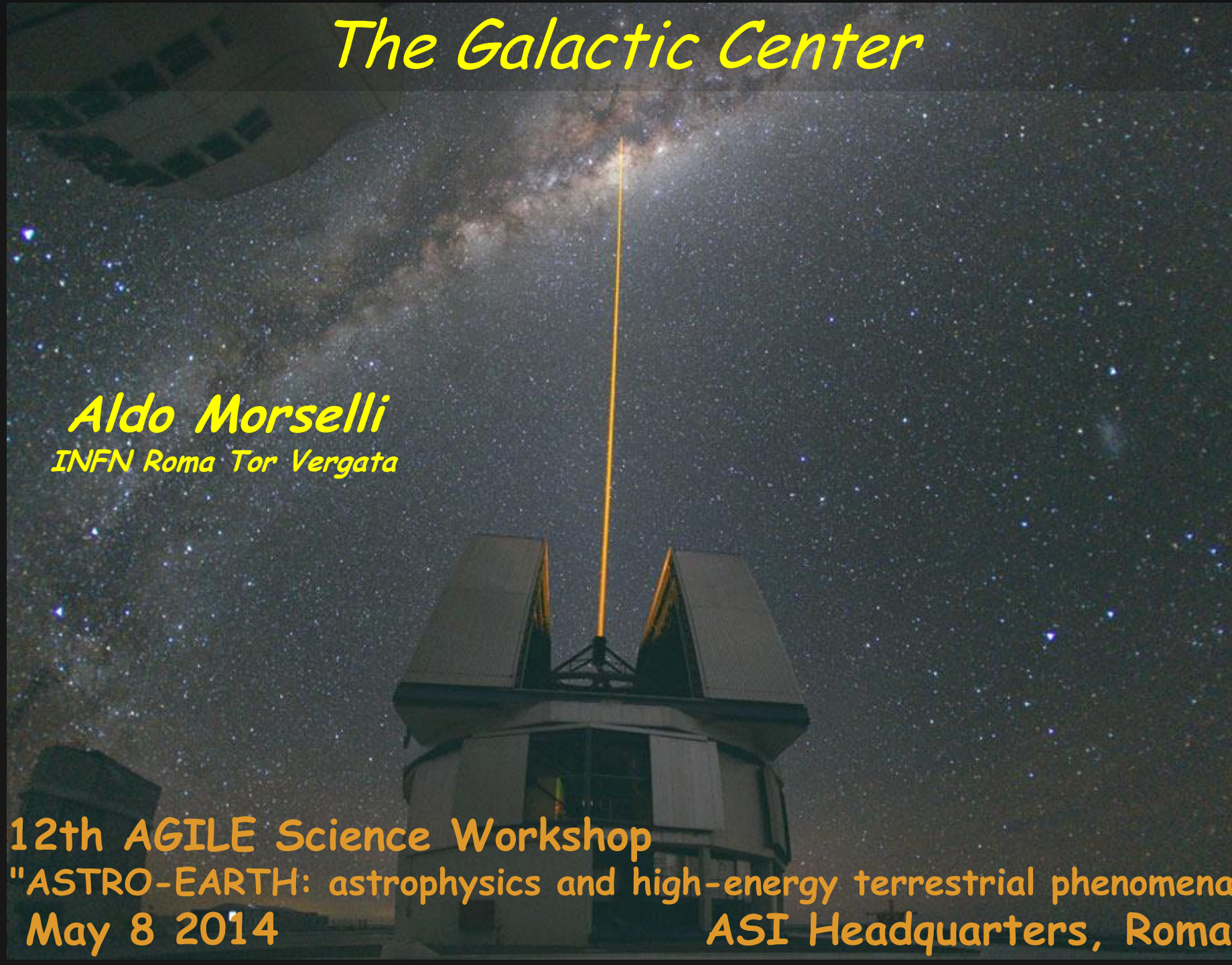
The Galactic Center



Aldo Morselli

INFN Roma Tor Vergata

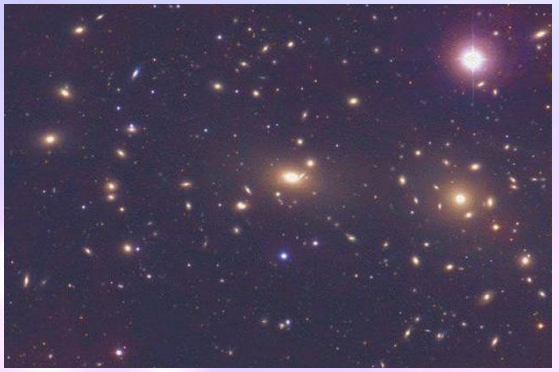
12th AGILE Science Workshop

"ASTRO-EARTH: astrophysics and high-energy terrestrial phenomena"

May 8 2014 ASI Headquarters, Roma

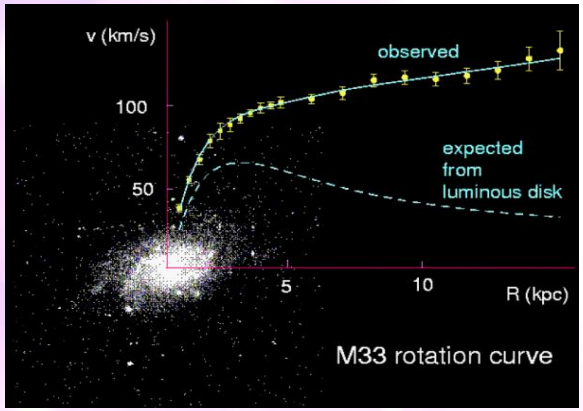
Dark Matter EVIDENCES

- In 1933, the astronomer Zwicky realized that the mass of the luminous matter in the Coma cluster was much smaller than its total mass implied by the motion of cluster member galaxies:



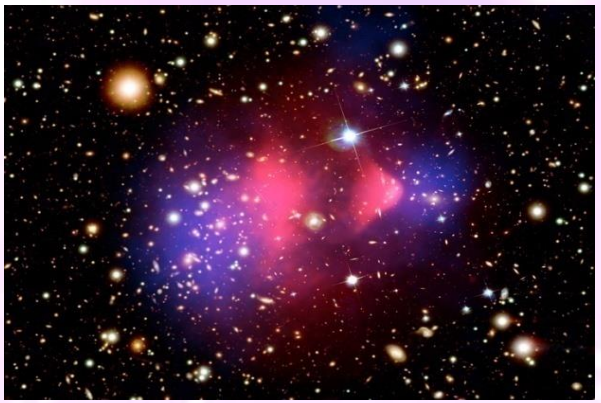
- Since then, many other evidences:

Rotation curves of galaxies

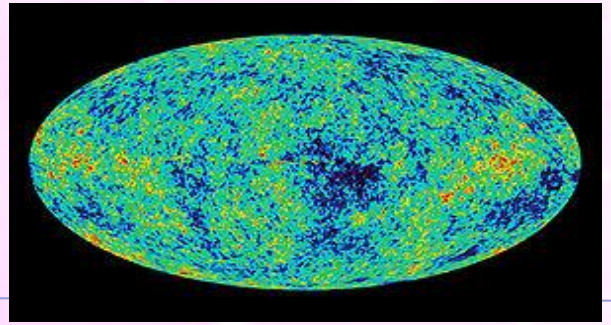


Gravitational lensing

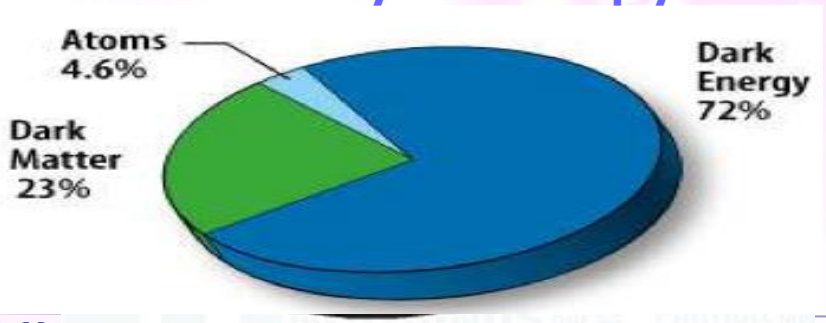
Bullet cluster



Structure formation as deduced from CMB



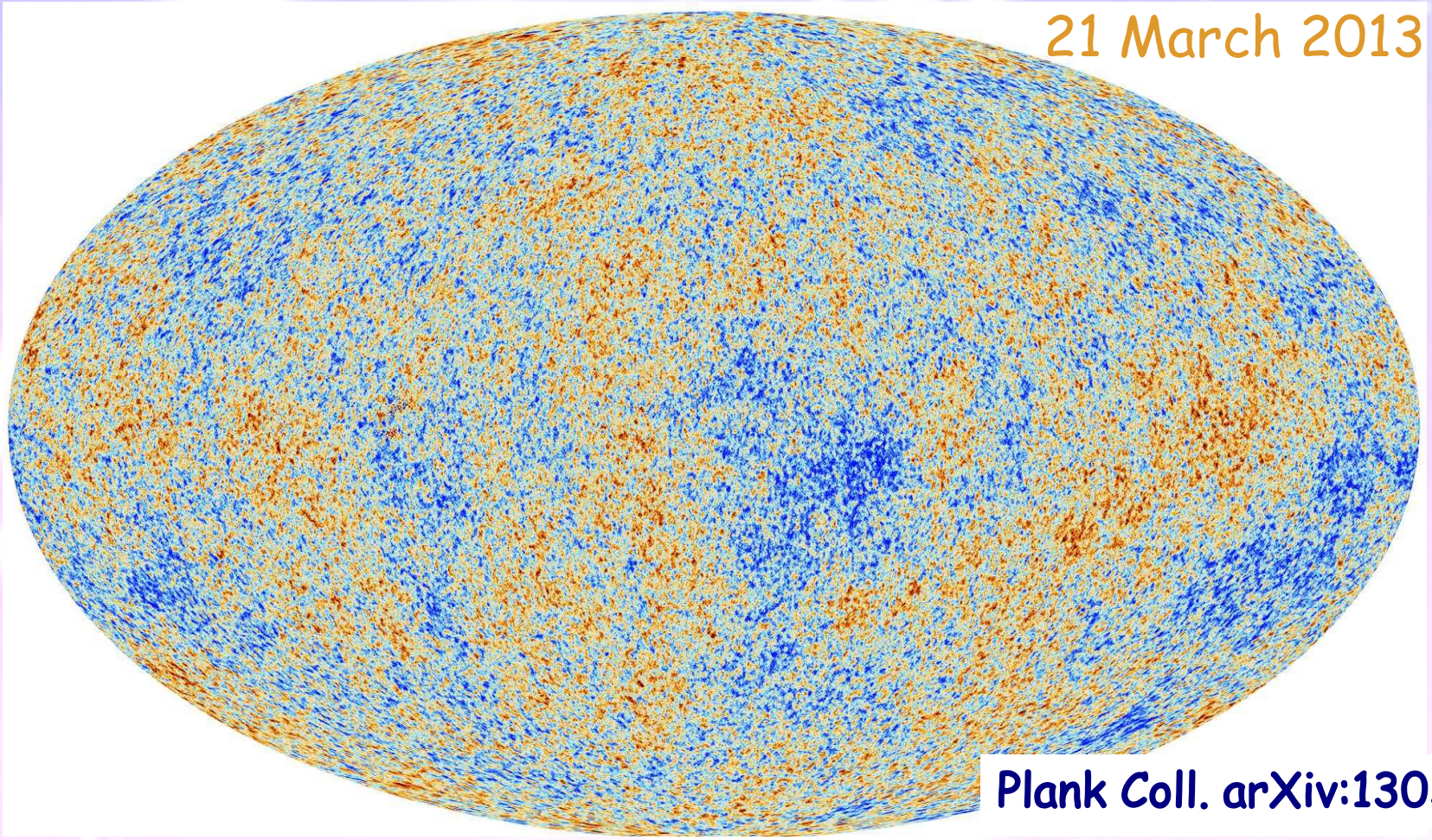
Data by WMAP imply:



$\Omega_b h^2 \approx 0.02$

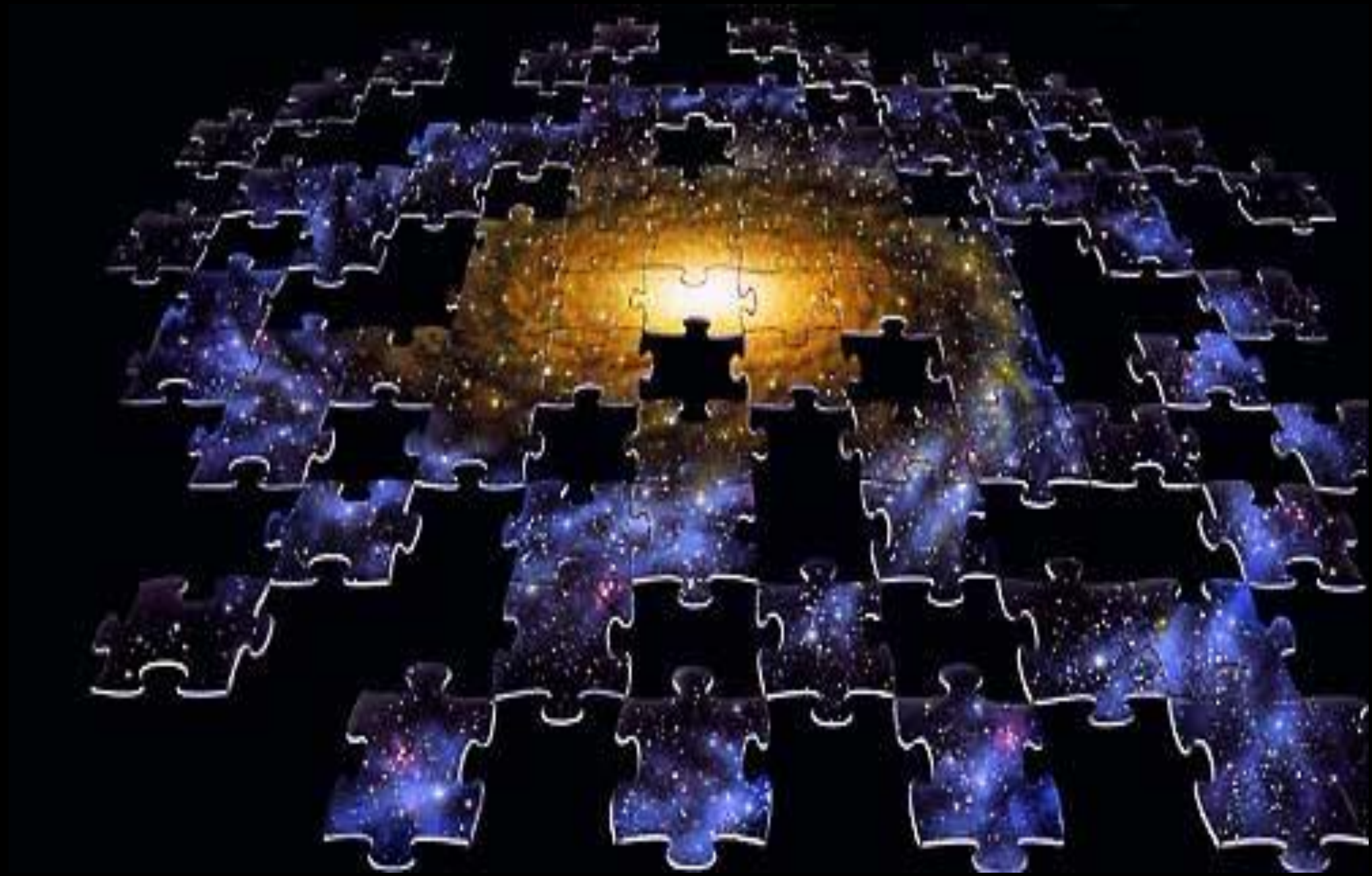
$\Omega_{DM} h^2 \approx 0.1$

The anisotropies of the Cosmic microwave background (CMB) as observed by Planck

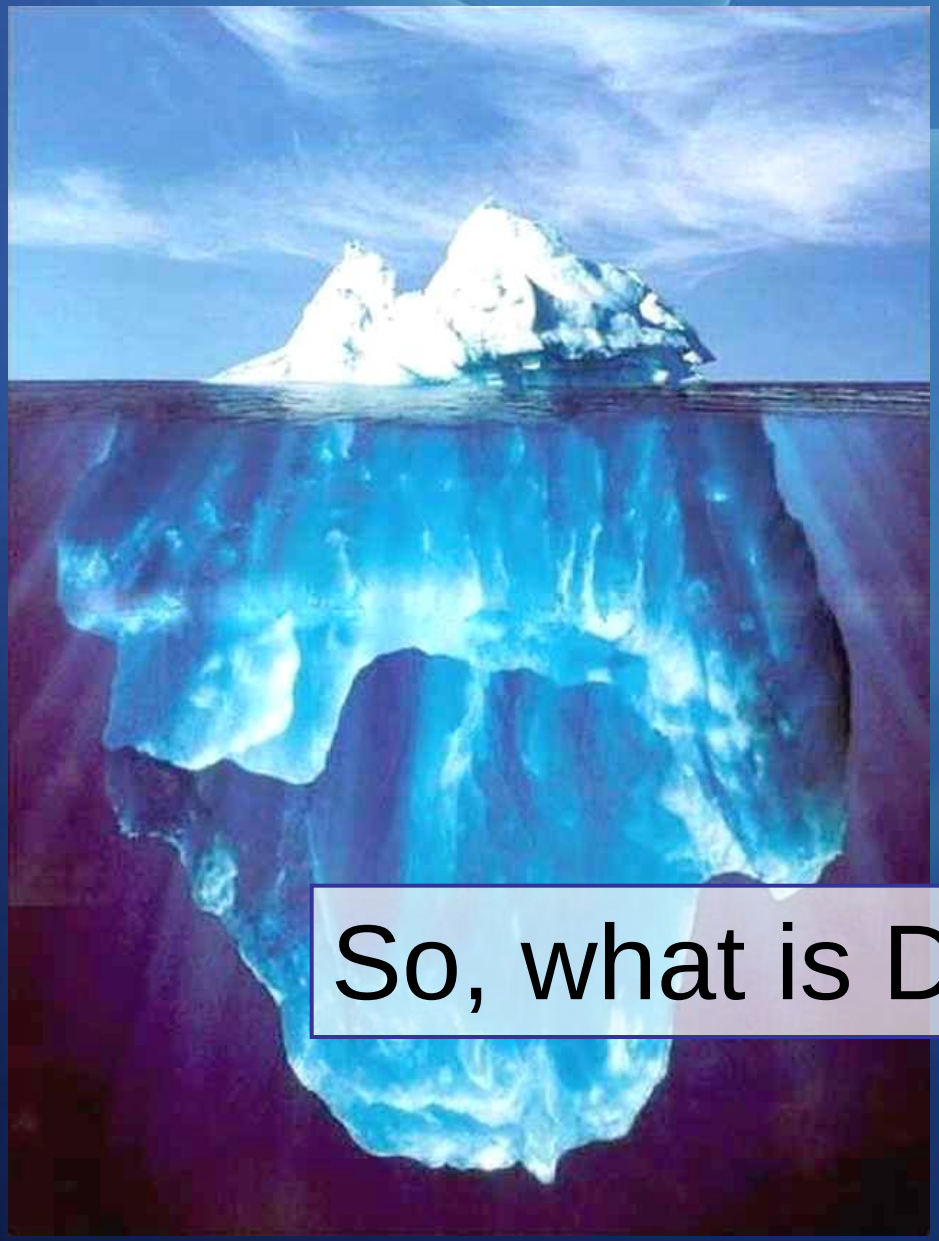


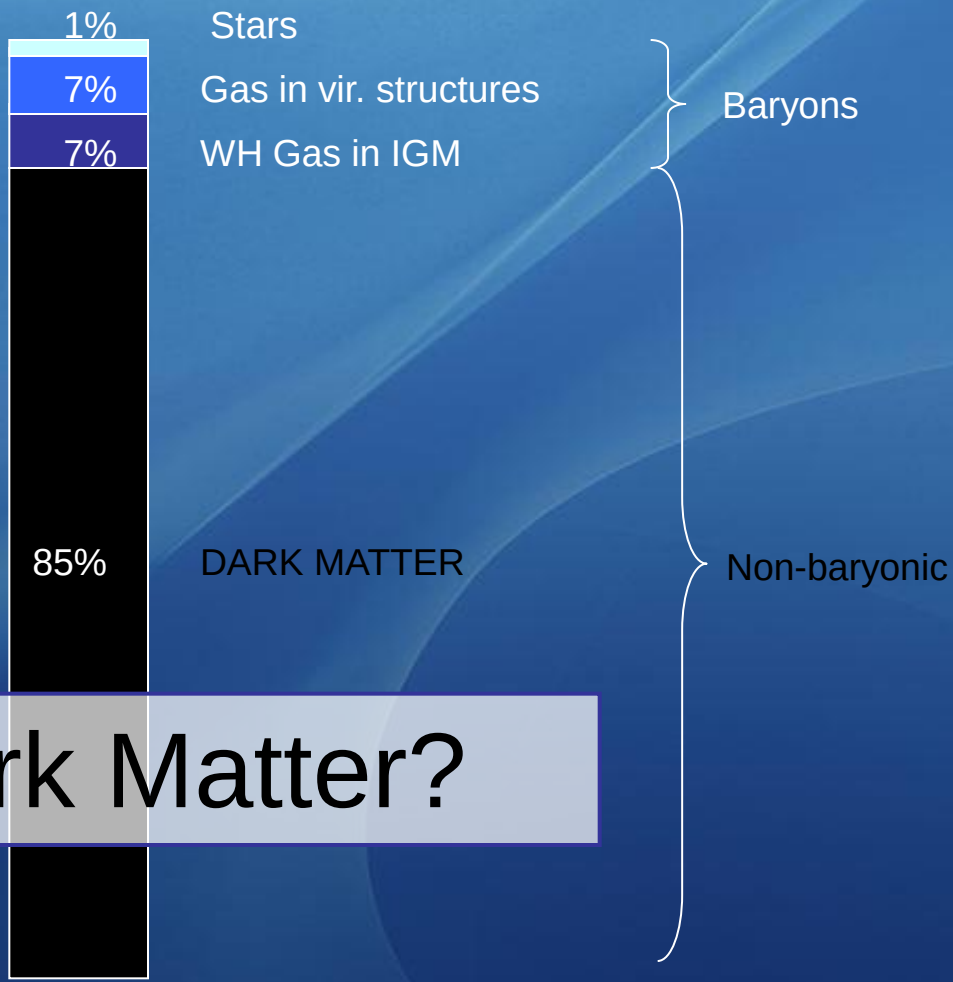
Plank Coll. arXiv:1303.5076

Dark Matter



An Inventory of Matter in the Universe

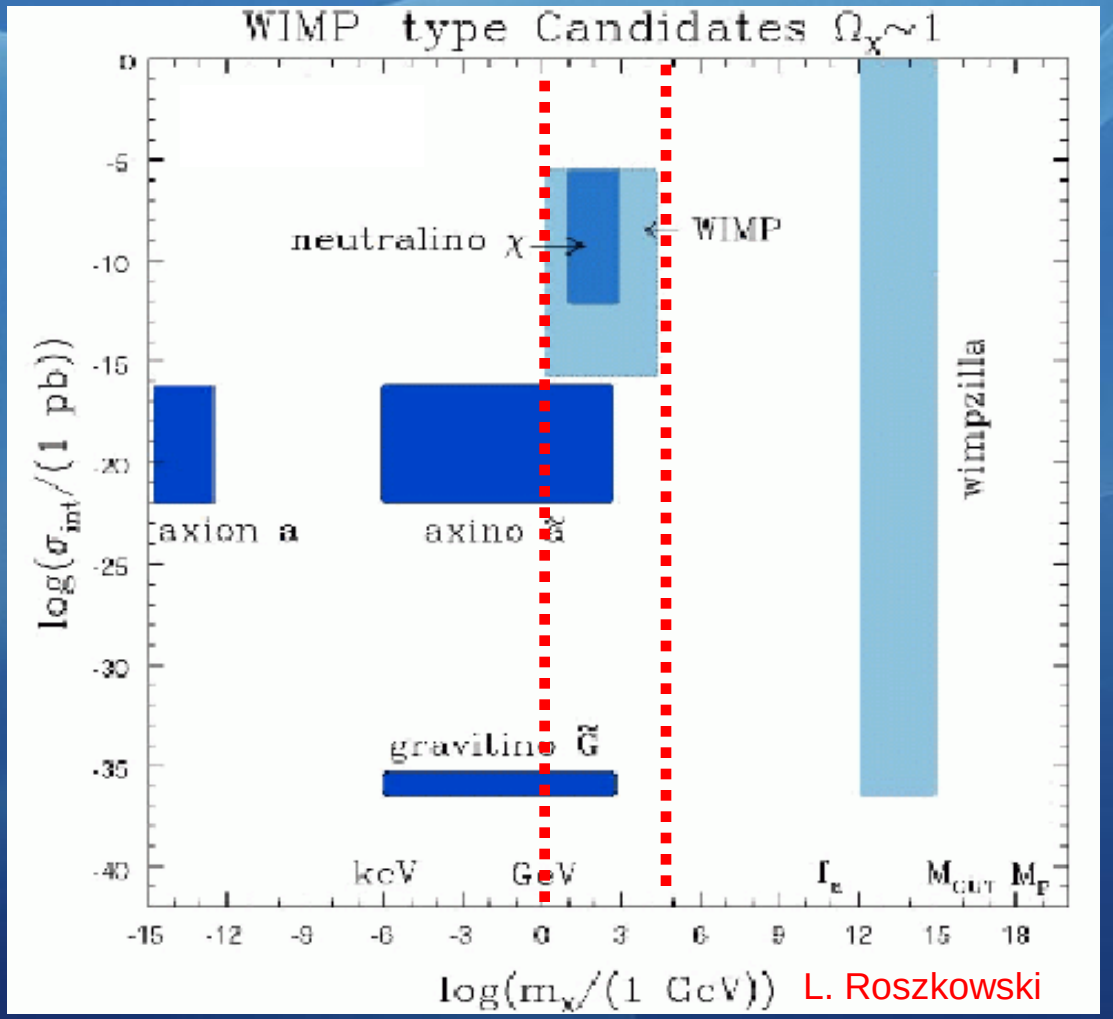




So, what is Dark Matter?

Dark Matter Candidates

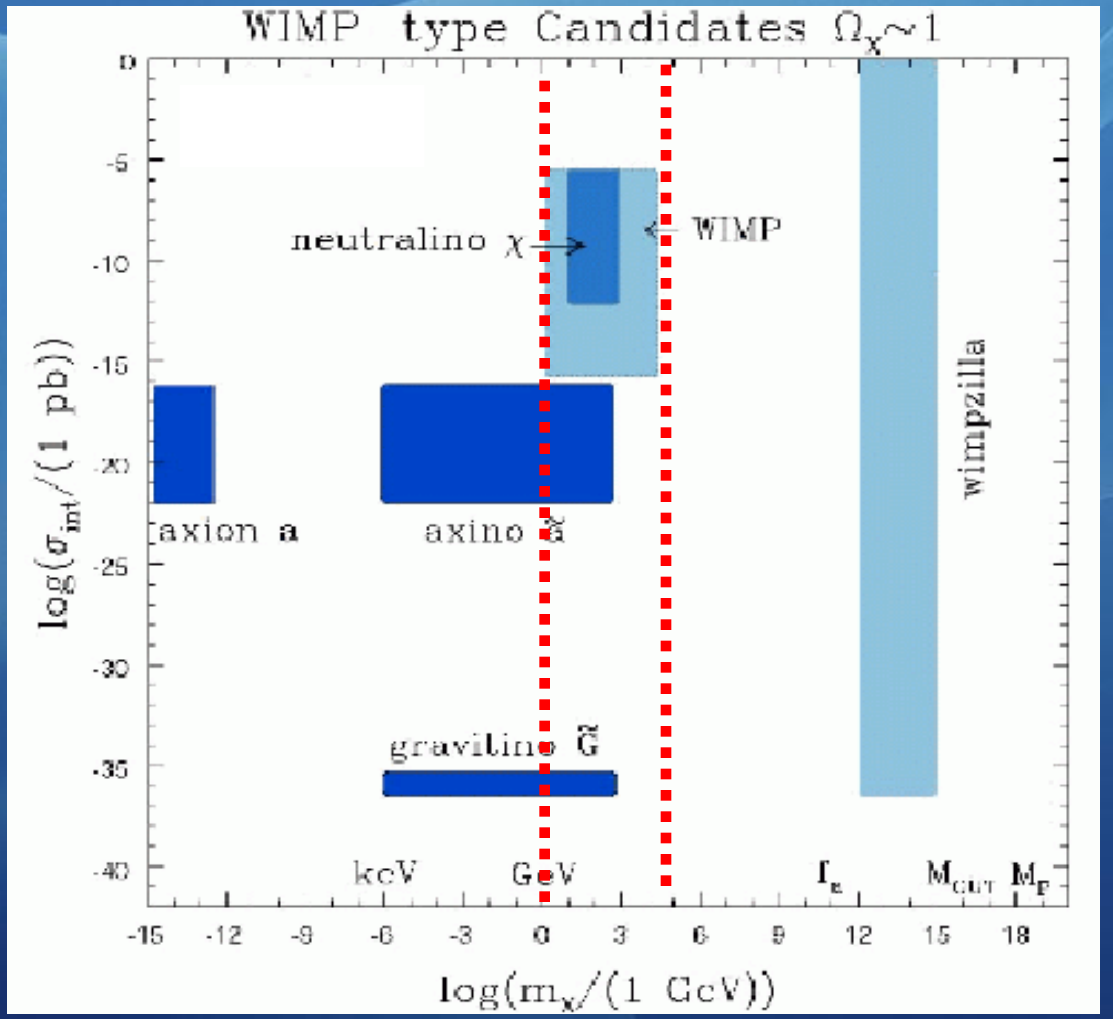
- Kaluza-Klein DM in UED
- Kaluza-Klein DM in RS
- Axion
- Axino
- Gravitino
- Photino
- SM Neutrino
- Sterile Neutrino
- Sneutrino
- Light DM
- Little Higgs DM
- Wimpzillas
- Q-balls
- Mirror Matter
- Champs (charged DM)
- D-matter
- Cryptons
- Self-interacting
- Superweakly interacting
- Braneworld DM
- Heavy neutrino
- NEUTRALINO
- Messenger States in GMSB
- Branons
- Chaplygin Gas
- Split SUSY
- Primordial Black Holes

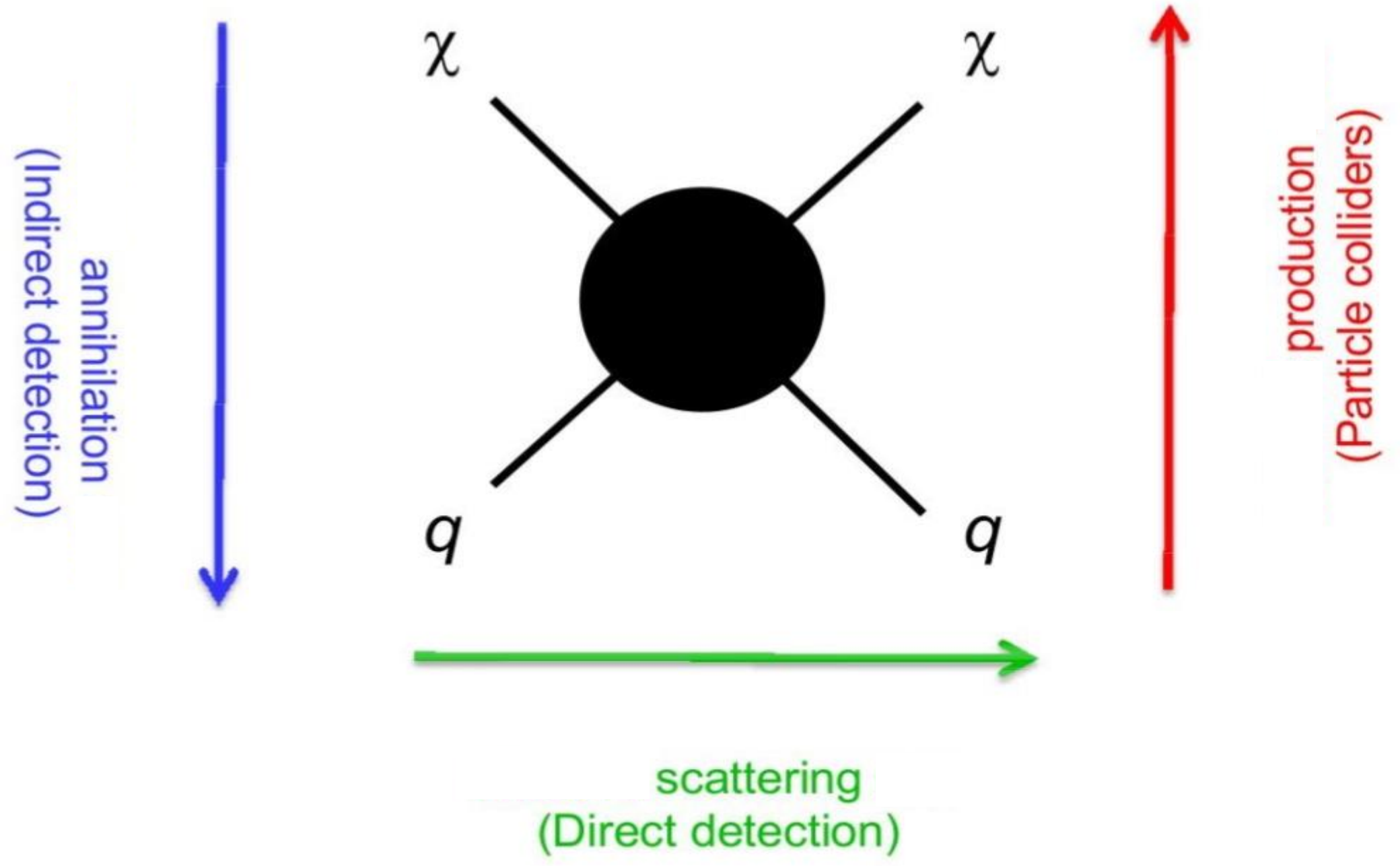


L. Roszkowski

Dark Matter Candidates

- Kaluza-Klein DM inUED
- Kaluza-Klein DM in RS
- Axion
- Axino
- Gravitino
- Photino
- SM Neutrino
- Sterile Neutrino
- Sneutrino
- Light DM
- Little Higgs DM
- Wimpzillas
- Q-balls
- Mirror Matter
- Champs (charged DM)
- D-matter
- Cryptons
- Self-interacting
- Superweakly interacting
- Braneworls DM
- Heavy neutrino
- **NEUTRALINO**
- Messenger States in GMSB
- Branons
- Chaplygin Gas
- Split SUSY
- Primordial Black Holes



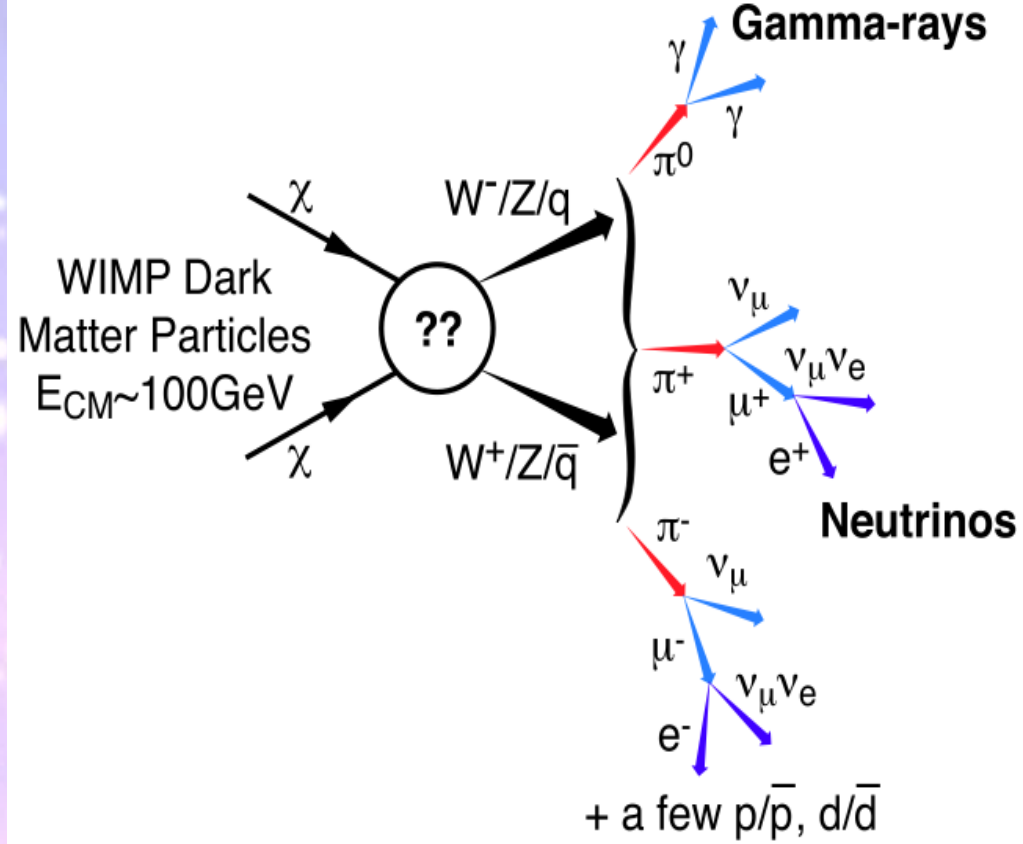

annihilation
(Indirect detection)
χ
χ
q
q
production
(Particle colliders)
scattering
(Direct detection)

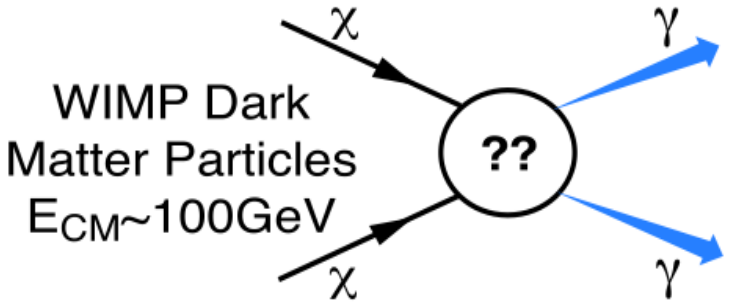
Neutralino WIMPs

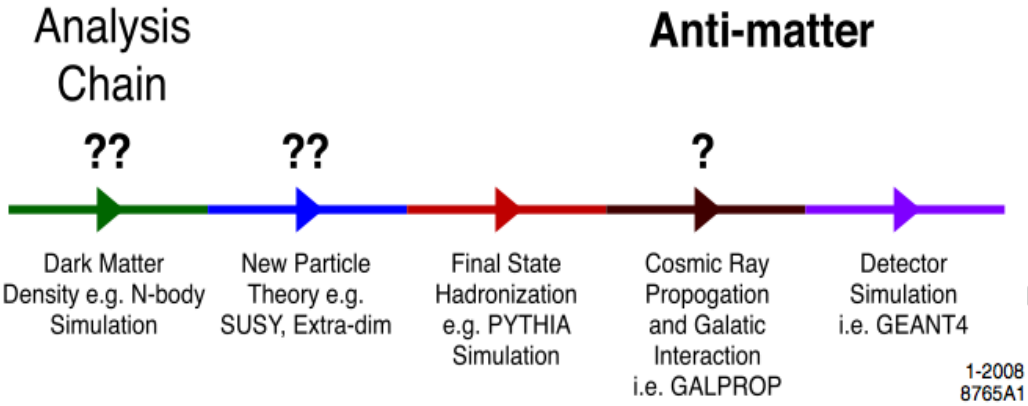
Assume χ present in the galactic halo

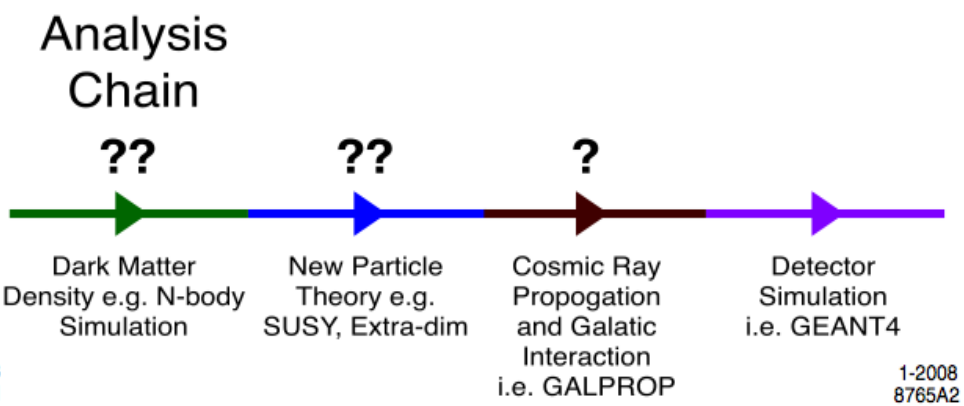
- χ is its own antiparticle => can annihilate in galactic halo producing gamma-rays, antiprotons, positrons….
- Antimatter not produced in large quantities through standard processes (secondary production through p + p --> anti p + X)
- So, any extra contribution from exotic sources (χ χ annihilation) is an interesting signature
- ie: χ χ --> anti p + X
- Produced from (e. g.) χ χ --> q / g / gauge boson / Higgs boson and subsequent decay and/ or hadronisation.

Annihilation channels





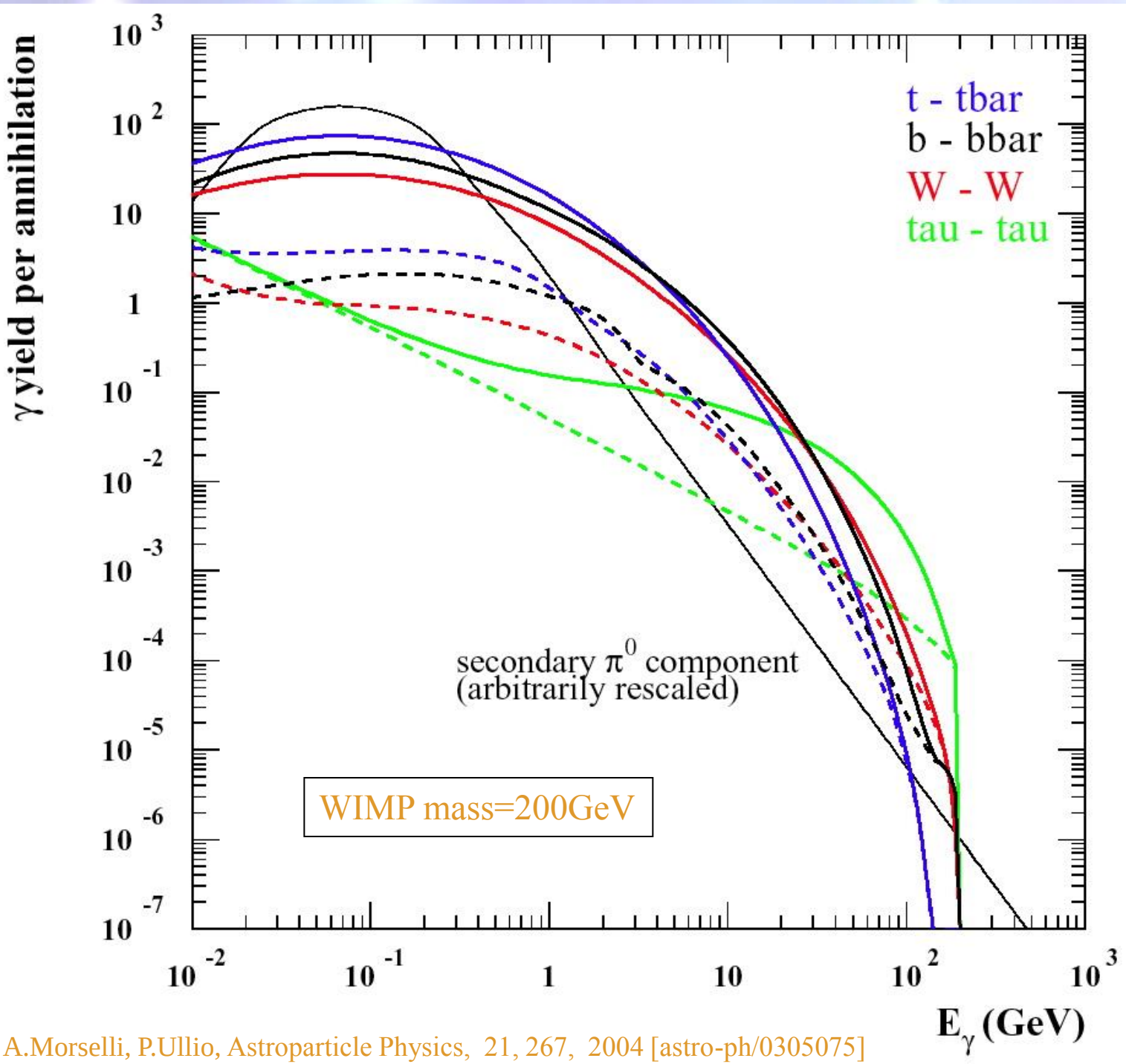




Differential yield for each annihilation channel

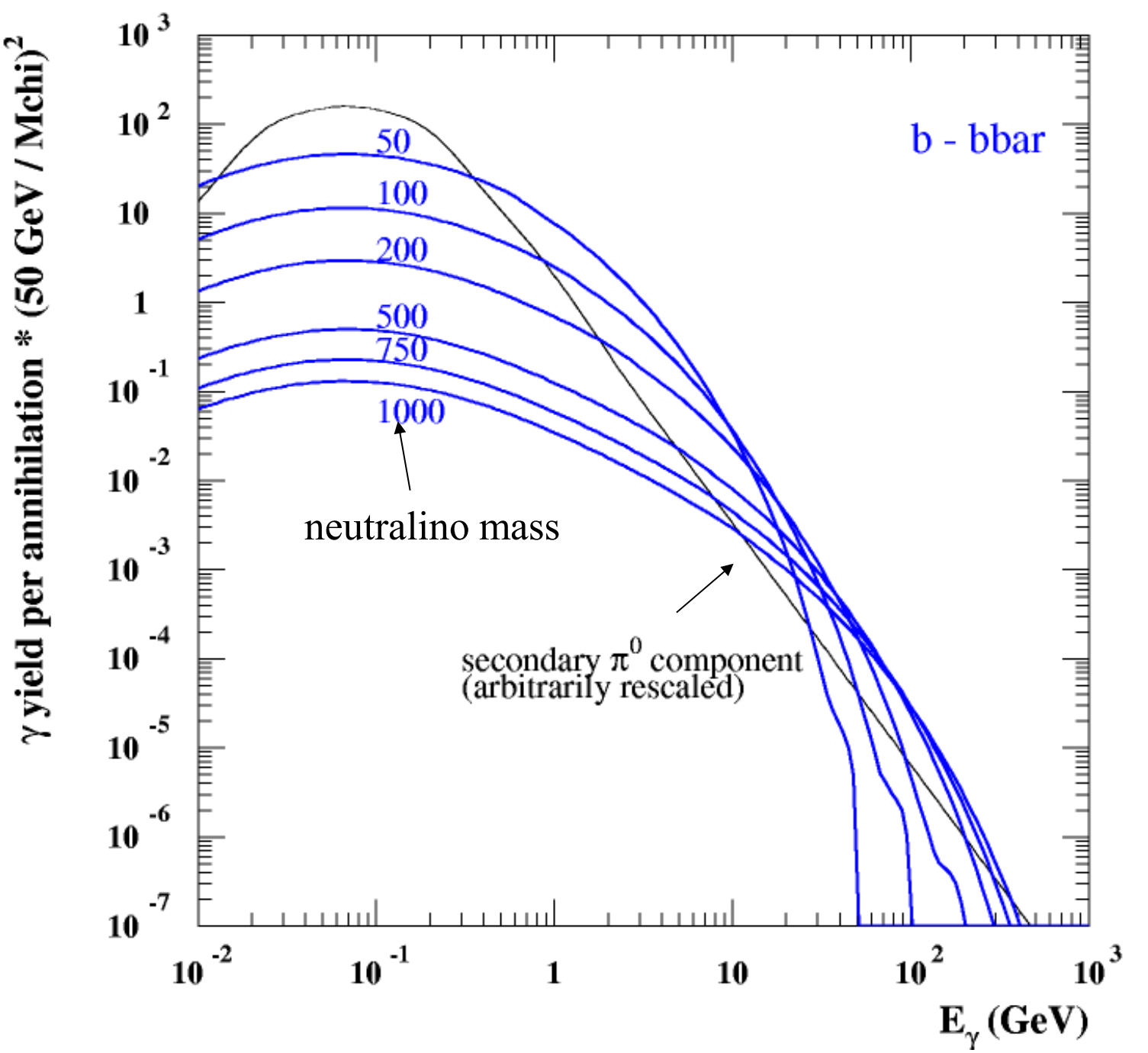
- Quite distinctive spectrum (no power-law)

- solid lines are the total yields, while the dashed lines are components not due to π^0 decays

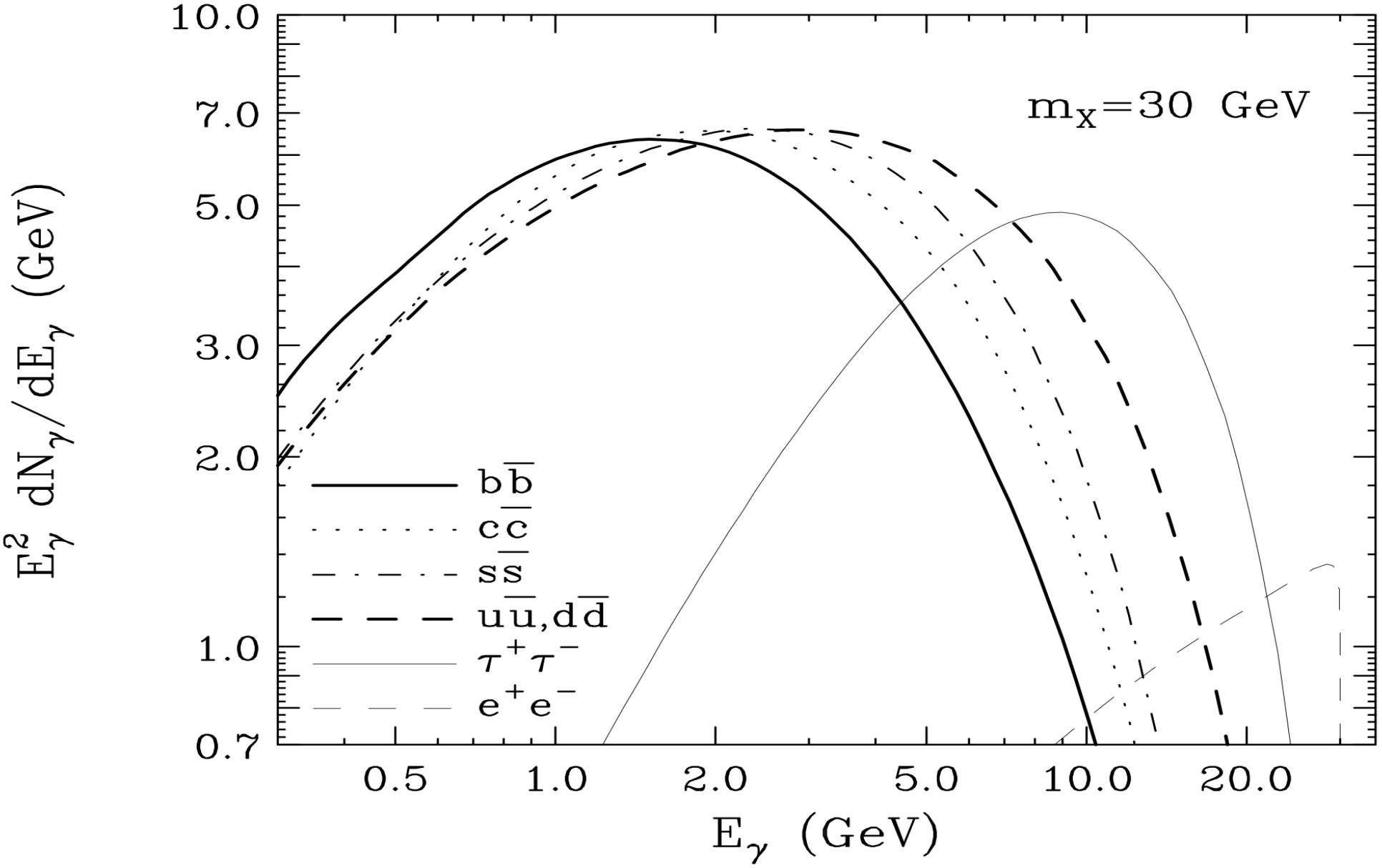


A.Cesarini, F.Fucito, A.Lionetto, A.Morselli, P.Ullio, Astroparticle Physics, 21, 267, 2004 [astro-ph/0305075]

Differential yield for b bar for different neutralino mass



Gamma rays produced per dark matter annihilation

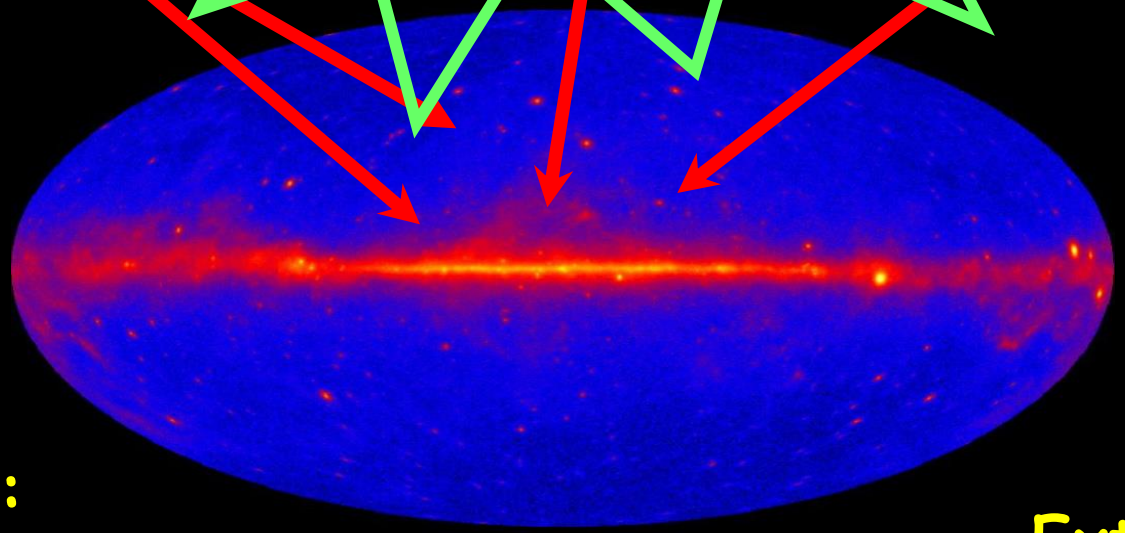


Search Strategies

Satellites:
Low background and good source id, but low statistics

Galactic center:
Good statistics but source confusion/diffuse background

Milky Way halo:
Large statistics but diffuse background



And electrons!

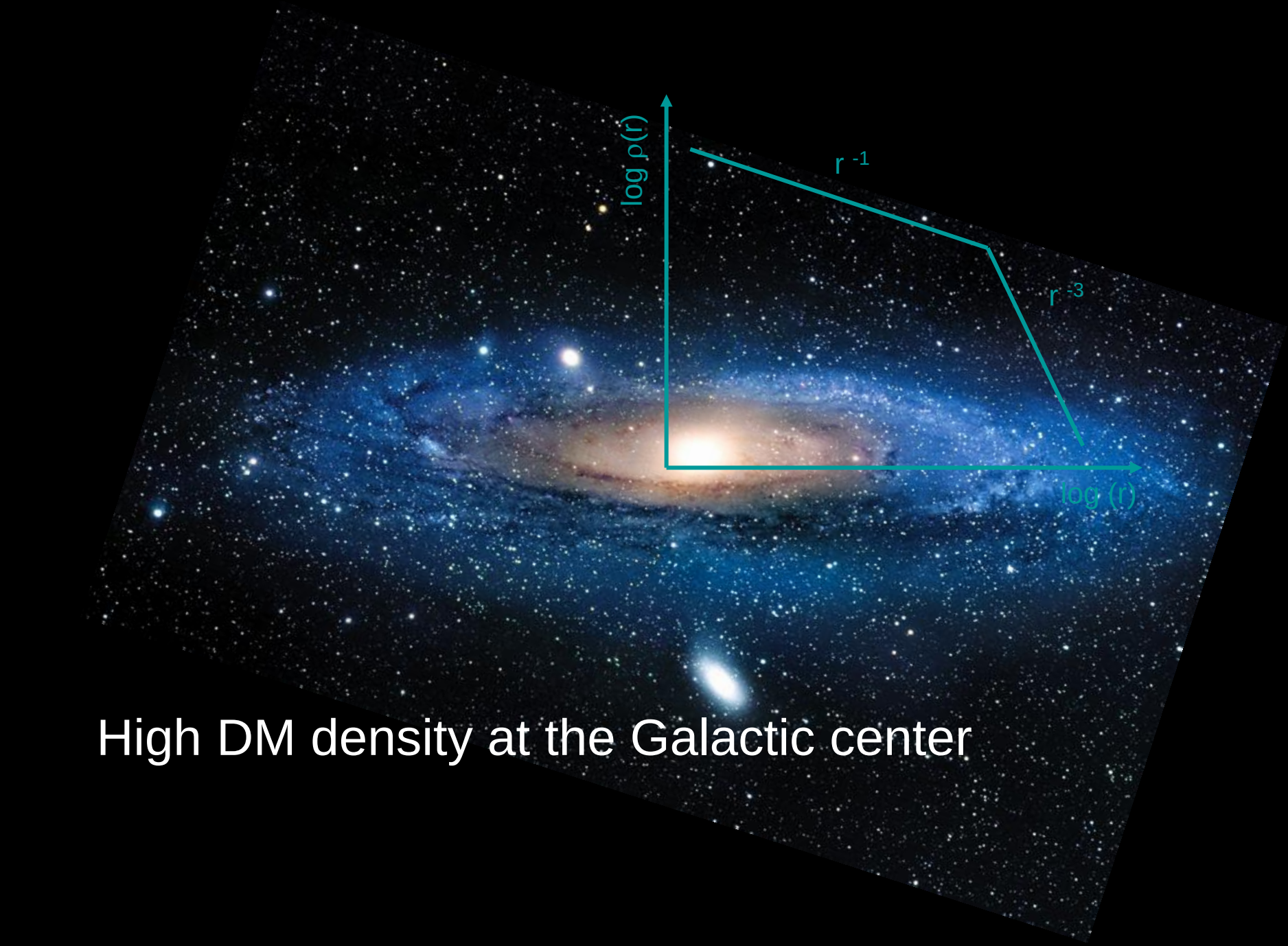
and Anisotropies

Spectral lines:
No astrophysical uncertainties, good source id, but low statistics

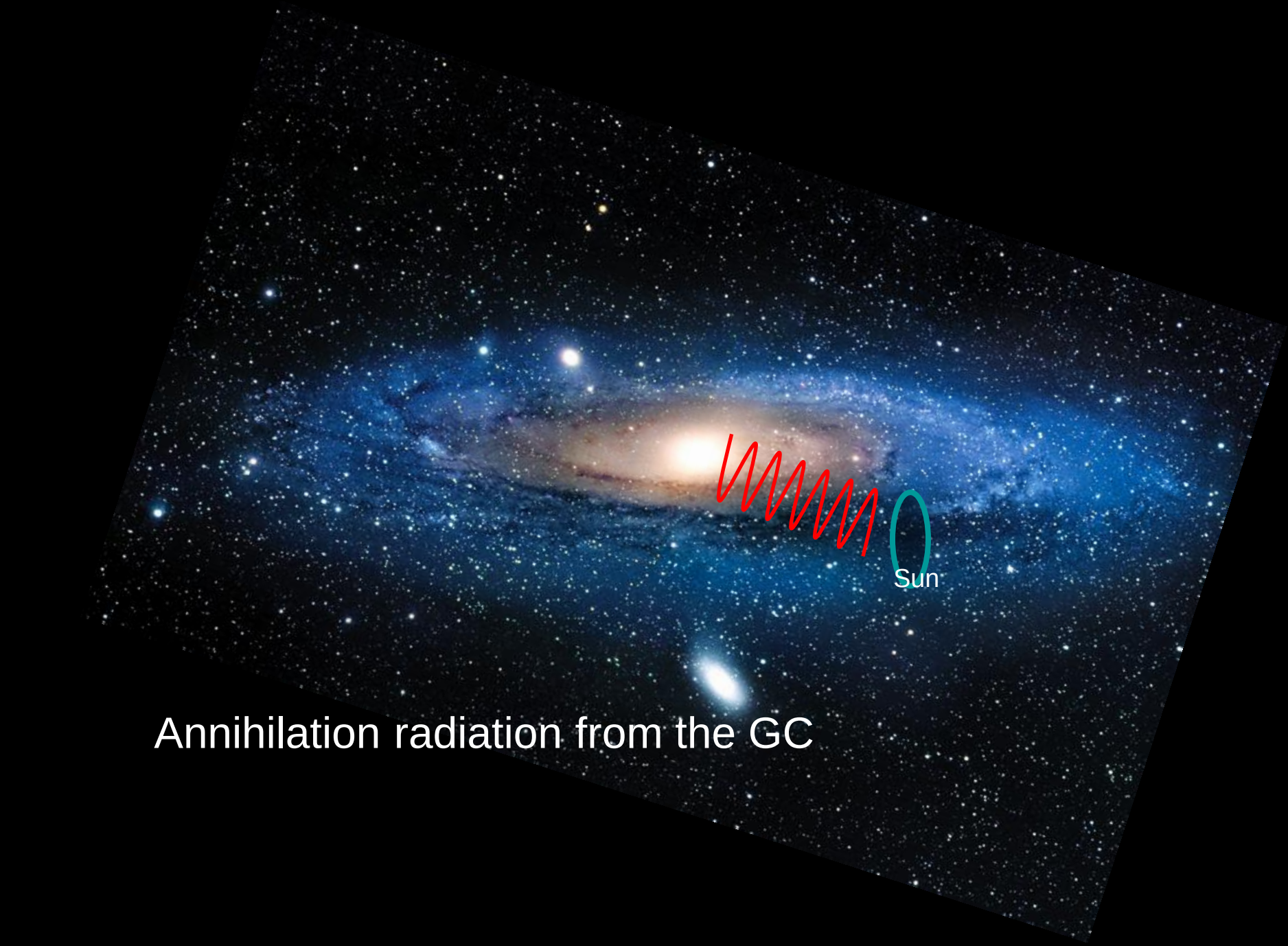
Galaxy clusters:
Low background but low statistics

Extra-galactic:
Large statistics, but astrophysics,galactic diffuse background

Pre-launch sensitivities published in Baltz et al., 2008, JCAP 0807:013 [astro-ph/0806.291



High DM density at the Galactic center



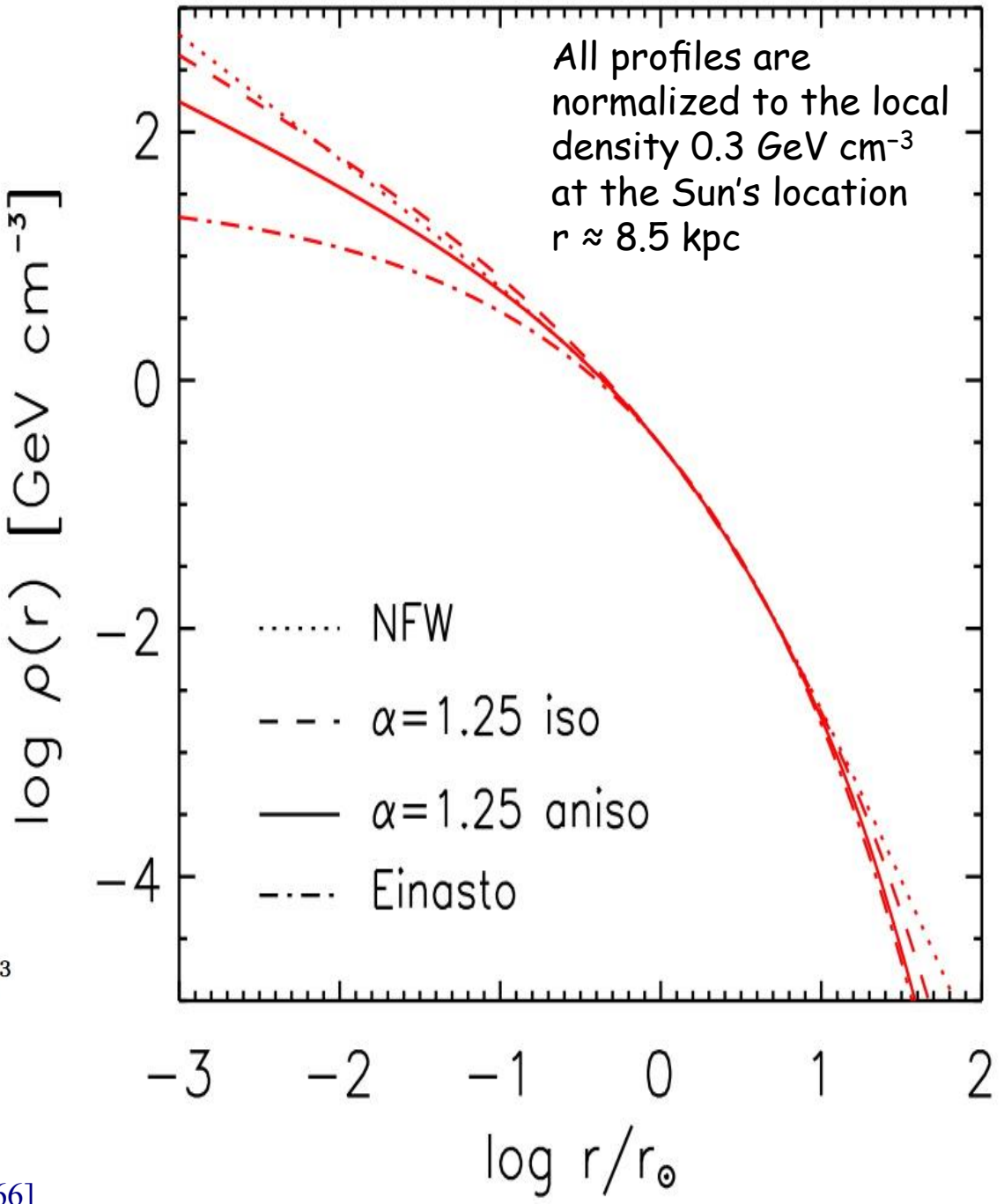
Annihilation radiation from the GC

Milky Way Dark Matter Profiles

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

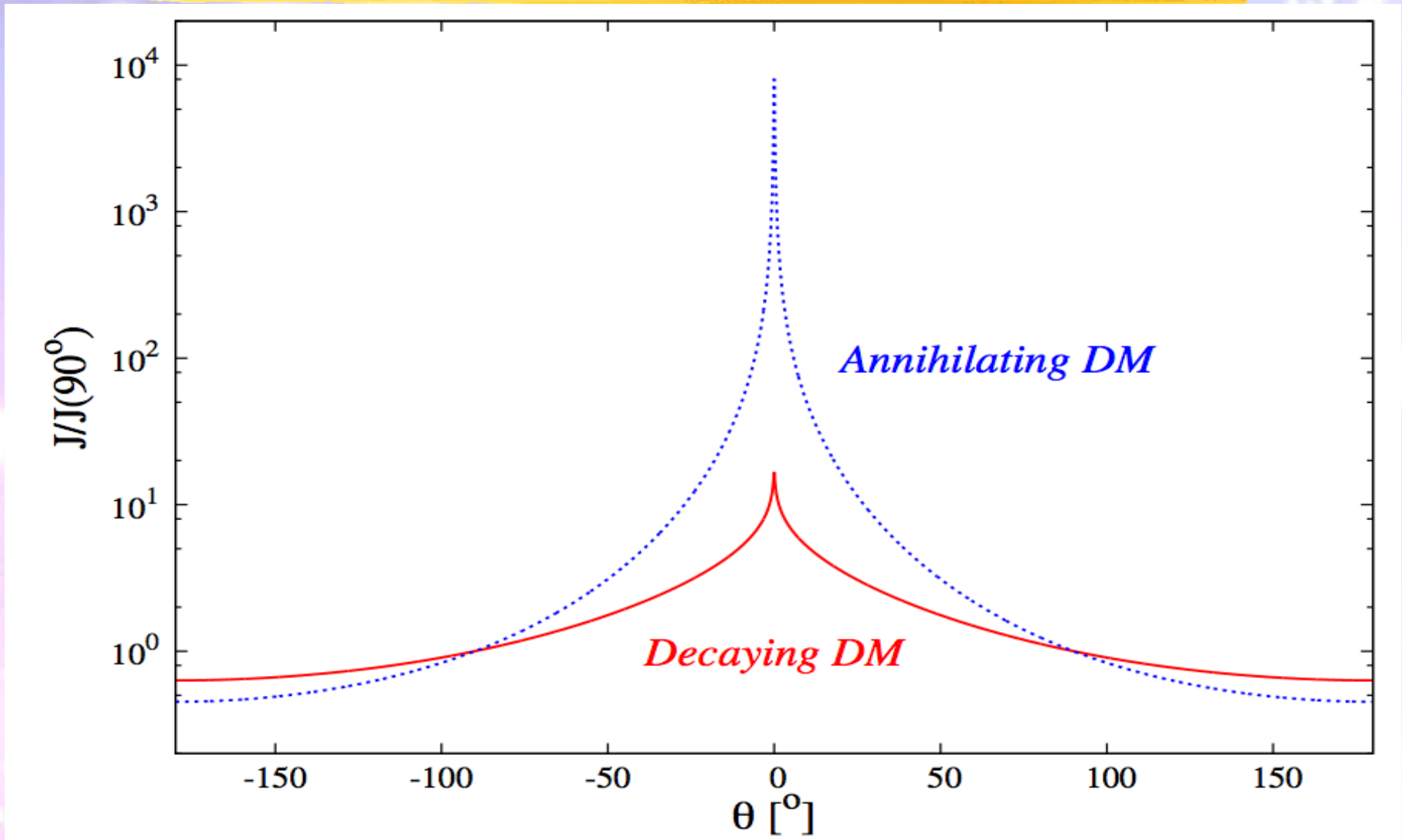
Halo model	α	β	γ	r_s in kpc
Cored isothermal	2	2	0	5
Navarro, Frenk, White	1	3	1	20
Moore	1	3	1.16	30

Einasto | $\alpha = 0.17$ $r_s = 20\,\mathrm{kpc}$ $\rho_s = 0.06\,\mathrm{GeV/cm^3}$



A.Lapi, A.Paggi, A.Cavaliere, A.Lionetto, A.Morselli, V.Vitale. A&A 510, A90 (2010) [arXiv:0912.1766]

Different spatial behaviour for decaying or annihilating dark matter

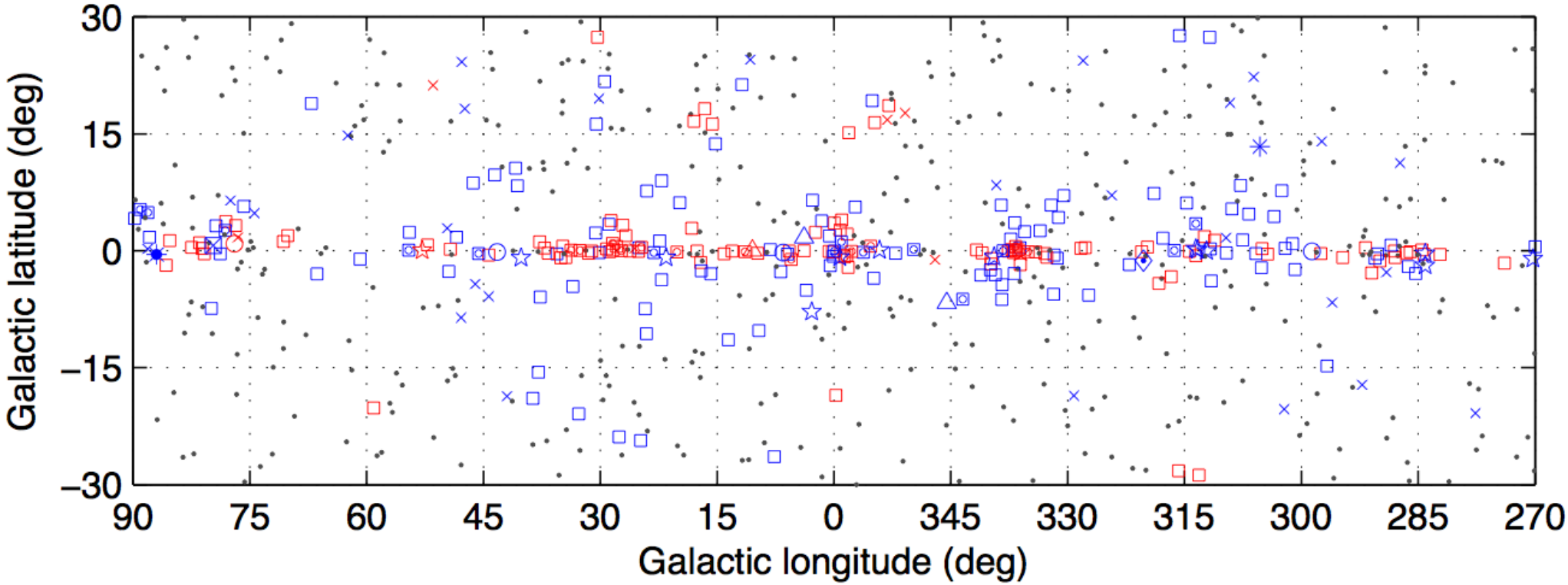


The angular profile of the gamma-ray signal is shown, as function of the angle θ to the centre of the galaxy for a Navarro-Frenk-White (NFW) halo distribution for decaying DM, solid (red) line, compared to the case of self-annihilating DM, dashed (blue) line

The Fermi LAT 2FGL Inner Galactic Region

August 4, 2008, to July 31, 2010

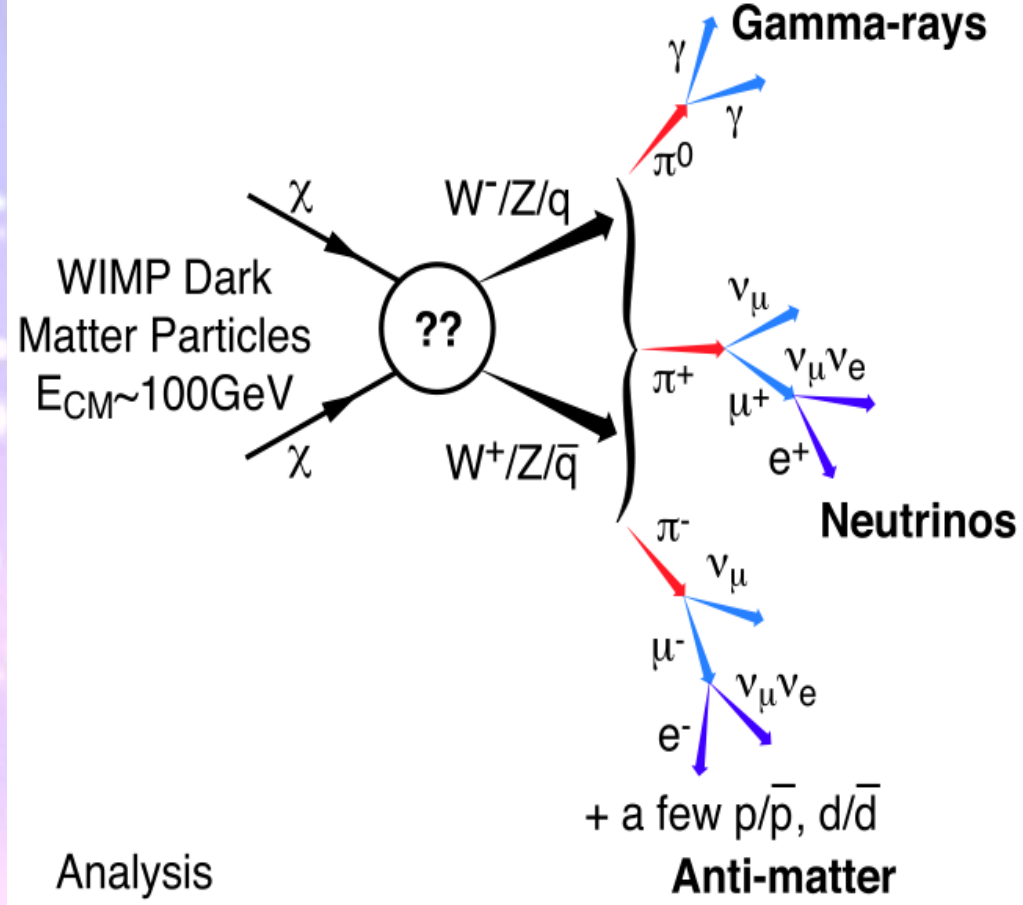
100 MeV to 100 GeV energy range

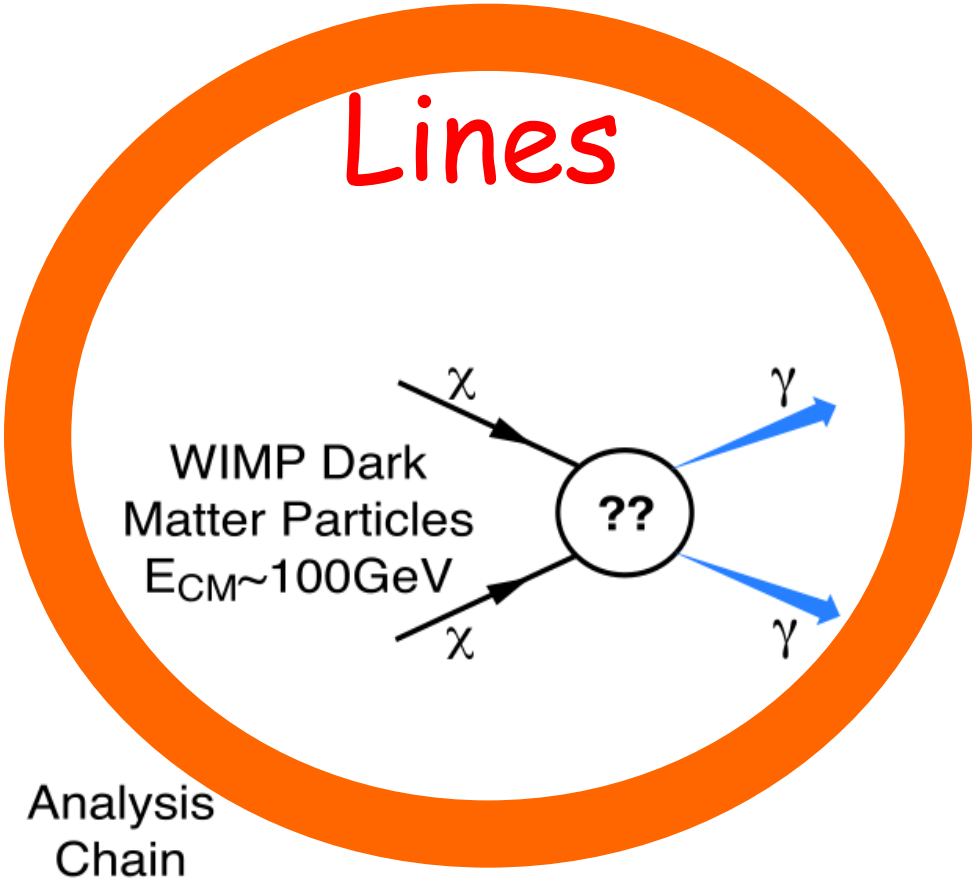


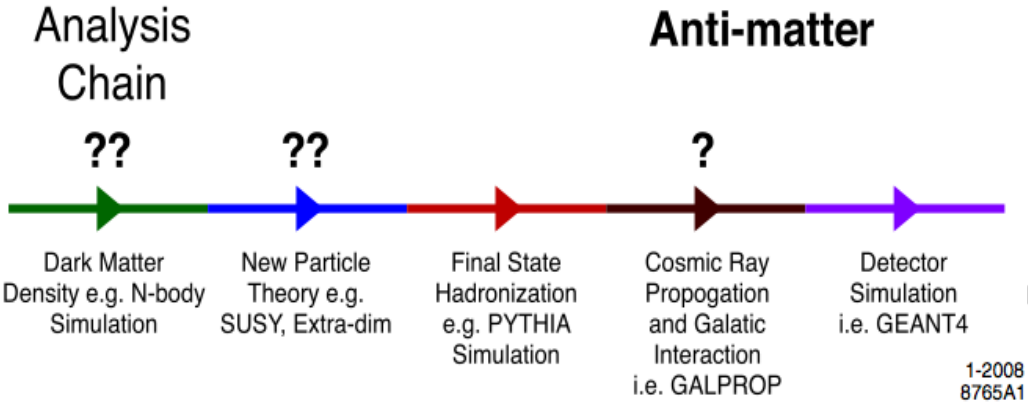
Fermi Coll. ApJS (2012) 199, 31
arXiv:1108.1435

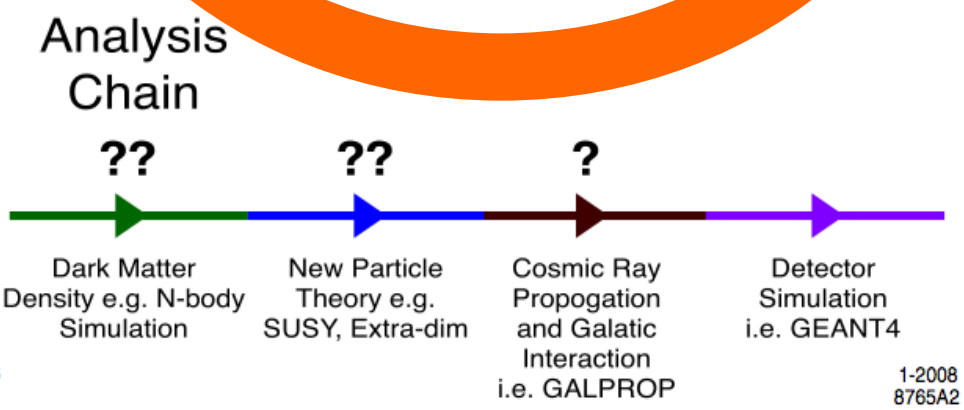
□ No association	⊡ Possible association with SNR or PWN	
× AGN	☆ Pulsar	△ Globular cluster
✳ Starburst Gal	◈ PWN	⊠ HMB
+ Galaxy	○ SNR	✷ Nova

Annihilation channels

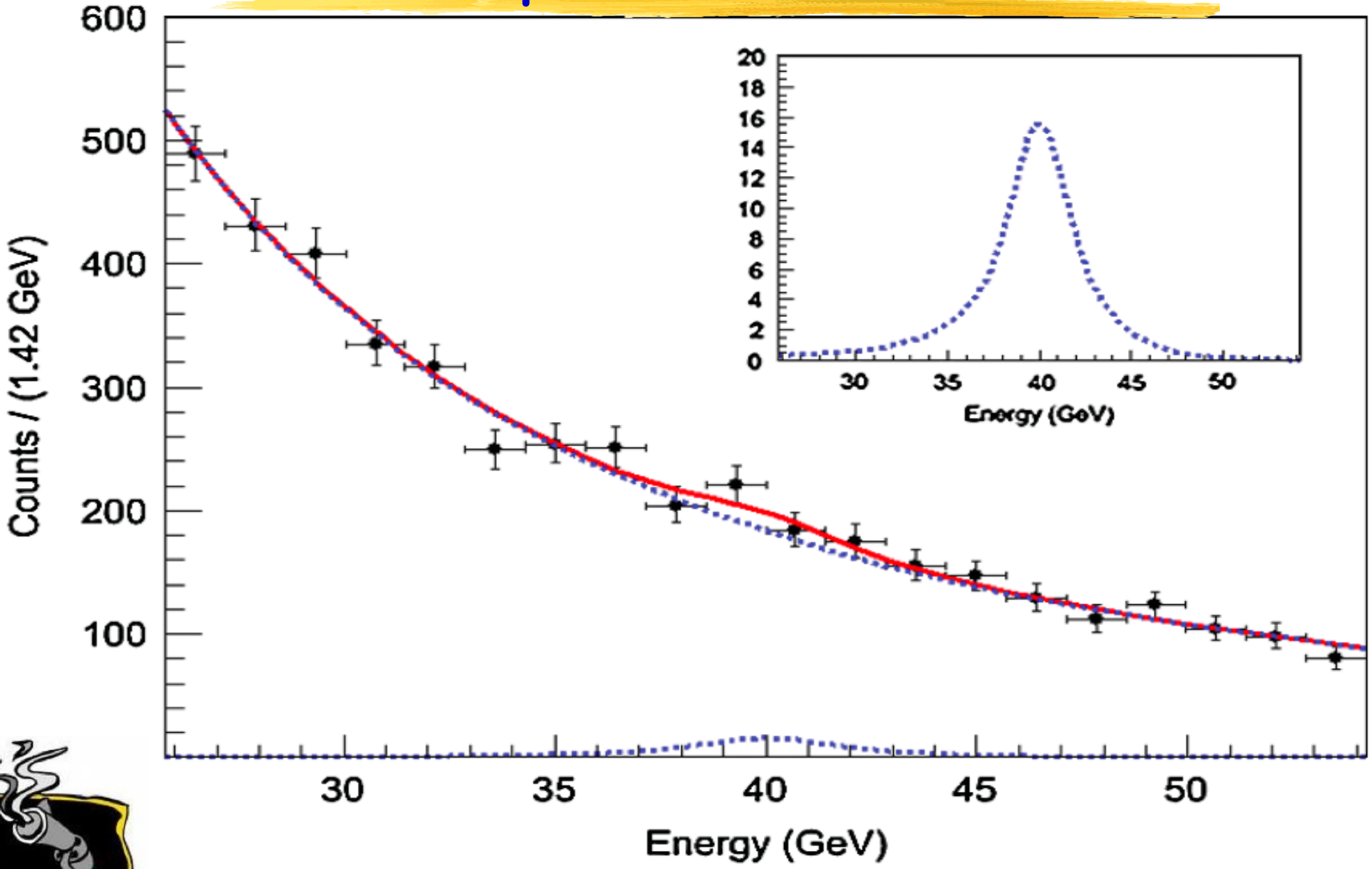




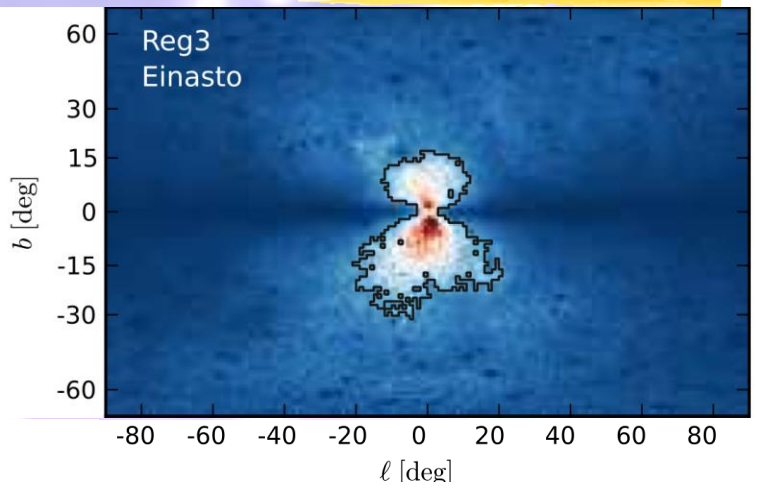


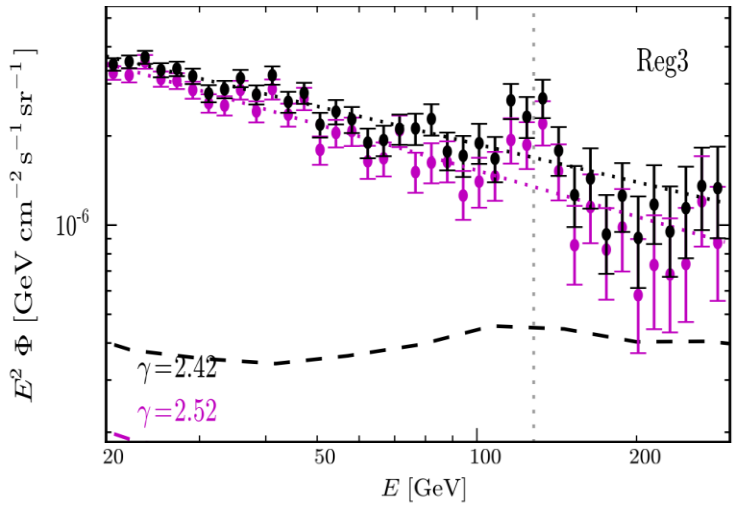


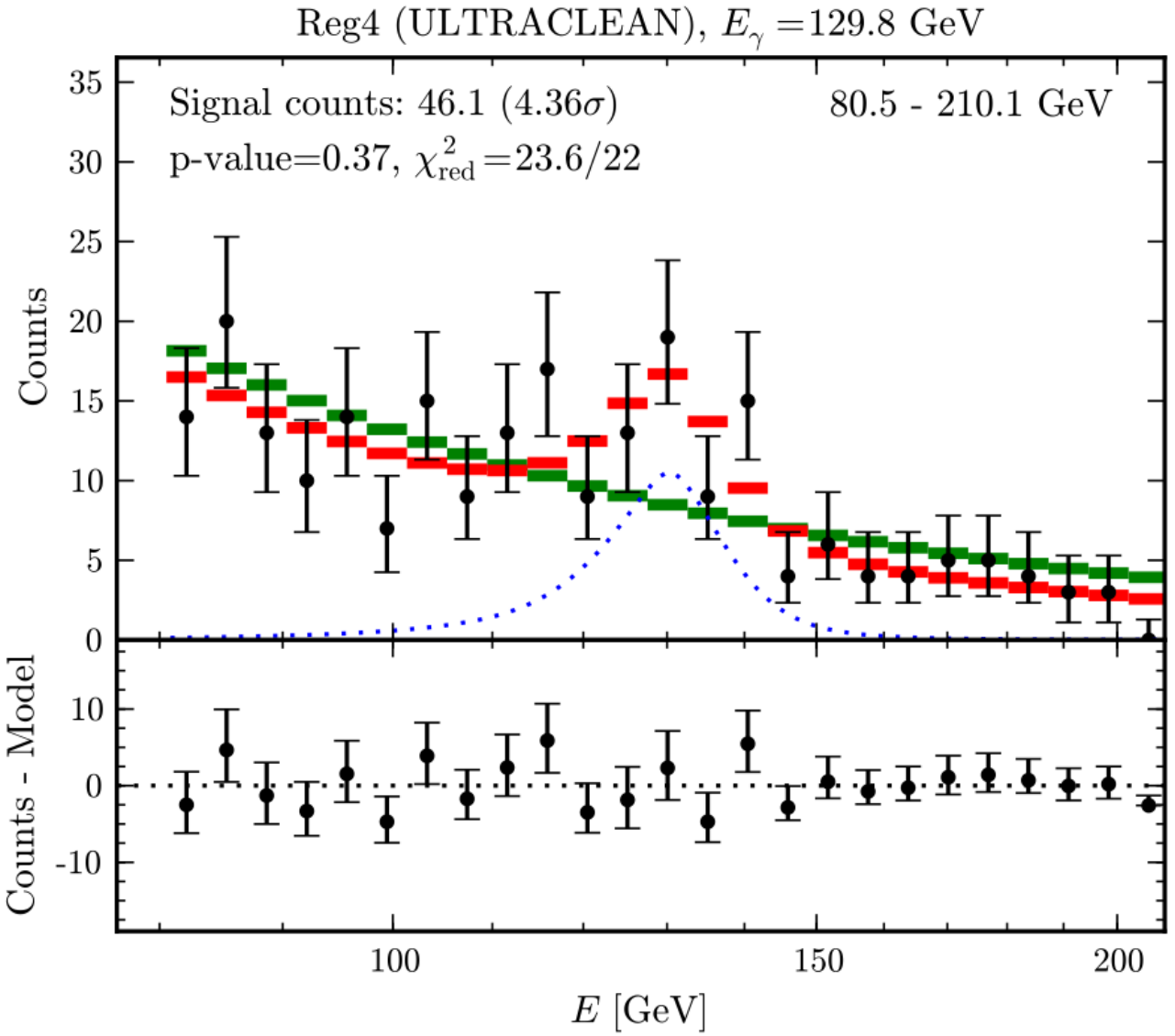
Wimp lines search



A line at ~ 130 GeV ?

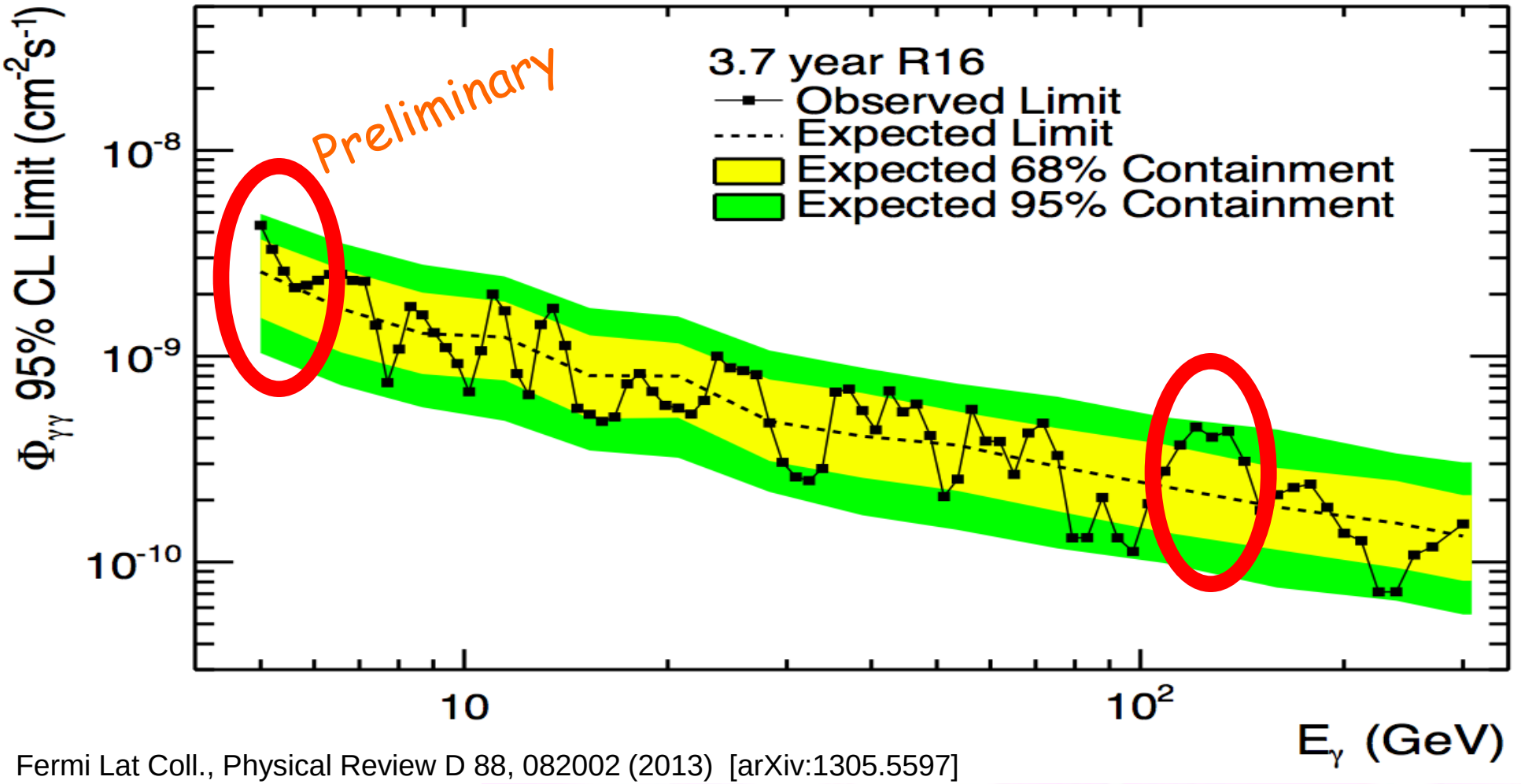






Weniger arXiv:1204.2797

Fermi-LAT Line Search Flux Upper Limits



Fermi Lat Coll., Physical Review D 88, 082002 (2013) [arXiv:1305.5597]

- Most of the limits fall within the expected bands.
- Near 135 GeV the limits are near the upper edge of the bands.
- The huge statistics at low energies mean small uncertainties in the collecting area can produce statistical significant spectral features.

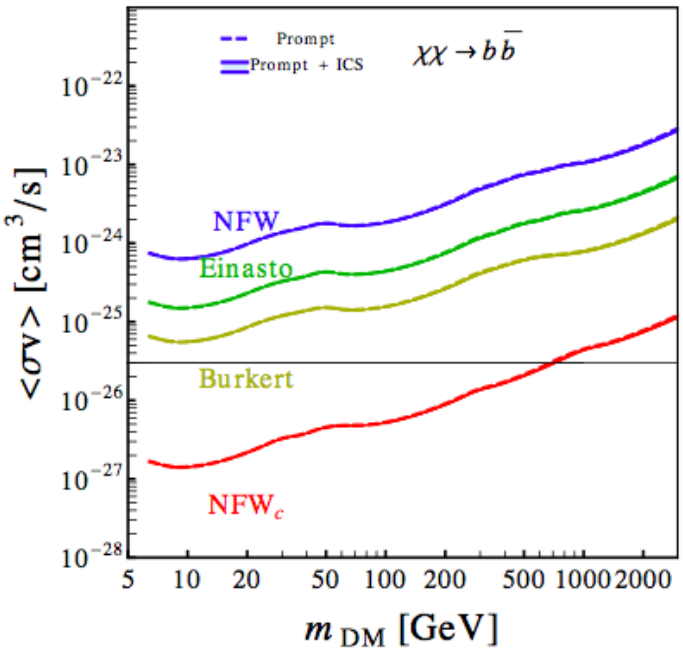
Constraints from the inner Galaxy

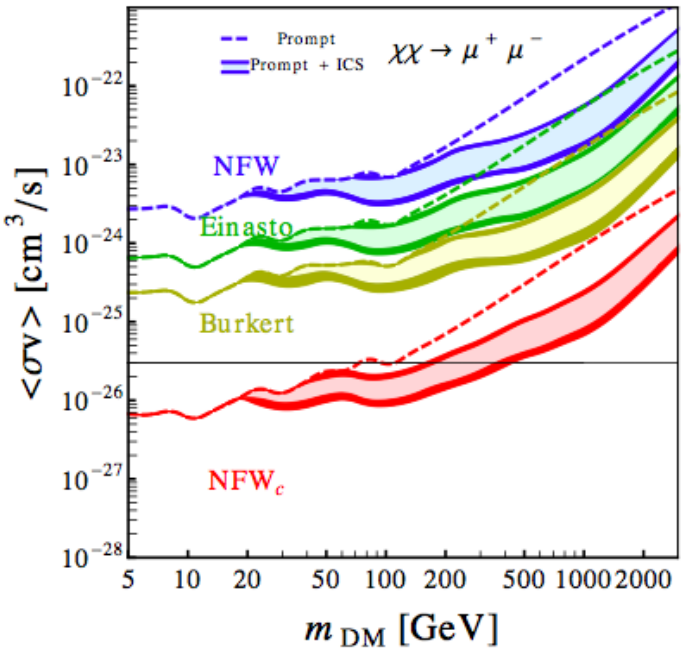
3 σ upper limits on the annihilation cross-section for different channels and halo profiles

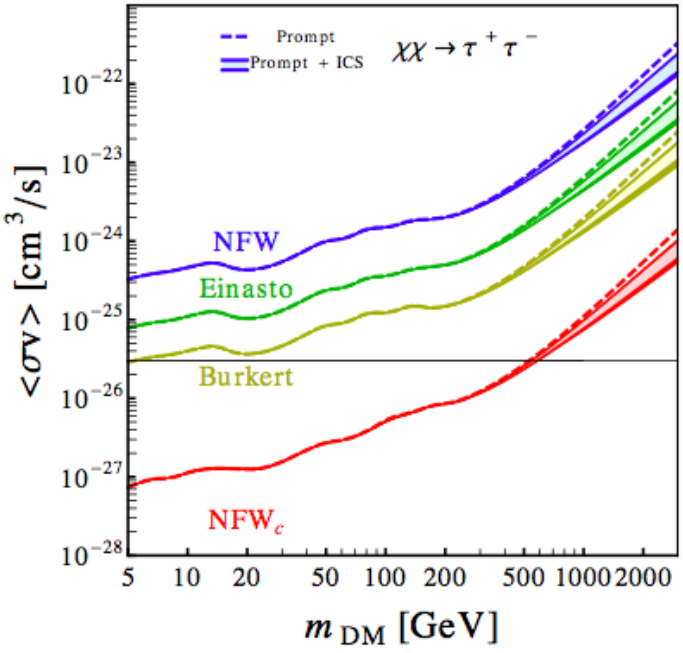
No assumption on background

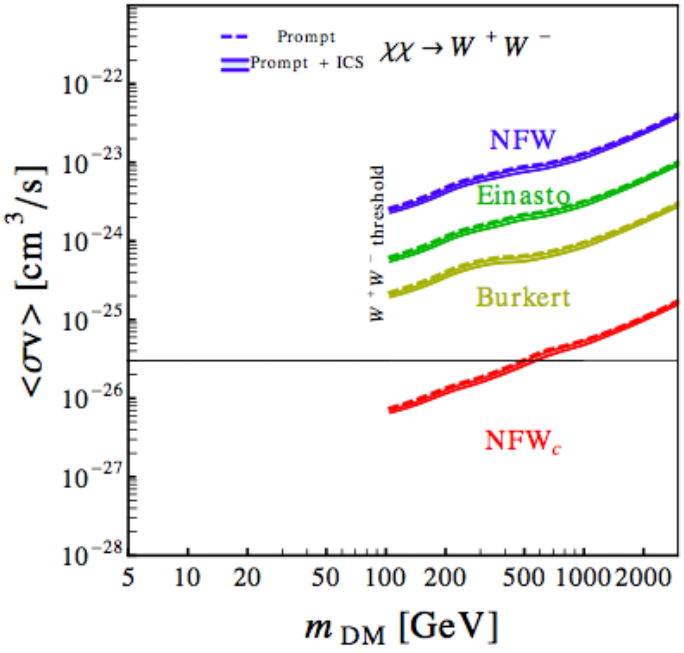
very robust result

Gomez-Vargas et al. JCAP 10 (2013) 029 arXiv:1308.3515









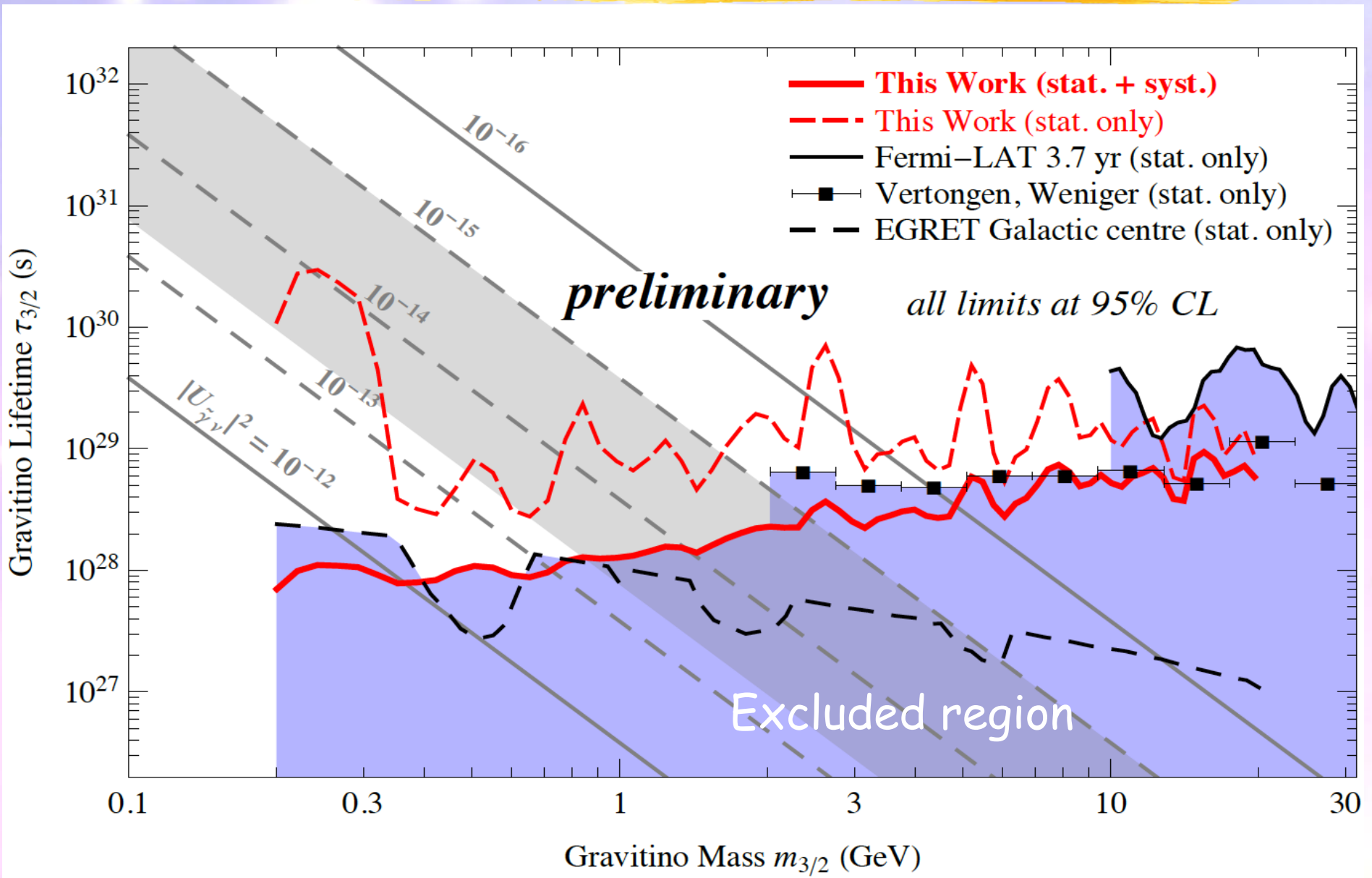
New Low Energy Line Search

Purpose:
To perform a spectral search for gamma-ray lines from 100 MeV to 10 GeV with the Fermi-LAT data
This would constrain models of gravitino decay, focus on the μνSSM (Lopez-Fogliani & C. Muñoz PRL 97(2006)041801)

People:
Andrea Albert (SLAC), Elliott Bloom (SLAC), Eric Charles (SLAC), German Gomez Vargas (PUC-Santiago/INFN-Roma2), Aldo Morselli (INFN Roma2) Carlos Muñoz (UAM/IFT Madrid), Michael Grefe (Hamburg), & Christoph Weniger (GRAPPA Amsterdam).

Data:
5.2 years of Pass 7 Reprocessed data
Fit for lines from 100 MeV to 10 GeV

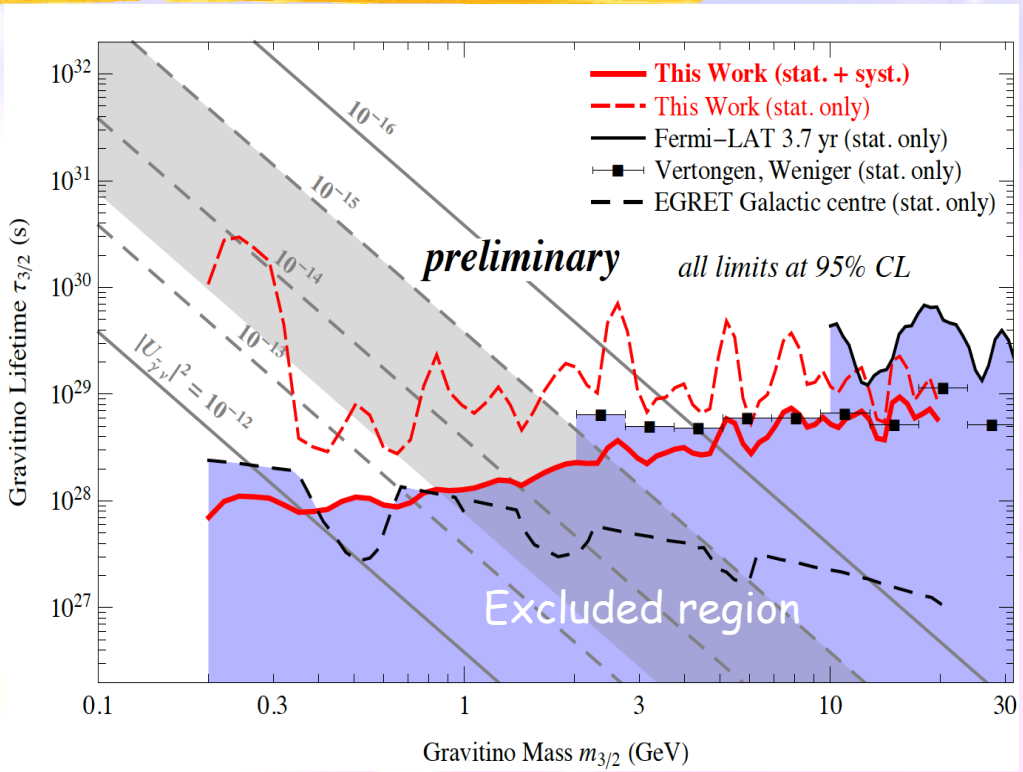
Preliminary Limits for |b|>60° RoI



New Low Energy Line Search

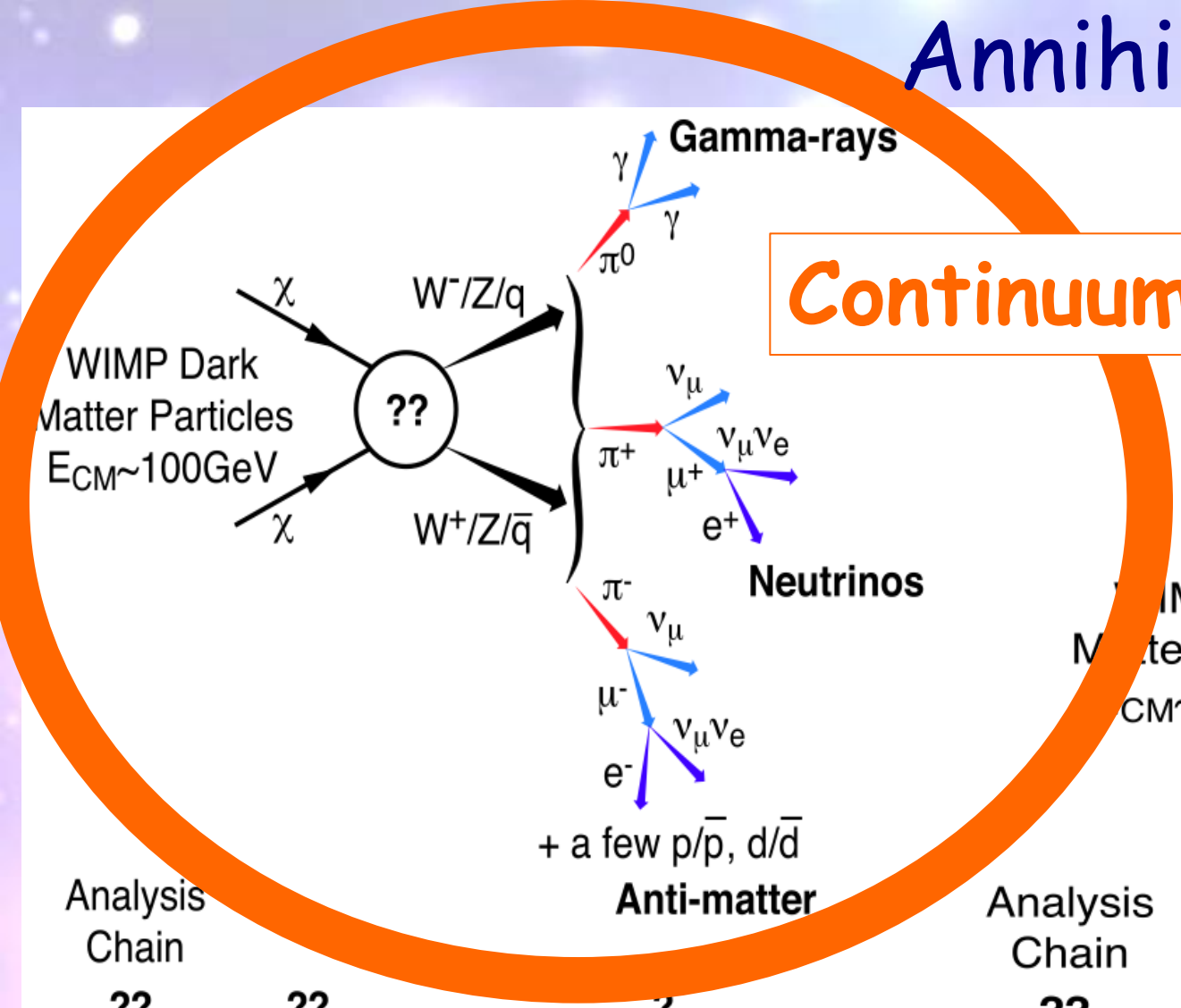
But this Analysis is Systematics Limited

- *Modeling effective area*
- *background emission*
- *not masking known point sources*: because the broad PSF of the LAT at low energies.

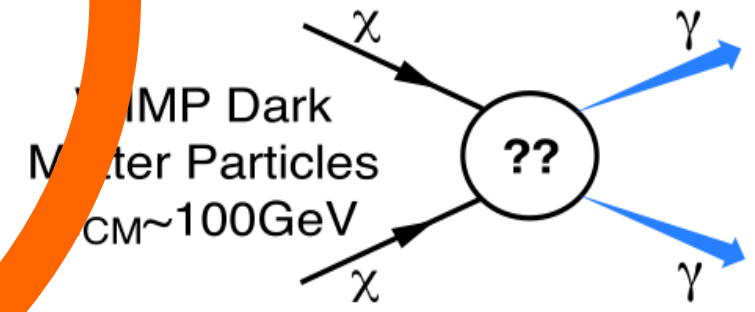


To improve the search a better energy and angular resolution at low energies is needed

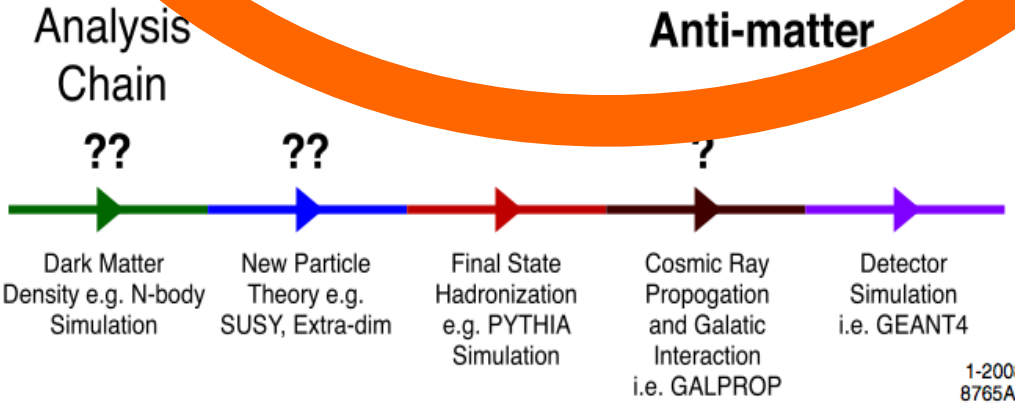
Annihilation channels

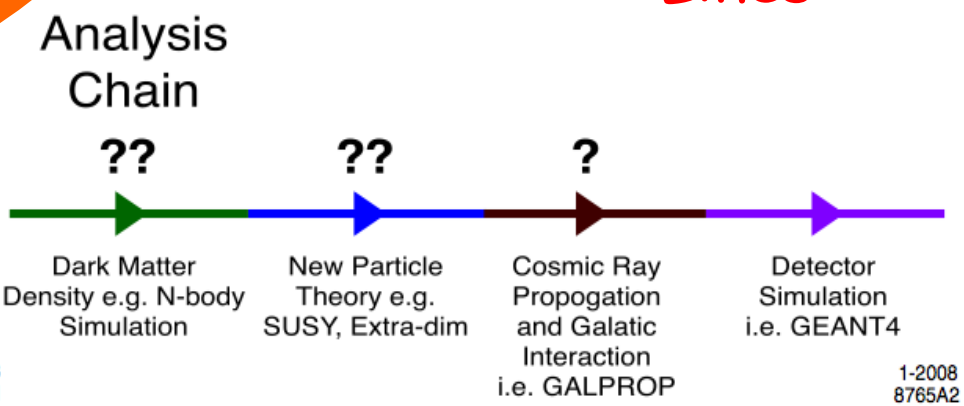


Continuum emission

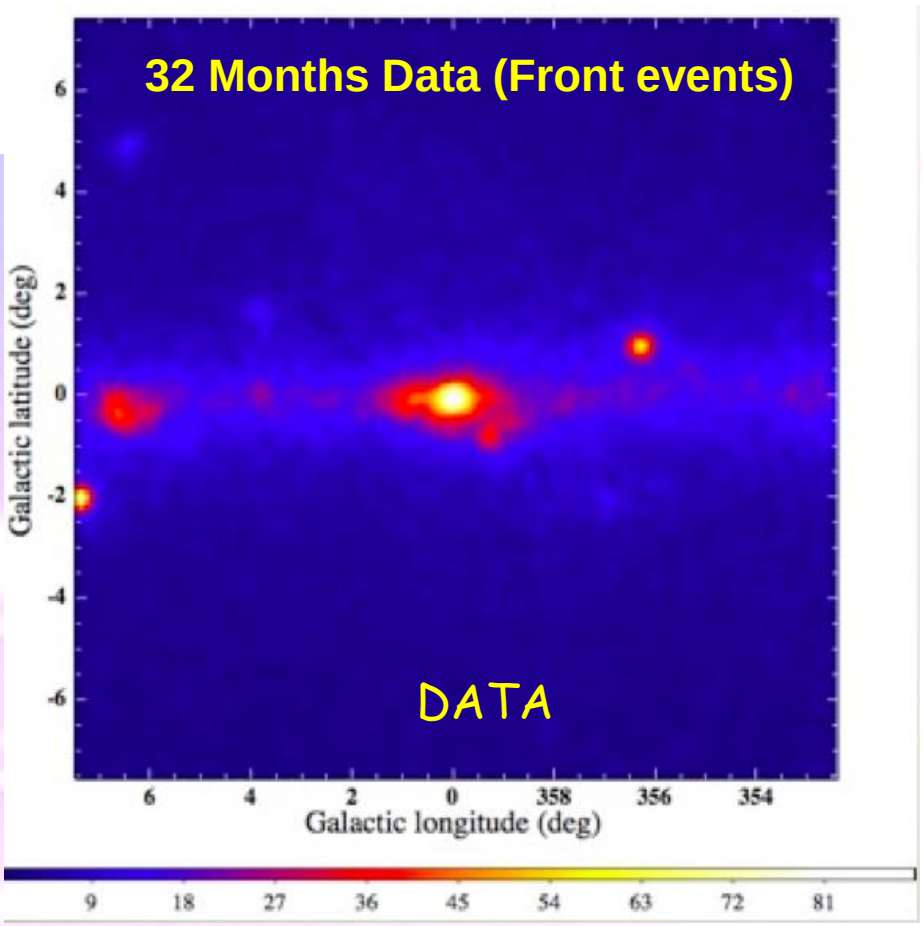


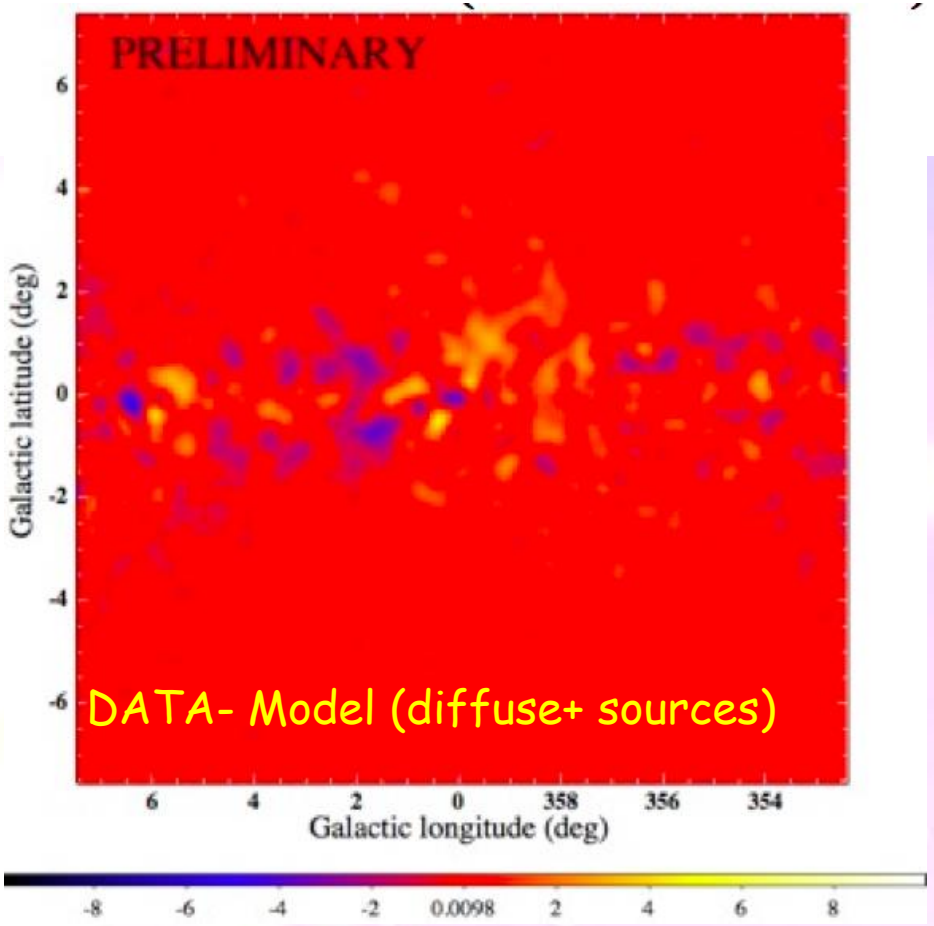
Lines





Residual Emission for 15 * 15 degrees around the Galactic center

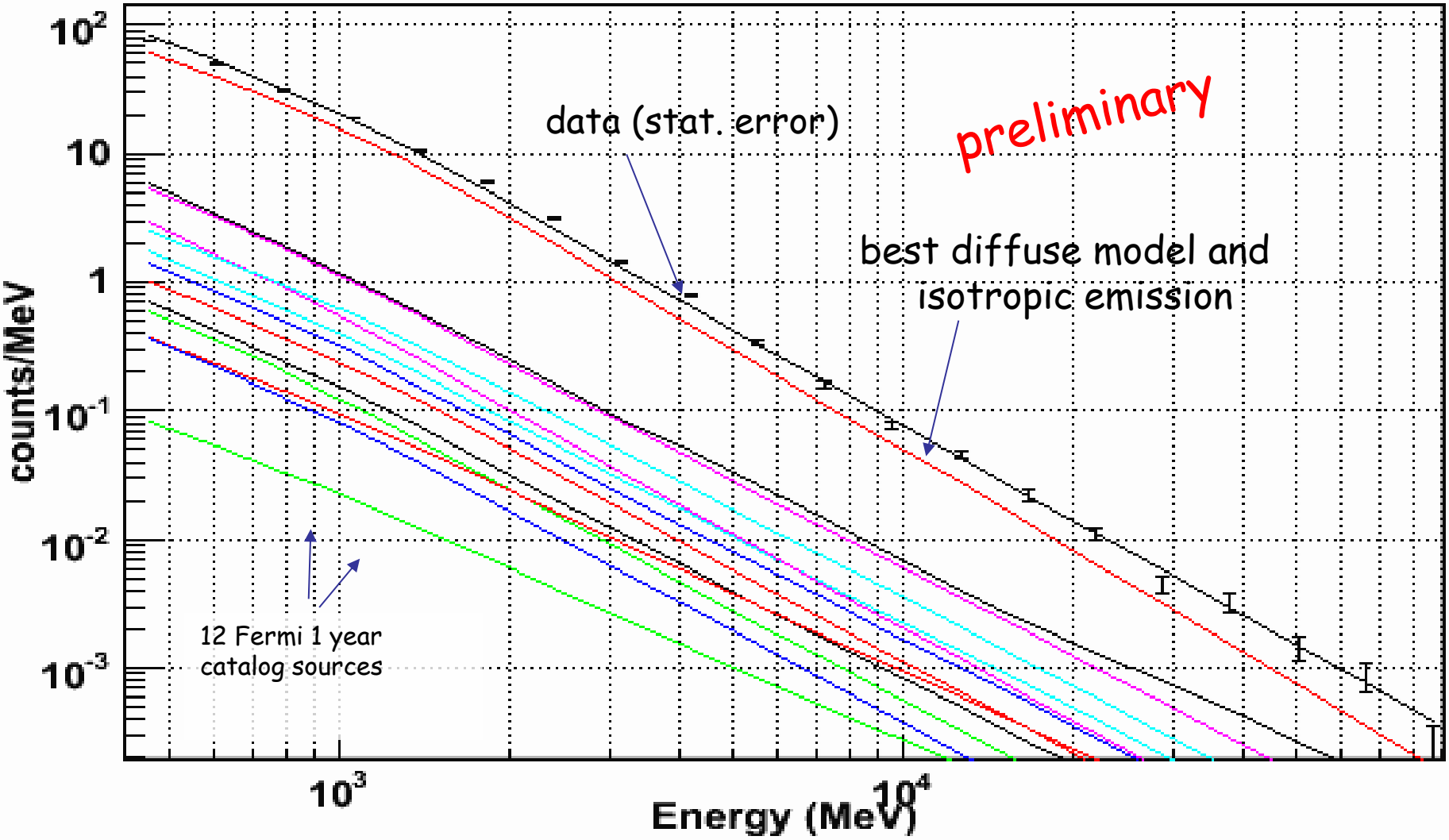




Diffuse emission and point sources account for most of the emission observed in the region.

Low-level residuals remain, the interpretation of these is work in-progress

Spectrum (E> 400 MeV, 7° x7° region centered on the Galactic Center analyzed with binned likelihood analysis)



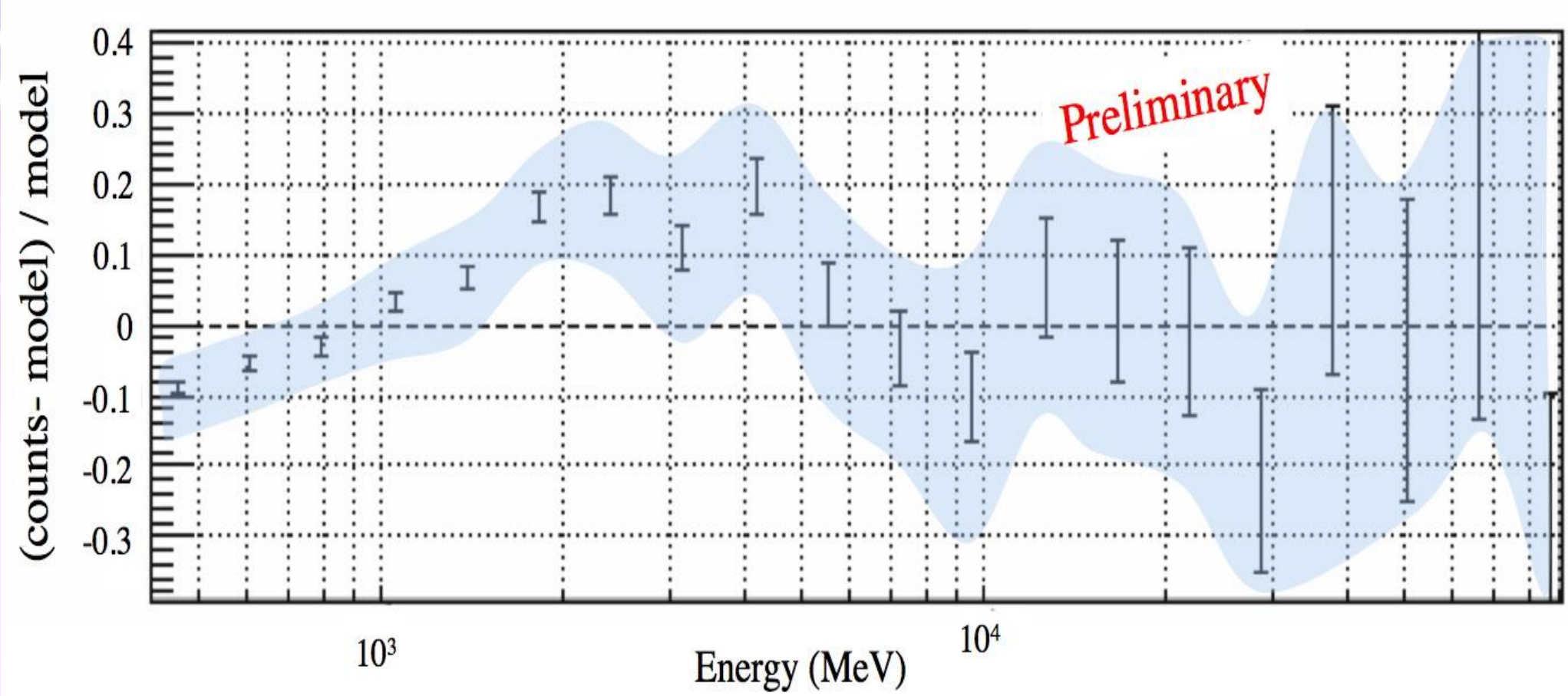
Fermi Coll. NIM A630 (2011) 147 [arXiv:0912.3828]

GC Residuals

7° x7° region centered on the Galactic Center

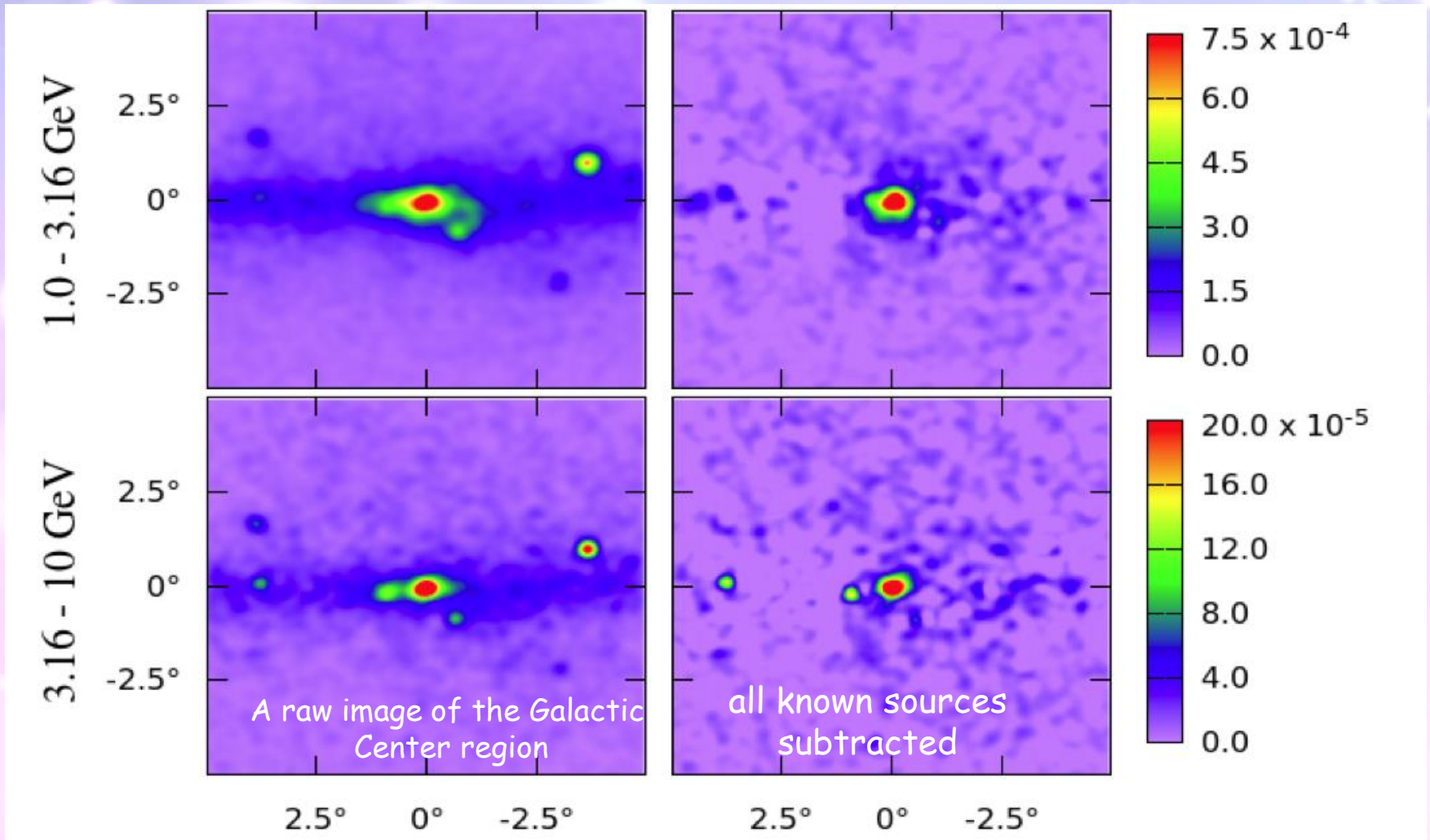
11 months of data, E >400 MeV, front-converting events analyzed with binned likelihood analysis)

- The systematic uncertainty of the effective area (blue area) of the LAT is ~10% at 100 MeV, decreasing to 5% at 560 MeV and increasing to 20% at 10 GeV



Fermi Coll. NIM A630 (2011) 147 [arXiv:0912.3828]

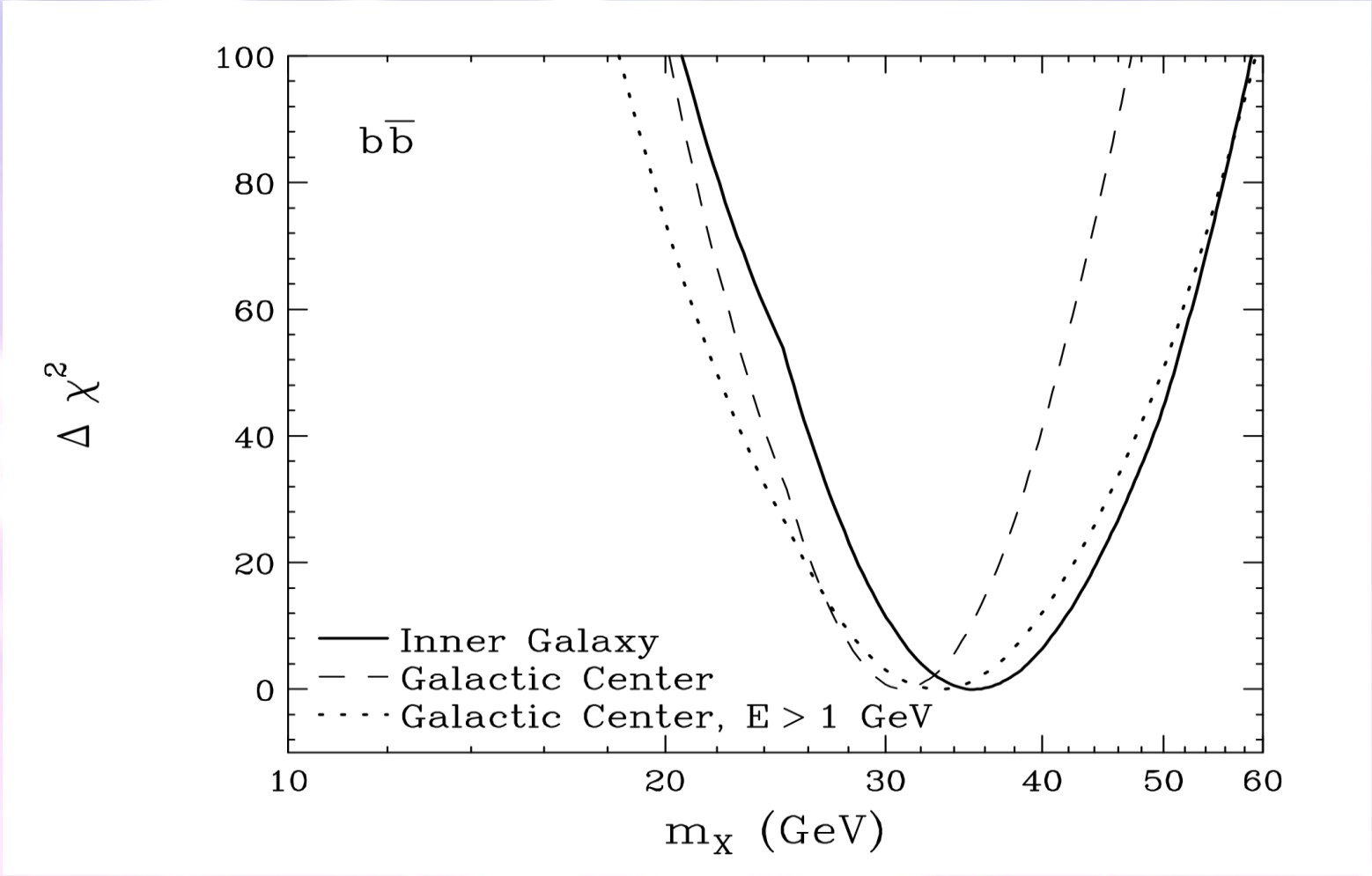
Galactic Center and Dark Matter



- Spatially extended excess of 1-3 GeV γ rays with a spectrum, angular distribution, and overall normalization that is in good agreement with that predicted by simple annihilating dark matter models"
- Well fit by a 31-40 GeV WIMP with $\langle\sigma v\rangle = (1.4 - 2.0) \times 10^{-26}$ cm^3/s
- approximately spherically symmetric and centered around the dynamical center of the Milky Way

A Compelling Case for Annihilating Dark Matter arXiv:1402.6703

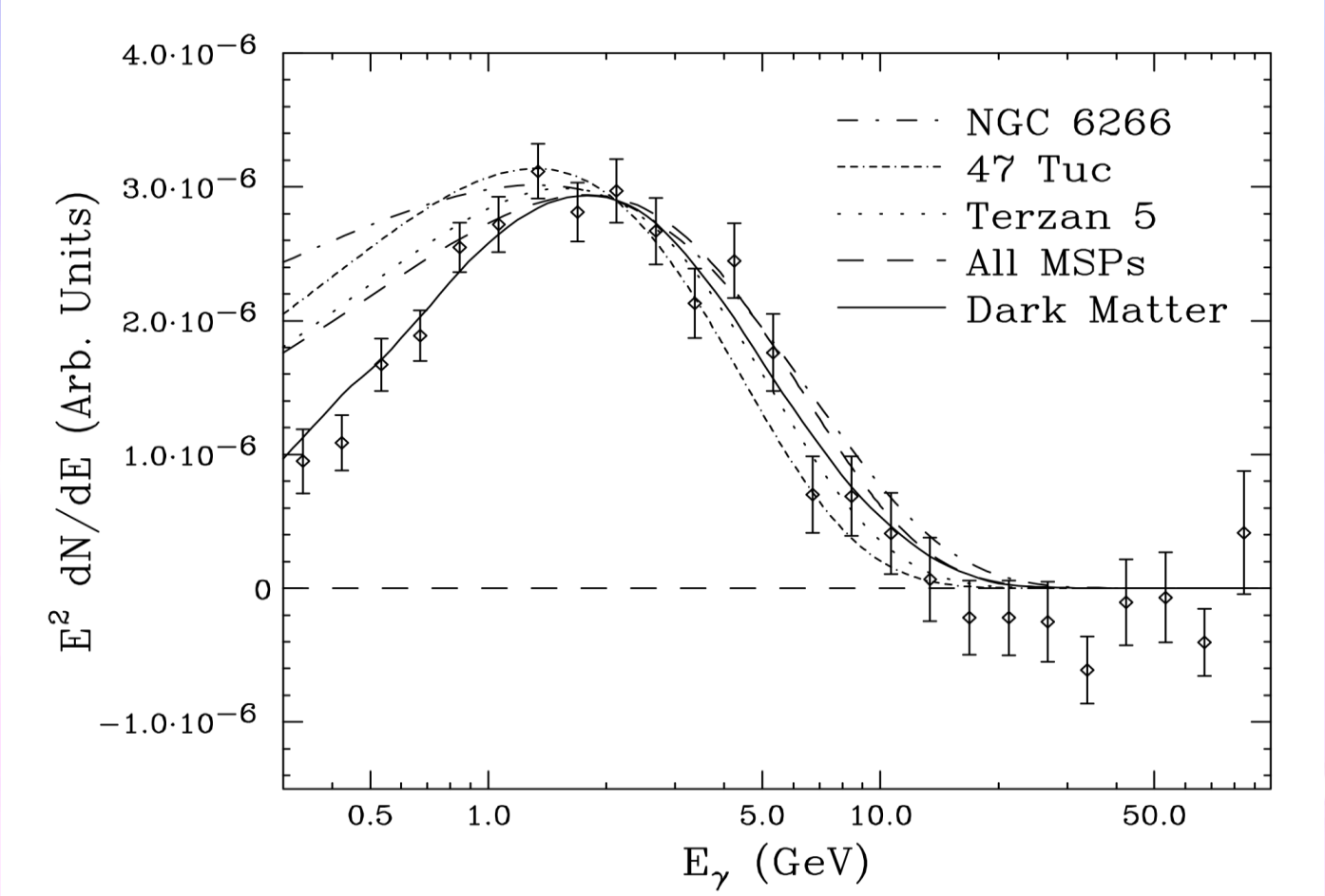
Galactic Center and Dark Matter



A comparison of the dark matter mass determination using the spectrum derived from our Inner Galaxy analysis (solid line) and using the spectrum derived from our Galactic Center analysis (dashed and dotted lines)

A Compelling Case for Annihilating Dark Matter arXiv:1402.6703

Galactic Center and Dark Matter



A comparison of the spectral shape of the gamma- ray excess from the sum of all millisecond pulsars detected as individual point sources by Fermi.The gamma-ray spectrum measured from millisecond pulsars and from globular clusters (whose emission is believed to be dominated by millisecond pulsars) is consistently softer than that of the observed excess at energies below ⇠1 GeV.

A Compelling Case for Annihilating Dark Matter arXiv:1402.6703

Very similar to the SNR pion bump problem

Origin of Cosmic Rays

Cosmic rays are particles (mostly protons) accelerated to relativistic speeds.

Despite wide agreement that supernova remnants (SNRs) are the sources of galactic cosmic rays, unequivocal evidence for the acceleration of protons in these objects is still lacking.

When accelerated protons encounter interstellar material they produce neutral pions, which in turn decay into gamma rays. This offers a compelling way to detect the acceleration sites of protons.

The identification of pion-decay gamma rays has been difficult because high-energy electrons also produce gamma rays via bremsstrahlung and inverse Compton scattering.

The π^0-decay bump

- Neutral pion-decay: in the rest-frame of the pion, the two γ rays have 67.5 MeV each (i.e. a line)

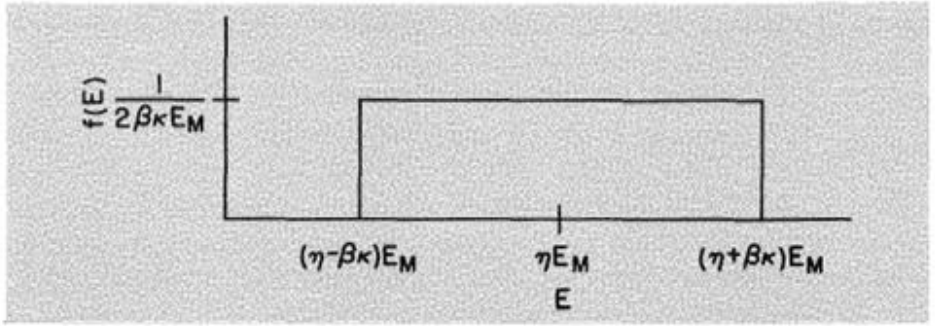
Stecker, 1971 (Cosmic gamma rays)

- Transforming into the lab-frame smears the line but keeps it symmetric about 67.5 MeV (in dN/dE)

Dermer, 1986

- Transforming to E2 dN/dE and drop in pion-production cross section destroys symmetry and generates the "bump"

Stecker, 1971 (Cosmic gamma rays)



Dermer, 1986

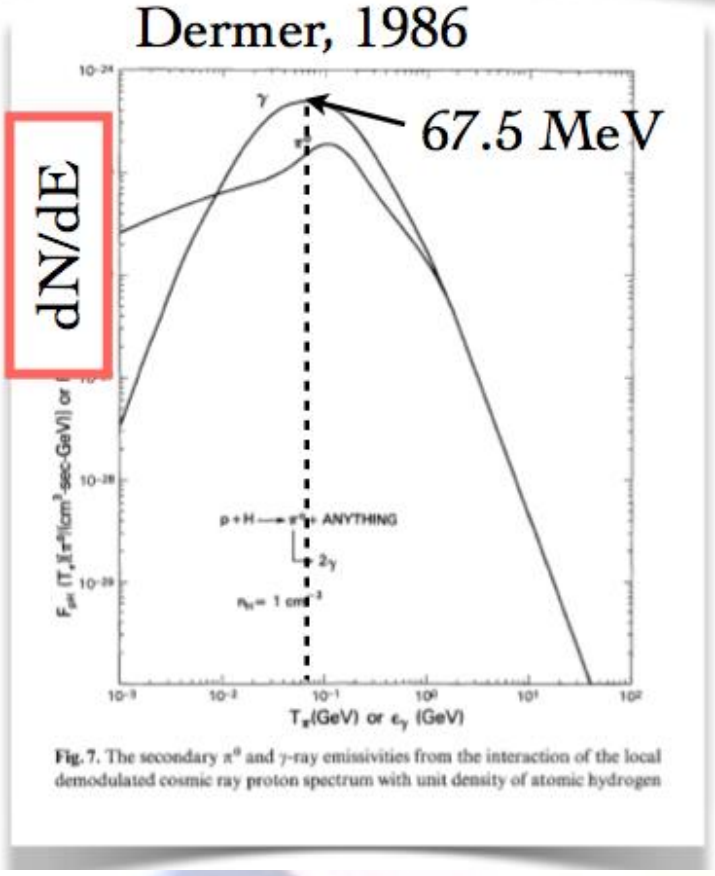
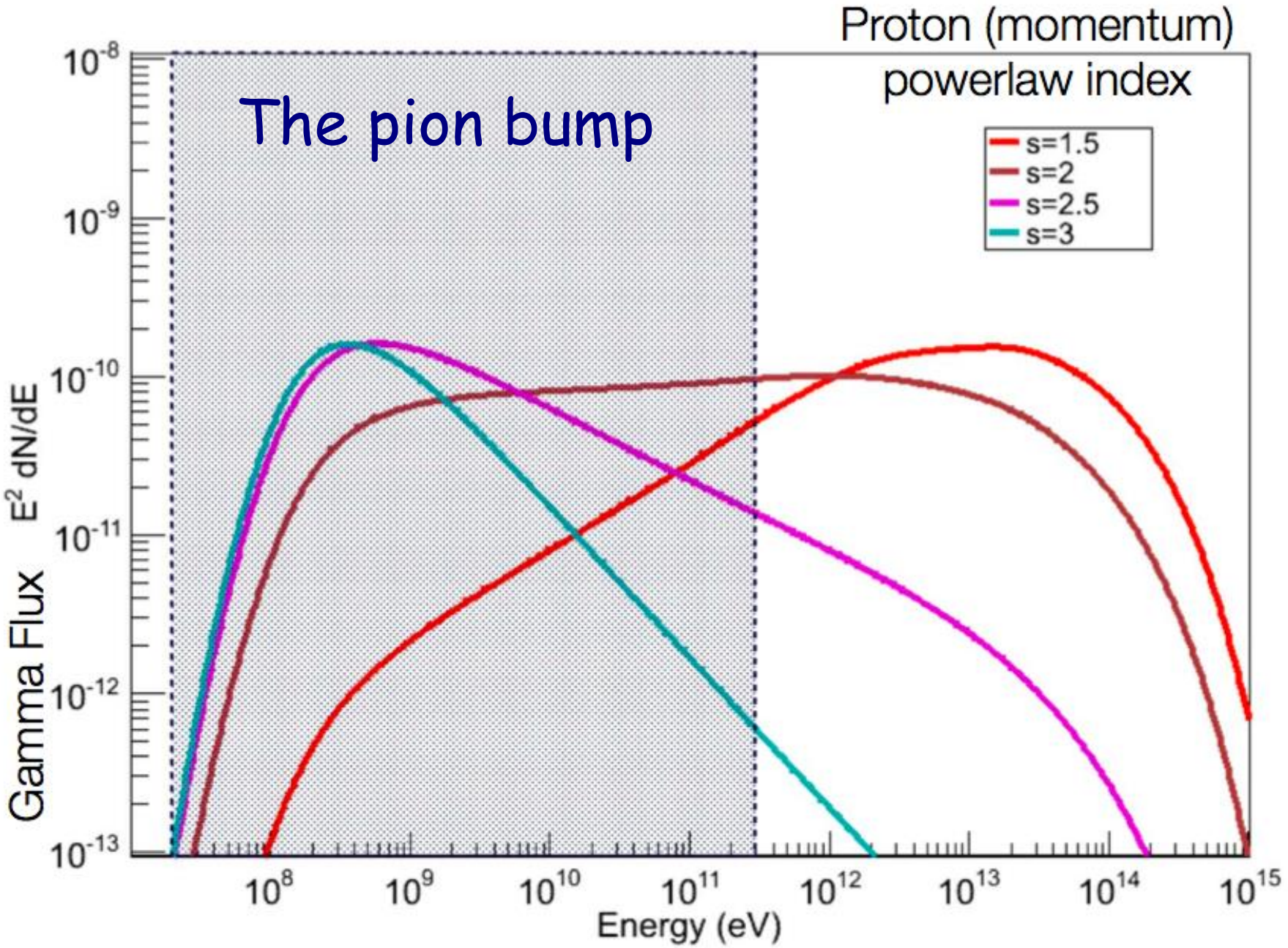


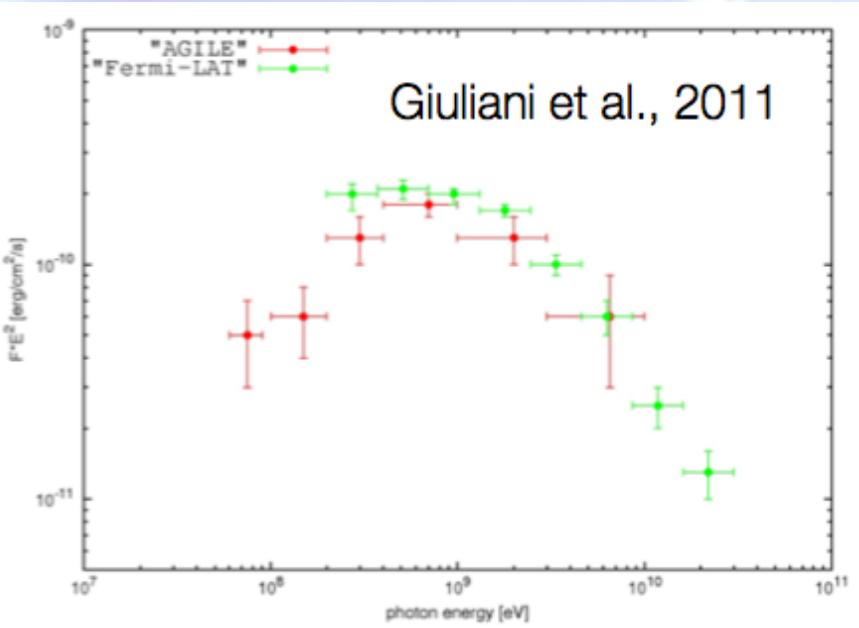
Fig. 7. The secondary π^0 and γ-ray emissivities from the interaction of the local demodulated cosmic ray proton spectrum with unit density of atomic hydrogen

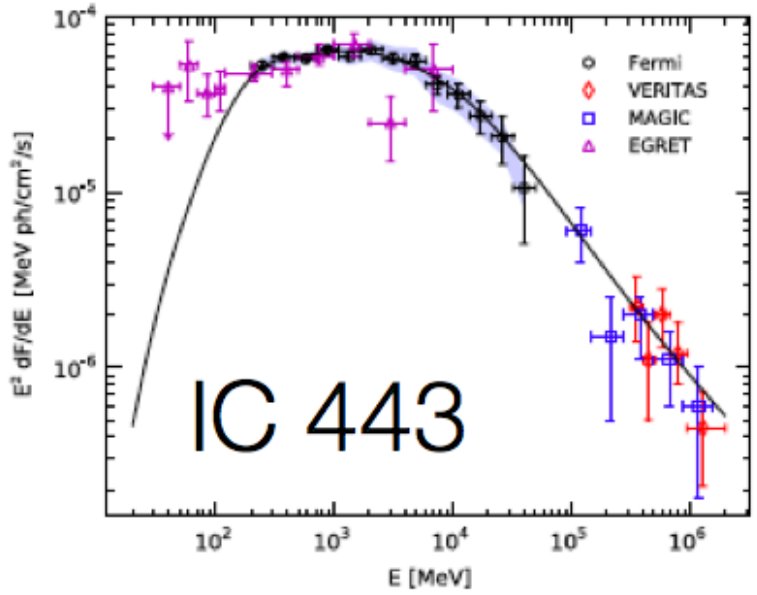


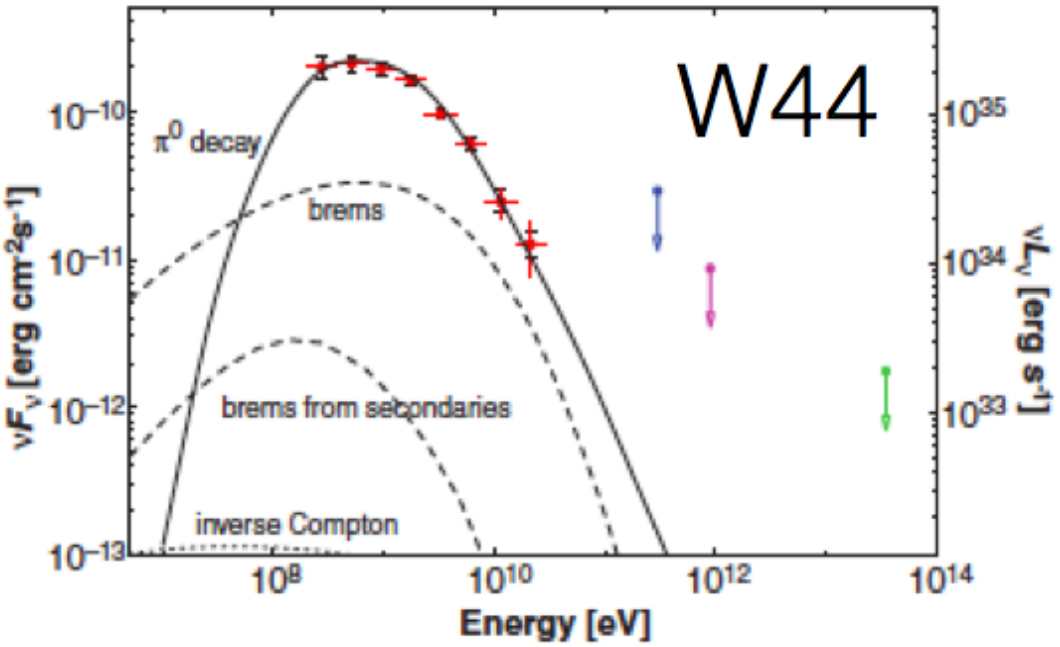
Smoking gun feature for accelerated protons

Early observations

- Seen with EGRET in the Galactic diffuse
- AGILE detection of "bump" in W44 (Giuliani et al., 2011)
- Previous Fermi-LAT analyses started at 200 MeV (rapidly changing effective area)

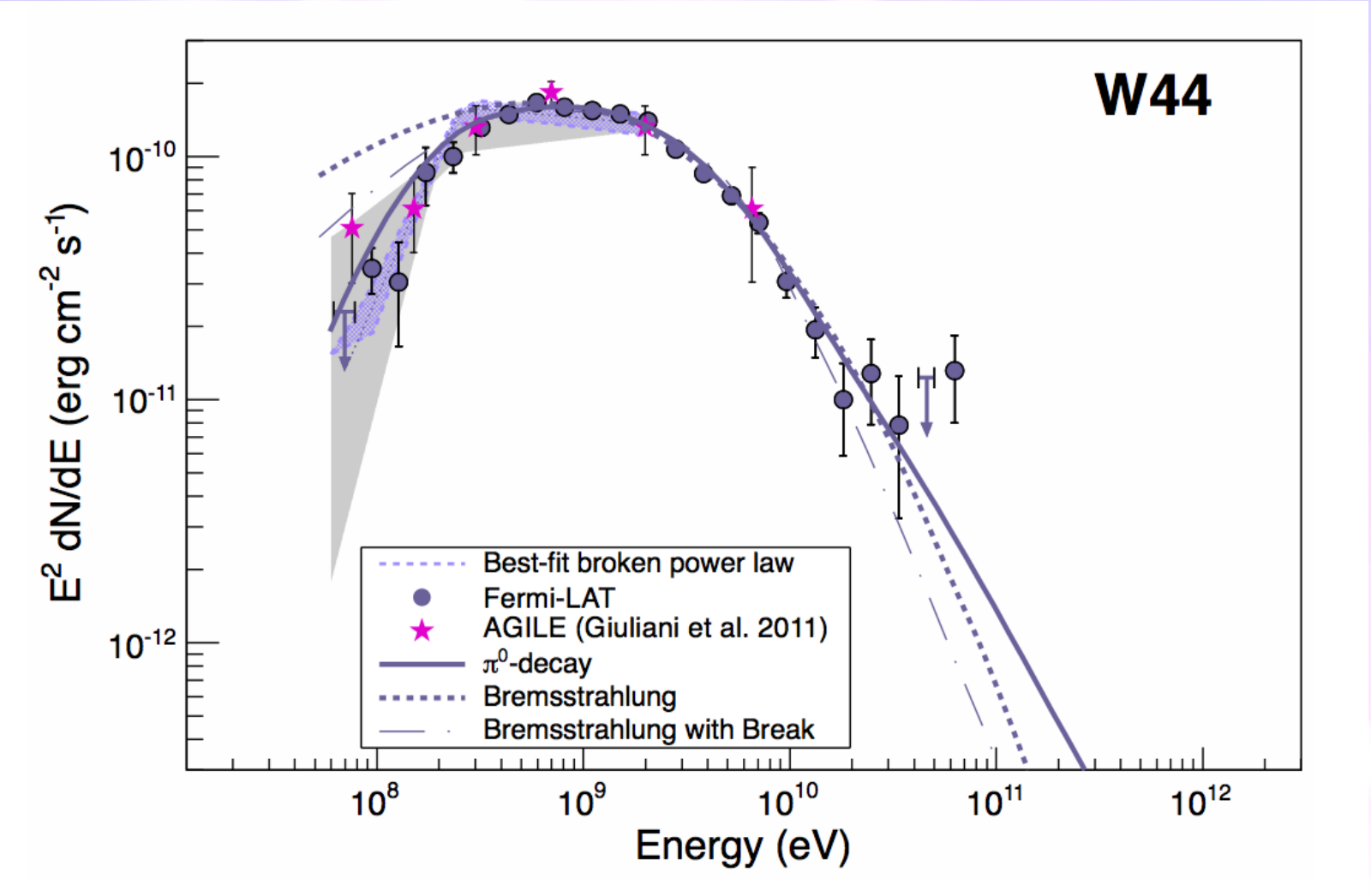






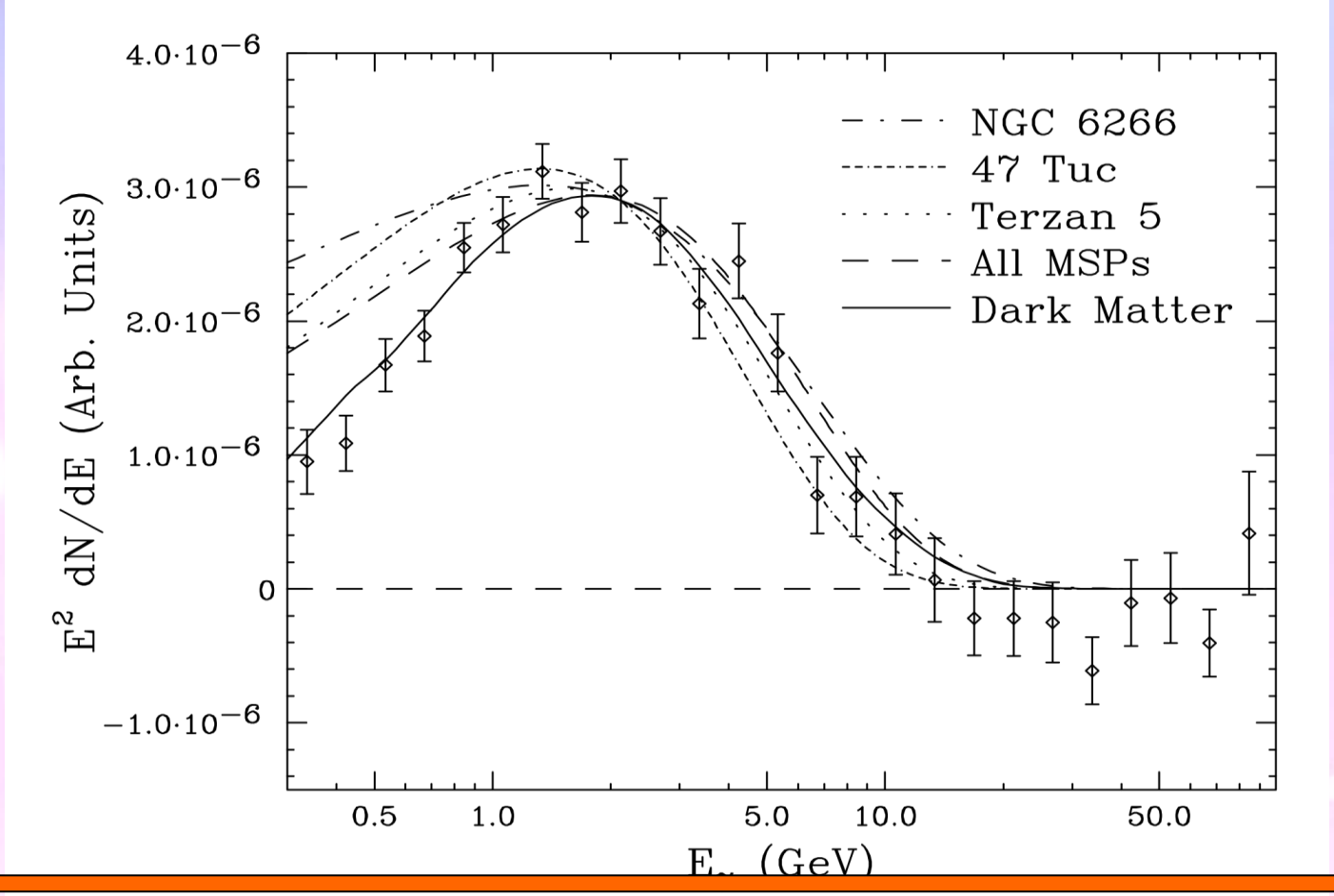
Detection of the Characteristic Pion-decay Signature in Supernova Remnants

Direct evidence that cosmic-ray protons are accelerated in SNR



Science 339, (2013) 807 [arXiv:1302.3307] 15 Feb. 2013

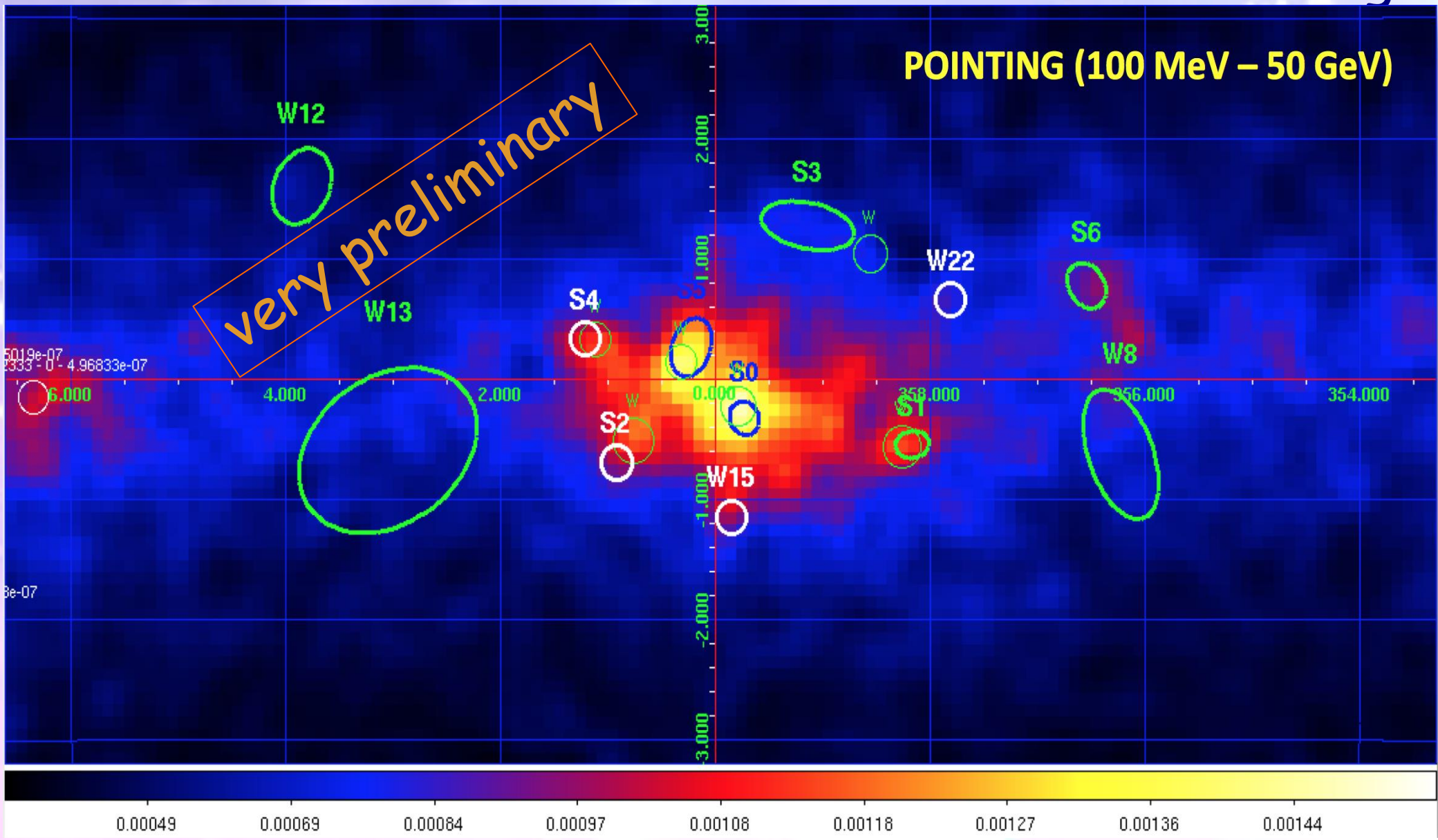
Galactic Center and Dark Matter



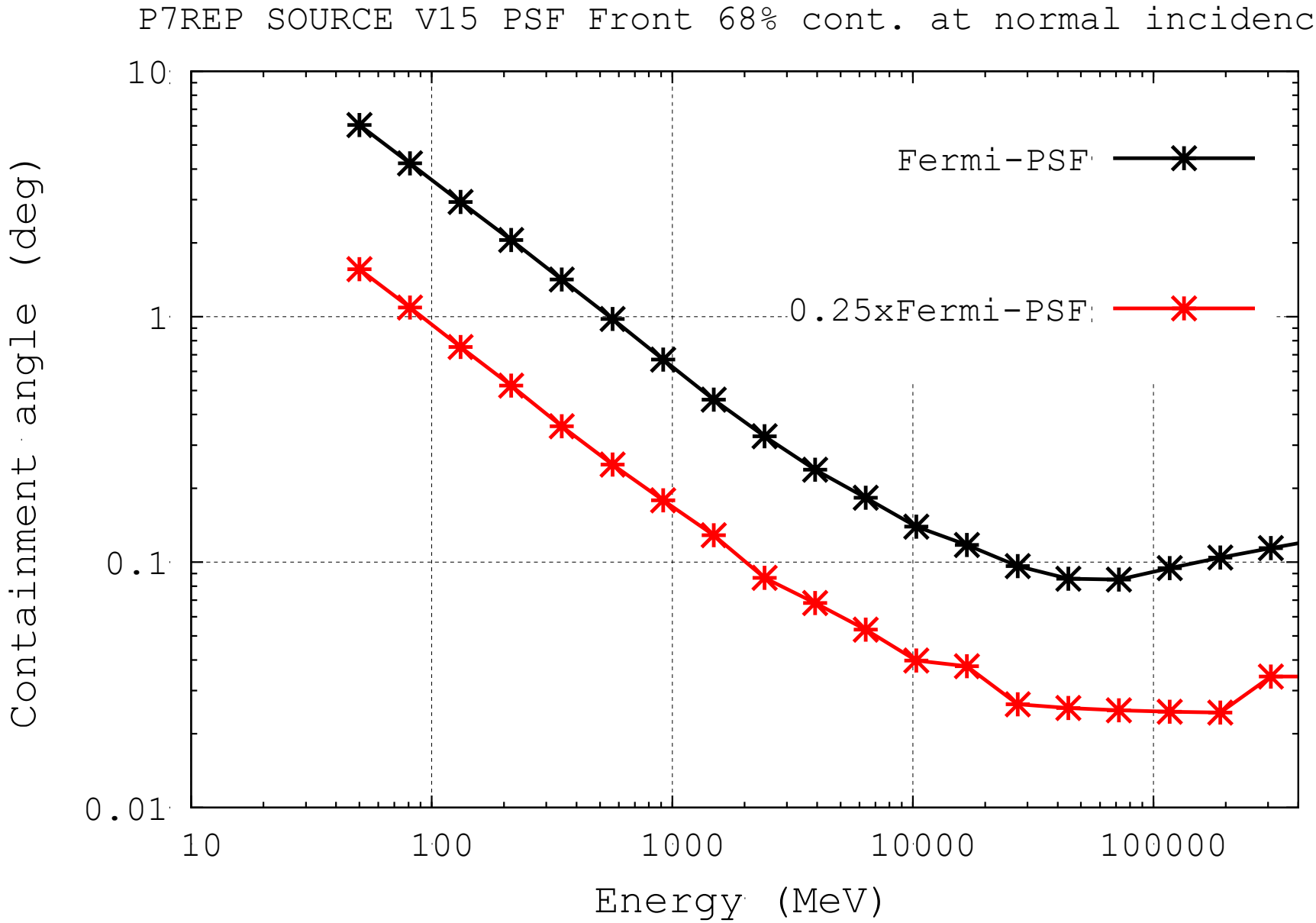
To improve the search a better energy and angular resolution at low energies is needed

A Compelling Case for Annihilating Dark Matter arXiv:1402.6703

AGILE Data from the Galactic Center are coming

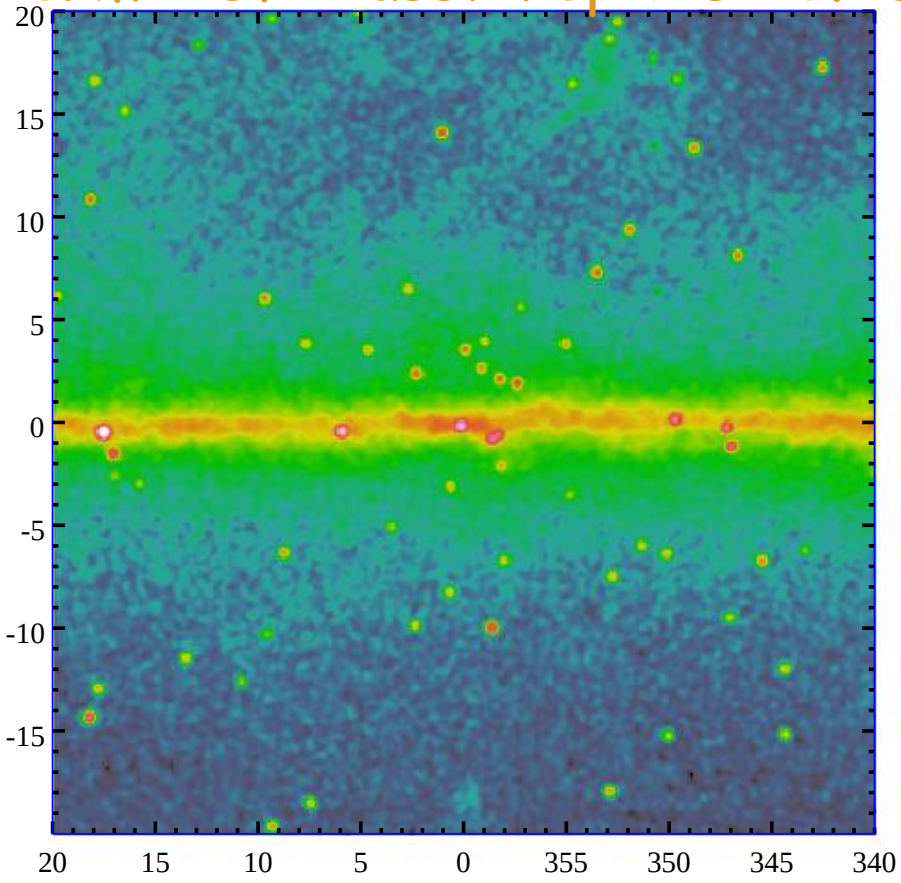


See the poster by V.Fioretti et al. outside

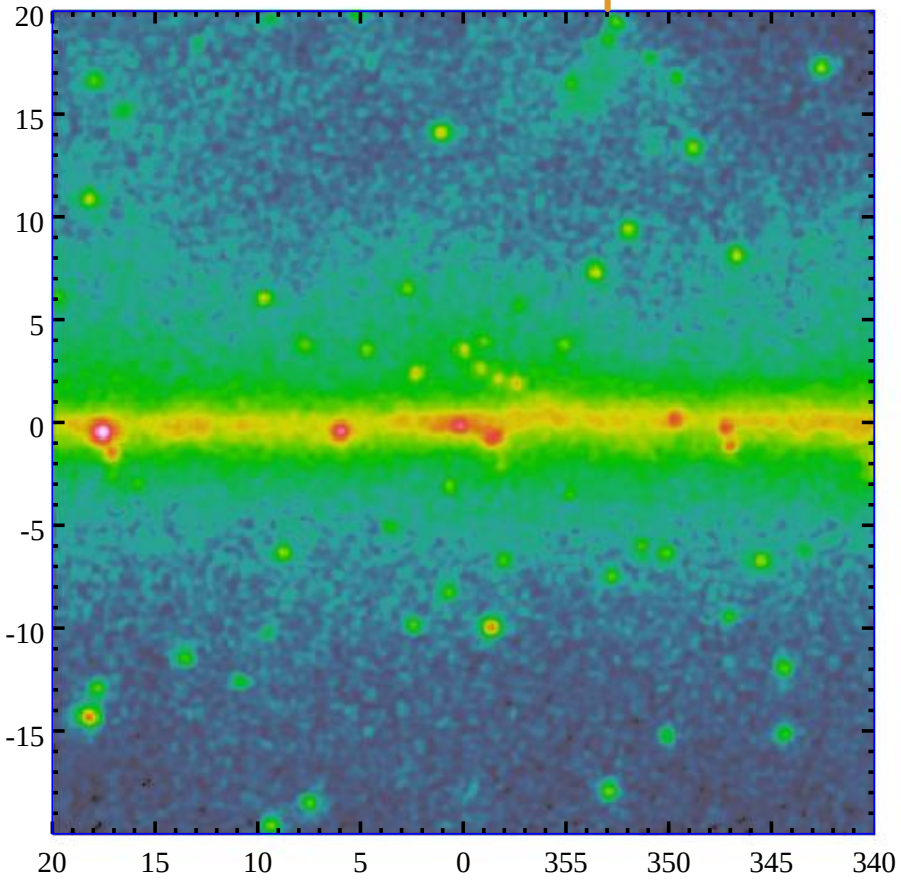

P7REP SOURCE V15 PSF Front 68% cont. at normal incidence
Containment angle (deg)
10
1
0.1
0.01
10
100
1000
10000
100000
Energy (MeV)
Fermi-PSF
0.25xFermi-PSF

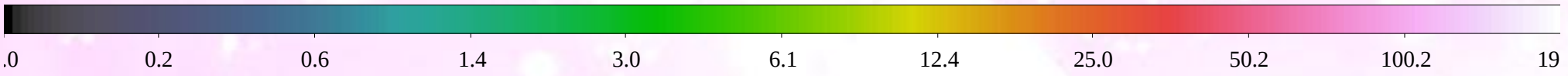
Galactic Center Region 1-5 GeV

Fermi PSF Pass7 rep v15 *0.25



Fermi PSF Pass7 rep v15 source



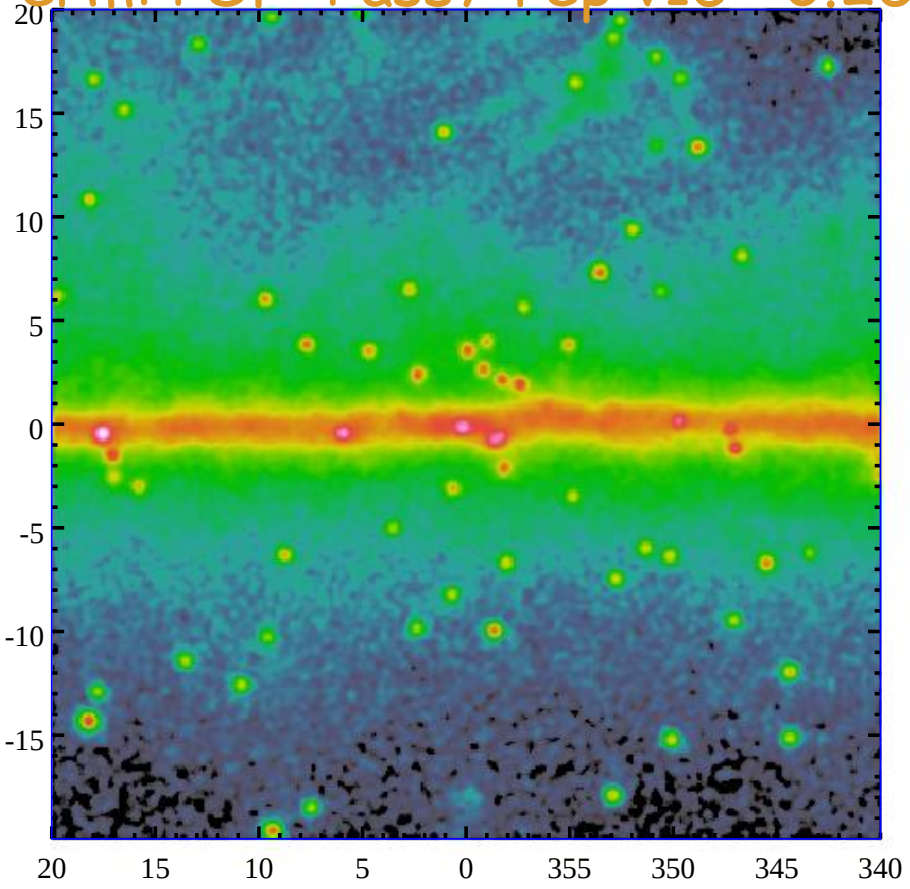


Sources from two years Fermi catalog , template ring model for diffuse

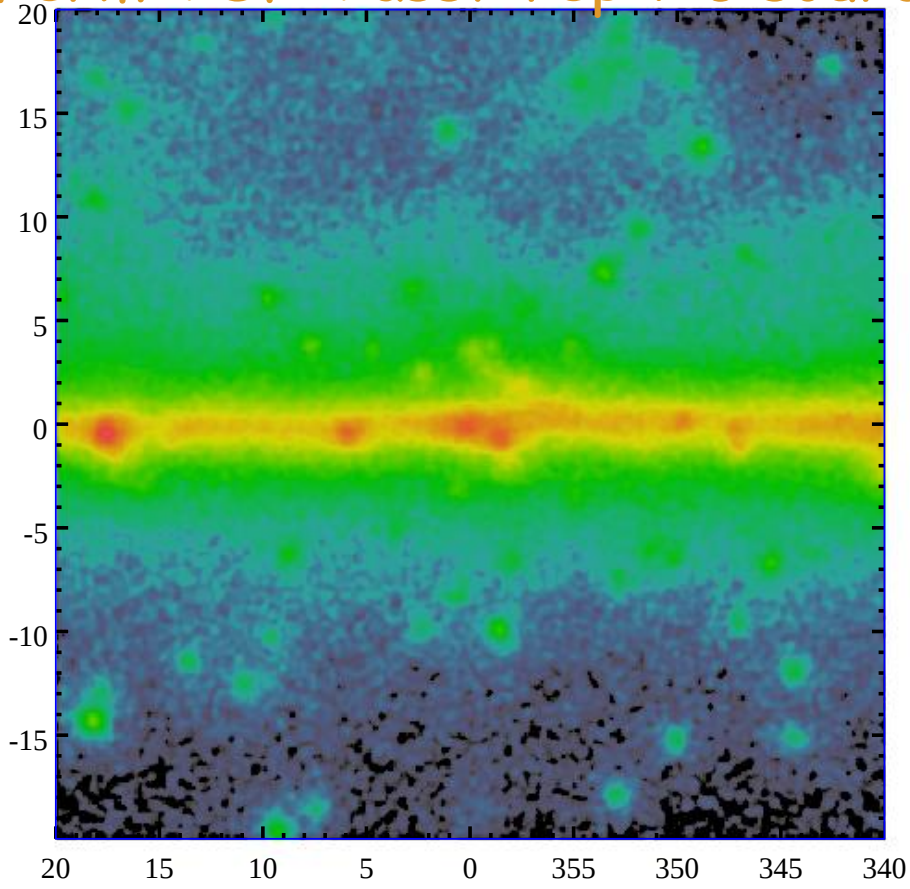
ApJ S 2012 199,31 [arXiv:1108.1435]

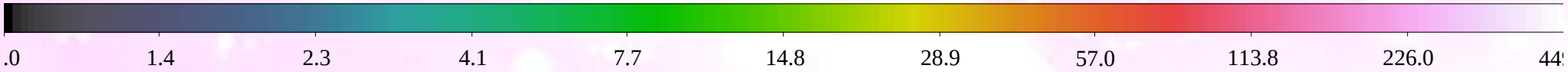
Galactic Center Region 0.2-1 GeV

Fermi PSF Pass7 rep v15 *0.25



Fermi PSF Pass7 rep v15 source

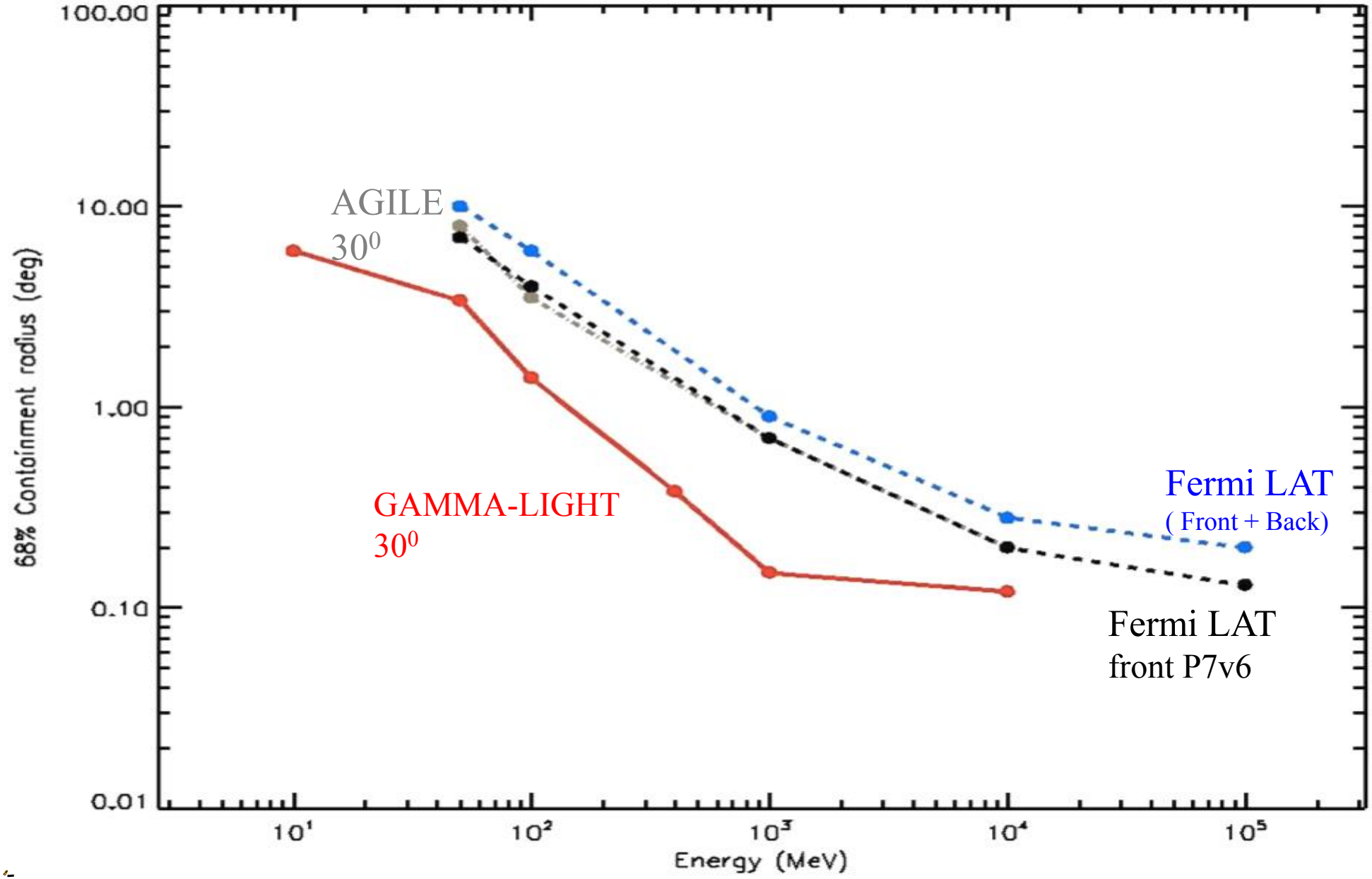




Sources from two years Fermi catalog , template ring model for diffuse,

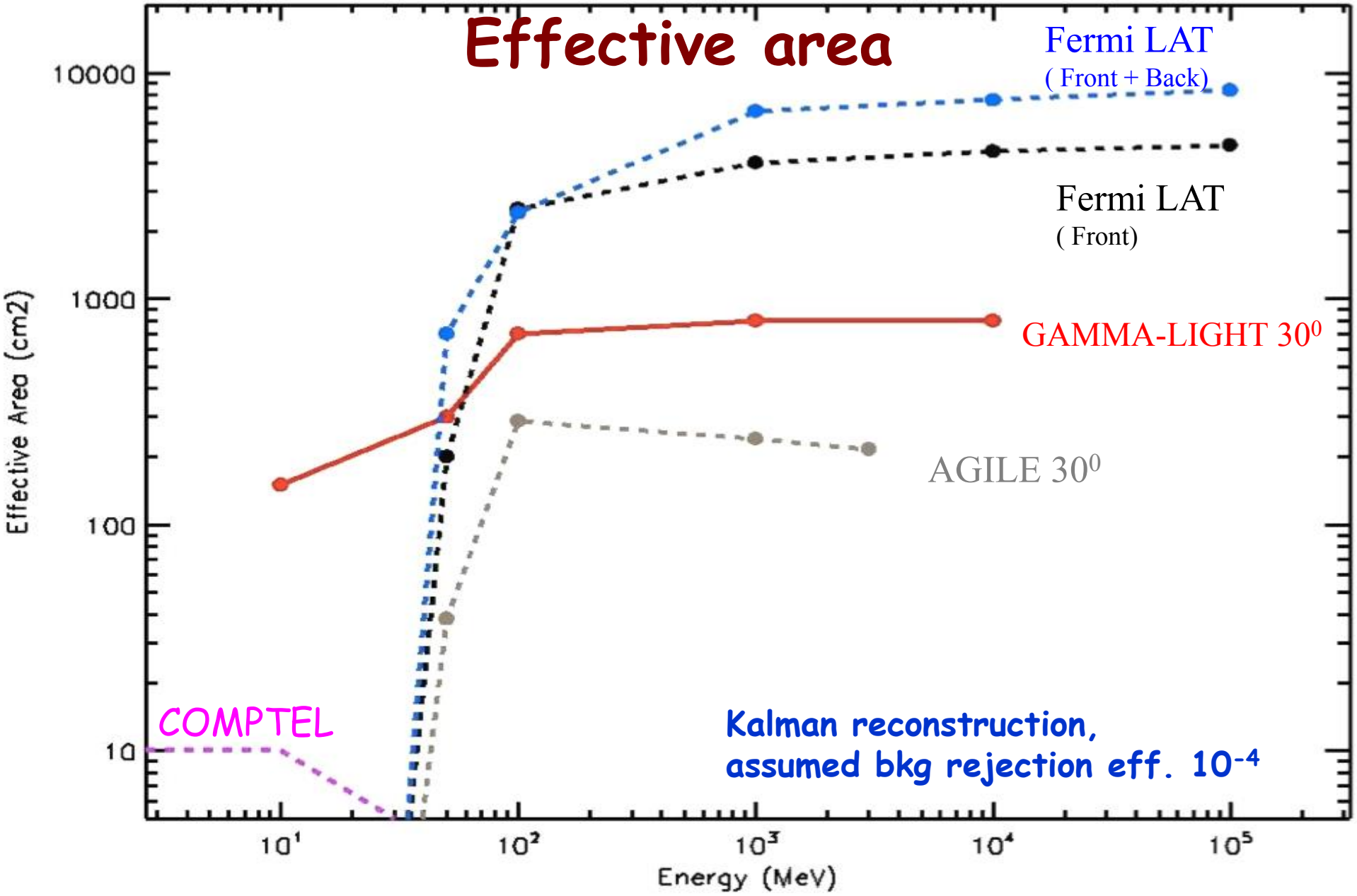
ApJ S 2012 199,31 [arXiv:1108.1435]

PSF (68% containment radius)

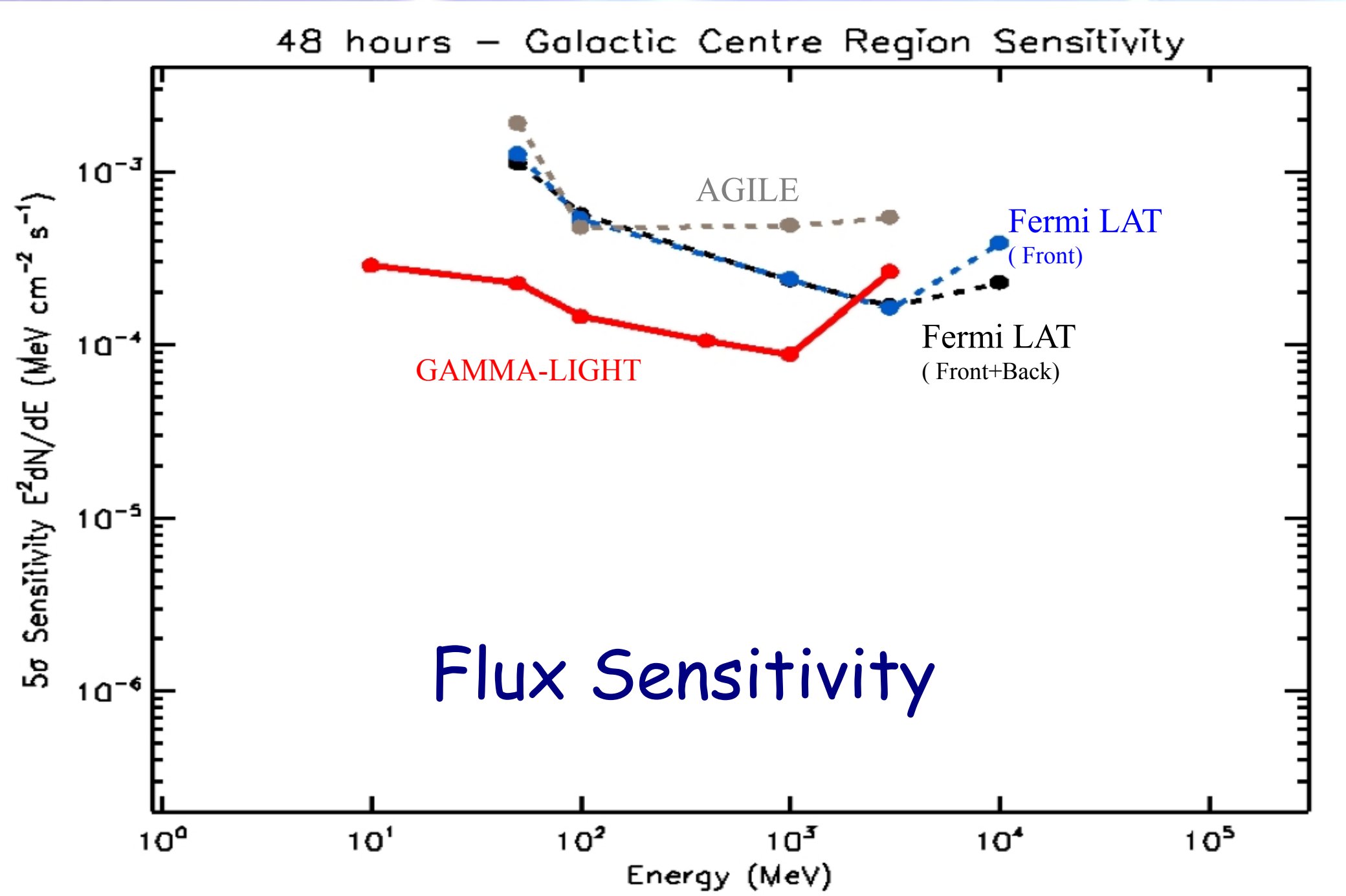


A.Morselli et al. , Nuclear Physics B Proc. Supp. 239–240 (2013) 193-198

Effective area



A.Morselli et al. , Nuclear Physics B Proc. Supp. 239–240 (2013) 193-198


48 hours – Galactic Centre Region Sensitivity
AGILE
Fermi LAT
(Front)
Fermi LAT
(Front+Back)
GAMMA-LIGHT
Flux Sensitivity
5σ Sensitivity E²dN/dE (MeV cm⁻² s⁻¹)
Energy (MeV)
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁰
10¹
10²
10³
10⁴
10⁵

4-6 June 2014 in Lisboa:
10 th SciNeGHE conference

(Science with the New Generation of High Energy Gamma-ray Experiments)

You are all invited

If you are interested

Università degli Studi di Roma "Tor Vergata"
Dipartimento di Fisica

SEMINARIO GENERALE

Jennifer Siegal-Gaskins
California Institute of Technology

Dark matter signals from the Inner Galaxy?

Venerdi' 16 Maggio 2012 ore 14.30

Aula Seminari " U. M. Grassano "

- **After the seminar ARAP 2013 Awards will be given for PhD thesis in Astroparticle Physics of the three Universita 'di Roma**
  - **Martina Cardillo**
  - **Francesco Palma**
  - **Edoardo Striani**

Thank you for the attention