Kagoshima Workshop on
Particles, Fields and Strings 2023

What can we learn from the direction of dark matter?

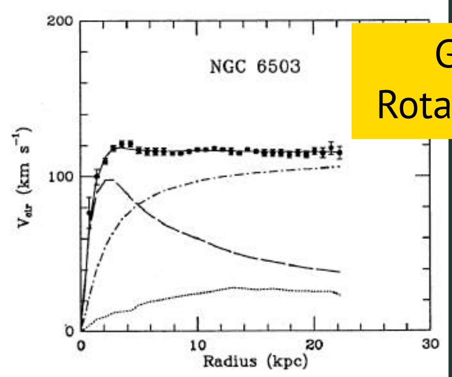
Keiko Nagao (Okayama Univ. of Sci.)
based on collaboration with KN, S. Higashino, T. Ikeda, R. Yakabe, T. Naka, K. Miuchi
arXiv:1707.05523 "Discrimination of anisotropy in dark matter velocity distribution with directional detectors"
arXiv:2211.13399 "Directional direct detection of light dark matter up-scattered by cosmic-rays from direction of the Galactic center"

preliminary

01

Introduction

Dark Matter



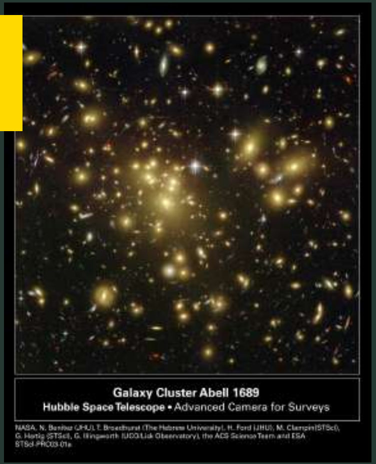
Galactic Rotation Curve

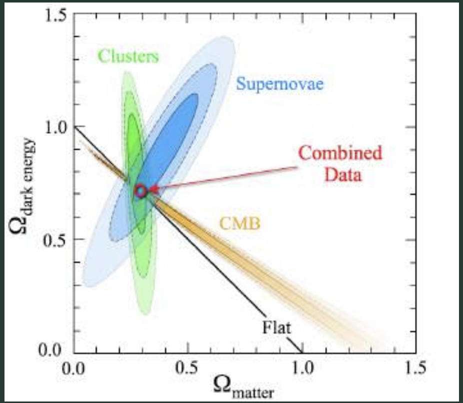
Begeman, Broeils, Sanders (1991)

Bullet cluster

X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/ D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

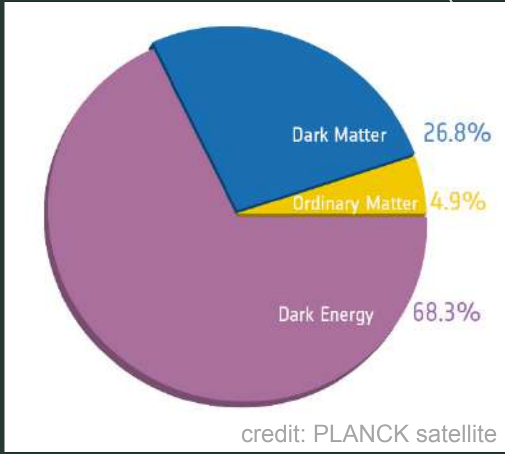
Gravitational Lensing





What is Dark Matter? (For particle physicists)

- No candidate in the SM!
  - Electrically neutral
  - stable
  - ~27% of the Universe
  - massive (at least in structure formation)



- Candidates
  - ✓ Weakly Interacting Massive Particles (WIMPs)
  - ✓ Axions, Axion Like Particles (ALPs)
  - ✓ Primordial black holes
  - ✓ Modified Gravity, ……

Approaches

LENSING

New Physics of BSM

GALACTIC CENTER

Symmetries

STRUCTURE

Structure

Interaction

Dark Matter

Spin

Density profile
in halo/subhalo

Dark sector?

Neutrinos?

Mass

Cold or Warm?

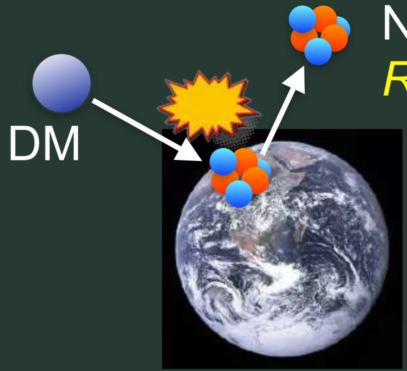
Velocity distribution

Stream

Direct Detection of WIMPs

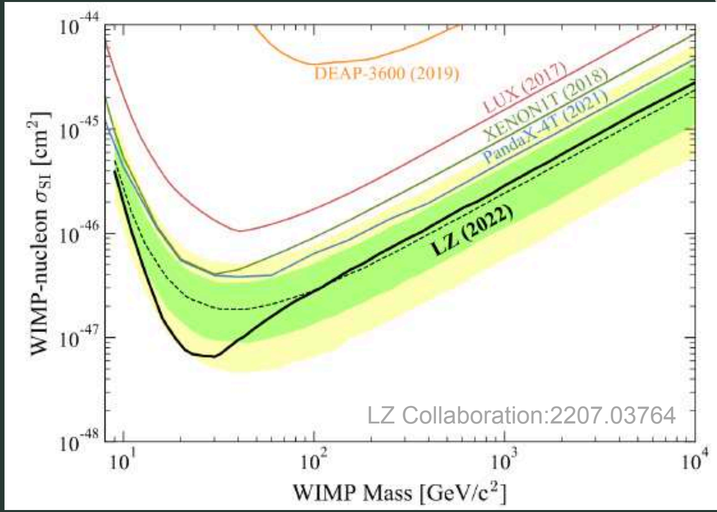
M. Goodman and E. Witten (1985)

- DM detection through DM-Nucleon scattering



Nuclear Recoil

Recoil Energy E_R (+time)

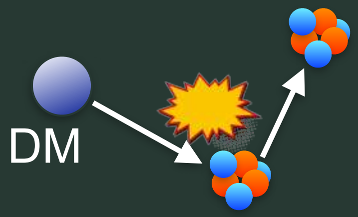


- Event rate R

$$\frac{dR}{dE_R} = \frac{N_T \rho_0}{m_\chi} \int^{v_{\max}} d\vec{v}\, f(\vec{v}) |\vec{v}| \frac{d\sigma(\vec{v})}{dE_R}$$

Directional Detection

- Next generation of direct detection



Nuclear Recoil
Recoil Energy E_R
*+ **DIRECTION** (+time)*

- Techniques
  - Gaseous detector *DRIFT, NEWAGE,DMTPC, MIMAC, …*
  - Solid detector (nuclear emulsion, crystals, …) *Emulsion, ZnWO4 crystal, …*
  - Non-directional detector (but directional information is used)

S-F Ge, J-L Liu, Q. Yuan, N. Zhou 2005.09480
Panda-X 2112.08957

How can we use directional info.?

- Direction of Flux

  Light DM up-boosted by cosmic-rays comes from direction of the Galactic center.

- Anisotropy of velocity distribution

  Velocity dist. of DM may be anisotropic.

- … And others? Comments are welcome!

Table Of Contents

02

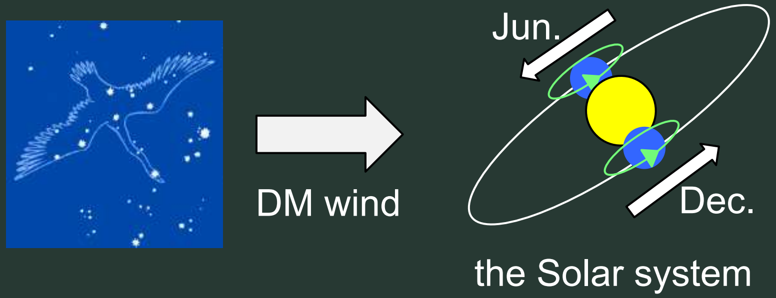
Directional Direct Detection

Next generation DM detection

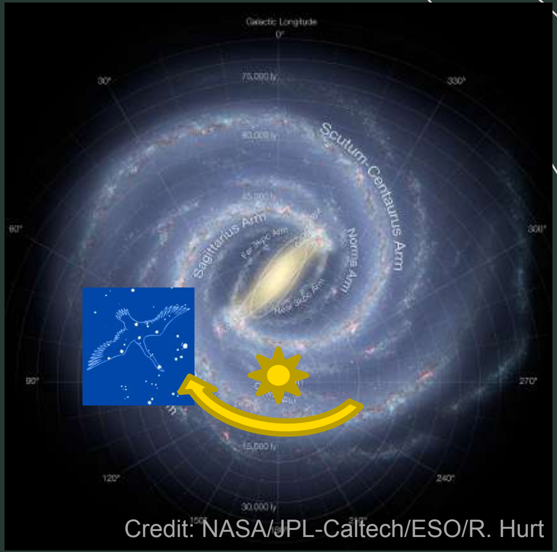
Why Direction?

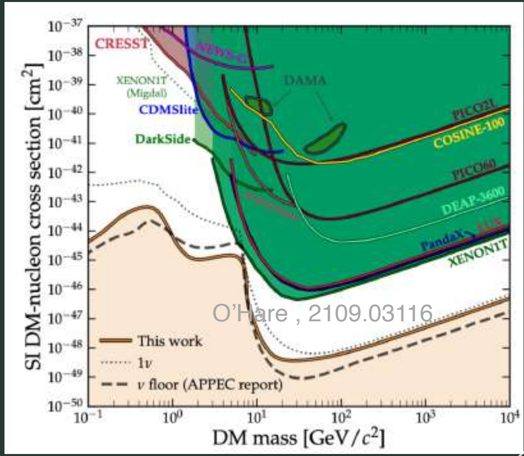
- Powerful background rejection
  - DM signal : from the Cygnus

    ⟺ Background : isotropic (?)

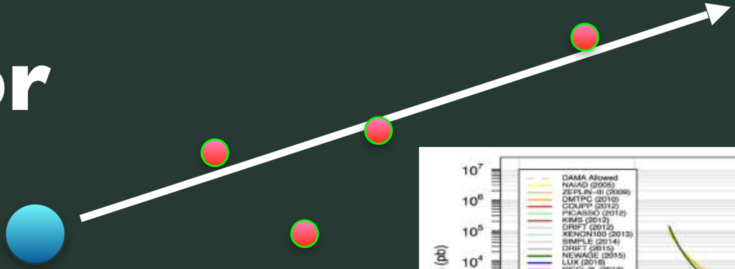


- Neutrino Floor (Fog)





Gaseous Detector



- Good Directionality

  Mean free path ~ μm

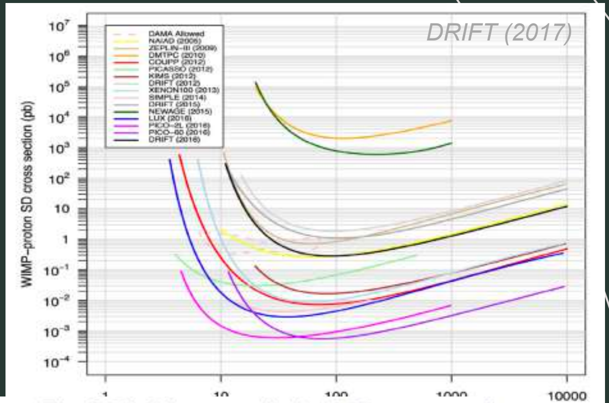
- Low Pressure

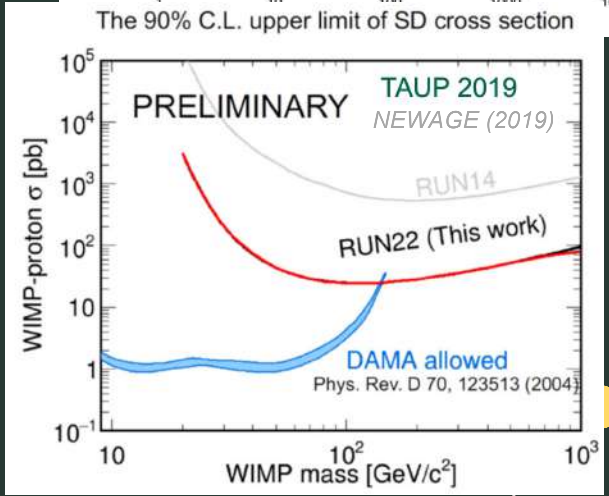
$$\frac{dR}{dE_R} = \frac{N_T \rho_0}{m_\chi} \int^{v_{\rm max}} d\vec{v}\, f(\vec{v})|\vec{v}| \frac{d\sigma(\vec{v})}{dE_R}$$

  large volume is required to enhance sensitivity.

- Typical target

  CF_4, SF_6, CS_2, CHF_3





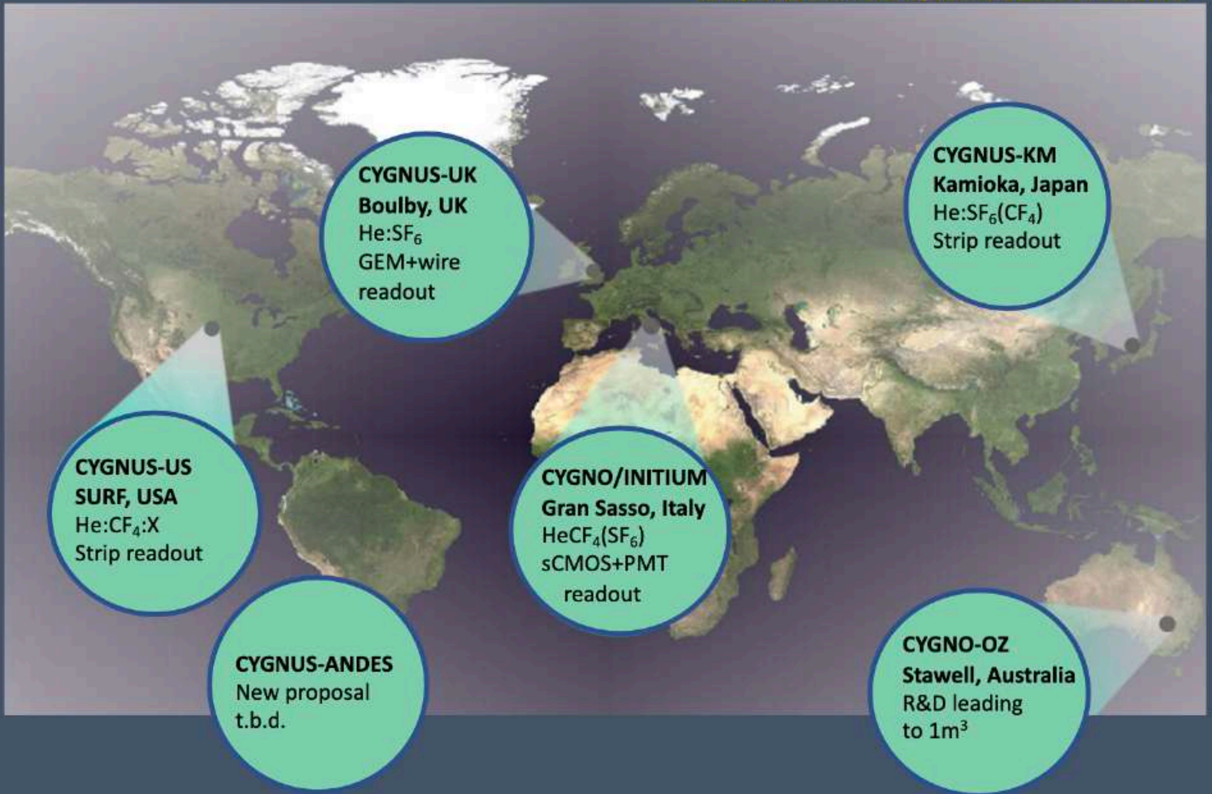
Long term CYGNUS Vision: Multi-site Galactic Recoil Observatory
with directional sensitivity to WIMPs and neutrinos

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

Nuclear Emulsion : NEWSdm

- Super-fine-grained emulsion for directionality
- High Density

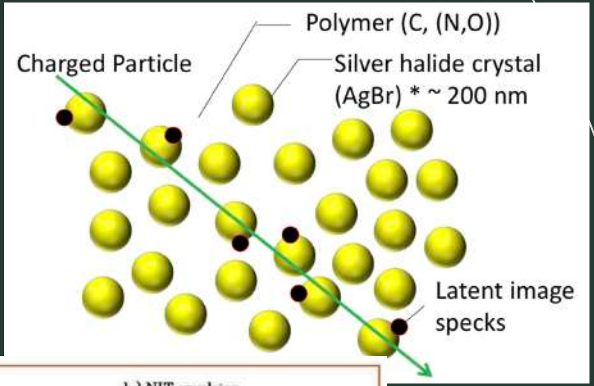
$$\frac{dR}{dE_R} = \frac{N_T \rho_0}{m_\chi} \int^{v_{\max}} d\vec{v}\, f(\vec{v}) |\vec{v}| \frac{d\sigma(\vec{v})}{dE_R}$$

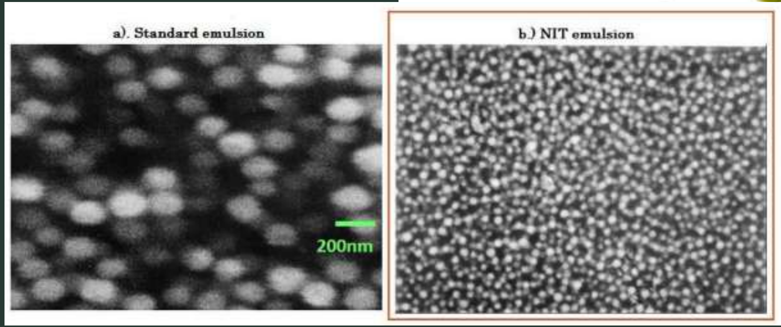
Easy to obtain large mass

- No time resolution…
- Target

p, C, N, O, Ag, Br

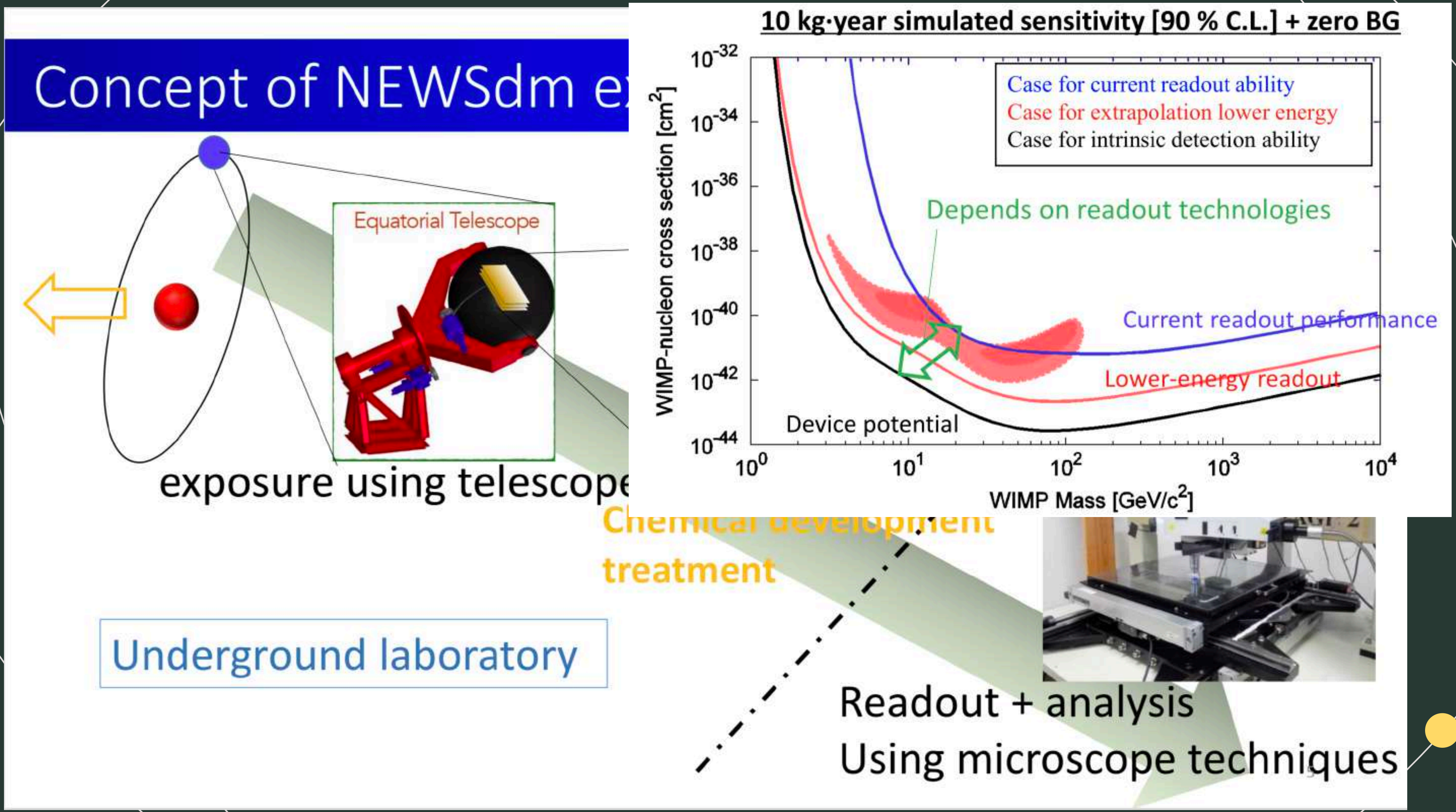
Slides by T. Naka





Naka et al., 1109.4485

Slides by T. Naka



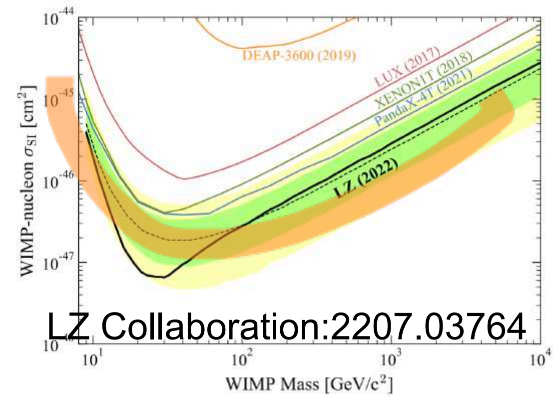
03

Anisotropy of boosted DM flux

Difficulty of Light DM Detection

- Light mass region
  - $\langle v_{DM} \rangle \sim 230$km/s << 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, …



- Heavy mass region

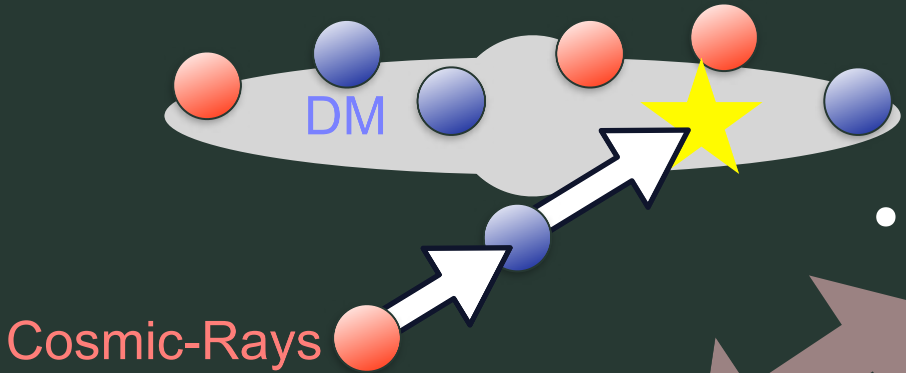
$$\Omega_{DM} = \frac{m_{DM} n_{DM}}{\rho_{DM}}$$

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

Less #DM is expected.

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

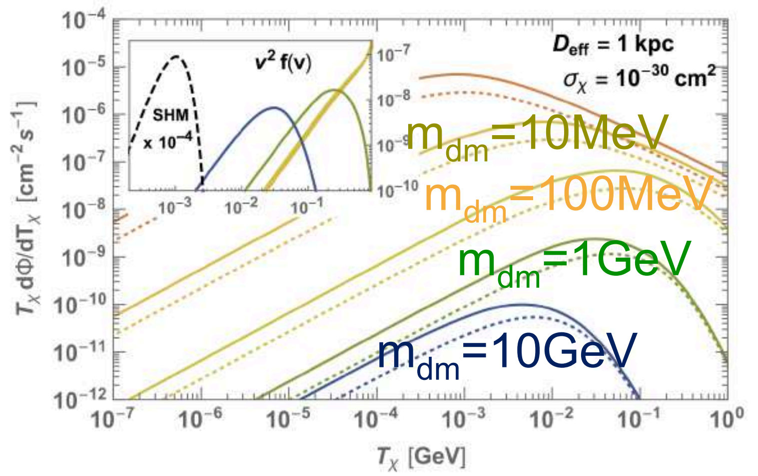
- Cosmic-Ray boosted DM (CR-DM)
  - NOT bounded by the Galactic escape velocity
  - $\langle v_{DM} \rangle$ depends on kinetic energy of CR
  - DM obtains additional kinetic energy to overcome the energy threshold after CR scatters the light DM.

T.Bringmann and M.Pospelov arXiv:1810.10543

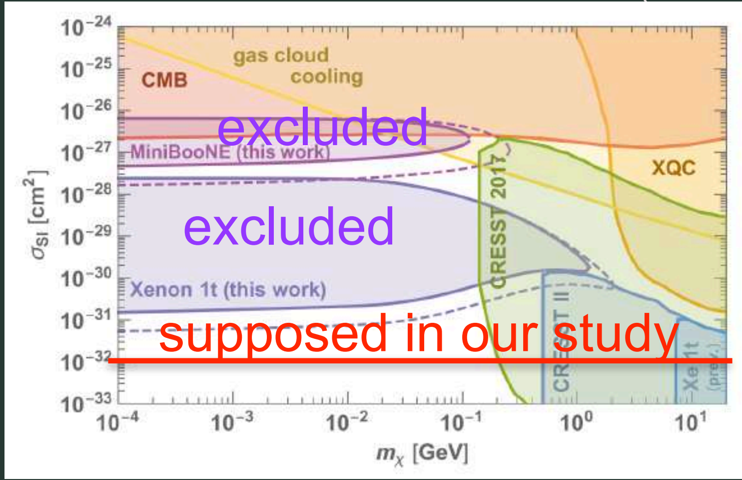
CR-DM

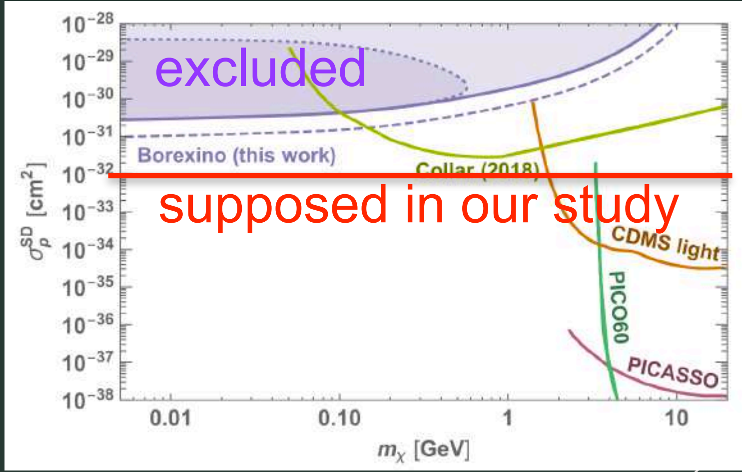
- Flux

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

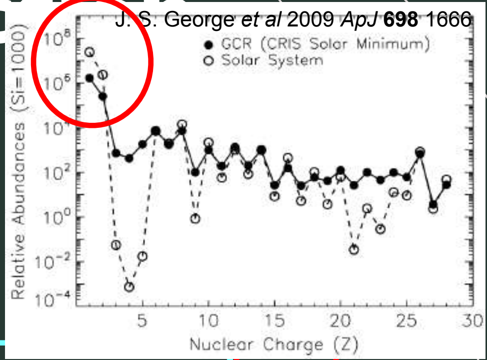


- Constraints



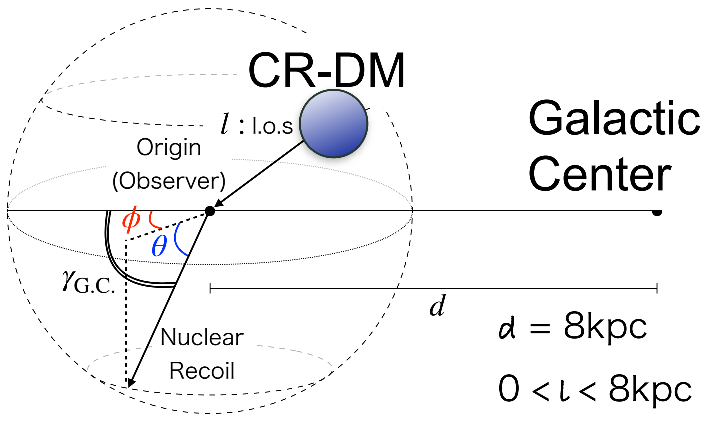


Flux of CR-DM for each direction

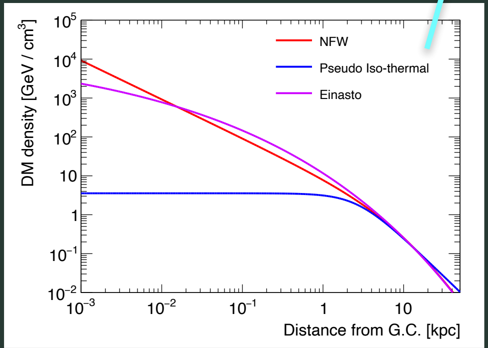


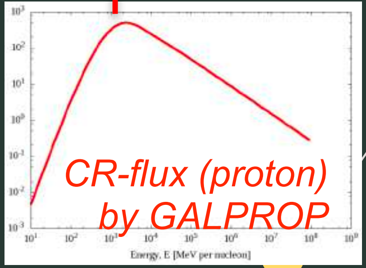
$$\frac{d\Phi_\chi}{dT_\chi d\theta d\phi} = \int_{T_\chi^{\rm min}}^{\infty} \frac{dT_p}{T_\chi^{\rm max}} \int dV \frac{\rho_\chi}{m_\chi}\frac{d\Phi_p}{dT_p}$$

$$= \int dl\, d\theta\, d\phi \cos\theta \; G_p^2(2m_\chi T_\chi) \frac{\sigma_{p\chi}}{4\pi m_\chi T_\chi^{\rm max}} \frac{\rho_s}{\left(1+\frac{r}{r_s}\right)^2 r/r_s}\frac{d\Phi_p}{dT_p}$$



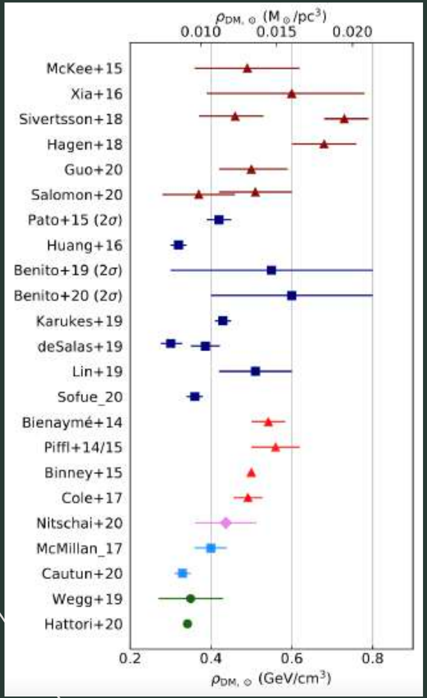
density profile?





DM density profile in the Galaxy

- Density near the Sun • Profiles



Salas,a, Widmark (2020)
2012.11477

ρ_χ(r~8kpc)
≈ 0.3-0.4GeV/cm^3

- 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

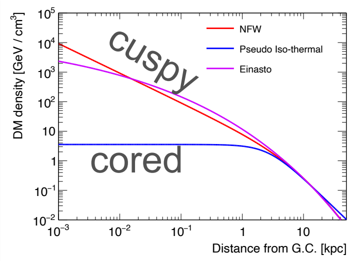
$$\rho_{Ein}(r) = \rho_0 \exp[2\alpha(1-(r/r_0)^{1/\alpha})]$$

better to fit the observations.

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

- Pseudo-isothermal profile

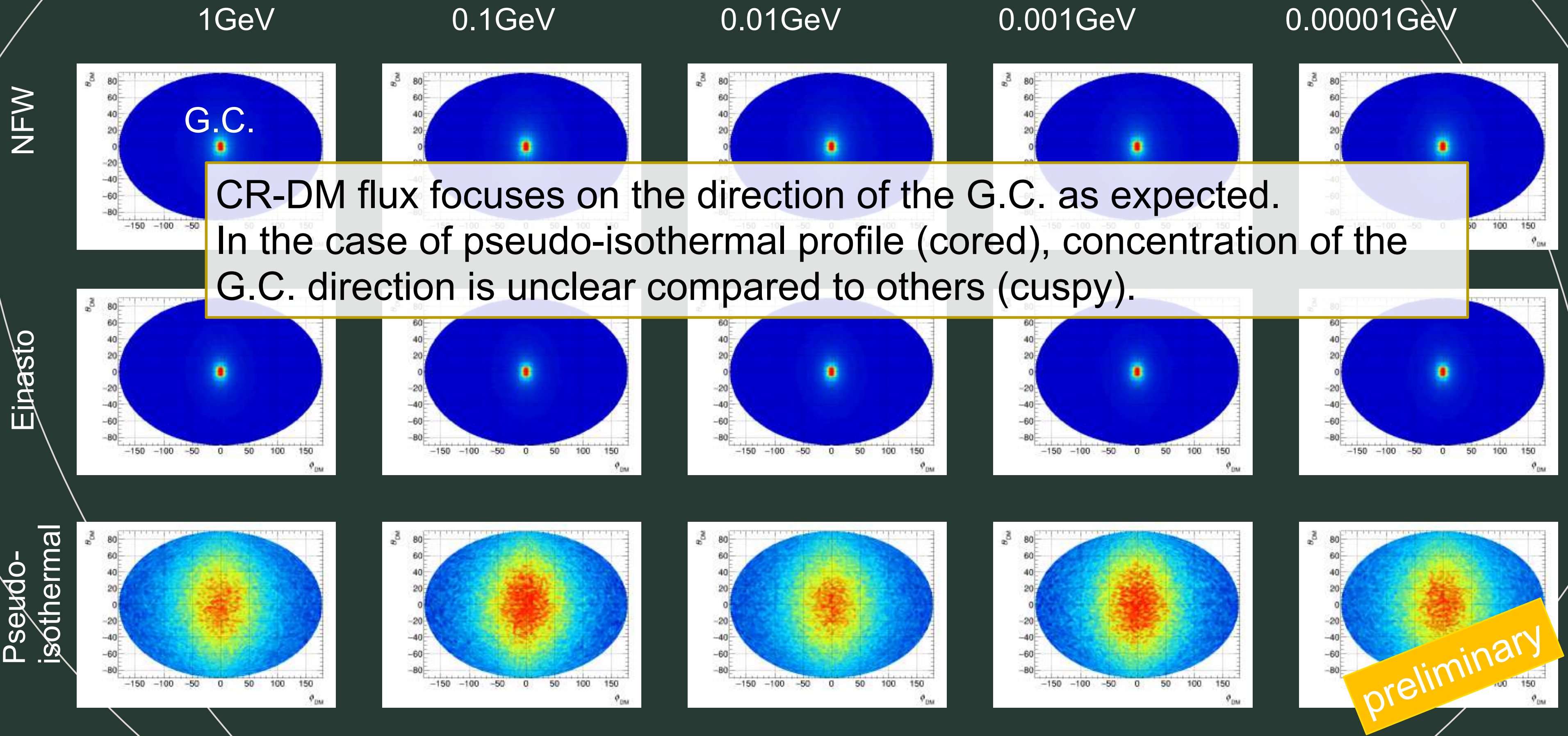
$$\rho_{Iso}(r) = \frac{\rho_0}{1+(r/r_0)^2}$$



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

CR-DM Flux in the sky

target: F



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).

Nuclear Recoils of CR-DM

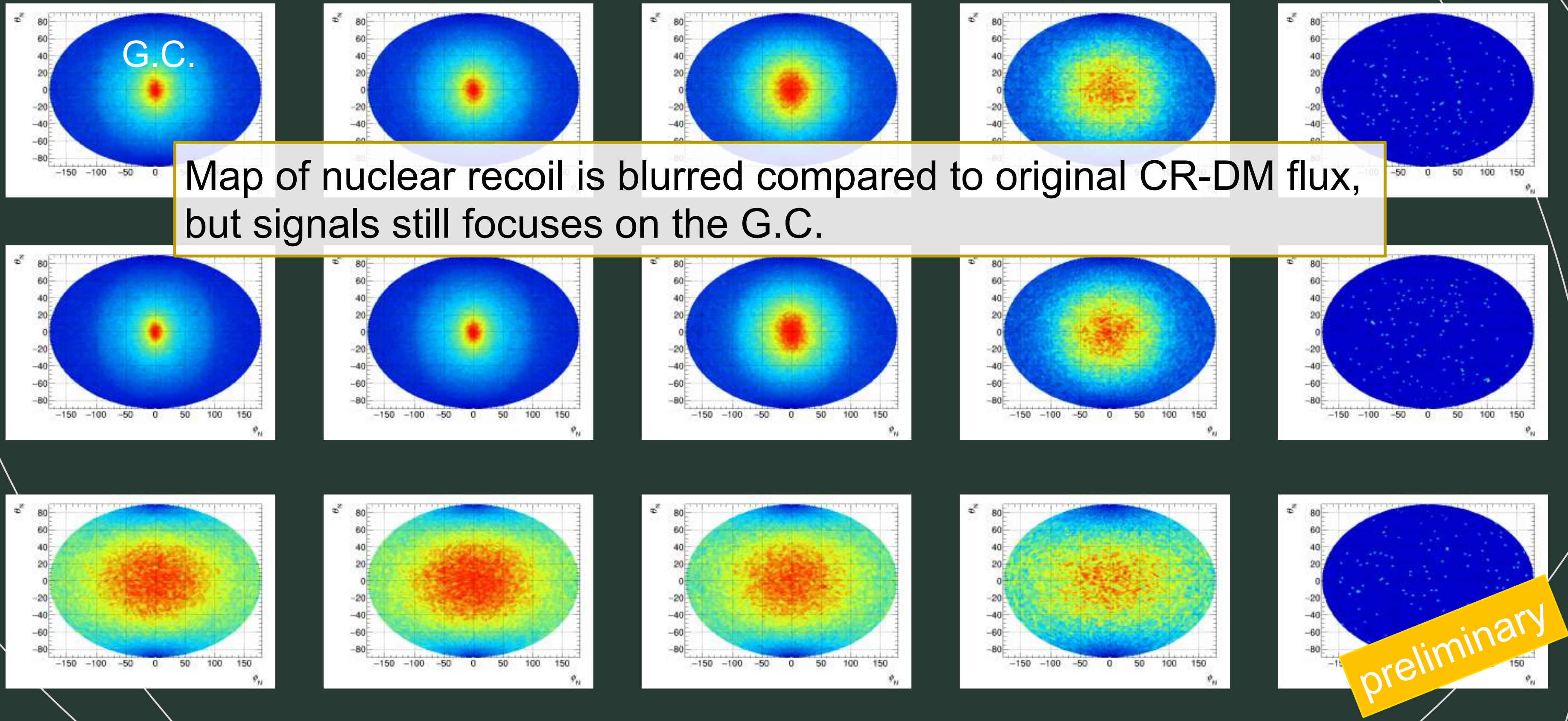
target: F

1GeV 0.1GeV 0.01GeV 0.001GeV 0.00001GeV

NFW

Einasto

Pseudo-isothermal

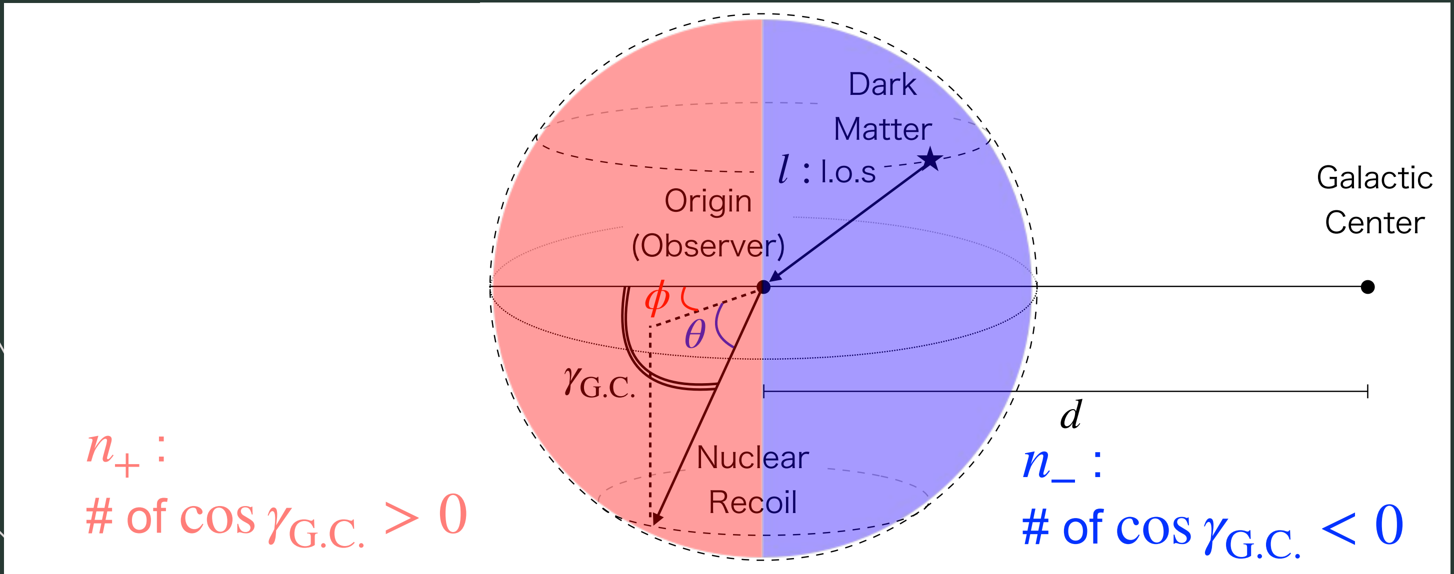


Map of nuclear recoil is blurred compared to original CR-DM flux, but signals still focuses on the G.C.

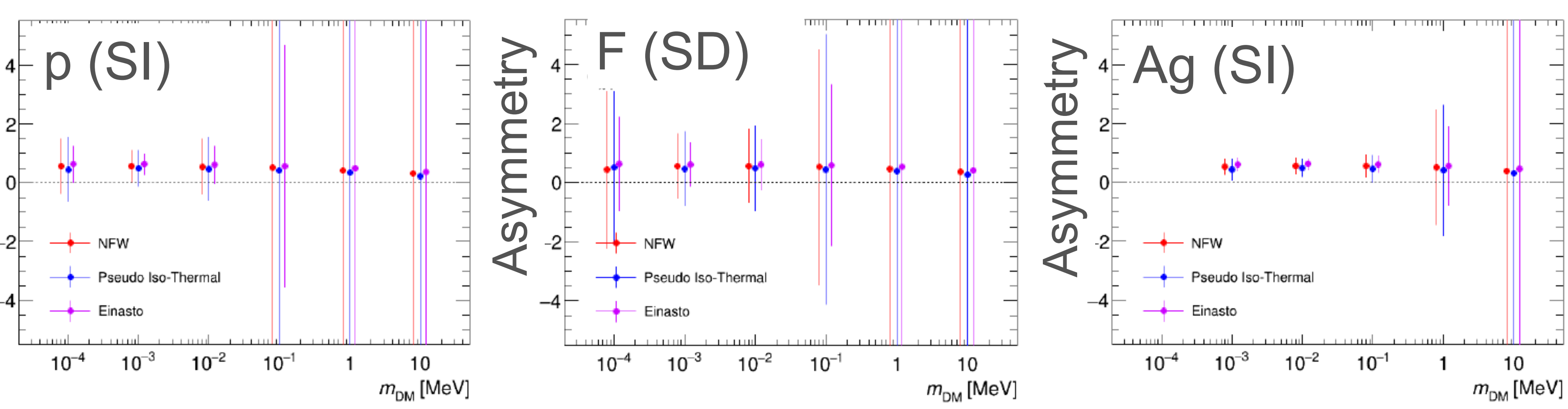
Asymmetry

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

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



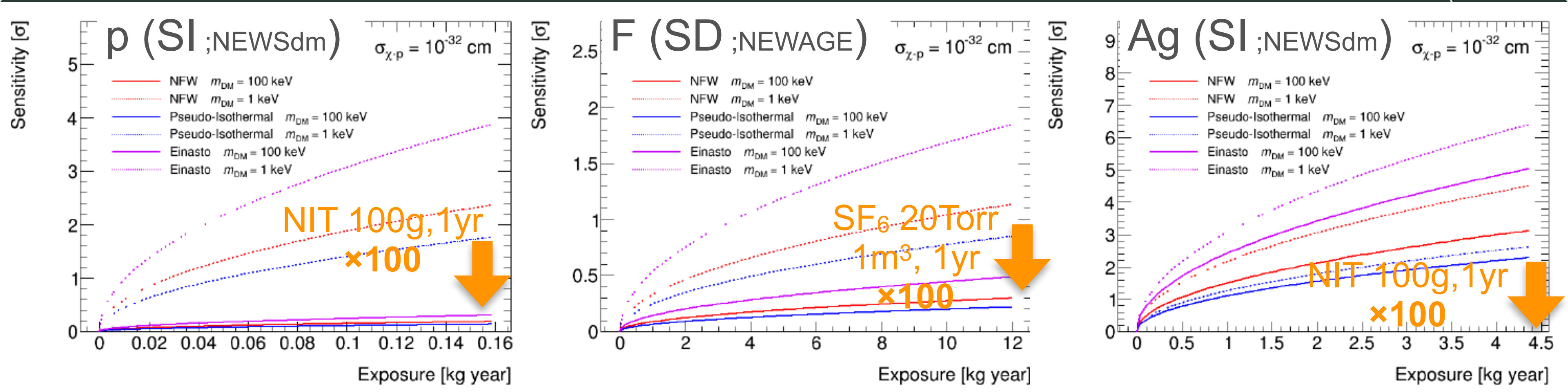
Asymmetry



- p, Ag : Nucl. Emulsion(NIT) 100g, 1yr ×20
- F : SF_6 20Torr 1m^3, 1yr ×20
- σ=10^-32 cm^2

☐ Hereafter, events with E_R causes inelastic scattering are omitted.

Sensitivity for Asymmetry

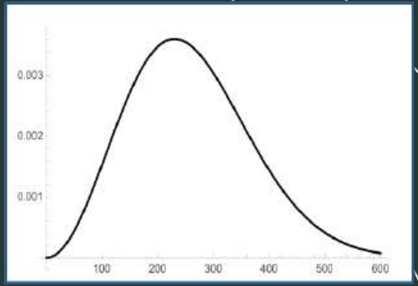


- NEWSdm has a vision to extend to O(1-10)kg in the future.
- Gas detector can also have sensitivity ~O(10) σ supposing Cygnus-1000 (1000m³). arXiv:2008.12587
- Both detections reach "asymmetry" within the scope of future upgrade plans.

04

Anisotropy of velocity dist.

Velocity Distribution



- Maxwell–Boltzmann (MB) distribution

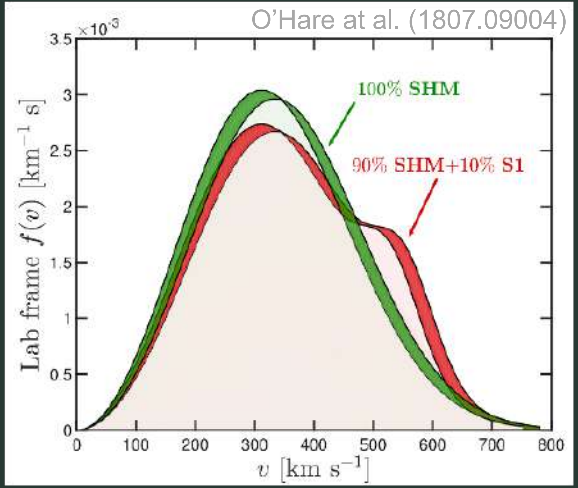
$$\frac{dR}{dE_R} = \frac{N_T \rho_0}{m_\chi} \int^{v_{\max}} d\vec{v}\, f(\vec{v}) |\vec{v}| \frac{d\sigma(\vec{v})}{dE_R}$$

$$f(v) = \frac{1}{(\pi v_0^2)^{3/2}} e^{-(v+v_E)^2/v_0^2}$$

Isotropic MB distribution is commonly supposed for DM velocity.

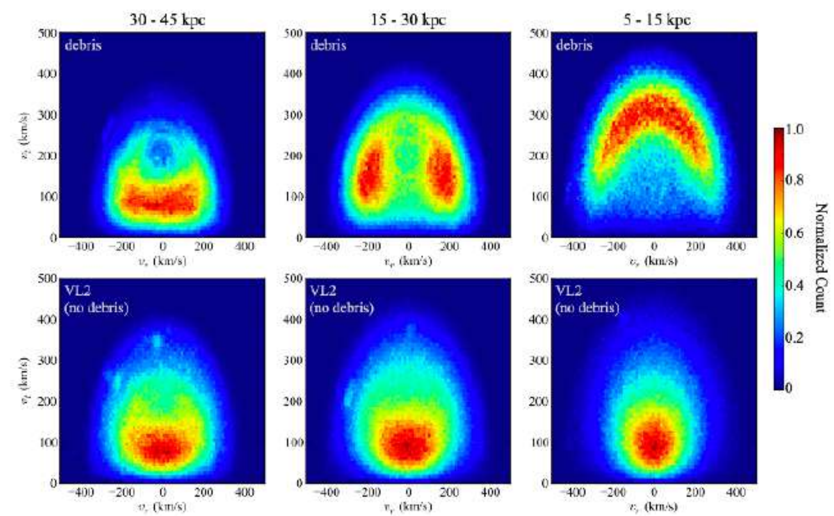
- f(v) may be anisotropic

S1 stream derived by SDSS-Gaia data has ~10% anisotropic component. Directional detection is suitable.

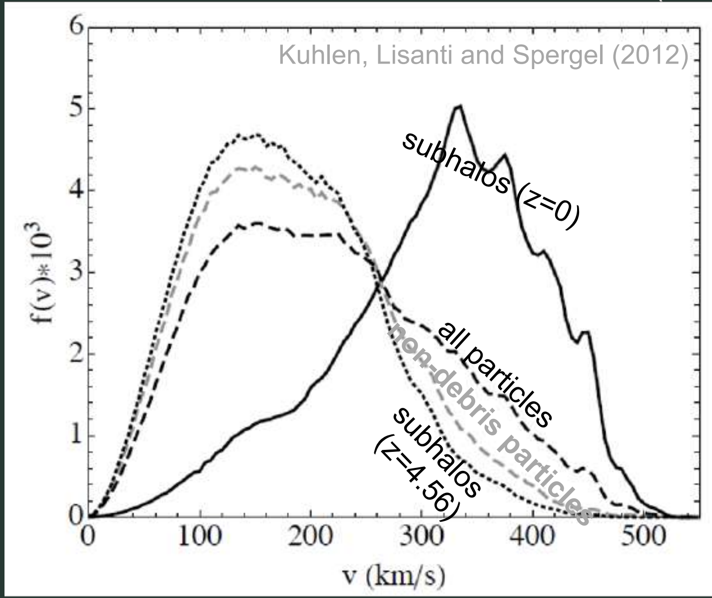


Debris Flow by Simulation

- Some N-body simulations suggest debris flow in the Galaxy



Lisanti and Spergel (2011)



Kuhlen, Lisanti and Spergel (2012)

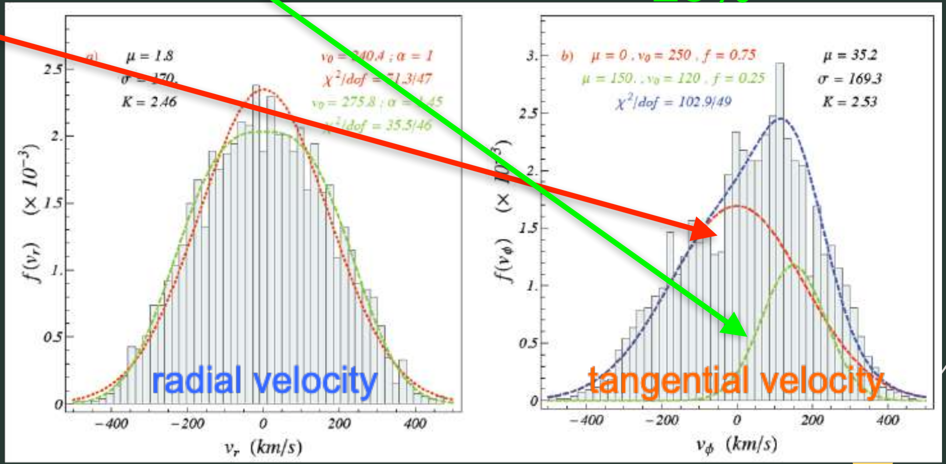
Simulation including baryons and gas

- DM follows baryons
- Anisotropic component

$$f(v_\phi) = \frac{1-r}{N(v_{0,\mathrm{iso.}})} \exp\left[-v^2/v_{0,\mathrm{iso.}}^2\right] + \frac{r}{N(v_{0,\mathrm{ani.}})} \exp\left[-(v-\mu)^2/v_{0,\mathrm{ani.}}^2\right]$$

anisotropic component 25%

isotropic component 75%

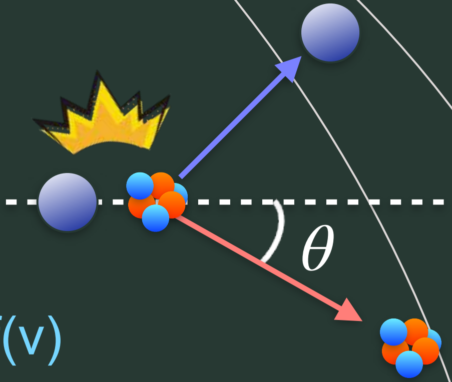


Ling, Nezri, Athanassoula, Teyssier (2009)
cf. David R. Law (2009) …

Simulation of DM detection

- Monte Carlo simulation

DM wind supposing f(v)

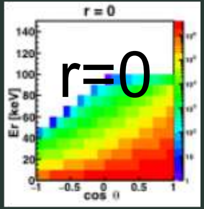


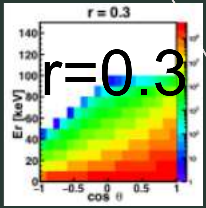
  - E_R and θ are obtained
  - Elastic scattering, No background, Perfect resolution
  - Target : F (light) /Ag (heavy)

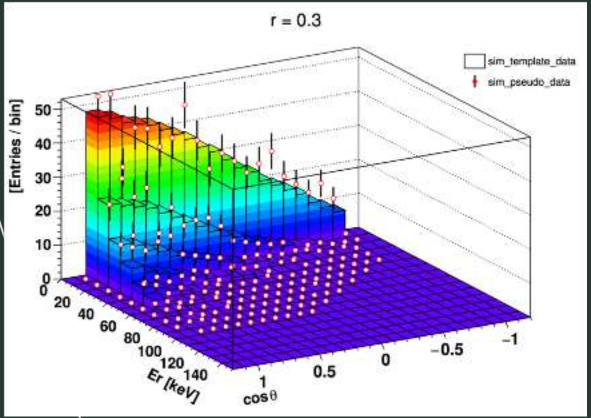
- Two kinds of Data
  - Template: Ideal data with sufficient statistics for isotropic MB/ anisotropic velocity dist.
  - Pseudo-experimental data: Data with insufficient statistics

Strategy for discrimination of anisotropy

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







Which template is more similar to pseudo-exp?

- Likelihood estimation

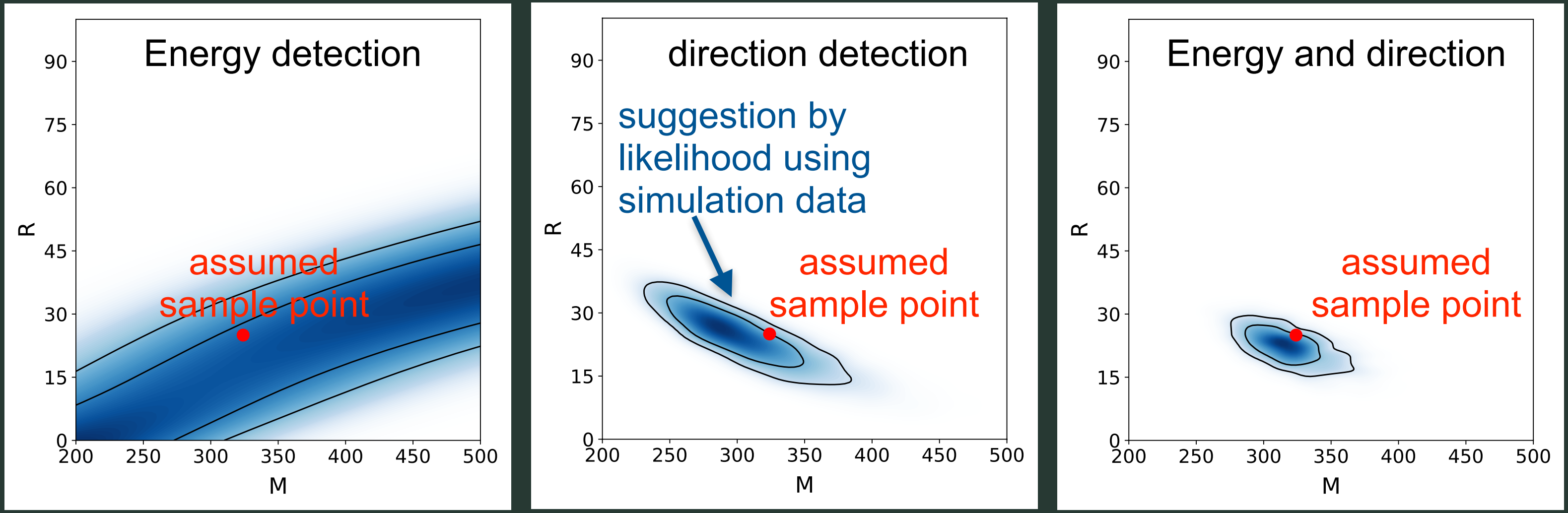
$$\mathcal{L} = \prod_{\text{bins}} P(r \mid \text{pseudo, template})$$

- χ^2 test

$$\chi^2 = \sum_{\text{bins}} \frac{(\text{pseudo} - \text{template})^2}{\text{pseudo}}$$

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

Sensitivity for anisotropy and mass



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

- Ethr=50keV
- target:Ag
- M_{dm}=300GeV
- #event: 10000

($\sigma_p=10^{-28}cm^2$, 1/kg/day)

Conclusion

- “Direction” of DM offers additional information to us.
- Density profile, velocity dist. and mass are discussed.
- Related to particle physics?