Interplay of Nuclear, Neutrino and BSM Physics at Low-Energies
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Searching for Afterglow: Light Dark Matter Boosted by SNν

國立臺灣大學
National Taiwan University

NCTS

NSTC 國家科學及技術委員會
National Science and Technology Council

Outline

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- Introduction

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- **The concept for supernova neutrino BDM**
  - Kinematics, BDM emissivity and flux
  - Time-of-flight for direct m_χ measurement
  - Case studies for SN in and off the GC

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- **Constraint and projected sensitivity**
  - From SN1987a and next galactic SN
  - On DM-ν and DM-e cross sections

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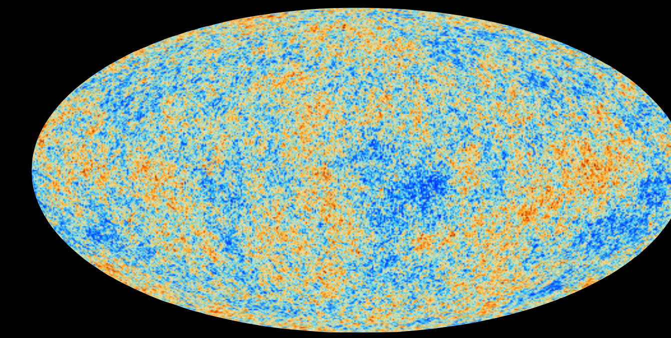
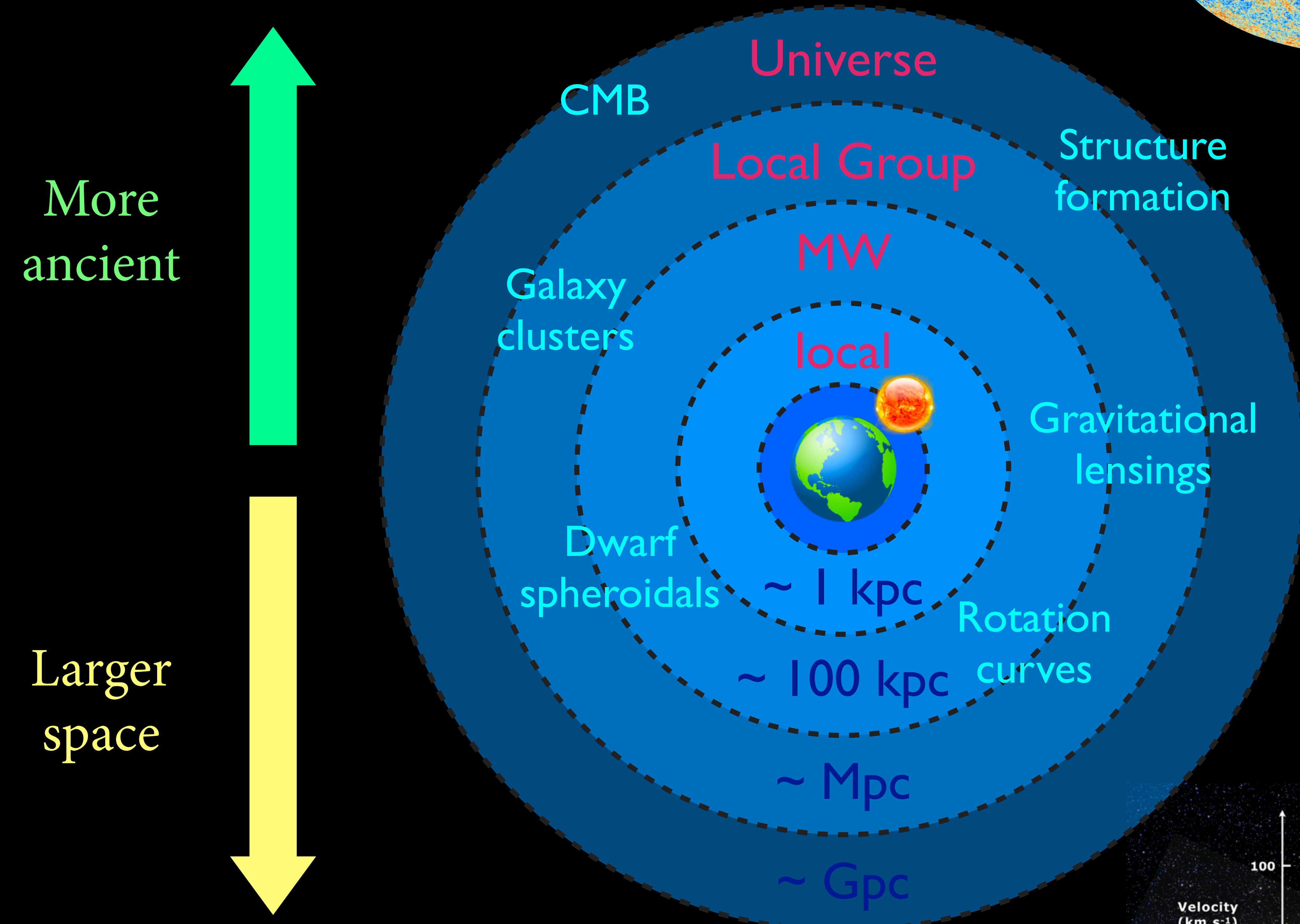
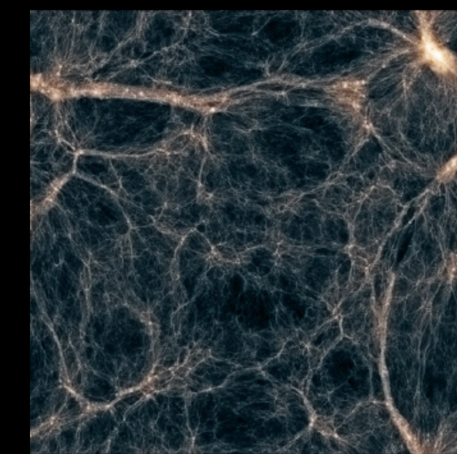
  - On DM-ν and DM-e cross sections
- **Summary**

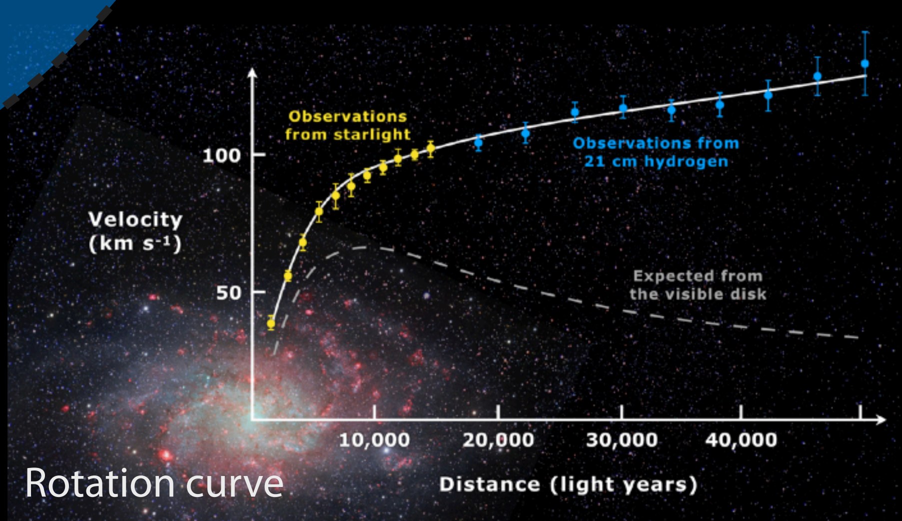
Introduction

Dark matter is *ubiquitous* in the Universe!









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

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

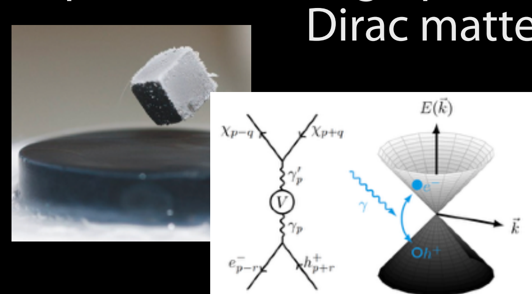
The DM probes: m_χ & σ

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

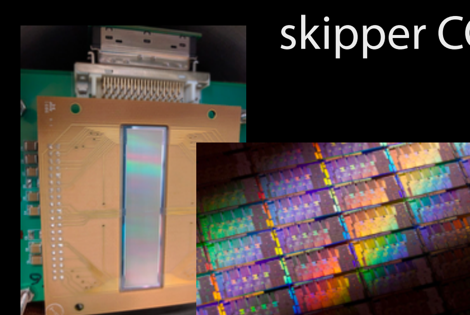
m_χ — eV — low temperature quantum effects — MeV — electron recoils — GeV — nucleus recoils — > TeV

Dark matter direct search

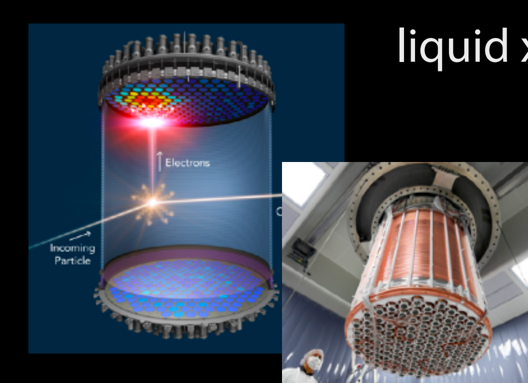
superconductor/graphene
Dirac matter…



semiconductor
skipper CCD



liquid xenon



not-to-scale

The DM probes: m_χ & σ

m_χ eV MeV GeV > TeV

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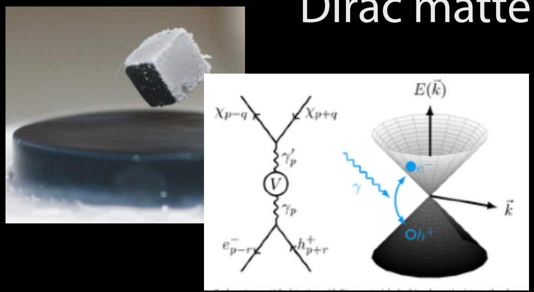

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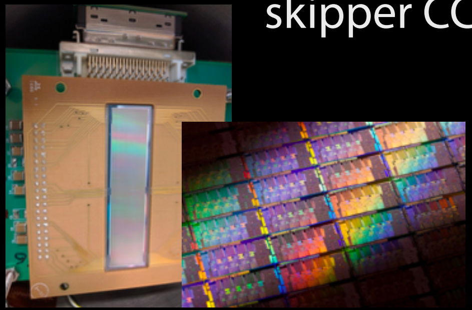

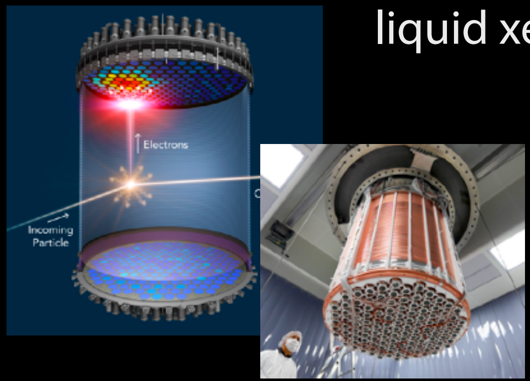

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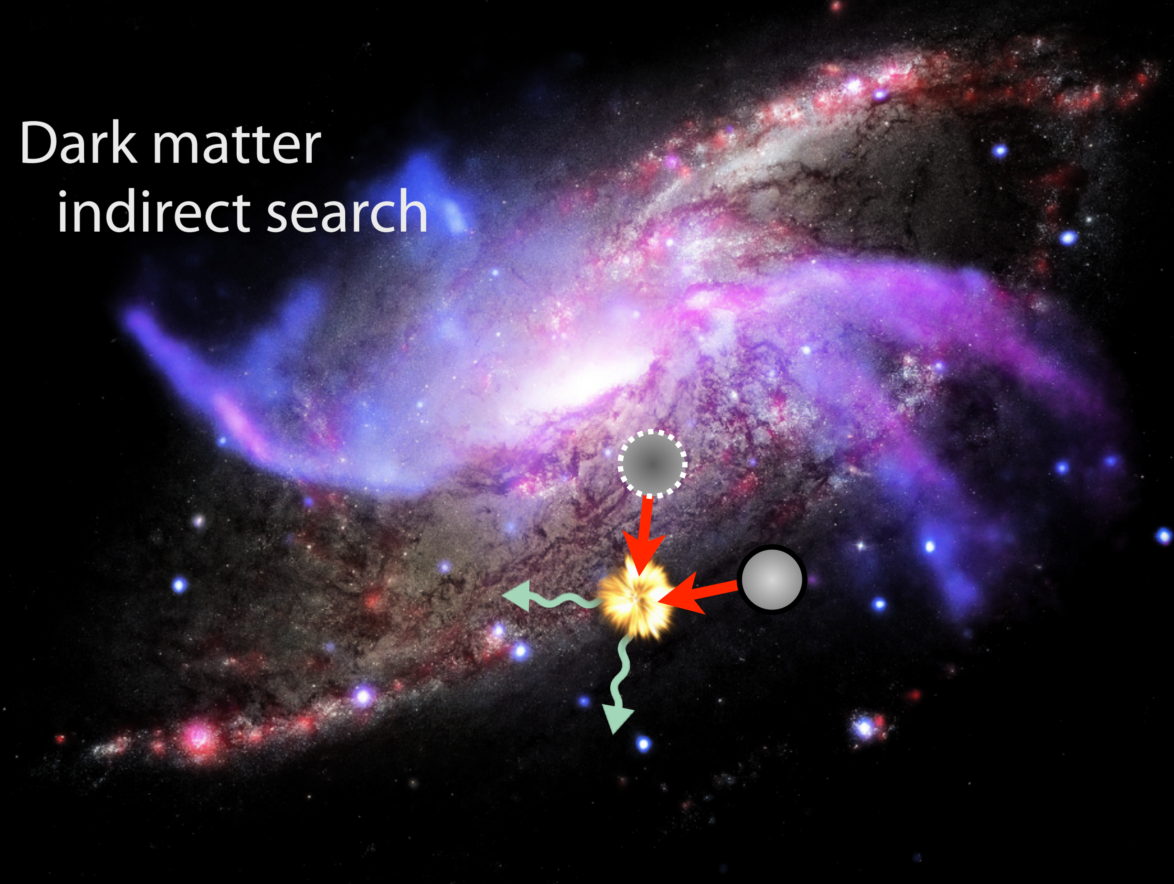
The DM probes: m_χ & σ

Dark matter
indirect search



m_χ eV MeV GeV > TeV

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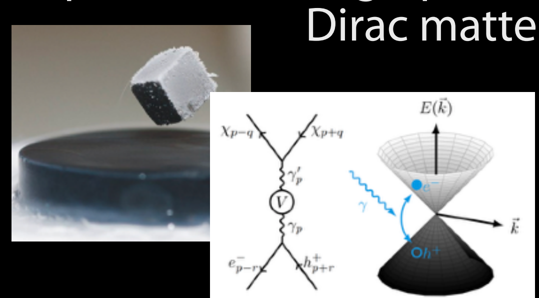

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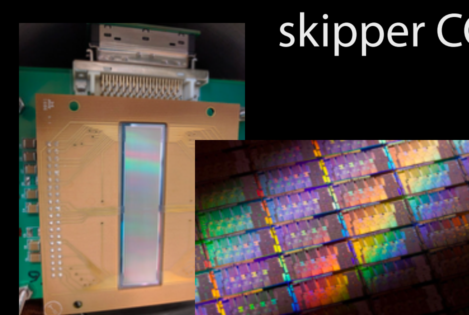

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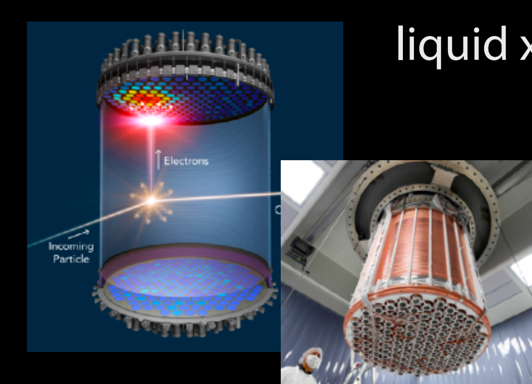

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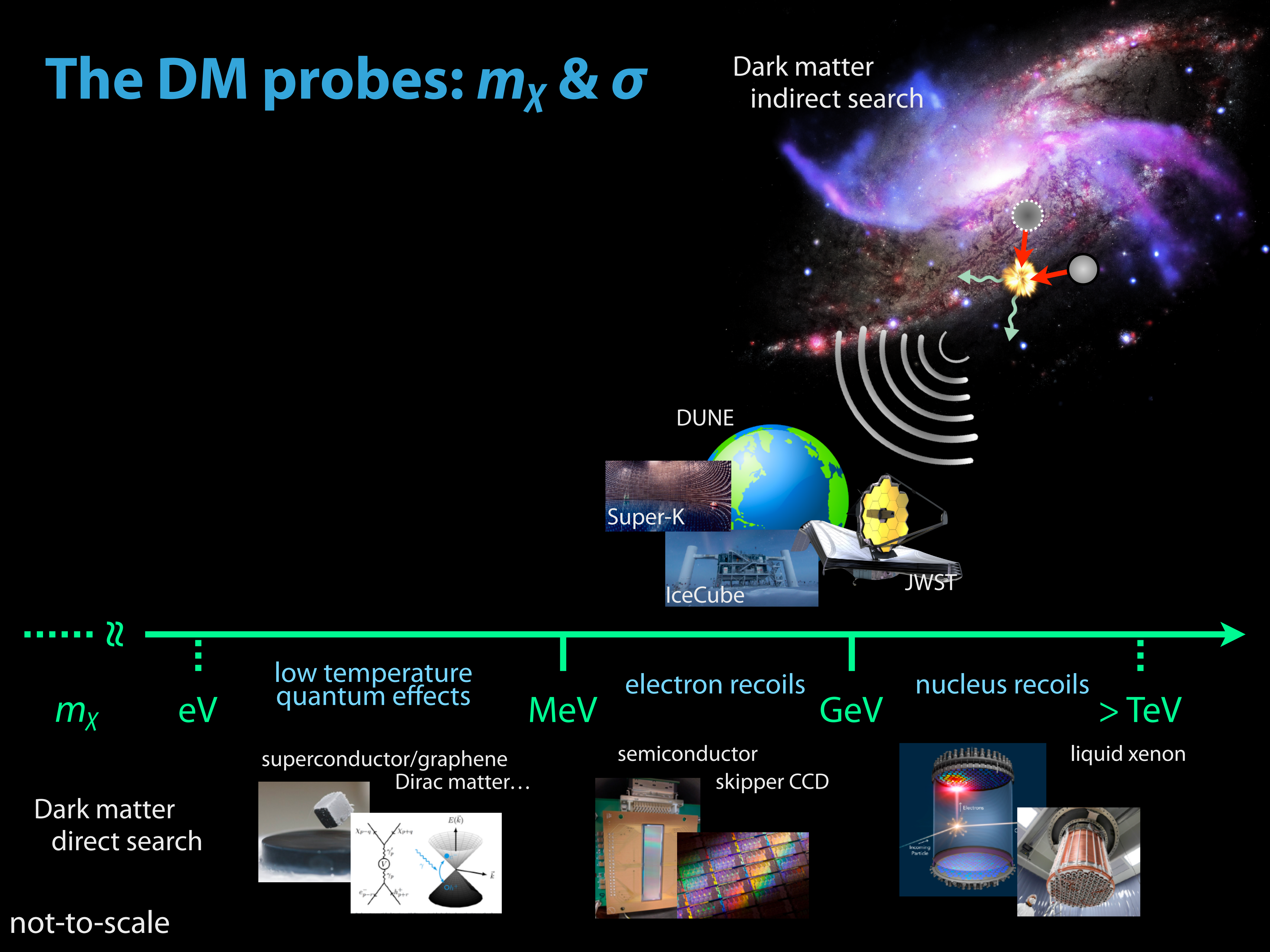
The DM probes: m_χ & σ
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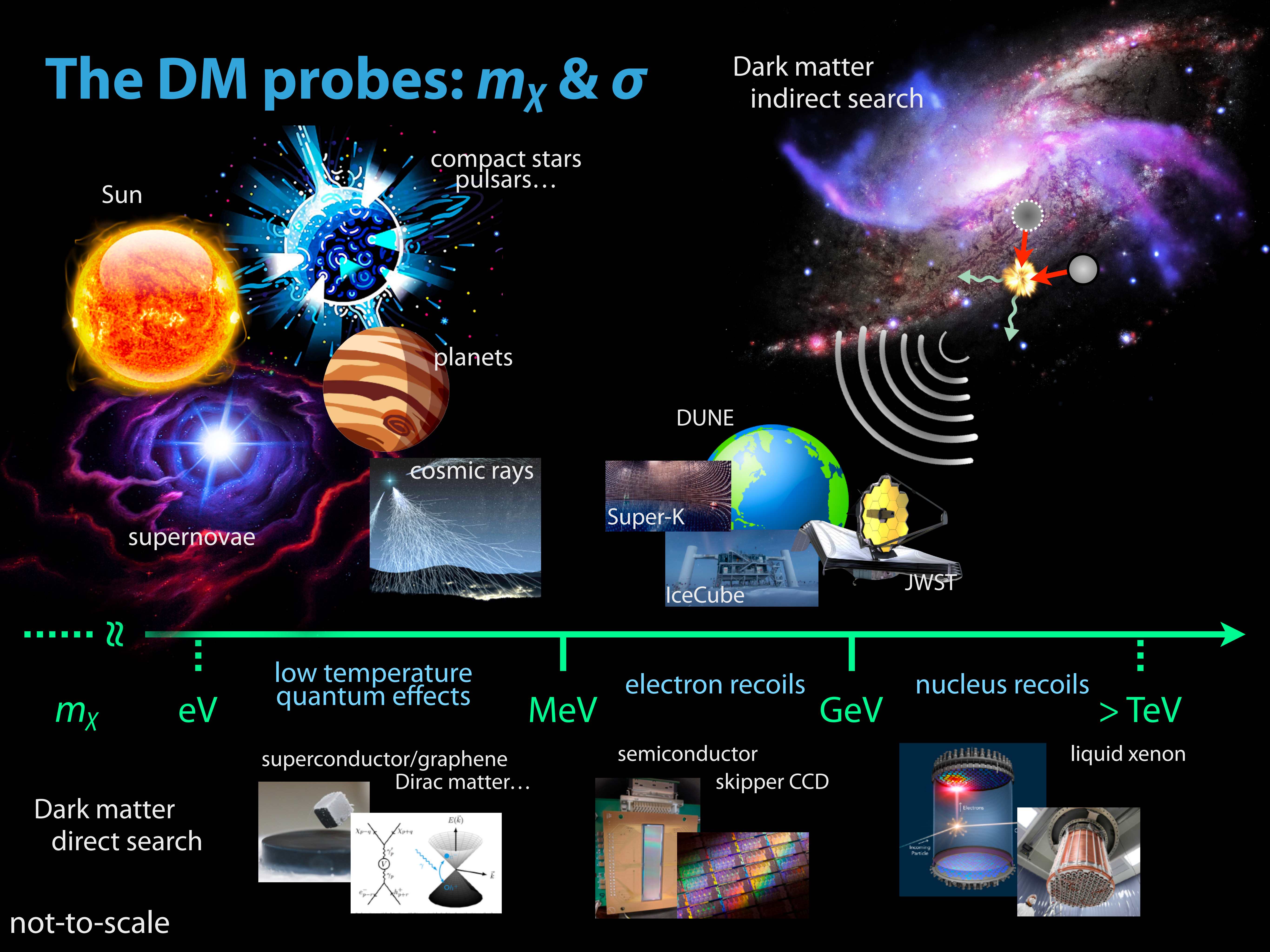
The DM probes: m_χ & σ
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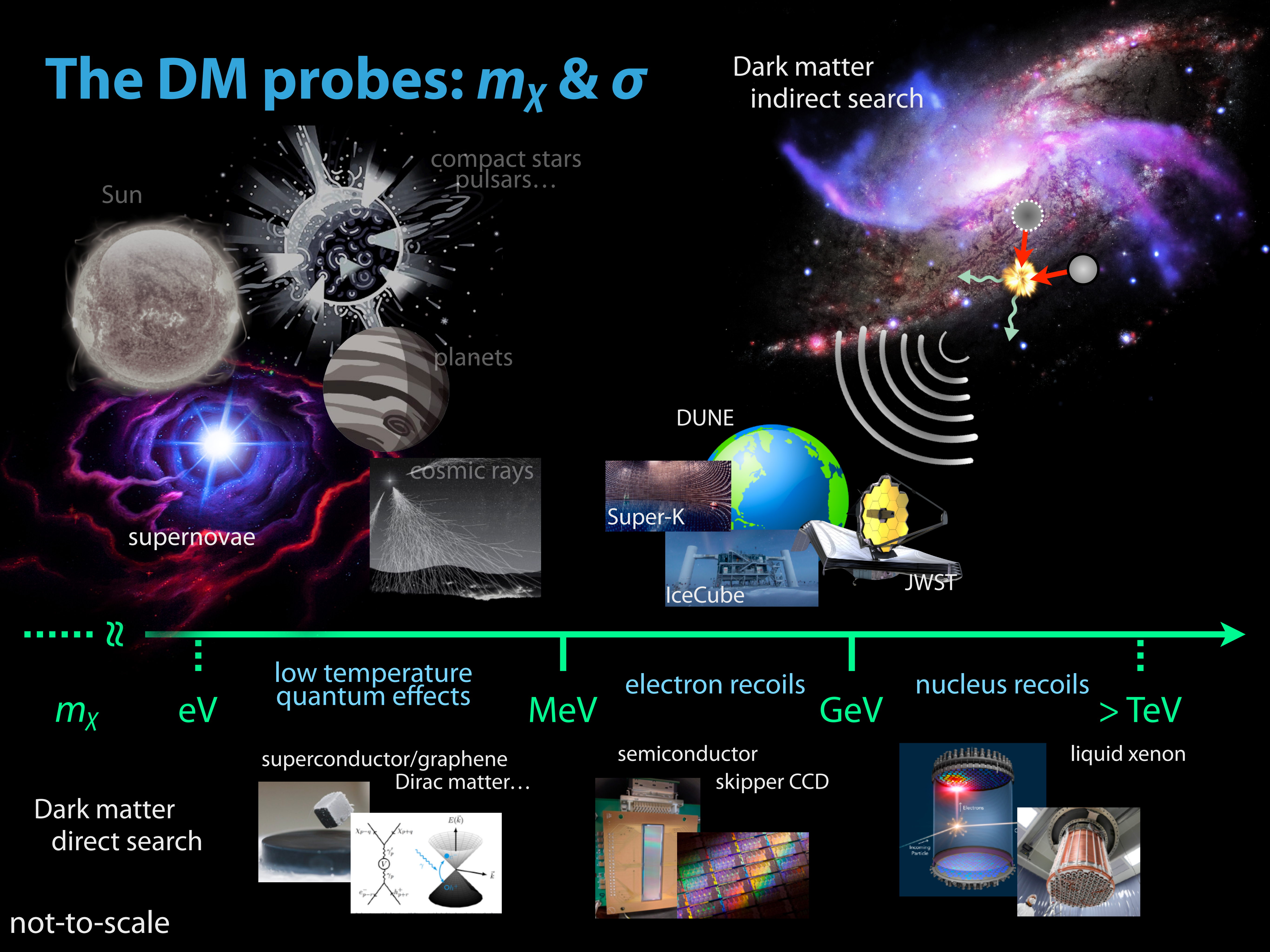
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The SNνBDM framework

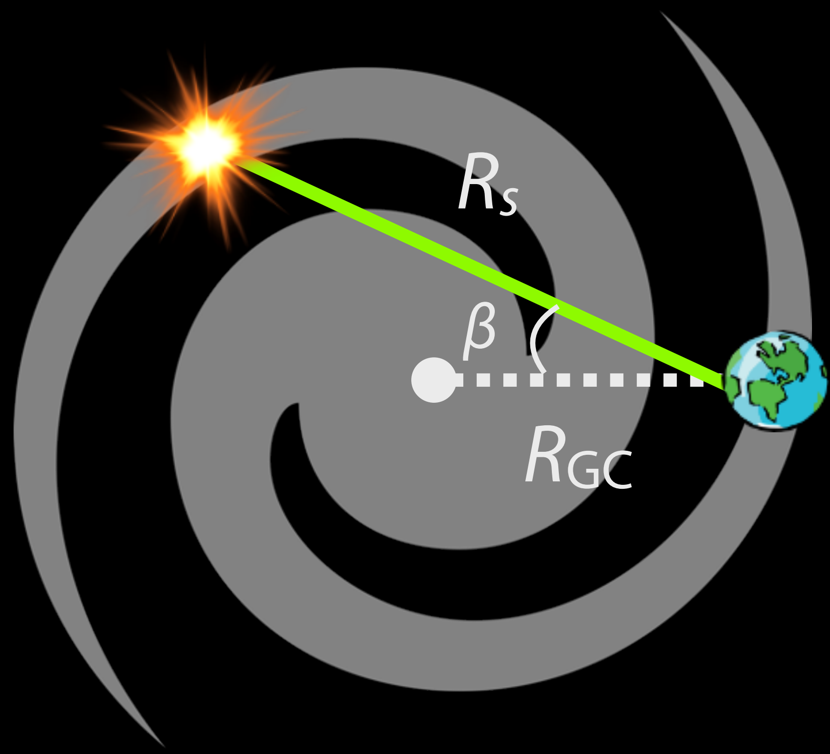
Galactic supernova

top-view

Galactic supernova

SN could be anywhere in MW

top-view



Galactic supernova

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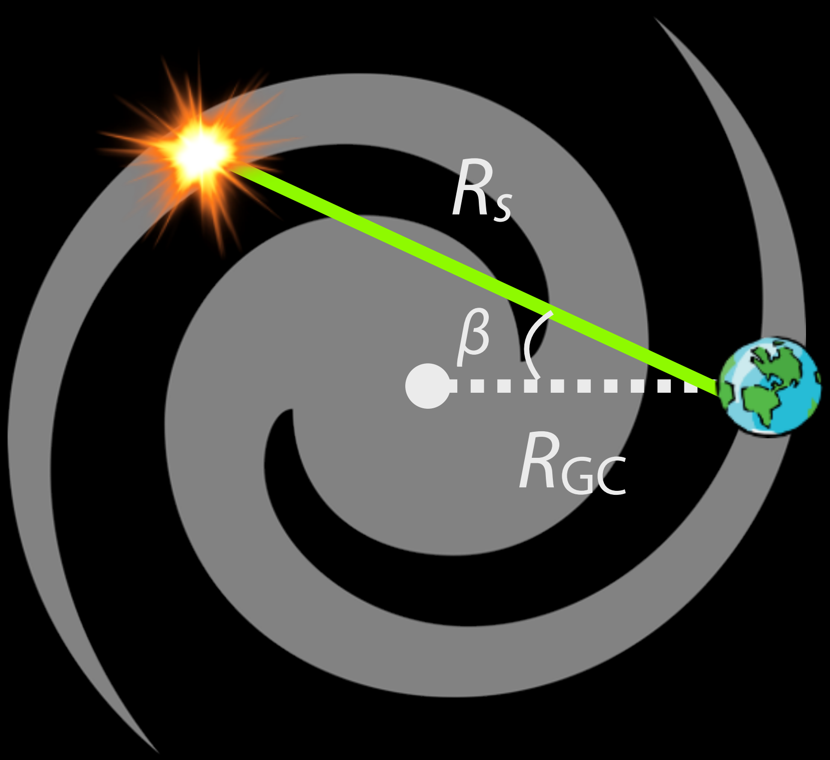
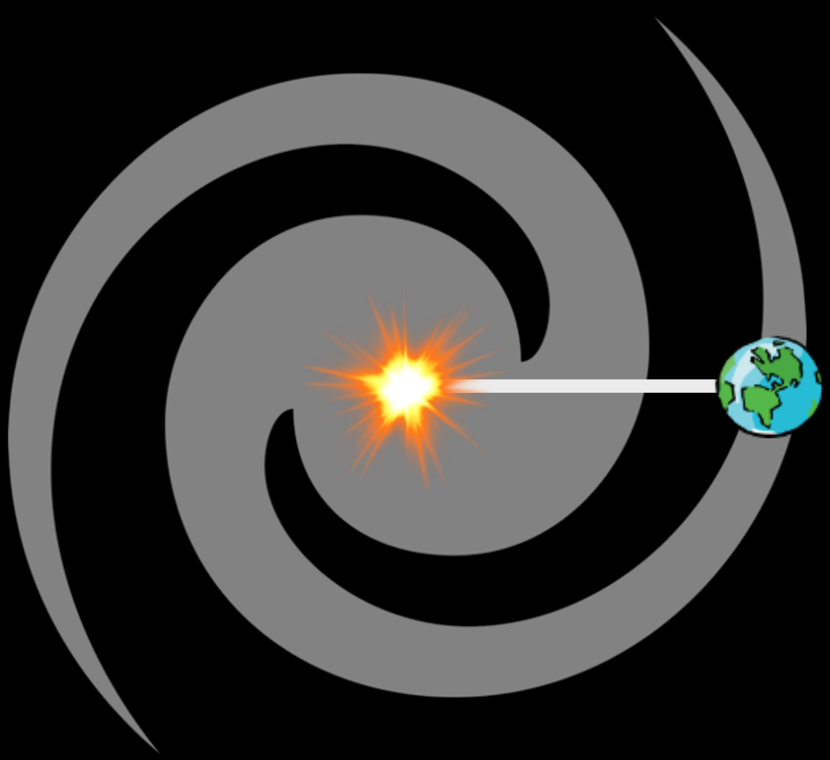
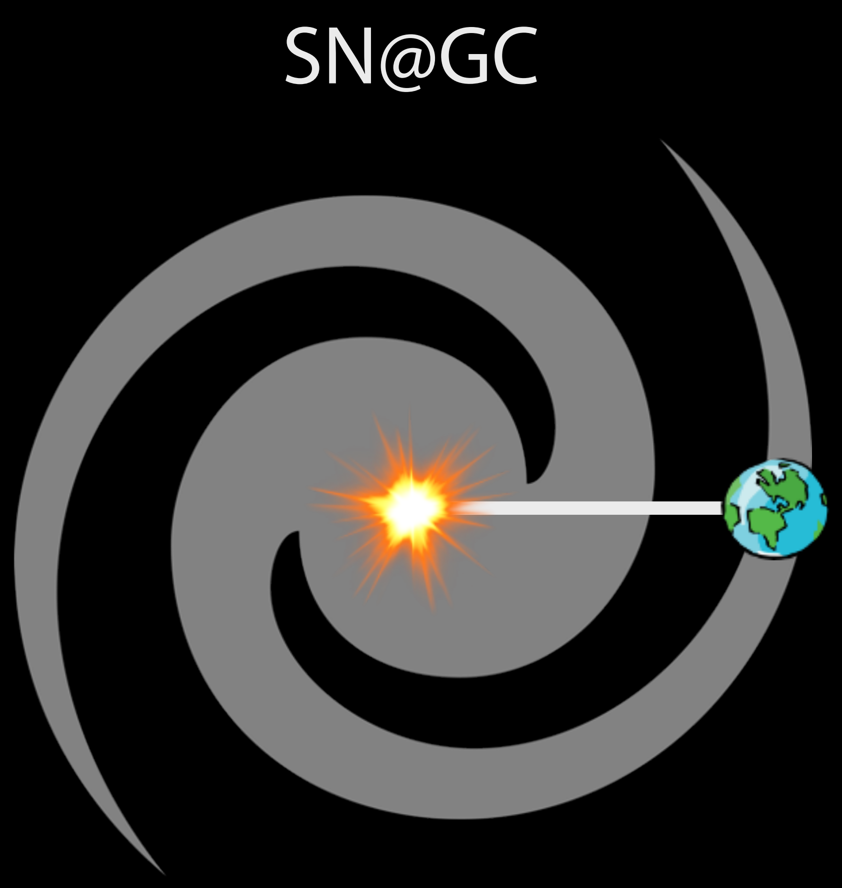
top-view



SN@GC



Galactic supernova



The *kinematics*

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

The *kinematics*

- Halo DM was scattered ($\sigma_{\chi\nu}$) by SNν and gets boosted (BDM)

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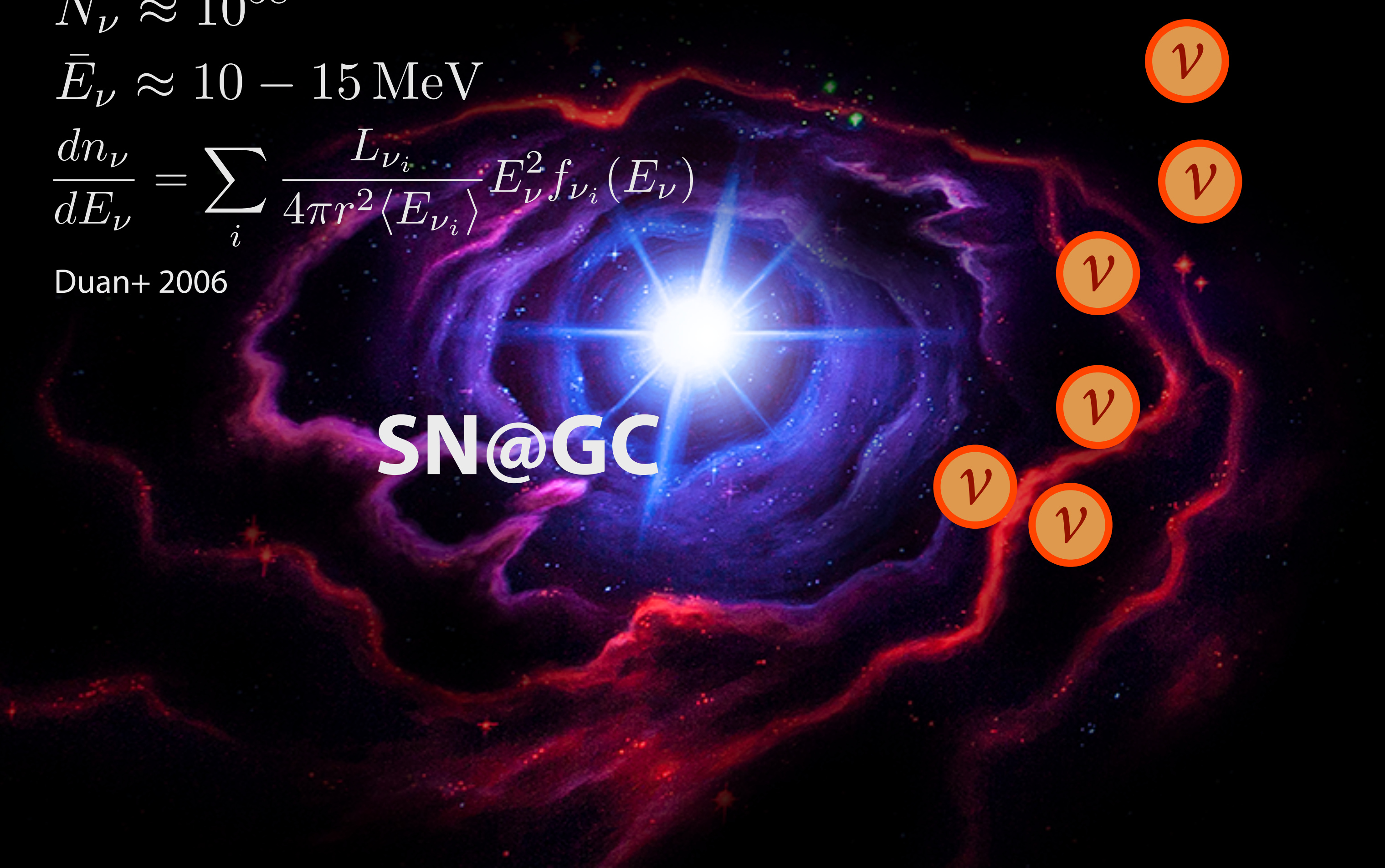

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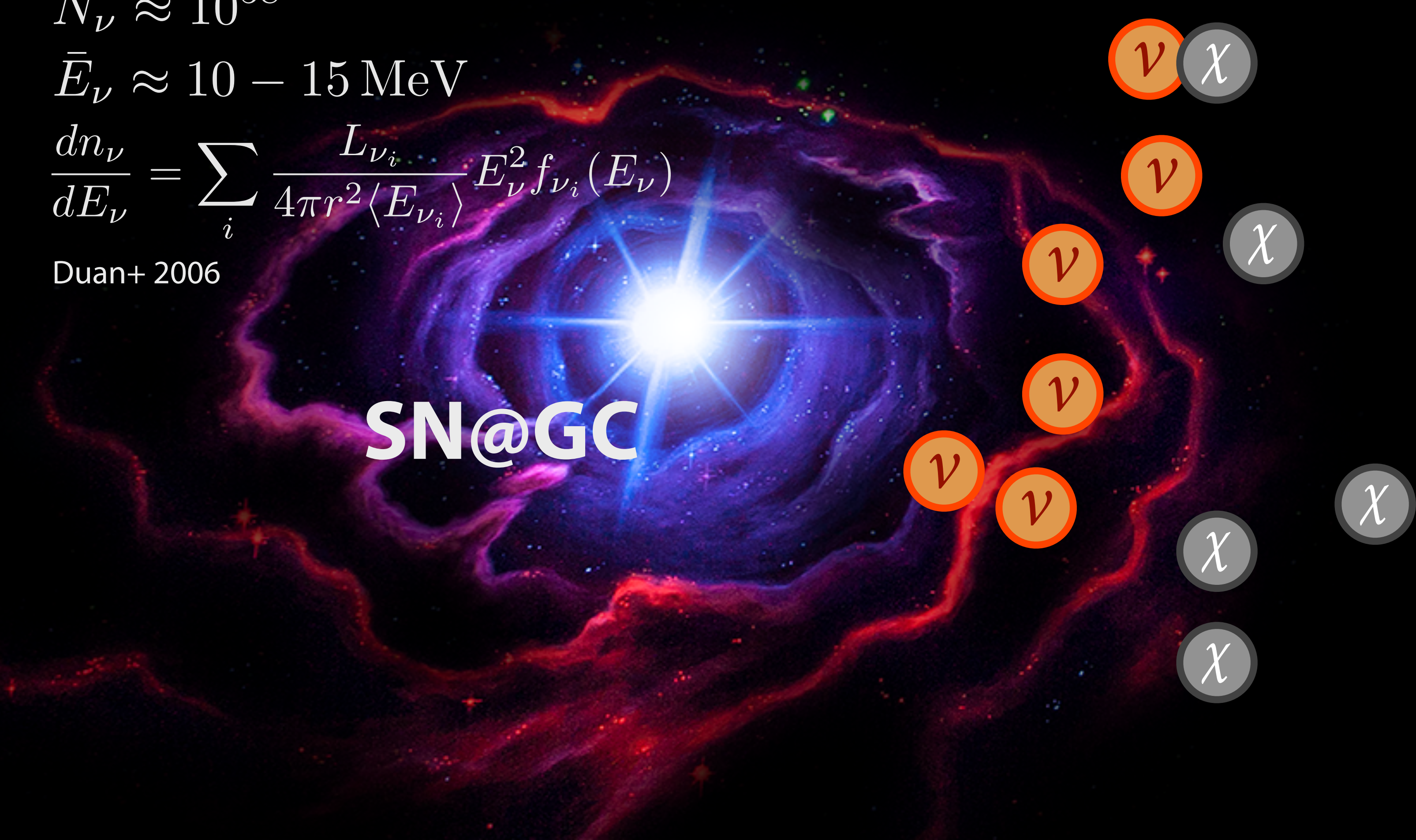

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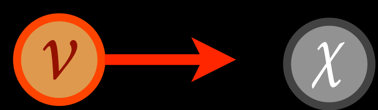
$$p_\chi = (m_\chi, \mathbf{0})$$



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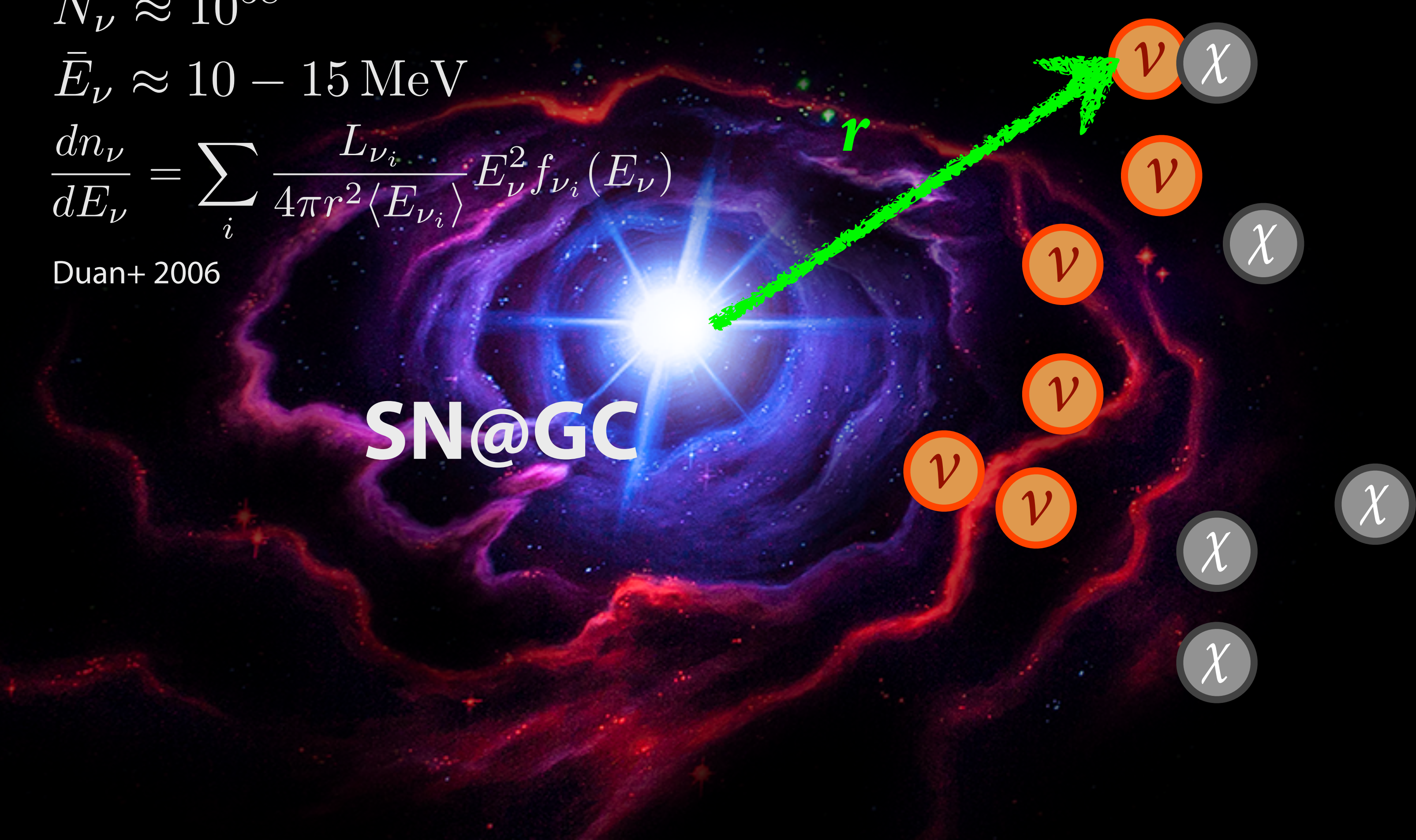

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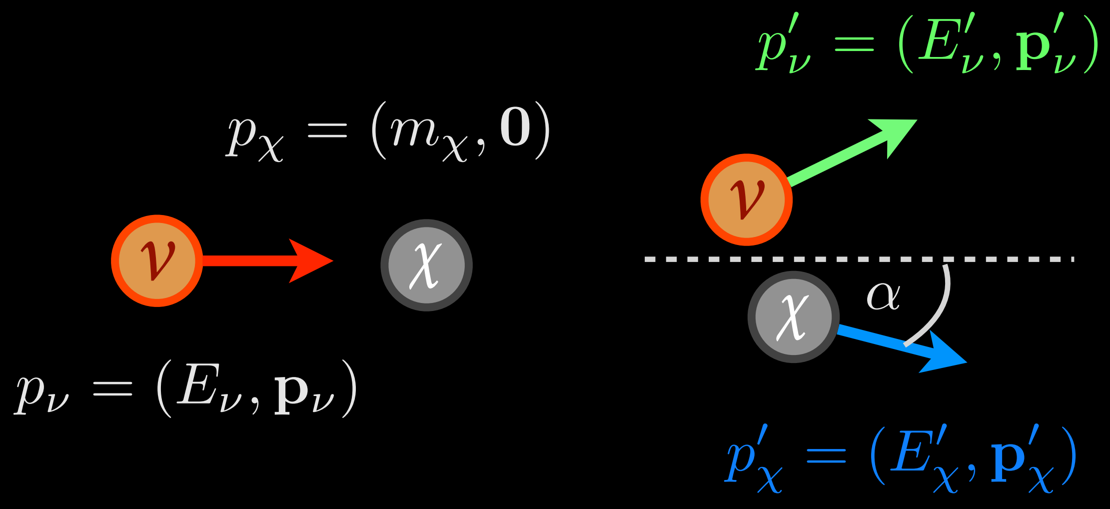

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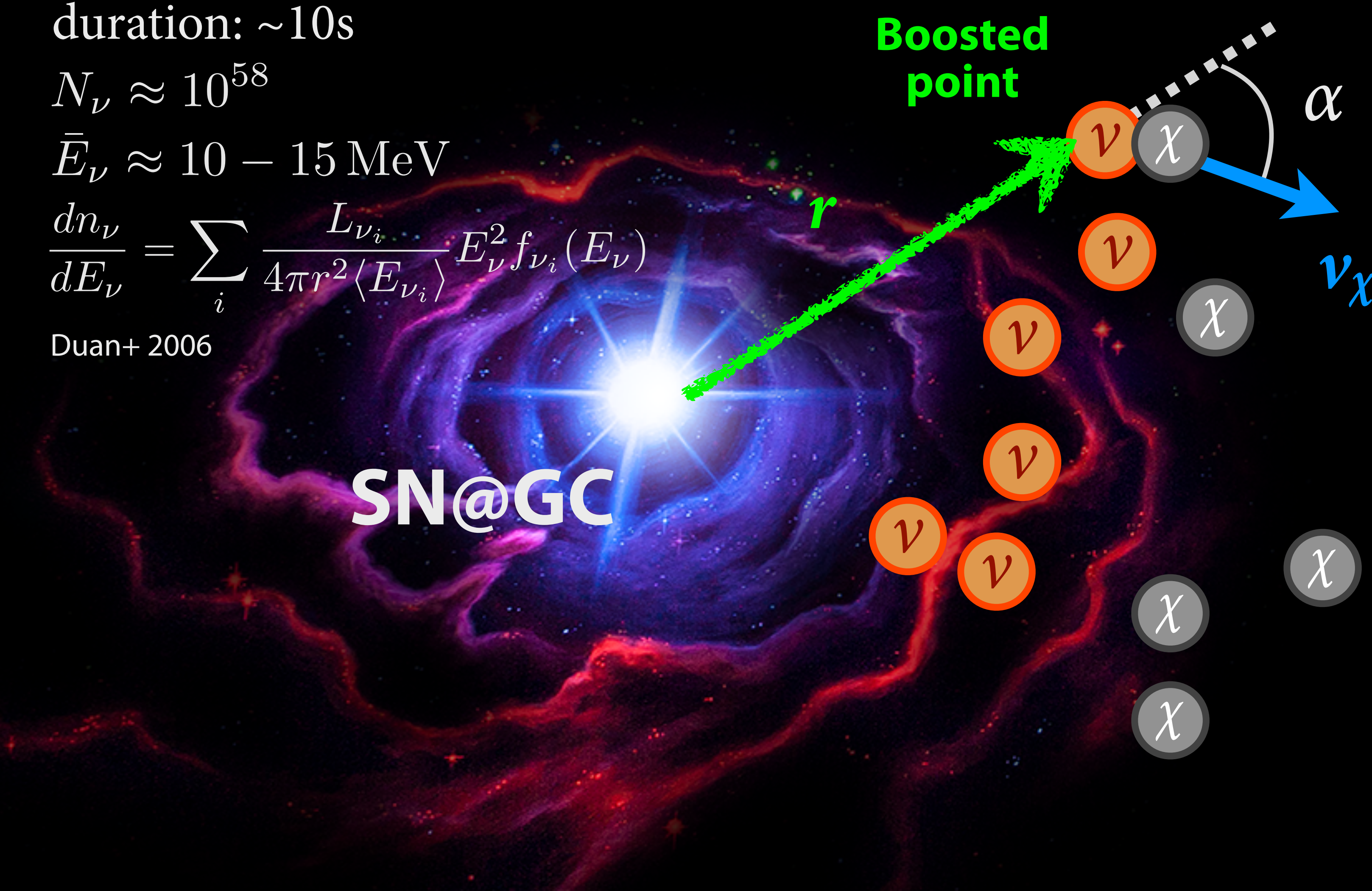


- After the boost

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

$$E'_\chi = m_\chi + E_\nu - E'_\nu$$

- The BDM kinetic energy T_χ

$$T_\chi = E_\nu - E'_\nu(\cos\alpha)$$

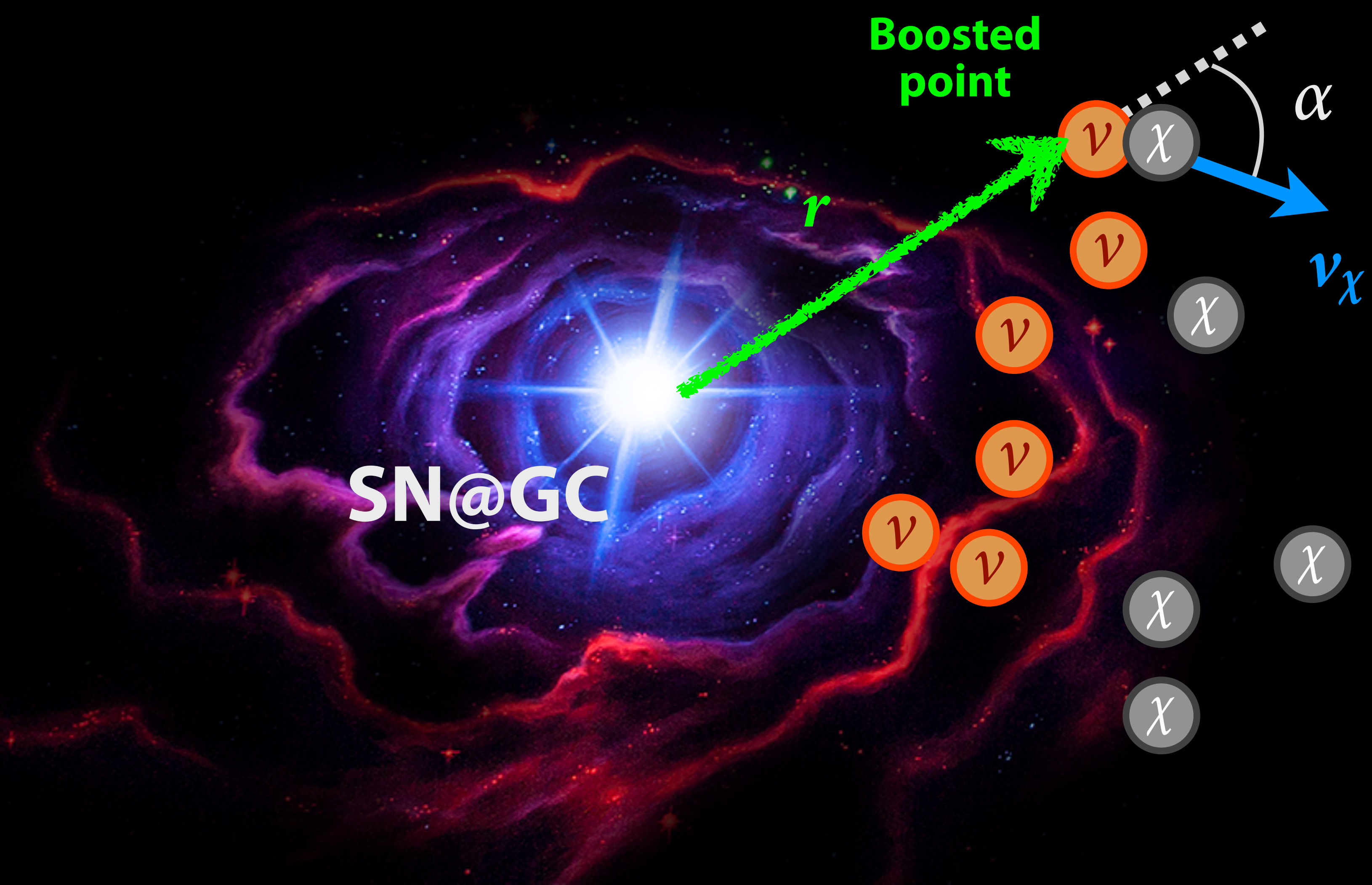
$$= \frac{E_\nu^2}{E_\nu + m_\chi/2}\left(\frac{1+\cos\theta_c}{2}\right)$$

with the scattering angles

Lab: $\alpha \in [0, \frac{\pi}{2}]$

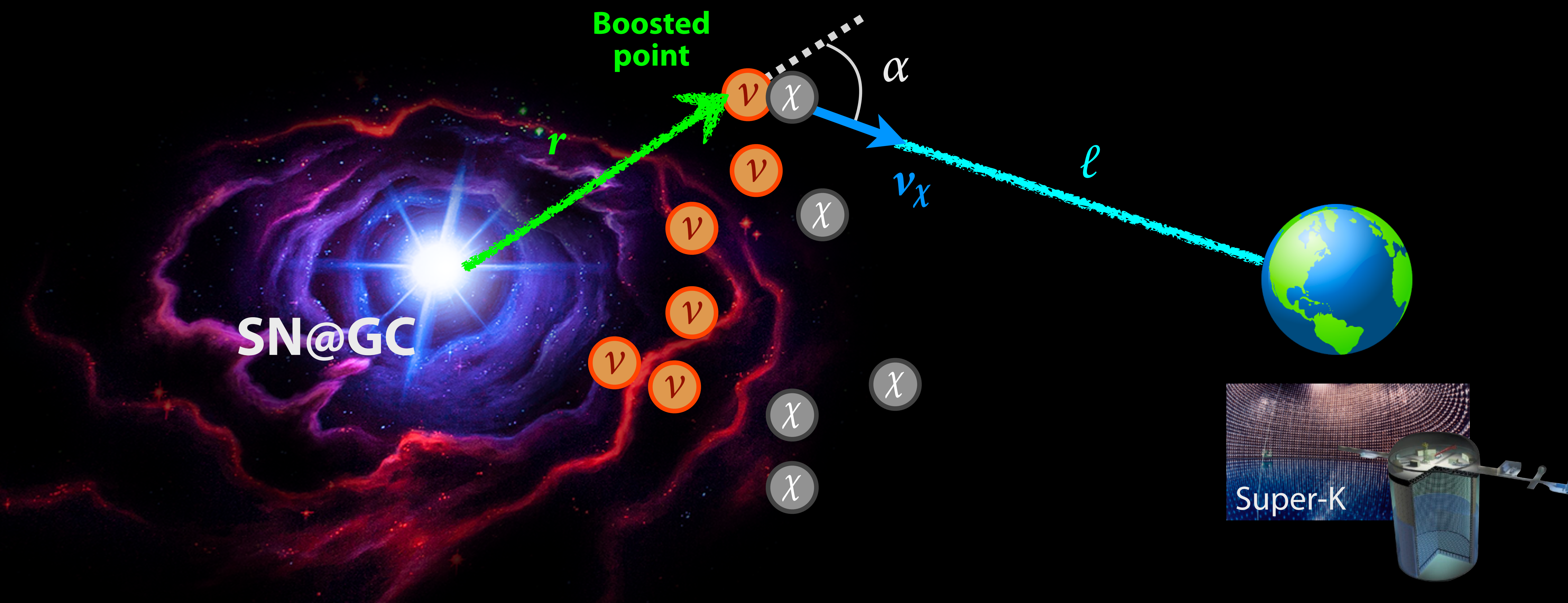
CM: $\theta_c \in [0, \pi]$

The *scattering angle a*



The *scattering angle α*

- Only α points toward Earth that is relevant



The *scattering angle α*

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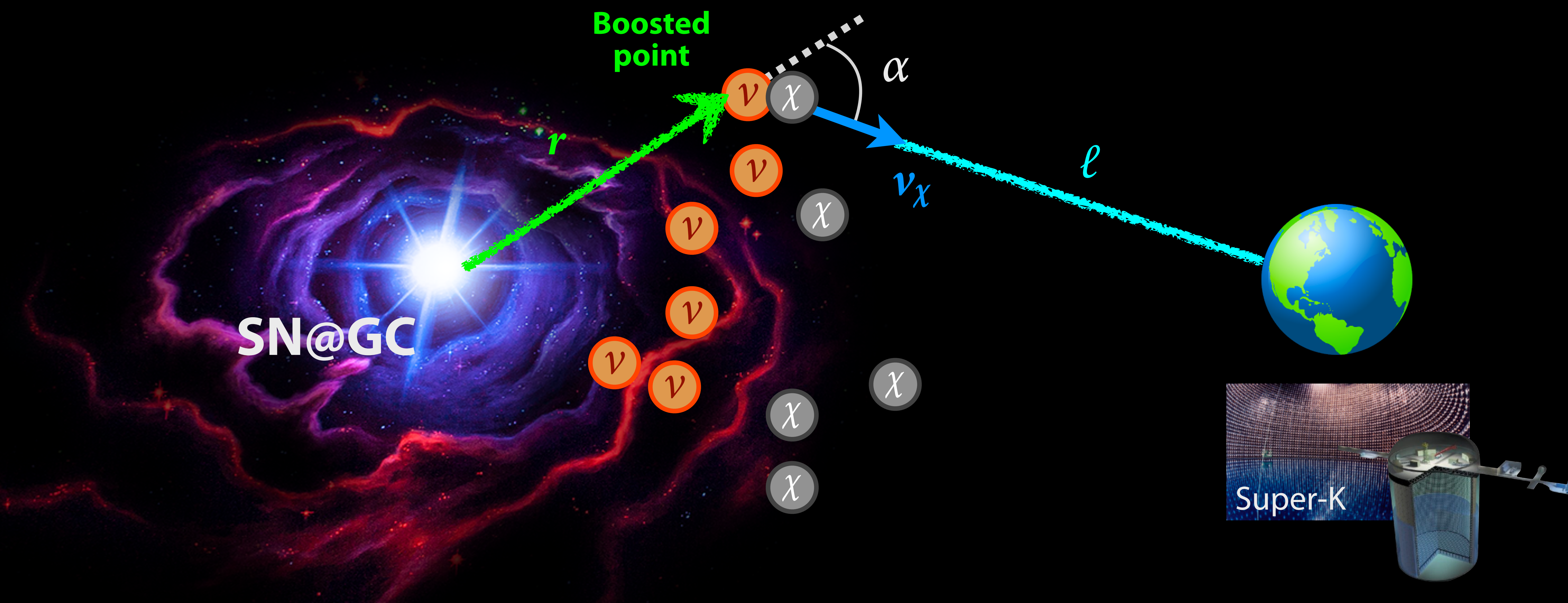
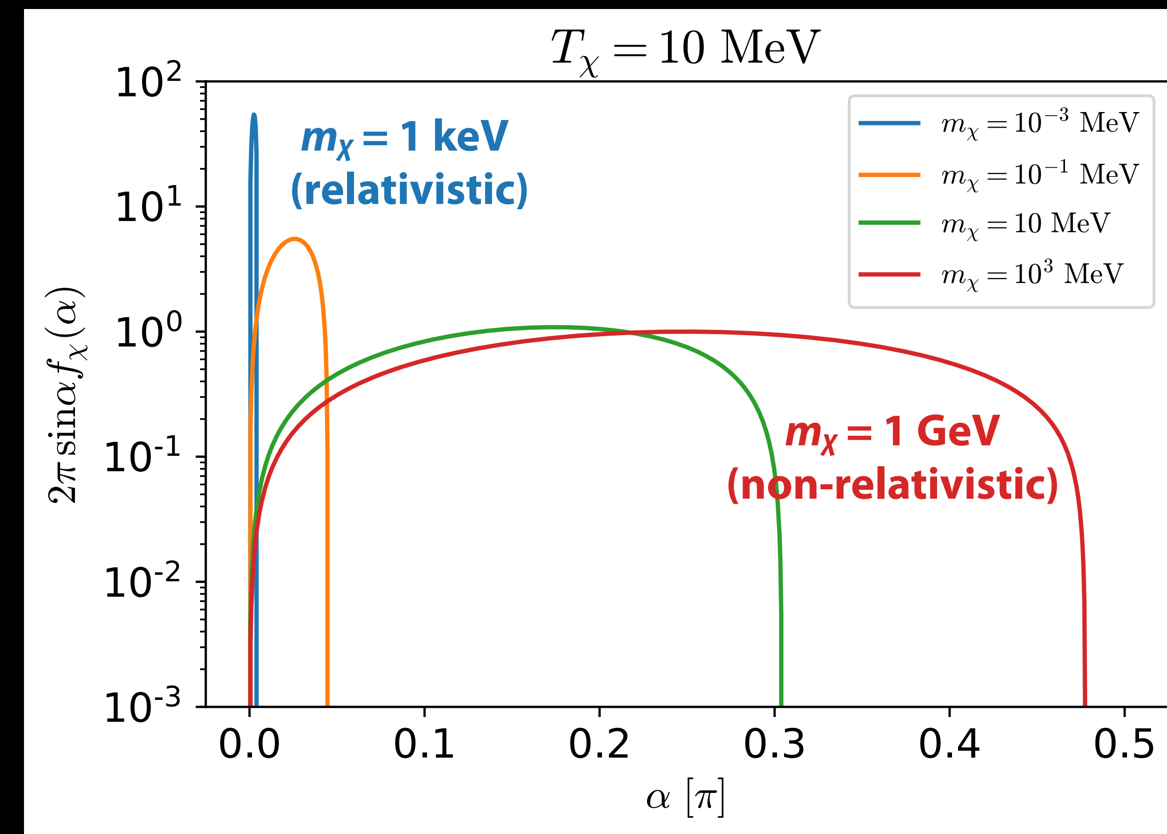
- BDM emissivity j_χ at α

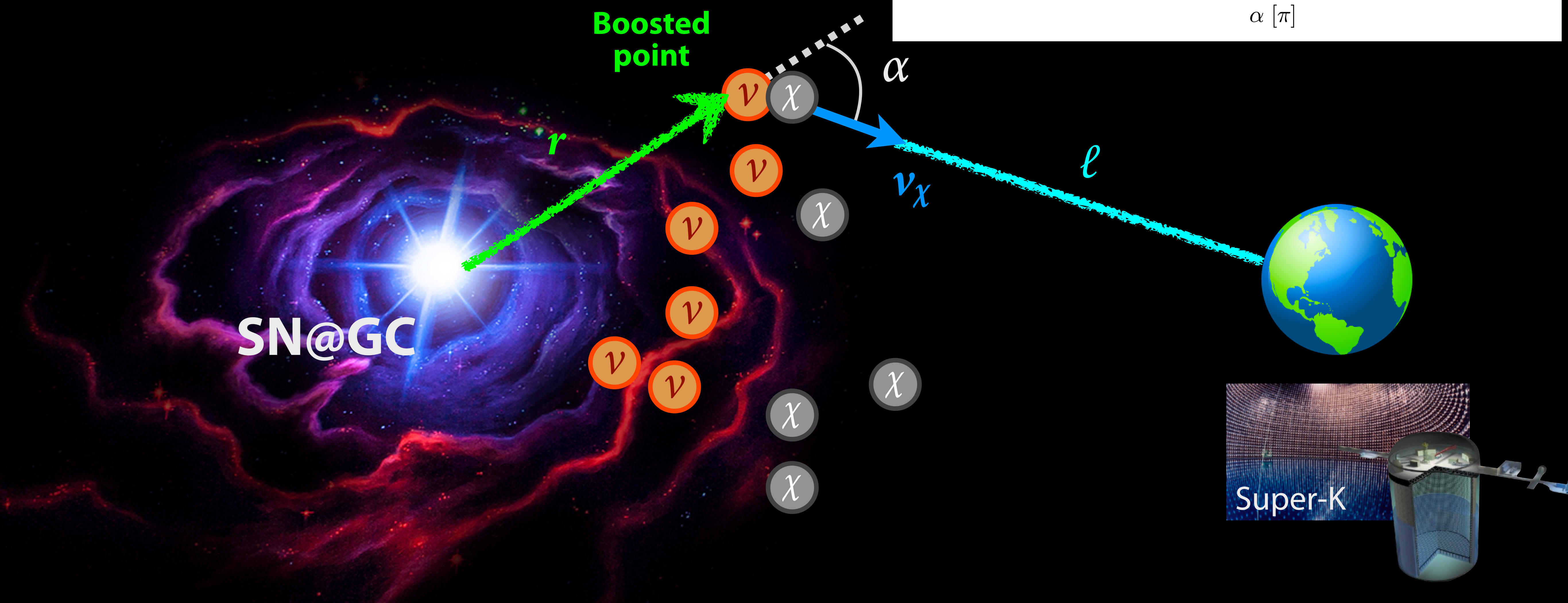


The *scattering angle* α

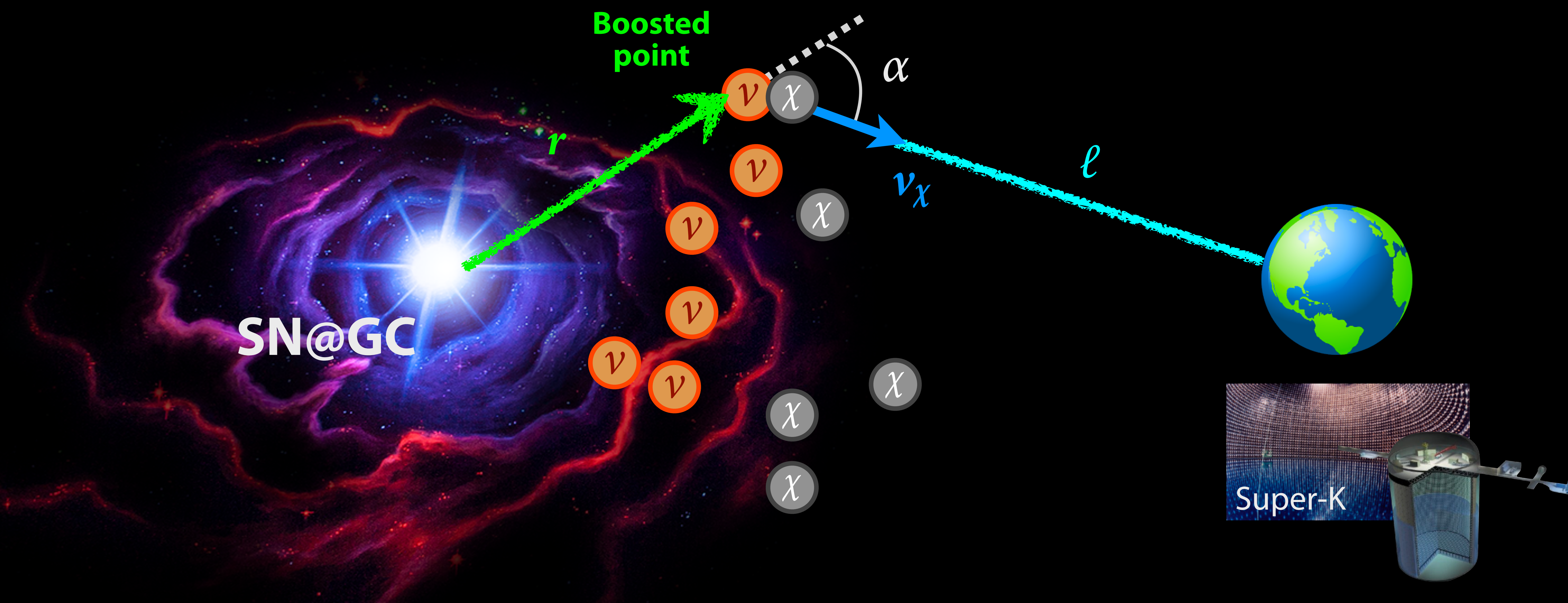
- Only α points toward Earth that is relevant
- BDM emissivity j_χ at α
- Distribution function f_χ for α

$$\int f_\chi(\alpha, E_\nu) d\Omega = 1$$



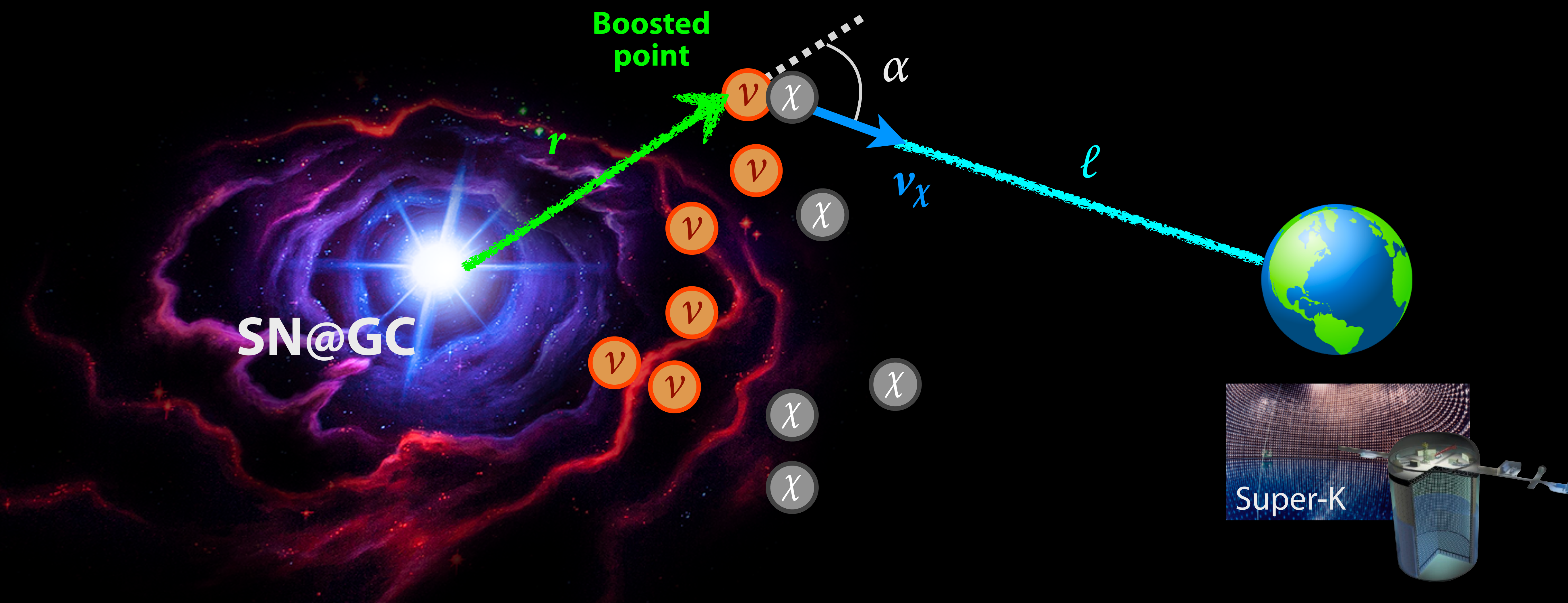


Timing the SNνBDM



Timing the SNνBDM

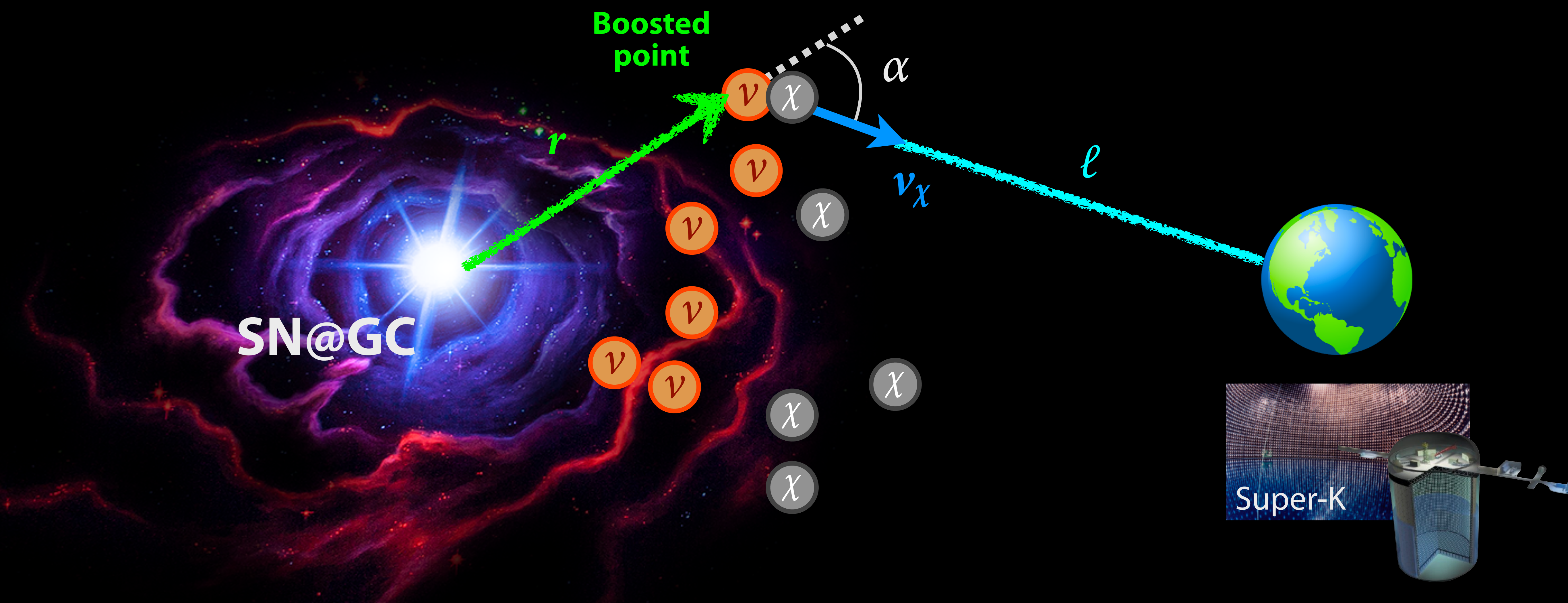
- The arrival time of BDM at Earth t', relative to the SN explosion



Timing the SNνBDM

- The arrival time of BDM at Earth t', relative to the SN explosion

$$t' = \frac{r}{c} + \frac{\ell}{v_\chi}$$



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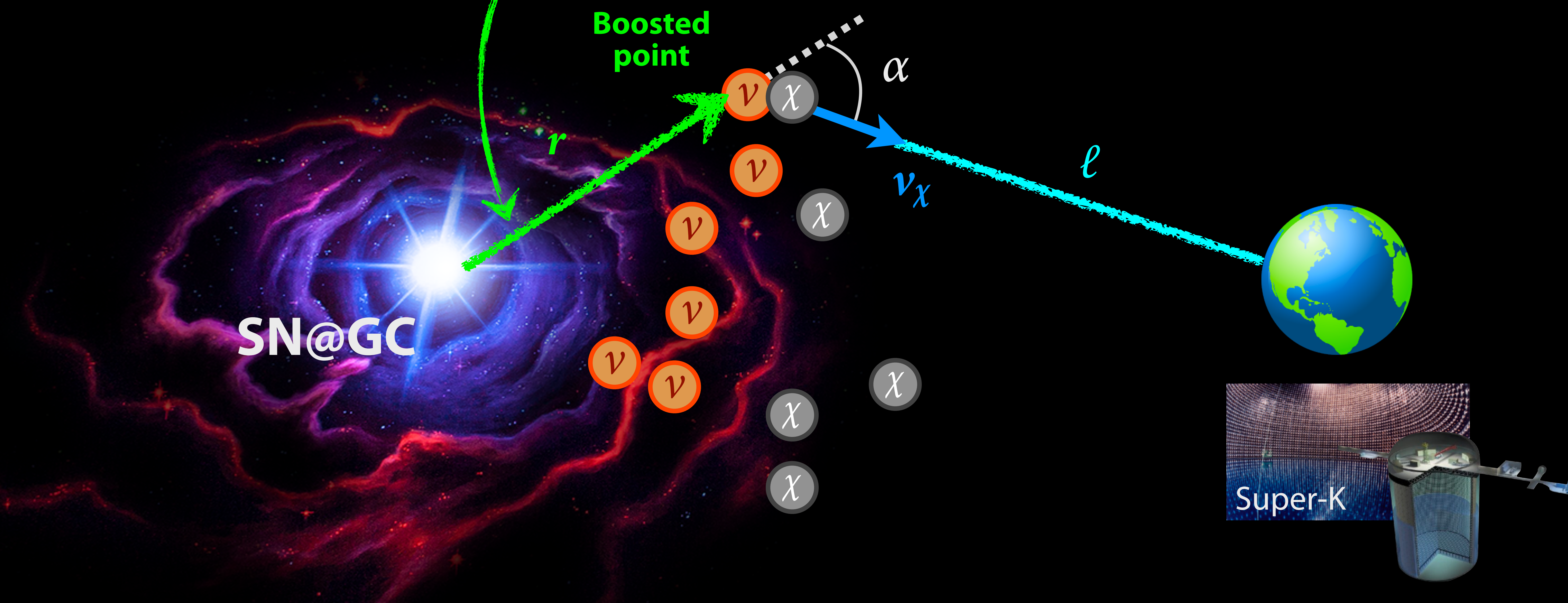

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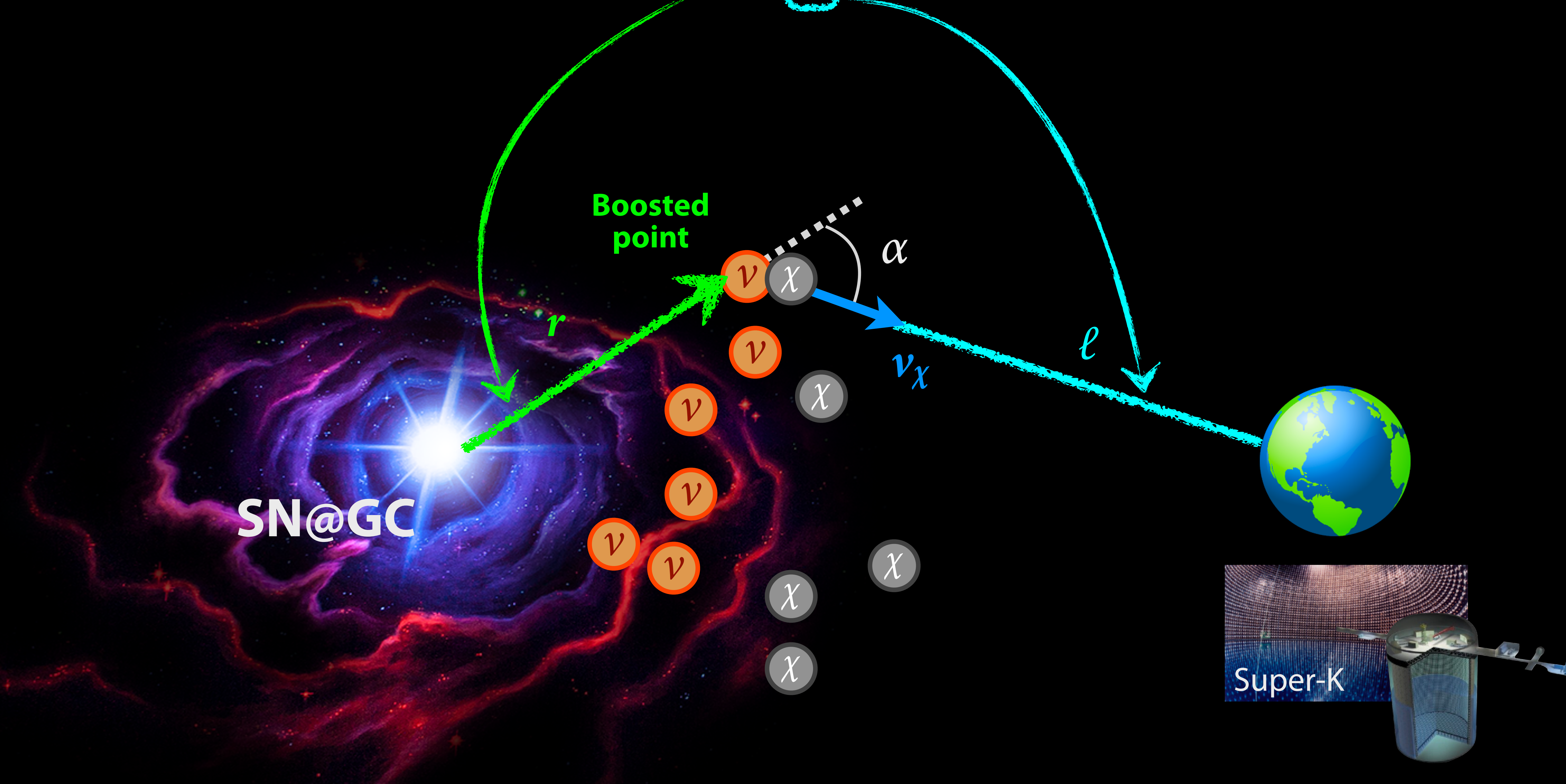

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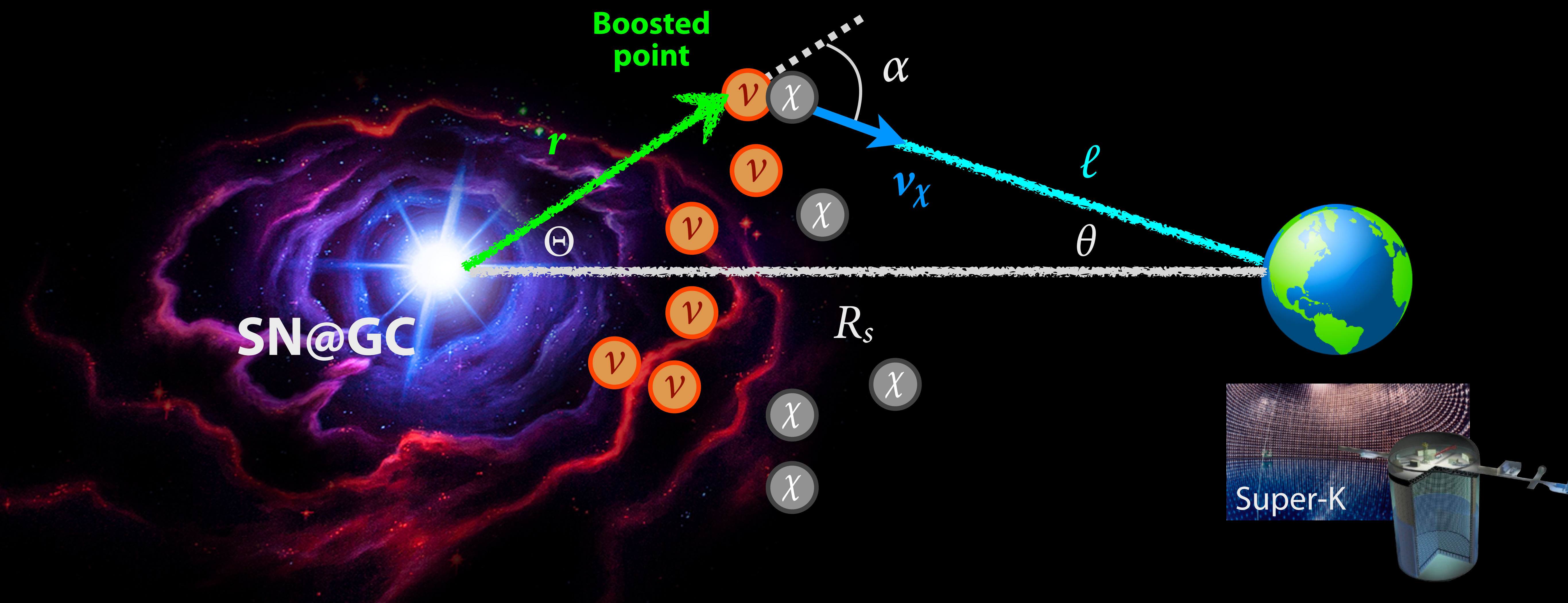
$$t' = \frac{r}{c} + \frac{\ell}{v_\chi} > \frac{R}{c}$$



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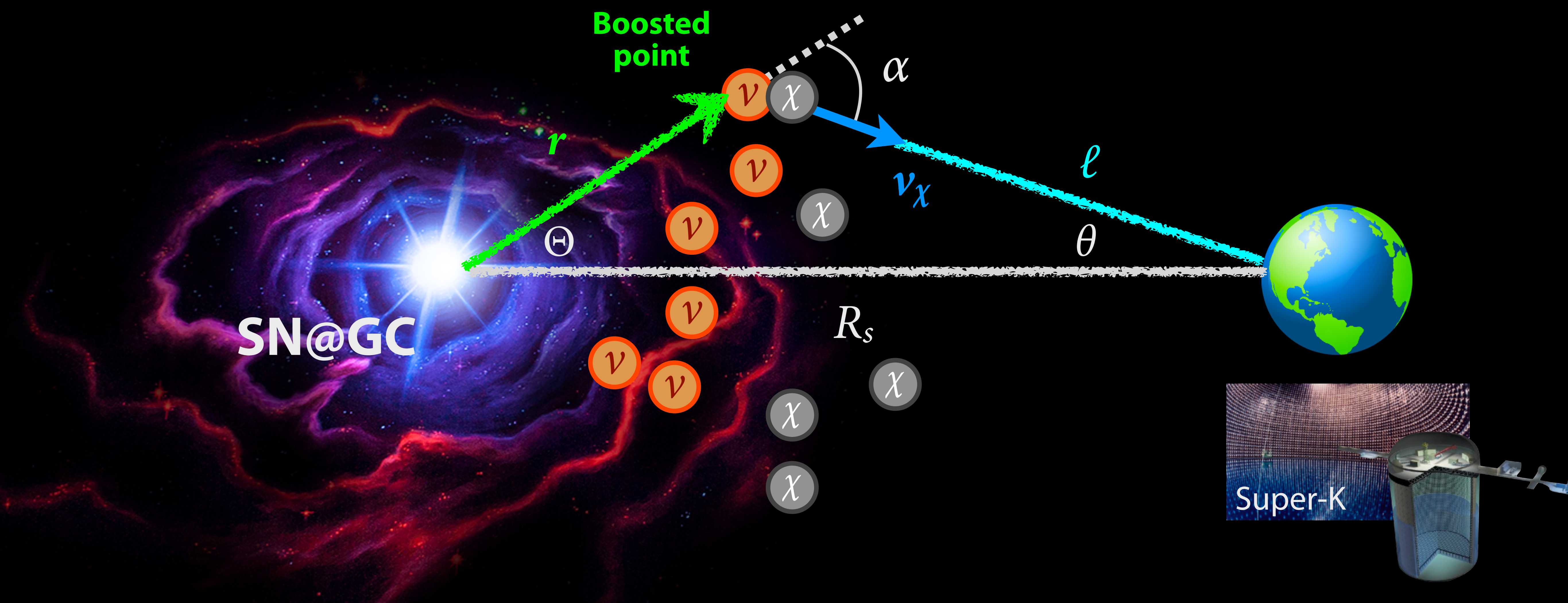

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- The arrival time of BDM at Earth t', relative to the SN explosion

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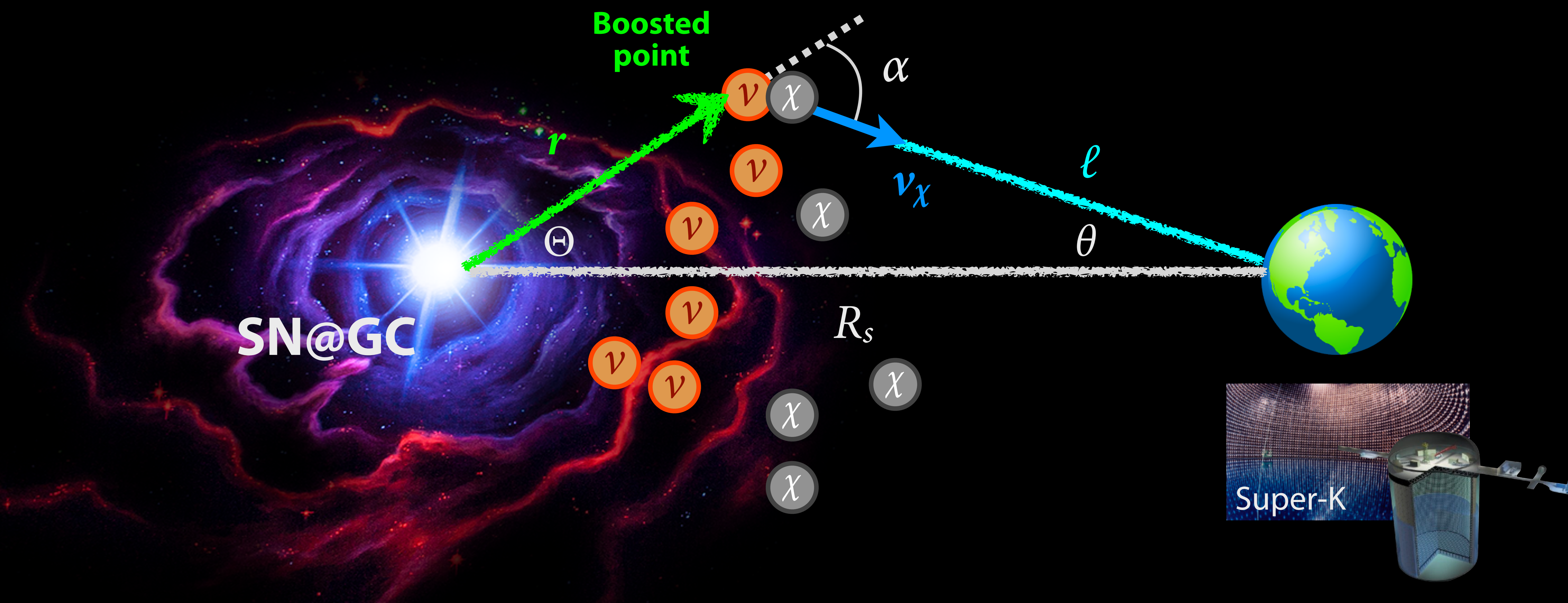
- SNν burst will be followed by time-evolving BDM afterglow



The BDM flux on Earth

- Halo DM is ***boosted***: $T_\chi \gg m_\chi$
- BDM emissivity at α: ***distribution function***

$$f_\chi(\alpha, E_\nu) = \frac{\gamma^2 \sec^3 \alpha}{\pi(1+\gamma^2 \tan^2 \alpha)^2}$$

- The BDM ***time-of-flight***:

$$t' = \frac{r}{c} + \frac{\ell}{v_\chi} > \frac{R}{c}$$

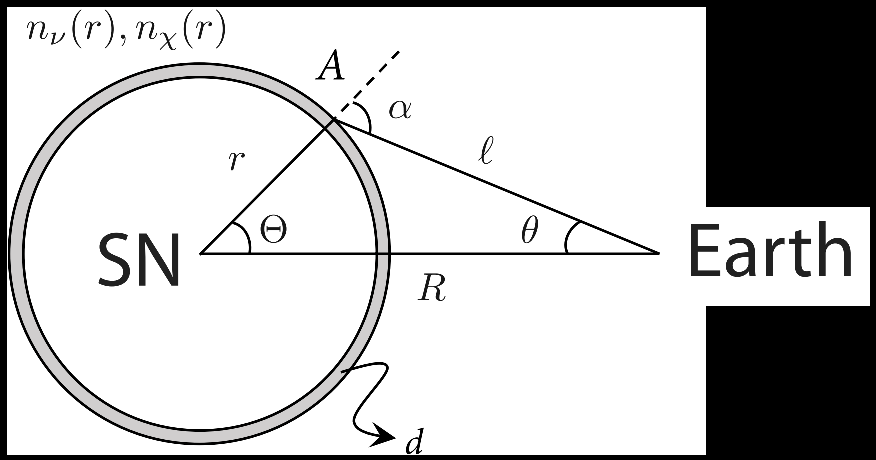
- The flux on Earth

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

$$j_\chi(r, T_\chi, \alpha) = c\sigma_{\chi\nu} n_\chi \left(\frac{dn_\nu}{dE_\nu}\right)\left(\frac{dE_\nu}{dT_\chi}\frac{v_\chi}{c}\right) f_\chi$$

DM profile

SNν spectrum



The BDM flux on the Earth

Bertone+ (2005)
Erkal+ (2019)

Time-evolving BDM flux: Time-of-flight

Bertone+ (2005)
Erkal+ (2019)

Time-evolving BDM flux: Time-of-flight

- DM profile

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

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- Defined a time-shifted coordinate $t = t' - R_s/c$: a delayed time relative to the arrival of SNν

Time-evolving BDM flux: Time-of-flight

- DM profile

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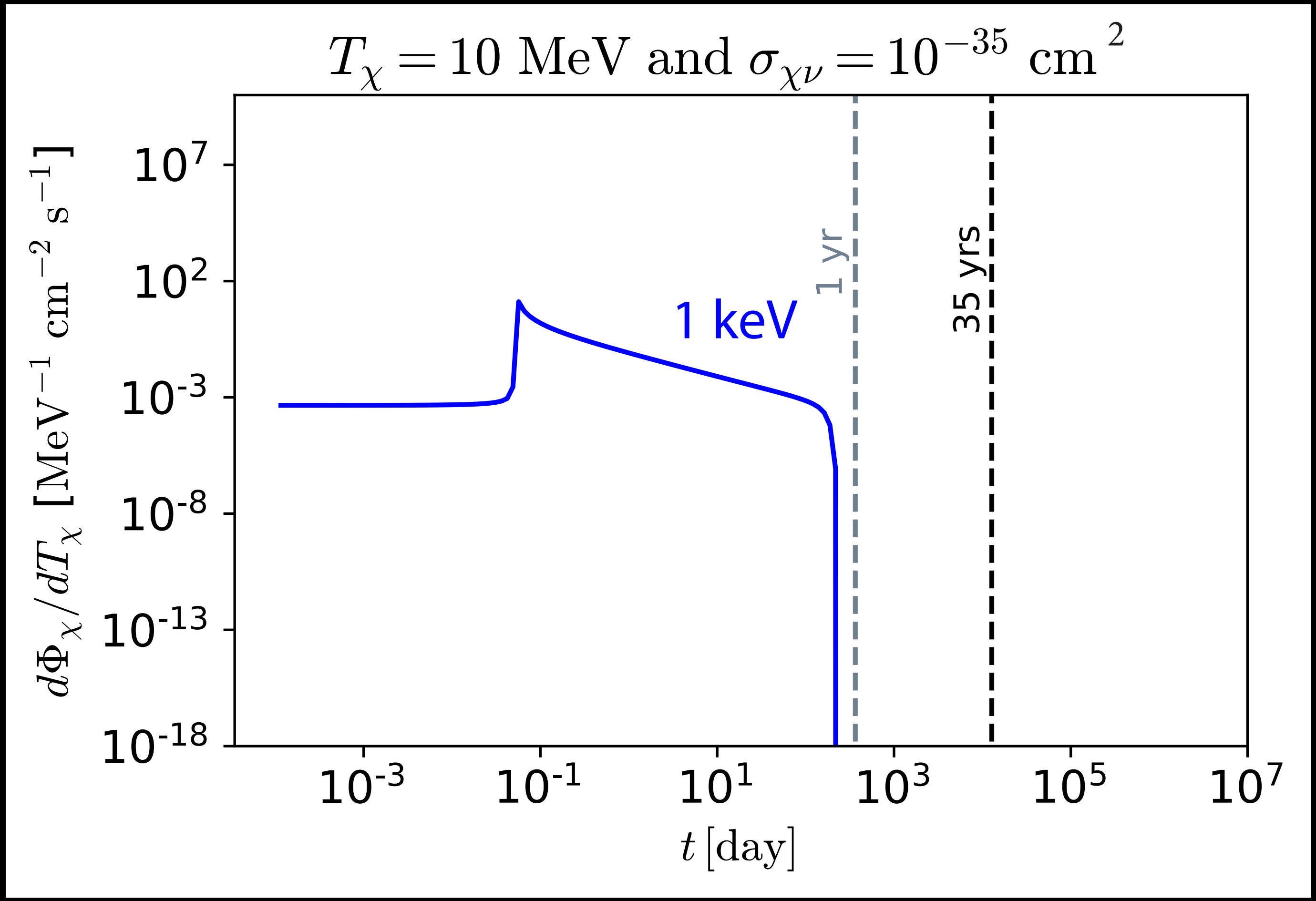

Bertone+ (2005)
Erkal+ (2019)

Time-evolving BDM flux: Time-of-flight

- DM profile

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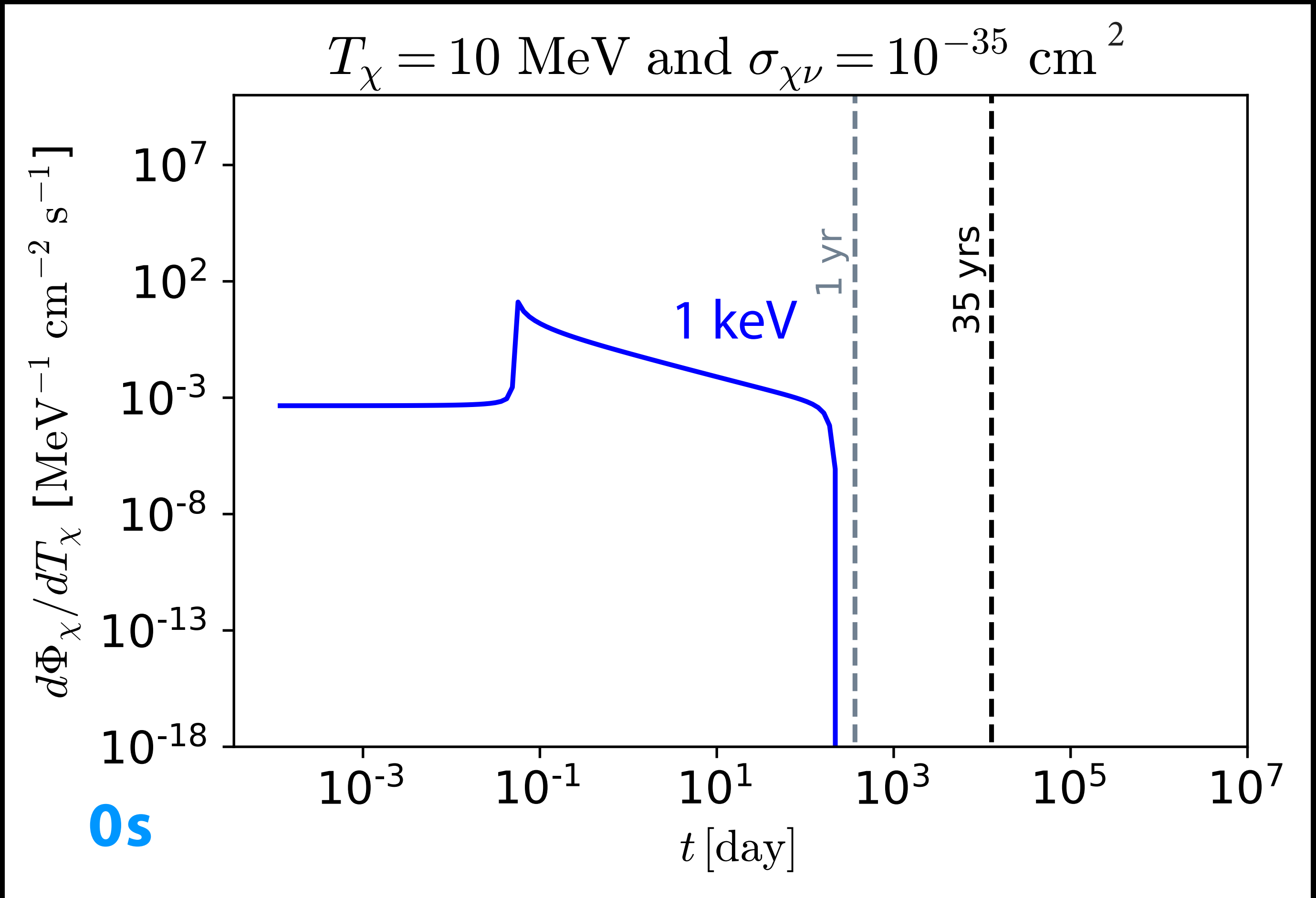

SNν burst detected on Earth

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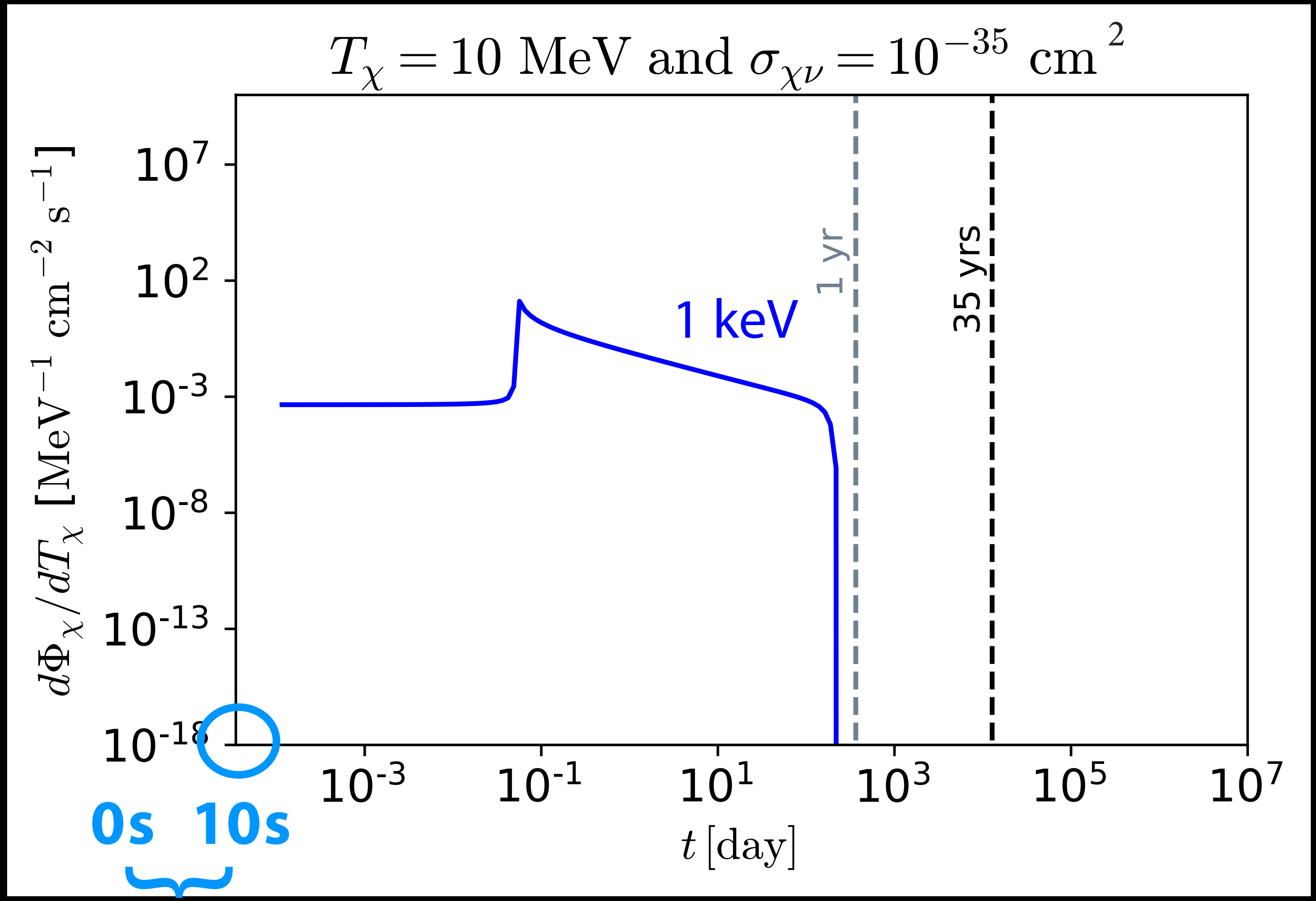

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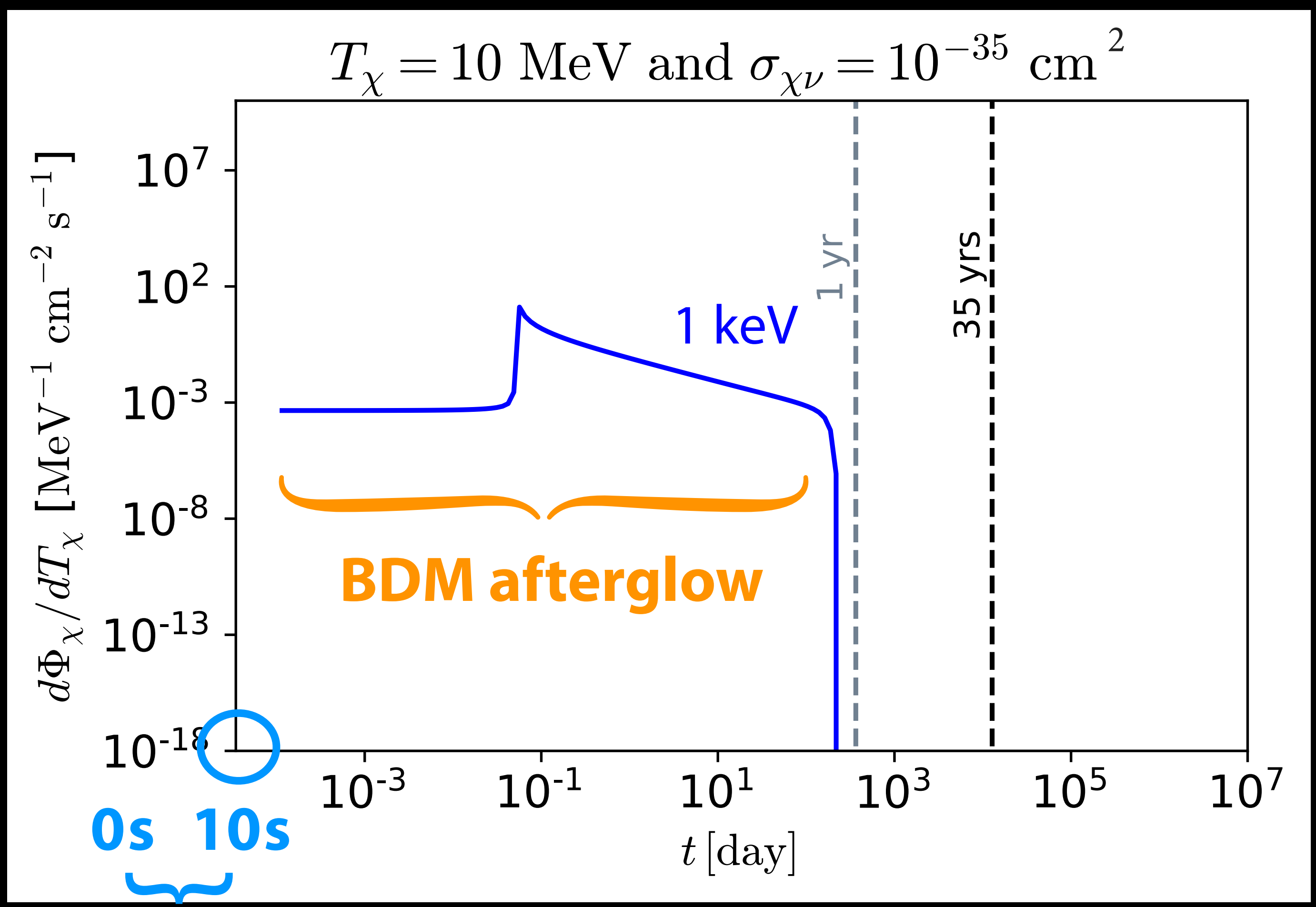

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Direct m_χ measurement

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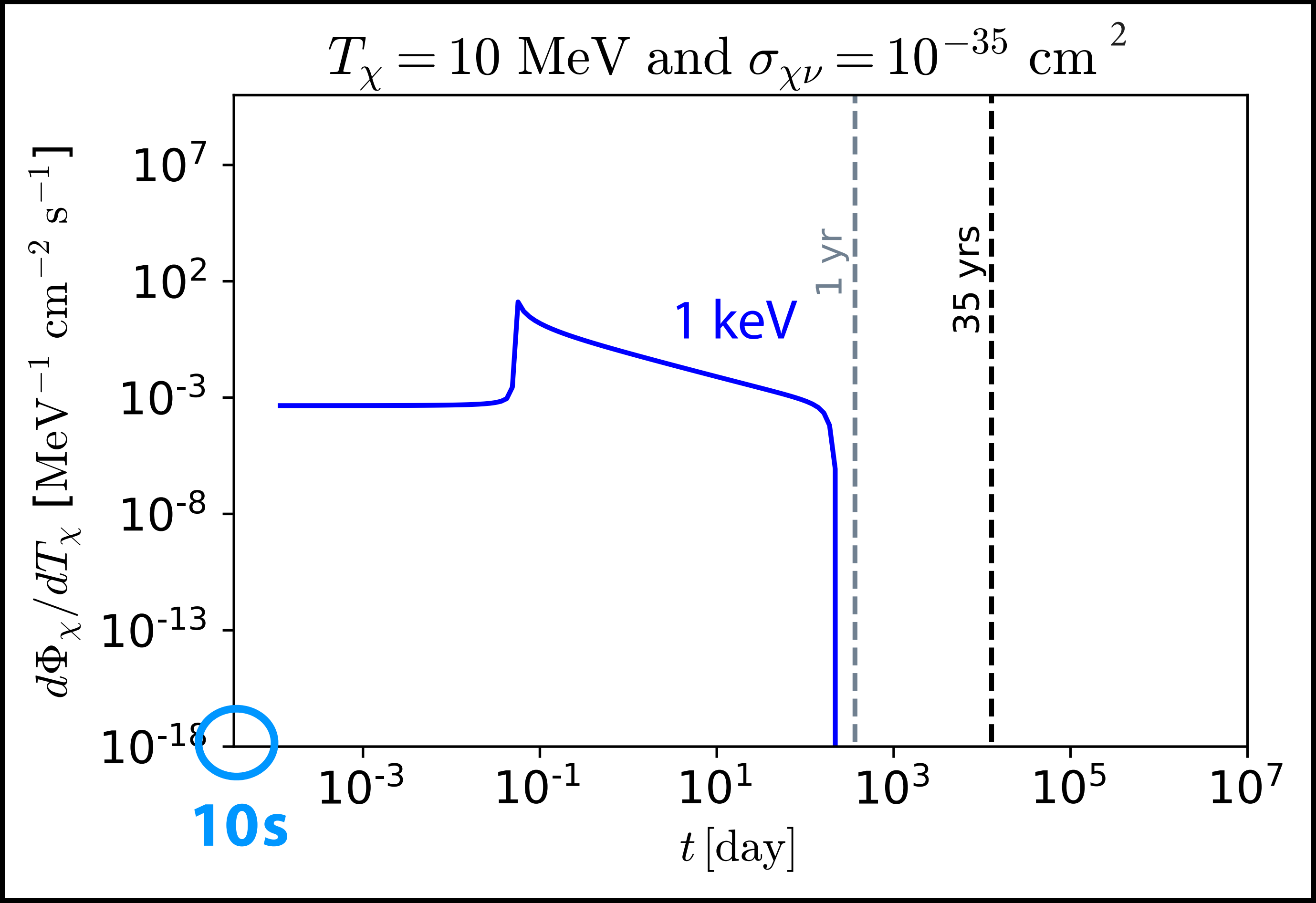

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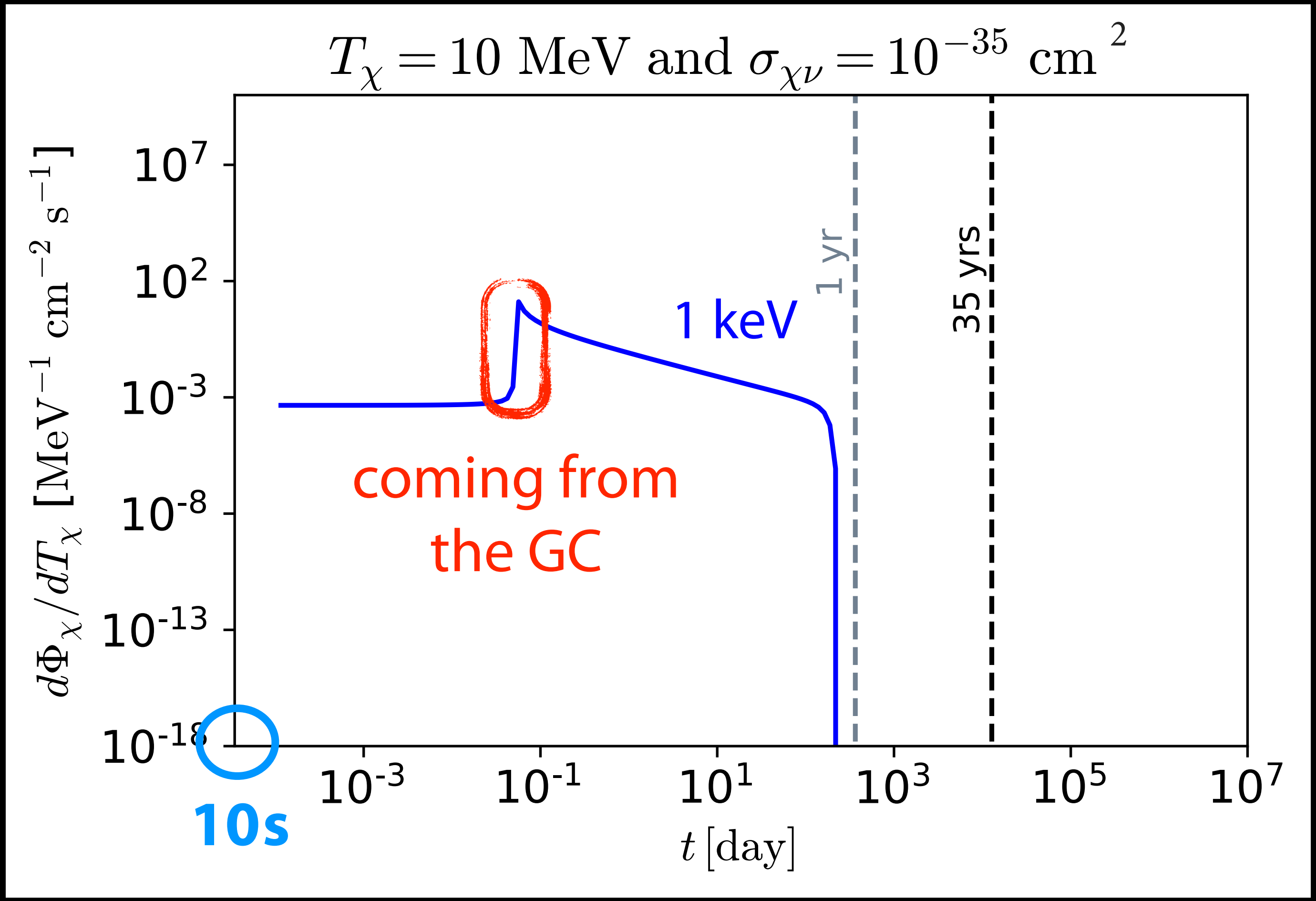

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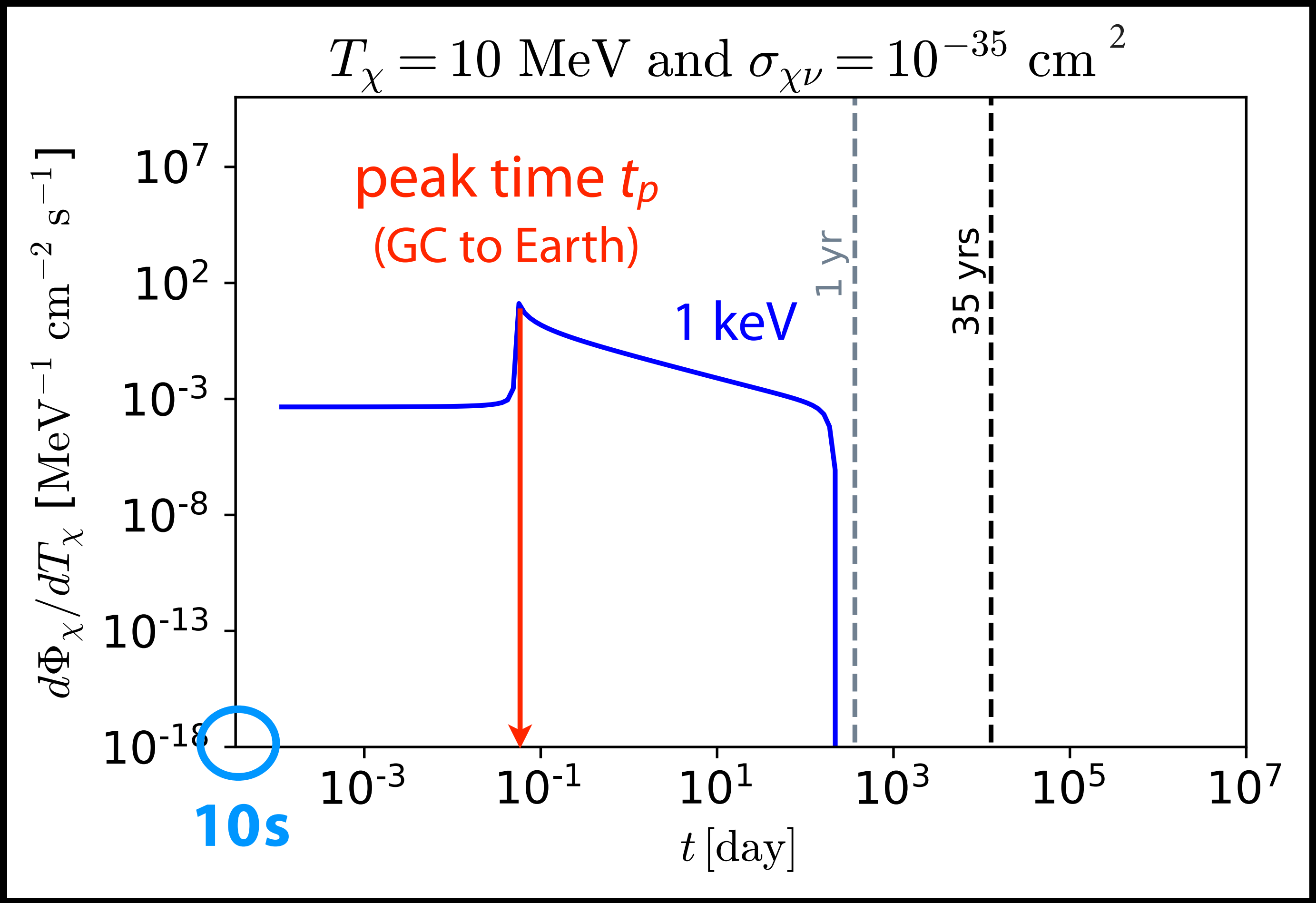

- Peak time $t_p \sim R_s(1/v_\chi - 1/c)$

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Direct m_χ measurement

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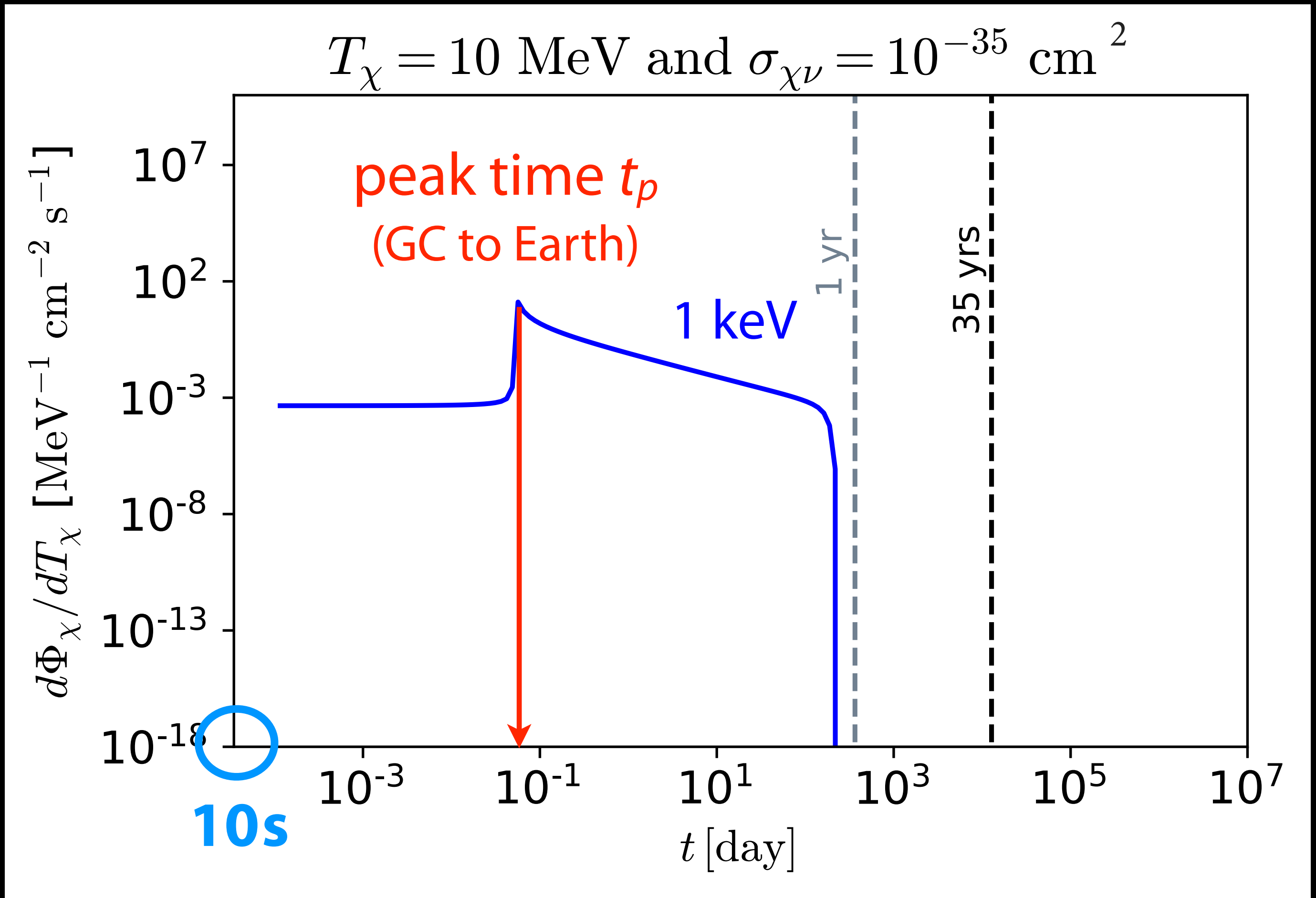

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- The BDM velocity

$$v_\chi = \sqrt{T_\chi(2m_\chi + T_\chi)}/(T_\chi + m_\chi)$$

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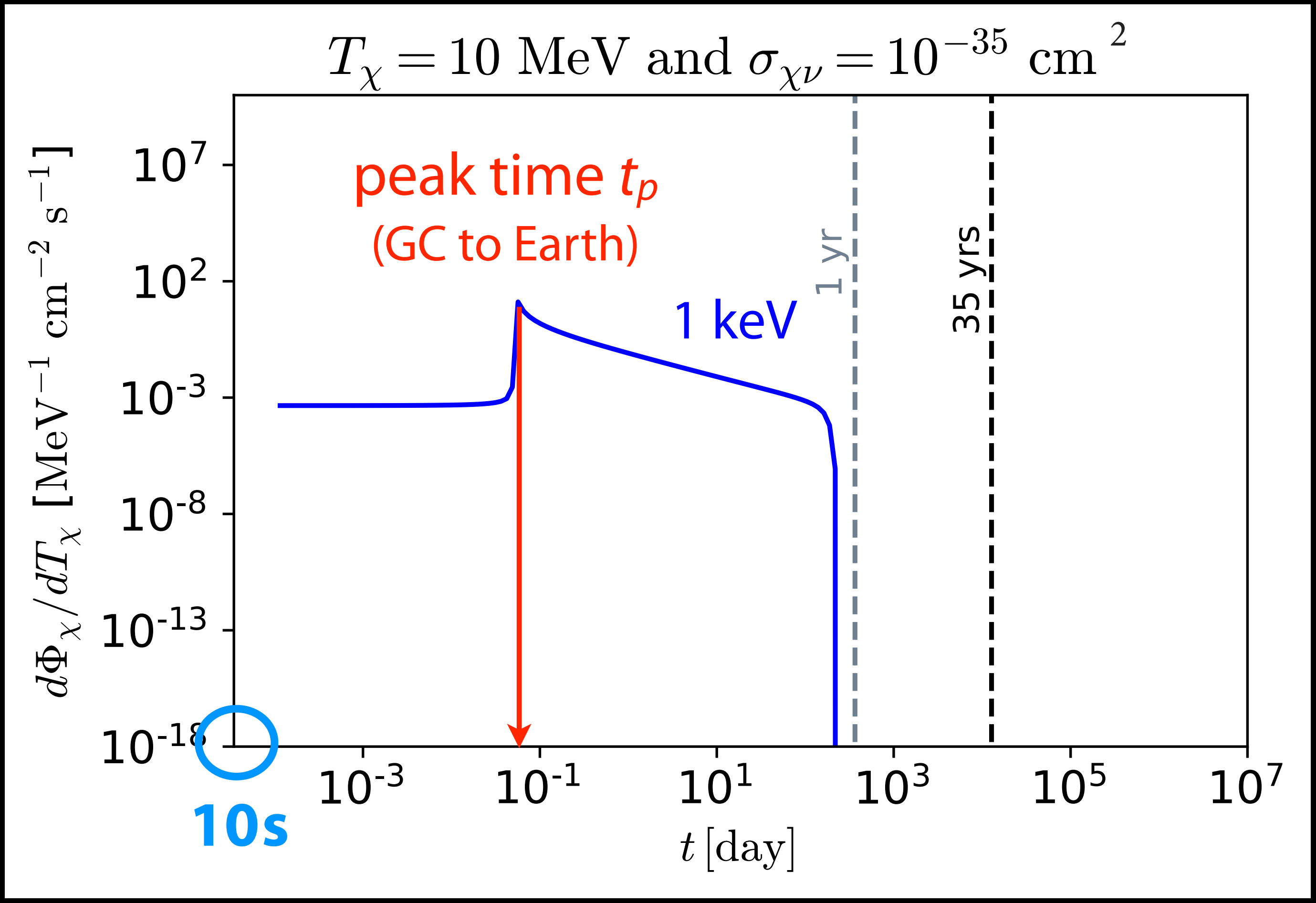

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- Given T_χ and t_p, the DM mass m_χ is measured directly

Direct m_χ measurement

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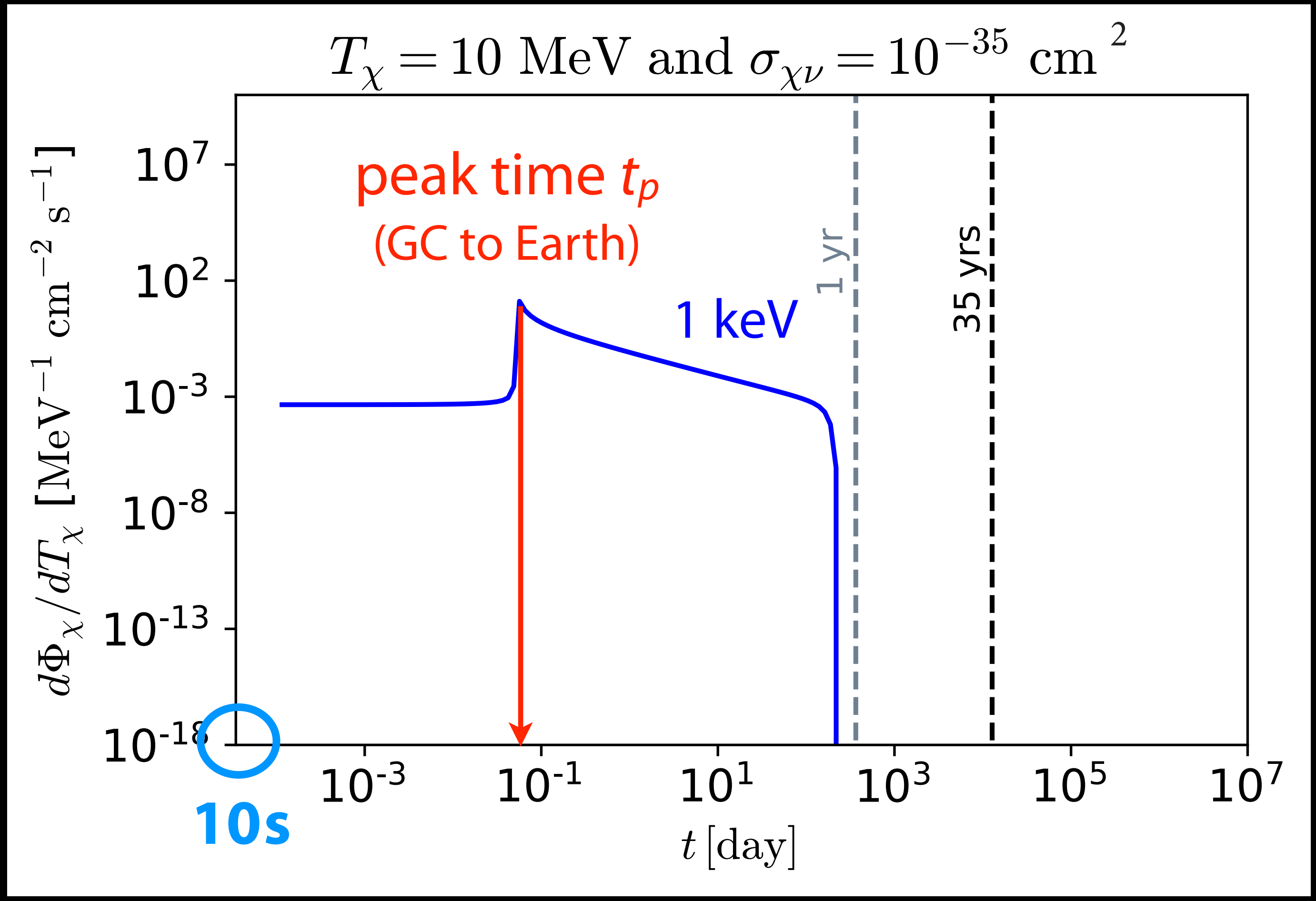

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$$v_\chi = \sqrt{T_\chi(2m_\chi + T_\chi)}/(T_\chi + m_\chi)$$

- Given T_χ and t_p, the DM mass m_χ is measured directly
- For direct search, the diff. recoil rate dR/dE_R

$$\frac{dR}{dE_R} \propto \frac{\sigma_{\chi n}}{m_\chi}$$

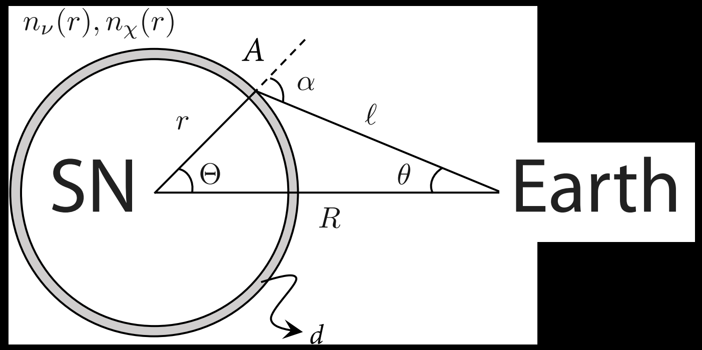
Determining the time of vanishing

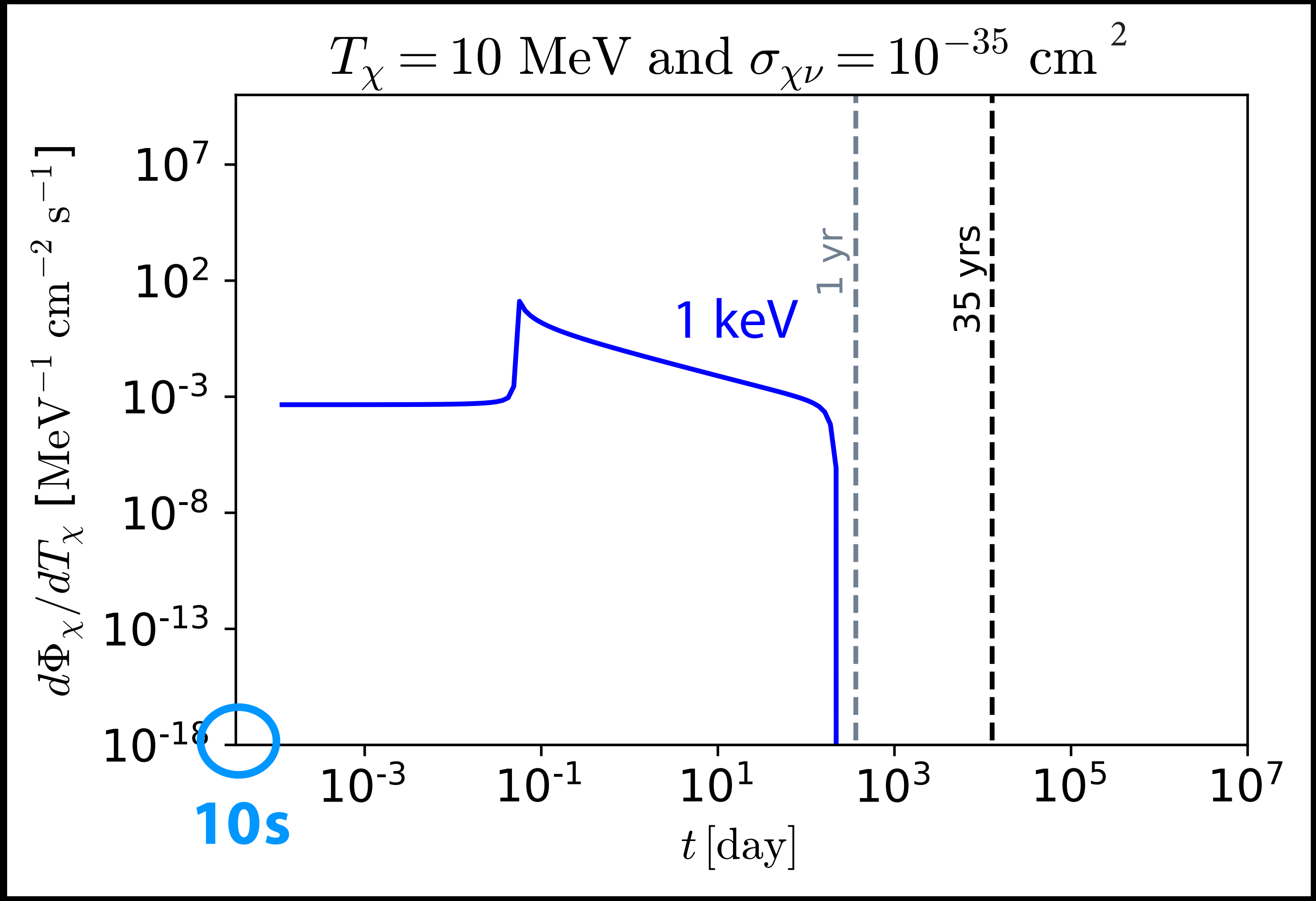
- The total propagation time

$$t' = \frac{r}{c} + \frac{\ell}{v_\chi}$$

- The distribution function for α

$$f_\chi(\alpha, E_\nu) = \frac{\gamma^2 \sec^3 \alpha}{\pi(1+\gamma^2 \tan^2 \alpha)^2}$$





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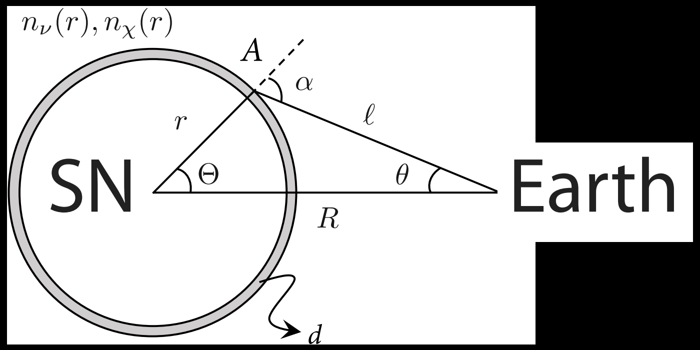

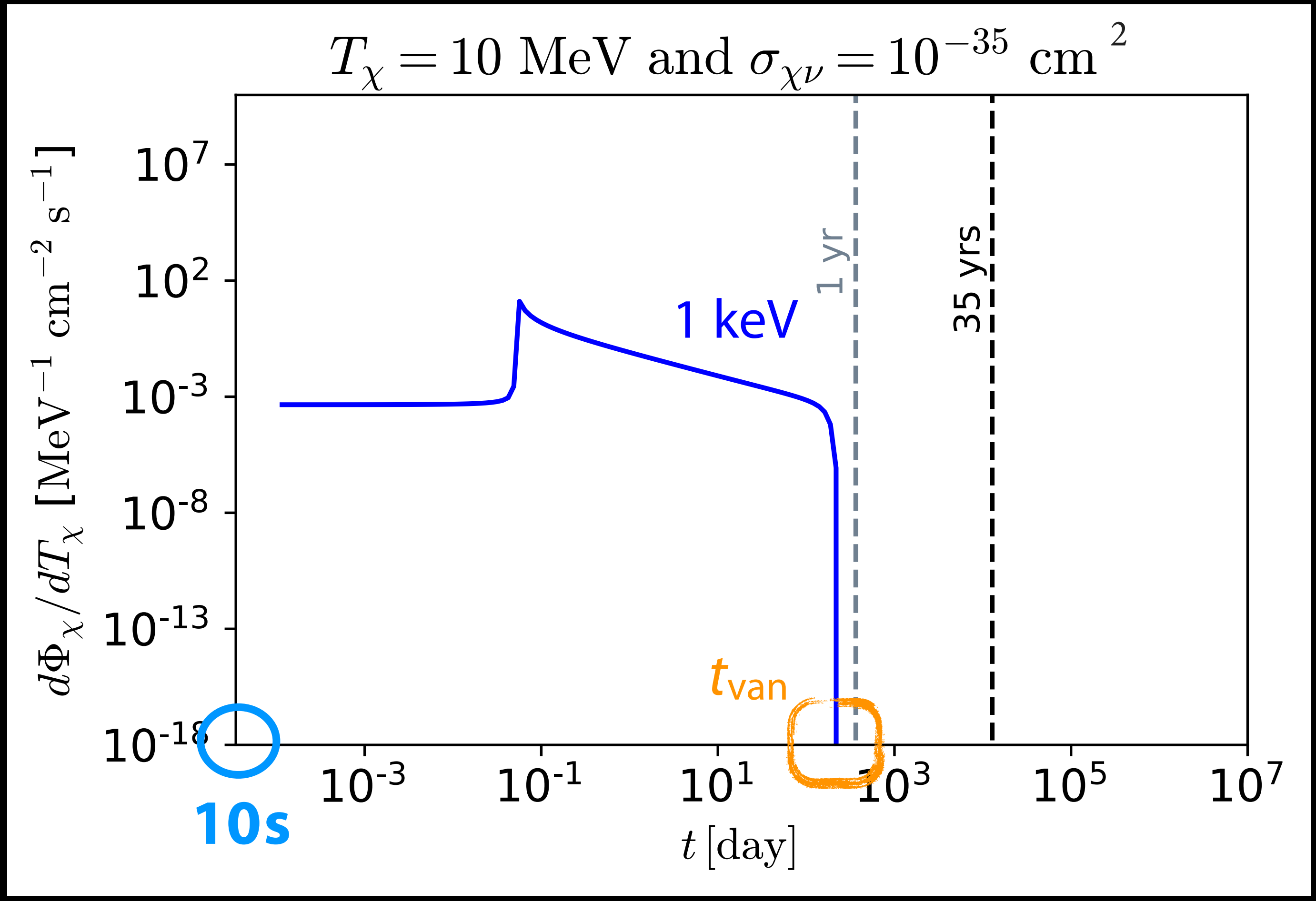

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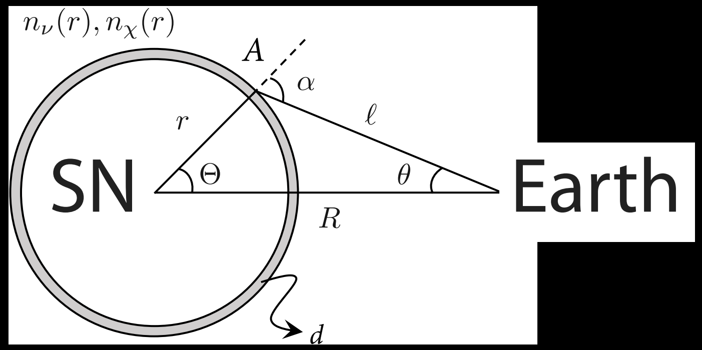

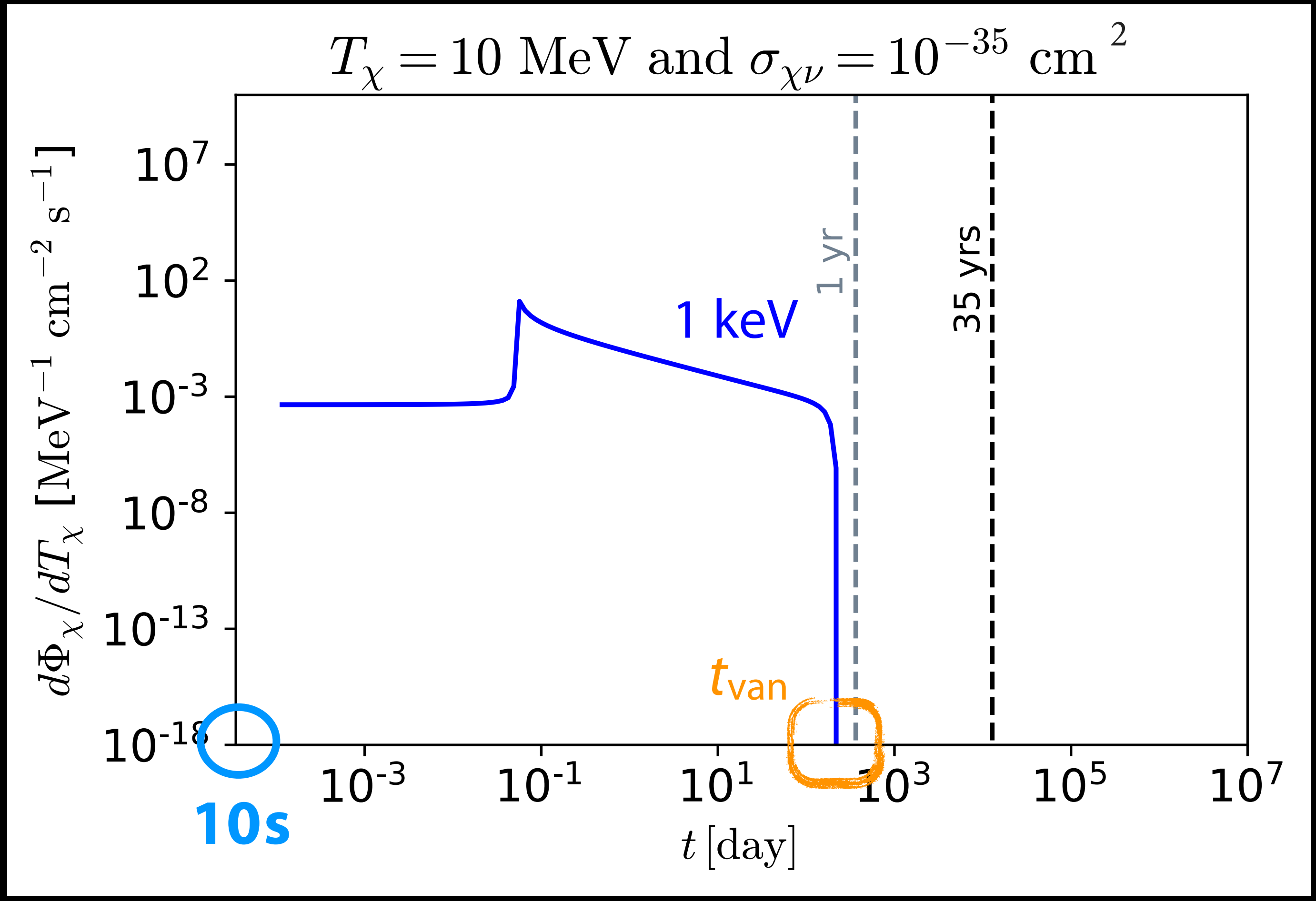

- The vanishing time t_{van}: the *duration* of the afterglow

Determining the time of vanishing

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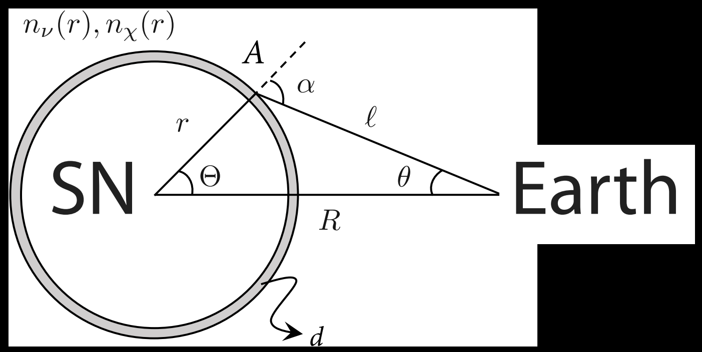

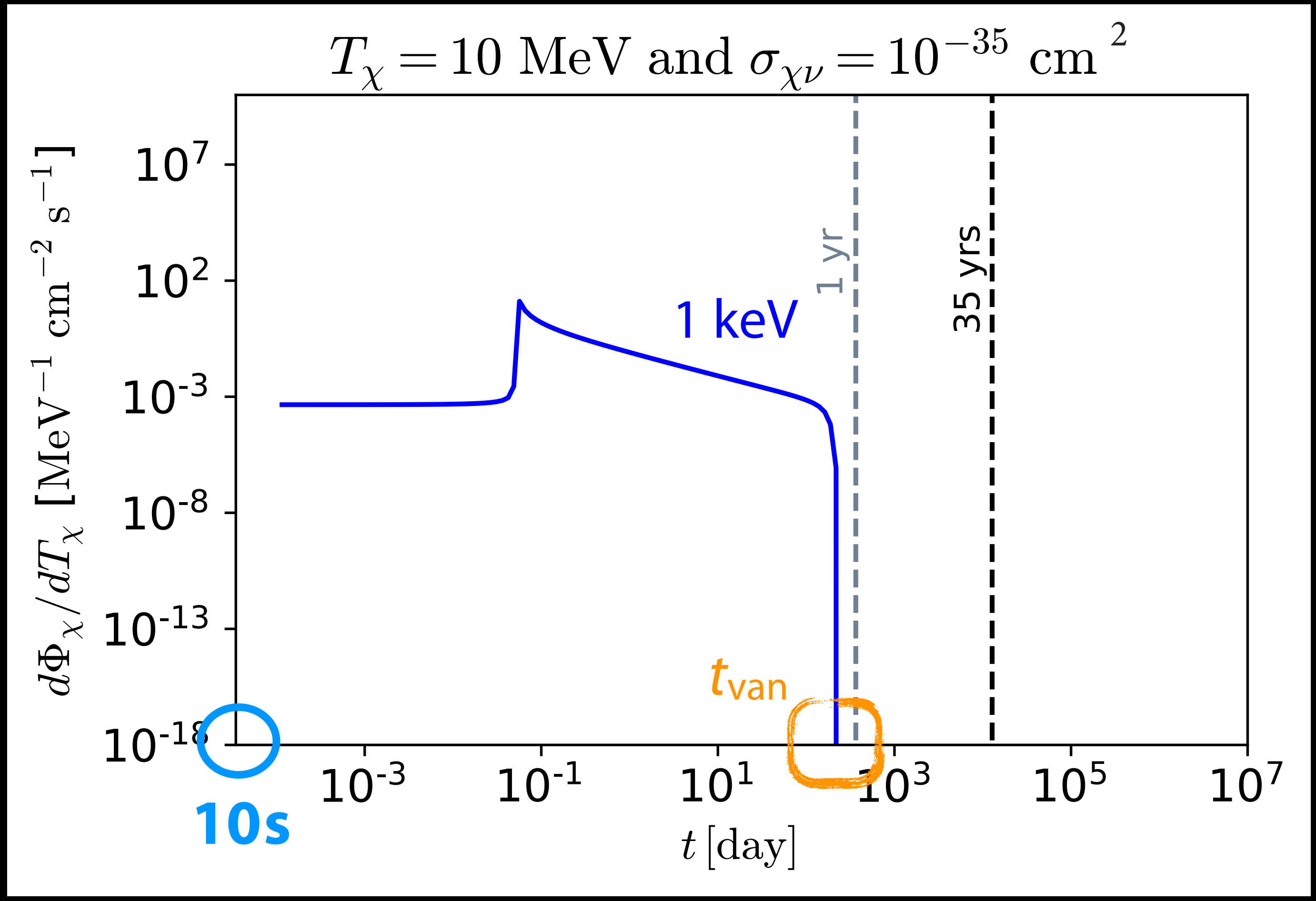

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max. t and $f_\chi(\alpha_m) = 0$

Determining the time of vanishing

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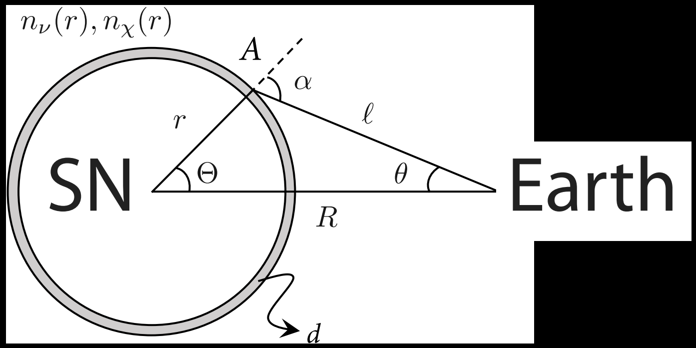

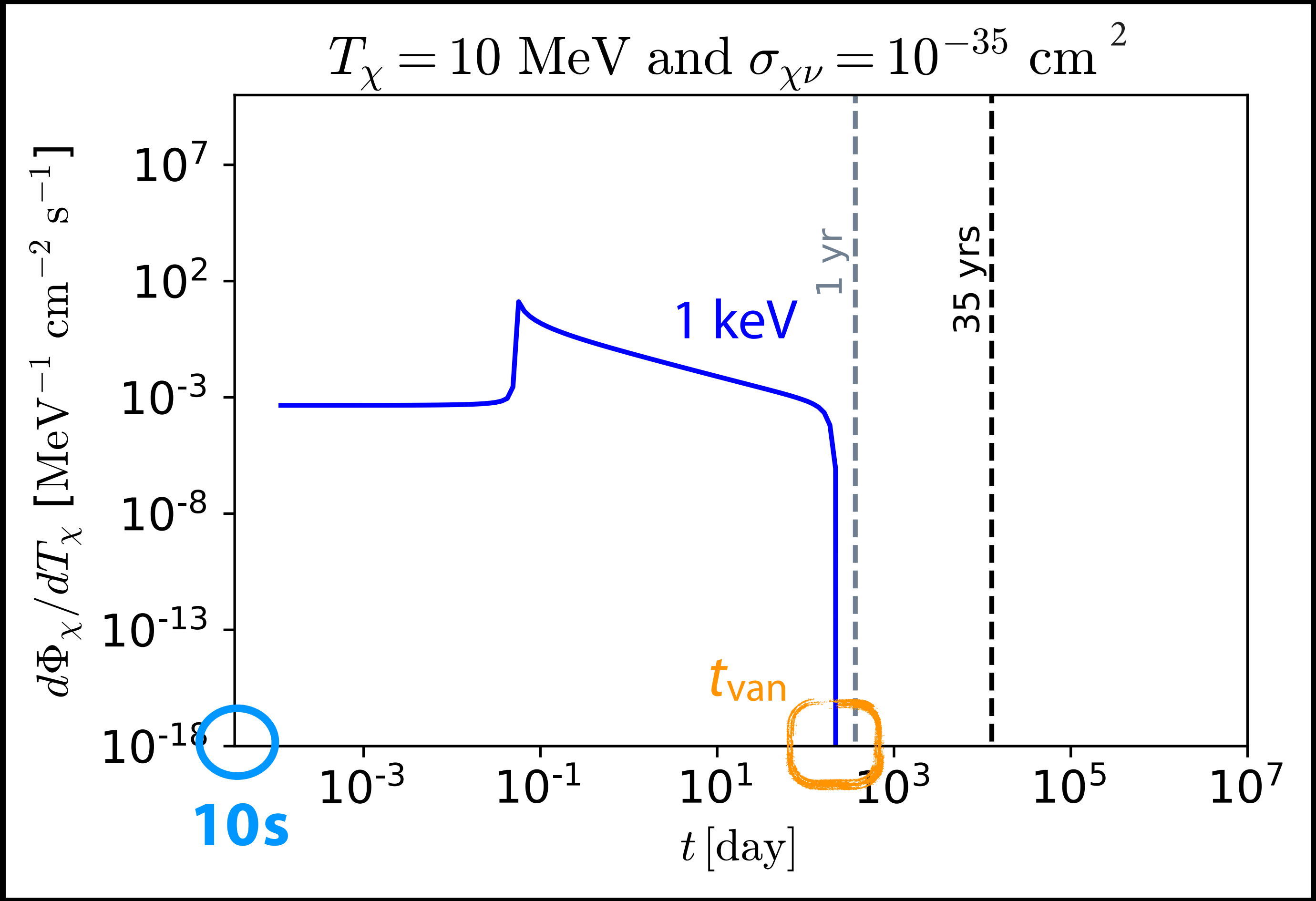

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- Can be derived by

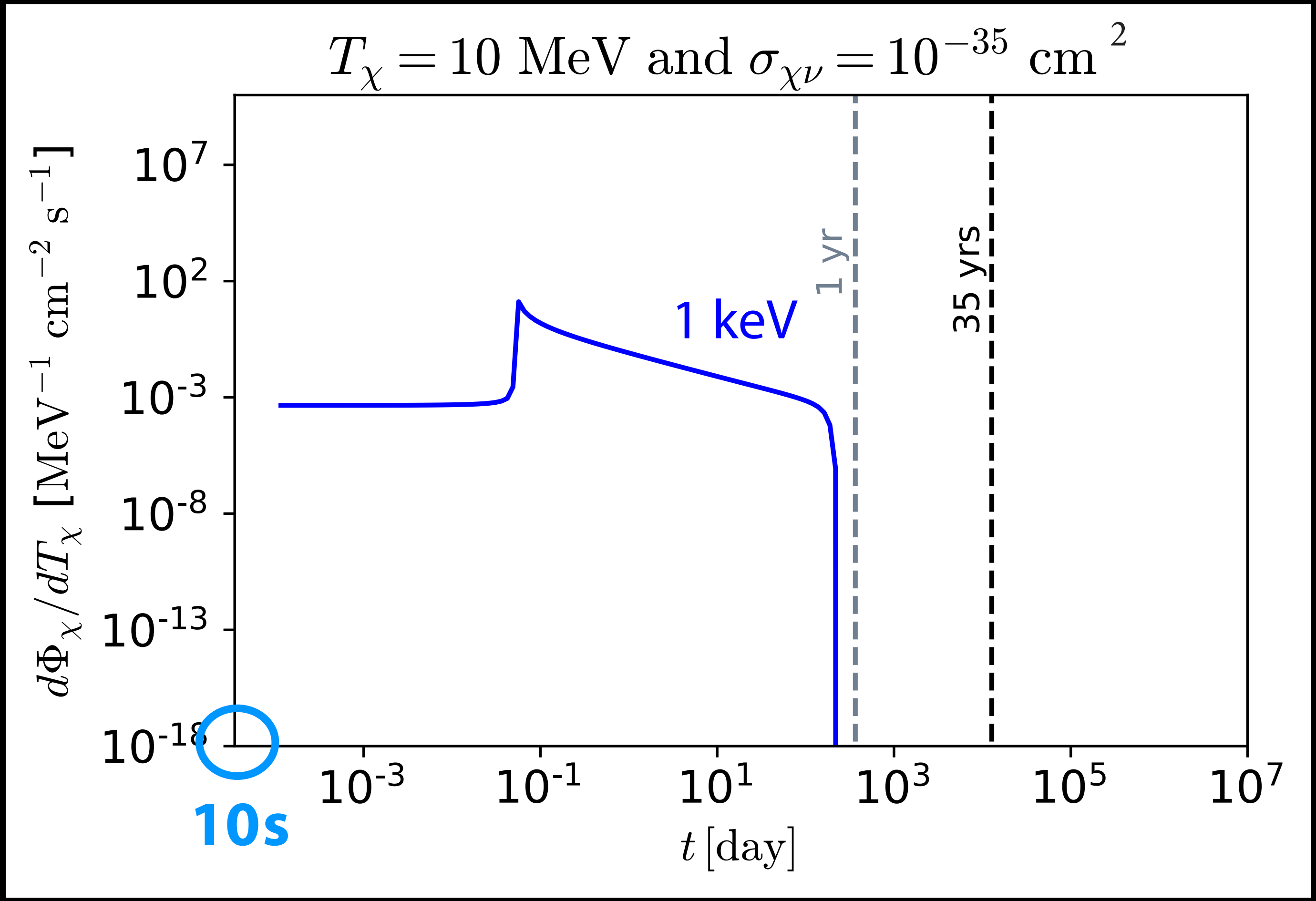
max. t and $f_\chi(\alpha_m) = 0$

which leads to the condition

$$\frac{\cos(\alpha_m - \theta)}{\cos\theta} = \frac{v_\chi(m_\chi)}{c}$$

BDM flux in MW & LMC

NFW for MW



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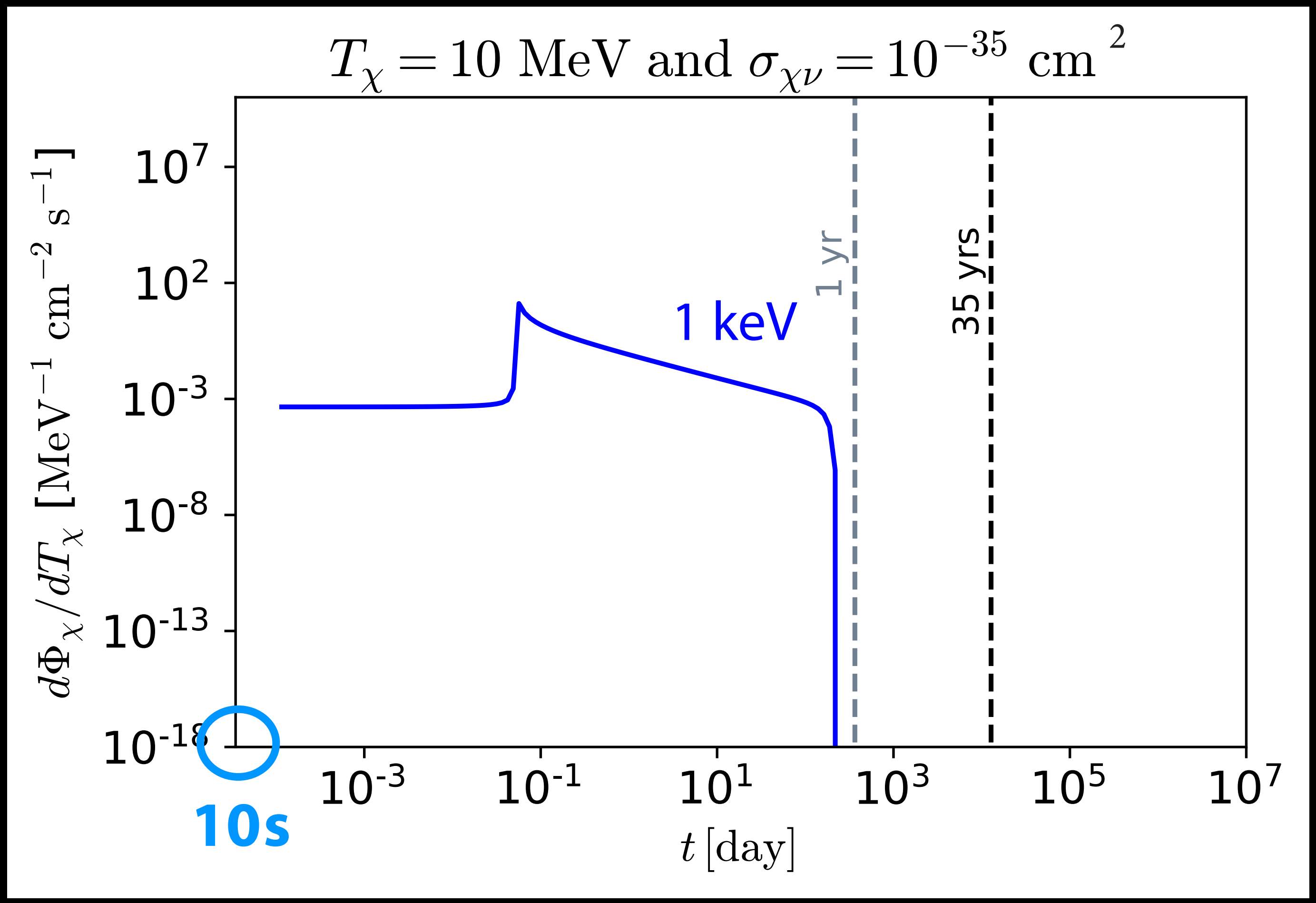

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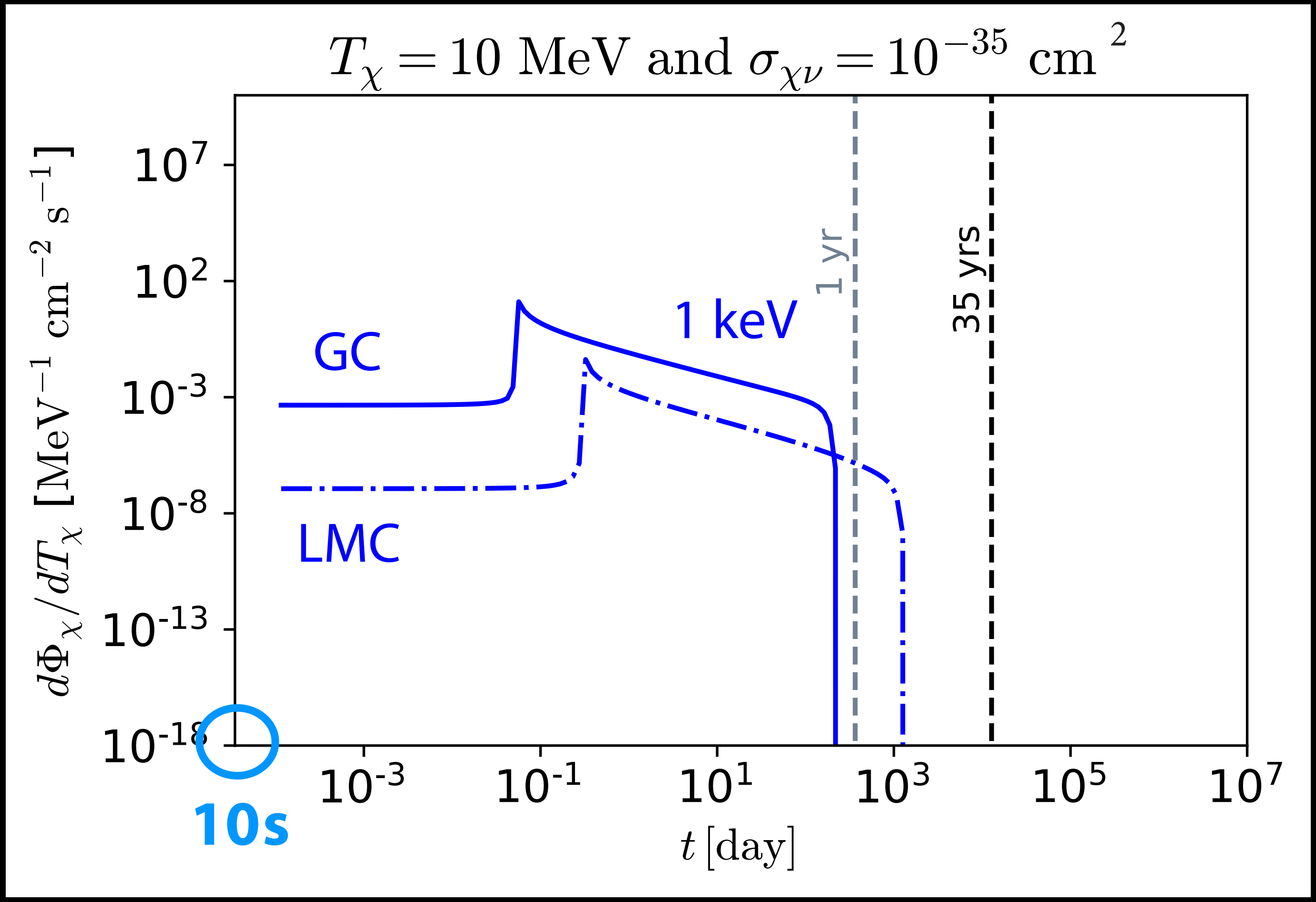

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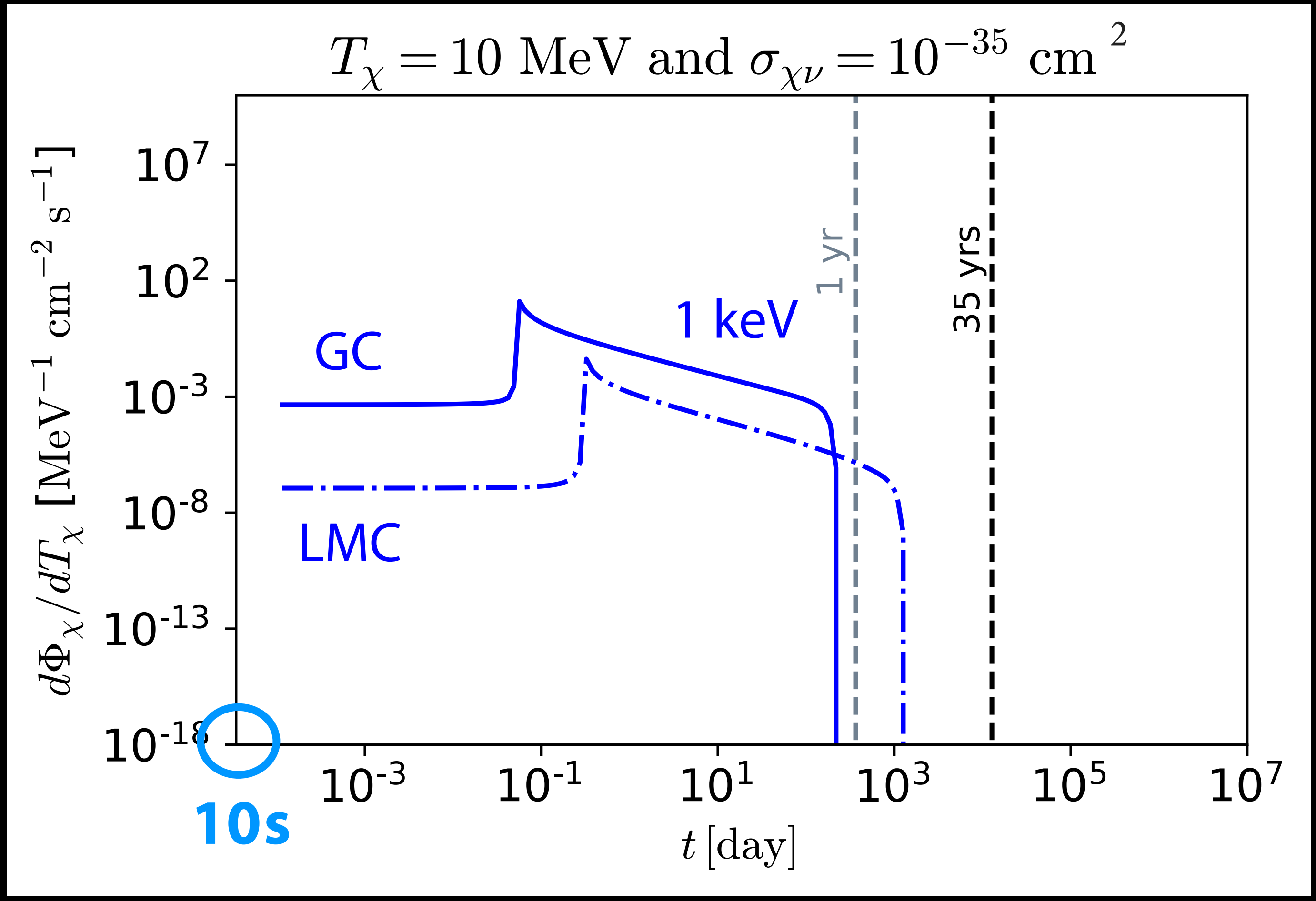

- t_p for LMC is delayed accordingly due to R_{LMC} = 50 kpc > R_{GC} = 8.5 kpc

BDM flux in MW & LMC

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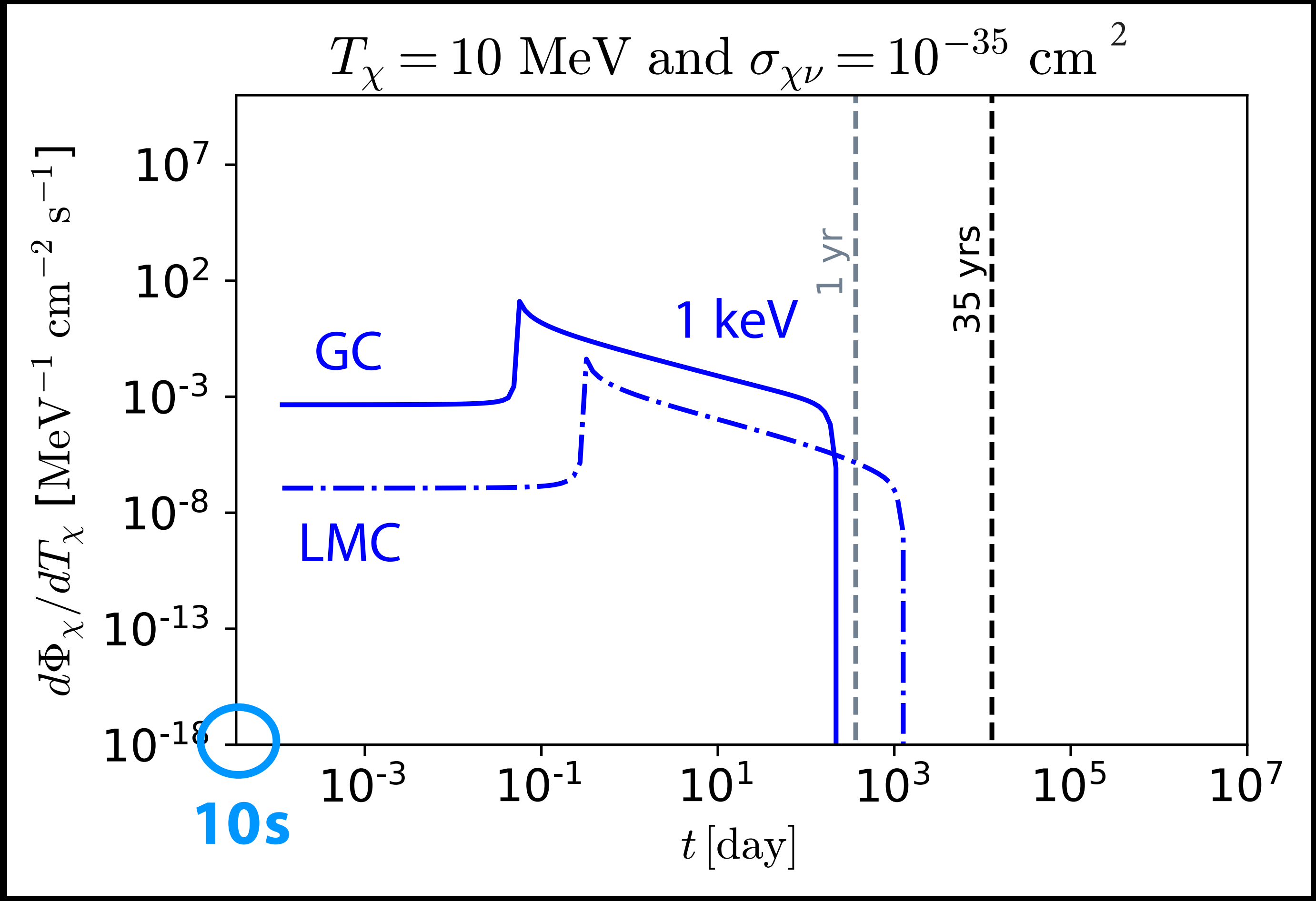

- t_p for LMC is delayed accordingly due to $R_{\mathrm{LMC}} = 50$ kpc > $R_{\mathrm{GC}} = 8.5$ kpc
- The LMC flux is smaller due to dilution from longer distance

BDM flux in MW & LMC

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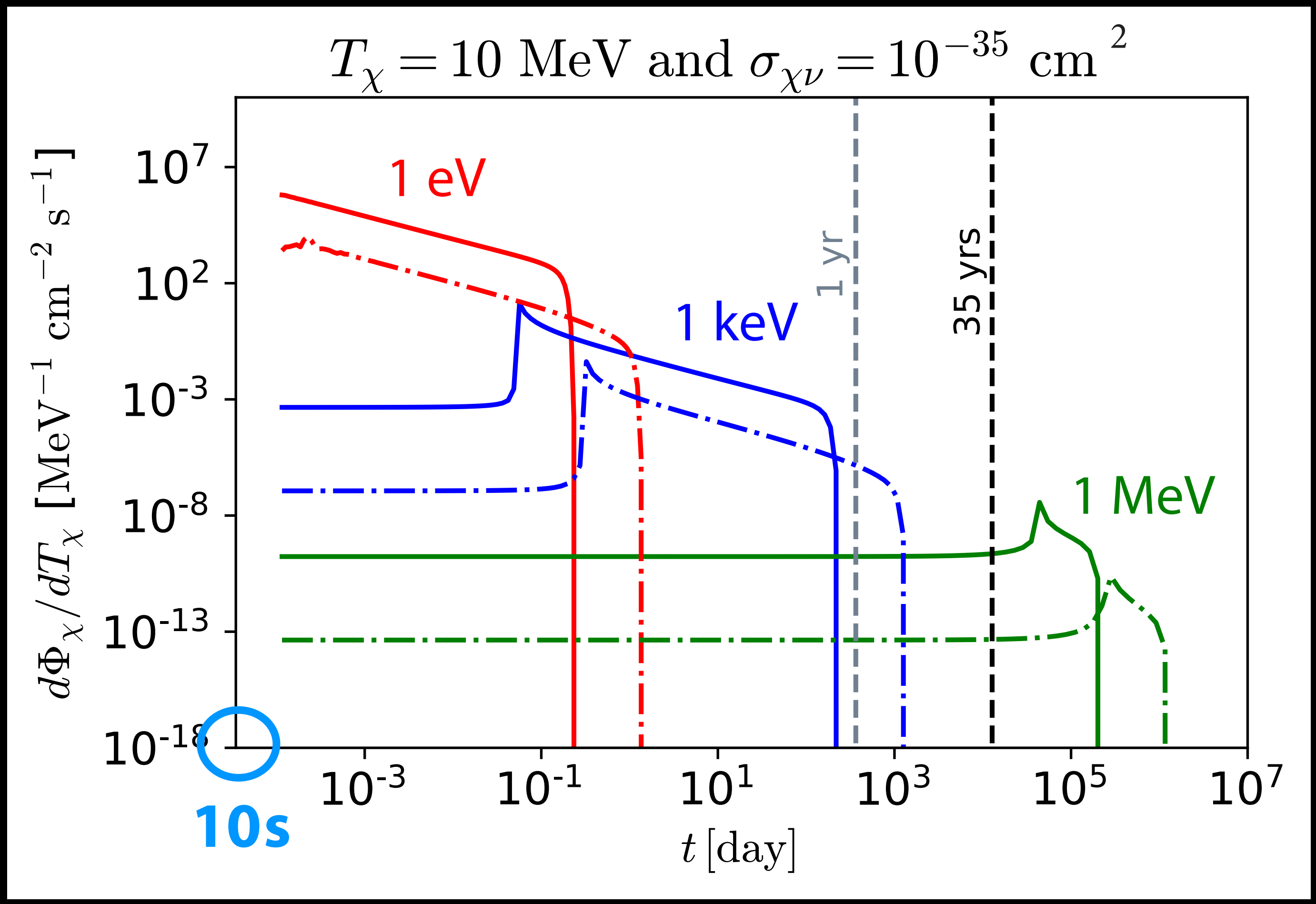
- BDM flux vs. m_χ



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BDM flux in MW & LMC

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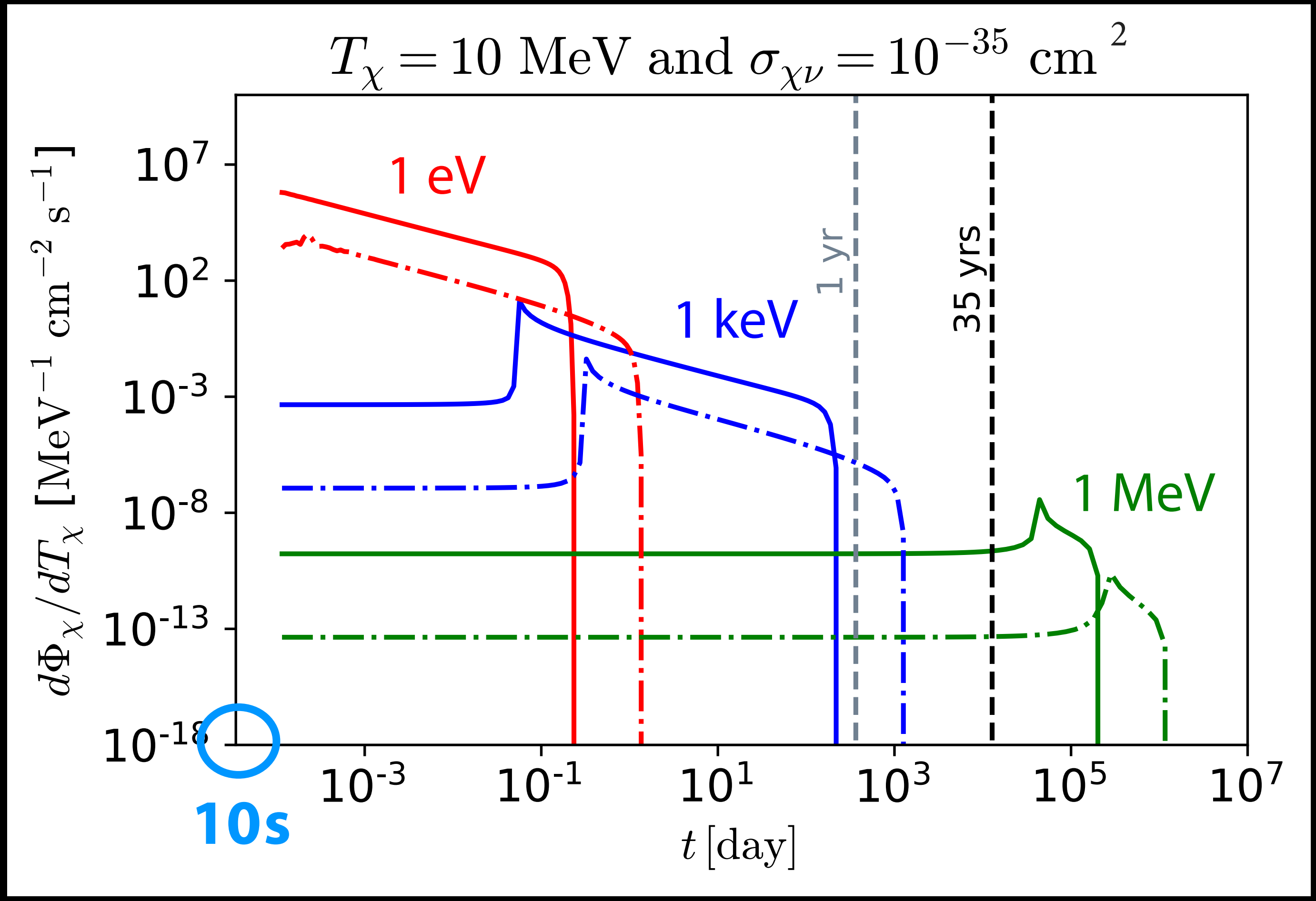
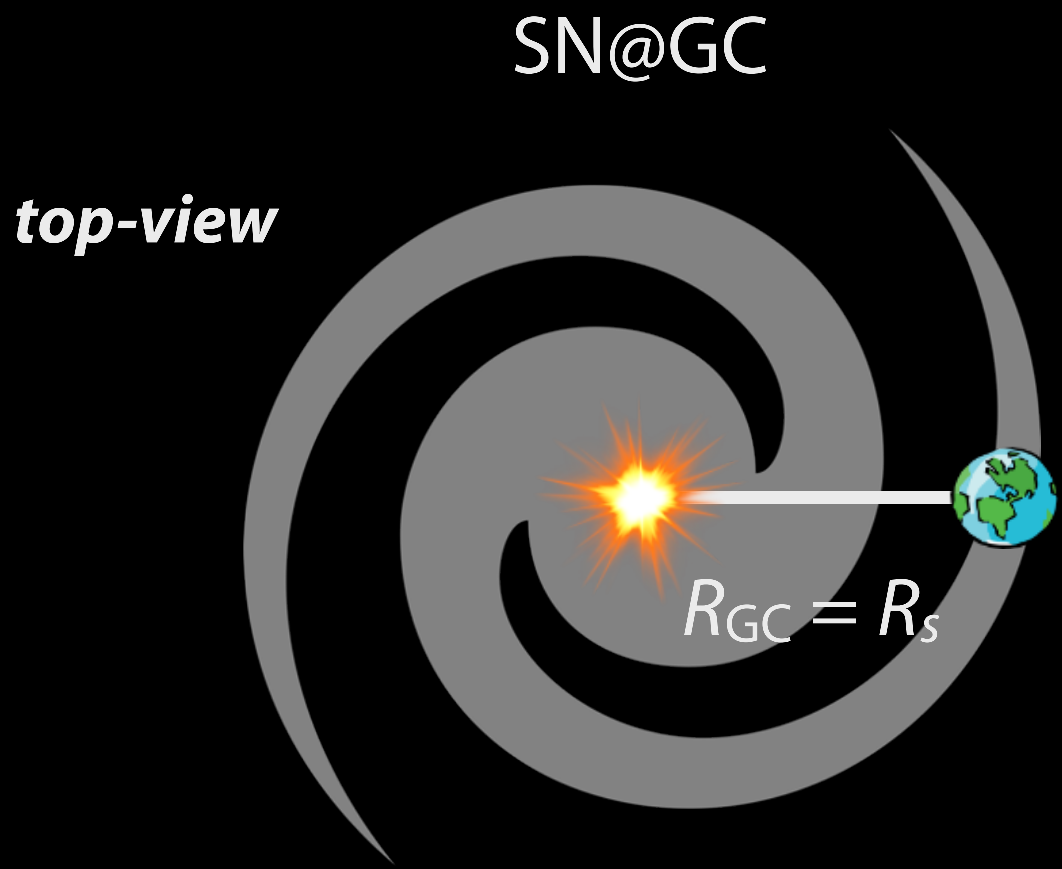
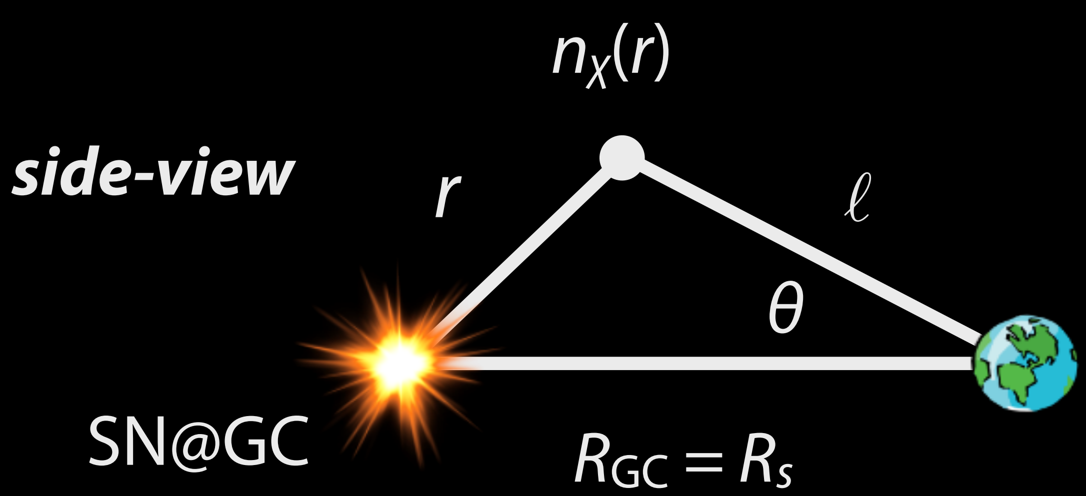


- t_p for LMC is delayed accordingly due to $R_{\mathrm{LMC}} = 50$ kpc > $R_{\mathrm{GC}} = 8.5$ kpc
- The LMC flux is smaller due to dilution from longer distance
- Lighter m_χ could have t_p smaller than t_0 due to $v_\chi \to c$

SN is off the GC





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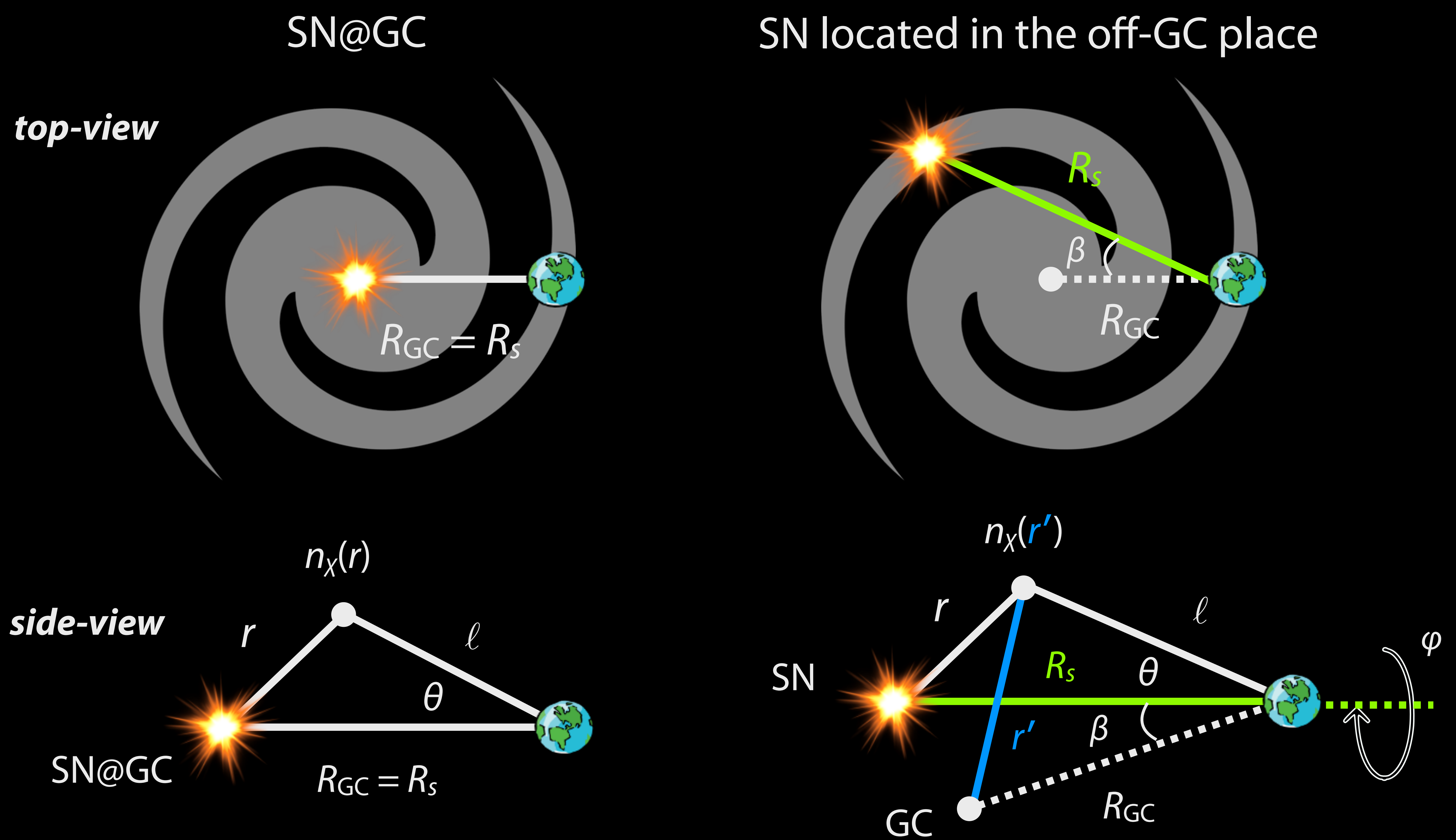
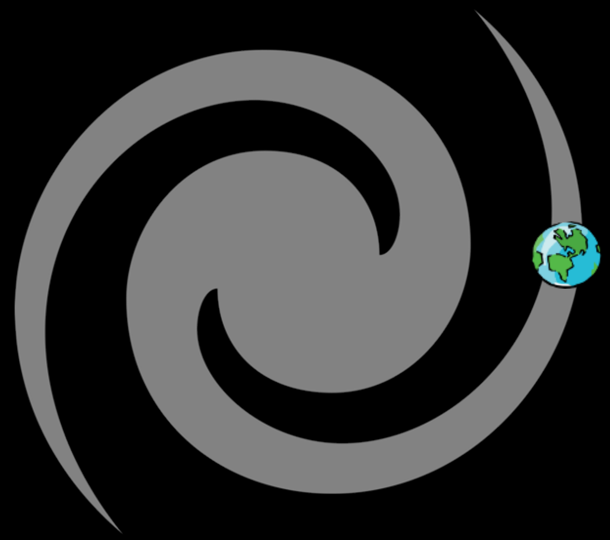
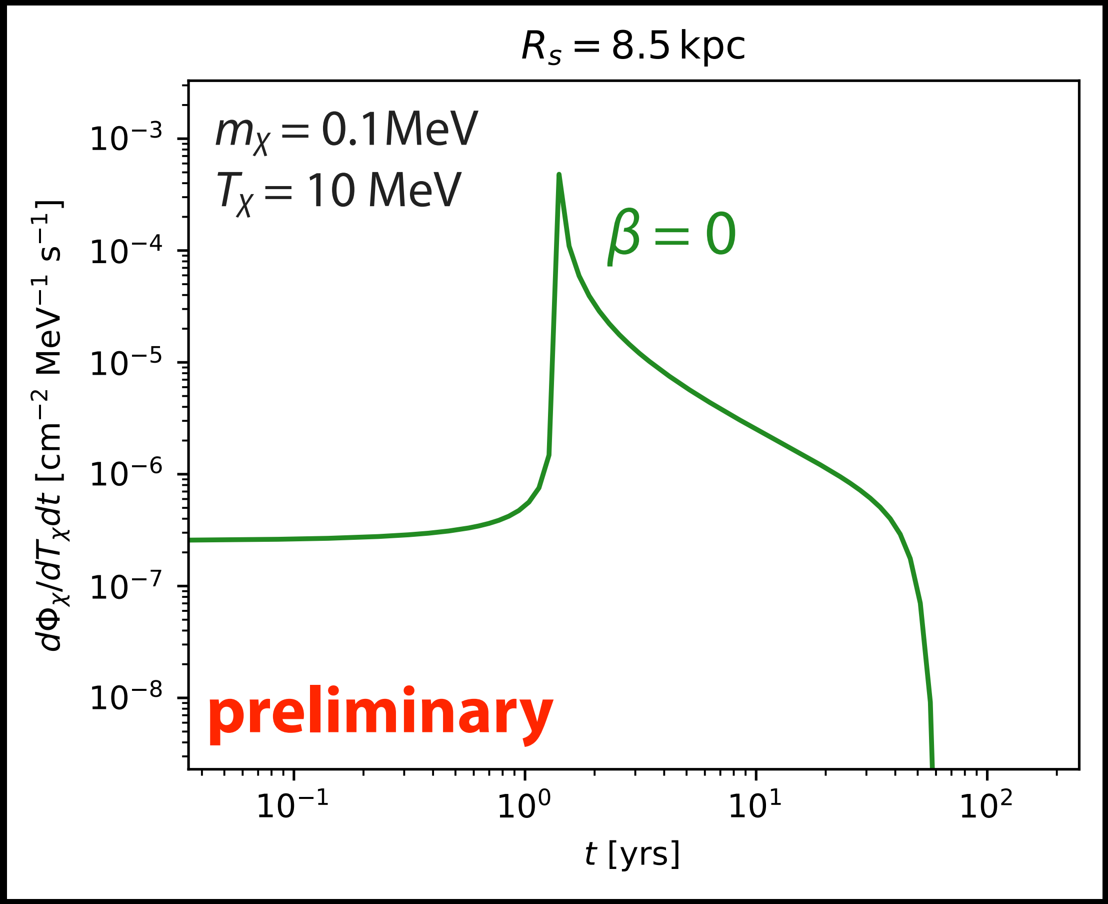
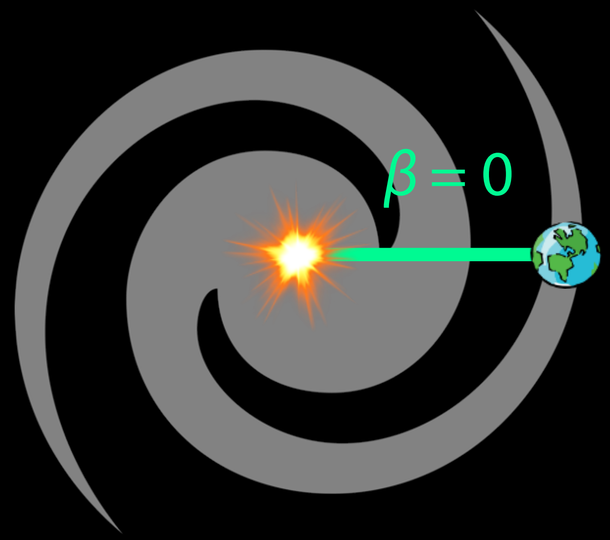




$R_S = 8.5$ kpc vs. β





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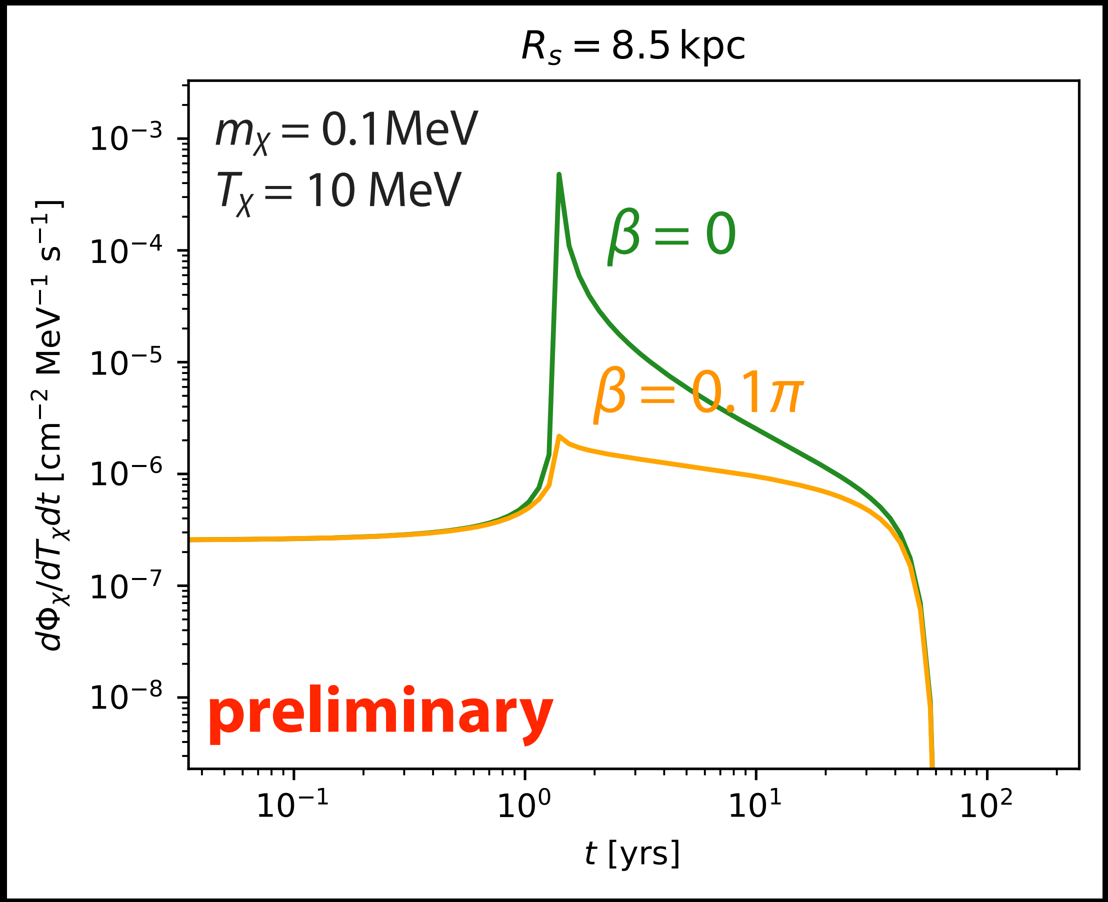

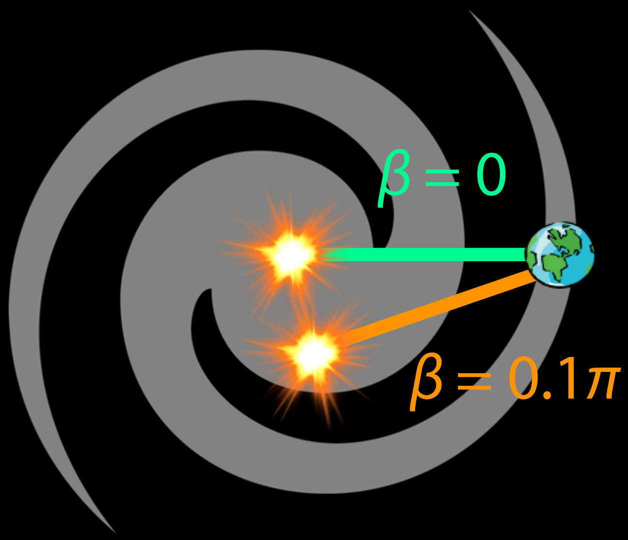

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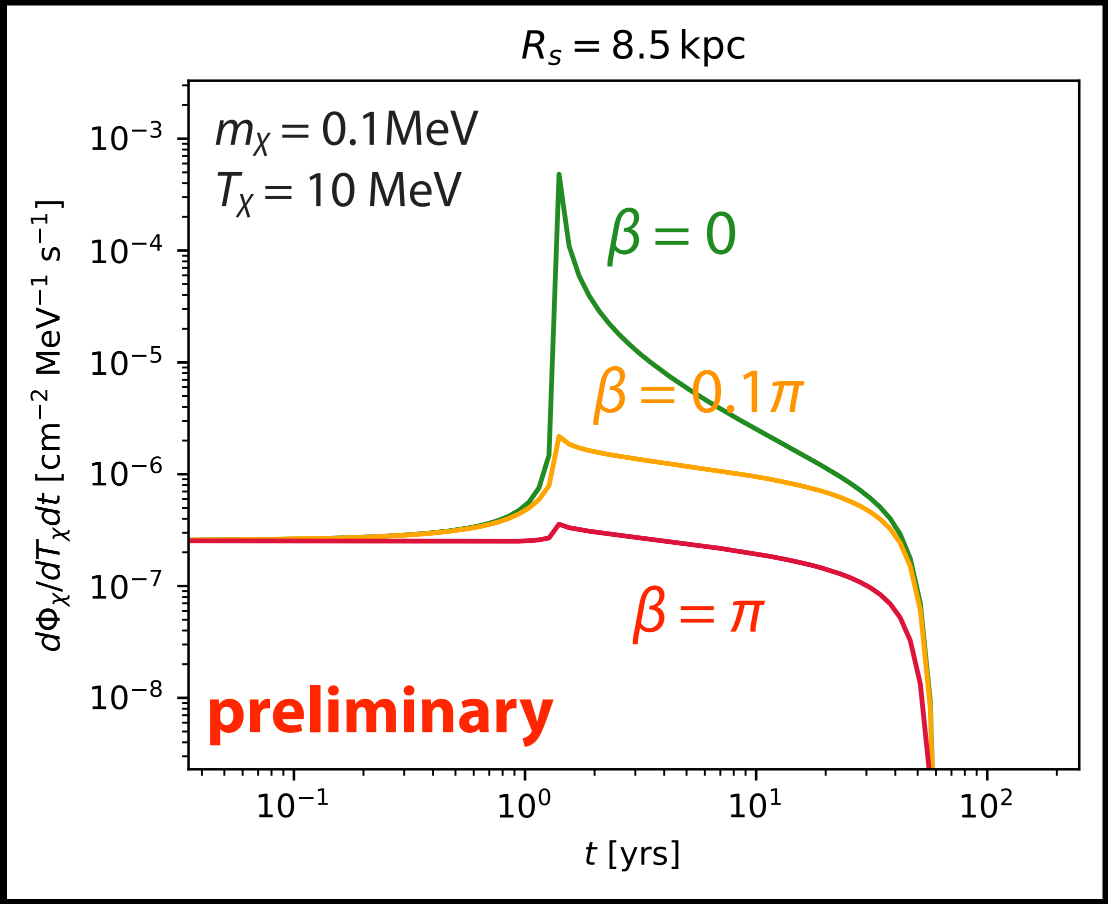

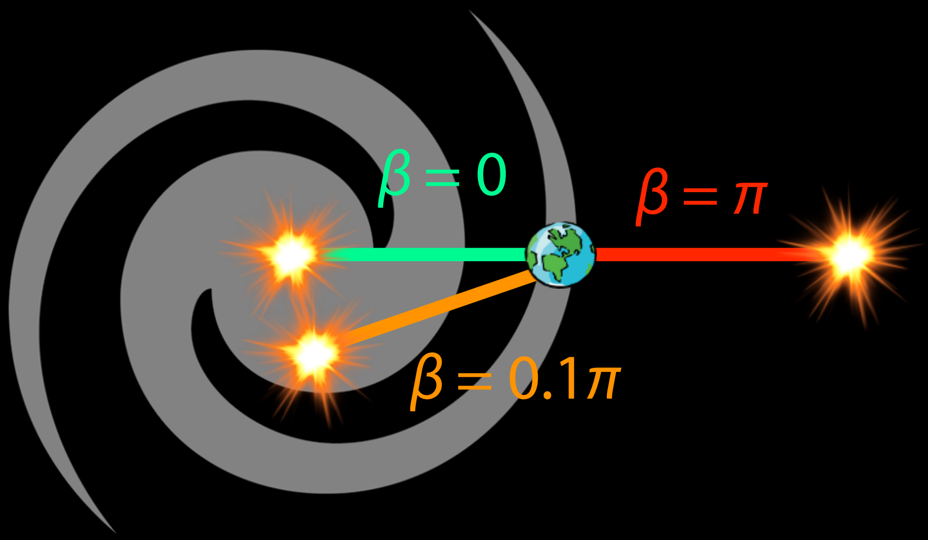

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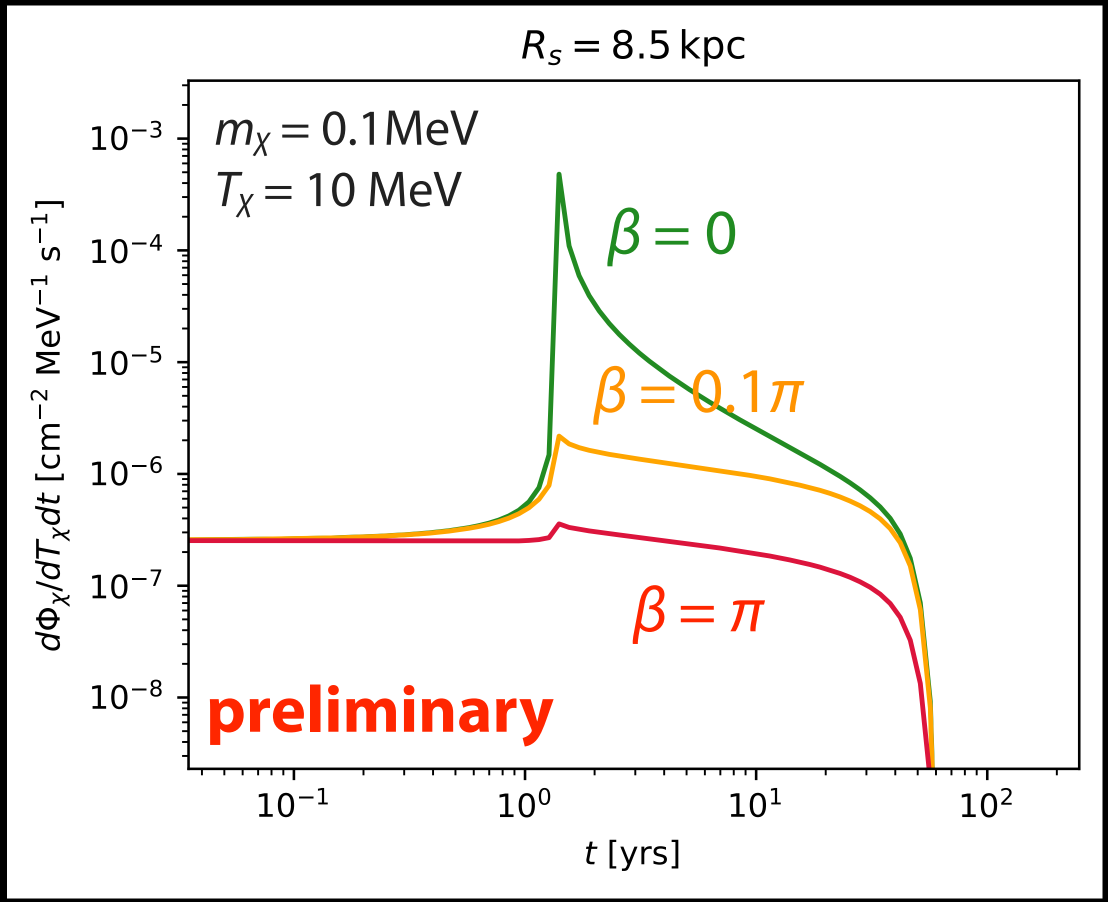
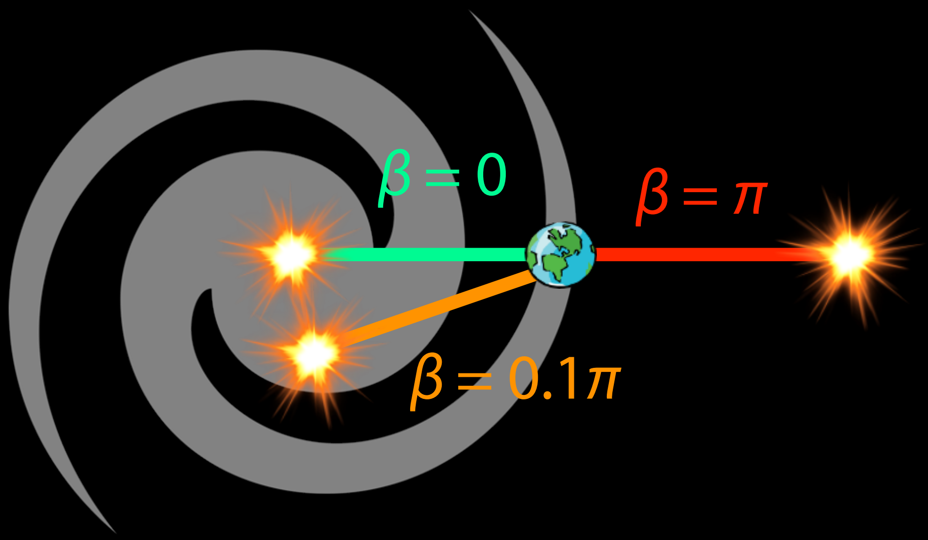
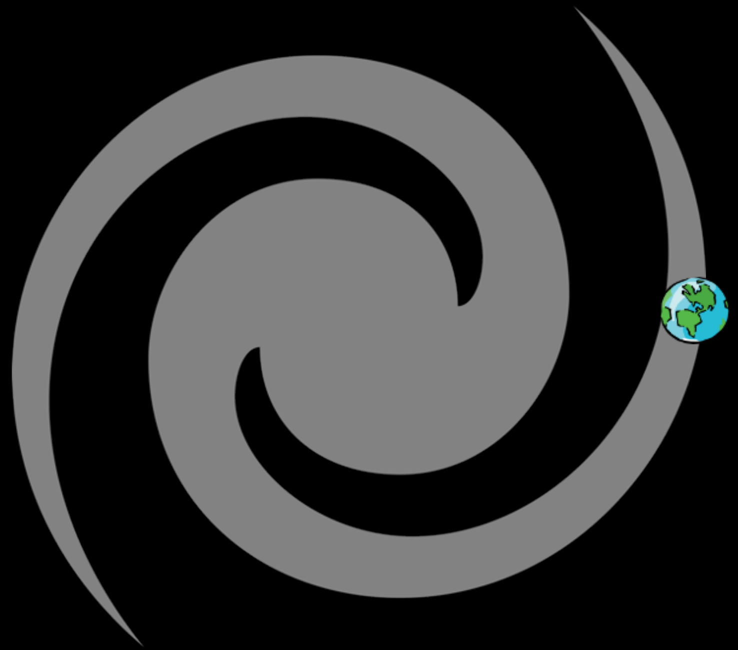
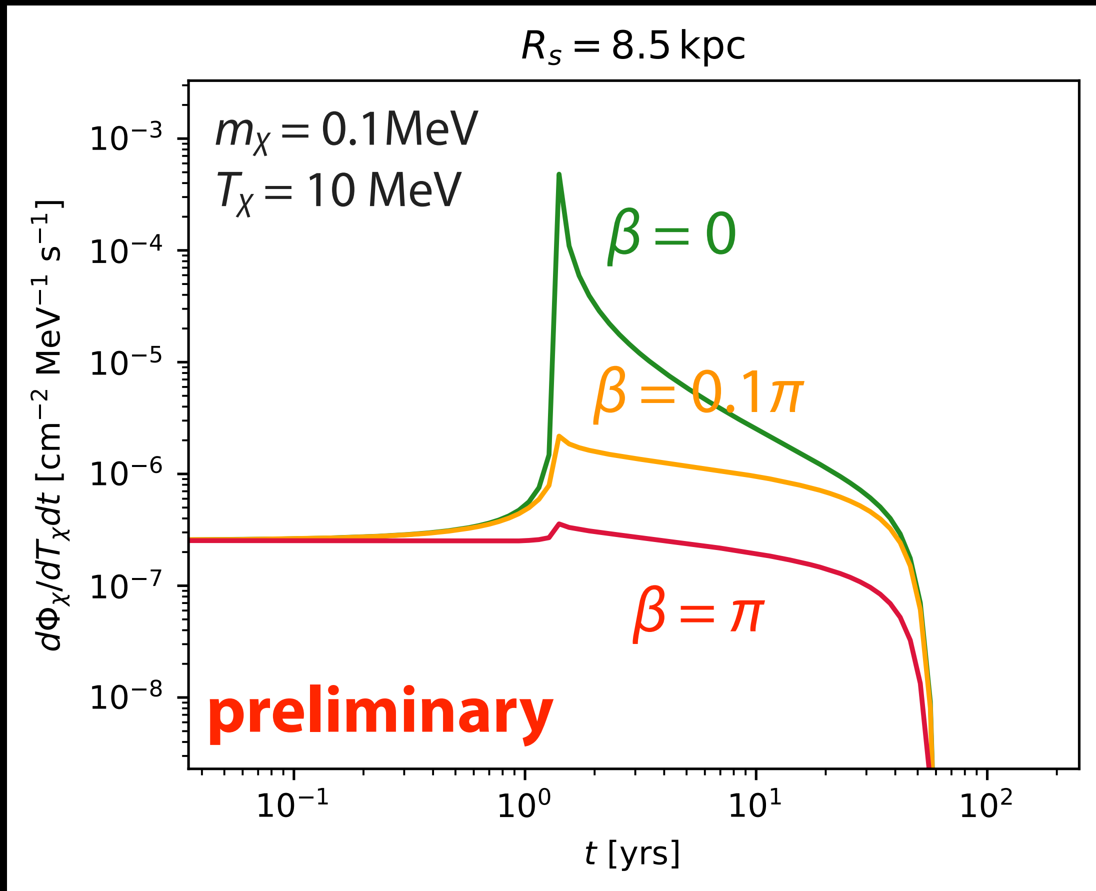


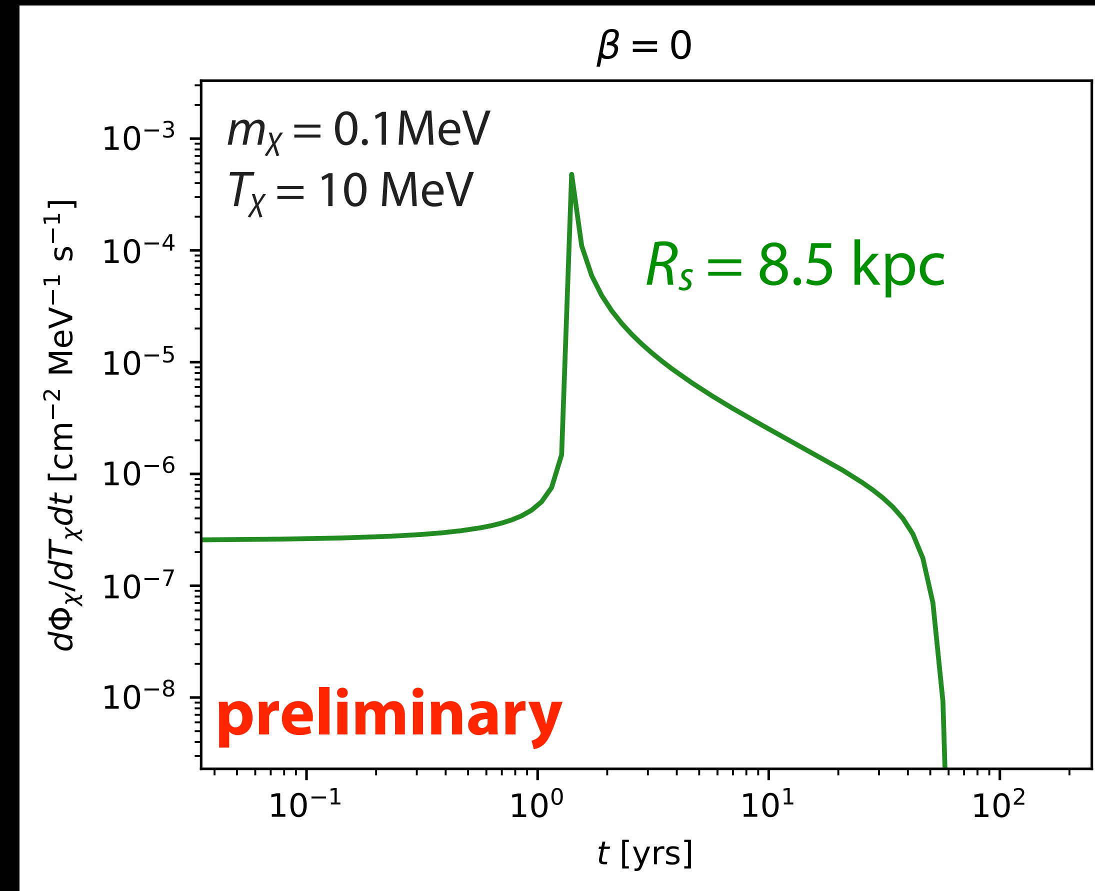


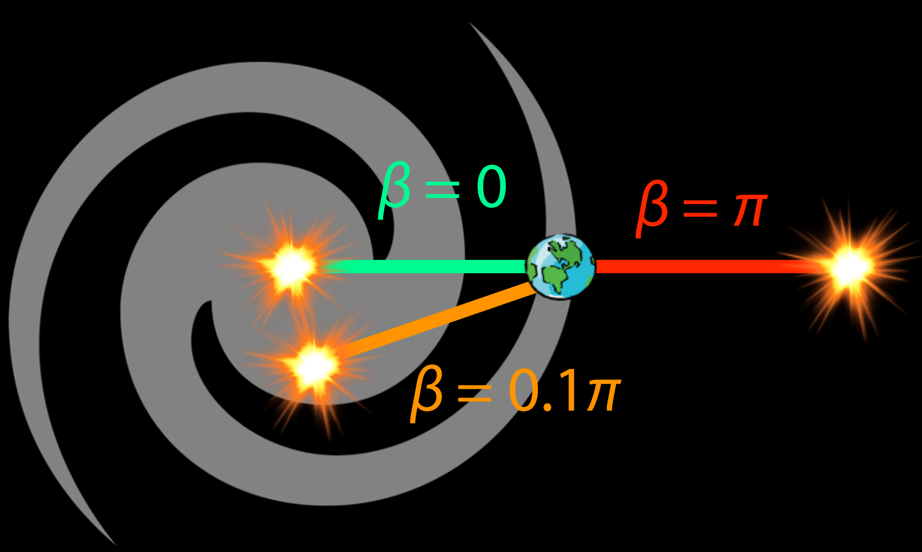
$R_s = 8.5$ kpc vs. β



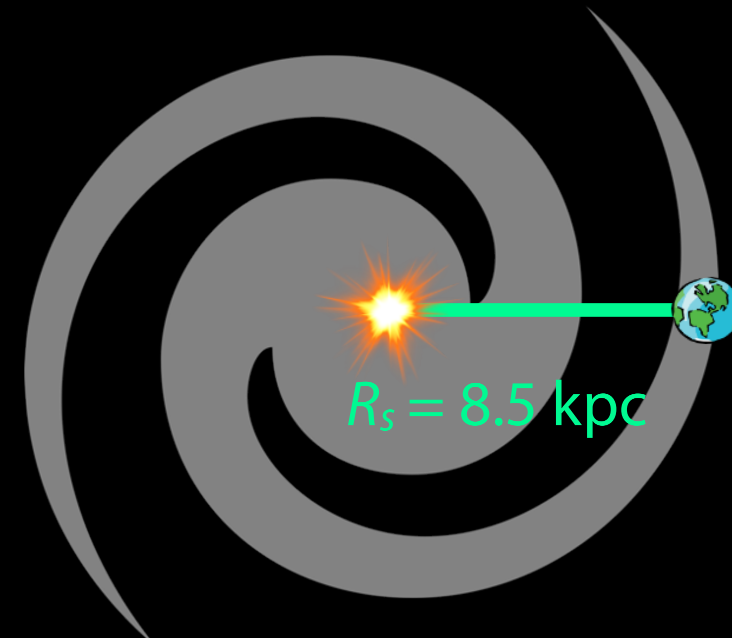
$\beta = 0$ vs. R_s



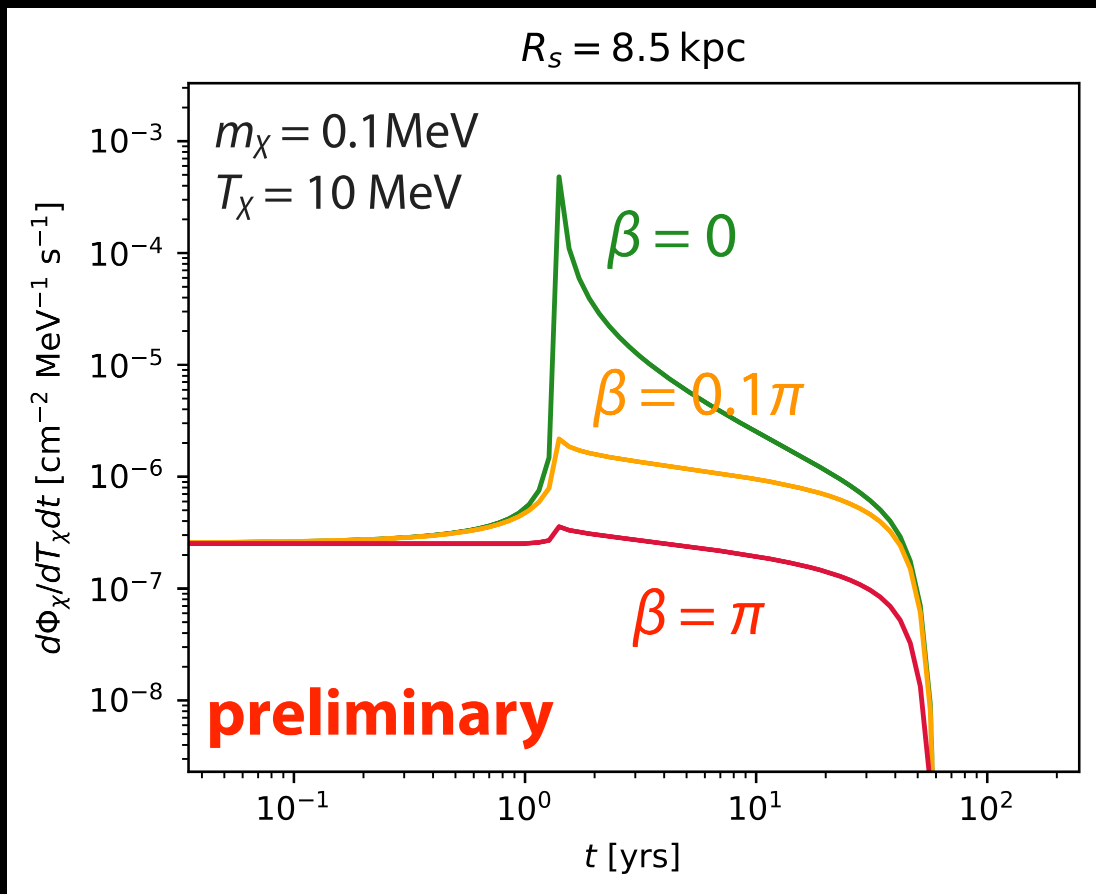


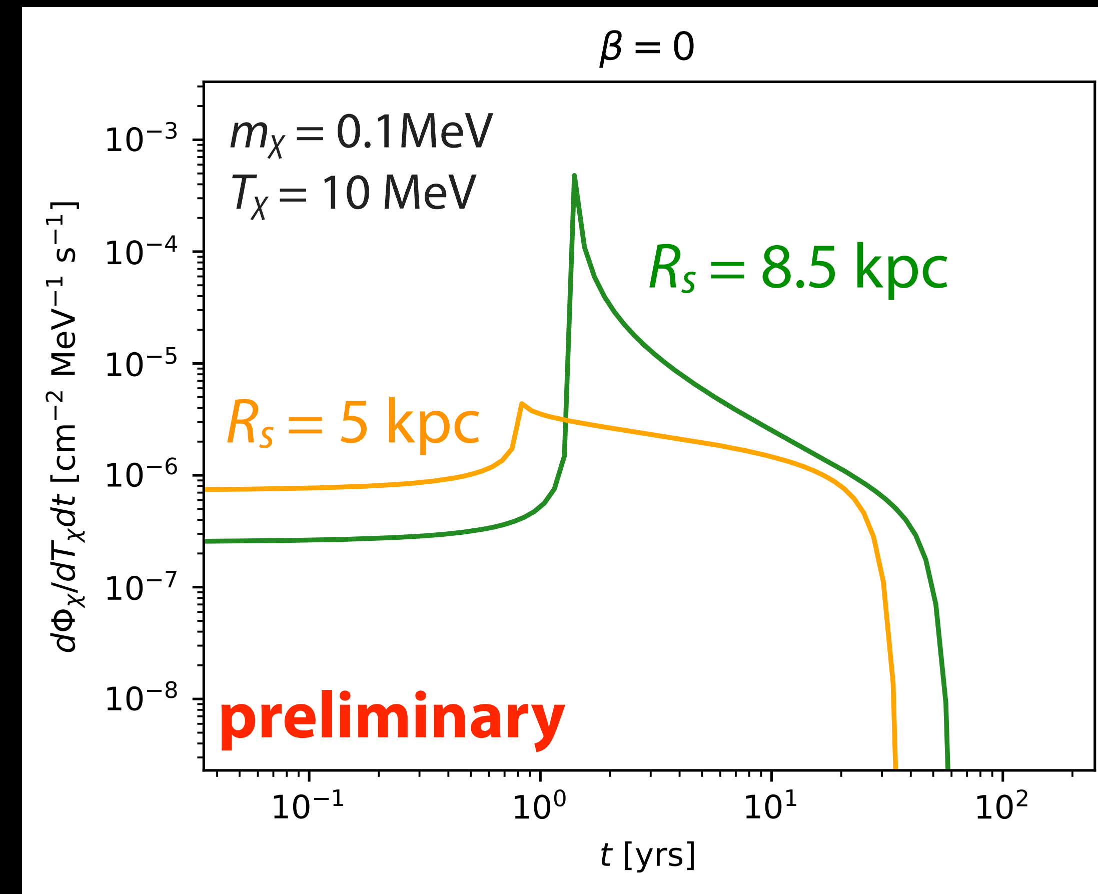


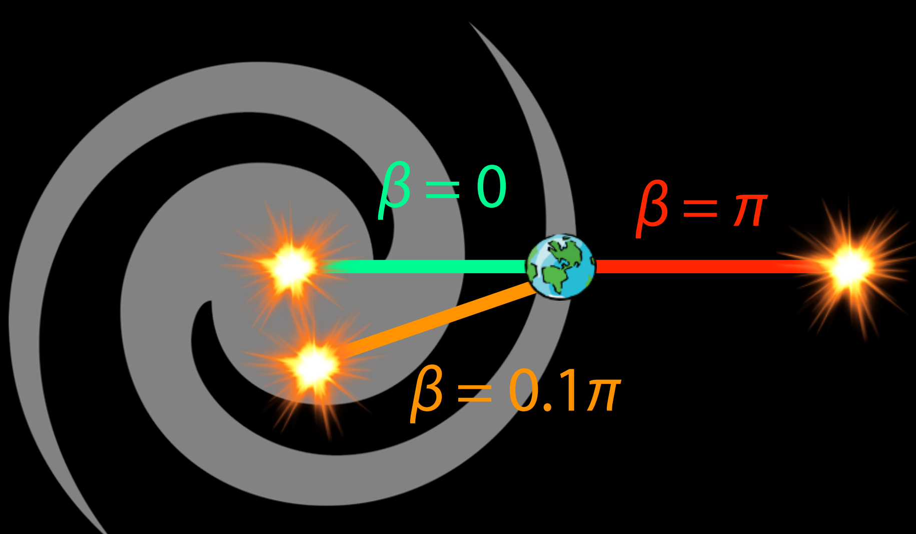
$R_s = 8.5$ kpc vs. β



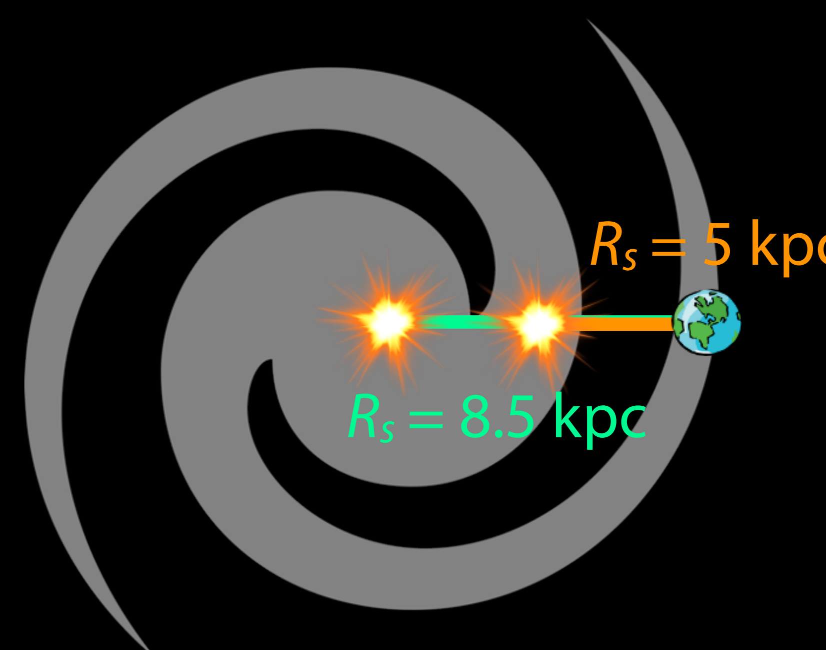
$\beta = 0$ vs. R_s



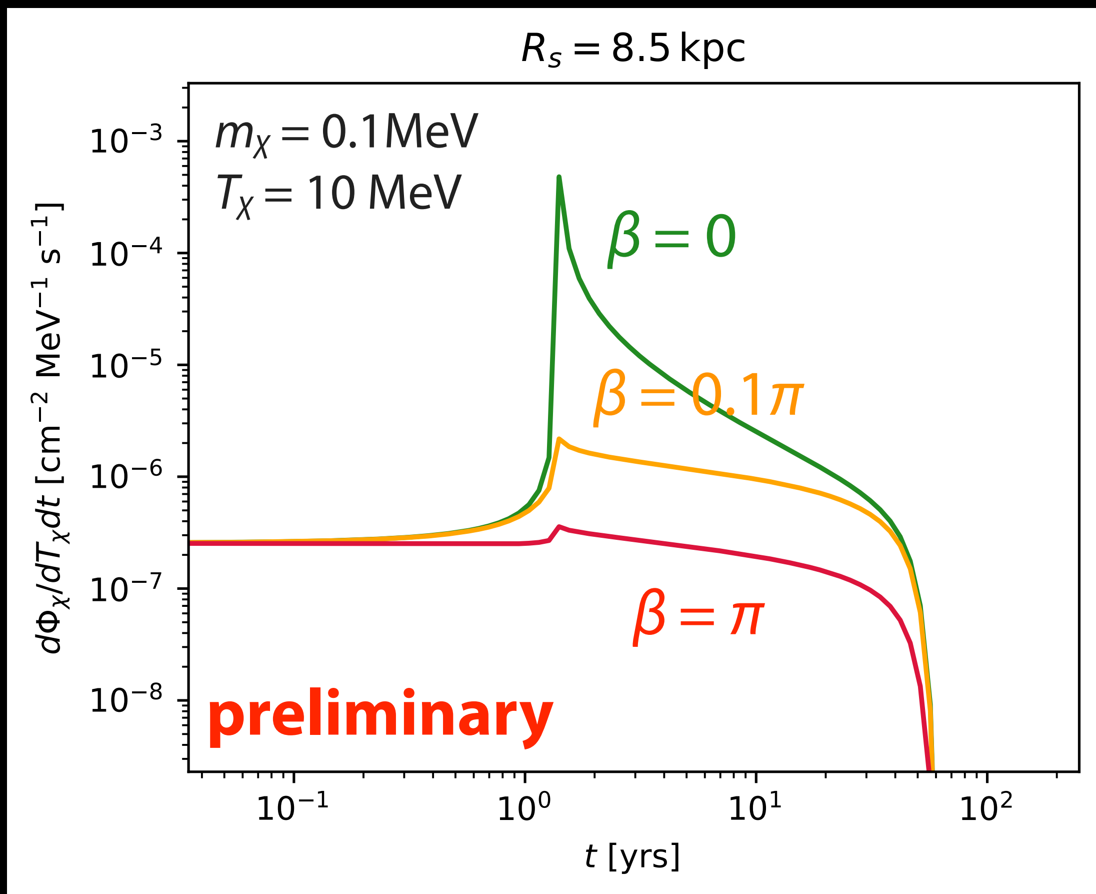


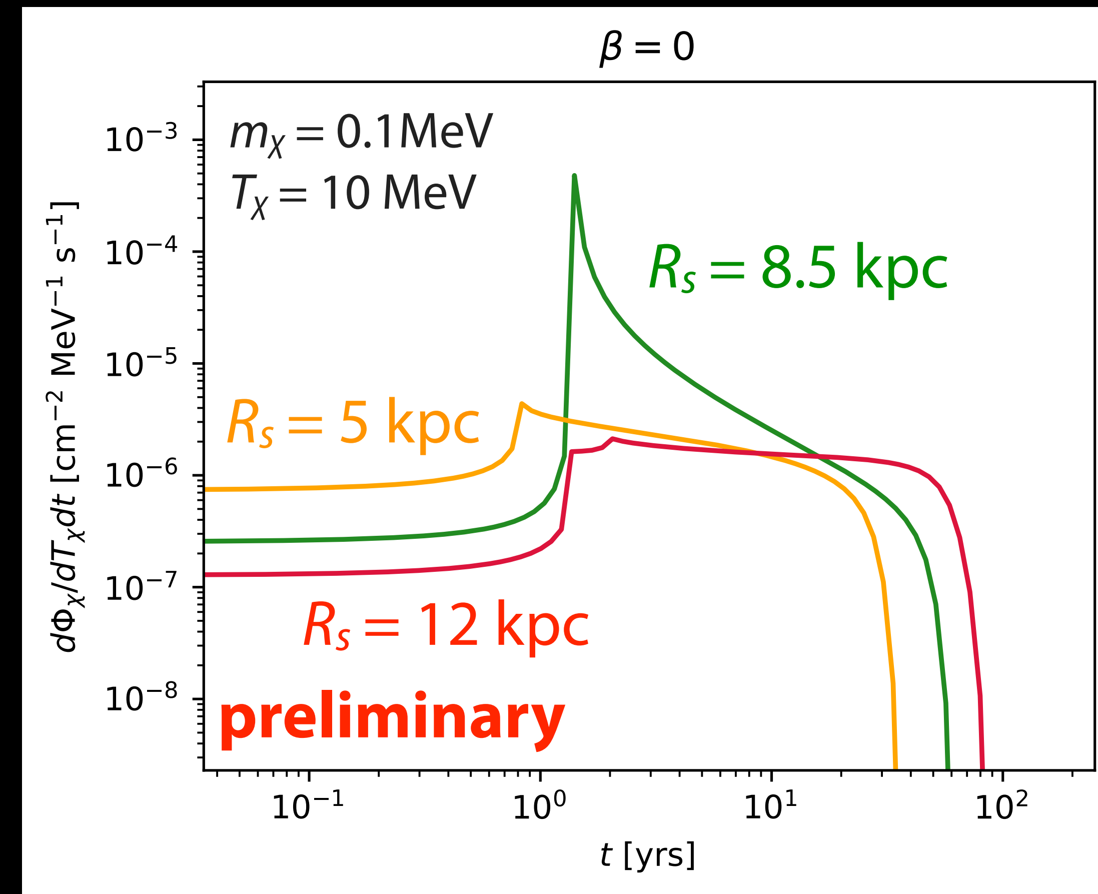


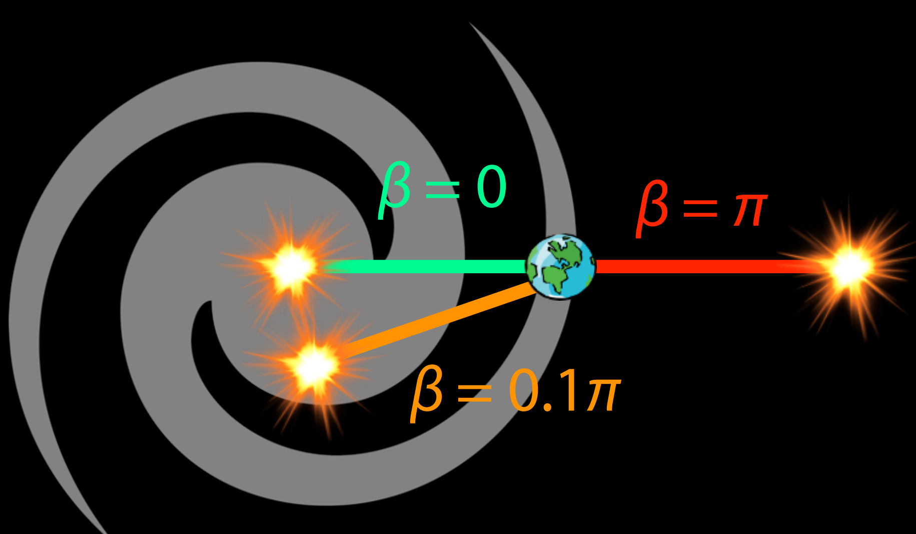
$R_s = 8.5$ kpc vs. β



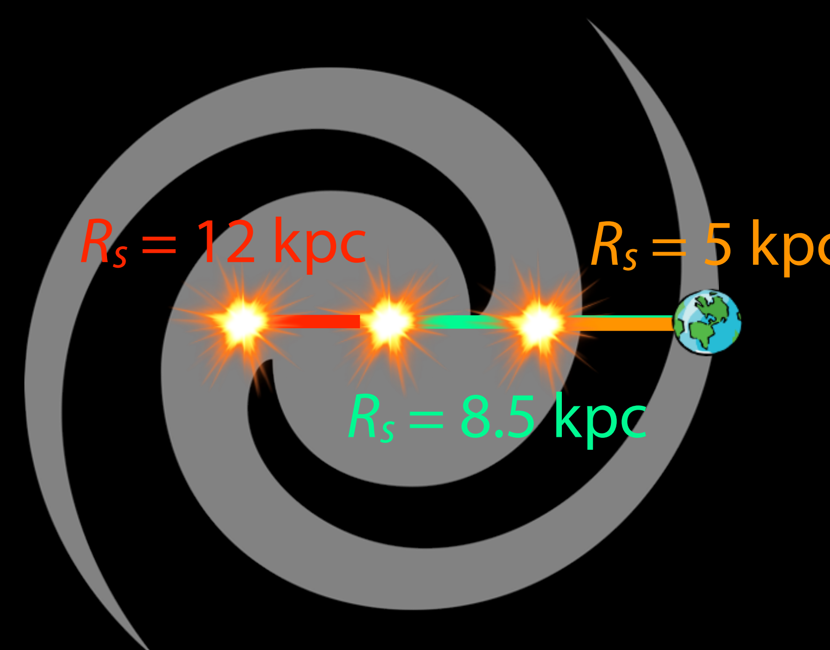
$\beta = 0$ vs. R_s







$R_s = 8.5$ kpc vs. β



$\beta = 0$ vs. R_s

Constraint and projected sensitivity

BDM event in the detector

BDM event in the detector

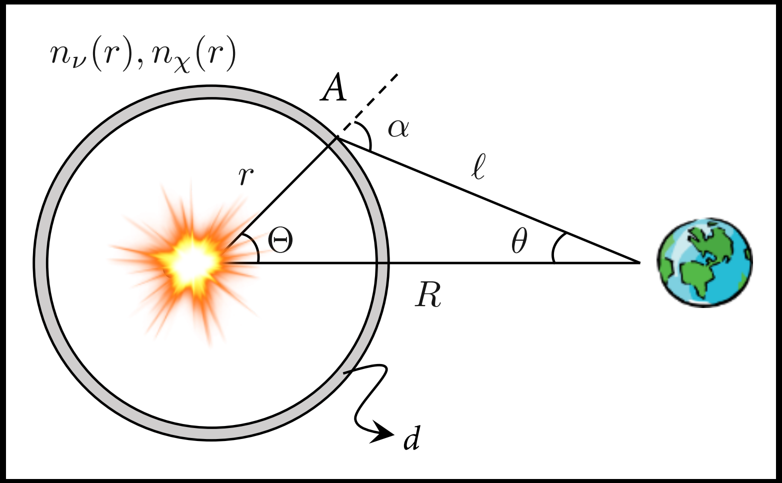
- The BDM event number estimation

$$N_\chi = N_e \sigma_{\chi e} \int_{t_0}^{t_{\mathrm{exp}}} dt \int_{T_{\mathrm{th}}}^{T_{\mathrm{max}}} dT_\chi \int_0^{\pi/2} 2\pi \sin\theta d\theta \frac{d\Phi_\chi}{dT_\chi d\Omega} \propto \sigma_{\chi e} \sigma_{\chi \nu}$$

BDM event in the detector

- The BDM event number estimation

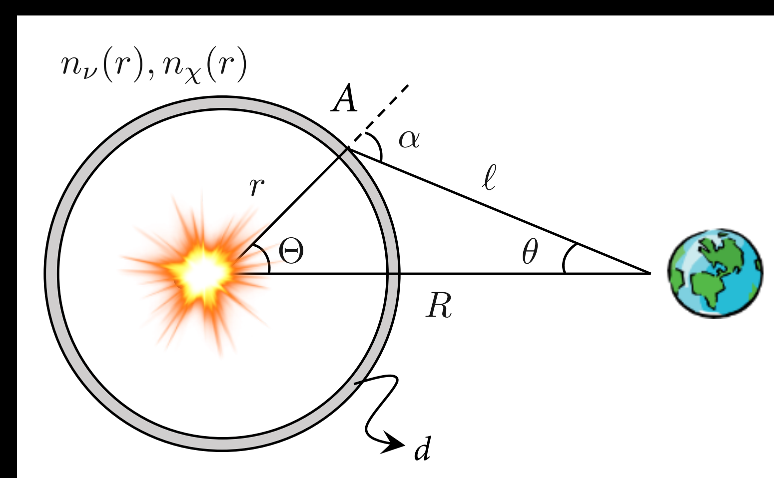
$$N_\chi = N_e \sigma_{\chi e} \int_{t_0}^{t_{\rm exp}} dt \int_{T_{\rm th}}^{T_{\rm max}} dT_\chi \int_0^{\pi/2} \underbrace{2\pi \sin\theta d\theta \frac{d\Phi_\chi}{dT_\chi d\Omega}}_{\text{sky of interest}} \propto \sigma_{\chi e}\sigma_{\chi\nu}$$



BDM event in the detector

- The BDM event number estimation

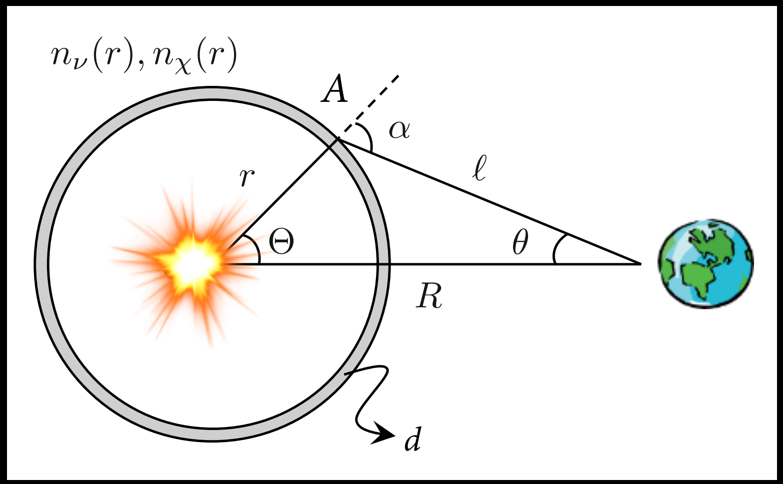
$$N_\chi = N_e \sigma_{\chi e} \int_{t_0}^{t_{\rm exp}} dt \underbrace{\int_{T_{\rm th}}^{T_{\rm max}} dT_\chi}_{\text{energy of interest}} \underbrace{\int_0^{\pi/2} 2\pi \sin\theta d\theta}_{\text{sky of interest}} \frac{d\Phi_\chi}{dT_\chi d\Omega} \propto \sigma_{\chi e}\sigma_{\chi\nu}$$



BDM event in the detector

- The BDM event number estimation

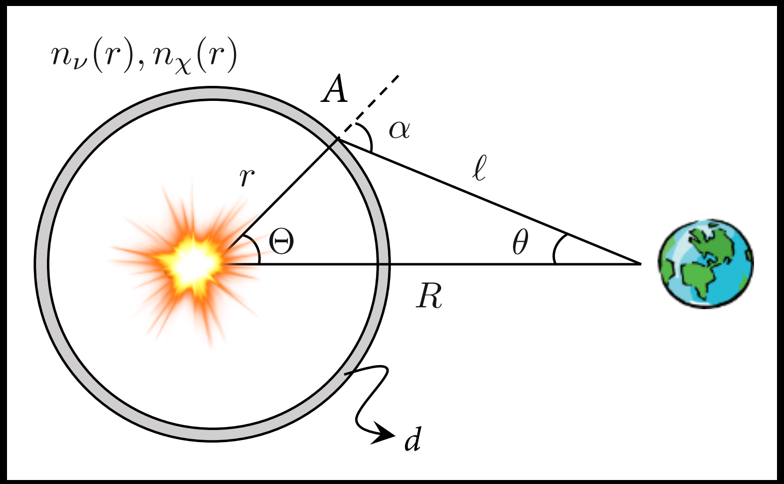
$$N_\chi = N_e \sigma_{\chi e} \underbrace{\int_{t_0}^{t_{\rm exp}} dt}_{\text{exposure time}} \underbrace{\int_{T_{\rm th}}^{T_{\rm max}} dT_\chi}_{\text{energy of interest}} \underbrace{\int_0^{\pi/2} 2\pi \sin\theta d\theta}_{\text{sky of interest}} \frac{d\Phi_\chi}{dT_\chi d\Omega} \propto \sigma_{\chi e}\sigma_{\chi\nu}$$



BDM event in the detector

- The BDM event number estimation

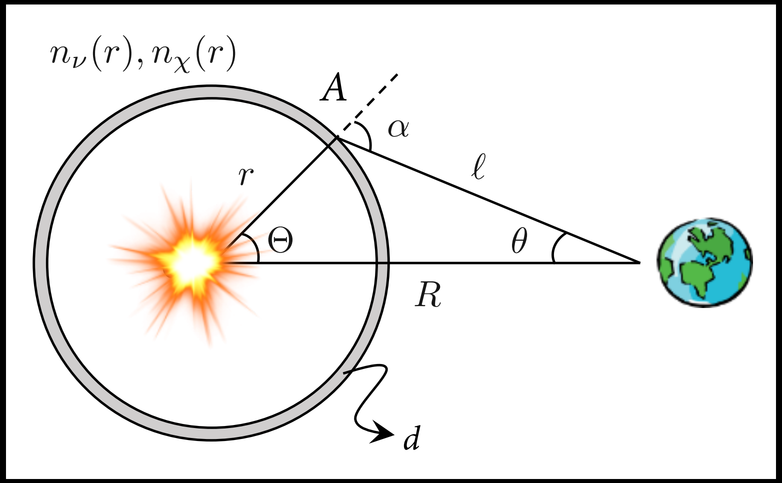
$$N_\chi = N_e \sigma_{\chi e} \underbrace{\int_{t_0}^{t_{\rm exp}} dt}_{\text{exposure time}} \underbrace{\int_{T_{\rm th}}^{T_{\rm max}} dT_\chi}_{\text{energy of interest}} \underbrace{\int_0^{\pi/2} 2\pi \sin\theta d\theta}_{\text{sky of interest}} \frac{d\Phi_\chi}{dT_\chi d\Omega} \propto \boxed{\sigma_{\chi e}\sigma_{\chi\nu}}$$



BDM event in the detector

- The BDM event number estimation

$$N_\chi = N_e \sigma_{\chi e} \underbrace{\int_{t_0}^{t_{\rm exp}} dt}_{\text{exposure time}} \underbrace{\int_{T_{\rm th}}^{T_{\rm max}} dT_\chi}_{\text{energy of interest}} \underbrace{\int_0^{\pi/2} 2\pi \sin\theta d\theta}_{\text{sky of interest}} \frac{d\Phi_\chi}{dT_\chi d\Omega} \propto \boxed{\sigma_{\chi e}\sigma_{\chi\nu}}$$

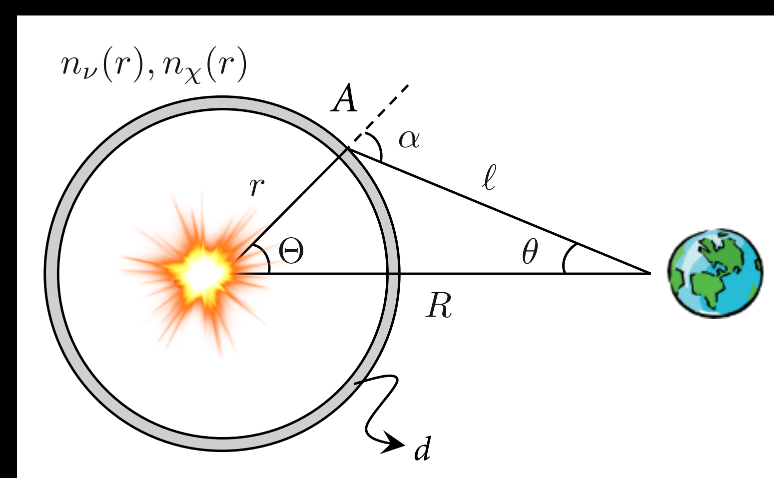


- Super-K and Hyper-K -like detectors: 22.5 and 225 ktons

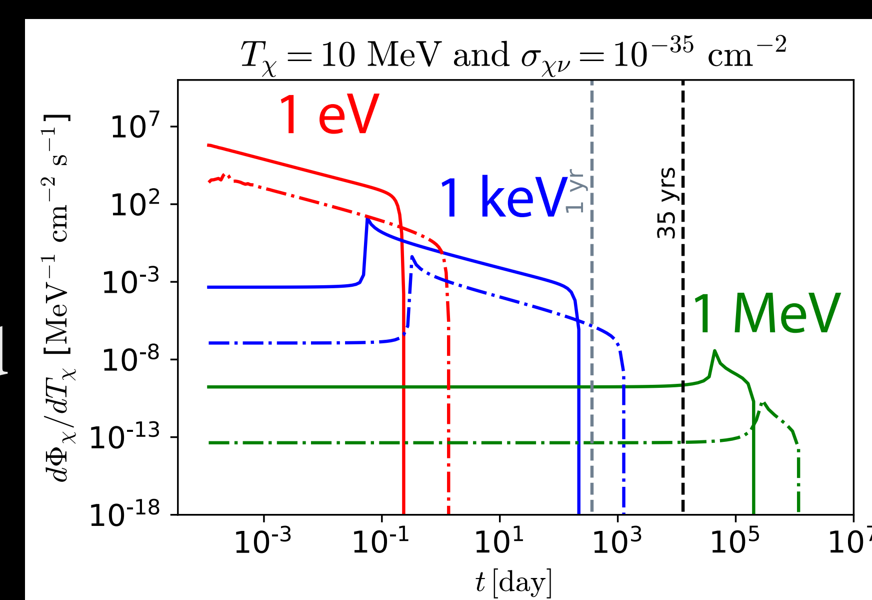
BDM event in the detector

- The BDM event number estimation

$$N_\chi = N_e \sigma_{\chi e} \underbrace{\int_{t_0}^{t_{\rm exp}} dt}_{\text{exposure time}} \underbrace{\int_{T_{\rm th}}^{T_{\max}} dT_\chi}_{\text{energy of interest}} \underbrace{\int_0^{\pi/2} 2\pi \sin\theta d\theta}_{\text{sky of interest}} \frac{d\Phi_\chi}{dT_\chi d\Omega} \propto \boxed{\sigma_{\chi e}\sigma_{\chi\nu}}$$



- Super-K and Hyper-K -like detectors: 22.5 and 225 ktons
- Exposure time: 10 s to $t_{\rm van}$ (duration of BDM flux, truncated at 35 yrs)



Directionality: θ-dependency

- The BDM event number

$$N_\chi = N_e \sigma_{\chi e} \int_{t_0}^{t_{\rm exp}} dt \int_{T_{\rm th}}^{T_{\max}} dT_\chi \underbrace{\int_{\Delta \cos\theta} 2\pi \sin\theta d\theta}_{\Delta\cos\theta = 0.05} \frac{d\Phi_\chi}{dT_\chi d\Omega} \propto \boxed{\sigma_{\chi e}\sigma_{\chi\nu}}$$

Directionality: θ-dependency

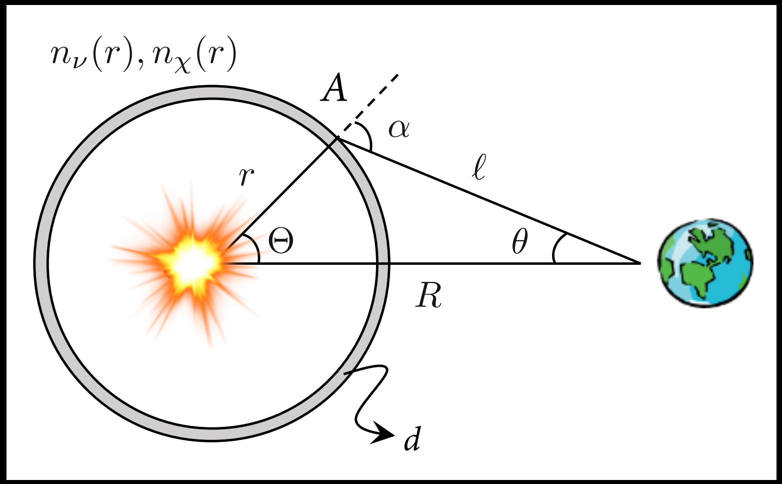
- The BDM event number

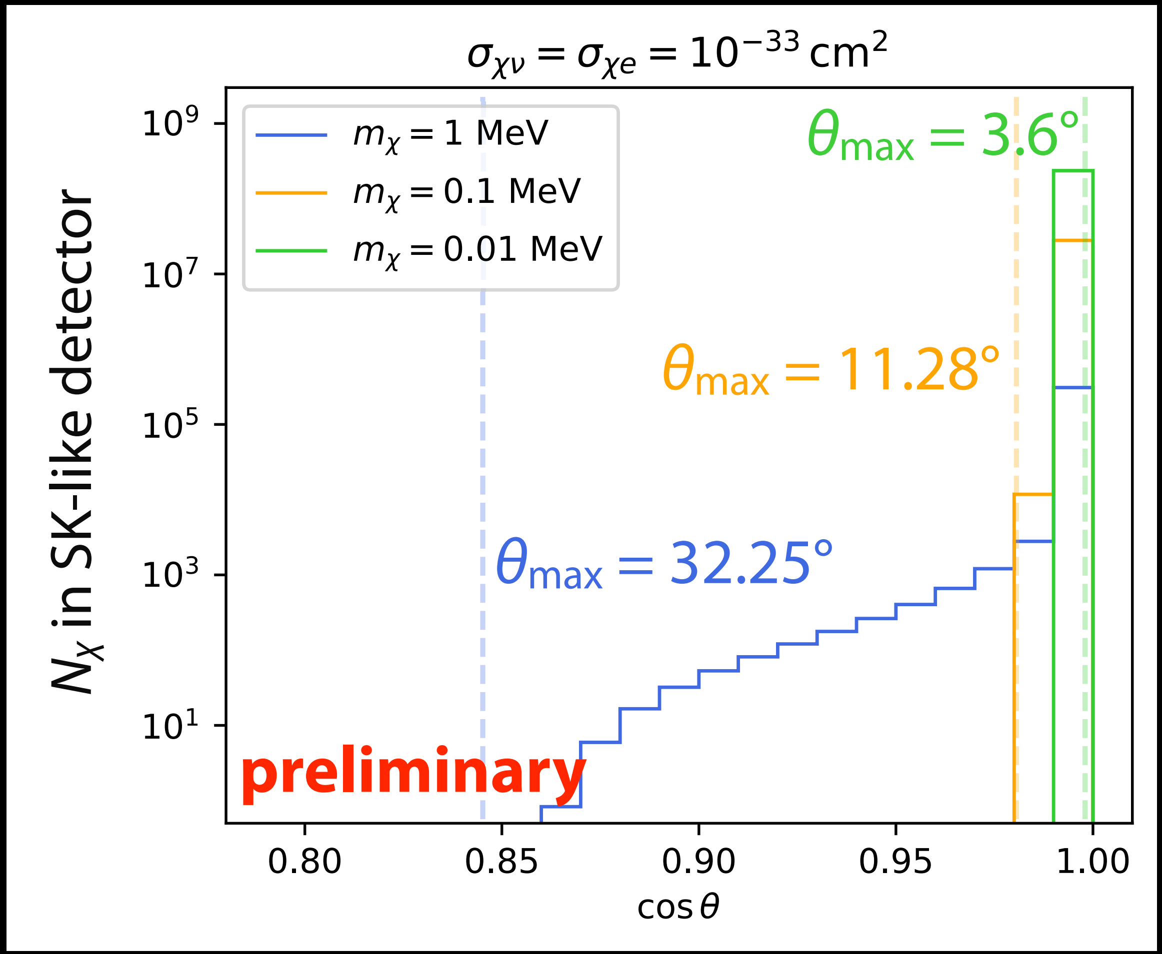
$$N_\chi = N_e \sigma_{\chi e} \int_{t_0}^{t_{\rm exp}} dt \int_{T_{\rm th}}^{T_{\rm max}} dT_\chi \underbrace{\int_{\Delta \cos\theta} 2\pi \sin\theta d\theta}_{\Delta\cos\theta = 0.05} \frac{d\Phi_\chi}{dT_\chi d\Omega} \propto \boxed{\sigma_{\chi e}\sigma_{\chi\nu}}$$

- N_χ depends on the open angle θ

$$\Delta\cos\theta = \cos\theta_{\rm min} - \cos\theta_{\rm max} = 0.05$$

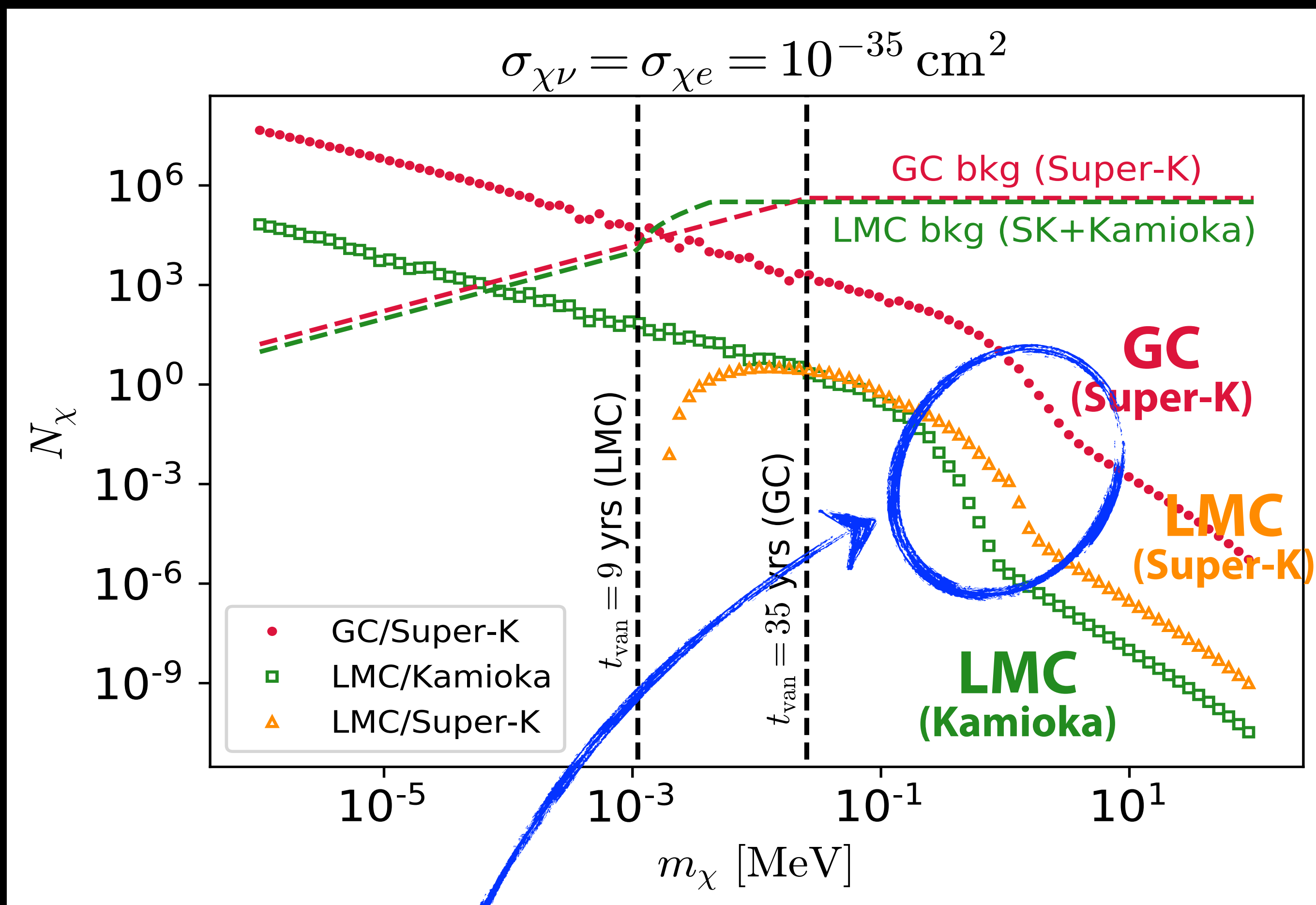
- Smaller m_χ has narrower window for θ





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

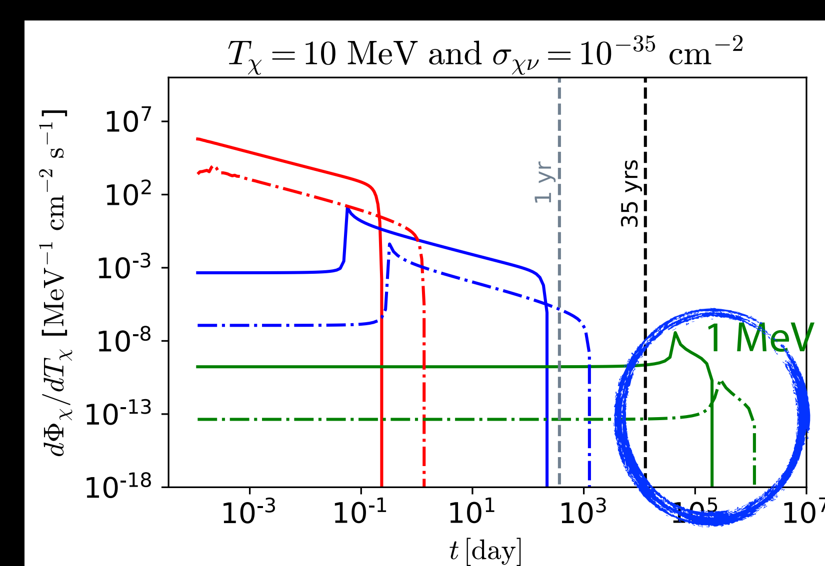
Total event and background



- The BDM event (taking $\sigma_{\chi\nu} = \sigma_{\chi e}$)

$$N_\chi = N_e \sigma_{\chi e} \int_{T_{\rm th}}^{T_{\rm max}} dT_\chi \int_{t_0}^{t_{\rm exp}} dt \frac{d\Phi_\chi}{dT_\chi}$$

- LMC (SN1987a):
  - Kamiokande: 1987-1996
  - Super-K: 1996 - present
- $m_\chi < 1.1$ keV has $t_{\rm van} < 9$ years, which is unobservable to Super-K
- GC case is similar



- The *rapid decreasing* of N_χ vs. m_χ indicates the tail part cannot be fully incorporated
- The background $N_b \sim 526 M_T t_{\rm exp}$ increases as $t_{\rm van} < t_{\rm cut} = 35$ yrs but saturates when $t_{\rm van} > t_{\rm cut}$

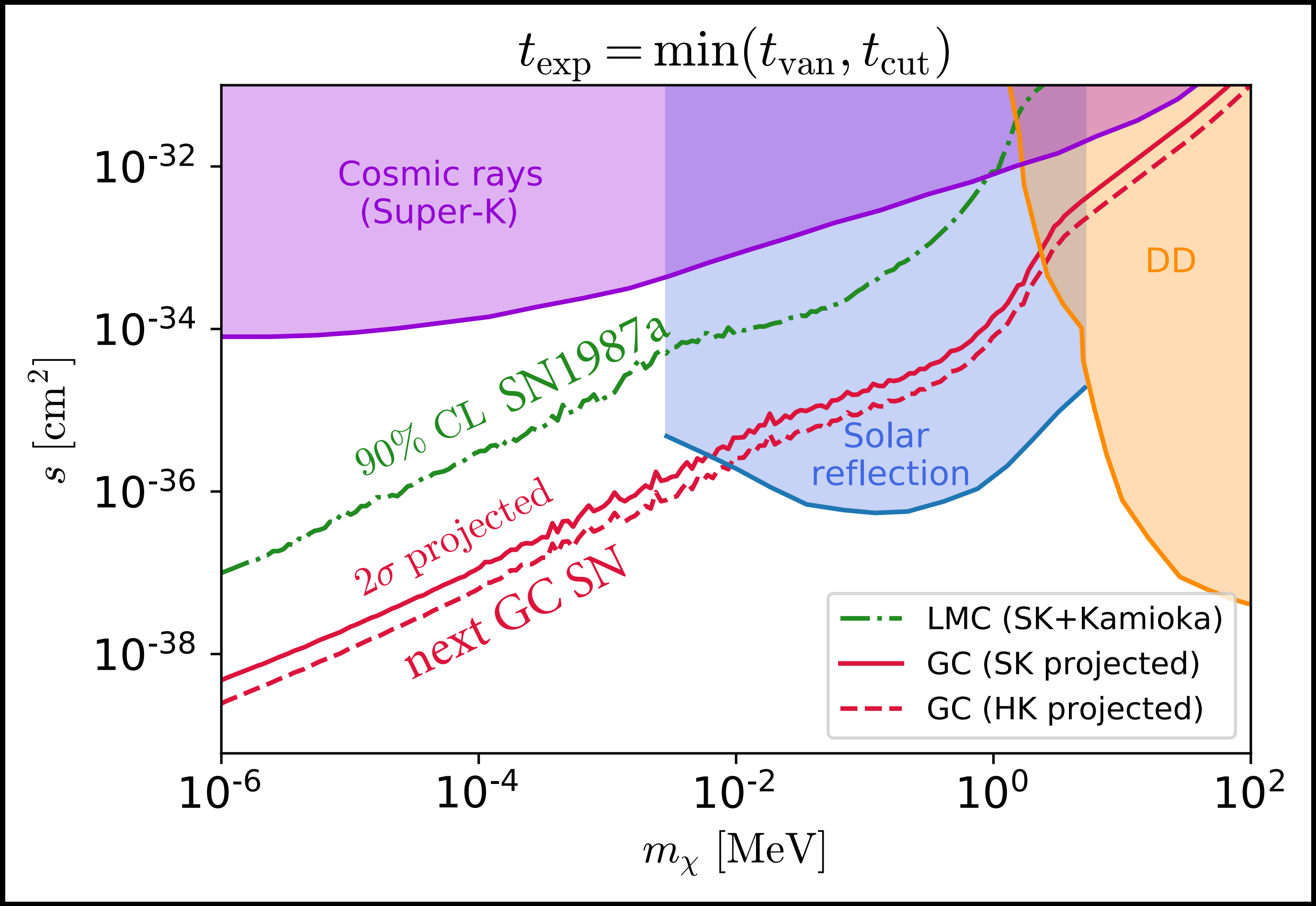
Hirata+ (1987)
Battistoni+ (2005)
Abe+ (SK) (2016)

Constraint and projected sensitivity

- Constraint and sensitivity are estimated by

$$\frac{N_\chi}{\sqrt{N_\chi + N_b}} = \begin{cases} 2.0, & \text{next GC SN} \\ 90\%\ \text{CL}, & \text{SN1987a} \end{cases} \quad \text{with background } N_b \simeq 526 \times M_T \times t_{\text{exp}}$$

- The constraint and sensitivity are placed on $s = \sqrt{\sigma_{\chi\nu}\sigma_{\chi e}}$ and assuming $\sigma_{\chi\nu} = \sigma_{\chi e}$



Summary

Summary

- SNν BDM possesses *time-of-flight* and *directionality*
  - Direct m_χ measurement
  - Determining vanishing time
  - Determining sky of interest
  - Event selection
- Complementary probe to DM direct search
- Provides better constraint and sensitivity for light DM
- Results for BDM due to SN not limited to the GC are presented

backups

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

BDM event and pheno realization

- The BDM event number

$$N_\chi = N_e \sigma_{\chi e} \int_{T_{\rm th}}^{T_{\rm max}} dT_\chi \int_{t_0}^{t_{\rm exp}} dt \frac{d\Phi_\chi}{dT_\chi} \propto \boxed{\sigma_{\chi e}\sigma_{\chi\nu}}$$

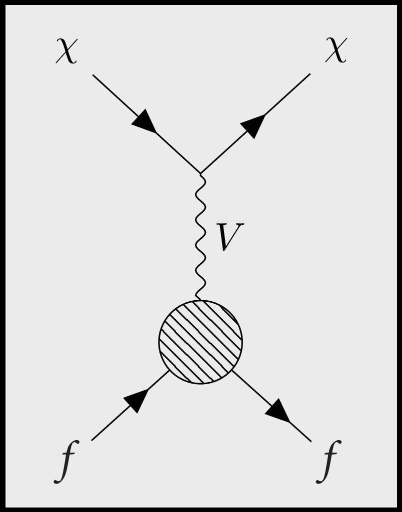
- Non-zero $\sigma_{\chi\nu}$ and $\sigma_{\chi e}$ can be realized with dark photon V with portal(s) to the Standard Model sector

$$\mathcal{L}_{\rm eff} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} - \frac{1}{2}m_V V_\mu V^\mu + \frac{\epsilon}{2}F_{\mu\nu}V^{\mu\nu} + g_\chi V_\mu J^\mu_\chi$$

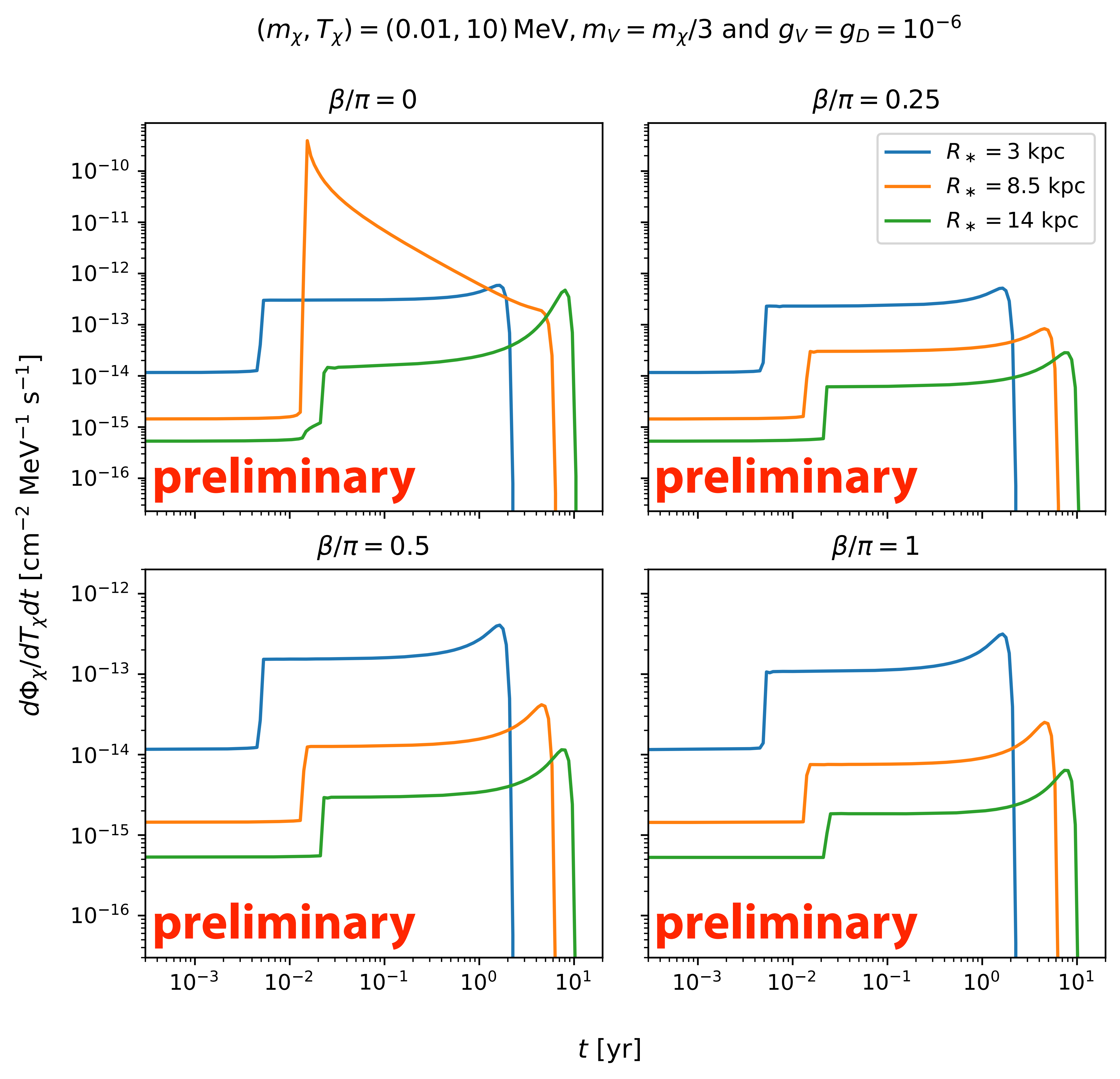
where $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$

- The kinetic mixing $\varepsilon F_{\mu\nu}V^{\mu\nu}$ provides a portal to SM photon and $e' V_\mu J^\mu$ provides extra portal(s) to other SM currents J^μ (eg. L_μ–L_τ or Z-mass mixing)

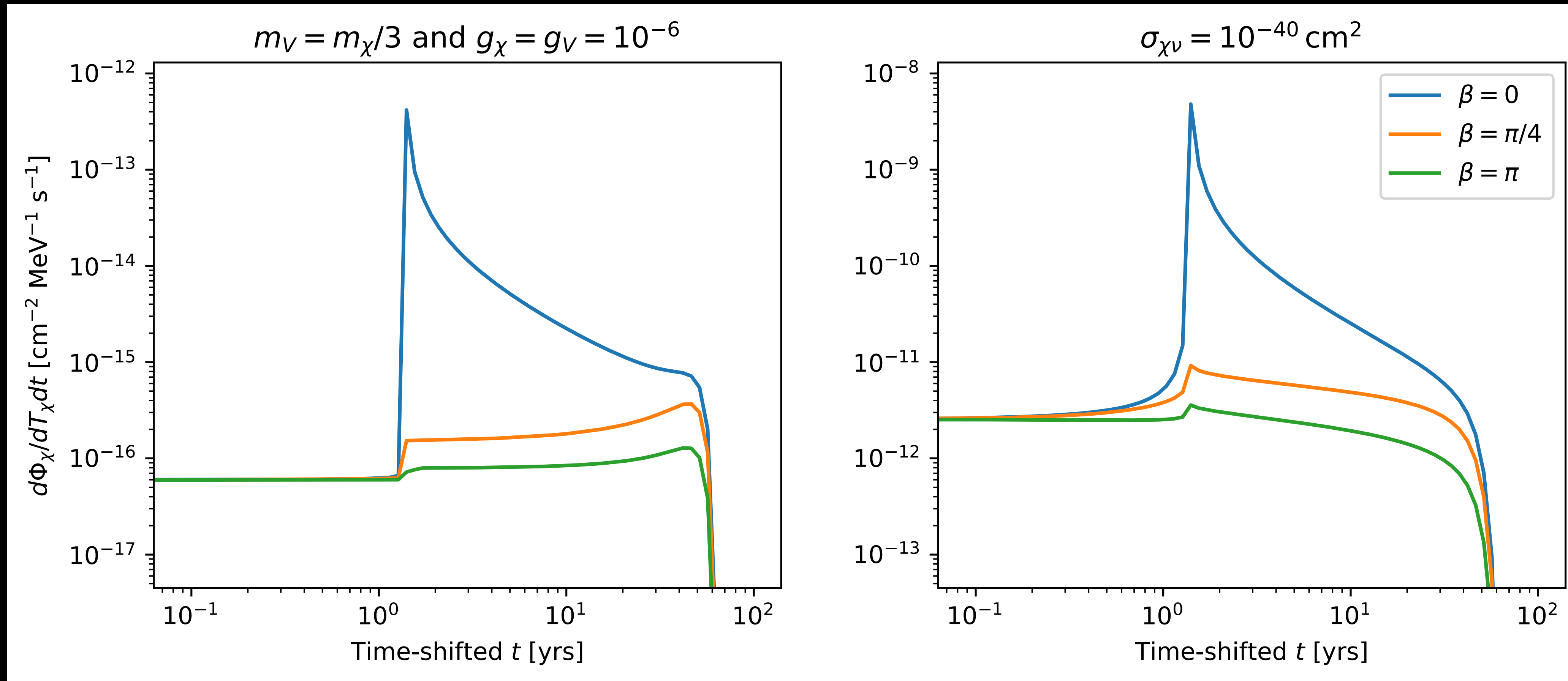
- Effectively, we have the following diagram for χ-f scattering where $f = e,\nu$

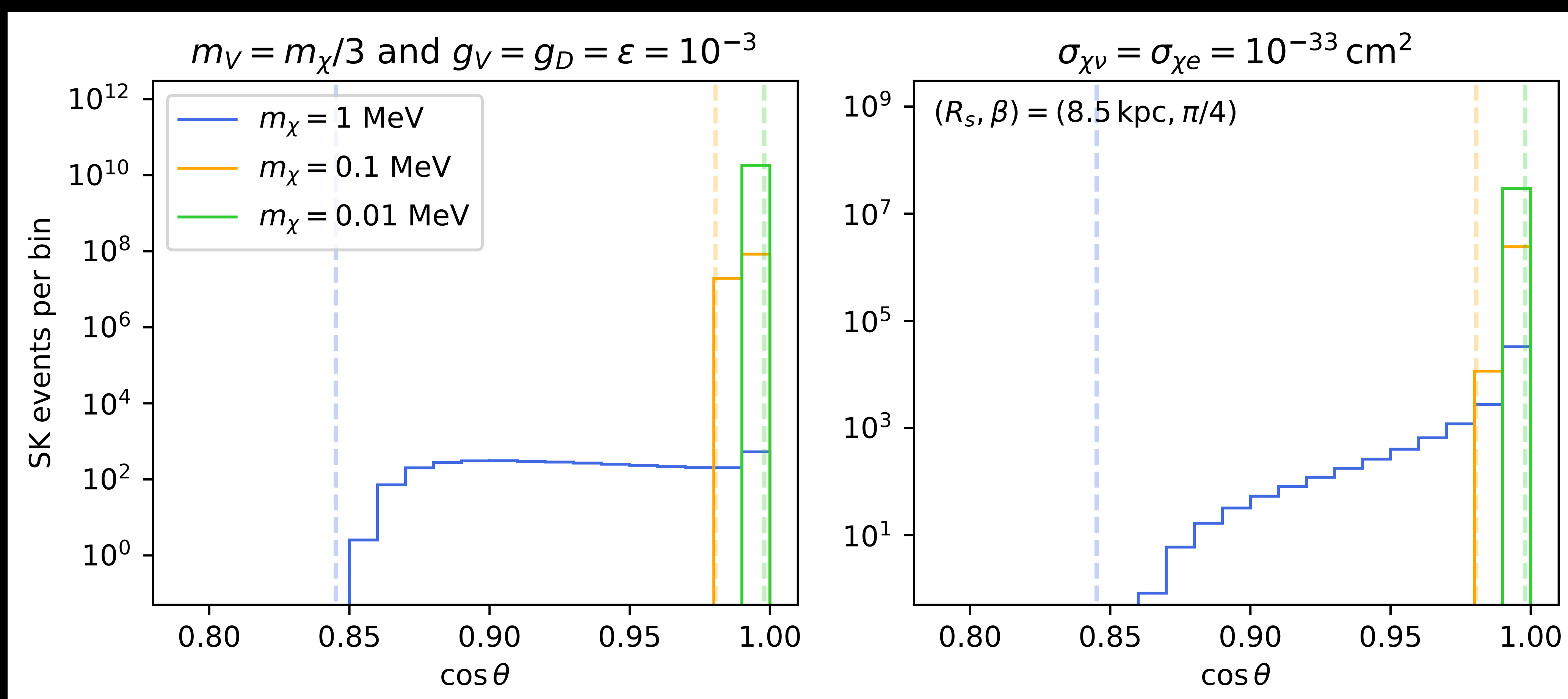


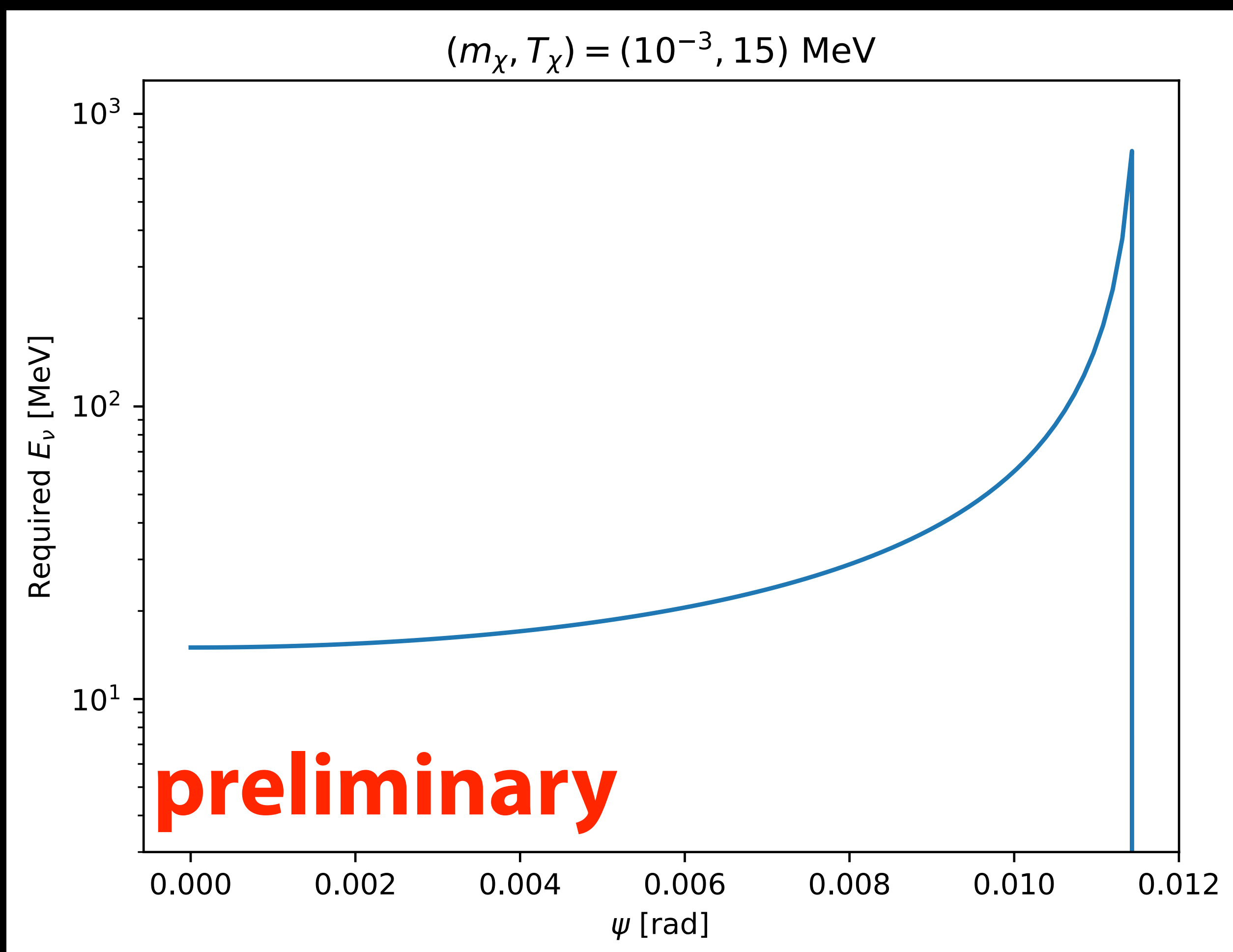
$$|\mathcal{M}_{\chi f}|^2 = \frac{2}{(t^2 - m_V^2)^2} g_\chi^2 e'^2 [s^2 + u^2 + 4t(m_f^2 + m_\chi^2) - 2(m_f^2 + m_\chi^2)^2]$$



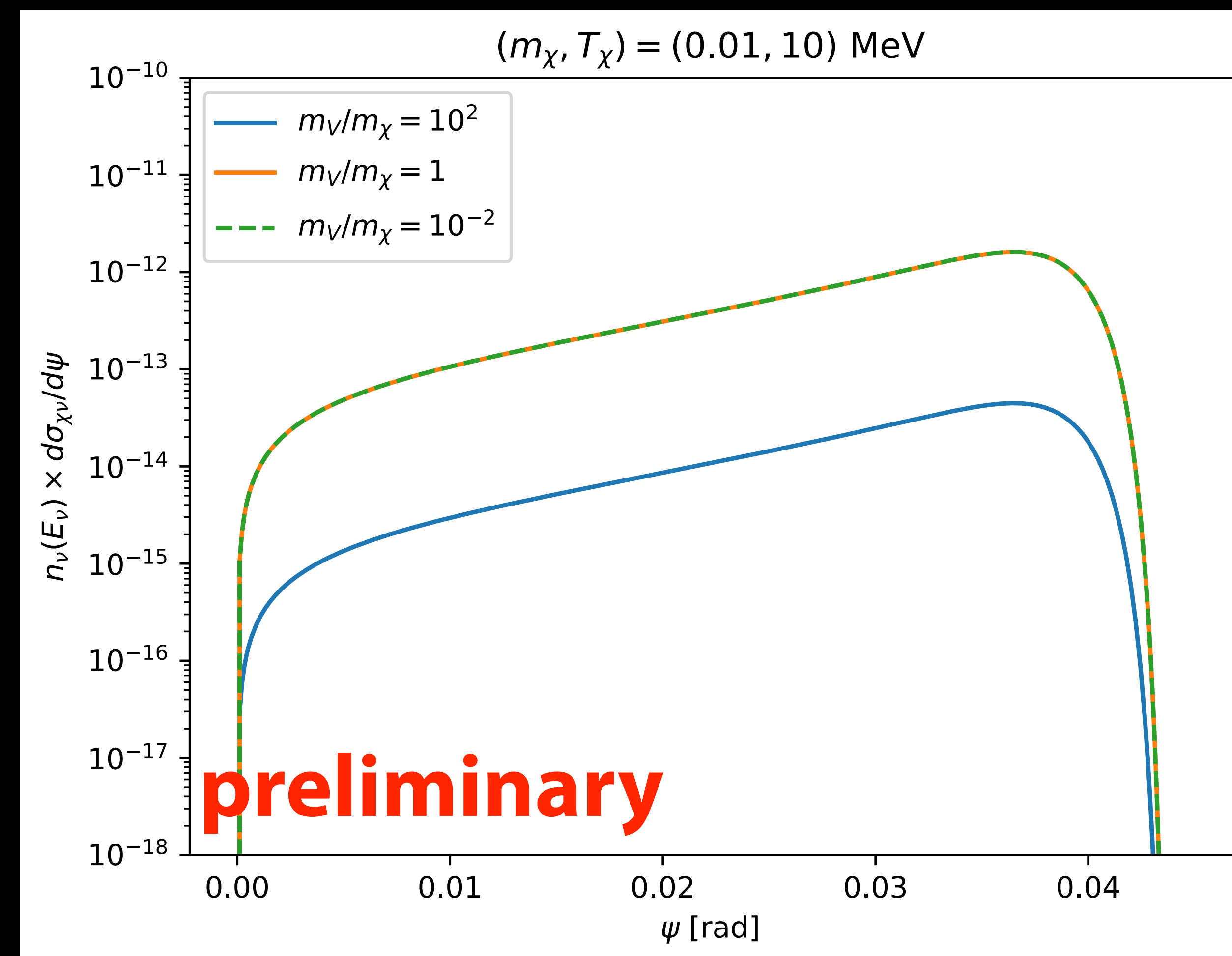
$(m_\chi, T_\chi) = (0.01, 10)$ MeV, $m_V = m_\chi/3$ and $g_V = g_D = 10^{-6}$
$\beta/\pi = 0$
$\beta/\pi = 0.25$
$\beta/\pi = 0.5$
$\beta/\pi = 1$
$R_* = 3$ kpc
$R_* = 8.5$ kpc
$R_* = 14$ kpc
$d\Phi_\chi/dT_\chi dt$ [cm^{-2} MeV^{-1} s^{-1}]
t [yr]
preliminary
preliminary
preliminary
preliminary


$m_V = m_\chi/3$ and $g_\chi = g_V = 10^{-6}$
$\sigma_{\chi\nu} = 10^{-40}\,\mathrm{cm}^2$
$d\Phi_\chi/dT_\chi dt$ [cm^{-2} MeV^{-1} s^{-1}]
Time-shifted t [yrs]
Time-shifted t [yrs]
$\beta = 0$
$\beta = \pi/4$
$\beta = \pi$

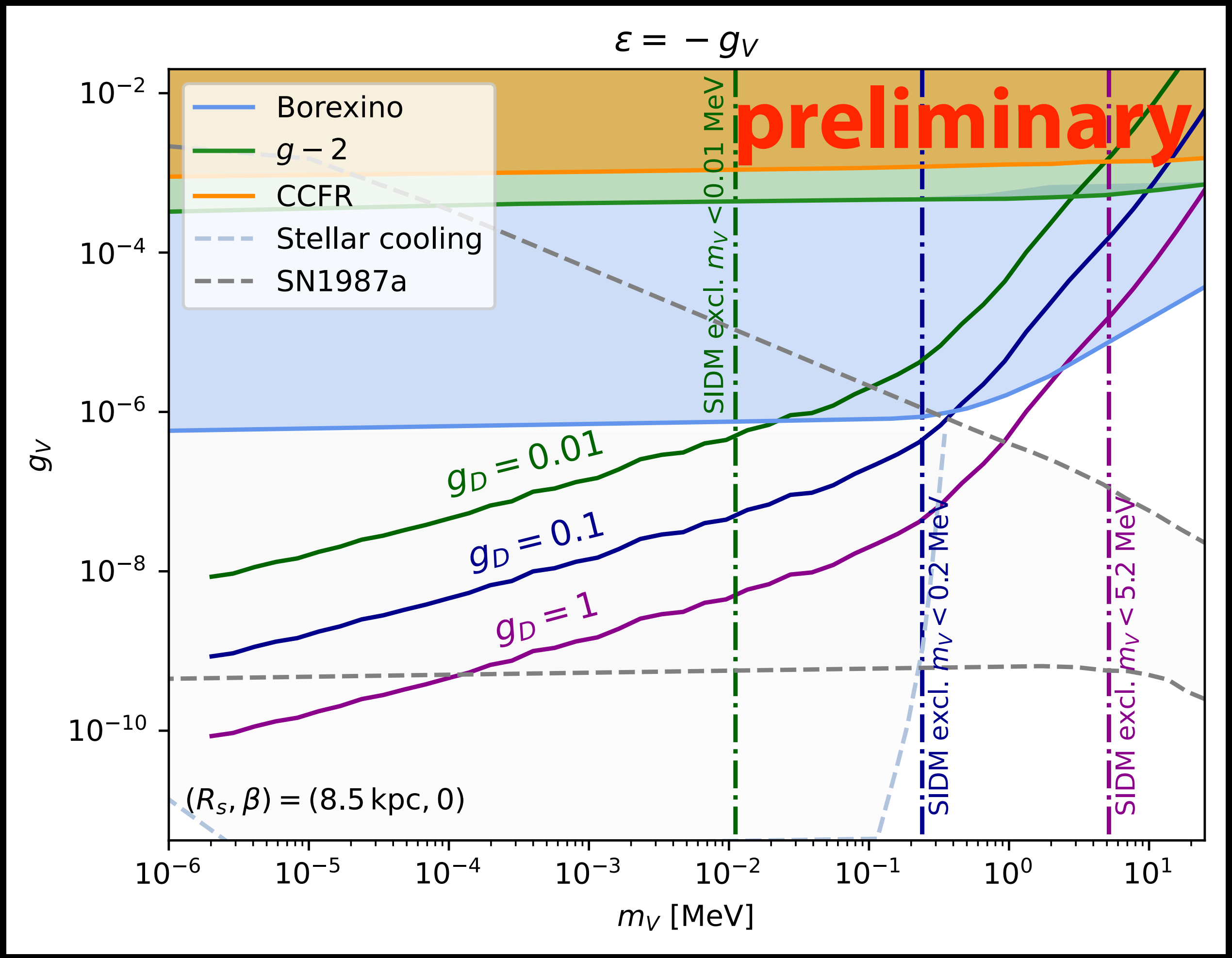

$m_V = m_\chi/3$ and $g_V = g_D = \varepsilon = 10^{-3}$
$\sigma_{\chi\nu} = \sigma_{\chi e} = 10^{-33}\,\mathrm{cm}^2$
SK events per bin
$m_\chi = 1$ MeV
$m_\chi = 0.1$ MeV
$m_\chi = 0.01$ MeV
$(R_s, \beta) = (8.5\,\mathrm{kpc}, \pi/4)$
$\cos\theta$
$\cos\theta$



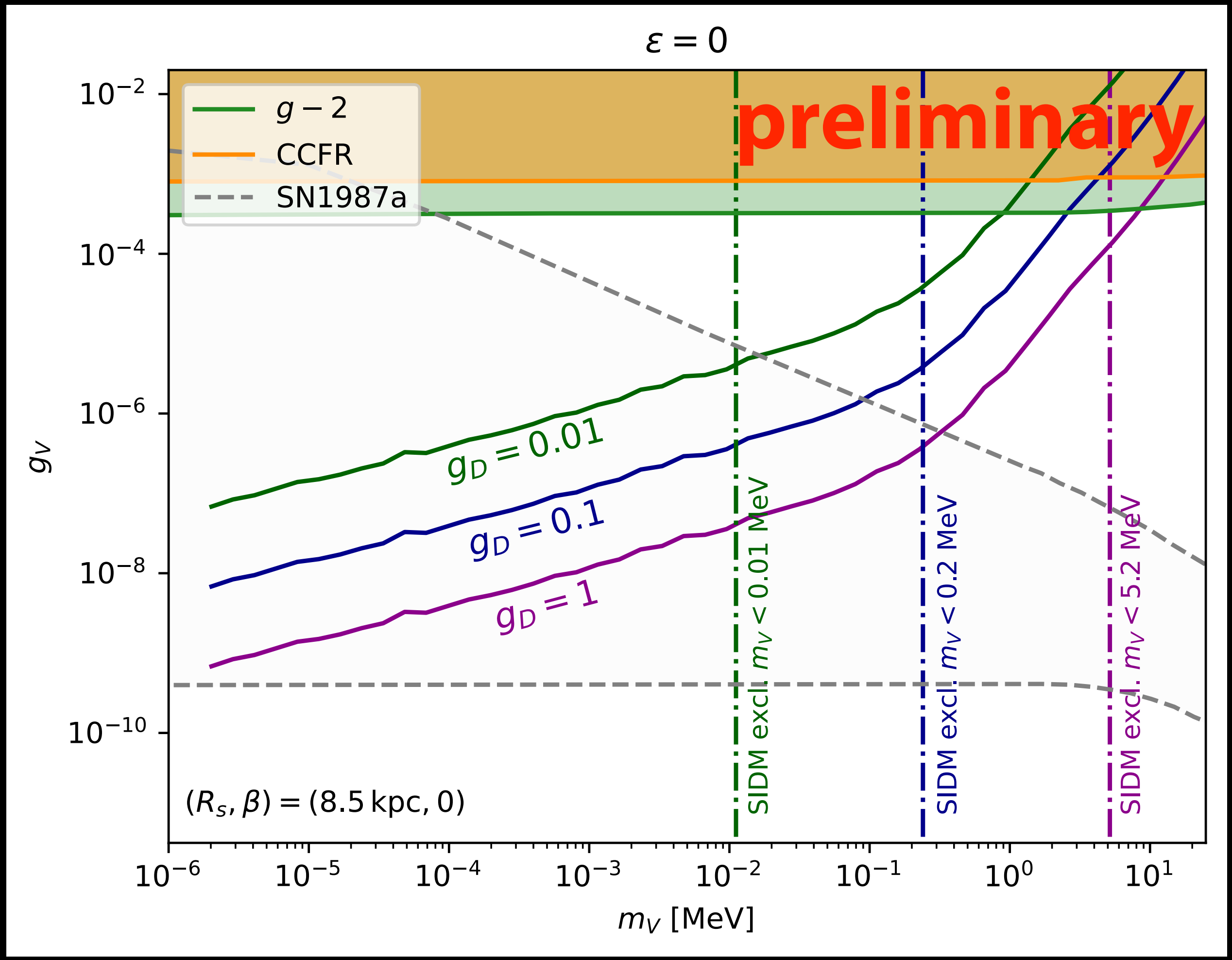
$(m_\chi, T_\chi) = (10^{-3}, 15)$ MeV
Required E_ν [MeV]
10^3
10^2
10^1
0.000
0.002
0.004
0.006
0.008
0.010
0.012
ψ [rad]
preliminary



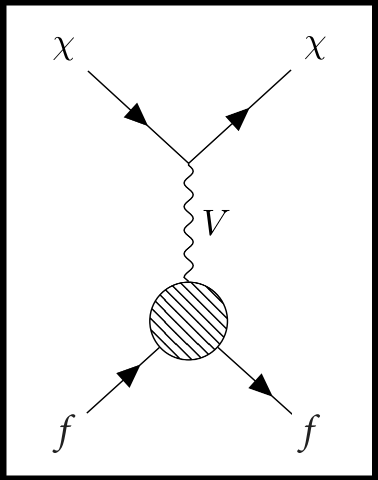
$(m_\chi, T_\chi) = (0.01, 10)$ MeV
$n_\nu(E_\nu) \times d\sigma_{\chi\nu}/d\psi$
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
$m_V/m_\chi = 10^2$
$m_V/m_\chi = 1$
$m_V/m_\chi = 10^{-2}$
0.00
0.01
0.02
0.03
0.04
ψ [rad]
preliminary



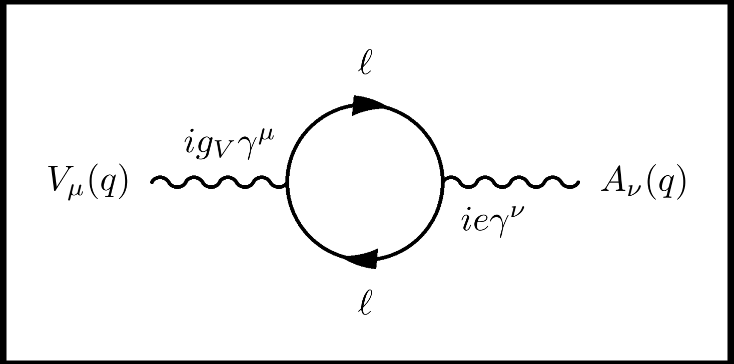
$\varepsilon = -g_V$
Borexino
$g-2$
CCFR
Stellar cooling
SN1987a
preliminary
SIDM excl. $m_V < 0.01$ MeV
SIDM excl. $m_V < 0.2$ MeV
SIDM excl. $m_V < 5.2$ MeV
$g_D = 0.01$
$g_D = 0.1$
$g_D = 1$
$(R_s, \beta) = (8.5\,\mathrm{kpc}, 0)$
g_V
m_V [MeV]



$\varepsilon = 0$
$g-2$
CCFR
SN1987a
preliminary
SIDM excl. $m_V < 0.01$ MeV
SIDM excl. $m_V < 0.2$ MeV
SIDM excl. $m_V < 5.2$ MeV
$g_D = 0.01$
$g_D = 0.1$
$g_D = 1$
$(R_s, \beta) = (8.5\,\mathrm{kpc}, 0)$
g_V
m_V [MeV]



χ
χ
V
f
f



ℓ
$ig_V\gamma^\mu$
$V_\mu(q)$
$A_\nu(q)$
$ie\gamma^\nu$
ℓ