

Recent results on Dark Matter searches with the Fermi LAT

Germán A. Gómez Vargas

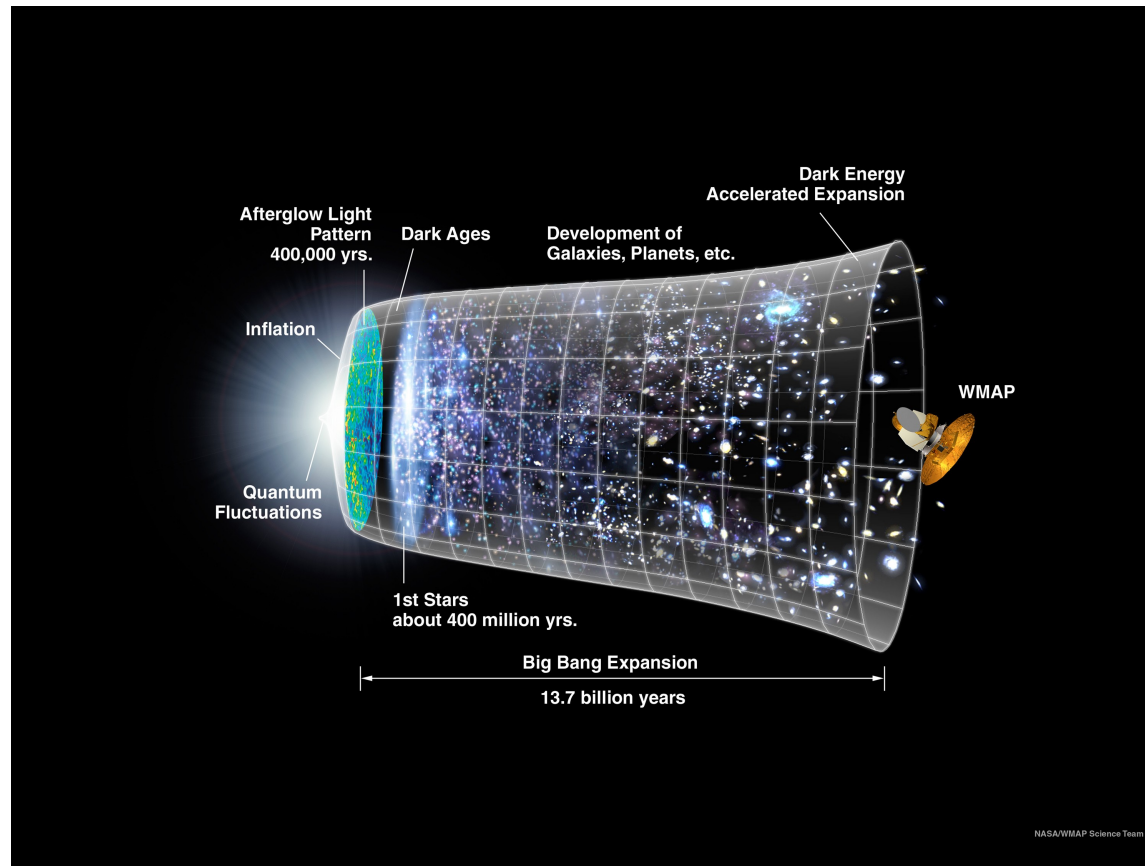
IFT UAM/CSIC & UAM Madrid
INFN Roma Tor Vergata

ON BEHALF OF THE:
Fermi-LAT collaboration

IFIC Seminar, Valencia 02/12/2013



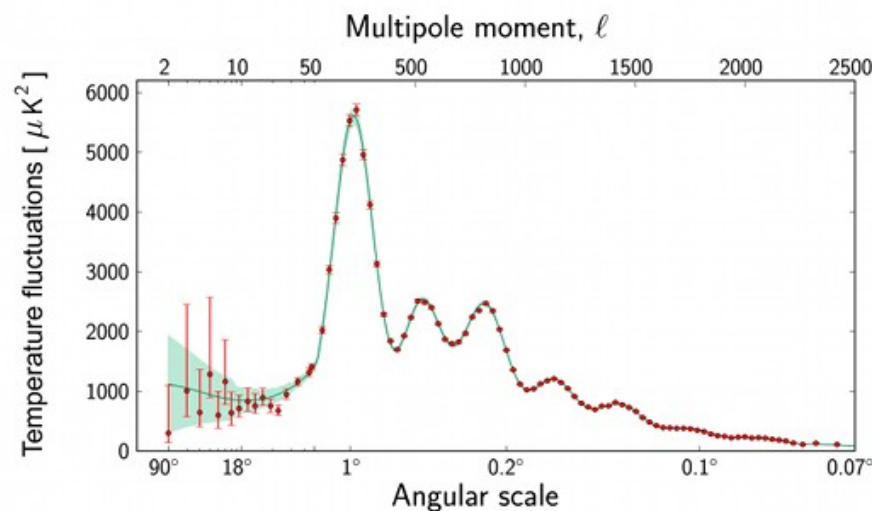
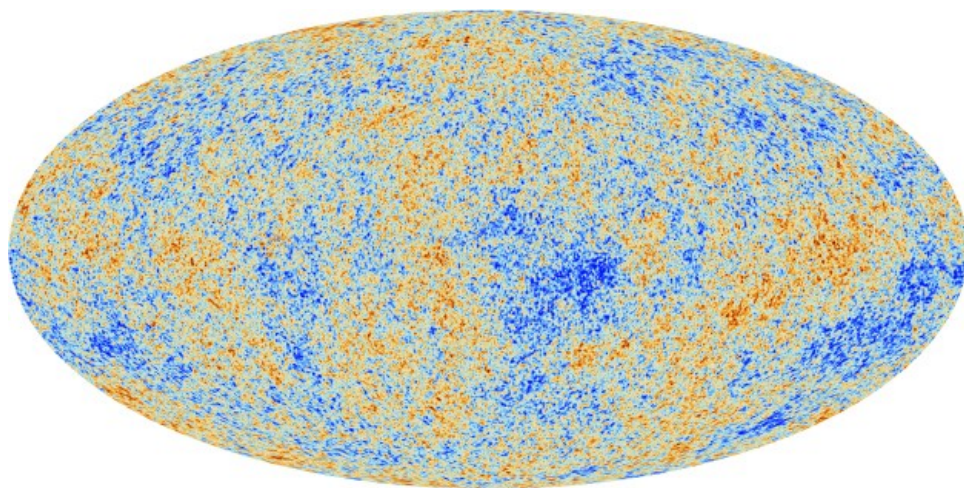
DARK MATTER EVIDENCES



- Evidences indicating the presence of dark matter (DM) can be obtained at very different scales: from cosmological ones through the analysis of the angular anisotropies in the cosmic microwave background radiation, down to galactic scales considering lensing and galaxy dynamics studies.

DARK MATTER EVIDENCES

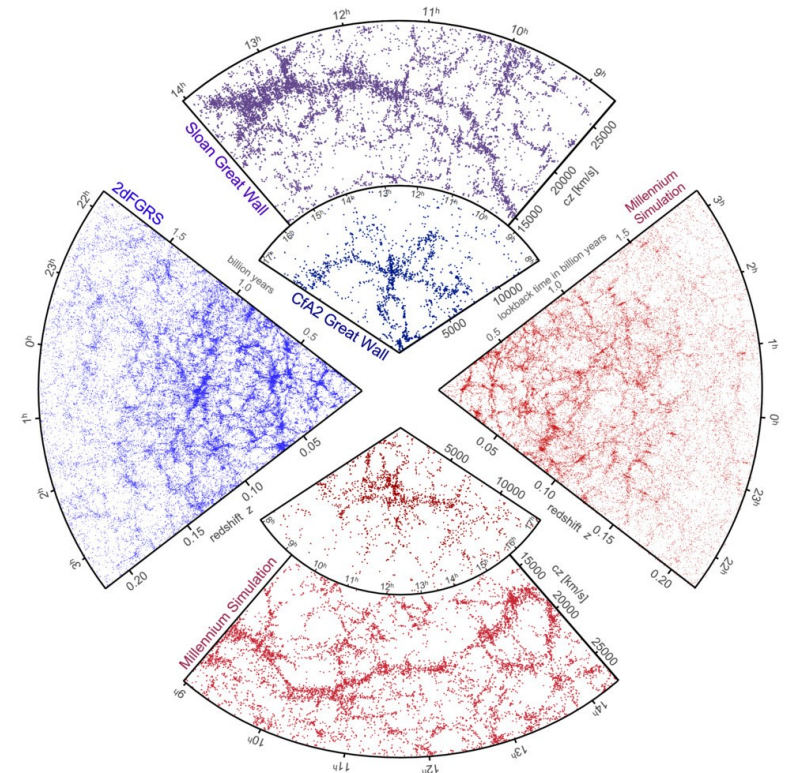
- At cosmological scales: ~ 100 Mpc



- The **height of the first peak** in the angular power spectrum of the cosmic microwave background is **proportional** to the amplitude of the **gravitational potential**.
- The **height of the second peak** is **proportional** to the **baryon content** of the primordial plasma.

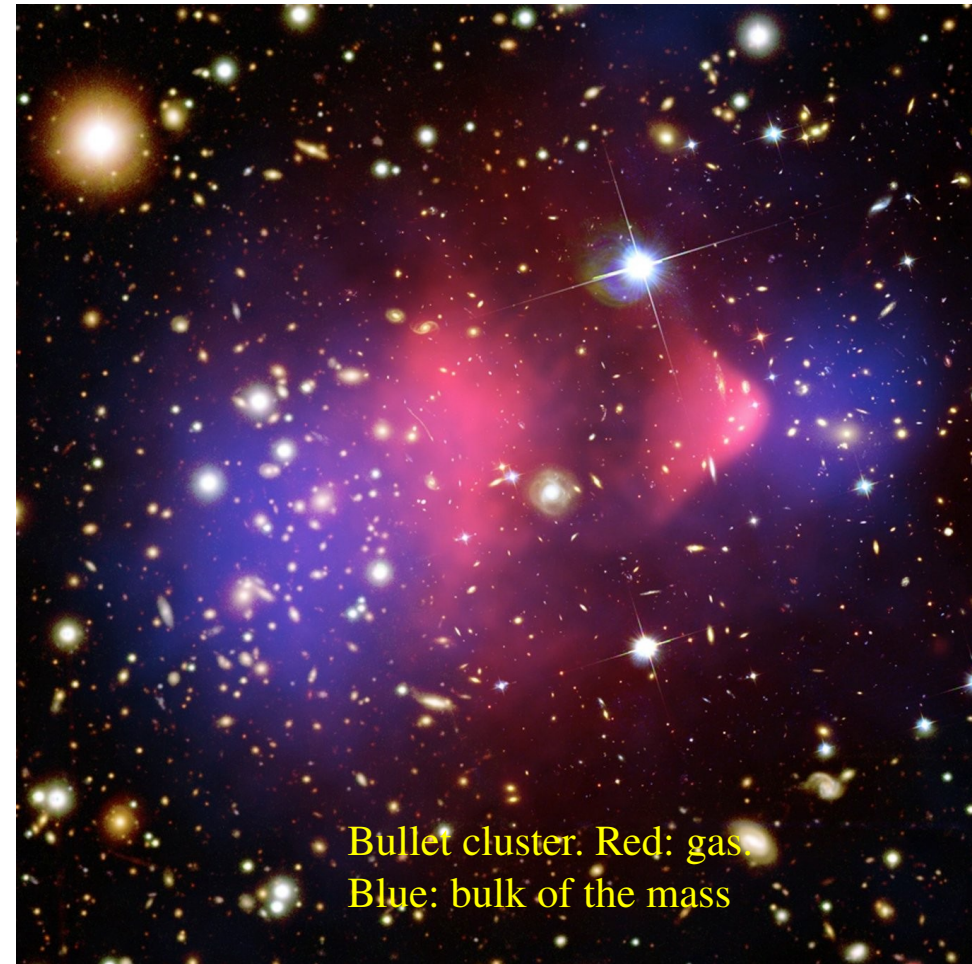
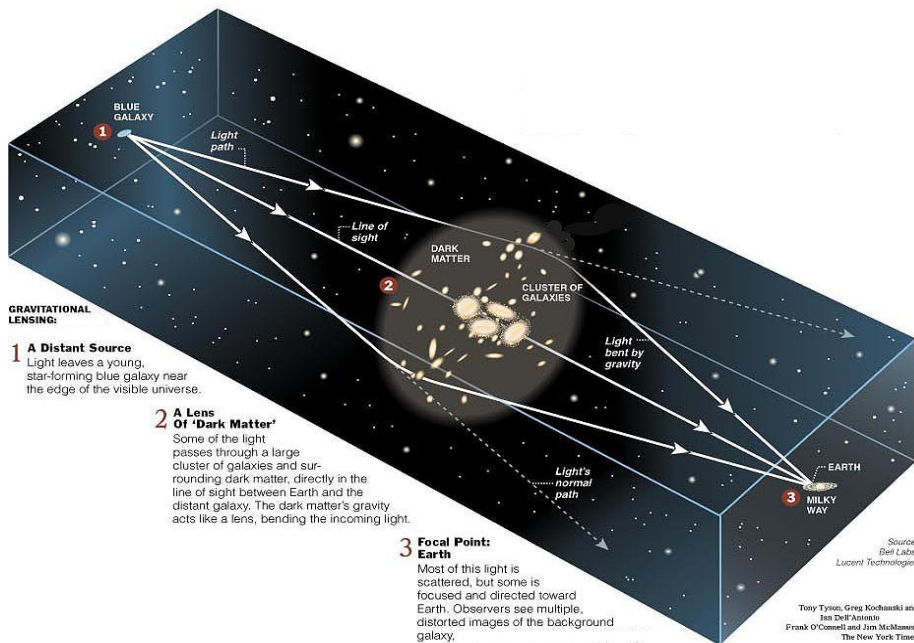
DARK MATTER EVIDENCES

- At cosmological scales: ~ 100 Mpc
- The evolution of perturbations in the universe.
- Small density perturbations grow to form the structures that we observe today in the universe
- The standard theory of structure formation requires Dark Matter and also that it must to be cold, i.e. it is, made of particles that have become non-relativistic well before the matter domination era, and that can therefore clump on small scales



DARK MATTER EVIDENCES

- 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

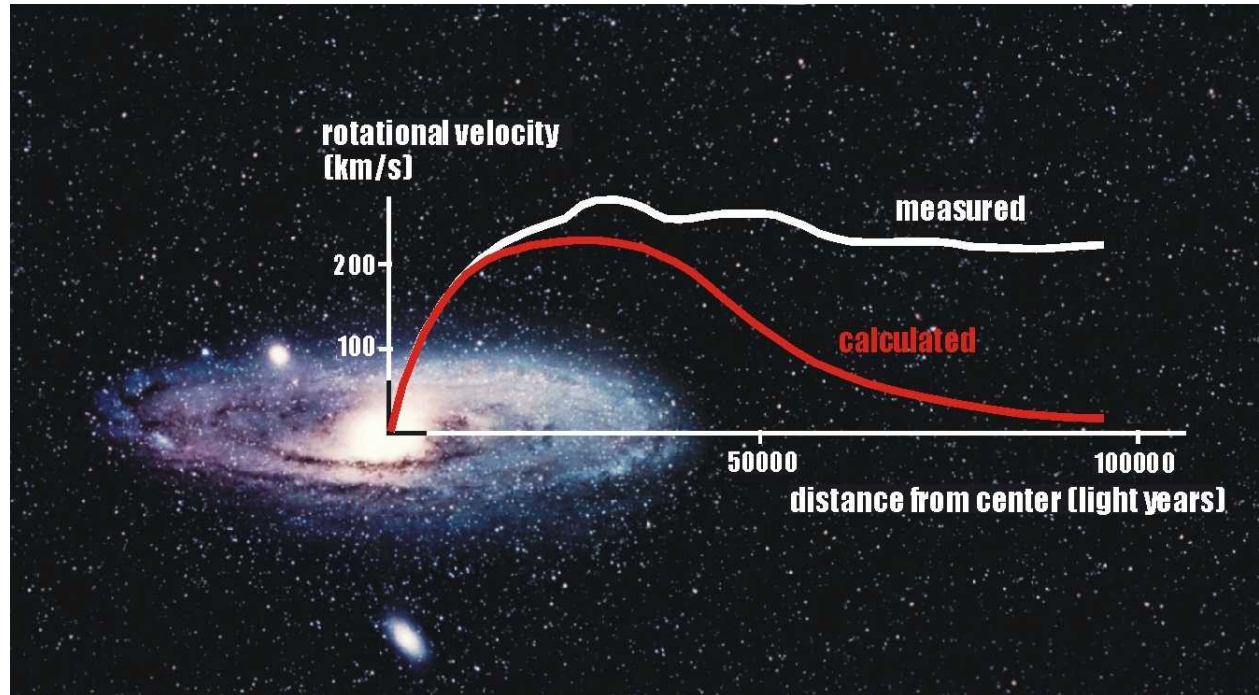


DARK MATTER EVIDENCES

- At galactic scales: ~10 kpc
- We can relate the velocity of stars and gas on galaxies with their orbits:

$$v^2 = \frac{GM(r)}{r}$$

- Observations reveal that v keeps constant when r increases.



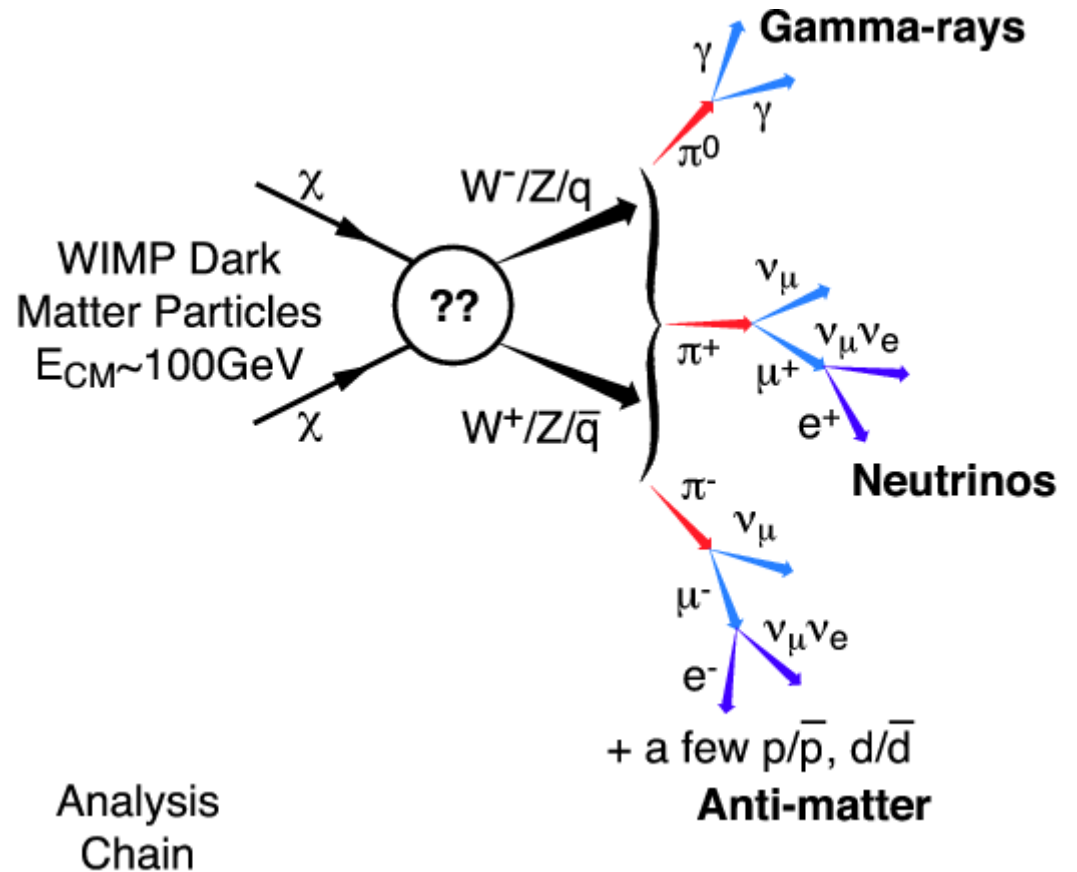
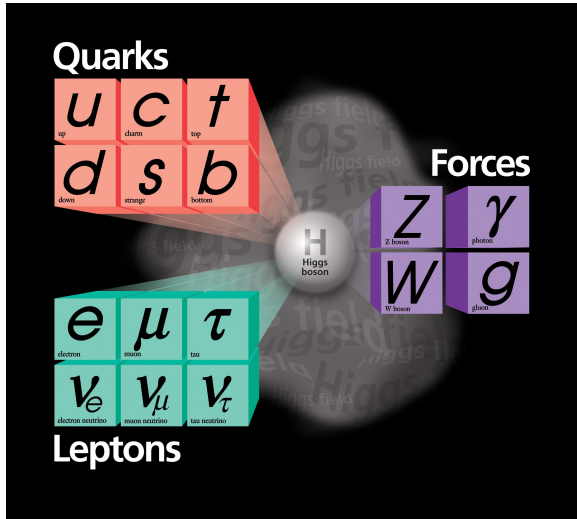
This discrepancy can be explained if $M(r)$ split into two components. One is visible and proportional to $1/r$, the other one is dark and proportional to r

DARK MATTER EVIDENCES

In conclusion:

- Dark Matter **clumps** in large **halos** around **galaxies**
making up **most** of their **mass** (Coma cluster and galactic rotation curves)
- Dark Matter is practically **collisionless** and **non-baryonic** (uncharged and uncolored) (Bullet cluster, BBN and acoustic oscillations in the CMB)
- Dark Matter **relic density** $\Omega_{DM} h^2 = 0.1199 \pm 0.0027$ (Planck+WMAP)
- Dark Matter particles are **stable** or at least their **lifetime is larger than the universe age**
- Dark Matter particles are **non-relativistic at decoupling** (structure formation)

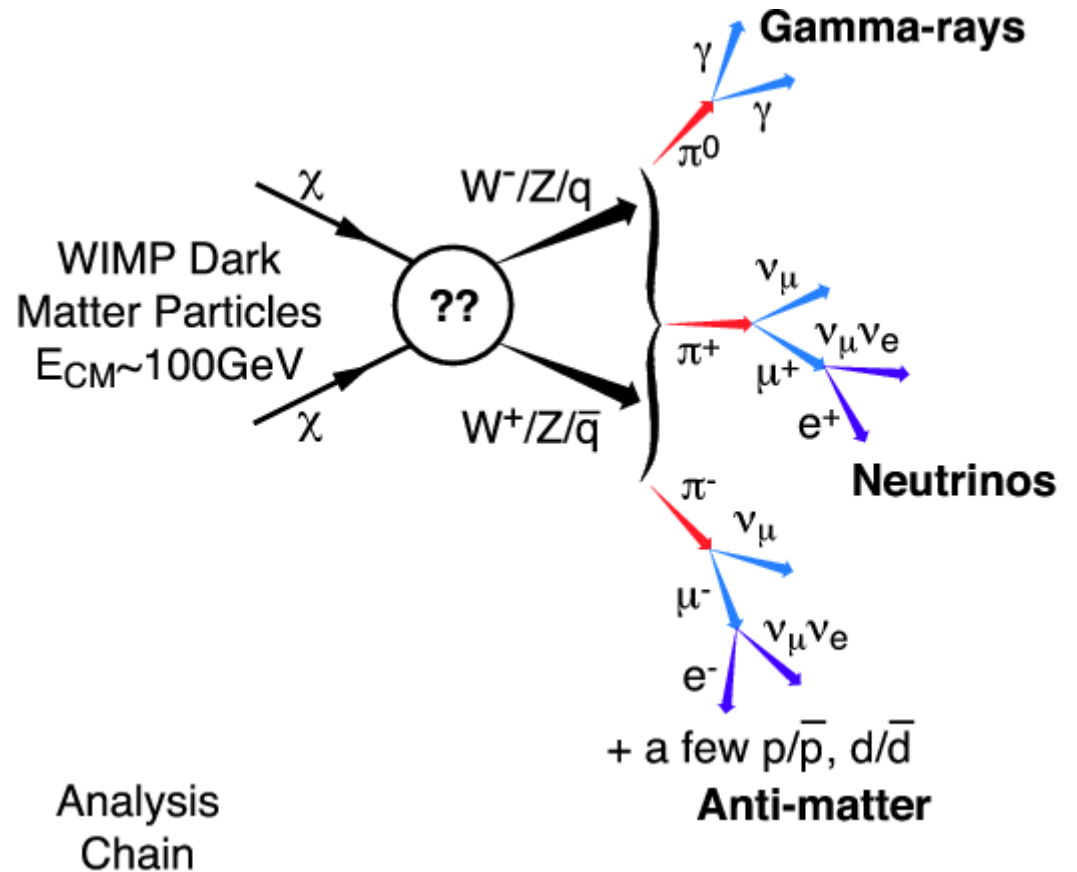
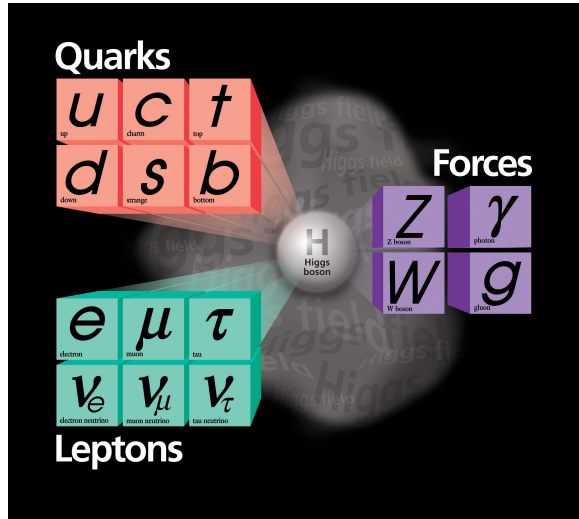
DARK MATTER INDIRECT SEARCHES



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

Baltz et.al. JCAP 0807 (2008) 013

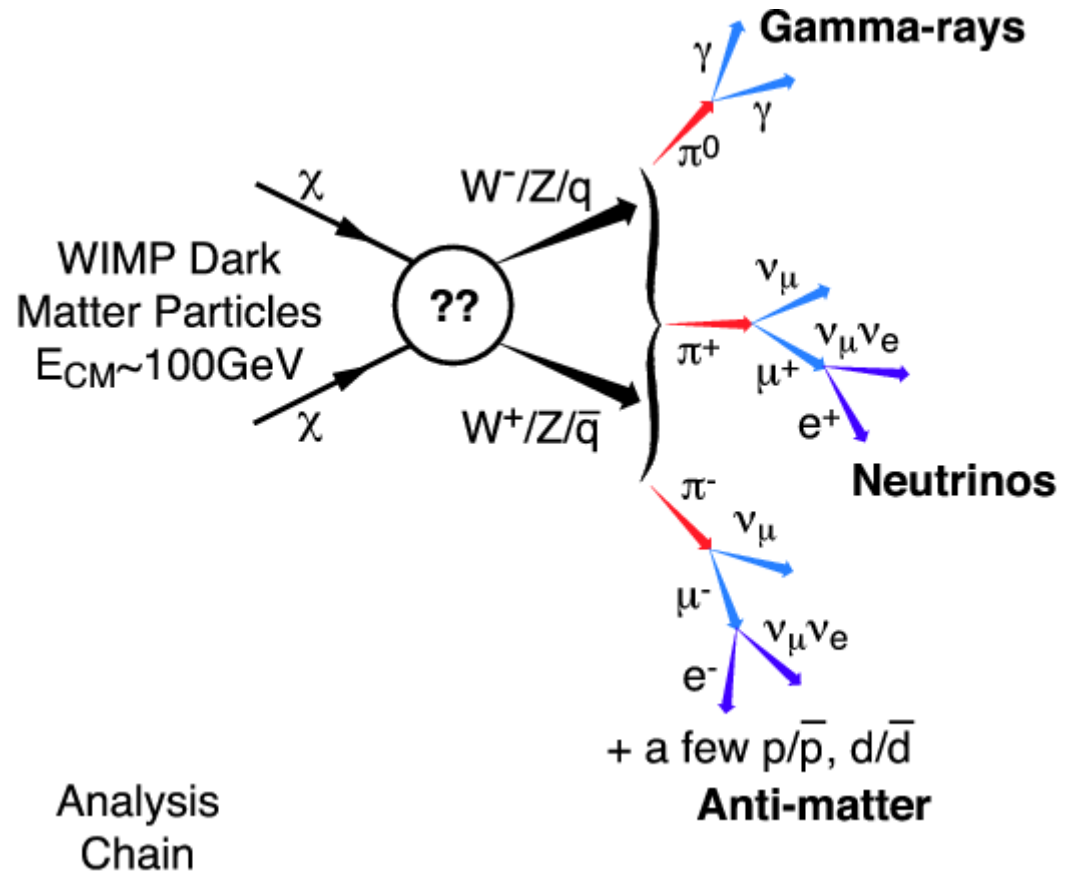
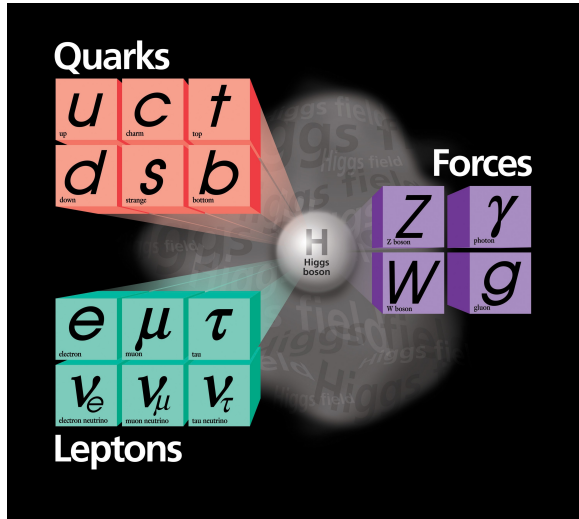
DARK MATTER INDIRECT SEARCHES



- SM particles created in **annihilation or decay** of dark matter particles would **induce** measurable **effects** in astrophysical **observations**, modifying **fluxes** and spatial **distribution** of **cosmic rays** arriving to the Earth

Baltz et.al. JCAP 0807 (2008) 013

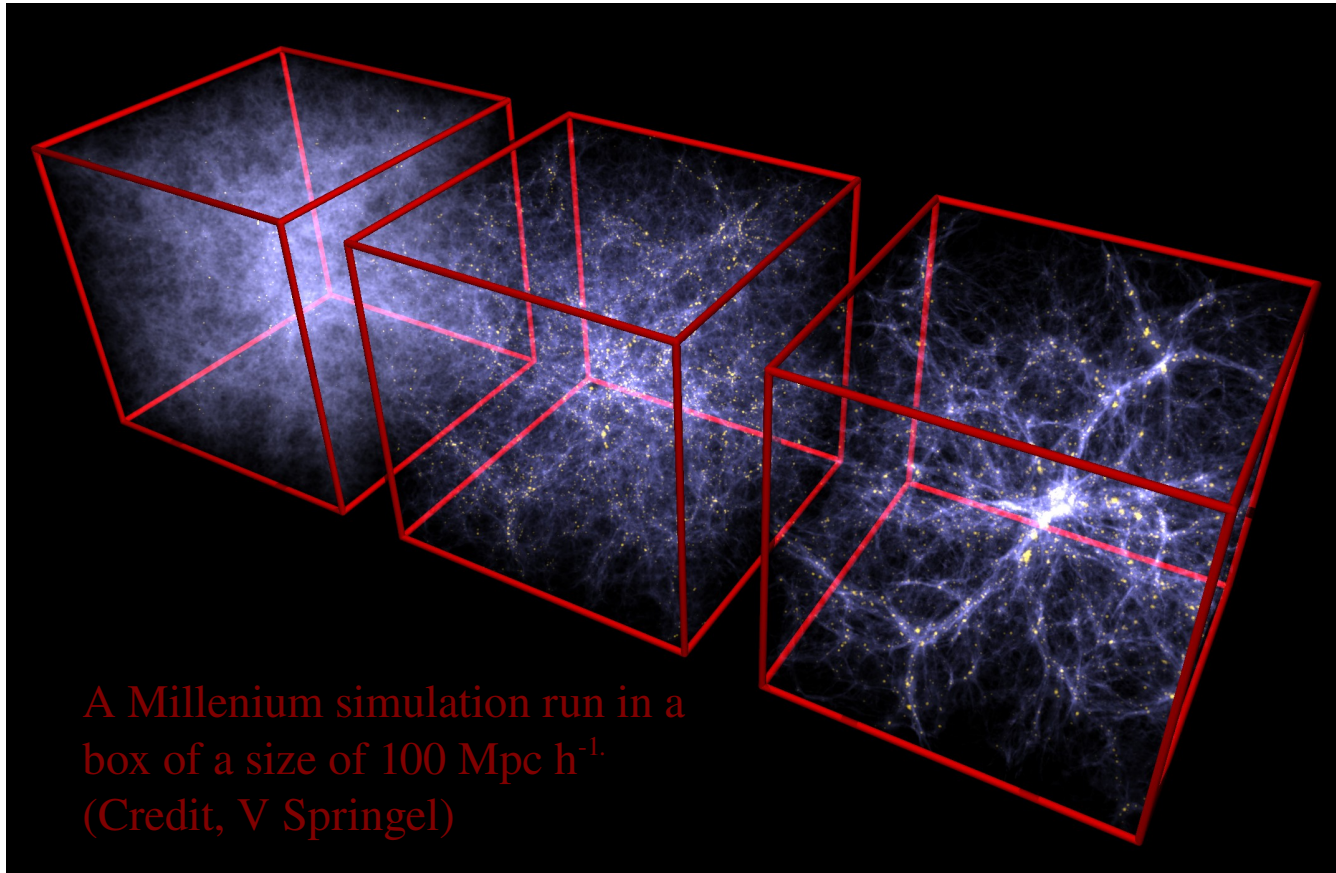
DARK MATTER INDIRECT SEARCHES



- **Gamma-rays** are special since they are only **marginally affected** by energy **losses**, therefore their **sources can be traced back**.

Baltz et.al. JCAP 0807 (2008) 013

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.

DARK MATTER INDIRECT SEARCHES

GAMMA-RAY FLUX

$$\Phi_{\gamma, ann} = \left(N_{\gamma, ann} \right) \times (\sigma_{ann} v) \times \left(\int \frac{\rho_{DM}^2}{m_{DM}^2} dV \right),$$

$$\Phi_{\gamma, dec} = \left(N_{\gamma, dec} \right) \times \left(\frac{1}{\tau_{dec}} \right) \times \left(\int \frac{\rho_{DM}}{m_{DM}} dV \right)$$

Particle Physics
Spectral information

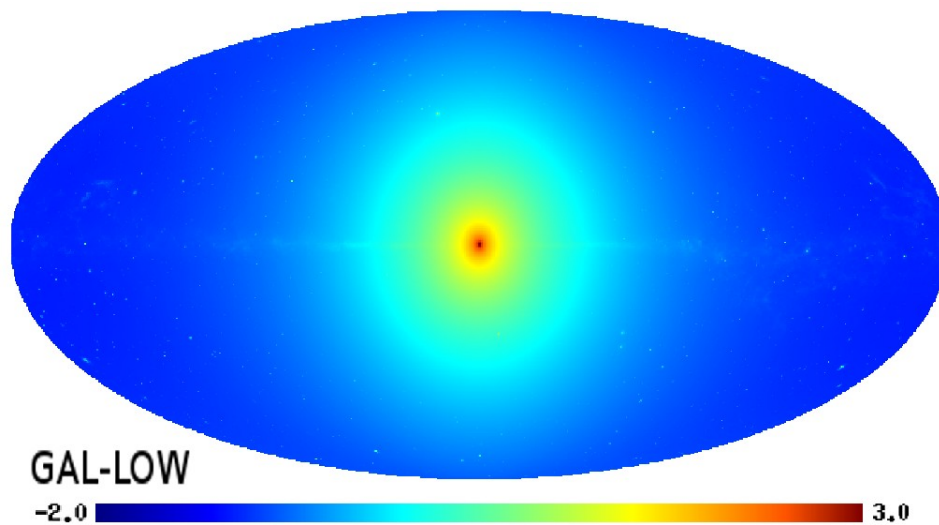
**DM Distribution
(J-Factor)**
Spatial information

$(\sigma_{ann} v)$ Thermally averaged ann. cross section, measures the connection of visible to dark matter in the case that DM is made of stable particles

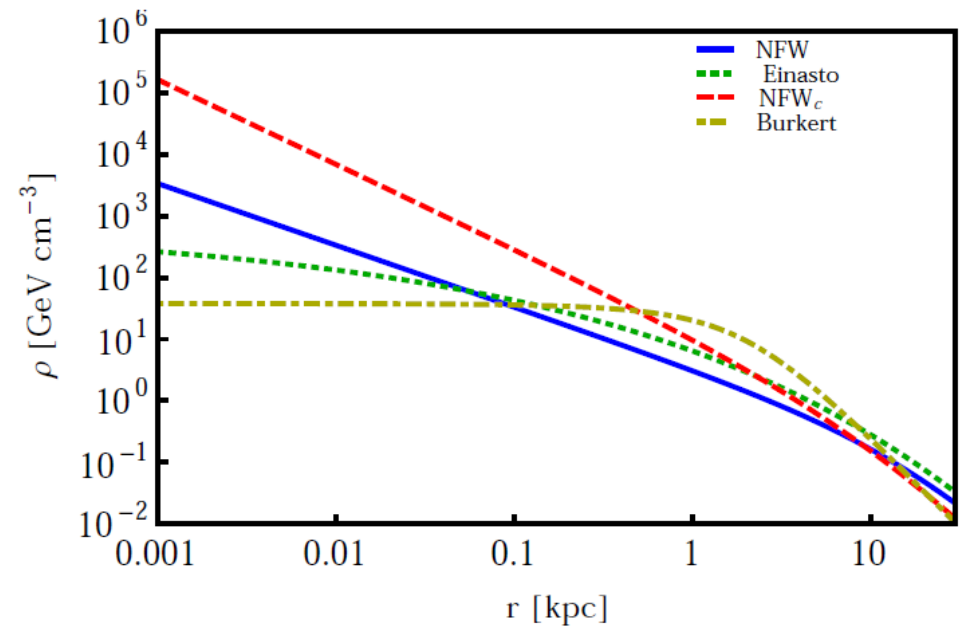
$\left(\frac{1}{\tau_{dec}} \right)$ Decay rate, measures the connection of visible to dark matter in the case that DM is made of unstable particles

DARK MATTER INDIRECT SEARCHES

GAMMA-RAY FLUX: ANNIHILATION INTO QUARKS

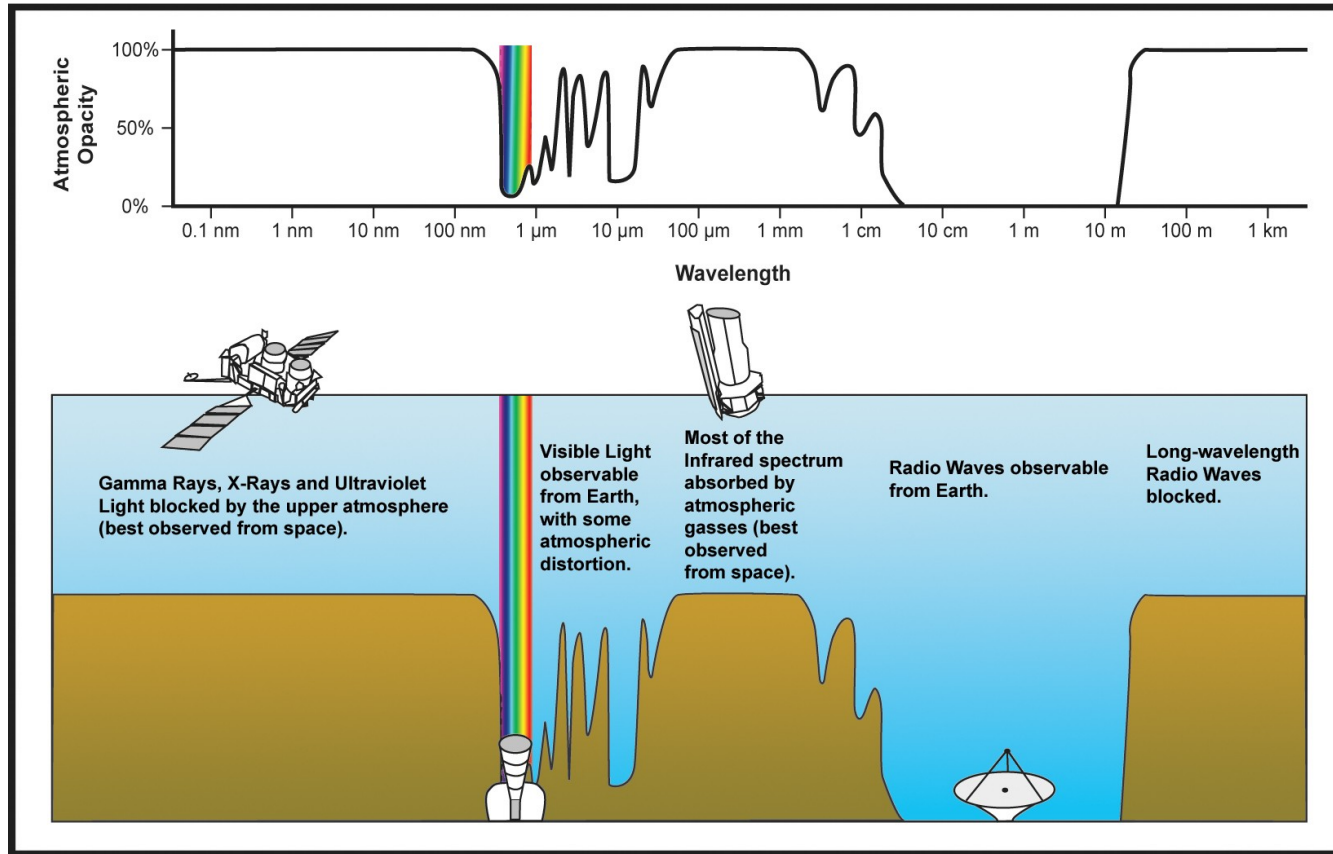


Emission from the smooth
MW halo, the contribution of
resolved subhalos in the
Aquarius Aq-A-1 halo



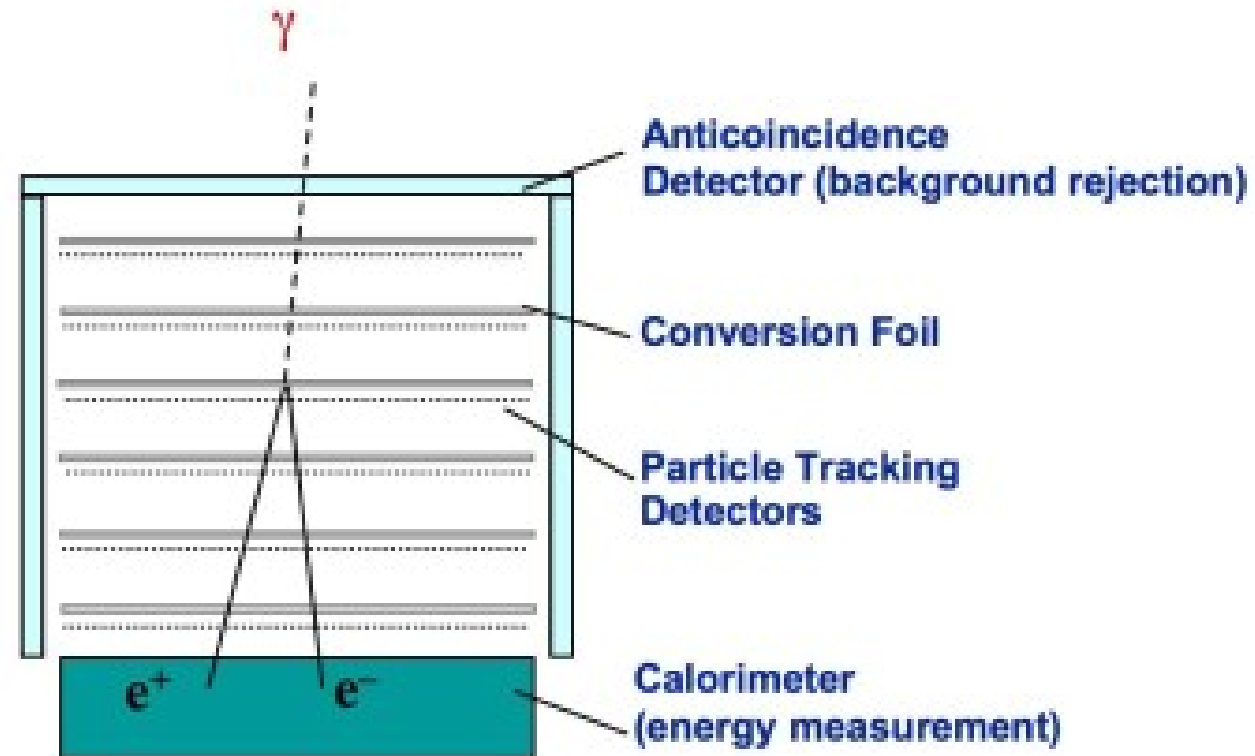
GAGV+ JCAP10(2013)029

OBSERVING THE GAMMA-RAY SKY



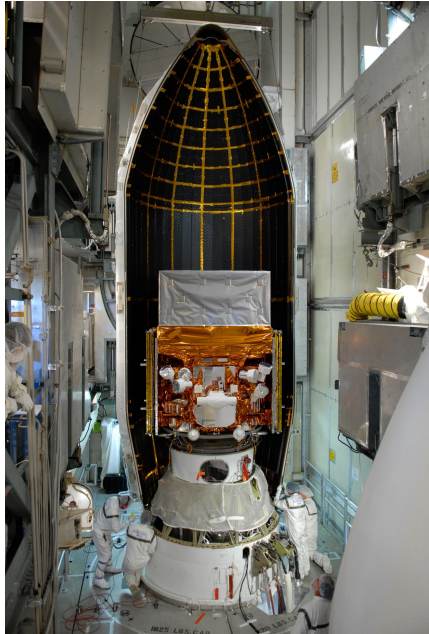
- A broad **gamma-ray** energy band is **screened** by Earth's **atmosphere**
- We must **observe** the **gamma-ray sky** from outside the planet **by spacecraft**

OBSERVING THE GAMMA-RAY SKY



- Gamma rays – matter interaction above few MeVs is dominated by pair production
- To detect high-energy gamma-rays we need pair conversion telescopes

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

Public Data Release:

All gamma-ray data made public within 24 hours (usually less)

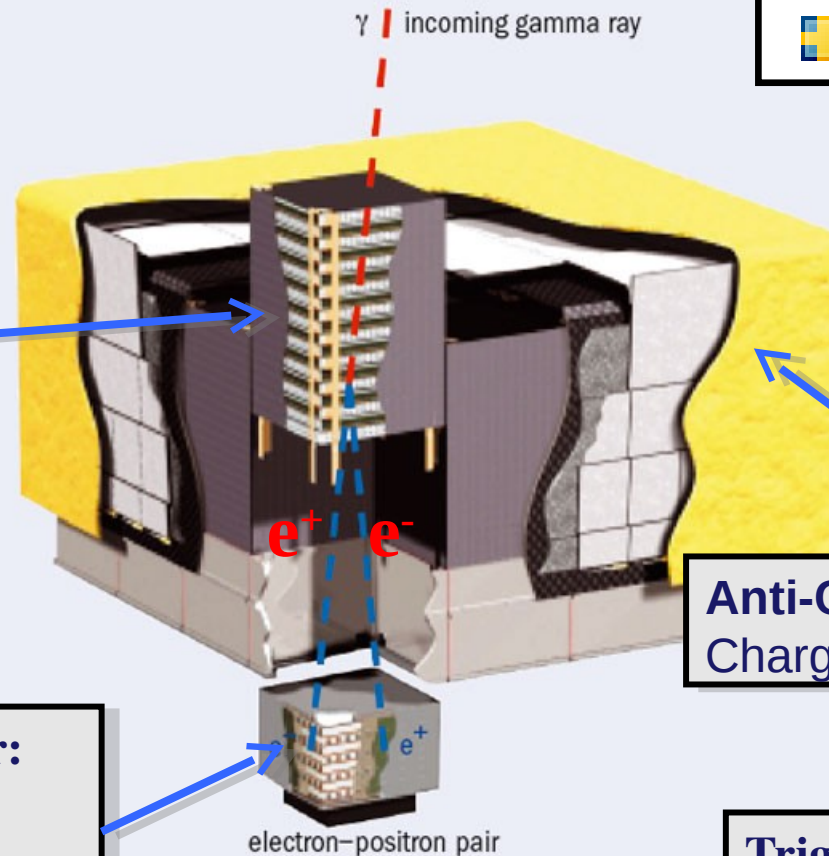
Fermi LAT Collaboration:

~400 Scientific Members,
NASA / DOE &
International
Contributions



Si-Strip Tracker:

convert gamma- $\rightarrow$ e⁺e⁻
reconstruct gamma
direction
EM v. hadron separation



Anti-Coincidence Detector:
Charged particle separation

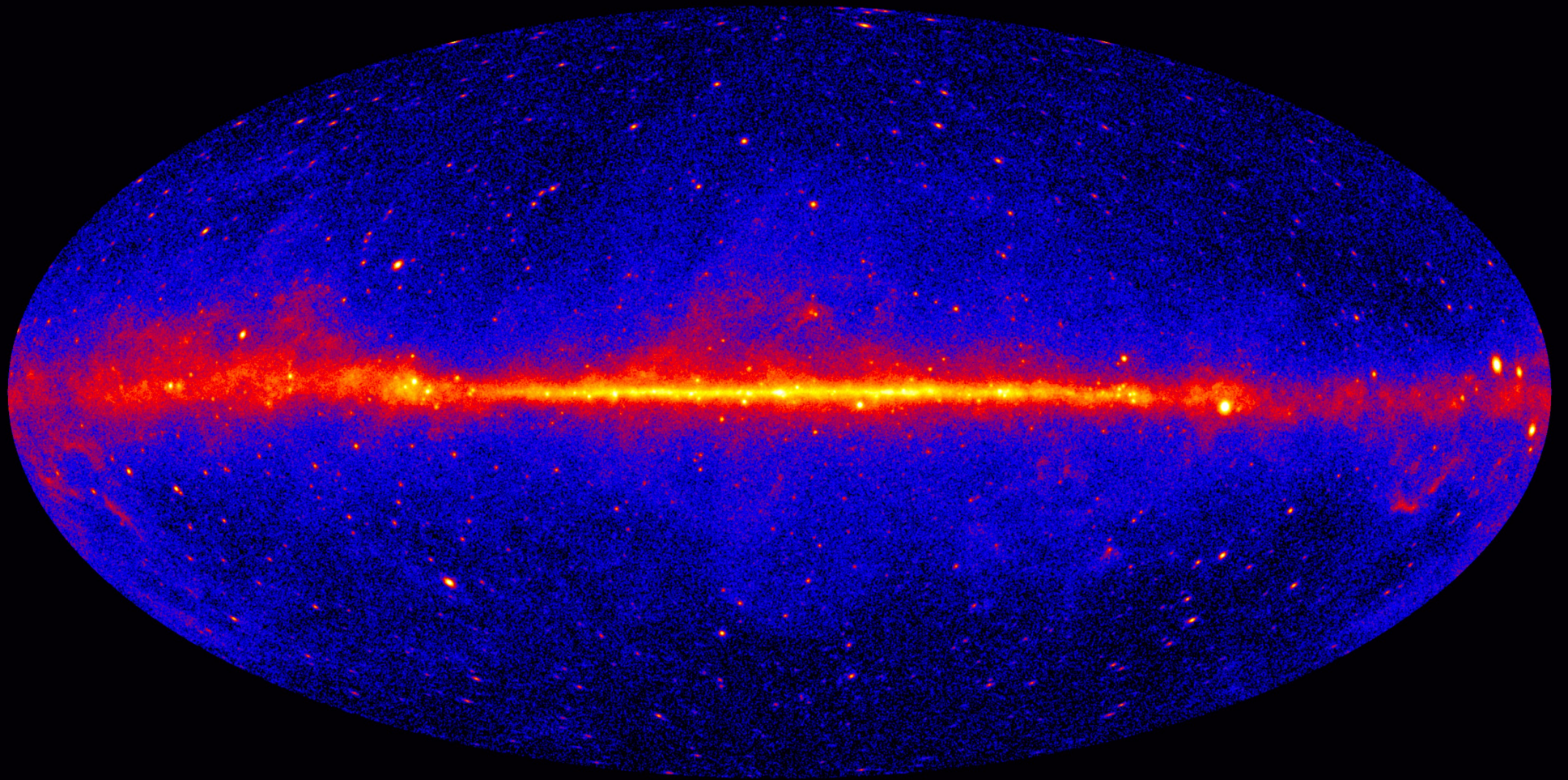
Hodoscopic CsI Calorimeter:

measure gamma energy
image EM shower
EM v. hadron separation

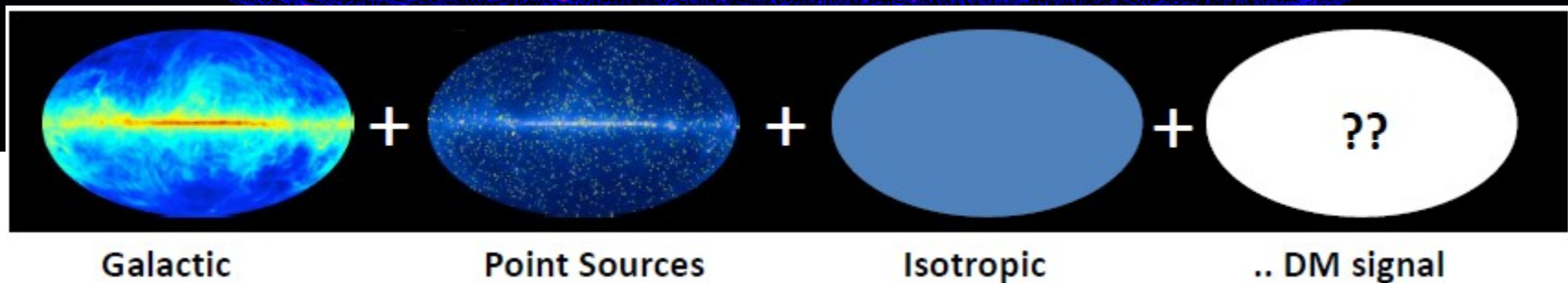
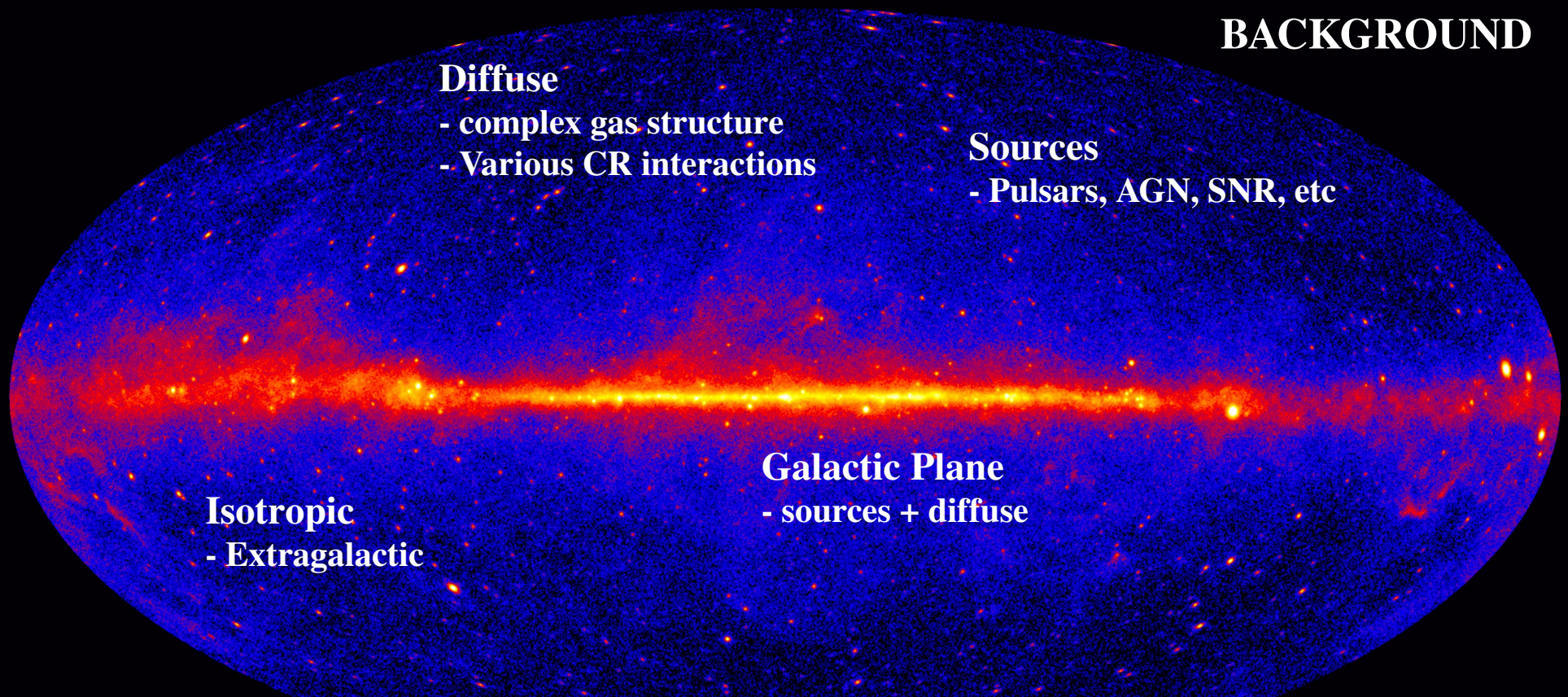
Trigger and Filter:

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.

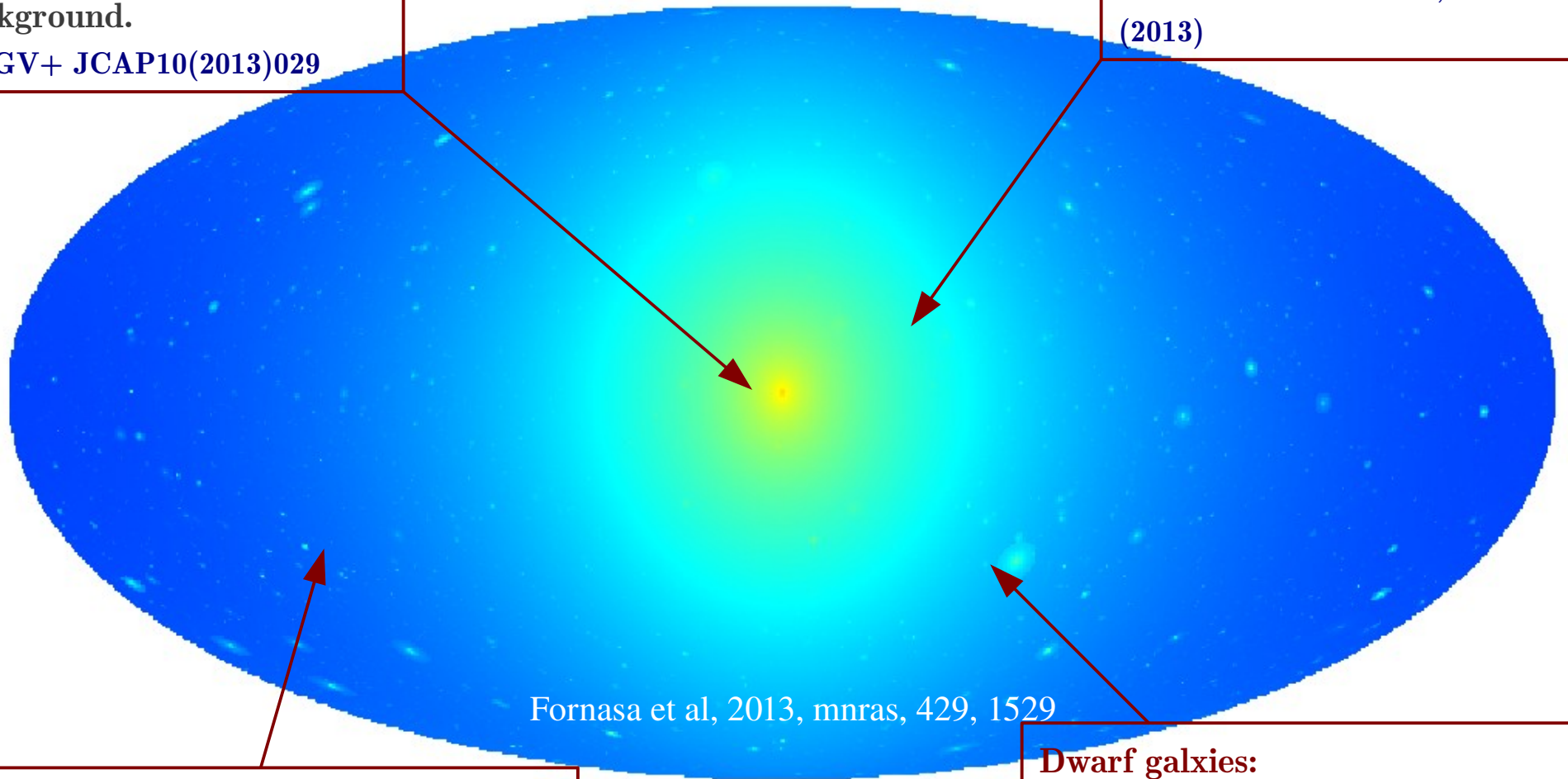
GAGV+ JCAP10(2013)029

Lines:

No astro uncertainties, but low sensitivity

Fermi PRD 86(2012)022002

Fermi+GAGV PRD 88, 082002 (2013)



Anisotropies:

Low statistics and low background.

Fermi+GAGV PRD 85(2012)083007

GAGV+ NIMA 2013 in press

Dwarf galaxies:

Low background, but low statistics

Fermi-LAT +GAGV arXiv: 1310.0828

Cahill-Rowley+ arXiv:1305.6921

Fermi-LAT+. 2011, PRL 107, 241302

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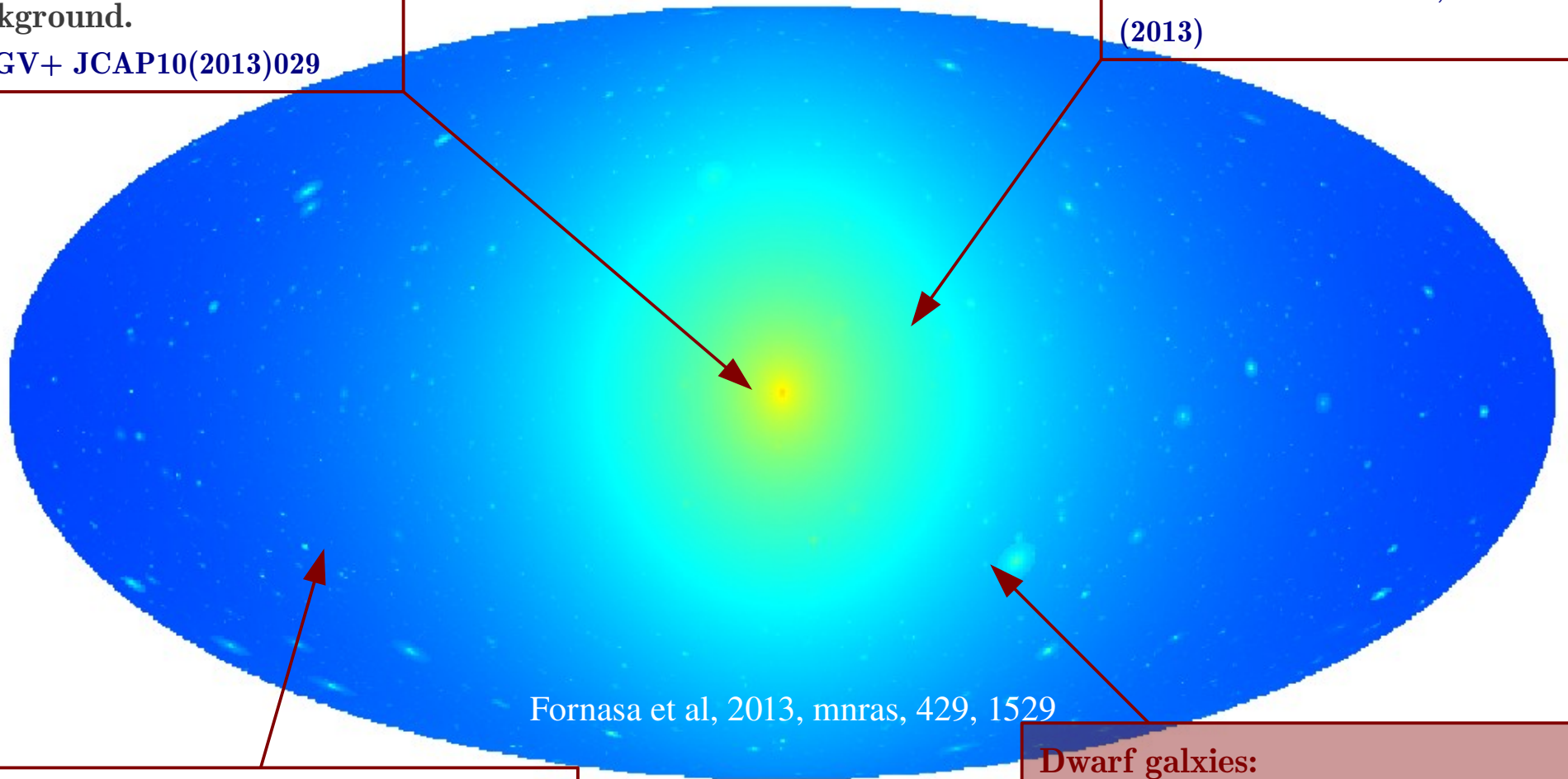
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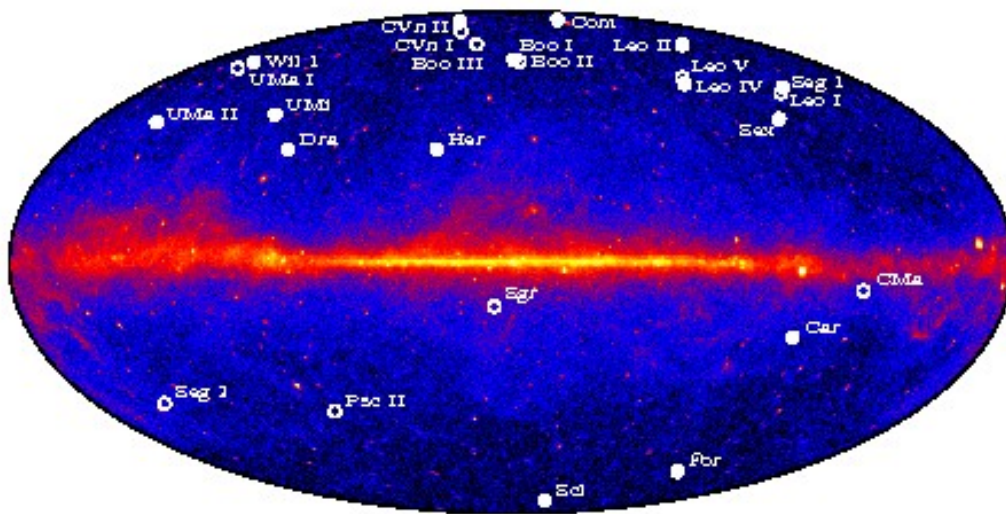
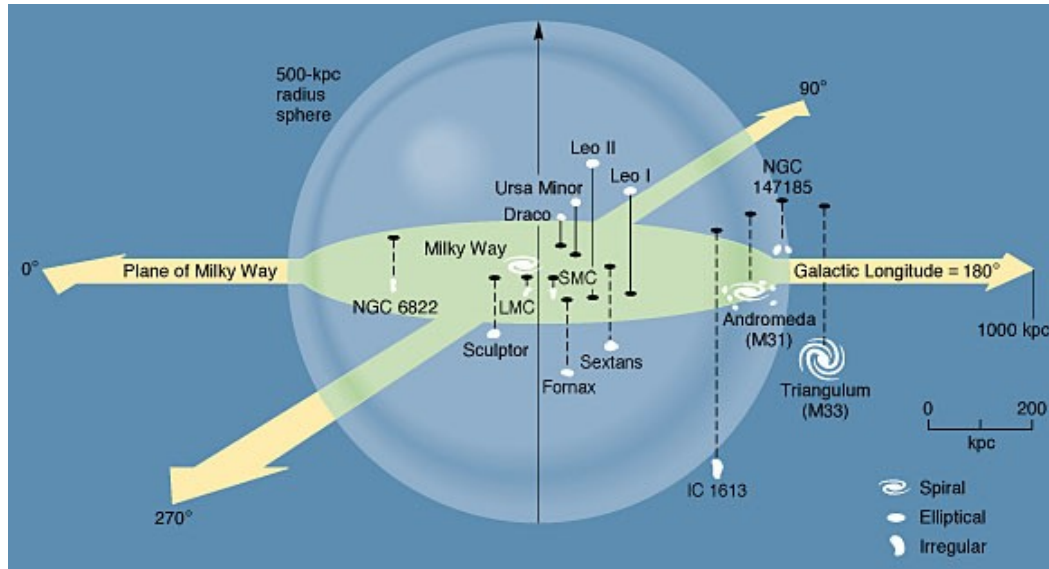
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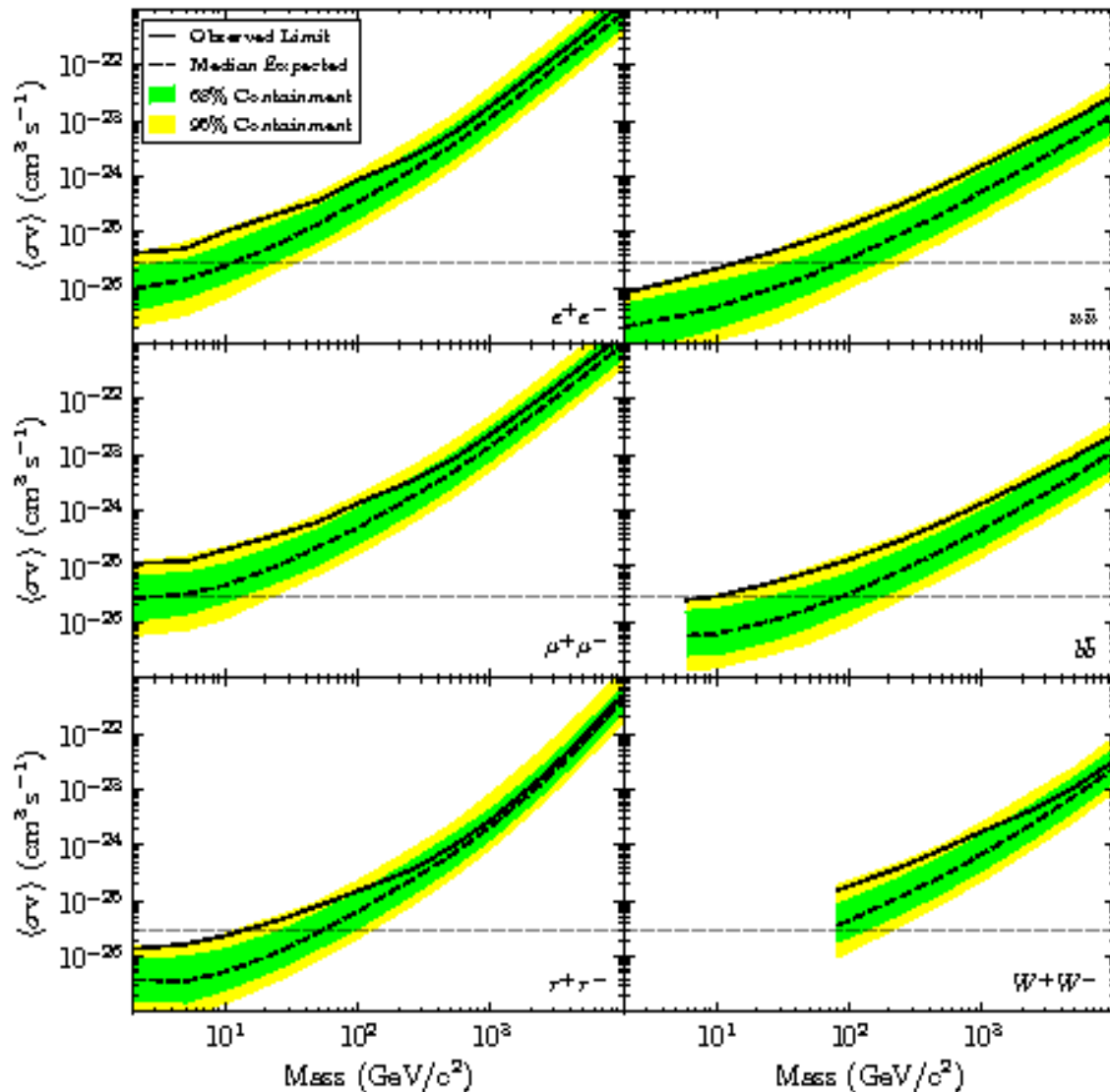
DWARF SPHEROIDAL GALAXIES



Fermi-LAT +GAGV 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

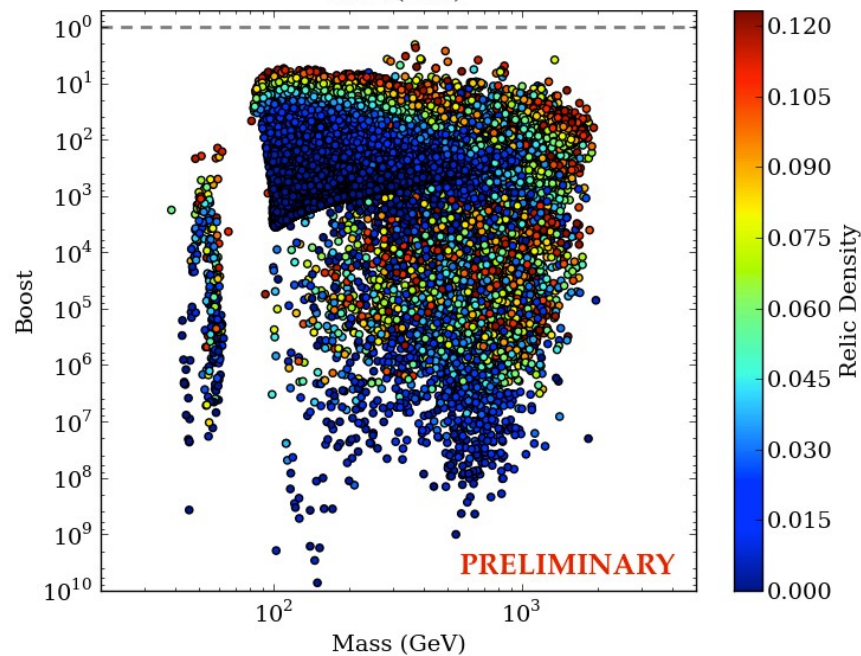
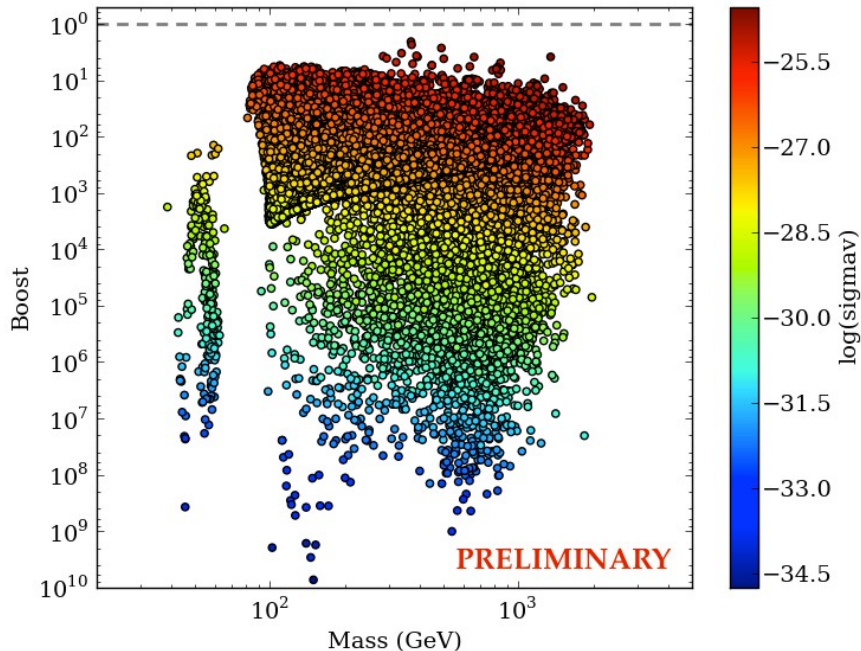


Fermi-LAT + GAGV arXiv: 1310.0828

- Current **limit close to thermal relic** X-section $< \sim 30$ 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

$$\langle \sigma v \rangle_{\text{UL}} / \langle \sigma v \rangle$$



pMSSM

$m_{\tilde{L}(e)1,2,3}$	100 GeV – 4 TeV
$m_{\tilde{Q}(q)1,2}$	400 GeV – 4 TeV
$m_{\tilde{Q}(q)3}$	200 GeV – 4 TeV
$ M_1 $	50 GeV – 4 TeV
$ M_2 $	100 GeV – 4 TeV
$ \mu $	100 GeV – 4 TeV
M_3	400 GeV – 4 TeV
$ A_{t,b,\tau} $	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 relevant ATLAS SUSY search publicly available as of the beginning of March 2013.
- Direct detection from Xenon 100.

TARGETS FOR DARK MATTER SEARCHES

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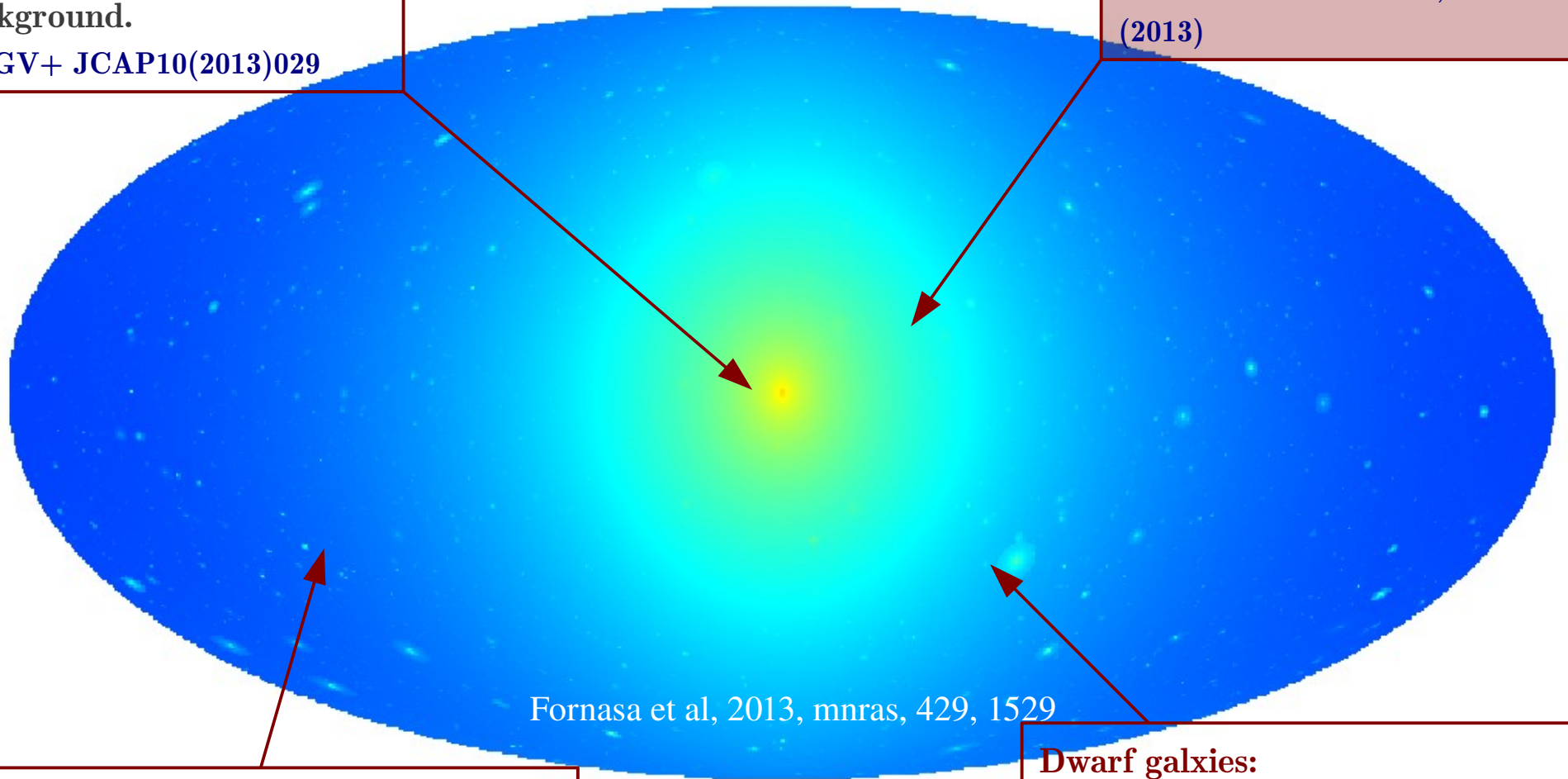
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Fermi+GAGV PRD 88, 082002 (2013)



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GAGV+ NIMA 2013 in press

Dwarf galaxies:

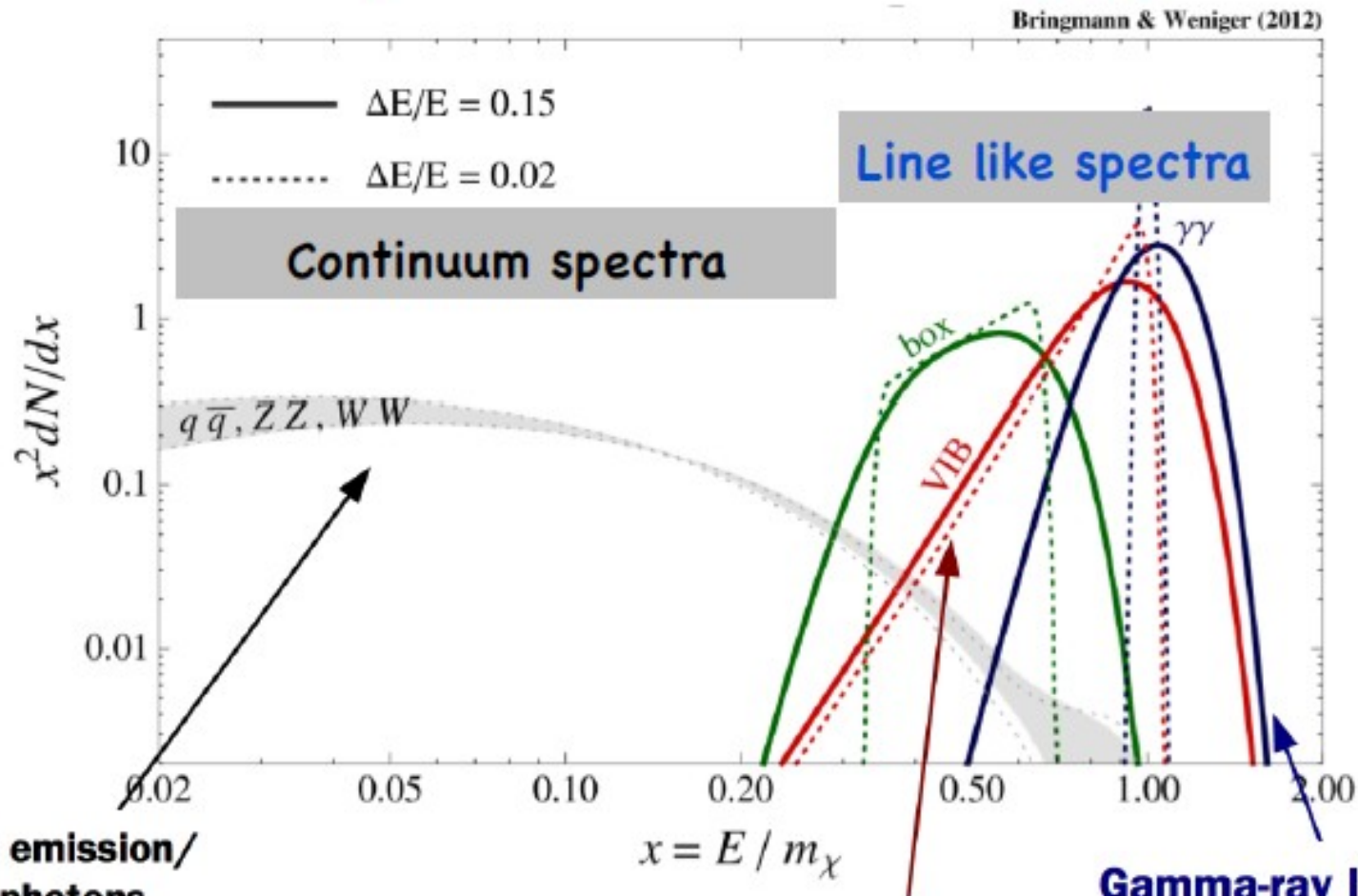
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Fermi-LAT+. 2011, PRL 107, 241302

GAMMA-RAY LINE



Continuum emission/ secondary photons

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

$$\chi\chi \rightarrow \bar{q}q \rightarrow \pi^0 \dots$$

$$\pi^0 \rightarrow \gamma\gamma$$

Internal Bremsstrahlung (IB)

- radiative correction to processes with charged final states
- Generically suppressed by $O(\alpha)$

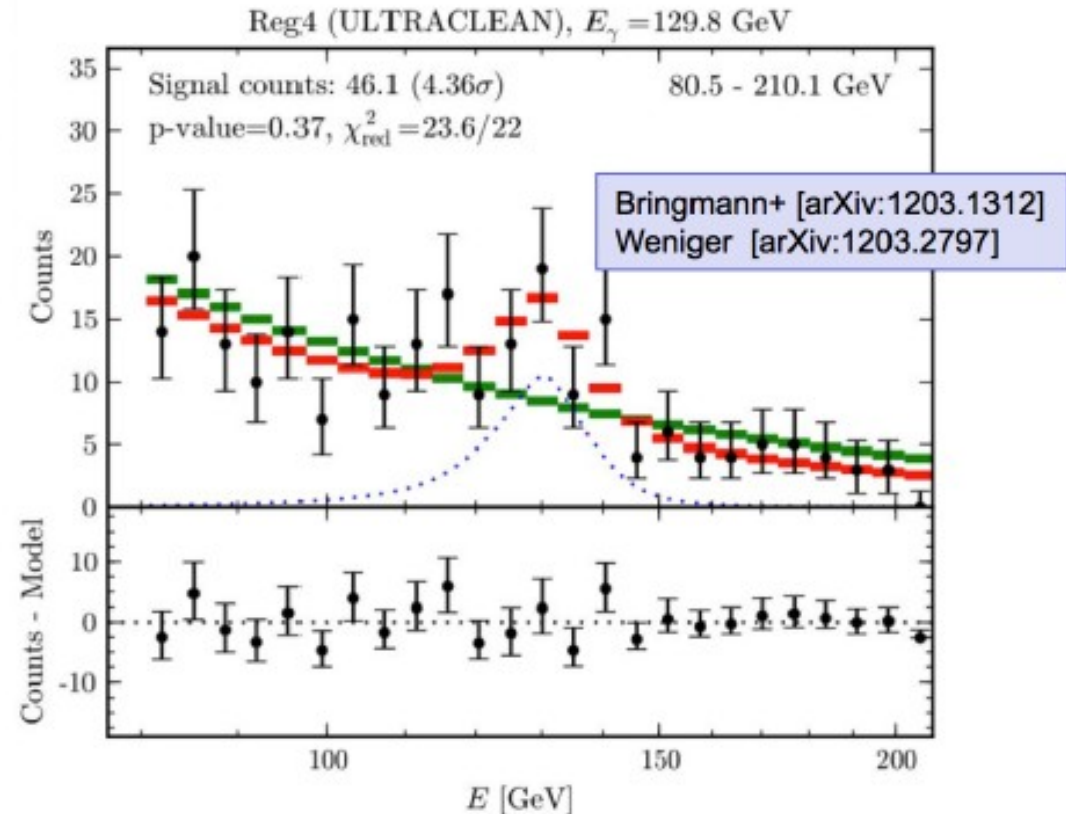
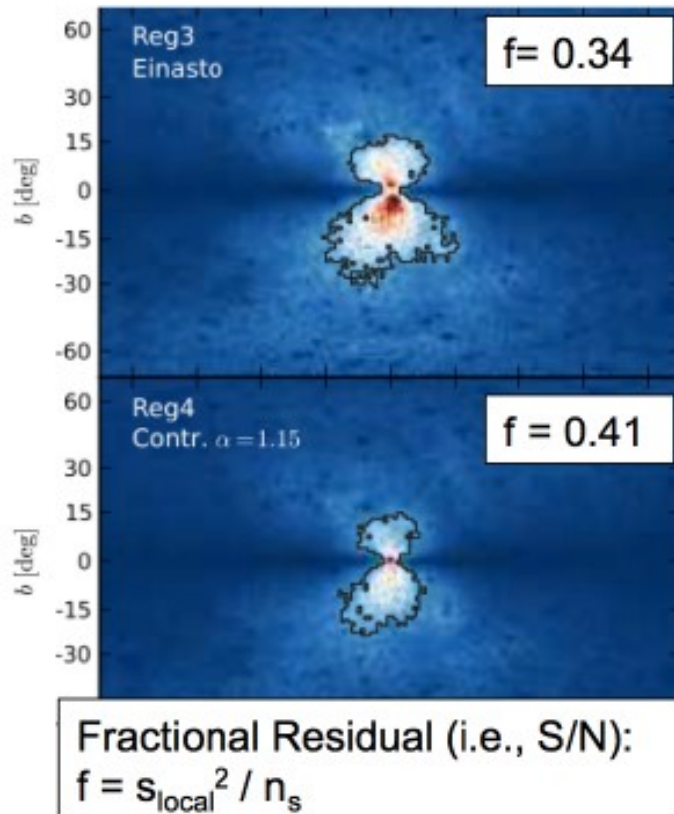
$$\chi\chi \rightarrow \bar{f}f\gamma$$

Gamma-ray lines

- from two-body annihilation into photons
- forbidden at tree-level, generically suppressed by $O(\alpha^2)$

$$\chi\chi \rightarrow \gamma\gamma$$

GAMMA-RAY LINE

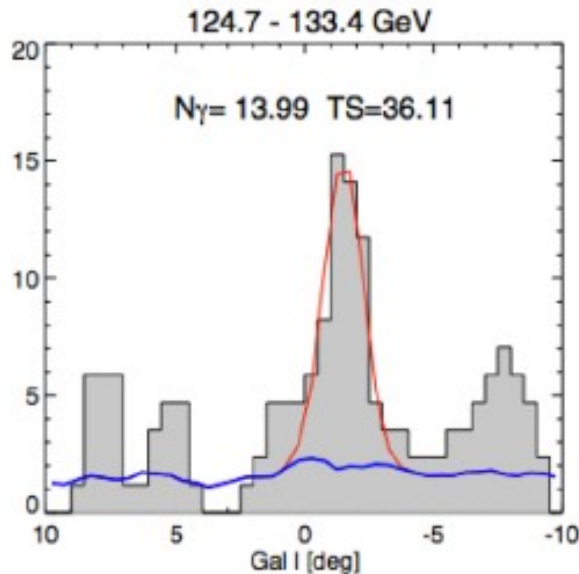


Bringmann et al. and Weniger showed evidence for a narrow spectral feature near 130 GeV and near the Galactic centre:

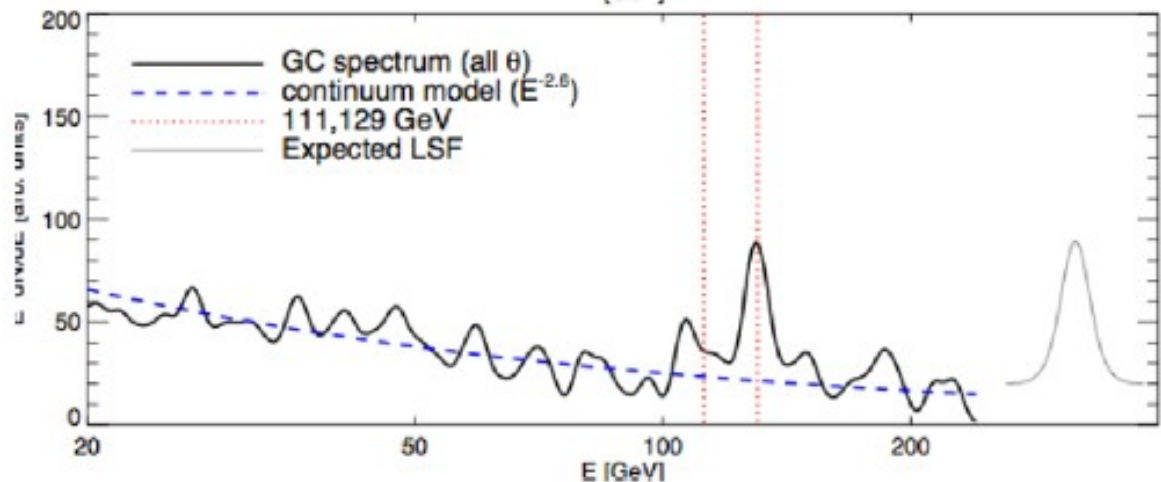
- Signal is particularly strong in 2 out of their 5 test sky regions, shown above.
- 4-5 σ (local), with S/N $\approx$ 30-60% in optimized regions of interest (ROI).

GAMMA-RAY LINE

Gal. Long. Profile at ~130GeV



Energy Spectrum from GC



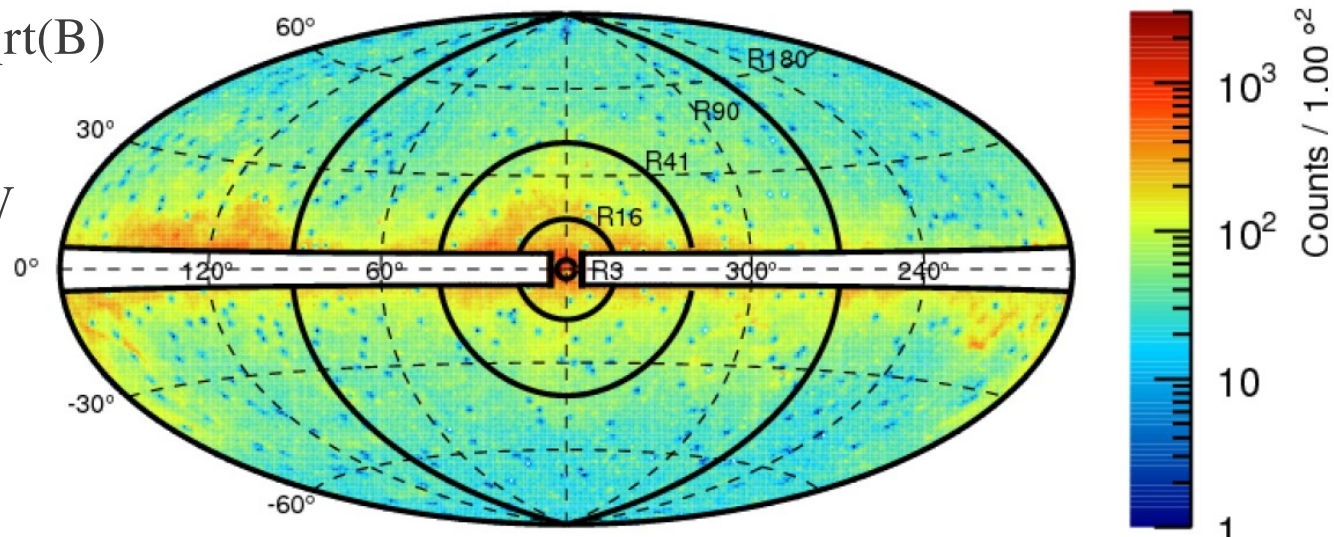
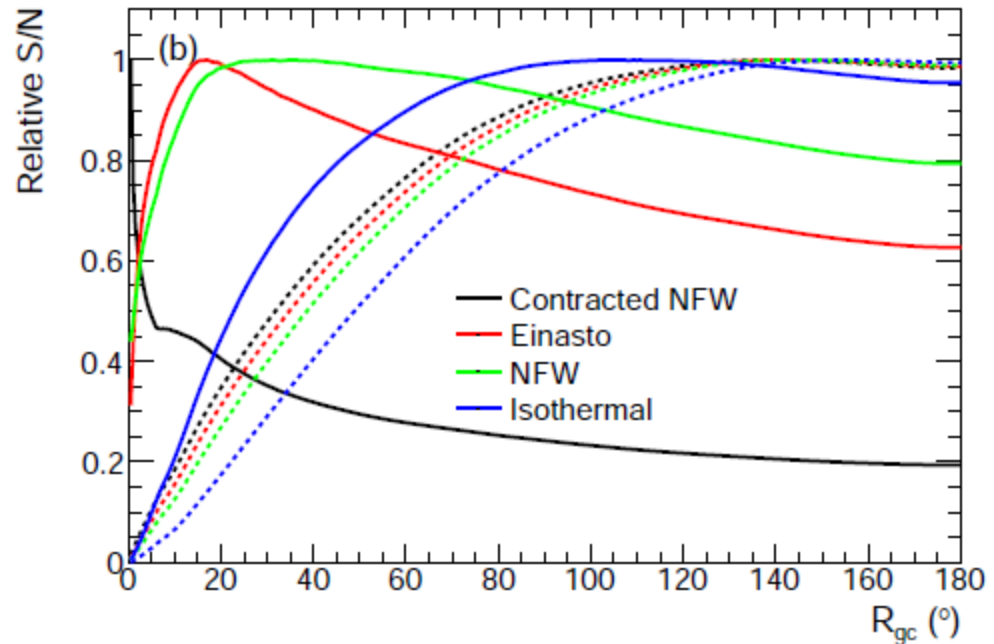
Su & Finkbeiner showed that the spectral feature was close to, but slightly (~1.5 deg) offset from, the Galactic centre [arXiv:1206.1616].

- Their likelihood analysis included a spatial morphology of signal, and data-driven model of Galactic astrophysical backgrounds.
- Claimed **6 σ statistical significance**, after a **trials factor of ~6000**, but acknowledge uncertainties of modeling the Galactic astrophysical backgrounds.

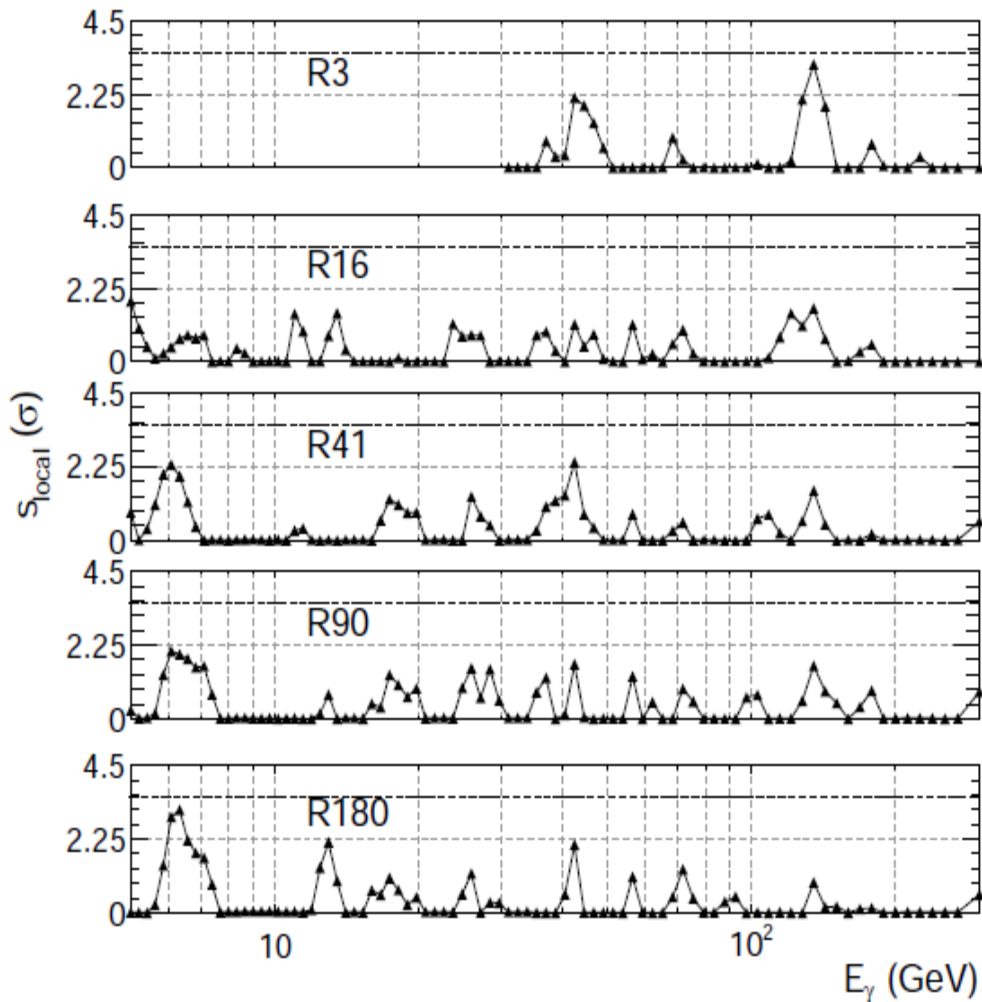
GAMMA-RAY LINE

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 ($>10\sigma$ 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)



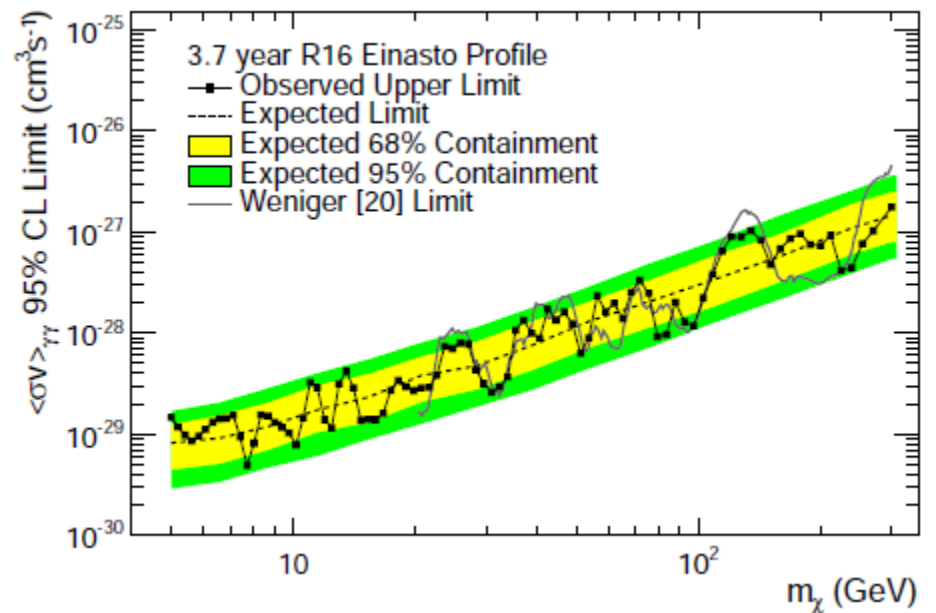
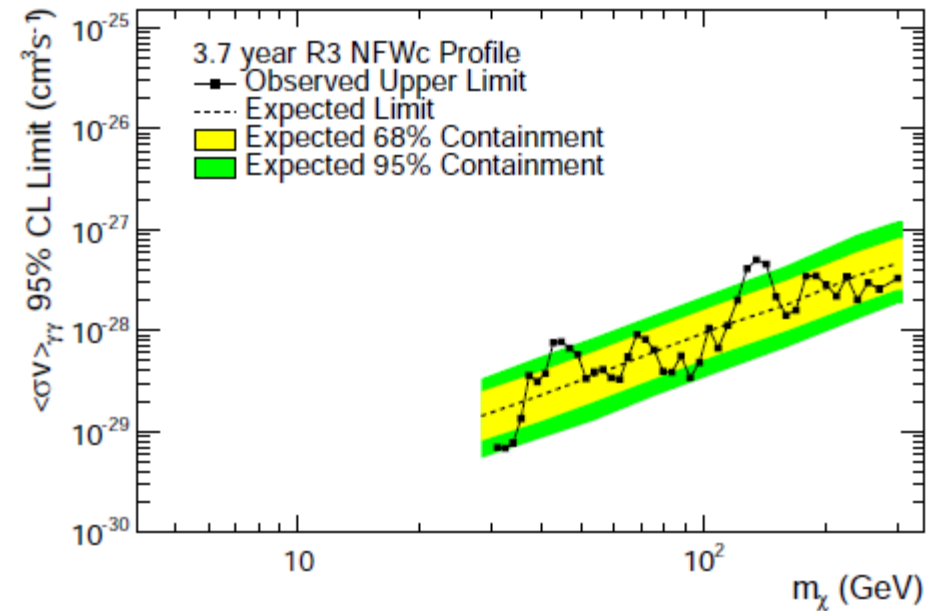
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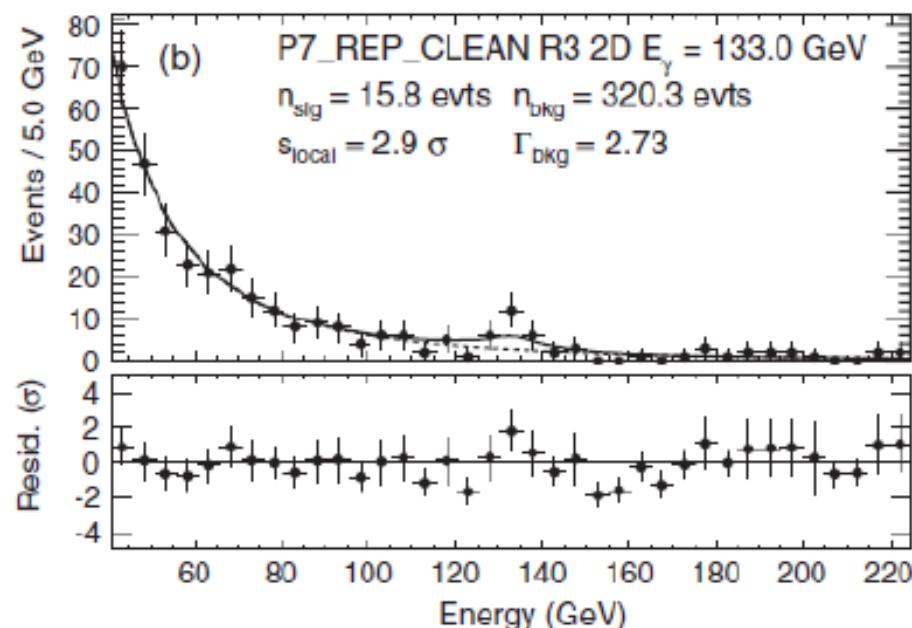
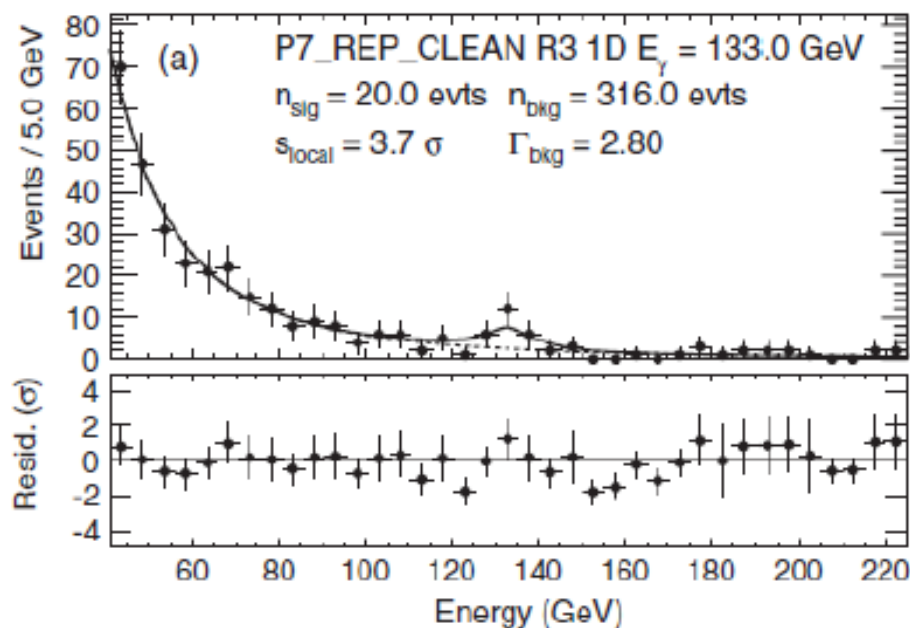
No globally significant lines detected

–All fits have global significance $< 2\sigma$

Fermi+GAGV PRD 88, 082002 (2013)

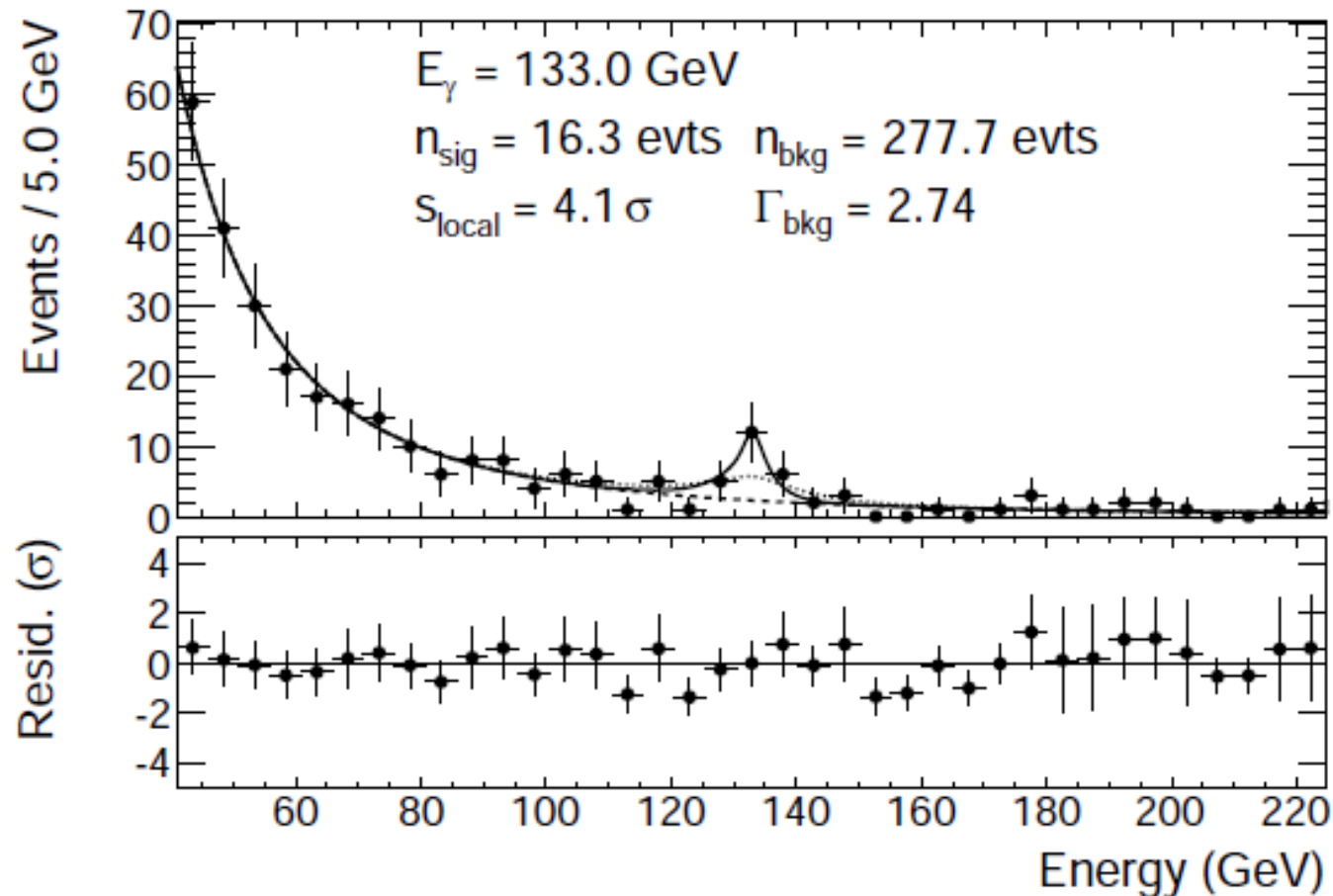


GAMMA-RAY LINE



- 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
- $<2\sigma$ global significance after trials factor

GAMMA-RAY LINE

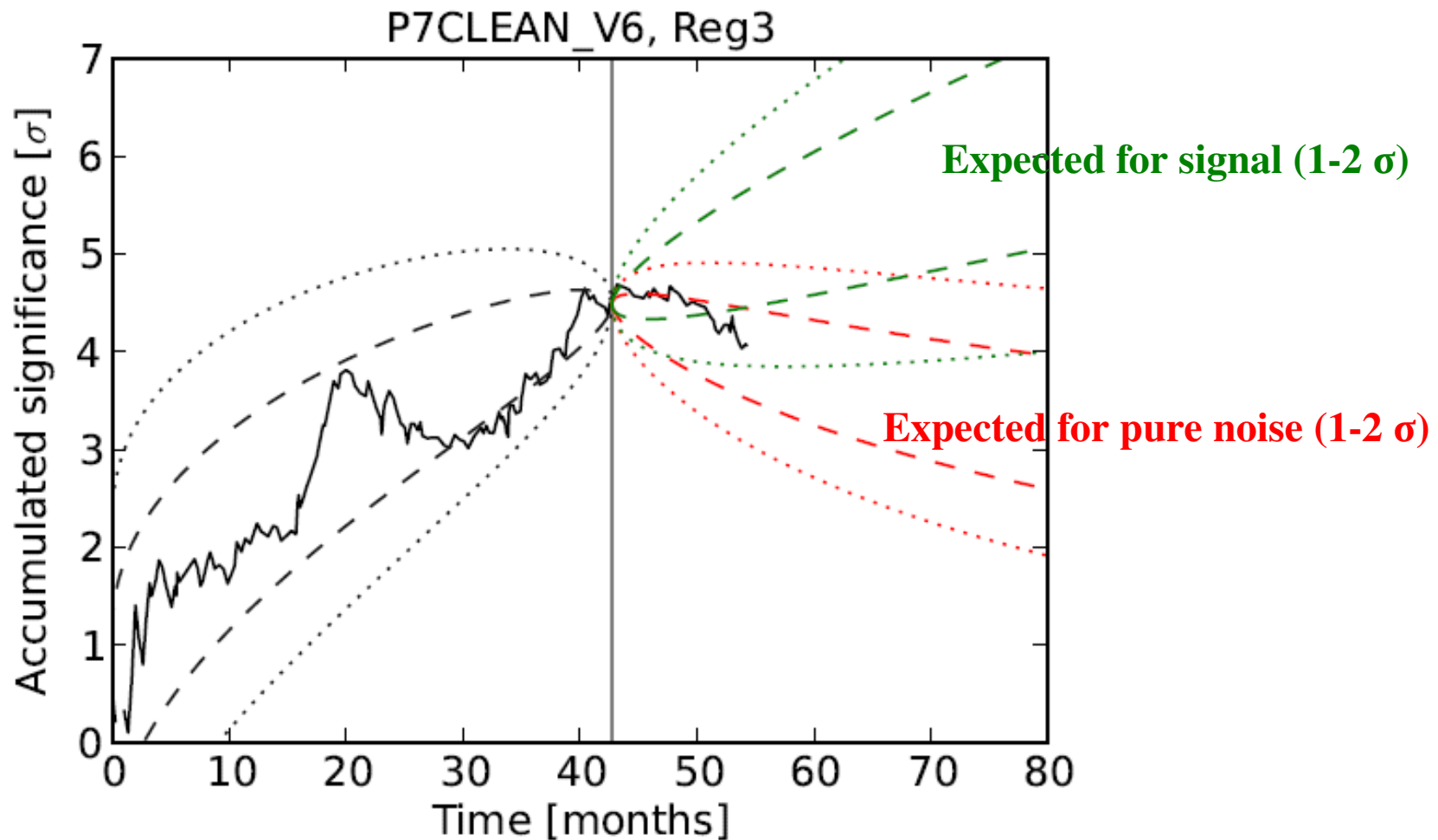


Let width scale factor float in fit (while preserving shape)

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

–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 results from the recent LAT line-search paper.

–Likely that the original putative line signal was a statistical fluctuation.
[arXiv:1303.1798](https://arxiv.org/abs/1303.1798)

Summary

The Fermi LAT team looks for indirect DM signals in a wide variety of methods

- ✓ So far no unambiguous DM signal detected.
- ✓ Strong constraints have been set.

We do not see any globally significant spectral line

Pros & Cons for ~ 130 GeV line

□ PROS

- ▶ Tantalizing signal ($>3\sigma$ local)
- ▶ Signal from the GC region
- ▶ No signal in Galactic plane
- ▶ Signal (roughly) consistent with expected DM profiles

□ CONS

- ▶ Similar signal in limb data (not as strong)
- ▶ Similar features at other energies
- ▶ Decreased in significance w/ more data and analysis improvements ('too' narrow line)
- ▶ Global significance (incl. trial factors) $\lesssim 2\sigma$ with Fermi energy scan and ROI:s
- ▶ Requires large $\gamma\gamma$ BR. Displaced from GC

Too soon for definite statements about the line:

More Fermi-LAT data + Pass 8 will give more information.

Cherenkov telescopes (HESS II). Future CTA, Gamma400...

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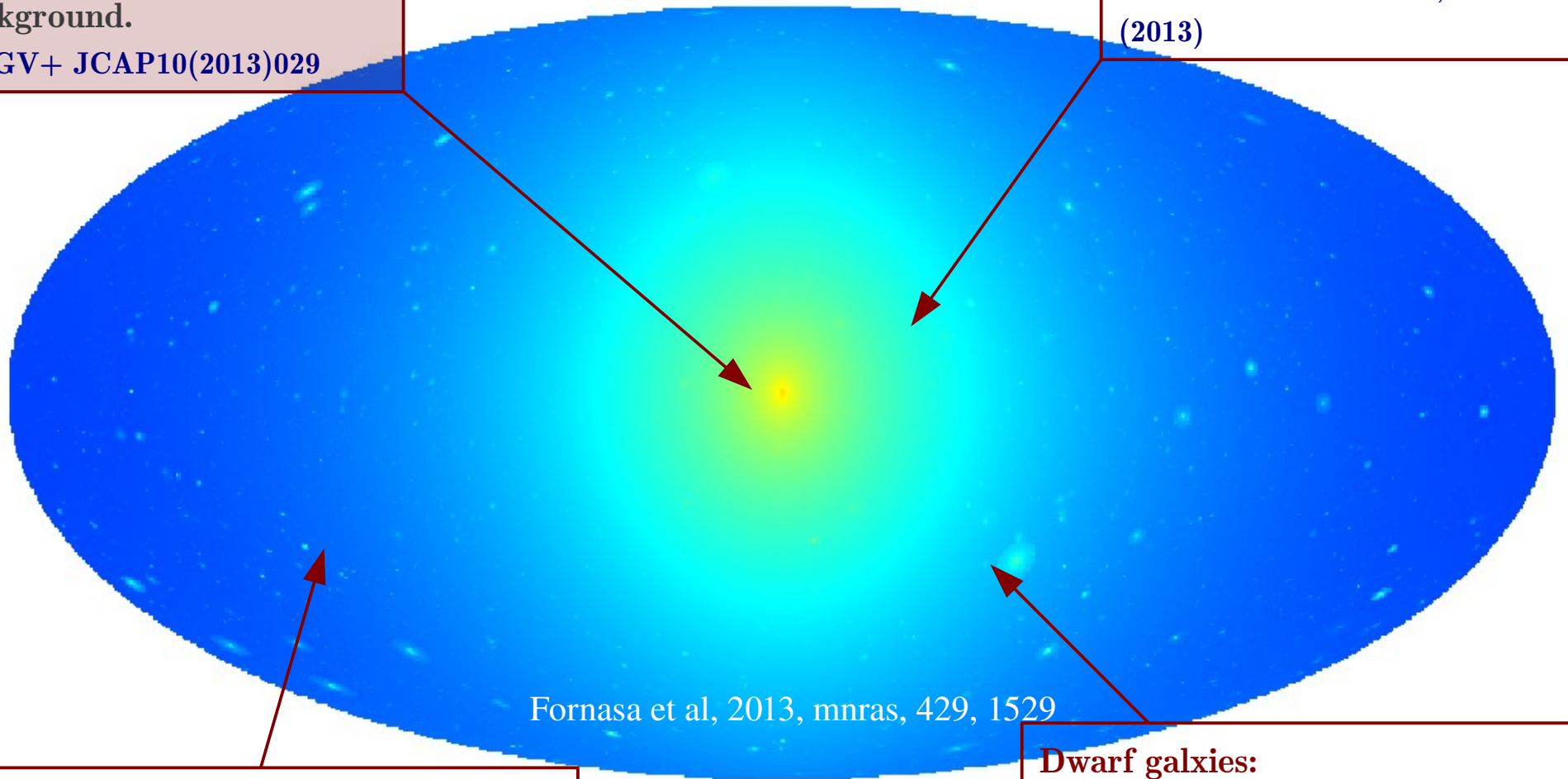
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Fornasa et al, 2013, mnras, 429, 1529

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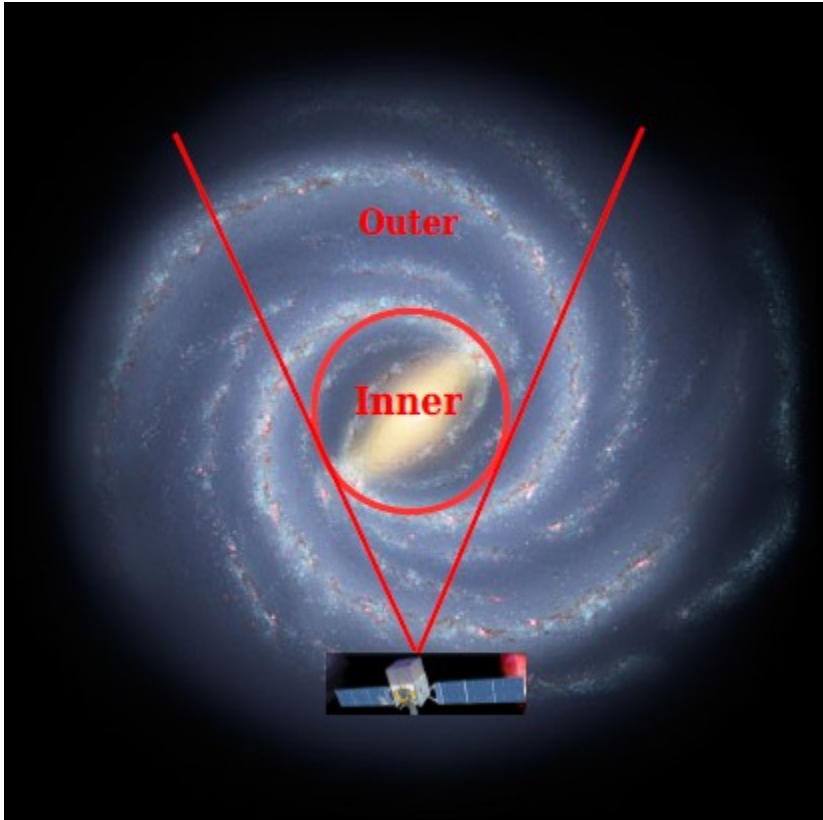
Cahill-Rowley+ arXiv:1305.6921

Fermi-LAT+. 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** (work in collaboration with Igor Moskalenko, Troy Porter and Simona Murgia, Stanford University).
- 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



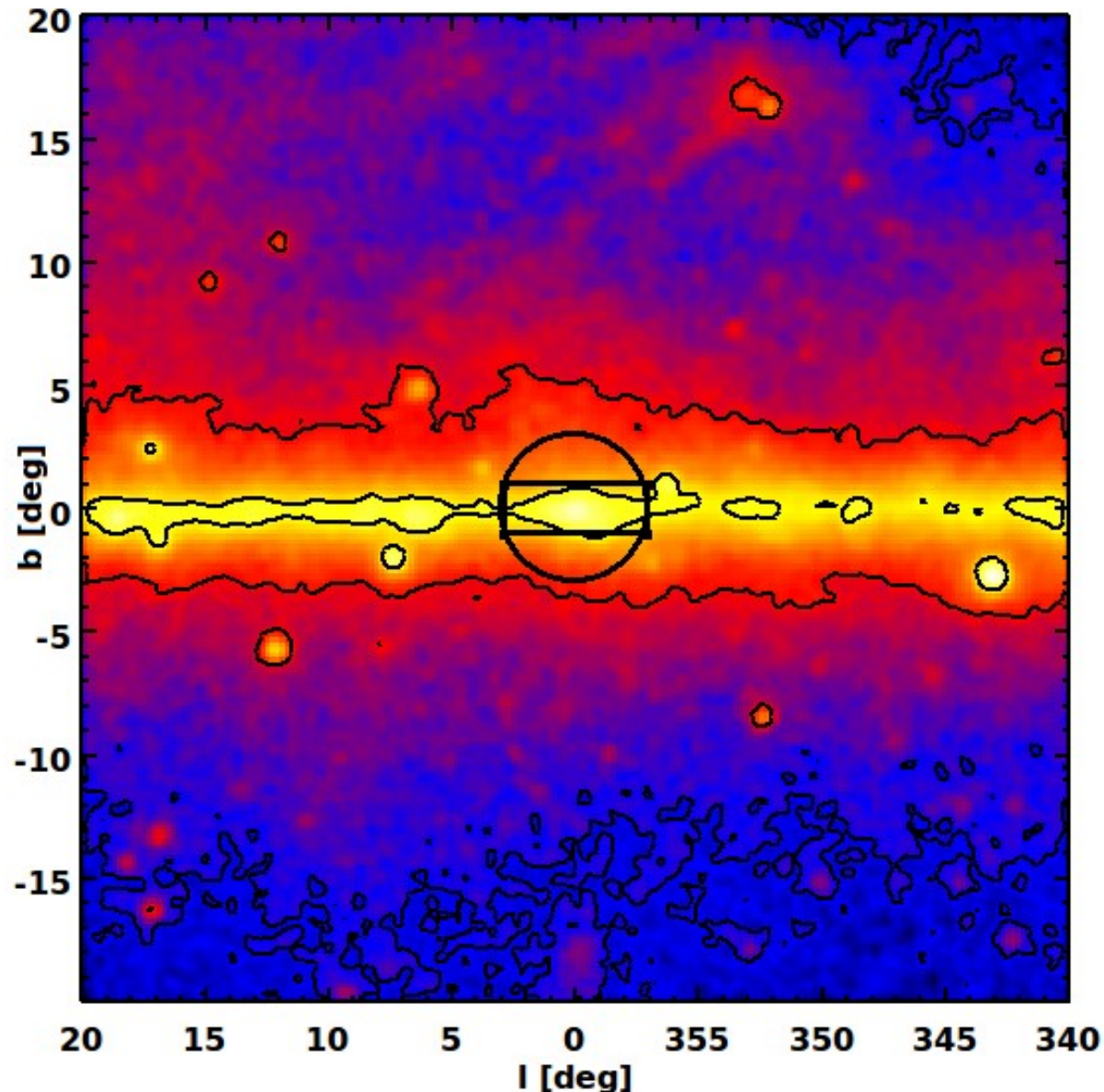
Emission from the inner Galaxy is made of:

- 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

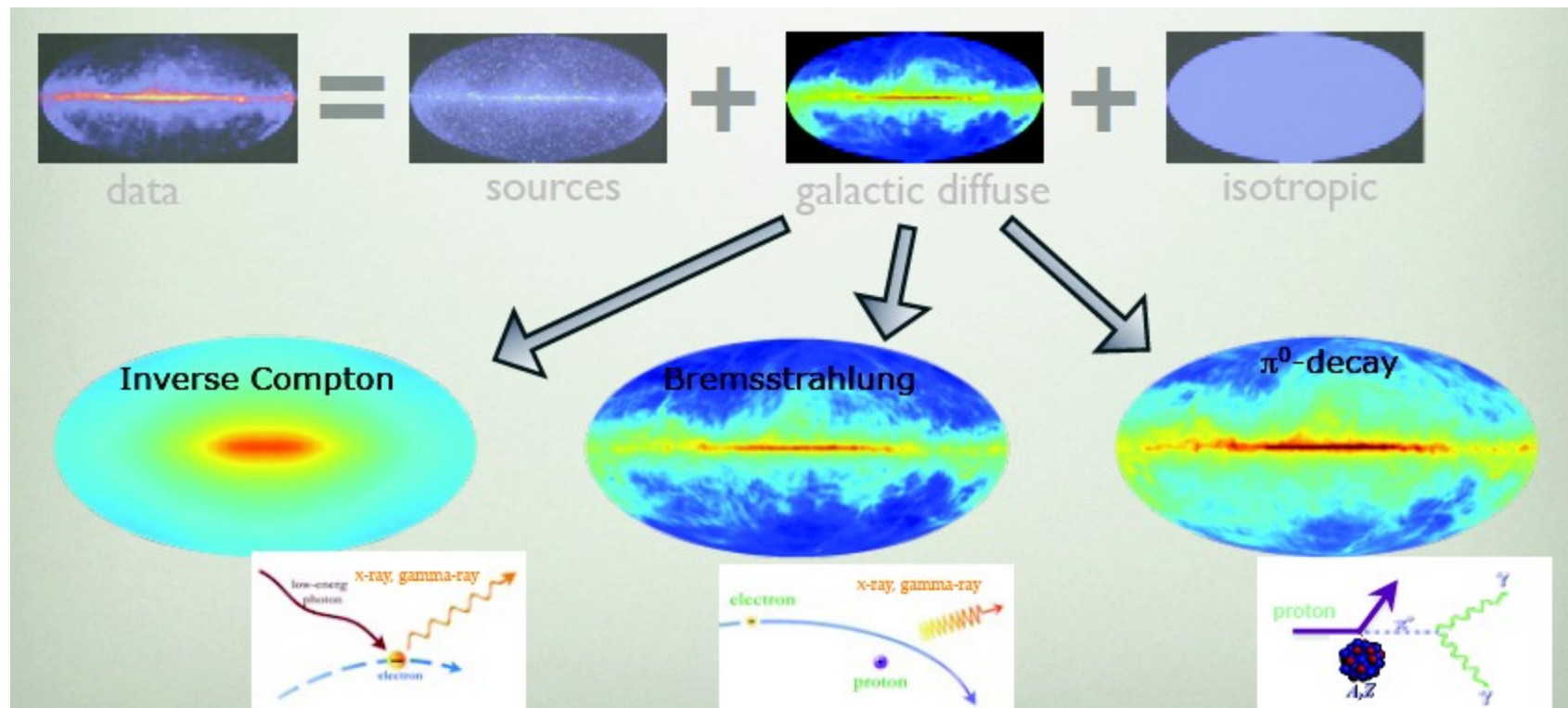
Gamma-ray flux 1-100 GeV

GAGV+ JCAP10(2013)029



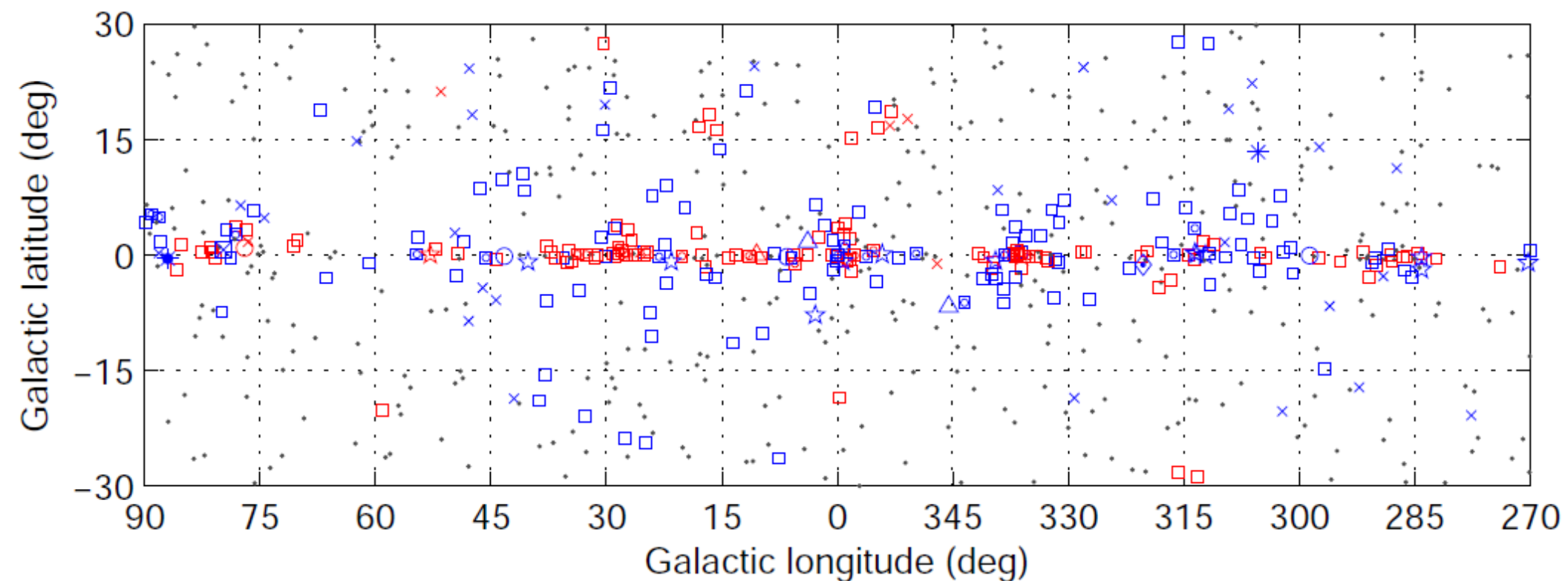
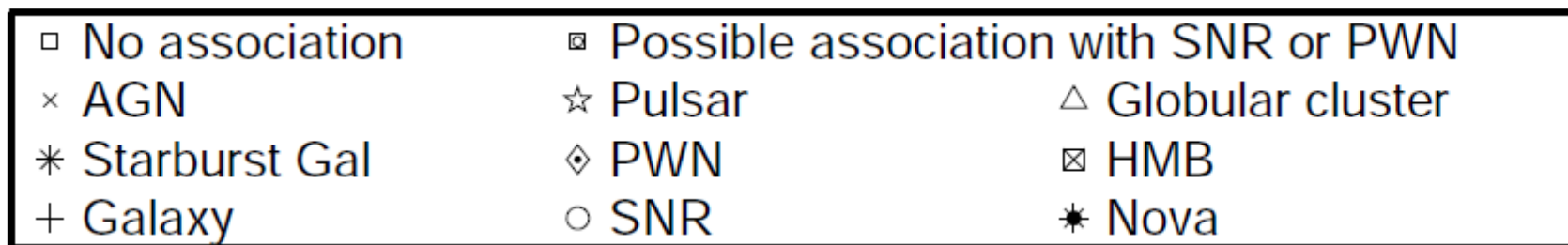
ASTRO ZOO IN GAMMA-RAY

- Diffuse emission.
 - Unresolved/undetected point sources
 - Interaction between CR and interstellar gas (pion decay and bremsstrahlung), and radiation fields (ICS).



ASTRO ZOO IN GAMMA-RAY

- Point sources 2FGL (Fermi Coll. Astrophys.J.Suppl. 199 (2012) 31)

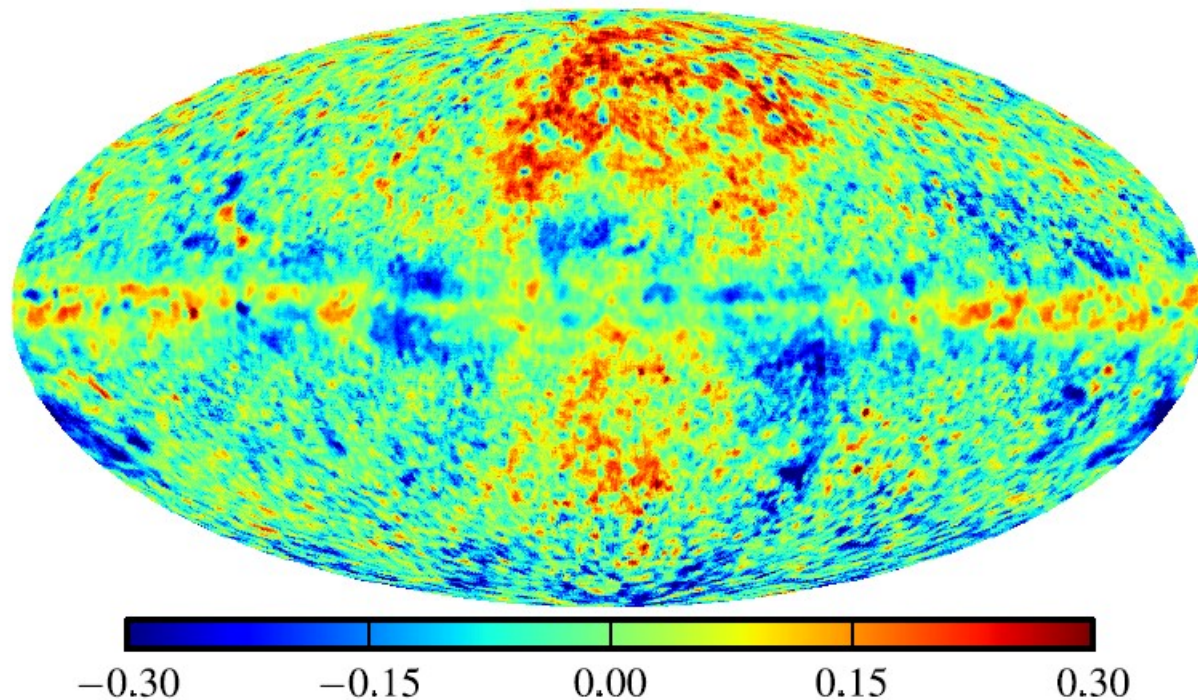


ASTRO ZOO IN GAMMA-RAY

- Point sources 2FGL
- Caveats:
 - Point sources characteristics depend on the diffuse model used in their extraction
 - Some diffuse emission regions (like in gas cloud regions) could be confused with point sources
 - Concentration of sources in the inner Galaxy creates confusion. Therefore it is difficult to distinguish between point sources and diffuse emission

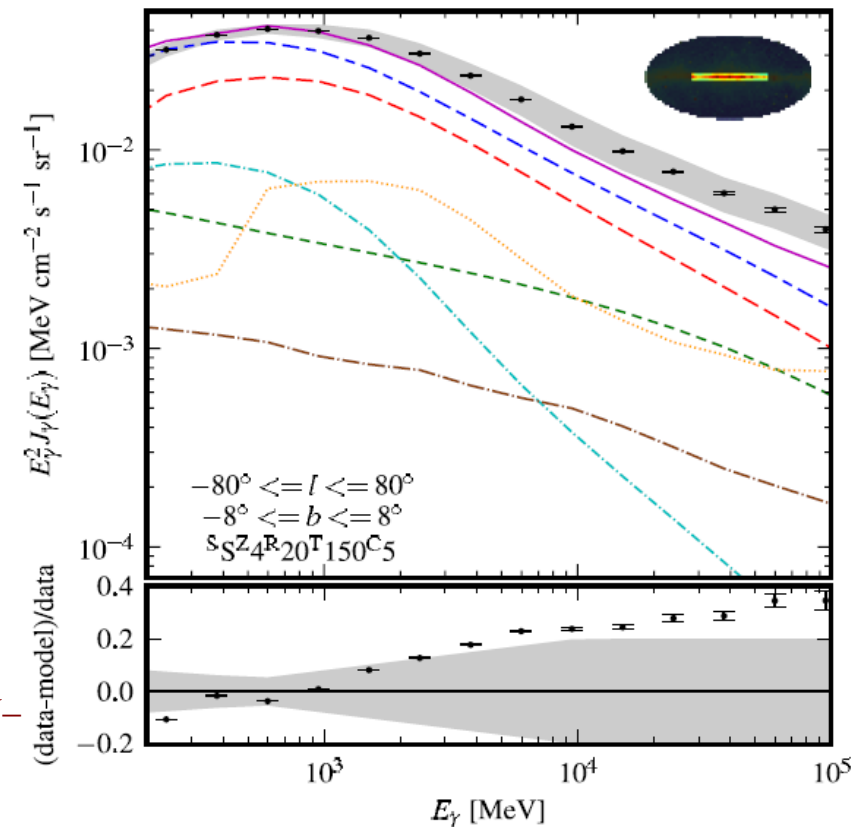
ALL SKY MODELING

- 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.

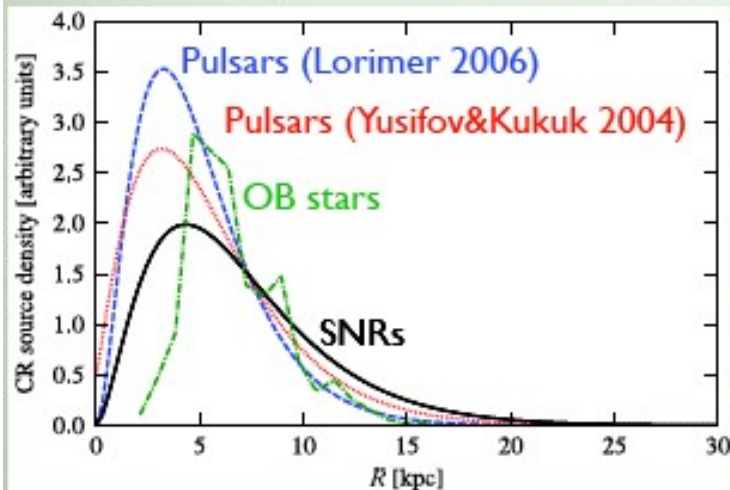
(Fermi-LAT Coll. The Ast. Journal, 750:3 (35pp), 2012)



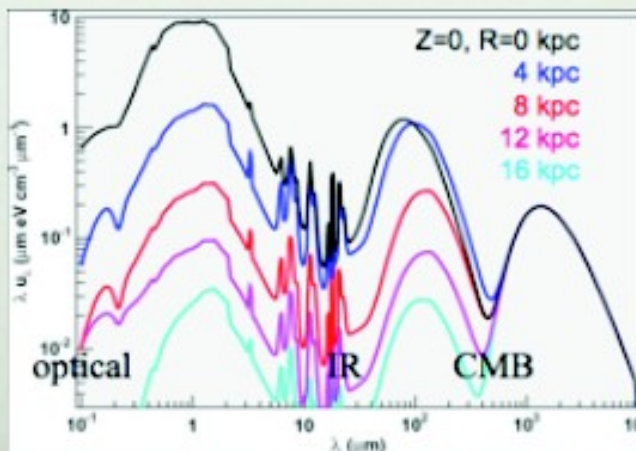
GALACTIC CENTER REGION

- Steep DM profiles predicted by CDM $\Rightarrow$ 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

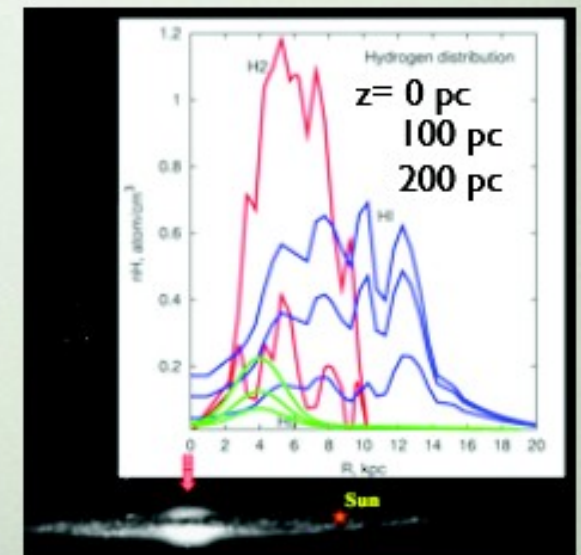
Cosmic ray source density



Interstellar radiation field

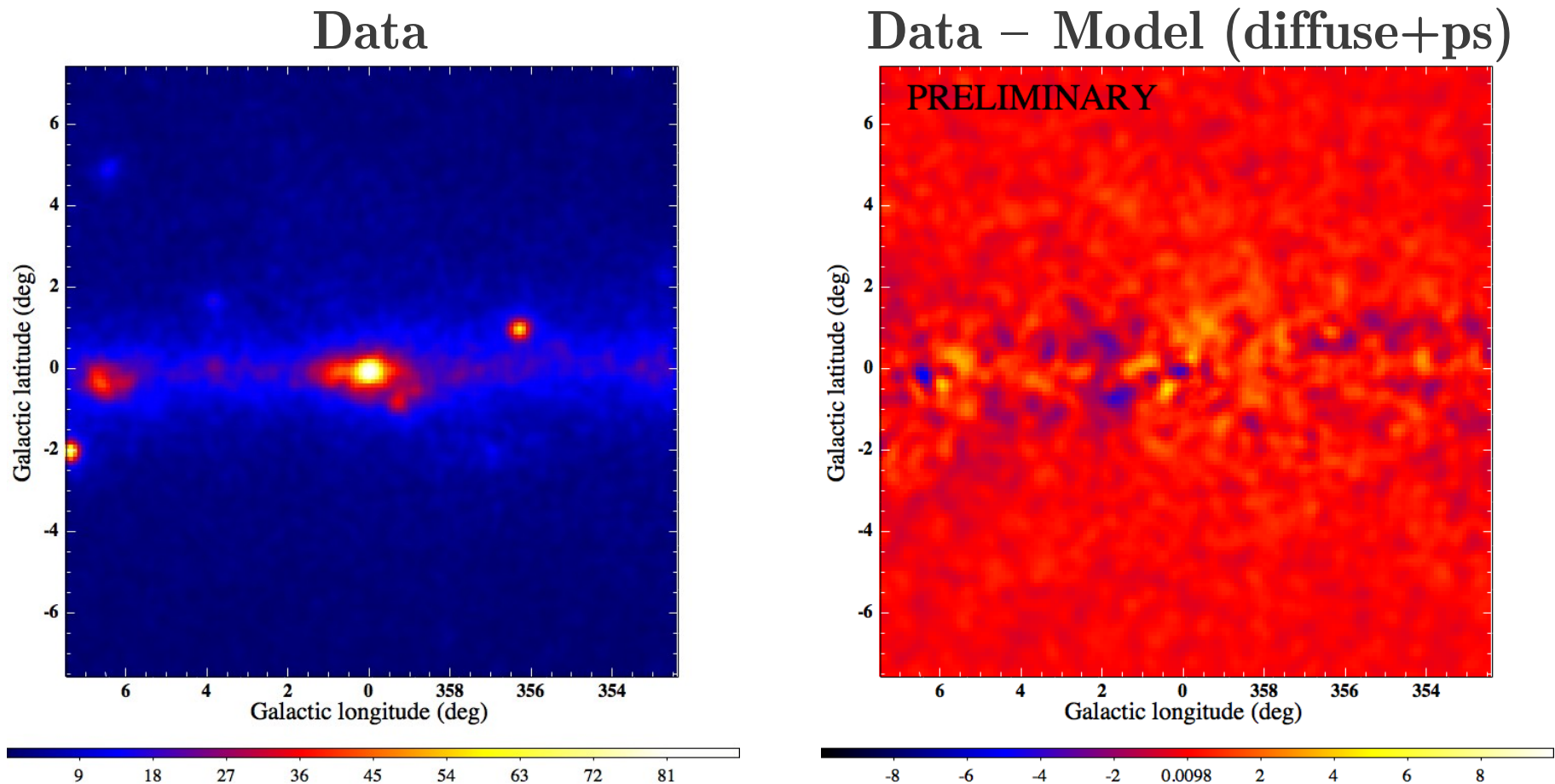


Average gas density



FERMI'S VIEW OF THE INNER GALAXY ($15^\circ \times 15^\circ$ REGION)

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



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

FERMI'S VIEW OF THE INNER GALAXY ($15^\circ \times 15^\circ$ 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).

DM-INDUCED GAMMA RAYS. AKA, EXPECTED DM SIGNAL

The gamma-ray flux from DM annihilation has two main contributions: prompt photons and photons induced via ICS. The former are produced indirectly through hadronization, fragmentation and decay of the DM annihilation products or by internal bremsstrahlung, or directly through one-loop processes. The second contribution is originated from electrons and positrons produced in the DM annihilations, via ICS off the ambient photon background.

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

Gamma-ray Flux

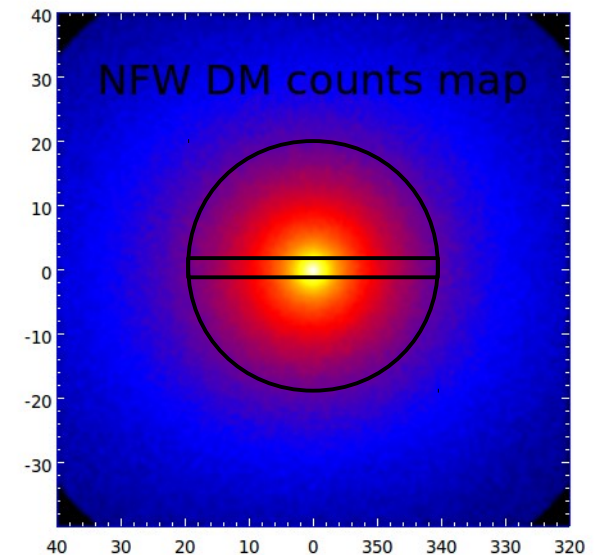
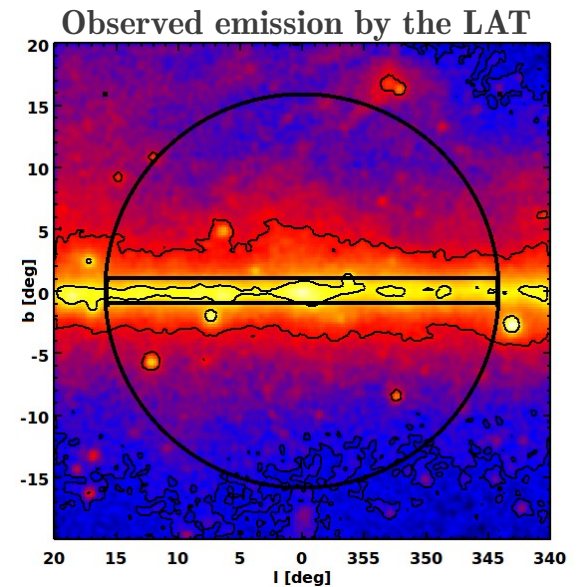
Particle Physics
Spectral
information

DM Distribution
(J-Factor)
Spatial
information

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

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.



DM DENSITY PROFILES

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

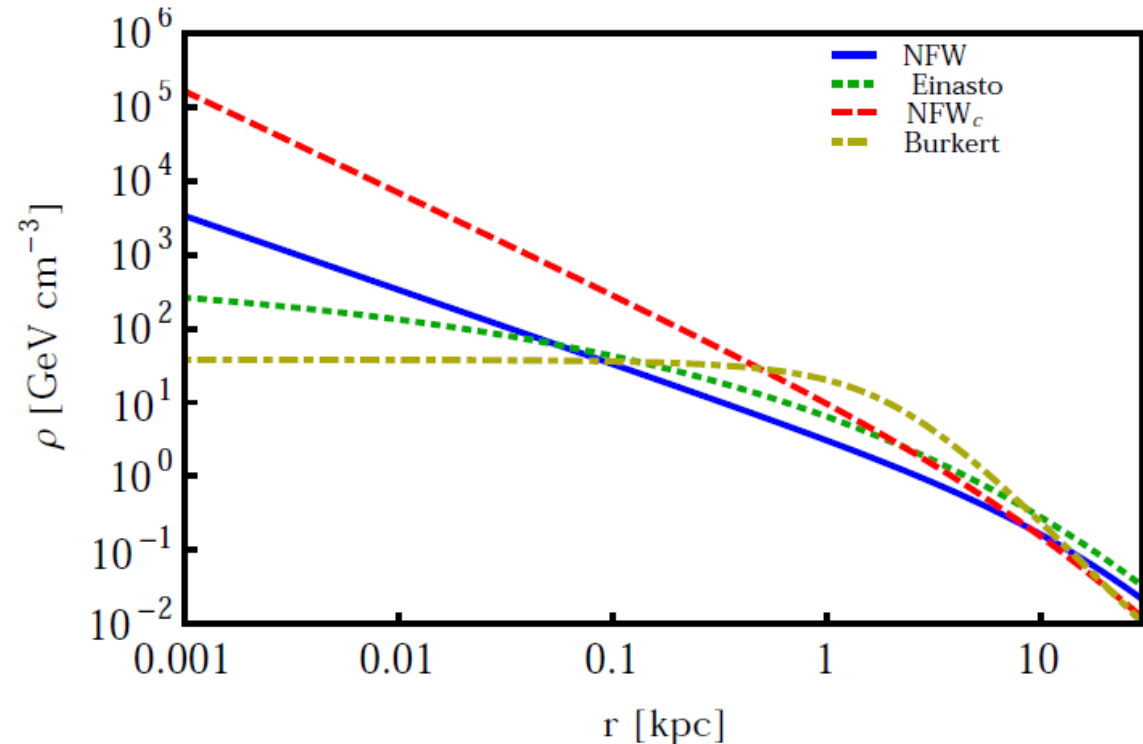
- NFW (Prada+04)
- Einasto (Catena&Ullio10).
- Burkert (inspired on Catena&Ullio10).
- **Adiabatically compressed NFW** (Prada+04).

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

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

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

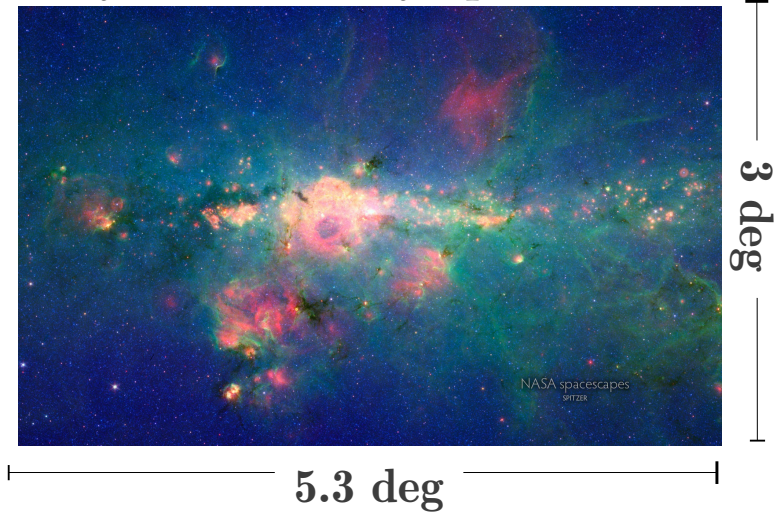
$$\rho_{\text{Burkert}}(r) = \frac{\rho_s r_s^3}{(r + r_s)(r^2 + r_s^2)}$$



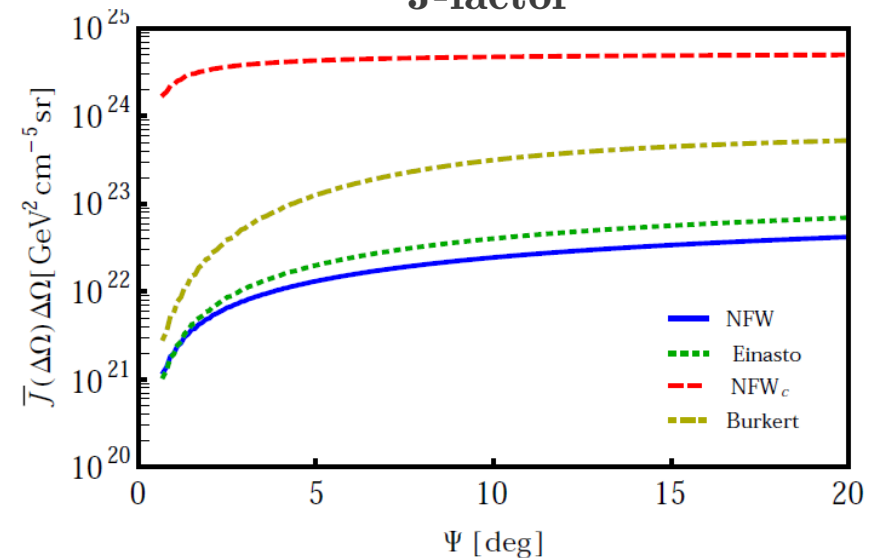
COMPRESSED PROFILES

- 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

Baryons as seen by Spitzer in IR



J-factor



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

PARTICLE PHYSICS MODELS

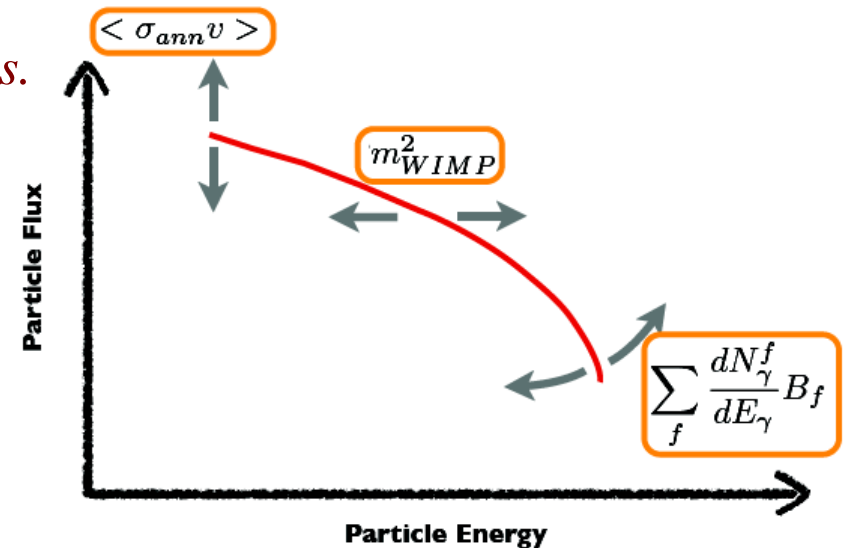
Particle physics factor:

Vanilla-like DM: *Prompt, FSR, and ICS processes.*

PPPC 4 DM ID tables: *used for prompt and FSR.*

DM mass range: *5 GeV – 3 TeV*

Channels: *bb, $\tau^+\tau^-$, $\mu^+\mu^-$, W^+W^-*



Inverse Compton Scattering calculation:

For heavy DM it can be dominant over prompt in the *Fermi*-LAT energy range used.

Numerical calculation of galactic CR diffusion-loss equation.

MIN, MED, MAX model + $b(E)$ suitable for GC region.

MIN and MAX models do not imply minimal or maximal expected gamma-ray signal, respectively.

ICS is more significant for leptonic channels

FERMI-LAT DATA ANALYSIS



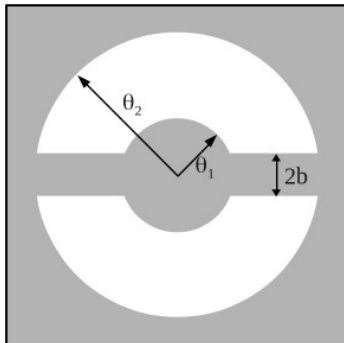
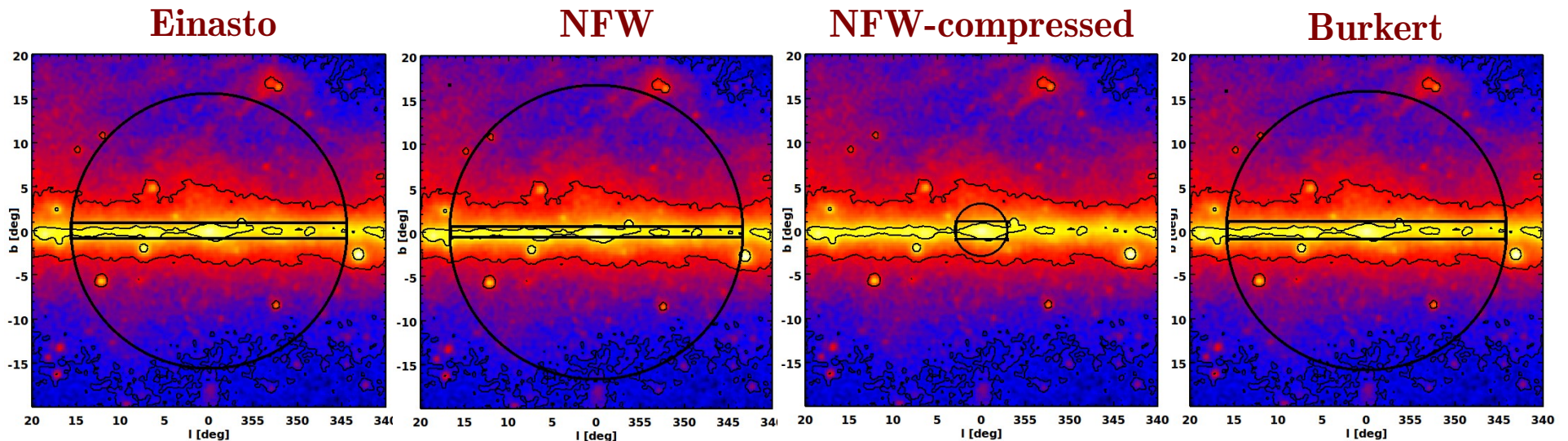
- Fermi-LAT: 2008 Aug. 4 – 2012 June 15.
- Energy range: 1-100 GeV.
- Class events: **Pass 7 V6 Ultraclean front conversion**. This choice reduces the cosmic-ray background contamination and takes advantage of a narrower PSF w.r.t. back-converting events
- Science tools: **V9r28**
- Region of analysis: **30 deg around the GC**
- We build a set of 0.2 deg/pixel resolution flux maps $f(E, l, b)$ at different energies.

FERMI-LAT DATA ANALYSIS

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

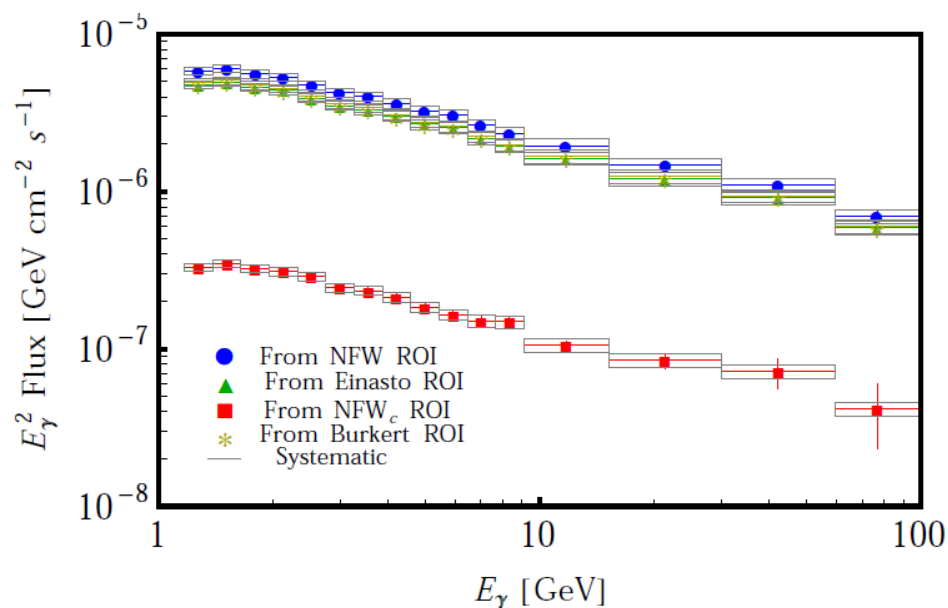
- *Signal*: J-factor maps for every DM density profile.
- *Noise*: Square root of the photon flux map.

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



Profile	θ_1 [°]	θ_2 [°]	$ b $ [°]	$\Delta\Omega$ [sr]	$\bar{J}(\Delta\Omega) \Delta\Omega$ [$\times 10^{22} \text{ GeV}^2 \text{ cm}^{-5} \text{ sr}$]	Flux (1 – 100 GeV) [$\times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$]
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



Energy spectrum as directly
obtained from the data

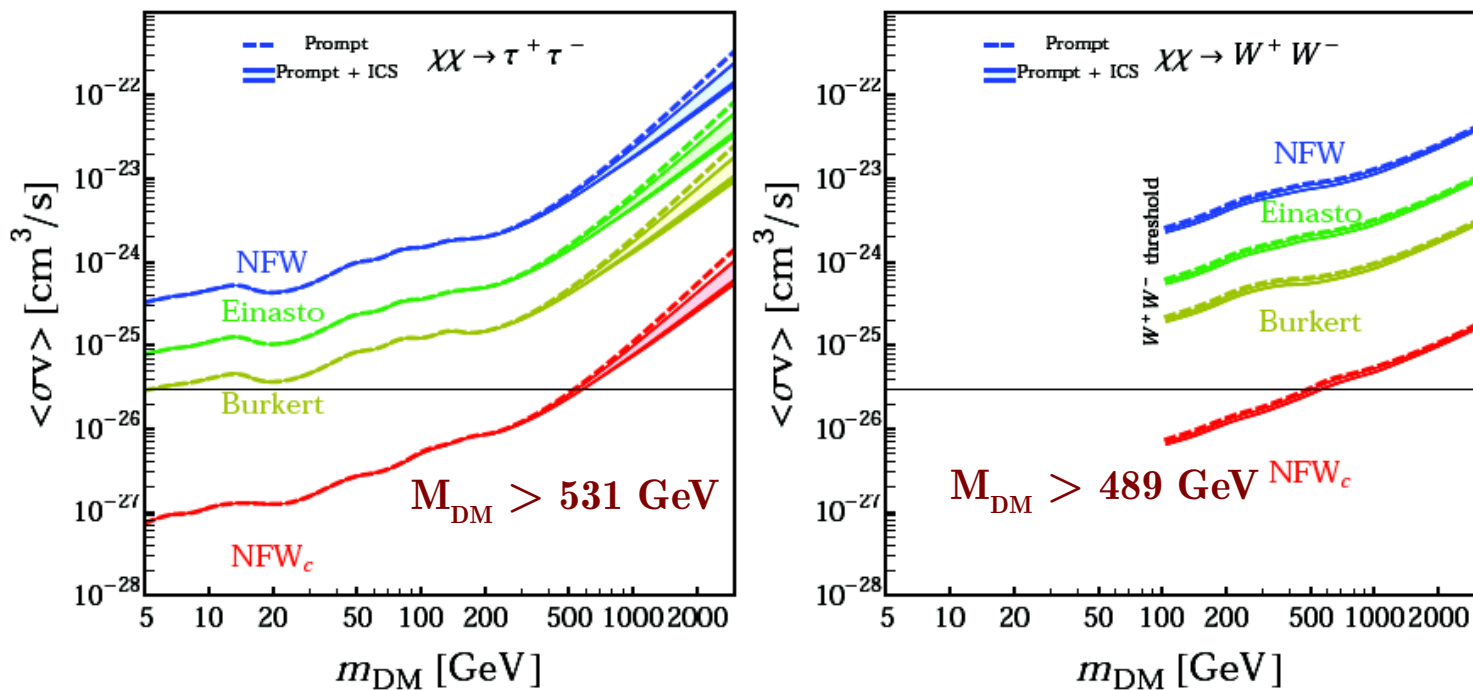
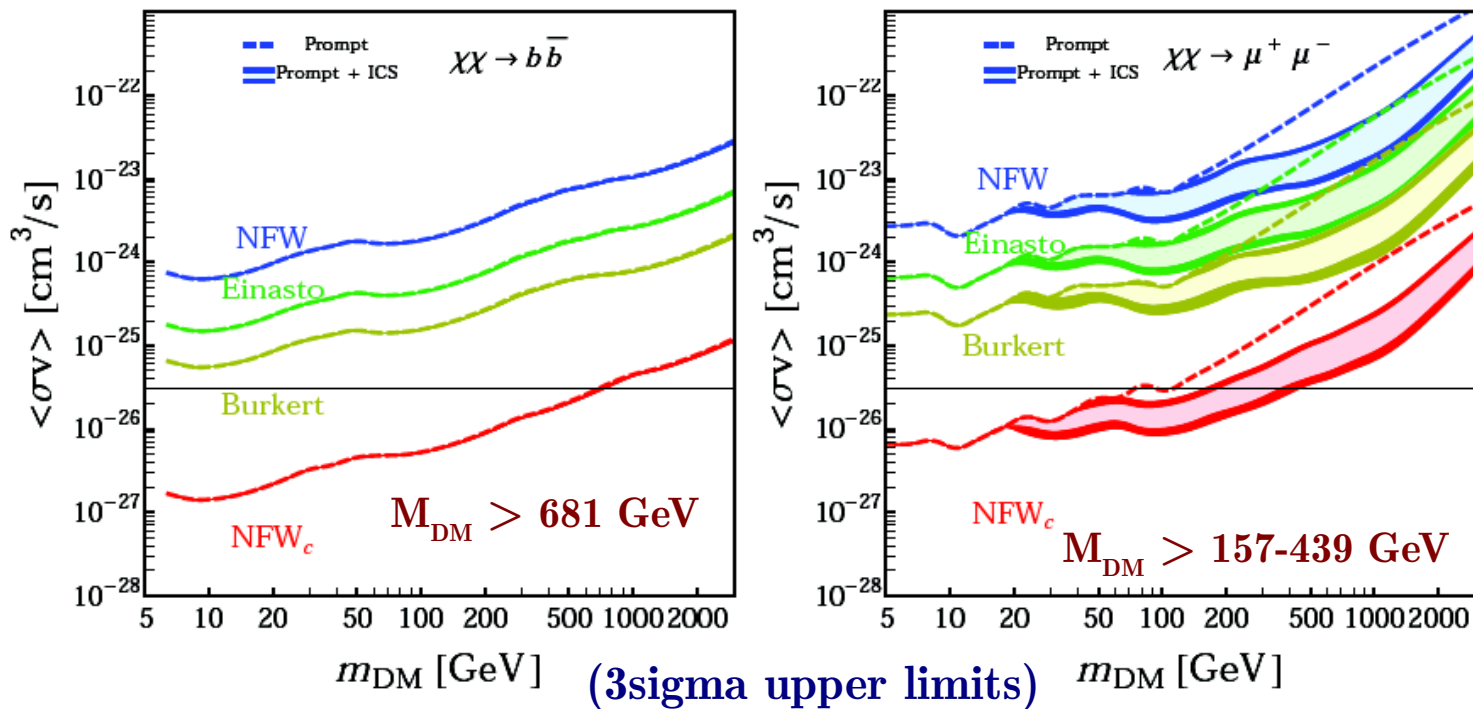
VS.

J-factors

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

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:



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% $b\bar{b}$ - 30% $\tau^+\tau^-$ for a Bino DM, and 100% W^+W^- for a Wino DM.
- Also, the value of $\langle\sigma v\rangle$ in the Galactic halo might be smaller than $3\times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$, e.g., in SUSY, in the early Universe coannihilation channels can also contribute to $\langle\sigma v\rangle$. Also, DM particles whose annihilation in the Early Universe is dominated by velocity dependent contributions would have a smaller value of $\langle\sigma v\rangle$ 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.

CONCLUSIONS

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.

TARGETS FOR DARK MATTER SEARCHES

Inner Galaxy:

Large statistics but diffuse background.

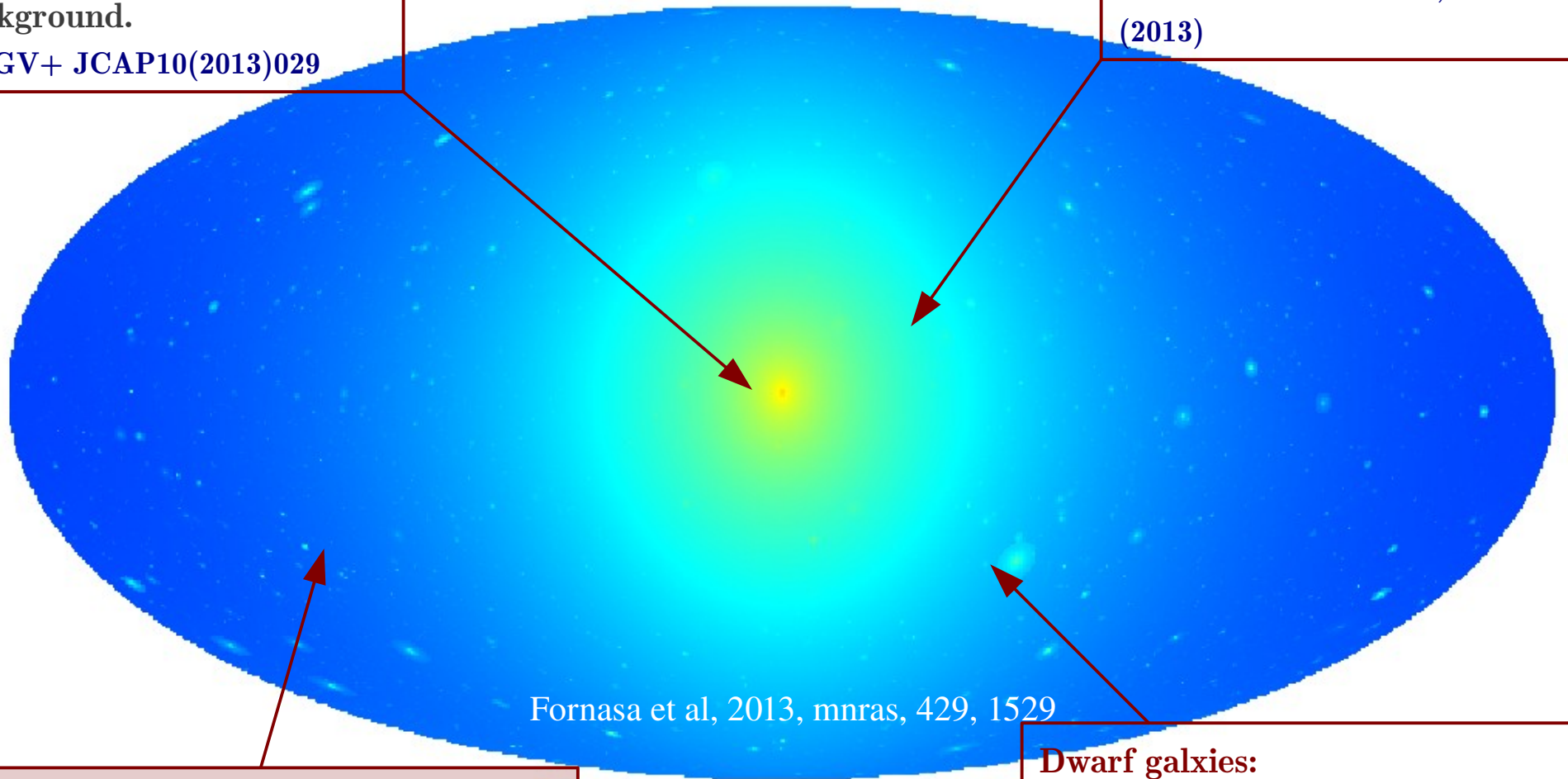
GAGV+ JCAP10(2013)029

Lines:

No astro uncertainties, but low sensitivity

Fermi PRD 86(2012)022002

Fermi+GAGV PRD 88, 082002 (2013)



Fornasa et al, 2013, mnras, 429, 1529

Anisotropies:

Low statistics and low background.

Fermi+GAGV PRD 85(2012)083007

GAGV+ NIMA 2013 in press

Dwarf galaxies:

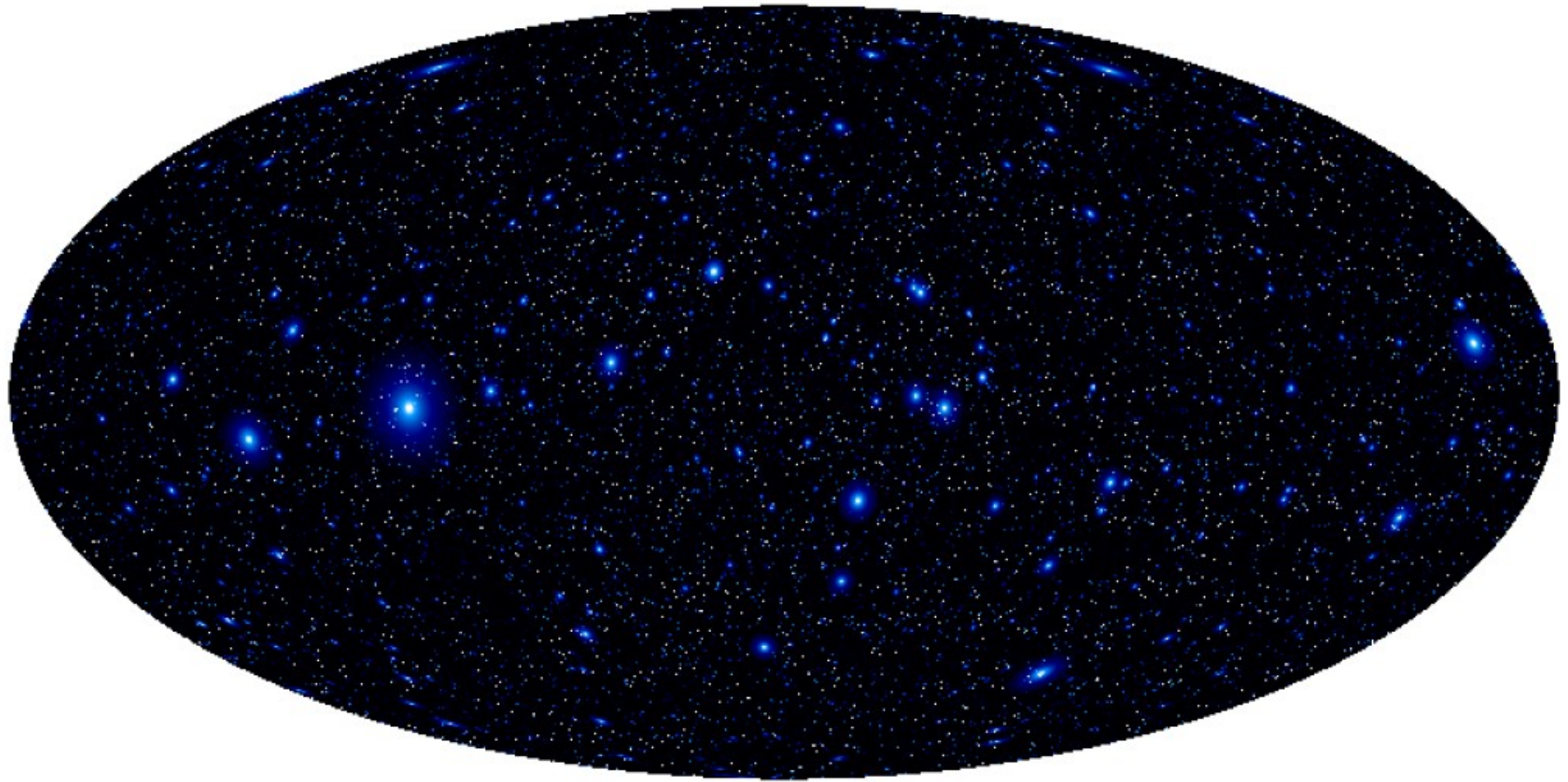
Low background, but low statistics

Fermi-LAT +GAGV arXiv: 1310.0828

Cahill-Rowley+ arXiv:1305.6921

Fermi-LAT+. 2011, PRL 107, 241302

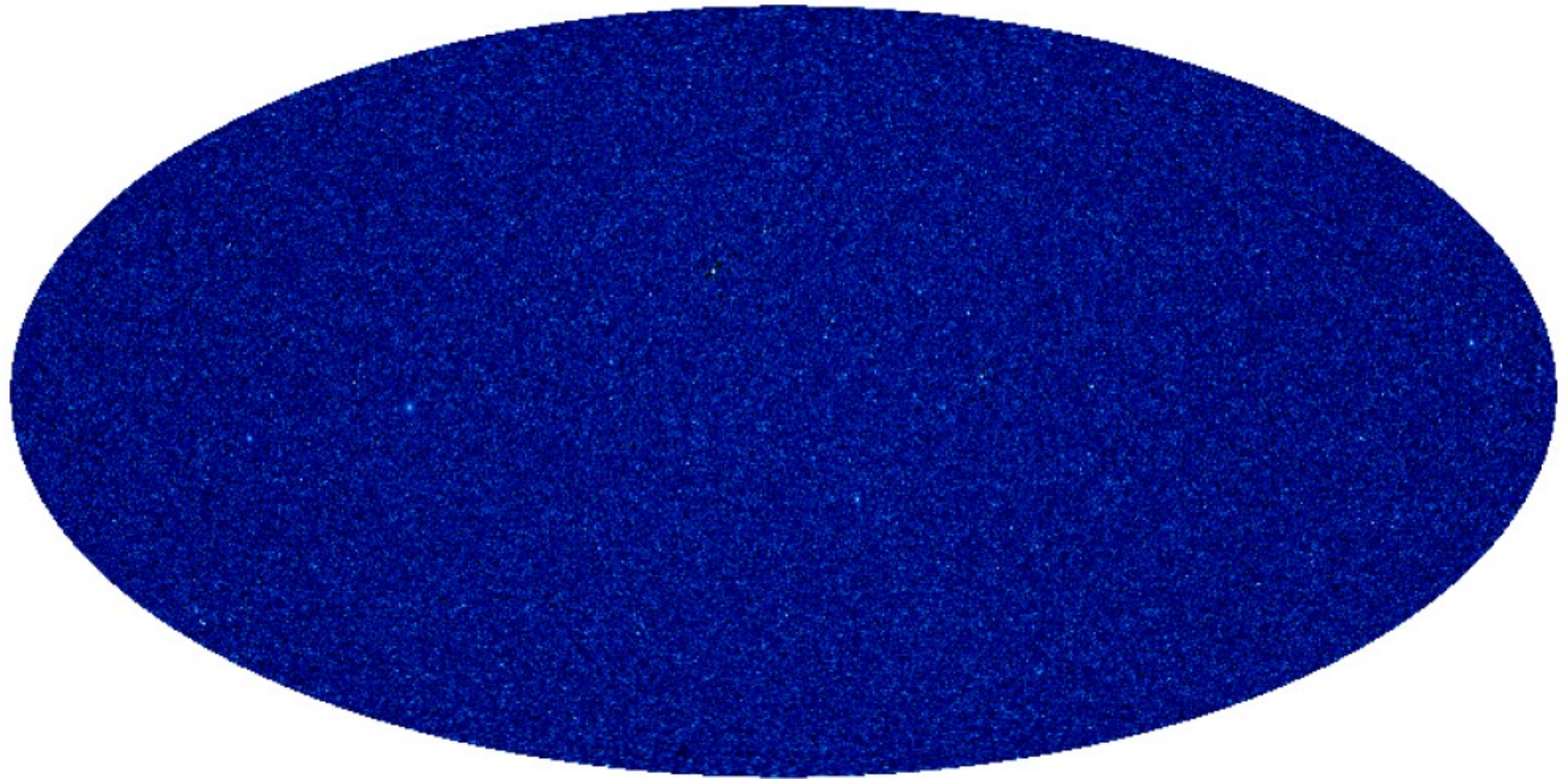
GAMMA-RAY INTENSITY FROM DARK MATTER ANNIHILATION IN GALACTIC SUBSTRUCTURE



-14  -9
 $\text{Log}_{10}(\text{Intensity} / \text{K} [10^{30} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}])$

Siegal-Gaskins
JCAP 0810 (2008) 040

THE SAME GAMMA-RAY MAP, BUT
SMOOTHED WITH A GAUSSIAN BEAM
OF $\sigma=0.1^\circ$



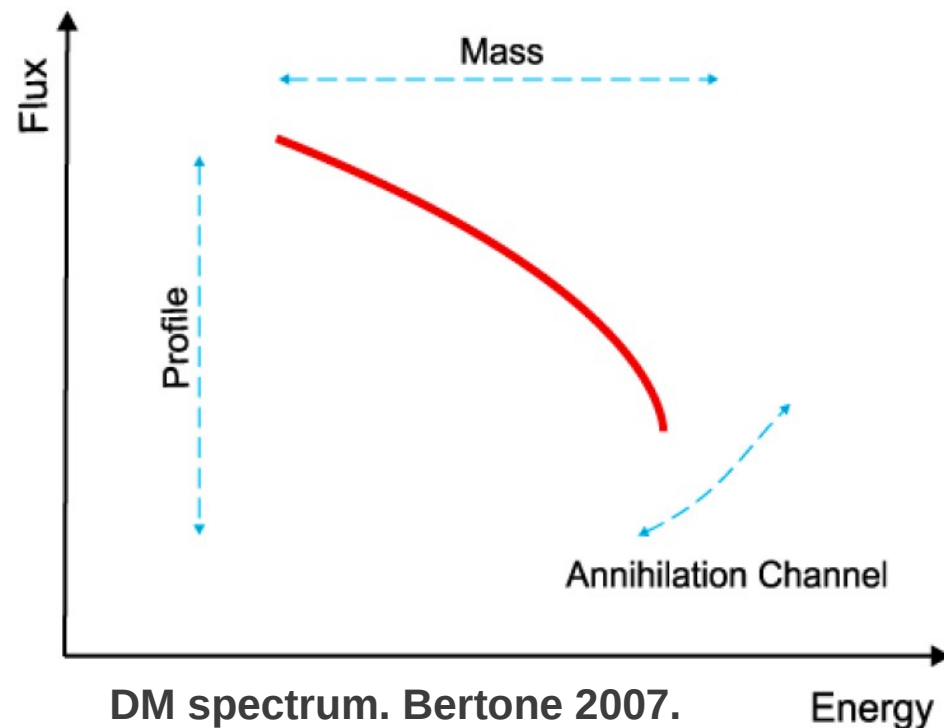
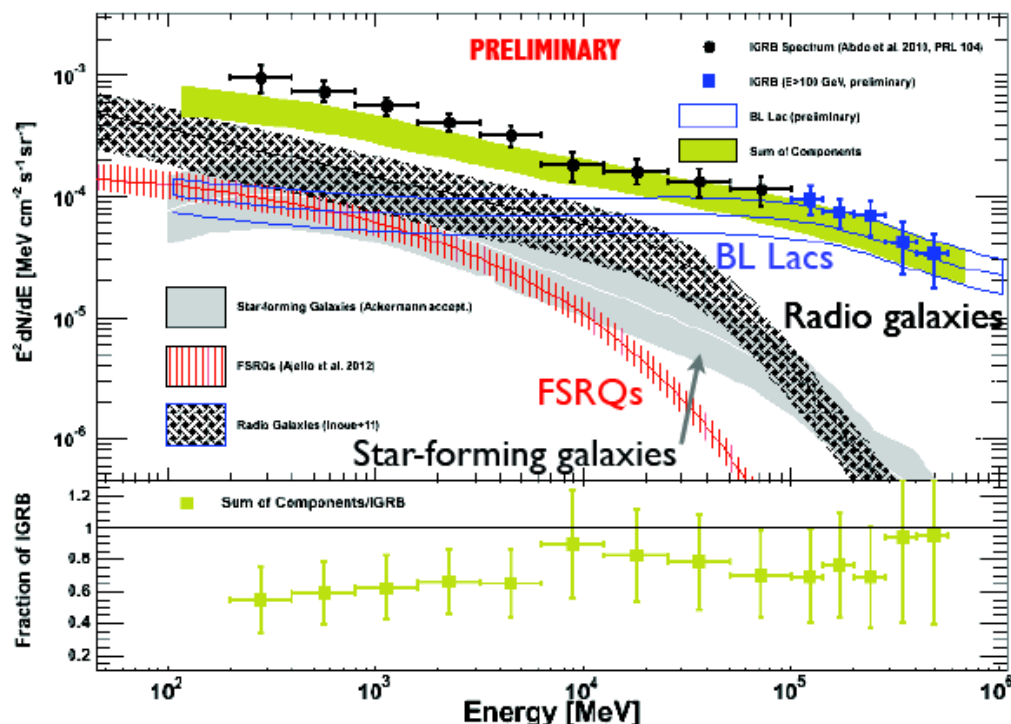
-12  -7
 $\text{Log}_{10}(\text{Intensity} / \text{K} [10^{30} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}])$

Siegal-Gaskins
JCAP 0810 (2008) 040

HOW TO SEEK FOR THOSE SIGNALS IN THE FERMI SKY?

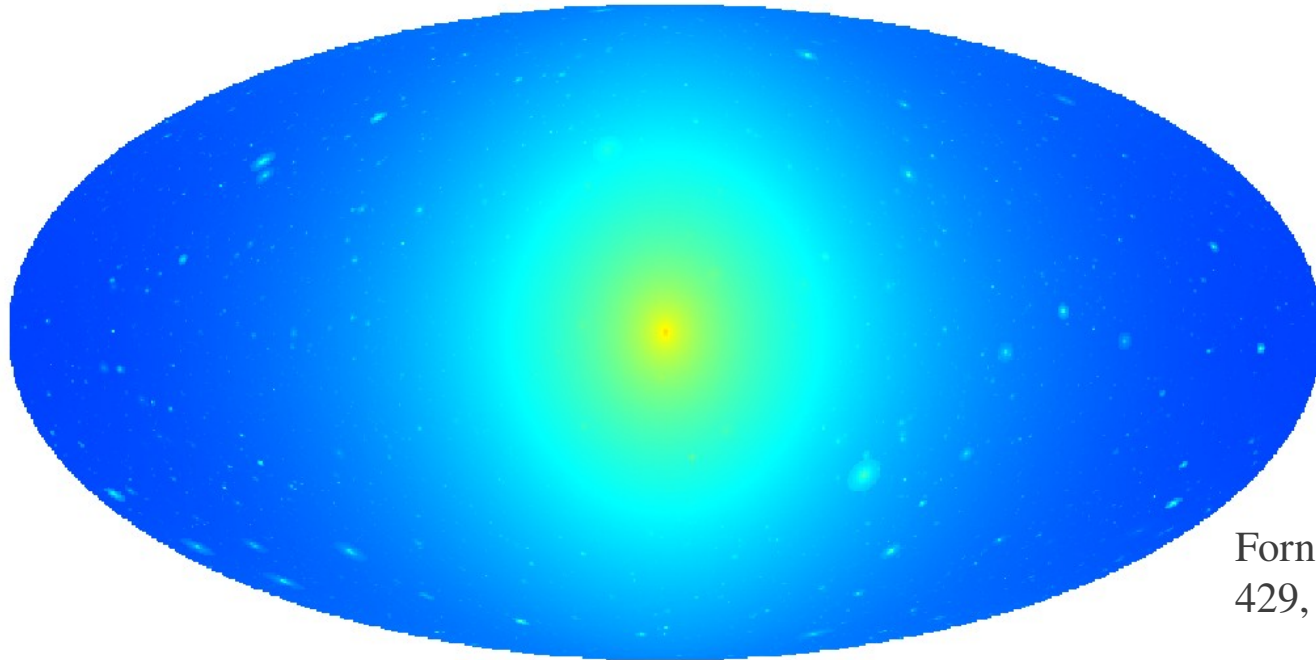
- That kind of **DM signal** will **contribute** to the so-called Isotropic Gamma-ray Background (**IGRB**).
- It is a **fainter component** of the **diffuse** emission **observed** by the Fermi-LAT.
- The **IGRB** is **considered** to have an **isotropic** or nearly isotropic distribution on the sky
- We can use **spectral** and/or **spatial** information to **disentangle** a possible DM **signal** in the **IGRB** from other contributors

SPECTRAL INFORMATION



- The IGRB spectrum is featureless and may have contributions from population sources of various kinds, including blazars, pulsars, and possible DM structures
- DM annihilate into Standard Model particles, the energy spectrum of this process strongly depends on the SM particles products, the density profile, and the DM mass. Since we don't know any of these properties disentangling a DM signal using only spectral information is a difficult task.

SPATIAL INFORMATION



Fornasa et al, 2013, mnras,
429, 1529

- diffuse emission that originates from one or more unresolved source populations will contain fluctuations on small angular scales due to variations in the number density of sources in different sky directions.
- the amplitude and energy dependence of the anisotropy can reveal the presence of multiple source populations and constrain their properties

ANGULAR POWER SPECTRUM (APS)

- We consider the APS as a metric for anisotropy.
- We decompose an intensity map $I(\Psi)$, with Ψ the sky direction, in spherical harmonics:

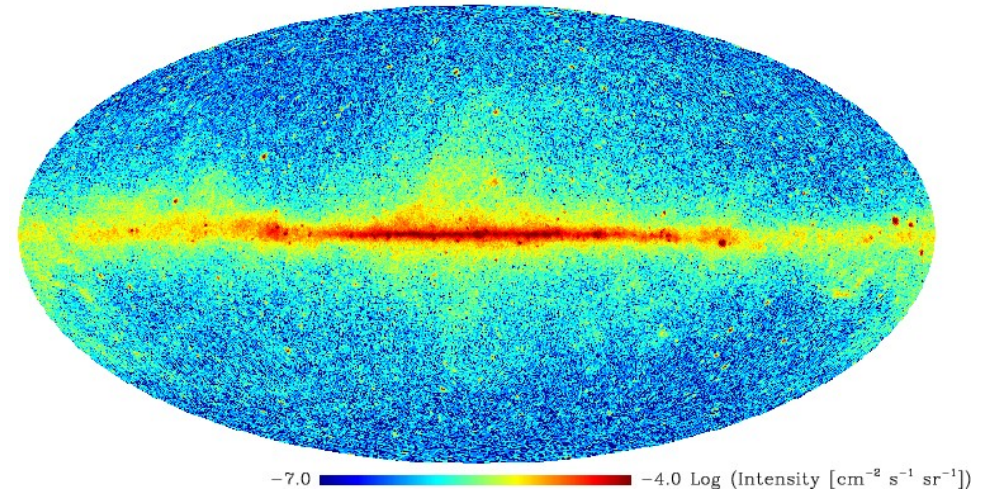
$$I(\Psi) = \sum_{lm} a_{lm} Y_{lm}(\Psi).$$

- The APS is given by the coefficients:

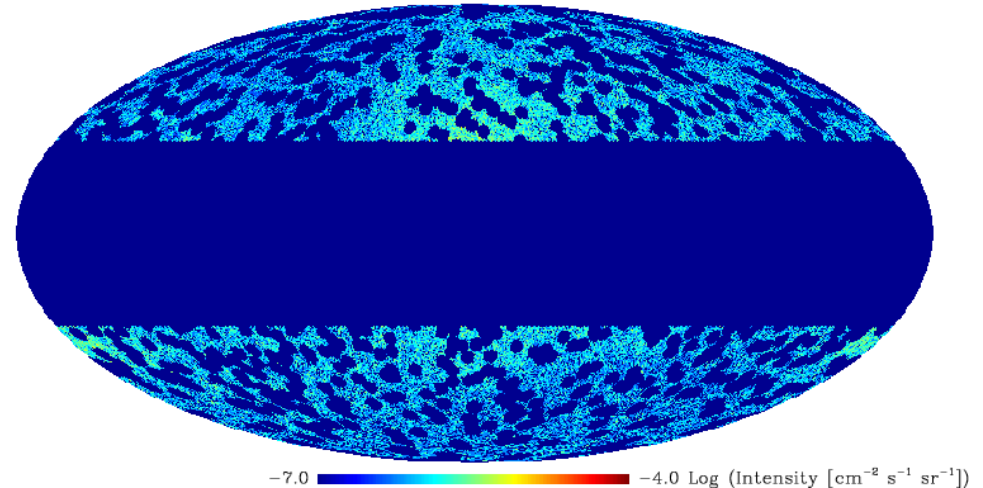
$$C_l = \langle |a_{lm}|^2 \rangle$$

- The intensity APS indicates the dimensionful size of intensity fluctuations and can be compared with predictions for source classes whose collective intensity is known or assumed

DATA (P6_V3 diffuse), 2.0–5.0 GeV



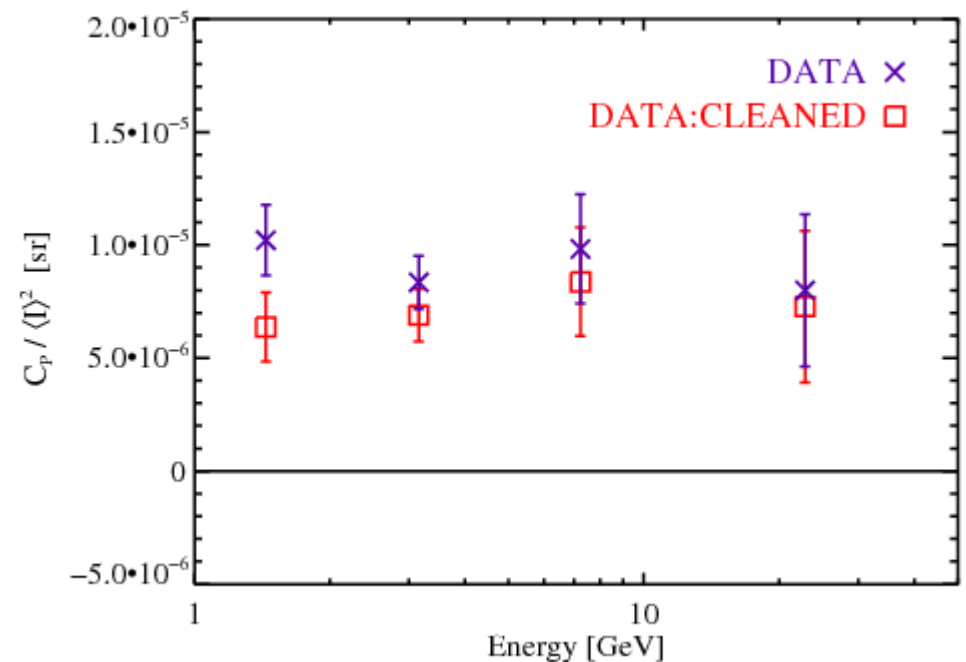
DATA (P6_V3 diffuse), 2.0–5.0 GeV



FERMI LAT MEASUREMENT OF APS

- **Data** from the first **22 months**
- **4 energy bins** (from 1 GeV to 50 GeV).
- **Masking** is applied covering point sources (**1 year Fermi catalog**) and the galactic plane ($|b| < 30$ deg).
- Galactic **diffuse contribution** to the high latitude emission is minimized by **subtracting** the Fermi-LAT recommended **model** of the Galactic foregrounds from the data, and then **calculating the APS of the residual map** -> **DATA:CLEANED**.

Angular power is detected with a significance up to 7σ .



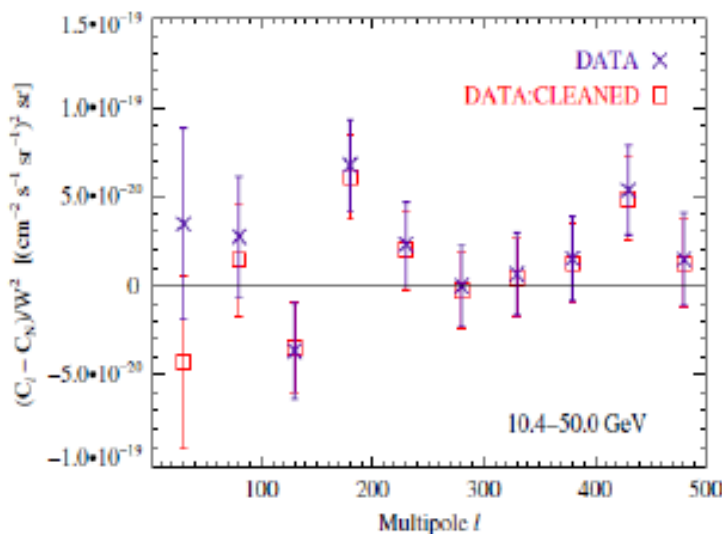
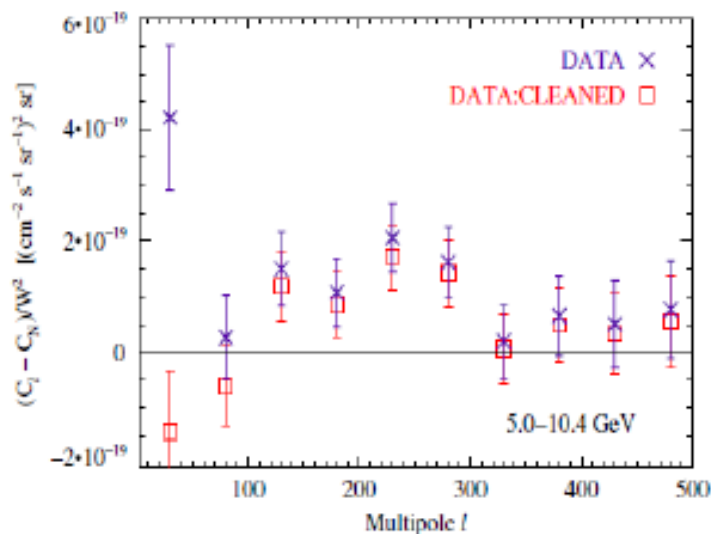
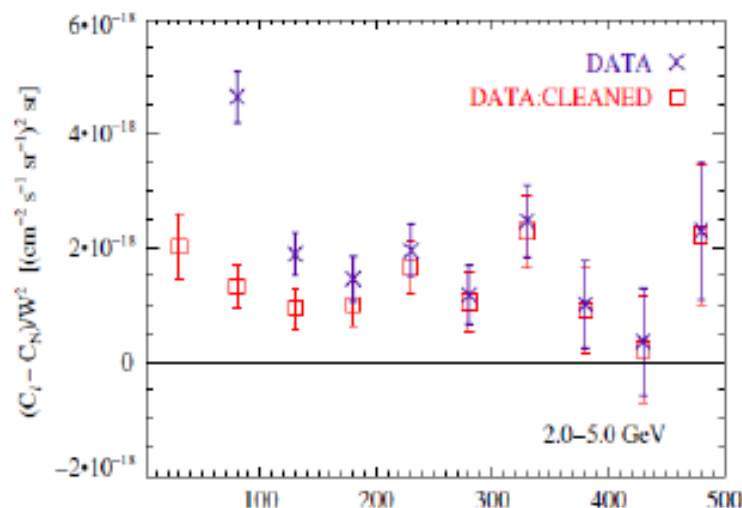
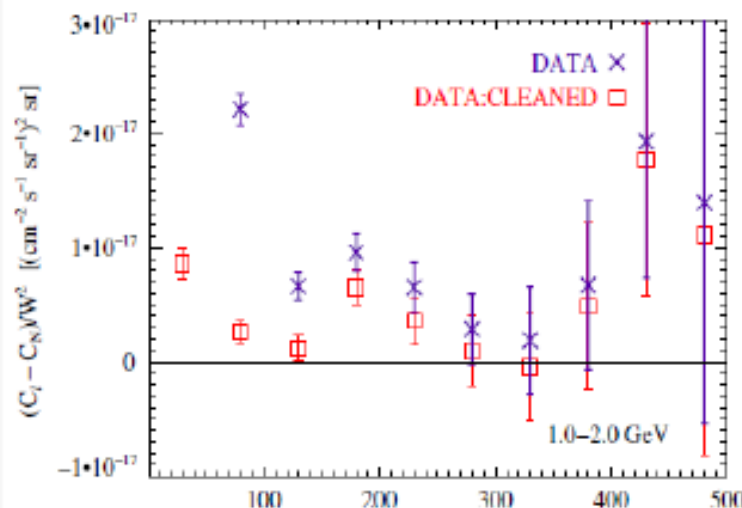
FERMI LAT MEASUREMENT OF APS

$E_{\min}$ [GeV]	$E_{\max}$ [GeV]	C_p $[(\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1})^2 \text{sr}]$
1.04	1.99	$4.62 \pm 1.11 \times 10^{-18}$
1.99	5.00	$1.30 \pm 0.22 \times 10^{-18}$
5.00	10.4	$8.45 \pm 2.46 \times 10^{-20}$
10.4	50.0	$2.11 \pm 0.86 \times 10^{-20}$

Best-fit to constant values over the multipole range $155 < l < 504$.
DATA-CLEANED

At low multipoles and higher energies the Galactic foreground contribution is important, as we expected.

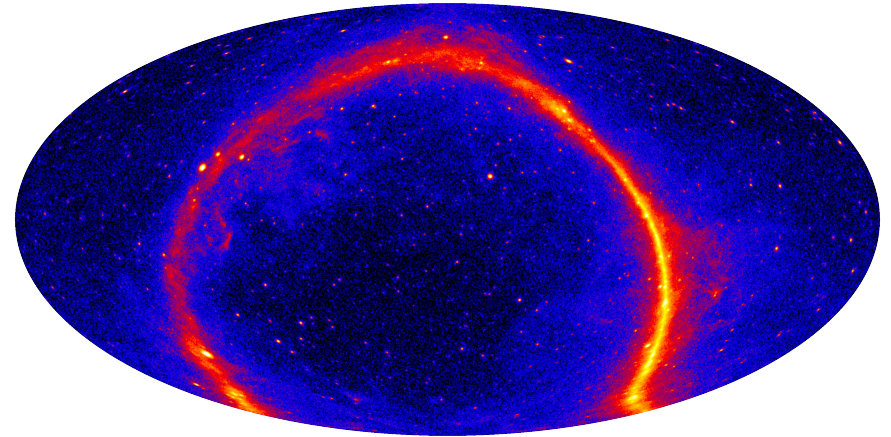
We use l larger than 155 and data-cleaned measurement to avoid it.



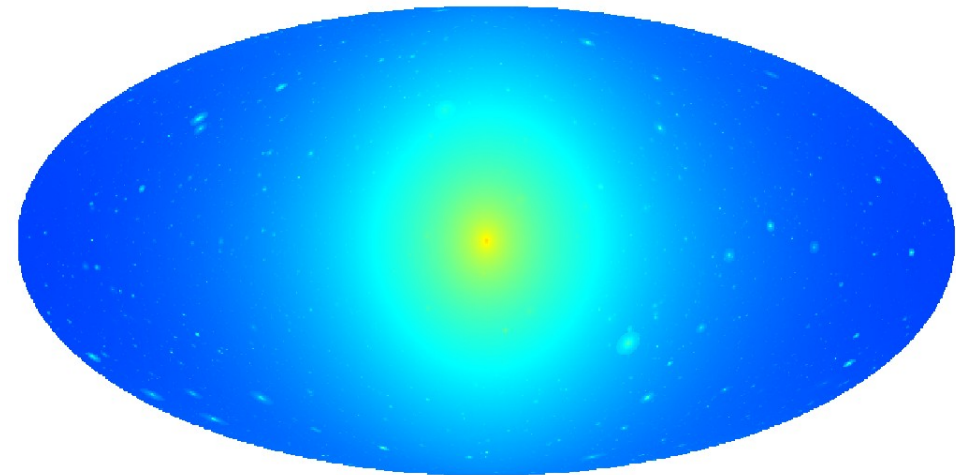
A JOINT PROJECT BETWEEN FERMI-LAT AND MULTIDARK

- Utilize high resolution numerical simulation of the Galactic and extragalactic DM distribution (Aquarius and Millenium II)
- Predict the DM anisotropy signal from annihilation and decay, accurately accounting for redshifting and extragalactic background light attenuation for extragalactic DM, and secondary emission from Galactic DM
- Extend and improve the Fermi LAT anisotropy measurement.
- Compare the predicted Angular Power Spectrum (APS) to the measurement to place constraints on DM nature.

Fermi-LAT Data



Dark Matter map from
Fornasa et al, 2013, mnras, 429, 1529

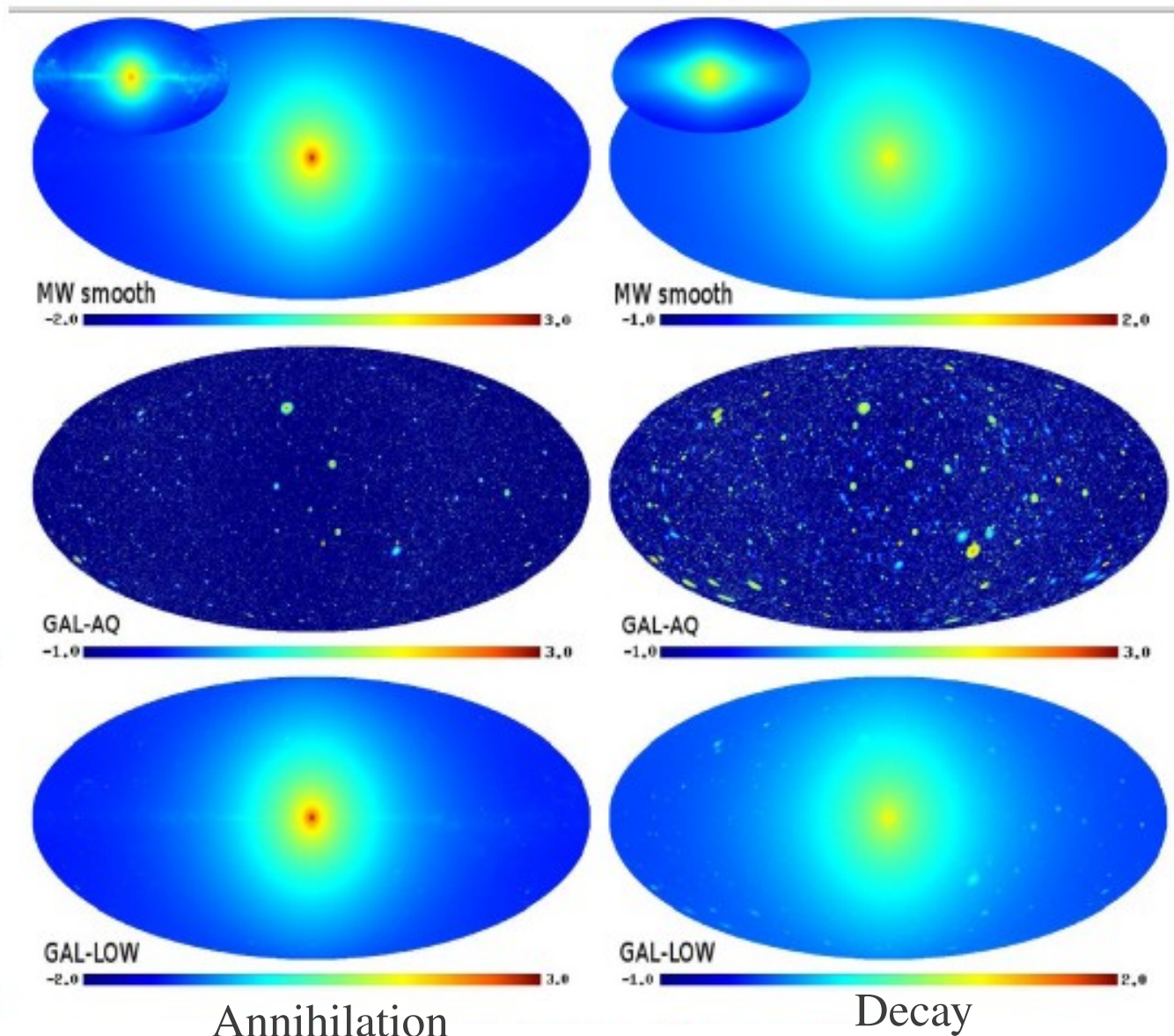


DARK MATTER MW MODEL

All-sky DM maps of the galactic gamma-ray emission at 4 GeV for DM annihilation (left) and decay (right).

First row: smooth halo is modeled as an Einasto profile based on Aquarius results (Springel et al. 2008; Navarro et al. 2008), renormalized to the local DM density.

Contribution from 3 mechanisms of emission: Prompt, ICS on both, CMB and ISRF, and hadronic.



DARK MATTER EXTRAGALACTIC

- **Resolved (sub)halos:**
- MS-II catalogs of halos and subhalos above the mass resolution of the simulations.
- 32 snapshots at different redshifts
- Each halo is considered with its own profile.

Subhalos of resolved and unresolved main halos

- They boost the luminosity of their hosts affecting the intensity and angular anisotropy spectra

the fraction of the host halo volume that is filled with substructures can be fitted with:

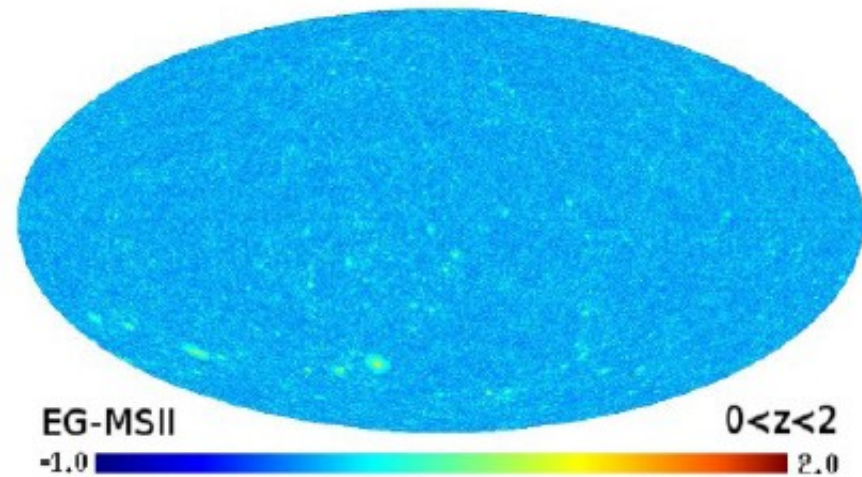
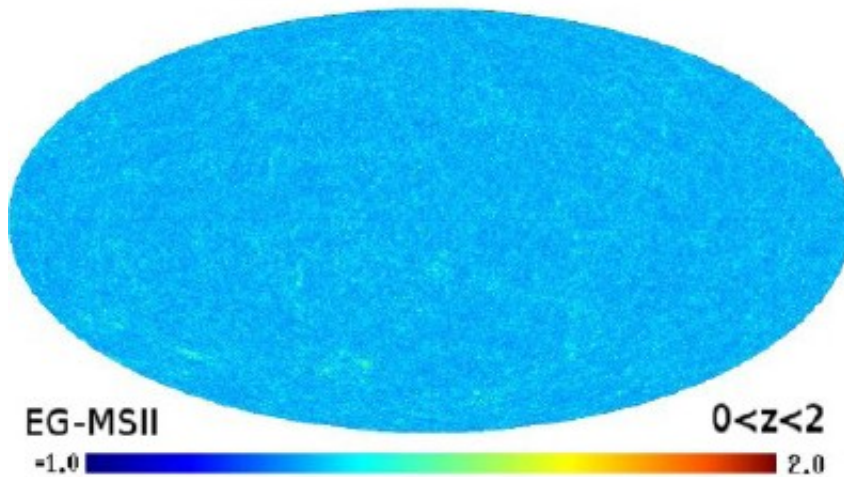
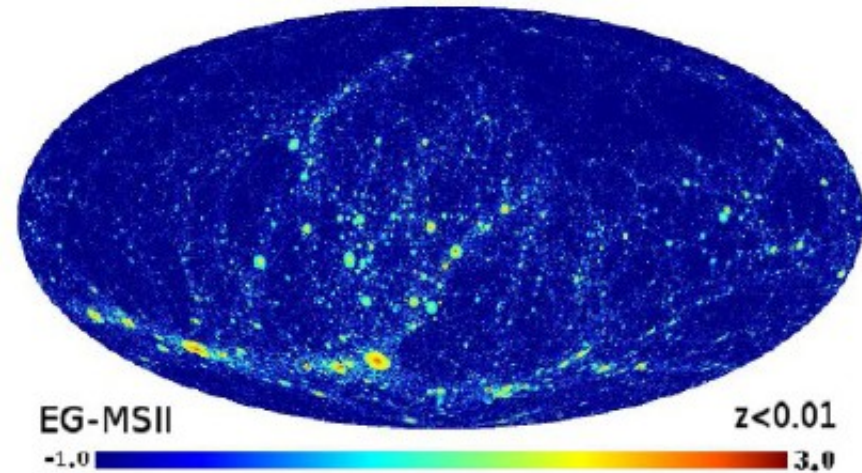
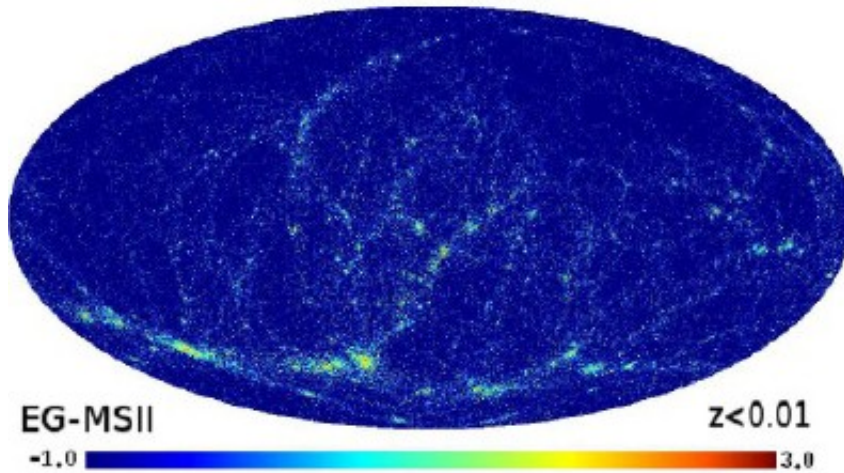
$$1 - f_s(r) = k \left(\frac{\rho_{smooth}(r)}{\rho_{smooth}(3.5 \text{ kpc} \times r_s)} \right)$$

- K controls the abundance of substructures
- $k=7e-3$ LOW scenario
- $K=0.15$ HIGH scenario

DARK MATTER EXTRAGALACTIC

Annihilation

Decay

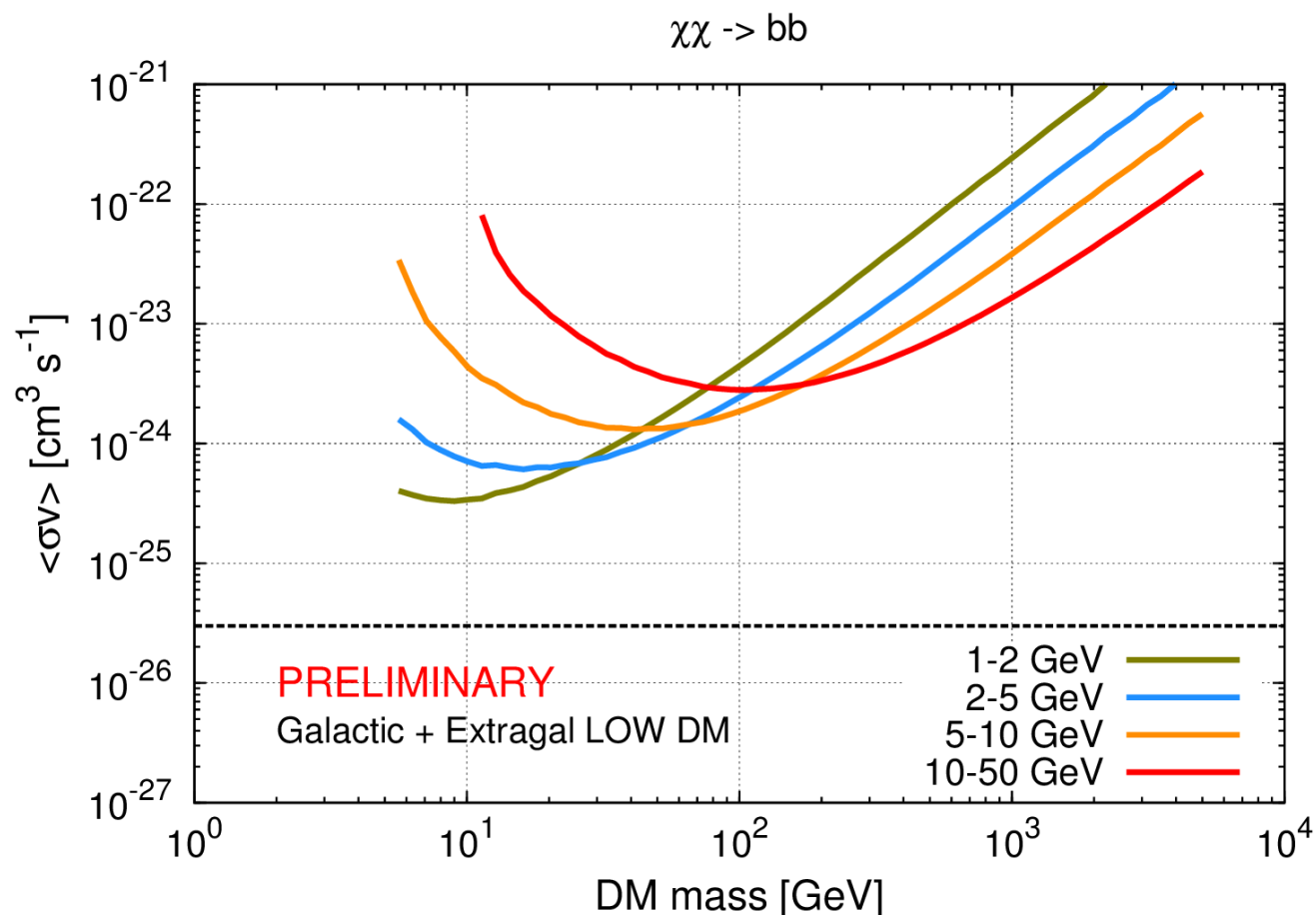


Dark Matter maps from
Fornasa et al, 2013, mnras, 429, 1529

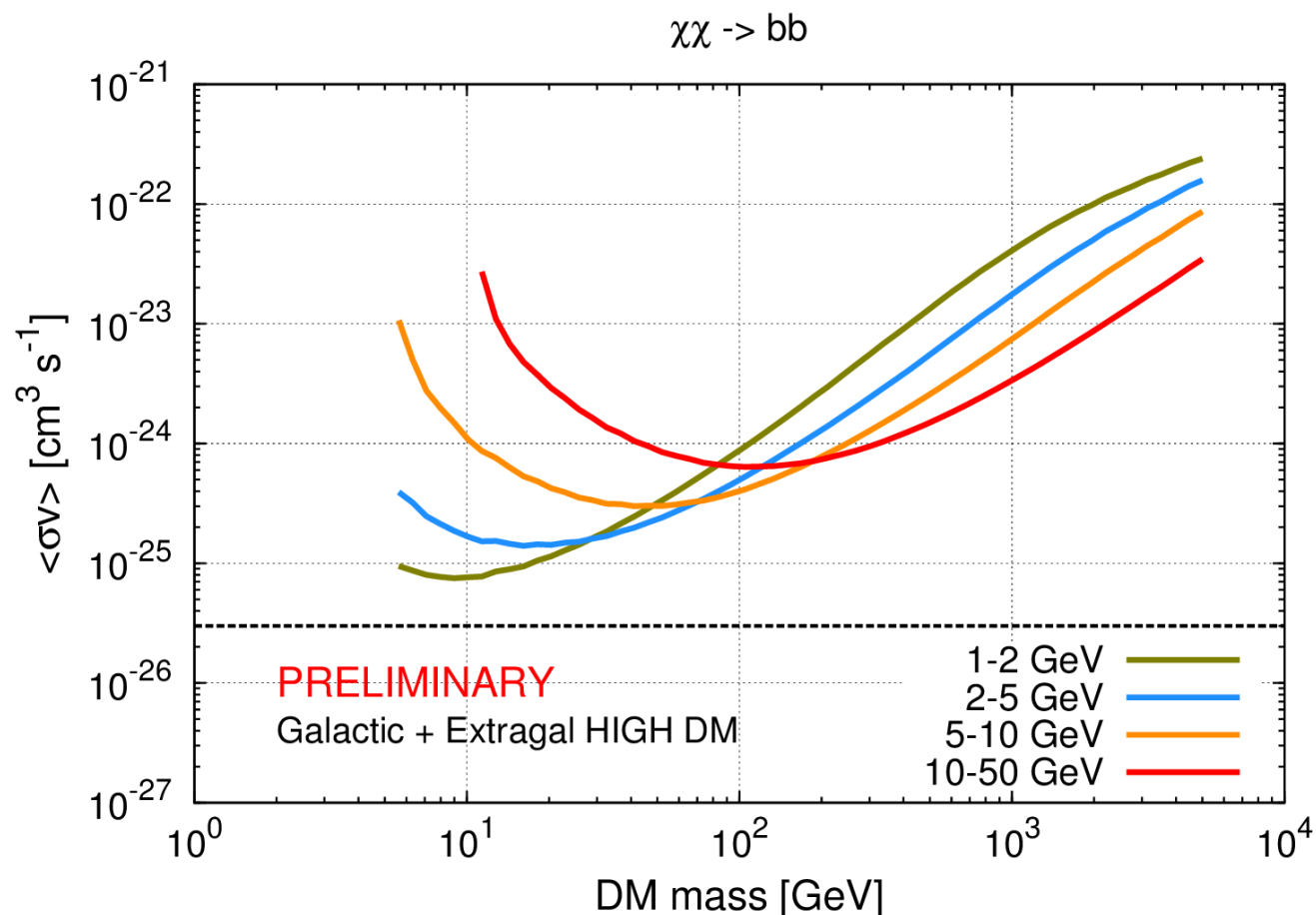
SETTING CONSTRAINTS

- To set constraints we use the foreground-cleaned C_p shown in table II of [Ackermann et al. 2012].
- There are four C_p values measured corresponding to four energy bins, 1-2 GeV, 2-5 GeV, 5-10 GeV, and 10-50 GeV. We use them independently to set limits.
- Requiring that the DM-induced intensity APS averaged in $155 < l < 204$ does not overshoot the measured C_p in the $155 < l < 504$ multipole range plus $1.64 \times$ error leads to 95% CL limits on $\langle \sigma v \rangle$.
- We know that the IGRB anisotropy has multiple contributors, therefore these constraints are conservative.
- Other contributors to IGRB anisotropy are not well known, but we already have constraints on the contribution of blazars [Cuoco et al. 2012]. We subtract this contribution from the measured C_p and require that the DM-induced APS does not overshoot this new limit.

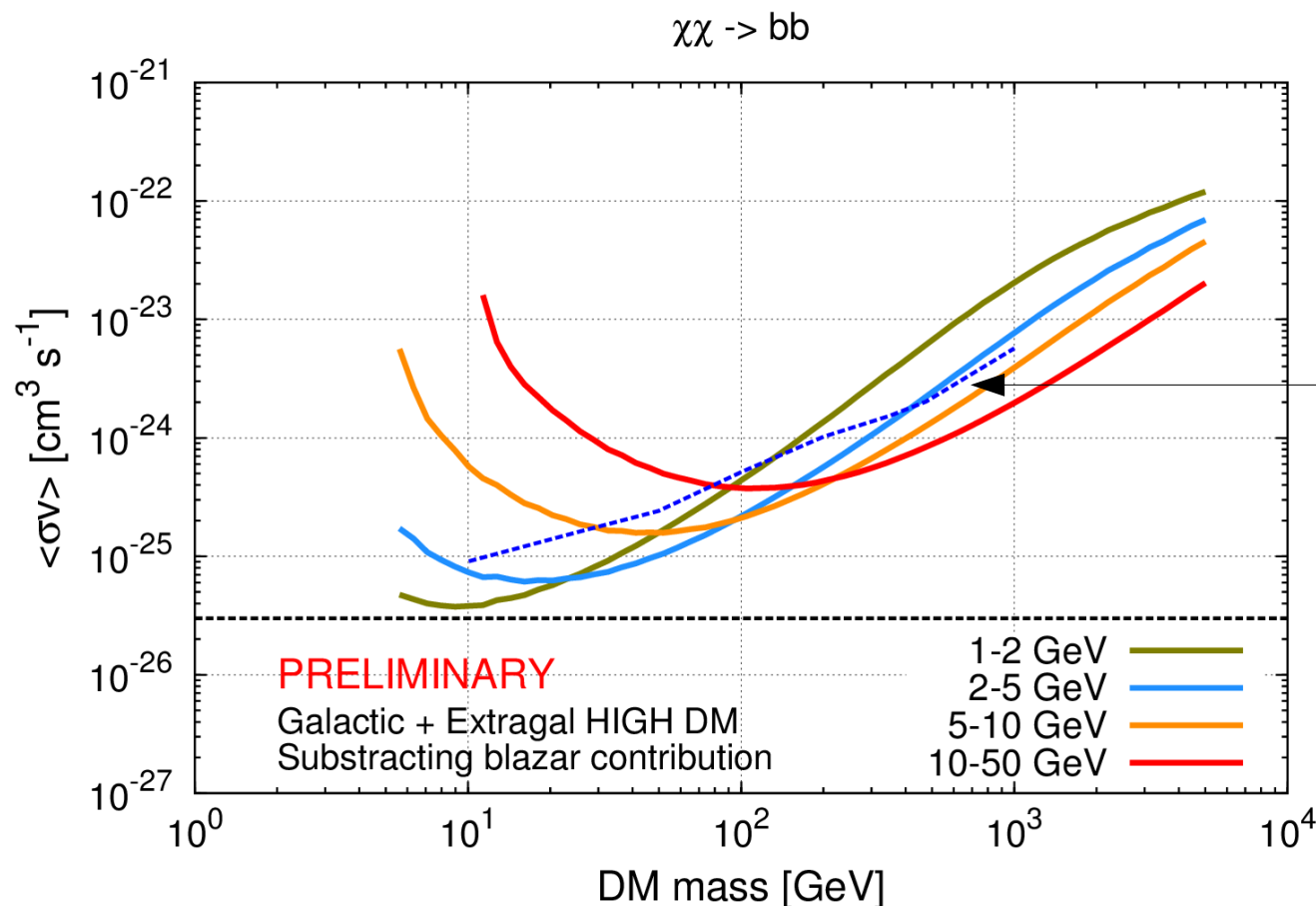
Annihilation into **b quarks**. Galactic structure and extragalactic halos are relatively poor in subhalos



Annihilation into **b quarks**. Galactic structure and extragalactic halos with large subhalo boost

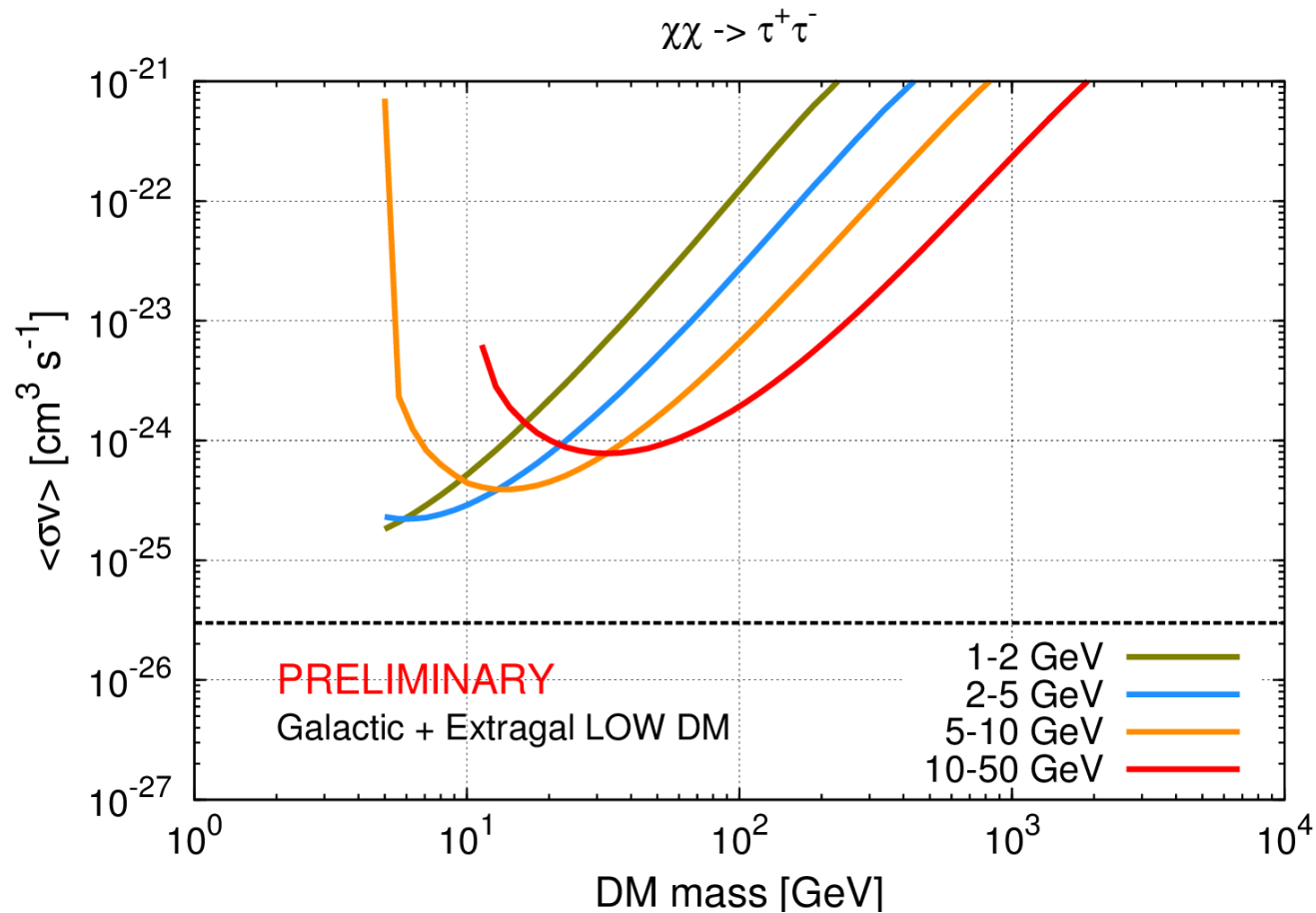


Annihilation into **b quarks**. Galactic structure and extragalactic halos with subhalo boost, and subtracting blazar contribution

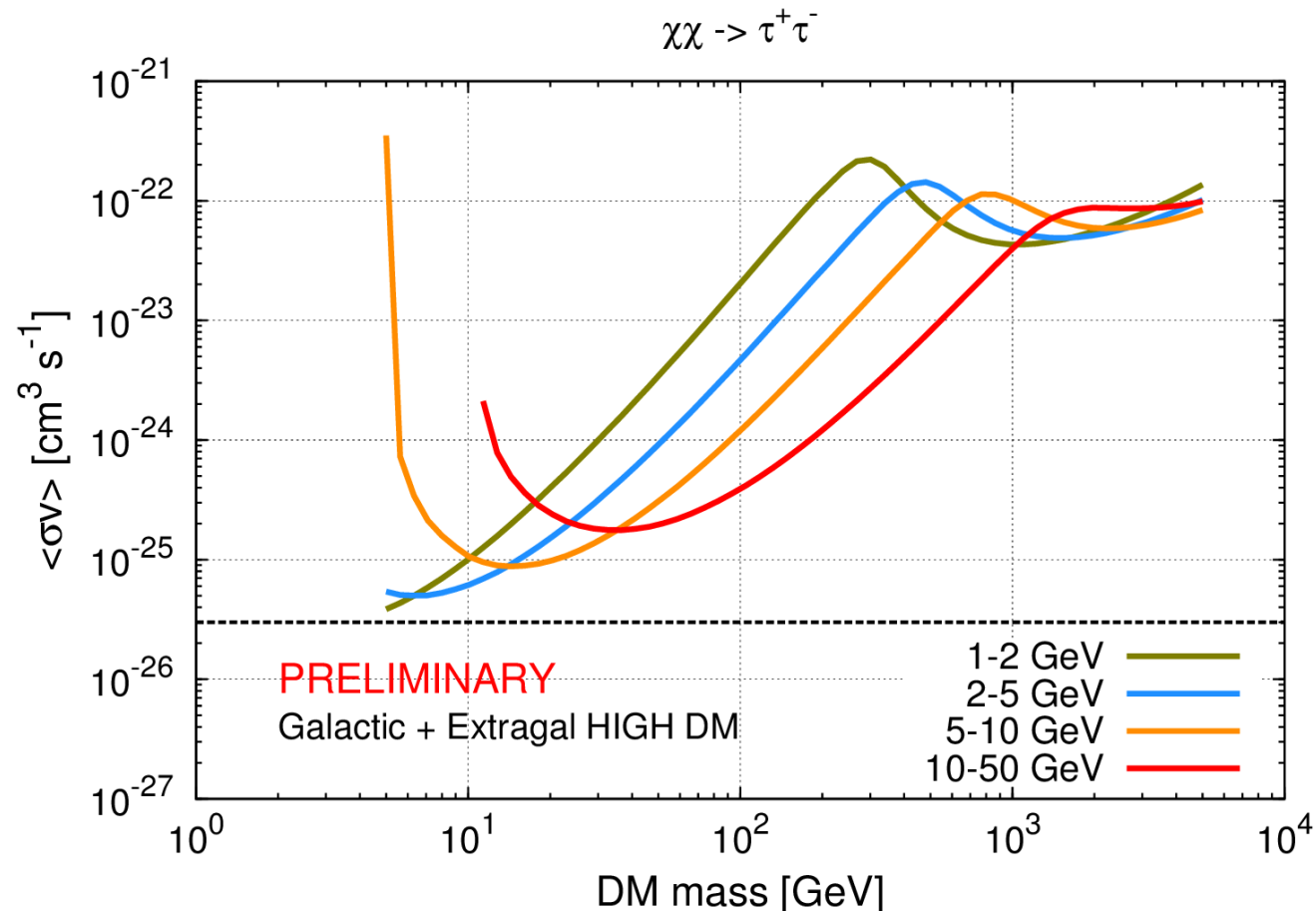


Ando & Komatsu
Phys. Rev. D 87,
123539 (2013)

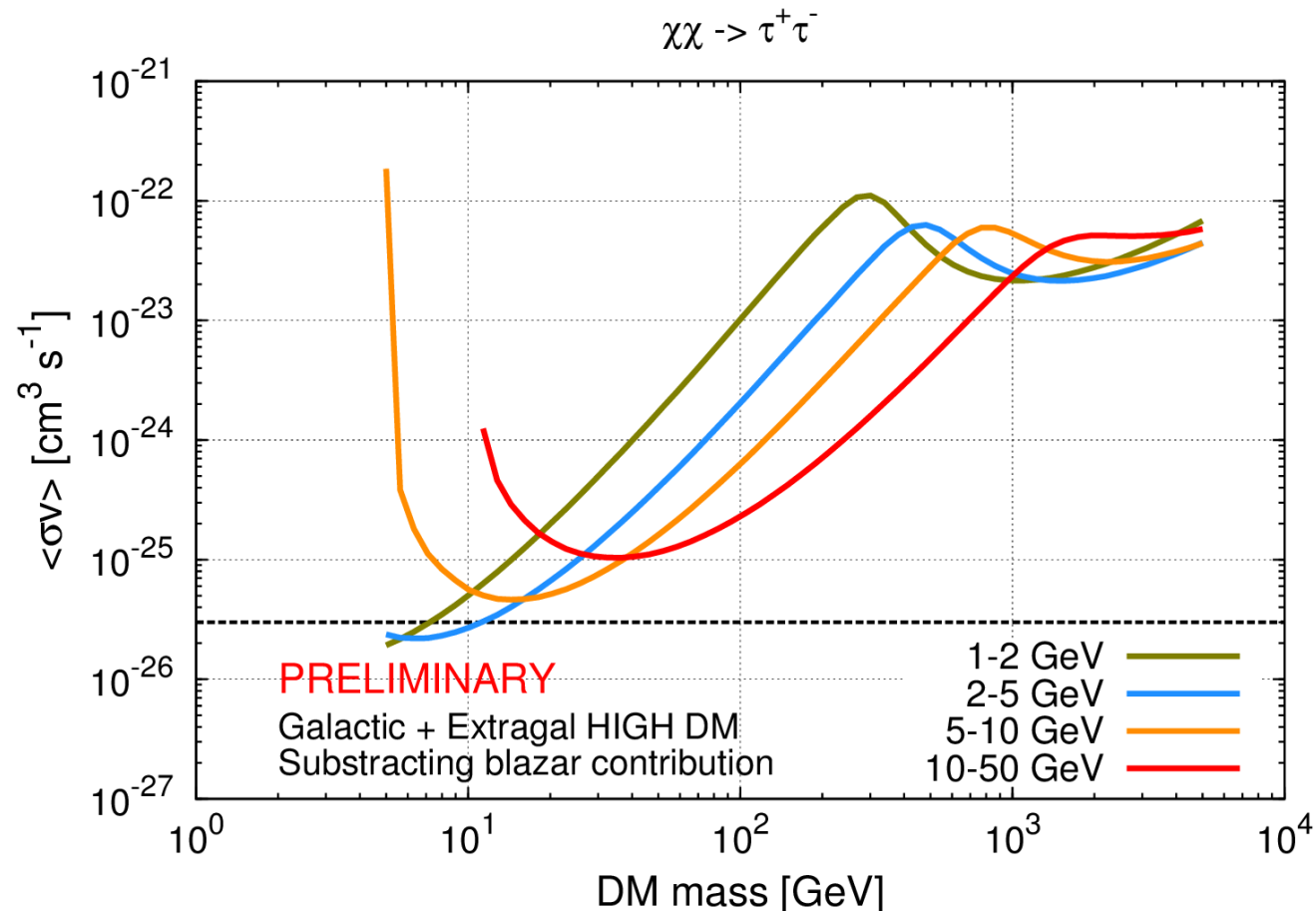
Annihilation into **tau leptons**. Galactic structure and extragalactic halos are relatively poor in subhalos



Annihilation into tau leptons. Galactic structure and extragalactic halos with large subhalo boost



Annihilation into τ leptons. Galactic structure and extragalactic halos with subhalo boost, and subtracting blazar contribution



SUMMARY AND OUTLOOK

- 95% CL limits on $\langle\sigma v\rangle$ for two different annihilation channels are derived using a measurement of anisotropies in the IGRB.
- The main uncertainty in the predictions obtained in [Fornasa et al. 2013] lies in the properties of low-mass subhalos, below the mass resolution of the simulations.
- Different values of the "subhalo boost" strongly affect the prediction for the DM-induced gamma-ray intensity and its anisotropies.
- The most stringent constraints on $\langle\sigma v\rangle$ are obtained when predictions for the DM-induced APS (with a HIGH subhalo boost) are compared with the APS measured by Fermi-LAT once the contribution from blazars is subtracted.
- We are currently updating the Fermi-LAT APS measurement using 45 months of data, we expect to improve the constraints presented.

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.

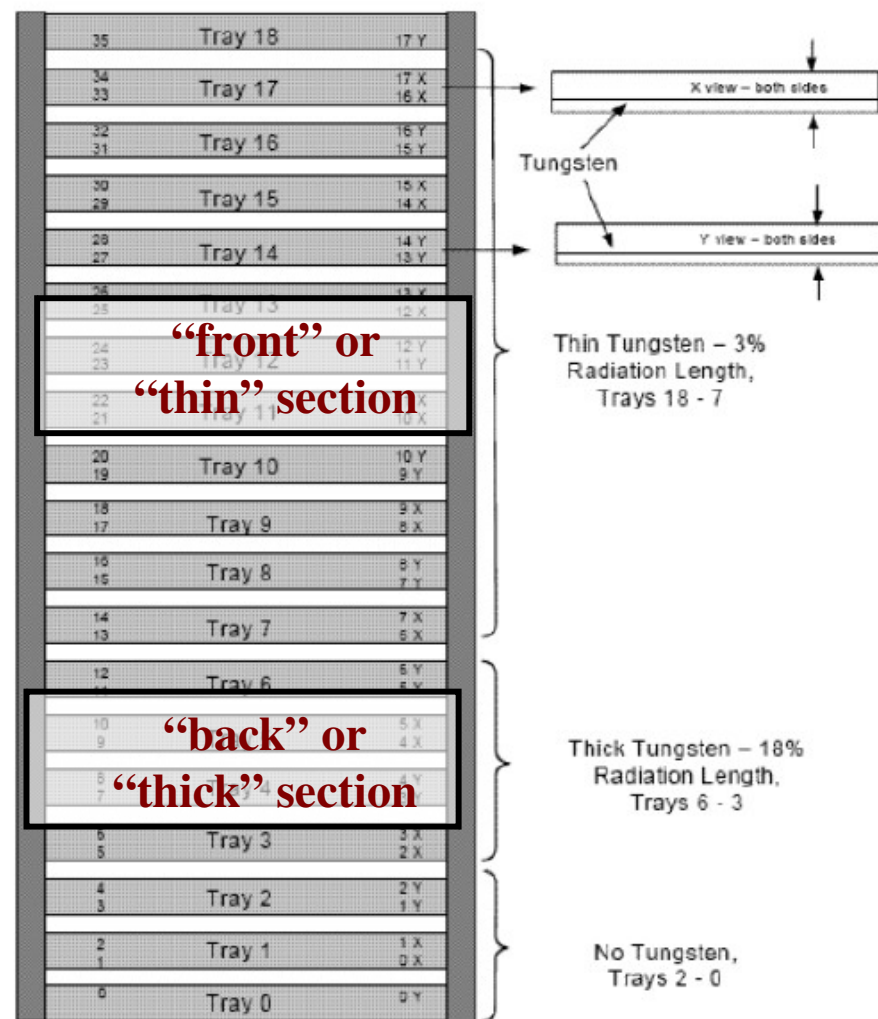
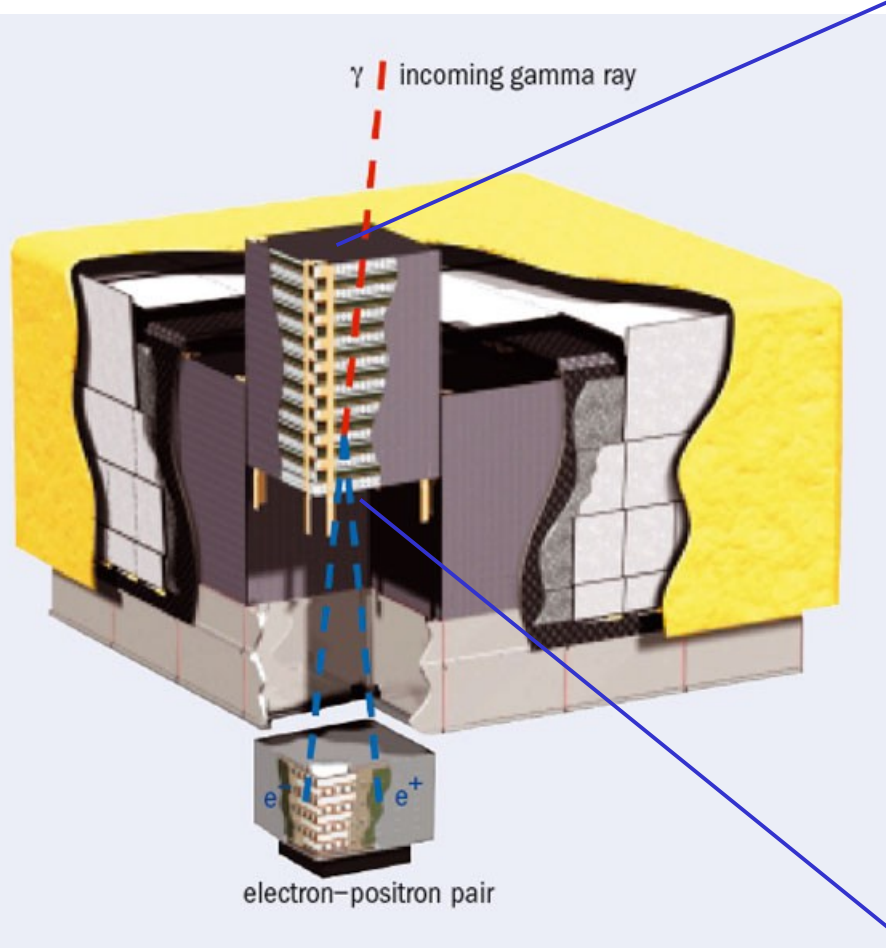
OUTLOOK

- 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 infrared 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

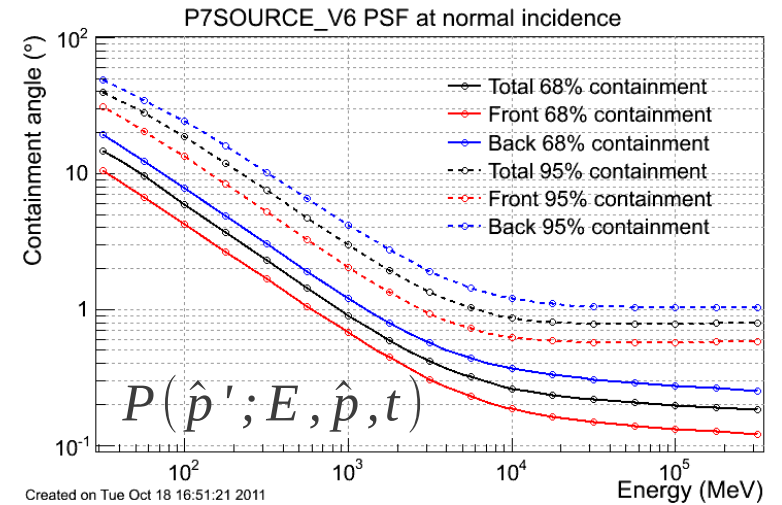
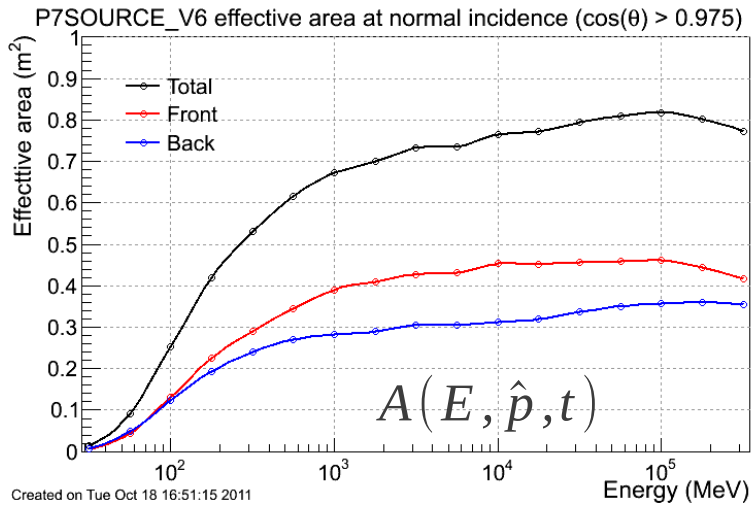


FROM FLUX TO COUNTS

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

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

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



- 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

