
# The search for cosmological annihilation signals with the Fermi-LAT

[arXiv:1501.05464, 1501.05301, 1605.02016, 1608.07289]

**Miguel A. Sánchez-Conde**

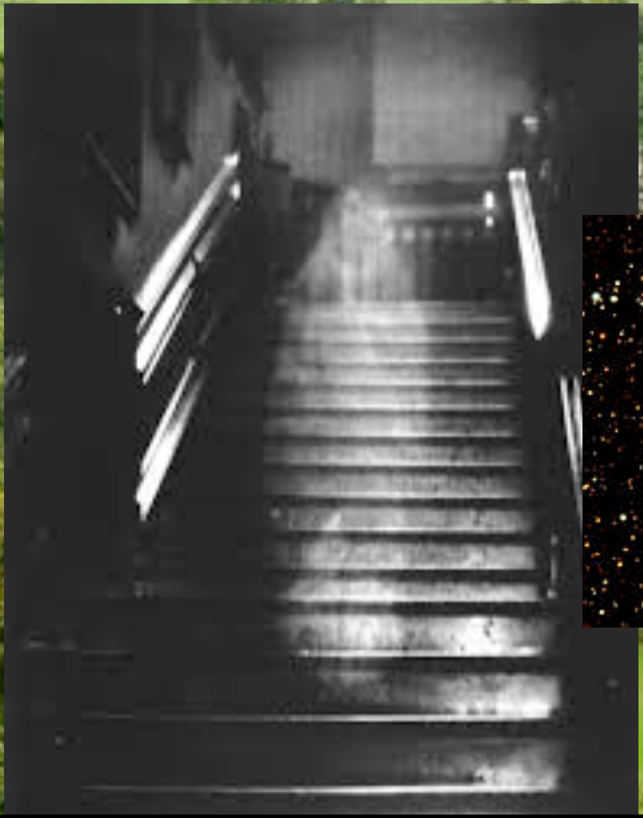
**ON BEHALF OF THE FERMI LAT COLLABORATION**

*Dark Matter from aeV to ZeV – 3rd IBS-MultiDark-IPPP workshop*

Lumley Castle, Durham, UK – November 21-25 2016

# SUCH A PERFECT PLACE!

# SUCH A PERFECT PLACE for the invisible!

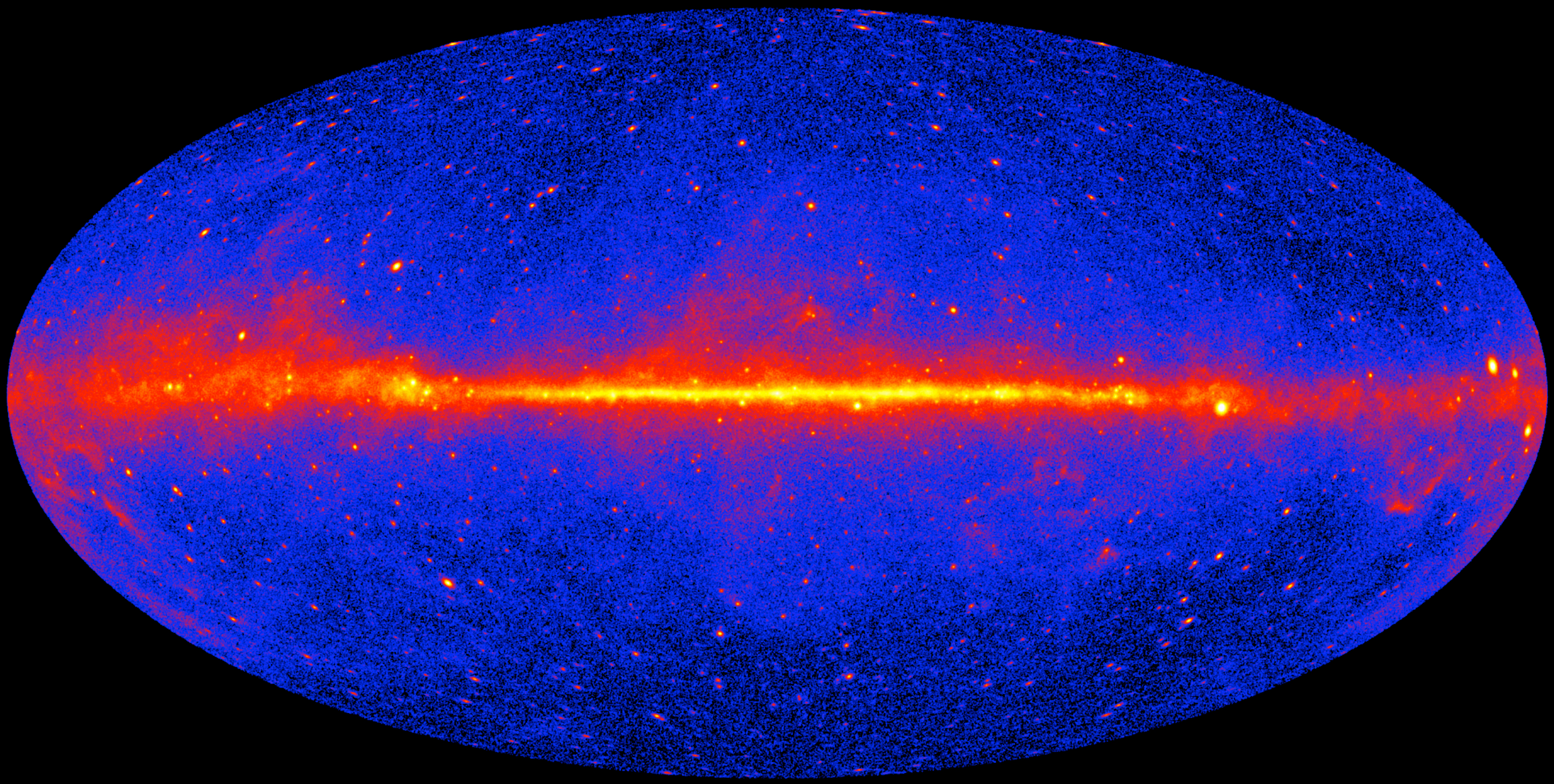


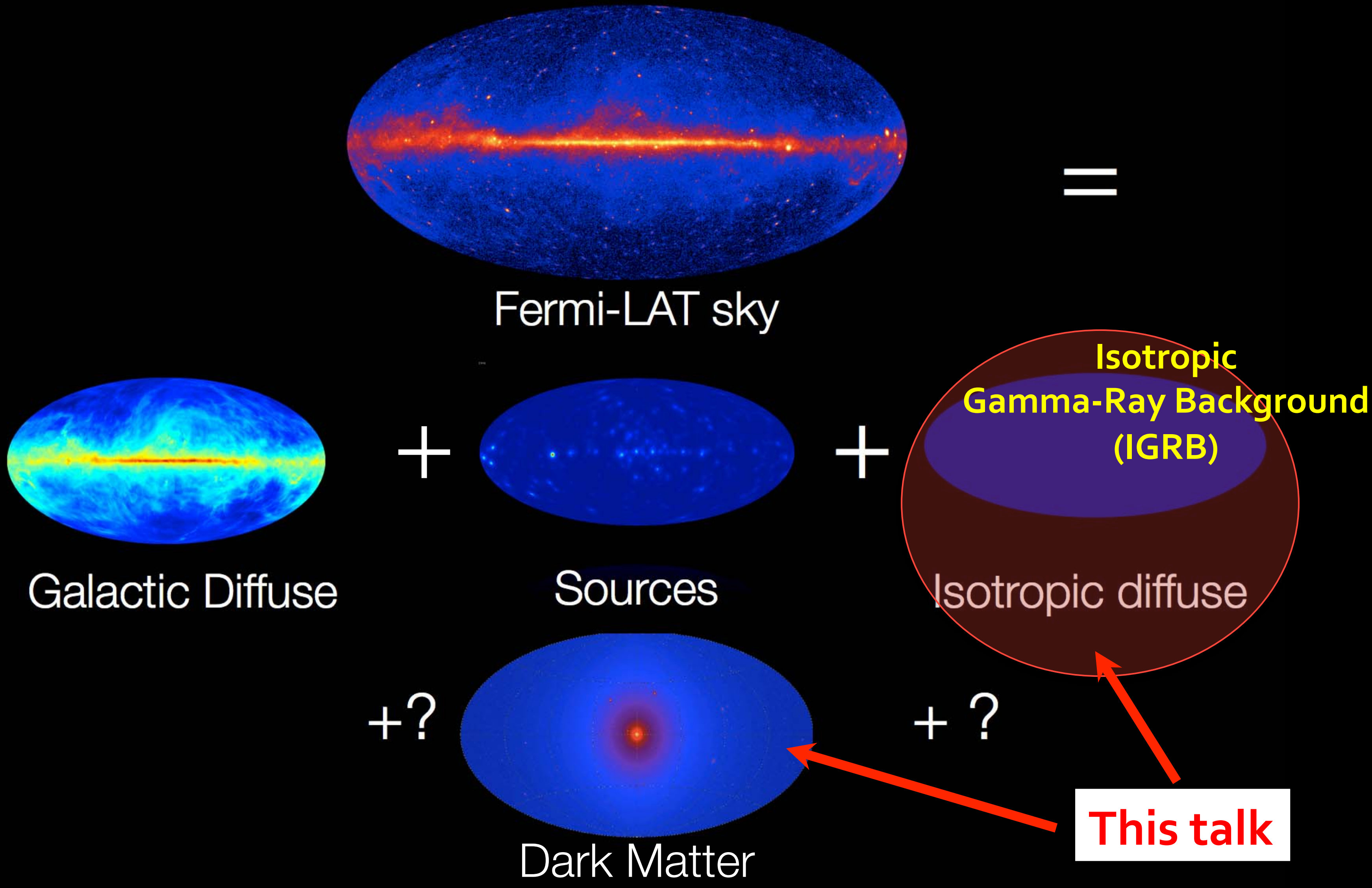
The ghost of Lady Lily Lumley coming to the conference

The ghost of Lady Lily Lumley seen around room fifty something last night

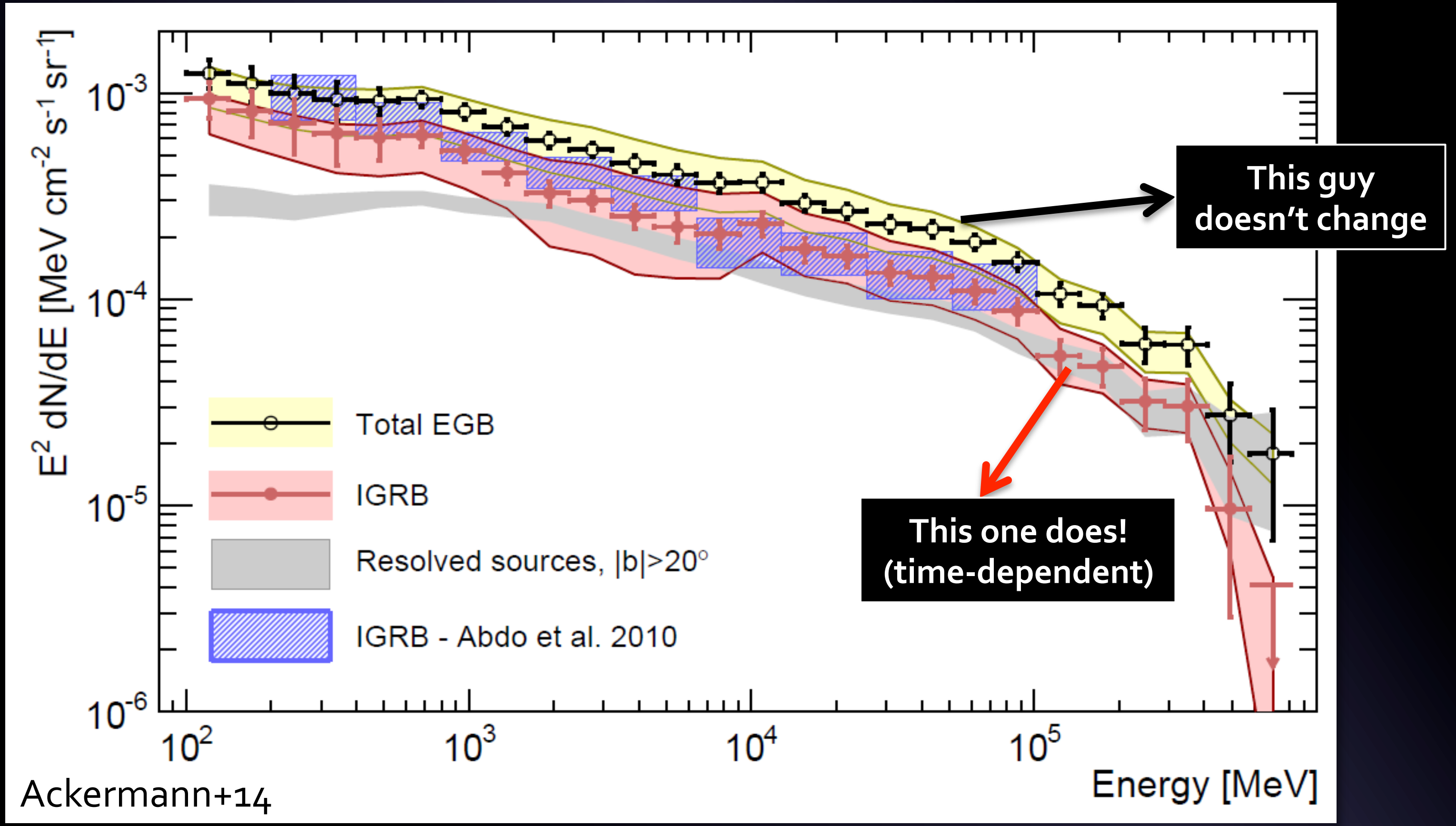
# THE GAMMA-RAY SKY above 1 GeV

5 years of Fermi LAT data




Fermi-LAT sky
=
Galactic Diffuse
+
Sources
+
Isotropic
Gamma-Ray Background
(IGRB)
Isotropic diffuse
+?
Dark Matter
+ ?
This talk

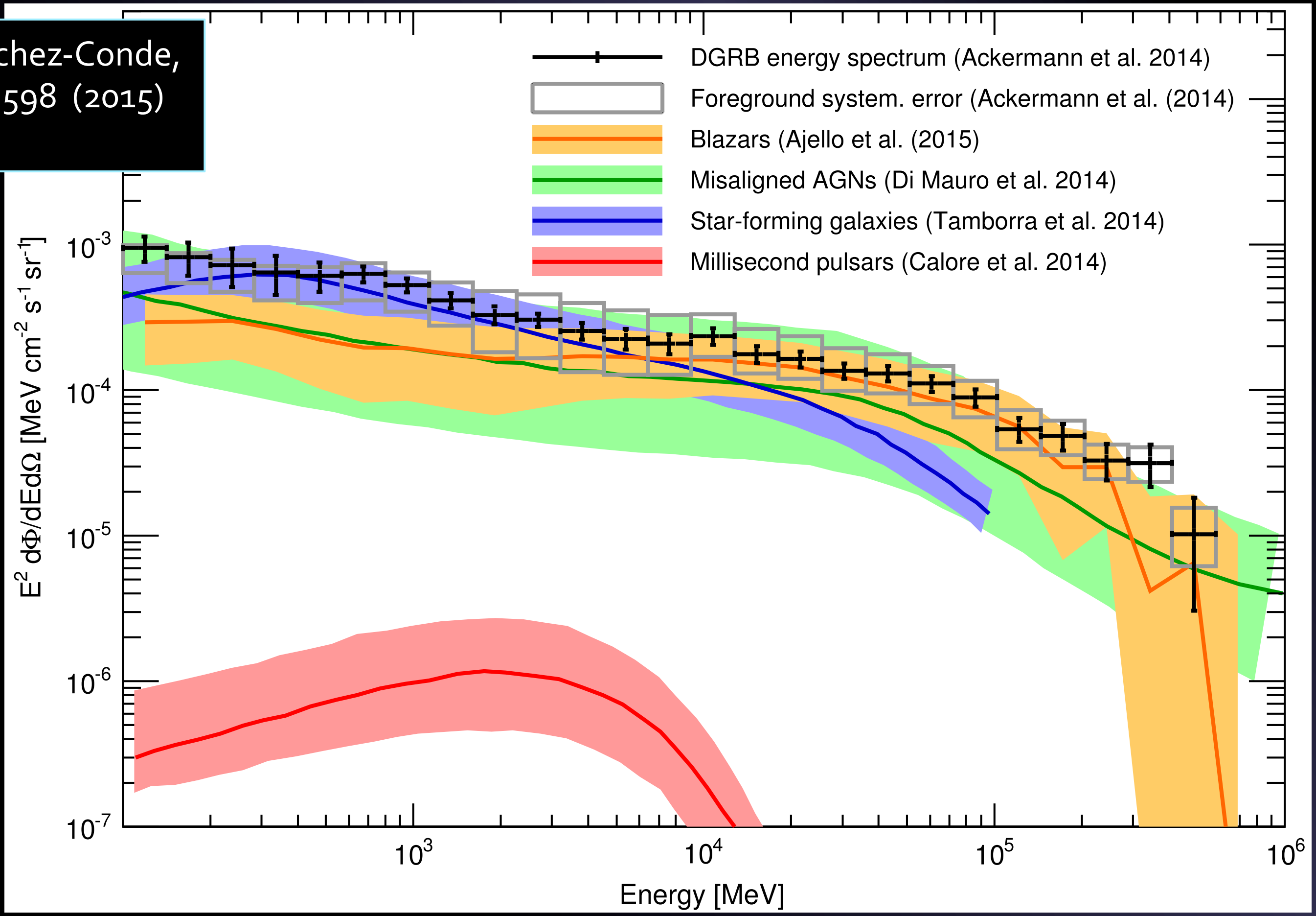
# The Fermi LAT IGRB intensity spectrum




- Energy range**: 100 MeV – 820 GeV**
- Significant **high-energy cutoff** feature in IGRB spectrum**,** consistent with simple source populations attenuated by EBL
- **~50% of total EGB** above 100 GeV now **resolved into individual LAT sources**

# Origin of the IGRB
## in the Fermi LAT energy range

Fornasa & Sánchez-Conde, Phys. Reports, 598 (2015) [1502.02866]



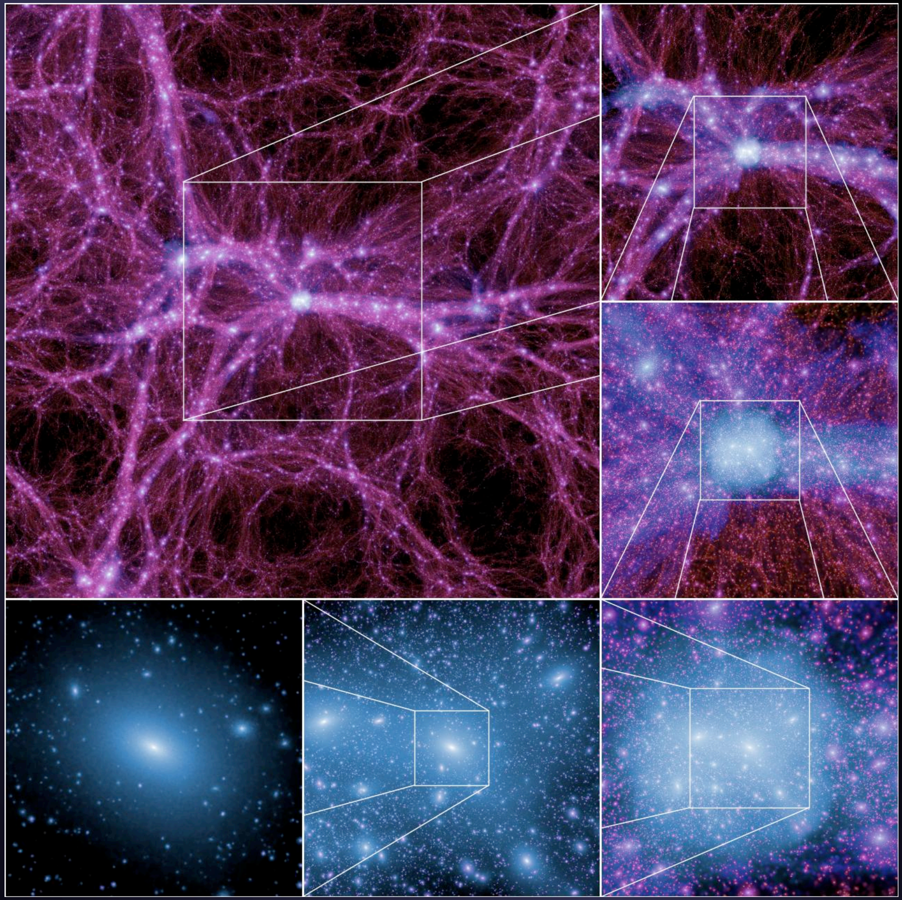

- Cumulative emission of unresolved sources
- Dark matter?

# Cosmological DM annihilation

DM halos and substructure *expected* at all scales down to a $M_{min} \sim 10^{-6}\ M_{sun}$.

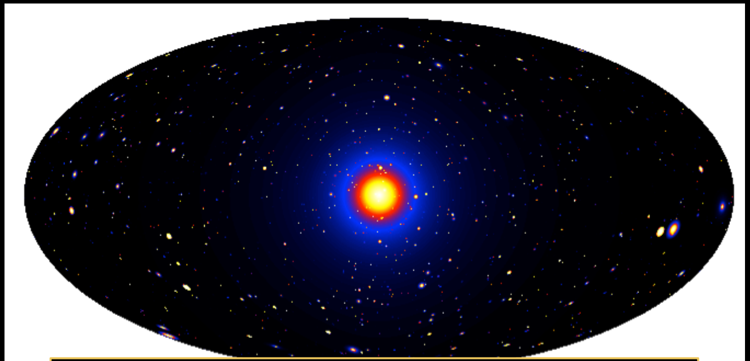
DM annihilation signal from all DM halos at all redshifts should contribute to the IGRB.

Lower redshifts ($z \leq 2$) contribute the most (EBL gamma-ray attenuation; ‘redshifted’ energy).



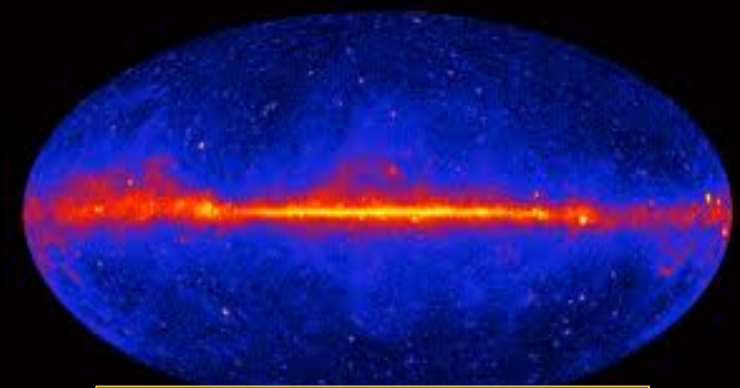
Zoom sequence from 100 to 0.5 Mpc/h
Millenium-II simulation boxes (Boylan-Kolchin+09)

# The IGRB as a powerful tool to probe the nature of the DM



DM-induced $\gamma$-ray (simulated) sky

VS.

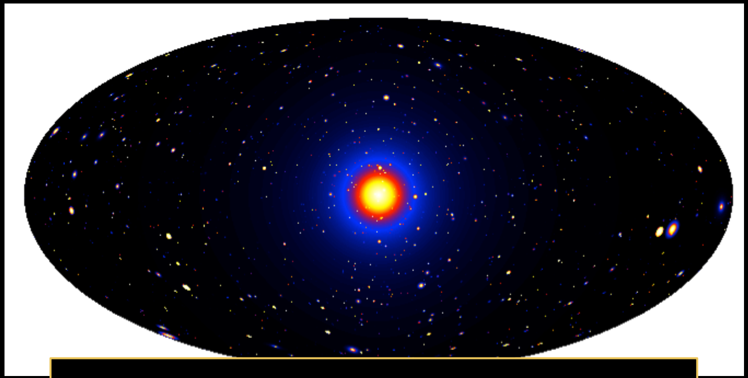


observed $\gamma$-ray sky

Two approaches possible:

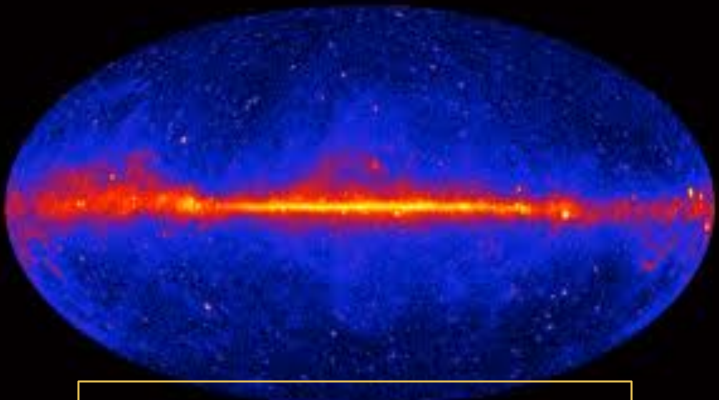
1. **INTENSITY** spectrum
2. Angular power spectrum of **ANISOTROPIES**

# The IGRB as a powerful tool to probe the nature of the DM



DM-induced
$\gamma$-ray (simulated) sky

VS.



observed $\gamma$-ray sky

Two approaches possible:

1. **INTENSITY** spectrum **This talk**
2. Angular power spectrum of **ANISOTROPIES** **Fornasa's**

# DM cosmological signal predictions

**FLUX from extragalactic DM annihilation**

$$\frac{d\phi}{dE_0} = \frac{\langle \sigma v \rangle}{8\pi} \frac{c\,(\Omega_{\rm DM}\rho_c)^2}{m_{DM}^2} \int dz e^{-\tau(E_0,z)} \frac{(1+z)^3}{H(z)} \zeta(z) \left.\frac{dN}{dE}\right|_{E=E_0(1+z)}$$

**WIMP annihilation cross-section**

**EBL attenuation (Domínguez+11)**

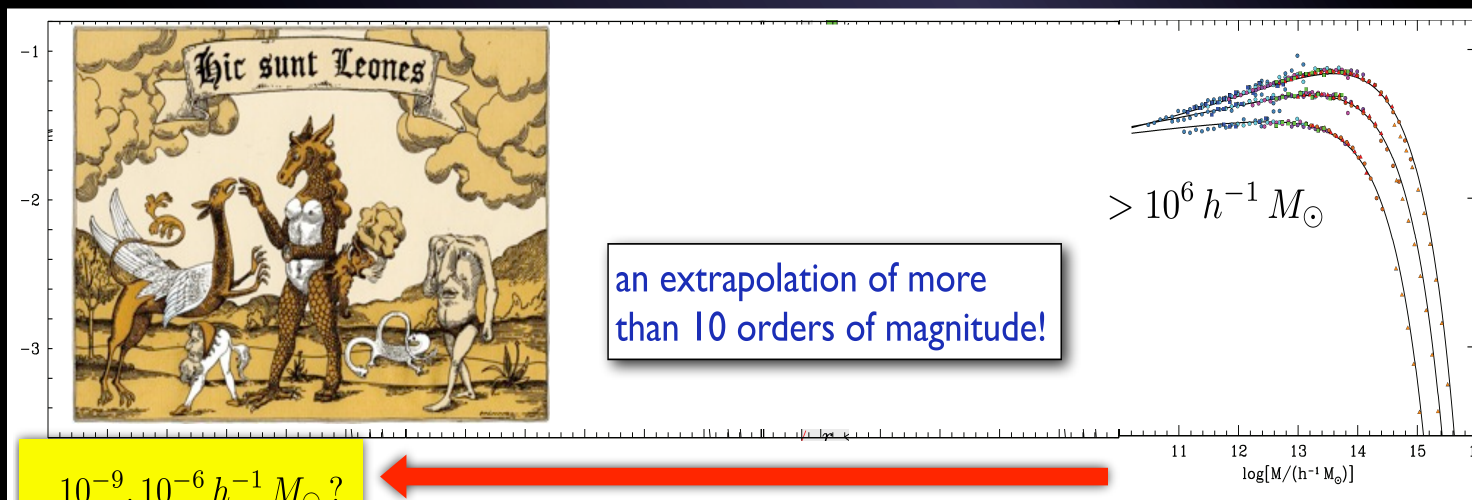
**"Flux multiplier"**

**WIMP-induced spectrum**

The **flux multiplier** is a measure of the *clumpiness* of the DM in the Universe, and is the *main source of theoretical uncertainty* in this game.

Uncertainties in this parameter traditionally huge!

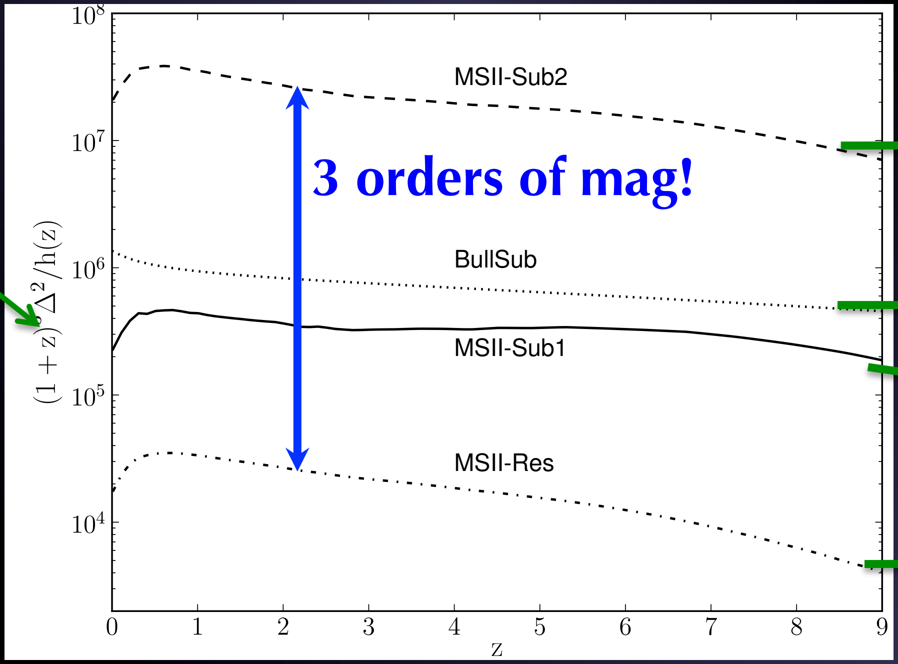
Simulations do not resolve the whole hierarchy of structure formation…




(Sefusatti, DSU13)

Previously, this was the common picture:

Normalized flux multiplier




Abdo+10

Most optimistic c(M) power-law extrapolation

Semi-analytical

Conservative power-law extrapolation

Only resolved halos in MSII

*Are all these scenarios realistic, i.e., well motivated in $\Lambda$CDM?*

In our work, these uncertainties are drastically reduced by means of:

- A better understanding at small halo masses, thanks to both recent theoretical and numerical developments.
- Two independent and complementary approaches to compute $\zeta(z)$.

# Flux multiplier: approaches

## HALO MODEL (HM)

Implies to describe the structure of individual halos and subhalos, and their cosmic evolution.

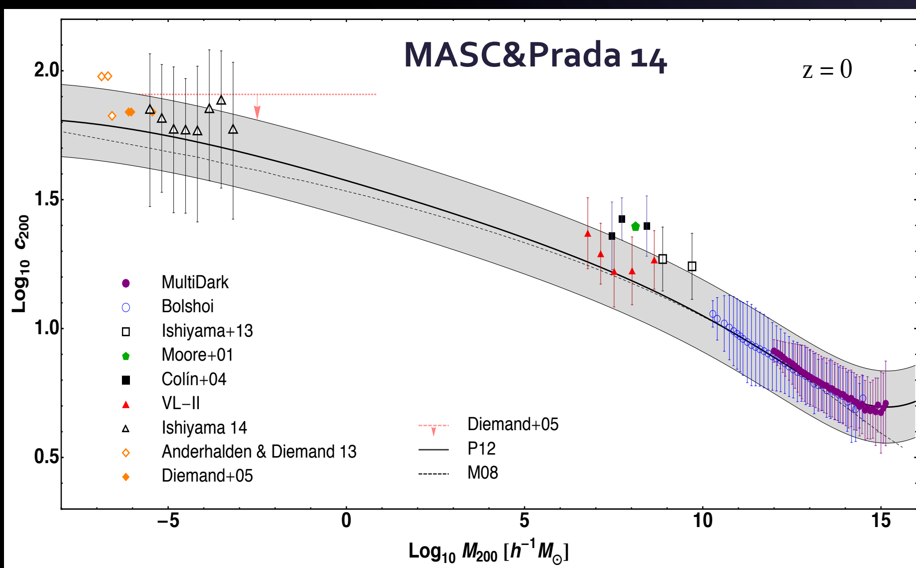
→ OUR BENCHMARK MODEL

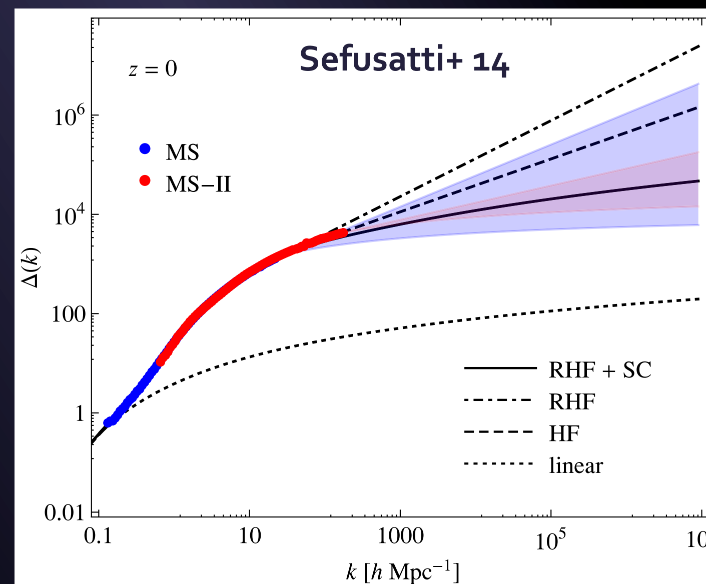
## non-linear matter POWER SPECTRUM (PS)

Directly measured in simulations.

→ Good to study uncertainties

(only one quantity extrapolated)

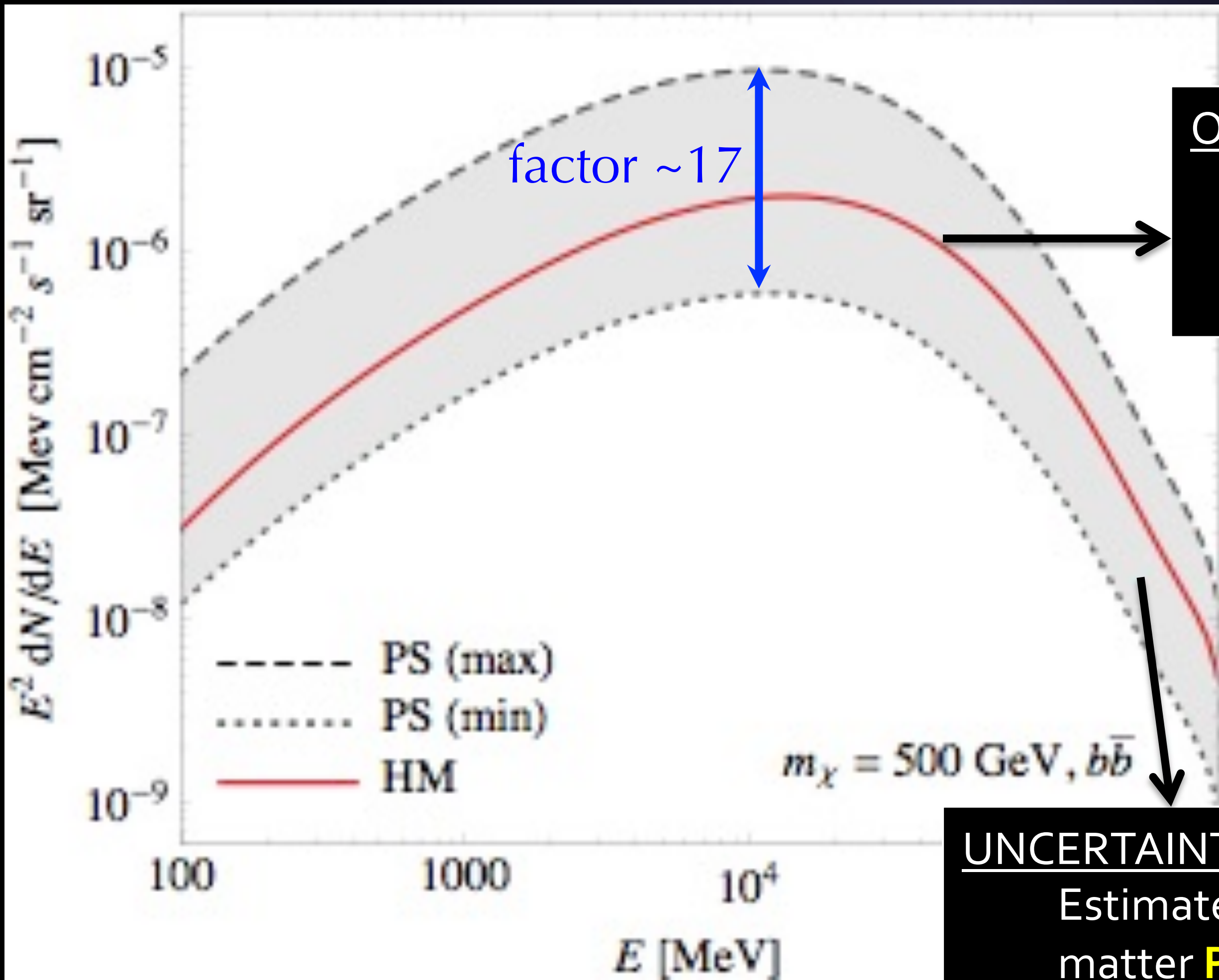



*Disclaimer*: both approaches use extrapolations over several orders of magnitude down to the smallest predicted mass scales.

# HM vs. PS predictions agree pretty well!

Ackermann+15, JCAP09(2015)008 [astro-ph/1501.05464]




<u>OUR BENCHMARK MODEL:</u>

calculated in **Halo Model** approach using the most up-to-date parameters.

<u>UNCERTAINTY BAND:</u>

Estimated by means of the non-linear matter **Power Spectrum** approach. It will directly translate into uncertainties in our DM limits.

# DM limits

**No statistically significant evidence of WIMP signals in the IGRB → set DM limits.**

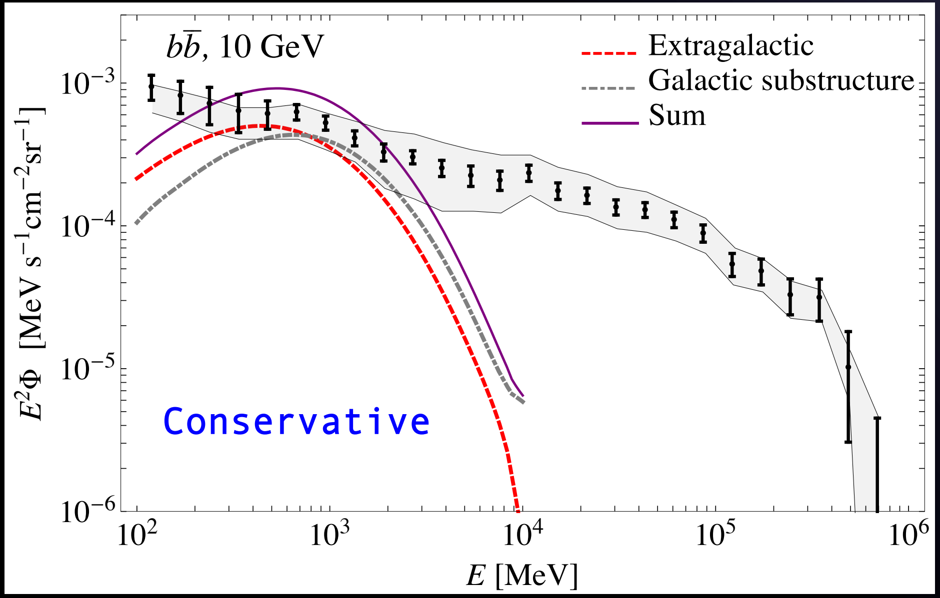
### *Conservative limits*

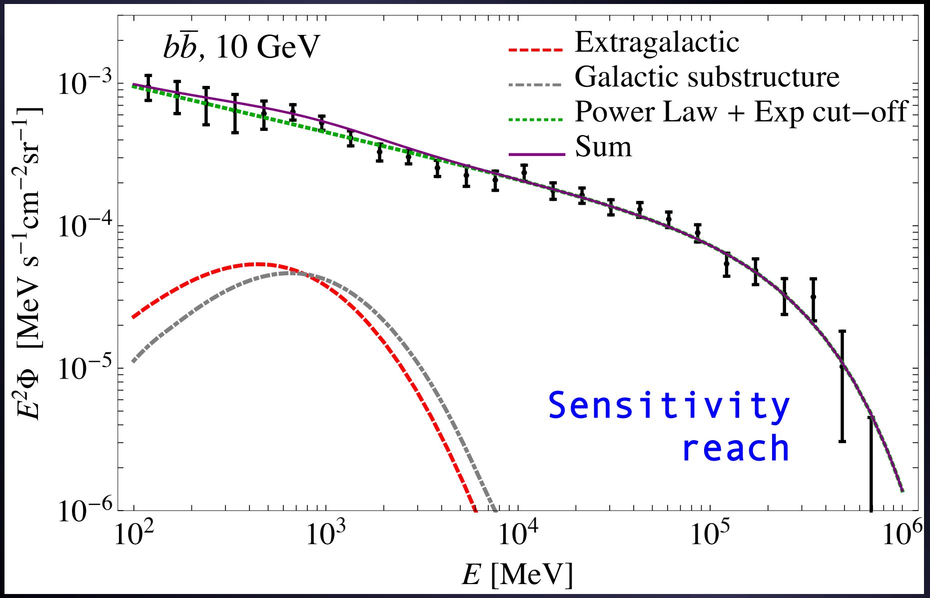
- Only DM. No astrophysical contributions to the measured IGRB.
- Not preferred Galactic diffuse model among those tested in IGRB measurement paper.

### *Sensitivity reach*

- Total astrophysical contribution fully explains the measured IGRB at all energies.
- We can entirely rely on a Galactic diffuse model to derive the IGRB.

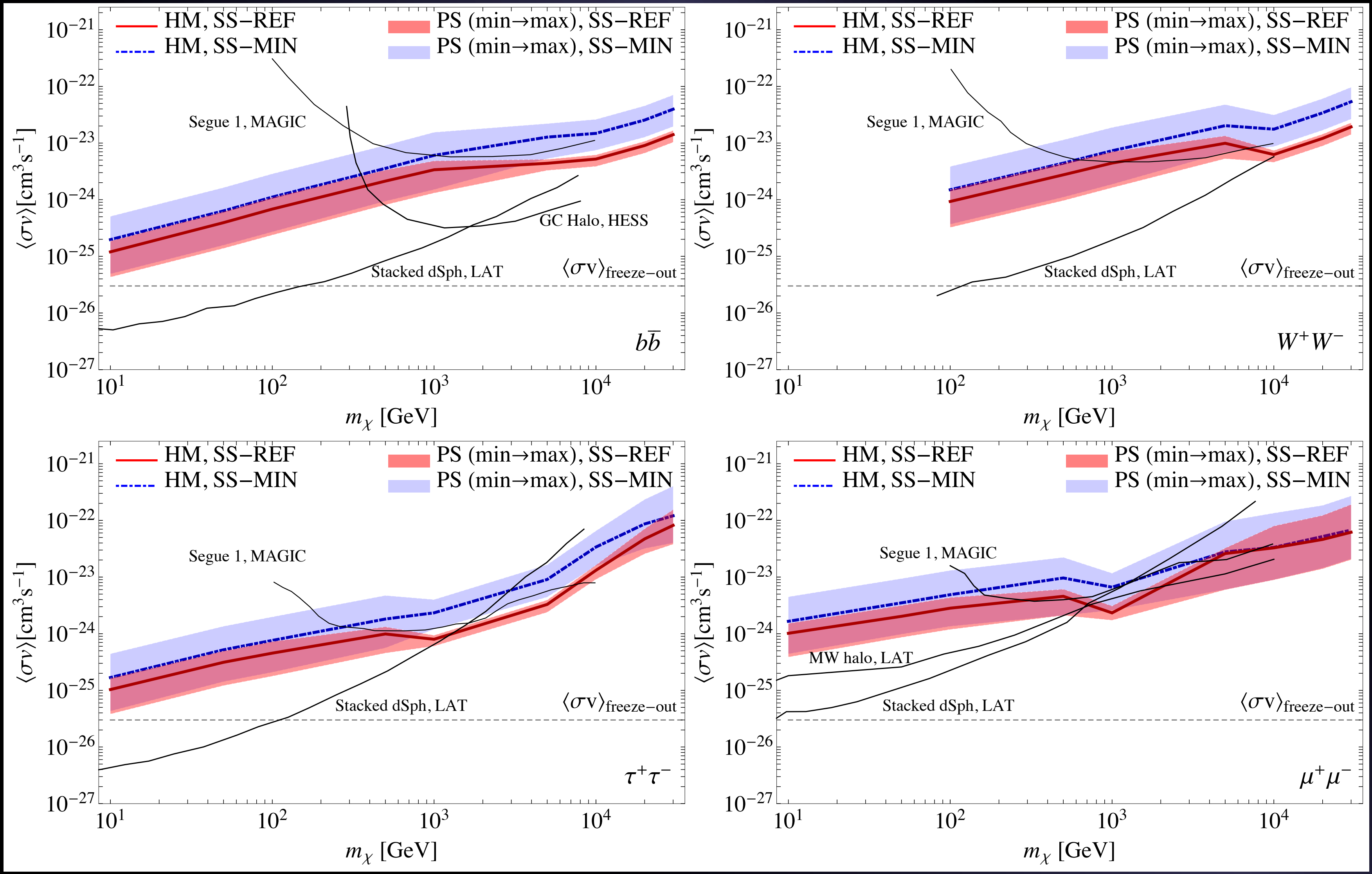
Ackermann+15, JCAP09(2015)008 [astro-ph/1501.05464]



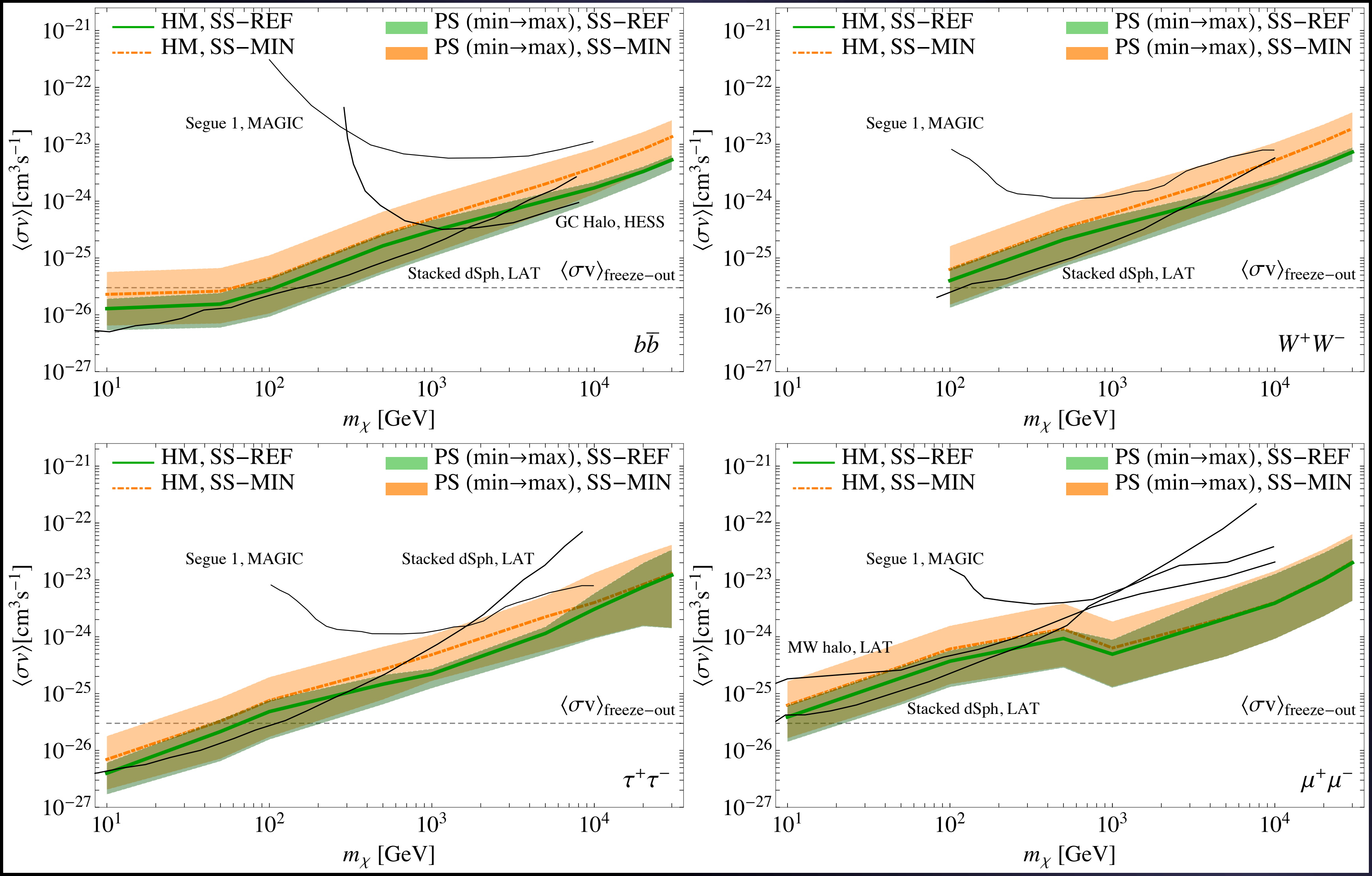

Examples of DM spectra at the border of being excluded at 2σ level

# Conservative limits




Ackermann+15, JCAP09(2015)008 [astro-ph/1501.05464]

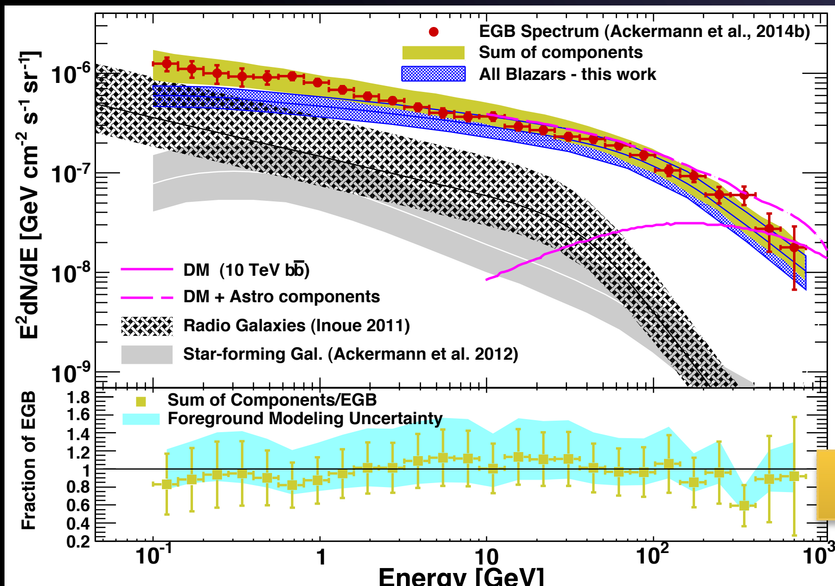
# Sensitivity reach

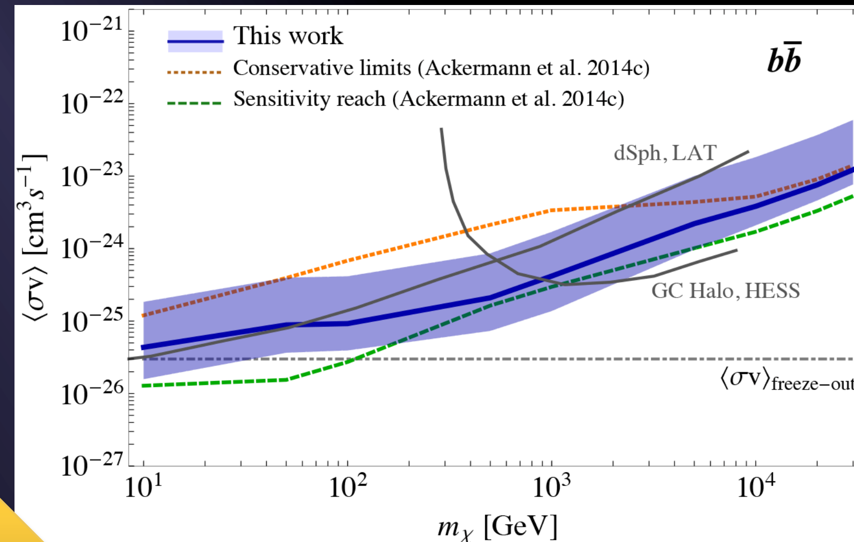


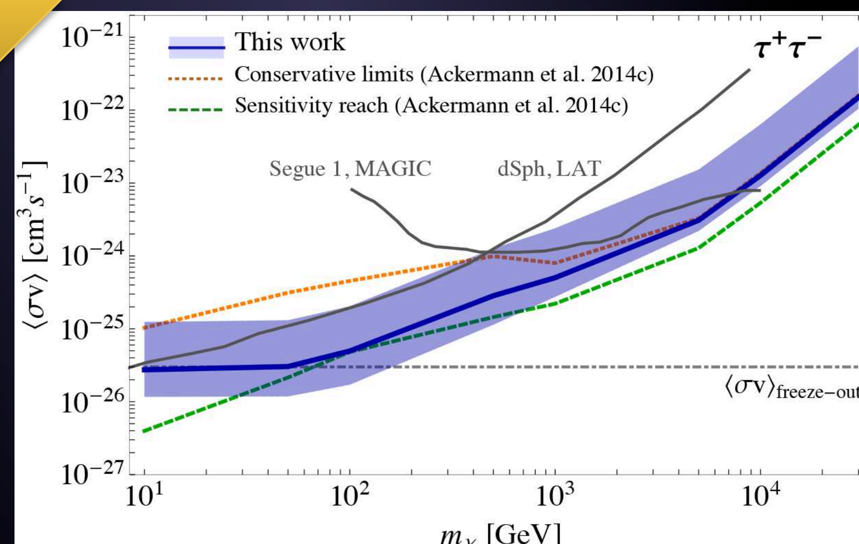

Ackermann+15, JCAP09(2015)008 [astro-ph/1501.05464]

# A more realistic scenario

Ajello+15



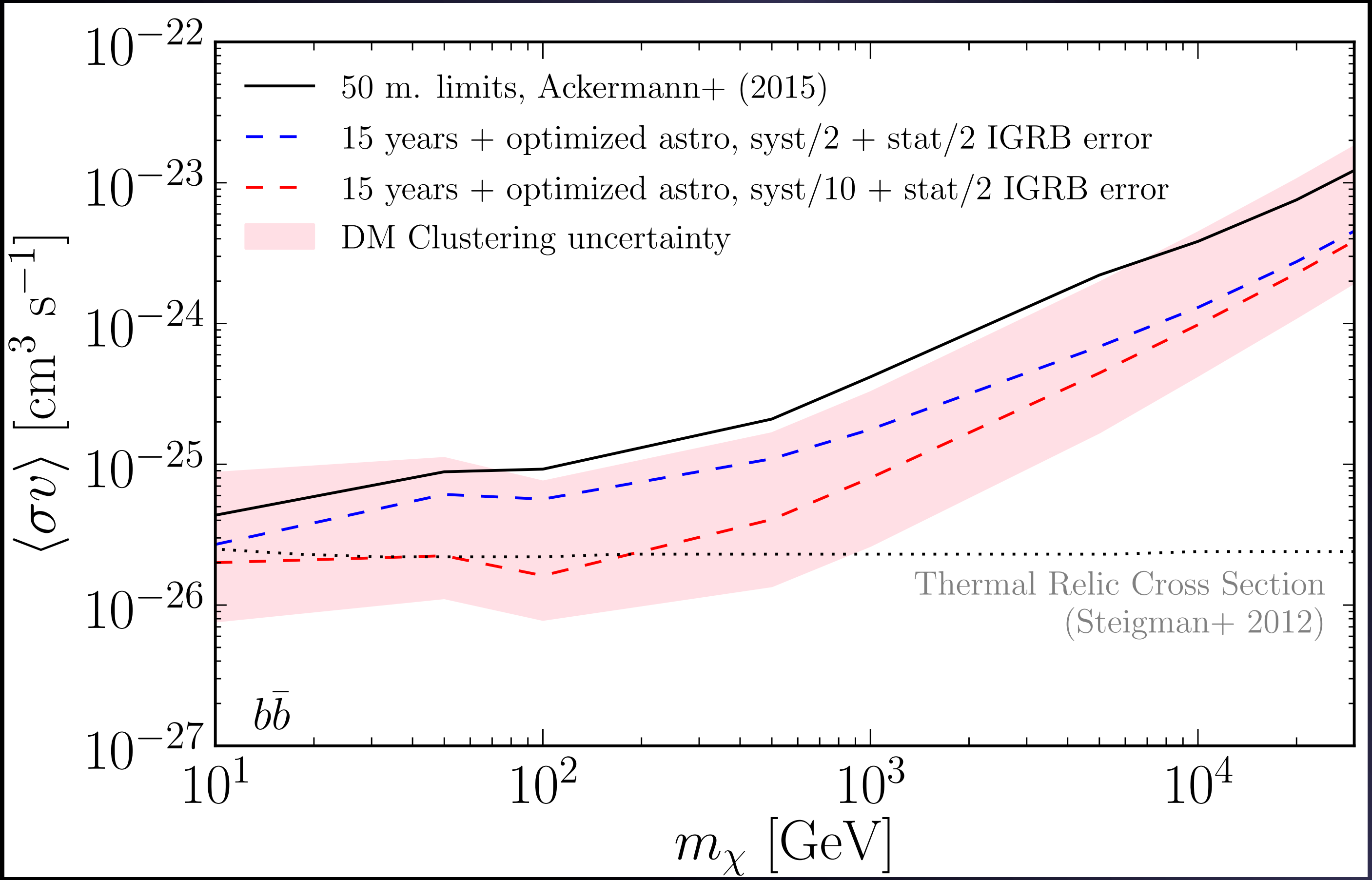




1. Astrophysical contribution to the IGRB derived as accurately as possible
2. DM constraints lie between conservative limit and sensitivity reach.

Ajello, Gasparrini, MASC+15

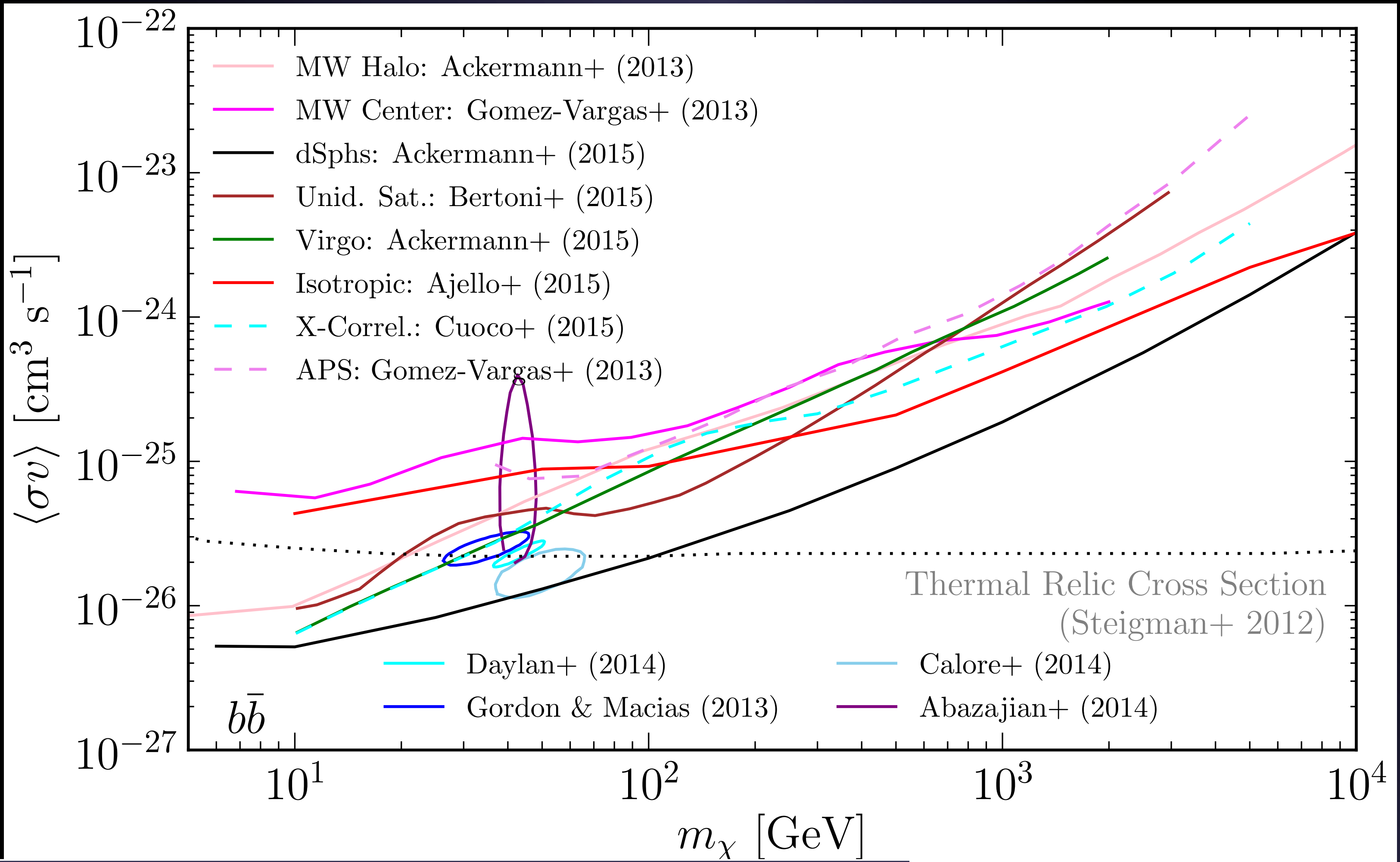
# Sensitivity projections

Expected evolution of the limits for 15 years of LAT data in the ‘realistic’ setup




Charles, MASC, et al., Phys. Reports, 636 (2016) [1605.02016]

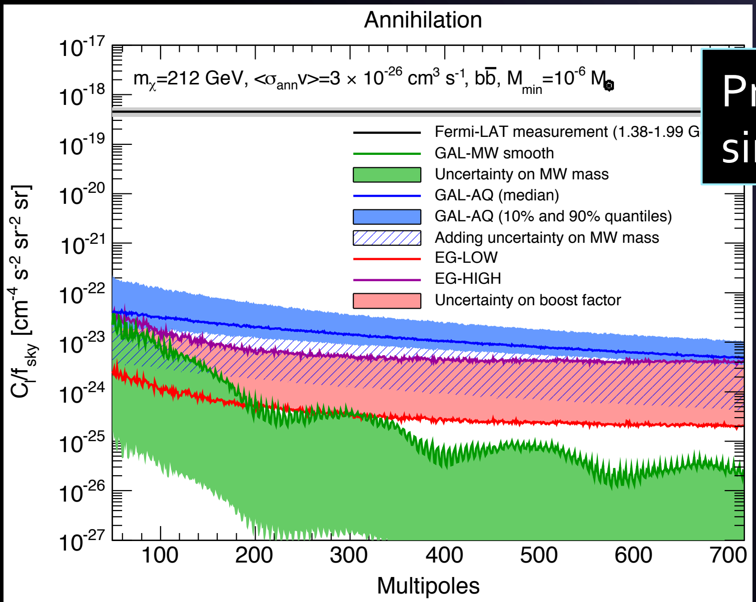
# Complementarity



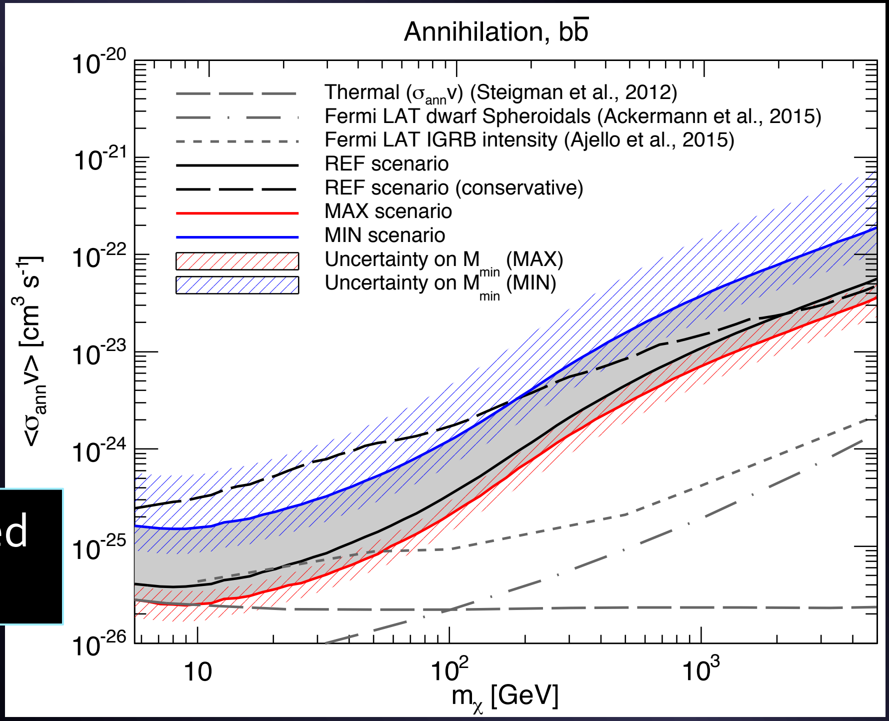

Charles, MASC, et al., Phys. Reports, 636 (2016) [1605.02016]

# DM constraints from IGRB anisotropies too!

Fornasa's talk




Predictions of DM-induced anisotropies from N-body simulations + semi-analytical models




Comparison between DM predictions and observed anisotropic sky yields competitive DM limits.

Fornasa+16, PRD accepted [1608.07289]

# Remarks

- **The IGRB is a powerful tool** to understand the nature of DM.
  - Both its intensity and anisotropy.

- **New predictions** for the cosmological DM annihilation signal.
  → Halo Model and Power Spectrum, which remarkably agree.
  → Theoretical uncertainty now a factor <20.

- LAT **IGRB intensity** spectrum used to set **new DM limits**:
  → Complementary to and competitive with other DM probes.
  → 15 years of LAT data will improve the 4.1 year limits by a factor ~2 to 5.

- IGRB **anisotropies** a powerful tool, too!
  → New measurement by the LAT.
  → Suggests the existence of two source populations!
  → New DM limits not as competitive as those from intensity IGRB.

[Fornasa's talk]

# THANKS!


Miguel A. Sánchez-Conde

(sanchezconde@fysik.su.se)

# ADDITIONAL MATERIAL

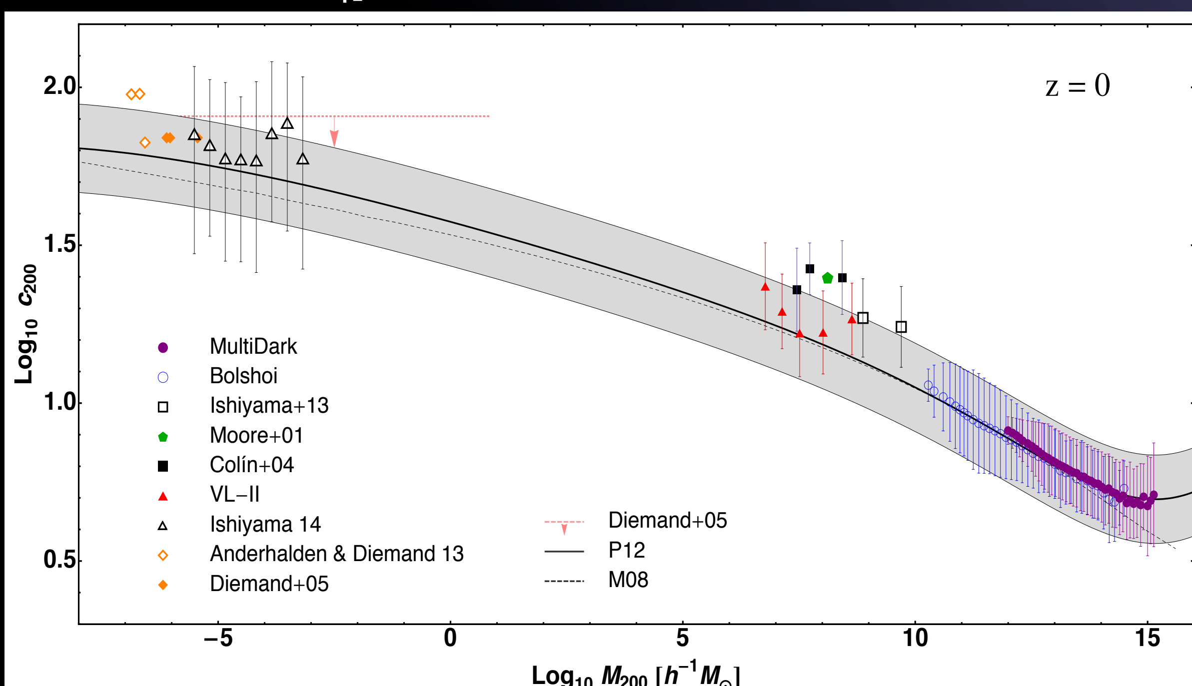
# HALO MODEL (I): bAsIcS

**Sum of DM annihilations in all halos, at all cosmic epochs.**

*FLUX MULTIPLIER*

$$\zeta(z) = \frac{1}{\Omega_{\rm DM}\rho_c}\int_{M_{\rm min}} \underbrace{dM\,\frac{dn}{dM}}_{\text{Halo mass function}}\,\underbrace{M\,\frac{\Delta_v(z)}{3}\langle F(M,z)\rangle}_{\text{Halo masses and concentrations}}$$

[MASC & Prada 2014]




Planck cosmology.

Prada+12 concentration-mass model.

NFW DM density profiles

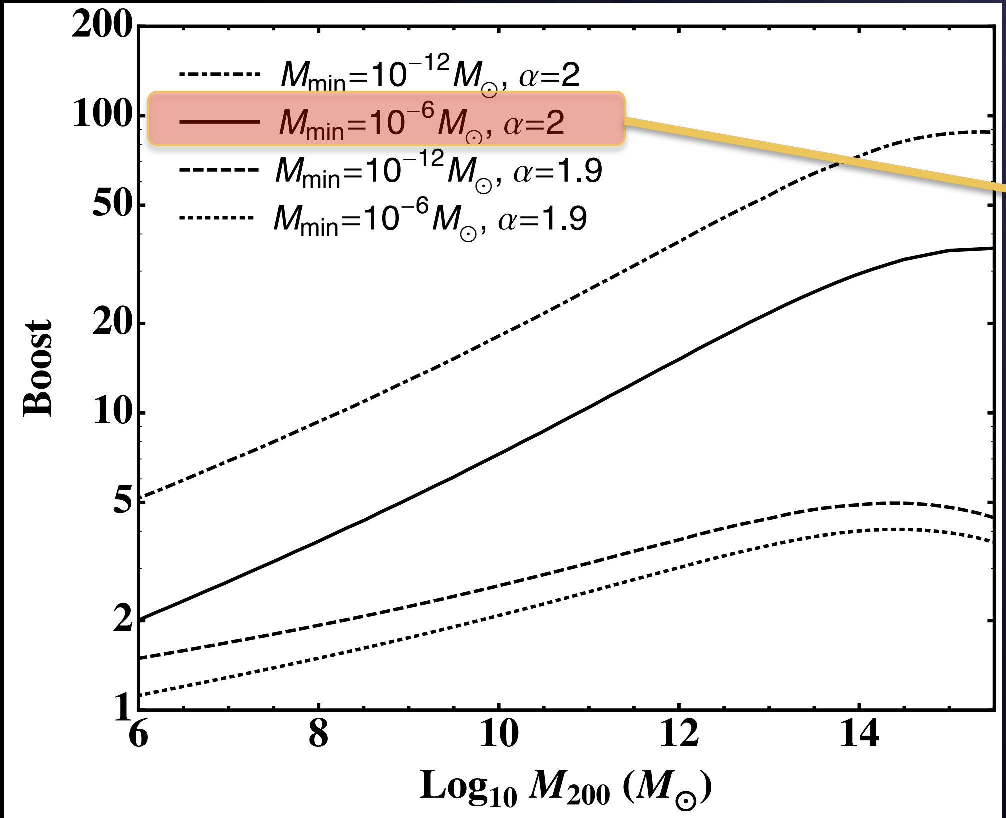
$M_{min} = 10^{-6}\ M_{sun}$

Tinker+08 HMF, with z=0 parameters as in Prada+12.

# HALO MODEL (II): substructure treatment

- Halo substructure expected at all mass scales down to $M_{min}$
  → enhancement (**boost**) of the DM signal expected

- Relevant parameters: *subhalo mass function* and *minimum subhalo mass*.




We adopt the fiducial model in MASC & Prada (2014)

It assumes that subhalos have similar internal properties as main halos.

$L = L_{host} * [1+B]$, so

B=0 → no boost

B=1 → $L_{host}$ x 2 due to subhalos

[MASC & Prada 2014]

# Subhalo concentrations? Yes.

- Difficulty in defining them:
  - More complex evolution compared to field halos.
  - Tidal forces modify the DM density profile
  - Reduced $R_{max}$, i.e. the radius at which $V_{max}$ is reached
- Solution: choose a definition independent of the profile

$$\boxed{c_{\rm V} = \frac{\bar{\rho}(R_{\rm max})}{\rho_c} = 2\left(\frac{V_{\rm max}}{H_0\, R_{\rm max}}\right)^2}$$

See also Diemand+08

- Still useful to compare to the standard $c_{200}$:

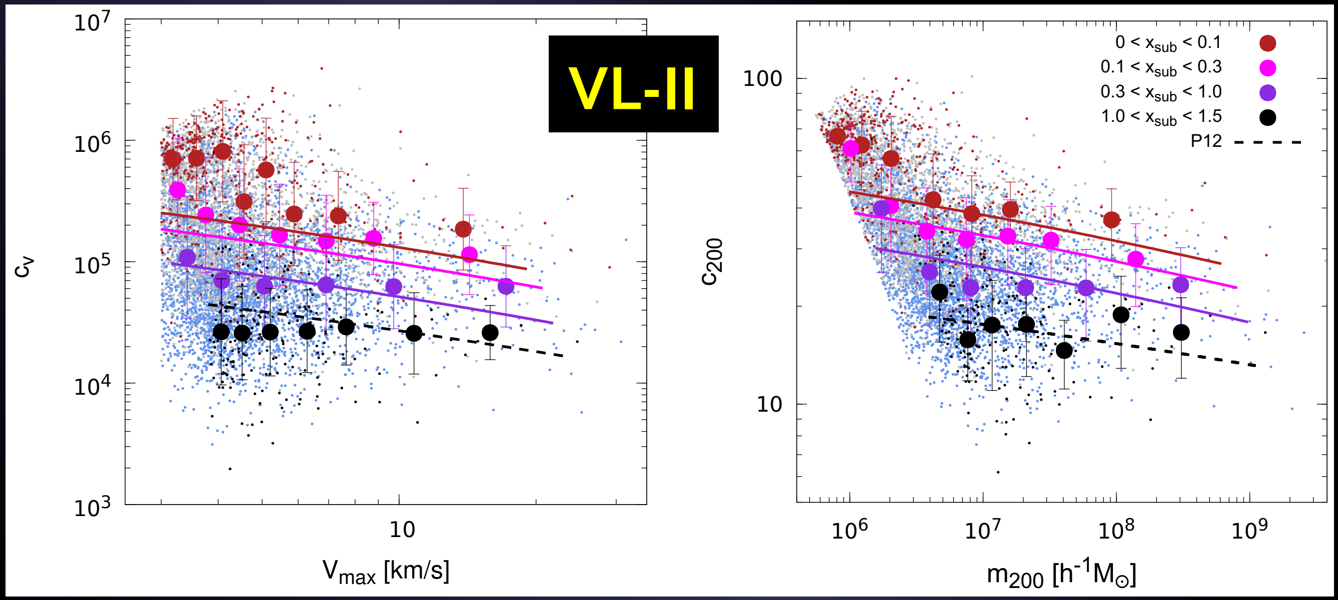
For NFW:
$$\boxed{c_{\rm V} = \left(\frac{c_\Delta}{2.163}\right)^3 \frac{f(R_{\rm max}/r_s)}{f(c_\Delta)}\,\Delta}$$

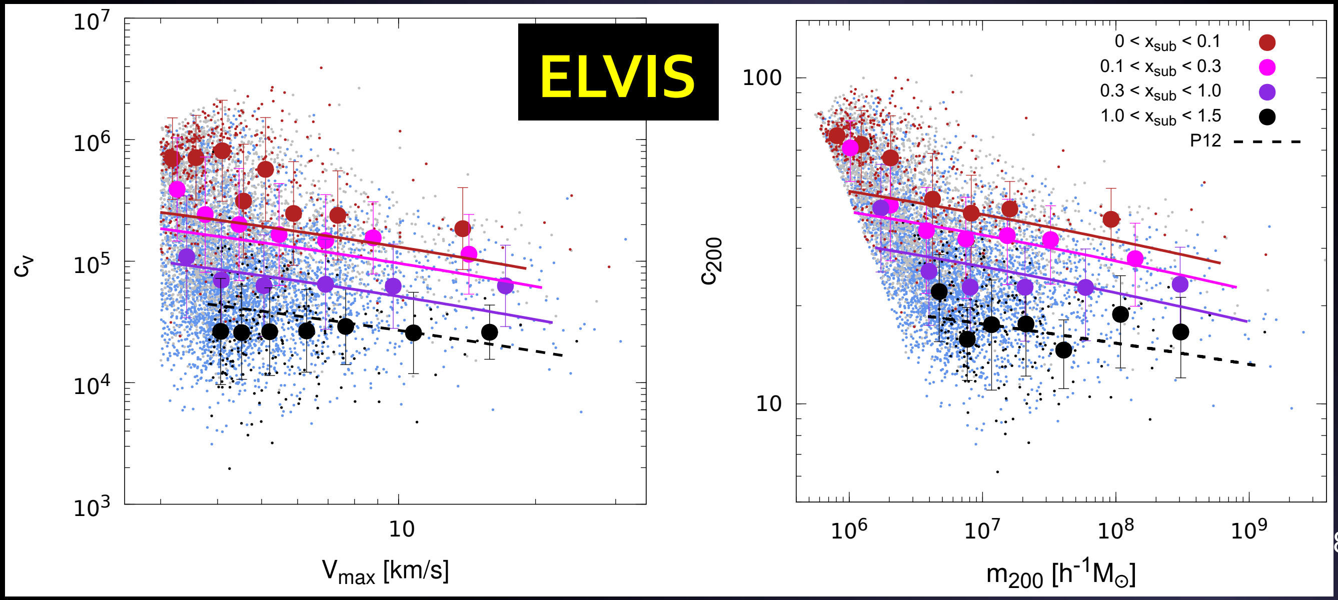
# $c_v$ results from VL-II and ELVIS

Median values

Four radial bins:

Clear **increase** of subhalo concentration as we approach the host halo center



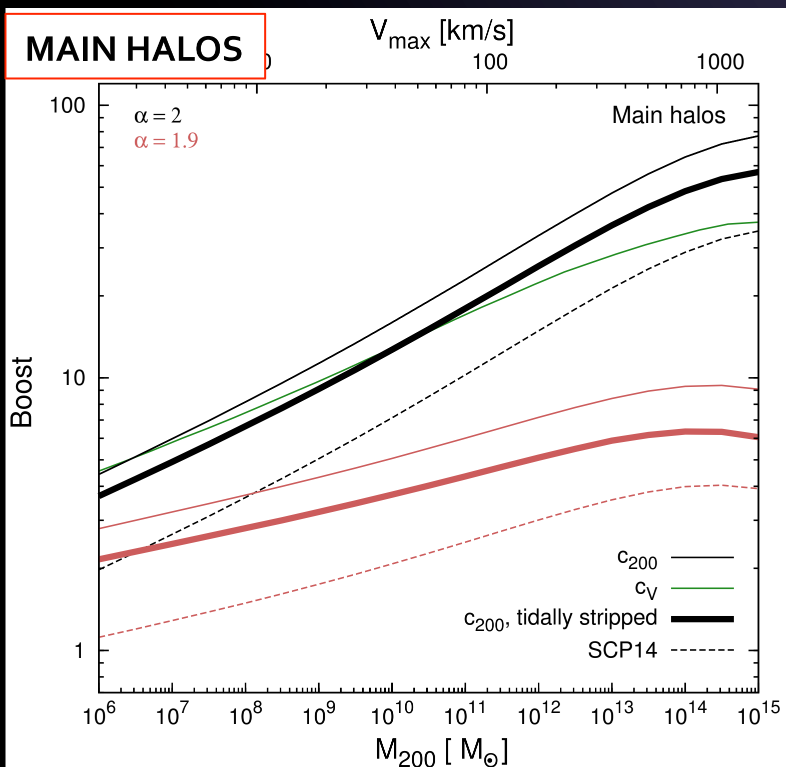




Moliné, MASC+ [1603.04057]

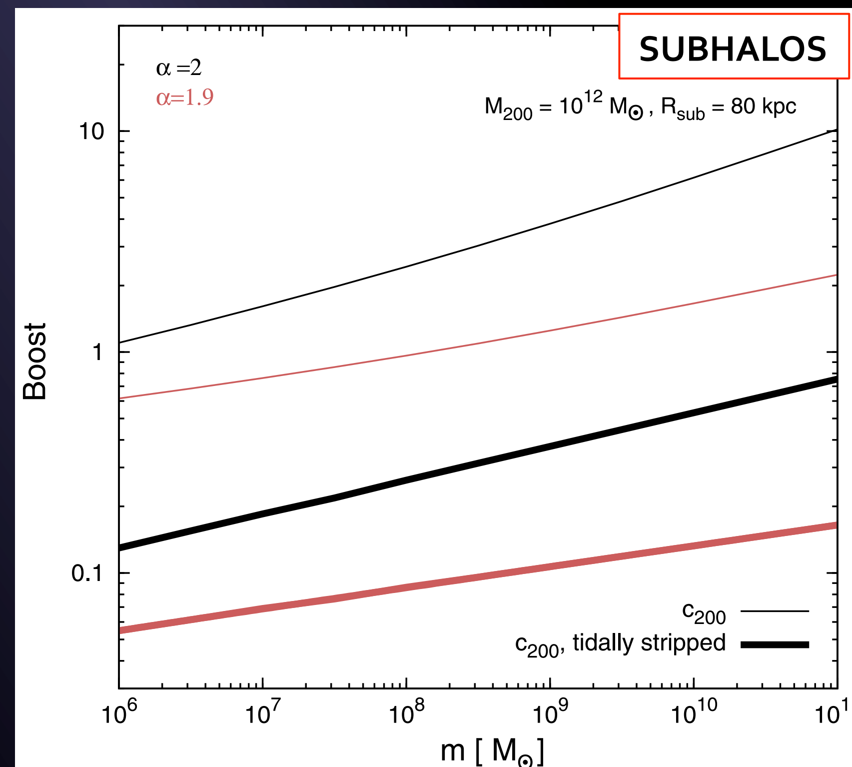
# Improved subhalo boost model

1. Make use of our best knowledge on subhalo concentrations.
2. Tidal stripping included (Roche criterium).

Moliné, MASC+ [1603.04057]




**Factor 2-3 larger boosts**




**Very small** boost for subhalos, e.g. **dwarfs**

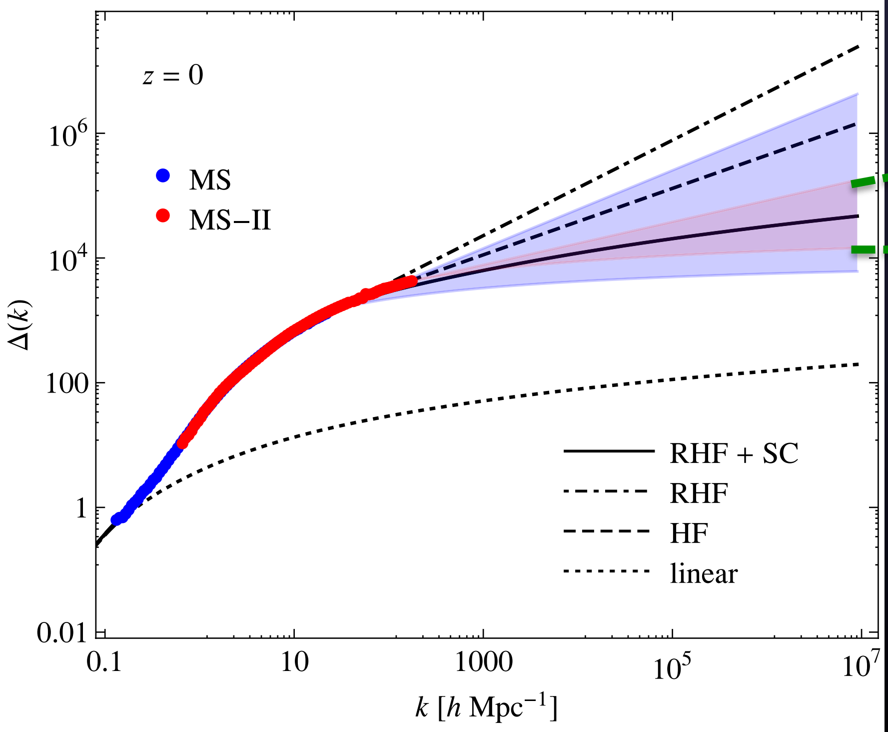
Agrees also with Bartels & Ando (2015) and Zavala & Afshordi (2015)

# POWER SPECTRUM APPROACH

***FLUX MULTIPLIER***

$$\zeta(z) \equiv \langle \delta^2(z) \rangle = \underbrace{\int^{k_{max}} \frac{d\,k}{k} \frac{k^3 P_{NL}(k,z)}{2\pi^2}}_{\text{Integral over the non-linear matter power spectrum, } P_{NL}} \equiv \int^{k_{max}} \frac{d\,k}{k} \underbrace{\Delta_{NL}(k,z)}_{\text{Adimensional } P_{NL}}$$

**$\Delta_{NL}$ is measured in simulations.**




Sefusatti, Zaharijas et al., MNRAS (2014)

MAX extrapolation to the lowest scales

MIN extrapolation to the lowest scales

We follow Sefusatti+14, which uses the Millenium simulations (MS and MS-II).

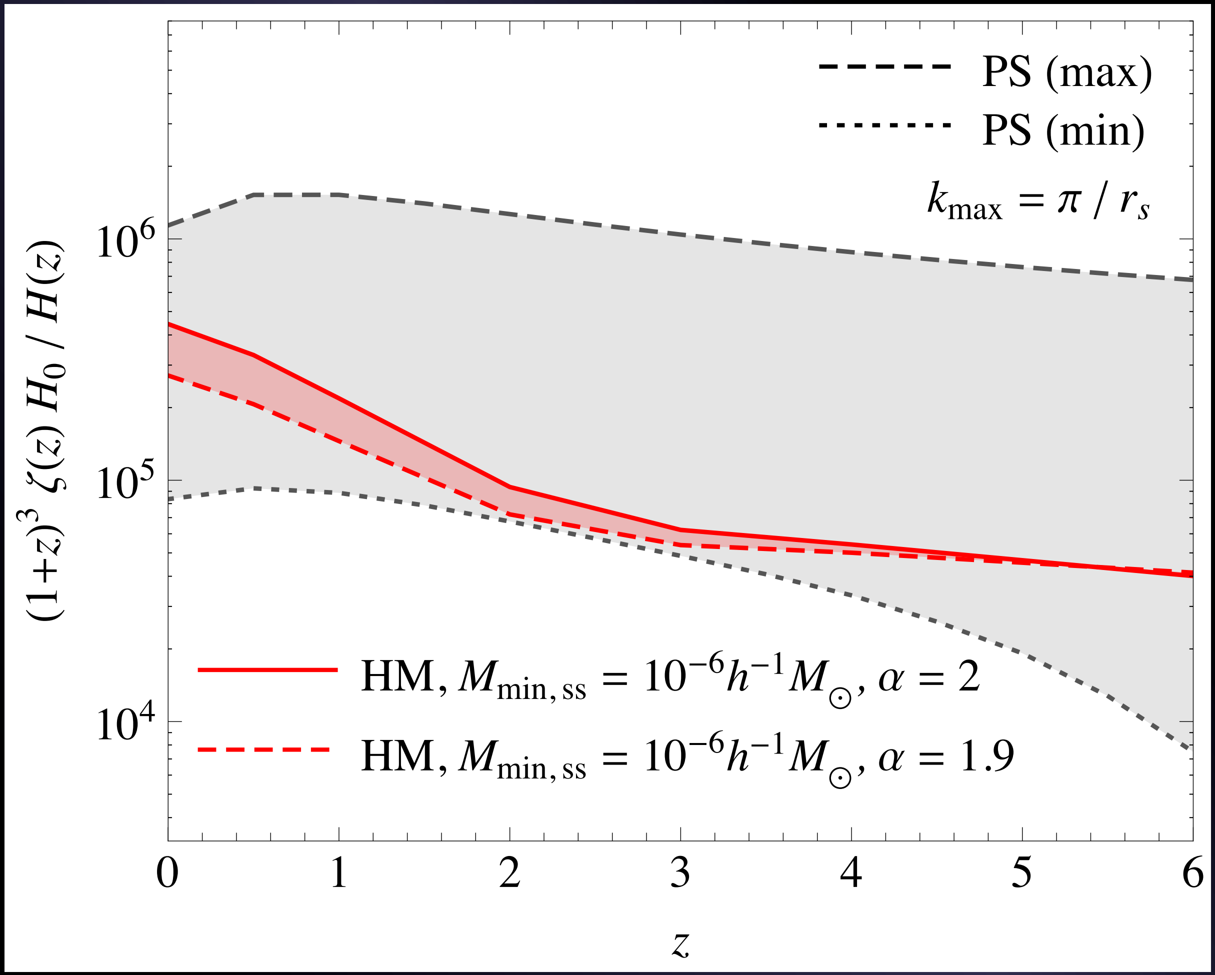
Results scaled to Planck cosmology.

Extrapolation to low masses with MS-II.

Substructure naturally accounted for.

# HM vs. PS predictions (I) redshift evolution

Normalized flux multiplier




Both the PS and HM results are fully consistent with each other.

Benchmark HM (solid line)within PS-min and PS-max, as expected.

Ackermann+15, JCAP09(2015)008 [astro-ph/1501.05464]

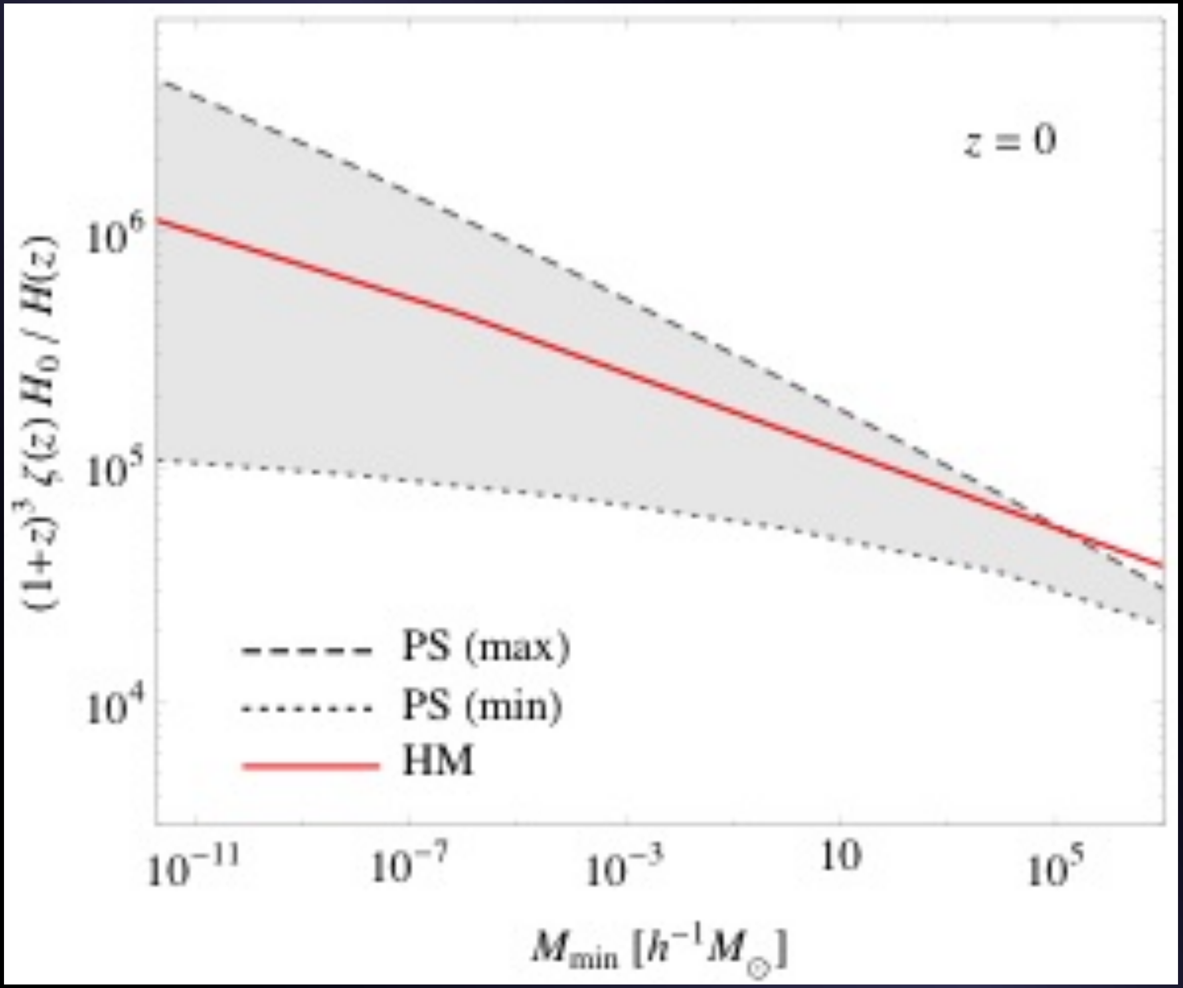
# HM vs. PS predictions (II) dependence on minimum halo mass

Normalized flux multiplier

Good agreement except at the highest (probably unrealistic) $M_{min}$ tested

PS-min nearly insensitive to $M_{min}$. Not true for PS-max.

Comparison at z=0 a fair estimate, since most of the DM signal comes from low z.




Ackermann+15, JCAP09(2015)008 [astro-ph/1501.05464]

# Galactic DM annihilation signal

- Would the Galactic DM signal be *sufficiently* isotropic?

  → if so, *added* to the extragalactic signal when setting the DM limits.

  → If not, treated as an additional *foreground*.

SMOOTH COMPONENT:

NFW DM density profile.
A factor ~16 difference between 20 and 90 degrees of latitude.

→ *Anisotropic* signal: additional foreground

GALACTIC SUBSTRUCTURE:

Factor ~2 anisotropy (Via Lactea II); in other prescriptions, only 10%.

→ Sufficiently *isotropic* signal: added to extragalactic when setting DM limits.

Two substructure scenarios: total Galactic boosts of 3 and 15 [MASC&Prada 14].

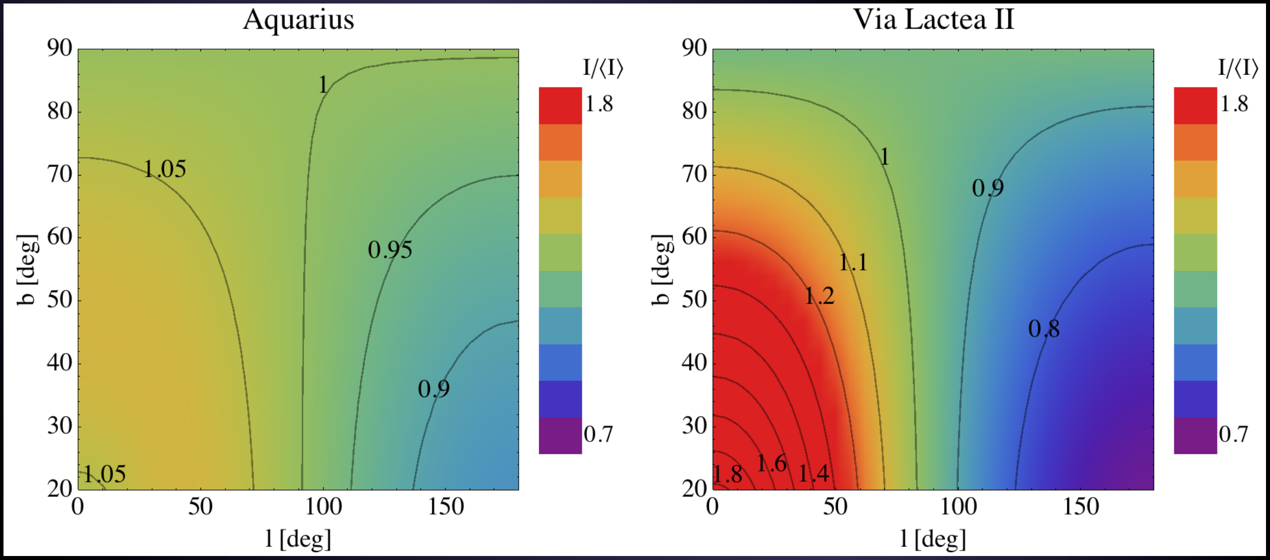
# Galactic DM annihilation signal: substructure

→ **Sufficiently isotropic signal**: added to the extragalactic signal when setting DM limits.

Substructures intensity relative to average value at |b|>20 deg

Factor ~2 anisotropy

In other prescriptions, only 10% anisotropy

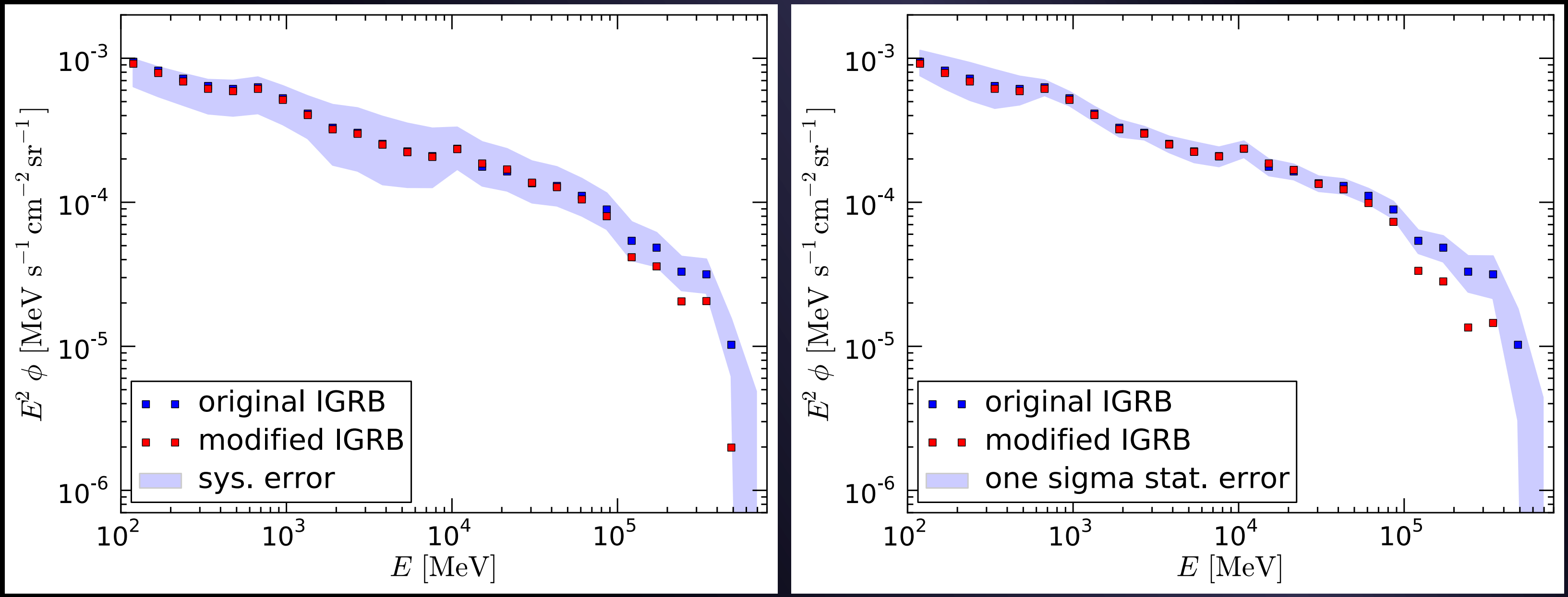



Following MASC & Prada (2014), we assume *two Galactic substructure scenarios:*

1. Annihilation boost of a factor 3 (Minimal $B_{Gal,substructure}$).
2. Annihilation boost of a factor 15 (Benchmark $B_{Gal,substructure}$).

(Both for $M_{min}=10^{-6}\ M_{sun}$, but assuming different slopes of the subhalo mass function)

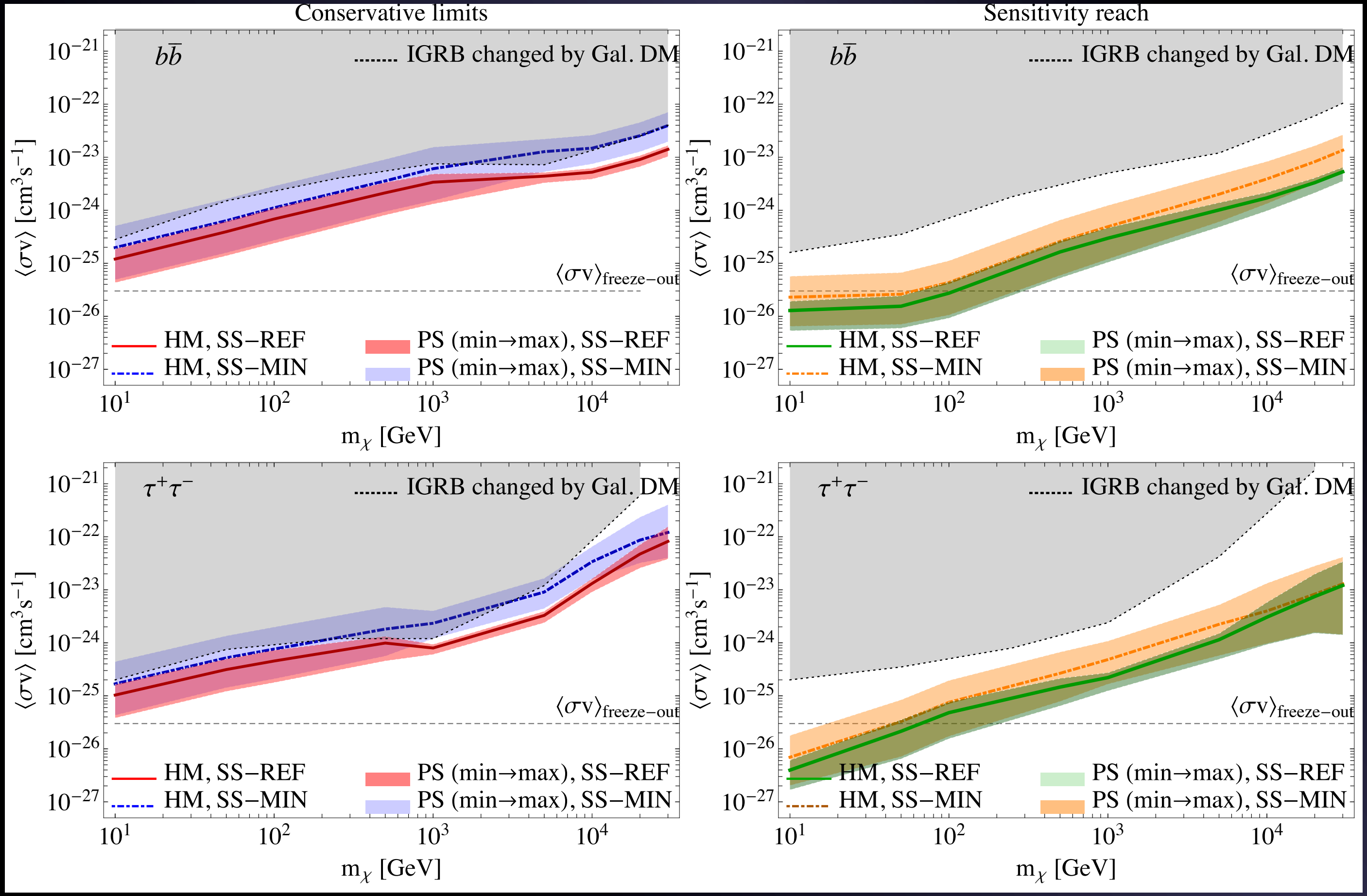
# Robustness of the IGRB in the presence of a Galactic DM signal




Ackermann+15, JCAP09(2015)008 [astro-ph/1501.05464]

# Robustness of the IGRB in the presence of a Galactic DM signal

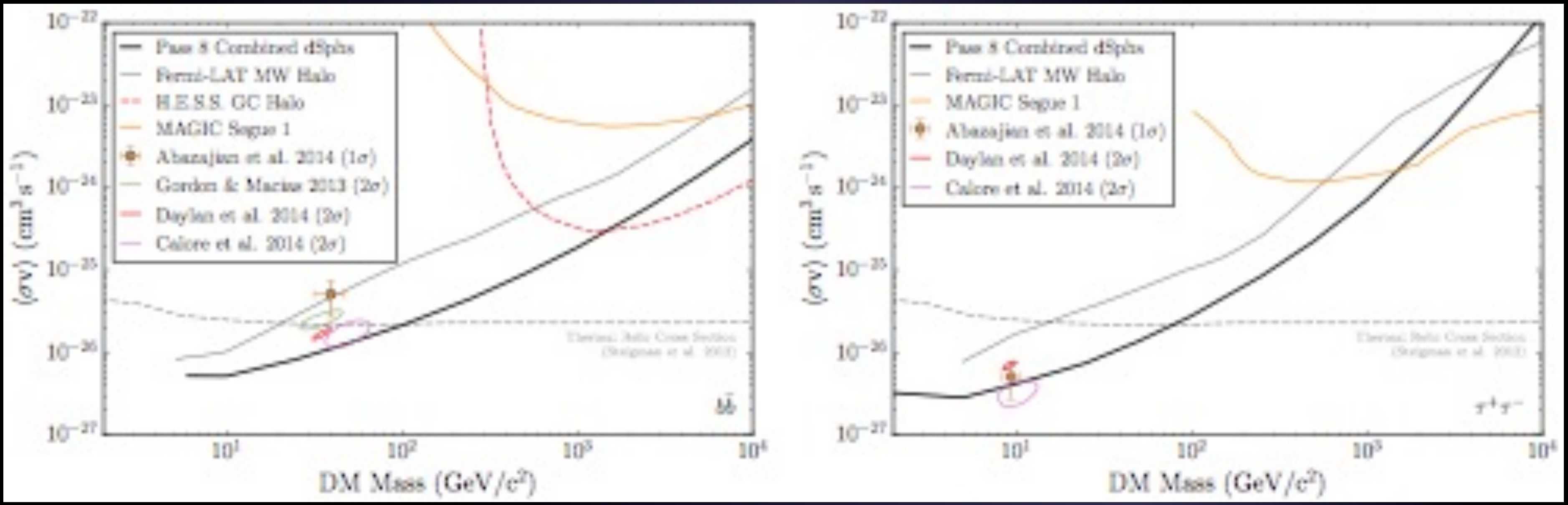
Ackermann+15, JCAP09(2015)008 [astro-ph/1501.05464]




Gray regions indicate DM annihilations cross sections which would alter the measured IGRB significantly due to the signal from Galactic smooth DM component.

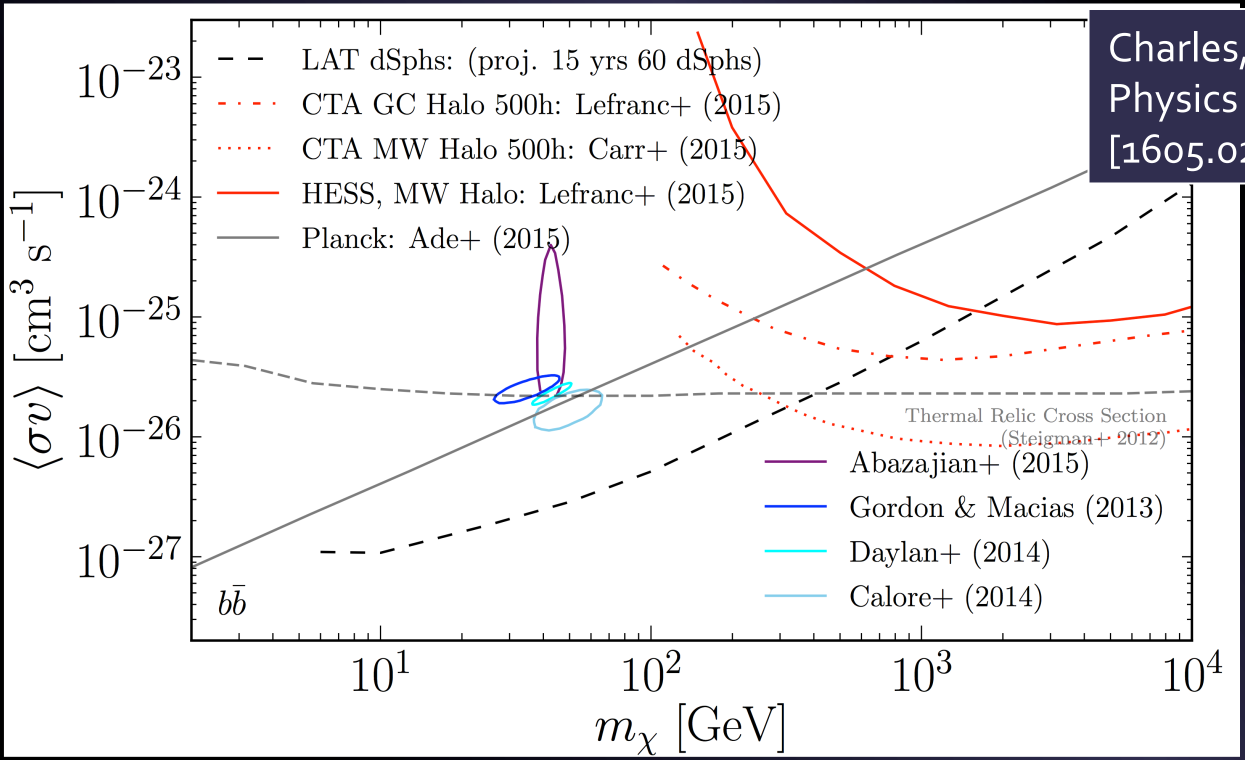
# (γ-ray) DM searches: today

[ Ackermann+15, the LAT collab., 1503.02641 ]




→ GC excess persists. Origin unclear.
→ Dwarfs the most promising independent way to test it.
→ Fermi LAT ruling out thermal WIMPs below ~100 GeV.
→ IACTs and HAWC competitive in the TeV energy range.

# ($\gamma$-ray) DM searches: tomorrow




Charles, MASC, et al., Physics Reports [1605.02016]

- → **Fermi + CTA** will (fully?) test the thermal cross-section value (by ~2020?)
- → **New instruments** from the ground and on space (CTA, GAMMA-400, HERD)
- → These limits only possible if:
  - → reliable J-factor estimates from dwarfs are available in the future
  - → Understand and control the systematics
- → As usual, **simulations** can guide us in the search!