Unraveling the History of the Universe and Matter Evolution with Underground Physics 2024
Mar. 5th 2024

Physics cases by direction sensitive dark matter searches

Keiko Nagao (Okayama Univ. of Sci.)

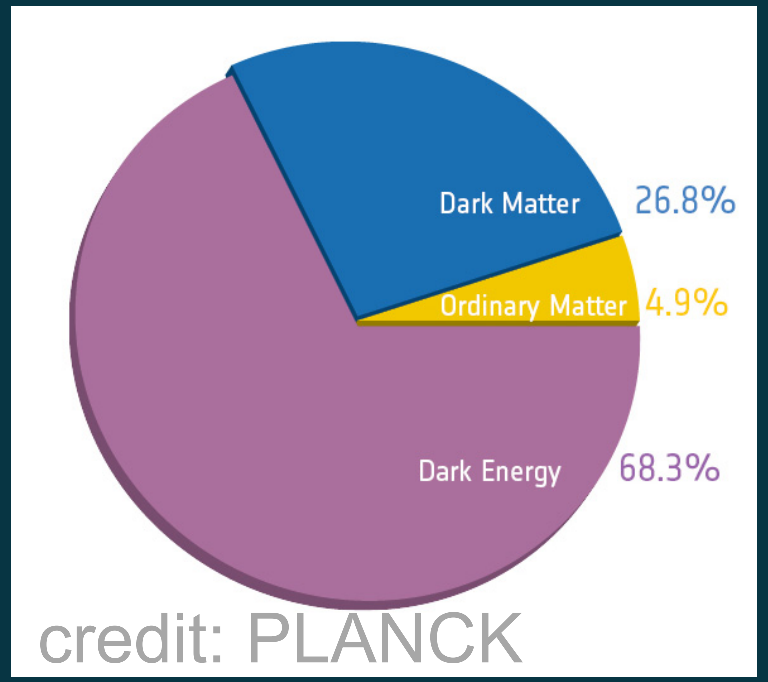
based on collaboration with KN, S. Higashino, T. Ikeda, R. Yakabe, T. Naka, K. Miuchi

arXiv:1707.05523, arXiv:2211.13399,

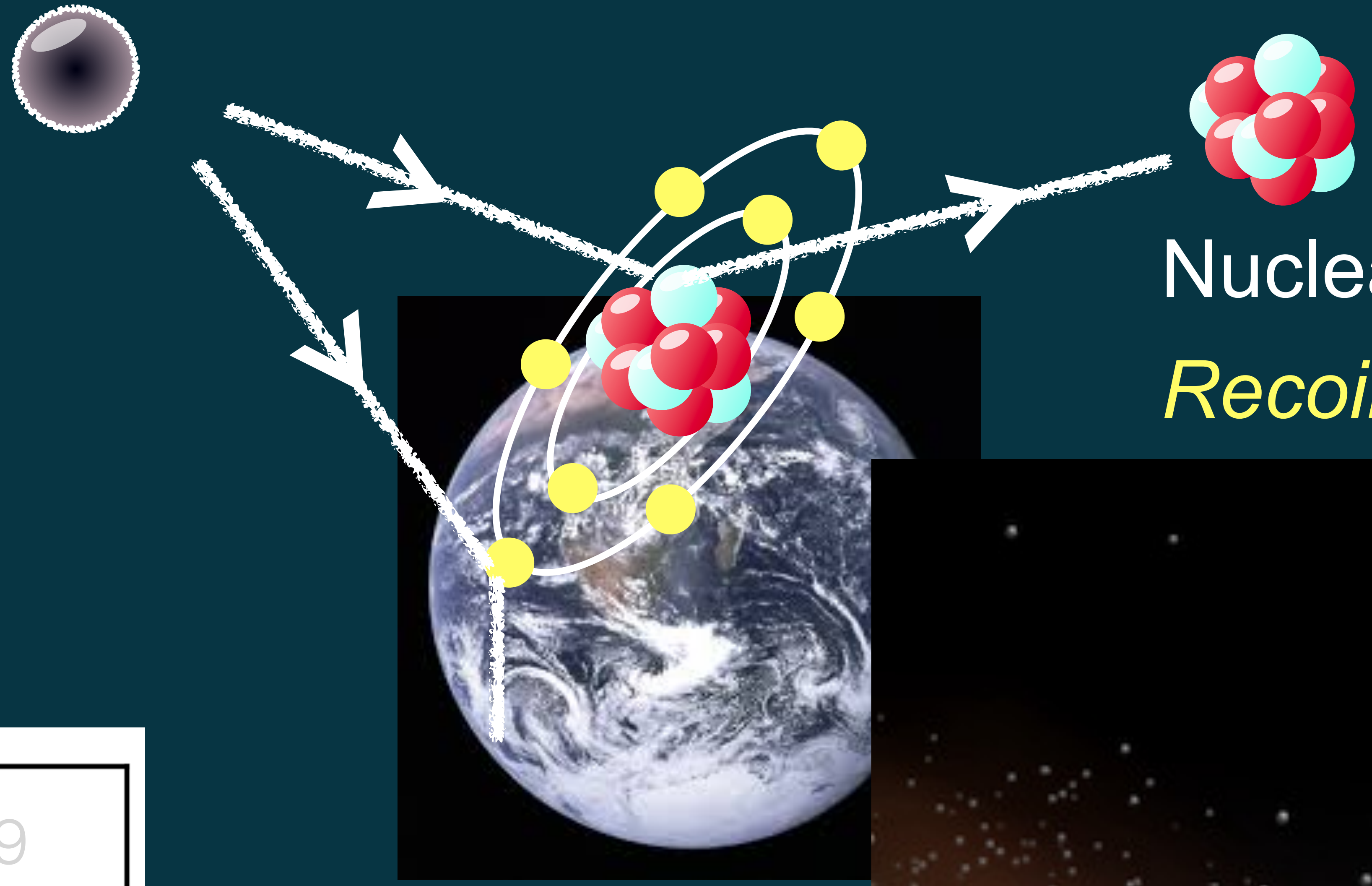
also work with T. Shimomura, Y. Uesaka (in progress)

See Higashino-san's
Naka-san's talks for
technical details.

Quick Introduction

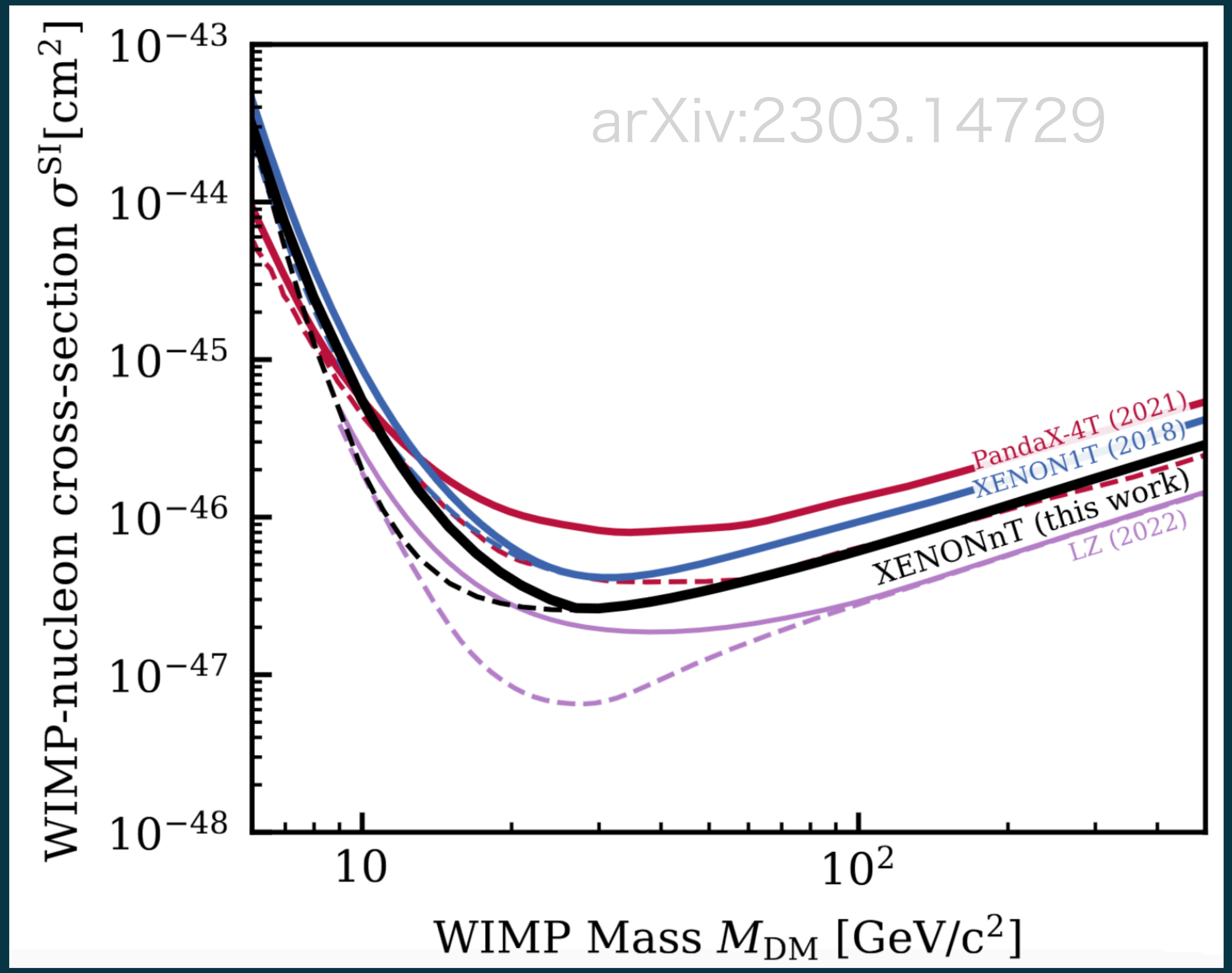


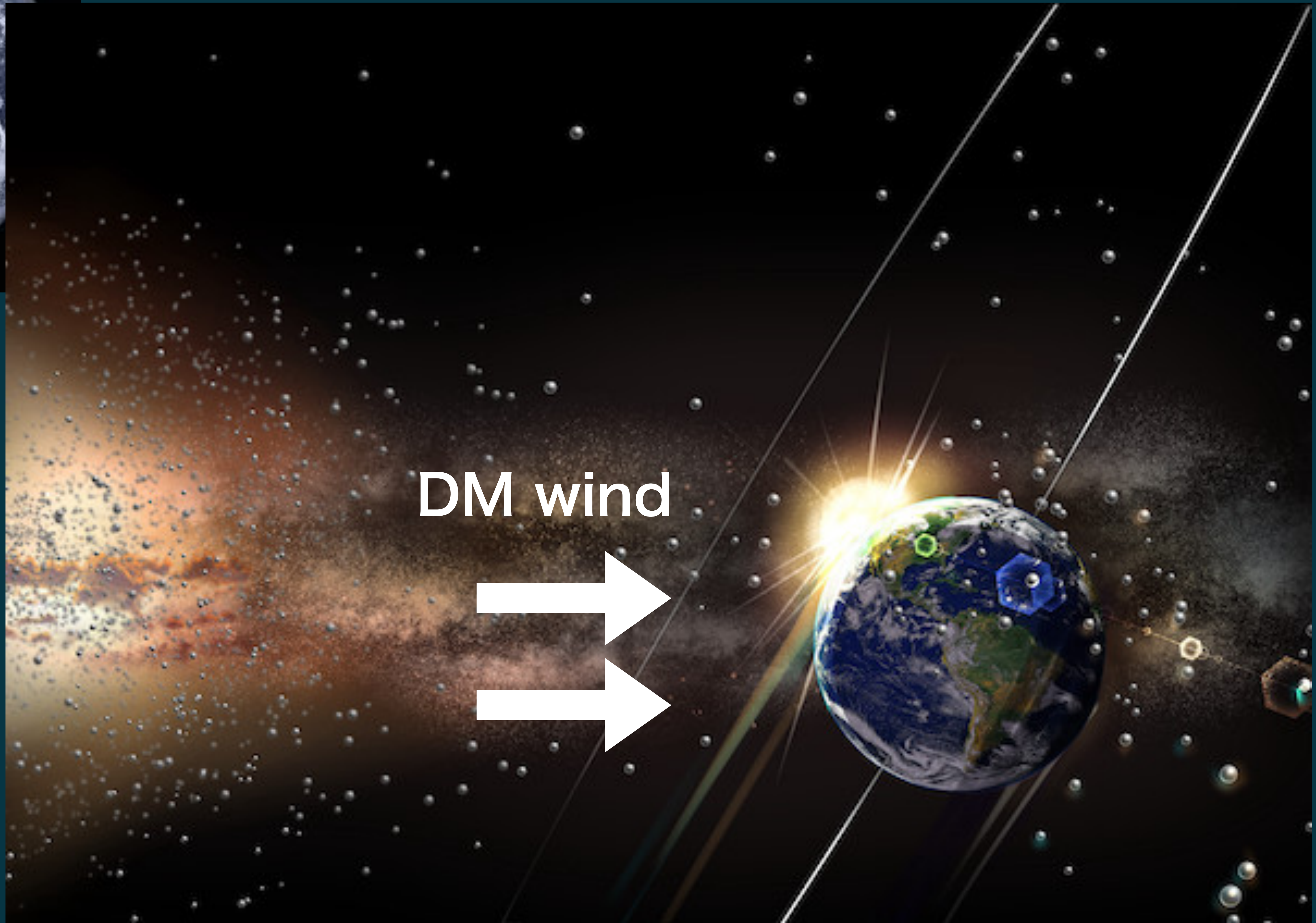
- Dark Matter
- Direct Detection
- Directional Detection



Nuclear Recoil

Recoil Energy E_R ***+ Direction!***

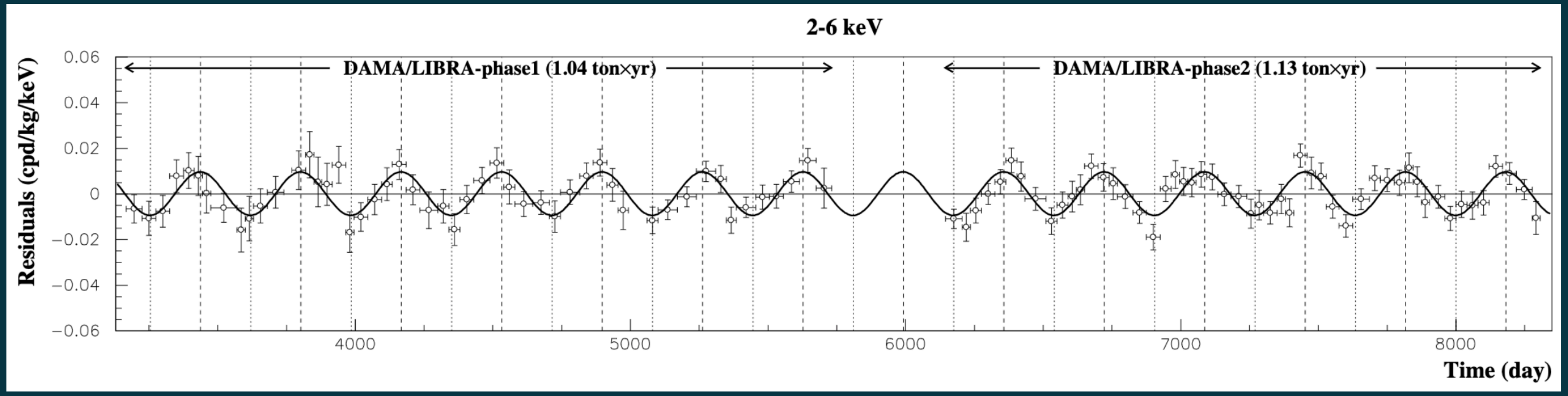




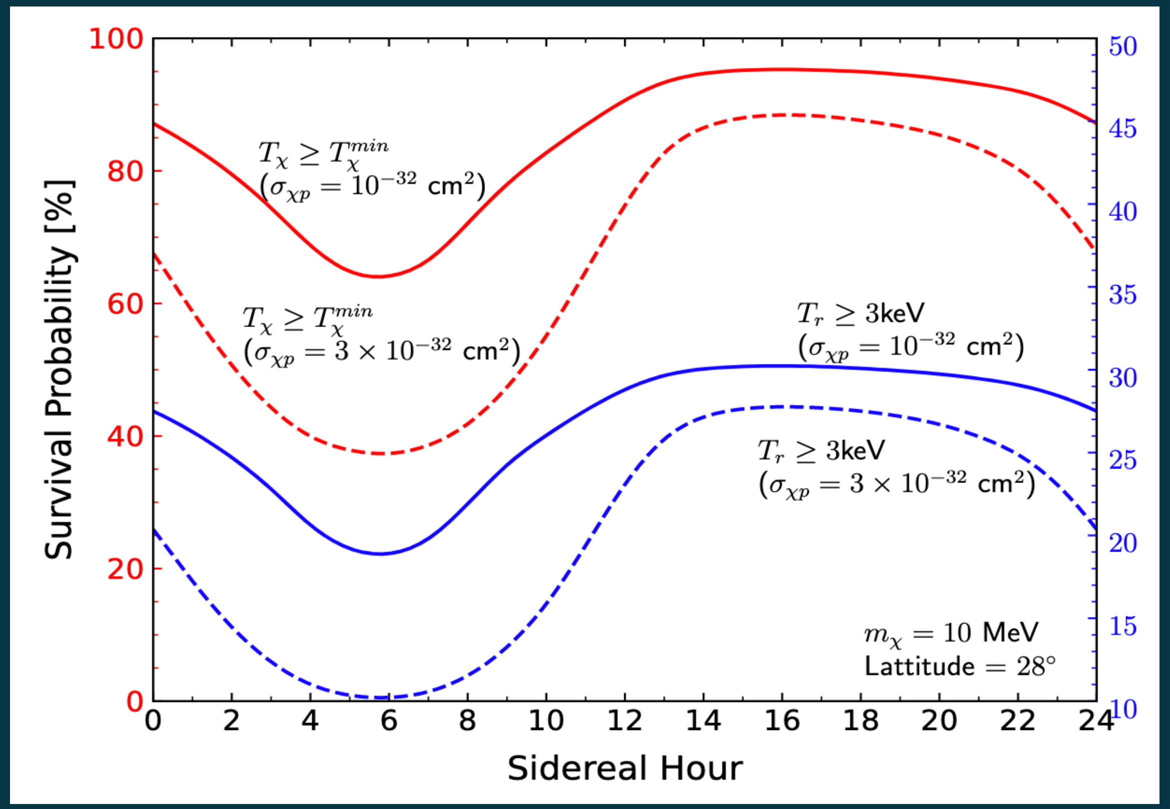
Let’s contemplate **direction** seriously.

How can we use directional info.?

R. Bernabei et al., arXiv:1805.10486



- Annual/Daily Modulation
- Anisotropy of Velocity Distribution
  - Velocity dist. of DM may be anisotropic.
- Cosmic Ray Boosted DM/Density Profile of DM
  - DM density is high in the Galactic center. We can check the feature using direction if DM is light. It can reflect the DM density profile of the Milky Way galaxy.
- … And others? Comments are welcome!



S.-F. Ge et al., arXiv:2005.09480

Outline

1. Introduction -WHY DIRECTION?-
2. Velocity Distribution
3. Cosmic Ray Boosted DM and Density Profile
4. Discussion

Velocity Distribution of DM

- Isotropic Maxwell-Boltzmann (MB) distribution is commonly supposed for DM velocity

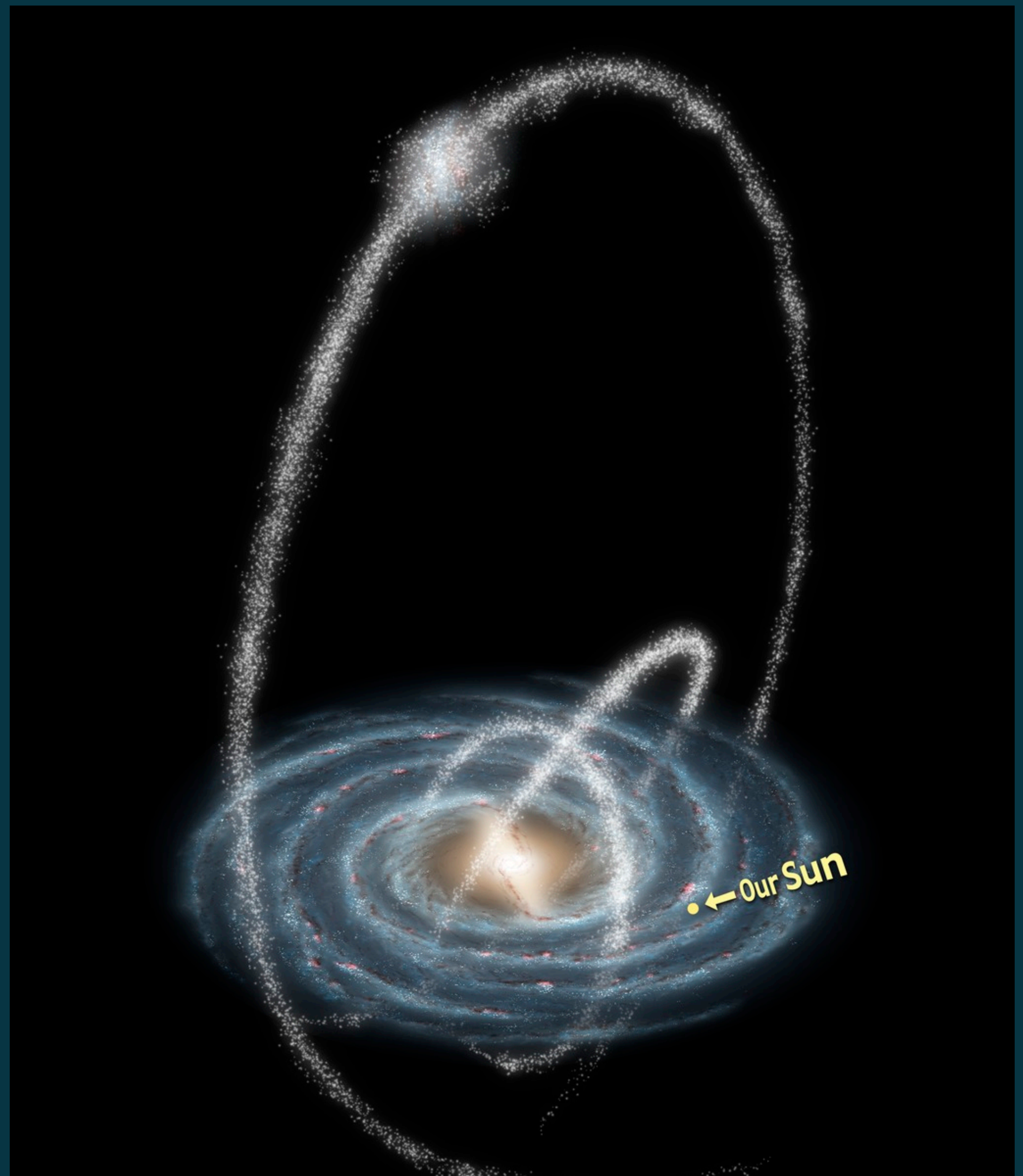
$$\frac{dR}{dE_R} = N_T \frac{\rho_{\rm DM}}{m_{\rm DM}} \int dv\ f(v) v \frac{d\sigma(v)}{dE_R}$$

$$f(v) = \frac{1}{\left(\pi v_0^2\right)^{3/2}} \exp\left[-\left(v + v_E\right)^2 / v_0^2\right]$$

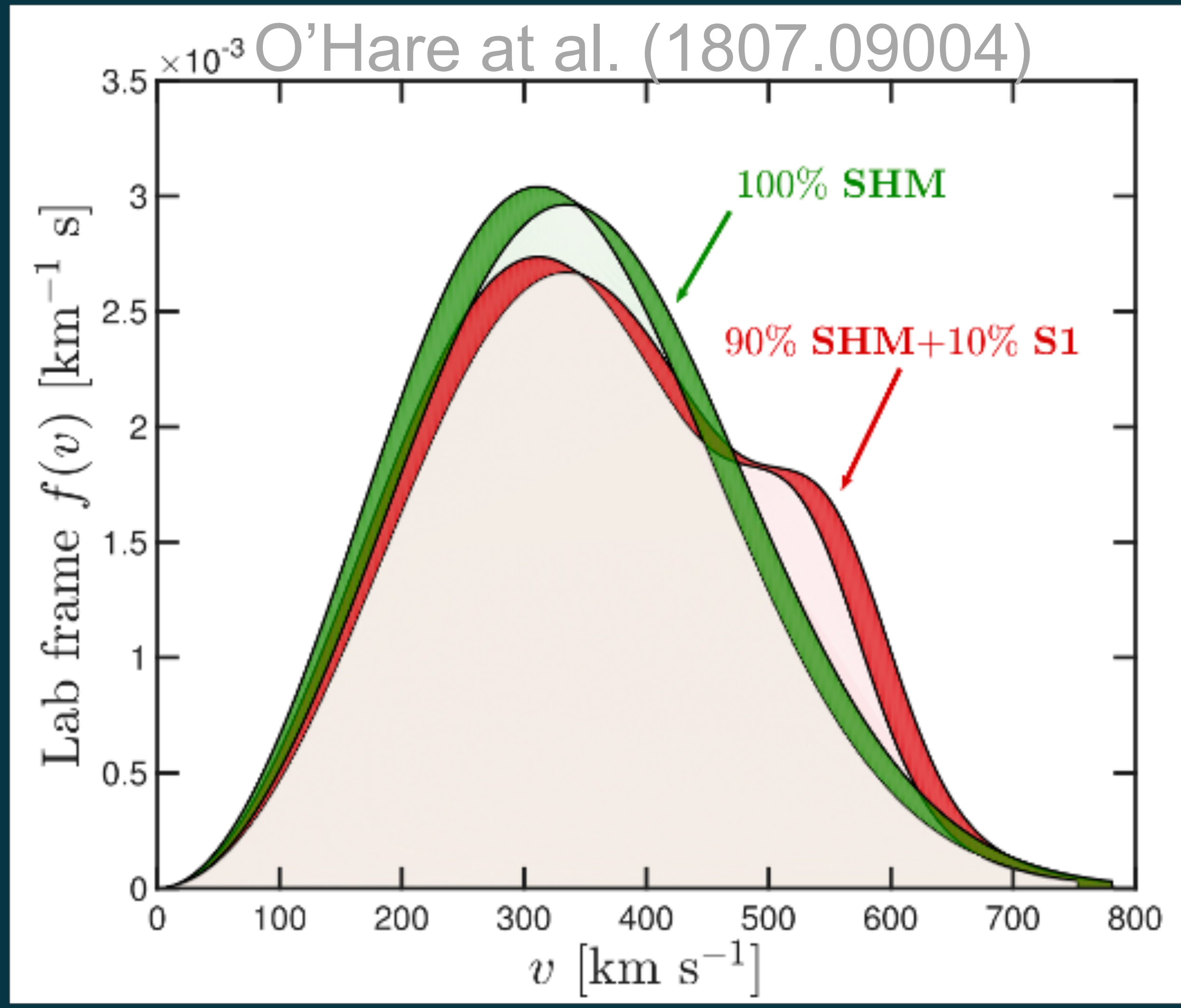
R: Event rate
N_T: #Target nuclei
$\rho_{\rm DM}$: Local DM density
$m_{\rm DM}$: DM mass
$f(v)$: Velocity distribution of DM
$\sigma(v)$: Cross section of DM and nuclei scattering
E_R: Recoil Energy

- Anisotropy of velocity distribution

  S1 stream derived by SDSS-Gaia data has ~10% anisotropic component.

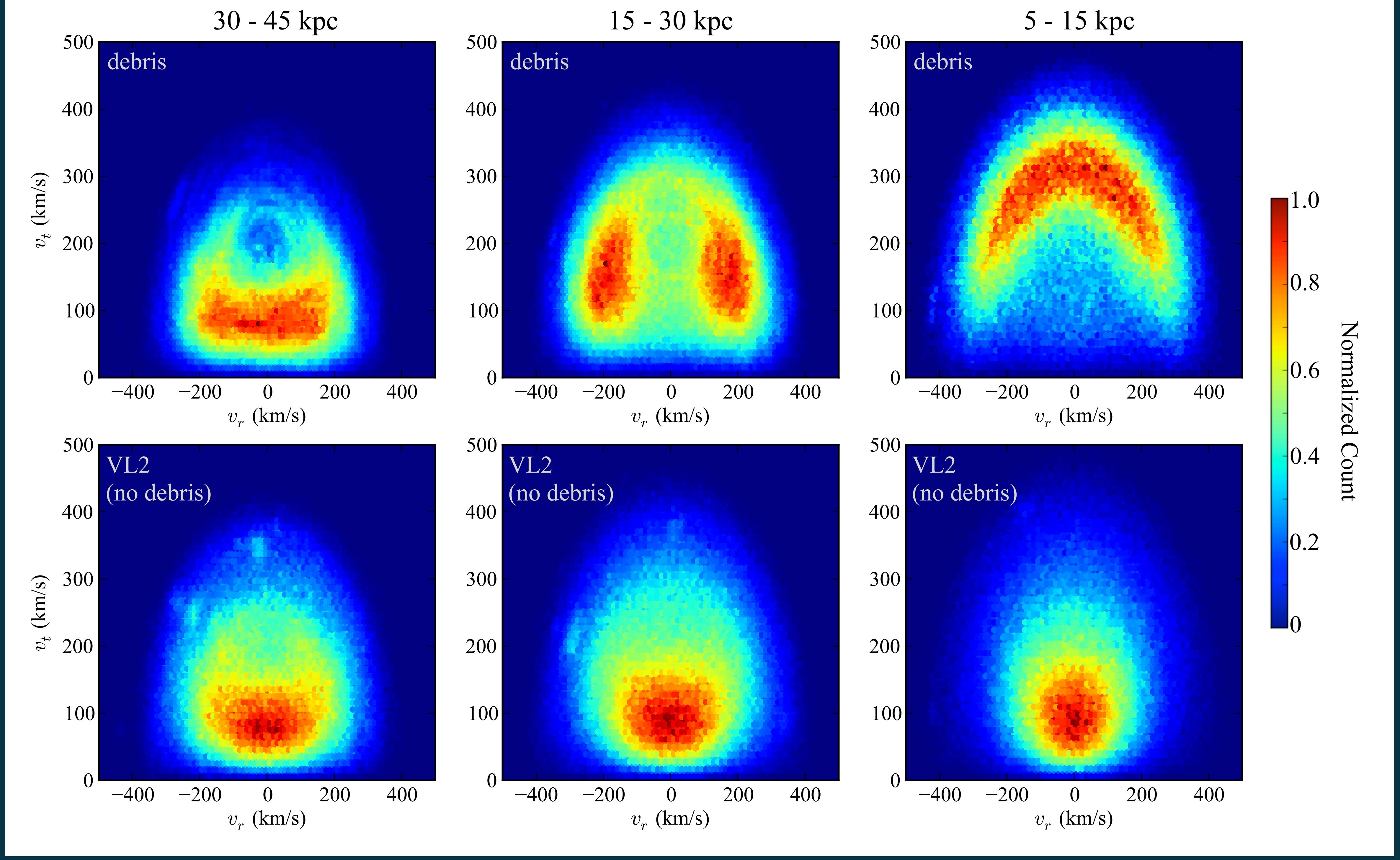


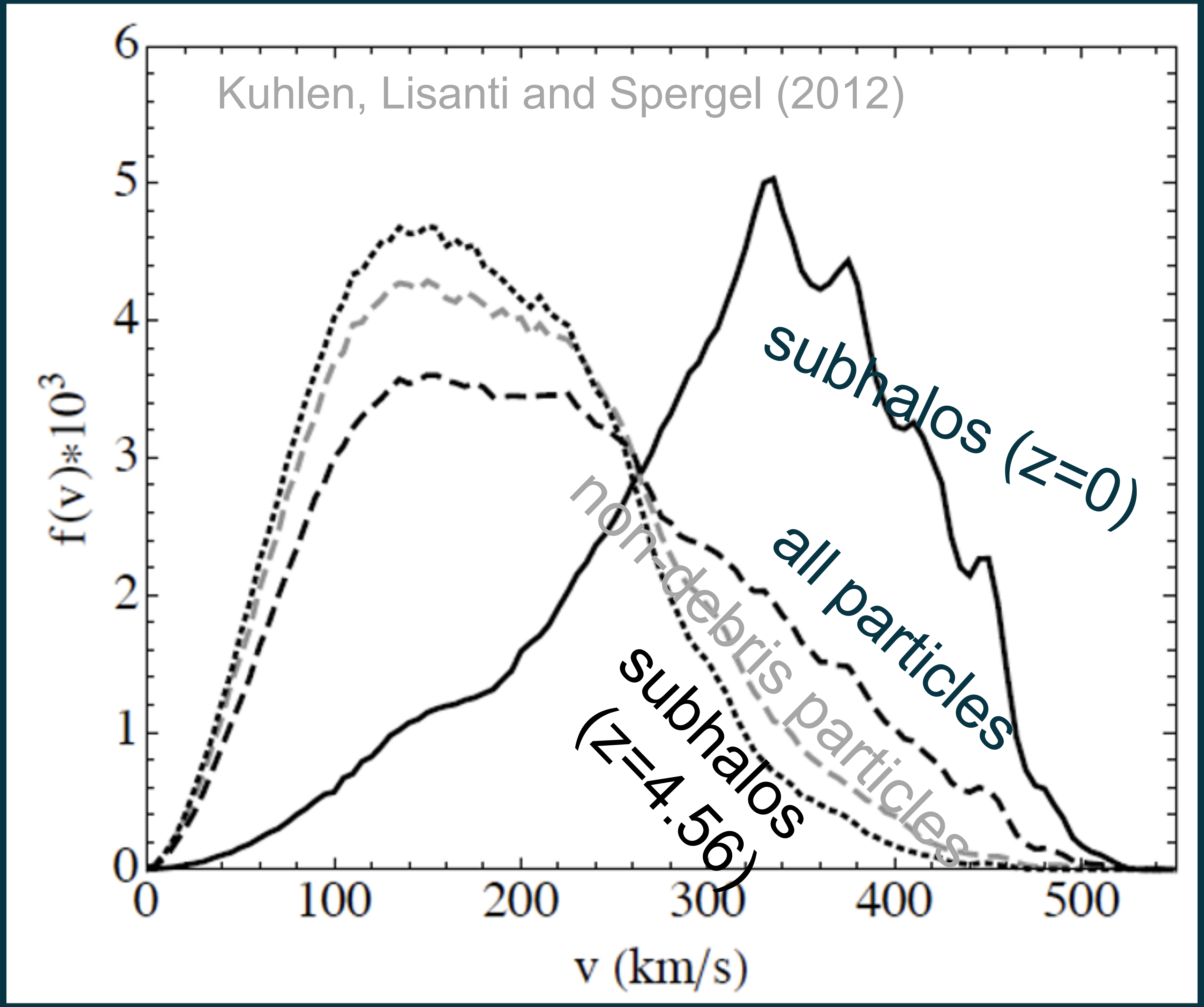
Credit: NASA/JPL-Caltech/R. Hurt (SSC/Caltech)



Debris Flow by Simulations

- Some N-body simulations suggest non-MB distribution due to debris flow in the Galaxy

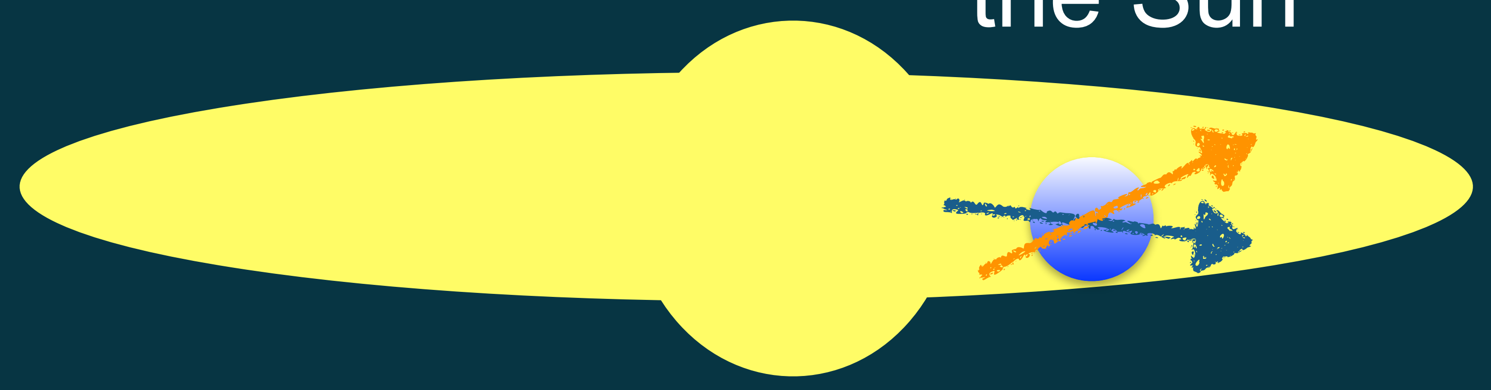


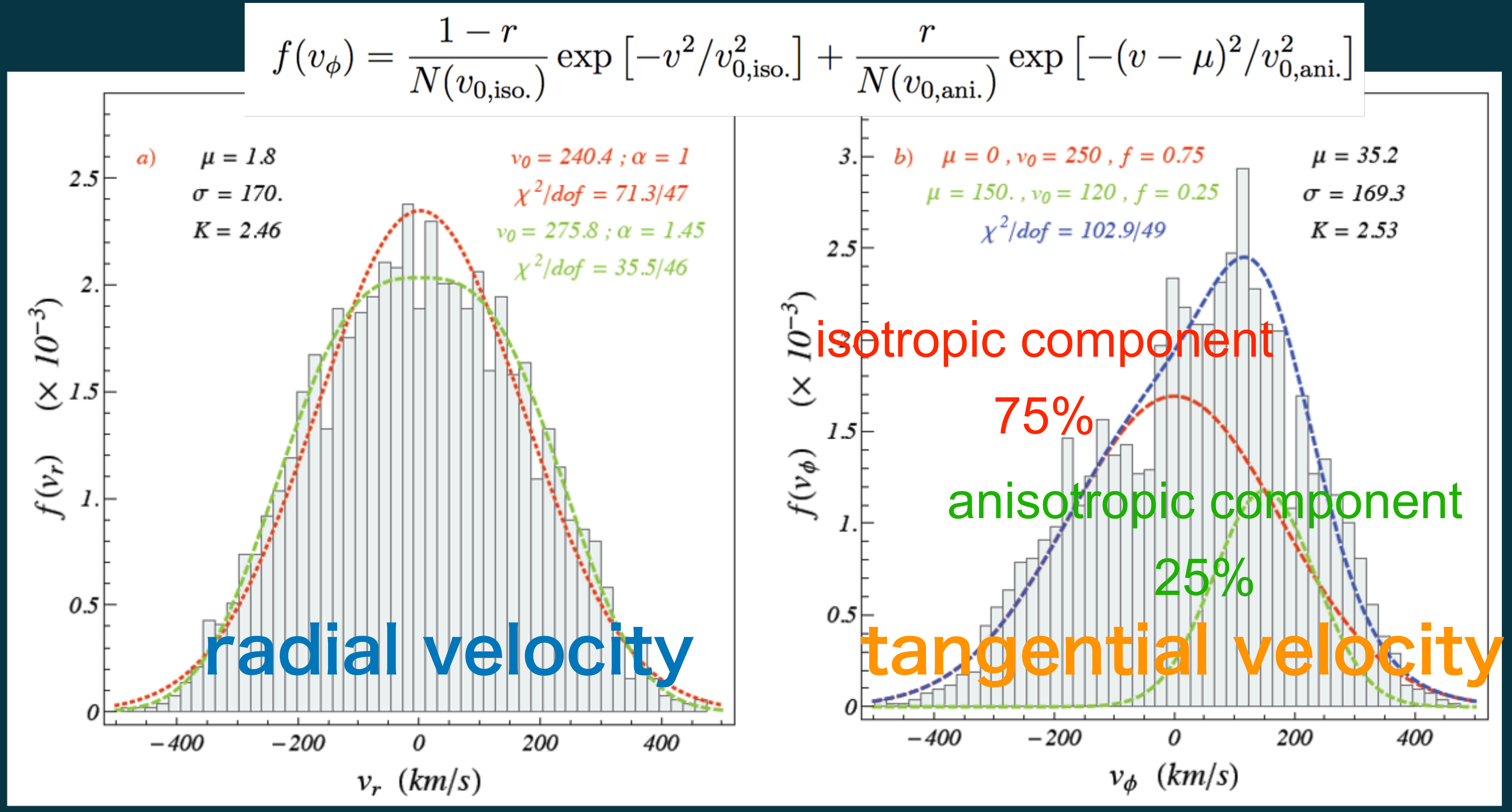


Lisanti and Spergel, arXiv:1105.4166

Simulation including baryons and gas

- DM follows baryons
- DM velocity has anisotropic component

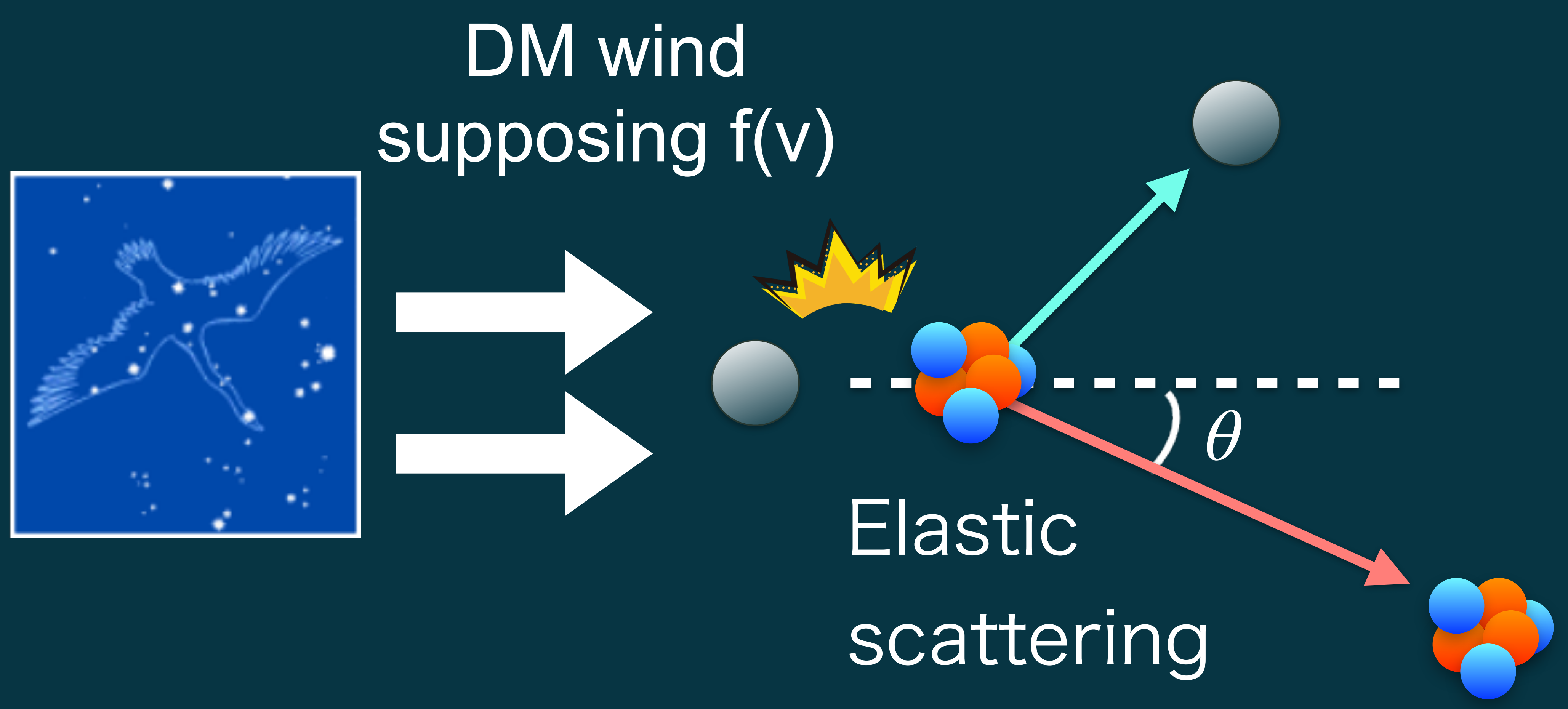




Can we see the anisotropy with directional detection?

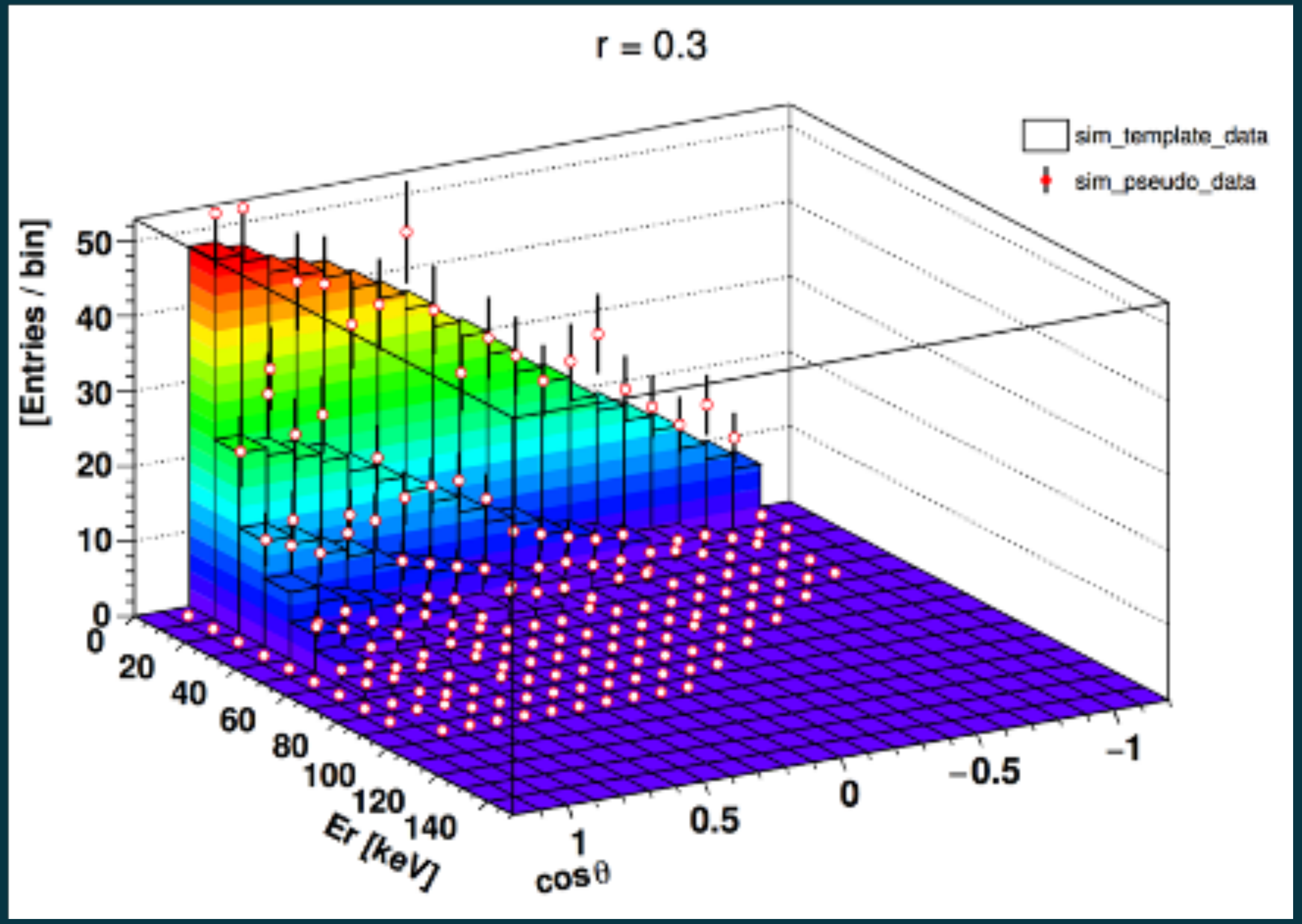
Simulation of DM detection

- Monte Carlo simulation of DM-Nucleus Scattering
  - E_R and θ are obtained
  - No background, Perfect resolution
  - Target : F (light) /Ag (heavy)



- Two kinds of Data
  - Template: Ideal data with sufficient statistics for isotropic MB/anisotropic velocity dist.
  - Pseudo-experimental data: Data with insufficient statistics

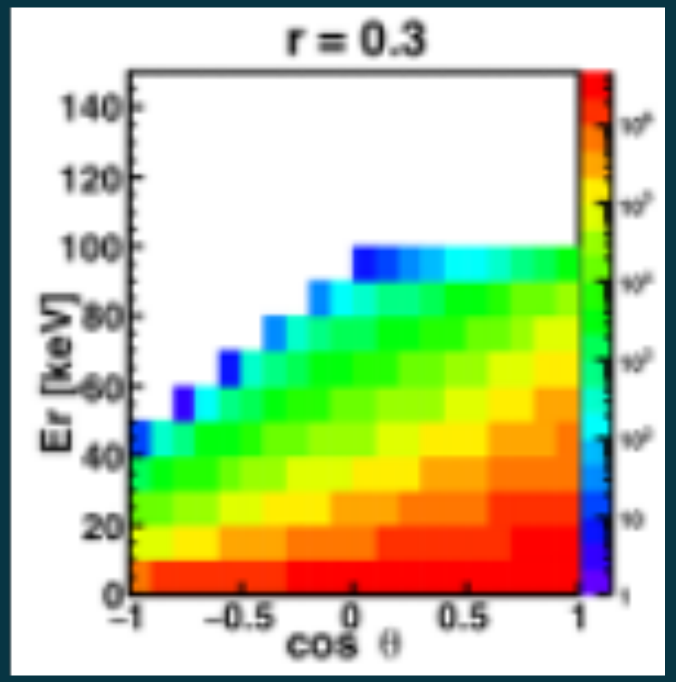
Strategy for discrimination of anisotropy



Ideal “**template**”
Many Data
(#10^8)

Which template is more similar to pseudo-exp?

“**Pseudo-experimental**” data
Fewer Data
(#10^3-10^4)

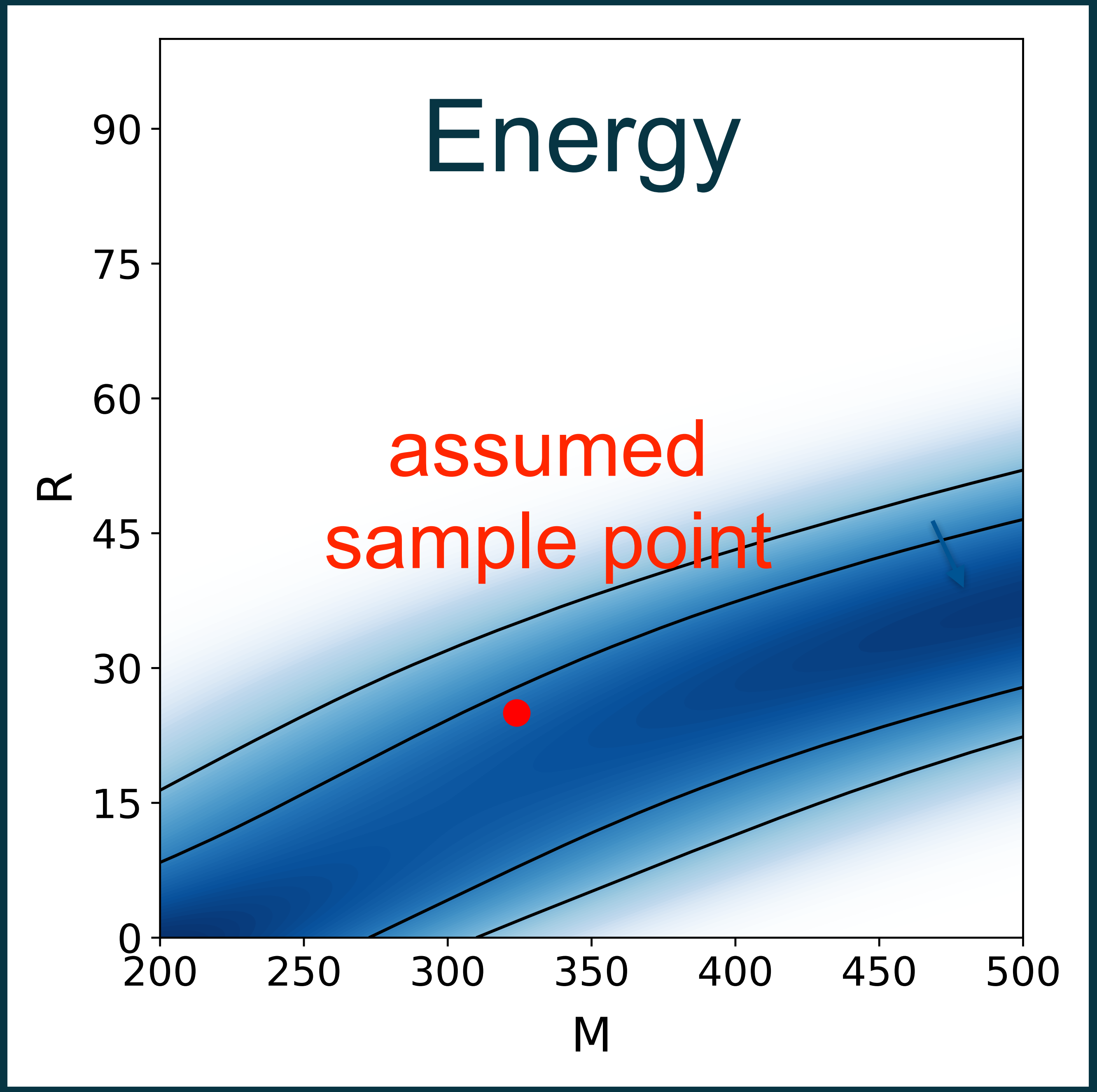


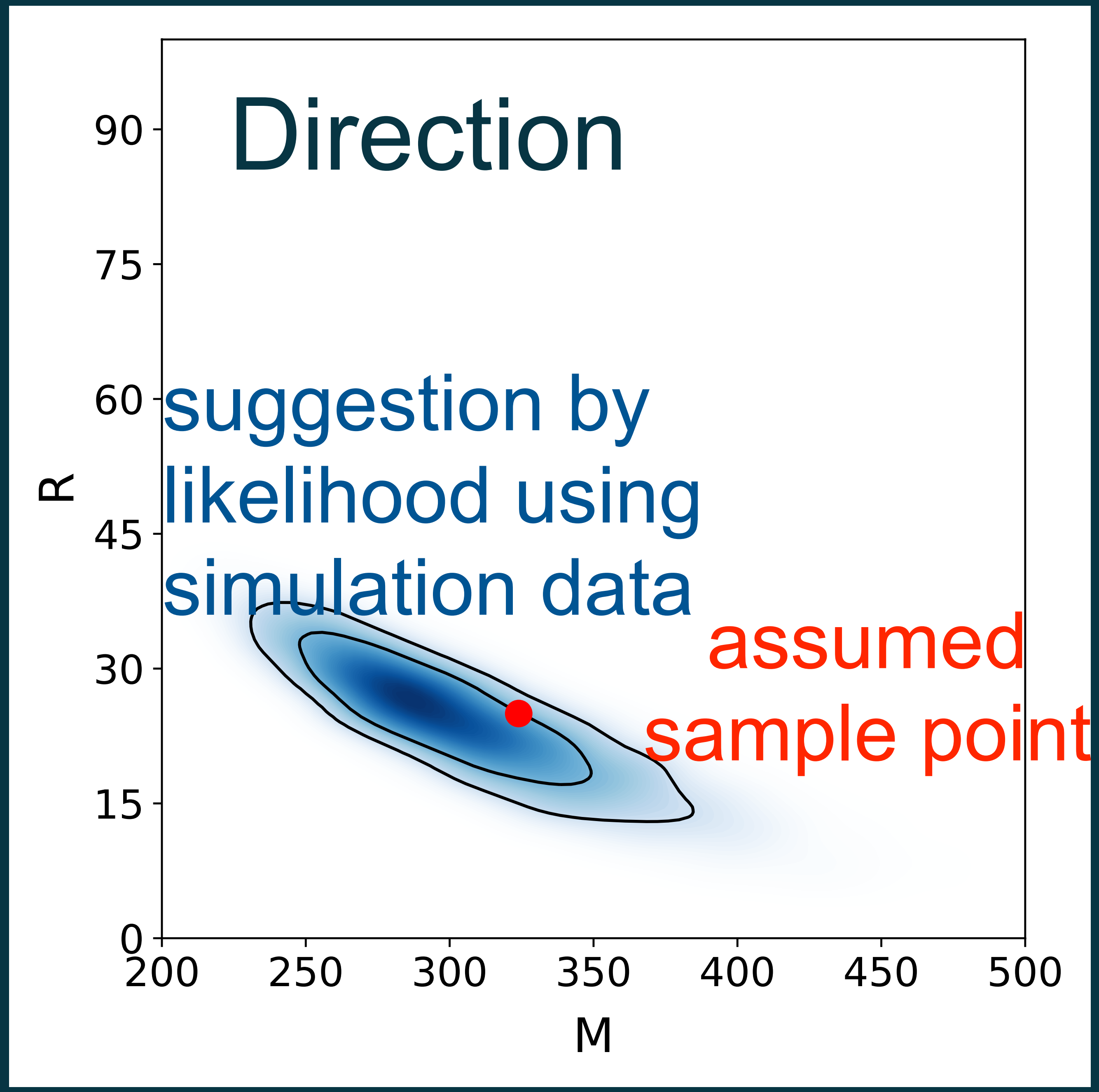
- Likelihood estimation

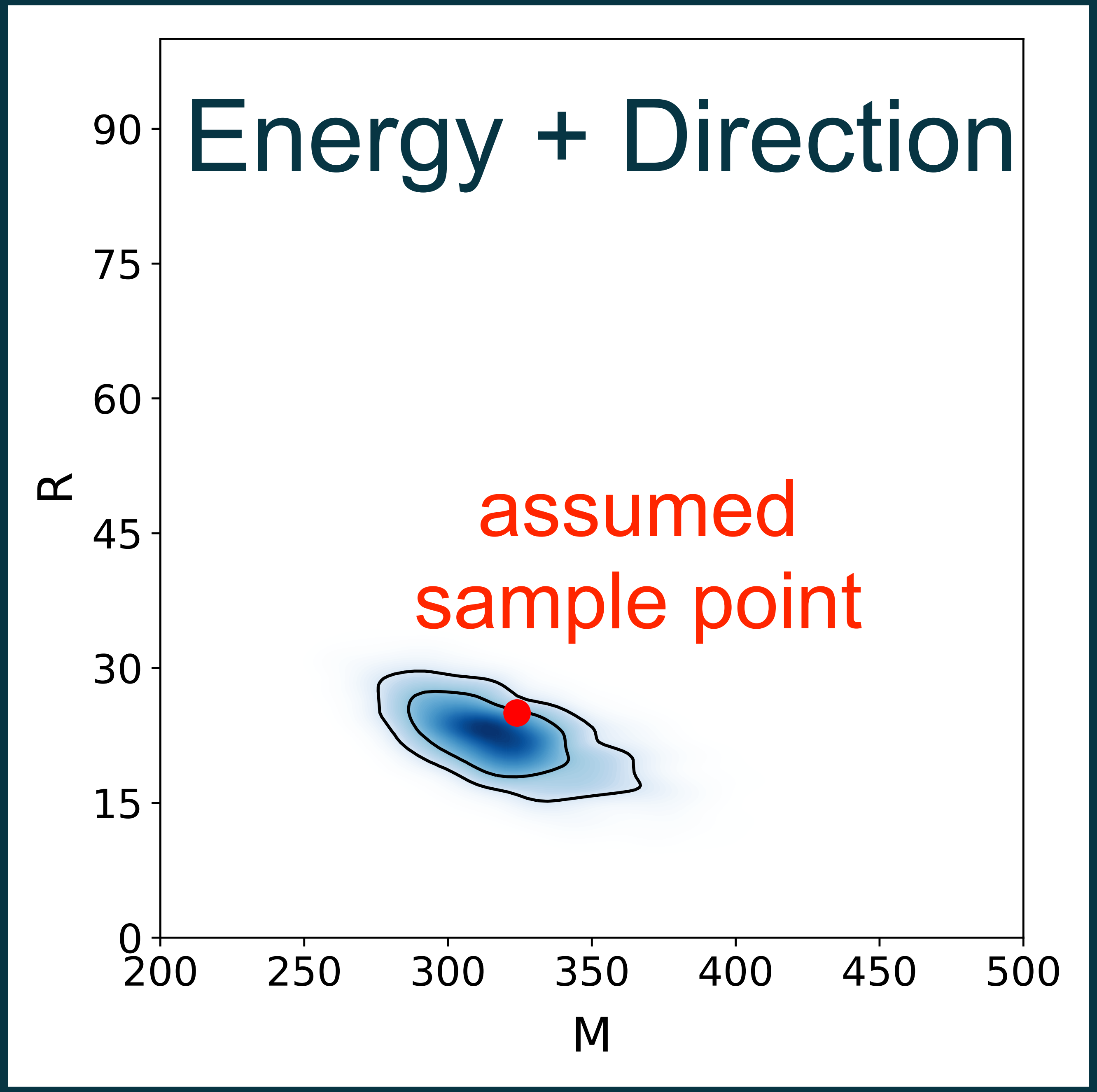
$$\mathcal{L} = \prod_{\text{bins}} P(r \mid \text{pseudo, template})$$

KN, T. Ikeda, R. Yakabe, T. Naka, K. Miuchi
arXiv:1707.05523

Sensitivity for anisotropy and mass







- Directional info. is helpful to determine both DM mass and anisotropy efficiently at the same time.

-Ethr=50keV
-target:Ag
-M_{dm}=324GeV
-#event: 10000
($\sigma_p=10^{-28}cm^2$, 1/kg/day)

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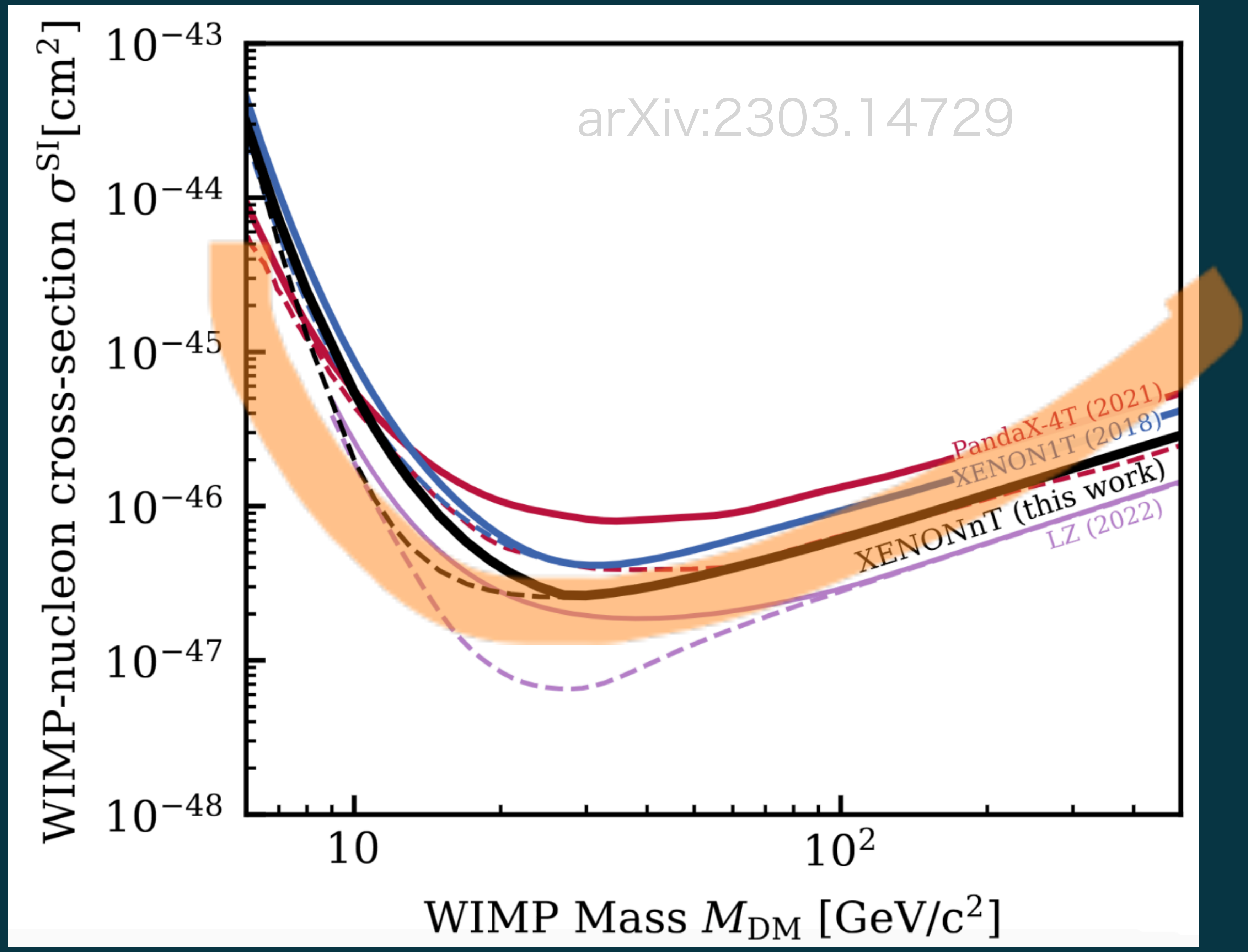
Difficulty of Light DM Detection

- Light DM
  - $\langle v_{\rm DM}\rangle$~230km/s $\ll c$
  - Kinetic energy ~$m_{\rm DM} v_{\rm DM}^2/2$
  - For light DM, getting enough kinetic energy to overcome energy threshold of detector is hard.



- Heavy DM

$$\Omega_{\rm DM} = \frac{m_{\rm DM} n_{\rm DM}}{\rho_{\rm cr}} = 0.27$$

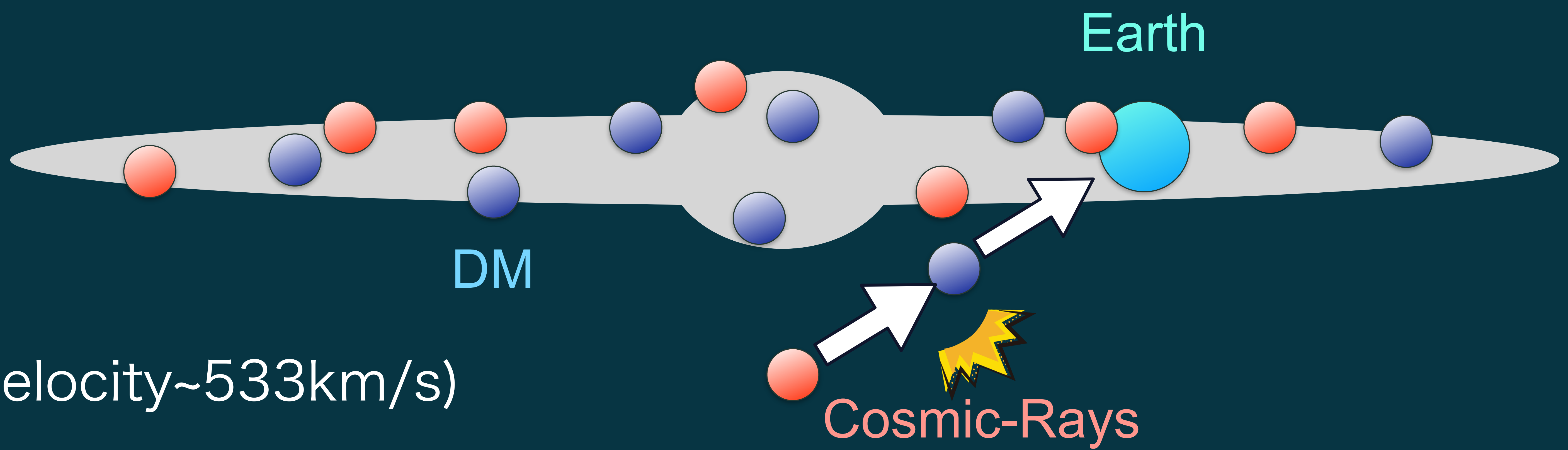
$$n_{\rm DM} \propto 1/m_{\rm DM}$$

Less #DM is expected.

→ Small ionization signals by DM-electron scattering (R. Essi et al. 2101.08275), Migdal effect (M. Ibe 1707.07258), Boosted DM, …

Cosmic-Ray Boosted DM

W. Yin 1809.08610
Y. Ema, F. Sala, R. Sato 1811.00520
T. Bringmann and M. Pospelov 1810.10543
…



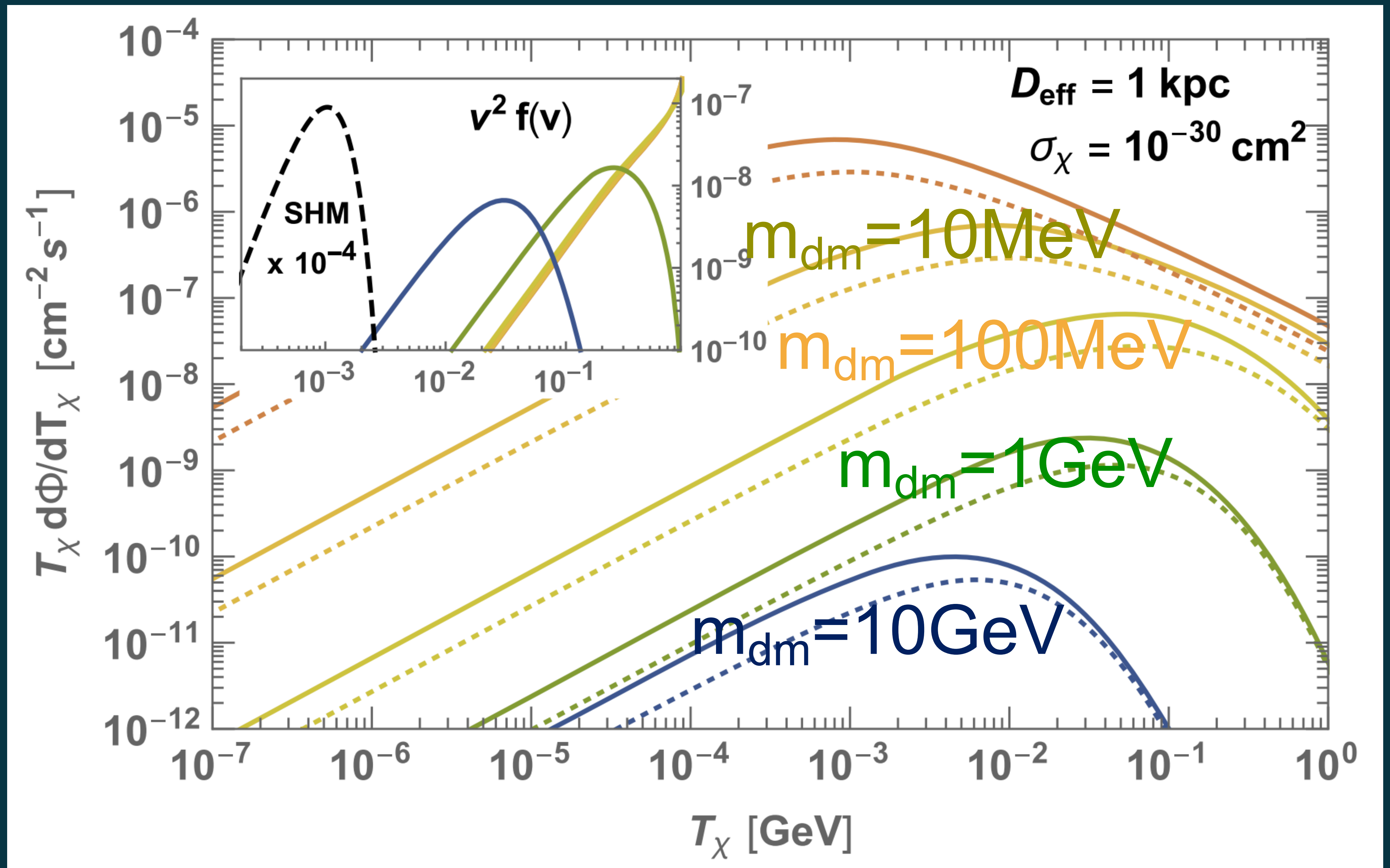
- Ordinary WIMPs
  - $\langle v_{\rm DM} \rangle$~230 km/s ; Slow
  - $v_{\rm DM} < v_{esc}$ (Galactic escape velocity~533km/s)

- Cosmic-Ray boosted DM (**CR-DM**)
  - NOT bounded by $v_{\rm esc}$
  - CR-DM can obtain additional kinetic energy to overcome the energy threshold after CR scattering if the DM is as light as O(10-1) GeV.

✳ **CR-DM will be boosted mainly from the Galactic center because DM is dense there! ⇨ Directional Detection**

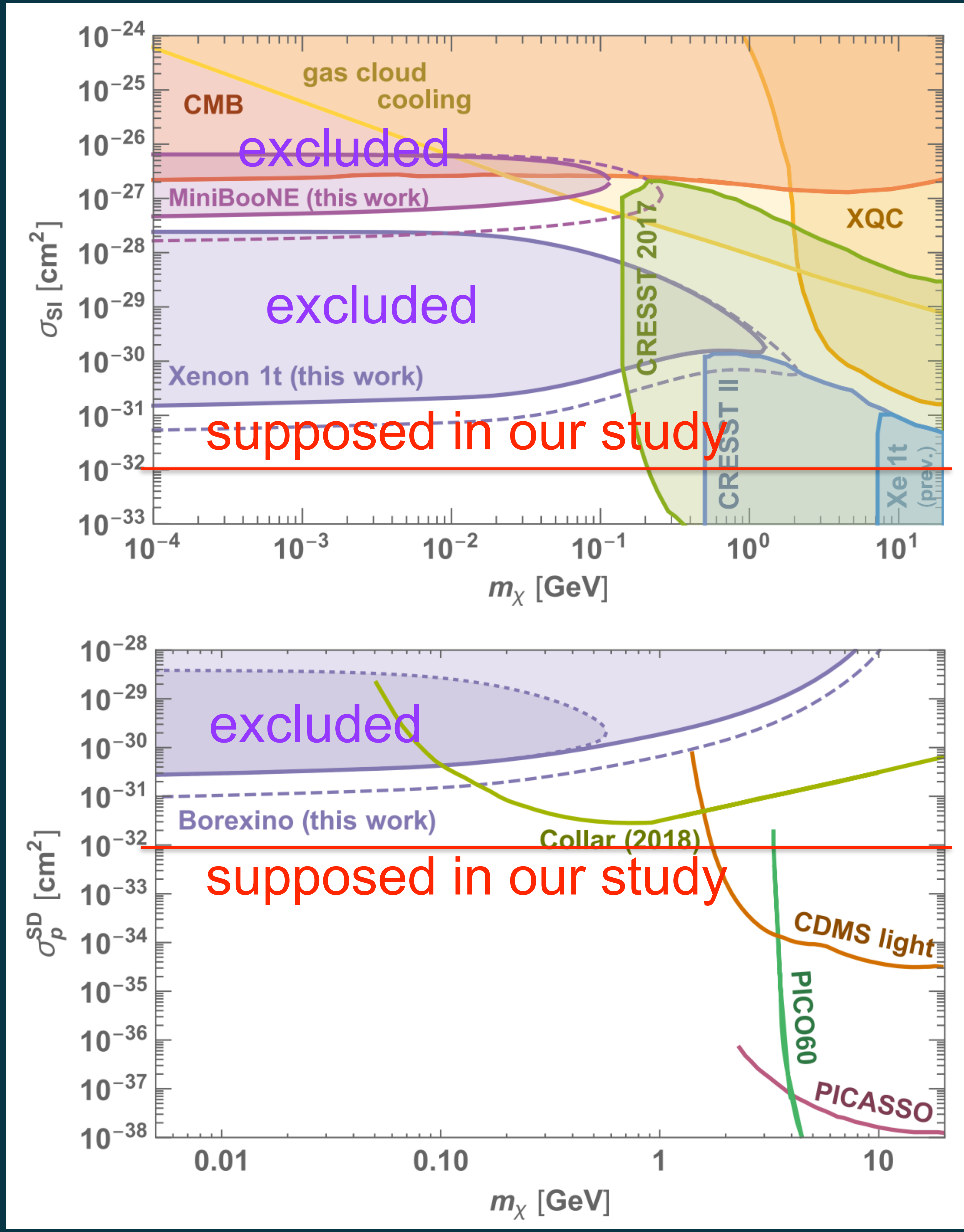
Constraints on CR-DM

- Flux



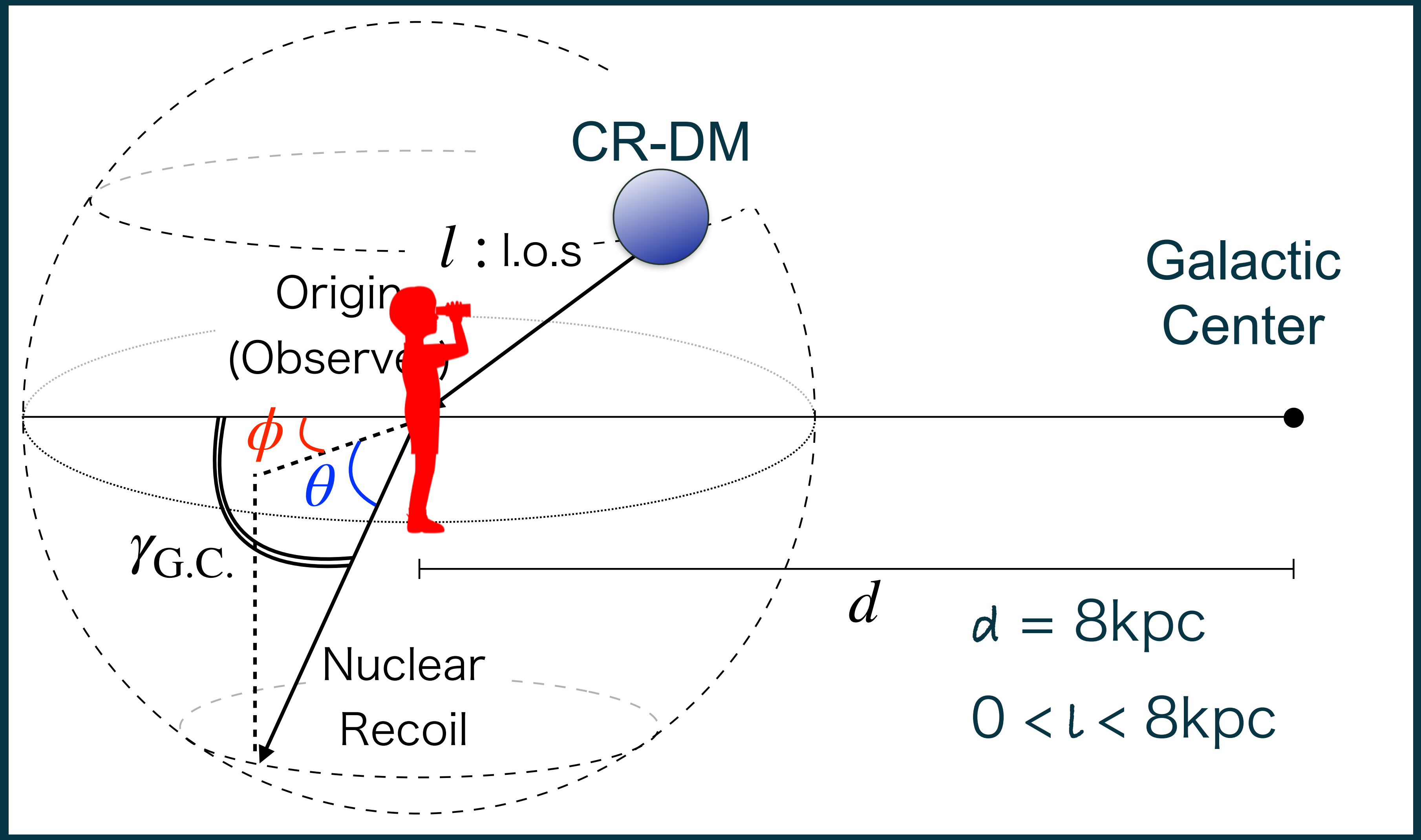
$$f(v) = \frac{m_\chi^2 \gamma^3}{\rho_\chi^{\rm local}} \frac{d\Phi_\chi}{dT_\chi}$$

- Constraints

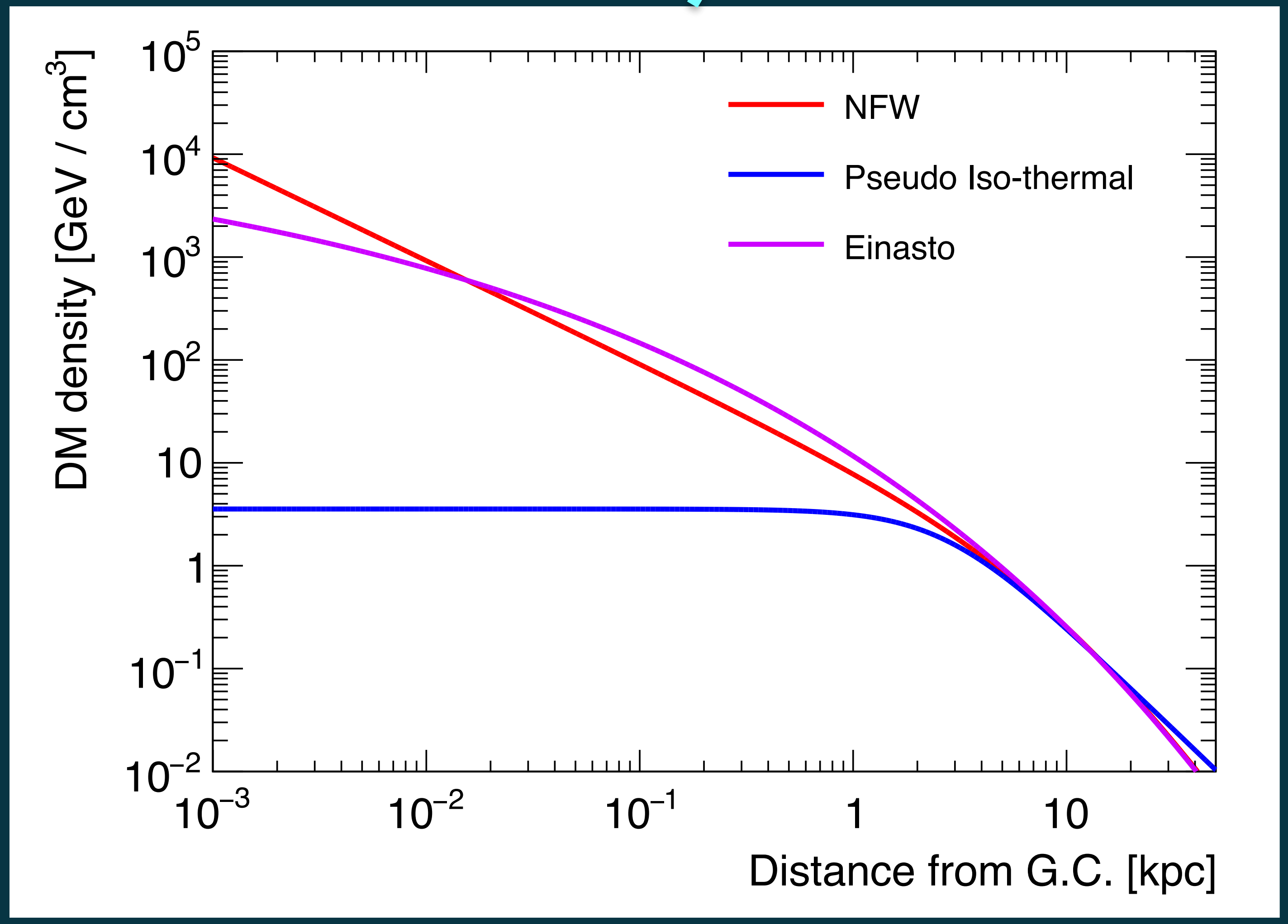


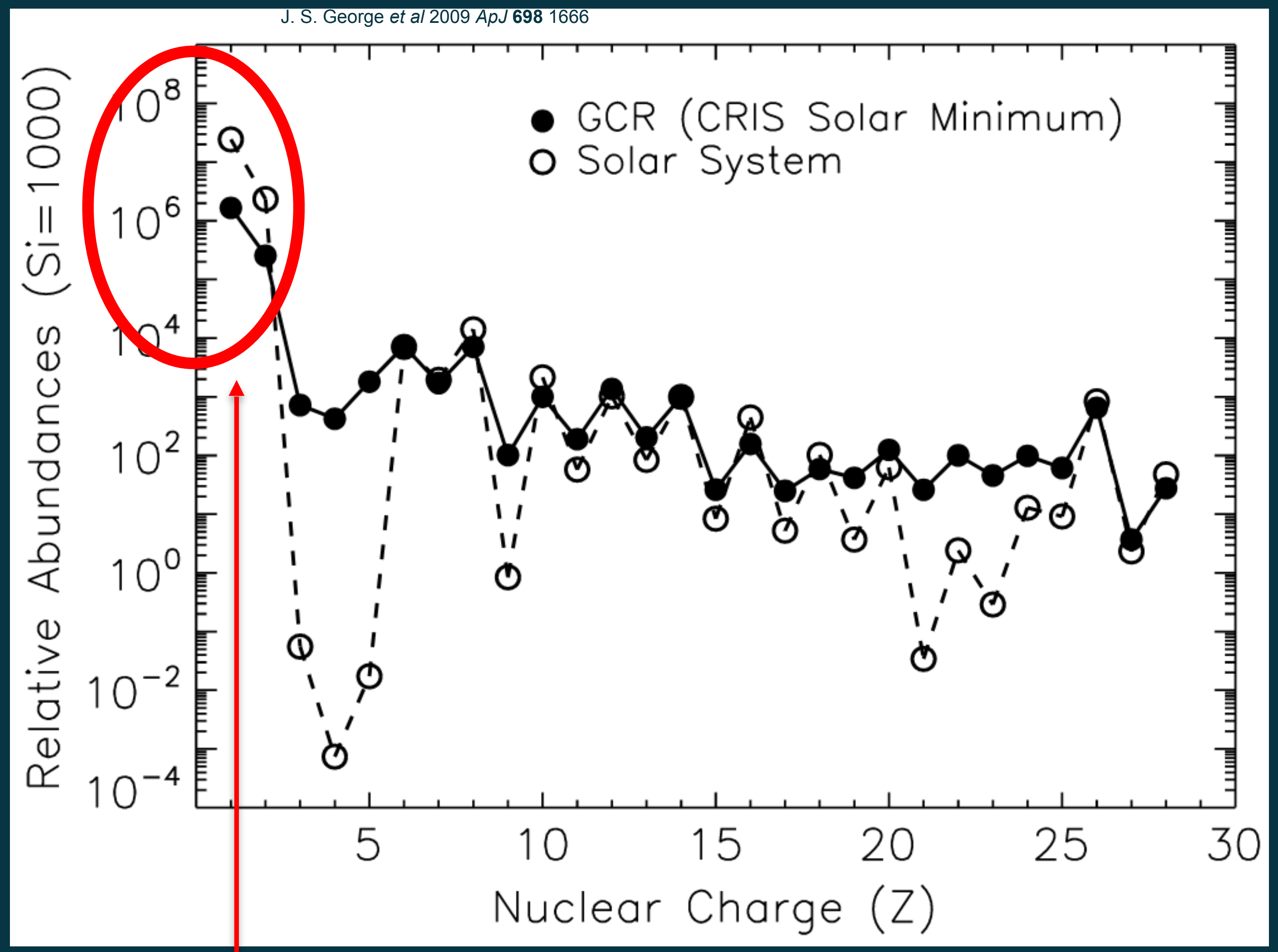
Flux of CR-DM for each direction

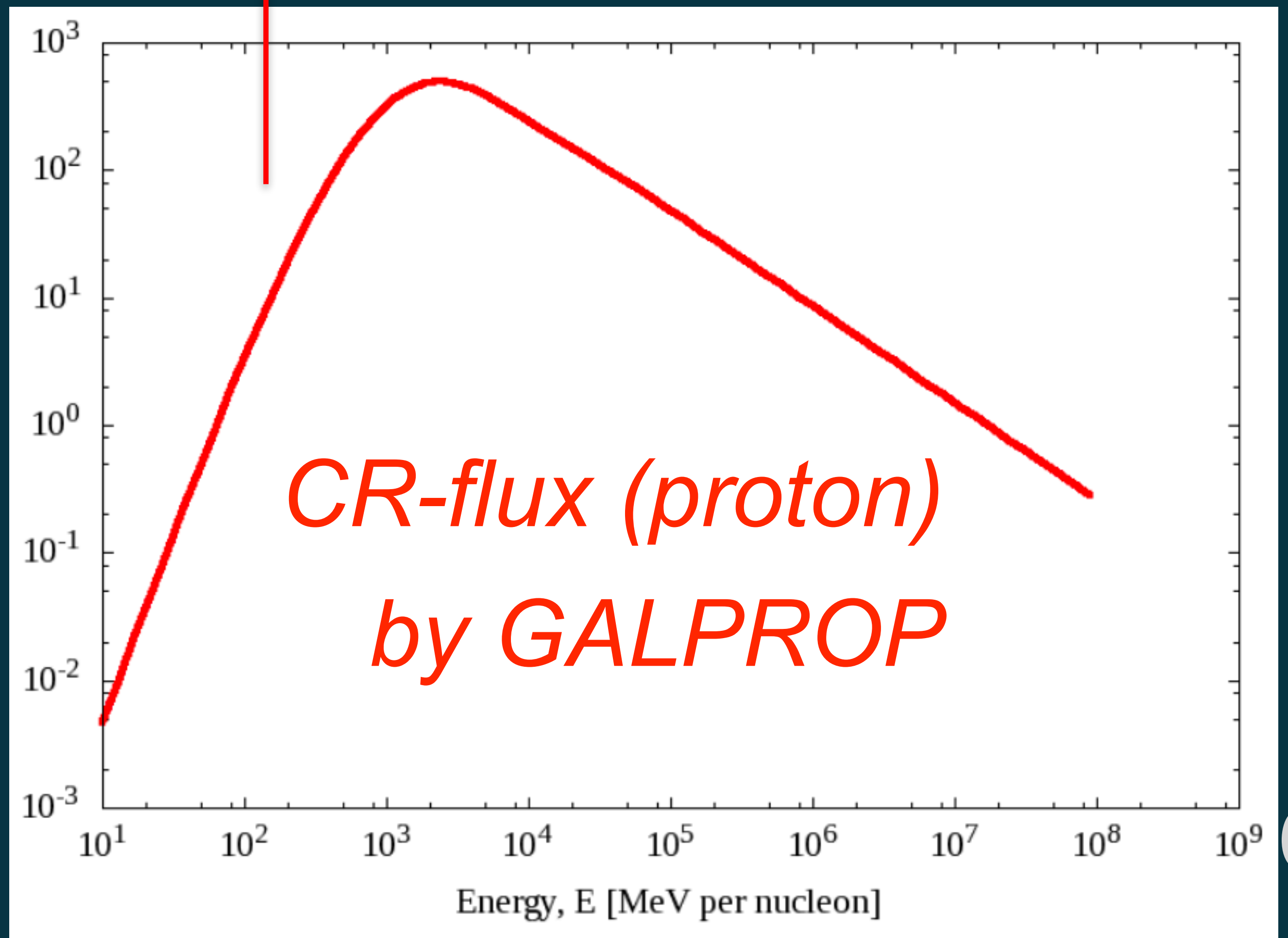
- $$\frac{d\Phi_\chi}{dT_\chi d\theta d\phi} = \int_{T_\chi^{\min}}^{\infty} \frac{dT_p}{T_\chi^{\max}} \int dV \frac{\rho_\chi}{m_\chi} \frac{d\Phi_p}{dT_p}$$
$$= \int dl d\theta d\phi \cos\theta \; G_p^2(2m_\chi T_\chi) \frac{\sigma_{p\chi}}{4\pi m_\chi T_\chi^{\max}} \frac{\rho_s}{\left(1+\frac{r}{r_s}\right)^2 r/r_s} \frac{d\Phi_p}{dT_p}$$



Density profile?

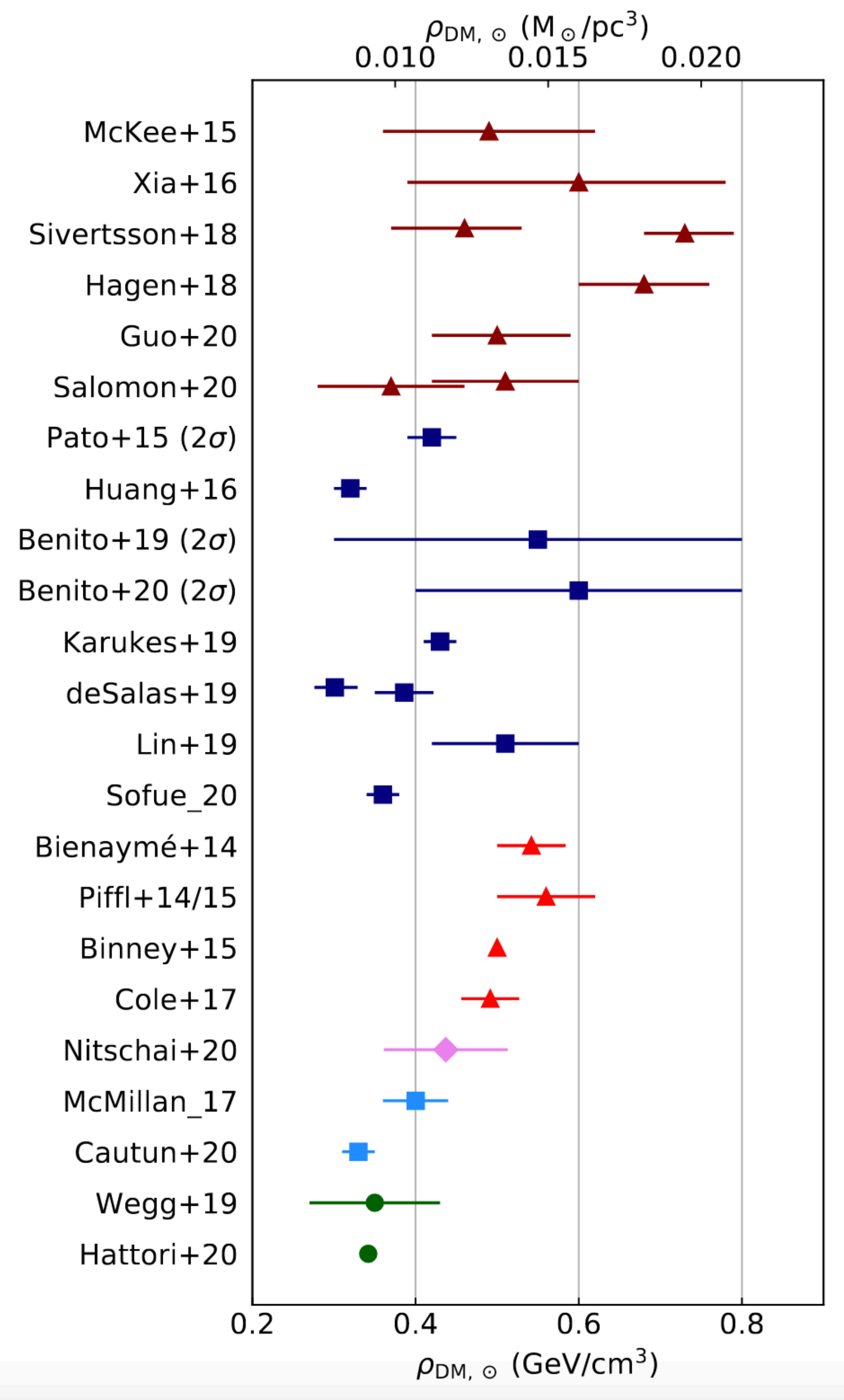






DM density profile in the MW Galaxy

- Local Density



Salas, Widmark
arXiv:2012.11477

ρ_X(r~8kpc)

≈ 0.3-0.4GeV/cm^3

- Density Profile
  - Navarro–Frenk–White (NFW) profile

$$\rho_{NFW}(r) = \frac{\rho_0}{(r/r_0)(1+r/r_0)^2}$$

J. Navarro, C. Frenk, S. White Astrophys. J. 490(1997)

  - Einasto profile

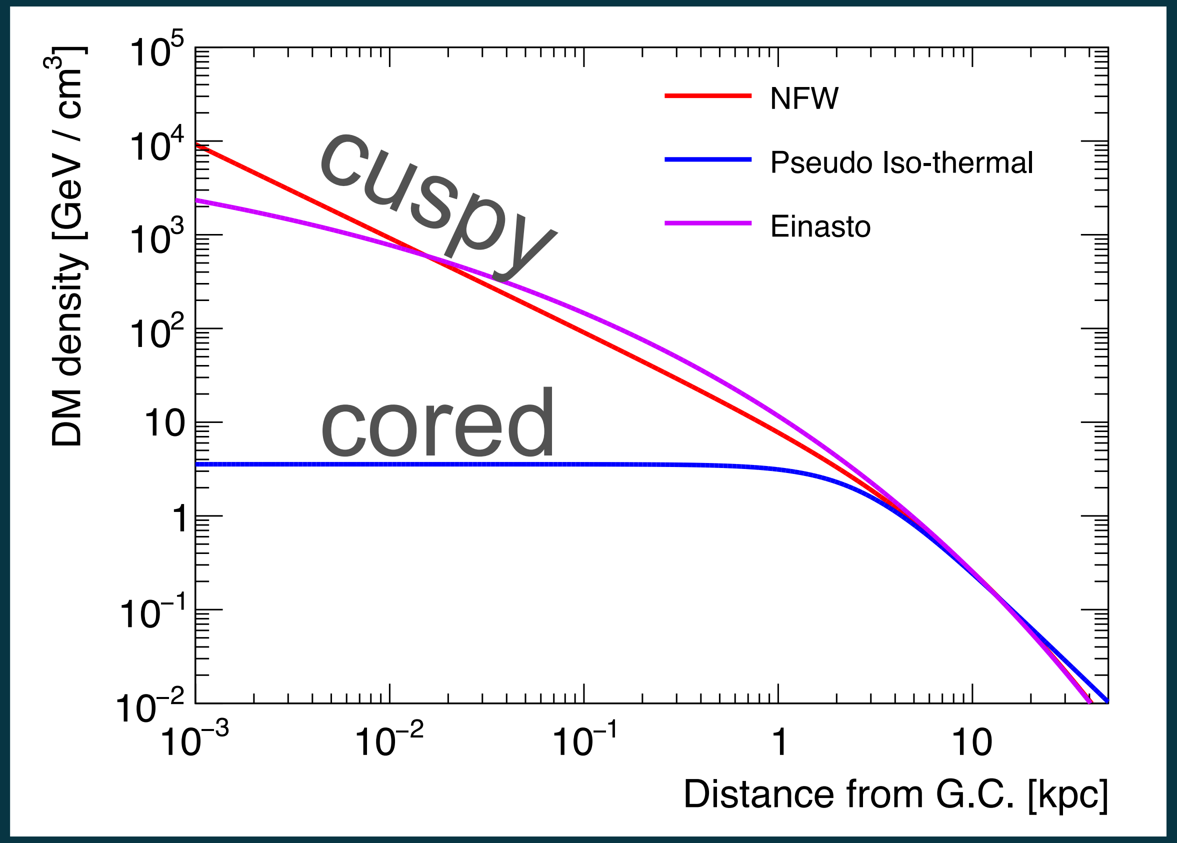
$$\rho_{Ein}(r) = \rho_0 \exp[2\alpha(1-(r/r_0)^{1/\alpha})]$$

J. Navarro et al. curves. Mon. Not. Roy. Astron. So

  - Pseudo-isothermal profile

$$\rho_{Iso}(r) = \frac{\rho_0}{1+(r/r_0)^2}$$

R. Jimenez, L. Verde, S. Pen, Mon. Not. Roy. Astron. So 339 (2003)



CR-DM Flux

NFW	Einasto	Pseudo-isothermal
cuspy	cuspy	cored

✳ How about the nuclear recoils?

Asymmetry

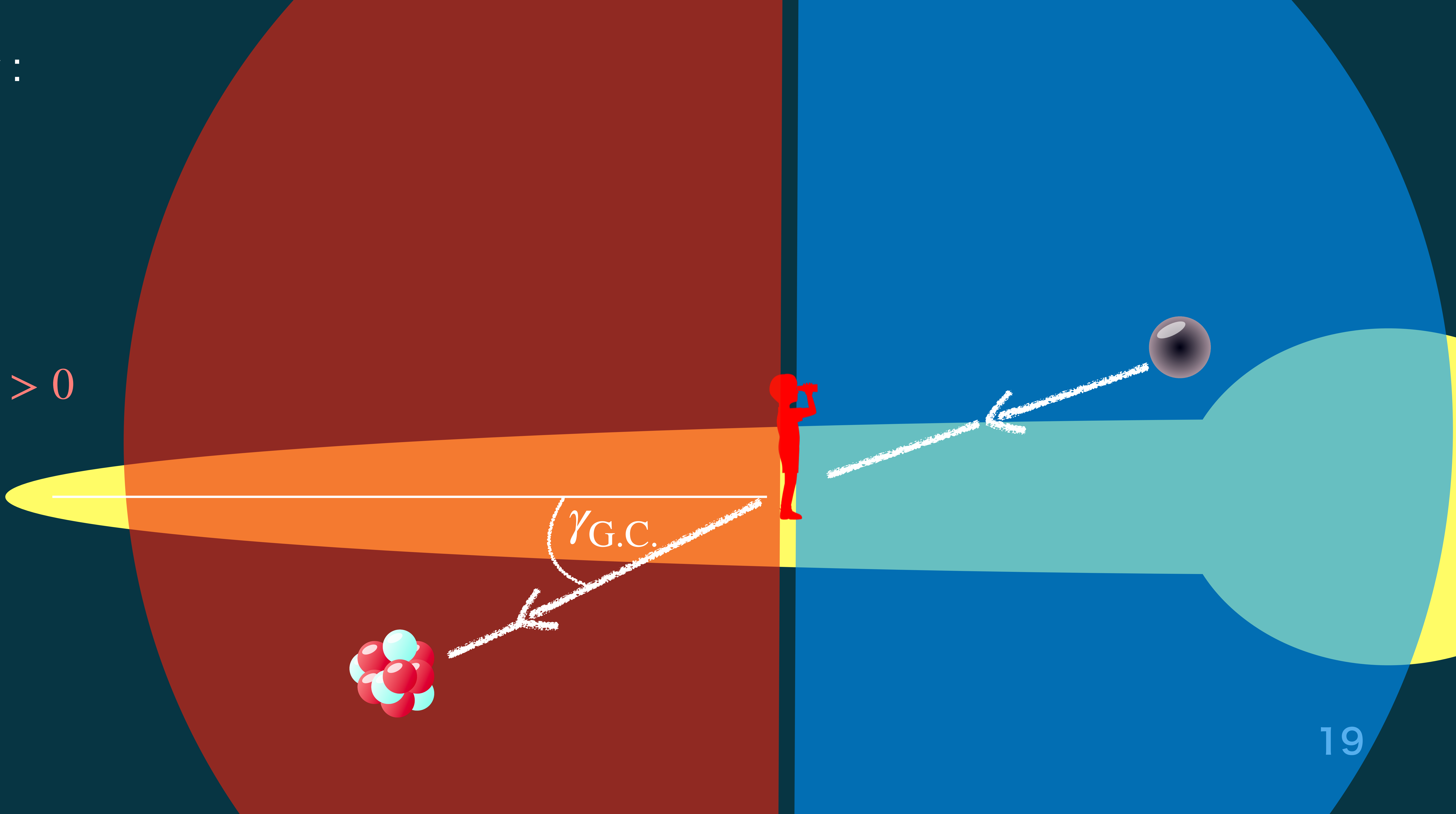
- How often does CR-DM come from the direction of G.C.?

Asymmetry parameter :

$$A = \frac{n_+ - n_-}{n_+ + n_-}$$

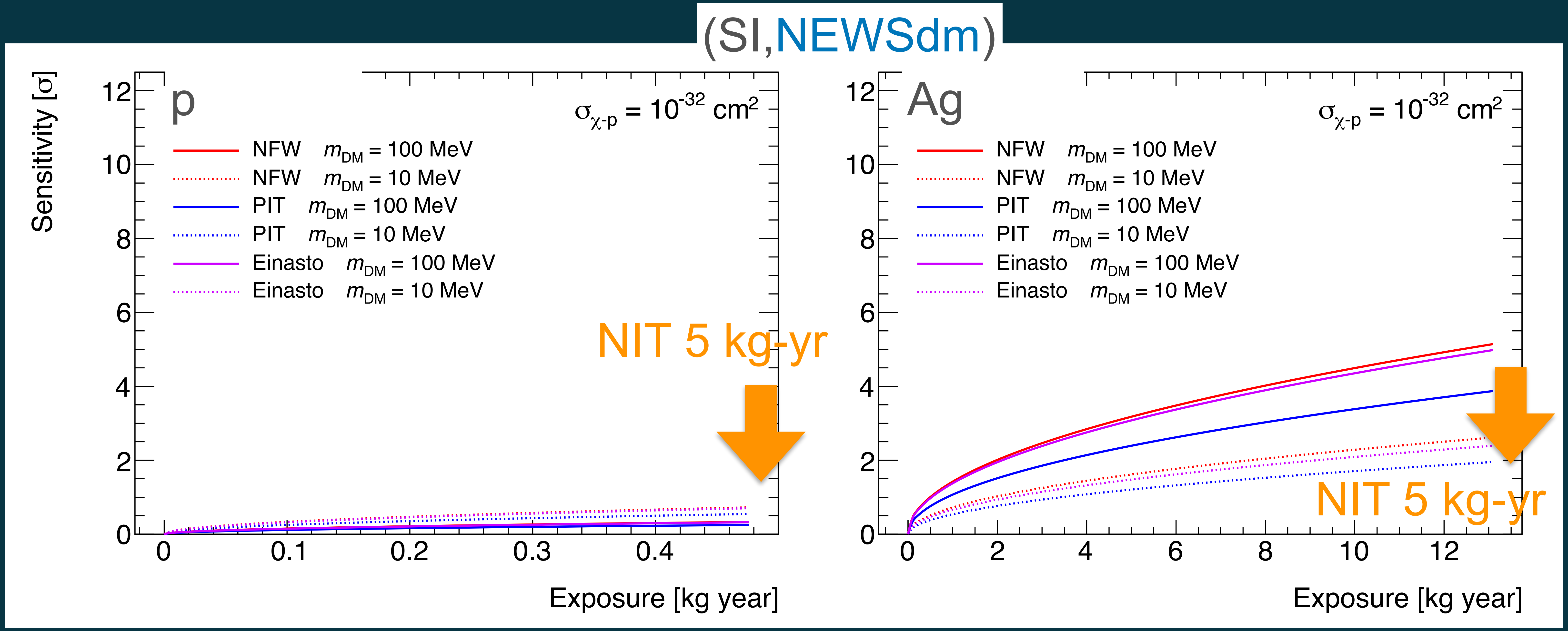
n_+ :
of $\cos \gamma_{\mathrm{G.C.}} > 0$

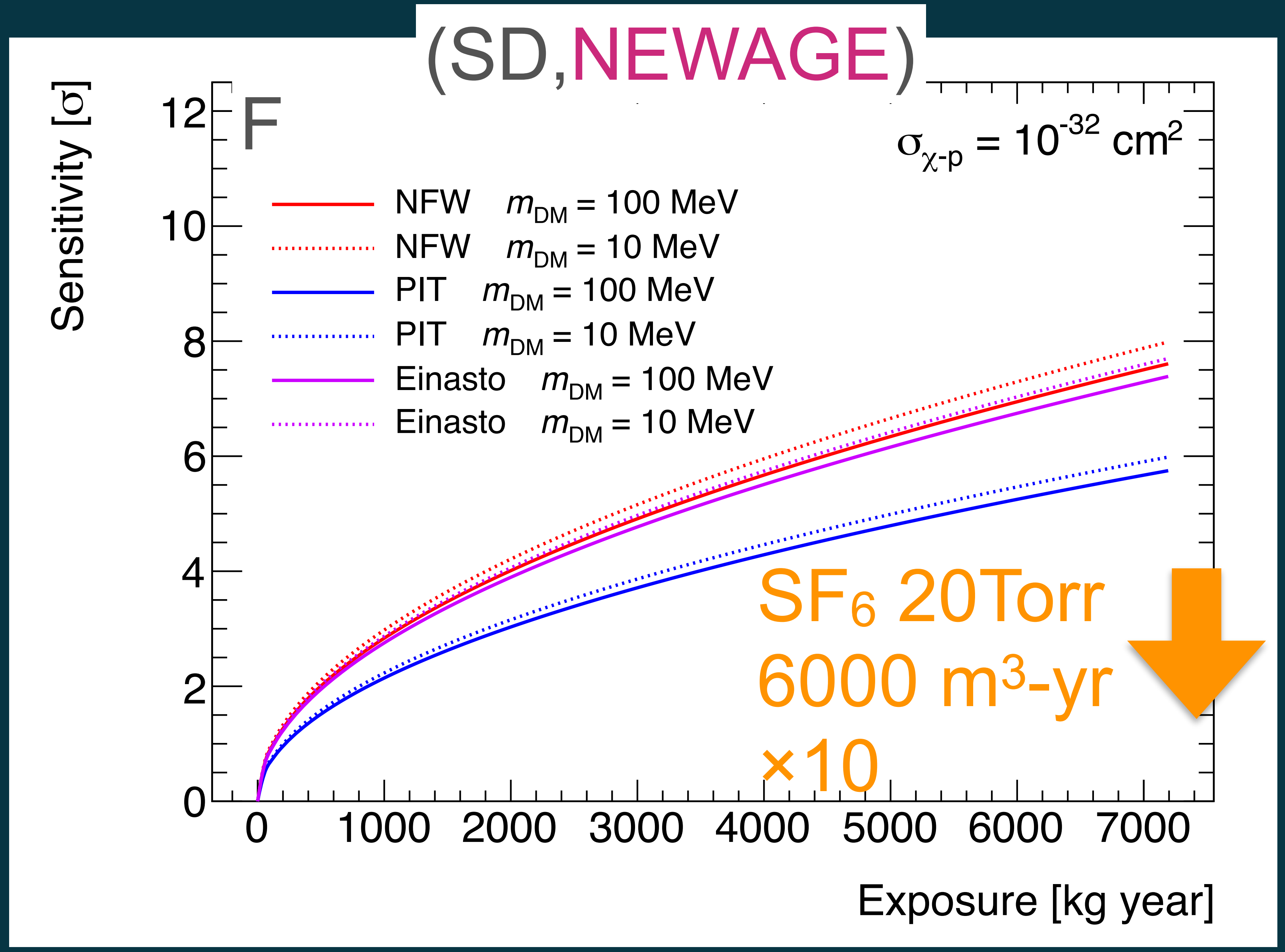
n_- :
of $\cos \gamma_{\mathrm{G.C.}} < 0$



Sensitivity to Asymmetry of nuclear recoil

KN, S. Higashino, T. Naka, K. Miuchi
arXiv:2211.13399





- Both detections are reaching **asymmetry** within the scope of future upgrade plans.
- Sensitivity for NFW is better than Pseudo-isothermal profile.
- Events with E_R causes inelastic scattering are omitted from the analysis.

Discussion

- Can we use the direction to further reveal information about dark matter?
- Anisotropy of DM velocity distribution suggested by observations and simulations.
- DM boosted by cosmic rays coming from the direction of the center of the MW galaxy.