Instituto de Física Teórica
UAM-CSIC

MultiDark
Multimessenger Approach for Dark Matter Detection

Fermi
Gamma-ray Space Telescope

Recent results on Dark Matter searches with the Fermi LAT

Germán A. Gómez Vargas

IFT UAM/CSIC & UAM Madrid

INFN Roma Tor Vergata

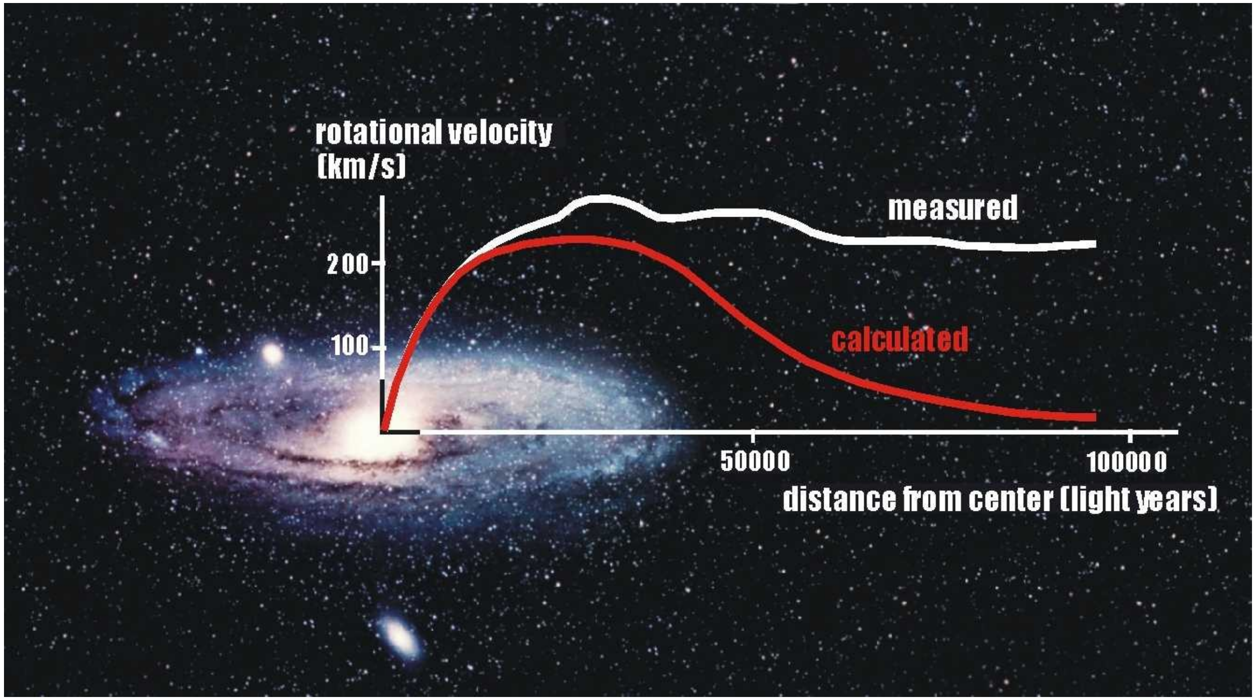
On behalf of the Fermi-LAT collaboration

HEP – Valparaiso, Chile

Dec 17th 2013

Dark Matter Evidence

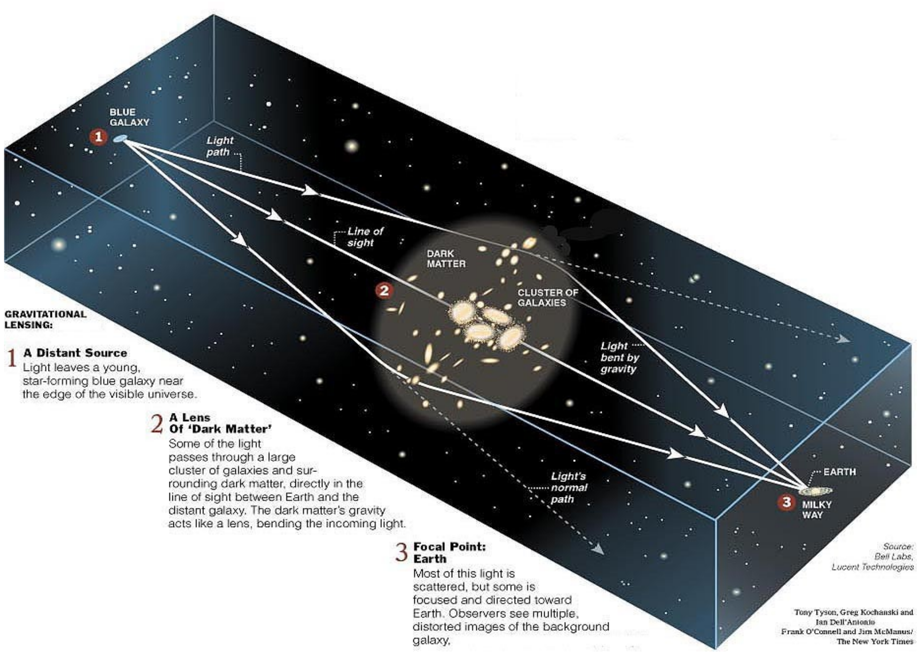
- At galactic scales: ~10 kpc
- In spiral galaxies like the Milky Way, the gravitational mass can be derived from observing the motions of stars and gas clouds in the disk as they orbit the center. Most spiral galaxies show flat rotation curves out as far as we can trace them, even where no more stars are visible.



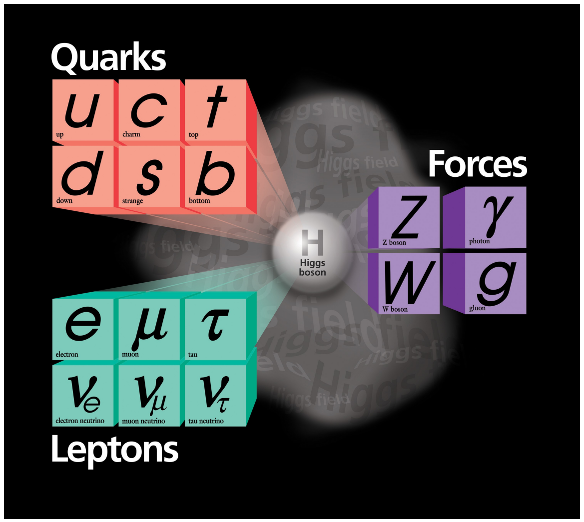
- Therefore we conclude that the gravitational mass is more than 10 times more massive than the luminous mass.

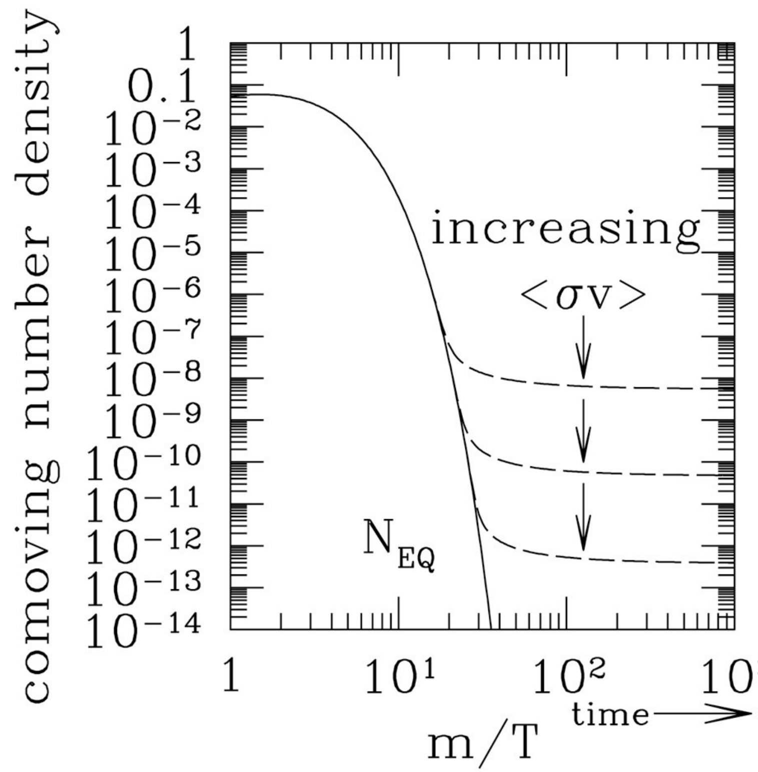
Dark Matter Evidence

- At galaxy cluster scales: 2-10 Mpc
  - In this systems the largest amount of visible matter in in the form of hot gas.
  - From gravitational lensing -> the total mass



Dark Matter Indirect Searches





- The dark matter paradigm can be probed detecting non-gravitational signals of the unseen matter.
- The SM does not provide any viable candidate.

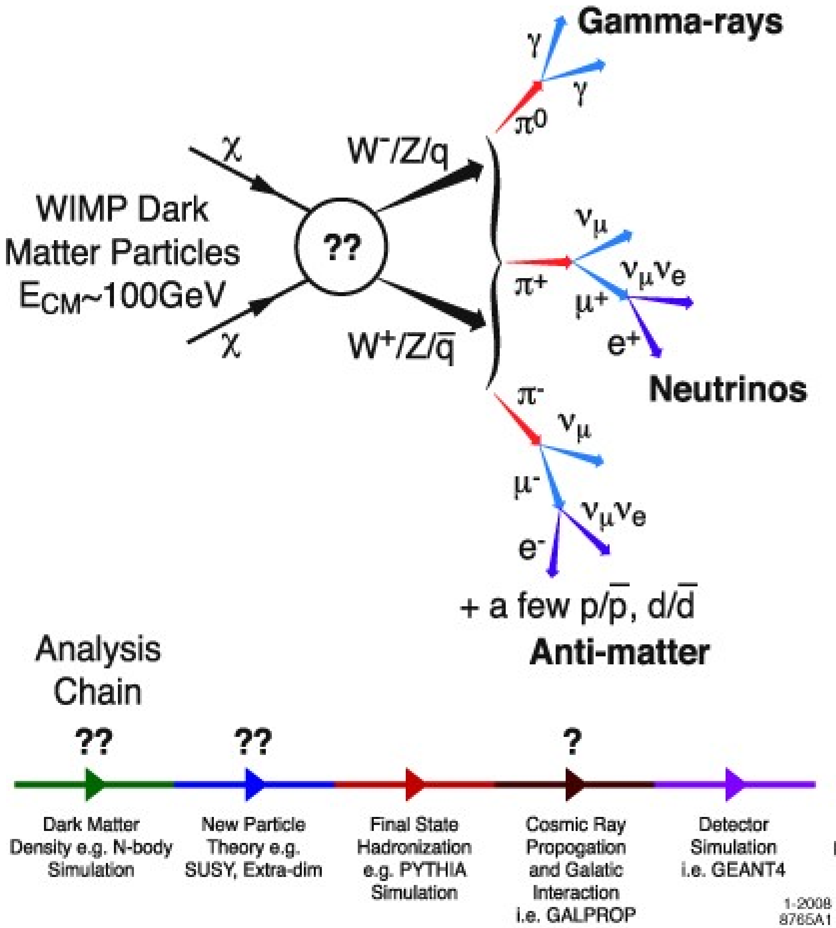
Assuming a new massive particle (~100 GeV) with weak interaction (~3x10^{-26} cm^2/s) particle physics predicts that this particle reproduce the DM relic density

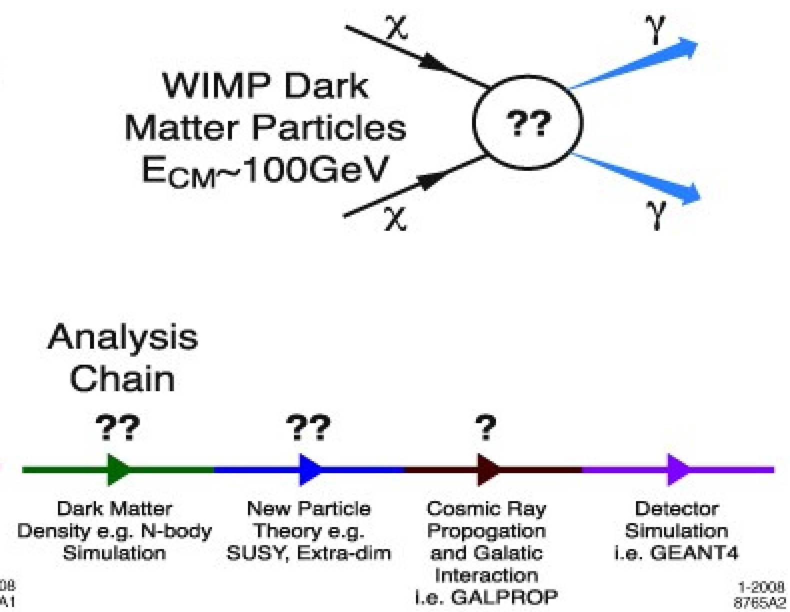
$$\Omega h^2 \approx \frac{3\times 10^{-27}\, cm^2/s}{\langle \sigma v \rangle}$$

$$\Omega_{DM} h^2 = 0.1199 \pm 0.0027 \, (Plank + WMAP)$$

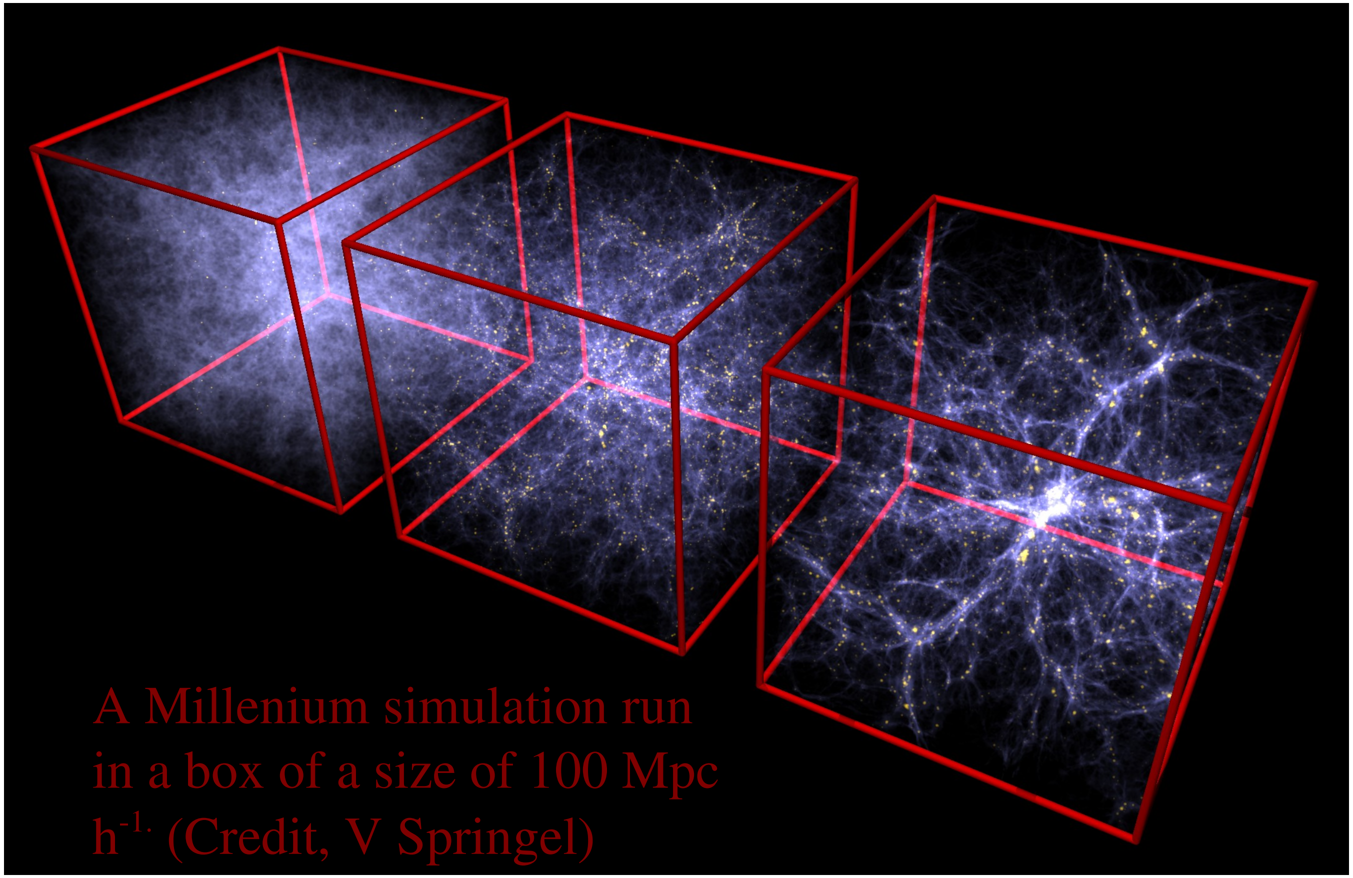
WIMP = Weakly Interacting Massive Particle – DM candidate (e.g. neutralino)

Dark Matter Indirect Searches





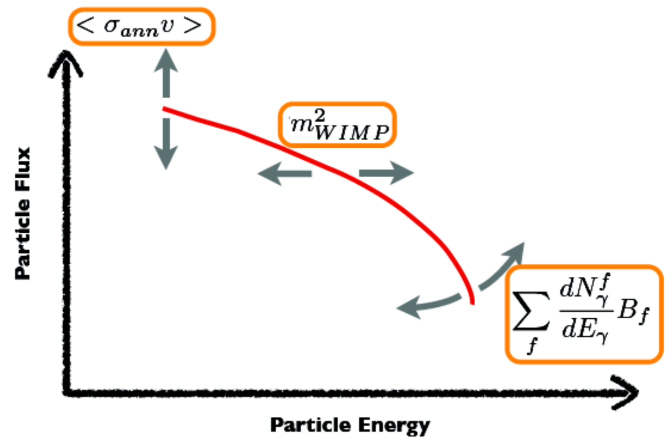
Dark Matter Indirect Searches

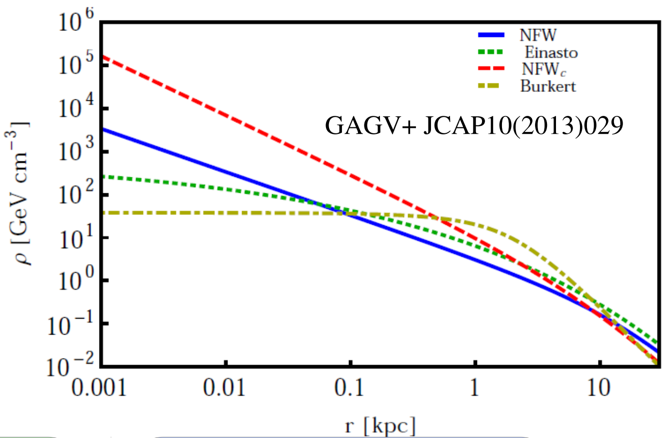


- The sources of dark matter-induced gamma-rays are determined by predictions from N-body simulations.
- These simulations track the evolution of structures and provide the distribution of dark matter structures around us.

DM-Induced Gamma rays.

WIMP = Weakly Interacting Massive Particle
– DM candidate (e.g. neutralino)
– Believe the Milky Way sits in a large spherical "halo" or cloud of DM
  - Non-relativistic (cold) DM





$$\left(\frac{d\Phi_\gamma}{dE_\gamma}\right)_{prompt} = \sum_i \frac{dN^i_\gamma}{dE_\gamma} \frac{\langle \sigma_i v \rangle}{8\pi m^2_{DM}} \bar{J}(\Delta\Omega)\Delta\Omega$$

Gamma-ray Flux

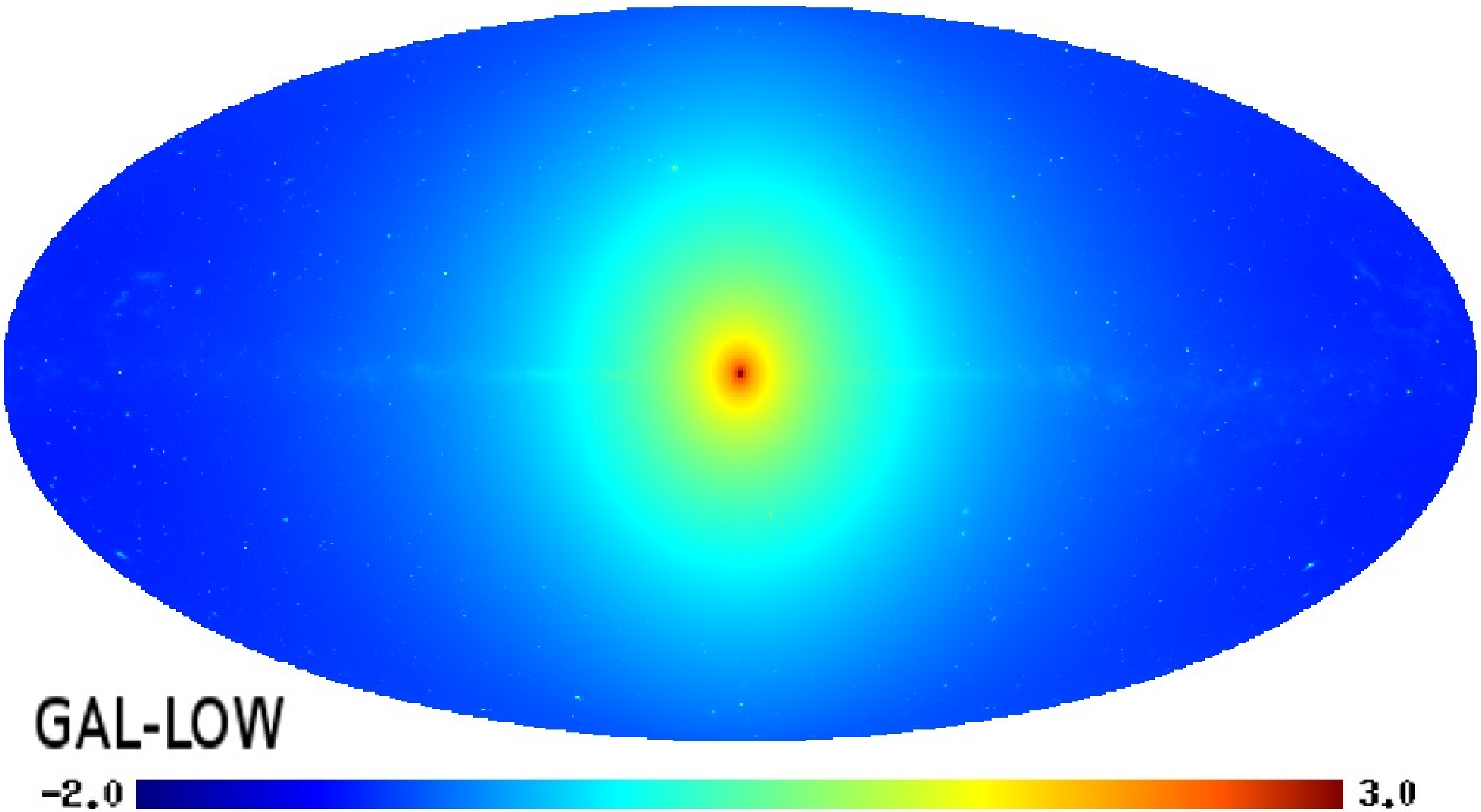
Particle Physics
Spectral information

DM Distribution
(J-Factor)
Spatial information

$$\bar{J}(\Delta\Omega) \equiv \frac{1}{\Delta\Omega} \int d\Omega \int_{l.o.s.} \rho^2(r(l,\Psi))\, dl$$

Dark Matter Indirect Searches

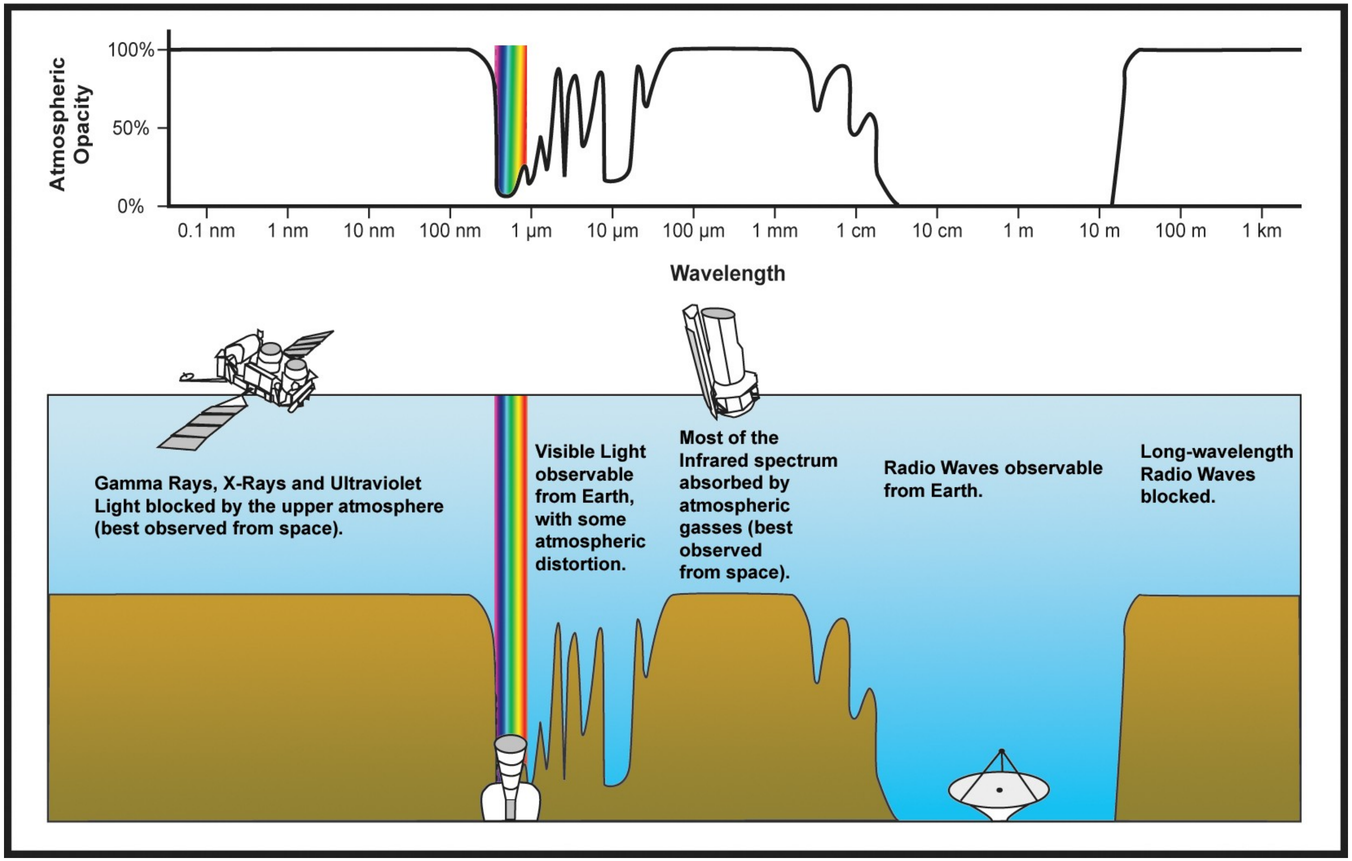
Gamma-ray Flux map: Annihilation into quarks



Emission from the smooth MW halo, the contribution of resolved subhalos in the Aquarius Aq-A-1 halo

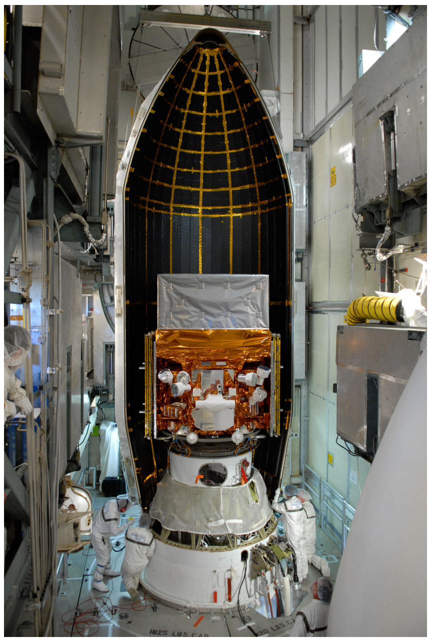
Fornasa et al, 2013, mnras, 429, 1529

Observing the gamma-ray sky



- A broad gamma-ray energy band is screened by Earth's atmosphere
- We must observe the gamma-ray sky from outside the planet by spacecraft

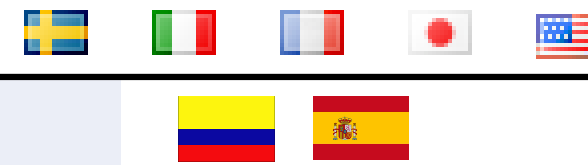
Fermi Large Area Telescope (LAT)

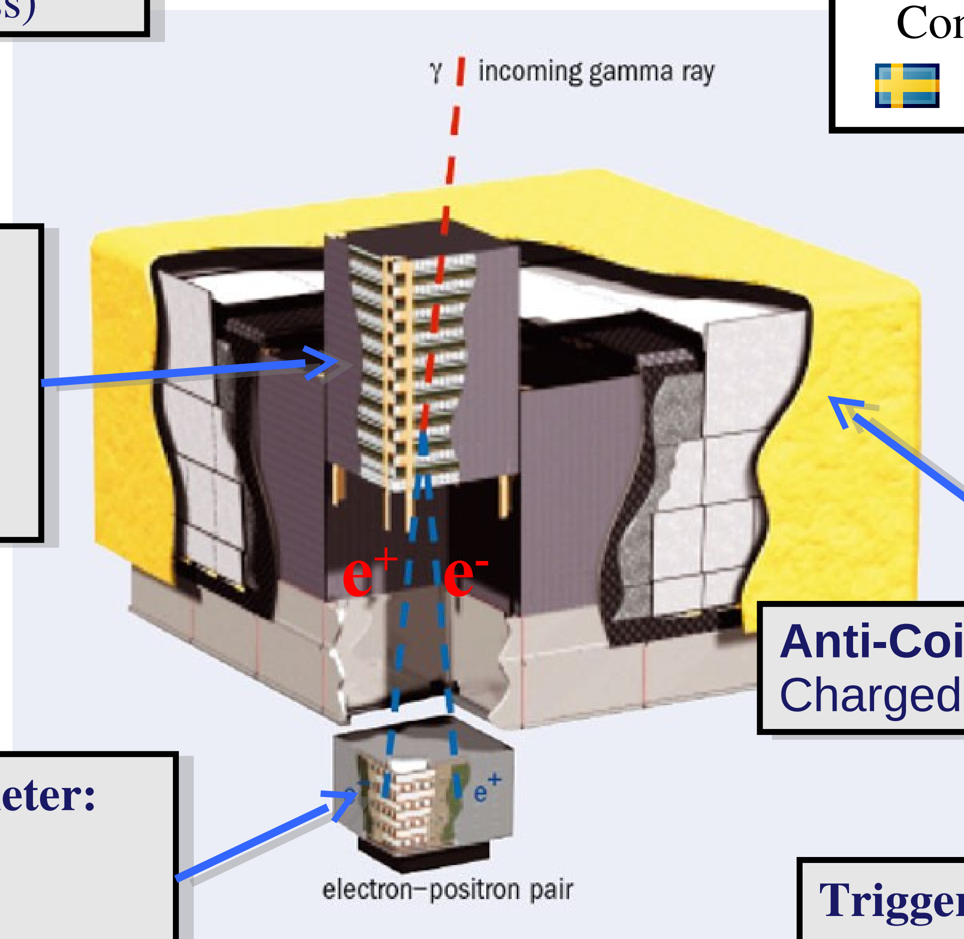
- On board the Fermi Gamma-ray Space Telescope. Launched June 11, 2008 aboard a Delta II 7920-H rocket. Starting taking data Aug. 2008
- 5 years mission, extended at least through 2016
- The Fermi-LAT collects high energy gamma rays (~20 MeV to > 300 GeV) with a large effective area (~6200 cm2) and a large field of view (2.4 sr)

Fermi-LAT

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



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



Si-Strip Tracker:
convert gamma->e^+e^-
reconstruct gamma direction
EM v. hadron separation

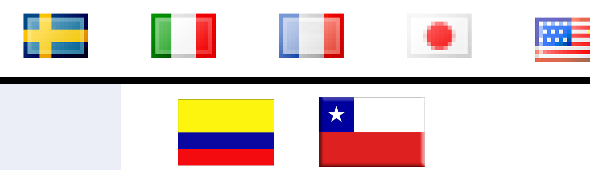
Anti-Coincidence Detector:
Charged particle separation

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

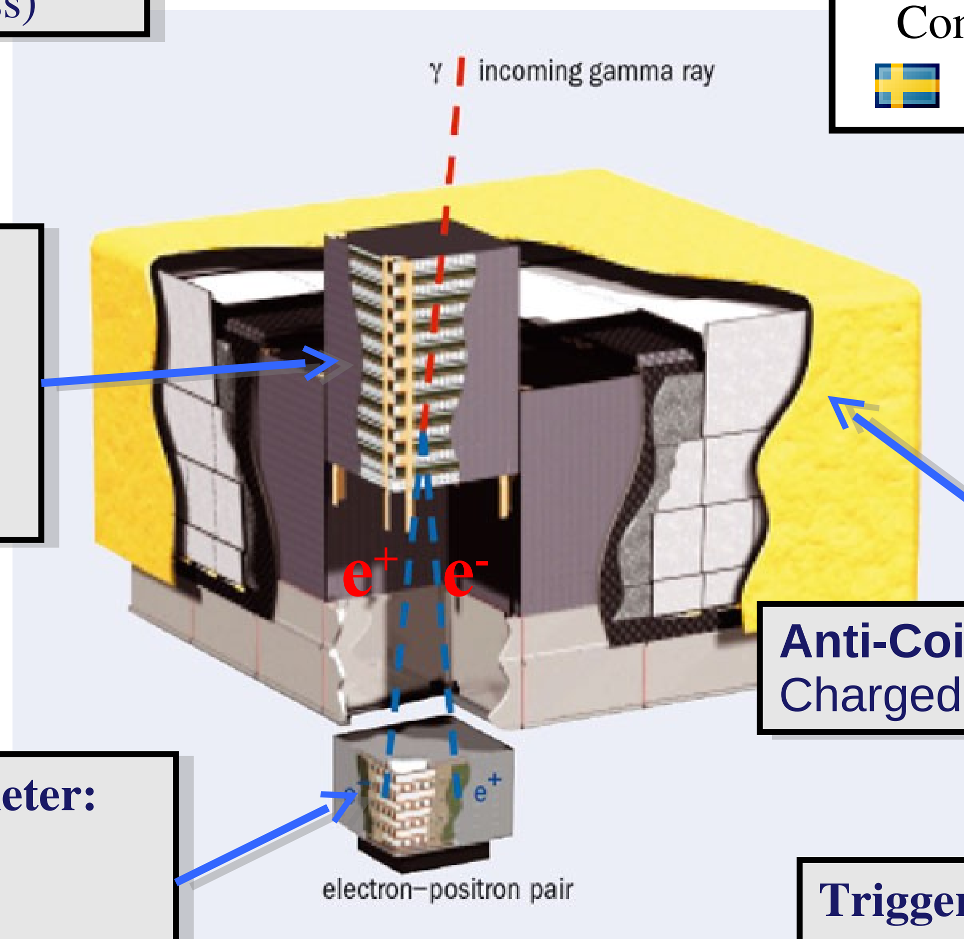
Trigger and Filter:
Reduce data rate from ~10kHz to 300-500 Hz

Fermi-LAT

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



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



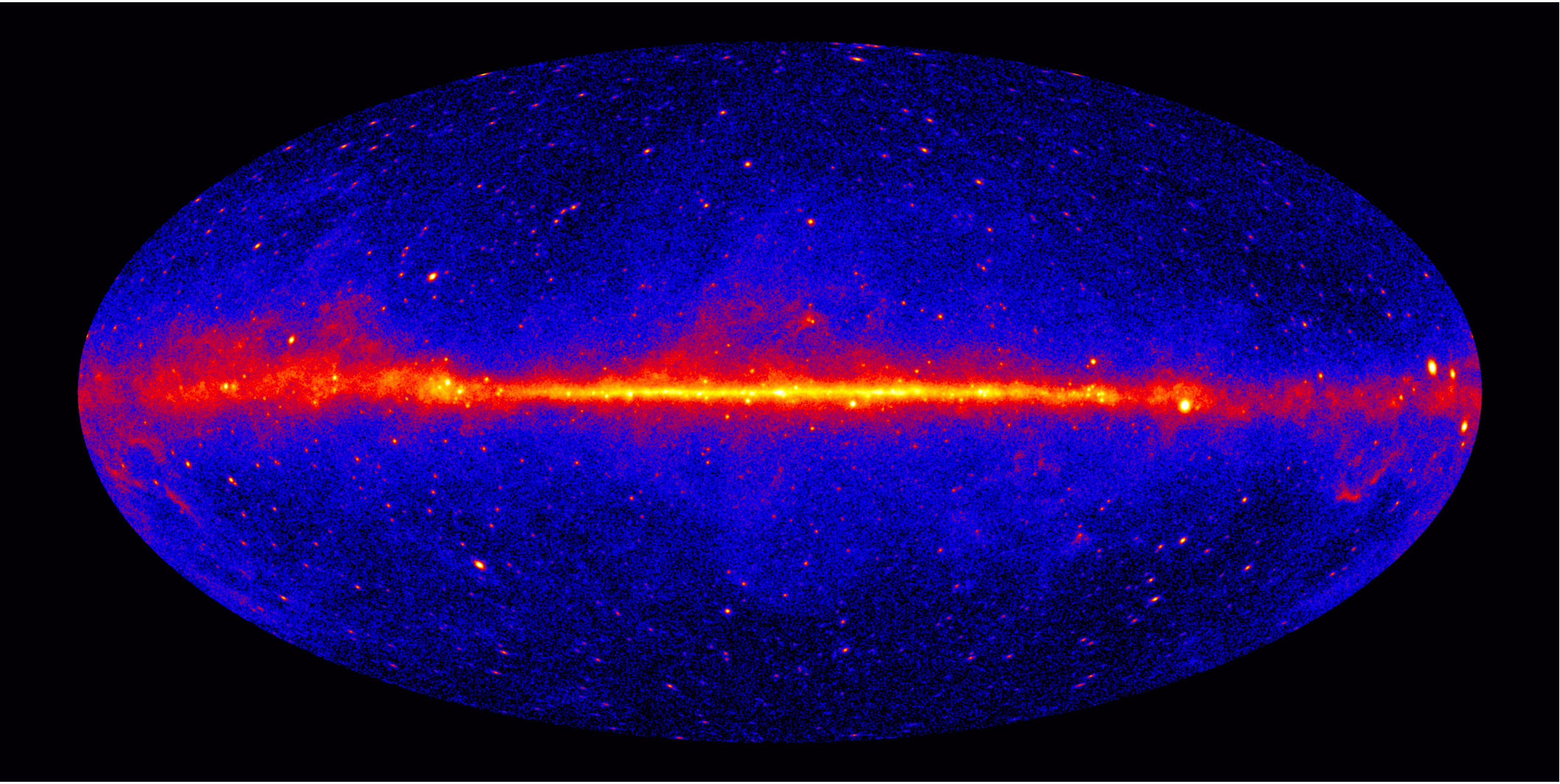
Si-Strip Tracker:
convert gamma->e^+e^-
reconstruct gamma direction
EM v. hadron separation

Anti-Coincidence Detector:
Charged particle separation

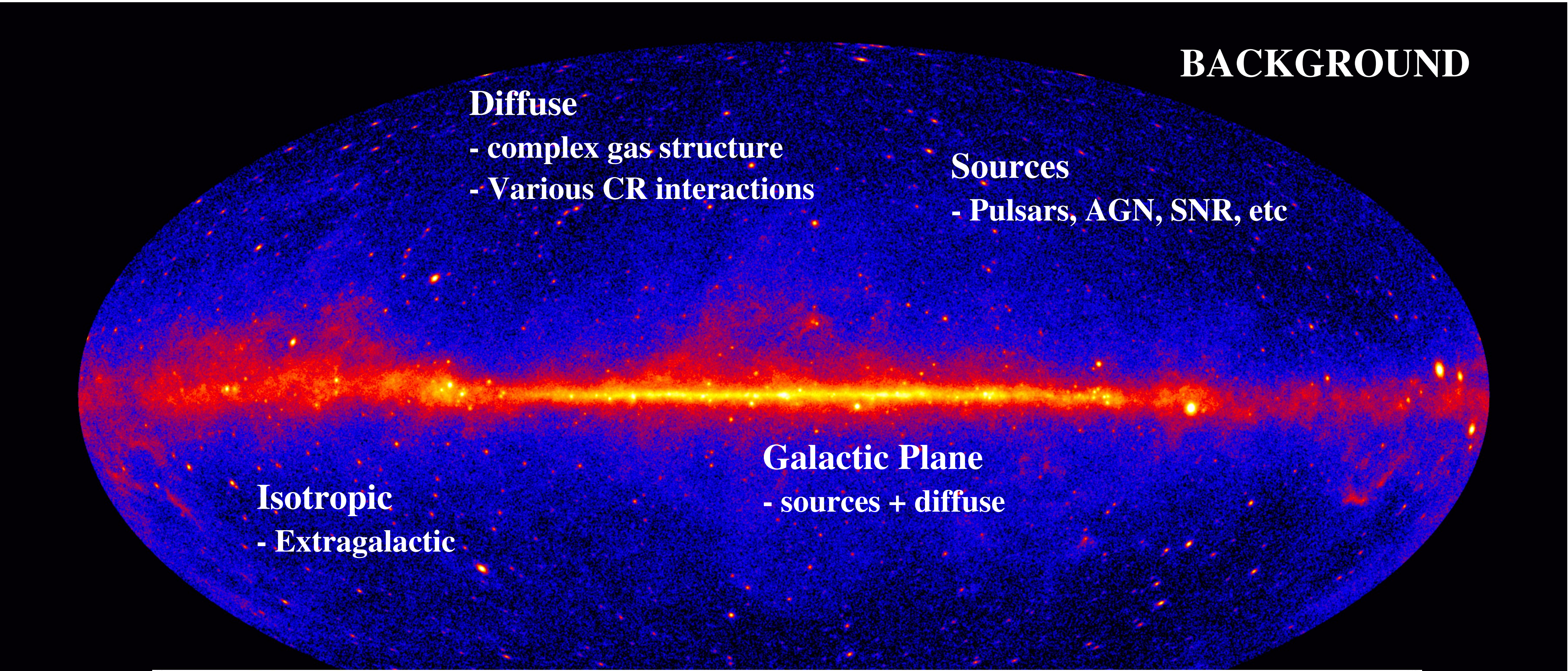
Hodoscopic CsI Calorimeter:
measure gamma energy
image EM shower
EM v. hadron separation

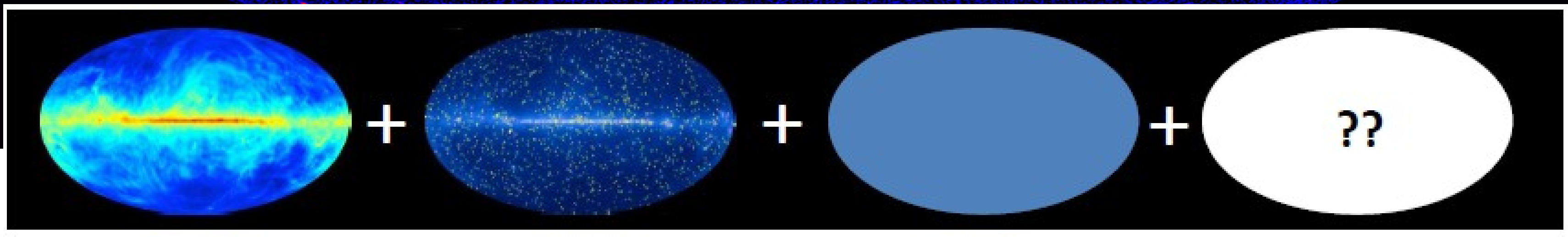
Trigger and Filter:
Reduce data rate from ~10kHz to 300-500 Hz

The Gamma-ray Sky as seen by the Fermi-LAT



The Gamma-ray Sky as seen by the Fermi-LAT

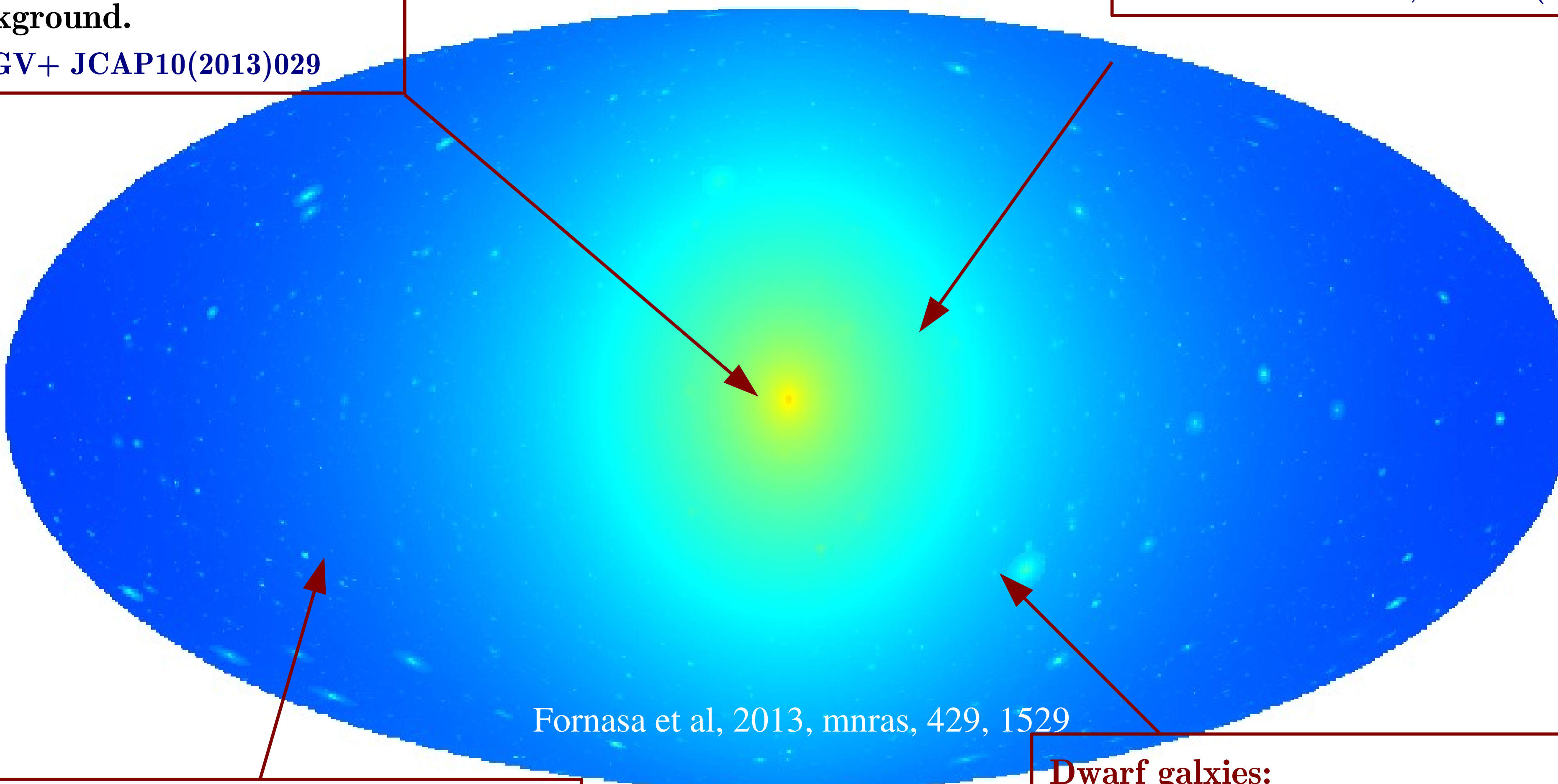




Targets for dark matter searches

Inner Galaxy:
Large statistics but diffuse background.
GAGV+ JCAP10(2013)029

Lines:
No astro uncertainties, but low sensitivity
Fermi Coll. PRD 86(2012)022002
Fermi Coll. PRD 88, 082002 (2013)



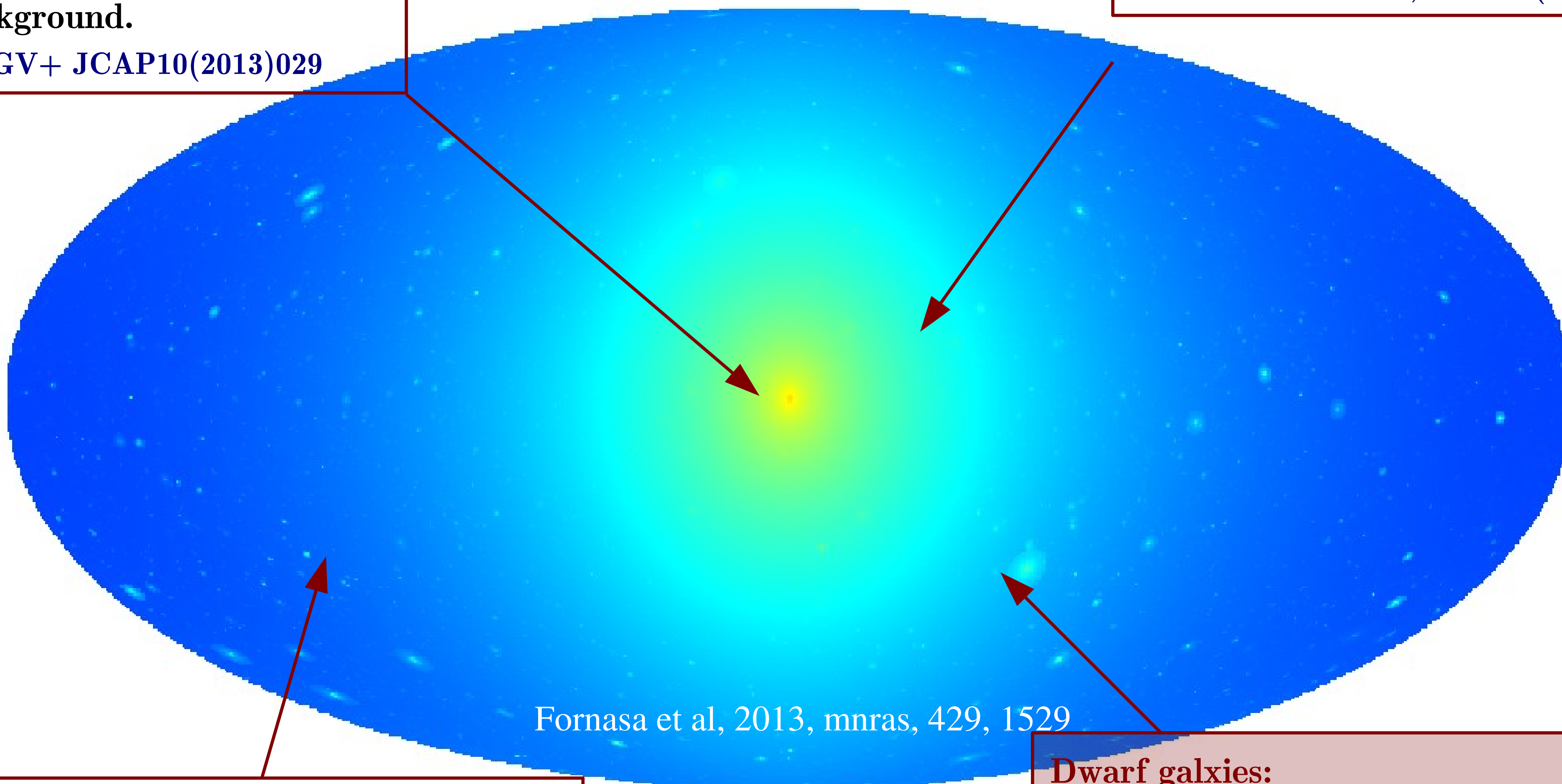
Anisotropies:
Low statistics and low background.
Fermi Coll. PRD 85(2012)083007
GAGV+ NIMA 2013 in press

Dwarf galxies:
Low background, but low statistics
Fermi Coll. arXiv: 1310.0828
Cahill-Rowley+ arXiv:1305.6921
Fermi Coll. 2011, PRL 107, 241302

Targets for dark matter searches

Inner Galaxy:
Large statistics but diffuse background.
GAGV+ JCAP10(2013)029

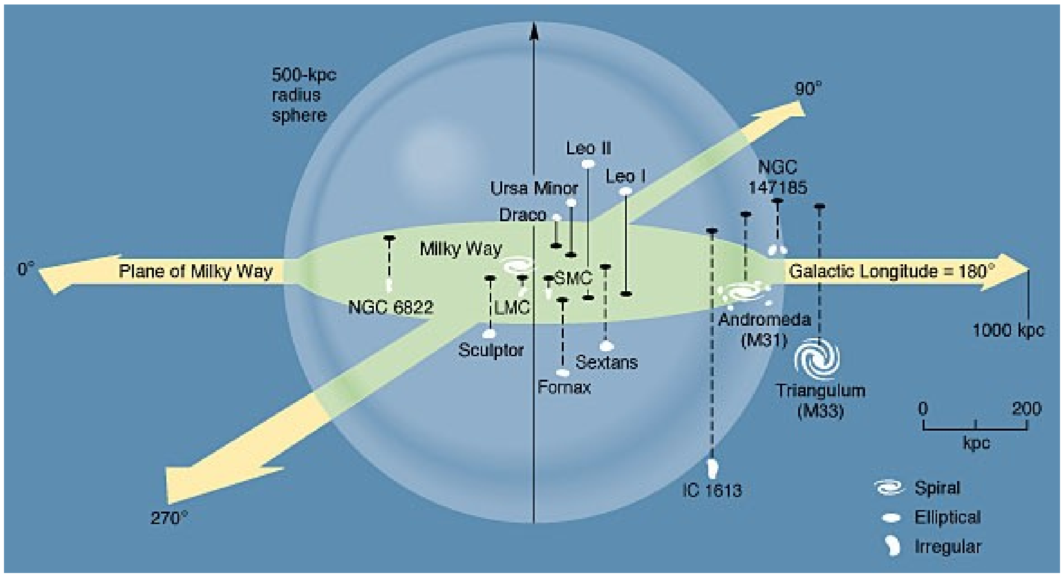
Lines:
No astro uncertainties, but low sensitivity
Fermi Coll. PRD 86(2012)022002
Fermi Coll. PRD 88, 082002 (2013)

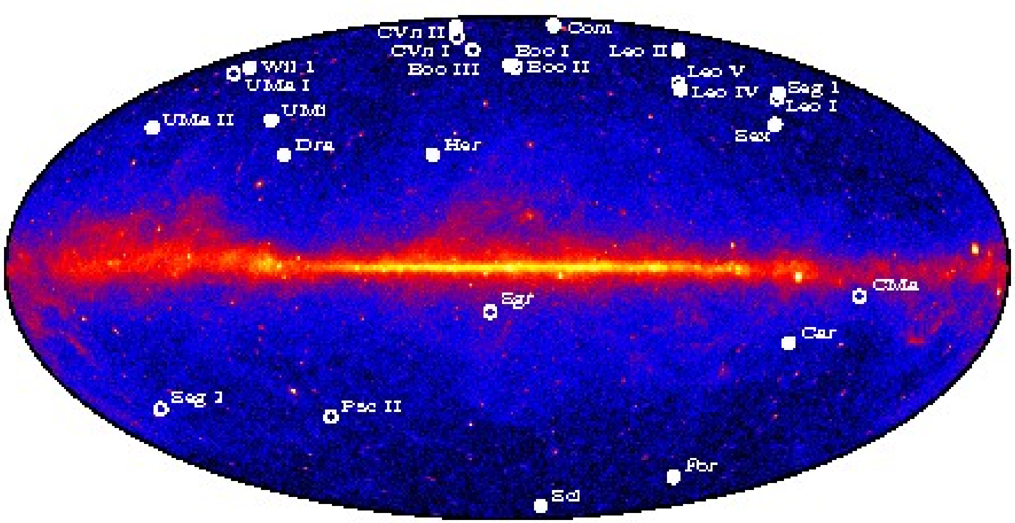


Anisotropies:
Low statistics and low background.
Fermi Coll. PRD 85(2012)083007
GAGV+ NIMA 2013 in press

Dwarf galxies:
Low background, but low statistics
Fermi Coll. arXiv: 1310.0828
Cahill-Rowley+ arXiv:1305.6921
Fermi Coll. 2011, PRL 107, 241302

Dwarf Spheroidal Galaxies

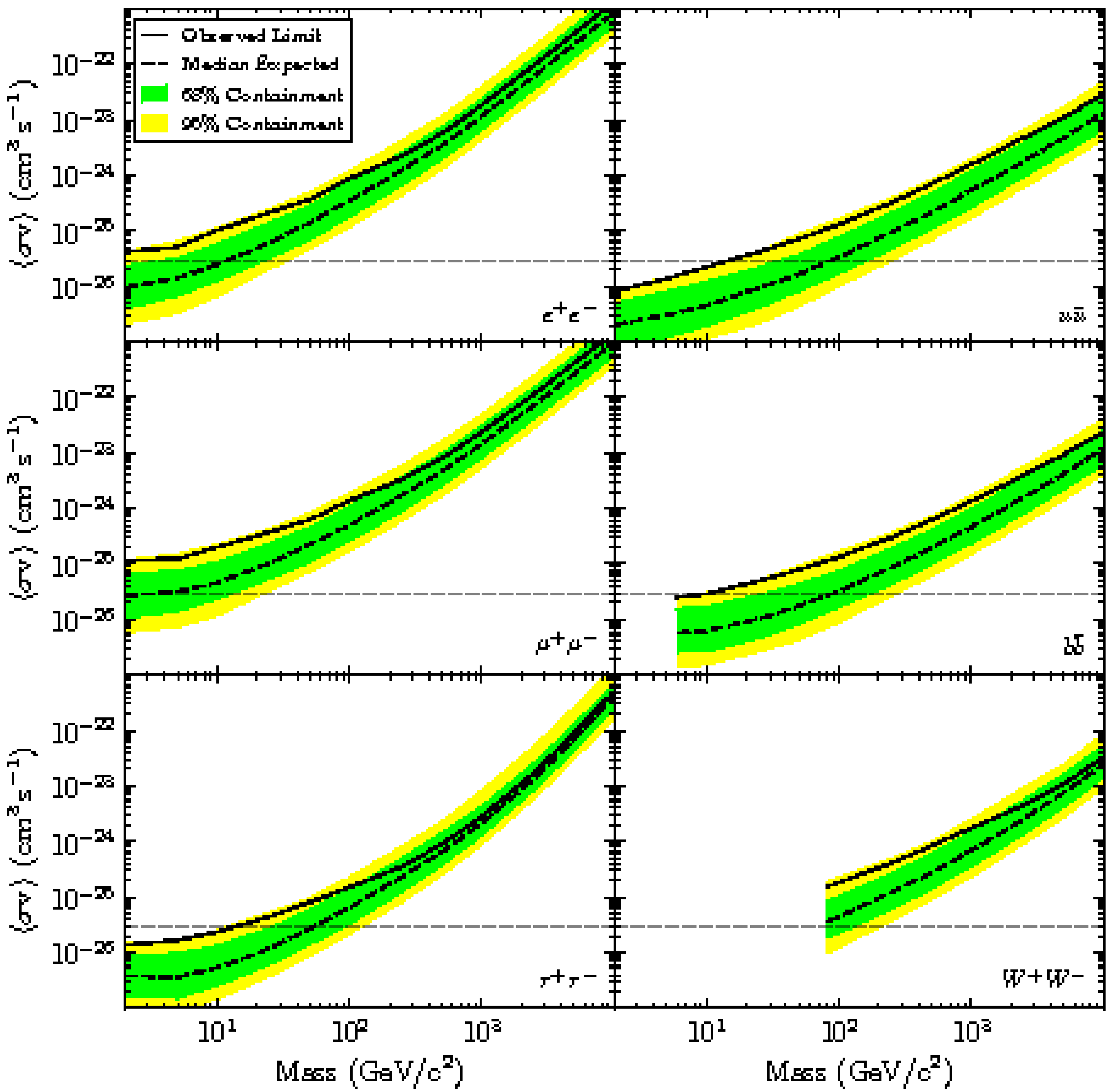




Fermi Coll. arXiv: 1310.0828

- Most dark-matter dominated objects in the universe (100 - 1000 times more dark matter than visible matter)
- Relatively close (25 - 150 kpc)
- High Galactic latitudes (minimize astrophysical foregrounds)
- Multi-wavelength observations show no mechanism for astrophysical gamma-ray production:
  - No active star formation (no energy injection)
  - No appreciable magnetic fields (no acceleration)
  - No gas or dust (no target material)

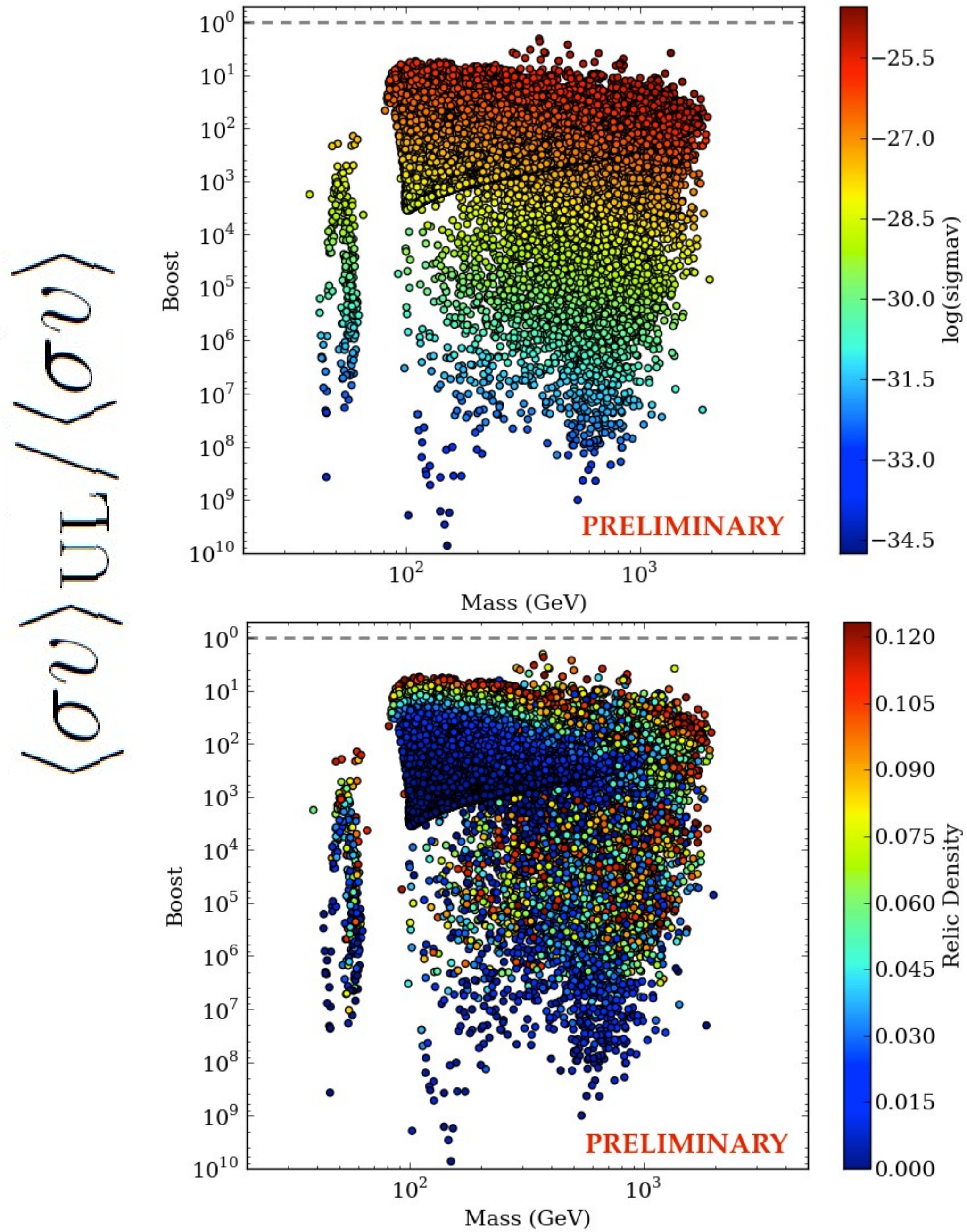
Dwarf Spheroidal Galaxies



Fermi Coll. arXiv: 1310.0828

- Current limit close to thermal relic X-section <~ 30 GeV
  - Different analysis techniques
  - Updated J factors and 4 years of data
  - Extended studies of sensitivity and systematics
- Prospects from upcoming surveys
  - deeper, larger sky coverage

Dwarf Spheroidal Galaxies



pMSSM parameter space scanned

$m_{\tilde{L}(e)_{1,2,3}}$	100 GeV – 4 TeV
$m_{\tilde{Q}(q)_{1,2}}$	400 GeV – 4 TeV
$m_{\tilde{Q}(q)_3}$	200 GeV – 4 TeV
$\lvert M_1 \rvert$	50 GeV – 4 TeV
$\lvert M_2 \rvert$	100 GeV – 4 TeV
$\lvert \mu \rvert$	100 GeV – 4 TeV
M_3	400 GeV – 4 TeV
$\lvert A_{t,b,\tau} \rvert$	0 GeV – 4 TeV
M_A	100 GeV – 4 TeV
$\tan\beta$	1 - 60
$m_{3/2}$	1 eV–1 TeV ($\tilde{G}$ LSP)

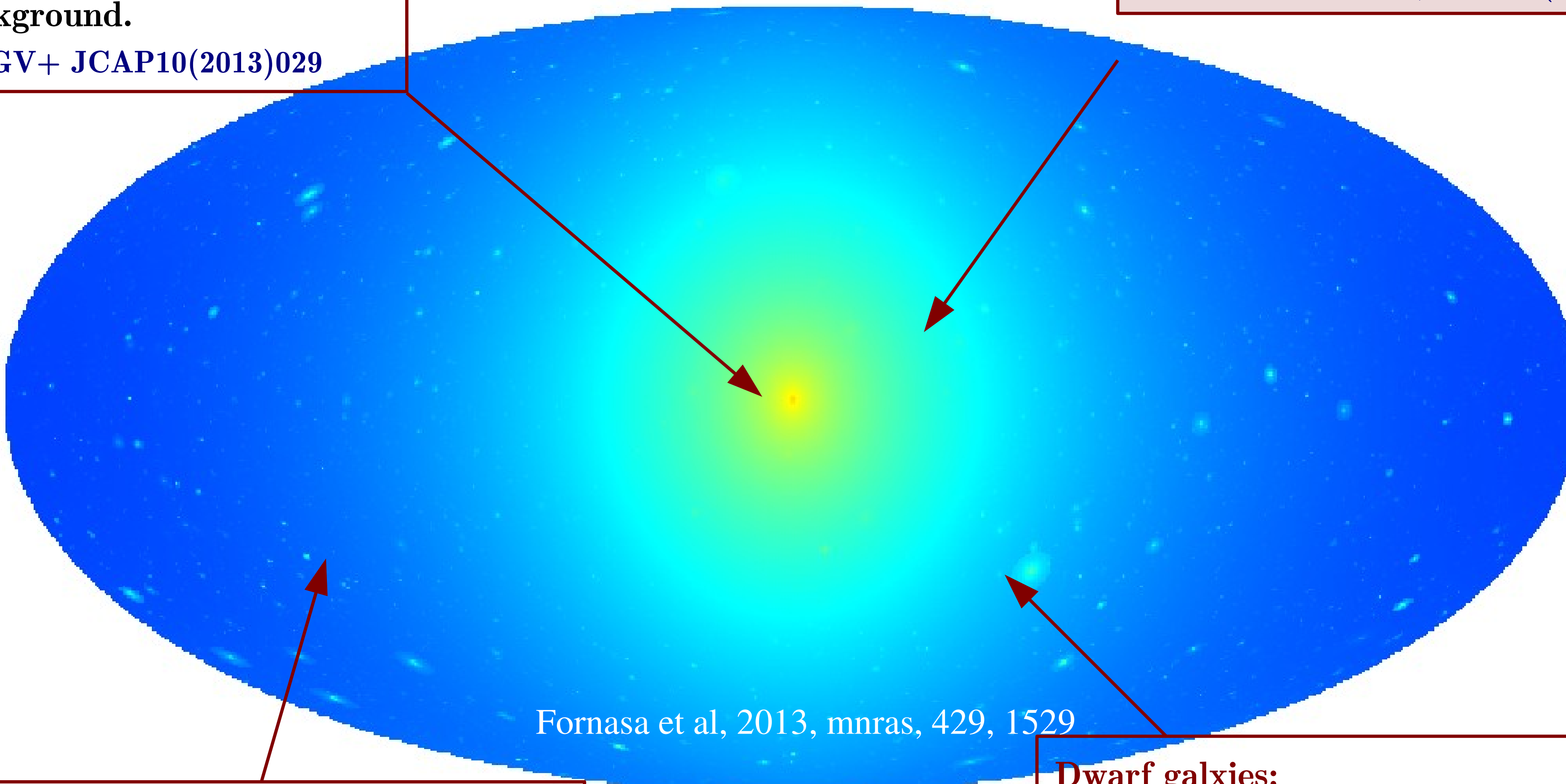
Cahill-Rowley+ arXiv:1305.6921

Every point in the plot satisfy relevant ATLAS SUSY search publicly available as of the beginning of March 2013. Also, direct detection limits from Xenon 100.

Targets for dark matter searches

Inner Galaxy:
Large statistics but diffuse background.
GAGV+ JCAP10(2013)029

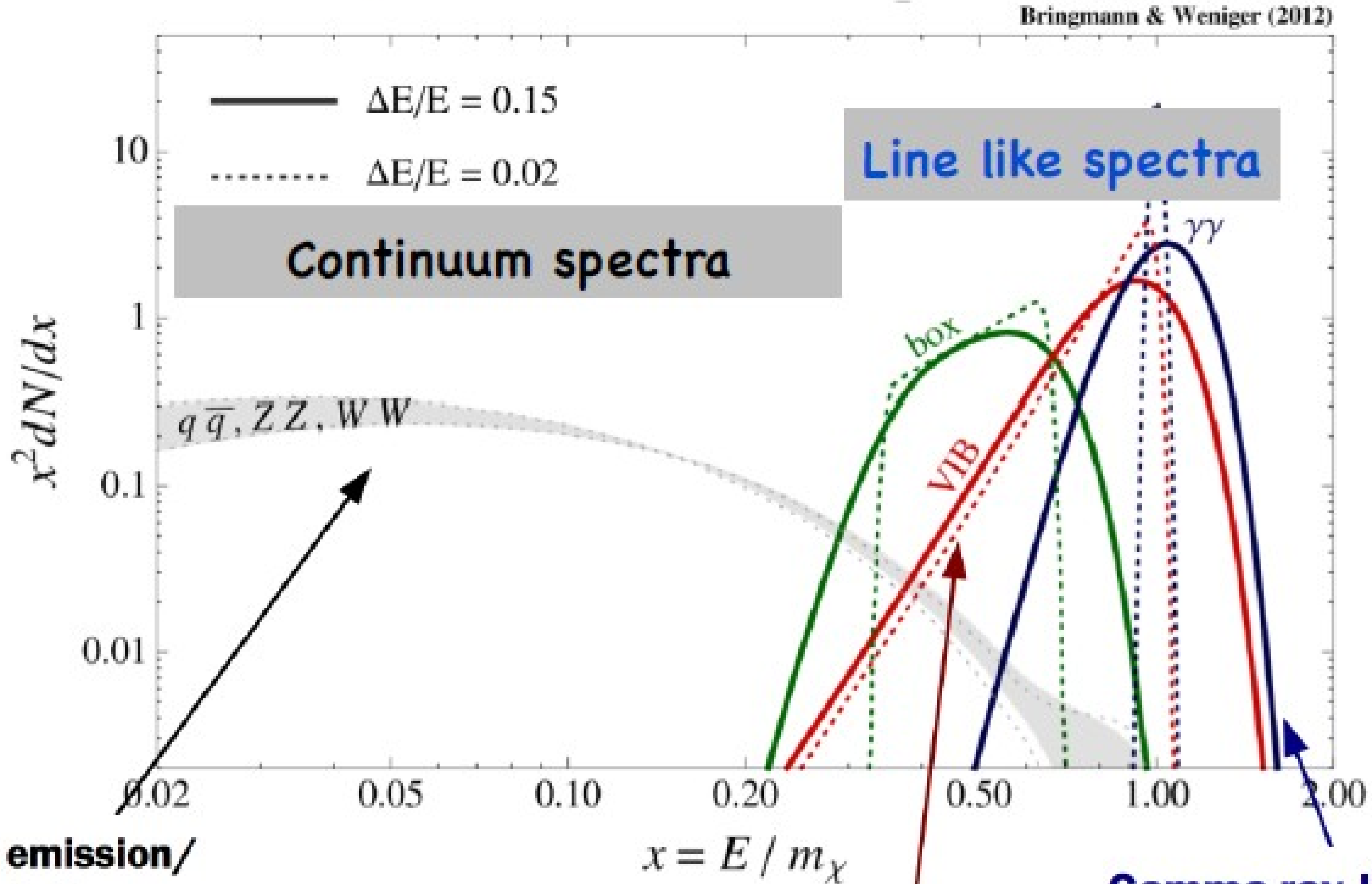
Lines:
No astro uncertainties, but low sensitivity
Fermi Coll. PRD 86(2012)022002
Fermi Coll. PRD 88, 082002 (2013)



Anisotropies:
Low statistics and low background.
Fermi Coll. PRD 85(2012)083007
GAGV+ NIMA 2013 in press

Dwarf galxies:
Low background, but low statistics
Fermi Coll. arXiv: 1310.0828
Cahill-Rowley+ arXiv:1305.6921
Fermi Coll. 2011, PRL 107, 241302

Gamma-ray line



Continuum emission/ secondary photons

- often largest component
- featureless spectrum
- difficult to distinguish from astrophysical background

$$\chi\chi \to \bar{q}q \to \pi^0 \dots$$
$$\pi^0 \to \gamma\gamma$$

Internal Bremsstrahlung (IB)

- radiative correction to processes with charged final states
- Generically suppressed by O(α)

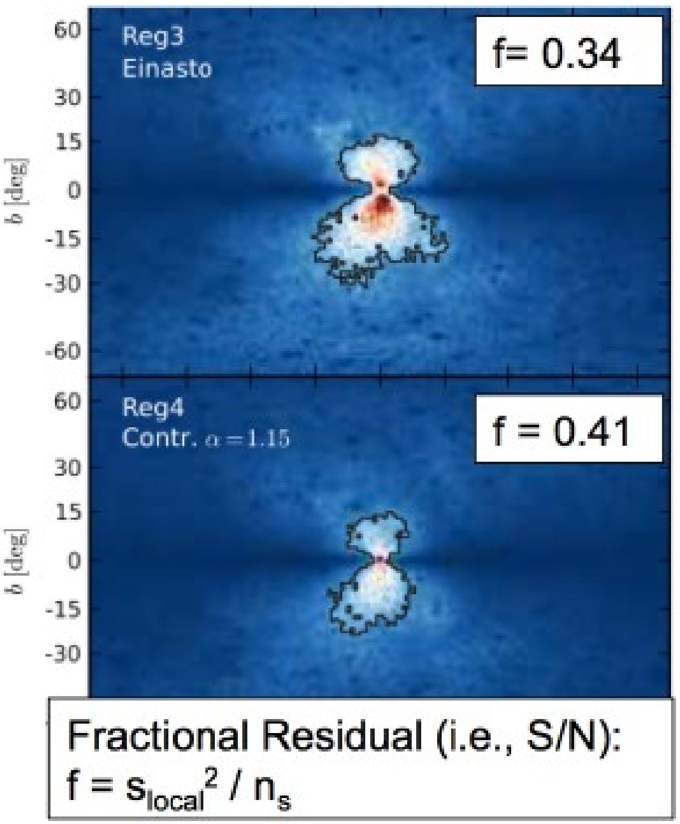
$$\chi\chi \to \bar{f}f\gamma$$

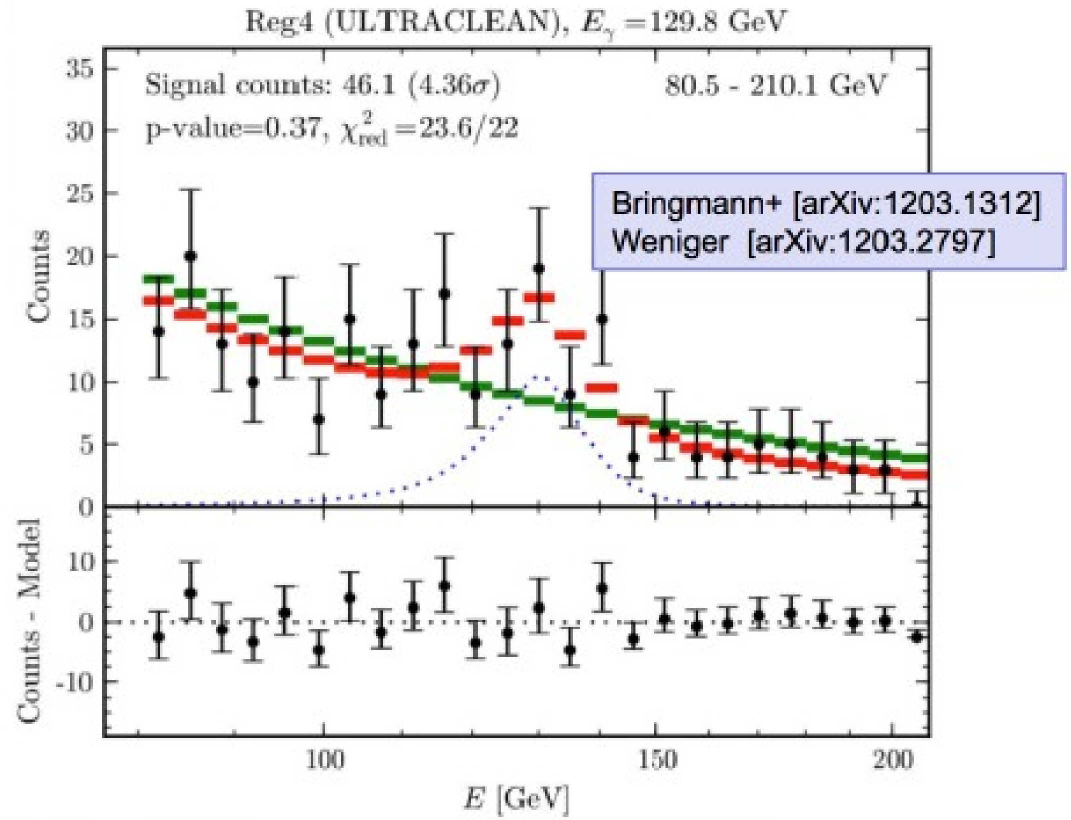
Gamma-ray lines

- from two-body annihilation into photons
- forbidden at tree-leve, generically suppressed by O(α²)

$$\chi\chi \to \gamma\gamma$$

GAMMA-RAY LINE





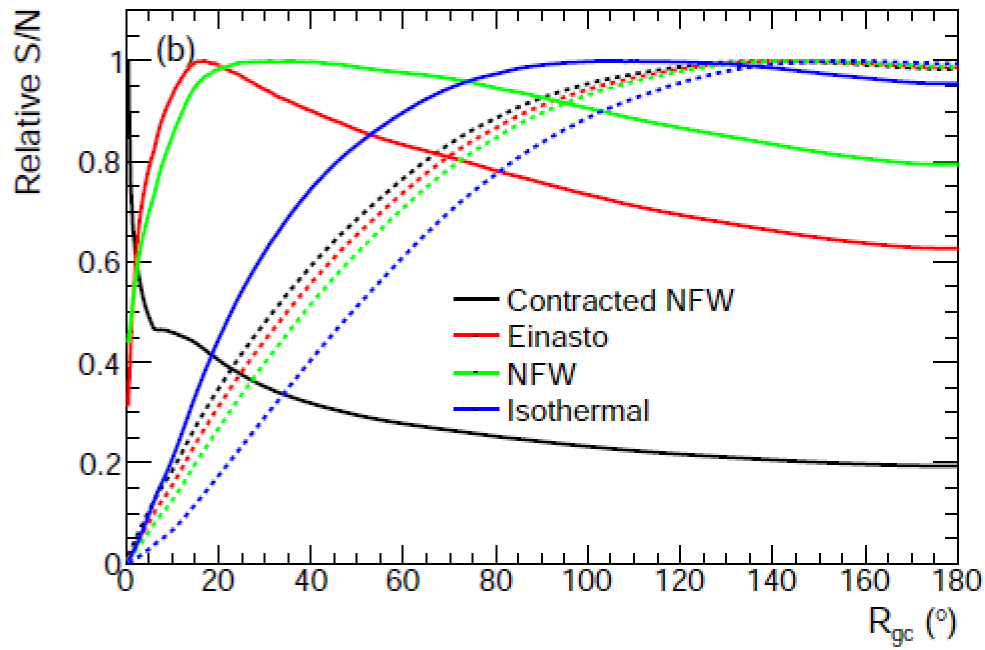
Bringmann et al. and Weniger showed evidence for a narrow spectral feature near 130 GeV and near the Galactic centre:

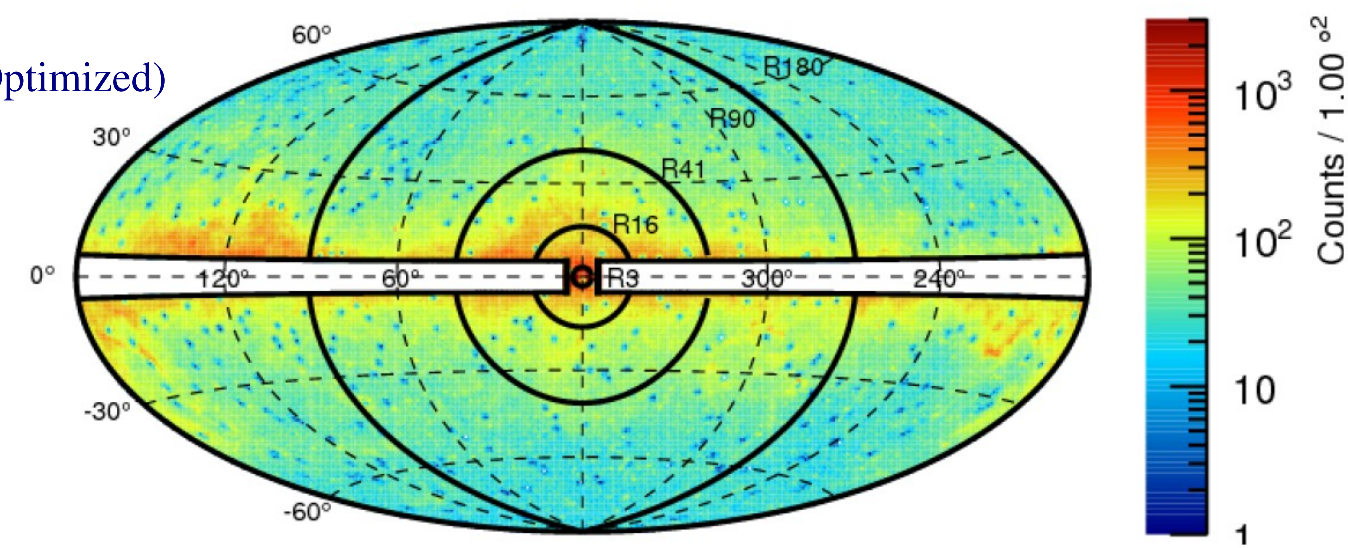
- Signal is particularly strong in 2 out of their 5 test sky regions, shown above.
- 4–5 σ (local), with S/N ≈30–60% in optimized regions of interest (ROI).

Gamma-ray line

Search for lines from 5 – 300 GeV using 3.7 years of data

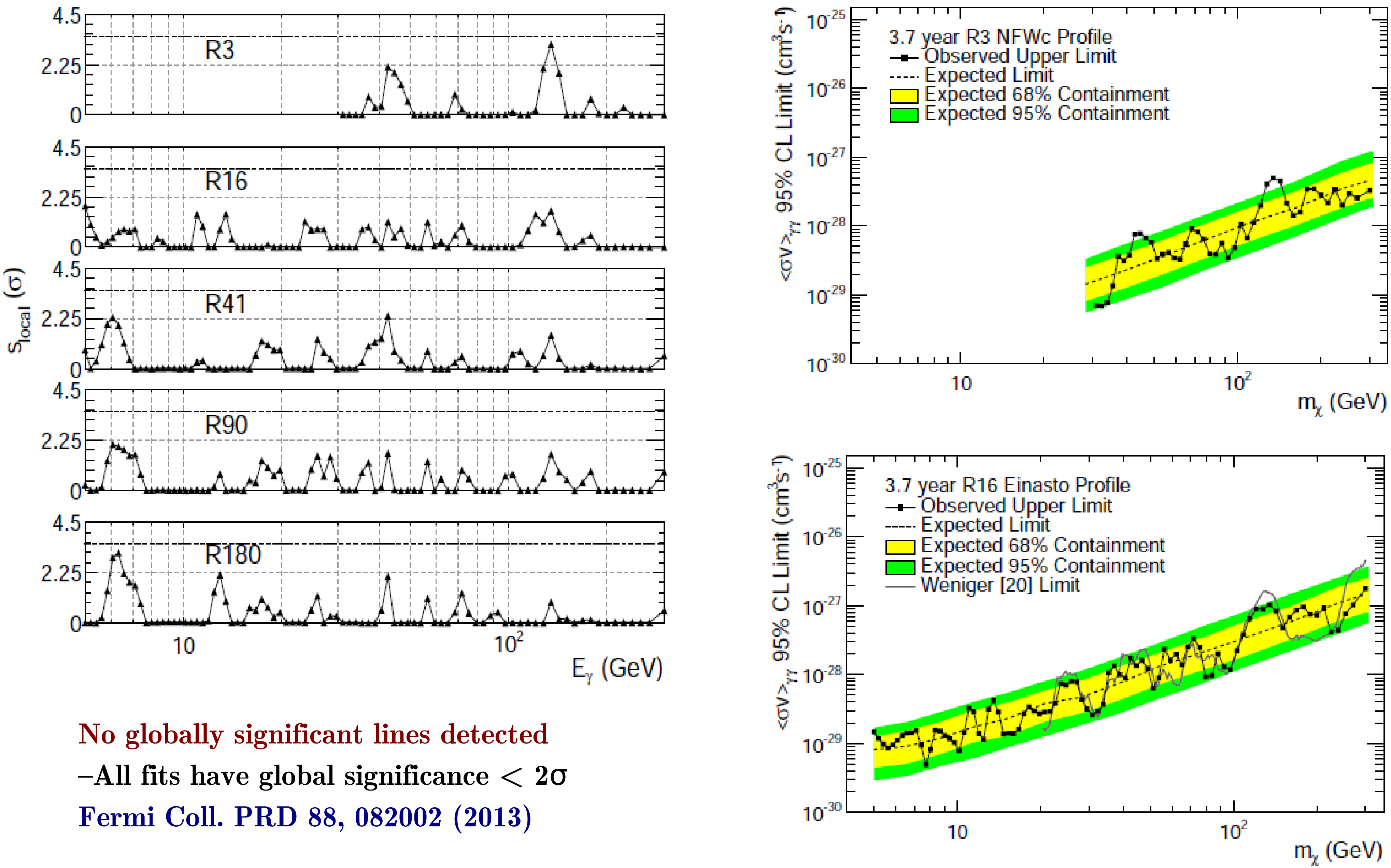
- Use P7REP_CLEAN (REP = "reprocessed")
  - P7 data with updated instrument calibrations
- Mask bright (>10σ for E > 1 GeV) 2FGL sources
- Optimize ROI for a variety of DM profiles
  - Find RGC that optimizes S/sqrt(B)
- Search in 5 ROIs
  - R3 (3 ° GC Circle, cont. NFW Optimized)
  - R16 (Einasto Optimized)
  - R41 (NFW Optimized),
  - R90 (Isothermal Optimized)
  - R180 (DM Decay)





Fermi Coll. PRD 88, 082002 (2013)

Gamma-ray line

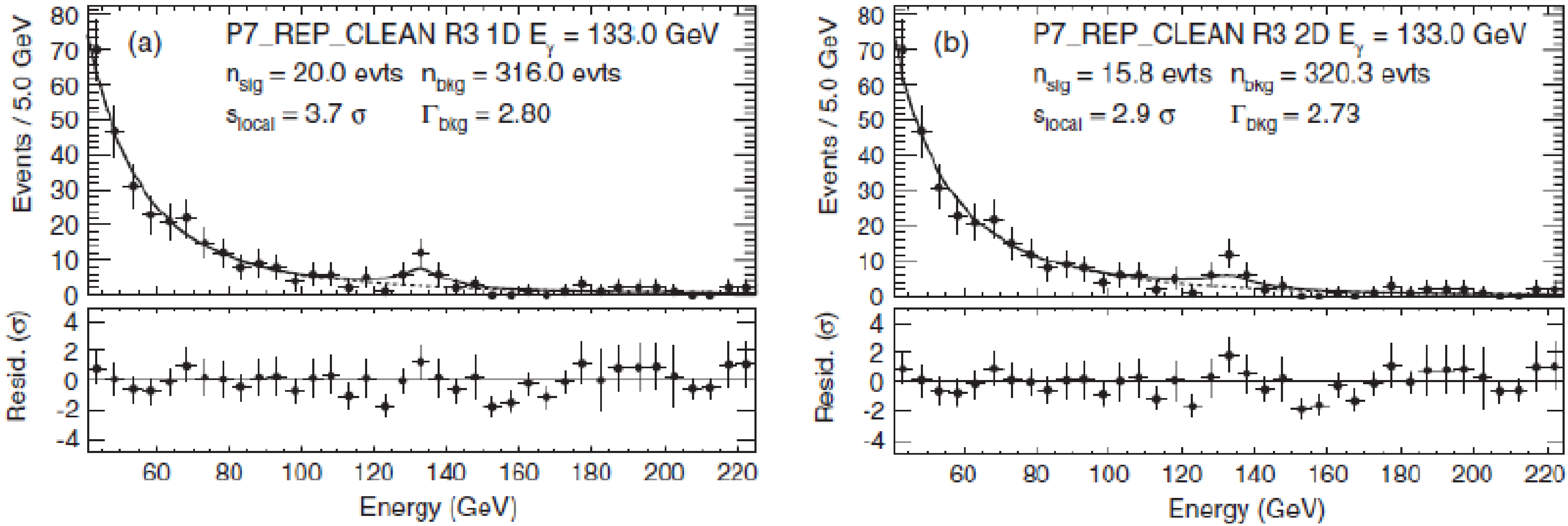


No globally significant lines detected

–All fits have global significance < 2σ

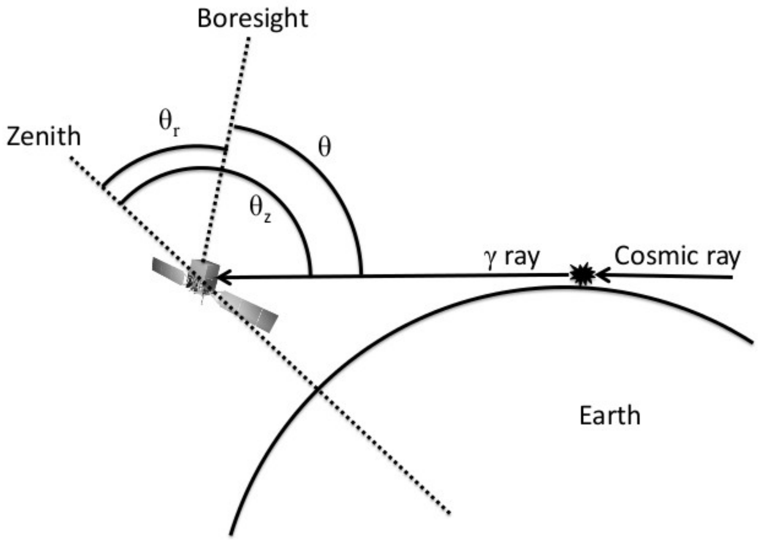
Fermi Coll. PRD 88, 082002 (2013)

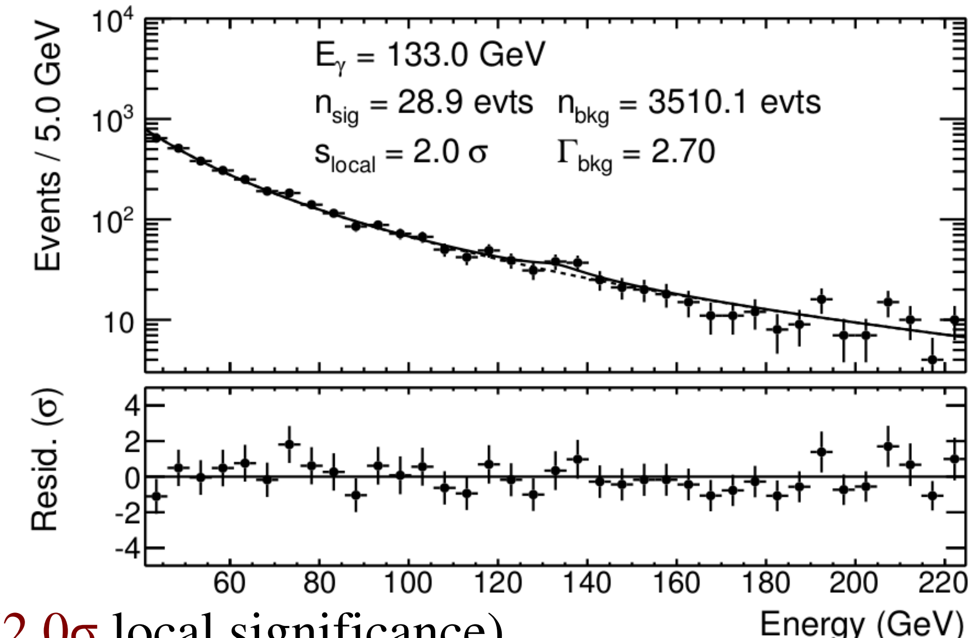
Gamma-ray line



- 3.7σ (local) 1D fit at 133 GeV with 4.4 year reprocessed data in R3
  - 1D PDF does not include of the energy reconstruction quality estimator, PE
- 2.9σ (local) 2D fit at 133 GeV with 4.4 year reprocessed data in R3
  - 2D PDF includes of the energy reconstruction quality estimator, PE
- <2σ global significance after trials factor

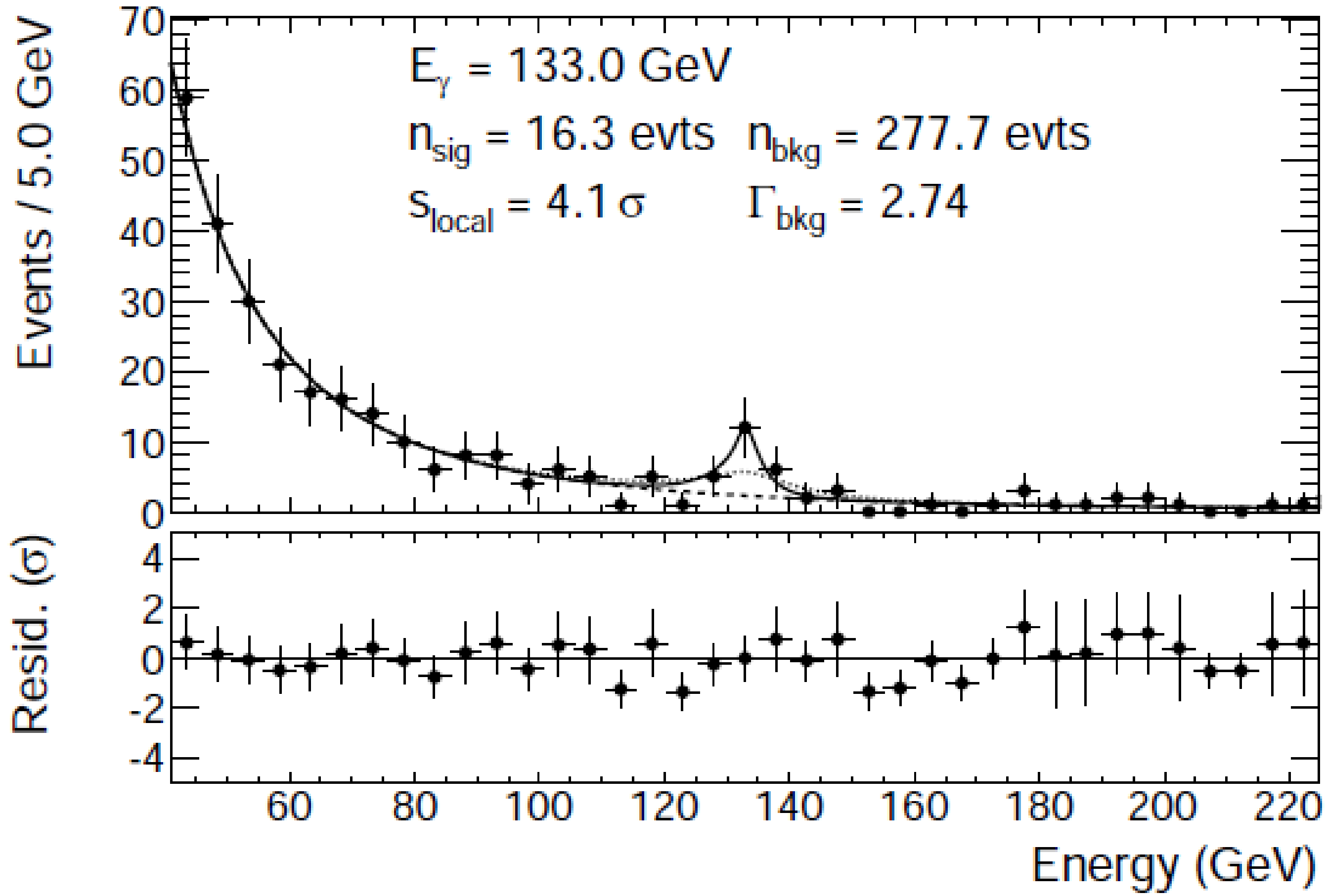
Gamma-ray line





- Line-like feature in the limb at 133 GeV (2.0σ local significance)
  - Appears when LAT is pointing at the limb
  - Surprising since limb should be smooth power-law
  - S/Nlimb ~ 14%, while S/NR3 ~ 61%
  - Limb feature not large enough to directly explain all the GC signal
- Dips in efficiency (less stringent Transient cuts → Clean cuts) below and above 133 GeV
  - Appear to be related with Calorimeter-Tracker event direction agreement
  - Could be artificially sculpting the energy spectrum

Gamma-ray line



Let width scale factor float in fit (while preserving shape)

$$s_\sigma = 0.32^{+0.30}_{-0.13}\ (95\%\ \mathrm{CL})$$

–Feature in data is narrower than expected energy resolution measured in beam tests and detector simulations

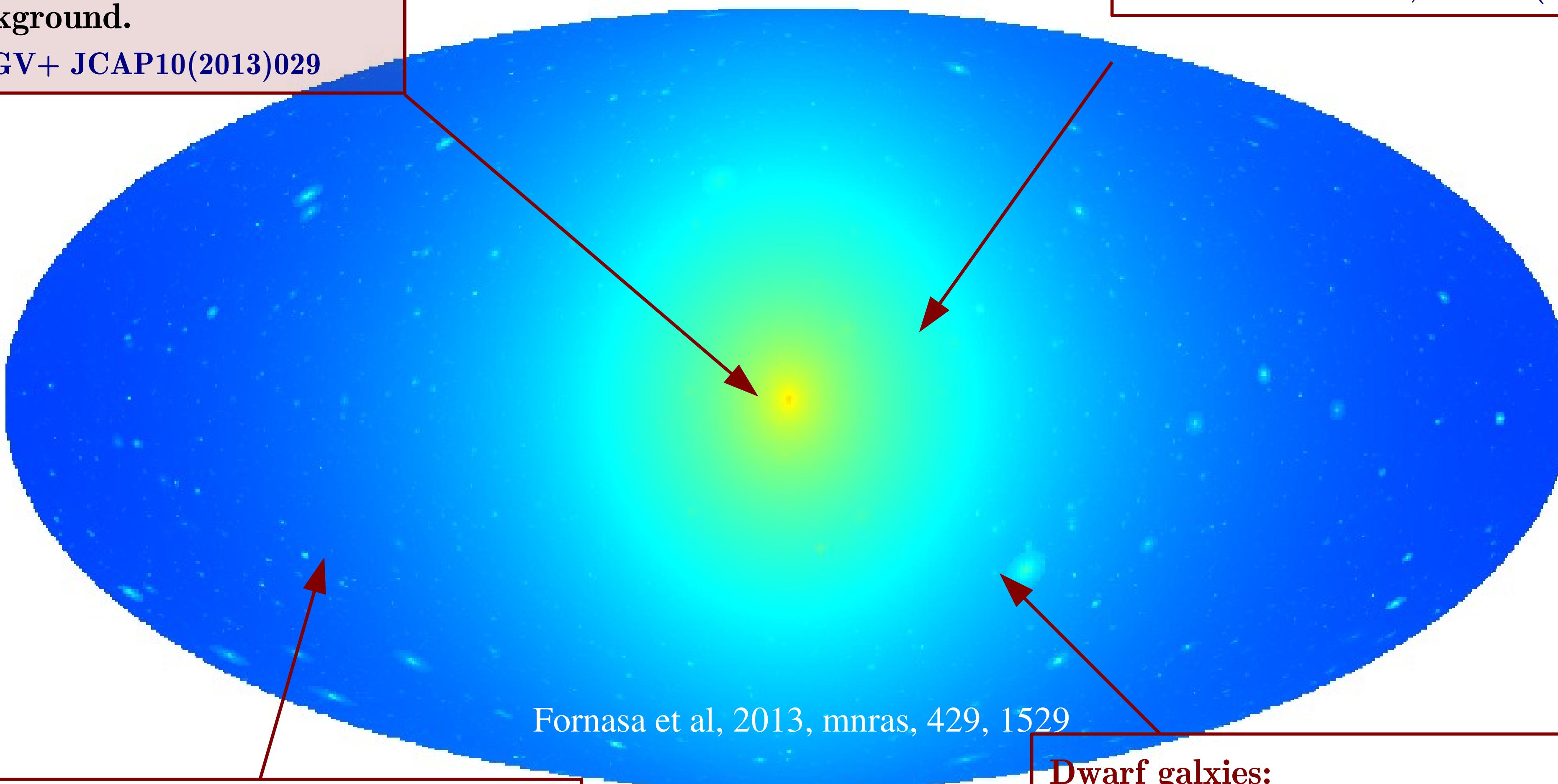
Summary

- We do not see any globally significant spectral line
- Pros
  - Tantalizing signal (>3sigma local)
  - Signal form the GC region
  - No signal in the Galactic plane
  - Signal (roughly) consistent with expected DM profiles
- Cons
  - Similar signal in limb data (not as strong)
  - Similar feature at other energies
  - Decreased in significance w/ more data and analysis improvements
  - Global significance (incl. trial factors) <2sigma
  - Requires large gamma-gamma Br displaced from GC
- More Fermi-LAT data + Pass 8 will give more information.
- Cherenkov telescopes (HESS II, CTA) and Gamma 400

Targets for dark matter searches

Inner Galaxy:
Large statistics but diffuse background.
GAGV+ JCAP10(2013)029

Lines:
No astro uncertainties, but low sensitivity
Fermi Coll. PRD 86(2012)022002
Fermi Coll. PRD 88, 082002 (2013)



Fornasa et al, 2013, mnras, 429, 1529

Anisotropies:
Low statistics and low background.
Fermi Coll. PRD 85(2012)083007
GAGV+ NIMA 2013 in press

Dwarf galxies:
Low background, but low statistics
Fermi Coll. arXiv: 1310.0828
Cahill-Rowley+ arXiv:1305.6921
Fermi Coll. 2011, PRL 107, 241302

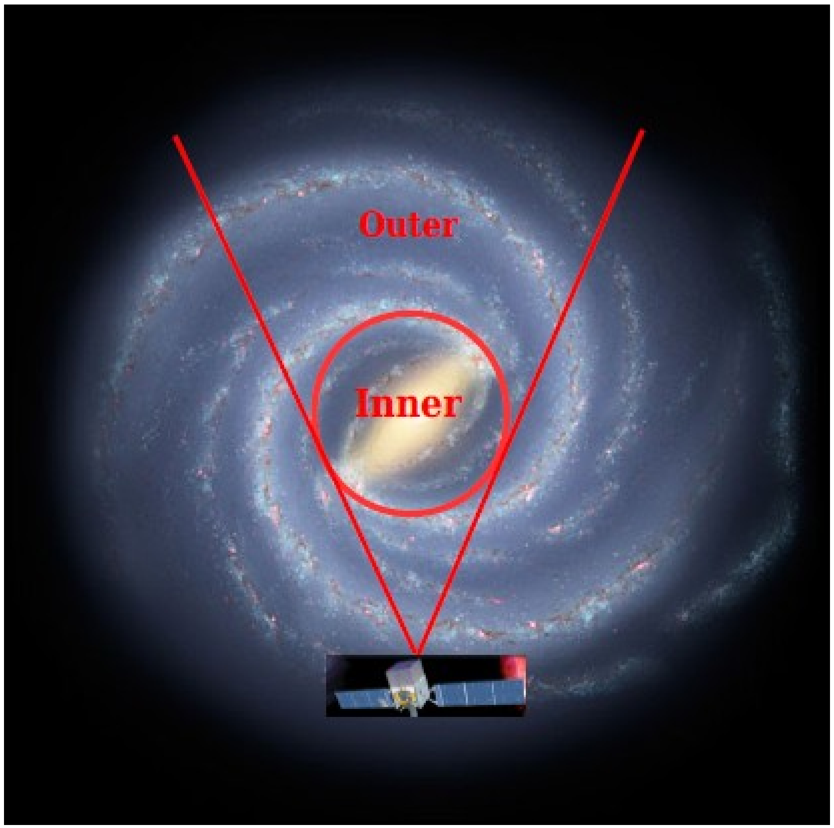
Dark Matter Searches in the Inner Galaxy with the *Fermi*-LAT

- DM-induced SM particles would appear as exotic contributions in astrophysical observations, they can affect fluxes and spatial distribution of CR, i.e. protons, antiprotons, electrons, positrons, gamma-rays and neutrinos measured at the Earth

- We need to measure those fluxes and understand the non-exotic contributions, i.e. the background .

- To set conservative constraints we don't need to understand the background, we can simply require that the expected DM signal does not exceed the measurement. (GAGV+ JCAP10(2013)029)

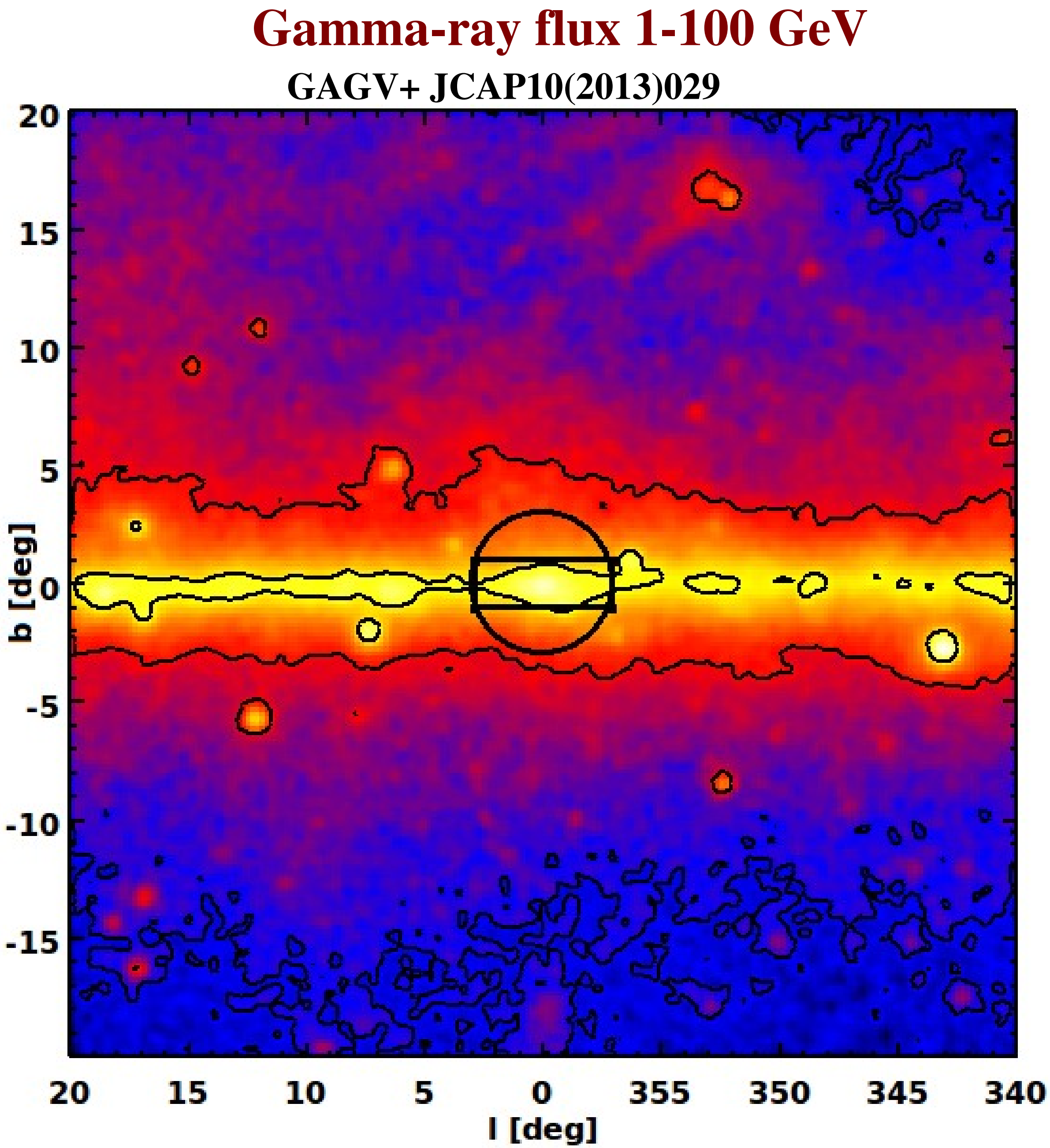
Inner Galaxy



Emission from the inner Galaxy is made of:

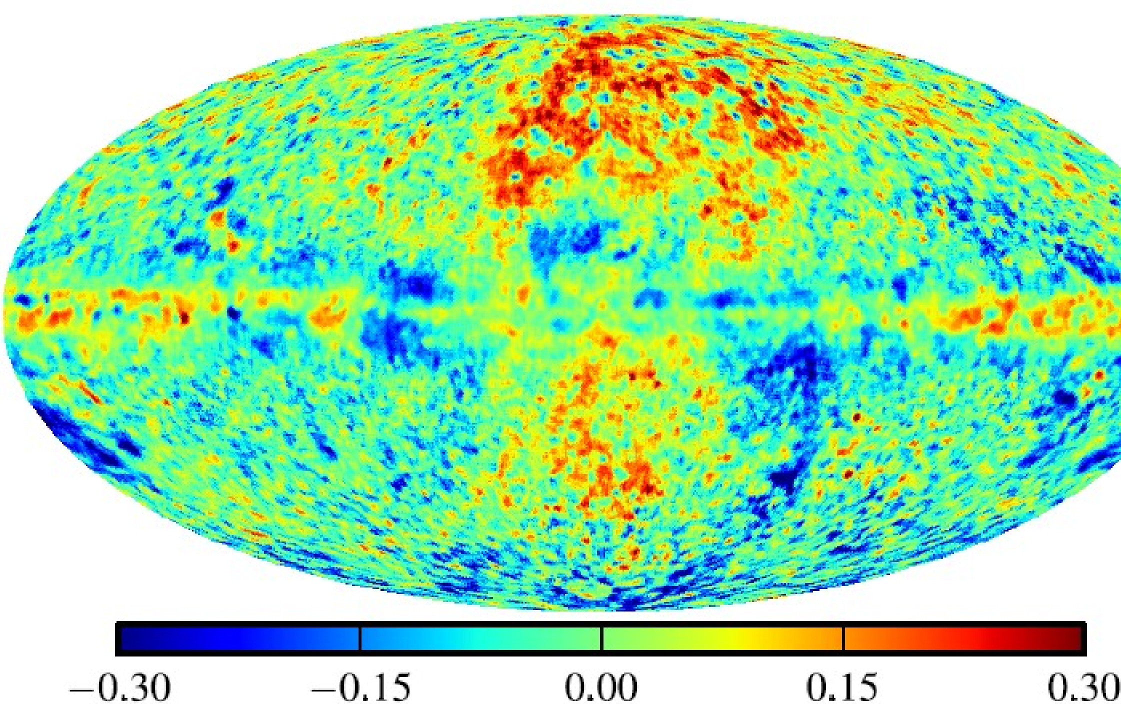
- Outer Galaxy
- True inner Galaxy
- Unresolved sources
- Point or small extended sources
- Extragalactic emission
- Possible DM contribution
- CR instrumental background
- Fermi lobes

Fermi-LAT view of the inner Galaxy



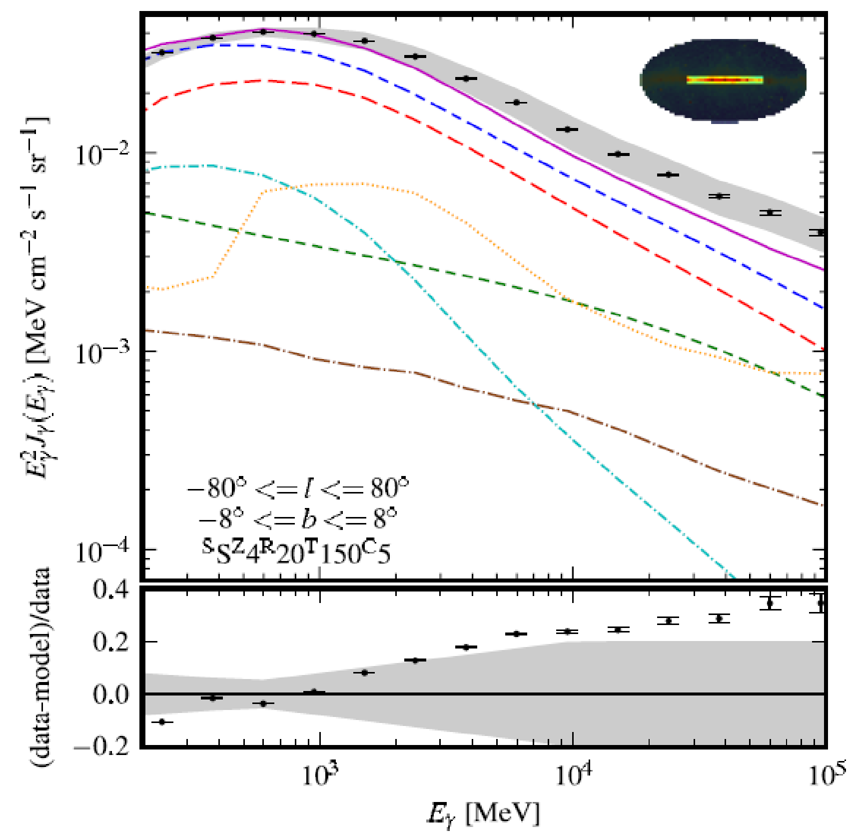
All sky modeling

- CR 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 (21 months, 200 MeV to 100 GeV, P6 DATACLEAN)
- On a large scale the agreement between data and prediction is overall good, however some extended excesses stand out.



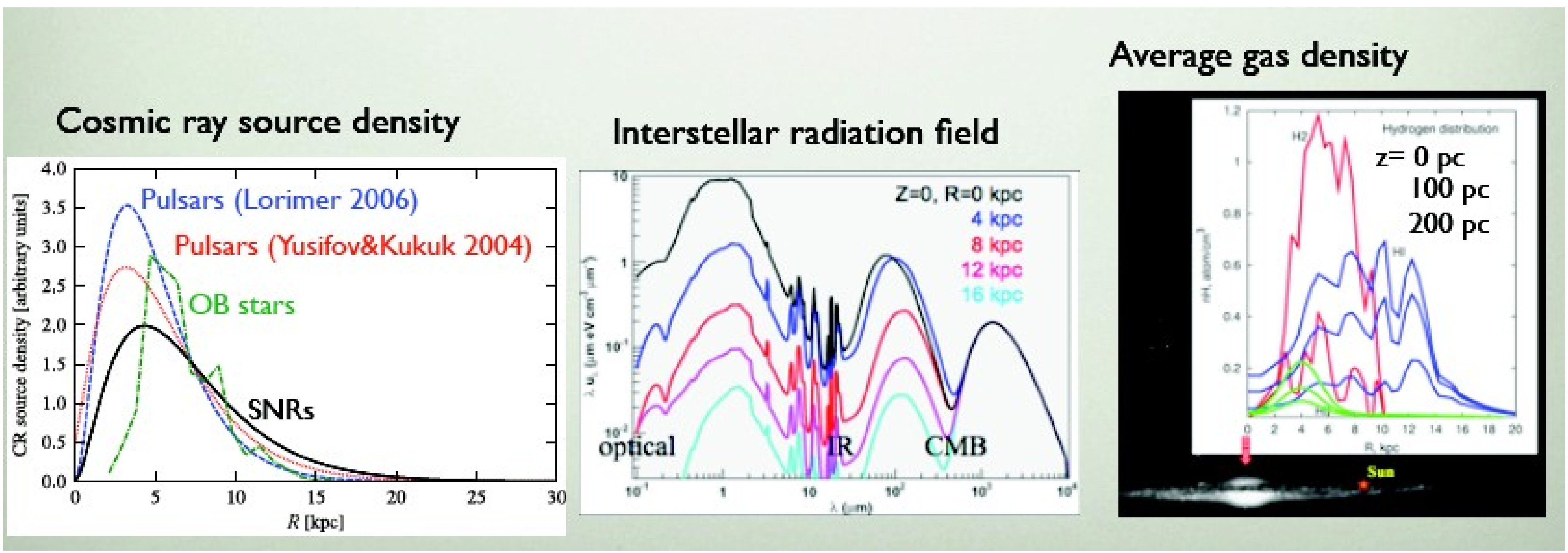
Fractional residual maps, (model – data)/data, in the energy range 200 MeV–100 GeV.

(Fermi-LAT Coll. The Ast. Journal, 750:3 (35pp), 2012)



Galactic Center region

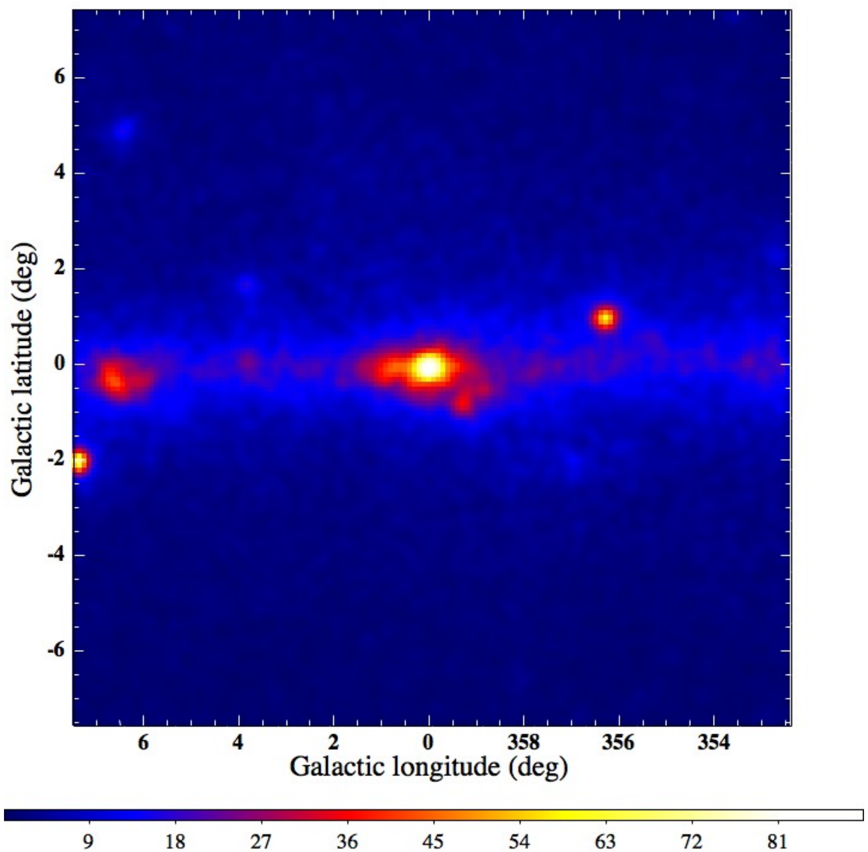
- Steep DM profiles predicted by CDM => Large DM annihilation/decay signal from GC!
- Good understanding of the conventional astrophysical background is crucial to extract a potential DM signal from this complex region of the sky:
  - Source confusion: many energetic sources near to or in the l.o.s. of the GC
  - Diffuse emission modeling: large uncertainties due to overlap of structures along the l.o.s. difficult to model



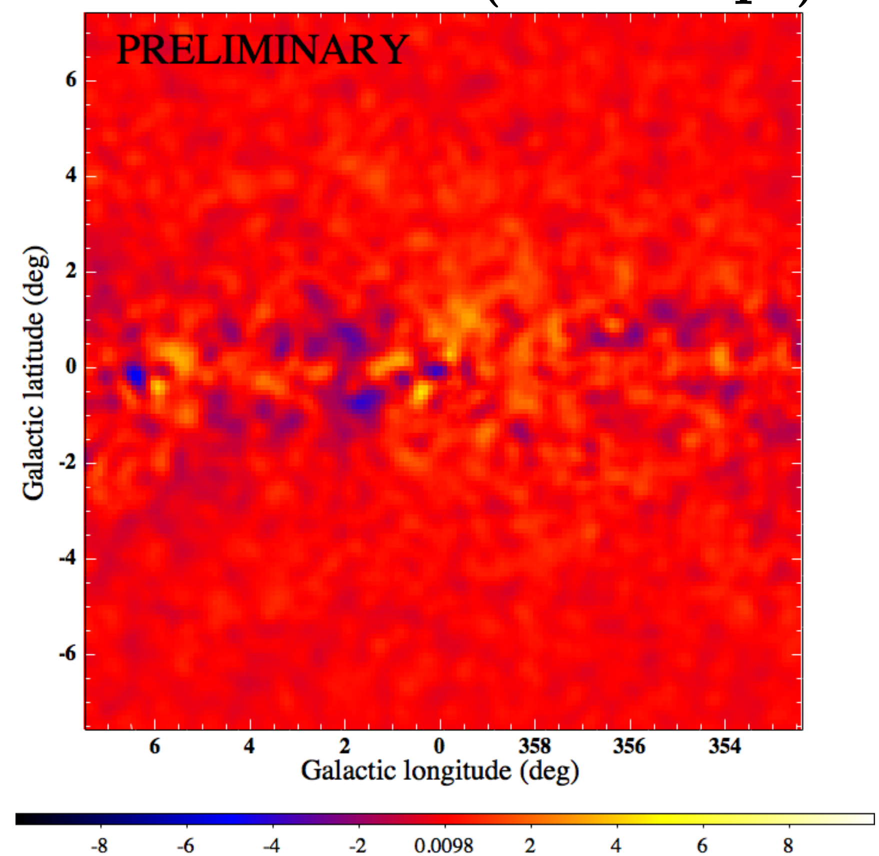
Fermi's View of the Inner Galaxy (15°x15° region)

Fermi LAT preliminary results with 32 months of data, E>1 GeV (P7CLEAN_V6, FRONT):

Data



Data – Model (diffuse+ps)



Diffuse emission and point sources account for most of the emission observed in the region.

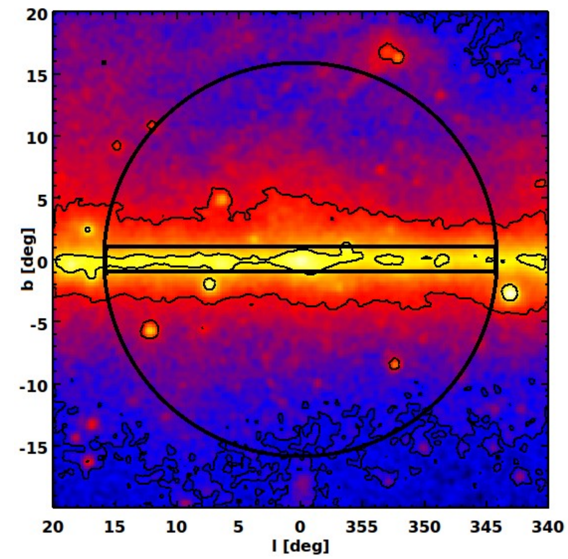
Fermi's View of the Inner Galaxy (15°x15° region)

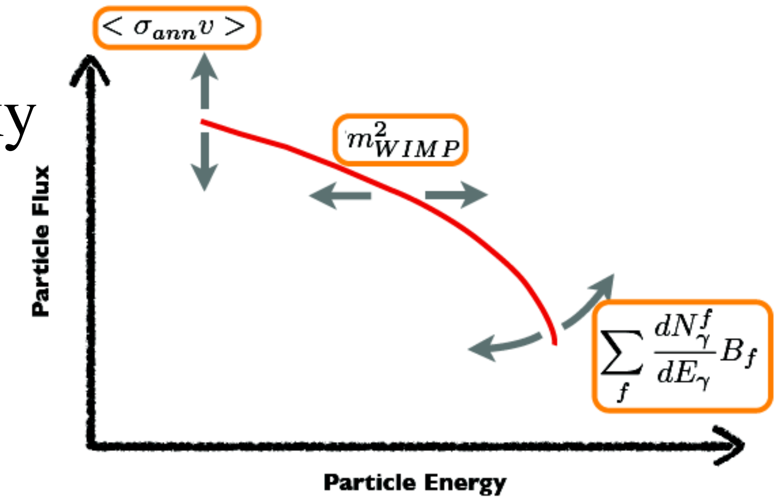
- DM would appear as an exotic contribution to the conventional gamma-ray emitters.
- However, our knowledge of astrophysical background is uncertain. This is currently a big limitation for the search of DM in the GC with gamma rays, which otherwise has a huge potential for discovery.
- Nevertheless, we can set conservative constraints on DM simply requiring that the expected DM signal does not exceed the measurement (GAGV+ JCAP10(2013)029).

Methodology

- Our analysis is conservative since it simply requires that the expected dark matter signal does not exceed the emission observed by the LAT in an optimized region around the GC.
- Since N-body simulations are not able to predict the DM distribution towards the GC, we use four well motivated DM profiles tuned to observables of the Milky Way.

Observed emission by the LAT





G. G-V et al. 2013. ArXiv:1308.3515

DM density profiles

We use realistic DM density profiles directly derived from MW observational data:

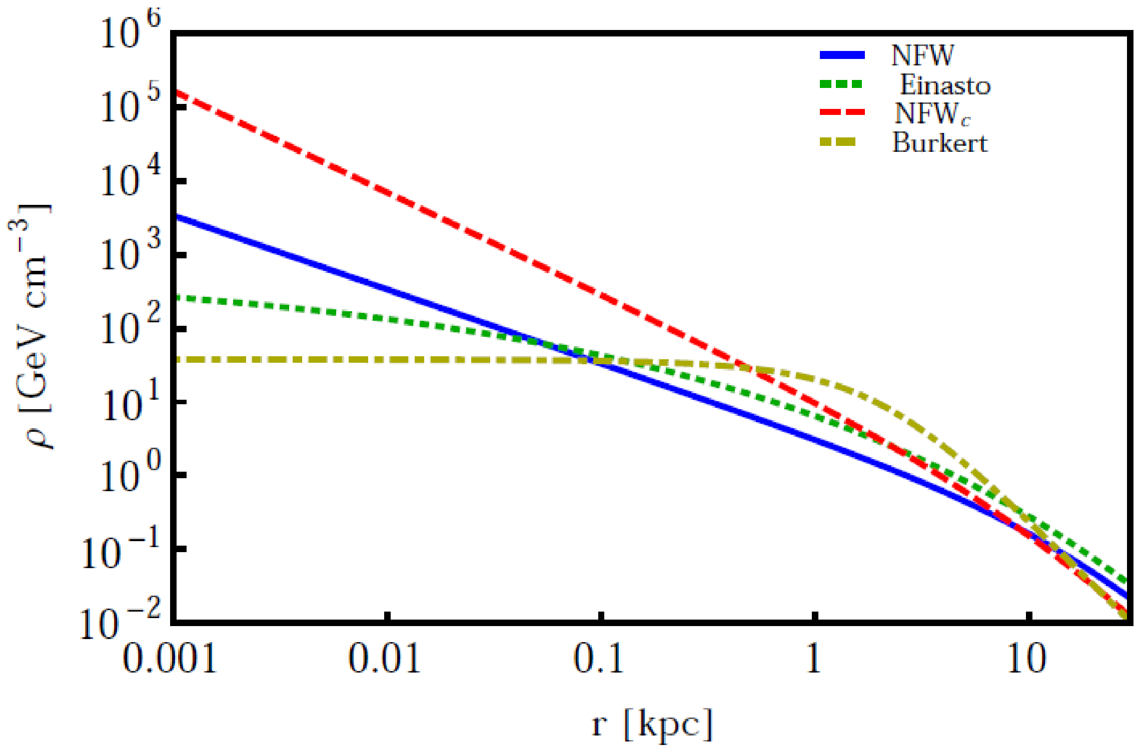
- NFW (Prada+04)
- Einasto (Catena&Ullio10).
- Burkert (inspired on Catena&Ullio10).
- **Adiabatically compressed NFW** (Prada+04).

Profile	α	β	γ	ρ_s [GeV cm^{-3}]	r_s [kpc]
Burkert	$--$	$--$	$--$	37.76	2
Einasto	0.22	$--$	$--$	0.08	19.7
NFW	1	3	1	0.14	23.8
NFW$_c$	0.76	3.3	1.37	0.23	18.5

$$\rho(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)^{\gamma} \left[1 + \left(\frac{r}{r_s}\right)^{\alpha}\right]^{\frac{\beta-\gamma}{\alpha}}}$$

$$\rho_{\mathrm{Ein}}(r) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha} - 1\right]\right\}$$

$$\rho_{\mathrm{Burkert}}(r) = \frac{\rho_s\ r_s^3}{(r + r_s)\ (r^2 + r_s^2)}$$



Contracted profiles

- DM-only simulations predict NFW or Einasto, but ordinary matter (baryons) dominates the central region of our Galaxy. Thus, baryons may significantly affect the DM distribution.
- As baryons collapse and move to the center they increase the gravitational potential, which in turn forces the DM to contract and increase its density.
- **Caution**: other baryonic effects may flatten the DM cusp:

1. Strong bursts of star formation with a series of multiple explosions
2. inner material expelled, causing a DM density decrease

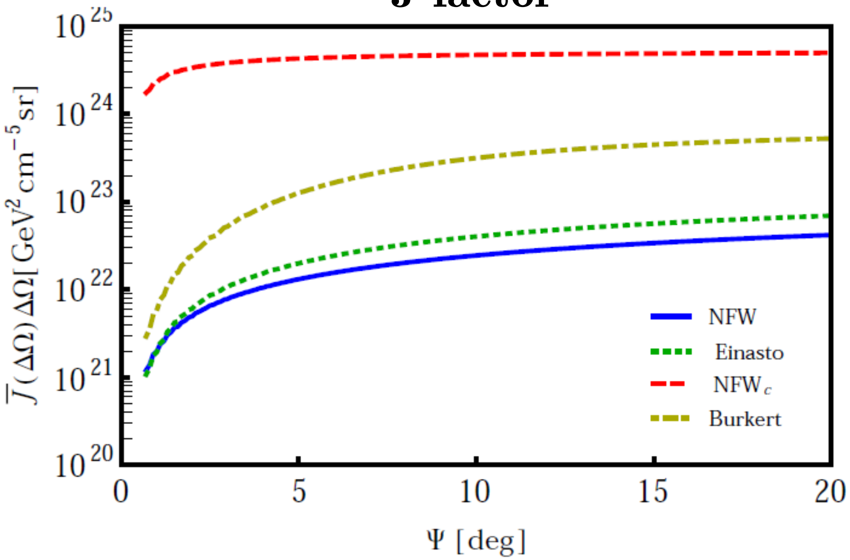
[Mashchenko+06, Mashchenko+08, Governato+10, Pontzen+12]

Baryons as seen by Spitzer in IR

3 deg

5.3 deg

J-factor



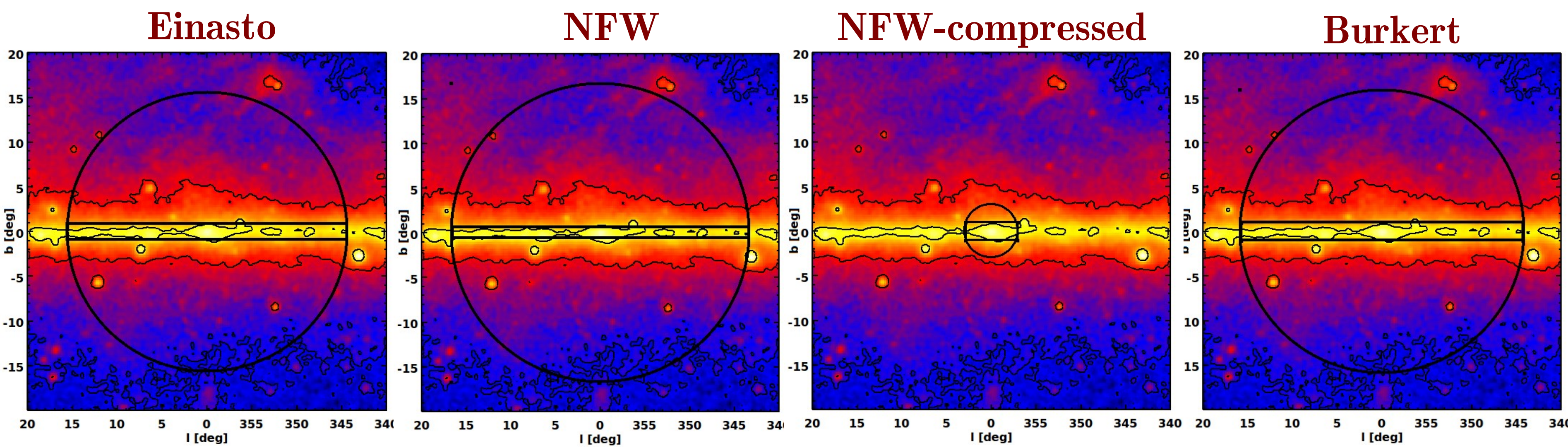
Fermi-LAT data analysis

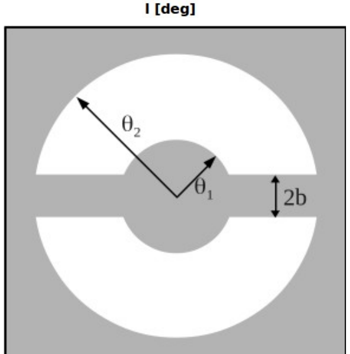
We choose the region of interest driven by an **S/N optimization**:

- *Signal*: J-factor maps for every DM density profile.

- *Noise*: Square root of the photon flux map.

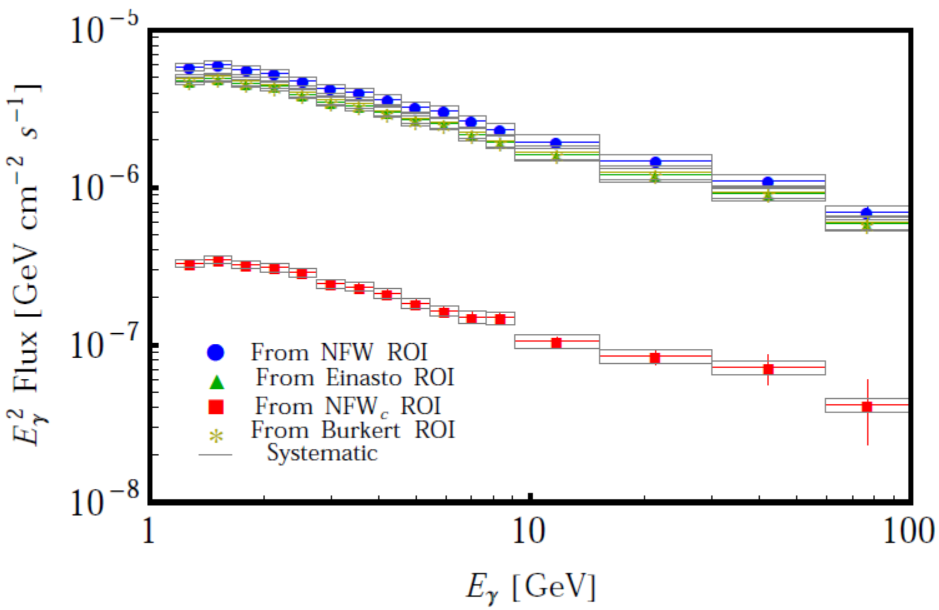
ROI's optimal parameters are those that make the S/N the largest for every profile





Profile	θ_1 [°]	θ_2 [°]	$\lvert b\rvert$ [°]	$\Delta\Omega$ [sr]	$\bar{J}(\Delta\Omega)\,\Delta\Omega$ [$\times10^{22}$ GeV^2 cm^{-5} sr]	Flux $(1-100$ GeV$)$ [$\times10^{-7}$ 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

Setting up constraints



Profile	$\bar{J}(\Delta\Omega)\,\Delta\Omega$ [$\times 10^{22}$ GeV^2 cm^{-5} sr]
Einasto	5.1
NFW	3.3
NFW$_c$	86.8
Burkert	41.9

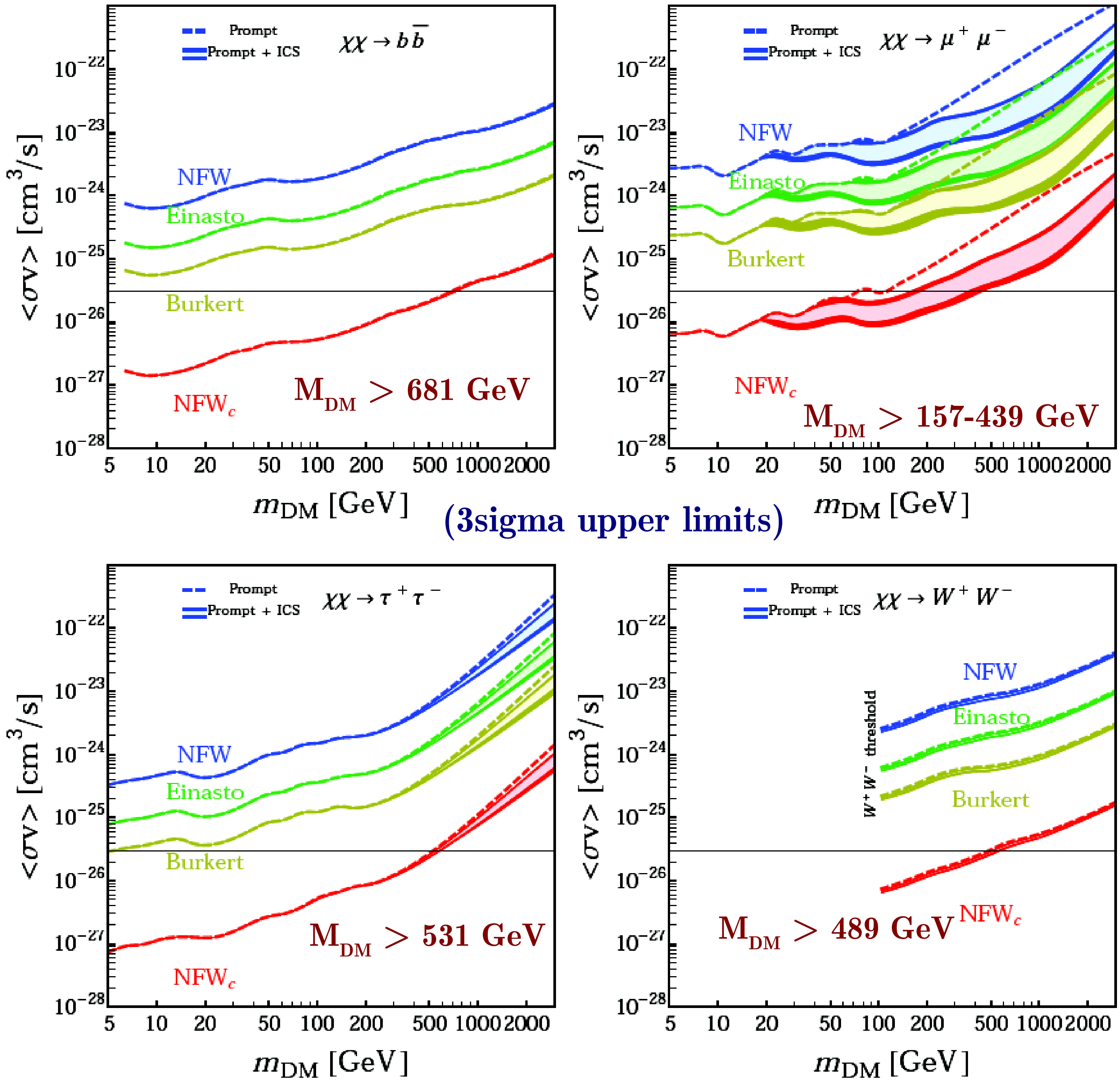
Energy spectrum as directly obtained from the data

VS.

J-factors

By comparing the inclusive energy spectrum extracted from the data for every ROI and the J-factors for every profile, we set DM constraints only requesting that the DM-induced gamma-ray emission *does not overshoot* the flux measurement at ***3sigma*** level.

Results:



Prompt
Prompt + ICS
$\chi\chi \rightarrow b\bar{b}$
NFW
Einasto
Burkert
NFW$_c$
M$_{DM}$ > 681 GeV
$\chi\chi \rightarrow \mu^+\mu^-$
M$_{DM}$ > 157-439 GeV
(3sigma upper limits)
$\chi\chi \rightarrow \tau^+\tau^-$
M$_{DM}$ > 531 GeV
$\chi\chi \rightarrow W^+W^-$
W^+W^- threshold
M$_{DM}$ > 489 GeV
<σv> [cm^3/s]
m_{DM} [GeV]

Theoretical caveats

- We have analyzed four annihilation channels but in general the final state will be a combination of them e.g., in SUSY, the neutralino annihilation modes are 70% bb - 30% tau+tau- for a Bino DM, and 100% W+W- for a Wino DM.
- Also, the value of <σv> in the Galactic halo might be smaller than $3x10^{-26}$ cm^3 s^{-1}, e.g., in SUSY, in the early Universe coannihilation channels can also contribute to <σv>. Also, DM particles whose annihilation in the Early Universe is dominated by velocity dependent contributions would have a smaller value of <σv> in the Galactic halo, where the DM velocity is much smaller, and can escape this constraint.
- Specific DM candidate signatures in the gamma-ray sky must be contrasted with observations in order to get more accurate model constraints.

Summary

Several astrophysical processes at work in the crowded GC region and their uncertainties make it extremely difficult to disentangle a DM signal from conventional emissions.

We derived constraints on the parameter space of generic candidates using Fermi-LAT inner Galaxy measurements.

We considered well motivated DM density profiles which are perfectly compatible with current observational data of the Milky Way.

A compressed DM profile allows to place much more stringent upper limits. Then thermal $\langle \sigma v \rangle$ excluded up to few hundreds GeV depending on channel

A large region of the vanilla WIMP parameter space models and contracted DM profiles are incompatible given the Fermi data.

Conclusions

- The best way to prove the DM paradigm is to detect signatures of the particle that made up the unseen matter needed to fit observations. In this talk I presented the current status of searches for particle DM signals in the data taken by the Fermi-LAT space telescope.
- Although we have not found a significant DM signal, we have been able to set interesting constraints on DM candidates.

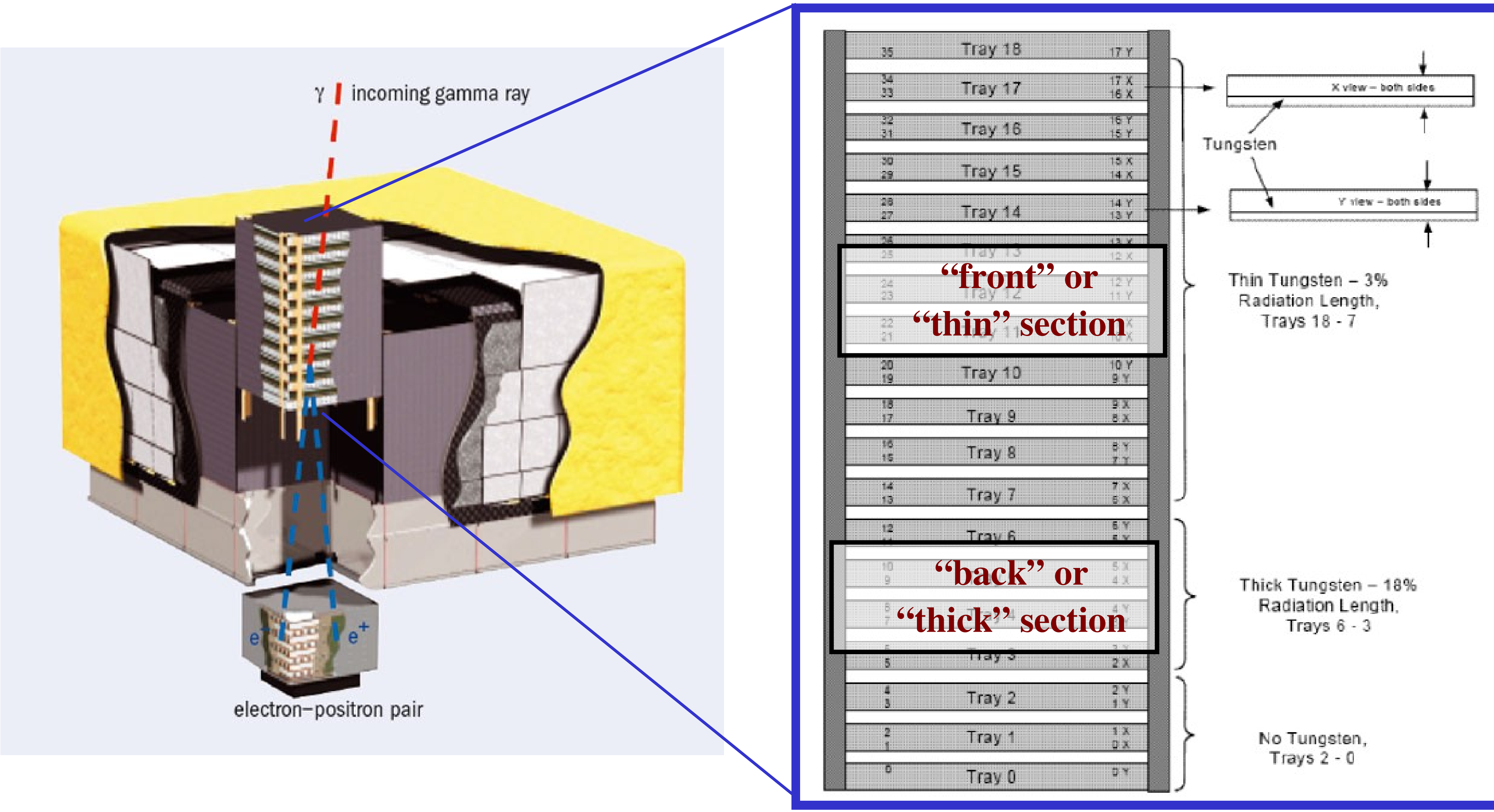
Outlook

- Looking further ahead, information from the inner region of our Galaxy and other important dark matter targets is continuously growing, not only the gamma-ray data from the Fermi-LAT or Cherenkov telescopes, also data in other wavelengths as microwave and infra-red from Planck.
- Multi-wavelength studies are bringing us a complete picture of the sky at high energies and exotic contributors as DM can be constrained more and more or even observed.

BACKUP SLIDES

Fermi-LAT

Front and Back

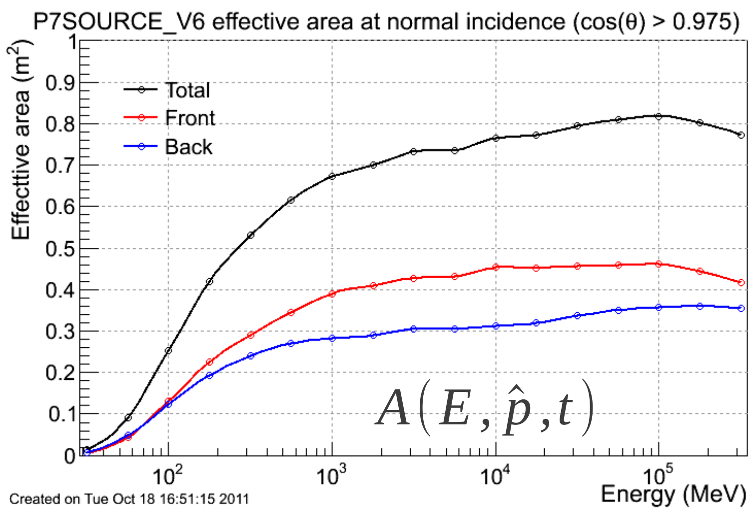


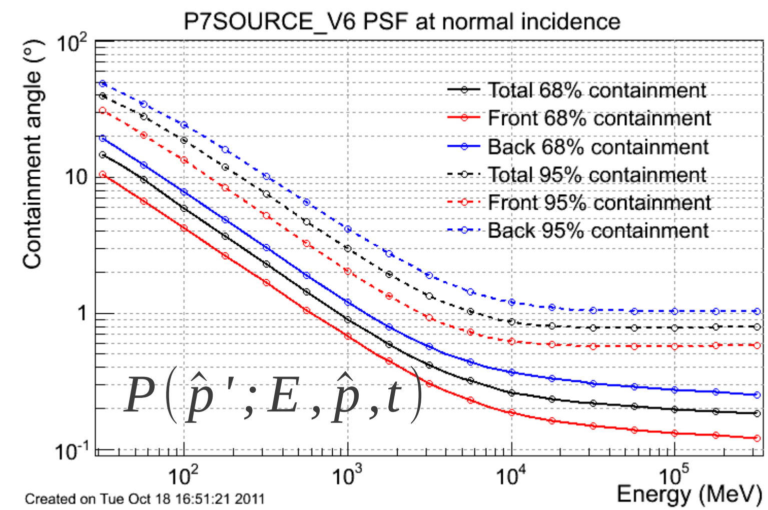
FROM FLUX TO COUNTS

$$S(E,\hat{p},t) = \sum_i S(E,\hat{p})\delta(\hat{p}-\hat{p}') + S_G(E,\hat{p}) + S_{EG}(E,\hat{p}) + \sum_l S_l(E,\hat{p},t)$$

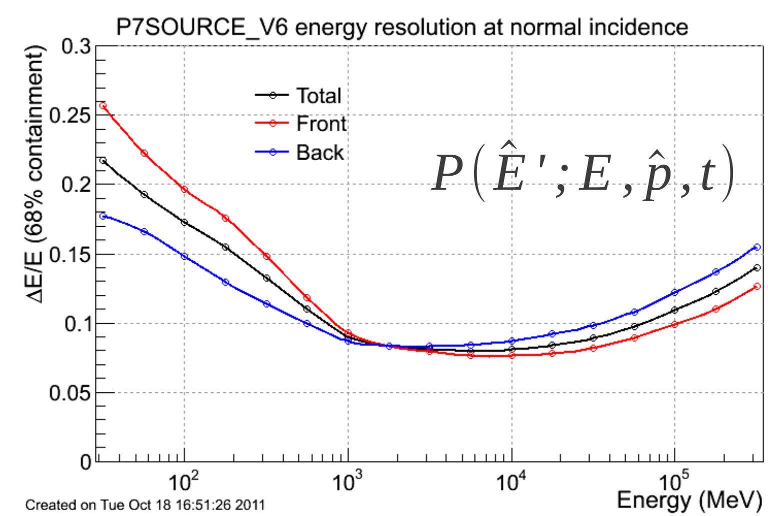
$$M_i = \sum_k \int_{SR} R(E',\hat{p}';E,\hat{p},t)S_k(E,\hat{p})dEd\hat{p}.$$

$$R(E',\hat{p}';E,\hat{p},t) = A(E,\hat{p},t)\times P(\hat{p}';E,\hat{p},t)\times D(E';E,\hat{p},t)$$

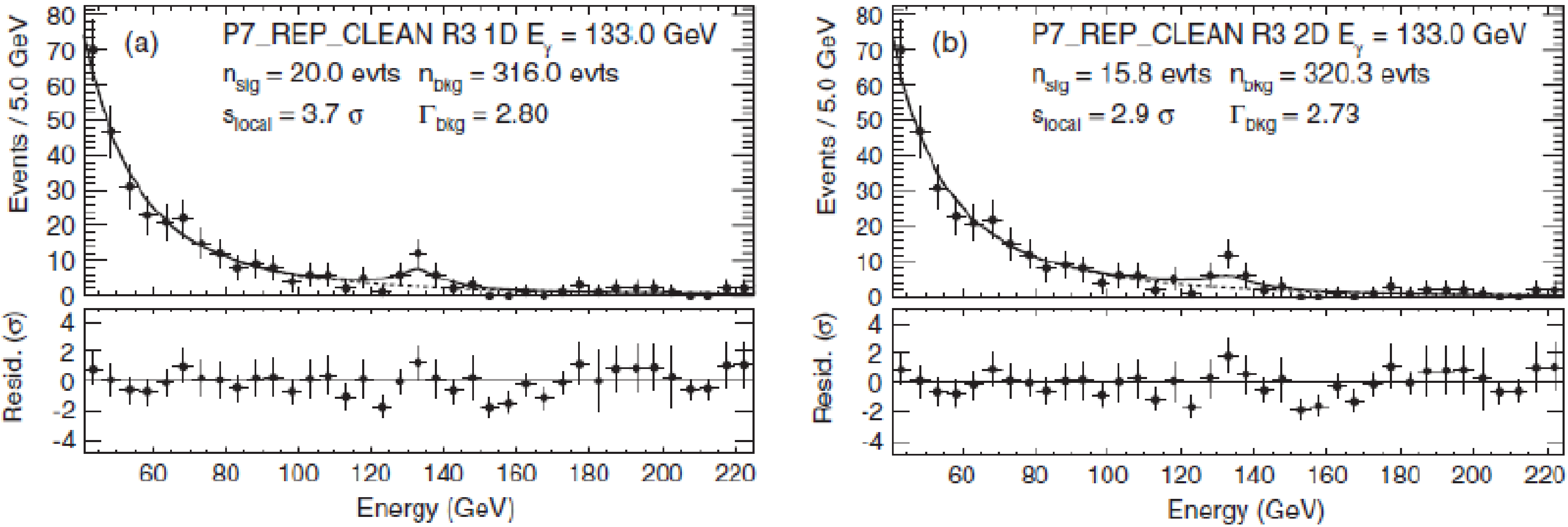




- E is the true photon energy emitted by the source
- $\hat{p}$ the true photon direction
- E' is the measured photon energy in the *Fermi*-LAT
- $\hat{p}'$ the measured photon direction by the *Fermi*-LAT

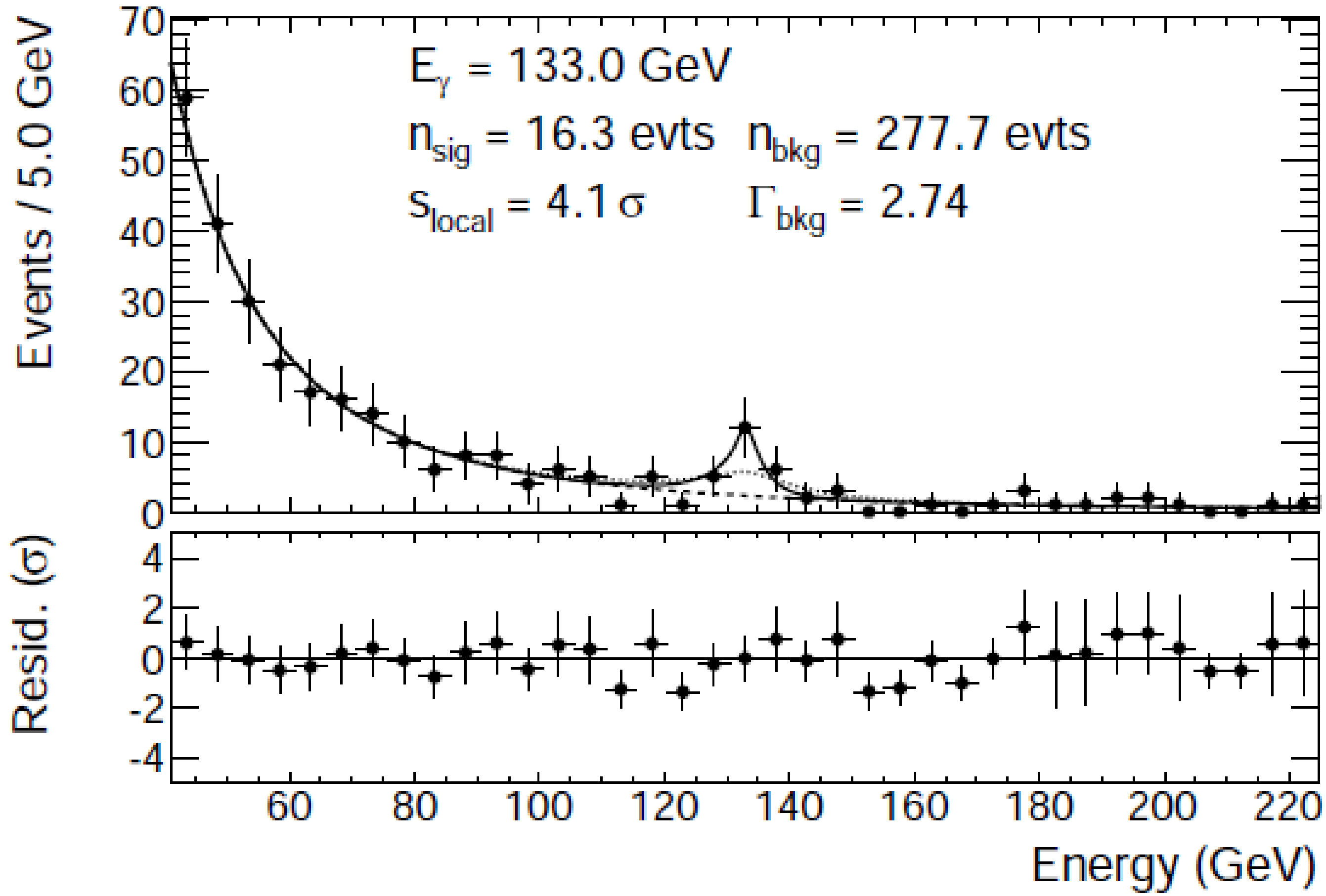


Gamma-ray line



- 3.7σ (local) 1D fit at 133 GeV with 4.4 year reprocessed data in R3
  - 1D PDF does not include of the energy reconstruction quality estimator, PE
- 2.9σ (local) 2D fit at 133 GeV with 4.4 year reprocessed data in R3
  - 2D PDF includes of the energy reconstruction quality estimator, PE
- <2σ global significance after trials factor

Gamma-ray line

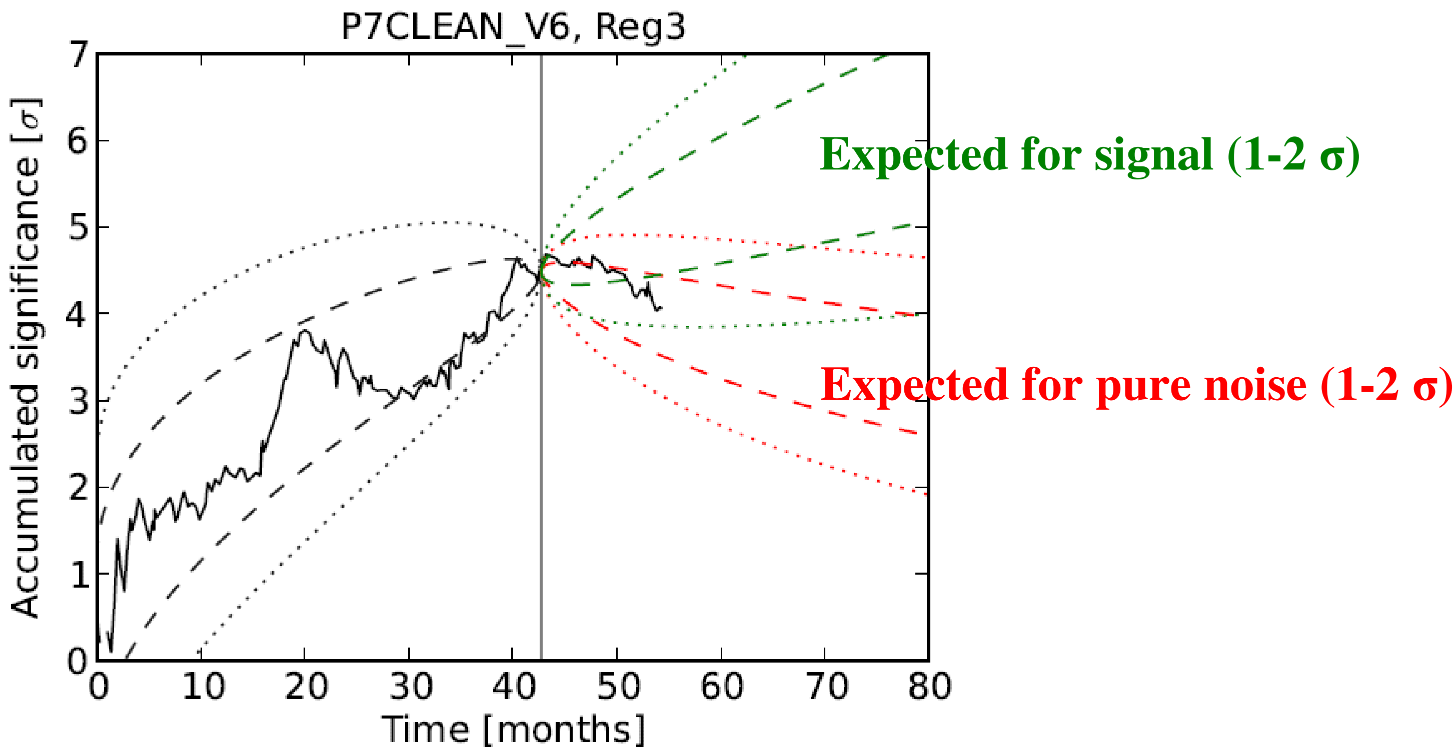


Let width scale factor float in fit (while preserving shape)

$$s_\sigma = 0.32^{+0.30}_{-0.13} \text{ (95\% CL)}$$

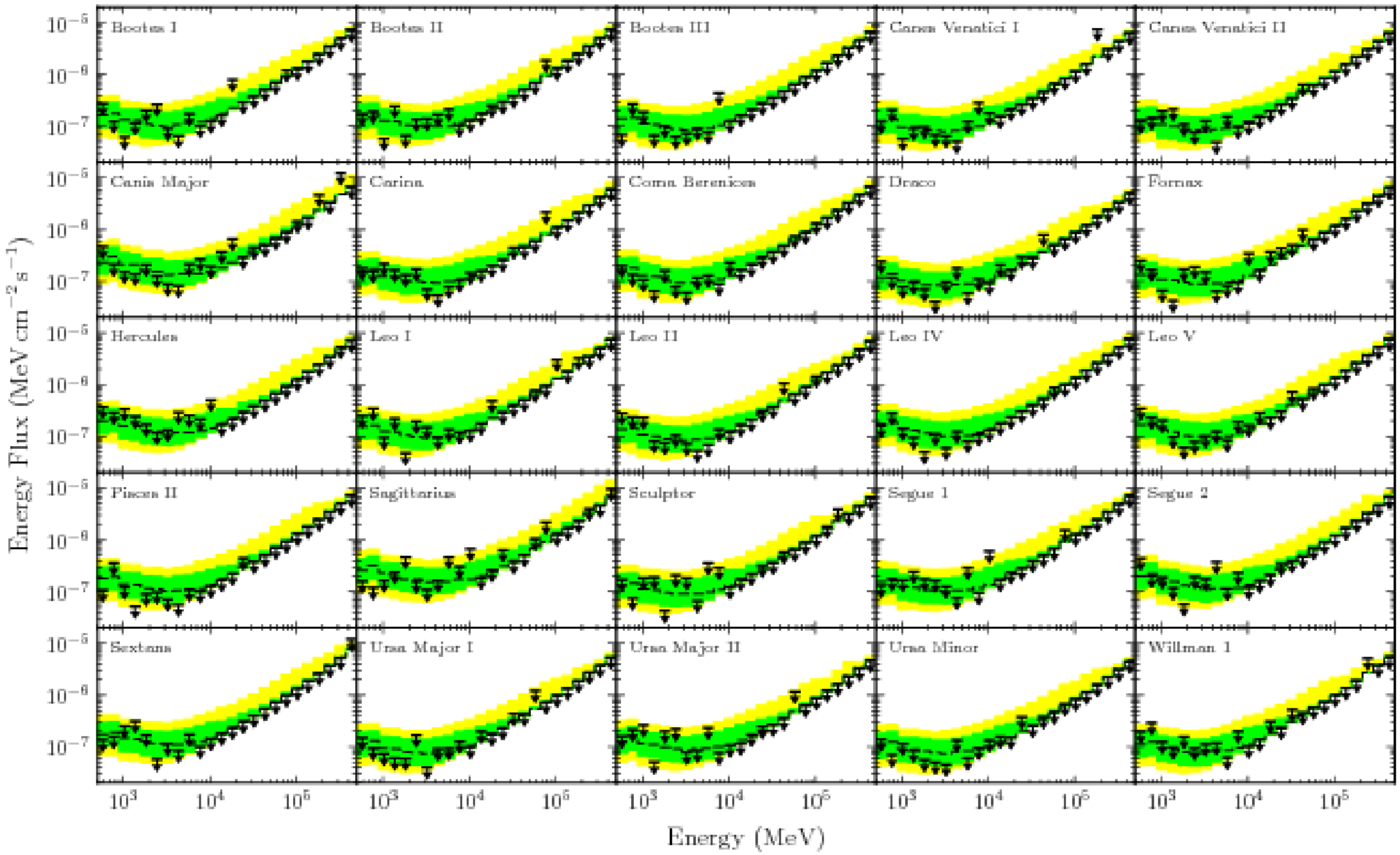
–Feature in data is narrower than expected energy resolution measured in beam tests and detector simulations

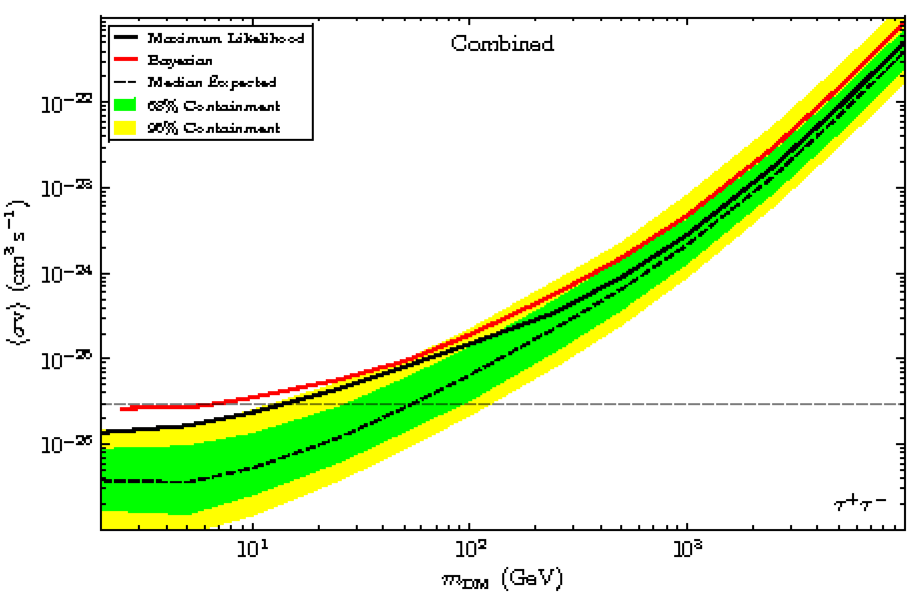
Gamma-ray line

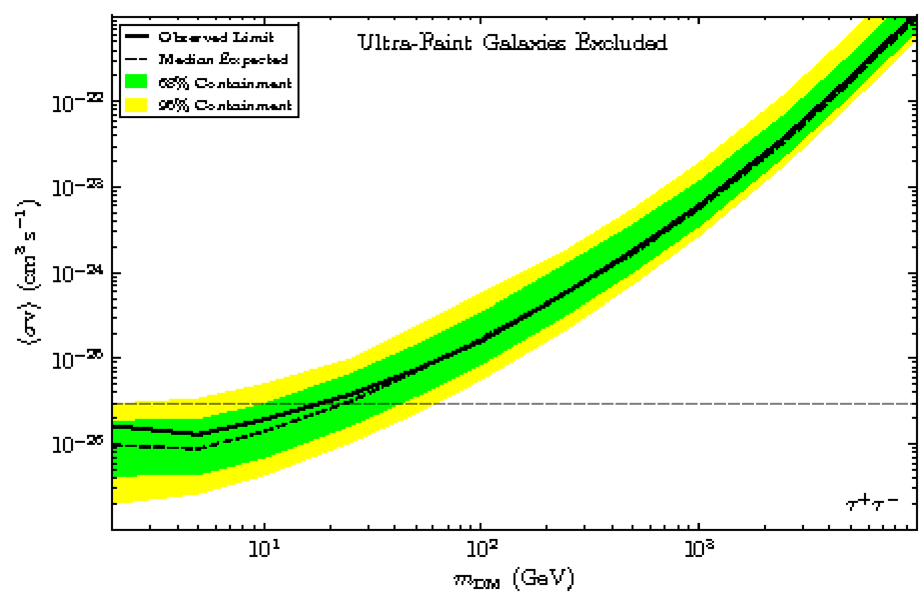


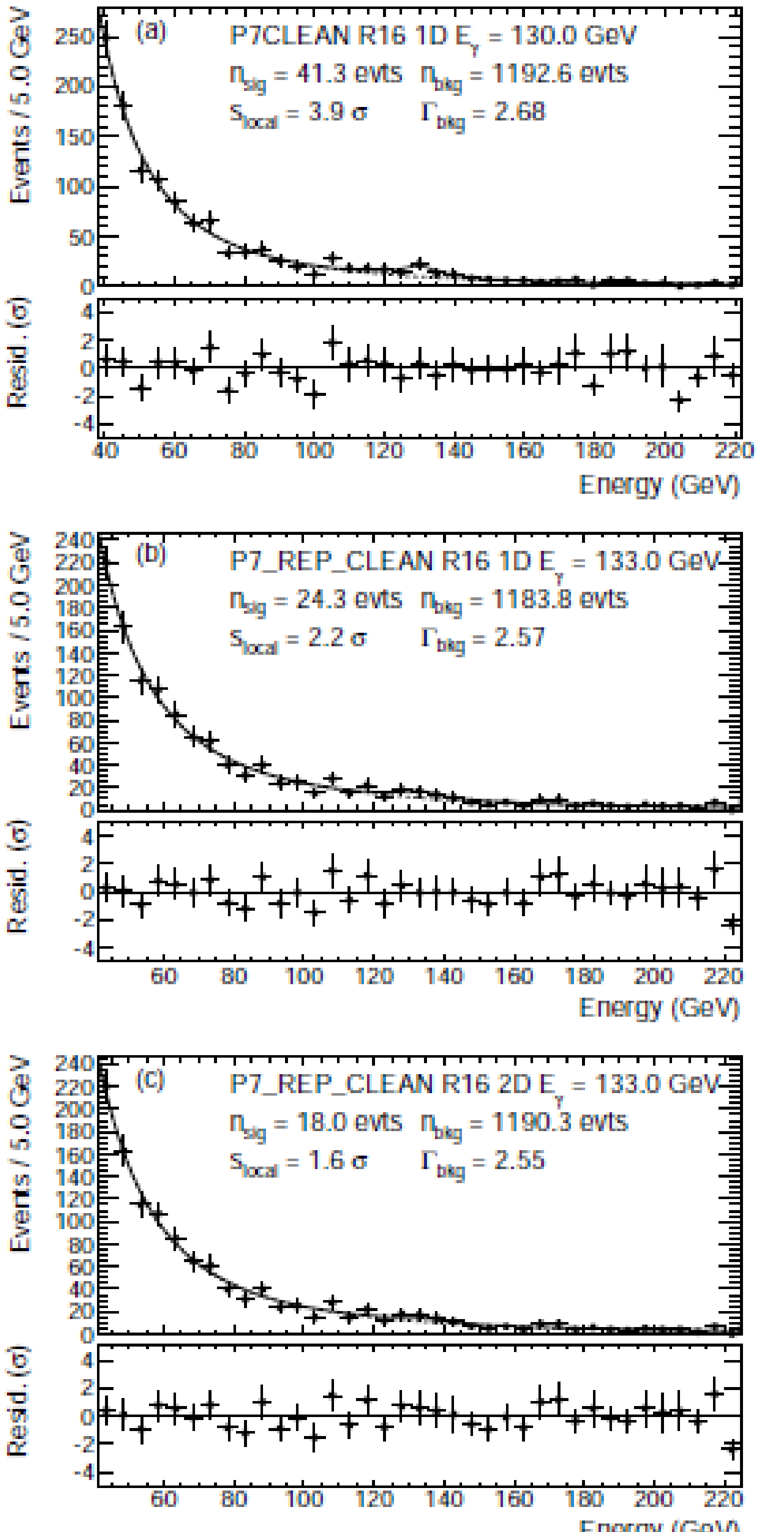
Weniger's updated results are consistent with the recent LAT line-search paper.

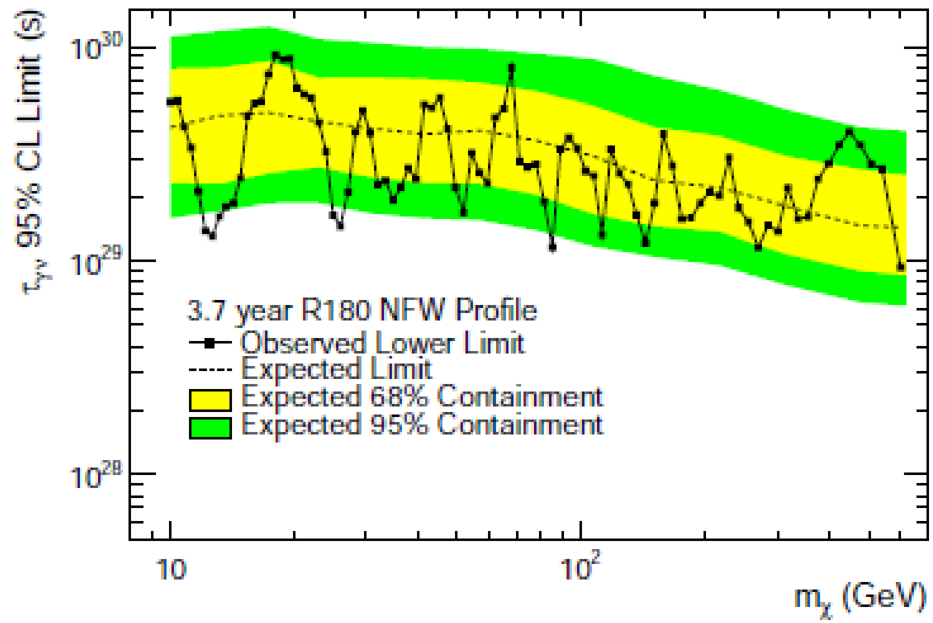
–P7CLEAN → P7REP_CLEAN dilutes the original significance of 4.3σ to 2.8σ and including 2d PDF to 2.4σ. And extending the data set to 4.4 years the local significance decreases to 2.0σ. ArXiv:1310.2953
–Likely that the original putative line signal was a statistical fluctuation. arXiv:1303.1798


Bootes I
Bootes II
Bootes III
Canes Venatici I
Canes Venatici II
Canis Major
Carina
Coma Berenices
Draco
Fornax
Hercules
Leo I
Leo II
Leo IV
Leo V
Pisces II
Sagittarius
Sculptor
Segue 1
Segue 2
Sextans
Ursa Major I
Ursa Major II
Ursa Minor
Willman 1
Energy Flux (MeV cm^{-2} s^{-1})
Energy (MeV)


Maximum Likelihood
Bayesian
Median Expected
68% Containment
95% Containment
Combined
$\tau^+\tau^-$
$\langle\sigma v\rangle$ (cm^3 s^{-1})
m_{DM} (GeV)


Observed Limit
Median Expected
68% Containment
95% Containment
Ultra-Faint Galaxies Excluded
$\tau^+\tau^-$
$\langle\sigma v\rangle$ (cm^3 s^{-1})
m_{DM} (GeV)


(a)
P7CLEAN R16 1D E_γ = 130.0 GeV
n_{sig} = 41.3 evts n_{bkg} = 1192.6 evts
s_{local} = 3.9 σ Γ_{bkg} = 2.68
Events / 5.0 GeV
Resid. (σ)
Energy (GeV)
(b)
P7_REP_CLEAN R16 1D E_γ = 133.0 GeV
n_{sig} = 24.3 evts n_{bkg} = 1183.8 evts
s_{local} = 2.2 σ Γ_{bkg} = 2.57
Events / 5.0 GeV
Resid. (σ)
Energy (GeV)
(c)
P7_REP_CLEAN R16 2D E_γ = 133.0 GeV
n_{sig} = 18.0 evts n_{bkg} = 1190.3 evts
s_{local} = 1.6 σ Γ_{bkg} = 2.55
Events / 5.0 GeV
Resid. (σ)
Energy (GeV)


$\tau_{\gamma\nu}$ 95% CL Limit (s)
10^{30}
10^{29}
10^{28}
10
10^2
m_χ (GeV)
3.7 year R180 NFW Profile
Observed Lower Limit
Expected Limit
Expected 68% Containment
Expected 95% Containment