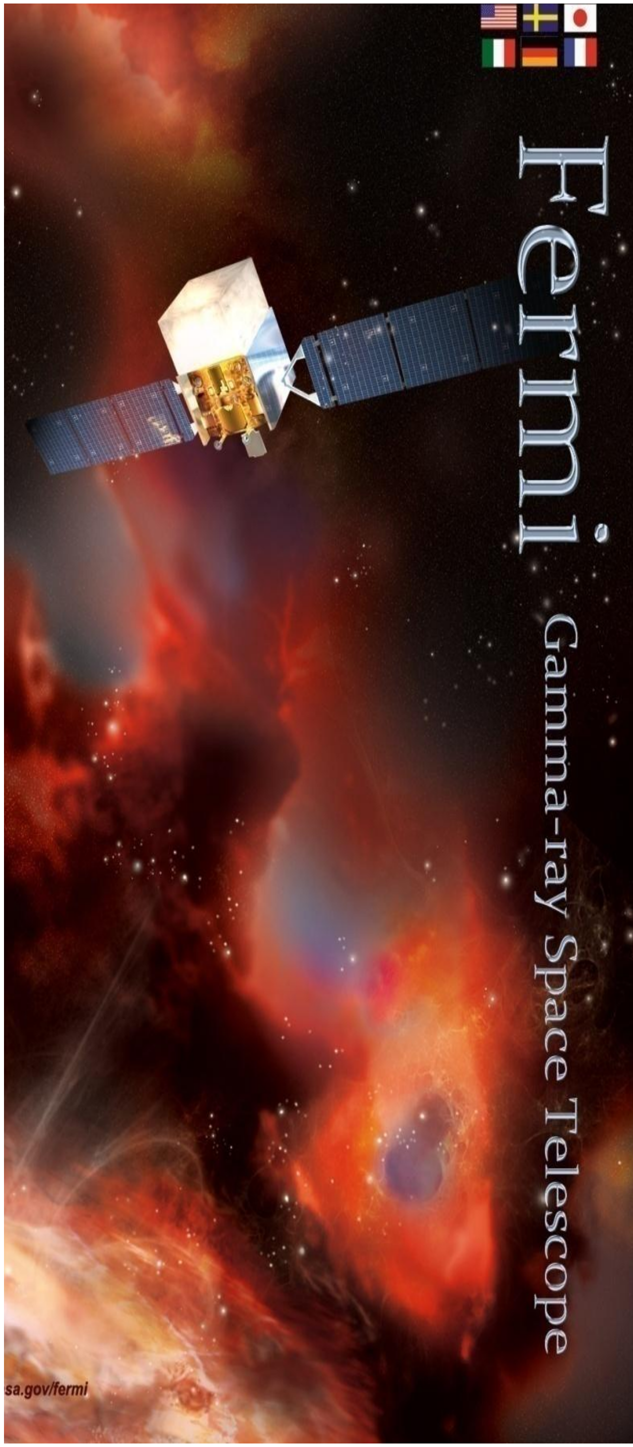


The search for cosmological annihilation signals with the Fermi-LAT

[astro-ph/1501.05464]
[astro-ph/1501.05301]

(M. Ajello)

A. Franckowiak, M. Gustafsson,

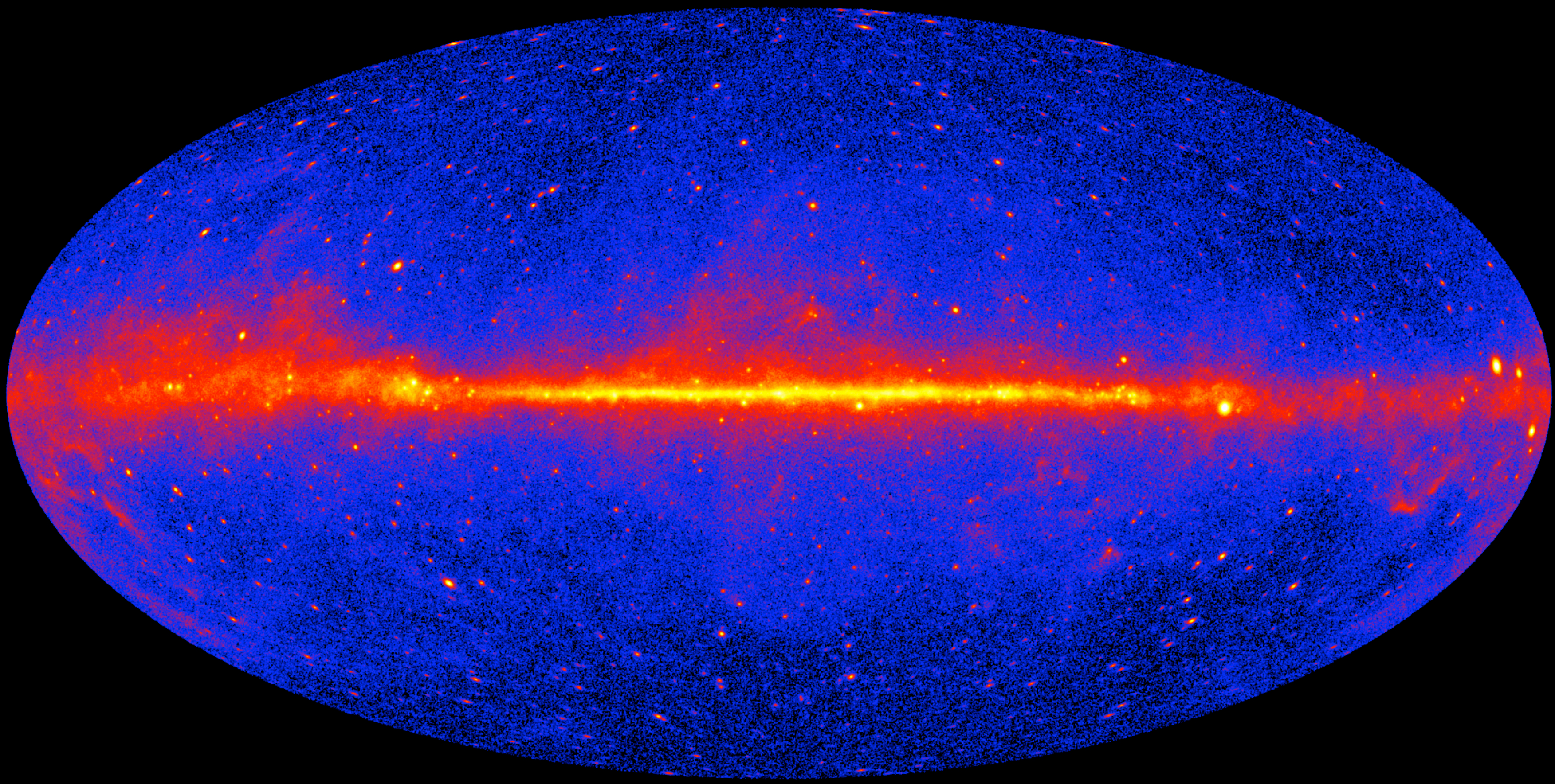
M. Sánchez-Conde and G. Zaharijas

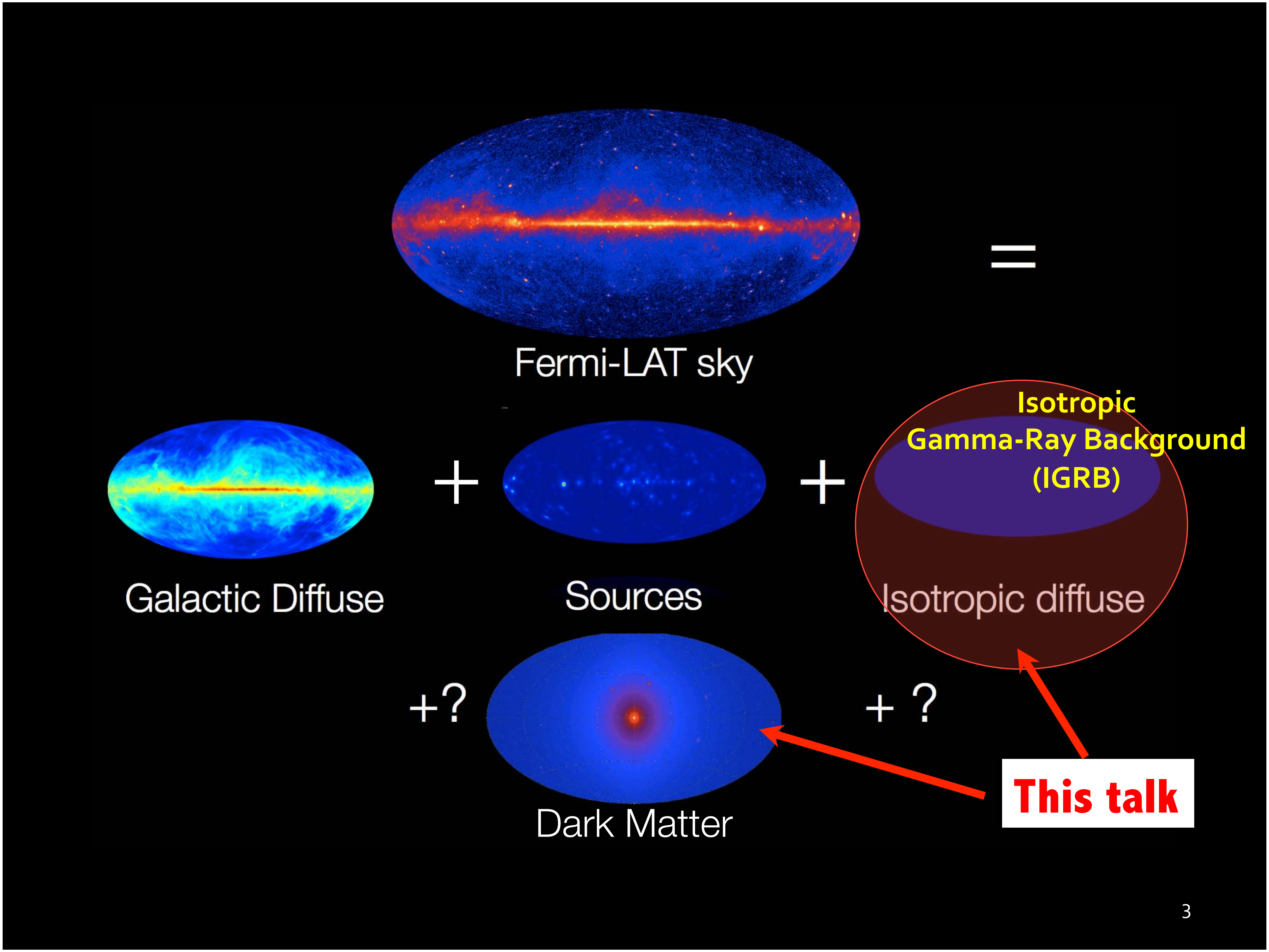
ON BEHALF OF THE FERMI LAT COLLABORATION

6th Fermi Symposium

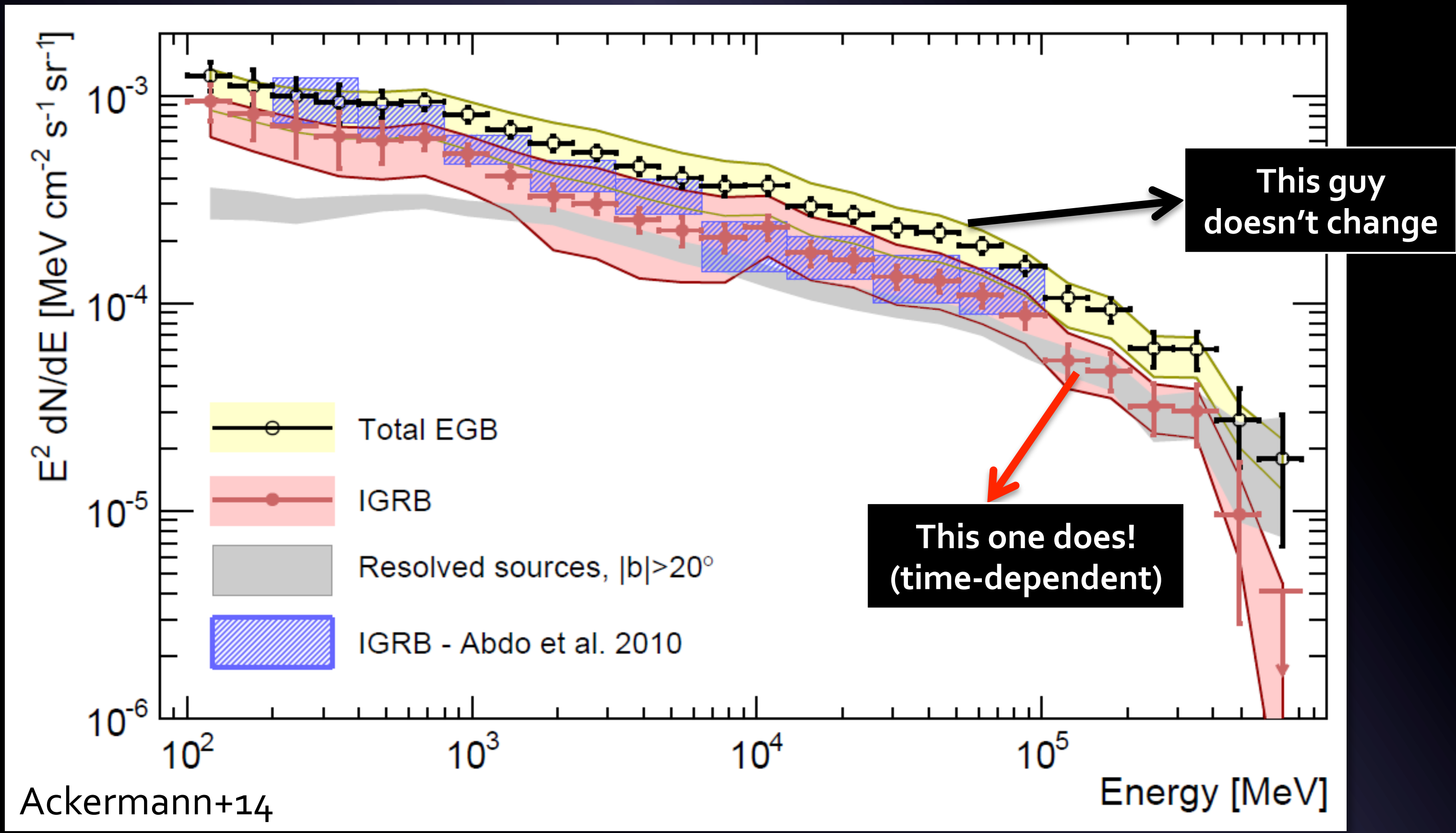
THE GAMMA-RAY SKY above 1 GeV

5 years of Fermi LAT data




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

The brand new Fermi LAT IGRB spectrum

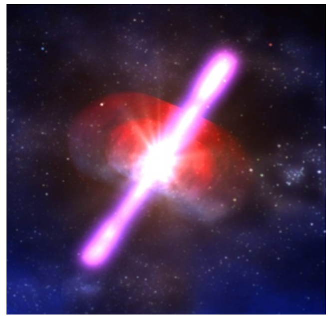


- **Extended energy range**: 200 MeV – 100 GeV ➔ 100 MeV – 820 GeV
- **Significant high-energy cutoff feature in IGRB spectrum,** consistent with simple source populations attenuated by EBL
- **~50% of total EGB above 100 GeV now resolved into individual LAT sources**

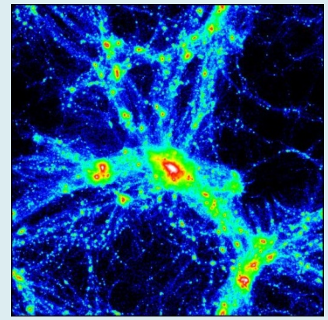
Origin of the Extragalactic Gamma-ray Background (EGB)
in the LAT energy range

[EGB == IGRB + individually resolved extragalactic sources]

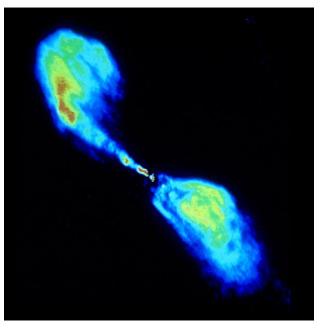
Blazars



GRBs



Dark matter annihilation / decay
(upper limits)

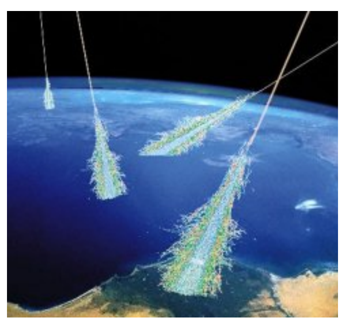


Radio galaxies

Galaxy clusters
(upper limits)

Unknown sources / processes

Star-forming galaxies



Cascades
(upper limits)

Ajello et al. 2015
Di Mauro & Donato 2015
Fornasa & Sánchez-Conde (2015)

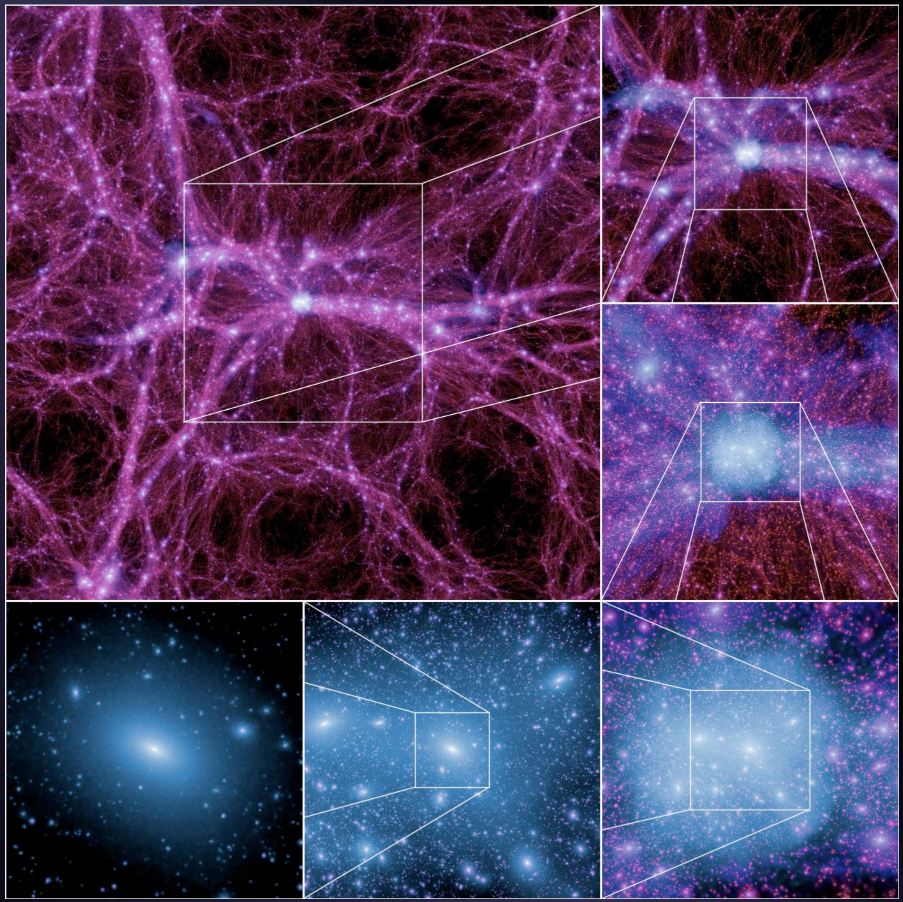
Cosmological DM annihilation

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

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

Gamma-ray attenuation due to the EBL and 'redshifting' effects should mean lower redshifts ($z \leq 2$) contribute the most.

We calculated the expected level of this cosmological DM annihilation signal in our work.



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

Theoretical predictions for the cosmological signal

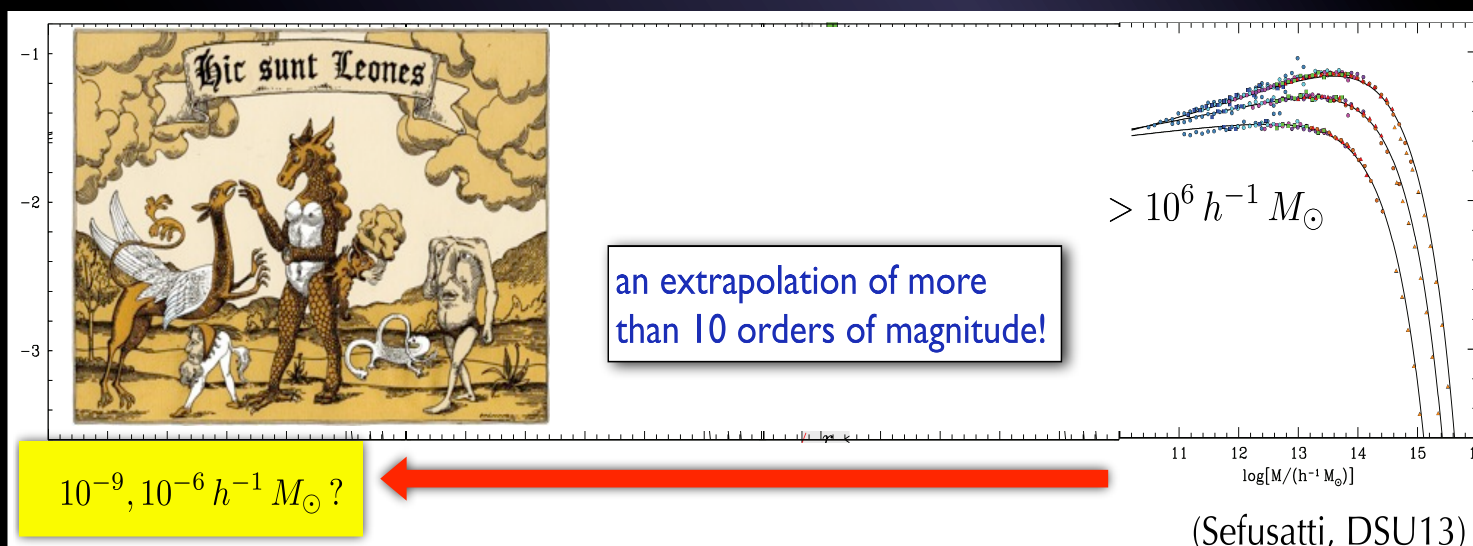
FLUX from extragalactic DM annihilation

$$\frac{d\phi}{dE_0} = \underbrace{\frac{\langle\sigma v\rangle}{8\pi}}_{\text{WIMP annihilation cross-section}} \frac{c\,(\Omega_{\rm DM}\rho_c)^2}{m^2_{DM}} \int dz \underbrace{e^{-\tau(E_0,z)}}_{\text{EBL attenuation (Domínguez+11)}} \frac{(1+z)^3}{H(z)} \underbrace{\zeta(z)}_{\text{“Flux multiplier”}} \underbrace{\left.\frac{dN}{dE}\right|_{E=E_0(1+z)}}_{\text{WIMP-induced spectrum}}$$

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.

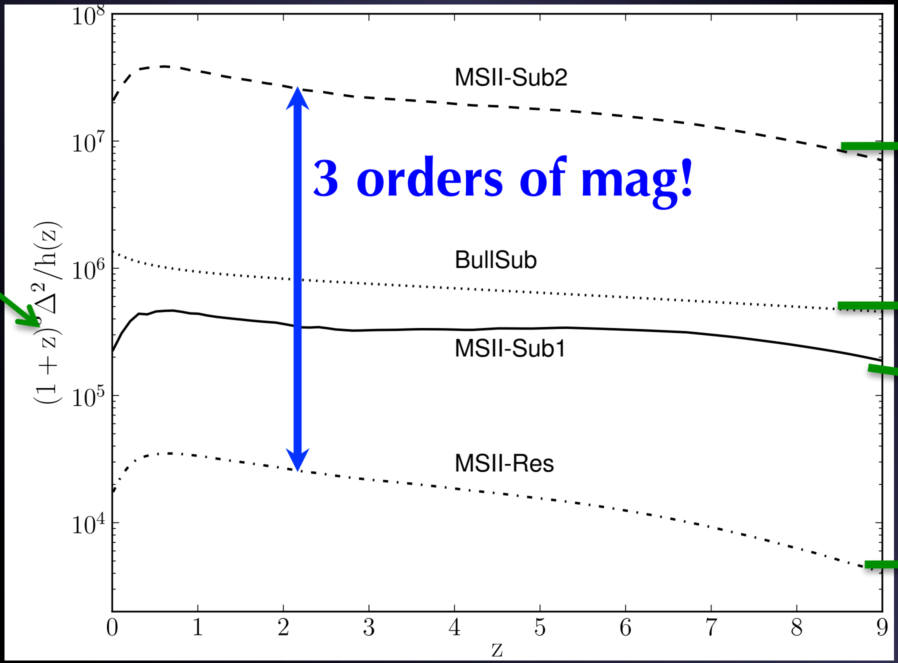
Uncertainties in this parameter traditionally huge!

Simulations do not resolve the whole hierarchy of structure formation…



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 ΛCDM?

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.

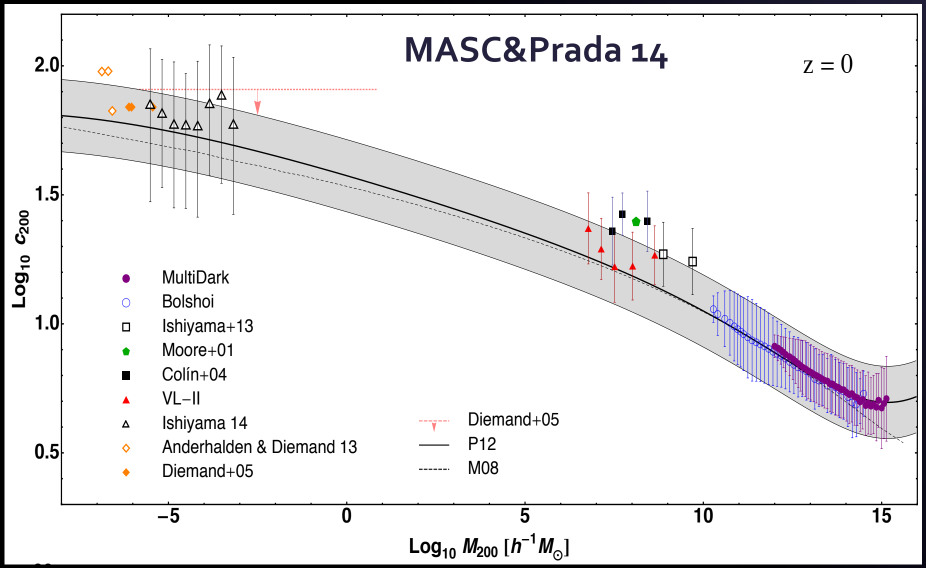
→ OUR BENCHMARK MODEL

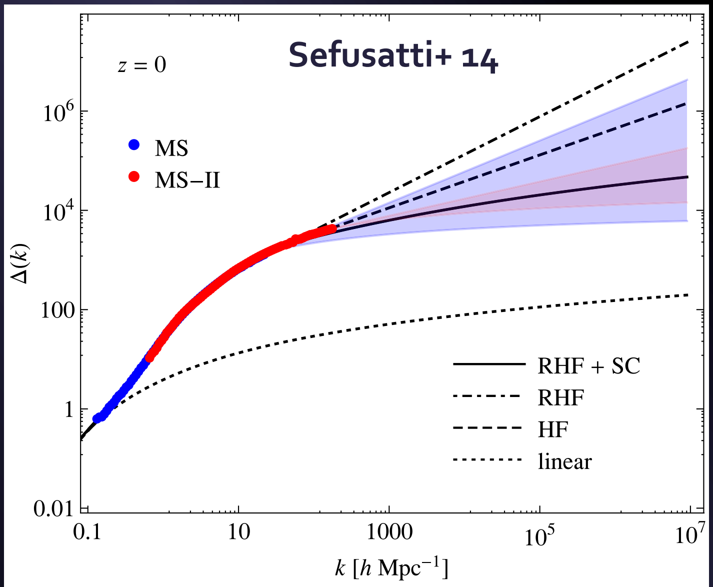
non-linear matter POWER SPECTRUM (PS)

Directly measured in simulations.

→ Good to study uncertainties

(only one quantity extrapolated)

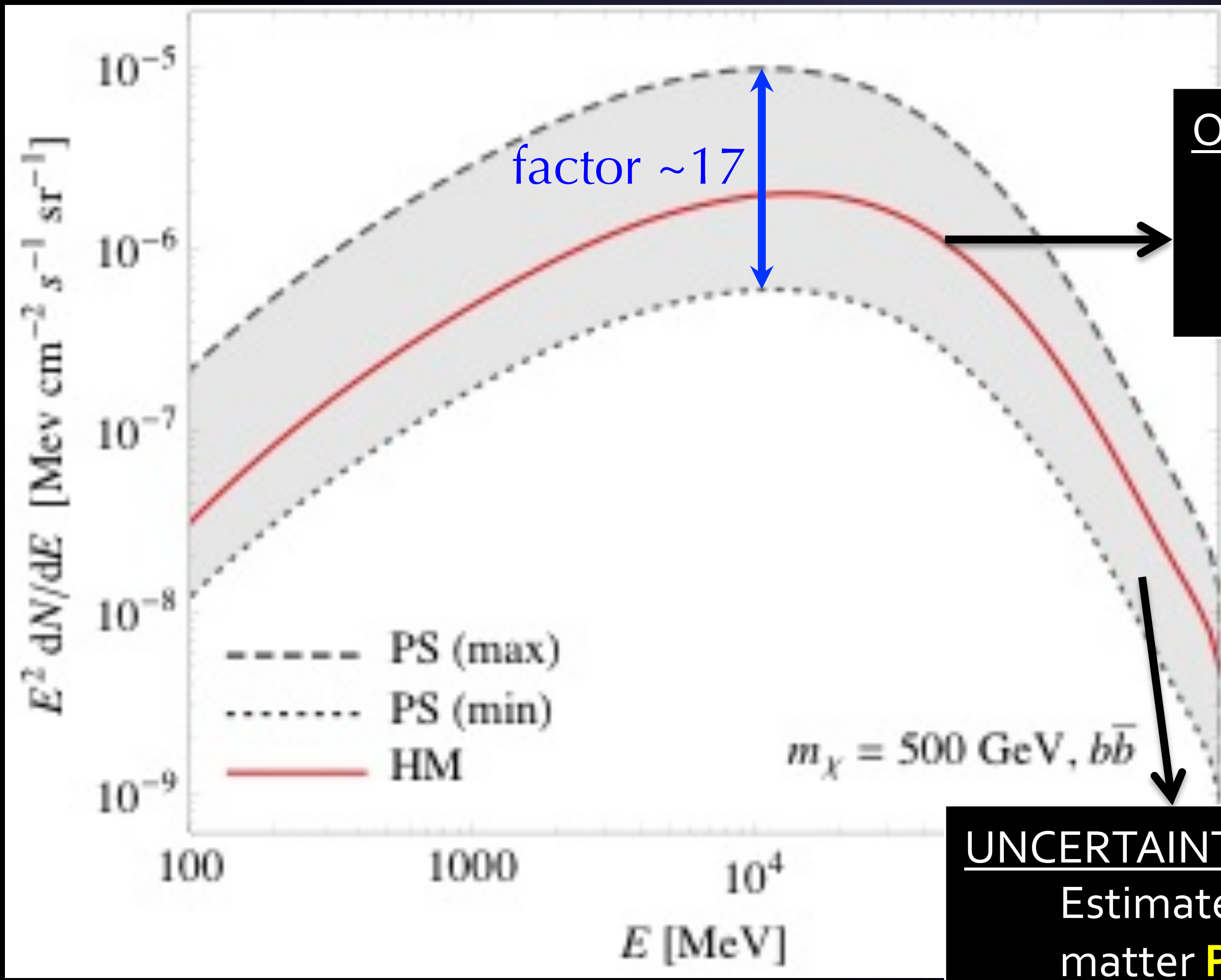




Disclaimer: both approaches use extrapolations over several orders of magnitude down to the smallest predicted mass scales.

HM vs. PS predictions (II)
(example of) DM annihilation fluxes

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



OUR BENCHMARK MODEL:
calculated in **Halo Model** approach using the most up-to-date parameters.

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

Isotropic emission: DM limits

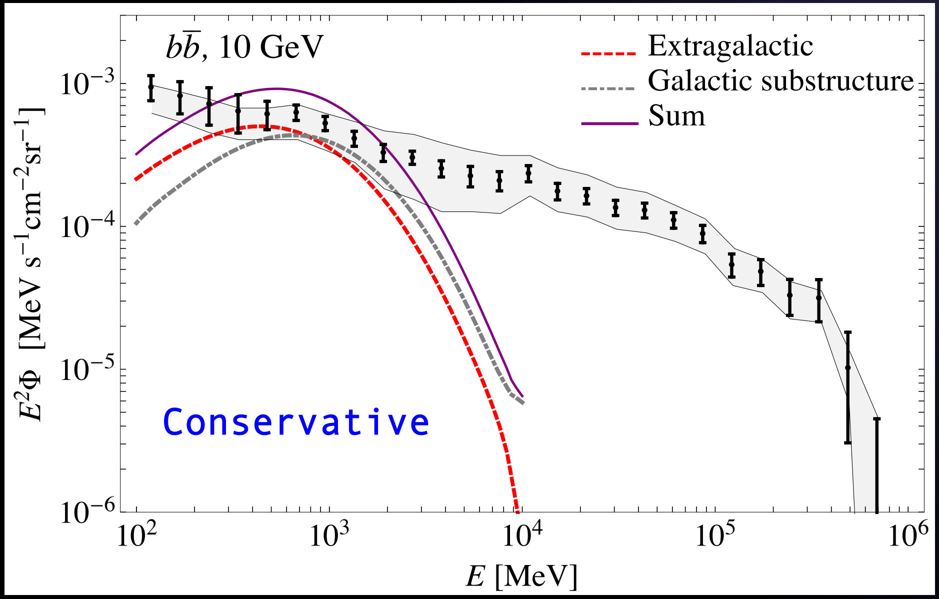
Conservative limits

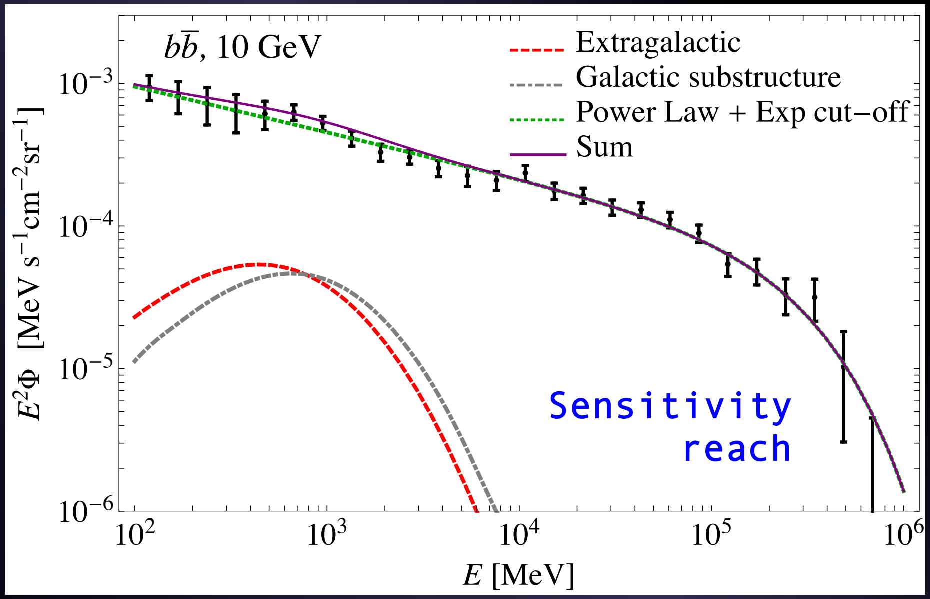
- Only DM. No astrophysical contributions to the measured IGRB.
- Not preferred Galactic diffuse model among those tested in IGRB measurement paper.

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.

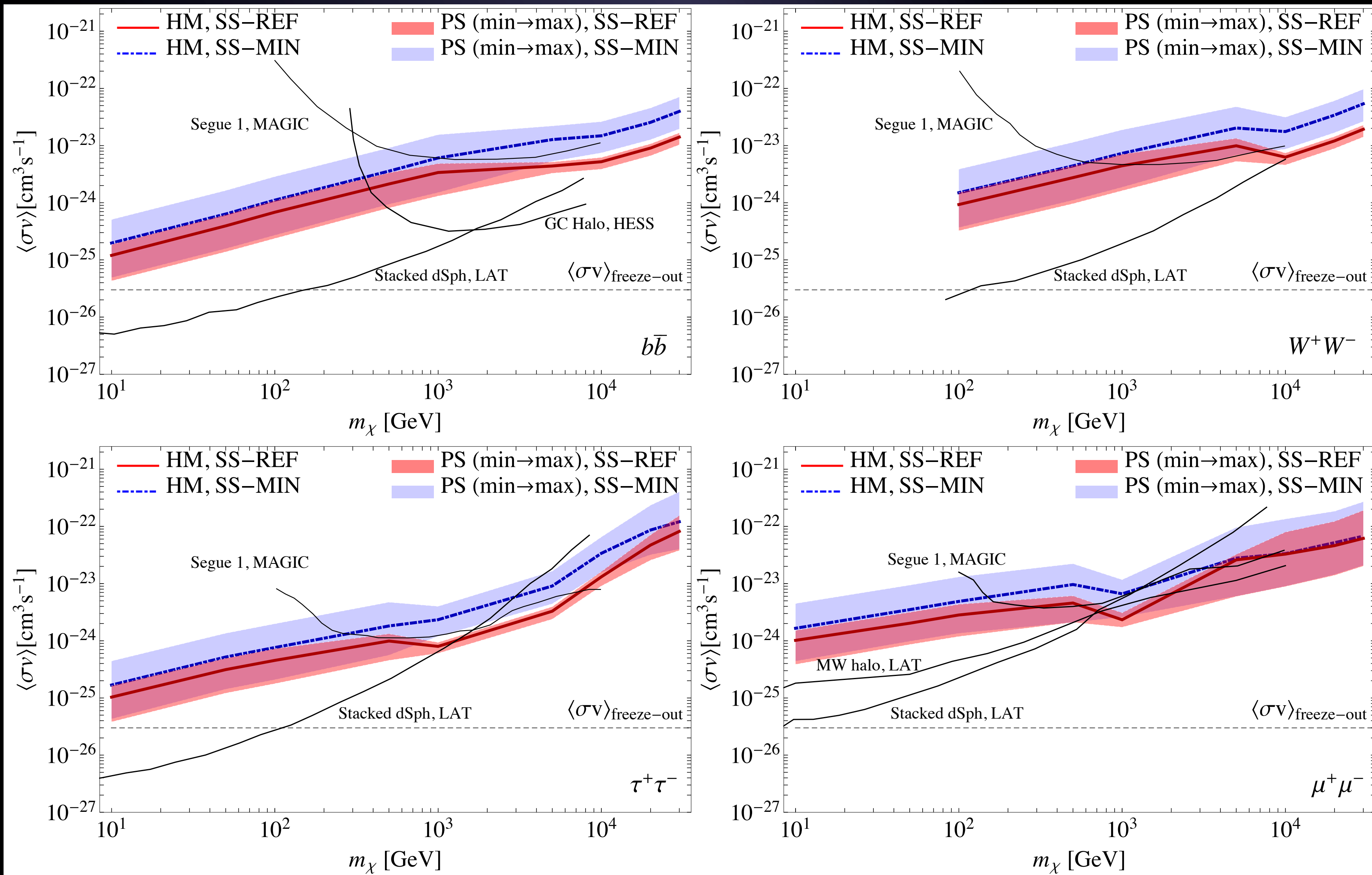
Ackermann+15, JCAP09(2015)008 [astro-ph/1501.05464]





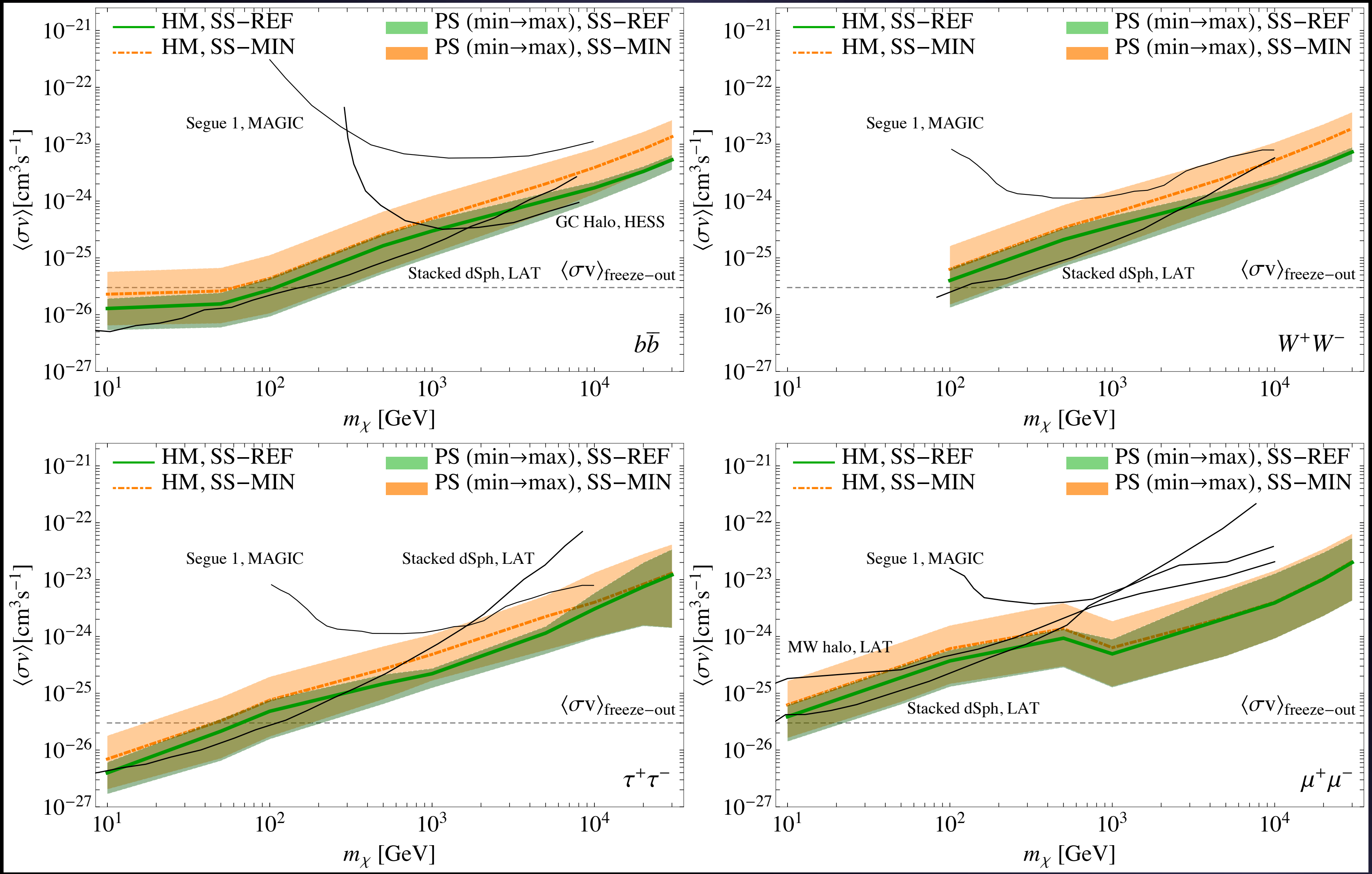
Examples of DM-produced gamma-ray spectra which are at the border of being excluded at 2σ level in our two procedures to set DM limits

Conservative limits



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

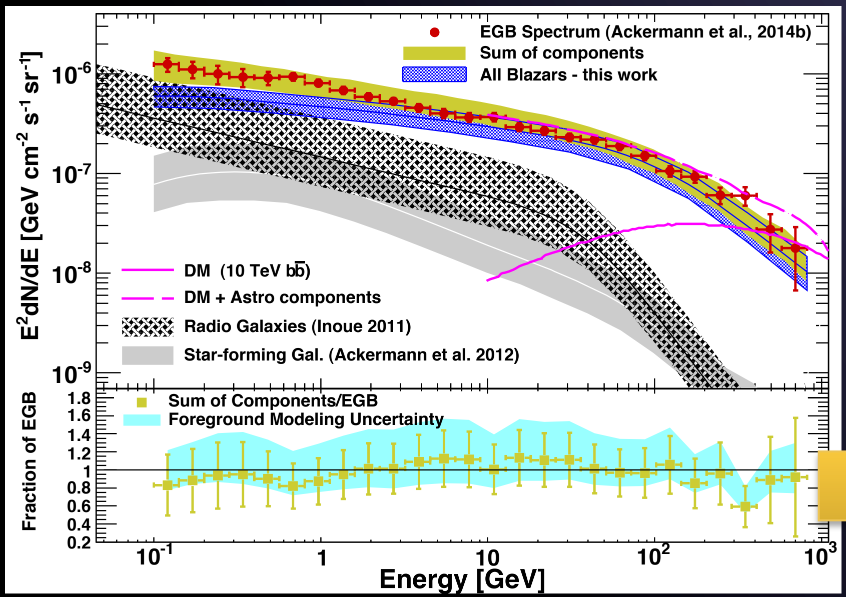
Sensitivity reach



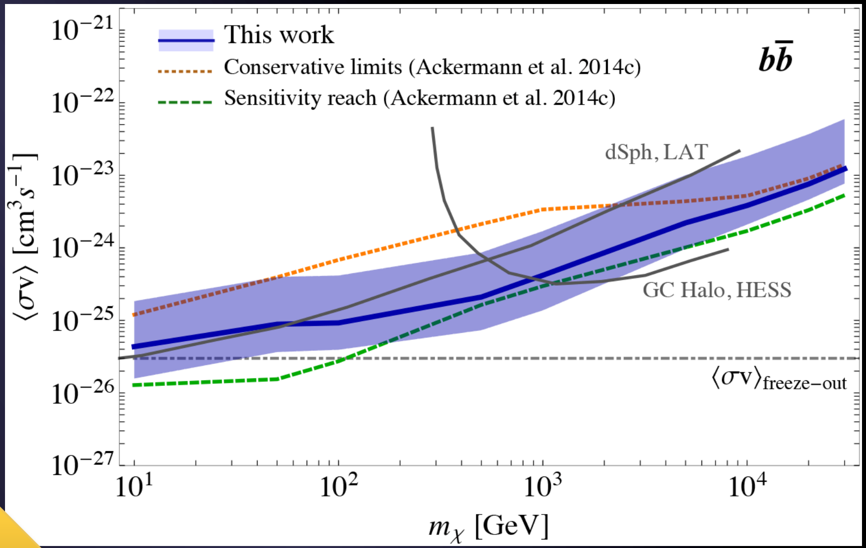
Ackermann+15, JCAP09(2015)008 [astro-ph/1501.05464]

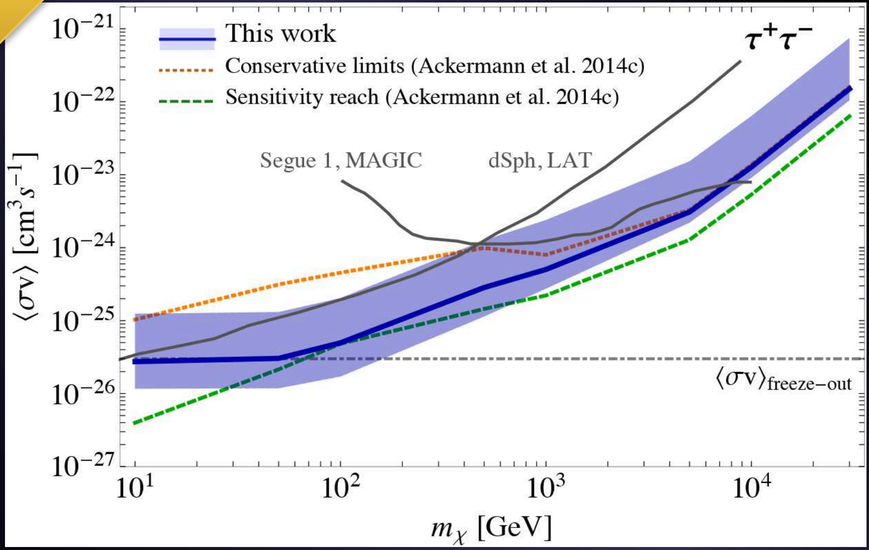
A more realistic scenario

Ajello+15



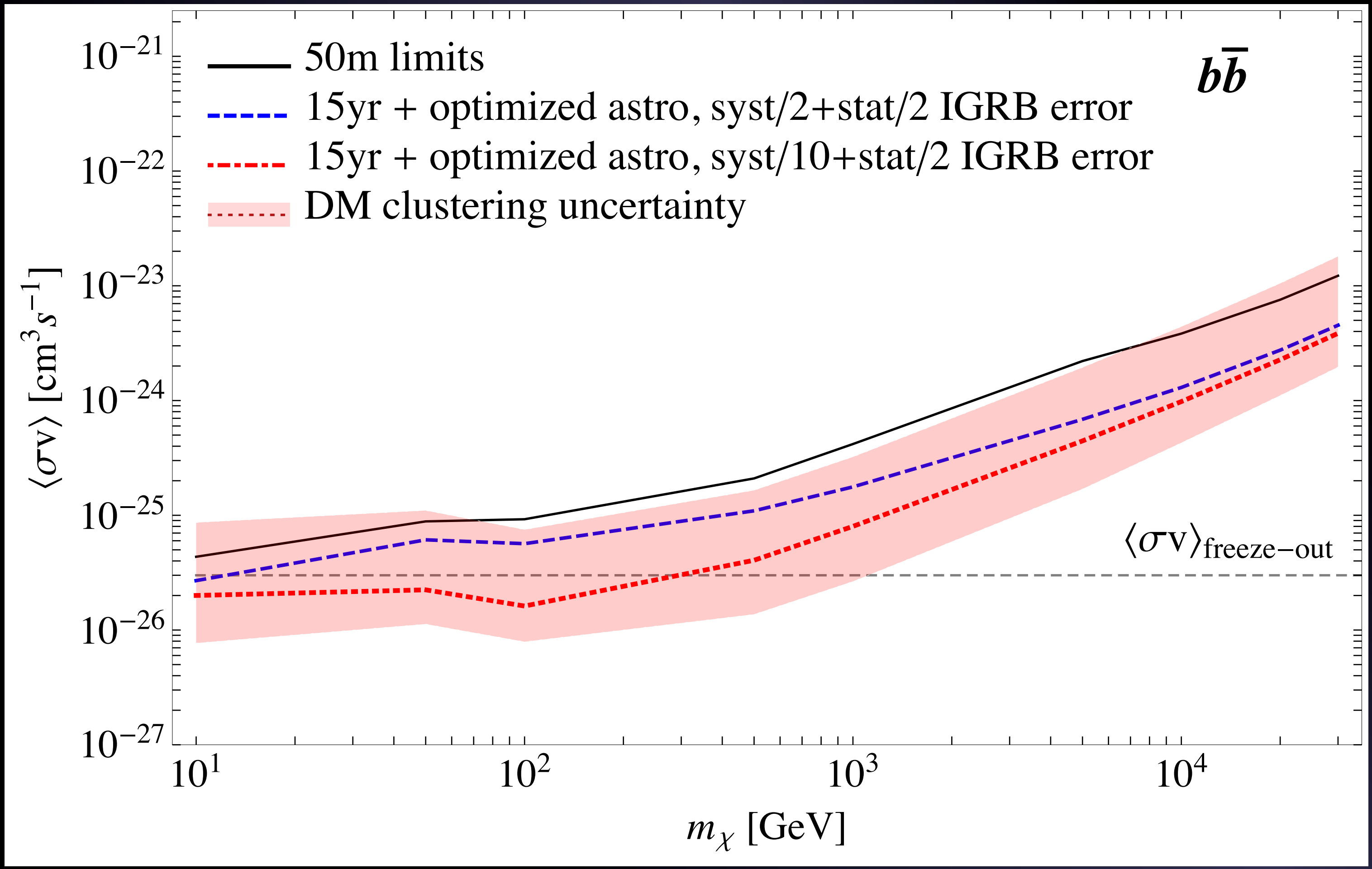
The case where the total contribution to the IGRB from conventional astrophysics is derived as accurately as possible leads to DM constraints that typically lie between the conservative limit and the sensitivity reach.





Ajello+15

Sensitivity projections



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

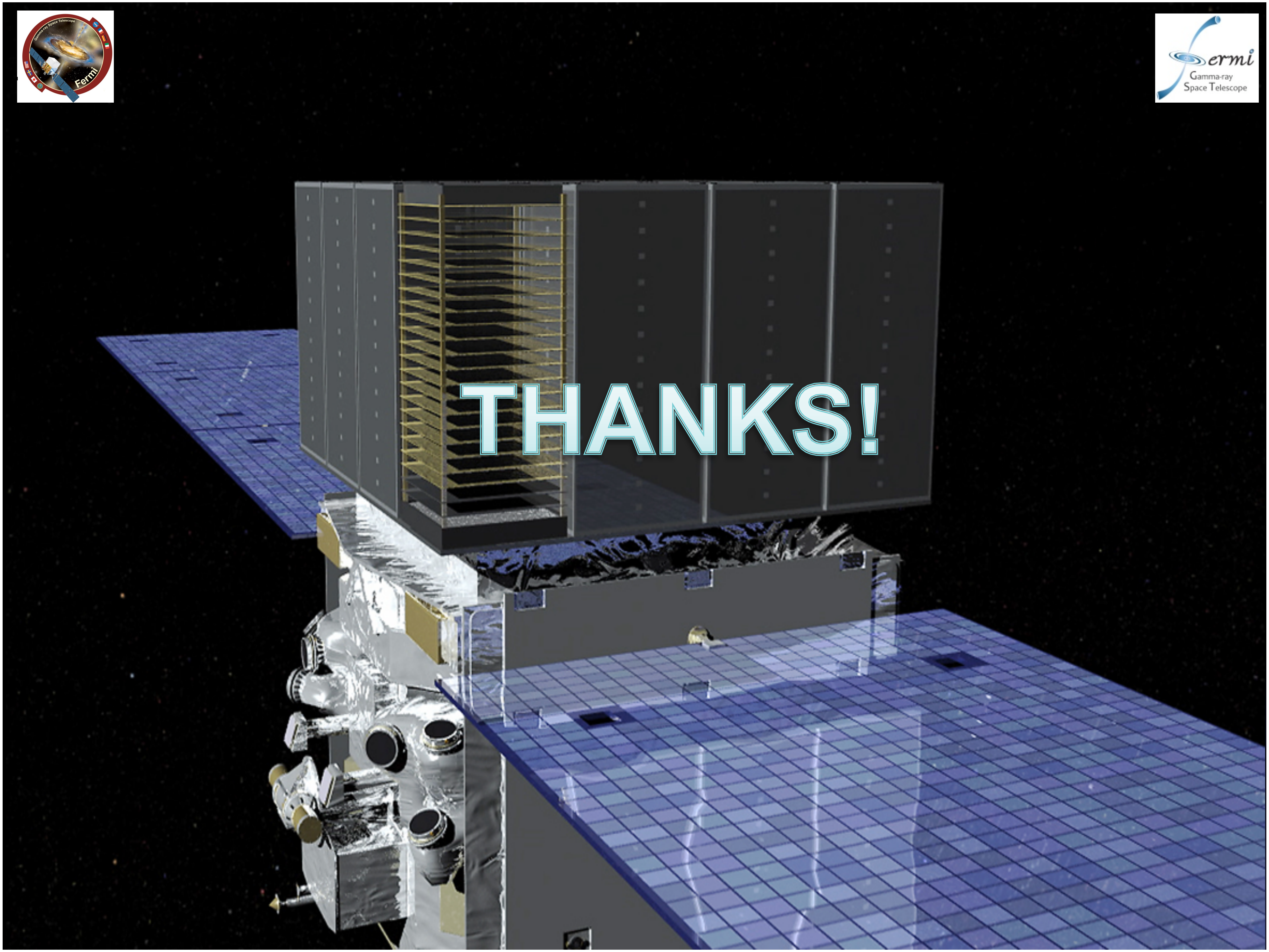
Remarks

- Goal: to use the new LAT IGRB spectrum up to 820 GeV to set DM limits.

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

- Two sets of DM limits:
  → Conservative and 'sensitivity reach', competitive with best DM limits.
  → Bracket a realistic scenario with a careful modeling of astrophysical contributions to the IGRB.

- 15 years of LAT data will improve the 4.1 year limits by a factor ~2 to 5.


THANKS!
Fermi
Gamma-ray Space Telescope

ADDITIONAL MATERIAL

Flux multiplier: approaches

We compute it in two ways:

1) **Halo model (HM)**: implies to describe the internal properties of individual halos and subhalos, and their cosmic evolution.

   → OUR BENCHMARK MODEL

2. **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.

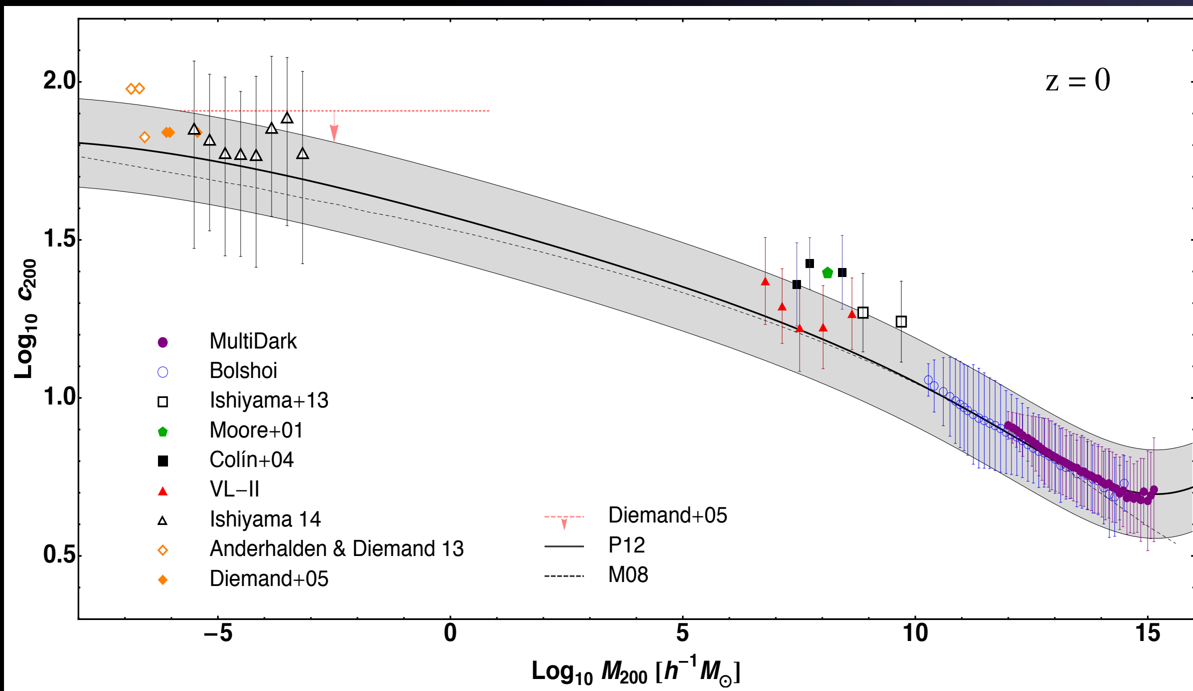
HALO MODEL (I): bAsIcS

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

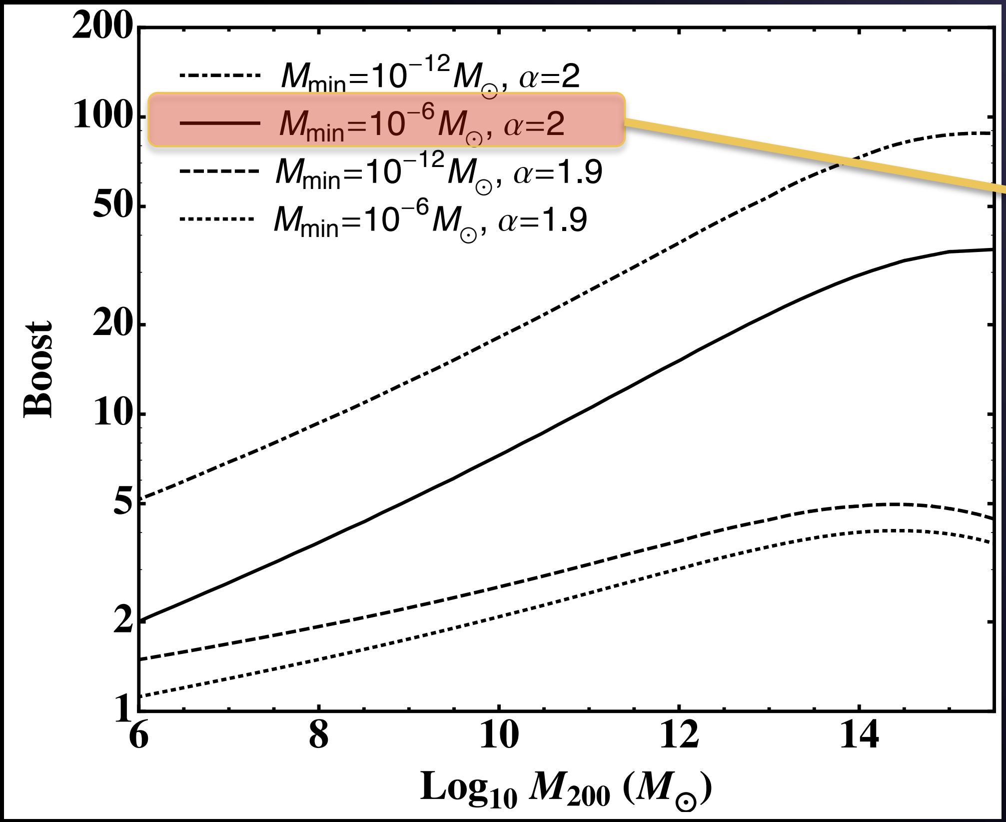
$M_{min} = 10^{-6}\,M_{sun}$

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

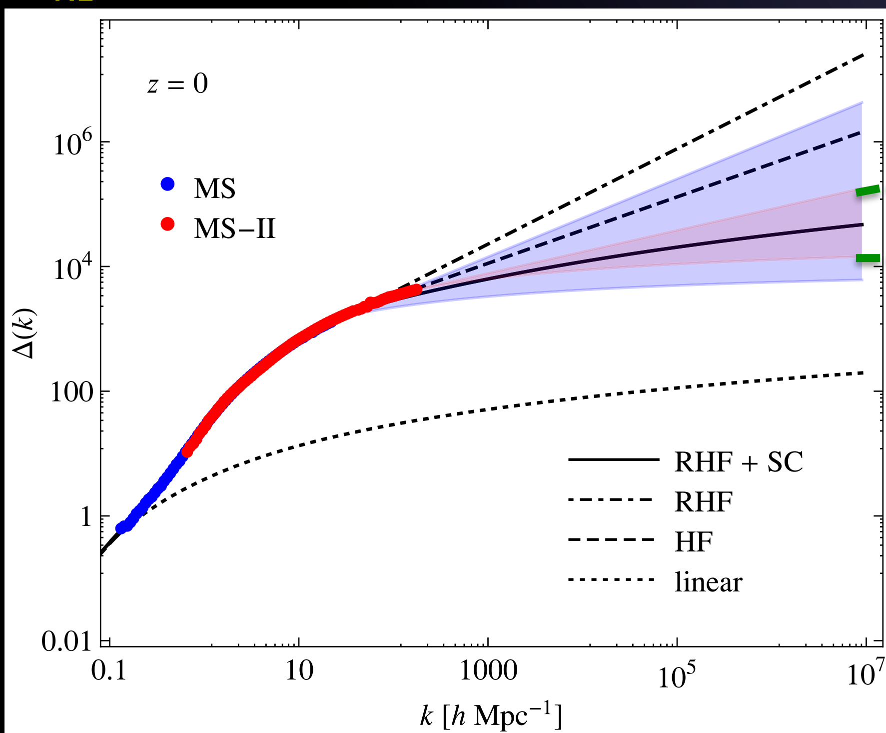
[MASC & Prada 2014]

POWER SPECTRUM APPROACH

FLUX MULTIPLIER

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

Δ_{NL} is measured in simulations.



MAX extrapolation to the lowest scales

MIN extrapolation to the lowest scales

Sefusatti, Zaharijas et al., MNRAS (2014)

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

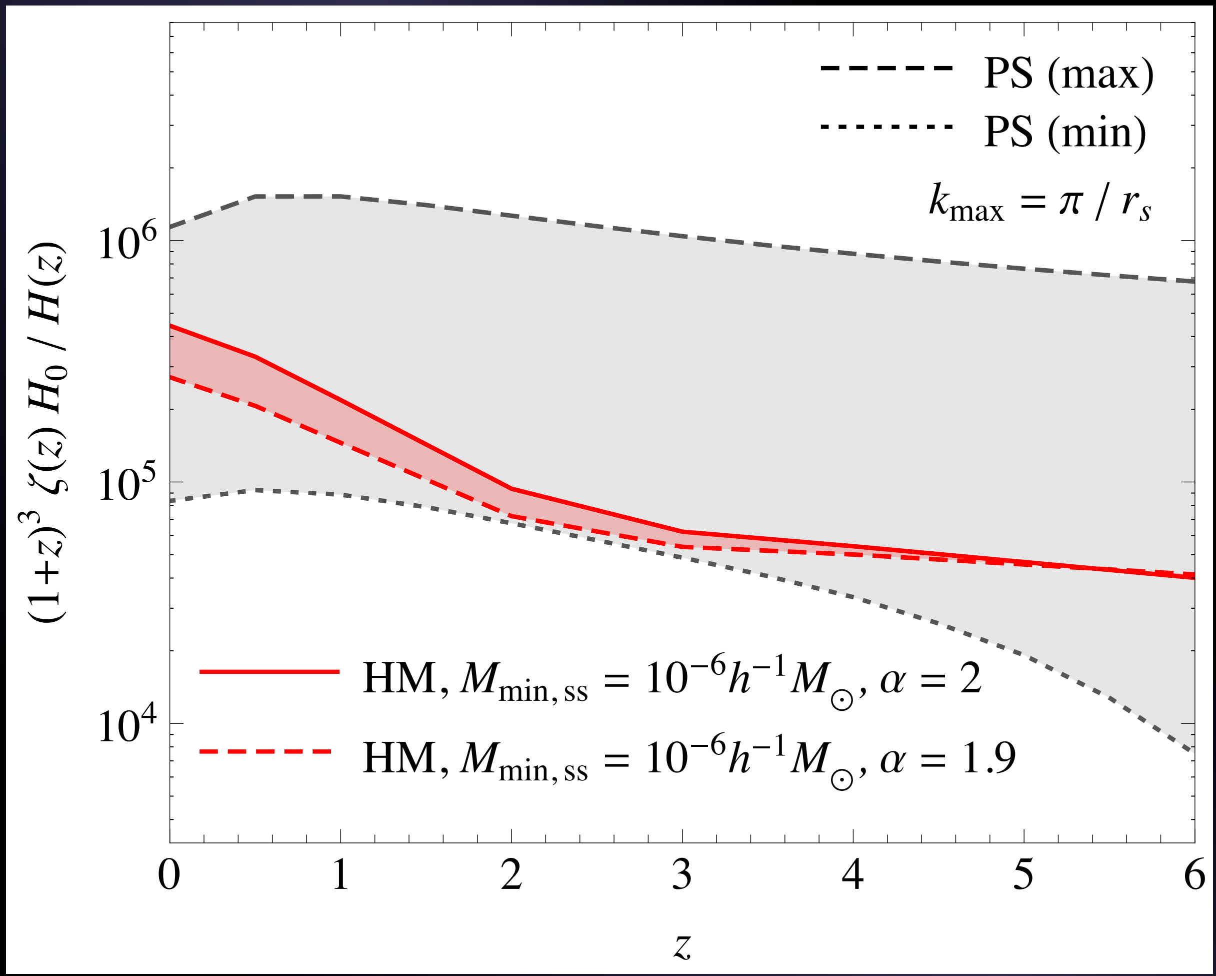
Results scaled to Planck cosmology.

Extrapolation to low masses with MS-II.

Substructure naturally accounted for.

HM vs. PS predictions (I) redshift evolution

Normalized flux multiplier



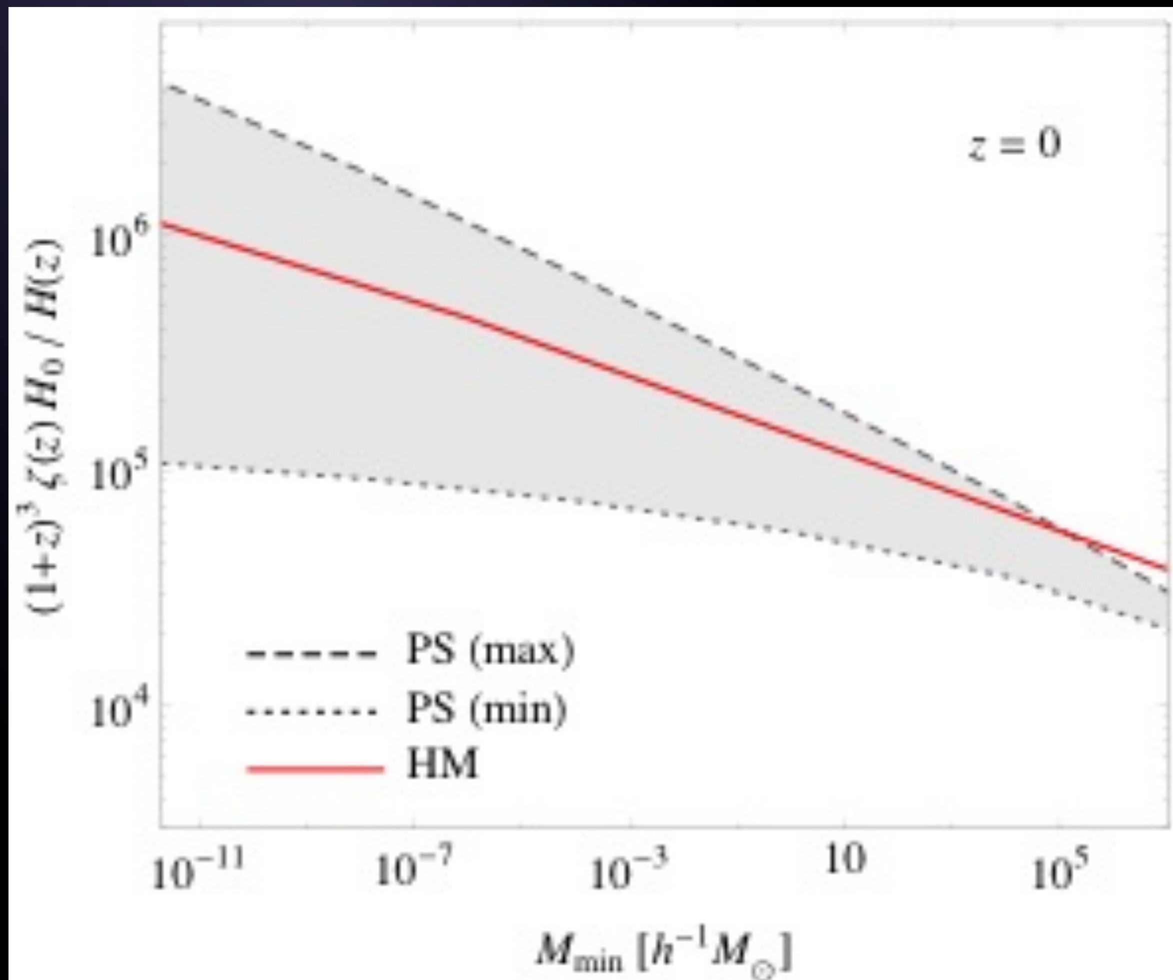
Both the PS and HM results are fully consistent with each other.

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].

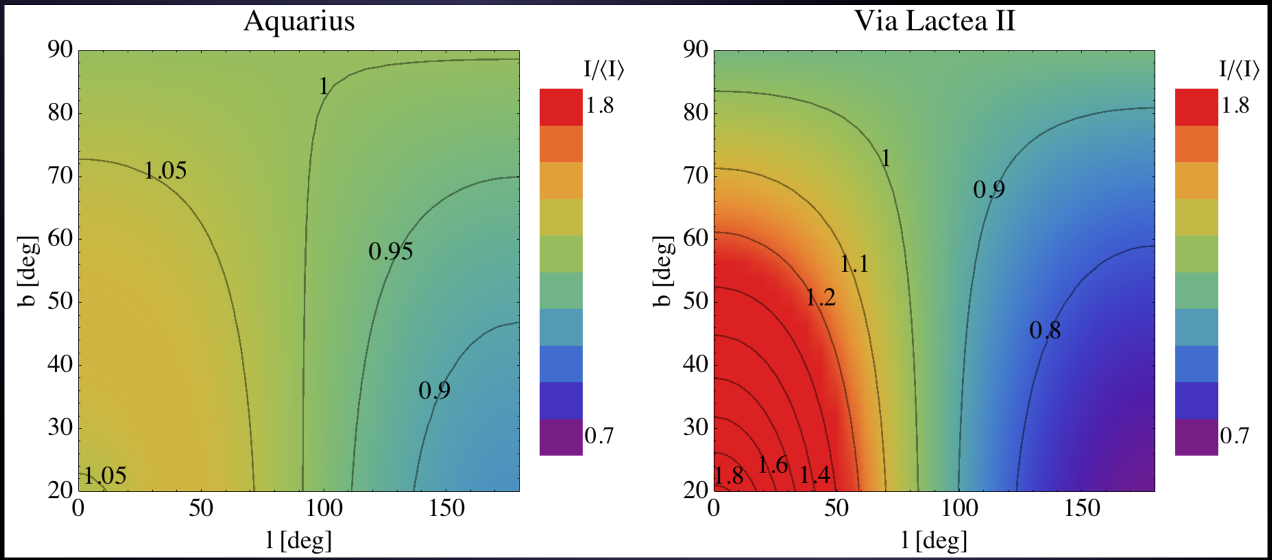
Galactic DM annihilation signal: substructure

→ **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

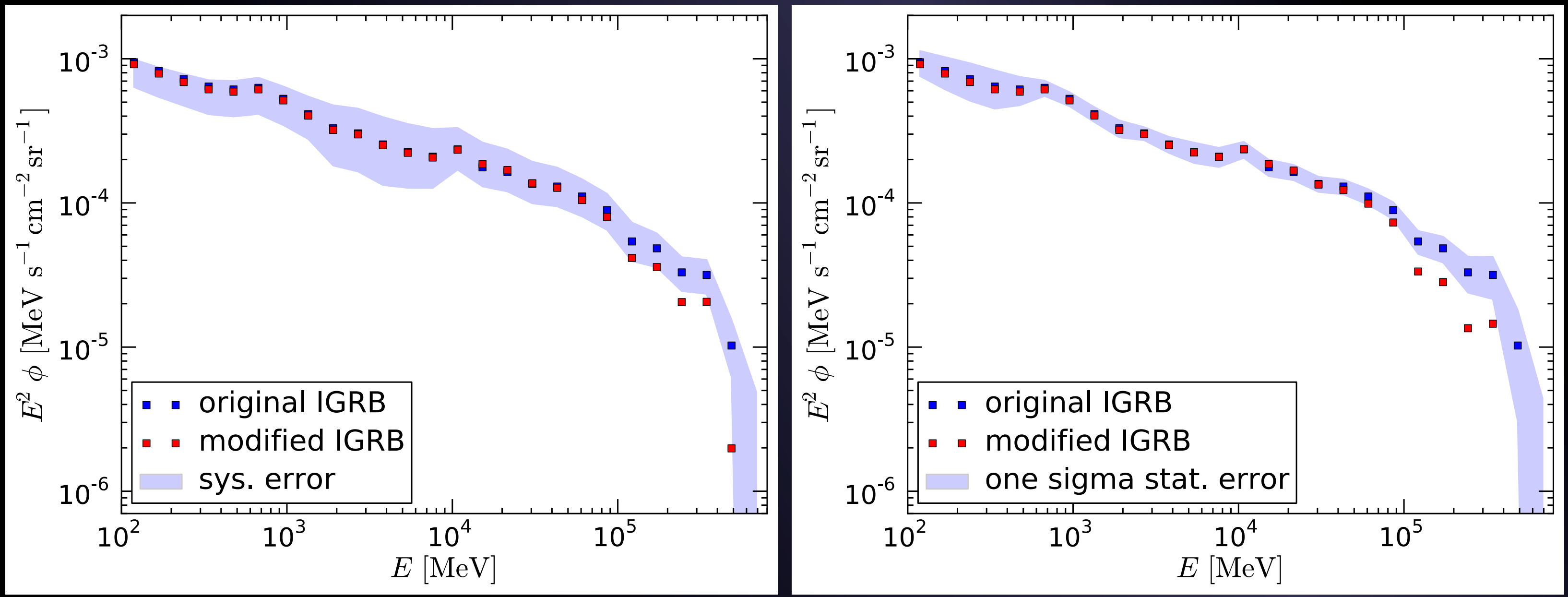


Following MASC & Prada (2014), we assume *two Galactic substructure scenarios:*

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)

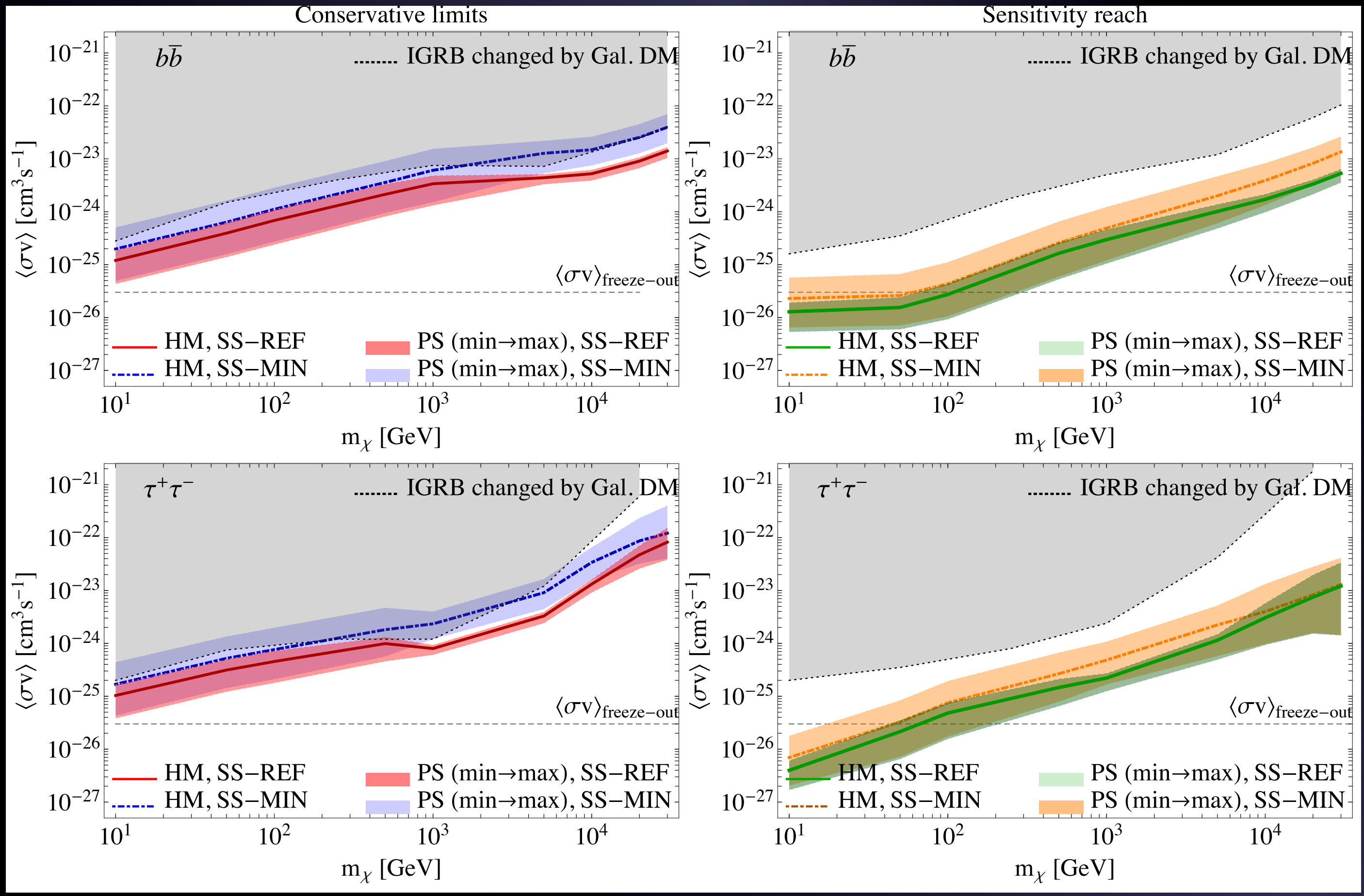
Robustness of the IGRB in the presence of a Galactic DM signal



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.