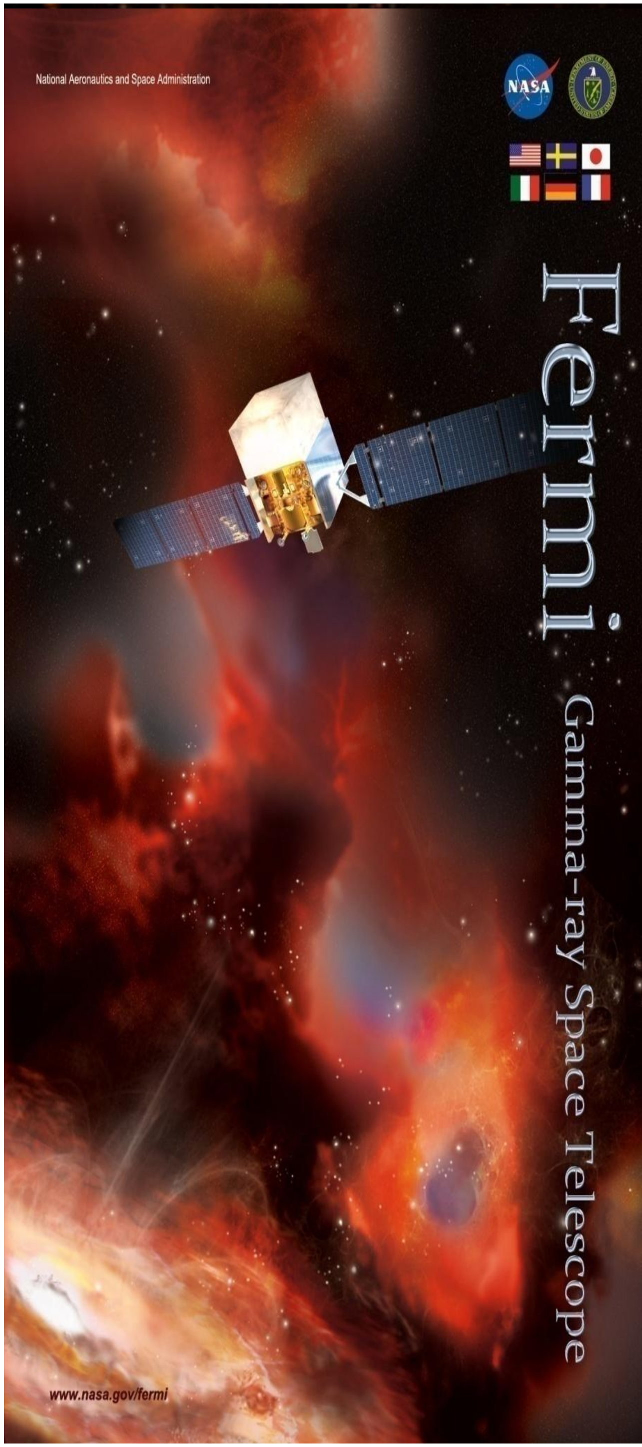


Fermi Gamma-ray Space Telescope

RECENT RESULTS FROM THE *FERMI* GAMMA-RAY SPACE TELESCOPE

Miguel A. Sánchez-Conde

SLAC KIPAC STANFORD UNIVERSITY

ON BEHALF OF THE FERMI LAT COLLABORATION

42nd SLAC Summer Institute, August 4-15, 2014

OBSERVATIONAL EVIDENCE OF DARK MATTER (DM)

Evidences have been reported at different scales.

Galactic scales

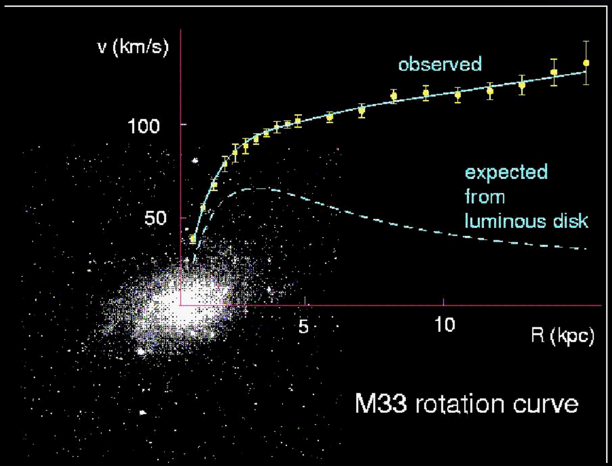
a) Rotation curves of spirals
b) Weak lensing
c) Velocity dispersions of satellite galaxies
d) Velocity dispersions in dSphs

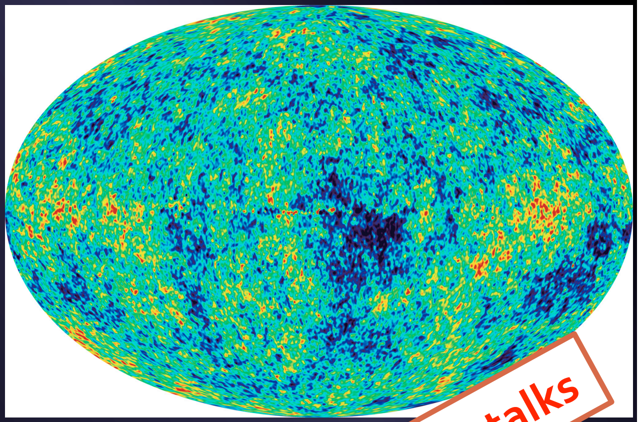
Galaxy clusters scales

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

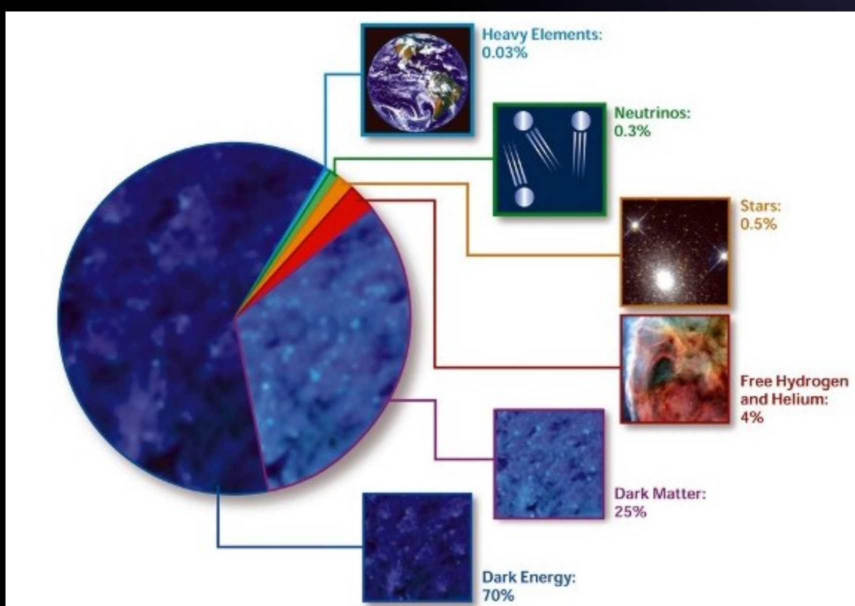


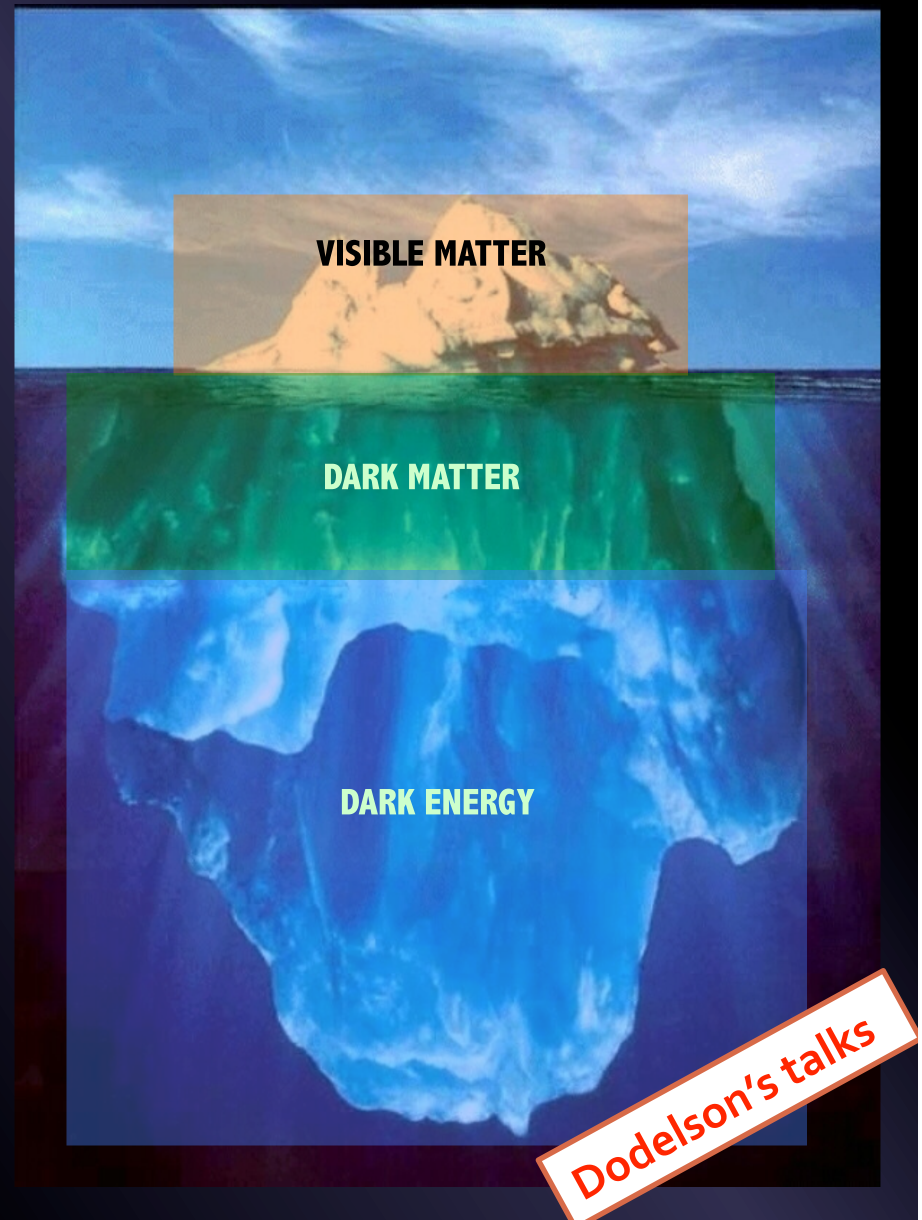


Strigari's talks

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.



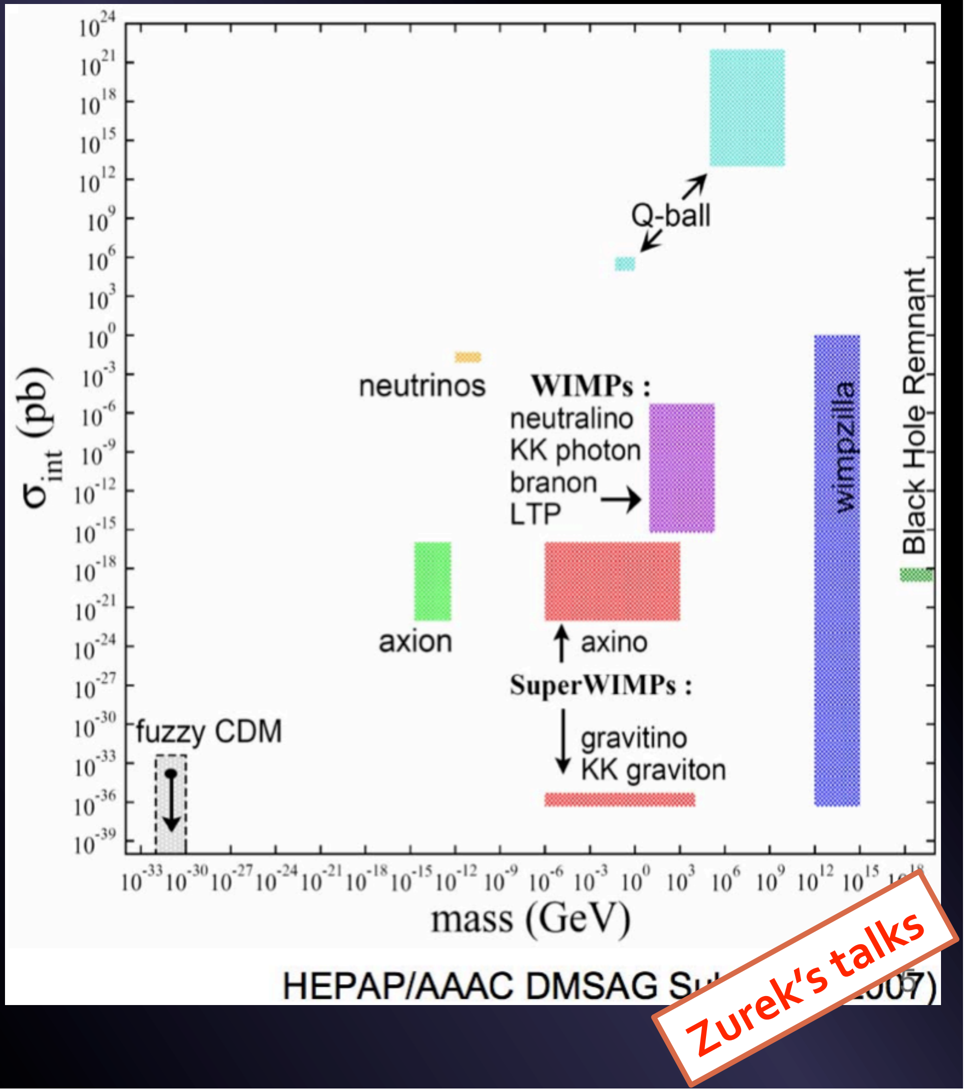


What could the DM be made of?

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



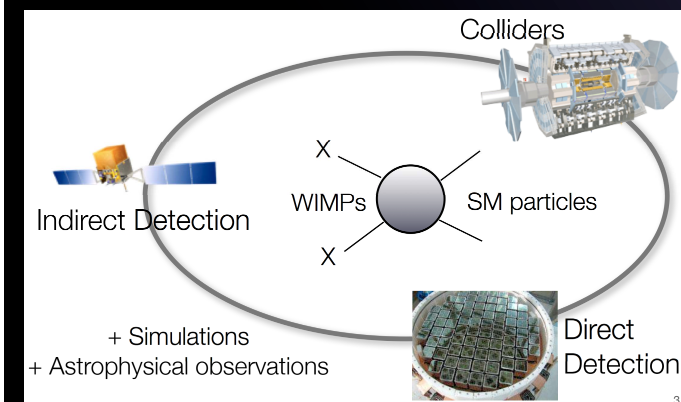
- No viable candidate in the Standard Model
  - ✓ The neutrino, the only non-baryonic DM candidate known to exist, is excluded.
- Huge plethora of possible candidates beyond the Standard Model

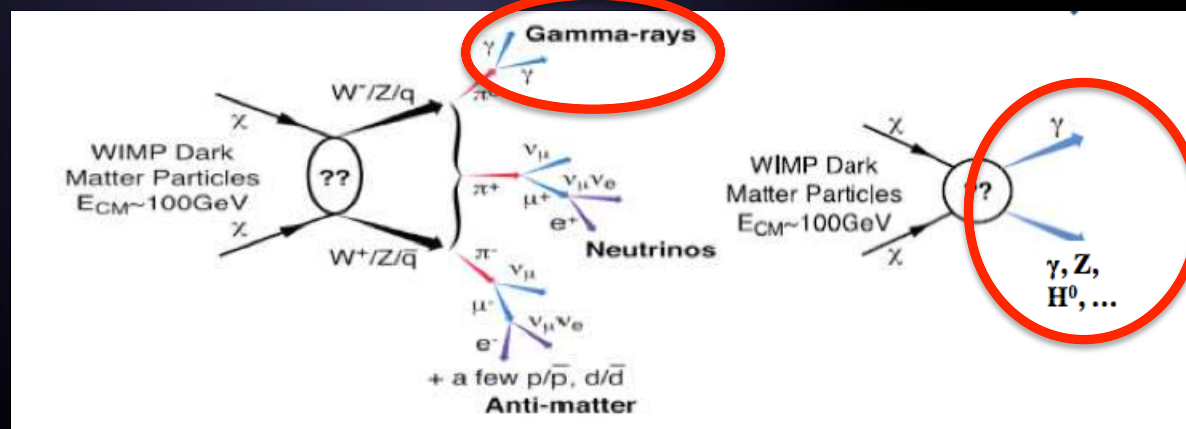
Gamma-rays from dark matter annihilations

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.

Siegal-Gaskins' talks

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

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...

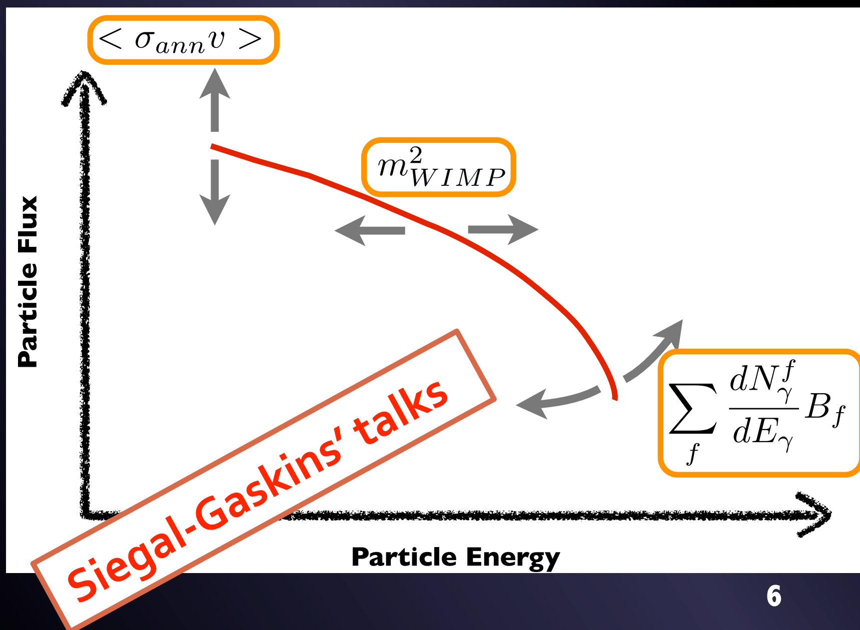
Particle physics

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

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

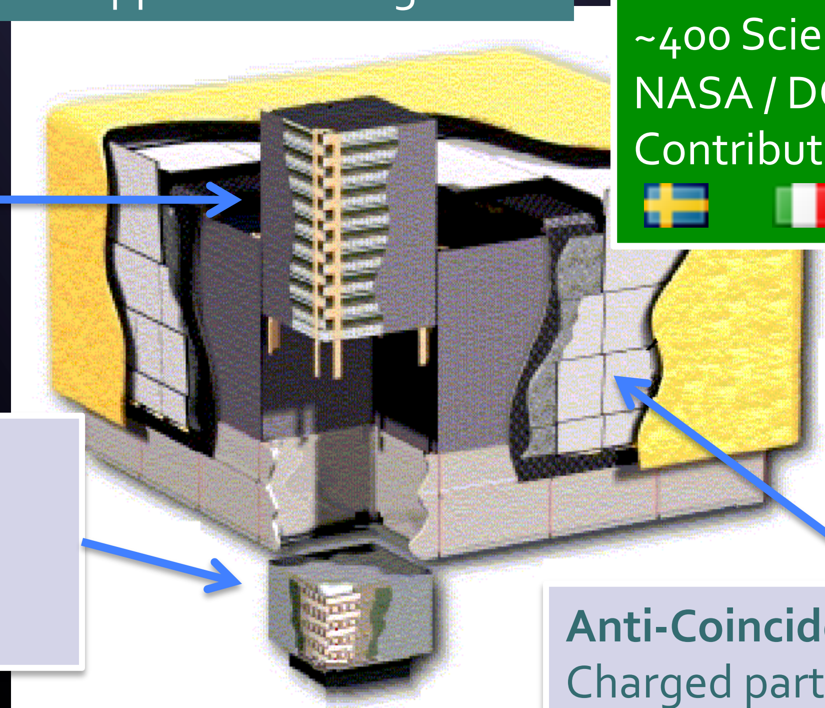
Siegal-Gaskins' talks

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

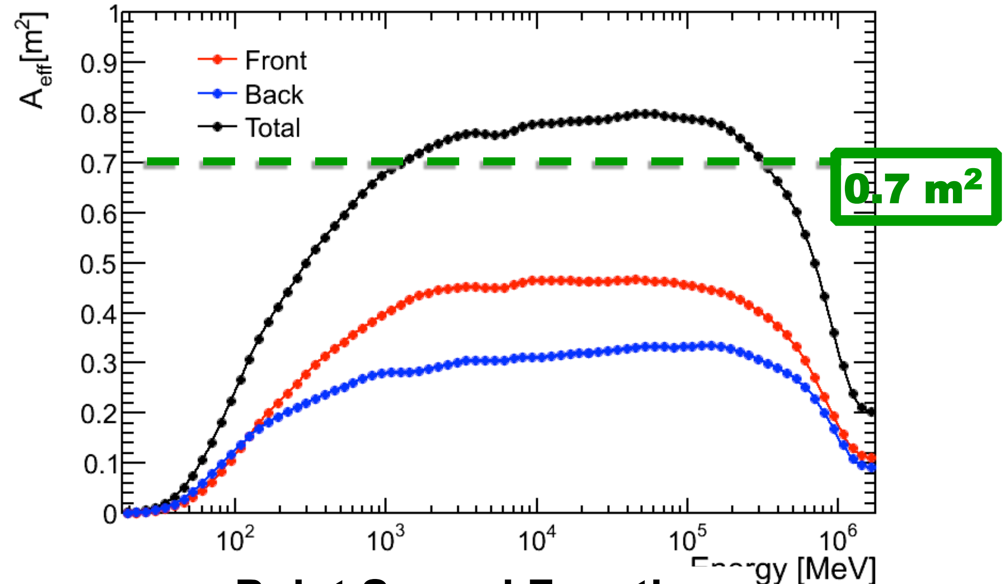
Trigger and Filter:
Reduce data rate from ~10kHz to 300-500 HZ

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

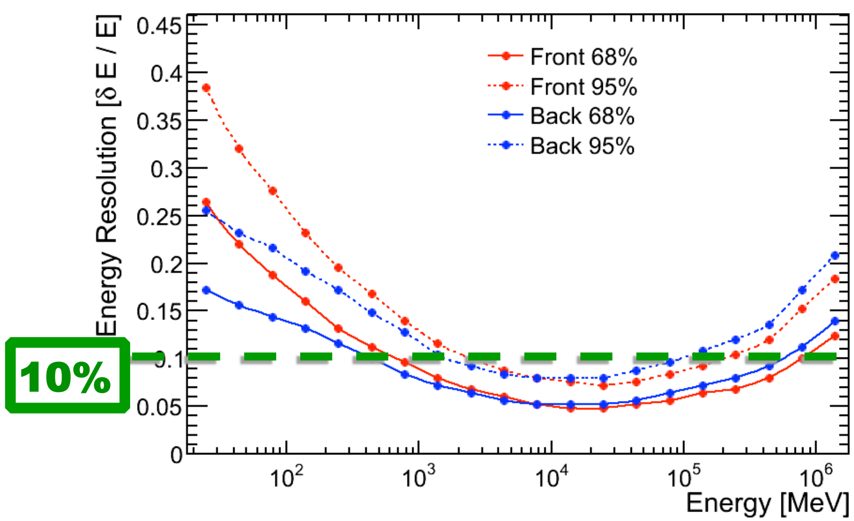
Fermi-LAT performance

All-Sky Coverage

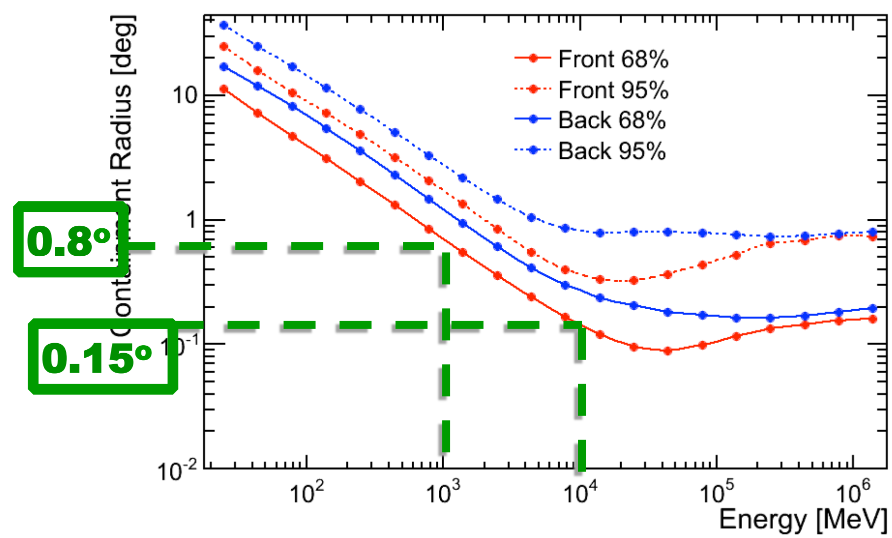
Effective Area



Energy Resolution

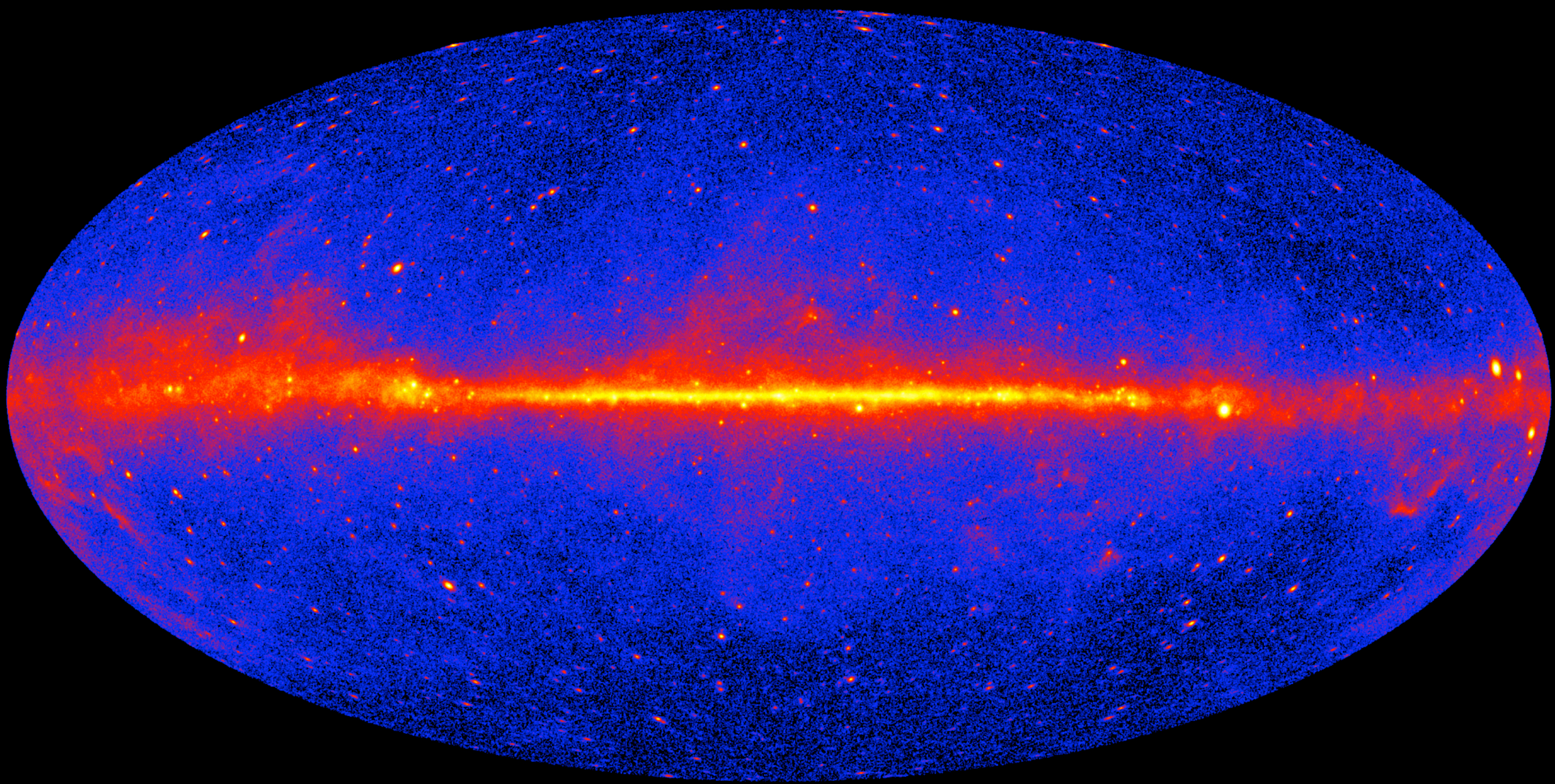


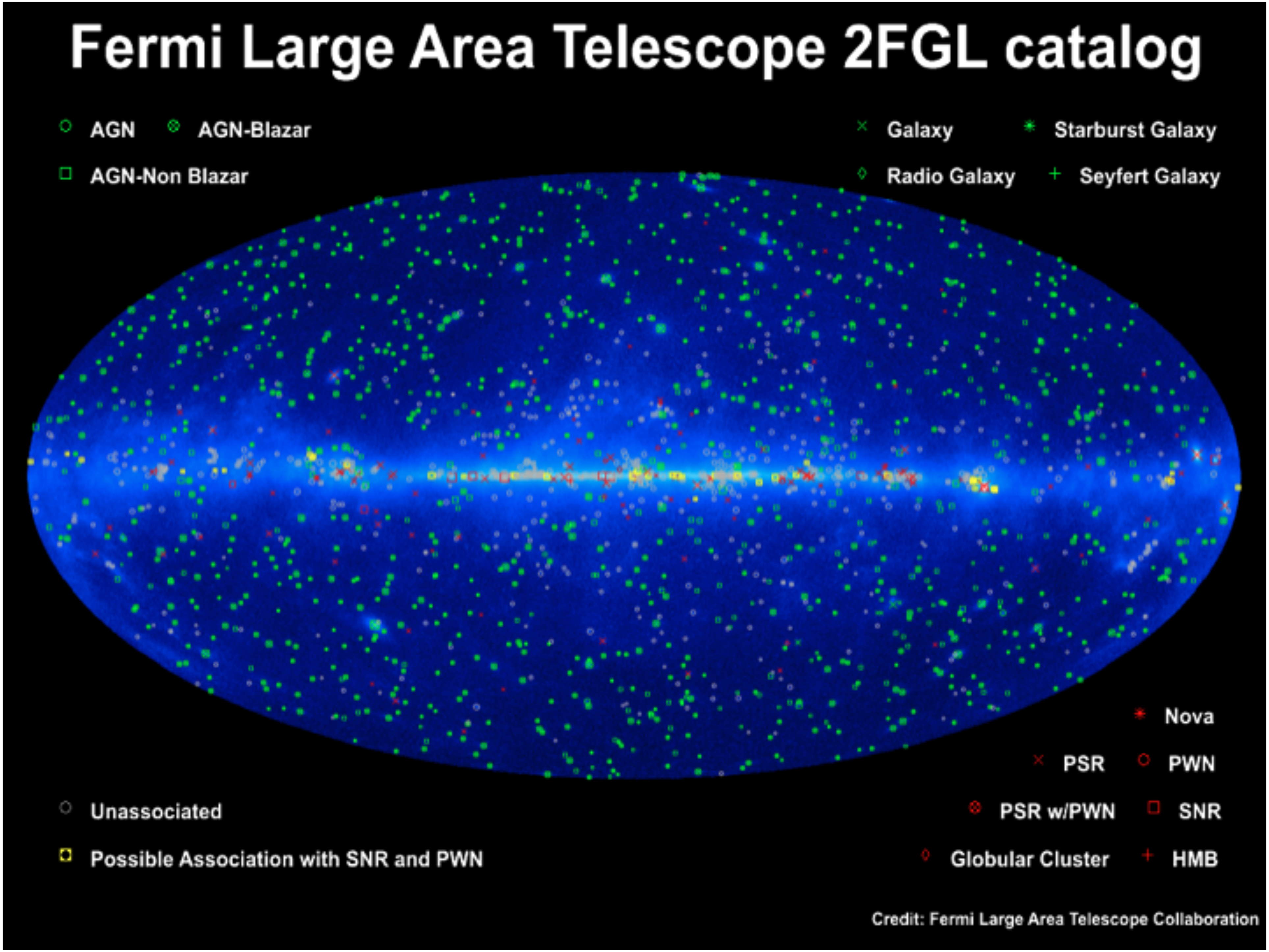
Point Spread Function



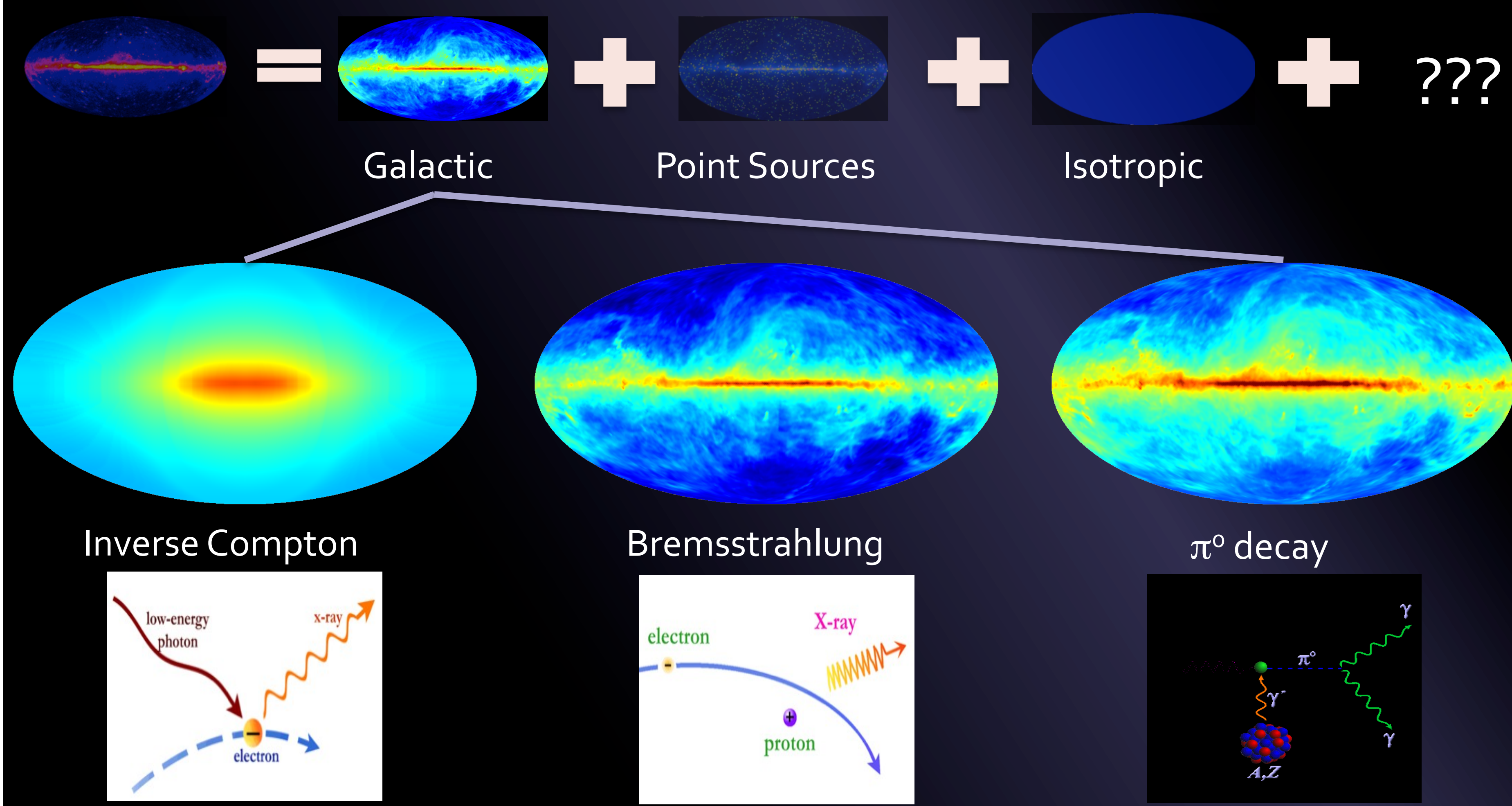
THE GAMMA-RAY SKY above 1 GeV

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



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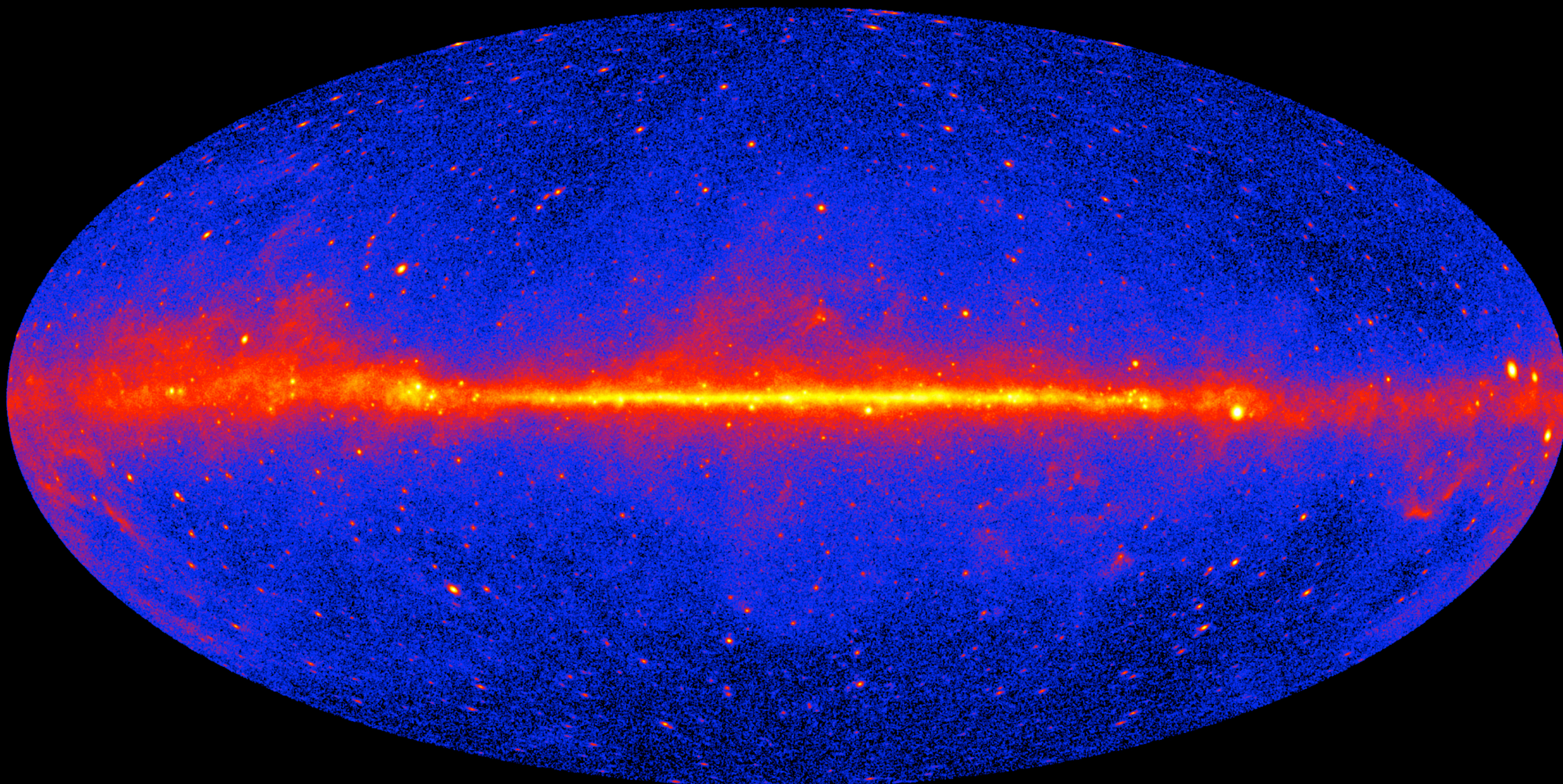
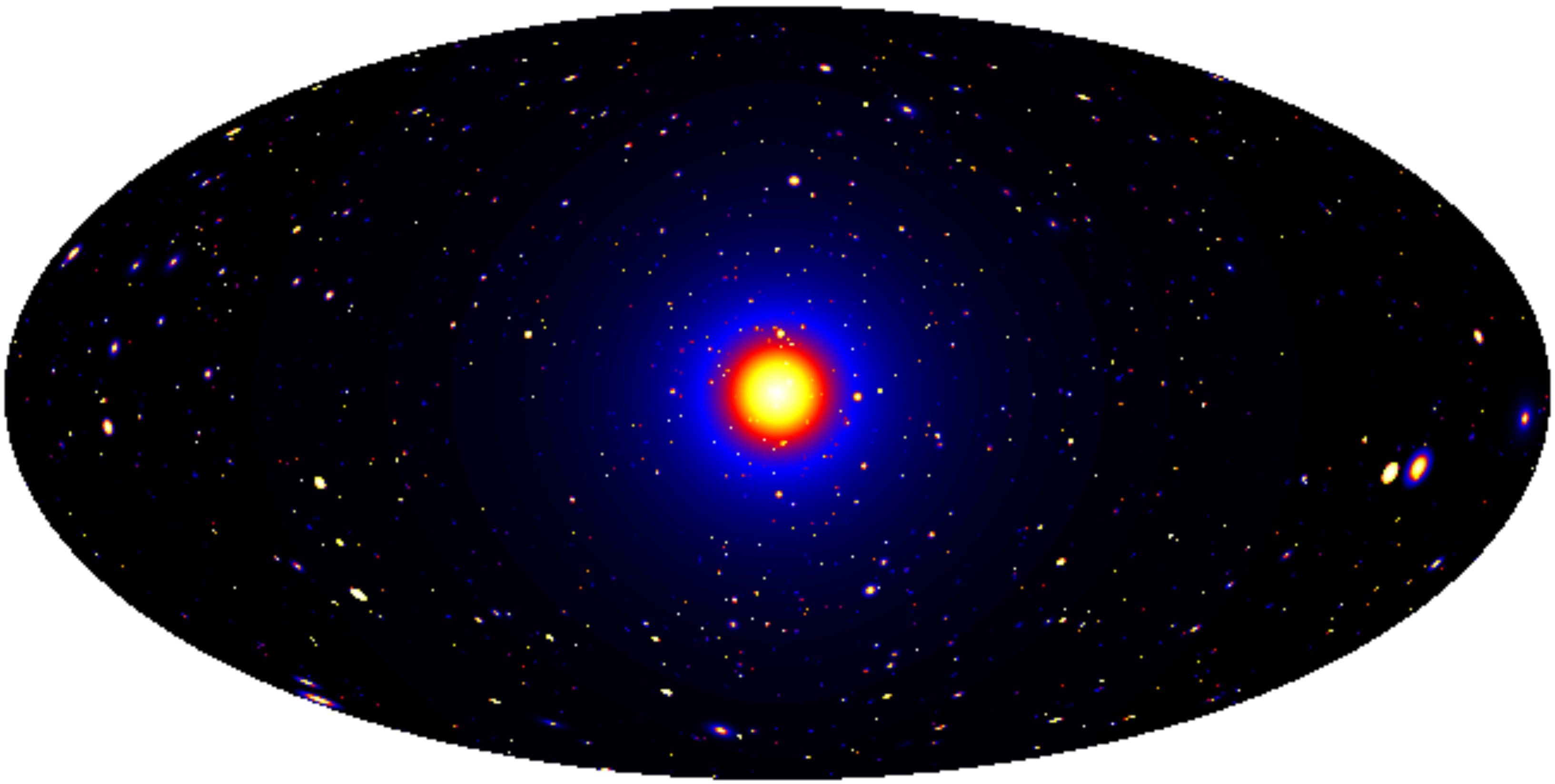


The DM-induced gamma-ray sky



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

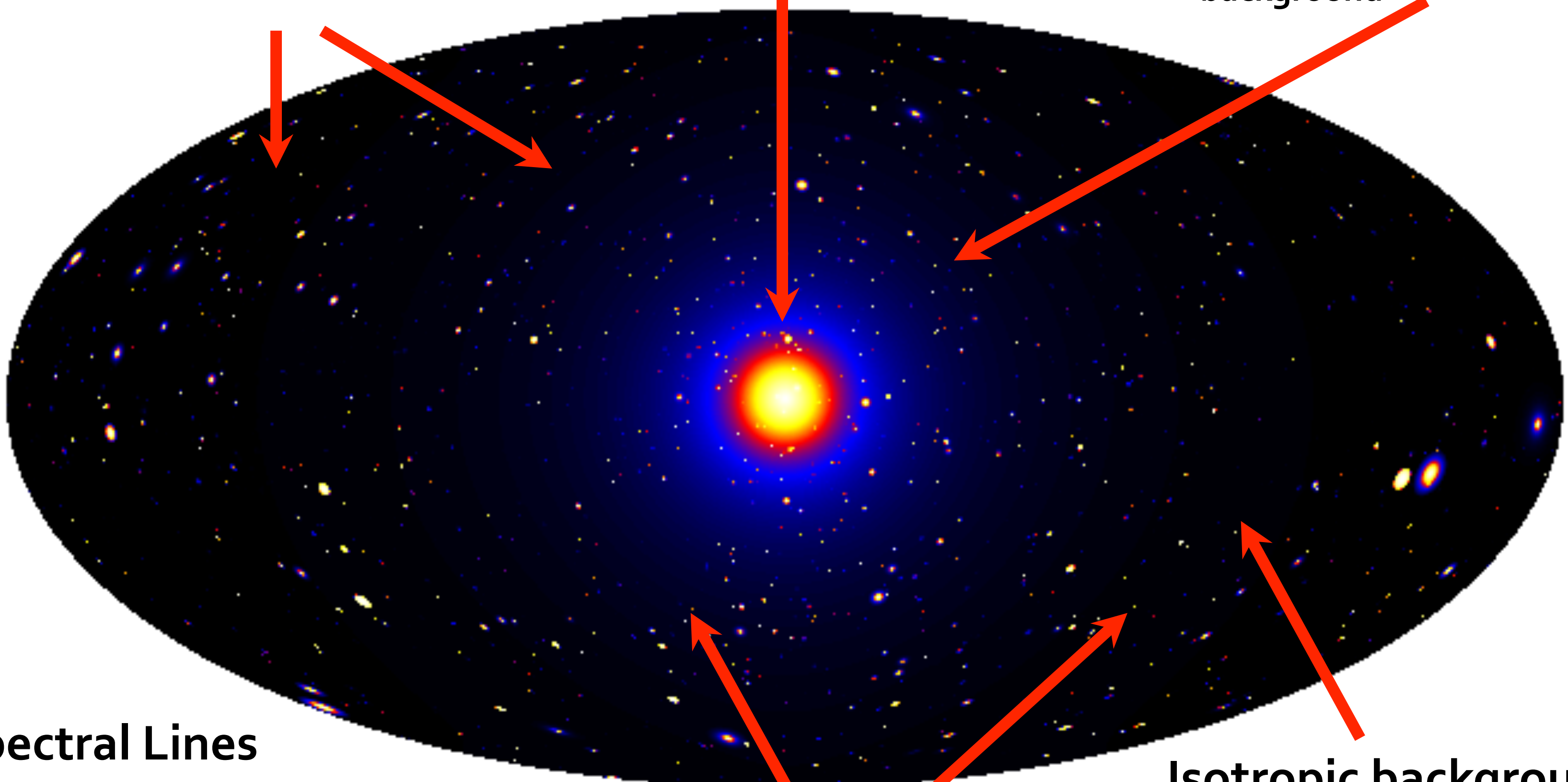
Low background and good source id, but low statistics

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]

Inner Galaxy

DM satellites

Line searches

Dark Matter Search Strategies

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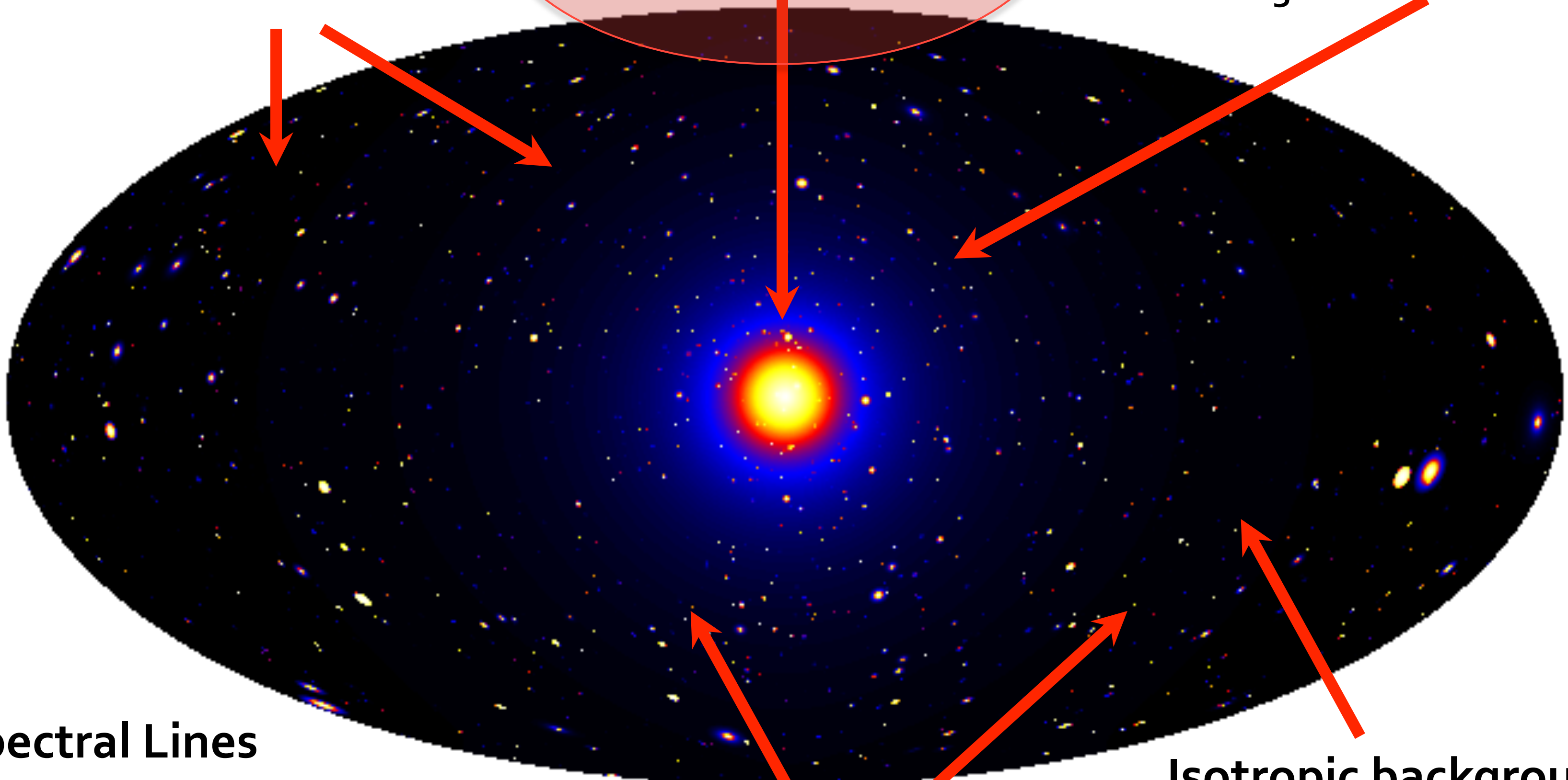

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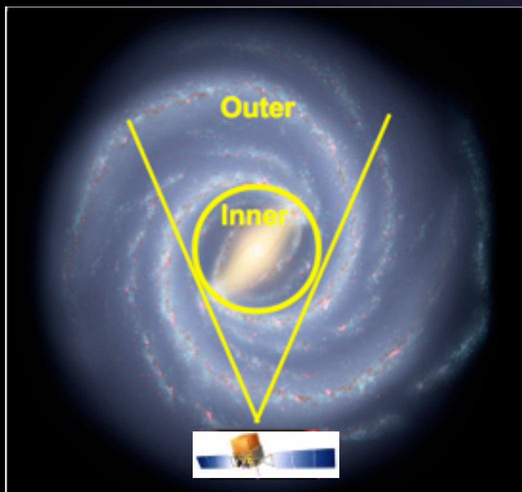
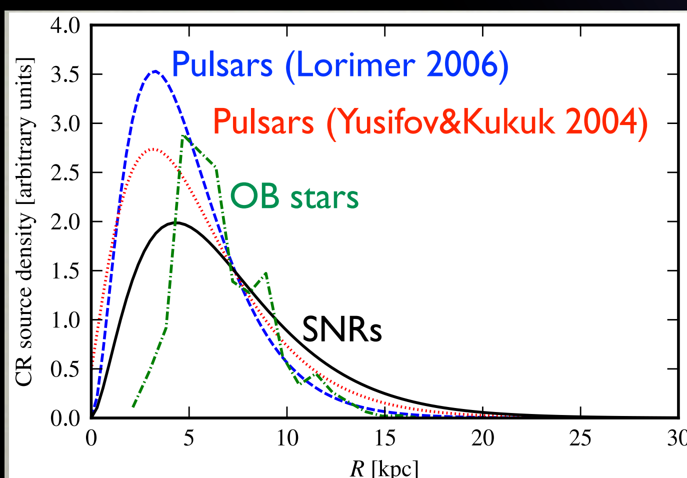
Galactic Center region

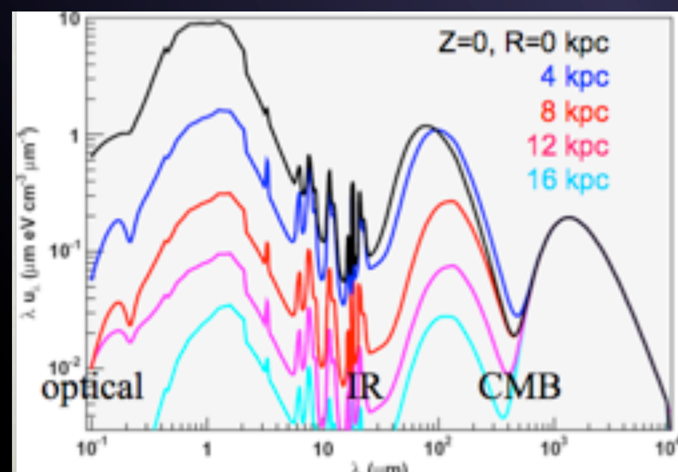


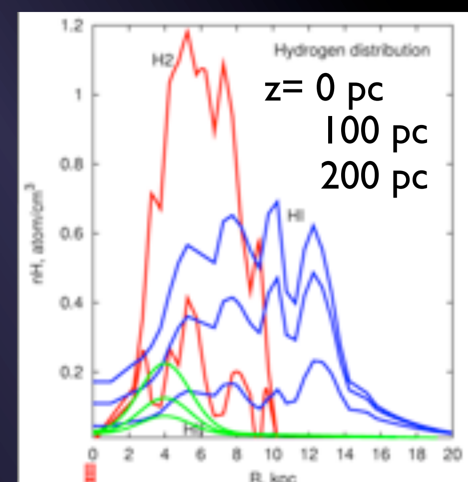
Source confusion: many sources close to the GC (or in the l.o.s.).

Diffuse emission modeling: large uncertainties in cosmic ray densities, interstellar radiation fields, gas densities…; also due to overlapping structures along the l.o.s.

Region intensively studied, e.g. Hooper & Linden 11, Boyarski+11, Abazajian & Kaplinghat 12, Abazajian+14, Daylan+14

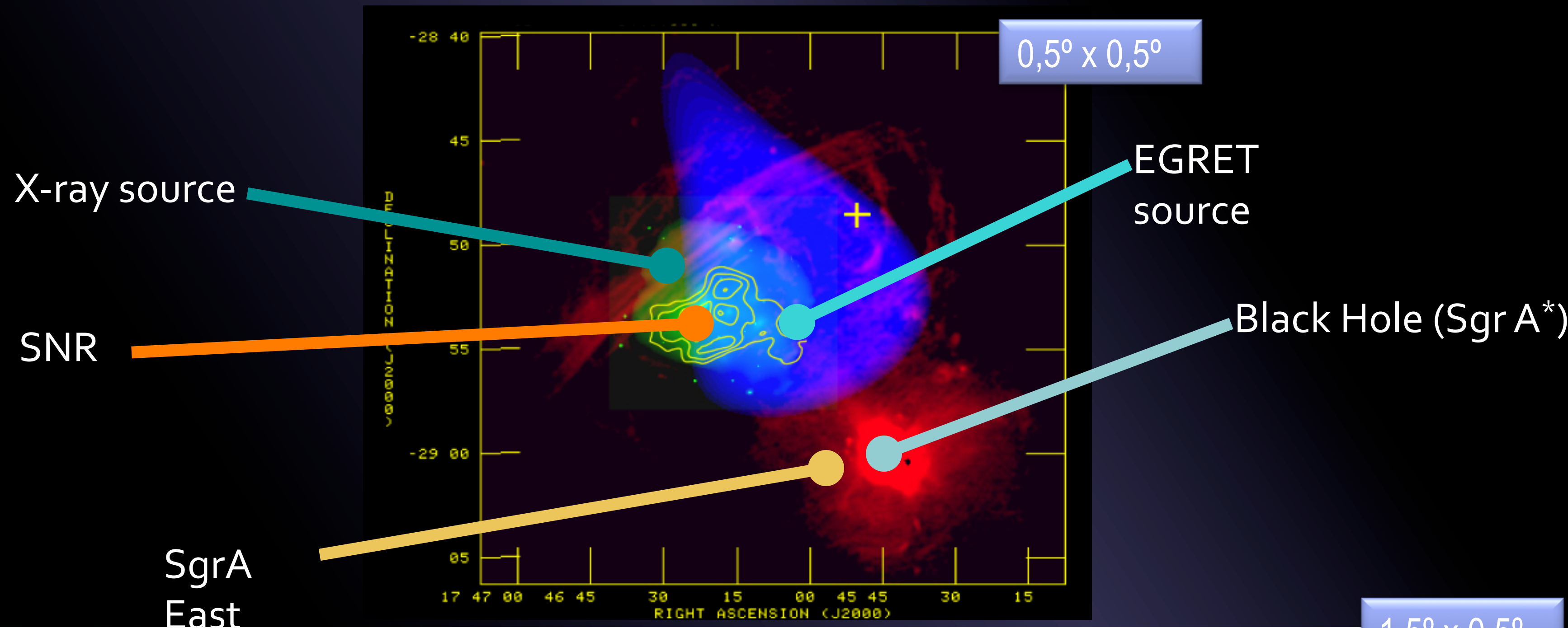


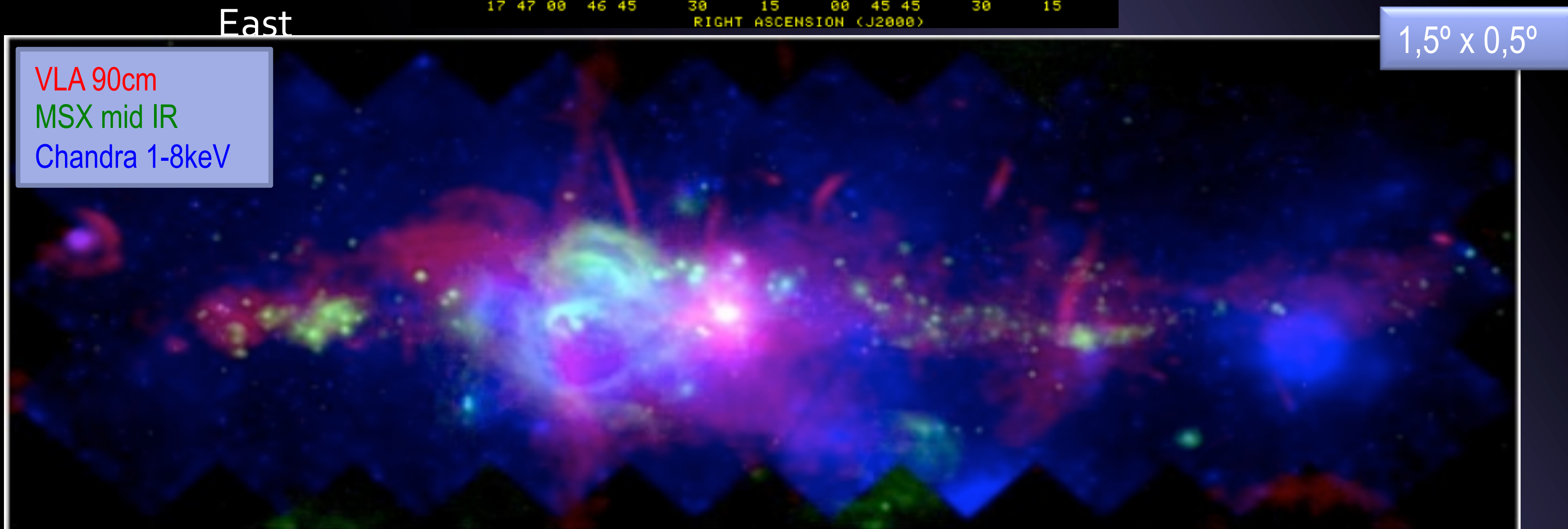




***Disclaimer**: This talk only on LAT work. Non-LAT work discussed by Siegal-Gaskins and Hooper*

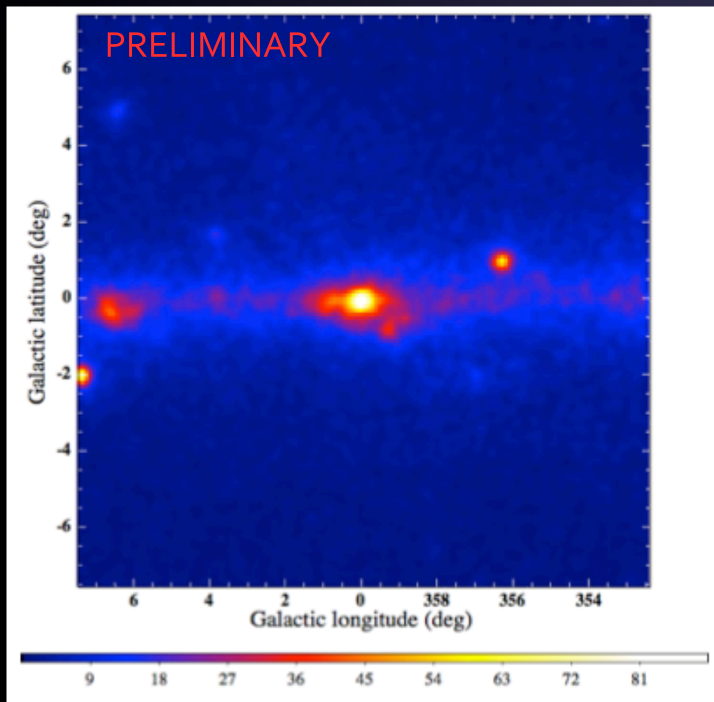
The Galactic Center is a crowded region !



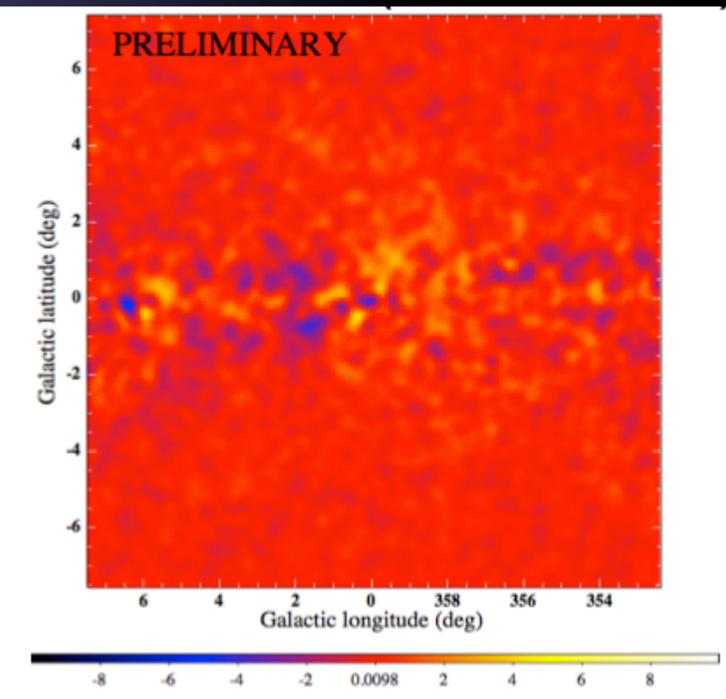


A refined Fermi analysis of the GC ongoing

P7CLEAN::Front, 32 months, 1-100 GeV



Residuals w.r.t. diffuse + sources



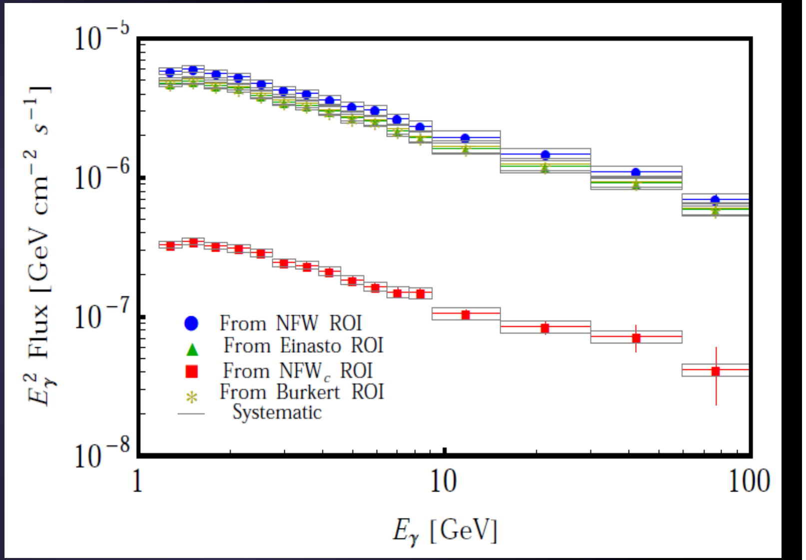
- An interstellar emission model is obtained by tuning a GALPROP-generated model to data over the sky.
  → used to estimate the foreground/background emission for the inner Galaxy.
- Data in the inner 15x15 deg are then fit using a maximum-likelihood method
  → determine the contributions by gamma-ray point sources and diffuse emission.
- Diffuse emission and known point sources account for most of the emission in the GC
- Subdominant structured residuals across the ROI
- Next steps: quantify residuals, study possible DM contributions

A simplified (DM-oriented) Inner Galaxy analysis

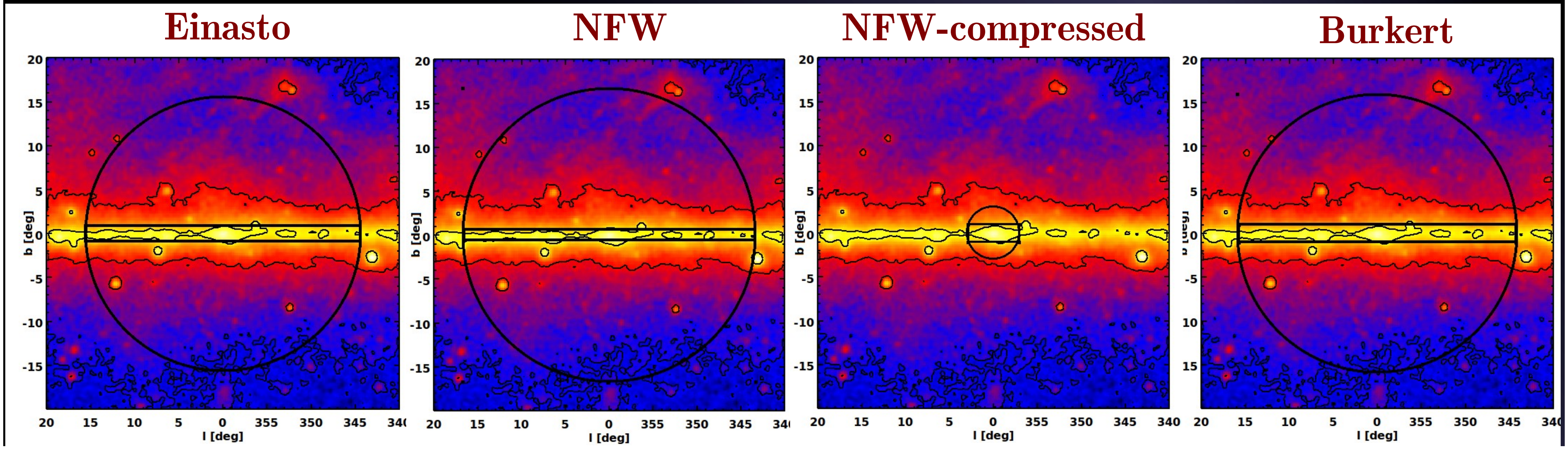
- Conservative constraints: expected DM signal doesn't exceed the measured Fermi gamma-ray emission in optimized ROIs
- Four DM density profiles compatible with observational data used.
- These include an adiabatically compressed NFW.

Profile	θ_1 [°]	θ_2 [°]	$\lvert b \rvert$ [°]	$\Delta\Omega$ [sr]	$\bar{J}(\Delta\Omega)\,\Delta\Omega$ [$\times 10^{22}$ GeV^2 cm^{-5} sr]	Flux (1 – 100 GeV) [$\times 10^{-7}$ cm^{-2}s^{-1}]
Burkert	0.8	15.9	0.8	0.225	41.9	32.1 ± 0.3
Einasto	0.7	15.6	0.7	0.217	5.1	31.4 ± 0.3
NFW	0.6	16.7	0.6	0.253	3.3	38.0 ± 0.3
NFW$_c$	1.0	3.0	1.0	0.005	86.8	2.2 ± 0.1

VS.



Inner galaxy spectrum

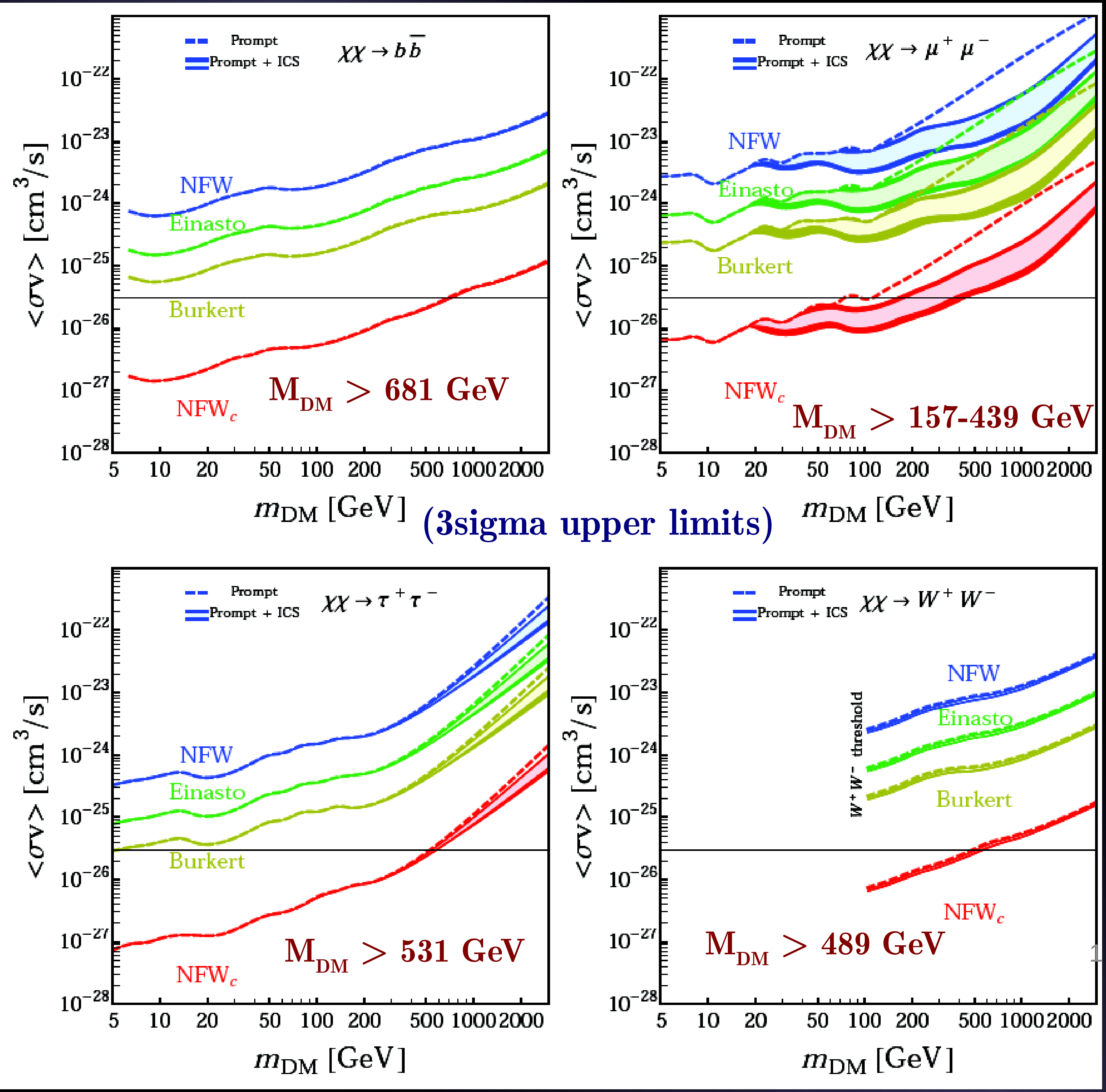


DM constraints from the Inner Galaxy

Conservative but robust exclusion limits

A modeling of the foregrounds will only lead to better constraints

[Gómez-Vargas+13]



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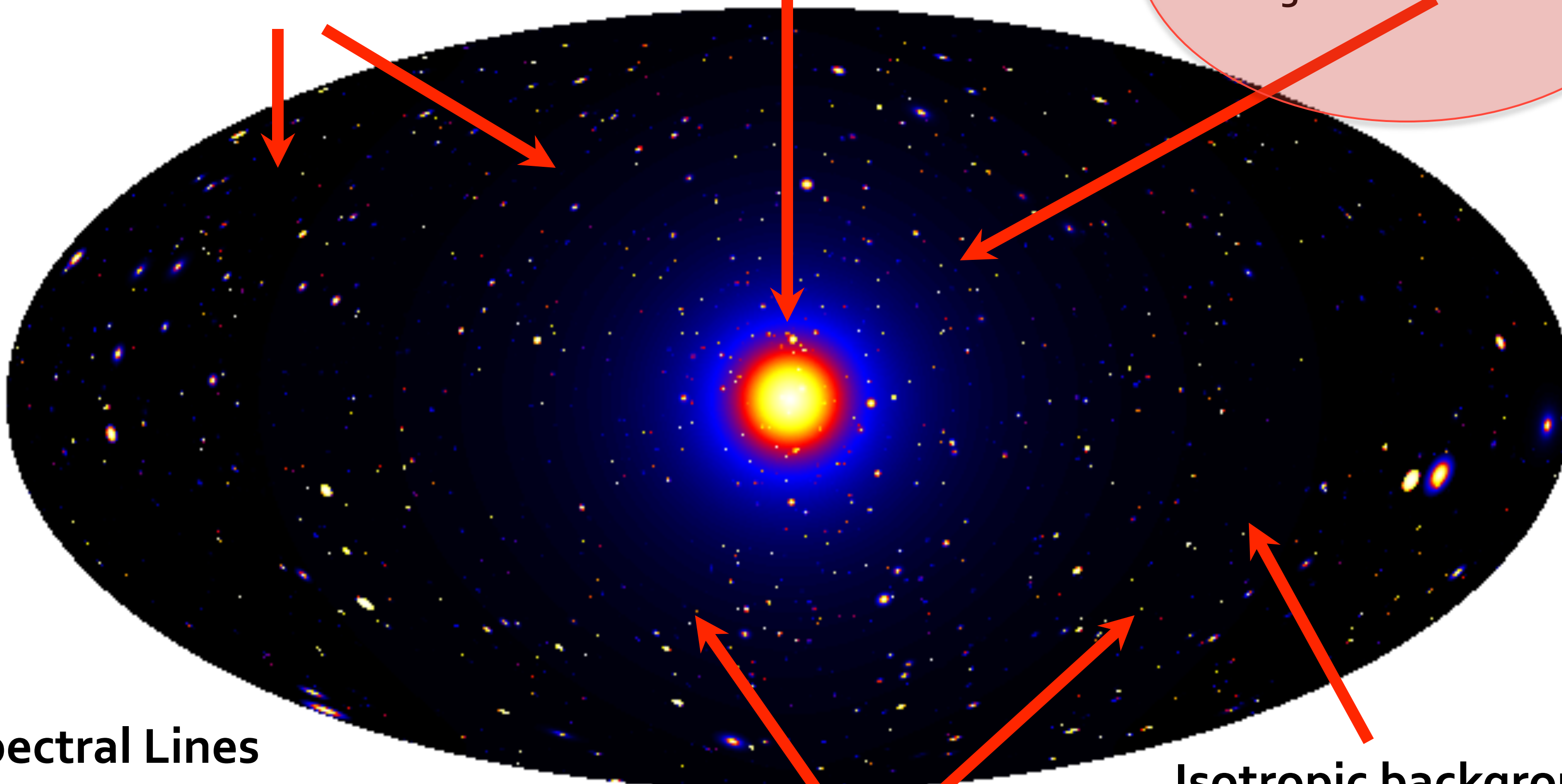

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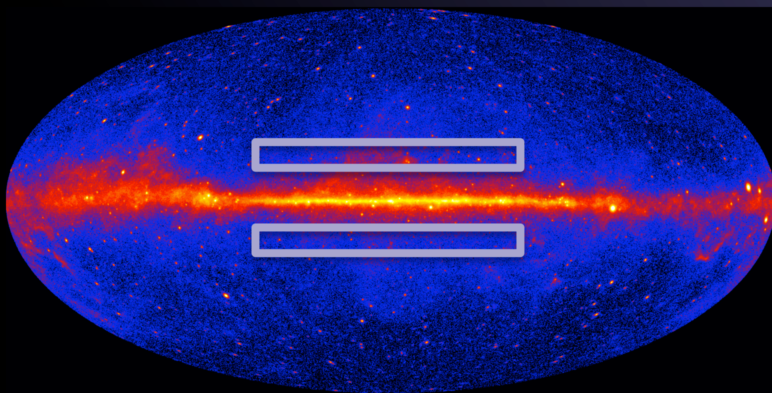
Isotropic background

Large statistics, but astrophysics, galactic diffuse background

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

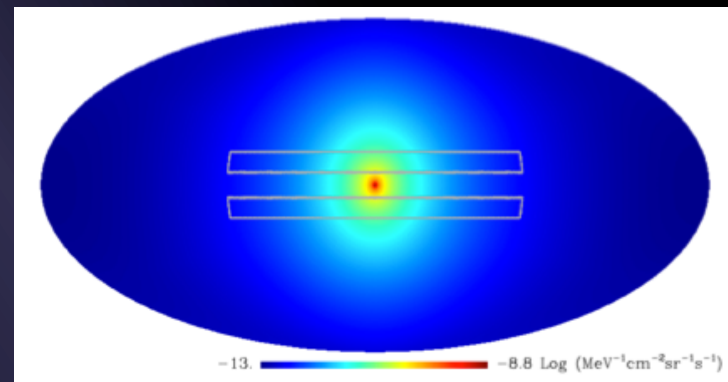
Galactic Center 'halo' with the LAT

Ackermann+12



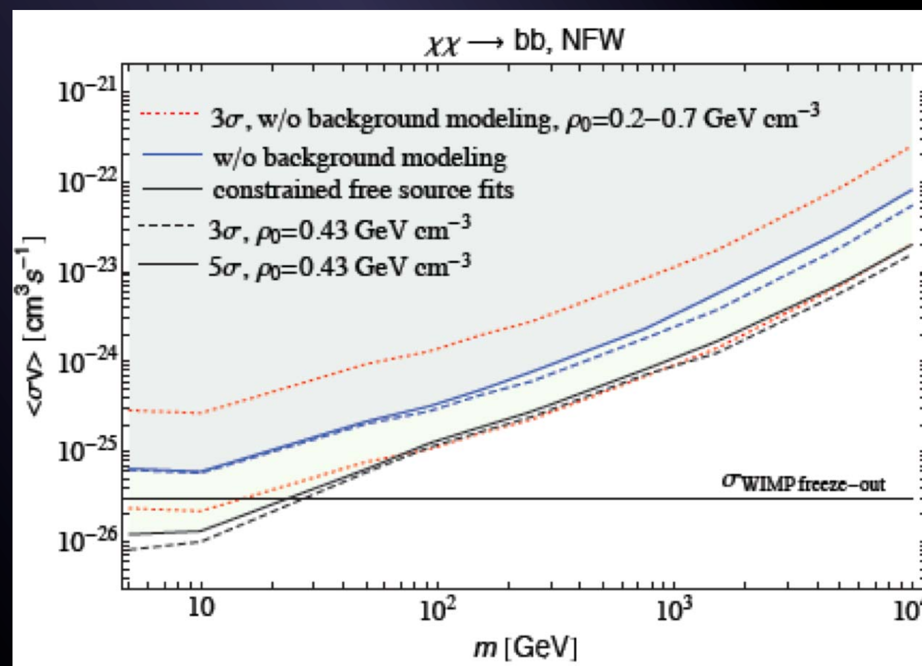
Fermi LAT data

vs.



Simulation of 250 GeV WIMP into bb

- Signal region: strip below and above the Galactic Plane
- Conservative limits: no modeling of the background
- More refined analysis (diffuse emission, sources) gives a factor ~5 improvement in the constraints.



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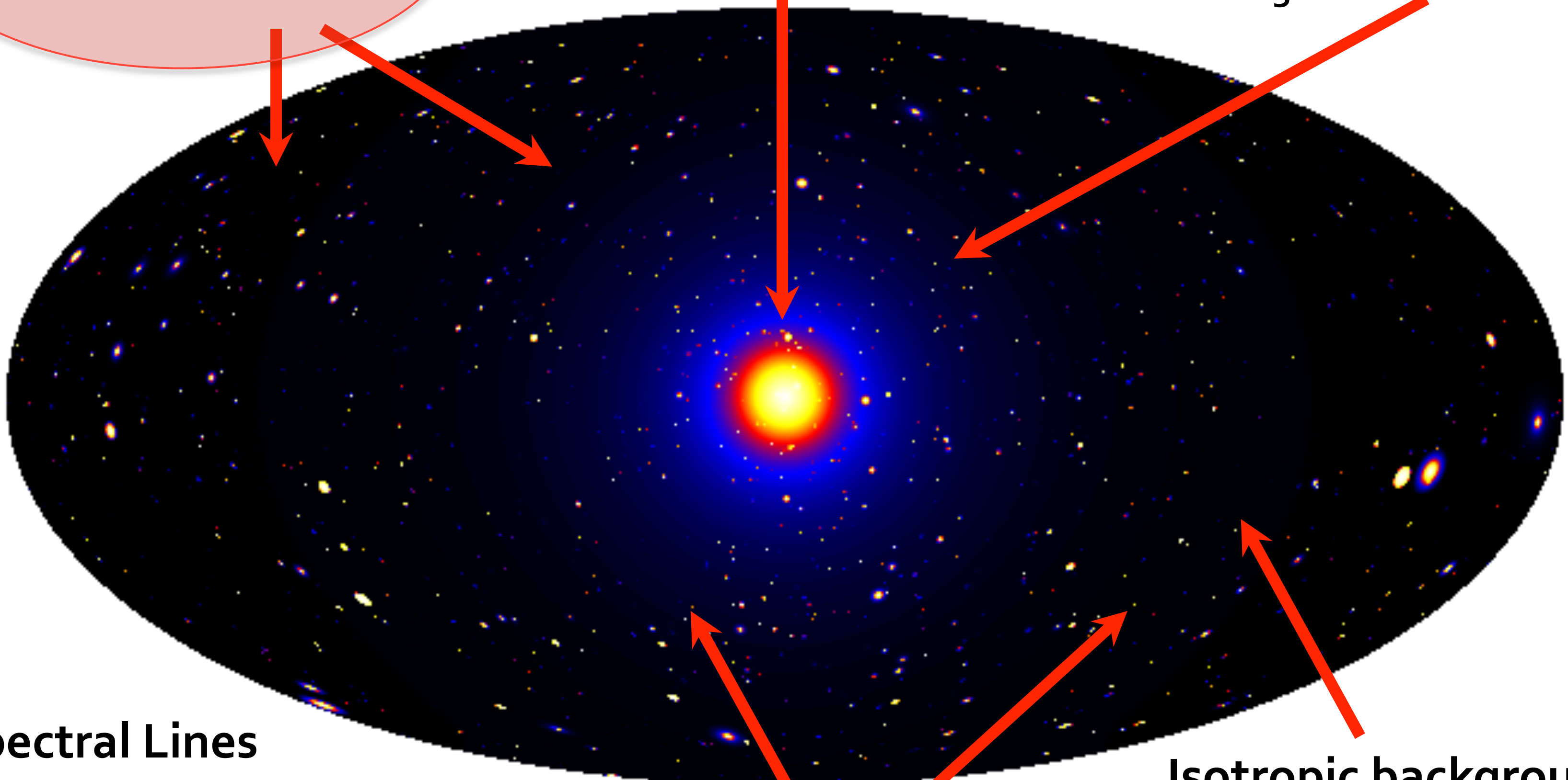

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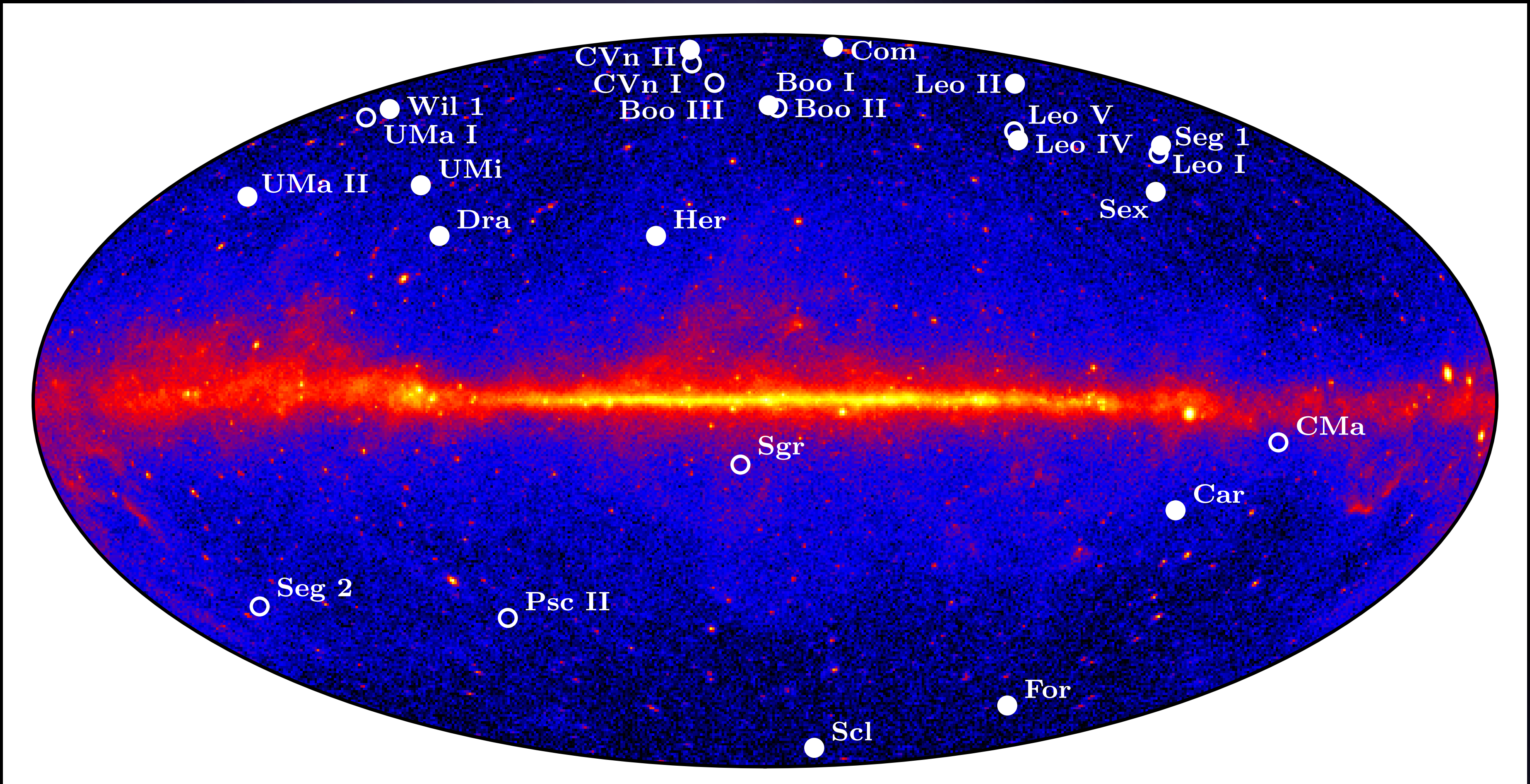
Dwarf Spheroidal satellite galaxies

- 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’

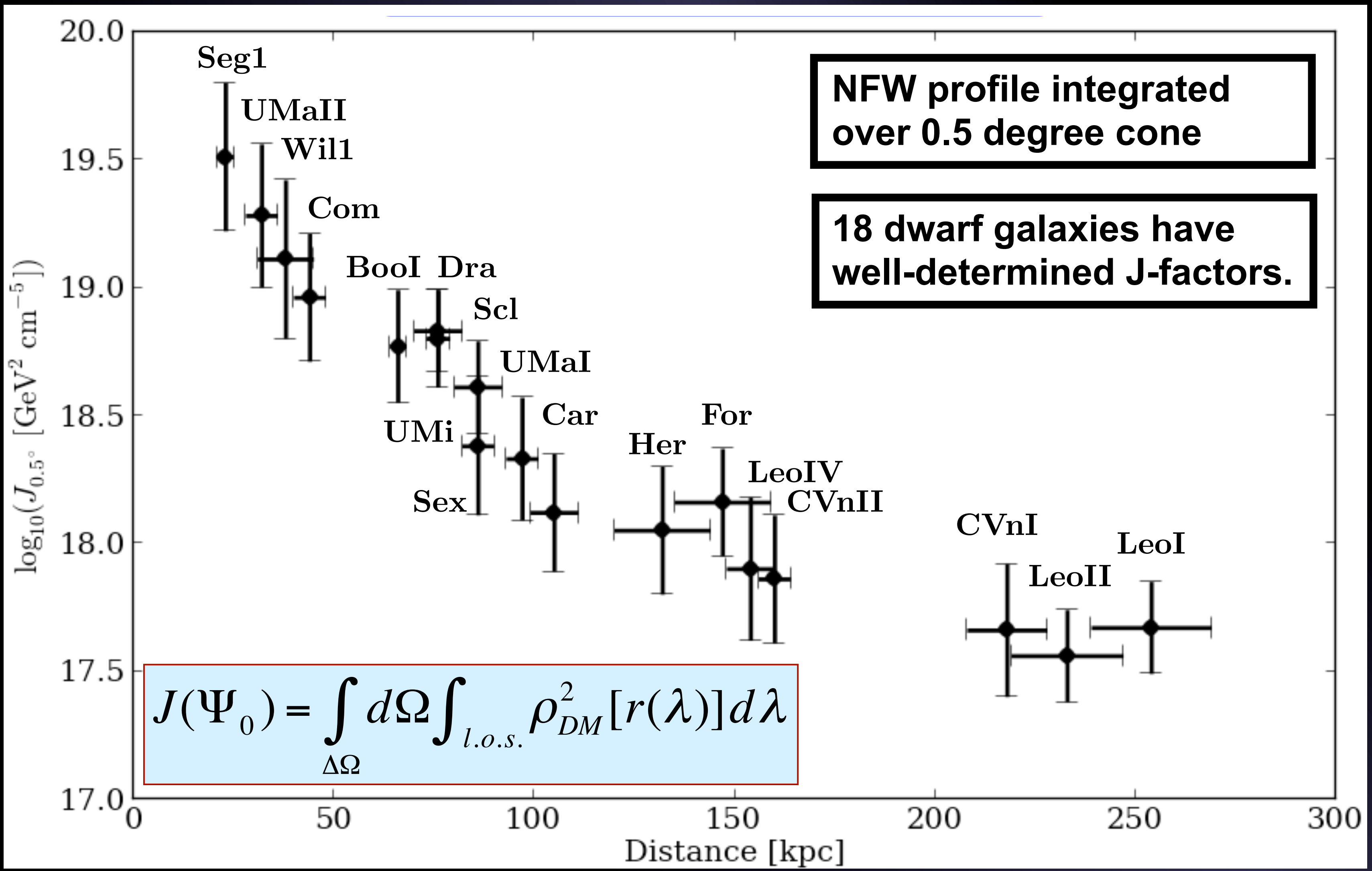


Ackermann+13 [astro-ph/1310.0828]

15 dwarfs analyzed

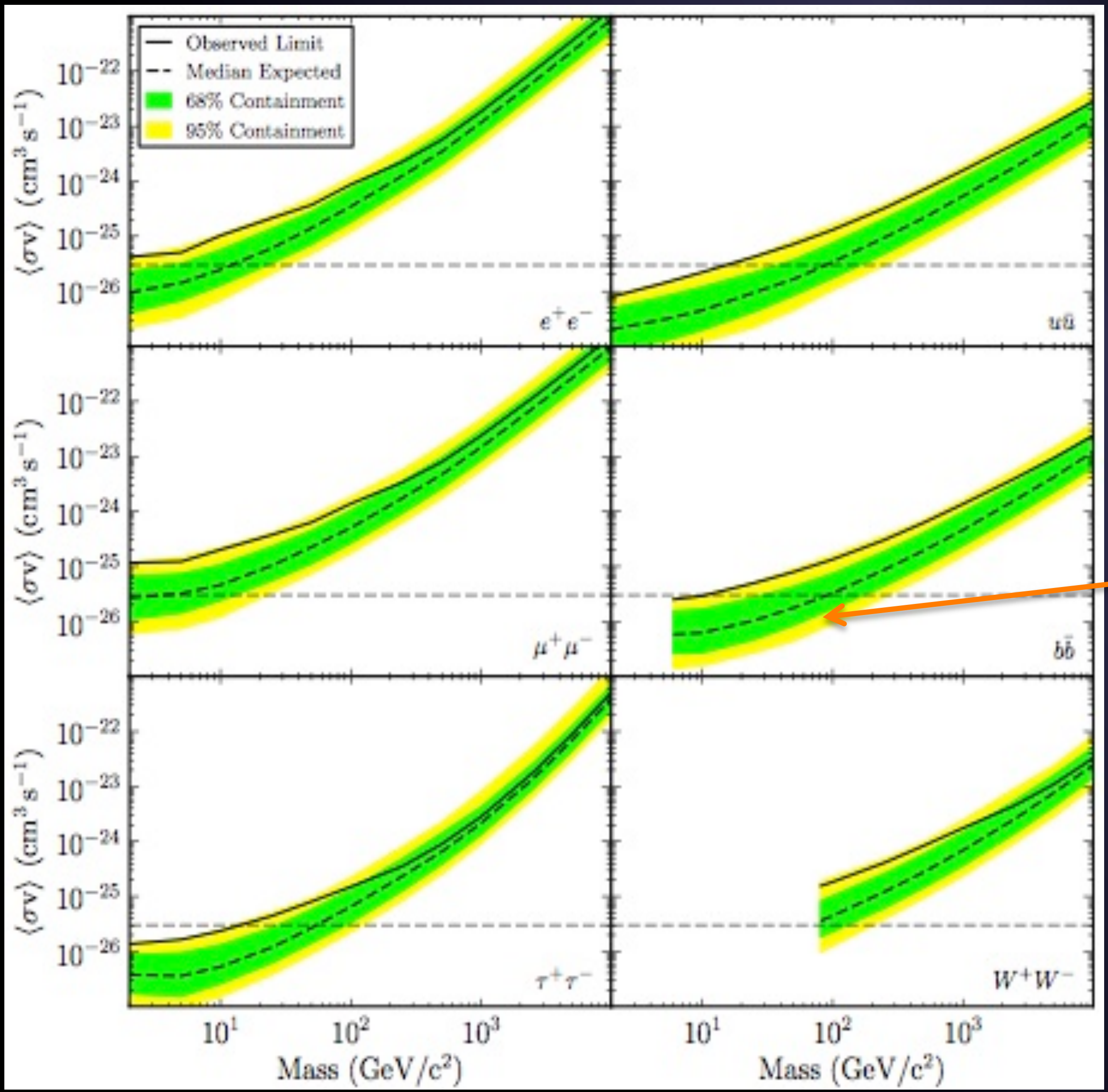
The higher the latitude the better in terms of astro foregrounds

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:

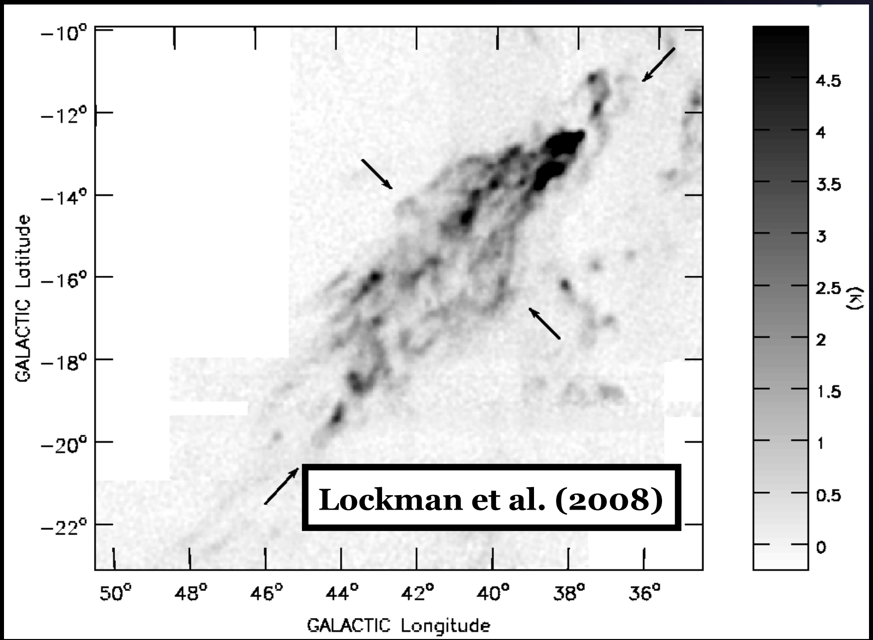
- 300 realizations at 5 random sky positions
- High Galactic lat (|b|>20°)
- >1° from LAT catalog sources

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.

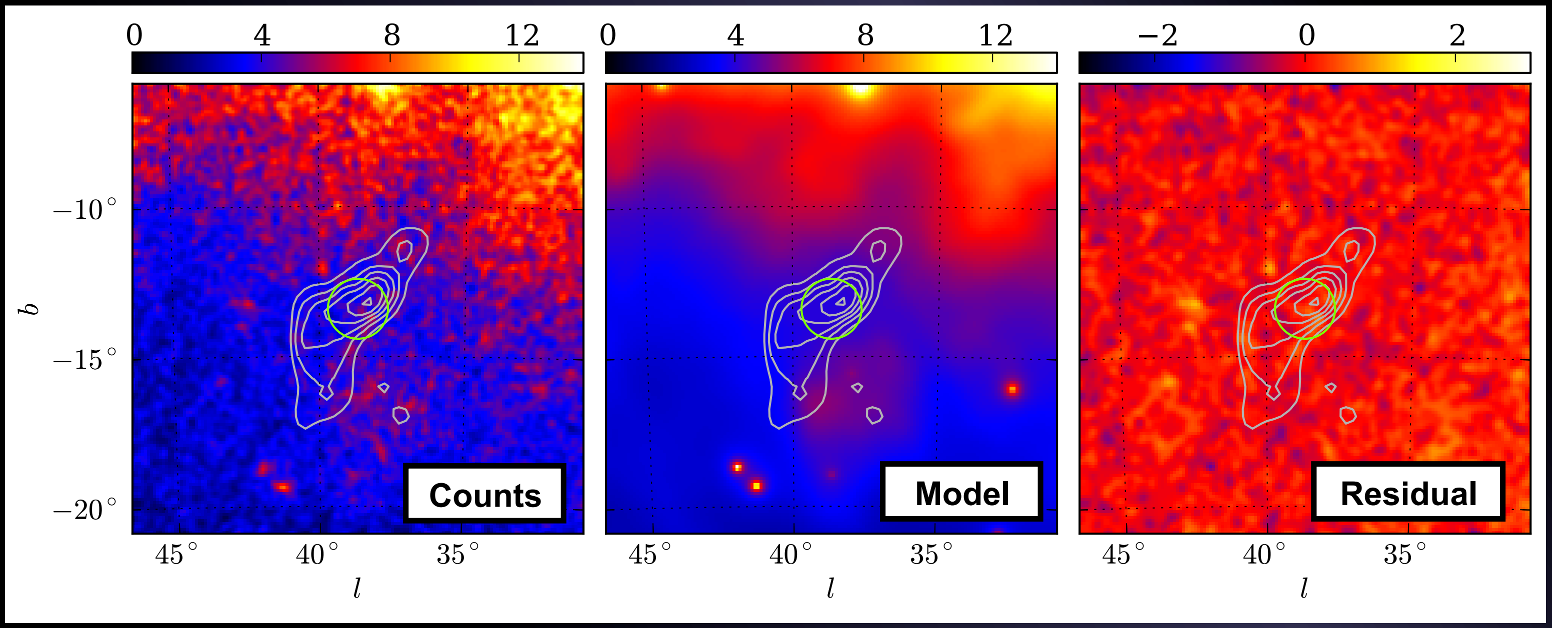


- Smith Cloud one of the best studied HVCs.
- HI gas mass of ~10^6 solar masses.
- 2 times closer than the closest dwarf galaxy
- It may be bounded by DM halo of ~10^8 solar masses (Nichols & Bland-Hawthorn 09) .

LAT analysis

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

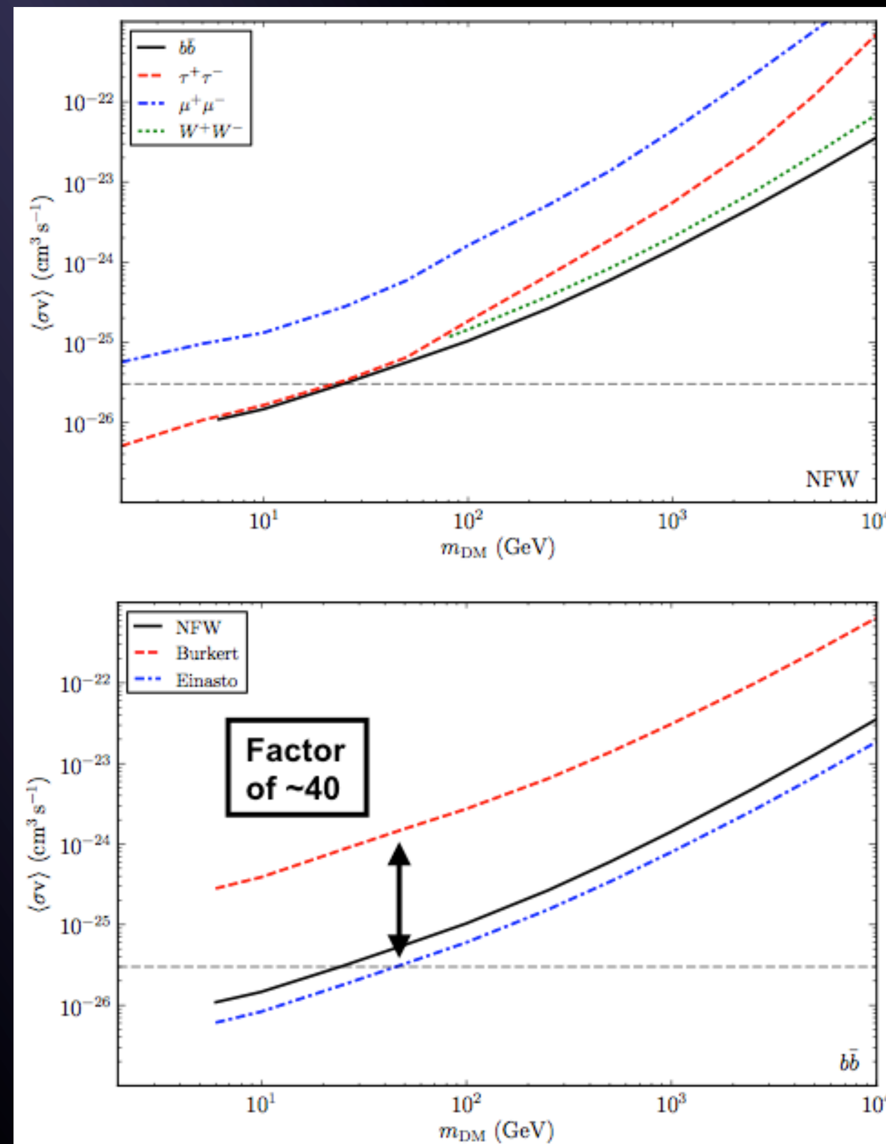
Drlica-Wagner, Gómez-Vargas, Hewitt, Linden, Tibaldo (2014) [astro-ph/ 1405.1030]

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}



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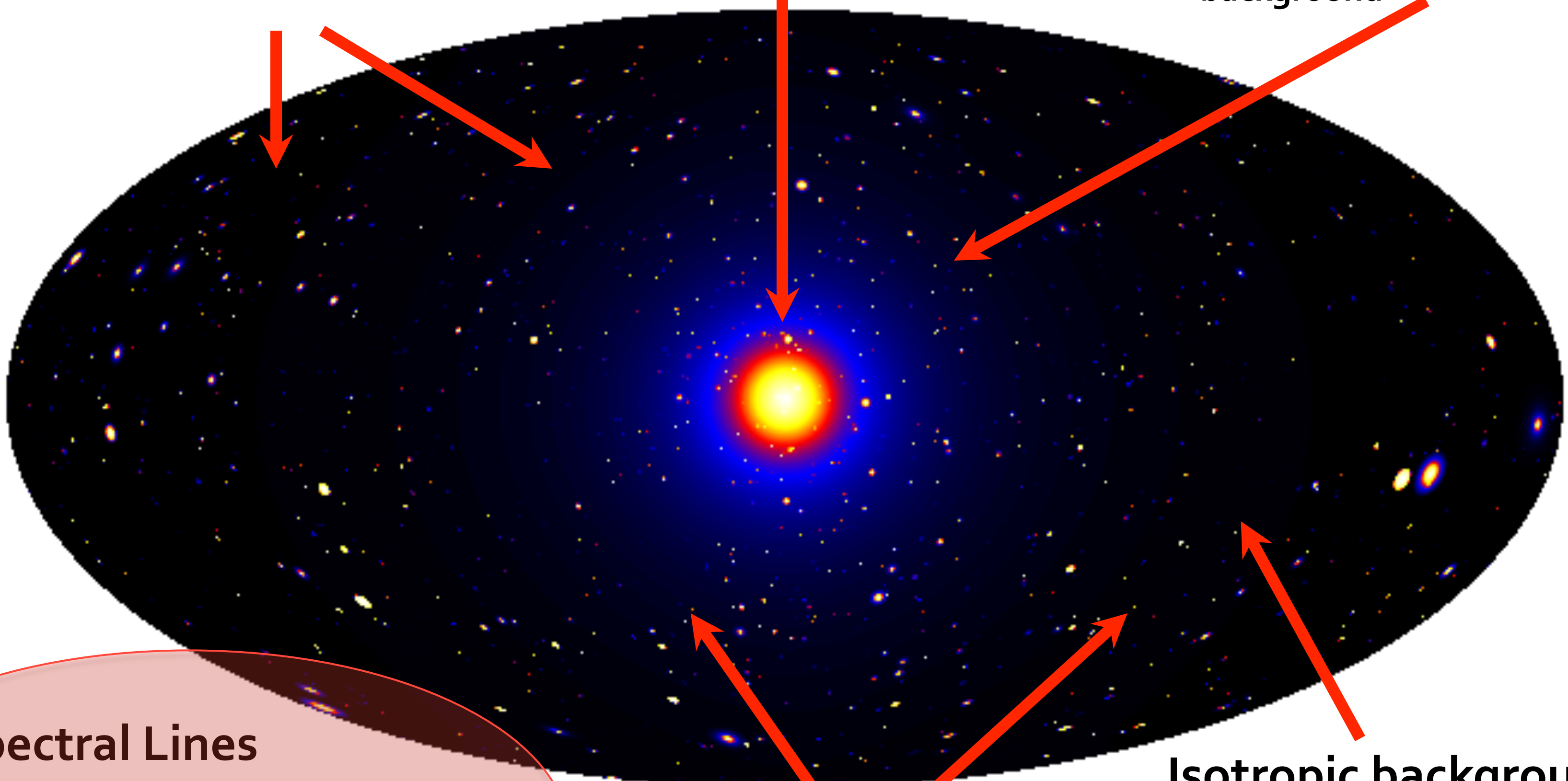

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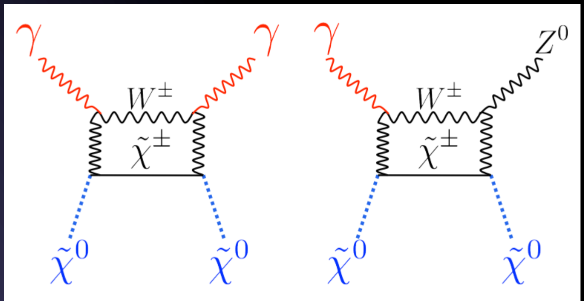
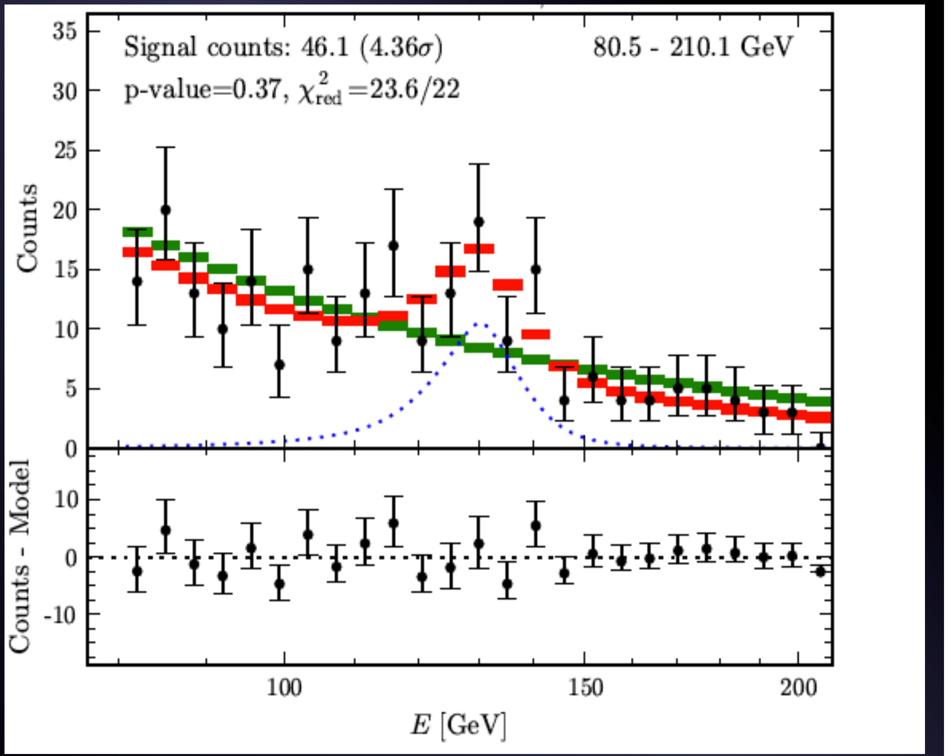
Both anisotropies and intensity!

Spectral lines search with the LAT

- Annihilation into γγ or γX (X = Z⁰, H⁰, …) will produce a distinct spectral feature
  - Clean signal
  - Low statistics
- No significant lines in 2 years of data including the Galactic Center and Galactic halo (Ackermann et al. 2012)
- ~4 years of data: external authors report a >4σ (local) spectral feature at ~130 GeV (Weniger 2012)

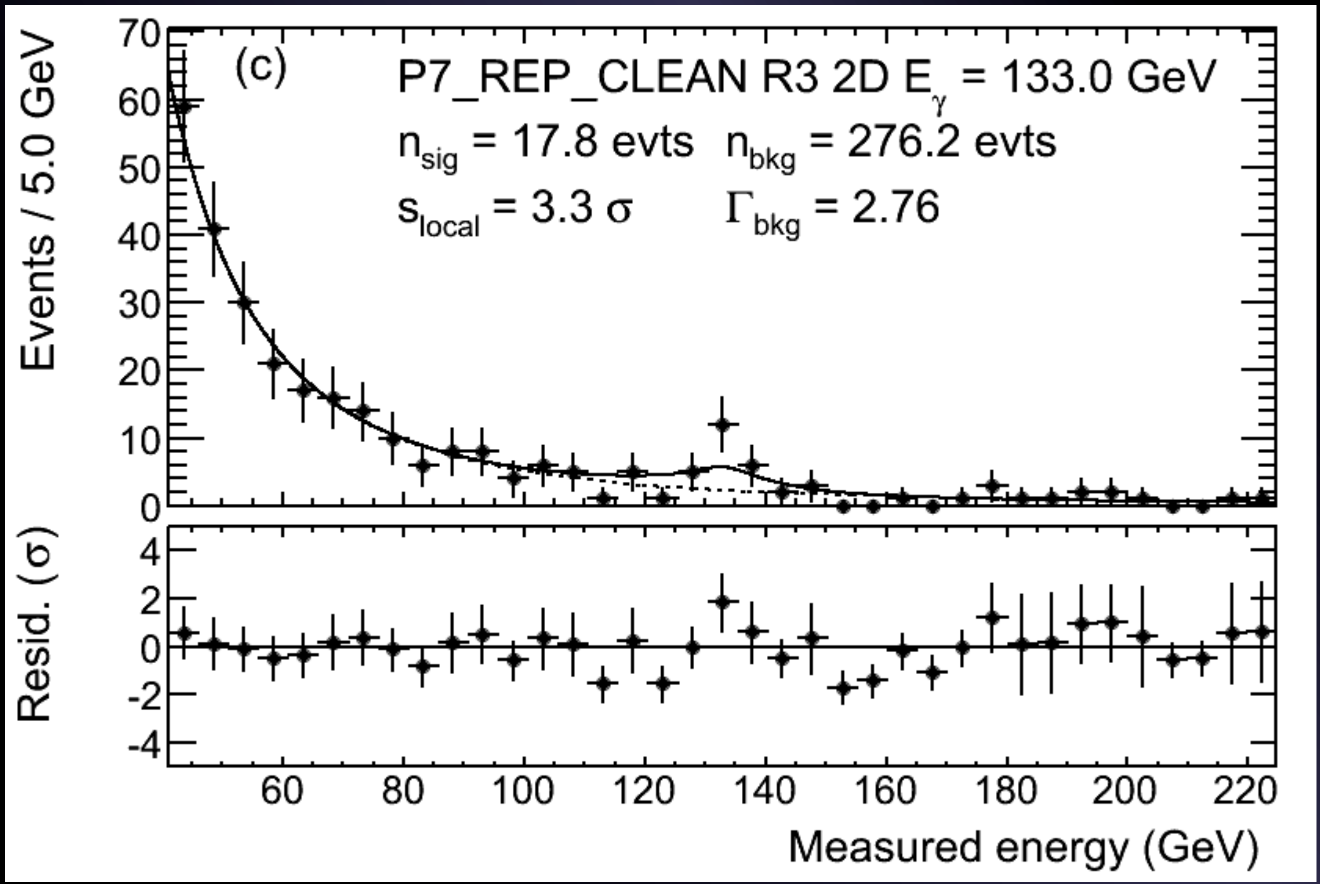




[Weniger 2012]

The line-like feature near 133 GeV as seen by the LAT team

High energy line search summary

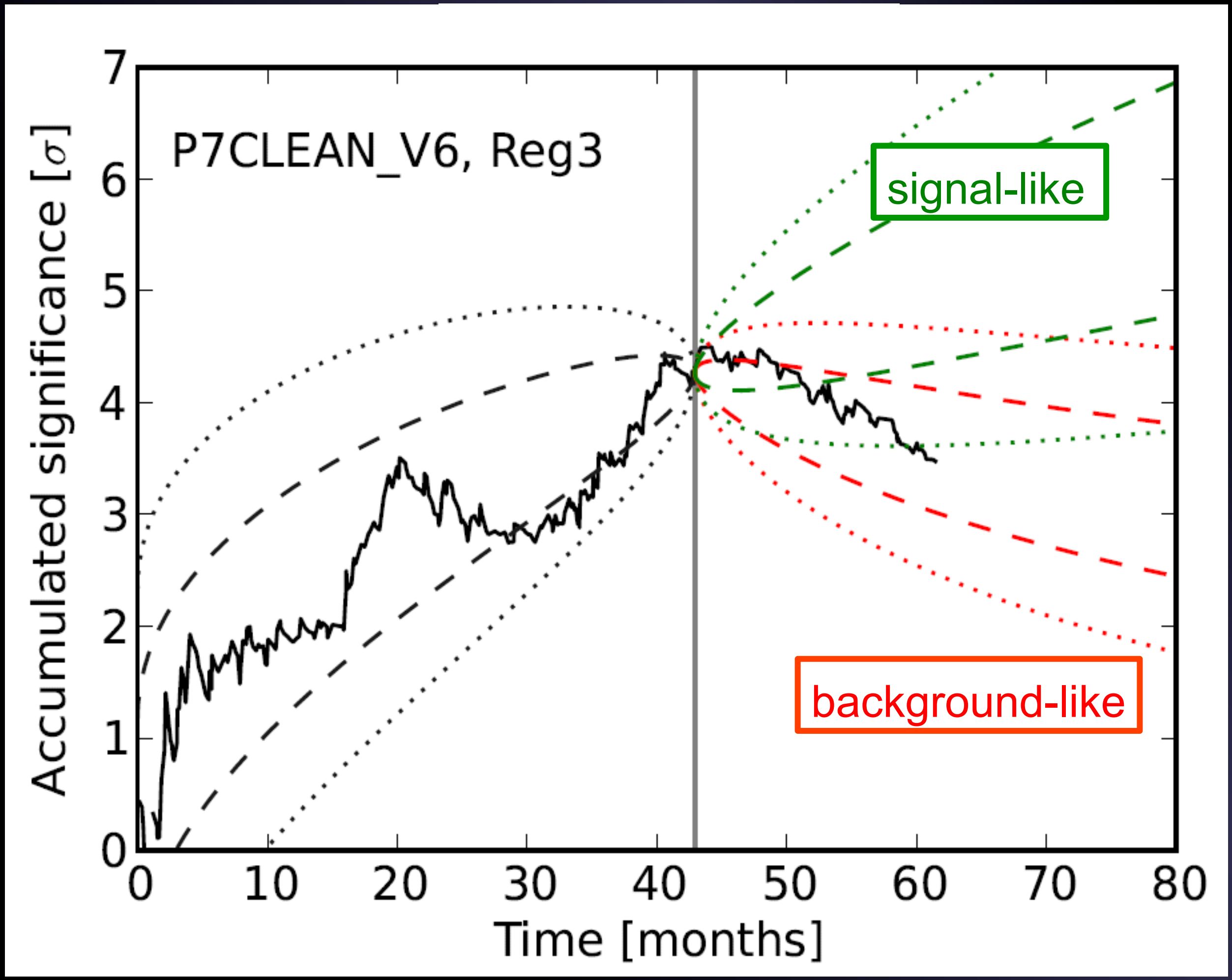


- 3.2σ (local) at 133 GeV with reprocessed data in a 3º region around the GC.
- Global significance is 1.5σ
- Also seen in the Earth Limb control sample at 2σ (local), but not large enough to explain all the GC signal.

133 GeV feature in 5.2 year dataset

Since spring 2012, the significance of the feature has declined

→ More "background-like"



Weniger et al (2013): http://fermi.gsfc.nasa.gov/ssc/proposals/alt_obs/white_papers_eval.html

Low energy line search

Albert, Gómez-Vargas, Grefe et al., JCAP submitted [astro-ph/1406.3430]

- Search between 100 MeV up to 10 GeV (previously unexplored energy range!).
- Regions of Interest optimized for annihilation and decay.

  → for decay, it constrains e.g. models of gravitino decay.
- Data: 5.2 years, P7 reprocessed Clean.
- At low energies, statistical uncertainties get very small (<1%)

  → systematics dominate

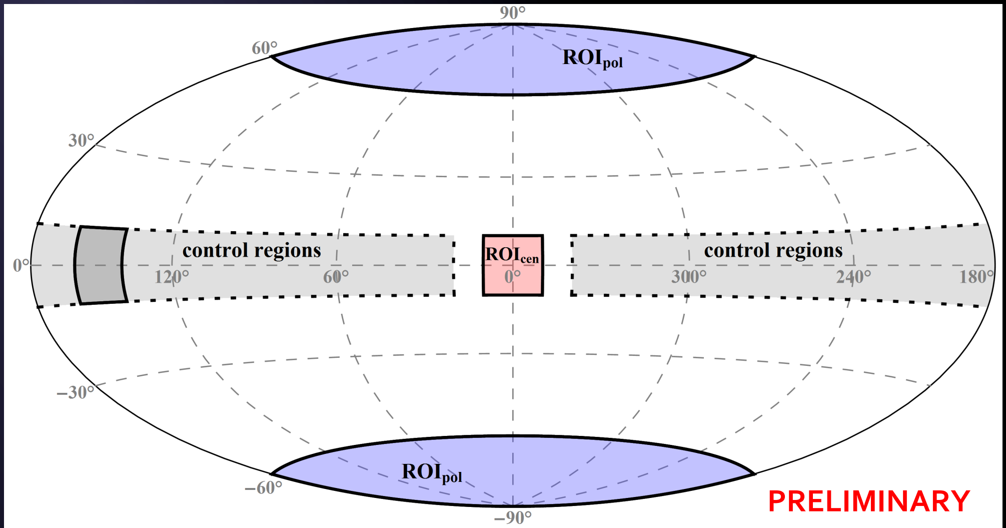
  → important to model them properly!

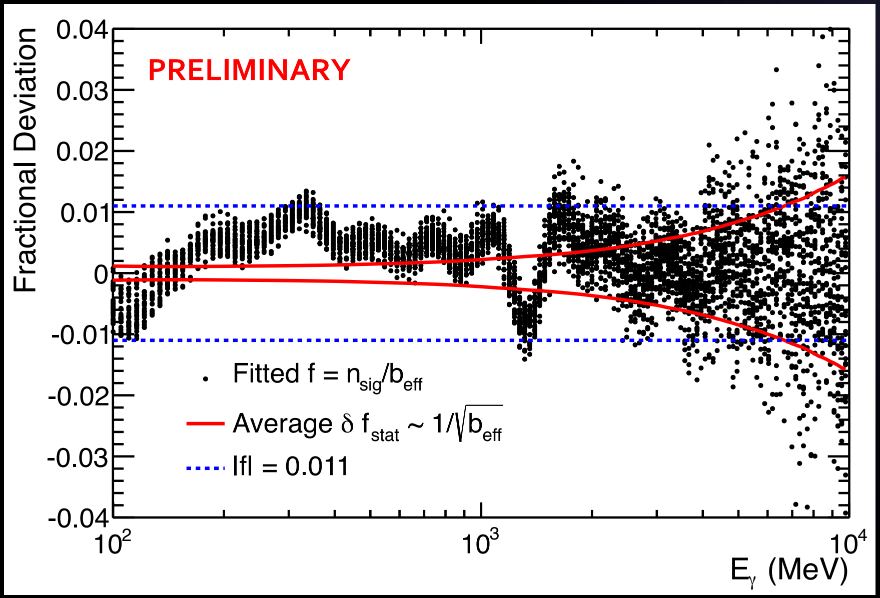
Low energy line search analysis

ROIs optimized for annihilation and decay.

Use Einasto profile as baseline.

NFW, Isothermal, Burkert, also considered.





Systematics offset the estimated number of signal events with respect to its true value .

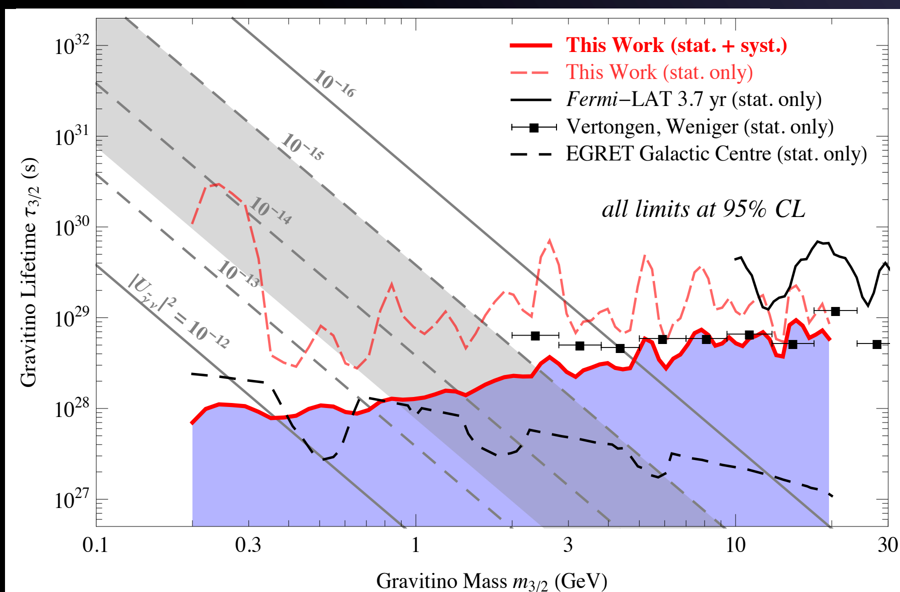
Estimate δf_{sys} by fitting for lines in control regions.

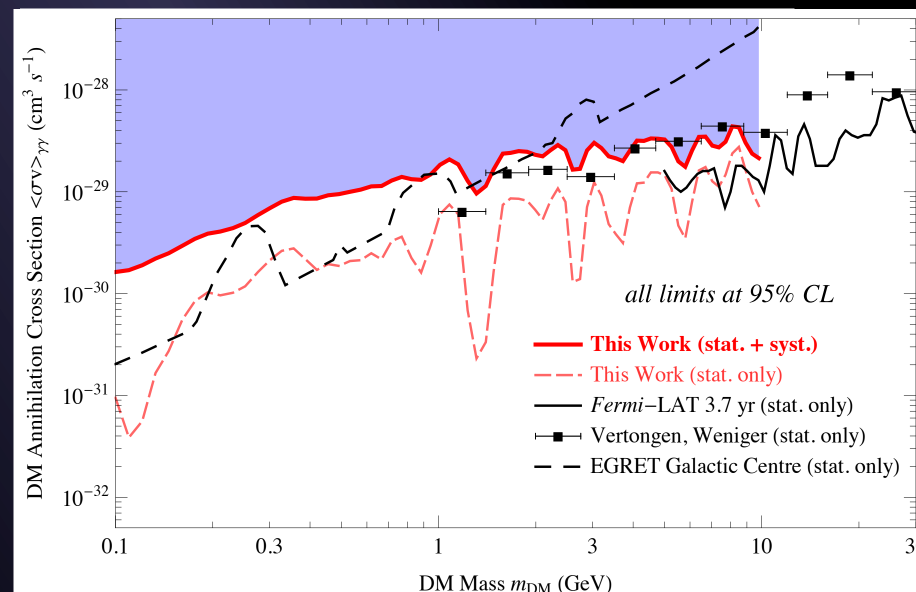
Below ~3 GeV the search is systematics-limited.

Line energy line search: limits

No globally significant lines detected:

→ flux upper limits in annihilation and decay ROIs

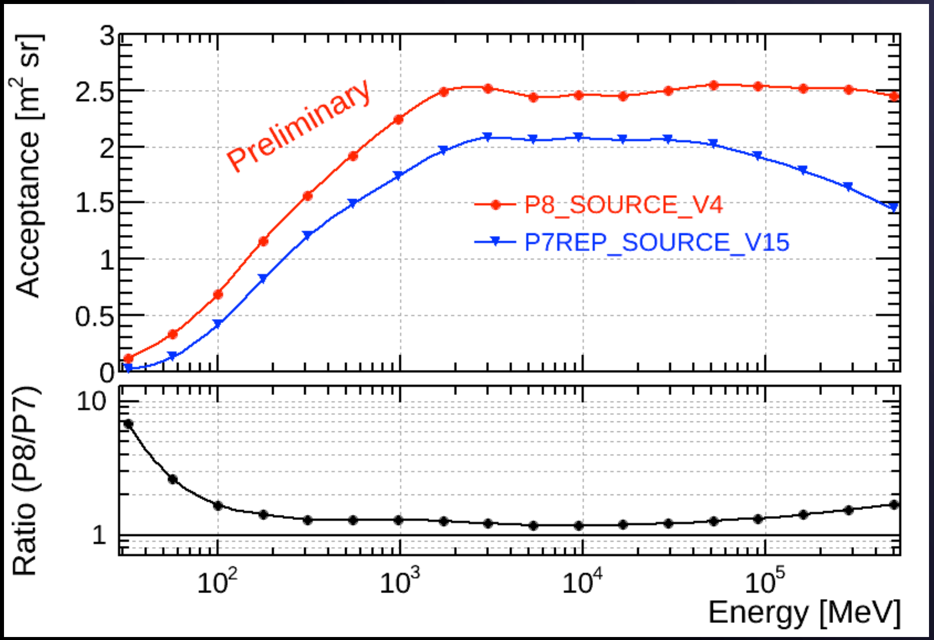


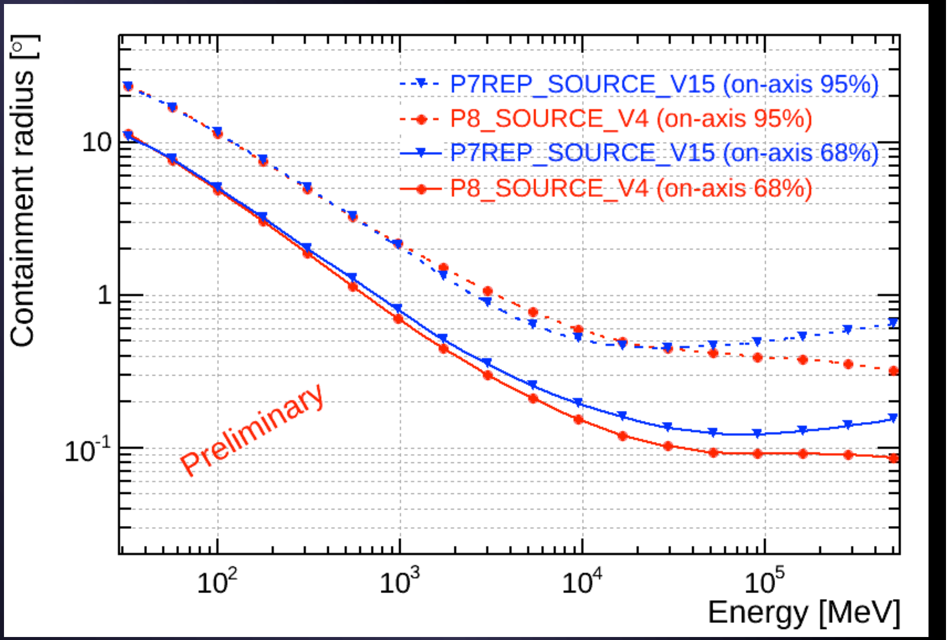


[Albert+14, JCAP submitted, astro-ph/1406.3430]

Exclude μνSSM gravitinos with masses larger than ~5 GeV or lifetimes smaller than ~10^{28} s as DM candidates.

THE FUTURE: Pass8 (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

Conclusions

- ✓ 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.

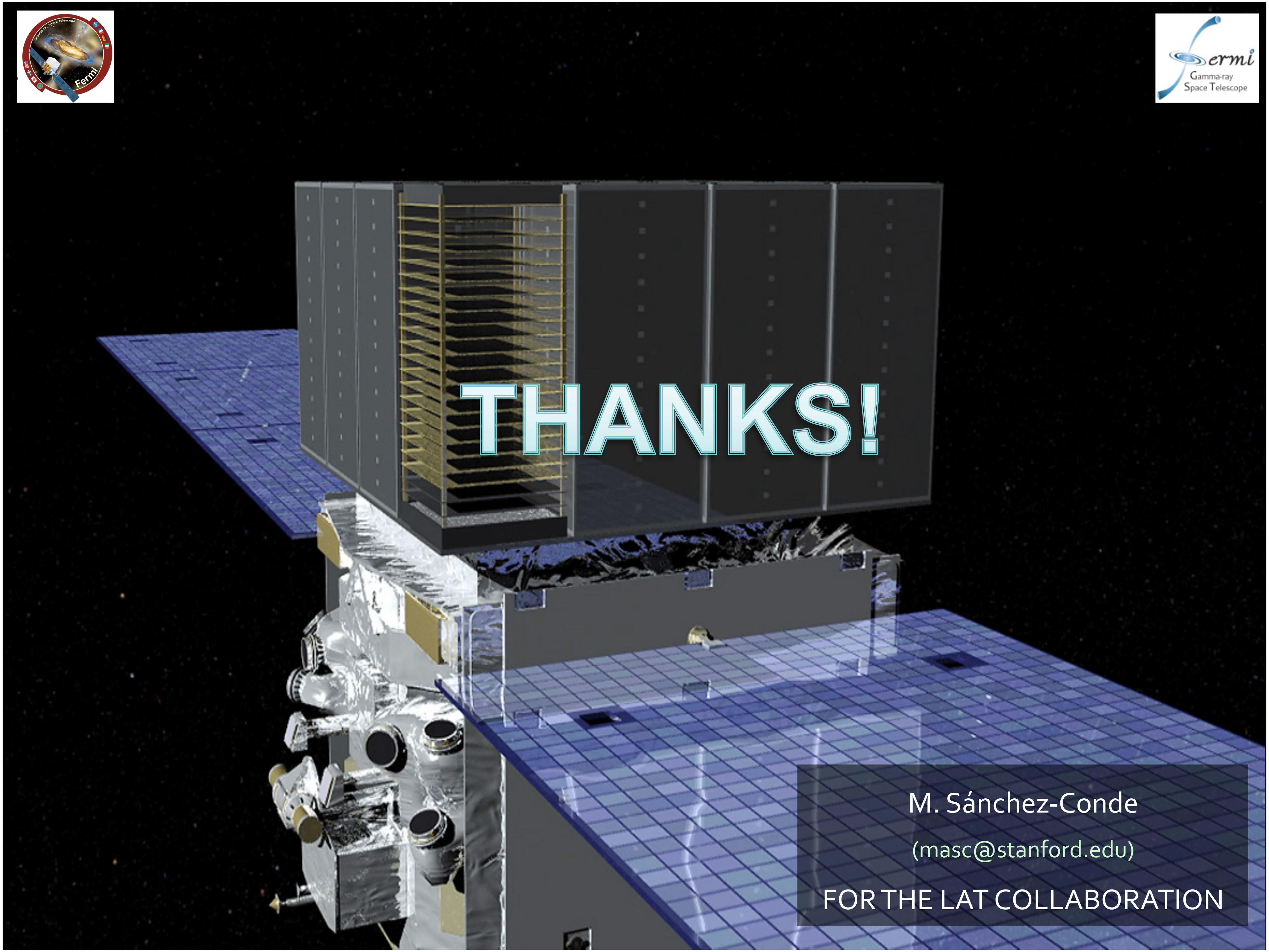
  → More than 150 Fermi LAT DM-related publications!

  → 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.

  → especially relevant for DM searches.


THANKS!
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FOR THE LAT COLLABORATION