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in collaboration with
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and
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Workshop on SM and Beyond 2024 / 3rd Gordon Godfrey

Exploring Light Dark Matter Boosted by Supernova Neutrinos in the Past and Present Universe

Based on

Phys. Rev. Lett. **133**, 111004 (2024)
Phys. Rev. D **108**, 083013 (2023)
Phys. Rev. Lett. **130**, 111002 (2023)

snorer dukes

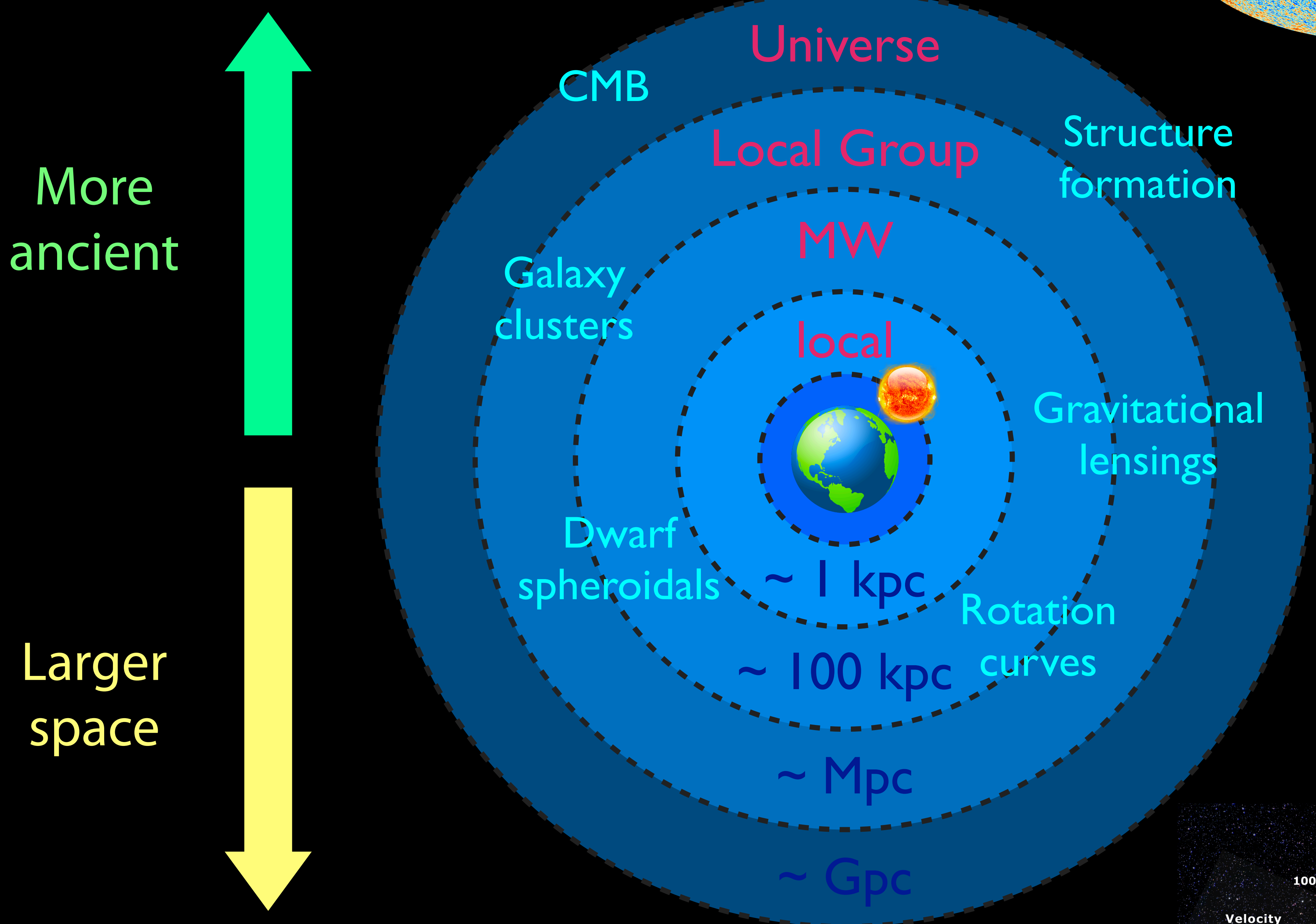
yenhsunlin

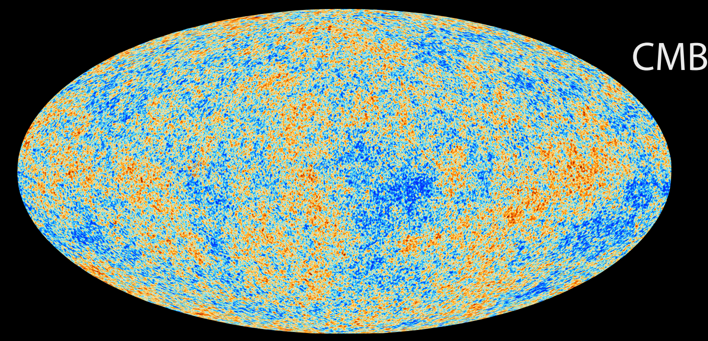
Outline

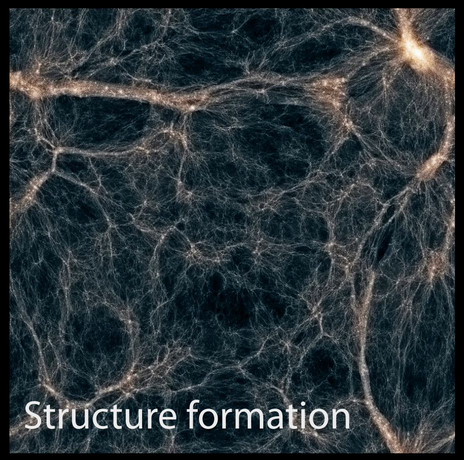
- Introduction to dark matter (DM)
- Supernova-neutrino-boosted DM (SNν BDM) and time-of-flight (ToF) for direct mass differentiation
- Diffuse SNν BDM flux from the high redshift to the present
- Constraints and sensitivities on DM-ν/e^- cross sections
- Summary

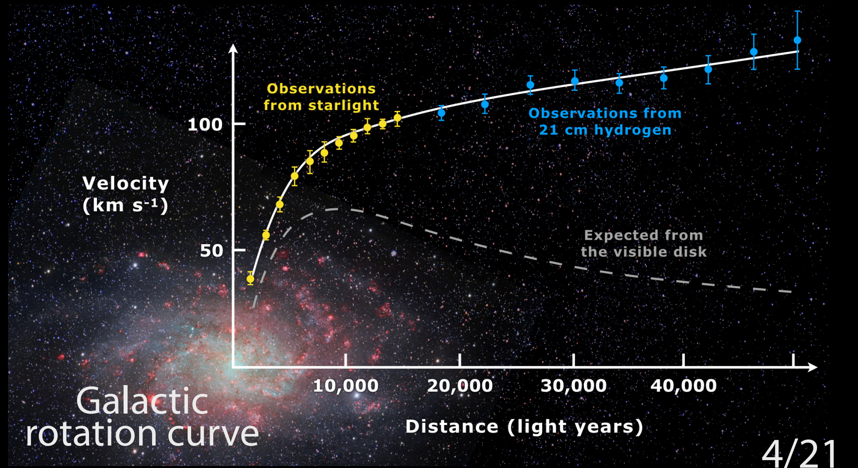
Introduction

Dark matter is ***ubiquitous*** in the Universe!

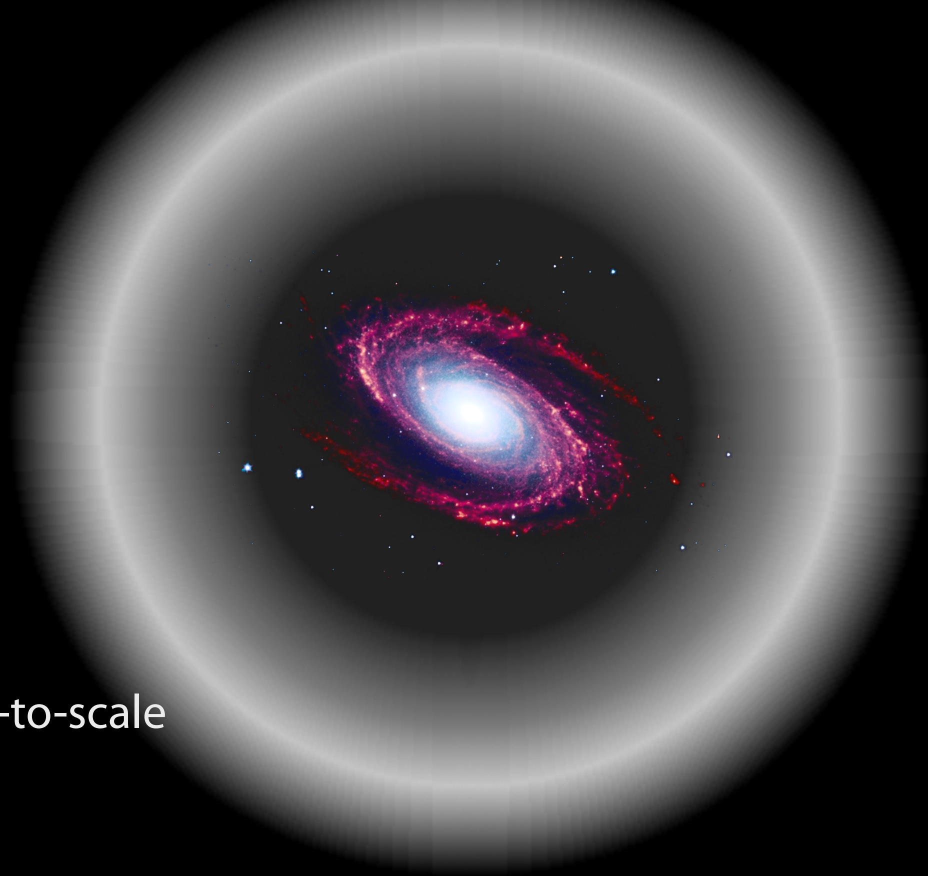








DM halo



not-to-scale

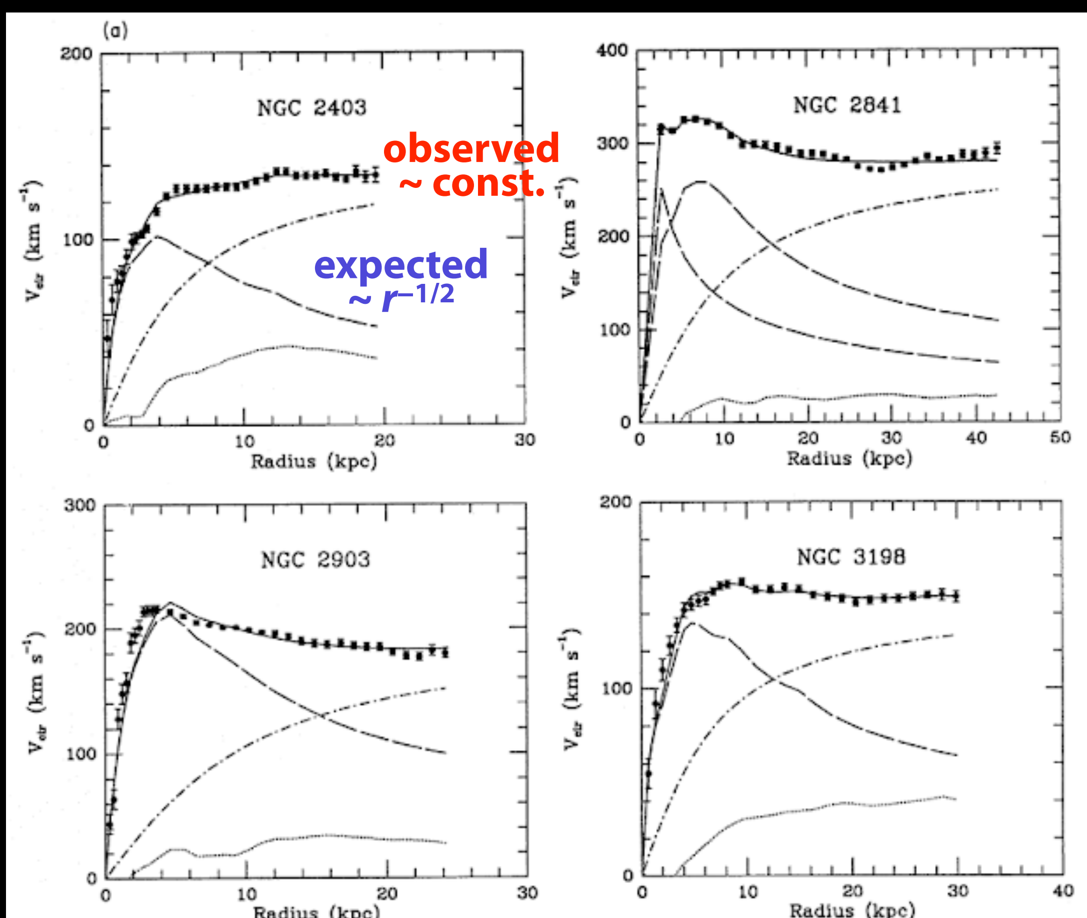
- Galaxies are generally enclosed by a large DM halo with radial density profile

Navarro+ 1996
Bertone+ 2004

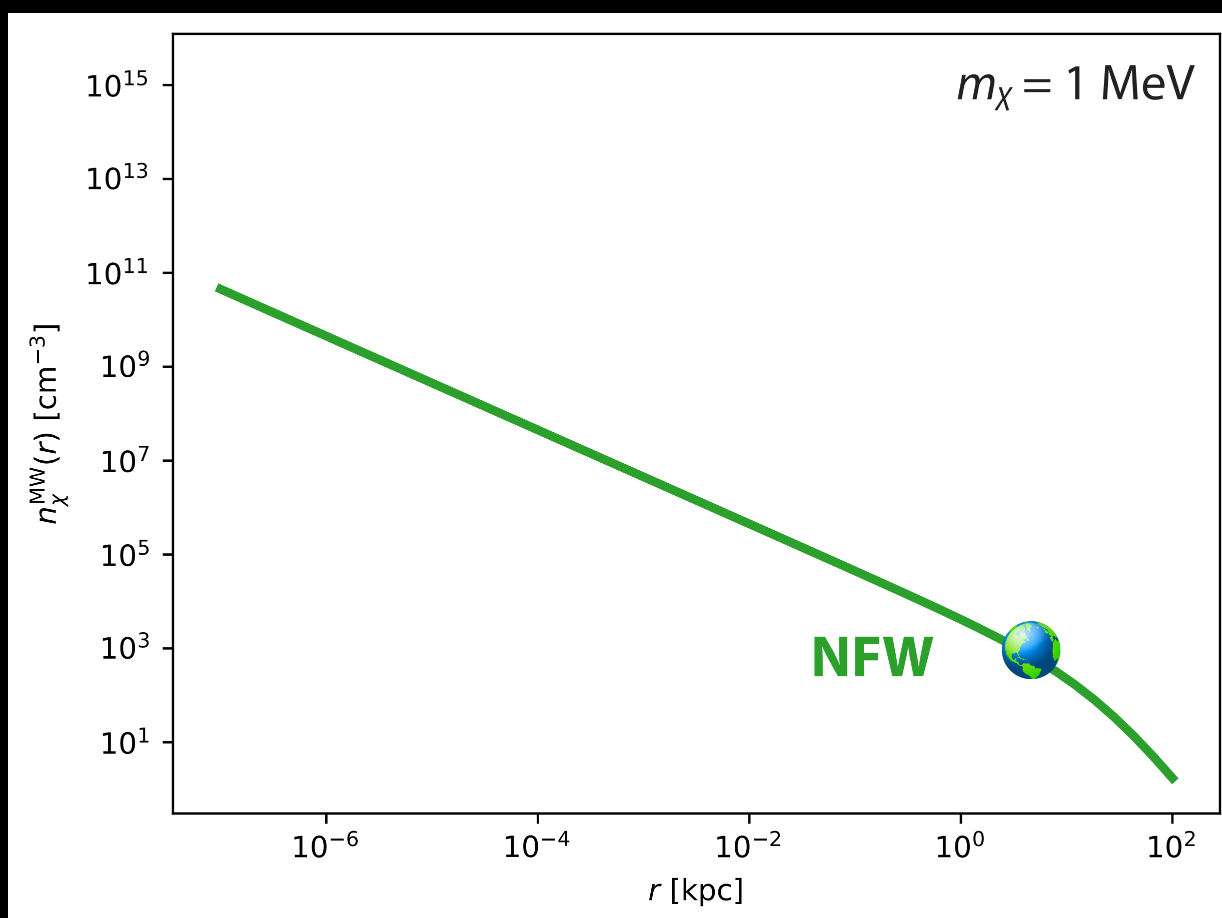
$$\rho_\chi(r) = \frac{\rho_s}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^n}$$

- Our MW is assumed following Navarro-Frenk-White (NFW) profile: $\rho_s = 184$ MeV cm^{-3}, $r_s = 24.4$ kpc and $n = 2$

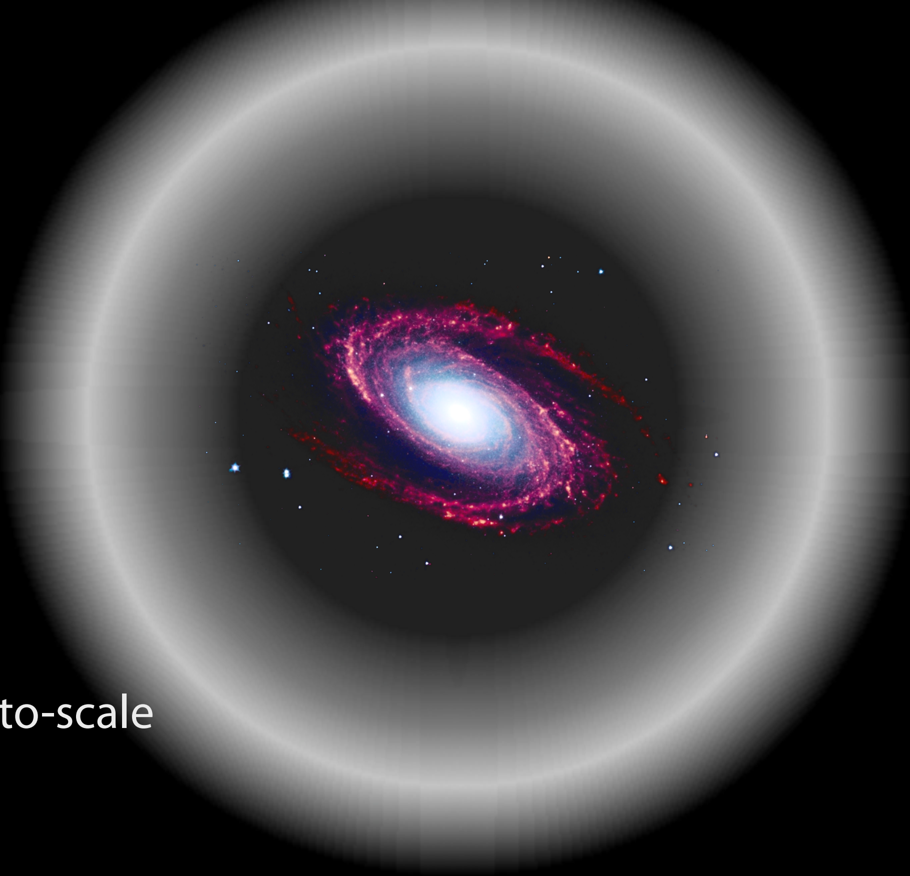
Velocity



Galactic rotation curves



DM halo



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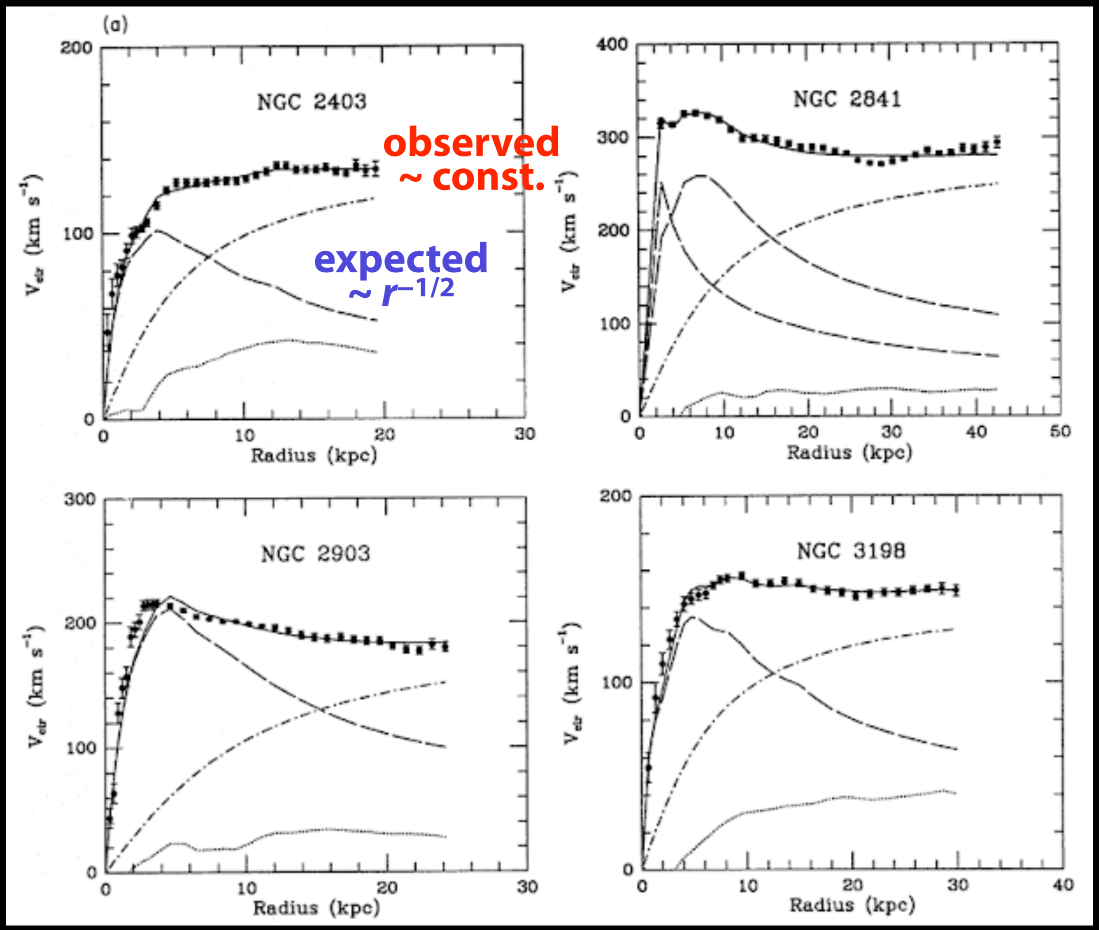
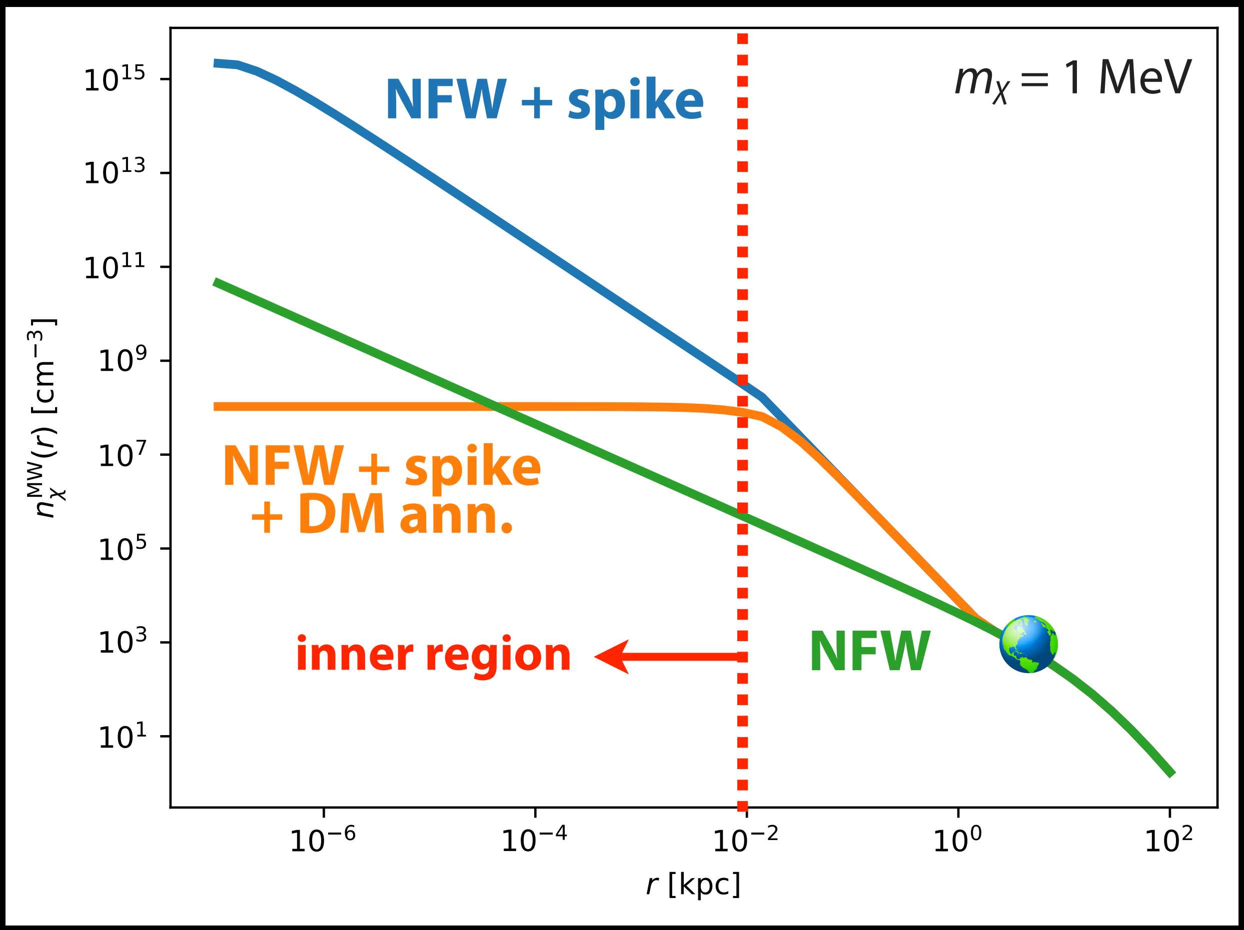
- Our MW is assumed following Navarro-Frenk-White (NFW) profile: $\rho_s = 184$ MeV cm^{-3}, $r_s = 24.4$ kpc and $n = 2$
- More sharp density spike could arise due to supermassive black hole in the galactic center

Gondolo+ 1999
Ullio+ 2001
Gnedin+2004
Cline+ 2023

Velocity



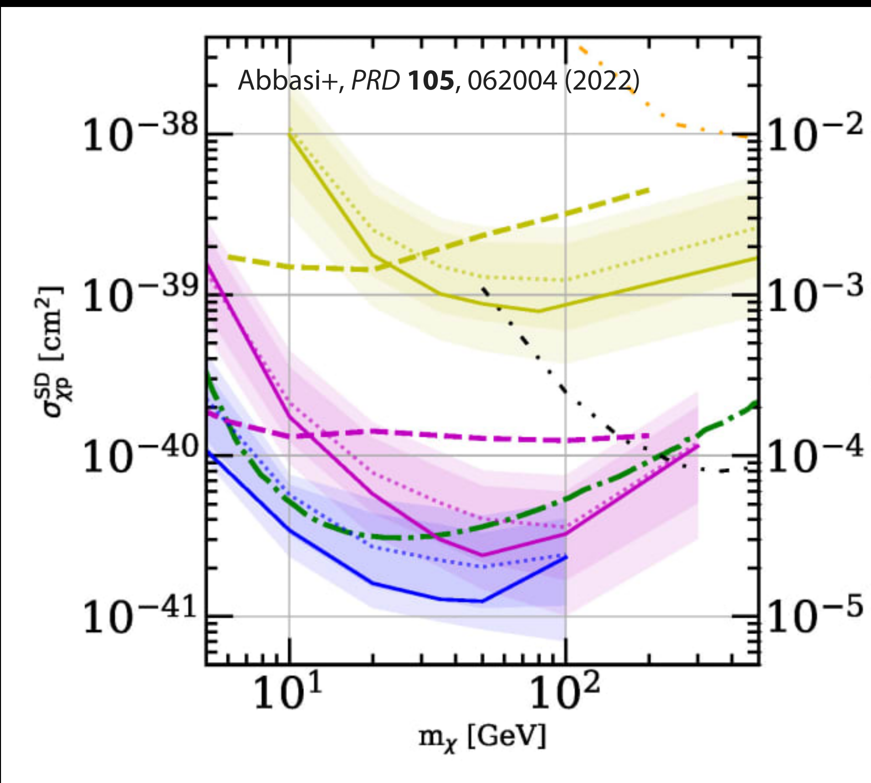


Galactic rotation curves

See: Jungman+, *PR* **267**, 195 (1996)
Bertone+, *PR* **405**,279 (2005)
Battaglieri+, 1707,04591
Knapen+, *PRD* **96**, 115021 (2017)
Lin (TASI2018), 1904.07915 (2019)
Essig+, 2203,08297
Billard+, *RPP* **85**, 056201 (2022)
Cooley+, 2209.07426
… for comprehensive reviews

Current constraints

Direct: Spin-dependent $\sigma_{\chi n}$



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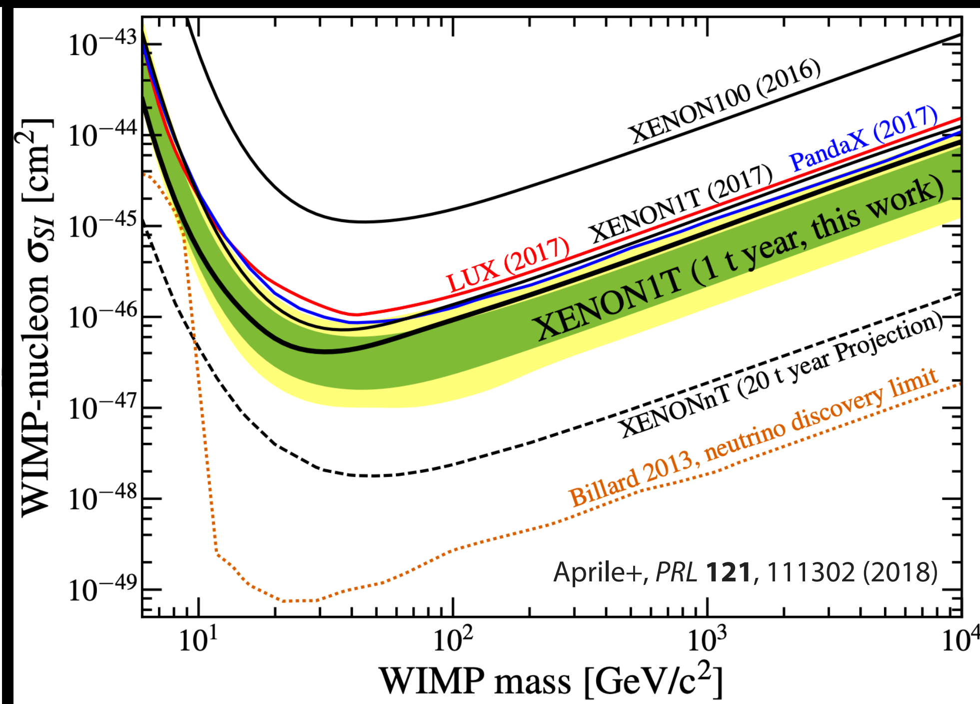
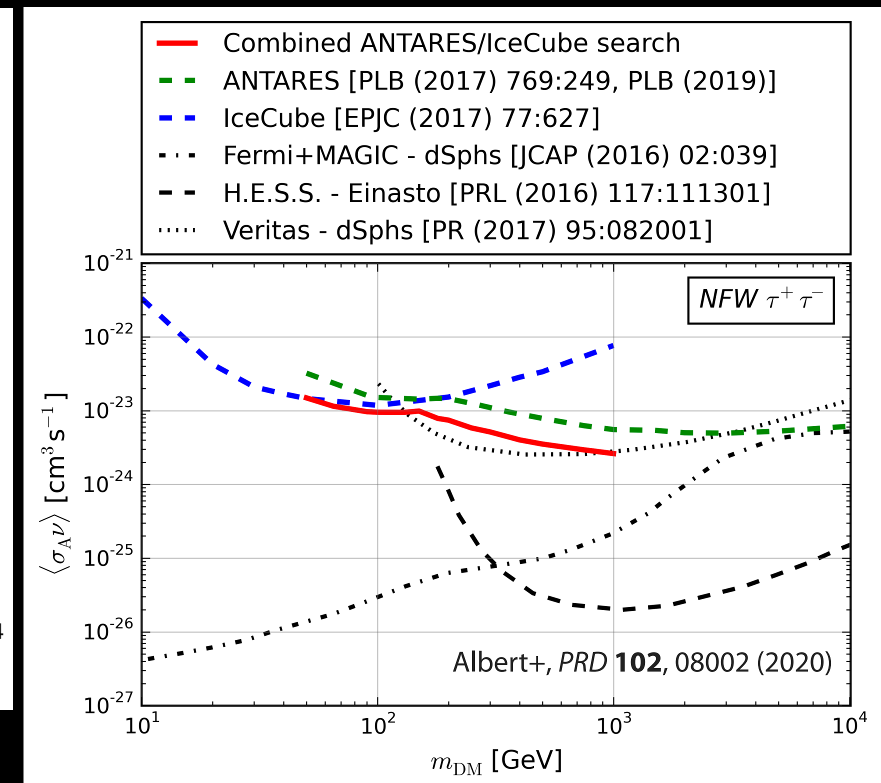


Indirect: Annihilation cross section $\langle \sigma v \rangle$



- The most stringent constraints happen around

$$\sigma_{\chi p}^{SD} \sim 10^{-41}\,\mathrm{cm}^2 \quad m_\chi \sim 30\,\mathrm{GeV}$$

$$\sigma_{\chi p}^{SI} \sim 10^{-47}\,\mathrm{cm}^2 \quad m_\chi \sim 30\,\mathrm{GeV}$$

$$\langle \sigma v \rangle \sim 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1} \quad m_\chi \sim 10\,\mathrm{GeV}$$

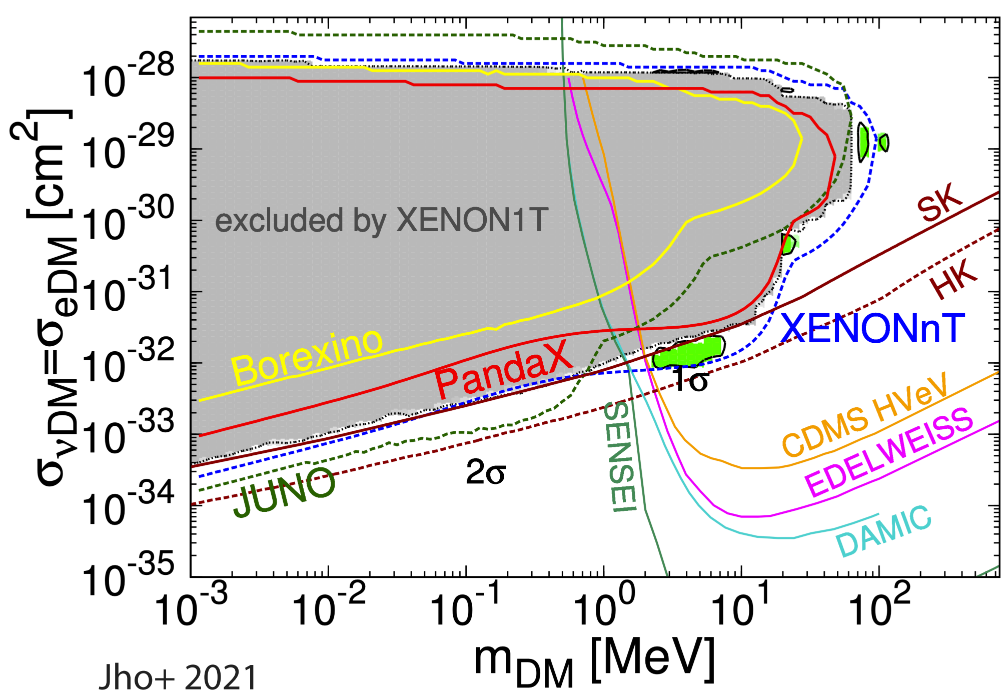
- But ***none*** of these can directly measure the ***cross section*** and ***mass*** concurrently

Origin of SNν BDM and direct m_χ differentiation

Origin of boosted DM

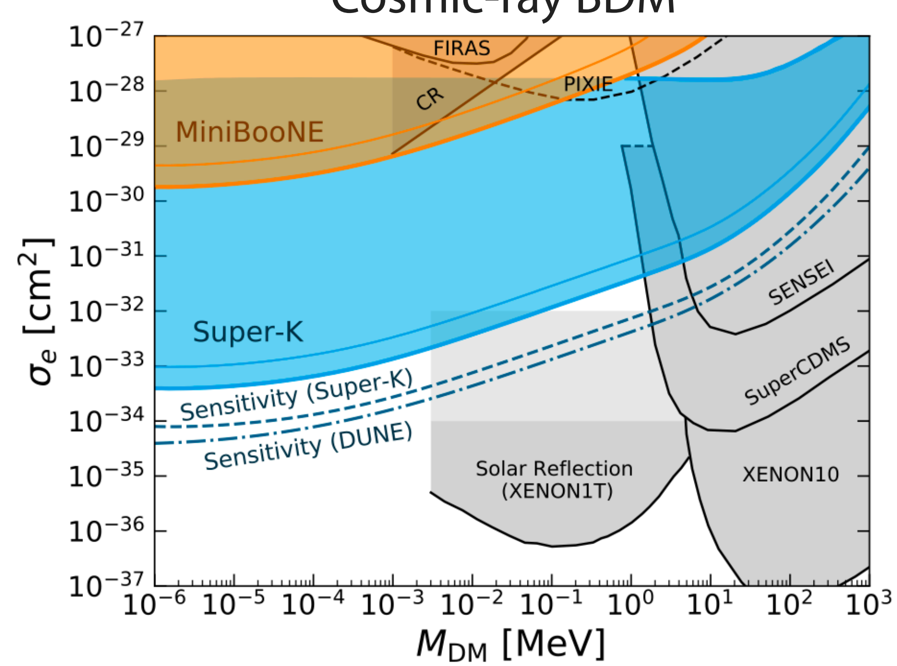
- DM in the halo can be boosted by high-energy cosmic particles, e.g. ν, e^-, p
- Boosted DM carries energy large enough to surpass the detection threshold, e.g. Super-K, DUNE

Cosmic-ν BDM



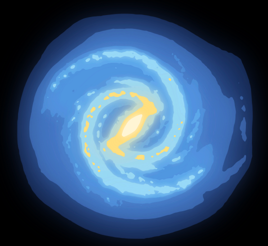
Jho+ 2021

Cosmic-ray BDM



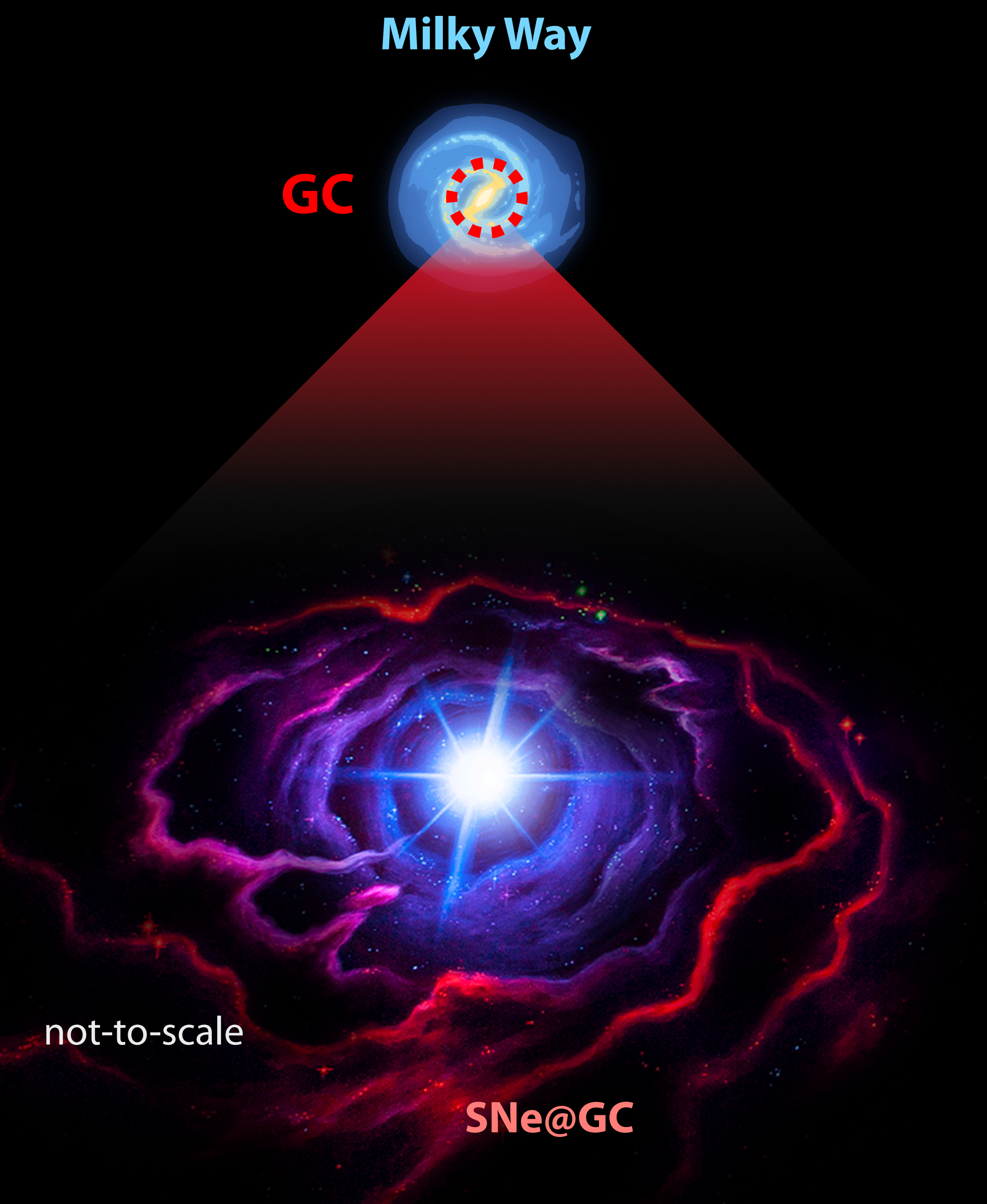
Ema+ 2019

Milky Way




Milky Way
GC


Milky Way
GC



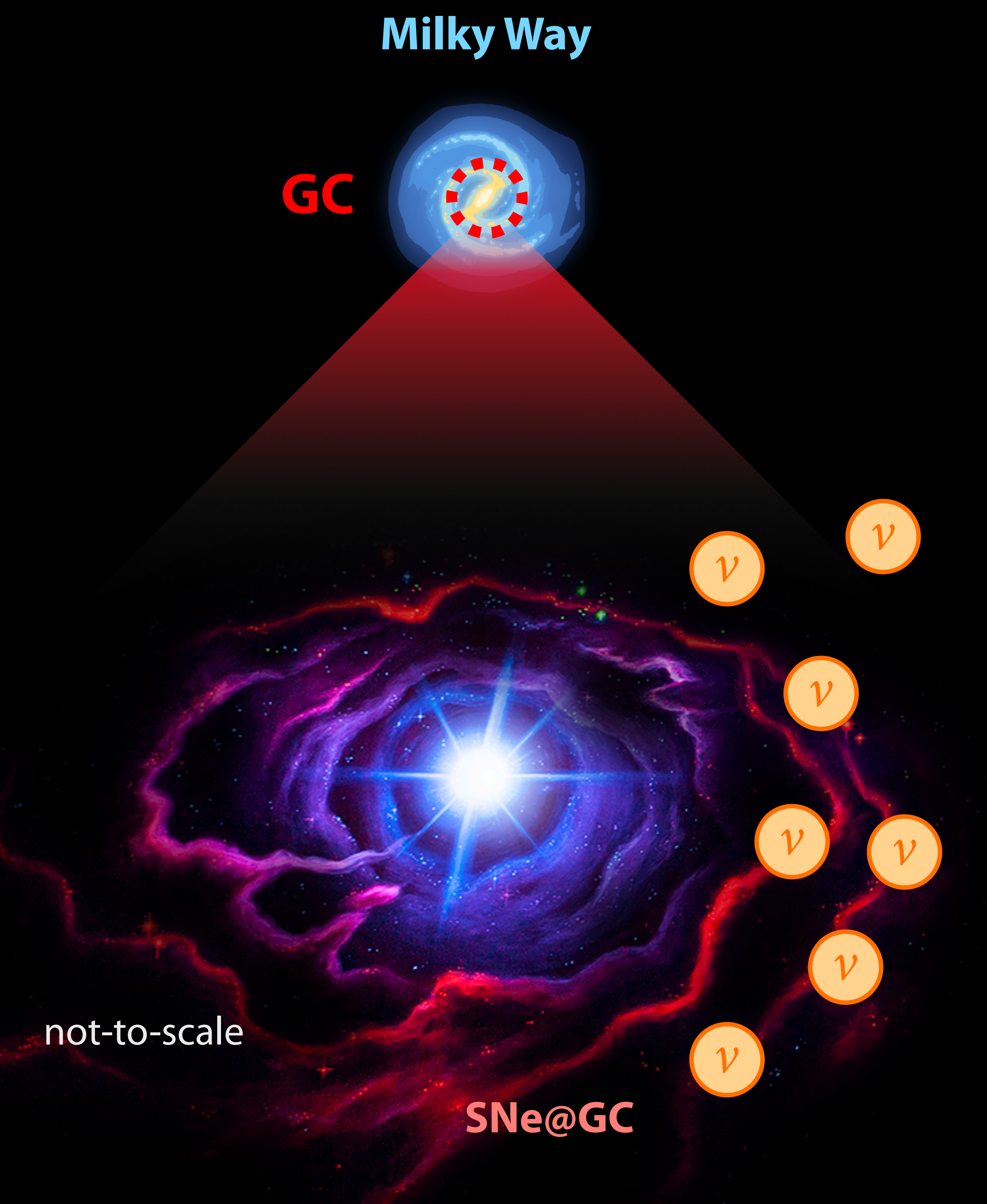
Duration: ~10 s

$N_\nu \approx 10^{58}$

$\bar{E}_\nu \approx 10 - 15\ \mathrm{MeV}$

$$\frac{d\phi_\nu}{dE_\nu} = \sum_i \frac{L_\nu}{4\pi r^2 \langle E_{\nu_i} \rangle} E_\nu^2 f_{\nu_i}(E_\nu)$$

Duan+ 2006



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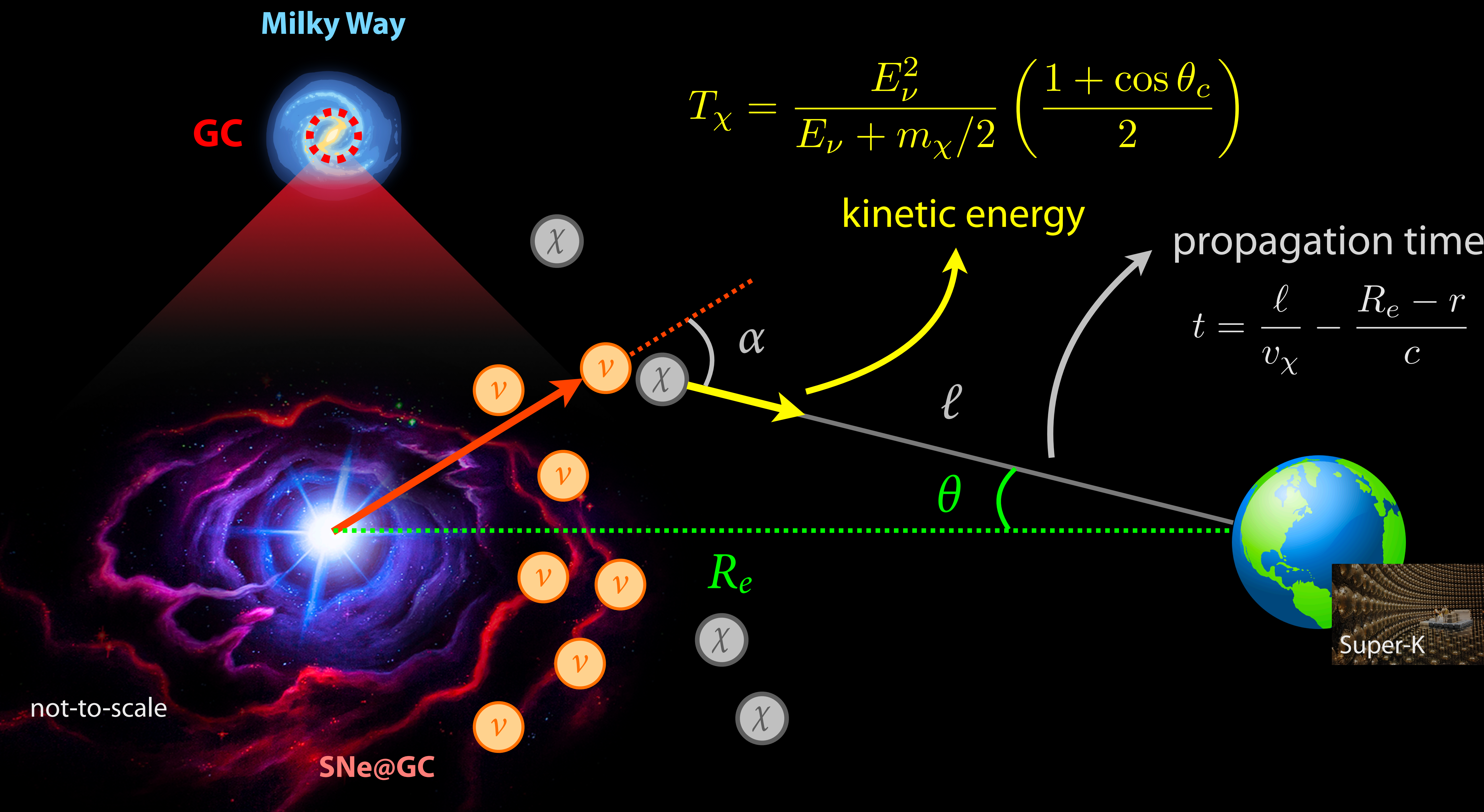

$$T_\chi = \frac{E_\nu^2}{E_\nu + m_\chi/2}\left(\frac{1+\cos\theta_c}{2}\right)$$

$$t = \frac{\ell}{v_\chi} - \frac{R_e - r}{c}$$

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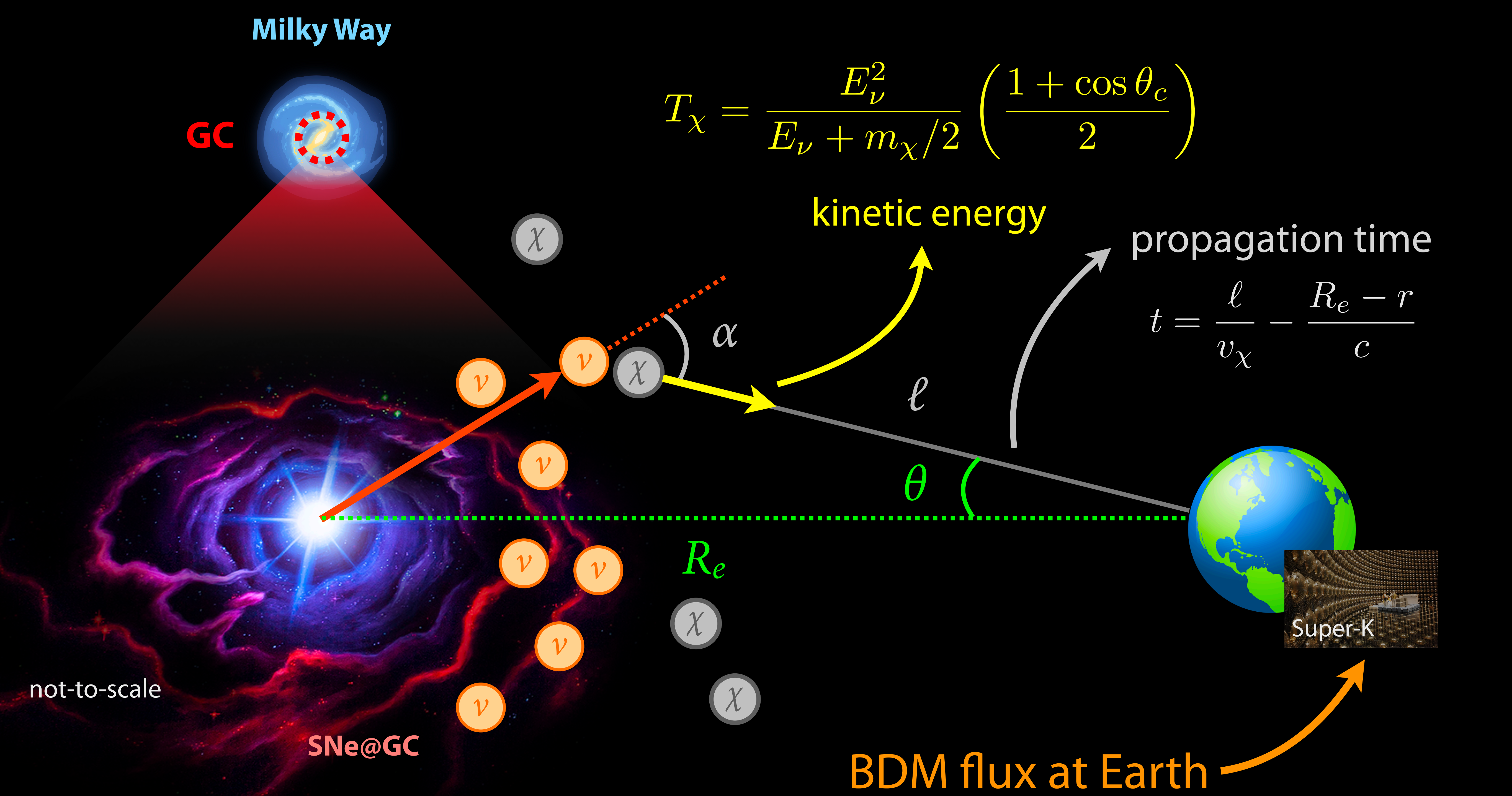

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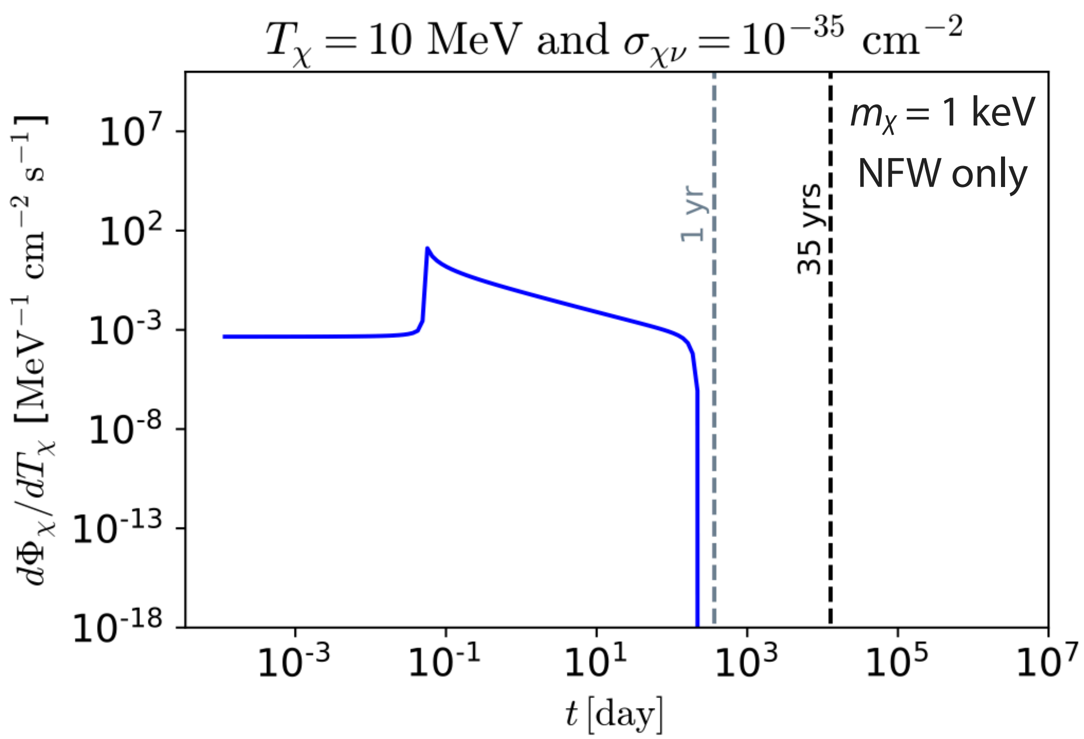
Duan+ 2006

$$\frac{d\Phi_\chi(T_\chi,t)}{dT_\chi} = 2\pi r \int_0^1 d\cos\theta \mathcal{J}\ j_\chi(r,T_\chi,\alpha)\Big|_{t'=\frac{r}{c}+\frac{\ell}{v_\chi}}$$

Inferring m_χ directly from the time-of-flight



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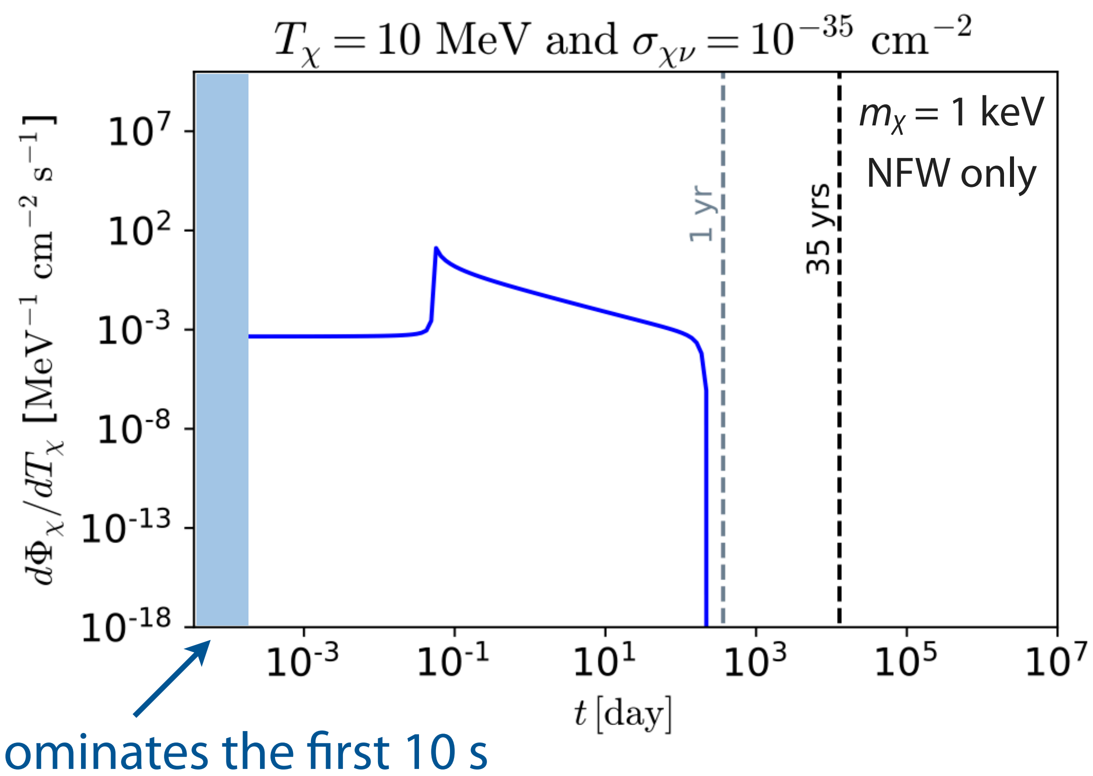

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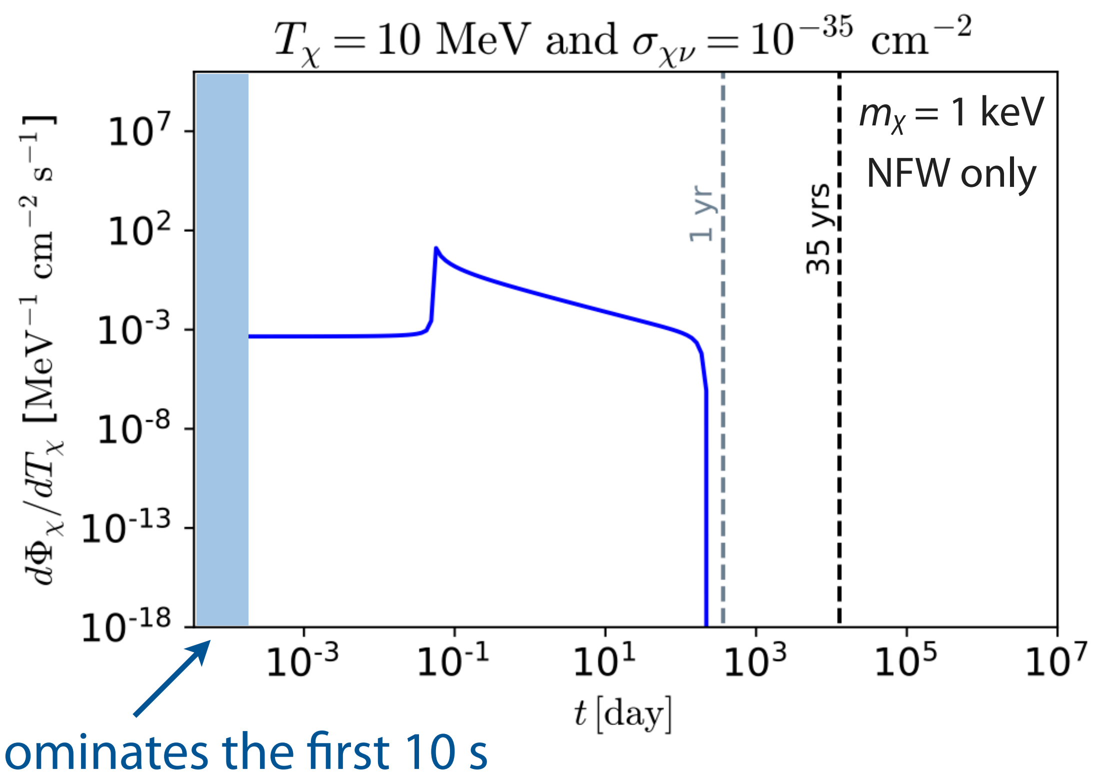
Inferring m_χ directly from the time-of-flight



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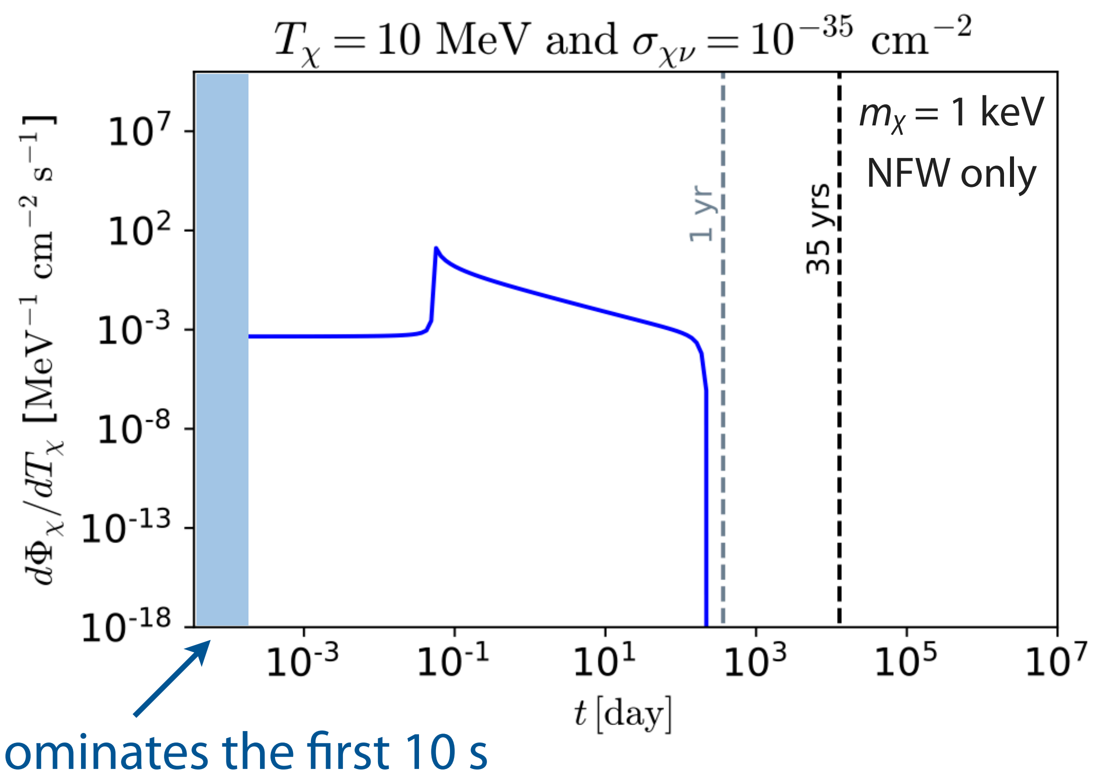

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$$t_{\text{delay}} \simeq 10 \text{ days} \times \left(\frac{\ell}{8 \text{ kpc}}\right)\left(\frac{m_\chi}{10 \text{ keV}}\right)^2\left(\frac{T_\chi}{10 \text{ MeV}}\right)^{-2}$$

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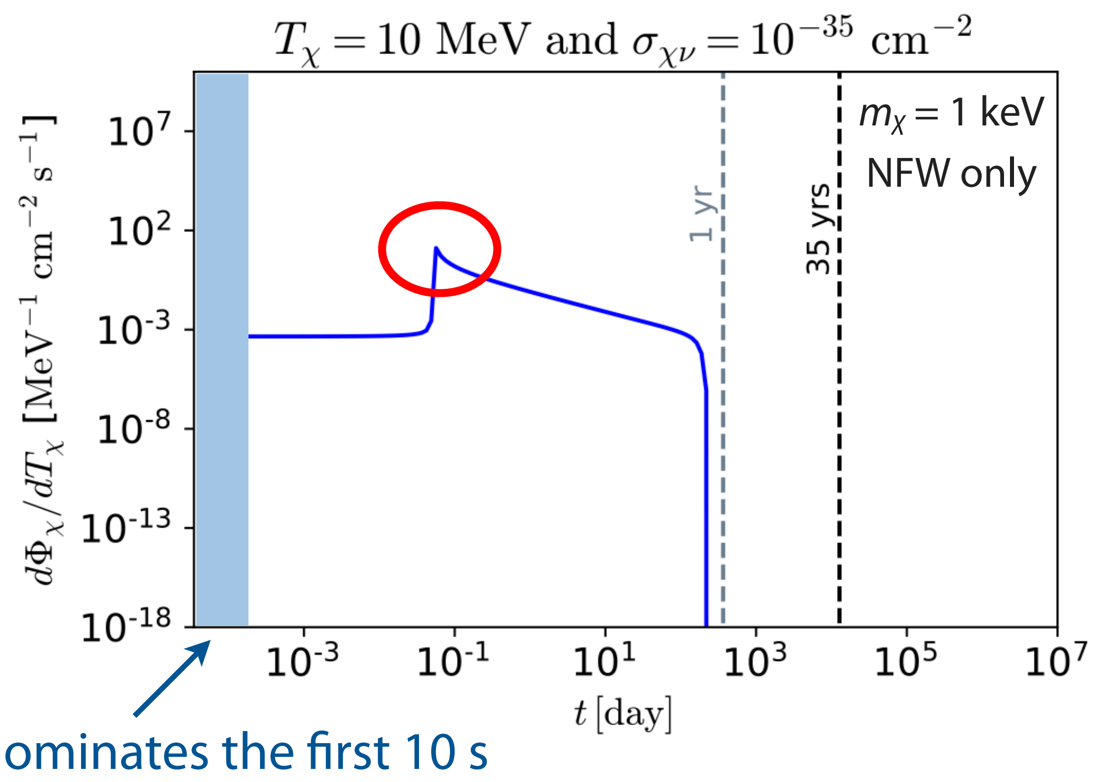

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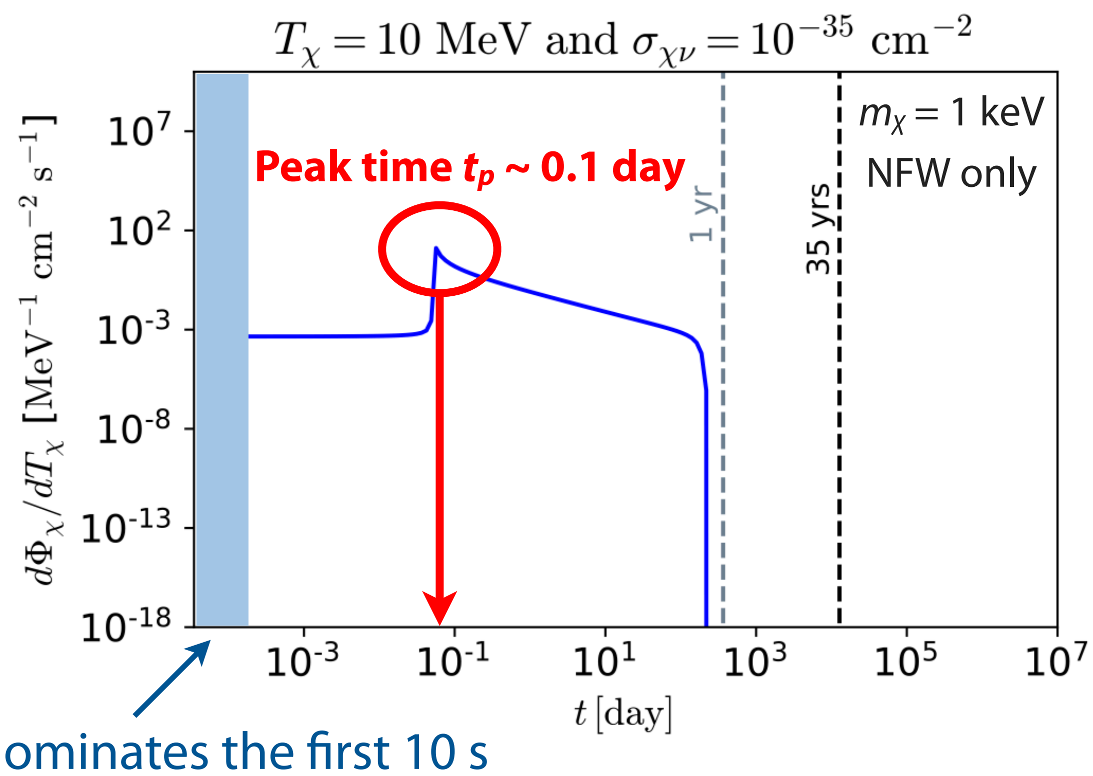

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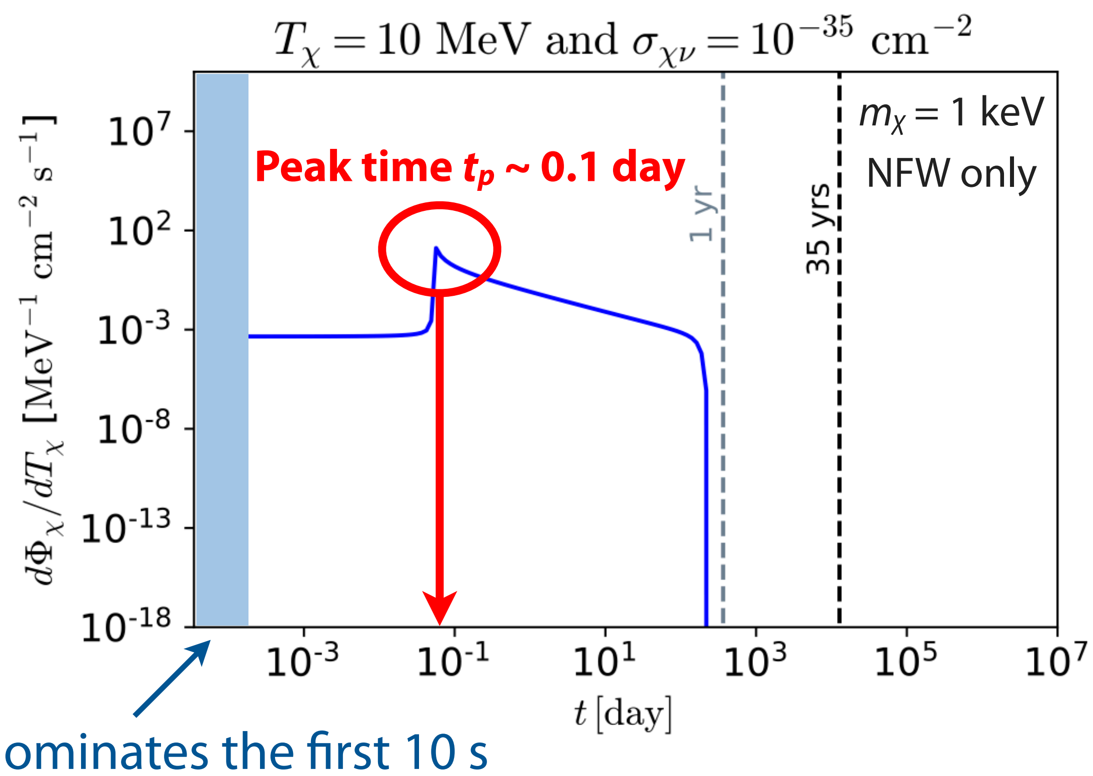

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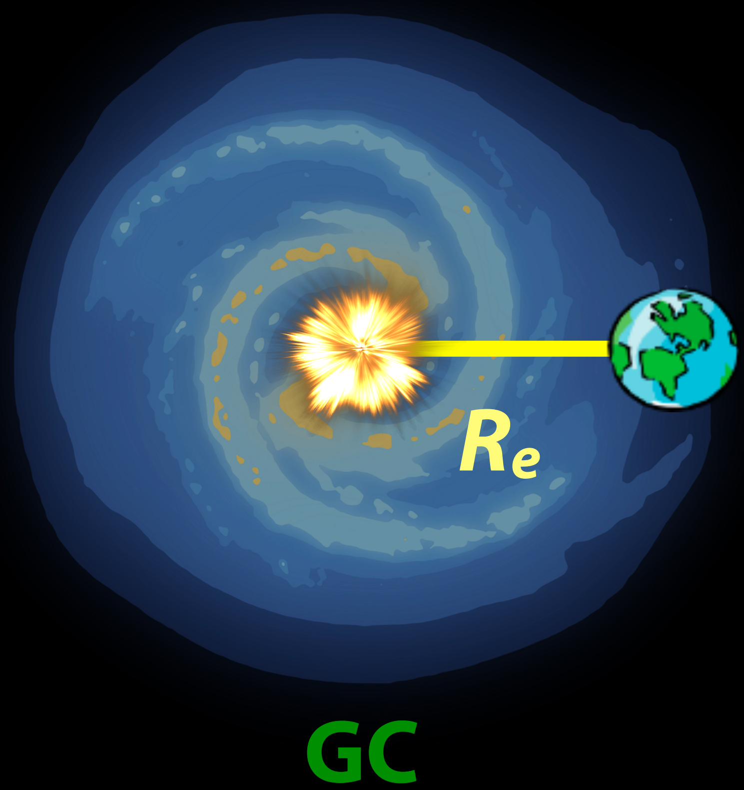
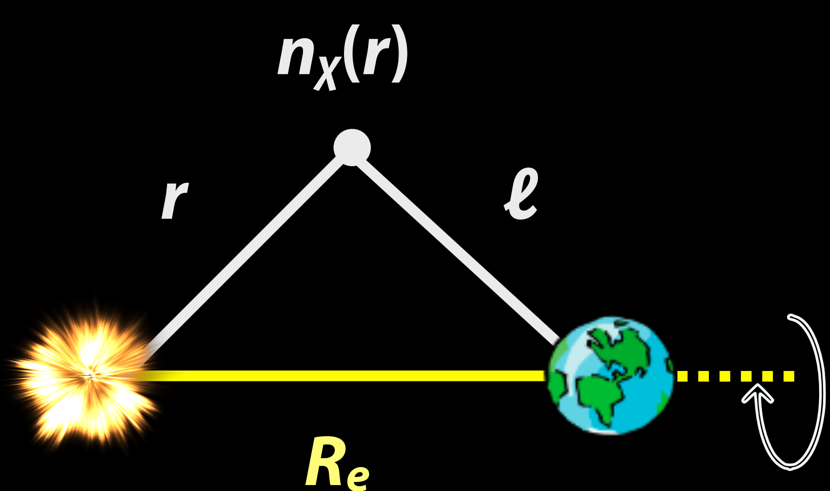
- The **peak time t_p** (coming from the GC with ℓ ~ 8.5 kpc) infers **DM mass m_χ** directly

$$m_\chi \simeq 9.7~{\rm keV} \times \left(\frac{t_p}{10~{\rm days}}\right)^{1/2}\left(\frac{T_\chi}{10~{\rm MeV}}\right)$$

top-view

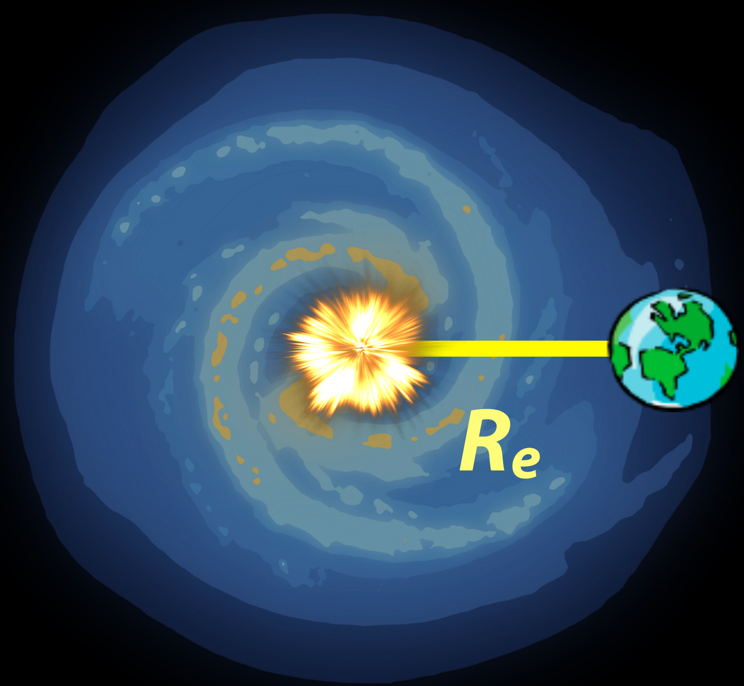


side-view

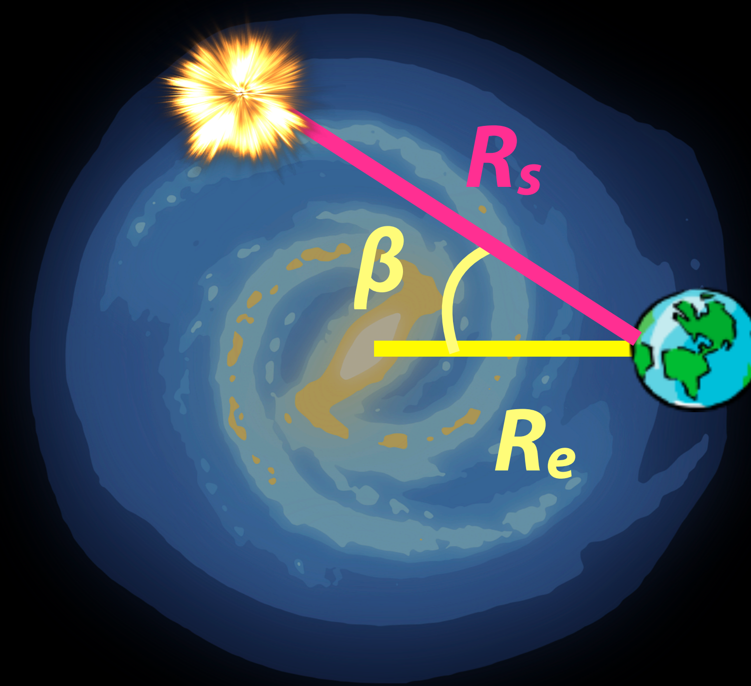


When SNe is NOT at the GC

top-view

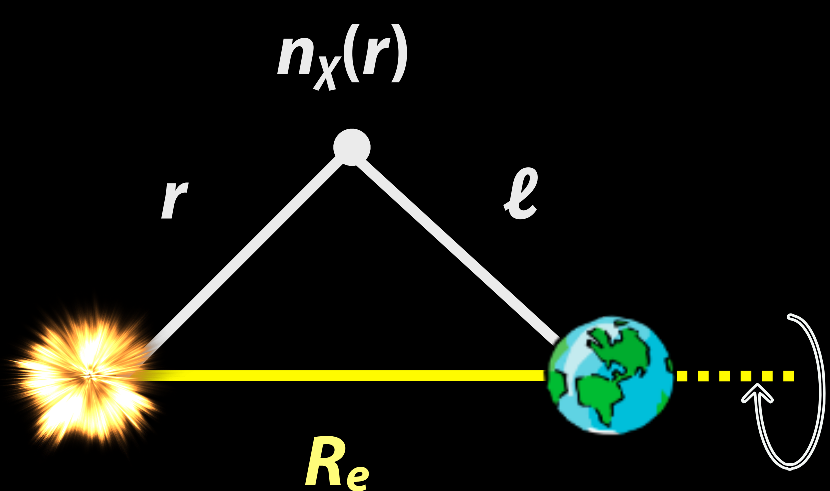


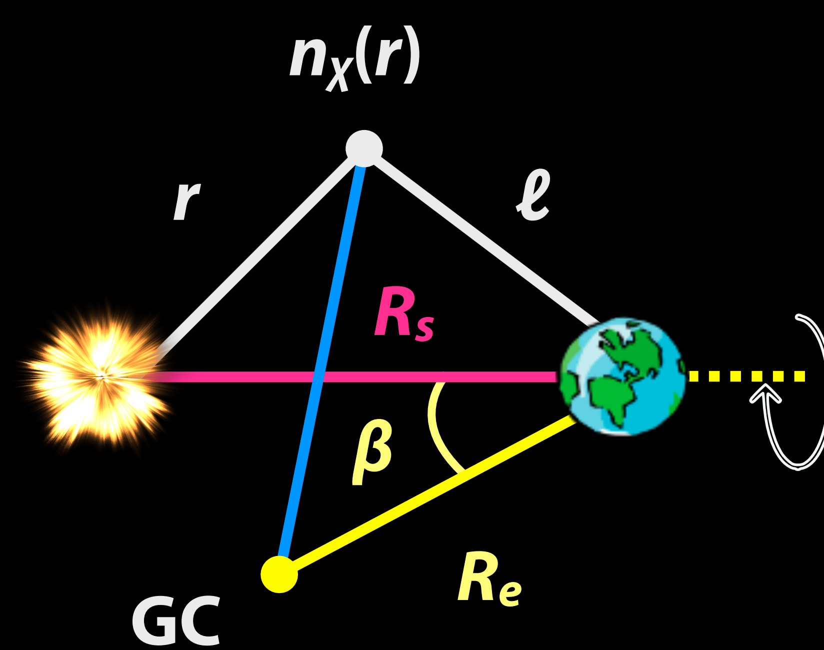
GC



off GC

side-view





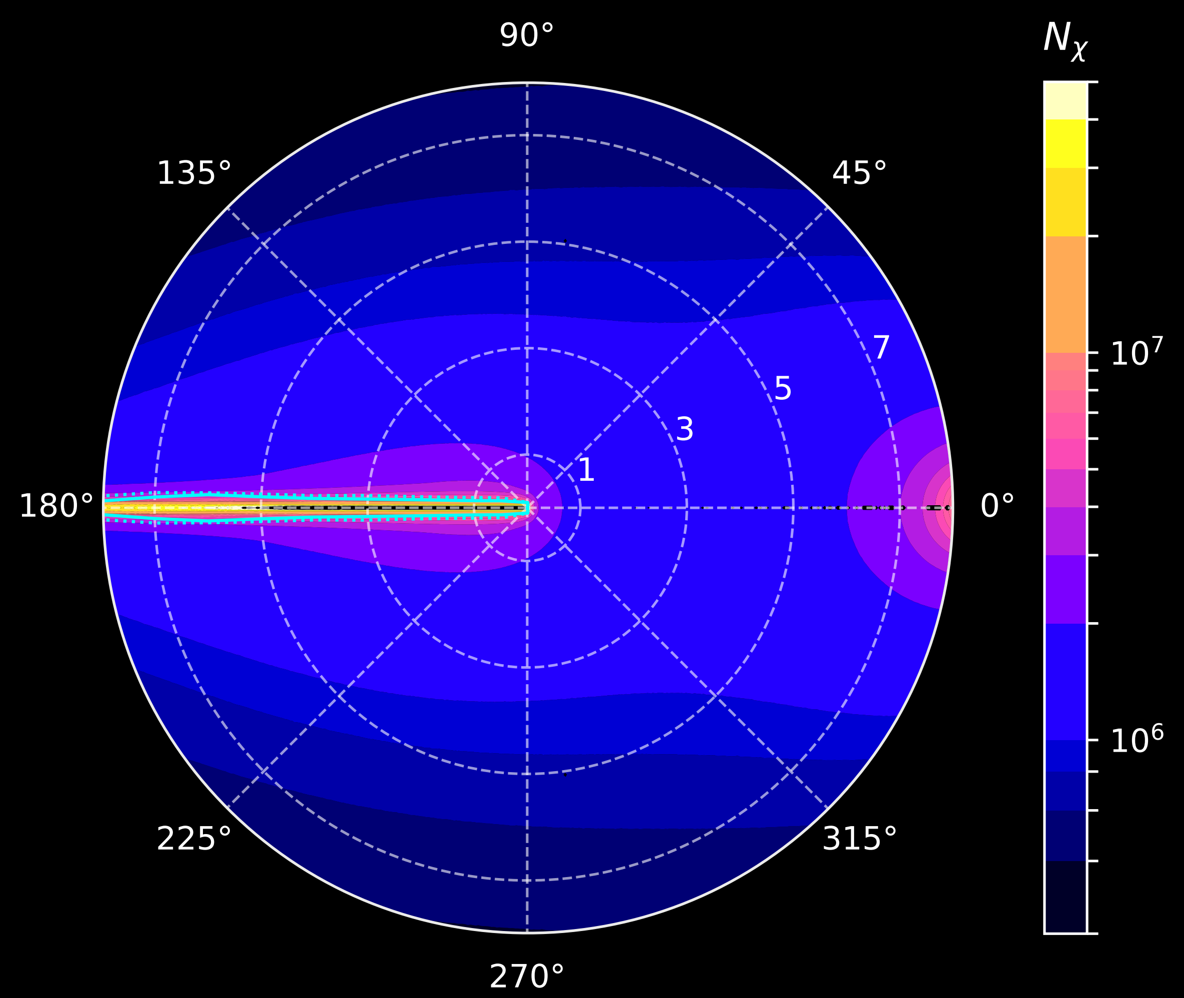
Map of Galactic SNν BDM events

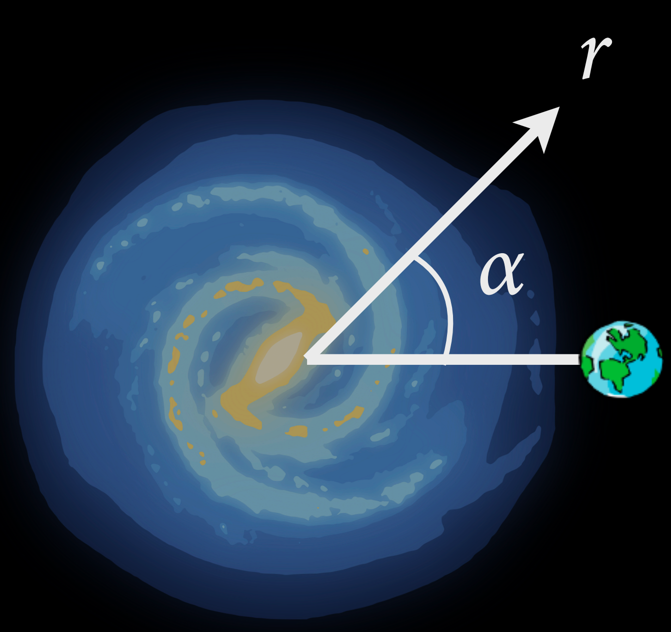
- Given the detector exposure time and the number of electron N_e, the BDM event number N_χ can be estimated by

$$N_\chi = \int_{10\,\mathrm{s}}^{t_{\max}} dt \int_{T_{\chi,\min}}^{T_{\chi,\max}} \frac{d\Phi_\chi(T_\chi, t)}{dT_\chi dt}$$

- N_χ at different locations in the MW

behind GC



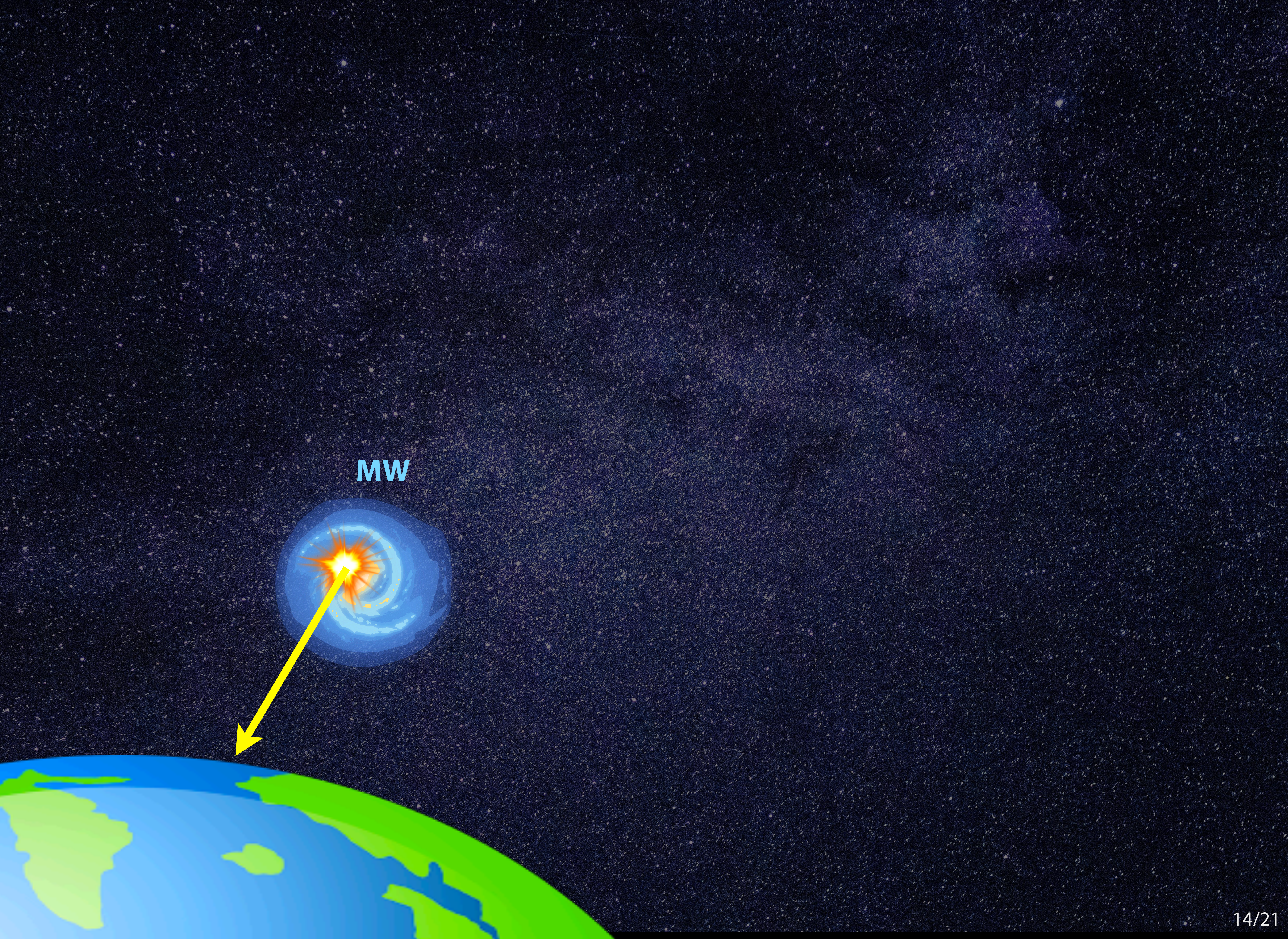


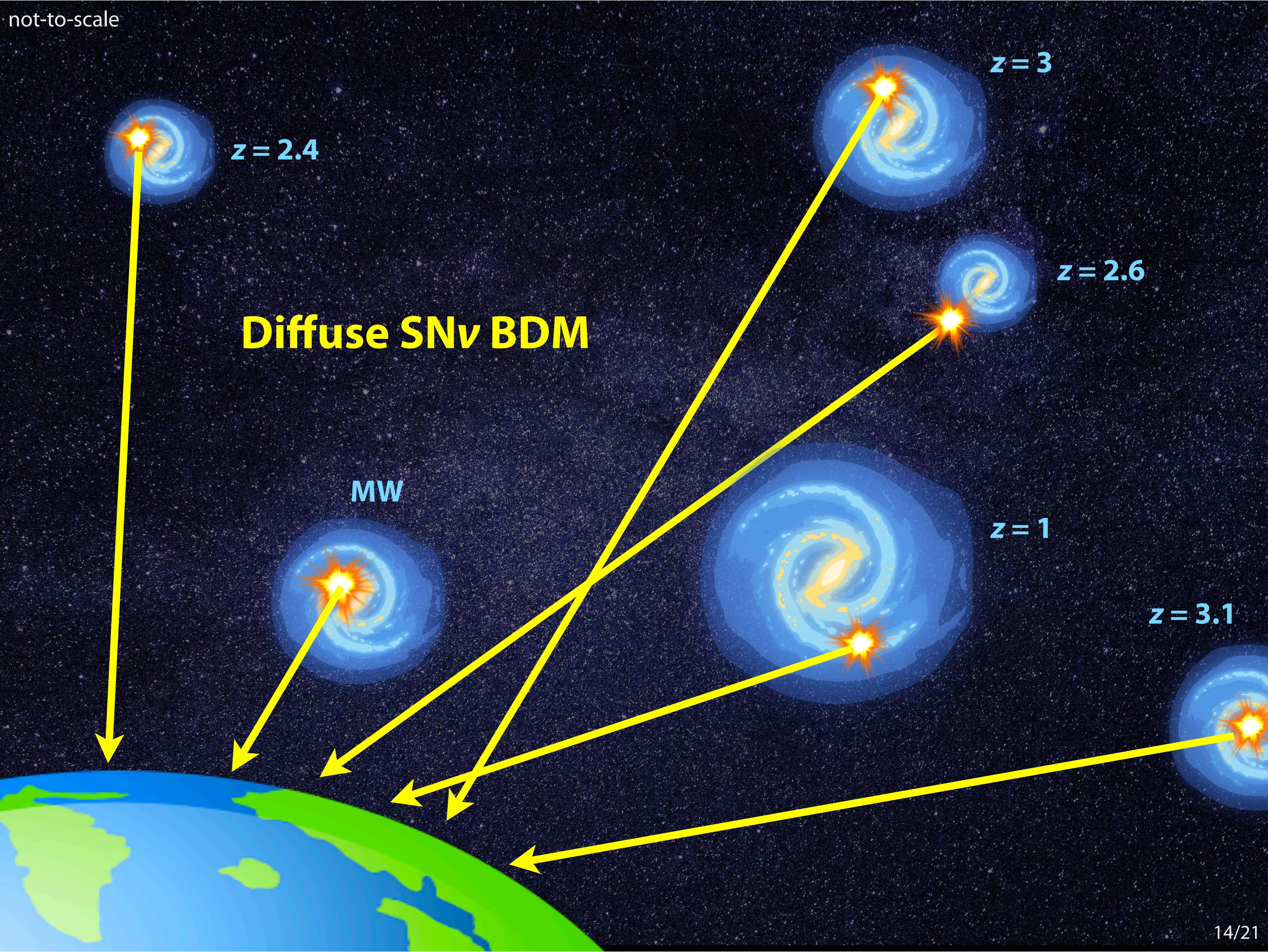
$m_\chi = 1\,\mathrm{keV}$ and $\sigma_{\chi\nu} = \sigma_{\chi e} = 10^{-35}\,\mathrm{cm}^2$

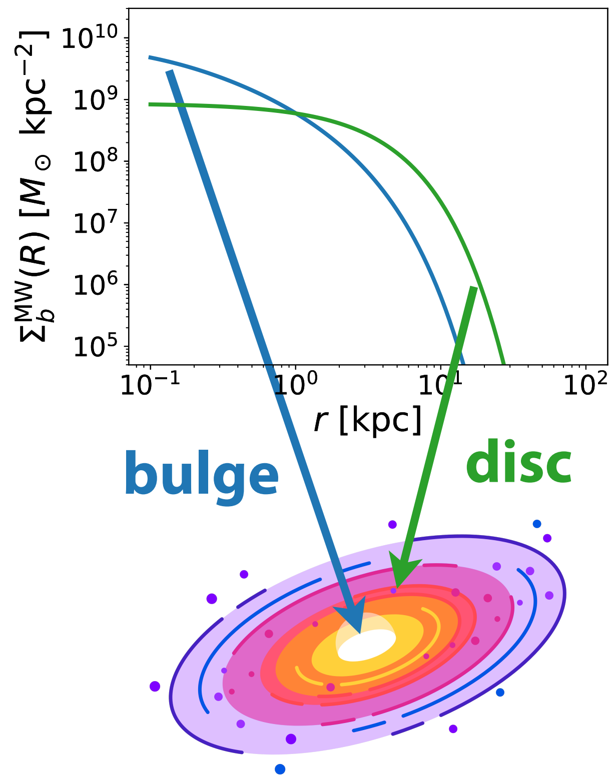
Diffuse SNν BDM from the present and past Universe


not-to-scale
MW

not-to-scale




not-to-scale
z = 2.4
z = 3
z = 2.6
Diffuse SNν BDM
MW
z = 1
z = 3.1



MW w/t $M_G = M_{MW}$

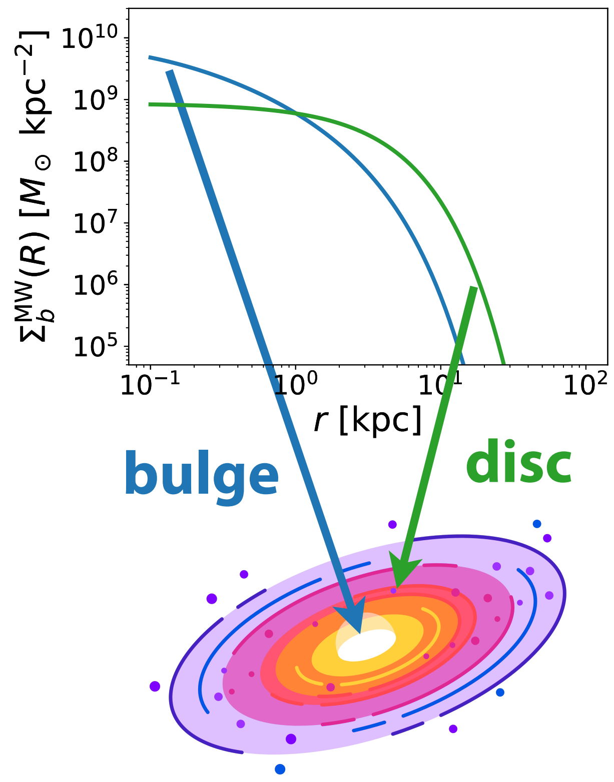
McMillan 2017

$$\rho_b(R,h) = \frac{\rho_{0,b}}{[1 + r'(R,h)/r_0]^{\alpha}} e^{-\frac{r'^2(R,h)}{r_{\rm cut}^2}}$$

$$\rho_d(R,h) = \frac{\Sigma_0}{2h_d} e^{-\frac{|h|}{h_d} - \frac{R}{Rd}}$$

r_0 and $r_{\rm cut} \propto M_G^{1/3}$

$R_m,\ R_d$ and $h_d \propto M_G^{1/2}$



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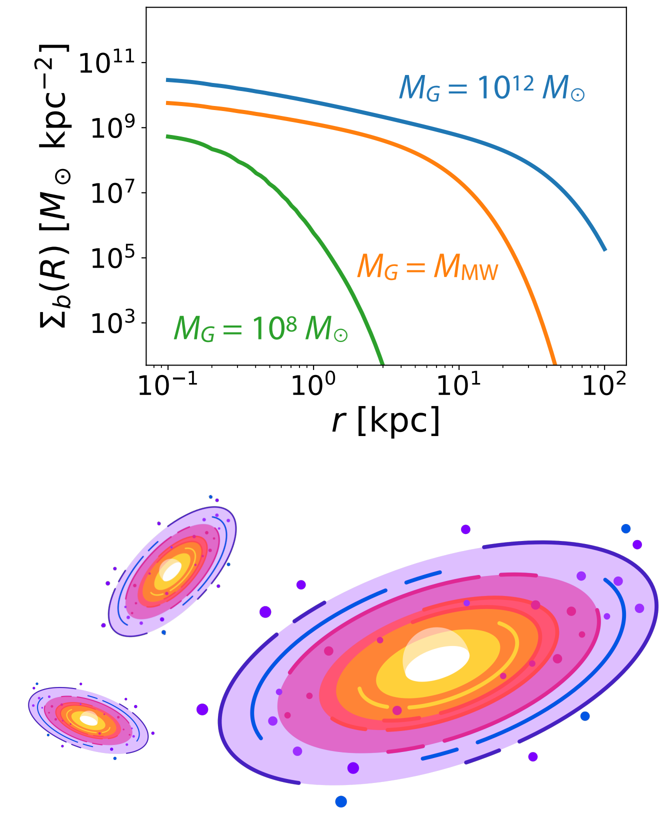
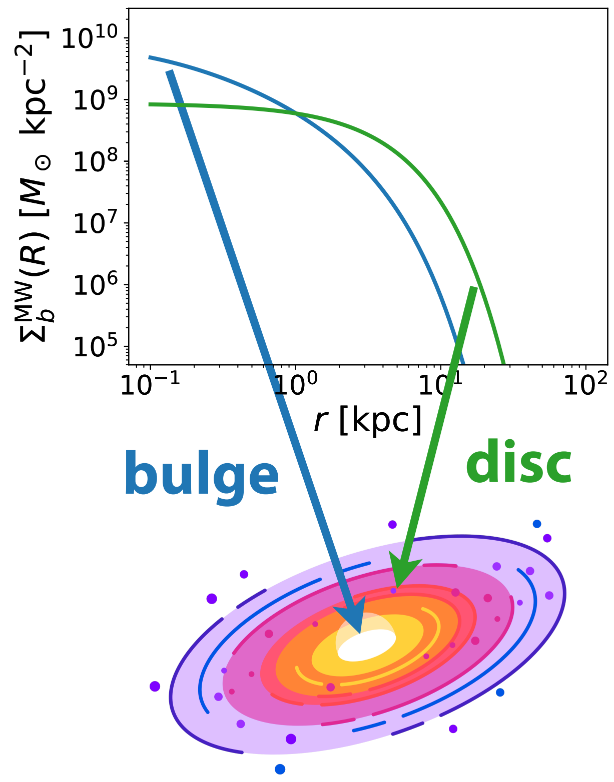


Galaxies w/t arbitrary M_G



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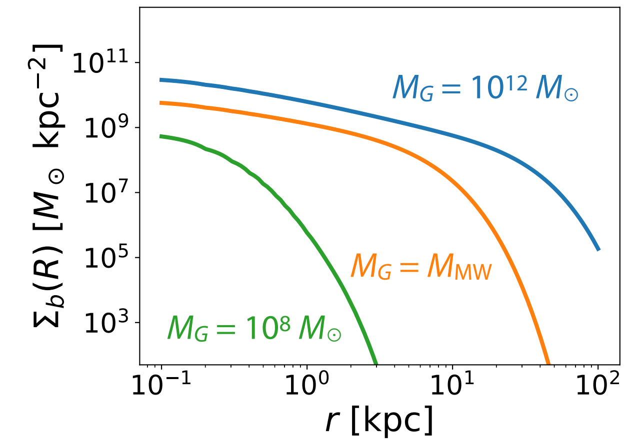

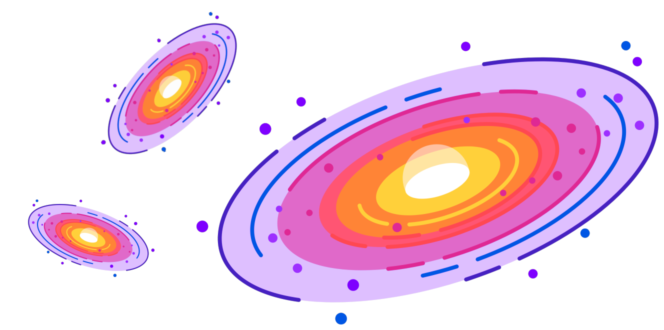

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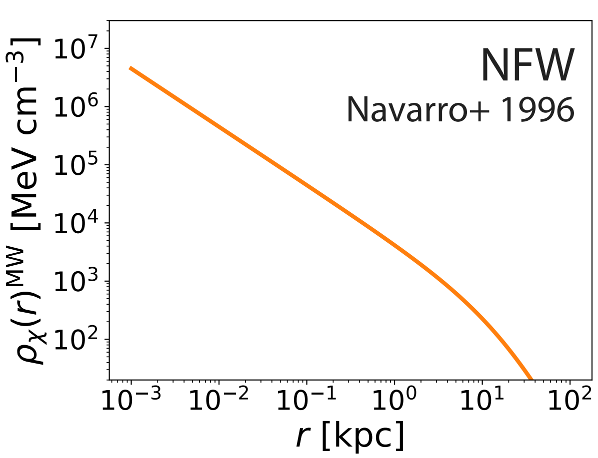

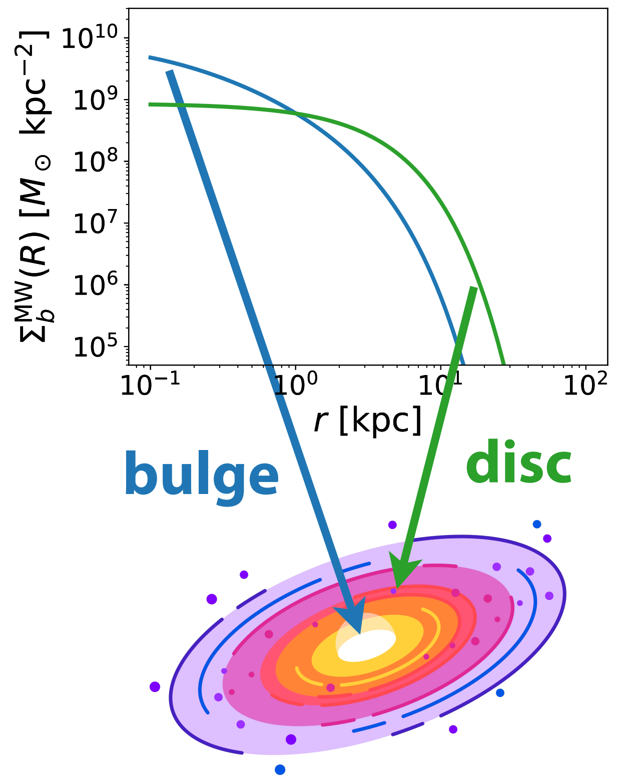

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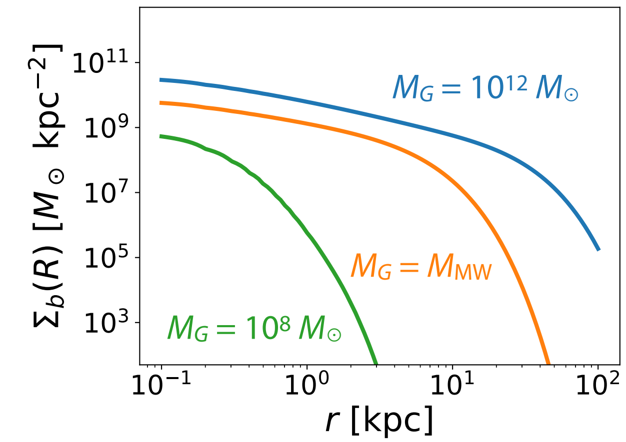
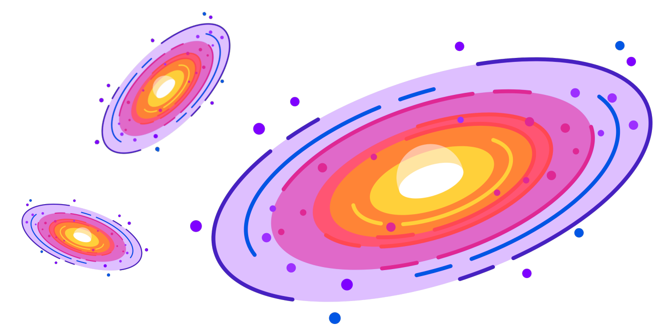
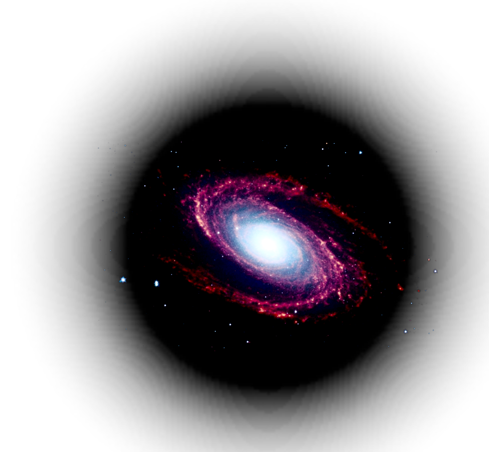
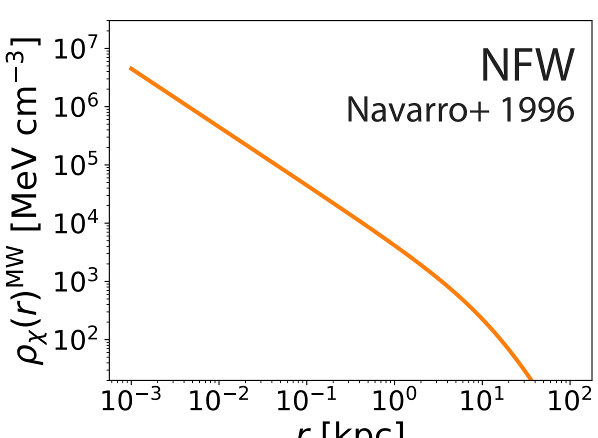




MW w/t $M_G = M_{\rm MW}$

Galaxies w/t arbitrary M_G

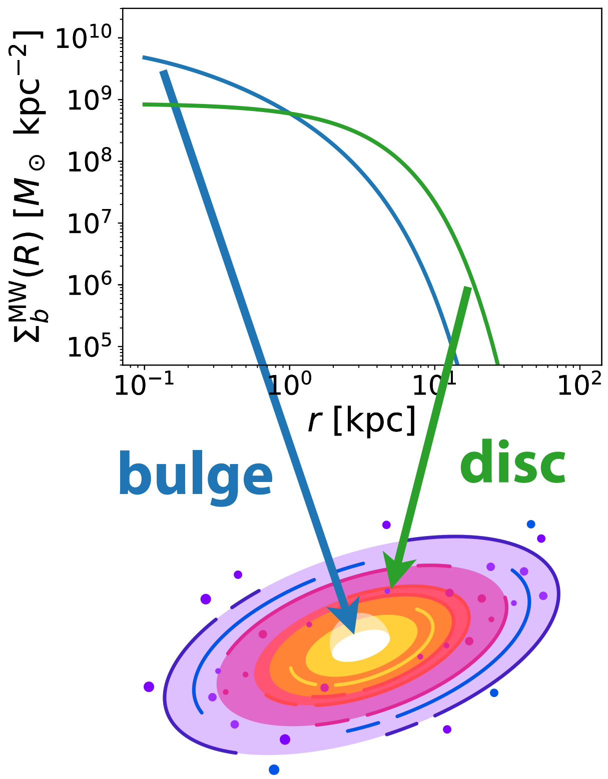




$$\rho_\chi(r) = \frac{\rho_s}{\frac{r}{r_s}(1 + \frac{r}{r_s})^n}$$

$$r_s \propto M_{\rm halo}^{1/3}$$

$$\rho_s = \frac{M_{\rm halo}}{\int \rho_\chi(r) d^3 r}$$



McMillan 2017

$$\rho_b(R,h) = \frac{\rho_{0,b}}{[1 + r'(R,h)/r_0]^\alpha} e^{-\frac{r'^2(R,h)}{r^2_{\rm cut}}}$$

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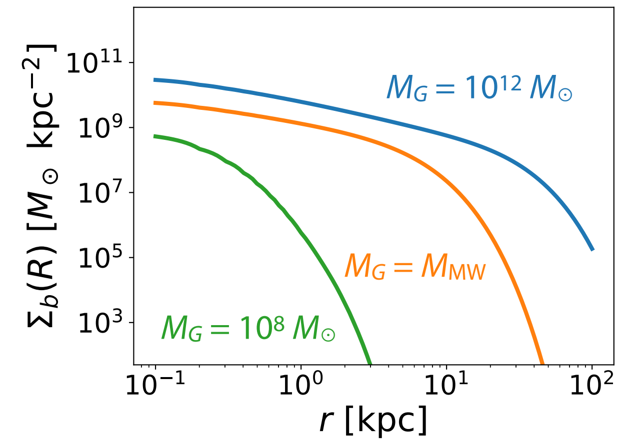

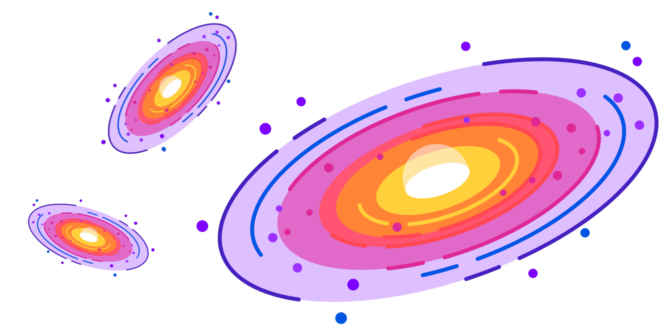

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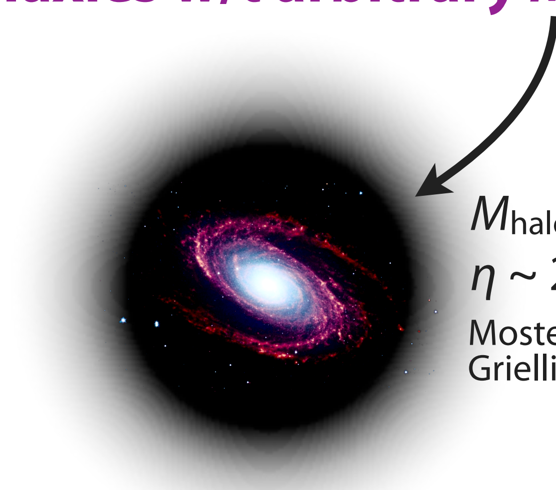
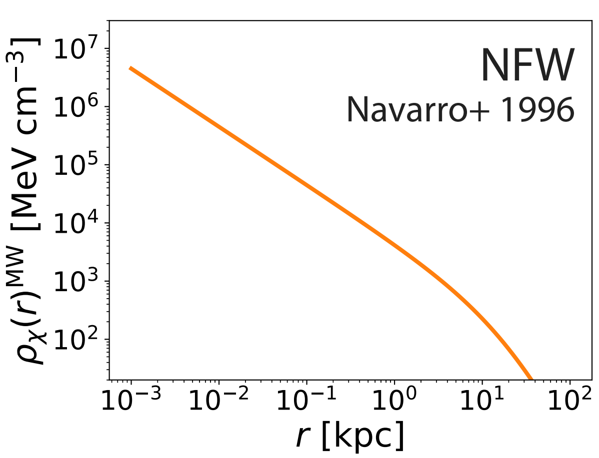


$M_{\rm halo} = \eta M_G$

η ~ 20 - 50

Moster+ 2010
Grielli+ 2020



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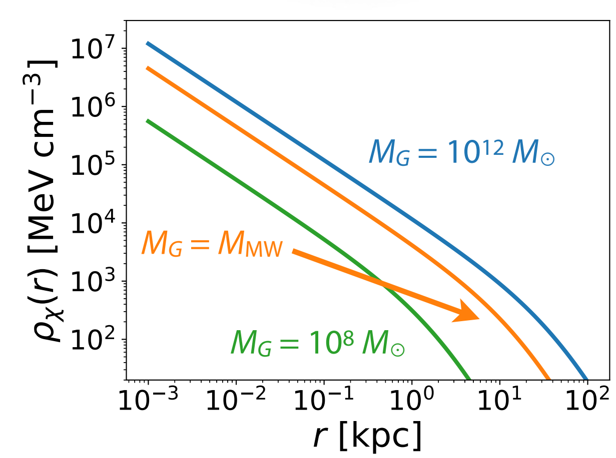

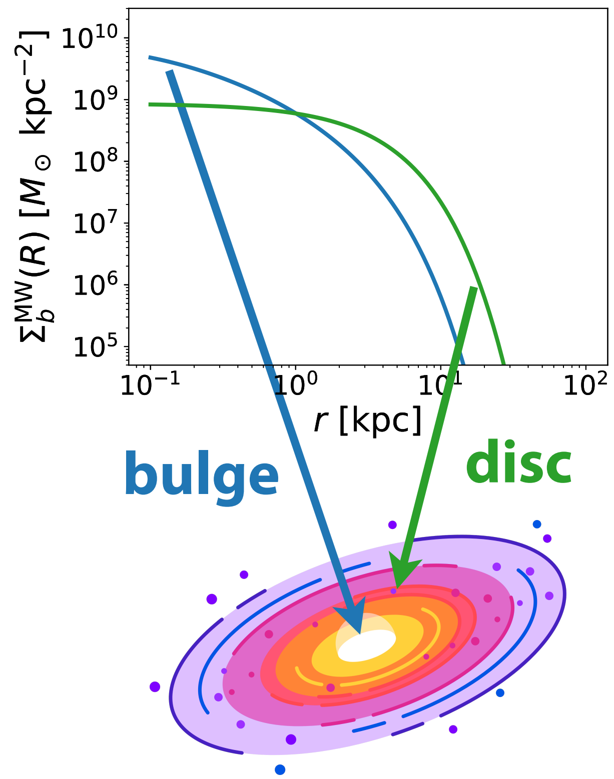

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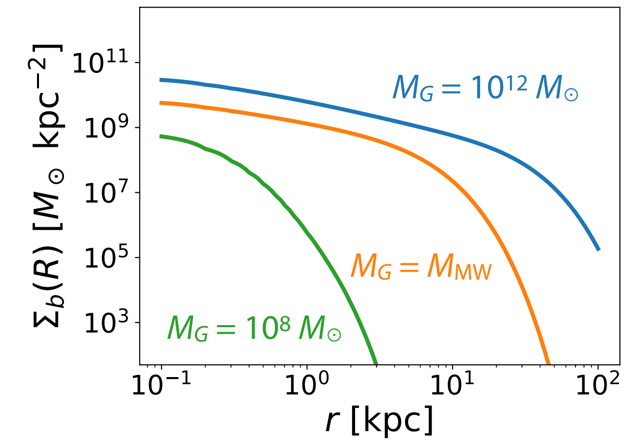
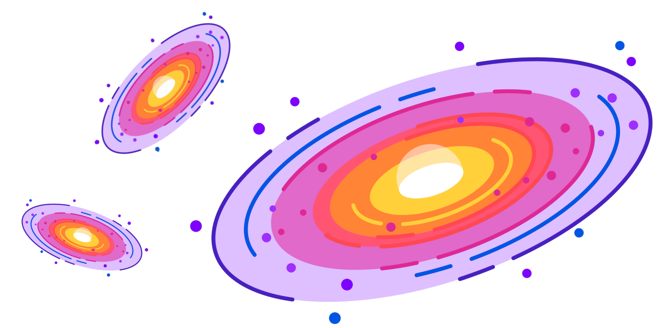


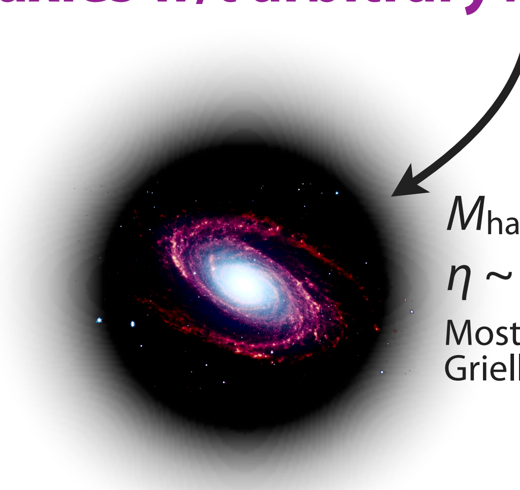


MW w/t $M_G = M_{MW}$

$$\frac{d\bar{N}_\chi}{dT_\chi} = \frac{1}{M_G} \int \underbrace{dR\ 2\pi R}_{dA}\, \Sigma_b(R) \frac{dN_\chi(R)}{dT_\chi}$$

Galaxies w/t arbitrary M_G

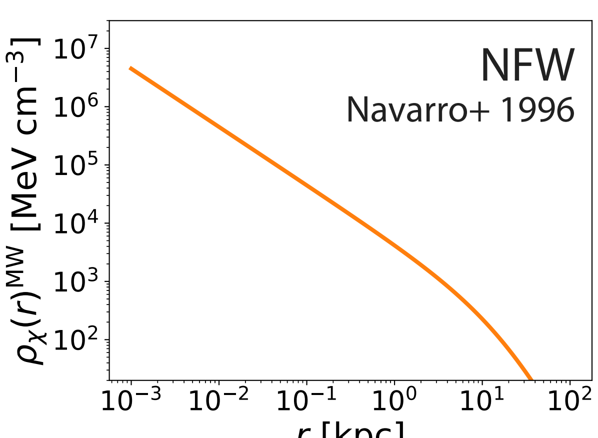
Average Diffuse SNν BDM spectrum per single galaxy w/t M_G



$M_{\rm halo} = \eta M_G$

$\eta \sim 20 - 50$

Moster+ 2010
Grielli+ 2020



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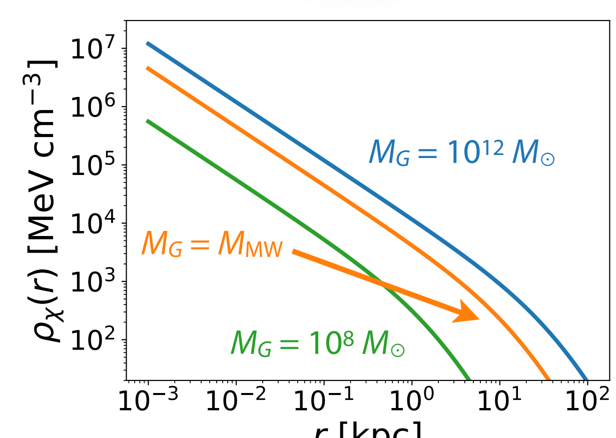


Diffuse SNν BDM (DBDM) flux

- The DBDM flux

$$\frac{d\Phi_\chi}{dT_\chi} = \frac{v_\chi}{H_0}\int_0^{z_{\max}} \frac{dz}{\epsilon(z)} \int dM_G \frac{d\Gamma_{\rm SN}(z)}{dM_G}\frac{d\bar{N}_\chi(M_G)}{dT'_\chi}, \quad T'_\chi(1+z)T_\chi$$

- Given the SN rate per coming volume per M_G at z

$$\frac{d\Gamma_{\rm SN}(z)}{dM_G} = \frac{dn_G(z)}{dM_G}\frac{\dot{\rho}_*(z)}{\dot{\rho}_*(0)}\frac{M_G}{M_{\rm MW}}R_{\rm SN,0}$$

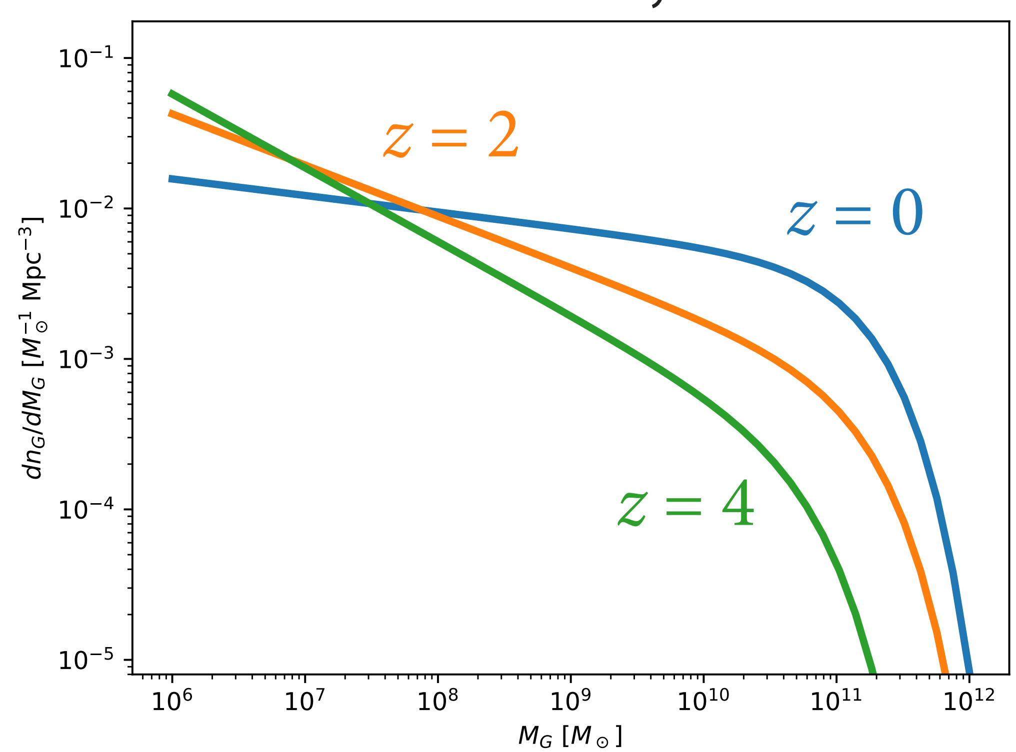
- The galactic number density per coming volume per M_G at z ($m = \log_{10}M_G/M_\odot$)

$$\frac{dn_G(z)}{dm} = \phi_0 \ln 10 \times 10^{(m-M)(1+\gamma)}e^{-10^{m-M_c}}$$

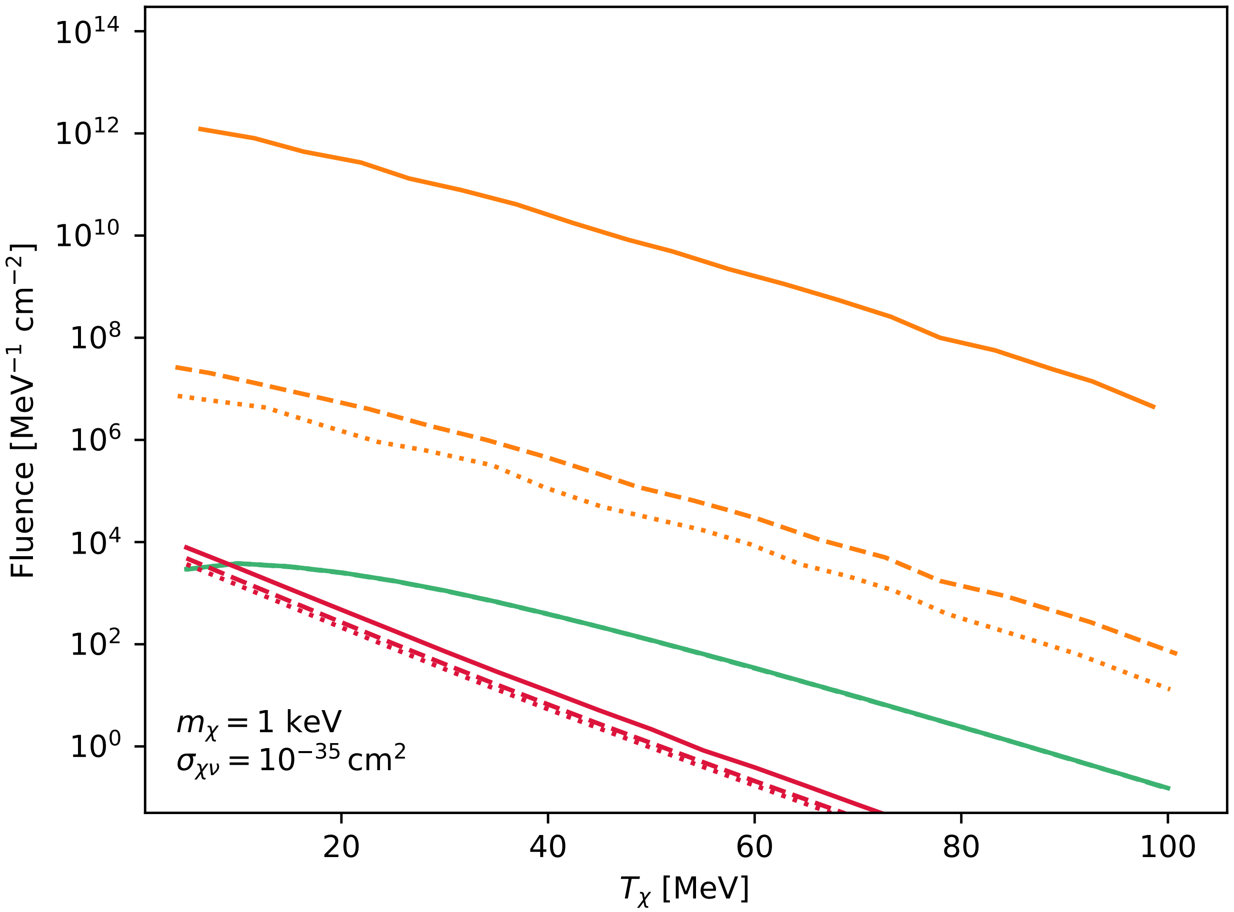
Conselice+ 2016

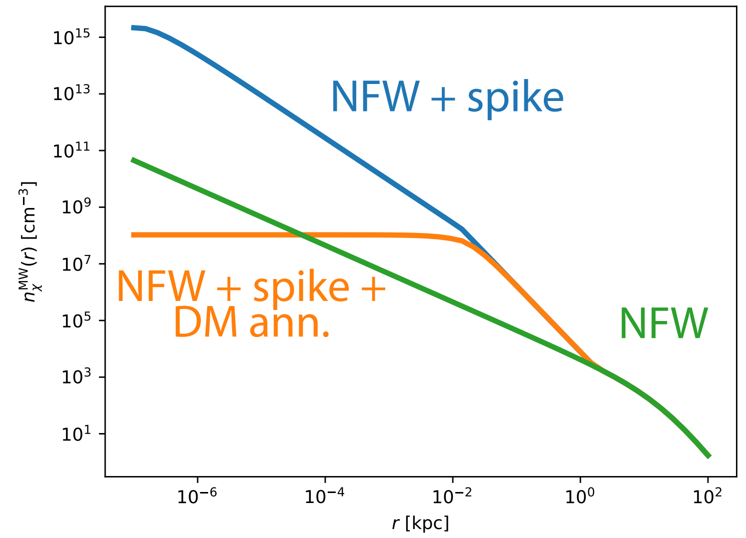
Redshift (z)	γ	$\log_{10}(M_c/M_\odot)$	ϕ_0 ($\times10^{-4}$) (Mpc^{-3})	References
0.0 – 0.7	−1.11	11.22	18.2	Fontana+04 [15] in Ref. [14]
0.7 – 1.0	−1.27	11.37	11.0	
1.0 – 1.4	−1.28	11.26	6.2	Fontana+06 [16] in Ref. [14]
1.4 – 1.7	−1.31	11.25	4.3	
1.8 – 2.2	−1.34	11.22	3.1	
2.2 – 2.6	−1.38	11.16	2.4	
2.6 – 3.0	−1.41	11.09	1.9	
3.0 – 3.5	−1.45	10.97	1.5	
3.5 – 4.0	−1.49	10.81	1.1	
4.0 – 4.5	−1.53	10.44	3.0	Song+16 [17] in Ref. [14]
4.5 – 5.5	−1.67	10.47	1.3	
5.5 – 6.5	−1.93	10.30	0.3	
6.5 – 8.0	−2.05	10.42	0.1	

Galactic number density at different z



The fluences





- We show the **fluences** for SN at different locations for comparison

$$\text{Fluence} = \int_{t_{\min}}^{t_{\max}} dt \frac{d\Phi_\chi}{dT_\chi}$$

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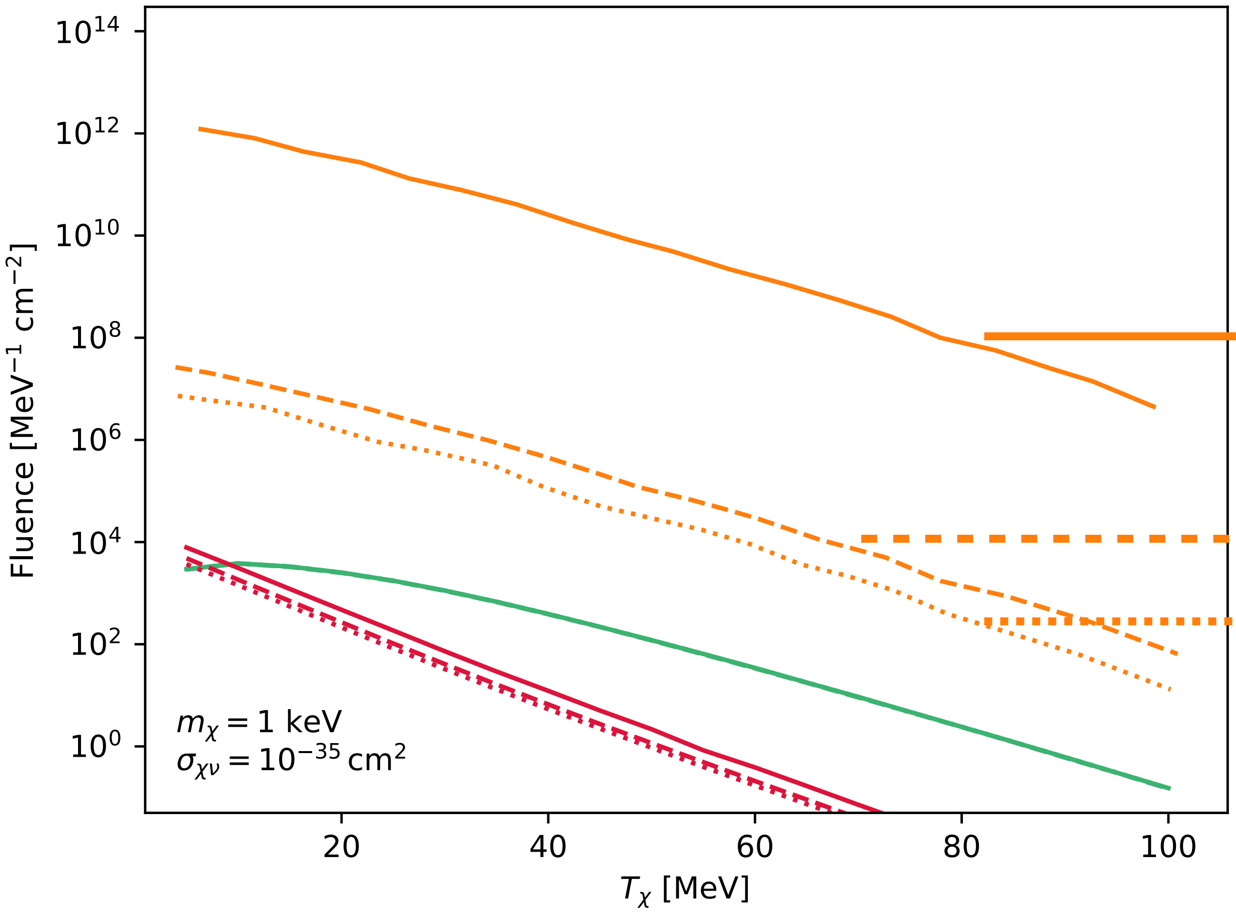

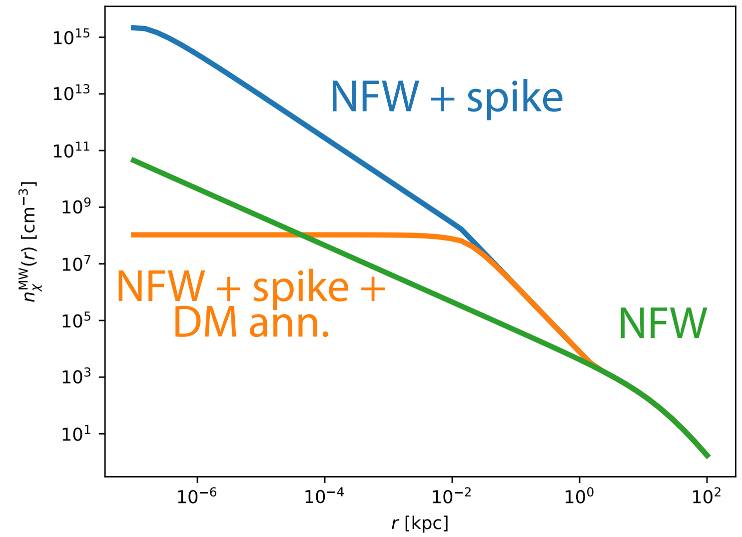

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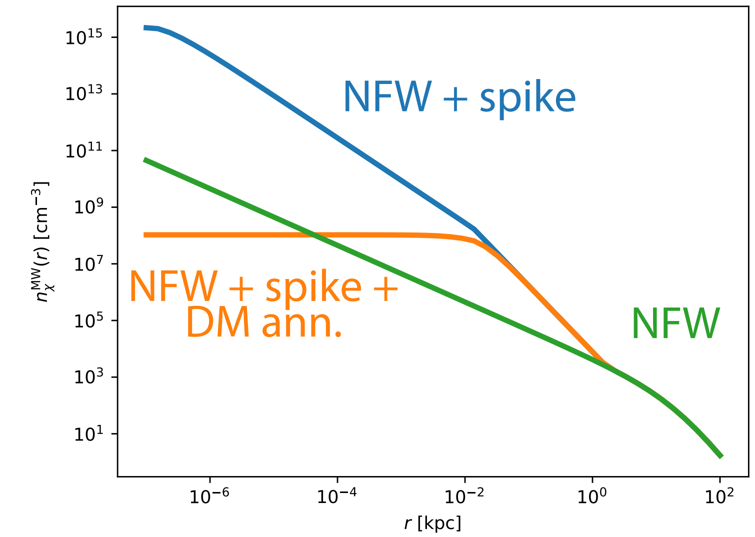

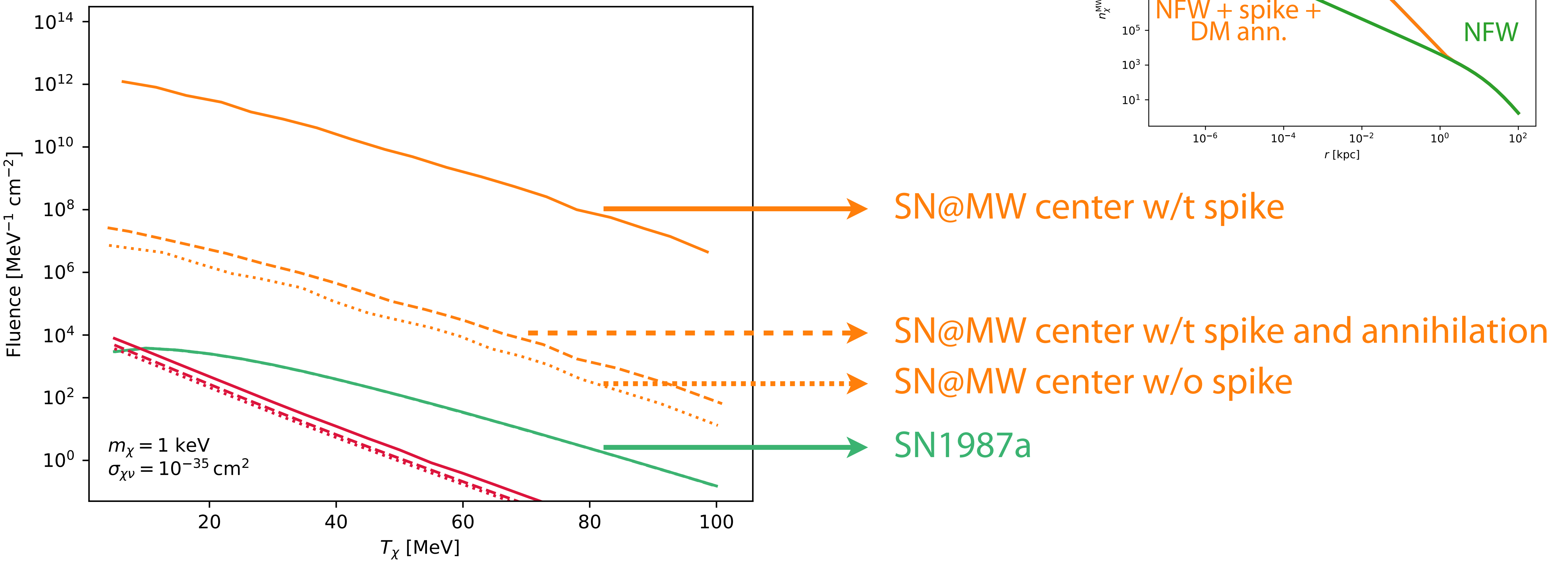

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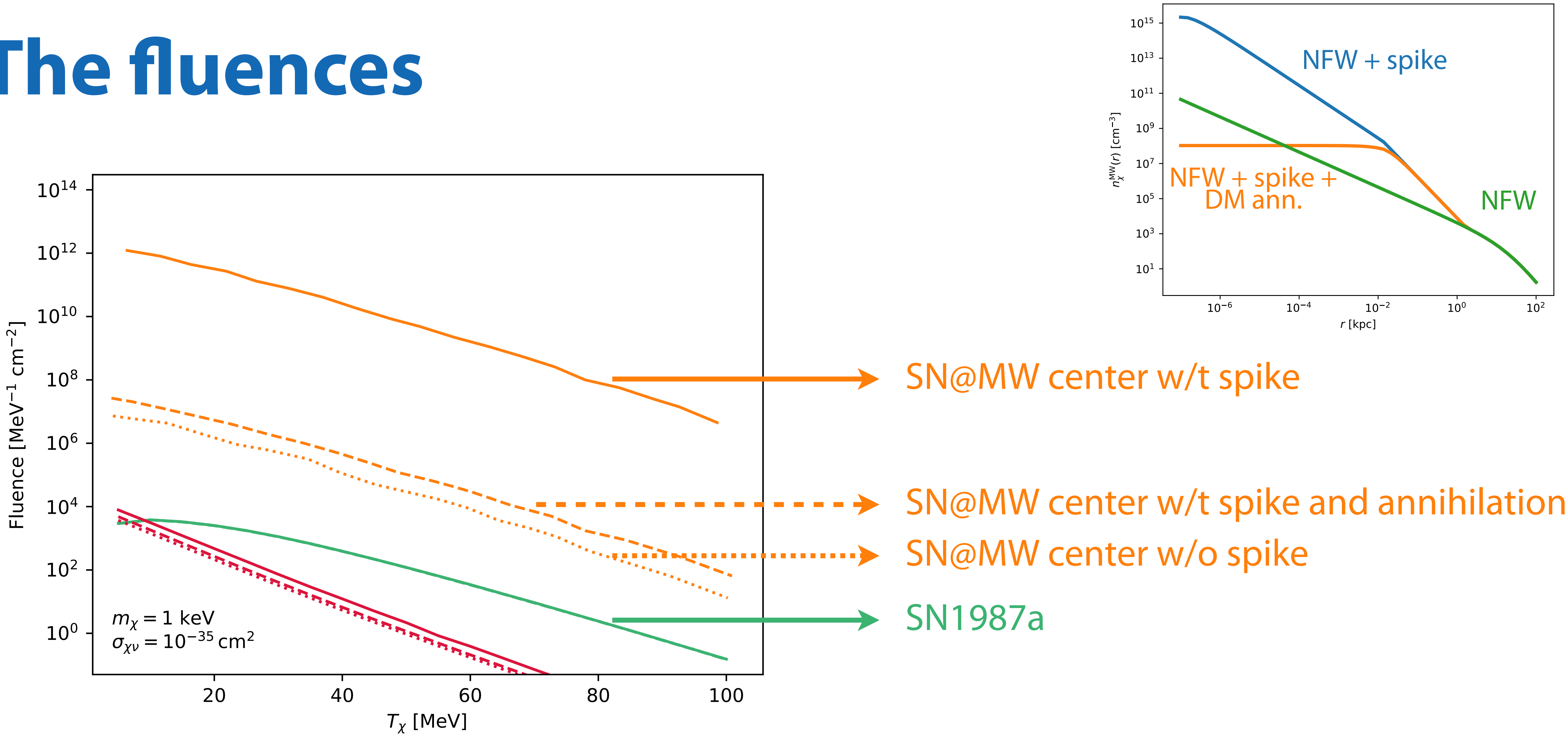

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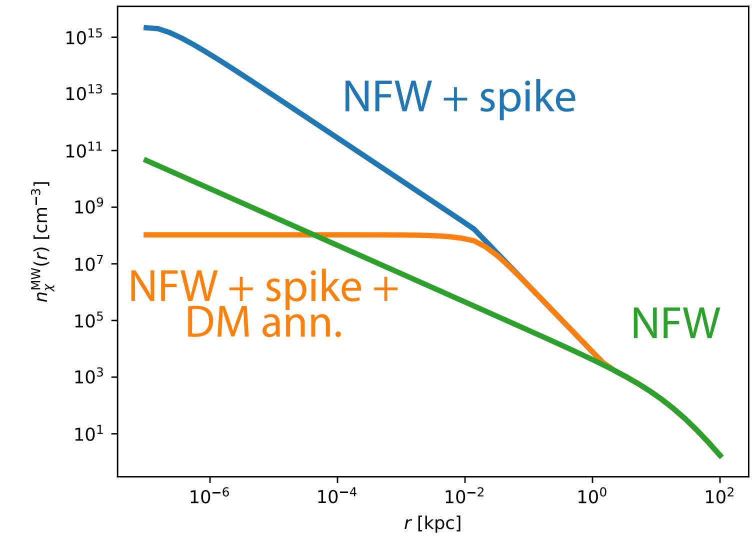

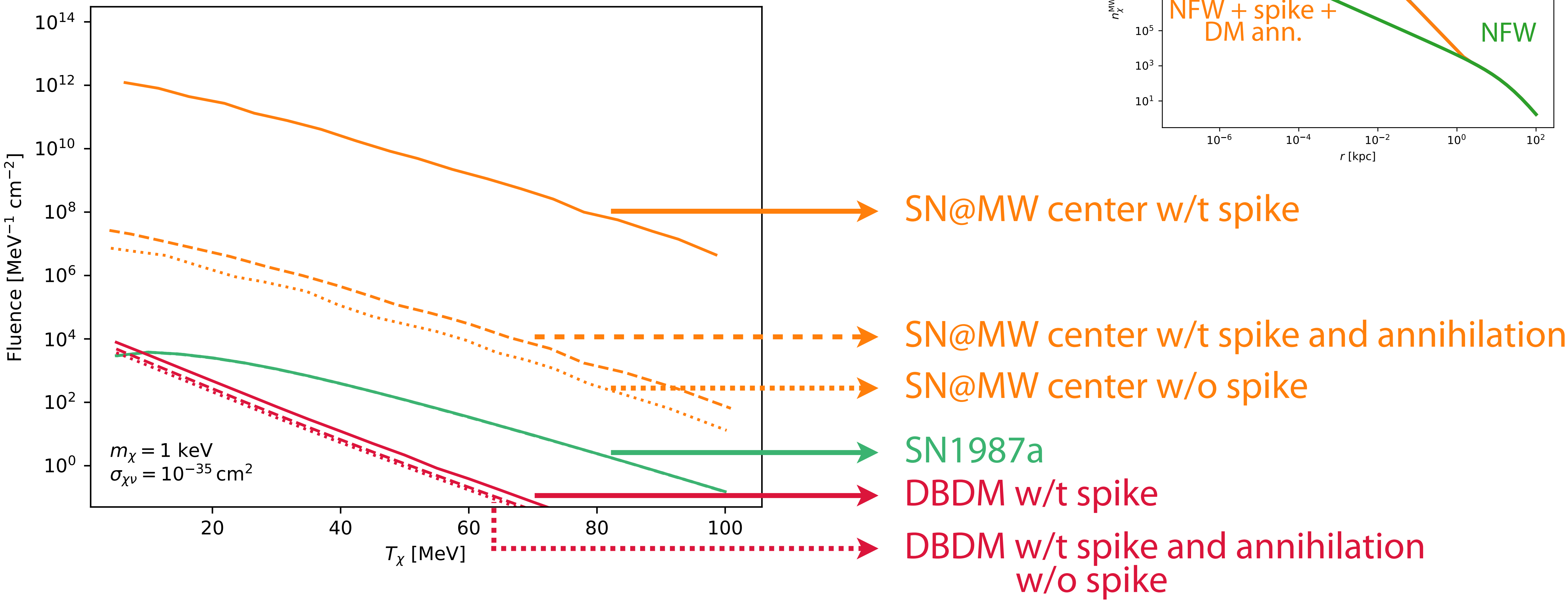

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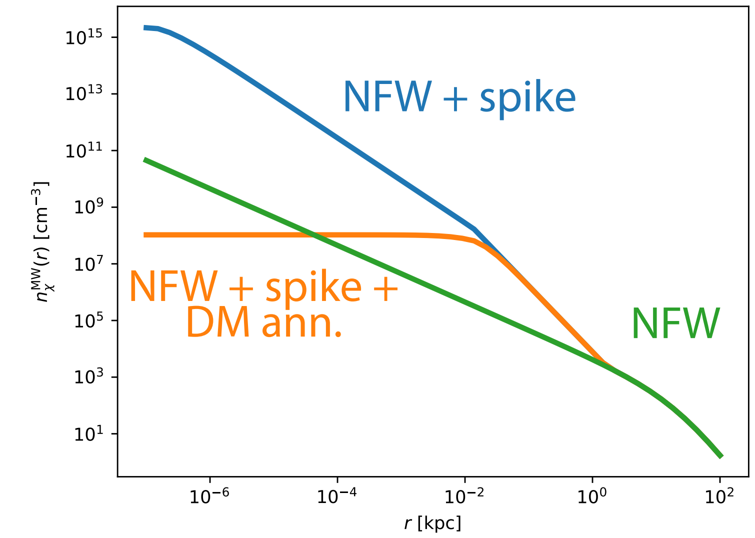

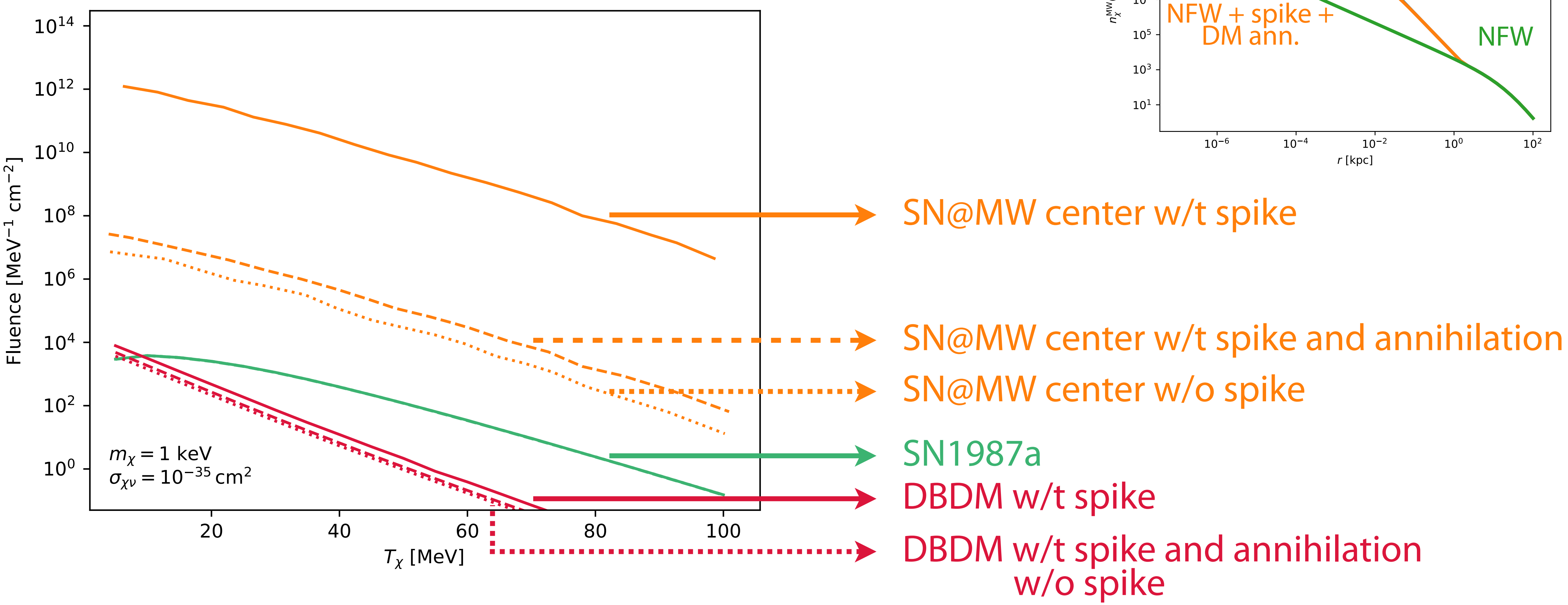

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- The effect of DM spike is highly sensitive to the SN location and becomes less apparent when the SN is farther away from the GC
- The DBDM is **robust against** the uncertainties related to DM spike

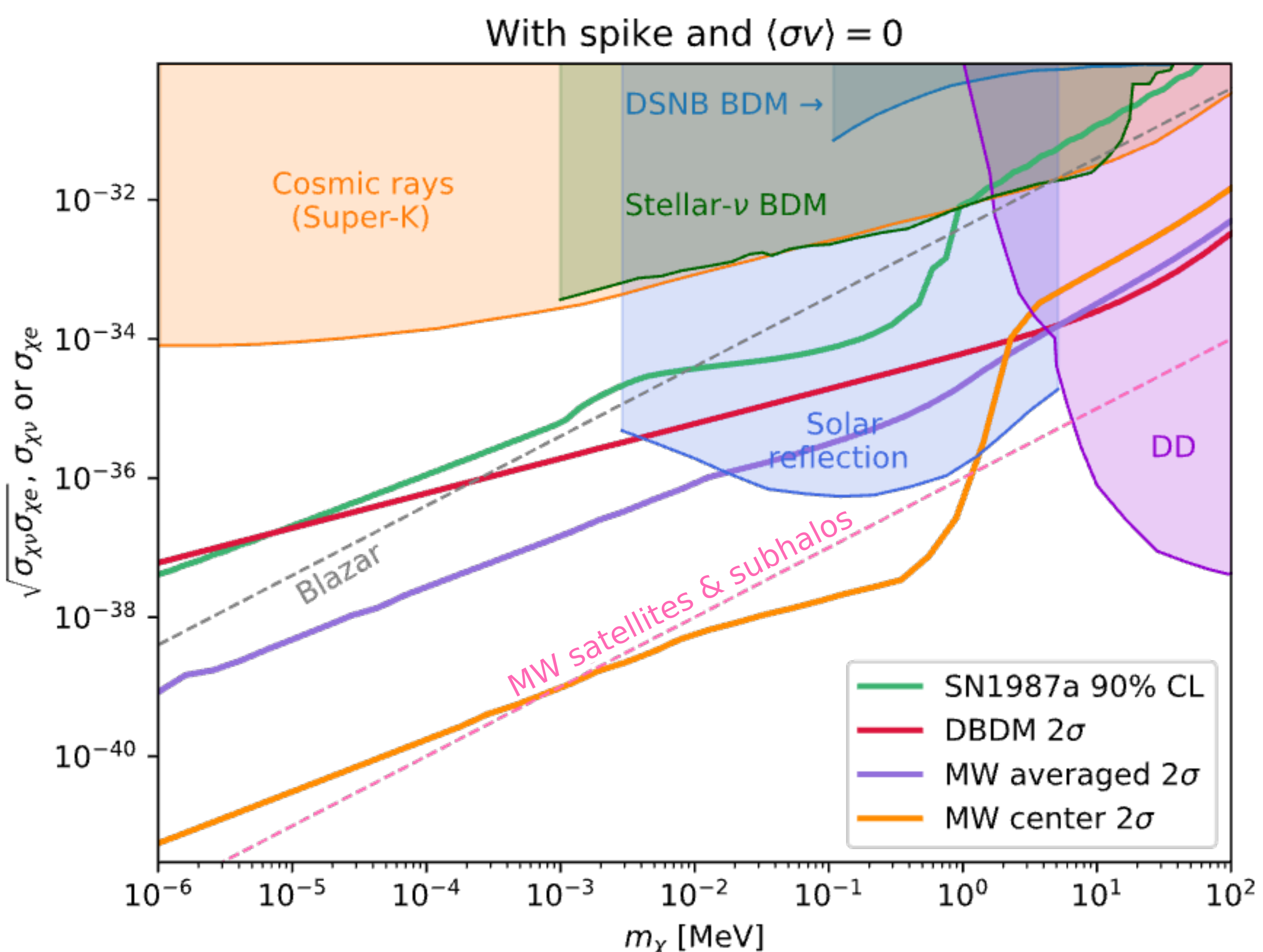
Constrain and projected sensitivities

Constraints and projected sensitivities

- Assuming cross sections $\sigma_{\chi\nu} = \sigma_{\chi e}$, we obtain the 2-sigma sensitivity by

$$\frac{N_s}{\sqrt{N_s + N_b}} = 2\sigma$$

  assuming Hyper-K detector and the background $N_b \sim 1.1\times10^5\ \mathrm{yr}^{-1}$
- The exposure time t_{exp} for DBDM is 5 years, while for MW SNν BDM it is up to 35 years



See Lin & Wu, *PRL* **133**, 111004 (2024) and refs. therein

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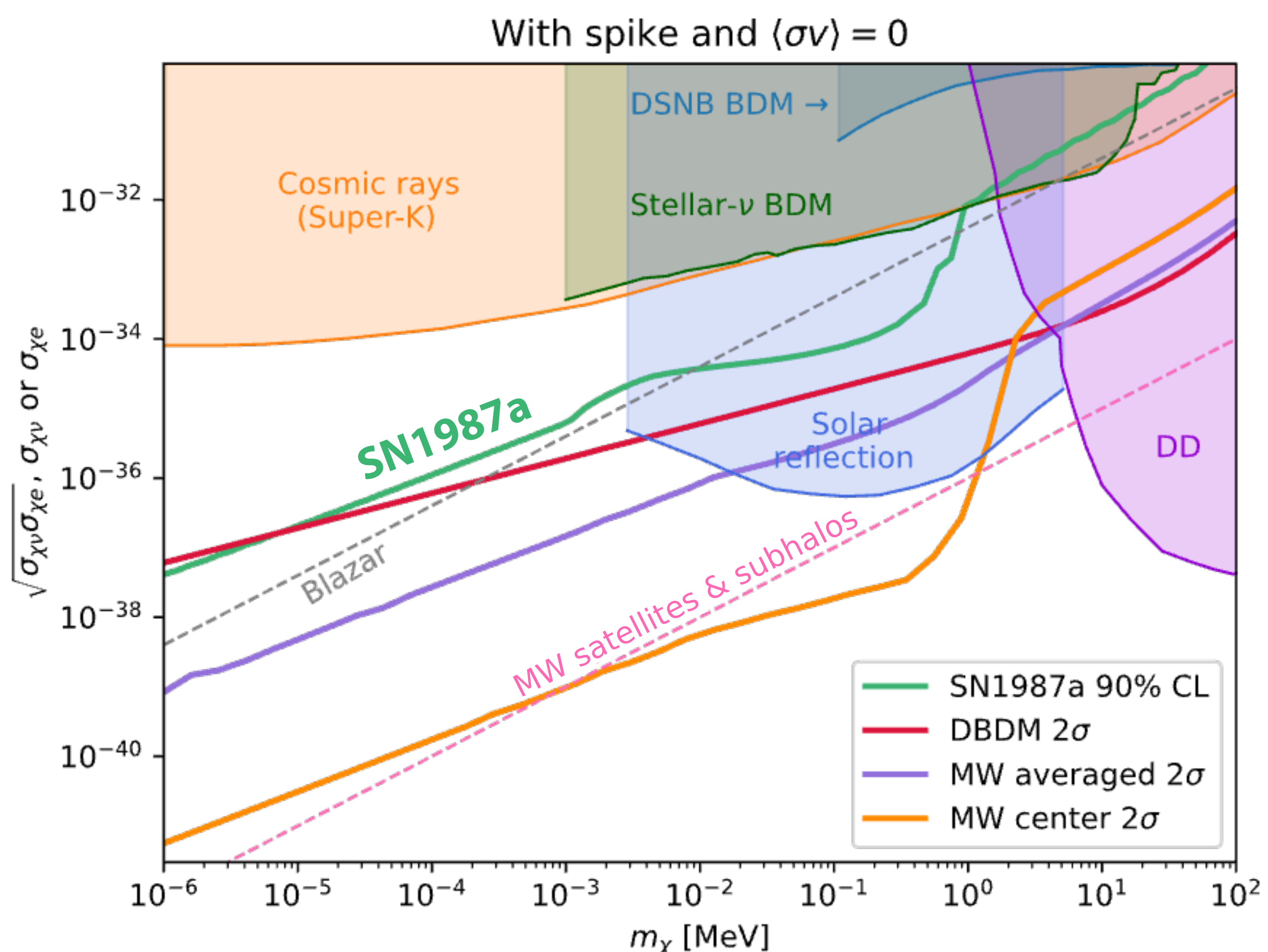

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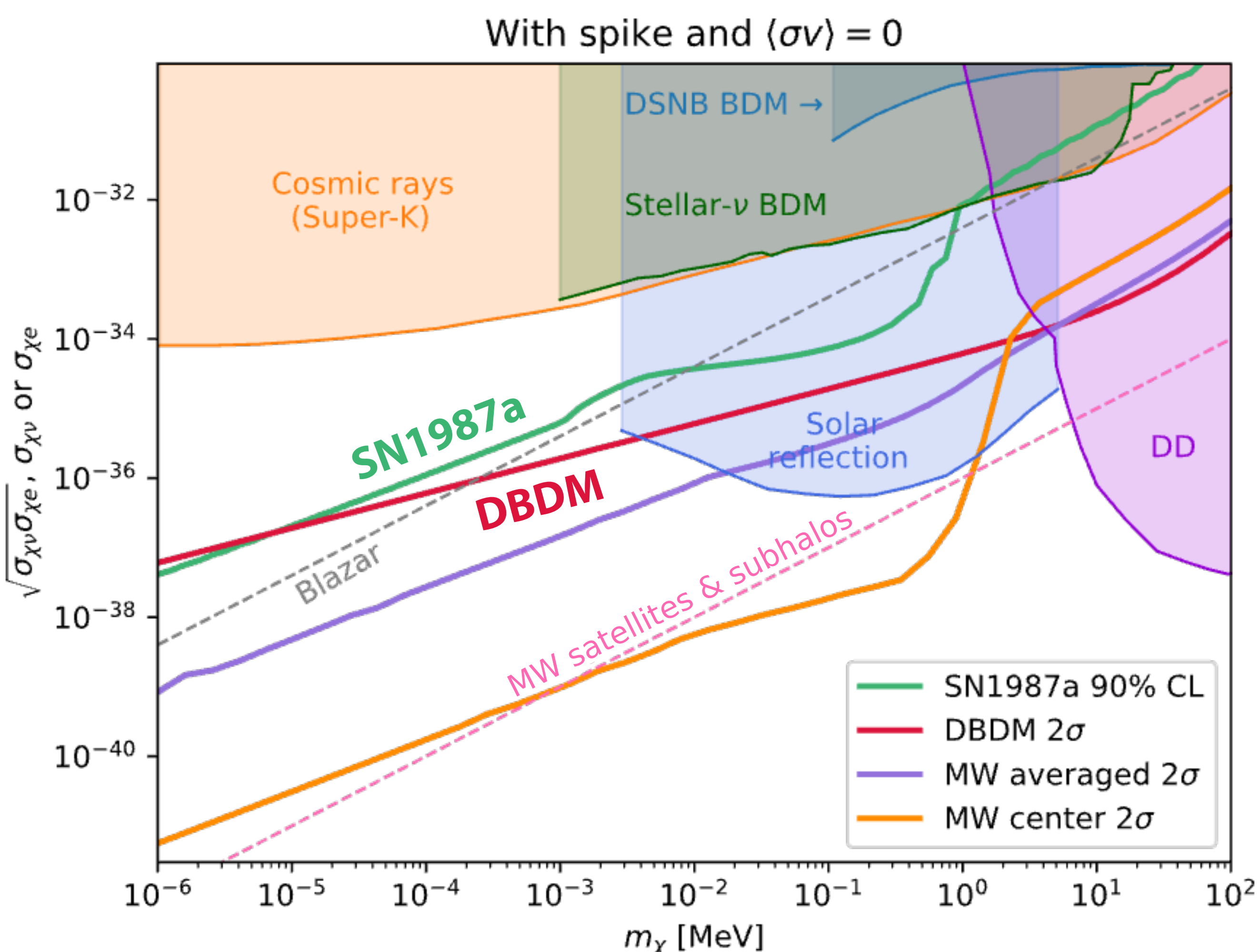

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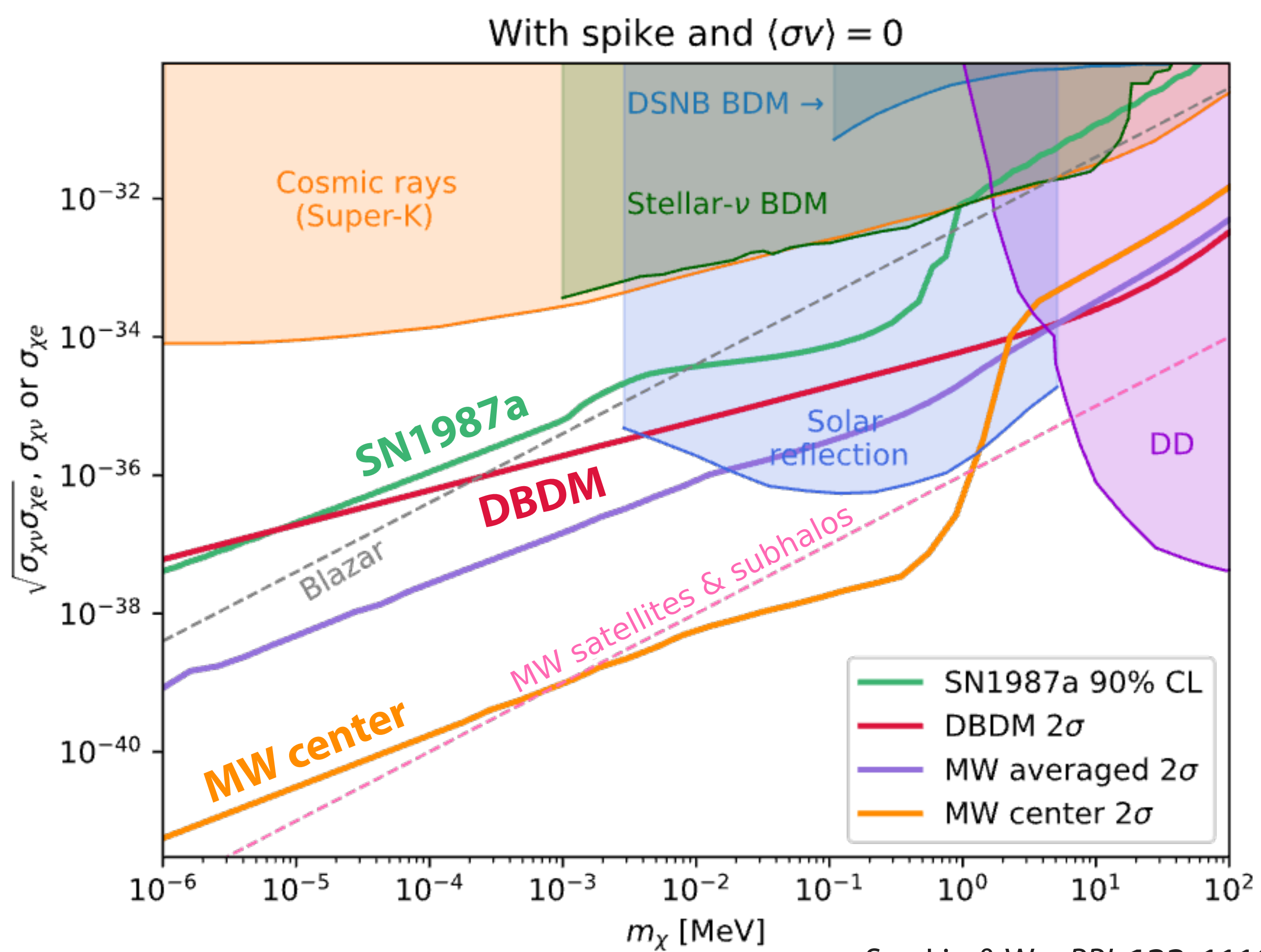

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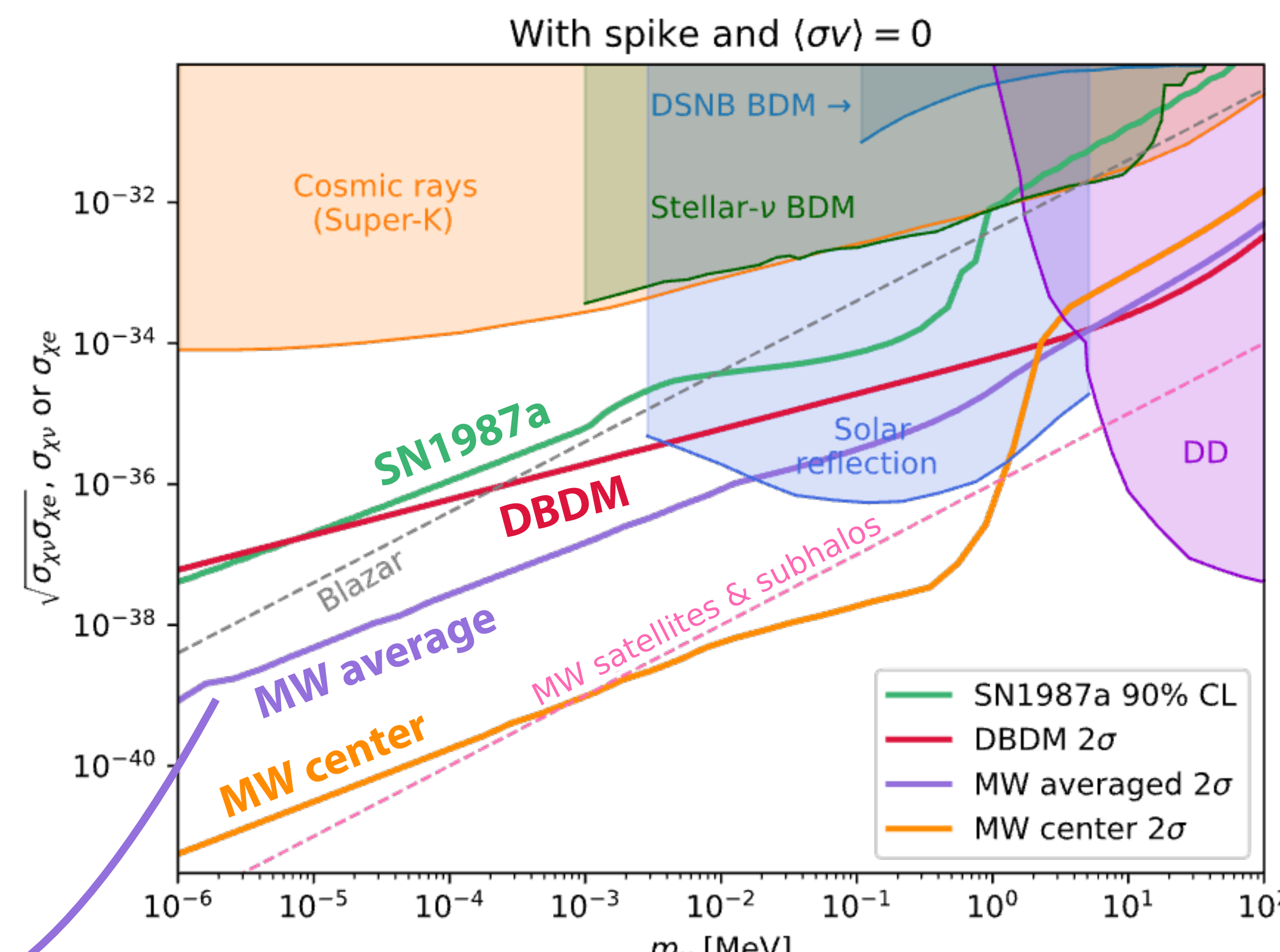

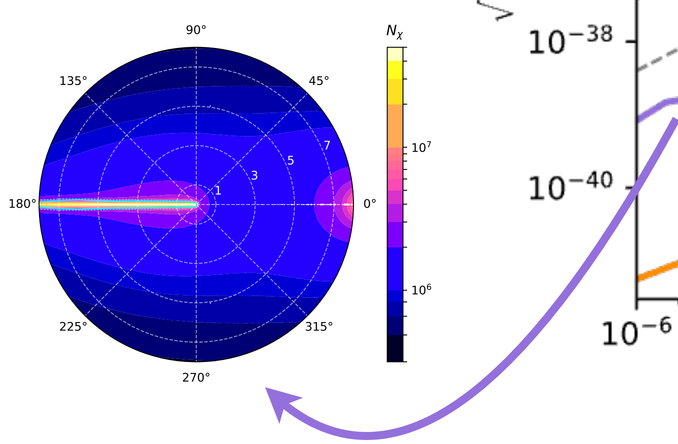

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Summary

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- SNν BDM offers a comprehensive and unified framework for probing light DM
- An innovative methodology to *directly measure DM mass* via *time-of-flight* is proposed
- Utilizing SNν BDM originating from SNe in galaxies throughout cosmic evolution forms a persistent and isotropic *diffuse BDM* (DBDM) flux
- DBDM is *robust against* uncertainties related to DM spikes, making it a reliable probe