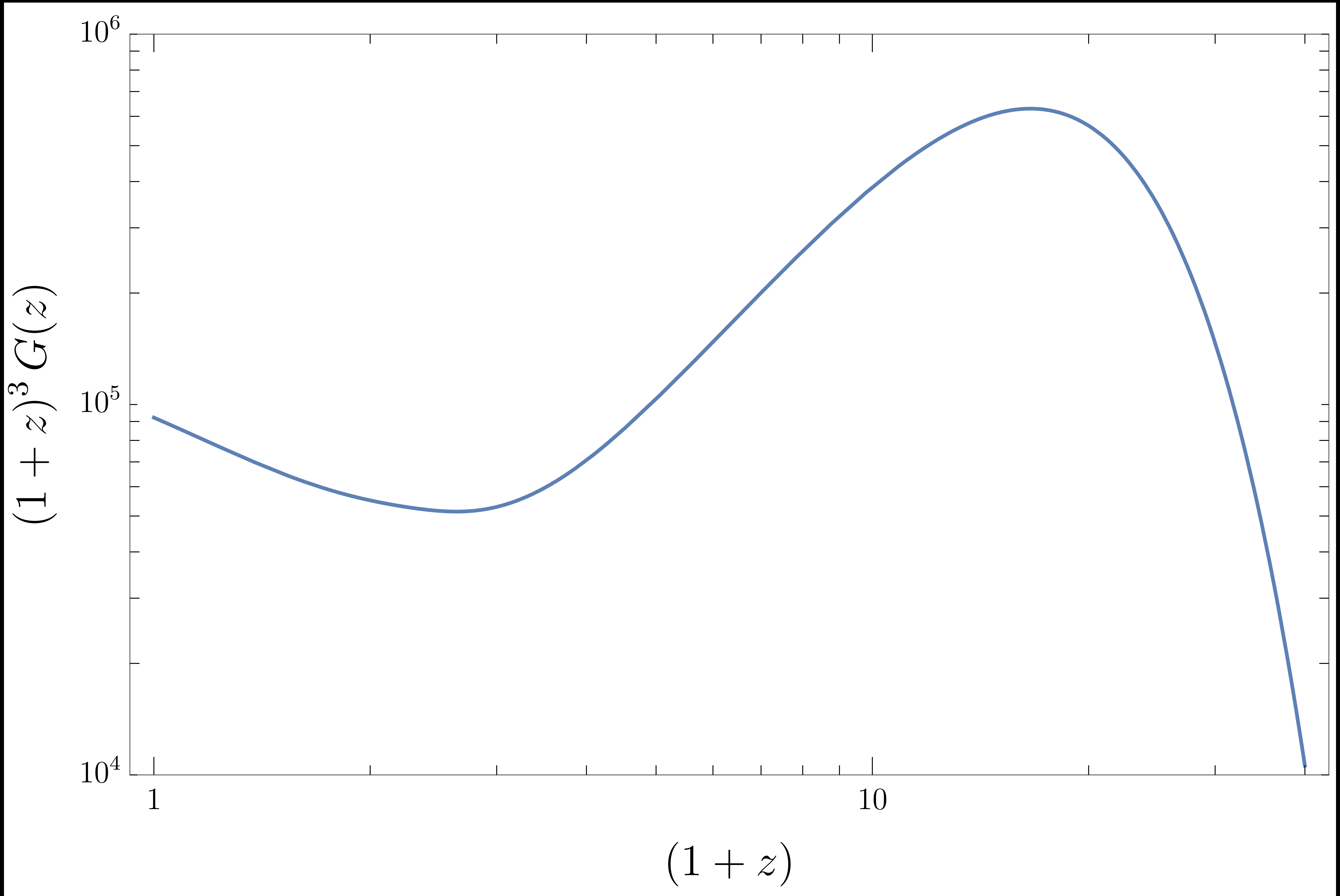
$$\frac{dn_{halo}(M,z)}{dM} = \frac{\rho_m(z)}{M^2} \frac{d\ln\sigma^{-1}}{d\ln M} f(\sigma, z)$$

[Prada et al. 1104.5130, or also found in Lopez-Honorez et al. 1303.5094]

- Final result

$$G(z) = \left(\frac{\Omega_{m,0}}{\Omega_{DM,0}}\right) \frac{\Delta}{3\Omega_m(z)} \int_{M_{min}}^{\infty} d\log M \frac{d\ln\sigma^{-1}(M,z)}{d\log M} f_\Delta(\sigma(M,z),z)\, \tilde{g}(c_\Delta(M,z))$$

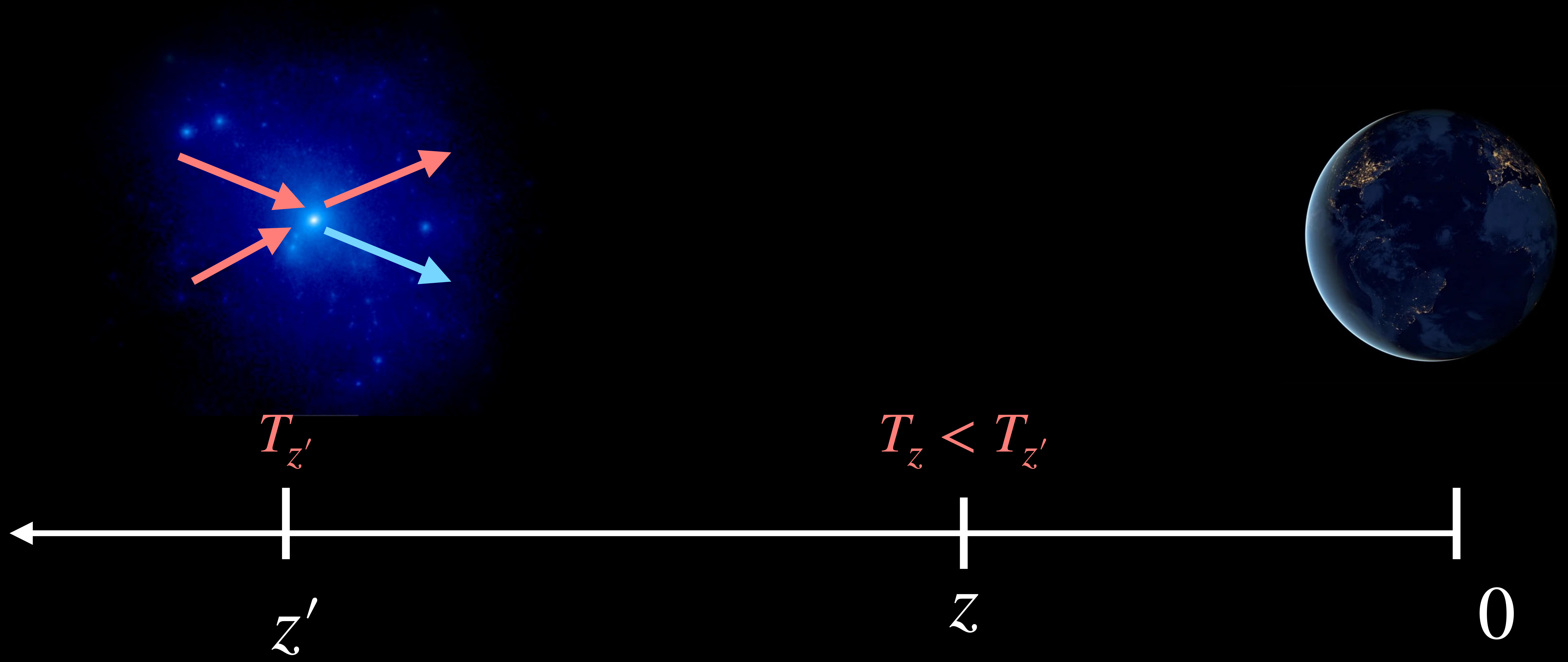
Cosmological boost factor



Boosted DM flux

General picture

For simplicity we reproduce here just one halo



Picture credit: NASA

Boosted DM flux
Derivation

The differential Boosted DM flux is computed by summing all contributions along the cosmological line of sight:

$$\frac{d\Phi_{\rm BDM}}{dT_z}(T_z, z) = \frac{(1+z^2)}{4\pi}\int_z^{\infty} \frac{dz'}{H(z')(1+z')^3}\sqrt{1-\left(\frac{m_\chi}{T_{z'}+m_\chi}\right)^2}\; Q_{BDM}(T_{z'}, z')$$

\# BDM particles per unit volume, unit time and unit energy

$$Q_{BDM}(T'_z, z') = \frac{1}{2}\langle\sigma v\rangle \frac{\rho_\chi^2(z')}{m_\chi^2} G(z')\delta\left(T_{z'} - \frac{m_\chi}{4}\right)$$

Boosted DM flux

Derivation

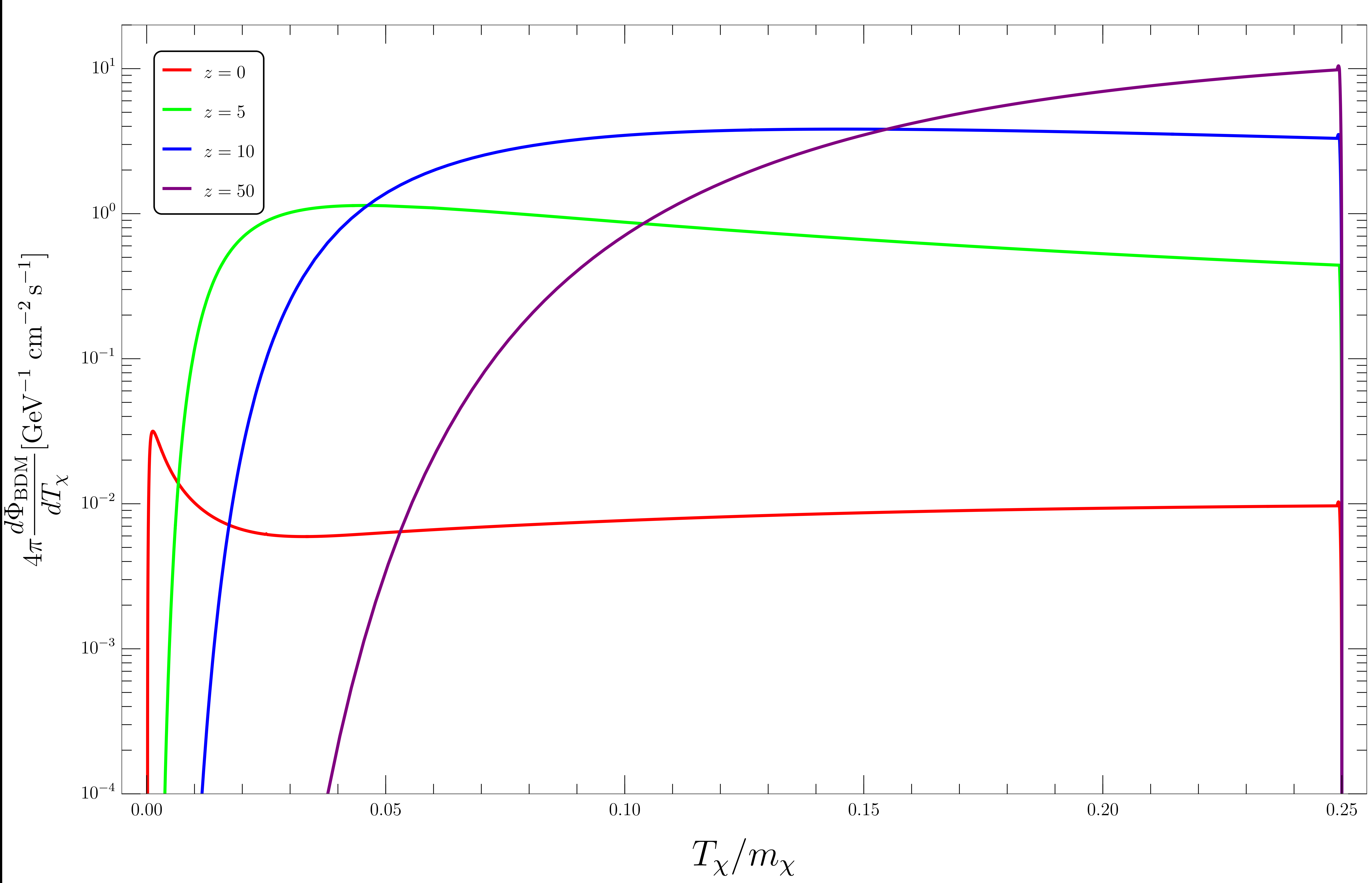
Final result

$$\frac{d\Phi_{\mathrm{BDM}}}{dT_z}(T_z, z) = \frac{(1+z)^2}{4\pi}\,\frac{\rho_\chi^2(z_*)}{m_\chi^2}\,\frac{\langle\sigma v\rangle\,B(z_*)}{(1+z_*)^2 H(z_*) m_\chi}\,\Theta(z_* - z)$$

where

$$\frac{1+z_*}{1+z} = \frac{3}{4}\left[\frac{T_z}{m_\chi}\left(\frac{T_z}{m_\chi}+2\right)\right]^{-\frac{1}{2}}$$

Boosted DM flux



$m_\chi = 100\,\text{MeV}$

$\langle \sigma v \rangle = 10^{-26}\ \text{cm}^3\,\text{s}^{-1}$

Non-negligible flux at high redshift!

Implication 1: Structure Formation

Implications for Structure Formation

BDM will have significant velocities, hence it can interfere with the gravitational collapse of structures

↓

Boosted Dark Matter will act as Warm Dark Matter, reducing power on scales below their free-streaming length

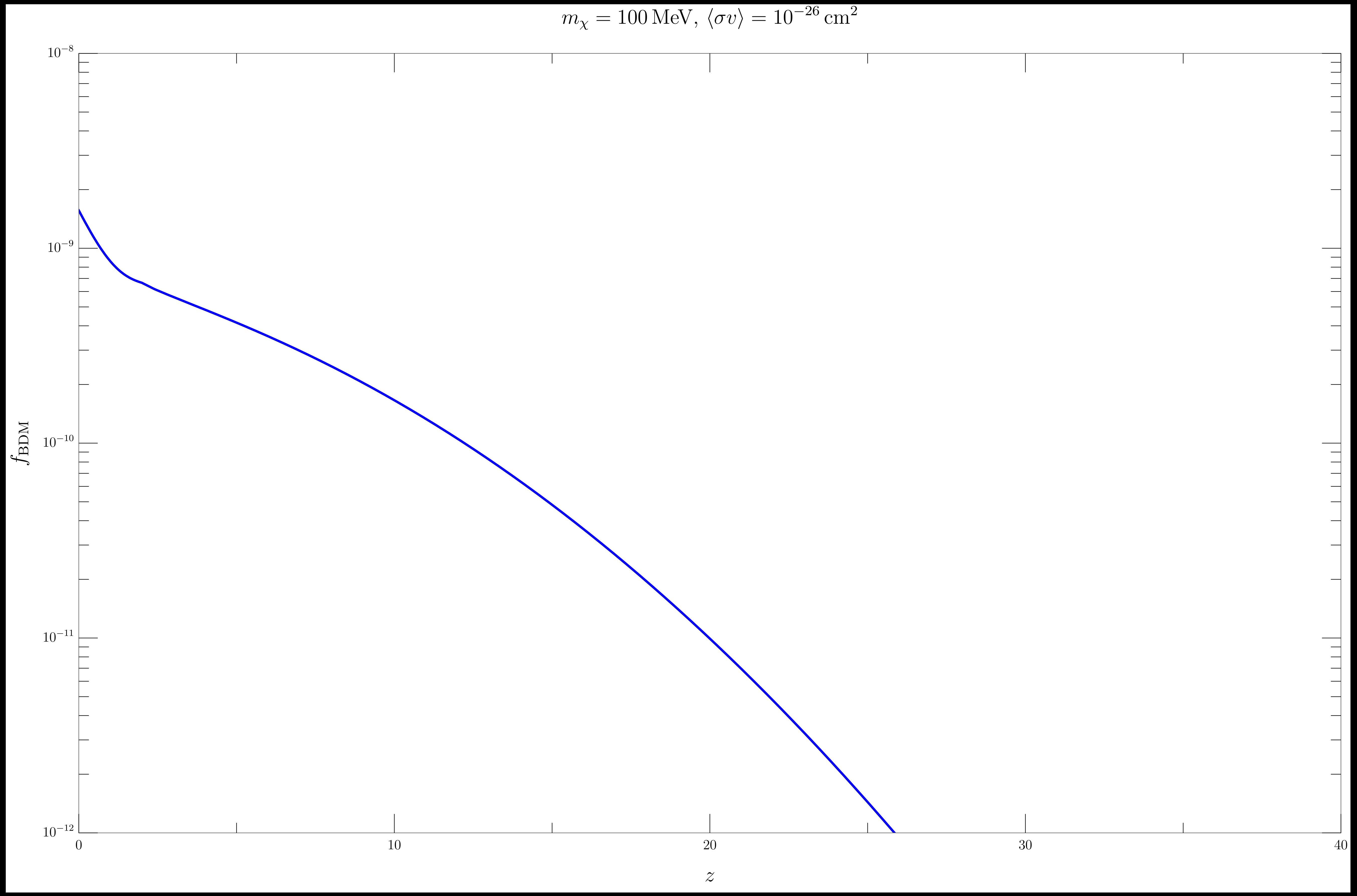
Implications for Structure Formation

Fraction of BDM particles

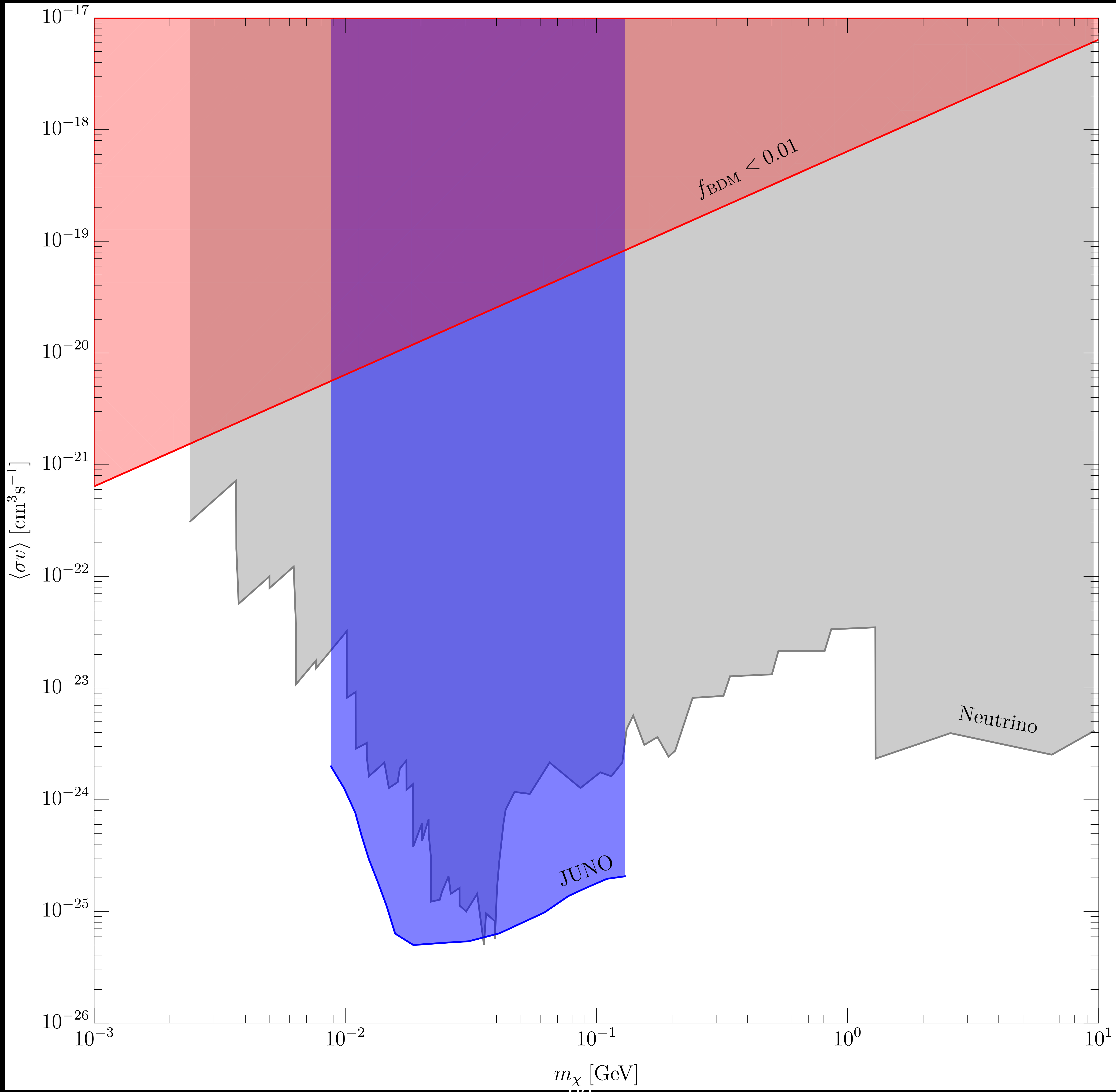
$$n_{BDM}(z) = \int \frac{4\pi}{v(T_z)} \frac{d\Phi}{dT_z} dT_z =$$

$$= \langle \sigma v \rangle \frac{(1+z)^3}{2\, m_\chi^2} \int_z^\infty dz' \, \frac{\rho_\chi^2(z') G(z')}{(1+z')^4 H(z')}$$

$$f_{BDM}(z) = \frac{n_{BDM}(z)}{n_{DM}(z)}$$



Implications for Structure Formation



Neutrino telescopes [Argüelles et al. 1912.09486]

JUNO sensitivity line [Akita et al. 2206.06755]

LSS constraints [Simon et al. 2203.07440]

Implication 2: Direct Detection Experiments

Implications for Direct Detection Experiments

Basics on DD

- Differential Rate per target mass of nucleus $\mathcal{T}$: $$\frac{dR_{\mathcal{T}}}{dT_{\mathcal{T}}} = \frac{1}{m_{\mathcal{T}}} \int_{T^{min}_{\chi,\mathcal{T}}(T_{\mathcal{T}})}^{\infty} dT_{\chi} \frac{d\sigma_{\chi\mathcal{T}}}{dT_{\mathcal{T}}} \frac{d\Phi_{BDM}}{dT_{\chi}}$$

`High speed particles!` [Bednyakov,Naumov 1806.08768]

$$\frac{d\sigma_{\chi\mathcal{T}}}{dT_{\mathcal{T}}} = \left(\frac{d\sigma_{\chi\mathcal{T}}}{dT_{\mathcal{T}}}\right)_{\text{coh}} + \left(\frac{d\sigma_{\chi\mathcal{T}}}{dT_{\mathcal{T}}}\right)_{\text{inc}} = \frac{\sigma^{\text{coh}}_{\text{SI},\mathcal{T}}}{T^{\text{max}}_{\mathcal{T}}} |F_{\text{SI},\mathcal{T}}(q)|^2 + \frac{\sigma^{\text{inc}}_{\text{SI},\mathcal{T}}}{T^{\text{max}}_{\mathcal{T}}} (1 - |F_{\text{SI},\mathcal{T}}(q)|^2)$$

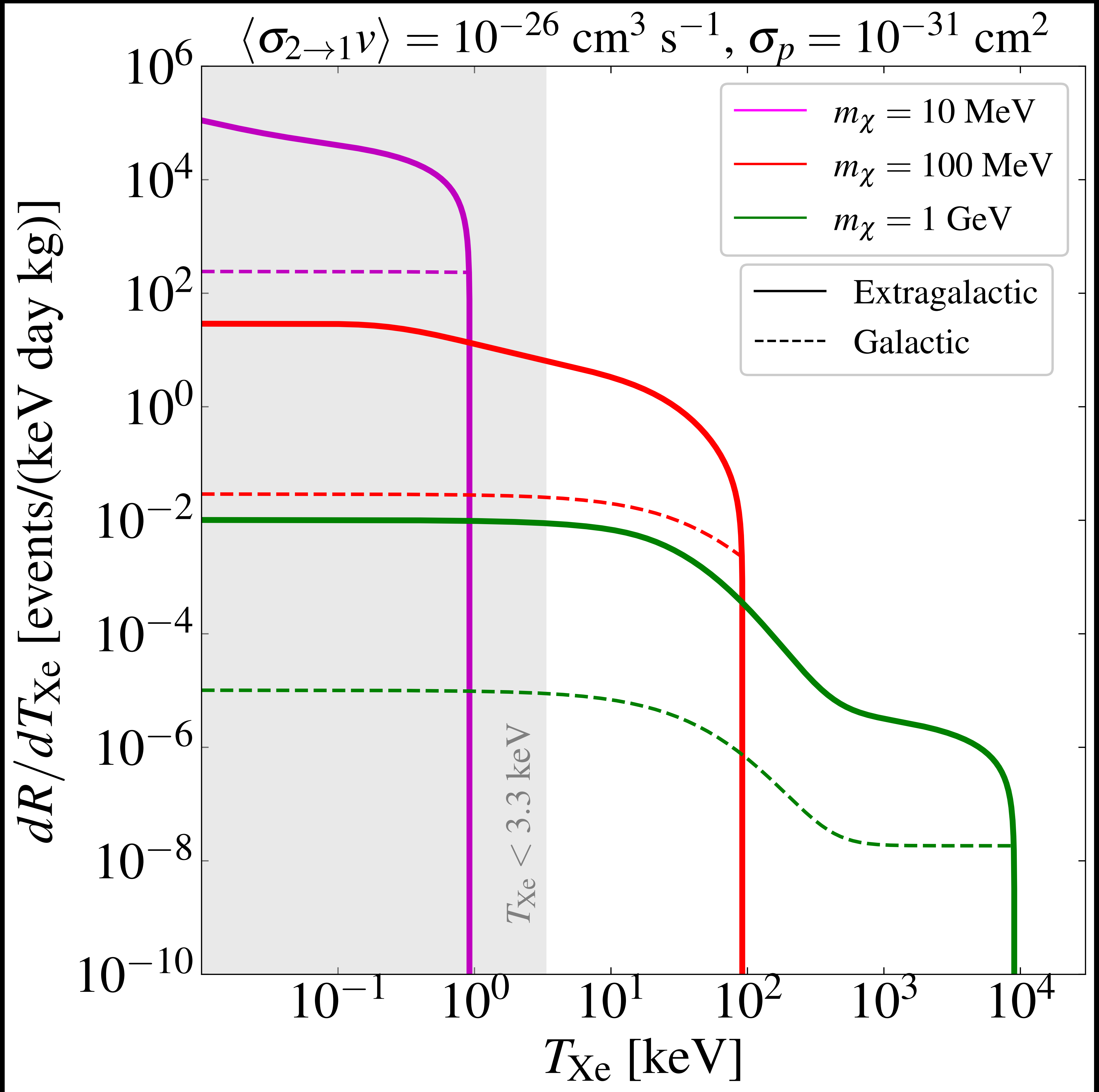
$$\sigma^{\text{coh}}_{\text{SI},\mathcal{T}} = \sigma_p \left(\frac{\mu_{\mathcal{T}}}{\mu_p}\right)^2 A^2_{\mathcal{T}} \qquad \sigma^{\text{inc}}_{\text{SI},\mathcal{T}} = \sigma_p \, A_{\mathcal{T}}$$

Implication for Direct Detection Experiments

Differential Rate

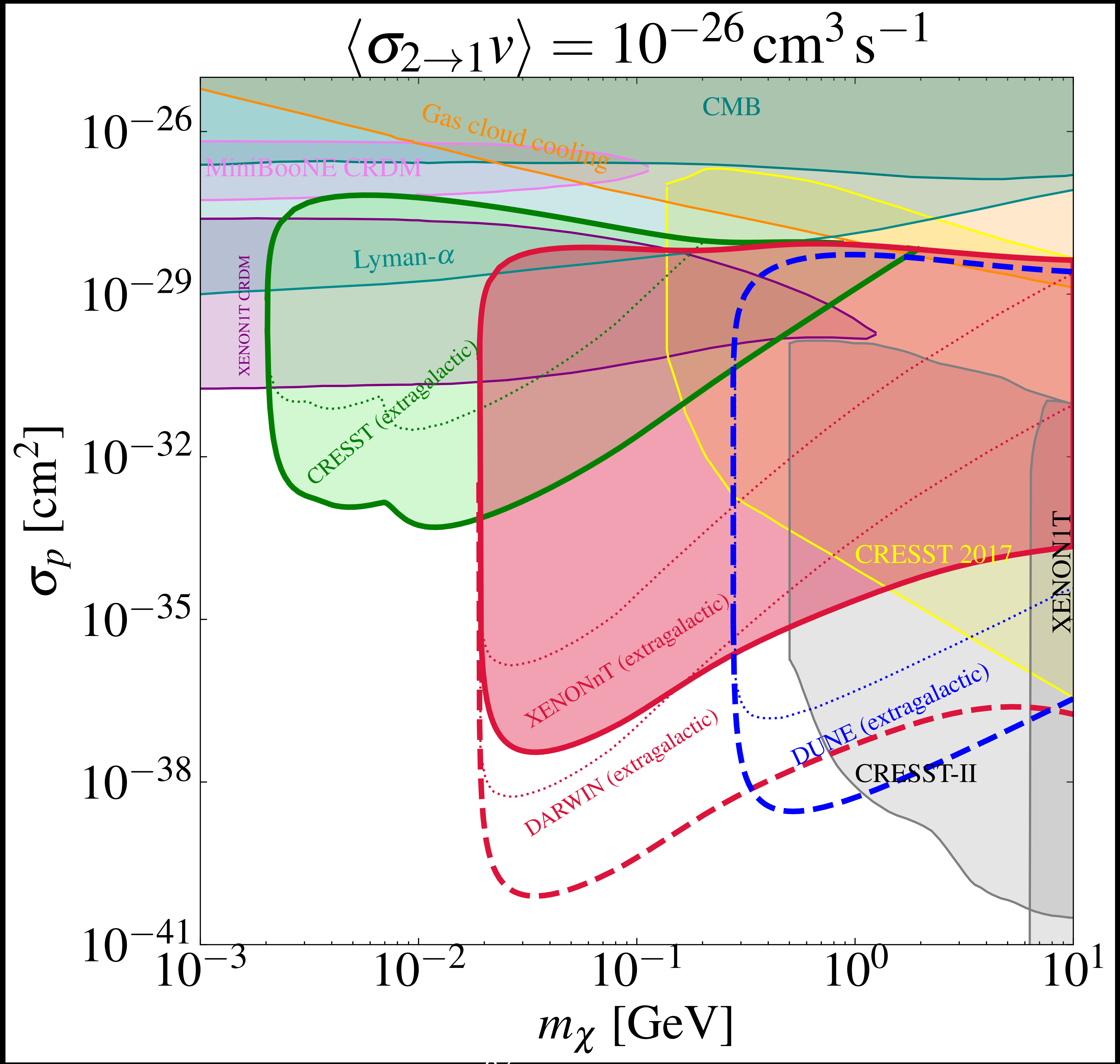
[Betancourt Kamenetskaia, Fujiwara, Ibarra, Toma 2511.12117]

Crucial Impact of the low energy tail of the flux



Implication for Direct Detection Experiments

Parameter Space



Conclusions

- We have studied the signals from a flux of boosted DM particles produced in the semi-annihilating process $\chi\chi -> \chi\nu^c$ coming from DM halos at high redshifts
- **Structure formation:** constraints are relevant when the neutrino signals from telescopes are suppressed
- **Direct Detection:** sizable rate in detectors, exceeding the galactic component

Thank you for your attention!

Back up

Boosted DM flux

Few details on the derivation of the flux 1/2

We have to sum the contributions along the geodesic/line-of-sight. Considering the line element defined as follows:

[e.g. Ullio+ 0207125]

$$ds^2 = dt^2 - R^2(t)\left[d\chi^2 + S^2(\chi)(d\theta^2 + \sin^2\theta\, d\phi^2)\right]$$

By solving the geodesics equation:

$$\frac{d\Phi}{dE_{z'}} = \frac{R_{obs}}{4\pi}\left(\frac{\Omega_{DM,0}\,\rho_{c,0}}{m_\chi}\right)^2 \frac{G(z)\langle\sigma v\rangle}{2}(1+z)^5(1+z')\frac{E_{z'}/m_\chi}{\sqrt{1+\left(\frac{1+z}{1+z'}\right)^2\left[\left(\frac{T_{z'}}{m_\chi}\right)^2-1\right]}}\frac{dN_{BDM}}{dE_{z'}}$$

Boosted DM flux

Few details on the derivation of the flux 2/2

We are interested in the differential flux as function of the observed energy:

$$\frac{d\Phi}{dE_z} = \frac{d\Phi/dE_{z'}}{dE_z/dE_{z'}} = \frac{R_{obs}}{8\pi}\left(\frac{\Omega_{\mathrm{DM},0}\,\rho_{c,0}}{m_\chi}\right)^2 \langle\sigma v\rangle\,(1+z)^3\int_{\chi_{\mathrm{obs}}}^{\infty} d\chi\,(1+z')^3\,G(z')\,\frac{dN_{\mathrm{BDM}}}{dE_{z'}}\,.$$

Where we can write

$$d\chi = \frac{d\chi}{dt'}\frac{dt'}{dz'}dz' = \frac{\sqrt{1-\left(m_\chi/E_{z'}\right)^2}}{R_{\mathrm{obs}}(1+z)H(z')}dz'$$