IAS Program on HEP 2024
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Yen-Hsun Lin
Academia Sinica

in collaboration with
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Meng-Ru Wu (AS) & *Henry T.-K. Wong* (AS)

Detecting afterglow signatures from light dark matter boosted by supernova neutrinos

Phys. Rev. Lett. **130**, 111002 (2023) [2206.06864]
Phys. Rev. D **108**, 083013 (2023) [2307.03522]
in prepration [24xx.xxxxx]

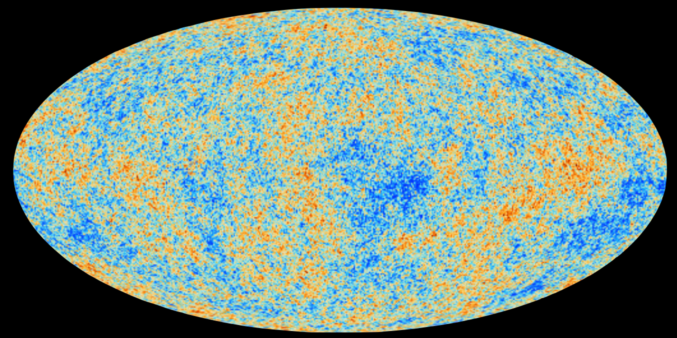
National Center for Theoretical Sciences

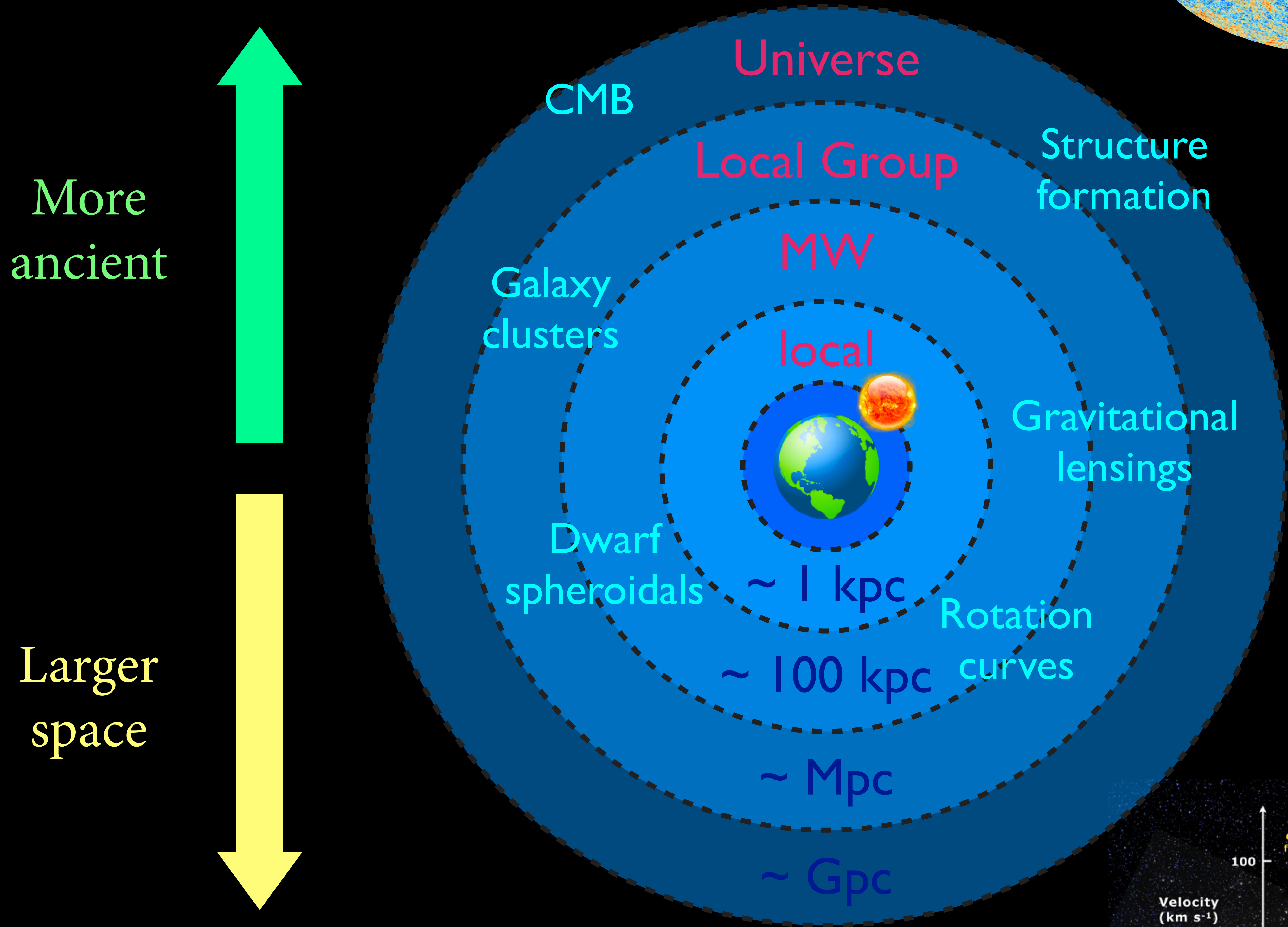
Outline

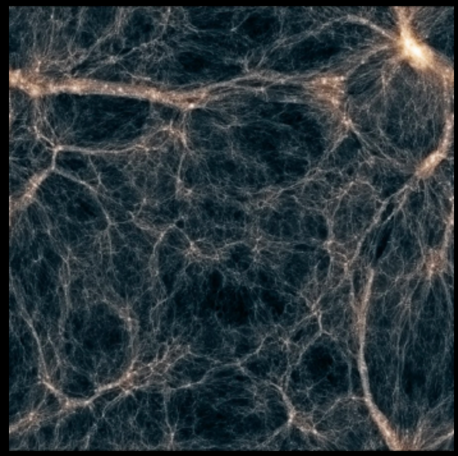
- **Introduction**
- **The concept for SNν boosted DM (SNν BDM)**
  - Kinematics, BDM emissivity and flux
  - Time-of-flight for direct m_χ measurement
  - Case studies for SNs located in and off GC
- **Constraint and projected sensitivities**
  - From SN1987a and the next galactic SN
  - On DM-ν and DM-e cross sections
- **BDM from early Universe**
- **Summary**

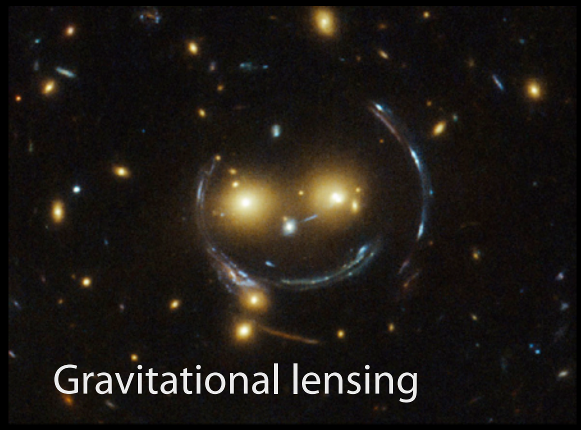
Introduction

Dark matter is *ubiquitous* in the Universe!

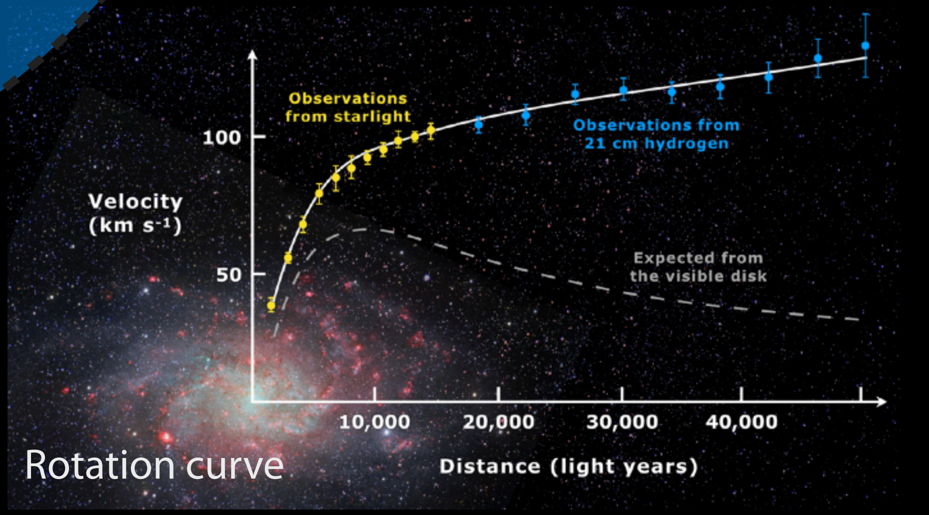








Gravitational lensing



Rotation curve

$1\,\mathrm{pc} \approx 2.06 \times 10^5\,\mathrm{AU} \approx 3.08 \times 10^{16}\,\mathrm{m}$

What is the essence of DM?

- Dark *matter* ➡ **mass m_χ**
- To *measure* ➡ DM-SM *interaction* ➡ **cross sections $\sigma_{\chi n,p,e\ldots}$, $\langle\sigma v\rangle$**

not-to-scale

The DM probes: m_χ & σ

not-to-scale

The DM probes: m_χ & σ

CDEX Collab.
LUX Collab.
SENSEI Collab.
XENON Collab.
Essig+ (2015)
Hochberg+ (2015)
Hochberg+ (2016)
Geilhufe+ (2019)
Kim+ (2020)
Kahn+ (2020)
Knapen+ (2020)…

m_χ — eV — MeV — GeV — > TeV

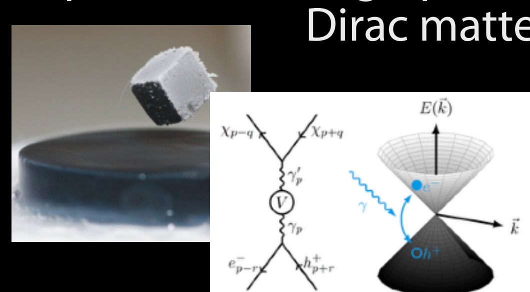
low temperature quantum effects (eV – MeV)

electron recoils (MeV – GeV)

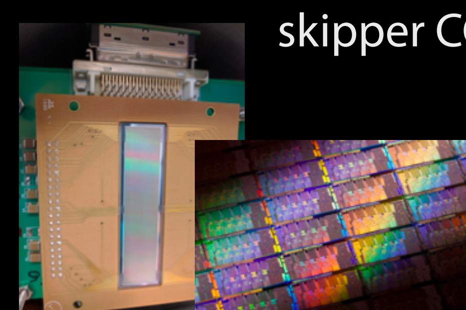
nucleus recoils (GeV – > TeV)

Dark matter direct search

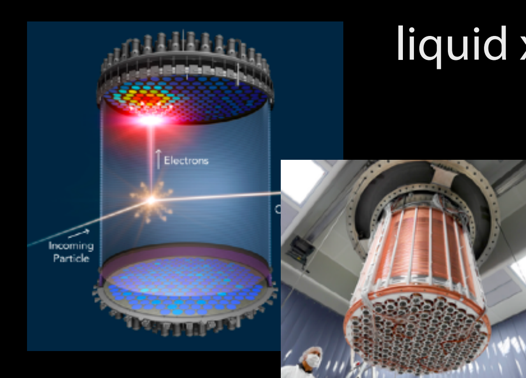
superconductor/graphene
Dirac matter…



semiconductor
skipper CCD



liquid xenon



not-to-scale

The DM probes: m_χ & σ

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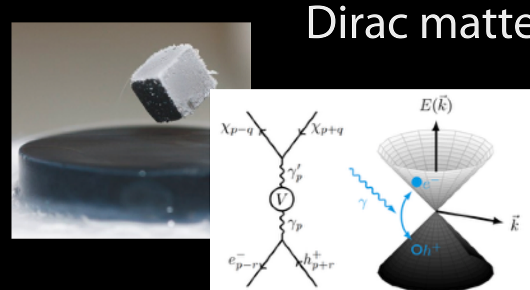

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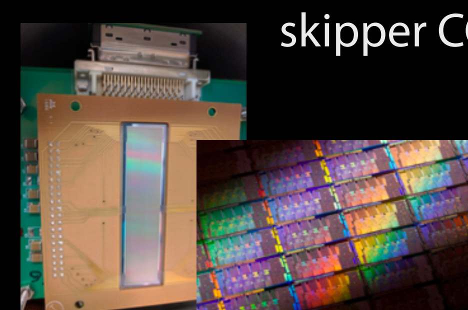

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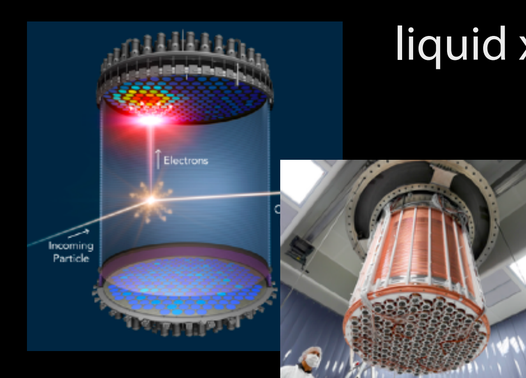
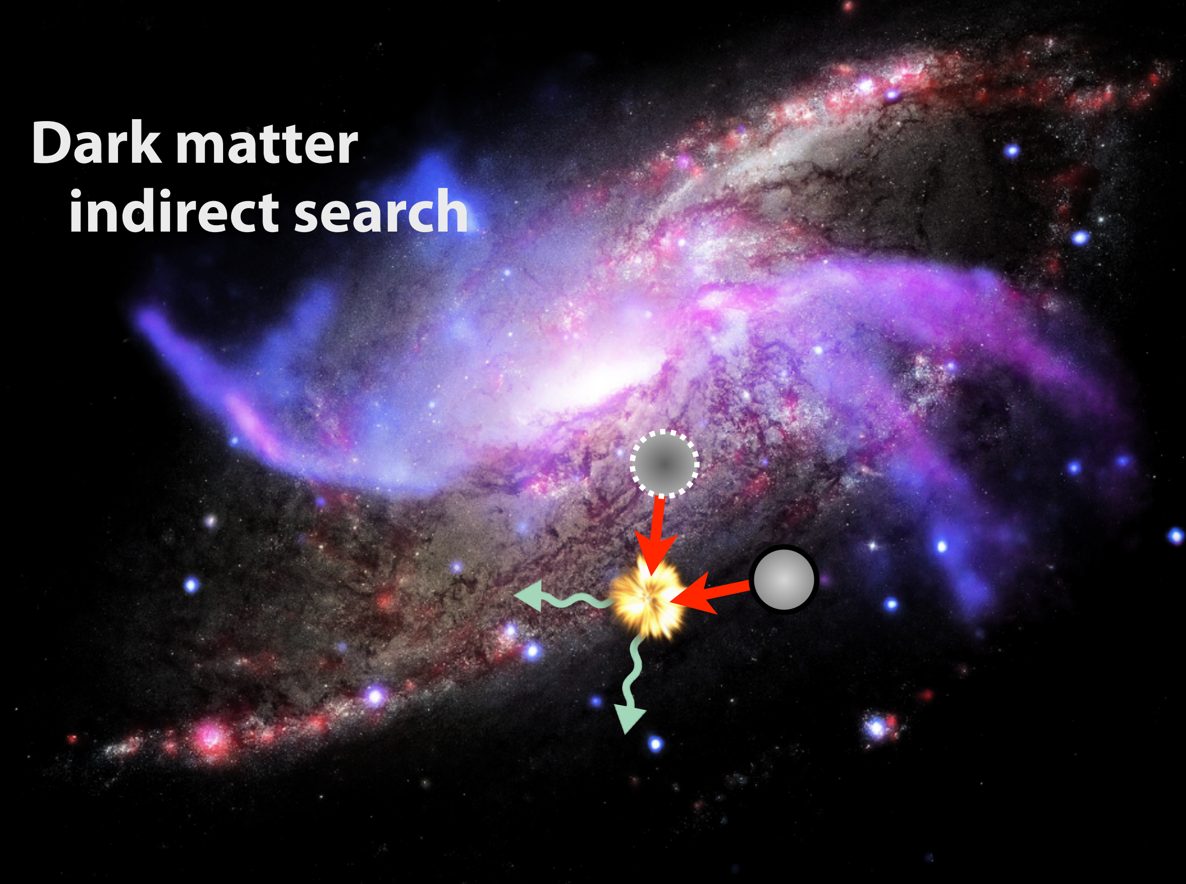


Dark matter direct search

not-to-scale

The DM probes: m_χ & σ



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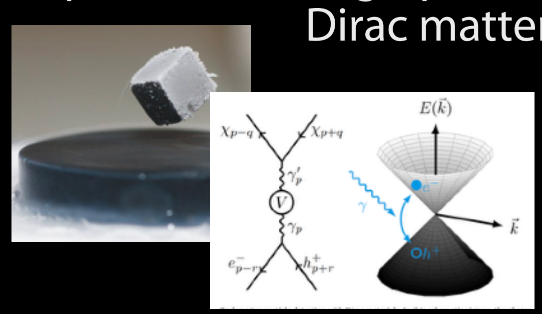
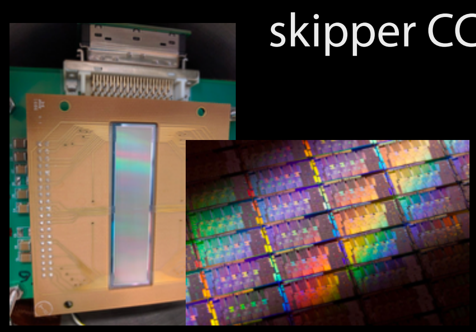


semiconductor
skipper CCD



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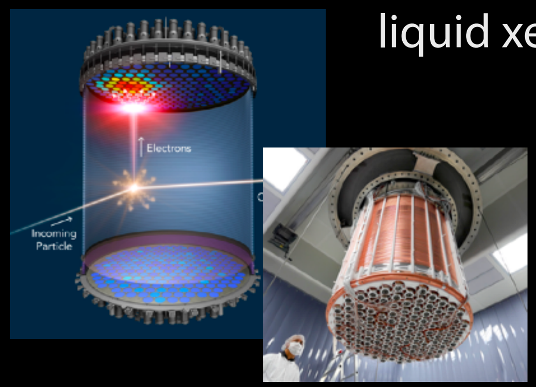

Dark matter direct search

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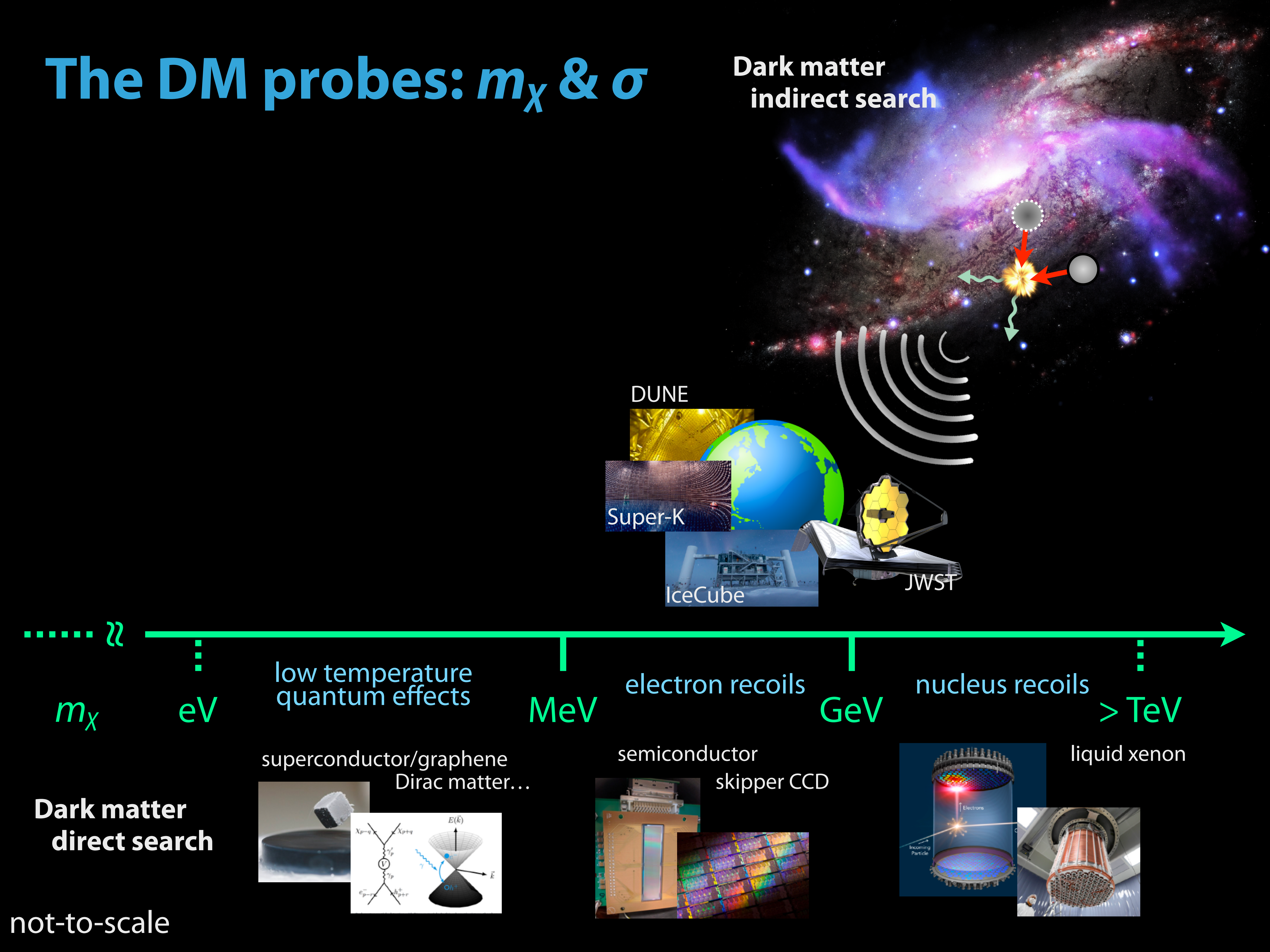
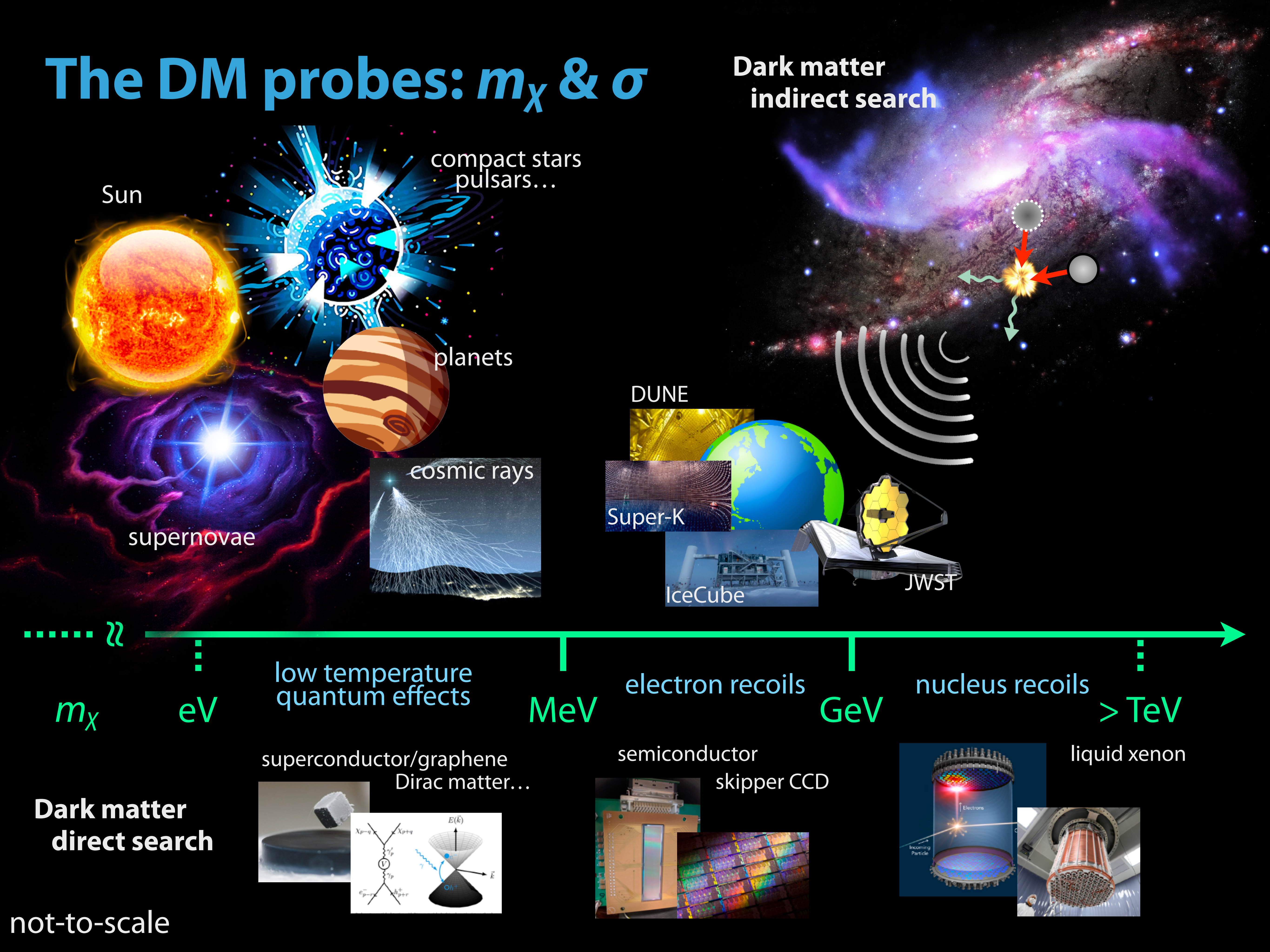


The DM probes: m_χ & σ
Dark matter indirect search
DUNE
Super-K
IceCube
JWST
m_χ
eV
low temperature quantum effects
MeV
electron recoils
GeV
nucleus recoils
> TeV
superconductor/graphene
Dirac matter…
semiconductor
skipper CCD
liquid xenon
Dark matter direct search
not-to-scale


The DM probes: m_χ & σ
Dark matter indirect search
Sun
compact stars pulsars…
planets
supernovae
cosmic rays
DUNE
Super-K
IceCube
JWST
m_χ
eV
low temperature quantum effects
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electron recoils
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superconductor/graphene Dirac matter…
semiconductor skipper CCD
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Dark matter direct search
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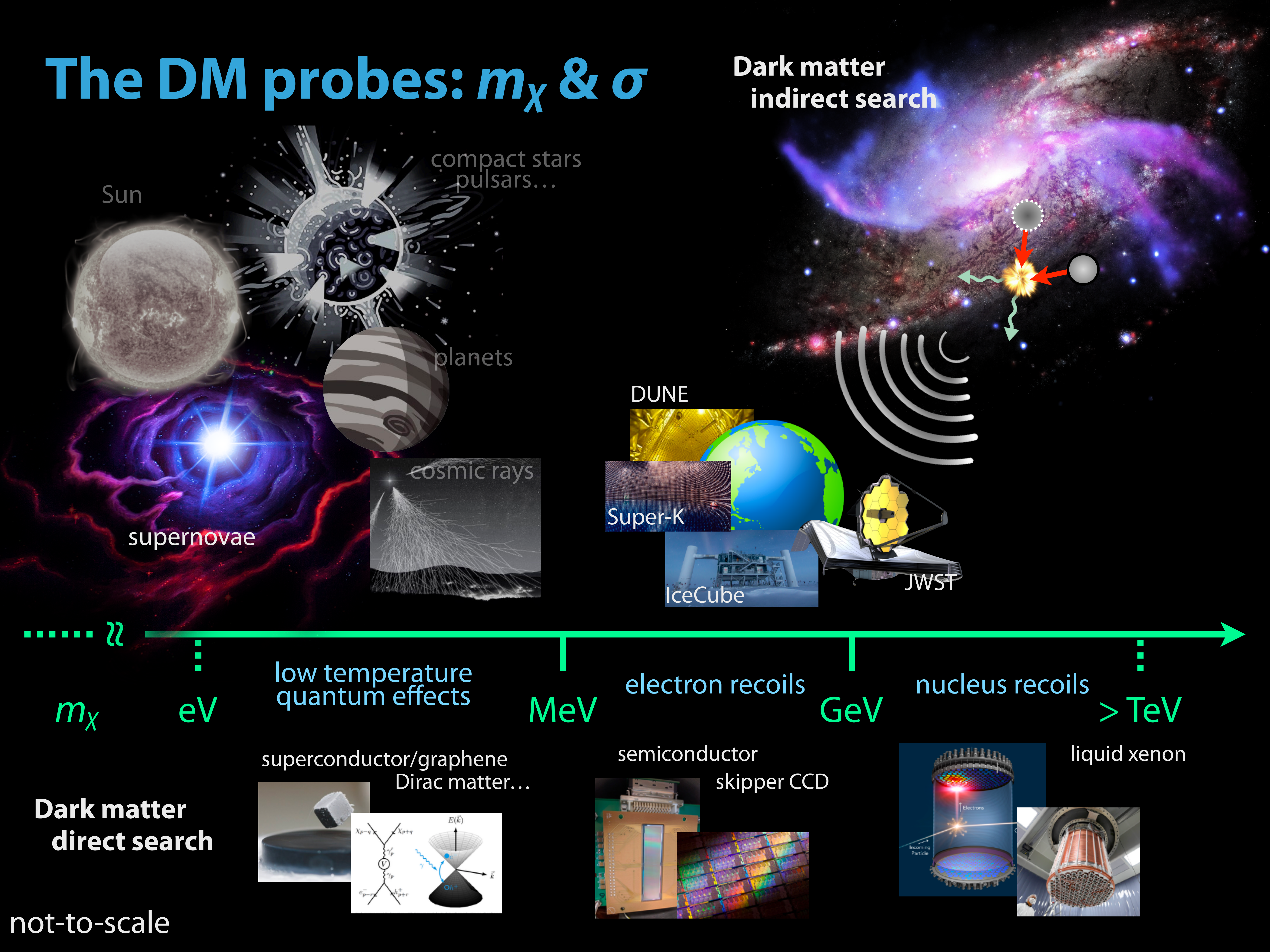
The DM probes: m_χ & σ
Dark matter indirect search
compact stars pulsars…
Sun
planets
supernovae
cosmic rays
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JWST
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superconductor/graphene
Dirac matter…
semiconductor
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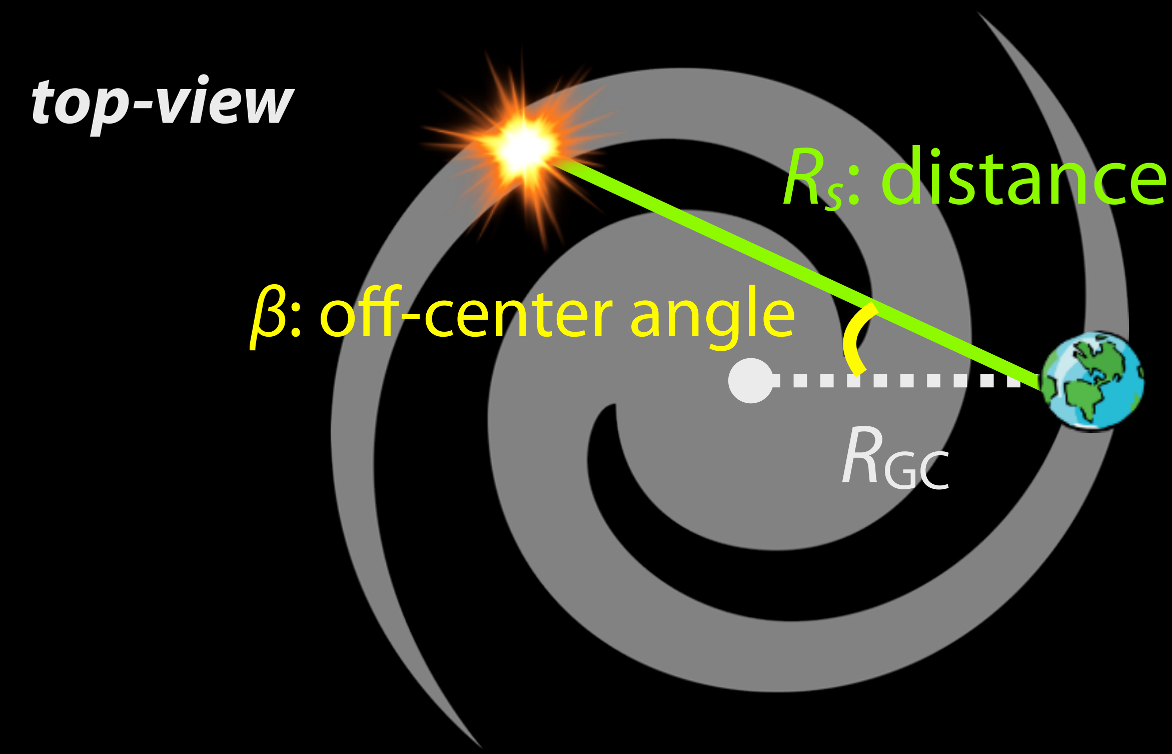
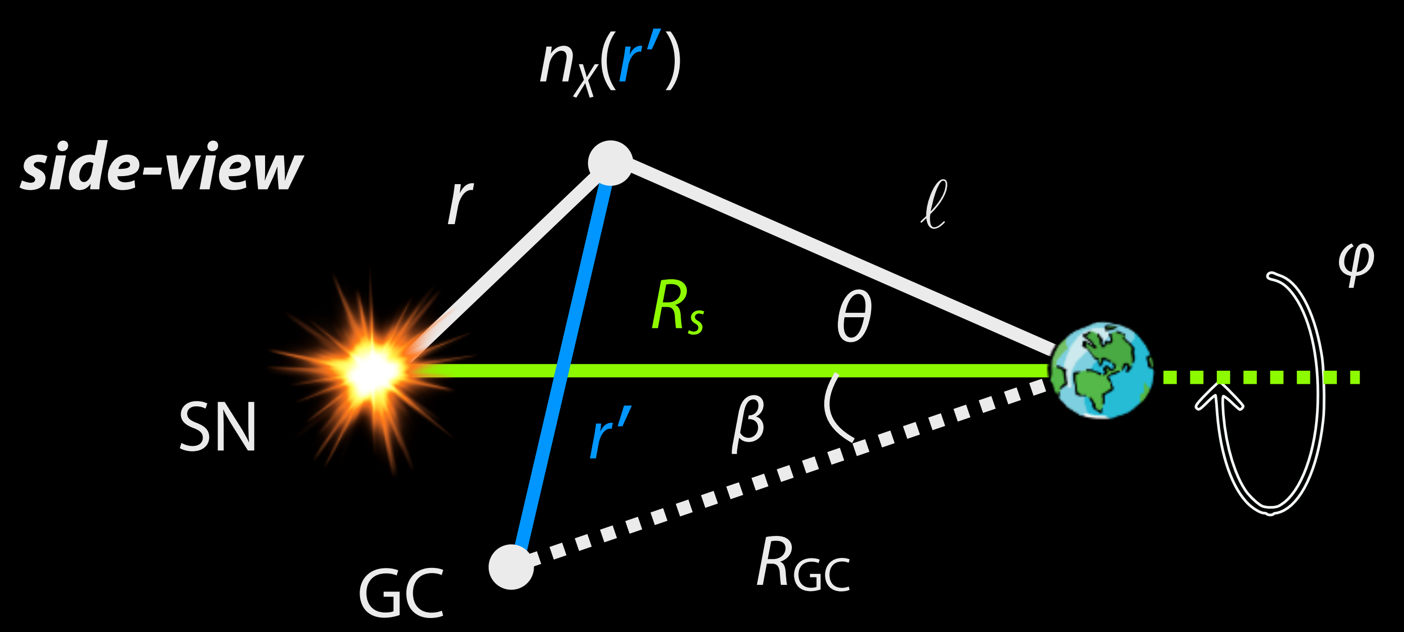
Dark matter direct search
not-to-scale

The SNνBDM

Galactic supernova

In practice





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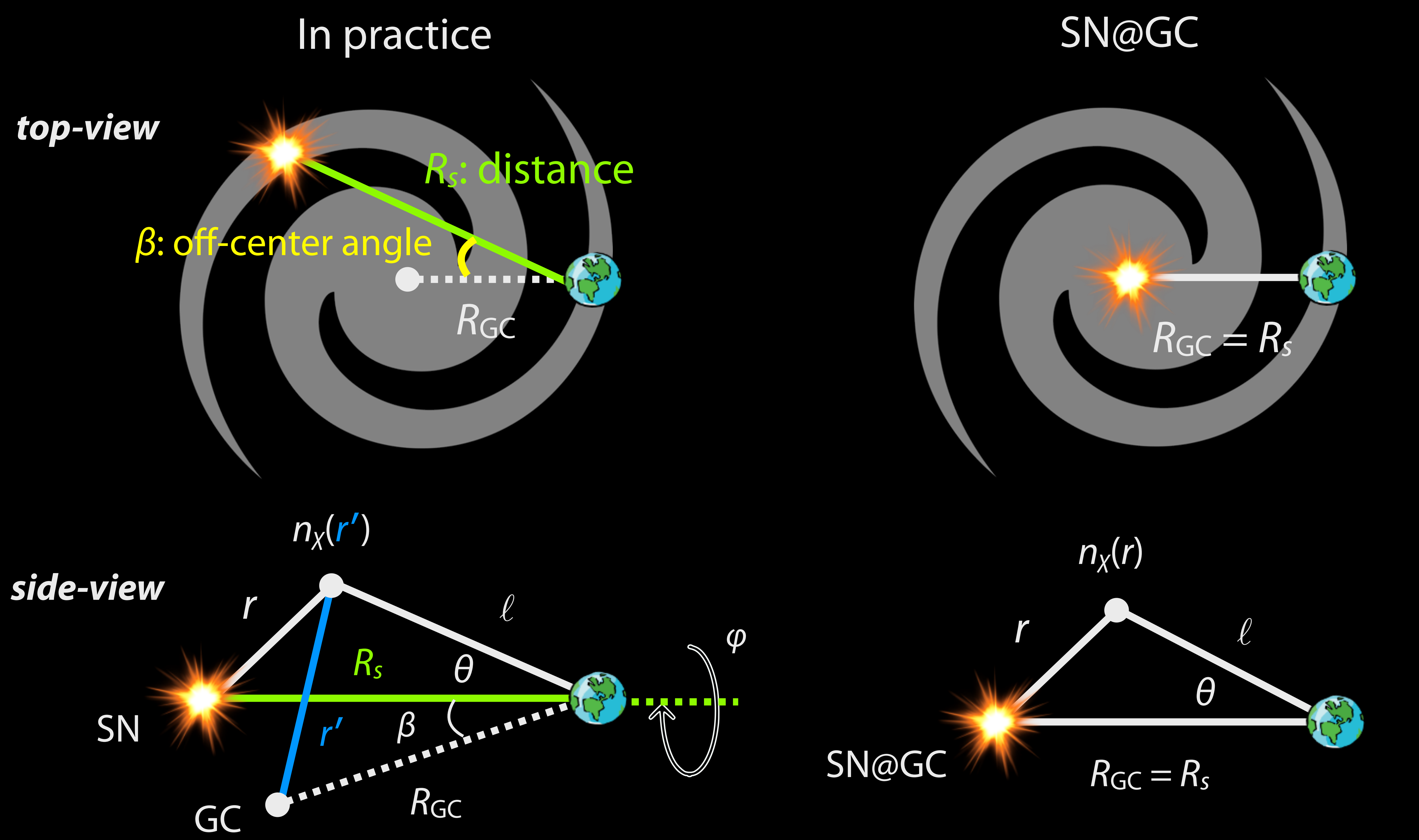

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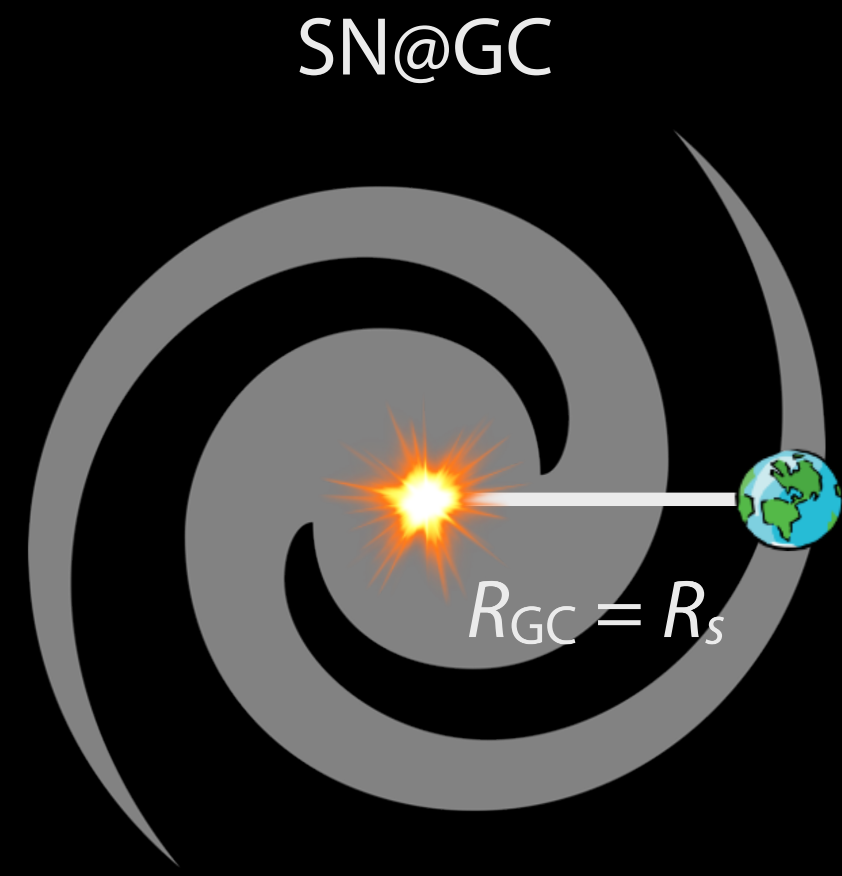
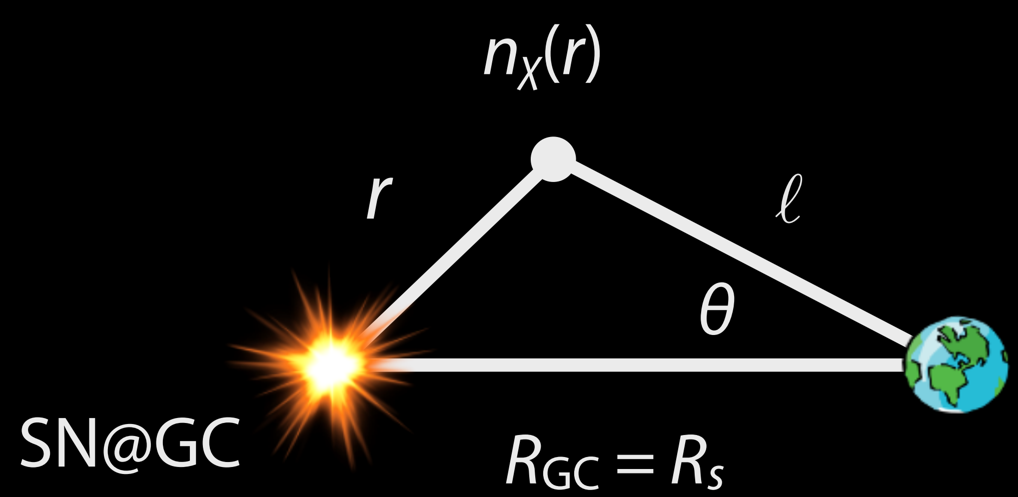
Galactic supernova





not-to-scale

Halo DM boosted by SNν

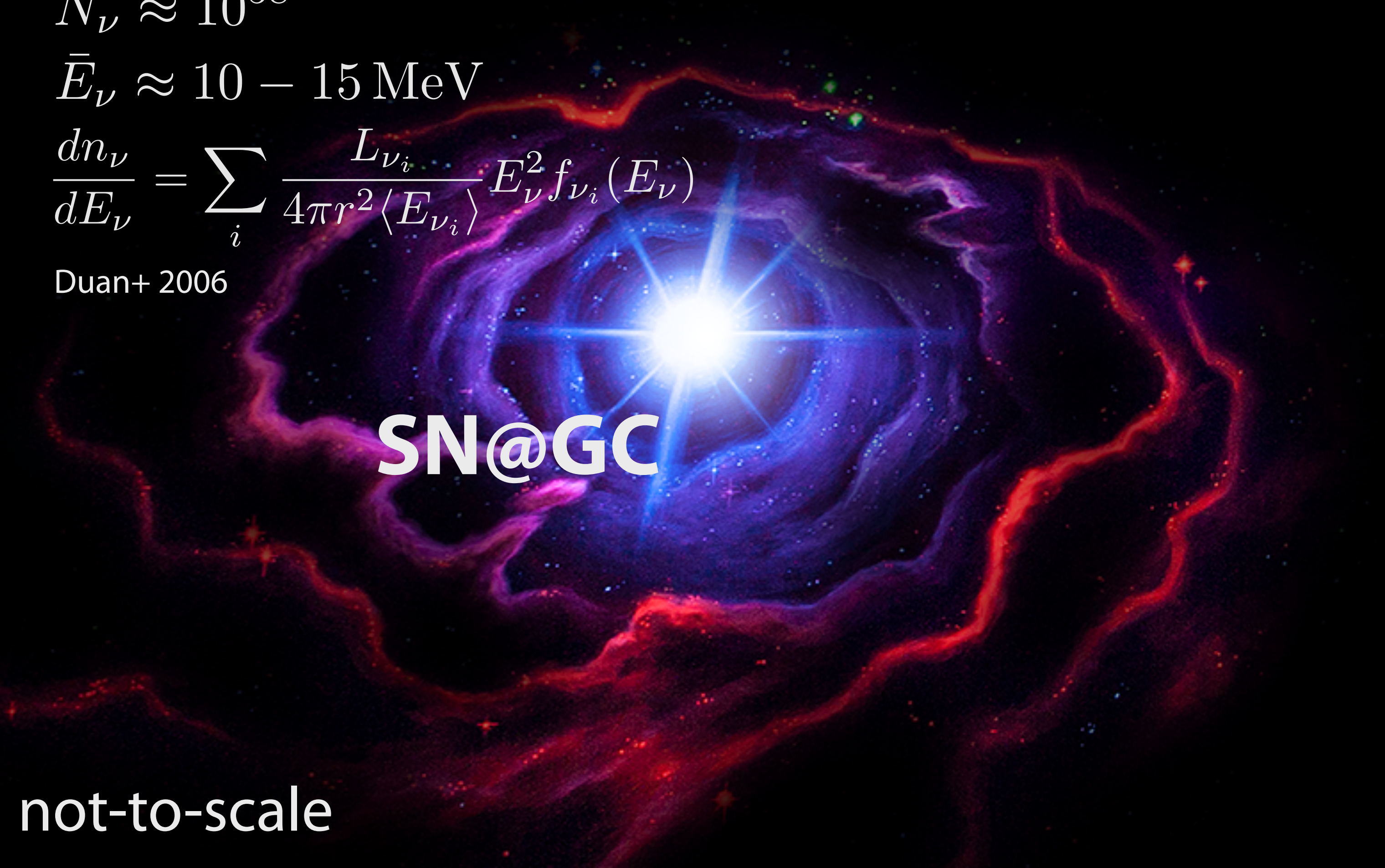
duration: ~10s

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

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

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

Duan+ 2006



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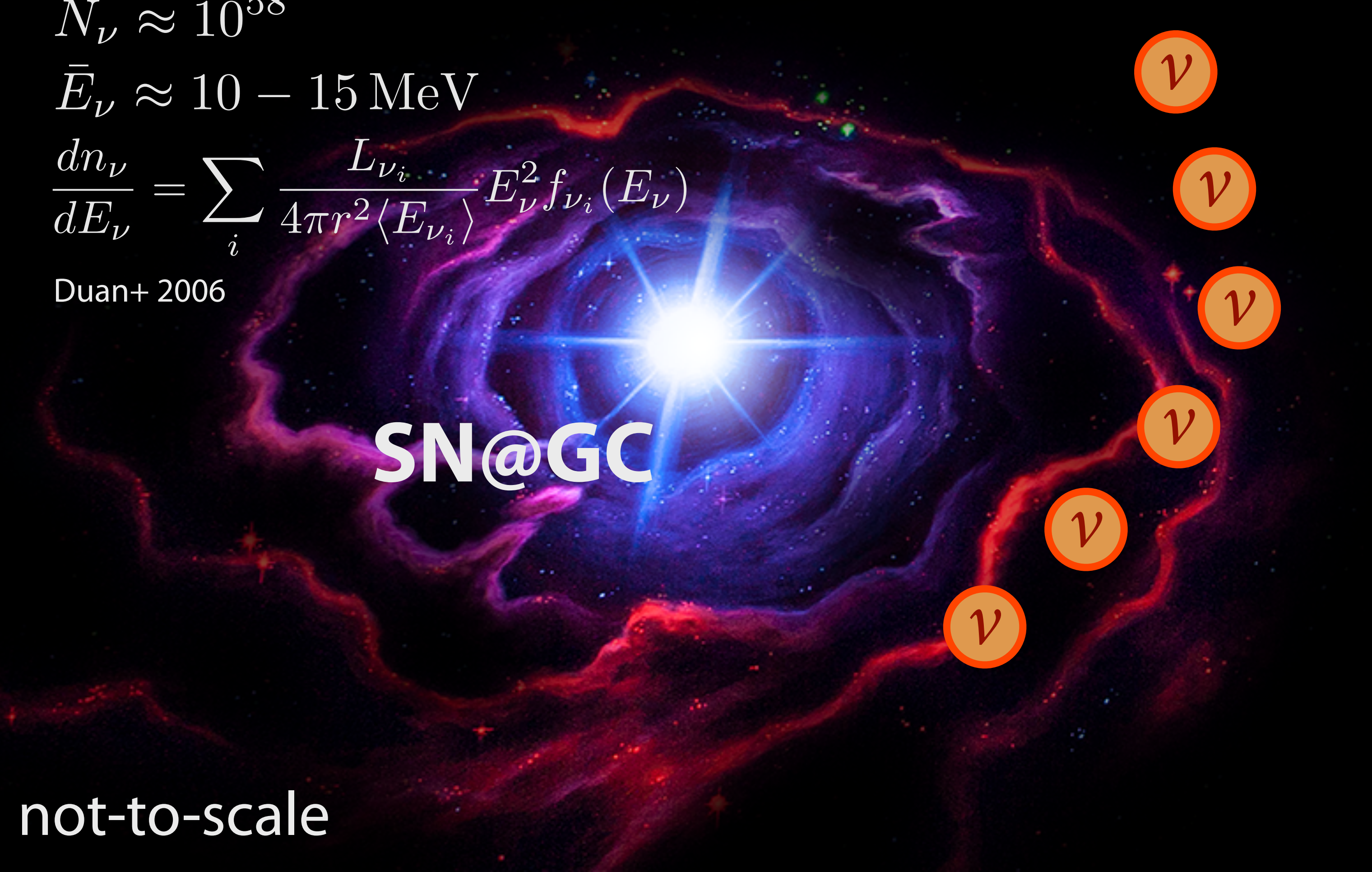

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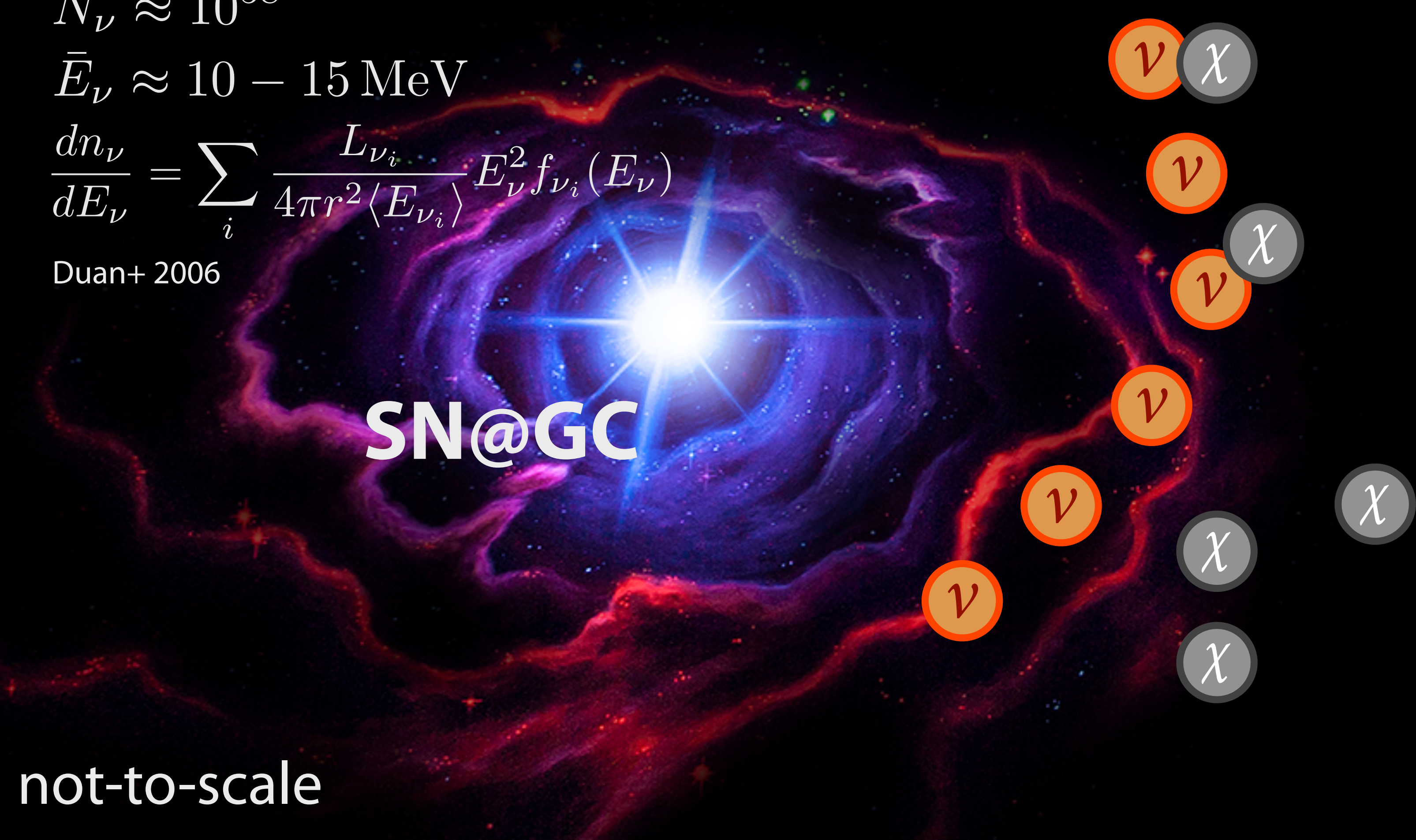

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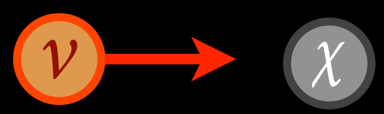
Halo DM boosted by SNν

$$p_\chi = (m_\chi, \mathbf{0})$$



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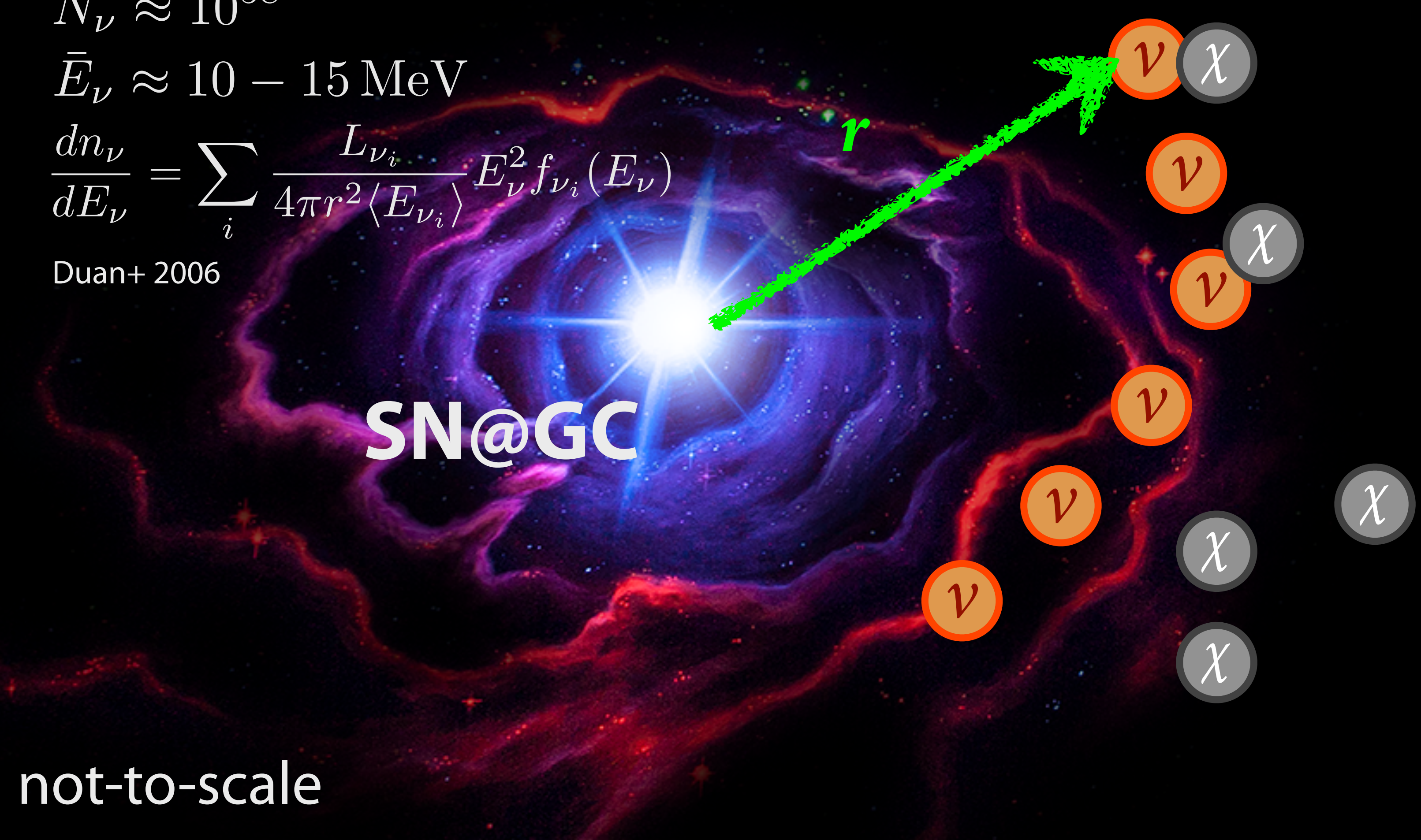

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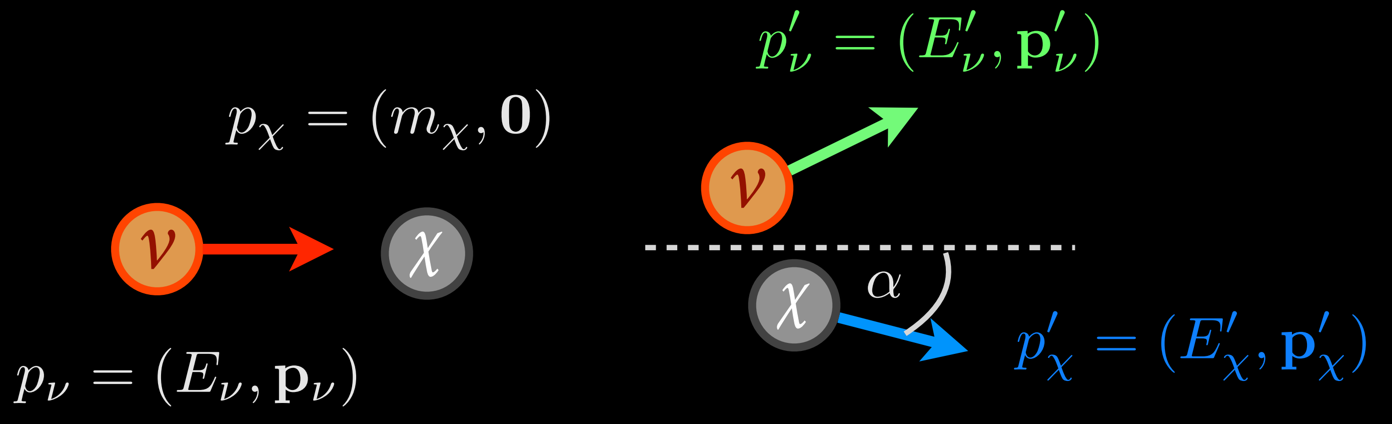
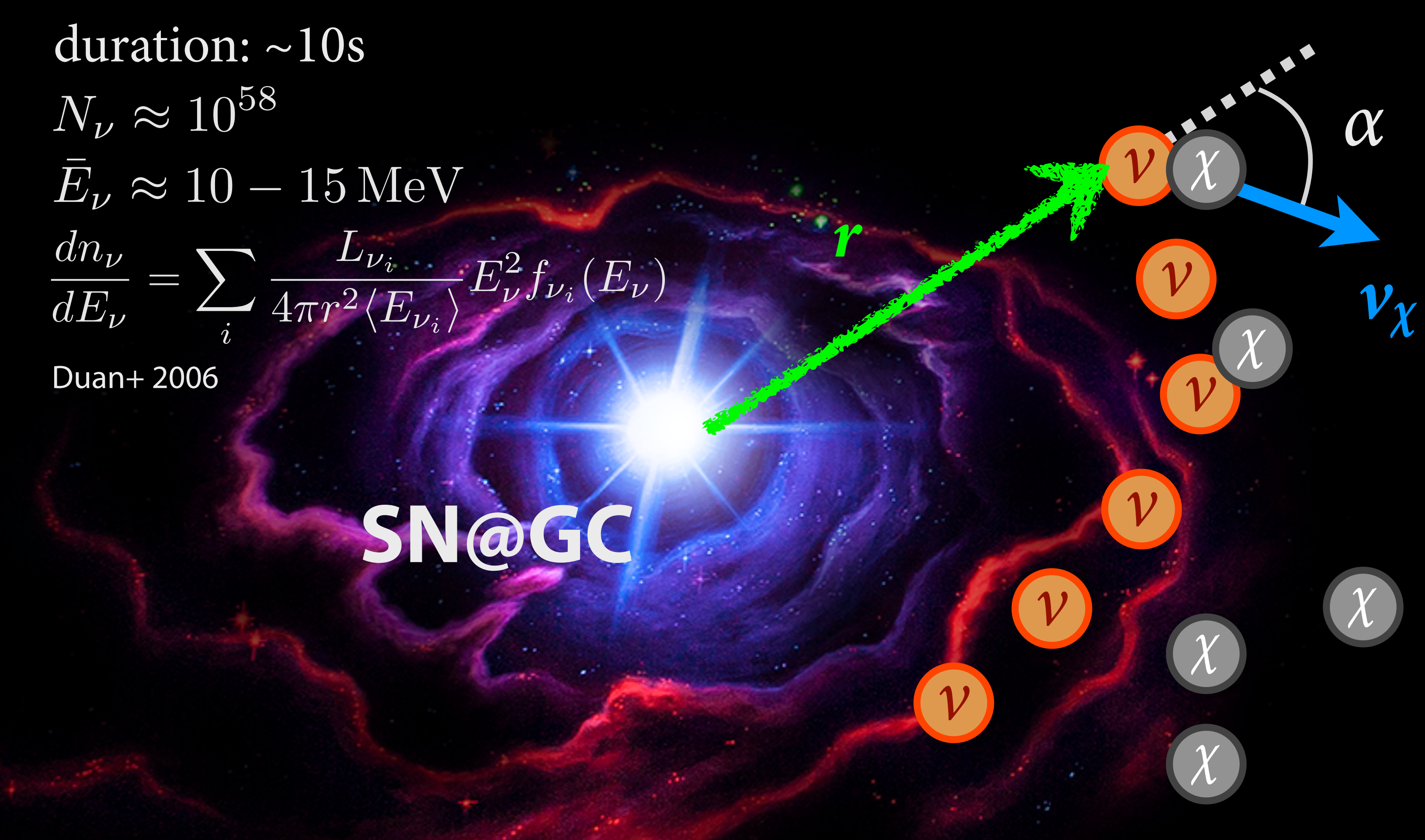
Halo DM boosted by SNν

- Non-zero DM-ν cross section $\sigma_{\chi\nu}$



- The BDM kinetic energy T_χ

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



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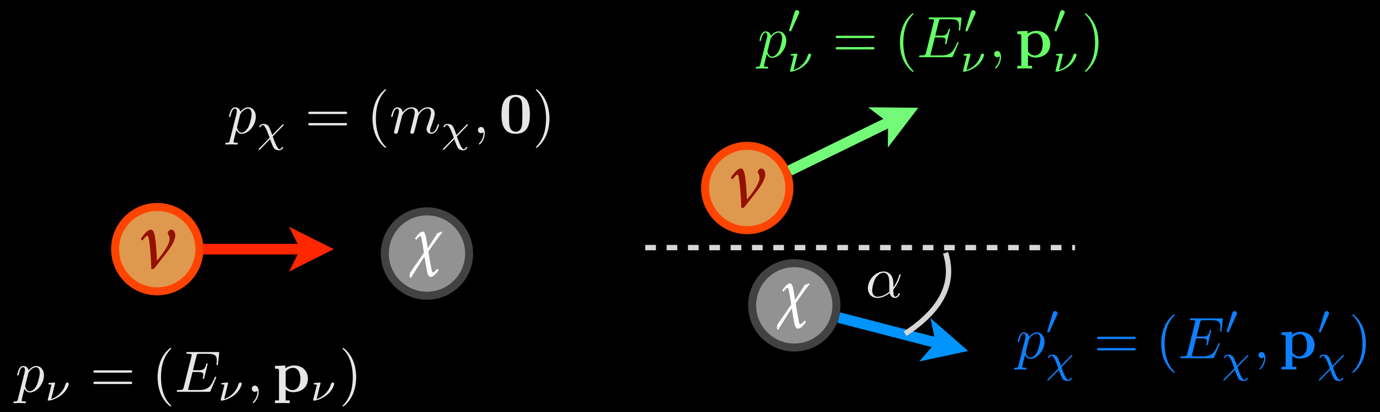

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- The angular distribution

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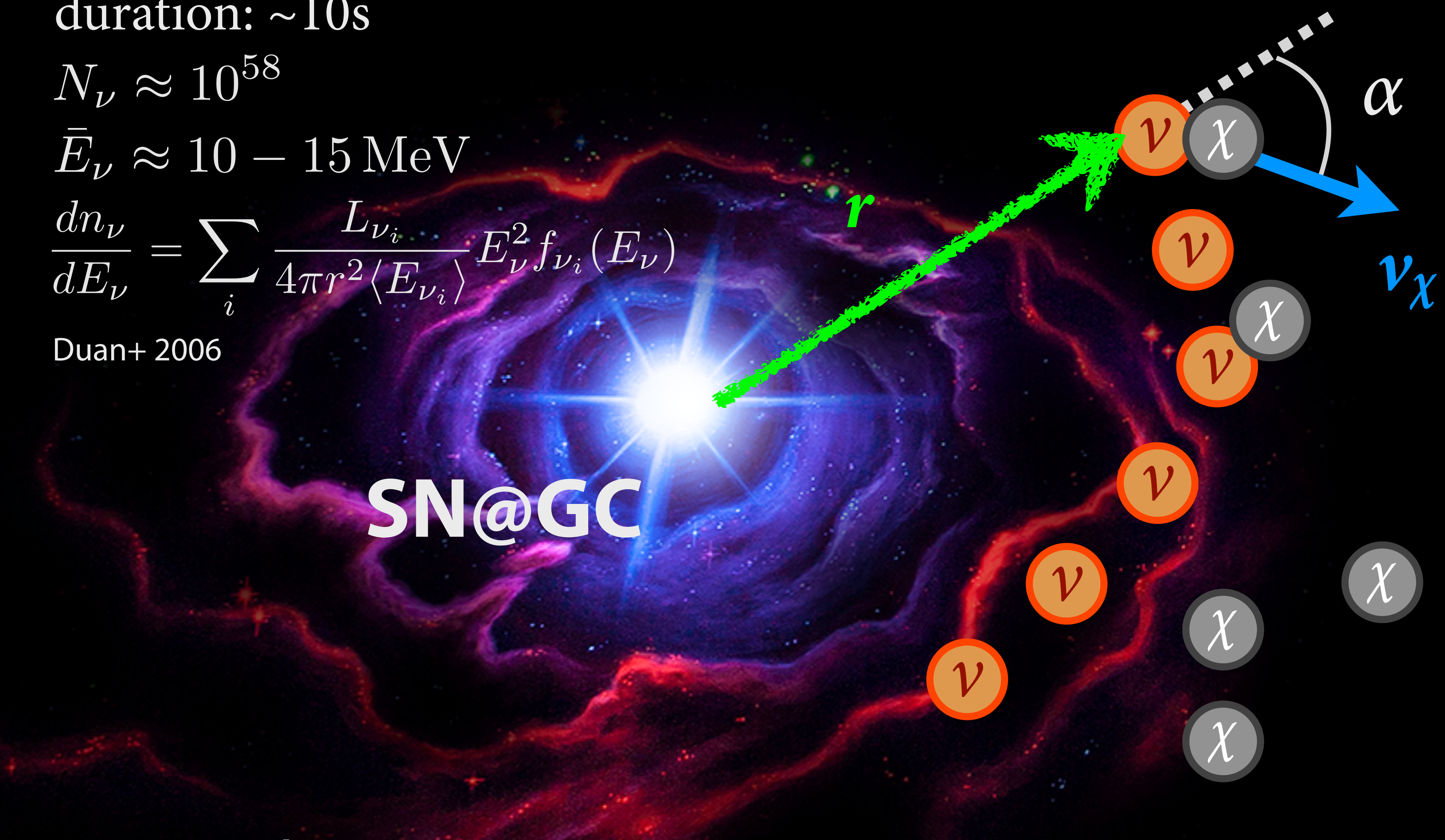

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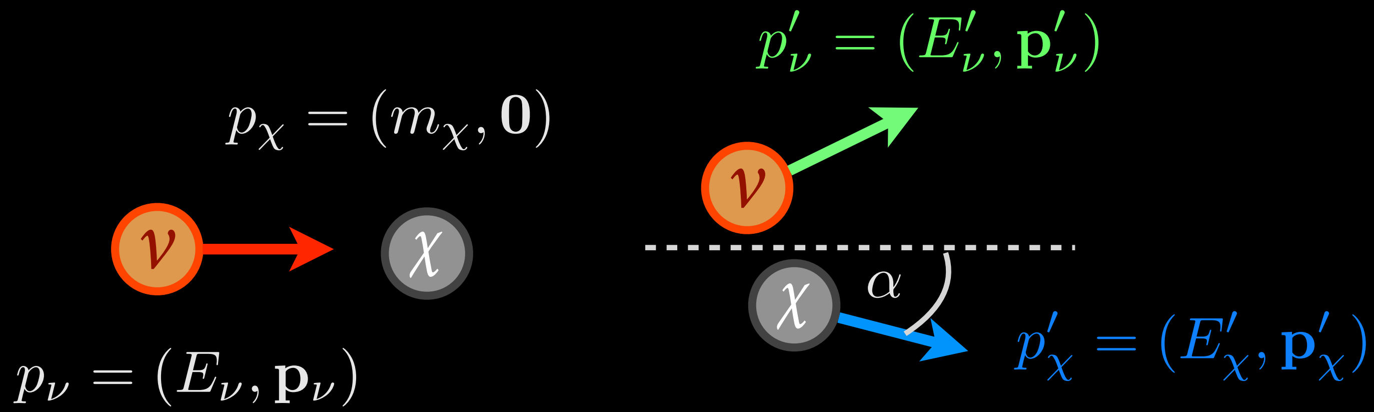

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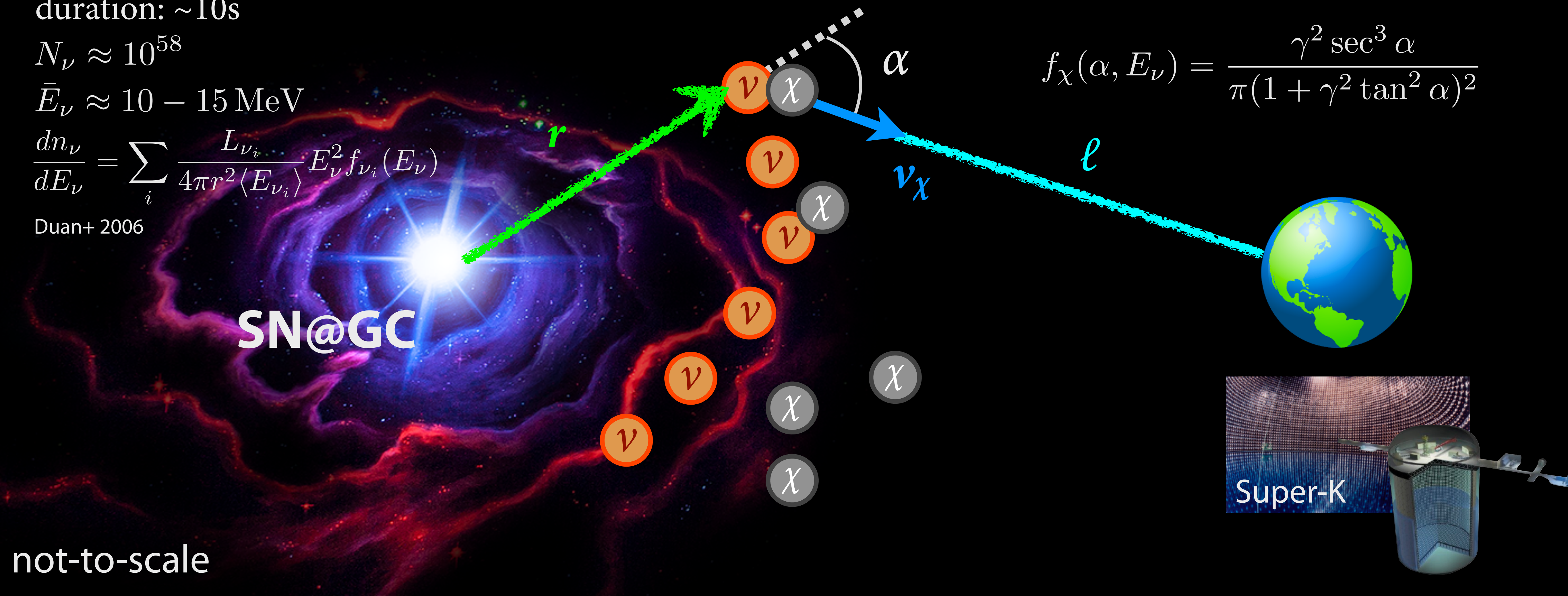

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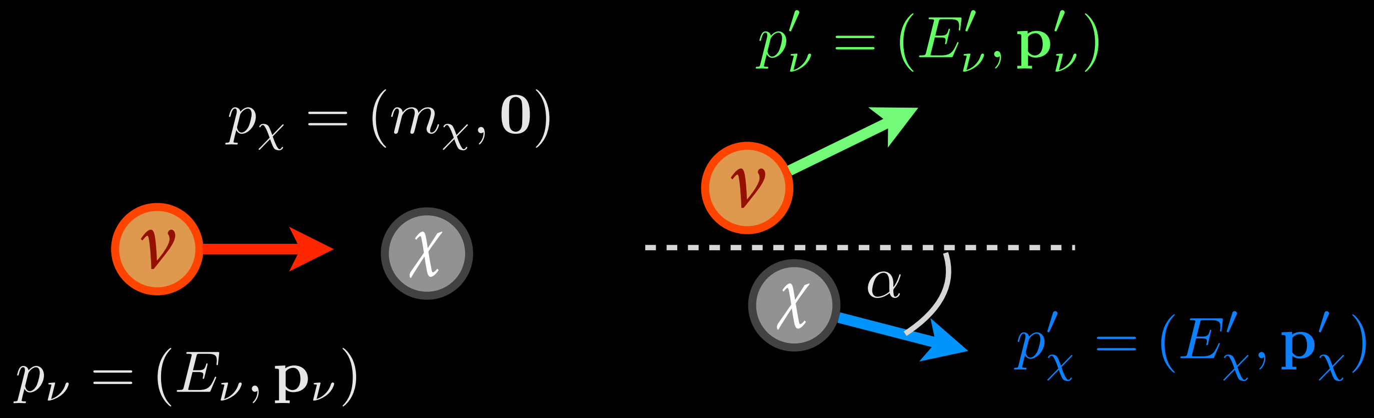

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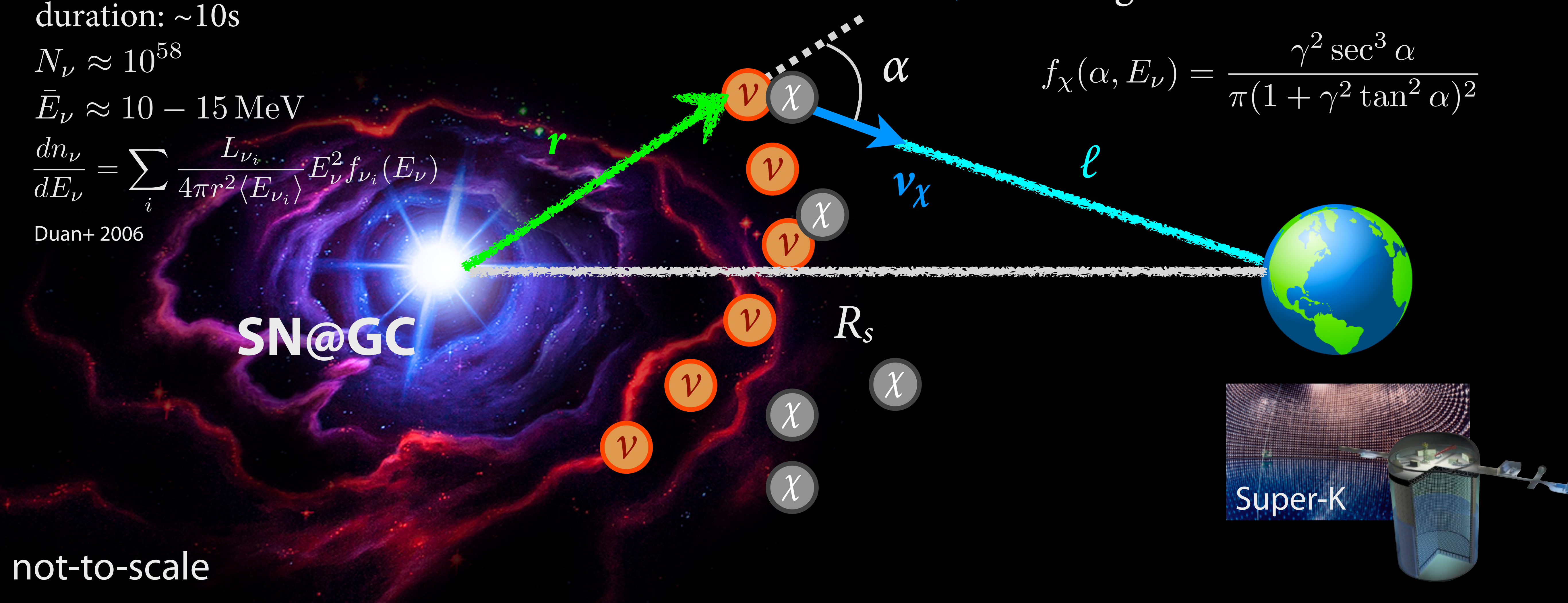
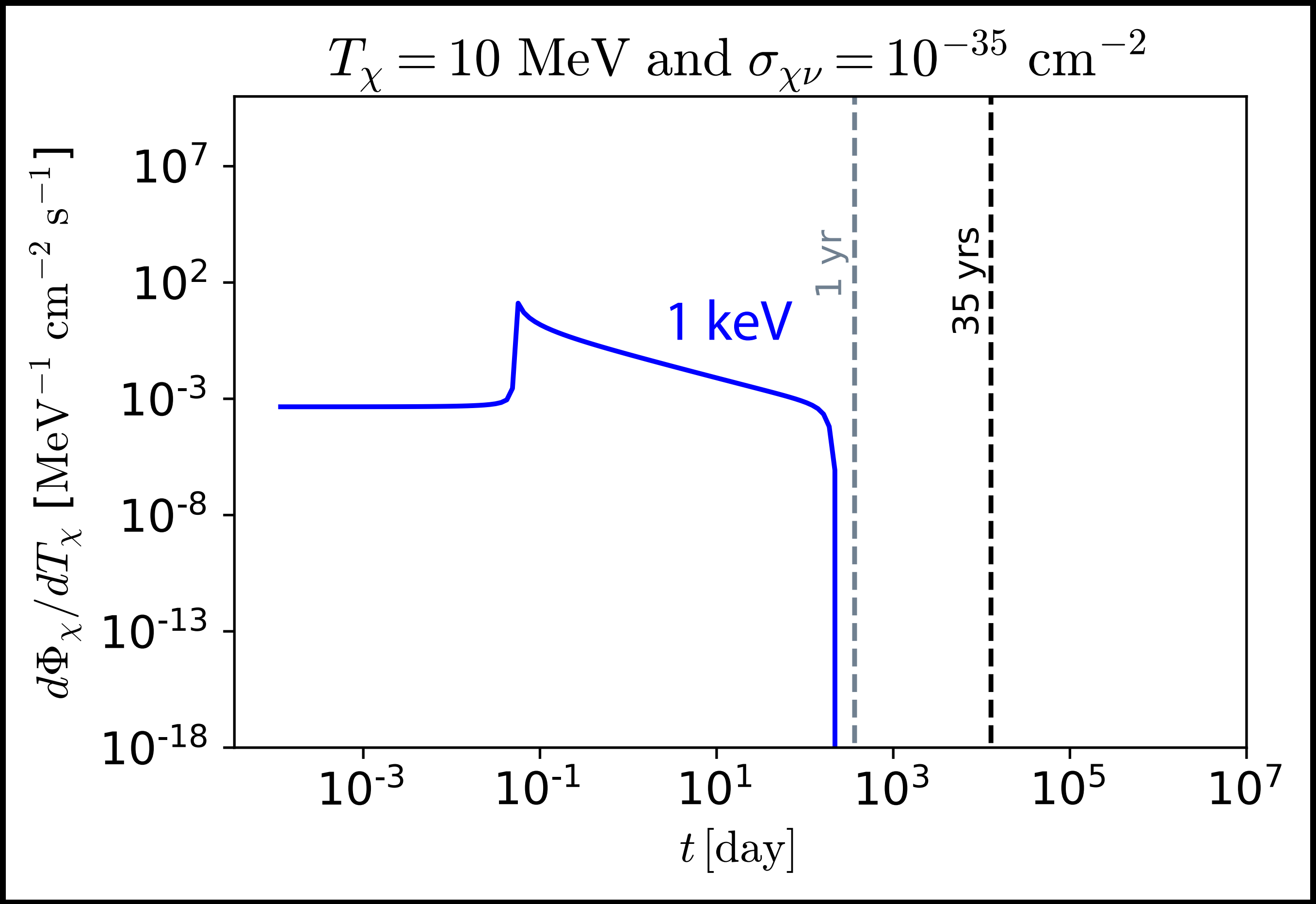


The BDM flux on the Earth

BDM flux at Earth

- BDM flux at Earth with m_χ = 1 keV and T_χ = 10 MeV

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



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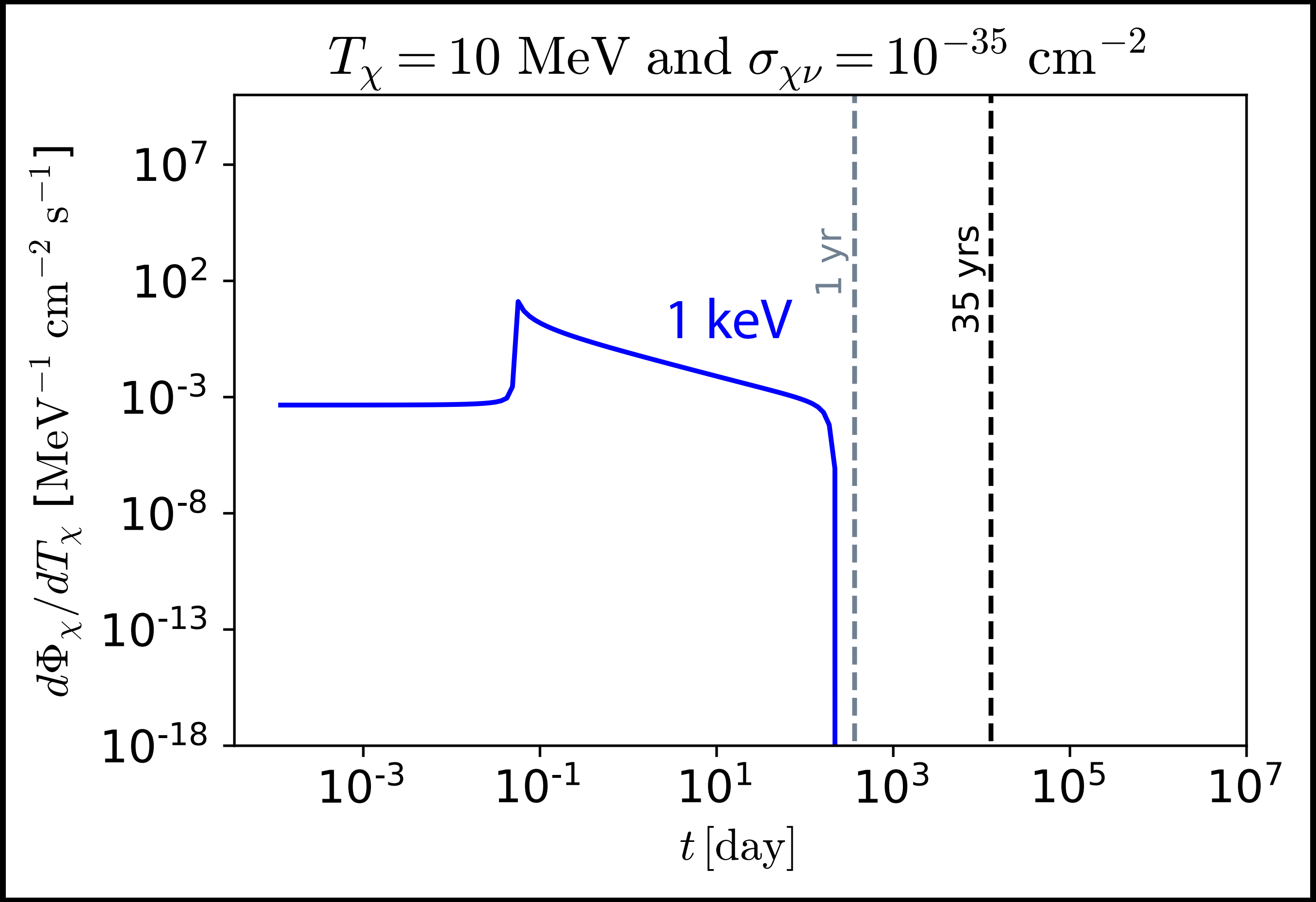
- BDM will arrive Earth later than SNν depending on where it was boosted



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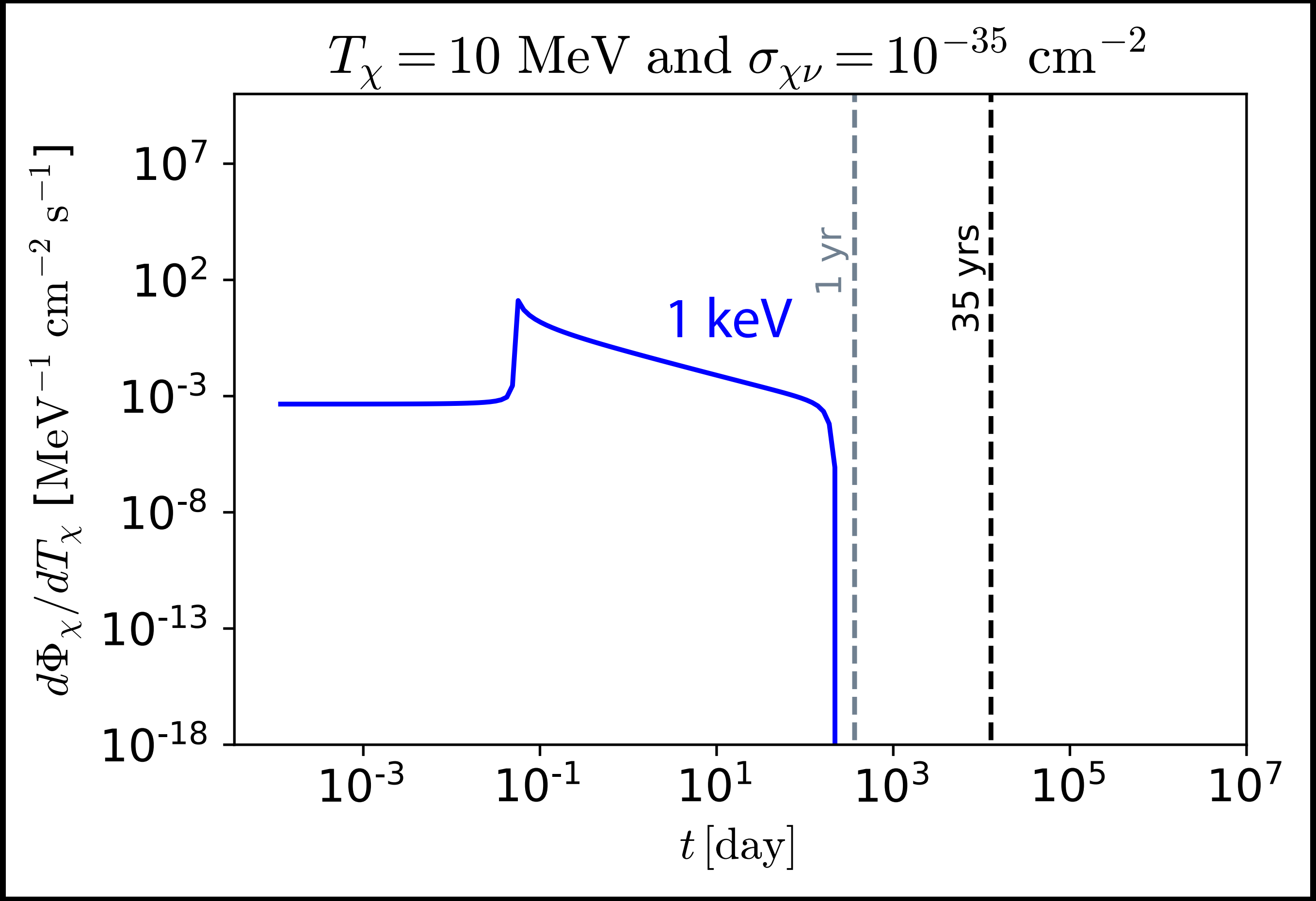
- **Time-zero *t* = 0** is ***calibrated by*** SNν



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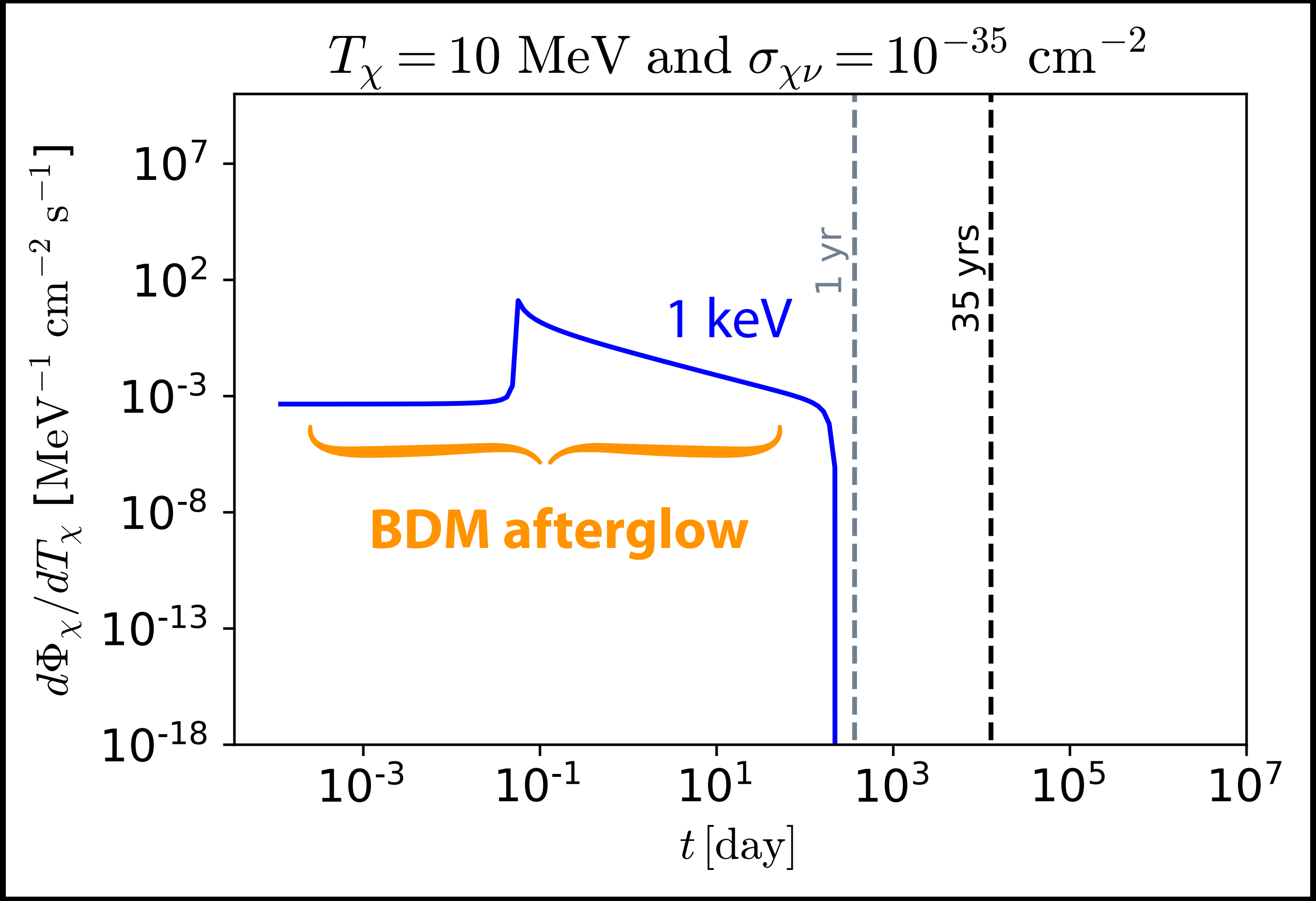

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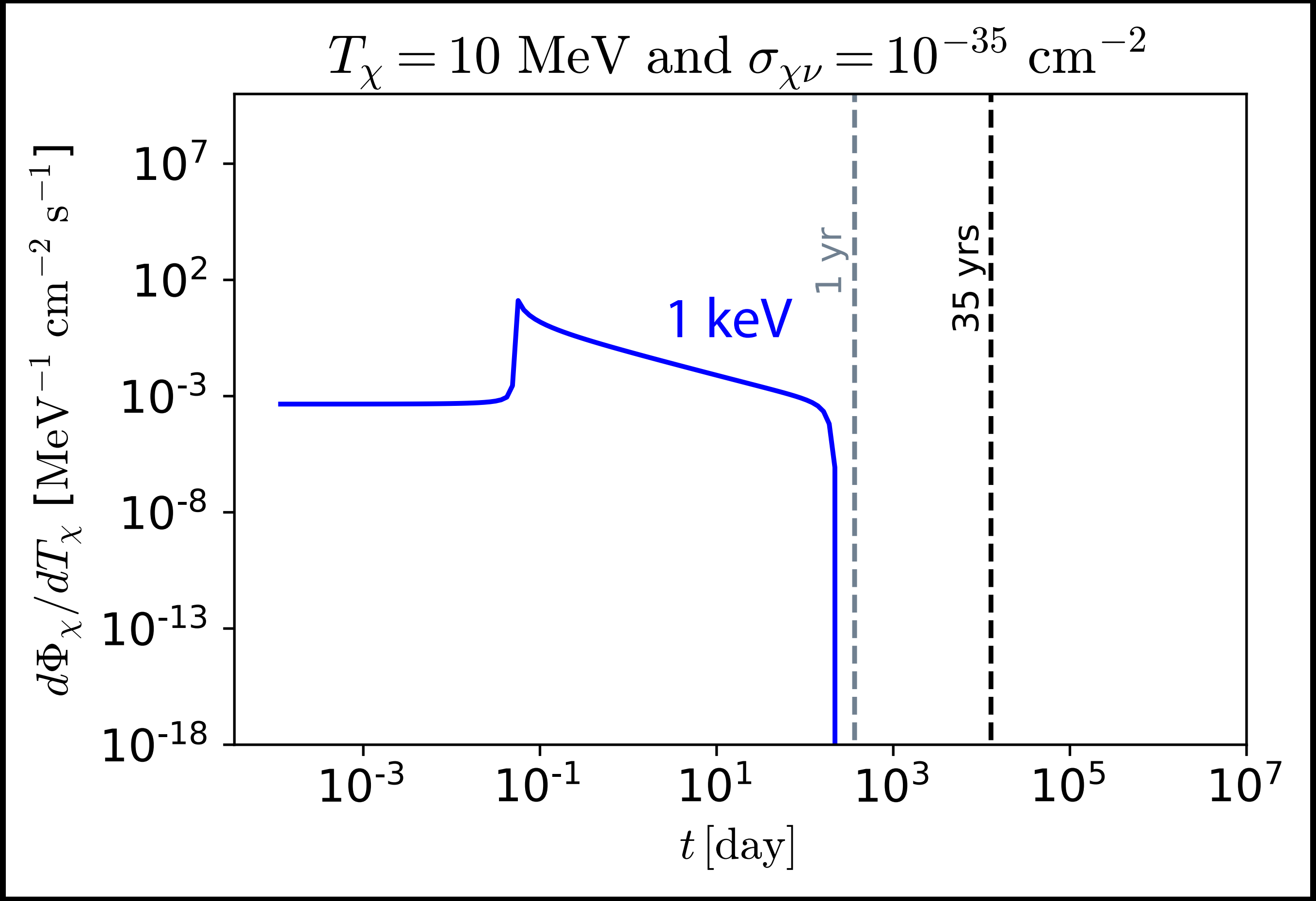

BDM flux at Earth

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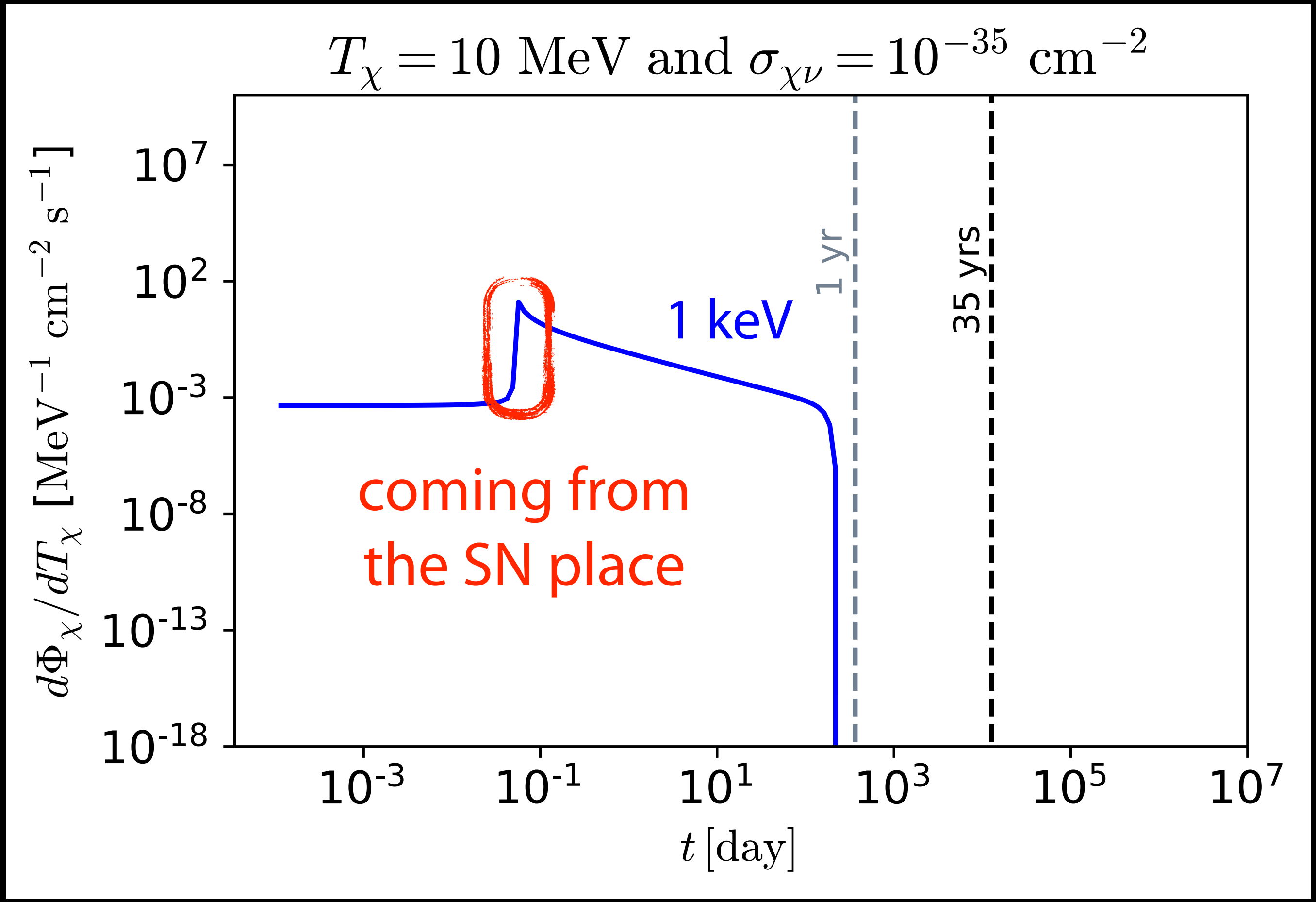

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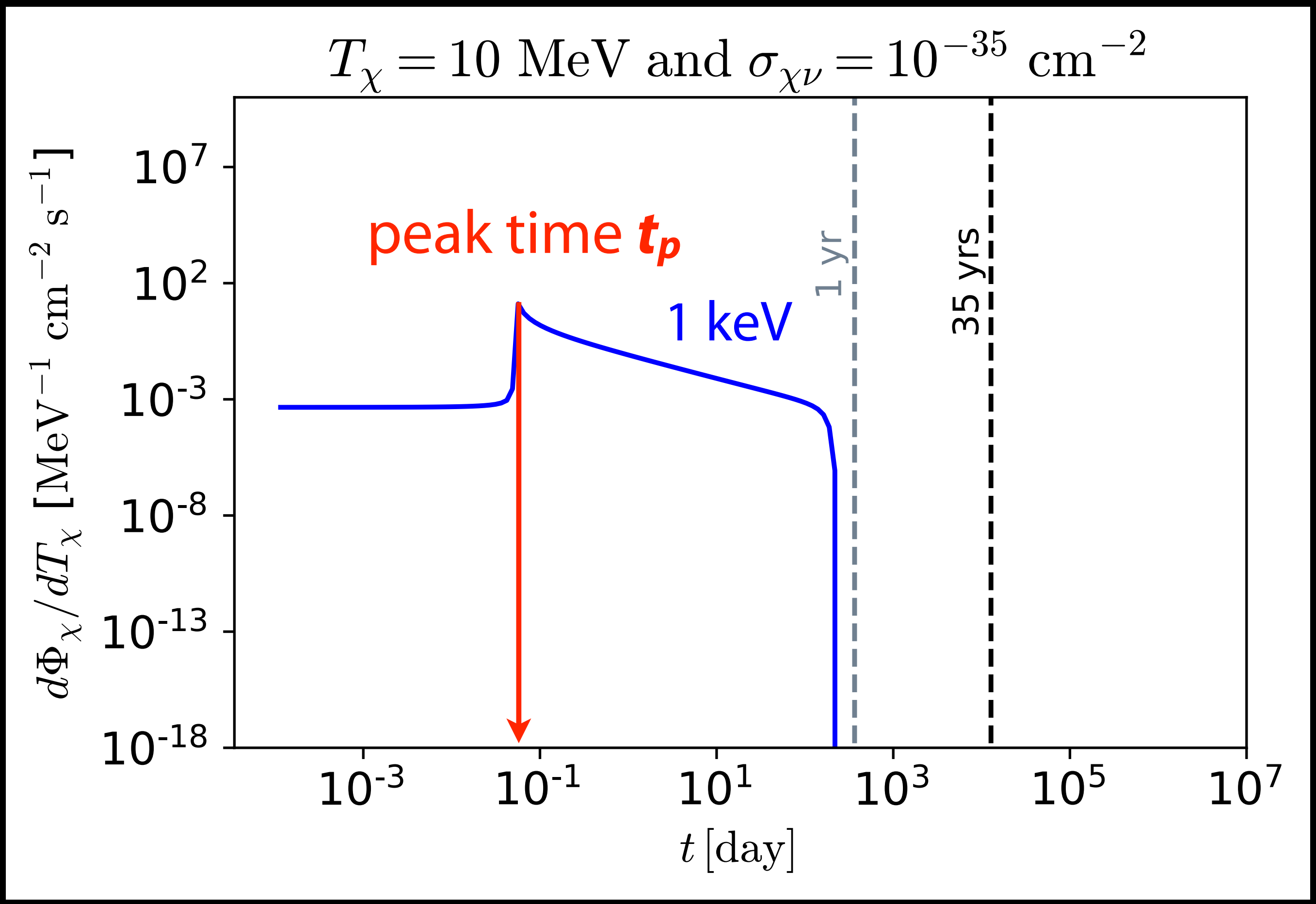


- The **peak** is contributed by the BDM coming from the SN place

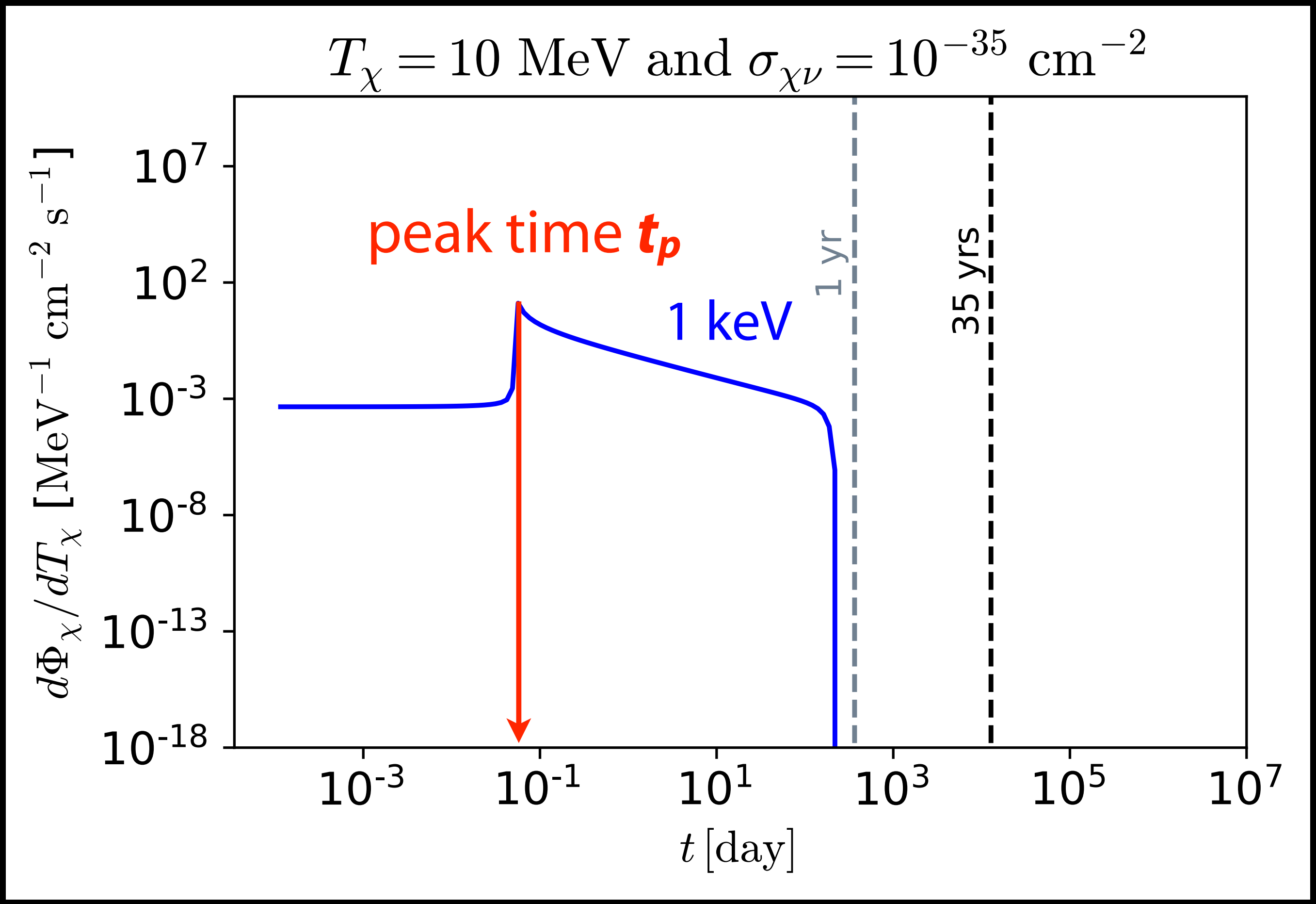
$$t_p = R_s\left(\frac{1}{v_\chi} - \frac{1}{c}\right) \simeq \frac{m_\chi^2}{2T_\chi^2}\frac{R_s}{c}$$

BDM flux at Earth

- BDM flux at Earth with $m_\chi = 1$ keV and $T_\chi = 10$ MeV

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

- BDM will arrive Earth later than SNν depending on where it was boosted
- **Time-zero $t = 0$** is ***calibrated by*** SNν



- The **peak** is contributed by the BDM coming from the SN place

$$t_p = R_s\left(\frac{1}{v_\chi} - \frac{1}{c}\right) \simeq \frac{m_\chi^2}{2T_\chi^2}\frac{R_s}{c}$$

- m_χ can be **directly measured**!

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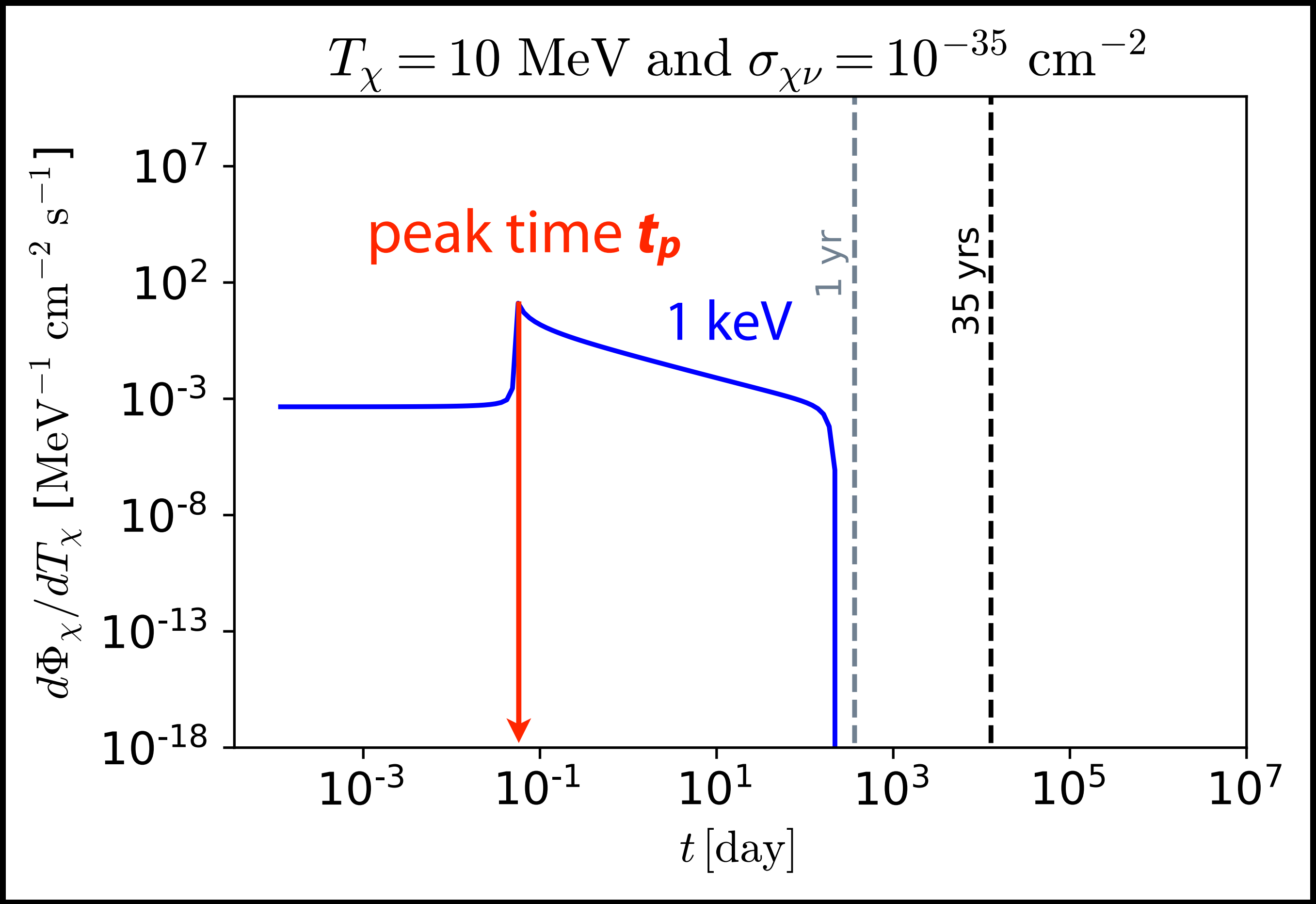

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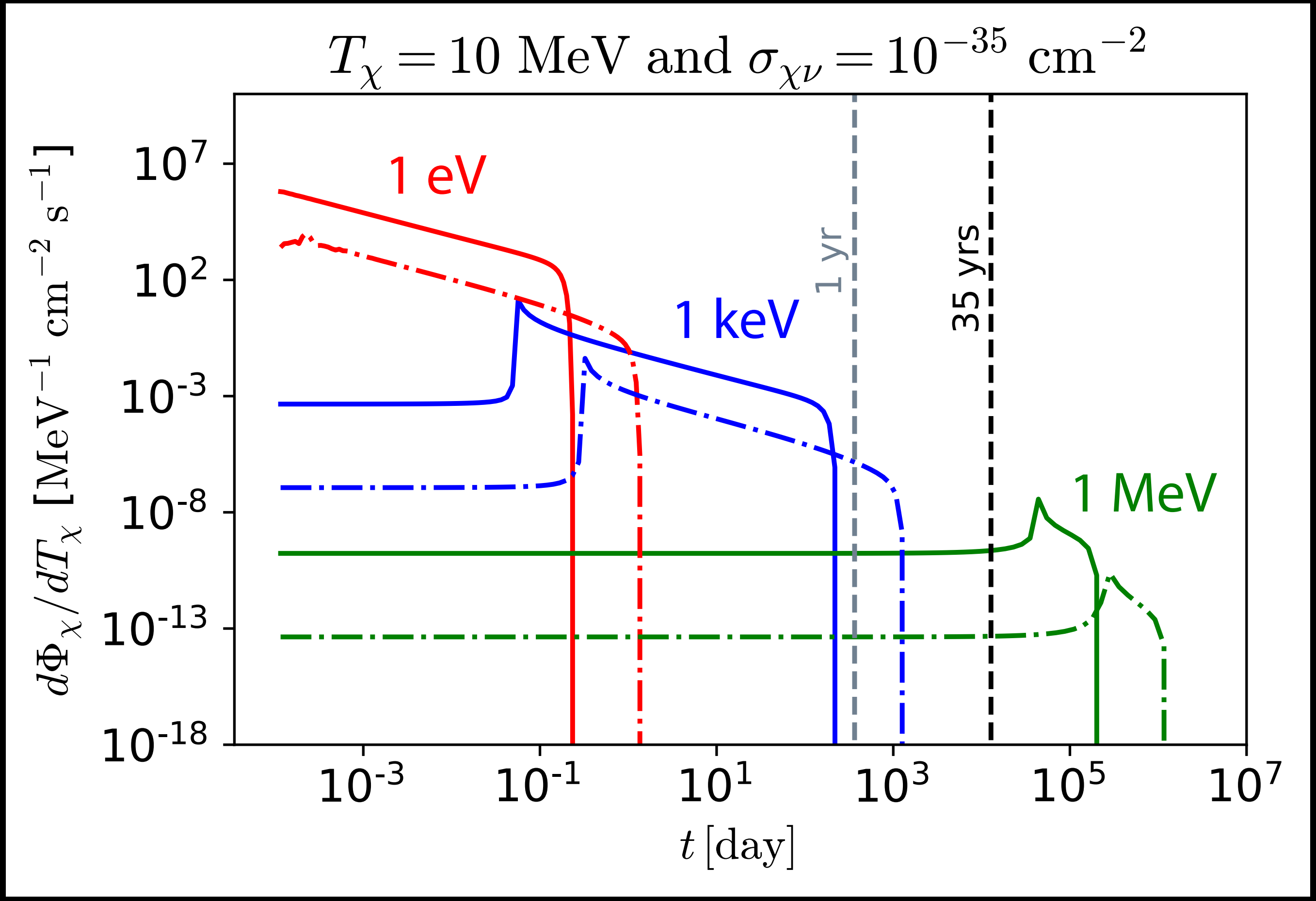
- m_χ can be **directly measured**!
- Time-dependent feature is ***independent of $\sigma_{\chi\nu}$***

BDM flux from GC & Large Magellanic Cloud

- DM profile

$$n_\chi(r) = \frac{\rho_s}{m_\chi}\frac{1}{\frac{r}{r_s}(1+\frac{r}{r_s})^n}, \quad (n, \rho_s, r_s) = \begin{cases} (2, 184\,\mathrm{MeV\,cm^{-3}}, 24.4\,\mathrm{kpc}), & \mathrm{MW} \\ (3, 68\,\mathrm{MeV\,cm^{-3}}, 31.9\,\mathrm{kpc}), & \mathrm{LMC\ (SN1987a)} \end{cases}$$

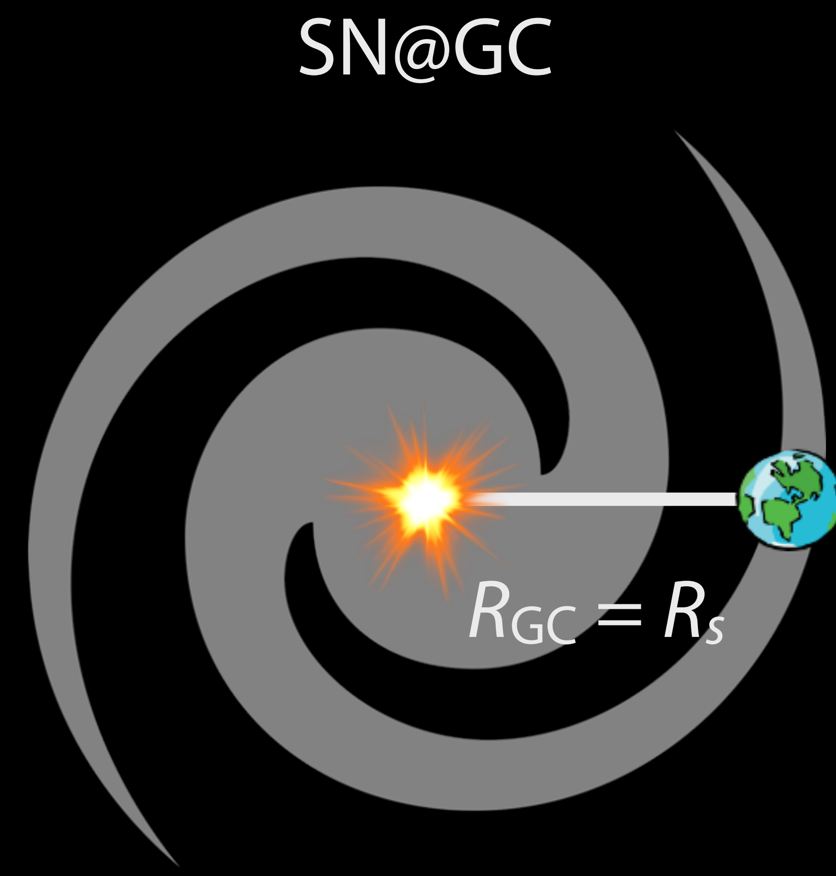
- BDM flux vs. m_χ

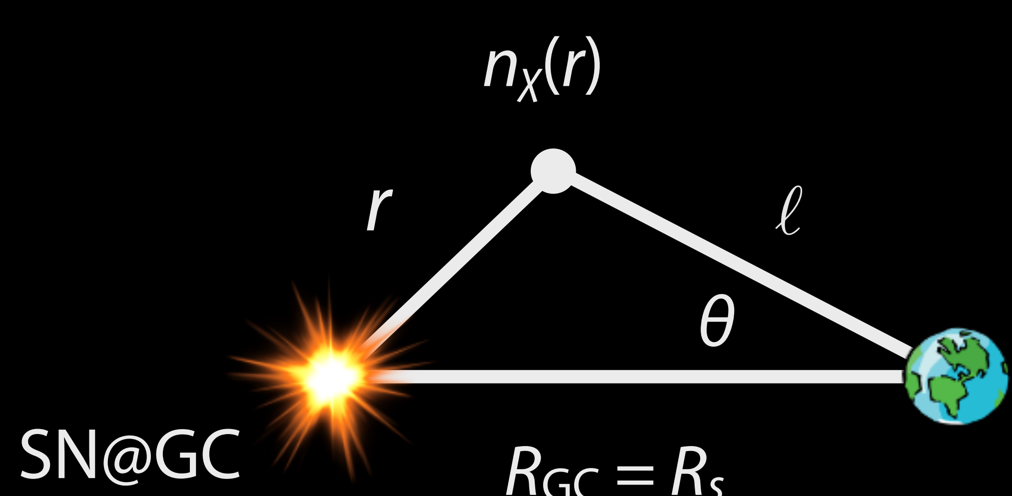


SN exploded in MW center

SN exploded in LMC center

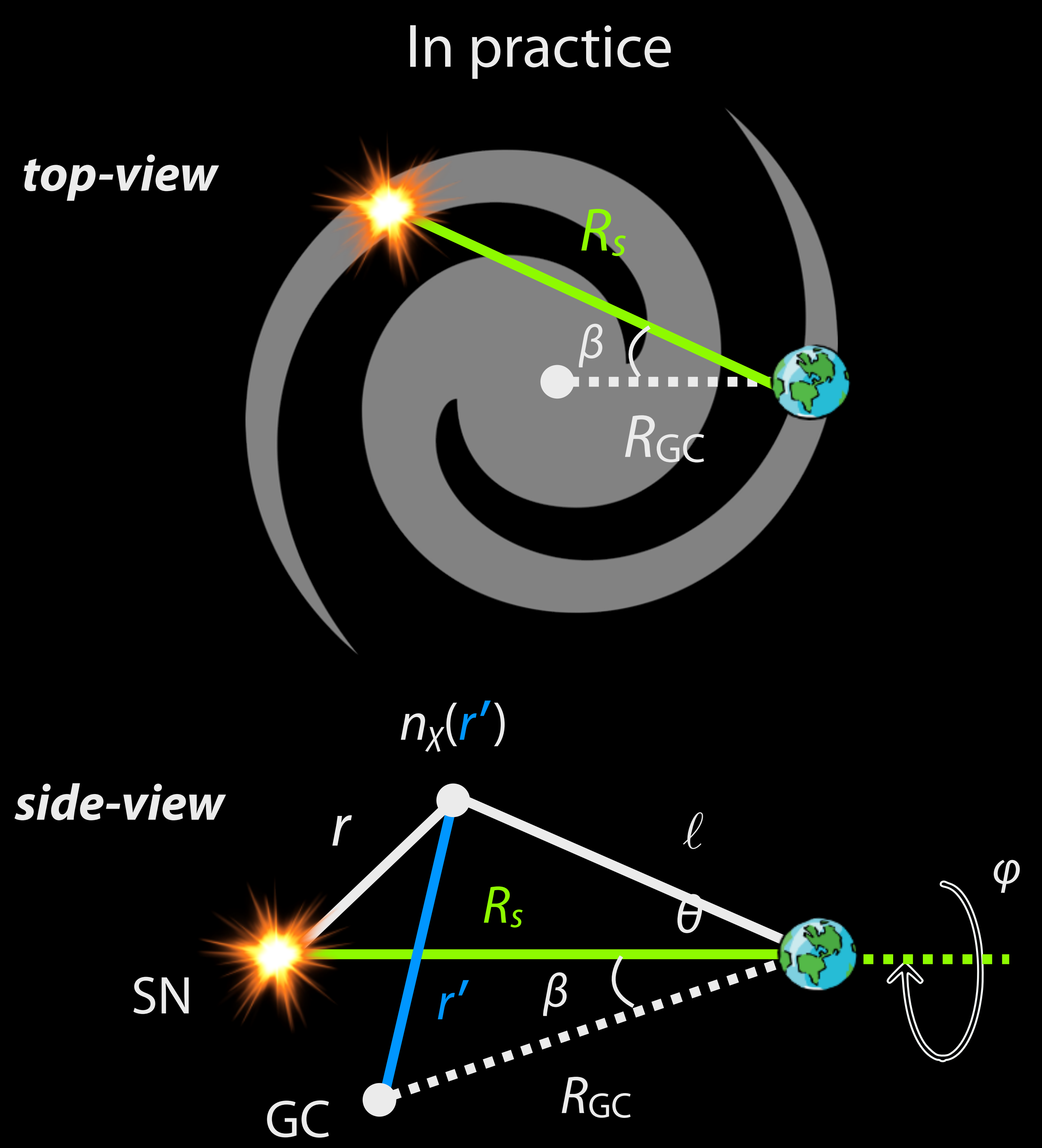
Galactic supernova





not-to-scale

Galactic supernova

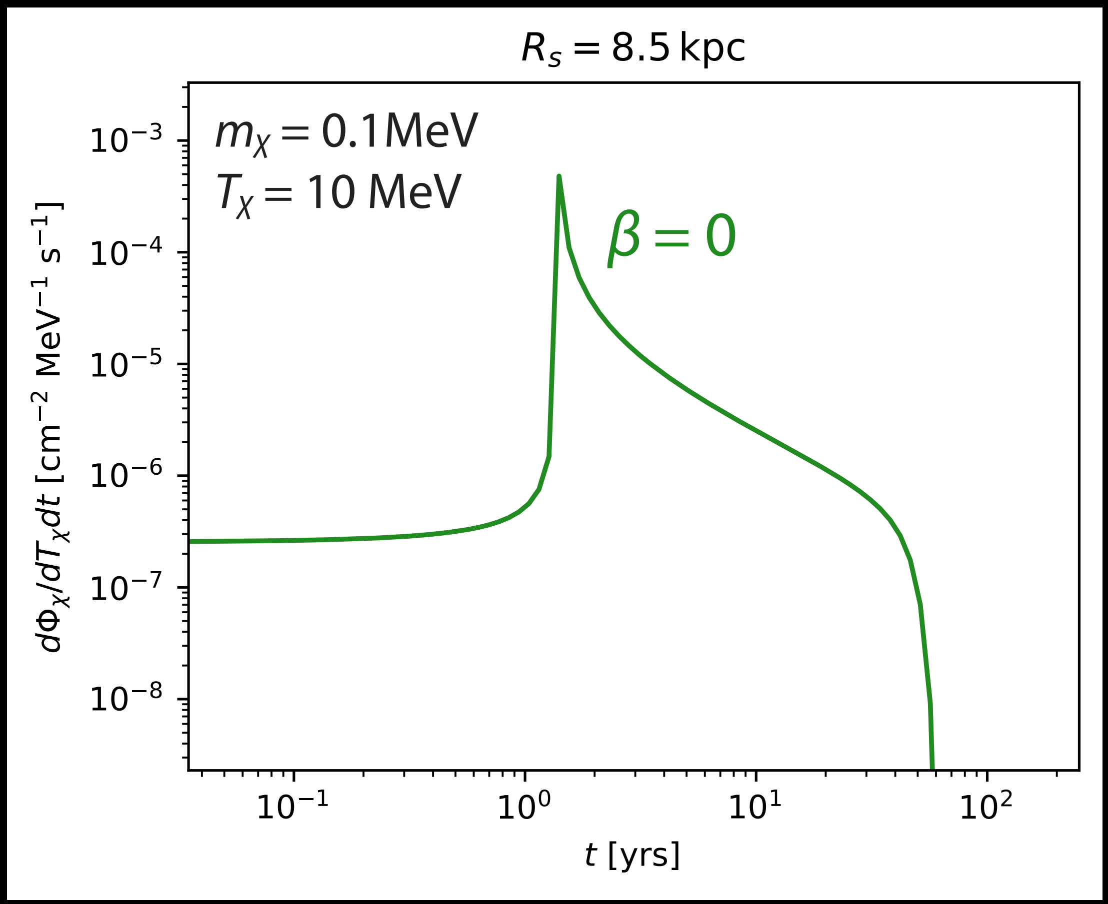


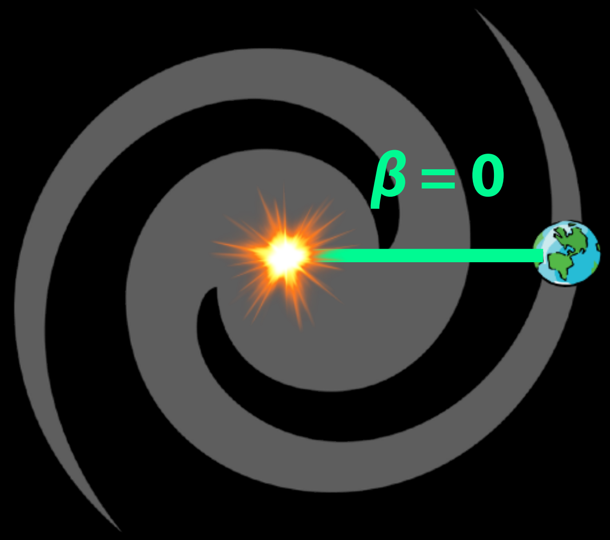
not-to-scale

BDM from various places in MW

$R_S = 8.5$ kpc vs. β

BDM from various places in MW





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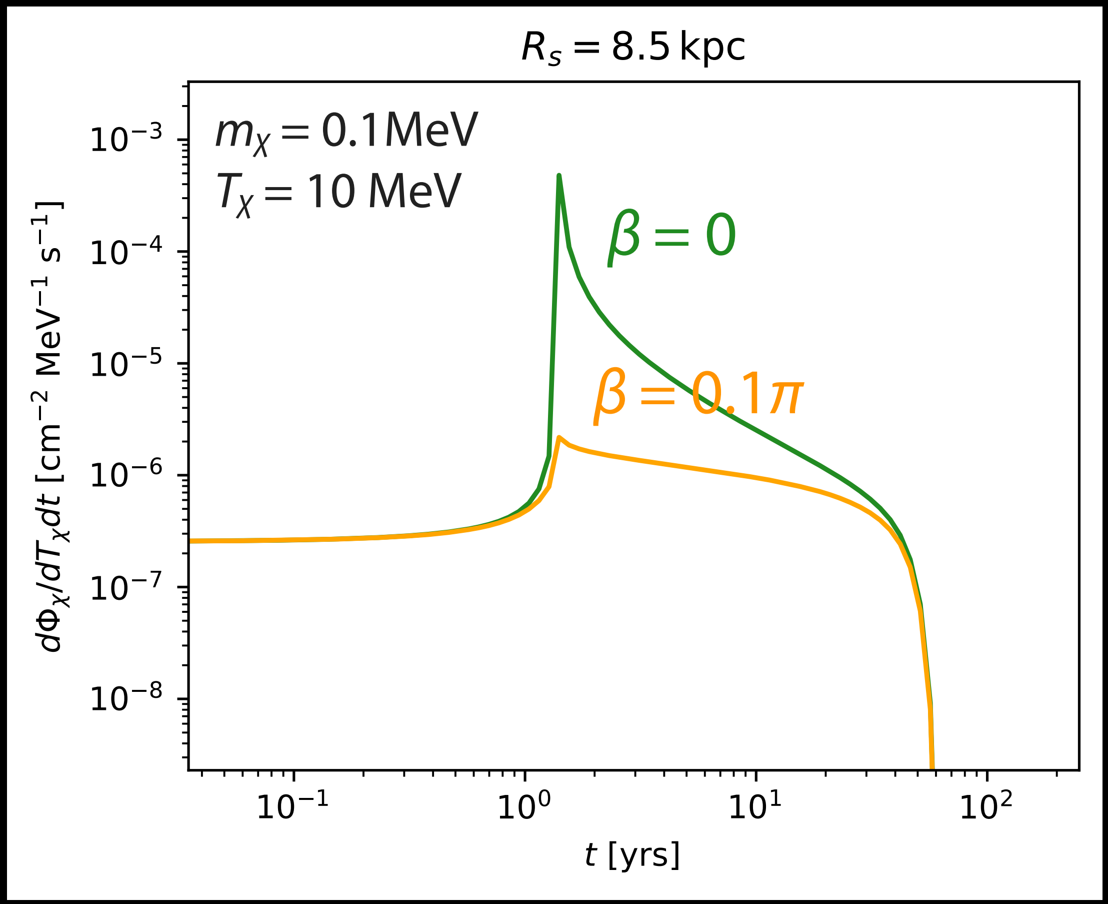

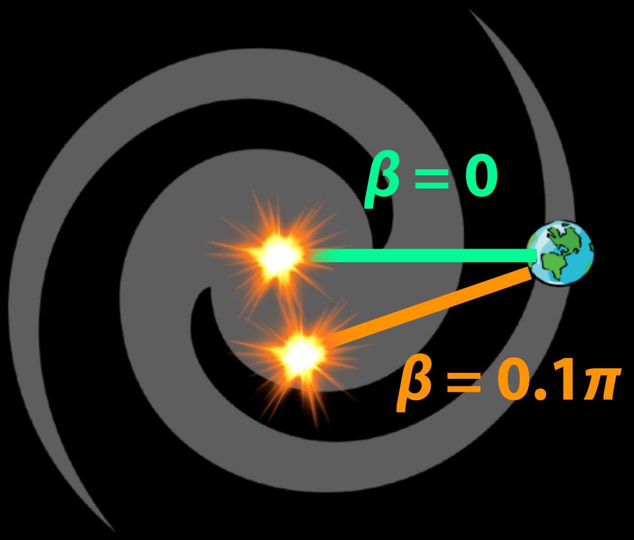

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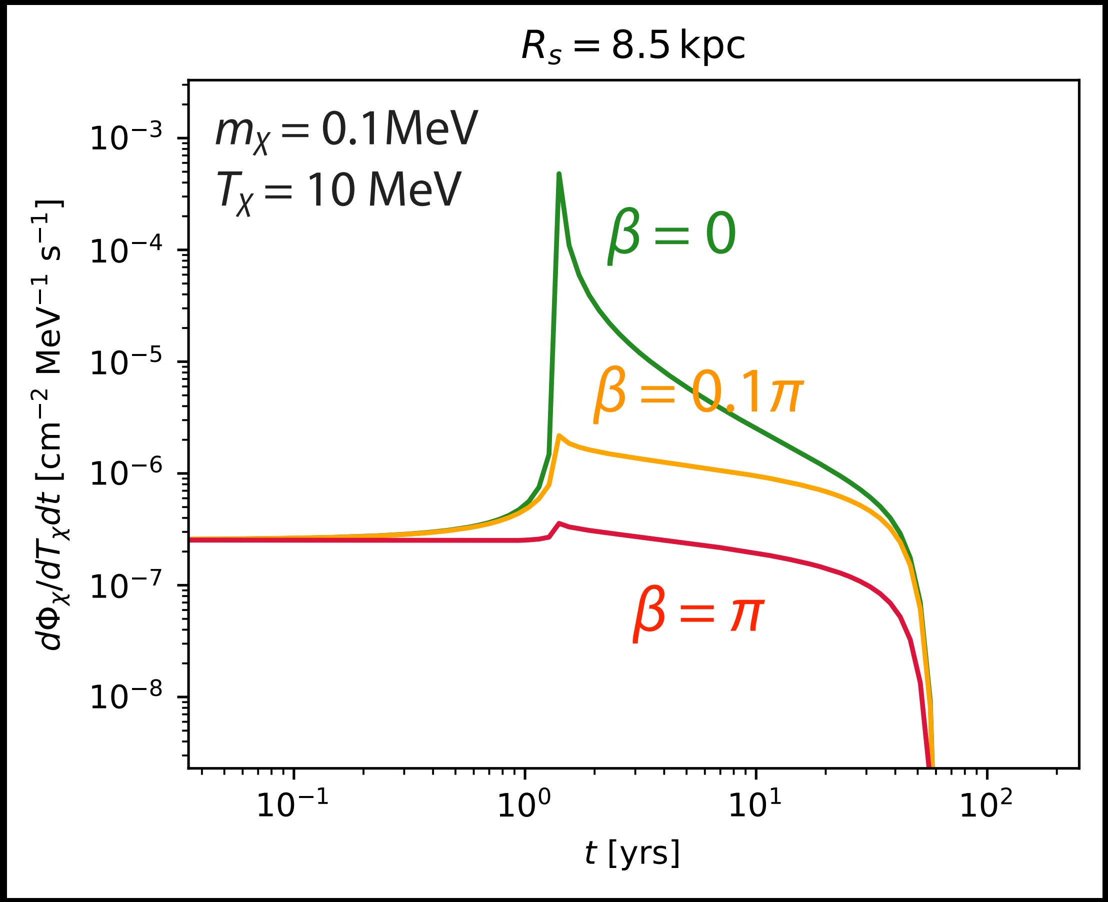

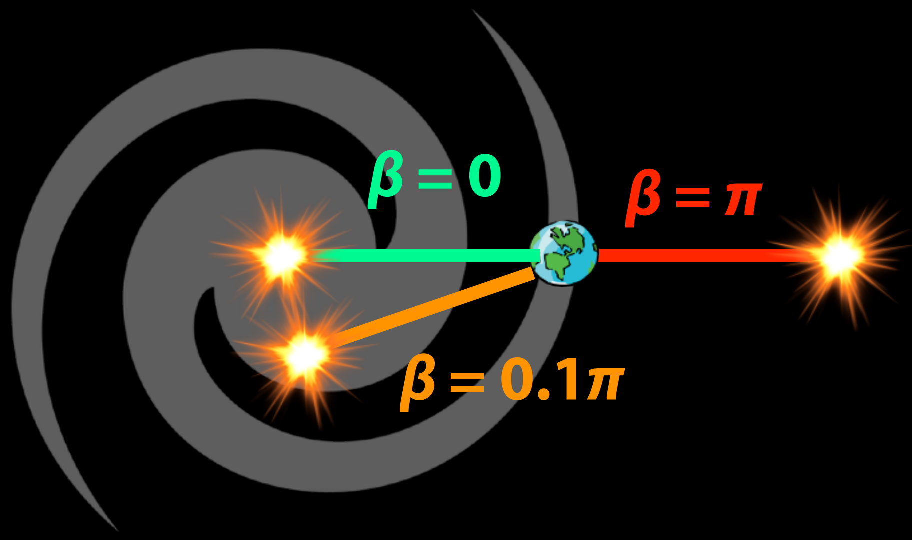

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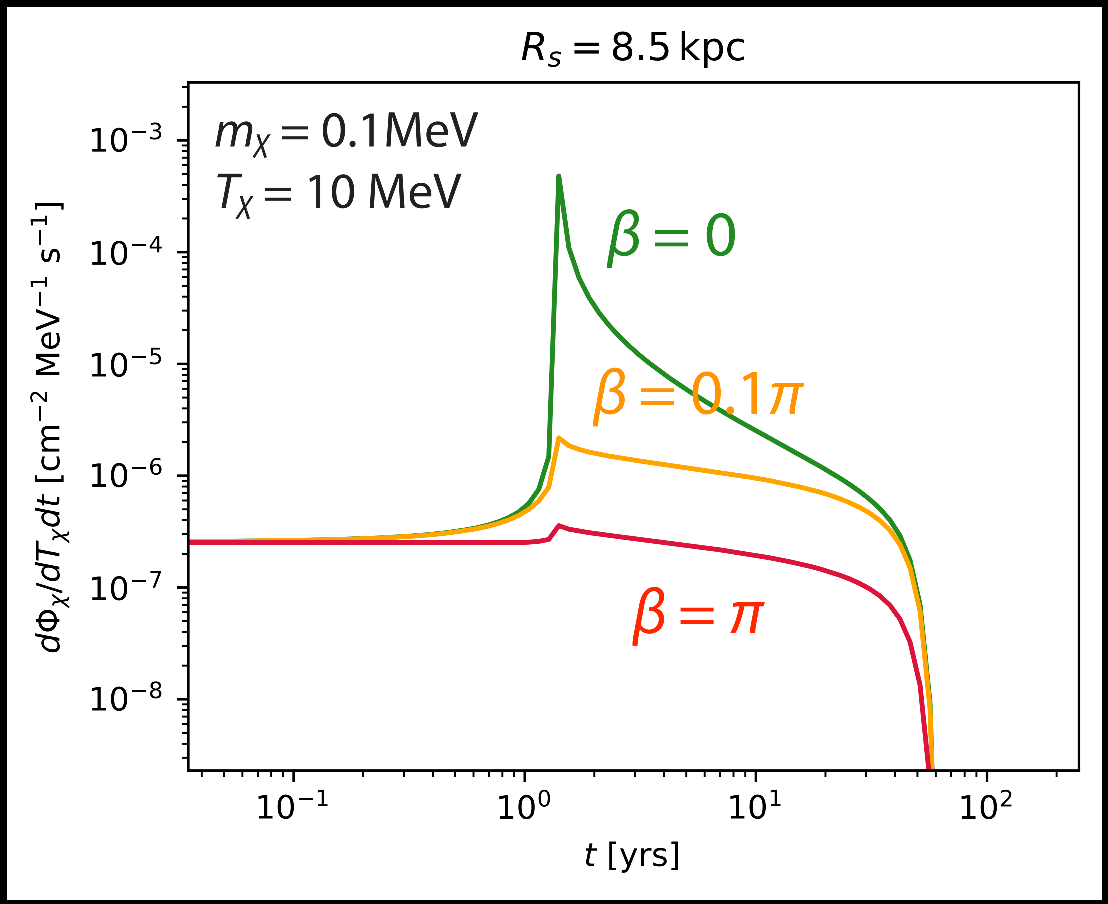
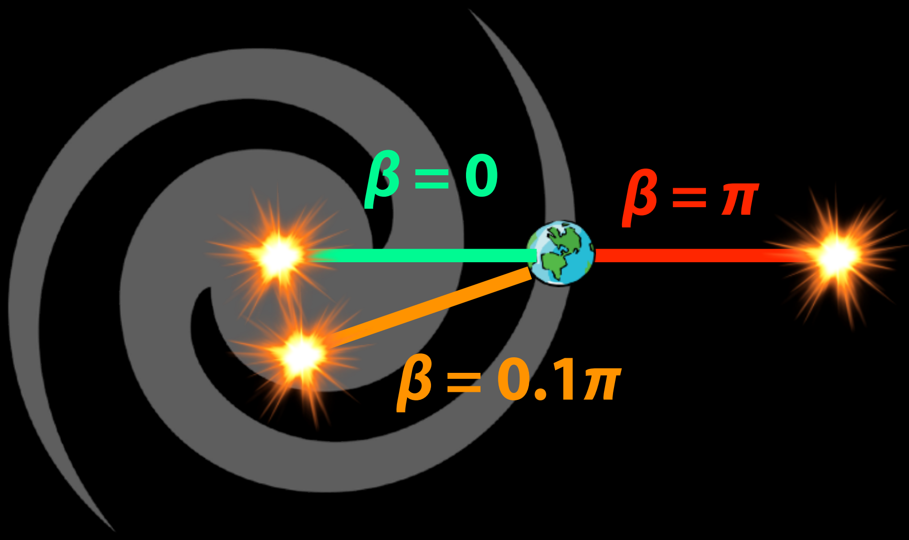
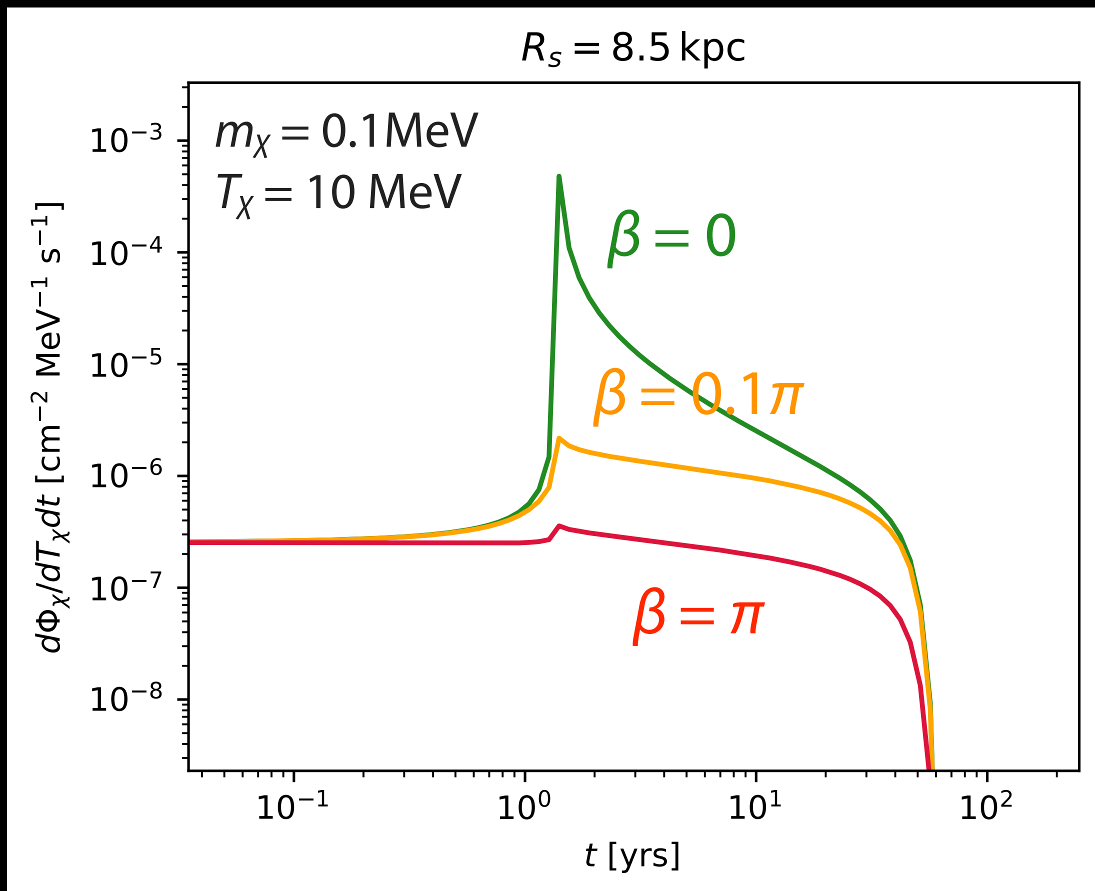


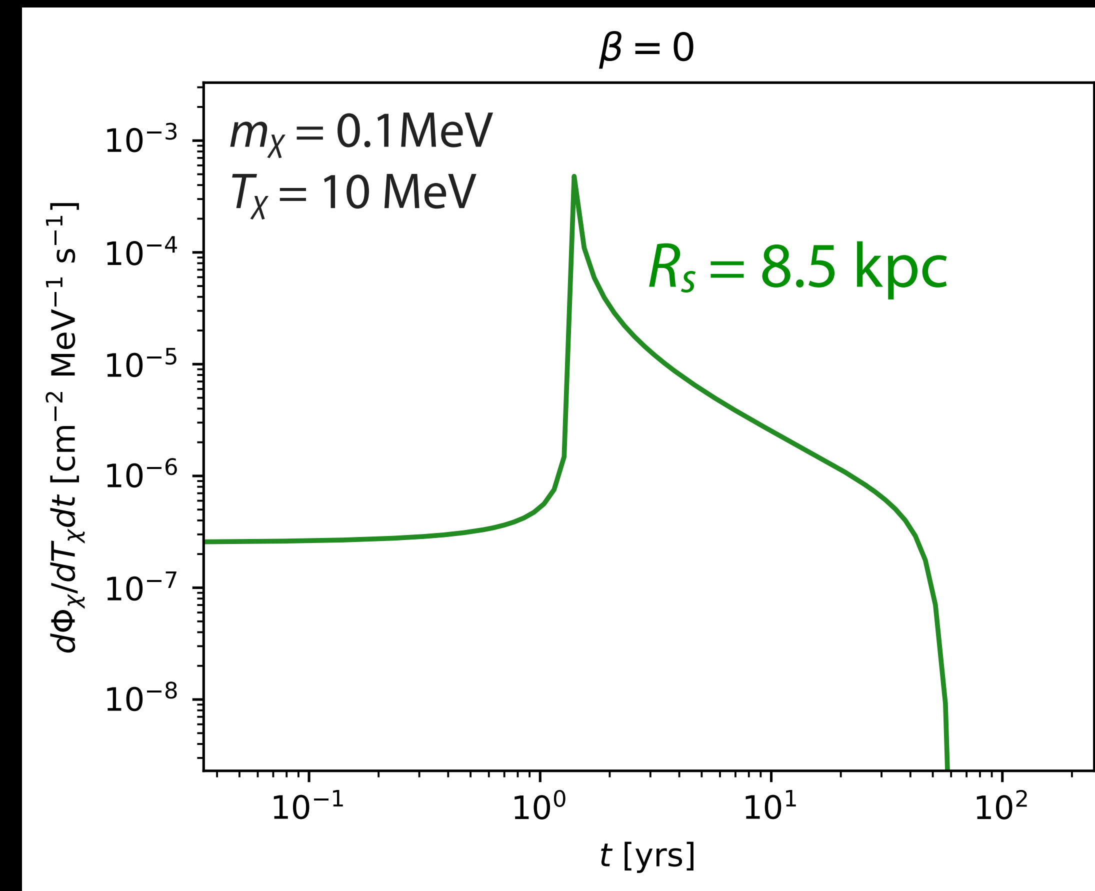


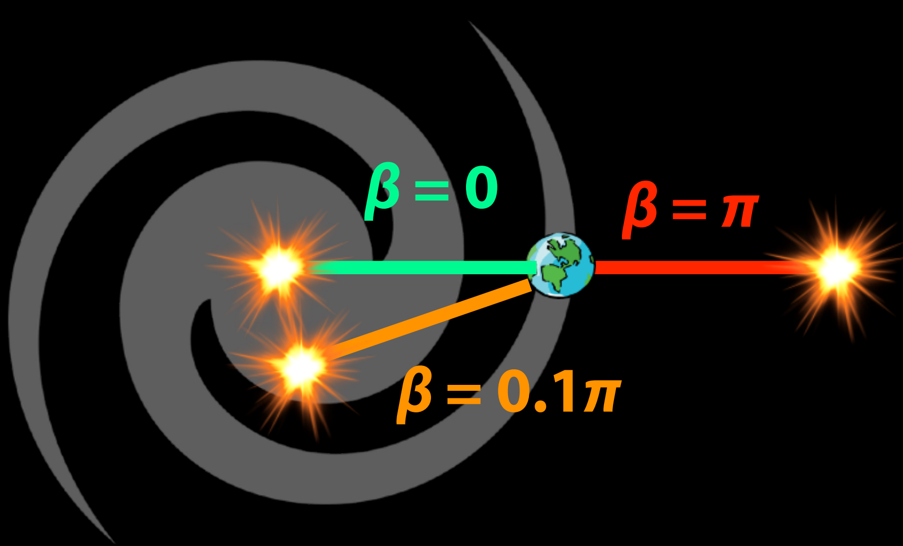
$R_s = 8.5$ kpc vs. β

$\beta = 0$ vs. R_s

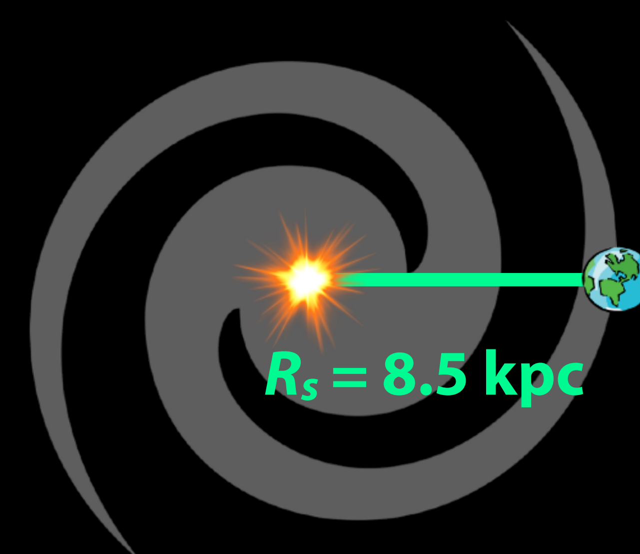
BDM from various places in MW





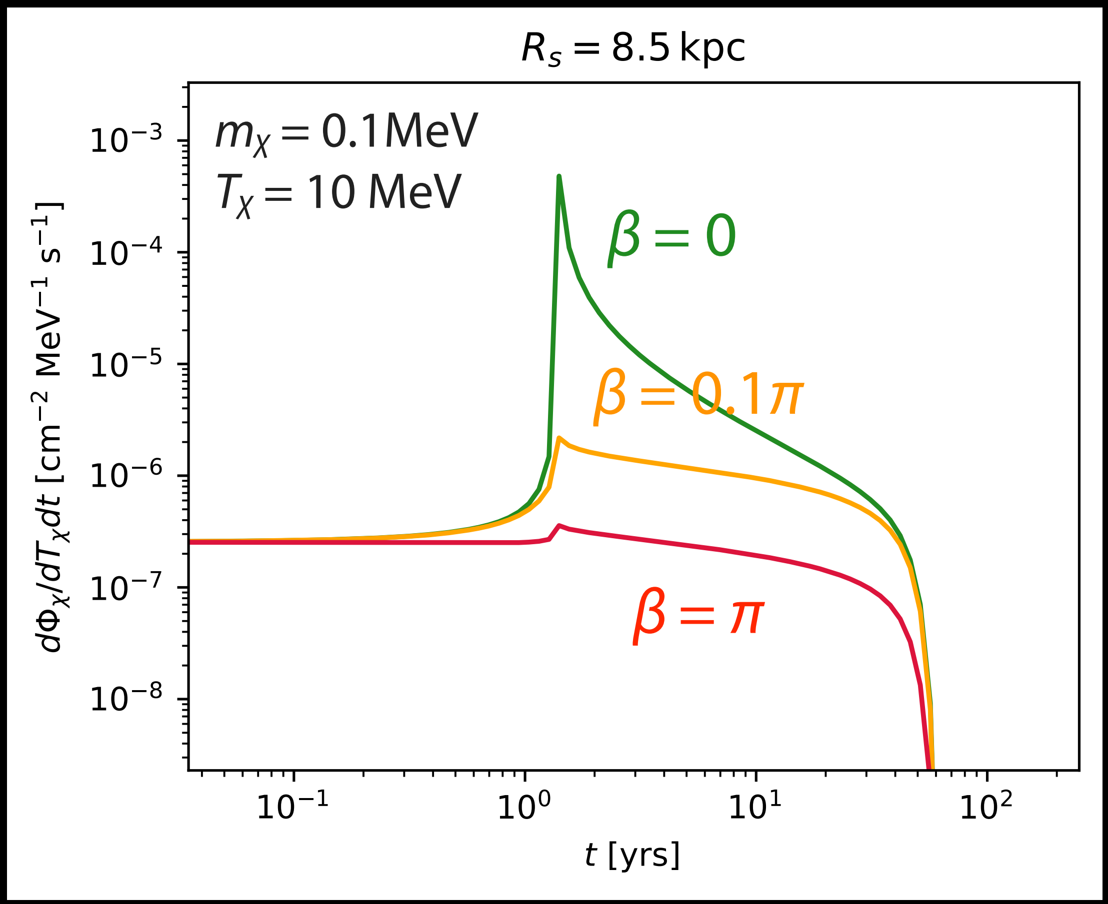


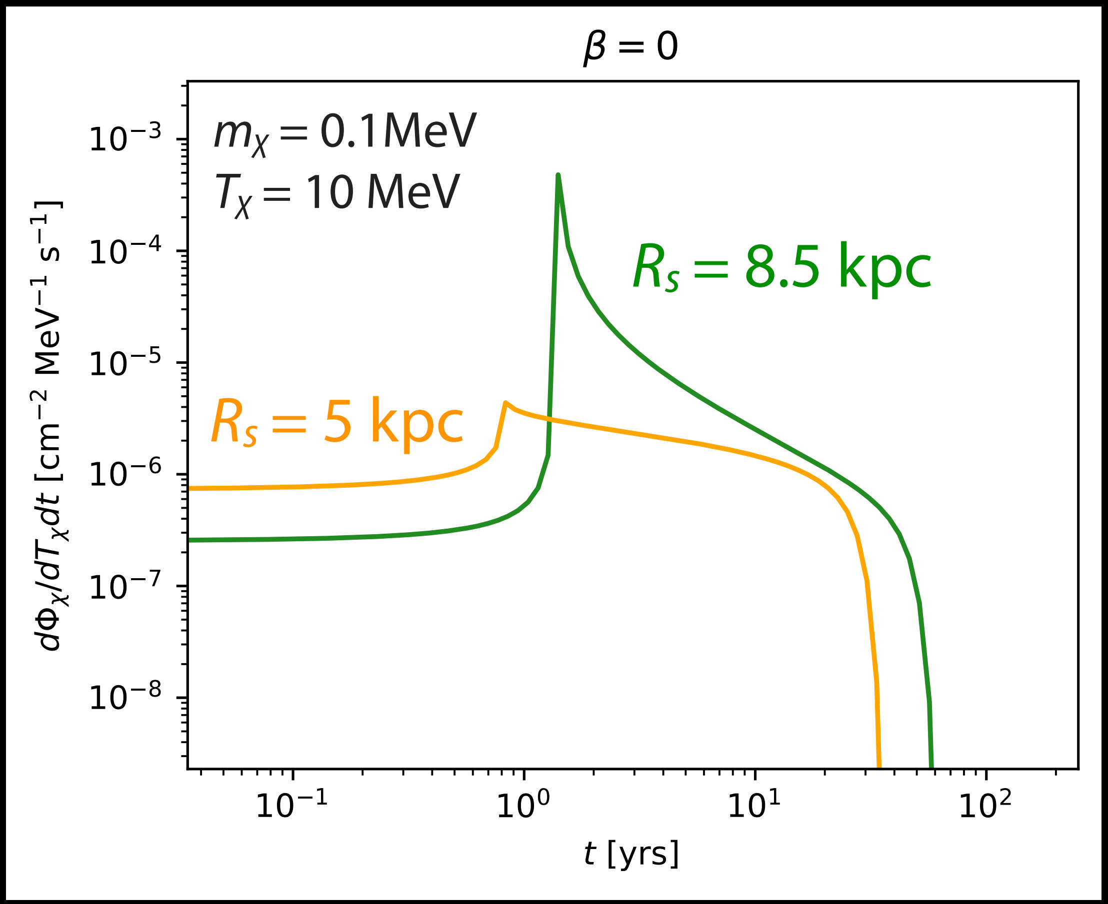
$R_s = 8.5$ kpc vs. β

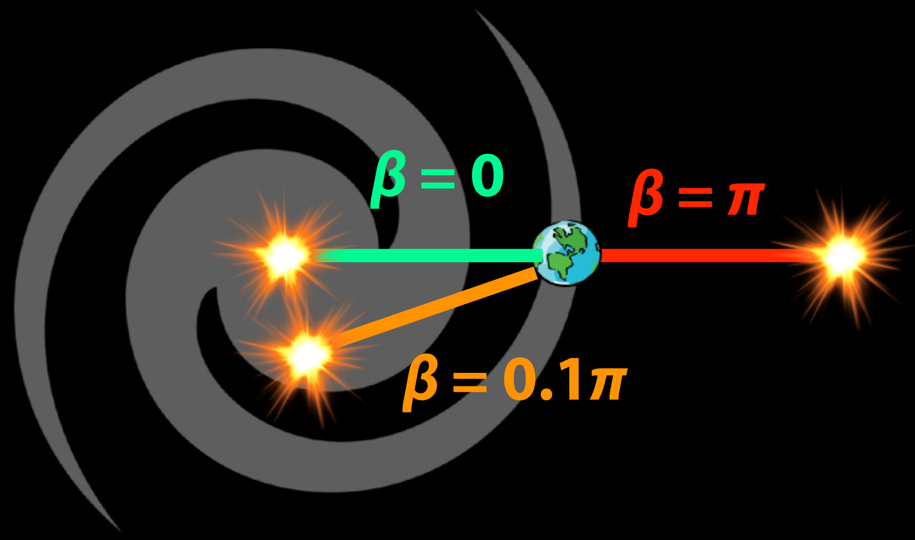


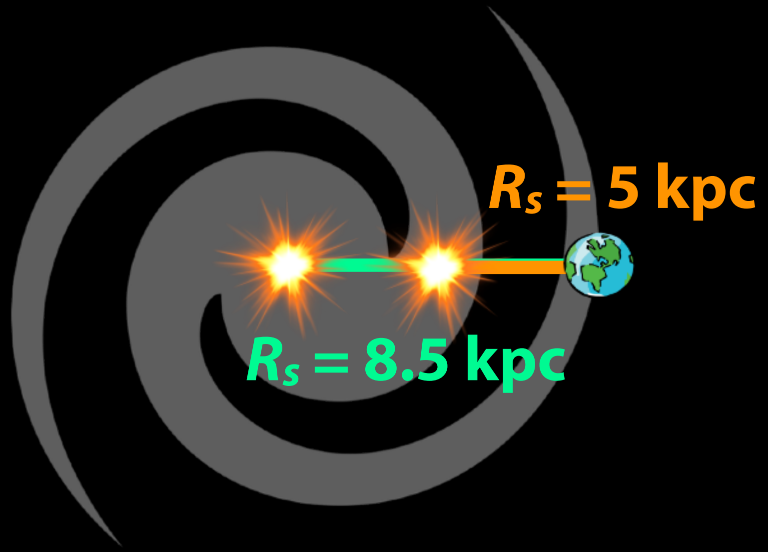
$\beta = 0$ vs. R_s

BDM from various places in MW





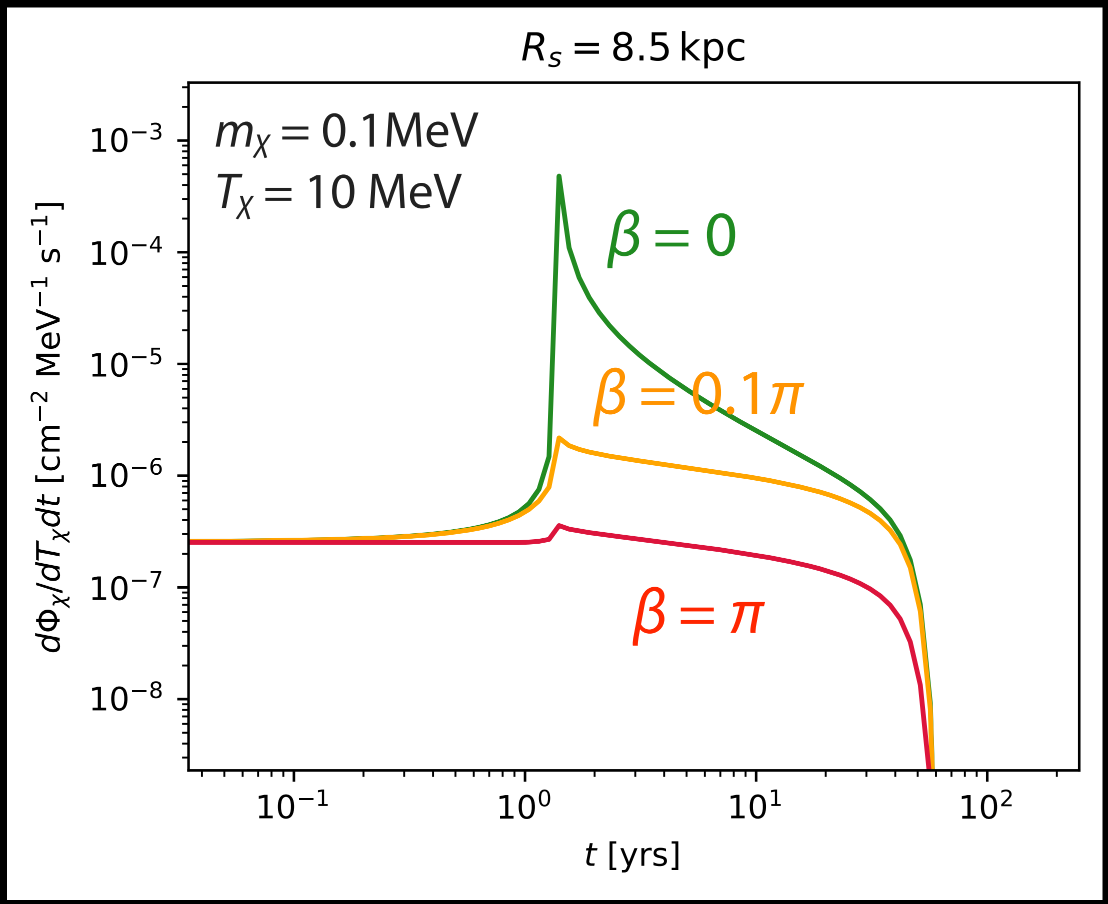


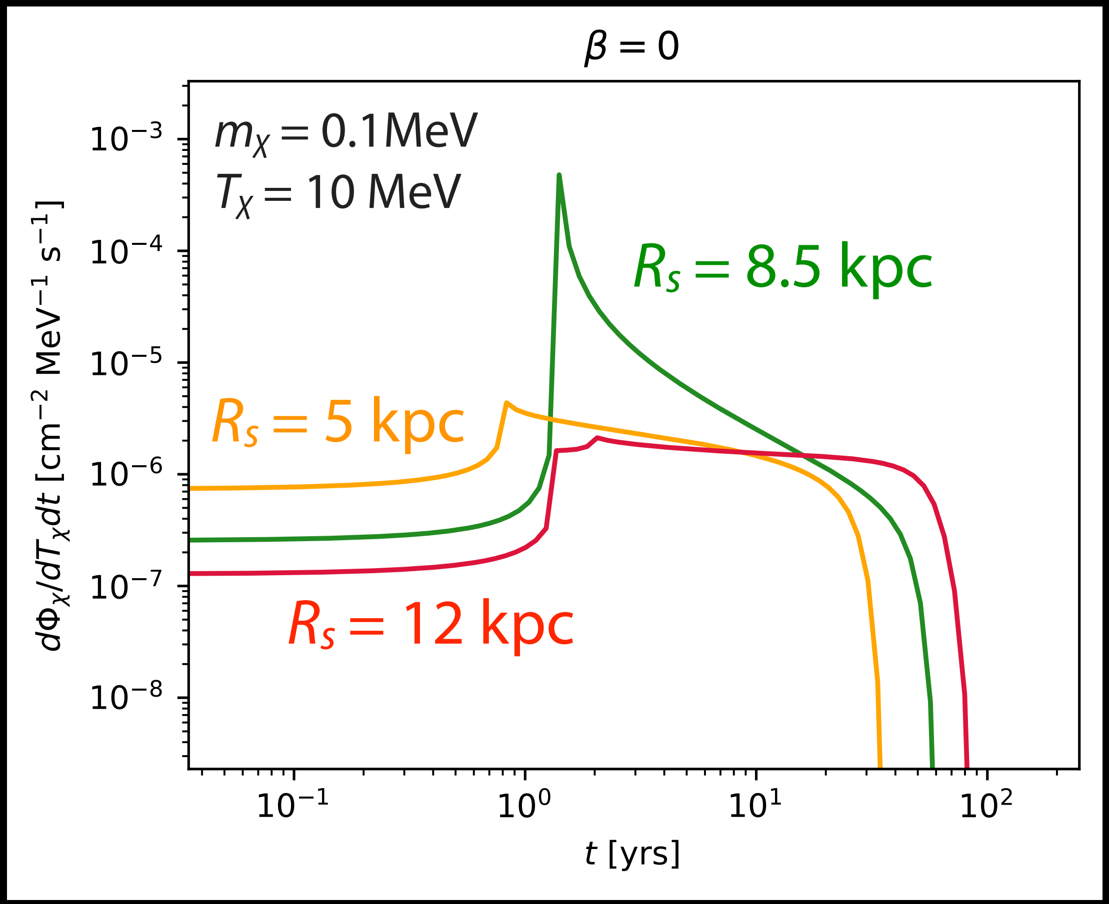


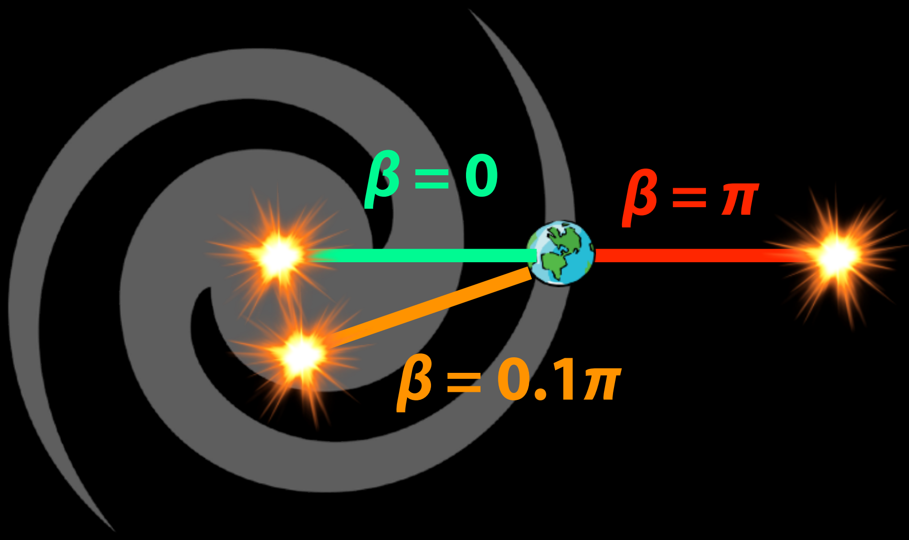
$R_s = 8.5$ kpc vs. β

$\beta = 0$ vs. R_s

BDM from various places in MW







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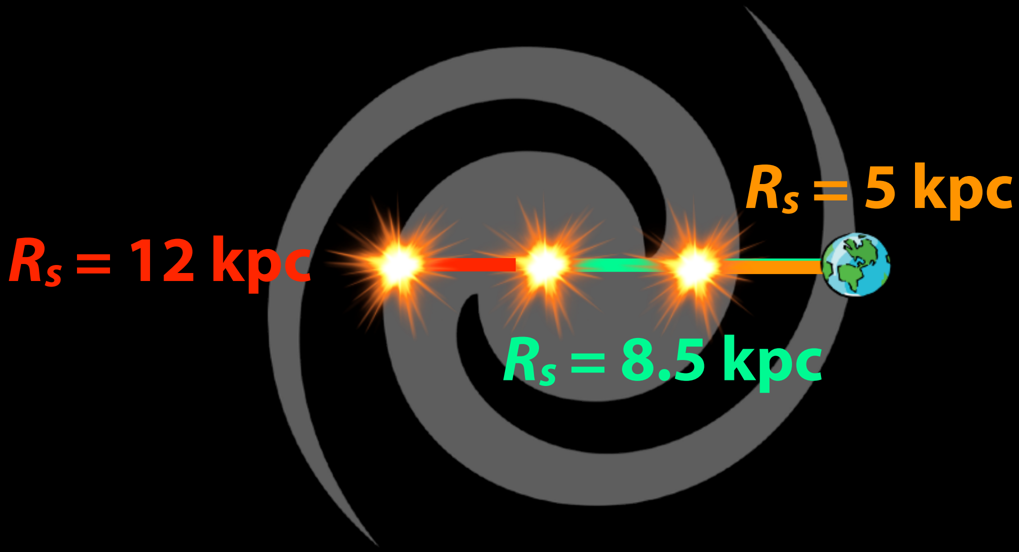


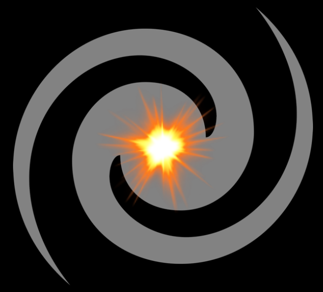
$\beta = 0$ vs. R_s

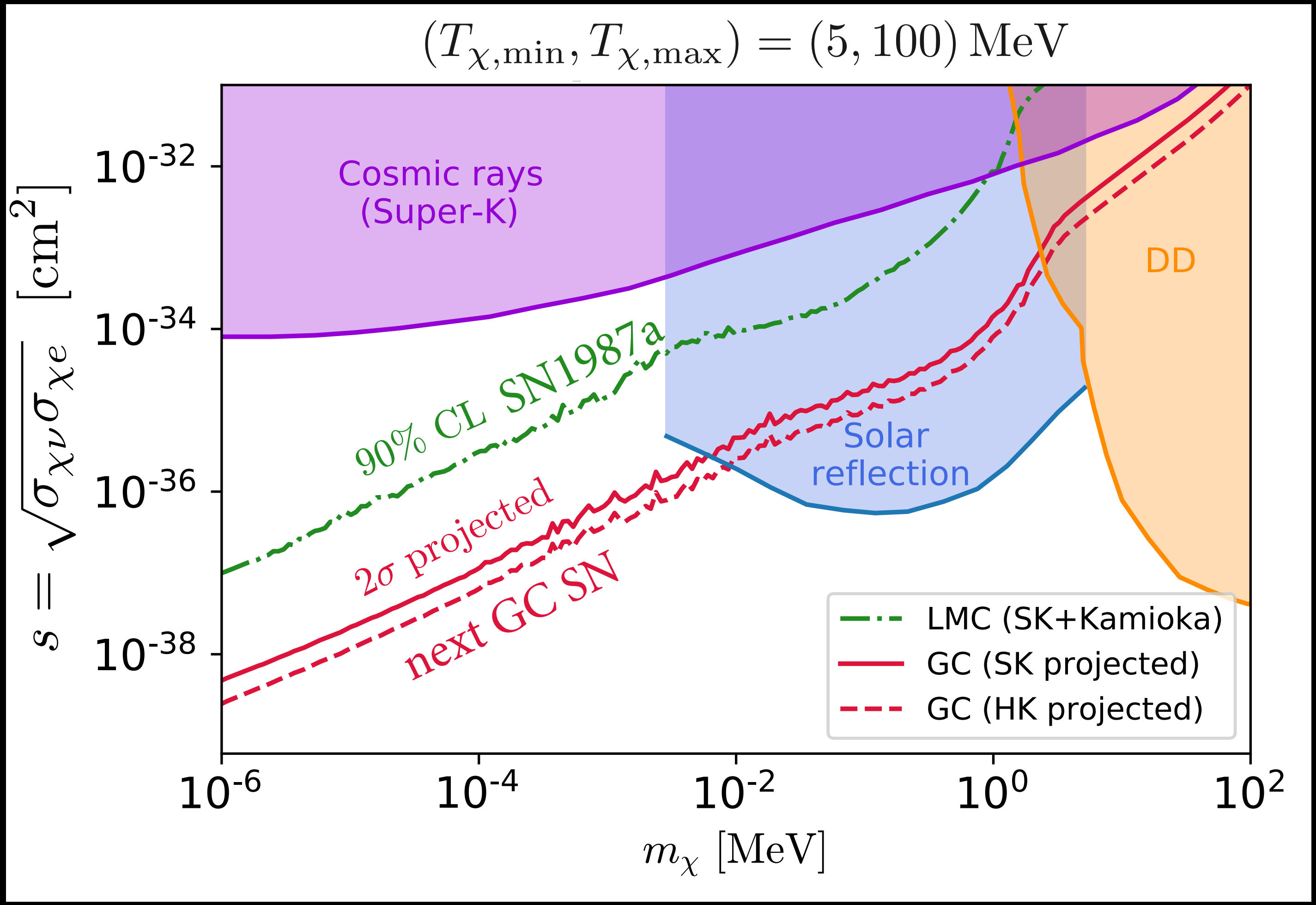
Constraint and sensitivity

Hirata+ (1987)
Battistoni+ (2005)
Abe+ (SK) (2016)
Lin+ (2023)

Constraints on $\sigma_{\chi\nu,e}$

- Consider total event and background counts within an exposure time $t_{\rm exp}$ = min($t_{\rm van}$, 35 years) with Kamiokande from 1987 - 1996 and Super-Kamiokande from 1996 on





($s = \sigma_{\chi e}$ for shaded regions from other bounds)

- Can provide complementary constraint on models that couple dark sector to SM leptons

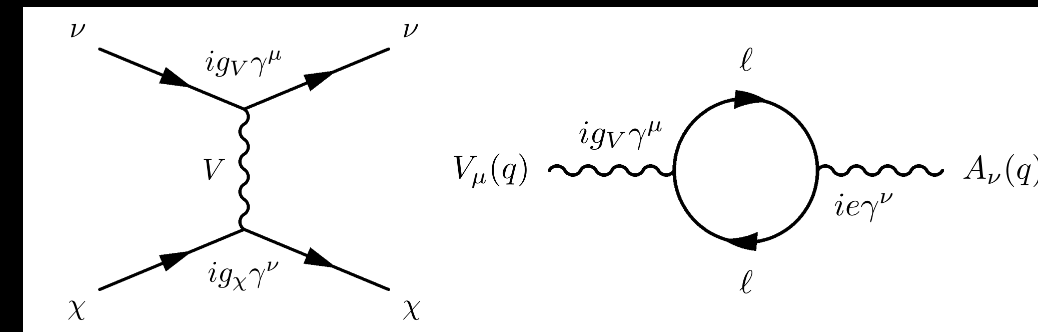
Holdom (1986)
He+ (1991)
Chang+ (2018)
Lin+ (2023)
…

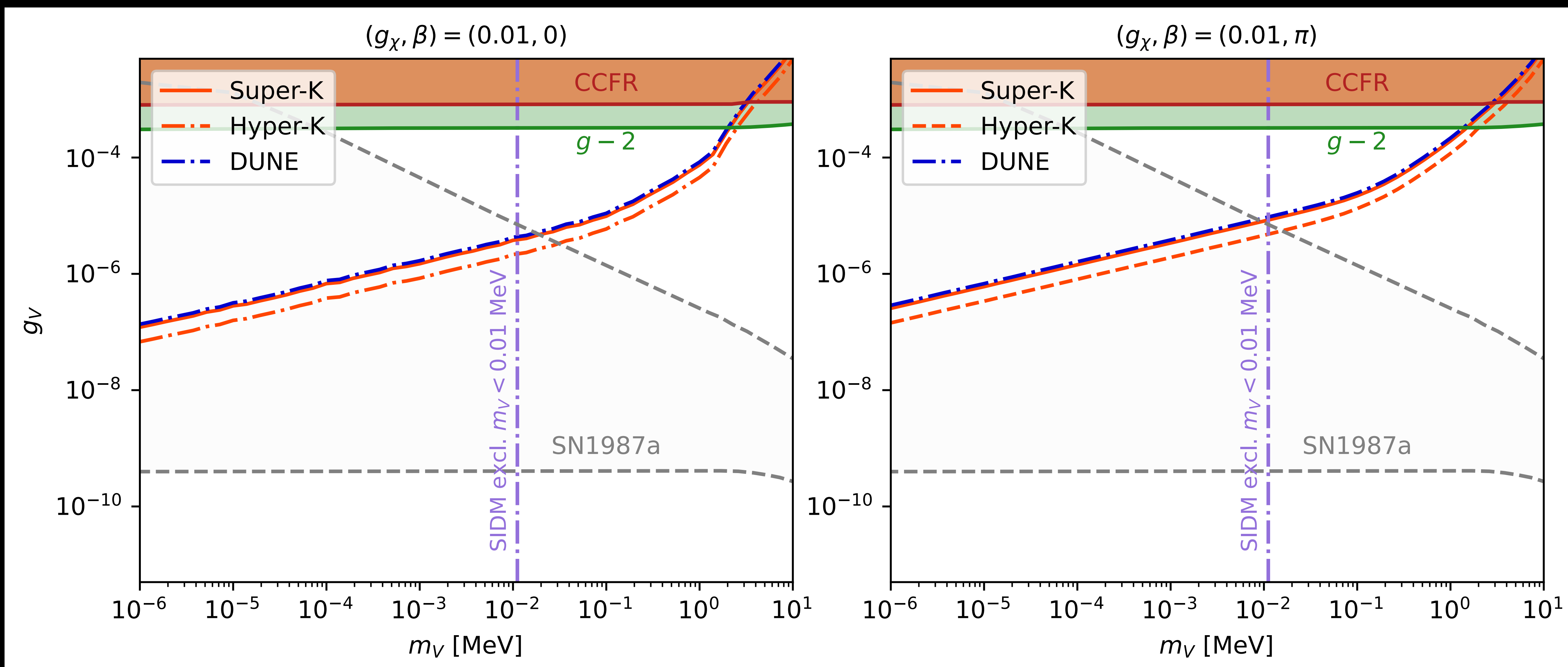
Sensitivity on couplings of $L_\mu - L_\tau$

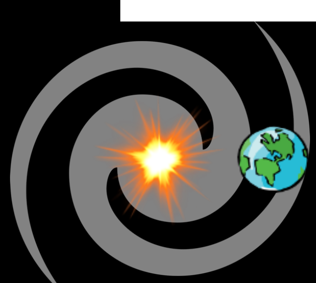
Assuming $\varepsilon = 0$

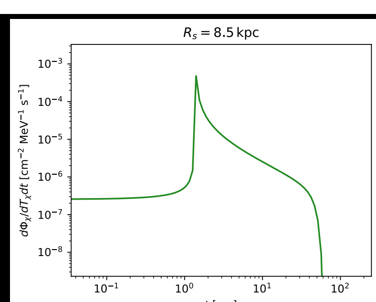
$$\mathcal{L}_{\chi,\mathrm{int}} \supset \frac{\varepsilon}{2} F_{\mu\nu} V^{\mu\nu} + g_\chi V_\mu \bar{\chi}\gamma^\mu \chi$$

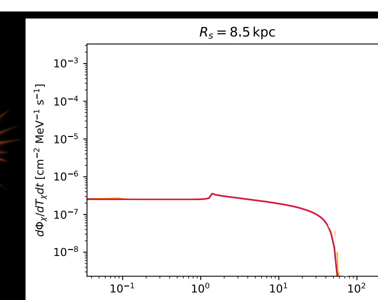
$$+ g_V V_\mu \left(\bar{\ell}\gamma^\mu \ell + \bar{\nu}\gamma^\mu P_L \nu\right)$$











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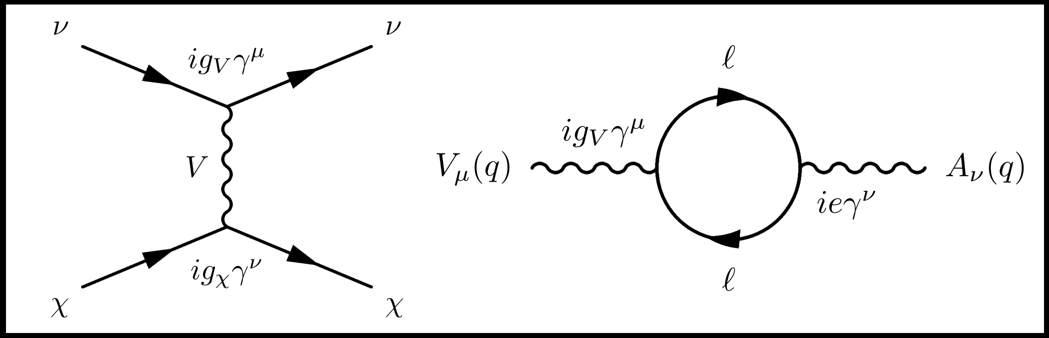
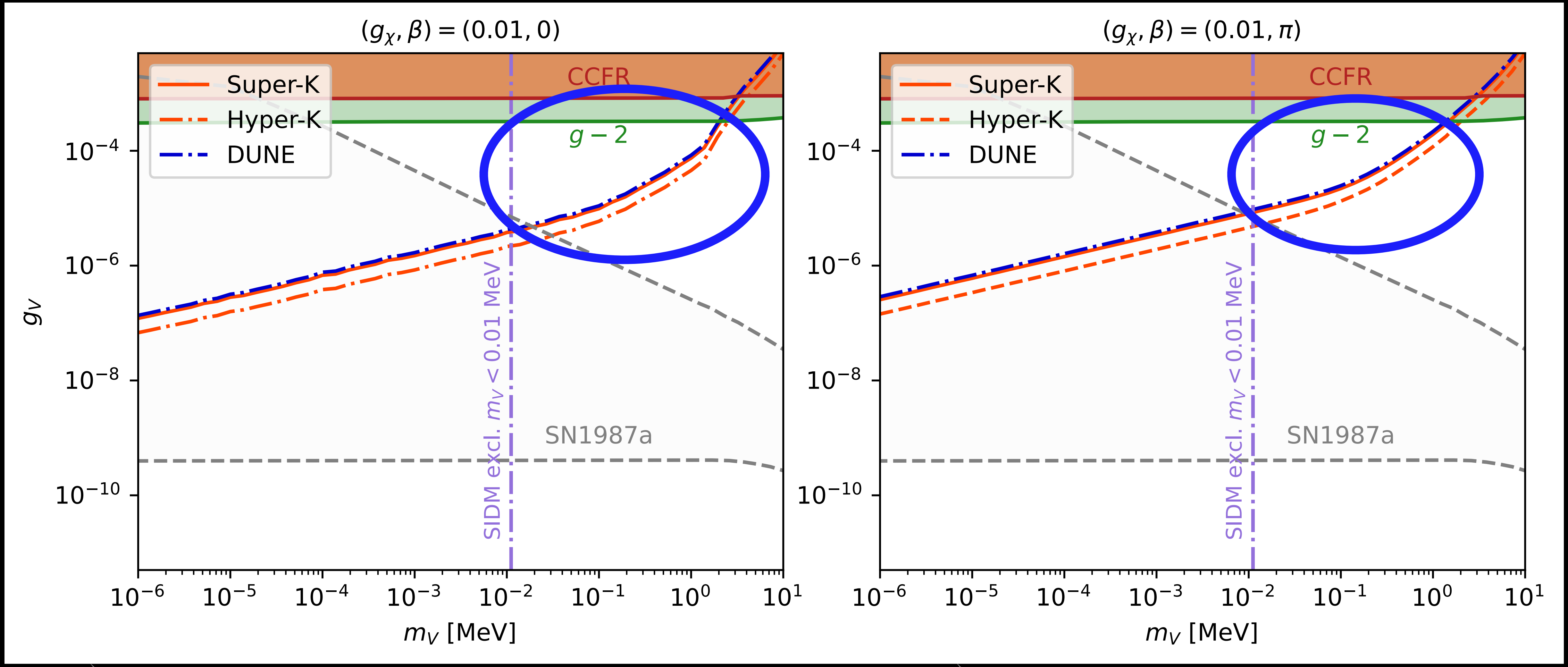
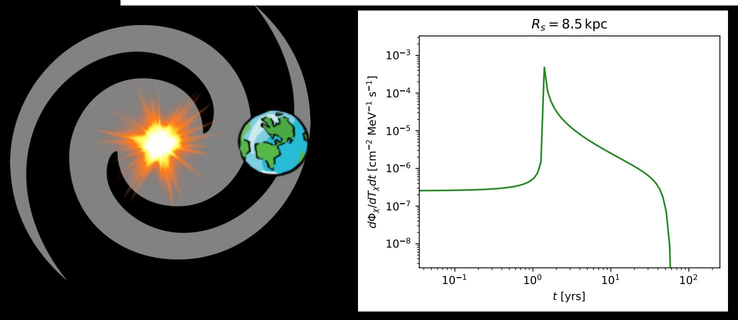
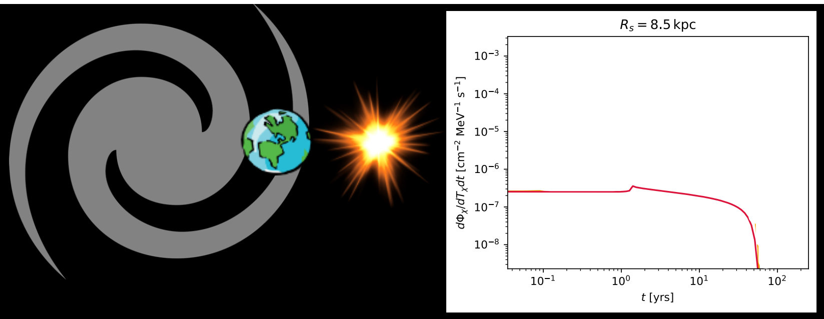








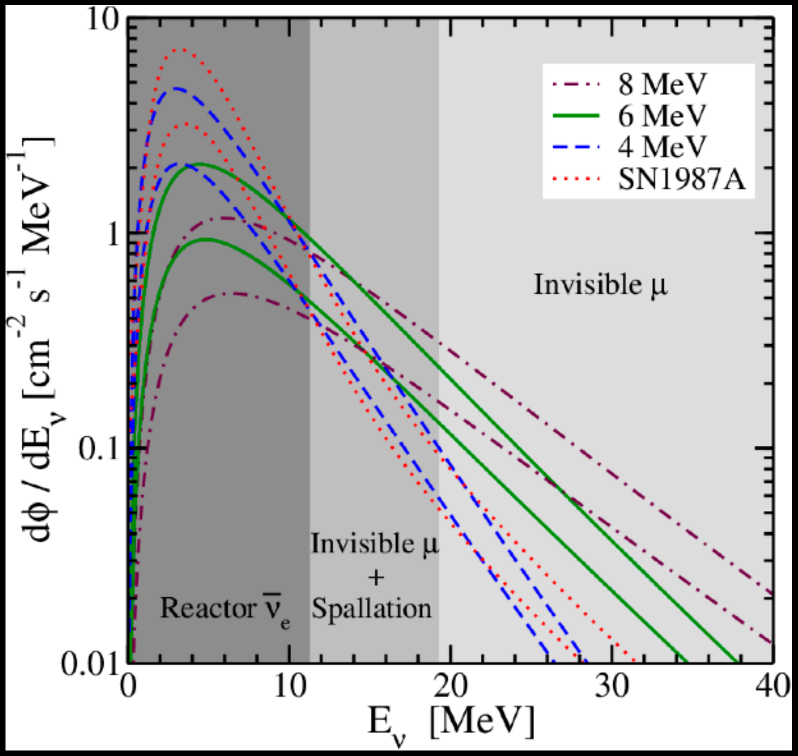
SNν BDM from early Universe

Diffuse SNν BDM from early Universe

- Mimic diffuse supernova neutrino background (DSNB)

$$\frac{d\Phi_{\rm DSNB}}{dE_{\bar{\nu}_e}} = \frac{c}{H_0}\int_0^{z_{\rm max}} dz \frac{R_{\rm CCSN}(z)}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}} \left.\frac{dN_{\bar{\nu}_e}}{dE'_{\bar{\nu}_e}}\right|_{E'_{\bar{\nu}_e}=(1+z)E_{\bar{\nu}_e}}$$

Beacom (2006)



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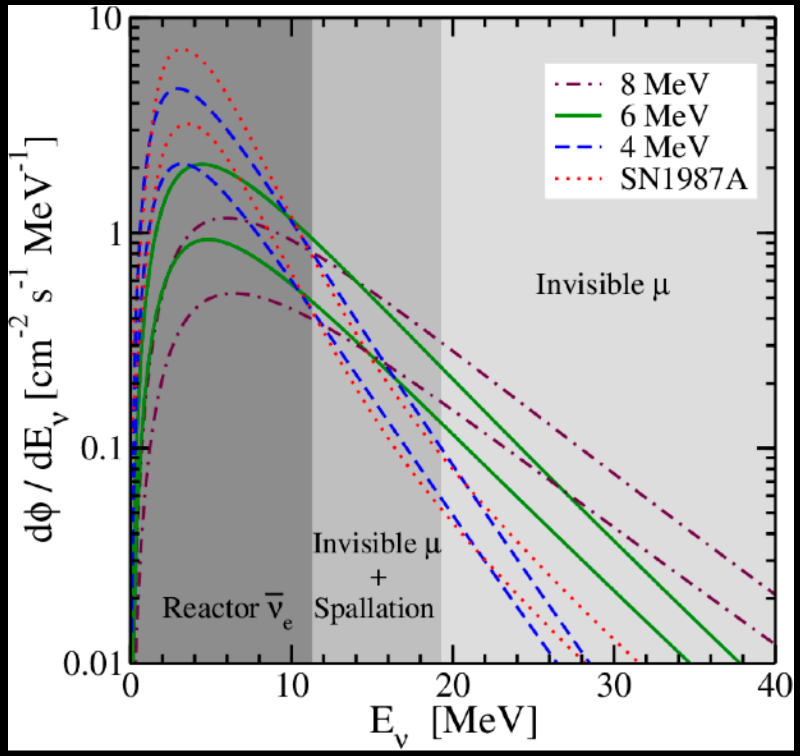
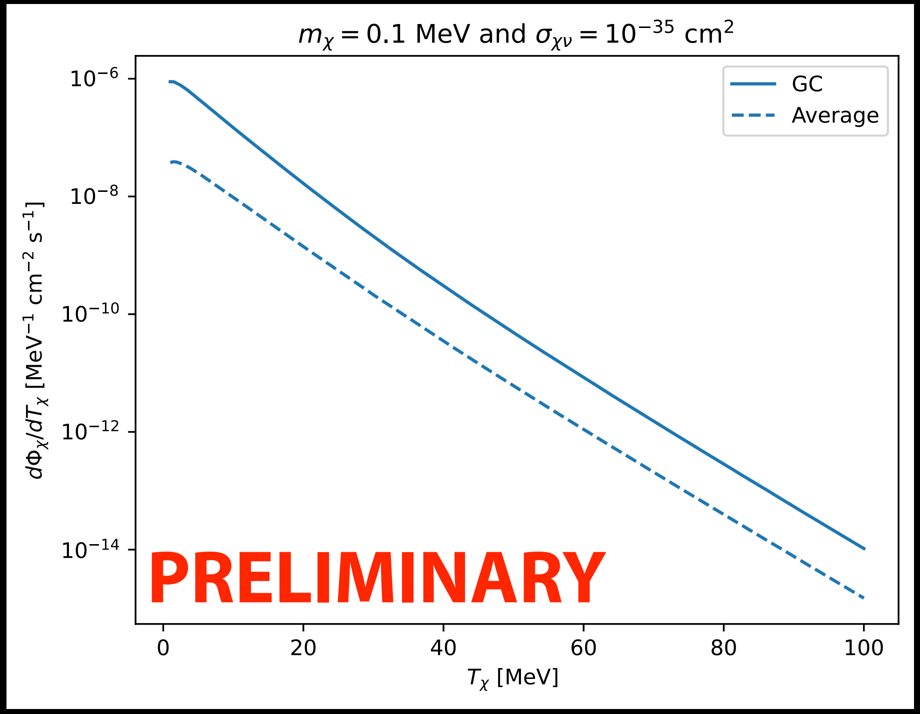


- Diffuse SNν BDM from early Universe

$$\frac{d\Phi_\chi}{dT_\chi} = \frac{c}{H_0}\int_0^{z_{\rm max}} dz \frac{v_\chi(z)}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}} R_{{\rm SN},G}(z) \left.\frac{dN_\chi}{dT'_\chi}\right|_{T'_\chi=(1+z)T_\chi}$$



Lin & Wu, *in prepration*

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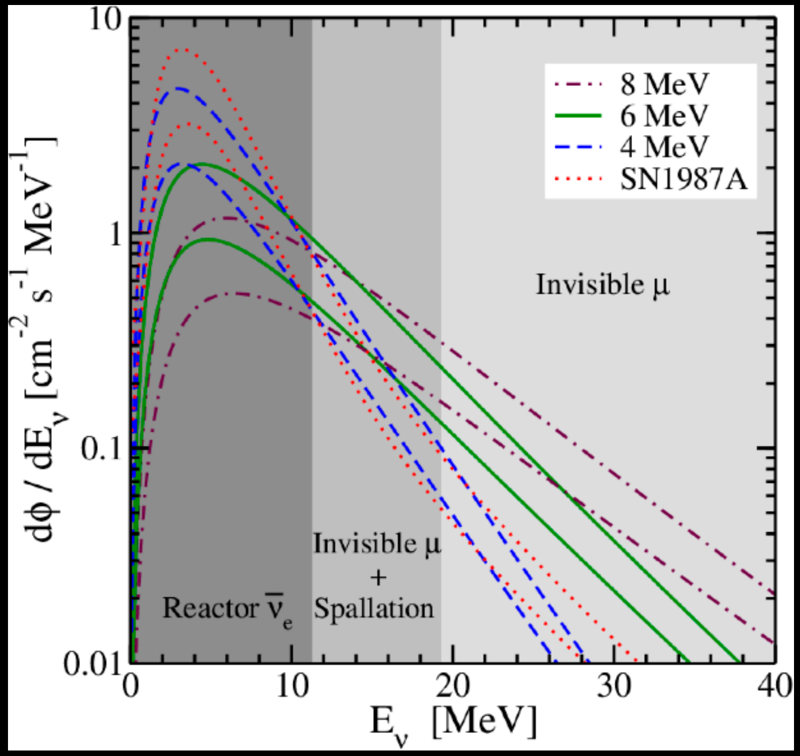

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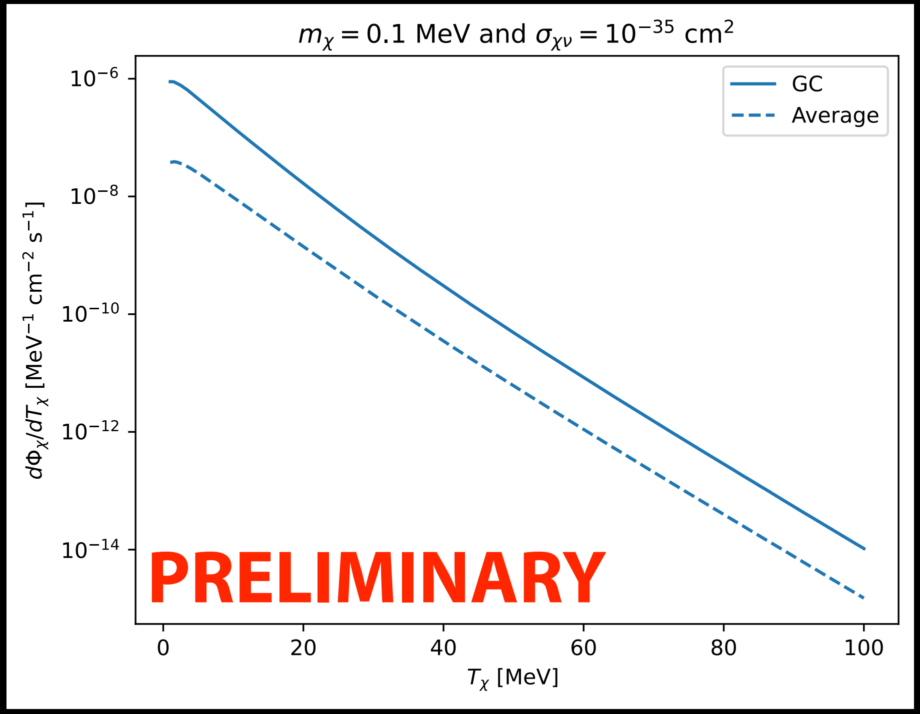
SN@GC

The most probable SN position



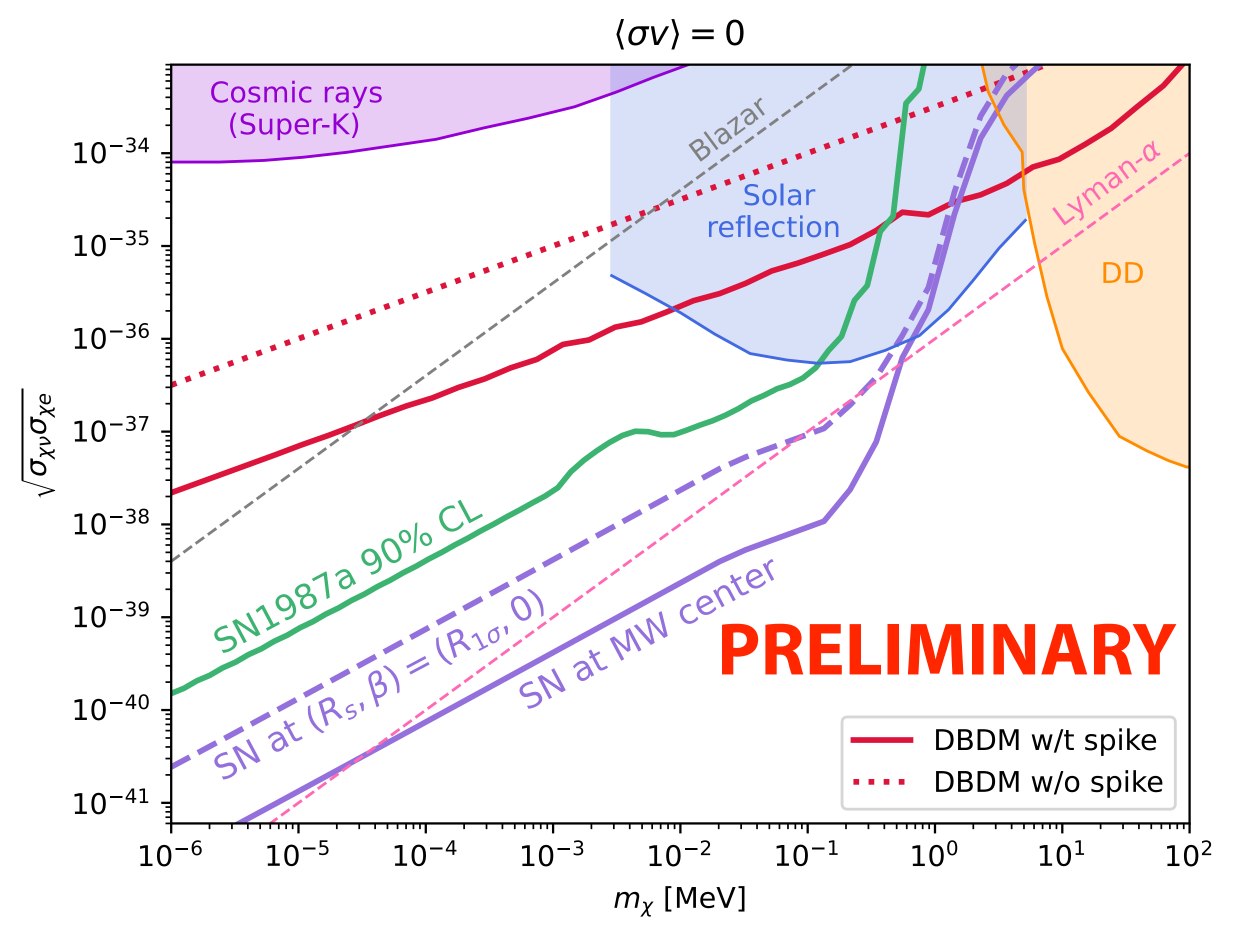
Lin & Wu, *in prepration*

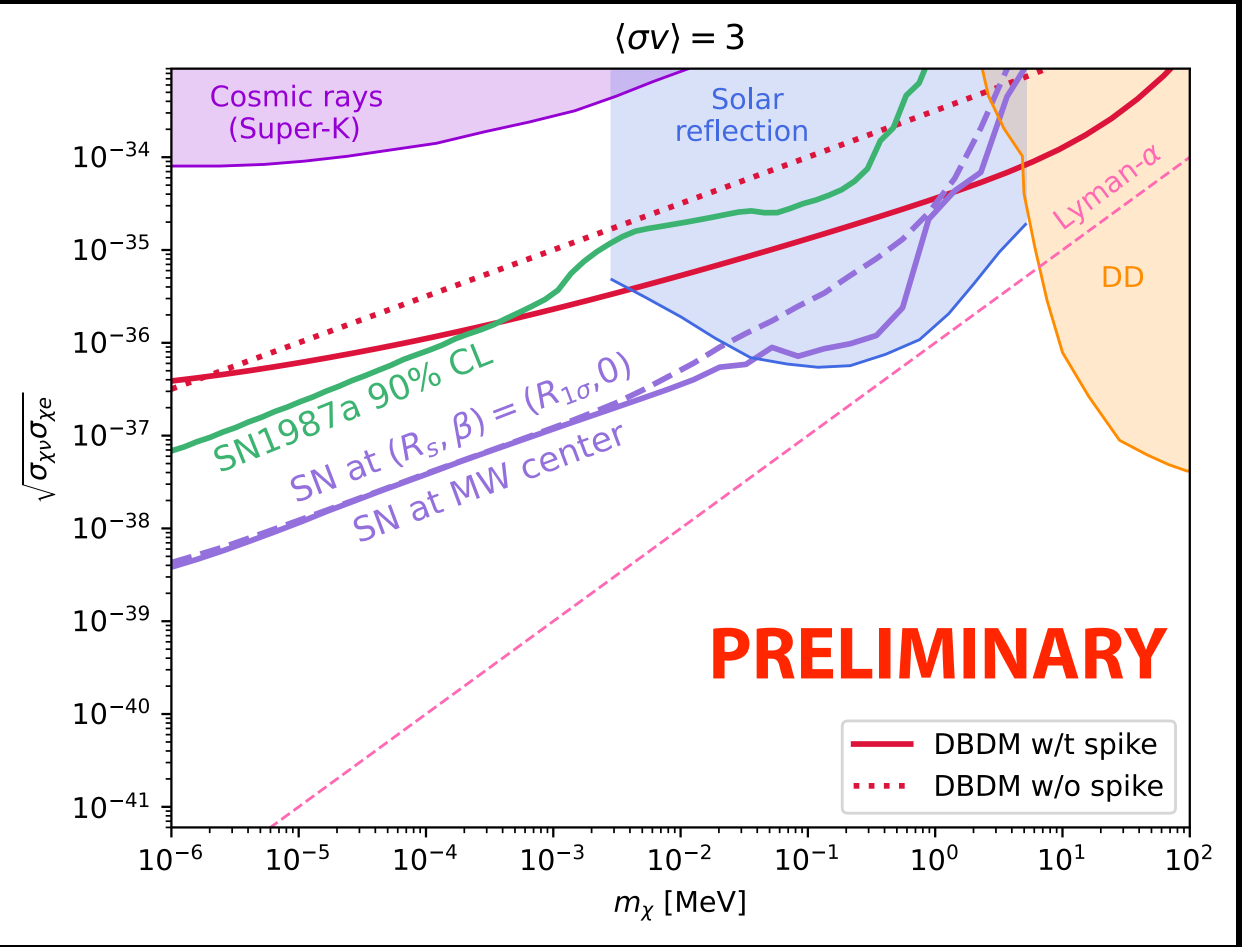
Diffuse SNν BDM projected sensitivity

- Assuming 2σ detection significance in 5 years

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

and $\sigma_{\chi\nu} = \sigma_{\chi e}$





Lin & Wu, *in prepration*

Summary

Summary

- The SNν BDM shows complementary constraints on $\sigma_{\chi\nu,e}$ and model parameters for light DM
- Time-dependent BDM flux facilitates:
  - Direct m_χ measurement
  - Background reduction (via controlling the detector exposure time)
  - and they are independent of $\sigma_{\chi\nu}$
- Framework is applied to both SNe located in and off-GC
- Diffuse SNν BDM from early Universe