Indirect Dark Matter Searches with Gamma-Rays: Constraints and Intriguing Hints

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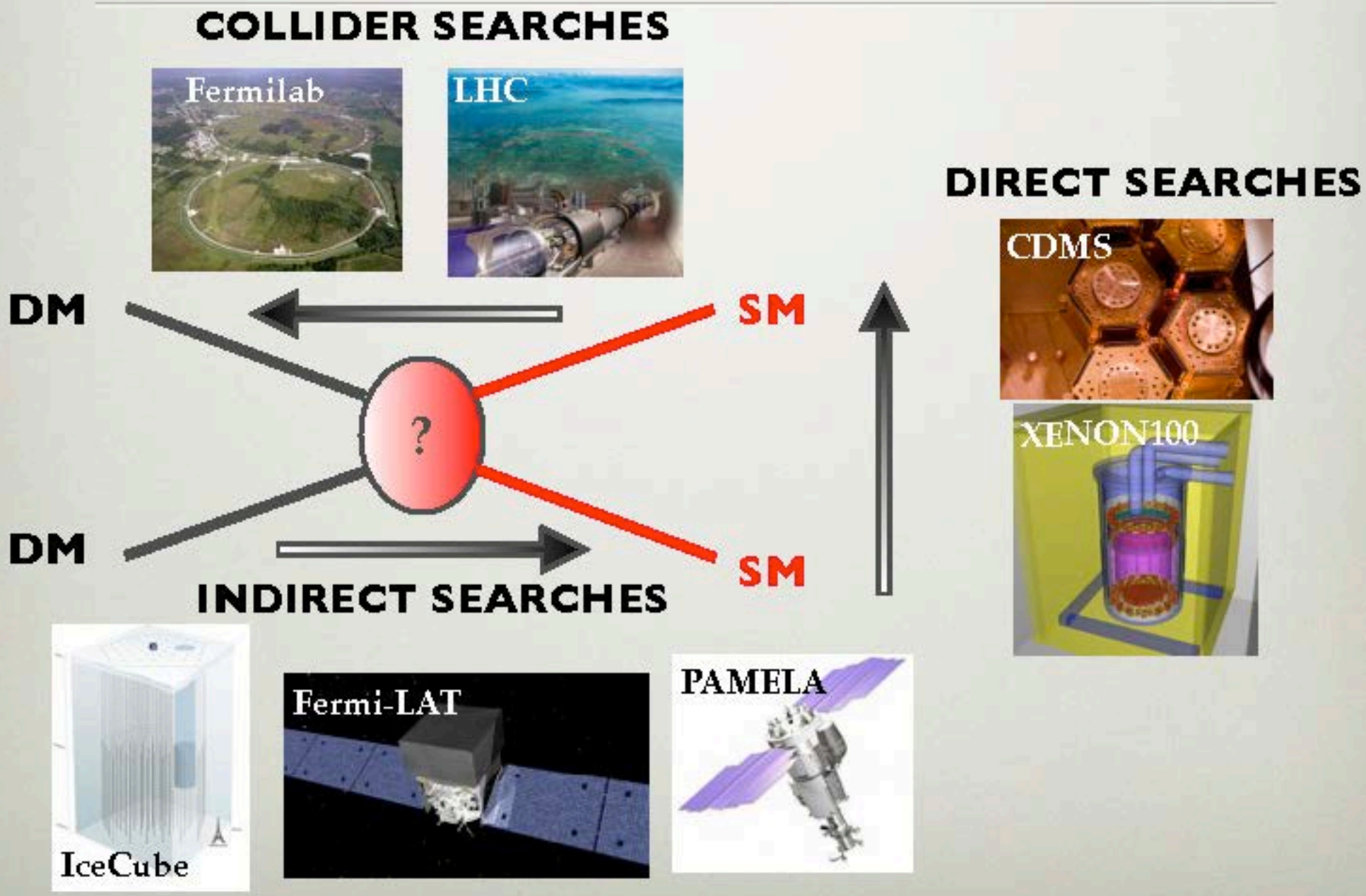
APEC Seminar
KAVLI IPMU, 30 Oct 2014

WIMP Searches

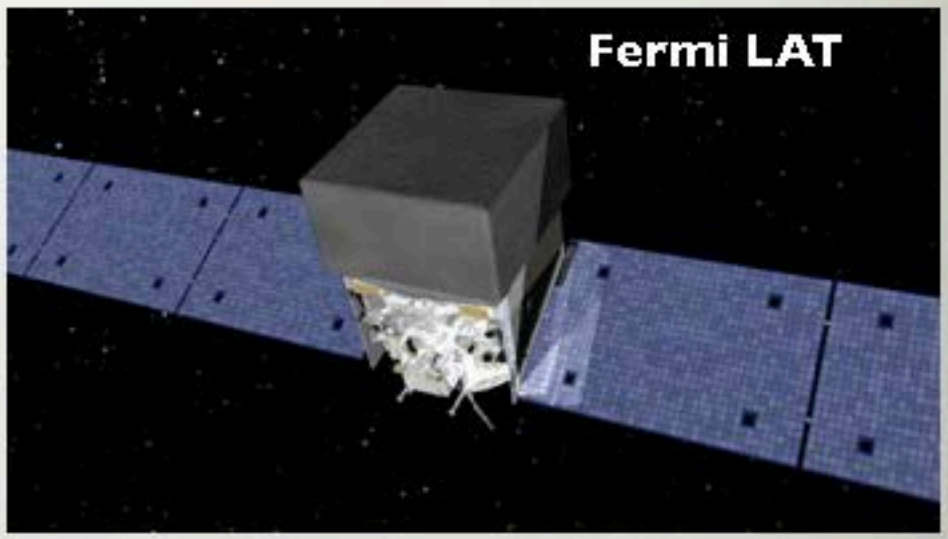


Gamma rays

ON THE GROUND

Imaging Atmospheric Cherenkov Telescopes (IACTs)

IN SPACE



WIMP Signal

- Gamma rays from DM annihilation:

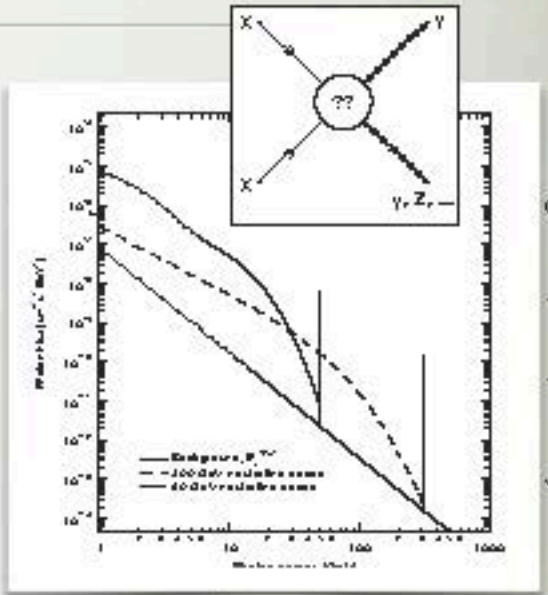
particle physics

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f$$

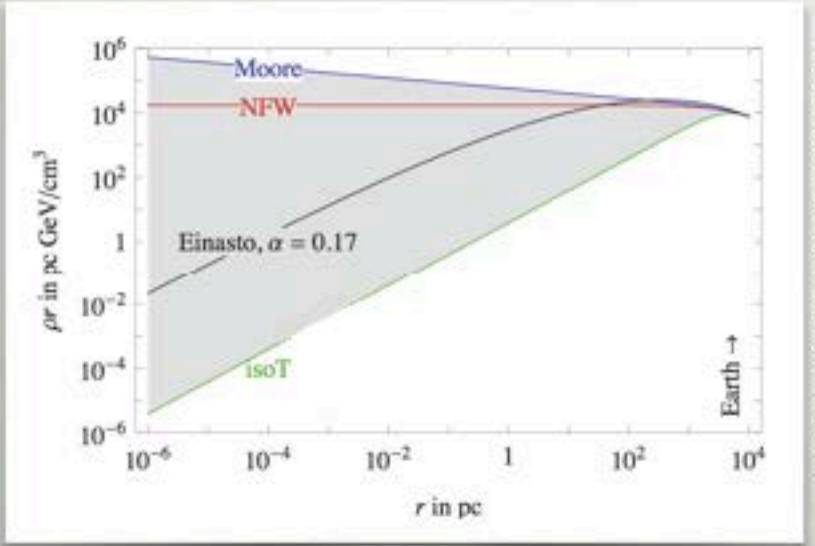
$$\times \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

J factor

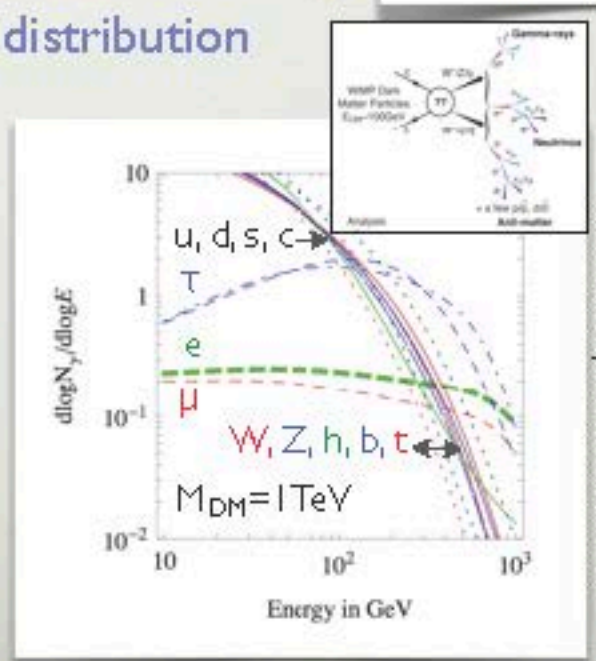
DM distribution



Bergstrom, Ullio, Buckley



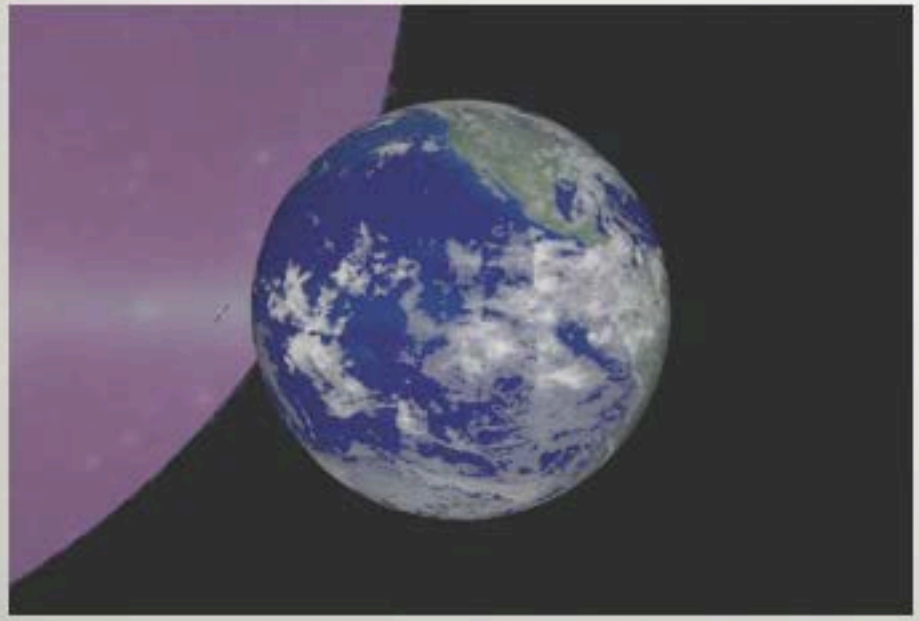
Bertone et al., arXiv:0811.3744



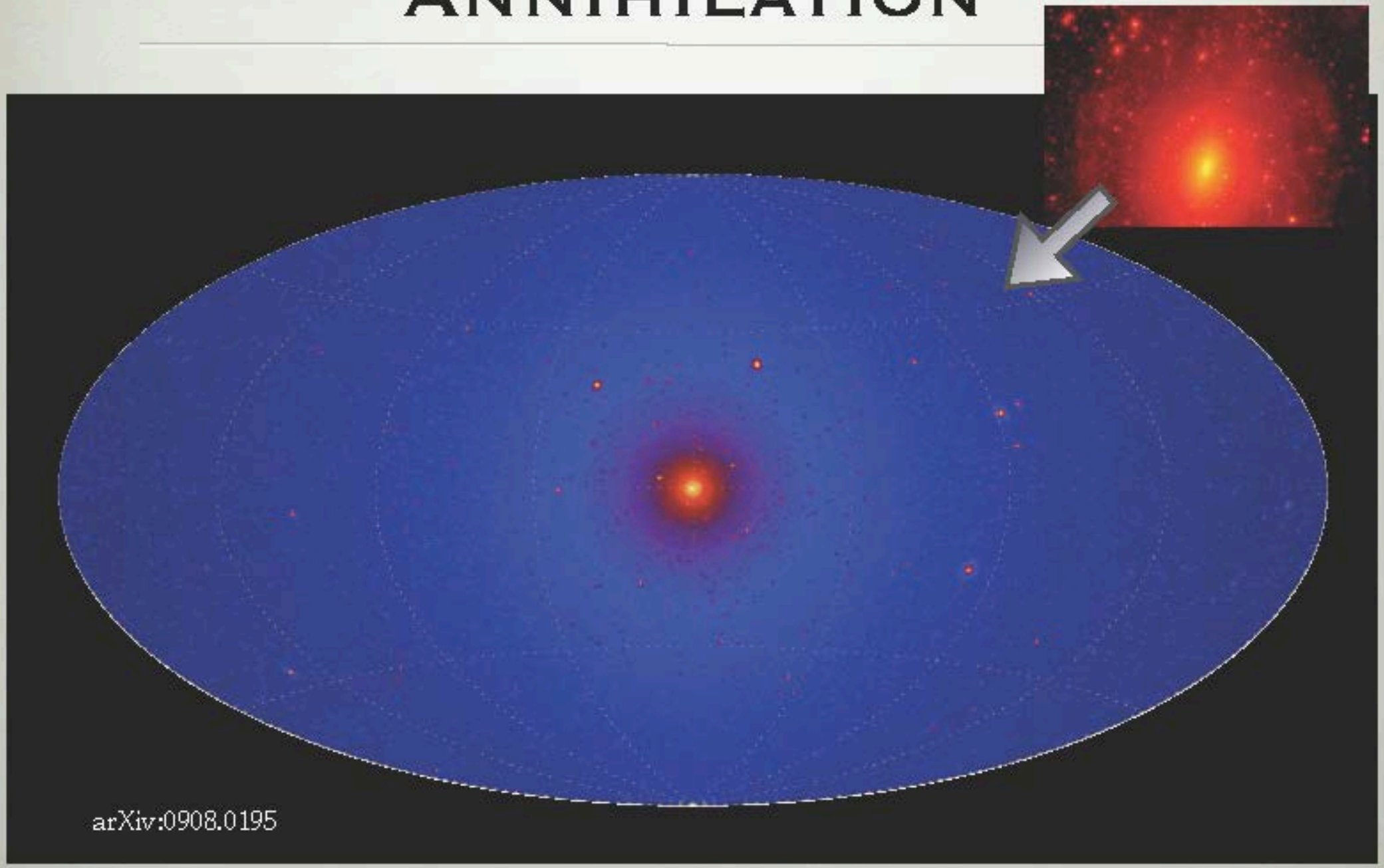
Cirelli et al, arXiv:0809.2409

Fermi Mission
The Large Area telescope

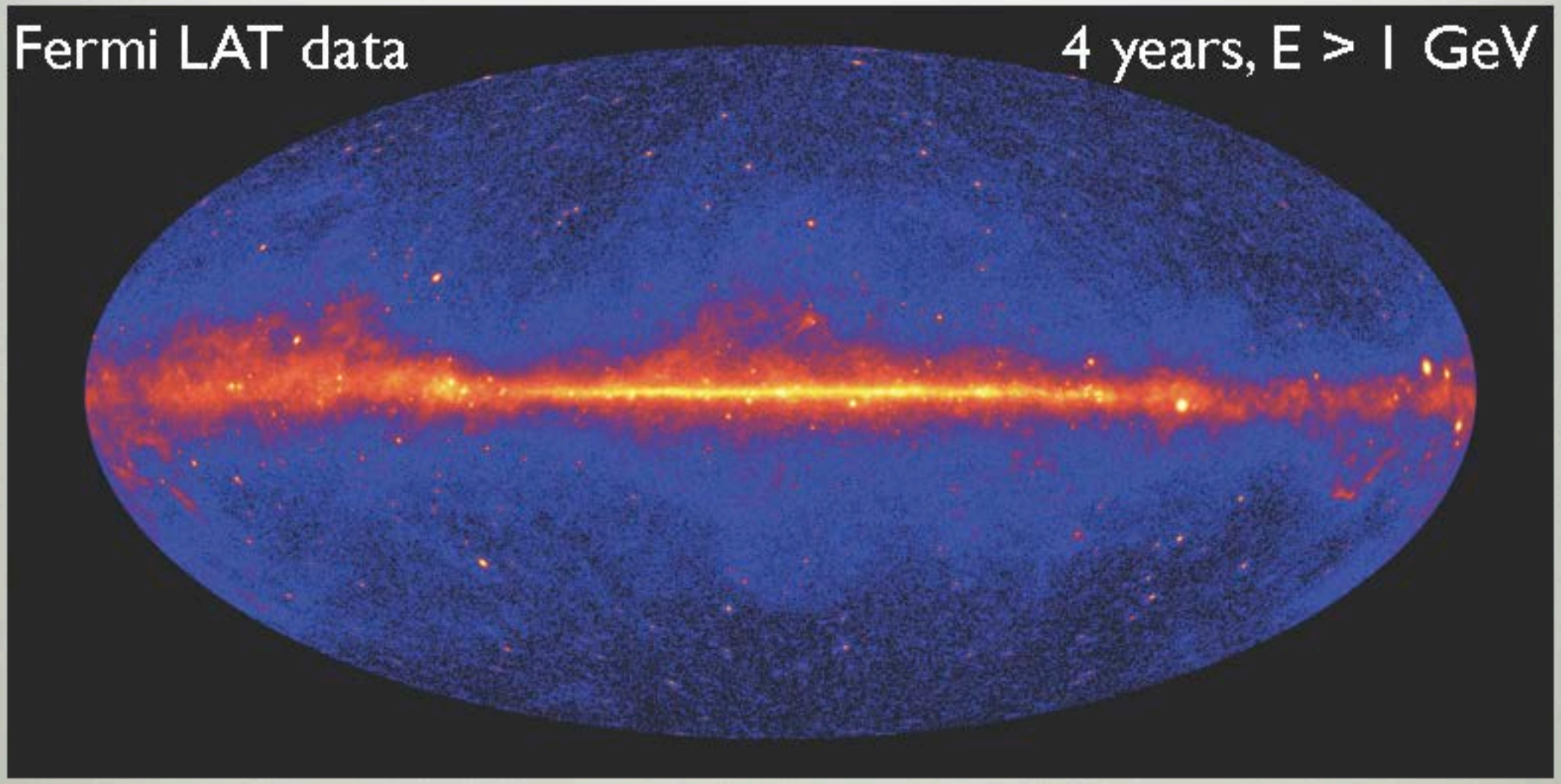
- The Fermi Large Area Telescope observes the gamma-ray sky in the 20 MeV to >300 GeV energy range with unprecedented sensitivity
- Orbit: 565 km, 25.6° inclination, circular. The LAT observes the entire sky every ~3 hrs (2 orbits)



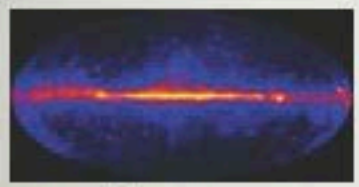
Gamma rays from DM Annihilation



The Fermi Sky



Understanding the Gamma-ray Sky



data

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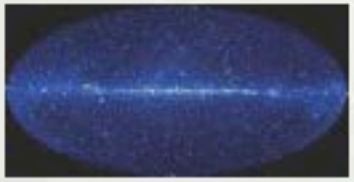
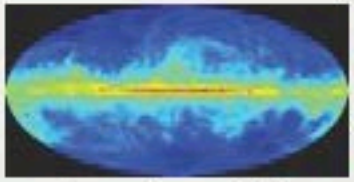


sources

+

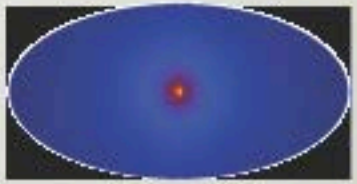


galactic diffuse

+

isotropic

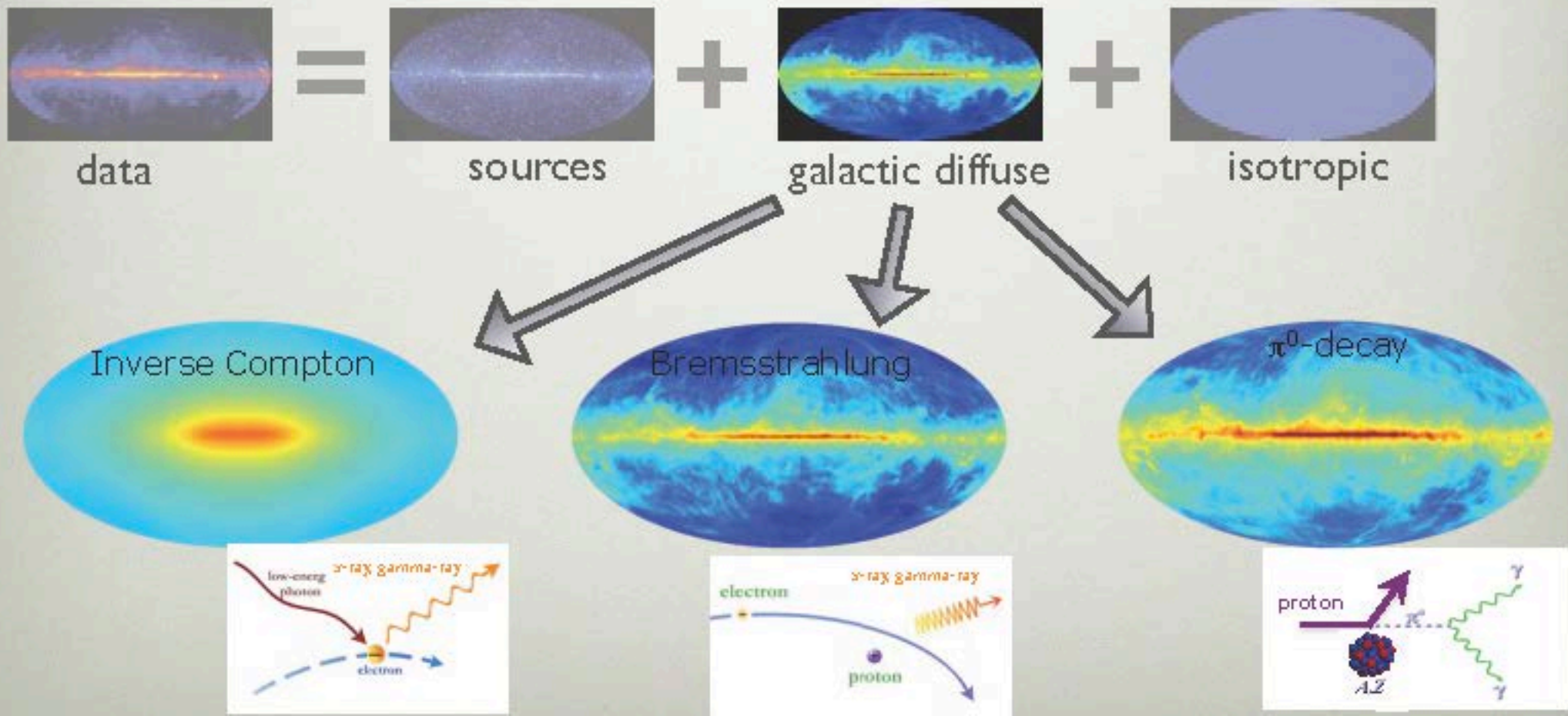
+



dark matter??

Galactic Gamma-Ray Interstellar Emission

- The diffuse gamma-ray emission from the Milky Way is produced by cosmic rays interacting with the interstellar gas and radiation field and carries important information on the acceleration, distribution, and propagation of cosmic rays.



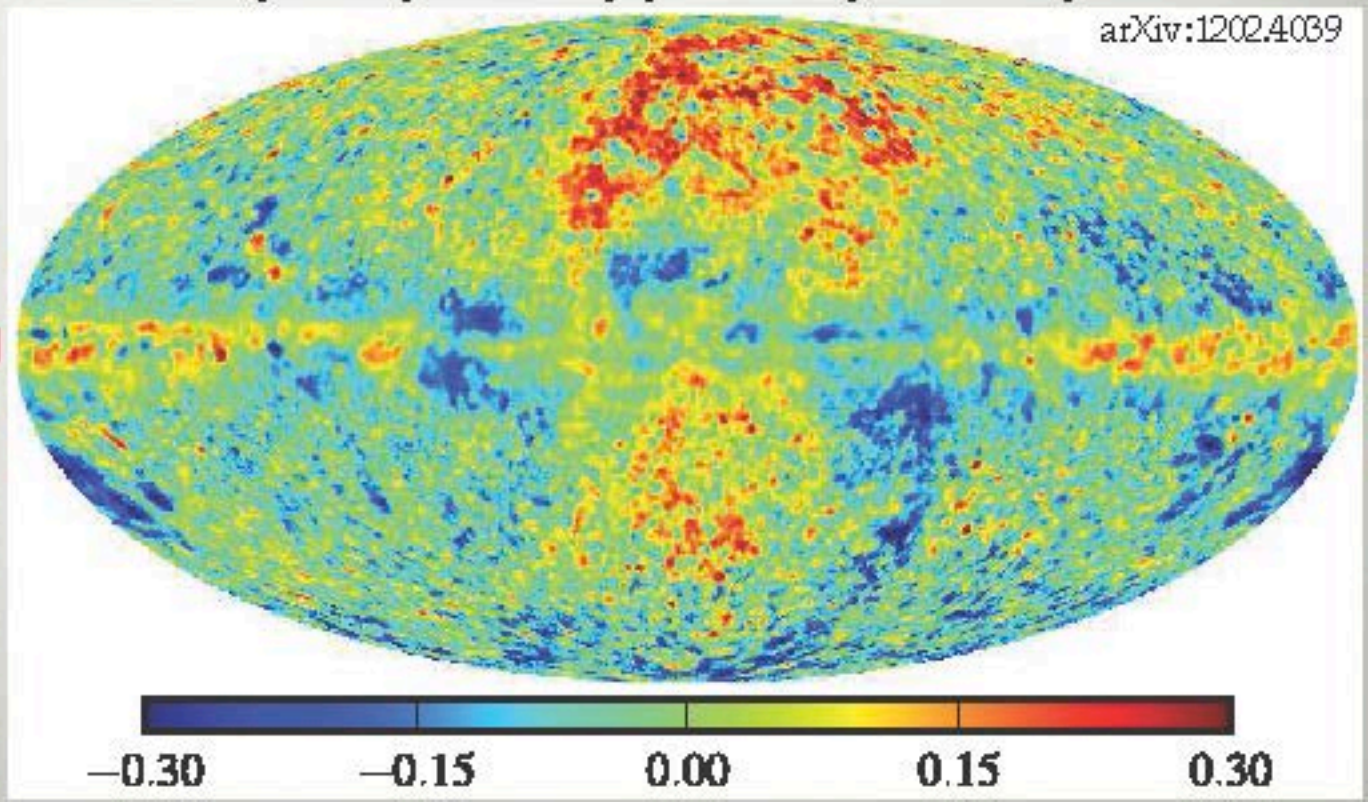
All Sky

- Cosmic ray origin, propagation, and properties of the interstellar medium can be constrained by comparing the data to predictions.
- Generate models (in agreement with CR data) varying CR source distribution, CR halo size, gas distribution (GALPROP, http://galprop.stanford.edu) and compare the predictions for gamma rays with Fermi LAT data

Fermi LAT data
21 months, 200 MeV-100 GeV

On a large scale the agreement between data and prediction overall is good, however some extended excesses and deficits stand out.

(data - prediction)/prediction) for example model



Inner Galaxy

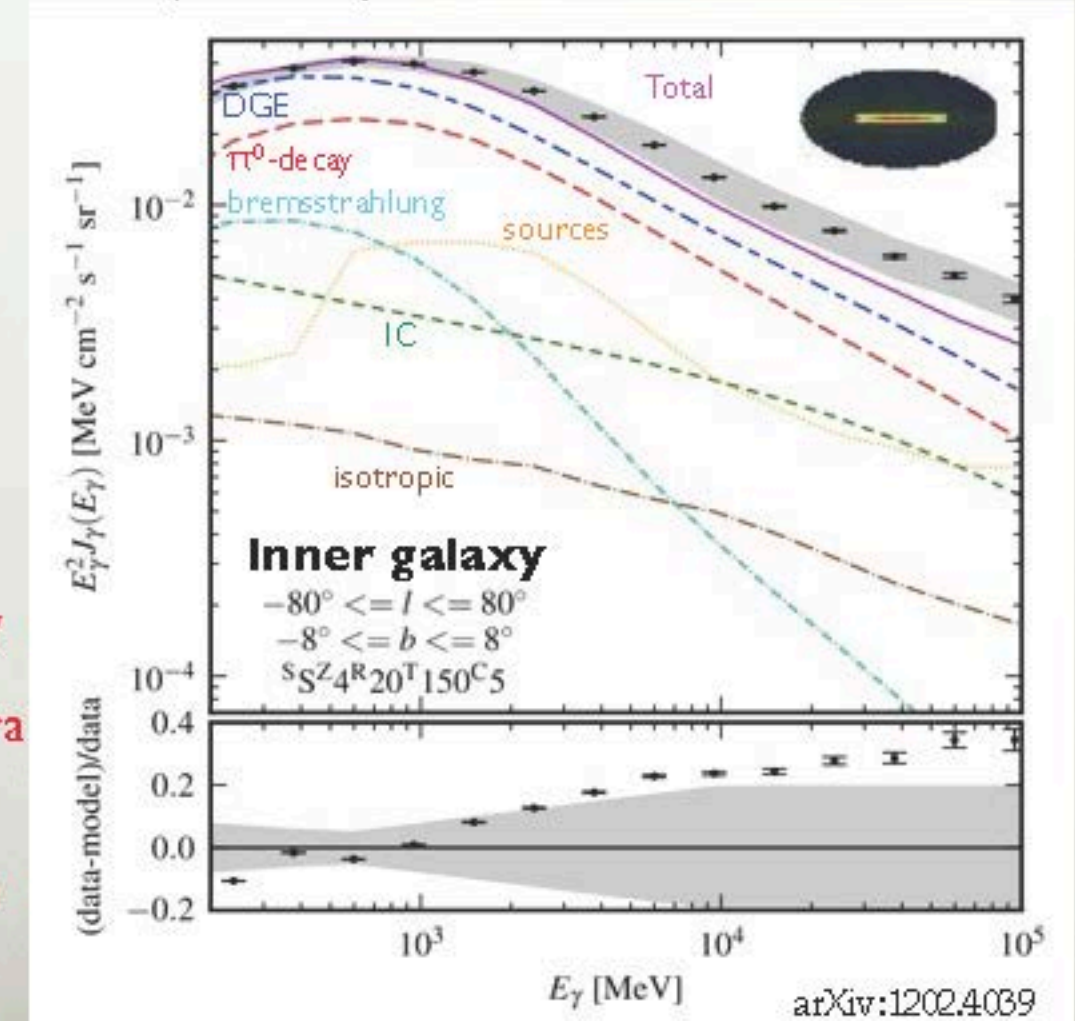
- Cosmic ray origin, propagation, and properties of the interstellar medium can be constrained by comparing the data to predictions.
- Generate models (in agreement with CR data) varying CR source distribution, CR halo size, gas distribution (GALPROP, http://galprop.stanford.edu) and compare with Fermi LAT data

Fermi LAT data
21 months, 200 MeV-100 GeV

Generally, models under-predict emission from inner Galaxy above ~1 GeV

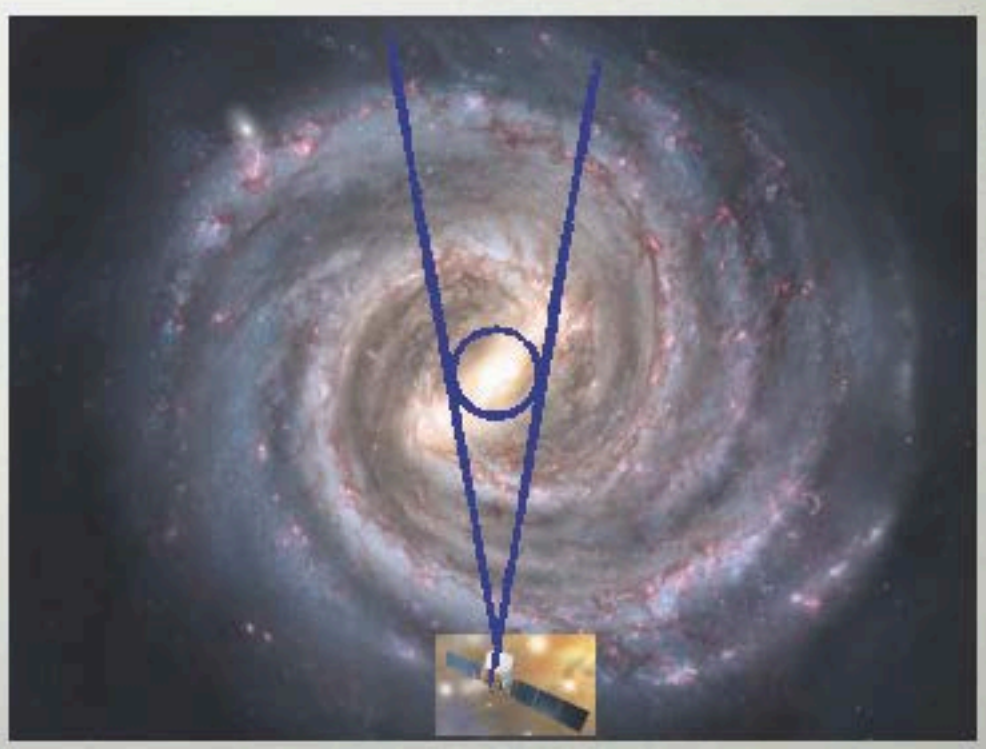
Some plausible explanations:

- unresolved point sources up to ~10 GeV
- failure of the locally measured CR spectra to represent the average for the Galaxy or, alternatively, to model a harder spectrum from freshly accelerated CR in the inner Galaxy



Galactic Center Region

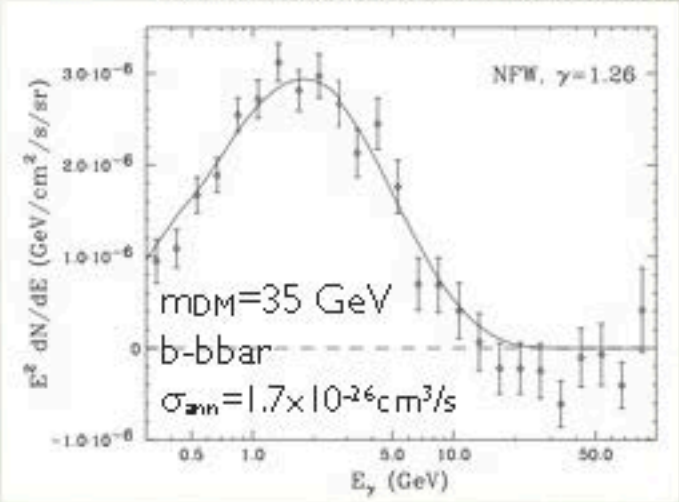
- Complex region: CR intensities, density of radiation fields and gas are highest; large uncertainties modeling the gamma-ray interstellar emission, significant foreground/ background contribution with long integration path over the entire Galactic disc
- Large density of gamma-ray sources: many energetic sources near to or in the line of sight of the GC, difficult to disentangle from interstellar emission
- A signal of new physics (dark matter annihilation/ decay) is also predicted to be largest here
- An excess in the Fermi LAT GC data was first cautiously claimed by Goodenough and Hooper (arXiv:0910.2998) consistent with a 25-30 GeV WIMP annihilating into b-bbar with an annihilation cross-section a few times larger than expected from an s-wave thermal relic ($9\times10^{-26}cm^3/s$) and a DM profile somewhat steeper than NFW (γ=1.1)



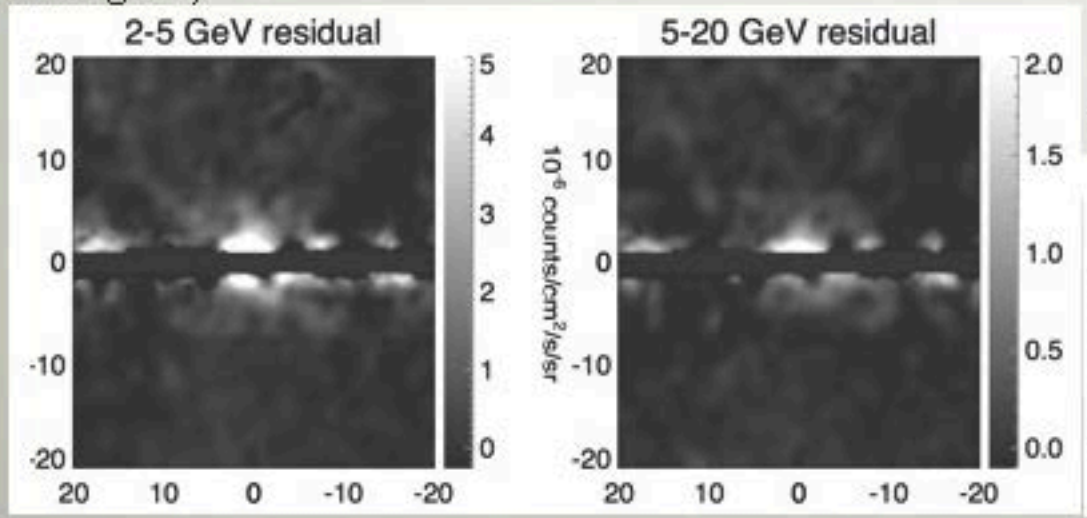
Current Status of GC DM Searches in Gamma-ray

- A re-analysis of the Fermi LAT data by Daylan et al (with more statistics, over 5 years, and improved event selection aimed at reducing background leakage in the search region) confirms the presence of an excess on top of the adopted background models
- The addition of the DM component improves the data-model agreement very significantly
- The signal can be modeled by DM annihilating into b-bbar with a mass of 31-40 GeV and $\sigma_{ann}=(1.4\text{-}2)\times10^{-26}\,cm^3/s$

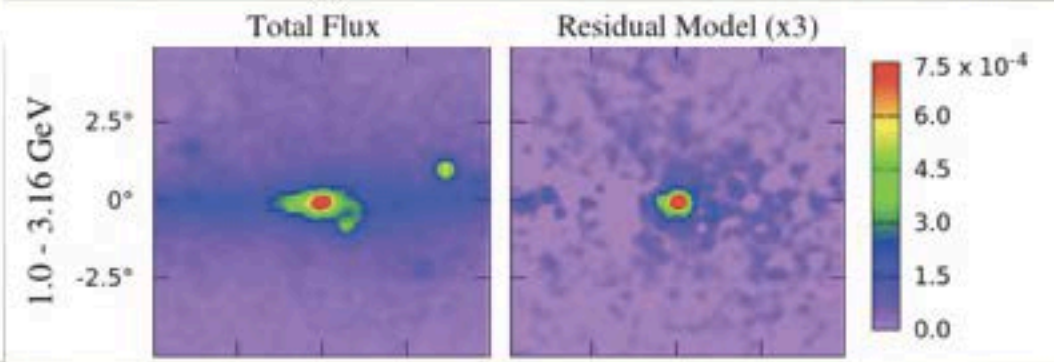
Daylan et al, arXiv:1402.6703



Inner galaxy



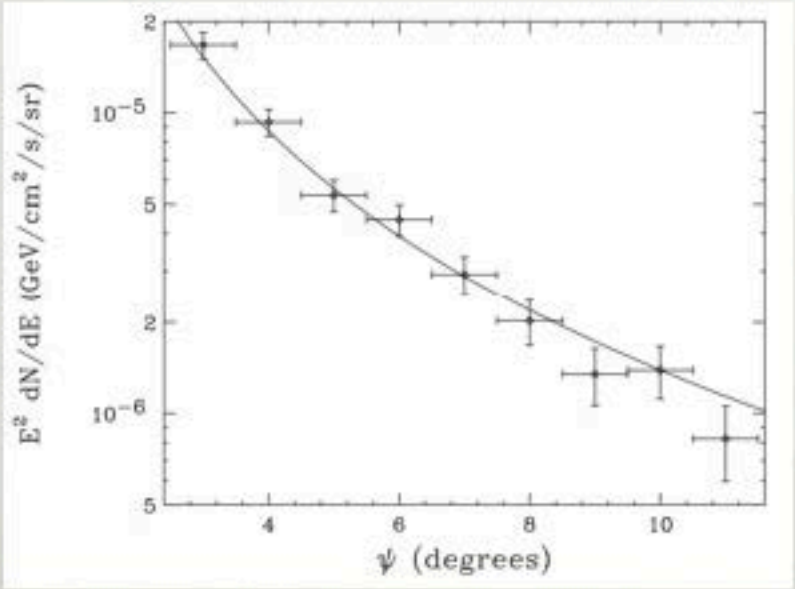
Galactic center region

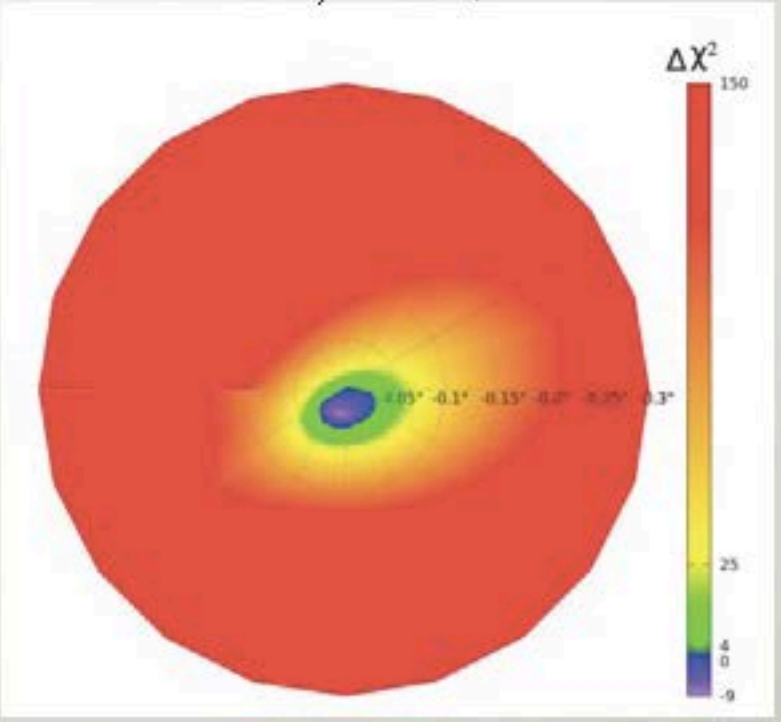


Current Status of GC DM Searches in Gamma-ray

- The morphology of the excess in Daylan et al is consistent with an NFW profile with slope γ=1.1-1.3 centered within 0.05° of Sgr A*. Deviations from the spherically symmetric morphology are disfavored
- Independent fits in annuli about the direction of the GC confirm the excess up to at least 10° from the Galactic plane following a steep NFW profile

Daylan et al, arXiv:1402.6703

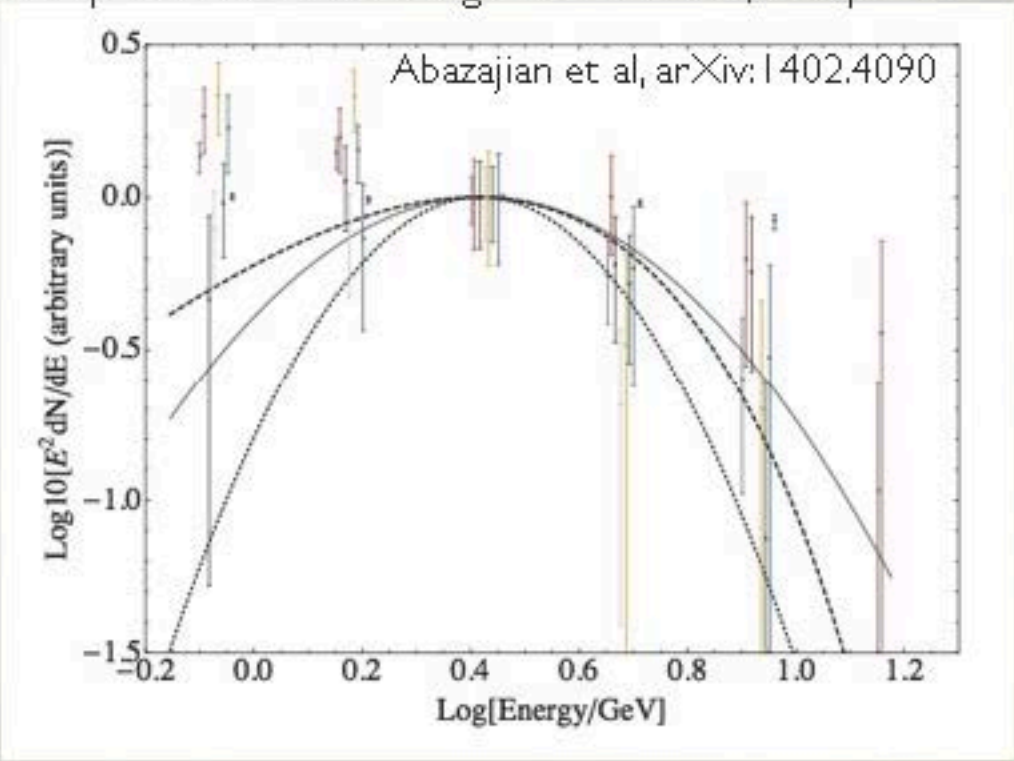




Current Status of GC DM Searches in Gamma-ray

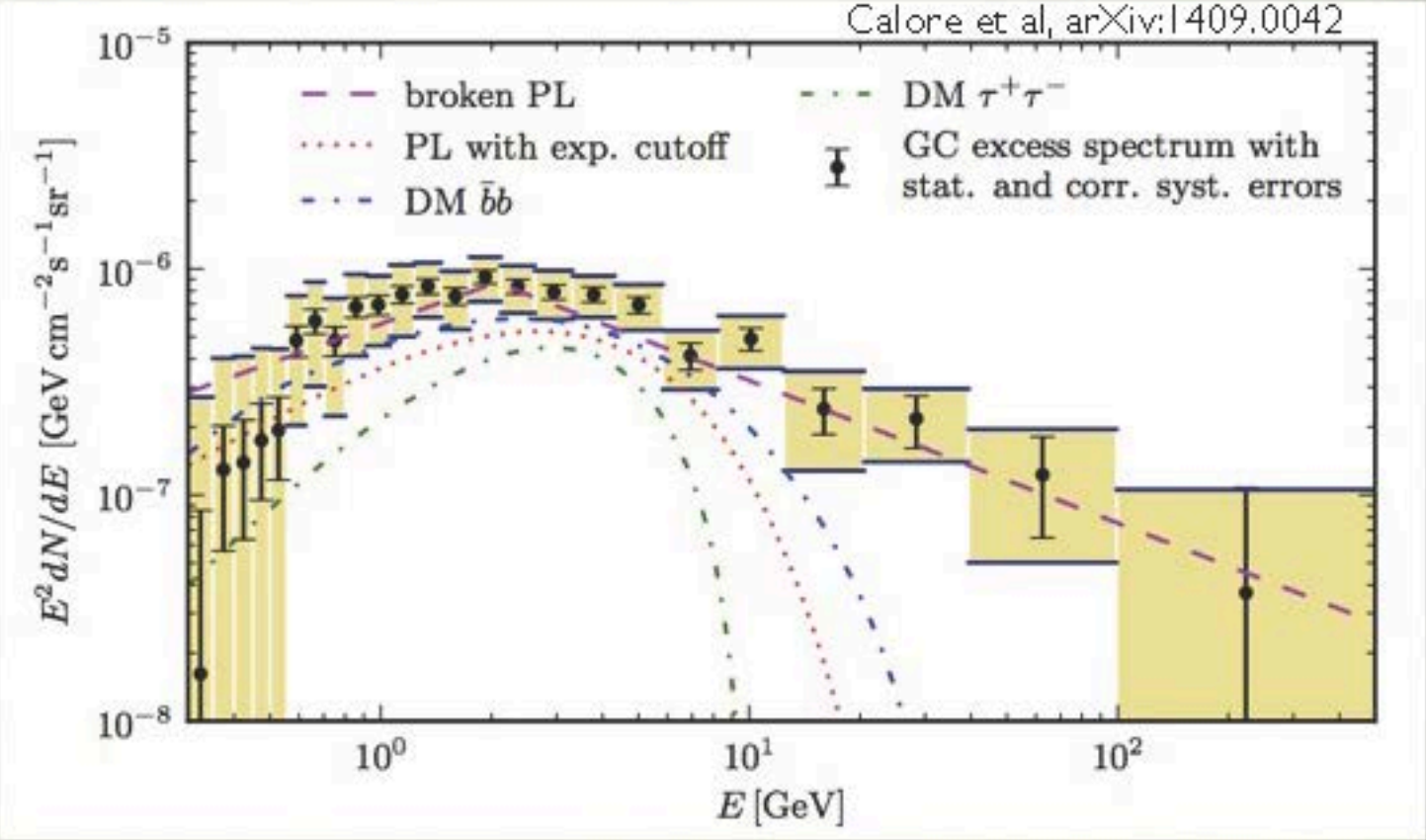
- A similar excess has been found by the work of Abazajian et al, focused on a 7°x7° region centered at the GC. In addition to DM, an unresolved pulsar interpretation is found plausible
- Based on globular clusters observations, observed signal is found to be consistent with 3000-5000 millisecond pulsars in a 1 kpc x 1 kpc region
- Can MSPs extend out to 10°?

GC extended excess, lines
MSP predictions based on globular clusters, data points



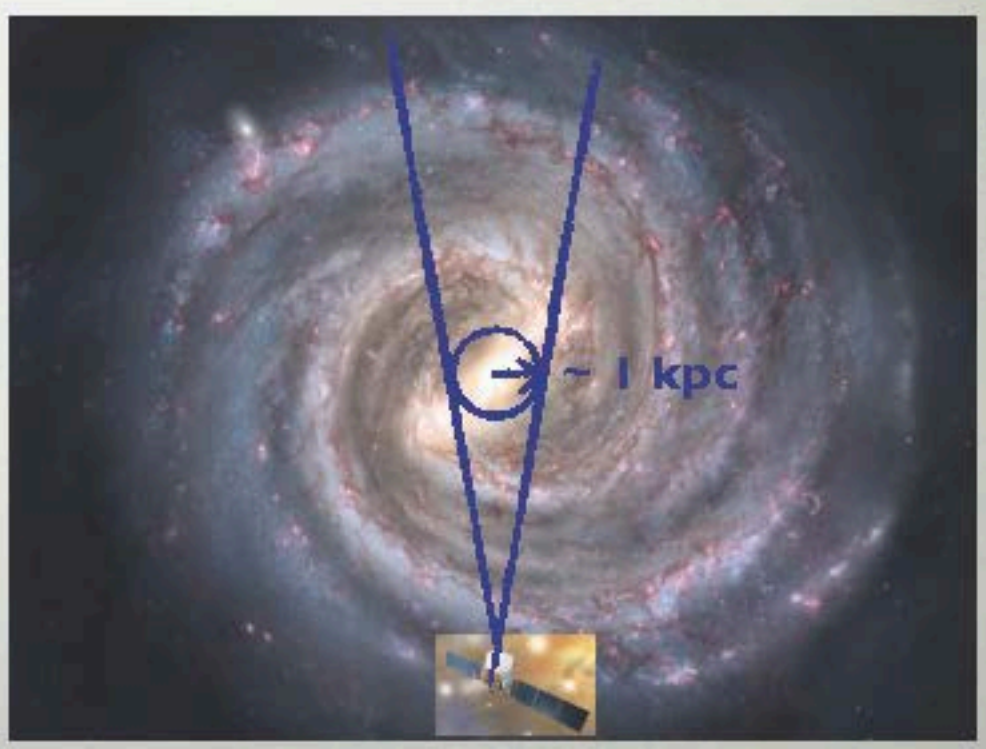
Current Status of GC DM Searches in Gamma-ray

- More extensive study of the background model systematics
- Broad range of diffuse emission models
- Results compatible with dark matter annihilation into b-bbar and a mass of ~50 GeV



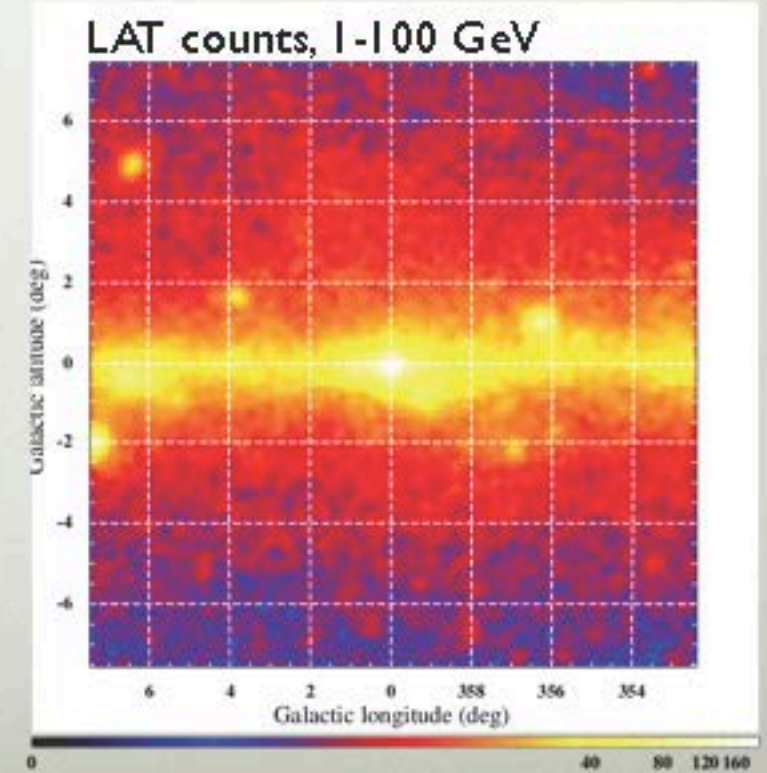
Galactic Center Region

- Focus on a 15°×15° region (~ 1 kpc) around Galactic center



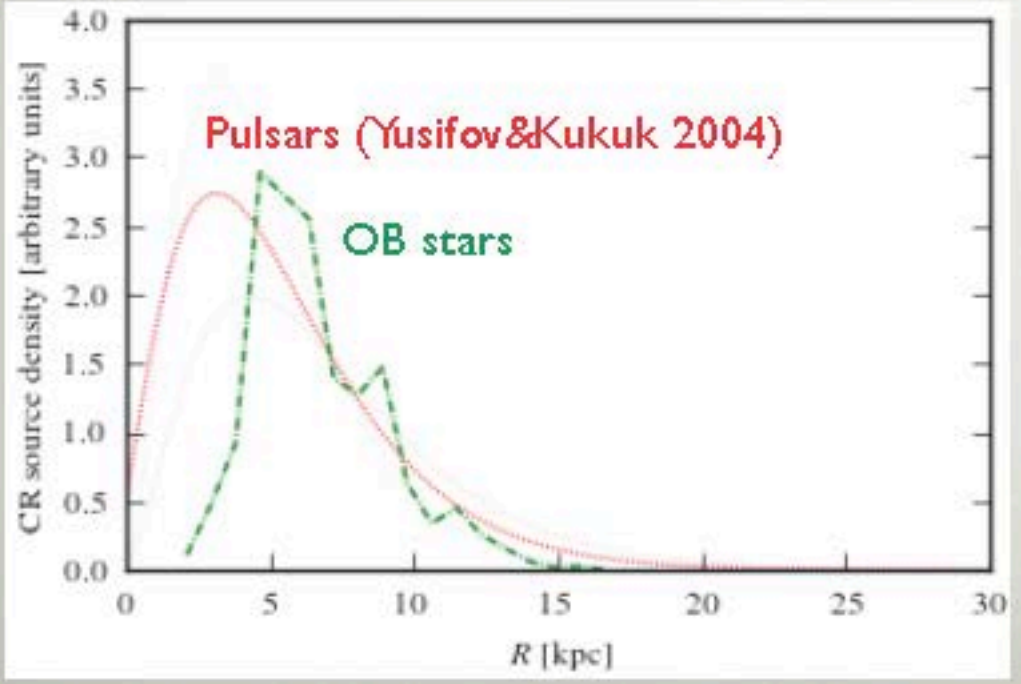
Galactic Center Region

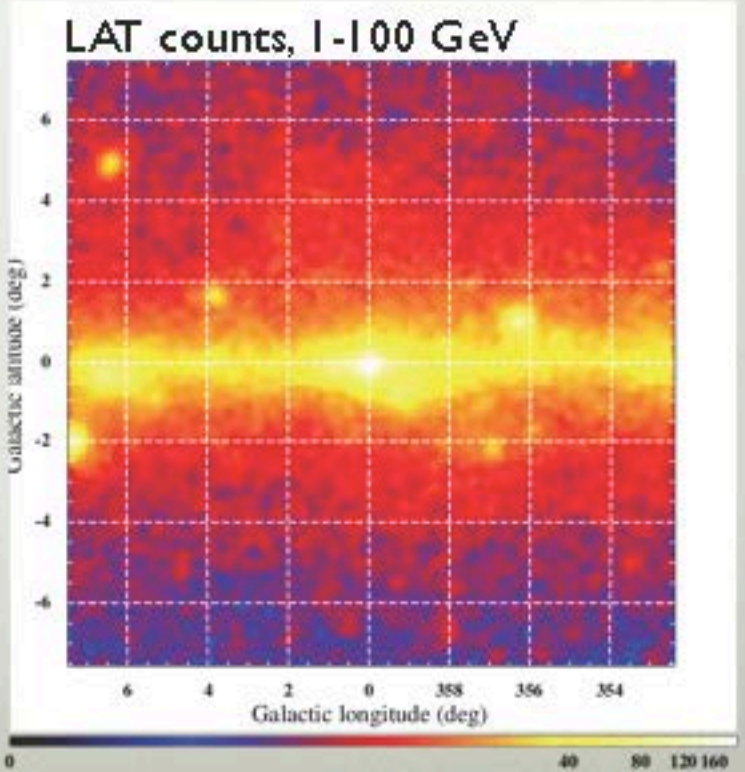
- Focus on a 15°×15° region (~ 1 kpc) around Galactic center
- Data selection: 1-100 GeV, CLEAN class, FRONT converting events (large effective area and narrow PSF); PASS 7 reprocessed; 62 months.



Modeling the Interstellar Emission

- Interstellar emission models: use GALPROP models with prop. parameters consistent with CR data and in good agreement with all-sky gamma-ray data, from *Ackermann et al, 2012, ApJ 750*. Select two models with broad range in the radial extent of the CR source distribution (Pulsars, OB stars) as baseline
- Tune the baseline models to gamma-ray data outside of the ROI for improved foreground/background determination





Background Tuning Procedure

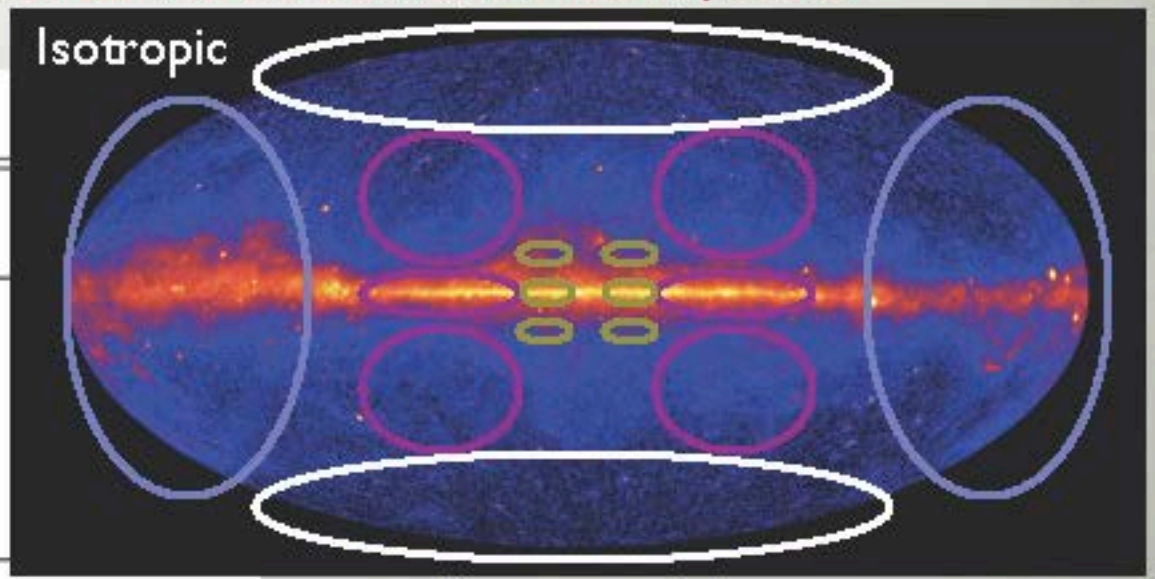
- Determine intensity for π^0 (from HI and H_2 gas) and IC contributions in galactocentric rings,
  - IC component divided in rings (dev. version of GALPROP), same boundaries as the gas: these additional degrees of freedom can compensate for uncertainies in the GALPROP model of the electron spectrum or ISRF used to calculate the IC templates
- Isotropic and Loop I (*Wolleben, 2007, ApJ 664*) emissions also fitted to the data
- Different sky regions are employed based on where the components that are fitted contribute most. Point source locations and spectra taken from the preliminary 3FGL.
- Regions containing structures not modeled or that might bias the fit results are not used to tune the IEM (Fermi bubbles, Cygnus region.)The 15°x15° region is also excluded

➡ Two tuning procedures: one adjusting intensity only, the other also allowing spectral adjustment (broken power law, break at ~2 GeV) for π^0 production within the solar circle. No freedom in IC spectrum

➡ Four variants for the foreground/background IEM: Pulsars/OB Stars, tuned intensity/index

Galactocentric ring boundaries.

Ring #	R_{min} [kpc]	R_{max} [kpc]	Longitude Range (Full)
1	0	1.5	$-10° \leq l \leq 10°$
2	1.5	2.5	$-17° \leq l \leq 17°$
3	2.5	3.5	$-24° < l < 24°$
4	3.5	8.0	$-70° < l < 70°$
5	8.0	10.0	$-180 \leq l \leq 180°$
6	10.0	50.0	$-180 \leq l \leq 180°$

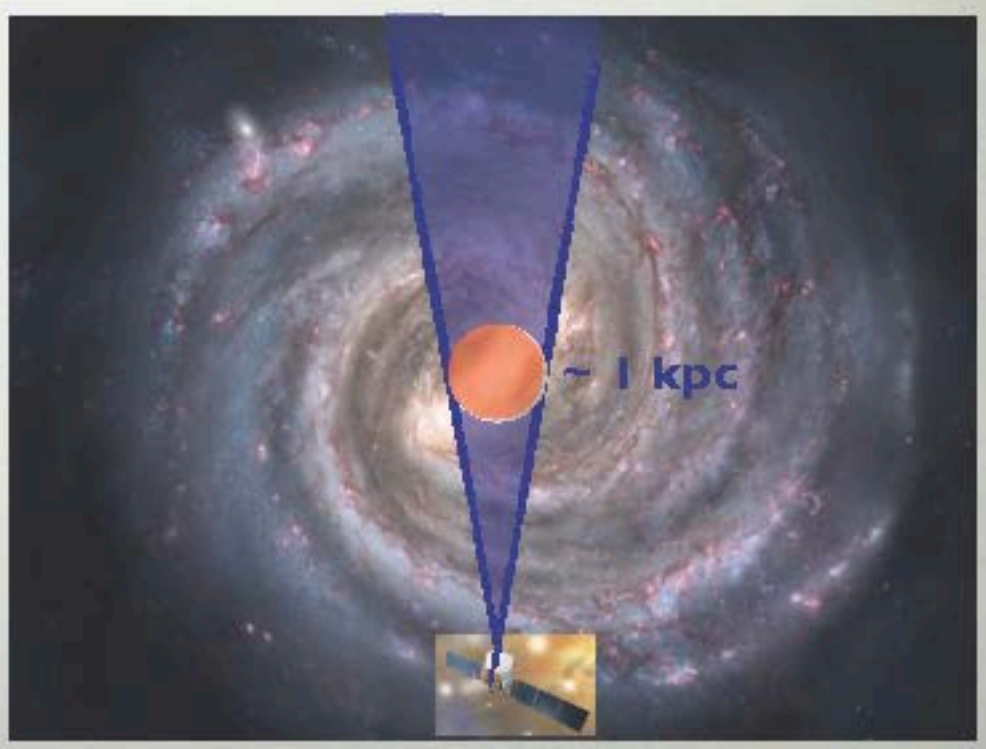


Modeling the 15°x15° ROI

- Model the emission from the 15°x15° ROI for each of the 4 foreground/background models
- Point sources in the region are determined consistently with these models - we do not use existing catalogs
  - identify preliminary locations of point source candidates by applying *PGWave* (*Damiani et al. 1997, ApJ, 483* wavelet algorithm, assumes flat background) to the data in 4 equally spaced LogE bins in the1-100 GeV range
  - for each of the (fixed) models, determine position and initial values of the spectra of the point source candidates (*Pointlike*)
  - obtain list of point source candidates with TS>9 for the analysis of the 15°x15° ROI

➡ Intensities for the innermost ring for HI/H_2 π^0, and IC are determined by fitting the data in this region concurrently with the point source candidates. Fore/background models held fixed

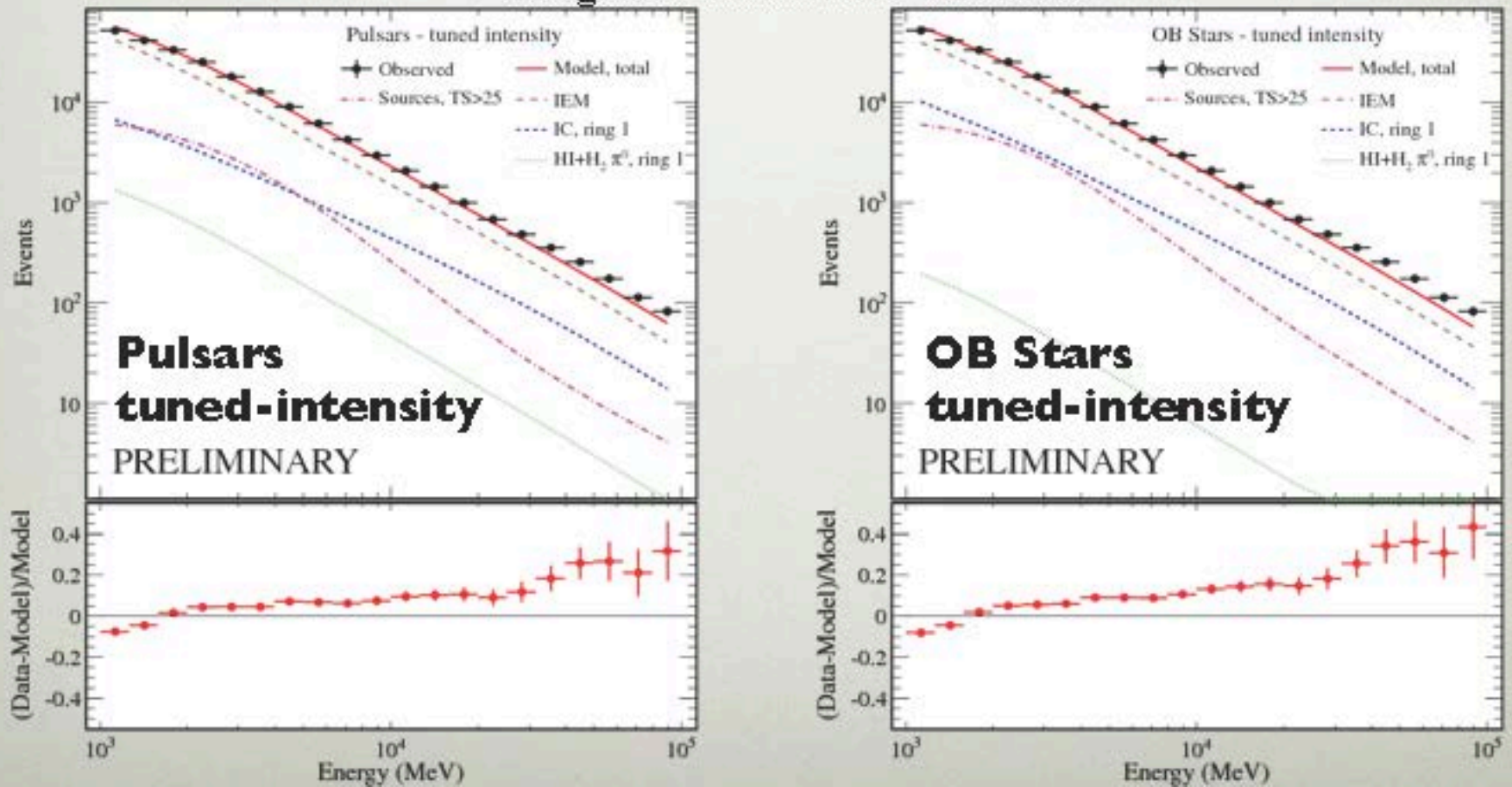
- Repeat procedure twice, until no significant point-like excesses are left in the residuals
- Bremsstrahlung and HII π^0 emissions are subdominant and are fixed to GALPROP prediction



Results

- The foreground/background accounts for most of the emission in the region.
- The data-model agreement is within 5-10% averaged over the 15°x15° ROI up to ~ 10 GeV. The models are too bright below ~2 GeV, and too dim above

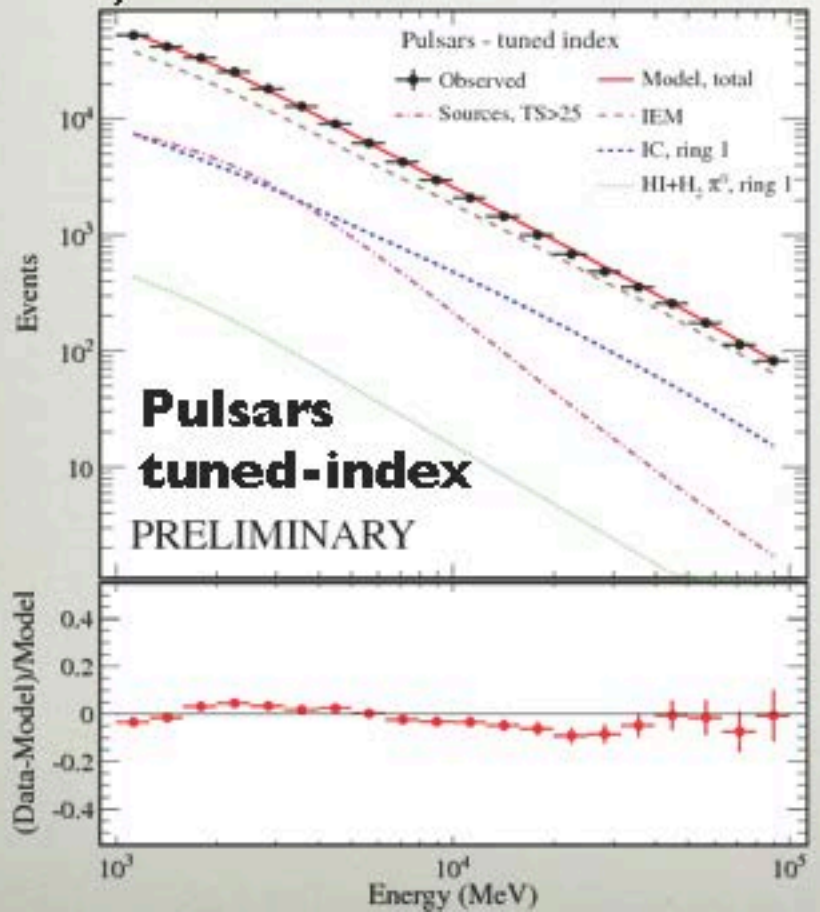
Integrated counts in 15°x15° ROI

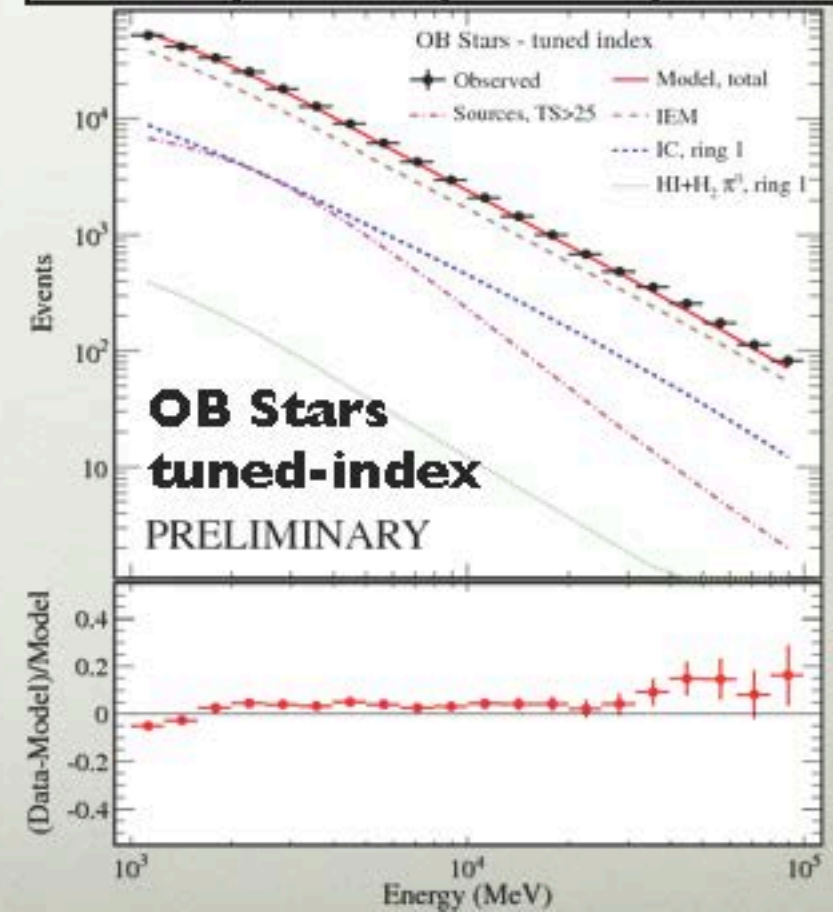


Results

- Agreement is better for tuned index models
- ➡ For all foreground/background models, the fitted IC emission for ring 1 is brighter than the gas emission and larger (7-30×) than predicted from GALPROP for the baseline models. This could be due to higher intensity of ISRF and/or higher CR lepton intensities than assumed
- Point source contribution comparable to IC
- HI/H_2 pi0 intensities are subdominant and less than predicted by GALPROP for the baseline models

Integrated flux in 15°x15° ROI, E>1GeV, 10^{-8} ph cm^{-2} s^{-1}			
IC, Ring 1	π^0, Ring 1	IC, IEM	π^0, IEM
41-59	1-8	24-33	151-164



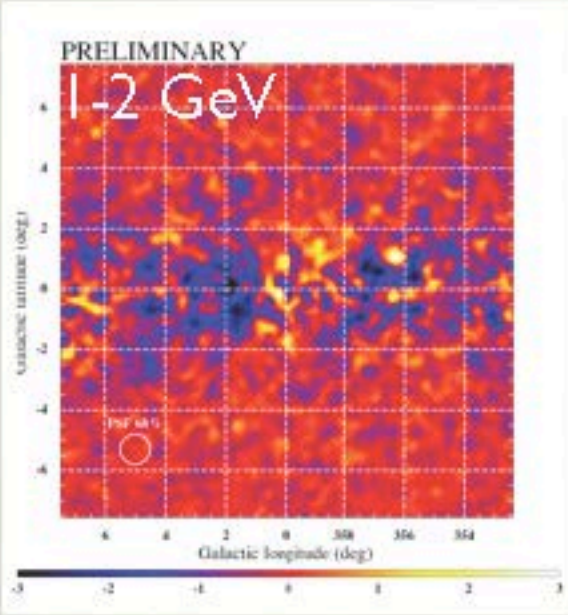


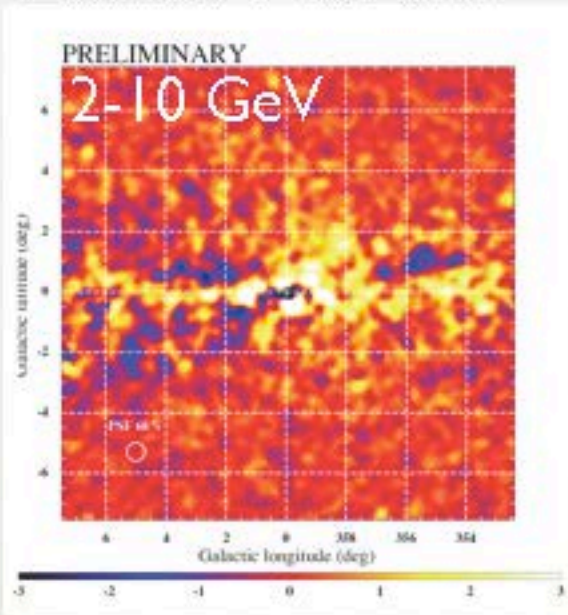
Results - Residual Maps

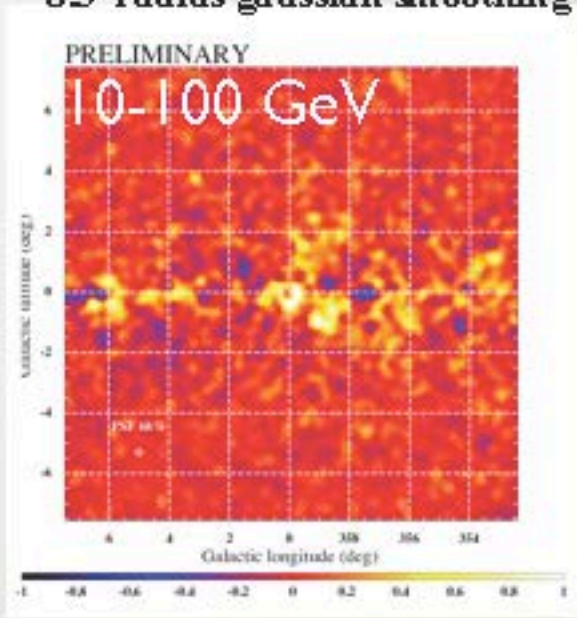
DATA-MODEL

Counts in 0.1°x0.1° pixels
0.3° radius gaussian smoothing

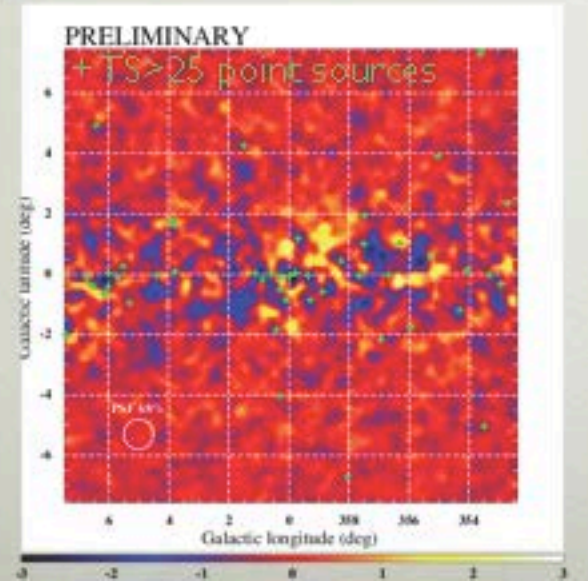
Pulsars, tuned-intensity

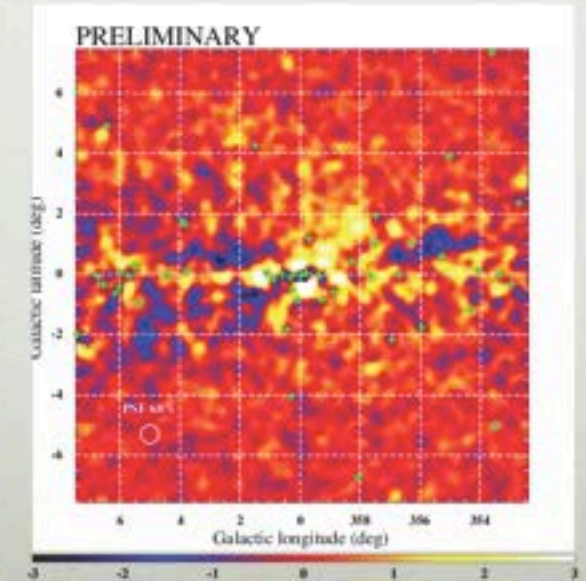


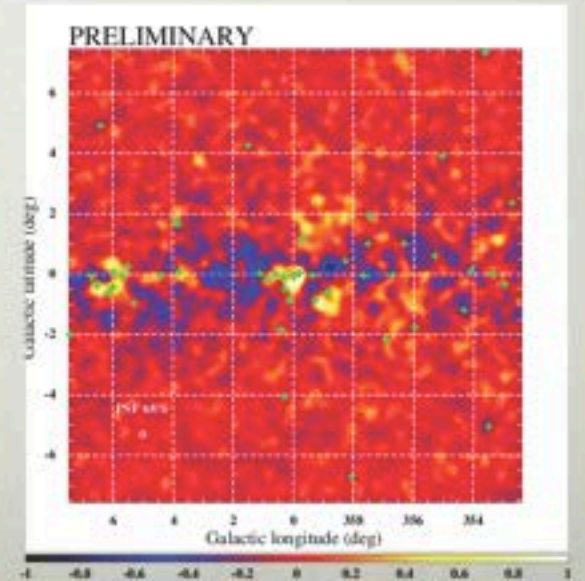




Pulsars, tuned-index



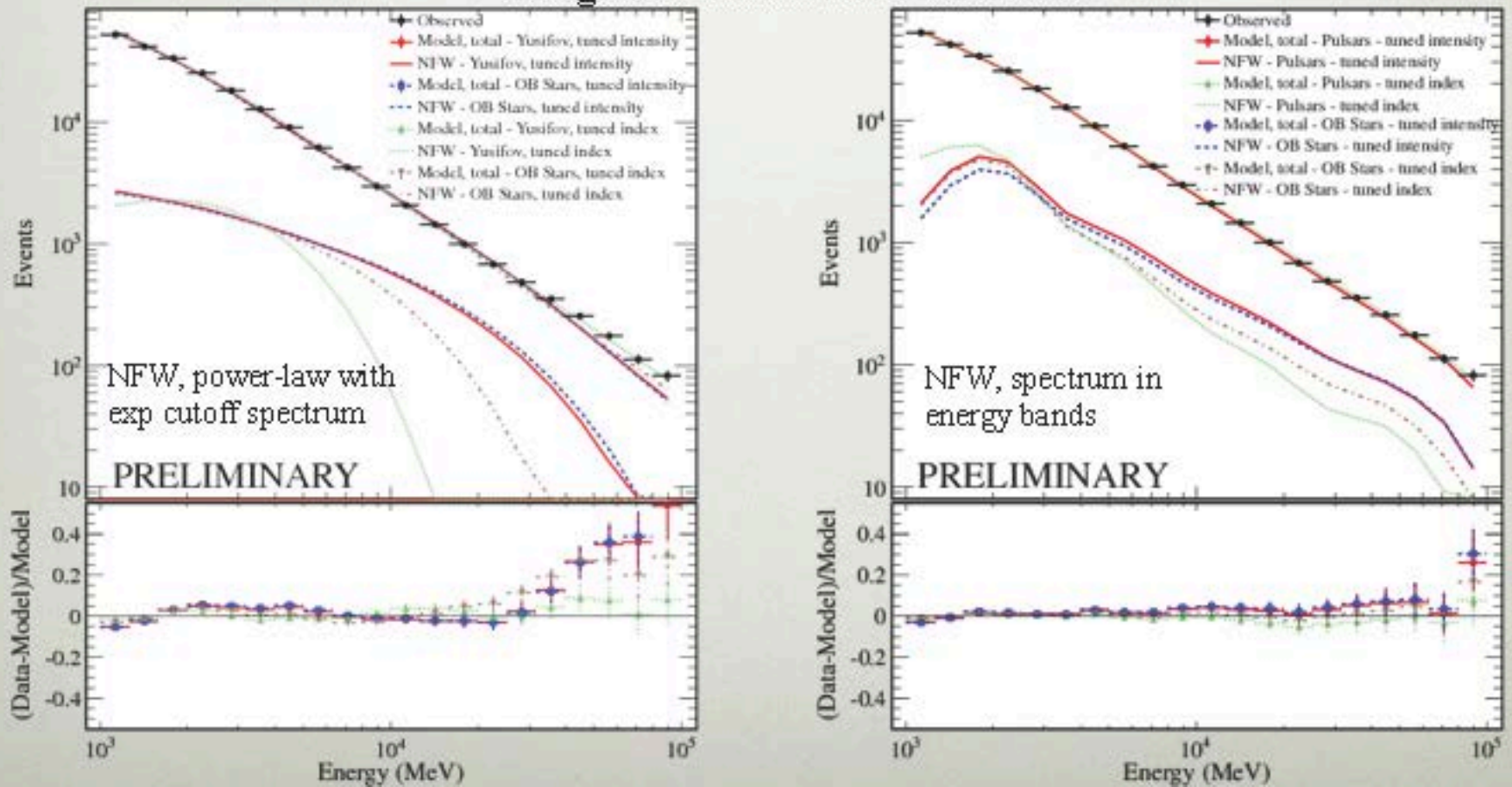




Additional Templates

- We test the possibility that an additional component centered at the GC contributes to the data (2D gaussians, Navarro-Frenk-White, or a gas-like distribution as proxy for unresolved sources)
- Peaked profiles with long tails (NFW, NFW contracted) yield the most significant improvements in the data-model agreement for the four variants of the foreground/background models. IC ring 1 contribution ~2-3x smaller than without additional component and HI ring 1 contribution is ~2-5x larger
- ➡ The predicted spectrum depends on the foreground/background models.

Integrated counts in 15°x15° ROI



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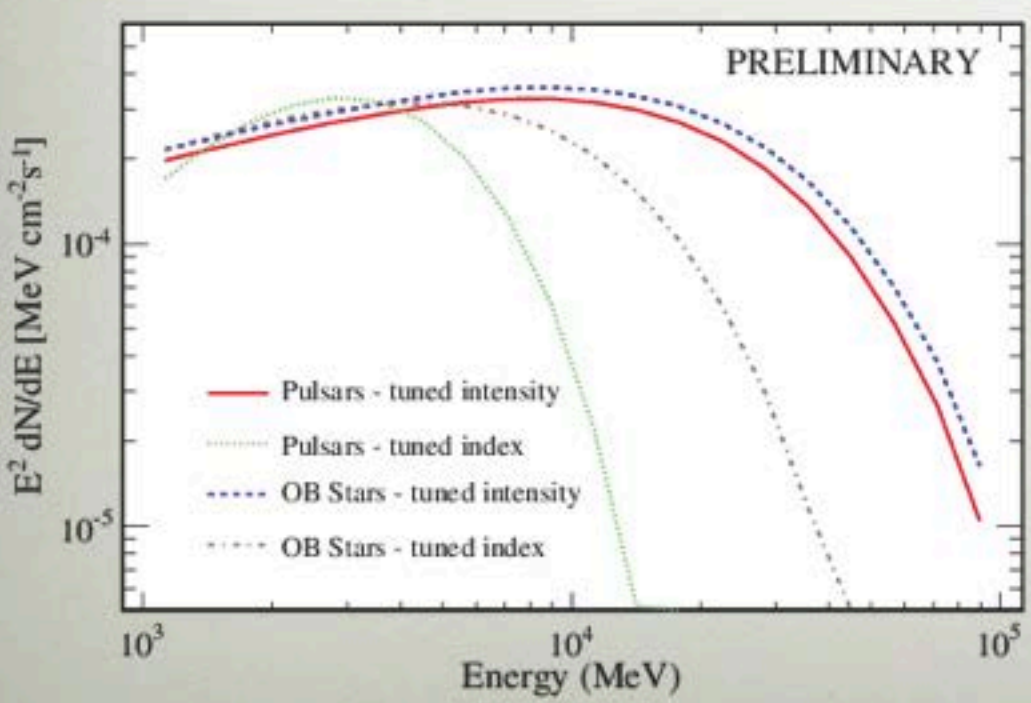
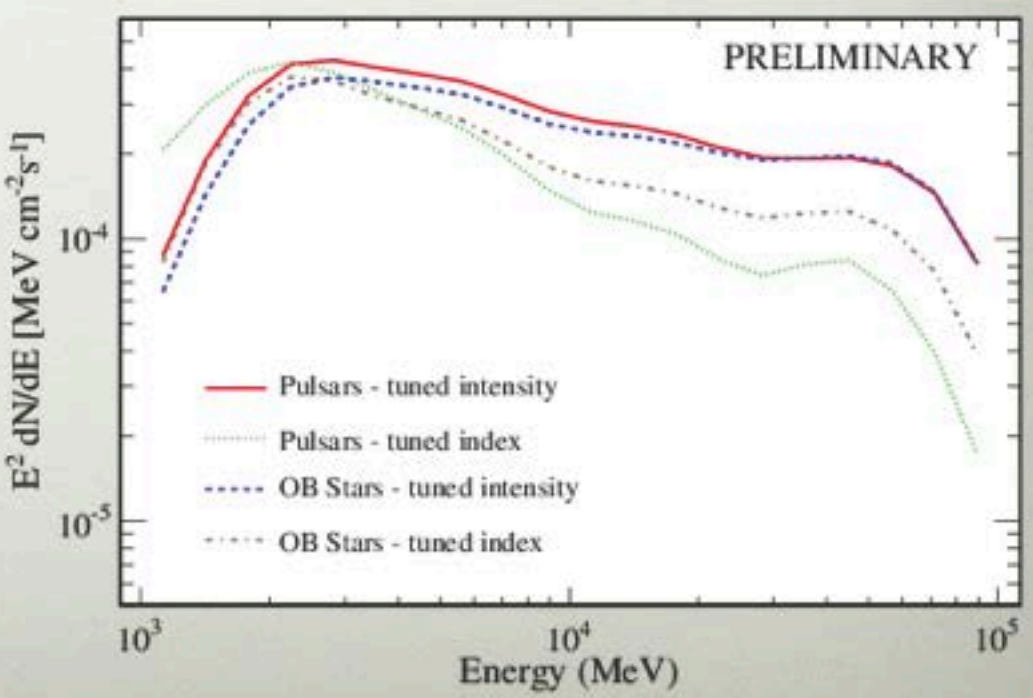
- ➡ The predicted spectrum depends on the foreground/background models.

Integrated flux in 15°x15° ROI, NFW component



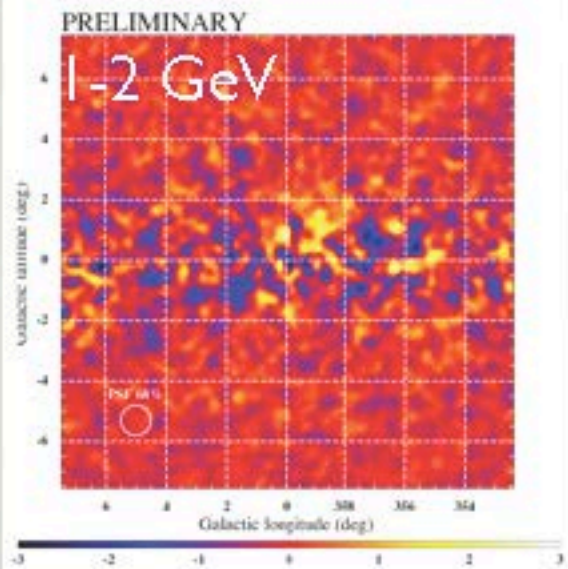


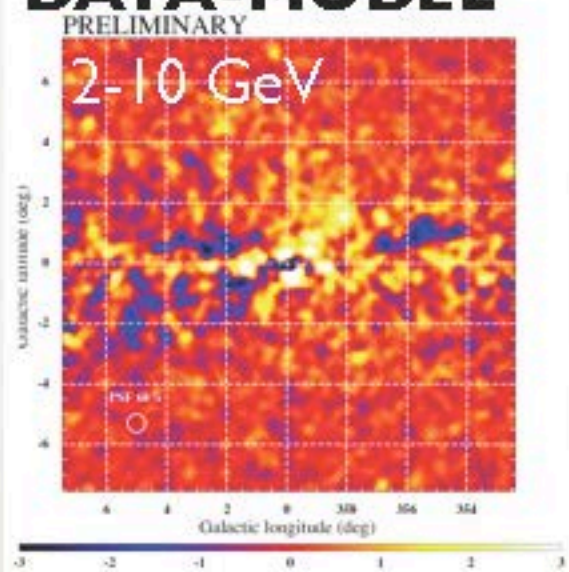
Additional Templates

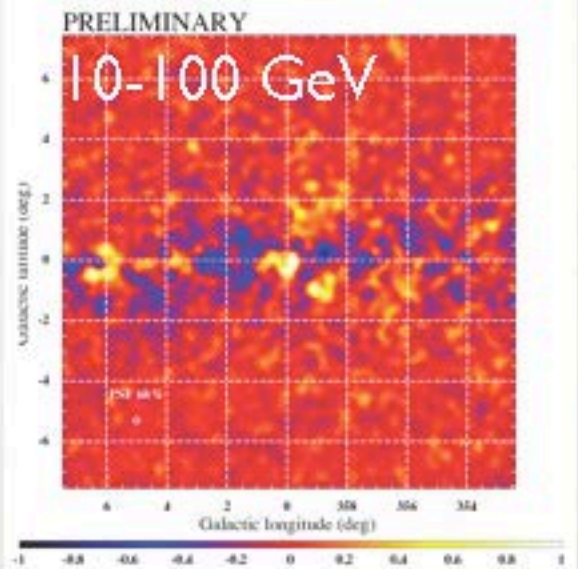
Counts in 0.1°x0.1° pixels
0.3° radius gaussian smoothing

Without NFW: **DATA-MODEL**

Pulsars, tuned-index

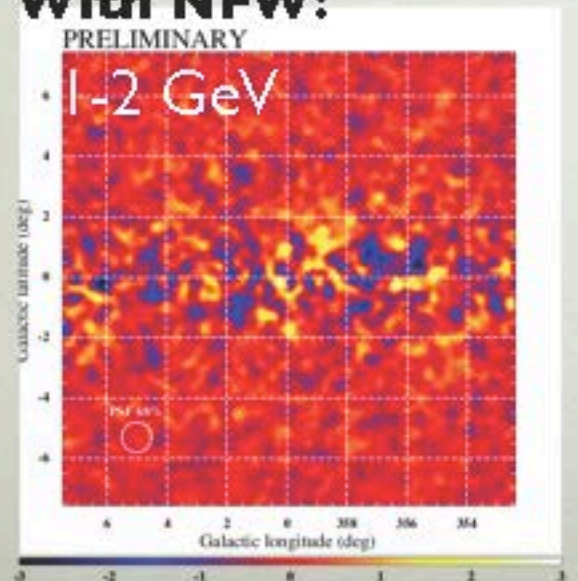


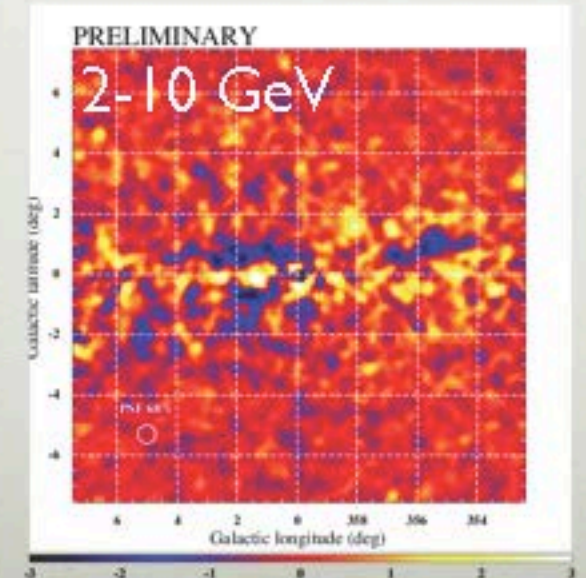


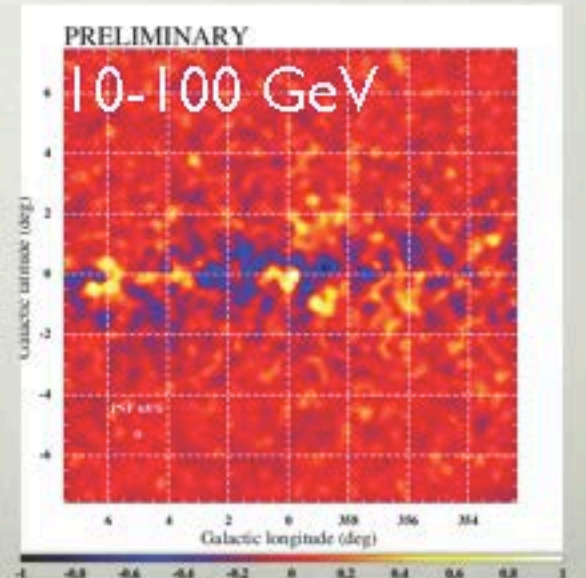


With NFW:

Pulsars, tuned-index

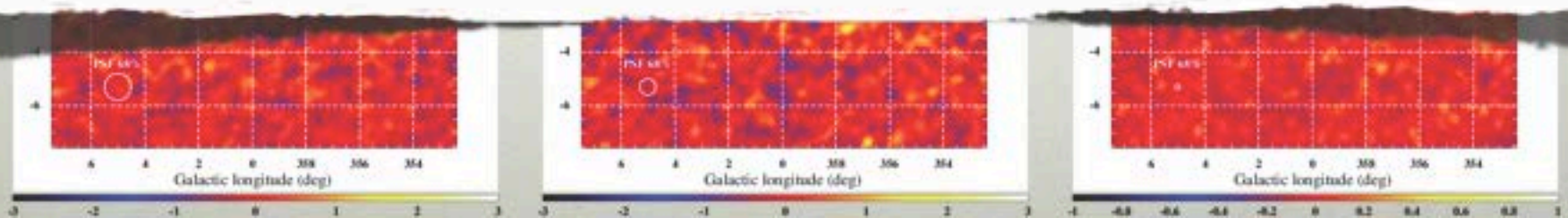






- We have systematically developed a set of models for the diffuse emission in the inner 15°×15° of the Milky Way, by fitting GALPROP-derived templates in a way not done before
- We determined the point sources as part of the development of this model
- We employ all sky data to constrain the foreground/background emission, excluding the 15°×15° region, <u>for different assumptions on the CR source distribution, gas intensity and spectral index, and IC intensity across galactocentric rings</u>
- We find:
  - IC emission from inner kpc is higher than predicted and is the dominant interstellar emission component in this region. We are exploring the origin of the enhanced IC in the IG to see what combination of ISRF and CR leptons best explains the data.
  - We find an enhancement approximately centered the Galactic center with a spectrum that peaks in the GeV range, that persist across the models we have employed. The spectral properties vary widely depending on the modeling of the interstellar emission
  - Foreground/background accounts for most of the emission. Its determination is crucial in extracting the contribution from the Galactic center region

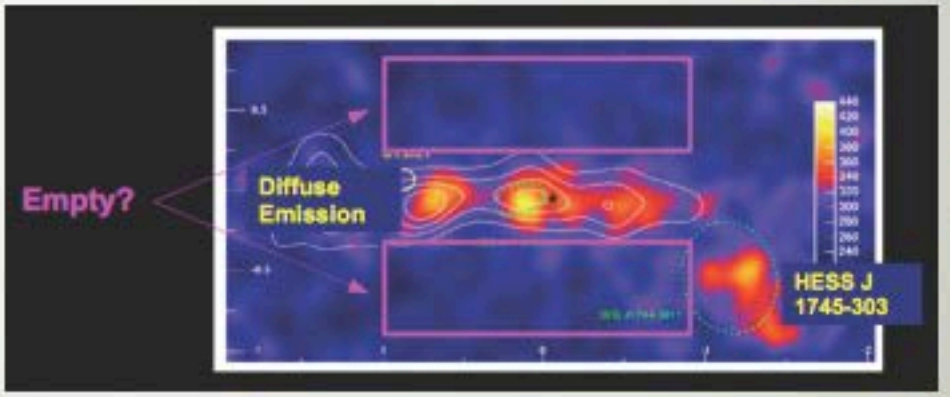
➡ We are further exploring the systematic uncertainties in the IEM, e.g. <u>gas distribution, ISRF, cylindrical symmetry</u>. This is crucial in determining properties of the IEM in the innermost kpc and to confirm the presence and properties of an additional component

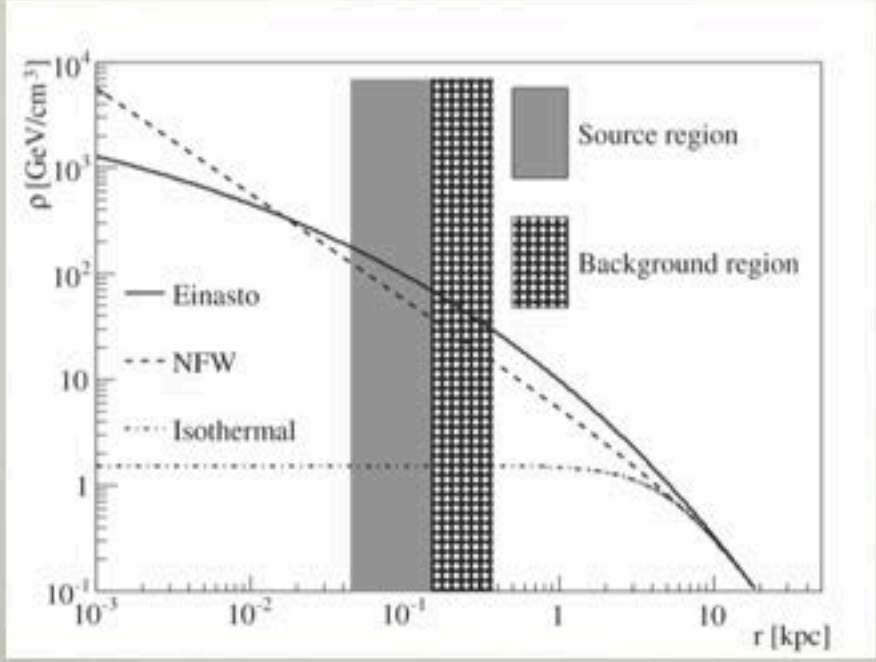


Pulsars,

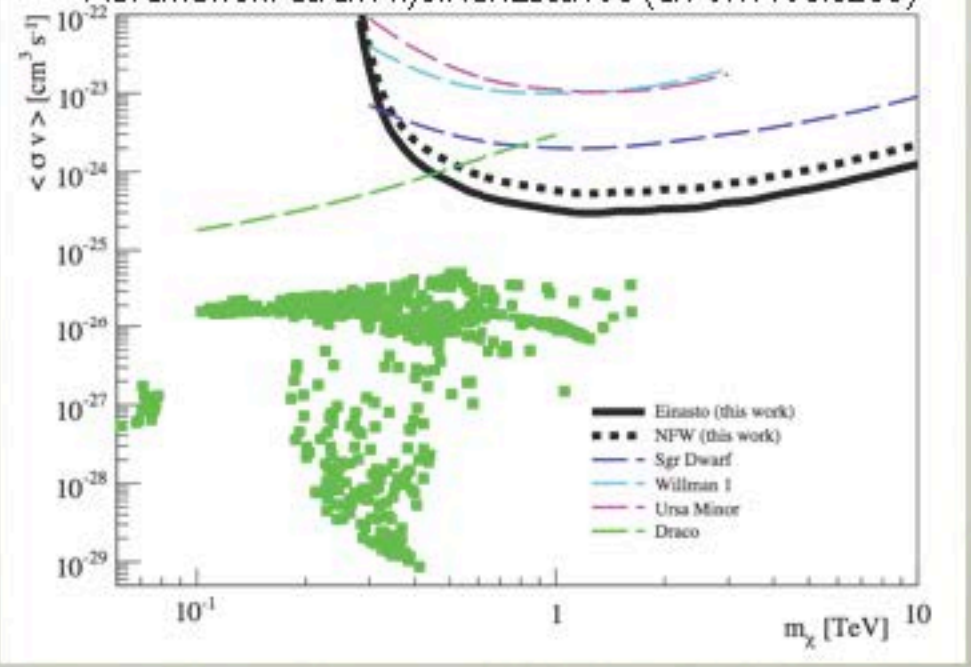
H.E.S.S.: Galactic Halo

- GC is complicated by astrophysics, look away from it!
- Signal region: relatively close to GC but "free" from astrophysical background
- Select a region where the contribution from DM is smaller for background subtraction (background region)
- Small dependence on DM profile



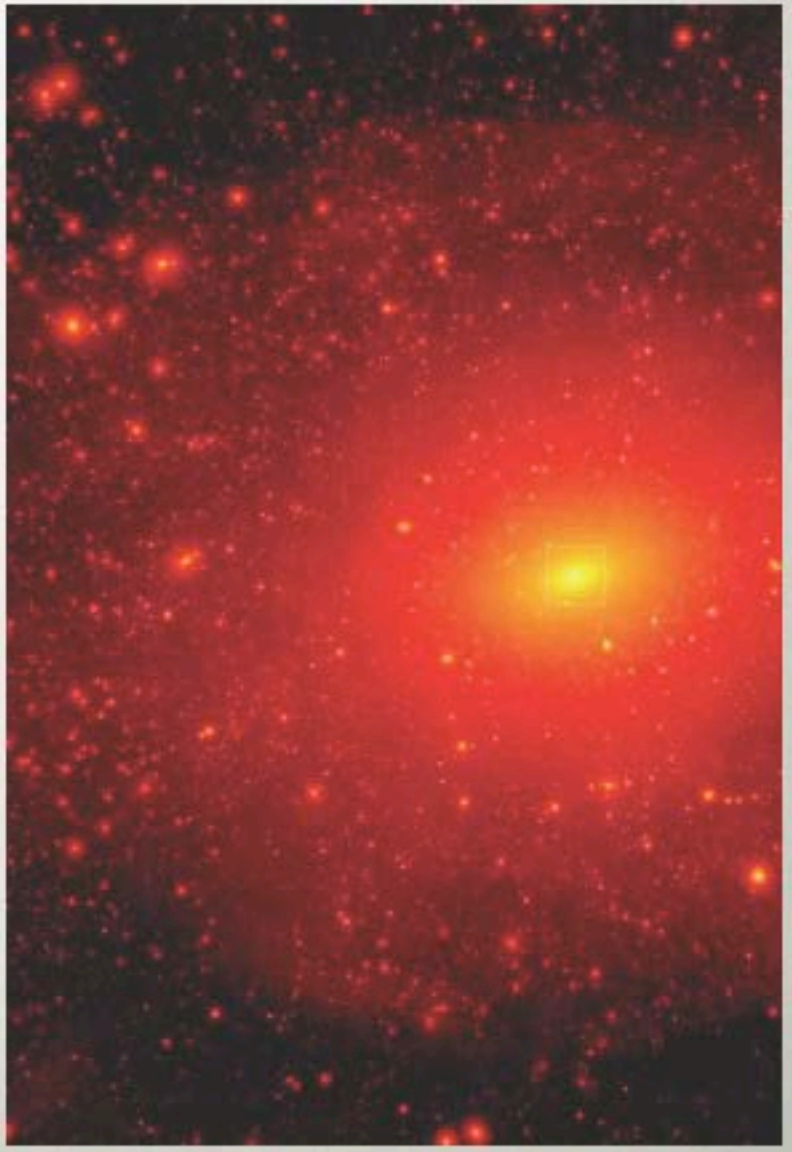


Abramowski et. al. Phys.Rev.Lett.106 (arXiv:1103.3266)



Dwarf Spheroidal Galaxies

- Optically observed dwarf spheroidal galaxies (dSph): largest clumps predicted by N-body simulation.
- Excellent targets for gamma-ray DM searches
  - Very large M/L ratio: 10 to ~> 1000 (M/L ~10 for Milky Way)
  - DM density inferred from the stellar data! Data so far cannot discriminate, in most cases, between cusped or cored dark matter profiles. However, Fermi's DM constraints with dSph do not have a strong dependence on the inner profile
  - Expected to be free from other gamma ray sources and have low dust/gas content, very few stars

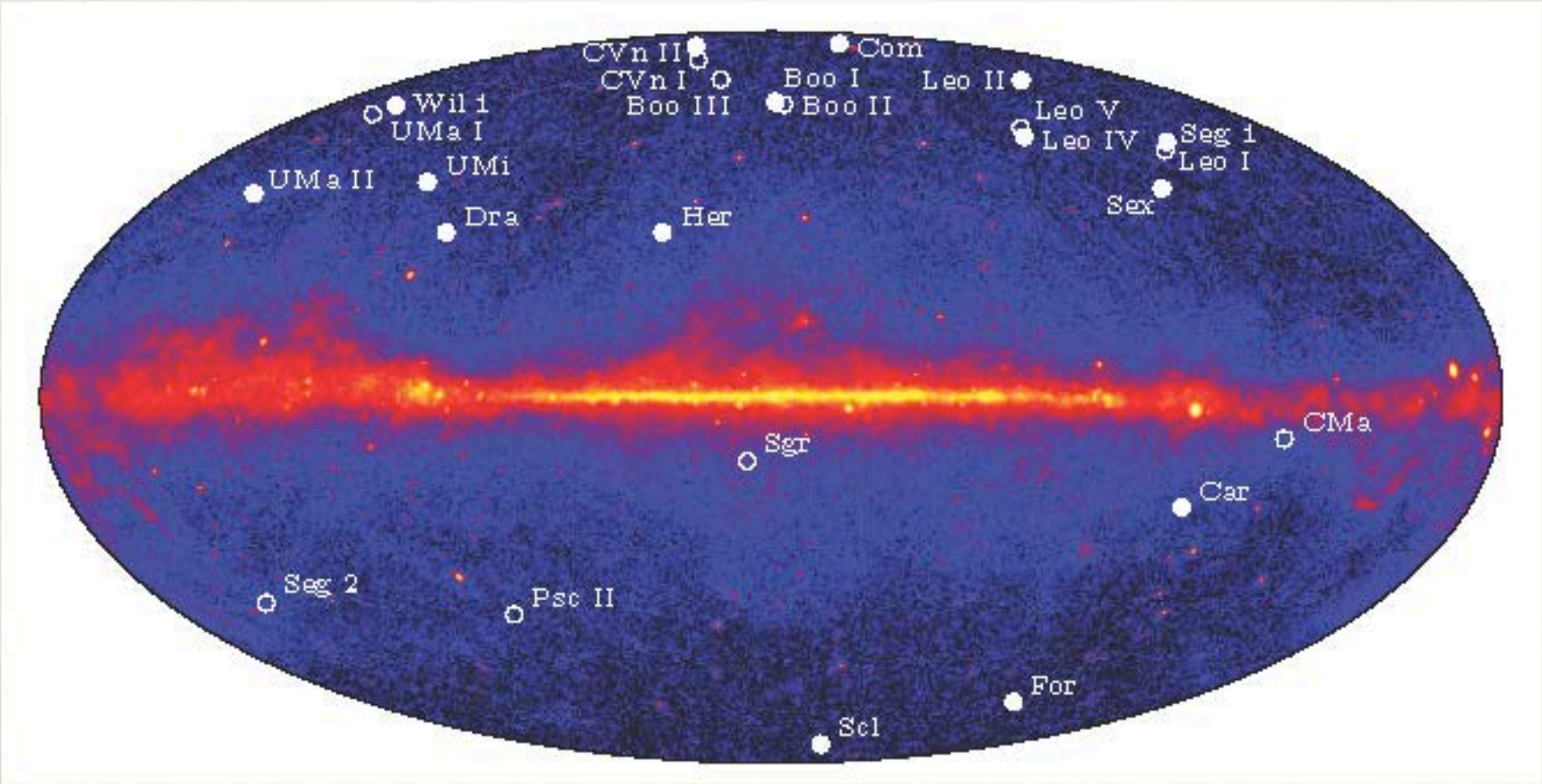


Dwarf Spheroidal Galaxies

Fermi LAT Collaboration, arXiv:1310.0828

- Search for a signal in 25 dSphs
- 4 years of data, 500 MeV-500 GeV, P7REP CLEAN

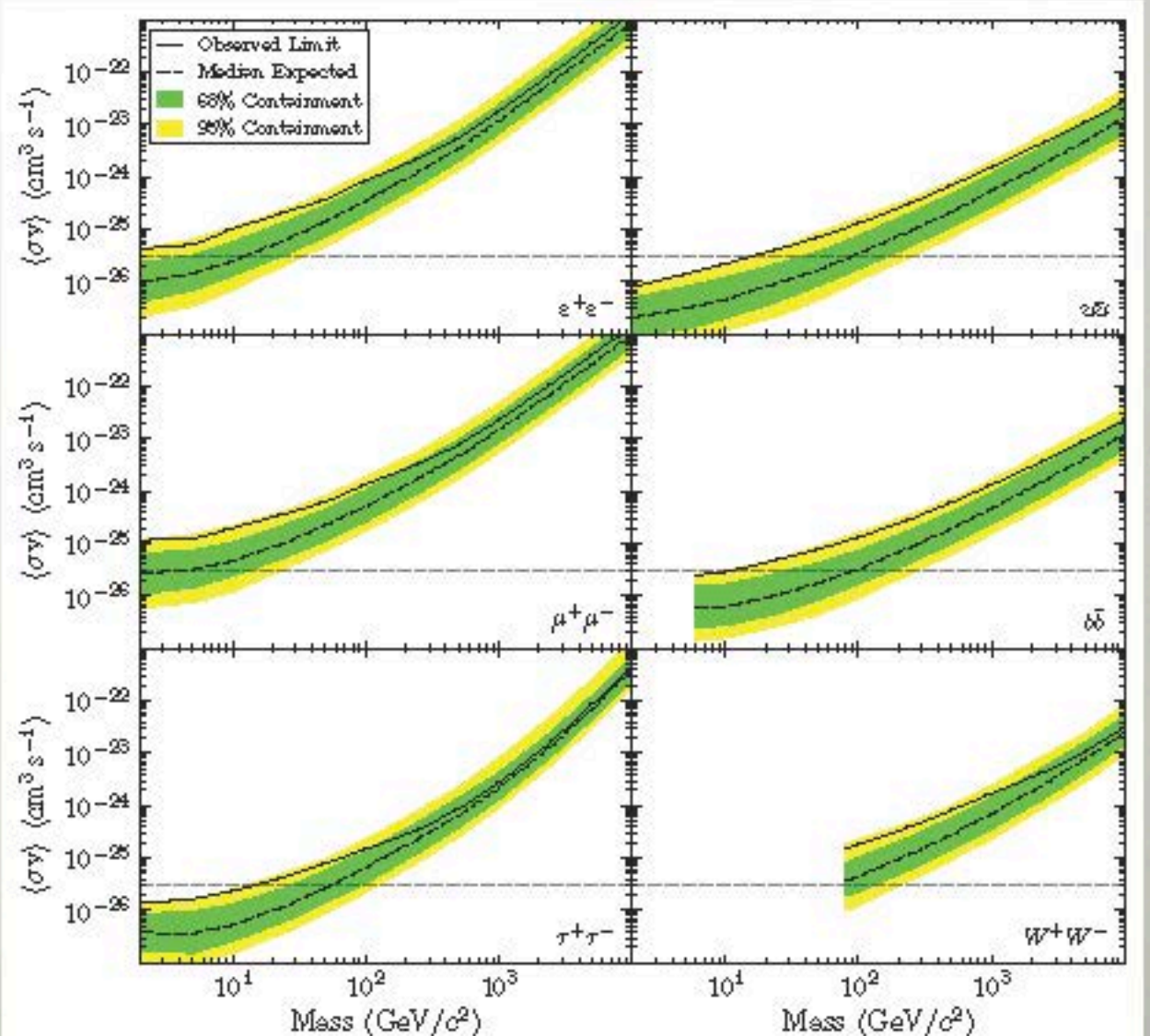
➡ No significant emission is found from any of the 25 dSphs



Dwarf Spheroidal Galaxies

Fermi LAT Collaboration, arXiv:1310.0828

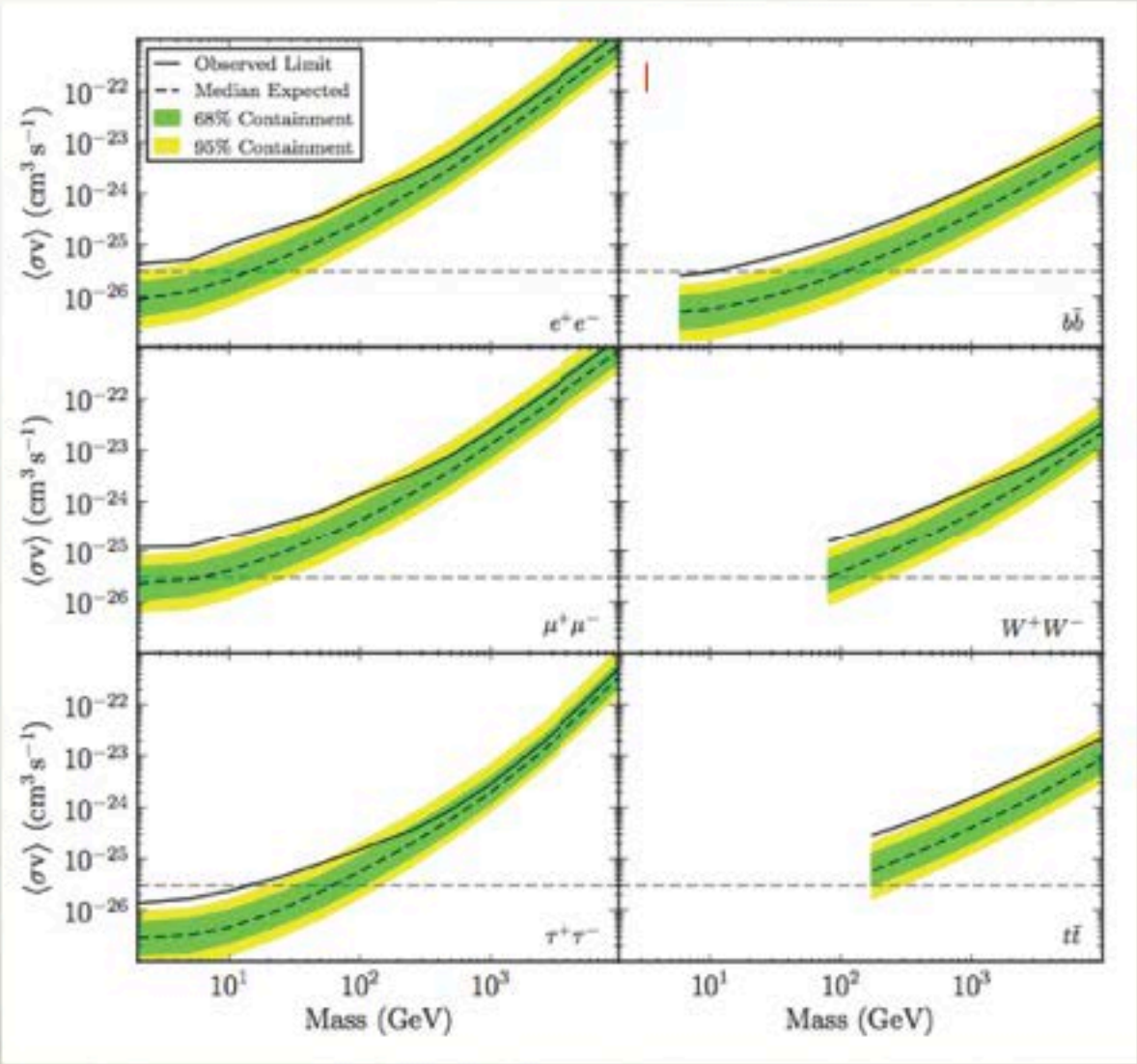
- No significant detection is found when assuming gamma-ray spectra corresponding to representative DM annihilation final states (e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, b-bbar, u-ubar, W^+W^-) and DM masses in the 2 GeV-1 TeV range
- Combine with the DM density inferred from the stellar data (assume NFW profile) to set constraints on the annihilation cross section
- Include 15 dSphs in the combined fit (include only dSphs with stellar kinematic data and non-overlapping ROIs)
- Largest deviation from the null hypothesis is for annihilation into b-bbar for masses in the 10-25 GeV range.
- Segue 1, Ursa Major II, and Willman 1 (large J-factors) primarily contribute to the deviation



Dwarf Spheroidal Galaxies

Fermi LAT Collaboration, arXiv:1310.0828

- Bands and median from simulations:



Dwarf Spheroidal Galaxies

Fermi LAT Collaboration, arXiv:1310.0828

- Significance of deviation (TS=8.7):

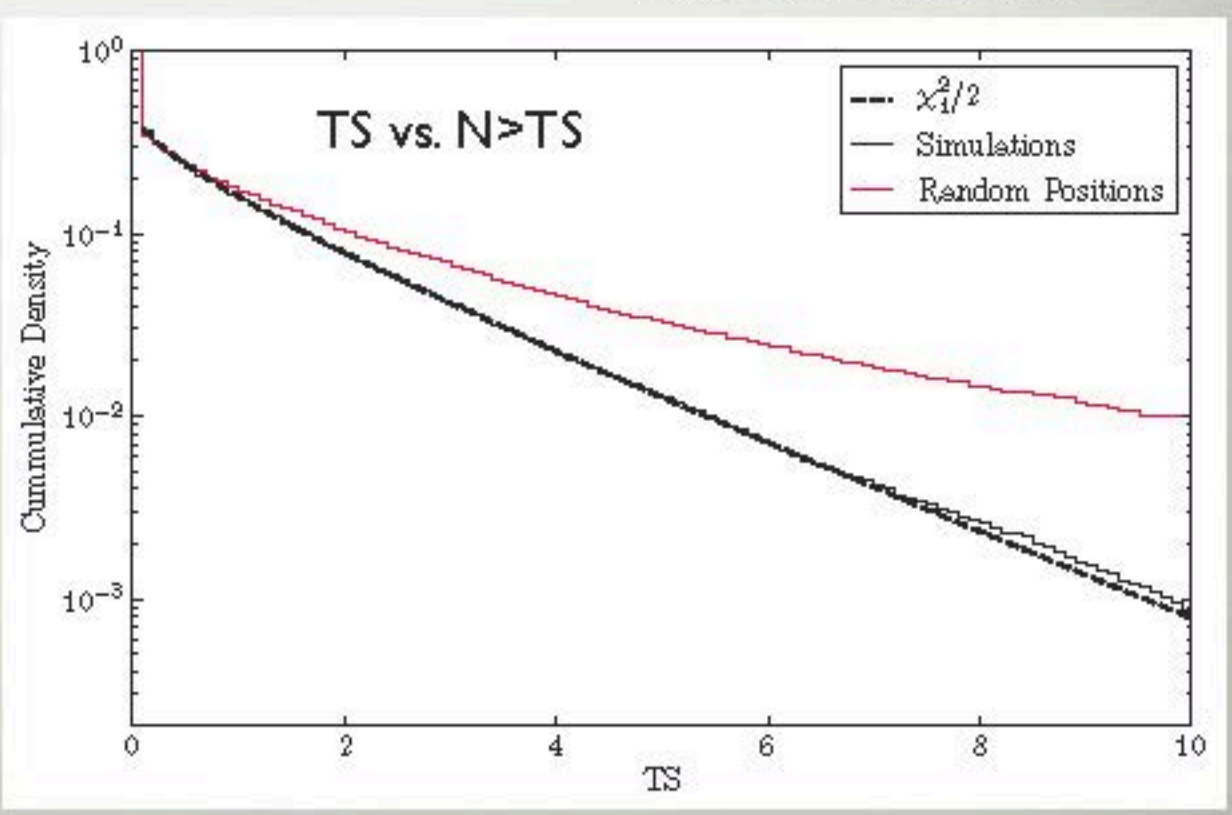
Determine distribution of TS values from individual fits of a 25 GeV $\bar{b}b$ annihilation spectrum to the null hypothesis

null hypothesis

$$\mathrm{TS} = -2\ln\left(\frac{\mathcal{L}(\mu_0, \hat{\theta} \mid \mathcal{D})}{\mathcal{L}(\hat{\mu}, \hat{\theta} \mid \mathcal{D})}\right)$$

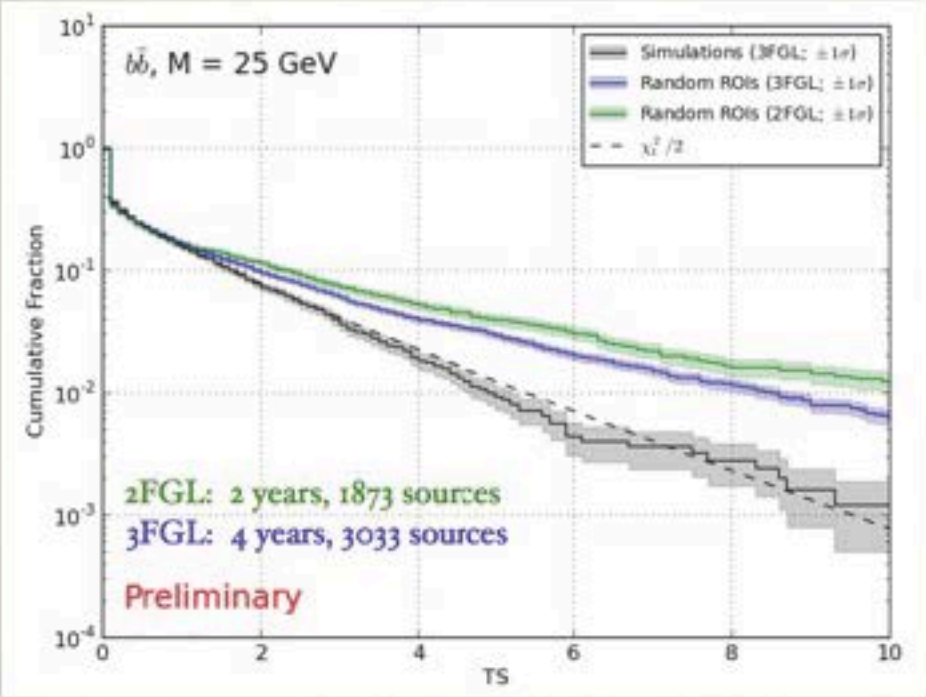
alternative hypothesis

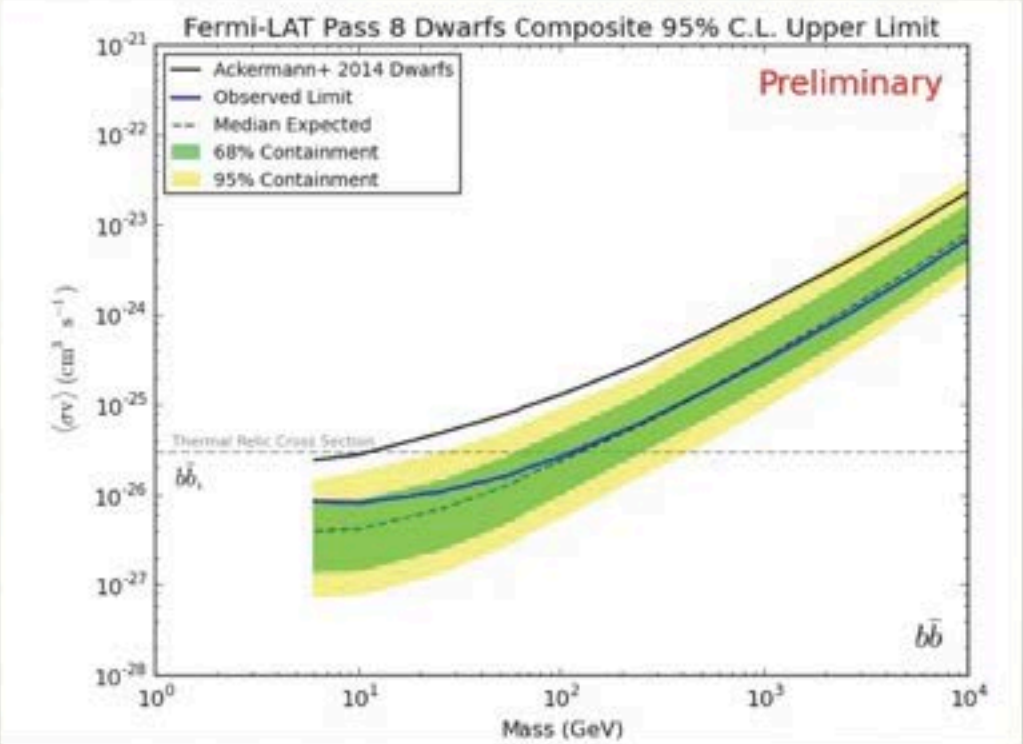
- Local significance:
  (simulations) p-value $=1.6\times10^{-3}$ (2.9σ)
- Global significance:
  (simulations) p-value $=2.4\times10^{-2}$ (2.0σ)
  (data) p-value $=8.3\times10^{-2}$ (1.4σ)



Update - Dwarf Spheroidal Galaxies

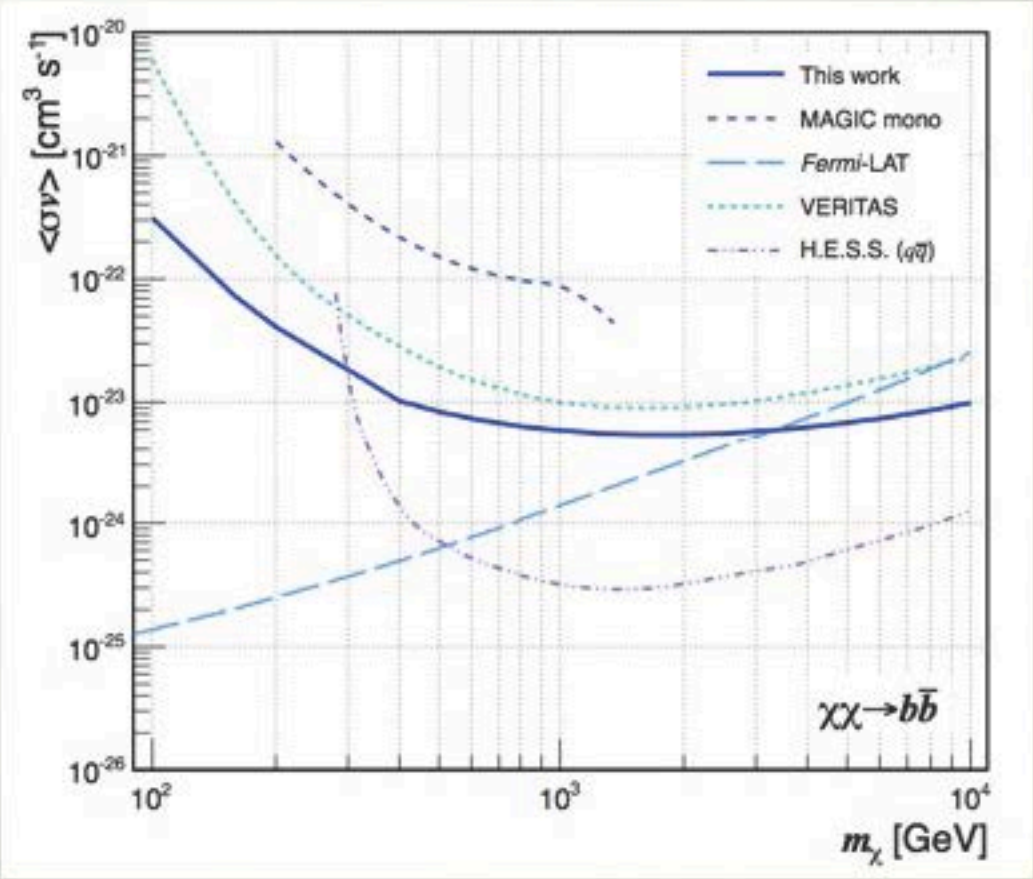
- Better agreement between simulations and data with preliminary 4 year point source catalog
- No significant excess is found
- Limits in mild tension with the GC excess





Dwarf Spheroidal Galaxies IACTs

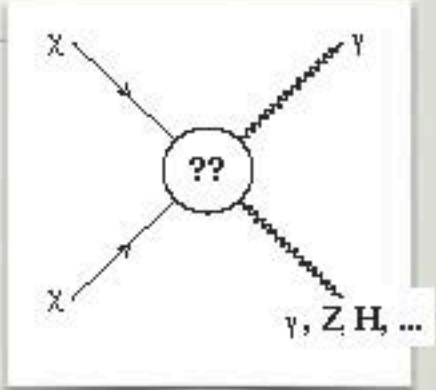
- Observations of dSphs with IACTs competitive with Fermi above DM masses ~3 TeV
- MAGIC latest results corresponding to 160 hrs of observation of Segue I are the strongest



Search for Spectral Lines: Hint of a Signal?

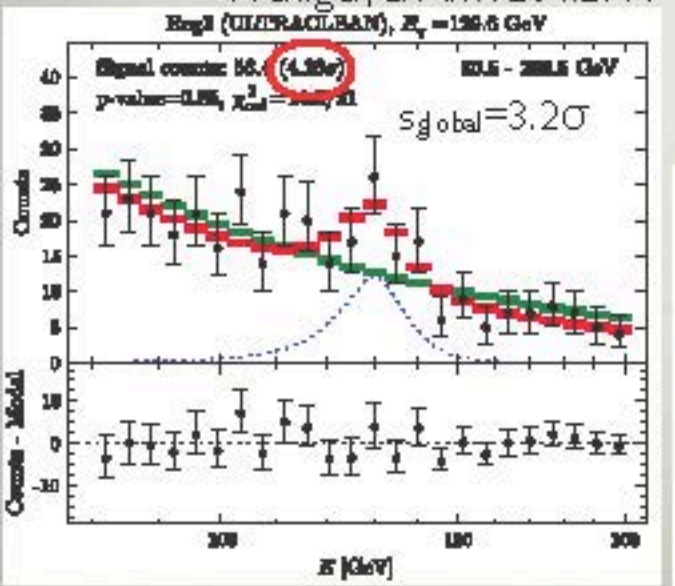
☺ "Smoking gun" signal of dark matter.

☹ The line signal is generally suppressed (but enhanced in some models!)

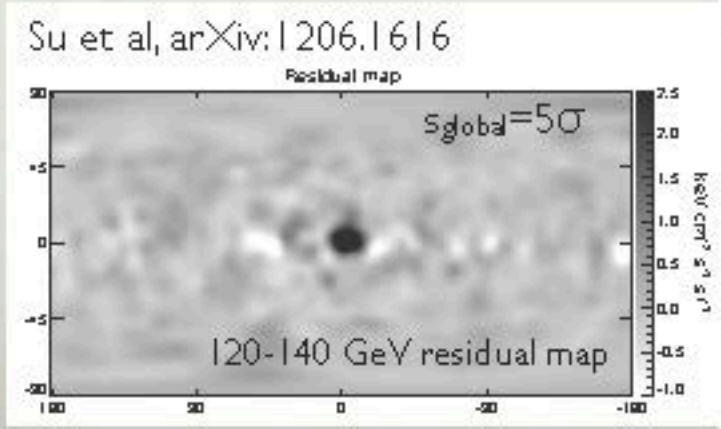


- Some evidence for a line at ~130 GeV was claimed (Bringmann et al, arXiv:1203.1312 (internal brem), Weniger, arXiv:1204.2797, Su et al, arXiv:1206.1616)
- More statistics, data reprocessing, and improved energy dispersion model yield a decrease in significance

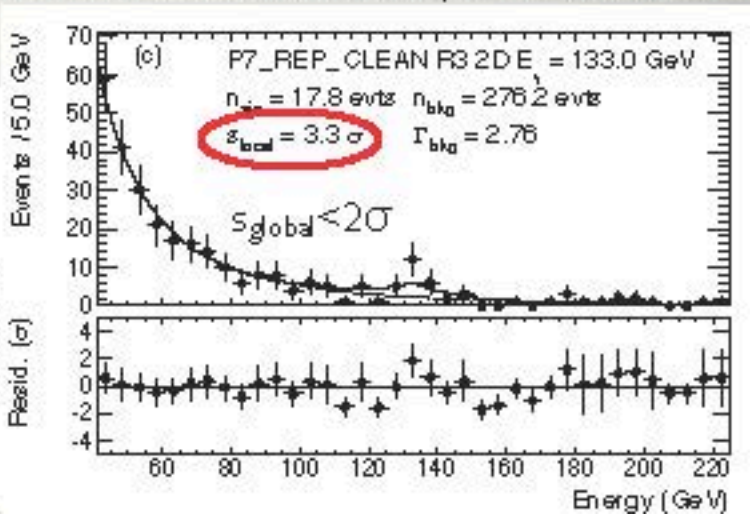
Weniger, arXiv:1204.2797



Su et al, arXiv:1206.1616



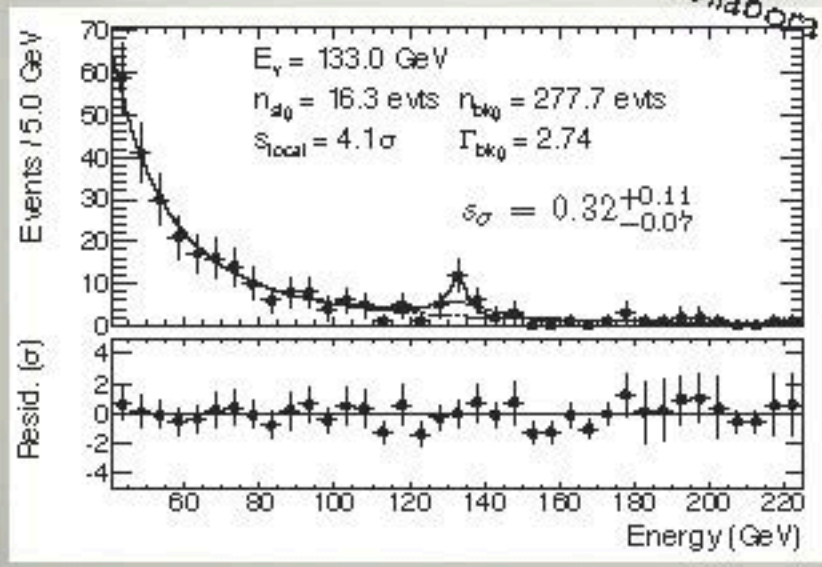
Fermi LAT Collaboration, arXiv:1305.5597

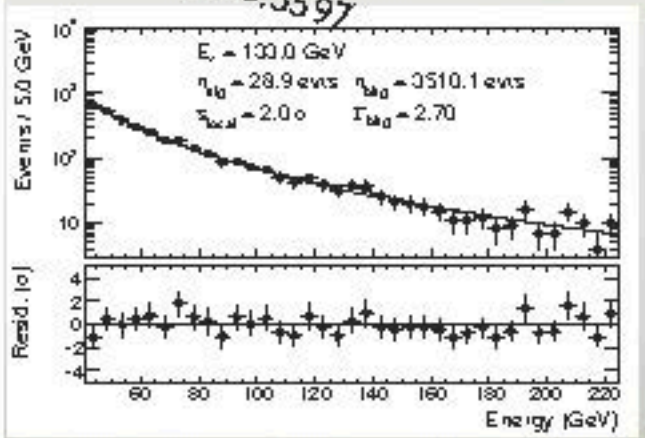


How Convincing Is This Signal?

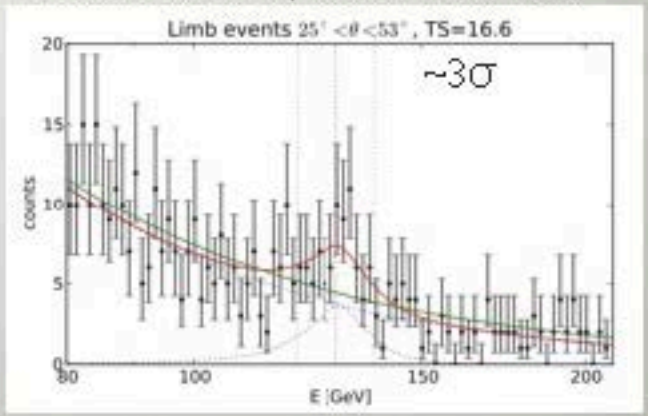
- The line feature in the data is narrower than the expected energy resolution by a factor 2-3
- Earth Limb: expected to be featureless. Find excess at putative line energy also when the LAT is pointing at the Limb. NB: feature appears in low-incidence angle events, but not in high-incidence angle events (both for GC and limb data)

Fermi LAT Collaboration, arXiv:1305.5597





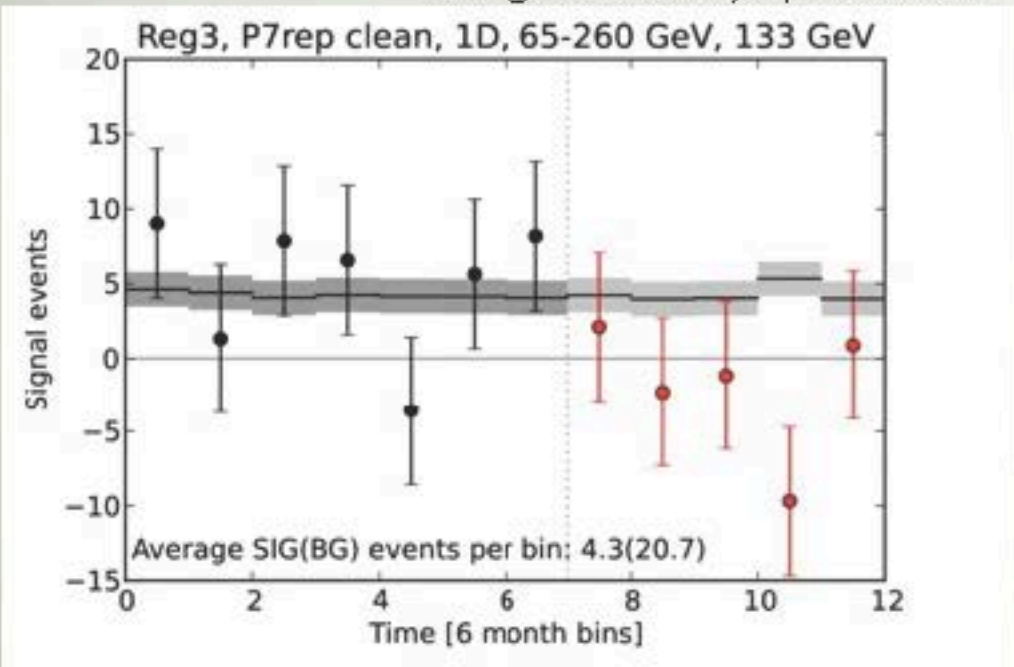
Finkbeiner et al, arXiv:1209.4562



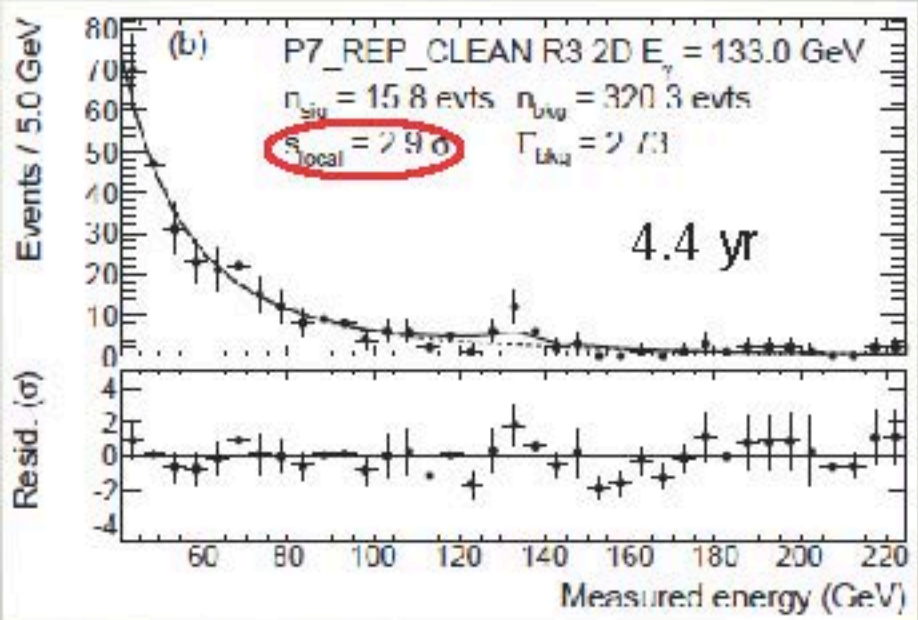
And It Might be going Away...

- Signal significance has been decreasing over time
- The evidence for a line signal is no longer very convincing
- Background fluctuation? Systematics?

Weniger, Sackler Symposium 2014

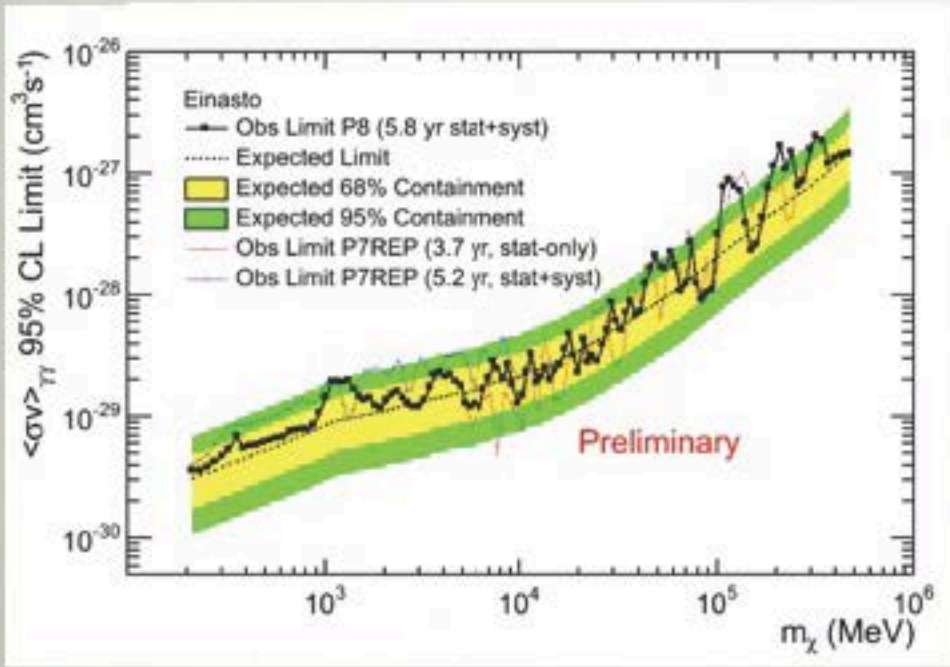


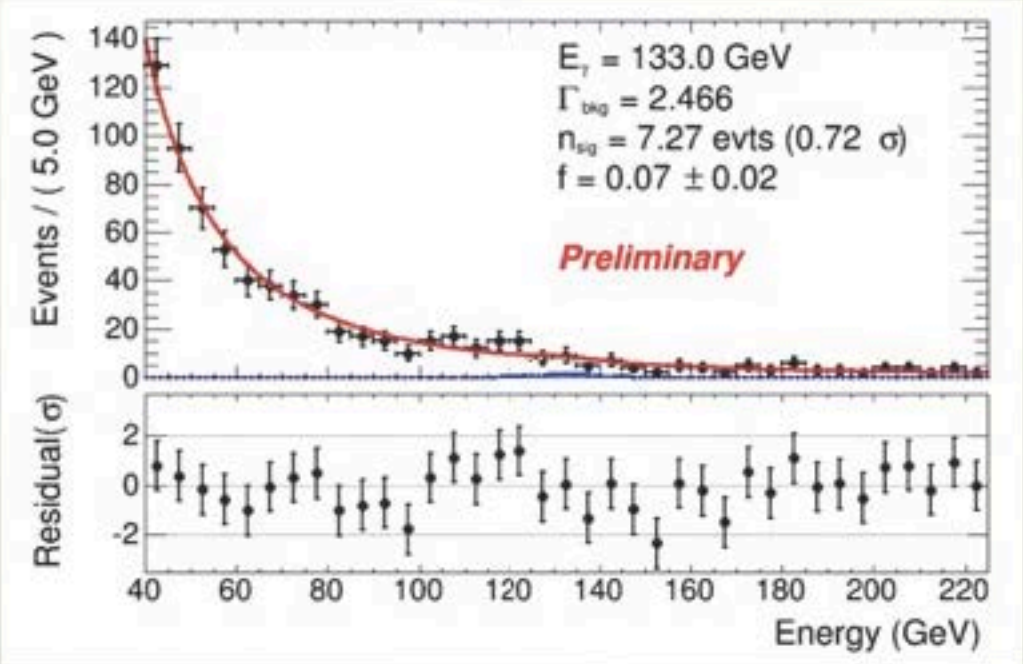
Fermi LAT Collaboration



UPDATE - LINES

- Updated results with new event level reconstruction (Pass 8) and more data
- No significant lines detected
- No significant feature at 133 GeV

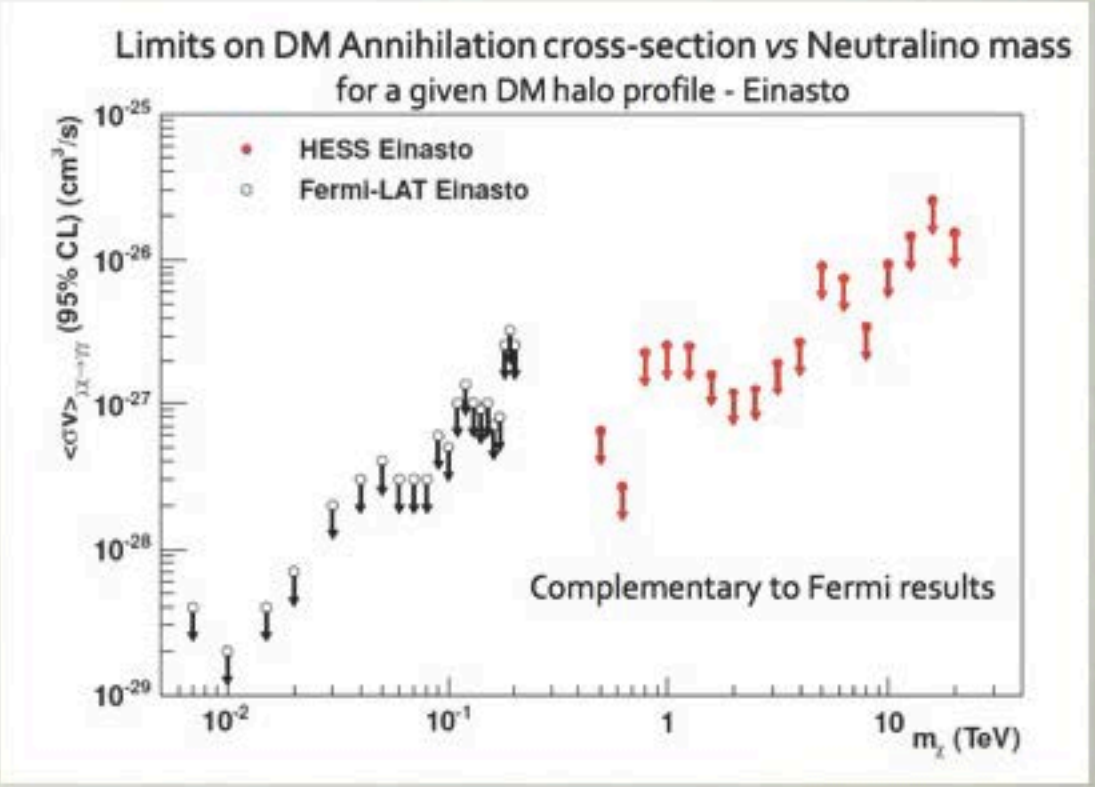




H.E.S.S. Line Results

- Search in Galactic center halo (~100 hrs) and around extra-galactic sources (~1200hrs)
- Future prospects: lower energy threshold for H.E.S.S. 2 will extend line search down to 80 GeV

Kieffer, TeVPA/IDM 2014



Summary/Outlook

- Intriguing hints of potential signals in gamma-ray data have been claimed and persist, e.g. few GeV excess in Galactic center in gamma-rays
- However the astrophysical background is currently a limitation for the Galactic center, were a dark matter signal is predicted to be brightest and has therefore huge potential in terms of discovery or setting constrains. More work and more data are required to better understand the data
- In the meanwhile, indirect dark matter searches continue to set strong constraints on the nature of DM
- Improvements in current experiments as well as upcoming experiments promise more interesting results to come

Thank you!