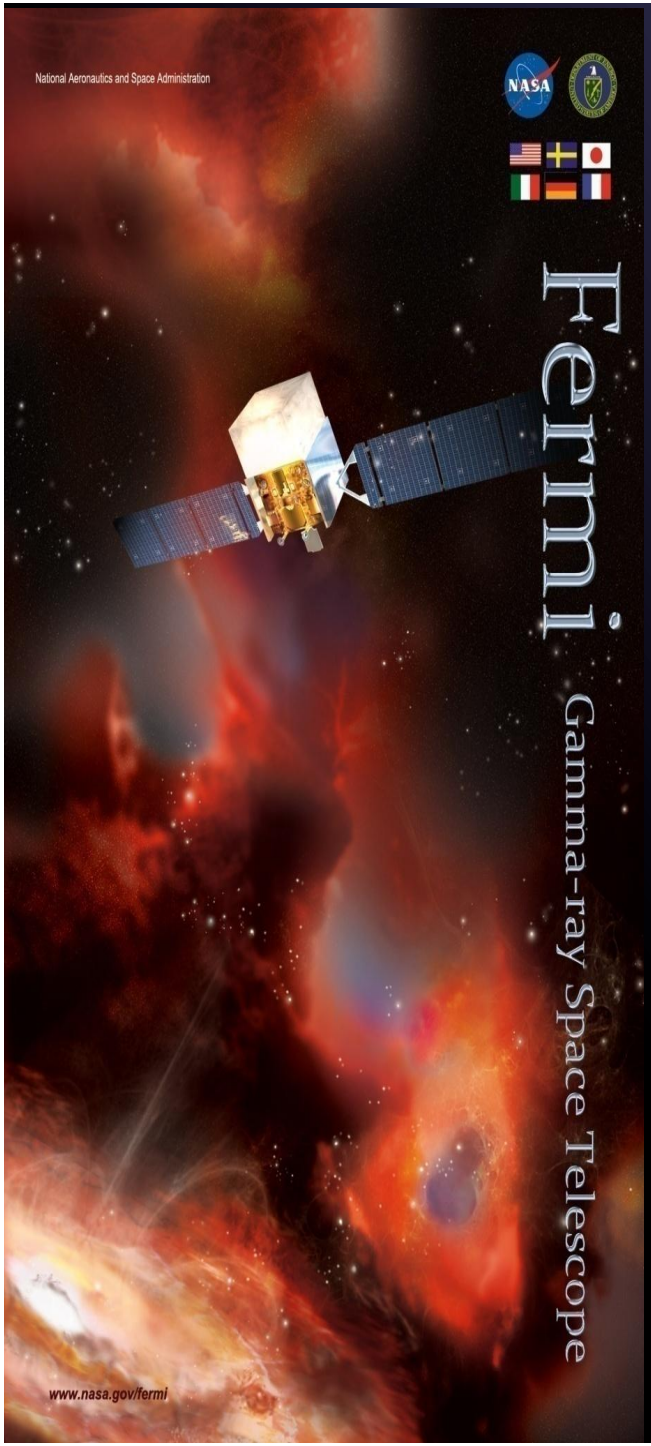


COSMOLOGICAL DARK MATTER ANNIHILATION SIGNALS:

THEORETICAL PREDICTIONS

Miguel A. Sánchez-Conde

SLAC KIPAC STANFORD UNIVERSITY

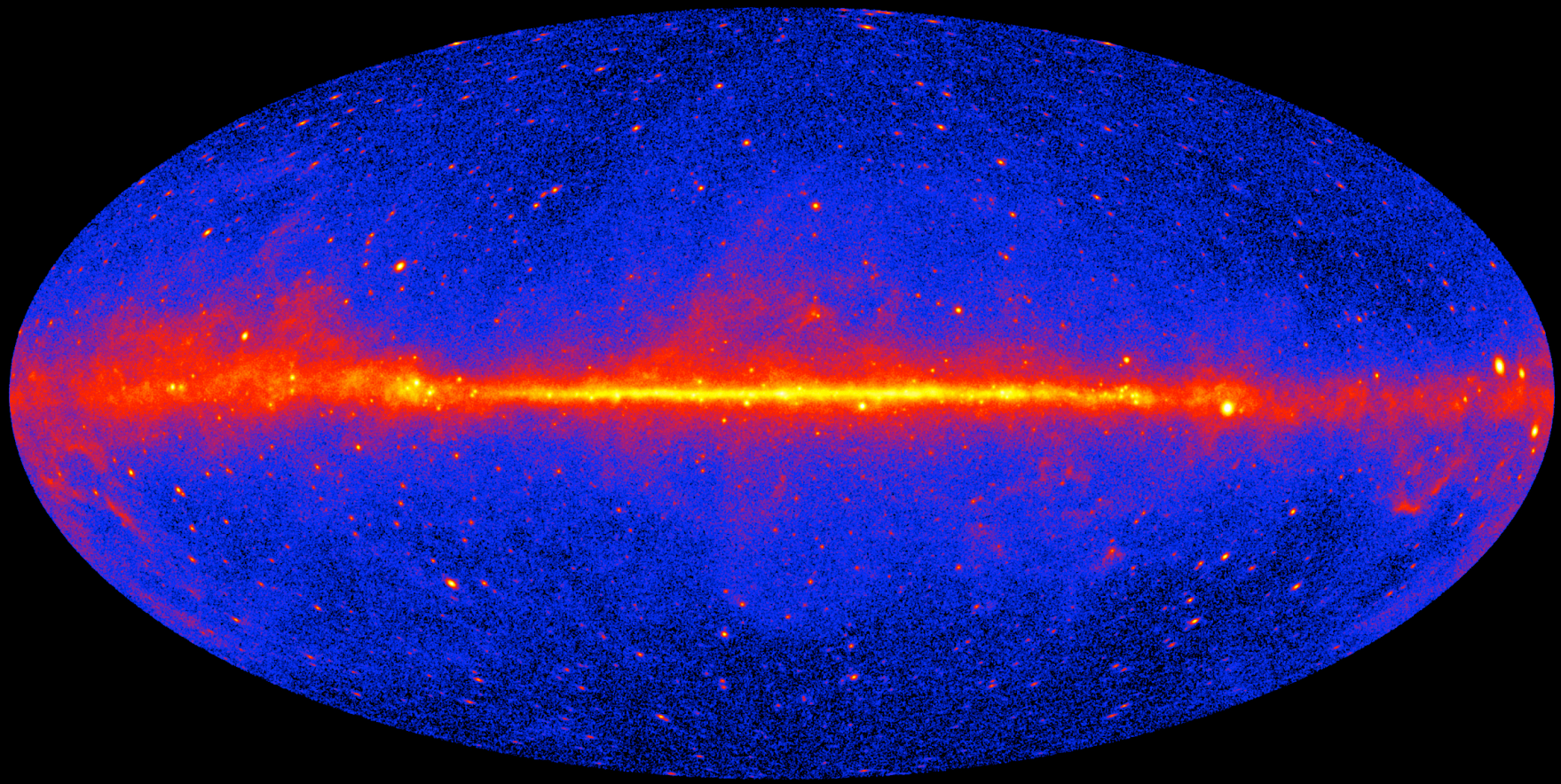
In collaboration with A. Franckowiak, M. Gustafsson and G. Zaharijas

ON BEHALF OF THE FERMI LAT COLLABORATION

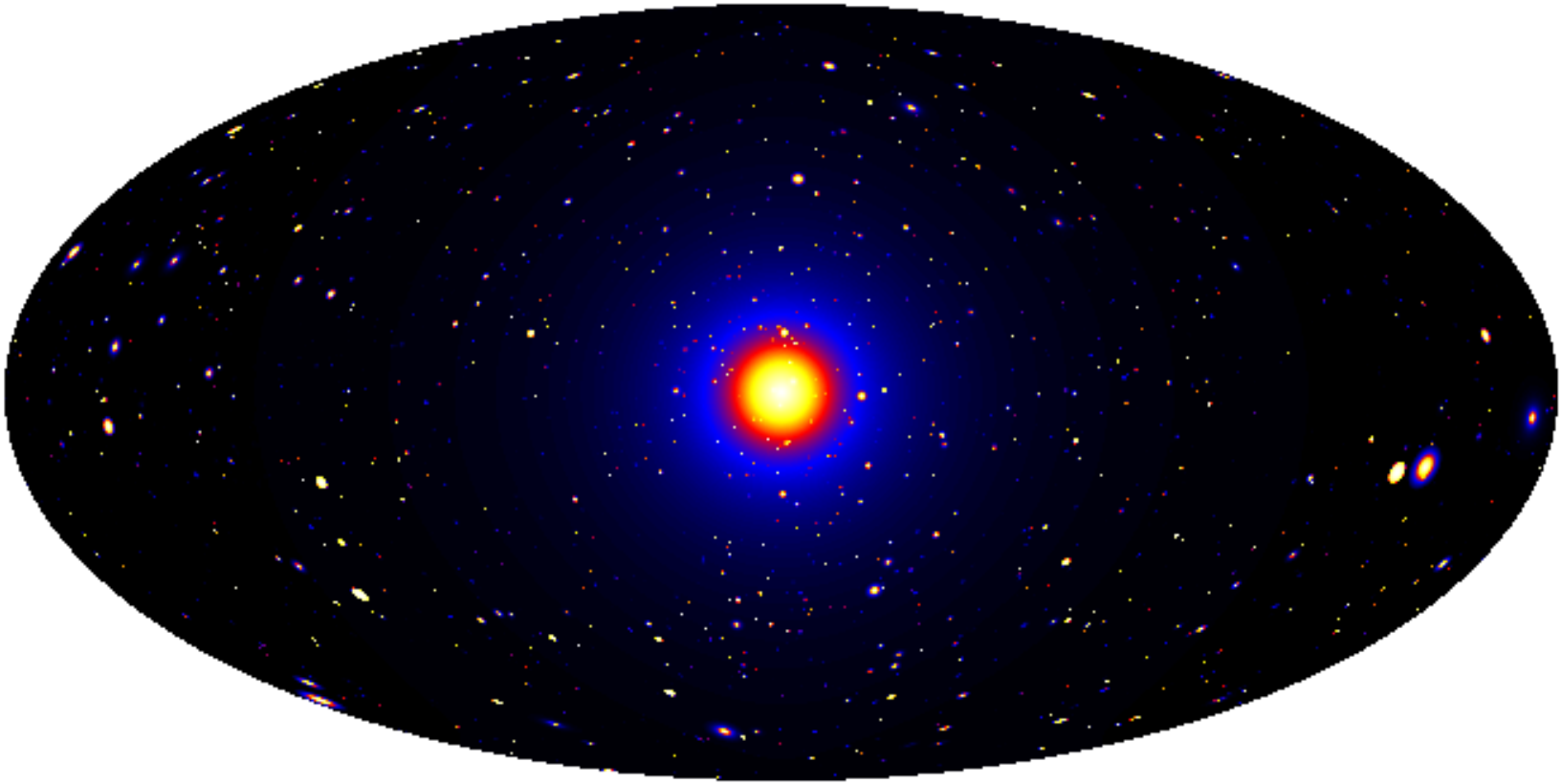
HEM 2014, Chicago, June 9-11, 2014

THE GAMMA-RAY SKY above 1 GeV

5 years of Fermi LAT data



The dark matter-induced gamma-ray sky



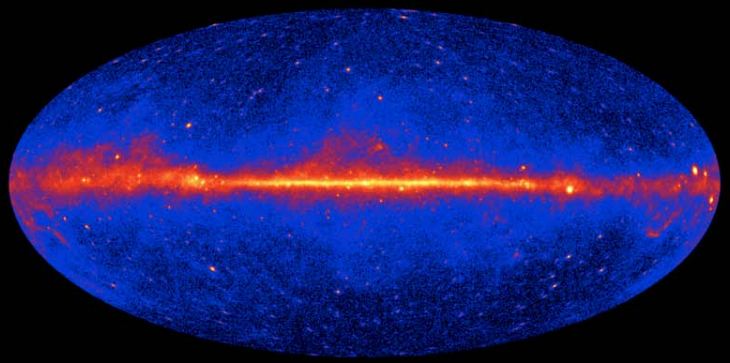
Dark Matter simulation:
Pieri+(2009) arXiv:0908.0195

Need to disentangle dark matter annihilations from conventional astrophysics.

Crucial to understand the astrophysical processes in great detail.

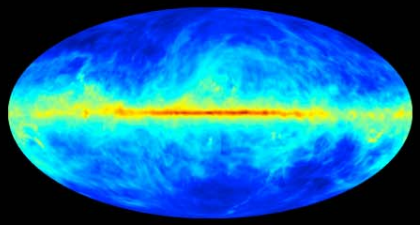
FOREGROUNDS

[Or the complexity of the gamma-ray sky]



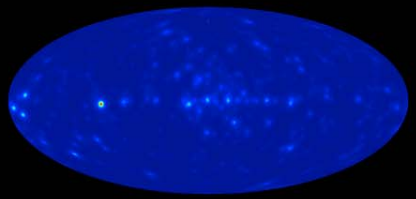
Fermi-LAT sky

=



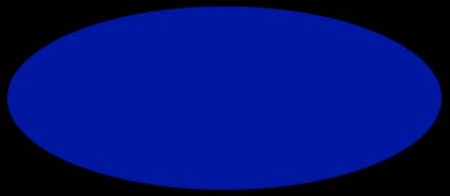
Galactic Diffuse

+



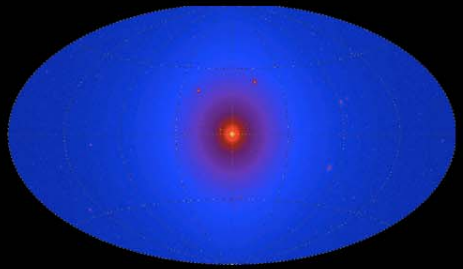
Sources

+



Isotropic diffuse

+?

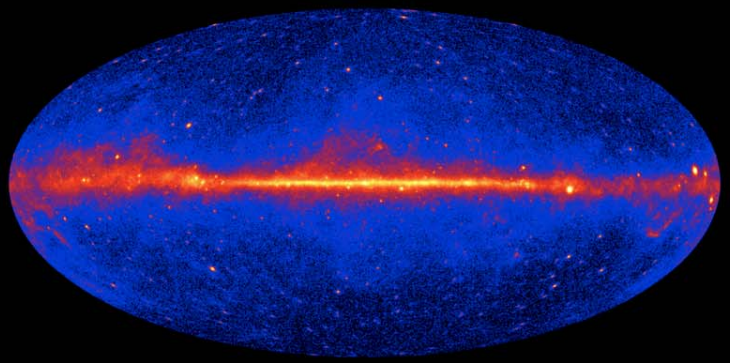


Dark Matter

+ ?

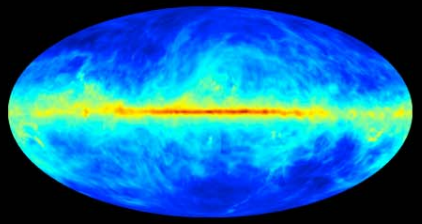
FOREGROUNDS

[Or the complexity of the gamma-ray sky]



Fermi-LAT sky

=



Galactic Diffuse

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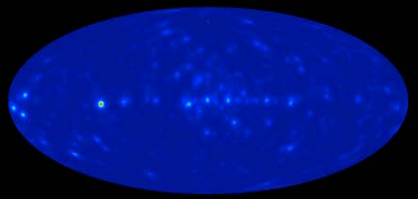

Sources

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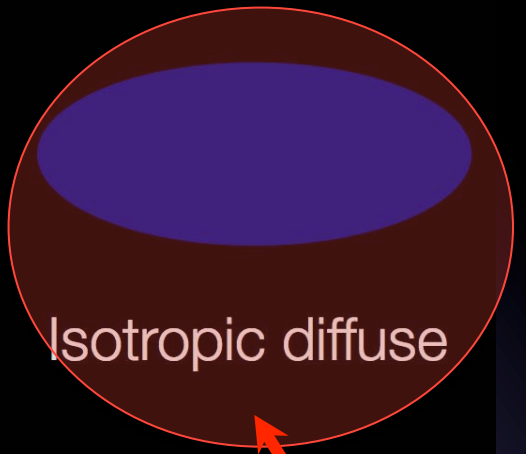

Isotropic diffuse

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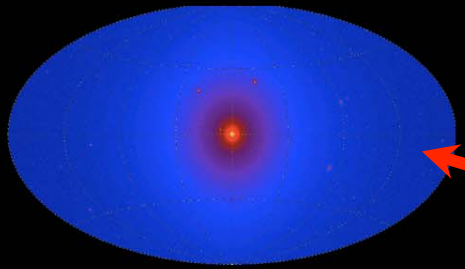


Dark Matter

+ ?

This talk

Dark Matter Search Strategies

Satellites

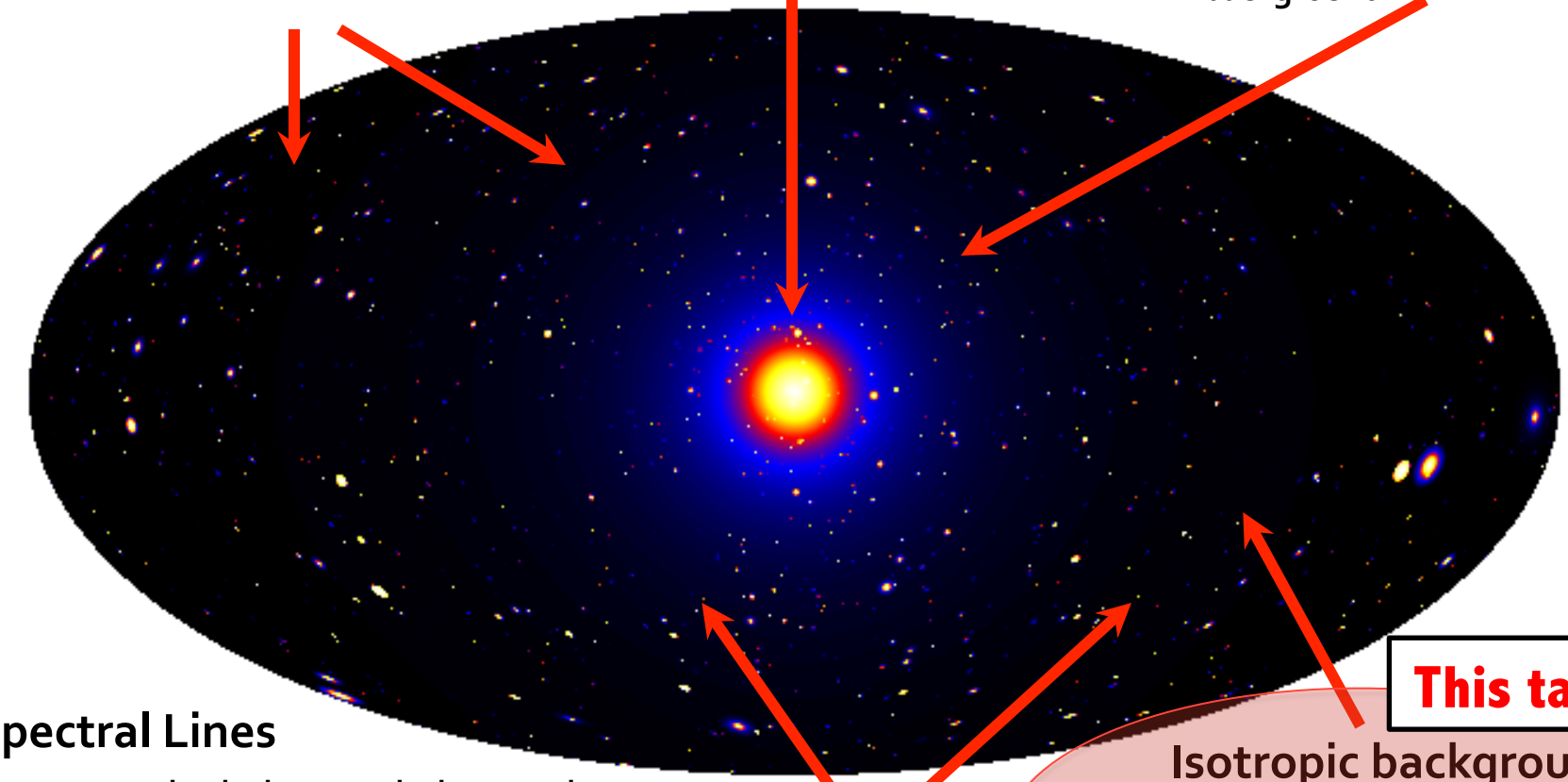
Low background and good source id, but low statistics

Galactic Center

Good Statistics, but source confusion/diffuse background

Milky Way Halo

Large statistics, but diffuse background



Spectral Lines

Little or no astrophysical uncertainties, good source id, but low sensitivity because of expected small branching ratio

Galaxy Clusters

Low background, but low statistics

This talk

Isotropic background

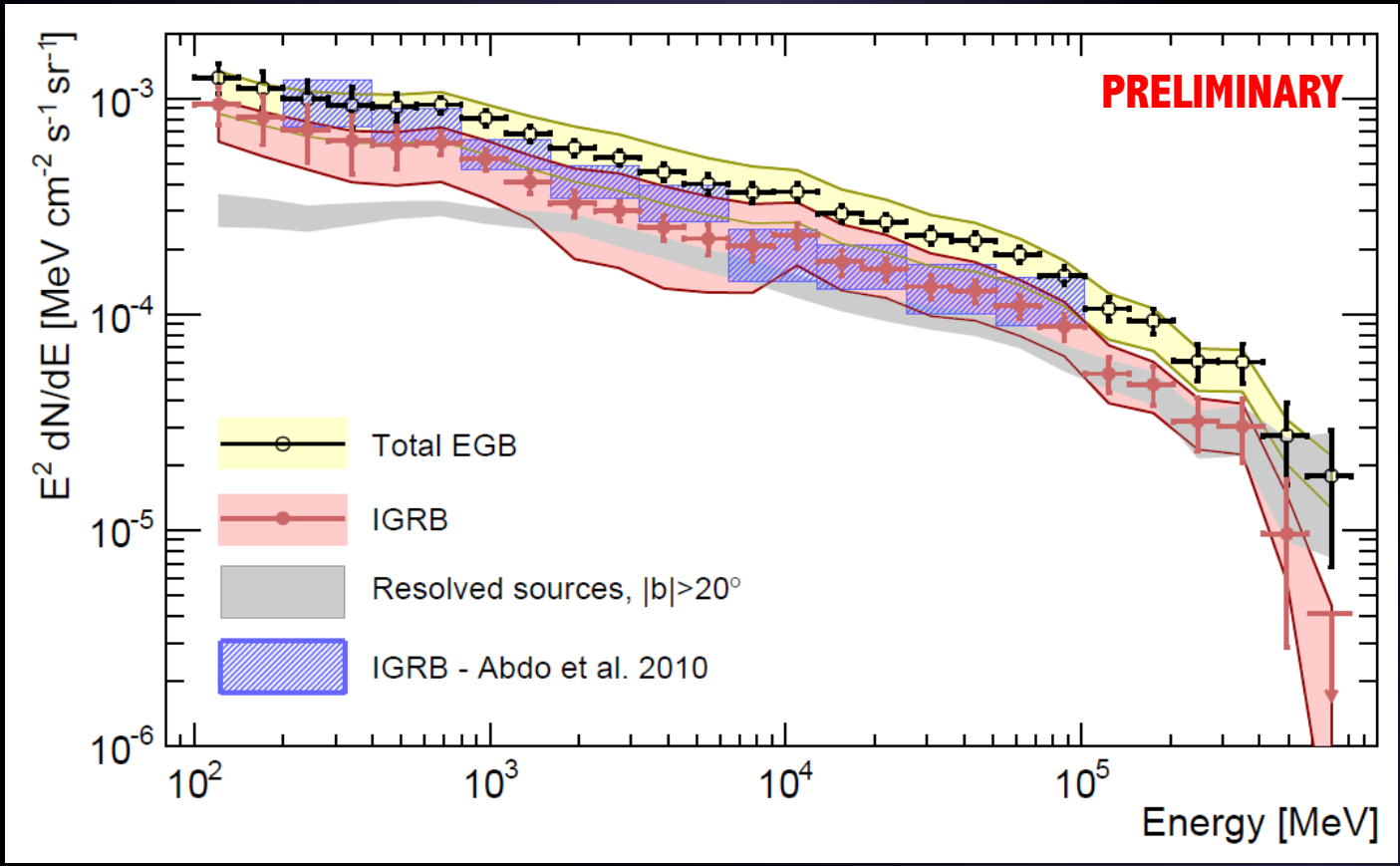
Large statistics, but astrophysics, galactic diffuse background

Both anisotropies and intensity!

Need to disentangle dark matter annihilations from conventional astrophysics.

Crucial to understand the astrophysical processes in great detail.

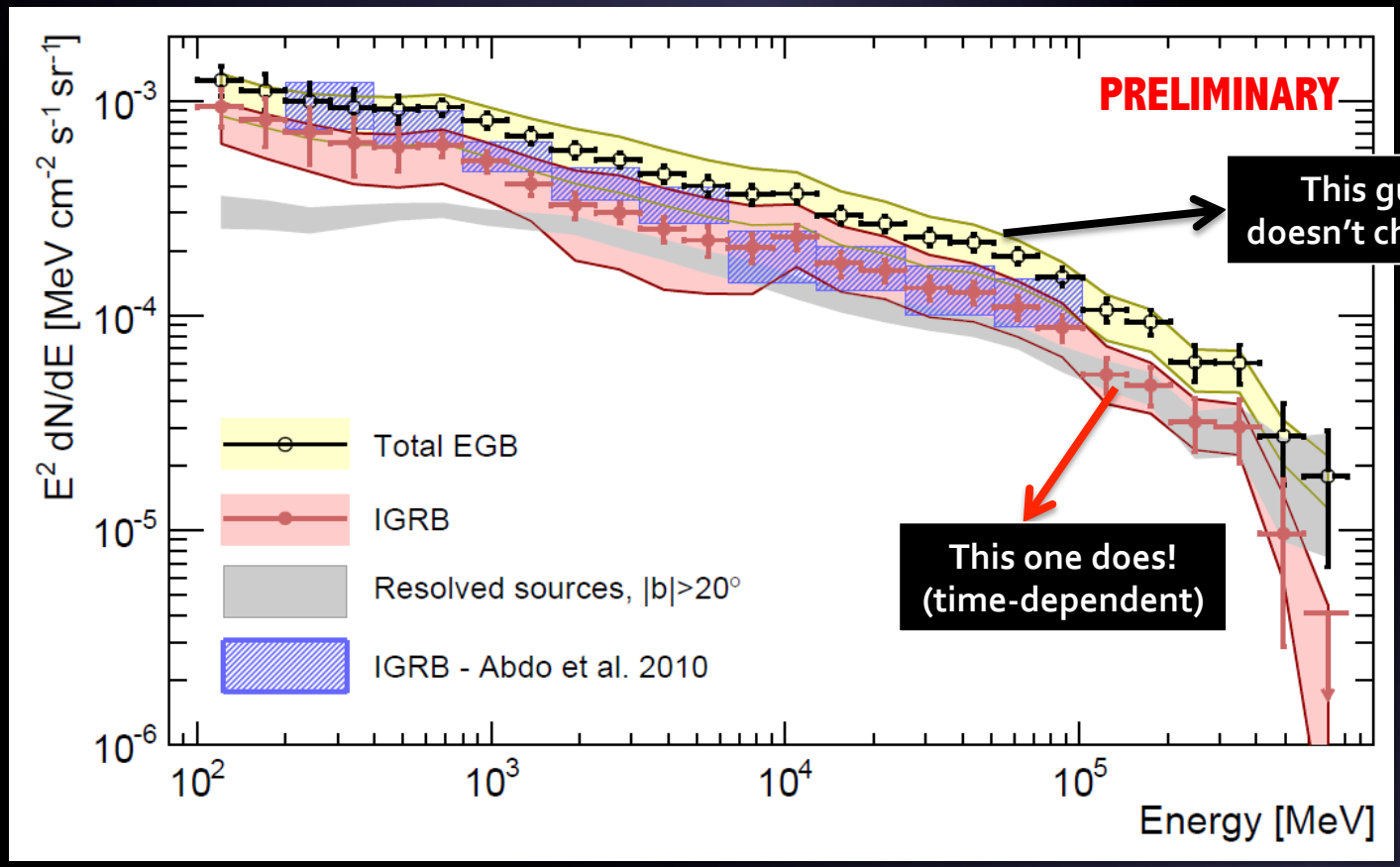
The brand new Fermi LAT IGRB spectrum



K. Bechtol's talk

- **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**

The brand new Fermi LAT IGRB spectrum



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Origin of the Extragalactic Gamma-ray Background (EGB)

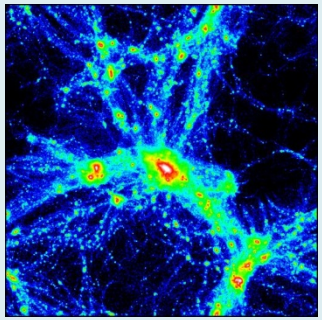
in the LAT energy range

[EGB == IGRB + individually resolved extragalactic sources]

Blazars

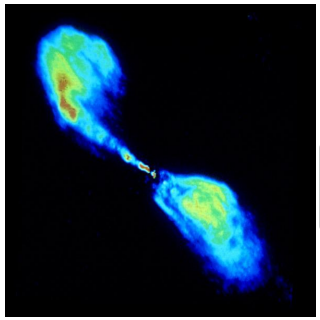
Ajello's talk

GRBs



Dark matter annihilation / decay
(upper limits)

THIS TALK



Radio galaxies

Di Mauro's talk

Galaxy clusters
(upper limits)

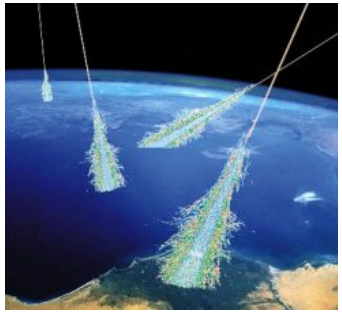
(See also Di Mauro's)

Unknown sources / processes

Star-forming galaxies

Fields' talk

Lacki's talk



Cascades
(upper limits)

Venters' talk

See also talks by Petrosian, Vernstrom…

Courtesy of K. Bechtol

THE DARK MATTER CONTRIBUTION TO THE EGB

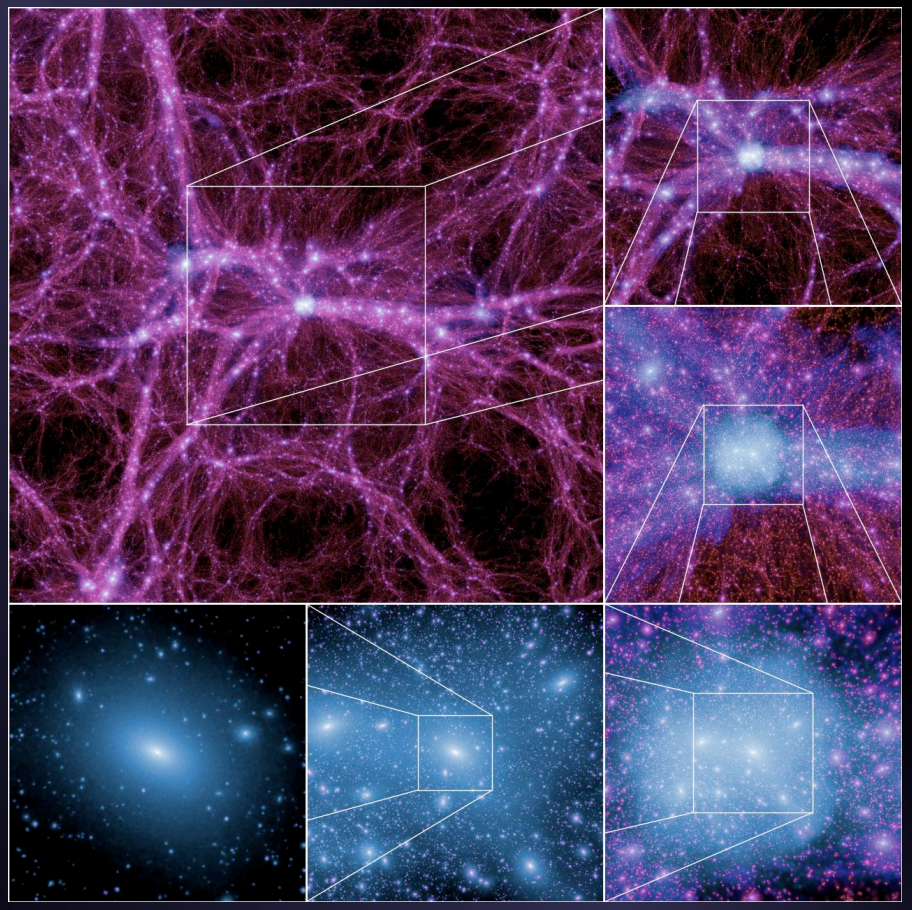
Cosmological DM annihilation

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 make lower redshifts ($z \leq 2$) to contribute the most.

Is this cosmological DM annihilation signal expected to be comparable to other possible contributors to the IGRB?



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

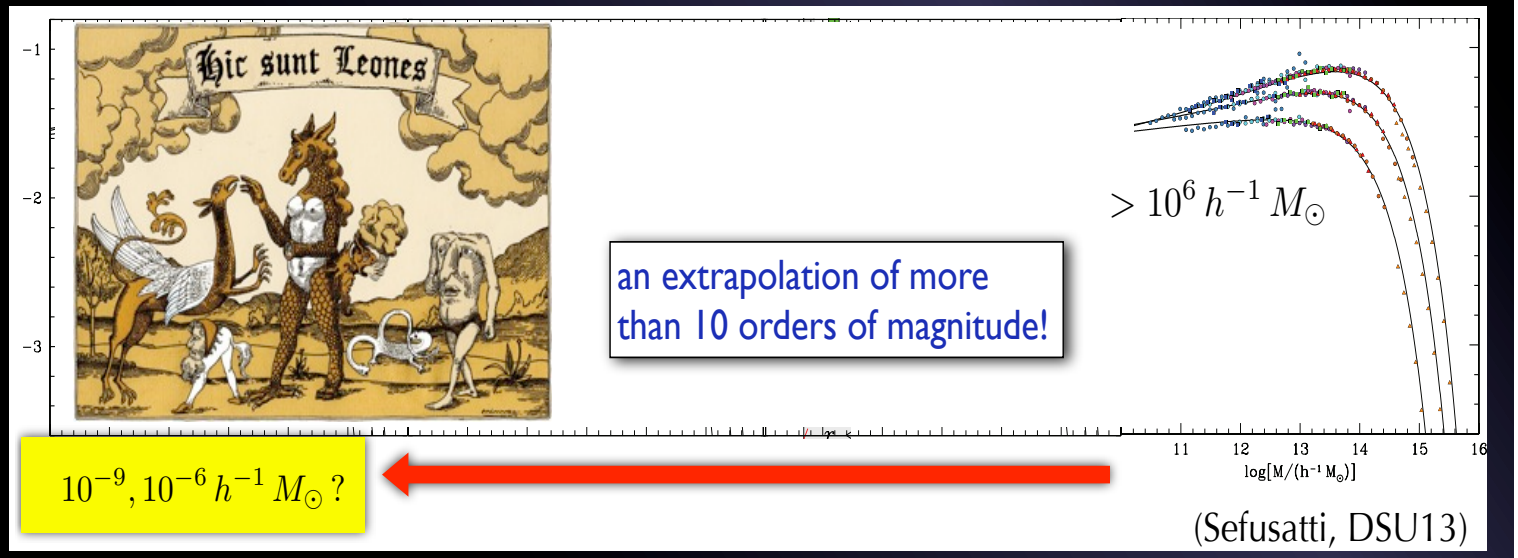
$$\frac{d\phi_\gamma}{dE_0} = \frac{\langle\sigma v\rangle}{8\pi}\frac{c}{H_0}\frac{\bar{\rho}_0^2}{m_{DM}^2}\int dz \frac{(1+z)^3\Delta^2(z)}{h(z)}\frac{dN_\gamma(E_0(1+z))}{dE}e^{-\tau(z,E_0)}$$

- Constant for a particular DM model
- "Flux multiplier"
- Redshifted DM spectrum
- EBL (Domínguez+11)

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...



How can we know about the internal properties (a.k.a. concentrations) of the smallest halos?

Two approaches taken so far:

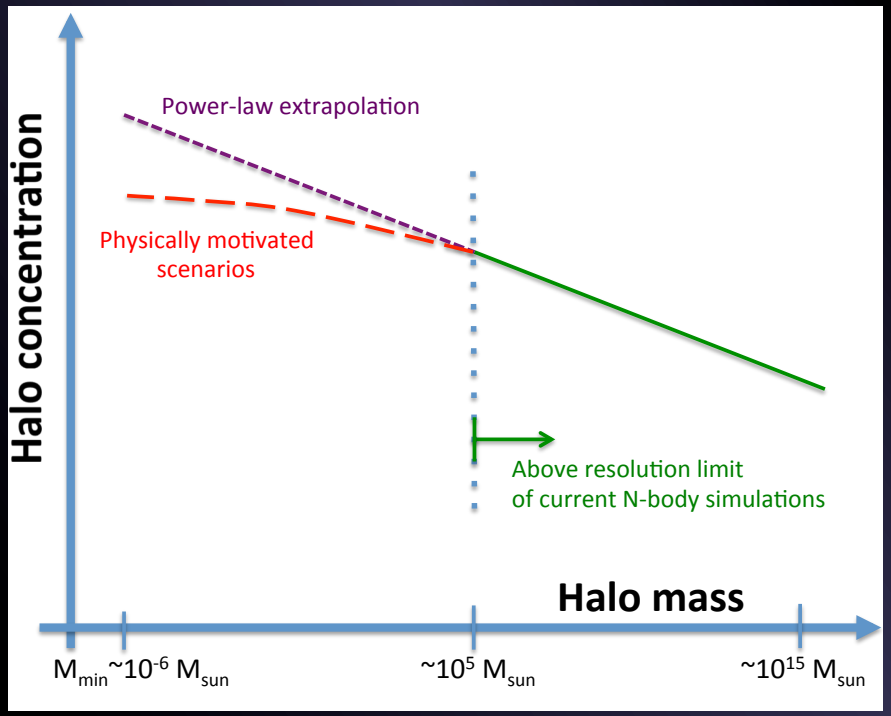
1) Power-law extrapolations below the resolution limit.

2) Physically motivated c(M) models that take into account the growth of structure in the Universe (tuned to match simulations above resolution limit).

Power-law extrapolations, e.g.:
Springel+08, Zavala+10, Pinzke+11, Gao+12

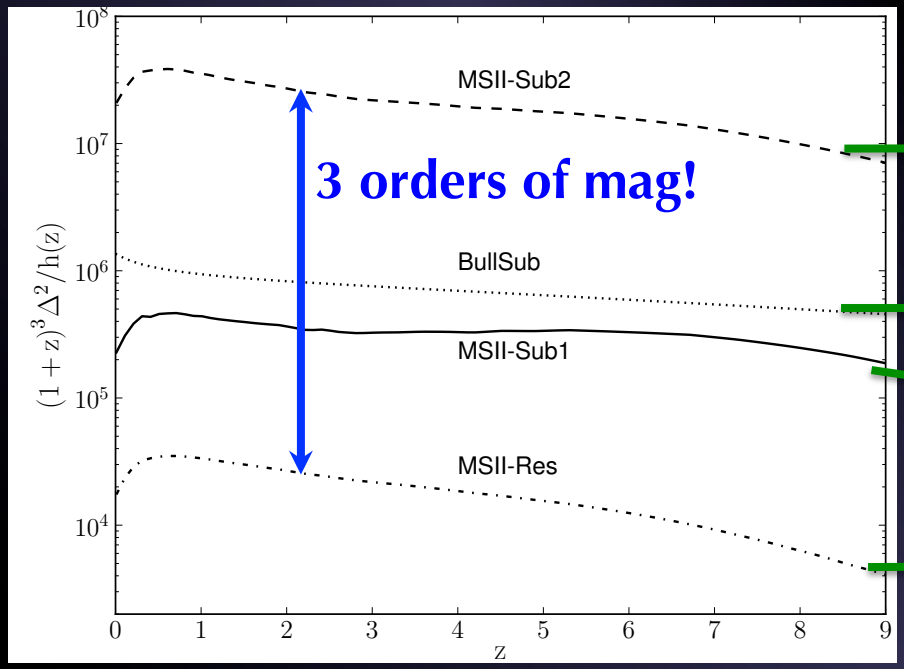
Non power-law extrapolations, e.g.:
Lavalle+08, Kuhlen+08, Kamionkowski+10, Pieri+11

See also Zavala+13



Previously, this was the common picture:

Are all these scenarios realistic, i.e., well motivated in ΛCDM?



Most optimistic c(M) power-law extrapolation

Semi-analytical

Conservative power-law extrapolation

Only resolved halos in MSII

Abdo+10

In our work, we will *drastically* lower these uncertainties by means of:

- A better understanding at small halo masses, thanks to both recent theoretical and numerical developments.
- Two independent and complementary approaches.

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.

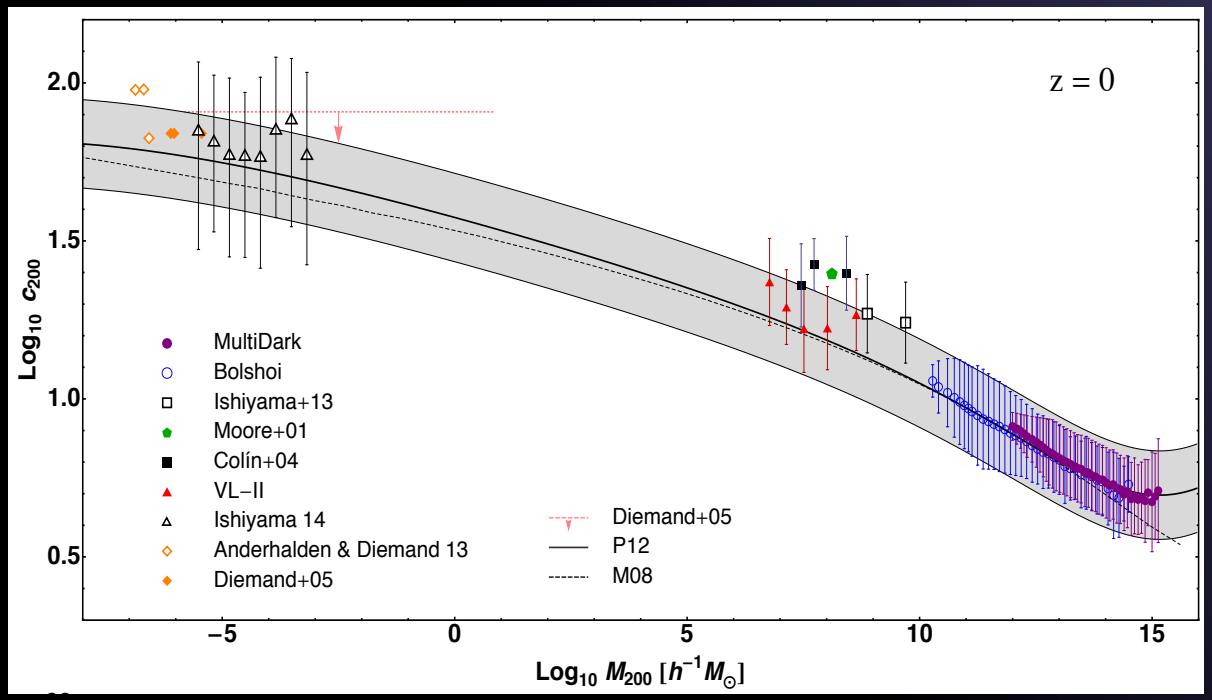
FLUX MULTIPLIER

$$\zeta(z) = \frac{1}{\Omega_{\rm DM}\rho_c} \int_{M_{\rm min}} dM \frac{dn}{dM} M \frac{\Delta_v(z)}{3} \langle F(M,z) \rangle$$

Halo mass function

Halo masses and concentrations

[MASC & Prada, 2014, MNRAS accepted]



Planck cosmology.

Prada+12 concentration-mass model.

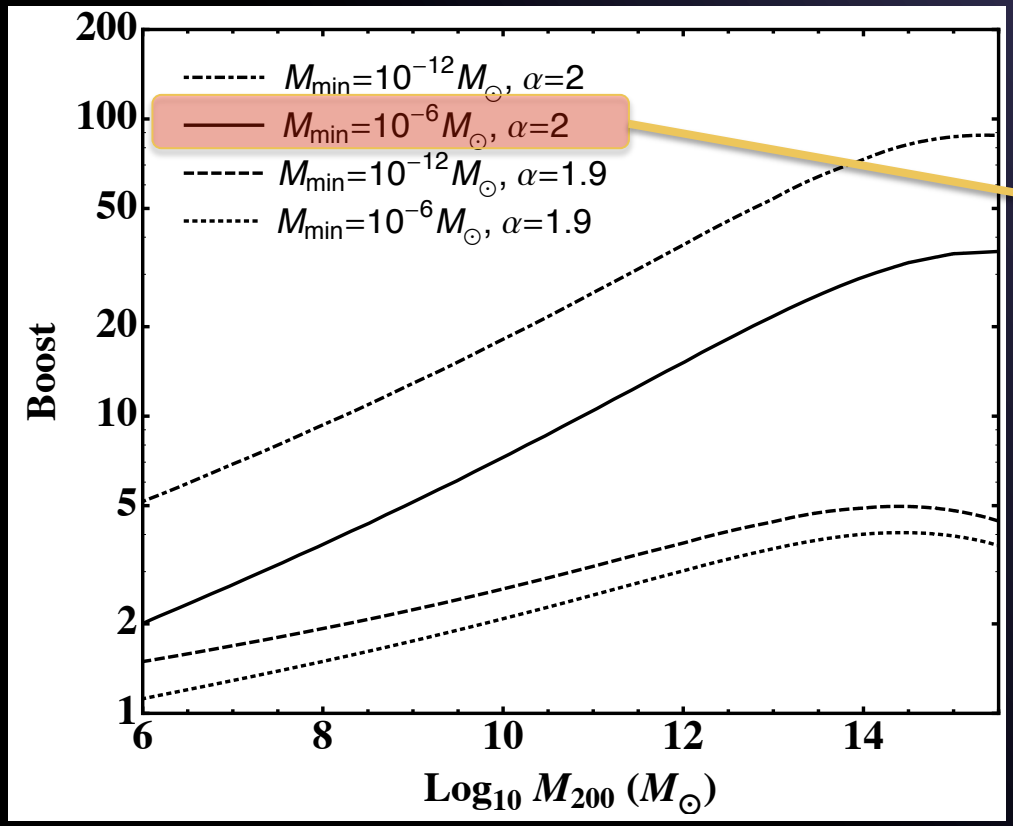
NFW DM density profiles

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

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, MNRAS accepted]

POWER SPECTRUM APPROACH

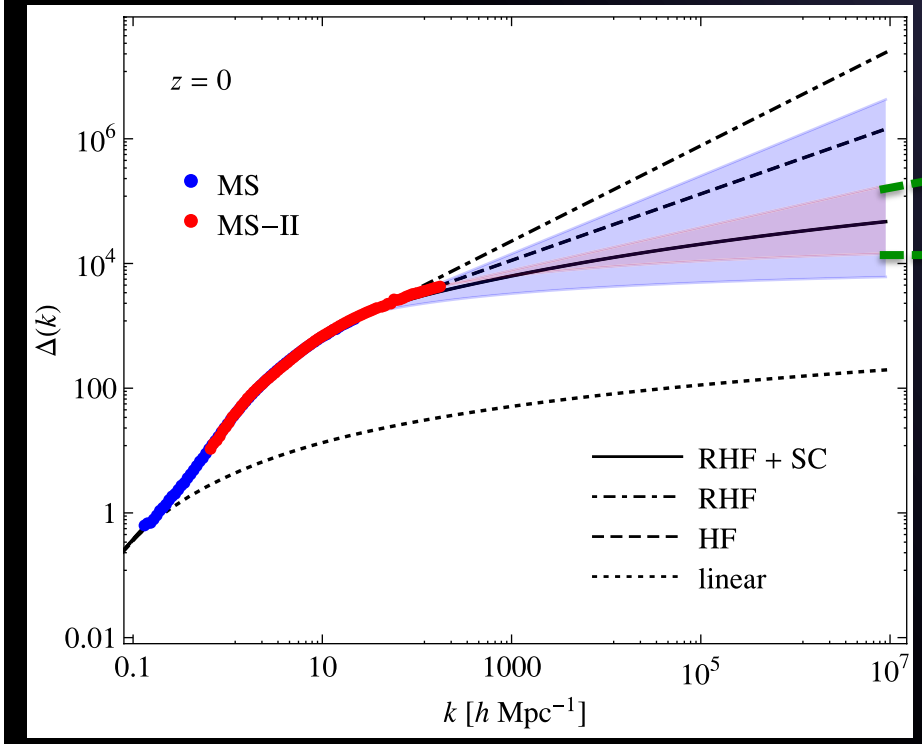
FLUX MULTIPLIER

$$\zeta(z) \equiv \langle \delta^2(z) \rangle = \int^{k_{max}} \frac{d\,k}{k} \frac{k^3 P_{NL}(k,z)}{2\pi^2} \equiv \int^{k_{max}} \frac{d\,k}{k} \Delta_{NL}(k,z)$$

Integral over the non-linear matter power spectrum, P_{NL}

Adimensional P_{NL}

Δ_{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.

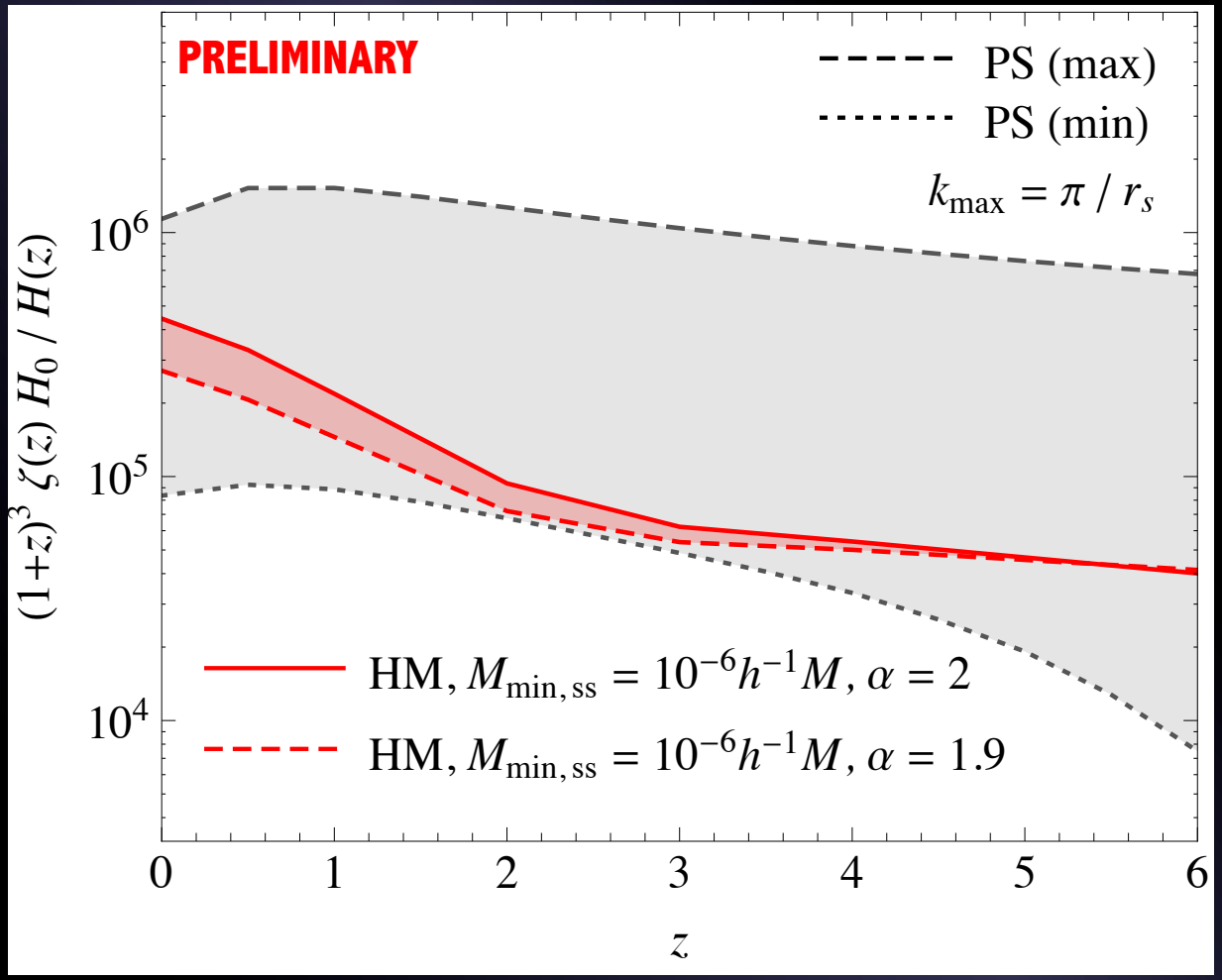
Substructure naturally accounted for.

HM vs. PS predictions (I)
redshift evolution

Normalized flux multiplier

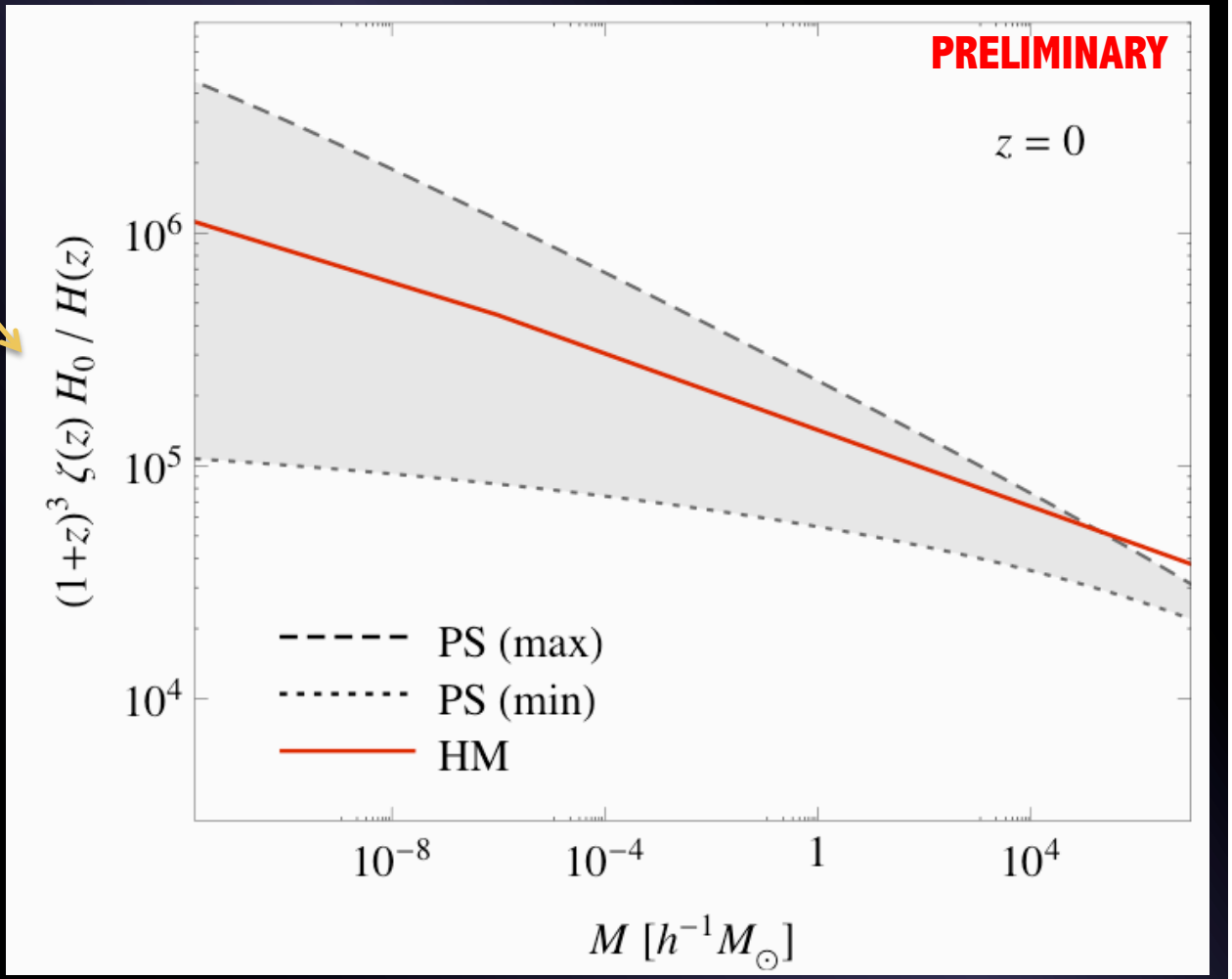
Both the PS and HM results are fully consistent with each other.

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



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

Normalized flux multiplier

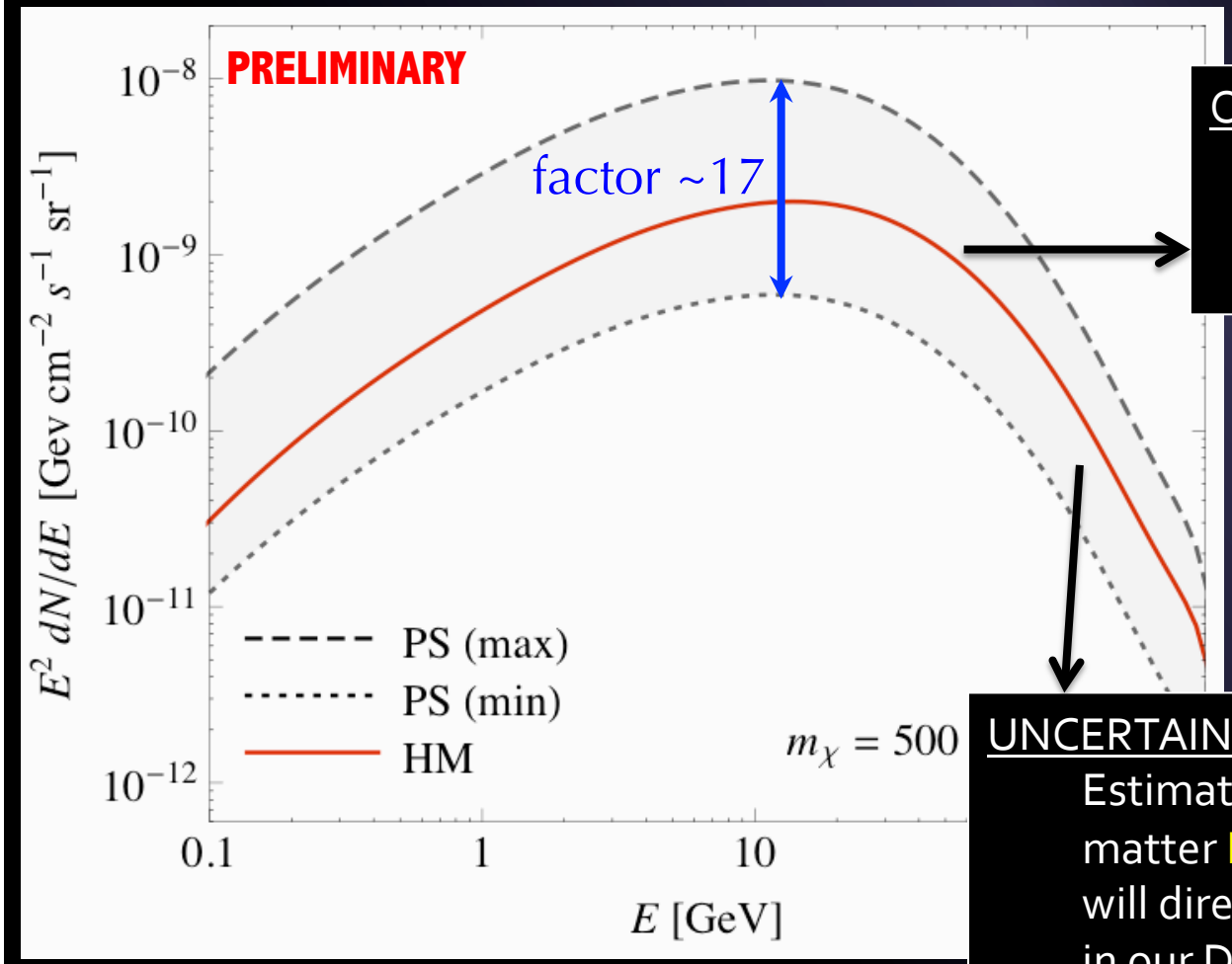


Good agreement except at the highest (probably unrealistic) M_{min} tested

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.

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



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.

[500 GeV WIMP annihilating to bb quarks]

Galactic DM annihilation signal ?

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

  → if so, we will *add* it to the extragalactic signal when setting the DM limits.

  → If not, we will treat it as an additional *foreground*.

- Two distinct components: smooth DM density profile and Galactic subhalos.

Smooth component:

- NFW DM density profile.
- 20 kpc for the scale radius; local DM density set to 0.2 GeV cm^{-3}
- For |b|> 20 deg, uncertainties in the inner slope not important.
- Main uncertainty coming from overall normalization (factor 2-4).
- A factor ~16 difference between 20 and 90 degrees of latitude.

→ Anisotropic signal: we'll treat it as an additional foreground!

Impact on DM limits will be discussed in Zaharijas's talk

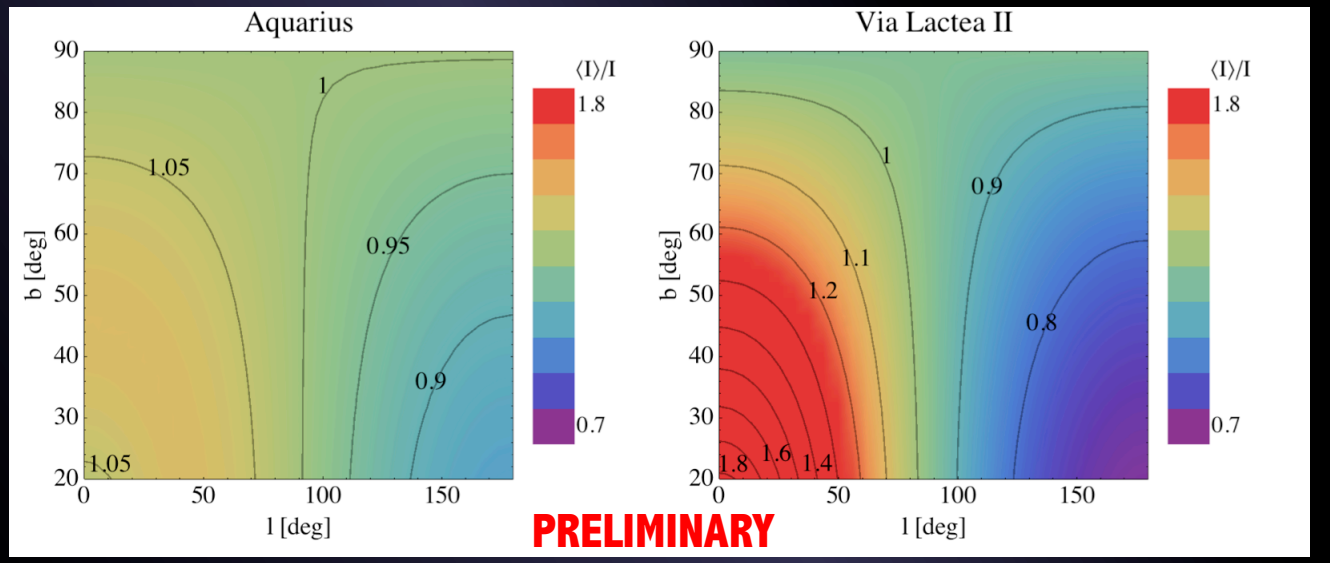
Galactic DM annihilation signal: substructure

→ **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)

Impact on DM limits will be discussed in Zaharijas's talk

Remarks

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

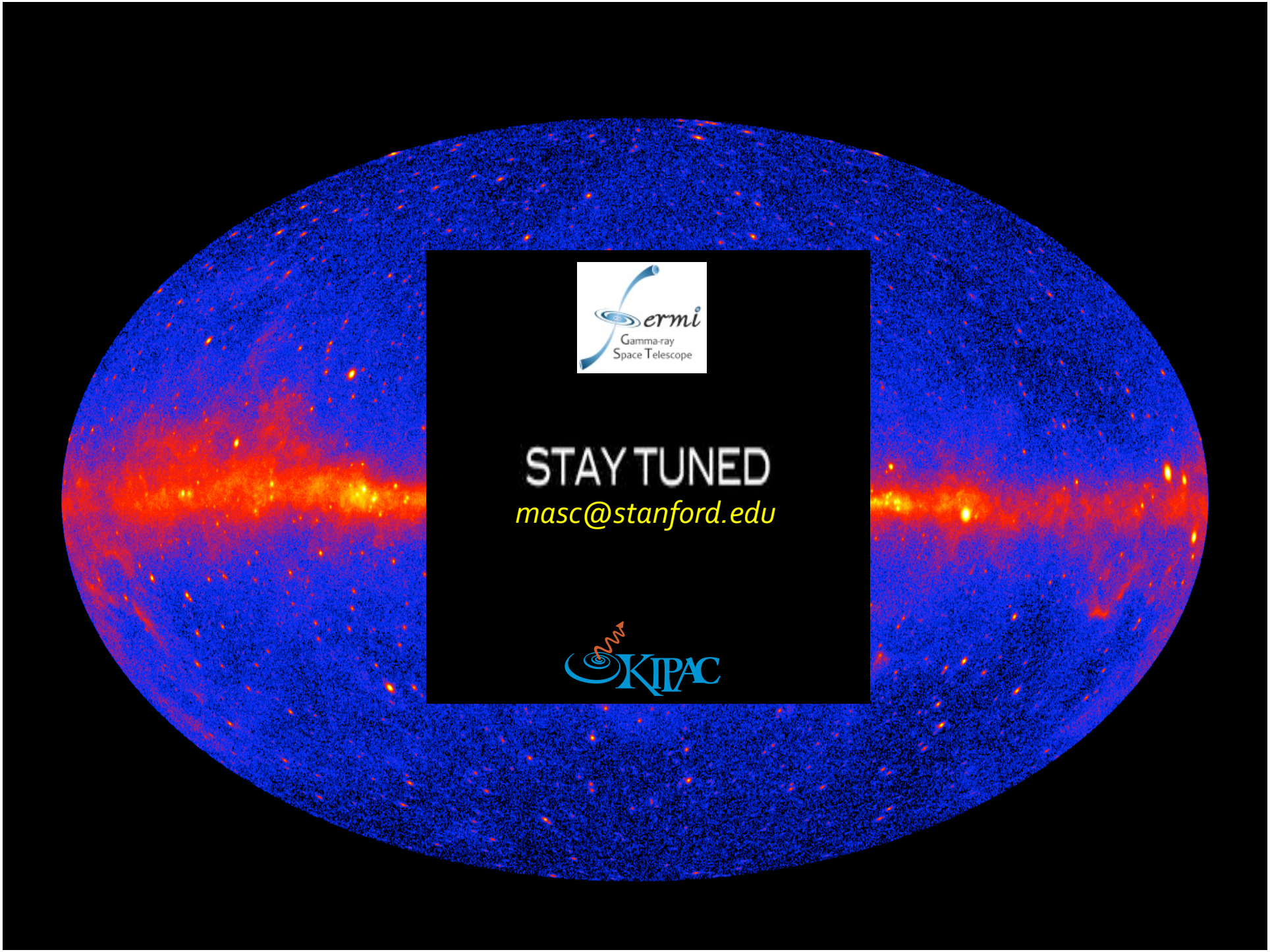
- New predictions for the cosmological DM annihilation signal, taking full advantage of our latest knowledge of structure formation in the Universe.

- Two different theoretical approaches: Halo Model and Power Spectrum, which remarkably agree.

- Theoretical uncertainty band drastically narrowed down to a factor <20.

- Galactic (both smooth and subhalos) and extragalactic DM emission treated in a consistent way for the first time.
  - Smooth contribution added as additional foreground.
  - Subhalo contribution assumed to be isotropic.

OUR DM LIMITS WILL BE PRESENTED BY G. ZAHARIJAS AFTER THIS TALK!


Fermi
Gamma-ray
Space Telescope
STAY TUNED
masc@stanford.edu
KIPAC