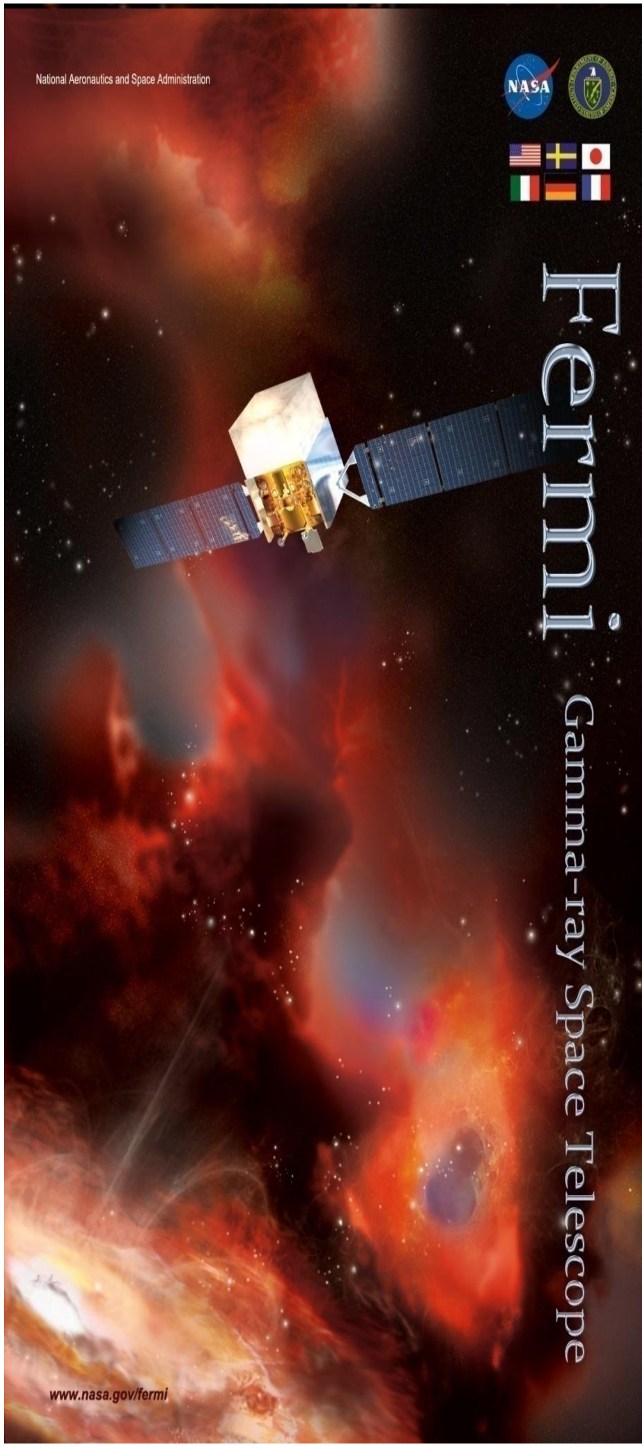


Fermi
Gamma-ray Space Telescope

RECENT RESULTS OF DARK MATTER SEARCHES WITH THE *FERMI*-LAT

Miguel A. Sánchez-Conde

Oskar Klein centre

Stockholm University

ON BEHALF OF THE FERMI LAT COLLABORATION

Amsterdam-Paris-Stockholm meeting, GRAPPA institute, September 30 2014

OBSERVATIONAL EVIDENCE OF DARK MATTER (DM)

Evidences have been reported at different scales.

Galactic scales

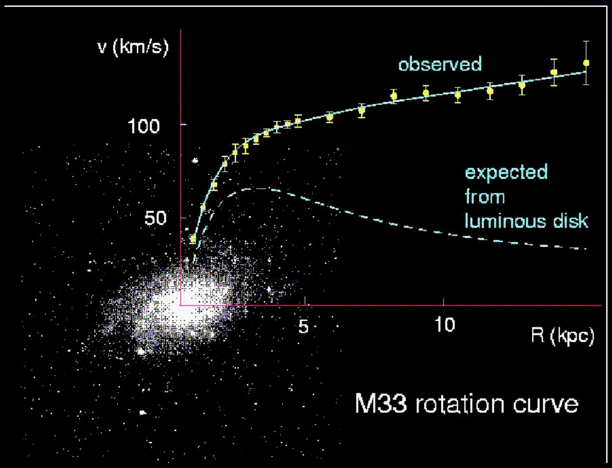
a) Rotation curves of spirals
b) Weak lensing
c) Velocity dispersions of satellite galaxies
d) Velocity dispersions in dSphs

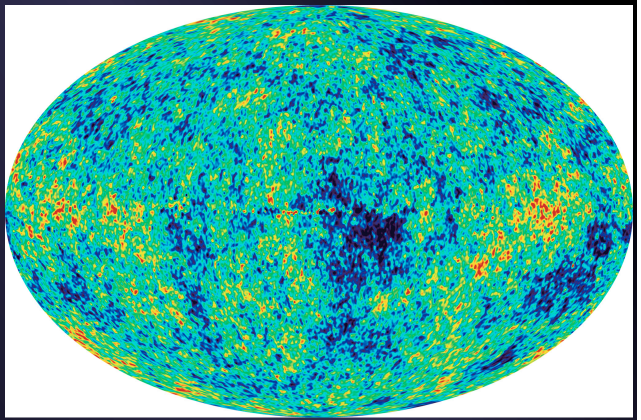
Galaxy clusters scales

a) Velocity dispersions of individual galaxies
b) Strong and weak lensing
c) Peculiar velocity flows
d) X-ray emission

Cosmological scales

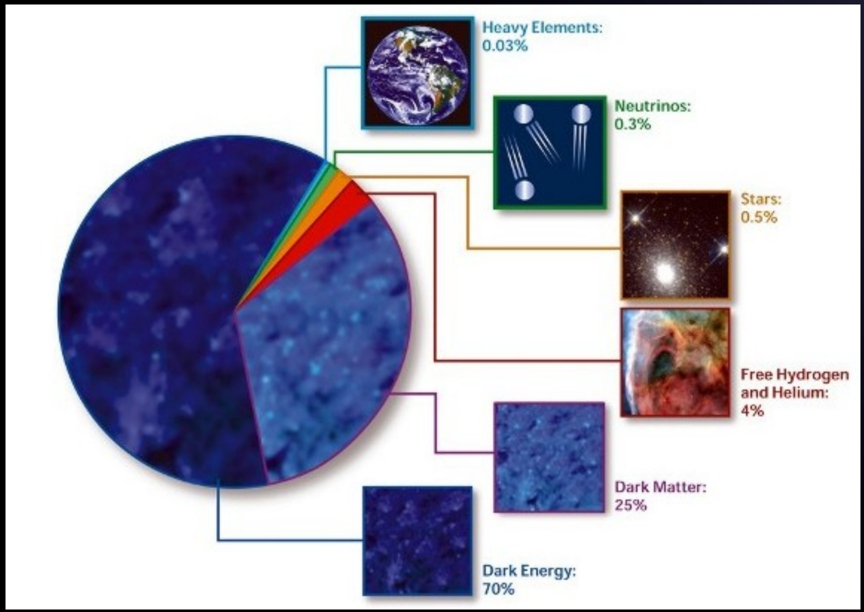
a) CMB anisotropies
b) Growth of structure
c) LSS distribution
d) BAOs
e) SZ effect

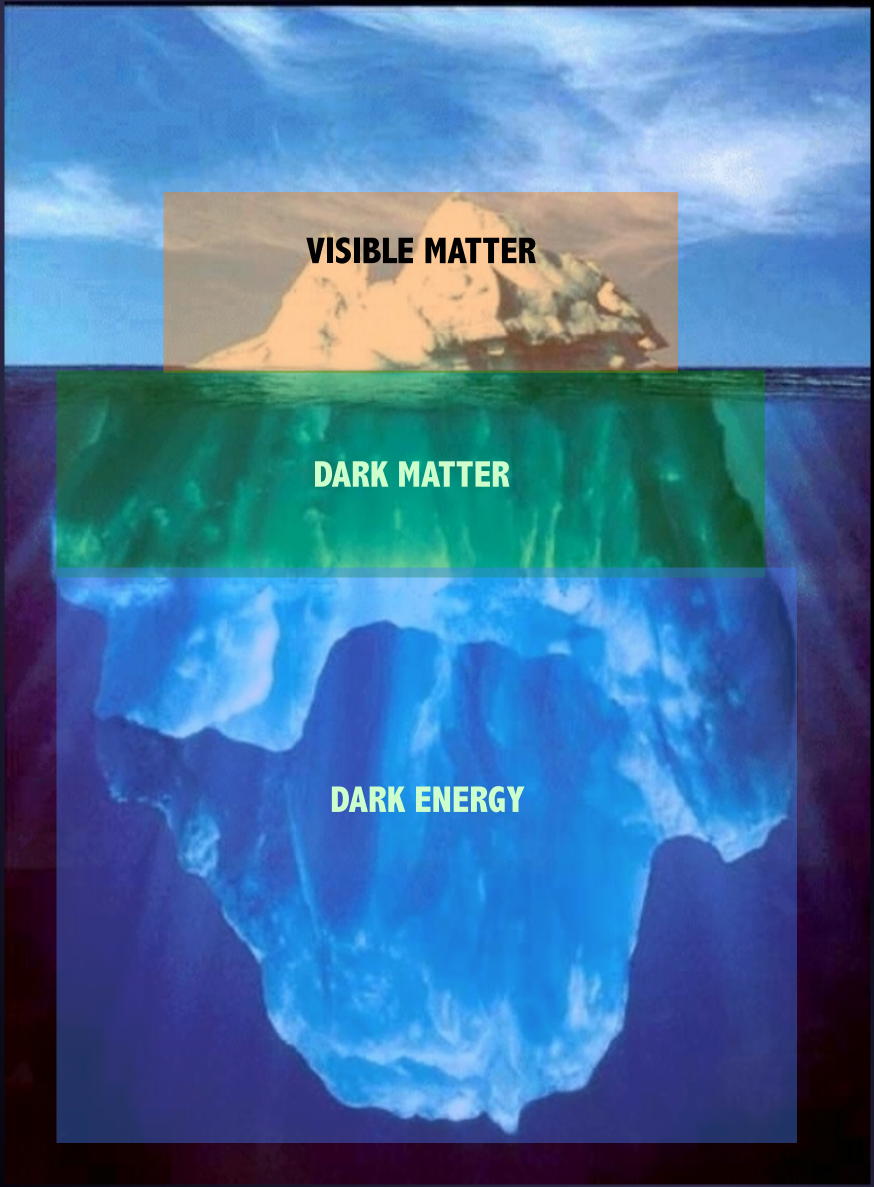




ΛCDM cosmology

- ✓ Settled in the Big Bang scenario.
- ✓ Non-baryonic DM needed to explain observations at different scales.
- ✓ Cold DM to explain the observed Large Scale Structure.
- ✓ Λ term to explain the measured cosmic acceleration.





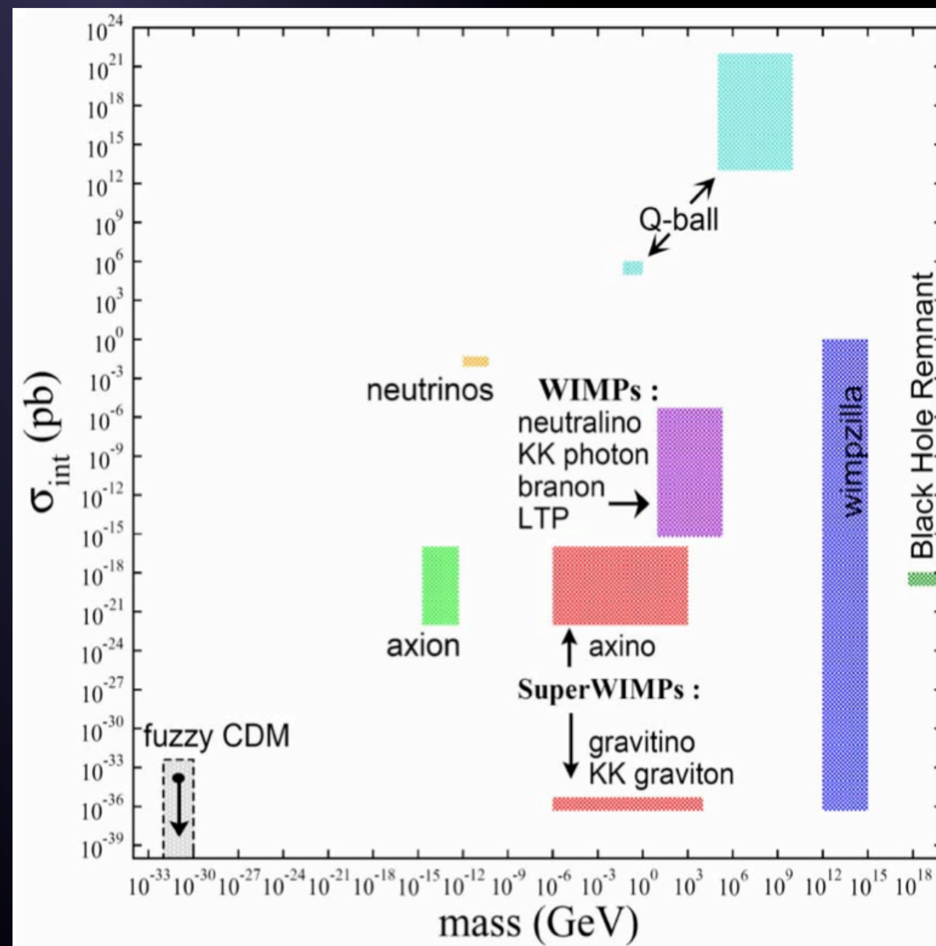
What could the DM be made of?

Most of the matter in the Universe must be in the form of non-baryonic DM.

WIMPs

1) Neutral.
2) Stable/long-lived: still present today since the early Universe.
3) Cold.
4) Reproduce the observed DM amount

- No viable candidate in the Standard Model
  - ✓ The neutrino, the only non-baryonic DM candidate known to exist, is excluded.
- Huge plethora of possible candidates beyond the Standard Model



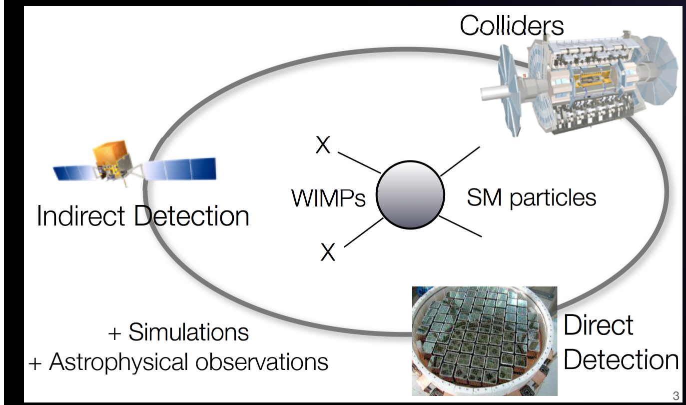
HEPAP/AAAC DMSAG Subpanel (2007)

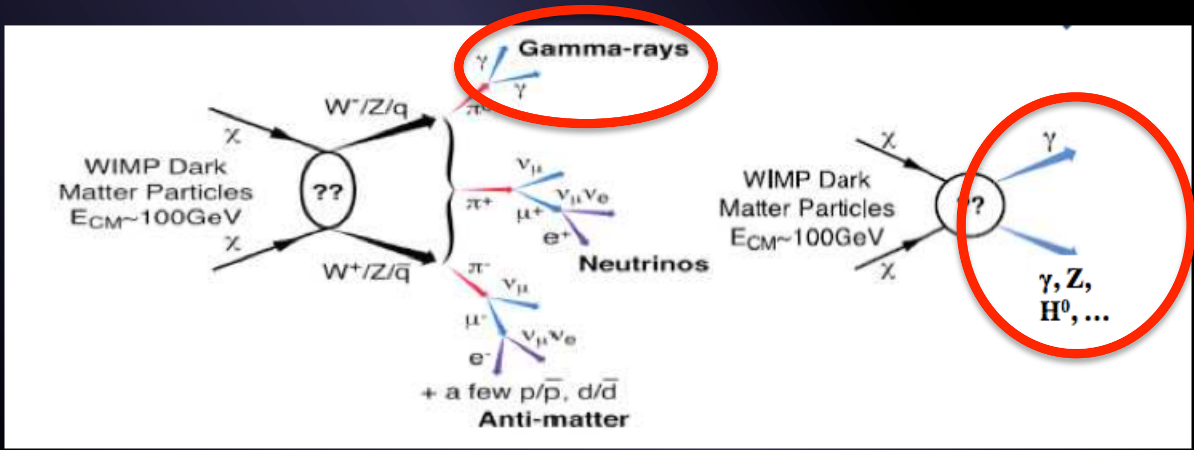
Gamma-rays from dark matter annihilations

A. **Direct detection:** scattering of DM particles on target nuclei (nuclei recoil expected).

B. **Indirect detection:** DM annihilation products (neutrinos, positrons, gammas…)

C. **Direct production** of DM particles at the lab.





Why gammas?

- ✓Energy scale of annihilation products set by DM particle mass
  - → favored models ~GeV-TeV
- ✓Gamma-rays travel following straight lines
  - → source can be known
- ✓[In the local Universe] Gamma-rays do not suffer from attenuation
  - → spectral information retained.

The DM annihilation γ-ray flux

$$F(E_\gamma > E_{th}, \Psi_0) = J(\Psi_0) \times f_{PP}\left(E_\gamma > E_{th}\right)$$

photons cm^{-2} s^{-1}

Astrophysics

Particle physics

Integration of the squared DM density

$$J(\Psi_0) = \frac{1}{4\pi} \int_{\Delta\Omega} d\Omega \int_{l.o.s.} \rho^2_{DM}[r(\lambda)]\, d\lambda$$

DM density squared

Where to search?

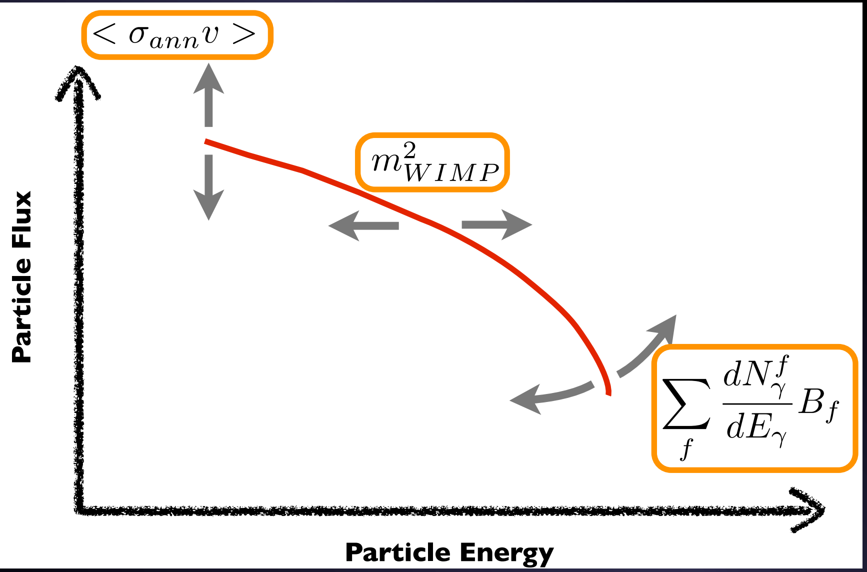
- Galactic Center
- Dwarf spheroidal galaxies
- Local galaxy clusters
- Nearby galaxies...

$$f_{PP} \propto \sum_f \frac{dN^f_\gamma}{dE_\gamma} B_f \frac{\langle \sigma \cdot v \rangle}{m_\chi{}^2}$$

N_g : number of photons per annihilation above E_{th}

<σ v>: cross section

m_χ: neutralino mass



Present gamma-ray observatories

E. range: 20 MeV - >1 TeV

E. resolution: ~10% @ GeV

FoV: ≈ 2.4 sr

Angular resolution: ~0.2º@10 GeV

Effective area ~ m^2

Fermi-LAT

E. range: 50 GeV - >10TeV

E. resolution: ~20%

FOV: ≈ 4 deg.

Angular resolution: ≈ 0.1º

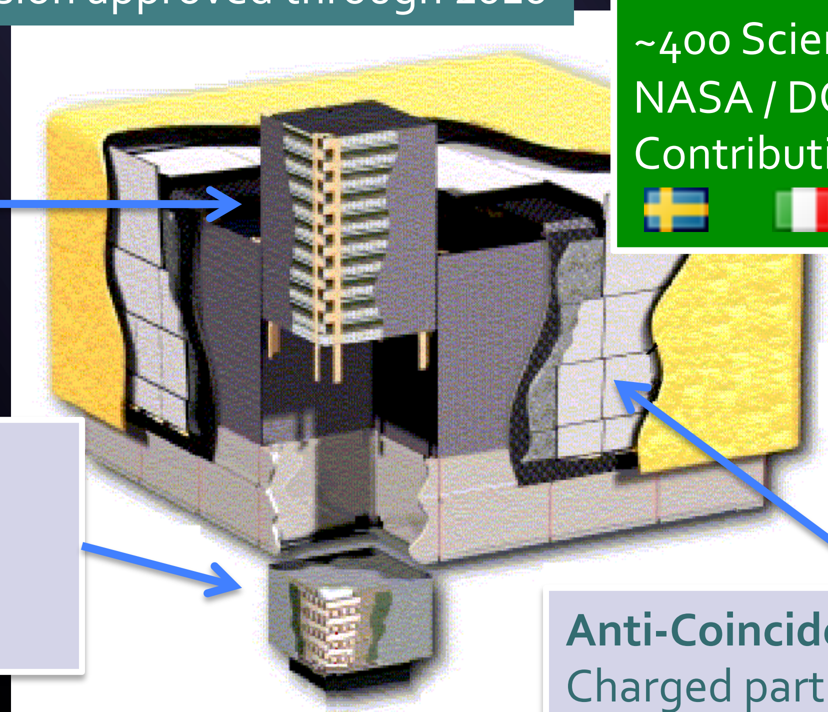
Effective area ~ 10^5 m^2

Typical Cherenkov telescope

The Fermi Large Area Telescope

LAUNCHED IN JUNE 2008
Mission approved through 2016

Fermi LAT Collaboration:
~400 Scientific Members,
NASA / DOE & International Contributions



Si-Strip Tracker:
convert $\gamma \rightarrow e^+e^-$
reconstruct γ direction
EM v. hadron separation

Hodoscopic CsI Calorimeter:
measure γ energy
image EM shower
EM v. hadron separation

Anti-Coincidence Detector:
Charged particle separation

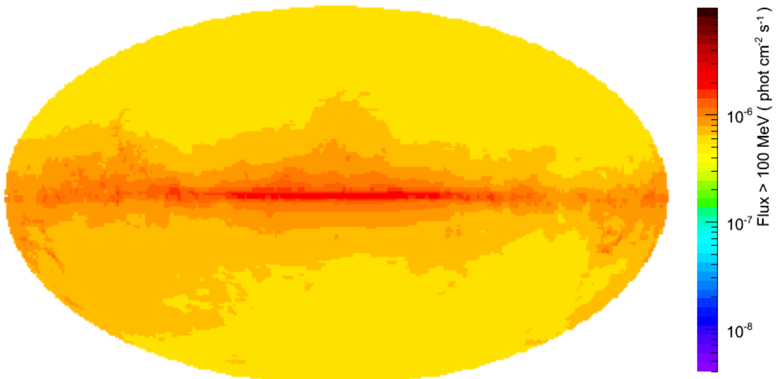
Sky Survey:
2.5 sr field-of-view
whole sky every 3 hours

Trigger and Filter:
Reduce data rate from ~10kHz to 300-500 HZ

Public Data Release:
All γ-ray data made public within 24 hours (usually less)

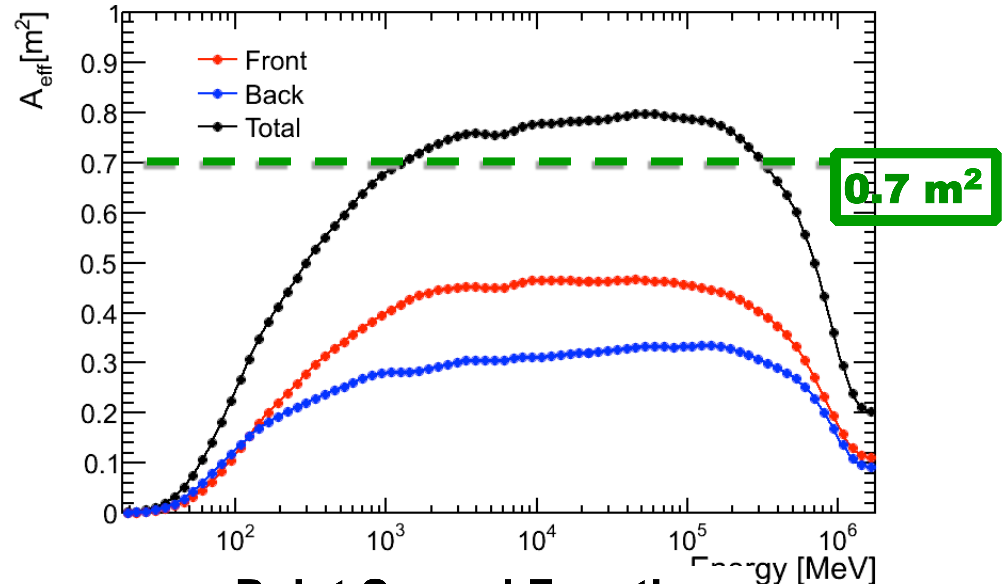
Fermi-LAT performance

All-Sky Coverage

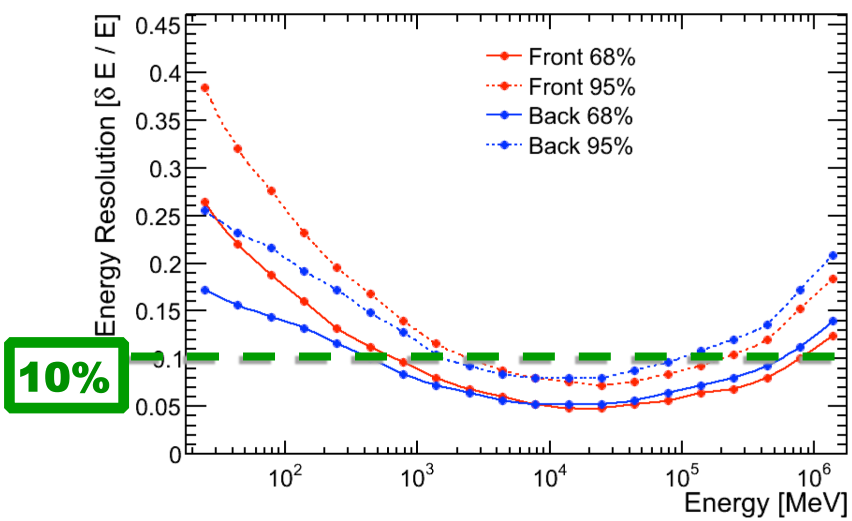


Every ~3 Hours

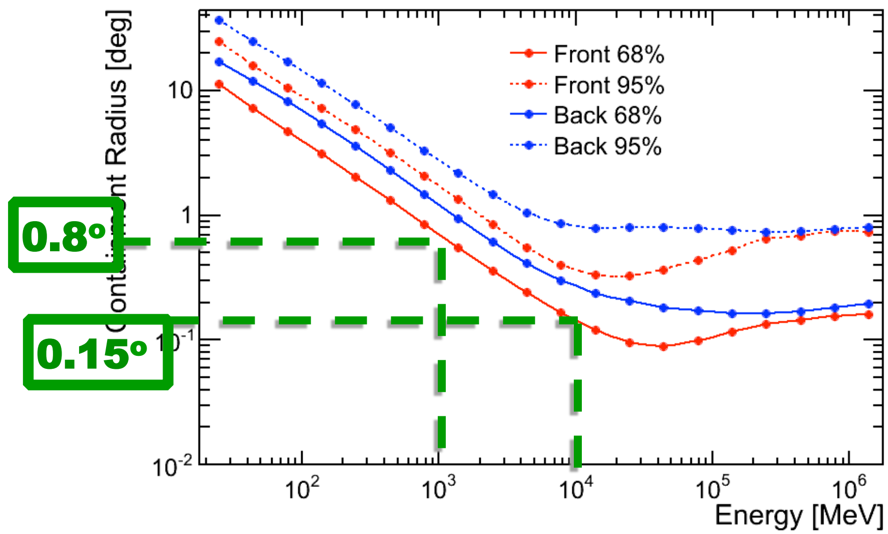
Effective Area



Energy Resolution

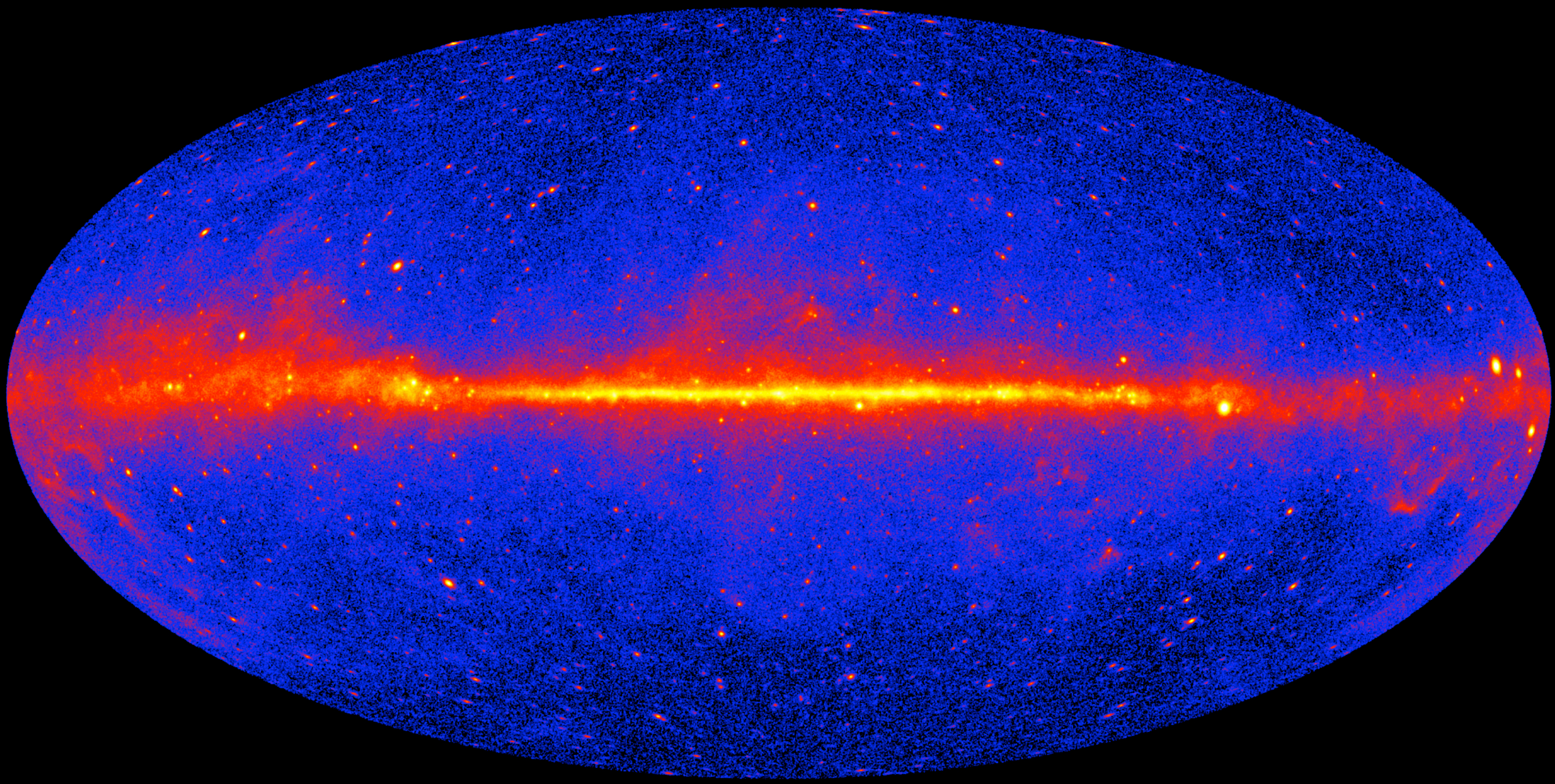


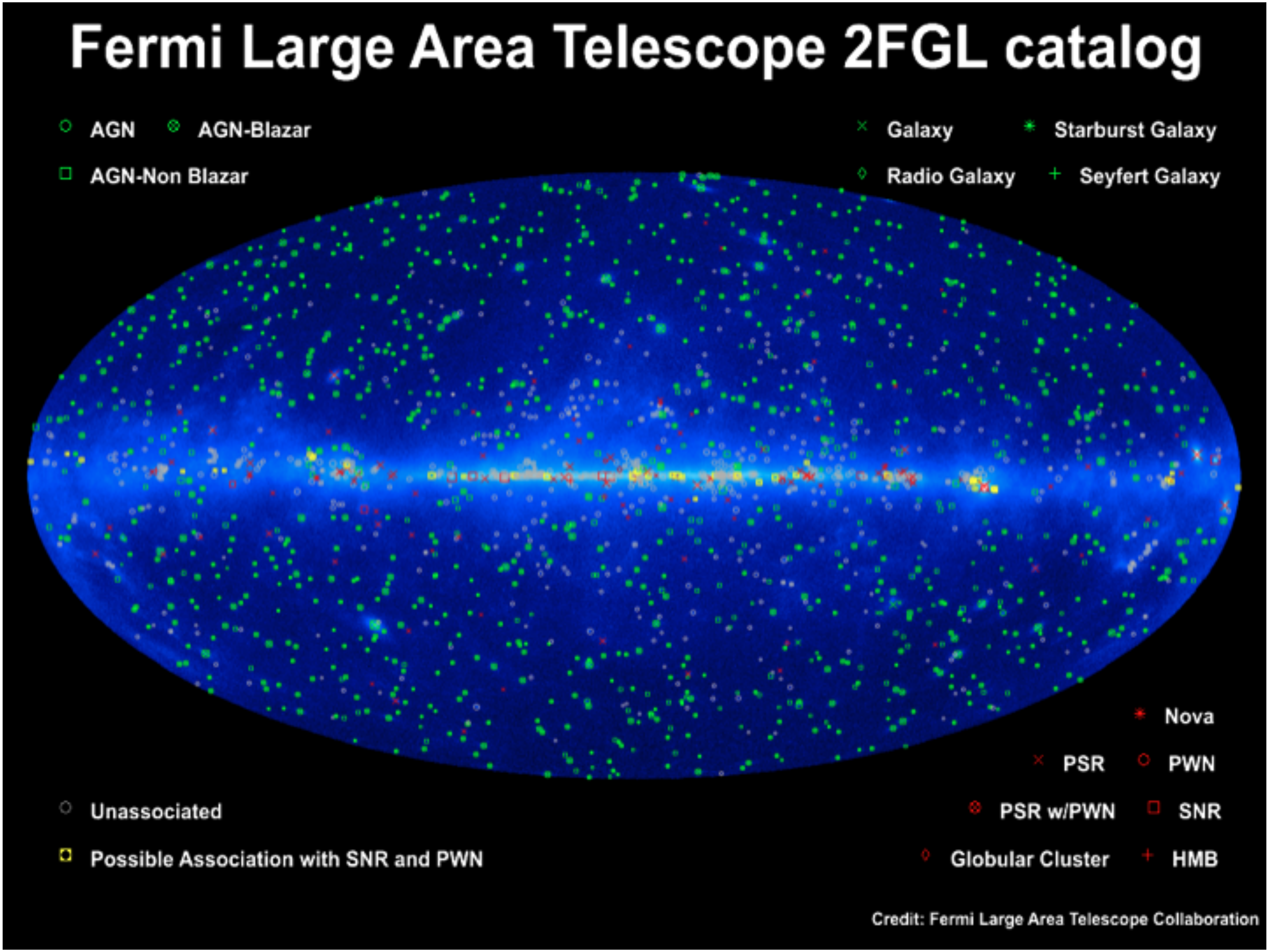
Point Spread Function



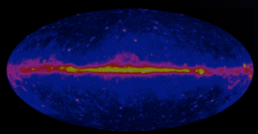
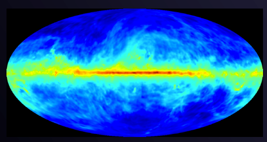
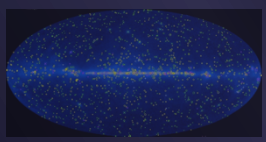
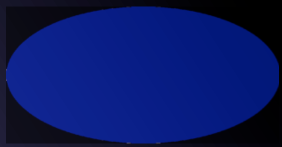
THE GAMMA-RAY SKY above 1 GeV

5 years of Fermi LAT data




Fermi Large Area Telescope 2FGL catalog
AGN
AGN-Blazar
AGN-Non Blazar
Galaxy
Starburst Galaxy
Radio Galaxy
Seyfert Galaxy
Nova
PSR
PWN
PSR w/PWN
SNR
Globular Cluster
HMB
Unassociated
Possible Association with SNR and PWN
Credit: Fermi Large Area Telescope Collaboration

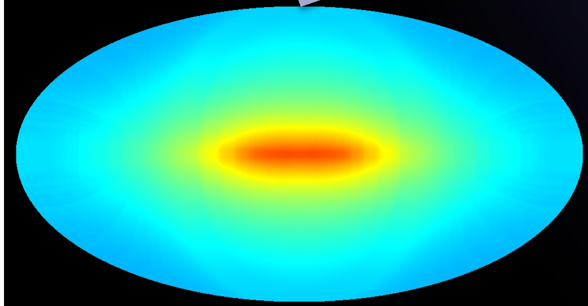
The complexity of the (Fermi) gamma-ray sky

 =  +  +  + ???

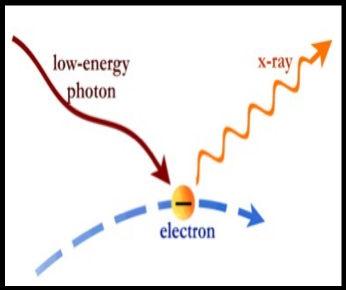
Galactic

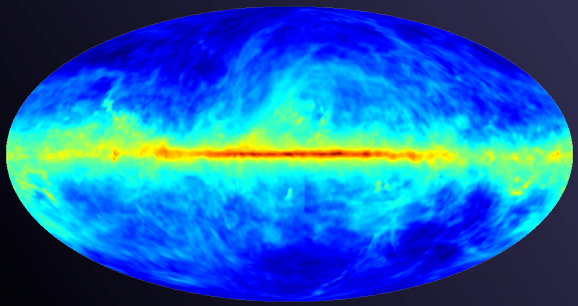
Point Sources

Isotropic

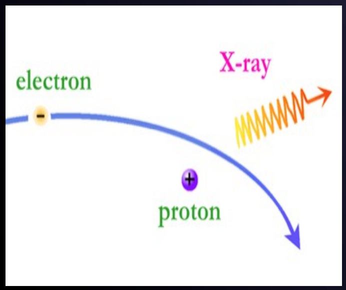


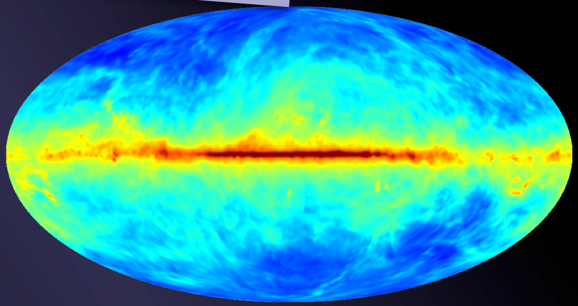
Inverse Compton



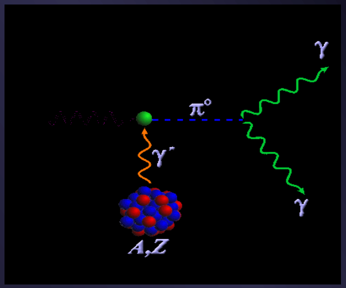


Bremsstrahlung



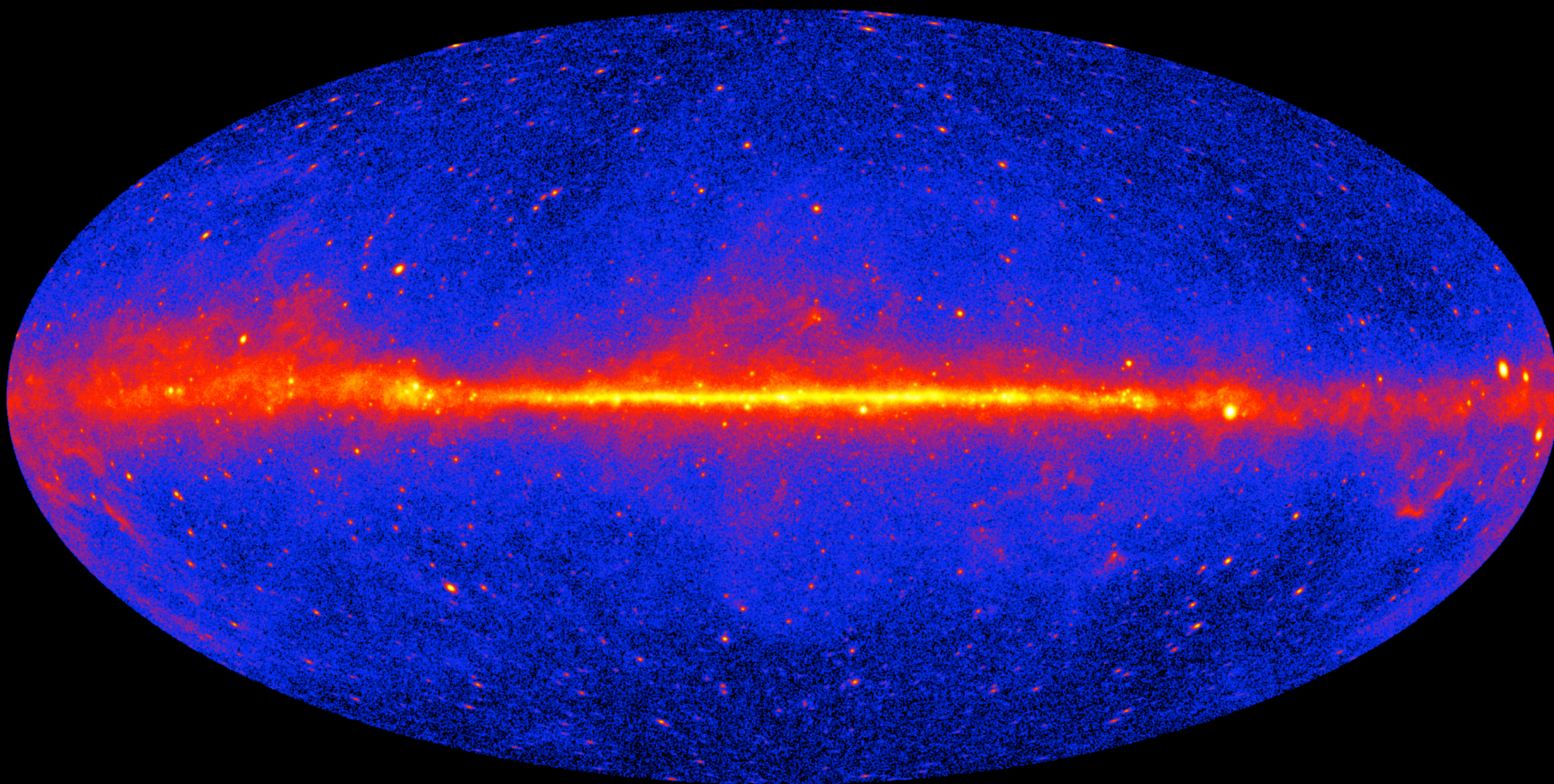


π^0 decay

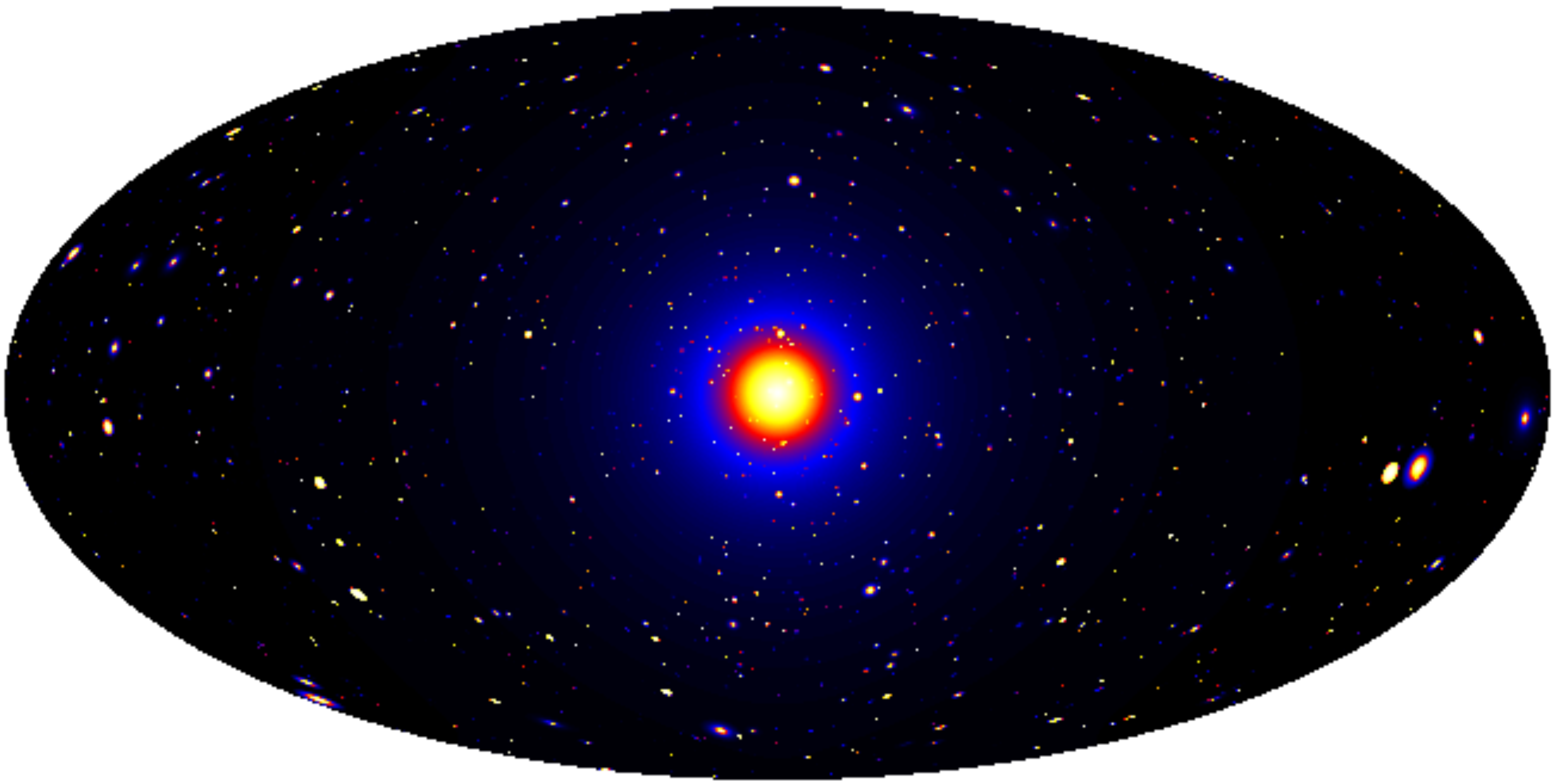


THE GAMMA-RAY SKY above 1 GeV

5 years of Fermi LAT data



The DM-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.

Dark Matter Search Strategies

Satellites

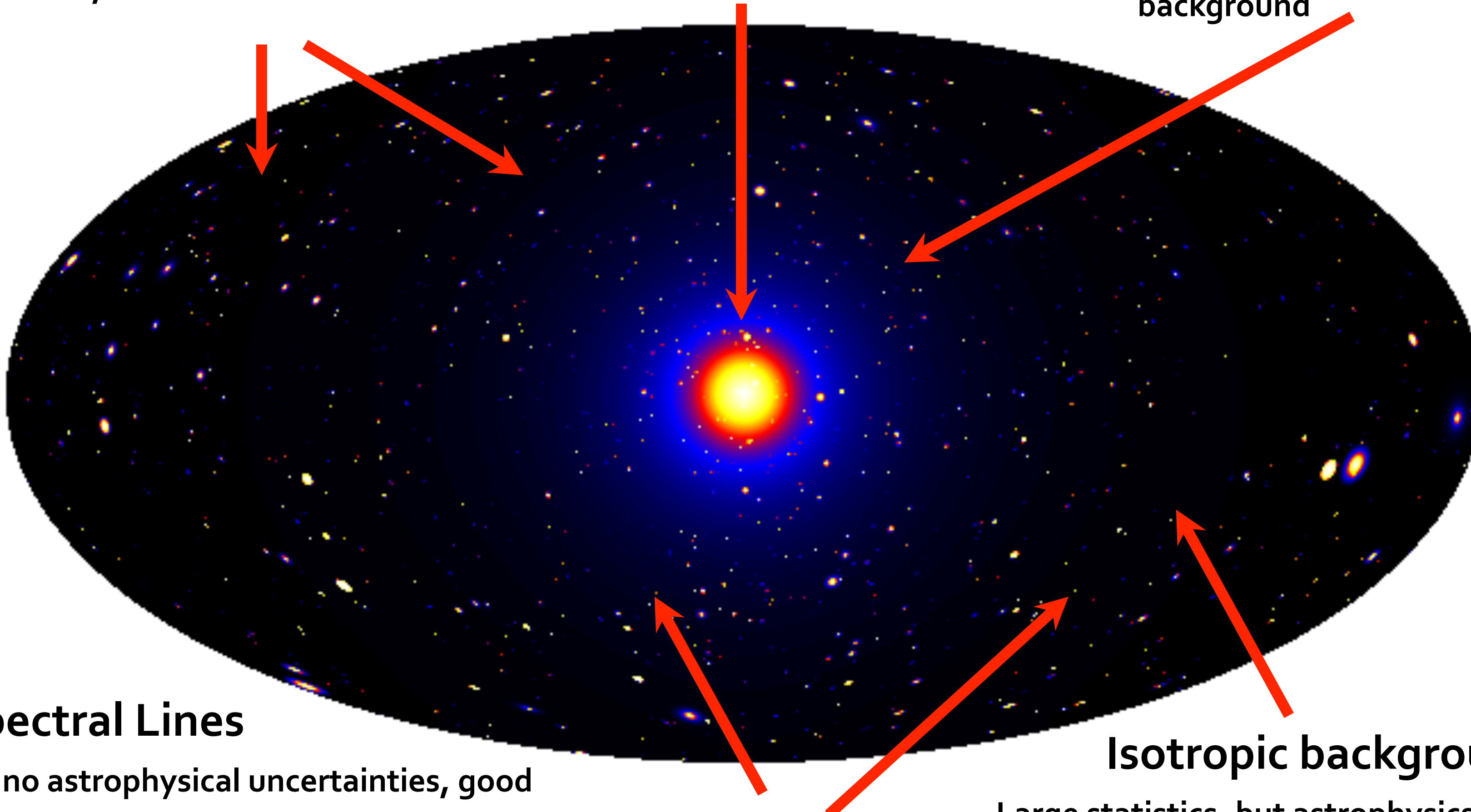
Low background and good source id, but low statistics

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. Astrophysical contamination

Isotropic background

Large statistics, but astrophysics, galactic diffuse background

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

HIGHLIGHTS

[FROM RECENT LAT WORK]

Dwarf satellite galaxies

Smith High Velocity Cloud

Isotropic Background

+ Line searches?

Dark Matter Search Strategies

Satellites

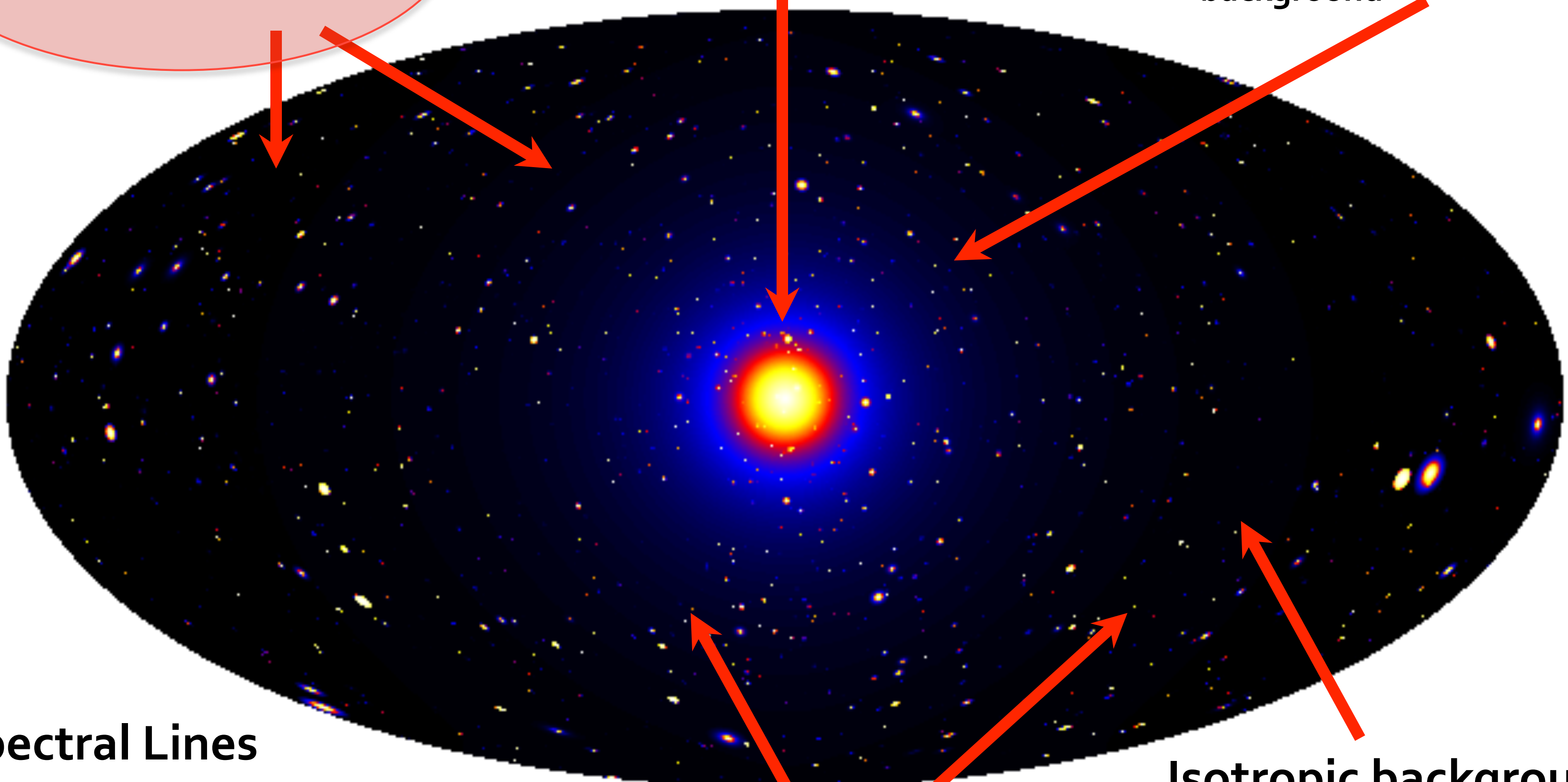
Low background and good source id, but low statistics

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. Astrophysical contamination

Isotropic background

Large statistics, but astrophysics, galactic diffuse background

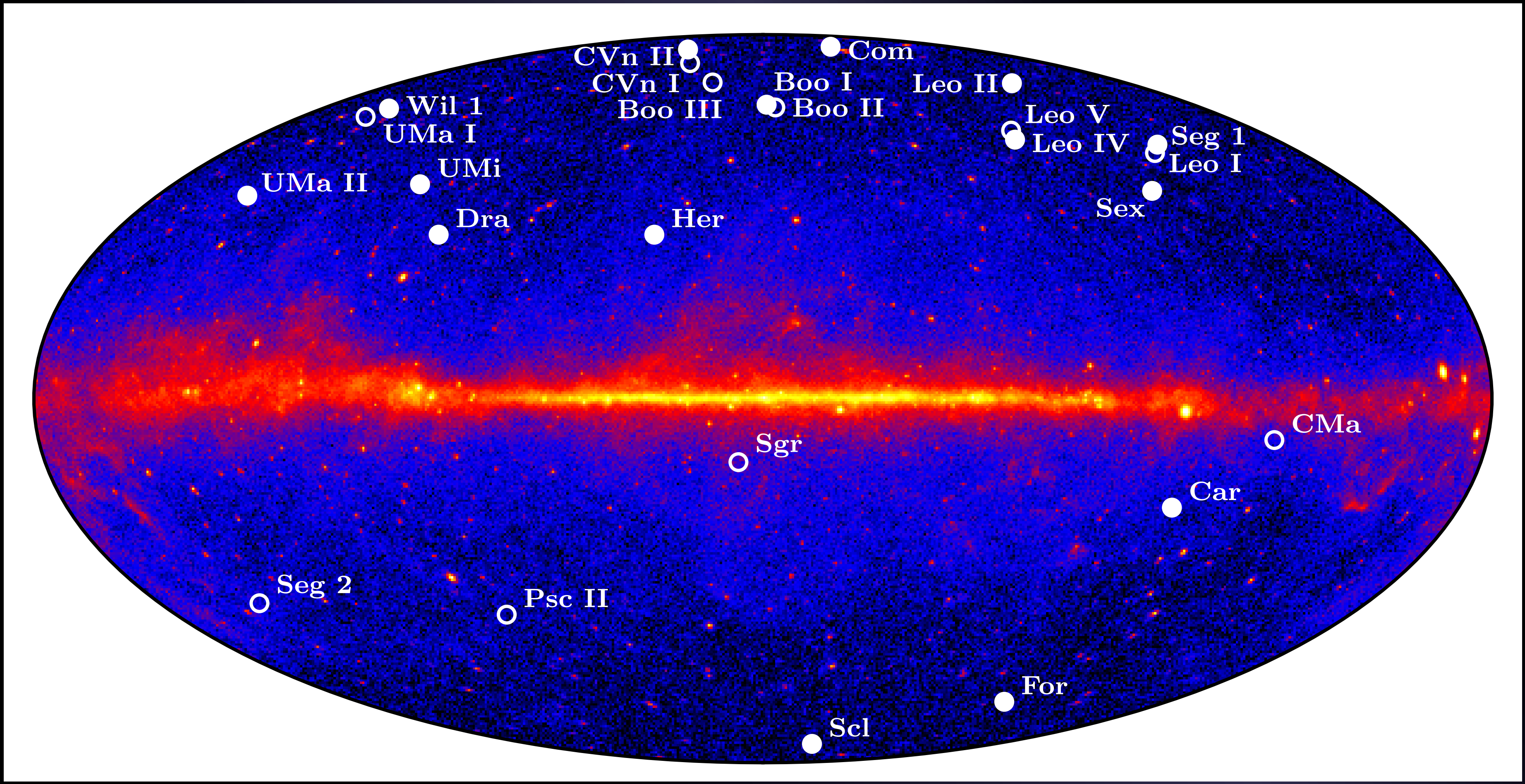
Dark Matter simulation: Pieri+(2009) arXiv:0908.0195

Dwarf Spheroidal satellite galaxies

- The most DM dominated systems in the Universe.
- Roughly two dozens dwarf spheroidal satellite galaxies of the Milky Way
- Several of them closer than 100 kpc from us
- Most of them expected to be free from any bright astrophysical gamma source.

  (Low content in gas and dust.)

‘Fermi dwarfs’

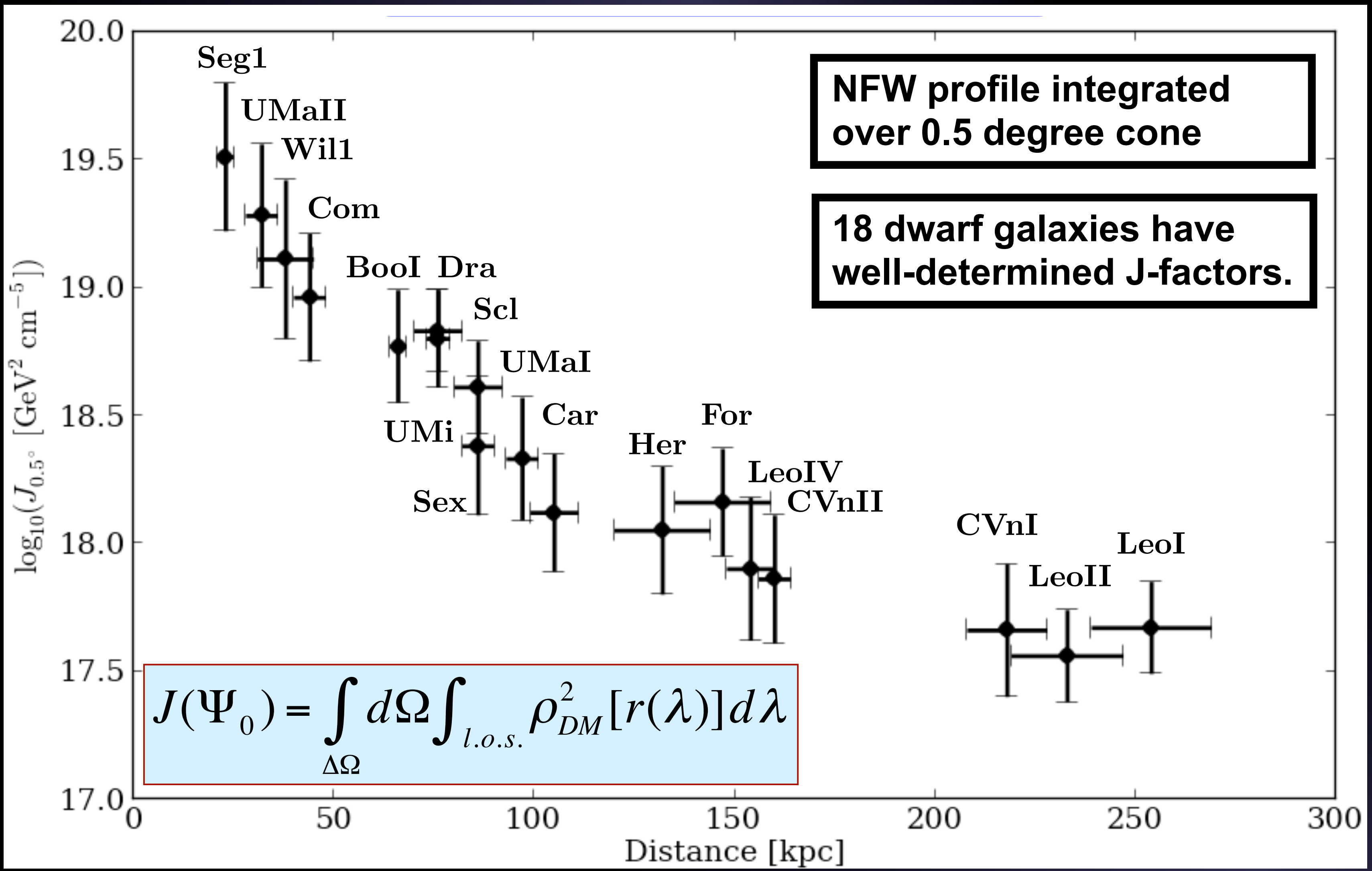


Ackermann+14 [astro-ph/1310.0828]

15 dwarfs analyzed

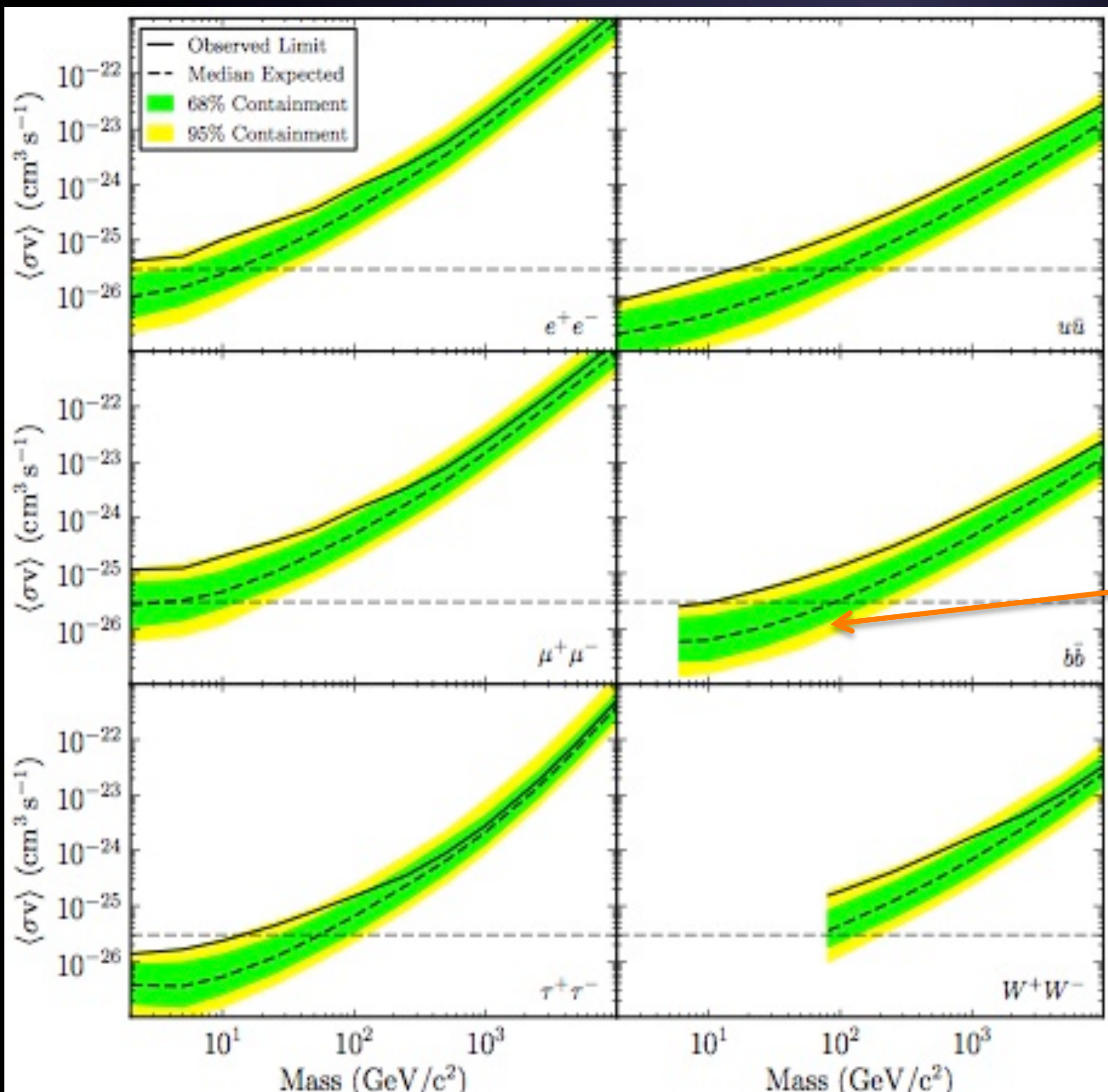
The higher the latitude the better in terms of astro foregrounds

Dwarf Galaxies' J-Factors



A.Drlica-Wagner DPF 2013

Combined limits at 95% C.L.



Joint likelihood analysis of 15 dwarf galaxies

4 years of data, 500 MeV – 500 GeV

J-factor uncertainties accounted for

Expected sensitivity calculated from the data:

- 300 realizations at 5 random sky positions
- High Galactic lat (|b|>20º)
- >1˚ from LAT catalog sources

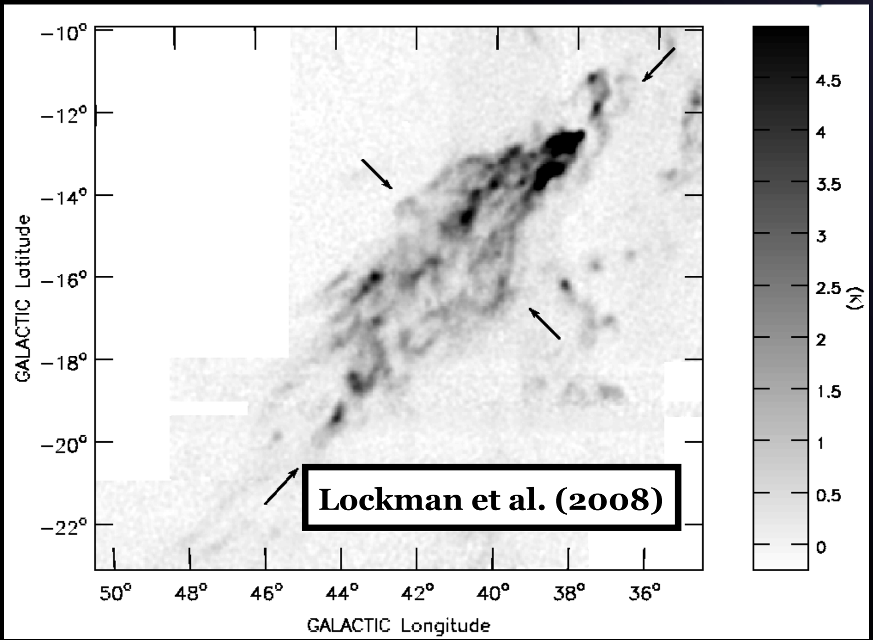
Largest excess (TS = 8.7) for 25 GeV WIMP to bb

Ackermann+14 [astro-ph/1310.0828]

High Velocity Clouds and DM:

The case of the Smith Cloud

- HVCs are coherent over-densities of HI gas covering 40% of the sky.
- Kinematically distinguishable from the Galactic Disk
- Origin unclear: some could be hosted by DM halos that failed to form galaxies:
  → potential targets for indirect detection of DM .
- Some gamma-rays from cosmic-ray interactions with the HI gas expected.



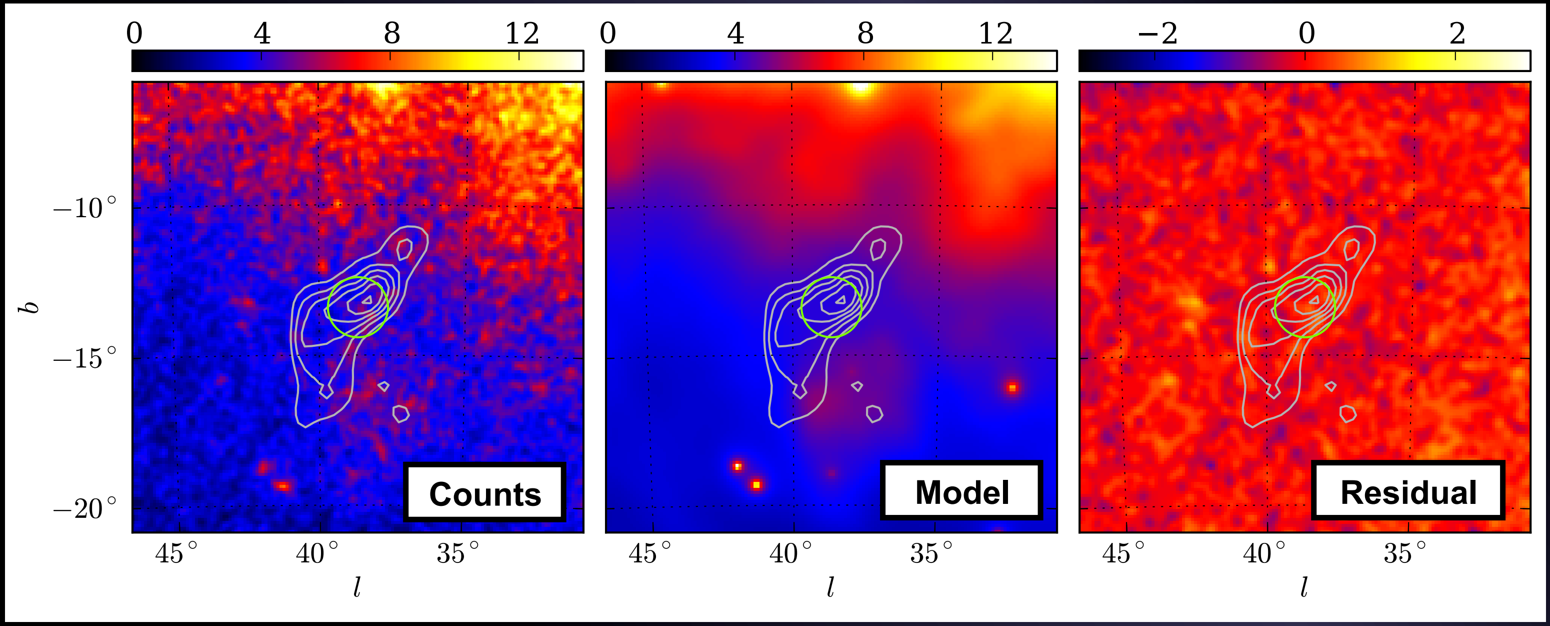
- Smith Cloud one of the best studied HVCs.
- HI gas mass of ~10^6 solar masses.
- 2 times closer than the closest dwarf galaxy
- It may be bounded by DM halo of ~10^8 solar masses (Nichols & Bland-Hawthorn 09) .

LAT analysis

Drlica-Wagner, Gómez-Vargas, Hewitt, Linden, Tibaldo (2014) [astro-ph/ 1405.1030]

Data: 5.2 years of data, Pass7 reprocessed, 500 MeV – 500 GeV

Challenge: very close to the Galactic plane, so diffuse emission modeling critical.



[Drlica-Wagner+14]

Standard Galactic interstellar emission model not used:

- Cloud removed from the model.
- Correct for dark Galactic gas using IR dust maps.
- Build GALPROP templates for generation of diffuse γ-rays.

No significant signal found → DM constraints.

DM constraints from the Smith Cloud

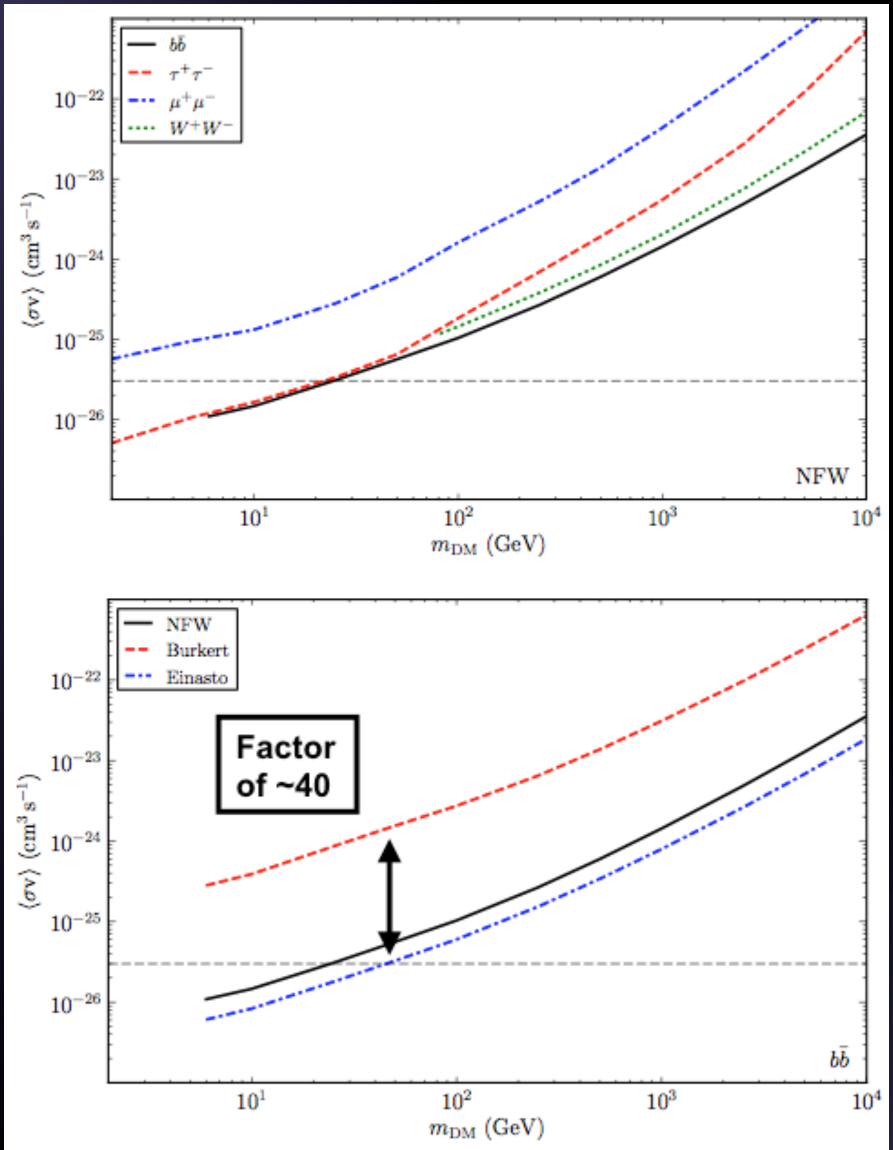
Drlica-Wagner, Gómez-Vargas, Hewitt, Linden, Tibaldo (2014) [astro-ph/ 1405.1030]

4 annihilation channels

3 DM density profiles.

Uncertainties in the DM distribution dominate over other systematic and statistical uncertainties.

Profile	r_s (kpc)	ρ_0 ($M_\odot$ kpc^{-3})	$M_{\rm tidal}$ ($M_\odot$)	J-factor (GeV^2 cm^{-5} sr)
NFW	1.04	3.7×10^7	1.1×10^8	9.6×10^{19}
Burkert	1.04	3.7×10^7	1.3×10^8	4.2×10^{18}
Einasto	1.04	9.2×10^6	2.0×10^8	1.8×10^{20}

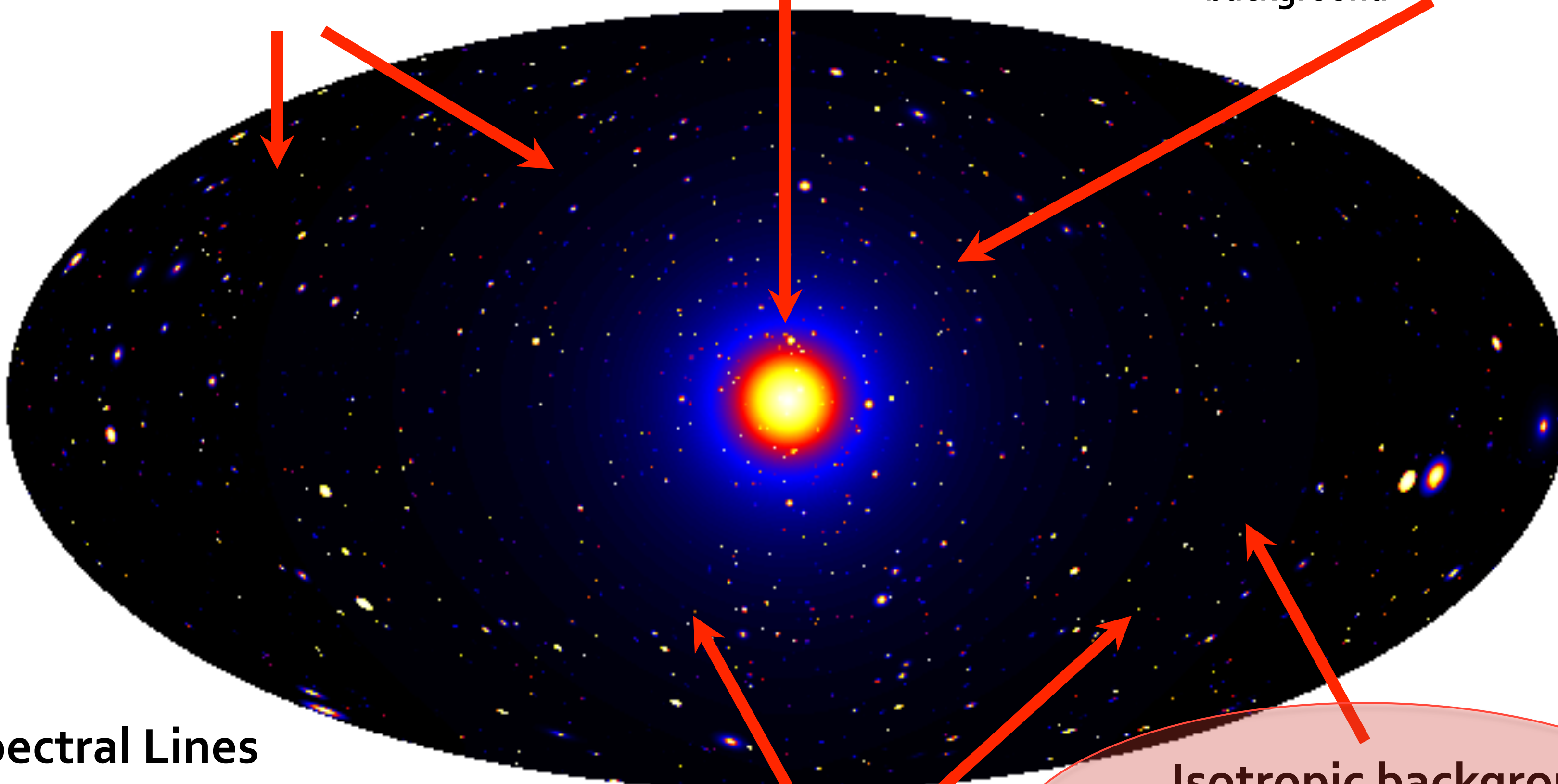


Dark Matter Search Strategies

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

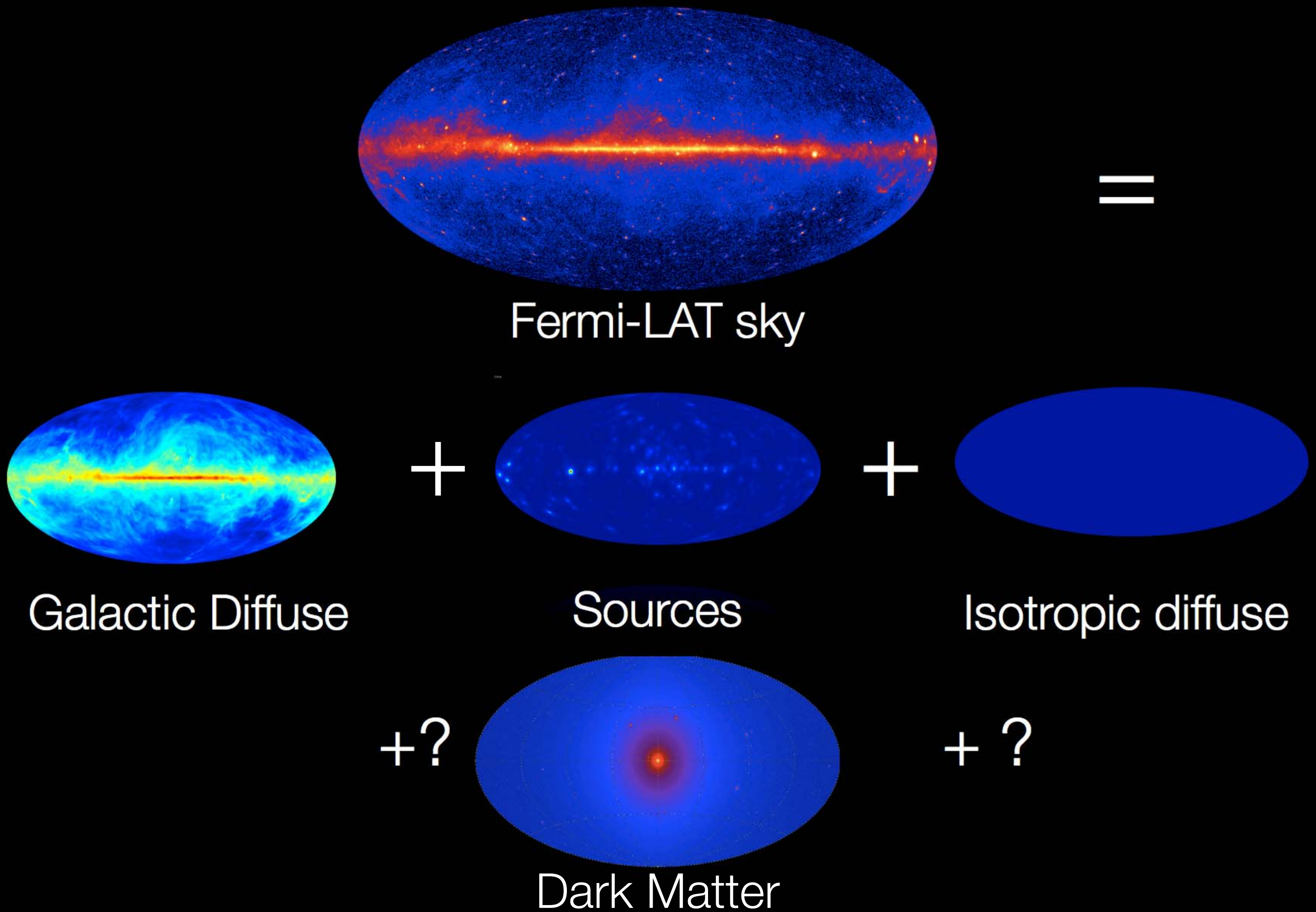


Spectral Lines
Little or no astrophysical uncertainties, good source id, but low sensitivity because of expected small branching ratio

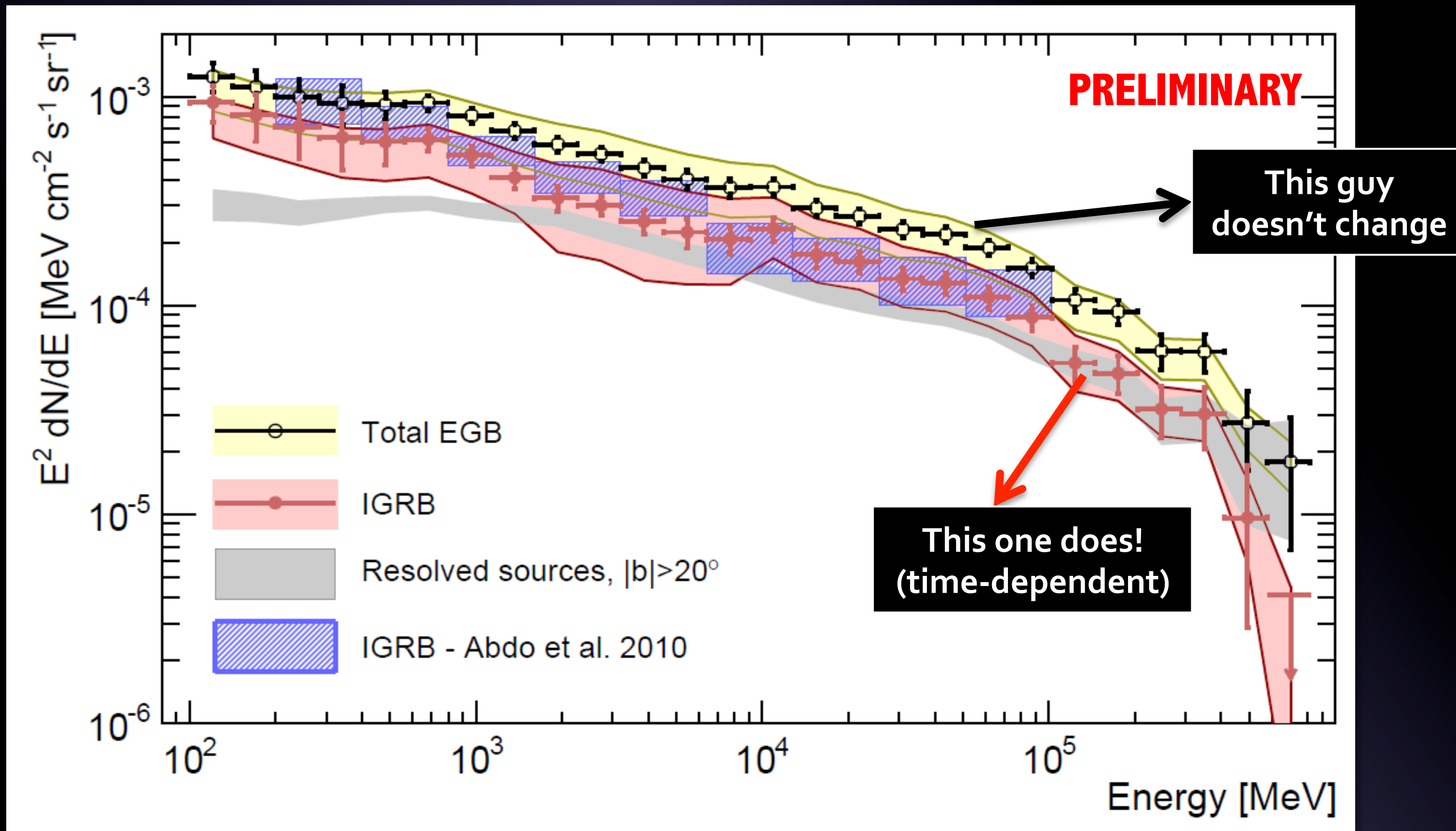
Galaxy Clusters
Low background, but low statistics. Astrophysical contamination

Isotropic background
Large statistics, but astrophysics, galactic diffuse background

The Isotropic Gamma-Ray Background (IGRB)



The brand new Fermi LAT IGRB spectrum



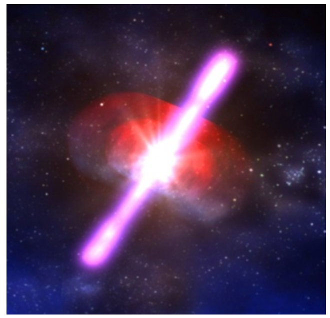
- **Extended energy range**: 200 MeV – 100 GeV ➔ 100 MeV – 820 GeV
- **Significant high-energy cutoff feature in IGRB spectrum,** consistent with simple source populations attenuated by EBL
- **~50% of total EGB above 100 GeV now resolved into individual LAT sources**

Origin of the Extragalactic Gamma-ray Background (EGB)

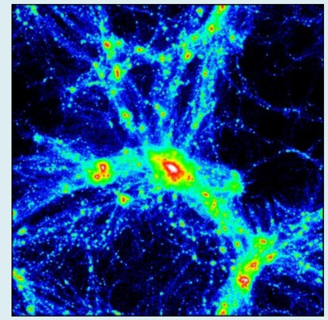
in the LAT energy range

[EGB == IGRB + individually resolved extragalactic sources]

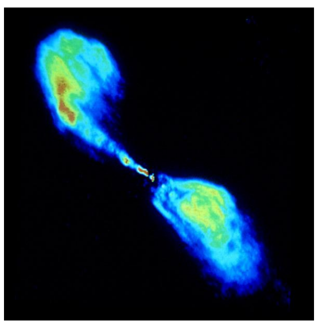
Blazars



GRBs



Dark matter annihilation / decay
(upper limits)

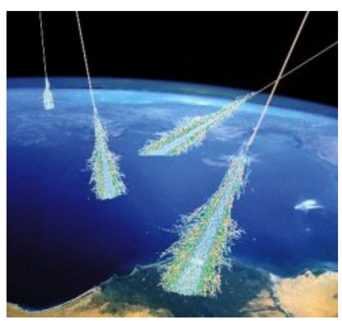


Radio galaxies

Galaxy clusters
(upper limits)

Unknown sources / processes

Star-forming galaxies



Cascades
(upper limits)

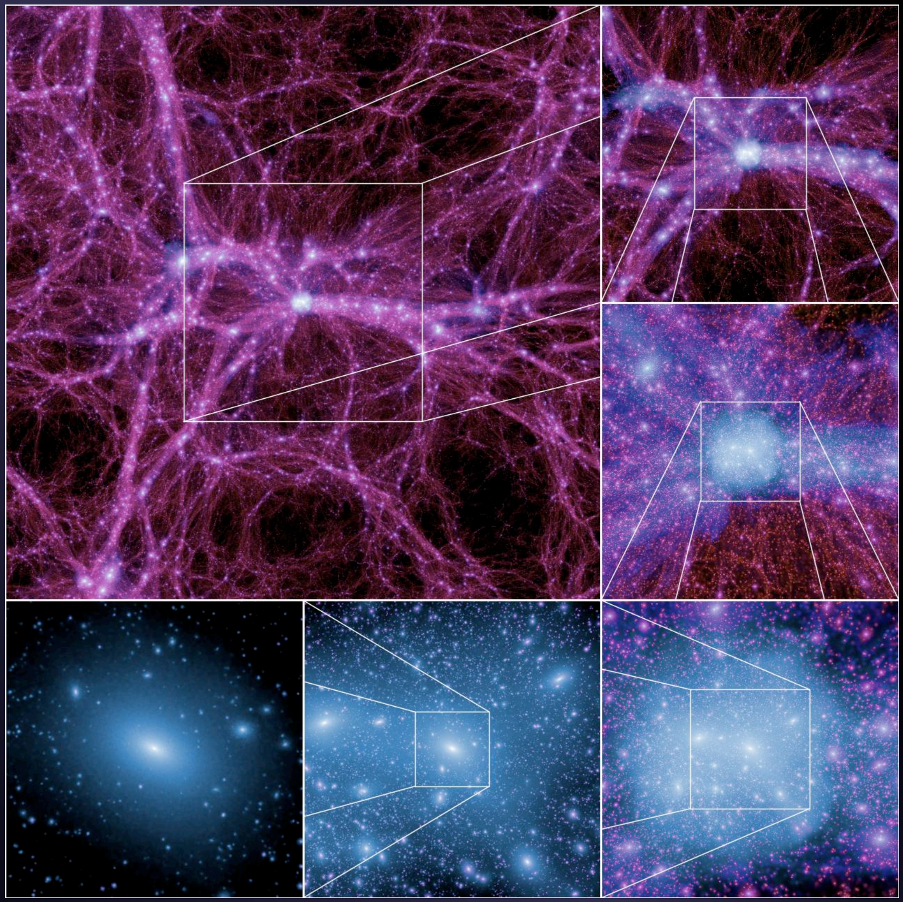
Cosmological DM annihilation

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 makes lower redshifts ($z \leq 2$) to 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

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

WIMP annihilation cross-section

EBL attenuation (Domínguez+11)

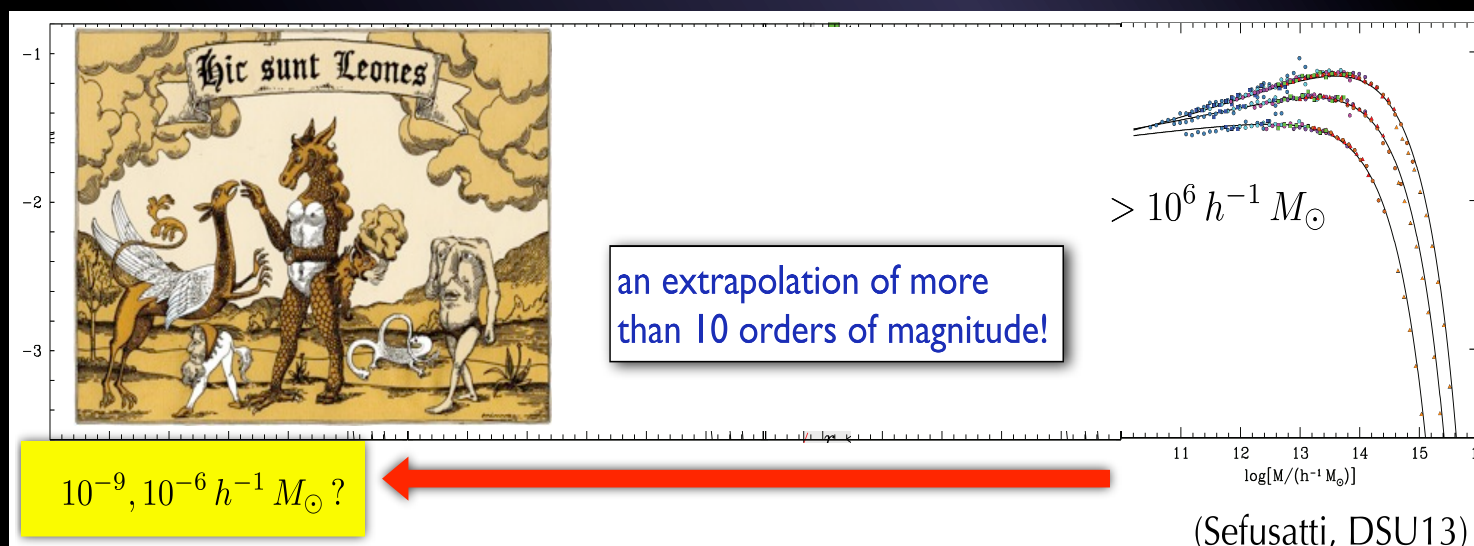
"Flux multiplier"

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!

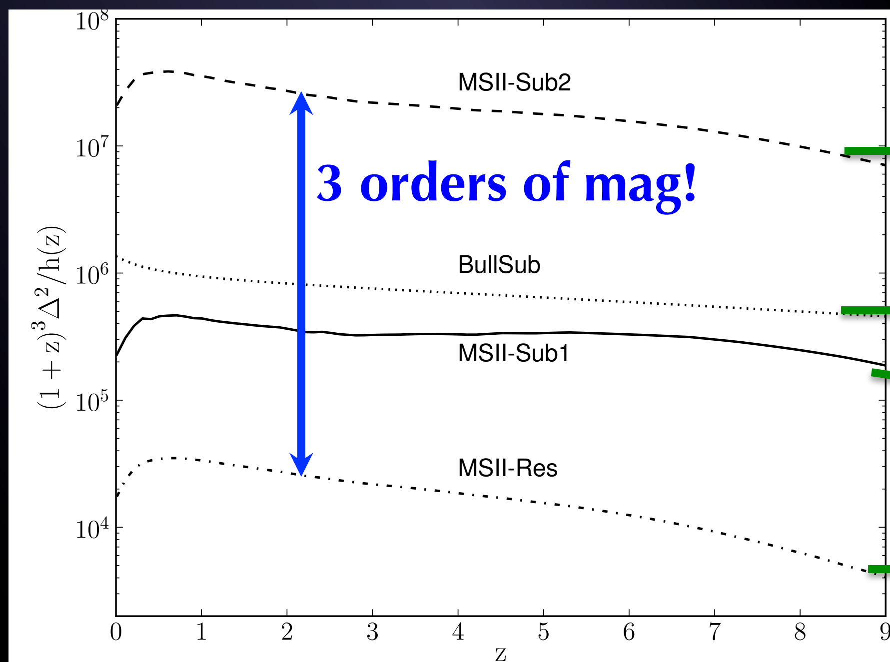
Simulations do not resolve the whole hierarchy of structure formation…



(Sefusatti, DSU13)

Previously, this was the common picture:

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



Abdo+10

Most optimistic c(M) power-law extrapolation

Semi-analytical

Conservative power-law extrapolation

Only resolved halos in MSII

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 ζ(z).

Flux multiplier: approaches

HALO MODEL (HM)

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

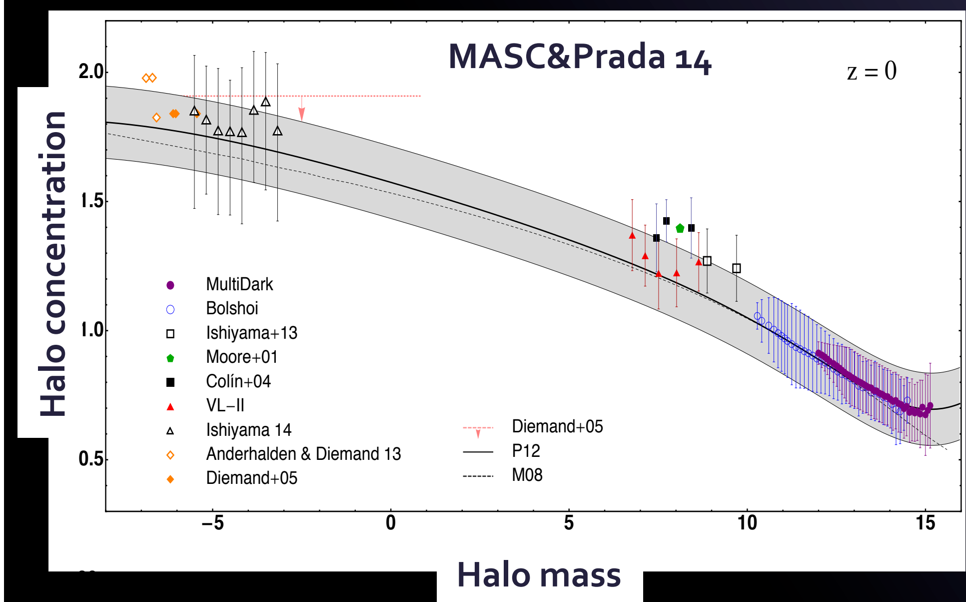
→ OUR BENCHMARK MODEL

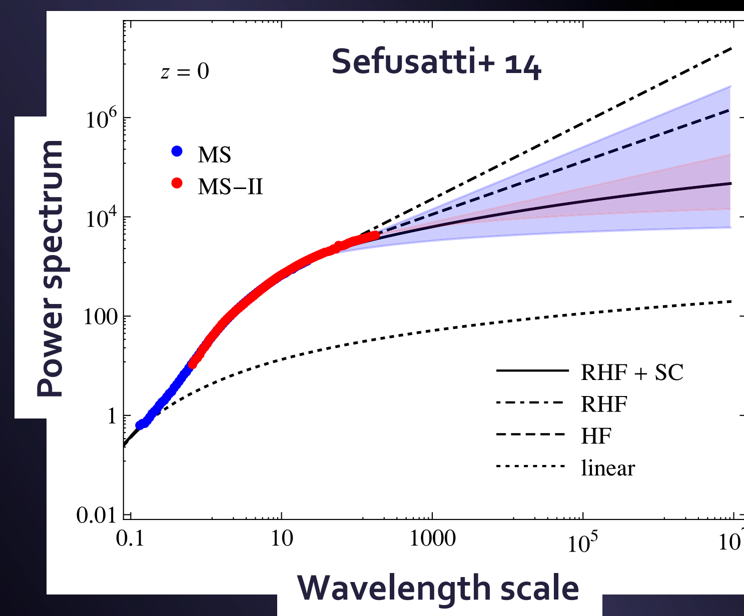
non-linear matter POWER SPECTRUM (PS)

Directly measured in simulations.

→ Good to study uncertainties

(only one quantity extrapolated)

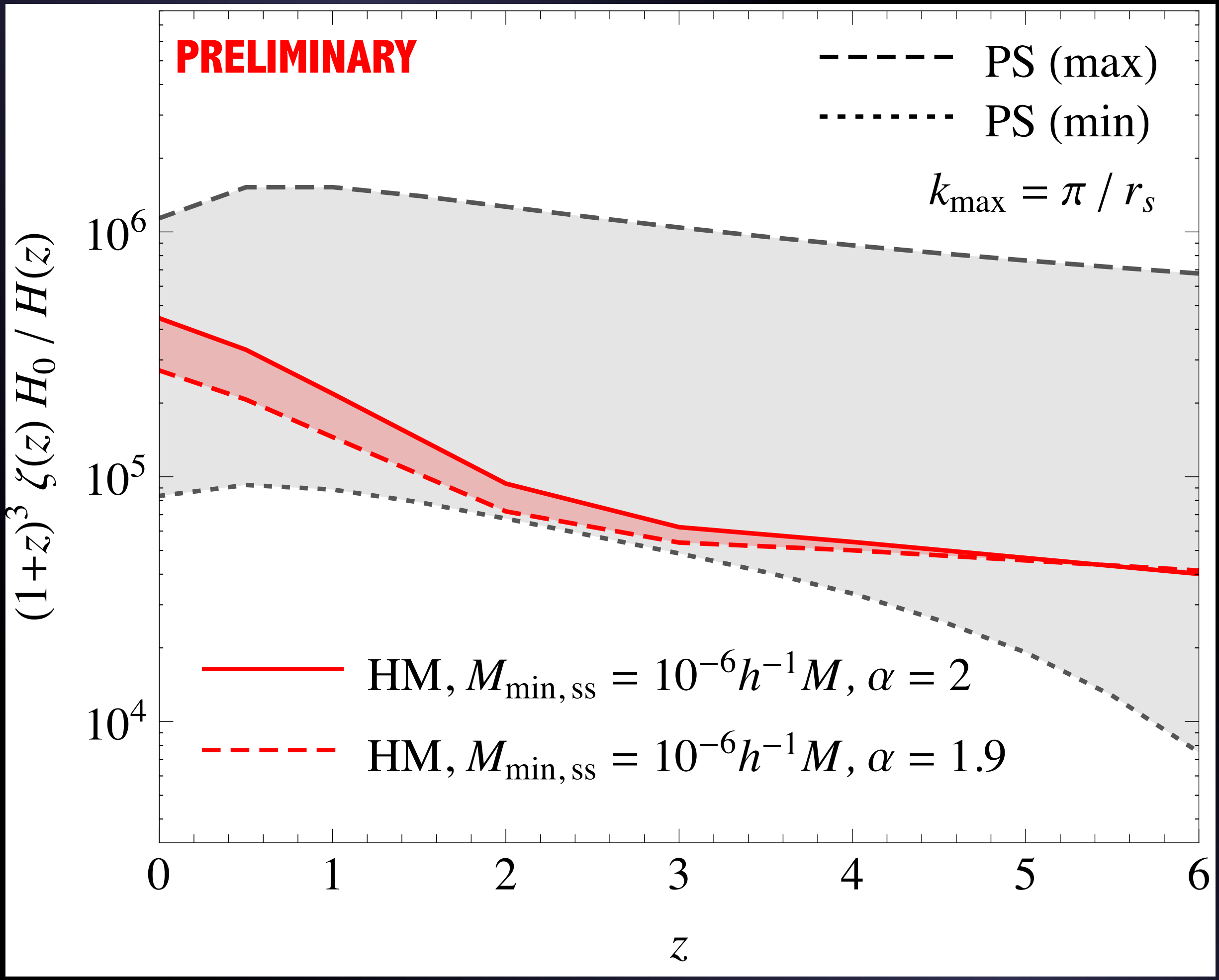




Disclaimer: both approaches use extrapolations over several orders of magnitude down to the smallest predicted mass scales.

HM vs. PS predictions (I) redshift evolution

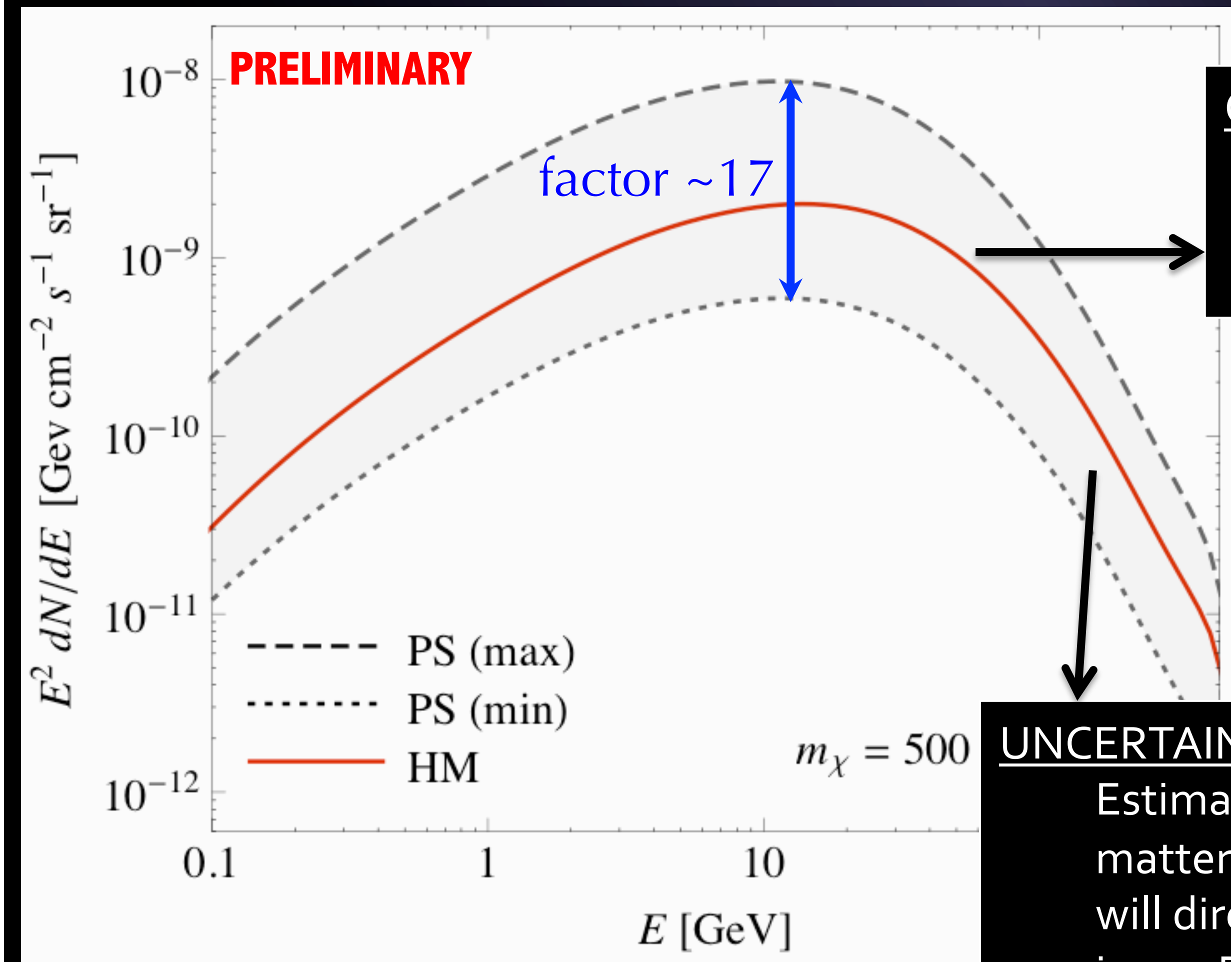
Normalized flux multiplier



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)
(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, *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.

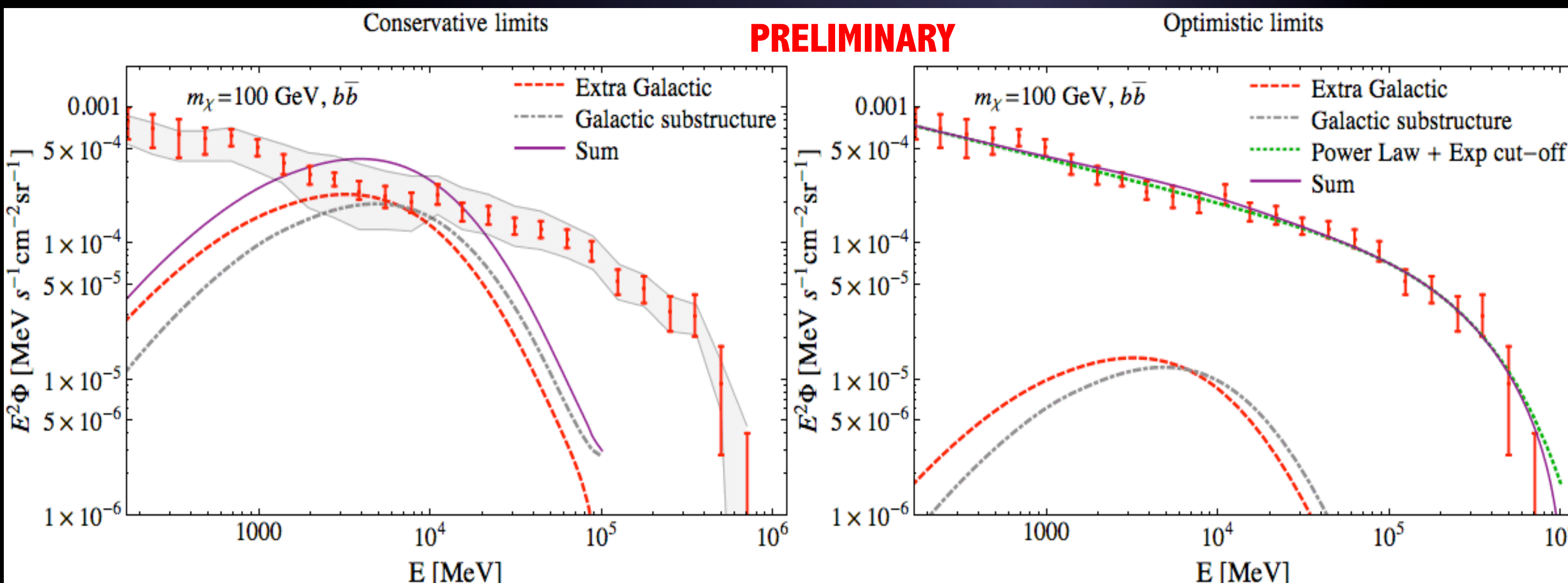
Two substructure scenarios: total Galactic boosts of 3 and 15 [MASC&Prada 14].

Isotropic emission: DM limits

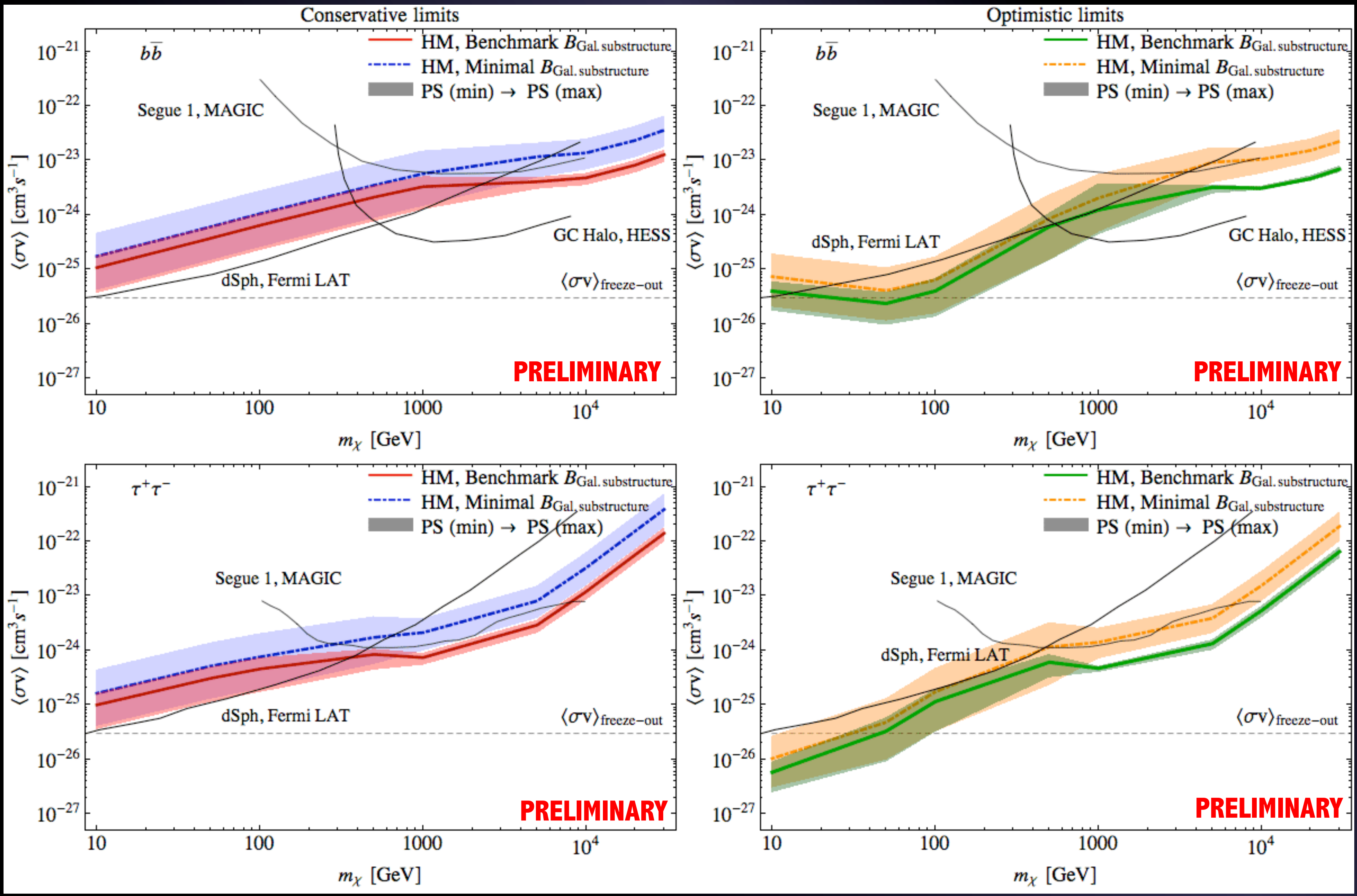
Two types of limits:

→ ***conservative***, no assumed astrophysical (non DM) contributions to the IGRB.
→ ***optimistic***, 100% of the IGRB assumed to be of astrophysical origin.

They should bracket the 'true' DM limits that would come from a precise knowledge of the astrophysical contributions.

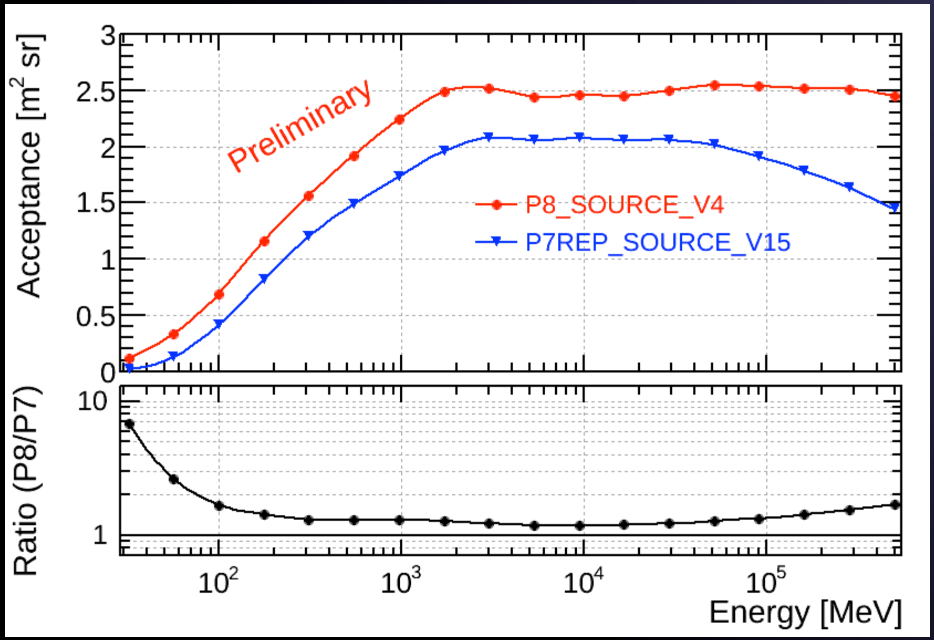


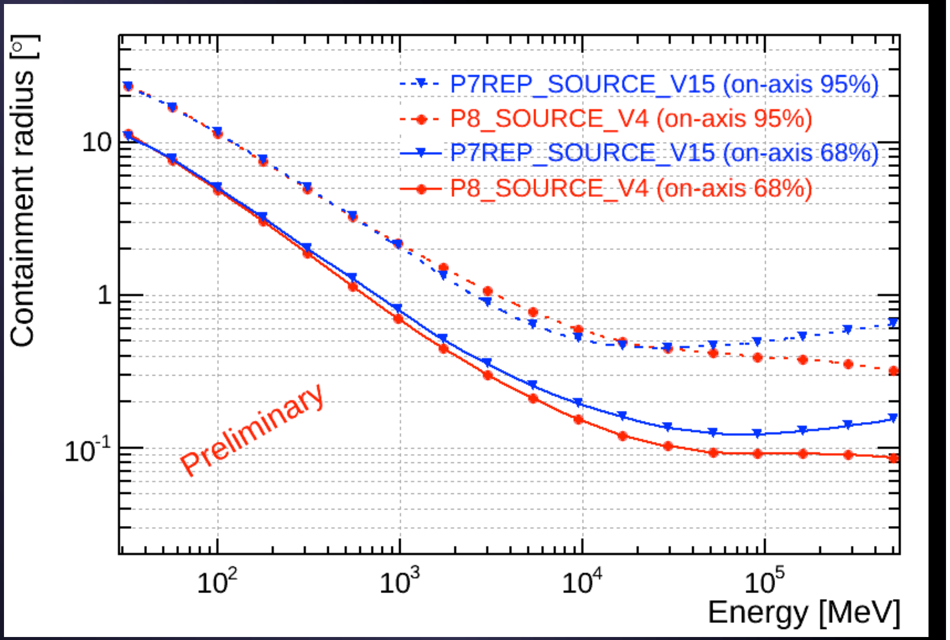
Isotropic emission: DM limits



Franckowiak, Gustafsson, MASC, Zaharijas for the LAT Collaboration, in prep.

THE FUTURE: Pass 8
(a.k.a. improved LAT performance)





Impacts for dark matter:

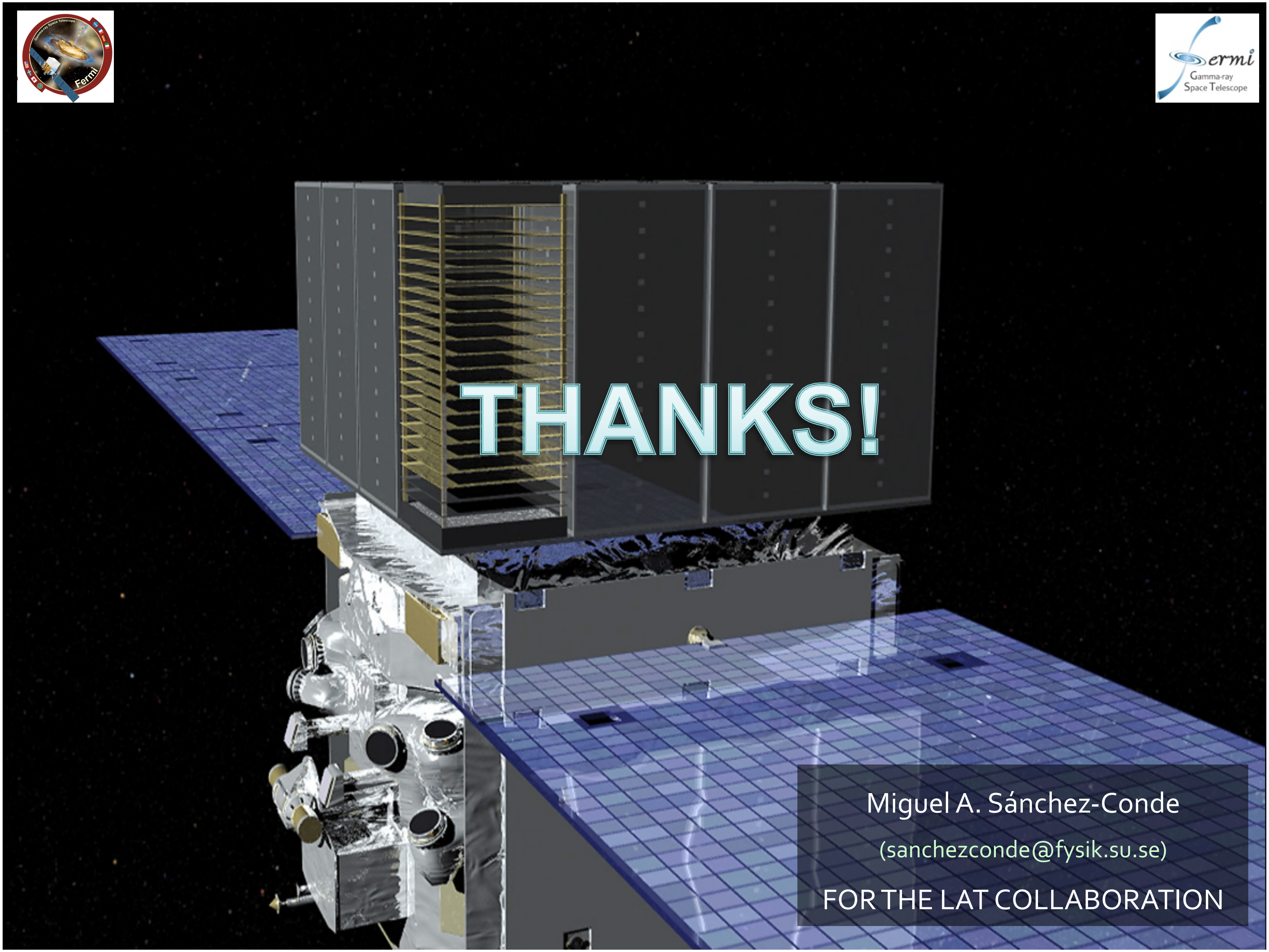
- Increased energy range <==> explore new mass parameter space
- Increased effective area <==> increased flux sensitivity
- Improved angular resolution <==> greater sensitivity to spatially extended sources
- Better background rejection
- New event classes <==> check systematic effects in event selection

Remarks

- ✓ The gamma-ray sky is a complicated place
  → critical to know the astrophysical foregrounds to study the DM case.

- ✓ Different targets observed, different DM scenarios explored.
  → More than 150 Fermi LAT DM-related publications!
  → No gamma-ray signal from DM annihilation (unequivocally) detected up to now.
  → LAT constraints beginning to rule out some interesting areas of parameter space for WIMP masses below ~30 GeV.

- ✓ Further improvements are on the way (a.k.a. Pass 8).
  → especially relevant for DM searches.


THANKS!
Miguel A. Sánchez-Conde
(sanchezconde@fysik.su.se)
FOR THE LAT COLLABORATION