Gamma-Ray Probes of Dark Matter Halo Substructure

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Outline—Dark Matter Substructure

1. Probing dark matter halo substructures?

   Indirect Detection!

2. Intensity Spectrum Probes

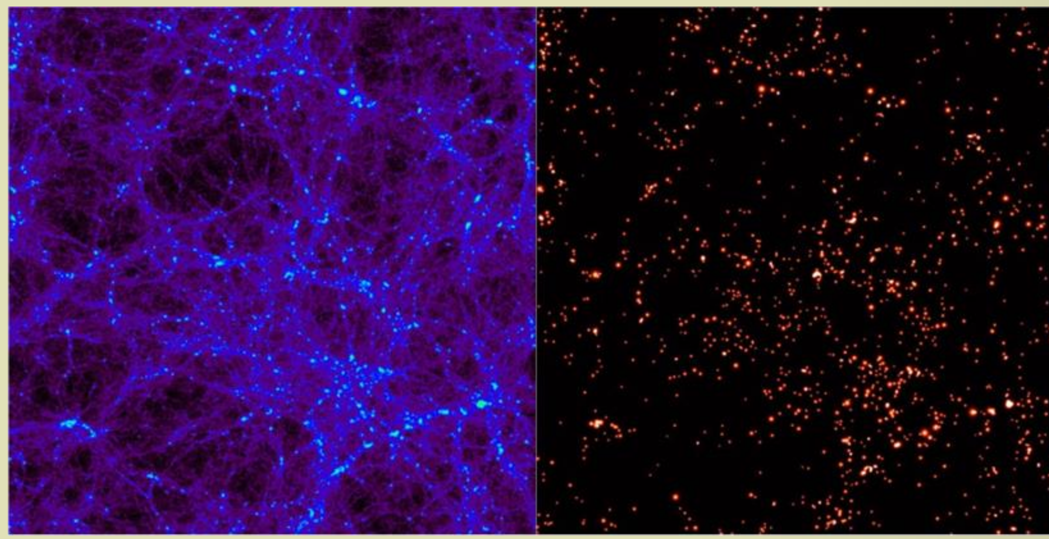
3. Anisotropy Spectrum Probes

Using results from several works in preparation with:
Bhaskar Dutta, Carsten Rott, John Beacom, Shunsaku Horiuchi, Kohta Murase, Basudep Dasgupta, Ranjan Laha, Kenny Ng.

Dark Matter Structure: Halos and Substructure

Accurate description of densest regions to explain indirect detection signals.

Image Credit: Via Lactea Project



Distribution from simulation.	Associated disjoint, spherical halo distribution.

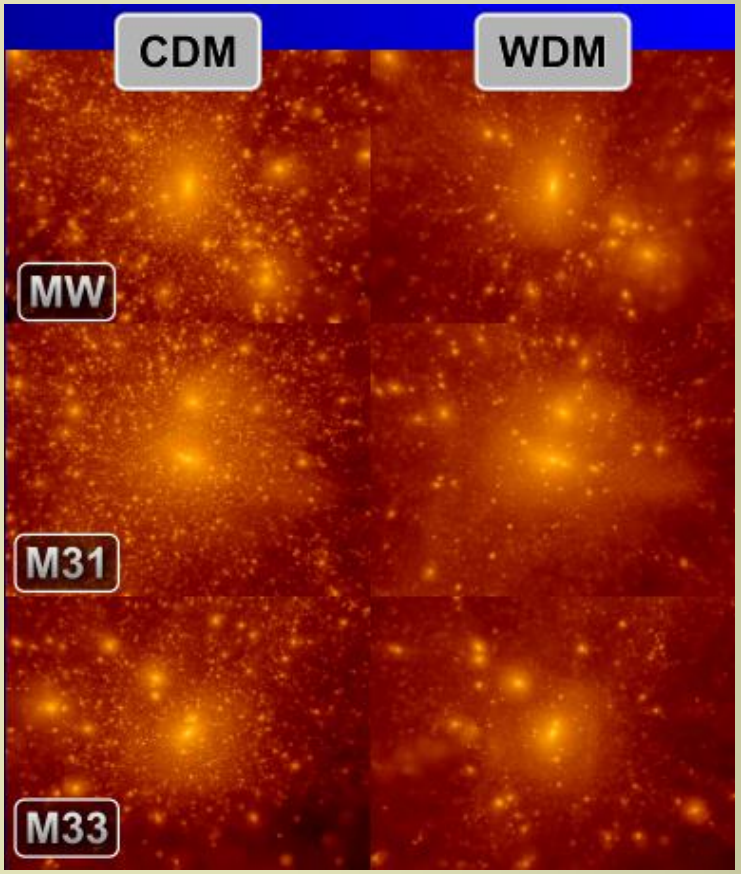
Image Credit: VIRGO Consortium/Alexandre Amblard/ESA

Beyond CDM?

- CDM + Baryons
- Multicomponent Dark Matter
- Warm Dark Matter
- Dark Matter Self-interactions
- …

Currently a hot topic at dwarf scales.

Big consequences for small scale structure.



http://www.clues-project.org/images/darkmatter.html
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Can observations constrain small scale structure?

Radiation?

- Star formation is inefficient in halos smaller than dwarf scales.
- Small substructures < $10^8\ M_\odot$ are too dark to observe.

Gravitational Lensing?

- Flux ratio anomalies of 4-image lenses.
- Seeing substructure down to $10^5 – 10^6\ M_\odot$?

Astrometric Microlensing?

- May see substructures down to $10^4\ M_\odot$ if they are very concentrated.

Perhaps indirect detection is the only "direct" way to probe very small scale structure…

Small-Scale Structures in Indirect Detection

- Extragalactic Diffuse Gamma Rays
- Nearby Galaxy Cluster Halos
- Galactic Halo Substructures

Scenarios:

1. Substructures are responsible for observation of dark matter annihilation.
2. Dark matter annihilation is seen in a region with negligible substructure (such as galactic center), but not in other regions.

Example 1: Substructure Impacting Discovery

Could substructure cause the Fornax Cluster to be brighter in annihilations than the galactic center?

Consider three recently published models of substructure:

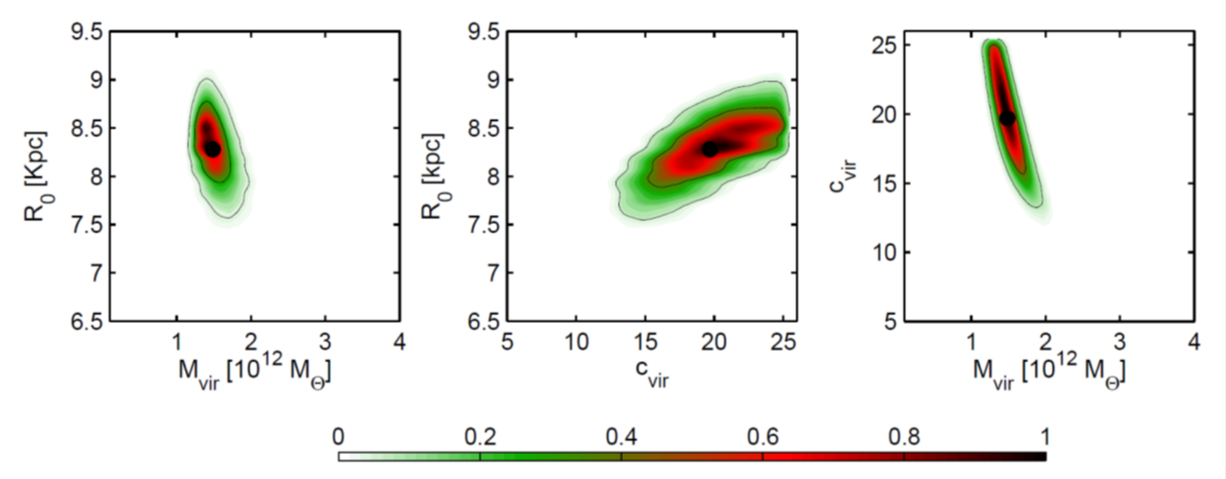
1) Gao et al. (2012), **G12**:
   - Based on the Phoenix and Aquarius simulations.
   - A fitting formula for the angular surface intensity of substructure.

2) Kamionkowski, Koushiappas, Kuhlen (2010), **K10**:
   - Density Probability Distribution Function profile.
   - Fit to the Via Lactea II simulation.
   - Suggested scaling for galaxy clusters by Sánchez-Conde et al. (2011).

3) Pinzke, Pfrommer, Bergstrom (2011), **P11**:
   - Used the Aquarius simulations and scaled up to cluster sized halos.
   - Found a double-power law fit the primary substructure intensity profile.
   - Scaled down to $M_{\rm min} = 10^{-6}\ M_\odot$. I also try $\boldsymbol{M_{min} = 10^{-12}\ M_\odot}$.

Galactic Halo Constraints from Kinematical Tracers

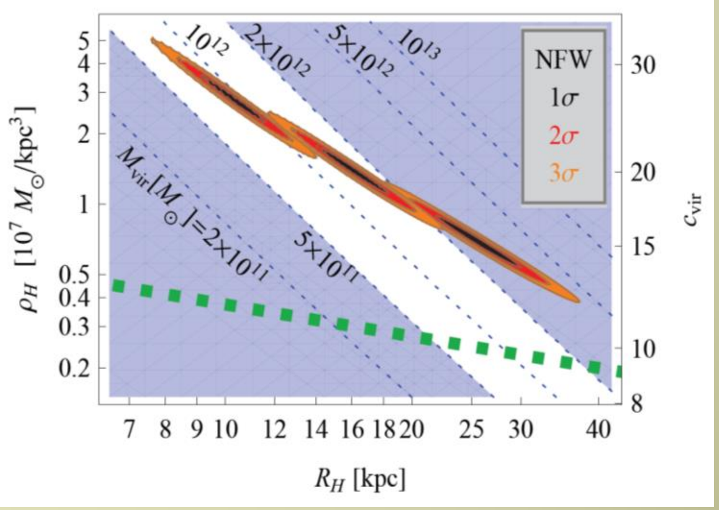
Catena, Ullio, JCAP 1008 (2010) 004



NFW profile

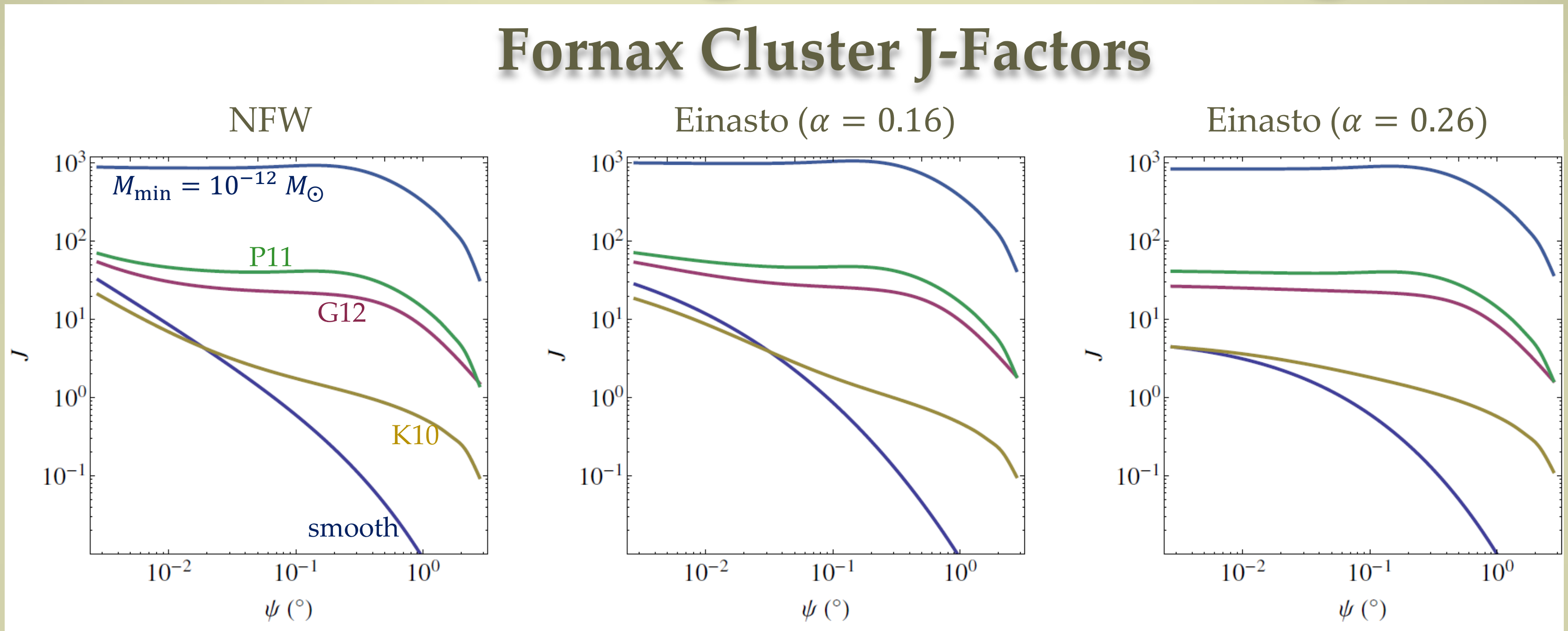
$$\rho(r) = \frac{\rho_s}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2}$$

Nesti, Salucci, arXiv:1304.5127

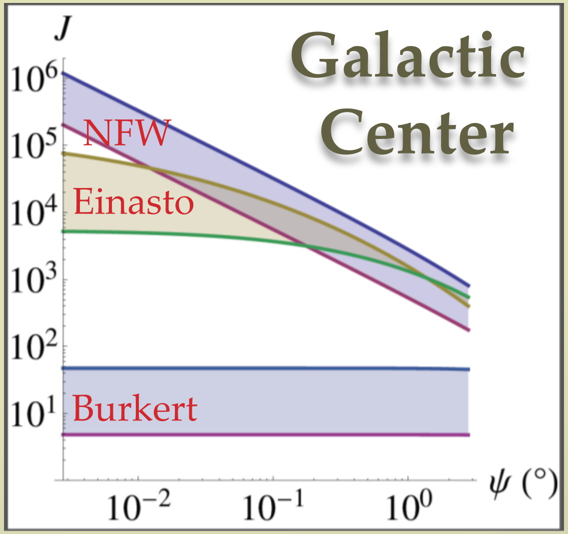


- The solar system velocity strongly constrains the value of $\rho_s r_s^2$.
- The J-factor goes roughly as $\rho_s^2 r_s$.

Potential Signal Strengths



A cored galactic halo profile may be dimmer than a Fornax cluster with a lot of substructure.



ψ is the observation angle from the center of the halo.

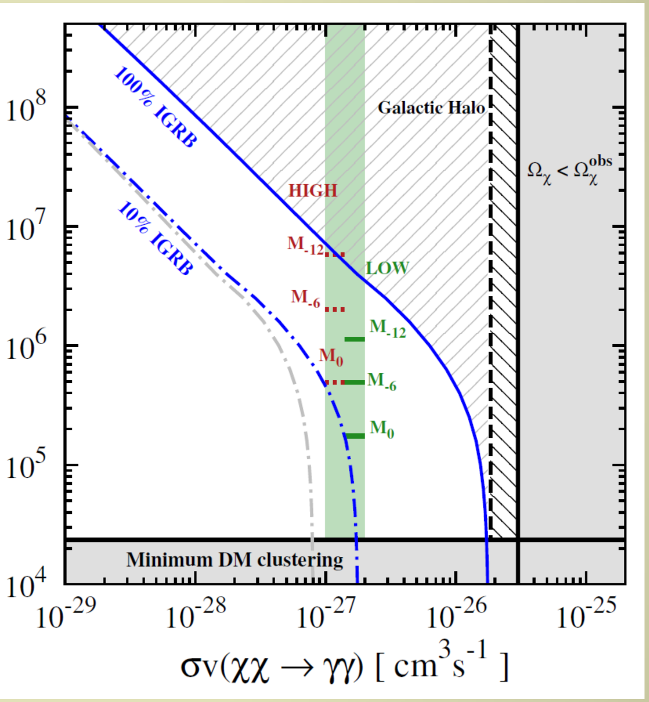
Example 2: Discovery Constraining Substructure

What if annihilations are observed in the galactic center, but not elsewhere?

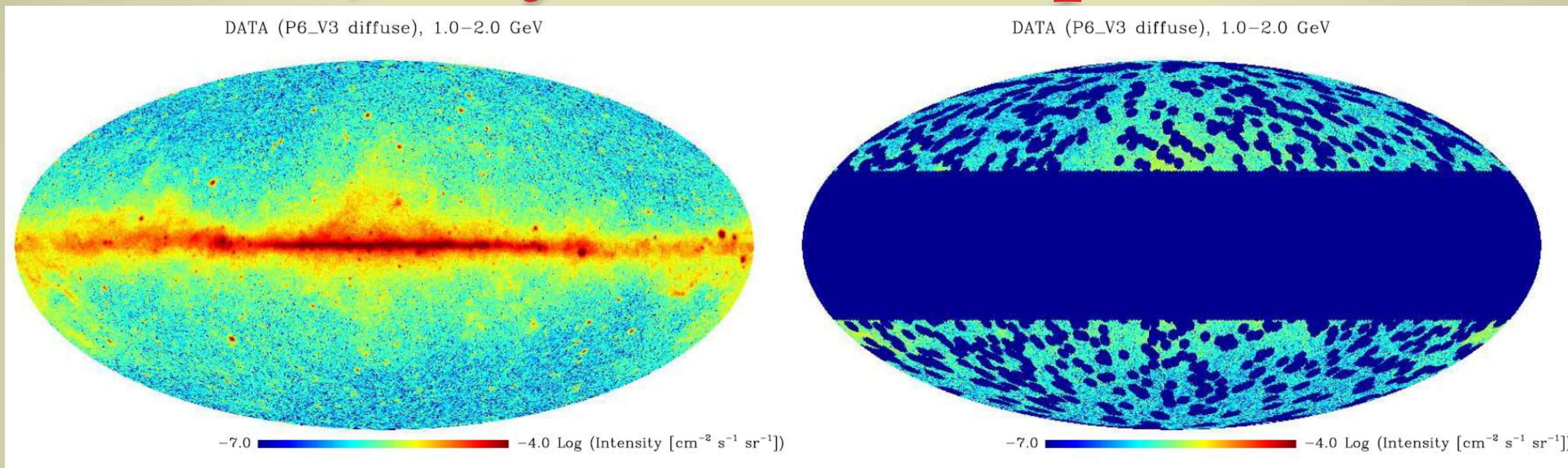
Kenny Ng (previous talk) just gave us examples of this.

Cross sections probed in galactic center would constrain substructure in extragalactic and galactic halos.

$$\frac{\langle \rho^2(z=0, M_{\min})\rangle}{\bar{\rho}^2}$$



Complementary Approach—γ-ray Anisotropies



Angular Power Spectrum C_ℓ

$$I(E,\boldsymbol{n}) - \langle I(E)\rangle = \sum_{\ell,m} a_{\ell m}(E) Y_m^\ell(\boldsymbol{n}) \qquad C_\ell(E) = \frac{1}{2\ell+1}\sum_m |a_{\ell m}(E)|^2$$

***Fluctuation* Angular Power Spectrum** $\widetilde{C_\ell}$

$$I(E,\boldsymbol{n}) - \langle I(E)\rangle = \langle I(E)\rangle \sum_{\ell,m} \tilde{a}_{\ell m}(E) Y_m^\ell(\boldsymbol{n}) \qquad \widetilde{C_\ell}(E) = \frac{1}{2\ell+1}\sum_m |\tilde{a}_{\ell m}(E)|^2$$

A few important details…

- **Anisotropies of a purely isotropic distribution is just shot noise.**

$$\widetilde{C_N} \simeq \frac{4\pi f_{\text{sky}}}{N_\gamma}$$

- **Angular power from multiple γ-ray emitting populations.**

$$C = C_1 + C_2 + \cdots$$

$$\tilde{C} = \left(\frac{I_1}{I}\right)^2 \widetilde{C_1} + \left(\frac{I_2}{I}\right)^2 \widetilde{C_2} + \cdots$$

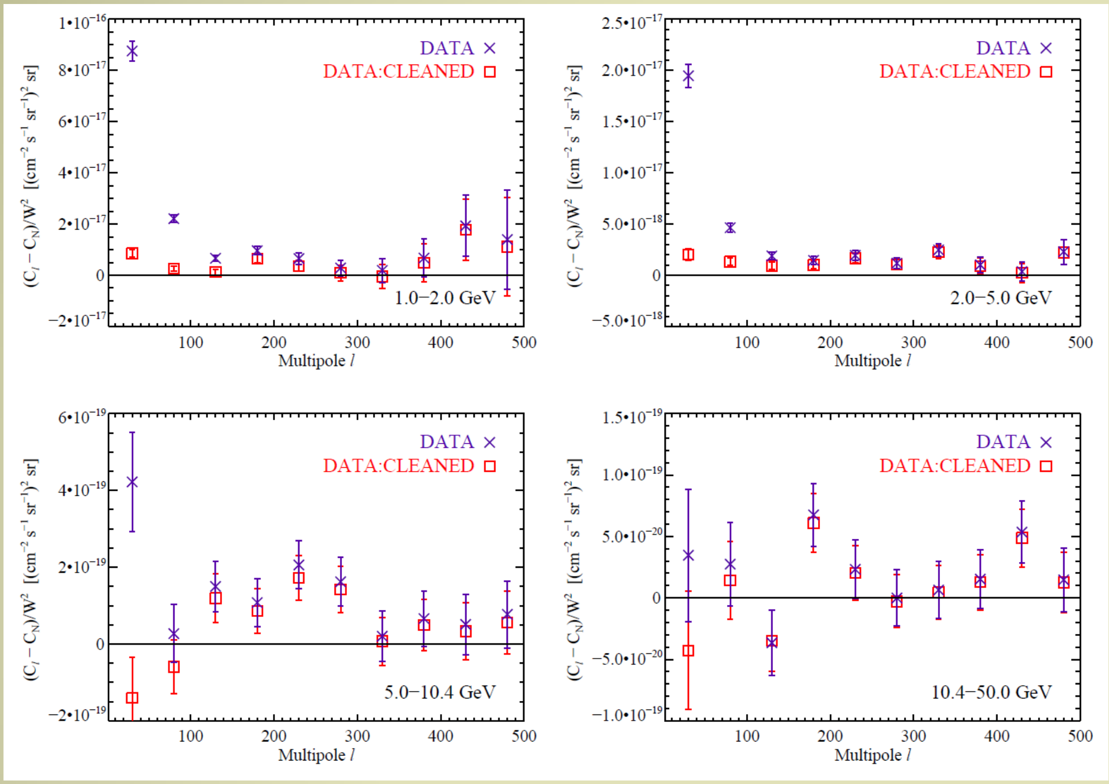
- **Statistical Error for weighted average over** $\ell_1 \leq \ell \leq \ell_2$.

$$\sigma_{\tilde{C}} \simeq \begin{cases} \dfrac{8\pi\sqrt{f_{\text{sky}}}\sigma_b e^{\sigma_b^2 \ell_1^2}}{N_\gamma}, N_\gamma \text{ small} \\ \\ \tilde{C}\sqrt{\dfrac{2}{f_{\text{sky}}(\ell_2^2 - \ell_1^2)}}, N_\gamma \text{ large} \end{cases}$$

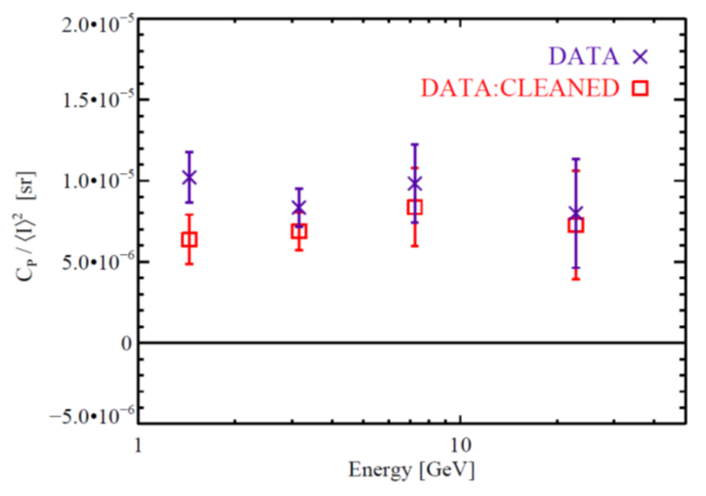
f_{sky} = fraction of sky unmasked.

σ_b = angular beam width.

Fermi-LAT Measurements



Fermi-LAT Collaboration, PRD85 (2012) 083007

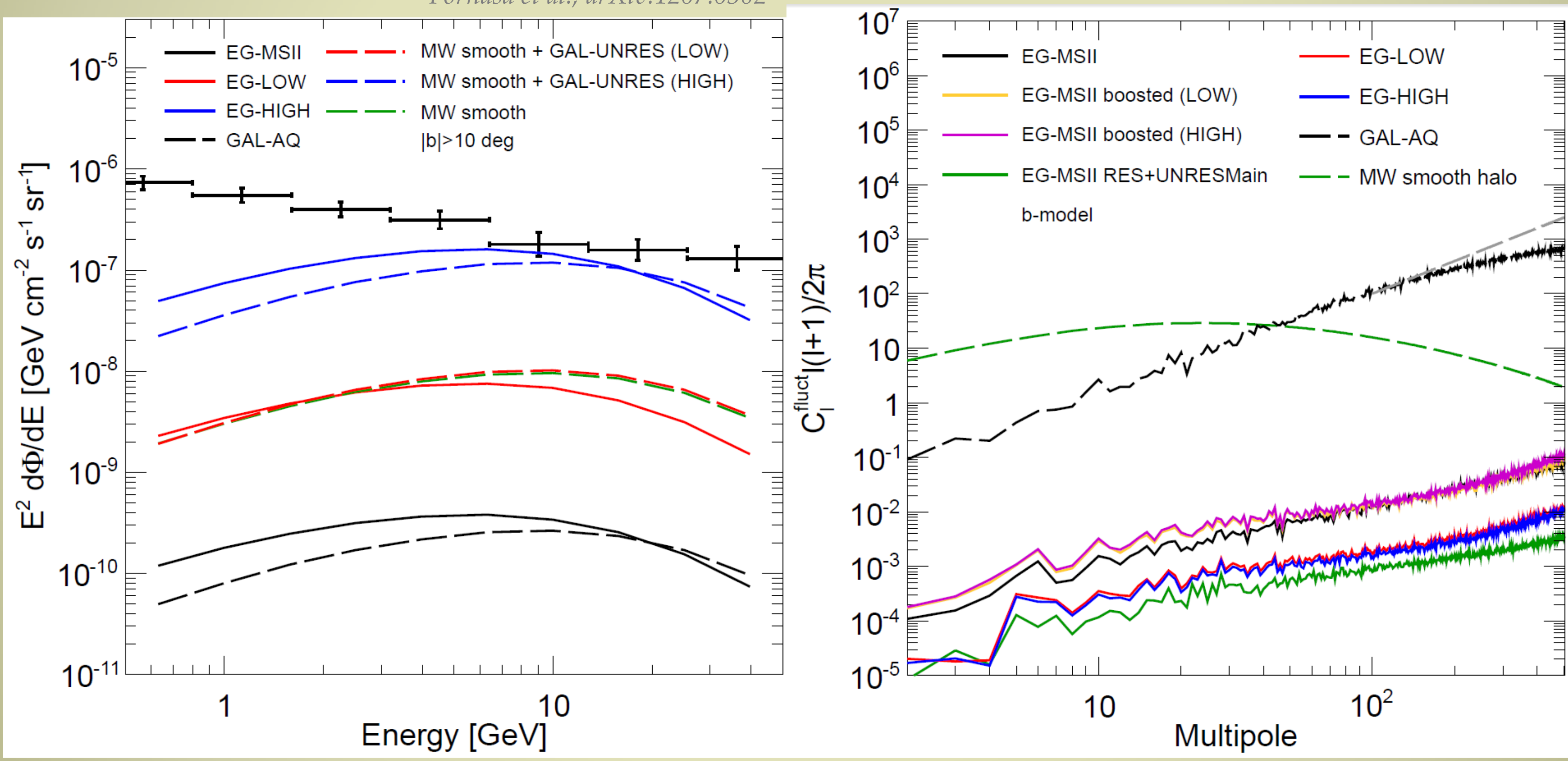


- Weighted average in each energy bin shows significant power consistent with no energy modulation.

- 4 energy bins
- Cleaned data = galactic foreground subtraction.
- Foreground contamination minimal for $\ell \geq 155$.

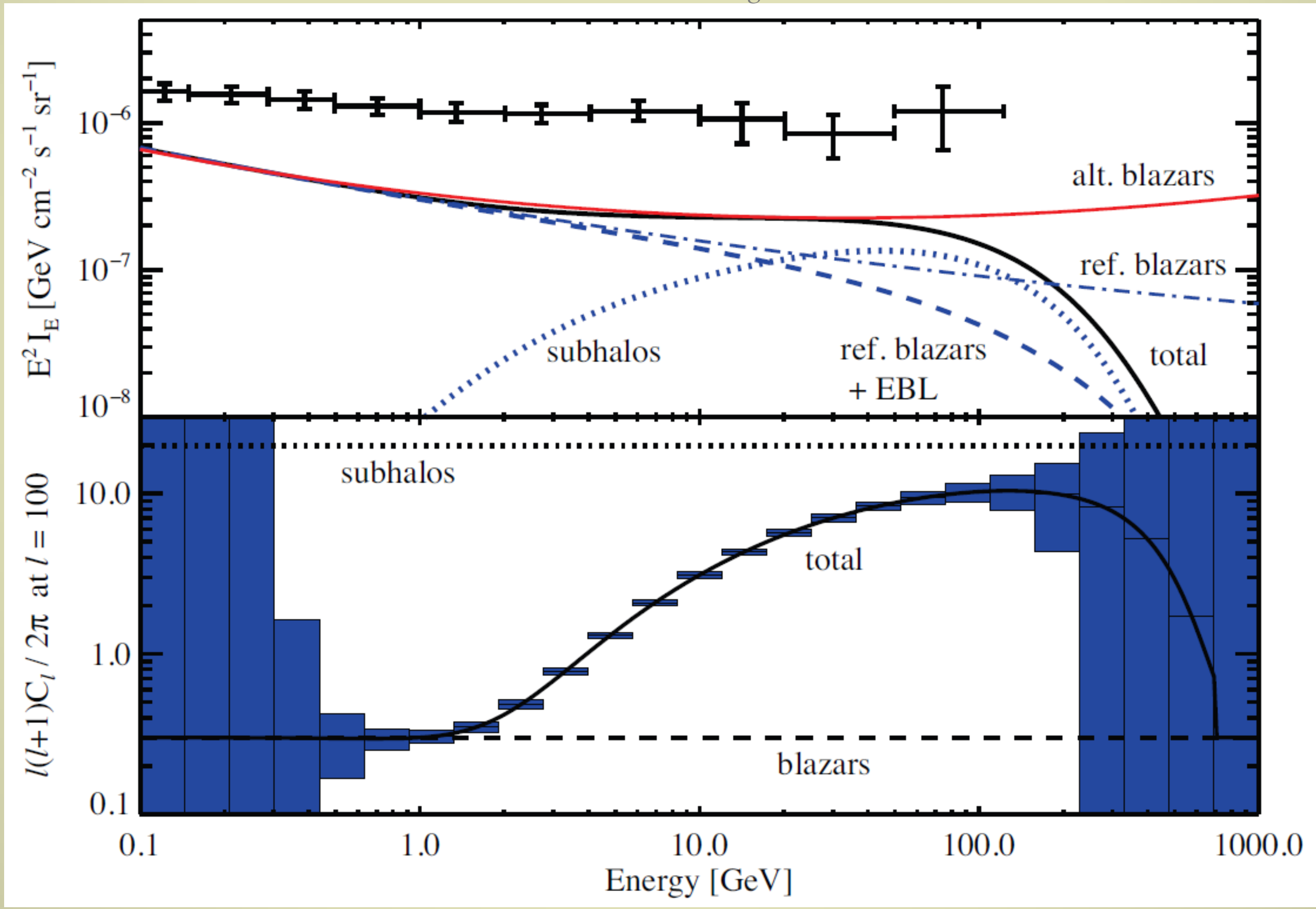
Fluctuation Angular Power Spectra from DM

Fornasa et al., arXiv:1207.0502



Anisotropy with Continuous Annihilation Spectra

Siegal-Gaskins, Pavlidou, PRL 102 (2009) 241301



Sensitivity to a Spectral Line

- **Intensity**

  Absence of a signal constrains $\frac{\Phi_{\rm DM}}{\Phi} < \frac{1}{\sigma_N} = \frac{1}{\sqrt{N_\gamma}}$.

- **Angular Power**

  Absence of power constrains $\frac{\Phi_{\rm sub}}{\Phi} < \sqrt{\frac{\sigma_{\tilde{C}}}{\tilde{C}_{\rm sub}}}$ which also initially goes like $N_\gamma^{-1/2}$.

  This is an independent probe of galactic substructure!

  Angular power is more sensitive to a spectral line if $\frac{\Phi_{\rm sub}}{\Phi_{\rm DM}} > \sqrt{\frac{N_\gamma \sigma_{\tilde{C}}}{\tilde{C}_{\rm sub}}}$.

The angular power spectrum presents a new paradigm for spectral line searches.

Conclusions

- The substructure content of dark matter halos is an active research topic in the literature.
  - Sensitive to particle dark matter properties and galaxy formation processes.
- Ironically, indirect detection may be the most direct probe of substructure.
- Constraints on substructure requires discovery of annihilation radiation, and depends on the mode of discovery.
- Intensity spectra provide information on the dark matter clumping factors.
- Anisotropy spectra provide independent information on galactic substructure.