



Turning Dark Matter Hints Into Dark Matter Discoveries

Mitchell Workshop on Collider and Dark Matter Physics
Texas A&M University
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THE OHIO STATE UNIVERSITY

What Does Discovering Dark Matter Mean?

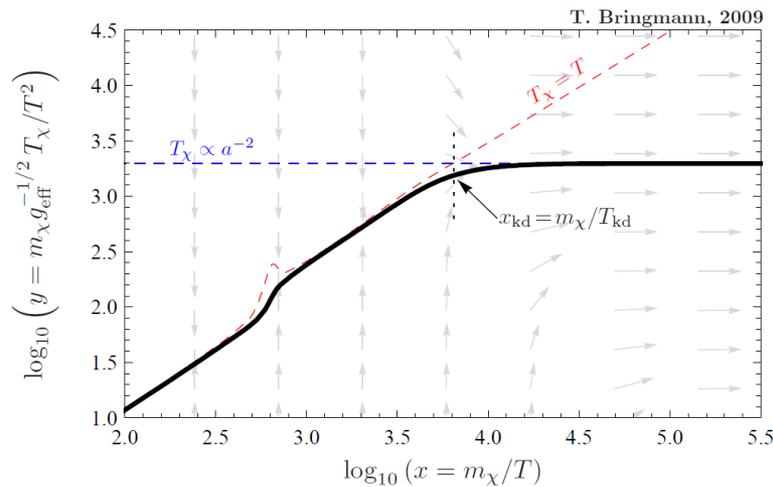
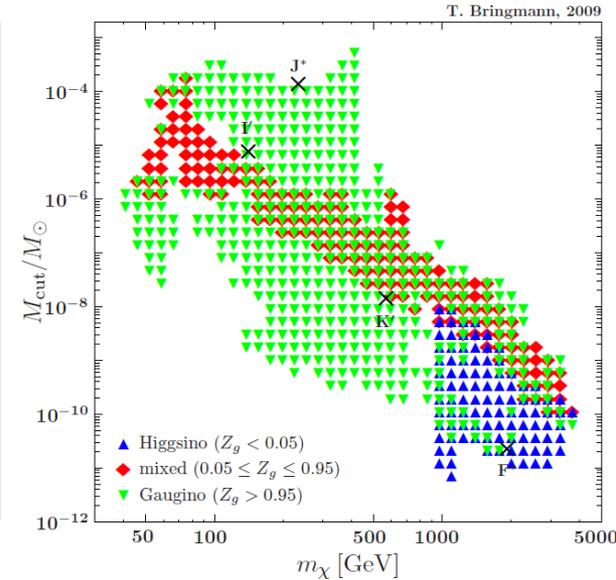
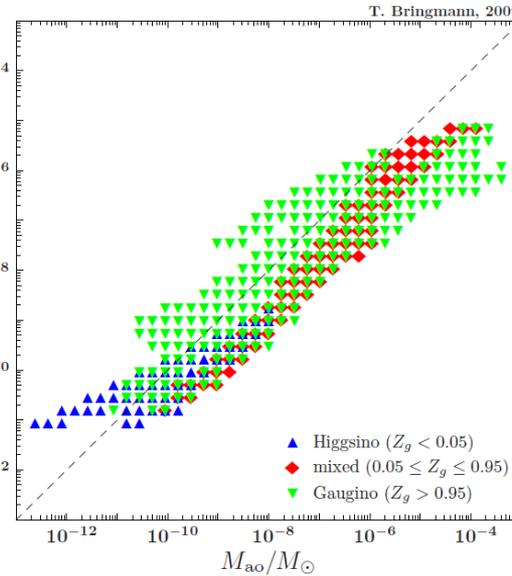
- ▶ Determining a theoretical framework that accounts for:
 - ▶ the astrophysical dark matter content.
 - ▶ the dark matter **particle** properties.
 - ▶ the dark matter **clustering** properties.
- ▶ In other words, establishing
a predictive standard model of dark matter.
- ▶ Hints of Direct DM Observations
 - ⇒ Predictions for **Future** Observations
 - ⇒ Verifications Bolster Confidence for Discovery.

Particle Properties

- ▶ Particle Mass(es)—hierarchy?
- ▶ Decay Rate? (indirect detection)
- ▶ Annihilation Cross Section
 - ▶ at abundance freeze-out (for thermal relics) $\langle\sigma v\rangle(T)$
 - ▶ dependence on velocity distribution (for indirect detection) $[\sigma v](v)$
- ▶ Standard Model Couplings
 - ▶ annihilation/decay branching fractions (indirect detection)
 - ▶ nucleon scattering cross sections (direct detection, star capture)
 - ▶ collider production of dark matter
- ▶ “Dark Sector” Couplings, BSM Couplings
 - ▶ self-interactions, dark forces? (halo shapes)
 - ▶ inelastic scattering (direct detection, halo shapes)
 - ▶ non-thermal relic production?

Clustering Properties Depend on Particle Properties

- ▶ Kinetic decoupling occurs when DM scattering rate $< H$.
- ▶ Overdense regions collapse.
- ▶ **Minimum mass** of collapsing structure may depend on
 - ▶ free streaming scale
 - ▶ acoustic oscillation scale



$$M_{\text{fs}} \approx \frac{4\pi}{3} \rho_{\chi} \left(\frac{\pi}{k_{\text{fs}}} \right)^3 = 2.9 \times 10^{-6} \left(\frac{1 + \ln \left(g_{\text{eff}}^{1/4} T_{\text{kd}} / 50 \text{ MeV} \right) / 19.1}{(m_{\chi} / 100 \text{ GeV})^{1/2} g_{\text{eff}}^{1/4} (T_{\text{kd}} / 50 \text{ MeV})^{1/2}} \right)^3 M_{\odot}$$

$$M_{\text{ao}} \approx \frac{4\pi}{3} \frac{\rho_{\chi}}{H^3} \Big|_{T=T_{\text{kd}}} = 3.4 \times 10^{-6} \left(\frac{T_{\text{kd}} g_{\text{eff}}^{1/4}}{50 \text{ MeV}} \right)^{-3} M_{\odot}$$

Clustering Properties

- I. **Cold, Heavy, Collisionless Dark Matter**
 - ▶ Kinetic decoupling immediately after number density freezeout
 - ▶ Short free-streaming scale
⇒ **SMALLER** volume structures collapse (small mass structures)
 - ▶ Early time decoupling
⇒ **DENSER** structures collapse (high scale density structures)
 - ▶ **Abundant Halo Substructure**



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

Clustering Properties

2. Collisional Dark Matter

- ▶ Scattering in early Universe with primordial plasma
 - ▶ can keep DM in kinetic equilibrium long after chemical freezeout
 - ▶ collapse happens with **smaller densities**
- ▶ Dark Matter Self-Scattering
 - ▶ modifies phase space distribution of dark matter
 - ▶ modified halo structure
 - less dense, cored halo centers.
 - ▶ **acoustic oscillations** can wash out small structures.

Collisionless



DM Collisional

$$\frac{\sigma}{m} = 2 \text{ barn/GeV}$$

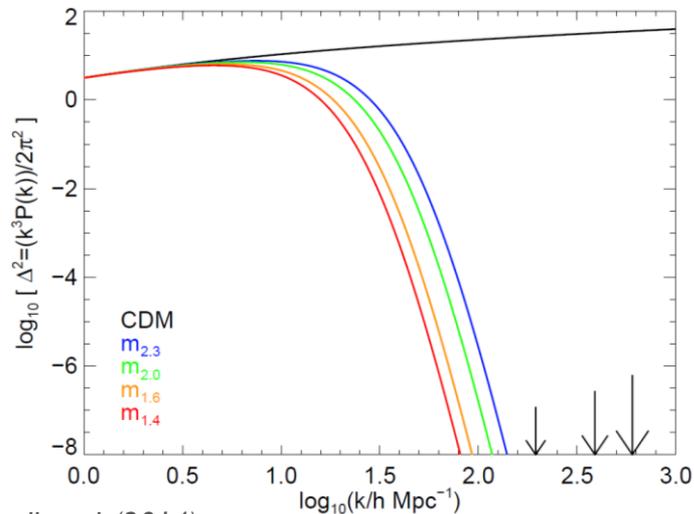
See talk by
Hai-Bo Yu

Rocha et al. (2013)

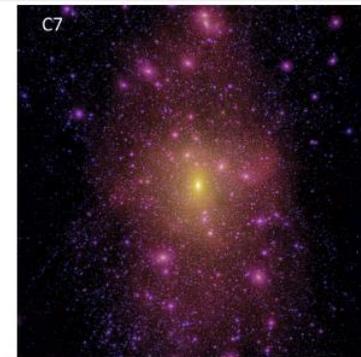
Clustering Properties

3. Warm Dark Matter

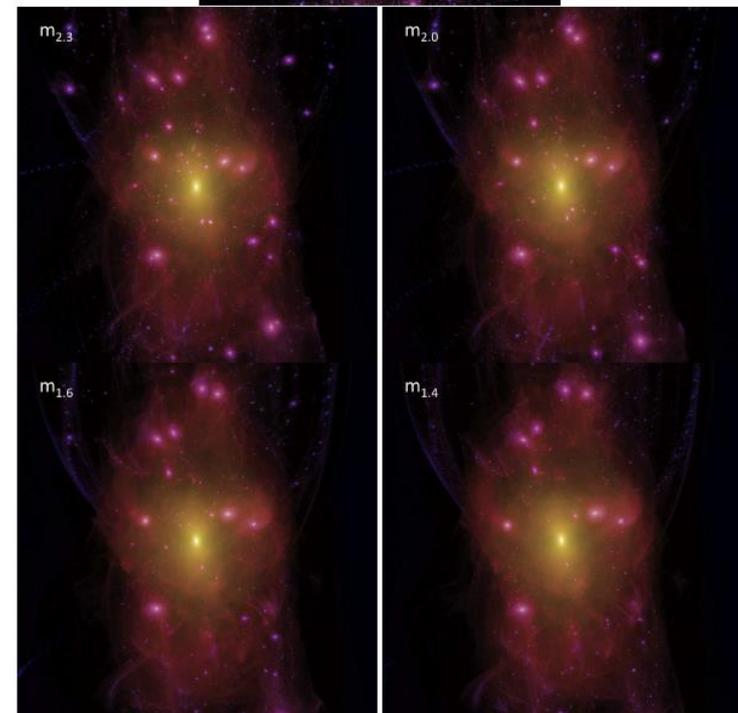
- ▶ small mass creates long free streaming scale
- ▶ late-time collapse produces low-density structure
- ▶ Limited Halo Substructure



Lovell et al. (2014)



Aquarius A-2



Clustering Properties

4. Non-thermal Dark Matter Relics

- ▶ The phase space distribution depends on the dark matter production mechanism.
- ▶ Can produce a skewed primordial power spectrum.
 - ▶ Modified halo distributions.
 - ▶ Modified subhalo abundance.

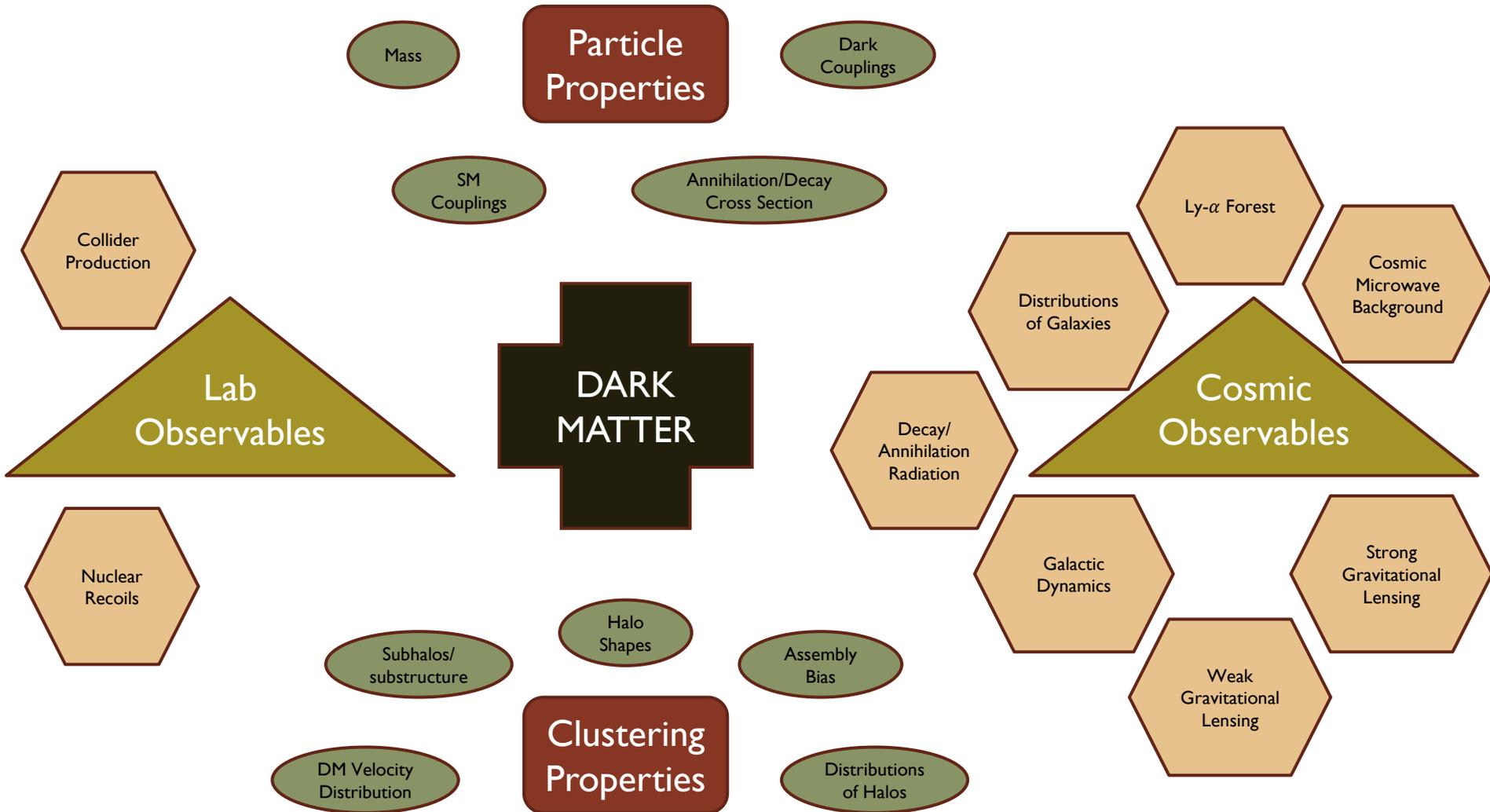
See talks by
Rouzbeh Allahverdi,
Kuver Sinha,
Michele Cicoli
for example models.

5. Some or all of the above?

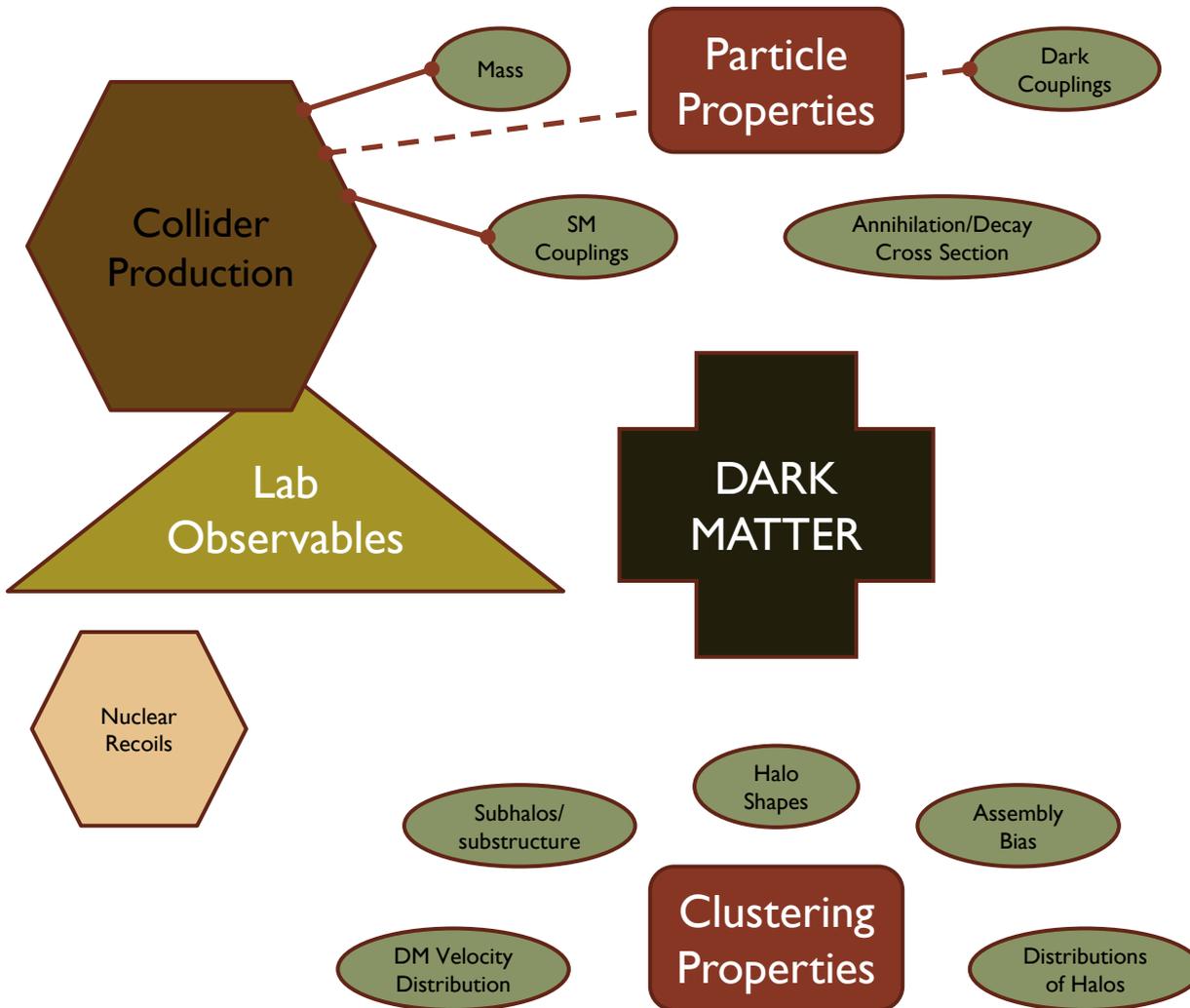
- ▶ Multi-component dark matter
- ▶ Dynamical Frameworks
- ▶ Mixed dark matter

See talks by
Howard Baer,
Keith Dienes,
Brooks Thomas,
David Sanford.

Fitting into a Global Picture



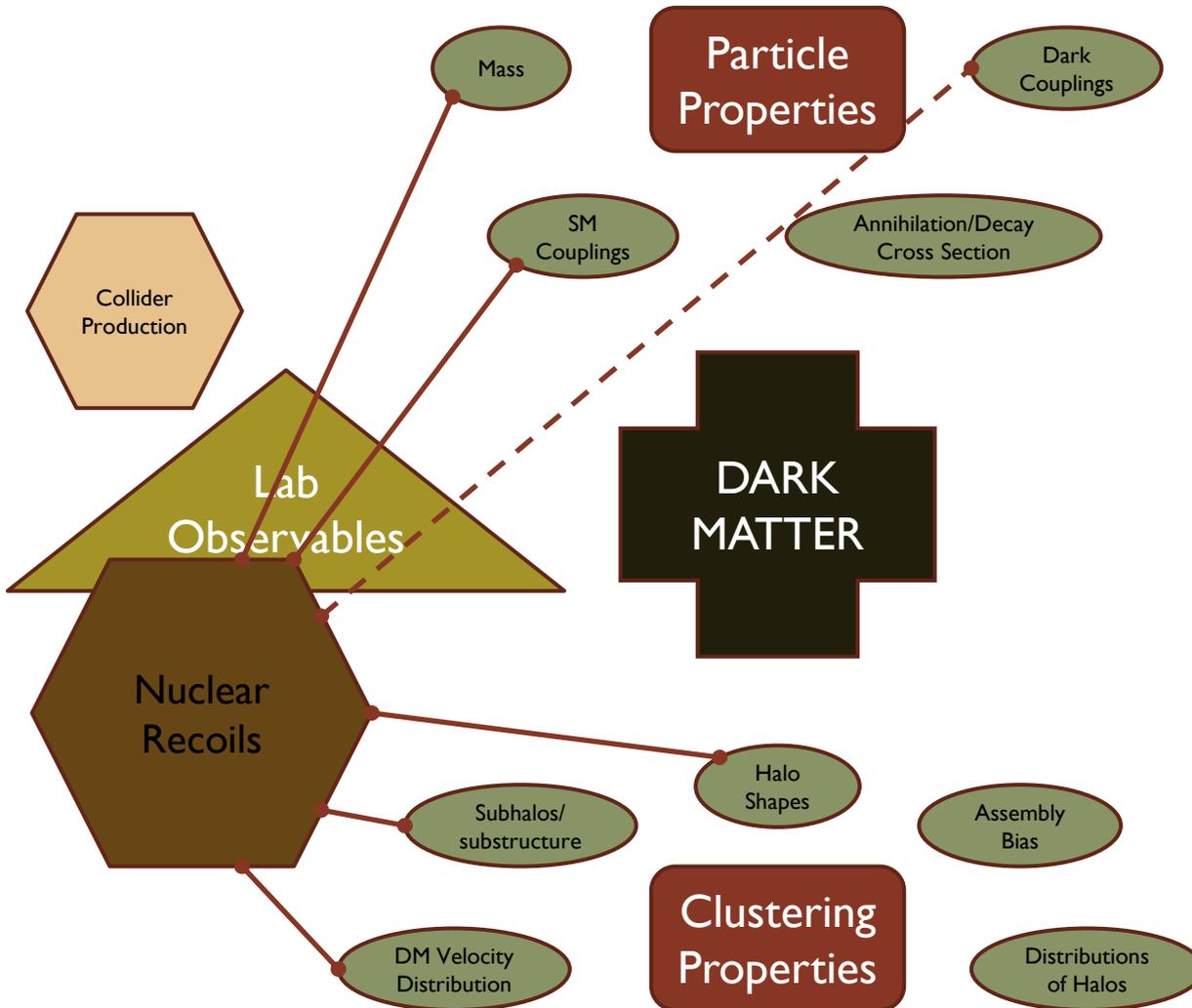
Fitting into a Global Picture: Collider



- ▶ Decay trees to the DM particle can probe some “dark sector” couplings.

More about probing DM with colliders in talks by:
John Paul Chou,
Mansoor Shamim,
Ze’ev Surujon,
Bibhushan Shakya,
Joel Walker,
Farinaldo Queiroz,
Shufang Su

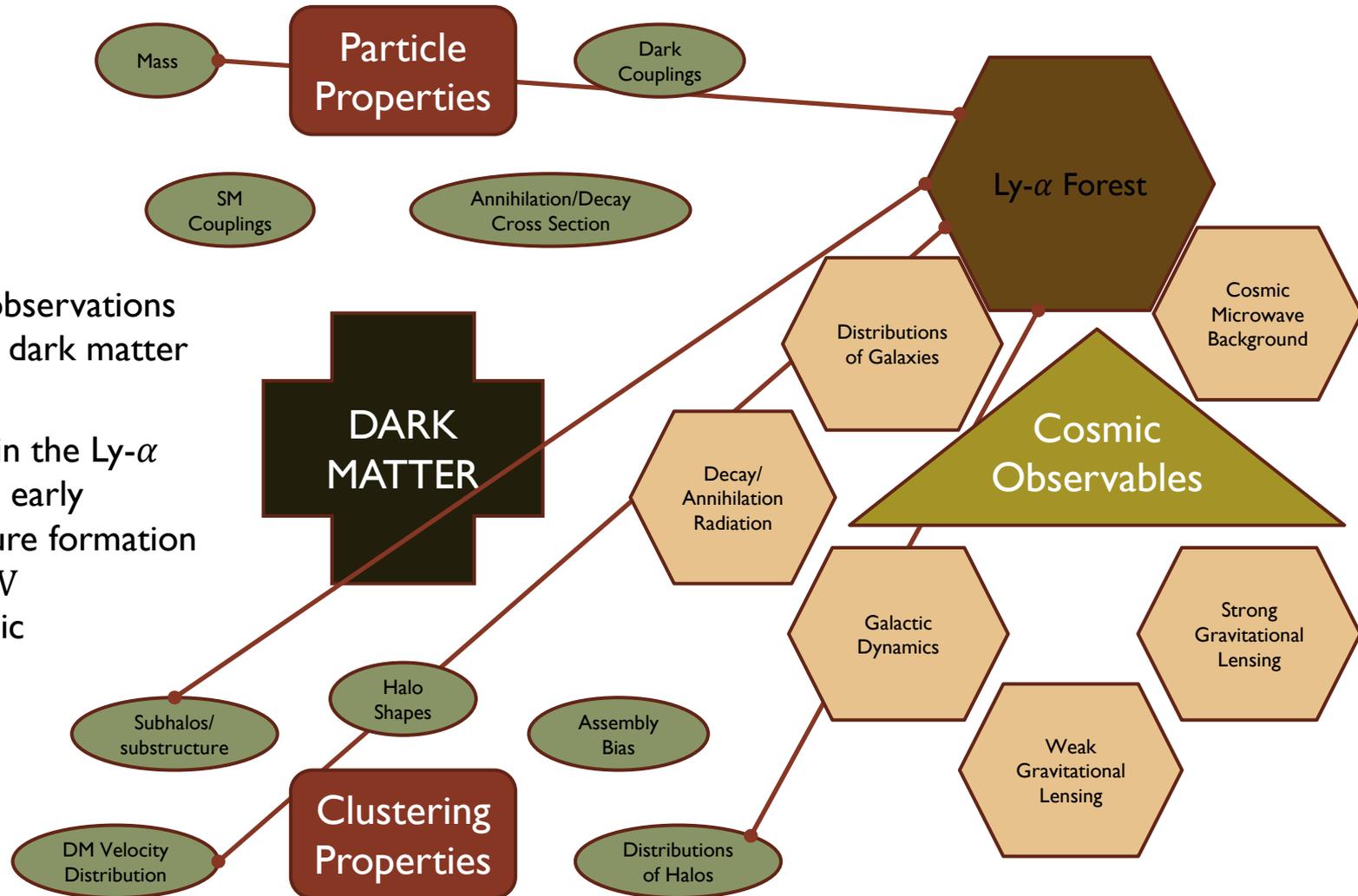
Fitting into a Global Picture: Direct Det.



- ▶ Clustering properties relevant only for **local** dark matter distribution.
- ▶ Some dark couplings can modify recoil rates.
 - ▶ E.g., excitement to higher energy states.

More about DM direct detection in talks by:
Carter Hall
Wolfgang Lorenzon
Ray Bunker
Andrew Sonnenschein

Fitting into a Global Picture: Astronomic

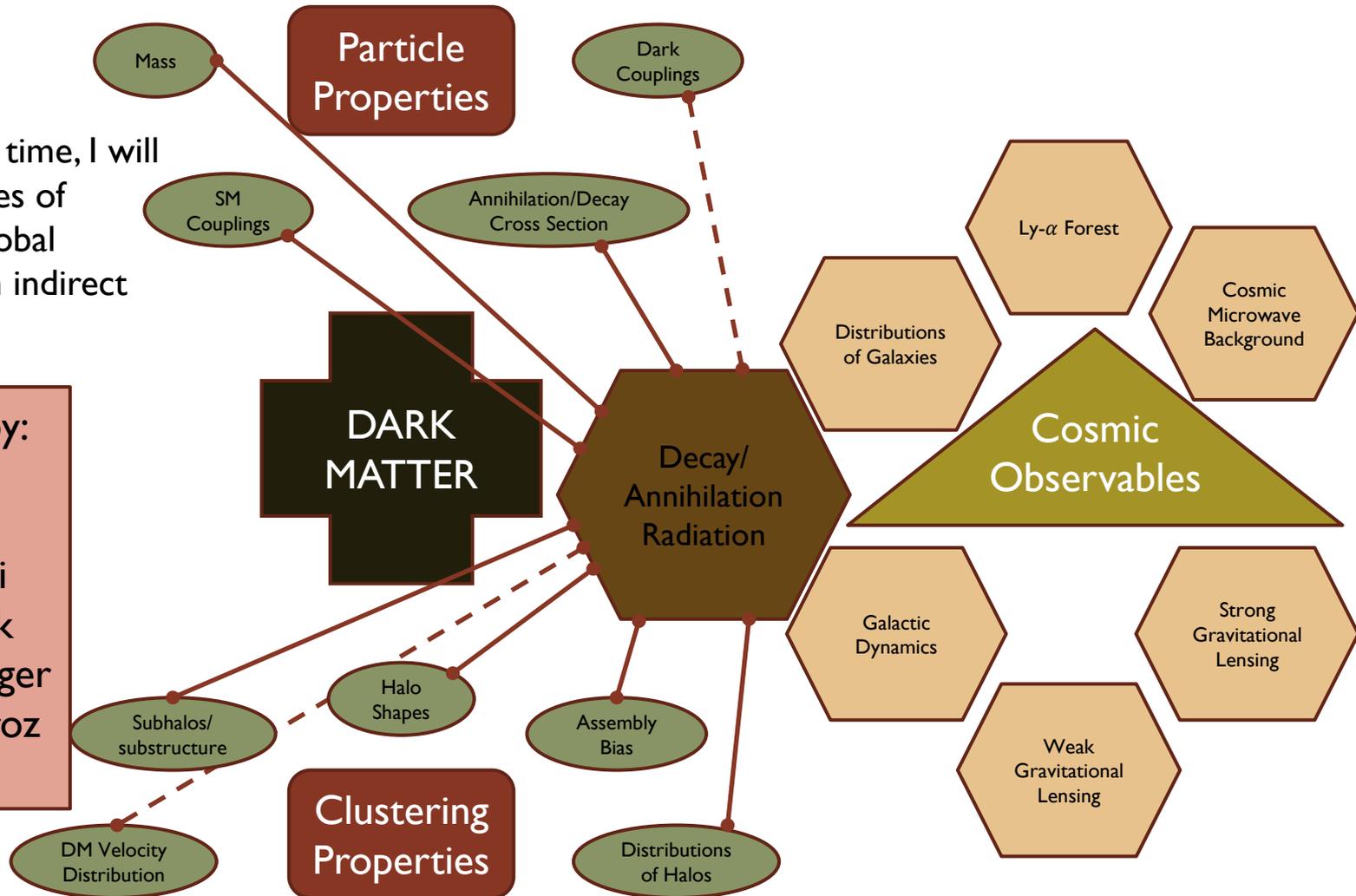


- ▶ Many cosmic observations depend on the dark matter distribution.
- ▶ E.g., structure in the Ly- α forest requires early enough structure formation $\Rightarrow m \gtrsim 2.5$ keV for thermal relic distributions.
Viel et al. (2013)

Fitting into a Global Picture: Indirect Det.

- ▶ With remaining time, I will provide examples of establishing a global framework with indirect detection.

See also talks by:
Yu Gao
Louis Strigari
Veronica Bindi
Jong-Chul Park
Matthias Danninger
Farinaldo Queiroz
Wei Xue



Outline

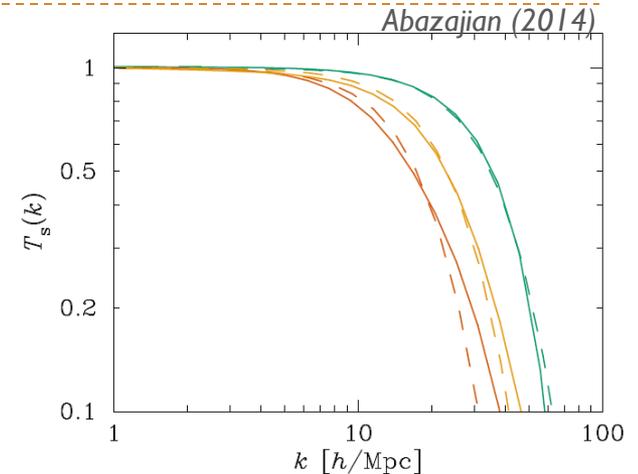
- ▶ Examples of current hints and some of their implied predictions.
 - ▶ How to establish both particle and clustering properties?
- ▶ Establishing clustering with flux methods
- ▶ Establishing clustering with anisotropy methods

Plausibility of Indirect Detection Hints

- ▶ The mode of discovery of indirect detection depends strongly on the particle and clumping properties.
- ▶ An observed hint gains additional plausibility if it is consistent with the expected first observations for the implied scenario.
 - ▶ Annihilation signals: along largest $\rho^2 ds$ lines of sight.
 - ▶ Decay signals: in large-volume fields of view.
 - ▶ Cold collisionless dark matter: halo cusps, substructure boosts.
 - ▶ Warm dark matter: cored halos, little substructure.

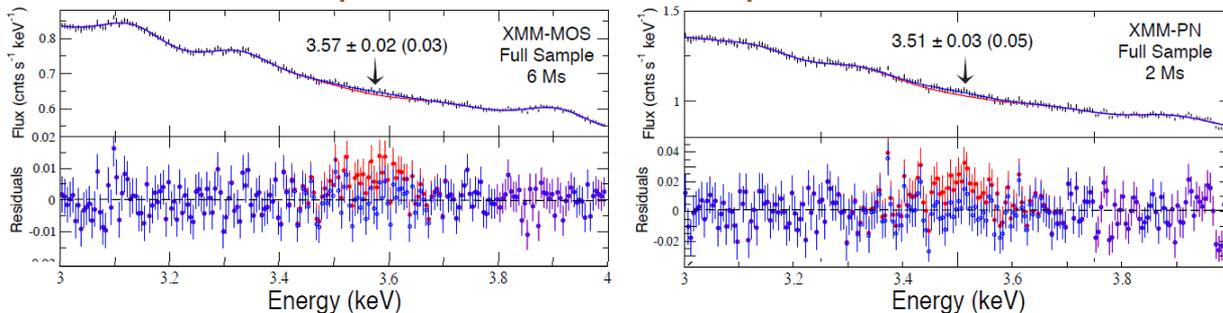
Hint 1: X-ray Line at 3.5 keV

- ▶ Photon line observed in Galaxy Clusters and Andromeda.
 - ▶ Consistent for warm dark matter (WDM).
- ▶ One dark matter interpretation:
 - ▶ Dark matter is resonantly produced 7 keV sterile ν .
 - ▶ Nonthermal transfer function similar to light WDM.
 - ▶ Decays to $\gamma + \nu$.
- ▶ Consequences for clustering/further signals:
 - ▶ Little structure below dSph scales/cored halo centers.
 - ▶ Possibility of full-sky diffuse detection in future.
 - ▶ Consequences for neutrino experiments.



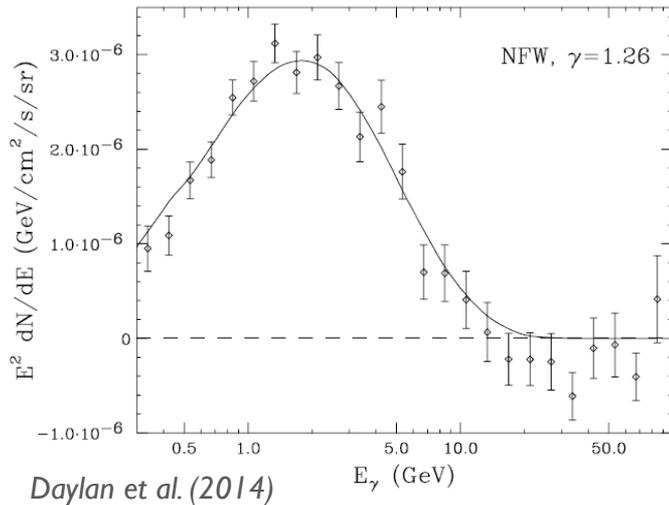
Other DM interpretations in talks by:
 Rouzbeh Allahverdi,
 Michele Cicoli,
 Ilia Gogoladze

This particular model can be ruled inconsistent if evidence of significant halo substructure is discovered.

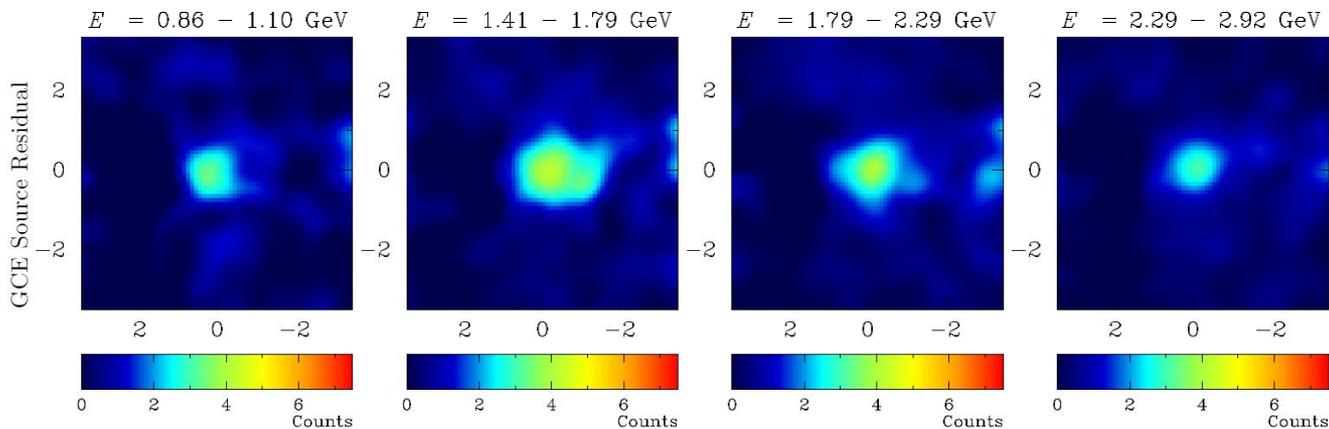


Bulbul et al. (2014), Boyarski et al. (2014)

Hint 2: GeV Galactic Center Excess



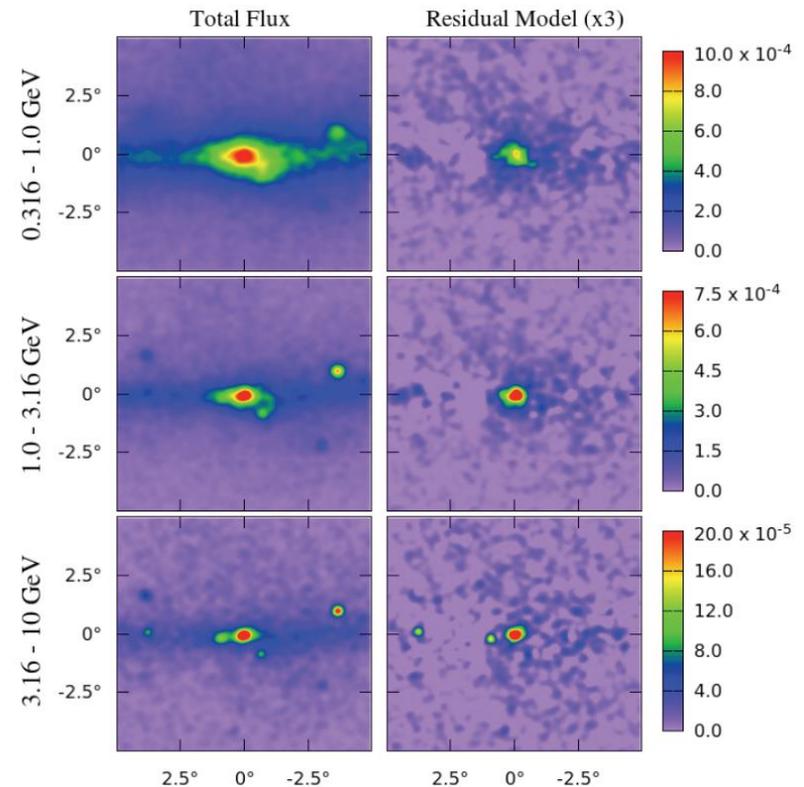
- ▶ Extended gamma-ray signal
 $0.1 < E < 1$ GeV
- ▶ Inconsistent with stellar morphology, and molecular gas morphology.
- ▶ Consistent with spherical, cuspy morphology.
- ▶ Difficult to argue this is not due to an extended population of unresolved pulsars.



Also see talks by:
Louis Strigari,
Jong-Chul Park,
Farinaldo Queiroz

Hint 2: GeV Galactic Center Excess

- ▶ We have a signal consistent with:
 - ▶ thermal relic annihilation,
 - ▶ annihilation to heavy quarks and/or leptons,
 - ▶ a 10-30 GeV WIMP.
- ▶ First detection of WIMP at a cuspy galactic center is the textbook expectation.
- ▶ In this scenario, the distributions of Milky Way and M31 satellites are unusual.

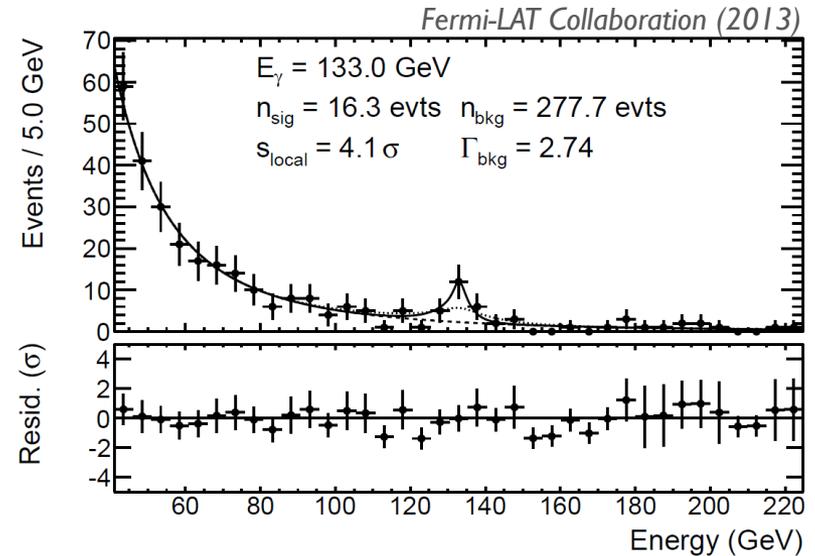


Hint 2: GeV Galactic Center Excess

- ▶ Predictions are robust:
 - ▶ Fermi-LAT hints of annihilation in the Dwarf Spheroidals should be expected to be just around the corner.
 - ▶ Diffuse gamma-ray observations will be probing Milky-Way halo substructure parameter space, especially with such cuspy density profiles.
- ▶ A lack of corresponding observations in dwarf galaxies and diffuse gamma-rays will put this DM interpretation in question.

Hint 3: The 135 GeV Line Case Study

- ▶ Gamma-ray excess from Galactic center.
- ▶ ~ 4 standard deviations above background.
- ▶ Source morphology consistent with spherical cusp.
- ▶ Some features of the signal made the dark matter explanation less compelling:
 - ▶ spectral line feature was narrower than the energy resolution.
 - ▶ a similar, though smaller, line in the Earth limb.



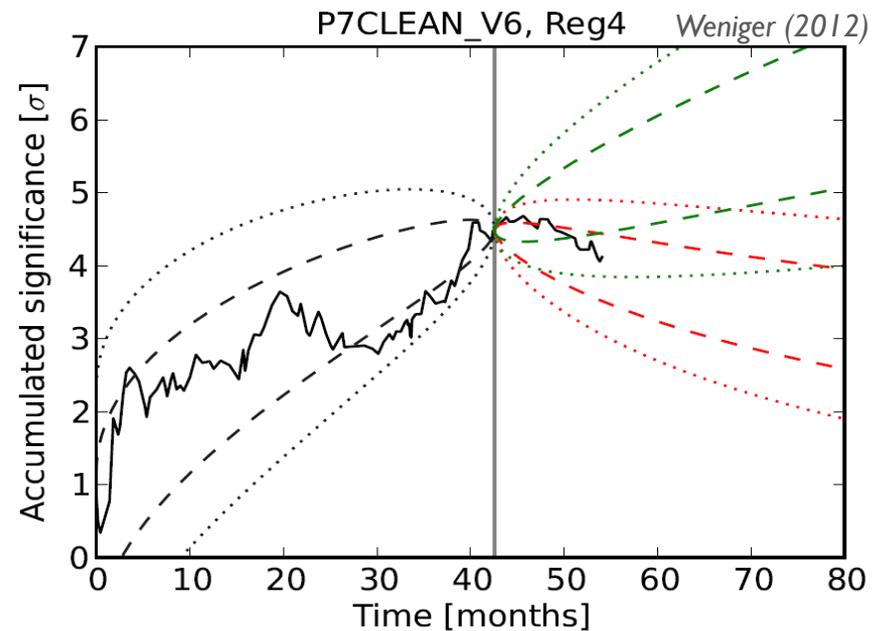
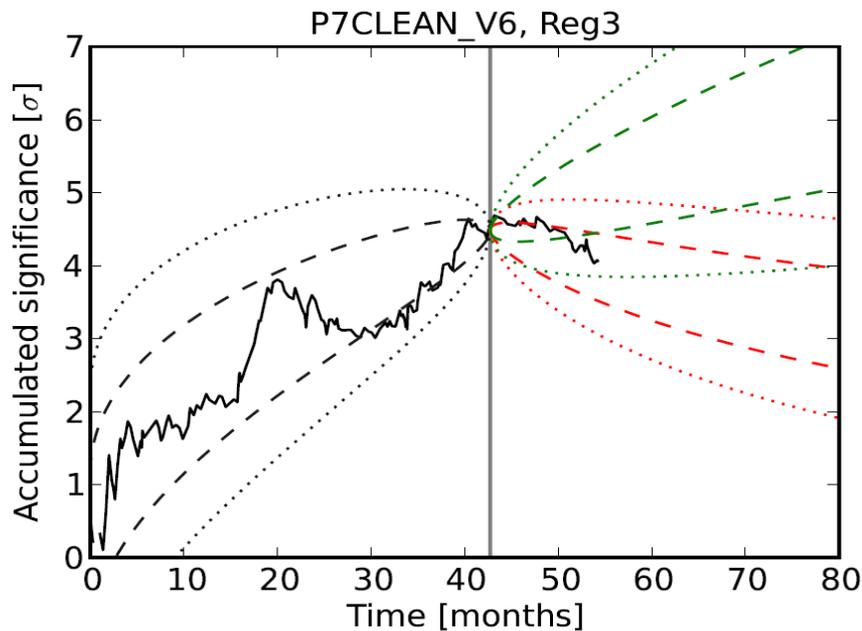
Hint 3: The 135 GeV Line Case Study

Predictions:

- ▶ If due to a systematic effect
 - ▶ the apparent signal will persist in all regions until the source is determined.
- ▶ If the signal is dark matter annihilation
 - ▶ the line will broaden and its significance will grow.
 - ▶ the line may be observed in other dark matter regions.
- ▶ If the signal is a statistical fluctuation
 - ▶ the signal will shrink and disappear.

Hint 3: The 135 GeV Line Case Study

- ▶ The fulfillment of the 3rd prediction gives support to the hypothesis that the line was a statistical fluctuation.



So Given an Indirect Detection Hint,
What is a Good Way to Turn it into
a Dark Matter Discovery?

What is a Good Way to Turn an Indirect Detection Hint to Dark Matter Discovery?

- ▶ We've seen a hint. Now that we know where to look, **go for the diffuse signal!**
 - ▶ It verifies the particle properties observed with the hint.
 - ▶ It establishes the clustering properties of dark matter—heretofore unobserved.

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

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

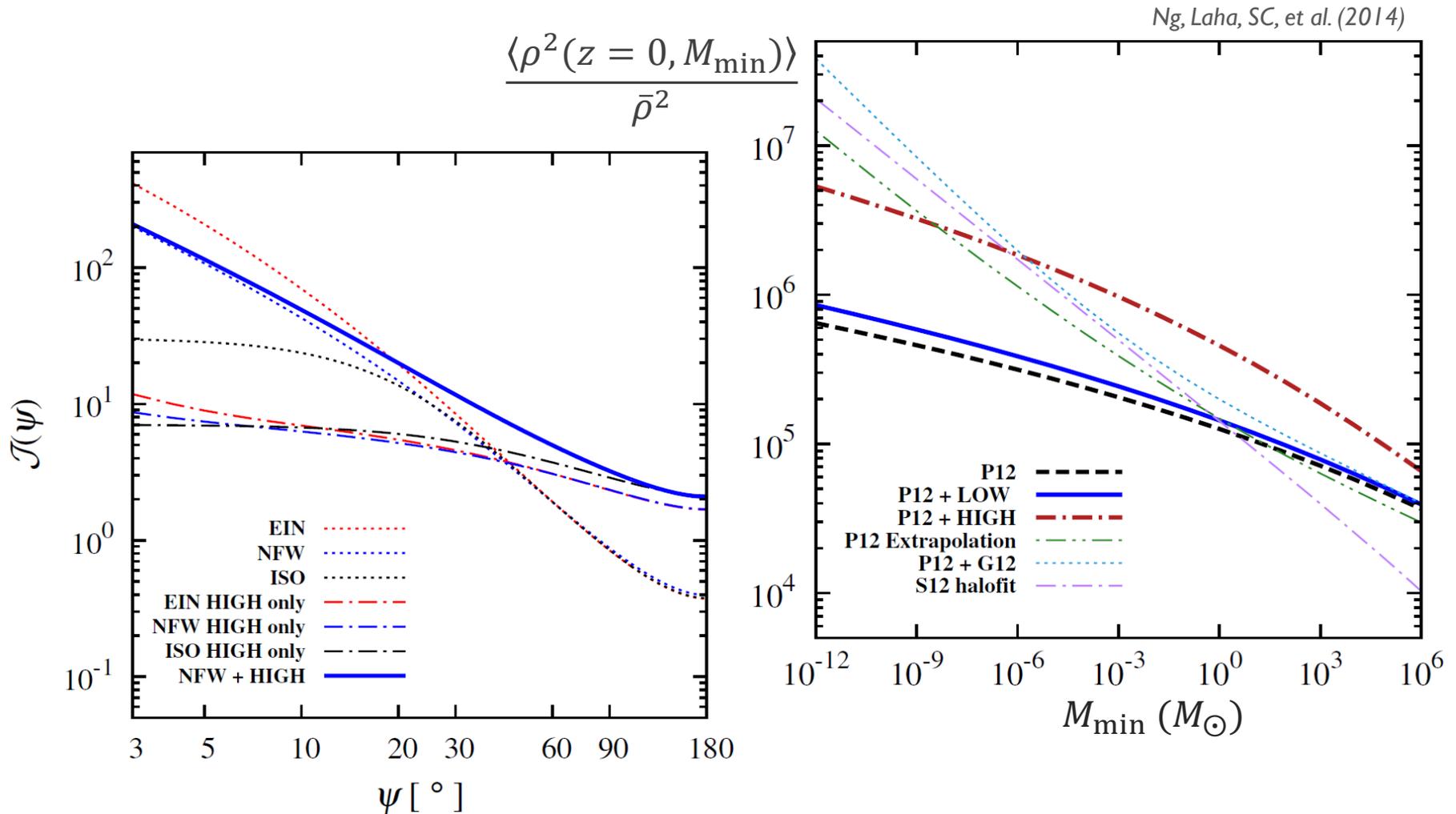
Ambiguity between σv and substructure contribution to $\langle \rho^2(z) \rangle$.

For local annihilations:

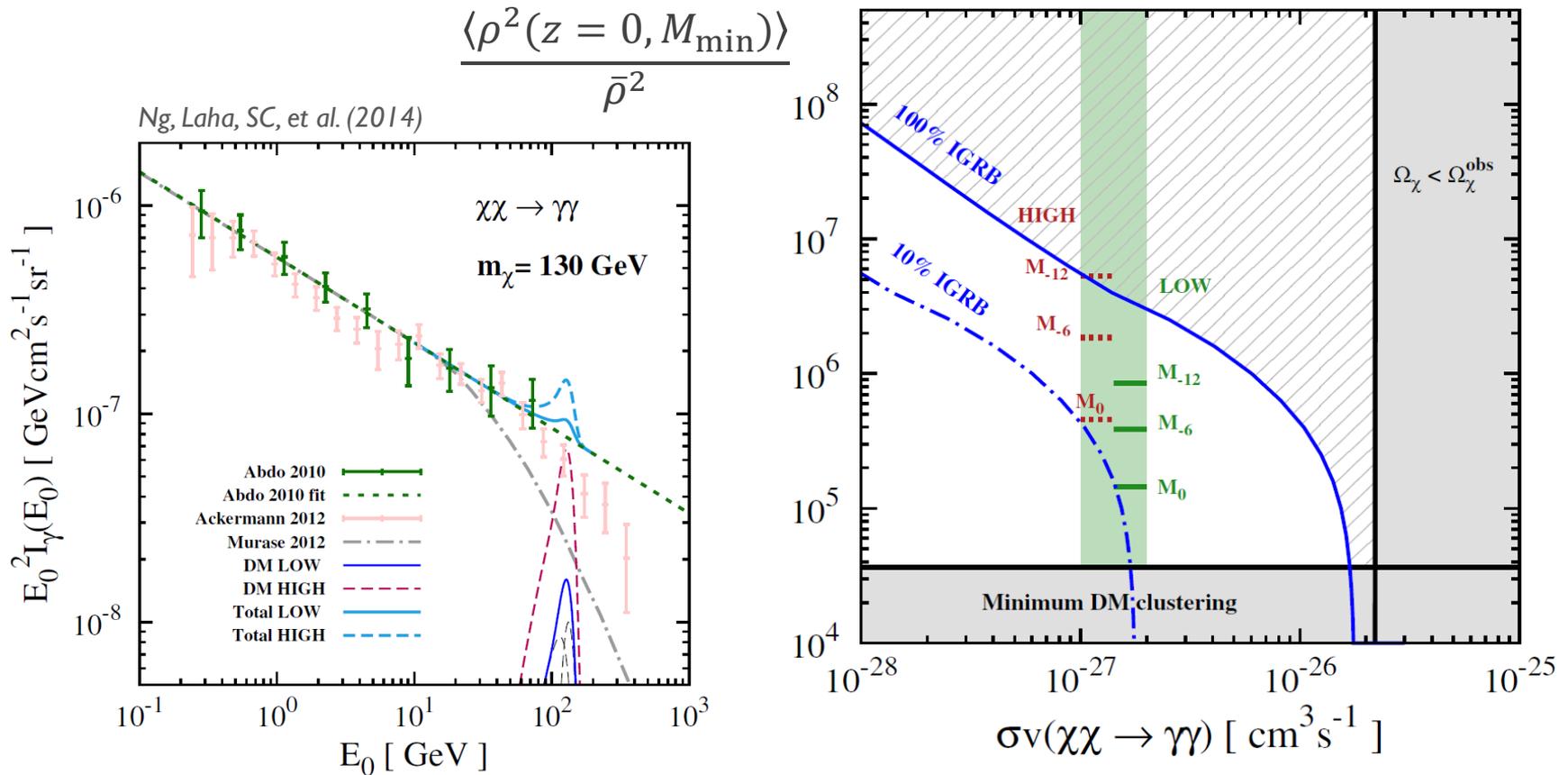
$$I(E, \mathbf{n}) = \frac{\sigma v}{8\pi m^2} \frac{dN_\gamma(E)}{dE} J(\mathbf{n}), \quad J(\mathbf{n}) = \int_{\text{line of sight}} ds \rho^2(s, \mathbf{n}).$$

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

Need Consistent DM Distribution for Observed Scenario

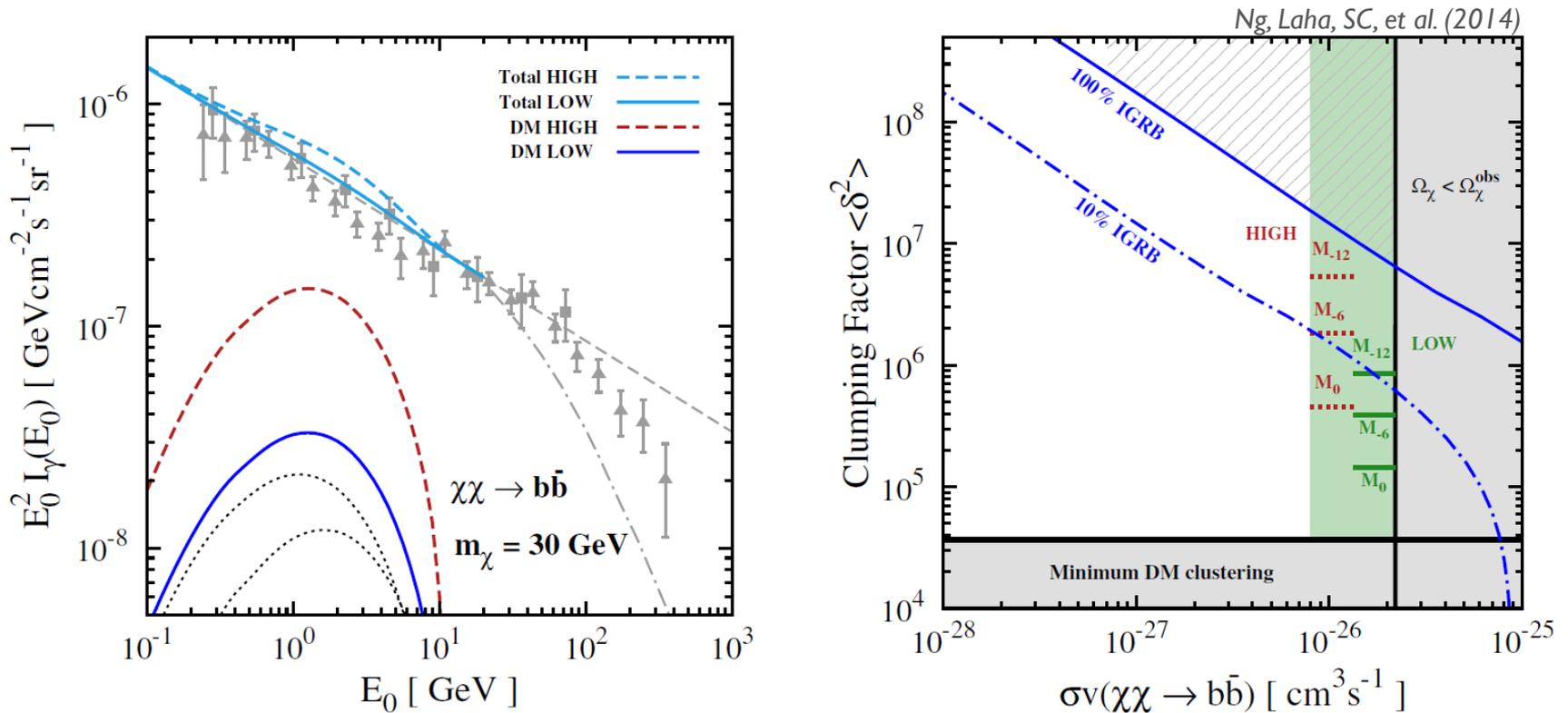


Flux Methodology: Spectral Line



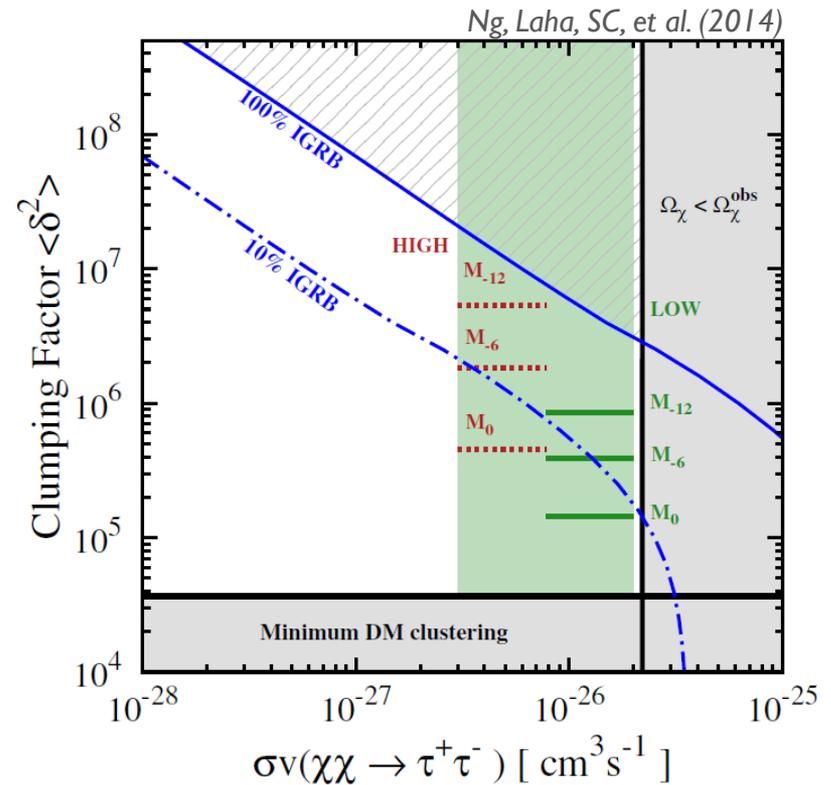
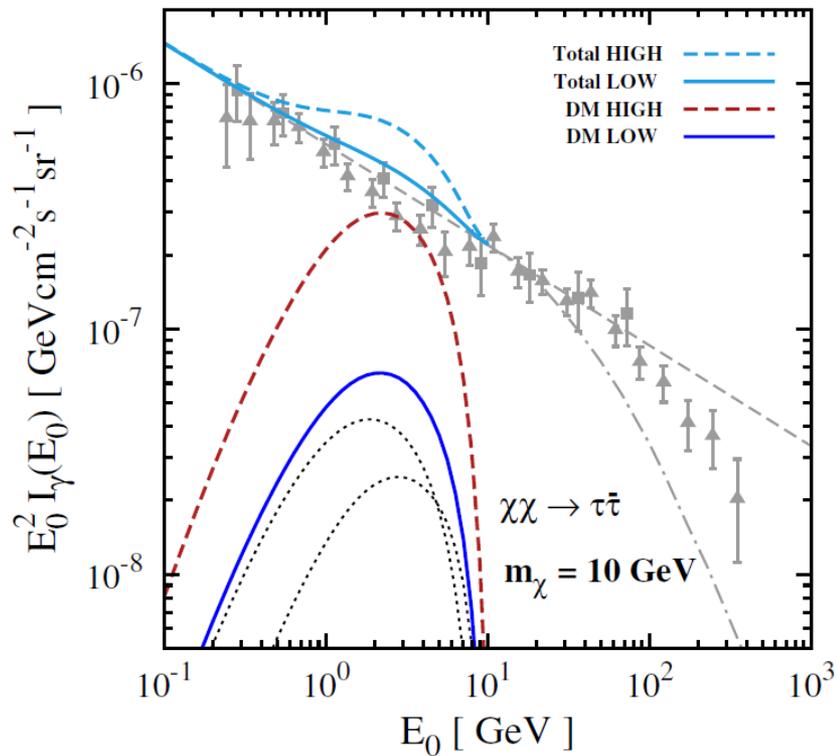
The lack of a 135 GeV line in the diffuse gamma-ray background for high substructure content further strains the plausibility of a dark matter interpretation.

Flux Methodology: GeV GC Excess



For annihilation to $b\bar{b}$, non-observation of the diffuse signal with Fermi-LAT is predicted to be plausible, but observation is still possible.

Flux Methodology: GeV GC Excess

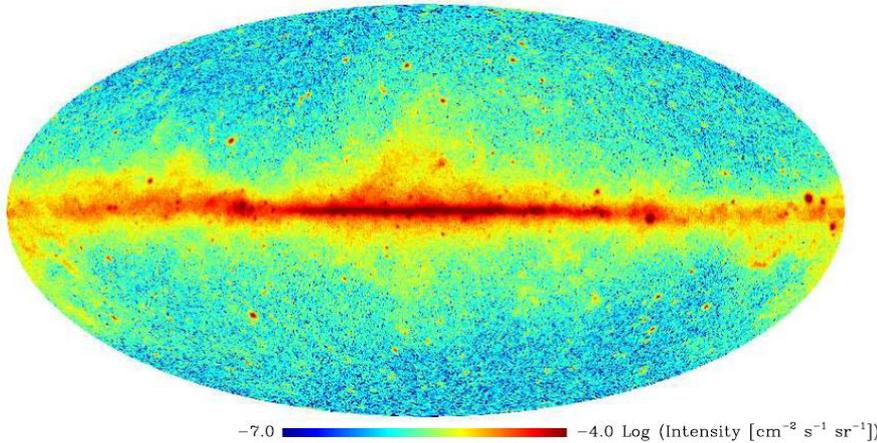


For dominant τ channel annihilation, expectations of large substructure content and full thermal relic abundance predict a likely detection of diffuse annihilation radiation.

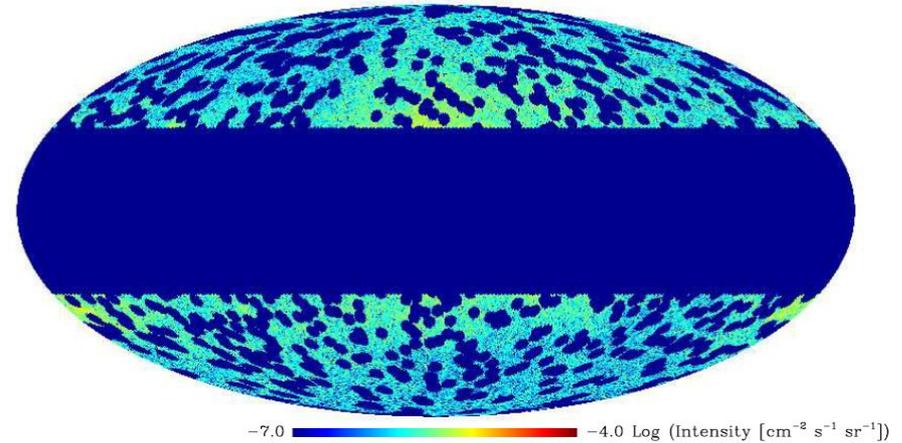
Complementary Approach: γ -ray Anisotropies

Fermi-LAT Collaboration (2012)

DATA (P6_V3 diffuse), 1.0–2.0 GeV



DATA (P6_V3 diffuse), 1.0–2.0 GeV



Angular Power Spectrum C_ℓ

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

Fluctuation Angular Power Spectrum \widetilde{C}_ℓ

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

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.**

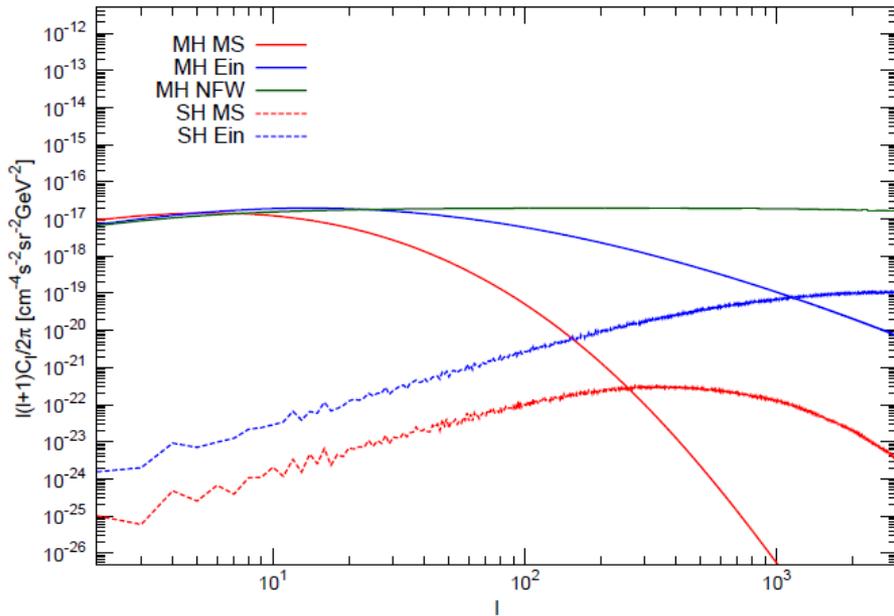
$$C = C_1 + C_2 + \dots$$

$$\widetilde{C} = \left(\frac{I_1}{I}\right)^2 \widetilde{C}_1 + \left(\frac{I_2}{I}\right)^2 \widetilde{C}_2 + \dots$$

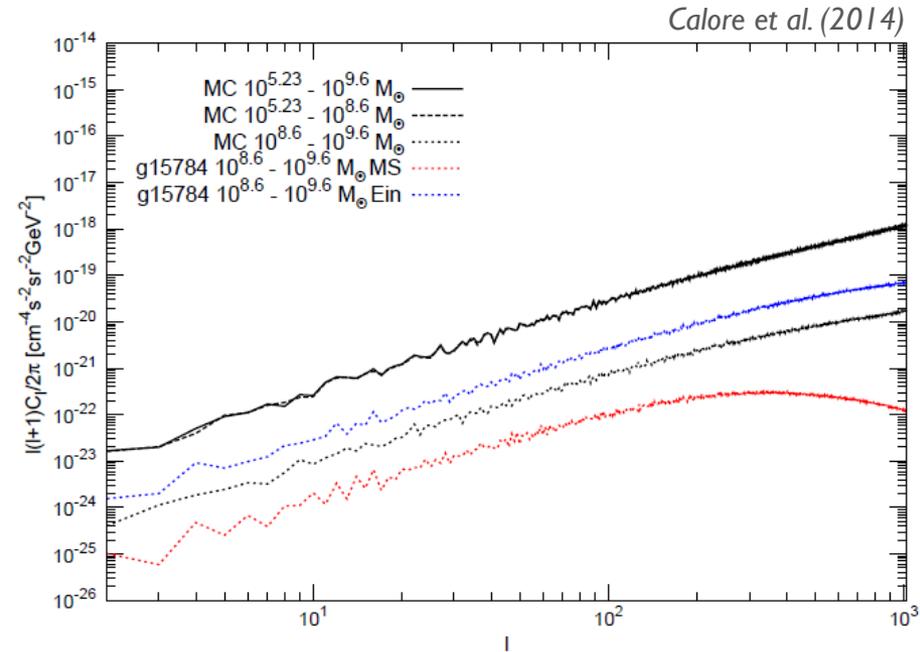
- ▶ **Statistical Error for weighted average over $\ell_1 \leq \ell \leq \ell_2$.**

$$\sigma_{\widetilde{C}} \propto \begin{cases} N_\gamma^{-1}, N_\gamma \text{ small} \\ N_\gamma^0, N_\gamma \text{ large} \end{cases}$$

\tilde{C} is sensitive to clustering properties

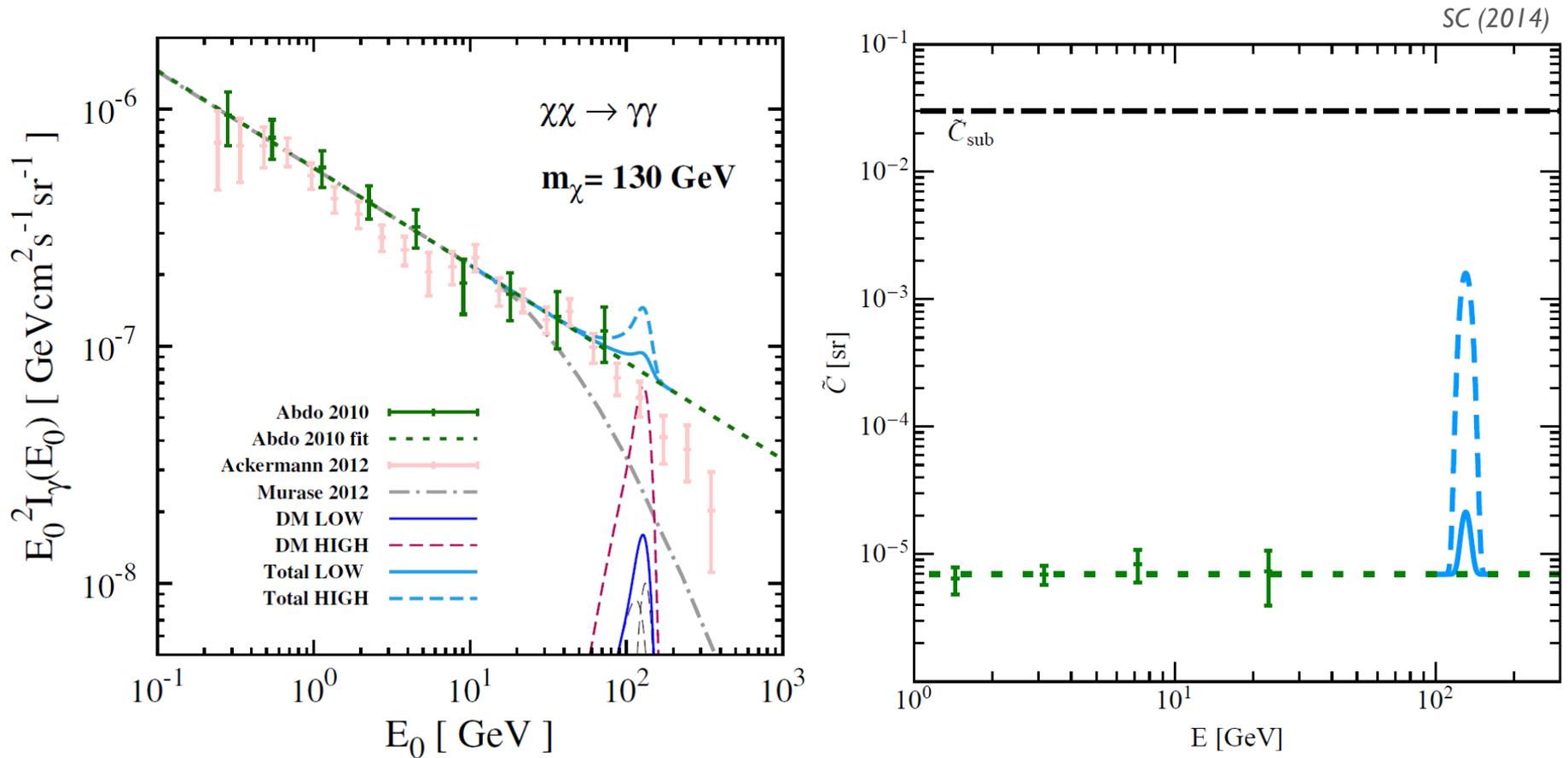


Sensitive to the density profile of the Galactic halo and subhalos (simulations).



Sensitive to the subhalo abundance and mass range (simulations).

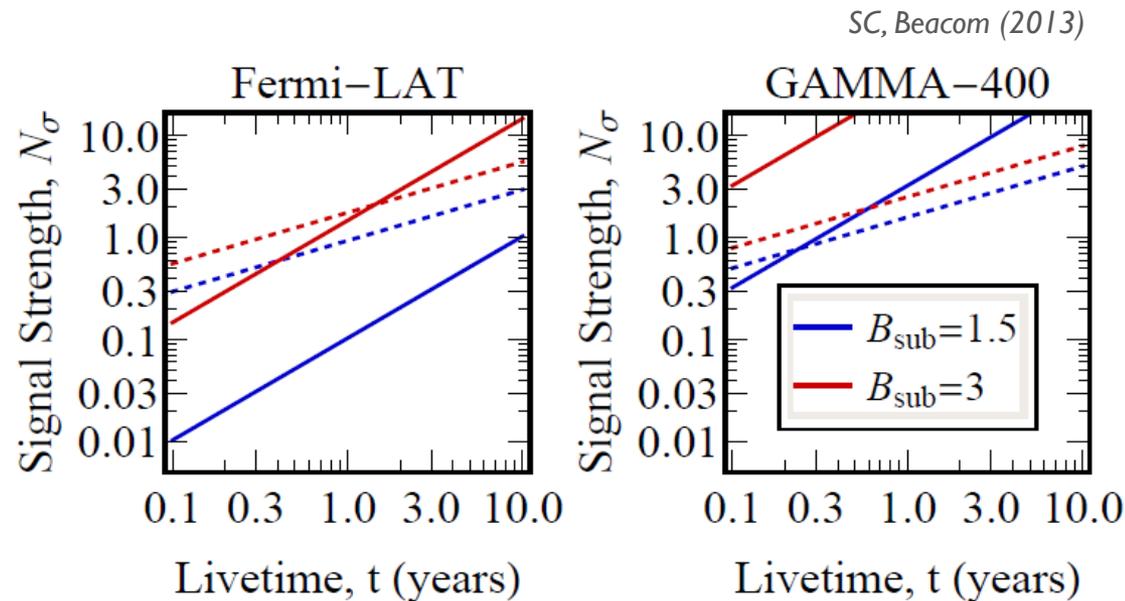
Anisotropy of a Spectral Line



Growth of Signal Strength

E.g., A 135 GeV Line

Signal Strength = Signal / Measurement Uncertainty



B_{sub} is the factor of intensity boost over a smooth halo signal, due to galactic subhalos.

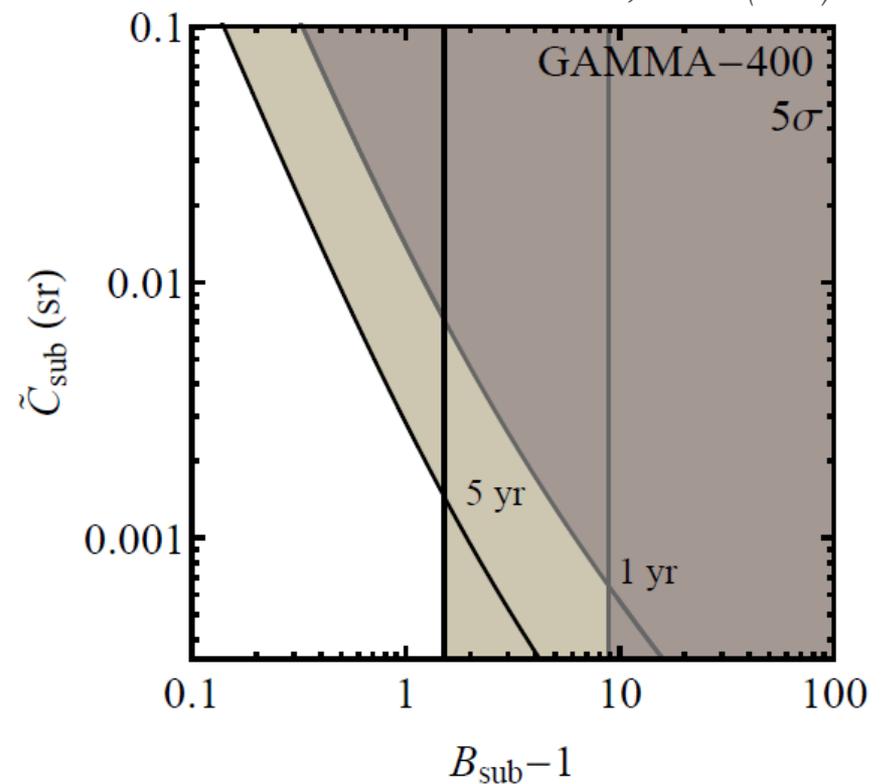
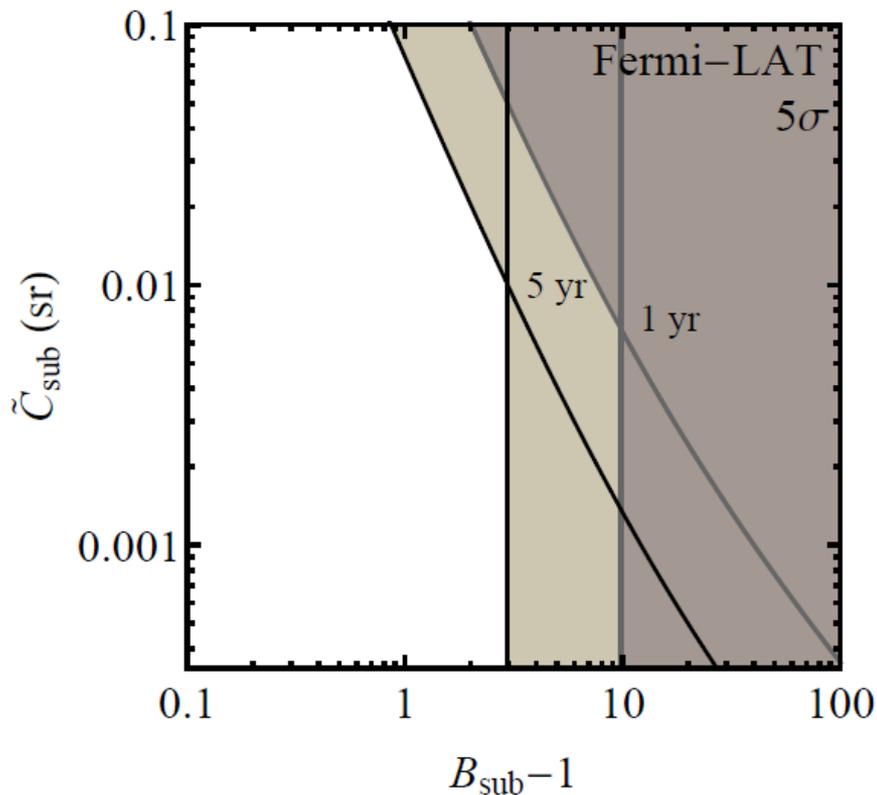
$\propto \sqrt{t}$ for flux (dotted lines)

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

Complementary Flux/Anisotropy 130 GeV Line Search in the Diffuse Bkg.

The Fluctuation Angular Power Spectrum (Clustering) vs. Substructure Intensity Boost

SC, Beacom (2013)



Conclusions

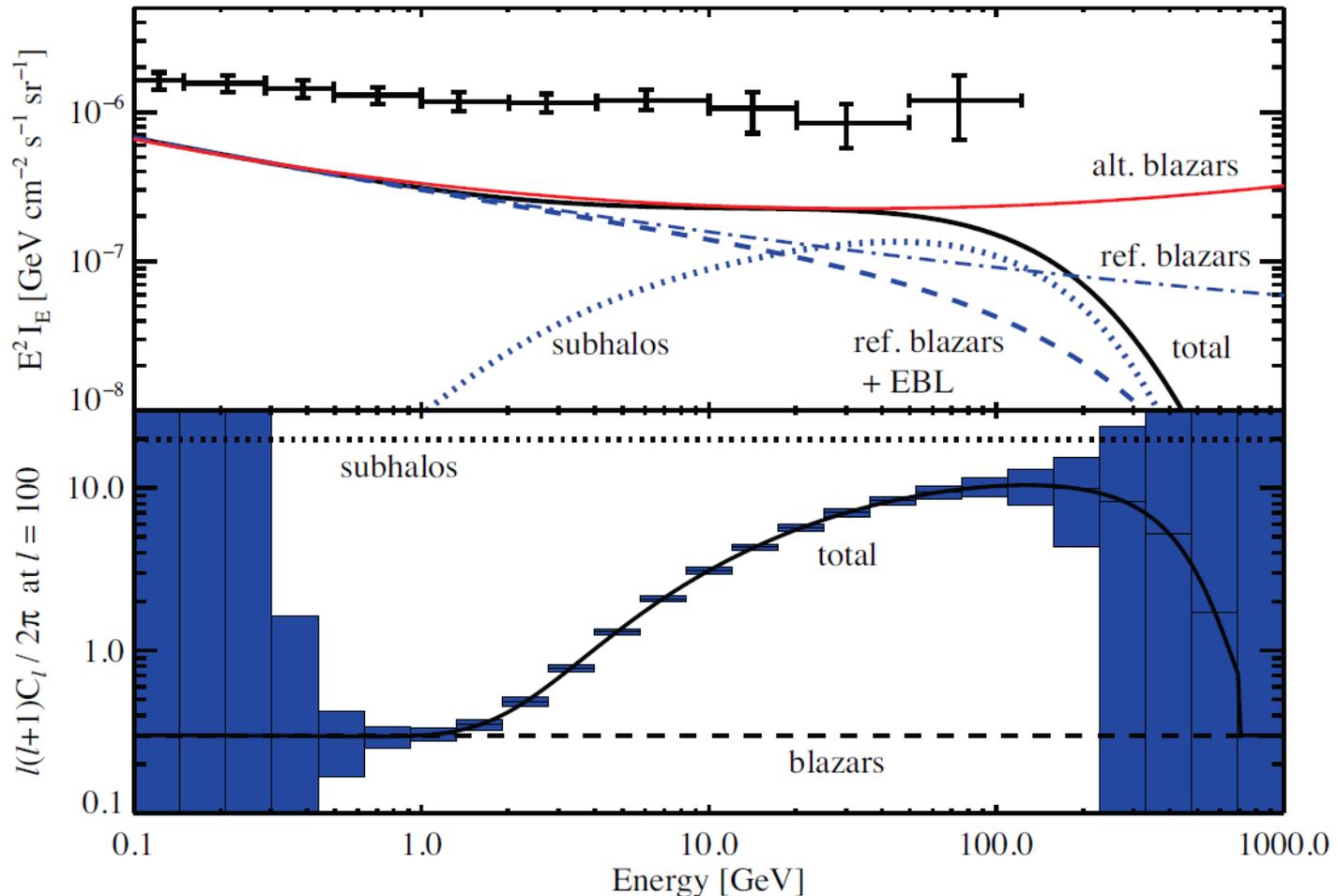
- ▶ Dark matter interpretations of astrophysical excess signals are difficult to assess.
- ▶ Good dark matter proposals should satisfy:
 - ▶ plausibility—it is the signal where discovery would be expected for the dark matter being proposed,
 - ▶ predictability—we know where to look for verification.
- ▶ Claim of dark matter discovery should establish a model that accounts for both the **particle** properties and **clustering** properties.
- ▶ Detection of the **diffuse dark matter signal** is particularly powerful for establishing confidence in the **discovery** of the nature of astrophysical dark matter.
- ▶ Both flux and anisotropy methods may prove important in the detection and interpretation of the dark matter emission.

Turning DM Hints into DM Discoveries

- ▶ Thanks for your attention, and **Happy Hunting!**

Anisotropy with Continuous Annihilation Spectra

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



Fluct. Angular Power Spectra from DM

Fornasa et al., arXiv:1207.0502

