the 2nd IITB-Hiroshima workshop on Neutrino Physics
2021. Oct. 26rd

Directional detection of cosmic-ray accelerated dark matter

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in collaboration with S. Higashino, T. Naka and K. Miuchi (in progress)

NEW AGE

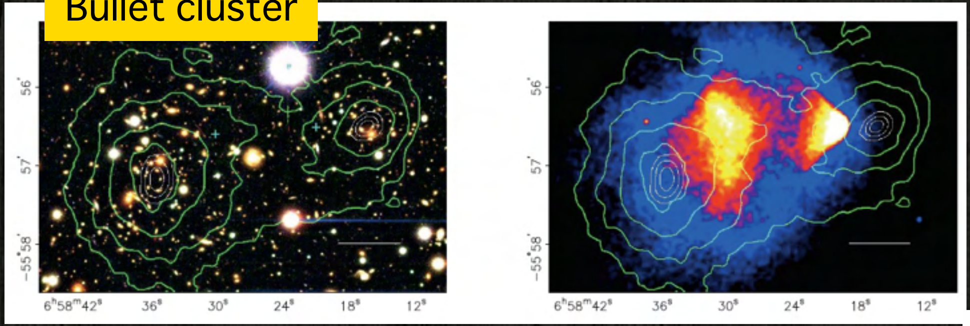
NEWSdm

1.
Introduction

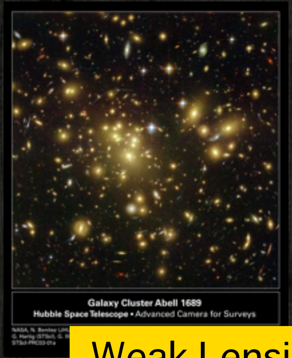
How can we detect the dark matter?

Dark Matter

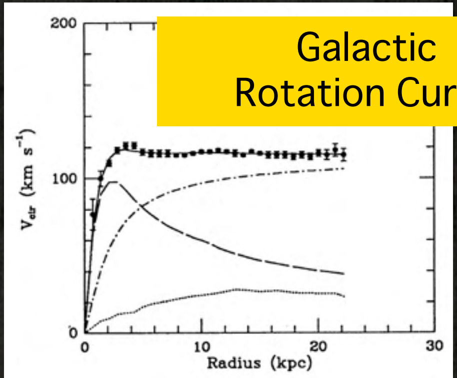
Bullet cluster



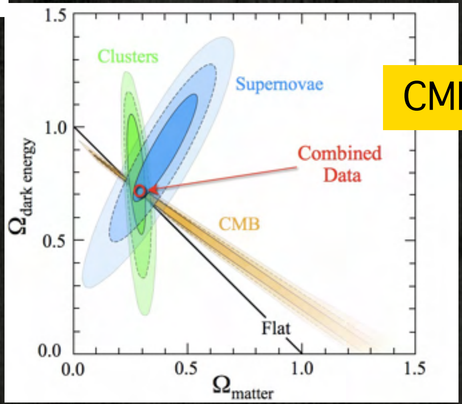
Weak Lensing



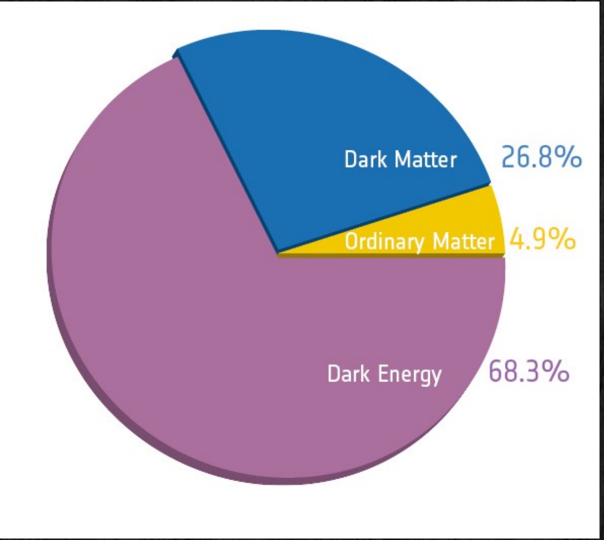
Galactic
Rotation Curve



CMB



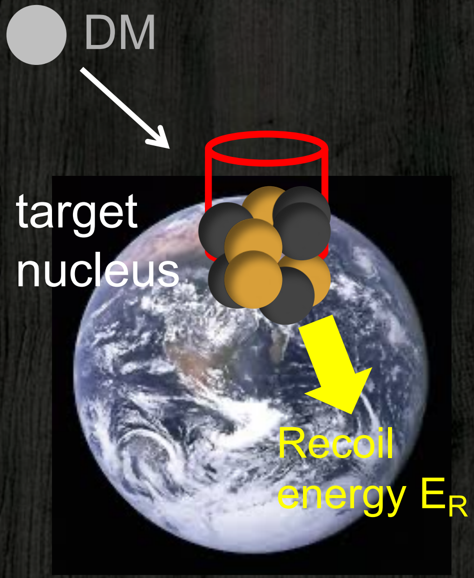
Dark Matter Candidates



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

Direct Detection

- Detecting recoil energy of DM-target scattering

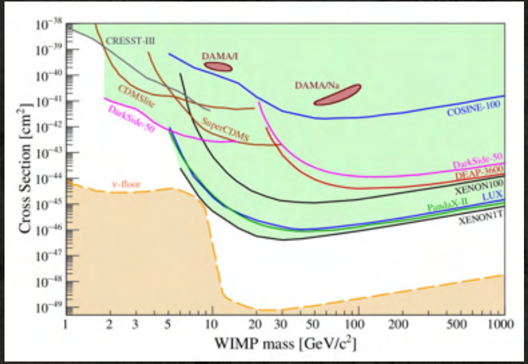


Differential event rate

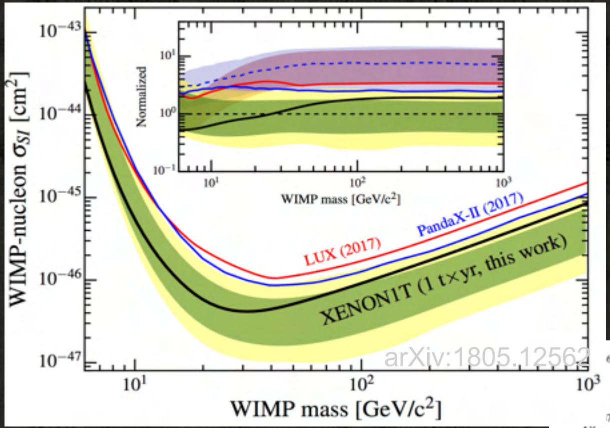
#target, #WIMP

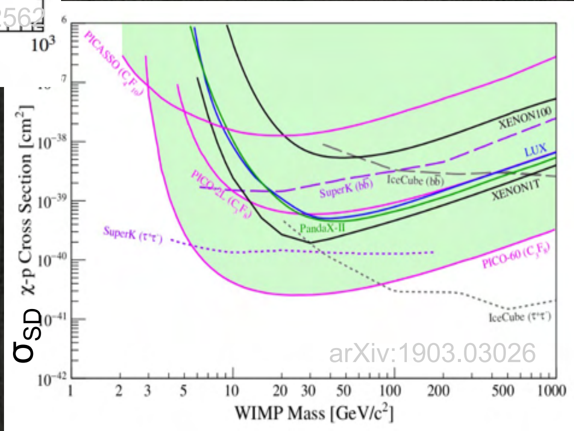
$$\frac{dR}{dE_R} = \frac{N_T \rho_0}{m_\chi} \int^{v_{\max}} d\vec{v}\, f(\vec{v}) |\vec{v}| \frac{d\sigma(\vec{v})}{dE_R}$$

1903.03026



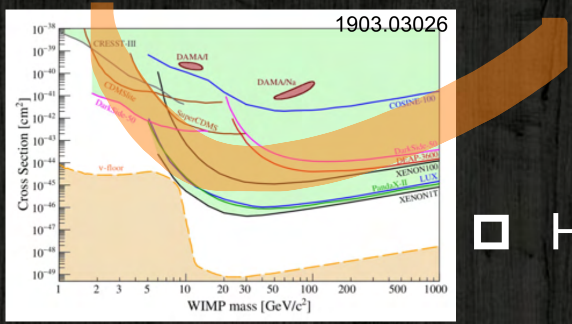
Constraint of Direct Detection

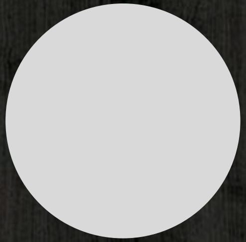




- Direct detection put the severe constraint to O(10-100) GeV DM.
- Lighter or heavier DM than ordinary WIMP ($m_\chi \sim$ O(100)GeV) are becoming popular.

Why direct detection is not sensitive to light and heavy mass region?





- Light mass region

  $\langle v_{DM} \rangle \sim 220$km/s

  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, Migdal effect, Cosmic-ray DM scattering, …

- Heavy mass region

  $\Omega_{DM} h^2 = 0.12$

  w/ $\Omega_{DM} = \rho_{DM}/\rho_c$

  $= m_{DM} n_{DM}/\rho_c$

  ⇒ $n_{DM} \propto 1/m_{DM}$

  Less #DM is expected for large m_{DM}

W. Yin arXiv:1809.08610
T.Bringmann and M.Pospelov arXiv:1810.10543

…

2.
Cosmic-ray boosted DM (CRDM)

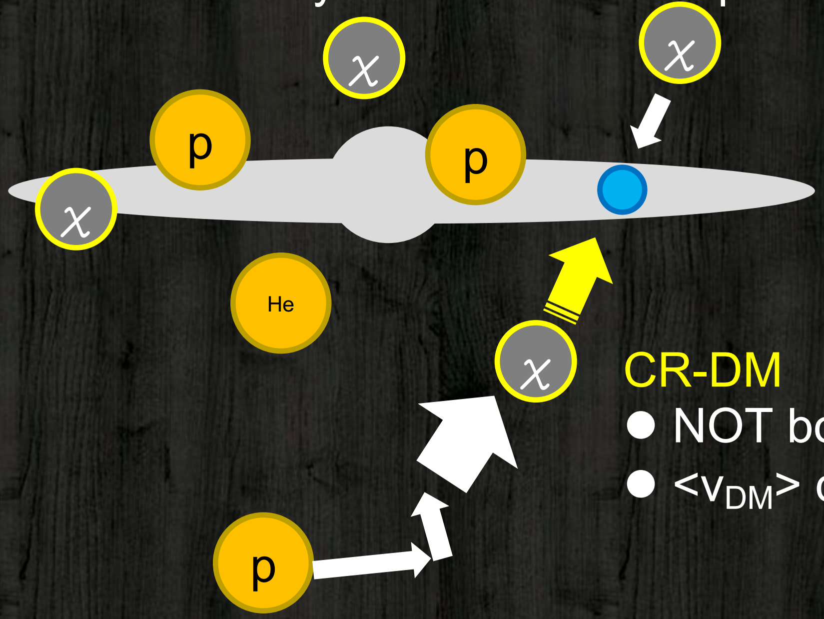
Can the light dark matter of sub-GeV mass be detected via DM-nucleus scattering?

T.Bringmann and M.Pospelov arXiv:1810.10543

Concept of CR Acceleration

Ordinary DM (WIMPs)

- $\langle v_{DM} \rangle \sim 230$ km/s
- bounded by the Galactic escape velocity 500-600 km/s



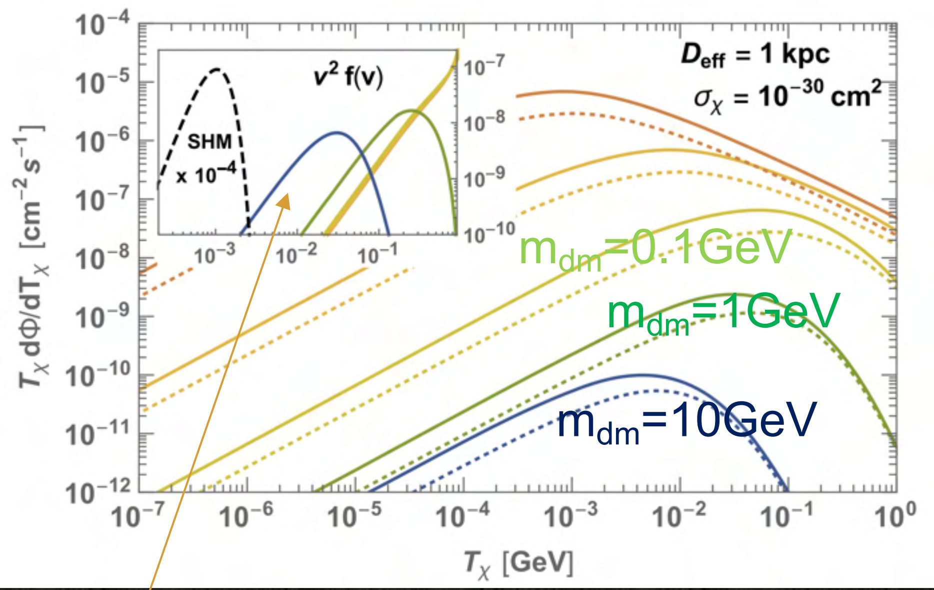
Cosmic-ray (CR) can scatter the light DM and DM obtains additional kinetic energy (CR-DM) to overcome the energy threshold.

CR-DM

- NOT bounded by the Galactic escape velocity
- $\langle v_{DM} \rangle$ depends on kinetic energy of CR

CR-DM

T.Bringmann, M.Pospelov

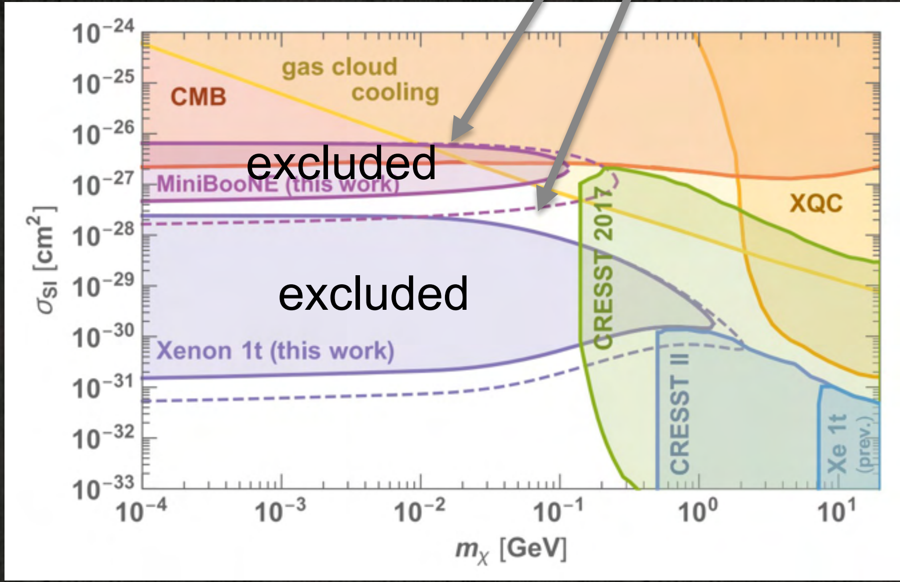


$$f(v) = \frac{m_\chi^2 \gamma^3}{\rho_\chi^{\mathrm{local}}} \frac{d\Phi_\chi}{dT_\chi}$$

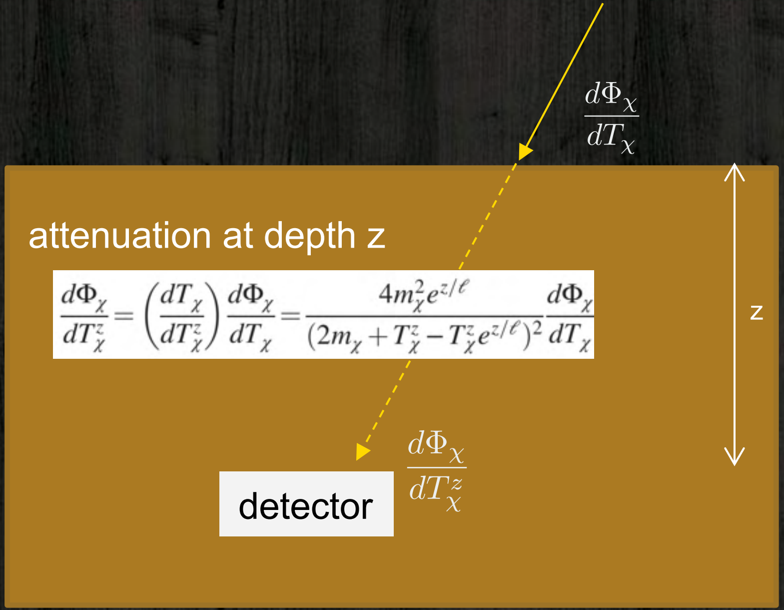
- Even if DM is as light as < O(1) GeV, direct detection can reach (give constraint to) the parameter region due to CR boost.

Attenuation of CR-DM

If σ is too large, due to scattering with atoms in underground
DM loses its kinetic energy < Ethr of detector. Such region cannot be constrained.



T.Bringmann, M.Pospelov



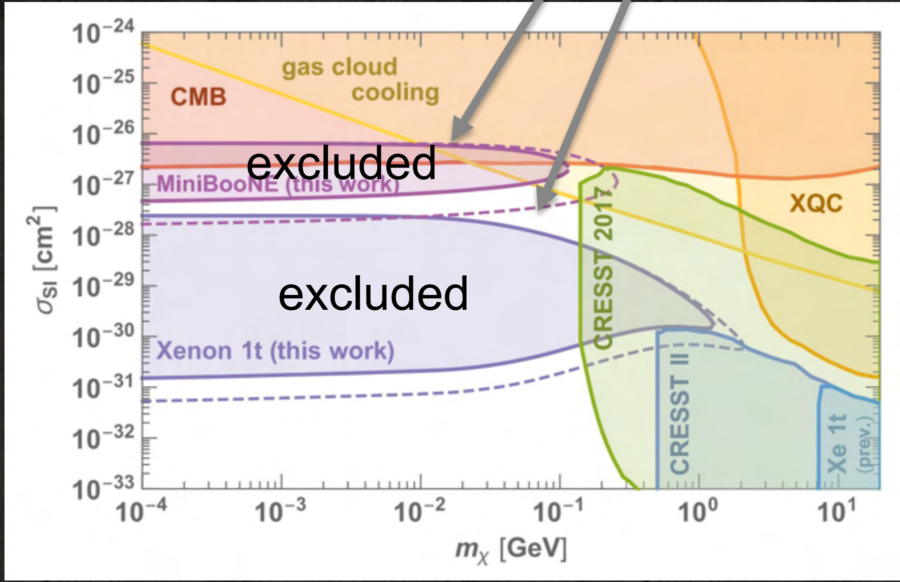
$$\frac{d\Phi_\chi}{dT_\chi^z} = \left(\frac{dT_\chi}{dT_\chi^z}\right)\frac{d\Phi_\chi}{dT_\chi} = \frac{4m_\chi^2 e^{z/\ell}}{(2m_\chi + T_\chi^z - T_\chi^z e^{z/\ell})^2}\frac{d\Phi_\chi}{dT_\chi}$$

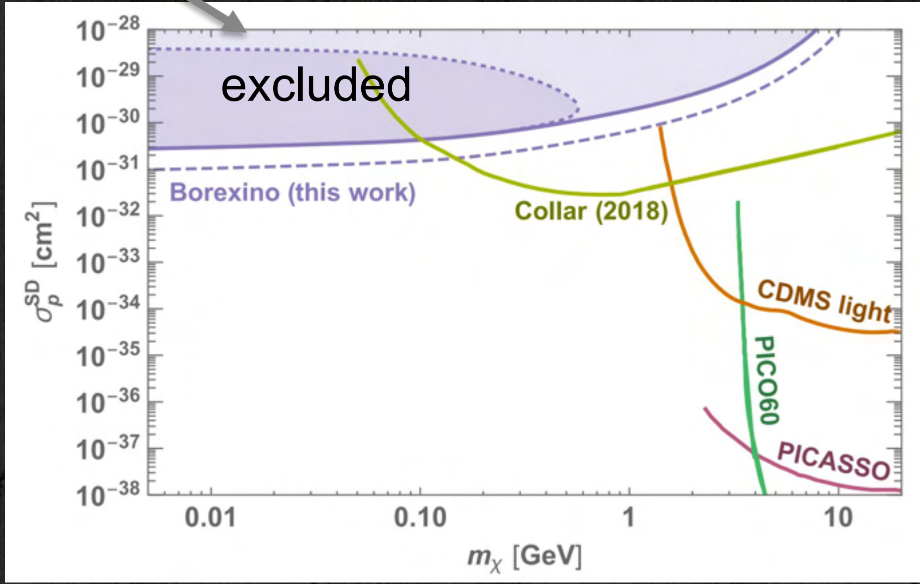
z=1400m (XENON, LNGS)

Constraints on σ_{SI} and σ_{SD}

T.Bringmann, M.Pospelov

If σ is too large, due to scattering with atoms in underground,
DM loses its kinetic energy < Ethr of detector. Such region cannot be constrained.



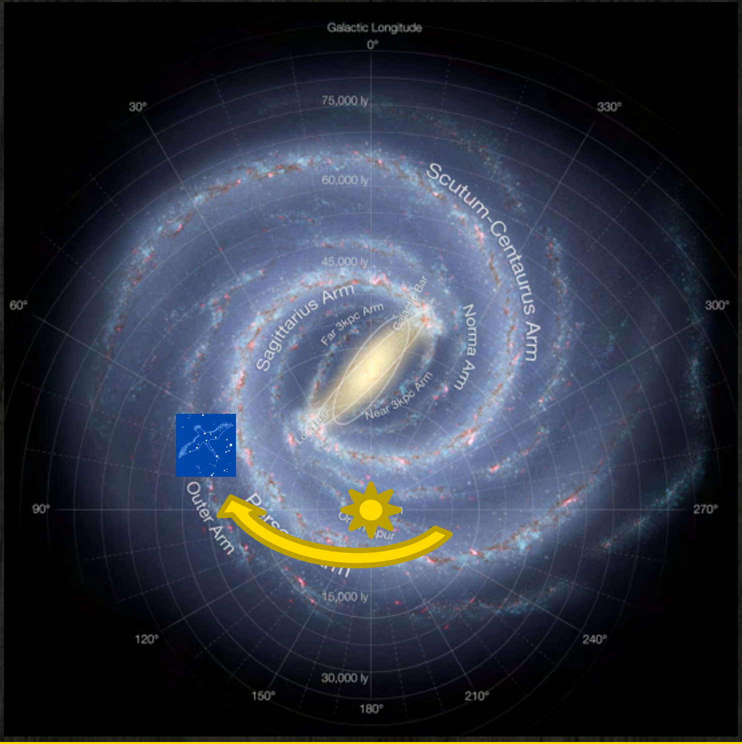


3. Directional Direct Detection

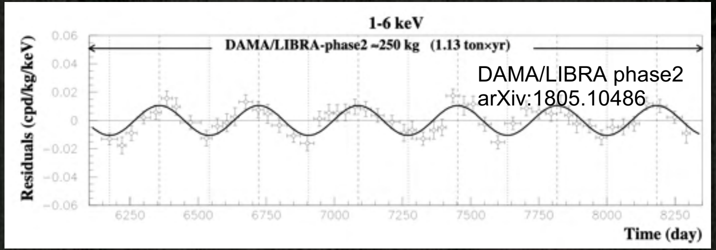
Why directional detection of DM?

Our motion in the Galaxy

- The Solar system is moving toward the Cygnus.



Annual modulation of the event rate is expected.

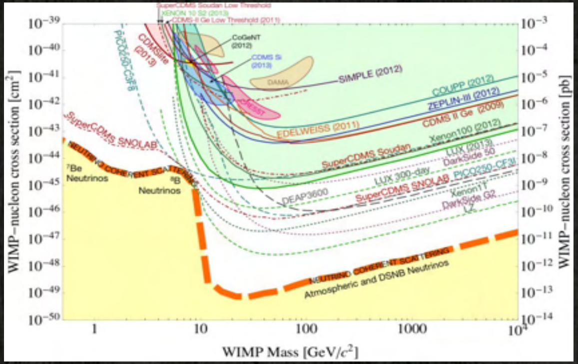


Credit: NASA/JPL-Caltech/ESO/R. Hurt

Advantages of directionality (1)

- Powerful background rejection
  - Background : isotropic
  - DM signal : come from direction of the Cygnus

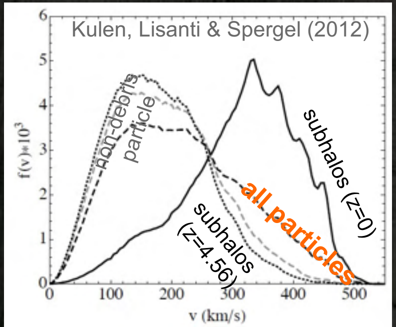
SNOWMASS report (2013)

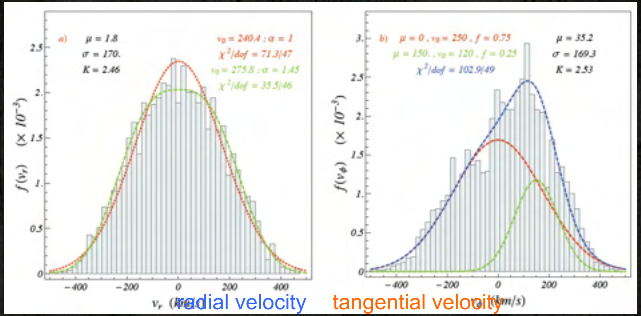


- Neutrino Floor

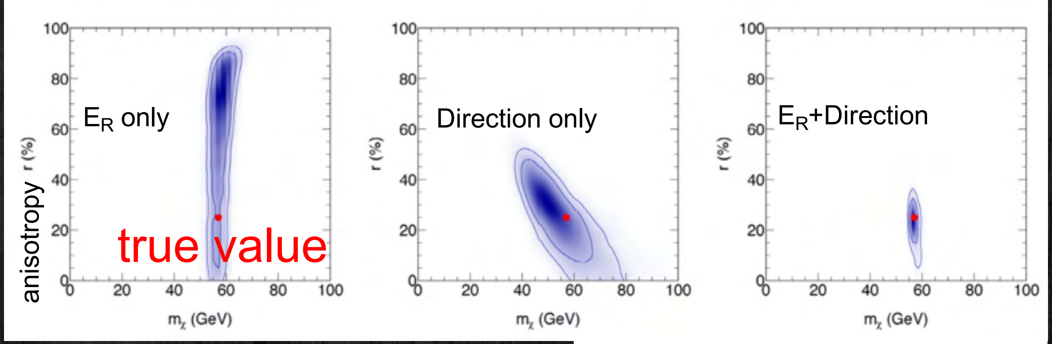
Advantages of directionality (2)

- Velocity distribution of DM
  - Isotropic Maxwell distribution is usually assumed as f(v)
  - Non-standard distribution, especially anisotropy is suggested by some N-body simulations





Ling, Nezri, Athanassoula & Teyssier (2009)



KN, Ikeda, Yakabe, Naka and Miuchi (2020)
also B. Morgan, A. Green, N. Spooner (2004)
O.Host, S. Hansen (2007), …

Achieving Directionality

- *Detectors that reconstruct the recoil trajectory*
  - *Gas-based TPCs*
  - *Nuclear Emulsions*

  (Gas-based TPCs and Nuclear Emulsions: See next two talks)
  - *Crystal defect spectroscopy*
  - *DNA strand detector*
  - *Planar targets (graphene)*
- *Detectors that indirectly determine the recoil direction*
  - *Anisotropic scintillators*
  - *Columnar recombination*
  - *Carbon nanotubes*

- Event-by-event recoil tracking in condensed matter is hard, but not impossible

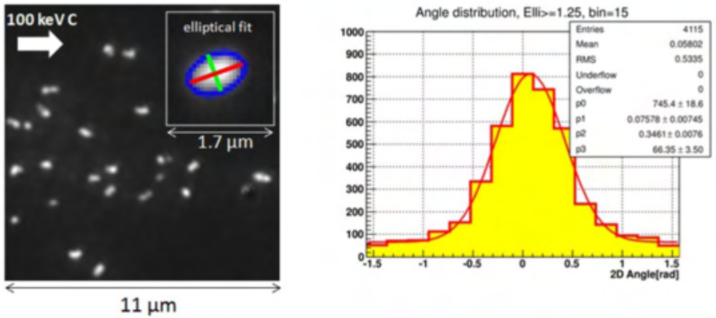


Figure 24: Left: Optical microscope image of 100 keV C ion tracks. Right: The corresponding distribution of major axis orientation determined from elliptical shape fitting for events whose ratio of lengths of major and minor axes exceeds 1.25.

Physics Reports 662 (2016)

Prototypes and Experiments (list is probably not comprehensive!)

Name	Technology	Directionality	Status
NEWAGE	Gas TPC, strip readout	3d	Running underground
DRIFT	Gas TPC, NID, wire readout	1.5d	Running underground
MIMAC	Gas TPC, strip readout	3d	Ran underground, scaling up
DMTPC	Gas TPC, optical readout	2d	Ran underground, scaled up, stopped
D^3 / Hawaii readout R&D	Gas TPC, pixel readout	3d	Prototypes evaluated, ran above-ground
New Mexico readout R&D	Gas TPC, NID, optical readout	2d	Prototypes evaluated
LEMON, ORANGE, INITIUM, CYGNO	Gas TPCs, CMOS + PMT optical readout	3d	Prototypes evaluated, funded to scale up
NEWSdm	Nuclear Emulsions	2d	Prototyping / going underground
PTOLEMY	Graphene	2d	Prototyping / going underground

All directional that have set limits use <=1m^3 gas TPCs
NEWAGE: best limit using directionality
DRIFT: best limit with a directional detector

Credit:Sven Vahsen's talk in Sendai Symposium

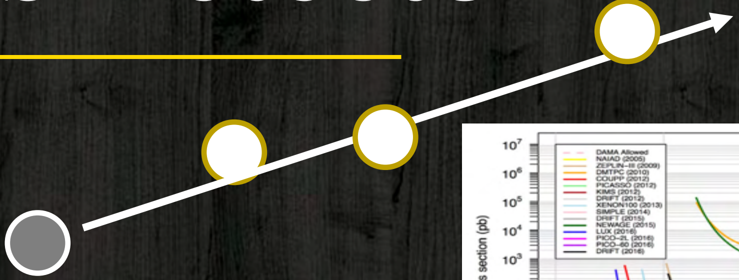
Gaseous Detector

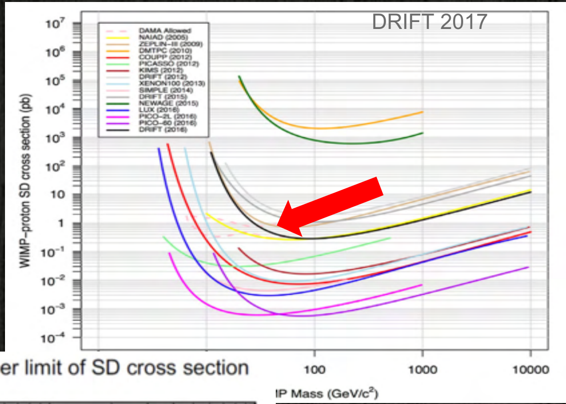
- Directionality
  Mean free path ~ μm
- Low Pressure

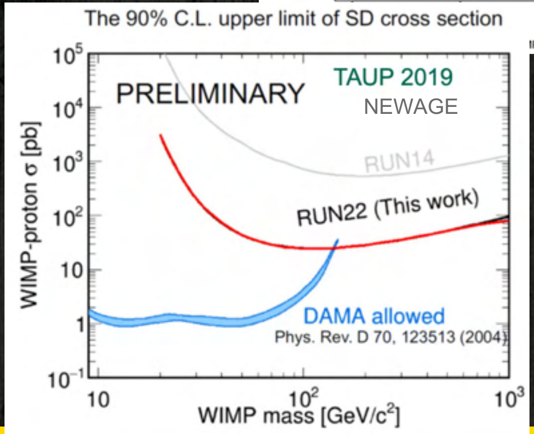
$$\frac{dR}{dE_R} = \frac{N_T \rho_0}{m_\chi} \int^{v_{\max}} d\vec{v}\ f(\vec{v})|\vec{v}| \frac{d\sigma(\vec{v})}{dE_R}$$

large volume is required to enhance sensitivity.

- Typical target
  CF_4, SF_6, CS_2, CHF_3



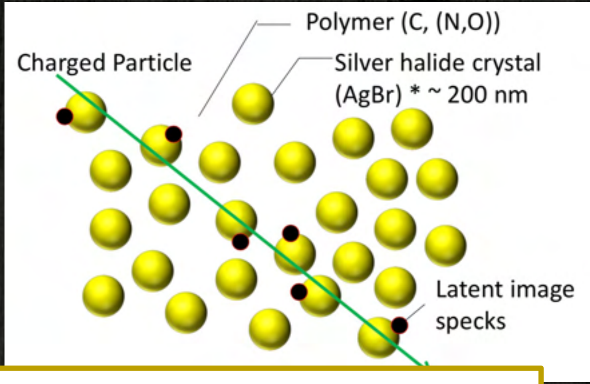




Solid detector

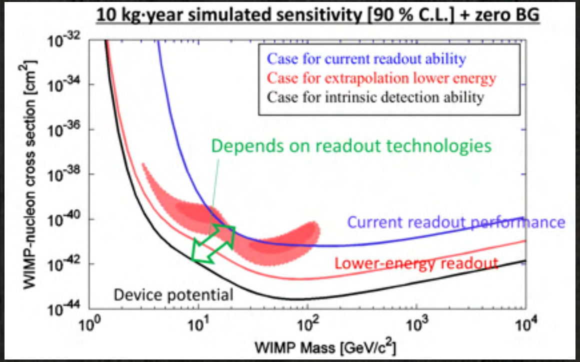
Slides by Naka.

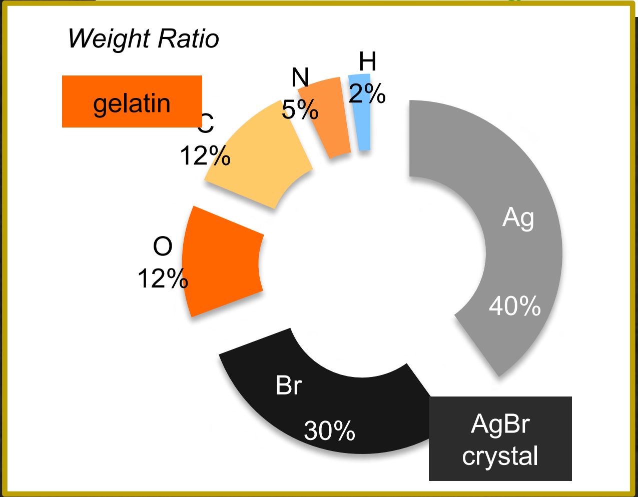
- Nuclear Emulsion=AgBr Crystal + gelatin
- Dense
  >> Easy to obtain large mass



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

- Target
  H, C, N, O, Ag, Br





“

What if we can detect the CR-DM with directionality? Can we see many CR-DM in the direction of the Galactic Center? It’s interesting!

4. Numerical result

Can we see CR-DM signals from the Galactic center?

Strategy of Numerical Simulation

DM profile $\rho_{DM}(r)$ $\sigma_{\chi i}$,He,…

G.C.
?

▼

CR-DM flux

DM
wind

▼ $\sigma_{\chi N}$, C, …

1.

▼

Evaluation

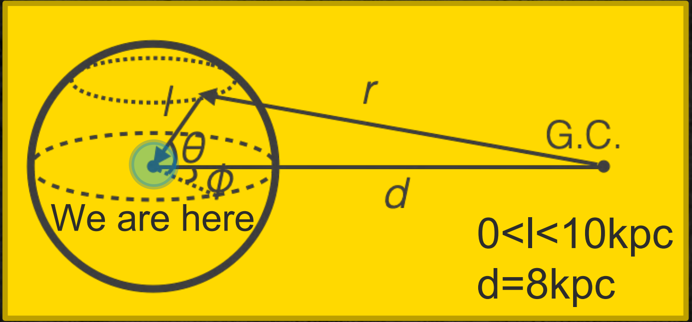
Detectability of CR-DM signals from the GC, DM profile dependence, …

Cal. of CR-DM flux

- CR-DM flux for each direction

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

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



$G_i(Q^2) = 1/(1+Q^2/\Lambda_i^2)^2$ hadronic elastic scattering form factor

$$T_\chi^{\max} = \frac{T_i^2 + 2m_i T_i}{T_i + (m_i + m_\chi)^2/(2m_\chi)}$$ maximum kinetic energy of DM

Cal. of CR-DM flux

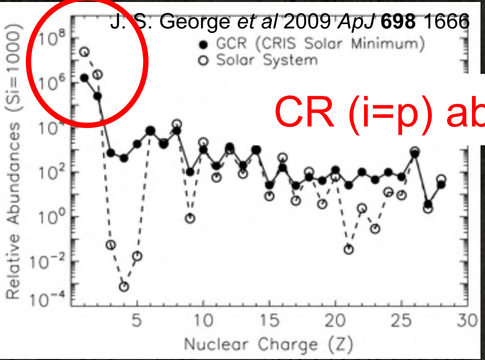
- CR-DM flux for each direction

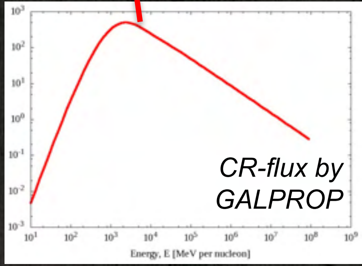
$$\frac{d\Phi_\chi}{dT_\chi d\theta d\phi} = \int_{T_\chi^{\min}}^{\infty} \frac{dT_p}{T_\chi^{\max}} \int dV \frac{\rho_\chi}{m_\chi} \frac{d\Phi_p}{dT_p}$$

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

DM profile

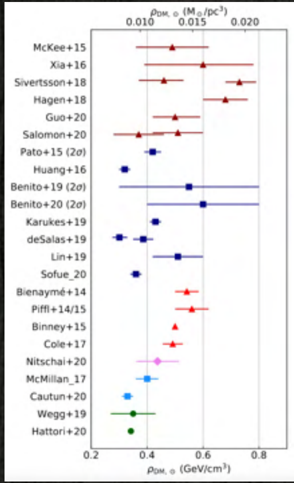
CR (i=p) flux



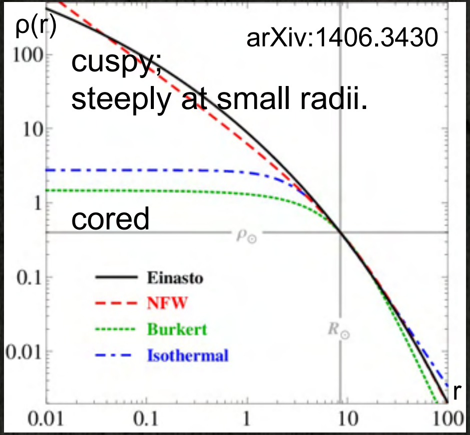


DM profiles of the Milky Way Galaxy

DM density near the Sun



Salas,a, Widmark (2020)
2012.11477



$\rho_\chi(r\sim 8\text{kpc})$
$\approx 0.3\text{-}0.4\,\text{GeV/cm}^3$

Profiles

- Navarro–Frenk–White (NFW) profile

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

- Einasto profile better to fit the observations.

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

- Pseudo-isothermal profile

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

T.Bringmann and M.Pospelov arXiv:1810.10543

Line-of-sight integral

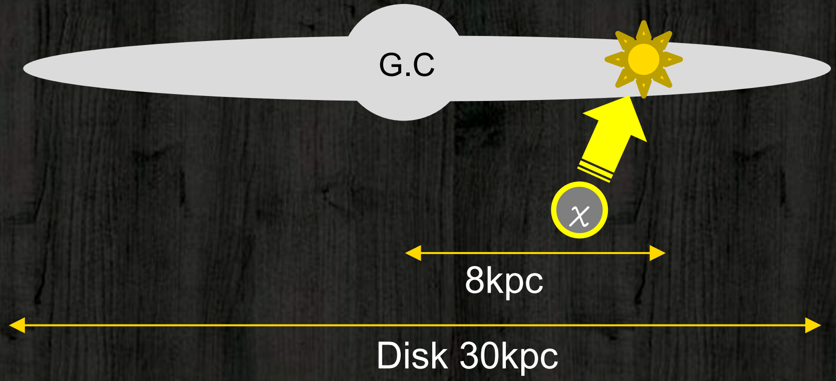
- CR-DM flux for each direction

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

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

DM profile

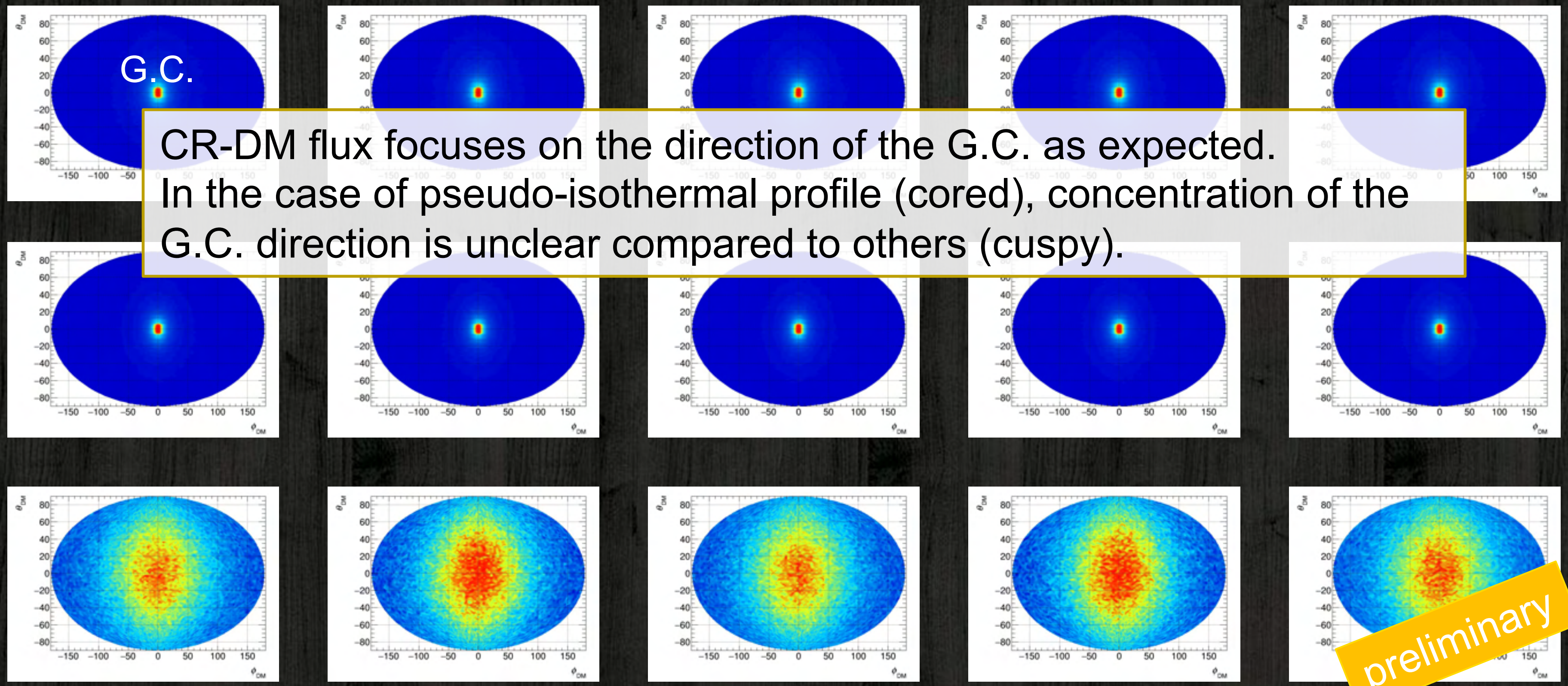
CR (i=p) flux



Result depends on full line-of-sight integration out to 1 kpc (10 kpc) in the original paper. We suppose l_{max}=10kpc in the numerical calculation.

CR-DM Flux in the sky

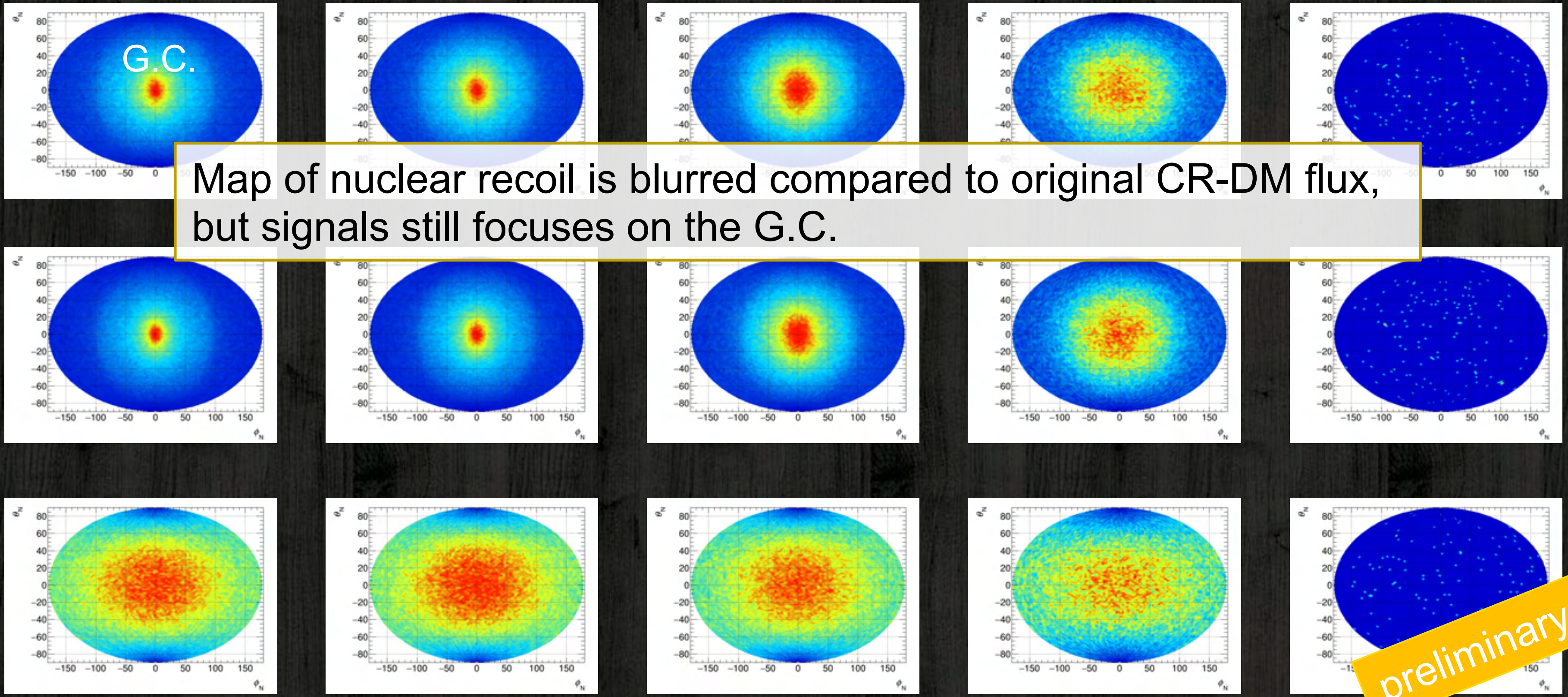
target: F



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).

m_χ dependence of Nuclear Recoil

target: F



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

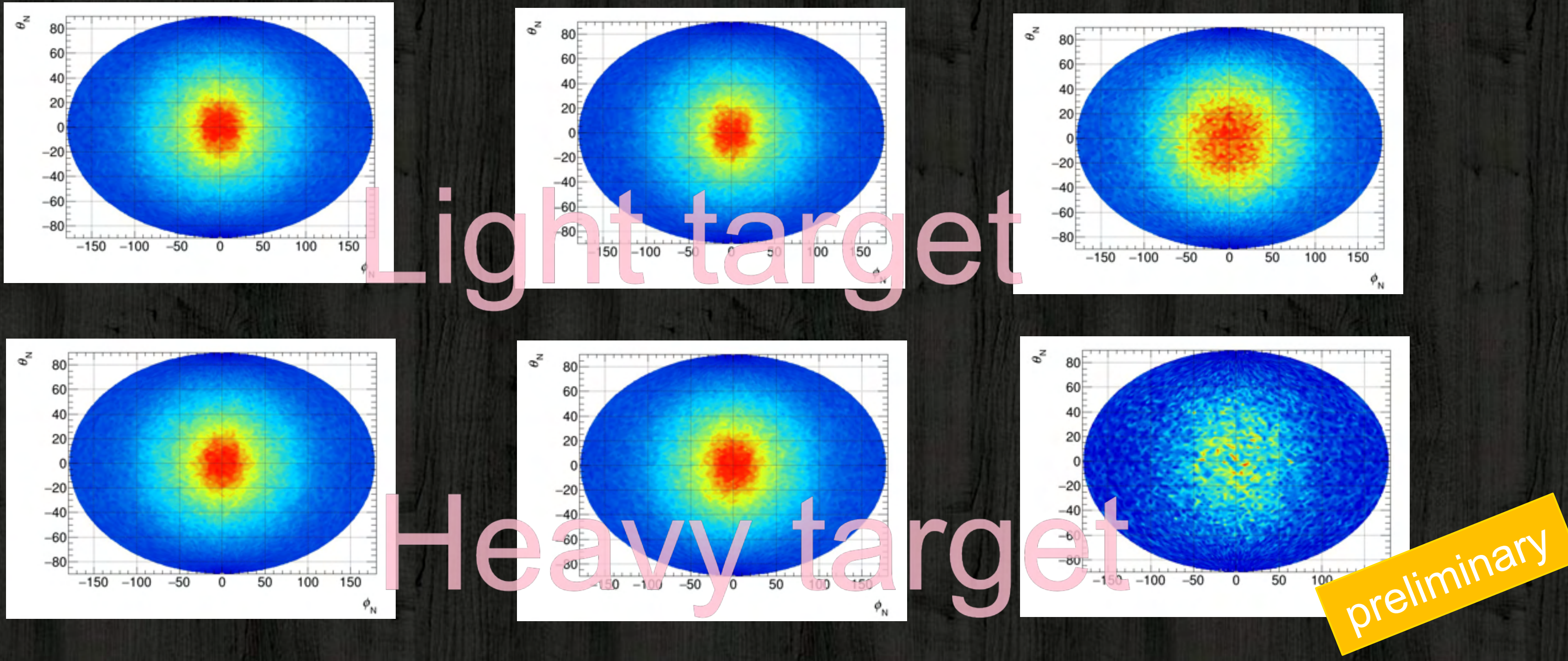
Target dependence of Nuclear Recoil

NFW

mχ=1GeV | mχ=0.01GeV | mχ=0.0001GeV

F

Ag



Summary and Outlook

- Celestial sphere maps for nuclear recoils caused by CR-DM are obtained. Nuclear recoils focus on the GC region and depend on DM profiles.
- I’ve discussed based on only CR-DM flux. How much events can we expect if we suppose the the CR-DM cross section, the energy threshold and the resolution of the detectors? Investigation of realistic detectability is future work…