
# Dark Matter Constraints from Isotropic gamma-ray fluxes

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<u>In collaborations with:</u>

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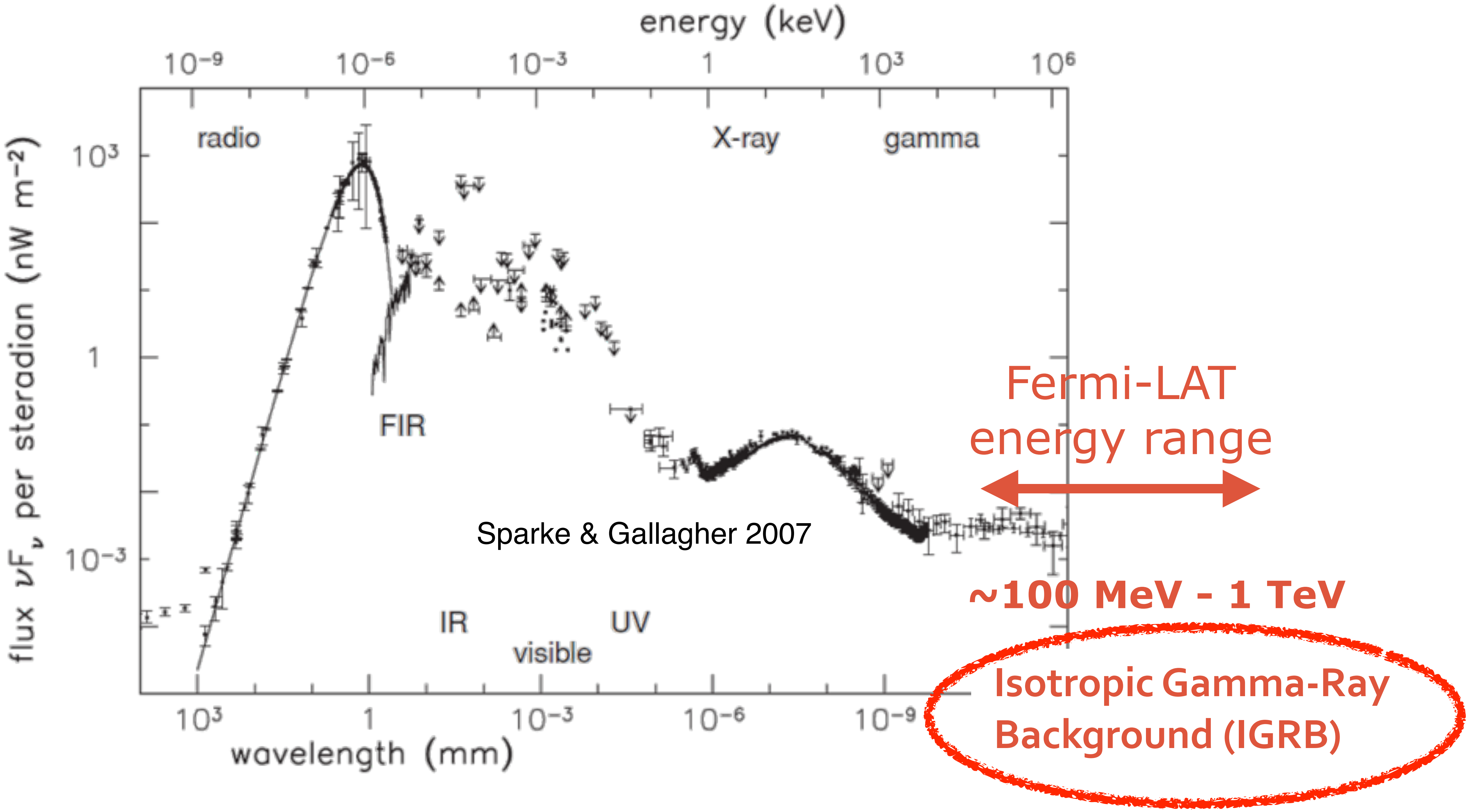
…and on behalf of the Fermi LAT collaboration

**Trieste, May 6, 2016**

# Extragalactic energy spectrum




How to use of the Fermi-LAT IGRB energy spectrum measurement to constrain/detect DM signals?

# Approaches for DM search in the IGRB

- Analysis of anisotropies in the 'isotropic' gamma-ray backgr.
  - ✓ 1-point PDF **Ben Safdi's talk**
  - ✓ angular power spectrum (or wavelets) **Mattia Fornasa's talk**
  - ✓ cross-correlations **Alessandro Cuoco's talk**

- Traditional use of IGRB's energy spectrum
  - ✓ CONs:
    - Only one handle (the Energy spectrum) to separate out a dark matter component
  - ✓ PROs:
    - Large photon count statistics (up to ~800 GeV)
    - (arguably) Less sensitive to uncertainties in modeling of angular and redshift distributions of DM and backgrounds

# Main challenges for this DM search

1. Derivation of the IGRB/EGB
   ✓ modeling the galactic diffuse emissions

2. Predictions of DM clustering (for DM annih. cross sections)
   (NB: not an issue for decaying DM signals)

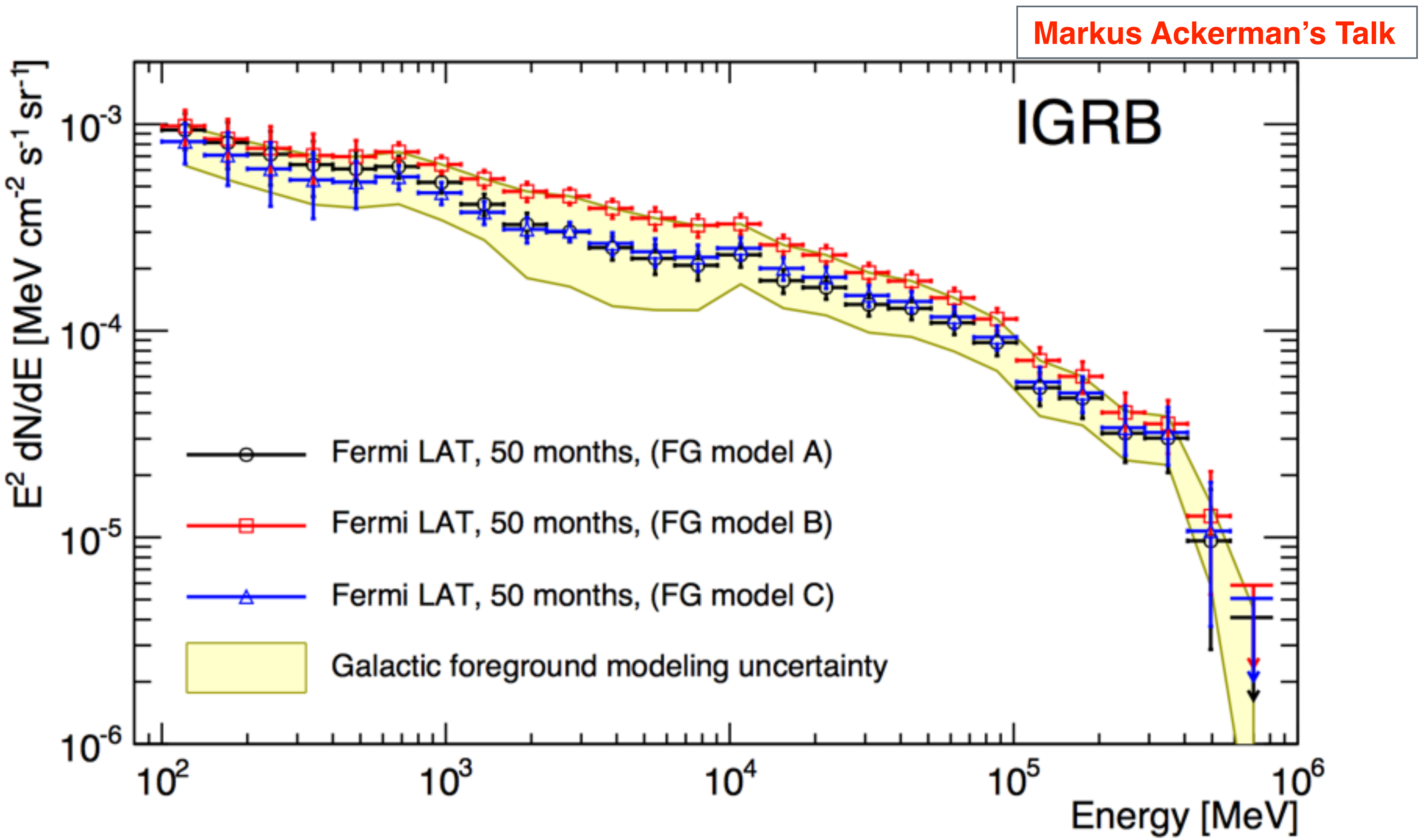
3. Incorporate ‘guaranteed’ extragalactic contributions to IGRB

# The Isotropic Gamma-ray Background (IGRB)

# energy spectrum

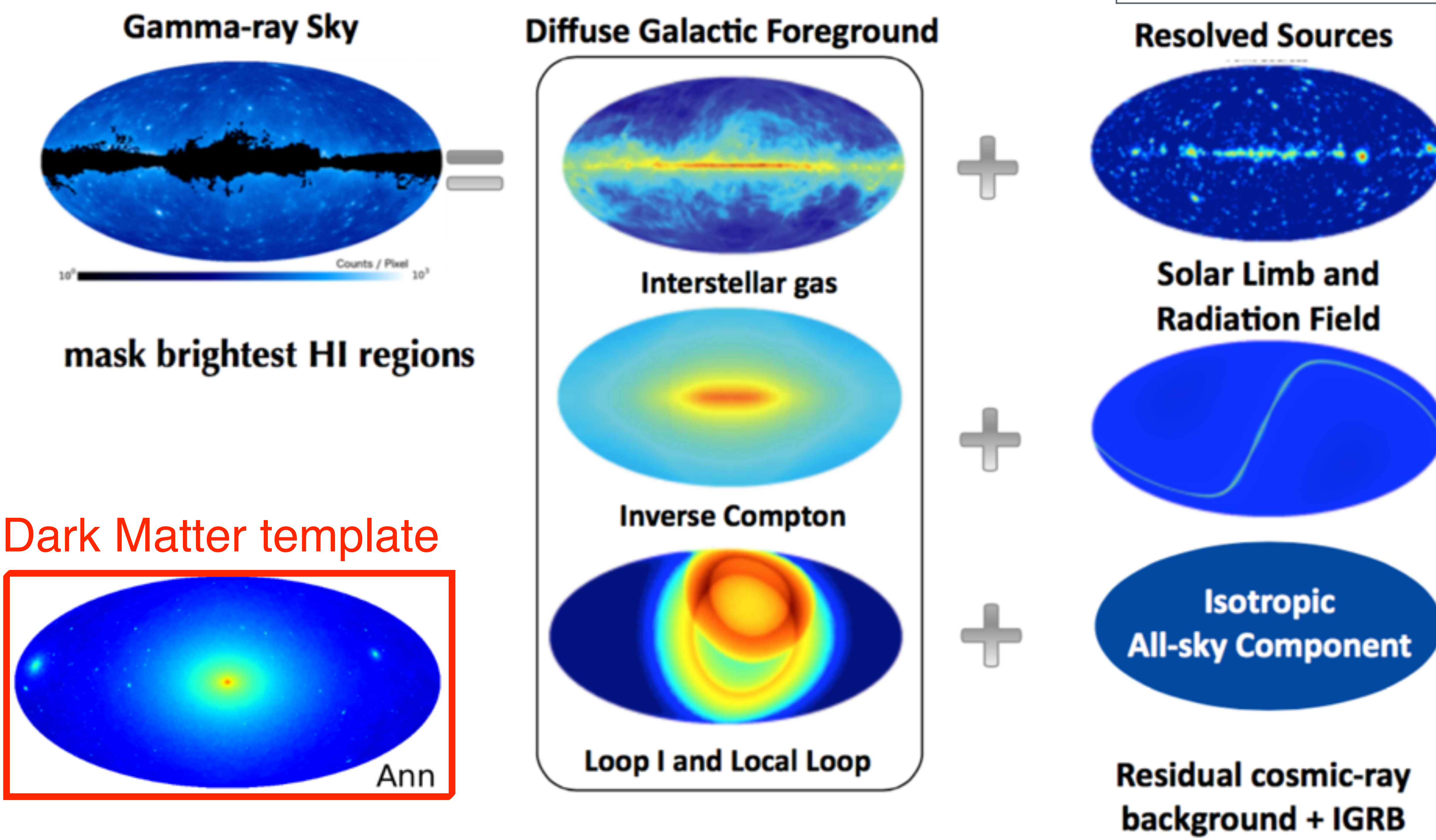
# The Fermi LAT IGRB spectrum

[Isotropic Gamma-Ray Background]



# Galactic diffuse emission: Template Fitting Procedure (maximum likelihood in each pixel and energy bin)

Markus Ackerman's Talk



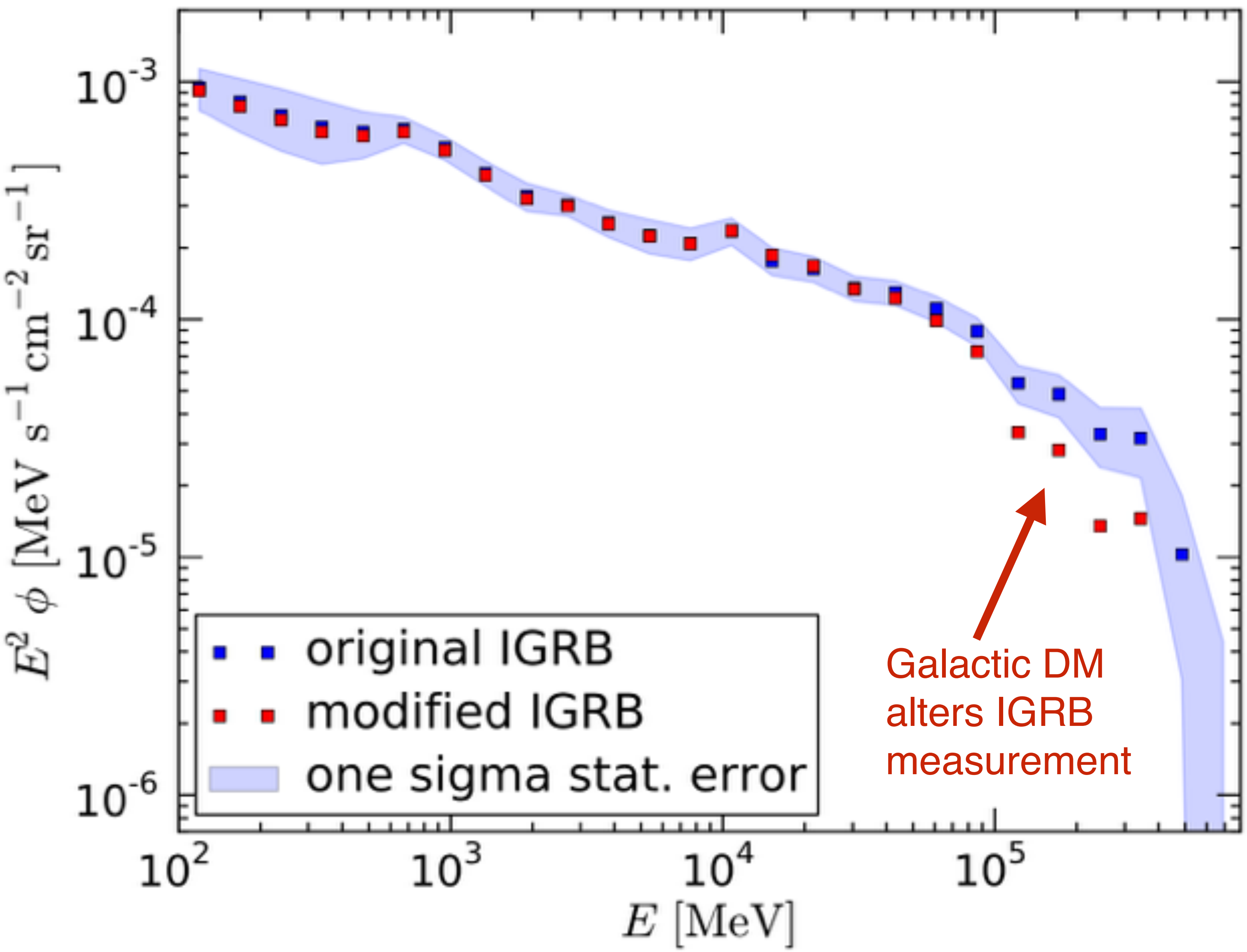
# A Comment on Galactic emission templates

- No Galactic DM template used in the IGRB measurement
- Could a Galactic DM gamma-ray signal effect the IGRB measurement?

Example:
A 5 TeV WIMP with

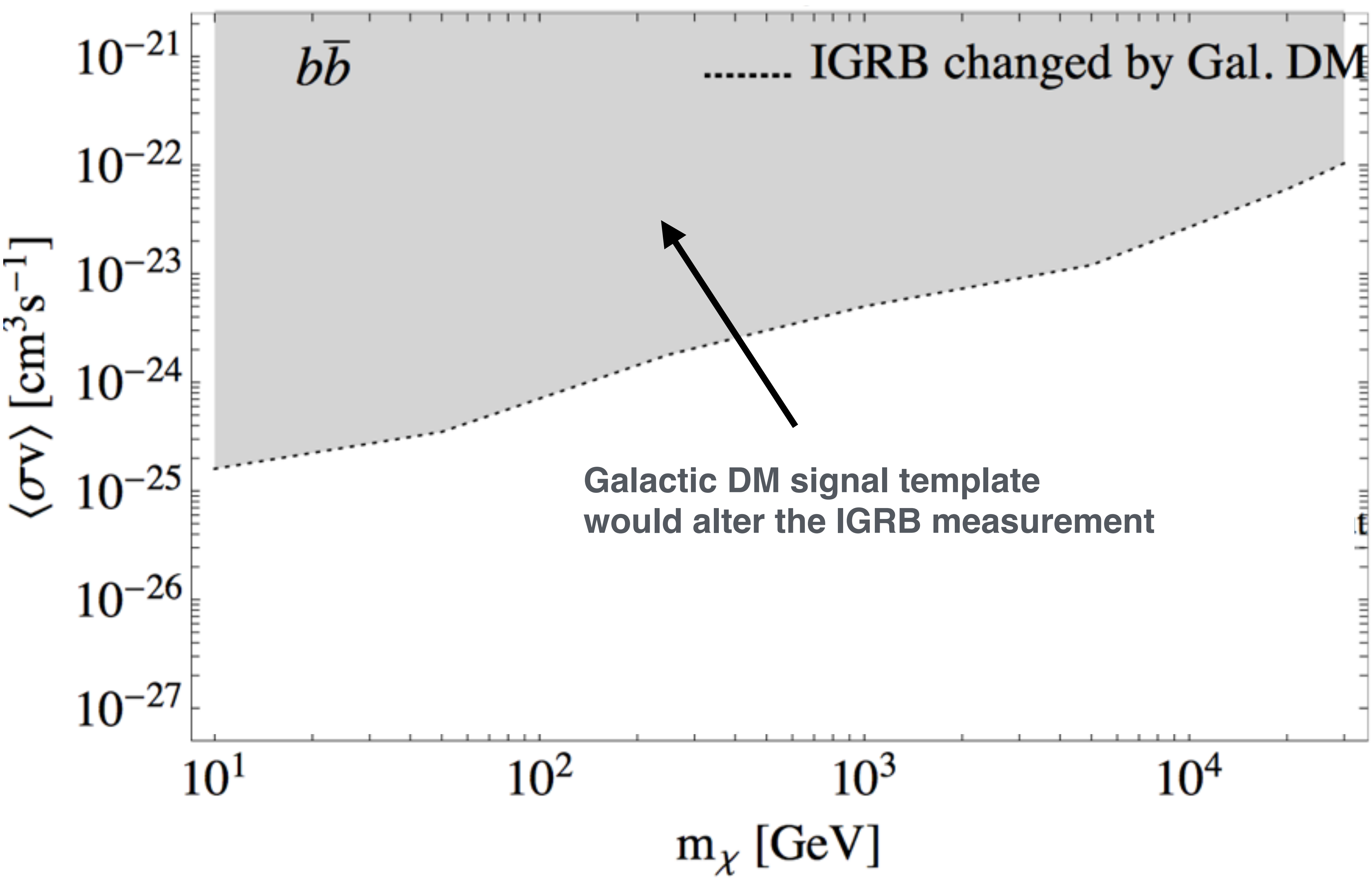
$$\langle \sigma v \rangle = 10^{-23} \mathrm{cm}^3/\mathrm{s}$$

into b-quarks modifies the IGRB measurement




(For NFW with local DM density of 0.2 GeV/cm$^3$)

# Region of `modified` IGRB



# The Extragalactic
# Dark Matter Signal Strength

# Extragalactic γ-rays from annihilating DM

$$n = \frac{\langle \sigma\, v \rangle}{2\, m_{DM}^2} \int_V d^3x\, \rho_{DM}^2(\vec{x})$$

# of annihilations per unit volume

$$\frac{d\phi_\gamma}{dE_0} = \frac{1}{8\,\pi} \frac{\langle \sigma\, v \rangle}{m_{DM}^2} \int dz\, \frac{(1+z)^3}{H(z)} \frac{dN_\gamma[E_0\,(1+z)]}{dE}\, e^{-\tau(z,E_0)} \rho^2(z)$$

observed spectrum

DM particle properties

geometry

spectrum at emission

Optical Depth

**Dark Matter Density**

Ullio *et al.* (2002)

# A *Power Spectrum* approach

$$\rho(z,\hat{\Omega}) = \bar{\rho}(z)\left[1+\delta(z,\hat{\Omega})\right] \rightarrow \rho^2(z) \simeq \bar{\rho}^2(z)\langle\delta^2(z,\hat{\Omega})\rangle$$

Dark matter power spectrum

See Tom Theuns' talk

$$\langle\delta(\vec{x})\delta(\vec{x}+\vec{r})\rangle = \frac{1}{(2\pi)^3}\int e^{ikr}P(k)$$

$$\zeta = \langle\delta(\vec{x})\delta(\vec{x})\rangle = \frac{1}{2\pi^2}\int dk\, k^2 P(k)$$

The Flux Multiplier

Non Linear DM power spectrum

$$\zeta(z) = \langle\delta^2(z,\hat{\Omega})\rangle = \int_0^{k_{max}} \frac{dk}{k}\frac{k^3\, P_{NL}(k)}{2\pi^2}$$

Serpico+ MNRAS, 2012

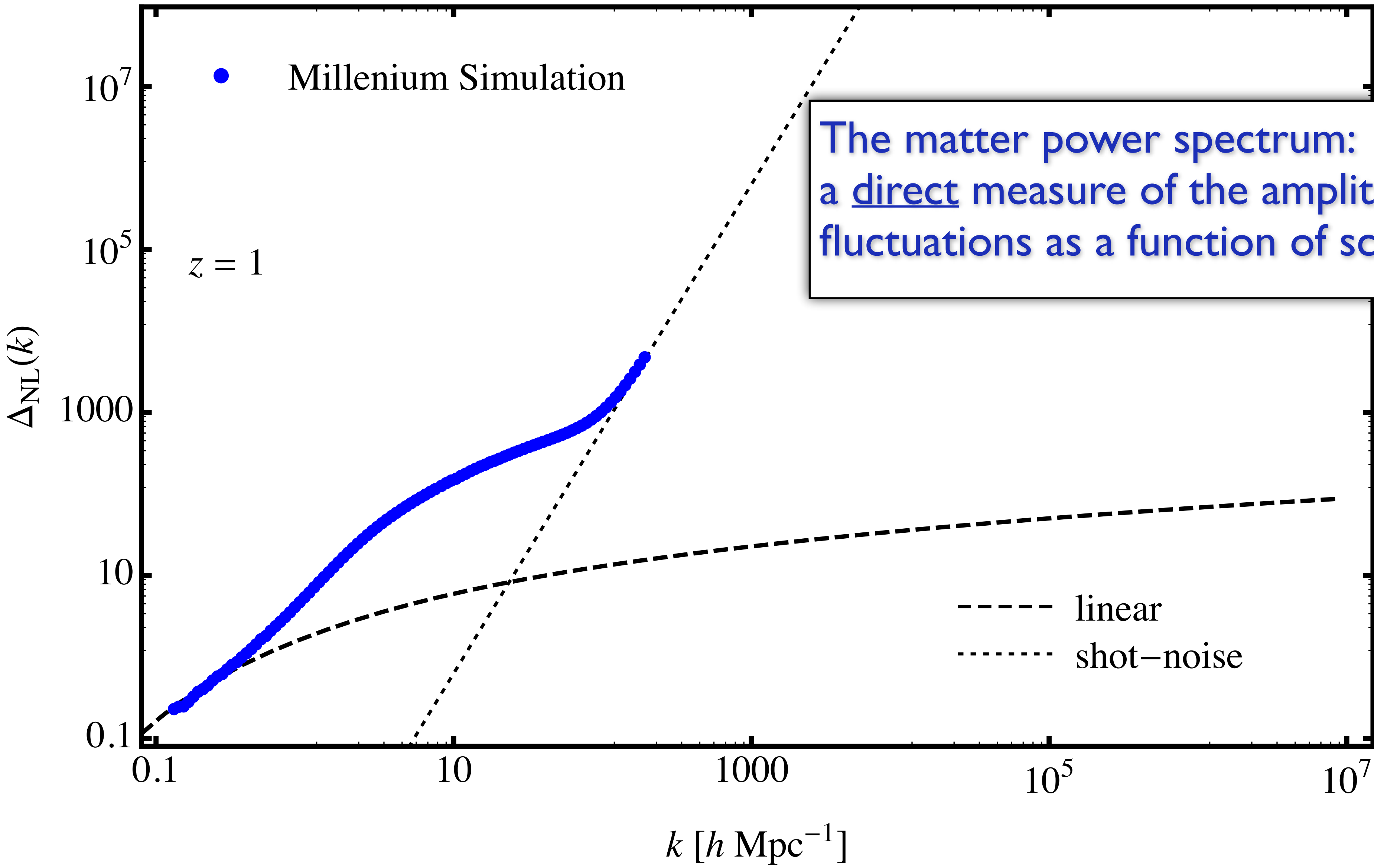
# A *Power Spectrum* approach

The Flux Multiplier

$$\zeta(z) = \langle \delta^2(z, \hat{\Omega}) \rangle = \int_0^{k_{max}} \frac{dk}{k} \Delta_{NL}(k)$$

$$\Delta_{NL}(k) \equiv \frac{k^3 P_{NL}(k)}{2\pi^2}$$

all-in-one function!




The matter power spectrum:
a direct measure of the amplitude of matter fluctuations as a function of scale.

Sufusatti+ MNRAS, 2014

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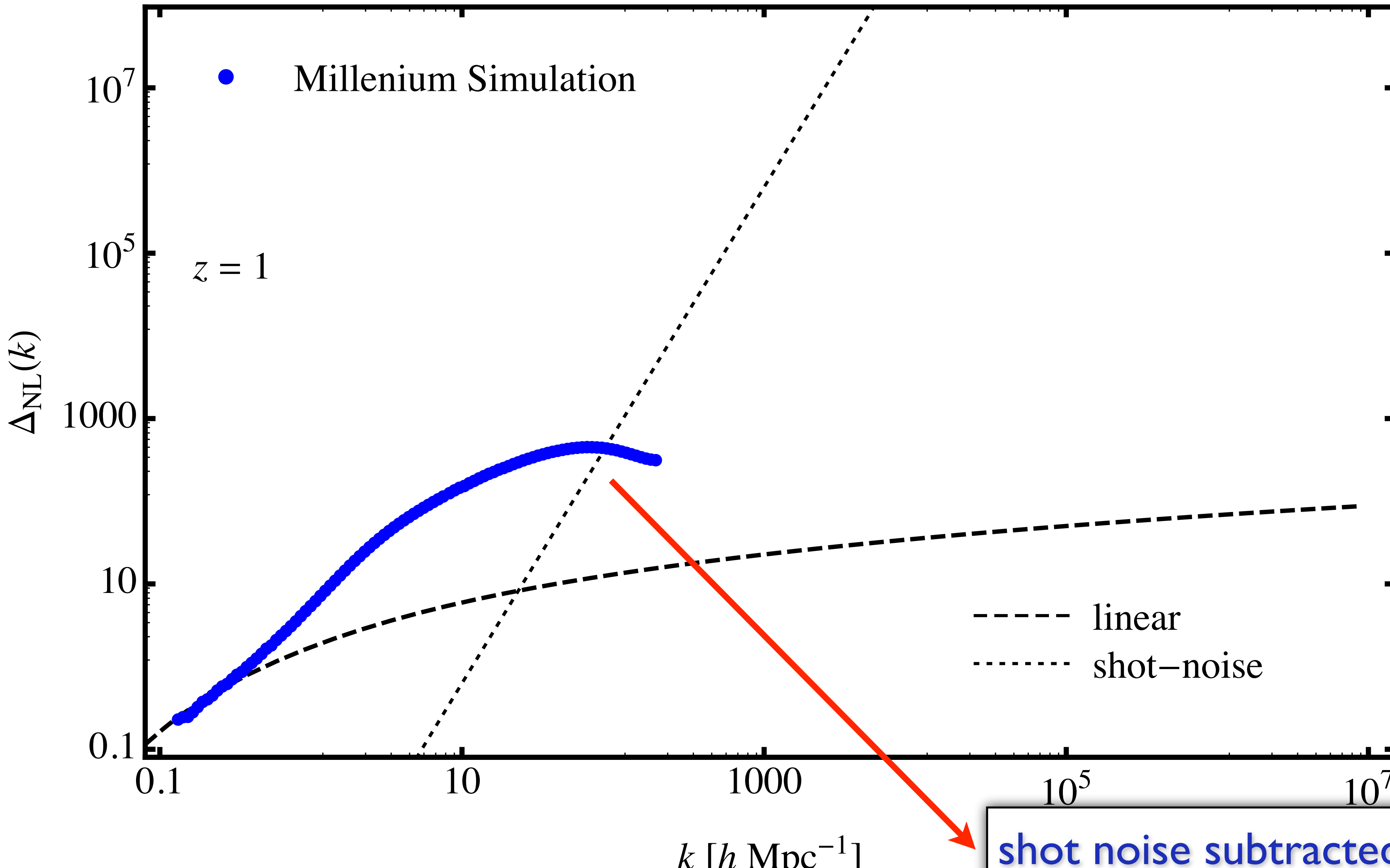


shot noise subtracted

Sufusatti+ MNRAS, 2014

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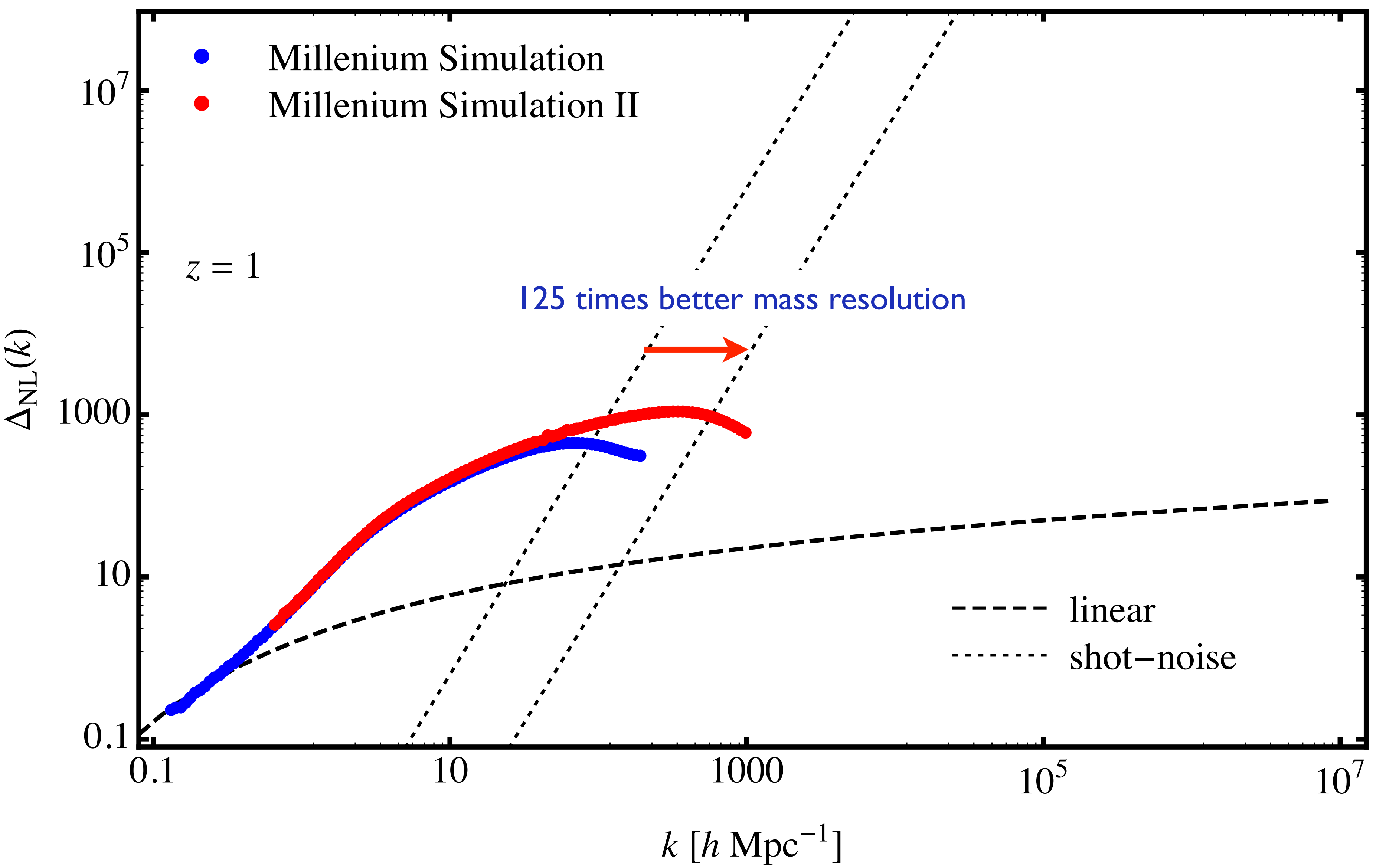


Sufusatti+ MNRAS, 2014

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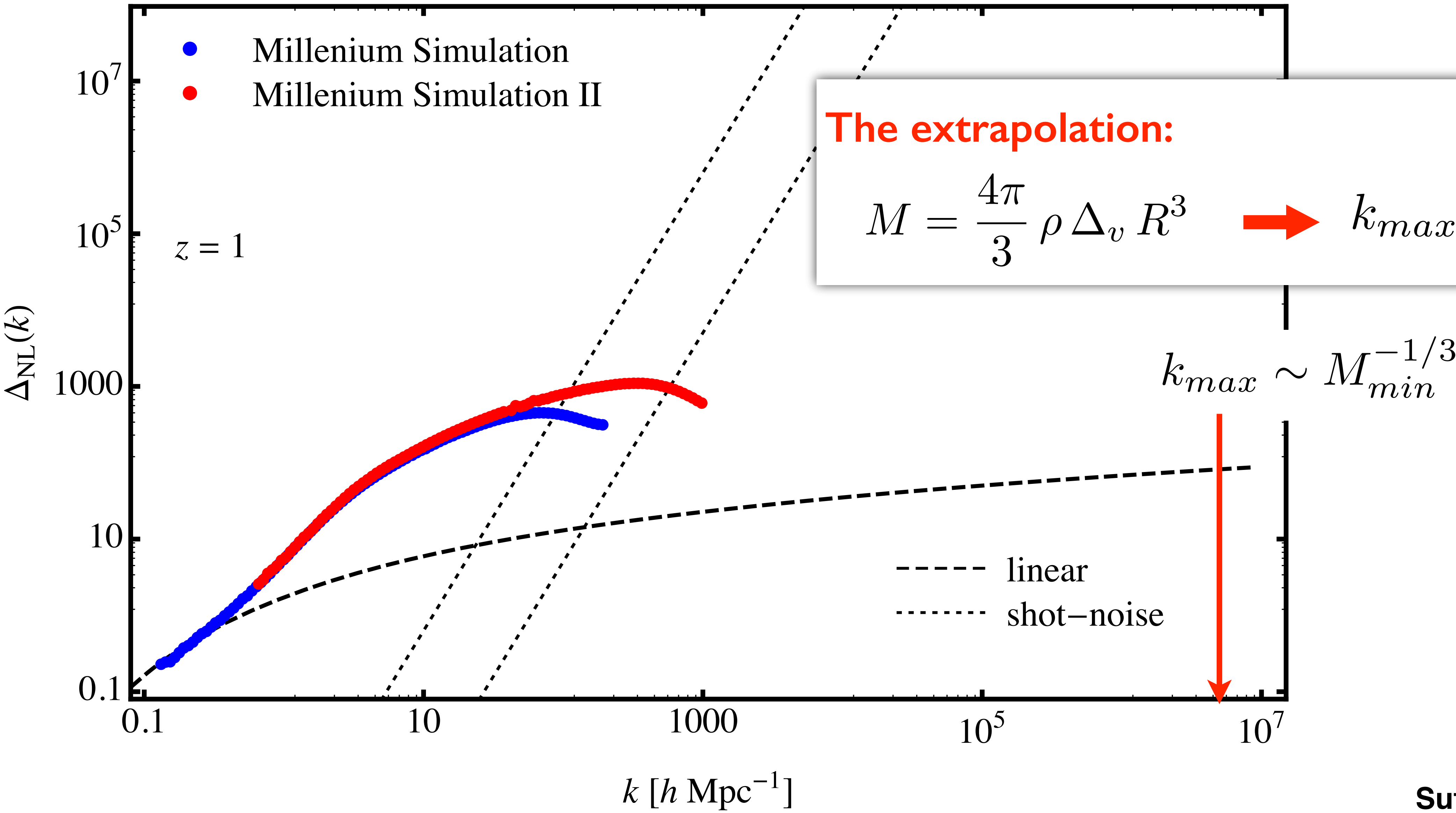


**The extrapolation:**

$$M = \frac{4\pi}{3} \rho \Delta_v R^3 \rightarrow k_{max} \sim M_{min}^{-1/3}$$

Sufusatti+ MNRAS, 2014

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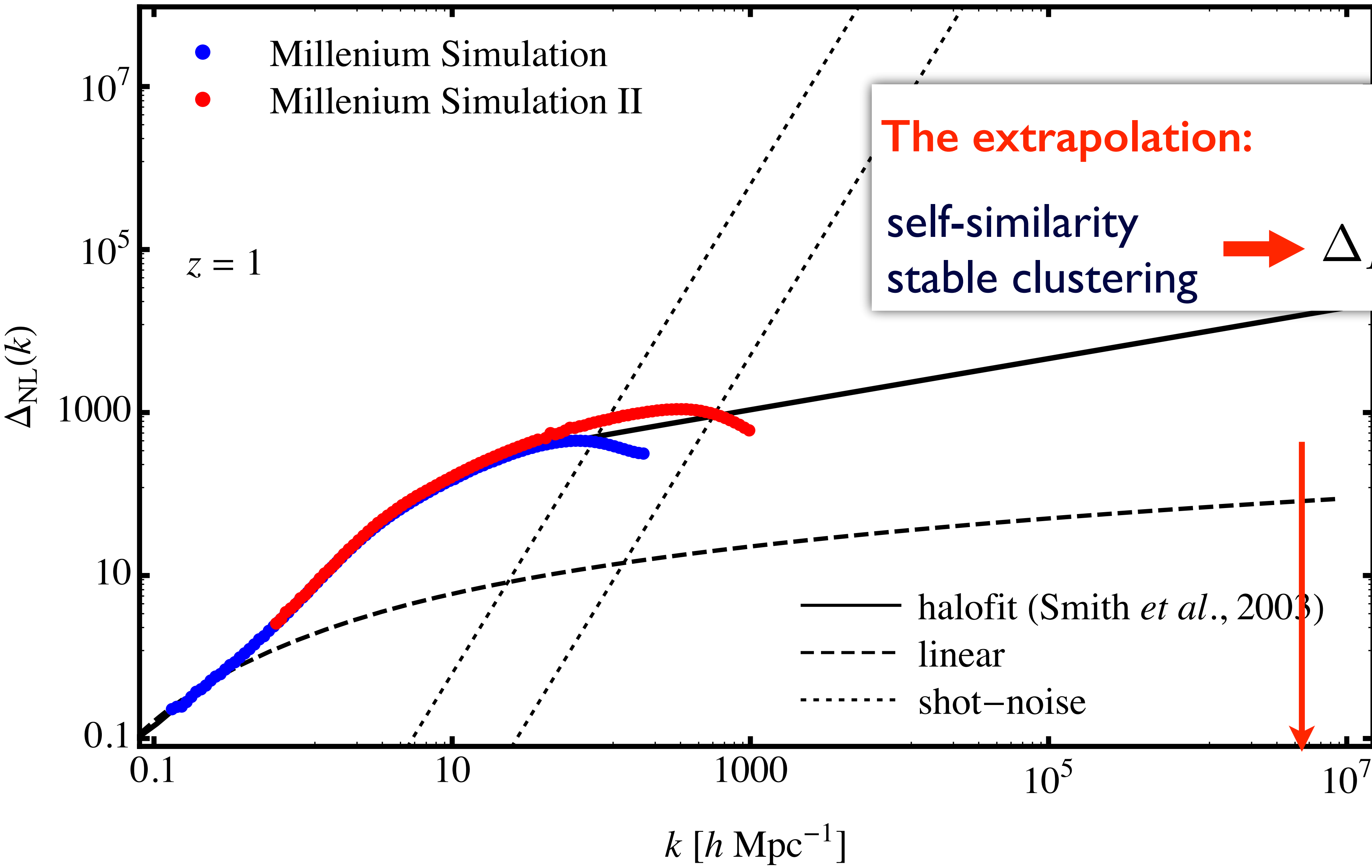


**The extrapolation:**

self-similarity
stable clustering

$$\Delta_{NL}(k) = \mathcal{F}[\Delta_L(k_L)]$$

$$\mathcal{F}(x) \sim x^{3/2}$$

Peebles '80
Hamilton et al. 91'
Peacock & Dodds '94

**Sufusatti+ MNRAS, 2014**

# Estimating uncertainties ...

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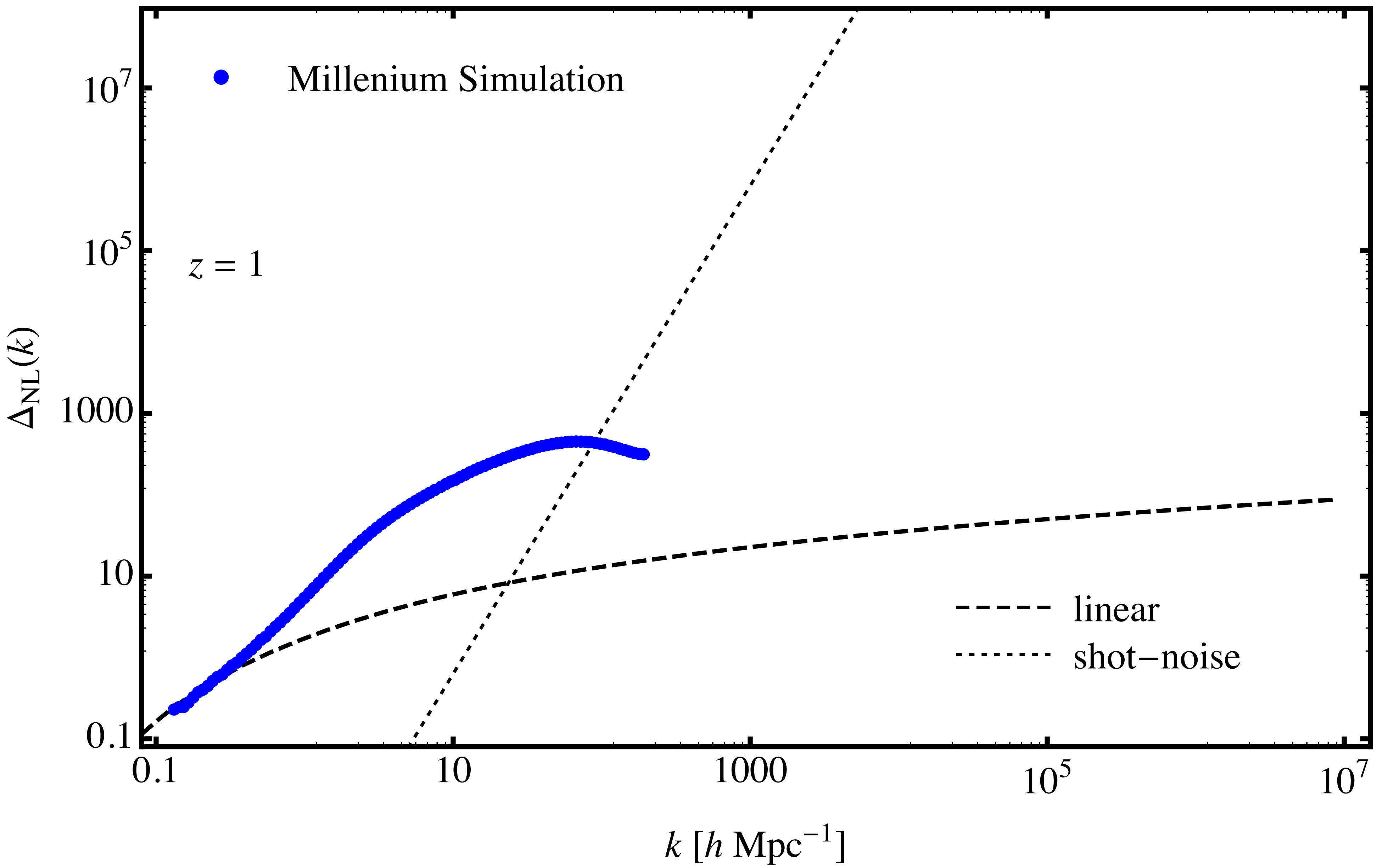


Sufusatti+ MNRAS, 2014

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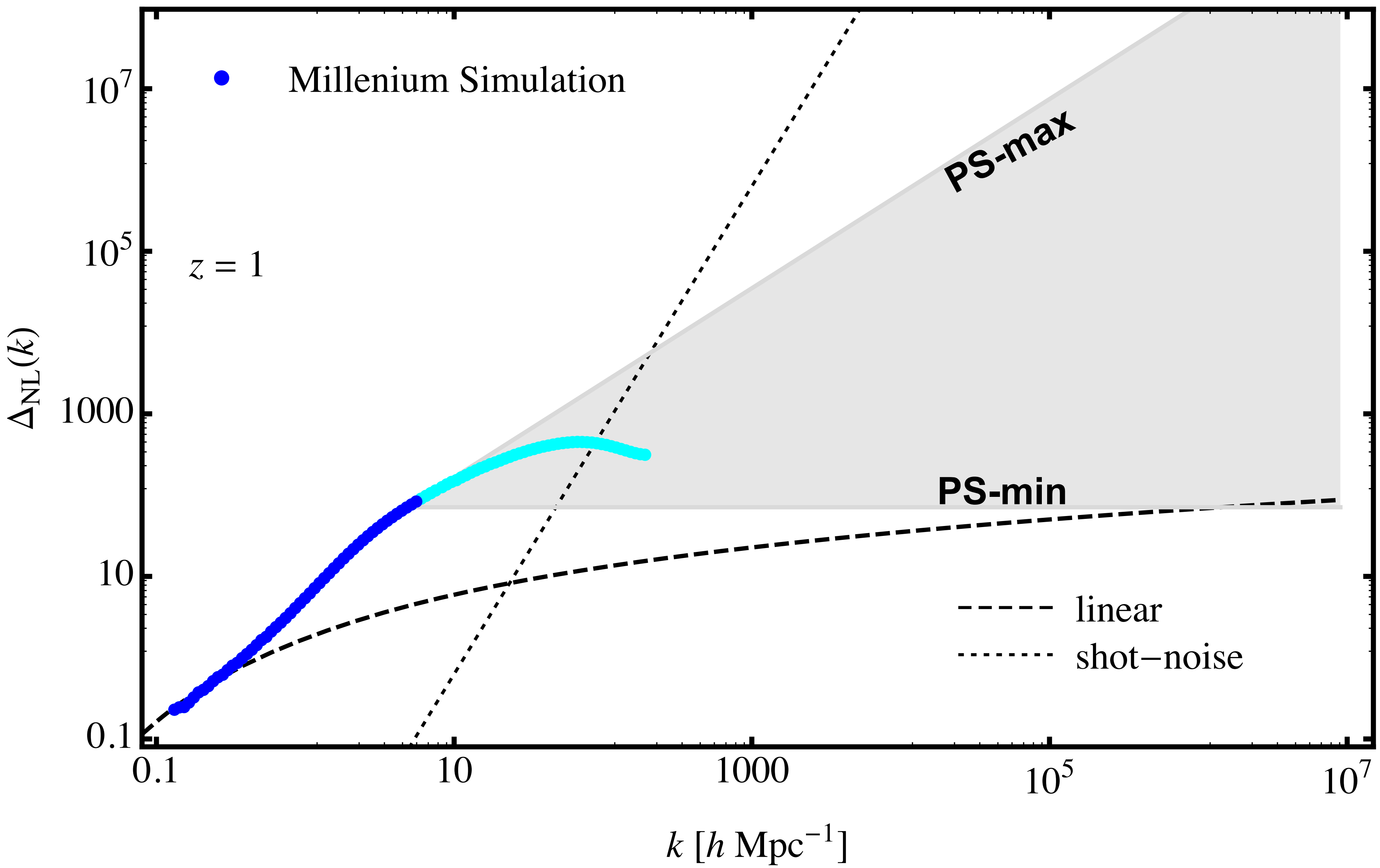


Sufusatti+ MNRAS, 2014

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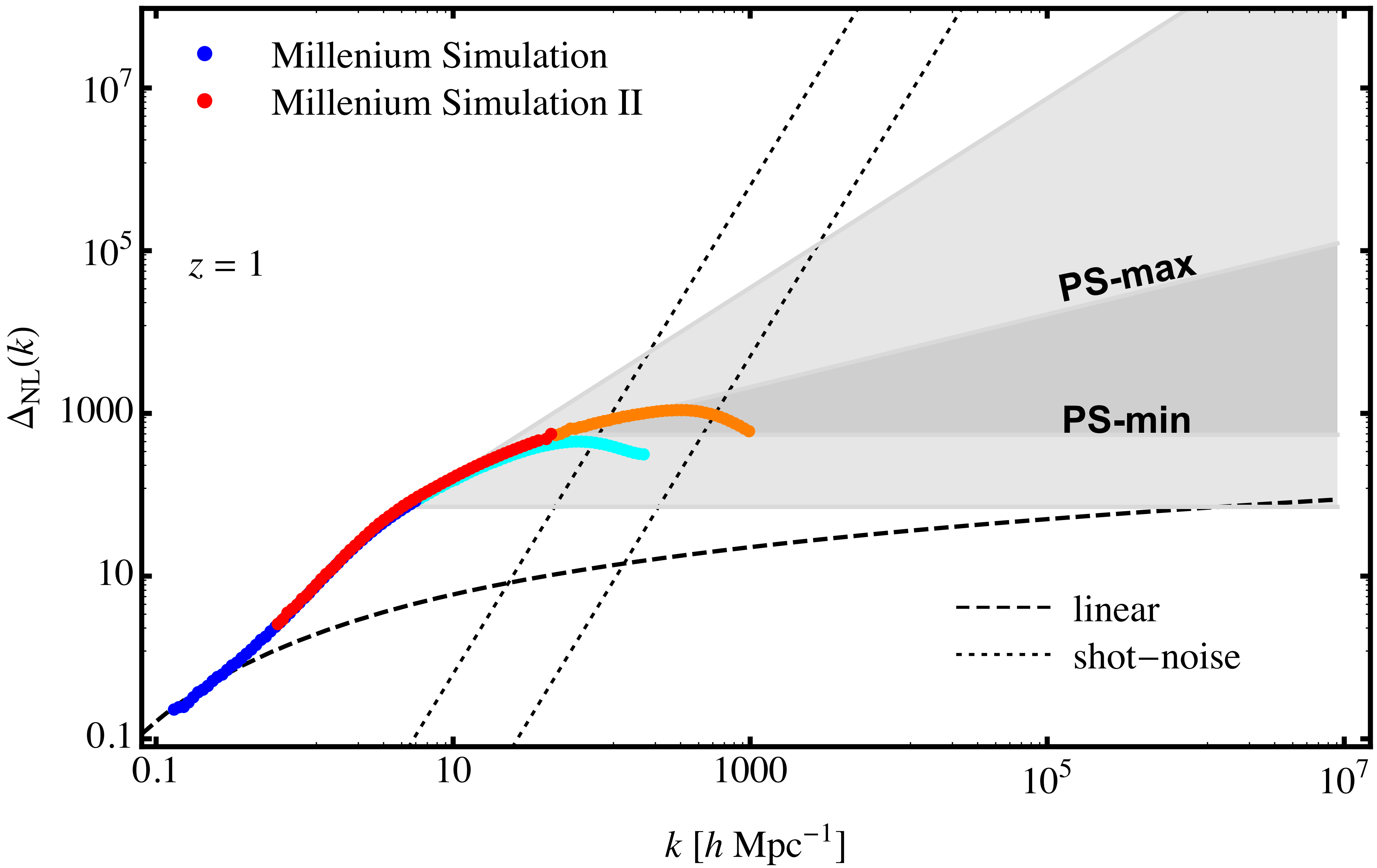



Sufusatti+ MNRAS, 2014

# The Halo Model approach

all DM particles belong to a DM *halo* of a given mass

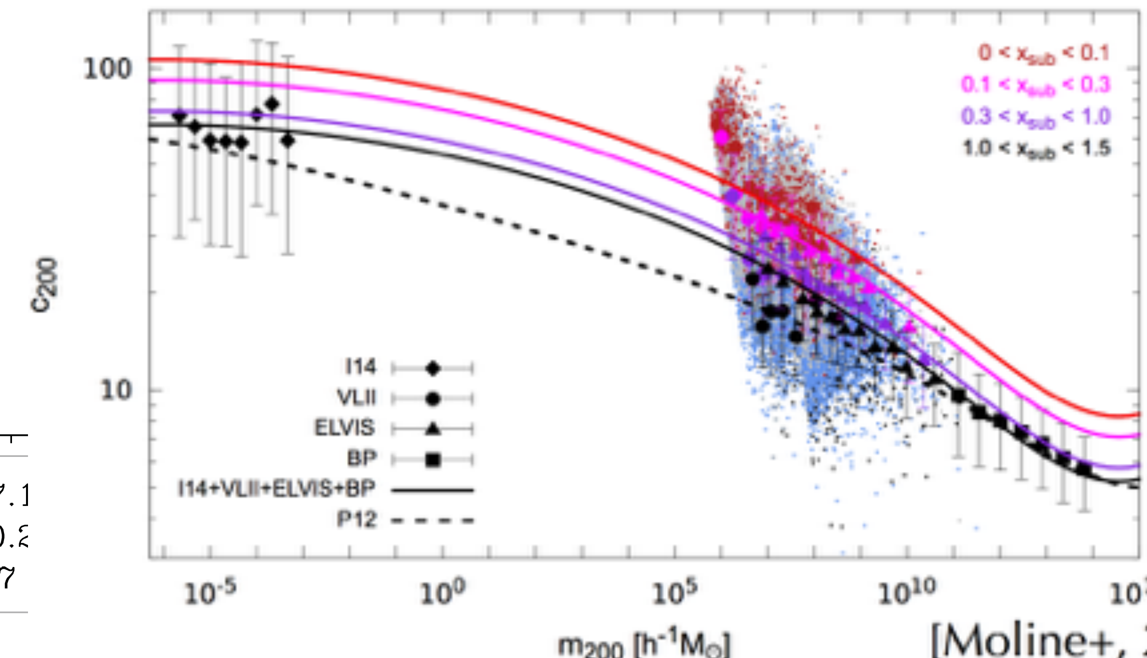
Flux multiplier

$$\zeta(z) = \frac{1}{\Omega_m \rho_c} \int_{M_{min}} dM \boxed{\frac{dn}{dM}} M \frac{\Delta_{vir}(z)}{3} \boxed{\langle F \rangle} \qquad F = \boxed{c_v^3(M,z)} \frac{\int_0^{c_v} dx x^2 \kappa^2(x)}{\left[\int_0^{c_v} dx x^2 \kappa(x)\right]^2}$$

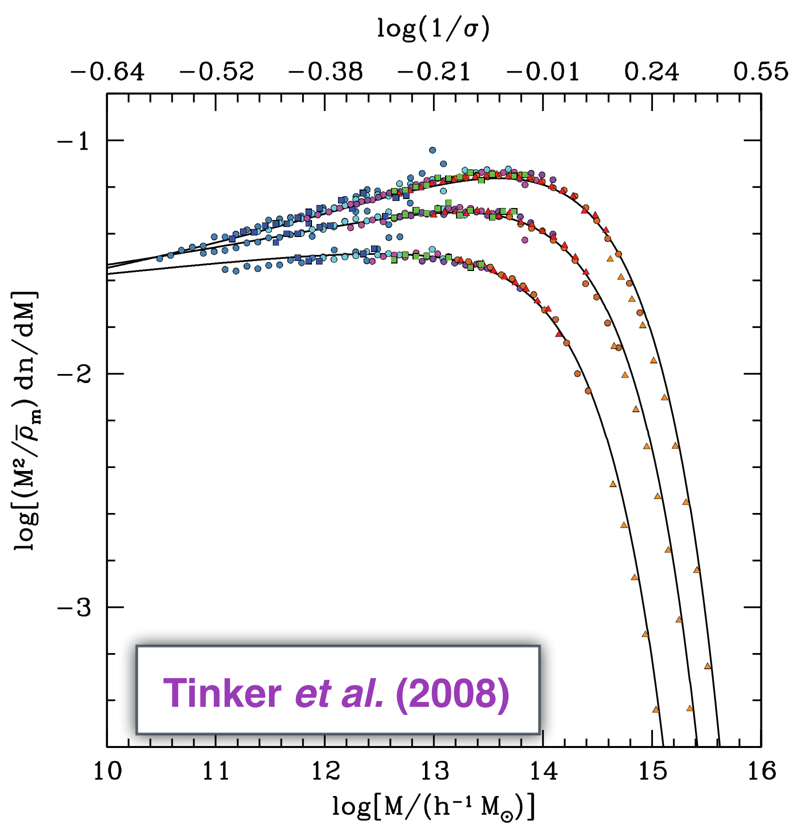
Ingredients:

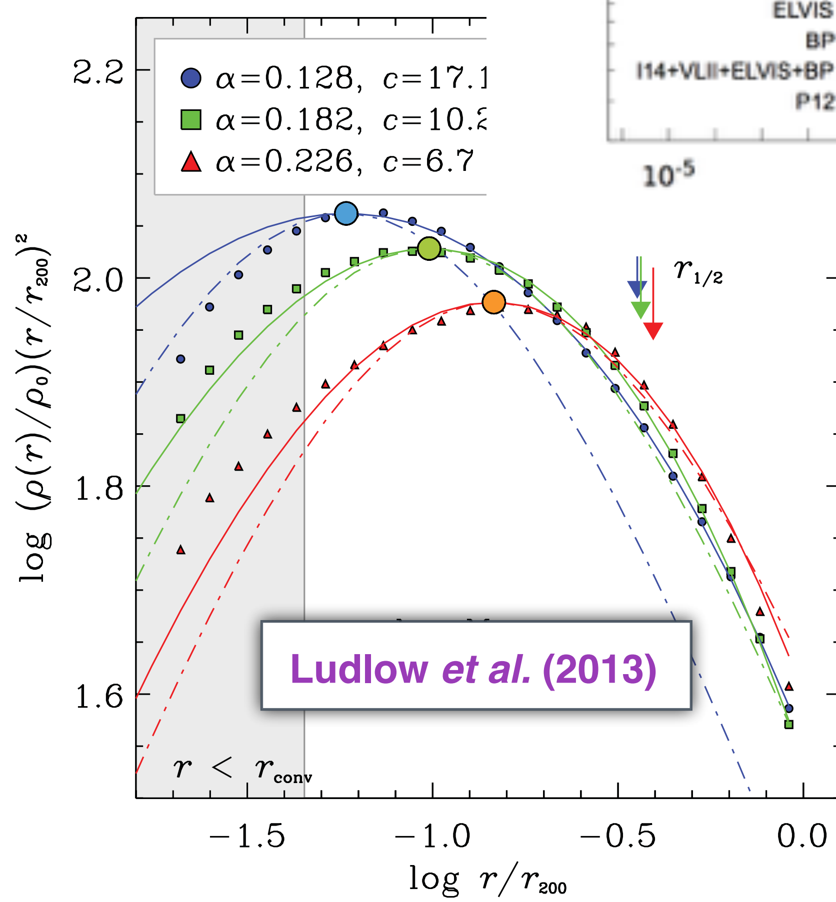
1. Halos mass function
2. Halos density profile (NFW, Einasto, etc ...)
3. Halos concentration

\+ all of the above for **subhalos**




[Moline+, 2016]

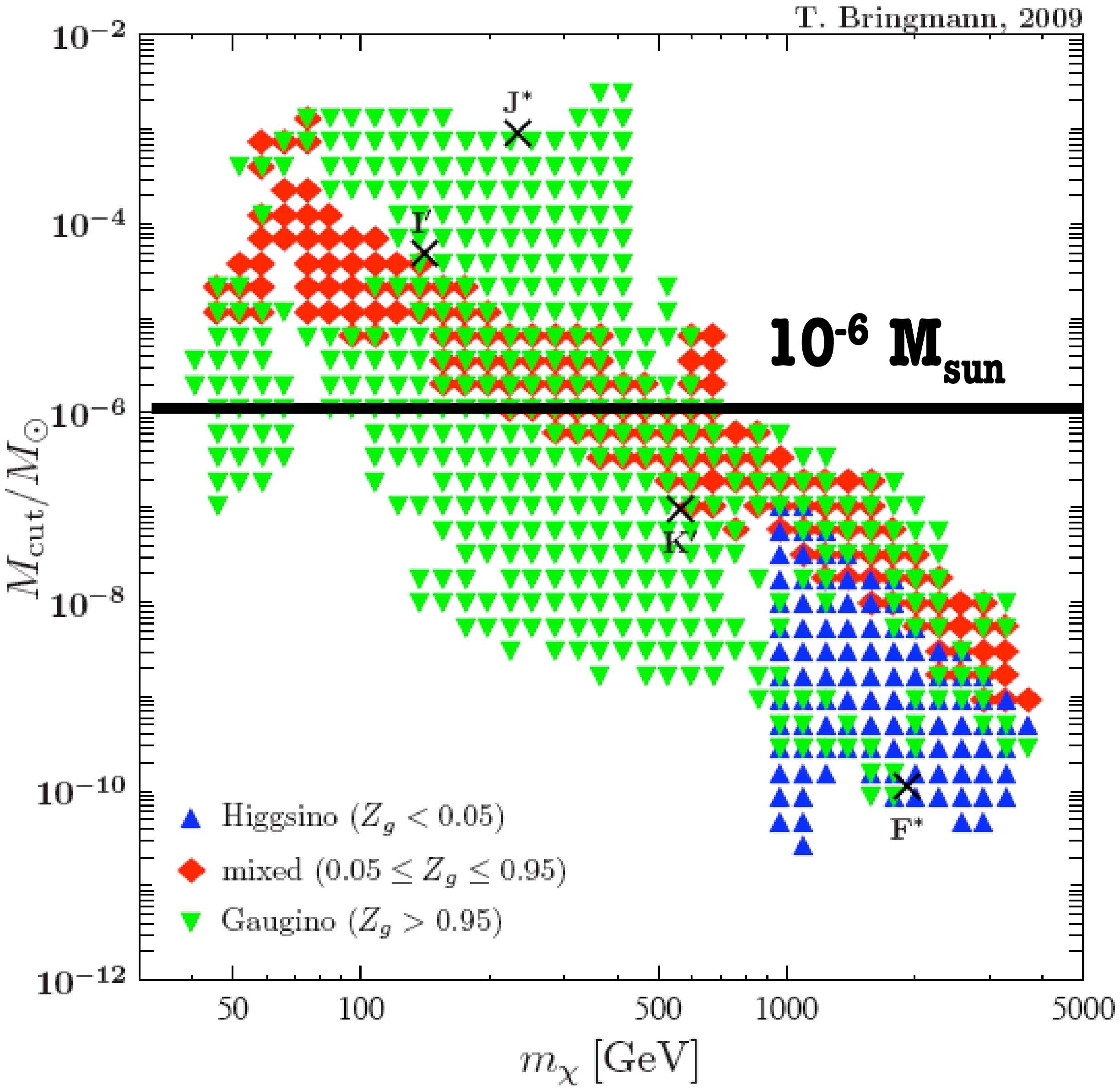



**See Shin'ichiro Ando's talk**

# The smallest scale ($k_{max}$) / minimal halo mass ($M_{min}$)

Typical $M_{min}$ for a WIMP = $10^{-6}$ $M_{sun}$




## Cut-off scale:

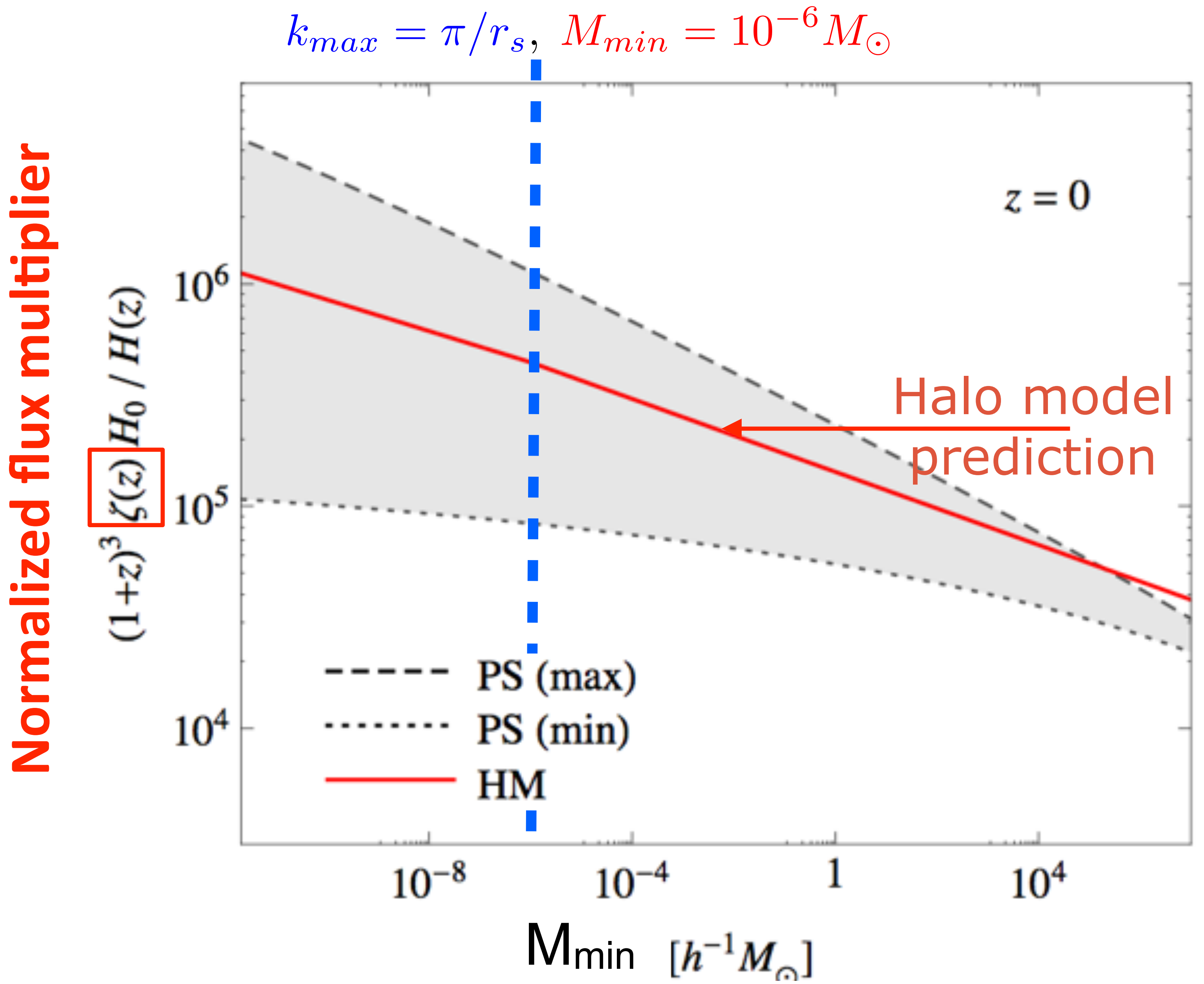
1. Depend on you DM particle candidate
2. Not necessarily any trivial relation between cut in $k_{max}$ and $M_{min}$

Here I will take: $$k_{max} = \frac{\pi}{r_s}$$

$$r_s = r_{200}(M_{min})/c_{200}(M_{min}, z)$$

c.f. Oliver Hahn's talk

## Dependence of $\zeta(z) = \langle \delta^2(z, \hat{\Omega}) \rangle$ on Minimal Halo Mass cut-off.




PS(min) only weakly dependent on $M_{min}$

PS(max) varies by order(s) of magnitude with $M_{min}$

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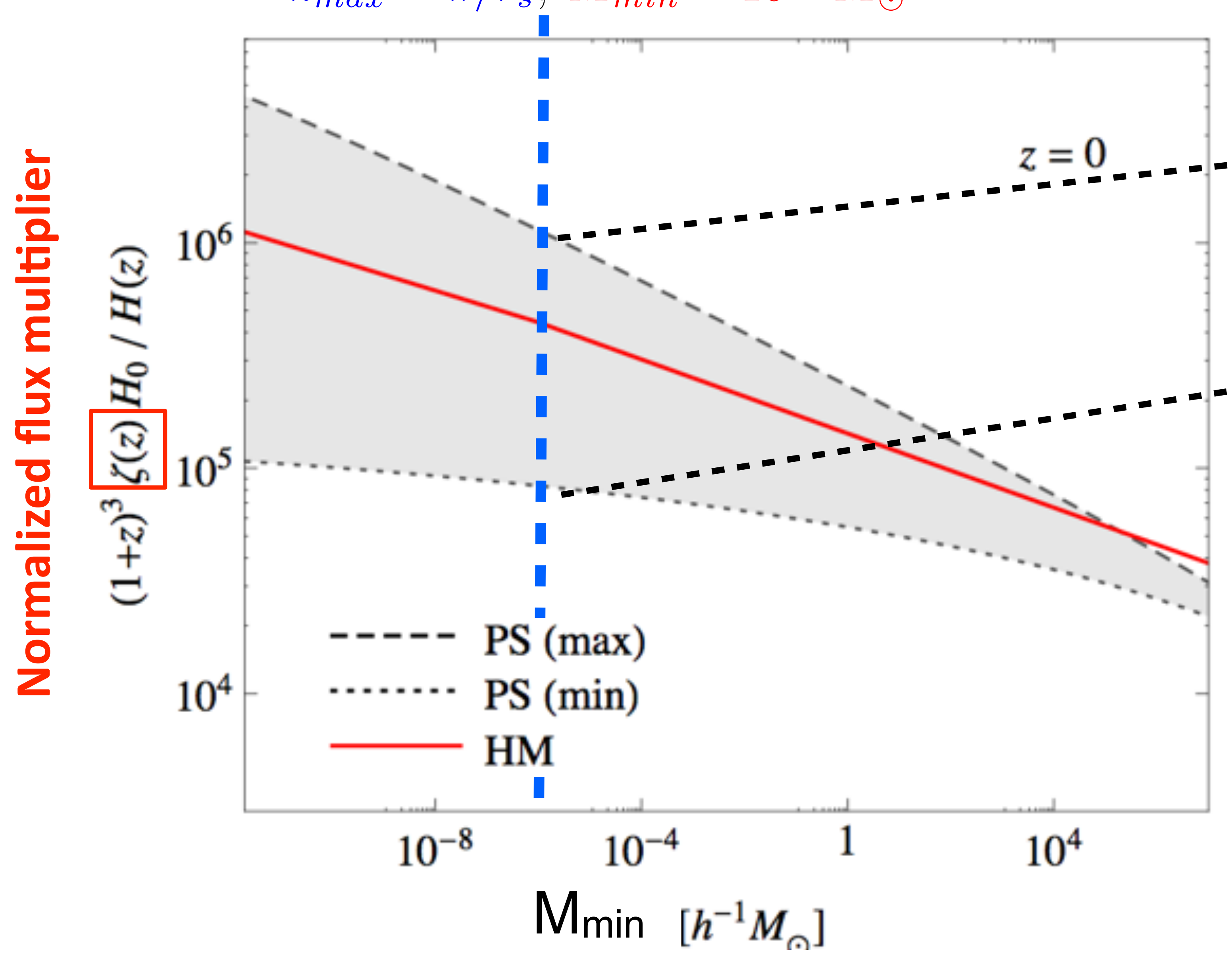


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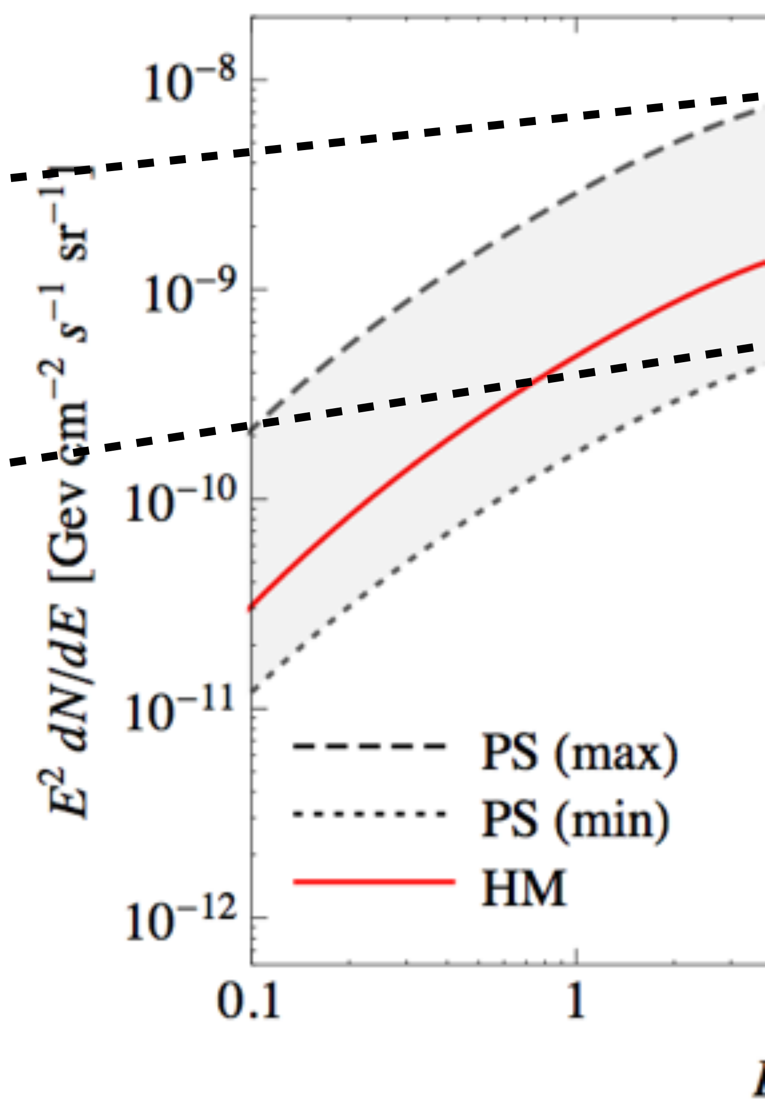


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DM example wit

into b-quarks an

# Dark Matter Limits

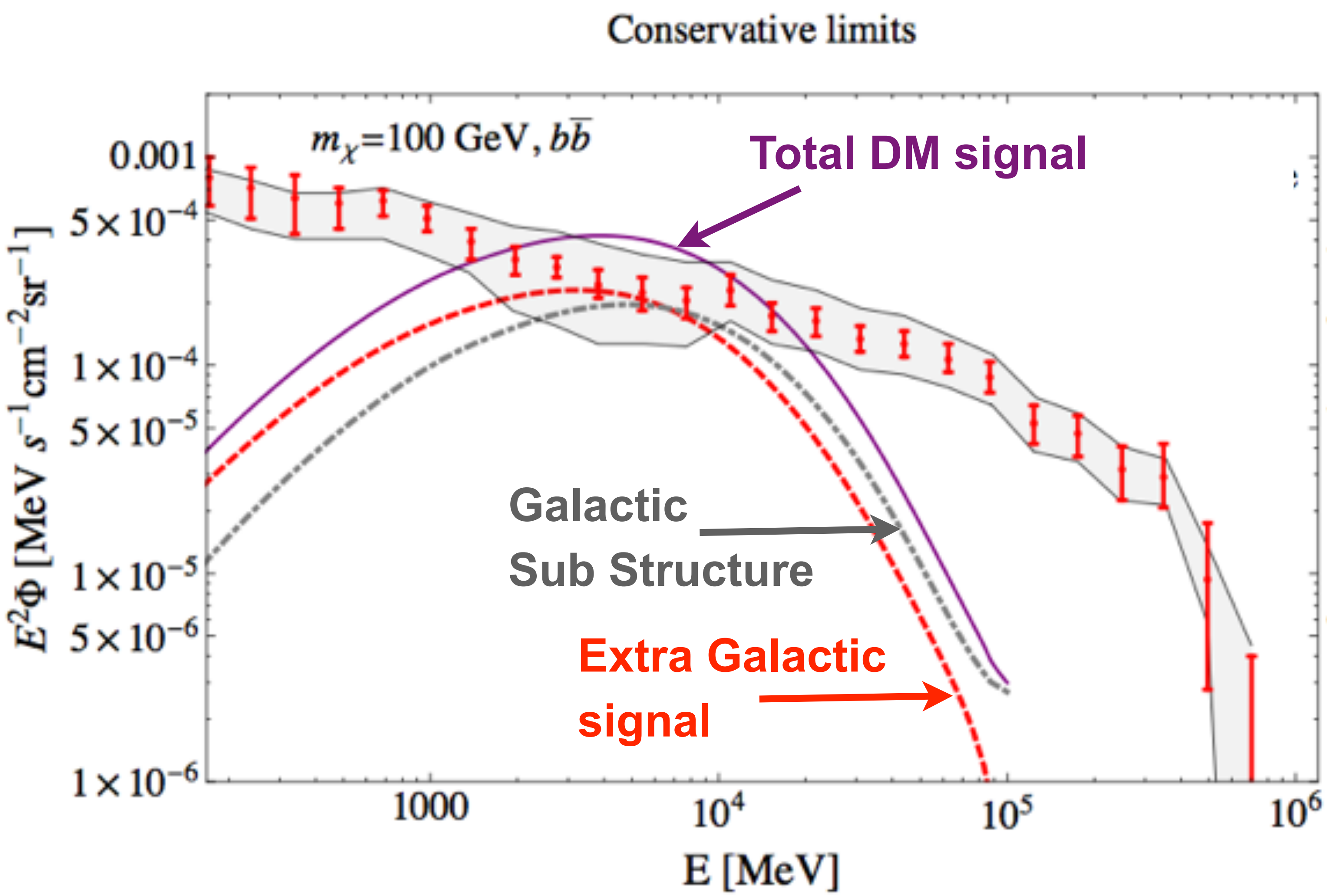
Fermi-LAT Collaboration,
JCAP 1509 (2015) 09, 008

# A. conservative limits:

**When DM signal overshoots data points by 2-sigma** (statistical).

**'Statistical' error-bars (**stat_Err+eff_Area +CR cont. uncert) **moved to upper edge of systematic uncertainty band**

**No assumptions on astrophysical isotropic contributions!**

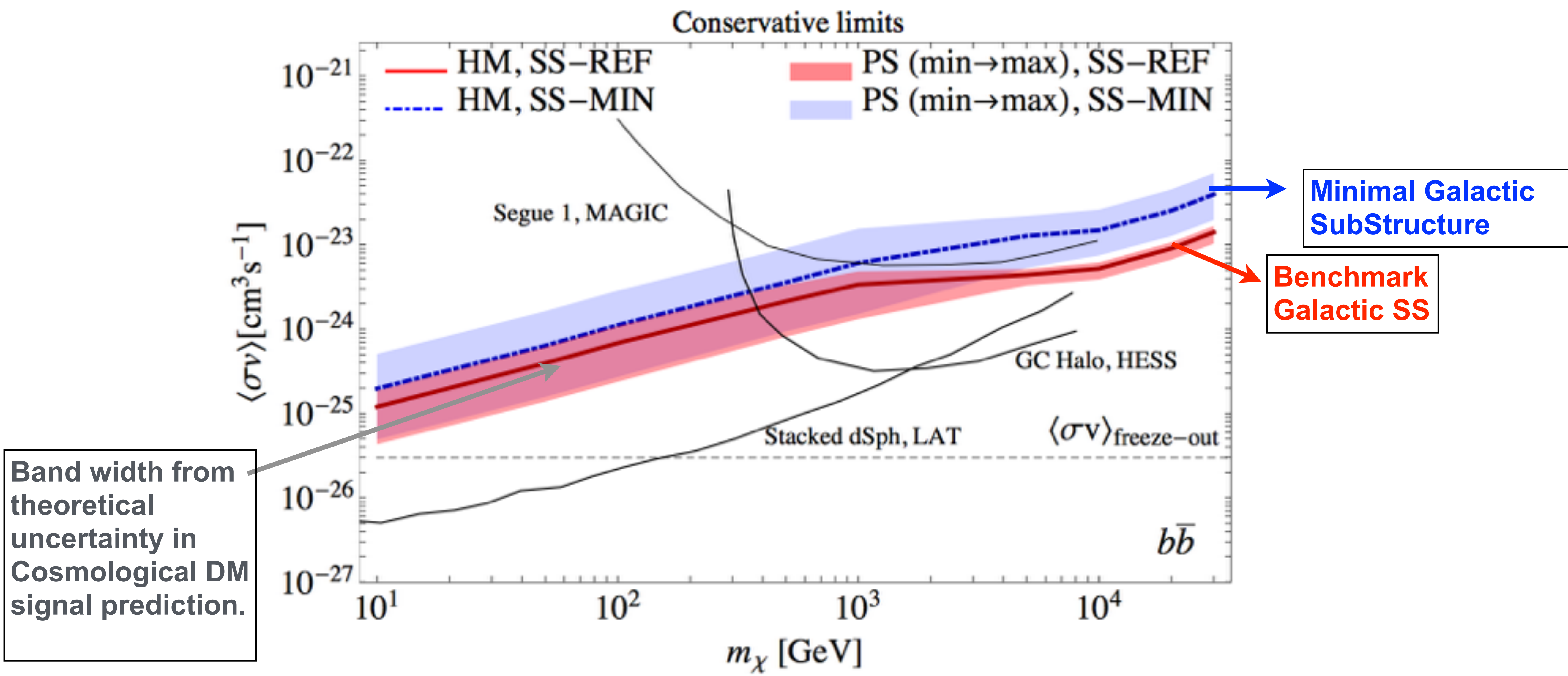



**Isotropic DM signal =**

**from Extra Galactic + Milky Way substructures**

Fermi-LAT Collaboration,
JCAP 1509 (2015) 09, 008

# A. conservative limits:




Annihilation into b-quarks ($M_{min}$ =$10^{-6}$ $M_{sun}$).

Fermi-LAT Collaboration,
JCAP 1509 (2015) 09, 008

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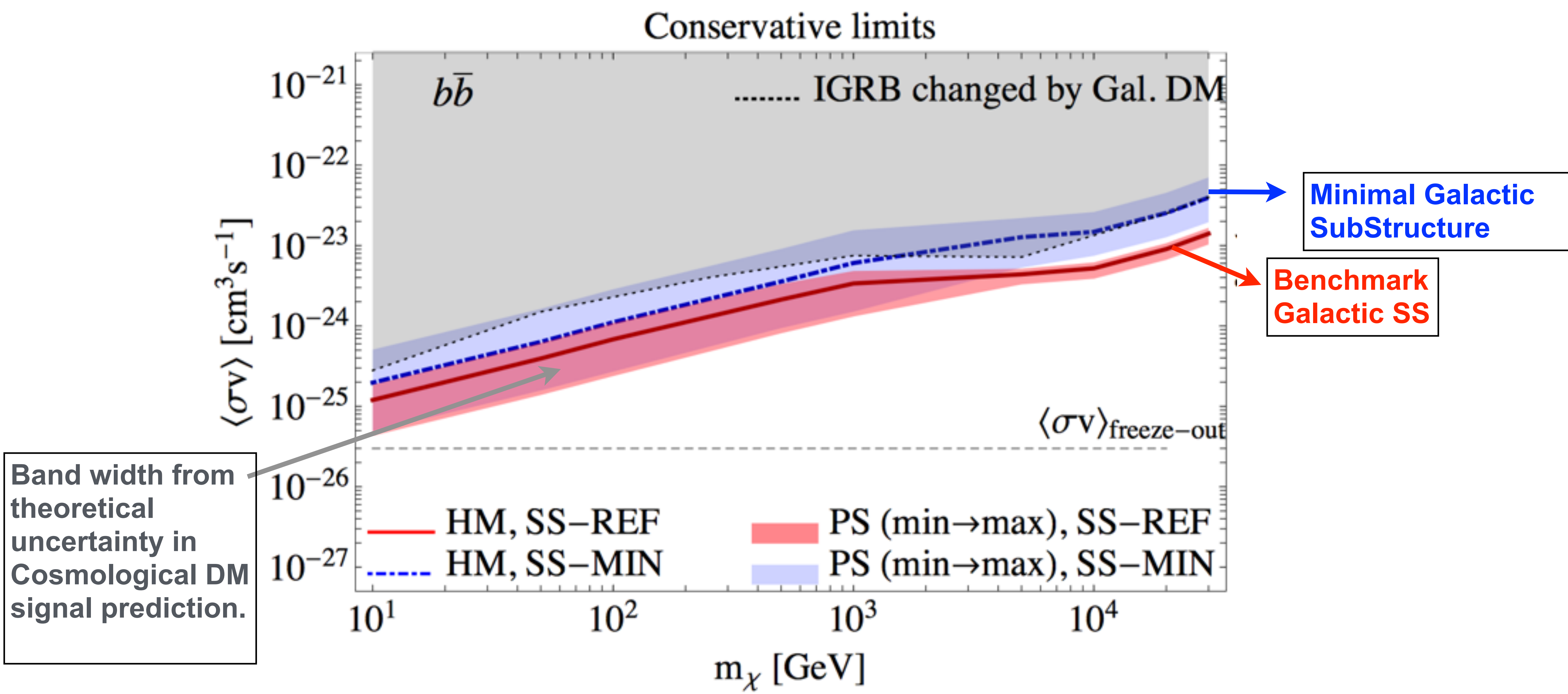



Annihilation into b-quarks ($M_{min} = 10^{-6} M_{sun}$).

Fermi-LAT Collaboration,
JCAP 1509 (2015) 09, 008

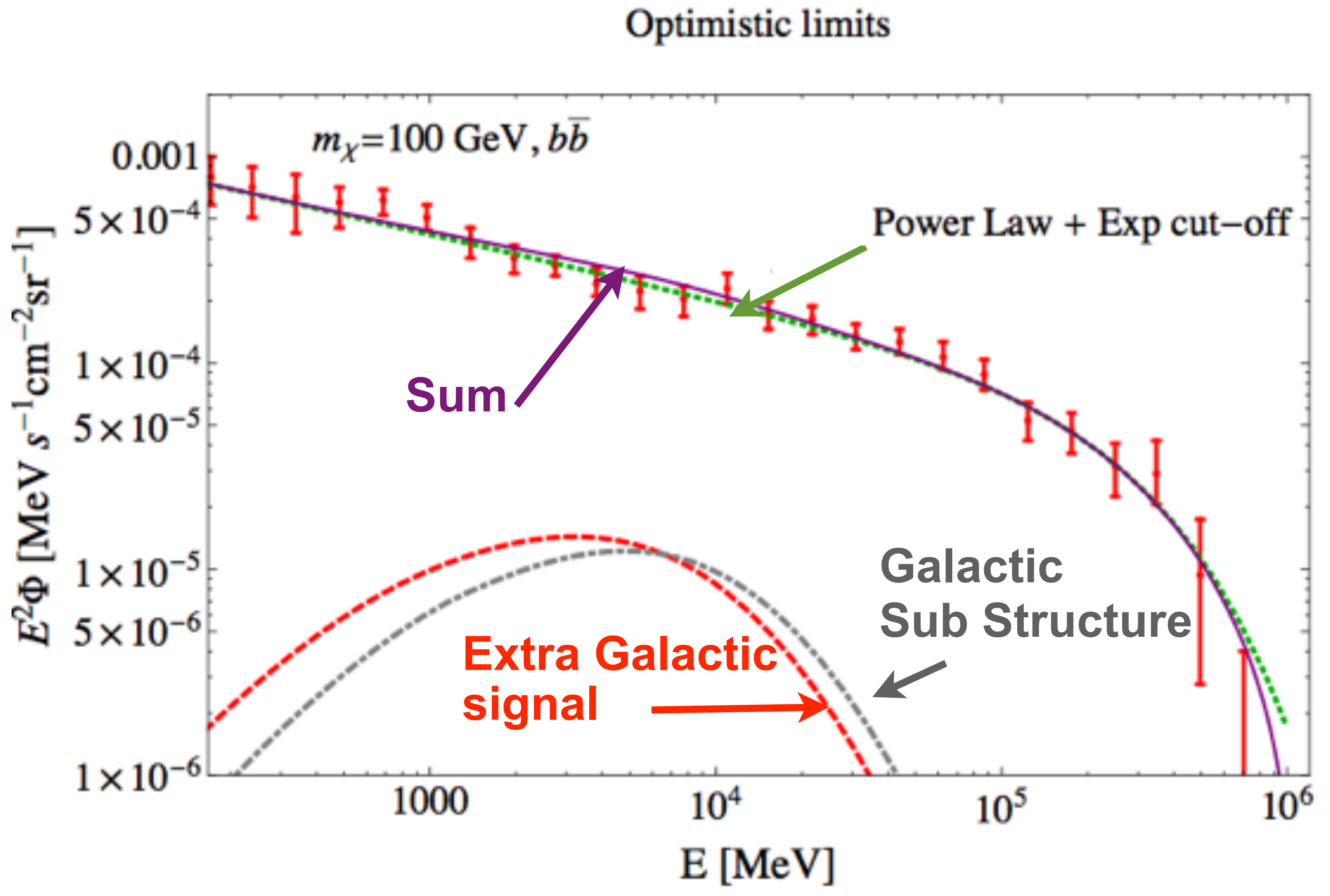
# B. "Sensitivity reach":

**Assume the astrophysical contributions sum up to:**

$$\frac{dN}{dE} = \alpha\ E^{-\beta}\ \exp\left(-\frac{E}{E_0}\right)$$

**Perform a Chi-square ($\chi^2$) fit including the DM signal**

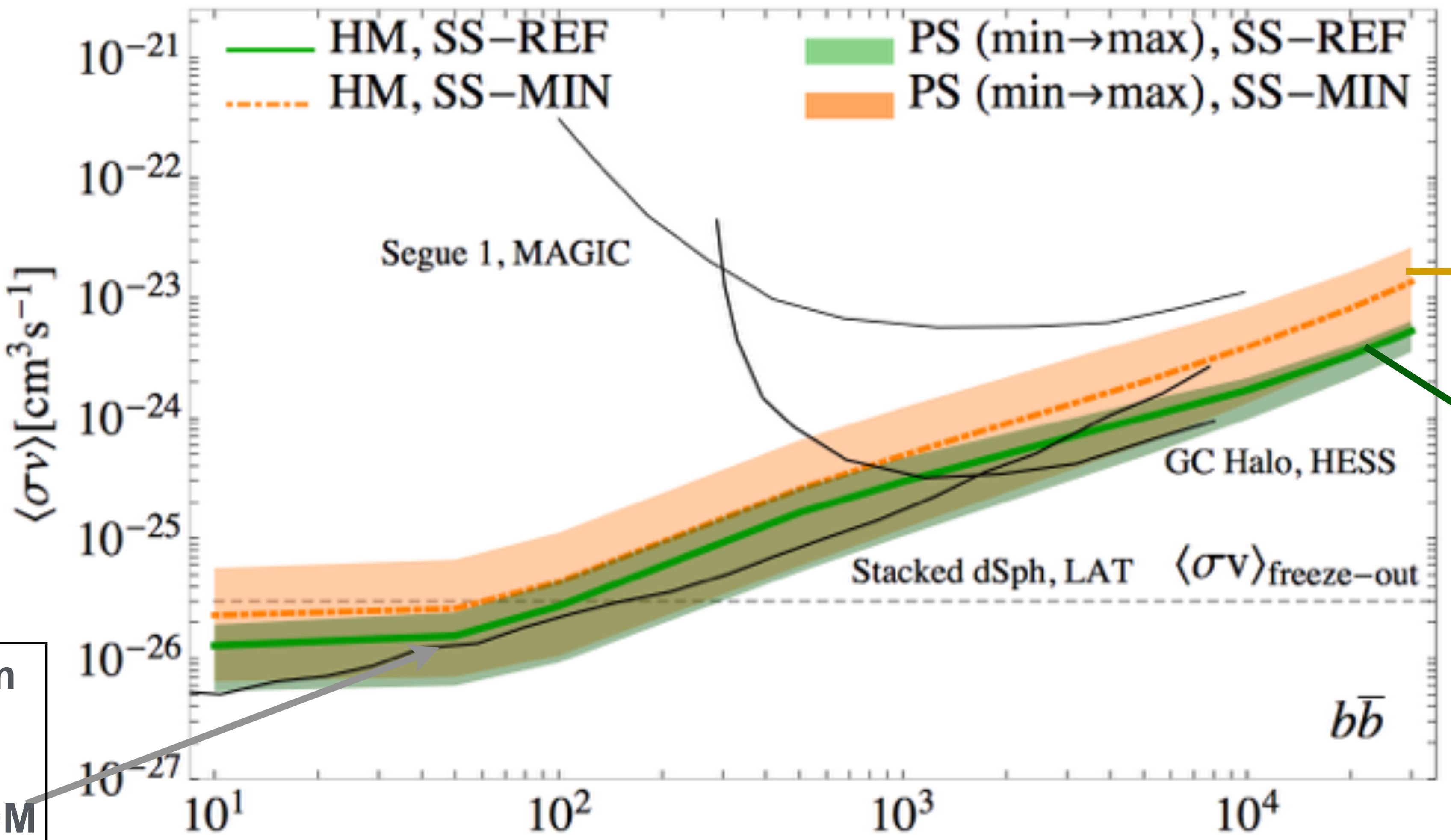
**Limit when DM signal worsens overall $\chi^2$ fit by +4** (2-sigma C.L.)




Note: The background model gives good fit. 26 (uncorrelated) data points with a reduced $\chi^2$ of 0.5 for 23 degrees-of-freedom. The 3 free parameters in the fit are: spectral index, norm and cut-off energy.

Fermi-LAT Collaboration,
JCAP 1509 (2015) 09, 008

# B. "Sensitivity reach":




Minimal Galactic SubStructure

Benchmark Galactic SS

Band width from theoretical uncertainty in Cosmological DM signal prediction.

Annihilation into b-quarks ($M_{min} = 10^{-6} M_{sun}$).

Fermi-LAT Collaboration,
JCAP 1509 (2015) 09, 008

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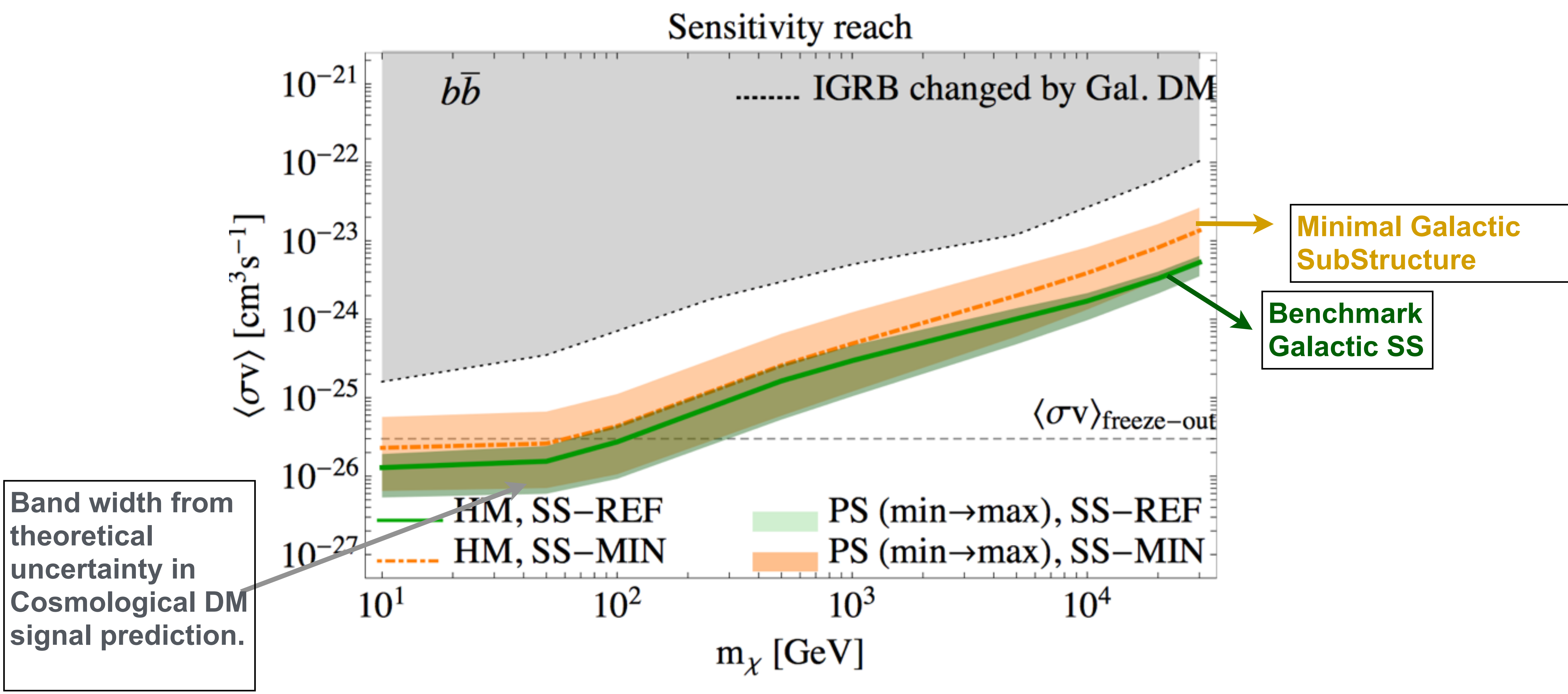


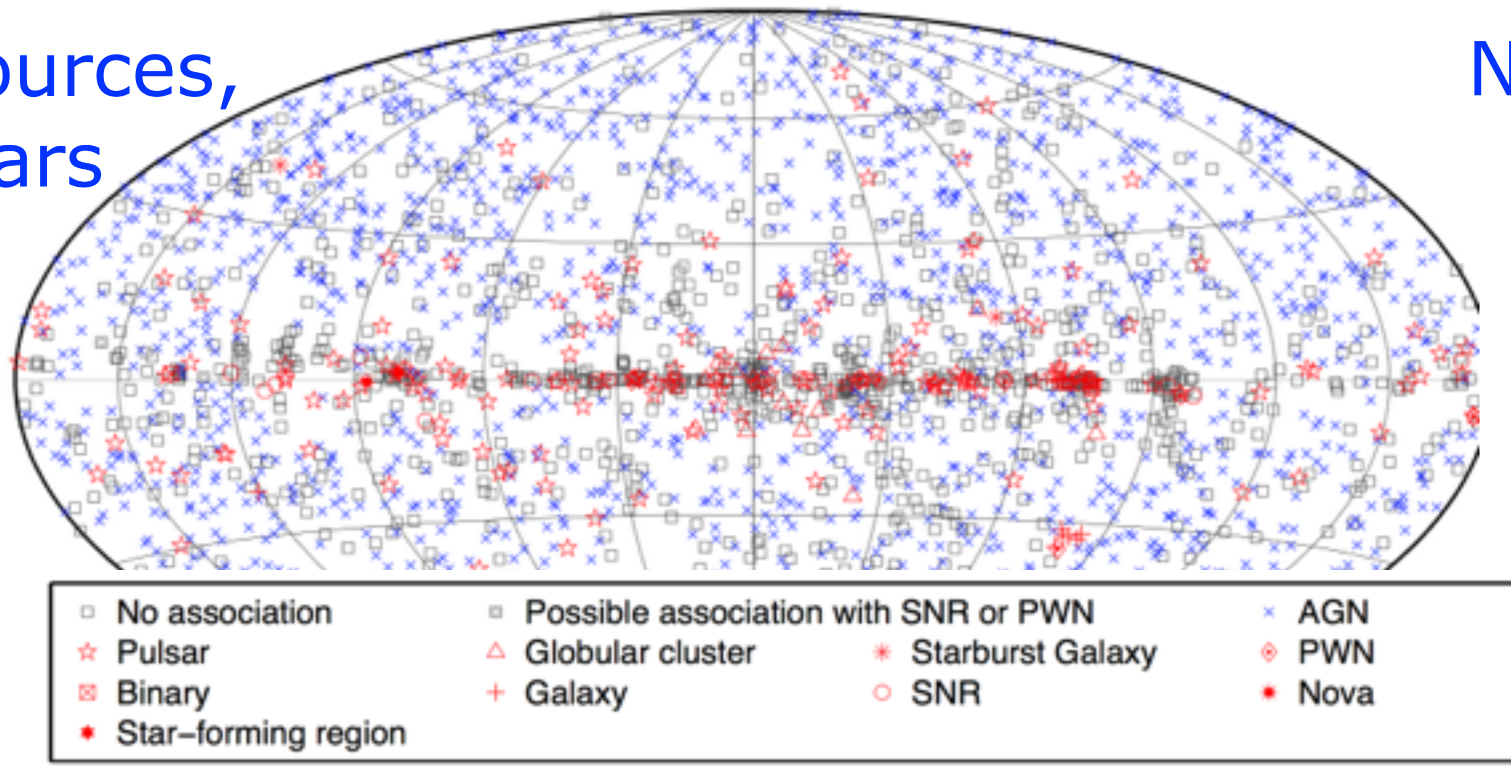

Annihilation into b-quarks ($M_{min} = 10^{-6}\, M_{sun}$).

# ‘guaranteed’ contributions to IGRB

# Origin of the Extragalactic Gamma-ray Background (EGB)

**[EGB == IGRB + individually resolved extragalactic sources]**

3FGL: 3033 sources,
—1100 Blazars




Numerous sub-treshold point sources

[Ajello+, ApJL, 2015)]

**Blazars.** Based on properties of resolved population (**~400 BL Lacs + FSRQs with redshift info**):
- luminosity function
- spectra
- red shift evolution

**Star-forming galaxies.**

**~5 detected** by Fermi-LAT, ans use of **correlation with radio and infrared band.**

[Ackermann et al. 2012ApJ 755 164A ]

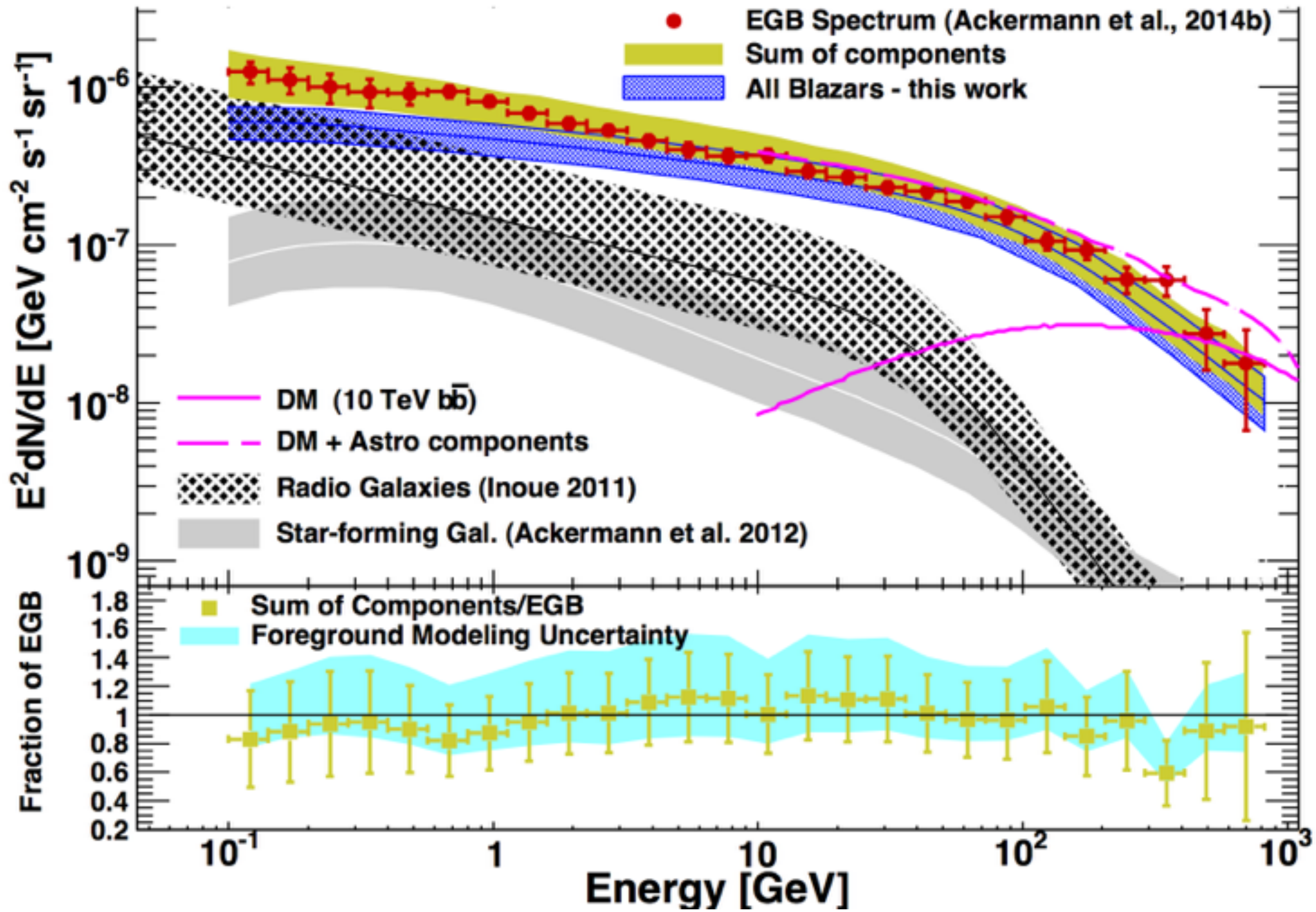
**Radio galaxies (MAGN)**

**~15 detected** by Fermi-LAT and use of **correlation with radio band**.

[Inoue 2011ApJ 733 66I]

See Mattia Di Mauro's talk

# Origin of the Extragalactic Gamma-ray Background (EGB)




$F_{i,ASTRO}$

[Ajello+, ApJL, 2015)]

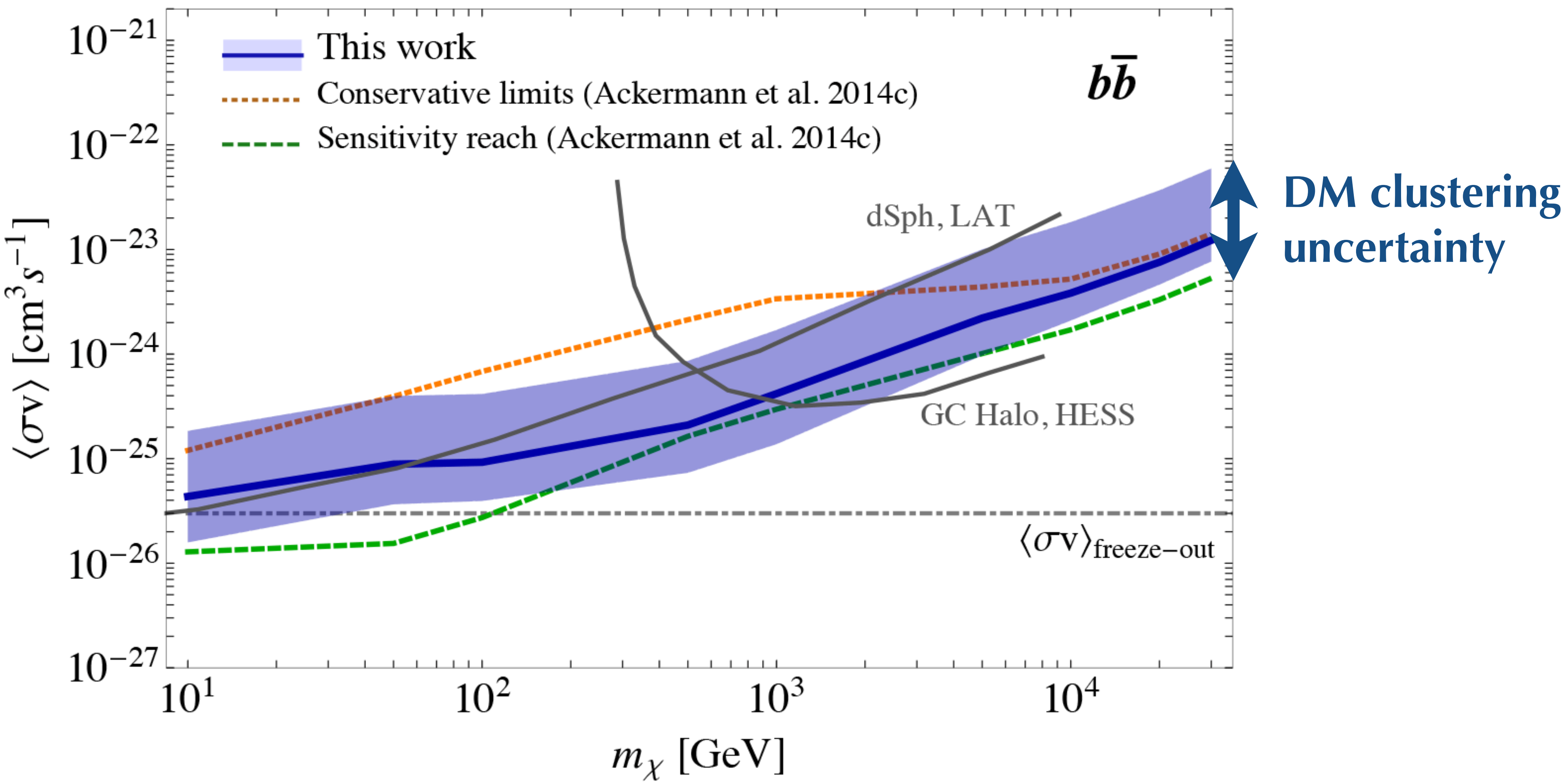
EGB can be explained by the contributions from blazars, radio and star-forming galaxies

→ limits on additional contributions — e.g. dark matter signals

# Combining Things Together

Uncertainty in galactic diffuse emission and unresolved sources:

$$\chi^2 = \underset{\mathscr{A}}{\mathrm{Min}} \left[ \sum_i^N \frac{(F_{i,EGB} - \mathscr{A} F_{i,ASTRO} - F_{i,DM})^2}{\sigma_i^2} + \frac{(1-\mathscr{A})^2}{\sigma_{\mathscr{A}}^2} \right]$$

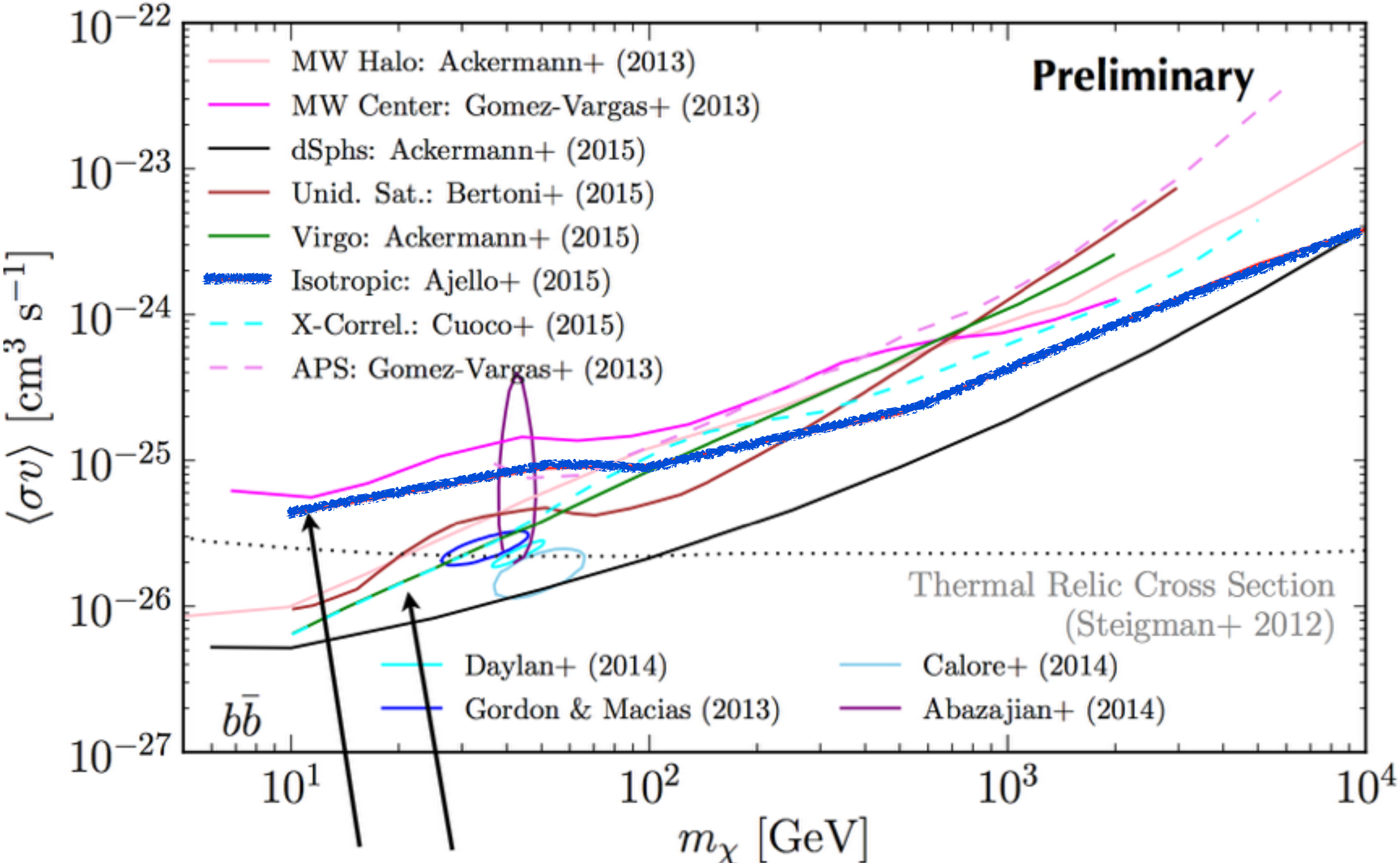



**Realistic setups (start to) probe generic prediction for WIMP models - thermal freeze out cross section.**

[Ajello+, ApJL, 2015)]

(see also diMauro+, PRD91 (2015), Cholis+ JCAP1402 (2014))

# Results for Different Search targets (for the b-quark Channel)




similar DM clustering assumptions

[Charles+, submitted to Physics Reports]

# Pass 8 IGRB/EGB measurement — ongoing

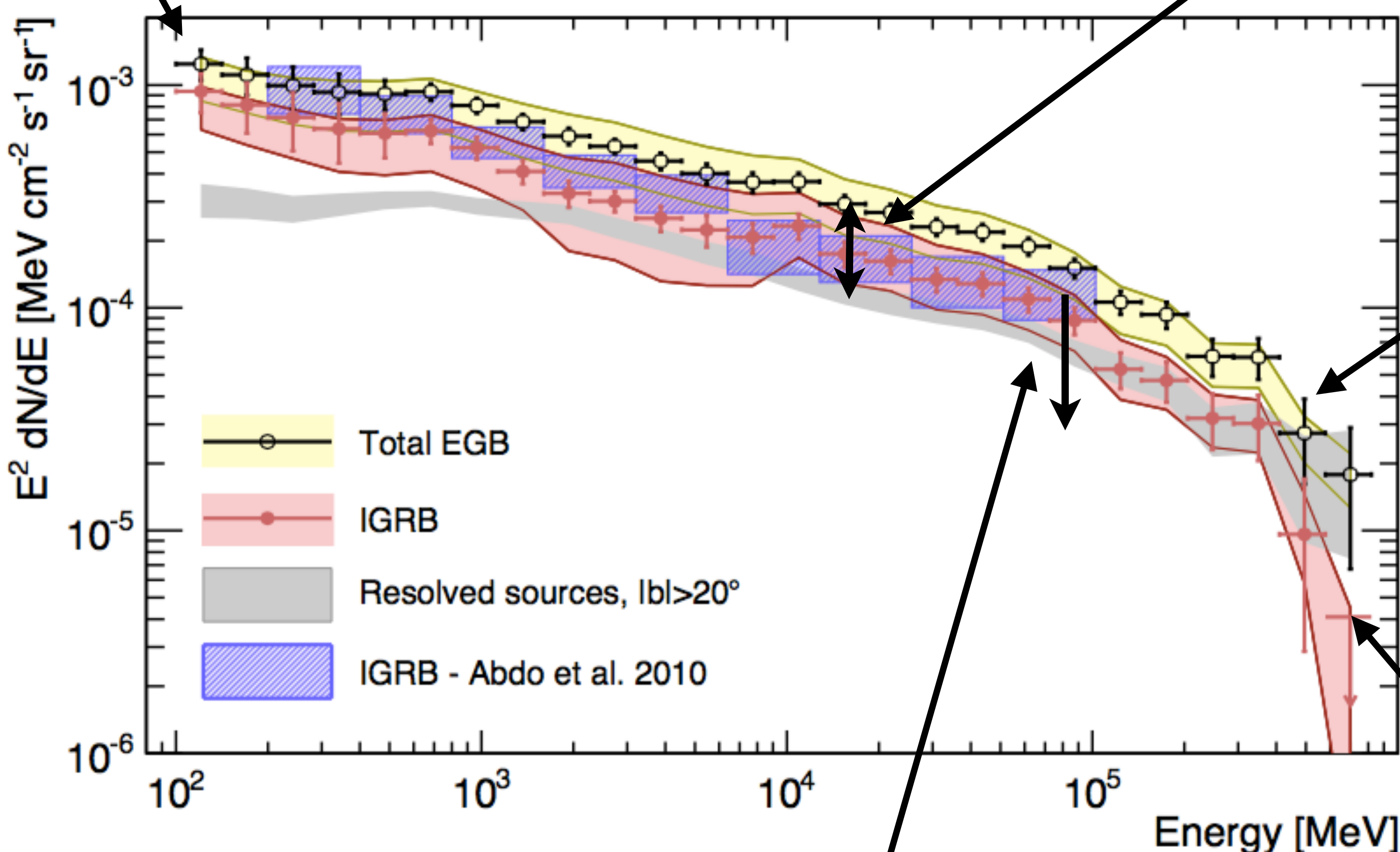
Markus Ackermans Talk

## Goals:

Better effective area at high energies / low energies.

Extend energy range

Reduce foreground modeling systematic uncertainty




Reduce high-energy statistical uncertainty

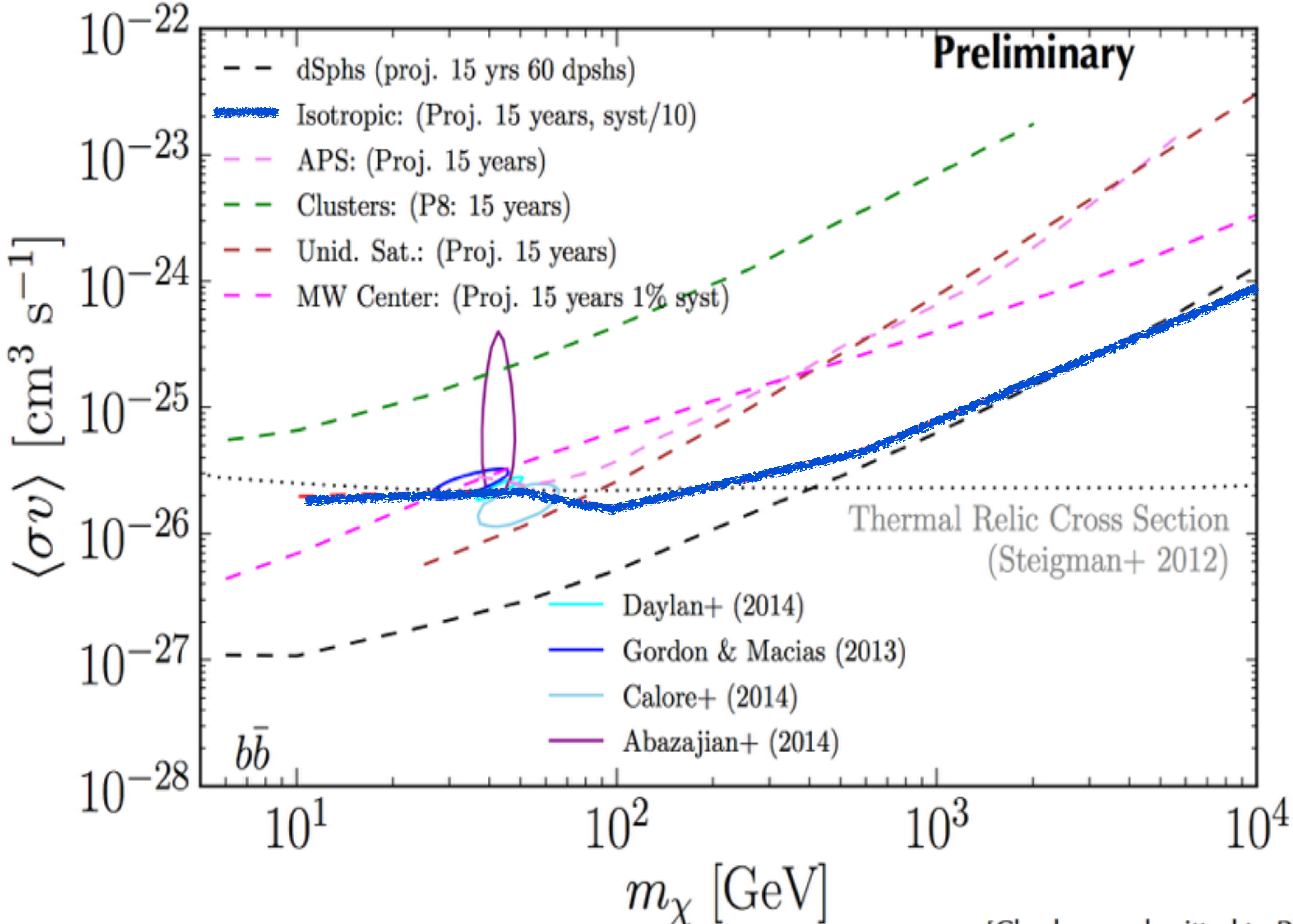
Resolve more sources.

Better high-energy PSF / PSF classes/ reduction of IGRB with respect to the EGB

Extend the measurement

Accurate energy reconstruction beyond 1 TeV.

# Projected Limits for b-quark Channel, for 15 Years of Data




[Charles+, submitted to Physics Reports]