Yen-Hsun Lin (林彥勳)
Physics Division, National Center for Theoretical Sciences, Taiwan
yenhsun@phys.ncku.edu.tw

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Dark Matter in Compact Objects, Stars, and in Low Energy Experiments
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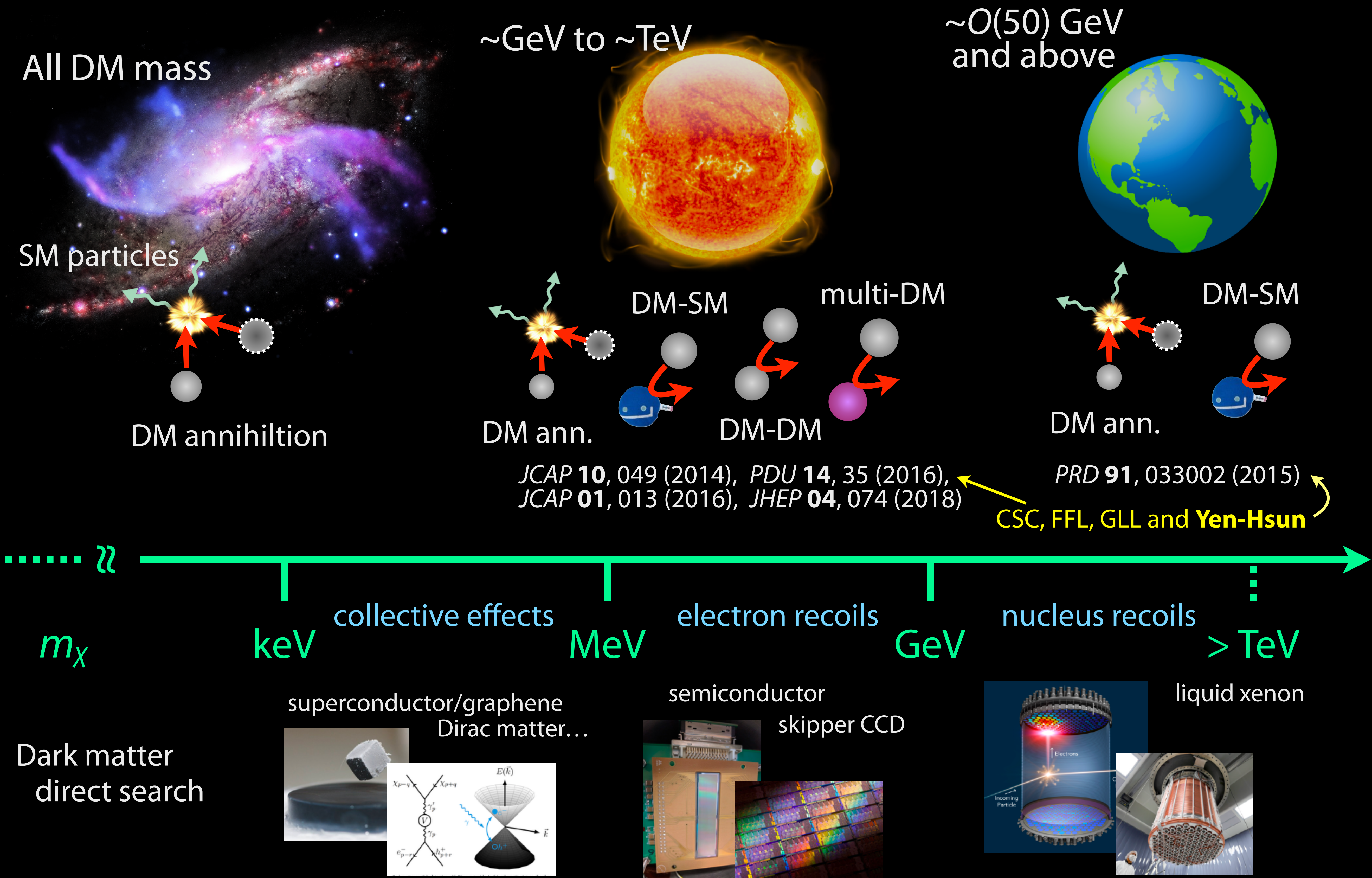
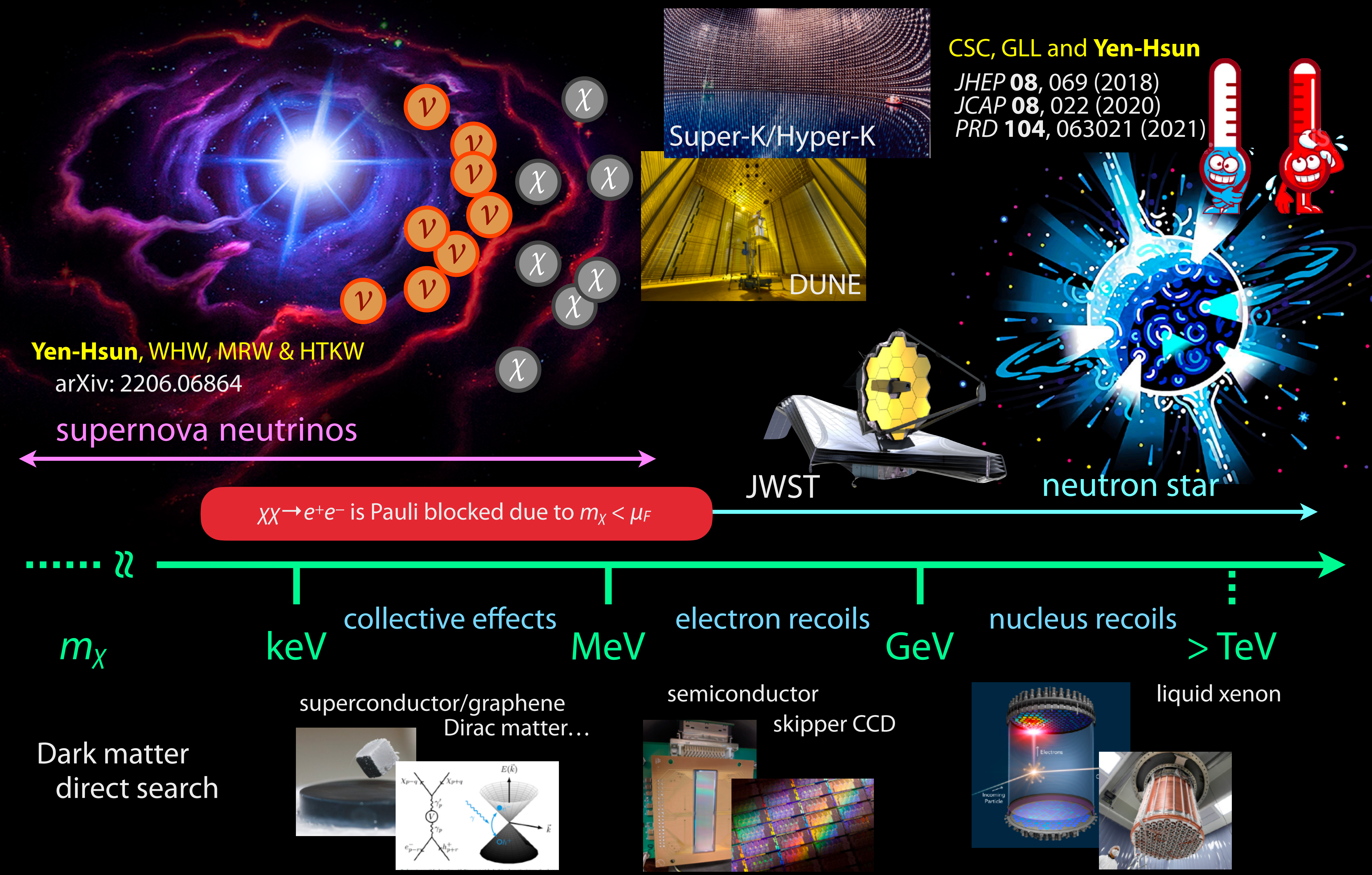
in collaboration with
Wen-Hua Wu (NTU), Meng-Ru Wu (AS/IAA) & Henry T.-K. Wong (AS)
arXiv: 2206.06864

Light Dark Matter Boosted by Supernova Neutrinos

Dark matter probes



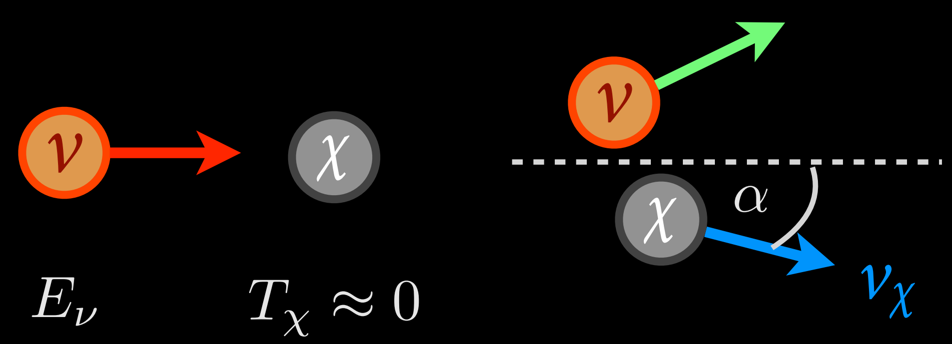
Dark matter probes



The SNνBDM and its flux

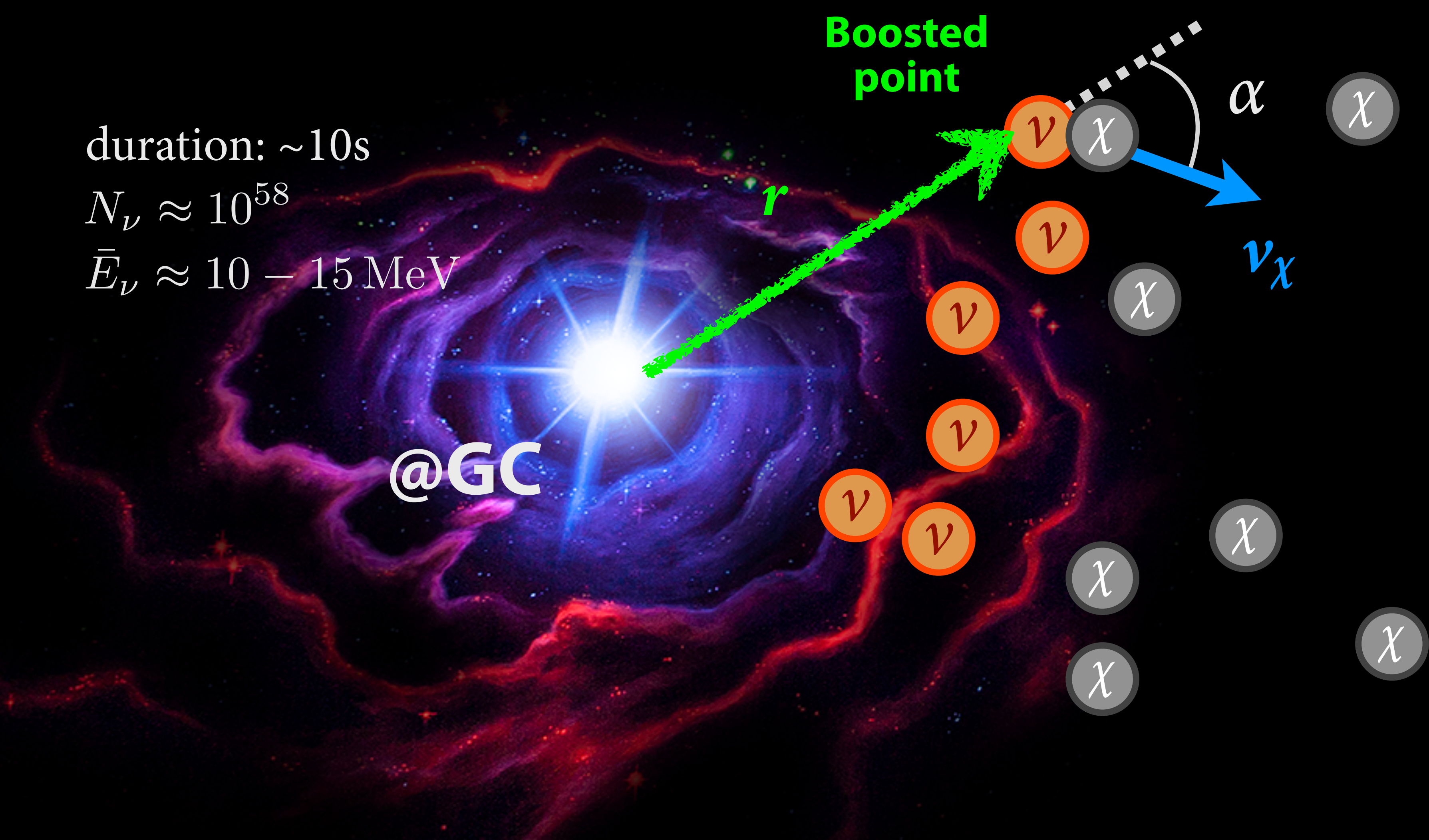
The framework

- SNν scatters with DM in the halo ($\sigma_{\chi\nu}$) and DM is being boosted (BDM)



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

$$\theta_c = 2\tan^{-1}(\gamma\tan\alpha), \quad \alpha \in [0, \tfrac{\pi}{2}]$$

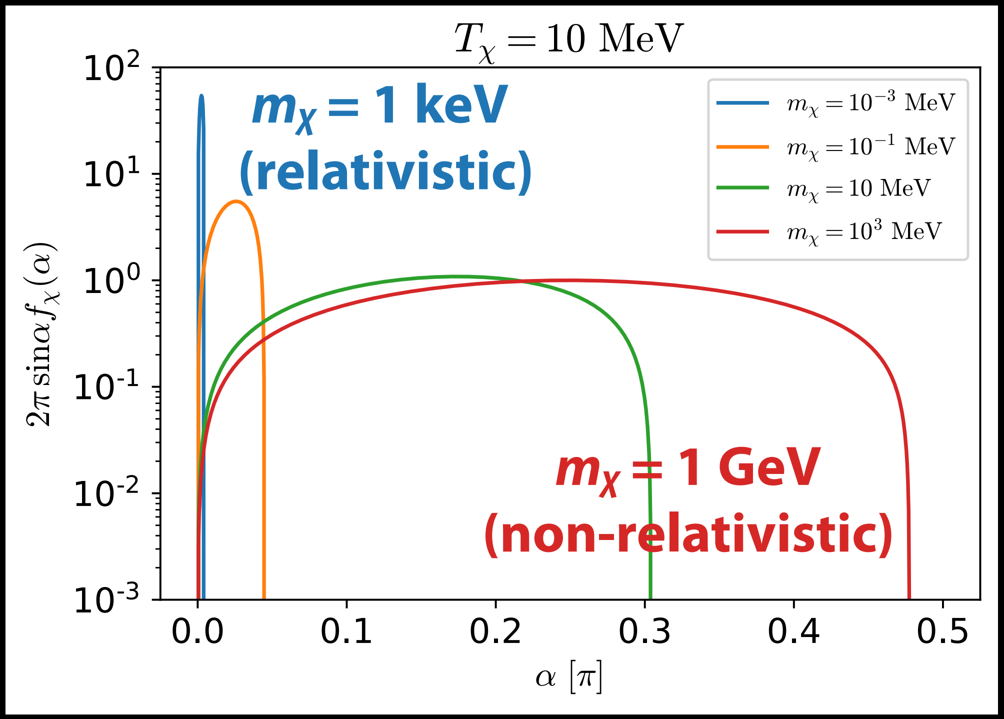


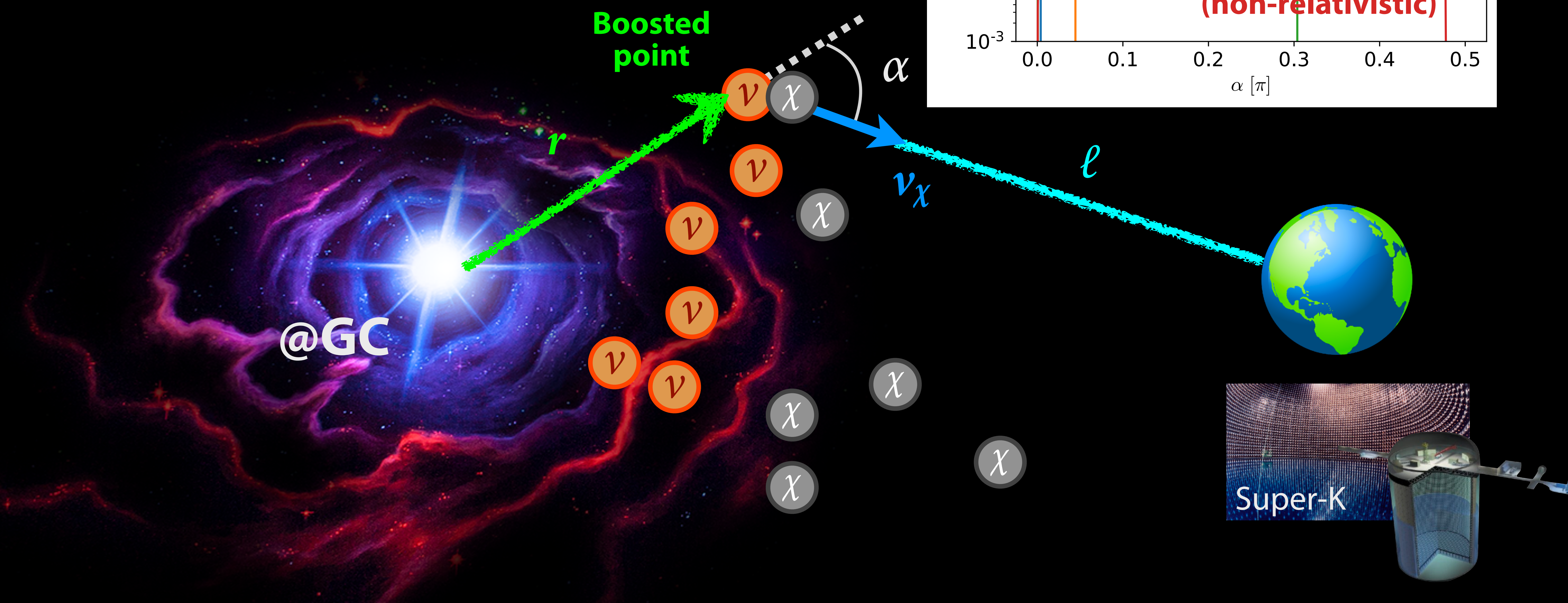
The framework

- Only α points toward Earth that could be detected: distribution function $f_\chi(\alpha,E_\nu)$

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

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



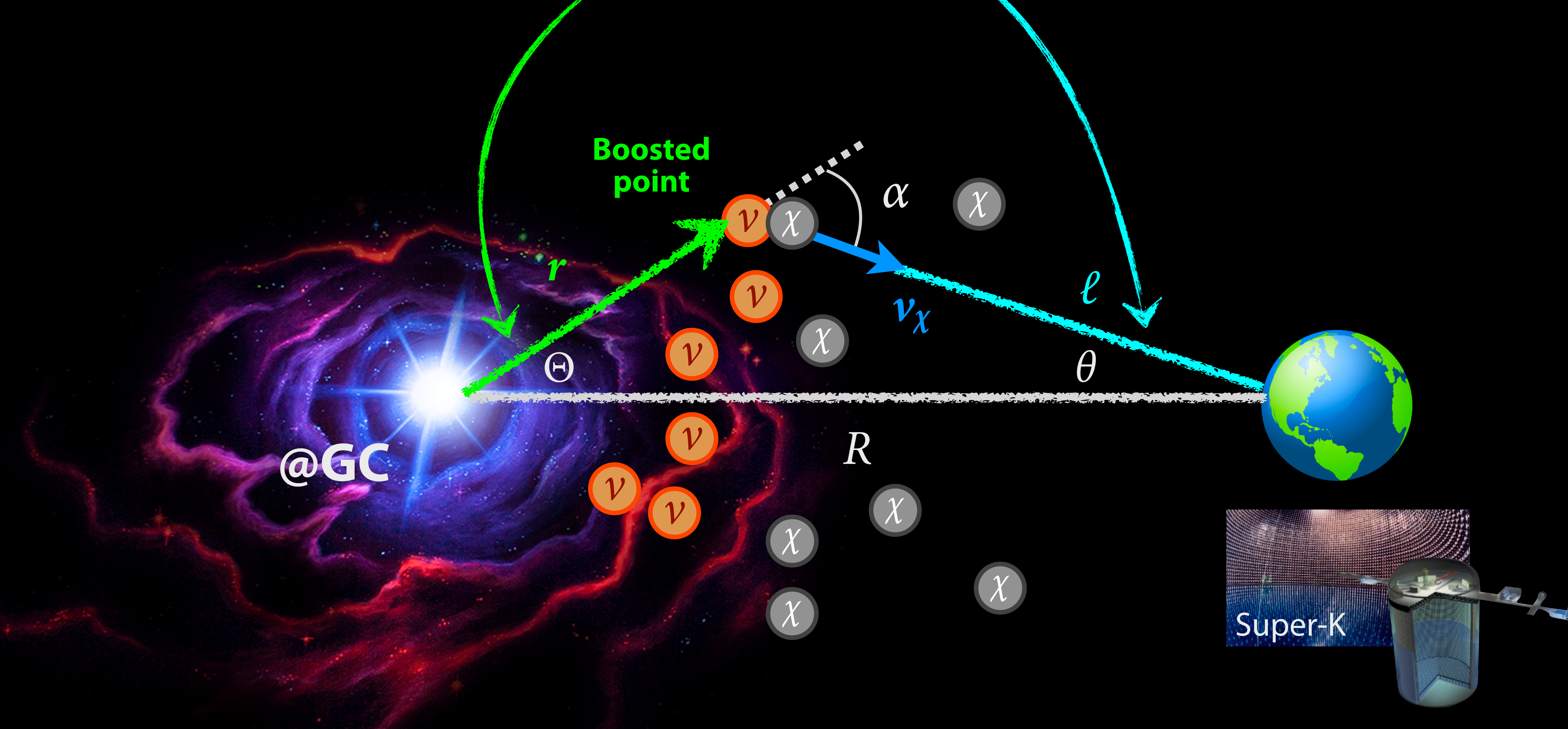


The framework

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

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

- The duration of BDM flux is much longer than the SNν flux

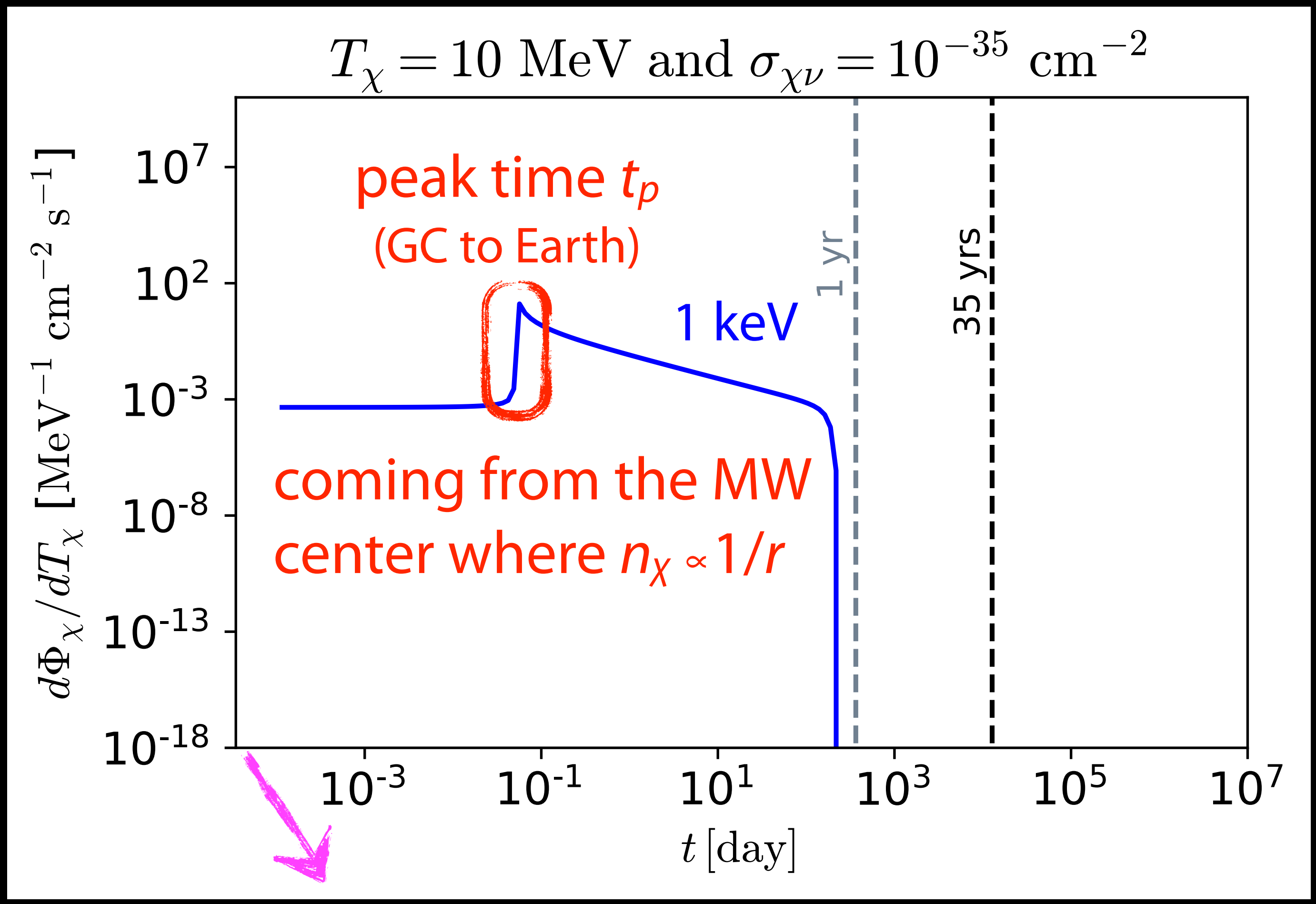


BDM flux and Time-of-flight (ToF)

- BDM flux at Earth (DM profile: NFW)

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

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



$t_0 = 10$ s: to avoid overlapping with SNν

- Peak time $t_p \sim R(1/v_\chi - 1/c)$
- The BDM velocity is determined by m_χ

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

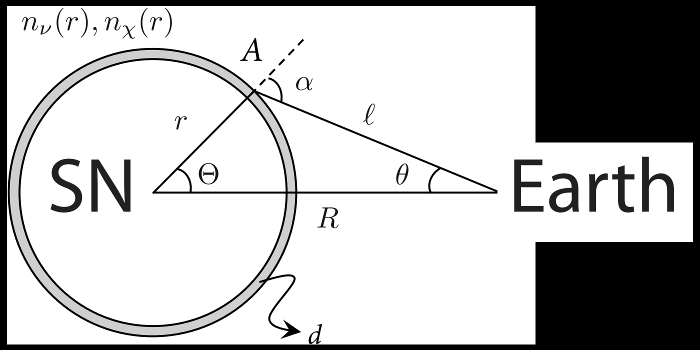
- Given T_χ and t_p, the DM mass m_χ is measured directly

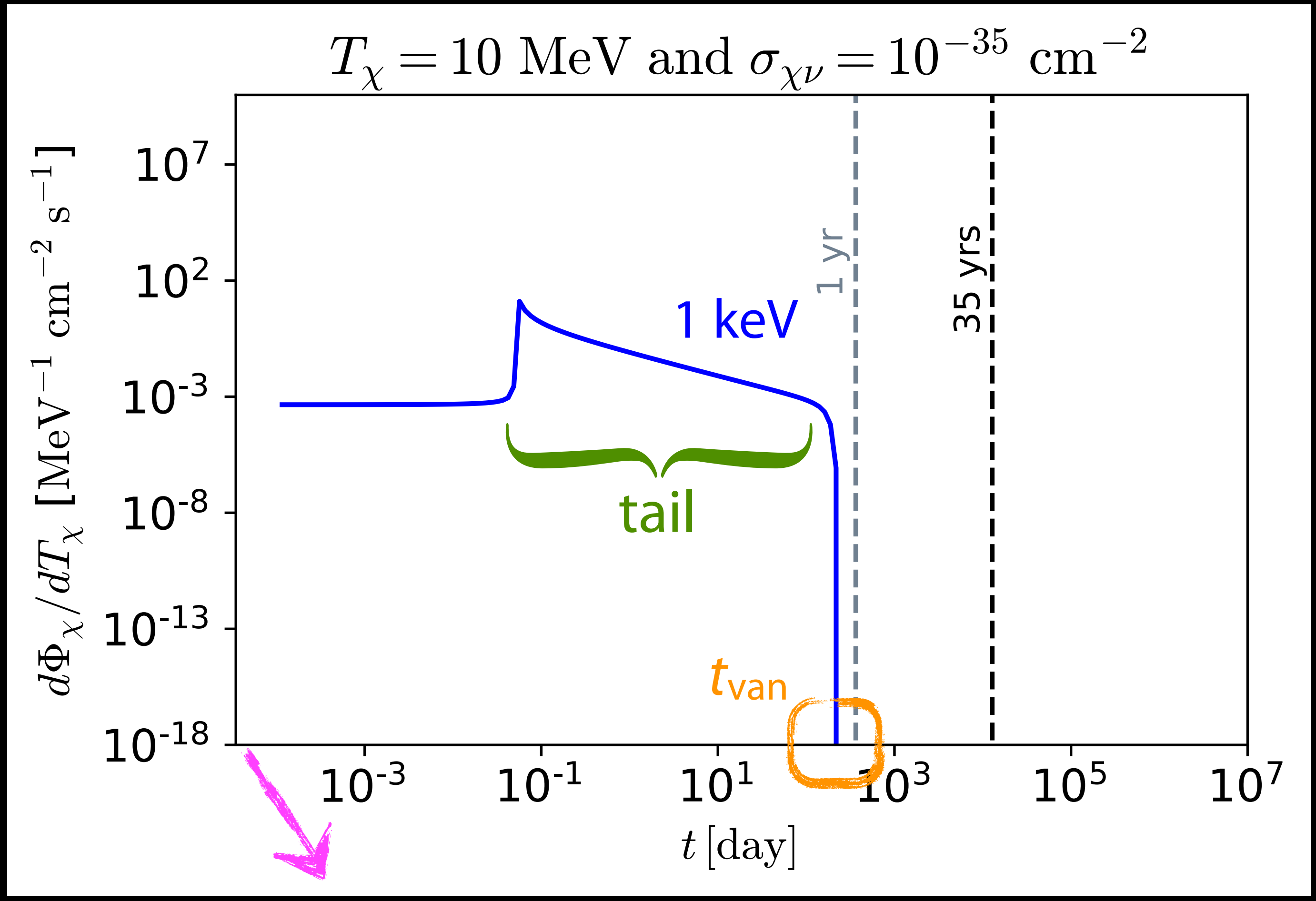
BDM flux and ToF

- The total propagation time (relative to the SN explosion)

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

with *time-shifted* coordinate $t = t' - R/c$





$t_0 = 10$ s: to avoid overlapping with SNν

- The vanishing time t_{van} is a result of

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

  which leads to the condition

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

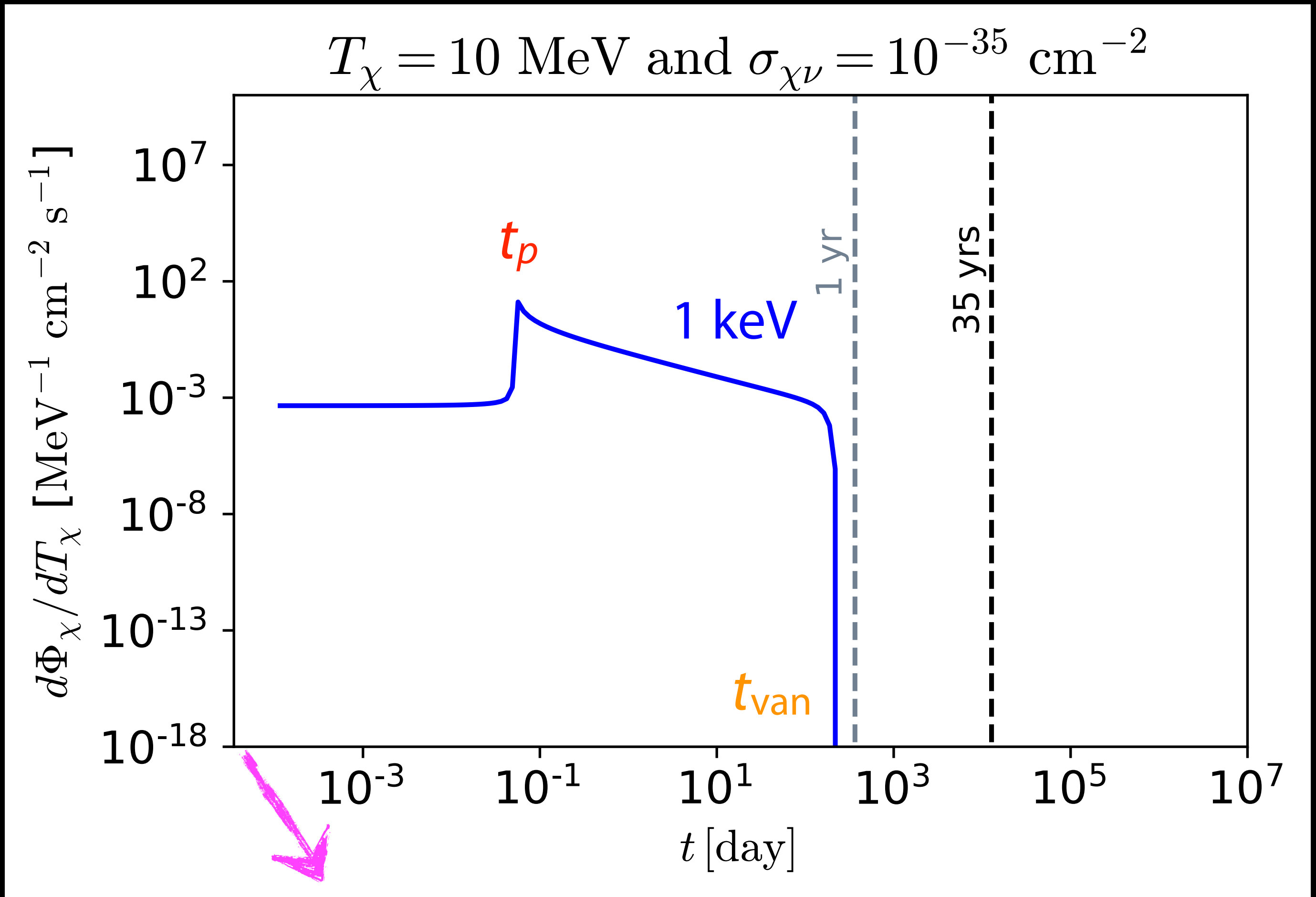
- The tail is contributed due to $t > t_p$: large scattering angle α close to the center

BDM flux and ToF

- The ToF information contained in BDM flux provides

  a. For constraint: $m_\chi \to t_{\rm van} \to$ minimizing exposure time $\to$ background suppression

  b. For observation: $t_p \to m_\chi \to$ direct DM mass measurement



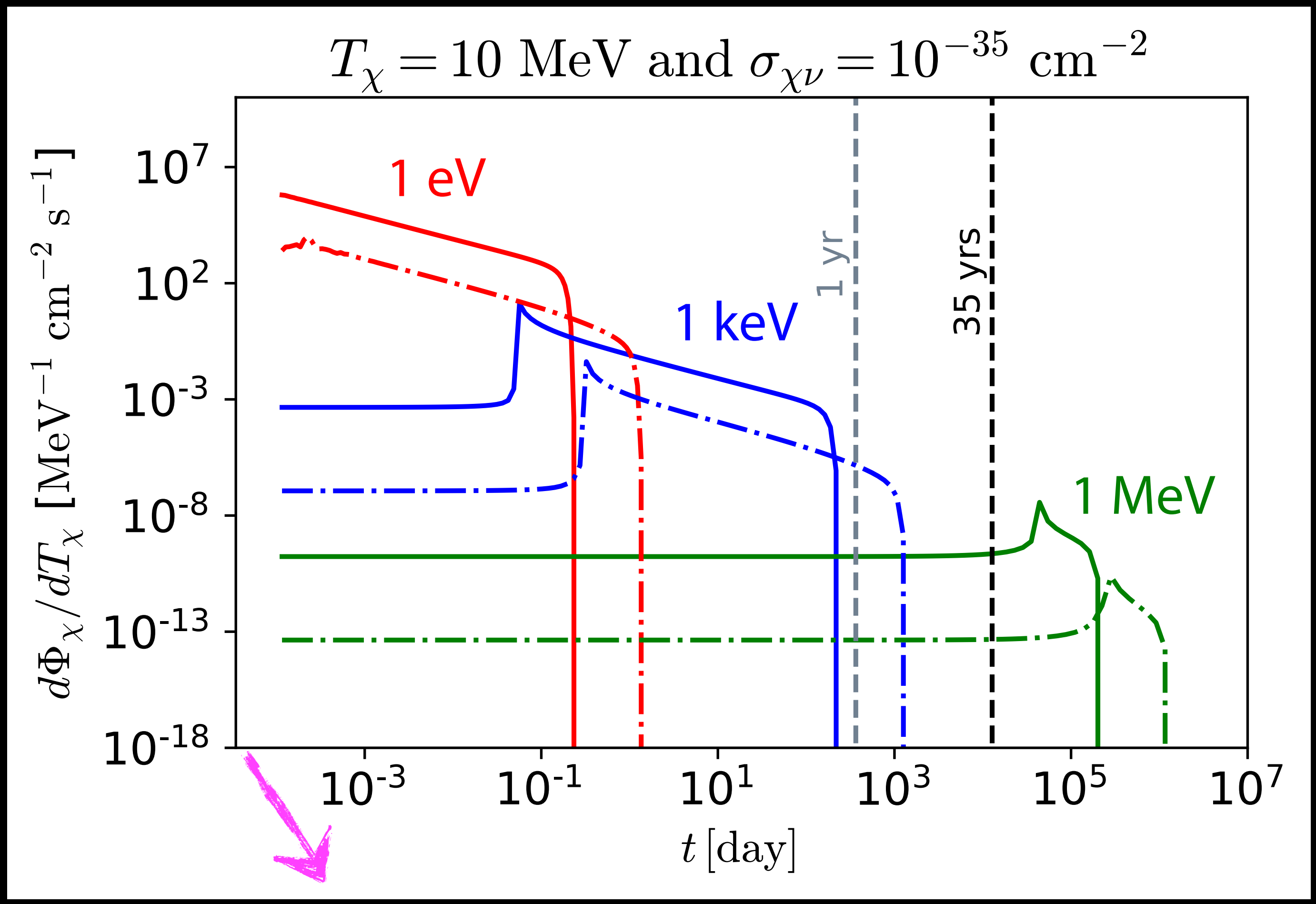
$t_0 = 10$ s: to avoid overlapping with SNν

BDM fluxes from MW & LMC

- 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



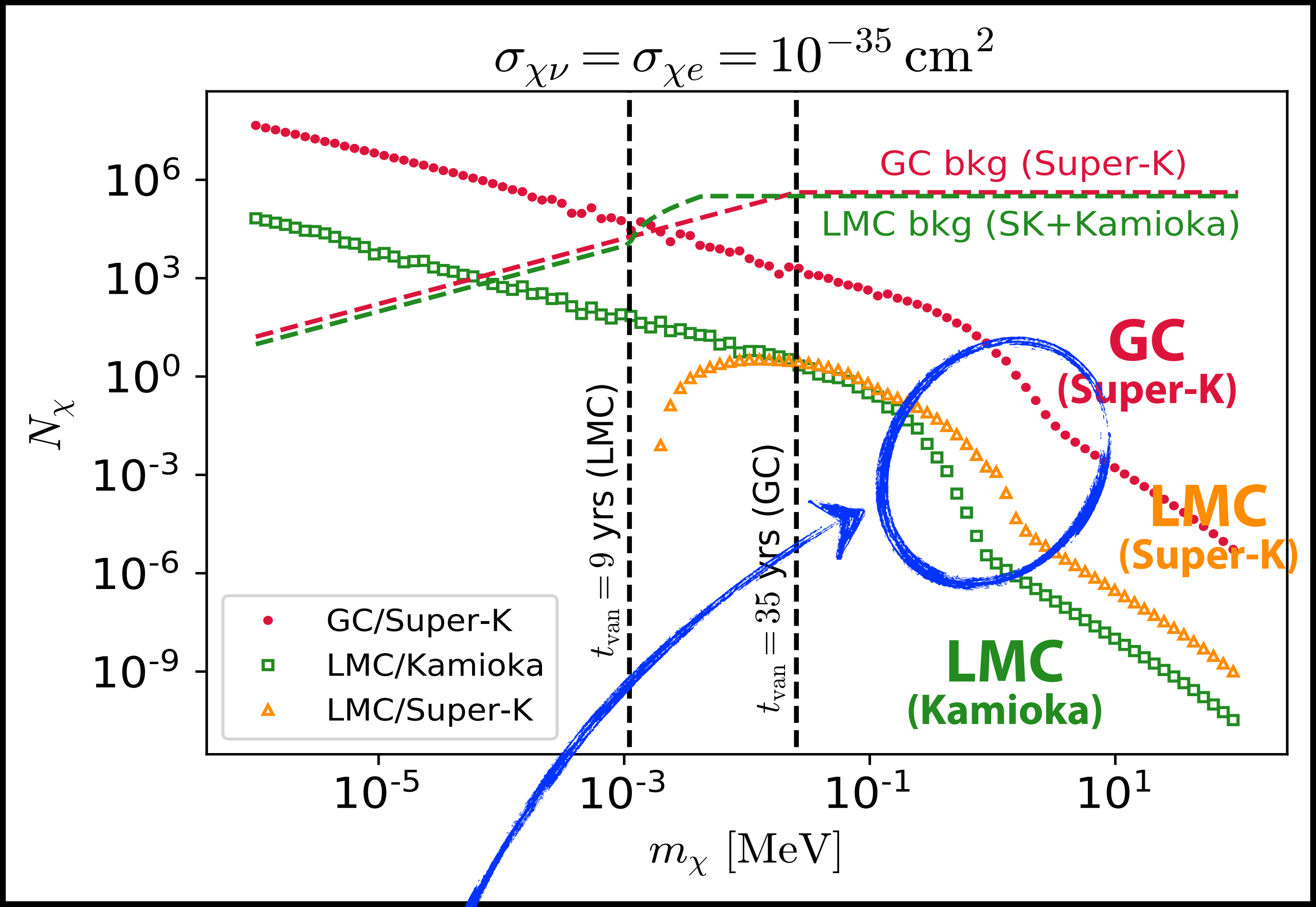
t_0 = 10 s: to avoid overlapping with SNν

- t_p for LMC is delayed accordingly due to R_{LMC} = 50 kpc > R_{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 $v_\chi \to c$

Constraint and sensitivity

Battistoni+ (2005)
Abe+ (2016)

BDM event and background

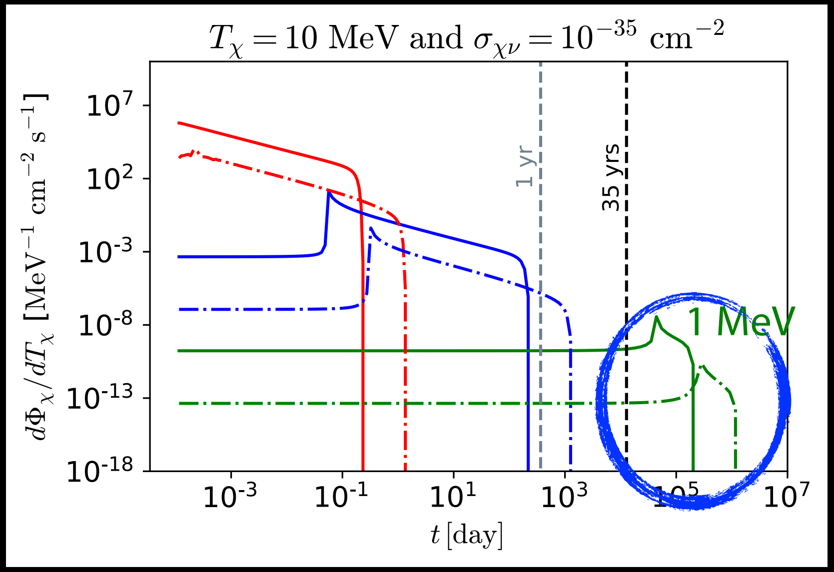


- The BDM event (taking $\sigma_{\chi\nu} = \sigma_{\chi e}$)

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

where $T_\chi = (5, 100)$ MeV and $t_0 = 10$ s and $t_{\rm exp} = \min(t_{\rm van}, t_{\rm cut} = 35\text{ yrs})$

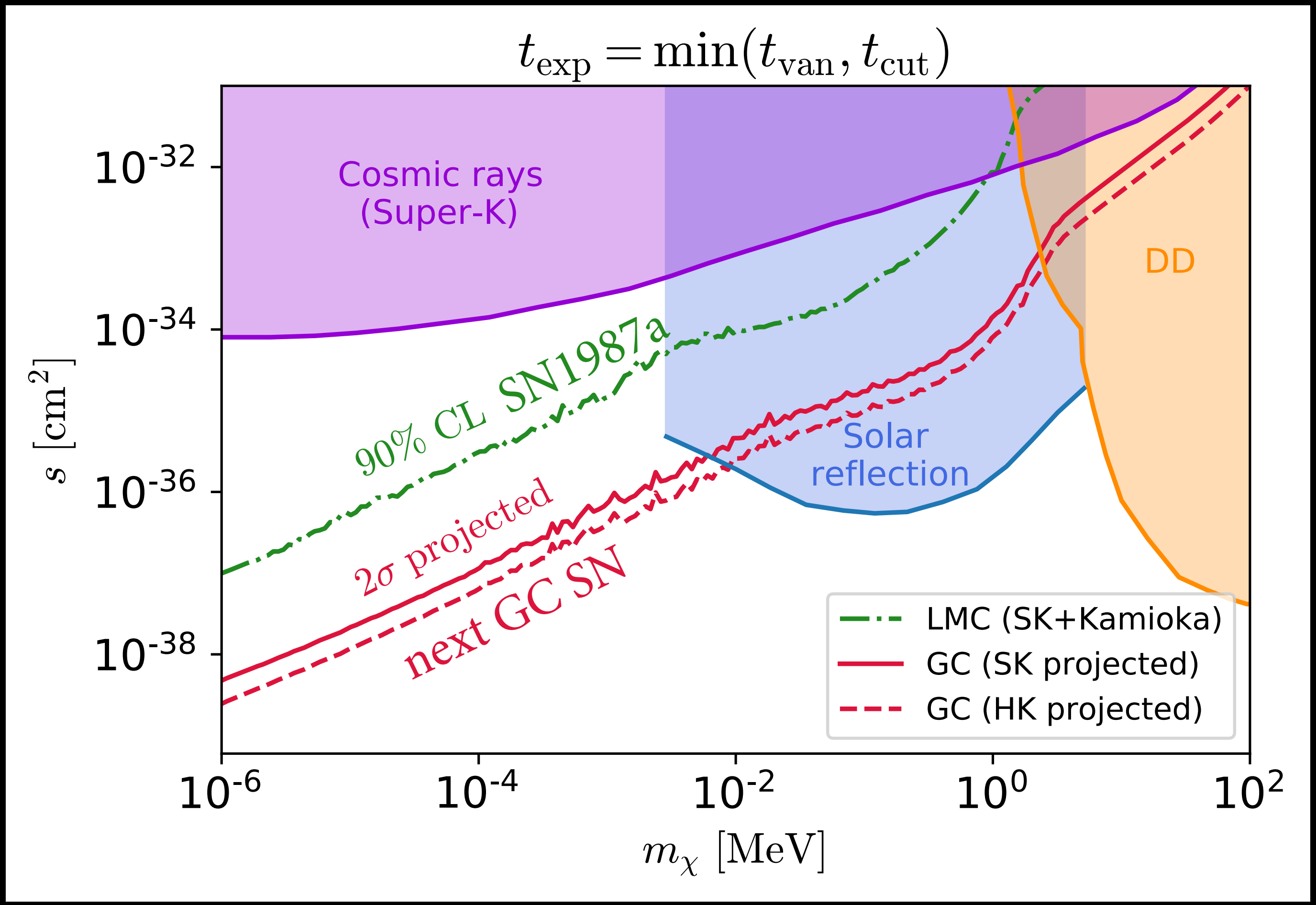
- LMC (SN1987a):
  - Kamiokande: 1987-1996
  - Super-K: 1996 - present
- $m_\chi < 1.1$ keV has $t_{\rm van} < 9$ years, which is unobservable to Super-K



- 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 $t_{\rm van} > t_{\rm cut}$

An+ (2018)
Cappiello+ (2019)
Aprile+ (2019)
…

Constraint and sensitivity



- The constraint and sensitivity

$$\sigma = \frac{N_\chi}{\sqrt{N_\chi + N_b}}$$

- It is placed on

$$s = \sqrt{\sigma_{\chi\nu}\sigma_{\chi e}}$$

- Existing constraints are placed on $\sigma_{\chi e}$ only, to compare, we let $\sigma_{\chi\nu} = \sigma_{\chi e}$ in our analysis

- The SN1987a from LMC already provides much improved constraint on s than the existing bounds with m_χ extends down to eV

- It is benefited from the background suppression due to $t_{\rm van}$

- The next GC SN can offer better sensitivity on DM

Summary & outlook

Summary & outlook

- The *first* using *Time-of-Flight* information to directly measure m_χ
- BDM posses the unique *time-dependent* feature that can be used to suppress the background and improves the sensitivity
- Constraint and sensitivity from SN1987a and the next GC SN, respectively, are presented with m_χ that is down to eV
- Future improvements and outlook:
    - Including angular resolution → further reduce the background
    - Off-center SN → may change the intensity and shape of the BDM flux
    - ……