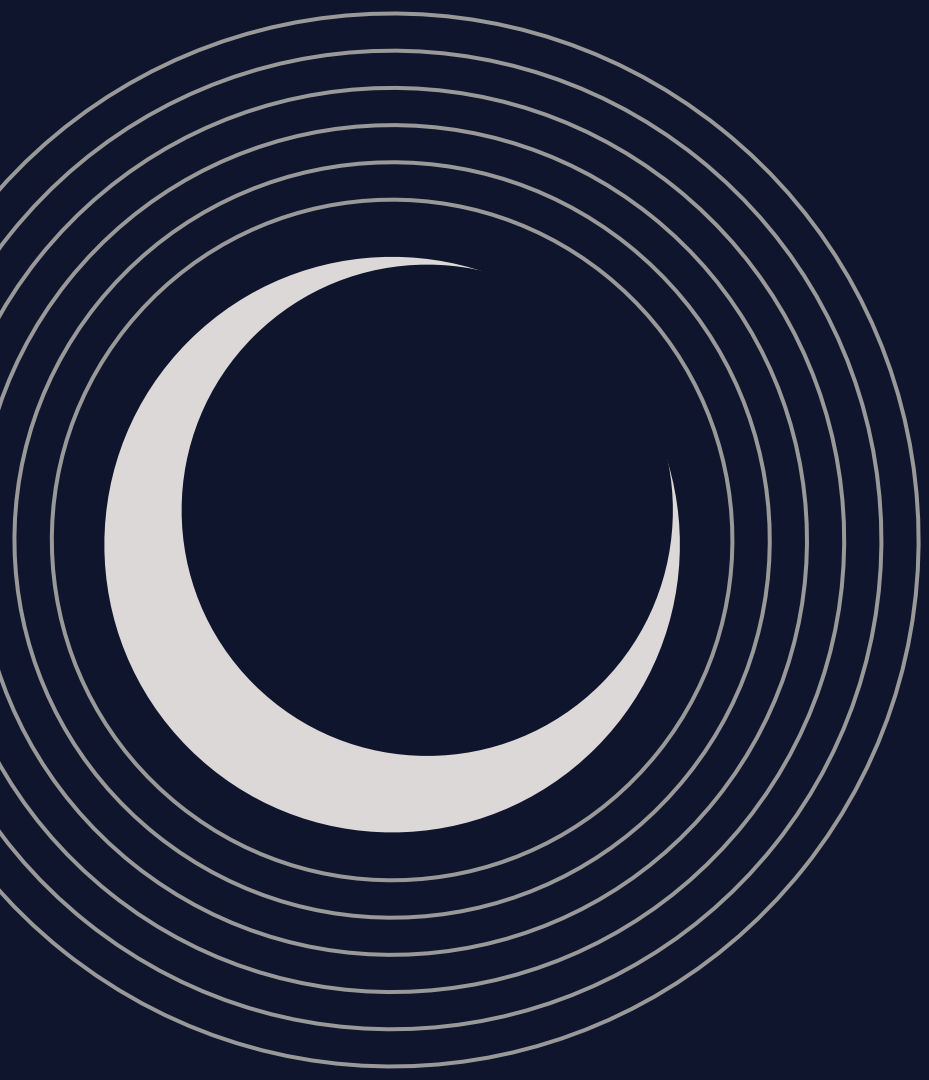
the Dark Side of the Universe (DSU2023)
10th Jul. 2023

Directional detection of dark matter boosted by cosmic rays from direction of the Galactic center

Keiko Nagao (Okayama Univ. of Sci.)
based on collaboration with KN, S. Higashino, T. Naka, K. Miuchi
arXiv:2211.13399 “Directional direct detection of light dark matter up-scattered by cosmic-rays from direction of the Galactic center”

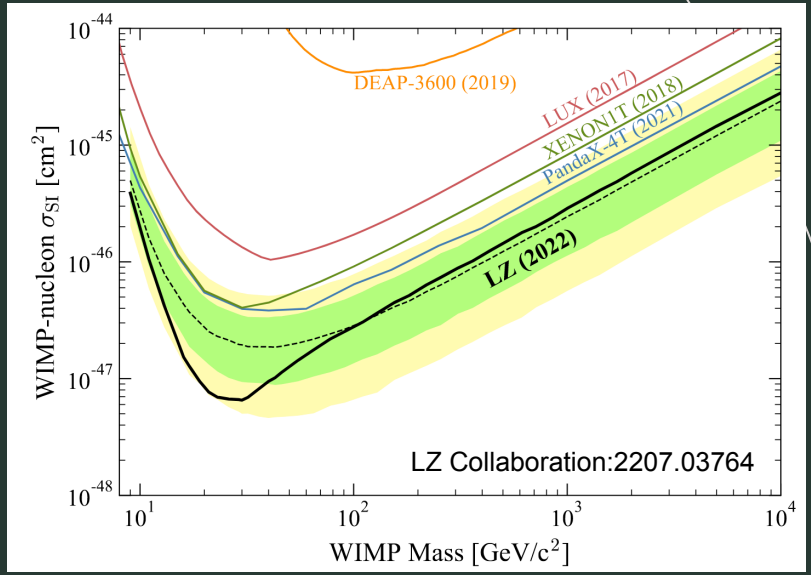


01

Cosmic Ray Boosted DM

Difficulty of Light WIMPs Detection

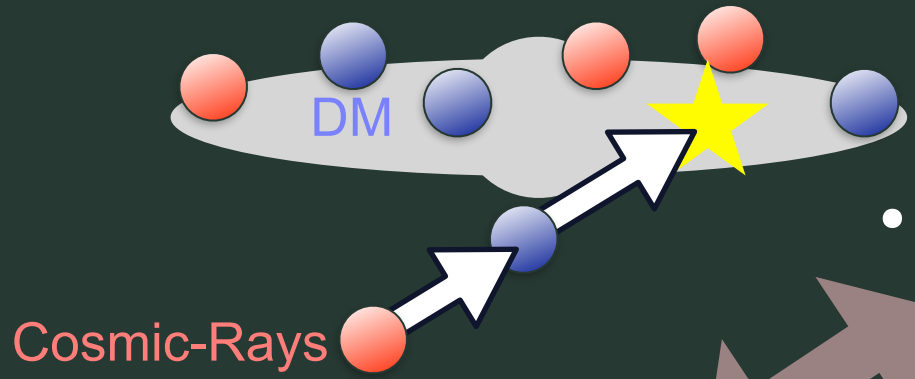
- Light DM
  - $\langle v_{DM} \rangle \sim 230\,km/s \ll c$
  - Kinetic energy $\sim m_{DM} v_{DM}^2/2$
  - For light DM, getting enough kinetic energy to overcome energy threshold of detector is hard.



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

Boosted DM

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



- Ordinary WIMPs
  - $v_{DM} << v_{esc}$
  - v_{DM}~230 km/s ; Slow

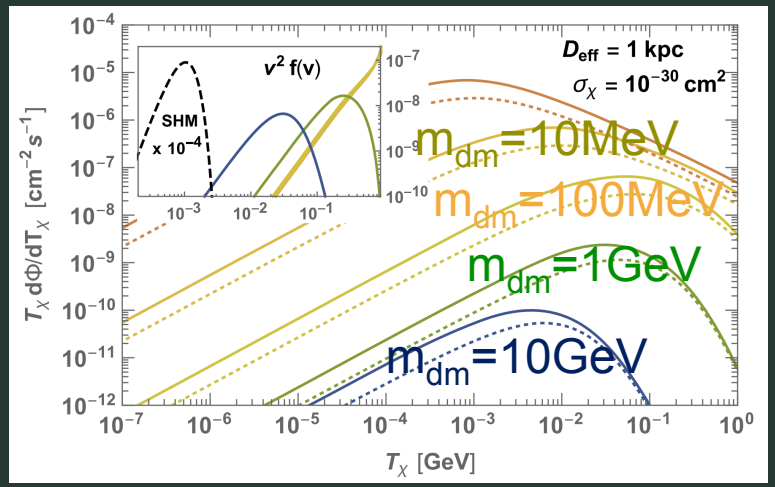
- Cosmic-Ray boosted DM (CR-DM)
  - NOT bounded by the Galactic escape velocity
  - DM obtains additional kinetic energy

  to overcome the energy threshold after CR scatters the light DM.

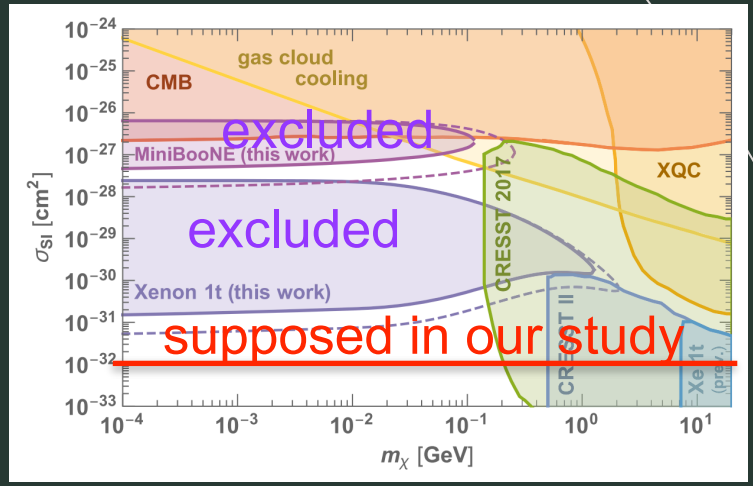
CR-DM

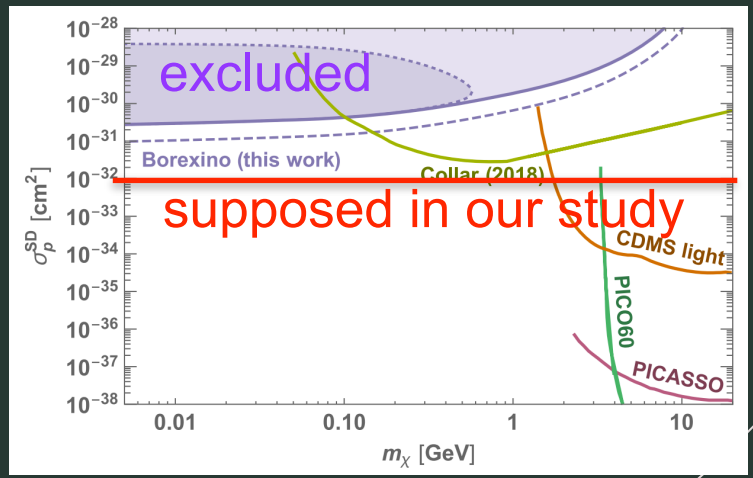
T.Bringmann and M.Pospelov arXiv:1810.10543

- Flux



- Constraints





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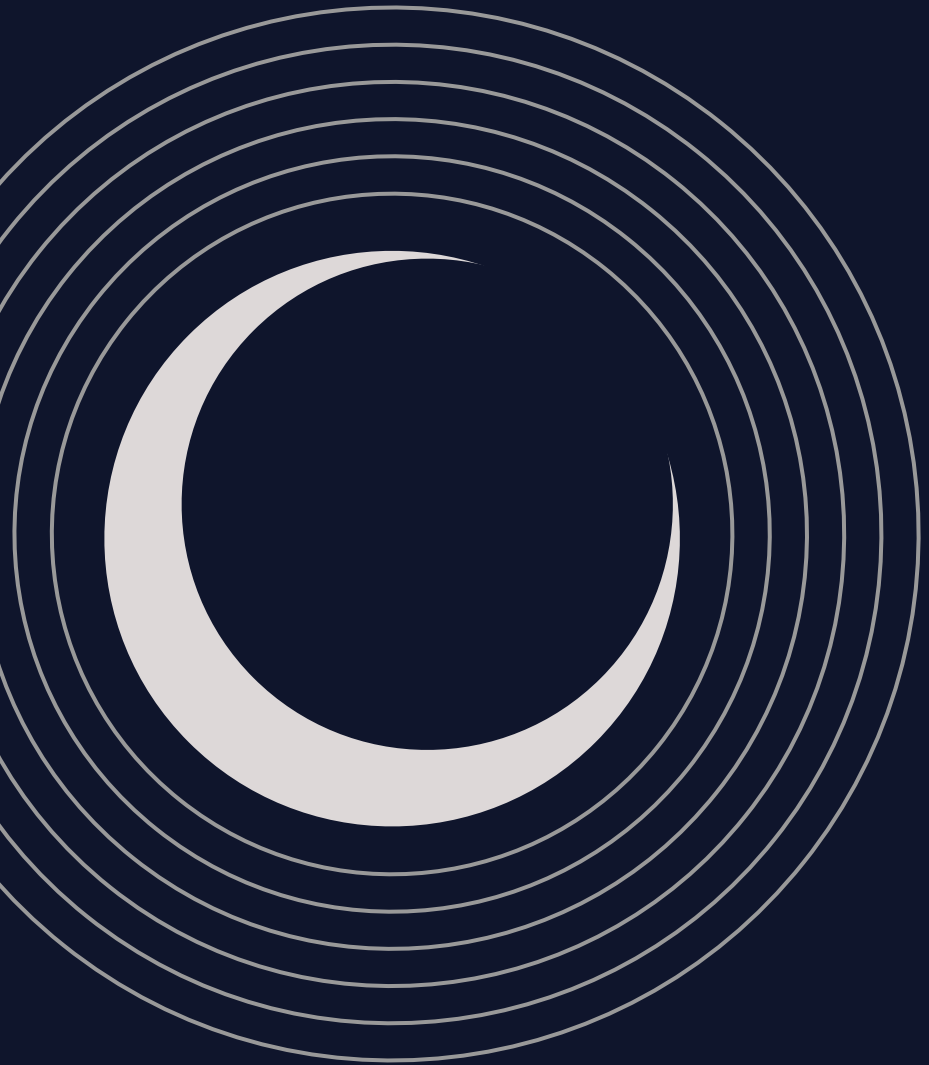
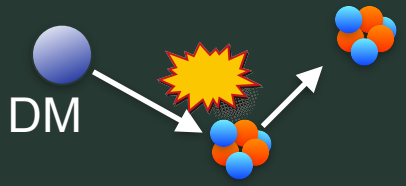


02

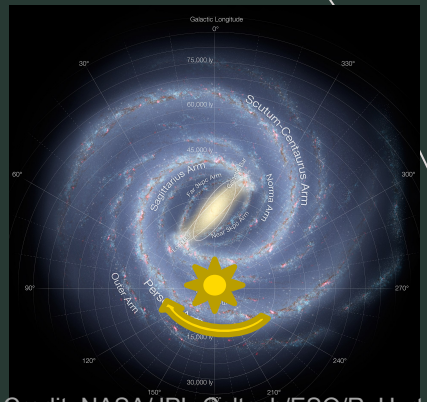
Directional Direct Detection

Directional Direct Detection of WIMPs

- Next generation of direct detection

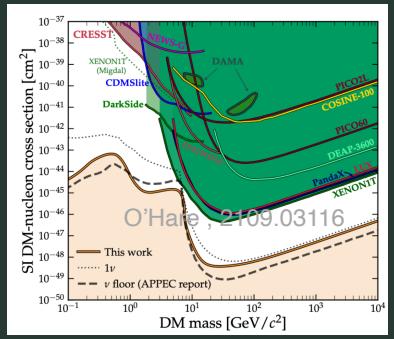


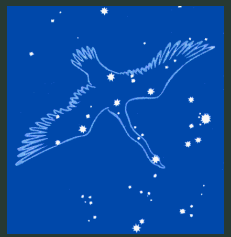
Recoil Energy E_R
+Direction



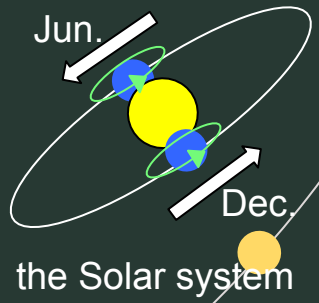
Credit: NASA/JPL-Caltech/ESO/R. Hurt

- Why direction?
  - DM wind will come from the direction of Cygnus
  - Neutrino Floor





DM wind



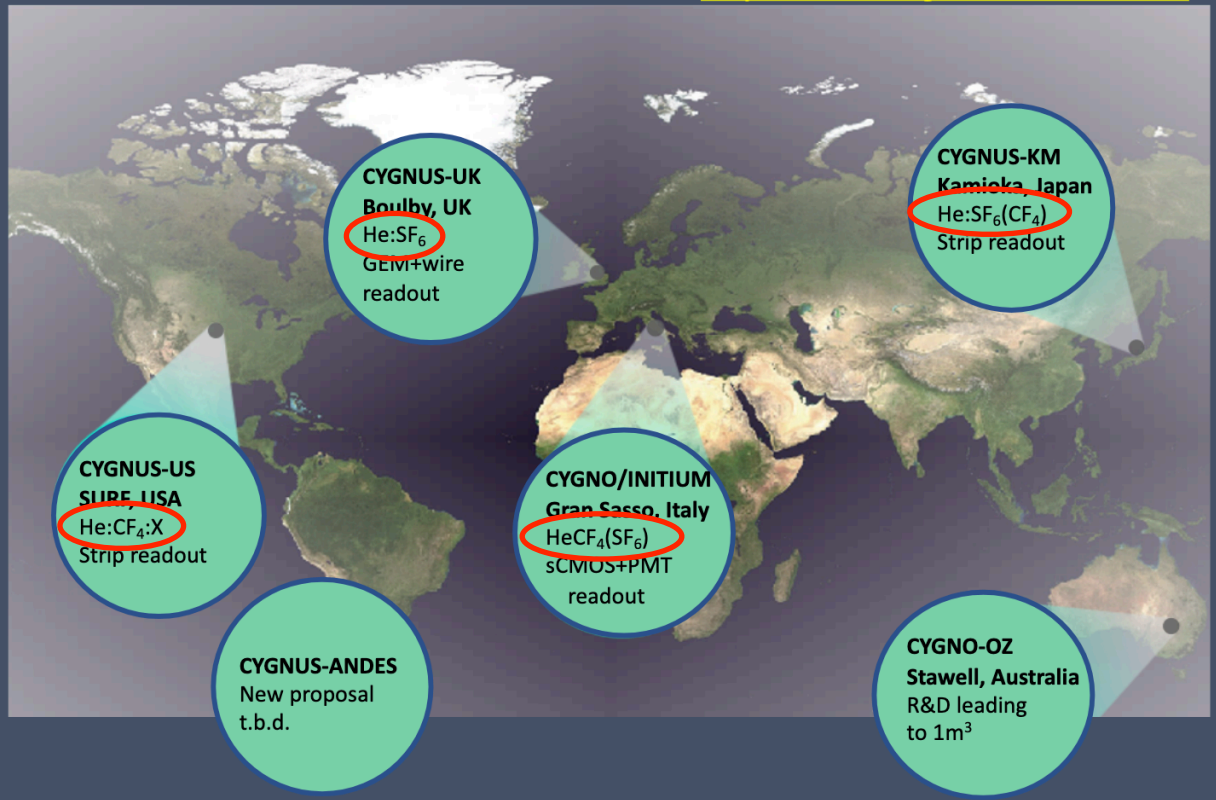
Long term CYGNUS Vision: Multi-site Galactic Recoil Observatory
with directional sensitivity to WIMPs and neutrinos

https://arxiv.org/abs/2008.12587

Proto Collaboration formed:

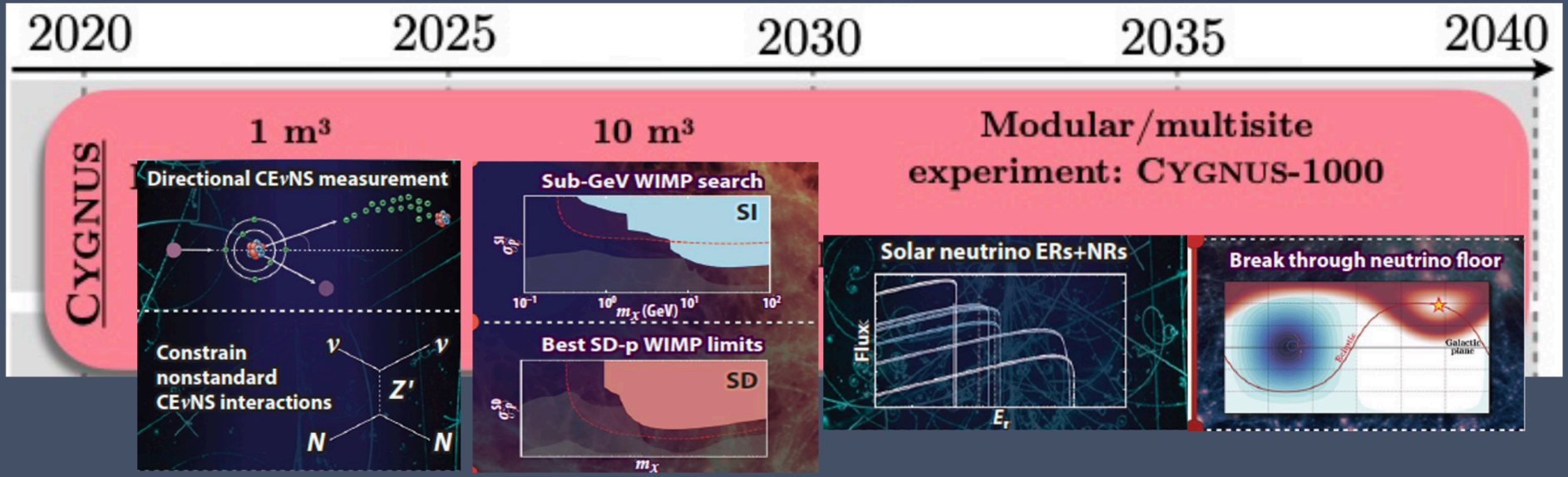
- 55+ signed members from the US, UK, Japan, Italy, Spain, China
- Six US faculty members
- Close collaboration and regular meetings on detector R&D and physics studies

New collaborators welcome!



Credit:Sven Vahsen's talk in SNOWMASS 2022

CYGNUS: US Program Vision

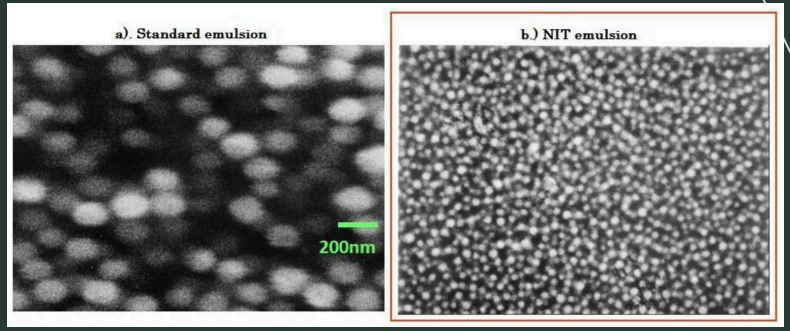


U.S. Site	SNS, Oak Ridge, TN	SURF, Lead, SD	International, multi-site (Utilize DUNE cavern?)
Approx. Detector Cost	~$0.5M+	~$5M	~$50 M, for 1000m³ in U.S. https://arxiv.org/abs/2008.12587

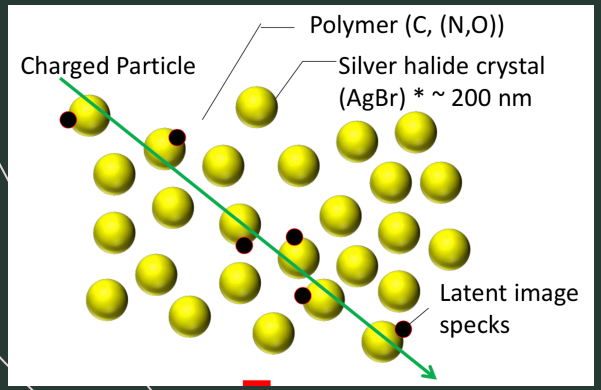
Nuclear Emulsion : NEWSdm

- Super-fine-grained emulsion for directionality
- High Density
- No time resolution…
- Target

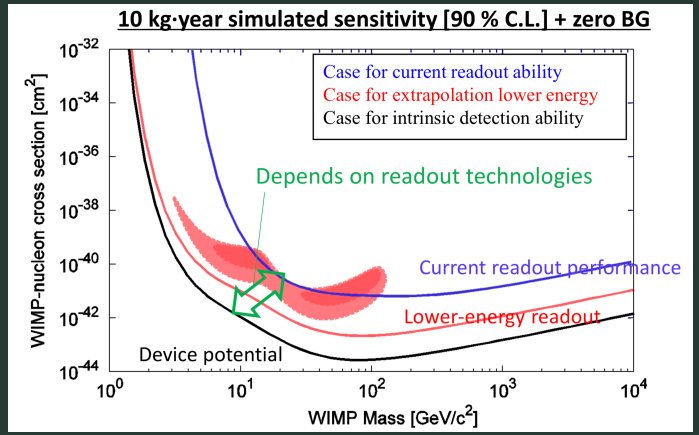
  p, C, N, O, Ag, Br



Naka et al., 1109.4485



Slides by T. Naka



03

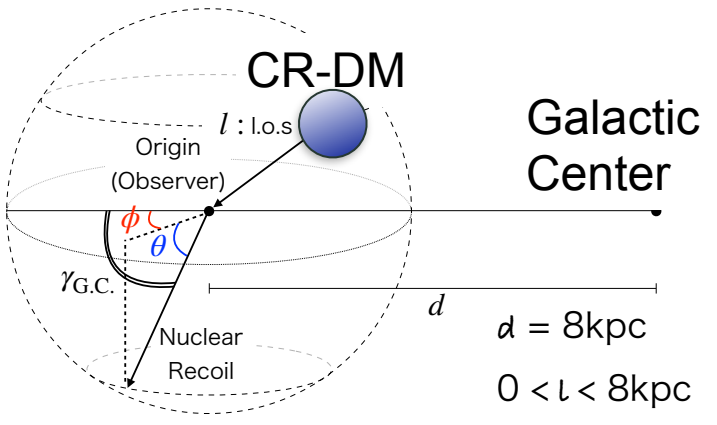
Directional Detection of CR-DM

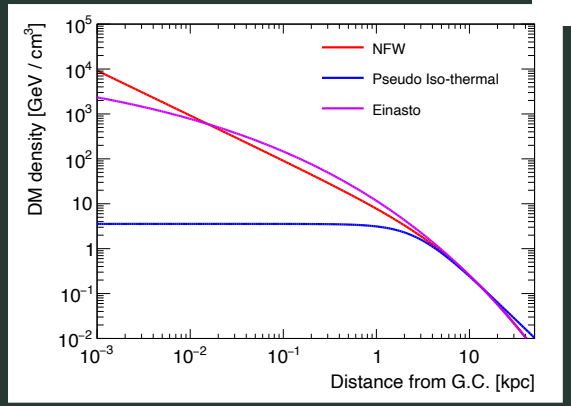
c.f. non-directional detection of CR-DM using directional information
S-F Ge, J-L Liu, Q. Yuan, N. Zhou 2005.09480
Panda-X 2112.08957

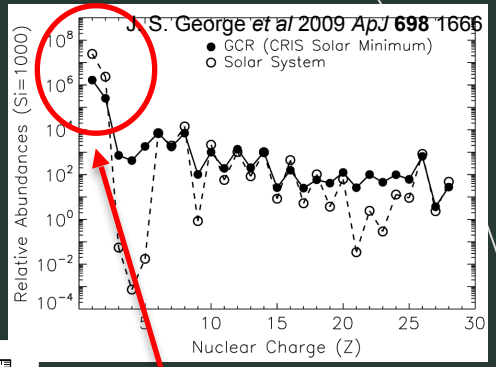
Flux of CR-DM for each direction

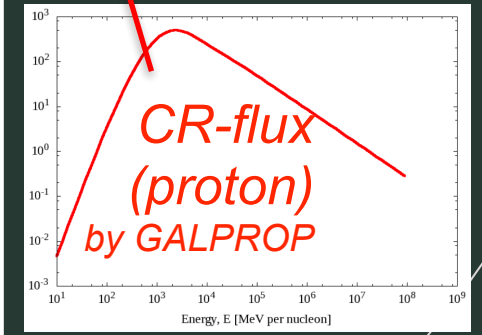
$$\frac{d\Phi_\chi}{dT_\chi d\theta d\phi} = \int l^2 dl \frac{1}{4\pi l^2} \sigma_{\chi p} \frac{\rho_\chi(r)}{m_\chi} \int_{T_i^{min}}^{\infty} dT_p \frac{d\Phi_p}{dT_p}$$

density profile









CR-flux (proton) by GALPROP

DM density profile in the Galaxy

- 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

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

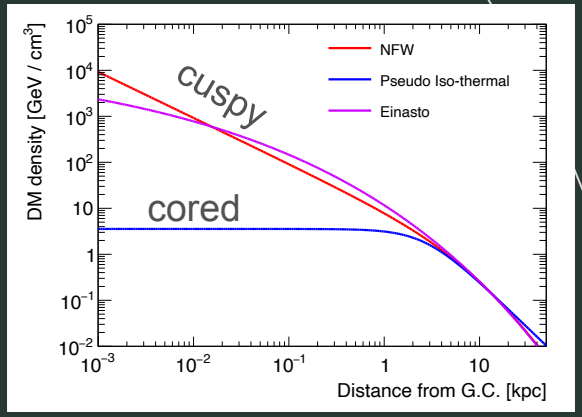
better to fit the observations.

J. Navarro et al. curves. Mon. Not. Roy. Astron. So 349 (2004)

- 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)



Sky Map of CR-DM flux

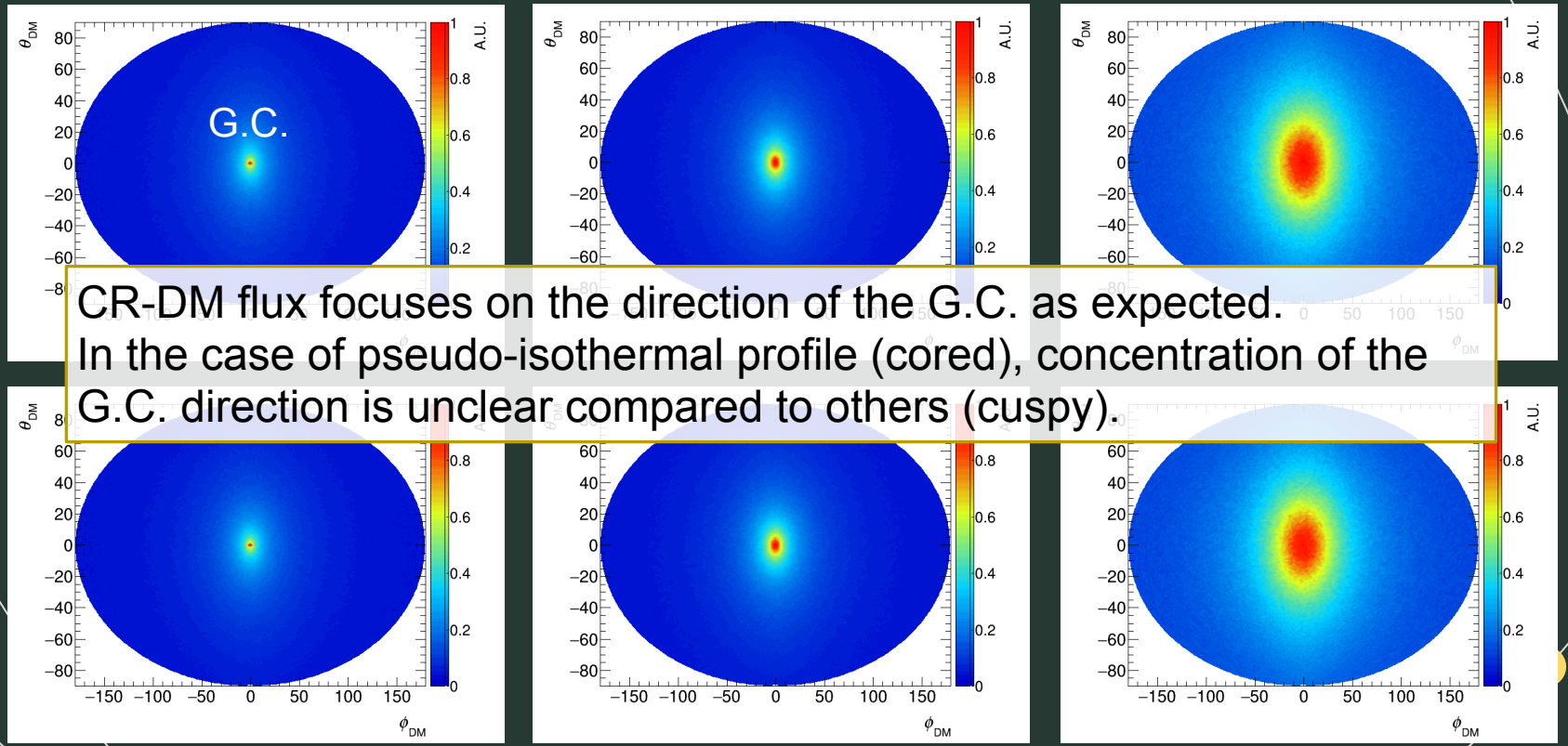
NFW

Einasto

Pseudo-isothermal

m_{DM}=100MeV

m_{DM}=1MeV



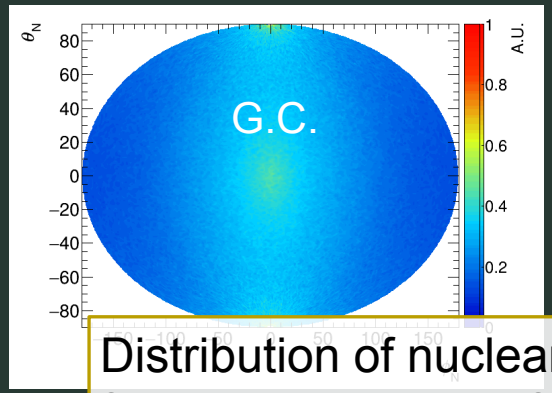
CR-DM flux focuses on the direction of the G.C. as expected.
In the case of pseudo-isothermal profile (cored), concentration of the G.C. direction is unclear compared to others (cuspy).

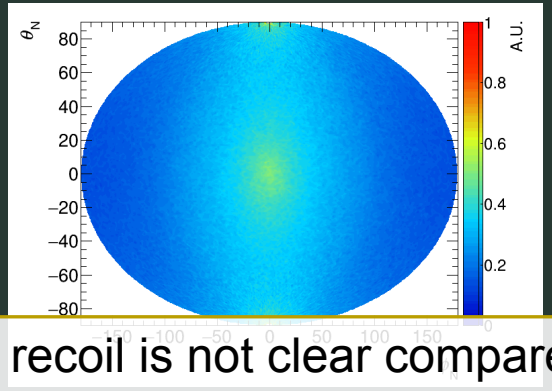
Distribution of Nuclear recoil

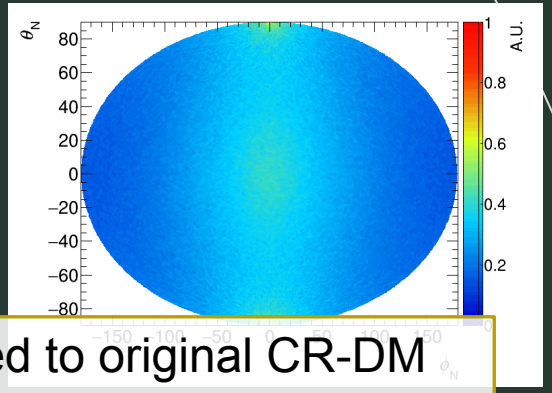
target: F

NFW | Einasto | Pseudo-isothermal

m_{DM}=100MeV

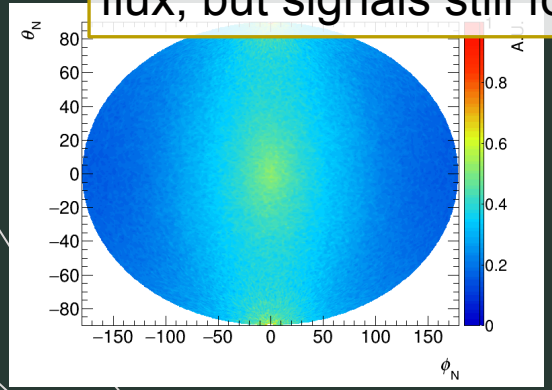


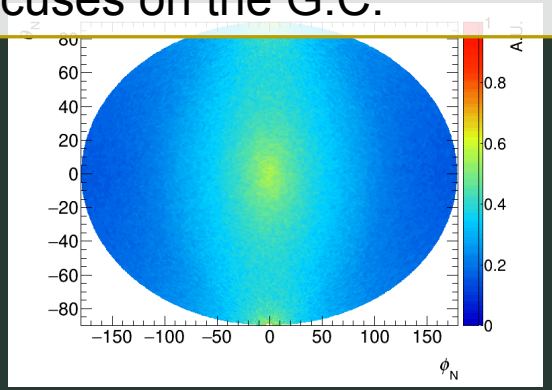


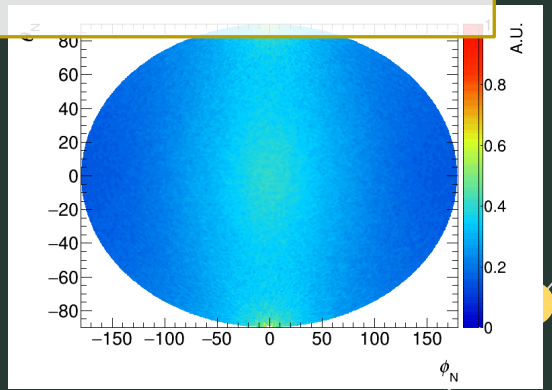


Distribution of nuclear recoil is not clear compared to original CR-DM flux, but signals still focuses on the G.C.

m_{DM}=1MeV

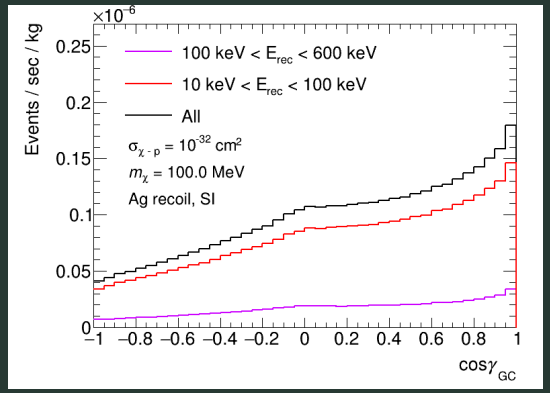
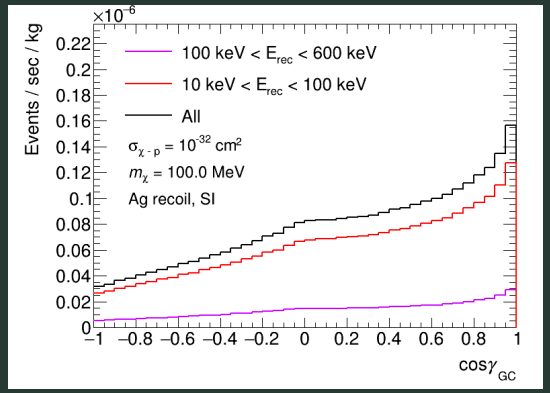
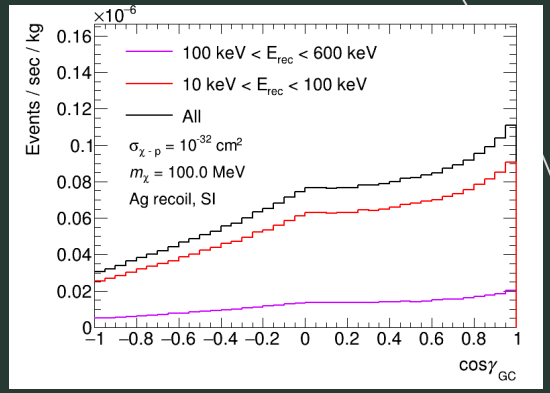
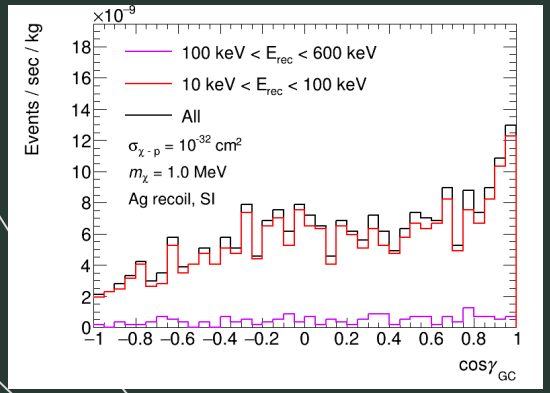
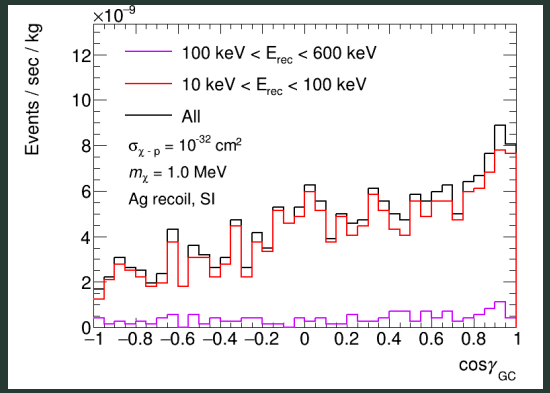
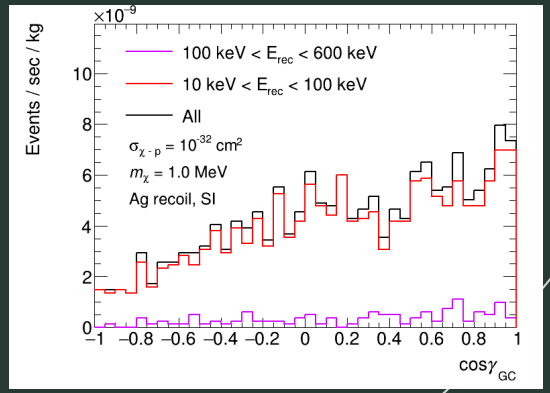






Recoil Energy of CR-DM (Ag)

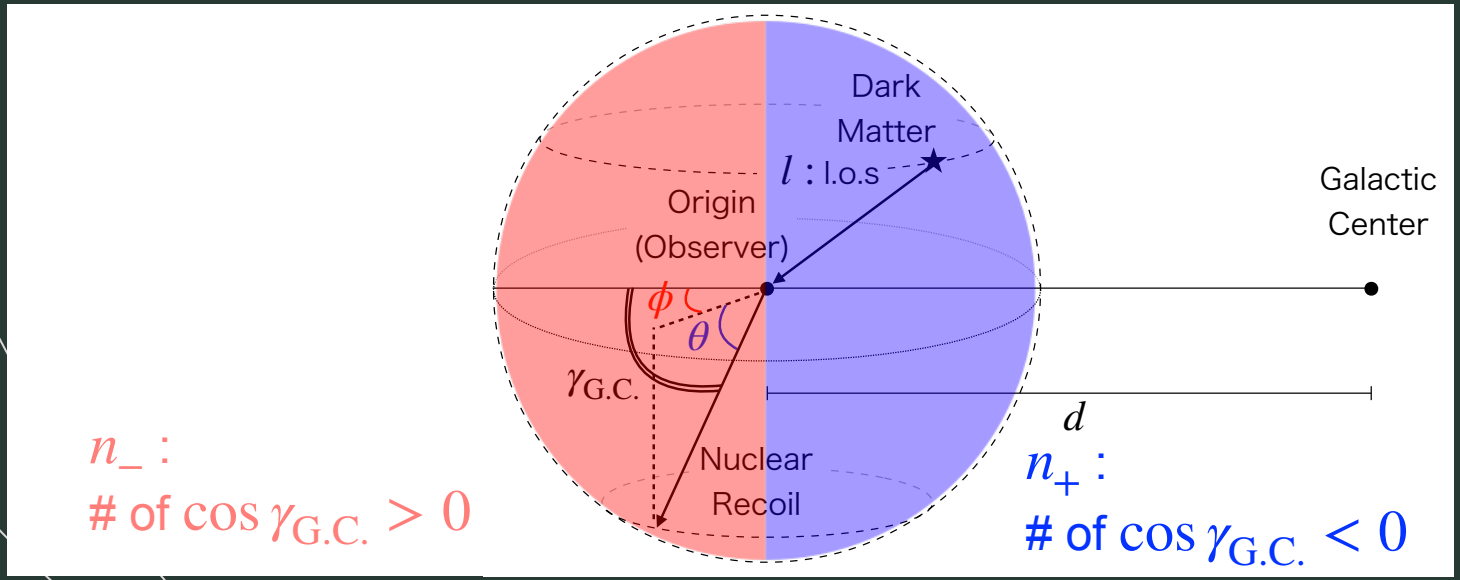
target: Ag

	NFW	Einasto	Pseudo-isothermal
100MeV			
1MeV			

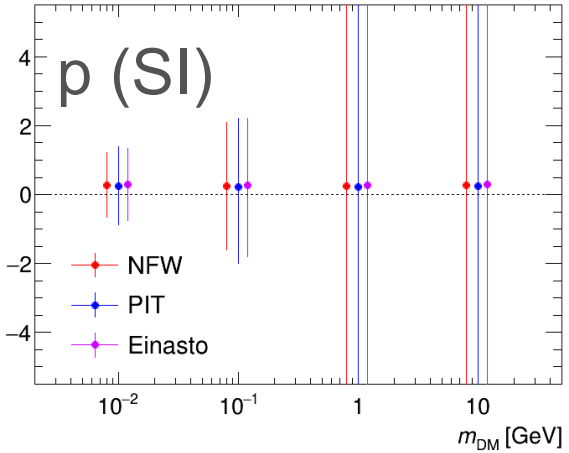
Asymmetry

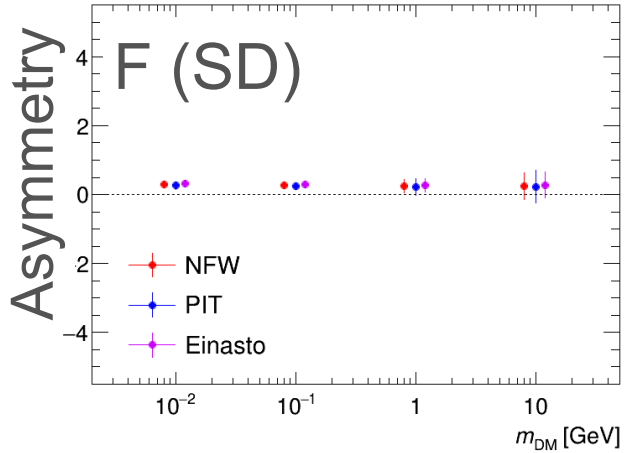
- How often does CR-DM come from the direction of G.C.?

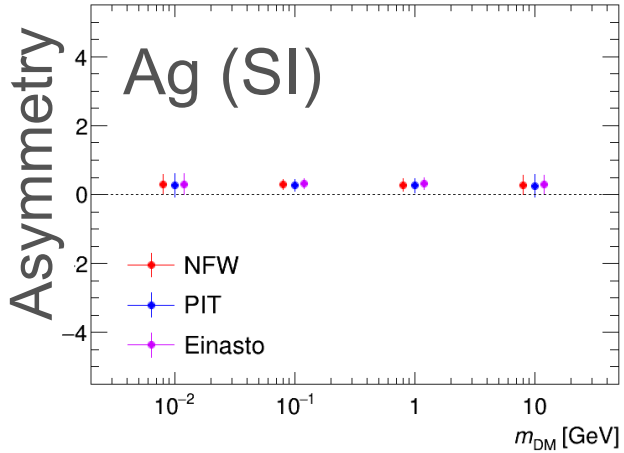
$$\text{Asymmetry}: \quad A = \frac{n_+ - n_-}{n_+ + n_-}$$



Asymmetry and Targets



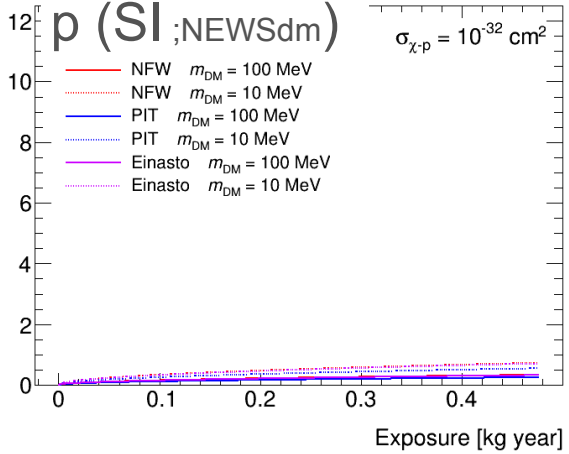


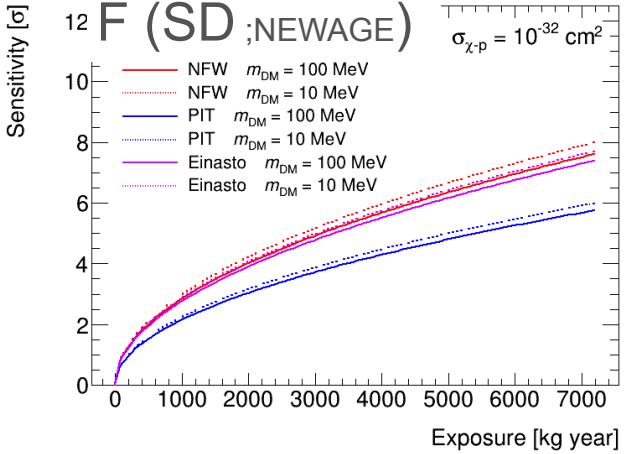


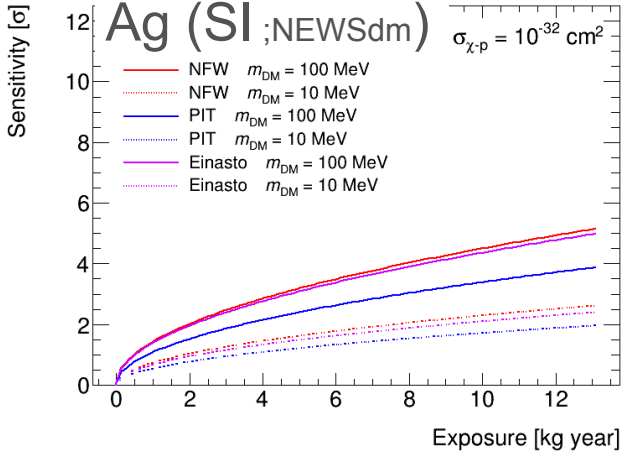
- p, Ag : Nuclear Emulsion 5.0 kg-yr
- F : SF_6 10k Torr $1m^3$, 6 yr
- $\sigma=10^{-32}$ cm^2

- Events with E_R causes inelastic scattering are omitted.

Sensitivity for Asymmetry







- NEWSdm has a vision to extend to O(1-10)kg in the future. → Asymmetry can be tested within the scope of the future upgrade plan.
- Gas detector can also have sensitivity ~> 5σ supposing 10 times of Cygnus-1000 (1000m^3). arXiv:2008.12587

Conclusion

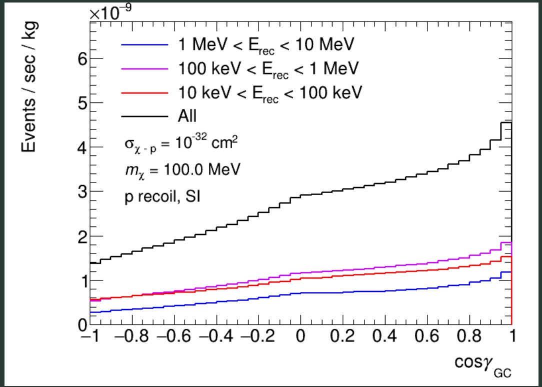
Most of cosmic ray boosted DM is expected to come from the direction of the Galactic center. The directional tendency can be tested by directional detectors within the future upgrade for CR-DM with 100-10 MeV mass.

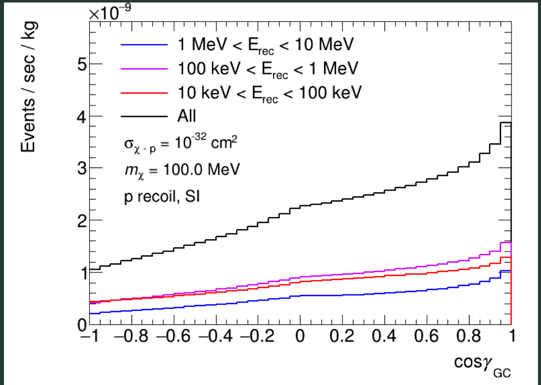
Recoil Energy of CR-DM (p)

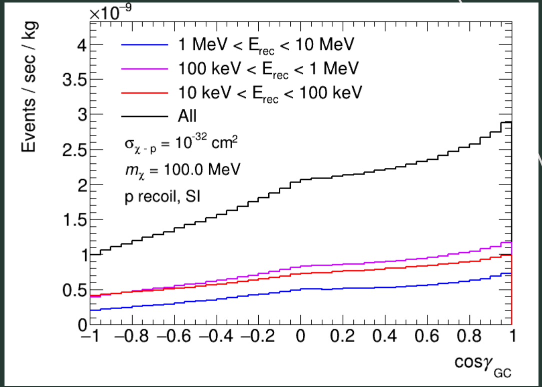
target: p

NFW | Einasto | Pseudo-isothermal

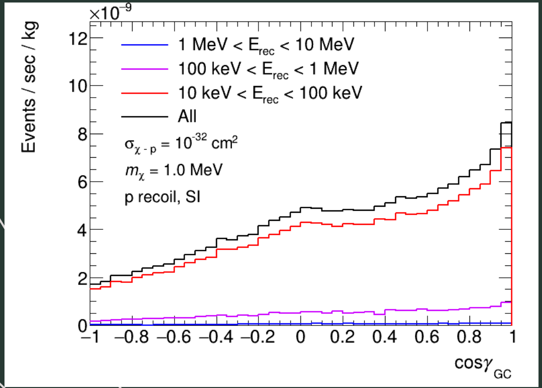
100MeV

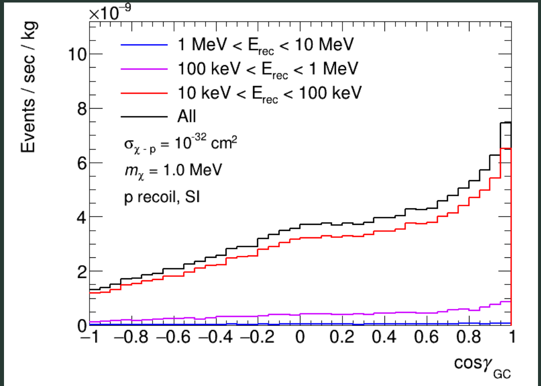


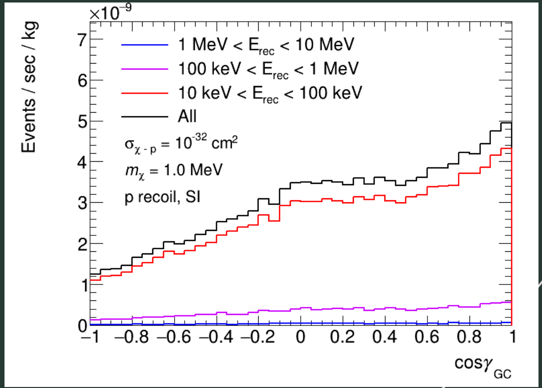




1MeV





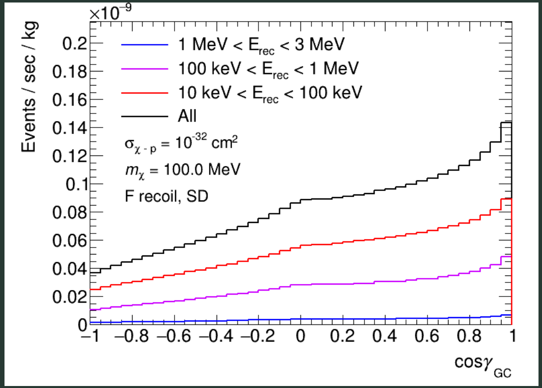


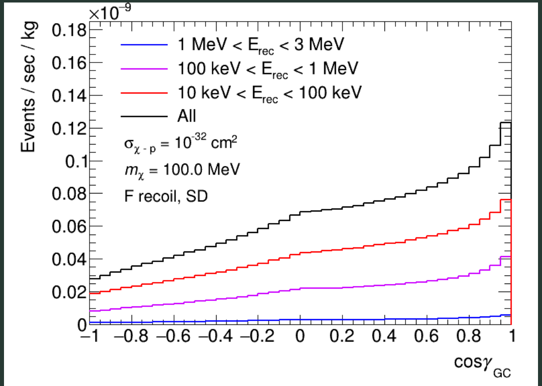
Recoil Energy of CR-DM (F)

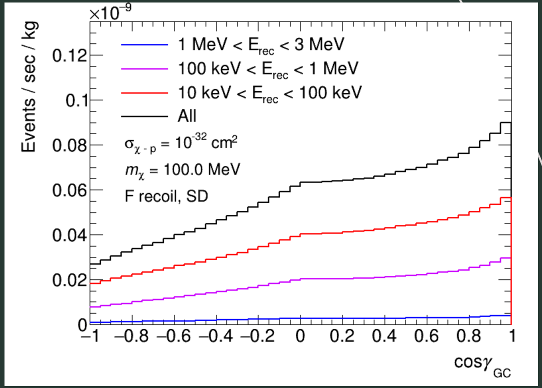
target: F

NFW | Einasto | Pseudo-isothermal

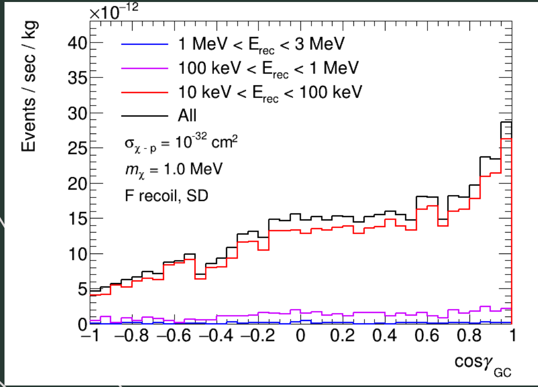
100MeV

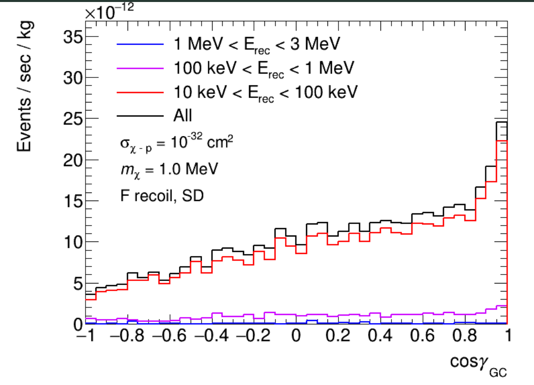


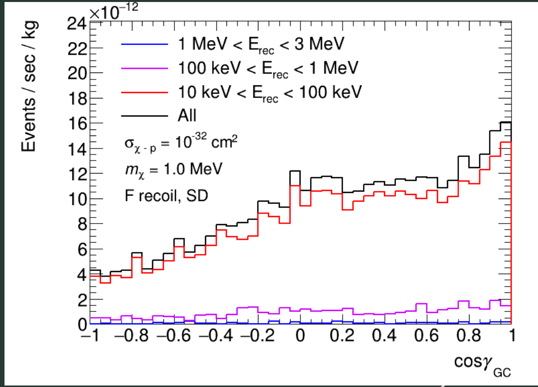




1MeV







Elastic scattering

- In the numerical study, elastic scattering of DM-target in detection is supposed.
- For scattering with high ER, the assumption is not valid. Thus we require events with de Broglie wave length of DM >> size of target nucleus, i.e. $E_{\text{elastic scattering}}$ = 10 (p), 3 (F), 0.6 (Ag) MeV, respectively.