Estimation of CALET's sensitivity for gamma-ray line emission
from dark matter annihilation with ROI optimization

暗黒物質対消滅由来のガンマ線に対する CALETの検出感度評価とROI最適化

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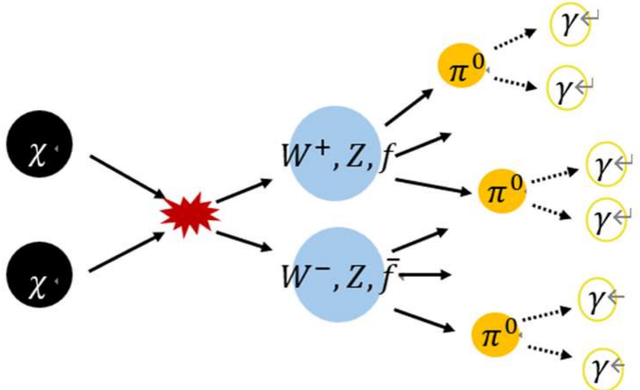
Background

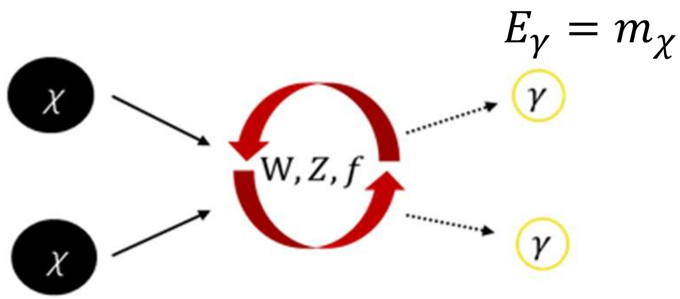
● Two representative gamma-ray signals from dark matter annihilation.

Tree-level annihilation



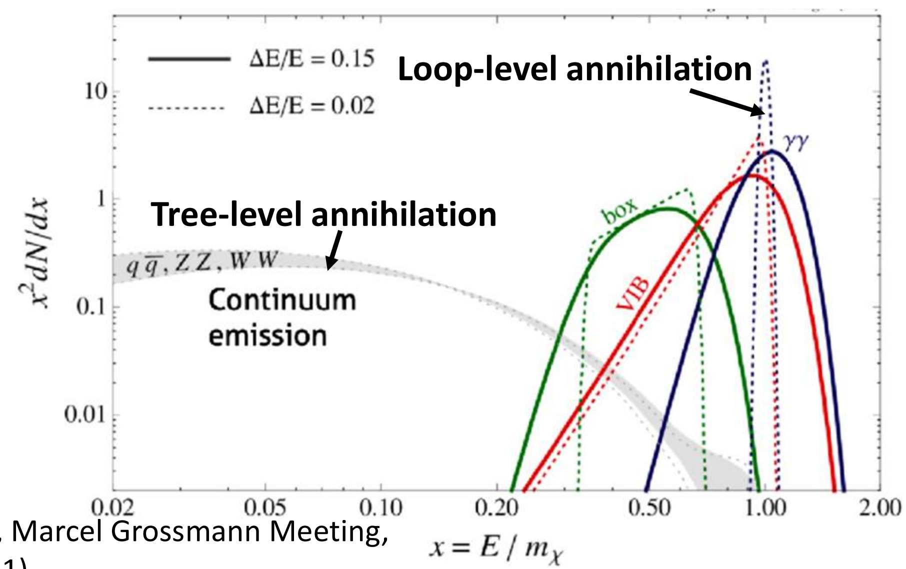
Produces a continuous gamma-ray spectrum.

Loop-level annihilation



Produces a monochromatic gamma-ray line.

A monochromatic gamma-ray line is easier to distinguish from the background.



Ricci et al, Marcel Grossmann Meeting, DM6 (2021).

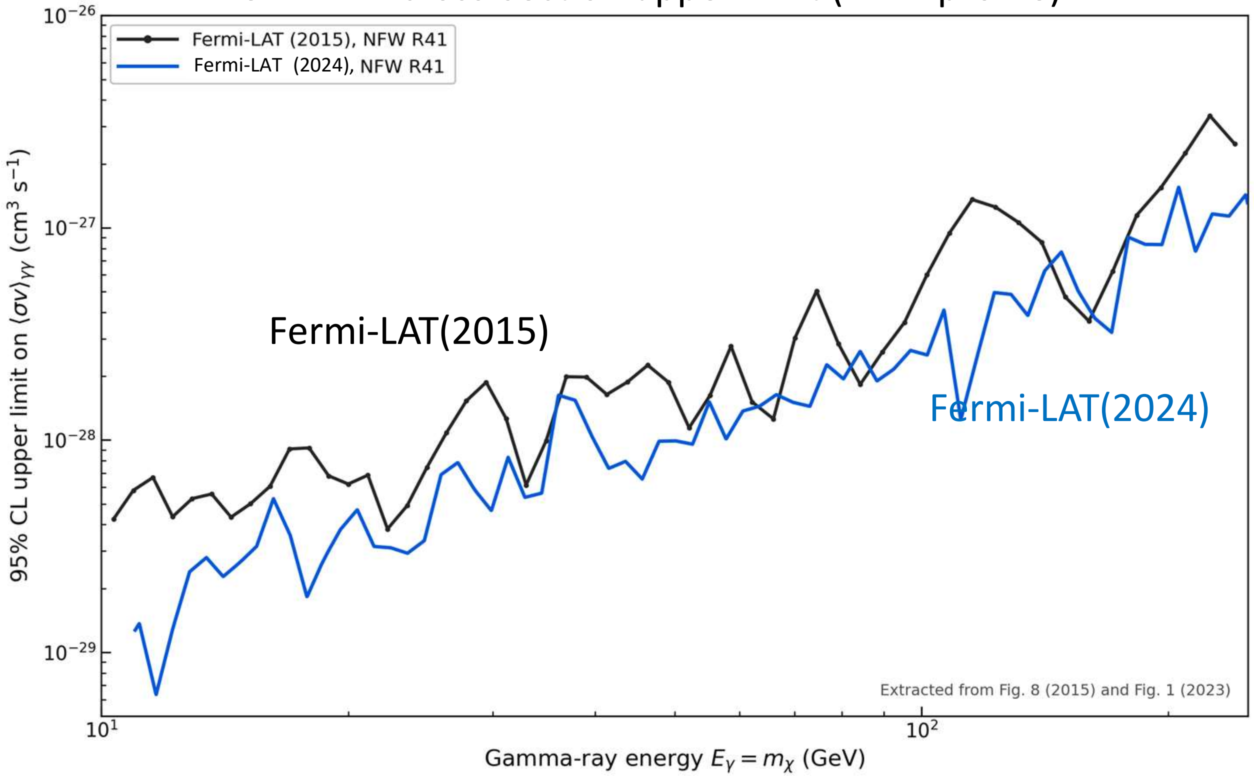
● Goal
- To evaluate CALET's sensitivity to monochromatic gamma-ray line from DM annihilation.
- Optimize the ROI(region of interest)
- for CALET's sensitivity

Previous Work: Fermi-LAT Gamma-Ray Line Searches

- No significant line-signal has benn not detected so far.

- Cross section upper limits $\langle \sigma v \rangle_{\gamma\gamma}$ are order of 10^{-29}- 10^{-2} $[\mathrm{cm}^3 \mathrm{s}^{-1}]$.

Fermi-LAT cross-section upper limit (NFW profile)



M. Ackermann et al. *Phy. Rev. D* **91**, 122002 (2015).

Luque et al., *Phys. Rev. D* **109**, L041301 (2024).

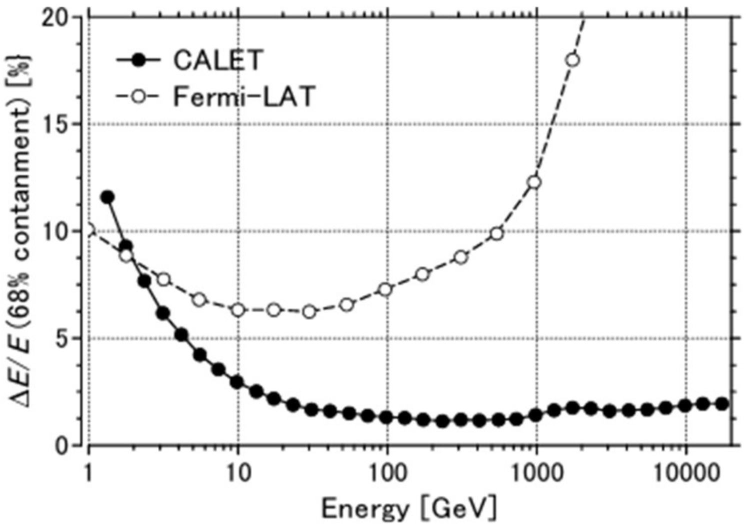
CALET's Energy Resolution and Effective Area

●Thick calorimeter: $30X_0$ compared to the Fermi-LAT calorimeter: 8.6 X_0

Atwood et al., ApJ 697, 1071 (2009)

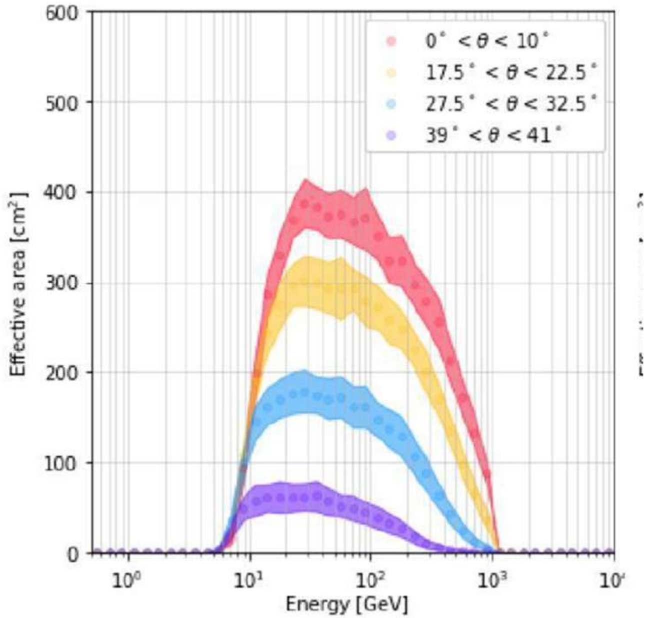
●CALET has good ～2% energy resolution at high energy

Energy resolution



Asaoka et al, Astropart. Phys. 91, 1 (2017)

Effective area for HE triggers



Mori et al, PoS(ICRC2023) 708 (2023)

Analysis Flow for Calculating the CALET's Sensitivity

● Prepare gamma-ray dataset (Fermi-LAT 17-year) ← Note that this sensitivity study doesn't use CALET flight data.

↓

● Caluculate flux spectrum for diffent ROIs by changing the radius from the Galactic Center.

↓

● Simulate expected CALET events using the CALET exposure and energy resolution based on the flux measured by Fermi-LAT.

↓

● Perform a likelihood analysis for a hypothetical line signal on the simulated CALET events for each ROI

↓

● optimize the ROI by selecting the one with the best limit for three halo models

↓

● Caluculate the expected cross-section upper limit for optimized ROI.

Evaluate sensitivity with this cross-section

Dataset

17 years (2008-2025) of Fermi-LAT gamma-ray event data(Pass 8 UltraClean class) were used.

● **Event selection**

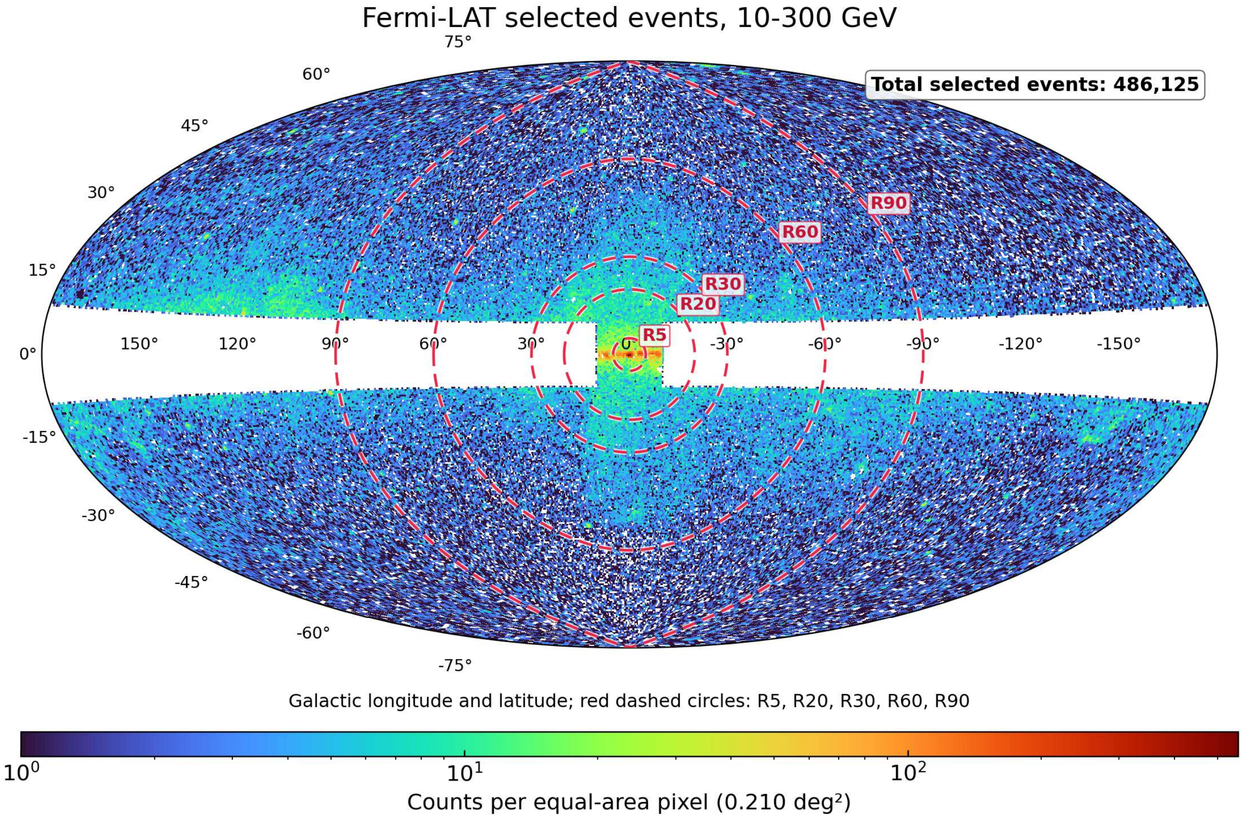
- Point-source masking(Fermi LAT catalog), a zenith-angle cut of < 105°, a rocking-angle cut of < 52°
- About 500,000 events were selected in the energy range from 10 to 300 GeV.

●ROI (Region Of Interest) cut

-The Galactic disk was excluded because the diffuse gamma-ray emission is strong there.

-The Galactic Center was included because the dark matter density is expected to be high.

-The ROI radius around the Galactic Center was varied from 3° to 180°.



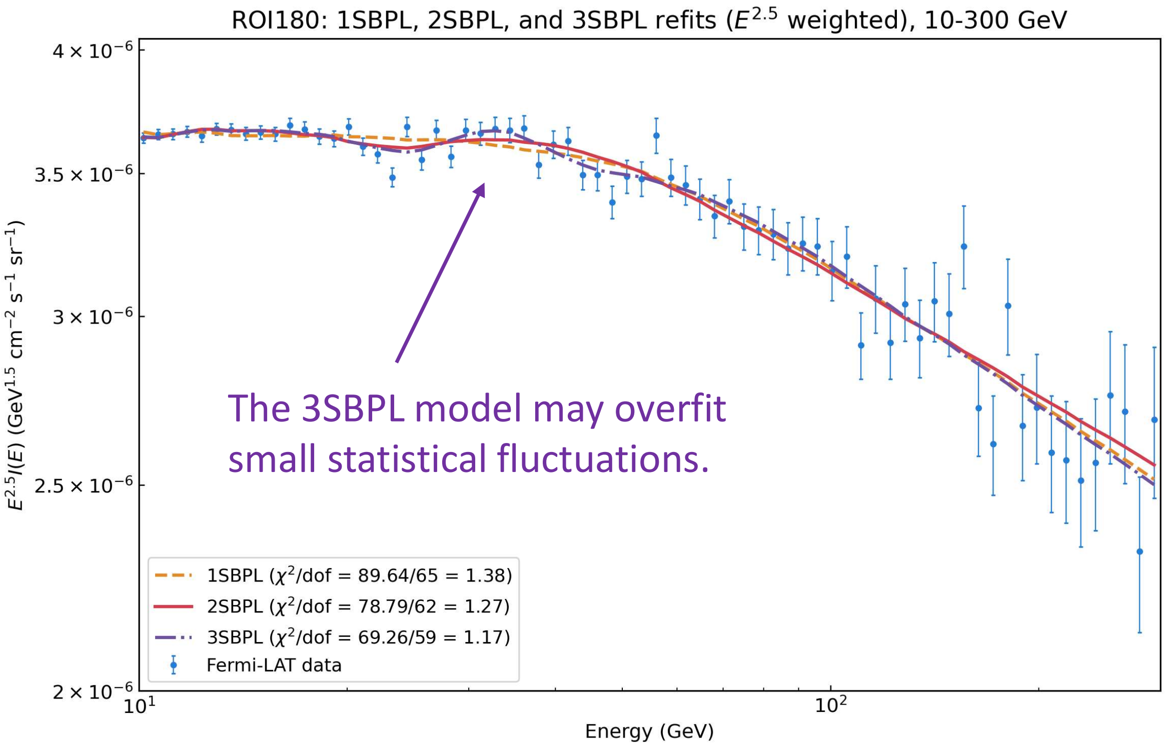
Fit Background models to Fermi-LAT events

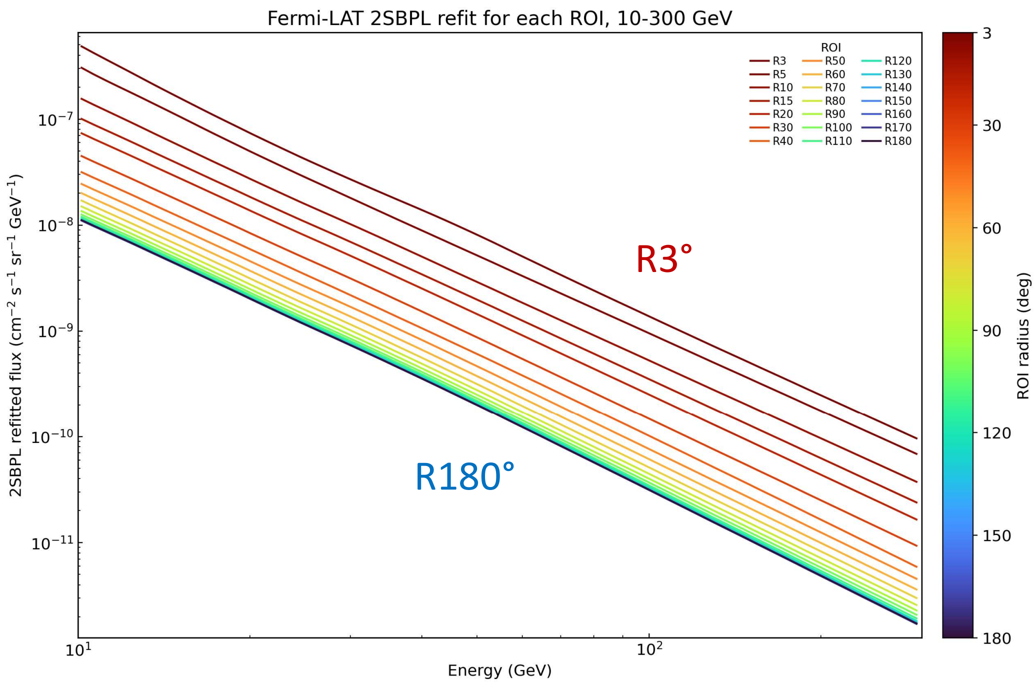
- Compare 3 types of background models, 1SBPL, 2SBPL, 3SBPL.

$$\phi_{\mathrm{nSBPL}}(E) = A(E/E_0)^{\gamma 0}\prod_{\mathrm{k=1}}^{\mathrm{n}}(1 + (\mathrm{E/E_{b,k}})^{\mathrm{s_k}})^{\Delta\gamma_{\mathrm{k}}/\mathrm{s_k}}$$

- Fit these models to Fermi-LAT gamma-ray data including the effect of energy resolution.

2SBPL model was chosen. → Fit 2SBPL model for each ROI 3°～180°





Simulation of CALET gamma-ray events

- Simulate CALET gamma-ray events from fitted Fermi-LAT flux (2SBPL)

One simulation

- Calculate the expected number of CALET gamma-ray events in each energy bin.

Expected number of events (μ_i) is flux × exposure × bin width

Fermi-LAT 2SBPL model flux

CALET exposure ($\mathrm{cm^2 s \cdot str}$)

(using CALET exposure between 10/2015 and 12/2022, multiplied by 2 to assume the CALET operation from 2015 to 2030)

- Sample the integer number of events in each bin (N_i) from a Poisson distribution:

$$N_i = \mathrm{Poisson}(\mu_i)$$

- Randomly assign an energy to each event from a uniform distribution.

Do this simulation 500 times to calculate upper limits.

Likelihood Analysis and Upper Limit Calculation

● **Likelihood fitting**

Fit the likelihood function to the simulated events and determine the best-fit parameter $(\hat{f}, \hat{\gamma})$ by maximize the likelihood.

$$\mathcal{L}(f, \gamma) = \prod_{i=1}^{N} f S(E_i) + (1-f) \mathrm{B}_{\mathrm{local}}(E_i, \gamma)$$

・ $S(E)$: gamma-ray signal model, Δ_{res}: Energy resolution

$\rightarrow \mathrm{S(E)} = \frac{1}{\sigma\sqrt{2\pi}} e^{-(E-E_j)^2/2\sigma^2}$ $\sigma = E_j \Delta_{res}(E_j)$

・ $\mathrm{B}_{\mathrm{local}}(\mathrm{E}, \gamma)$: background model in a search window

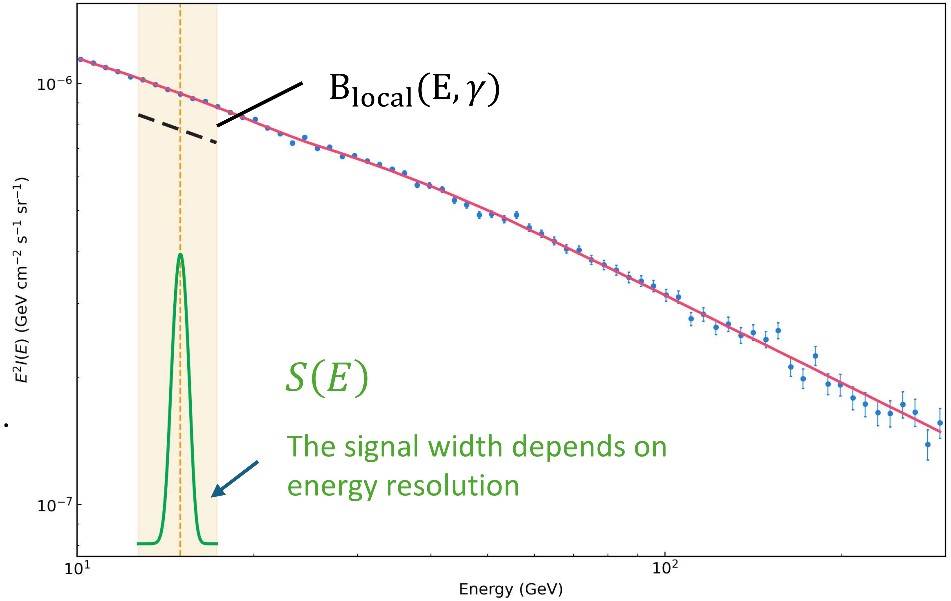
$\rightarrow \mathrm{B}(E, \gamma) \propto E^{-\gamma}$

● **Upper limit calculation**

Calculate the 95% one-sided CL upper limit is determined by

$$\Delta\log\mathcal{L} = \log\left[\frac{\mathcal{L}(f_{UL}, \gamma_{f_{UL}})}{\mathcal{L}(\hat{f}, \hat{\gamma})}\right] = -1.35$$

Ackermann et al, Phys. Rev. D 86, 022002 (2012).



● **Flux and cross-section upper limits**

Convert the signal-fraction upper limit f_{UL} into the flux upper limit and the annihilation cross-section upper limit.

$$\Phi_{UL} = \frac{N f_{UL}}{\varepsilon(\mathrm{E})}$$

$$\langle\sigma v\rangle_{\mathrm{UL}} = 5.99 \times 10^{-2} \cdot \frac{1}{2} \cdot \Phi_{UL} \cdot m_{\chi}{}^{2} \cdot \frac{1}{J_{ann}(\Delta\Omega)}$$

N: the number of events in a search window

$\varepsilon(\mathrm{E})$: CALET exposure

m_χ: dark matter mass

$J_{ann}(\Delta\Omega)$: J-factor describing dark matter density in the ROI

Line Search Window widths

- The search window size depends on the center energy E_j and energy resolution Δ_{res}.

$$E_{min,max} = E_j \pm nE_j\Delta_{res}$$

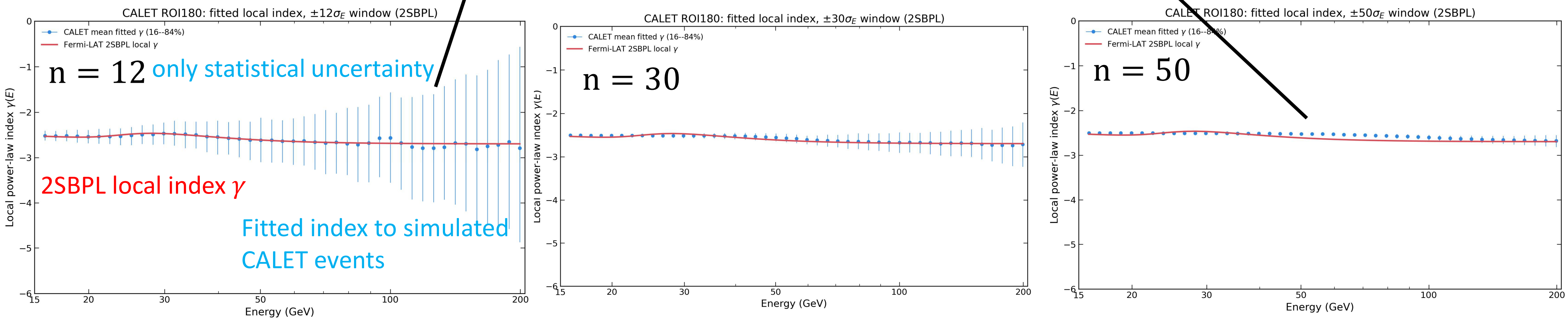
Window size parameter

- Chosen window widths

Below 100GeV: n =12   Above 100GeV: n =30

For smaller window, the statistical uncertainty becomes larger at high energy.

For wider window, the systematic difference between the fitted index of simulated CALET data and the index of the Fermi-LAT 2SBPL becomes larger.



ROI Optimization

● The cross-section upper limit was calculated for each ROI radius from 3° to 180° in the energy range of 15-200GeV.
→ Chose the best ROI that minimize the upper limit.

● The best ROI varies depending on energy.

NFW: R60°-R110° Einasto:R30°-R70° Isothermal:R90° - R110°

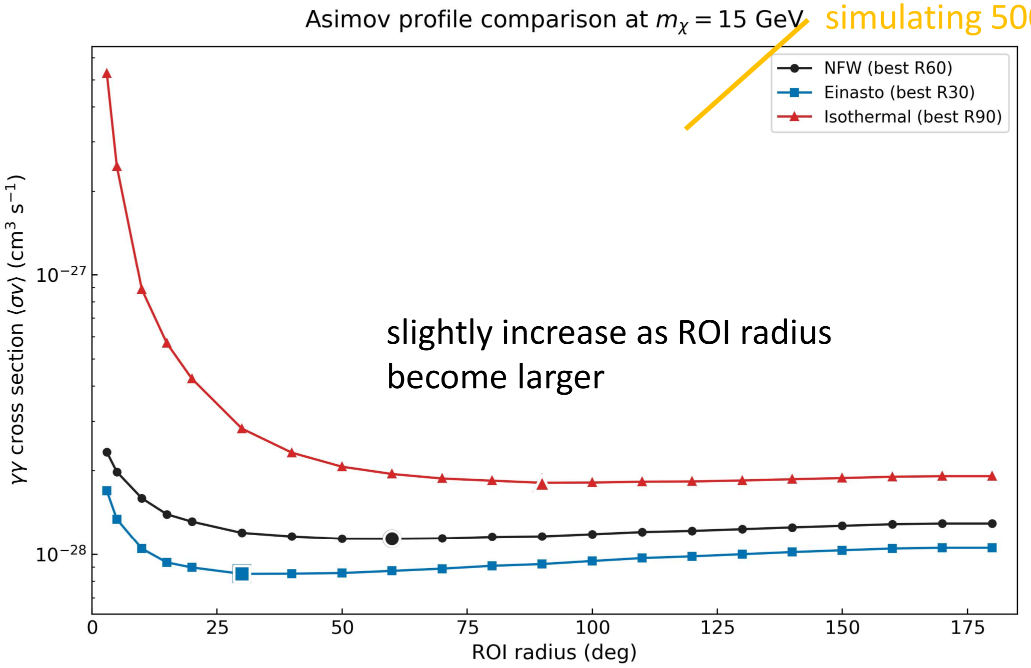
Dark matter density distribution
-->model dependent
- **NFW** Navarro et al, ApJ 490 493(1997)

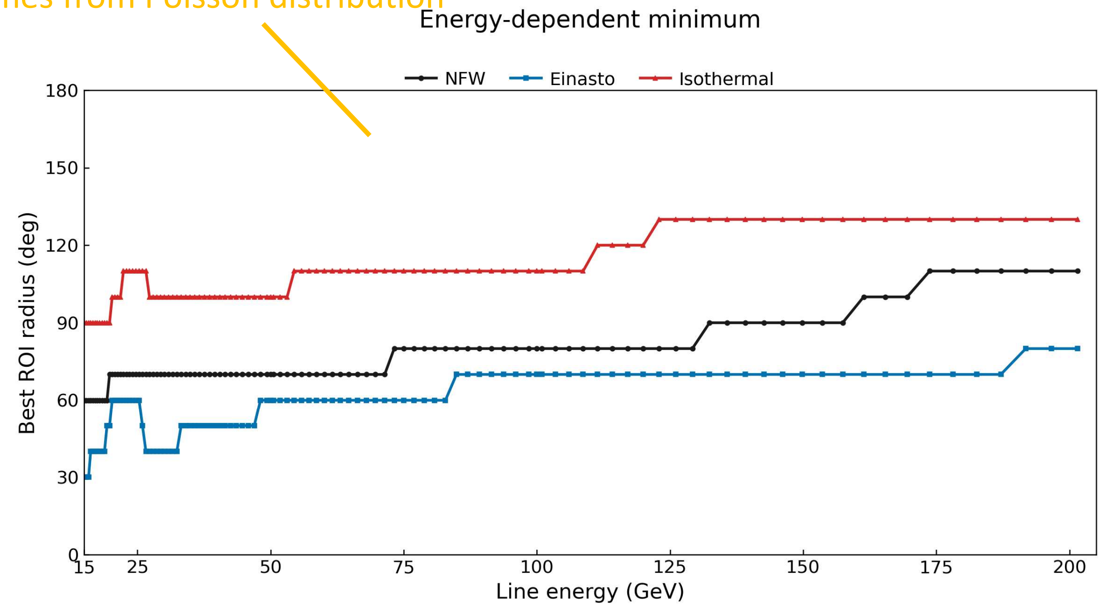
A profile with high density at the Galactic center.
- Einasto Einasto, Trudy Astrofiz. Inst. Alma-Ata 5, 87 (1965)

A smoother profile than NFW.
- ISO Bahcall & Soneira, ApJS 44, 73 (1980)

A profile with a flat central density.

For ROI optimization:
Use expected CALET events (Asimov) before simulating 500 times from Poisson distribution



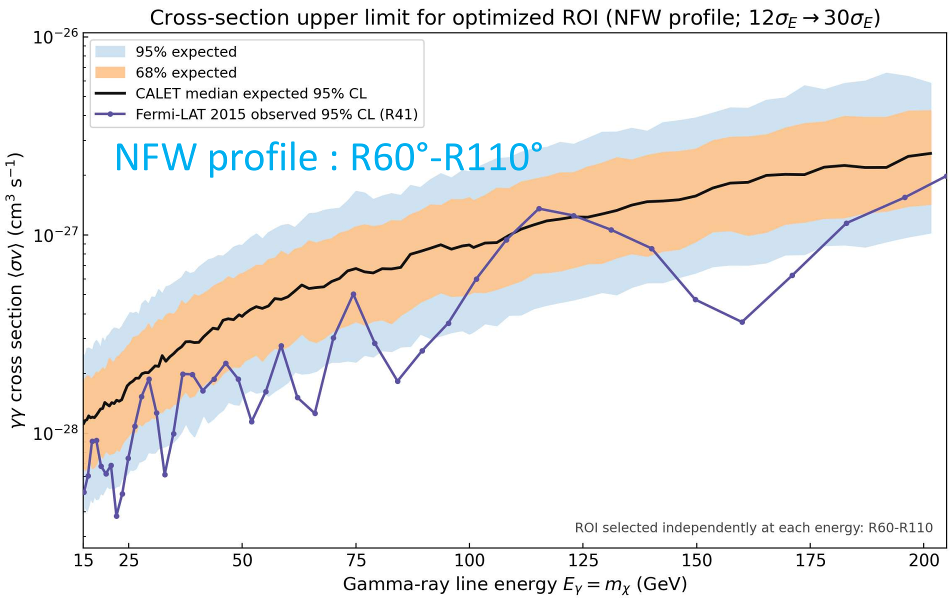


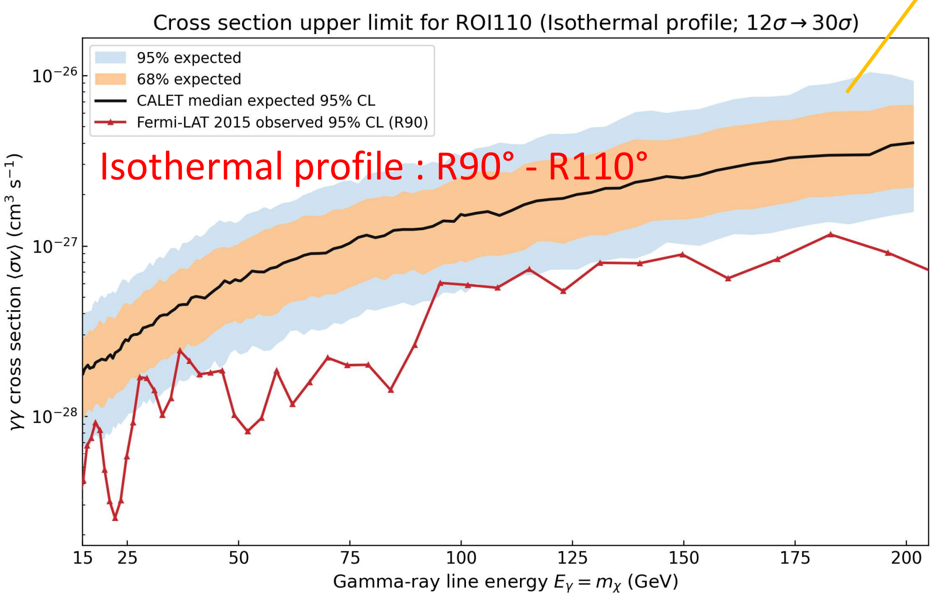
Results for optimized ROI

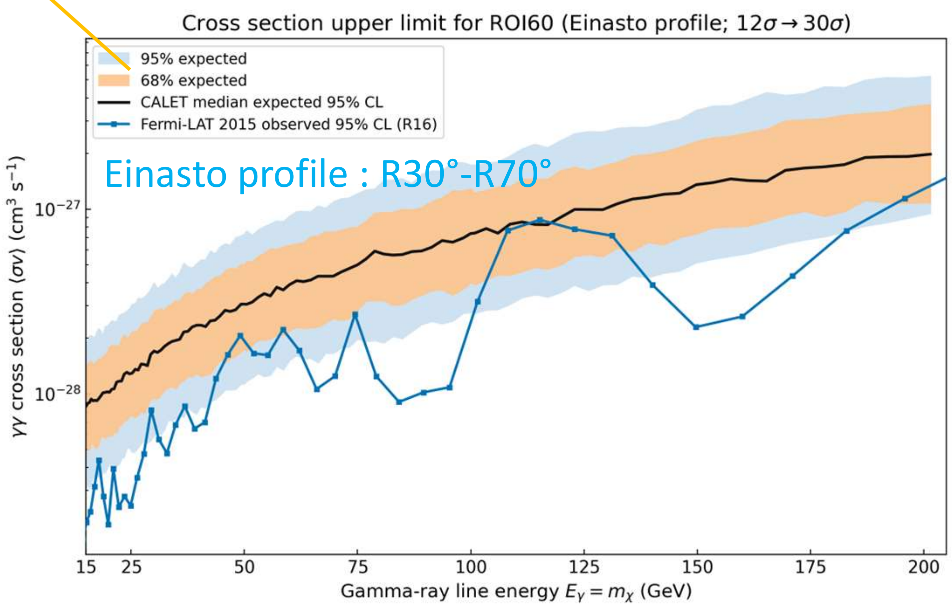
- The cross-section upper limit was calculated using the optimized ROI at each energy for each dark matter density profile.

- The CALET sensitivity reaches the order of 10^{-28}-10^{-2} $[\mathrm{cm^3 s^{-1}}]$.

Use 500 times simulated CALET even







Summary

● CALET gamma ray events were simulated using 17 years of Fermi-LAT gamma-ray data.

● The ROI dependence of the expected cross-section upper limit was evaluated.

NFW: R60°-R110° Einasto:R30°-R70° Isothermal:R90° - R110°

● Finally, the upper limit for optimized ROI was calculated in the energy range 15-200 GeV with 500 times trial.

The CALET sensitivity reaches the order of 10^{-28}-$10^{-27}[\mathrm{cm}^3\mathrm{s}^{-1}]$.

Future Work

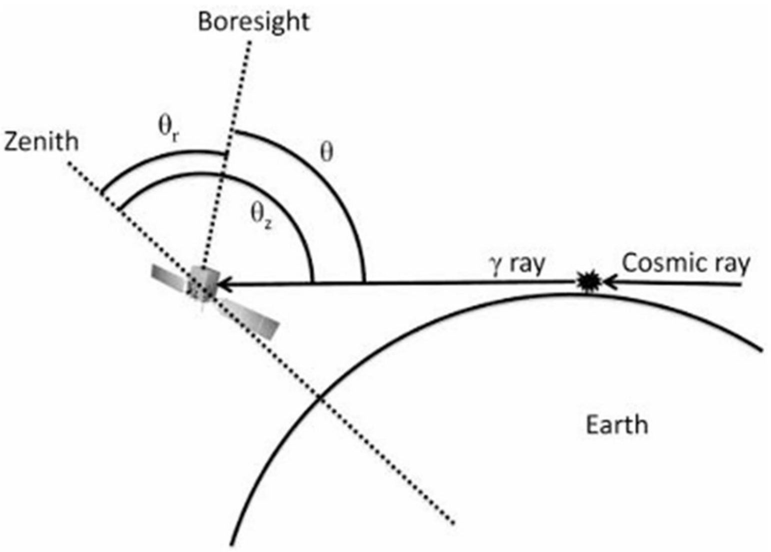
● Analyze wider energy range

Above 200 GeV, the number of events becomes too small to analyze using the current method. We need to another statistical method such as Feldman-Cousins method that is used for low number observations.

Thanks to CALET's good energy resolution the non-observance of events in a narrow energy range may yield a stronger limit than the spectral analysis used in this work.

Appendix

Event selection



Ackermann et al., Phys. Rev. D 88, 082002 (2013)

● **Zenith angle**: The angle between the zenith direction and the incoming gamma-ray direction.

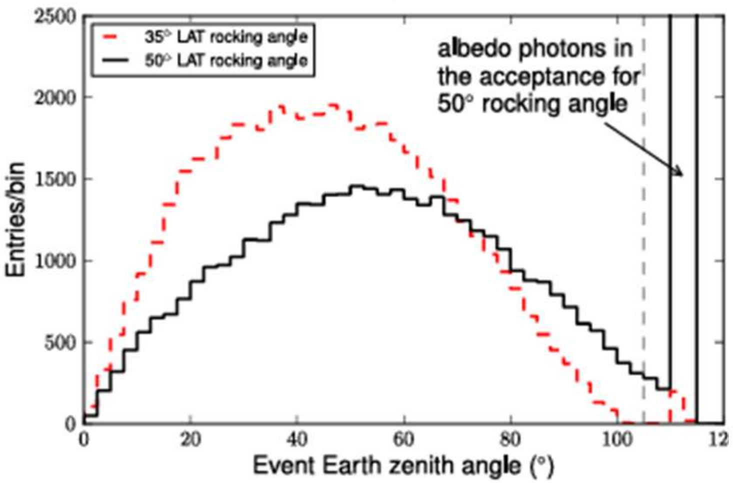
● **Rocking angle**: The angle between the zenith direction and the instrument's pointing direction.

●**Point-source mask** is angular-resolution-dependent circle.

$$\theta = \max(0.2°, 2 \times \langle\theta_{68}(\mathrm{E})\rangle)$$

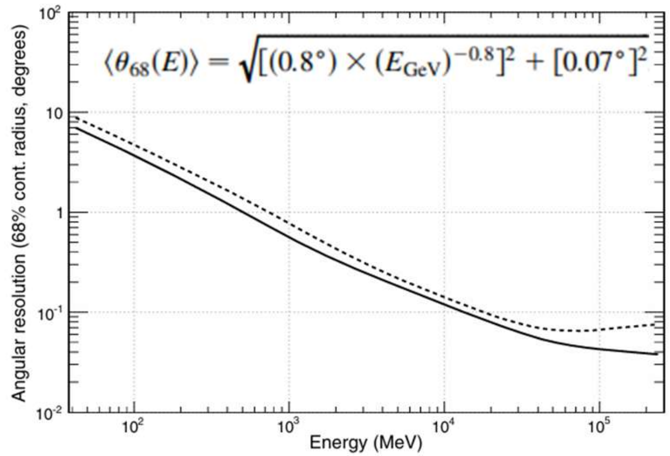
Point-source is based on Fermi-LAT 4FGL-DR4 catalog.

a zenith-angle cut of < 105°



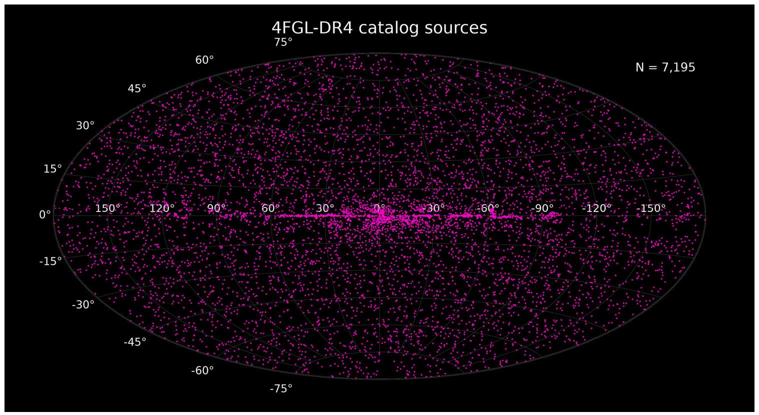
Edmonds, Ph.D. thesis, Stanford Univ. (2011)

Angular-resolution



W. Atwood et al, Astrophys. J. 697, 1071 (2009).

Point-source



Dark matter density profile

Consistent with N-body simulation.

NFW: proportional to r^{-1} near Galactic Center

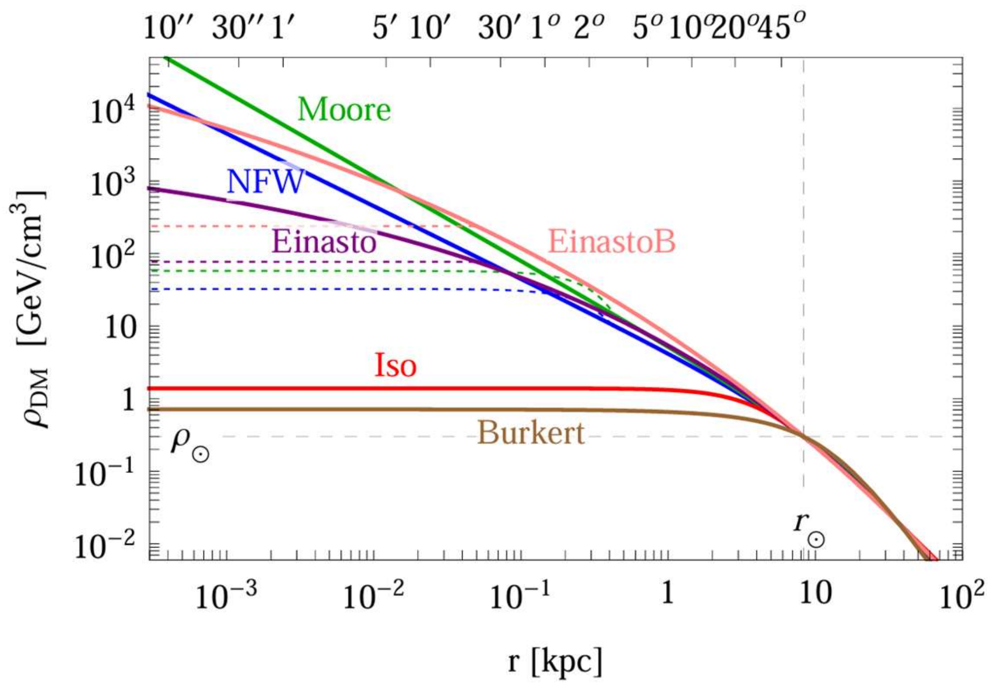
$$\rho_{\mathrm{NFW}}(\mathrm{r}) = \rho_s \frac{\mathrm{r_s}}{\mathrm{r}}\left(1 + \frac{\mathrm{r}}{\mathrm{r_s}}\right)^{-2}$$

Einasto: smoother than NFW

$$\rho_{\mathrm{Einasto}}(\mathrm{r}) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{\mathrm{r}}{\mathrm{r_s}}\right)^{\alpha} - 1\right]\right\}$$

Isothermal : motivated by the observation of galactic rotation curve

$$\rho_{\mathrm{Iso}}(\mathrm{r}) = \frac{\rho_s}{1 + (\mathrm{r}/\mathrm{r_s})^2}$$



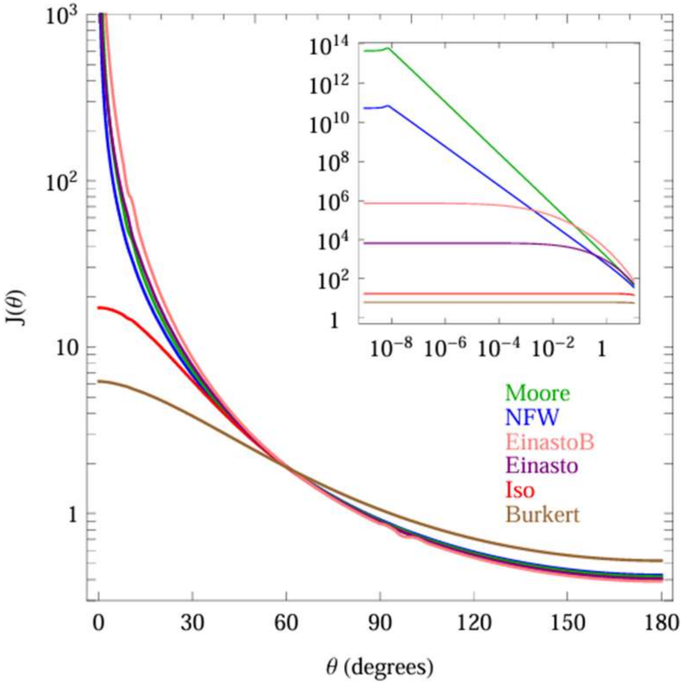
Cirelli et al., JCAP 03, 051 (2011)

J factor

The density on the line of sight from earth.
Dark matter annihilation need two particle.

-> ρ^2

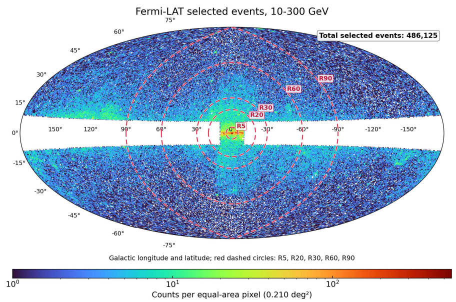
$$J(\theta) = \int_{\text{l.o.s}} \frac{ds}{r_\odot} \left(\frac{\rho(r(s,\theta))^2}{\rho_\odot}\right)$$

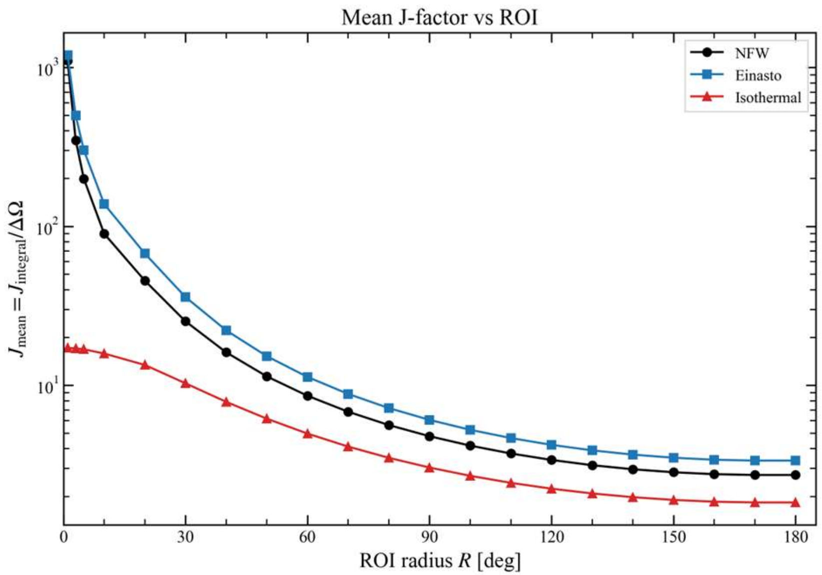


Cirelli et al., JCAP 03, 051 (2011)

The average of J-factor over ROI.

$$J_{mean} = \frac{4}{\Delta\Omega} \int \int_{\text{ROI}} dbd\ell \cos b J(\theta(b,\ell))$$





Energy-Resolution Correction

● Calculate the expected number of CALET gamma-ray events, considering the effect of energy resolution.
Expected number of events reconstructed by the detector is

$$\mu_{\mathrm{i}} = \sum_{\mathrm{j}} \phi_{2\mathrm{SBPL}}\,(\mathrm{E_j^{true}}) \cdot \varepsilon(\mathrm{E_j^{true}}) \cdot \mathrm{R_{ij}}(\mathrm{E_i^{rec}}|\mathrm{E_j^{true}})$$

i: reconstructed-energy bin
j: true-energy bin

Fermi-LAT 2SBPL model flux

CALET exposure ($\mathrm{cm^2 s \cdot str}$)
(assuming the CALET operation from 2015 to 2030)

The probability that the true energy $\mathrm{E_j^{true}}$ is recorded as $\mathrm{E_i^{rec}}$. (The probability depends on the energy resolution.)

$$\mathrm{D}(\mathrm{E^{rec}}|\mathrm{E_j^{true}}) = \frac{1}{\sqrt{2\pi}\sigma_{\mathrm{E}}(\mathrm{E_j^{true}})} \exp[-\frac{(\mathrm{E^{rec}} - \mathrm{E_j^{true}})^2}{2\sigma_{\mathrm{E}}^2(\mathrm{E_j^{true}})}]$$

$$\mathrm{R_{ij}}(\mathrm{E_i^{rec}}|\mathrm{E_j^{true}}) = \int_{\mathrm{E_{i,min}}}^{\mathrm{Ei,max}} \mathrm{D}(\mathrm{E^{rec}}|\mathrm{E_j^{true}})\mathrm{dE^{rec}}$$

Δ_{res}: Energy resolution

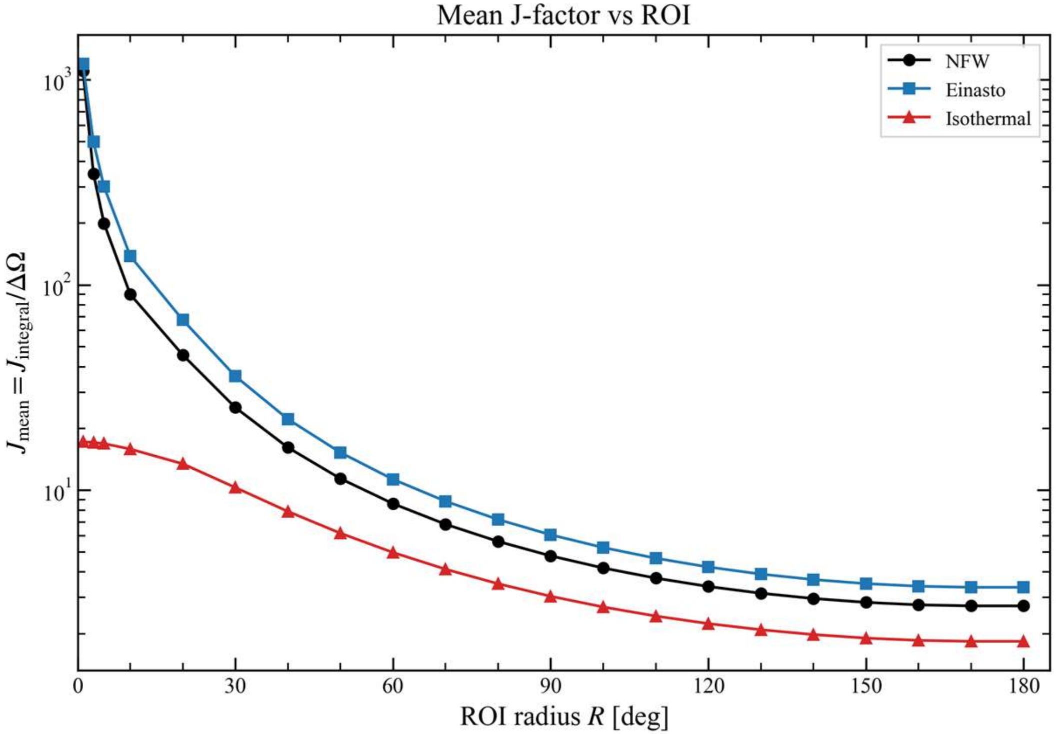
$$\sigma_{\mathrm{E}}(E_j) = E_j \Delta_{res}(E_j)$$

Why Does the Cross-Section Upper Limit Become Nearly Constant?

J-factor and the flux upper limit decrease at almost the same rate as the ROI radius increase.
These two effects cancel each other out in the equation below, making the cross-section upper nearly constant.

$$\langle \sigma v \rangle_{\mathrm{UL},j} \propto \Phi_{UL,j} \cdot {m_\chi}^2 \cdot \frac{1}{J_{ann}(\Delta\Omega)}$$

ROI averaged J-factor for each profile



Flux upper limit for each ROI at each energy