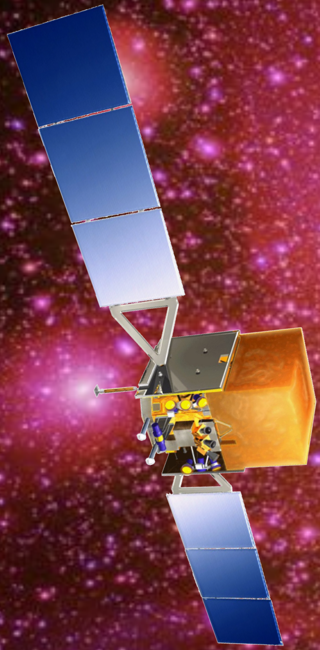
# The sky seen by Fermi and the future of gamma-ray astroparticle physics




*Aldo Morselli*

*INFN Roma Tor Vergata*


**Astroparticle Physics and Cosmology 2013**

Inside

**Fundamental Physics, CMB and LSS in the light of Planck satellite and DES**

Instituto de Física Teórica UAM-CSIC

Madrid, 23 October 2013

Past decades saw precision studies of 5 % of our Universe -> Discovery of the Standard Model

The LHC is delivering data

We are just at the beginning of exploring 95 % of the Universe.

Exciting prospects

R.-D. Heuer, CERN General Director 36th International Conference on High Energy Physics ICHEP2012, Closing Talk

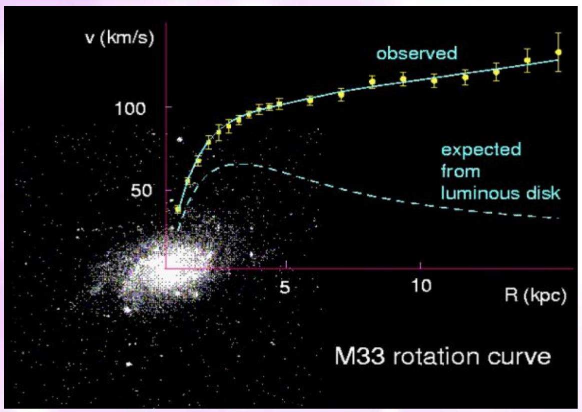
ICHEP2012 Melbourne

# Dark Matter EVIDENCES

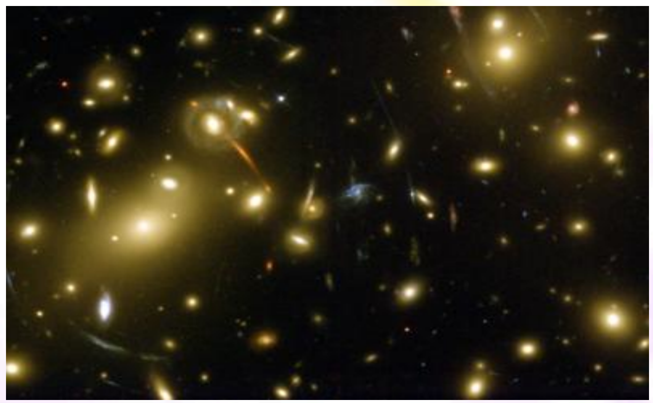
- In 1933, the astronomer Zwicky realized that the mass of the luminous matter in the Coma cluster was much smaller than its total mass implied by the motion of cluster member galaxies:

- Since then, many other evidences:

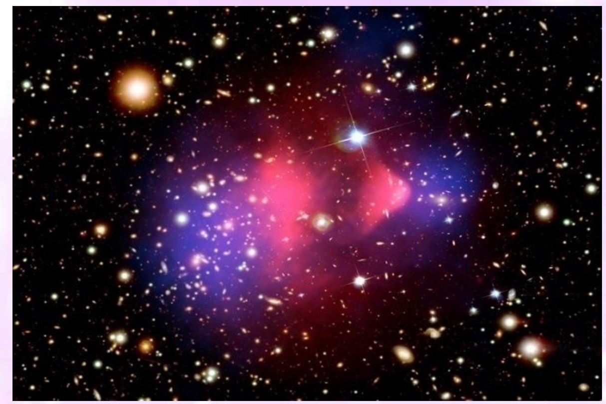
Rotation curves of galaxies



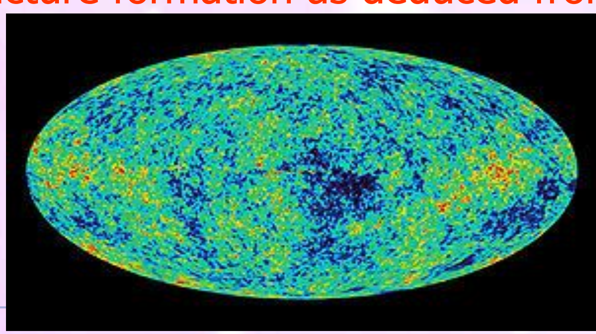

Gravitational lensing



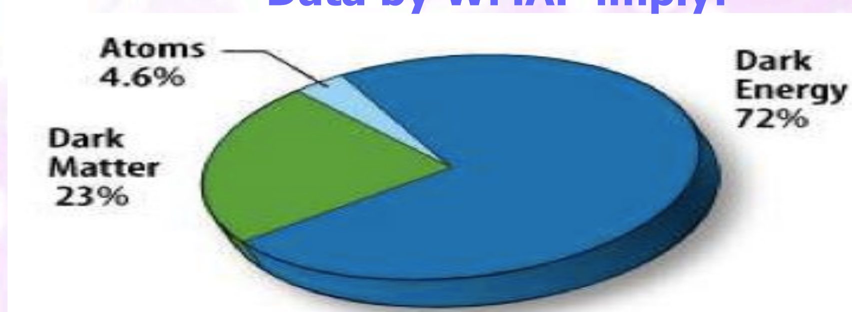
Bullet cluster



Structure formation as deduced from CMB



**Data by WMAP imply:**

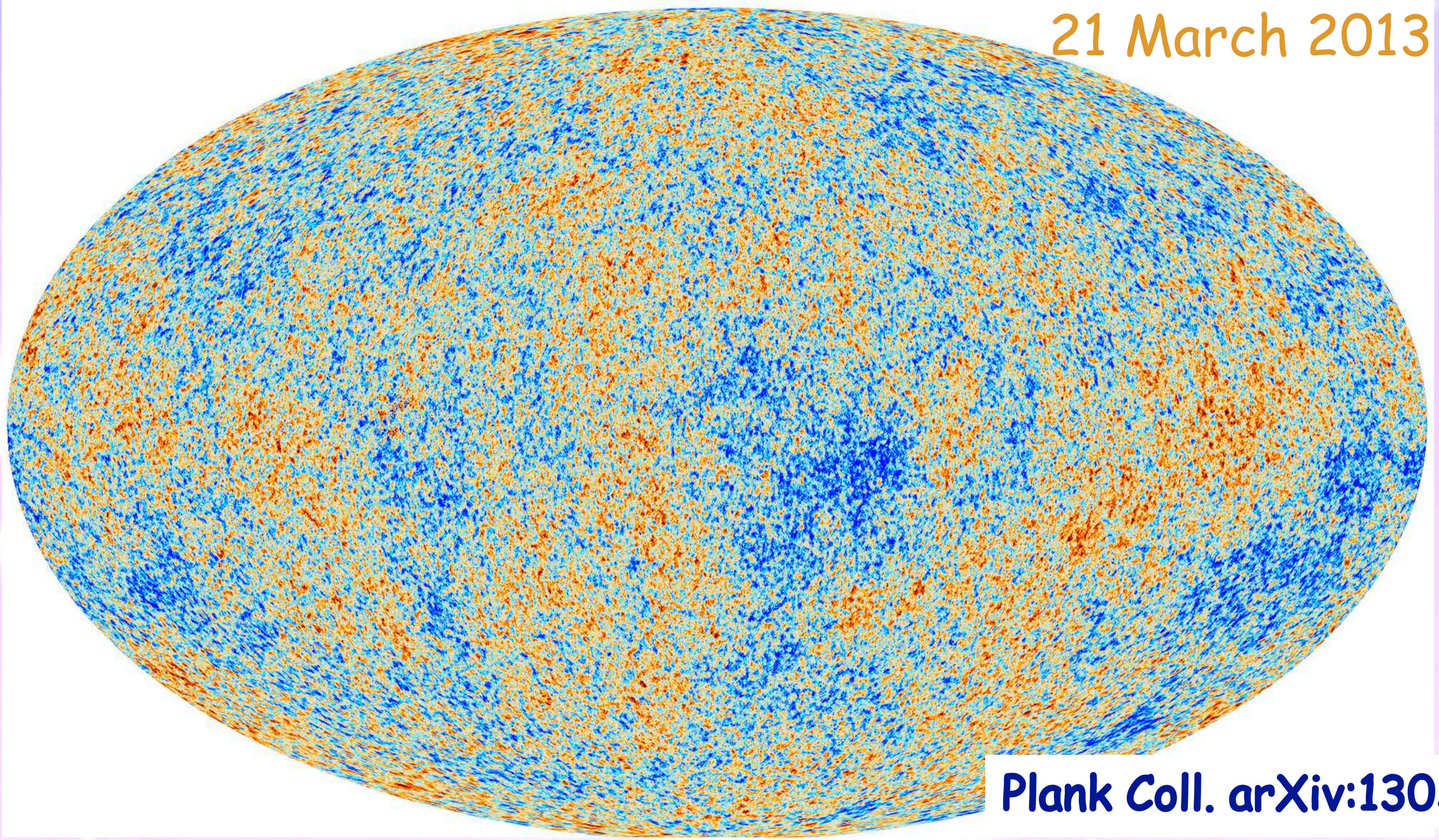



$\Omega_b h^2 \approx 0.02$

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

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

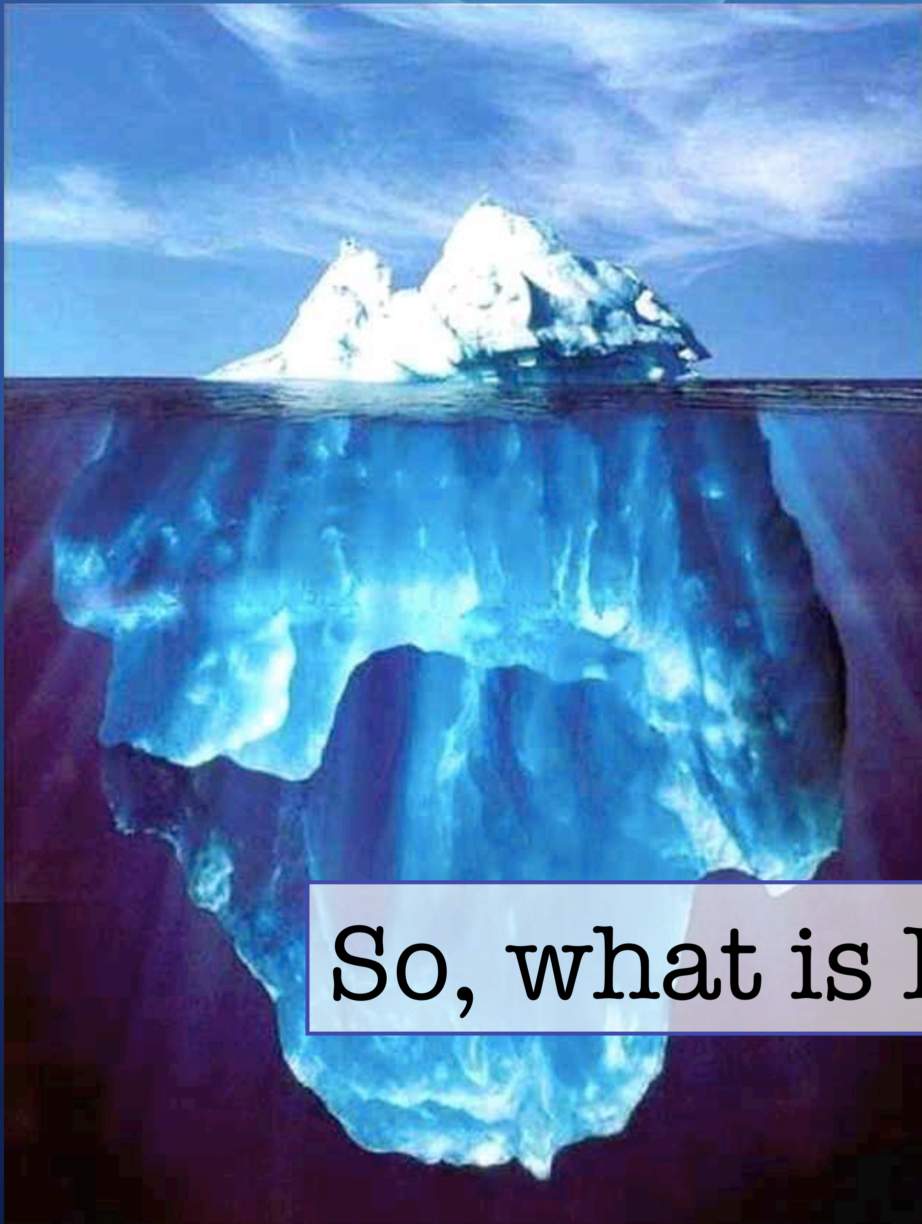
21 March 2013

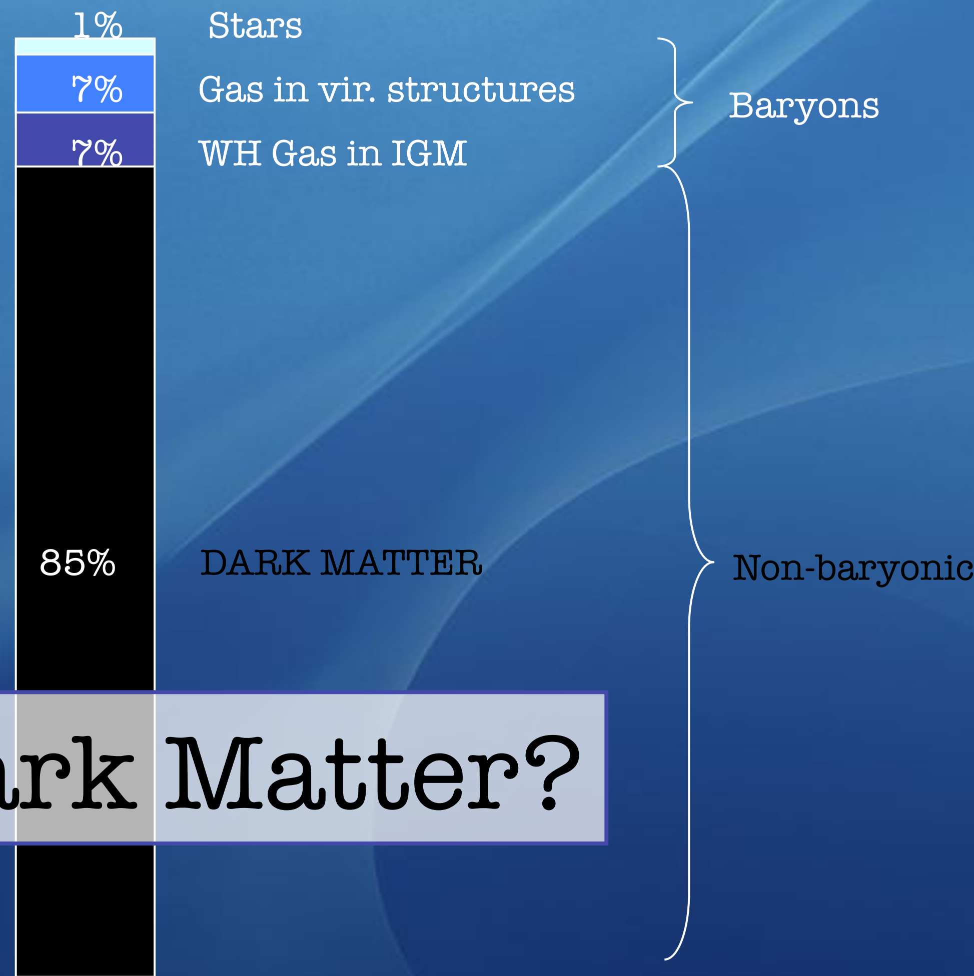


**Plank Coll. arXiv:1303.5076**

# Dark Matter

# An Inventory of Matter in the Universe

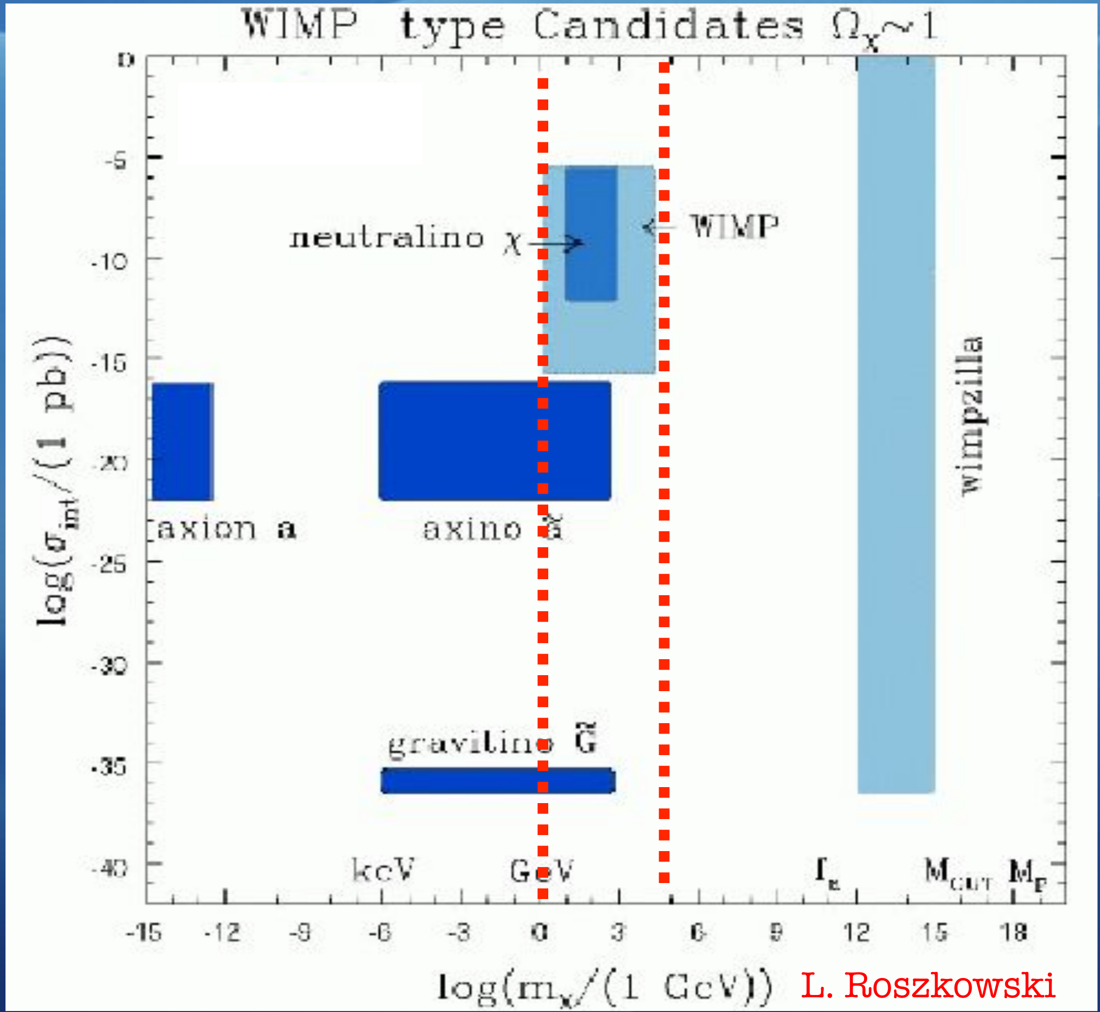





So, what is Dark Matter?

# 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



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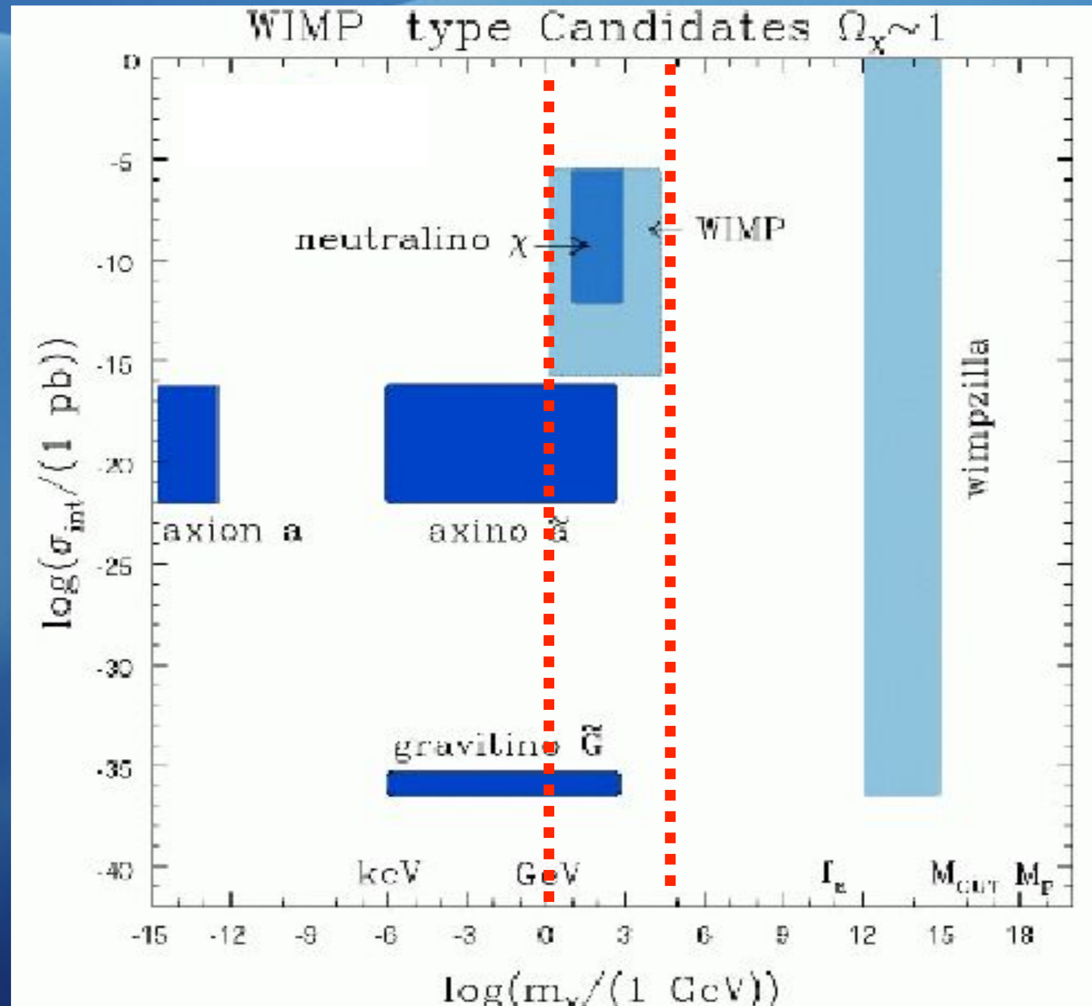
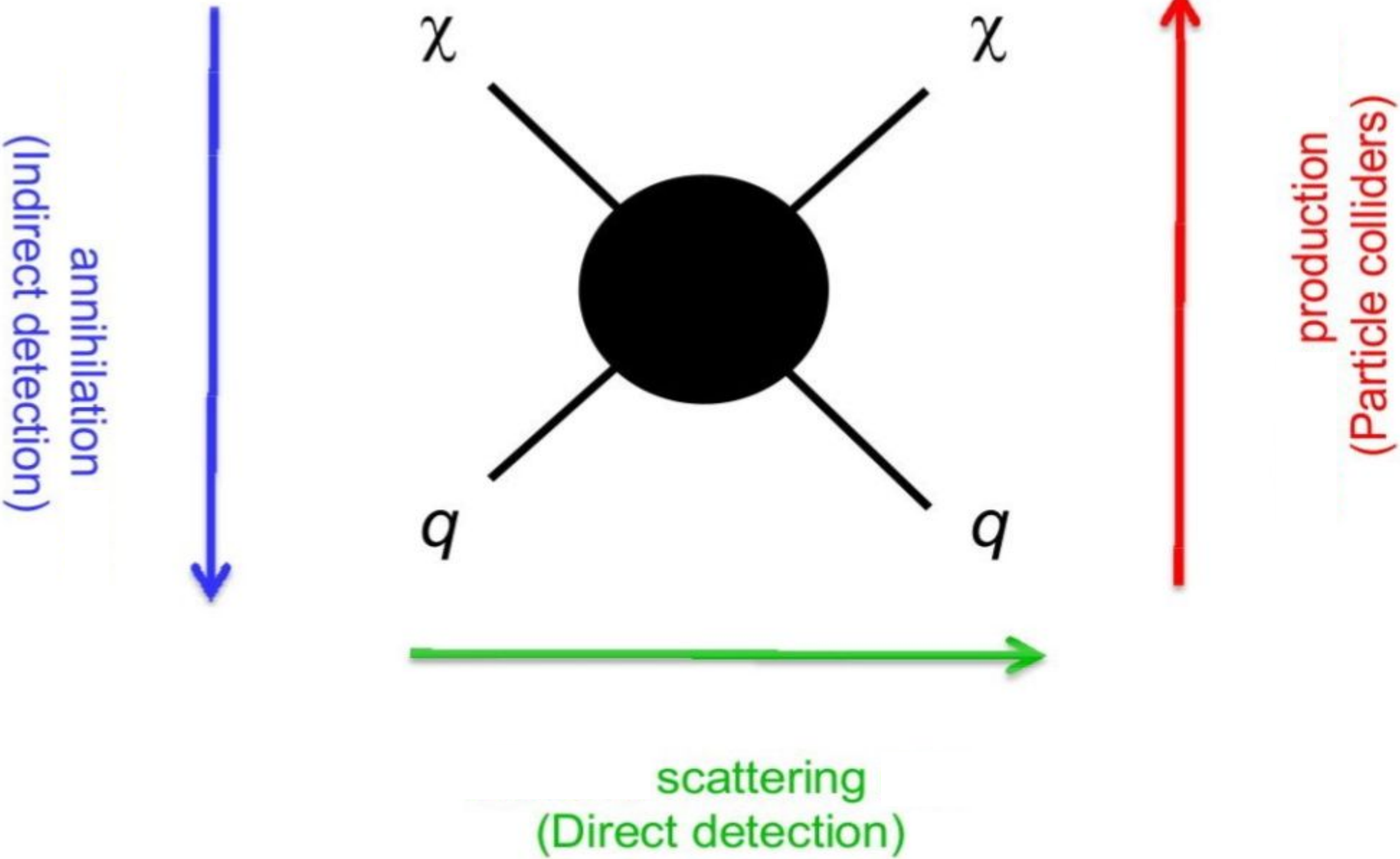
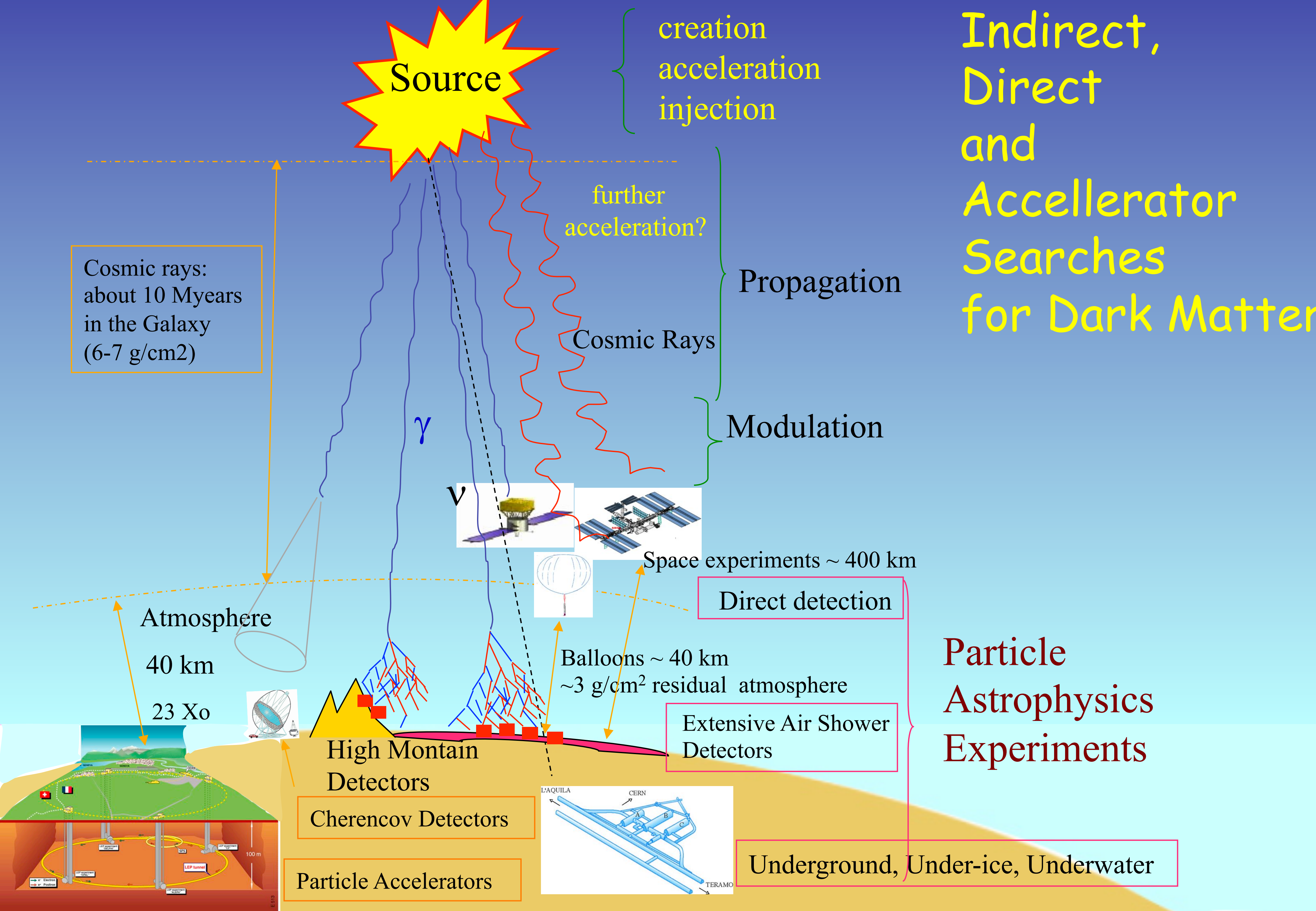
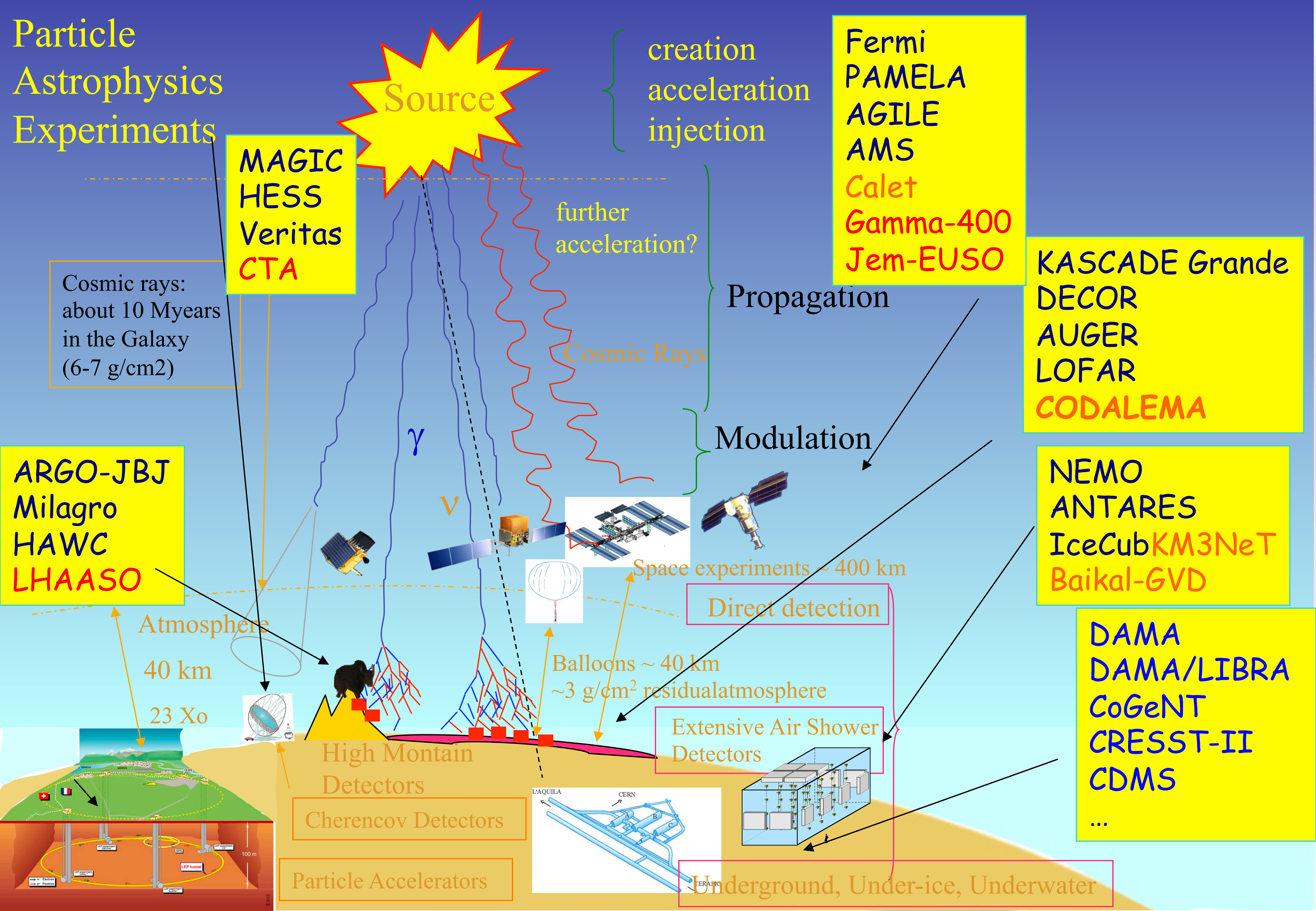



χ
χ
q
q
annihilation
(Indirect detection)
production
(Particle colliders)
scattering
(Direct detection)

# Indirect, Direct and Accellerator Searches for Dark Matter





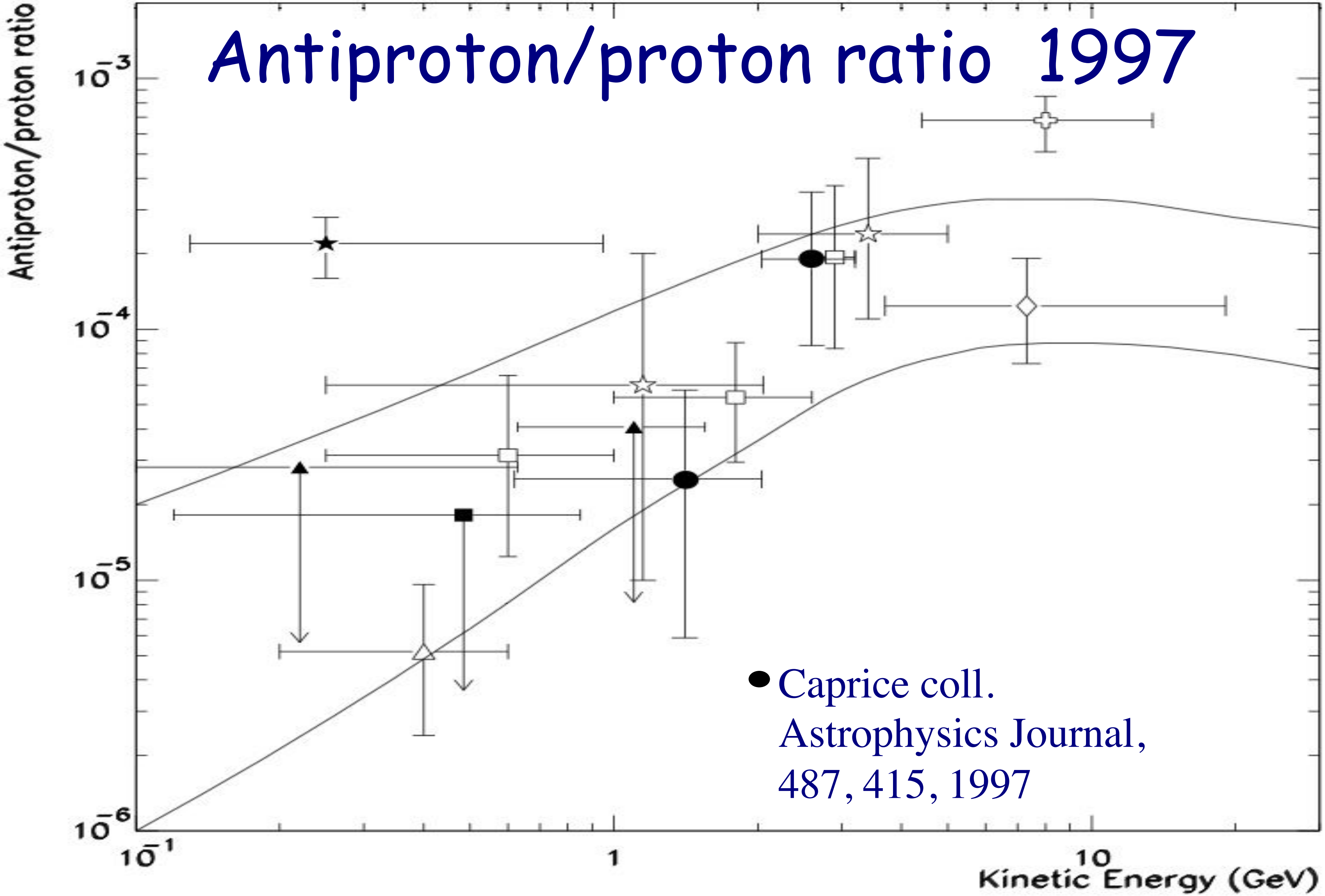
Particle Astrophysics Experiments
Source
creation
acceleration
injection
Fermi
PAMELA
AGILE
AMS
Calet
Gamma-400
Jem-EUSO
MAGIC
HESS
Veritas
CTA
further acceleration?
Cosmic rays: about 10 Myears in the Galaxy (6-7 g/cm2)
Propagation
KASCADE Grande
DECOR
AUGER
LOFAR
CODALEMA
Cosmic Rays
γ
Modulation
ν
ARGO-JBJ
Milagro
HAWC
LHAASO
NEMO
ANTARES
IceCubKM3NeT
Baikal-GVD
Space experiments ~ 400 km
Direct detection
Atmosphere
40 km
23 Xo
Balloons ~ 40 km
~3 g/cm² residualatmosphere
DAMA
DAMA/LIBRA
CoGeNT
CRESST-II
CDMS
...
Extensive Air Shower Detectors
High Montain Detectors
Cherencov Detectors
Particle Accelerators
L'AQUILA
CERN
Underground, Under-ice, Underwater

# Neutralino WIMPs

Assume $\chi$ present in the galactic halo

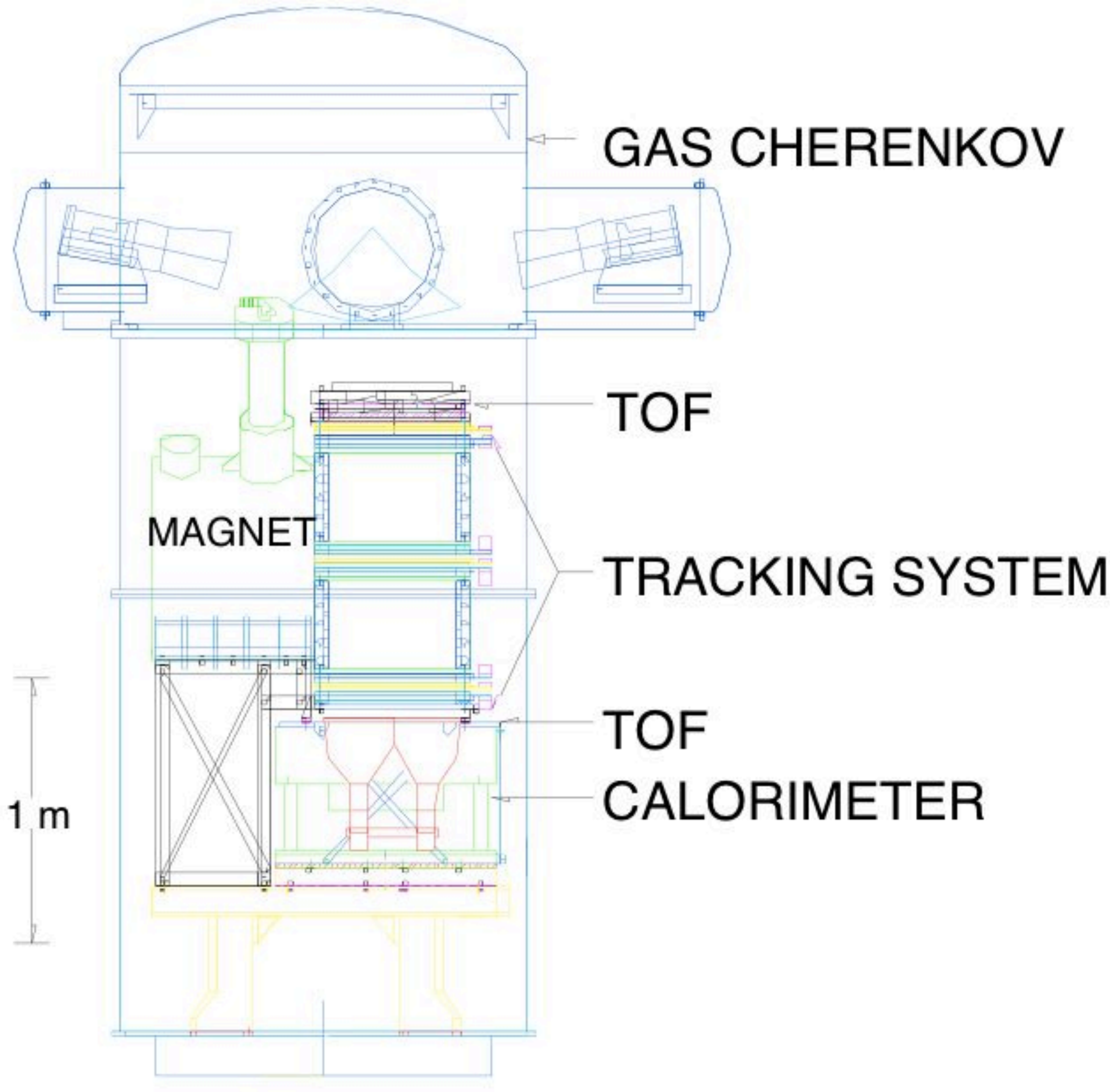
- $\chi$ is its own antiparticle **=>** can annihilate in galactic halo producing gamma-rays, antiprotons, positrons….
- Antimatter not produced in large quantities through standard processes (secondary production through p + p **-->** anti p + X)
- So, any extra contribution from exotic sources ($\chi$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

# Antiproton/proton ratio 1997




- Caprice coll. Astrophysics Journal, 487, 415, 1997

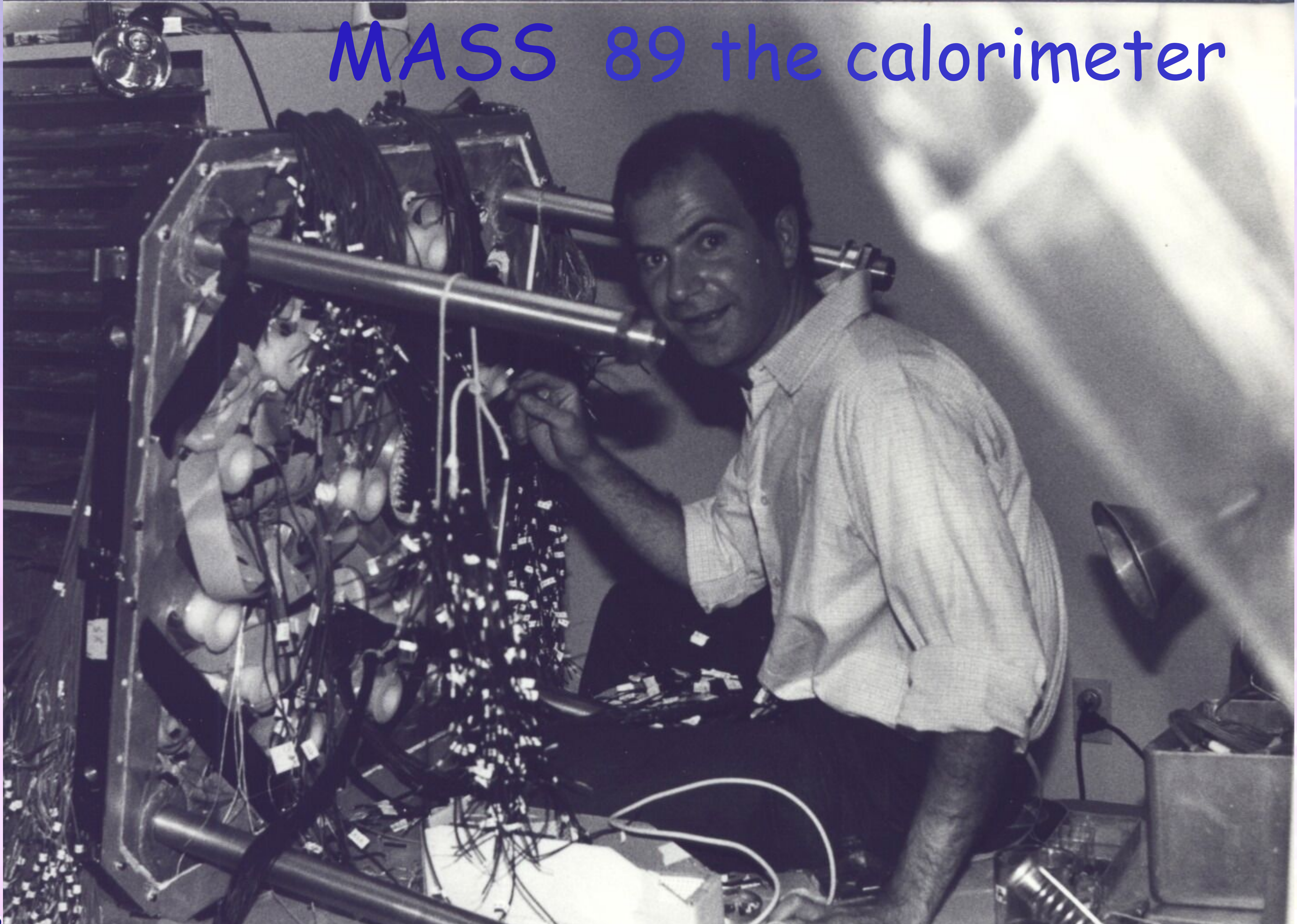
# MASS Matter Antimatter Space Spectrometer




5 September 1989


HOLD

# MASS 89 the calorimeter




MASS 89 flight

MASS 89 flight


MASS 89

# PAMELA

**P**ayload for **A**ntimatter **M**atter **E**xploration and **L**ight Nuclei **A**strophysics

In orbit on June 15, 2006, on board of the DK1 satellite by a Soyuz rocket from the Bajkonour launch site.

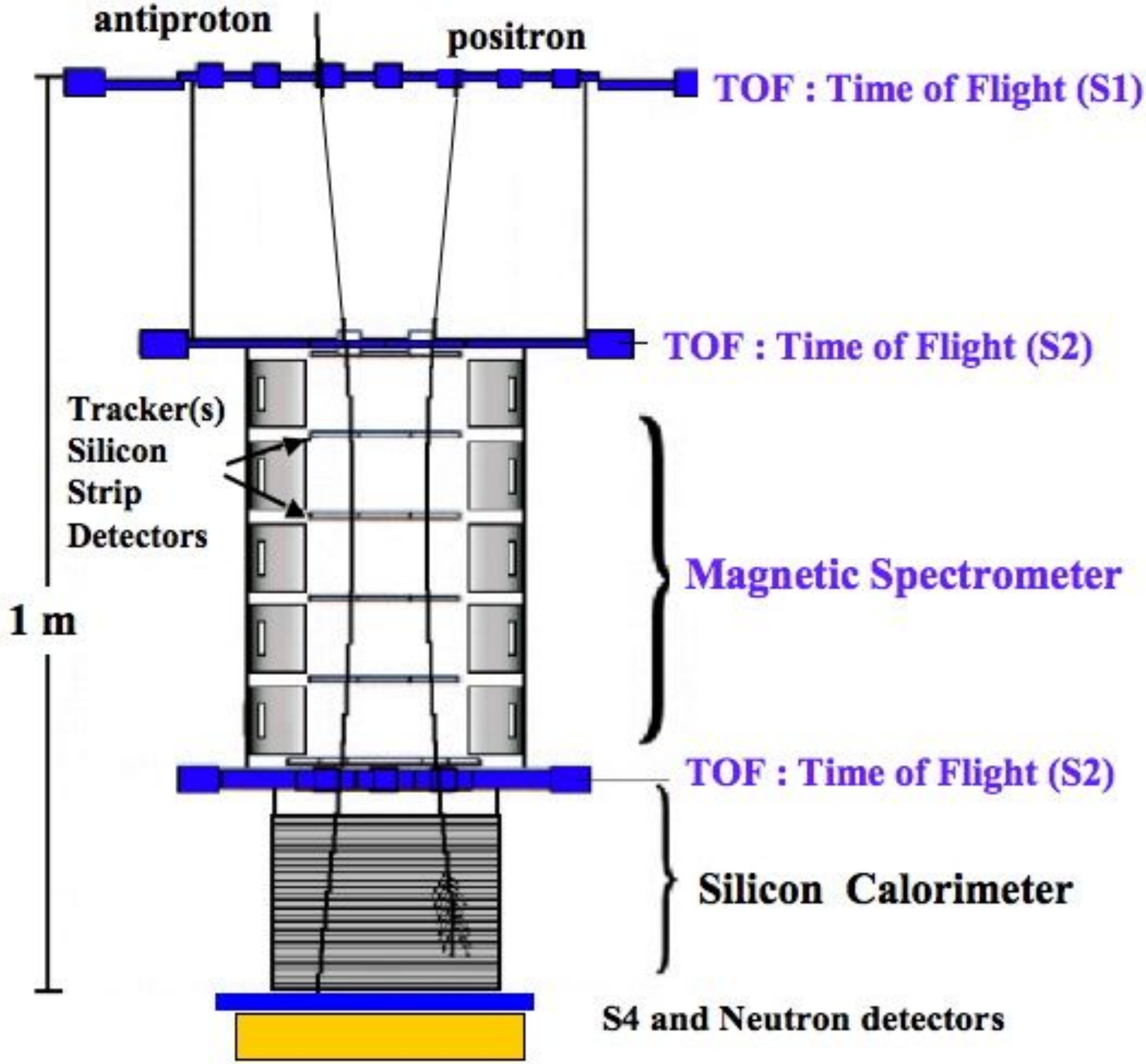
First switch-on on June 21 2006

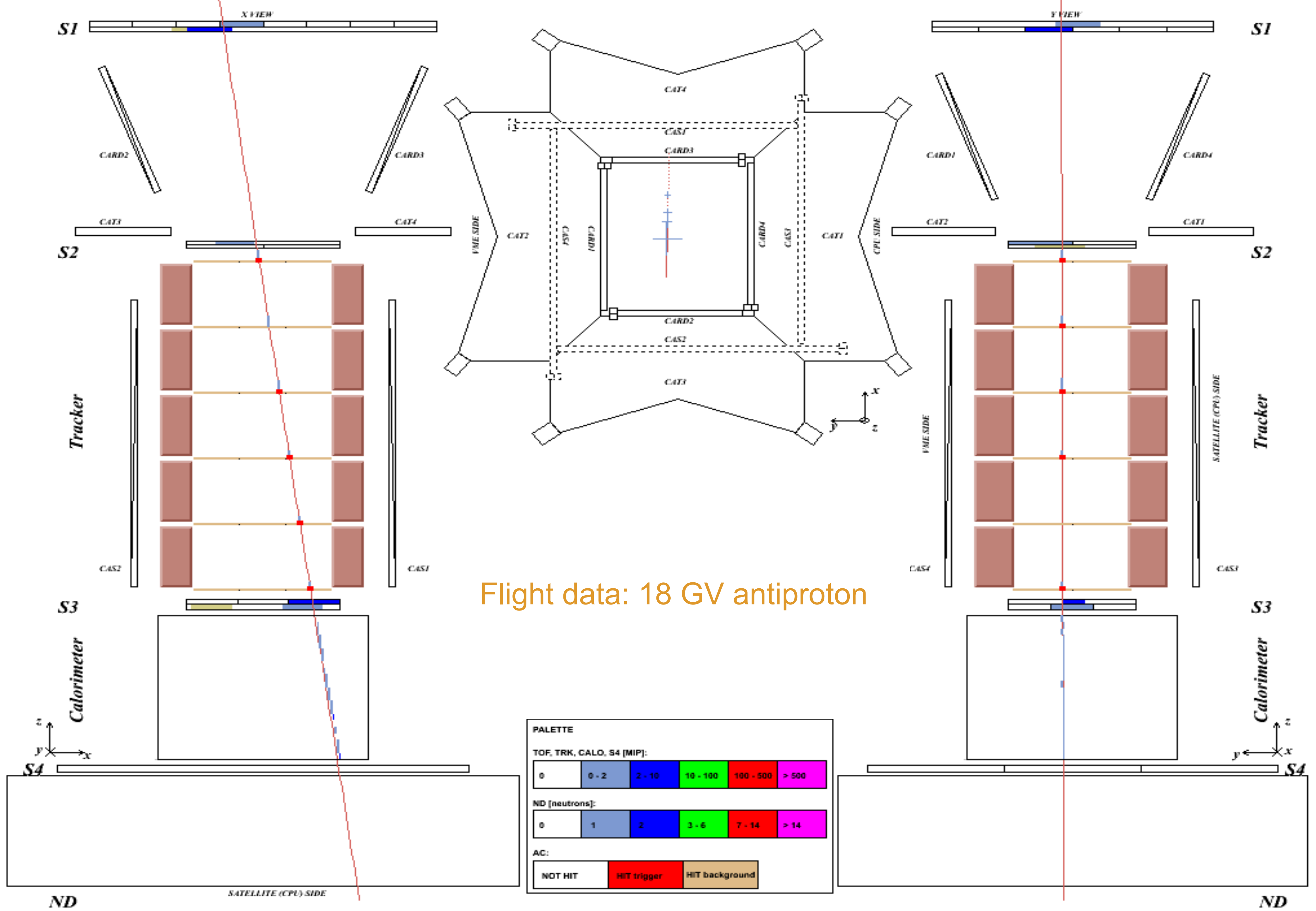
From July 11  Pamela is in continuous data taking mode

- ~ 6 years from PAMELA launch

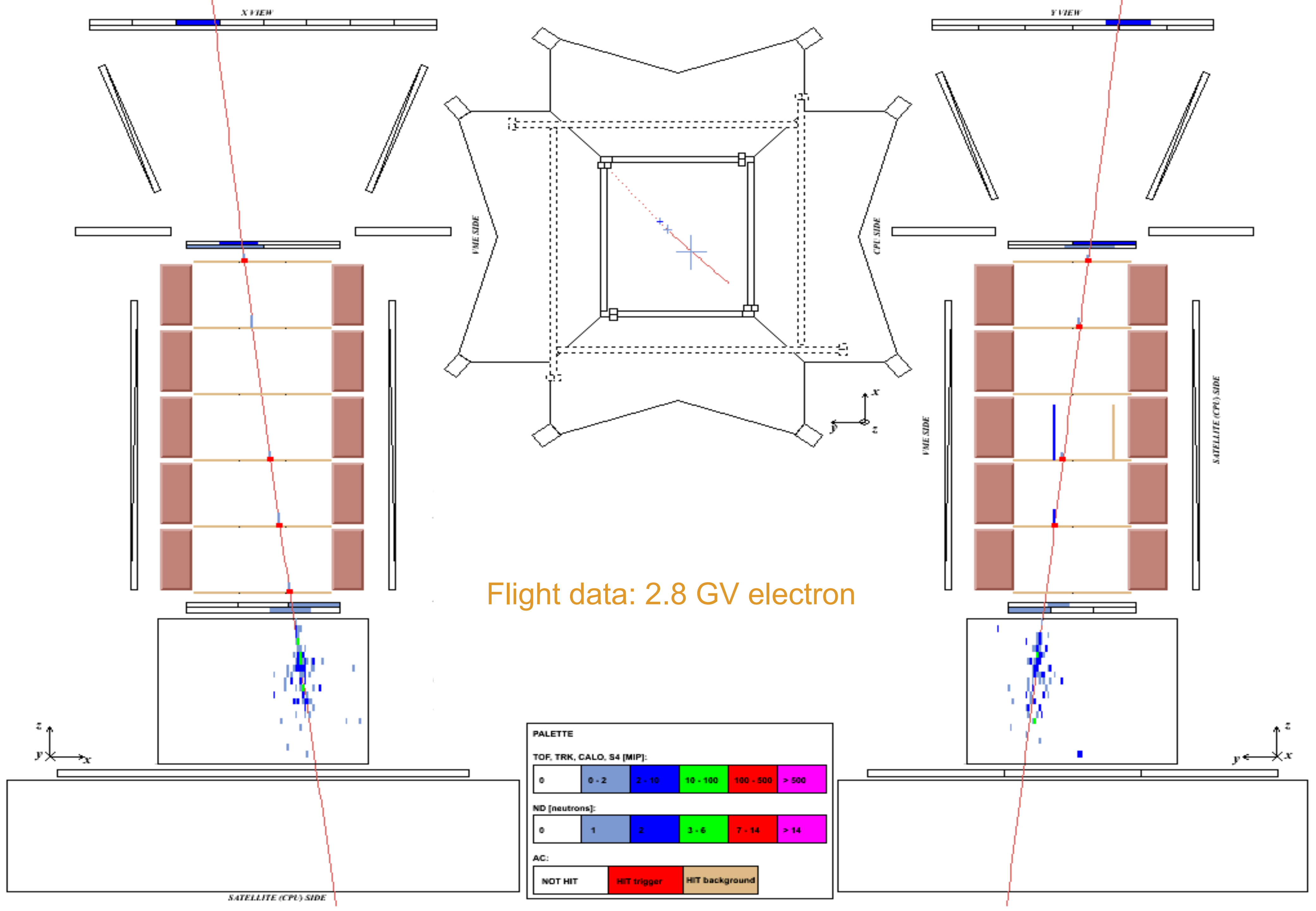
- Launched in orbit on June 15, 2006, on board of the DK1 satellite by a Soyuz rocket from the Bajkonour cosmodrom.

# Pamela


antiproton
positron
TOF : Time of Flight (S1)
TOF : Time of Flight (S2)
Tracker(s)
Silicon
Strip
Detectors
1 m
Magnetic Spectrometer
TOF : Time of Flight (S2)
Silicon Calorimeter
S4 and Neutron detectors

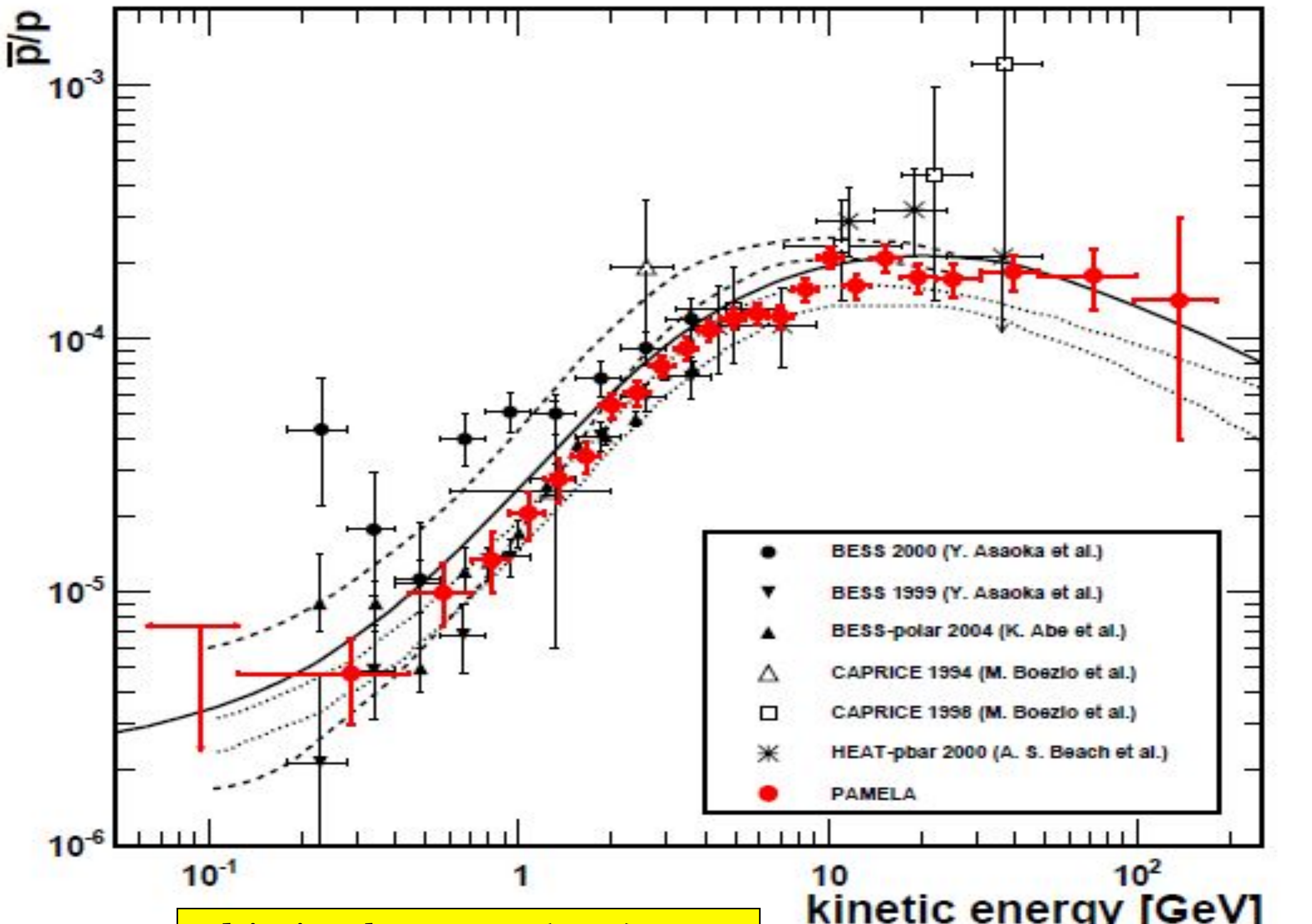

X VIEW
Y VIEW
S1
S2
S3
S4
ND
Tracker
Calorimeter
CARD1
CARD2
CARD3
CARD4
CAT1
CAT2
CAT3
CAT4
CAS1
CAS2
CAS3
CAS4
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
Flight data: 18 GV antiproton
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background

Flight data: 2.8 GV electron



# Antiproton-to-proton ratio

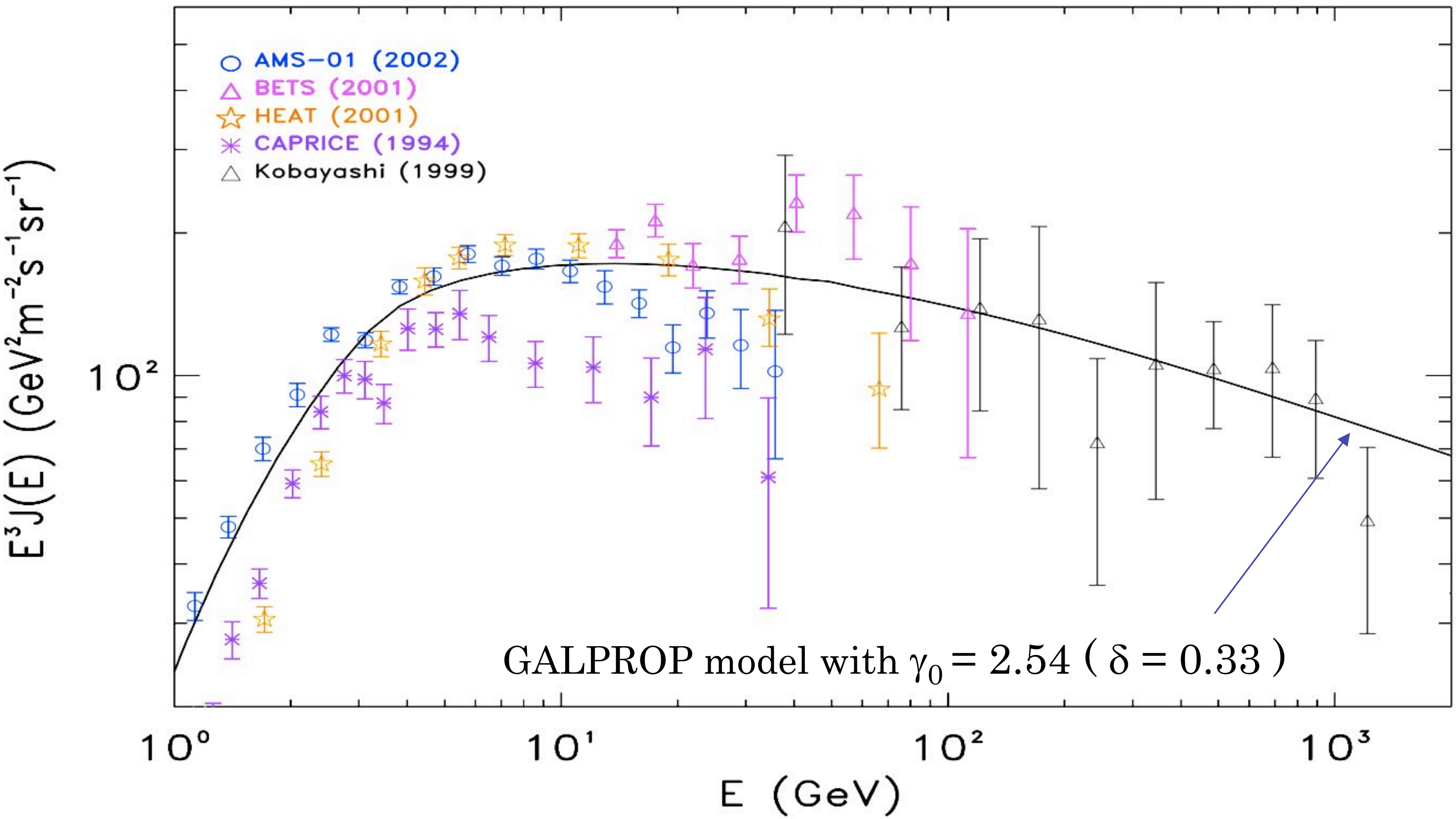
- Overall agreement with pure secondary calculation




Adriani et al. - PRL 105 (2010) 121101

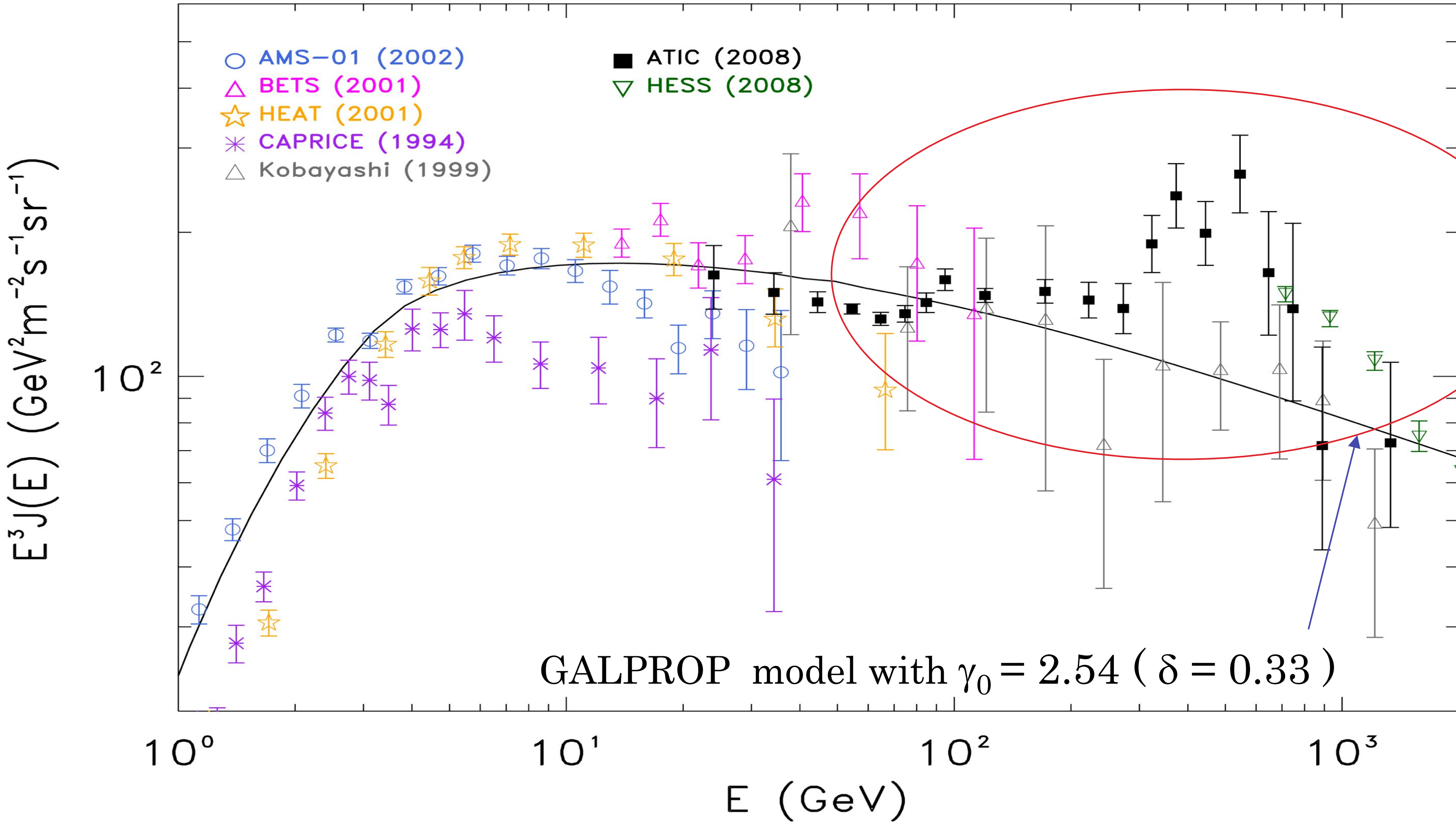
# The situation before 2008

## Electron + positron spectrum



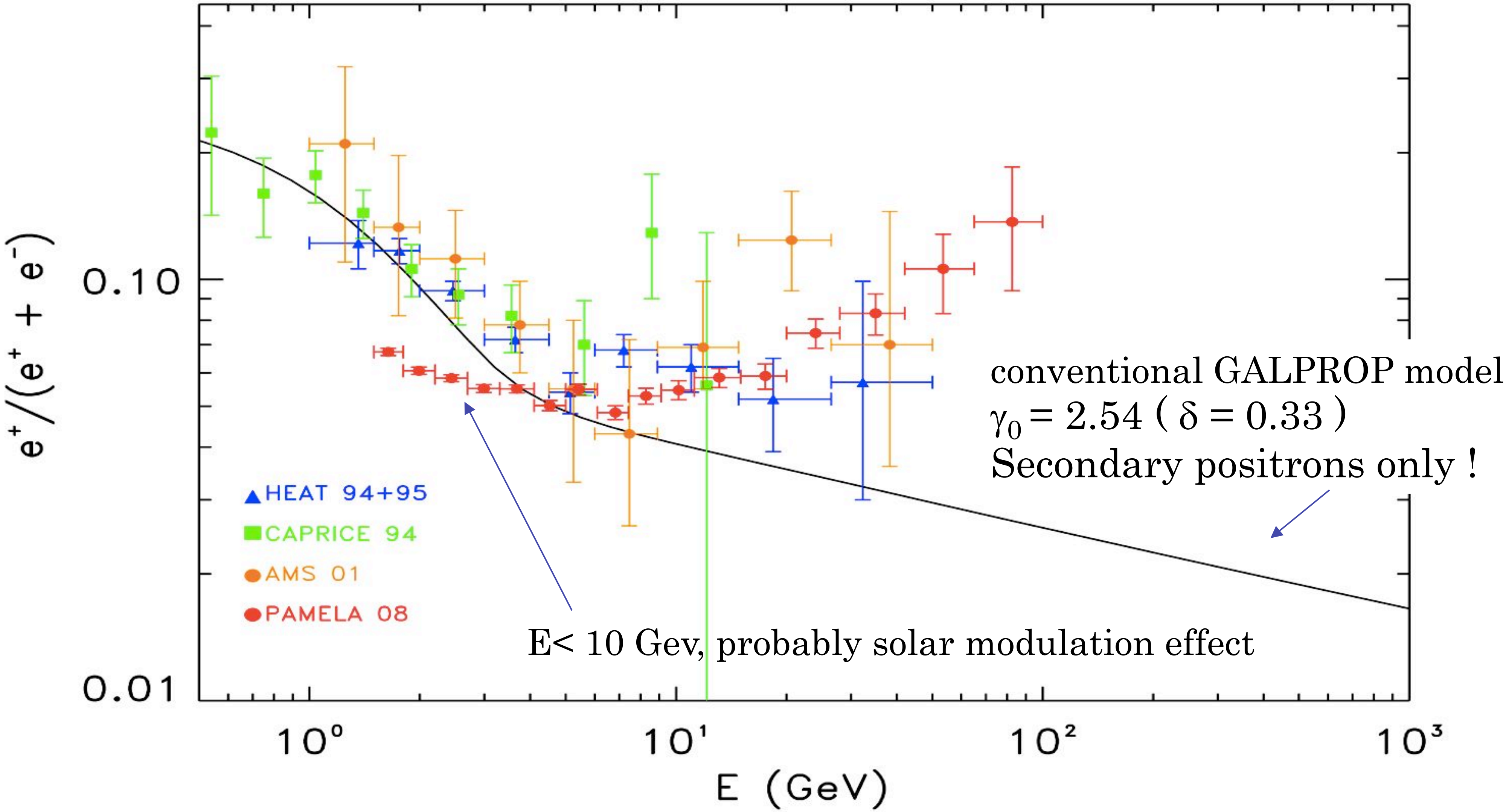

Data were compatible with conventional large-scale Galactic models of CRs tuned to fit gamma-ray data and other observables

# 2008: Results from ATIC and HESS




Data clearly call for major changes to the conventional model:
Nearby sources (e.g. pulsar) or dark matter annihilation/decay models have been proposed to explain those data

# 2009: PAMELA results

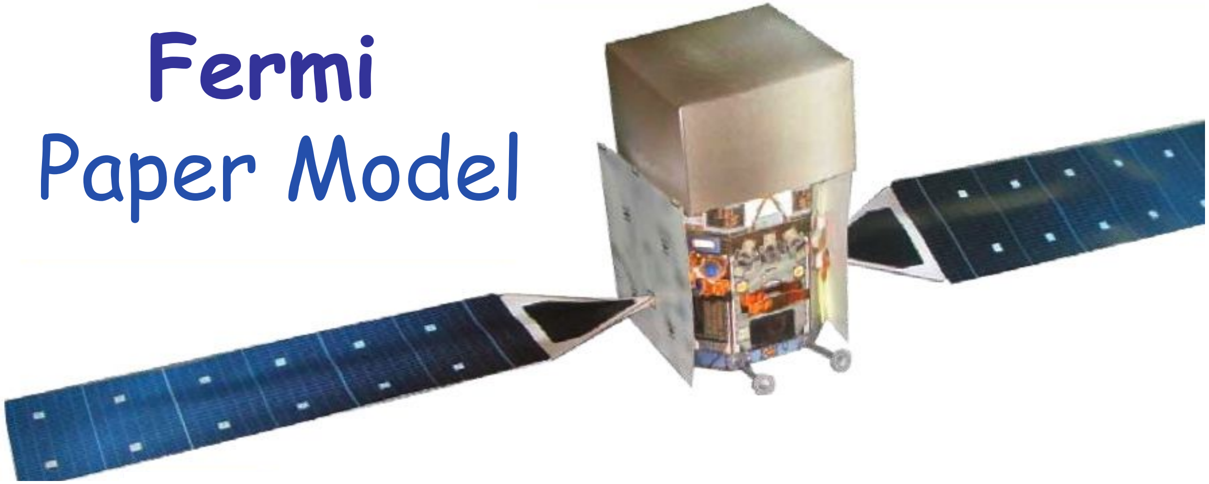


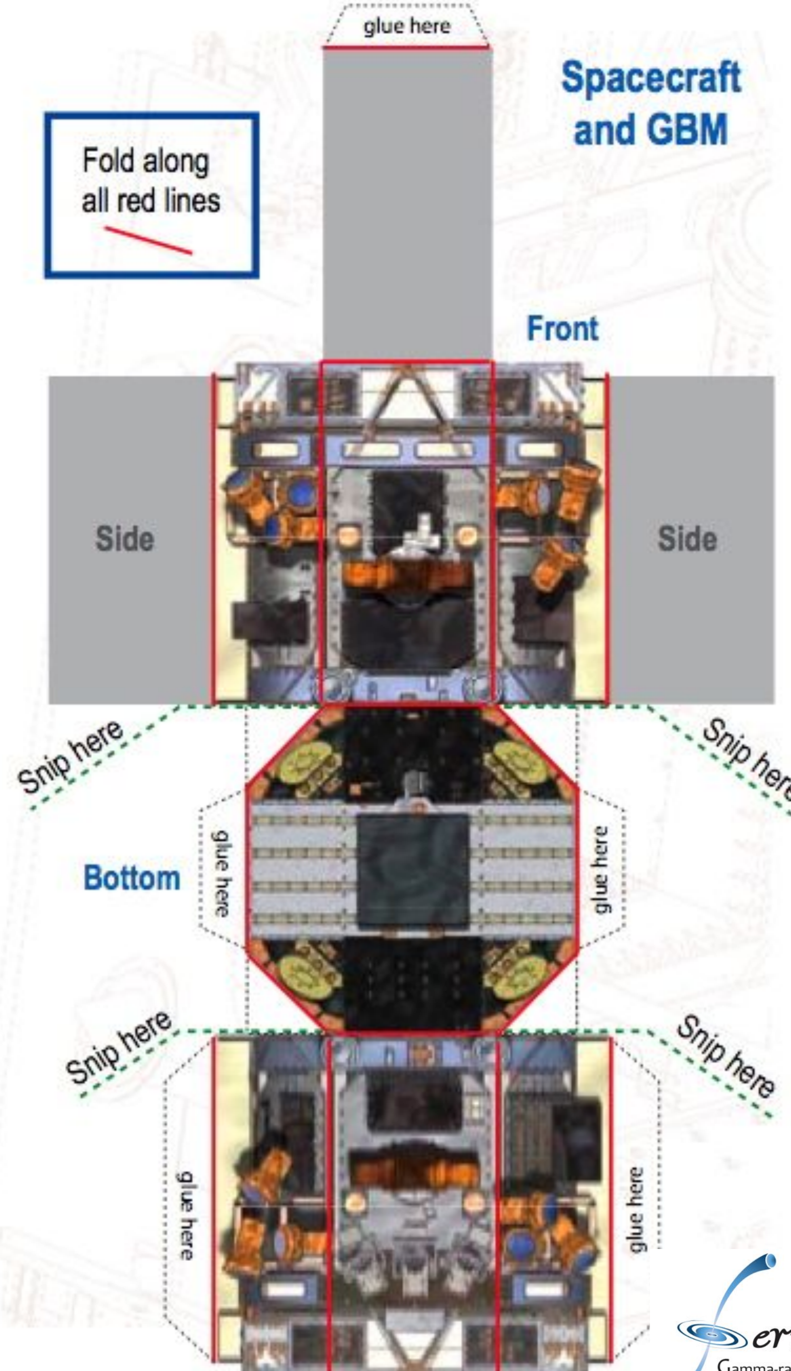

$e^+/(e^+ + e^-) \propto E^{-\gamma p + \gamma 0 - \delta}$ $\gamma p$: proton source power-index

It improves only adopting very soft electron spectra (high $\gamma_0$ )


Fermi
Gamma-ray Space Telescope
Happy 5th Birthday Fermi !!
11 June 2008

# Fermi Paper Model





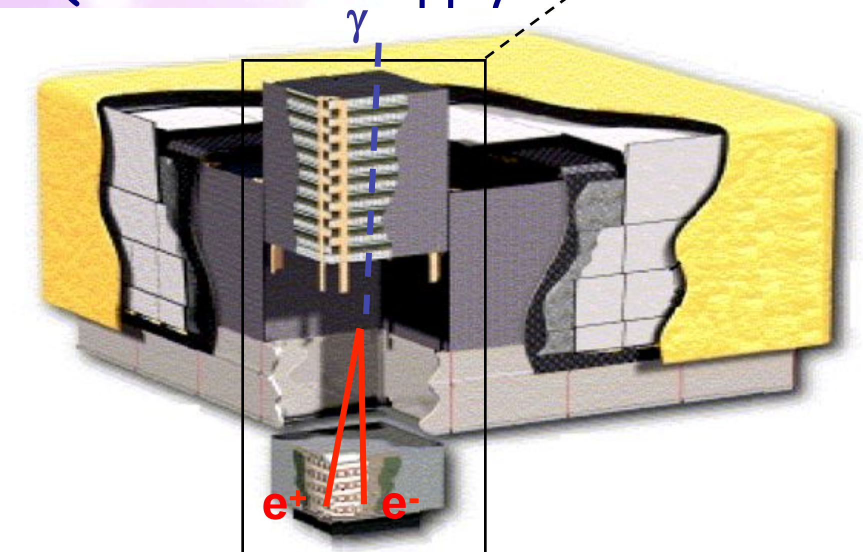

http://people.roma2.infn.it/~aldo/GLASTpaperModel.pdf

Fermi Gamma-ray Space Telescope

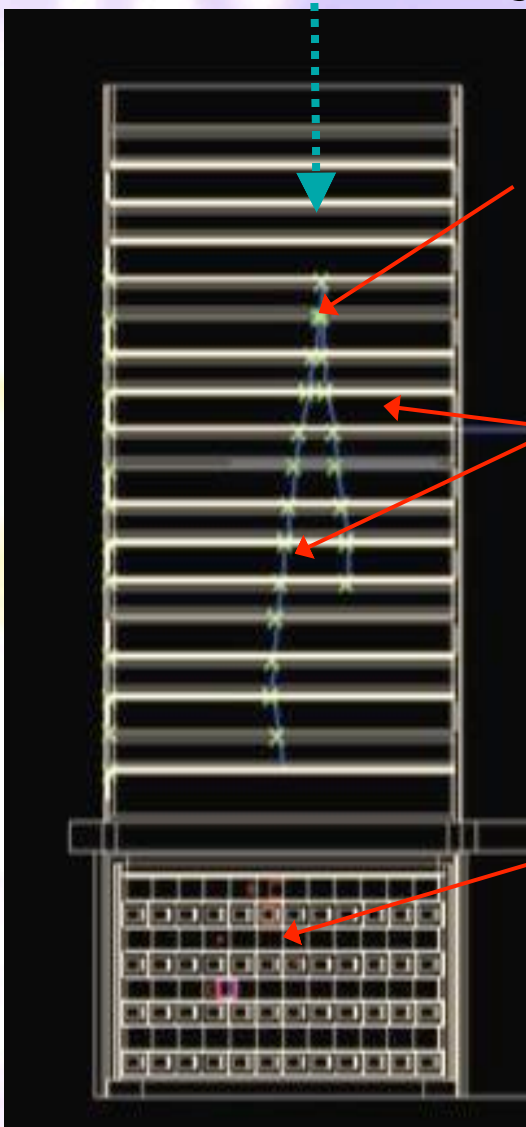
# How Fermi LAT detects gamma rays

4 x 4 array of identical towers with:

- Precision Si-strip tracker (TKR)
  - With W converter foils
- Hodoscopic CsI calorimeter (CAL)
- DAQ and Power supply box




An anticoincidence detector around the telescope distinguishes gamma-rays from charged particles



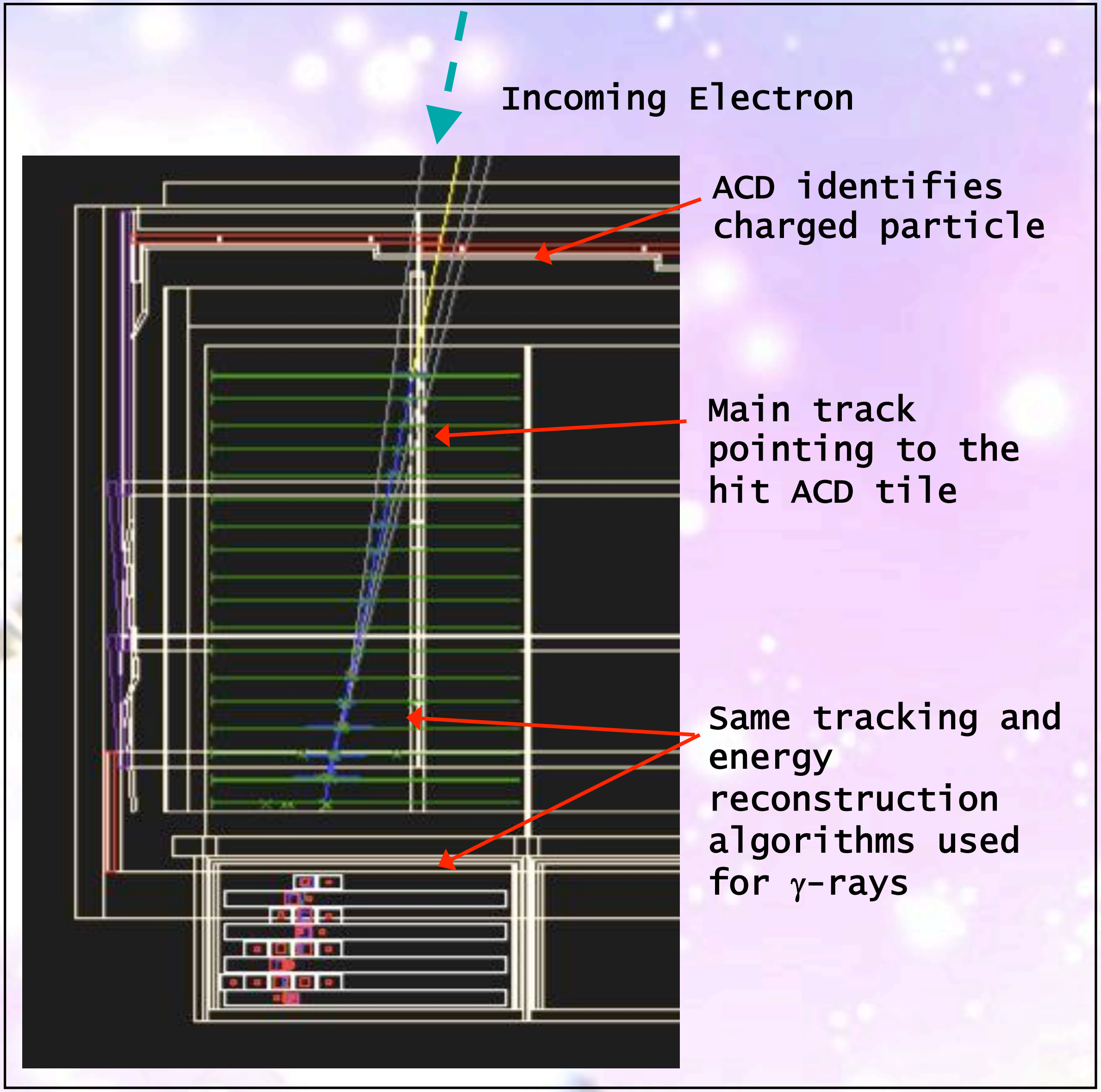
# How Fermi LAT detects electrons

## Trigger and downlink

- LAT triggers on (almost) every particle that crosses the LAT
  - ~ 2.2 kHz trigger rate
- On board processing removes many charged particles events
  - But keeps events with more that 20 GeV of deposited energy in the CAL
  - ~ 400 Hz downlink rate
- Only ~1 Hz are good $\gamma$-rays

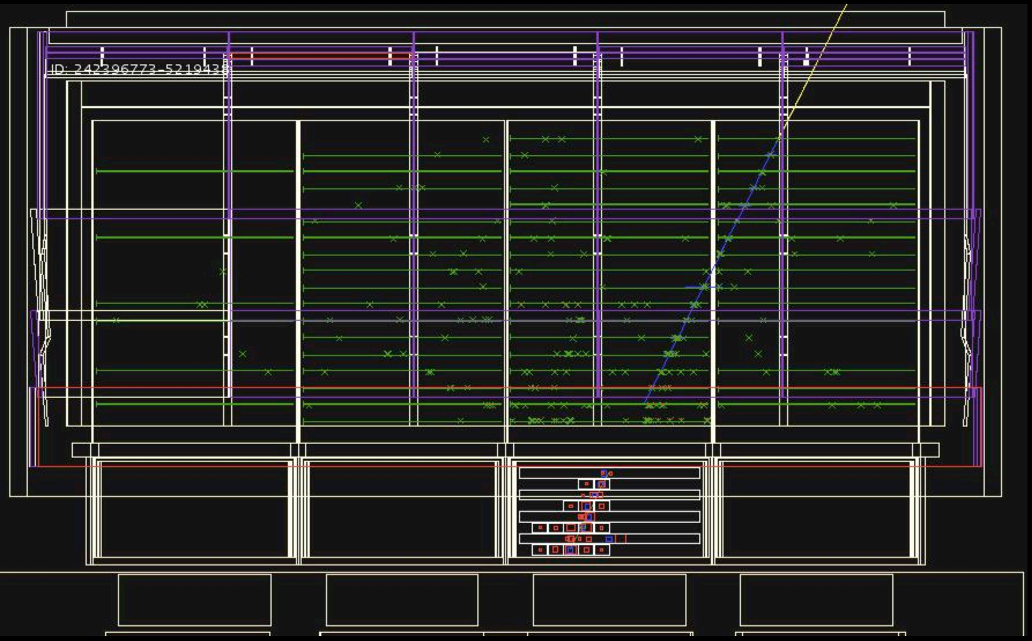
## Electron identification

- The challenge is identifying the good electrons among the proton background
  - Rejection power of $10^3$ – $10^4$ required
  - Can not separate electrons from positrons

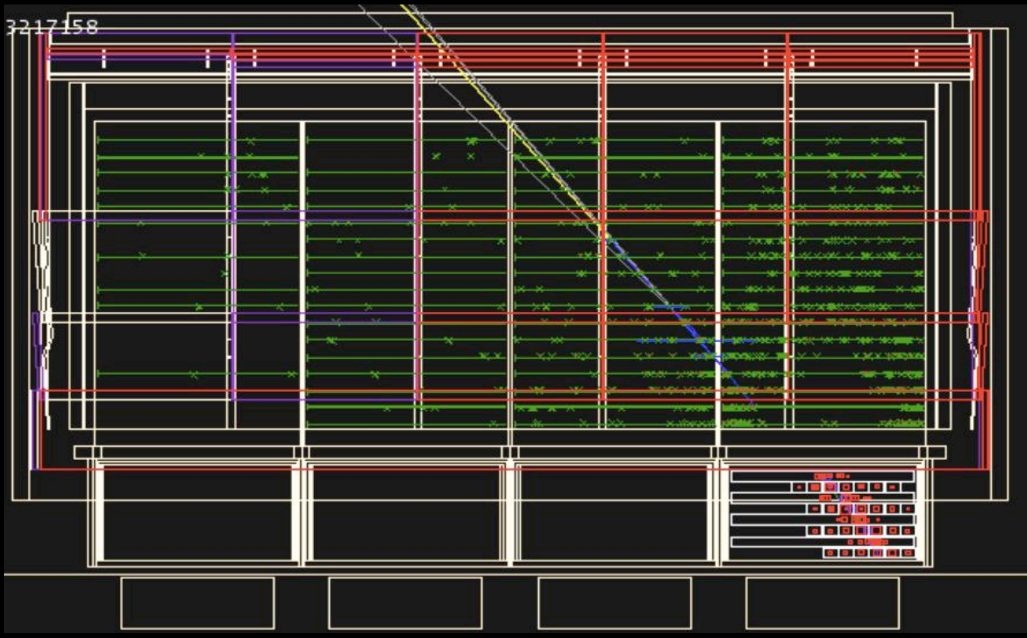


# Event topology

**A candidate electron (recon energy 844 GeV)**



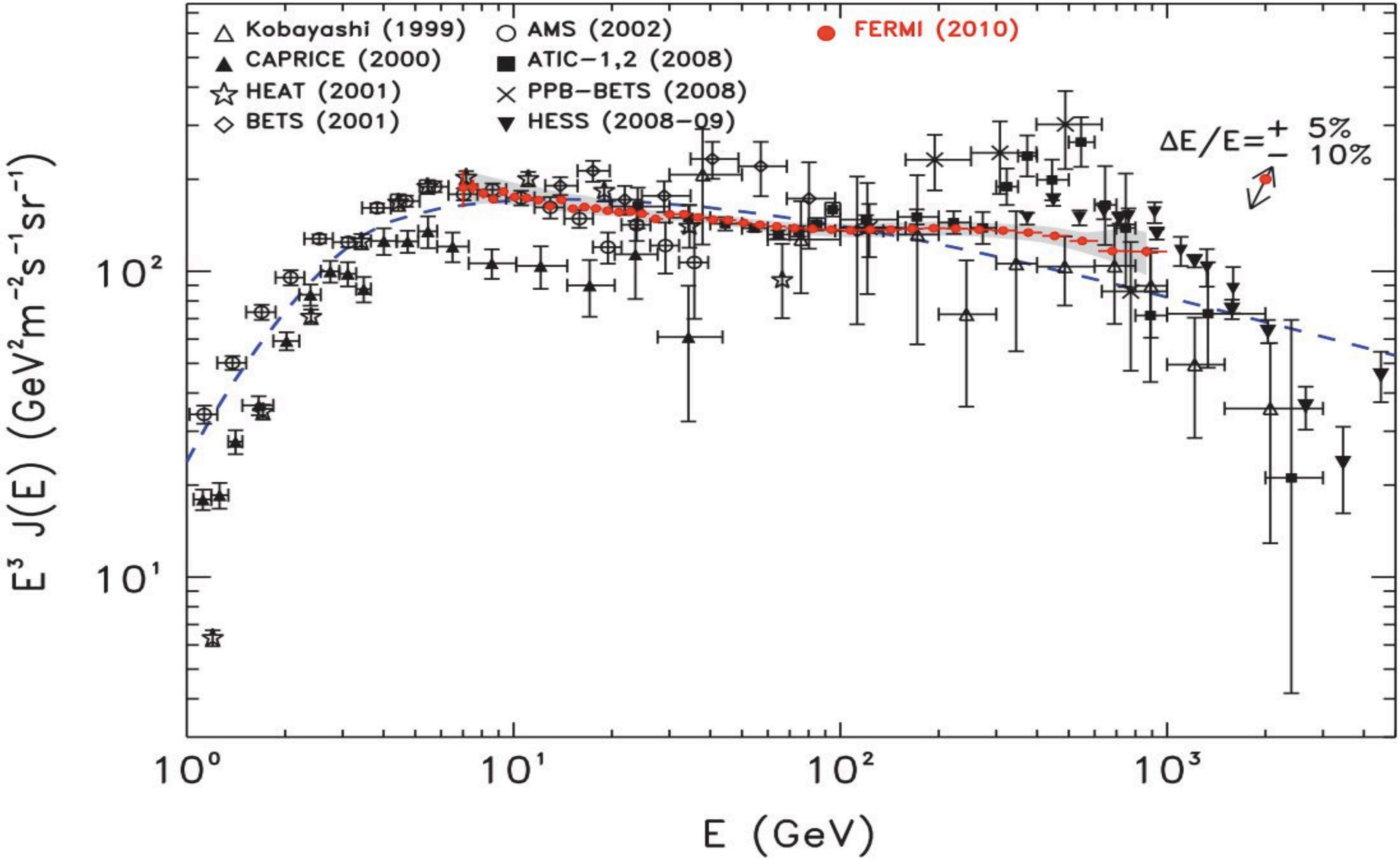
**A candidate hadron (raw energy > 800 GeV)**



- TKR: clean main track with extra-clusters very close to the track
- CAL: clean EM shower profile, not fully contained
- ACD: few hits in conjunction with the track

- TKR: small number of extra clusters around main track
- CAL: large and asymmetric shower profile
- ACD: large energy deposit per tile

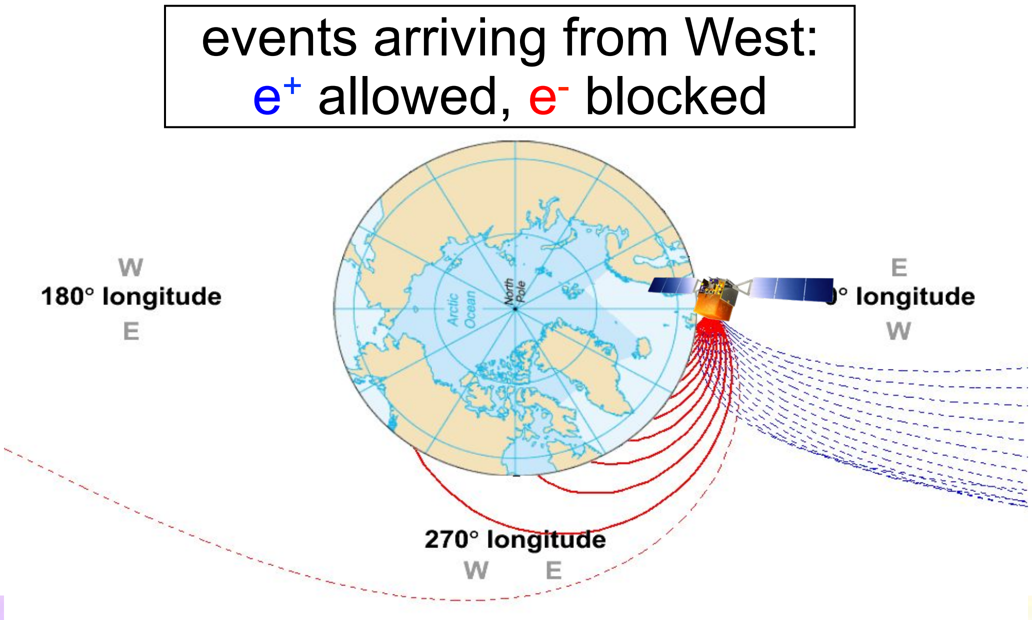
# Fermi Electron + Positron spectrum

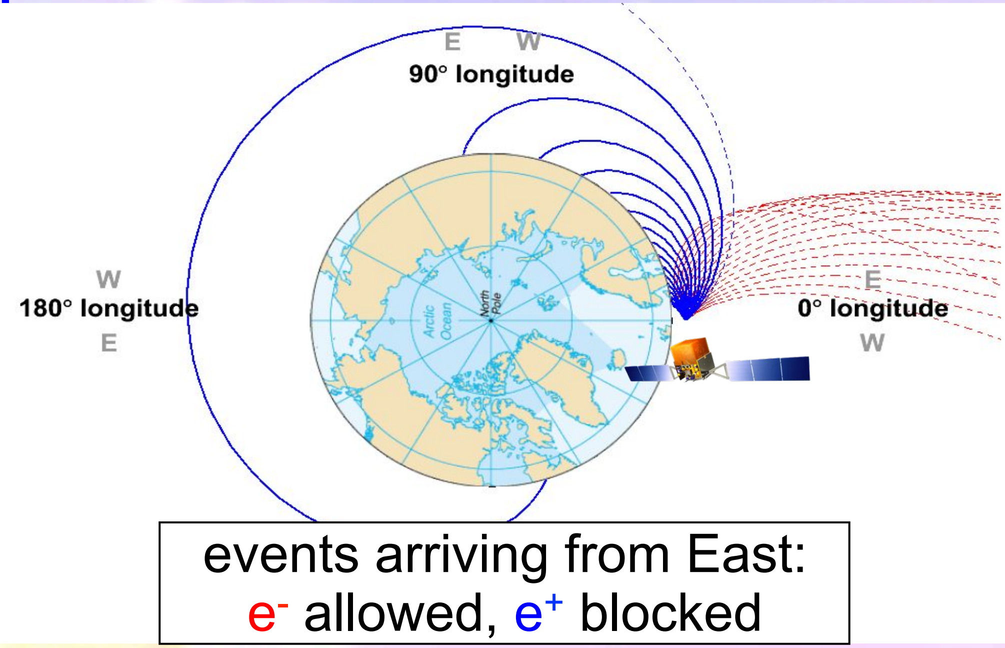



**Extended Energy Range (7 GeV – 1 TeV) One year statistics (8M evts)**

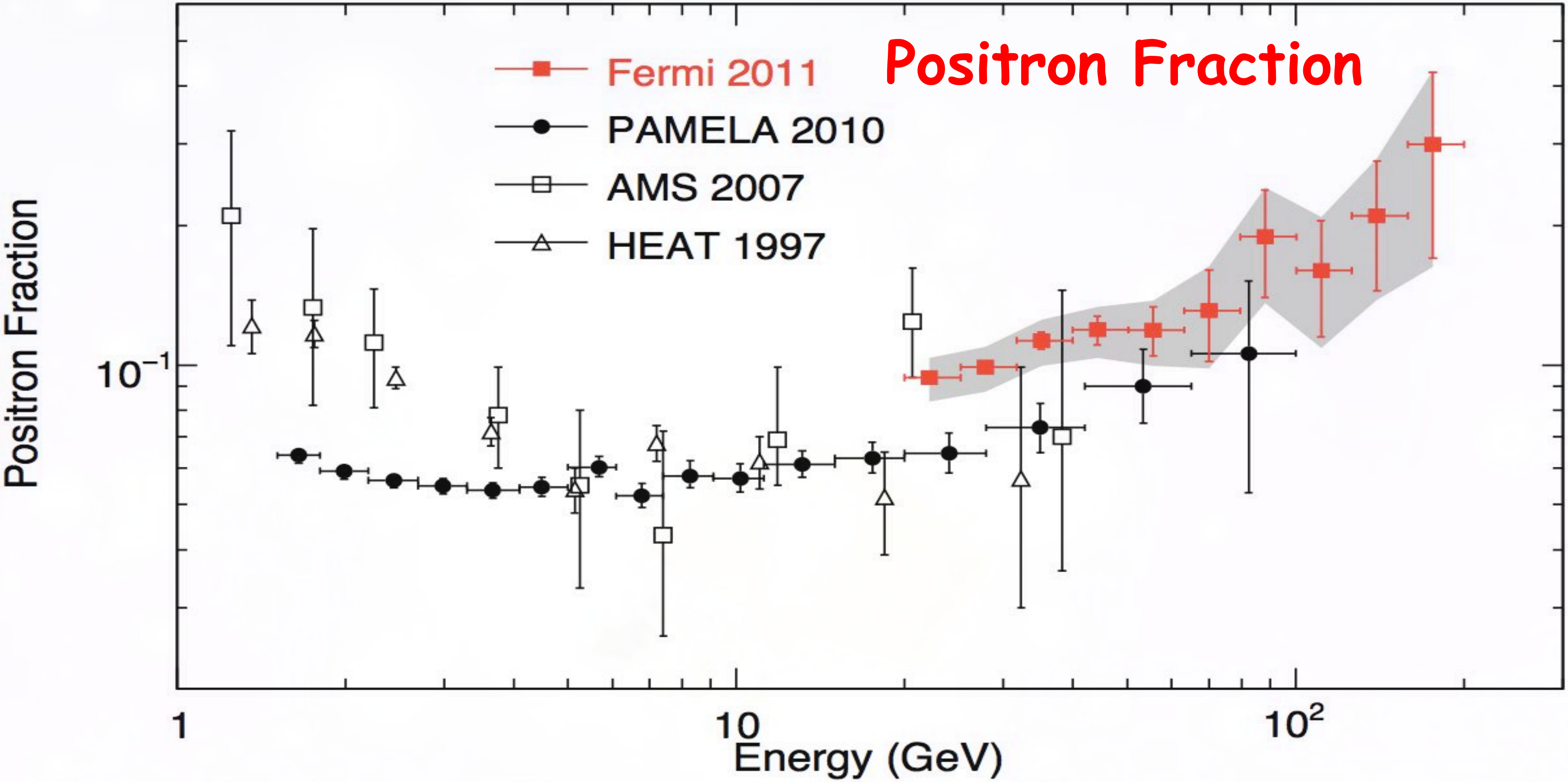
Fermi LAT Coll. Physical Review D, 82 092004 (2010) [arXiv:1008.3999]

# Geomagnetic field + Earth shadow = directions from which only electrons or only positrons are allowed




- For some directions, $e^-$ or $e^+$ forbidden
- Pure $e^+$ region looking West and pure $e^-$ region looking East
- Regions vary with particle energy and spacecraft position
- To determine regions, use code by Don Smart and Peggy Shea (numerically traces trajectory in geomagnetic field)
- Using International Geomagnetic Reference Field for the 2010 epoch




**The Fermi-LAT has measured the cosmic-ray positron and electron spectra separately, between 20 and 130 GeV, using the Earth's magnetic field as a charge discriminator**

- **Two independent methods of background subtraction produce consistent results**
- **The observed positron fraction is consistent with the one measured by PAMELA**

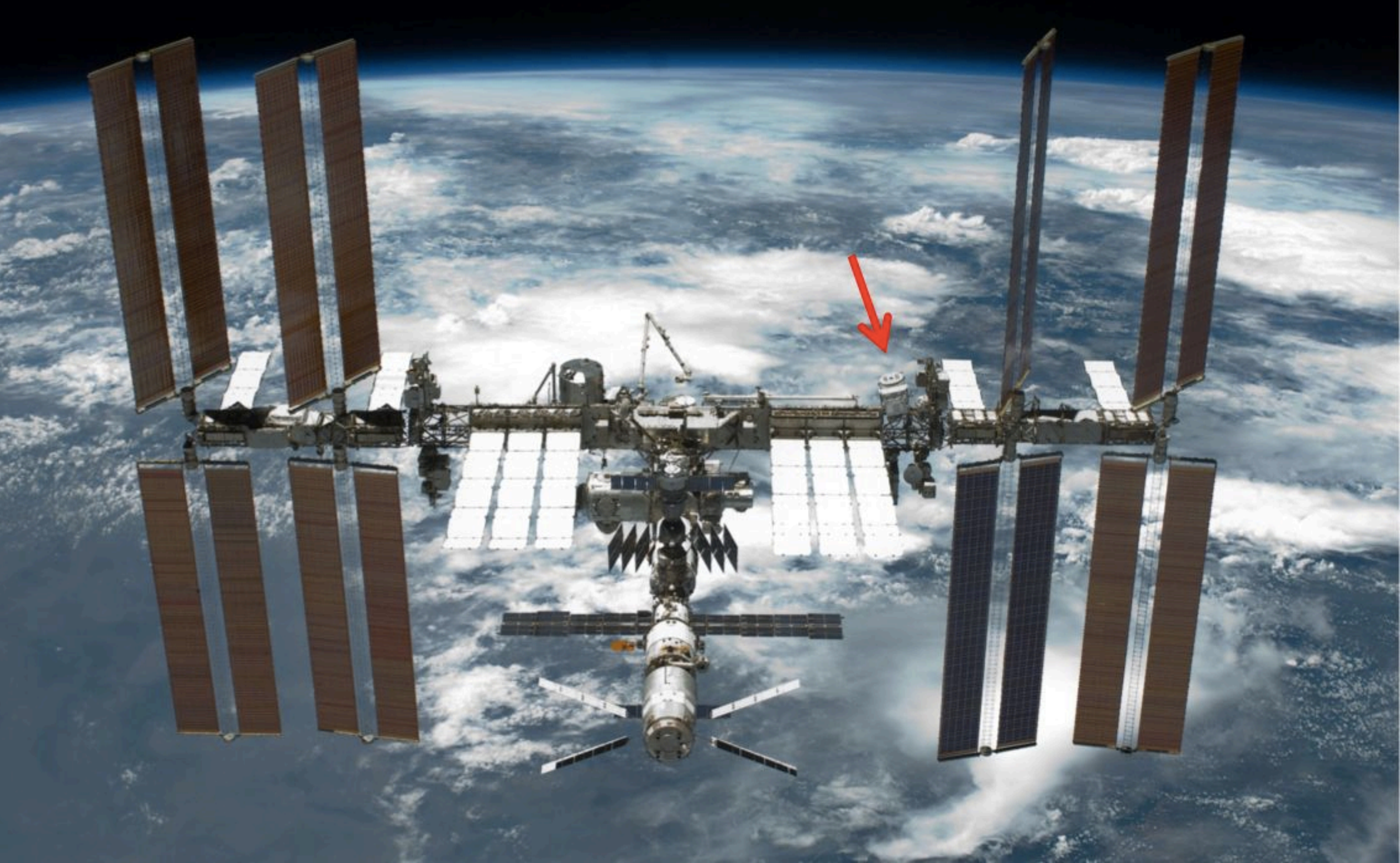
**Differences between different experiments below few GeV's probably due to charge-sign-dependent modulation but still under study**

Fermi Coll., PRL, 108 (2012) 011103 arXiv:1109.0521

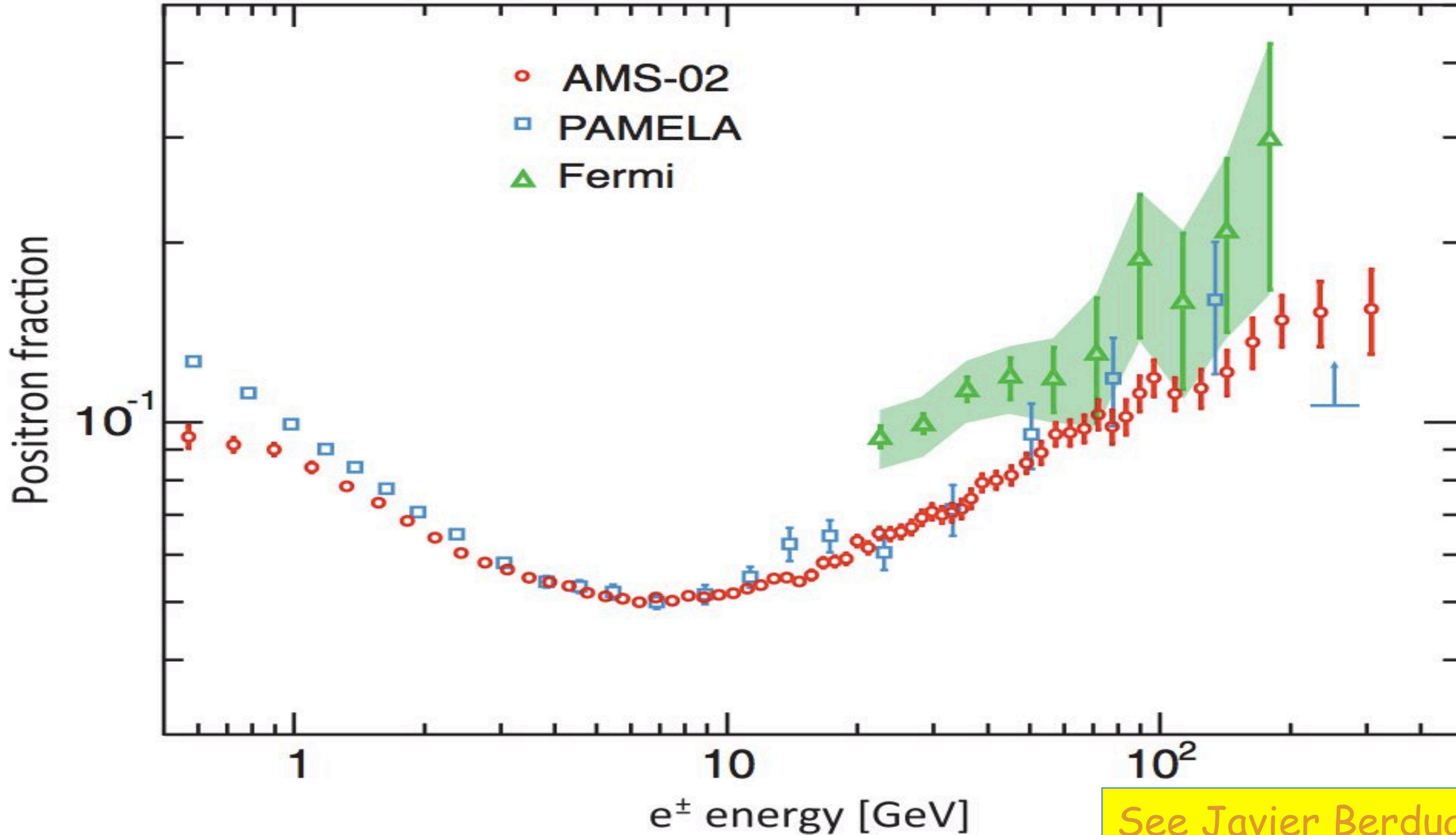

AMS-02 launch
19 May 2011


May 16, 2011 @ 08:56 AM
AMS-02

# AMS-02



# Positron Fraction



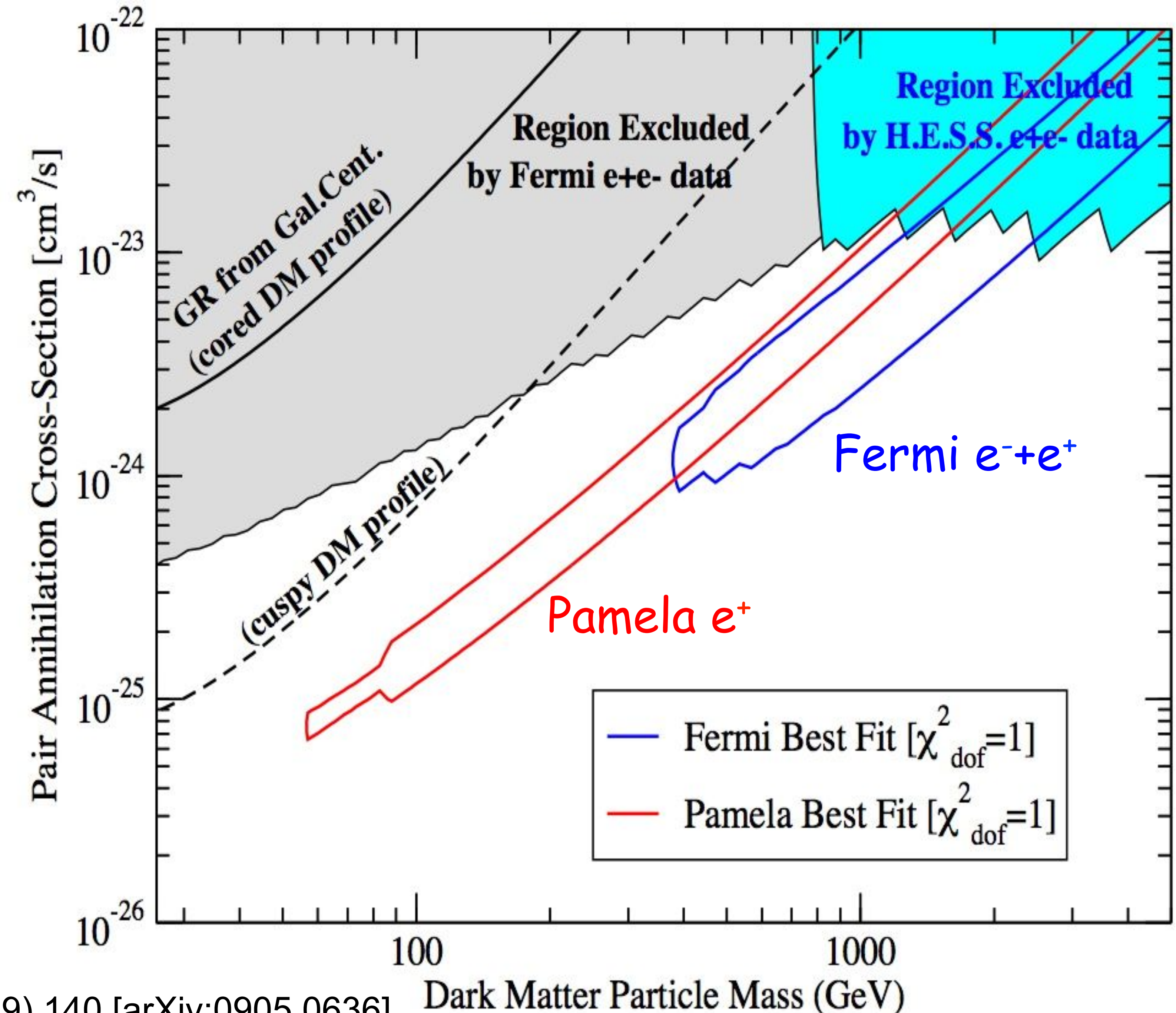

See Javier Berdugo talk

Pamela, Astropart. Phys. 34, 1 (2010) and arXiv:1308.0133

Fermi Coll., PRL, 108 (2012) 011103 arXiv:1109.0521 AMS: PRL 110, 141102 (2013)

# Lepto-philic Models

here we assume a democratic dark matter pair-annihilation branching ratio into each charged lepton species: 1/3 into e+e-, 1/3 into μ+ μ- and 1/3 into τ+ τ- Here too antiprotons are not produced in dark matter pair annihilation.




Astrp Phys.32 (2009) 140 [arXiv:0905.0636]

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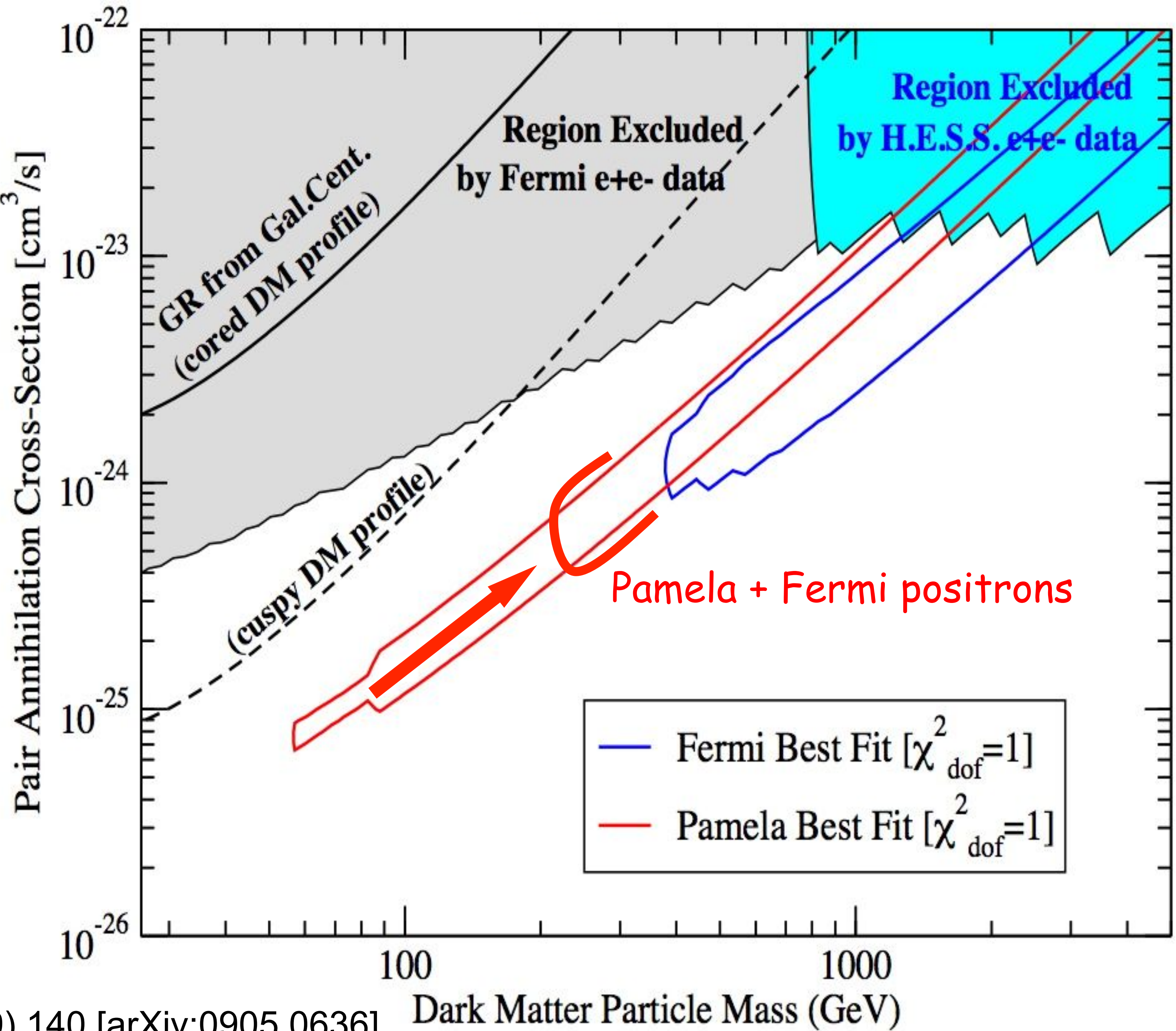


update of Astrp Phys.32 (2009) 140 [arXiv:0905.0636]

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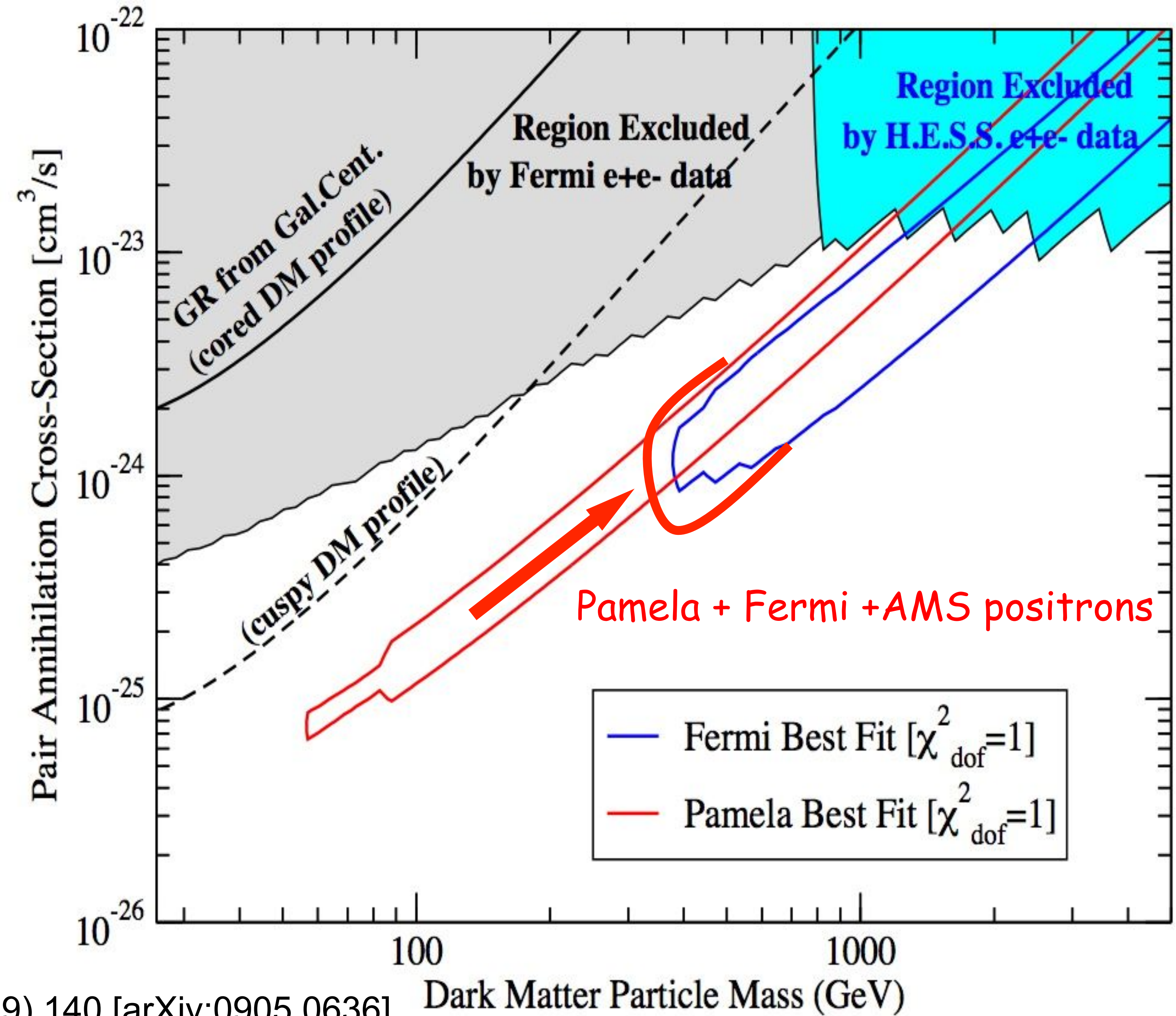



update of Astrp Phys.32 (2009) 140 [arXiv:0905.0636]

# Pulsars

1. On purely energetic grounds they work (relatively large efficiency)

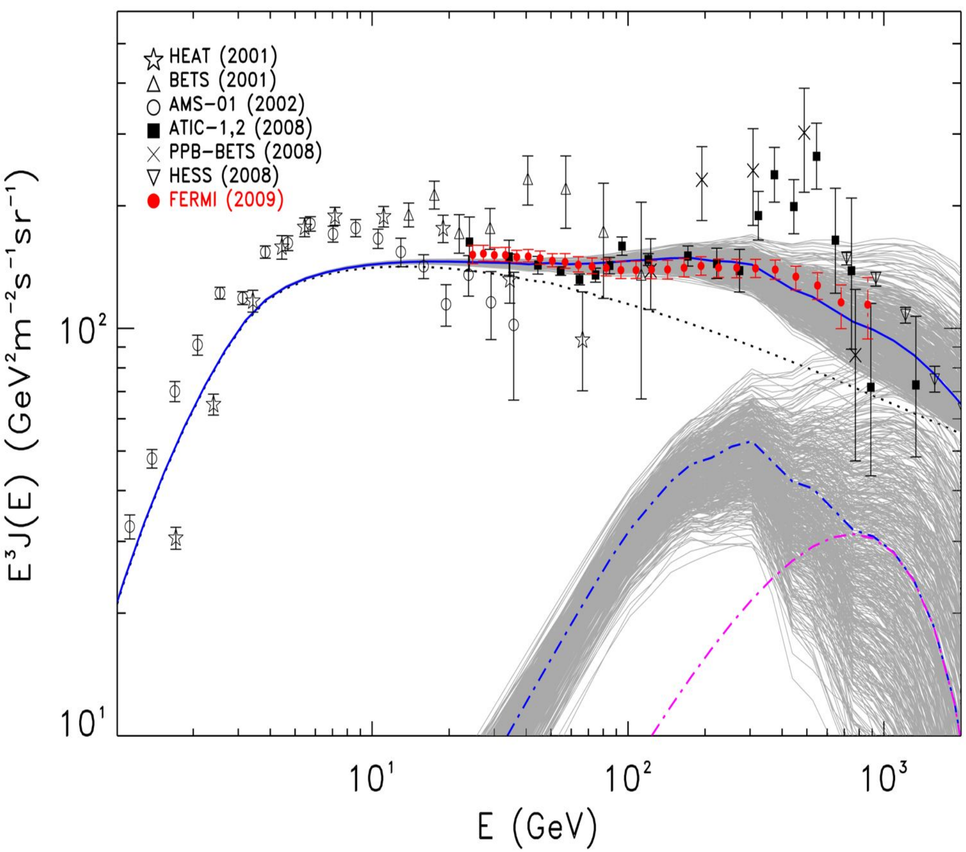
2. On the basis of the spectrum, it is not clear
   1. The spectra of PWN show relatively flat spectra of pairs at Low energies but we do not understand what it is
   2. The general spectra (acceleration at the termination shock) are too steep

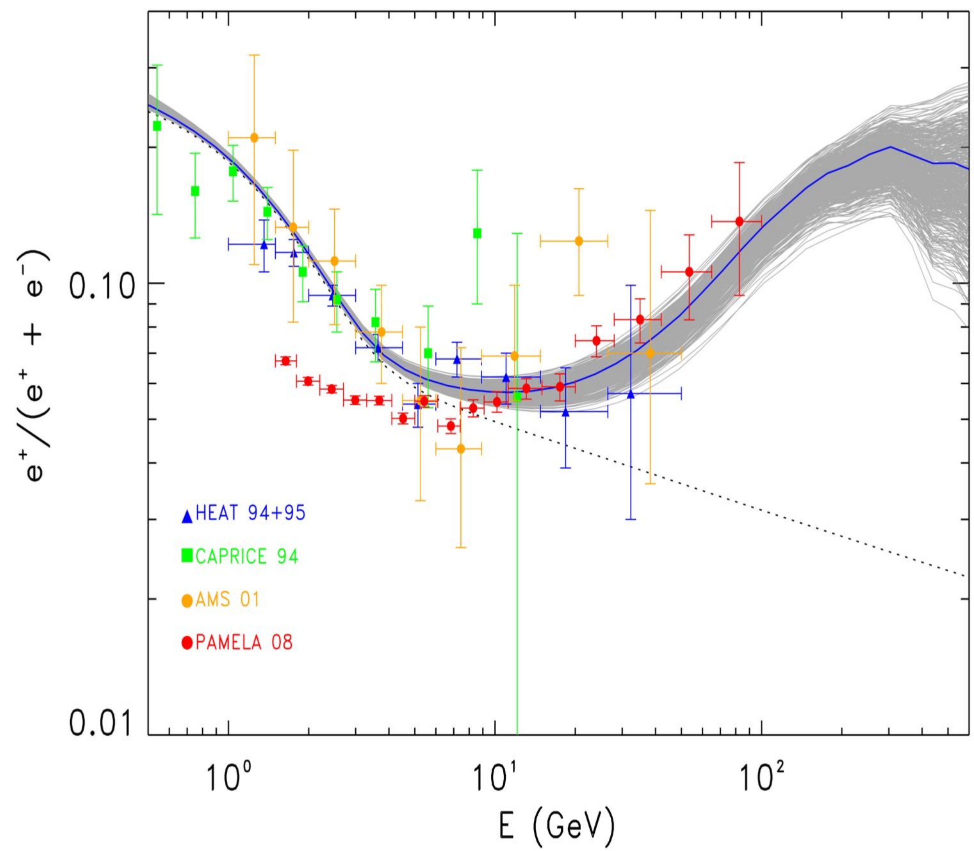
The biggest problem is that of escape of particles from the pulsar
   1. Even if acceleration works, pairs have to survive losses
   2. And in order to escape they have to cross other two shocks

New Fermi data on pulsars will help to constrain the pulsar models

# What if we randomly vary the pulsar parameters relevant for e+e- production?

***(injection spectrum, e+e- production efficiency, PWN "trapping" time)***

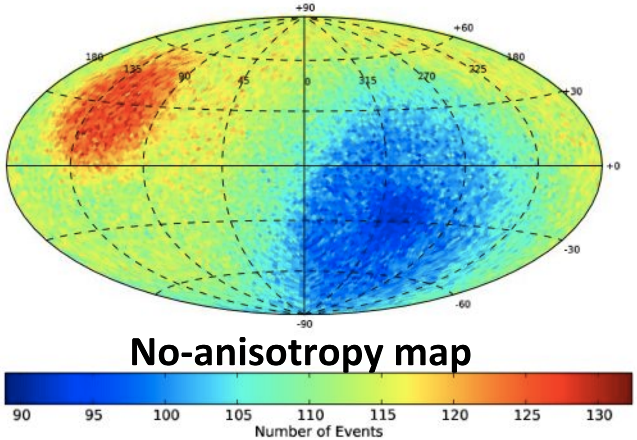


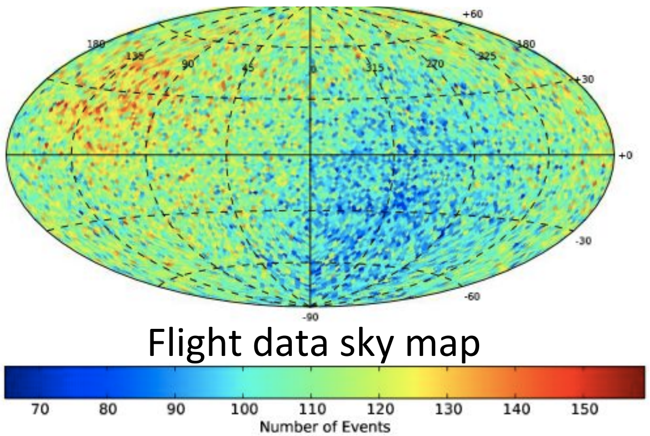

***Under reasonable assumptions, electron/positron emission from pulsars offers a viable interpretation of Fermi CRE data which is also consistent with the HESS and Pamela results.***

D.Grasso et al. Astropart. Phys. 32 (2009), pp.140 [arXiv:0905.0636]

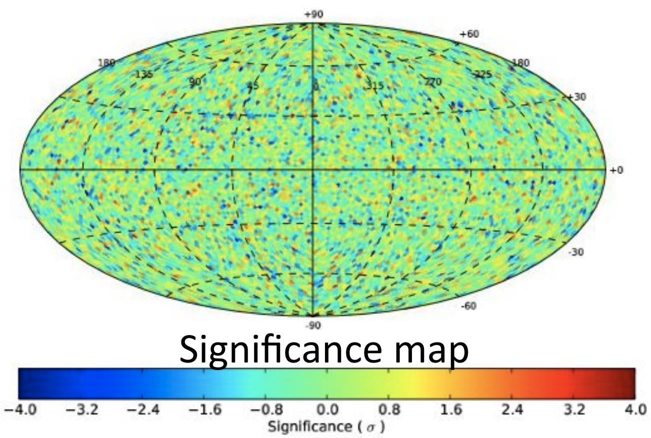
# Cosmic Ray Electrons Anisotropy




No-anisotropy map



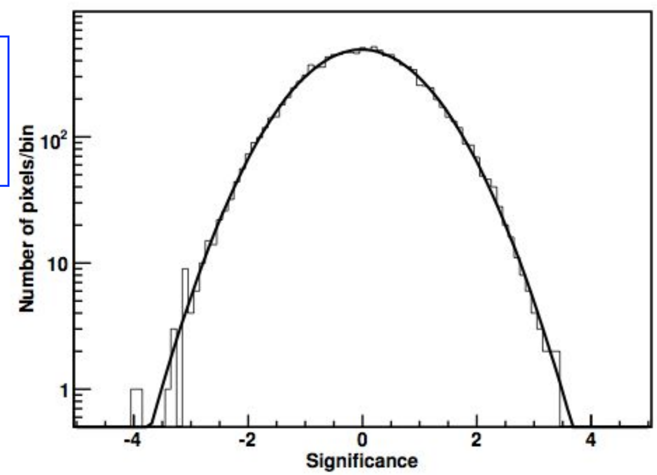

Flight data sky map




Significance map

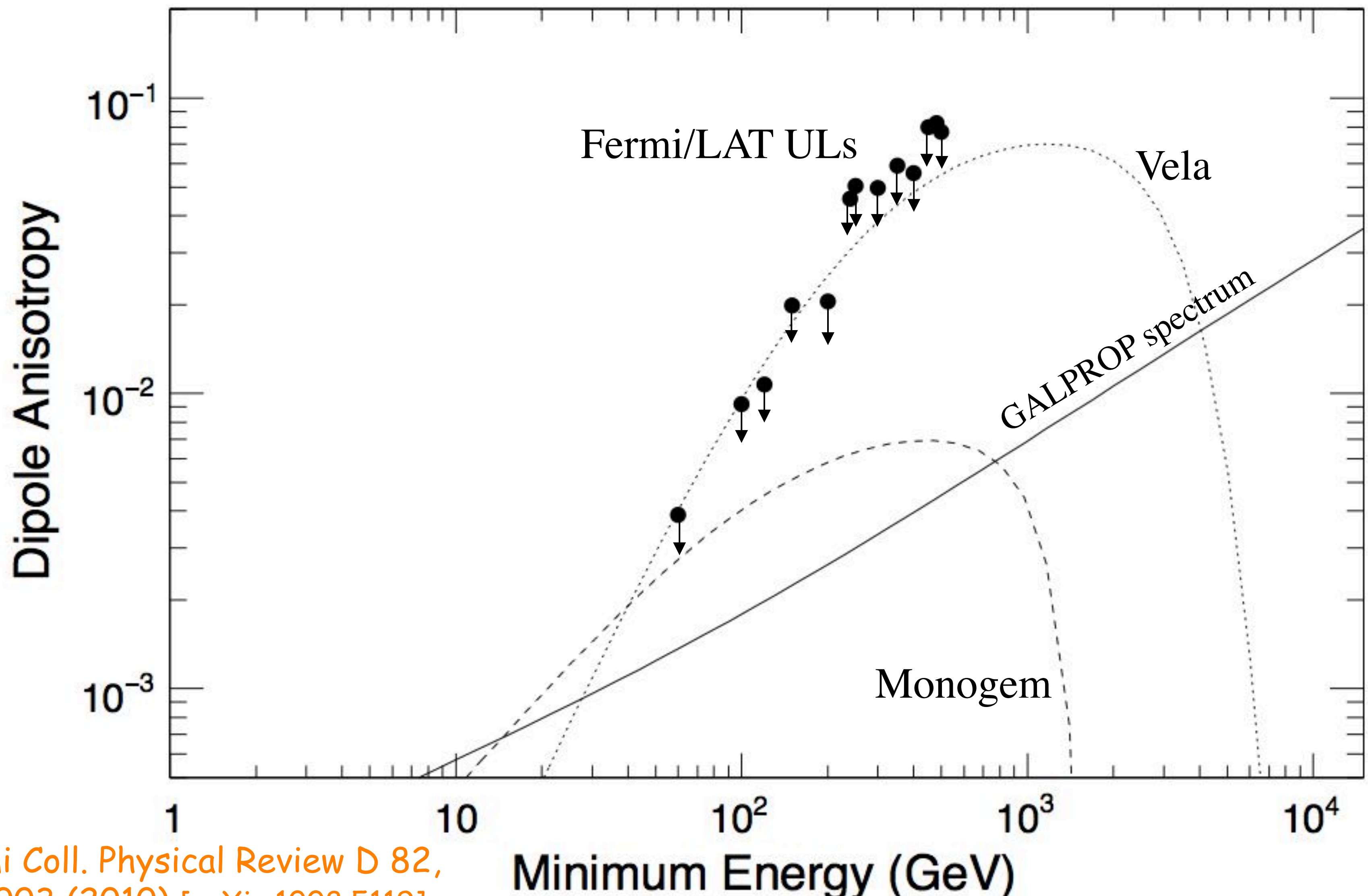
<u>the levels of anisotropy expected for Geminga-like and Monogem-like sources</u> (i.e. sources with similar distances and ages) <u>seem to be higher than the scale of anisotropies excluded by the results</u>
However, it is worth to point out that the model results are affected by large uncertainties related to the choice of the free parameters

Distribution of significance, fitted by a Gaussian →




Fermi Coll. Physical Review D 82, 092003 (2010) [arXiv:1008.5119]

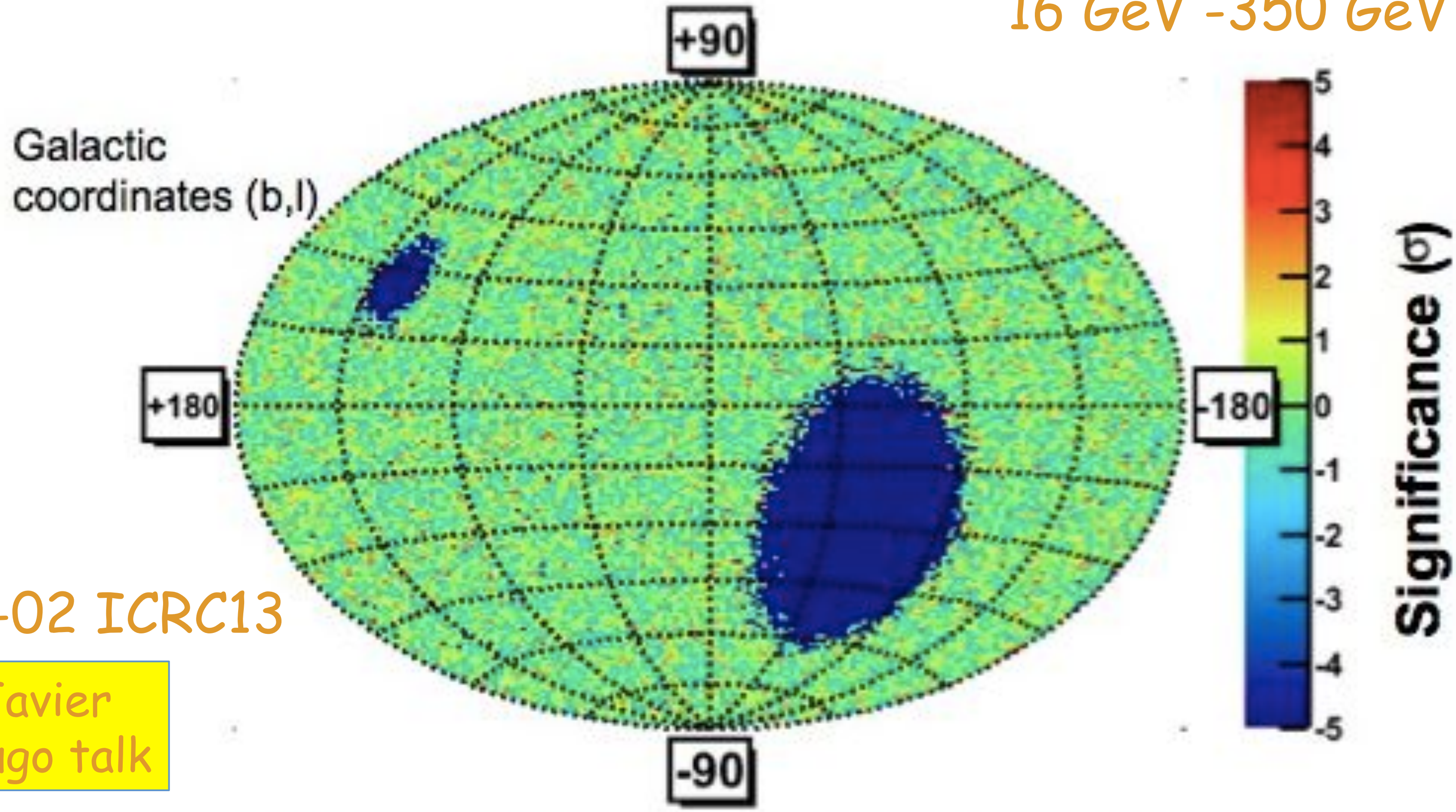
# electron + positron expected anisotropy in the directions of Monogem and Vela




Fermi Coll. Physical Review D 82, 092003 (2010) [arXiv:1008.5119]

# Dipole anisotropy in the positron ratio

16 GeV -350 GeV



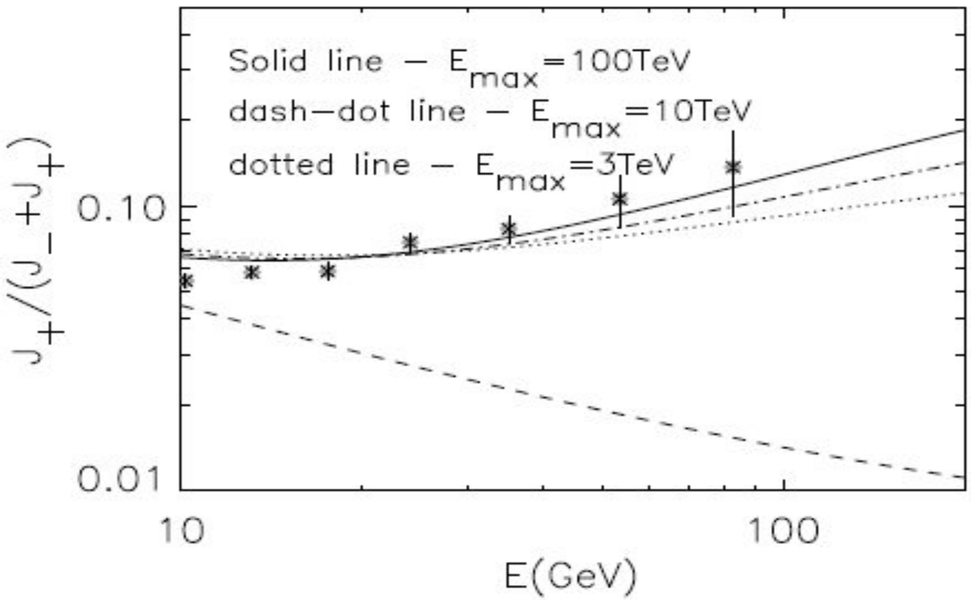

AMS-02 ICRC13

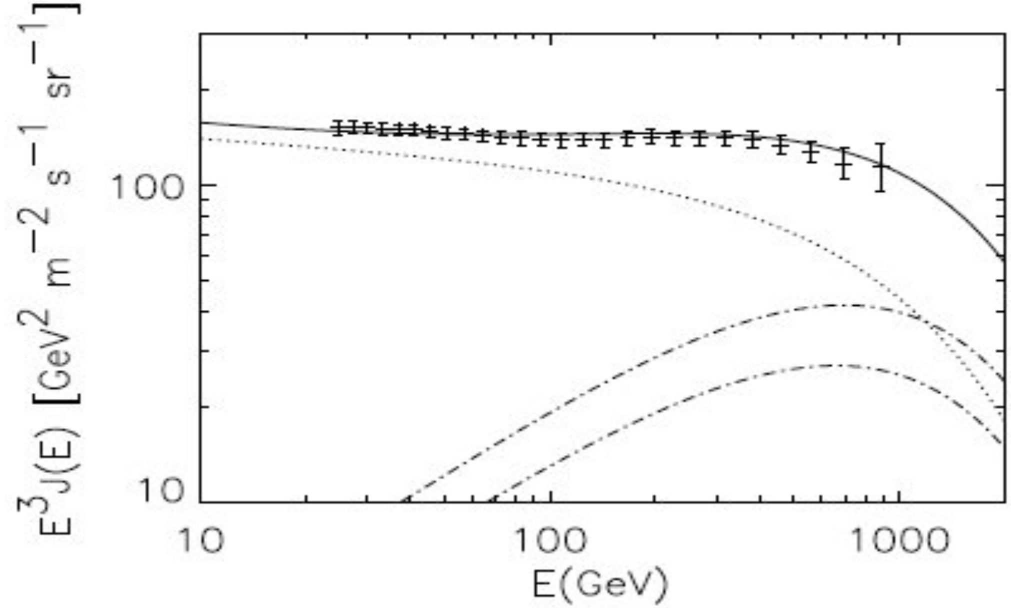
See Javier Berdugo talk

**The fluctuations of the positron ratio $e^+/e^-$ are isotropic**

**$\delta \leq 0.030$ at the 95% confidence level**

# other Astrophysical solution



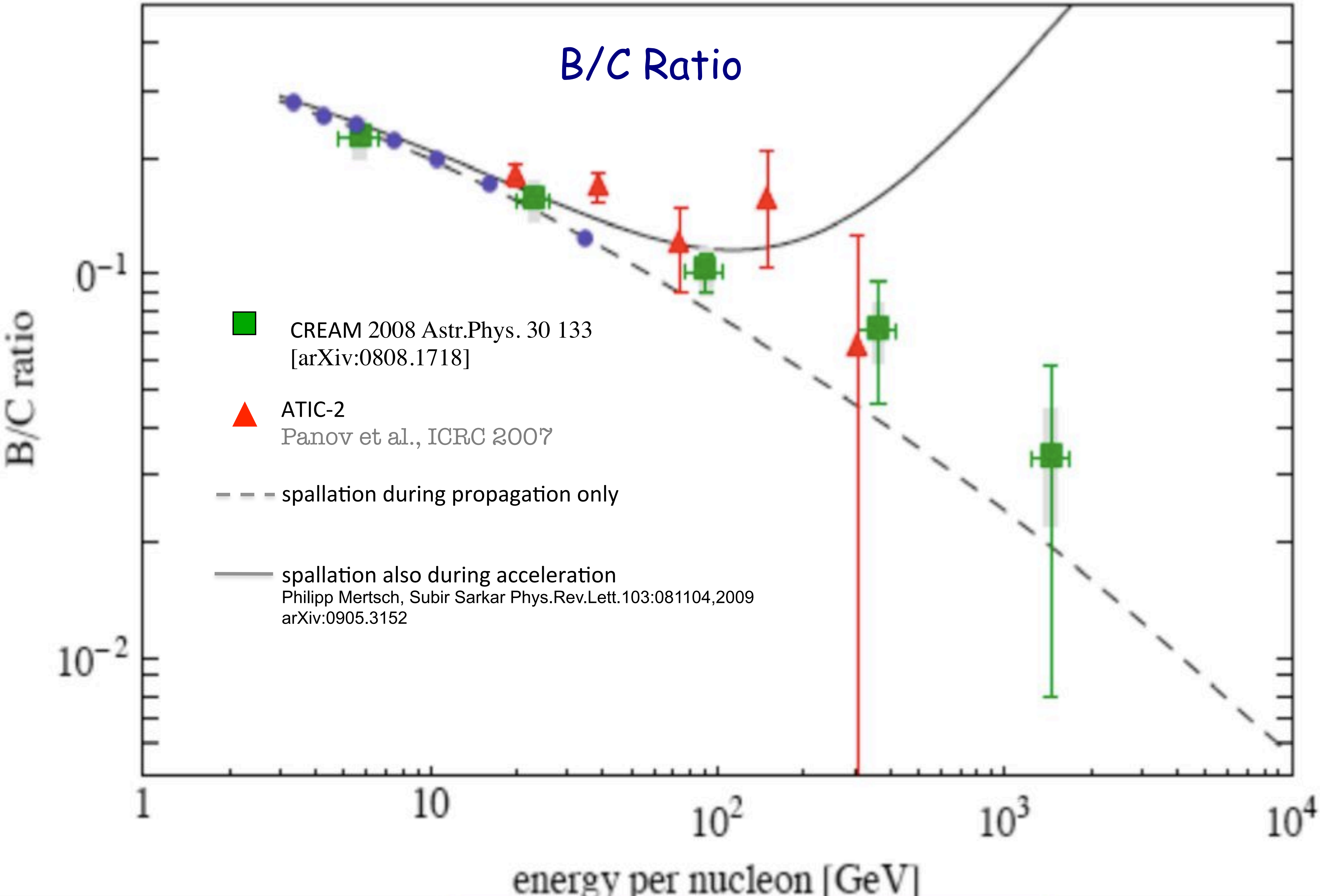

• Positrons created as secondary products of hadronic interactions inside the sources

• Secondary production takes place in the same region where cosmic rays are being accelerated

-> Therefore secondary positron have a very flat spectrum, which is responsible, after propagation in the Galaxy, for the observed positron excess

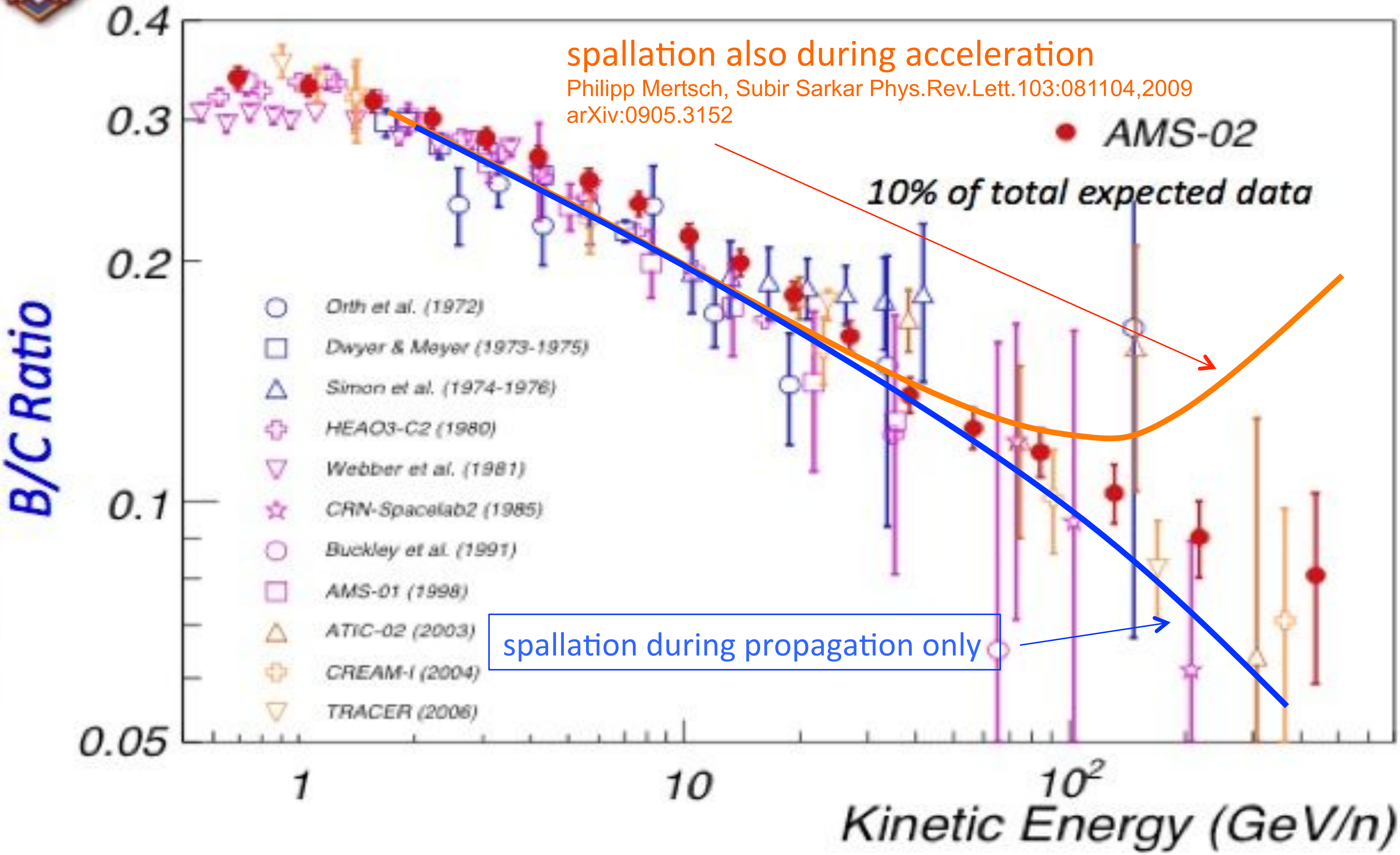
Blasi, arXiv:0903.2794

# B/C Ratio

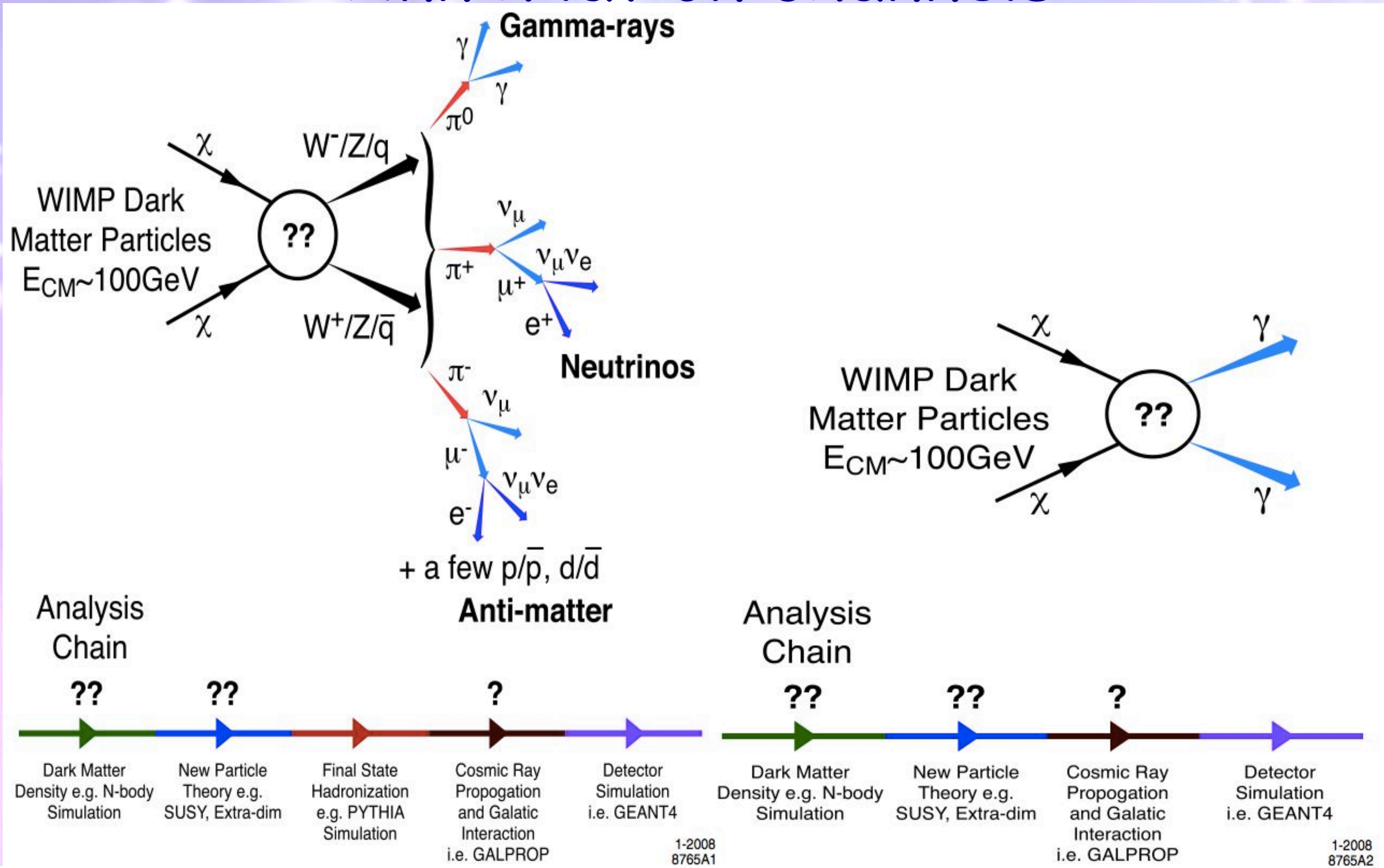


CREAM 2008 Astr.Phys. 30 133
[arXiv:0808.1718]
ATIC-2
Panov et al., ICRC 2007
spallation during propagation only
spallation also during acceleration
Philipp Mertsch, Subir Sarkar Phys.Rev.Lett.103:081104,2009
arXiv:0905.3152
B/C ratio
energy per nucleon [GeV]

# Boron-to-Carbon ratio compared with previous data



# Annihilation channels



# Signal rate from Supersymmetry

gamma-ray flux from neutralino annihilation

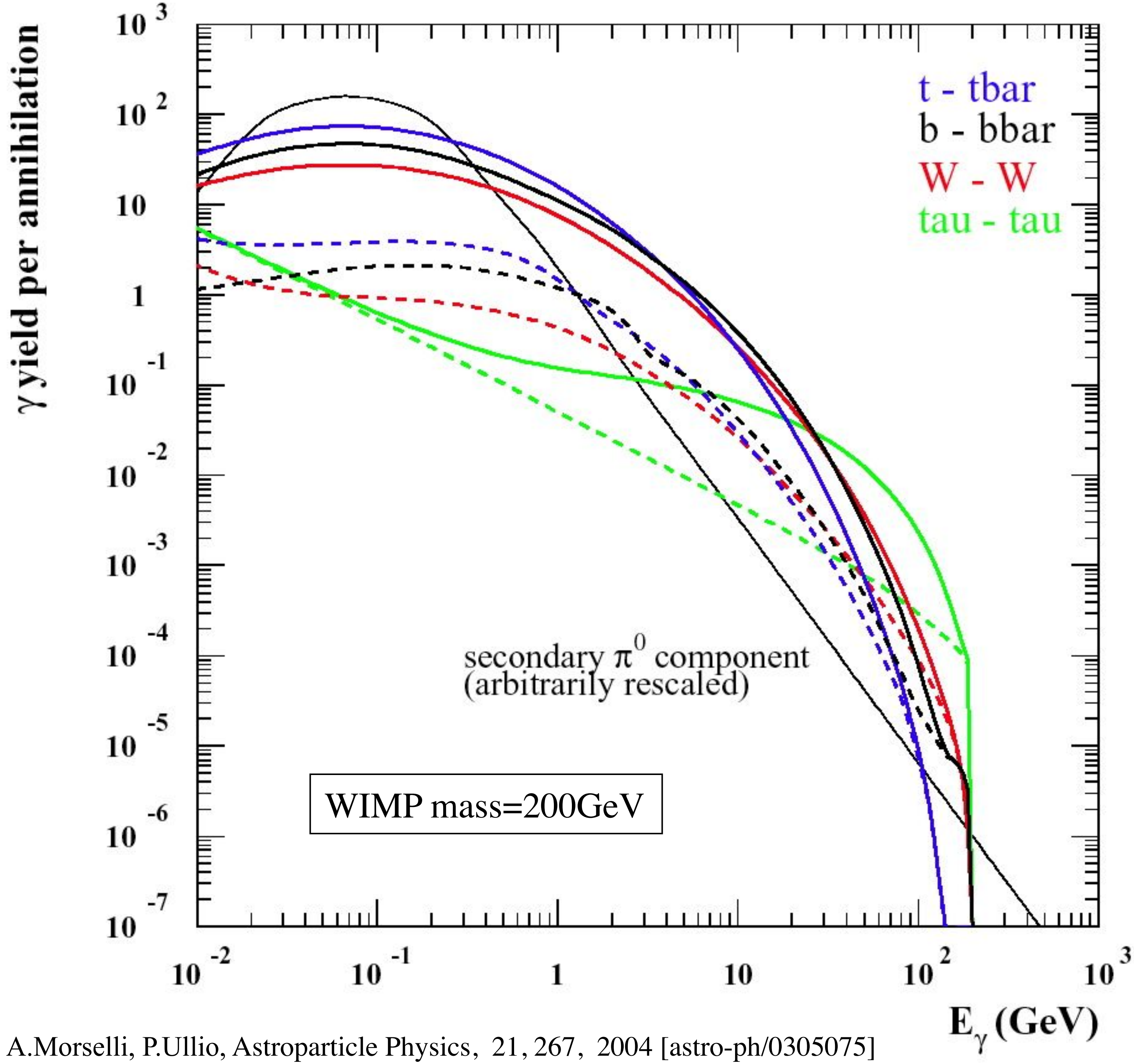
$$\phi(E,\Delta\Omega) \propto \left(\frac{\sigma v}{m_\chi^2}\right) \int_{l.o.s} \int_{\Delta\Omega} \rho^2(l)\,dl\,d\Omega)$$

governed by supersymmetric parameters

$J(\varphi)$:

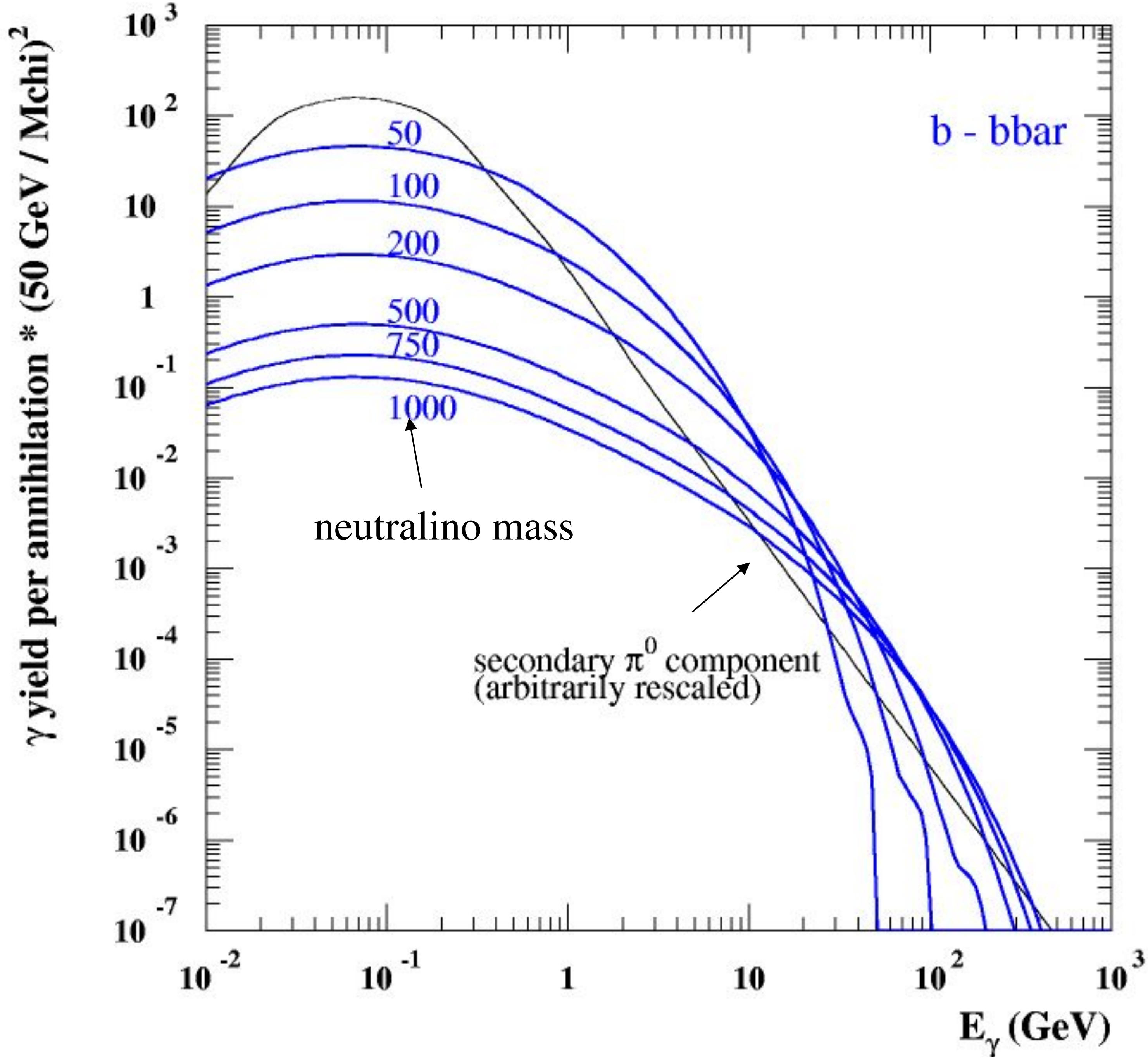
governed by halo distribution

# Differential yield for each annihilation channel




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

# Differential yield for b bar




The low energy window (<100 MeV) is important even for a 1 TeV DM Mass !!

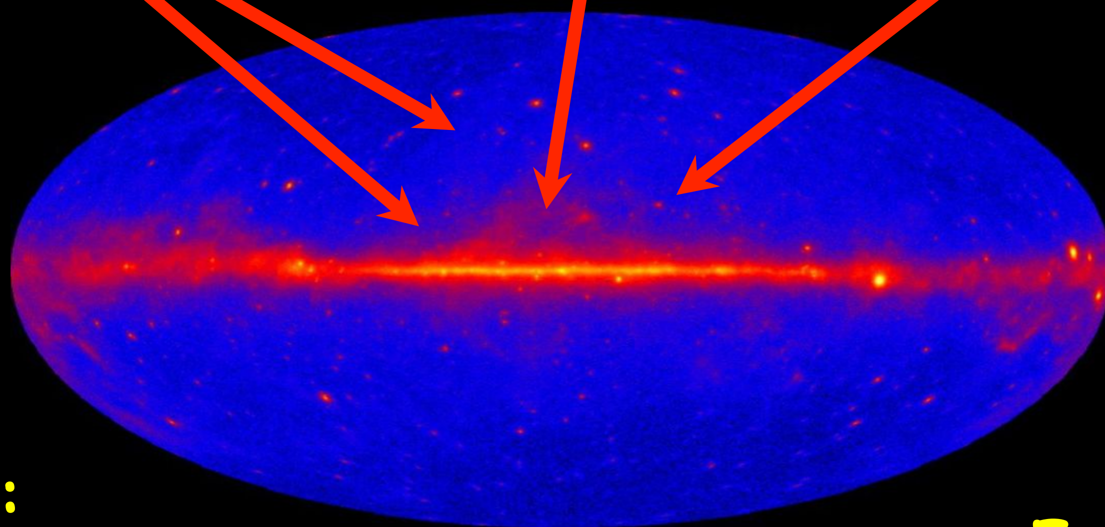
A.Cesarini, F.Fucito, A.Lionetto, A.Morselli, P.Ullio, Astroparticle Physics, 21, 267-285, 2004 [astro-ph/0305075]

# 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

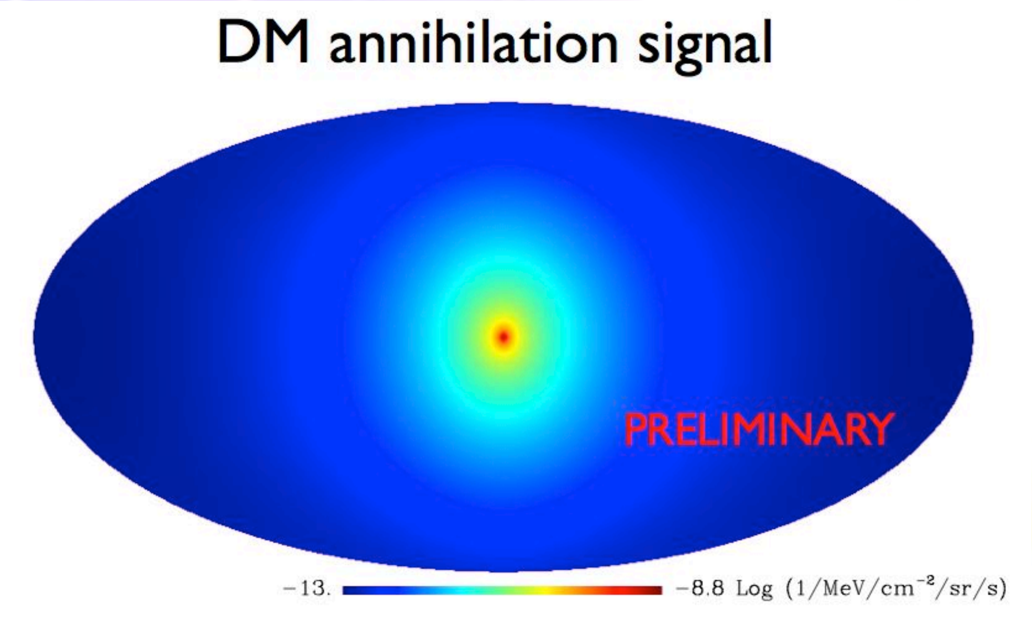
**Galaxy clusters:**
Low background but low statistics

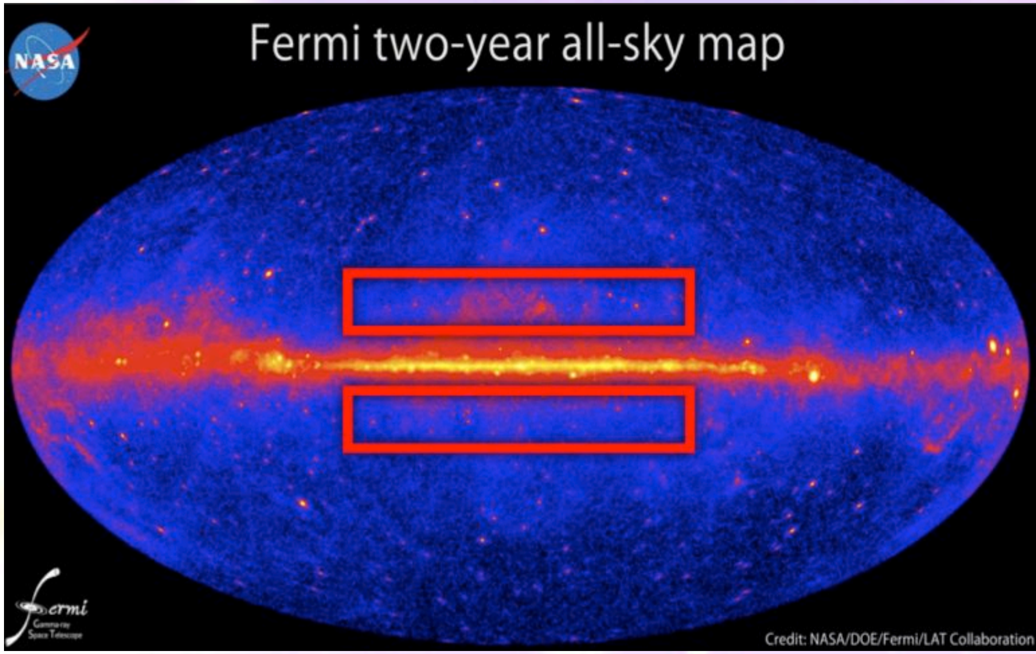
**Extra-galactic:**
Large statistics, but astrophysics,galactic diffuse background

Pre-launch sensitivities published in Baltz et al., 2008, JCAP 0807:013 [astro-ph/0806.2911]

# Constraints from the Milky Way halo

testing the LAT diffuse data for a contribution from a Milky Way DM annihilation/decay signal




2 years of data   1-100 GeV energy range

ROI: 5° <|b|<15° and |l|<80°, chosen to:

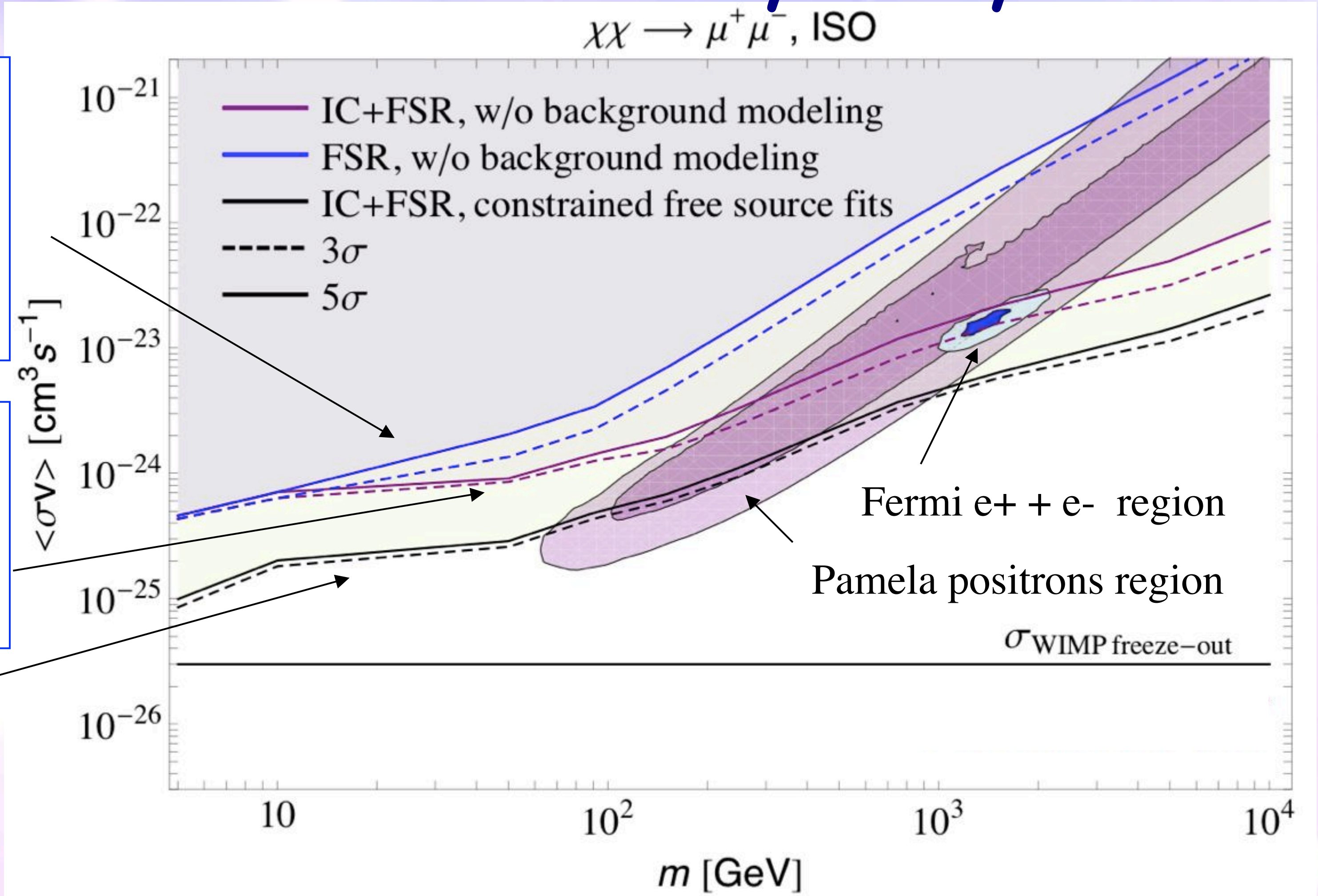
- minimize DM profile uncertainty (highest in the Galactic Center region)
- limit astrophysical uncertainty by masking out the Galactic plane and cutting-out high- latitude emission from the Fermi lobes and Loop I

# Constraints from the Milky Way halo

only photons produced by muons (no electrons) to set "no-background limits"

"no-background limits" including FSR +IC from dark matter

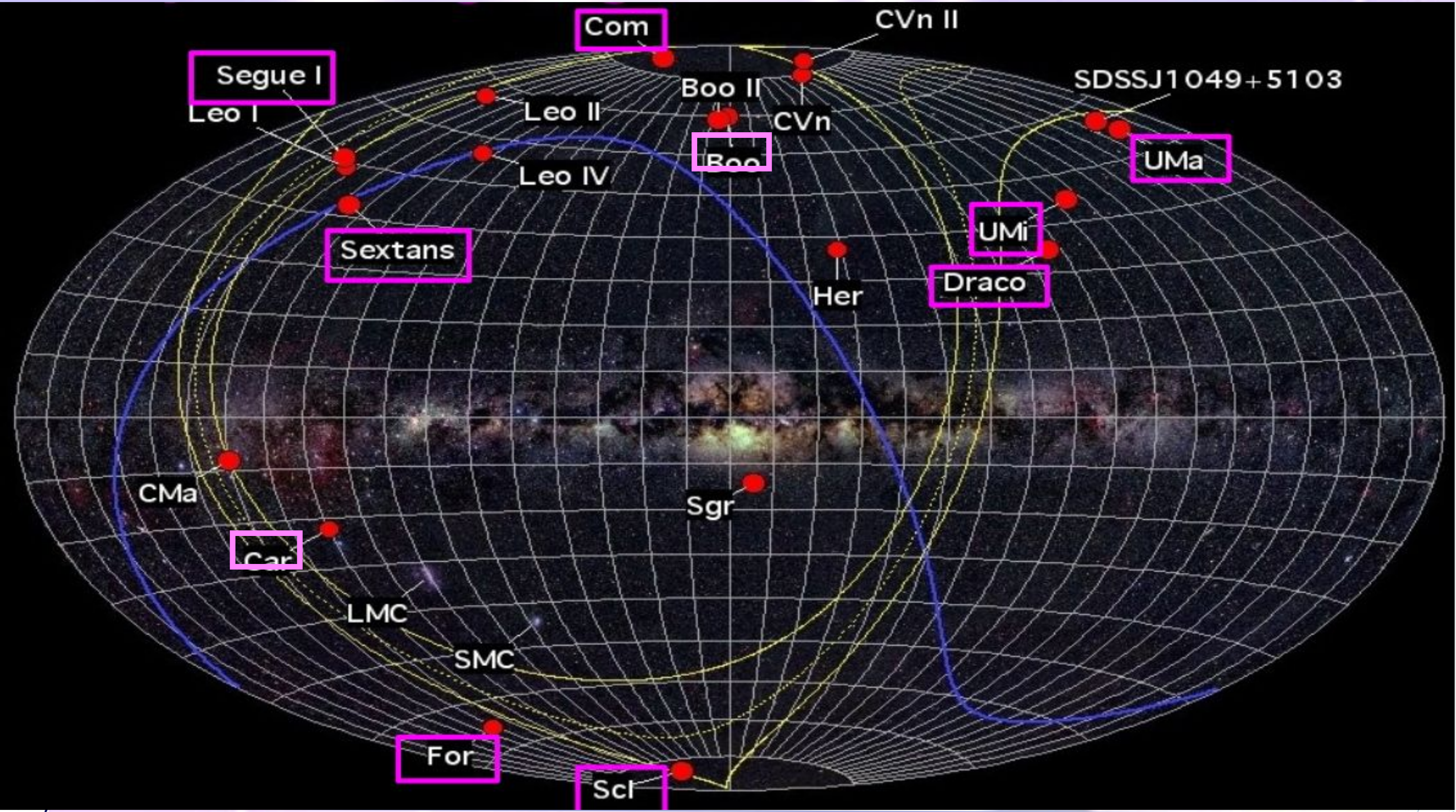
limits from profile likelihood and CR sources set to zero in the inner 3 kpc



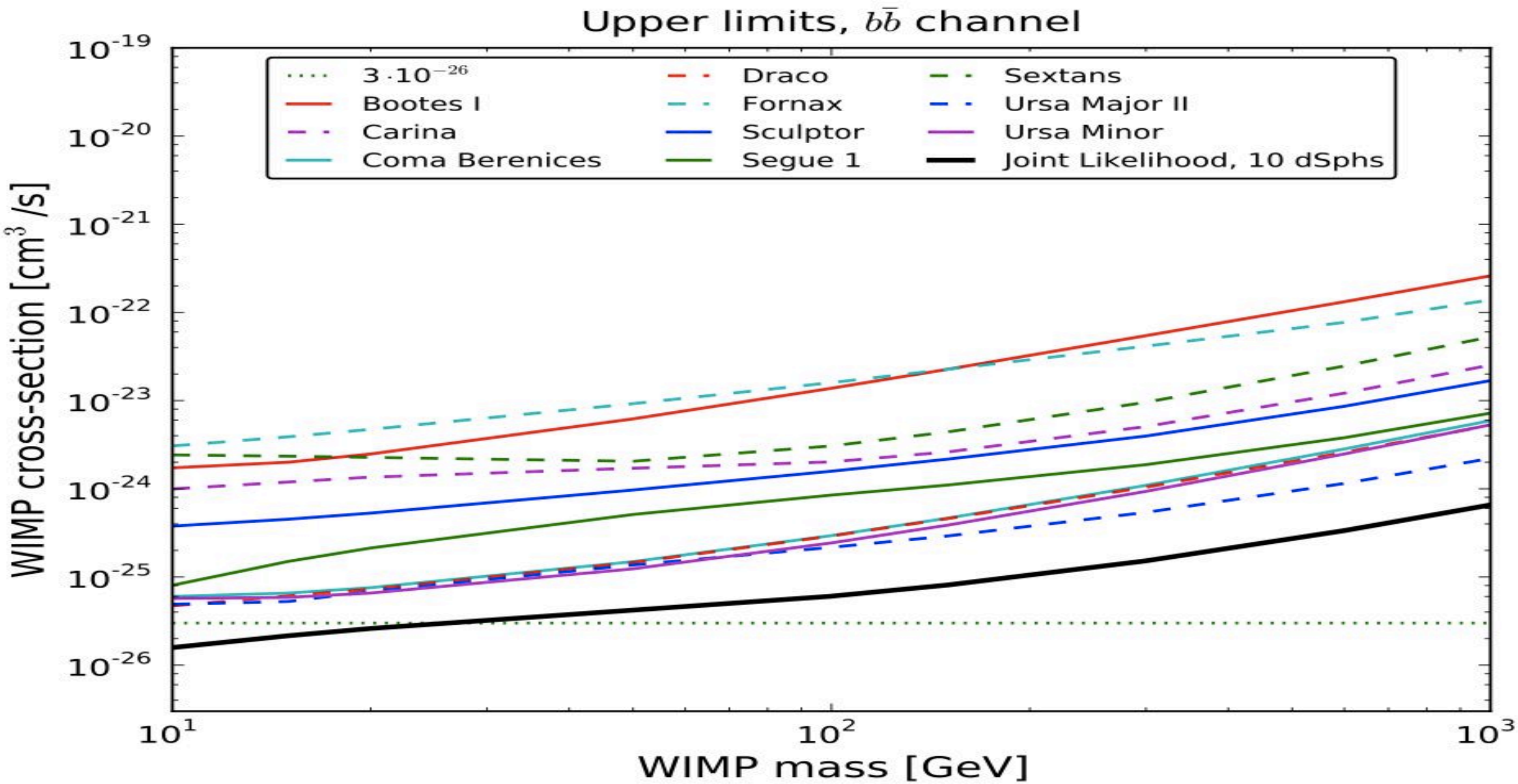

DM interpretation of PAMELA/Fermi CR anomalies disfavored

Fermi Coll.ApJ 761 (2012) 91 [arXiv:1205.6474]

# Dwarf spheroidal galaxies (dSph) : promising targets for DM detection



# Dwarf Spheroidal Galaxies combined analysis

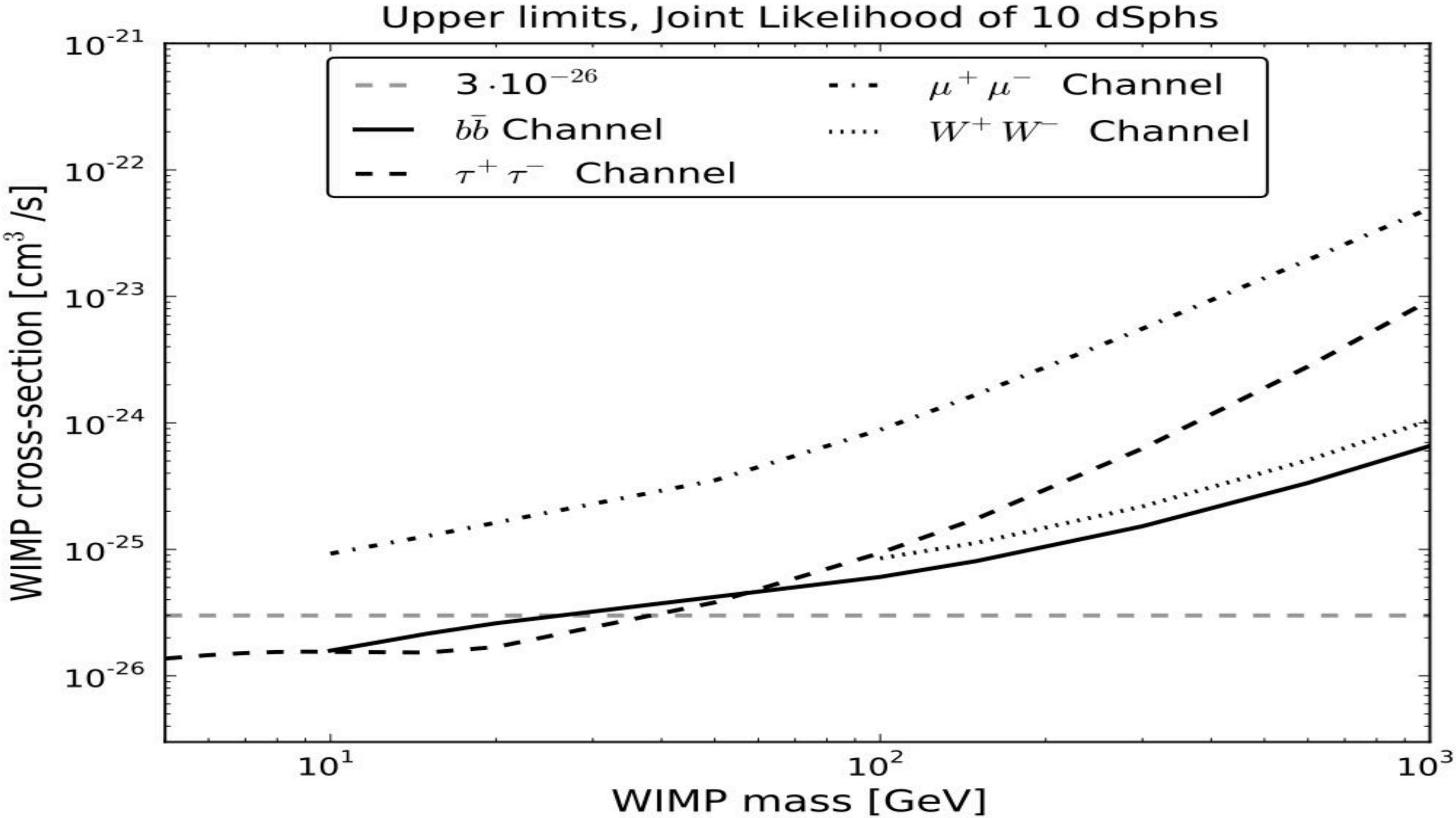



**robust constraints including J-factor uncertainties from the stellar data statistical analysis**

NFW. For cored dark matter profile, the J-factors for most of the dSphs would either increase or not change much

Fermi Lat Coll., PRL 107, 241302 (2011) [arXiv:1108.3546]

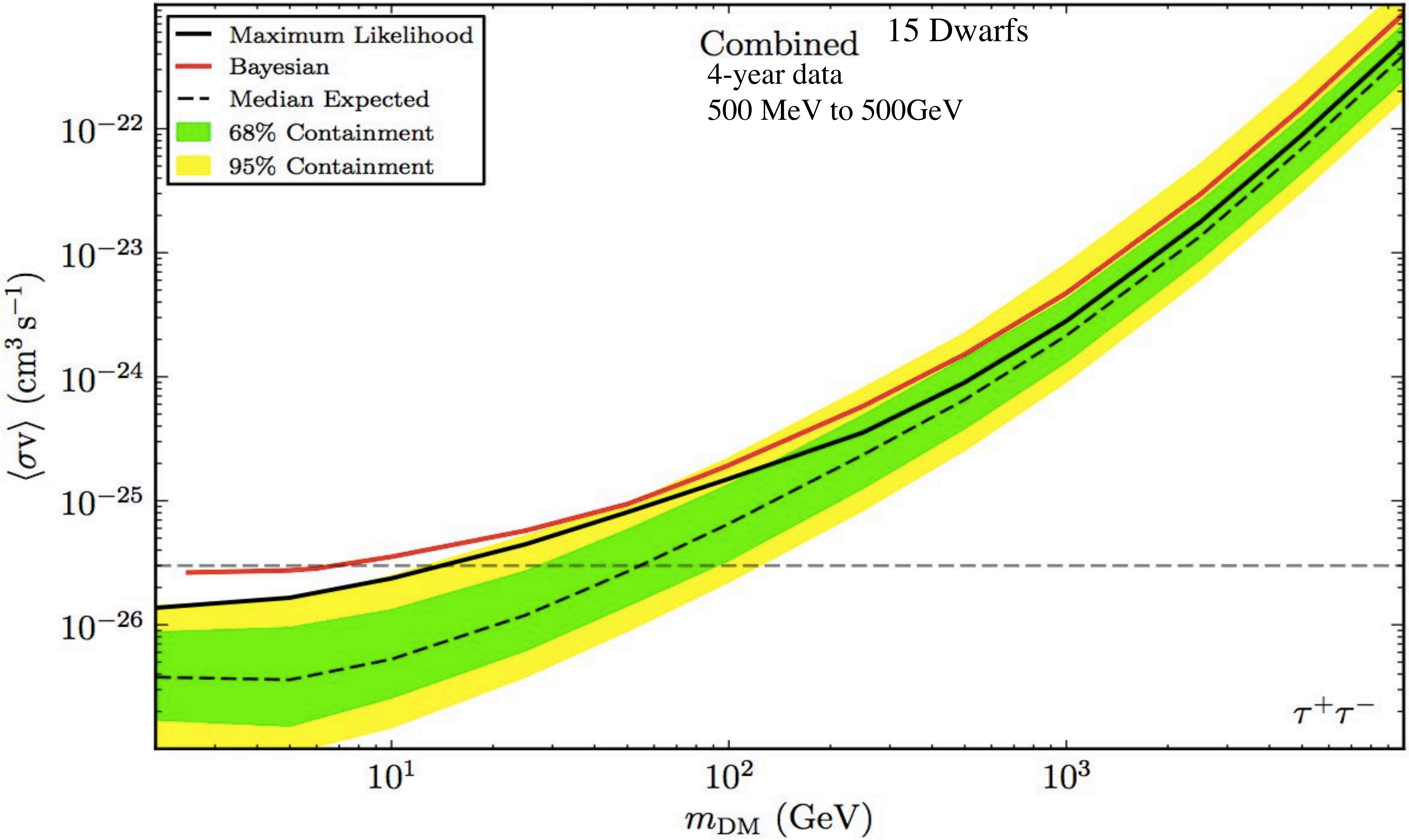
# Dwarf Spheroidal Galaxies combined analysis




**robust constraints including J-factor uncertainties from the stellar data statistical analysis**

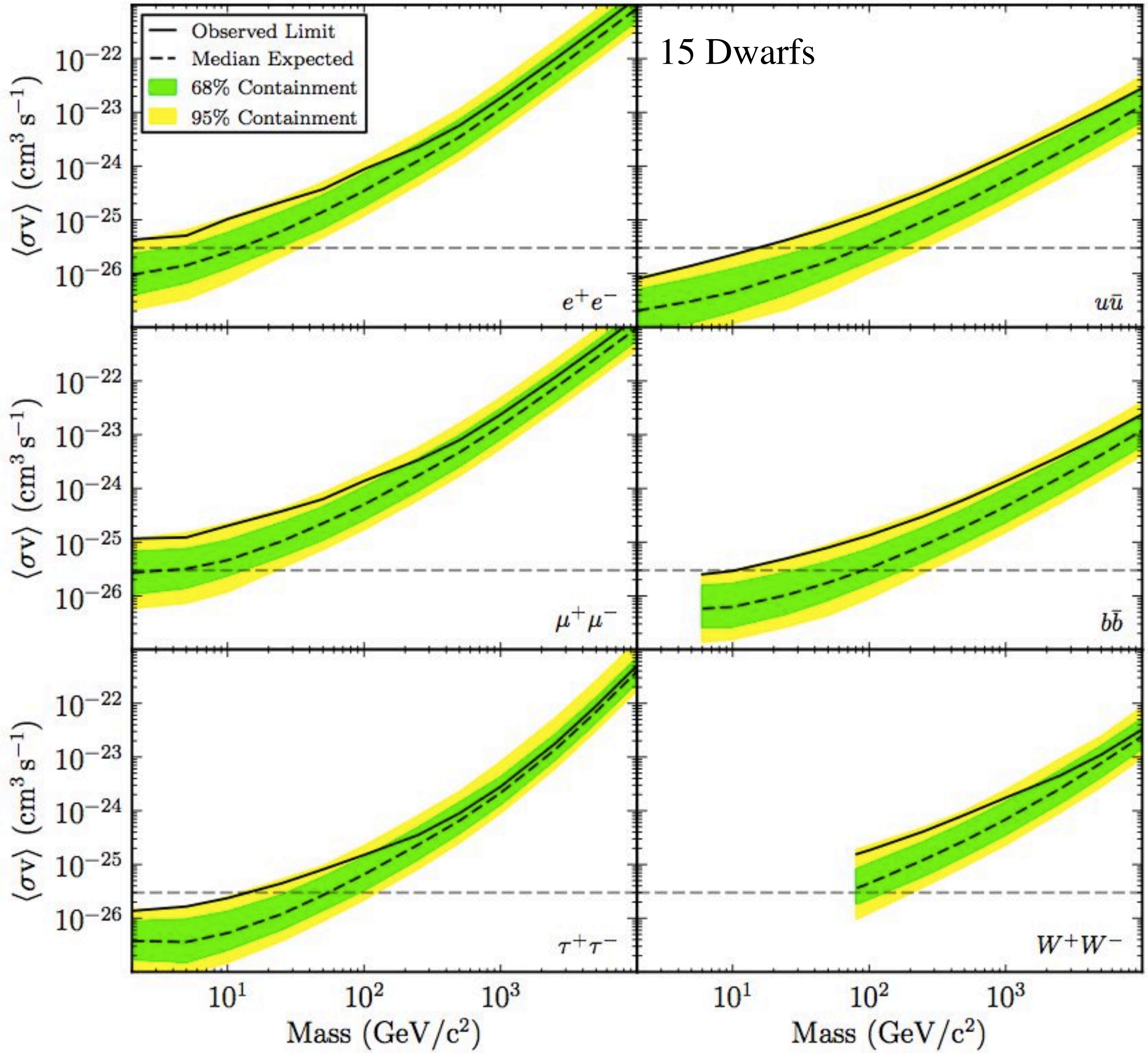
Fermi Lat Coll., PRL 107, 241302 (2011) [arXiv:1108.3546]

# Dwarf Spheroidal Galaxies upper-limits




M.Ackermann et al., [Fermi Coll.] PRD sub.[arXiv:1310.0828]

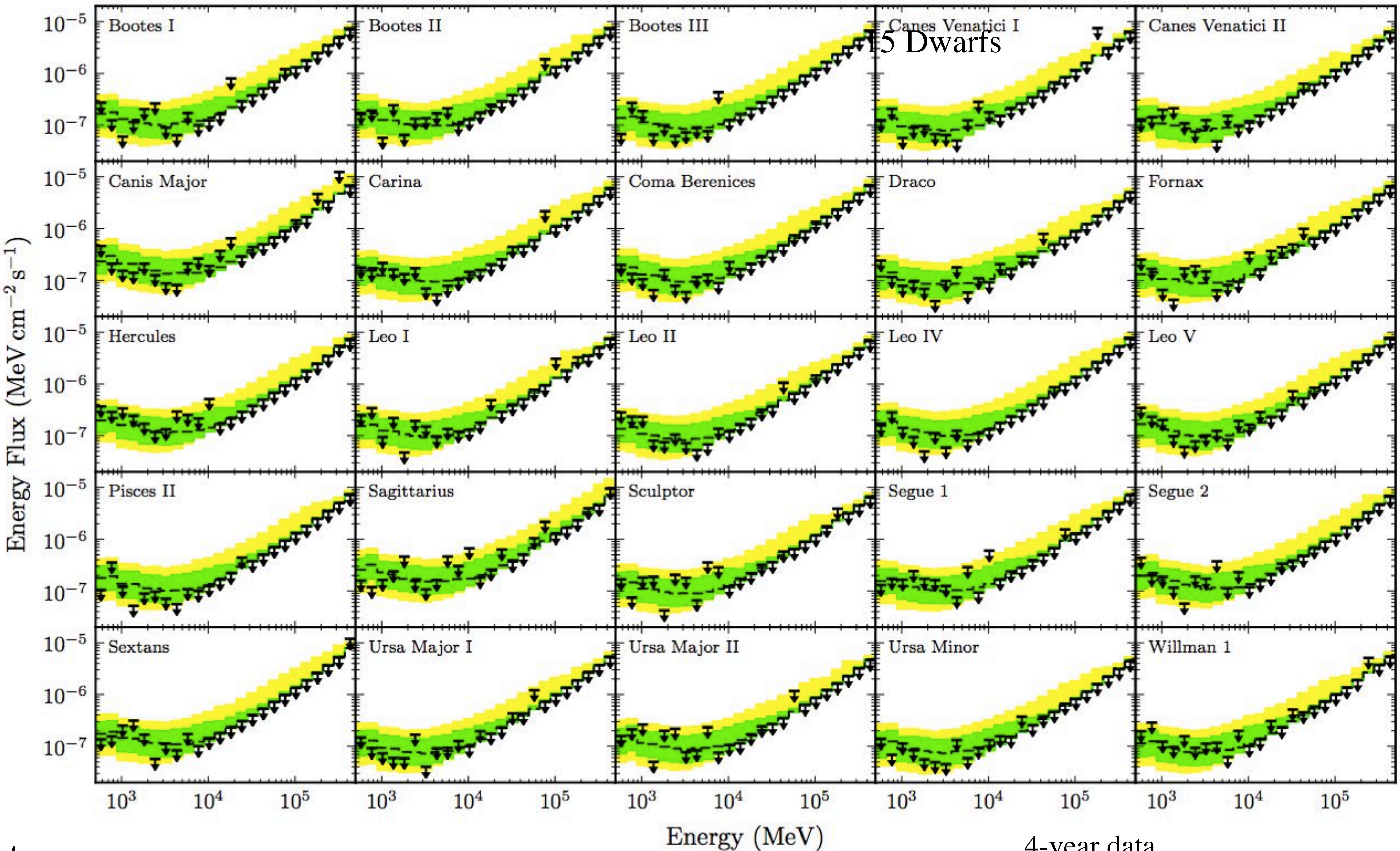
# Dwarf Spheroidal Galaxies upper-limits




15 Dwarfs
4-year data
500 MeV to 500GeV

M.Ackermann et al., [Fermi Coll.] PRD sub. [arXiv:1310.0828]

# 25 Dwarf Spheroidal Galaxies upper-limits

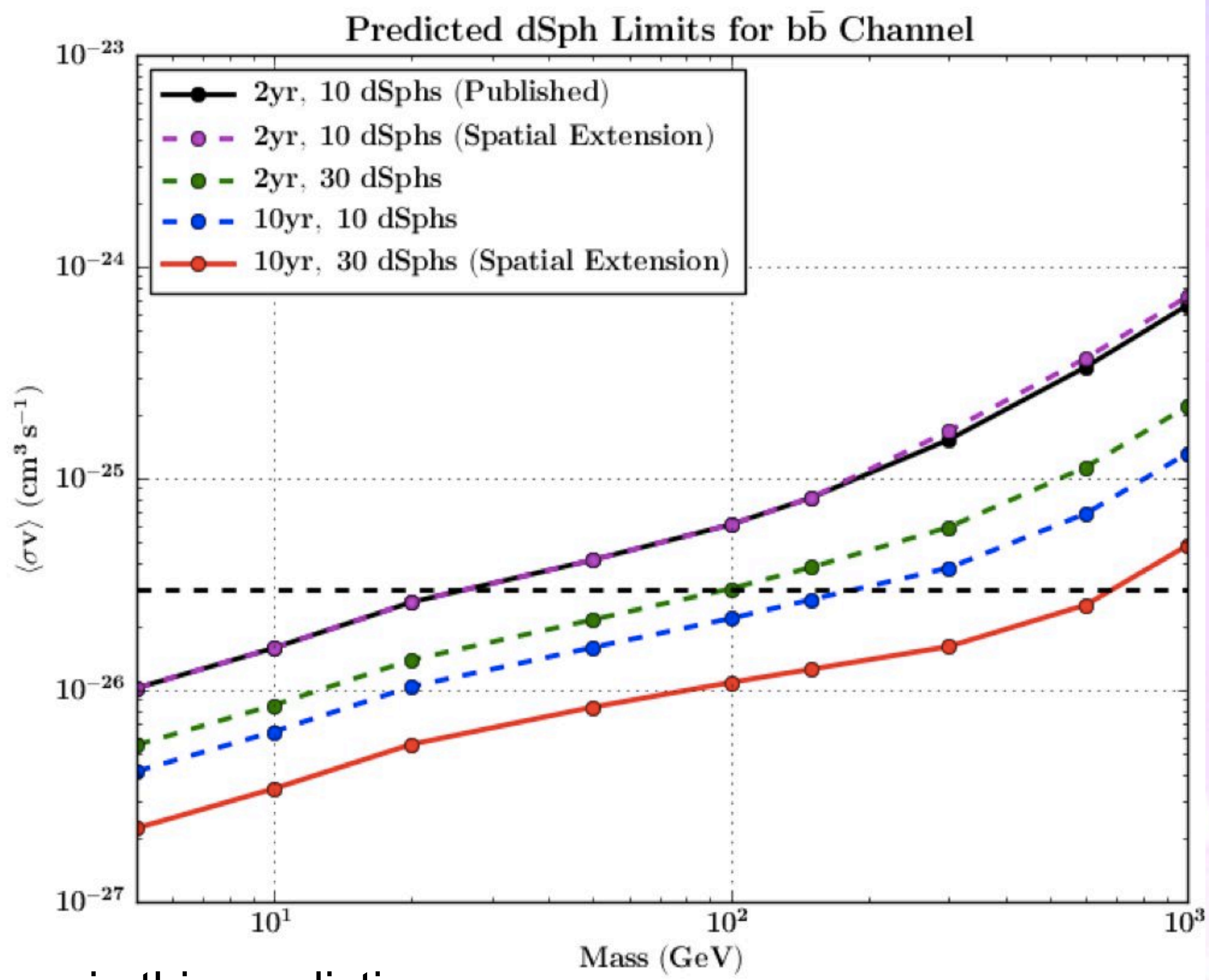



4-year data
500 MeV to 500GeV

M.Ackermann et al., [Fermi Coll.] PRD sub.[arXiv:1310.0828]

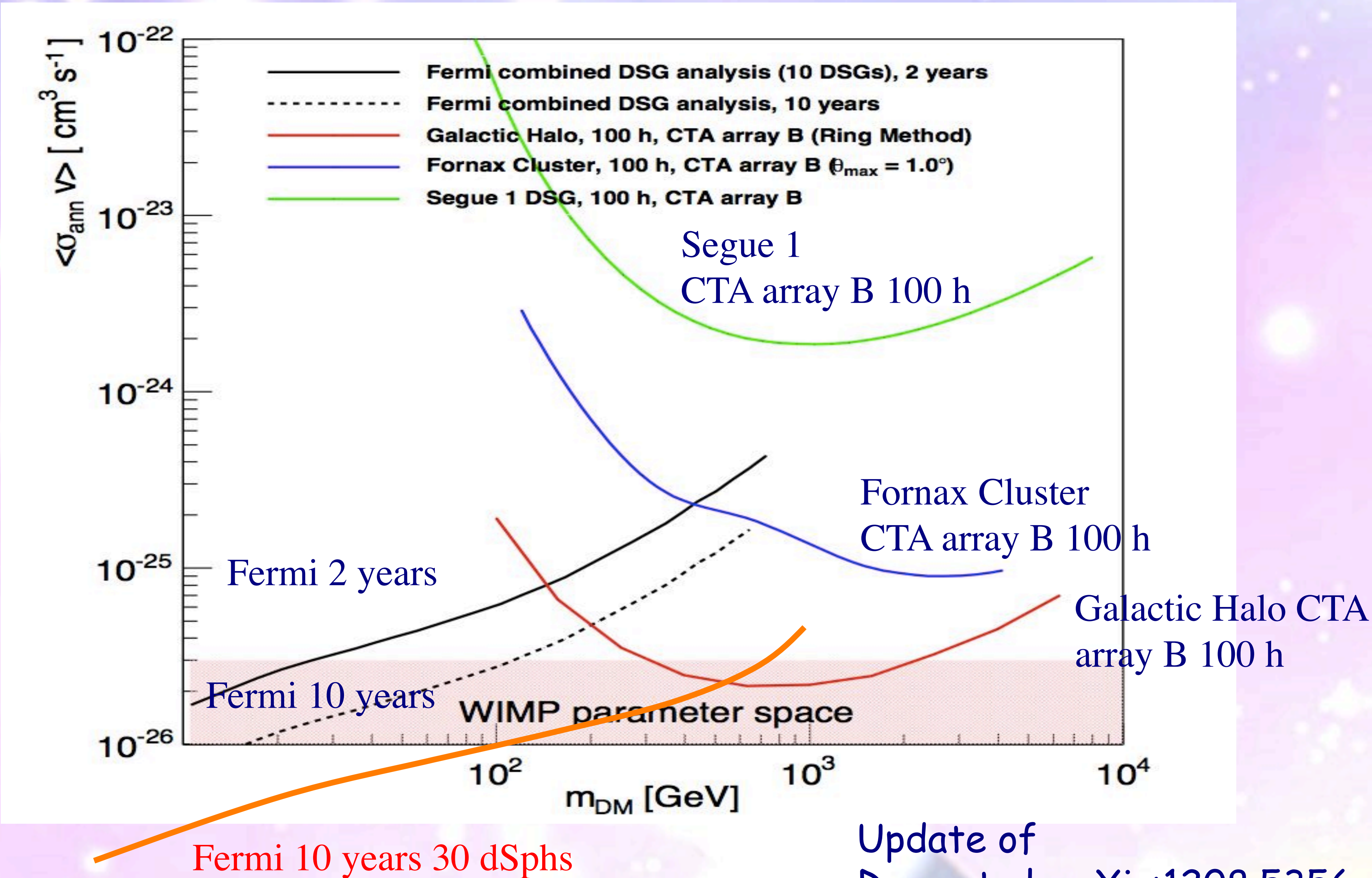
# DM limit improvement estimate in 10 years with the composite likelihood approach (2008- 2018)

- 10 years of data instead of 2(5x)
- 30 dSphs (3x) (supposing that the new optical surveys will find new dSph)
- -10% from spatial extension (source extension increases the signal region at high energy E > 10 GeV, M > 200 GeV )



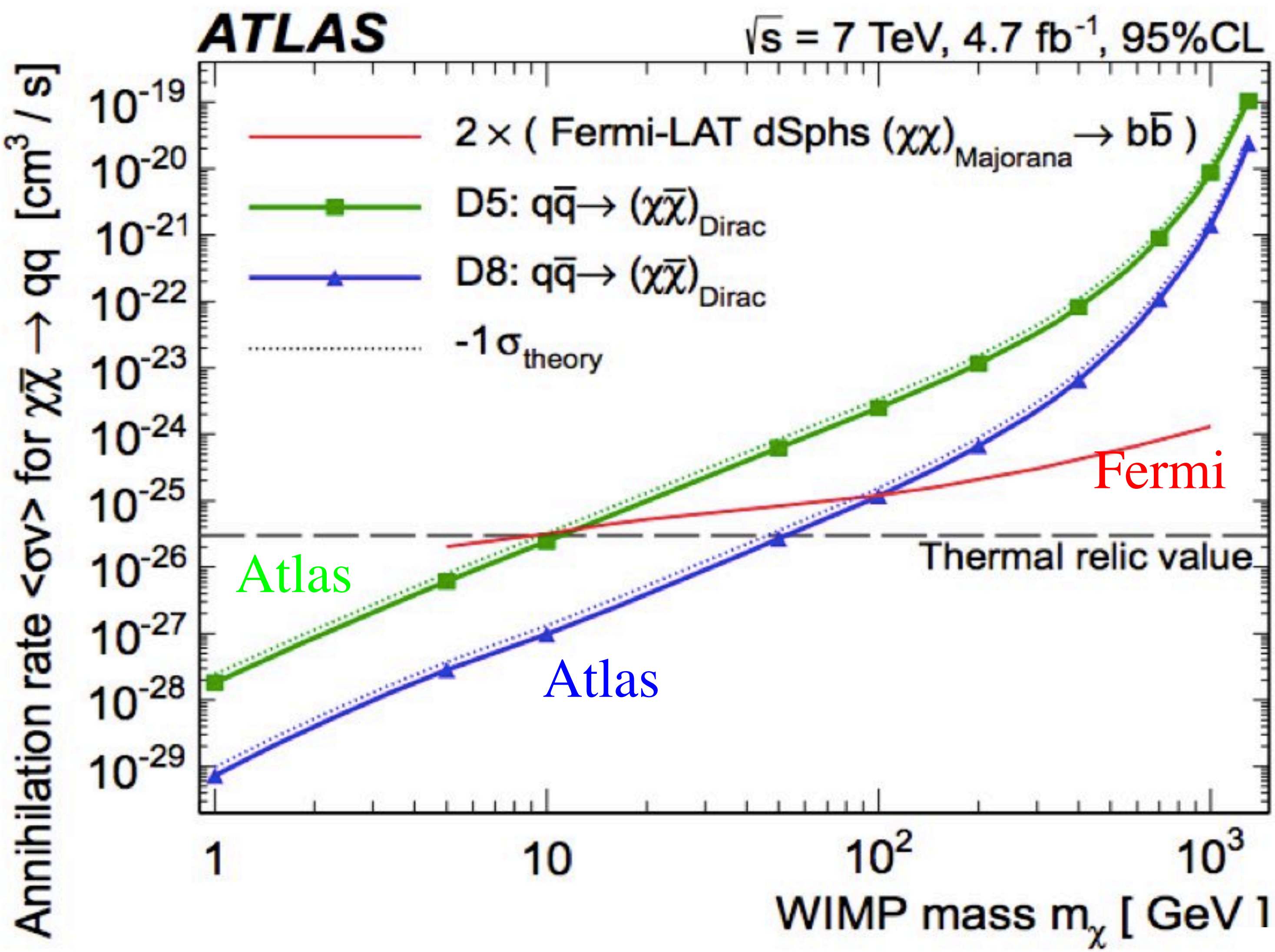

- There are many assumptions in this prediction
- Doesn't deal with a possible detections.

# Dwarf Spheroidal Galaxies upper-limits




Update of
Doro et al. arXiv:1208.5356

# ATLAS-Fermi Results

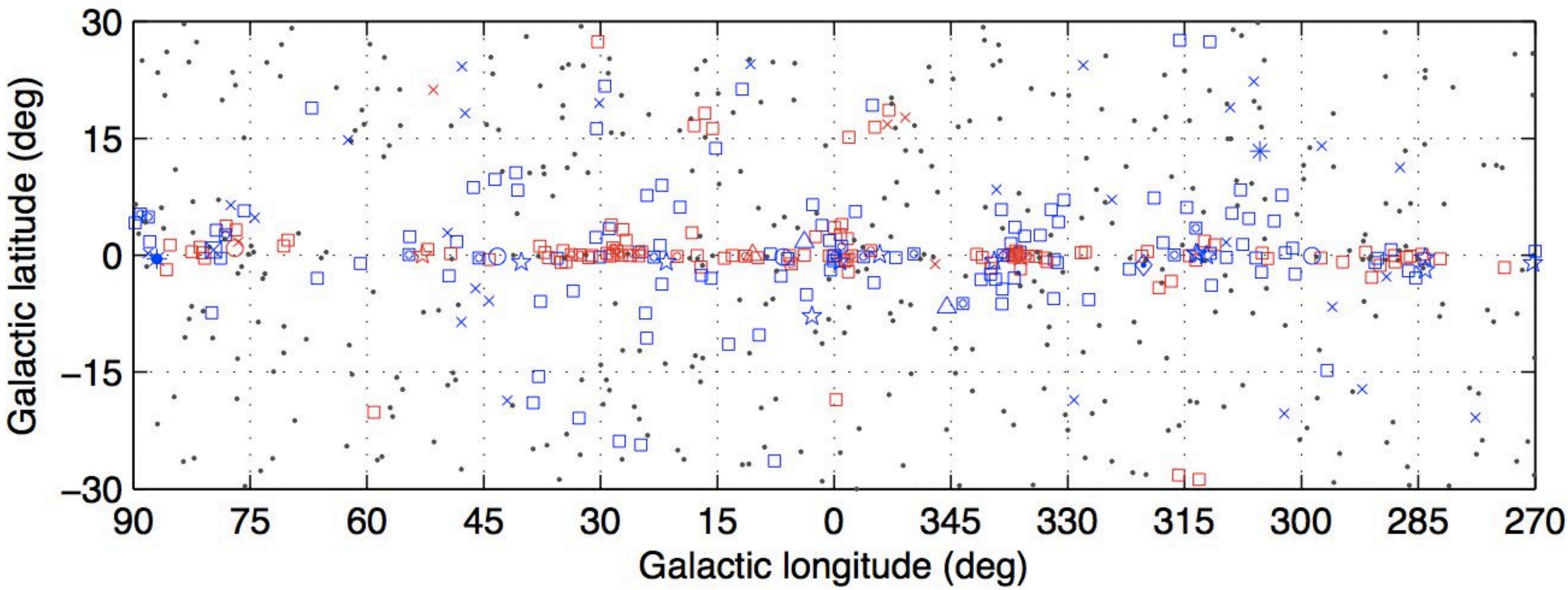



Atlas Coll. arXiv:1210.4491

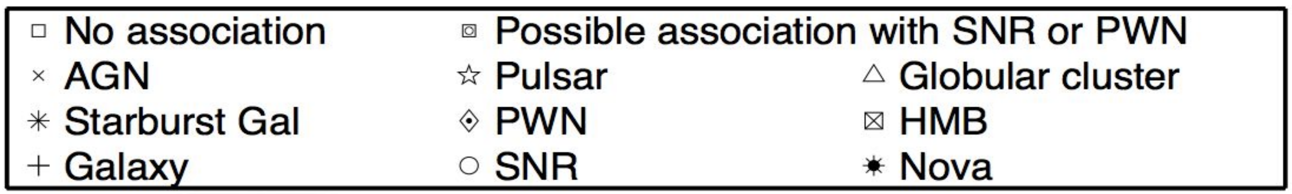
# The Fermi LAT 2FGL Inner Galactic Region

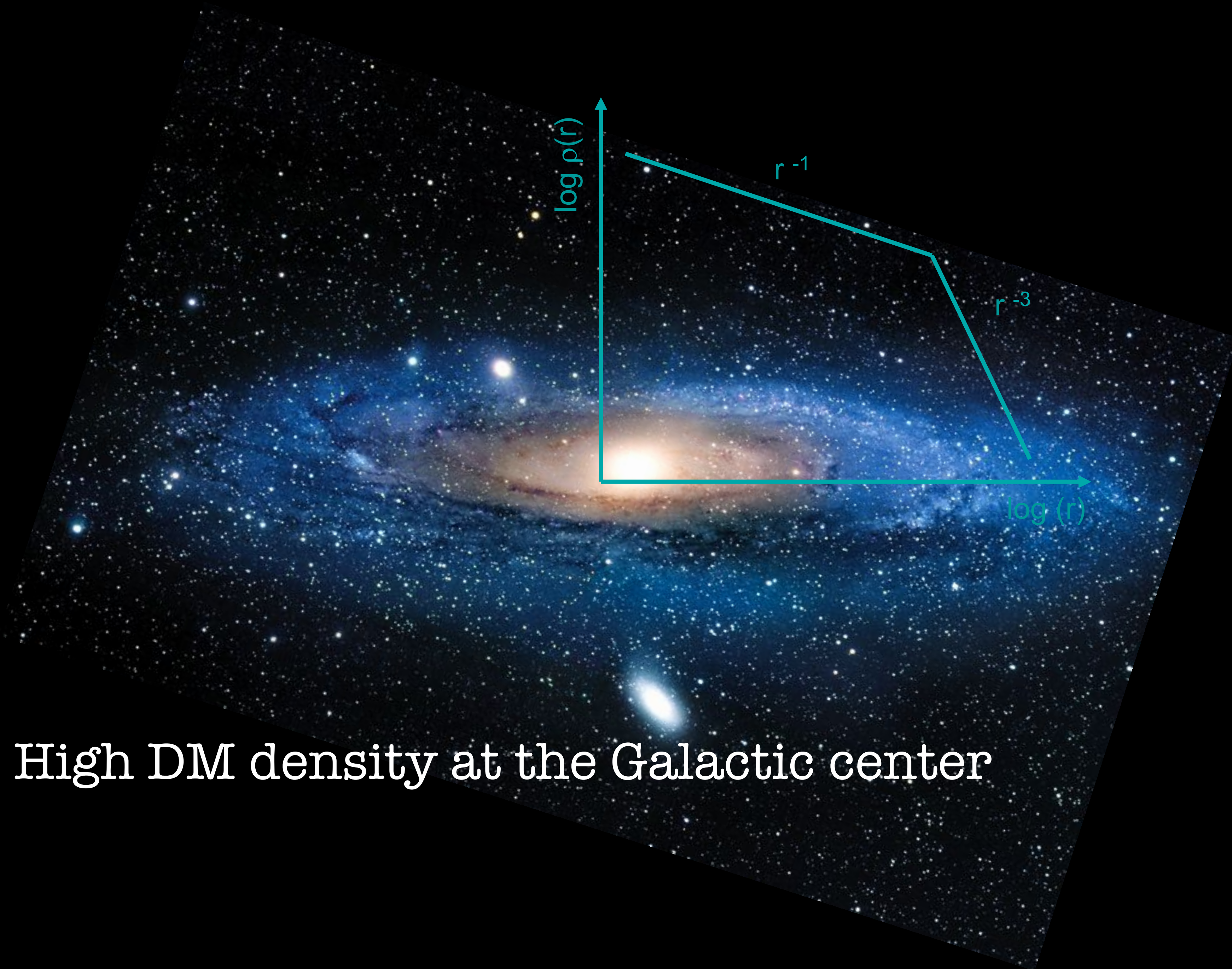
August 4, 2008, to July 31, 2010

100 MeV to 100 GeV energy range




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





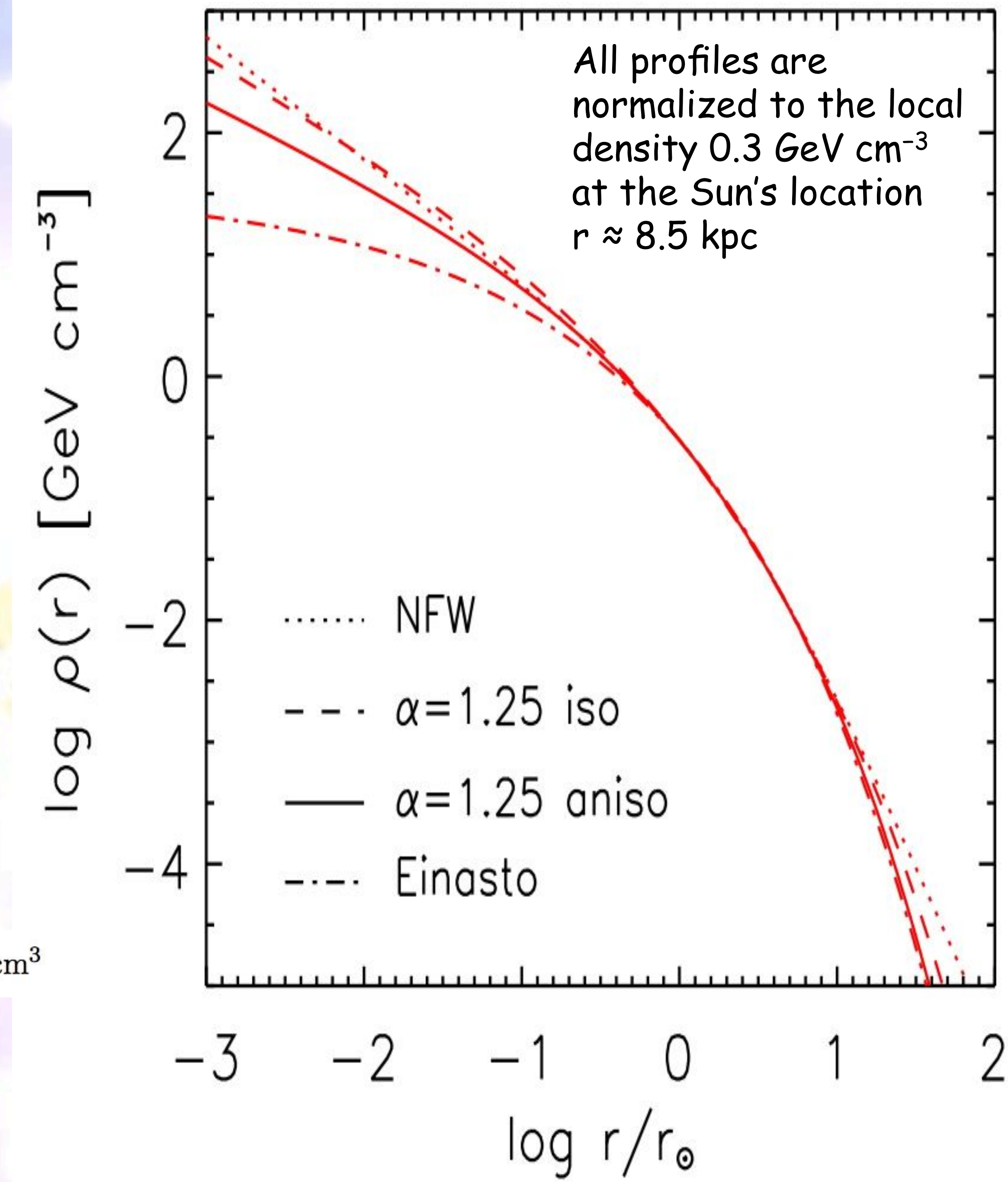

High DM density at the Galactic center

# Milky Way Dark Matter Profiles

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

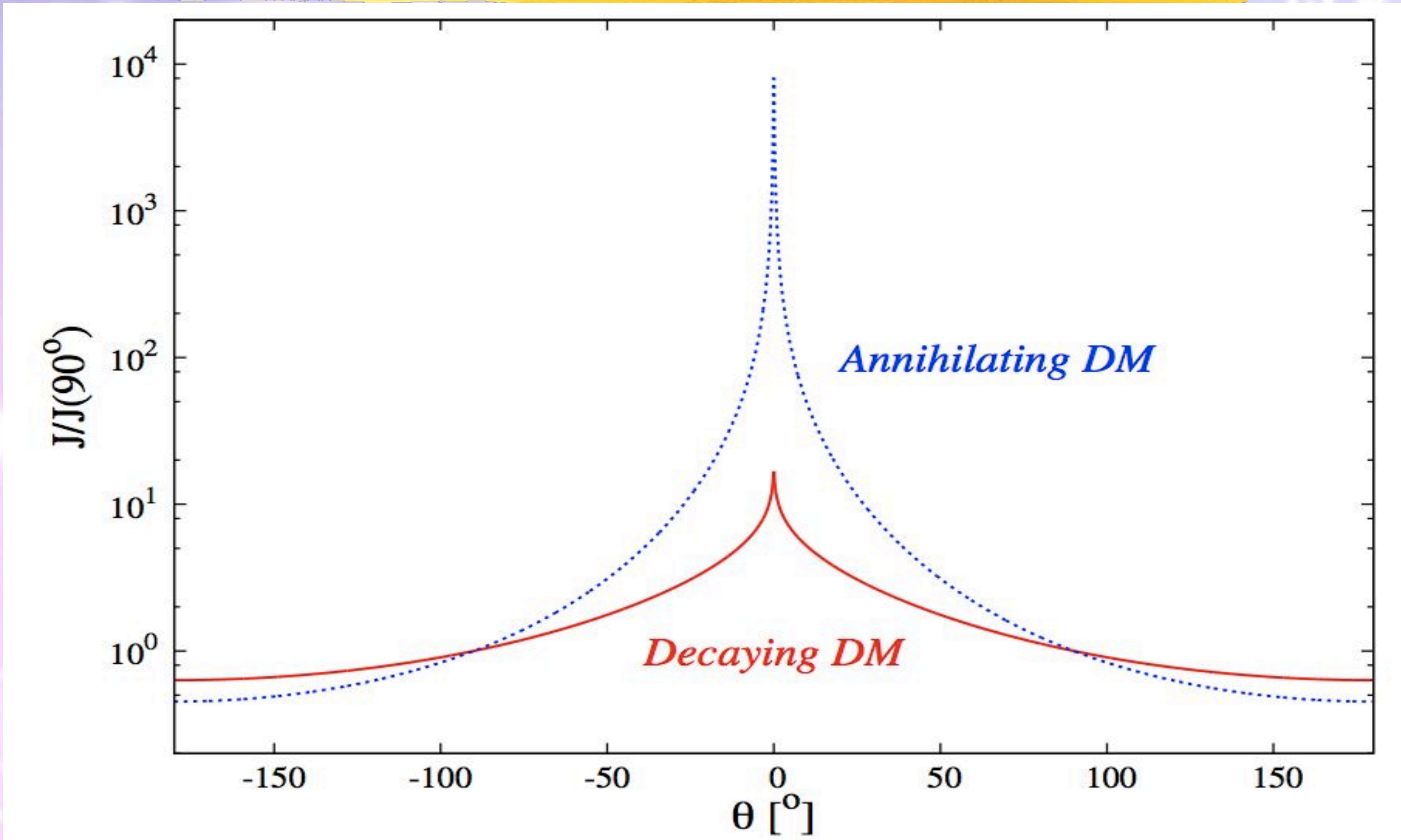
| Halo model | $\alpha$ | $\beta$ | $\gamma$ | $r_s$ in kpc |
|---|---|---|---|---|
| Cored isothermal | 2 | 2 | 0 | 5 |
| Navarro, Frenk, White | 1 | 3 | 1 | 20 |
| Moore | 1 | 3 | 1.16 | 30 |

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



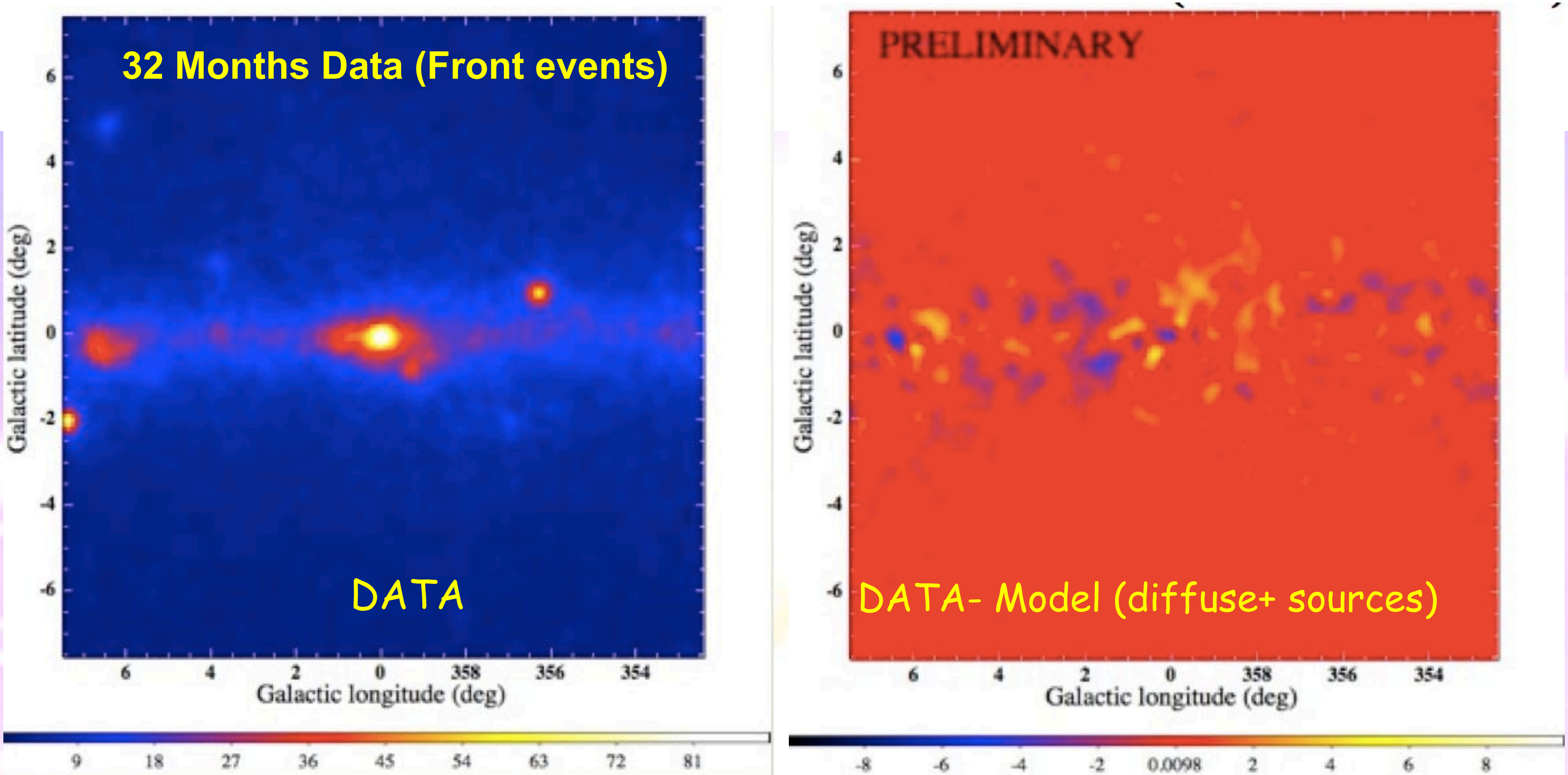

A.Lapi et al. arXiv:0912.1766

# Different spatial behaviour for decaying or annihilating dark matter




The angular profile of the gamma-ray signal is shown, as function of the angle $\theta$ 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

# 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**

Papers are forthcoming and will include dark matter results.

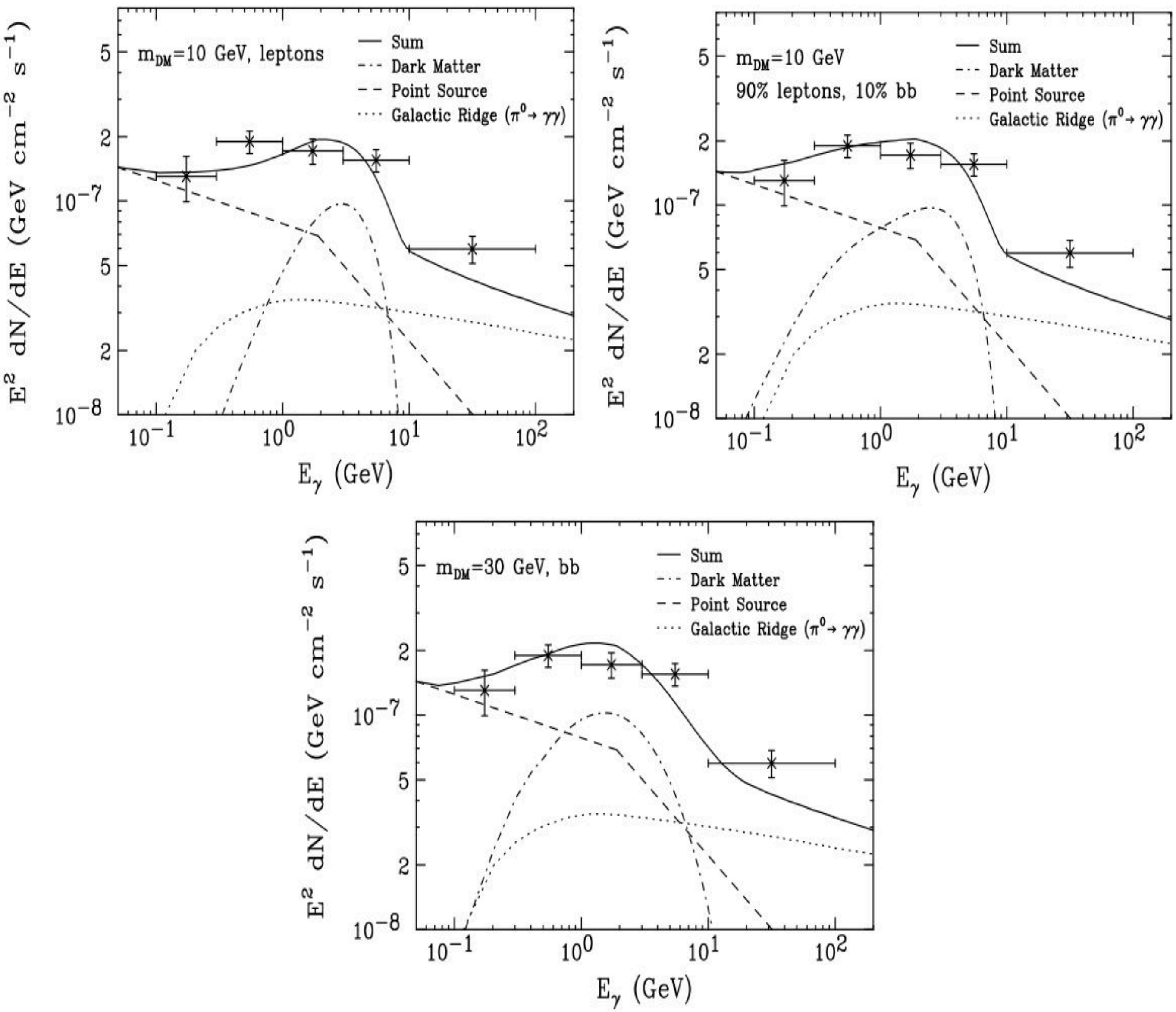
# DM in the galactic center?

D. Hooper and T.Linden, 2011.
arXiv:1110.000

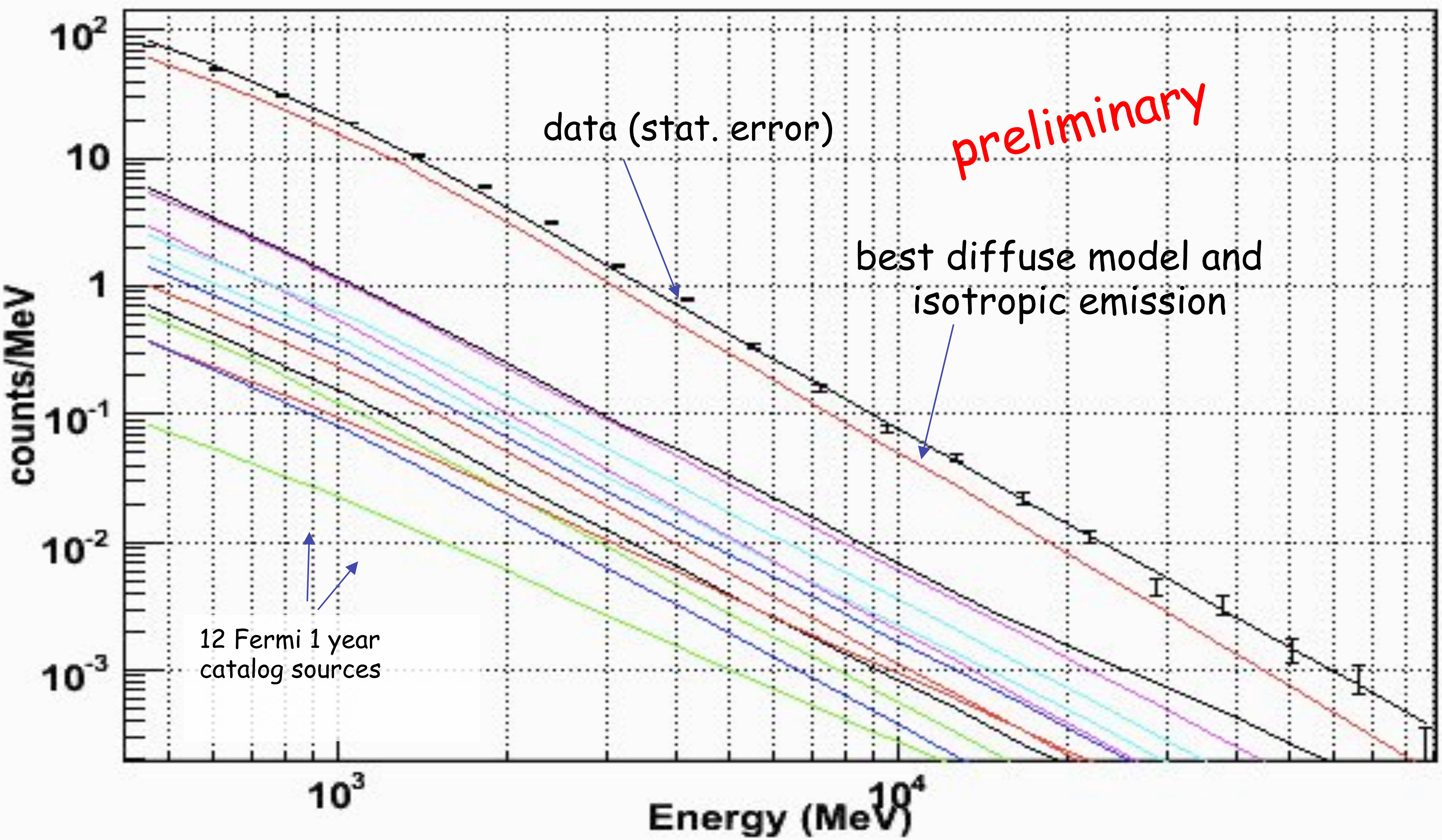
Using the remarkable source of public Fermi-LAT data!

To improve, need better angular and energy resolution in the 1 – 20 GeV range.

Eventually, a gamma-ray line at the DM mass could be seen – would be very convincing!



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

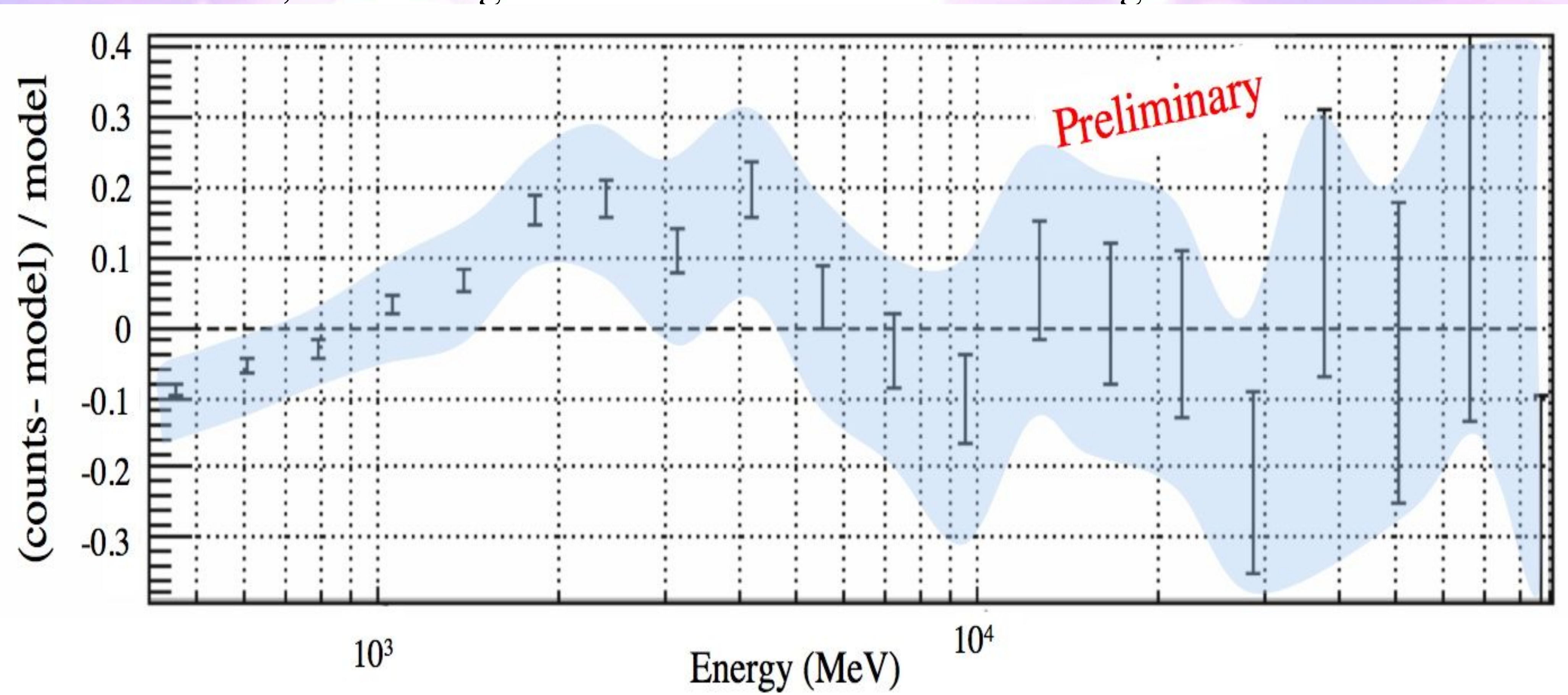



Fermi Coll. NIM A630 (2011) 147 [arXiv:0912.3828]

# 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 bump and LHC and direct detection results

- We revisit MSSM scenarios with light neutralino as a dark matter candidate in view of the latest LHC and dark matter direct and indirect detection experiments. We show that scenarios with a very light neutralino (~ 10 GeV) and a scalar bottom quark close in mass, can satisfy all the available constraints from LEP, Tevatron, LHC, flavour and low energy experiments and provide solutions in agreement with the bulk of dark matter direct detection experiments DAMA/LIBRA, CoGeNT and CRESST-II

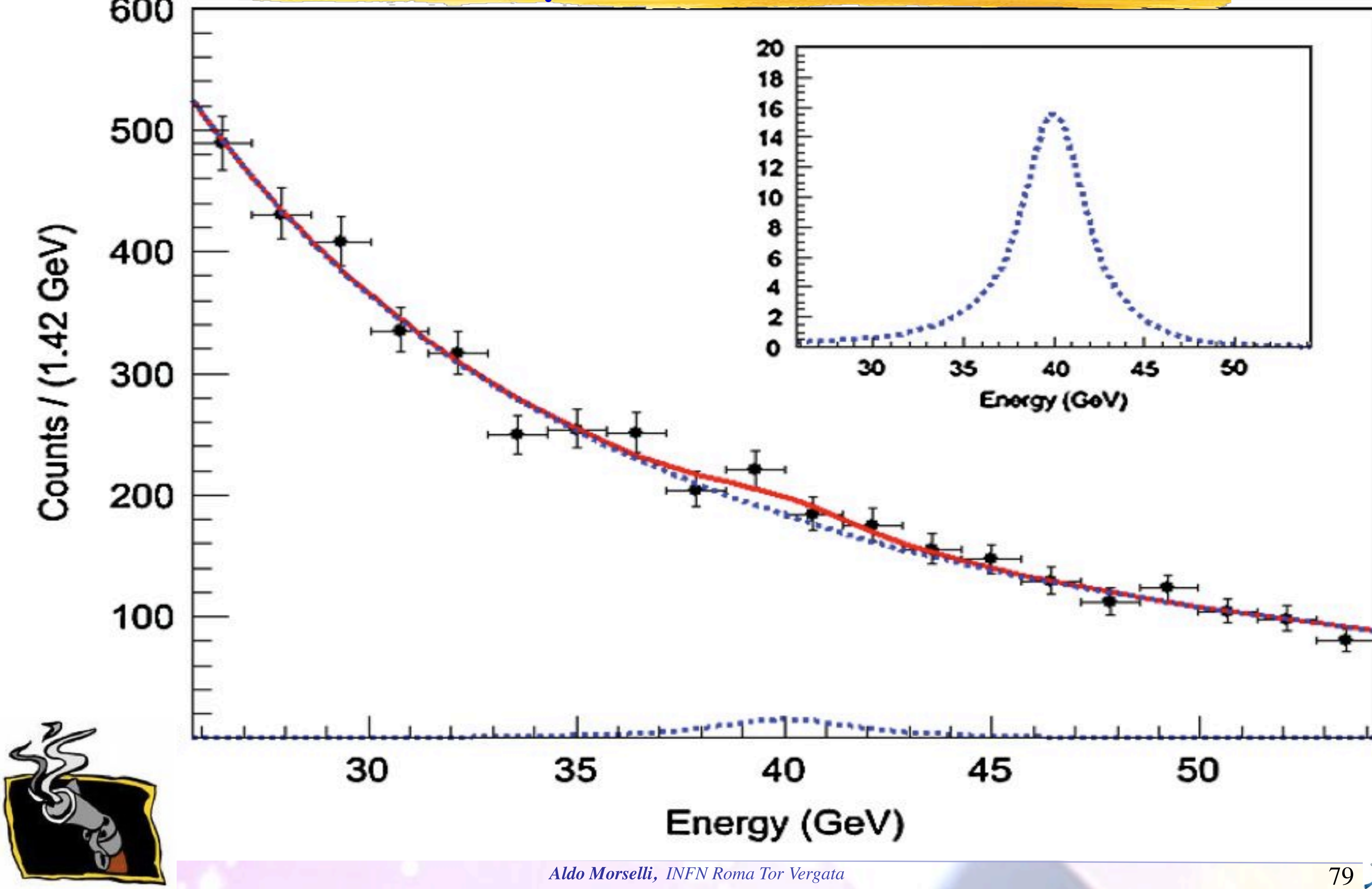
Alexandre Arbey, Marco Battaglia, Farvah Mahmoudi, arxiv:1308.2153

# 5-7 GeV bump produced by pulsar population ?

- we find that millisecond pulsars can account for no more than ~10% of the Inner Galaxy's GeV excess

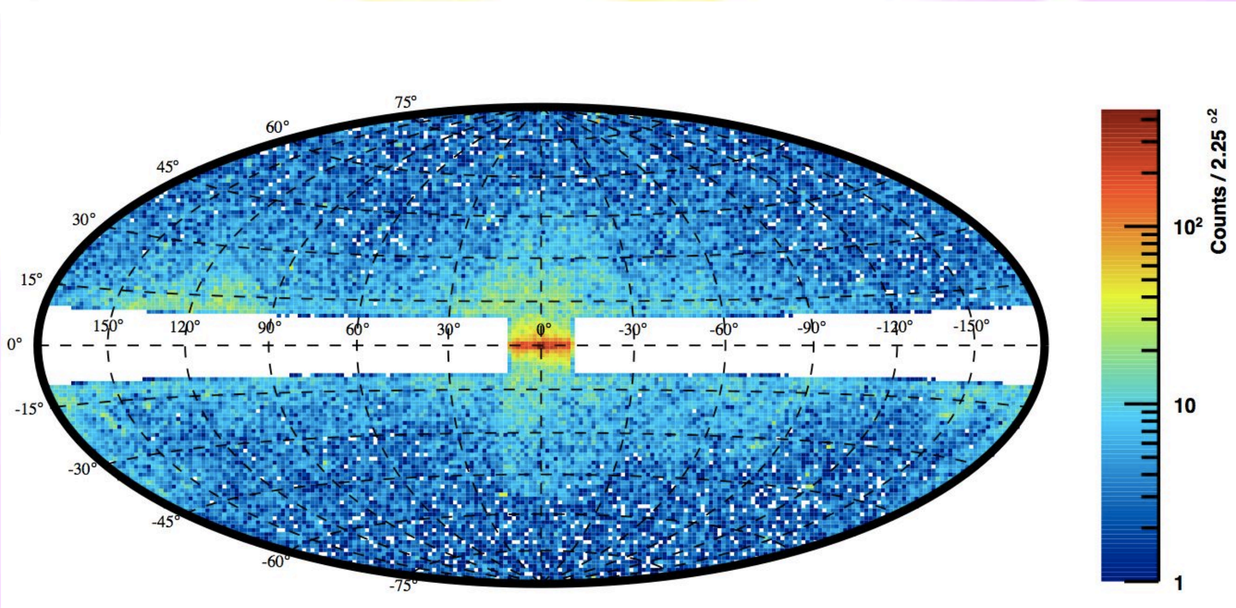
Dan Hooper, Ilias Cholis, Tim Linden, Jennifer Siegal-Gaskins, Tracy Slatyer arXiv:1305.0830v1

# Wimp lines search



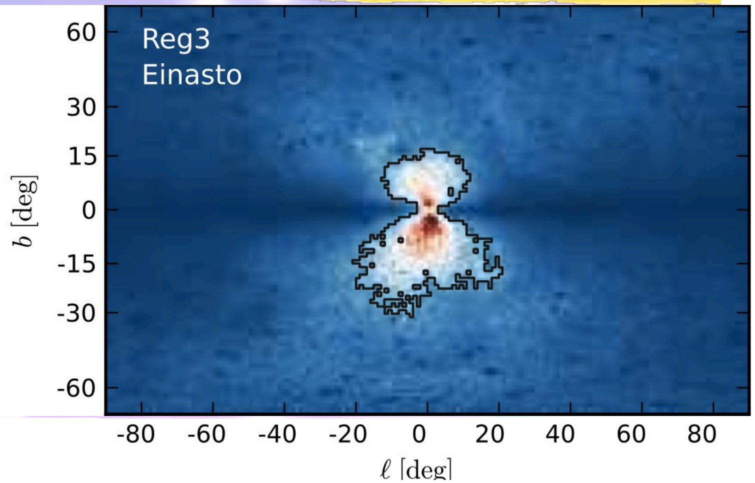
# Search for Spectral Gamma Lines

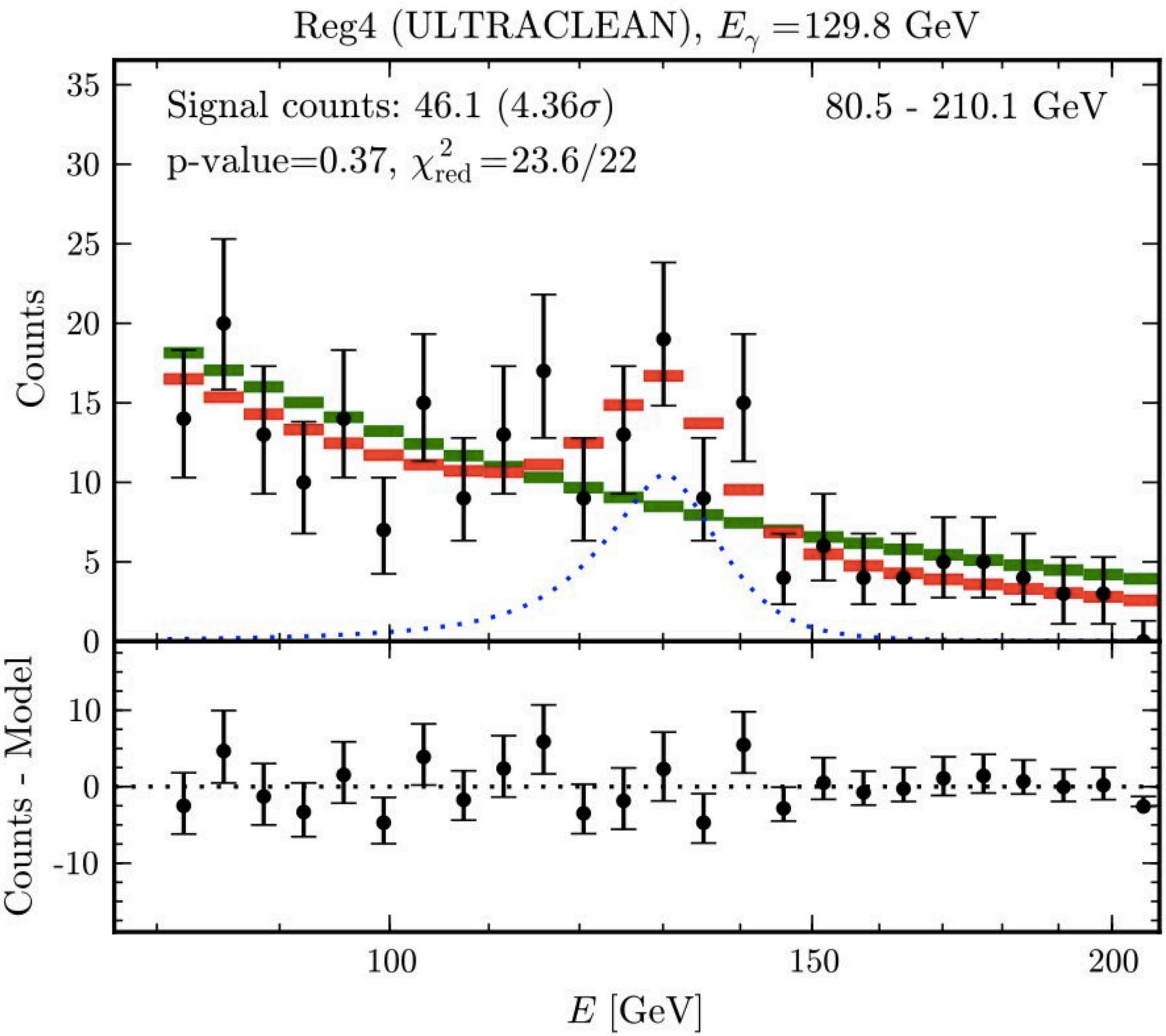
- Smoking gun signal of dark matter
- Search for lines in the first 23 months of Fermi data (7-200 GeV en.range)
- Search region $|b|>10^{\circ}$ plus a $20^{\circ} \times 20^{\circ}$ square centered at the galactic center
- For the region within $1^{\circ}$ of the GC, no point source removal was done as this would have removed the GC
- For the remaining part of the ROI, point sources were masked from the analysis using a circle of radius 0.2 deg
- The data selection includes additional cuts to remove residual charged particle contamination.

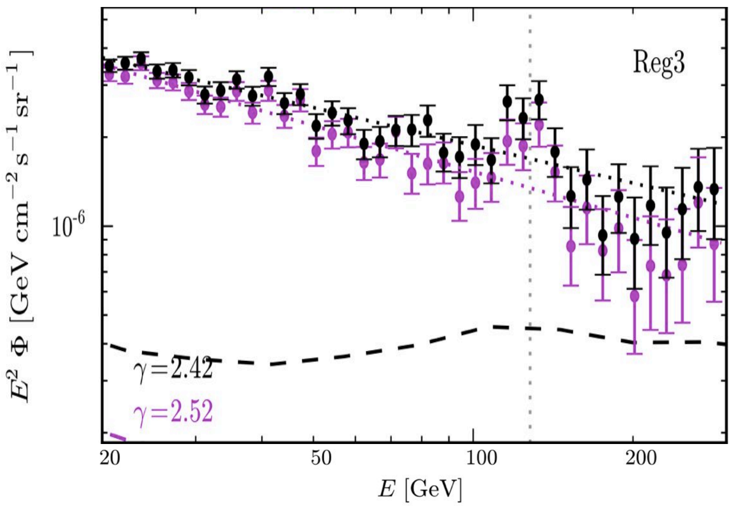



Region-of-interest for line search

# A line at ~ 130 GeV ?

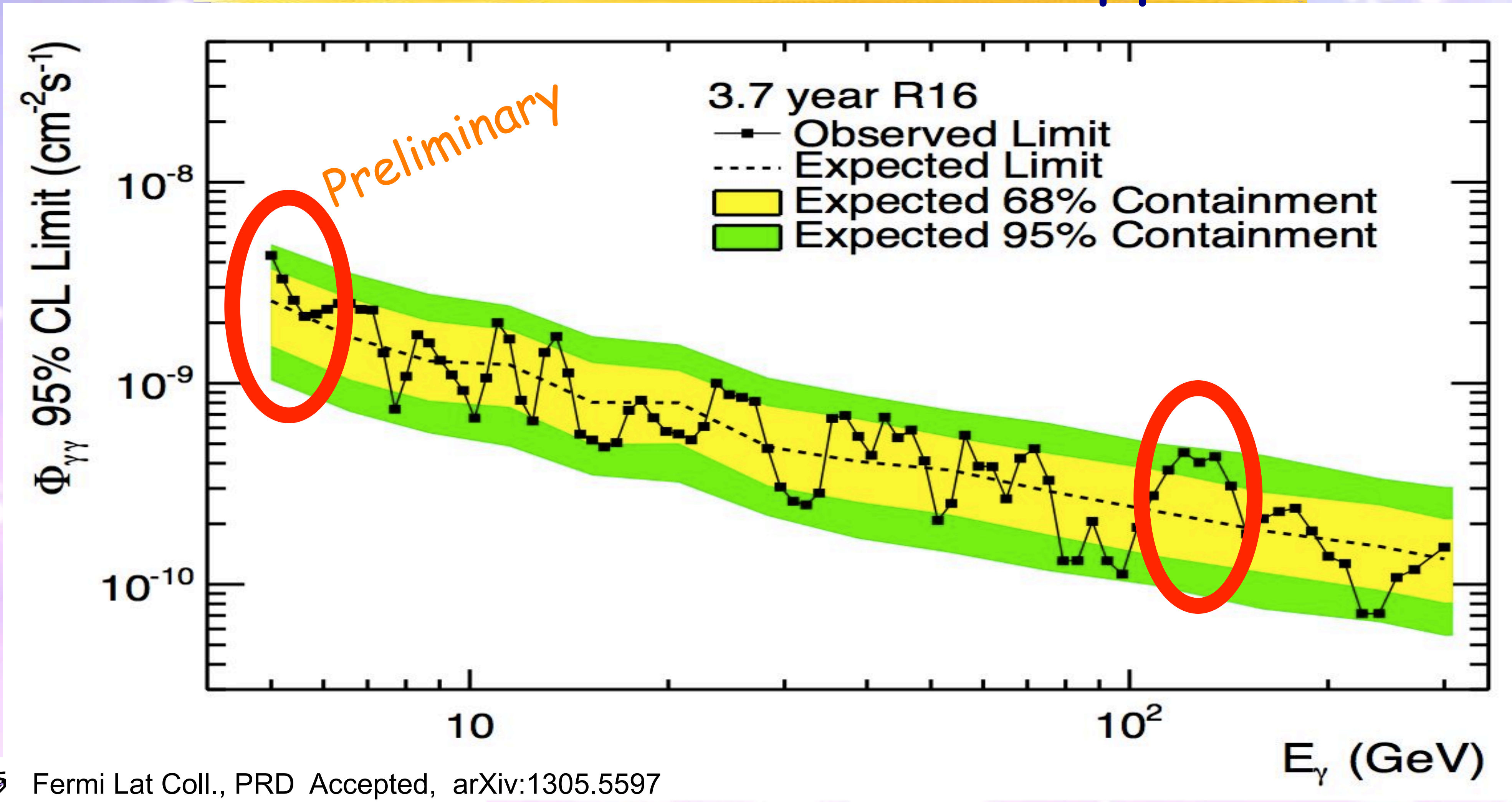



Weniger arXiv:1204.2797

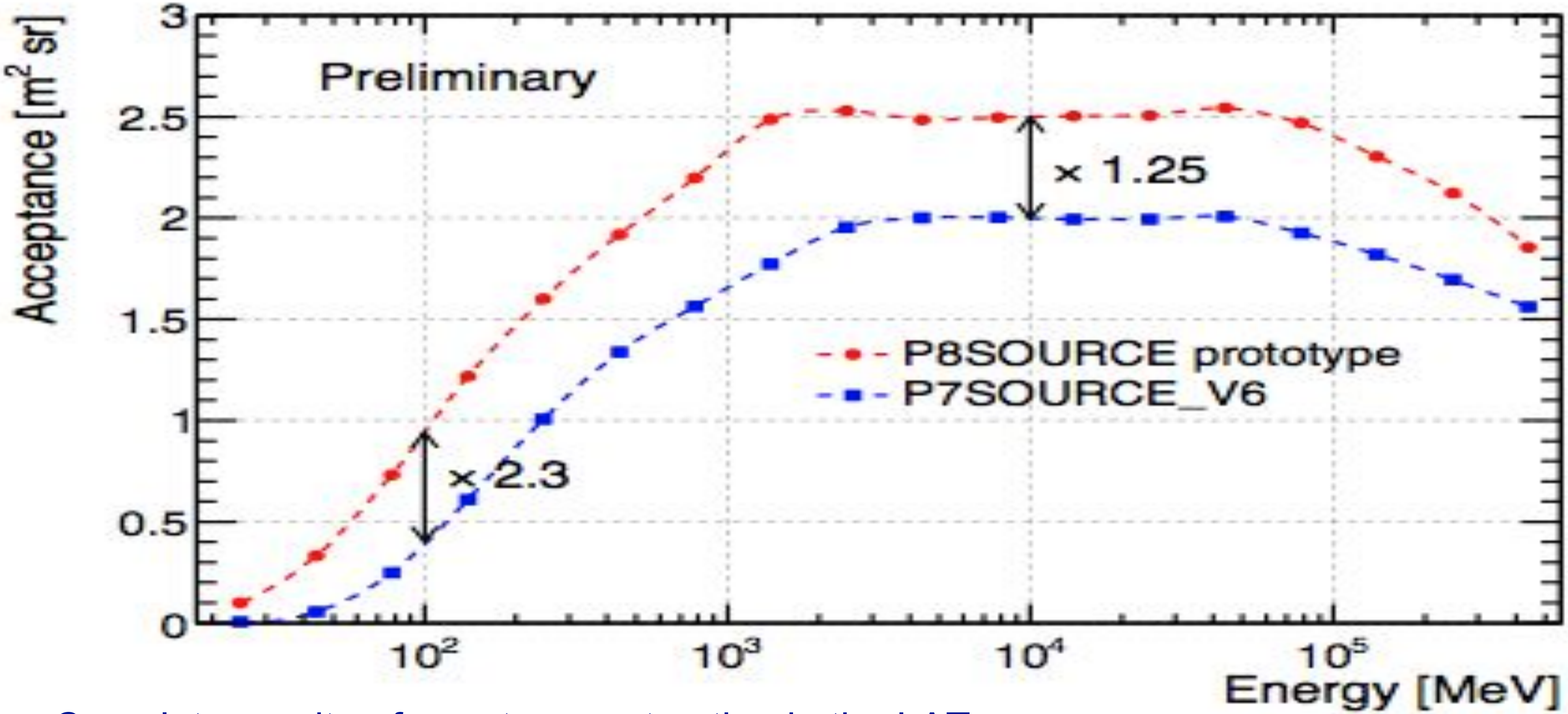
# Fermi-LAT Line Search Flux Upper Limits




Fermi Lat Coll., PRD Accepted, 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.

# Fermi-LAT New Instrument Response Functions ( Pass 8 )




- Complete rewrite of event reconstruction in the LAT
  - Well beyond original motivation of suppressing cosmic-ray pileup
- Significant improvements wrt Pass7 performance
  - Larger acceptance, Increased energy range (low and high energy)
- Will be used for 5 year catalog and LAT analyses starting 2014

Arxiv 1303.3514

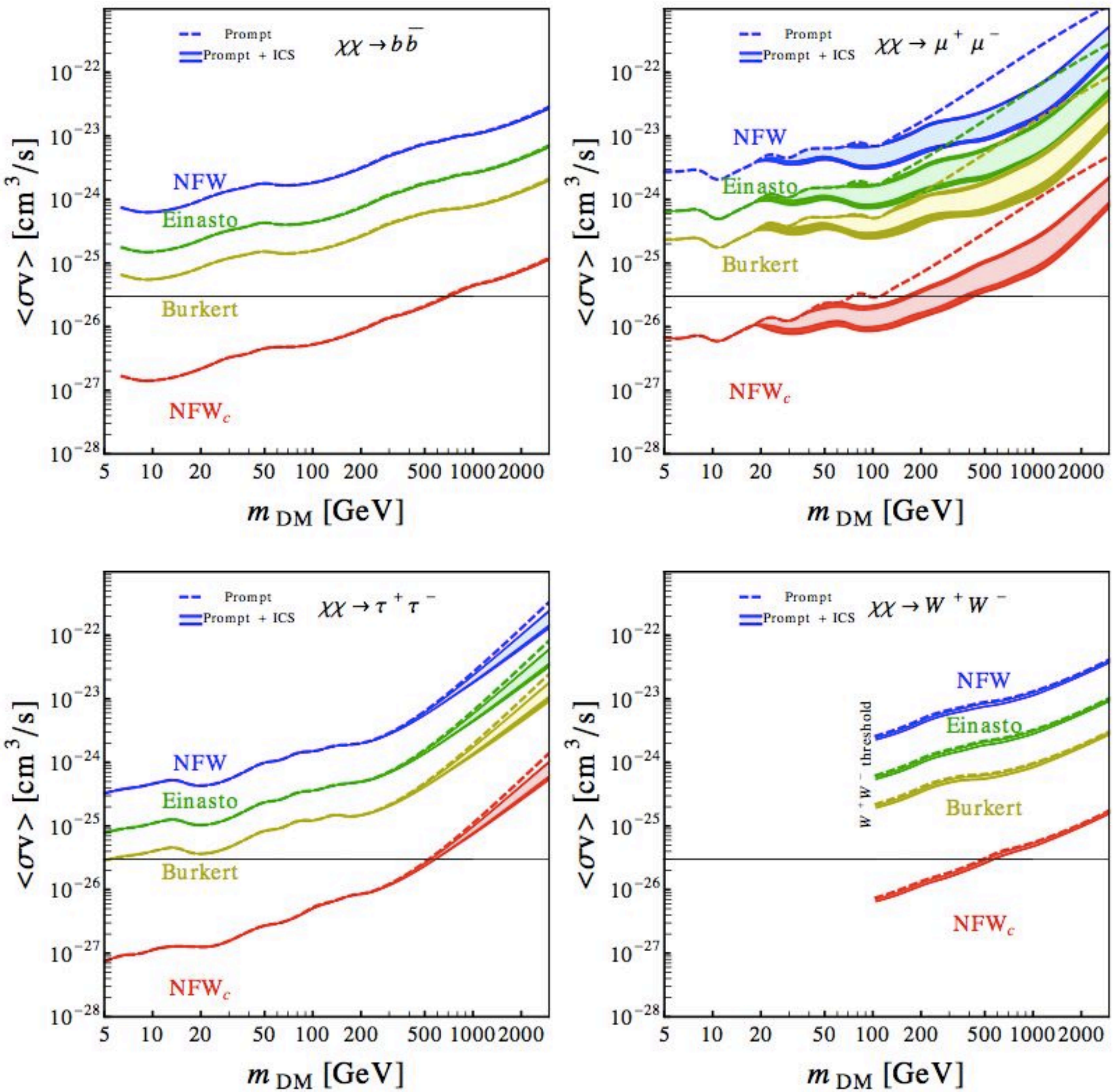
# Constraints from the inner Galaxy

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

**No assumption on background. Very robust result**

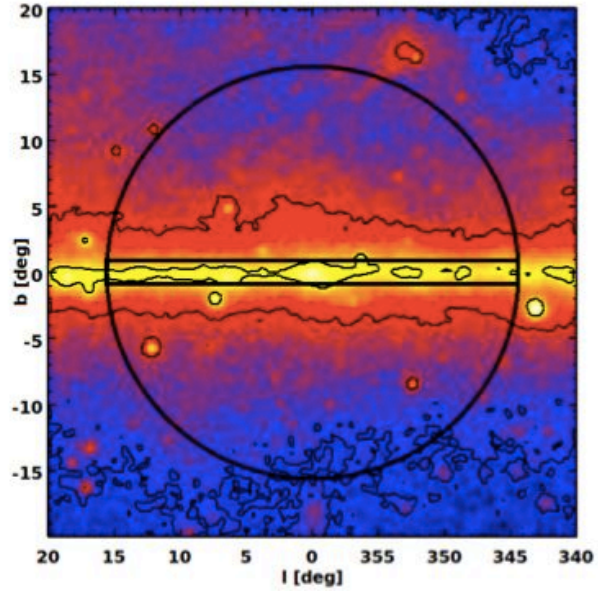
Gomez-Vargas et al. JCAP 10 (2013) 029, (16 October) arXiv:1308.3515

For more info See Gomez-Vargas Ph.D. thesis defense next Monday

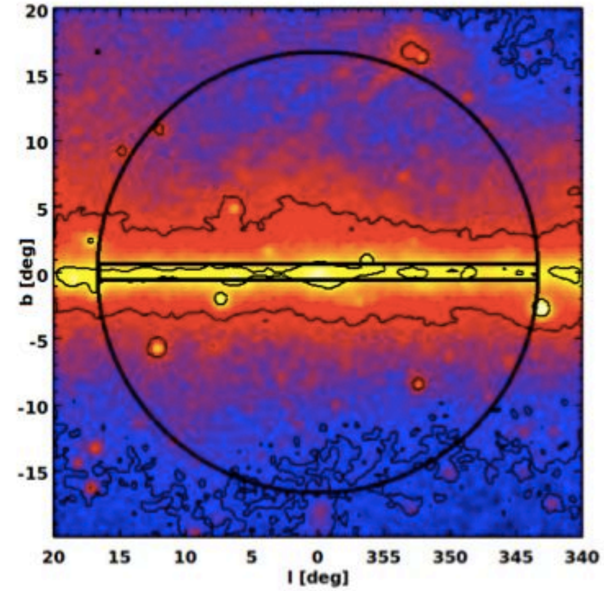


# Constraints from the inner Galaxy

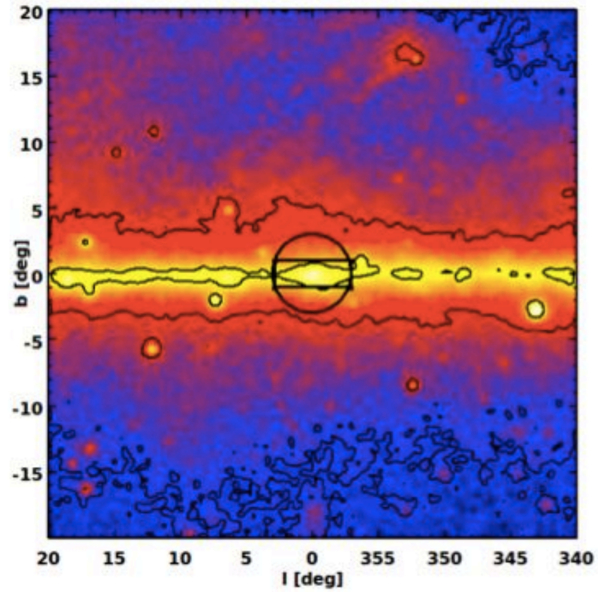
## Optimized ROI for each profile



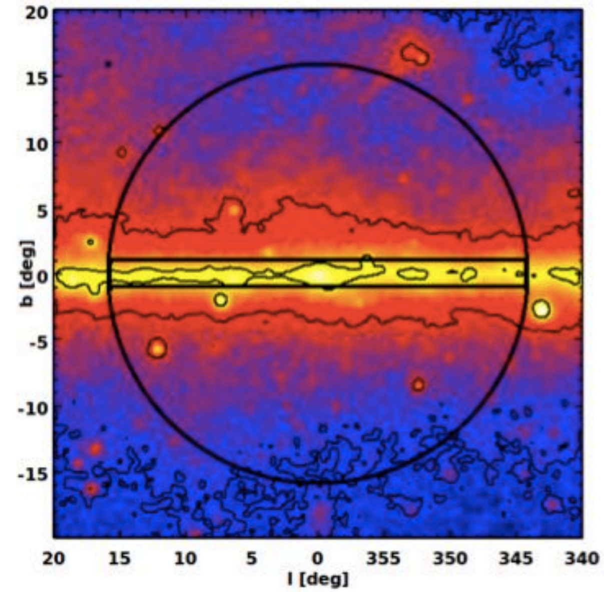

Einasto




NFW



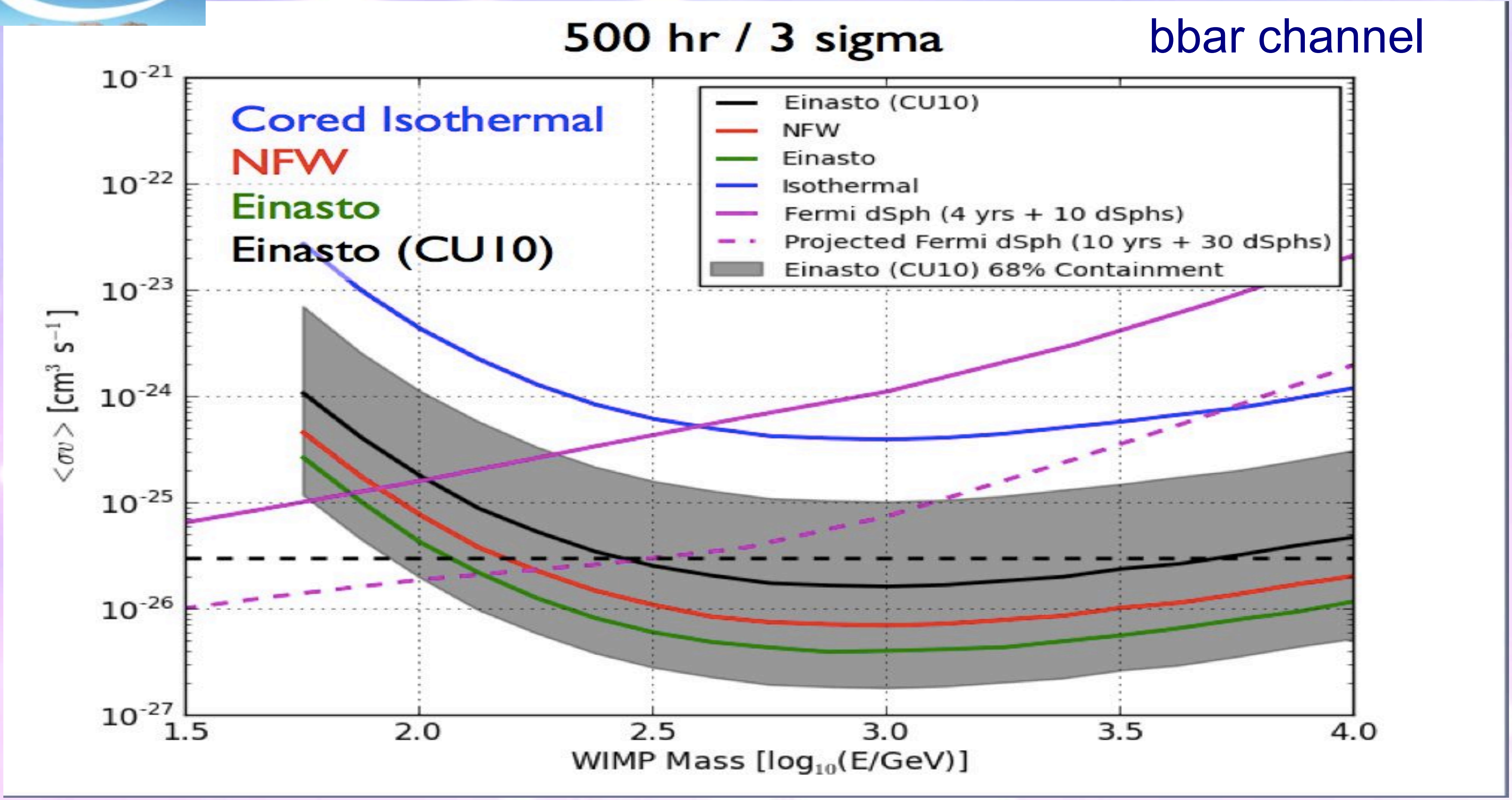

NFWc




Burkert

Gomez-Vargas et al. JCAP sub., arXiv:1308.3515

# CTA and Galactic Center

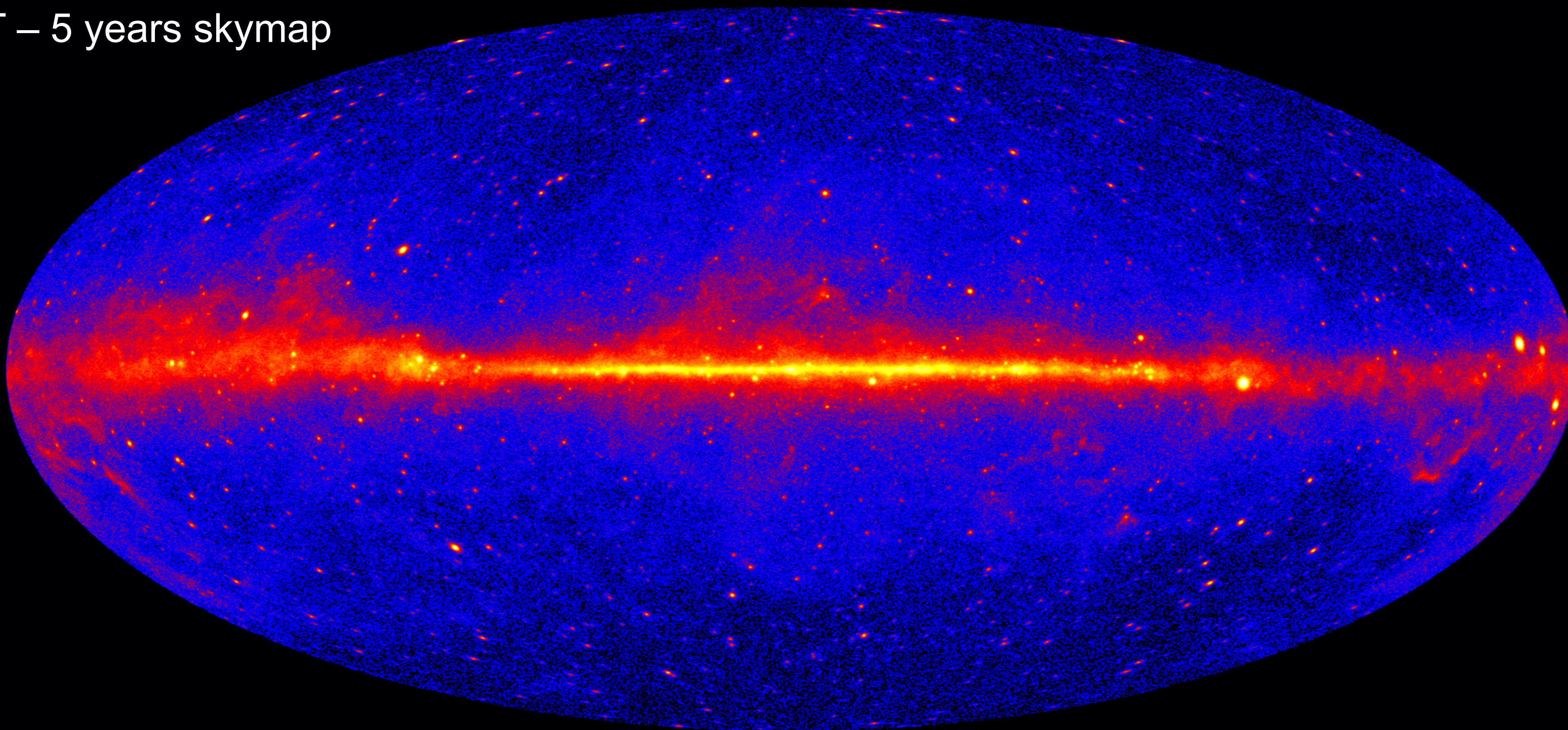


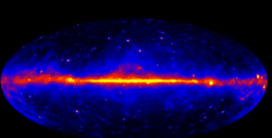
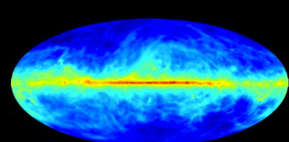
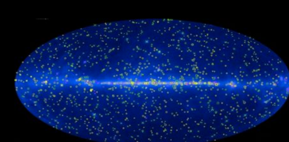
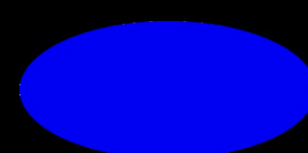

Models with thermal relic cross section should be detectable assuming an extrapolation of the DM density profile consistent with CDM simulations

# Not only Dark Matter

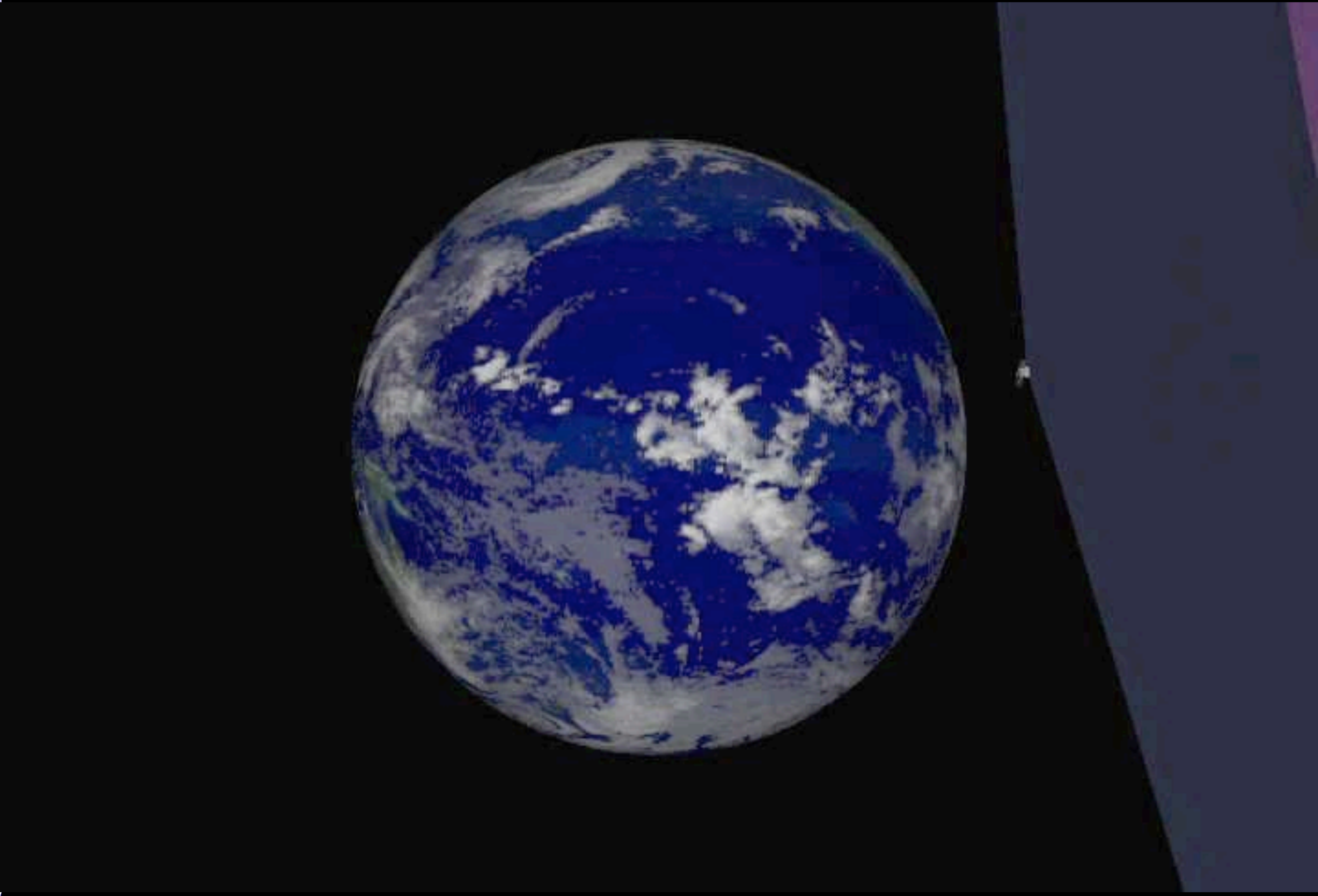
# Discovering the gamma-ray sky

LAT – 5 years skymap

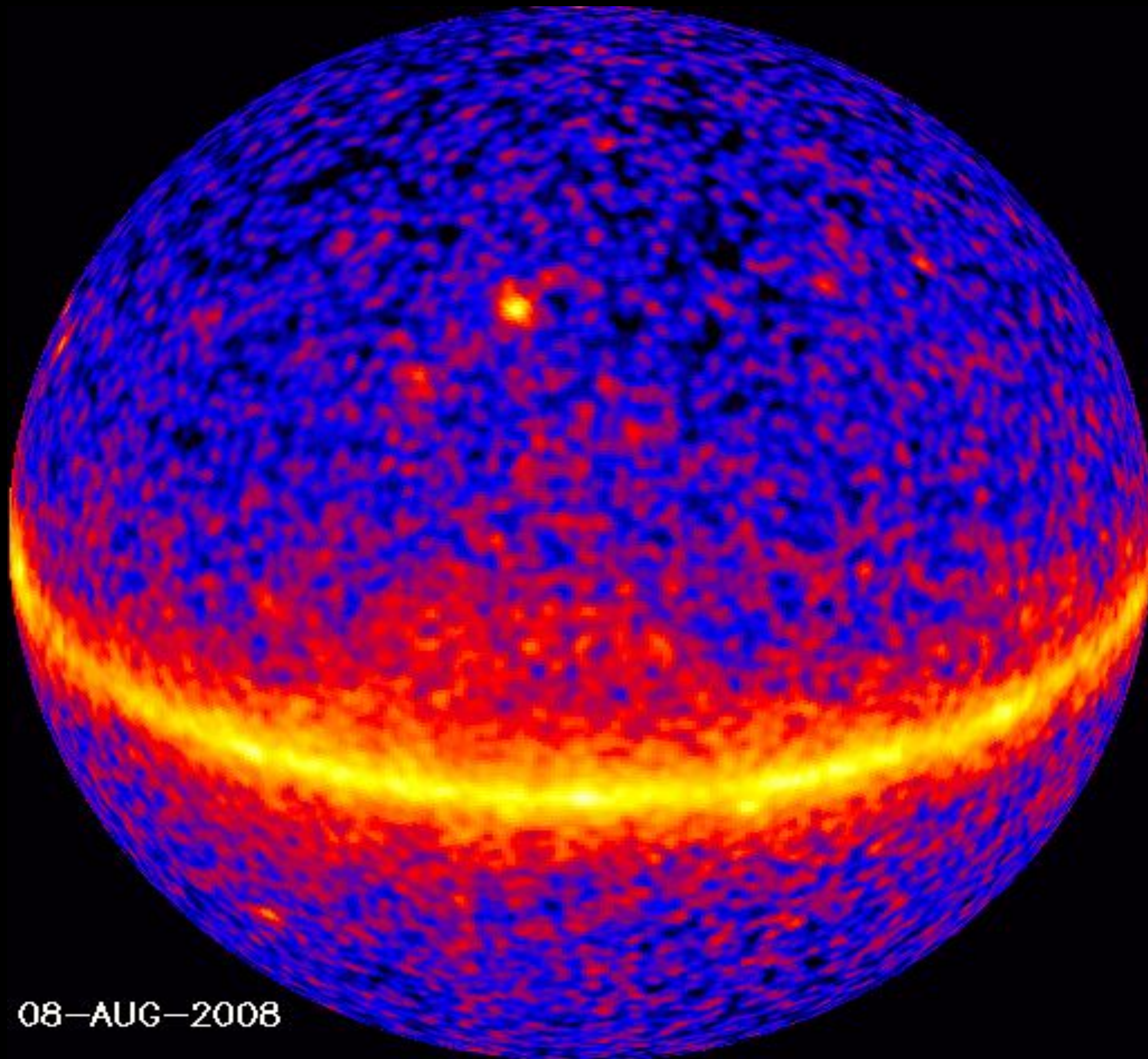


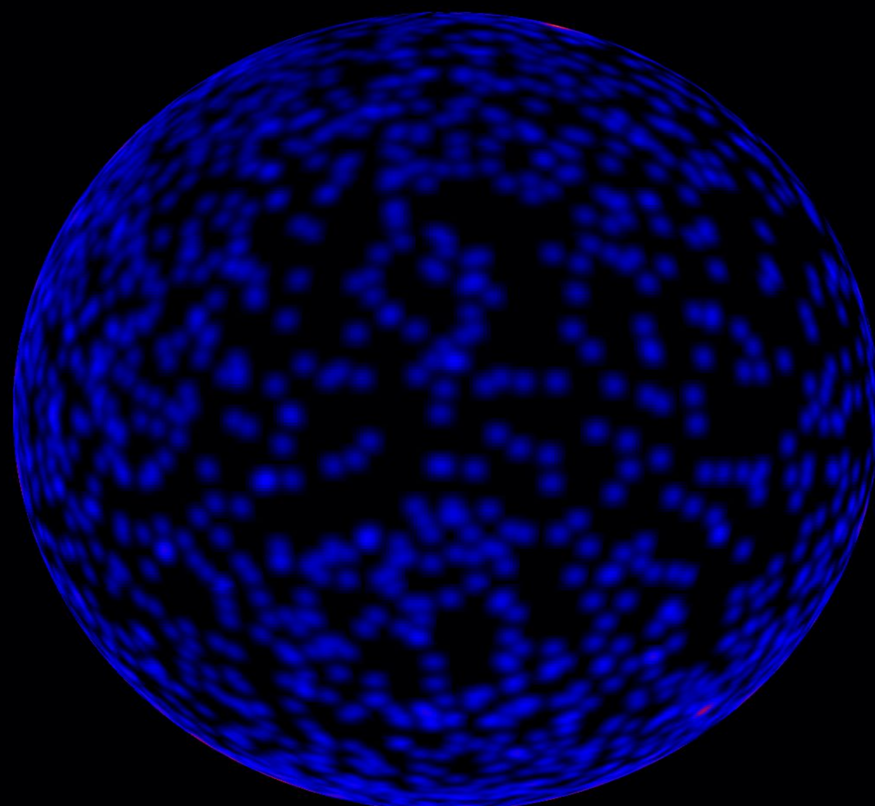
 =  +  +  + ???

GeV Sky | Galactic | Point Sources | Isotropic



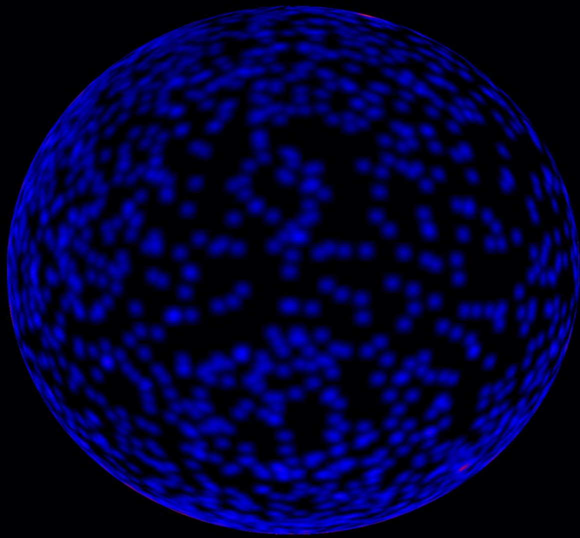
# Daily Gamma-ray Sky



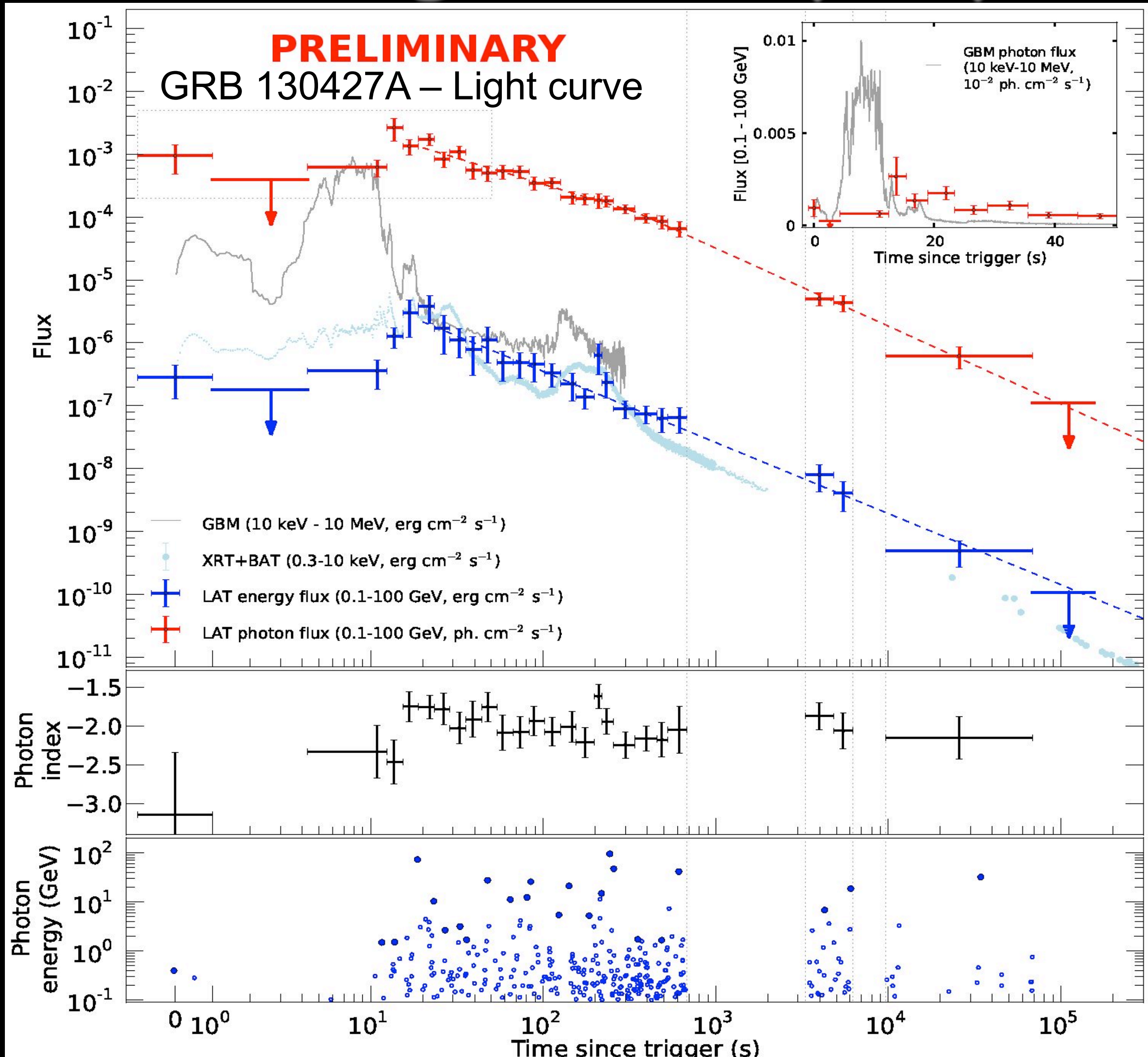


8 may 2013

# Surprises from the gamma-ray sky



GRB 130427A
- APOD 8 may 2013



# "A nearby ordinary monster"

- "Monster"
  - Highest gamma-ray fluence (>$10^{-3}$ erg cm$^{-2}$)
  - Highest observed gamma-ray energy (95 GeV)
  - Longest lived gamma-ray emission (19 hours)
  - Second brightest optical flash (7th magnitude)
  - Within the closest 5% of GRBs (z = 0.34)
- "Ordinary"
  - Would not have been detected by *Fermi* at z > 4
- Represents a chance to study a "typical" GRB up close
  - Nearby GRBs tend to be sub-luminous

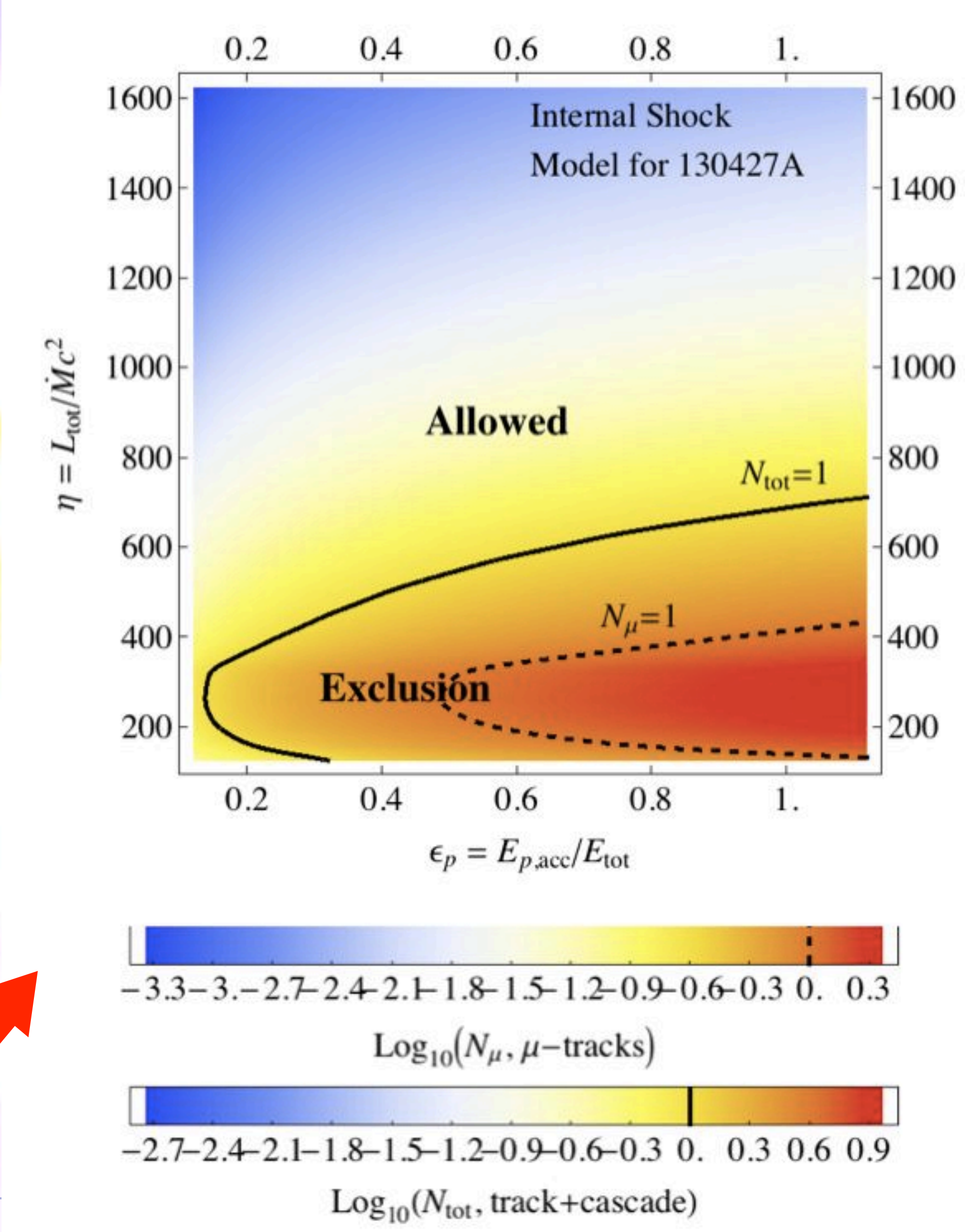
Science Paper accepted, soon on the press

# First neutrinos-gamma-rays connection

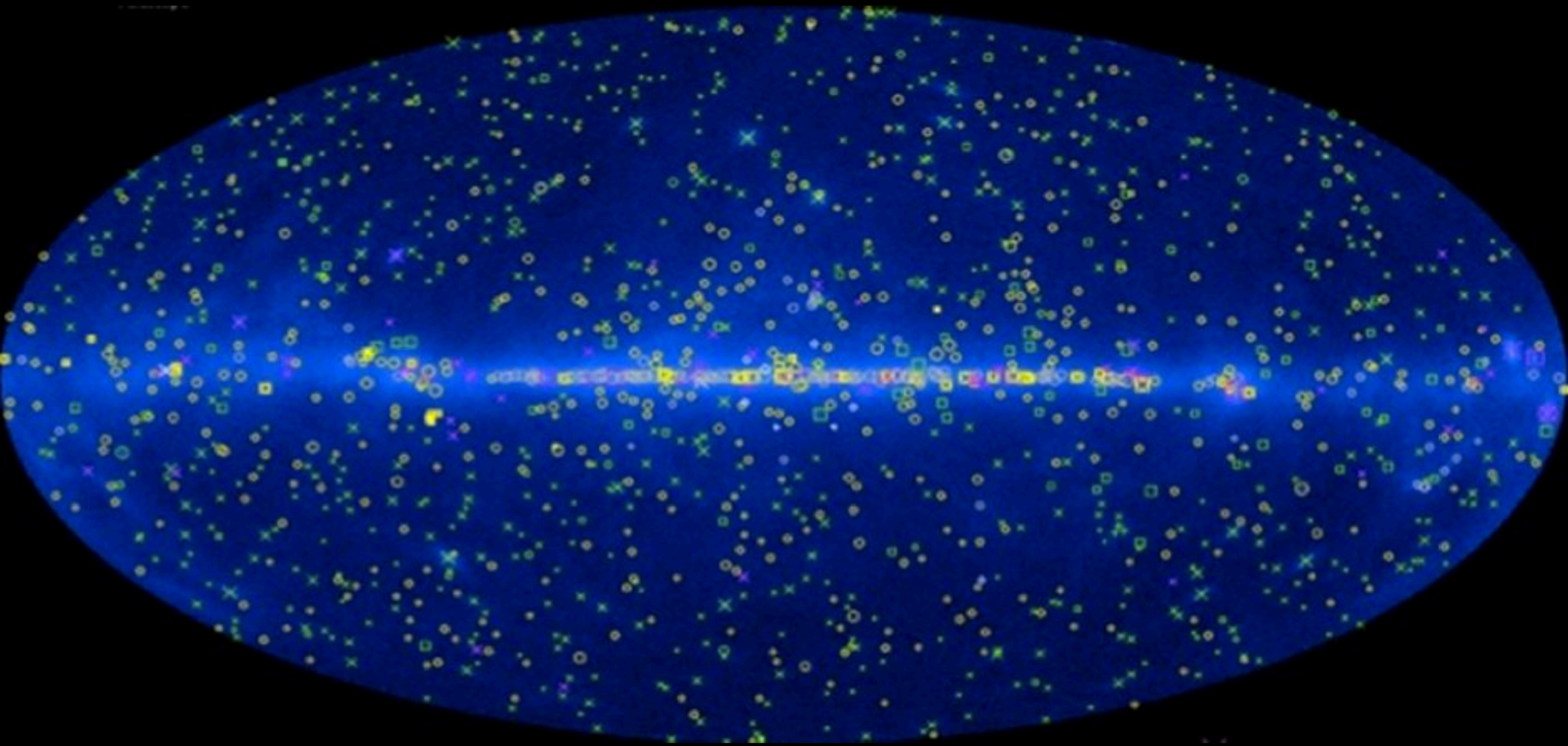
- IceCube neutrino non-detection can provide valuable information about this GRB's key physical parameters such as the emission radius , the bulk Lorentz factor, baryon load portion η and the energy fraction converted into cosmic rays $\varepsilon_p$

Gao et al., arXiv:1305.6055

Just an example



# Fermi 2FGL catalog



> 1800 sources
> 10 source classes
known classes (AGN, Pulsars, PWN, SNR...)
New emitters (Novae, ms PSR, starbursts,
~30% unidentified

Nolan et al.[Fermi Coll.]: ApJS, 199 (2012) 31

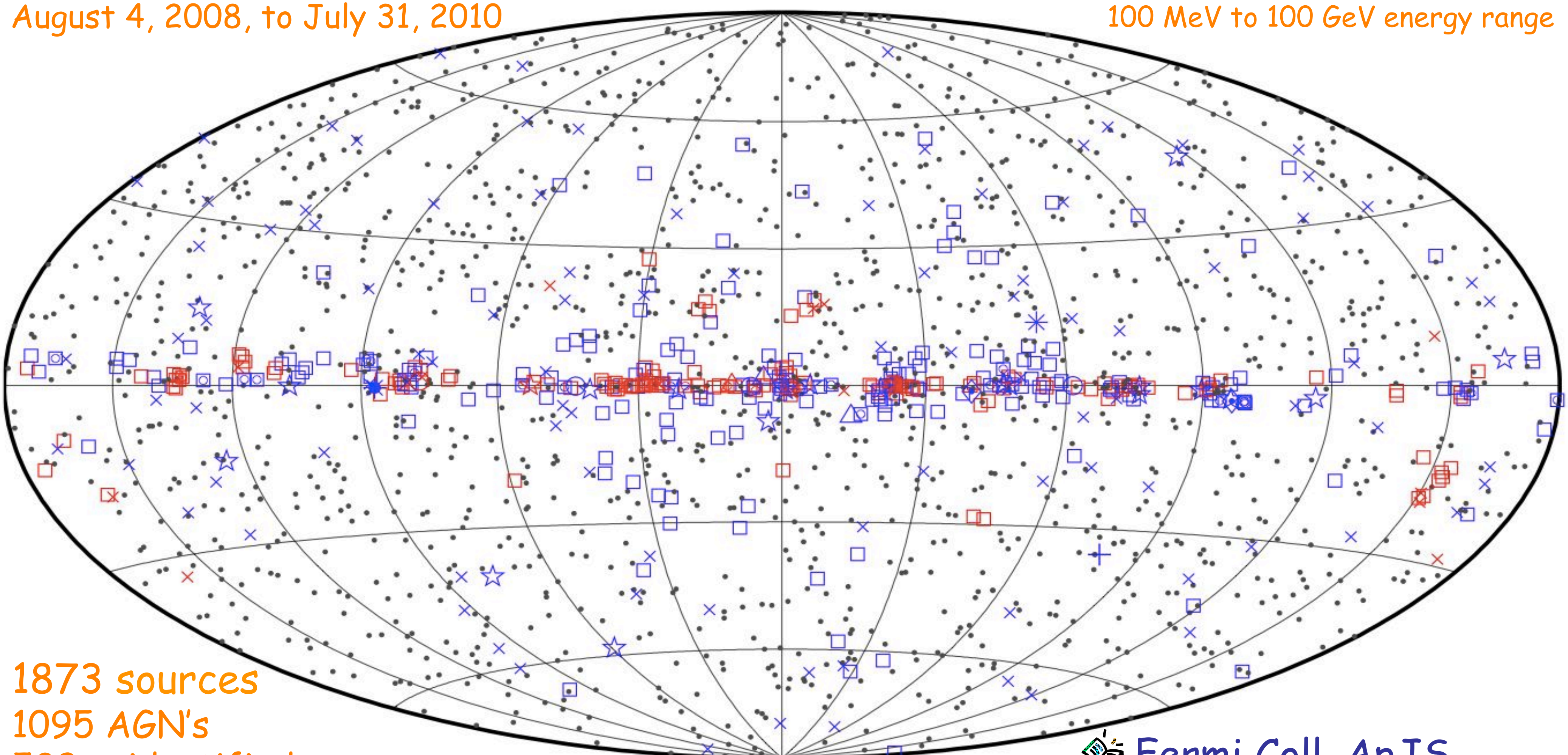
**3FGL in preparation**

# The Fermi LAT 2FGL Source Catalog

http://fermi.gsfc.nasa.gov/ssc/data/access/lat/2yr_catalog/

August 4, 2008, to July 31, 2010

100 MeV to 100 GeV energy range

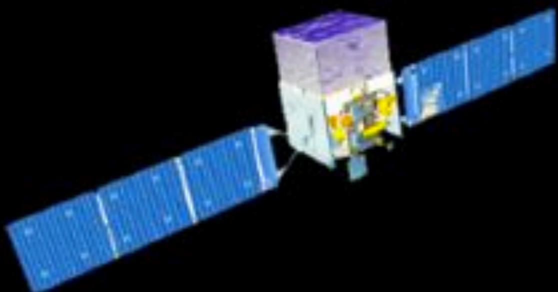


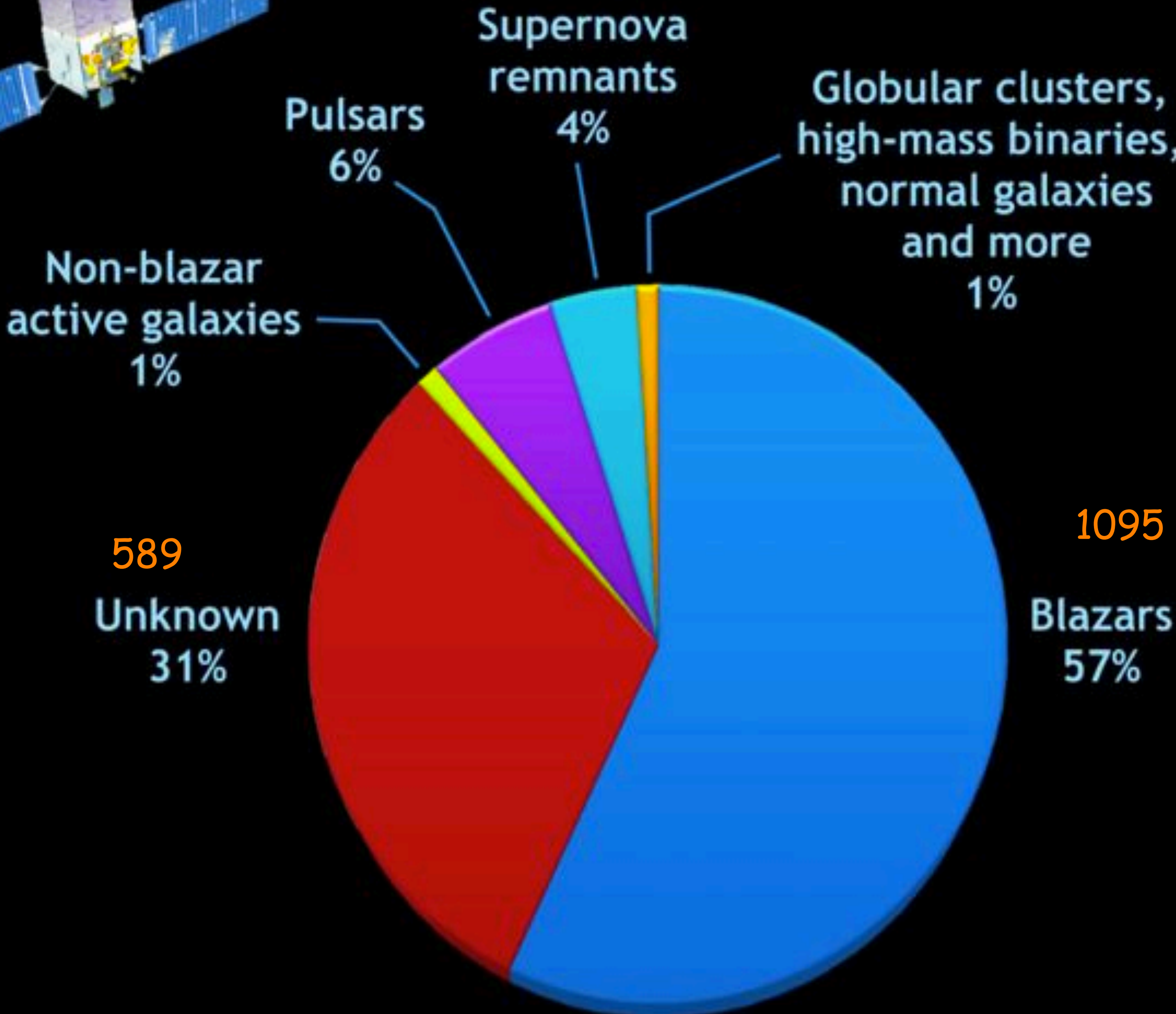
1873 sources
1095 AGN's
589 unidentified

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

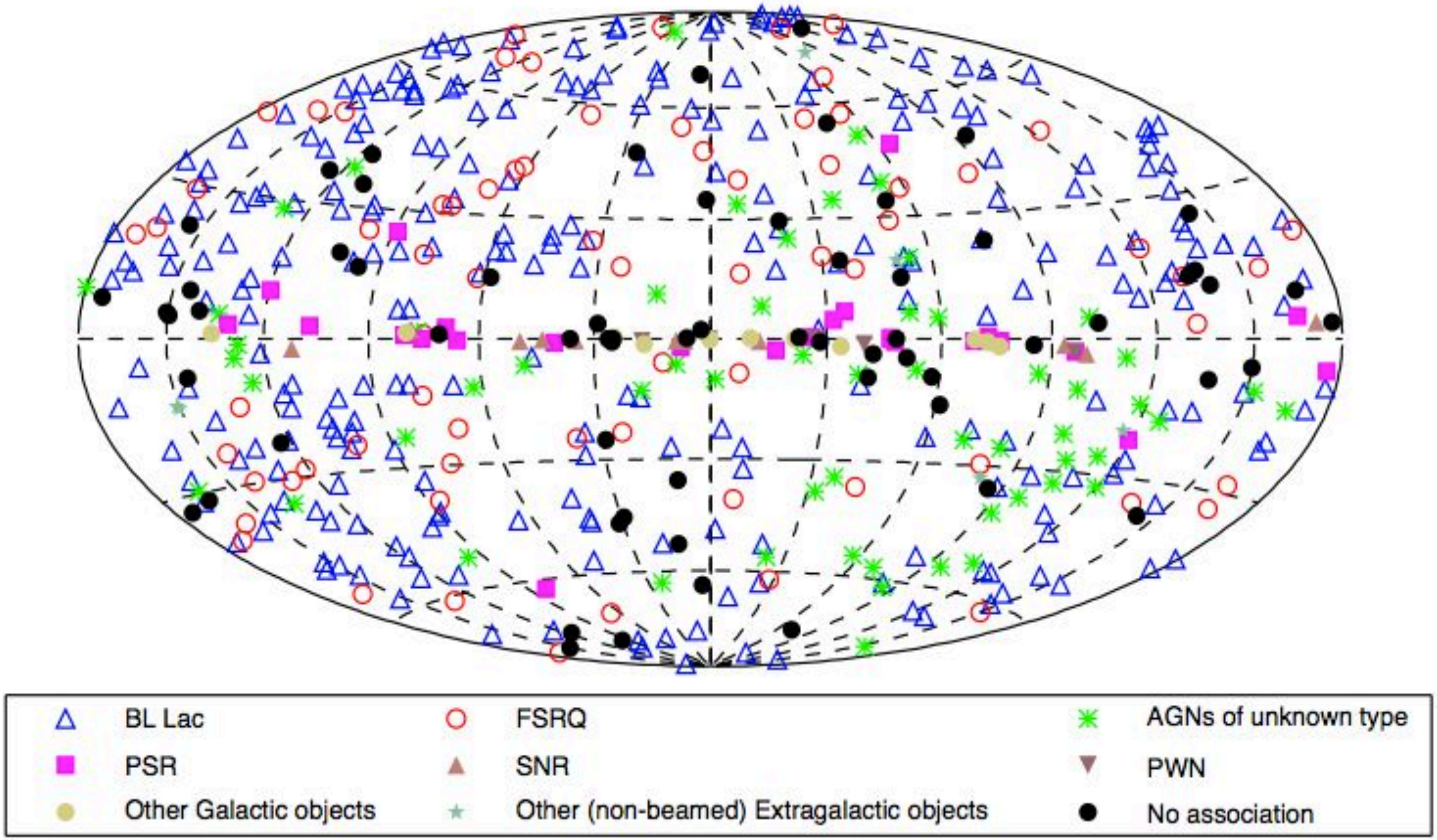
Fermi Coll. ApJS (2012) 199, 31
arXiv:1108.1435
**3FGL in preparation**

# What has Fermi found: The LAT two-year catalog





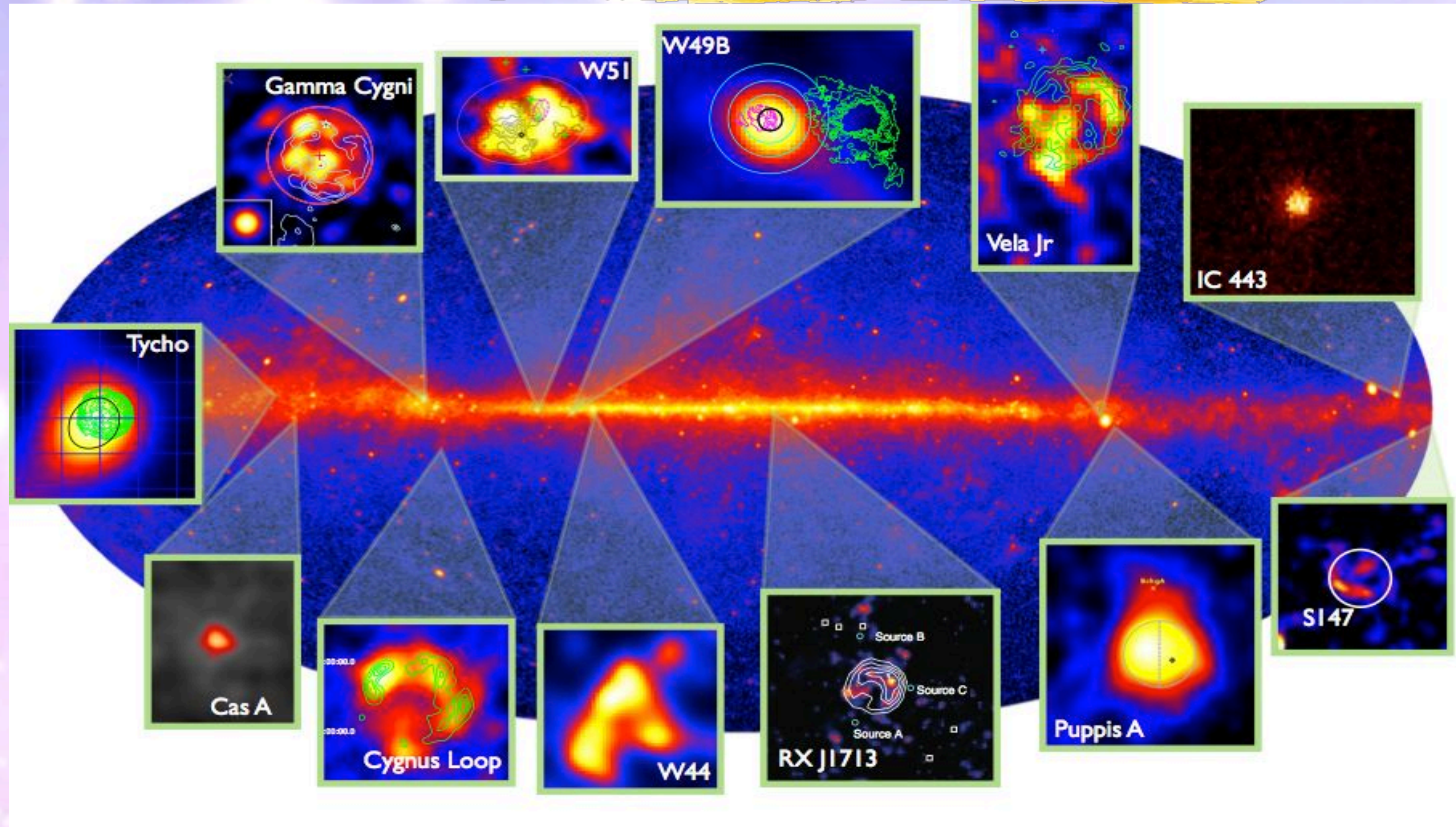
# Hard Source List




First catalog of source above 10 GeV     514 sources

ApJS sub. [arXiv:1306.6772]

# SuperNova Remnants - towards a catalog




- 25 published SNRs + 30 candidates in 2FGL
- Requires combination of spatial and energy information
- Diffuse emission modeling is a key systematic uncertainty

# 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 $\pi^0$-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)

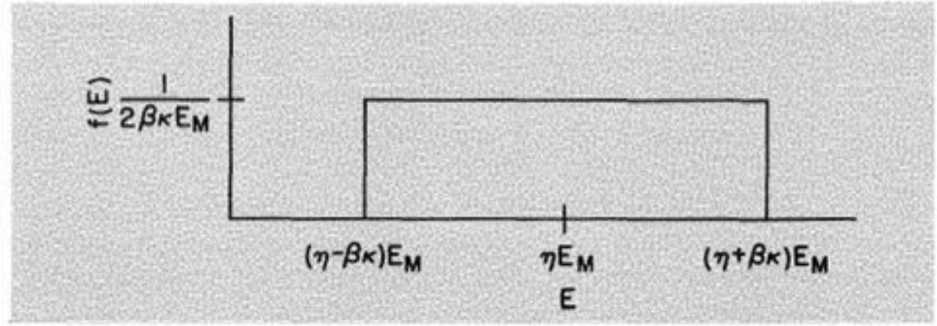
Stecker, 1971 (Cosmic gamma rays)

- 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

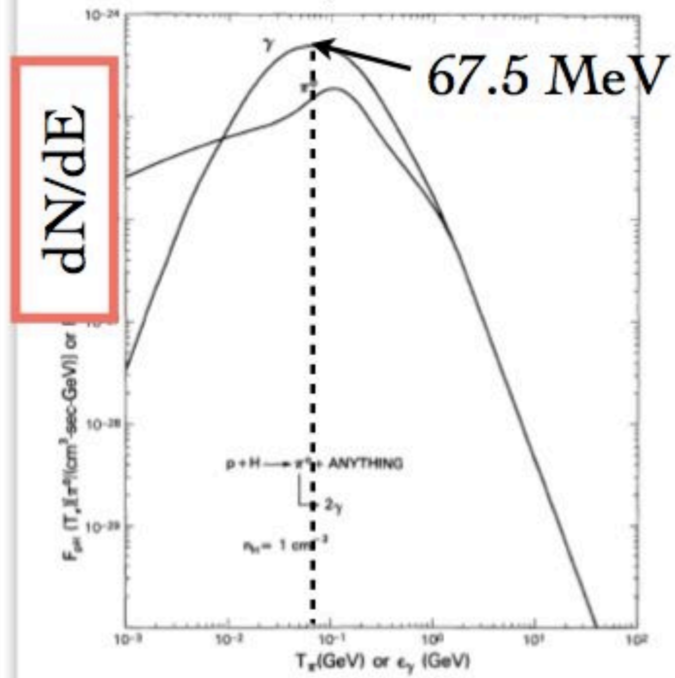
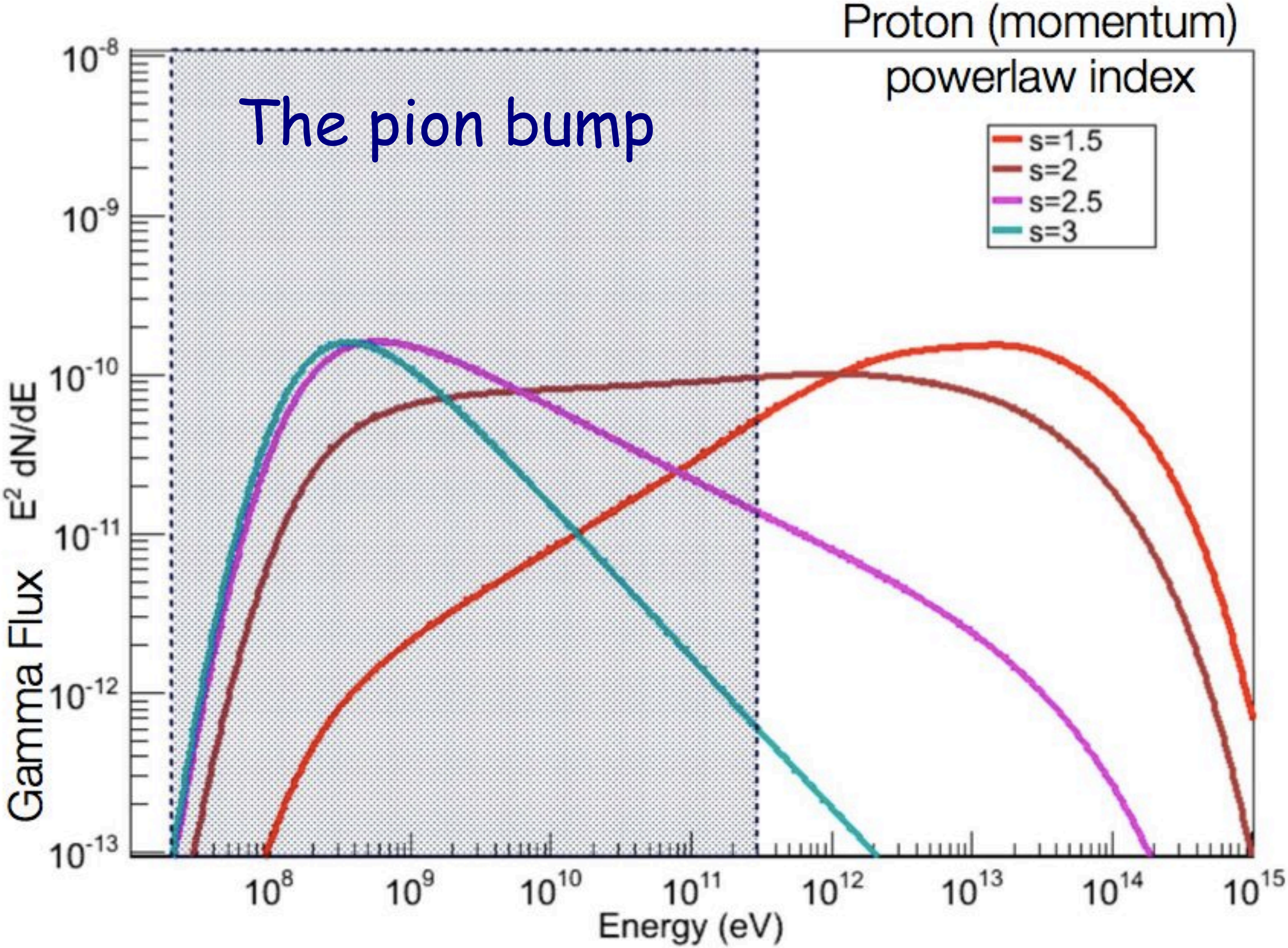


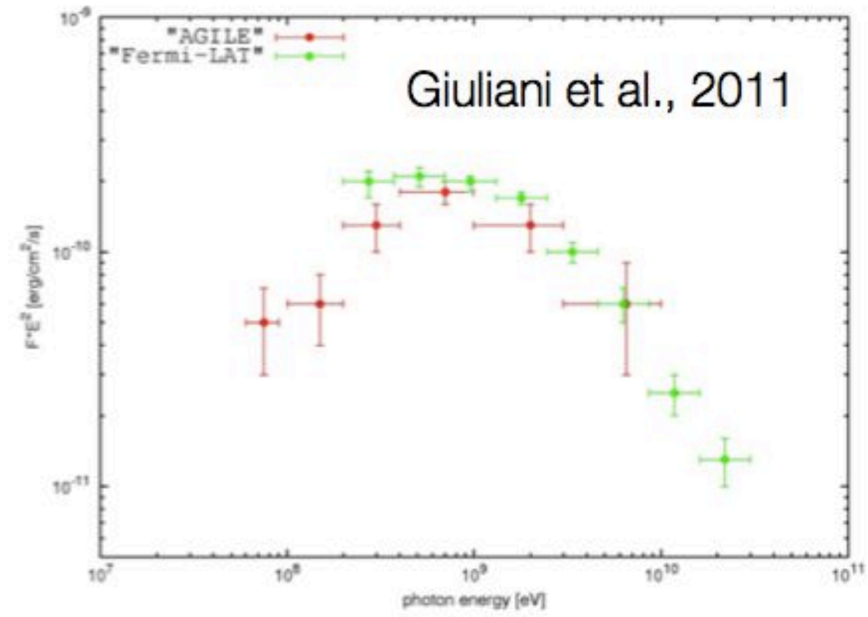

Fig. 7. The secondary $\pi^0$ and $\gamma$-ray emissivities from the interaction of the local demodulated cosmic ray proton spectrum with unit density of atomic hydrogen

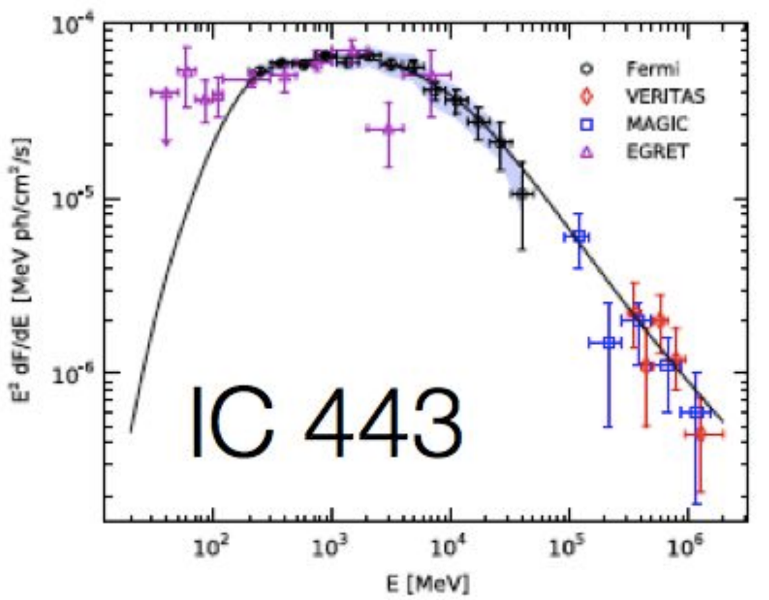


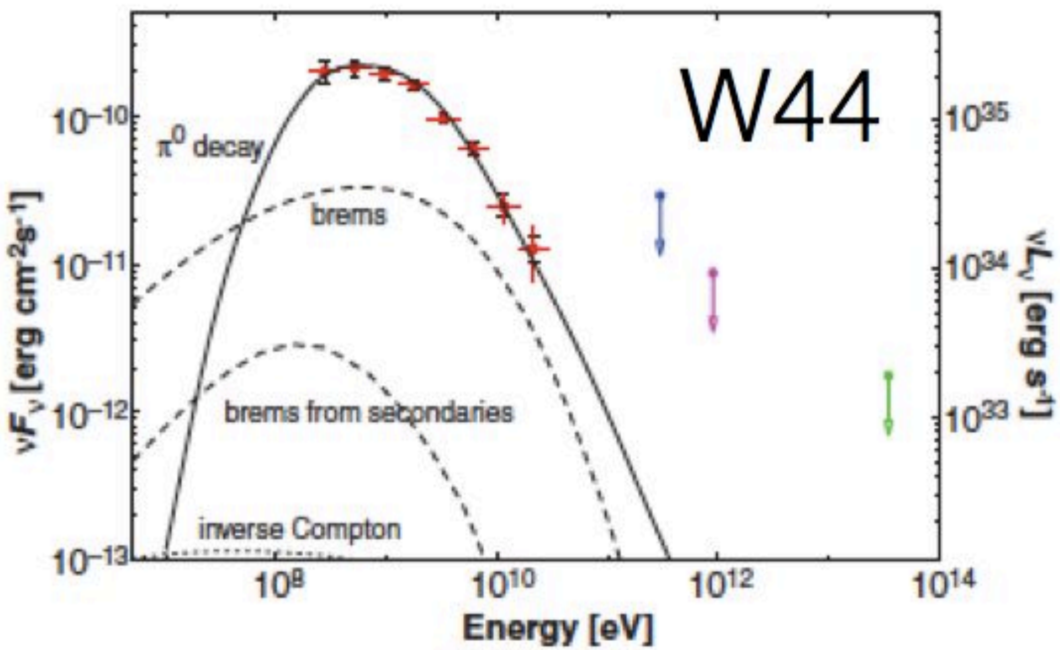

Smoking gun feature for accelerated protons

# Earlier 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)



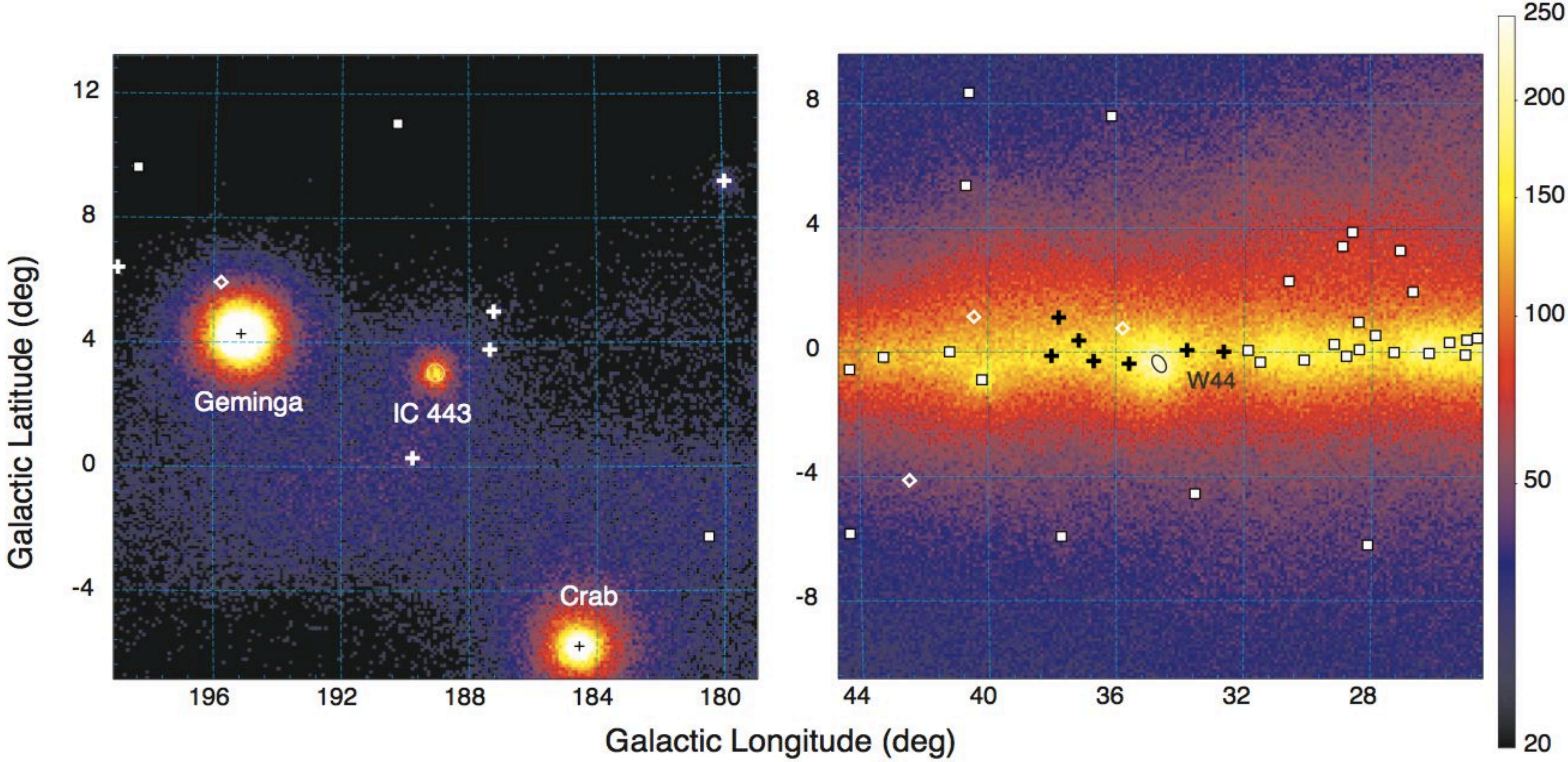



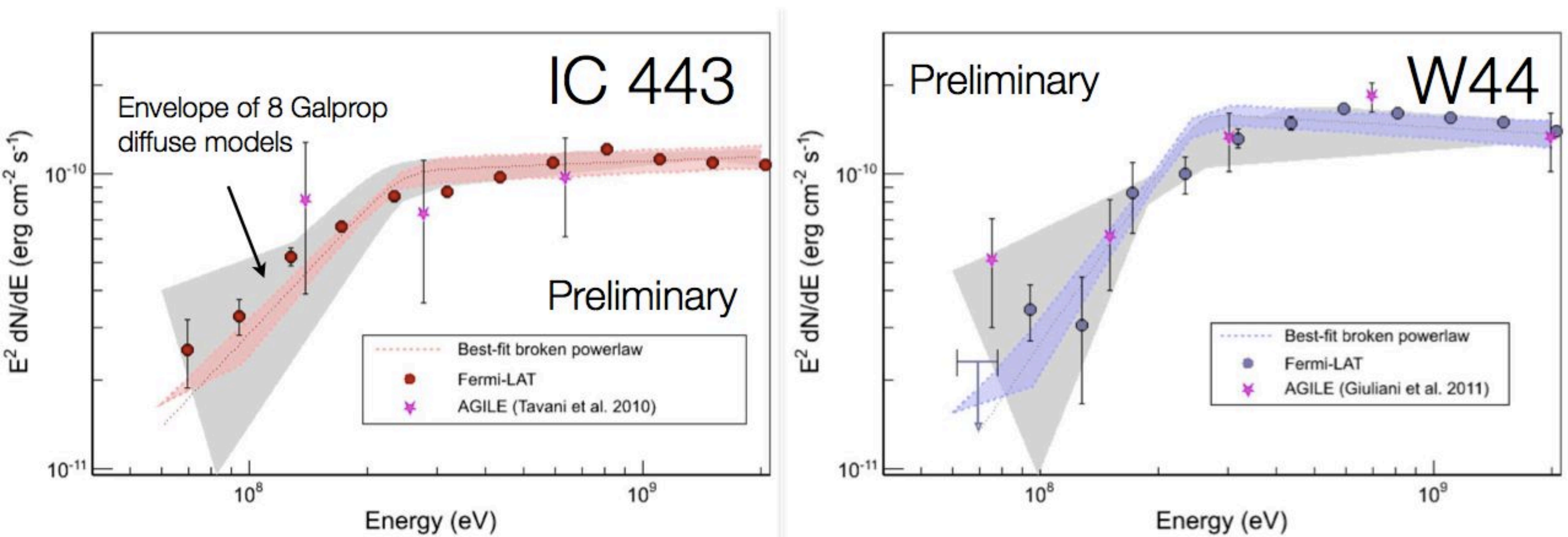
# New Fermi Large Area Telescope analysis:

Time range: 2008 August, 4th to 2012 July 16th

Gamma-ray count maps of the 20° × 20° fields around **IC 443** and **W44** in the energy range 60 MeV to 2 GeV

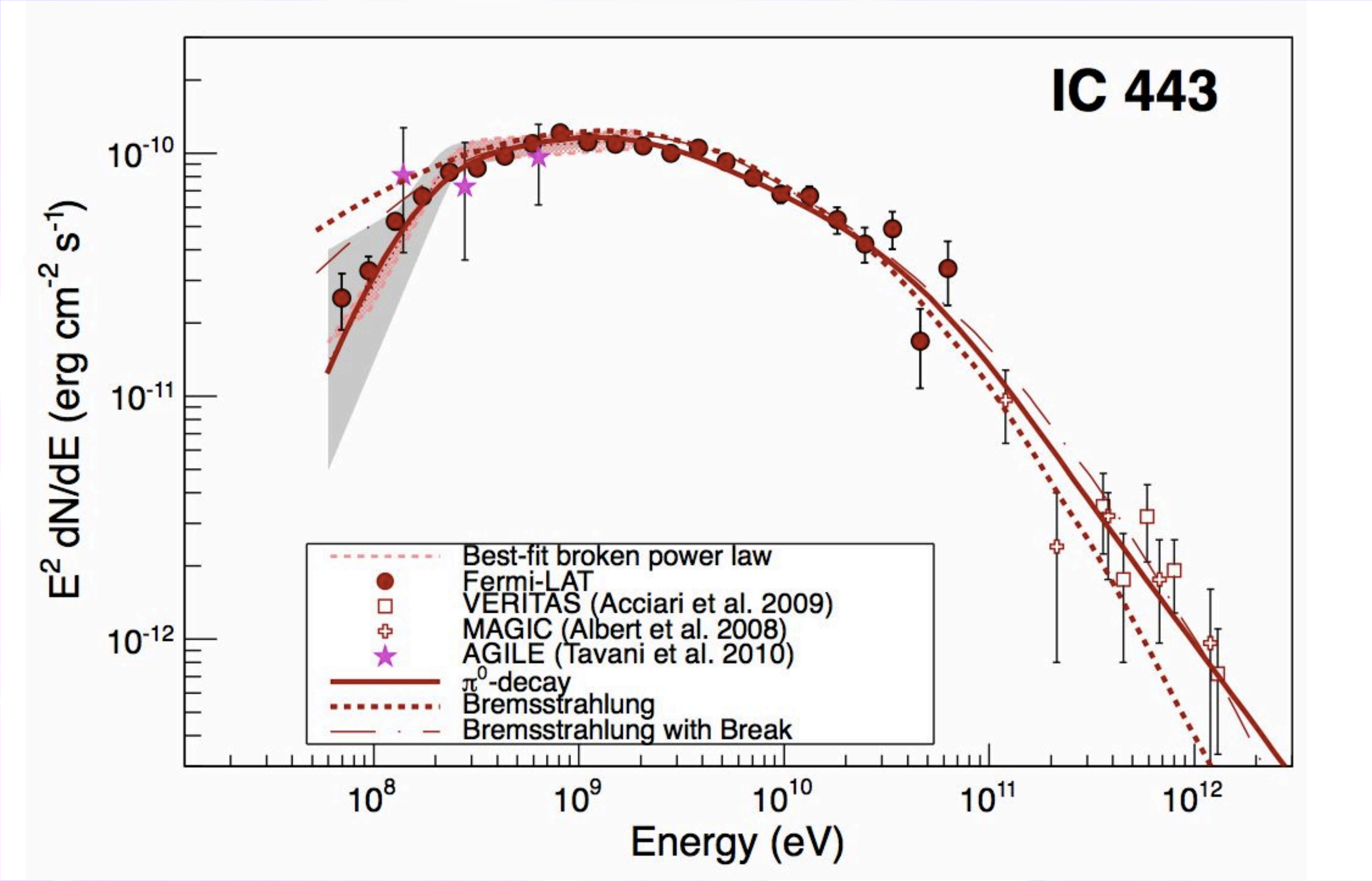


# Energy spectra down to 60 MeV




- Clear indication of a low-energy “turnover”
- Gray systematic error band estimated from 8 Galprop models of diffuse emission

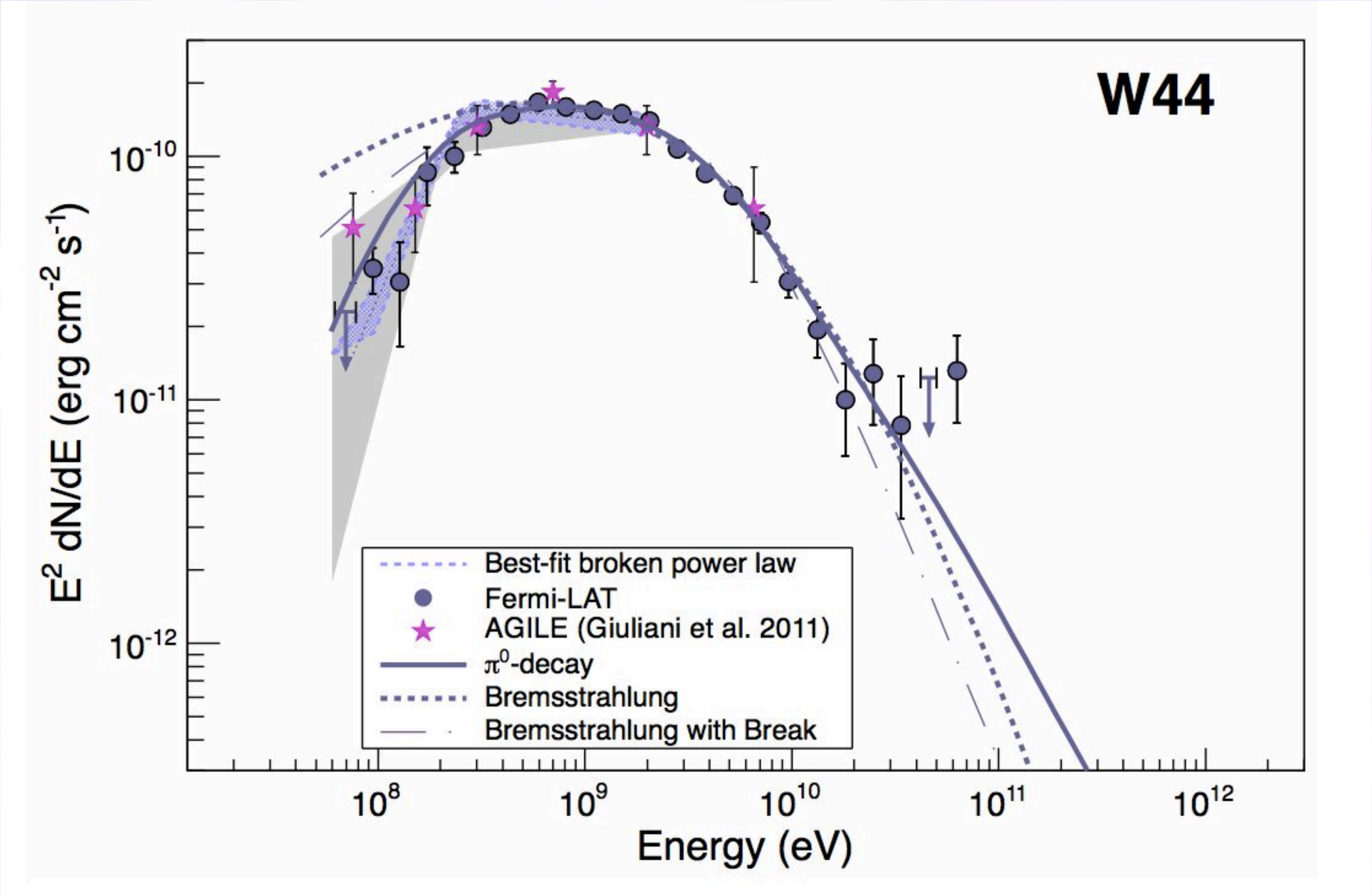
# Detection of the Characteristic Pion-decay Signature in Supernova Remnants
# Direct evidence that cosmic-ray protons are accelerated in SNR




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

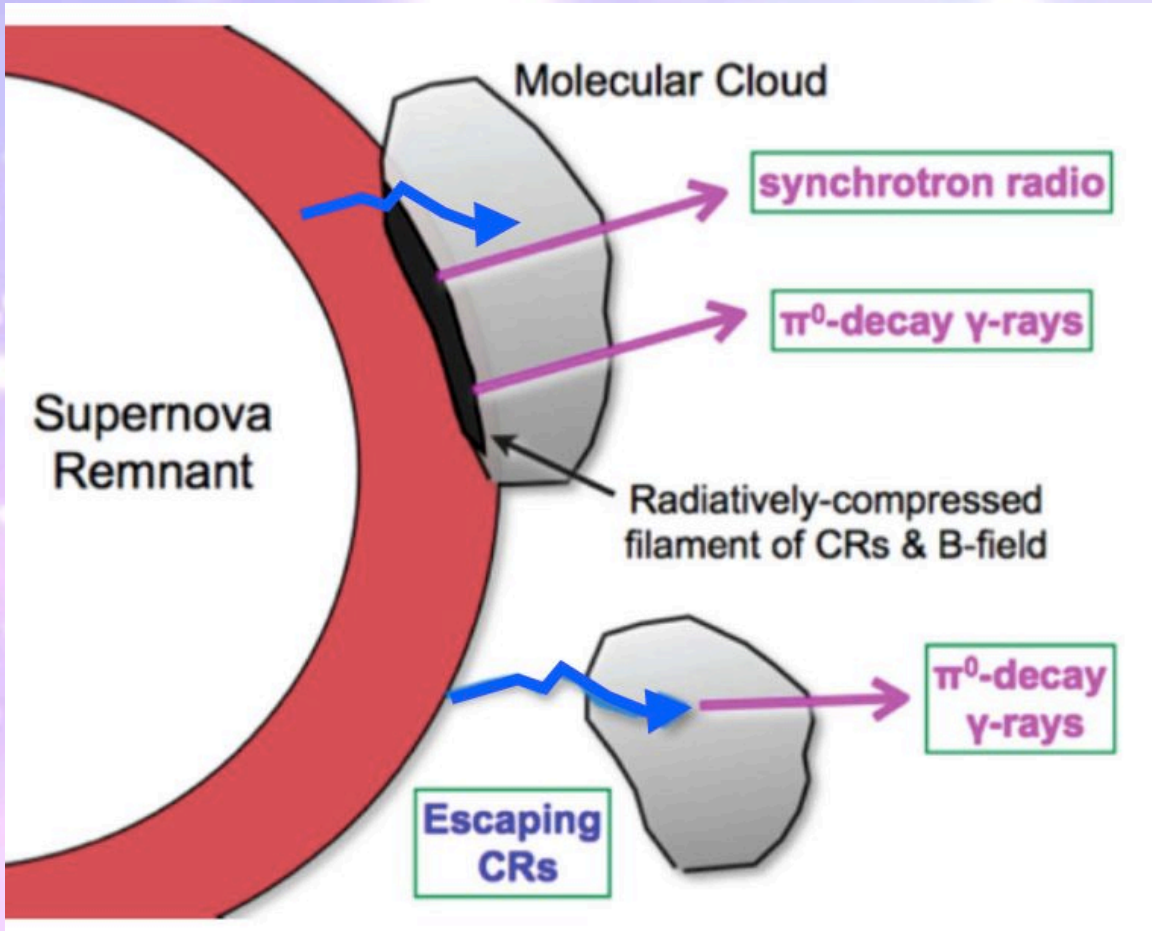
# Detection of the Characteristic Pion-decay Signature in Supernova Remnants

# Direct evidence that cosmic-ray protons are accelerated in SNR



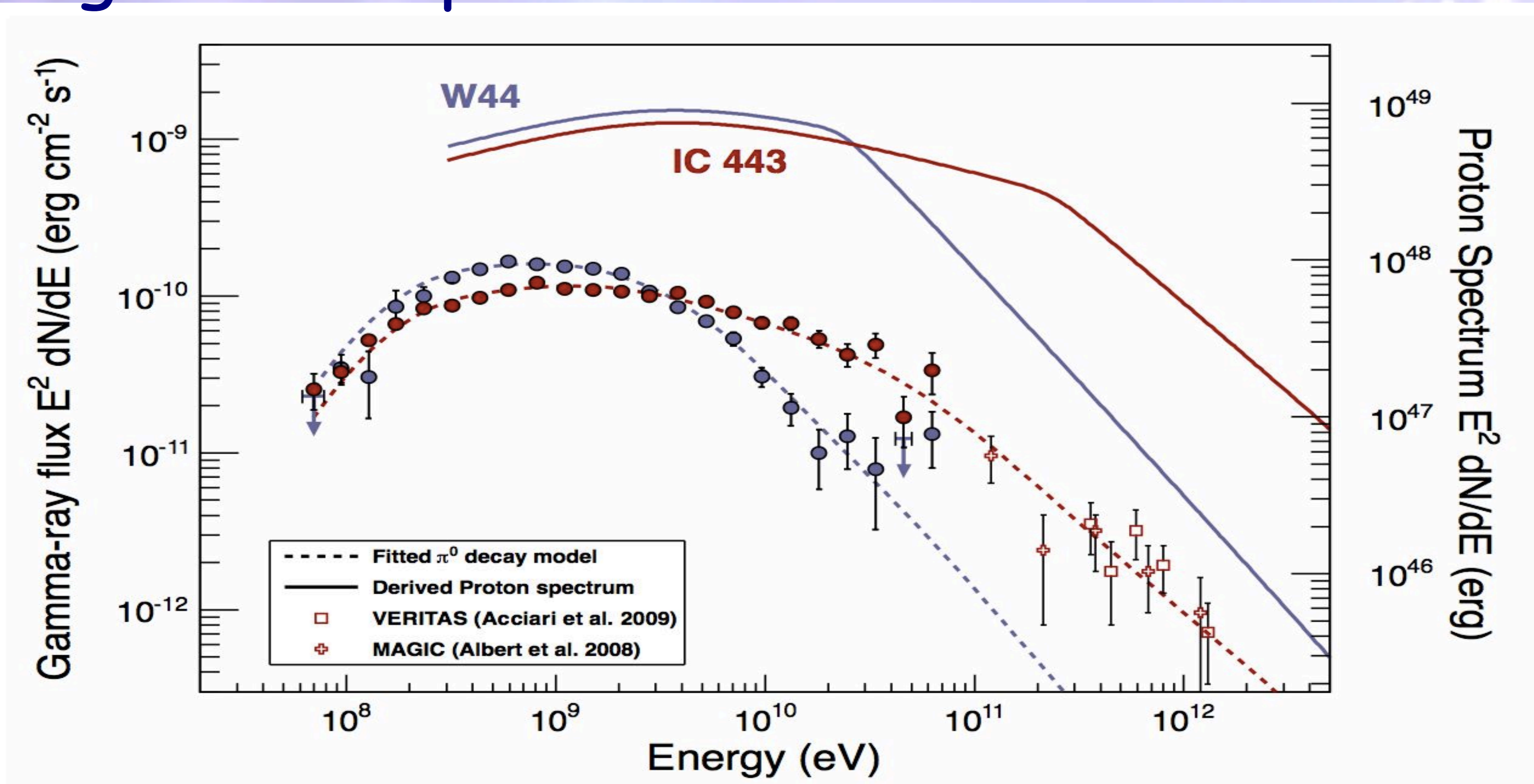

Science 339, (2013) 807 [arXiv:1302.3307] 15 Feb. 2013

# Emission mechanism




- Emission site: probably downstream of shock (upstream expect harder spectrum) i.e. inside the SNR
- **Crushed cloud**: CRs and MC simultaneously compressed. Reacceleration of the "sea" of CRs.
- **Passive cloud**: CRs escape and interact with cloud. Fresh acceleration of CRs.

# Resulting Proton spectrum




$$\frac{dN_p}{dp} \propto p^{-s_1}\left[1+\left(\frac{p}{p_{\rm br}}\right)^{\frac{s_2-s_1}{\beta}}\right]^{-\beta}$$

IC 443

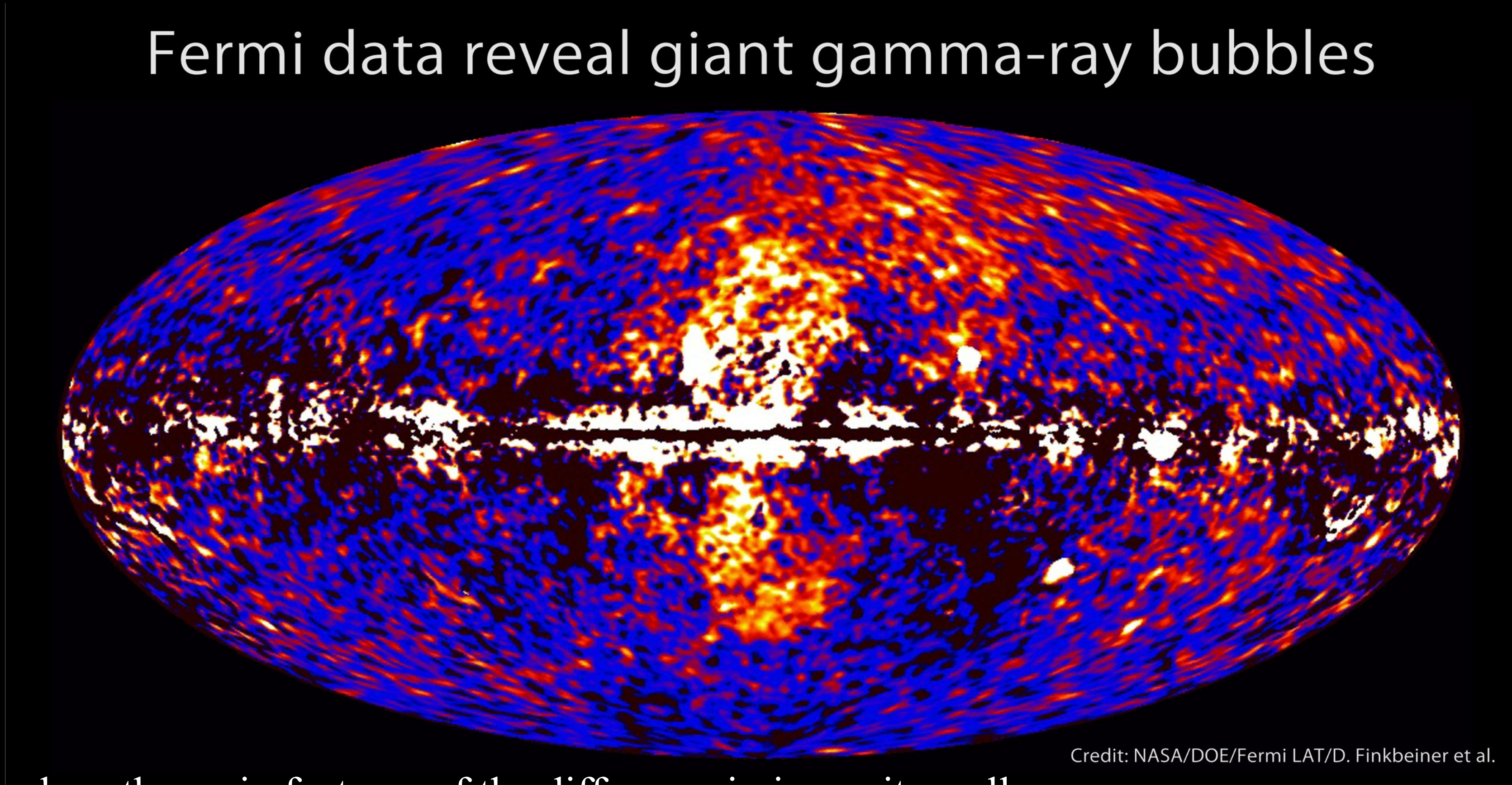
s1 = 2.36±0.02, s2 = 3.1±0.1 $p_{br}$ =239±74 GeV $c^{-1}$

W44

s1 = 2.36±0.05, s2 = 3.5±0.3 $p_{br}$ =22± (22±8) GeV $c^{-1}$

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

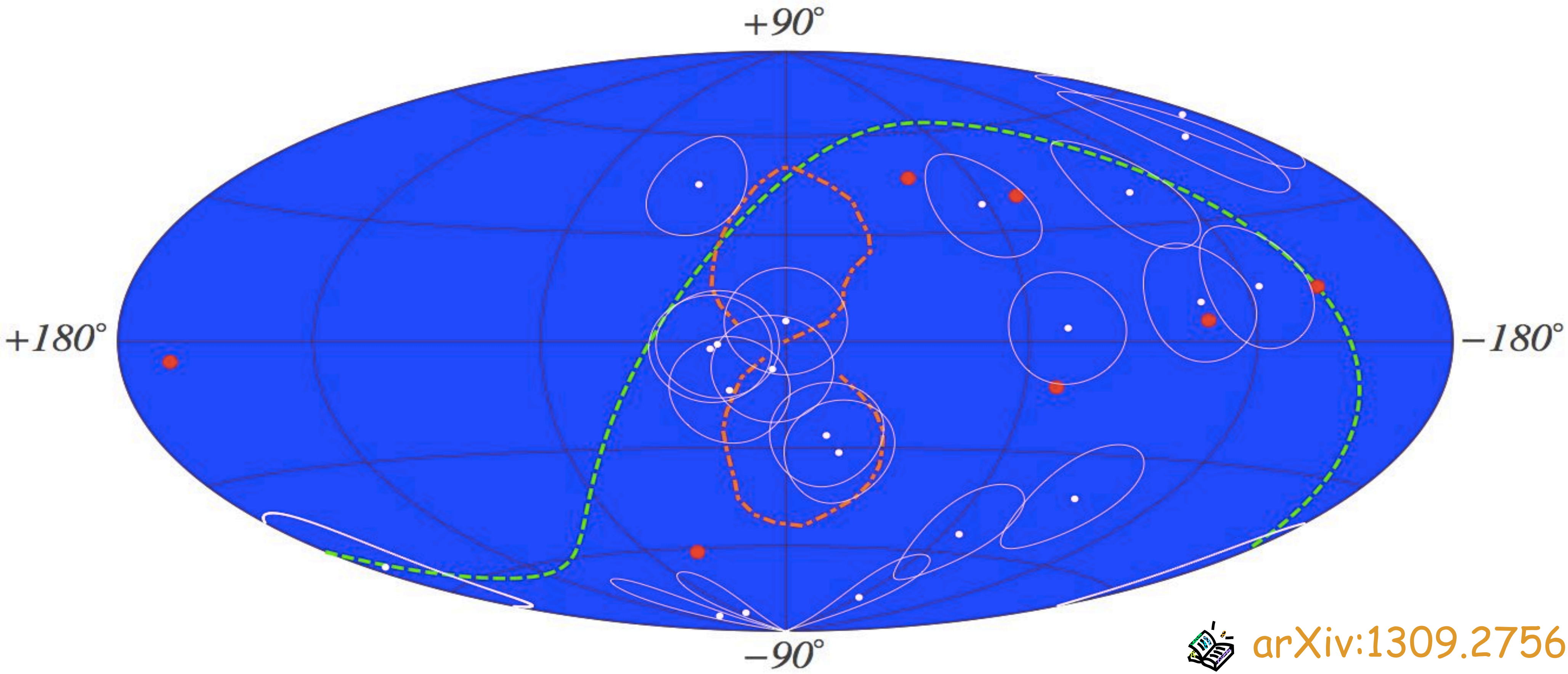
# NASA press release




- ✧ Models reproduce the main features of the diffuse emission quite well
- ✧ Discrepancies between the physical model and high-resolution data (residuals) are the gold mines of new phenomena!
- ✧ Every extended source and/or process that is not included into the model pops up and exposes itself as a residual

# Fermi Bubble

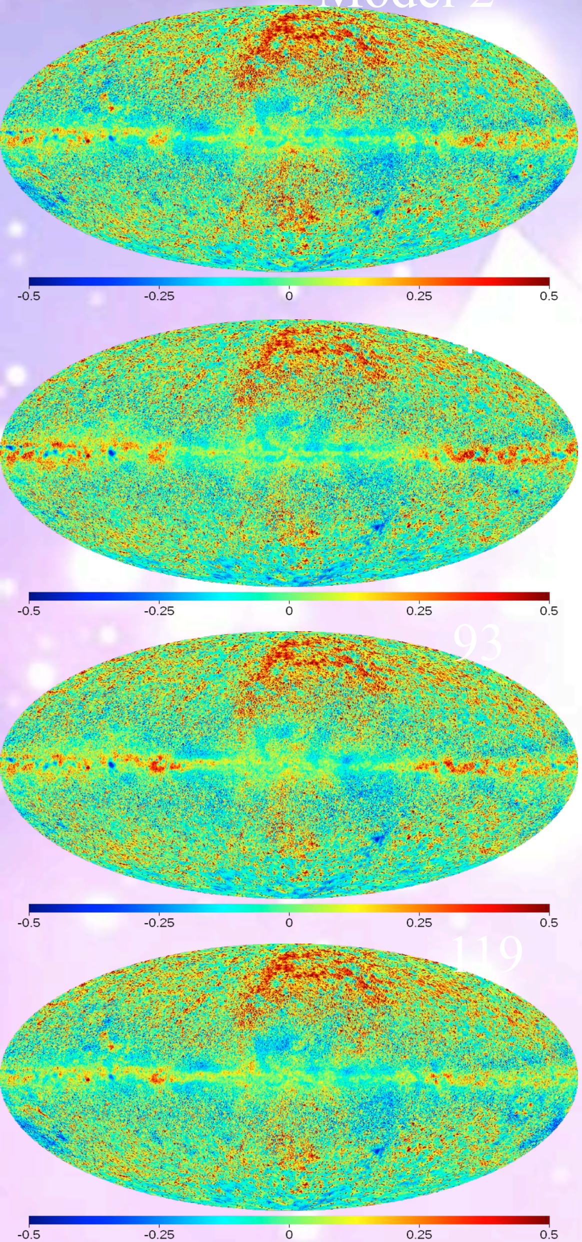
# The Galactic Center Origin of a Subset of IceCube Neutrino Events

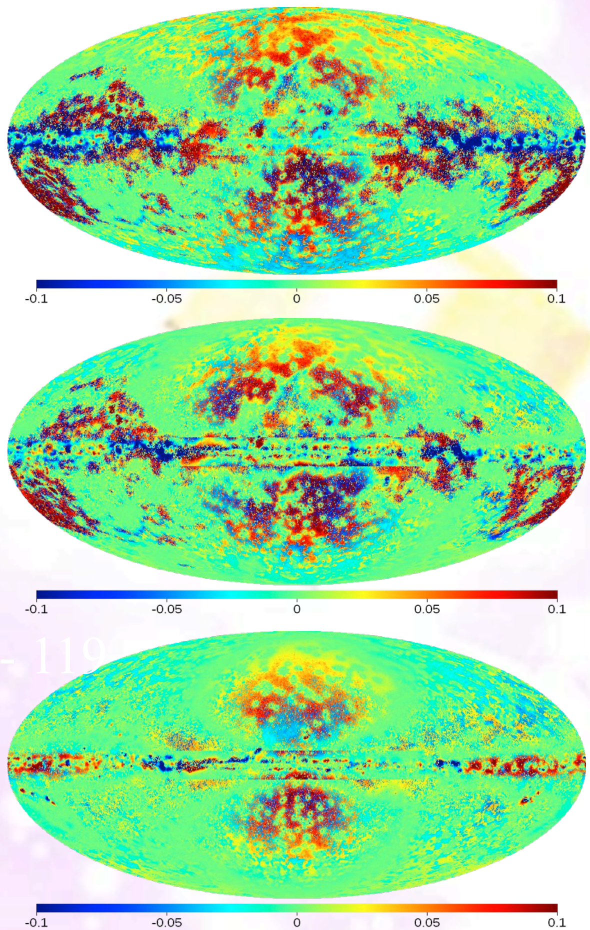



arXiv:1309.2756

- IceCube neutrino events in Galactic coordinates. The 21 shower-like events are shown with 15◦ error circles around the approximate positions (small white points) reported by IceCube [1]. The 7 track-like events are shown as larger red points. Also shown are the boundaries of the Fermi bubbles (dot-dashed line) and the Equatorial plane (dashed line).

# Large scale study: residuals




- Agreement for models is overall good, but features are visible in residuals at ~% level
- Difference between illustrative models shown in right maps : structure due to variations of model parameters

- Models details:
  2: SNR$^{Z}$4$^{R}$20$^{T}$150$^{C}$5
  44: Lorimer$^{Z}$6$^{R}$20$^{T}\infty^{C}$5
  93: Yusifov$^{Z}$10$^{R}$30$^{T}$150$^{C}$2
  119: OB$^{Z}$8$^{R}$30$^{T}\infty^{C}$2

# What's next ?

# New projects in space

- ISS-Cream launch planned for 2014
- CALET CALorimetric Electron Telescope launch planned for 2014
- arXiv:1302.1257
- Gamma-light (Proposed to ESA but not approved )

http://agenda.infn.it/getFile.py/access?contribId=67&resId=0&materialId=slides&confId=4267

- JEM EUSO launch tentatively planned for 2017

Dolores Rodriguez-Frias later

- Gamma-400 launch foreseen by end 2018

100 MeV – 3 TeV, an approved Russian $\gamma$-ray satellite. Energy resolution (100 GeV) ~ 1 %. Effective area ~ 0.4 m2. Angular resolution (100 GeV) ~ 0.01°.

**Science with Gamma-400 Workshop** http://cdsagenda5.ictp.it/full_display.php?ida=a1311

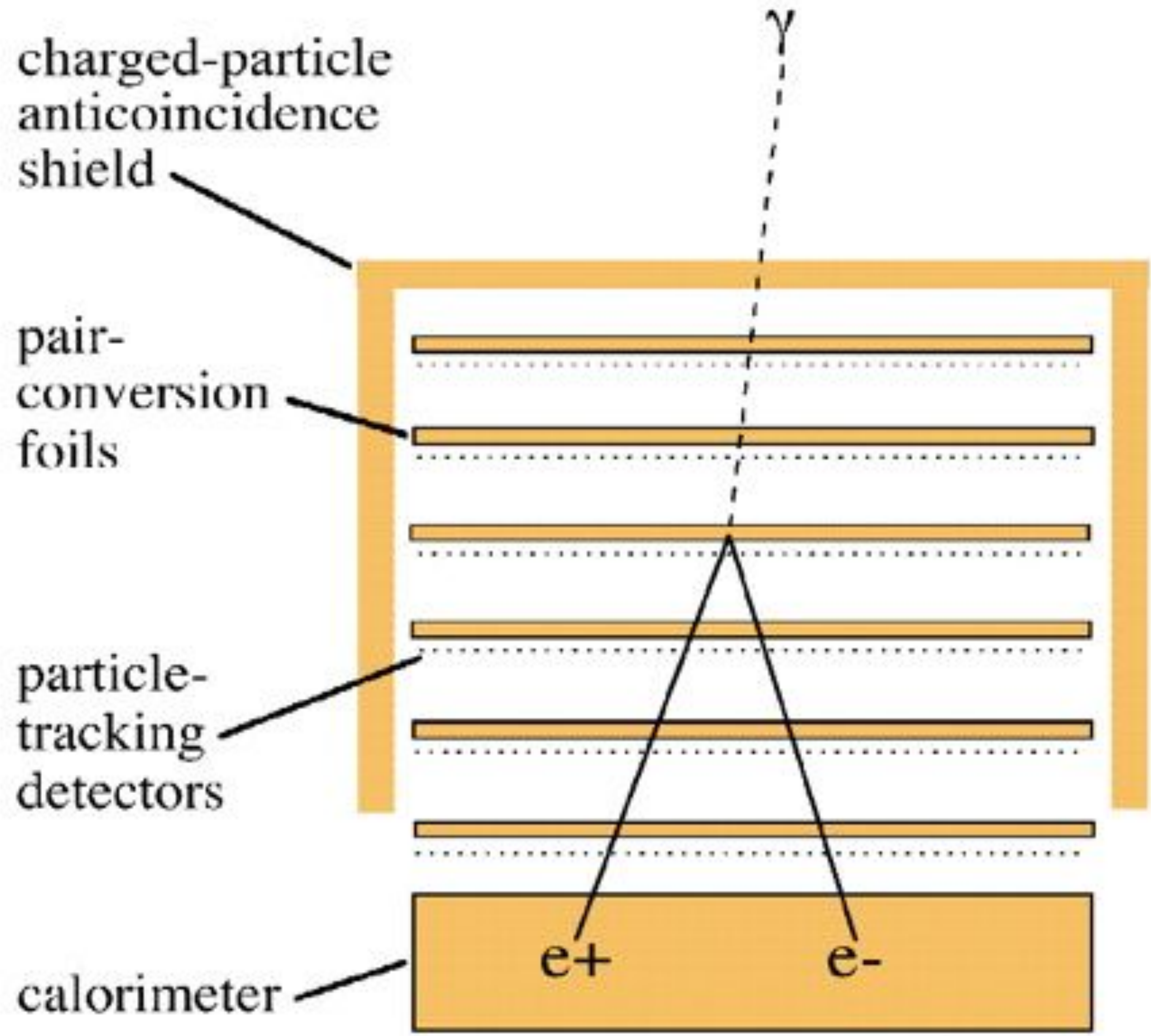
- DAMPE: Satellite of similar performance as Gamma-400.

An approved Chinese $\gamma$-ray satellite. Planned launch 2015-16.

- HERD: Instrument on the planned Chinese Space Station.

Energy resolution (100 GeV) ~ 1 %. Effective area ~ 1 - 2 m2. Angular resolution (100 GeV) ~ 0.01°. Planned launch around 2020.

# Elements of a pair-conversion telescope




(energy measurement)

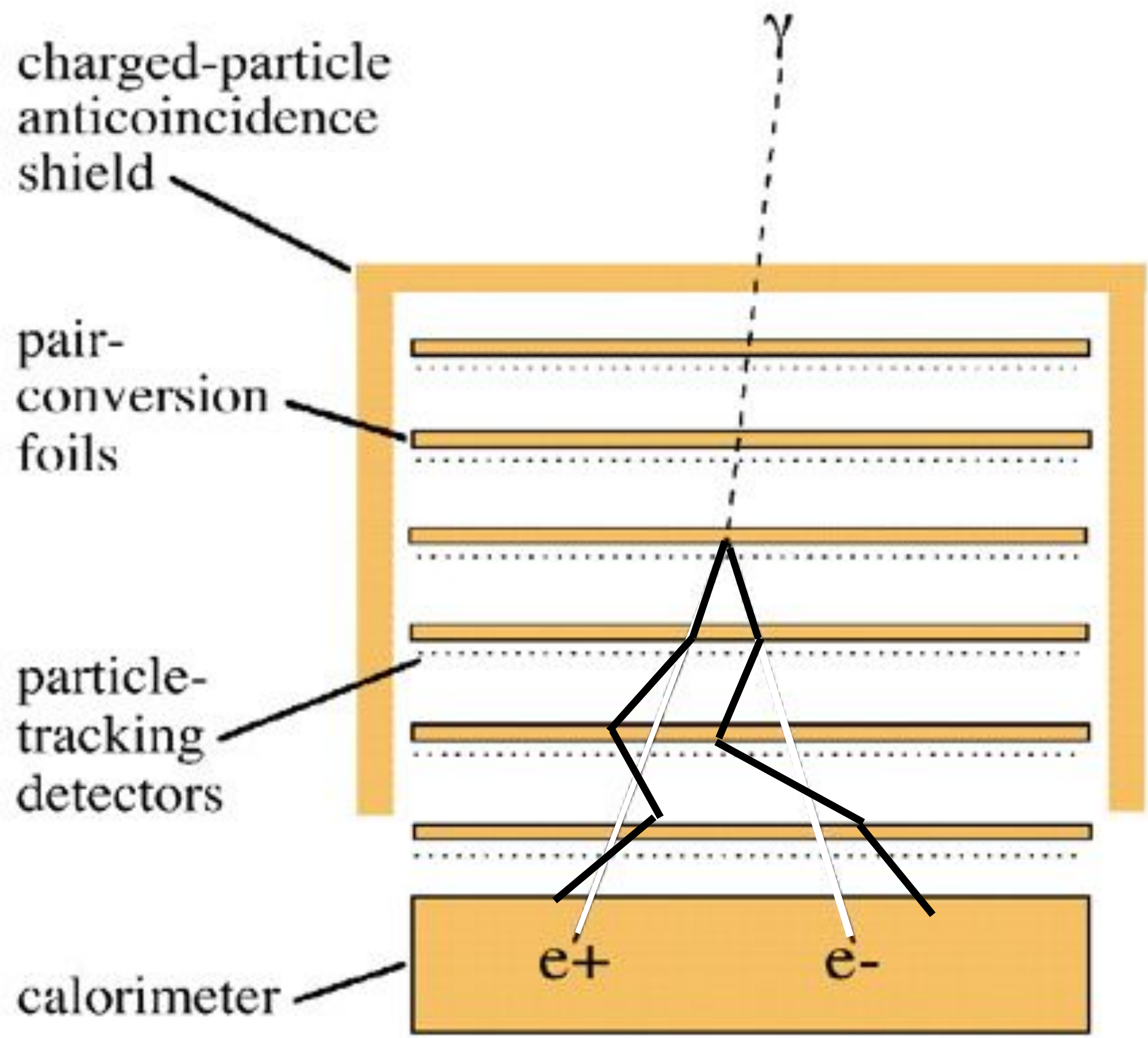
- photons materialize into matter-antimatter pairs:

  $E_\gamma \; \text{-->} \; m_{e^+}c^2 + m_{e^-}c^2$

- electron and positron carry information about the direction, energy and polarization of the $\gamma$-ray

# Elements of a pair-conversion telescope

(more realistic scheme)

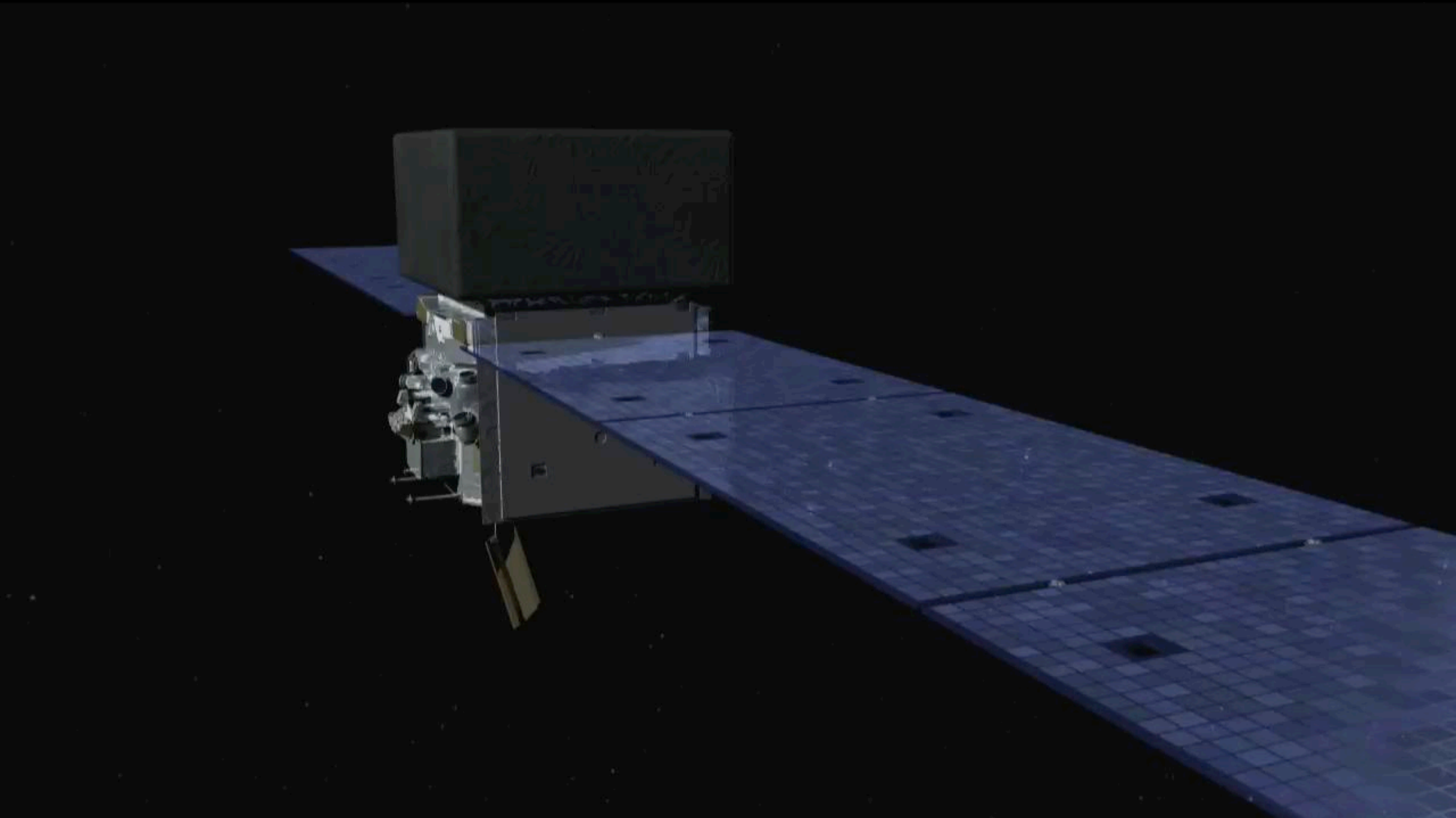



(energy measurement)

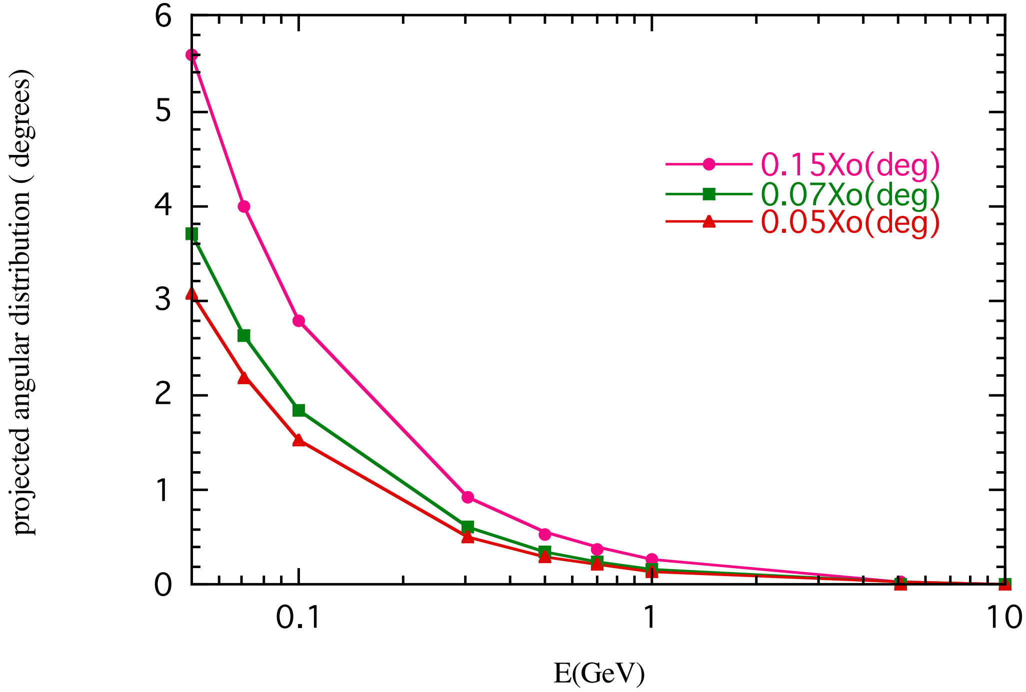
- photons materialize into matter-antimatter pairs:

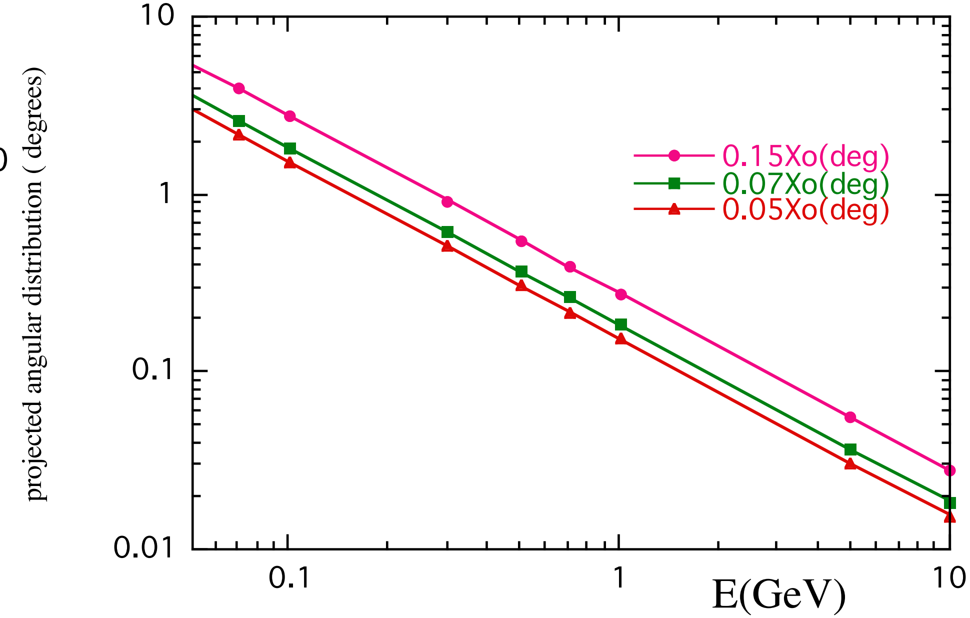
  $E_{\gamma}$ --> $m_{e^+}c^2 + m_{e^-}c^2$

- electron and positron carry information about the direction, energy and polarization of the γ-ray



# Multiple Scattering

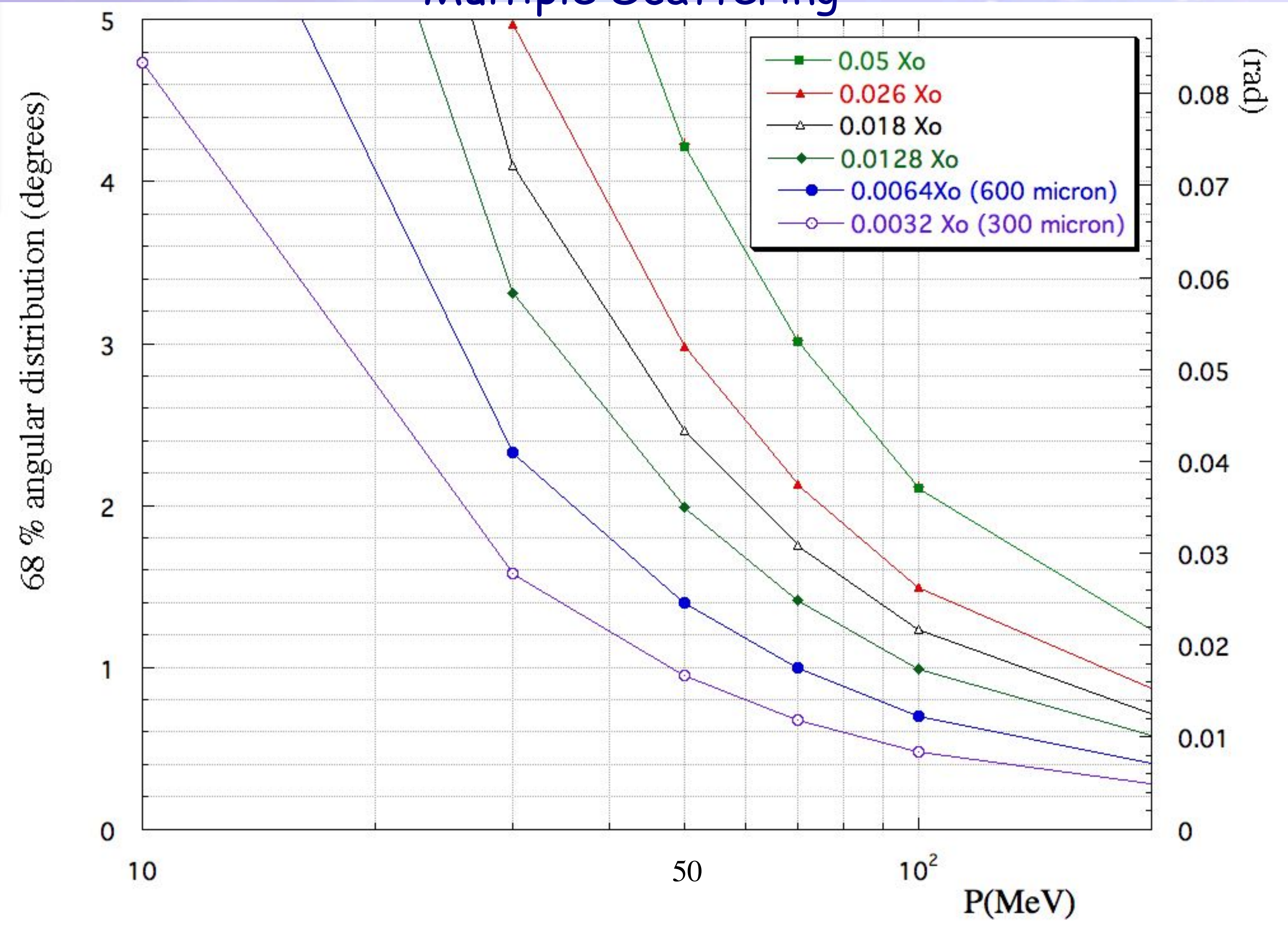


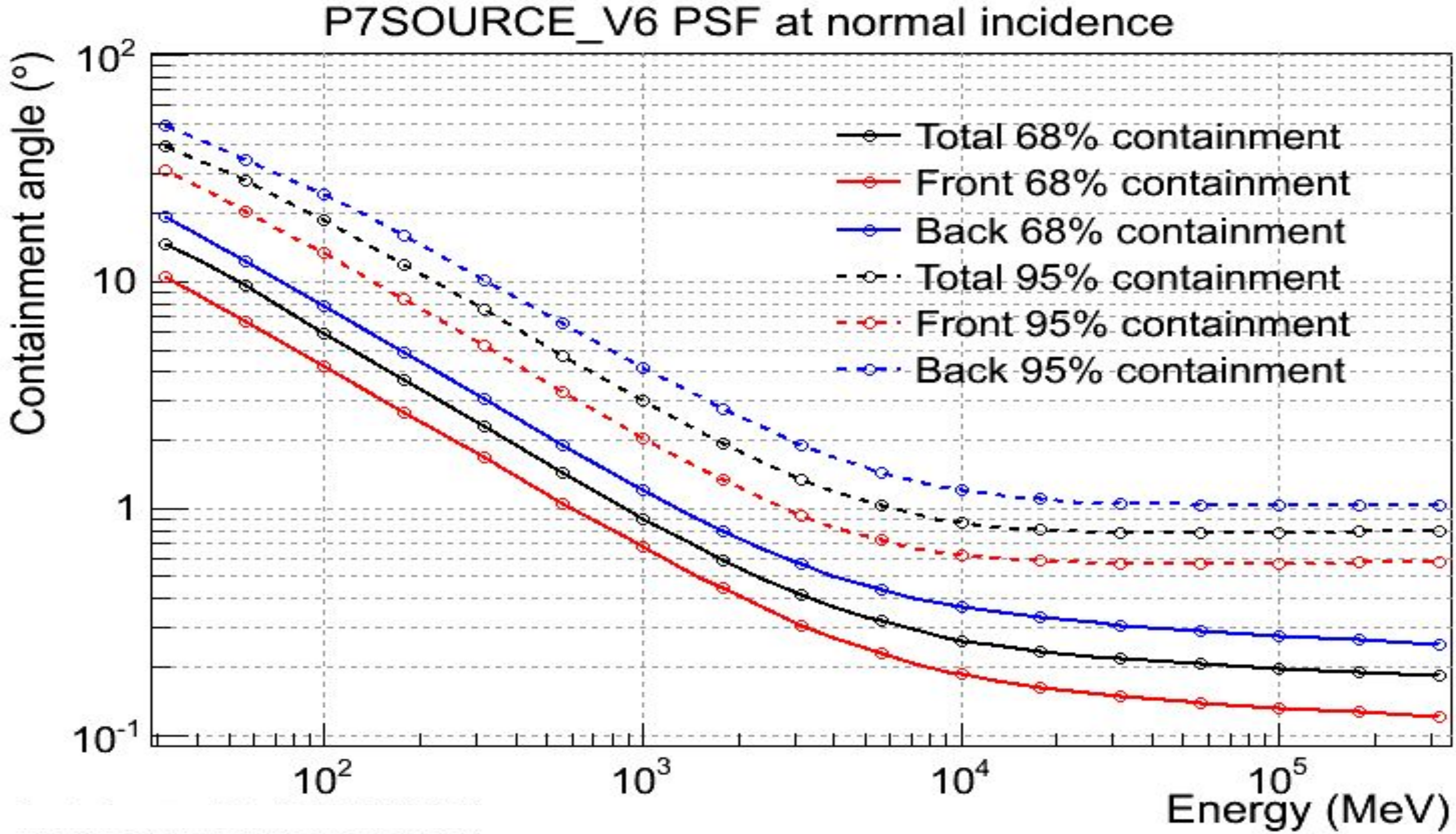

$$\theta_0 = \theta_{plane}^{rms} = \frac{1}{\sqrt{2}}\theta_{space}^{rms}$$

$$\theta_0 = \frac{13.6MeV}{\beta cp} z\sqrt{x/X_0}\,[1 + 0.038\ln(x/X_0)]$$

# Multiple Scattering



# Fermi Instrument Response Function




http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

$N\gamma_s$ = number of photons from source
$N\gamma_B$ = number of photons from background
$\Delta\Omega$ = solid angle around dth source
$A_{eff}$ = Effective area ( Area* efficiency )
x = converter plane in radiation lengh

# Sensitivity

depends on field of view

$$N_{\gamma s} = \Phi_s(cm^{-2}) * A_{eff} * \Delta T$$

$$N_{\gamma B} = \Phi_B(cm^{-2}sr^{-1}) * \Delta\Omega * A_{eff} * \Delta T$$

depends on angular resolution

Sensitivity

number of σ

$$N_{\gamma s} \geq 5(N_{\gamma B})^{-\frac{1}{2}}$$

$$\Delta\Omega \sim \pi\theta^2 \sim \pi E^{-2} x$$

$$\Phi_s \geq \frac{5}{E}\left(\frac{\Phi_B * x}{A_{eff} * \Delta T}\right)^{-\frac{1}{2}}$$

# Sensitivity

good detector

small converter plane

$$\Phi_s \geq \frac{5}{E}\left(\frac{\Phi_B * x}{A_{eff} * \Delta T}\right)^{-\frac{1}{2}}$$

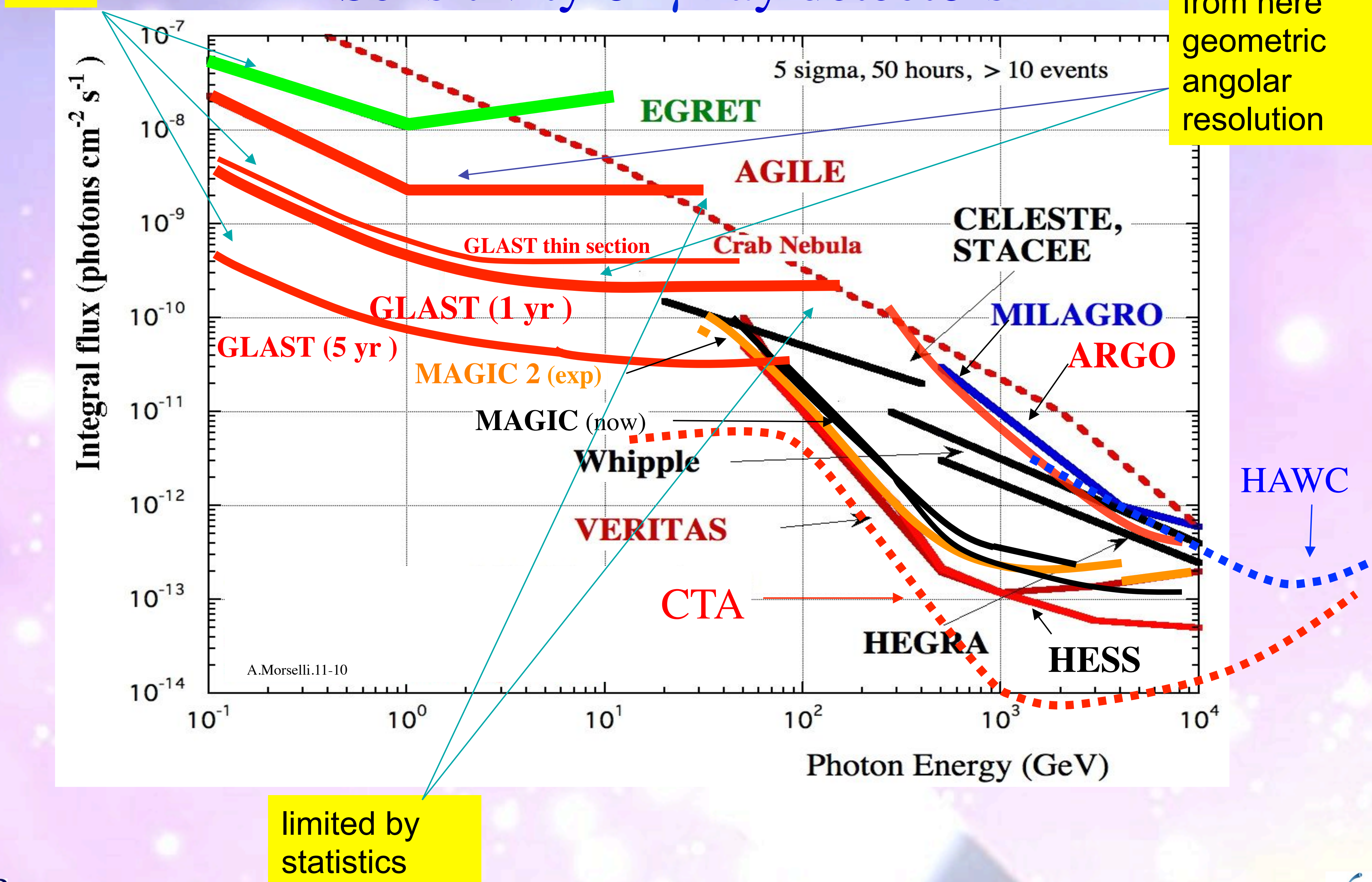
large effective area
(large geometric area and large total conversion efficiency )

large field of view

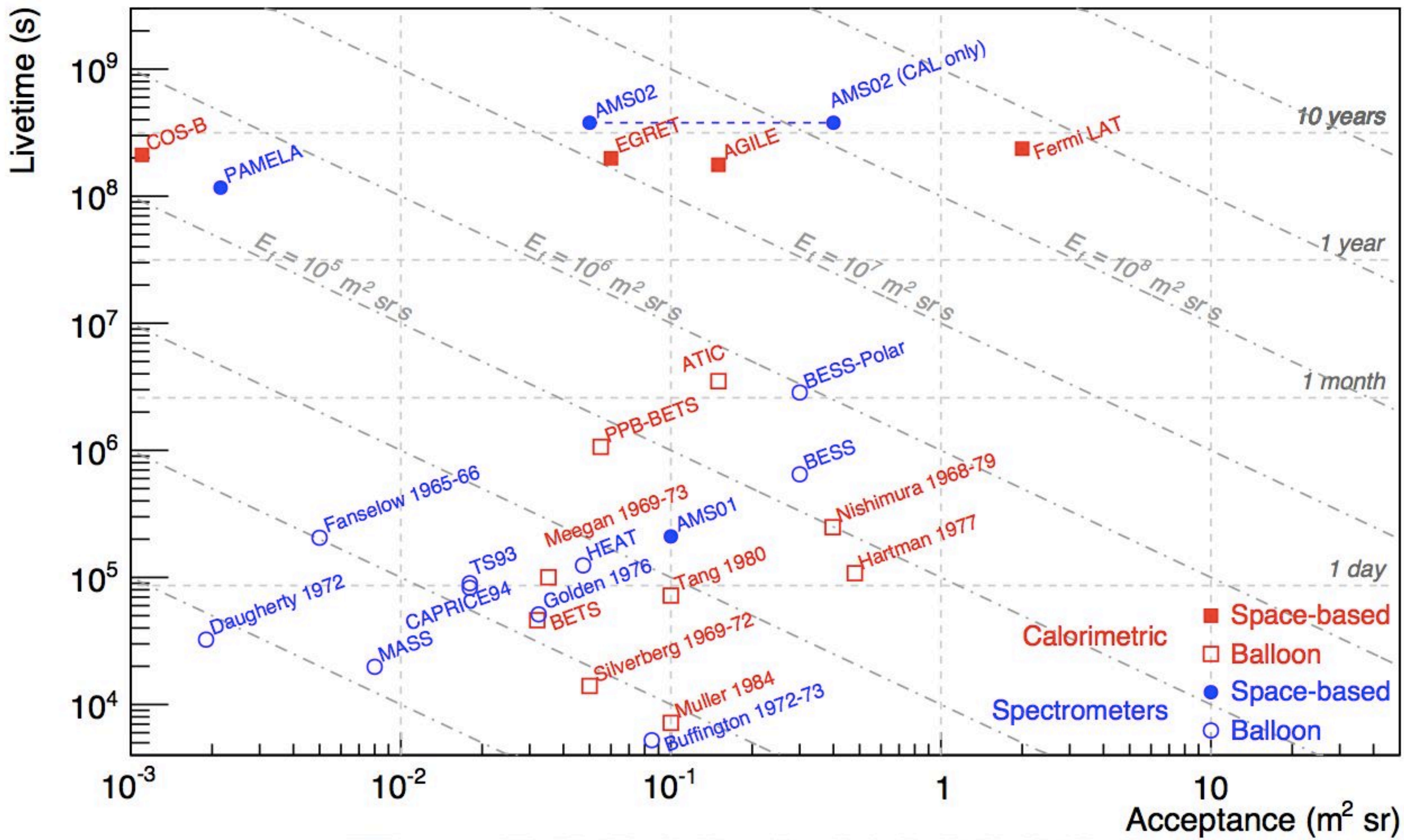
$A_{eff}$ = Effective area ( Area* efficiency )

x = converter plane in radiation lengh

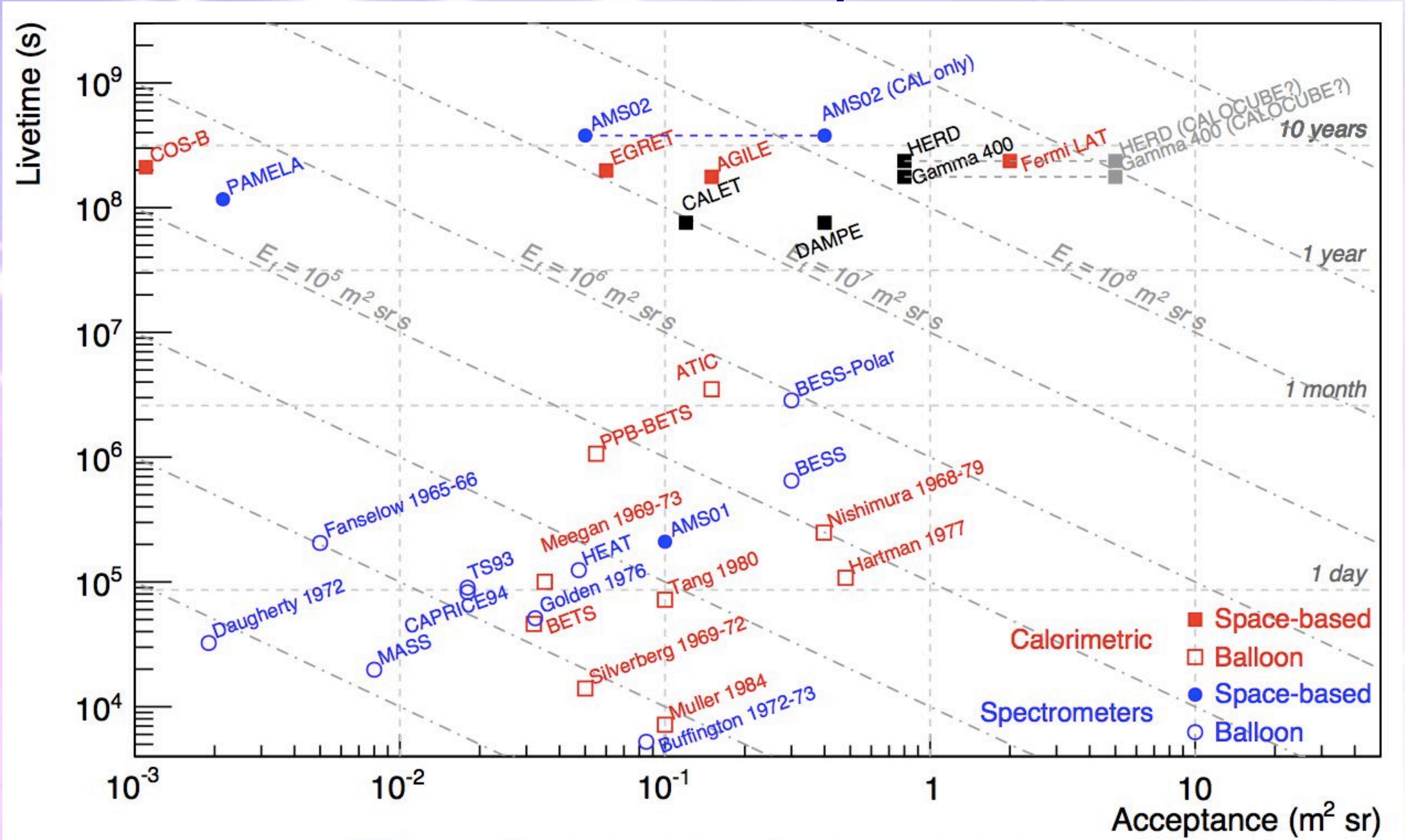
# Sensitivity of γ-ray detectors

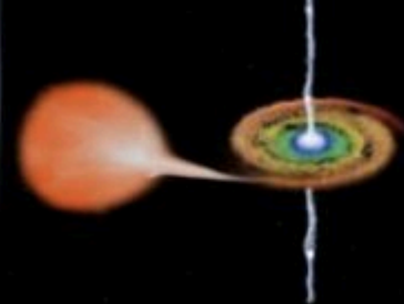
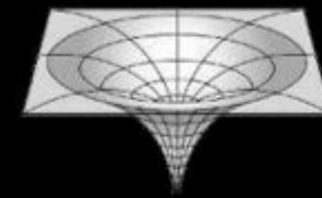


# Gamma and CR Experiments

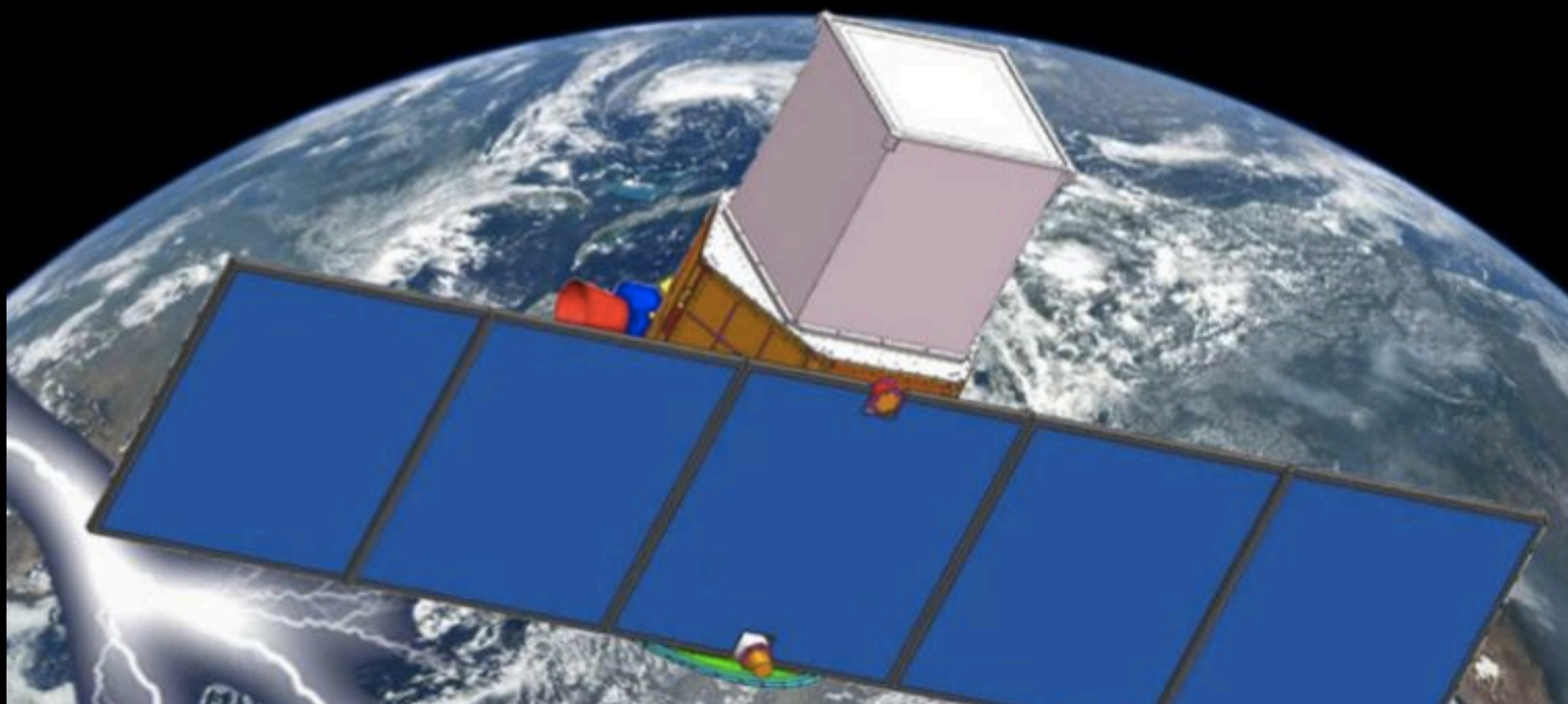


# Gamma and CR Experiments





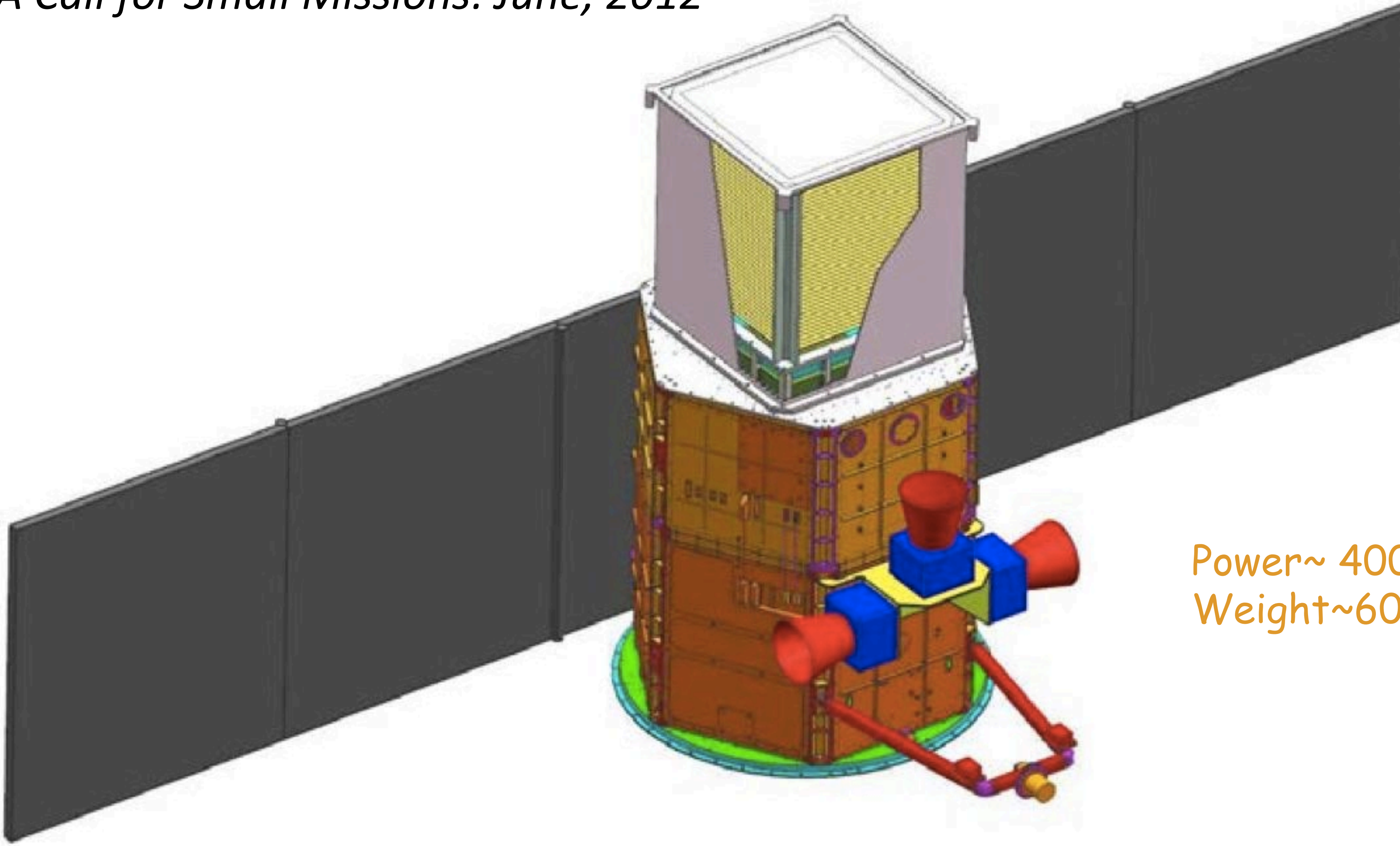
# Gamma-Light



http://people.roma2.infn.it/~morselli/Morselli_Scineghe_rr2.pdf

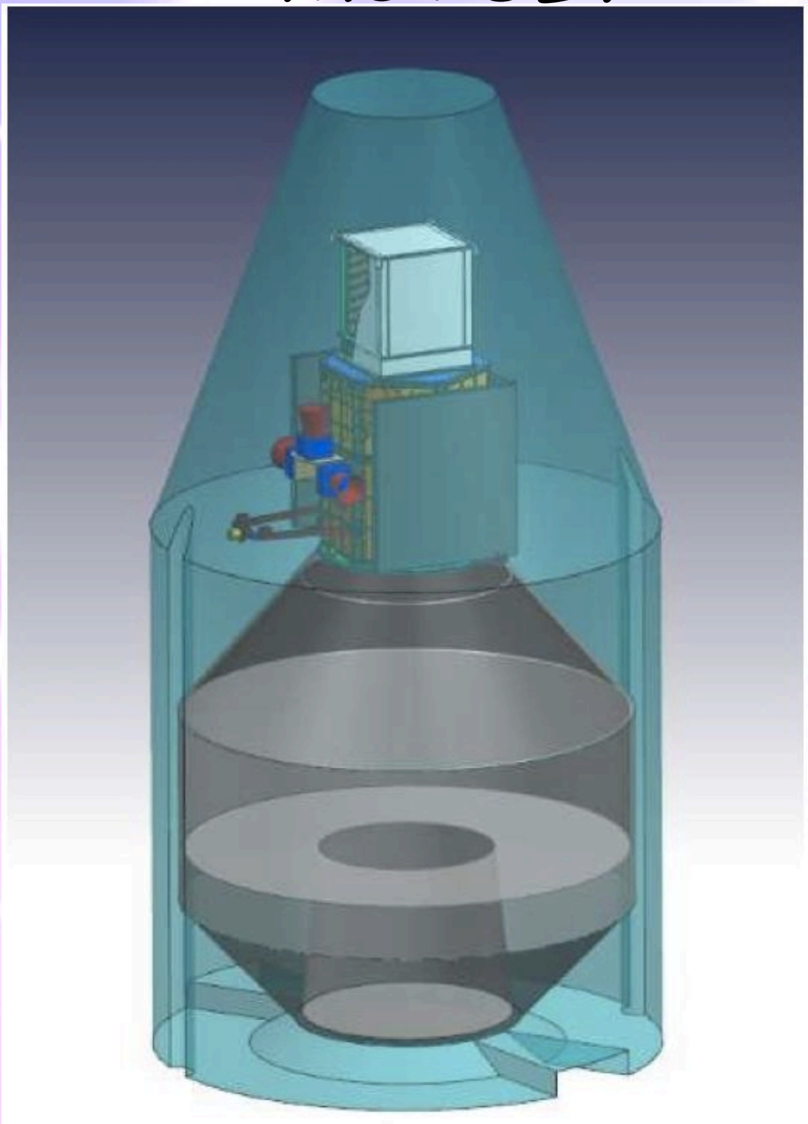
# Gamma-light payload

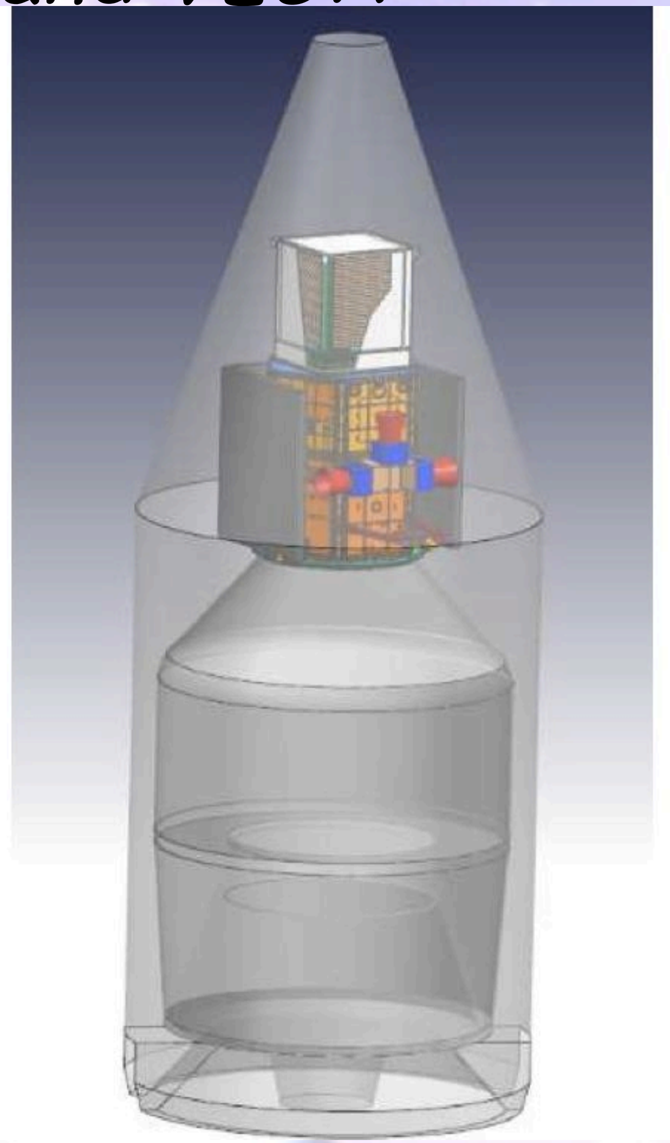
*ESA Call for Small Missions: June, 2012*



Power~ 400 W
Weight~600 Kg

# GAMMA-LIGHT satellite launch configurations for the PSLV and VEGA





- a companion satellite similar to G-LIGHT can be accomodated.

# Gamma-light scheme

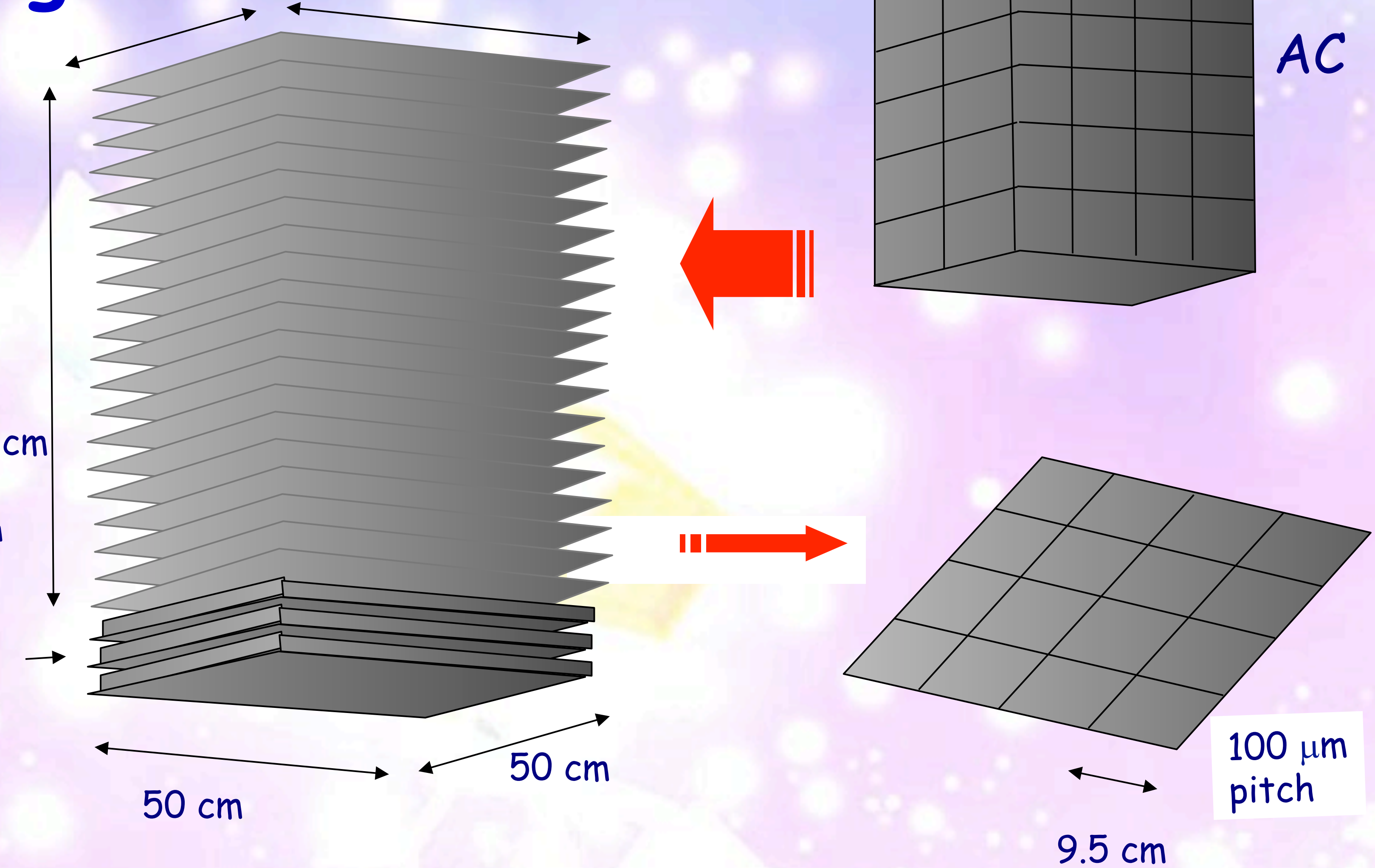
40+1 x-y planes
100 $\mu$m pitch
each
~0.025 $X_0$

Tot~ 1 $X_0$

54.7 cm

height of a plane 1.3 cm

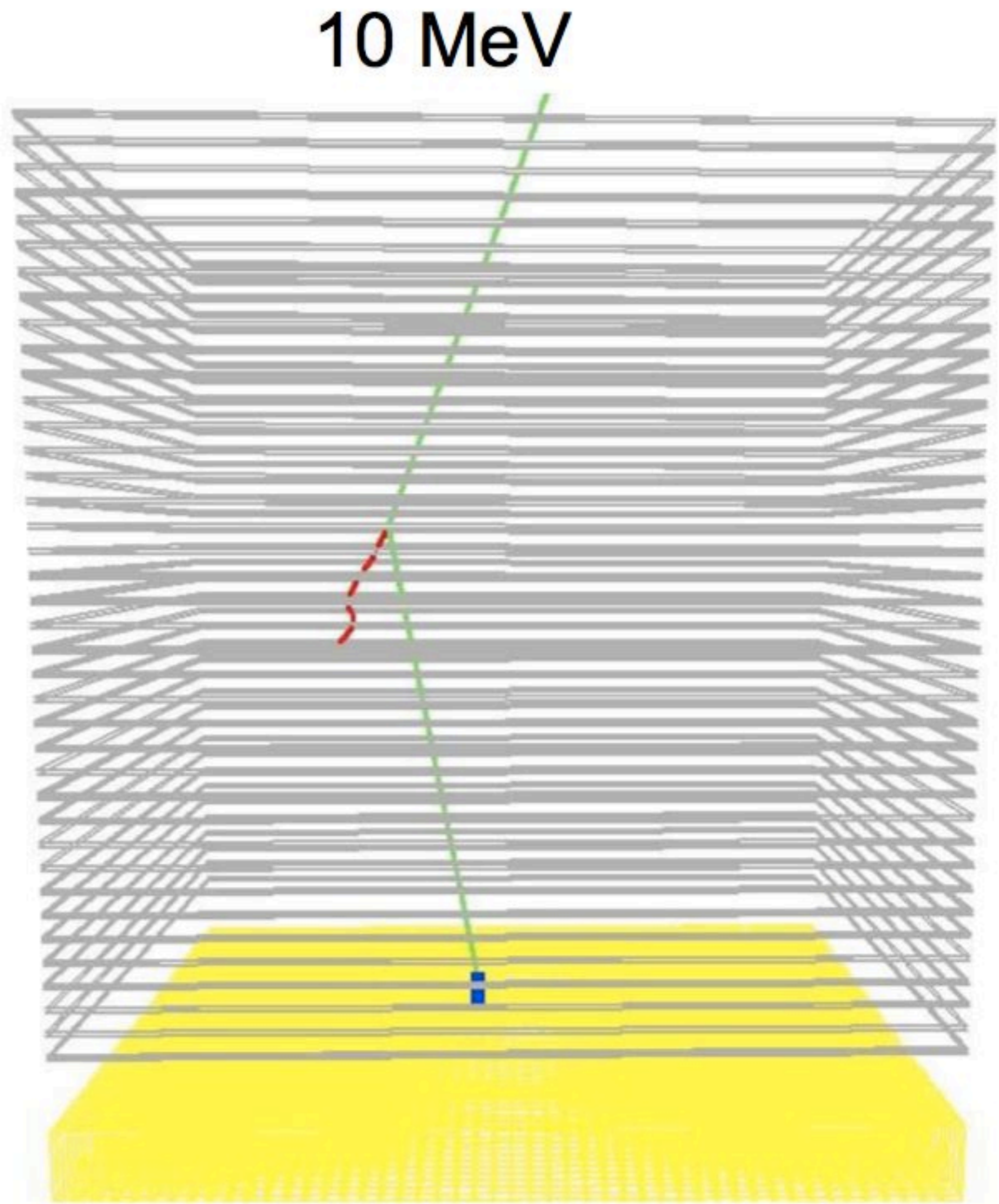
2 Xo Calorimiter



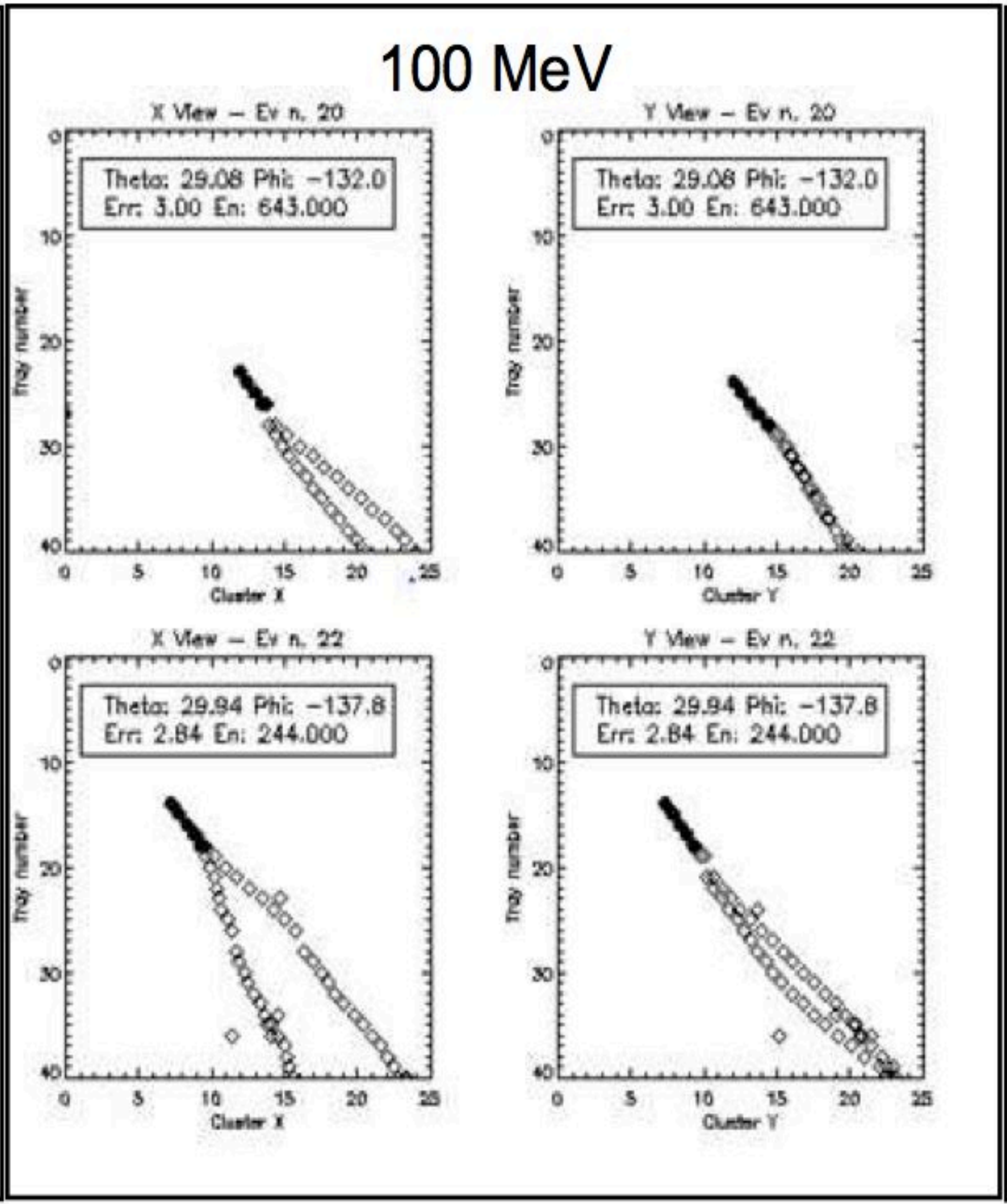

*Compton scattering **and** pair production telescope*

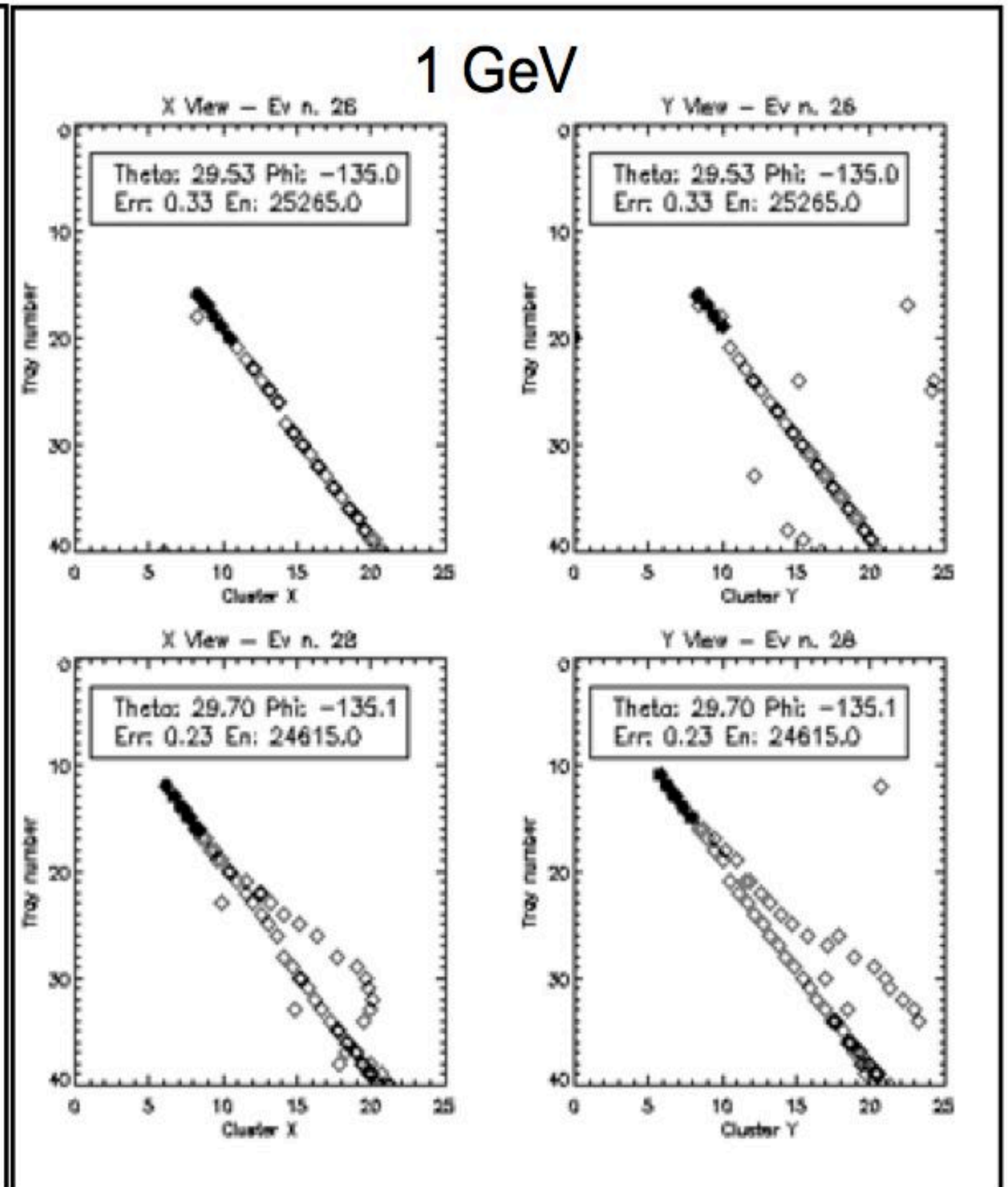
# Gamma-LIGHT Simulation

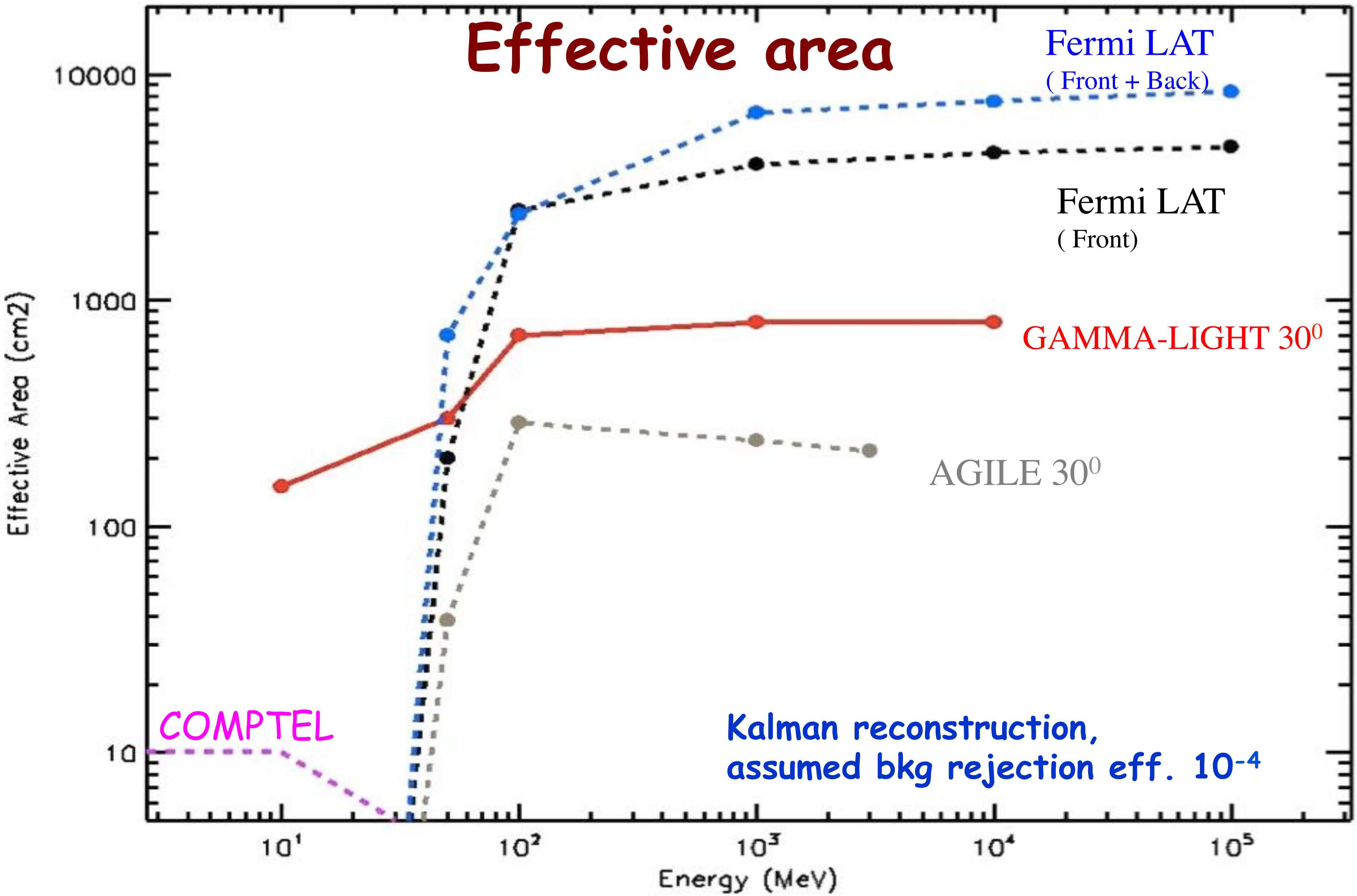
*Compton interaction of a 10 MeV photon producing a low-energy single-track electron, and depositing energy in the Calorimeter for a $30^0$ incidence*



# Gamma-light *Simulation*

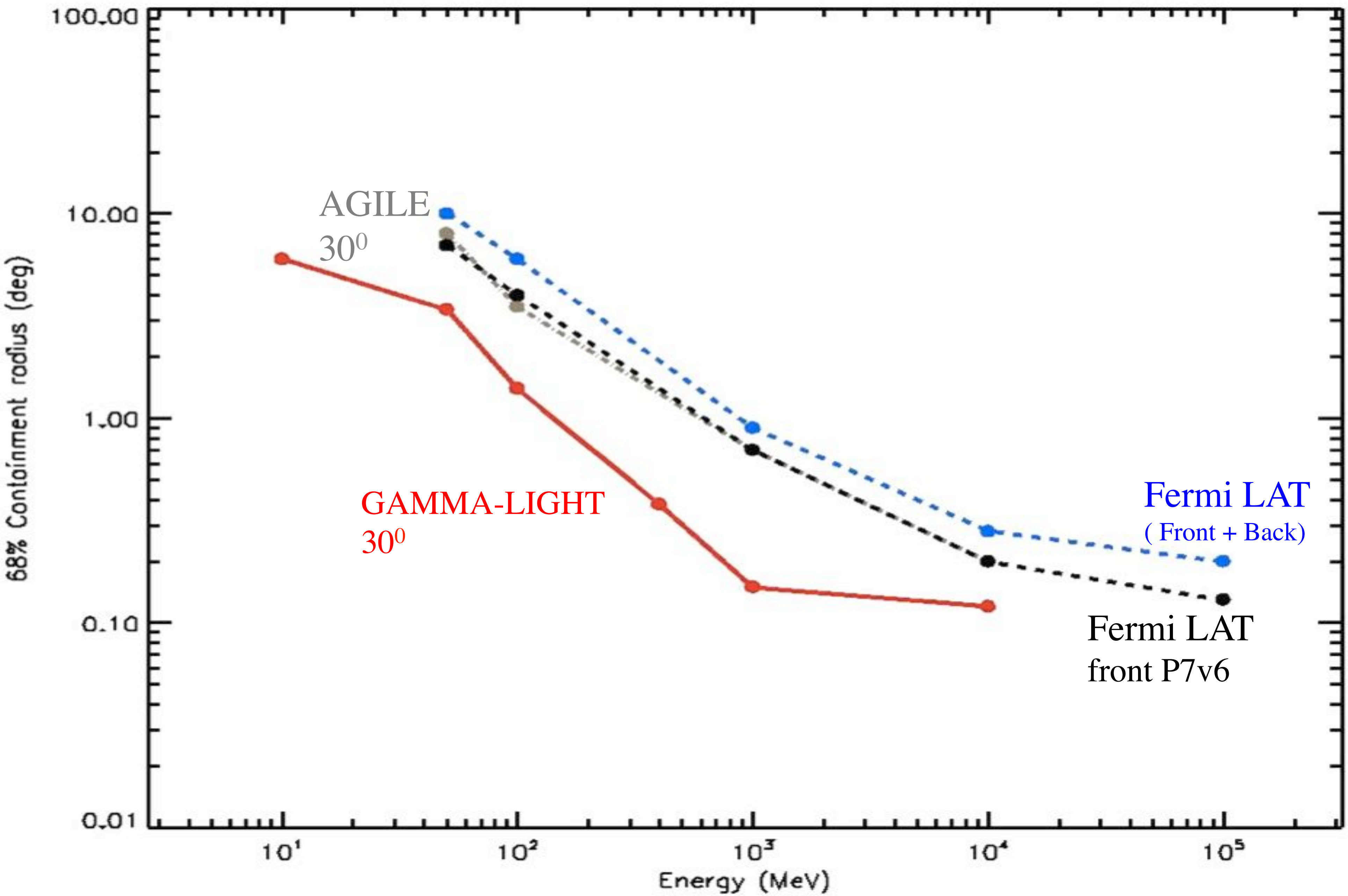


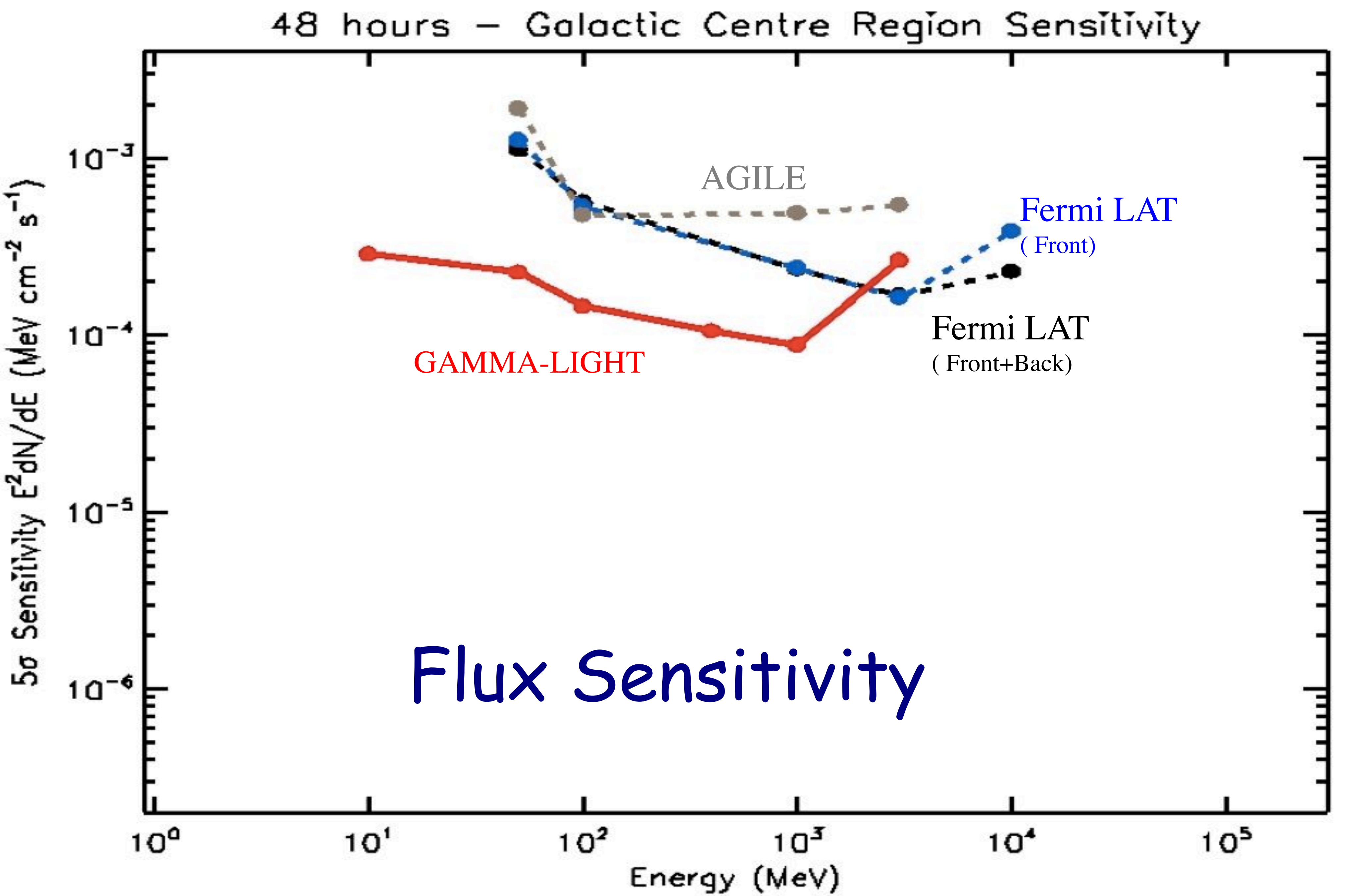






A.Morselli et al. , Nuclear Physics B Proc. Supp. 239–240 (2013) 193-198

# PSF (68% containment radius)




48 hours – Galactic Centre Region Sensitivity
5σ Sensitivity E²dN/dE (MeV cm⁻² s⁻¹)
Energy (MeV)
AGILE
Fermi LAT
( Front)
Fermi LAT
( Front+Back)
GAMMA-LIGHT
Flux Sensitivity

# Astrophysics Objectives of GAMMA-LIGHT

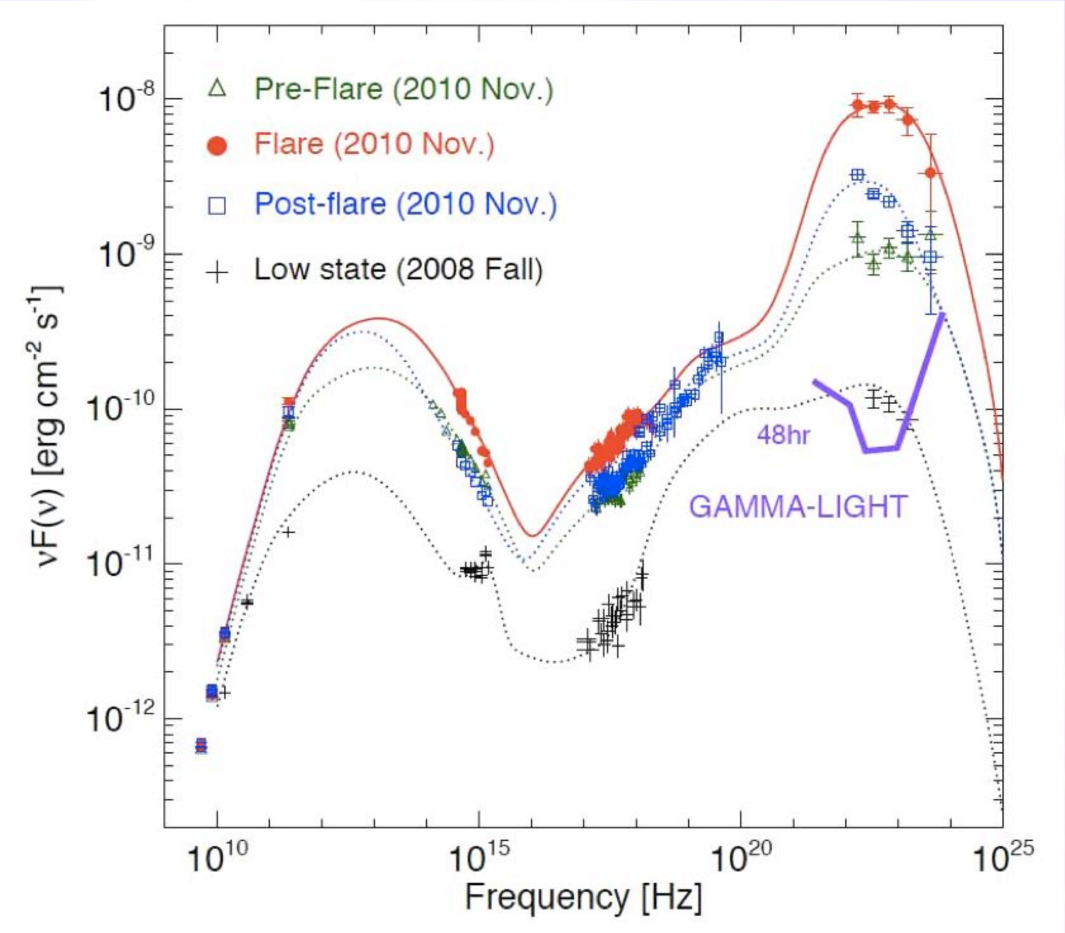
- 1. Search of Dark Matter gamma-ray signatures in the Galaxy and in particular in the Galactic Center region;
- 2. Resolving the Galactic Center region in gamma-rays: the central BH region, GeV and TeV sources, nebulae, compact sources, SNRs;
- 3. Resolving the diffuse emission in the Galactic plane, relation with cosmic-ray propagation, star forming regions in the Galactic plane; extending the cosmic-ray propagation and emission properties of the "Fermi bubbles" to the lowest energies below 100 MeV;
- 4. Resolving spatially and spectrally SNRs and addressing the origin and propagation of cosmic- rays;
- 5. Polarization studies of gamma-ray sources;

# Astrophysics Objectives of GAMMA-LIGHT (cont.)

- 6. Detection of soft gamma-ray pulsars in the range 10-100 MeV, and pulsar wind nebulae studies;
- 7. Detection of compact objects, microquasars, relativistic jets in the range 10 MeV - 1 GeV resolving the issue of hadronic vs. leptonic jets for a variety of sources (e.g., Cyg X-3);
- 8. Detection and localization of transients and exotic sources with much improved sensitivity;detection of Crab Nebula gamma-ray flares with excellent sensitivity down to 10 MeV;
- 9. Blazar studies down to 10 MeV, excellent positioning resolving source confusion;
- 10. GRB excellent capability in the range 10 MeV - 5 GeV; sub-millisecond timing capability in the range 0.3-100 MeV.

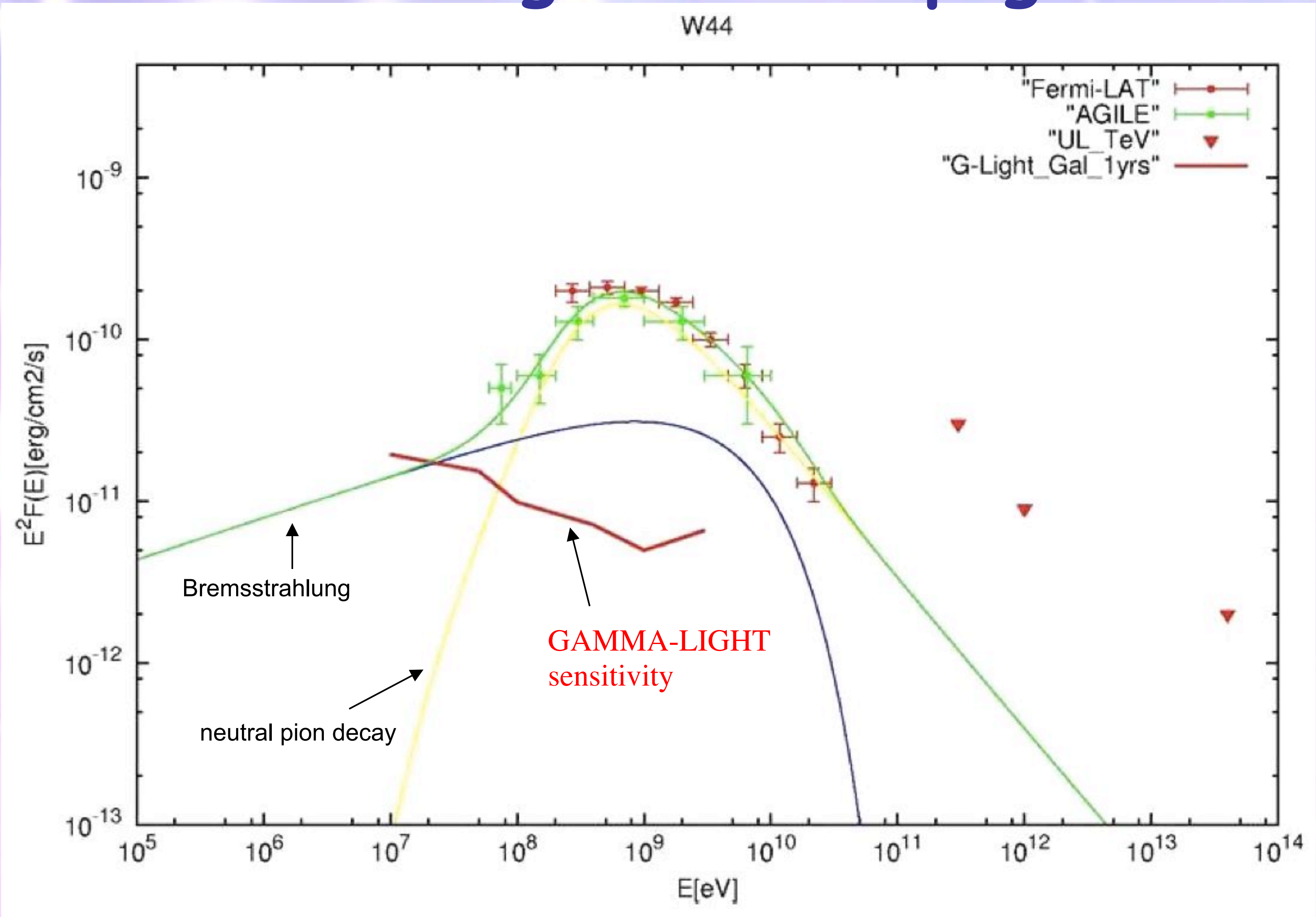
# Extragalactic Sources, Blazars, MeV Blazars

## *Multi-epoch SEDs of the FSRQ 3C454.3*



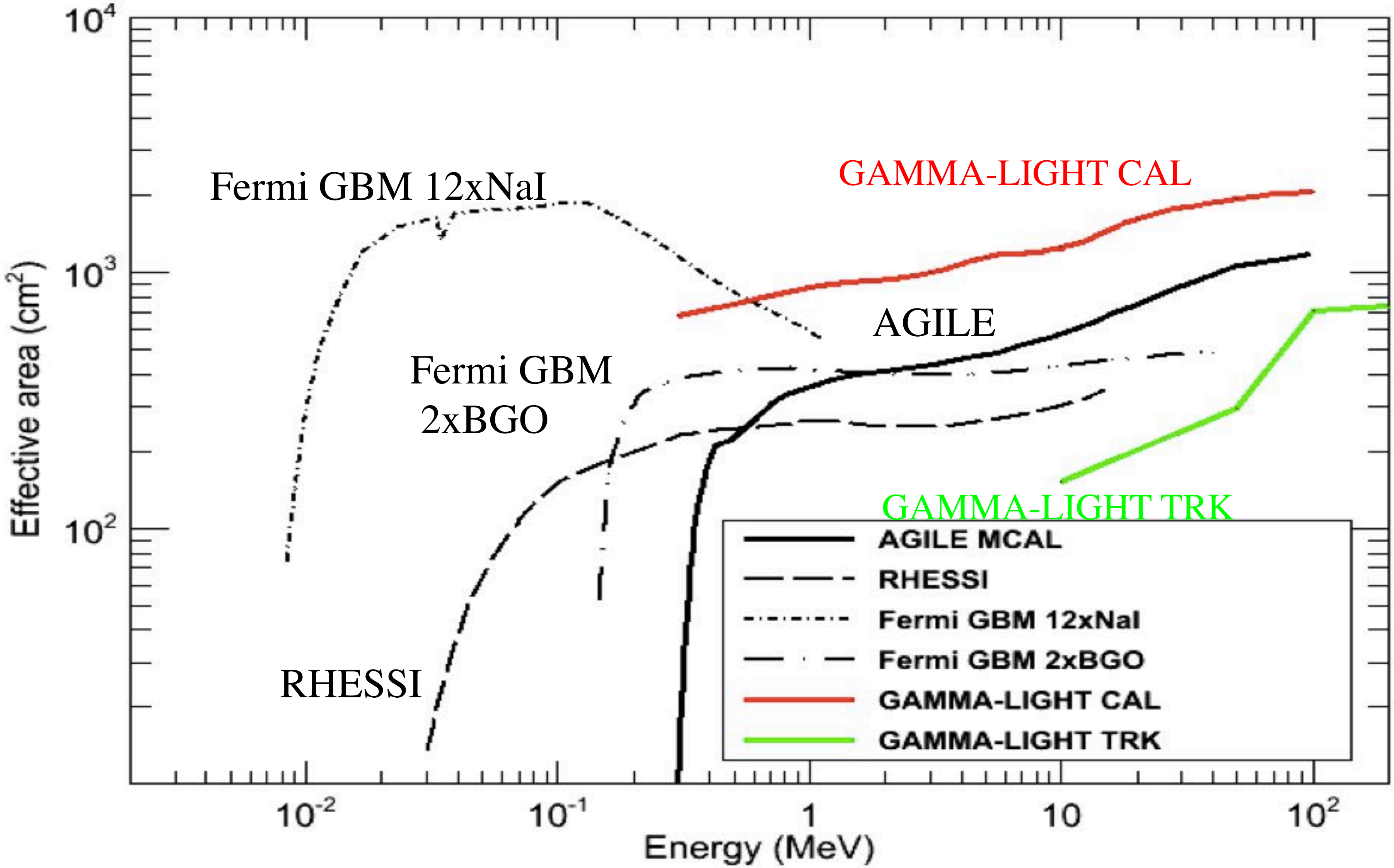

*G-LIGHT will allow us to investigate daily (or sub-daily) SEDs during gamma-ray super- flares. The 5-sigma G-LIGHT differential sensitivity (purple line) is computed for an integration time of 48 hours*

# SNRs and the Origin and Propagation of CRs




- *gamma-ray spectrum of SNRs W44. The red curve shows the expected GAMMA-LIGHT sensitivity for a 1-year effective time integration.*

# Earth Studies Objectives of GAMMA-LIGHT: Terrestrial Gamma-Ray Flashes



# Gamma-400

Approved mission by ROSCOSMOS

Scientific payload mass 4100 kg (rocket changed from Zenith to Proton-M) Power budget 2000 W – Telemetry downlink capability 100 GB/day – Lifetime ~ 10 yrs

Originally devoted Gamma rays study (30 GeV – 1 TeV) & high-energy electrons and positrons.

On going study for a revision of the project

- Launch foreseen by end 2018 unique opportunity to configure the apparatus for :

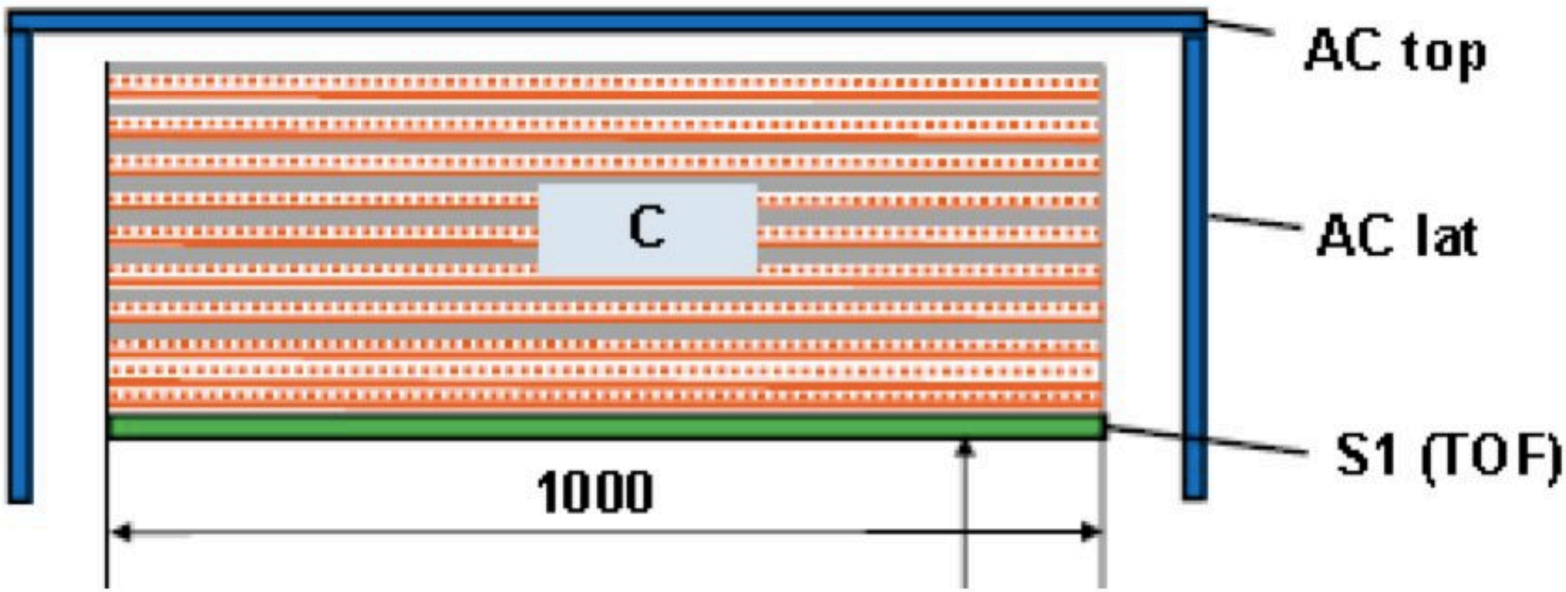
- gamma-rays from 100 MeV < up to 300 GeV
- proton & nuclei in cosmic-rays up to the "knee"
- electrons/positrons beyond TeV energy range

# GAMMA-400: steps during 2012/13

- Definition through MC simulations of the best configuration for a dual instrument for photons (30 MeV - > 300 GeV) and cosmic rays (electrons > 1 TeV and high- energy cosmic-ray nuclei, p and He spectra close to the "knee" region (1014 – 1015 eV)
- ⇒ **GAMMA-400/E2**;
- Agreement on a jointly defined apparatus that, taking into account the currently available resources, optimizes the scientific performance and significantly improves over the previous B1 version ⇒ **GAMMA-400/B2**
- Development, construction and test of a prototype of homogeneous calorimeter with 130 CsI(Tl) cubic crystals.
- Agreement on the preparation (in progress) of a MoU between Russian Agencies and INFN for the Russian funding of the design and construction of the Converter/Tracker by INFN:
- – 10 planes (20 views, 10X and 10Y), planar dimensions ~ 1 m2, 2000 silicon strip detectors

# GAMMA-400

## B2 detectors: Converter/Tracker




- 8 layers W $0.8X_0$ + 8 planes Si (x,y)
- 2 layers of Si (x,y), no W

# GAMMA-400

## E2 vs. B2 Trackers

| Parameter | B2 | E1 |
|---|---|---|
| N. towers | 4 | 4 |
| N. Planes | 10 | 25 |
| Converter (W) thickness ($X_0$) | 0.1 | 0.03 |
| Plane spacing (cm) | 3.5 | 2.8-3.0 (TBD) |
| Si sensor dim. (cm) | 9.7x9.7 | 9.7x9.7 |
| Implant strip pitch (μm) | 80 or 120 | 80 or 120 |
| Readout strip pitch (μm) | 240 | 240 |
| Readout channels/plane | 15360 | 15360 |
| Total readout channels | 153600 | 384000 |
| Total Silicon detector number | 2000 | 5000 |

the ideal detector will be Gamma-Light on top of Gamma-400

# Gamma-400 cont.

The collaboration

- Firenze, Pisa, Pavia, Roma2, Trieste =>=>=> PAMELA FERMI AGILE community

- At present:
  Russian, Italian, US collaboration
- Expressed interest from France, Spain and Sweden (KTH & OKC theorists and experimentalists)
- Current scientific interest from the TeV community ( CTA)
- Ongoing contacts with the multi-wavelength community

- Open to possible contribution and collaborations

# Gamma - 400 Orbit

The GAMMA-400 space observatory will be installed on the Navigator space service platform produced by Lavochkin Research and Production Association.

Two variants of orbit are possible:

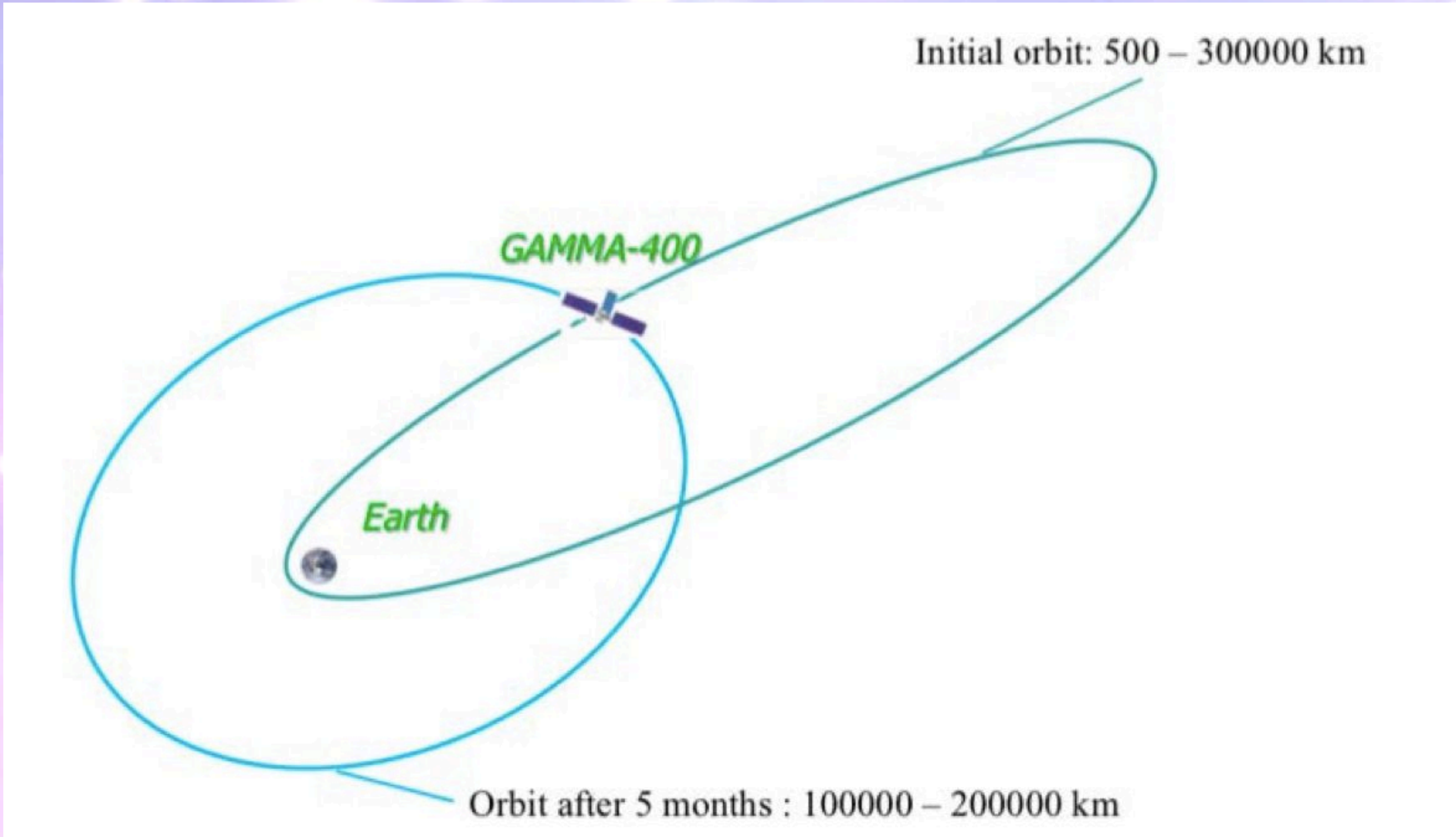
- Lagrange point L2
- high-elliptical orbit.

The initial high-elliptical orbital parameters are:
an apogee of 300 000 km, a perigee of 500 km, and an inclination of 51.8 deg

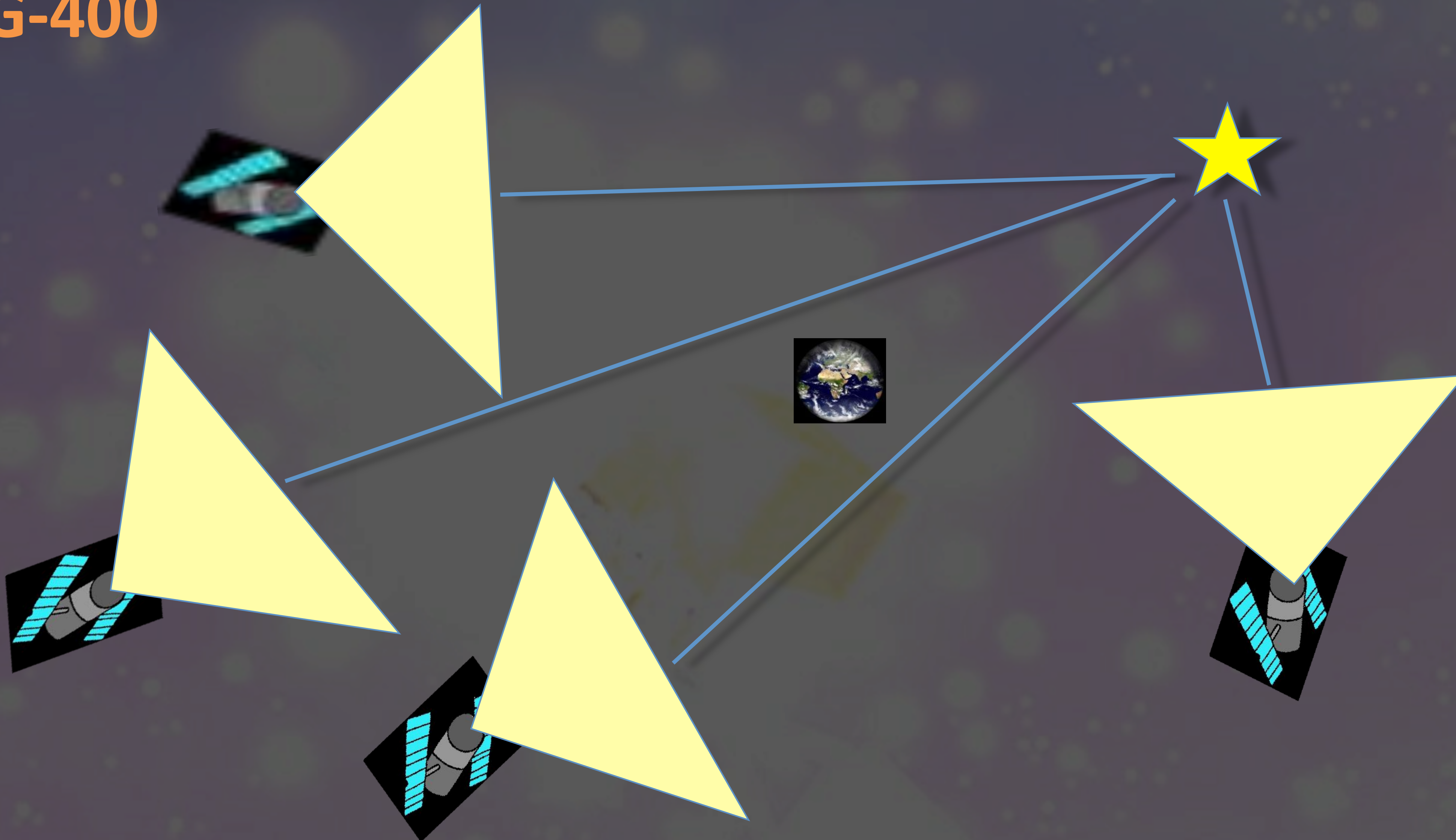
The launch of the GAMMA-400 space observatory is planned in 2018.

The expected mission duration is longer than 7 years

# Gamma-400 Orbit



# G-400



NEWS & ANALYSIS

***Science*, 20 May 2011**

SPACE SCIENCE

# Chinese Academy Takes Space Under Its Wing

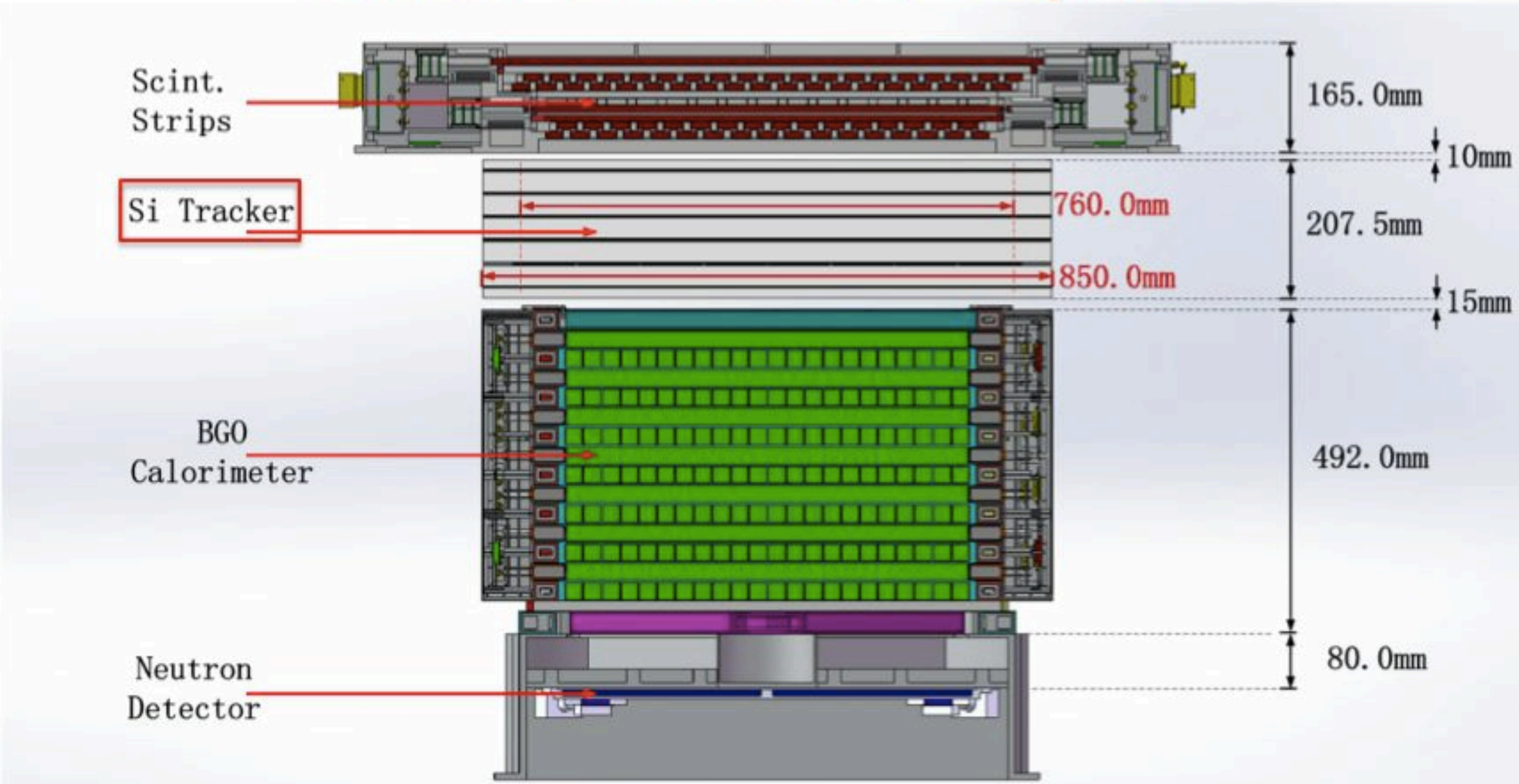
**LOFTY AMBITIONS**

| Mission | Chief scientist | Goals | Estimated launch |
|---|---|---|---|
| HXMT | Li Tipei, CAS Institute of High Energy Physics and Tsinghua University | Survey of x-ray sources; detailed observations of known objects | 2014 |
| Shijian-10 | Hu Wenrui, CAS Institute of Mechanics | Study physical and biological systems in microgravity and strong radiation environment | Early 2015 |
| KuaFu Project | William Liu, Canadian Space Agency and CAS Center for Space Science and Applied Research | Study solar influence on space weather | Mid-2015 |
| Dark Matter Satellite | Chang Jin, CAS Purple Mountain Observatory | Search for dark matter; study cosmic ray acceleration | Late 2015 |
| Quantum Science Satellite | Pan Jianwei, University of Science and Technology of China | Quantum key distribution for secure communication; long-distance quantum entanglement | 2016 |

**Strategic Priority Research Program in Space Science**

***Dark Matter Particle Explorer Satellite***

# DAMPE Detector Layout



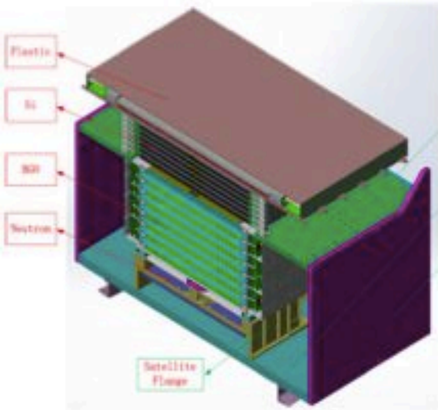

- Scintillator strips, Silicon tracker, BGO calorimeter, neutron detector
- Combine a γ-ray space telescope with a deep imaging calorimeter
  - Silicon tracker/converter + BGO imaging calorimeter
    - Total ~33 $X_0$ → deepest detector in space

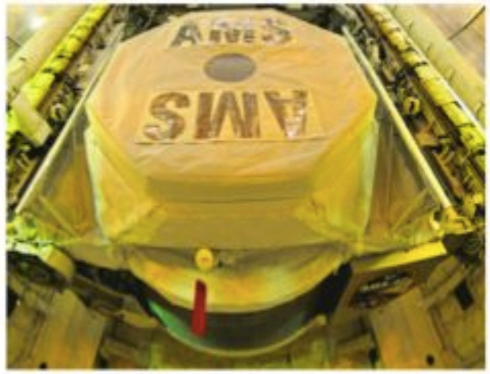
# DAMPE Tracker Components

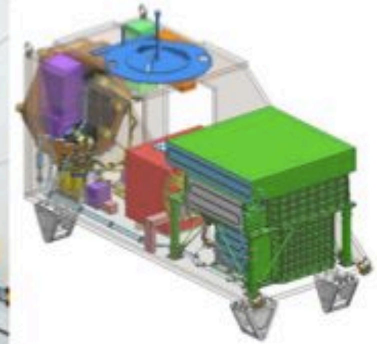
- Silicon sensor (Hamamatsu)
  - use AGILE specification
- FE ASIC (Gamma Medica-Ideas)
  - use updated version of the AMS-02 ASICs, already available thanks to INFN Perugia R&D
- Electronics (INFN Pg, DPNC for specs)
  - use updated version of the AMS readout and power electronics
- Silicon ladder (INFN Pg +DPNC)
  - similar to AMS-02
- Silicon plane and tracker assembly (DPNC + INFN Pg)
  - based on AMS-02 experience

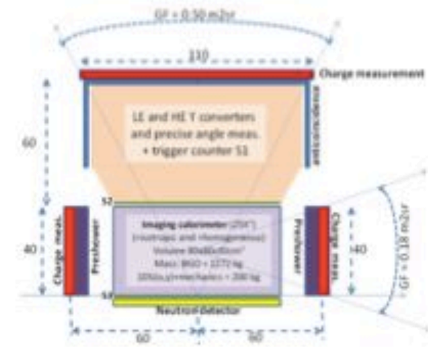
Proven technologies and profiting from previous experiences!

# DAMPE and other detectors



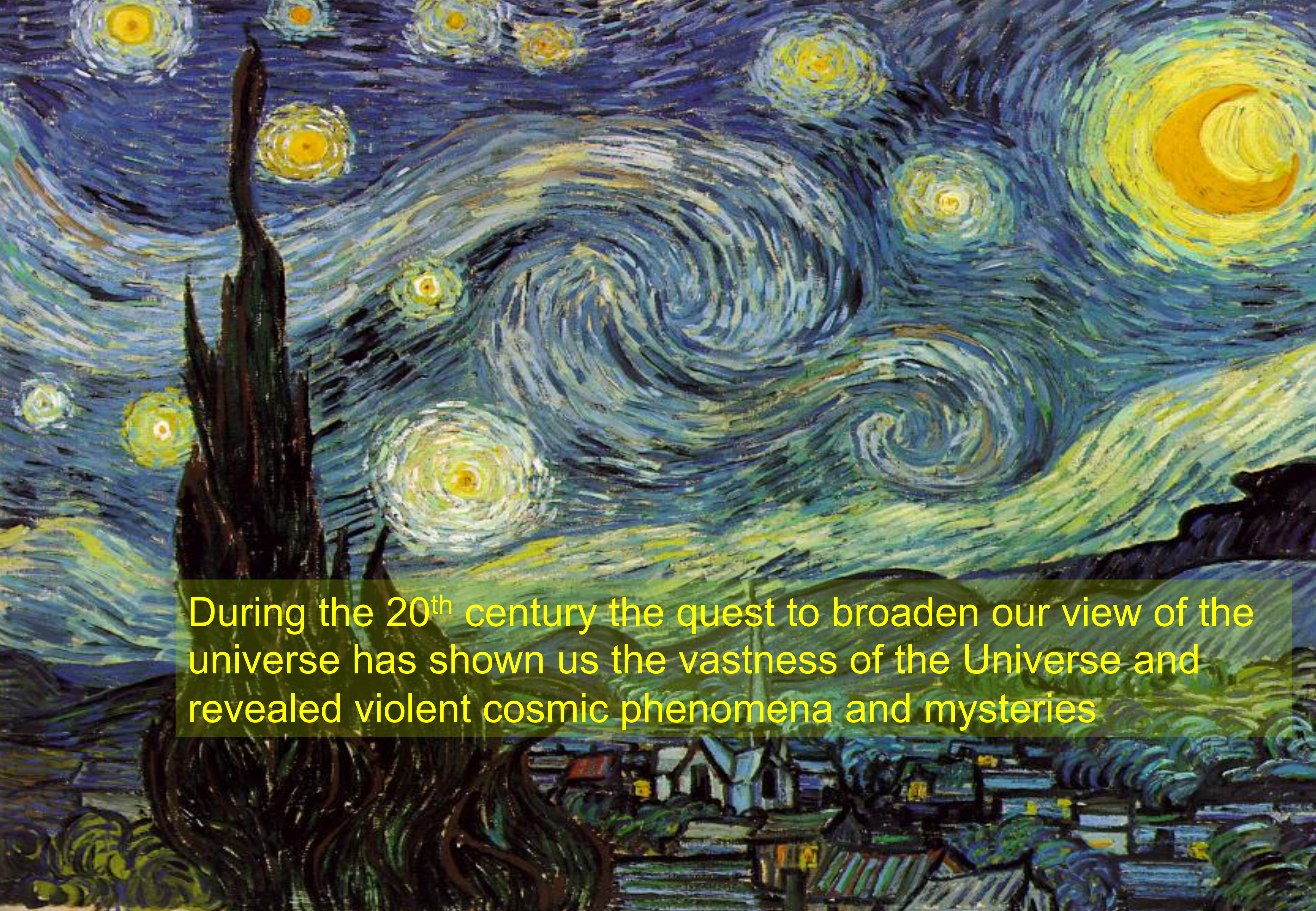






| | DAMPE | AMS-02 | Fermi LAT | CALET | GAMMA-400 |
|---|---|---|---|---|---|
| Energy range (GeV) | 5 - $10^4$ | 0.1 - $10^3$ | 0.02 - 300 | 1 - $10^3$ | 0.1 – 3 $10^3$ |
| e/γ Energy res.@100 GeV (%) | 1.5 | 3 | 10 | 2 | 1 |
| e/γ Angular res.@100 GeV (°) | 0.1 | 0.3 | 0.1 | 0.1 | 0.01 |
| e/p discrimination | $10^5$ | $10^5$ - $10^6$ | $10^3$ | $10^5$ | $10^6$ |
| Calorimeter thickness ($X_0$) | 31 | 17 | 8.6 | 30 | 25 |
| Geometrical accep. ($m^2sr$) | 0.4 | 0.09 | 1 | 0.12 | 0.5 |


For long time we saw the sky tranquil and calm



During the $20^{th}$ century the quest to broaden our view of the universe has shown us the vastness of the Universe and revealed violent cosmic phenomena and mysteries


The future?


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
thank you for the attention