Title: Probing the Small Scale Structure of Dark Matter with Indirect Detection

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Abstract: Direct observation of the small scale structure of matter in the Universe provides potentially important information about a wealth of physics, from complex galaxy evolution processes to fundamental particle properties of dark matter. Detecting this fine structure in dark matter, though, is notoriously difficult. Dark matter indirect detection--through observation of radiation products of particle annihilation--may be the most direct method for observing small scale structure. However, in an observed signal, the amount of dark matter clustering is degenerate with the annihilation cross section. This talk outlines ways this degeneracy may be broken with indirect detection alone. Scenarios are discussed where either abundant substructure leads to discovery of annihilation radiation (revealing properties of the substructure), or a discovery strongly constrains the presence of significant dark matter halo substructure.

Probing the Small Scale Structure of Dark Matter with Indirect Detection

Sheldon Campbell

February 25, 2014

Perimeter Institute for Theoretical Physics Seminar

Outline—Dark Matter Halo Substructure

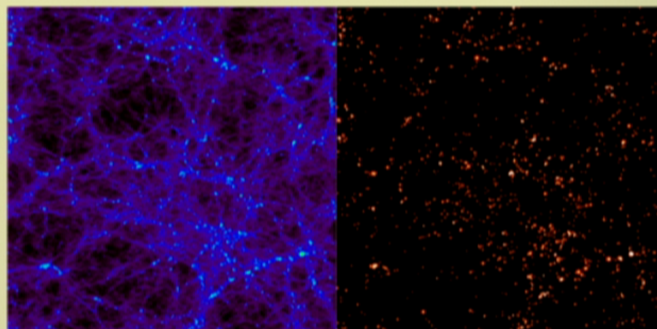
1. **Dark Matter structures as halos and substructures.**
   - What physics determines the halo substructure population?
2. **Probing halo substructures? Indirect Detection!**
3. **Intensity Spectrum Probes**
   - Nearby Galaxy Clusters
   - Diffuse Extragalactic Gamma-Rays
   - Unassociated Point Sources
4. **Anisotropy Spectrum Probes**
   - Galactic Halo Anisotropy
   - Small Angle Anisotropies at high galactic latitudes

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

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

CDM Prescription for SS

Aquarius A-1, Springel et al., MNRAS 391(2008),1685.

Subhalo Mass Function

$$\frac{dn_{\mathrm{sub}}}{dM_{\mathrm{sub}}}(M, M_{\mathrm{sub}}, r) \propto M_{\mathrm{sub}}^{-1.9}$$

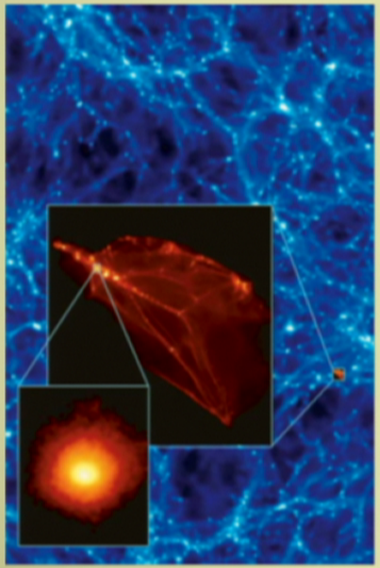
Density distribution within each subhalo

- smooth profile
- sub-substructures

Streams as many small subhalos in close proximity?

Mass of Smallest DM Structures?

J. Diemand, B. Moore, J. Stadel, Nature 433 (2005)

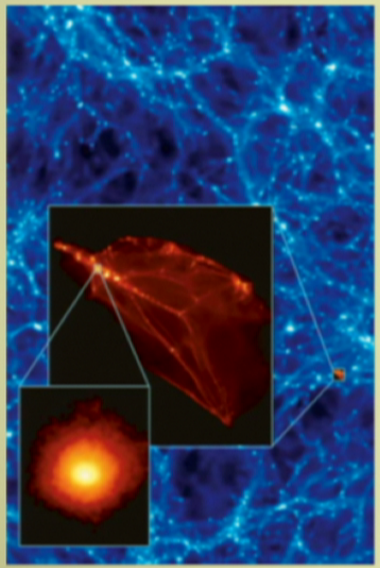


- **Significant remaining population of primordial halos?**
  - Scale of DM free streaming?
  - Scale of acoustic oscillations?
  - Other scale responsible for power spectrum cut-off?
- **Population of highly concentrated, tidally stripped cores?**

Potentially big effects for some indirect detection signals.

Mass of Smallest DM Structures?

J. Diemand, B. Moore, J. Stadel, Nature 433 (2005)



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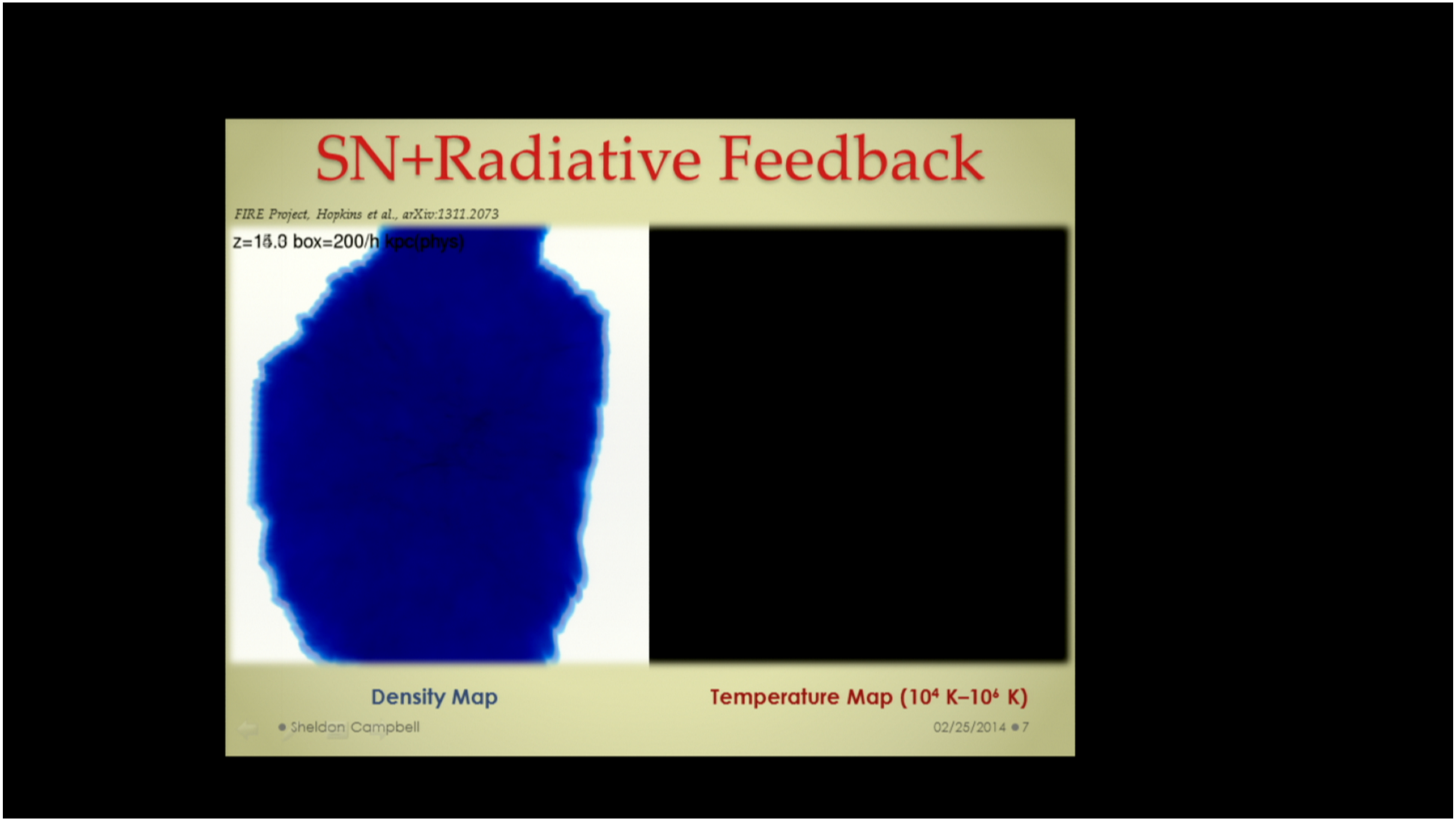
Does Baryon Physics Change Predictions?

- Cause Destruction or Evolution of Substructure?
- Strip subhalos of gas, quench star formation?

E.g.

- supernova feedback
- stellar radiative feedback
- active galactic nucleus feedback
- ram pressure stripping



SN+Radiative Feedback
FIRE Project, Hopkins et al., arXiv:1311.2073
box=200/h kpc(phys)
Density Map
Temperature Map (10⁴ K–10⁶ K)
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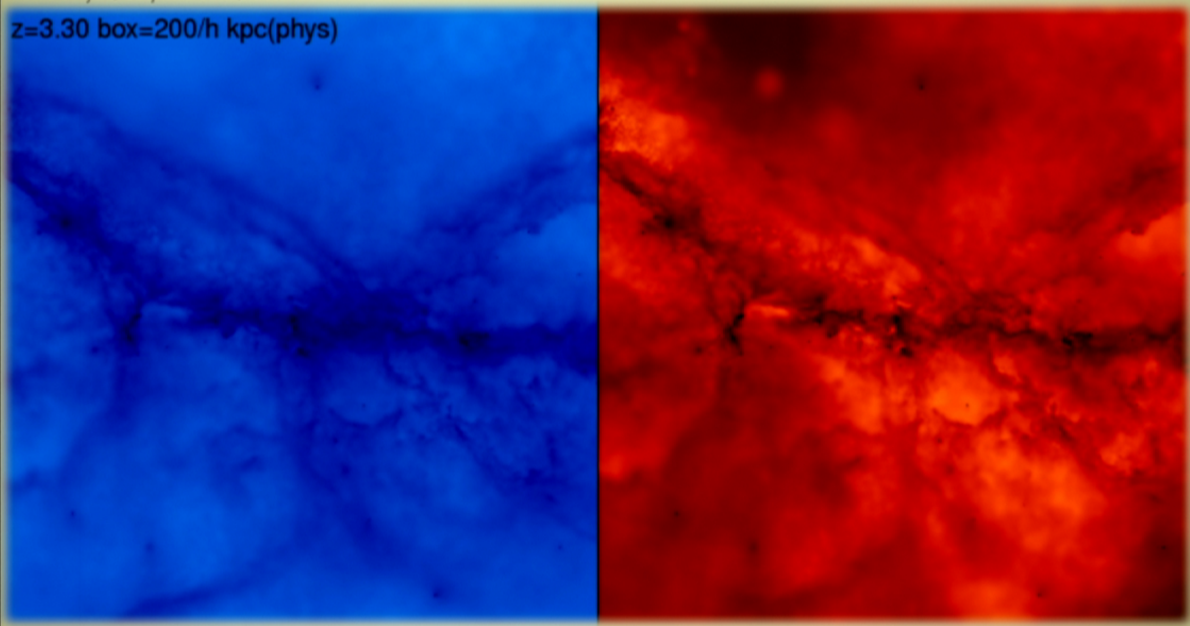
SN+Radiative Feedback

FIRE Project, Hopkins et al., arXiv:1311.2073



Density Map

Temperature Map (10^4 K–10^6 K)

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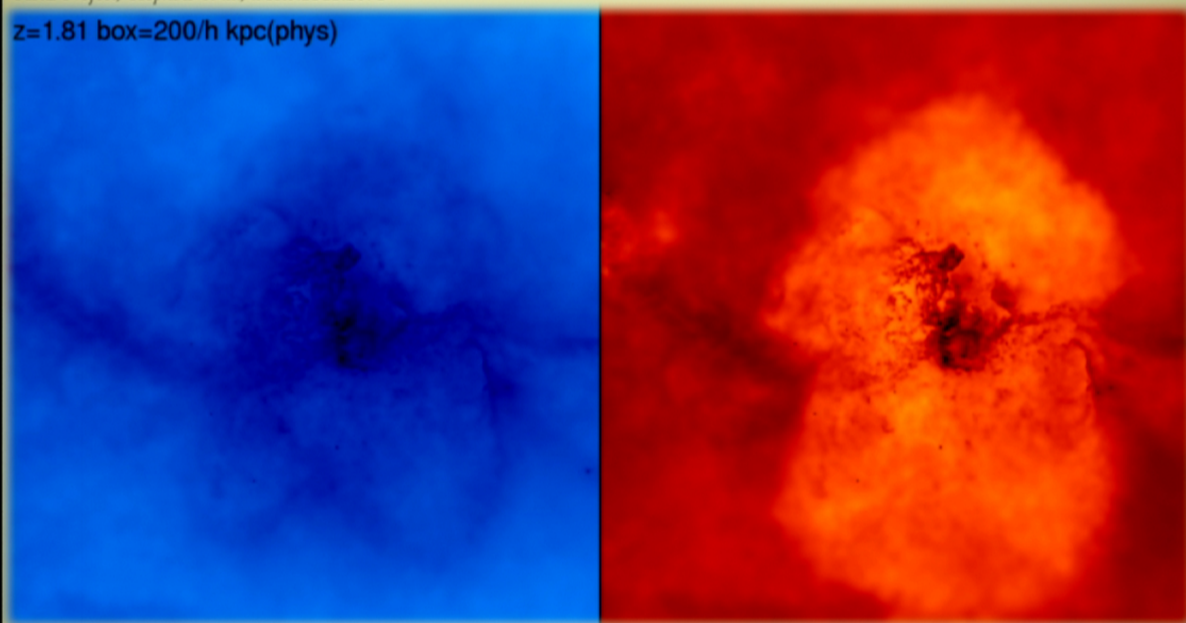
SN+Radiative Feedback

FIRE Project, Hopkins et al., arXiv:1311.2073



Density Map **Temperature Map (10^4 K–10^6 K)**

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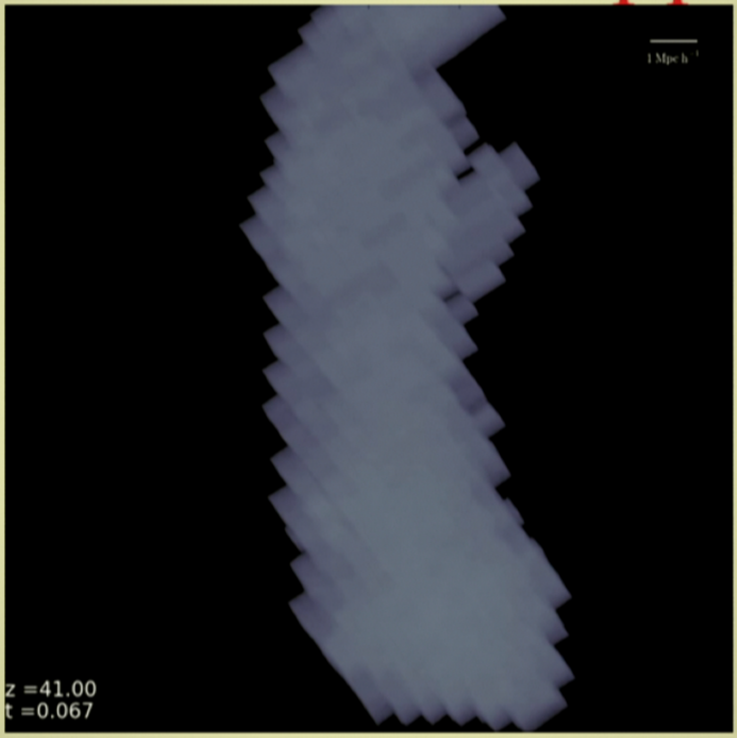
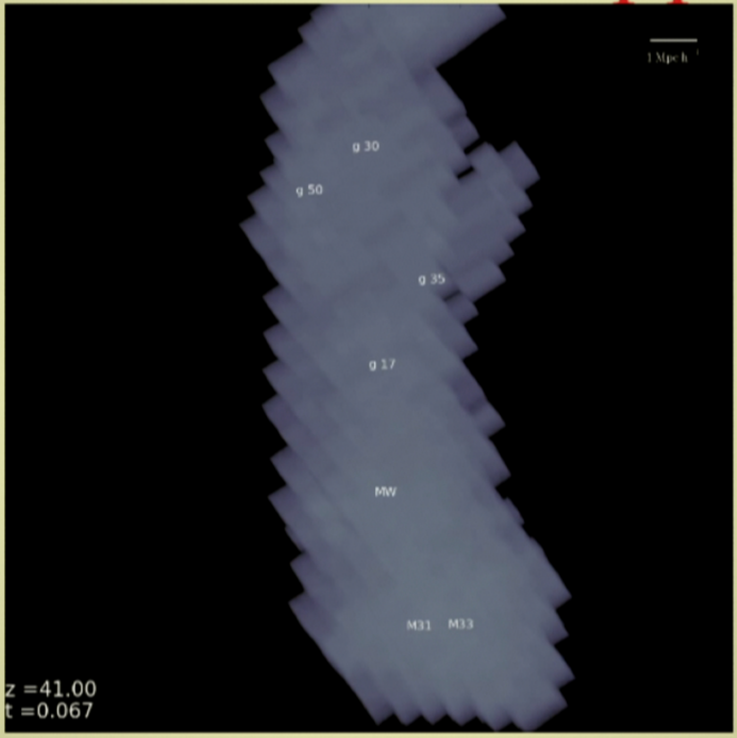
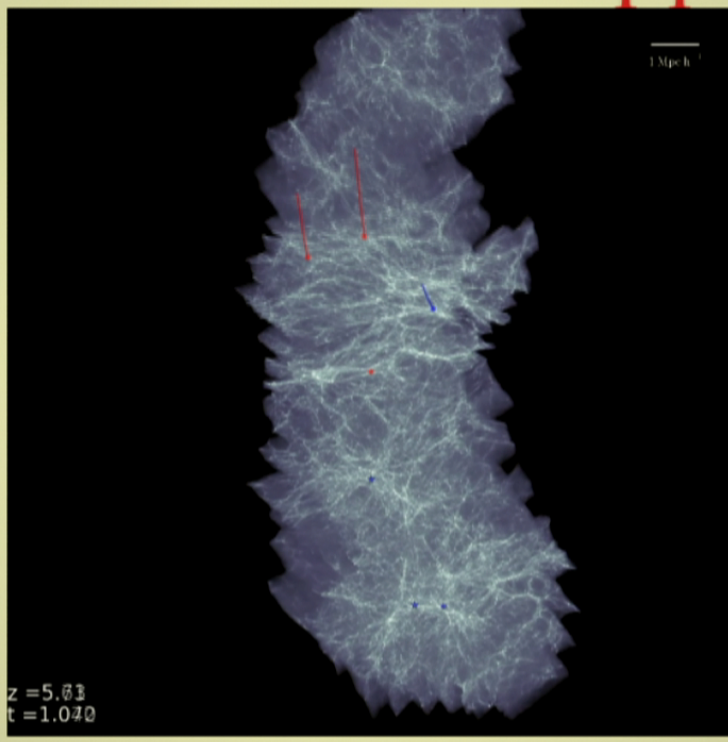
Ram Pressure Stripping



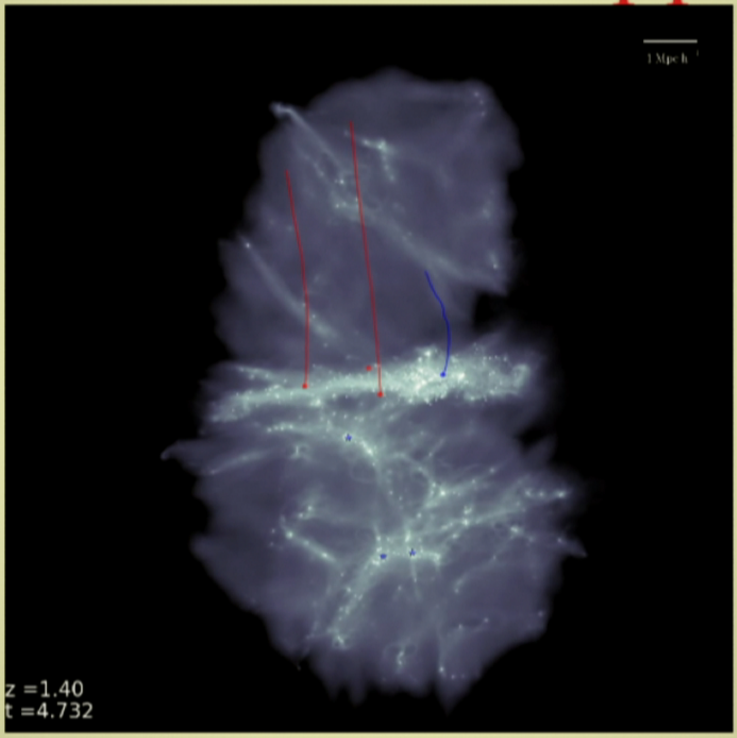
Ram Pressure Stripping



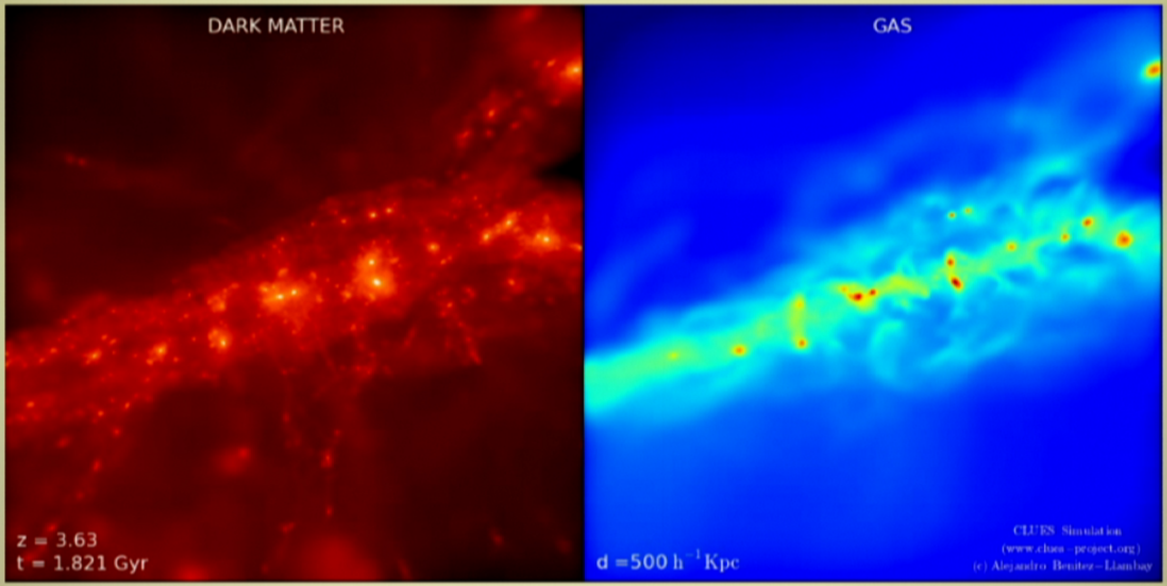
Ram Pressure Stripping



Ram Pressure Stripping



Ram Pressure Stripping



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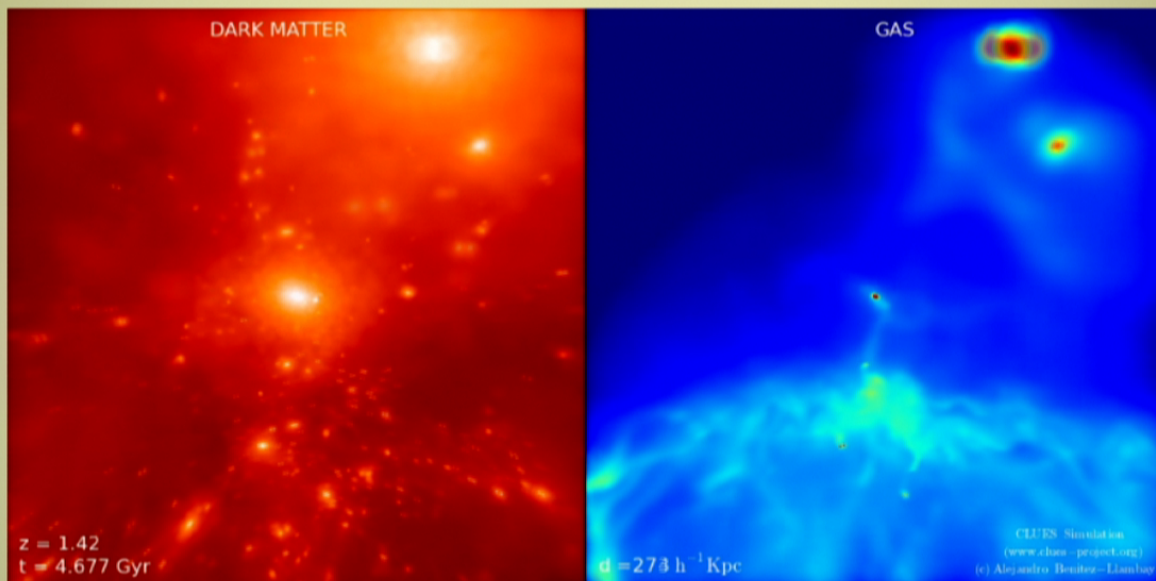
Ram Pressure Stripping



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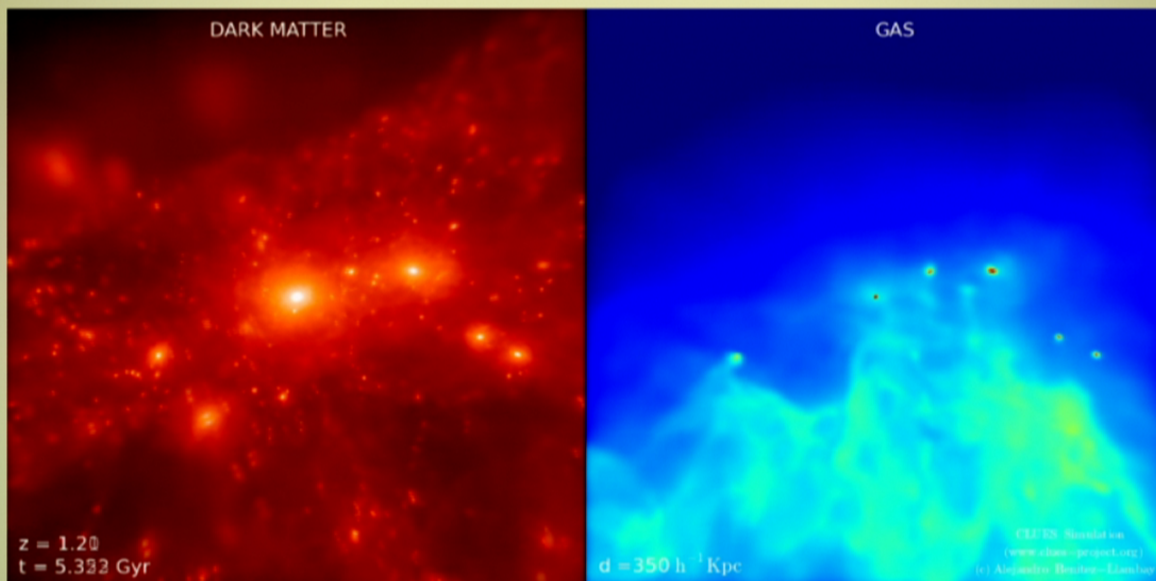
Ram Pressure Stripping



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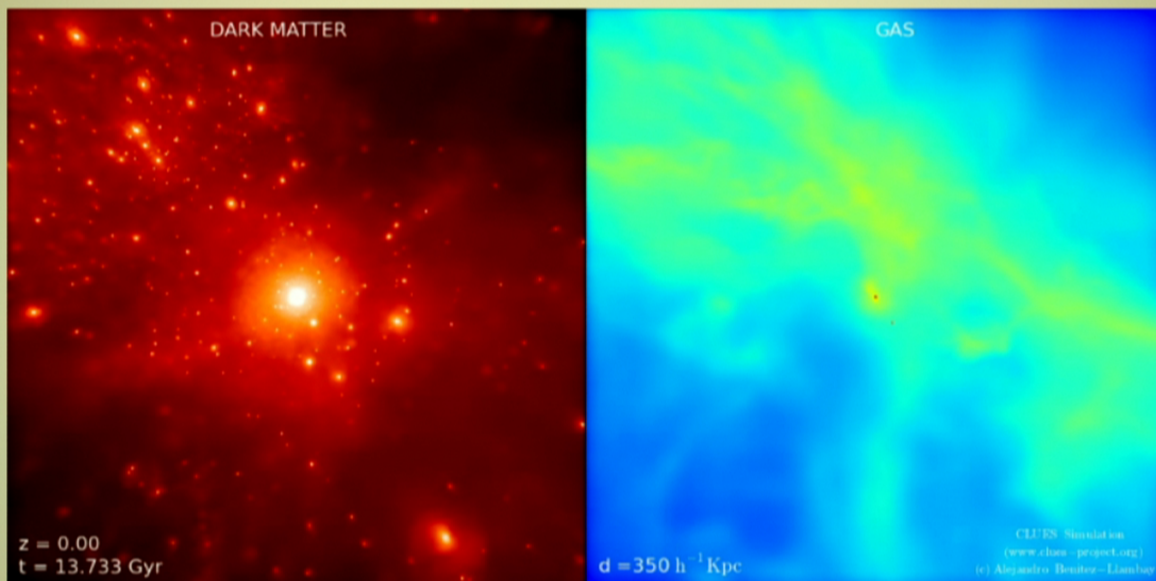

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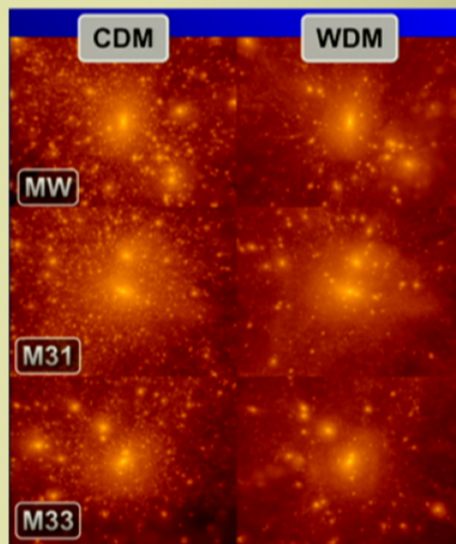
Beyond Cold Dark Matter

- Warm Dark Matter
- Dark Matter Self-interactions
- Multicomponent Dark Matter
- …

Currently a hot topic at dwarf galaxy scales.

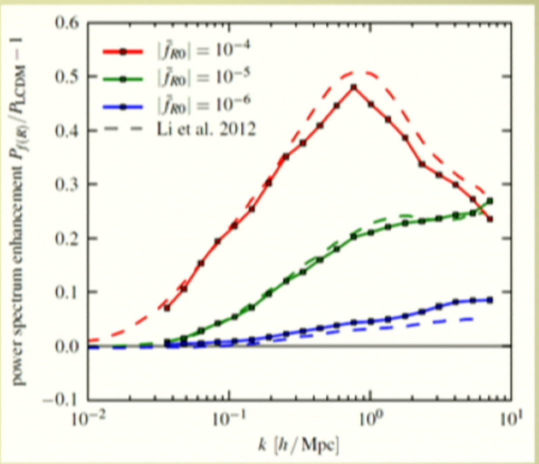
Big consequences for small scale structure.



http://www.clues-project.org/images/darkmatter.html
Copyright S. Gottlober, G. Yepes, A. Klypin, A. Khalatyan

Beyond ΛCDM and GR

- **Hu-Sawicki $f(R)$ gravity can mimic Gen. Rel., but give excess power on sub-Mpc scales.**



Puchwein, Baldi, Springel, arXiv:1305.2418
Hellwing, Li, Frenk, Cole, arXiv:1305.7486
Zhao, arXiv:1312.1291
Hellwing, Barreira, Li, Frenk, Cole, arXiv:1401.0706

Can observations constrain small scale structure?

Radiation?

- Star formation is inefficient in halos smaller than dwarf galaxy scales.
- Small substructures likely too dark to probe via baryonic/atomic processes.

Gravitational Lensing?

- Strong gravitational lenses may constrain substructure models, but will need a large sample of lenses.

Perhaps indirect detection is the most "direct" way to probe small scale structure.

- Observed radiation from the annihilation or decay of astrophysical dark matter.

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Dark Matter Clustering in Indirect Detection

S-wave annihilation intensity in direction $\boldsymbol{n}$:

$$I(E,\boldsymbol{n}) = \frac{\sigma v}{8\pi m^2}\int \frac{dz}{H(z)}\frac{dN_\gamma\big((1+z)E\big)}{dE}\frac{\rho^2(z,\boldsymbol{n})}{(1+z)^3}e^{-\tau_{E,z}}$$

Ambiguity between σv and substructure contribution to $\langle\rho^2(z)\rangle$.

For local annihilations:

$$I(E,\boldsymbol{n}) = \frac{\sigma v}{8\pi m^2}\frac{dN_\gamma(E)}{dE}J(\boldsymbol{n}), \qquad J(\boldsymbol{n}) = \int_{\text{line of sight}} ds\ \rho^2(s,\boldsymbol{n}).$$

Ambiguity between σv and substructure contribution to the J-factor.

Breaking the cross-section/ small-scale-structure degeneracy

If σv is constant:

- Observe a signal from two regions with known relative density,
- Look for spatial variations of a signal.

The second point can be used to constrain the correct halo density profile and halo substructure.

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:

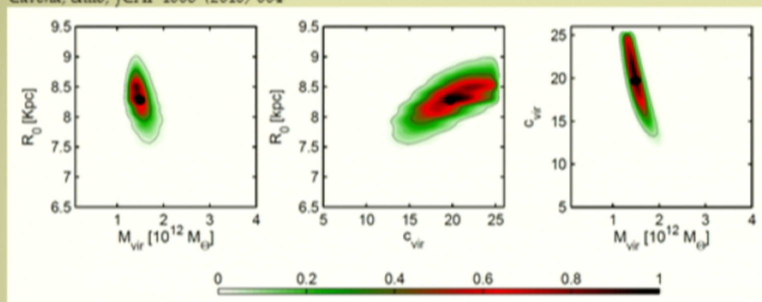
1) Gao et al. (2012), **G12**:
   - Based on the Phoenix and Aquarius simulations.
   - A fitting formula for the angular surface intensity of substructure.

2) Kamionkowski et al. (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 et al. (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 $M_{\min} = 10^{-6}\ M_{\odot}$. I also try $M_{\min} = 10^{-12}\ M_{\odot}$.

Constraints from Kinematical Galactic Tracers

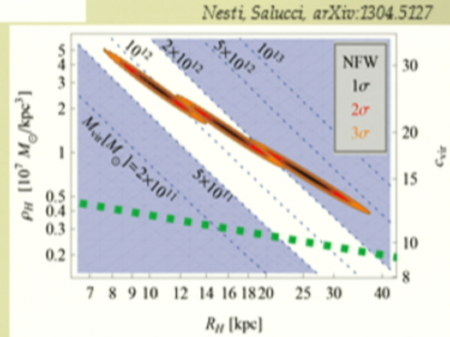
Catena, Ullio, JCAP 1008 (2010) 004



NFW profile

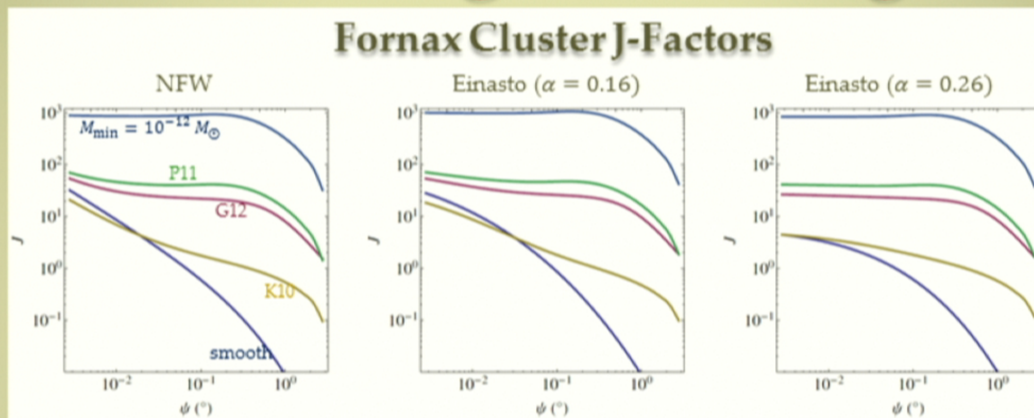
$$\rho(r) = \frac{\rho_s}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2}$$

Nesti, Salucci, arXiv:1304.5127

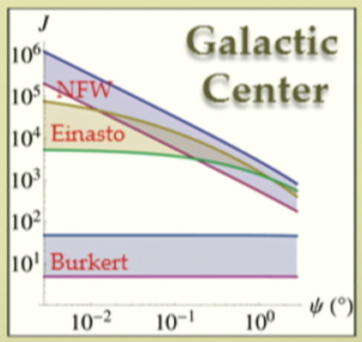


- The solar system velocity strongly constrains the value of $\rho_s r_s^2$.
- The J-factor goes roughly as $\rho_s^2 r_s$.

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.

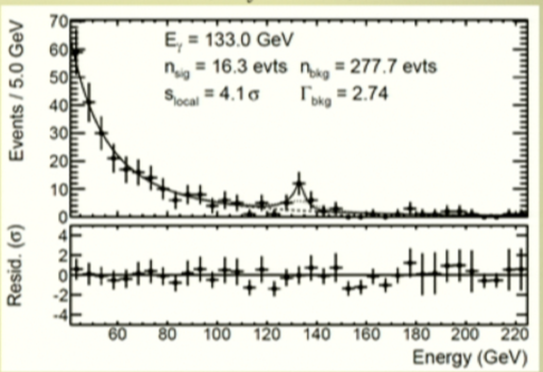
SC, Dutta, Rott, In Prep.

Example 2: Discovery Constraining Substructure

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

The 130 GeV Fermi line is a perfect example of this!

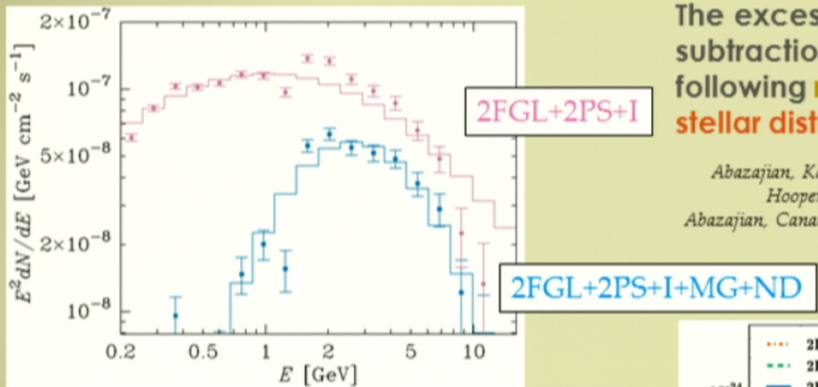
Fermi-LAT Collaboration, Phys. Rev. D88, 082002 (2013)



Instrumental Effect?
- Narrower than energy resolution.
- Seen in Earth limb.
- Located at same energy as recently discovered reconstruction inefficiencies.

Not Instrumental Effect?
- Earth limb line is smaller.
- No line in anti-Region-of-Interest.
- Lack of recent "signal" photons. (Was it fluctuating high before? Or low now?)

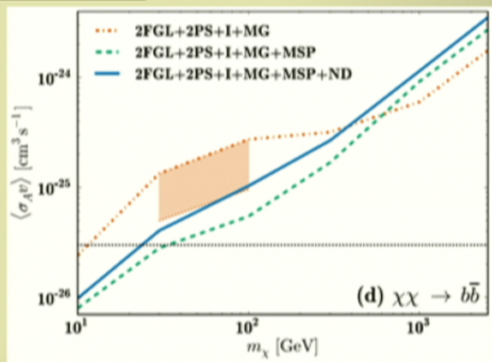
Another great example of this is the Galactic Center Extended source.



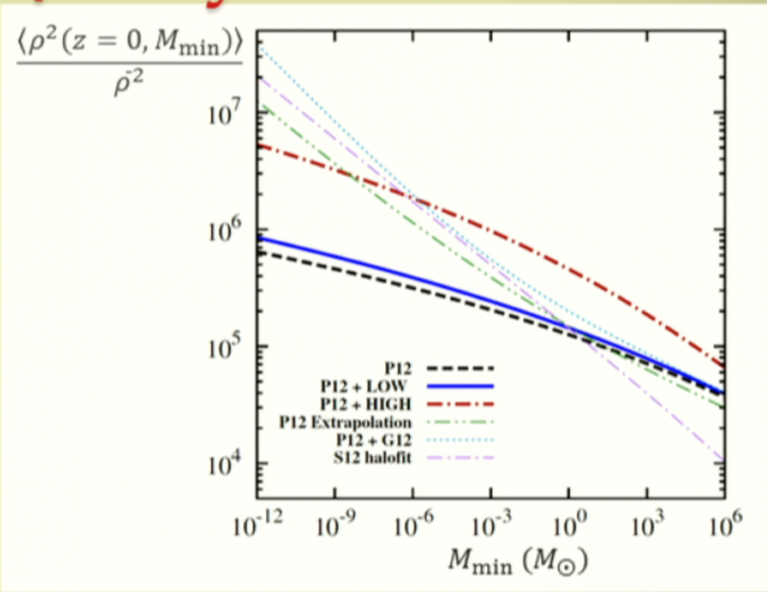
The excess persists after ideal subtractions of diffuse emission following **molecular gas** and **stellar distributions**.

Abazajian, Kaplinghat, Phys. Rev. D86, 083511 (2012)
Hooper, Slatyer, Phys. Dark Univ. 2, 118 (2013)
Abazajian, Canac, Horiuchi, Kaplinghat, arXiv:1402.4090

Allowing for best-fit population of 3000-5000 unresolved **milli-second pulsars** makes the excess insignificant.



No Signal in Isotropic Diffuse γ Rays Limits SS



Ng, Laha, SC, et al., arXiv:1310.1915

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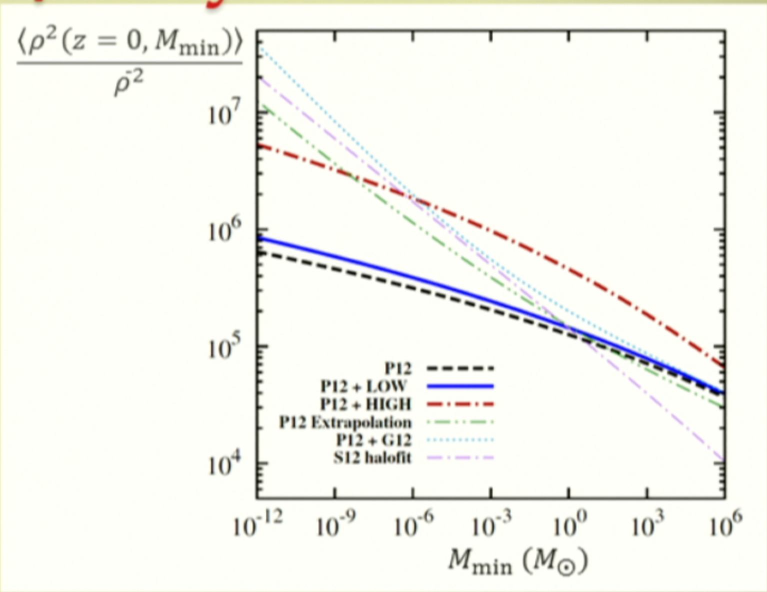
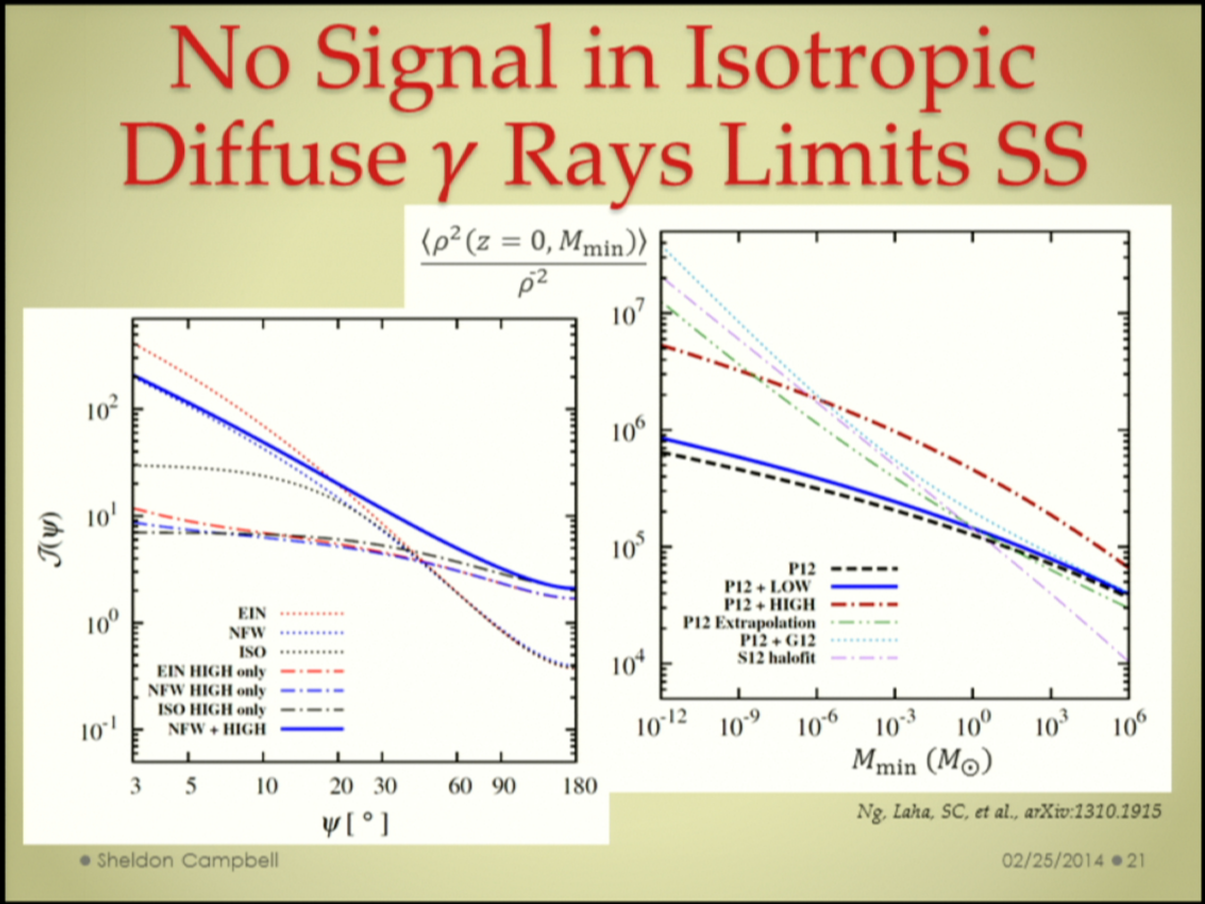
No Signal in Isotropic Diffuse γ Rays Limits SS



Ng, Laha, SC, et al., arXiv:1310.1915


No Signal in Isotropic Diffuse γ Rays Limits SS
$\frac{\langle \rho^2(z=0, M_{\min}) \rangle}{\bar{\rho}^2}$
$\mathcal{J}(\psi)$
ψ [°]
EIN
NFW
ISO
EIN HIGH only
NFW HIGH only
ISO HIGH only
NFW + HIGH
P12
P12 + LOW
P12 + HIGH
P12 Extrapolation
P12 + G12
S12 halofit
$M_{\min}$ ($M_\odot$)
Ng, Laha, SC, et al., arXiv:1310.1915
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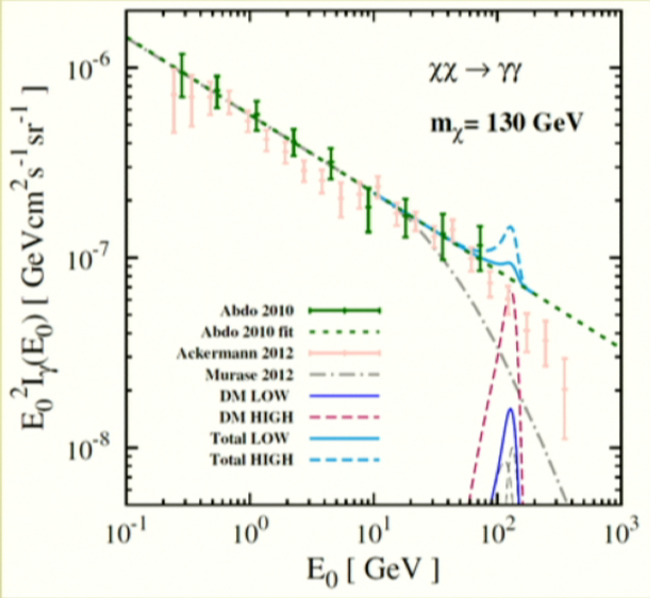
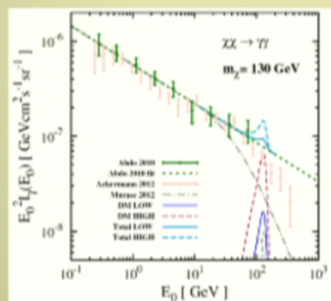
Halo Clumping Constraints from Isotropic Gamma-Rays

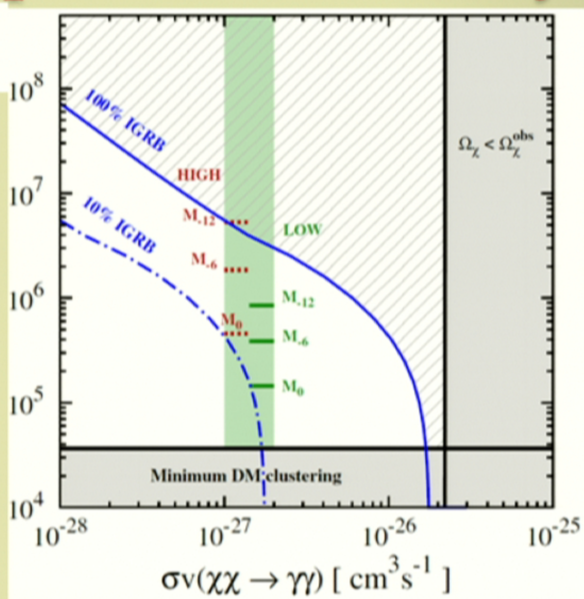


Ng, Laha, SC, et al., arXiv:1310.1915

Halo Clumping Constraints from Isotropic Gamma-Rays

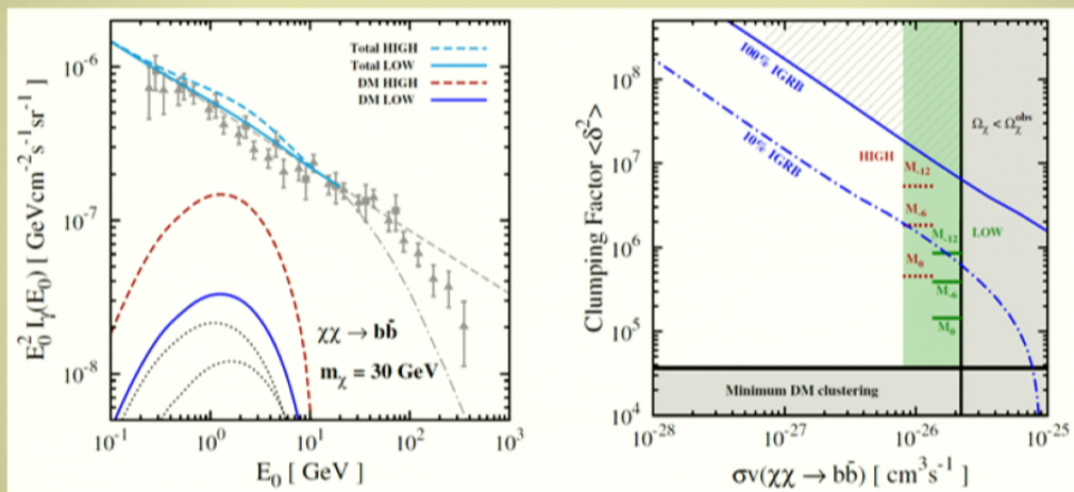
$$\frac{\langle \rho^2(z=0, M_{\min}) \rangle}{\bar{\rho}^2}$$





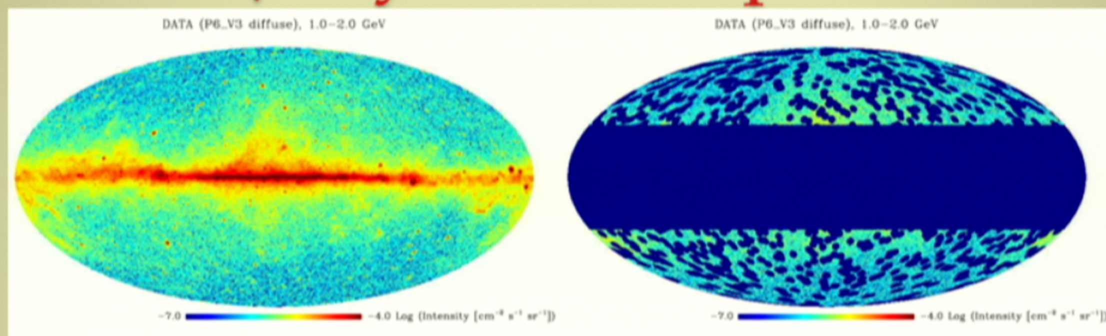
Ng, Laha, SC, et al., arXiv:1310.1915

Excess Continuous γ-rays From Galactic Center



Ng, Laha, SC, et al., arXiv:1310.1915

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.**

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

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

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

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

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

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

$f_{\rm sky}$ = fraction of sky unmasked.

σ_b = angular beam width.

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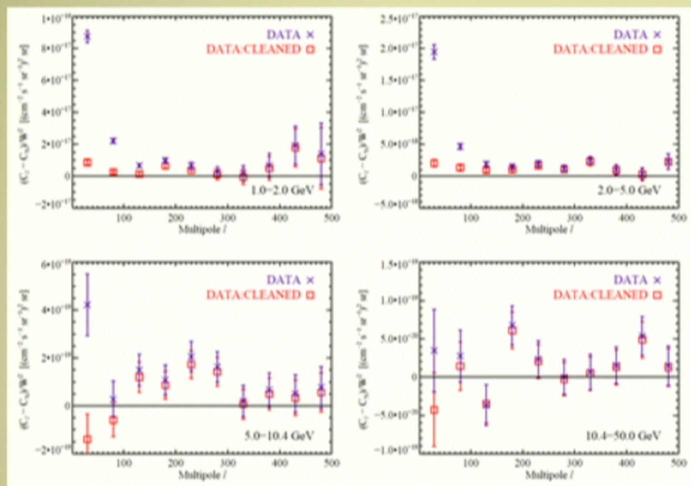
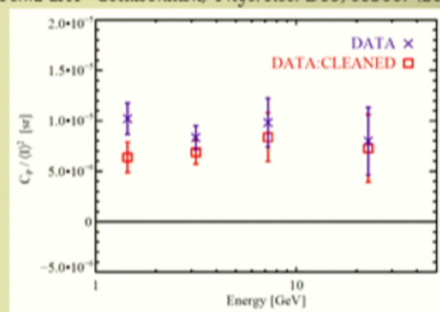
Fermi-LAT Measurements



Fermi-LAT Collaboration, Phys. Rev. D85, 083007 (2012)

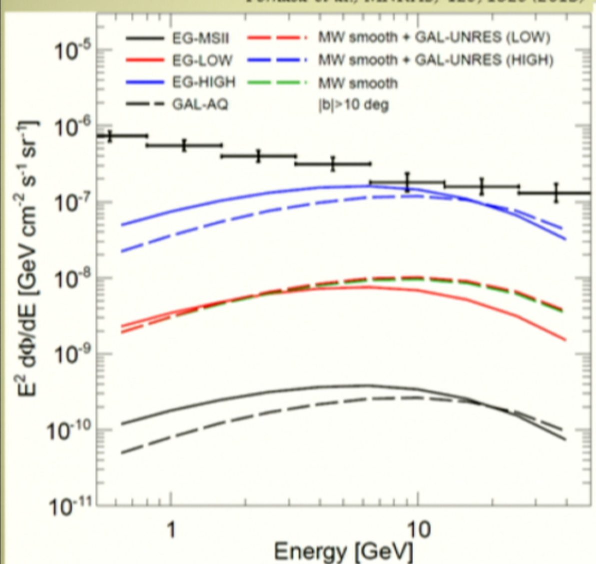


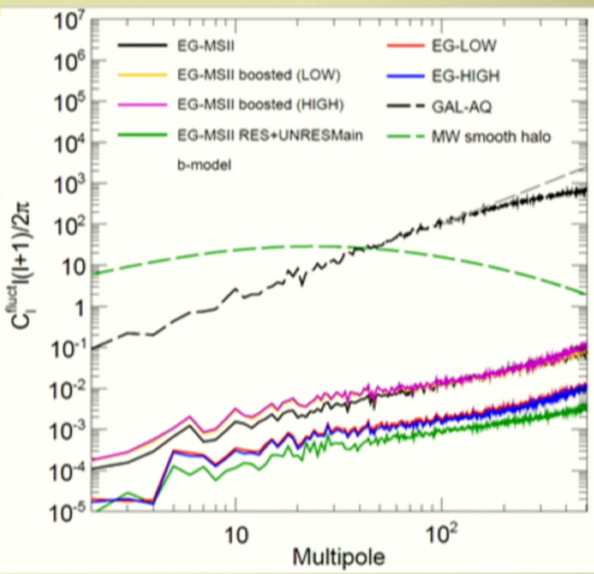
- 4 energy bins
- Cleaned data = galactic foreground subtraction.
- Foreground contamination minimal for $\ell \geq 155$.

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

Fluctuation Angular Power Spectra from DM

Fornasa et al., MNRAS, 429, 1529 (2013)





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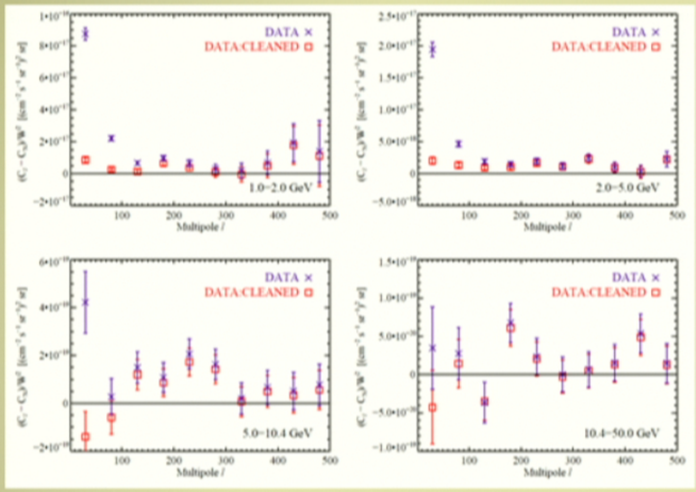
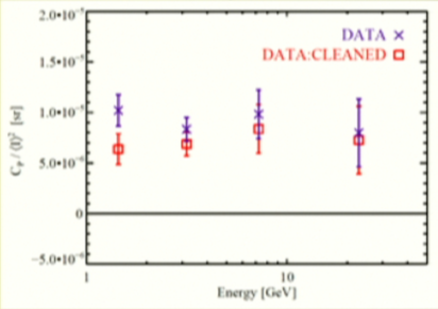
Fermi-LAT Measurements



Fermi-LAT Collaboration, Phys. Rev. D85, 083007 (2012)

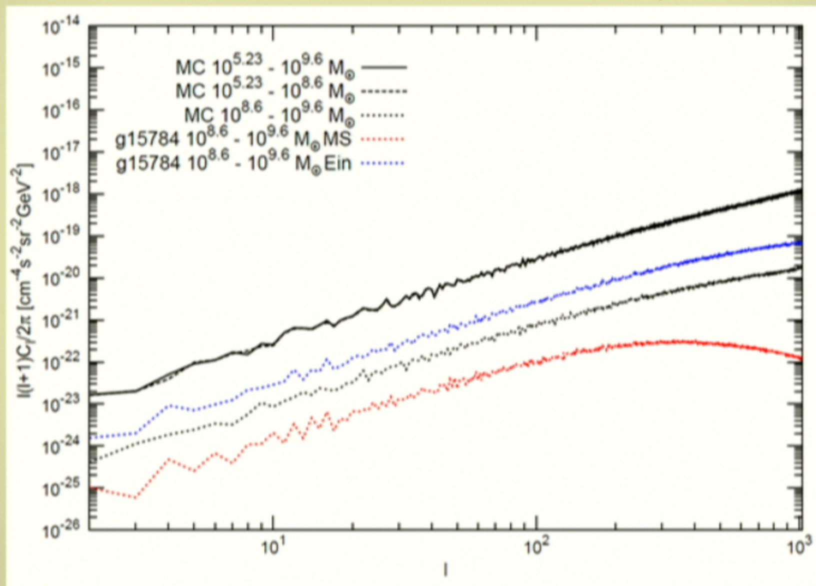


- Weighted average in each energy bin shows significant power consistent with no energy modulation.

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

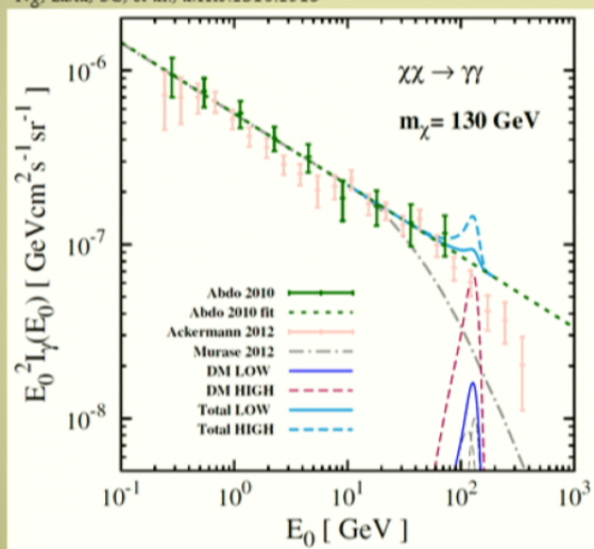
Small-Scale-Structure may dominate the angular power

Calore et al., arXiv:1402.0512

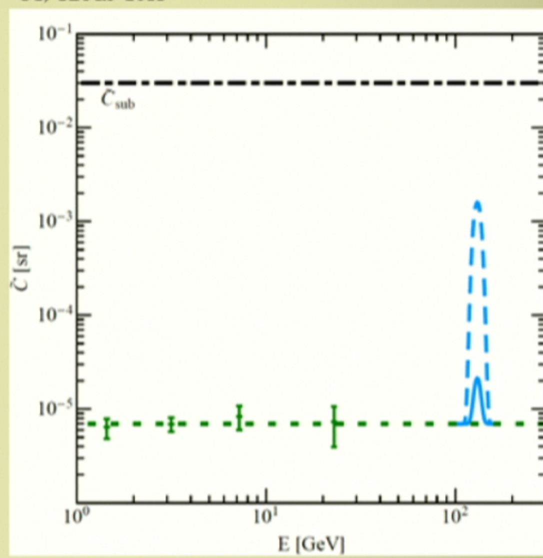


Anisotropy of a Spectral Line

Ng, Laha, SC, et al., arXiv:1310.1915



SC, CETUP 2013



Sensitivity to a Spectral Line

- **Signal Flux**

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

- **Angular Power**

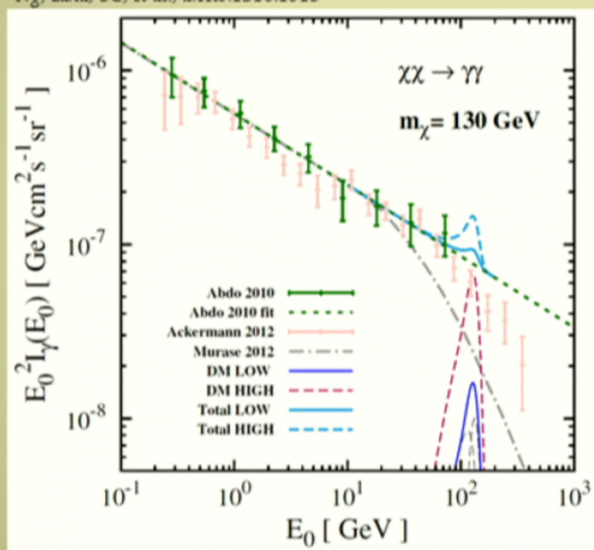
Absence of power constrains $\frac{\Phi_{\mathrm{sub}}}{\Phi} < \sqrt{\frac{\sigma_{\tilde{C}}}{\tilde{C}_{\mathrm{sub}}}}$ which also initially goes like $N_\gamma^{-1/2}$.

This is an independent probe of galactic substructure!

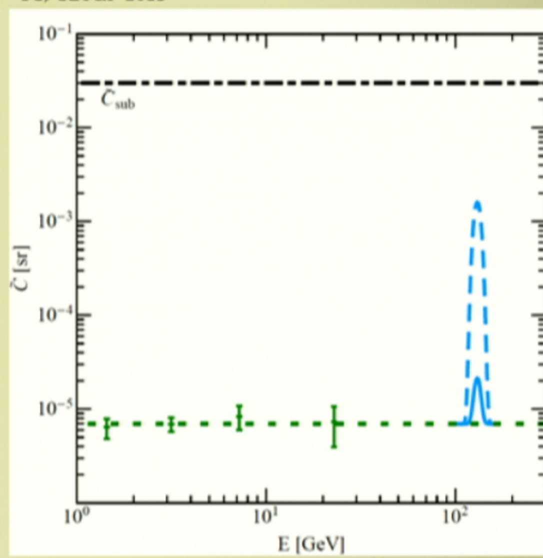
Angular power is more sensitive to a spectral line if $\frac{\Phi_{\mathrm{sub}}}{\Phi_{\mathrm{DM}}} > \sqrt{\frac{N_\gamma \sigma_{\tilde{C}}}{\tilde{C}_{\mathrm{sub}}}}$.

Anisotropy of a Spectral Line

Ng, Laha, SC, et al., arXiv:1310.1915



SC, CETUP 2013



Sensitivity to a Spectral Line

- **Signal Flux**

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

- **Angular Power**

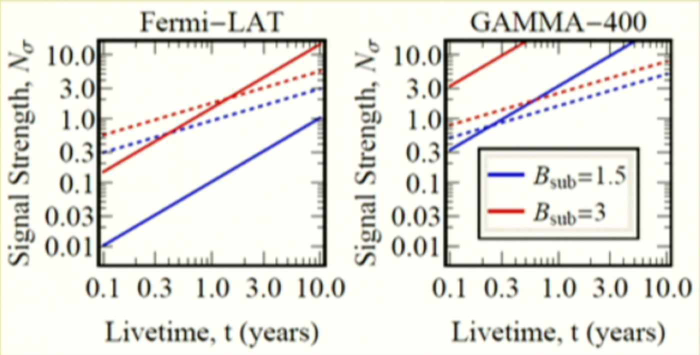
  Absence of power constrains $\frac{\Phi_{\mathrm{sub}}}{\Phi} < \sqrt{\frac{\sigma_{\tilde{C}}}{\tilde{C}_{\mathrm{sub}}}}$ which also initially goes like $N_\gamma^{-1/2}$.

  This is an independent probe of galactic substructure!

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

Growth of Signal Strength E.g., The Fermi Line

Signal Strength = Signal / Measurement Uncertainty



SC, Beacom, arXiv:1312.3945

$\propto \sqrt{t}$ for flux (dotted lines)

$\propto t$ for angular power (solid lines)

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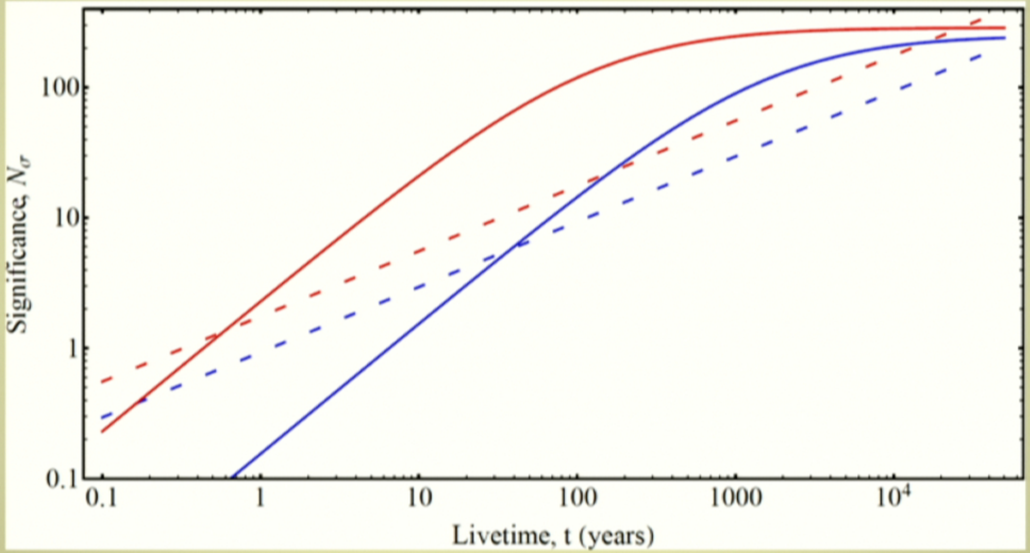
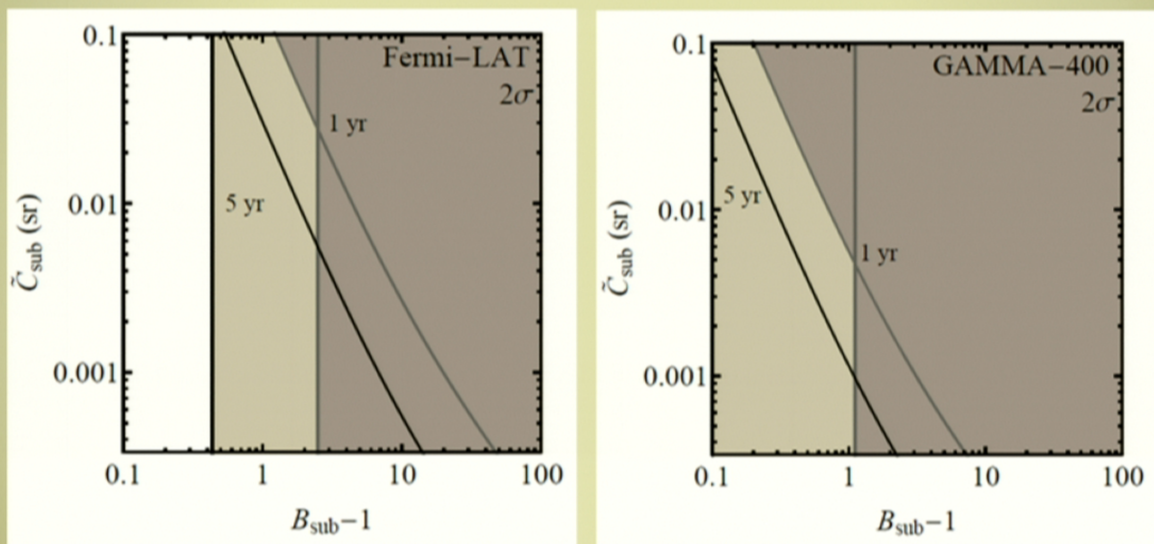
Linear Growth of the Anisotropy Signal Stops When No Longer Shot Noise Dominated

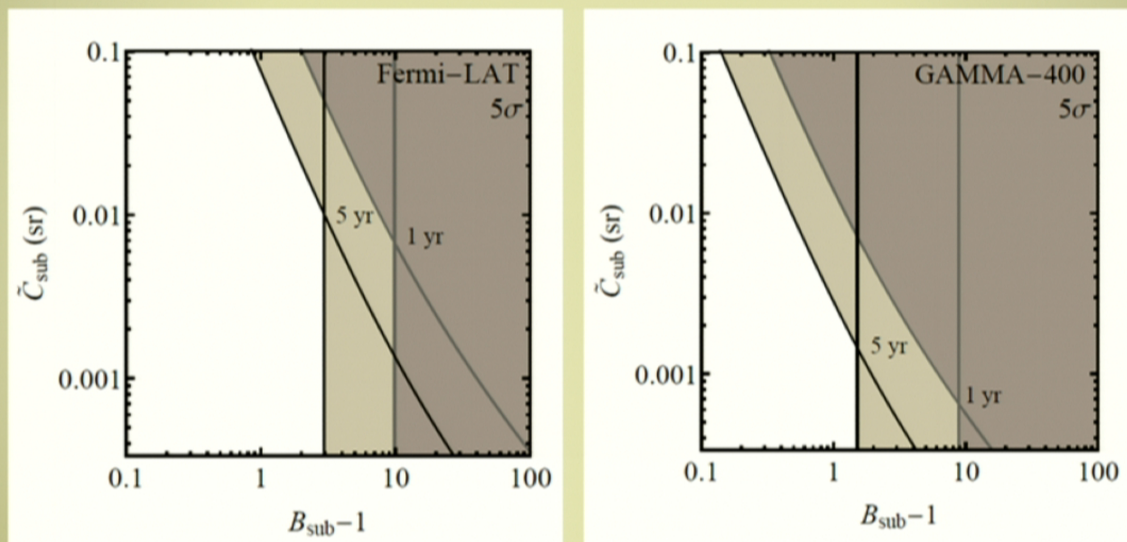


Complementary DGRB Flux+Angular Line Search



SC, Beacom, arXiv:1312.3945

Complementary Flux+Angular Line Search



SC, Beacom, arXiv:1312.3945

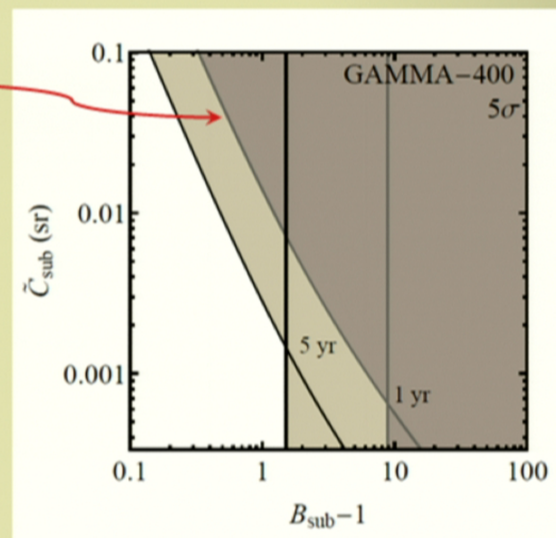
Complementary Flux+Angular Line Search

Warning: photon counts here are probably too low for such a confident signal.

The standard statistics don't apply at such low counts?

Studies for a proper statistical description are under way.

The curves may change, but the story remains the same.



SC, Beacom, arXiv:1312.3945

Conclusions

- The substructure content of dark matter halos is an active research topic.
  - Potentially sensitive to particle dark matter properties, galaxy formation processes, and non-general relativistic gravity.
- 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, complementary to the intensity.