Astroparticle Physics from Space

status of current research

1. Sources of
   High Energy Particles

2. DARK MATTER

Paolo Lipari
INFN-SPACE/3

LNF 18th september 2013

Victor Hess

101 years of **Cosmic Rays**

August 1912
First "glimpse" of a
a "new world"

"High Energy Universe"

The first questions:

1. What is the nature
of the High Energy “Radiation” ?

[Relativistic particles,
with extraordinarily broad Energy range]

2. What are the properties
of these particles ?

[Birth and development of particle physics]

New questions:

Where (and when), and how
are the relativistic particles produced ?

How do they propagate from their sources
to the Earth ?

These questions remain (to a very large extent) open
and costitute fundamental elements of
“AstroParticle Physics”

We now know about the existence of

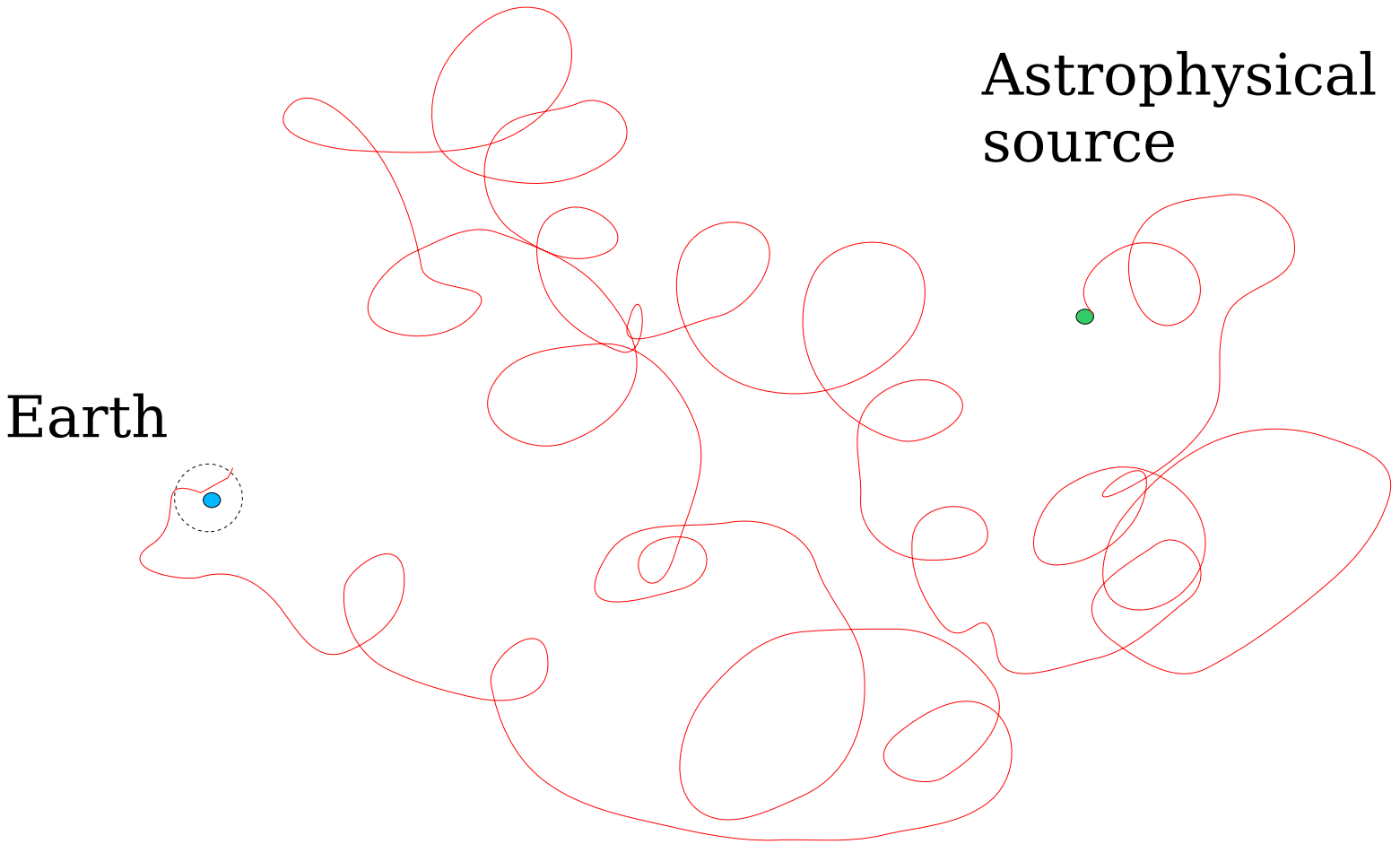
ASTROPHYSICAL ACCELERATORS

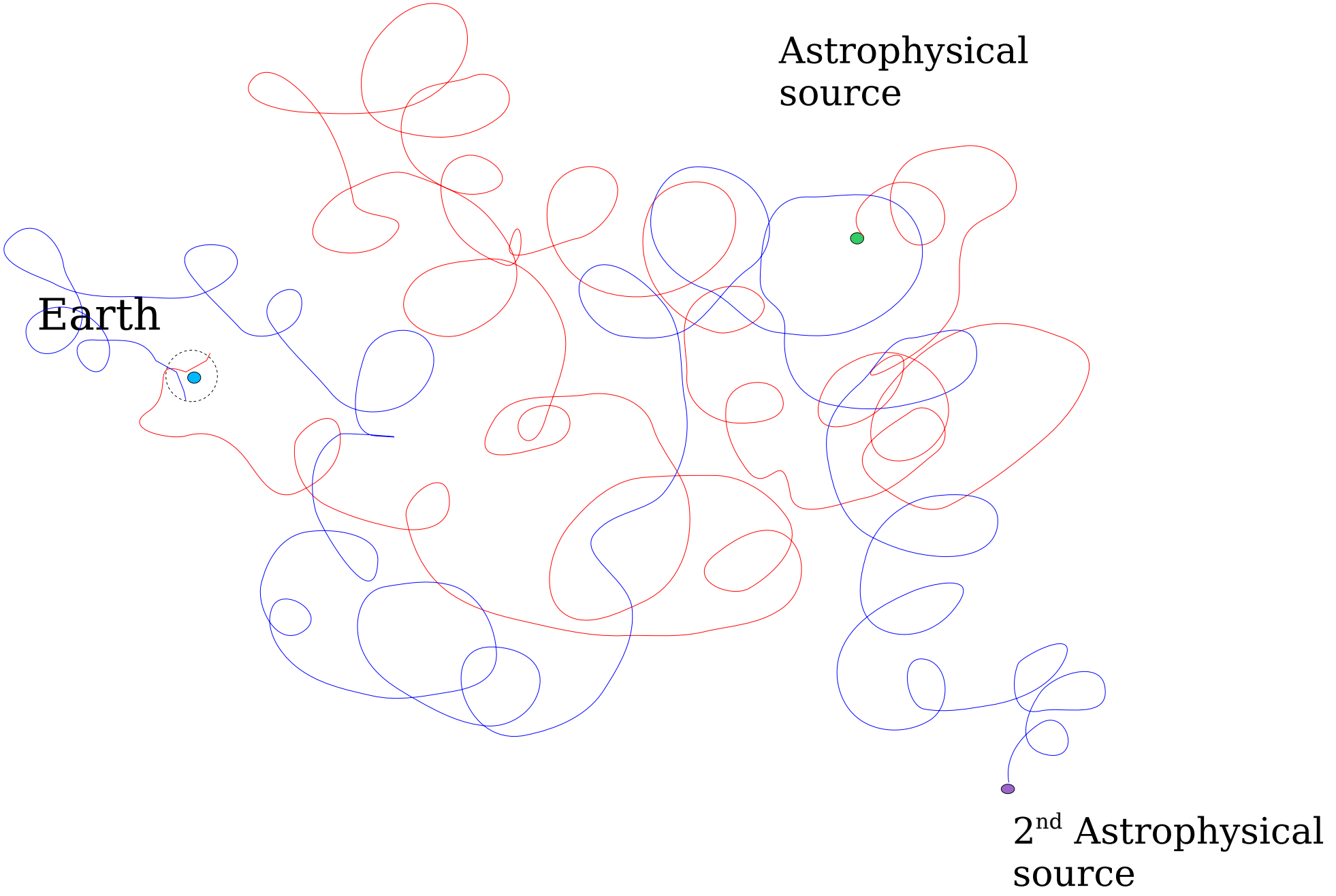
The most “extreme” environments in the present Universe.
Laboratories to test fundamental laws of Physics

What is the nature and structure of the accelerators ?

What is the mechanism for particle acceleration ?

How particles propagate from the sources to the Earth ?


Astrophysical
source
Earth


Astrophysical source
Earth
2nd Astrophysical source

Flux of Cosmic Rays
Integration over Volume and over time
from sources of an unknown nature and position.

$$n(E, \vec{r}_\odot) = \frac{4\pi}{\beta\, c} \int d\Omega\ \phi(E, \Omega; \vec{r}_\odot)$$

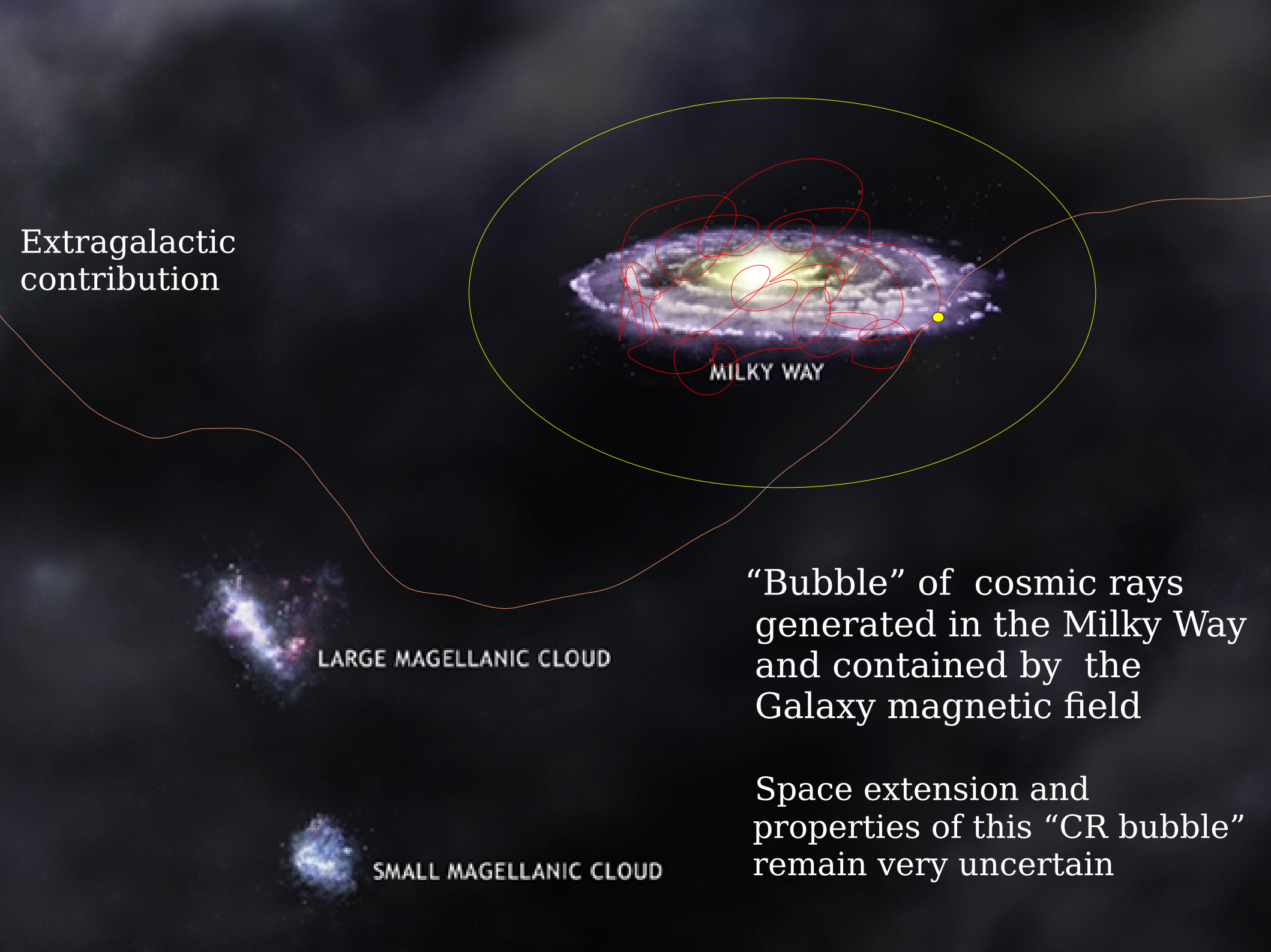
number density of CR

Flux of CR

$$n(E, \vec{r}_\odot, t_{\rm now}) = \int d^3r \int dt \int dE_0\ q(E_0, \vec{r}, t)\ P(\vec{r}_\odot, E,\ \vec{r}, E_0, t)$$

Integration over space and time
[sum over all sources in the Galaxy
and in the universe]

Propagation function
[probability that the particle
is a volume d^3r around the sun


Extragalactic
contribution
MILKY WAY
LARGE MAGELLANIC CLOUD
SMALL MAGELLANIC CLOUD
“Bubble” of cosmic rays
generated in the Milky Way
and contained by the
Galaxy magnetic field
Space extension and
properties of this “CR bubble”
remain very uncertain

Relativistic Particles from other sources:

Dark Matter annihilation (or decay).

$$\chi + \overline{\chi} \rightarrow \text{secondaries}$$

$$\chi(\overline{\chi}) \rightarrow \text{secondaries}$$

$$\chi + \chi \rightarrow e^+ + \overline{p} + \gamma + \nu_j + \ldots$$

$$e^- + p + \gamma + \overline{\nu_j} + \ldots$$

Relativistic Particles from other sources:

Dark Matter annihilation (or decay).

$$\chi + \overline{\chi} \rightarrow \text{secondaries}$$

$\chi(\overline{\chi}) \rightarrow$ Excess of rare (anti)-particles in cosmic rays

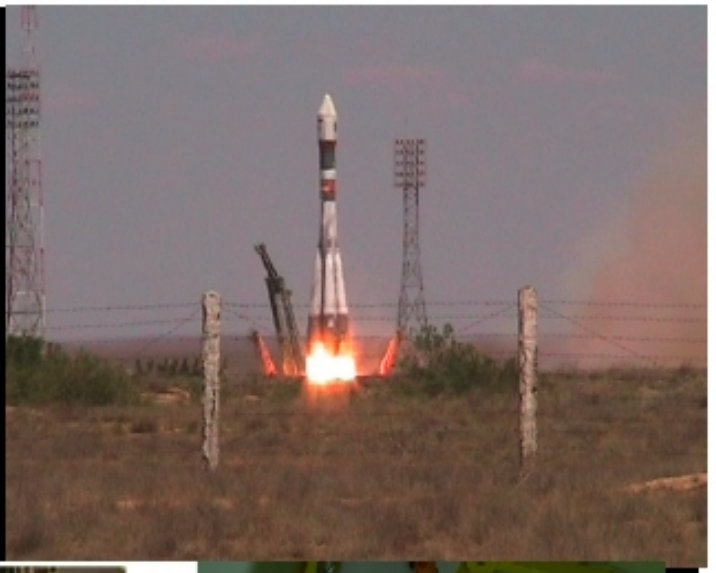
Direct imaging of Annihilation (Decay) sites

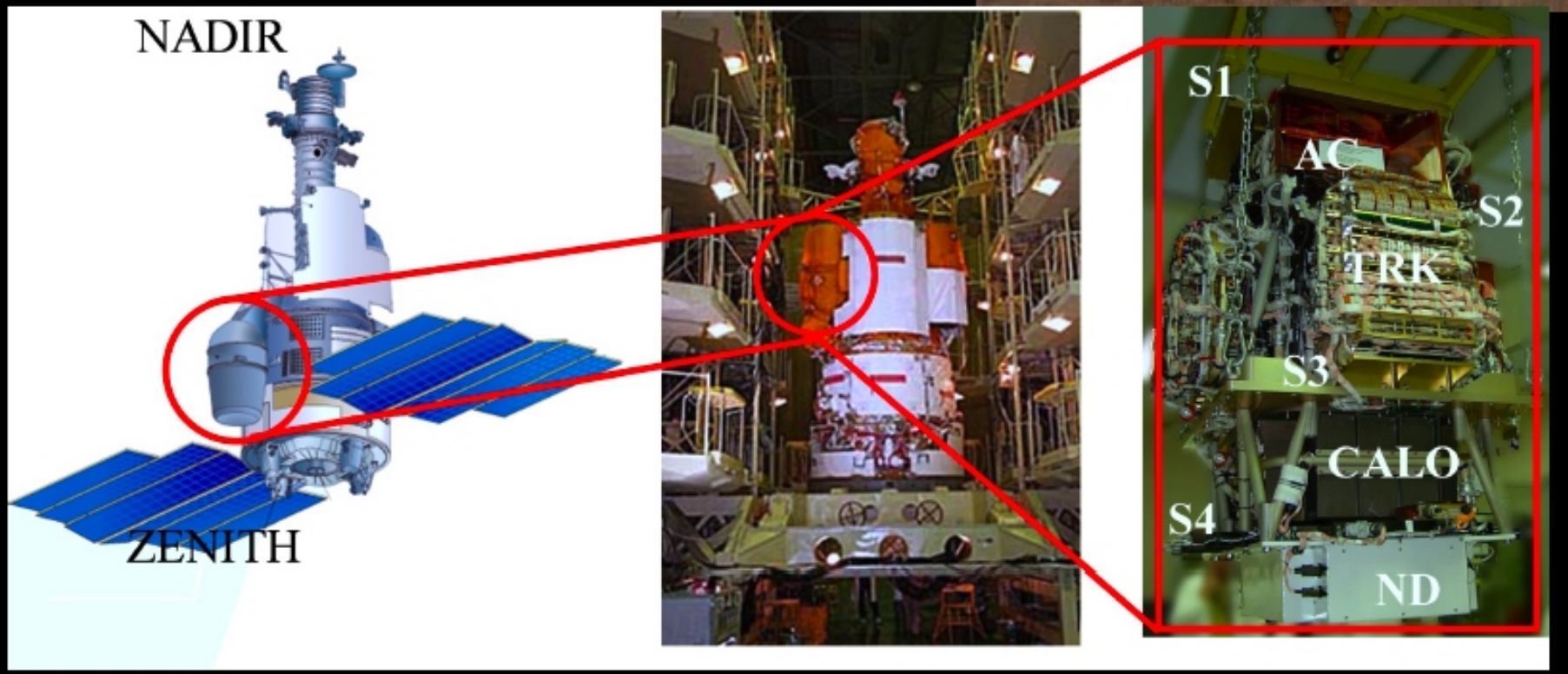
$$\chi + \chi \rightarrow e^+ + \overline{p} + \gamma + \nu_j + \ldots$$

$$e^- + p + \gamma + \overline{\nu_j} + \ldots$$

PAMELA, launched on June 15th 2006 Soyuz-U rocket

7 years out of 3 originally foreseen

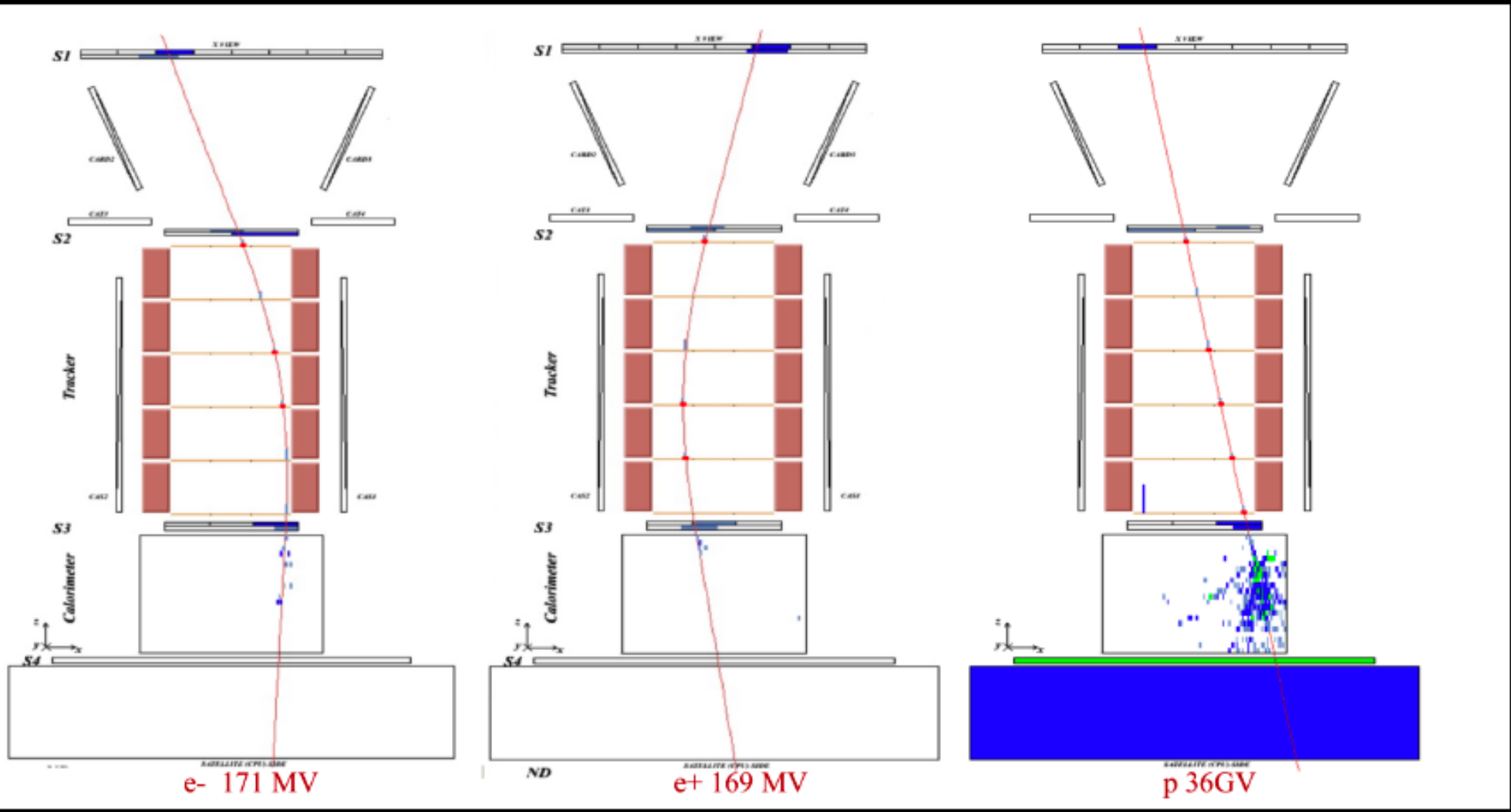


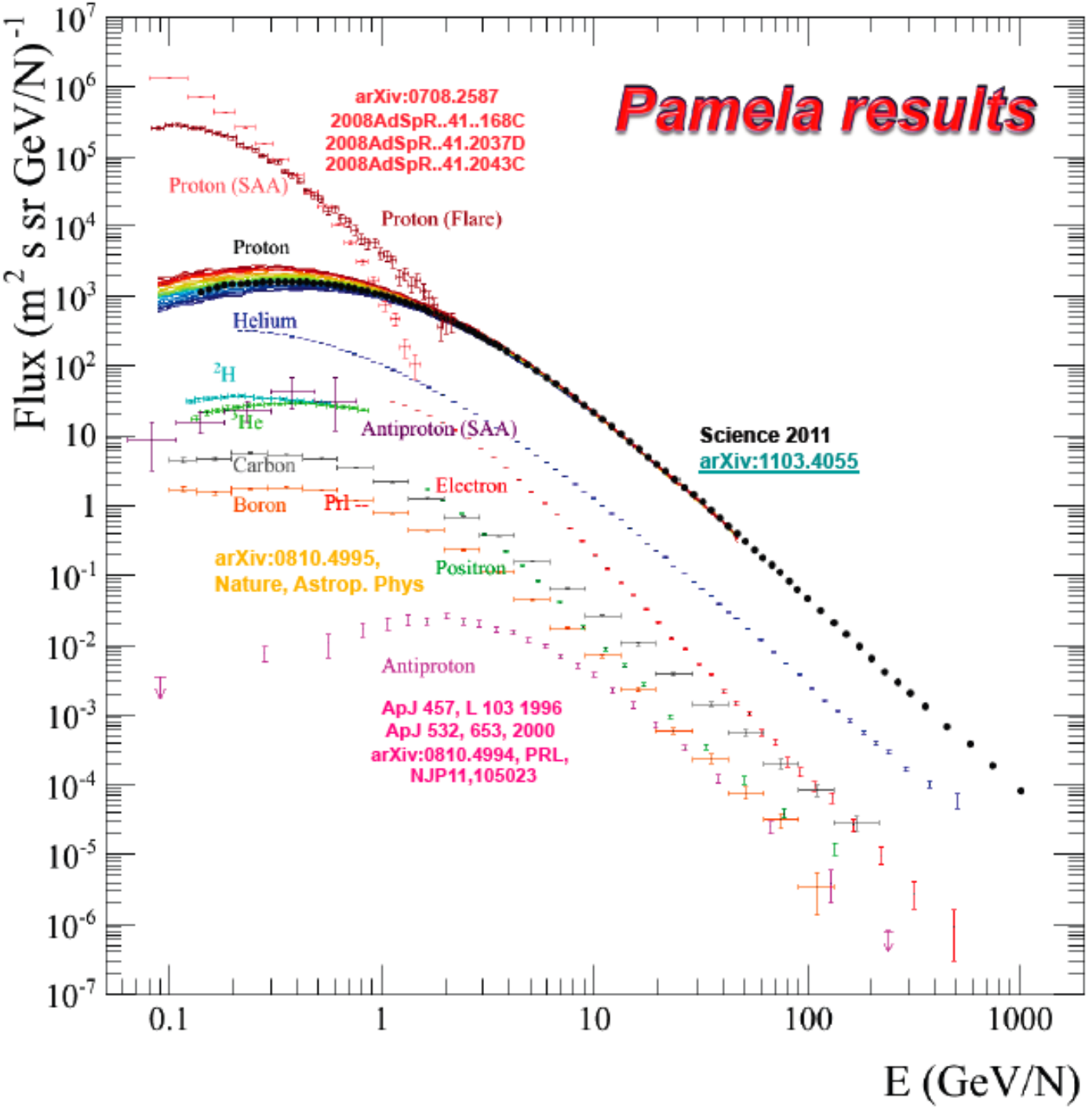


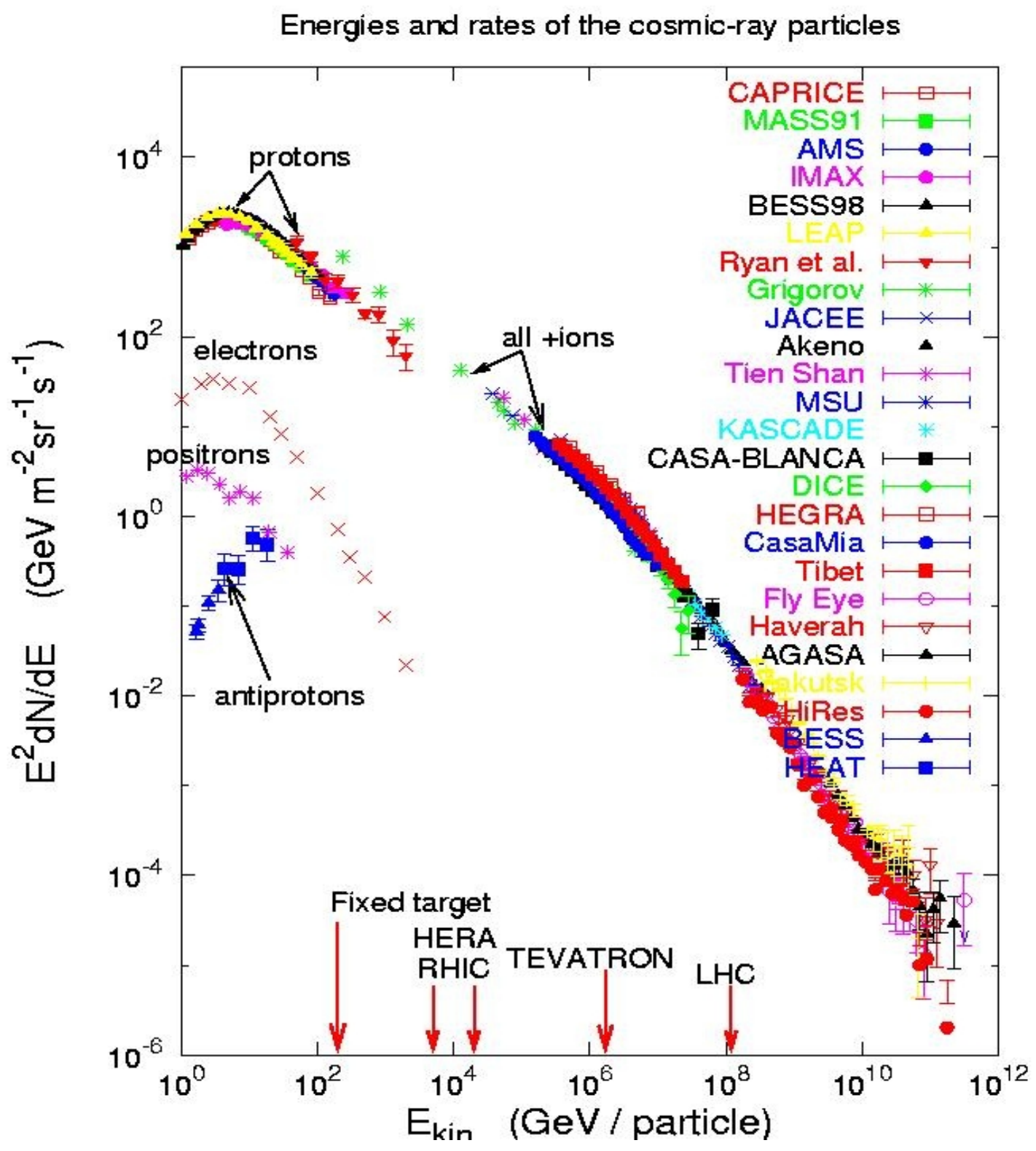
Electrons

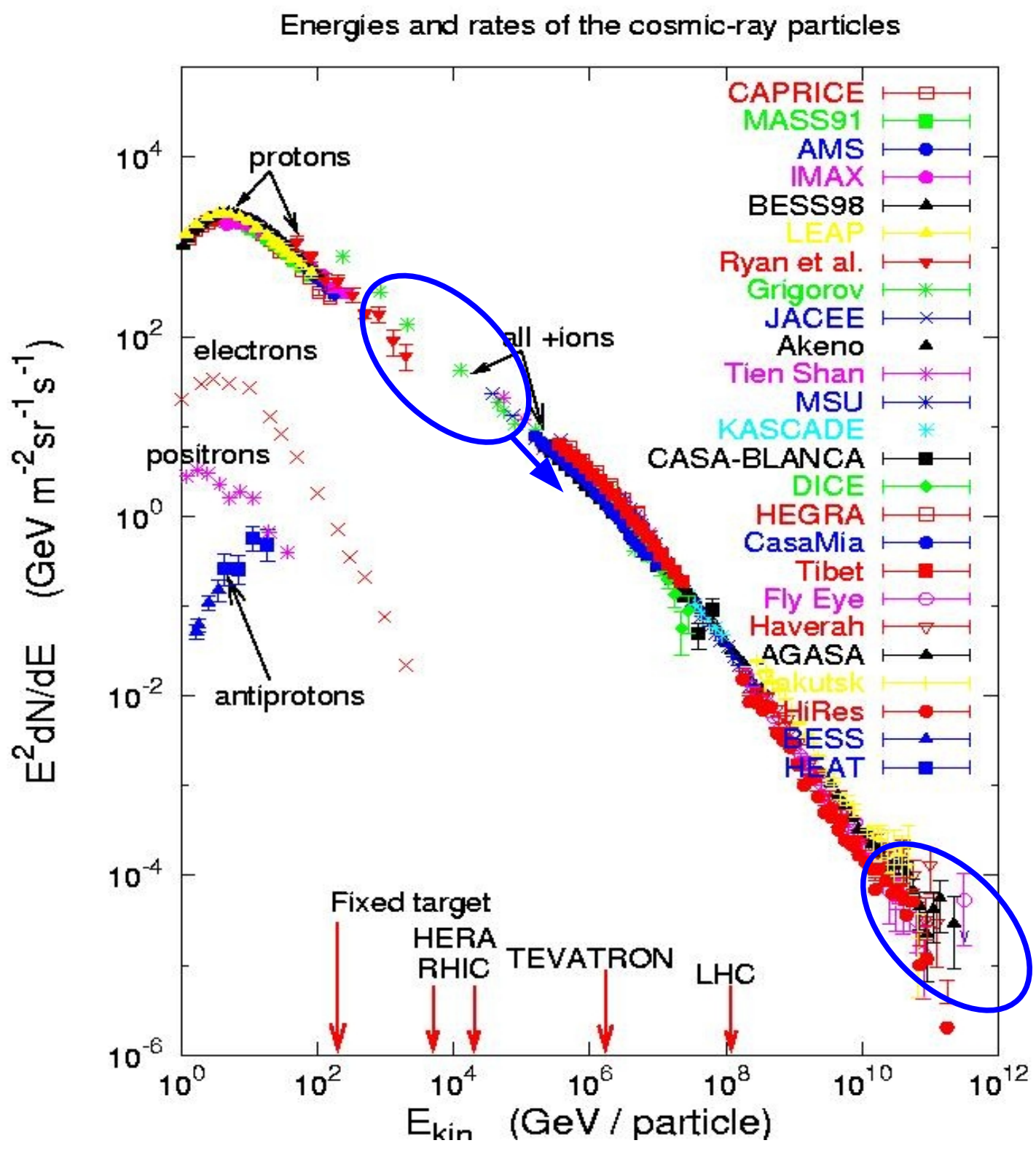
Positrons

Protons




Pamela results
arXiv:0708.2587
2008AdSpR..41..168C
2008AdSpR..41.2037D
2008AdSpR..41.2043C
Proton (SAA)
Proton (Flare)
Proton
Helium
^{2}H
^{3}He
Antiproton (SAA)
Carbon
Boron
Prl
Electron
Positron
arXiv:0810.4995,
Nature, Astrop. Phys
Antiproton
ApJ 457, L 103 1996
ApJ 532, 653, 2000
arXiv:0810.4994, PRL,
NJP11,105023
Science 2011
arXiv:1103.4055
Flux (m^2 s sr GeV/N)$^{-1}$
E (GeV/N)
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0.1
1
10
100
1000


Energies and rates of the cosmic-ray particles
protons
electrons
positrons
antiprotons
all +ions
CAPRICE
MASS91
AMS
IMAX
BESS98
LEAP
Ryan et al.
Grigorov
JACEE
Akeno
Tien Shan
MSU
KASCADE
CASA-BLANCA
DICE
HEGRA
CasaMia
Tibet
Fly Eye
Haverah
AGASA
Yakutsk
HiRes
BESS
HEAT
Fixed target
HERA
RHIC
TEVATRON
LHC
E^2dN/dE (GeV $m^{-2}sr^{-1}s^{-1}$)
E_{kin} (GeV / particle)


Energies and rates of the cosmic-ray particles
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HEAT
Fixed target
HERA
RHIC
TEVATRON
LHC
E^2dN/dE (GeV $m^{-2}sr^{-1}s^{-1}$)
E_{kin} (GeV / particle)

Intimate Relation between :

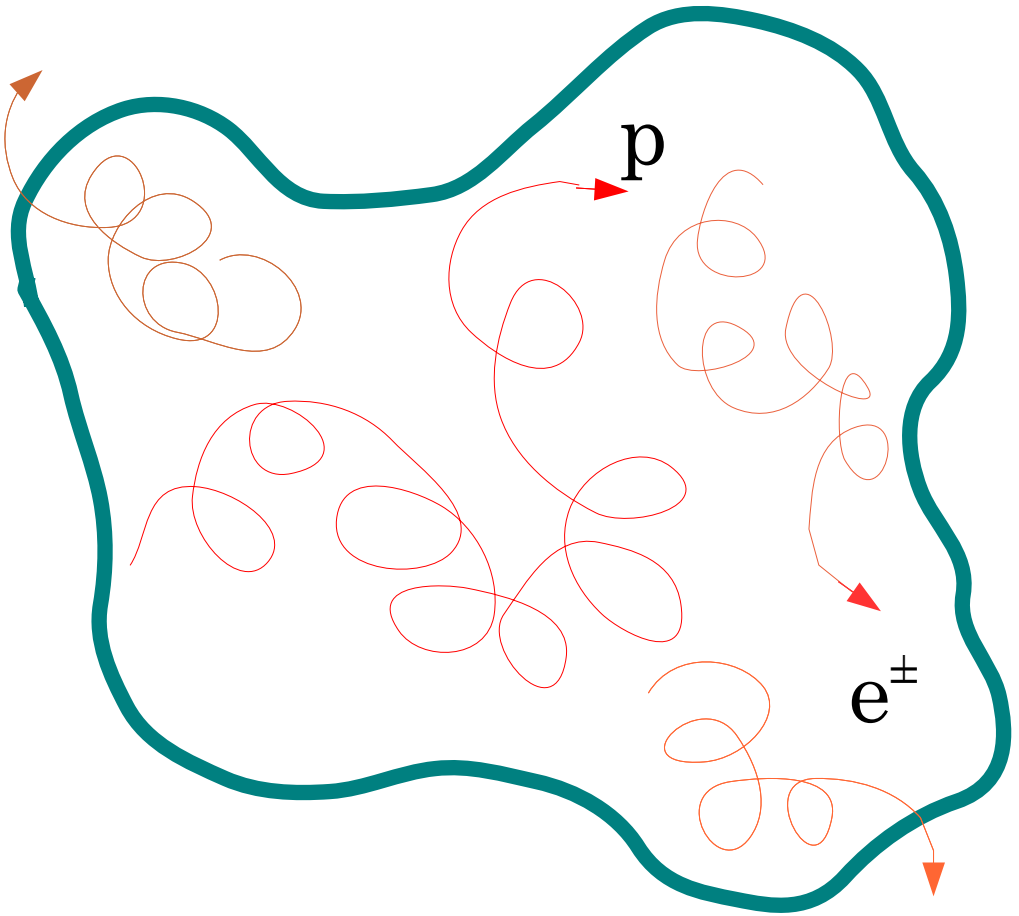
Cosmic Ray Physics

Gamma Astronomy

Neutrino Astronomy

Gravitational Waves

Cosmic Ray Accelerator



Astrophysical object accelerating particles to relativistic energies

Contains populations of relativistic protons, Nuclei electrons/positrons

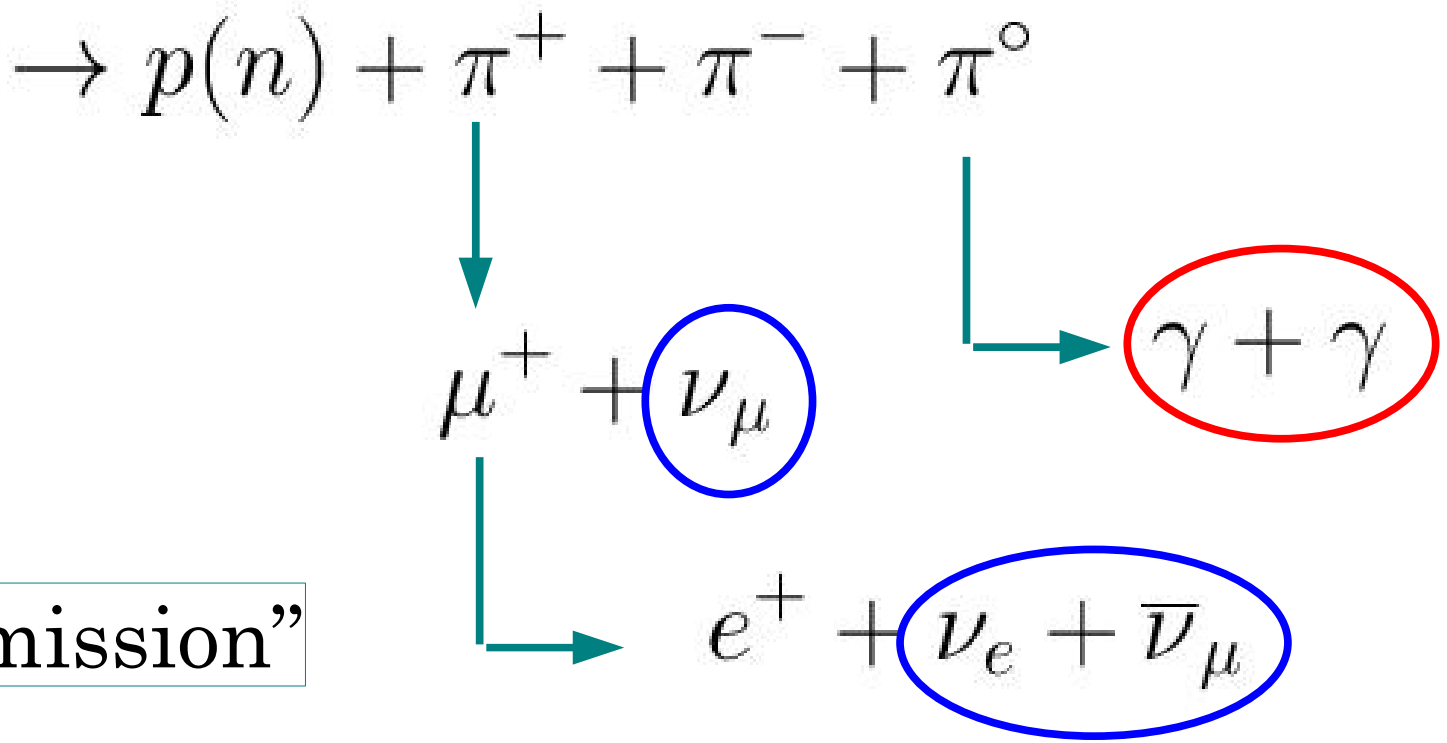
Emission of

COSMIC RAYS

PHOTONS

NEUTRINOS

$$p + \text{target} \rightarrow \text{many particles}$$



"Hadronic Emission"

$$e^\mp + B \rightarrow e^\mp + \gamma_{\text{synchrotron}}$$

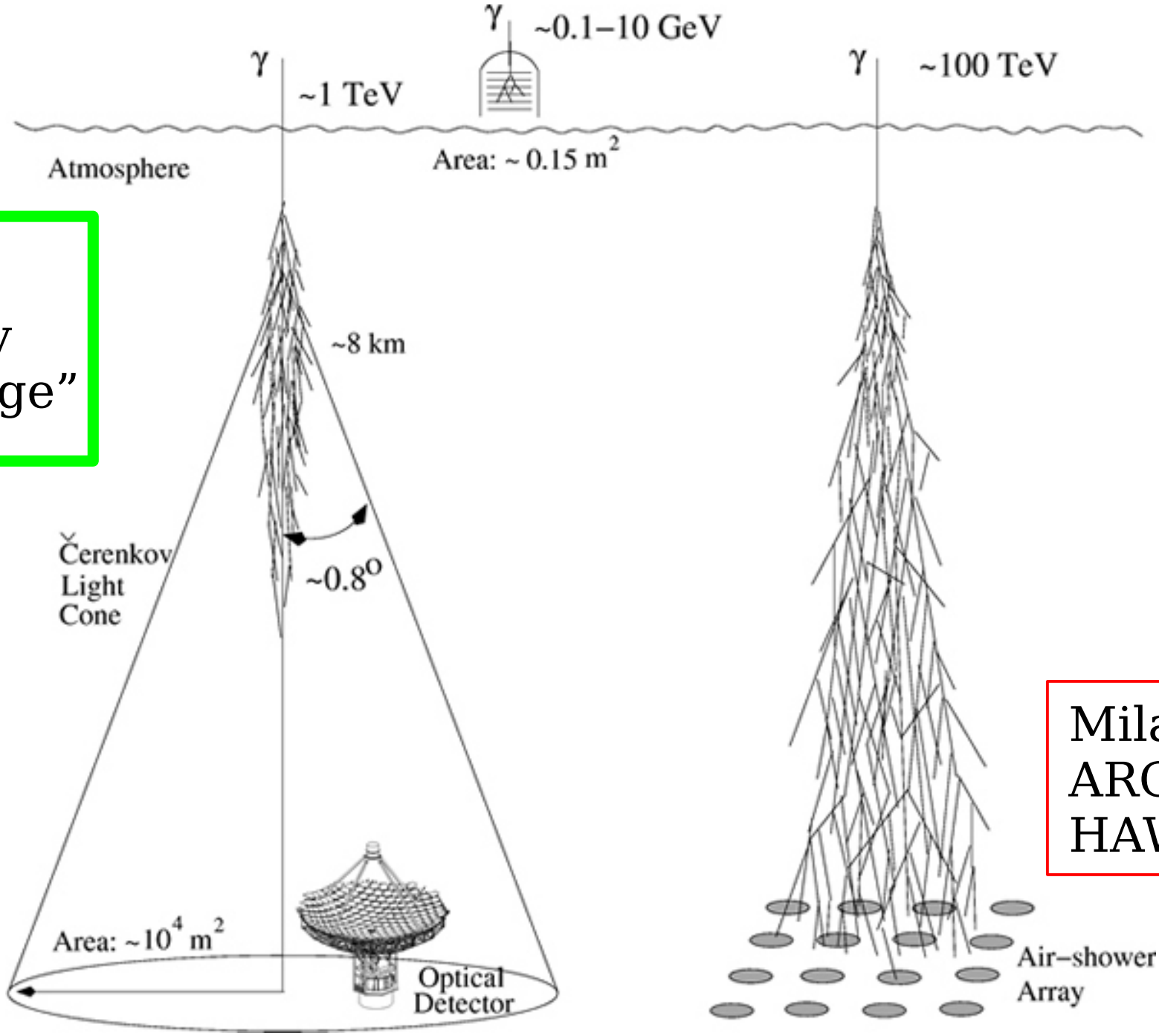
"Leptonic Emission"

$$e^\mp + \gamma_{\text{soft}} \rightarrow e^\mp + \gamma_{\text{Inverse Compton}}$$

AGILE
Fermi

Gamma
Astronomy
“Golden Age”

Hess
Magic
Veritas

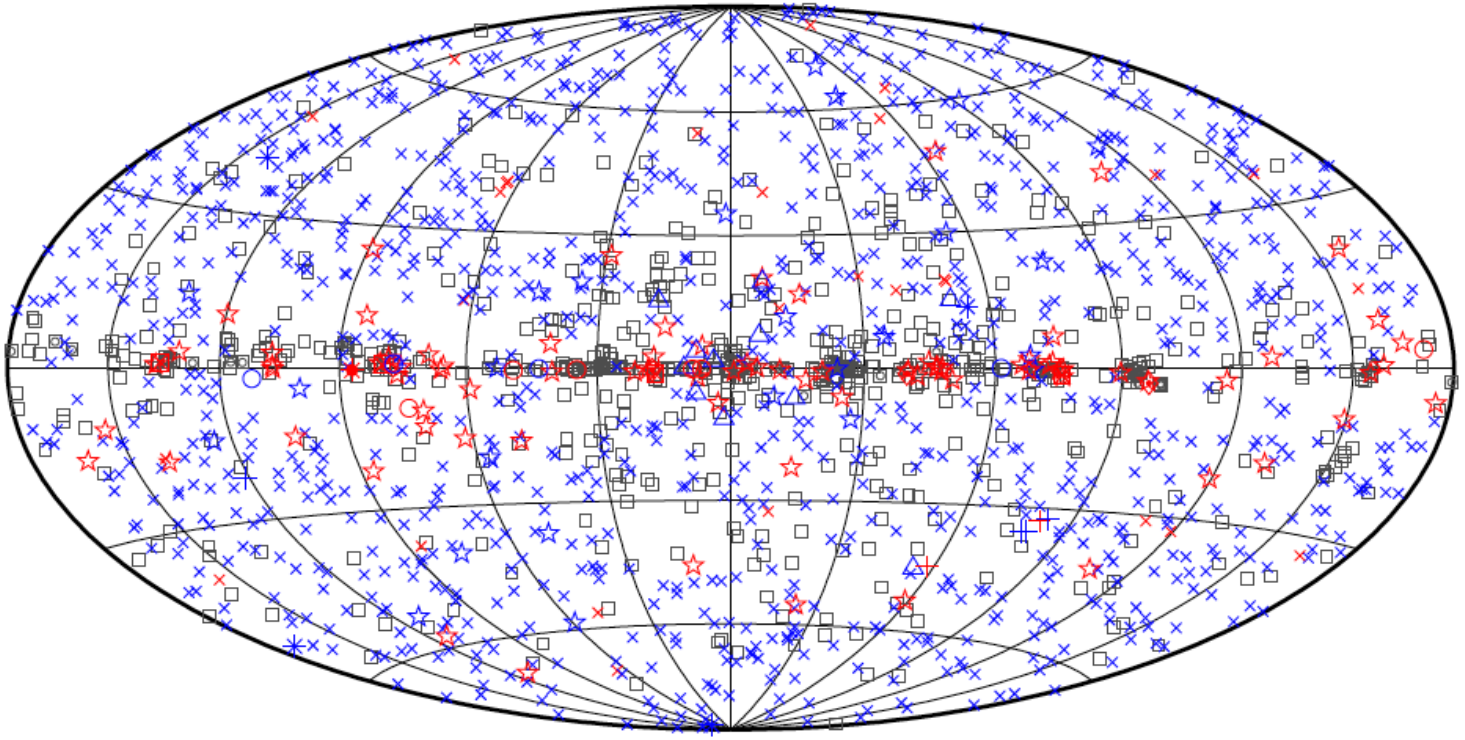


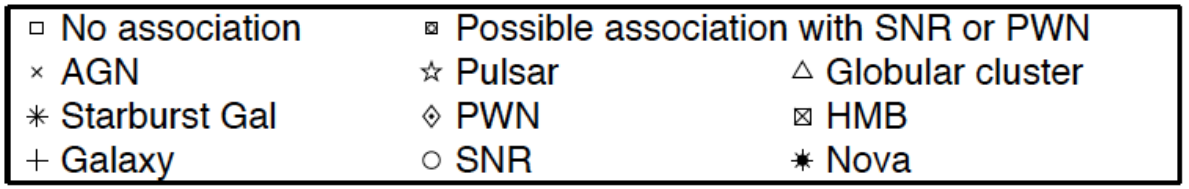
Milagro
ARGO
HAWC

2FGL

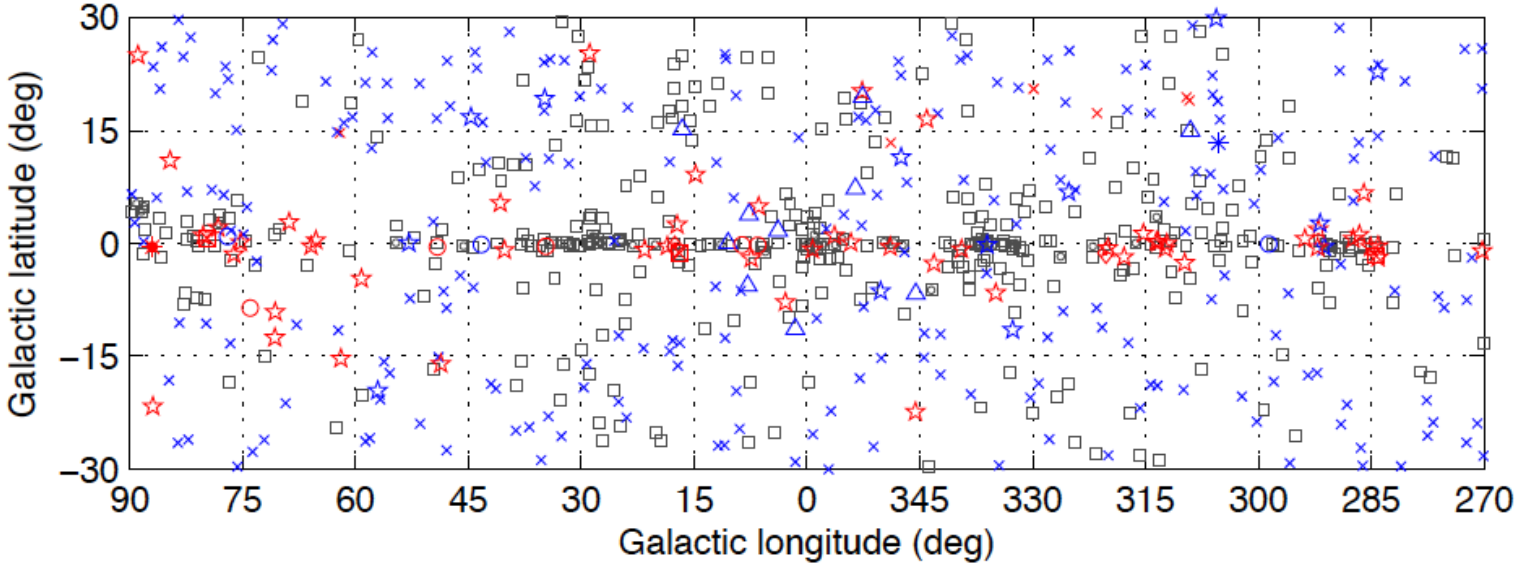
2nd FERMI Catalog

24 months of observations

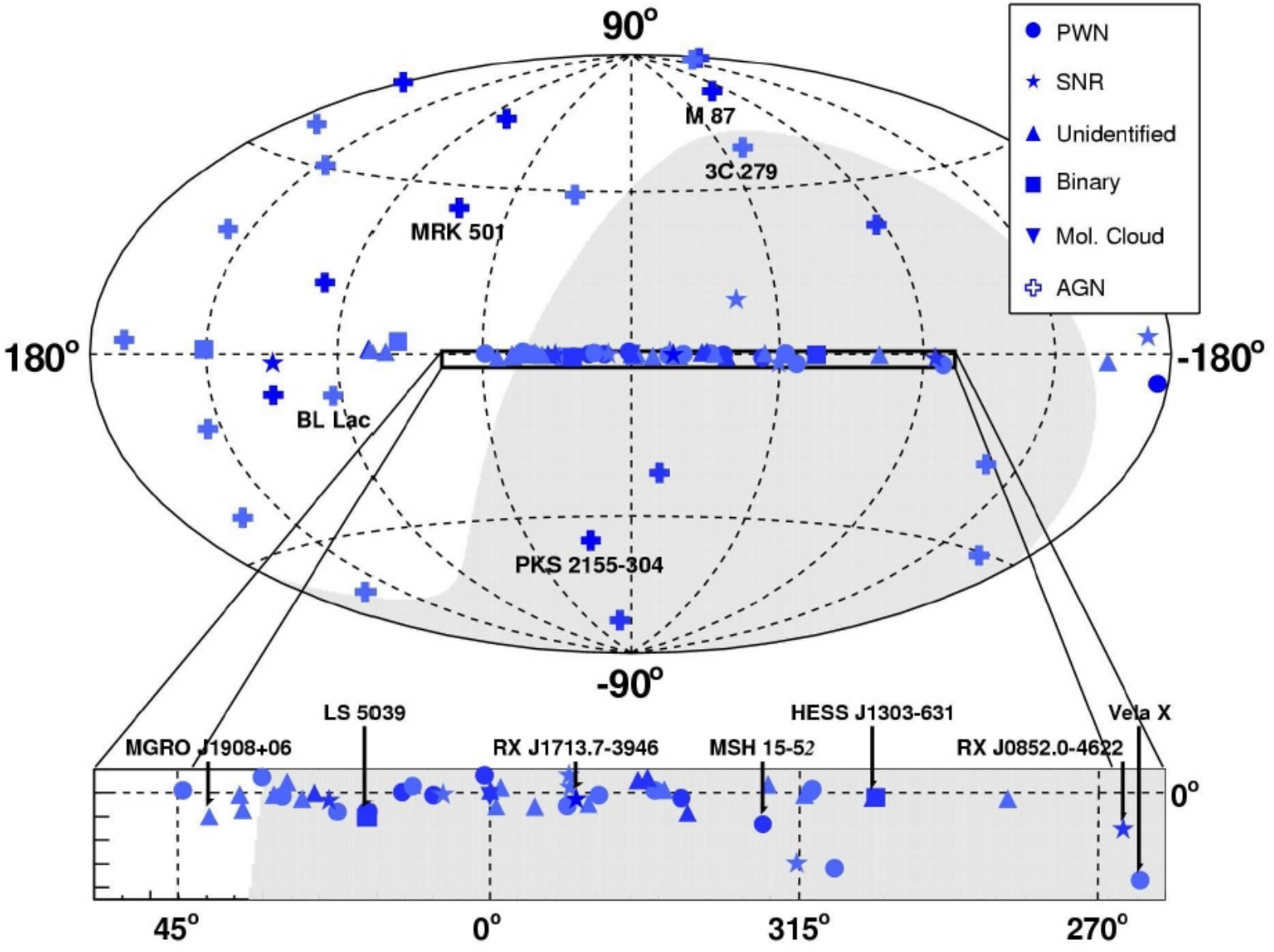




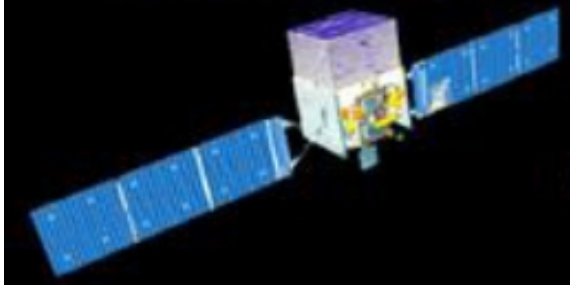
1873 sources

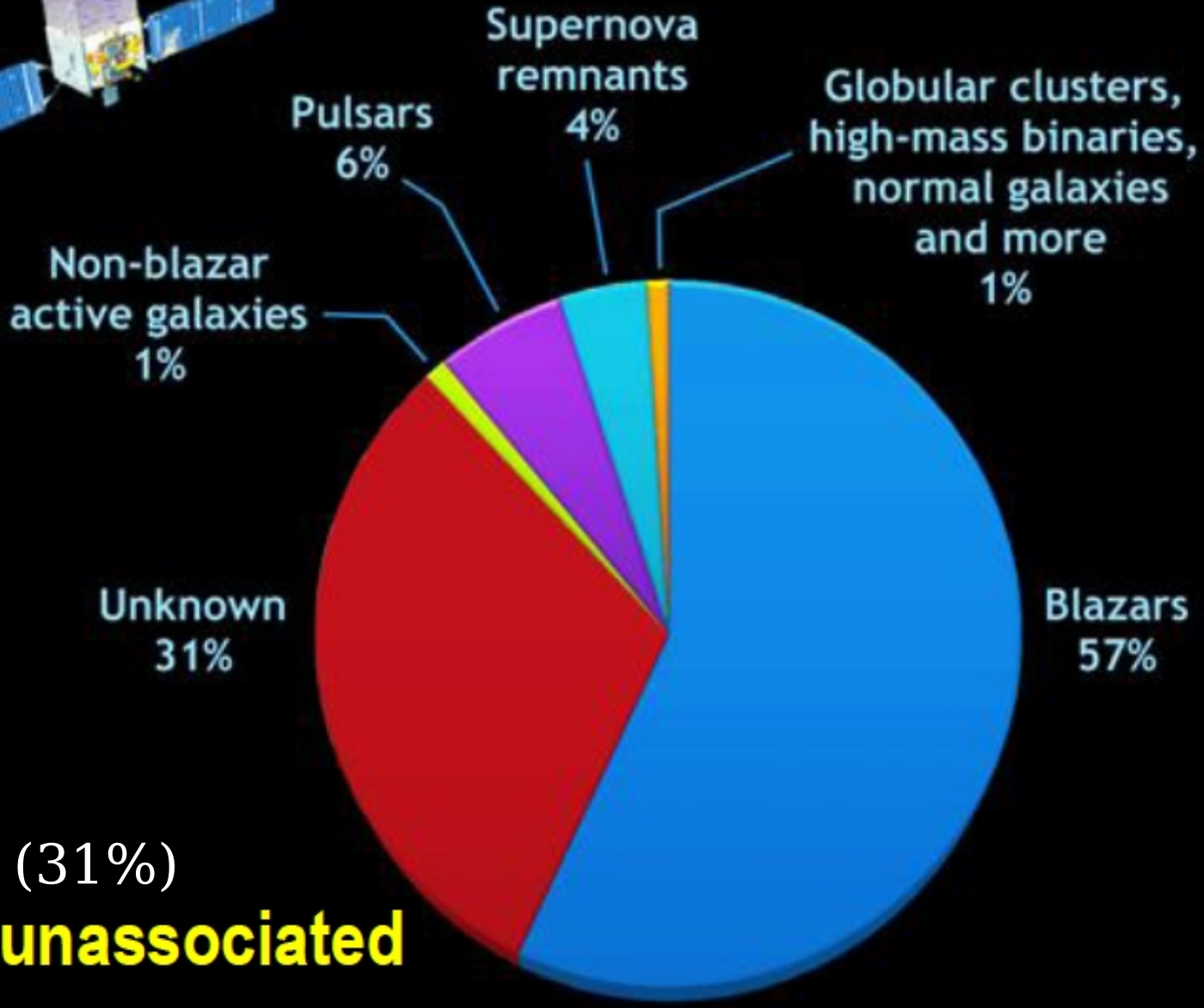


TEV SKY (> 140 source)



What has Fermi found: The LAT two-year catalog





575 (31%)

Many unassociated sources…

Credit: NASA/Goddard Space Flight Center

- SUN (“laboratory” for CR acceleration)

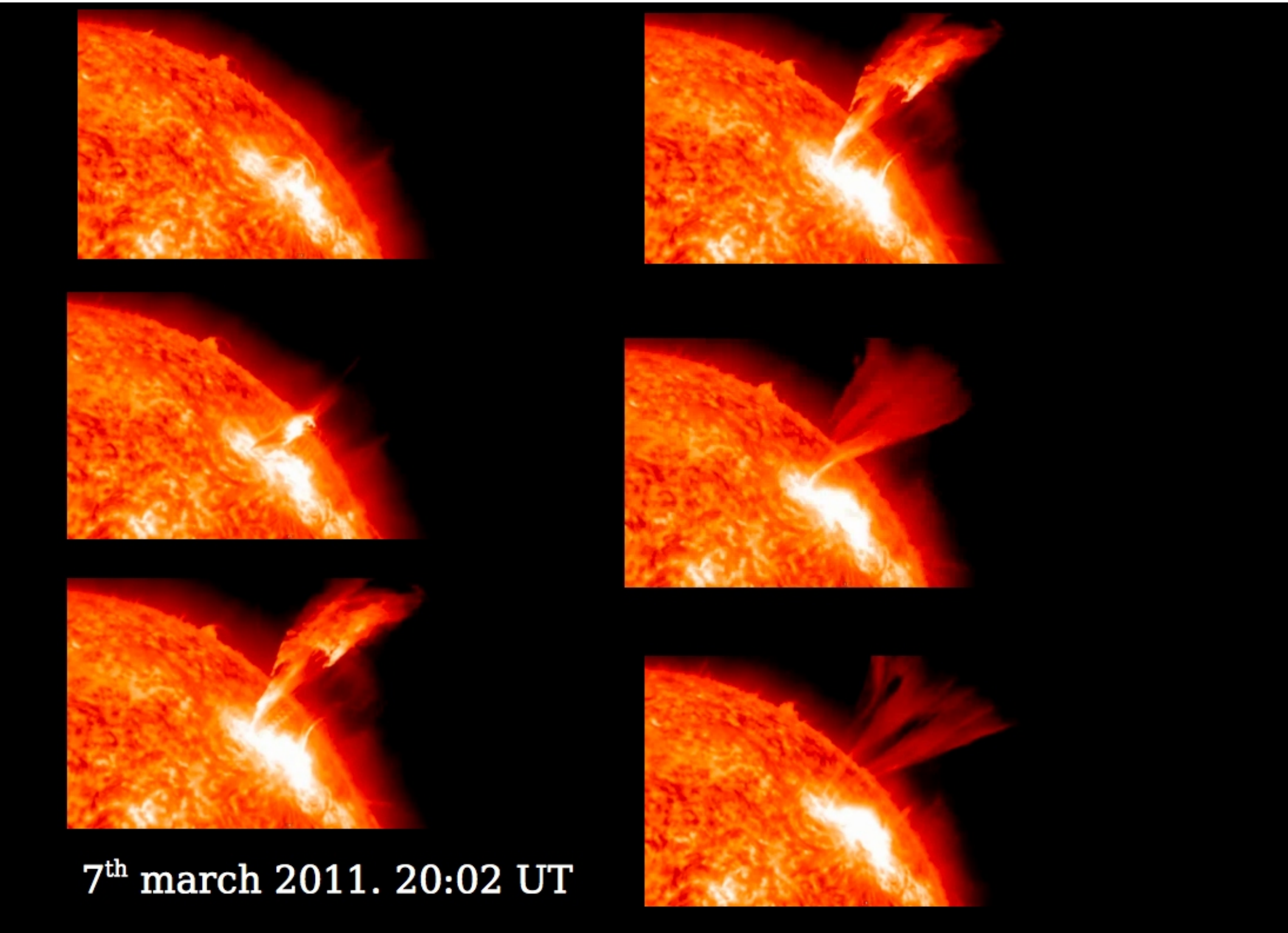
- SuperNova Remnants (SNR)
- PULSARS (PSR)
- Pulsar Wind Nebulae (PWN)
- Binary Systems

Galactic

- Active Galactic Nuclei (AGN)
- Gamma Ray Bursts (GRB)

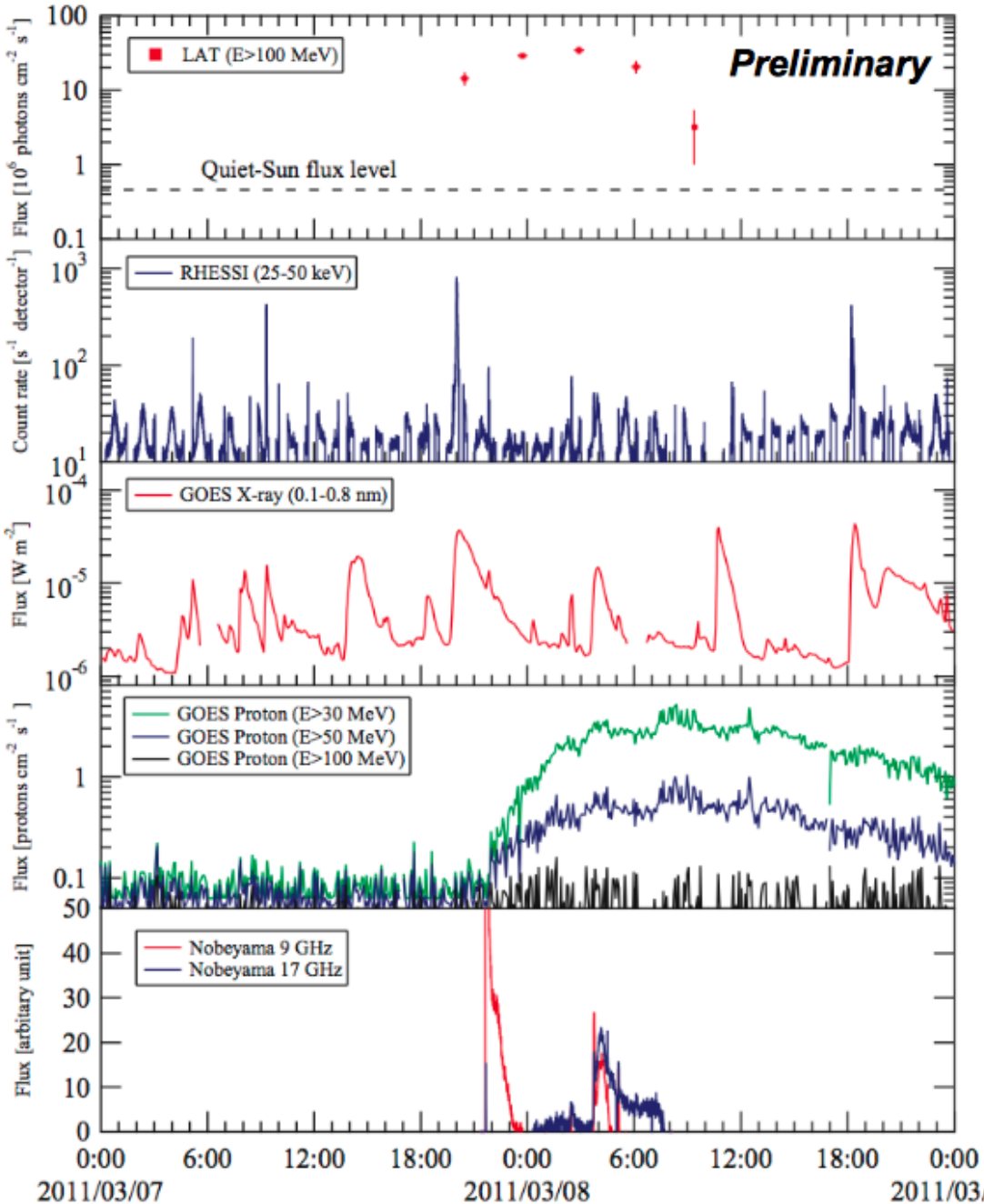
extra-Galactic

- ....novae, globular clusters, starburst galaxies, ...New Objects ?

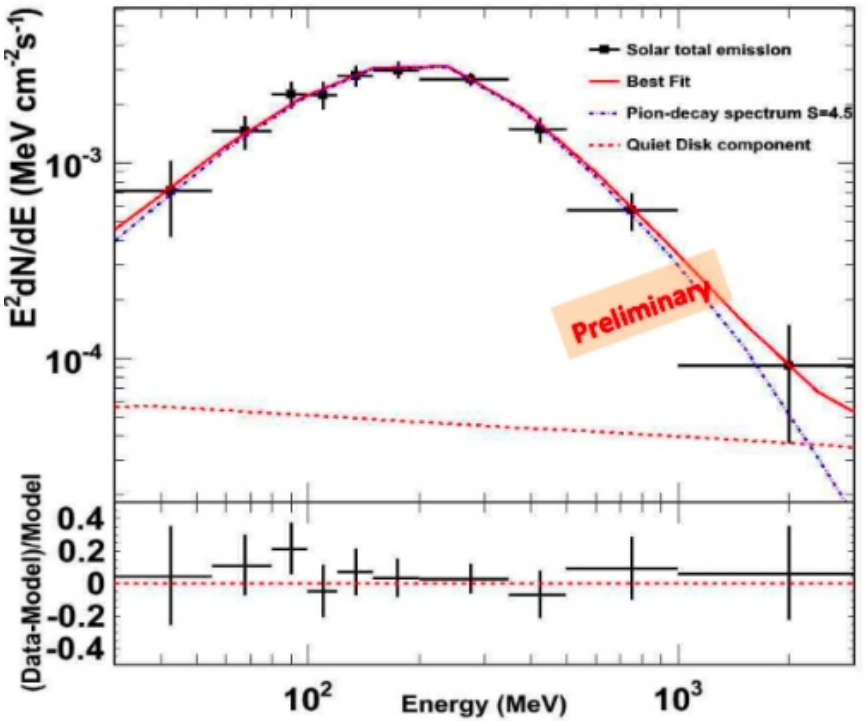

7th march 2011. 20:02 UT


This aurora image was taken on March 10, 2011 by Zoltan Kenwell near Edmonton, Alberta, Canada.
©2011 Zoltan Kenwell

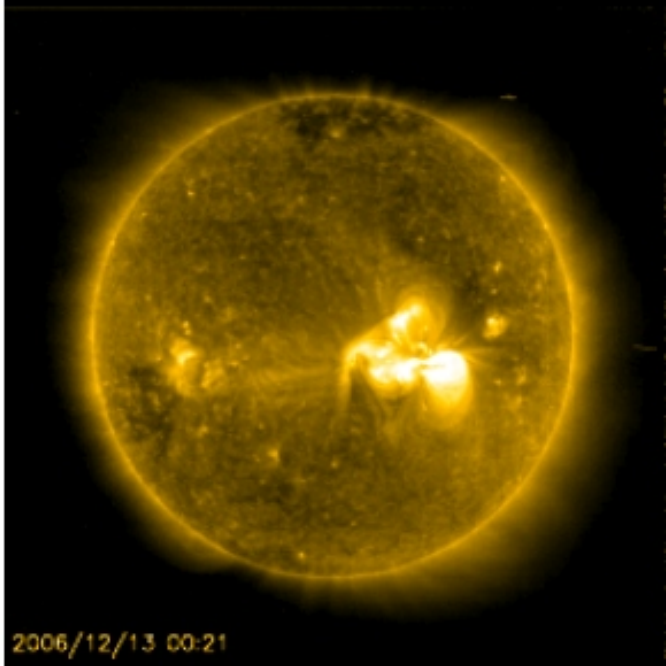
Multi-wavelength light curve

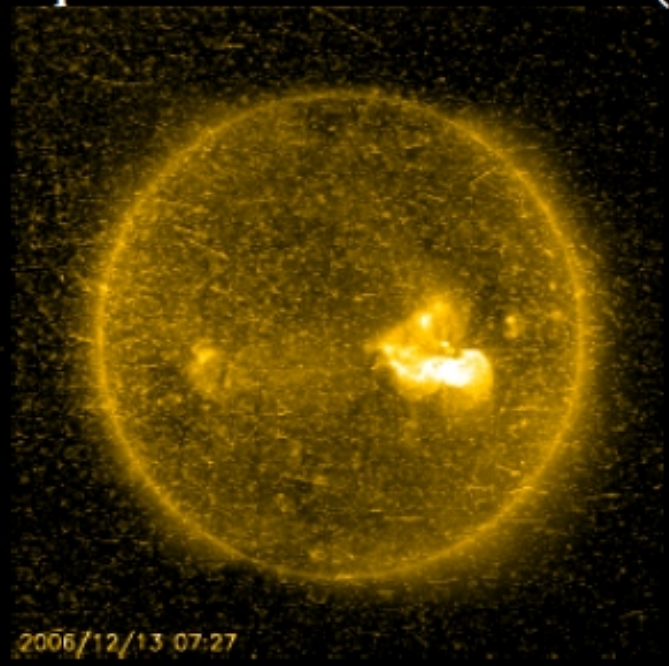


- **Following M3.7 flare at ~20 UT on March 7, Fermi-LAT detected long-lasting HE emission over ~12 hours**
- **LAT flux showed clear rising profile**

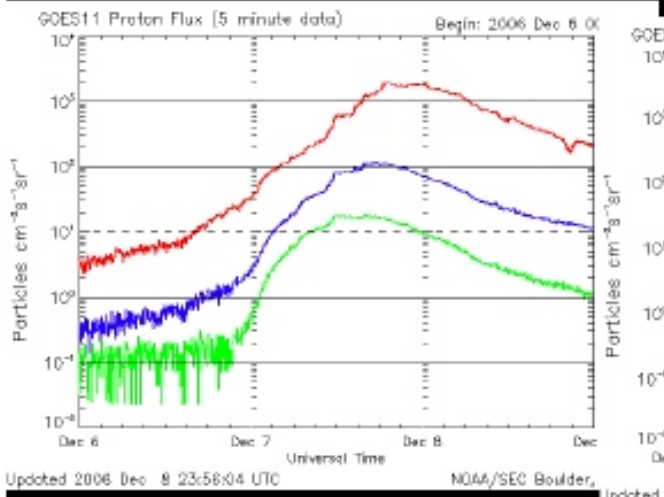


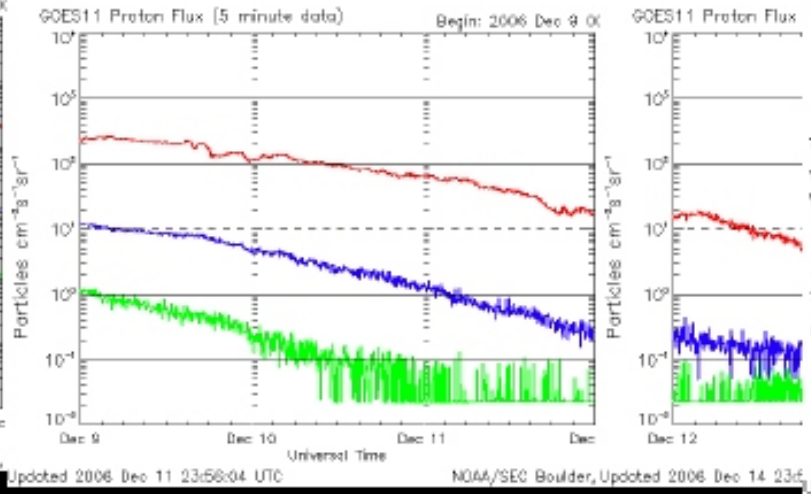
Solar particle events (1 AU)

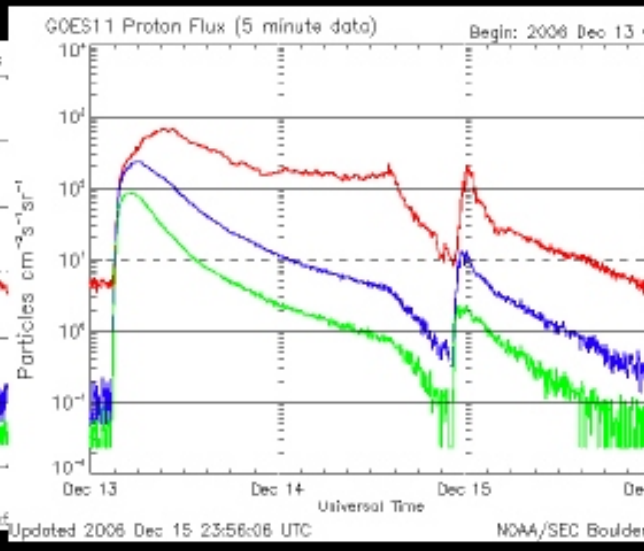




Bazileskaya ICRC332
Carbone ICRC845



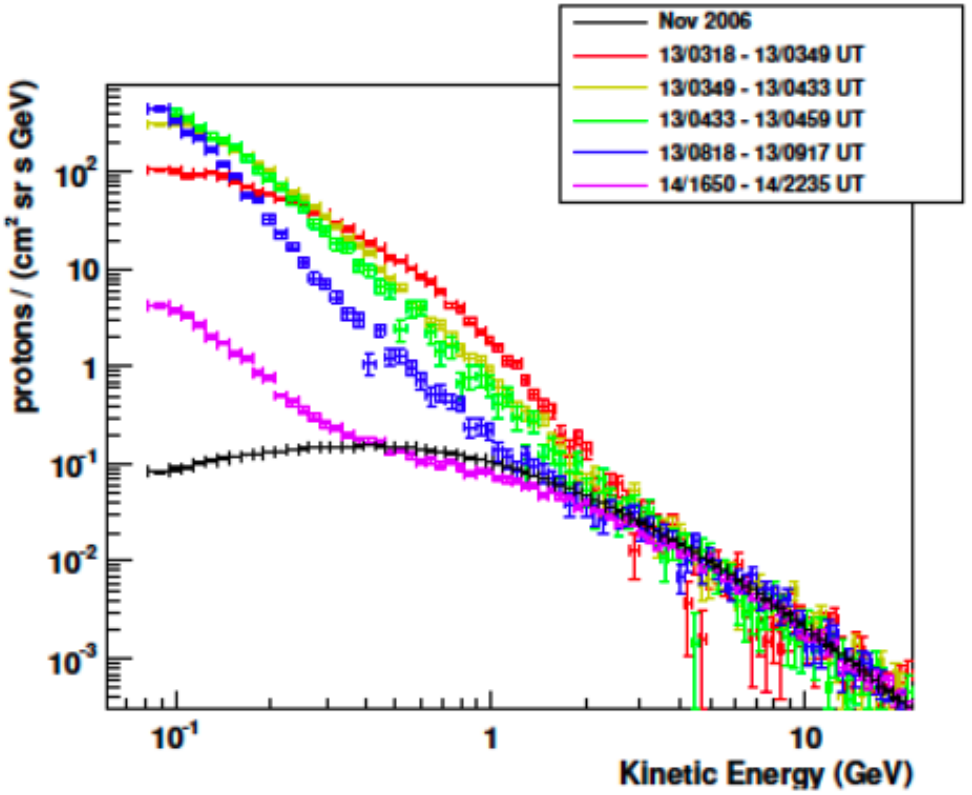


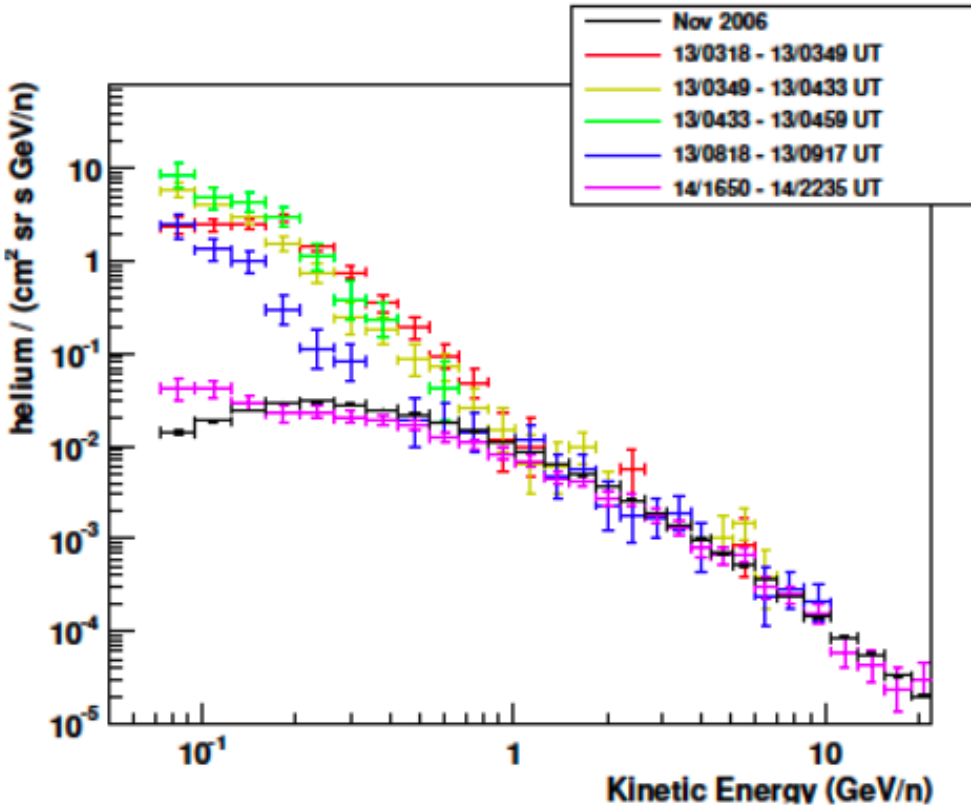


PAMELA: Solar Flare 13/dec/2006

13 Dec 2006
Solar Flare

Adriani et al. – submitted to APJ





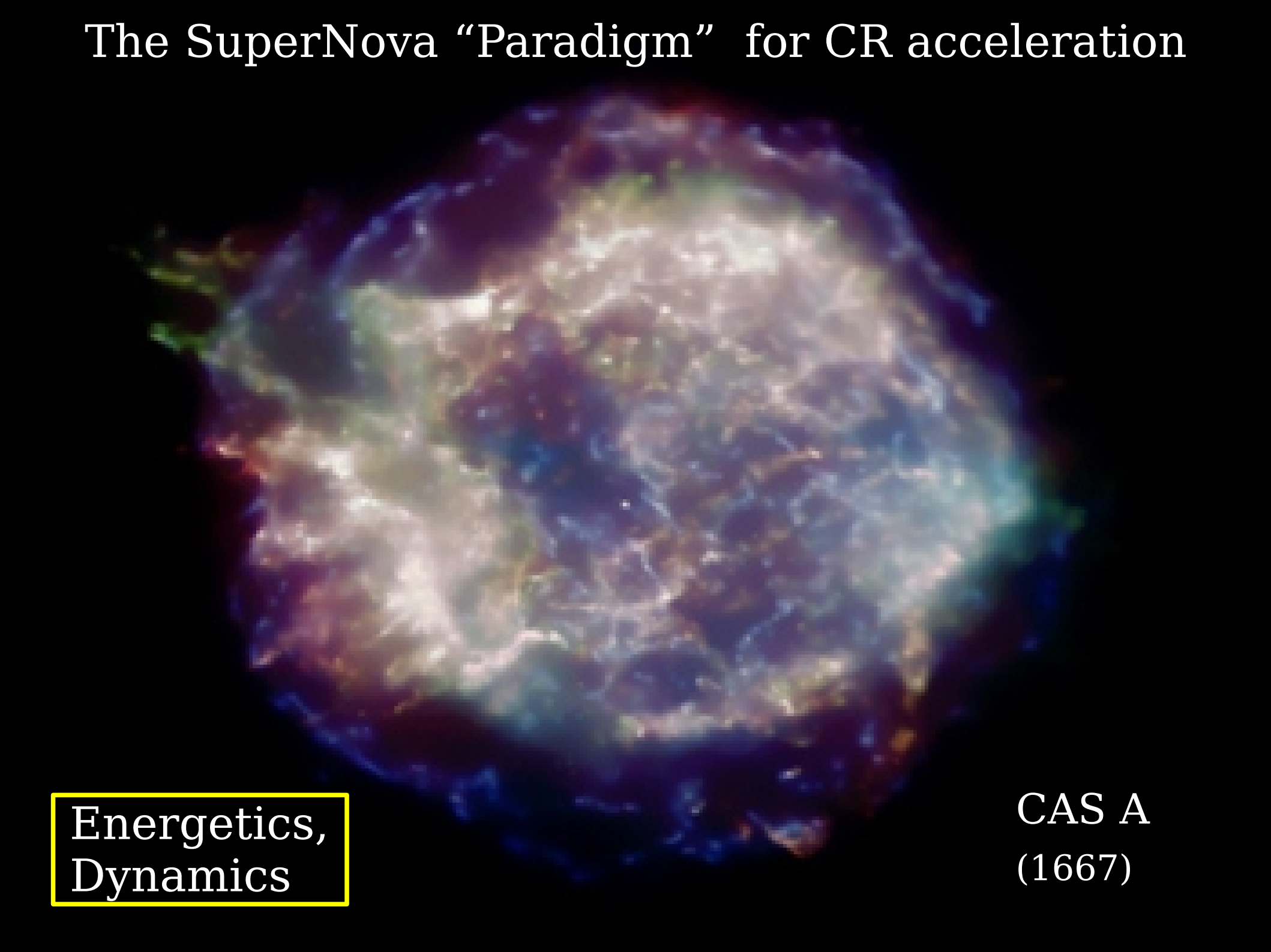
Identification of the Astrophysical Sources of COSMIC RAYS.

The "SNR paradigm"
for galactic Cosmic Rays

Debate about the acceleration sites of UHECR (Ultra High Energy Cosmic Rays).

Candidate sites:
AGN's
GRB's

The SuperNova “Paradigm” for CR acceleration

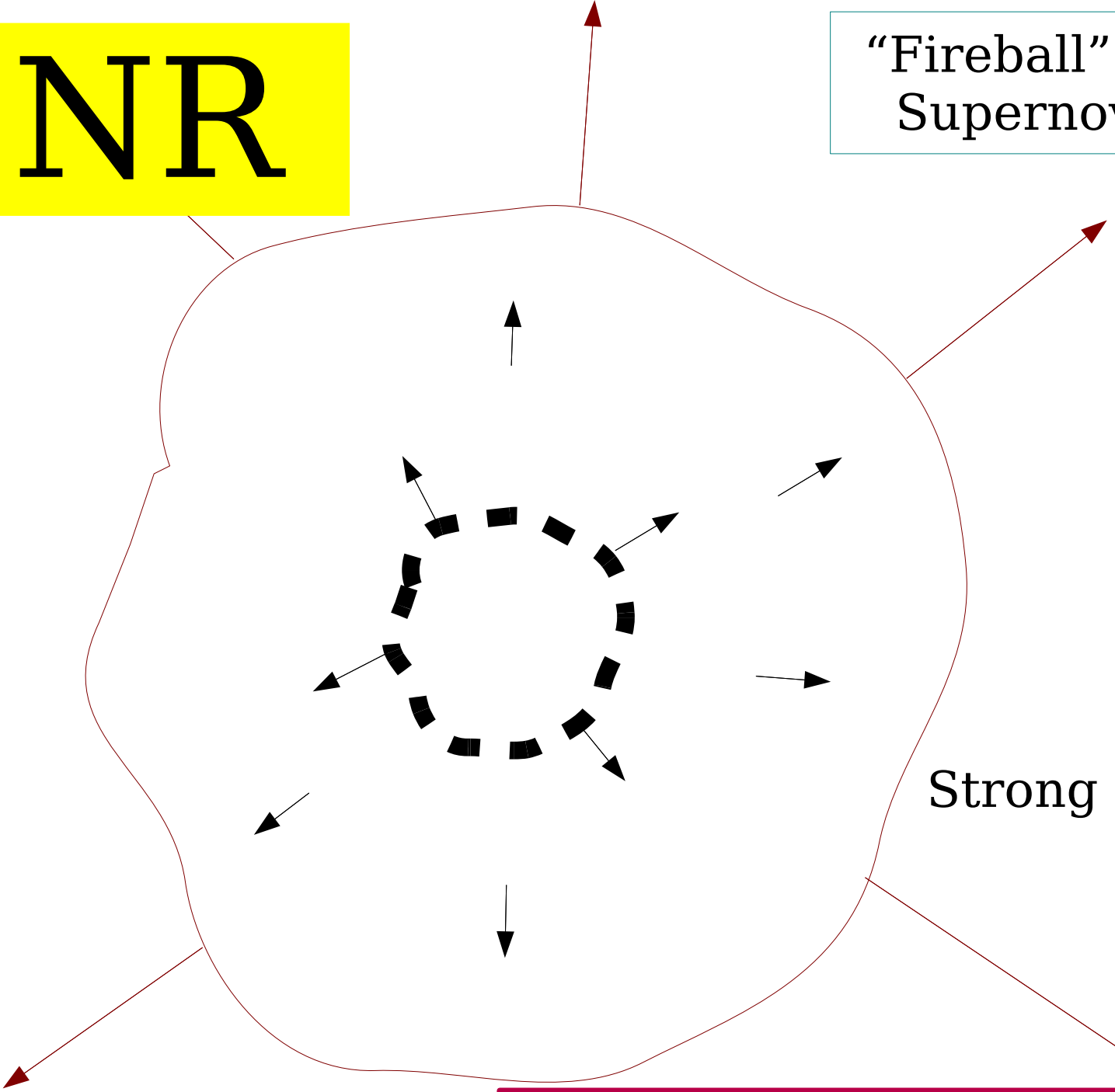


Energetics,
Dynamics

CAS A
(1667)

SNR

"Fireball" of an Supernova explosion



Interstellar Gas

Strong Shock

Fermi 1st order acceleration

$$q(E) \propto E^{-(2+\varepsilon)}$$

$$L_{\text{SN kinetic}}^{\text{Milky Way}} \simeq E_{\text{SN}}^{\text{Kinetic}} \, f_{\text{SN}}$$

$$L_{\text{SN kinetic}}^{\text{Milky Way}} \simeq \left[1.6 \times 10^{51} \text{ erg}\right] \left[\frac{3}{\text{century}}\right]$$

$$M = 5 \, M_{\odot}$$

$$v \simeq 5000 \text{ Km/s}$$

$$L_{\text{SN kinetic}}^{\text{Milky Way}} \simeq 1.5 \times 10^{42} \, \frac{\text{erg}}{\text{s}}$$

Power Provided by SN is sufficient
with a conversion efficiency of 15-20 %
in relativistic particles

SuperNova 393A
RX J1713.7-3946

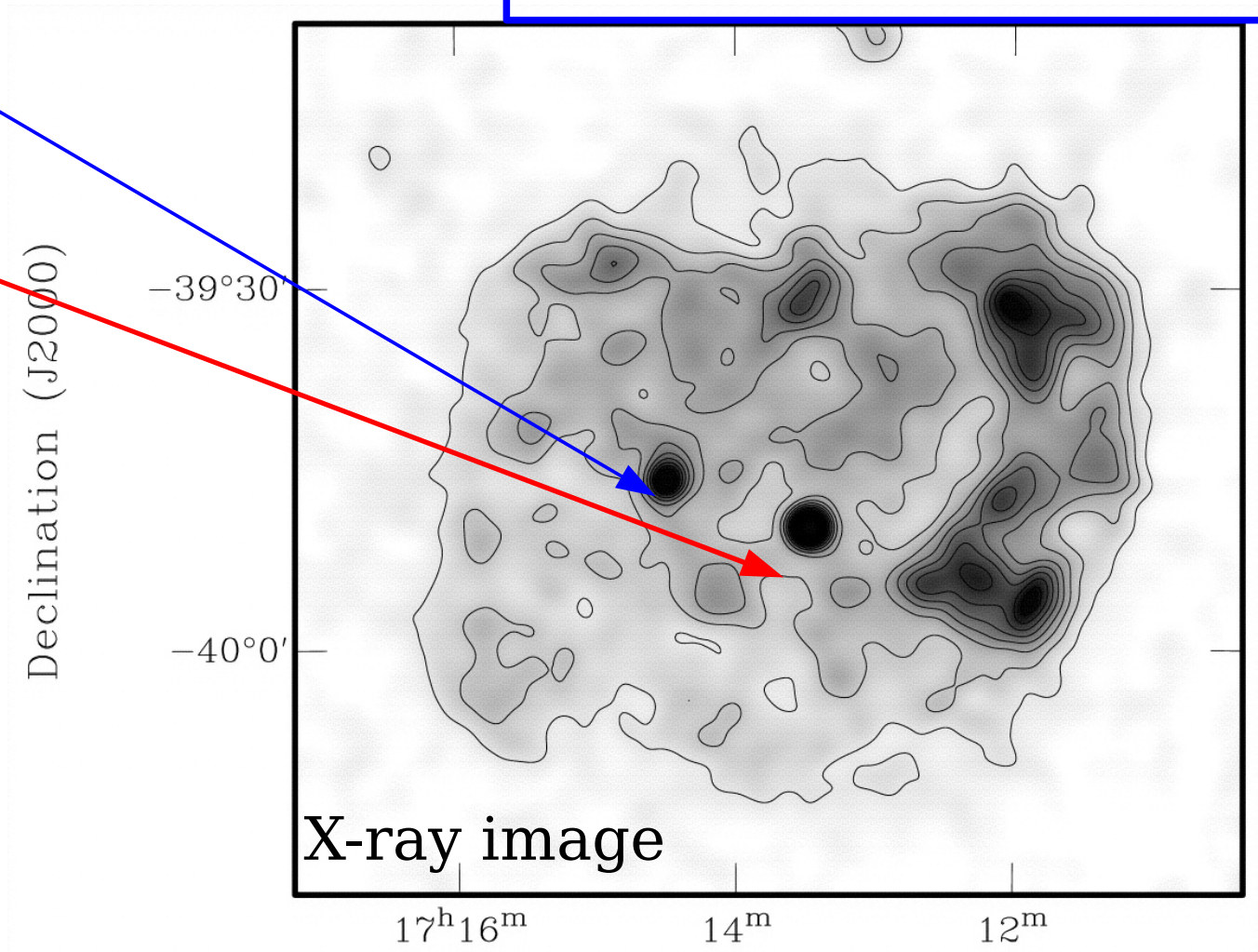
Observed in AD 393
By chinese court astromers
22-october, 19-november

(Re)-discovered in 1996
by the Roentgen Satellite

Foreground star

Neutron Star


之幷斬其從弟緒司馬道子由是失勢禍亂成矣
太元十六年十一月癸巳月奄心前星占曰太子憂是
時太子常有篤疾
太元十七年九月丁丑歲星熒惑填星同在亢氐占曰
三星合是謂驚位絕行內外有兵喪與飢改立王公
太元十八年正月乙酉熒惑入月占曰憂在宮中非賊
乃盜也一曰有亂臣若有戮者二十一年九月帝暴崩
內殿兆庶宣言夫人張氏潛行大逆于時朝政闇緩不
加顯戮但黙責而已又王國寶邪狡卒伏其辜
太元十八年二月有客星在尾中至九月乃滅占曰藏

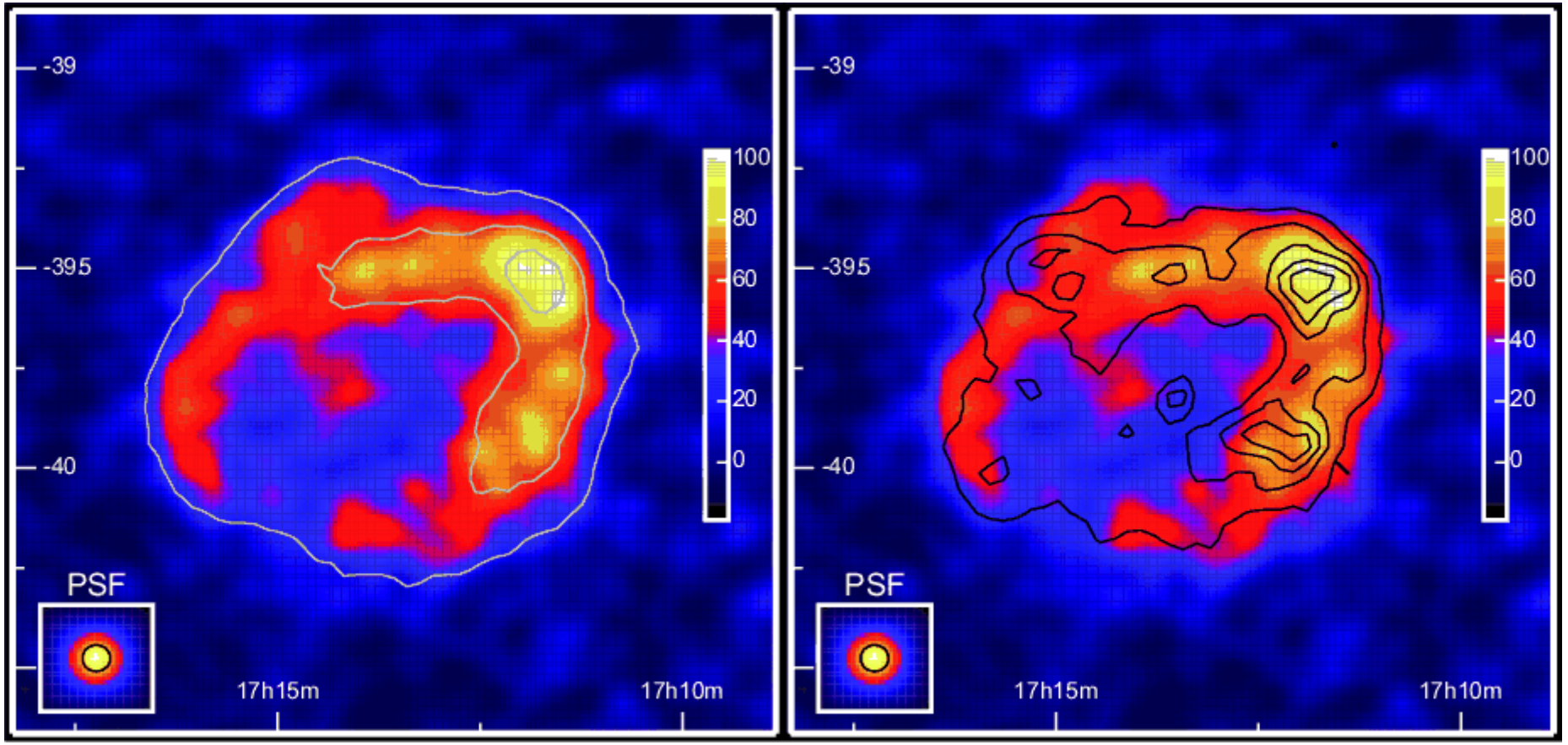


Detected in 2004 by HESS in TeV gamma rays

HESS Telescope

Observations with TeV photons

SuperNova RX J1713.7-3946

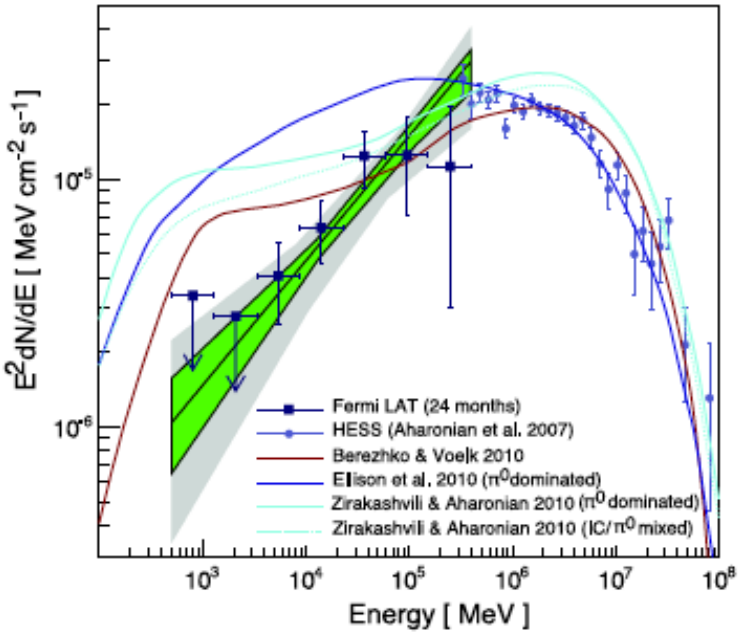


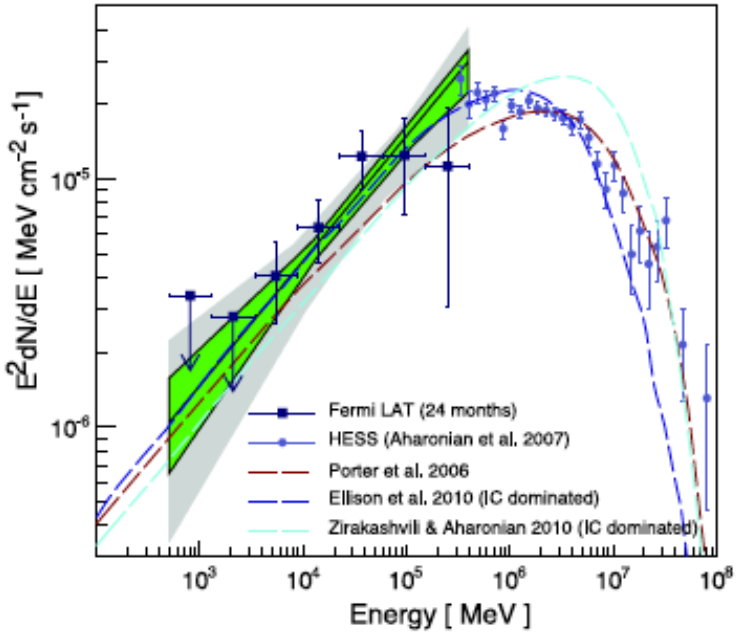
Comparison with ROSAT observation

Observations of the young Supernova remnant RX J1713.7−3946
with the *Fermi* Large Area Telescope

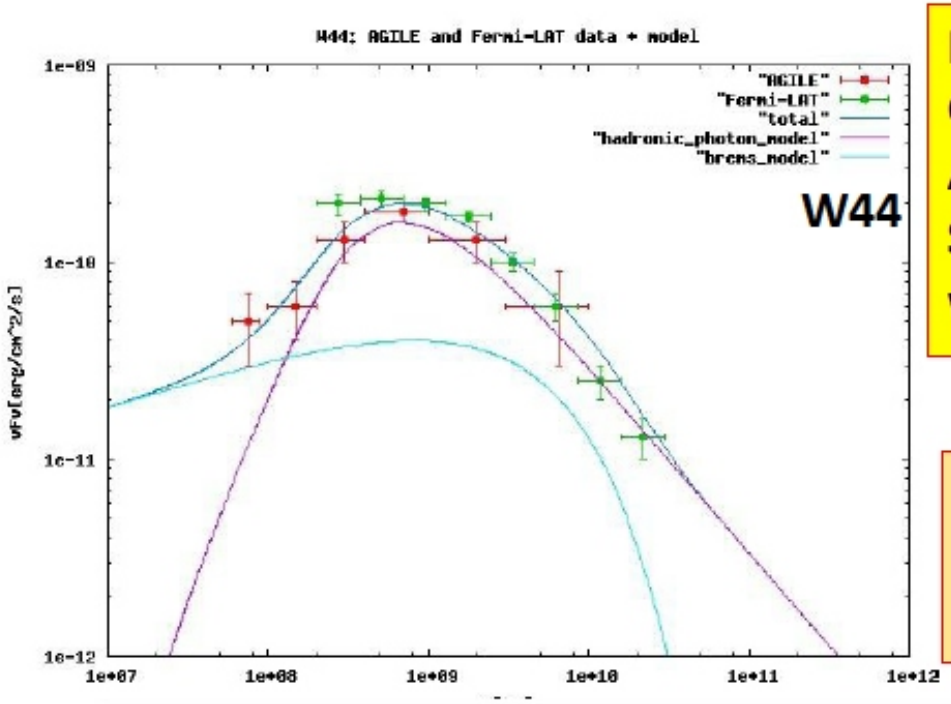
astro-ph/1103.5727.

Favors
leptonic interpretation.





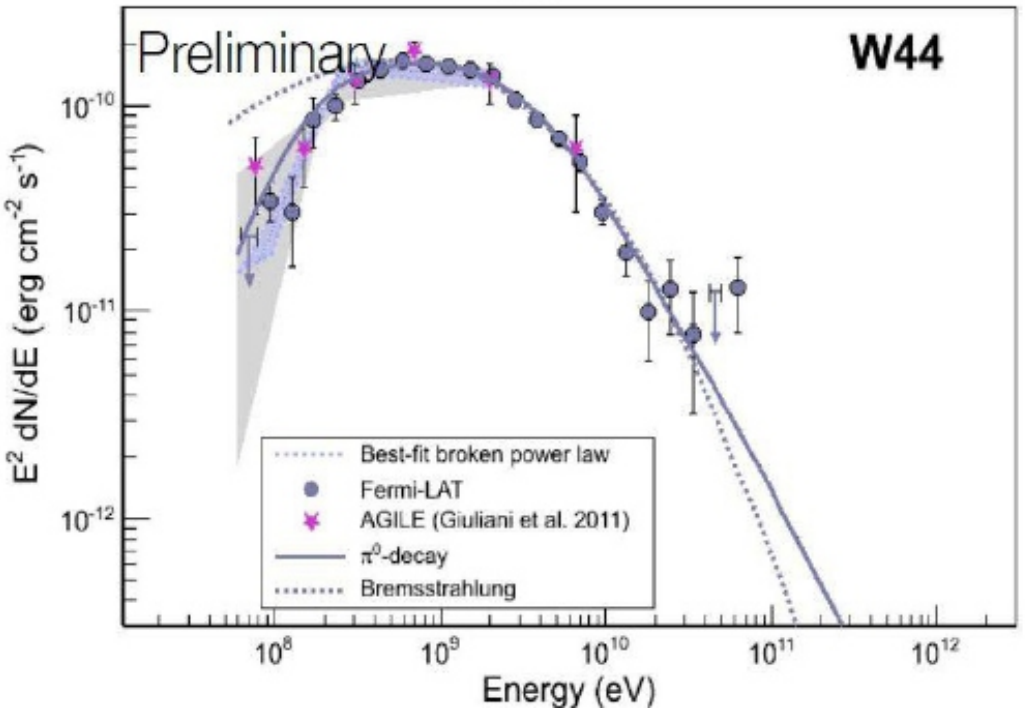
AGILE-GRID



PROOF OF HADRONIC COSMIC-RAY ACCELERATION IN THE SUPERNOVA REMNANT W44: THE π^0 SPECTRUM

(Giuliani A., Cardillo M., et al., ApJ Letters, 742, L30, 2011)

***Fermi-*LAT**

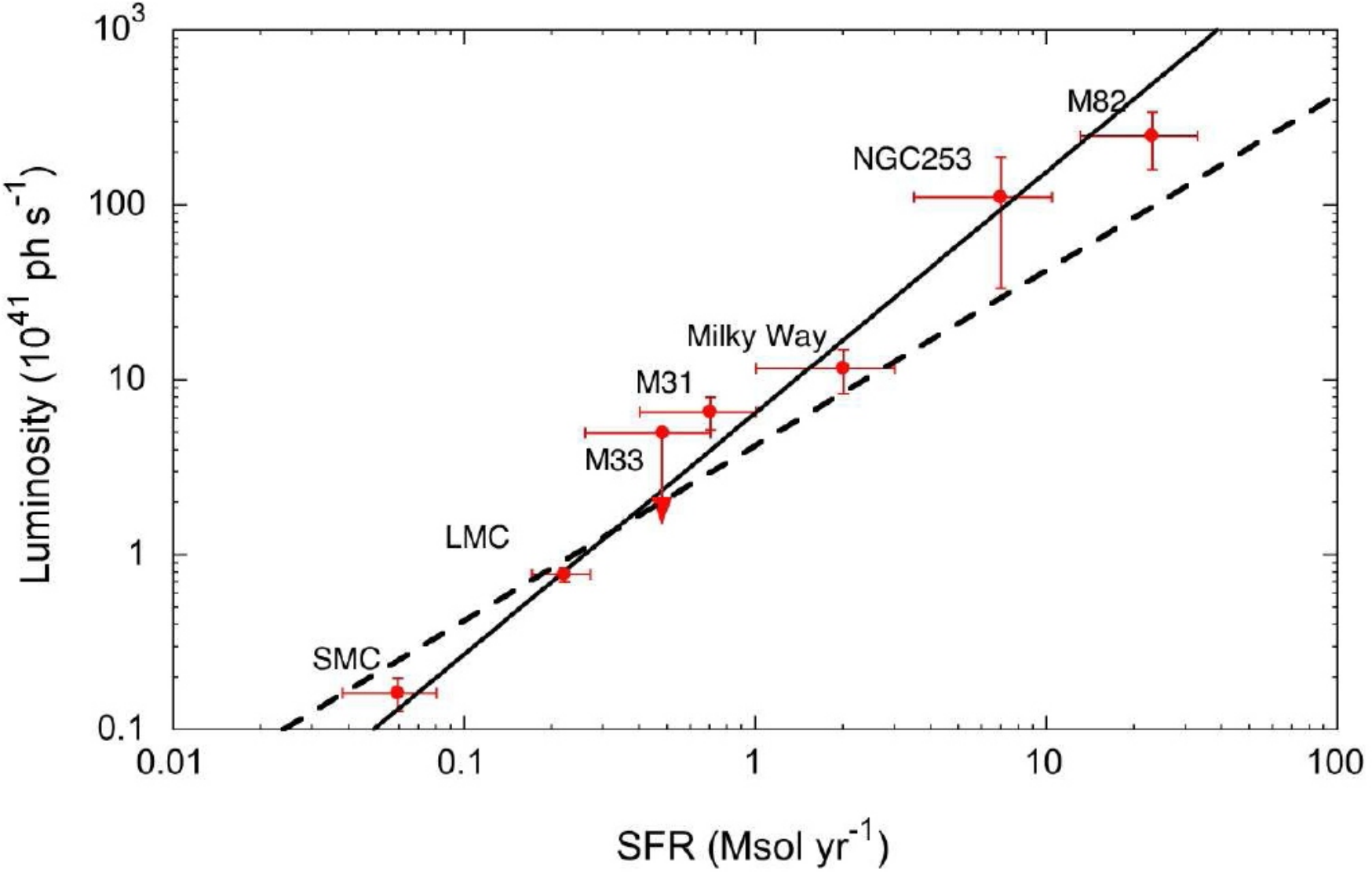


(Funk S. et al., Science, in press 2012)

From FERMI:

Table 1. Properties and gamma-ray characteristics of Local Group and nearby starburst galaxies (see text).

Galaxy	d kpc	$M_{\rm HI}$ 10^8 $M_\odot$	$M_{\rm H_2}$ 10^8 $M_\odot$	SFR $M_\odot$ yr^{-1}	F_γ 10^{-8} ph cm^{-2} s^{-1}	L_γ 10^{41} ph s^{-1}	$\tilde{q}_\gamma$ 10^{-25} ph s^{-1} H-atom^{-1}
MW	...	$35 \pm 4^{(7)}$	$14 \pm 2^{(7)}$	$1 - 3^{(19)}$	...	$11.8 \pm 3.4^{(28)}$	2.0 ± 0.6
M31	$780 \pm 33^{(1)}$	$73 \pm 22^{(8)}$	$3.6 \pm 1.8^{(14)}$	$0.35 - 1^{(19)}$	0.9 ± 0.2	6.6 ± 1.4	0.7 ± 0.3
M33	$847 \pm 60^{(2)}$	$19 \pm 8^{(9)}$	$3.3 \pm 0.4^{(9)}$	$0.26 - 0.7^{(20)}$	< 0.5	< 5.0	< 2.9
LMC	$50 \pm 2^{(3)}$	$4.8 \pm 0.2^{(10)}$	$0.5 \pm 0.1^{(15)}$	$0.20 - 0.25^{(21)}$	$26.3 \pm 2.0^{(25)}$	0.78 ± 0.08	1.2 ± 0.1
SMC	$61 \pm 3^{(4)}$	$4.2 \pm 0.4^{(11)}$	$0.25 \pm 0.15^{(16)}$	$0.04 - 0.08^{(22)}$	$3.7 \pm 0.7^{(26)}$	0.16 ± 0.04	0.31 ± 0.07
M82	$3630 \pm 340^{(5)}$	$8.8 \pm 2.9^{(12)}$	$5 \pm 4^{(17)}$	$13 - 33^{(23)}$	$1.6 \pm 0.5^{(27)}$	252 ± 91	158 ± 75
NGC253	$3940 \pm 370^{(6)}$	$64 \pm 14^{(13)}$	$40 \pm 8^{(18)}$	$3.5 - 10.4^{(24)}$	$0.6 \pm 0.4^{(27)}$	112 ± 78	9 ± 6



Luminosity (E >100 MeV) versus star formation rate (SFR).
Dashed line: Linear relation
Solid line : Power law best fit

PULSARS

Proposed as possible Accelerators of e+ e-

CRAB Nebula

$$P_{\mathrm{Crab}} = 0.0334 \text{ s}$$

$$\dot{P}_{\mathrm{Crab}} = 4.2 \times 10^{-13} \text{ s}$$

$$(\Delta P_{\mathrm{Crab}})_{\mathrm{year}} = 13.2 \times 10^{-6} \text{ s}$$

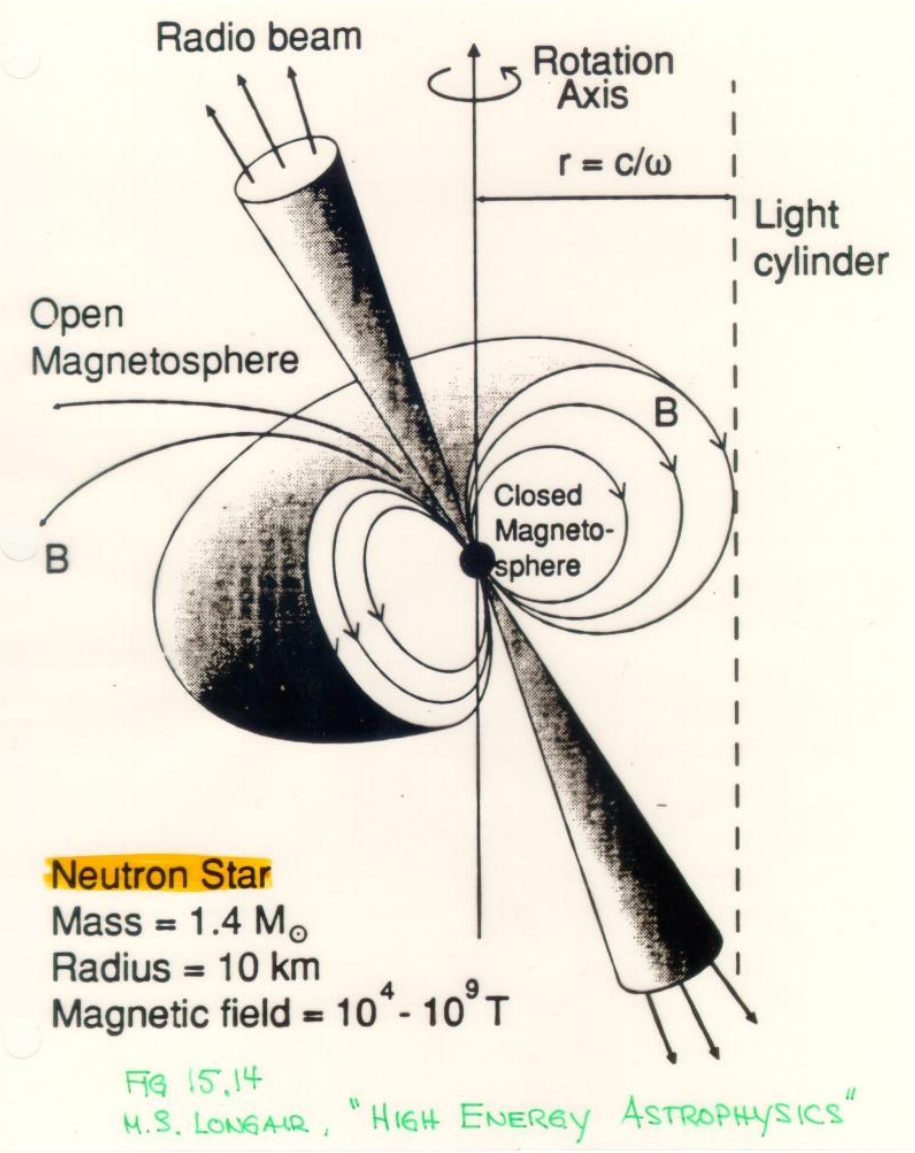
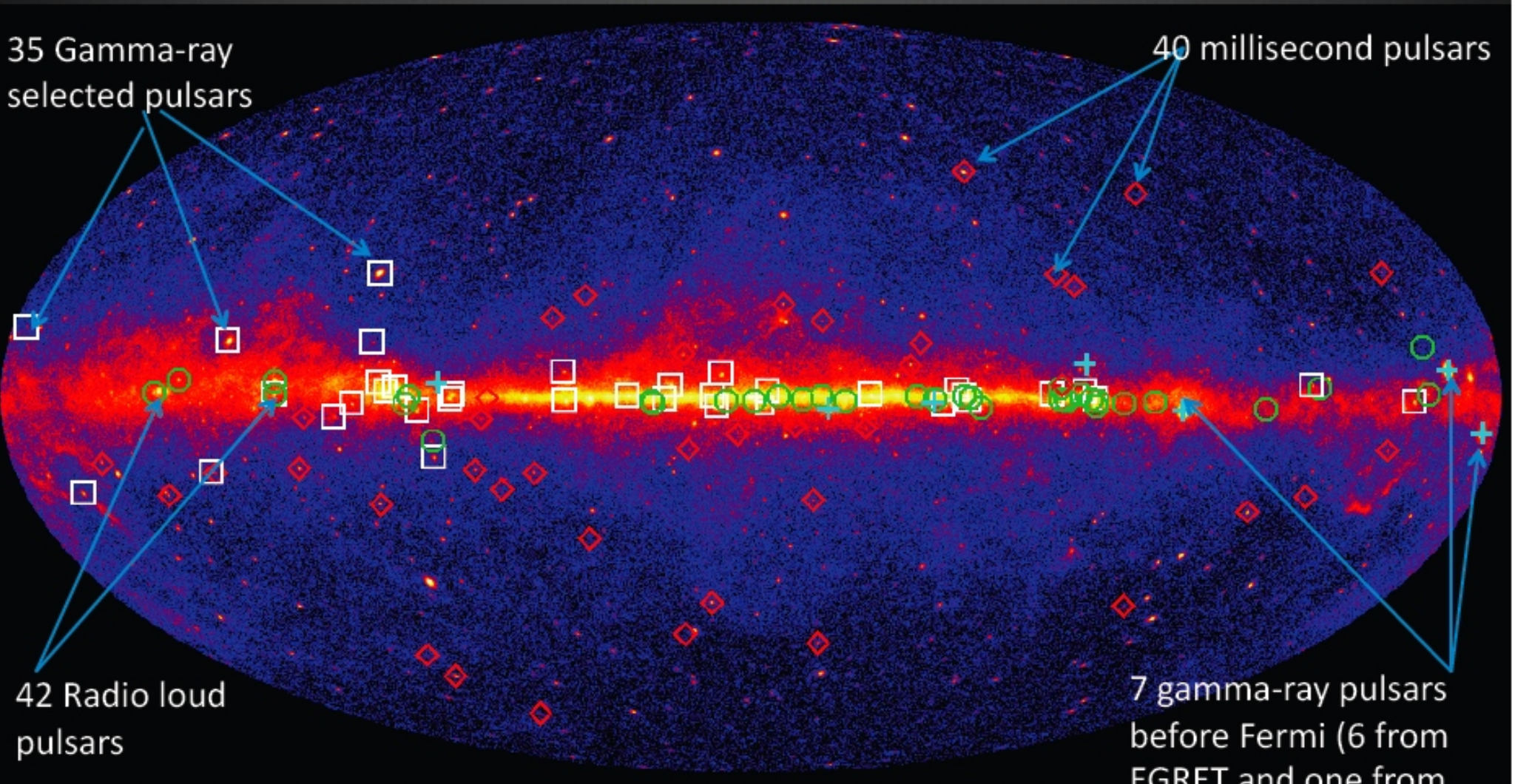


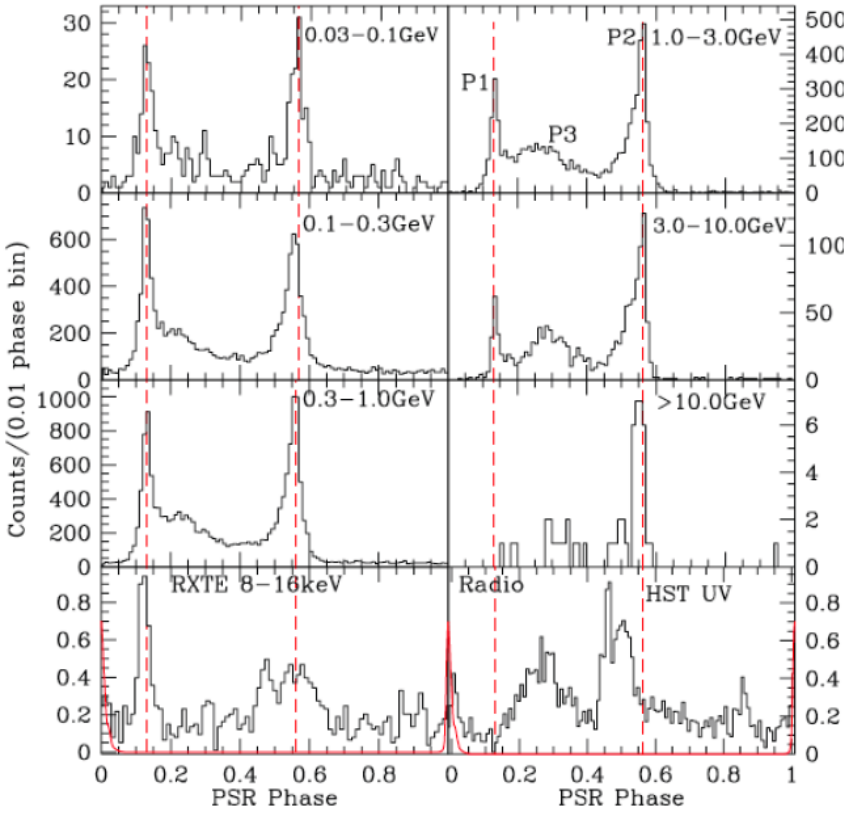
FIG 15.14
M.S. LONGAIR, "HIGH ENERGY ASTROPHYSICS"

117 Gamma-ray Pulsars

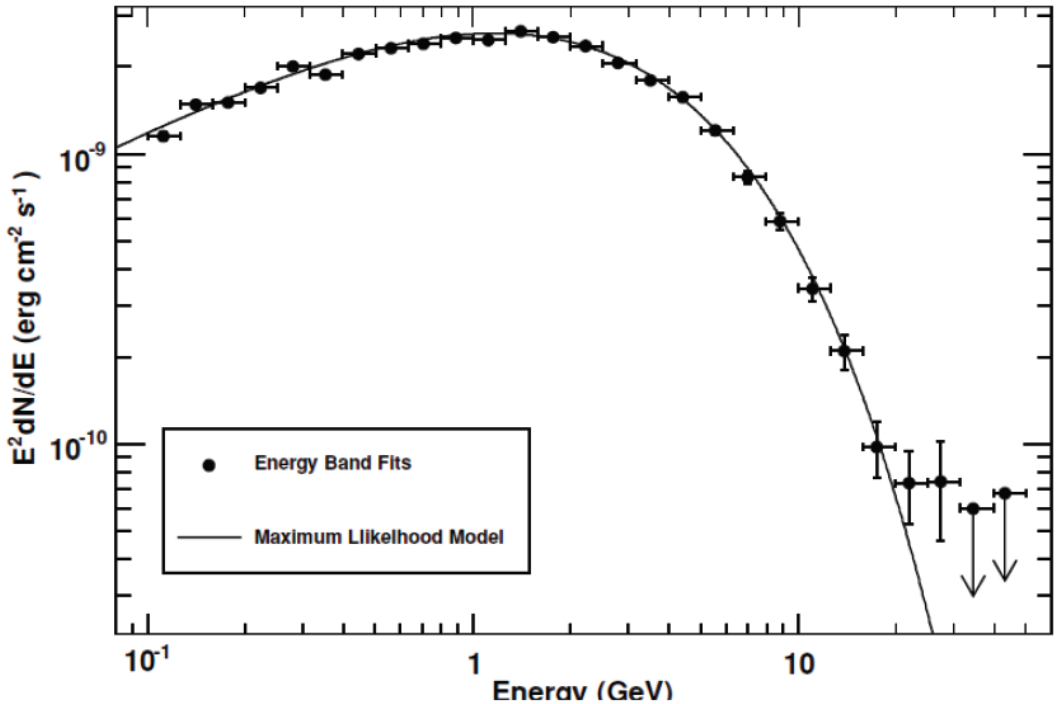


- Second Fermi-LAT pulsar catalog

VELA



Light Curves

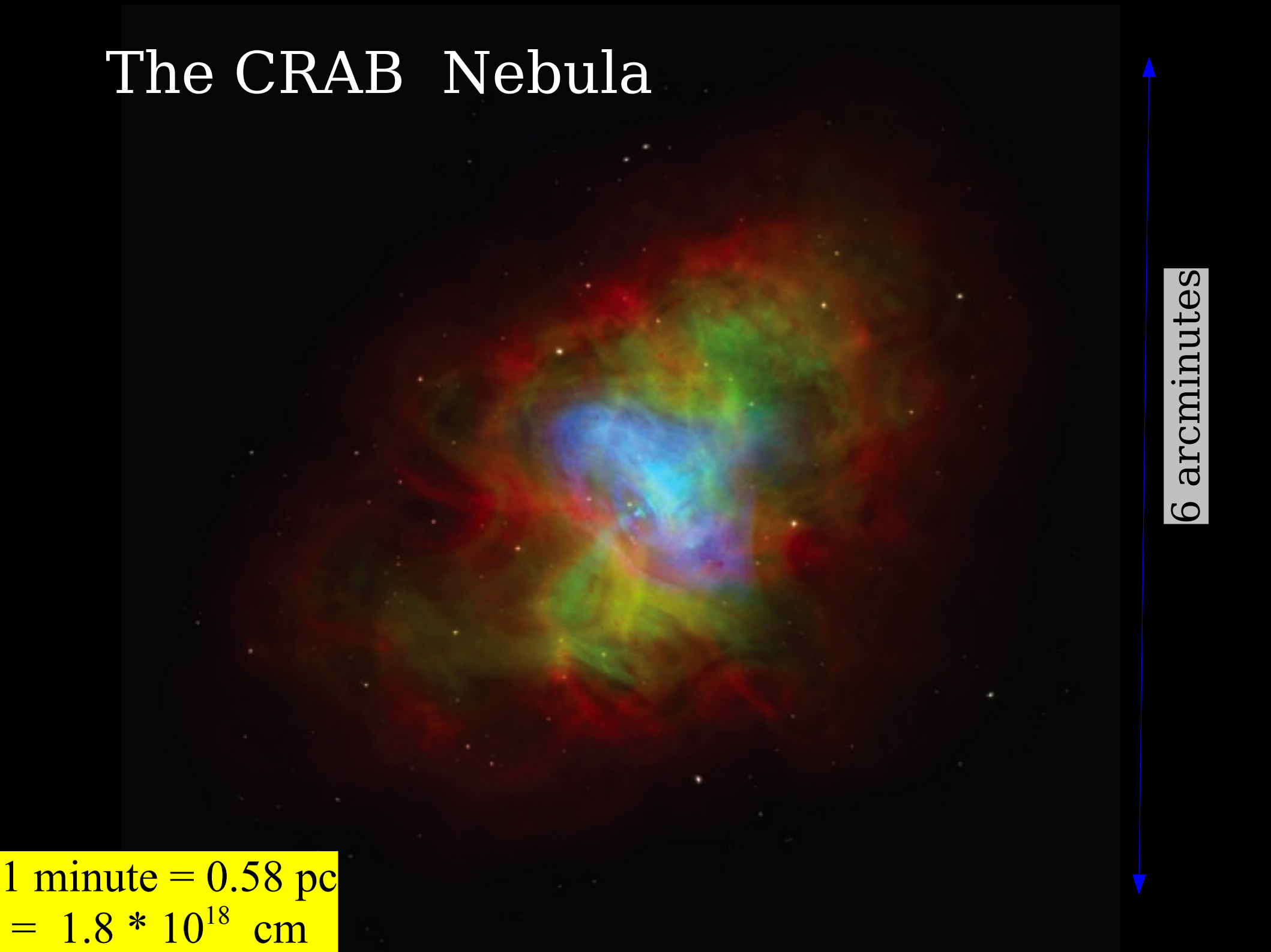


Energy spectrum

$$N(E) \propto E^{-\Gamma_\gamma} \exp[-(E/E_c)^b]$$

Fig. 4. Vela light curves at optical, X-ray, and γ-ray energies [58], binned to 0.01 of the pulsar phase. The main peaks P1, P2 and P3 are labeled in the top right panel. The bottom left panel shows the 8 – 16 keV *RXTE* light curve [59] along with the radio pulse profile (dashed lines). At lower right, the 4.1 – 6.5 eV *HST*/STIS NUV light curve [60] is shown.

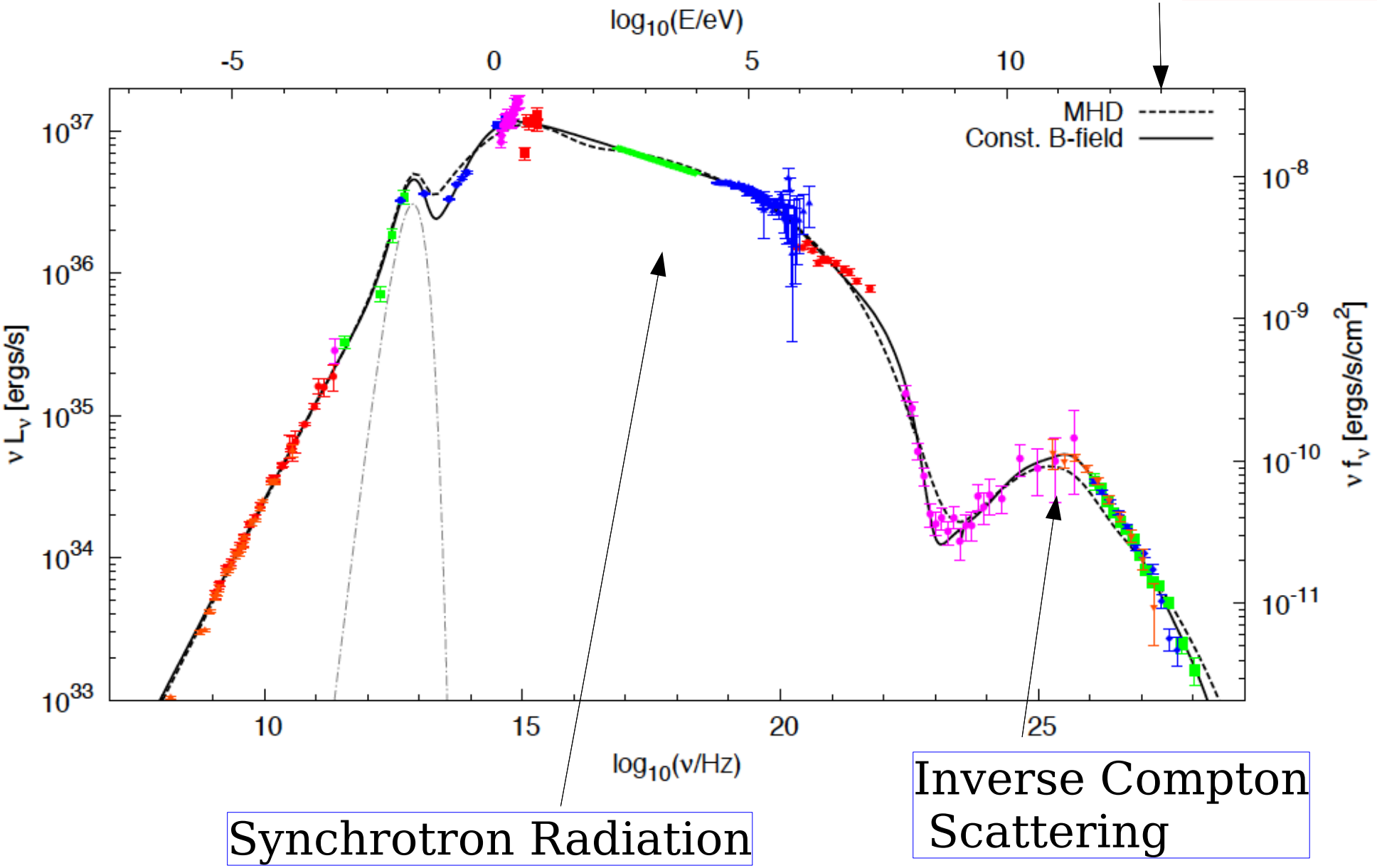
The CRAB Nebula



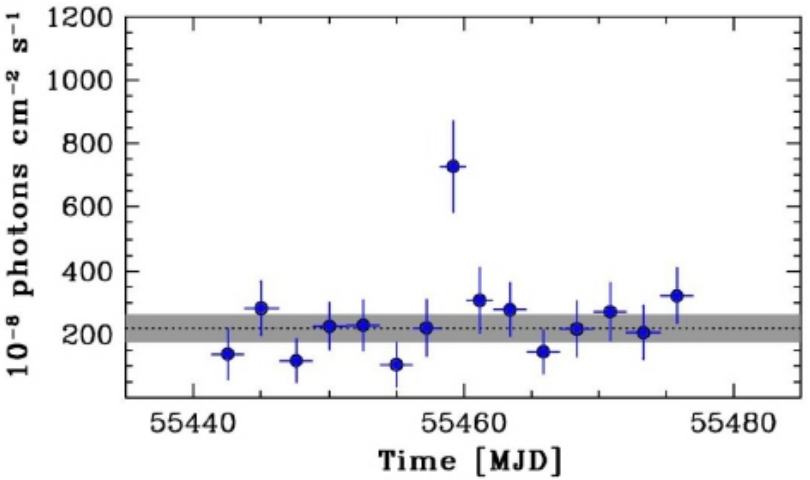
CRAB Nebula Energy Spectrum

SSC (Self Synchrotron Coompton) model emission

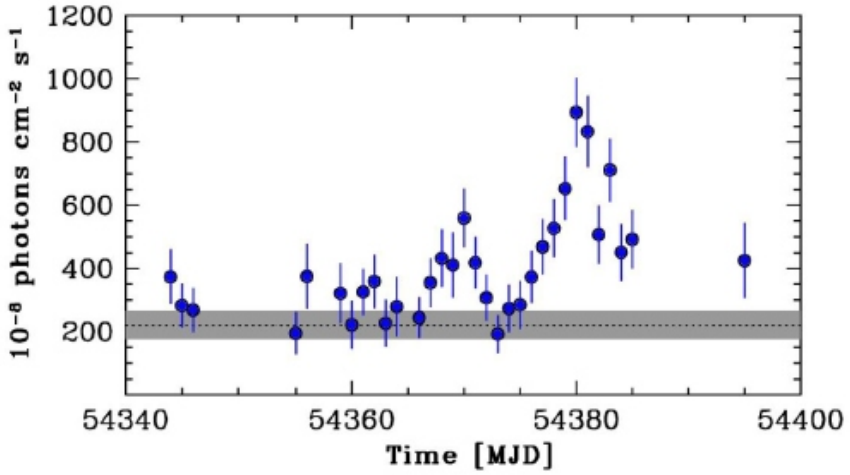
10 TeV !!



AGILE discover of flaring of the CRAB

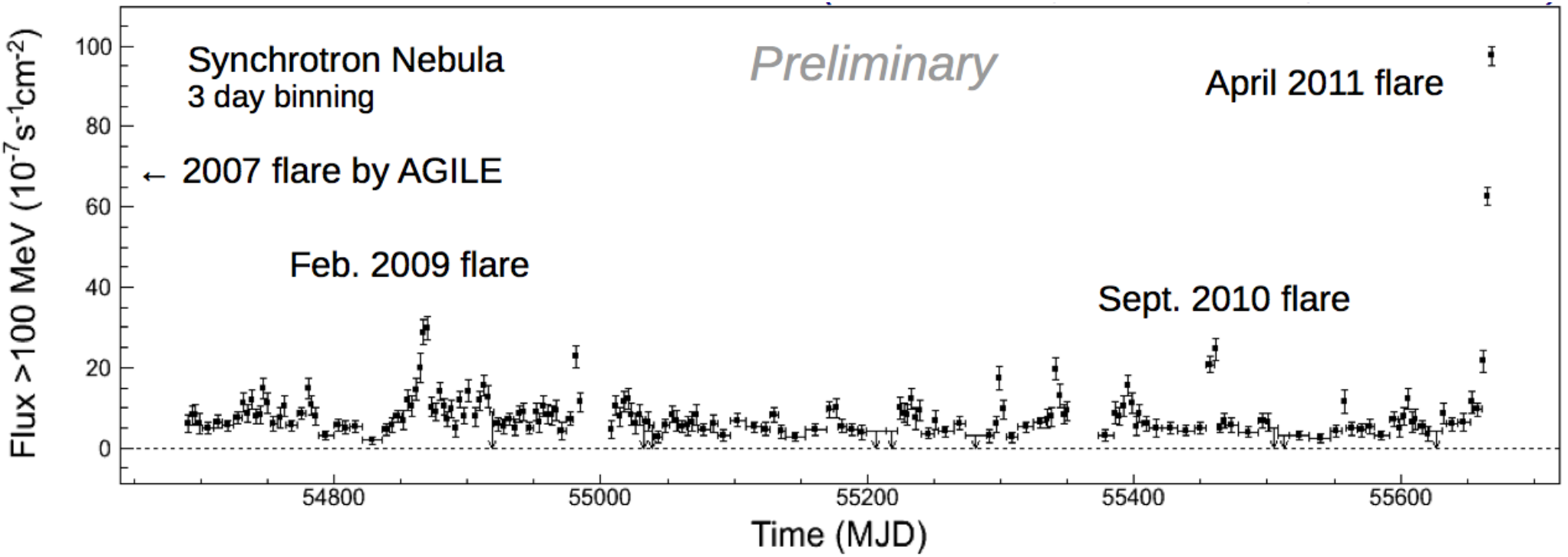


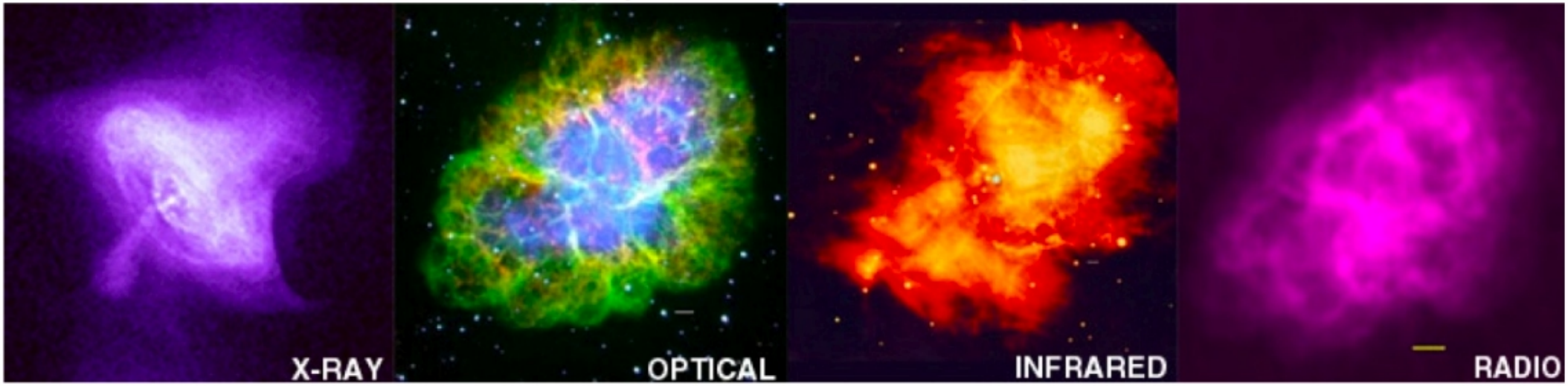
2sep – 8 oct 2010



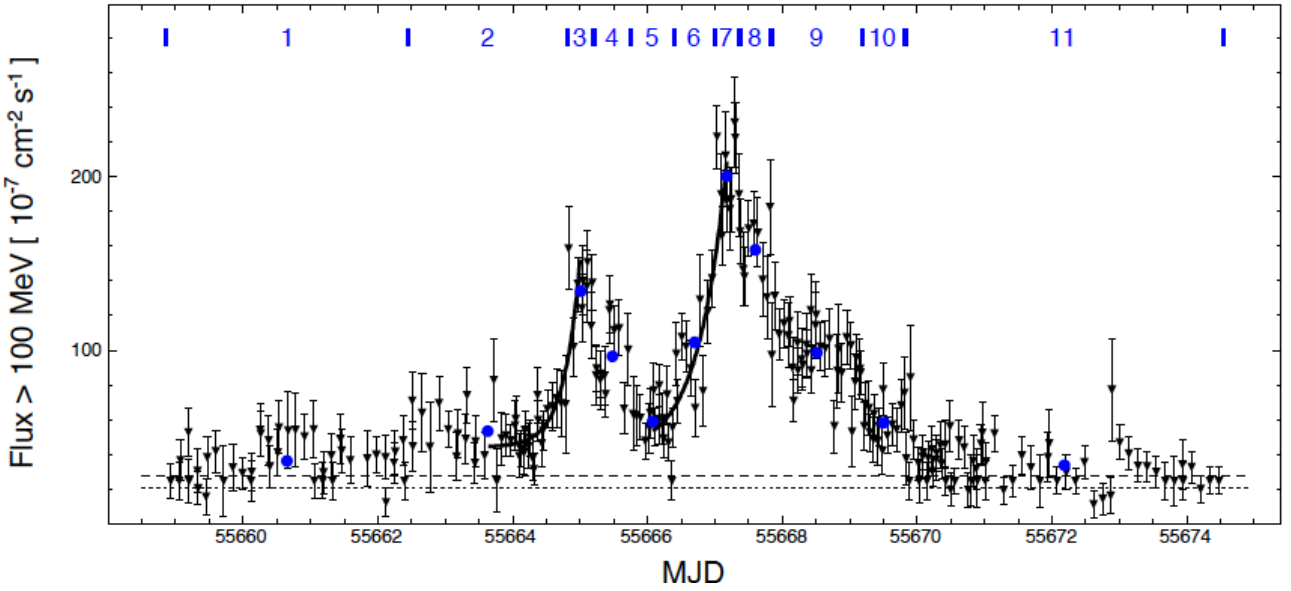
27sep – 12 oct 2007
[discovery “in the drawer”

CRAB NEBULA Flaring [!]





April 2011 CRAB flare



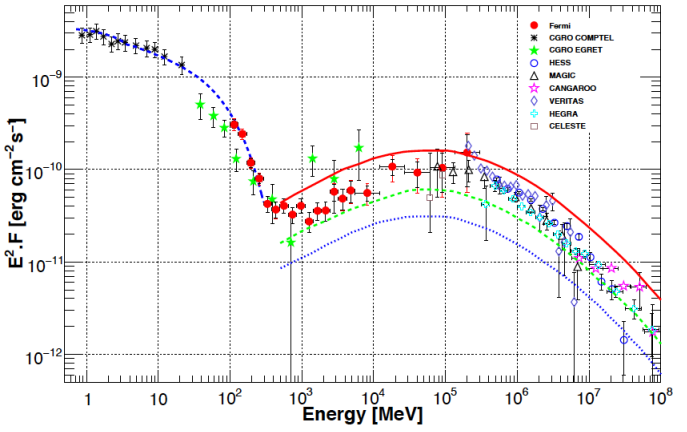
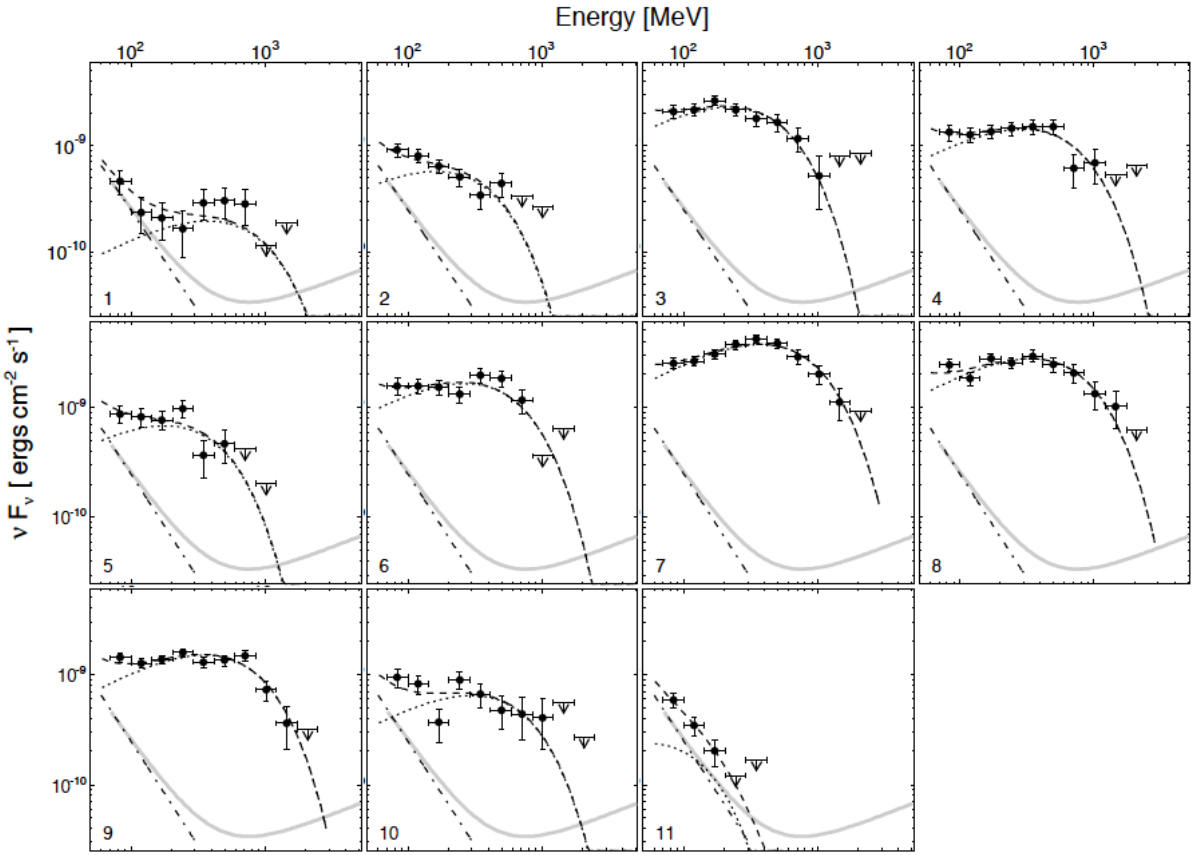
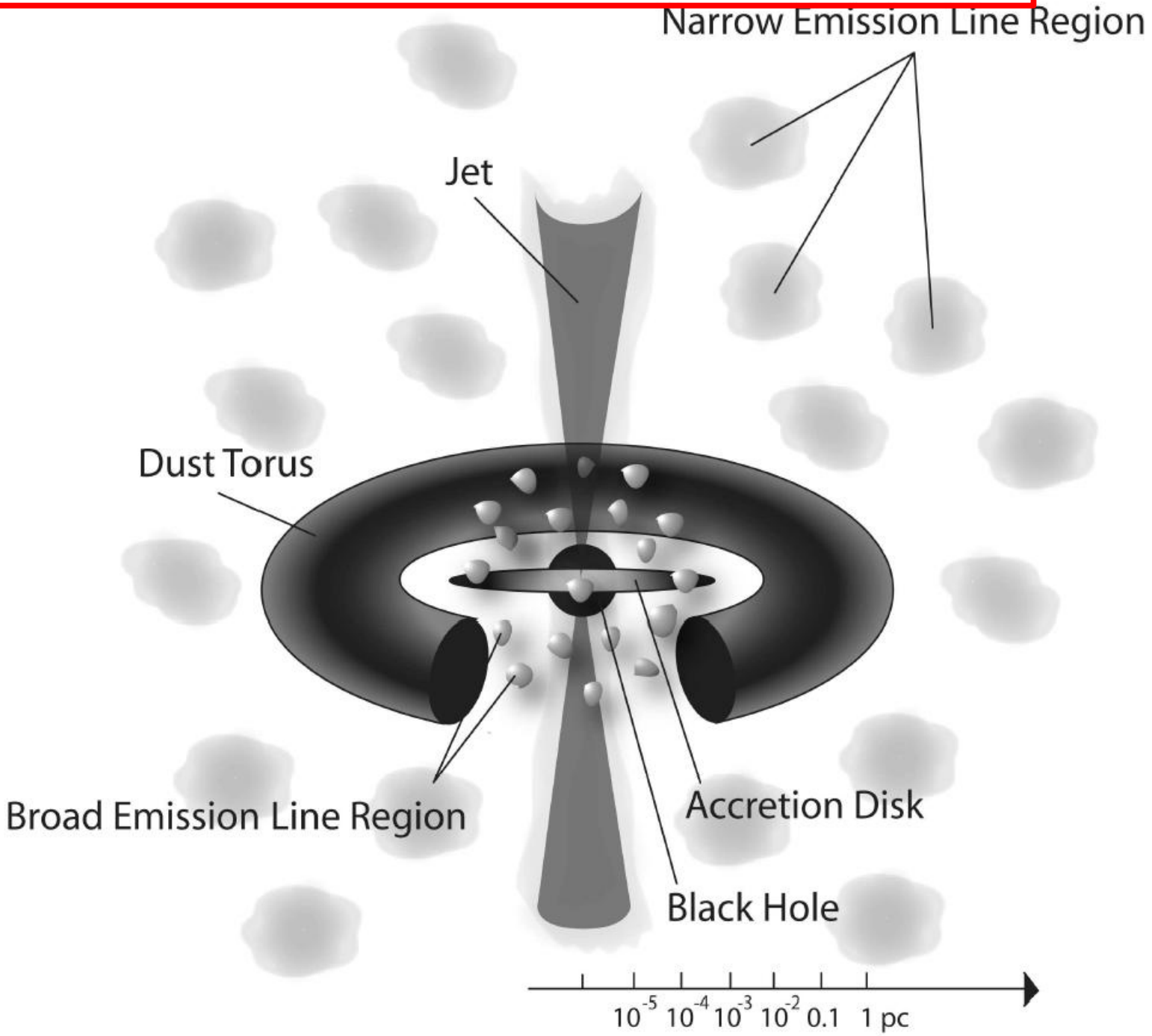


FIG. 9.— The spectral energy distribution of the Crab Nebula from soft to very high energy γ-rays. The fit of the synchrotron component, using COMPTEL and LAT data (blue dashed line), is overlaid. The predicted inverse Compton spectra from Atoyan and Aharonian (1996) are overlaid for three different values of the mean magnetic field: 100 μG (solid red line), 200 μG (dashed green line) and the canonical equipartition field of the Crab Nebula 300 μG (dotted blue line). References: CGRO COMPTEL and EGRET: Kuiper et al. (2001); MAGIC: Albert et al. (2008); HESS: Aharonian et al. (2006); CANGAROO: Tanimori et al. (1997); VERITAS: Celik (2007); **HEGRA: Aharonian et al. (2004); CELESTE: Smith et al. (2006)**

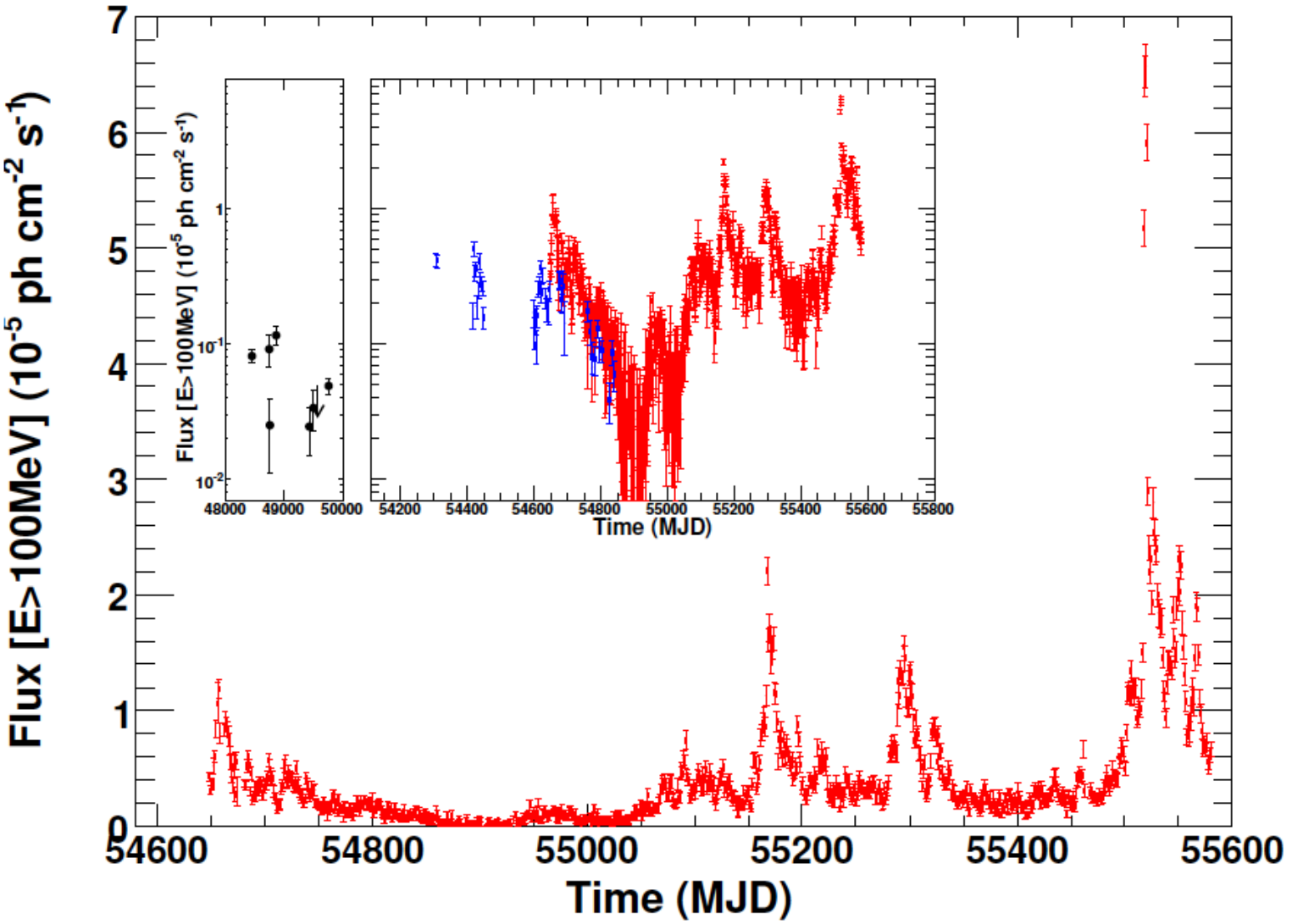


ACTIVE GALACTIC NUCLEI

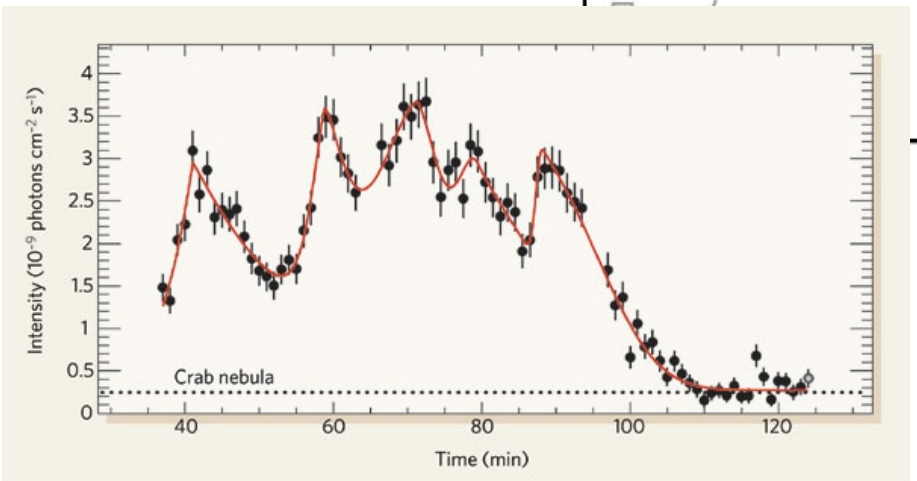


Mk 501

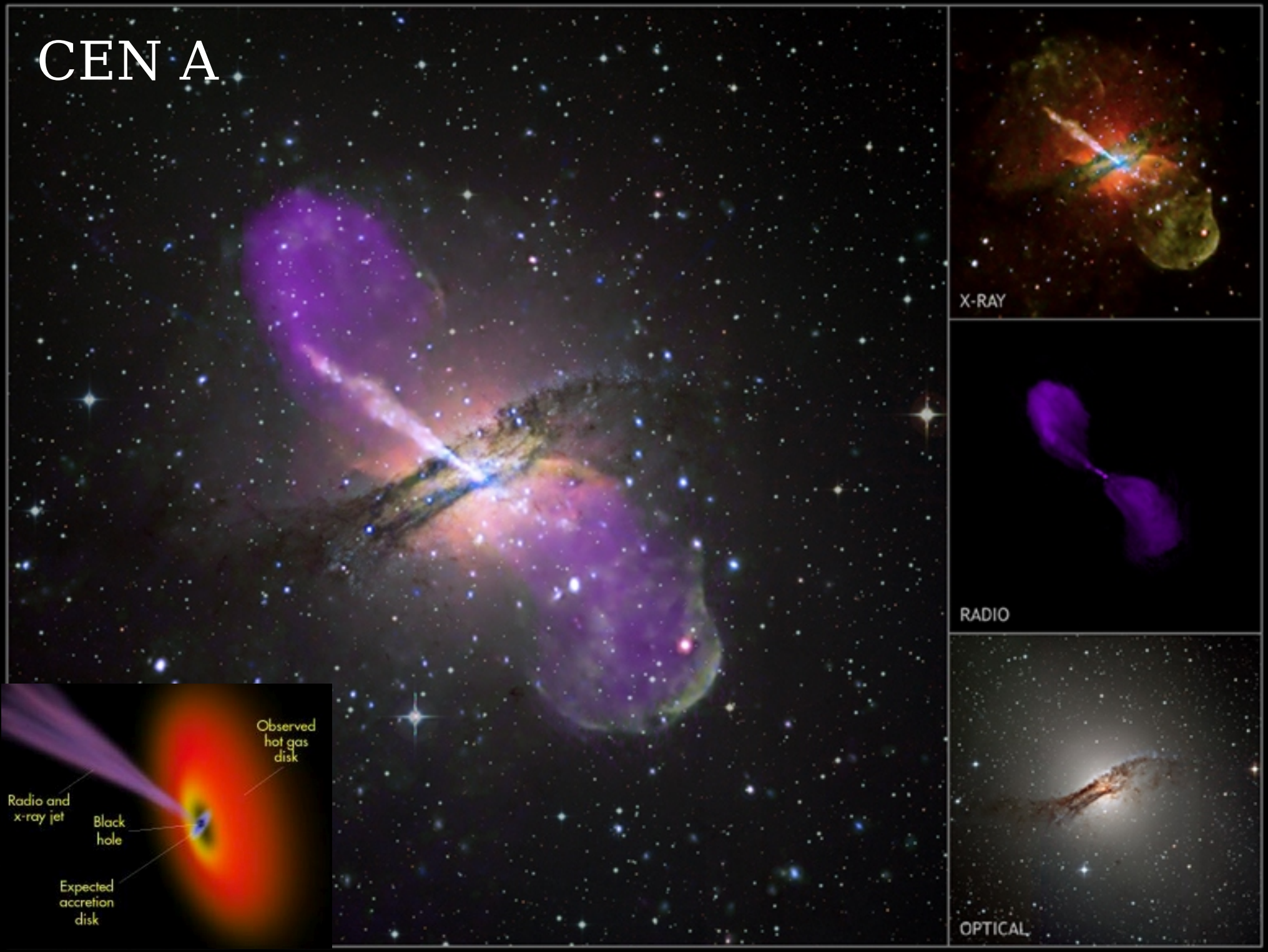
$$L_{iso} \approx 10^{50} \text{ erg s}^{-1}$$



PKS 2155-304



(Very rapid time variations)

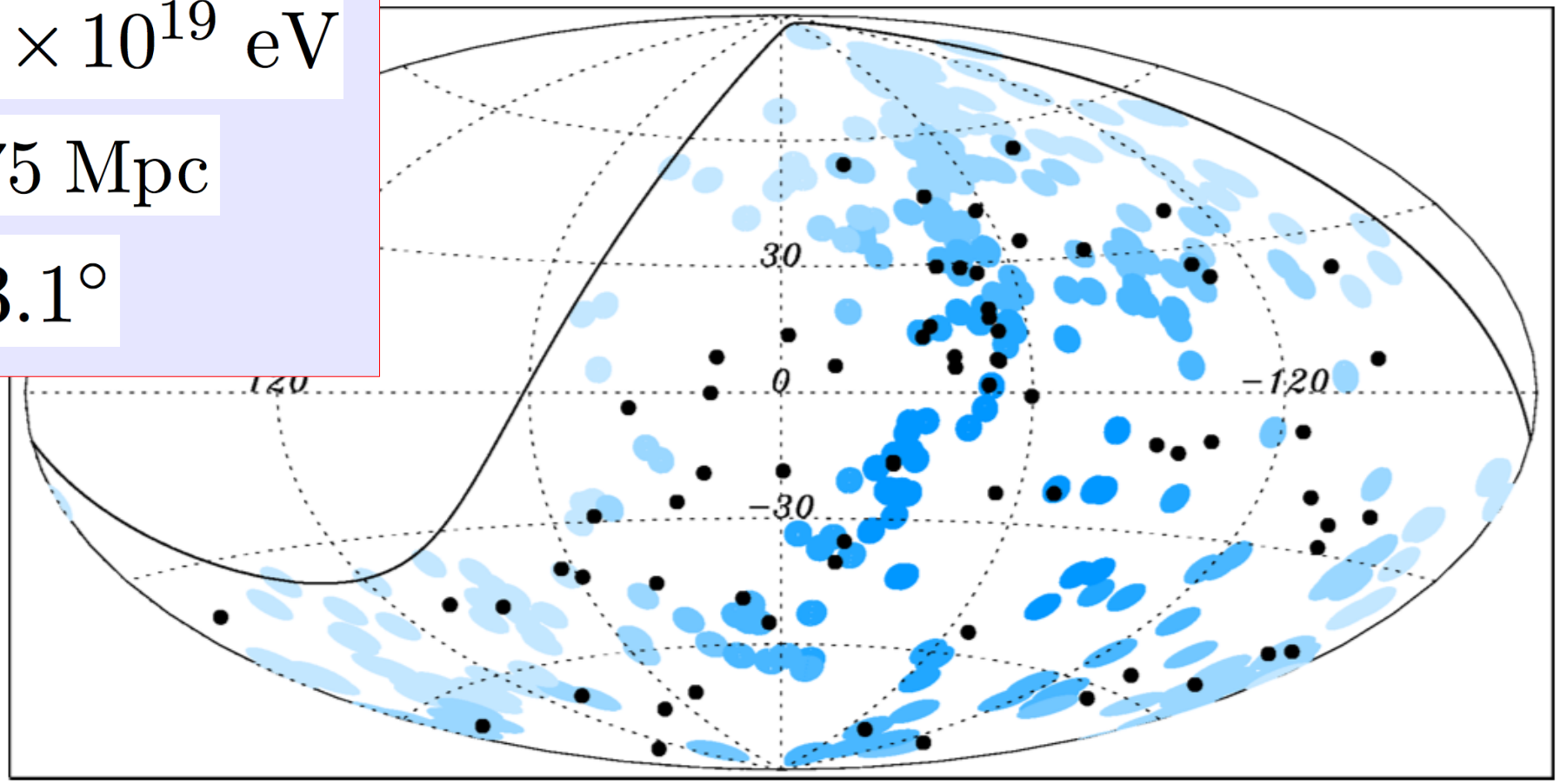

CEN A
X-RAY
RADIO
OPTICAL
Observed hot gas disk
Radio and x-ray jet
Black hole
Expected accretion disk

AUGER result on Correlations with the VCV AGN catalogue
November 2008. Update september 2010.

6×10^{19} eV

75 Mpc

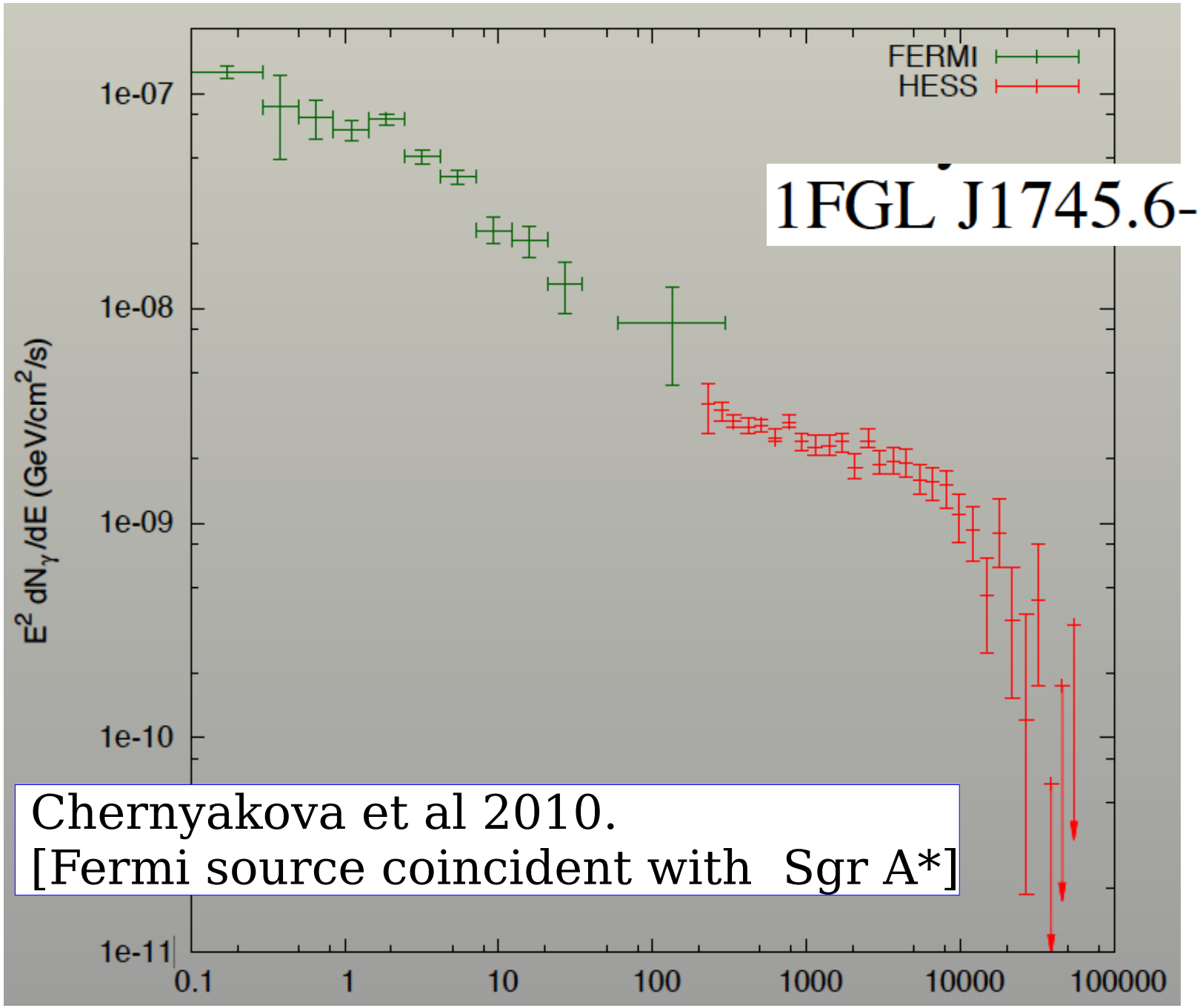
3.1°



Significant dilution
[but not disappearance]
of the statistical significance

14 ev. 8 coincid. (2.9)
13 ev. 9 coincid. (2.7)
42 ev. 12 coincid.(8.8)

Galactic Center

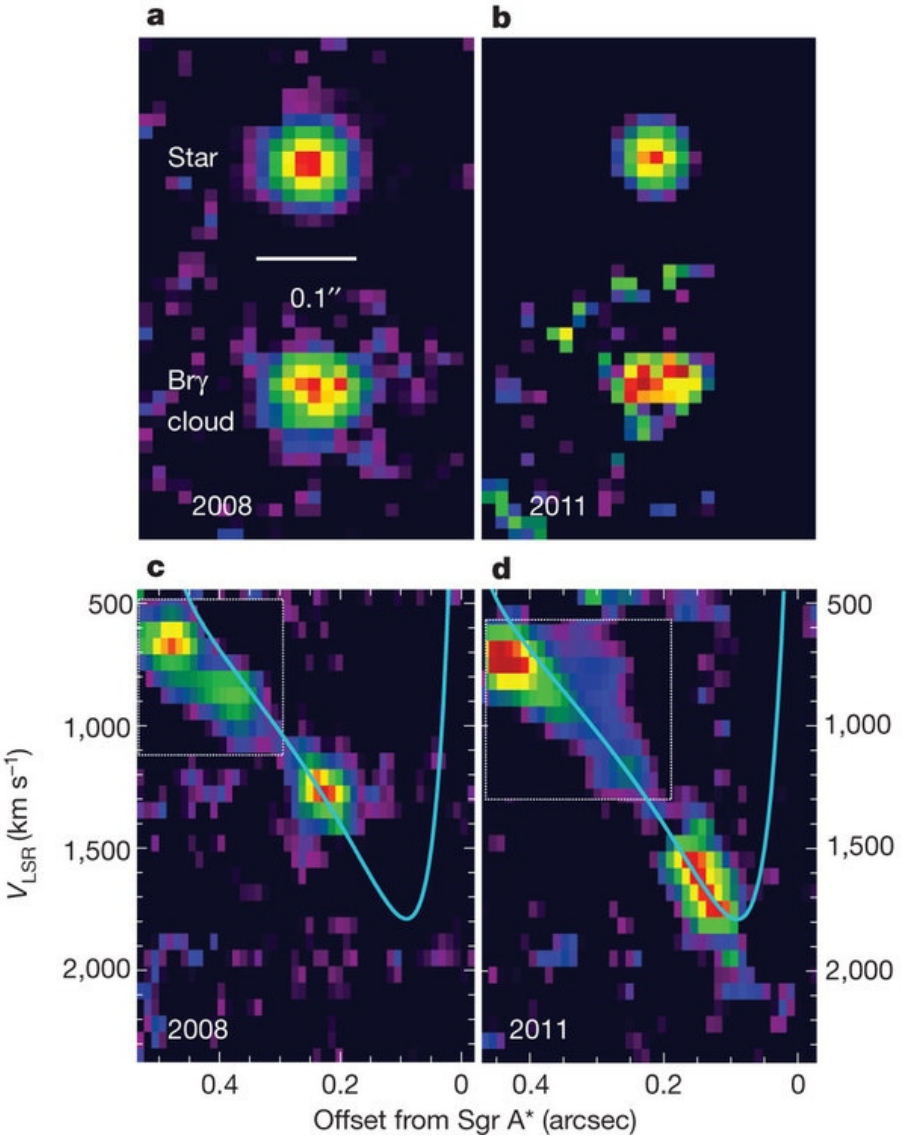


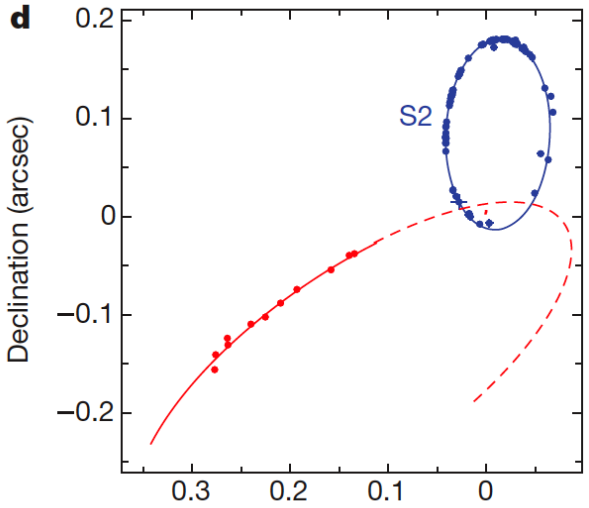
Chernyakova et al 2010.
[Fermi source coincident with Sgr A*]

doi:10.1038/nature10652

A gas cloud on its way towards the supermassive black hole at the Galactic Centre

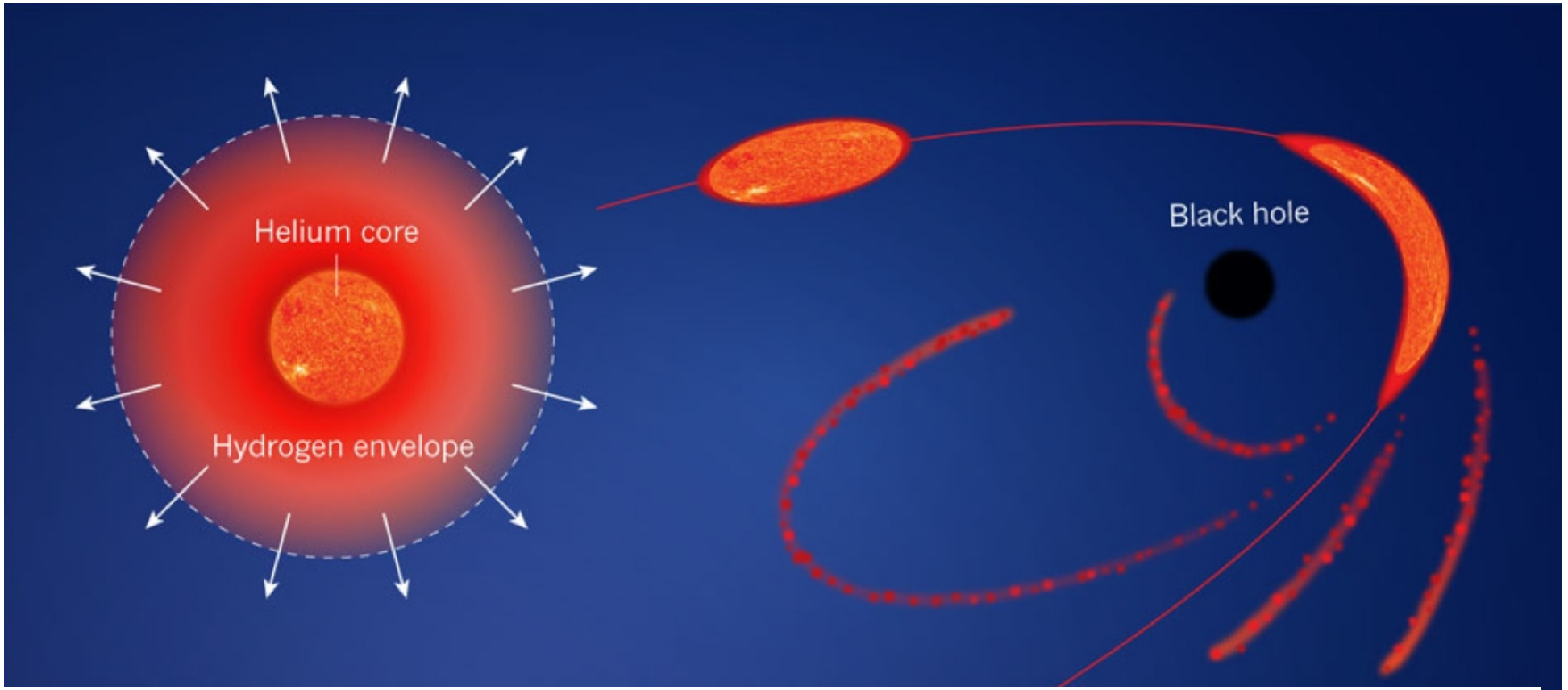
S. Gillessen[1], R. Genzel[1,2], T. K. Fritz[1], E. Quataert[3], C. Alig[4], A. Burkert[4,1], J. Cuadra[5], F. Eisenhauer[1], O. Pfuhl[1], K. Dodds-Eden[1], C. F. Gammie[6] & T. Ott[1]





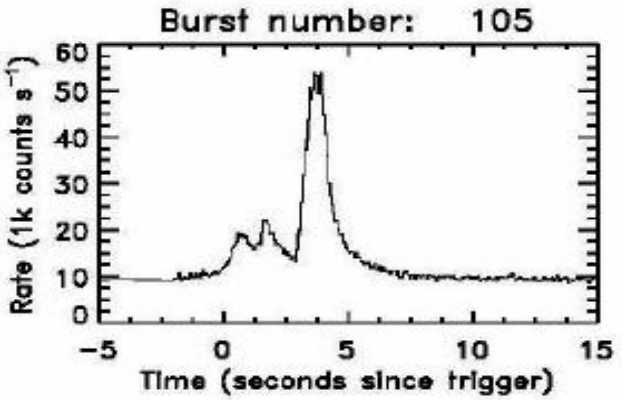
Infalling gas
from the disruption of a star.

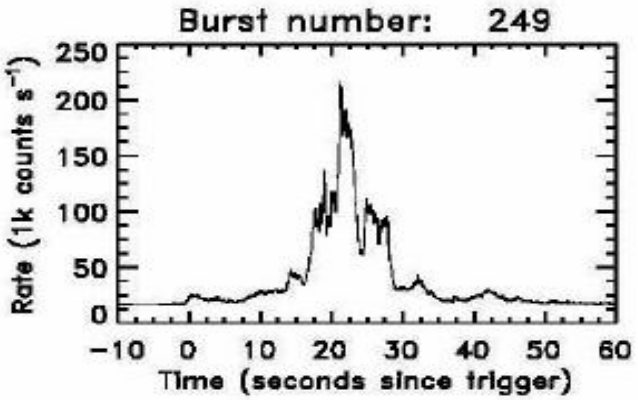
Gas will reach the BH horizon
In 2013

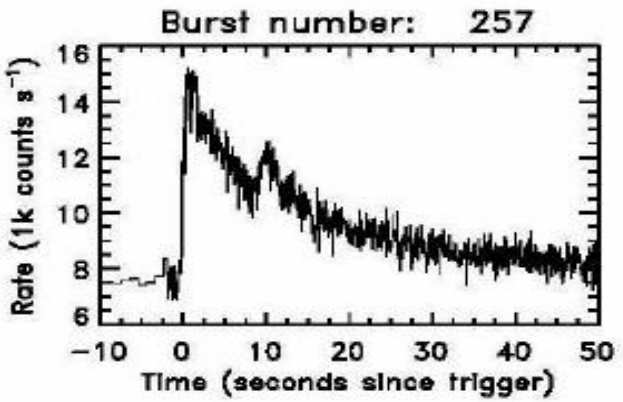


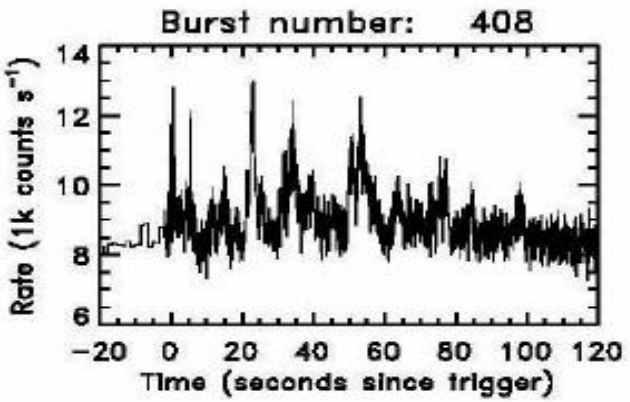
The helium-rich core of a red-giant star that had previously lost its hydrogen envelope moves on an almost parabolic orbit (red) towards a supermassive black hole. The sequence of blobs illustrates the progressive distortion of the star's core due to the tidal pull of the black hole. After the point of closest approach to the black hole, the core is completely disrupted, with part of the resulting debris being expelled from the system and part being launched into highly eccentric orbits, eventually falling onto the black hole. Accretion of this debris gives rise to the intense ultraviolet–optical flare that has been observed by Gezari and colleagues[1].

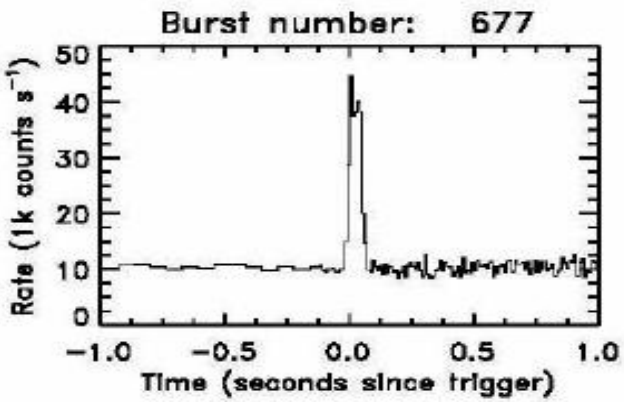
GAMMA RAY BURSTS (GRB's)

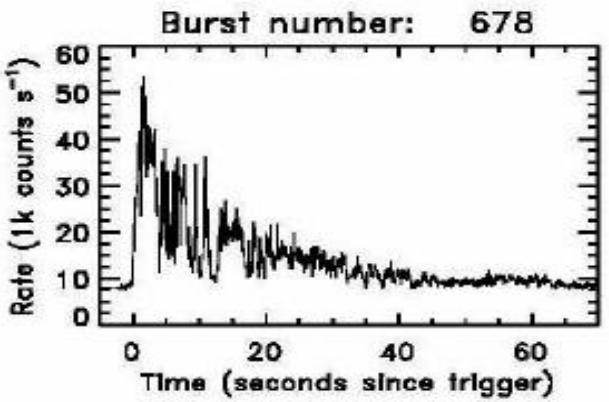




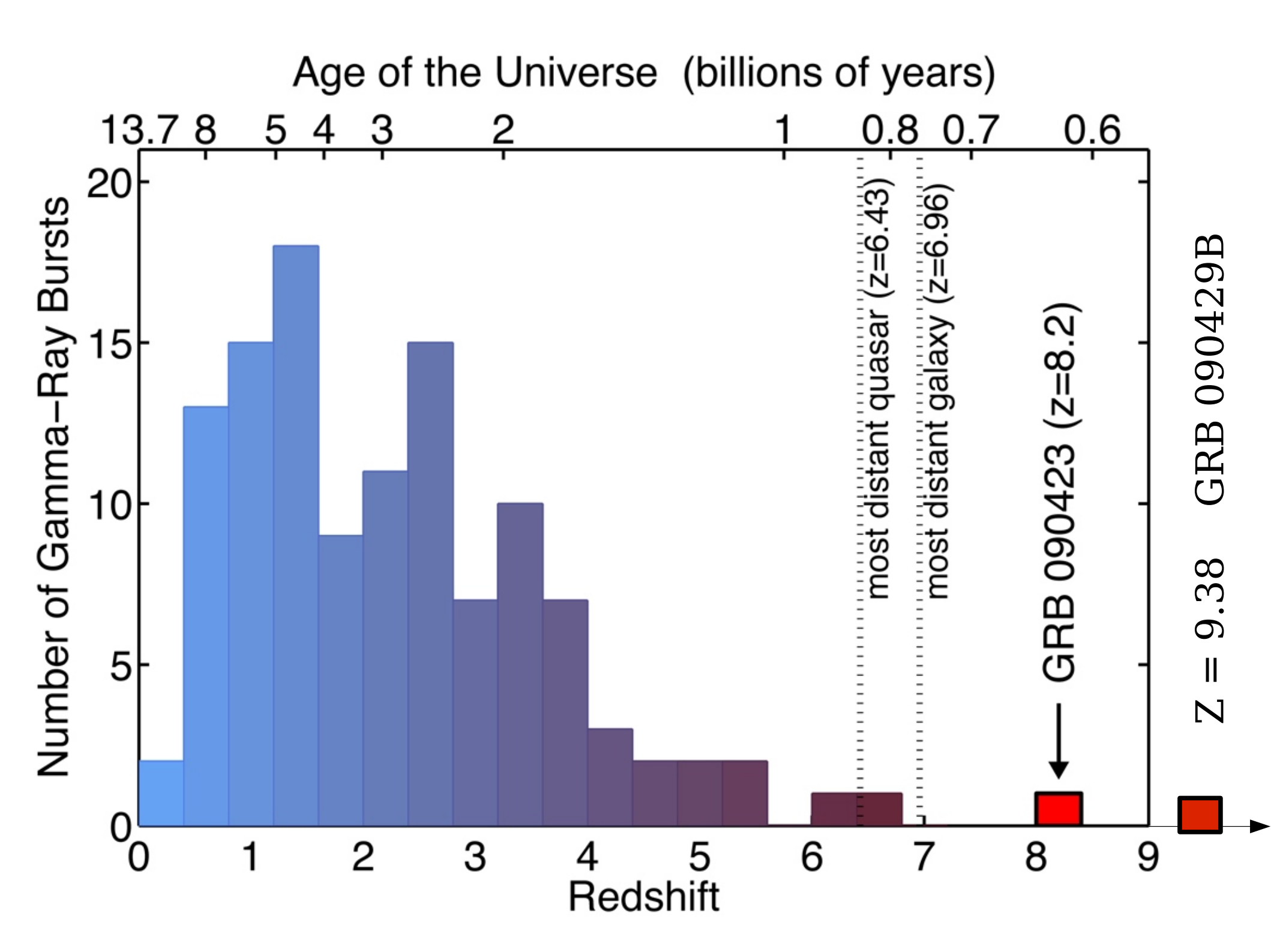






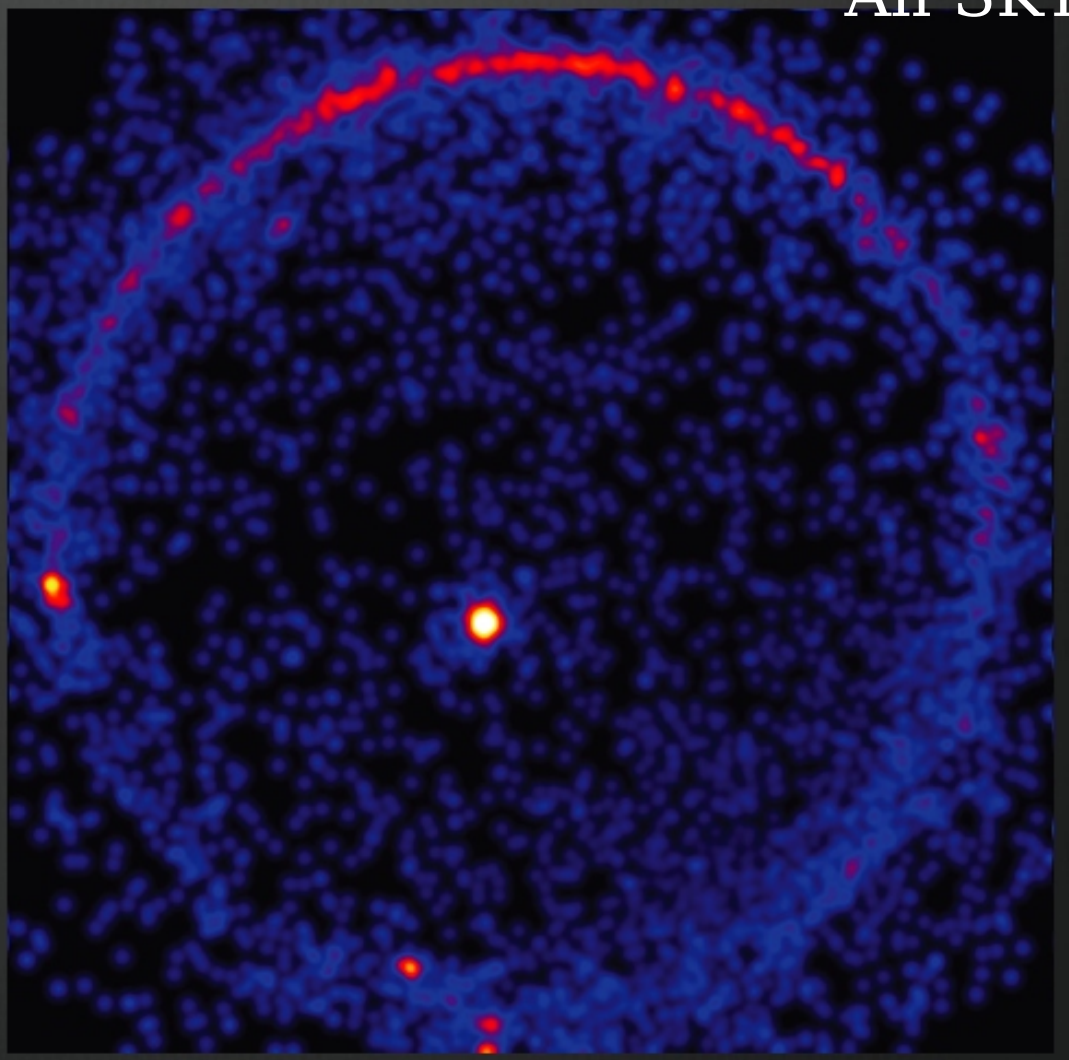


Proposed source of the CR


Age of the Universe (billions of years)
13.7
8
5
4
3
2
1
0.8
0.7
0.6
Number of Gamma–Ray Bursts
0
5
10
15
20
0
1
2
3
4
5
6
7
8
9
Redshift
most distant quasar (z=6.43)
most distant galaxy (z=6.96)
GRB 090423 (z=8.2)
Z = 9.38 GRB 090429B

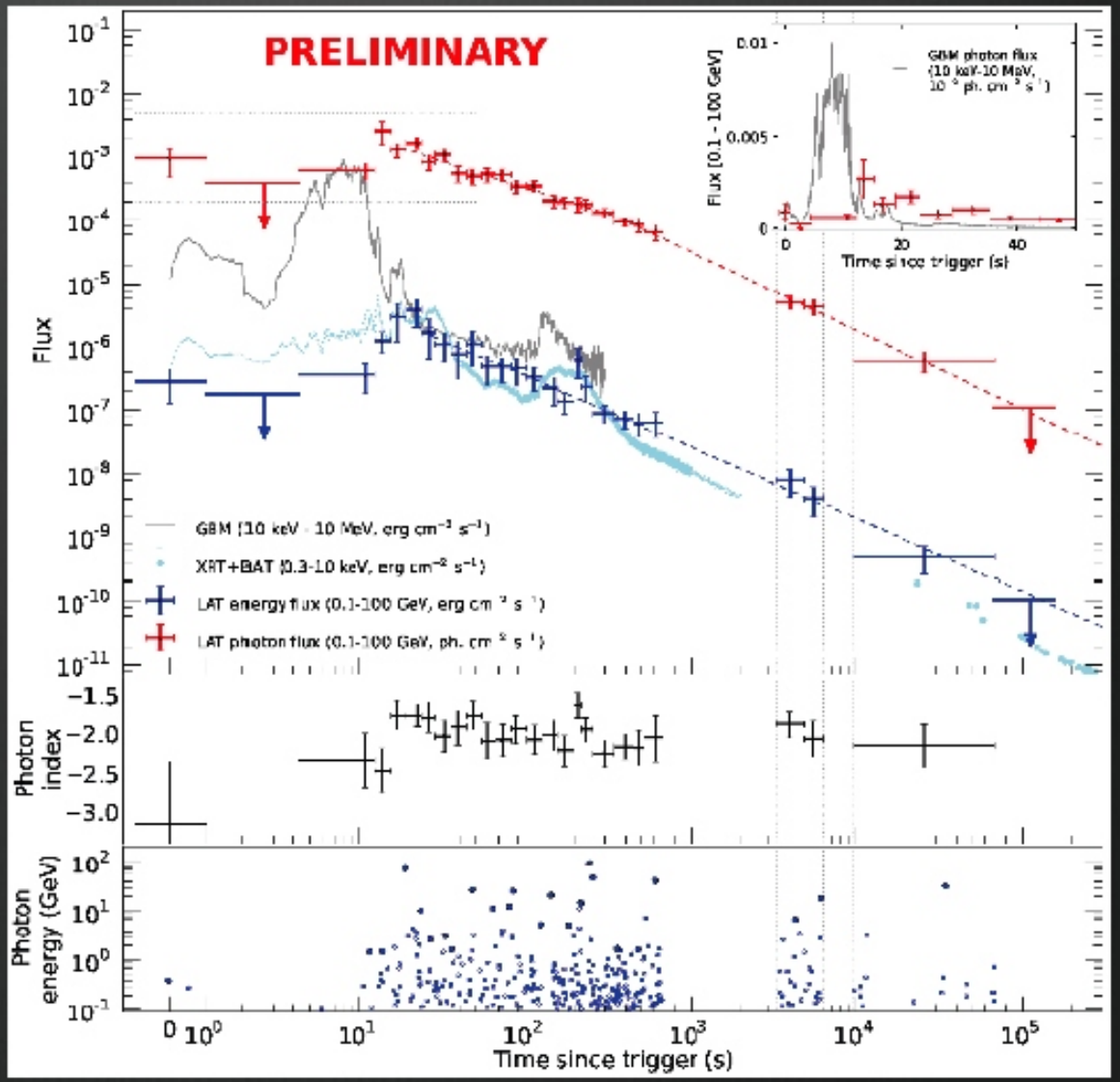
GRB130427A – A nearby ordinary monster

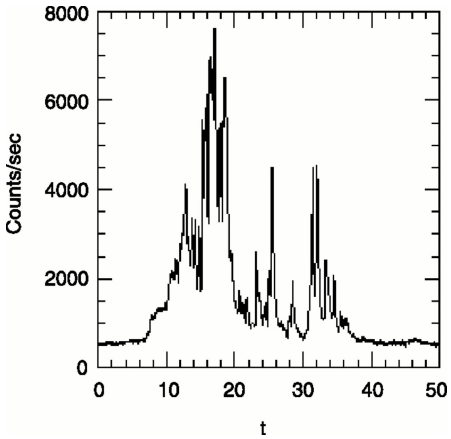
- Redshift = 0.34
- One of the brightest GRBs in gamma-rays ever detected
- Highest energy photon (95 GeV)
- Longest lasting GeV emission – LAT detected emission for over 20 hours



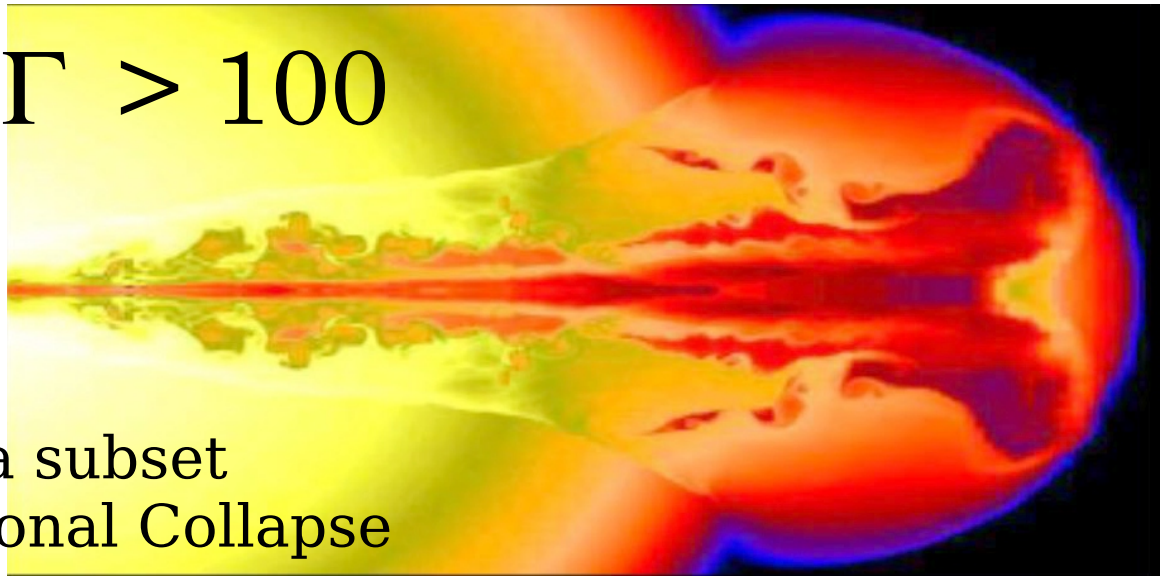
GRB139427A Long lived GeV Emission

- The very high energy photons at late times are inconsistent with the standard model that the afterglow emission is produced by synchrotron emission from electrons accelerated in the forward shock of the ejecta

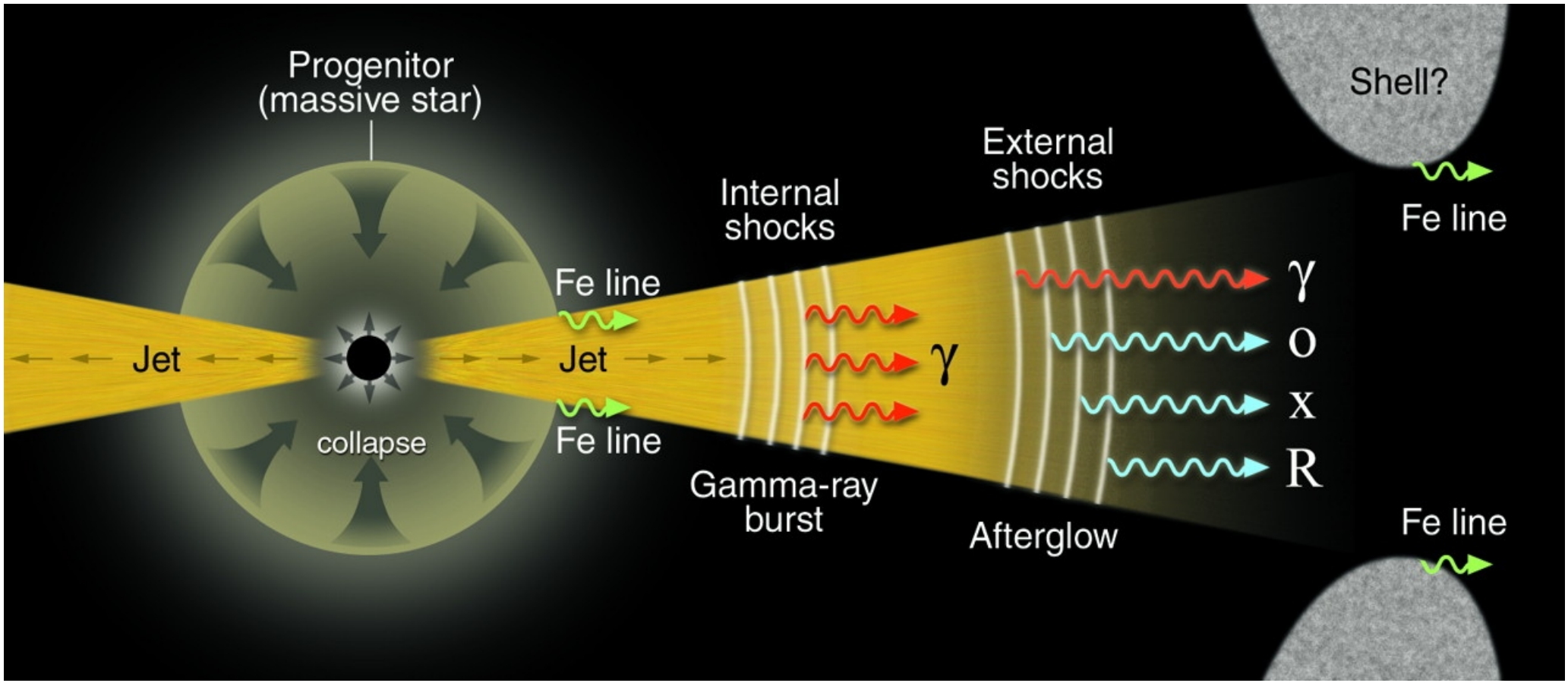




$\Gamma > 100$



GRB : associated with a subset
of SN Stellar Gravitational Collapse



GRBs and Gravitational Waves

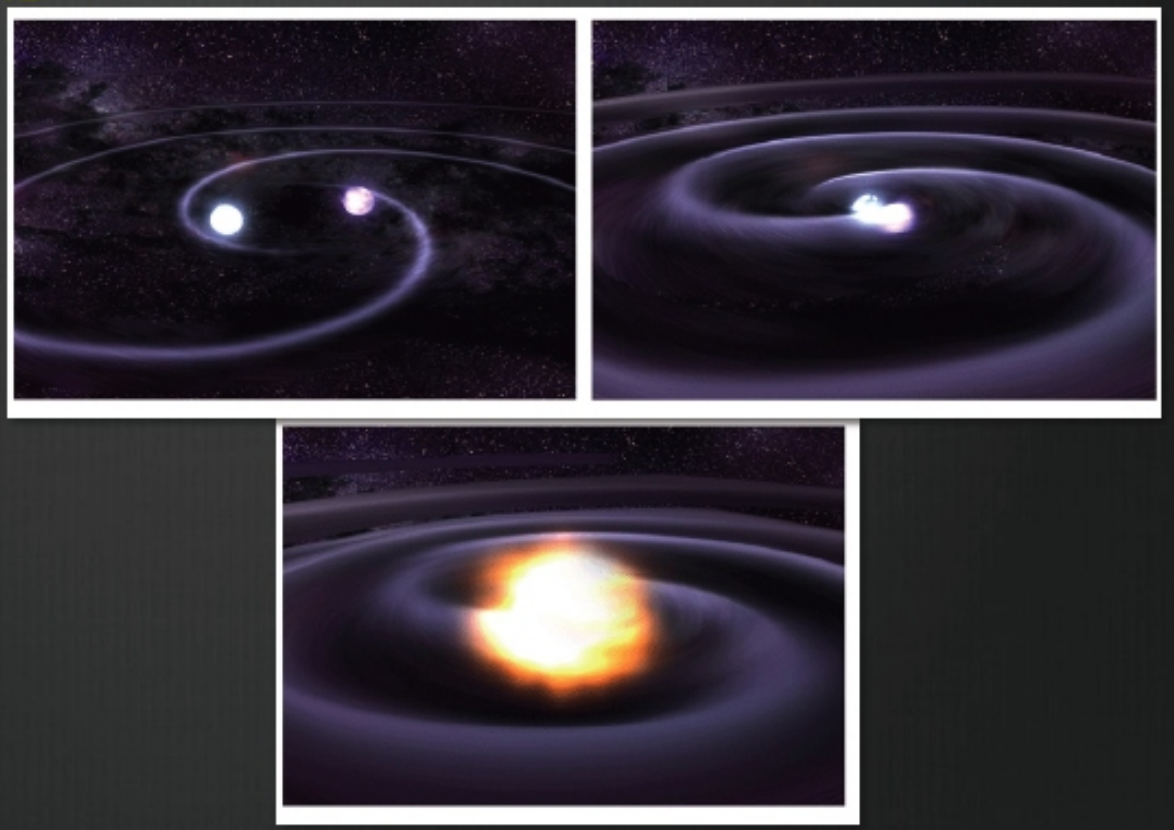
Fermi-GBM and Advanced LIGO (>2016) should see coincident Gravitational wave/Electromagnetic emission or rule out NS-BH mergers as the progenitors of short GRB

Large rate of short bursts in GBM is key to coincident detections

GBM Short GRBs in ALIGO horizon:

$N(z<0.11, \text{NS-NS}) \sim 2^{+4}_{-1}\ \text{yr}^{-1}$

$N(z<0.22, \text{NS-BH}) \sim 8^{+6}_{-3}\ \text{yr}^{-1}$



- Both observations bring complementary information: ALIGO → inspiral characteristics ; *Fermi* → jet properties & environment

COSMIC RAY PROPAGATION

Particle propagation Study of “SPACE” (magnetic fields, turbulence,….)

GEOSPHERE

HELIOSPHERE

LOCAL INTERSTELLAR SPACE

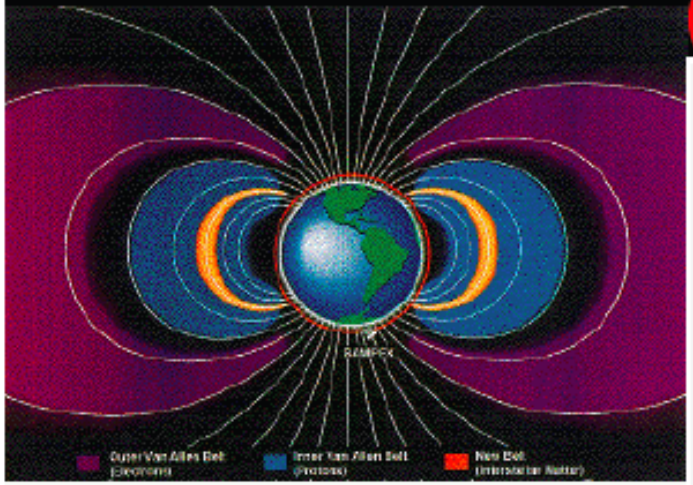
MILKY WAY

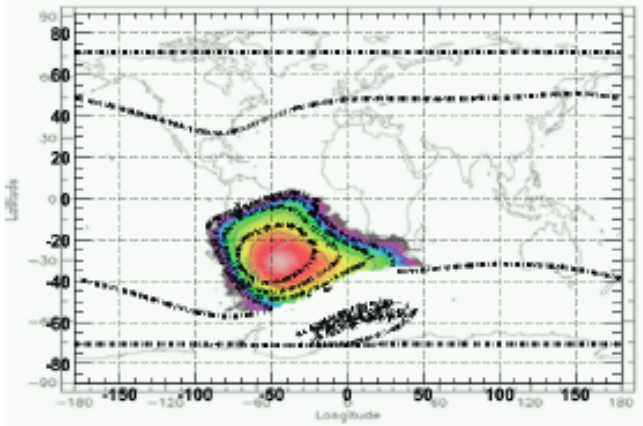
CLUSTERS of GALAXIES

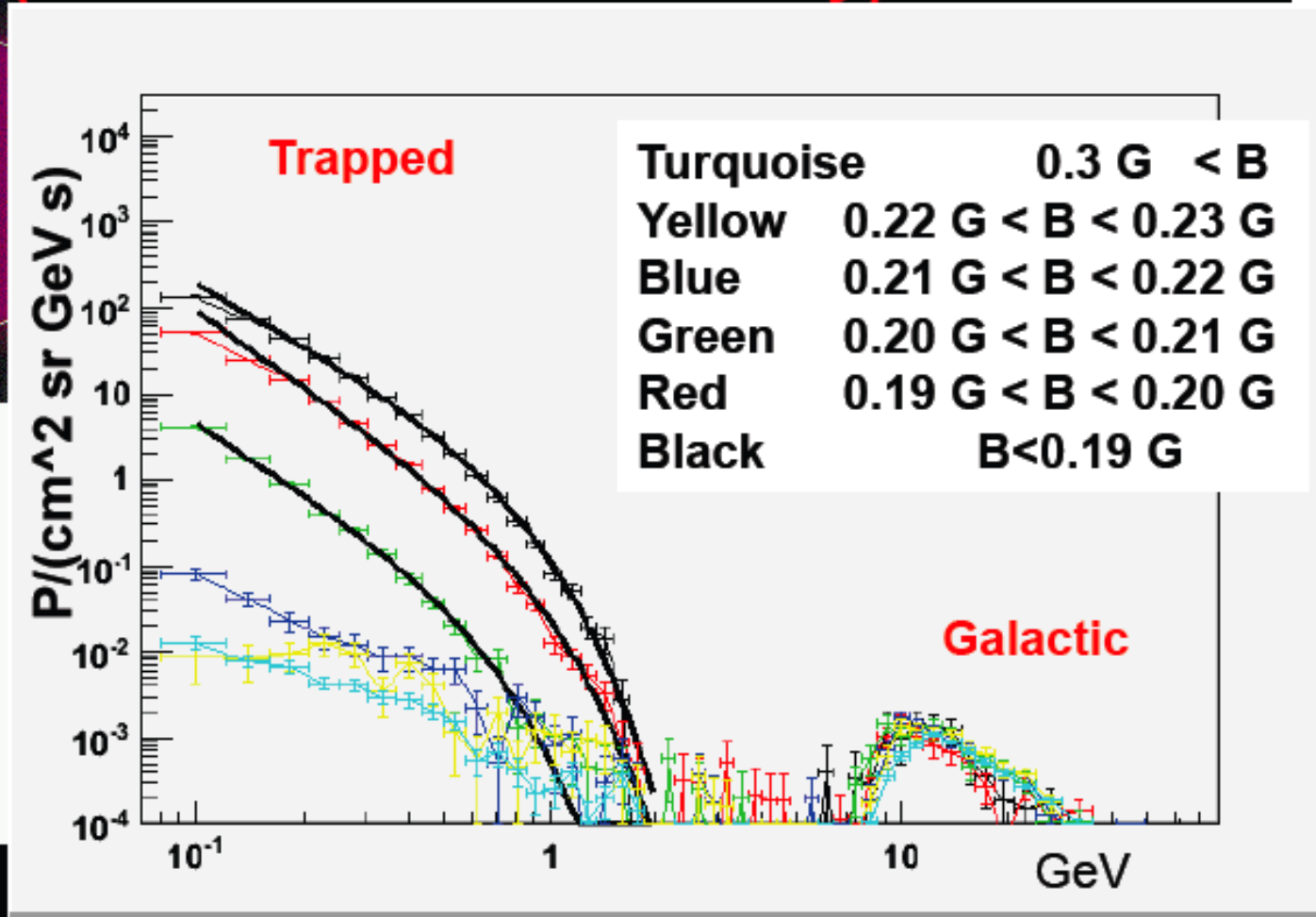
The large scale UNIVERSE

Trapped proton flux in the Van Allen belt (South Atlantic Anomaly)

Arxiv 0810.4980v1





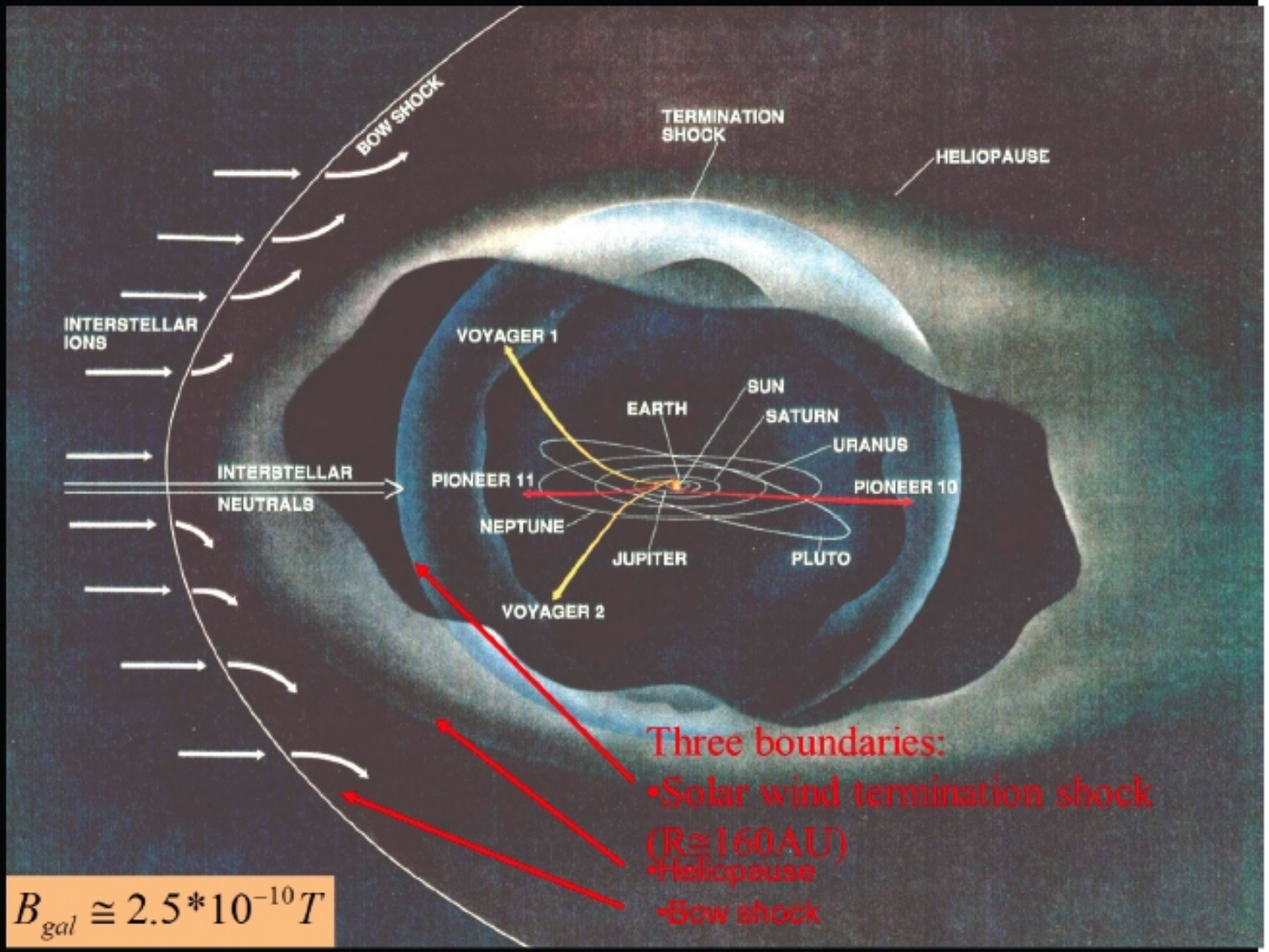


Integral Pamela flux (E>35 MeV)

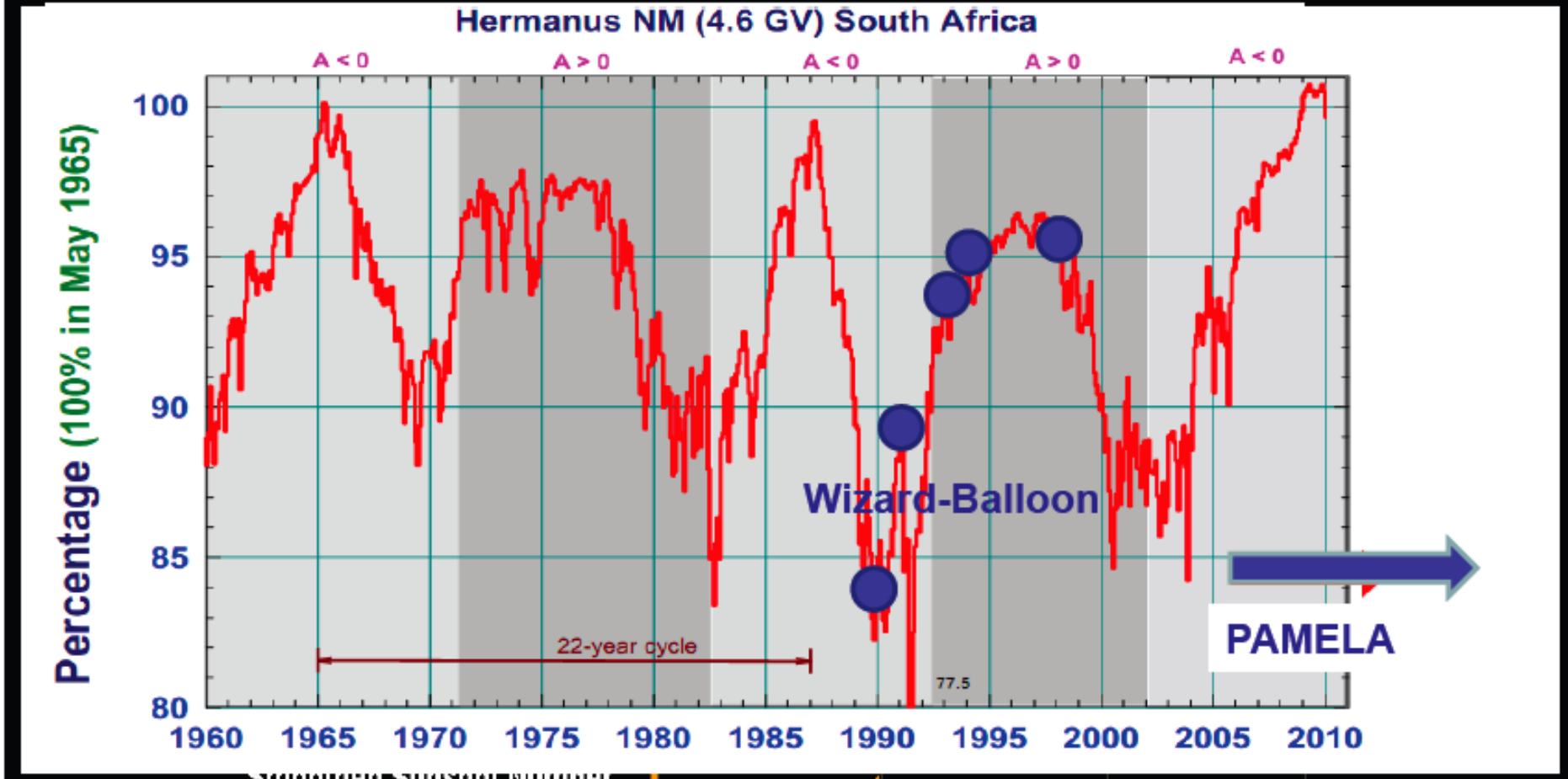
(PSB97 plot by SPENVIS project, model by BIRA-IASB)

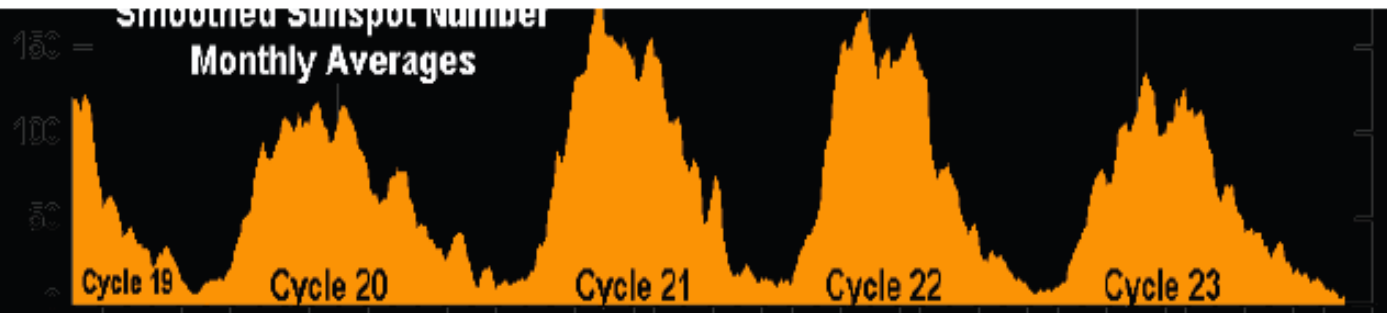
	A	γ_0	γ_1	χ^2/ndf
nero	0.11±0.01	6.0±0.4	3.1±0.5	7.1
rosso	(2.3±0.3) 10^{-2}	5.9±0.5	2.6±0.6	6.8
verde	(5±3) 10^{-4}	8.1±1.8	4.7±1.8	10.

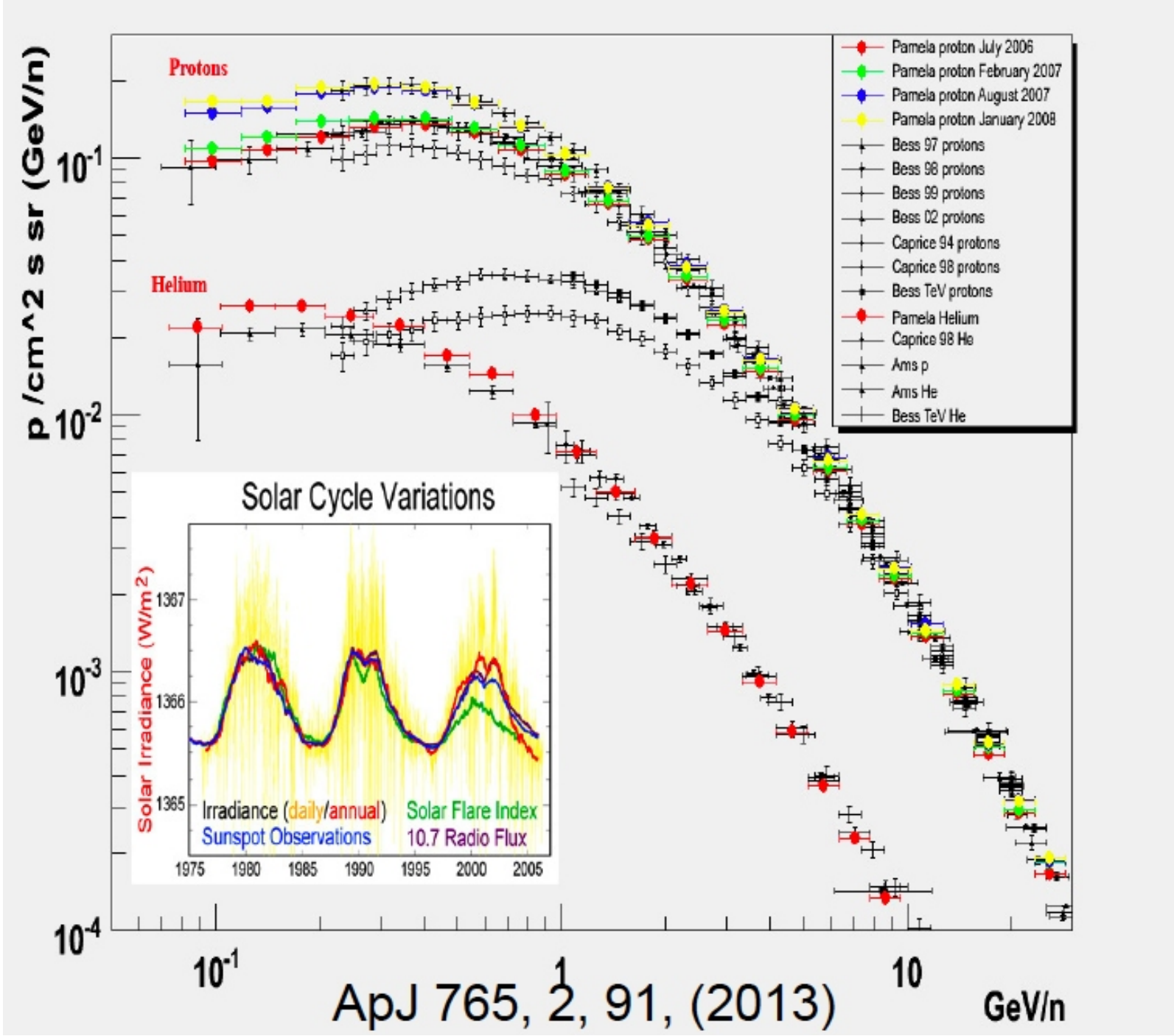
Heliosphere and long term solar modulation (100 AU)

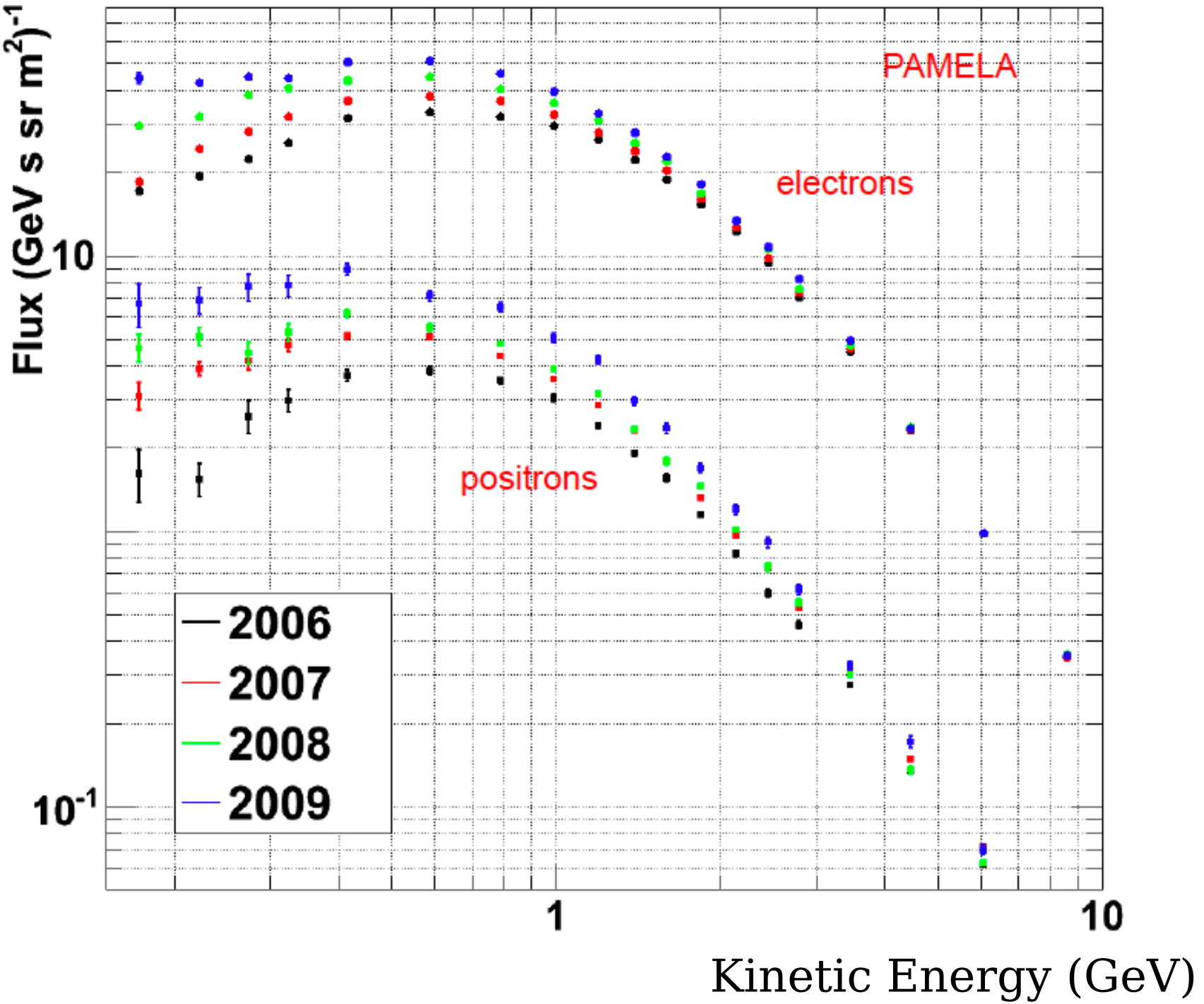


Solar modulation at minimum of solar cycle 23-24: 2006-2013

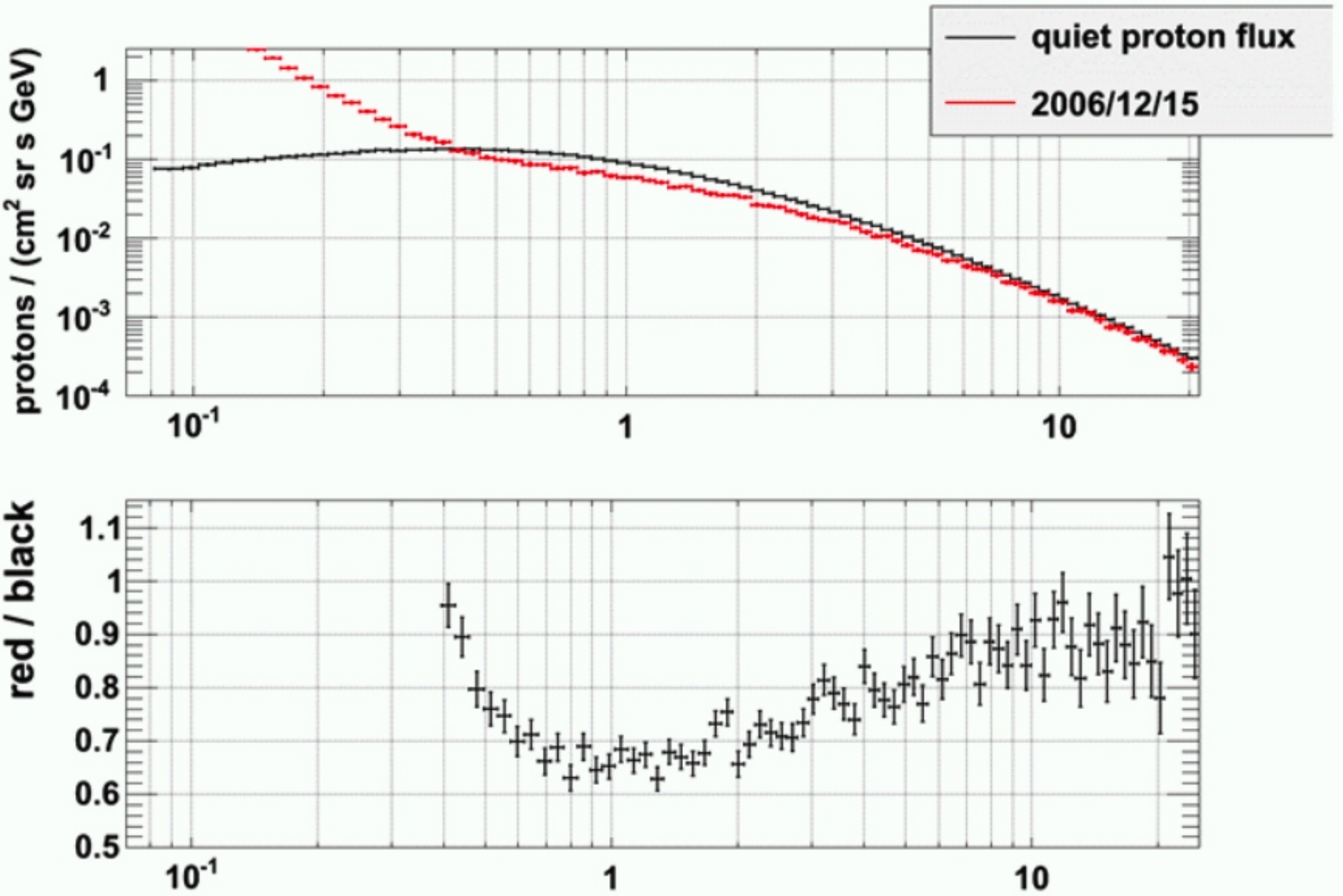




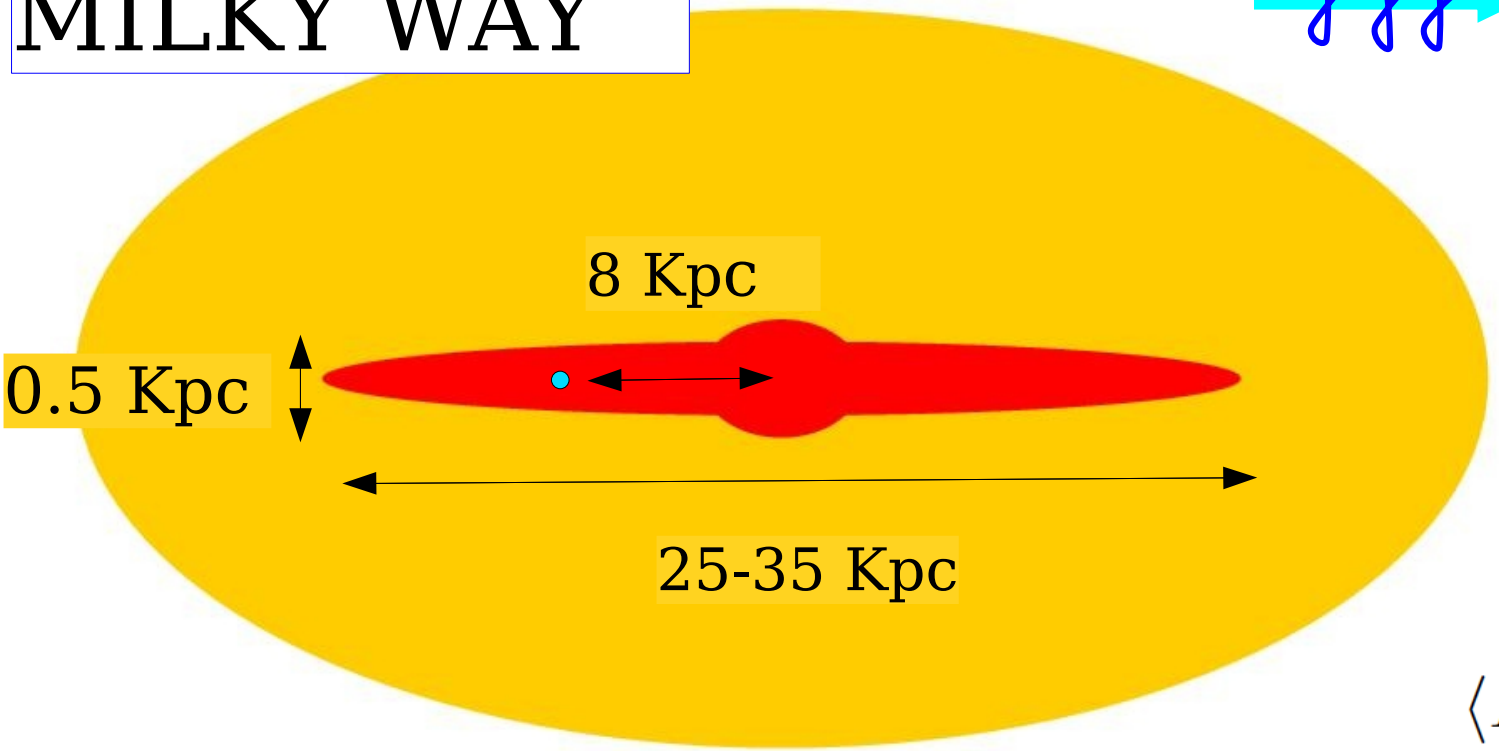

Protons
Helium
Pamela proton July 2006
Pamela proton February 2007
Pamela proton August 2007
Pamela proton January 2008
Bess 97 protons
Bess 98 protons
Bess 99 protons
Bess 02 protons
Caprice 94 protons
Caprice 98 protons
Bess TeV protons
Pamela Helium
Caprice 98 He
Ams p
Ams He
Bess TeV He
p /cm^2 s sr (GeV/n)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Solar Cycle Variations
Solar Irradiance (W/m 2)
1367
1366
1365
1975
1980
1985
1990
1995
2000
2005
Irradiance (daily/annual)
Sunspot Observations
Solar Flare Index
10.7 Radio Flux
10^{-1}
1
10
GeV/n
ApJ 765, 2, 91, (2013)

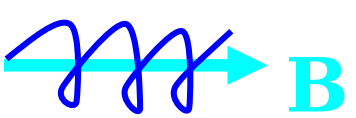

PAMELA
electrons
positrons
2006
2007
2008
2009
Flux (GeV s sr m^2)$^{-1}$
10
10^{-1}
1
10
Kinetic Energy (GeV)

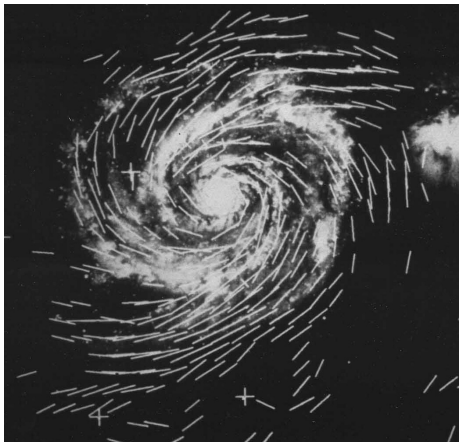
Forbush decrease



MILKY WAY







$$r_L = \frac{p_\perp c}{q\,B}$$

$$\langle B_{\rm MW} \rangle \simeq 3\ \mu{\rm Gauss}$$

$$r_L = \frac{1.08\ {\rm Kpc}}{Z} \left[\frac{E}{10^{18}\,{\rm eV}}\right] \left[\frac{\mu{\rm Gauss}}{B}\right]$$

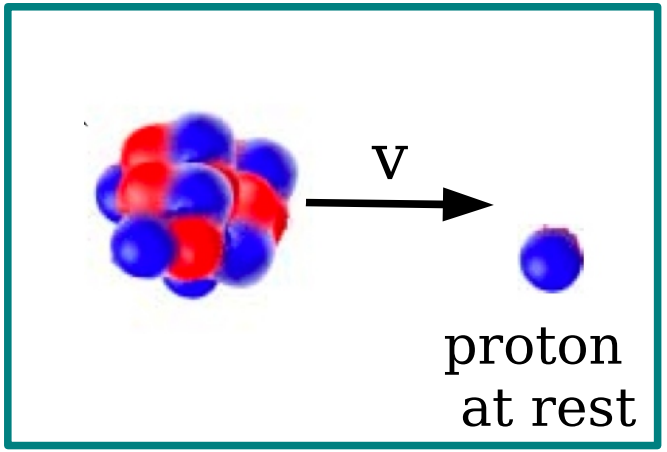
$$r^p_{\rm Larmor}(100\ {\rm GeV}) \simeq 3.6 \times 10^{-8}\ {\rm Kpc}$$

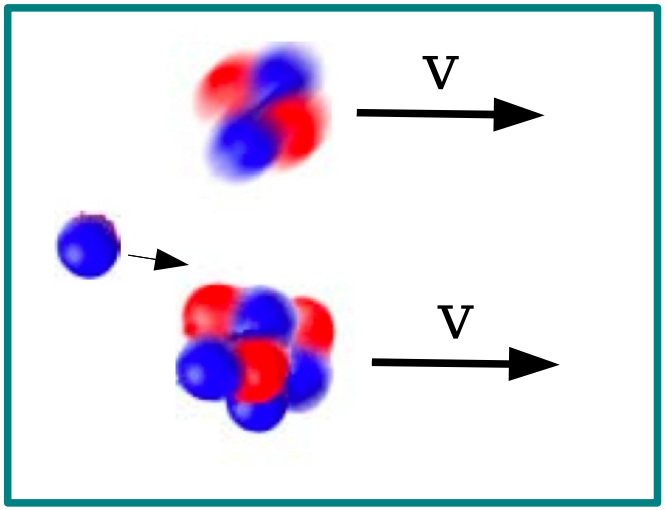
$$r^p_{\rm Larmor}(10^{20}\ {\rm eV}) \simeq 36\ {\rm Kpc}$$

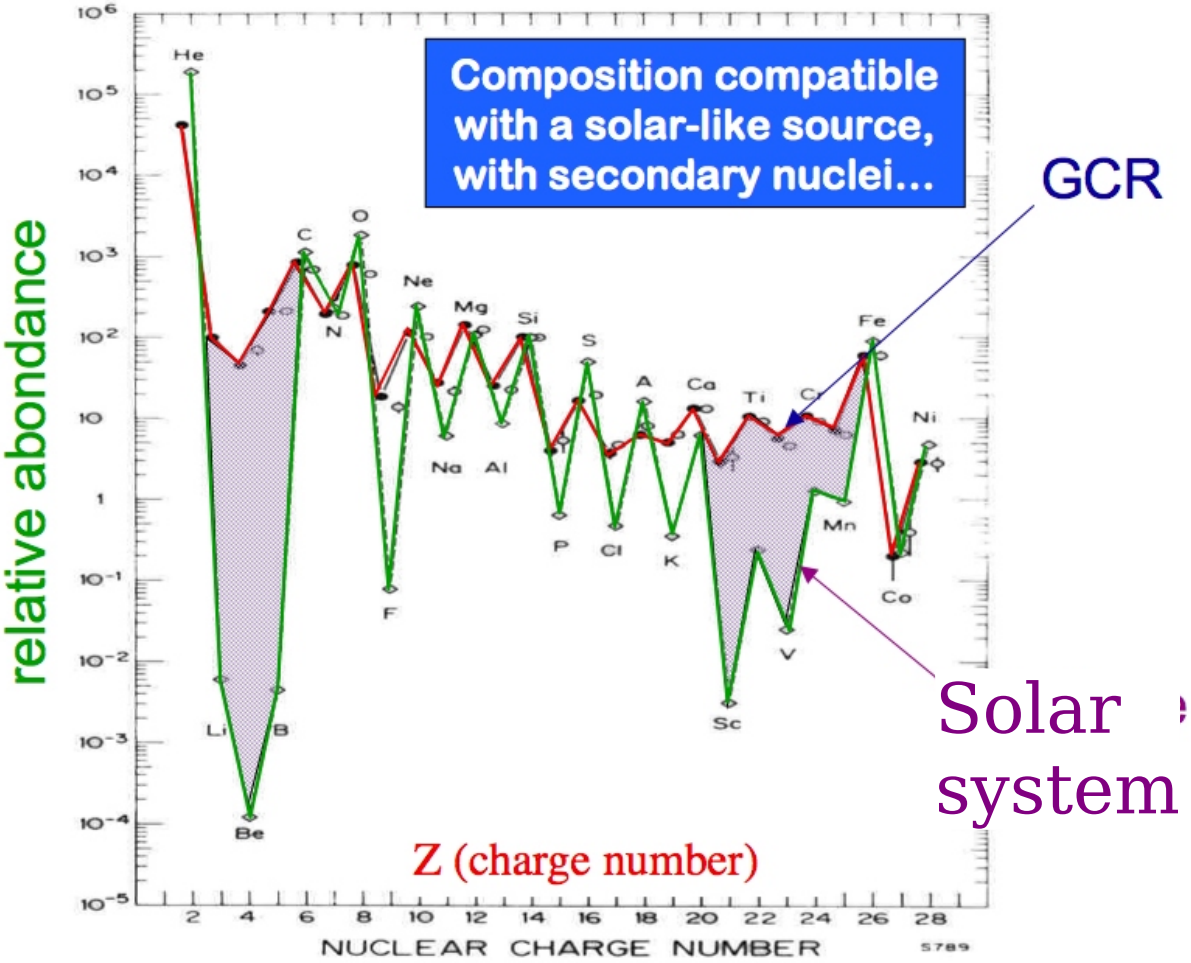
- Diffusion approximation
- Maximum energy for containment

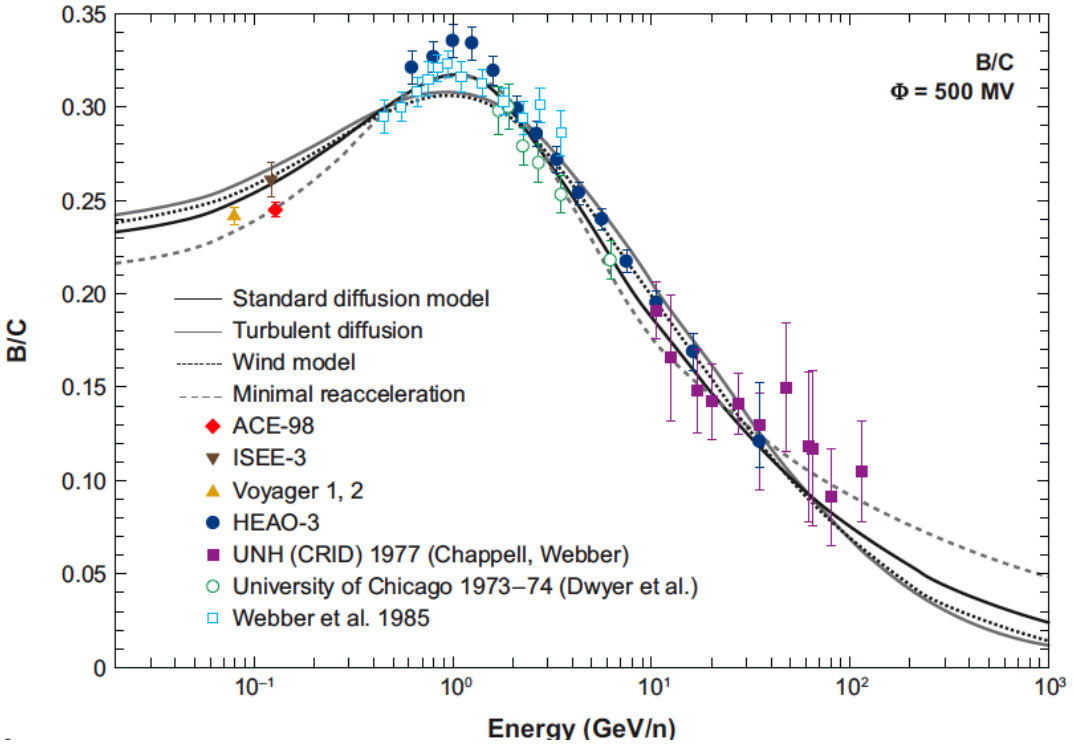
$$r^{\rm Fe}_{\rm Larmor}(10^{20}\ {\rm eV}) \simeq 1.4\ {\rm Kpc}$$

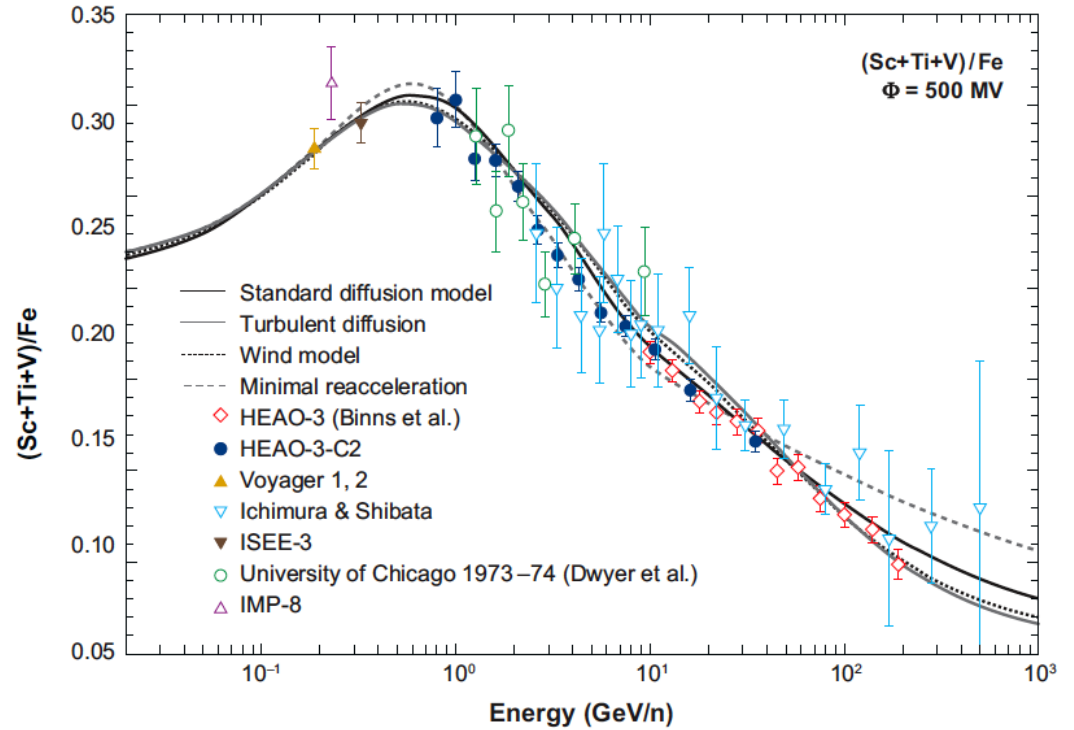
Nuclear Fragmentation
(collisions with the Inter Stellar Medium)











Column density

$$X(E) = \langle \rho \rangle \; T(E)$$

Escape faster at higher E

$$X(E) \propto E^{-\delta}$$

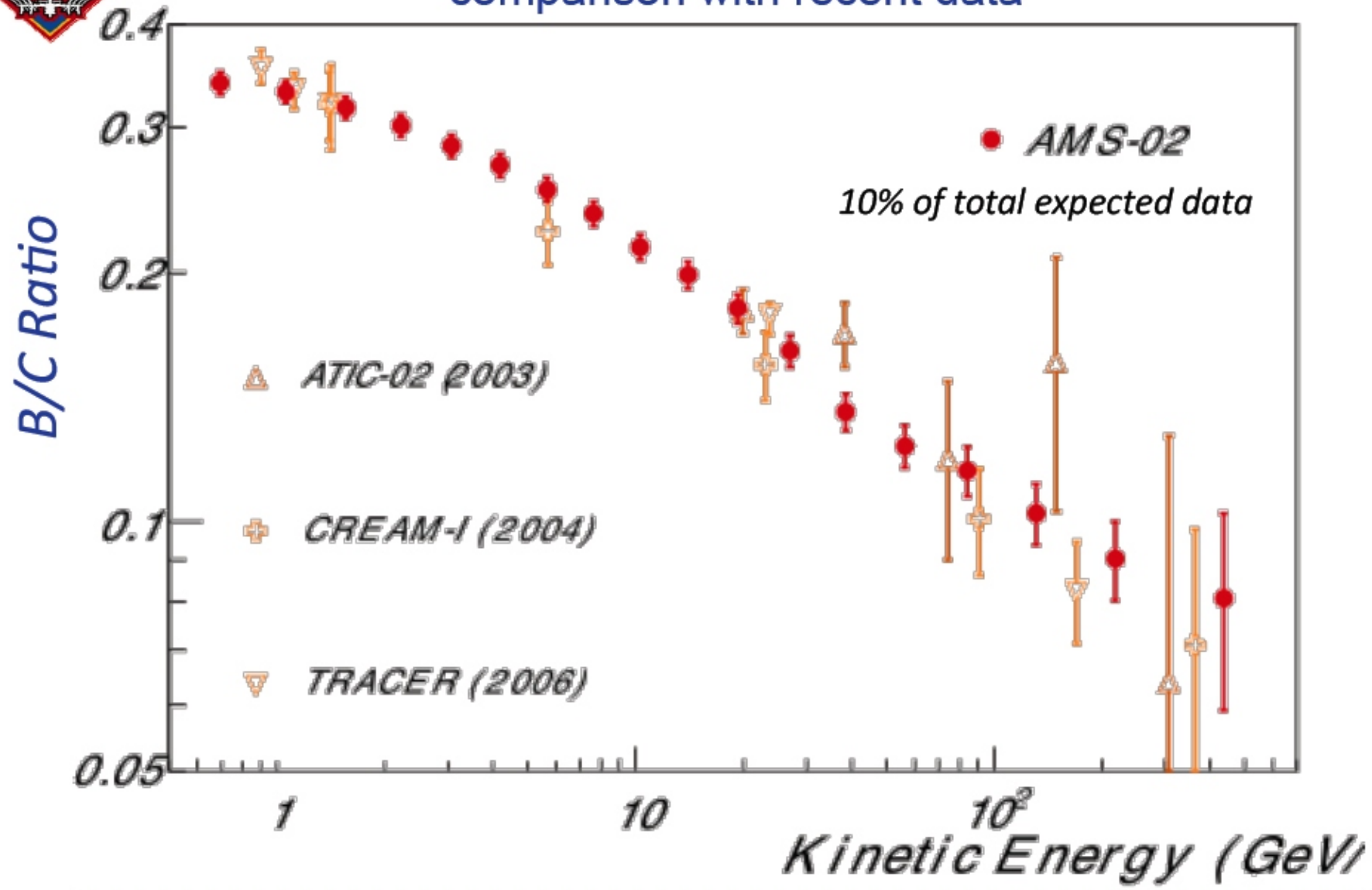
$$\delta \simeq 0.4 \div 0.6$$

$$\frac{\langle \rho \rangle}{m_p} \simeq 0.2 \text{ cm}^{-3}$$

(extended halo)

Boron-to-Carbon ratio

comparison with recent data

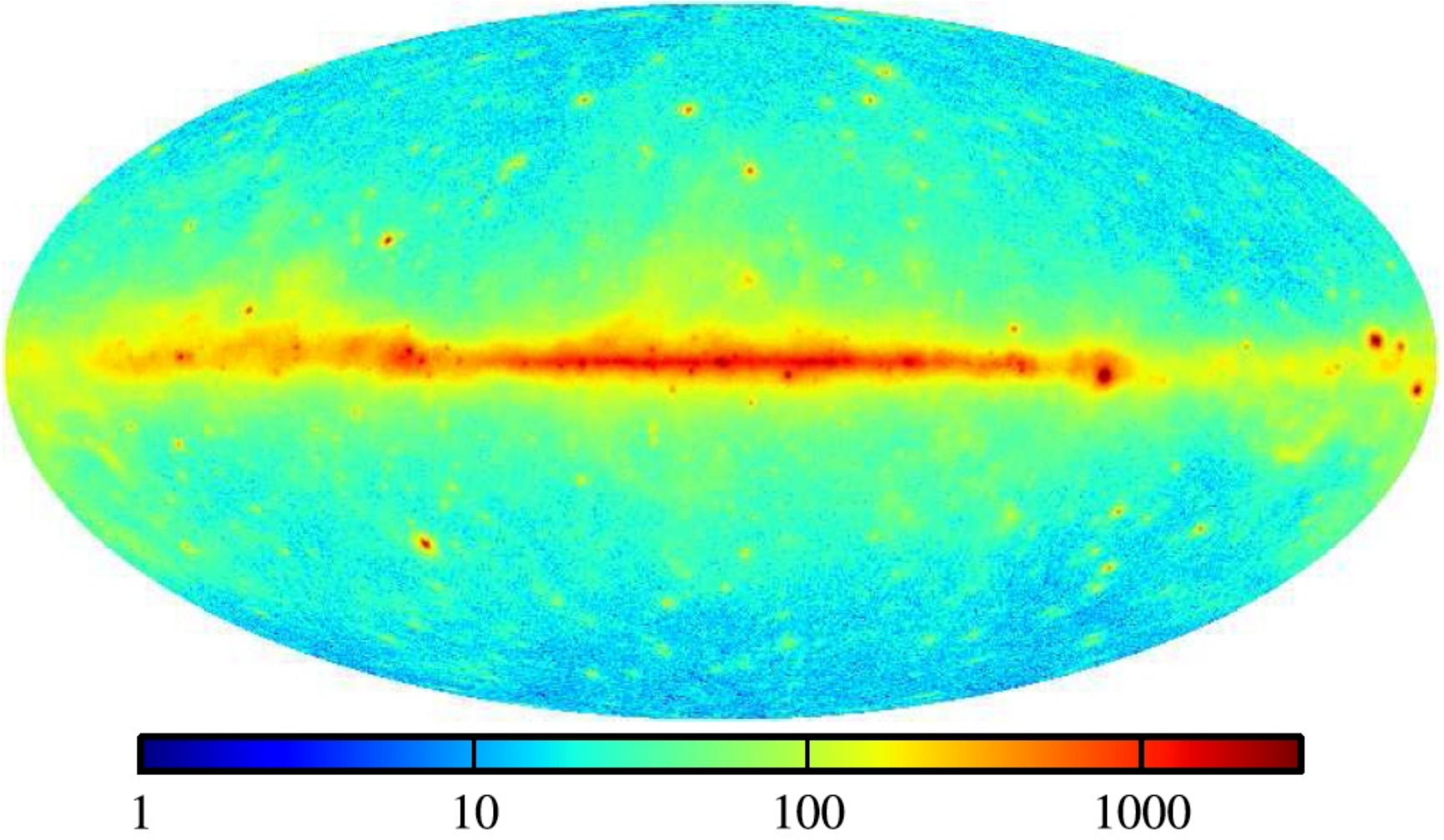


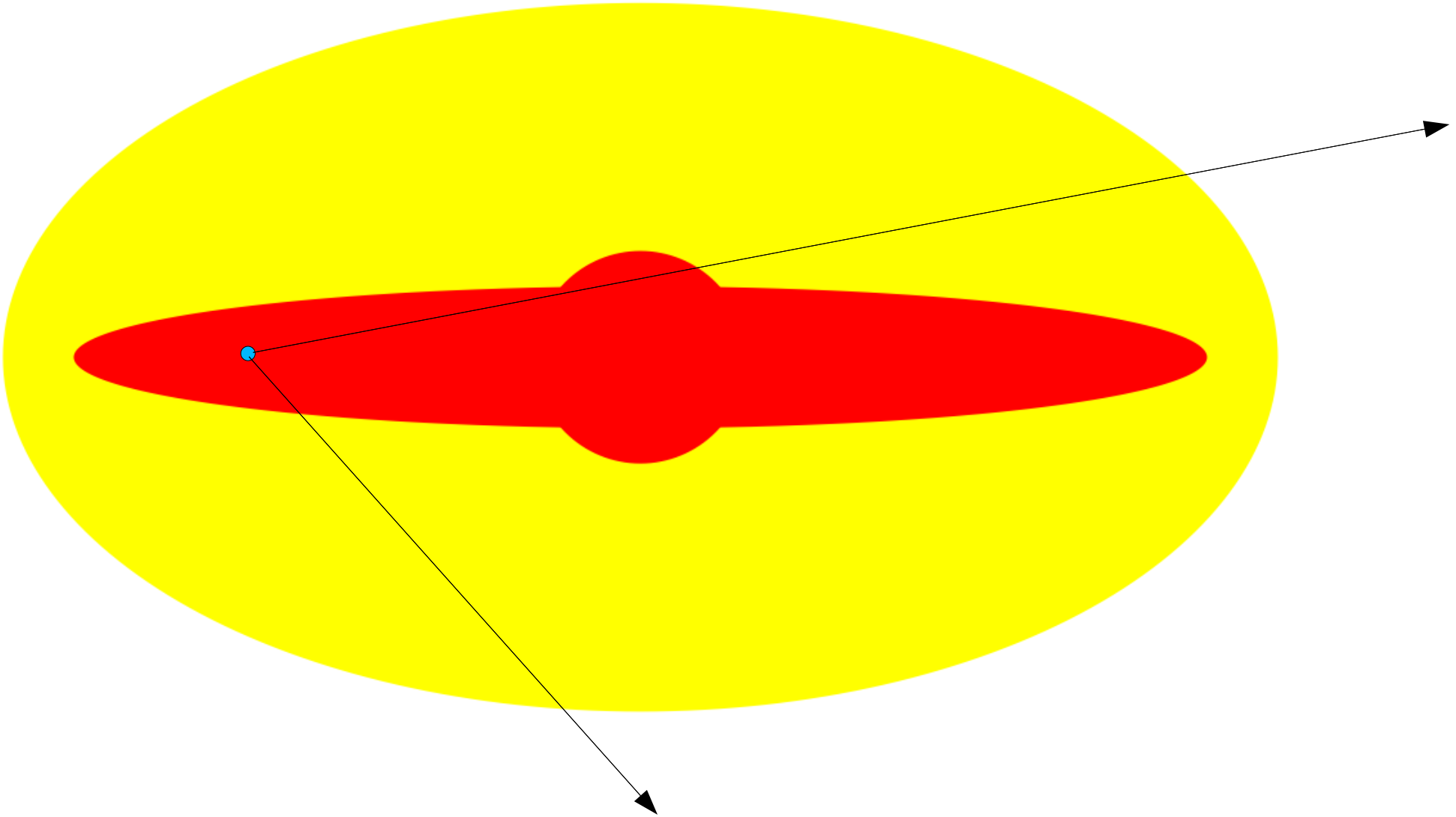
Diffuse Emission

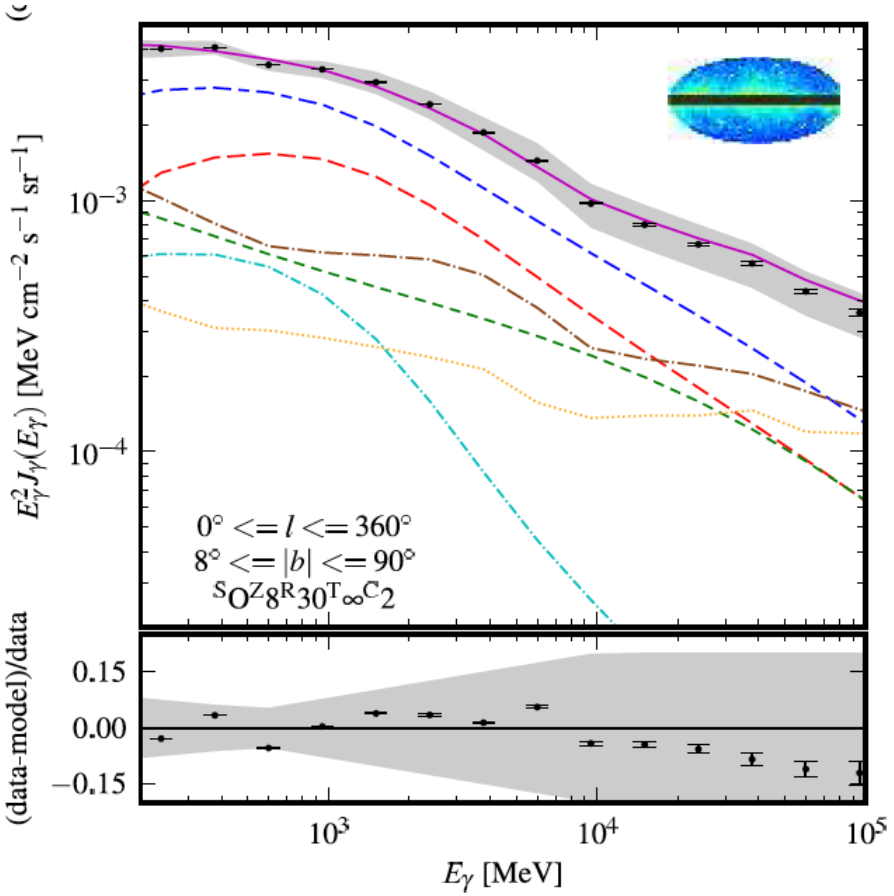
Fermi–LAT counts

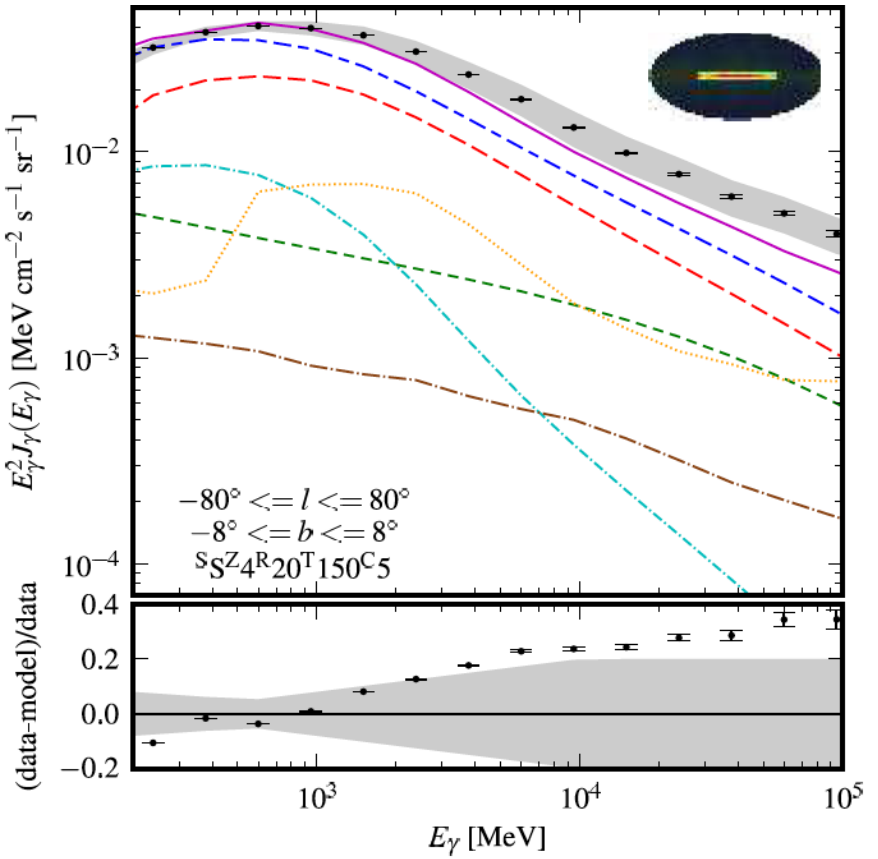
energy range 200 MeV to 100 GeV

Galactic coordinates









$$p + p_{\text{i.s.m.}} \rightarrow \pi^\circ + \ldots$$

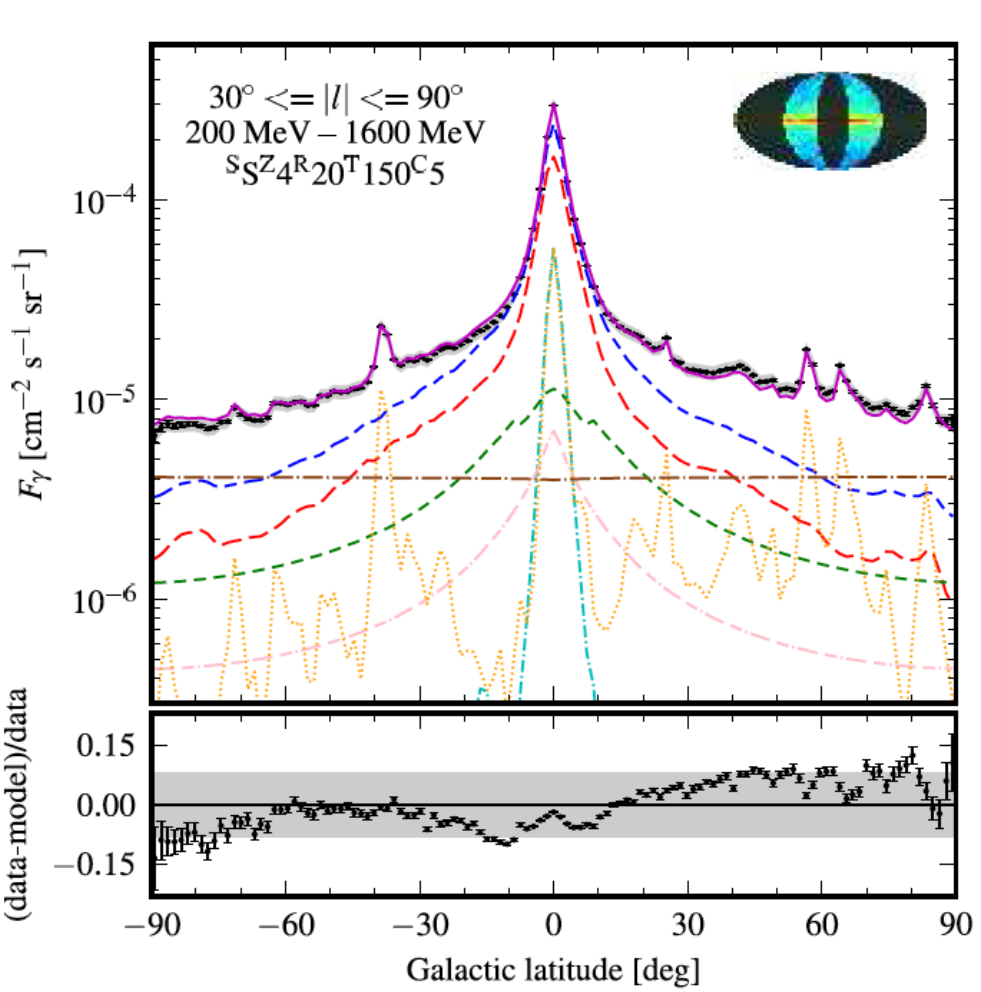
$$\pi^\circ \rightarrow \gamma + \gamma$$

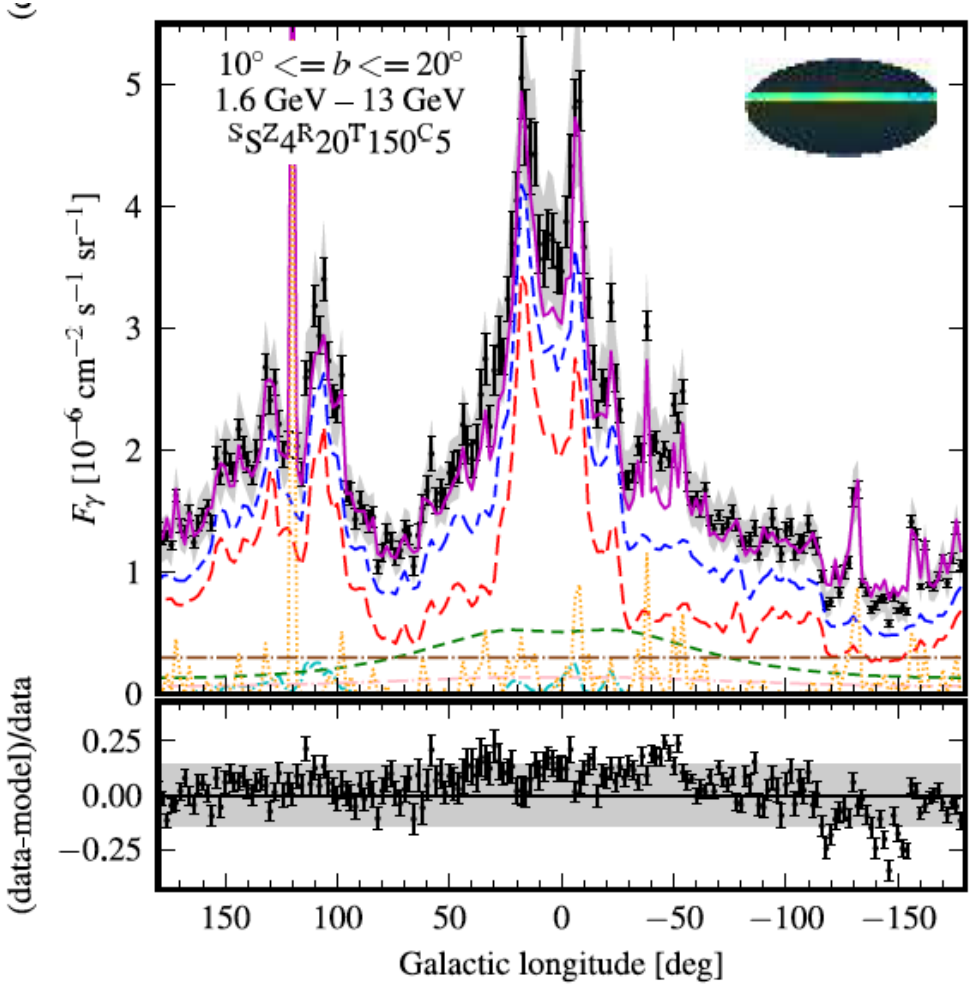
Inverse Compton

$$e^\pm + Z \rightarrow e^\pm + \gamma + Z$$

Bremsstrahlung

$$e^\pm + Z \rightarrow e^\pm + \gamma + Z$$





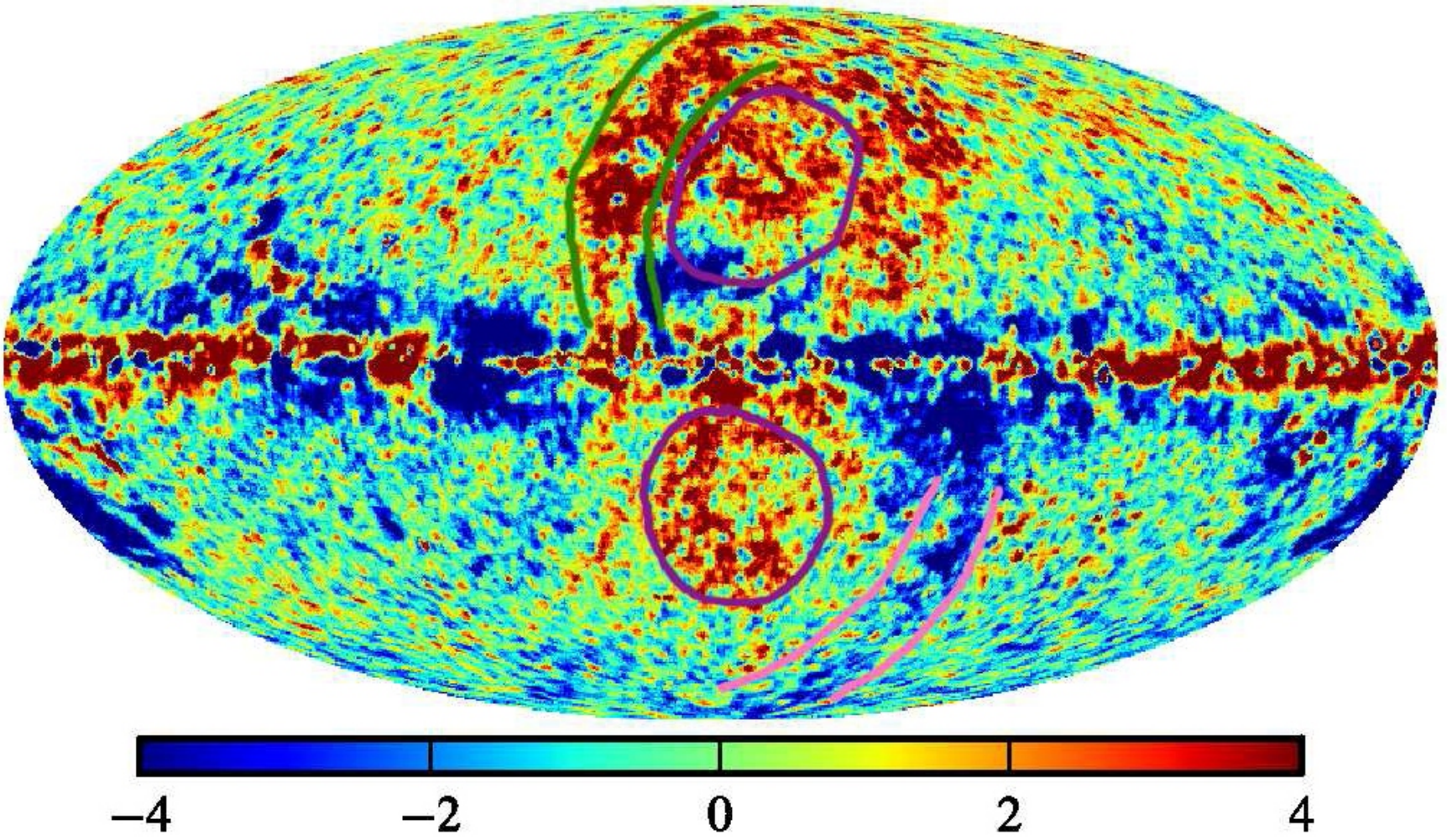
Description reasonably succcessful.
But several ambiguities and open problems remain.

Residual maps in units of standard deviation

model $^{S}S^{Z}4^{R}20^{T}150^{C}5$

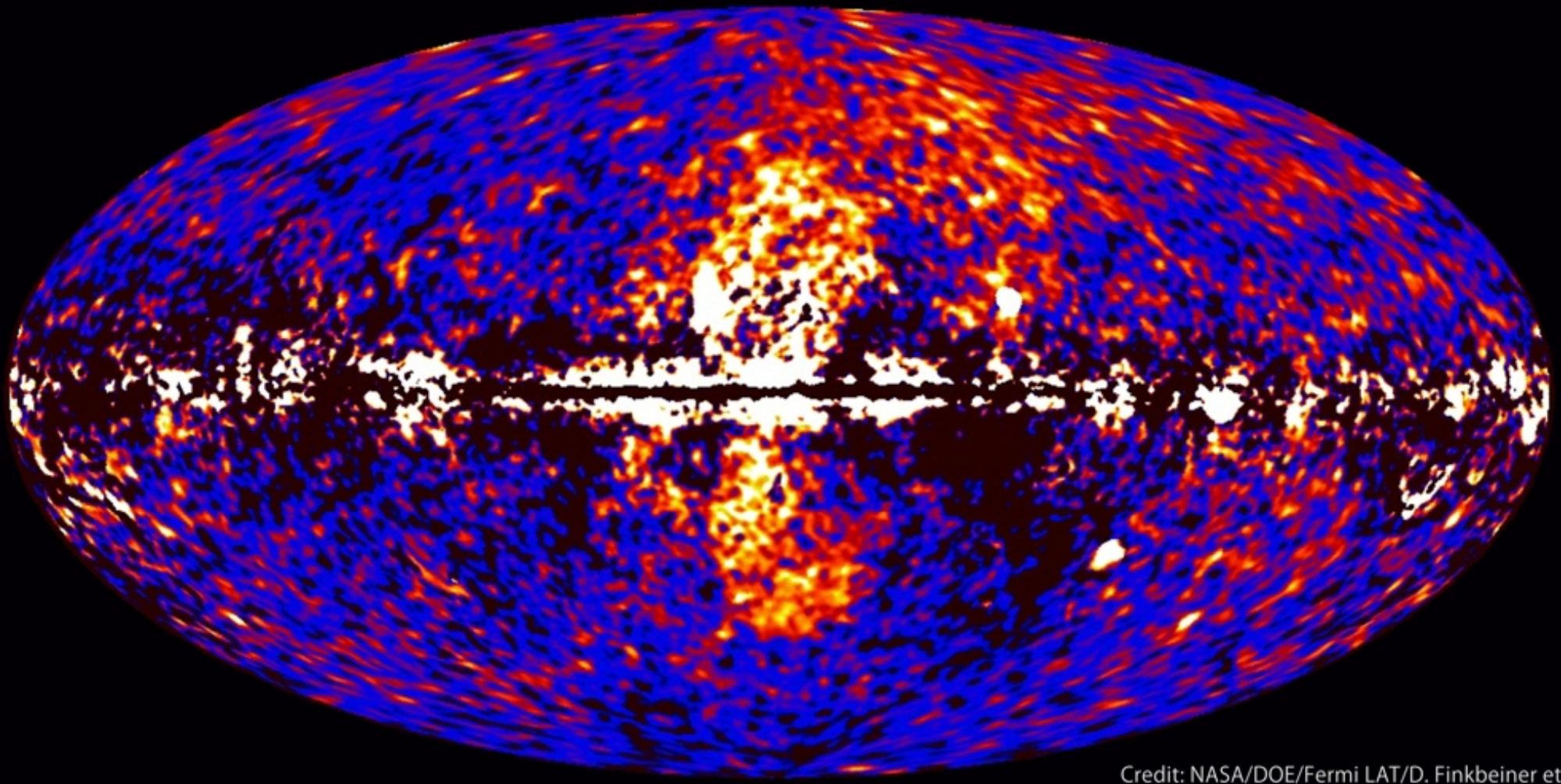
Loop I (green)

Magellanic stream (pink)



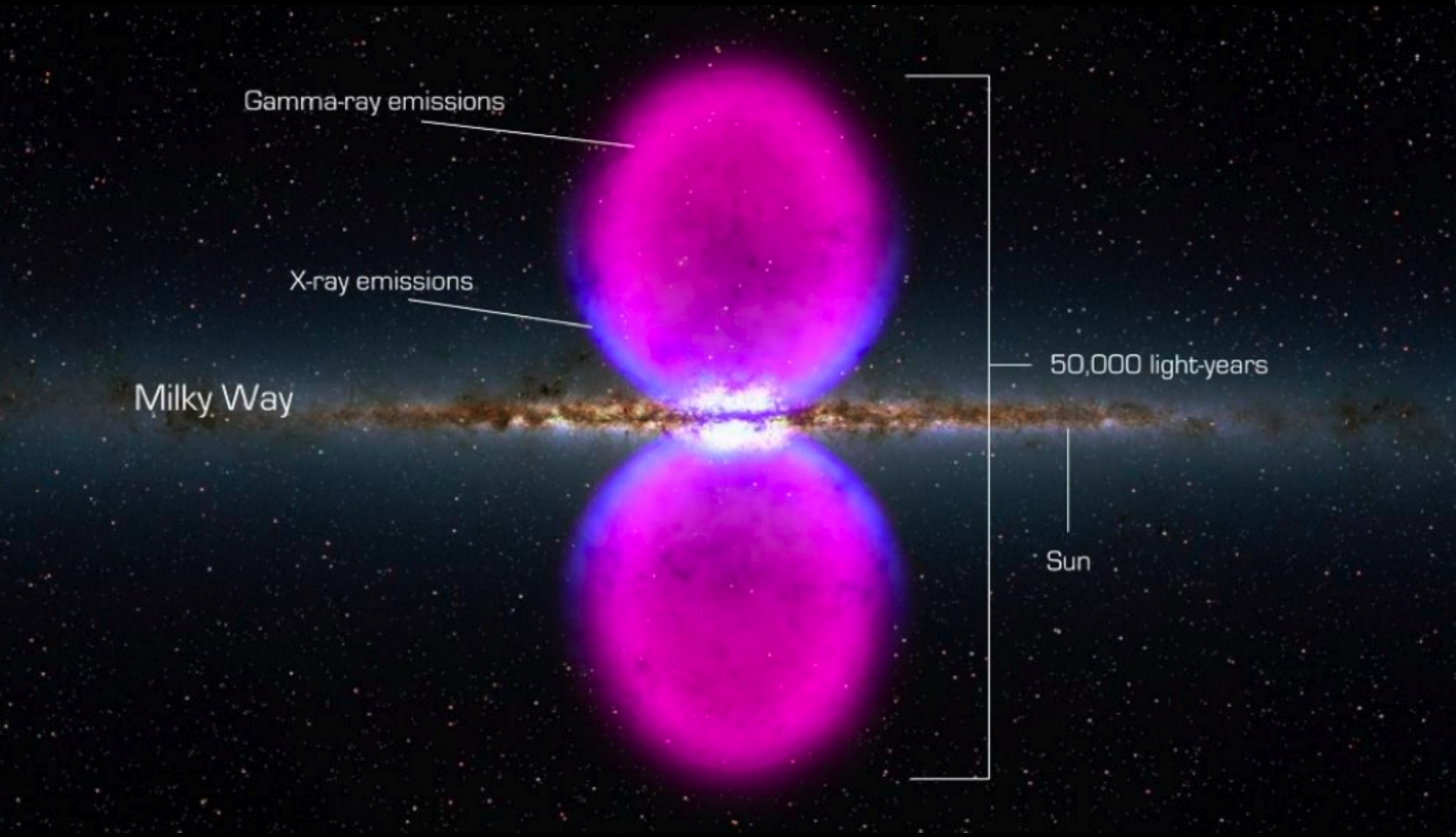
Scientific American news. Title:

Hidden in Plain Sight: Researchers Find Galaxy-Scale Bubbles Extending from the Milky Way



Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.

M. Su, T. R. Slatyer, D. P. Finkbeiner,
"Giant Gamma-ray Bubbles from Fermi-LAT: AGN Activity or Bipolar Galactic Wind?,"
Astrophys. J. **724**, 1044-1082 (2010). [arXiv:1005.5480 [astro-ph.HE]].



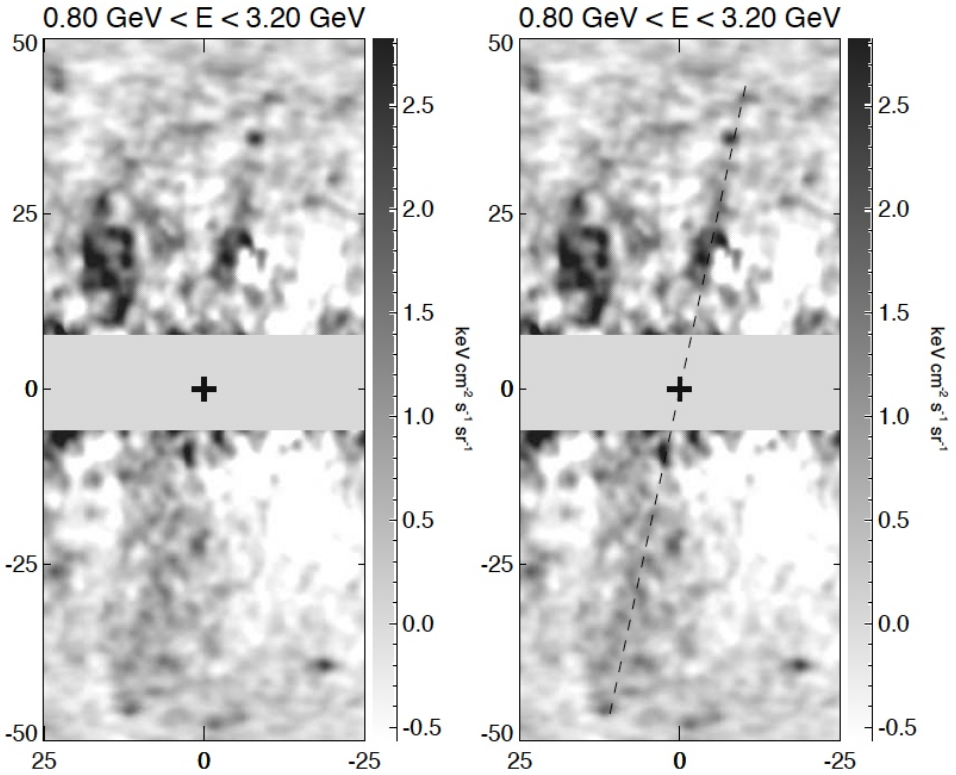
Artist's view of the “Fermi bubbles”

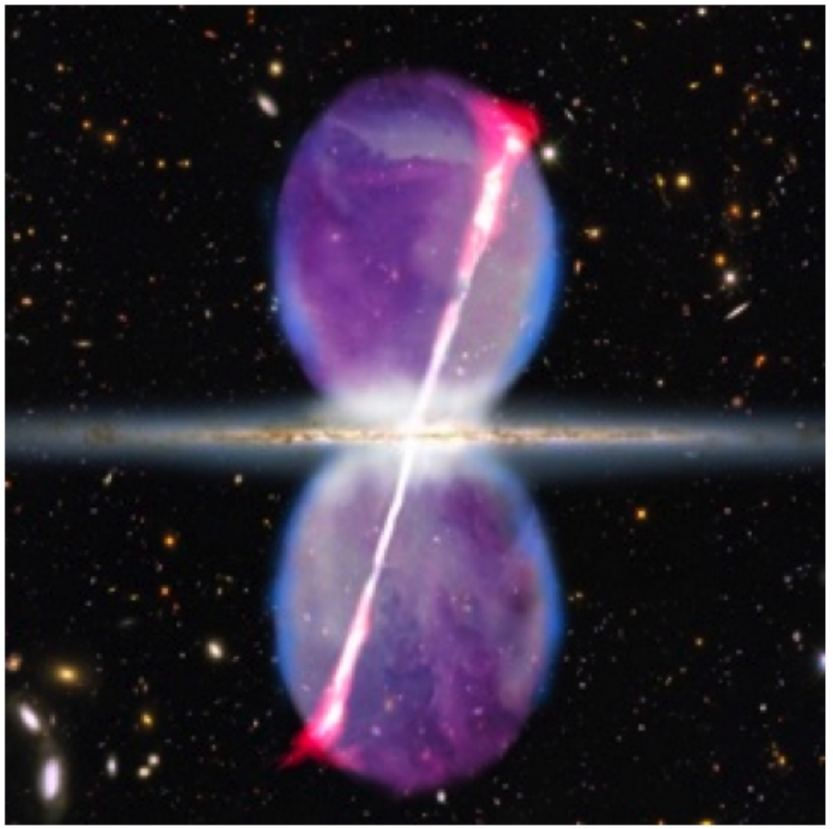
News | Space

Vestiges of Violence: Towering Gamma-Ray Jets Point to Past Outbursts from Milky Way's Black Hole

Black hole jets had previously been detected in other galaxies, but not in ours

By Jot





BUBBLES AND JETS: An artist's conception of the Milky Way shows the recently discovered Fermi bubbles, as well as the dual gamma-ray jets for which evidence has just emerged.
Image: David A. Aguilar (CfA)

The Cosmic Ray spectra

“Positron Anomaly” discovered by Pamela

Sharp feature at 220 GV [Pamela] [?]

proton/nuclei/electron/positron/antiproton acceleration

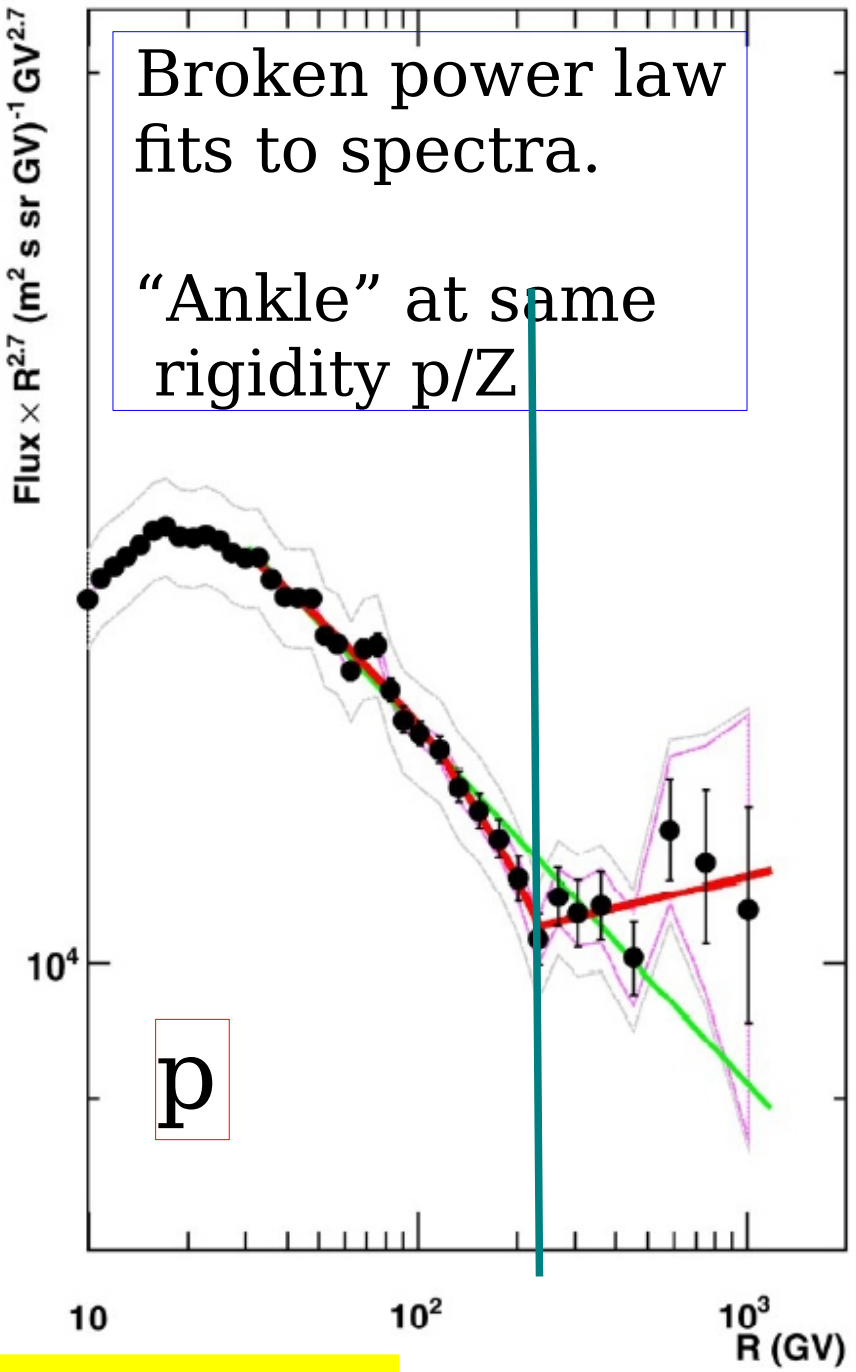
Anisotropies [Milagro, Argo, IceCube, ….]

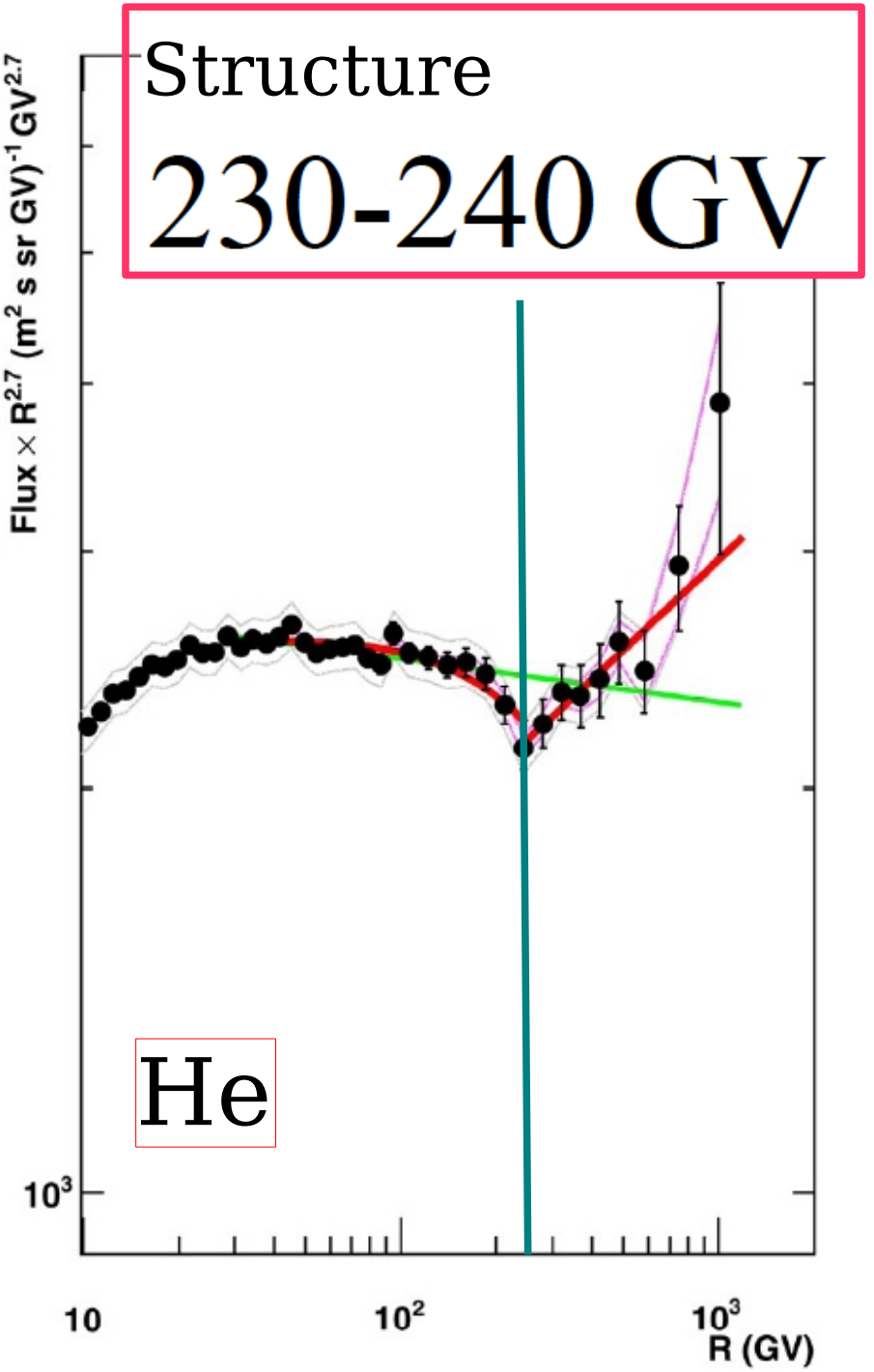
The Knee

From the “knee” to the “ankle” [Kascade Grande]

Galactic to extra-galactic transition

UHECR [Auger, HiRes, Telescope Array]

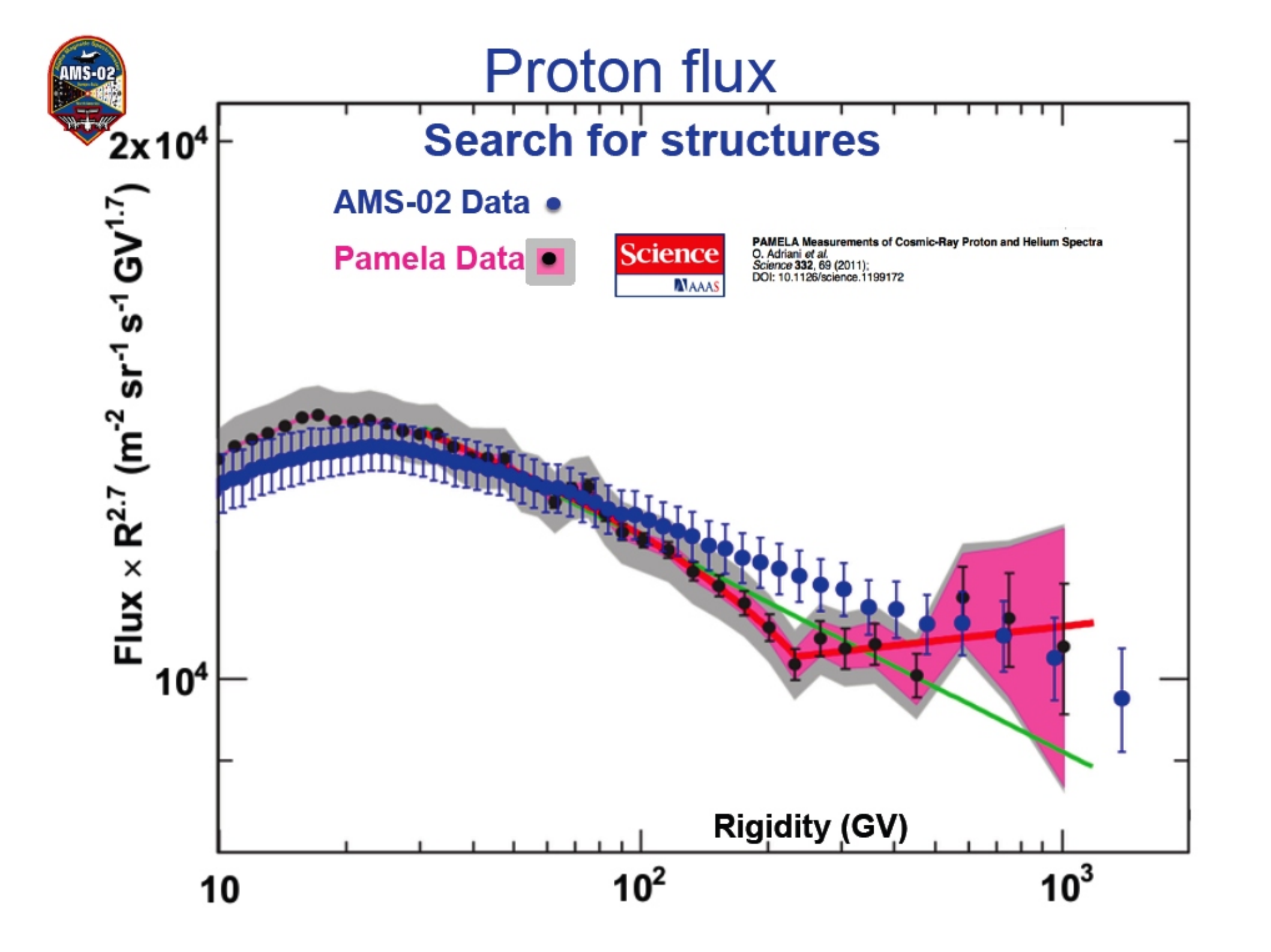

Broken power law fits to spectra.
"Ankle" at same rigidity p/Z
Flux × R^2.7 (m^2 s sr GV)^-1 GV^2.7
10^4
p
10
10^2
10^3
R (GV)


Structure
230-240 GV
Flux × R^2.7 (m^2 s sr GV)^-1 GV^2.7
10^3
He
10
10^2
10^3
R (GV)

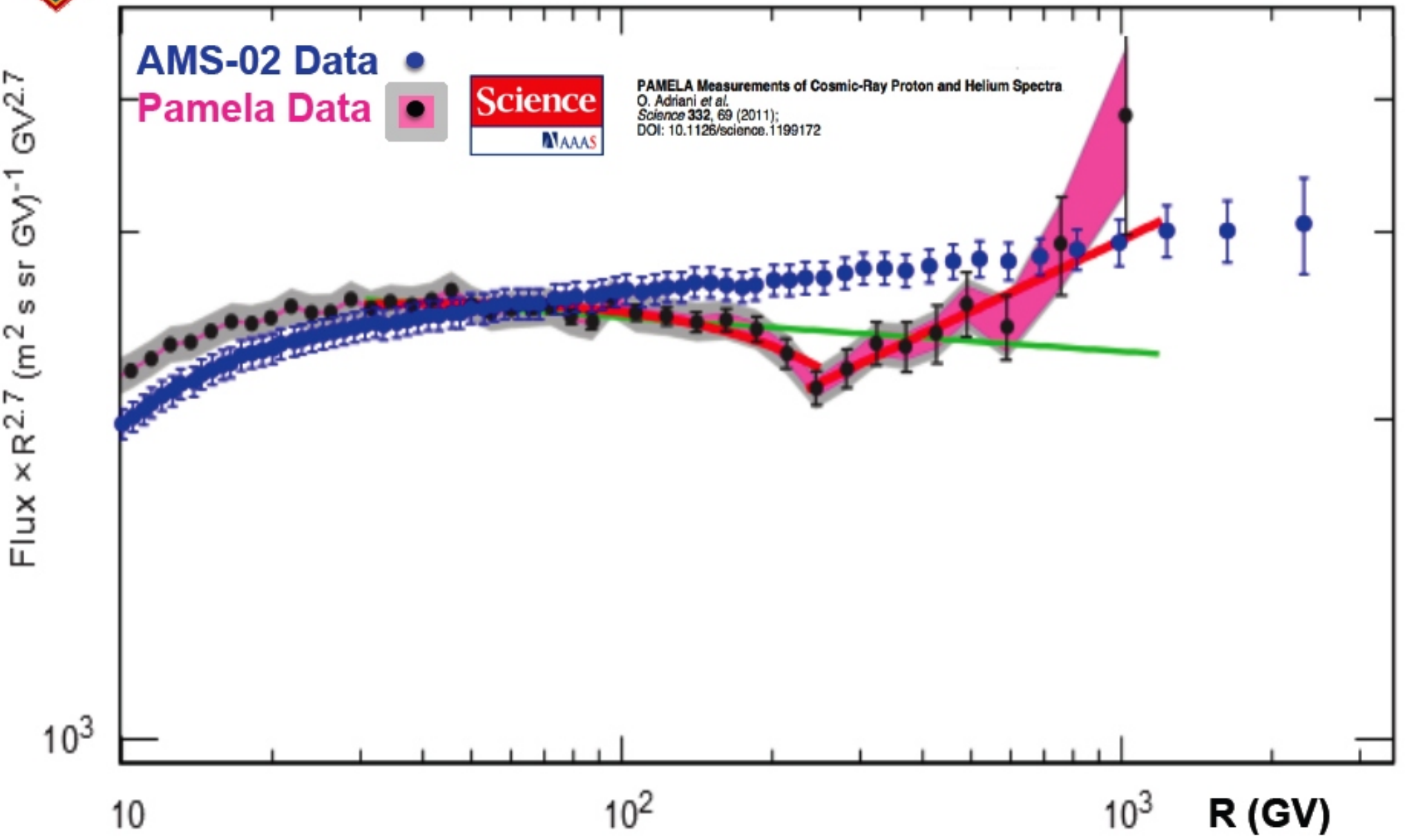
PAMELA


May 16, 2011

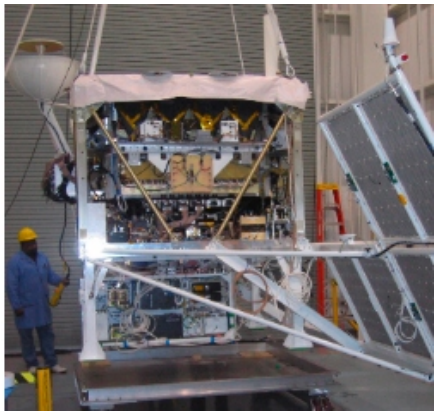
Proton flux

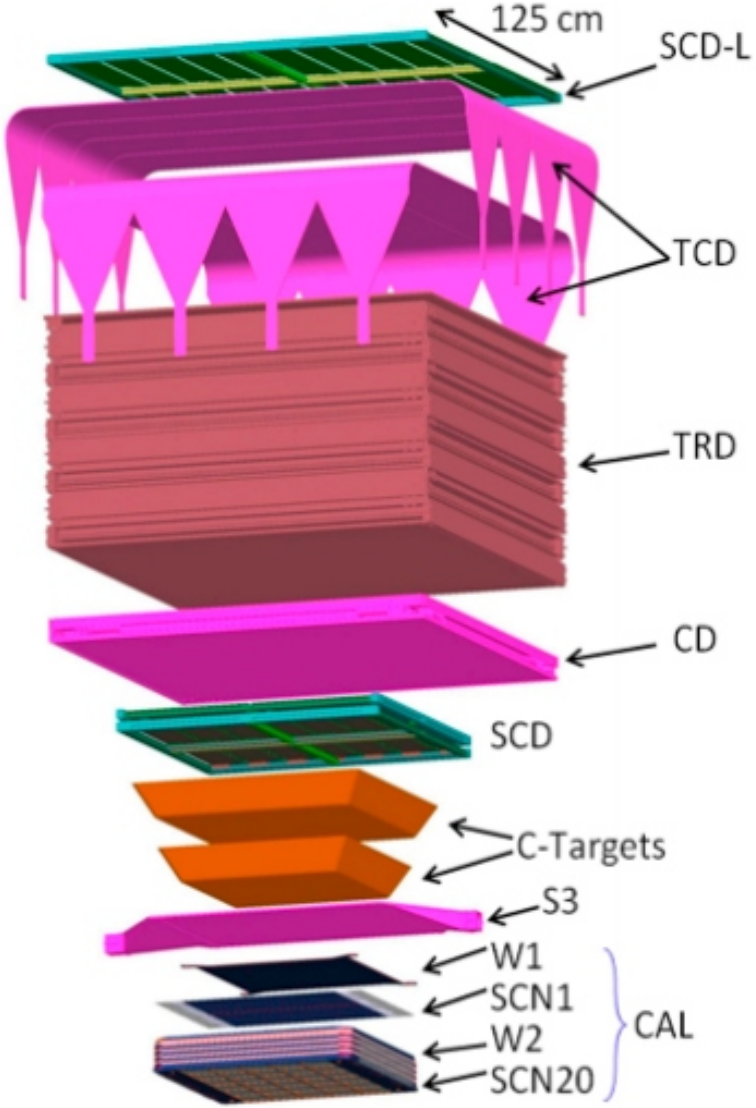

Search for structures
AMS-02 Data
Pamela Data
Science
AAAS
PAMELA Measurements of Cosmic-Ray Proton and Helium Spectra
O. Adriani et al.
Science 332, 69 (2011);
DOI: 10.1126/science.1199172
Flux × R^2.7 (m^-2 sr^-1 s^-1 GV^1.7)
2x10^4
10^4
Rigidity (GV)
10
10^2
10^3

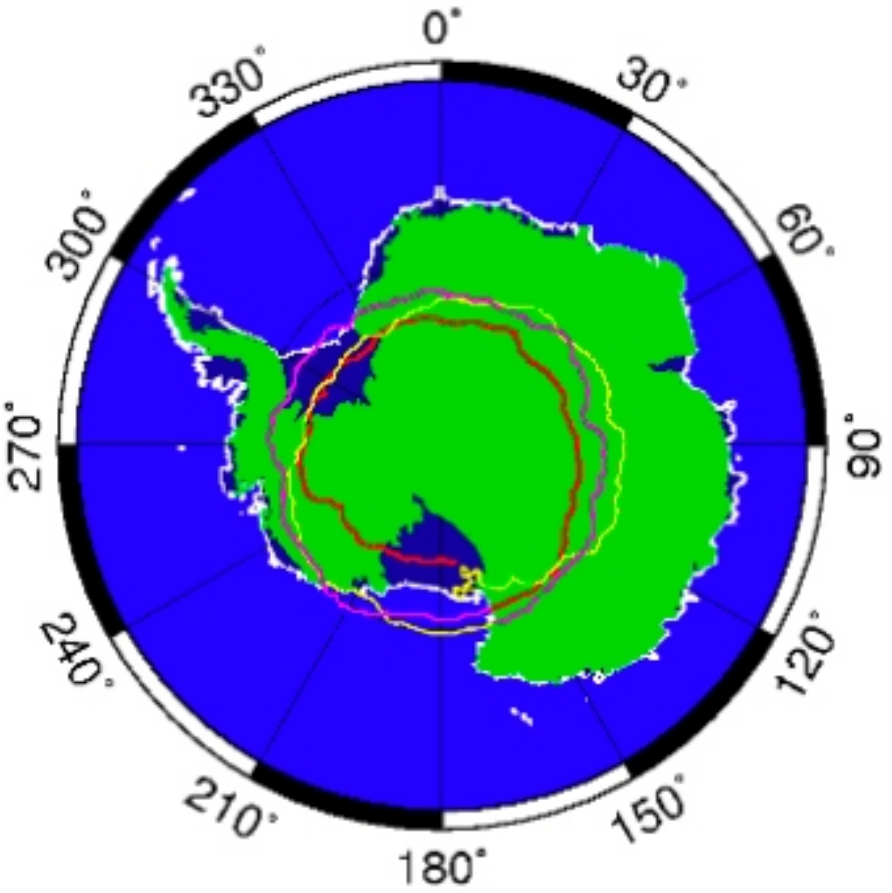
Helium flux
Search for structures



CREAM (calorimeter on balloon)
(5 flights in Antartica. Total of 156 days)

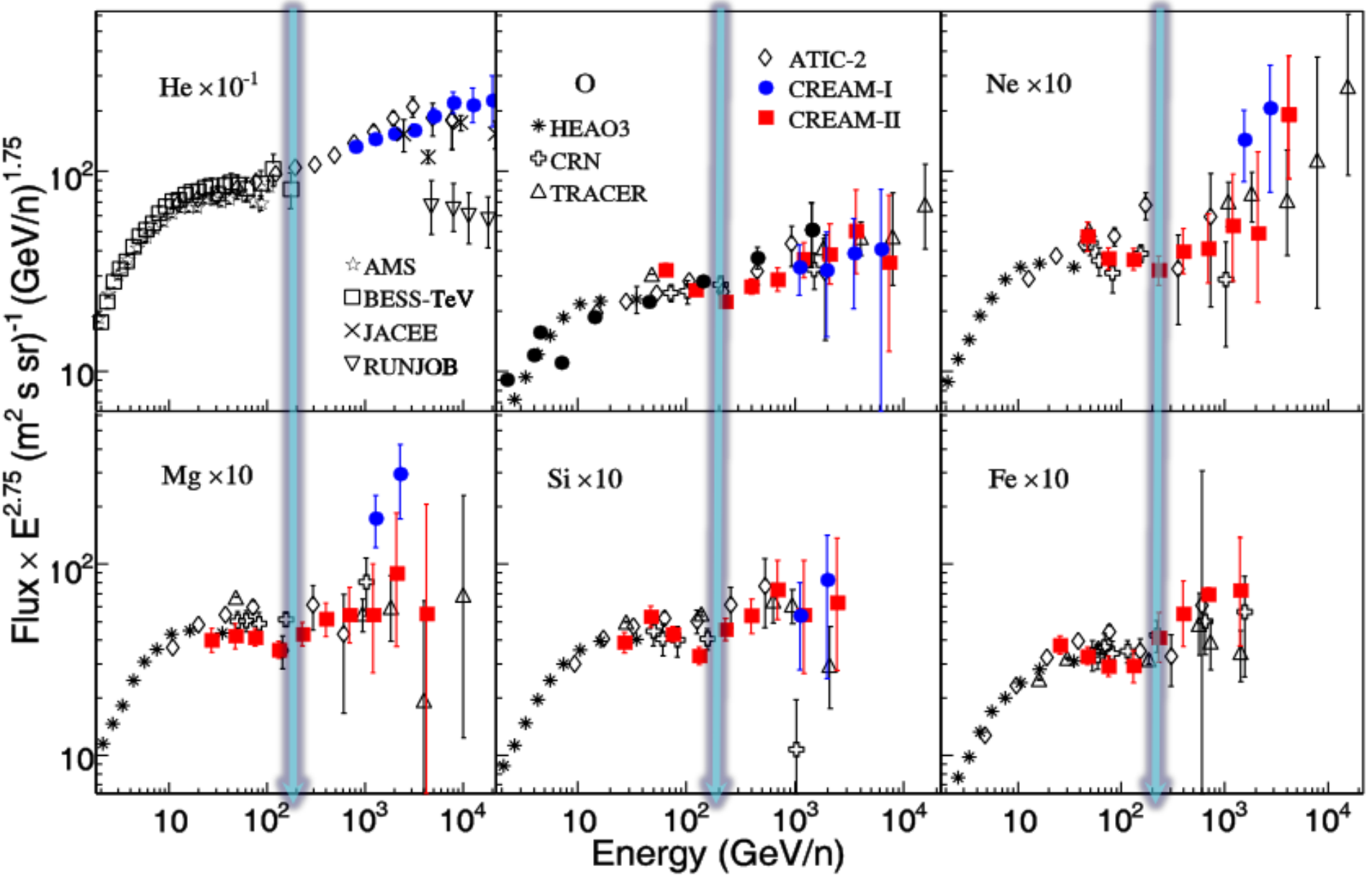


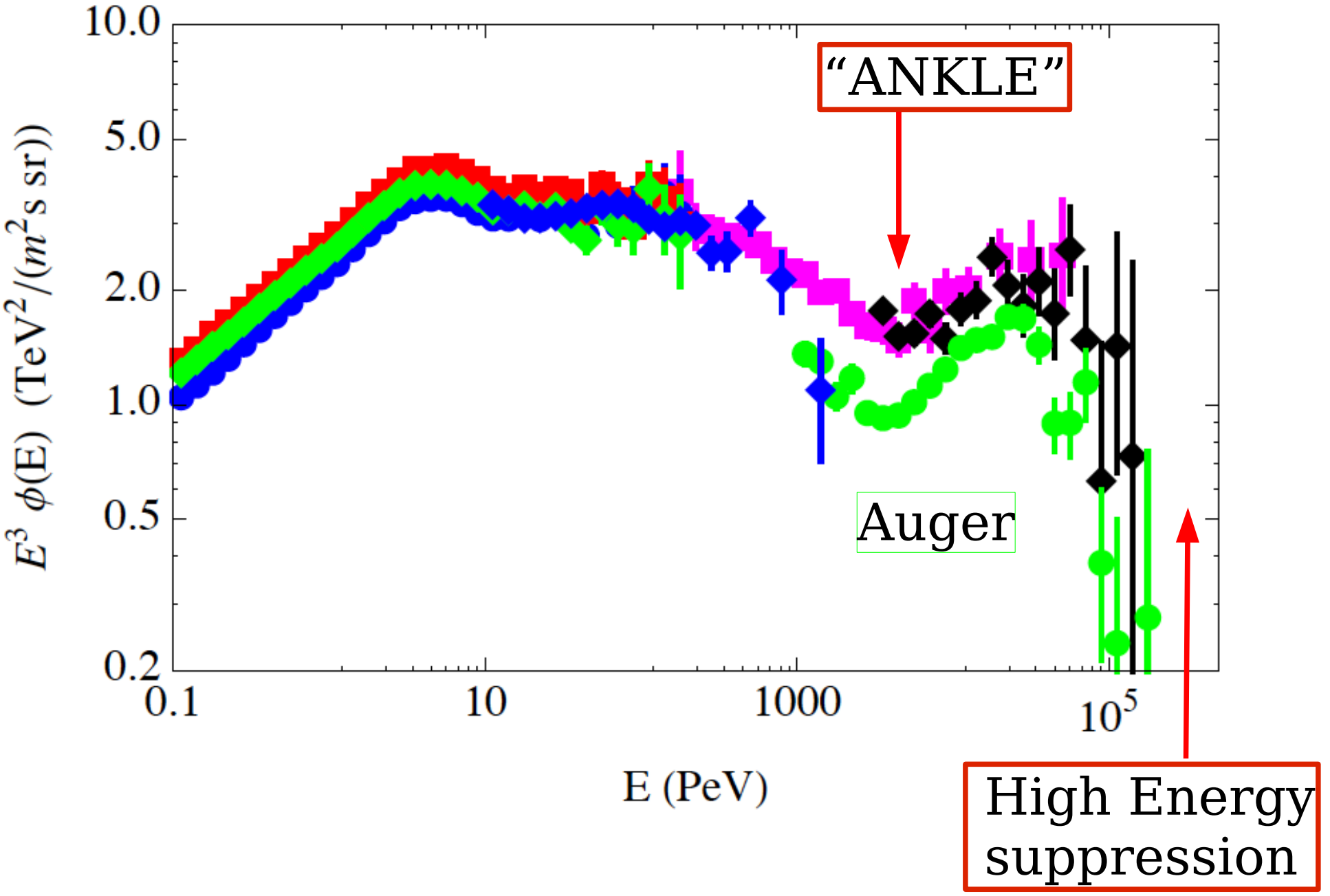


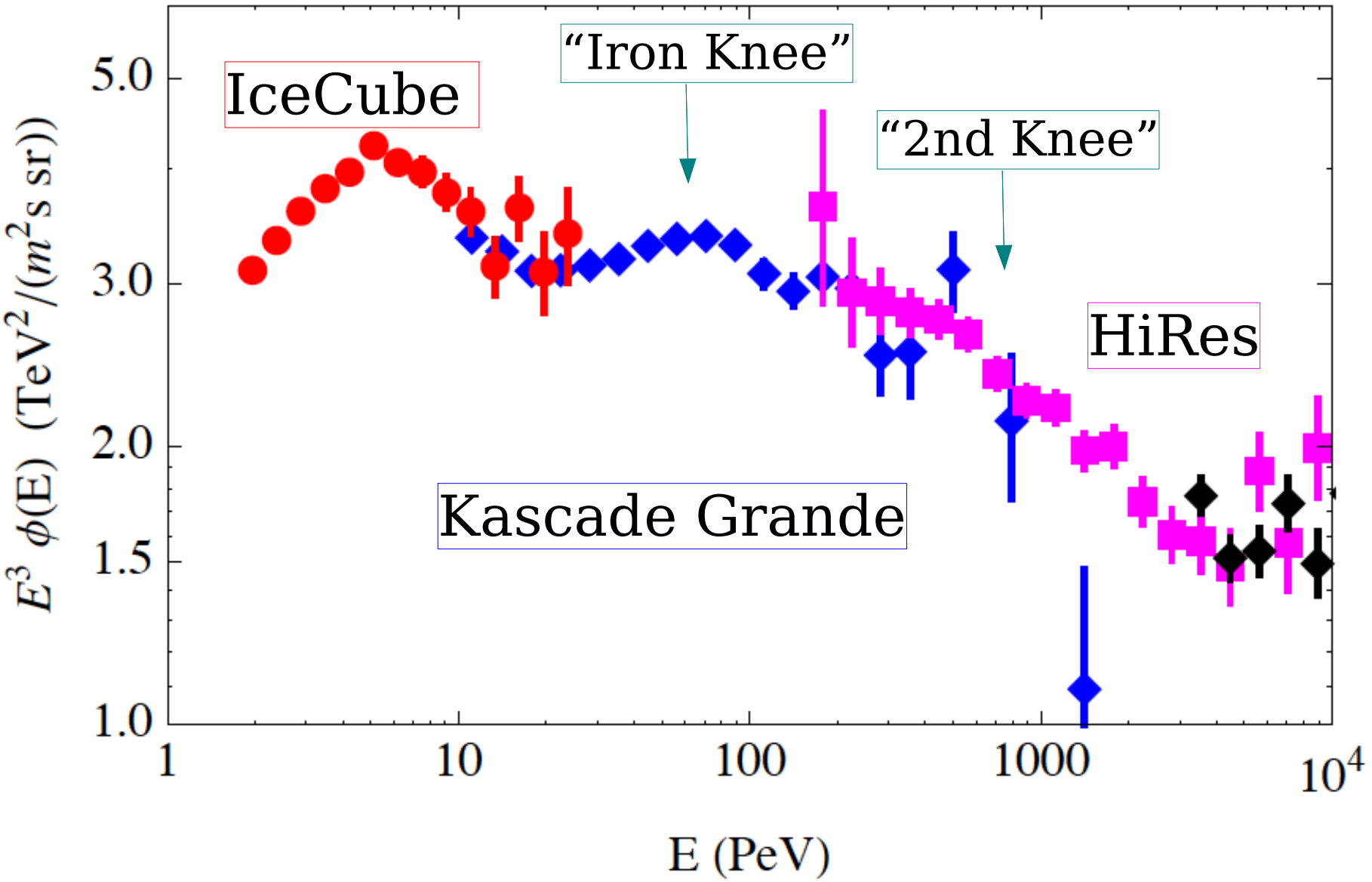


Cream 5 trajectory
37 days 12/2009-01/2010

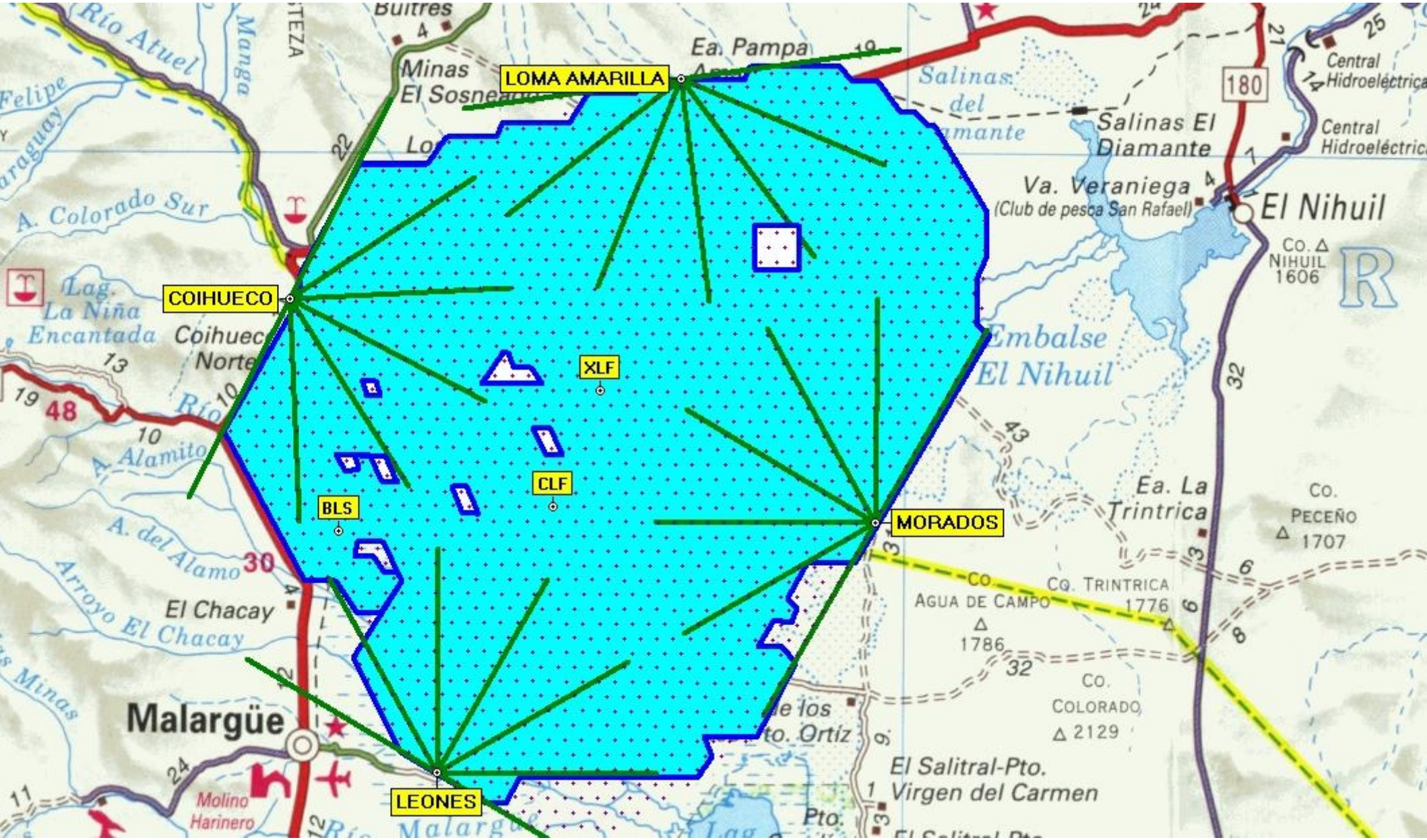
Discrepant hardening




10.0
5.0
2.0
1.0
0.5
0.2
0.1
10
1000
10^5
$E^3\ \phi(E)\ (\mathrm{TeV}^2/(m^2 \mathrm{s\ sr}))$
E (PeV)
"ANKLE"
Auger
High Energy suppression

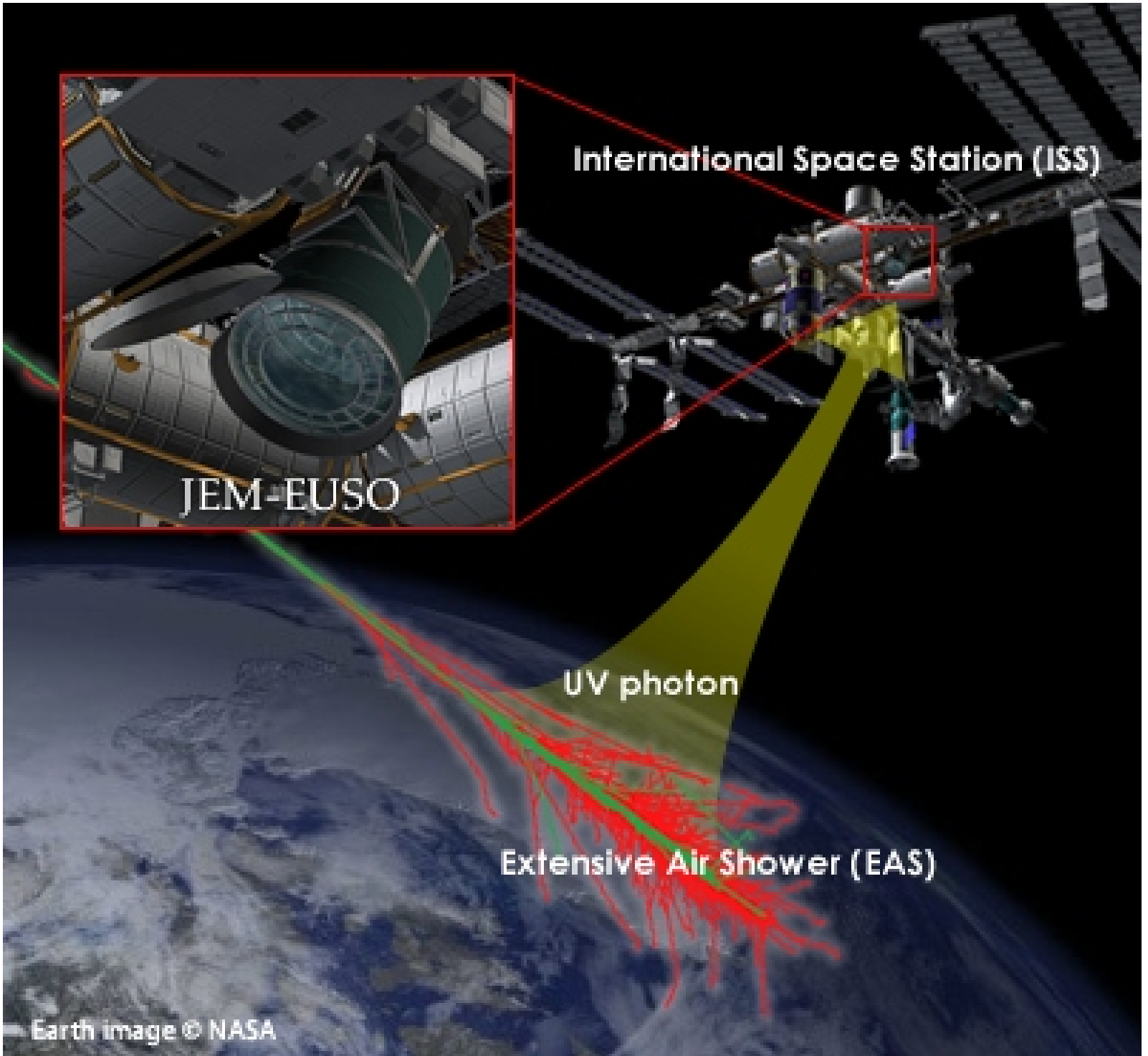

IceCube
“Iron Knee”
“2nd Knee”
HiRes
Kascade Grande
5.0
3.0
2.0
1.5
1.0
1
10
100
1000
10^4
$E^3\ \phi(E)\ (TeV^2/(m^2 s\ sr))$
E (PeV)

Auger detector in Argentina: 3000 Km^2



AUGER detector in ARGENTINA

Detection of UHECR from SPACE (see JEM EUSO presentation)



Dark Matter

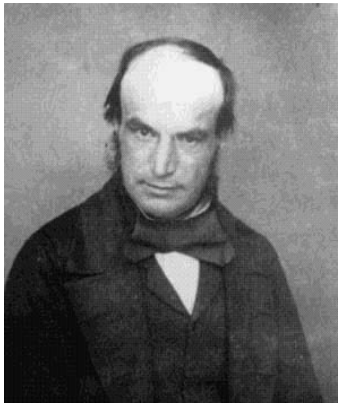
Cold Dark Matter

Cornelia Parker. (Tate Gallery, London)

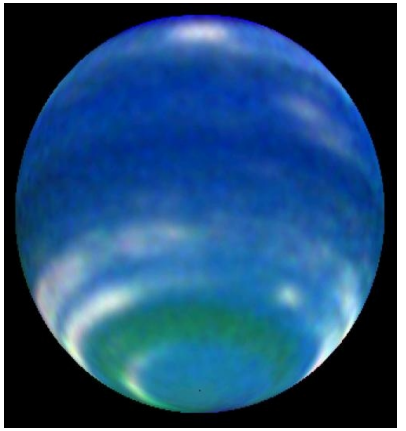
Uranus orbital anomalies

Prediction + Discovery of Neptune (23/24 september 1846)

Urbain Le Verrier

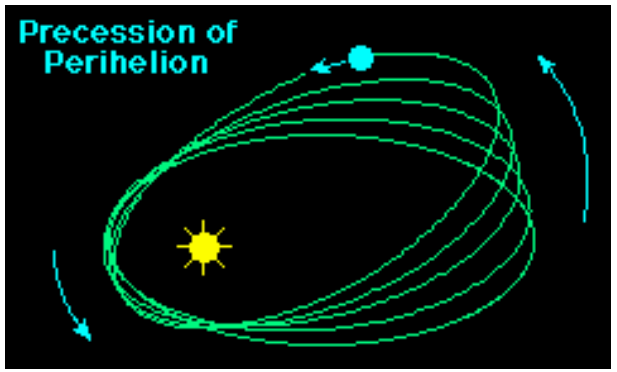


John Couch Adams

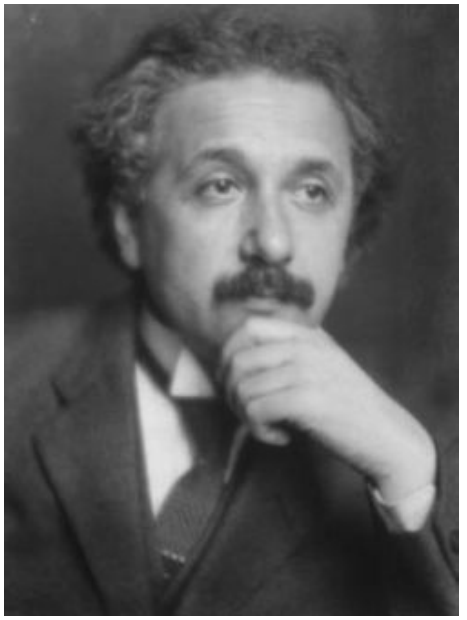


Mercury orbital anomalies

Extra 43''/century perihelion precession



New dynamics
General Relativity
(1916 Albert Einstein)



Does Dark Matter Really Exist ?

Is “MOND” (Modified Newtonian Dynamics”) a viable alternative ?

THE ASTROPHYSICAL JOURNAL, **270**:365–370, 1983 July 15

A MODIFICATION OF THE NEWTONIAN DYNAMICS AS A POSSIBLE ALTERNATIVE TO THE HIDDEN MASS HYPOTHESIS[1]

M. MILGROM
Department of Physics, The Weizmann Institute of Science, Rehovot, Israel; and
The Institute for Advanced Study
Received 1982 February 4; accepted 1982 December 28

Why is "DARK MATTER" the "prevalent paradigm"

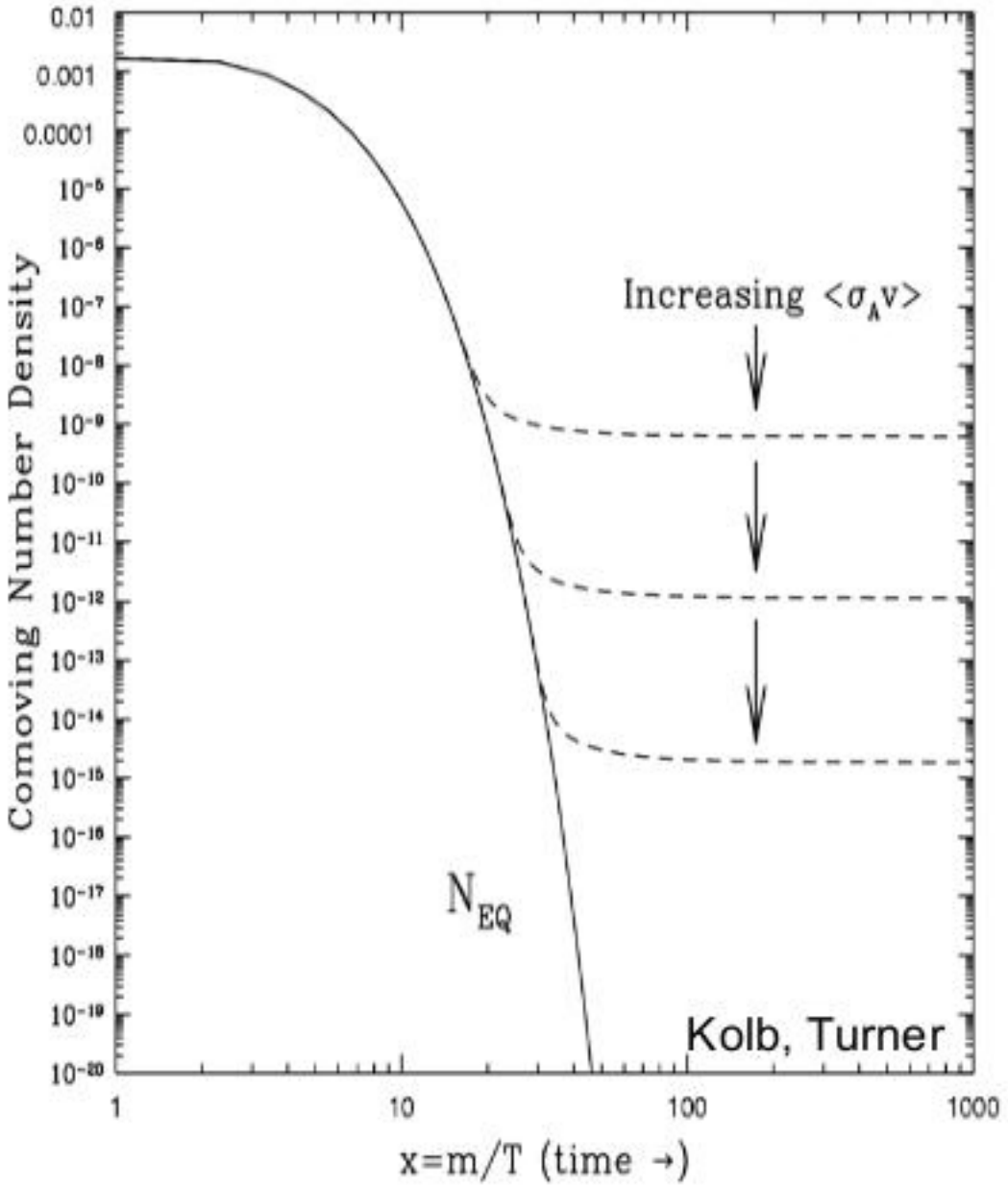
1. Theoretical difficulties in constructing
   a consistent, covariant theory. [Resolved by Bekenstein]

2. Remarkable success of the "Dark Matter" paradigm
   in describing the structure formation in our universe.
   Relation between the
   Large scale galaxy distribution.
   Anisotropies in the Cosmic Background Radiation.

3. The "BULLET CLUSTER" (Clowe et al 2006).
   (Cluster 1E0657-558: 2 colliding clusters at z=0.296)
   "A direct empirical proof of the existence of DM"
   Clear separation between Baryons and Mass.
   [other similar objects discovered (MACS J0025.4-1222)]

Counter examples ? The "Train wreck cluster"
(Abell 520)

Concept of thermal relic [WIMP] :



$$\chi + \chi \leftarrow f + \overline{f}$$

$$\chi + \chi \rightarrow f + \overline{f}$$

Annihilation cross section determines the "Relic Abundance"

$$\Omega_j^0 \simeq 0.3 \left[\frac{3 \times 10^{-26}\ \mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle \sigma\, v \rangle} \right]$$

"Relic abundance" estimate in standard Cosmology
(simplest treatment)

$$\Omega_\chi \simeq \left(\frac{16\,\pi^{5/2}}{9\,\sqrt{\pi}}\right) \frac{G^{3/2}\,T_0^3}{H_0^2\,(\hbar c)^{3/2}\,c^3} \frac{\sqrt{g^*}}{\langle\sigma\,v\rangle}$$

$$\Omega_\chi \simeq 0.2$$

$$\langle\sigma\,v\rangle \simeq 3\times 10^{-26}\ \frac{\mathrm{cm}^3}{\mathrm{sec}}$$

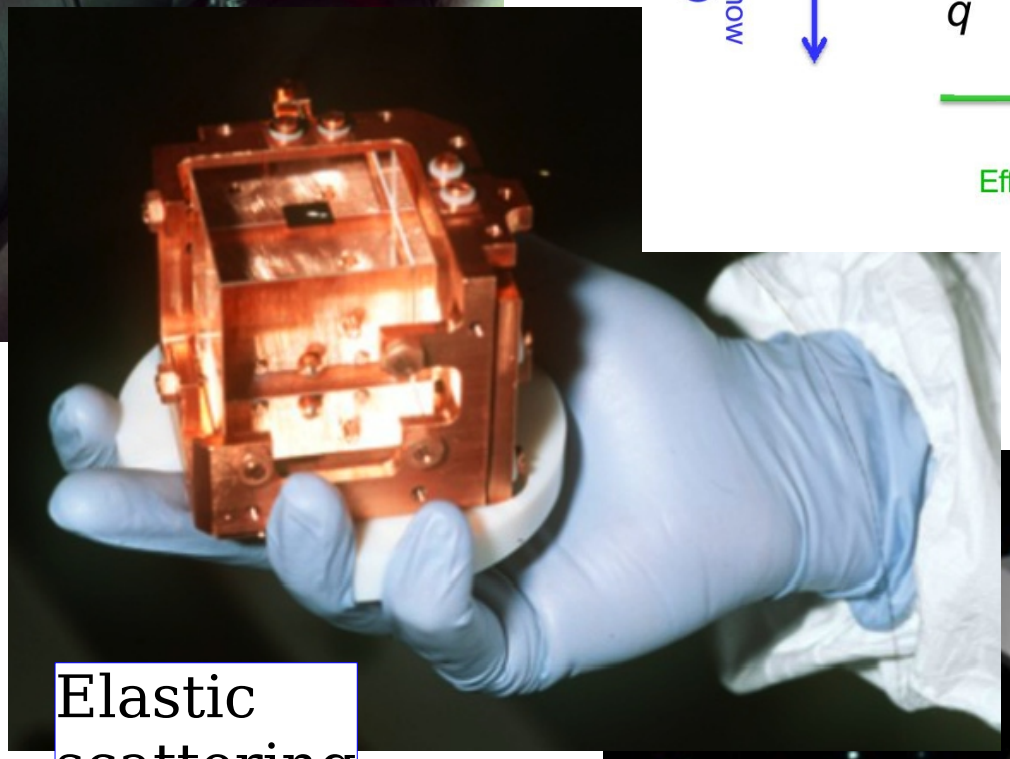
$$\sigma \simeq \frac{\alpha^2}{M^2}$$

$$M \simeq \frac{\hbar\,c}{\sqrt{\sigma/\alpha^2}} \simeq 140\ \mathrm{GeV}$$

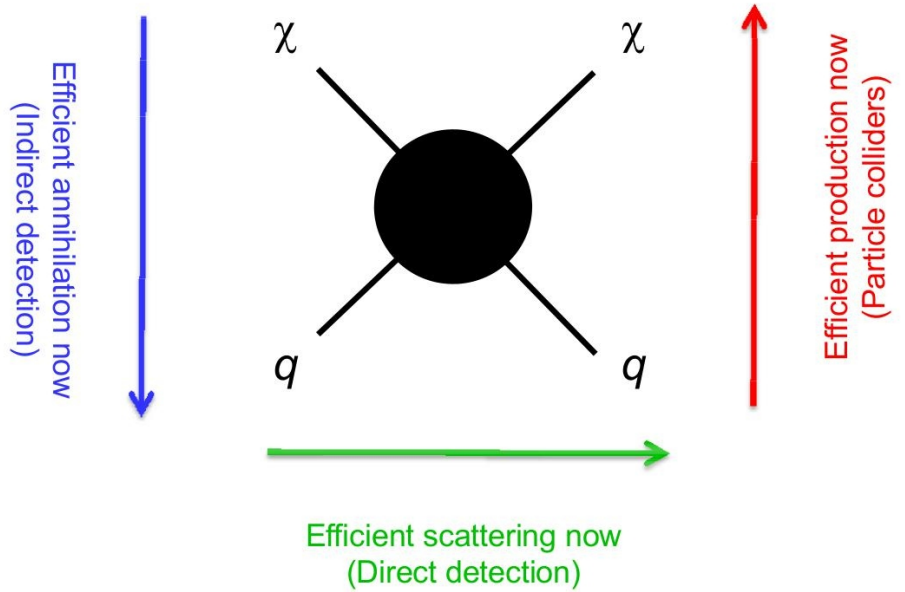
Connection with
Weak (Fermi) scale ?!
[and perhaps supersymmetry]

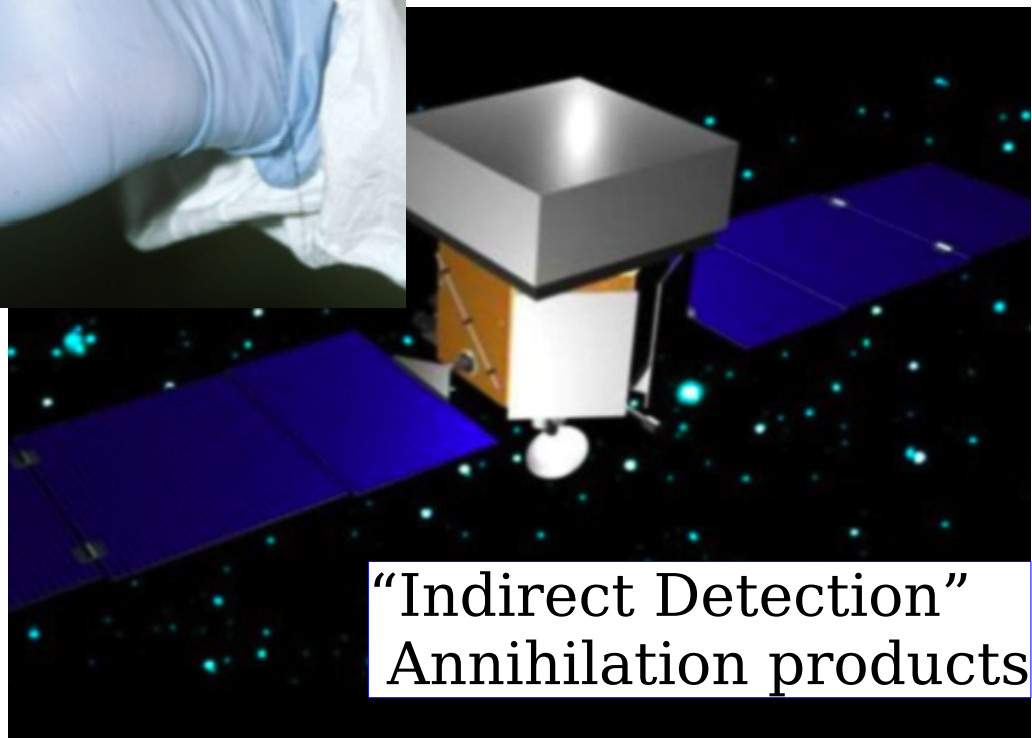
The "WIMP's Miracle" ?

Creation
in accelerators



Elastic
scattering

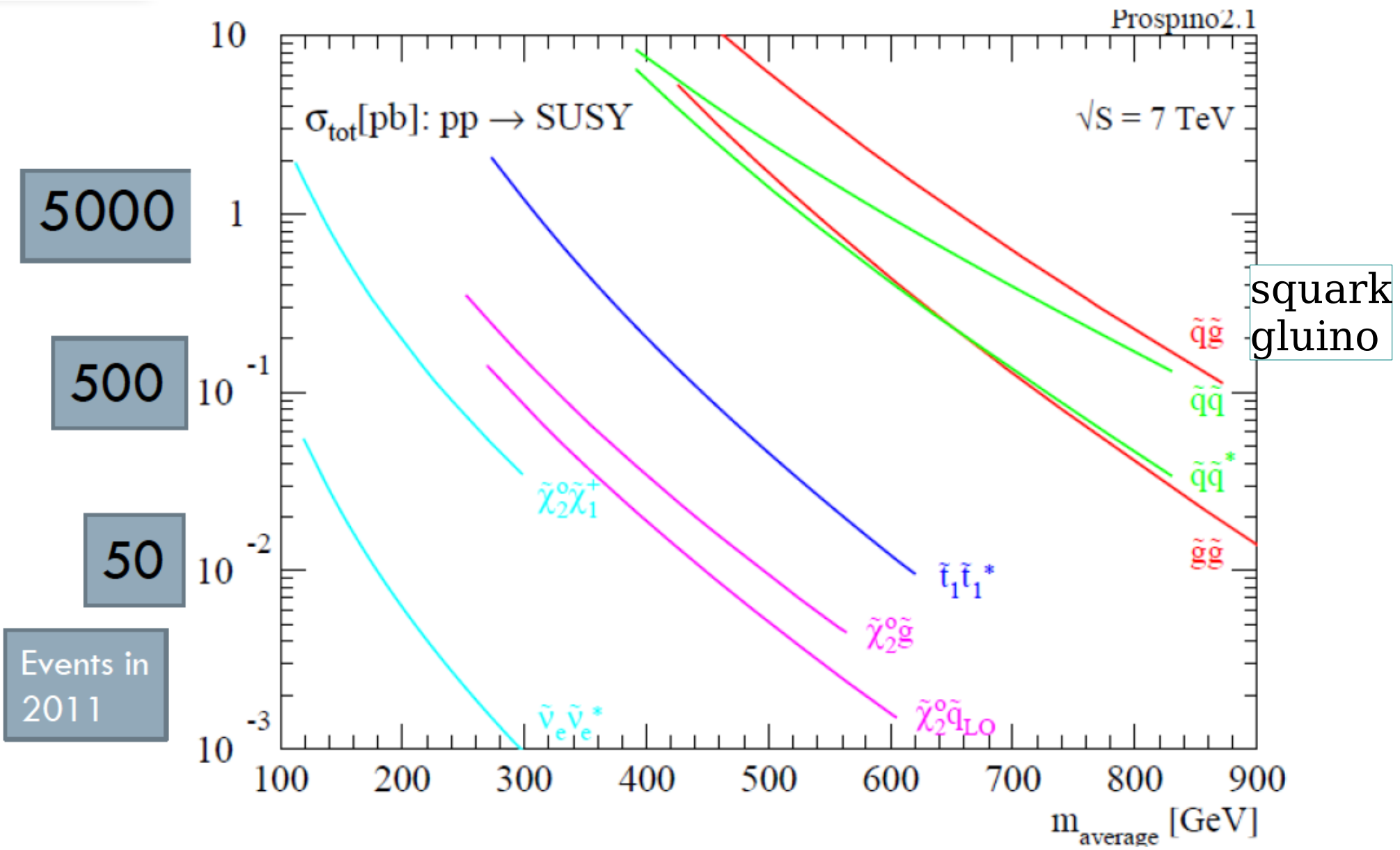




"Indirect Detection"
Annihilation products

3 Roads to test the
WIMP hypothesis

LHC (7 TeV) creation of Super-Symmetric Particles



5000

500

50

Events in 2011

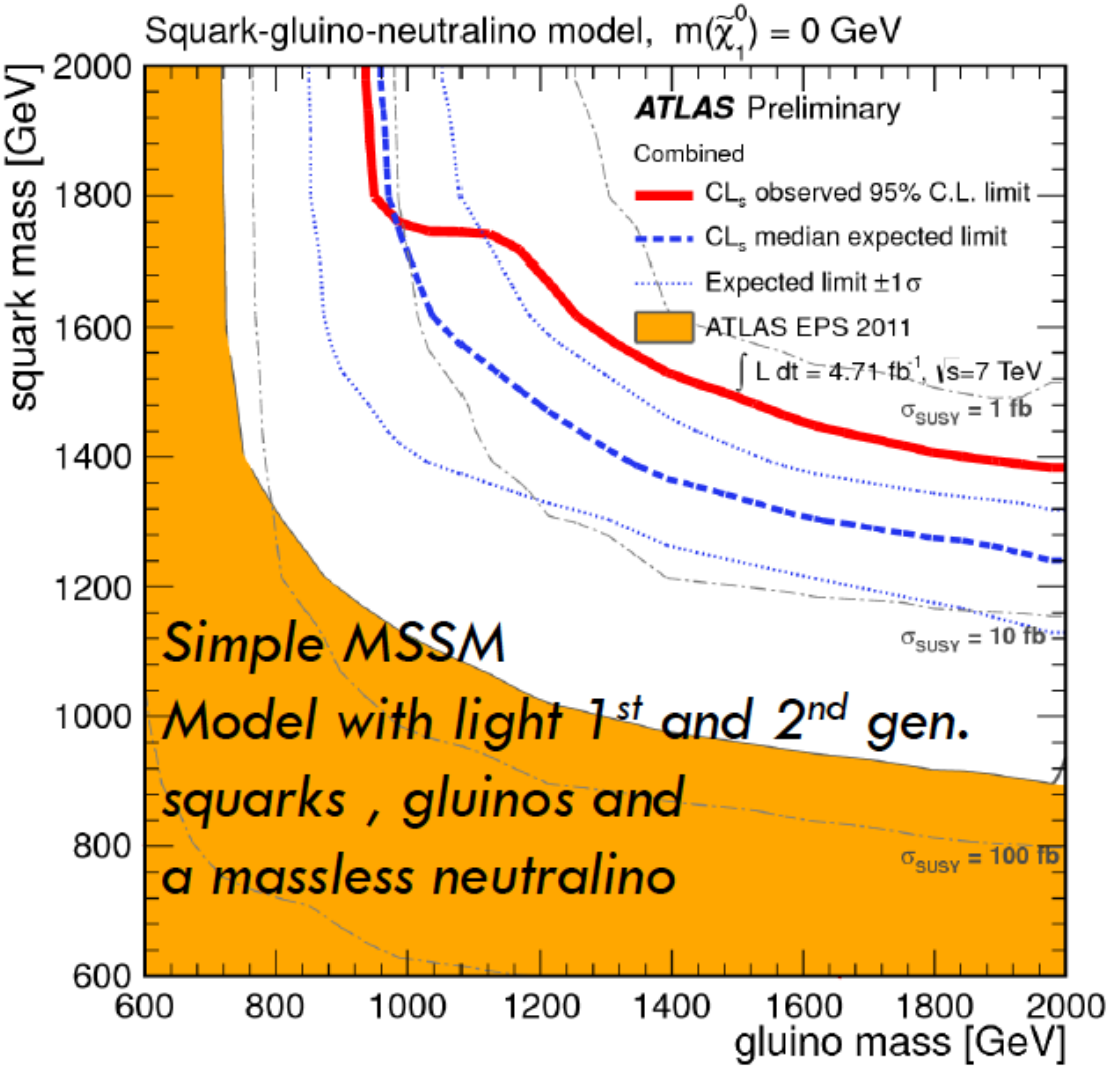
squark
gluino

From ATLAS seminar (S. Caron)

ATLAS limits on the gluino and squark mass

(similar results from CMS)

No evidence for Supersymmetry at LHC



The lower limits on the masses of the supersymmetric partners of quarks and gluons (if they exist) are approaching 1000 GeV

What is the significance of the non-detection of Supersymmetry at LHC ?

Is SuperSymmetry “cornered”

Is the “SUSY Paradigm”
(at least in its most *“Natural”* version)
seriously challenged ?

What is the significance of the non-detection of Supersymmetry at LHC ?

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(at least in its most *“Natural”* version)
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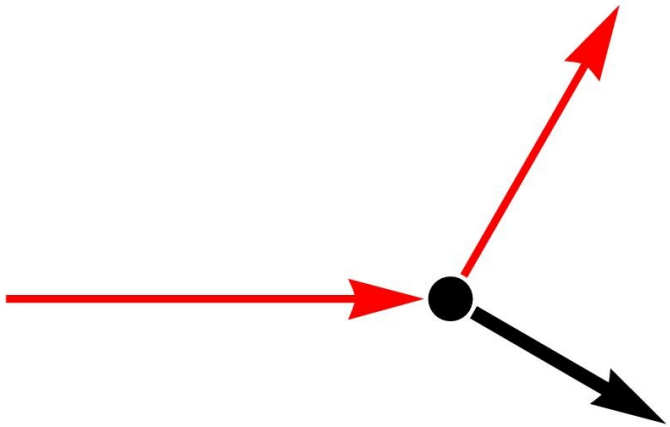
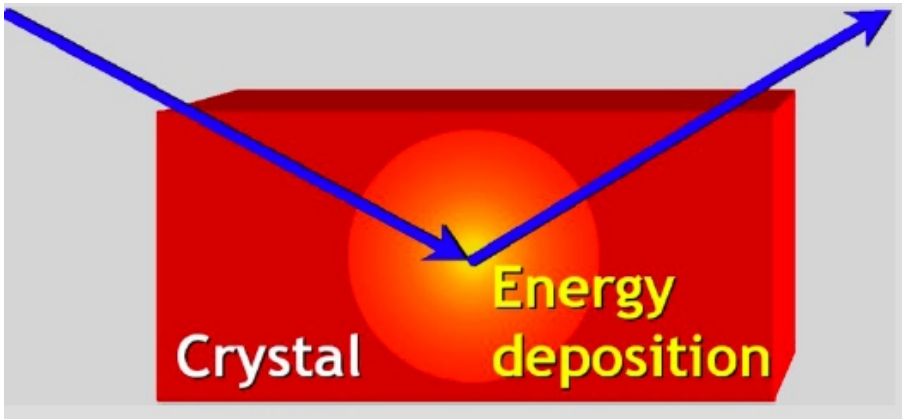
Alternatives to the “WIMP ansatz”
(AXION,.....)
Perhaps Dark Matter is something we have not yet imagined

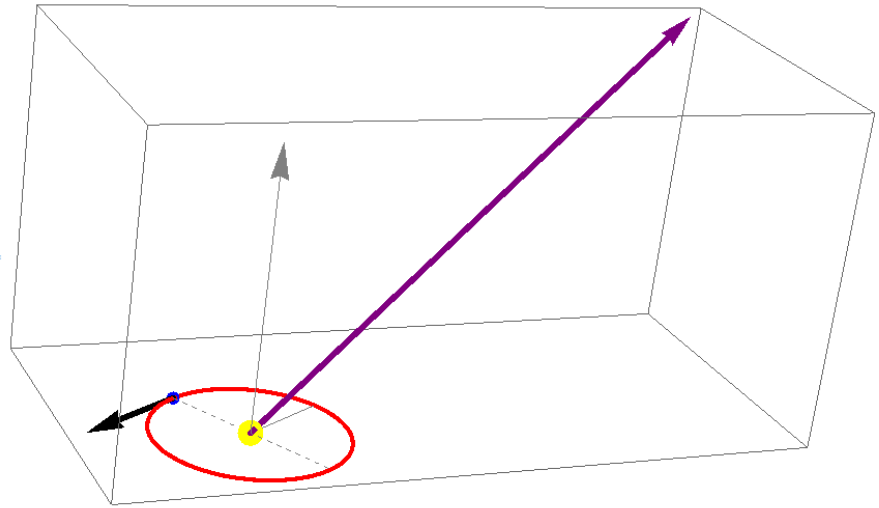
"Direct" Search for Dark Matter

Elastic scattering

$$\chi + A \rightarrow \chi + A$$







"Seasonal Modulation "

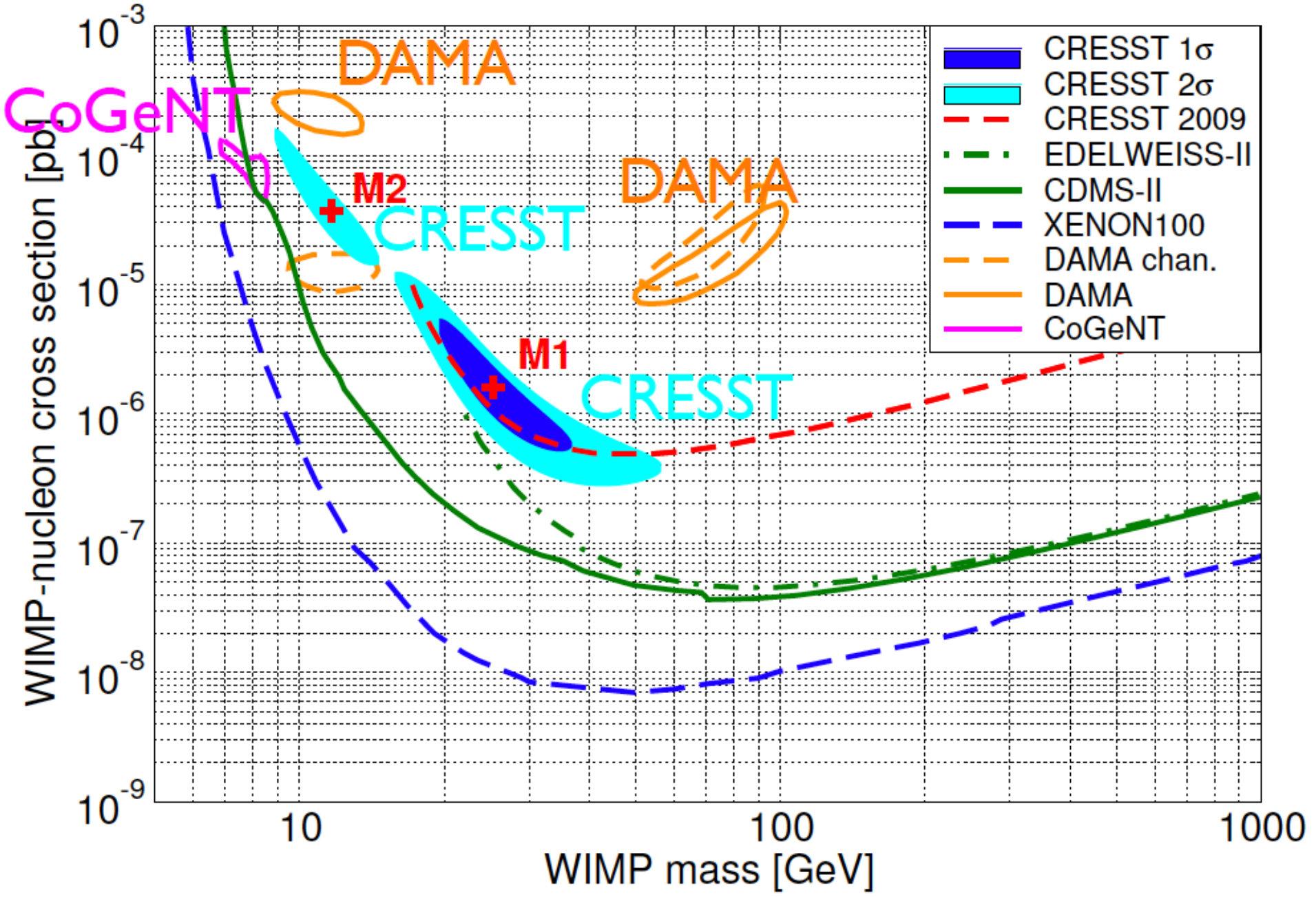
$$\vec{w}_{\oplus}(t) = \vec{w}_{\odot} + \vec{v}_{\rm orbit}(t)$$

$$w_{\oplus}(t) \simeq w_{\odot} + \sin\gamma \; v_{\rm orbit} \; \cos[\omega(t - t_0)]$$

DAMA/Libra effect+claim
Cogent, CRESST "hints"

Limits XENON, CDMS,..

Results in conflict (or serious tension).
How can one reconcile them?



“INDIRECT searches” for Dark MATTER

Positrons, Antiprotons and DM

Pamela/Fermi/AMS Positron (electron) anomaly

Gamma Rays and DM

Evidence for lines ?

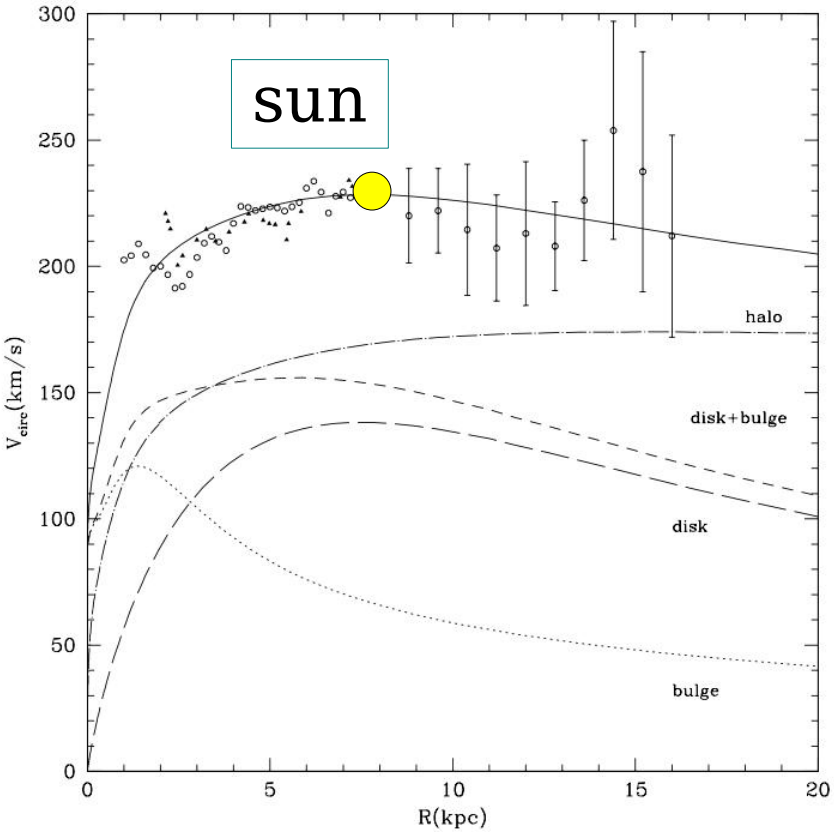
Neutrinos and DM (no time here)

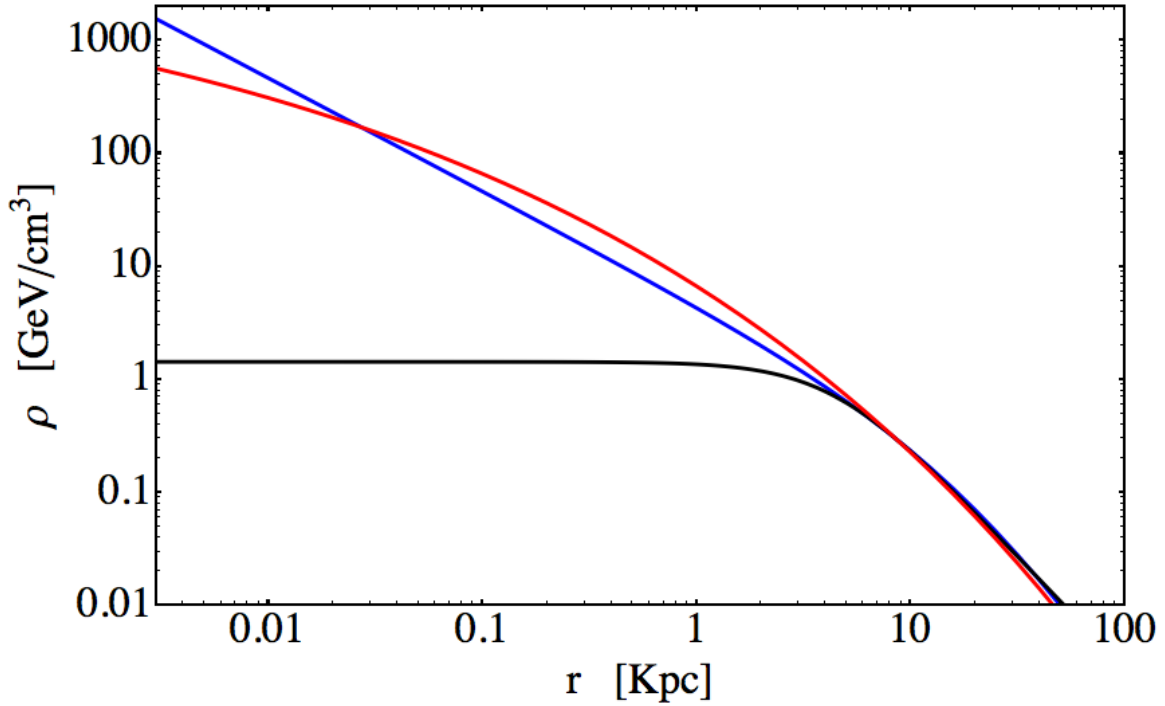
DM in the Milky Way

$$\rho_{\rm isothermal}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

$$\rho_{\rm NFW}(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$

$$\rho_{\rm Einasto}(r) = \rho_s \exp\{-(2/\alpha)[(r/r_s)^\alpha - 1]\}$$





Density distribution

determined by
Rotation velocity measurements

"Cusp" at GC

derived by N-body simulations

Problem of fluctuations
"Boost factor"

Power generated by DM annihilations in the Milky Way halo

$$\frac{dN_{\chi\chi\to X}}{d^3x\,dt} = \frac{1}{2}\, n_\chi^2(\vec{x})\ \langle\sigma\, v\rangle$$

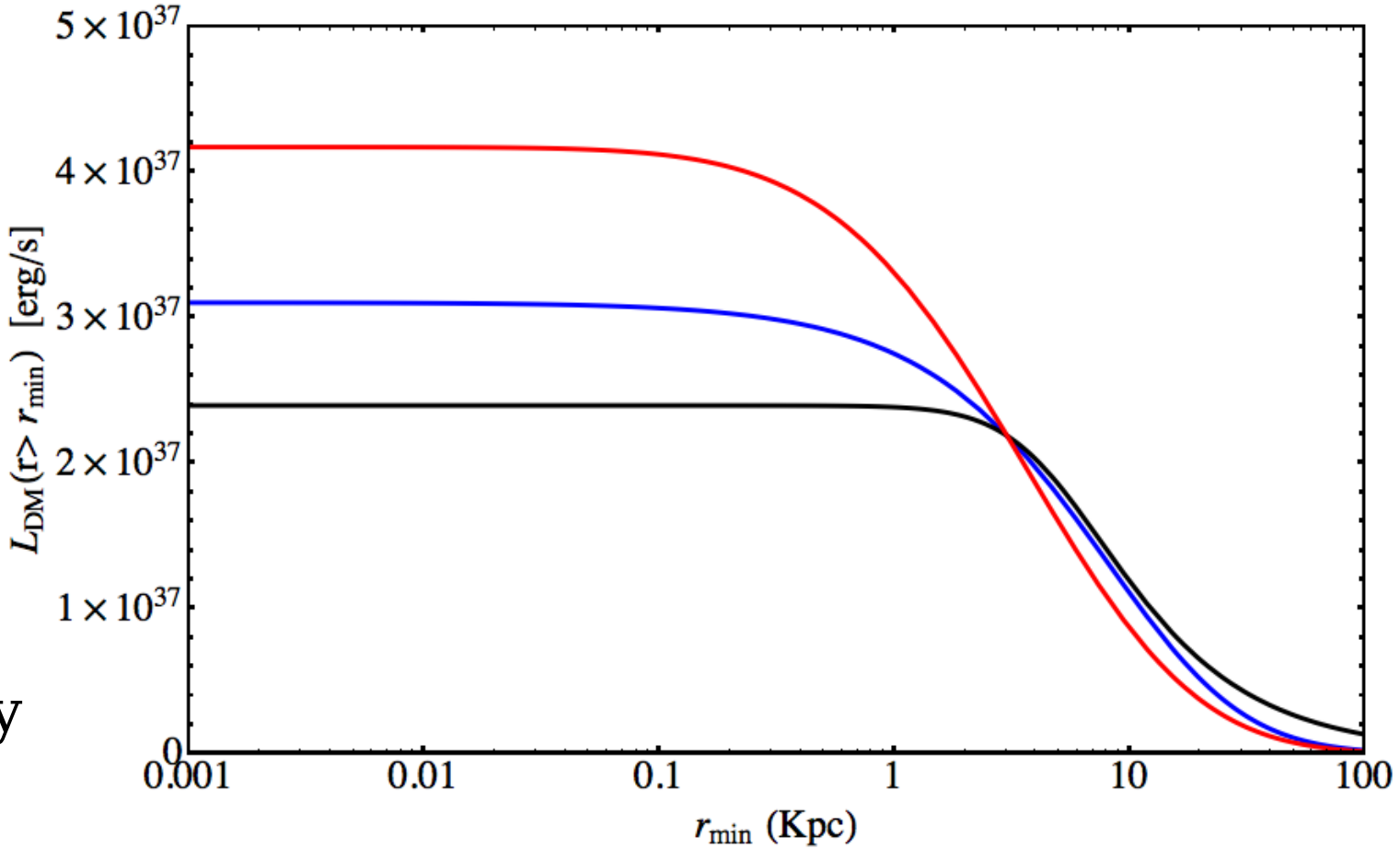
$$\frac{dL_{\rm DM}}{d^3x}(\vec{x}) = \frac{\rho^2(\vec{x})}{m_\chi}\ \langle\sigma\, v\rangle$$

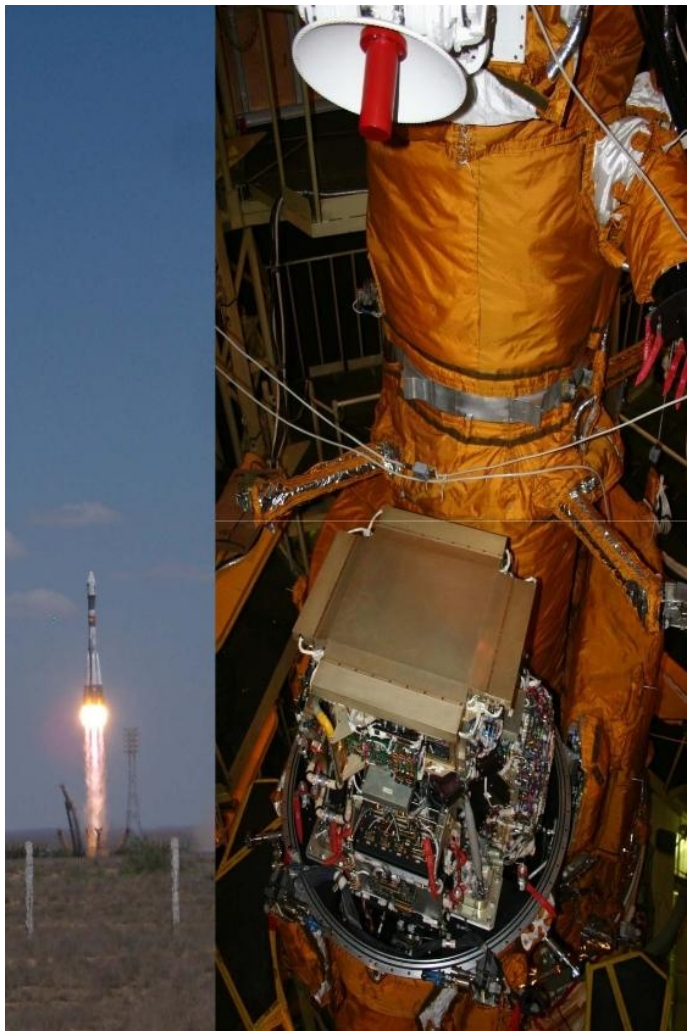
$$L_{\rm DM} \propto \frac{\langle\sigma\, v\rangle}{m_\chi}$$

$$L_{\rm DM} \simeq 3\times 10^{37}\ {\rm erg\ s^{-1}} \left[\frac{\langle\sigma\, v\rangle}{3\times 10^{-26}\ ({\rm cm^3 s})^{-1}}\right] \left[\frac{100\ {\rm GeV}}{m_\chi}\right]$$

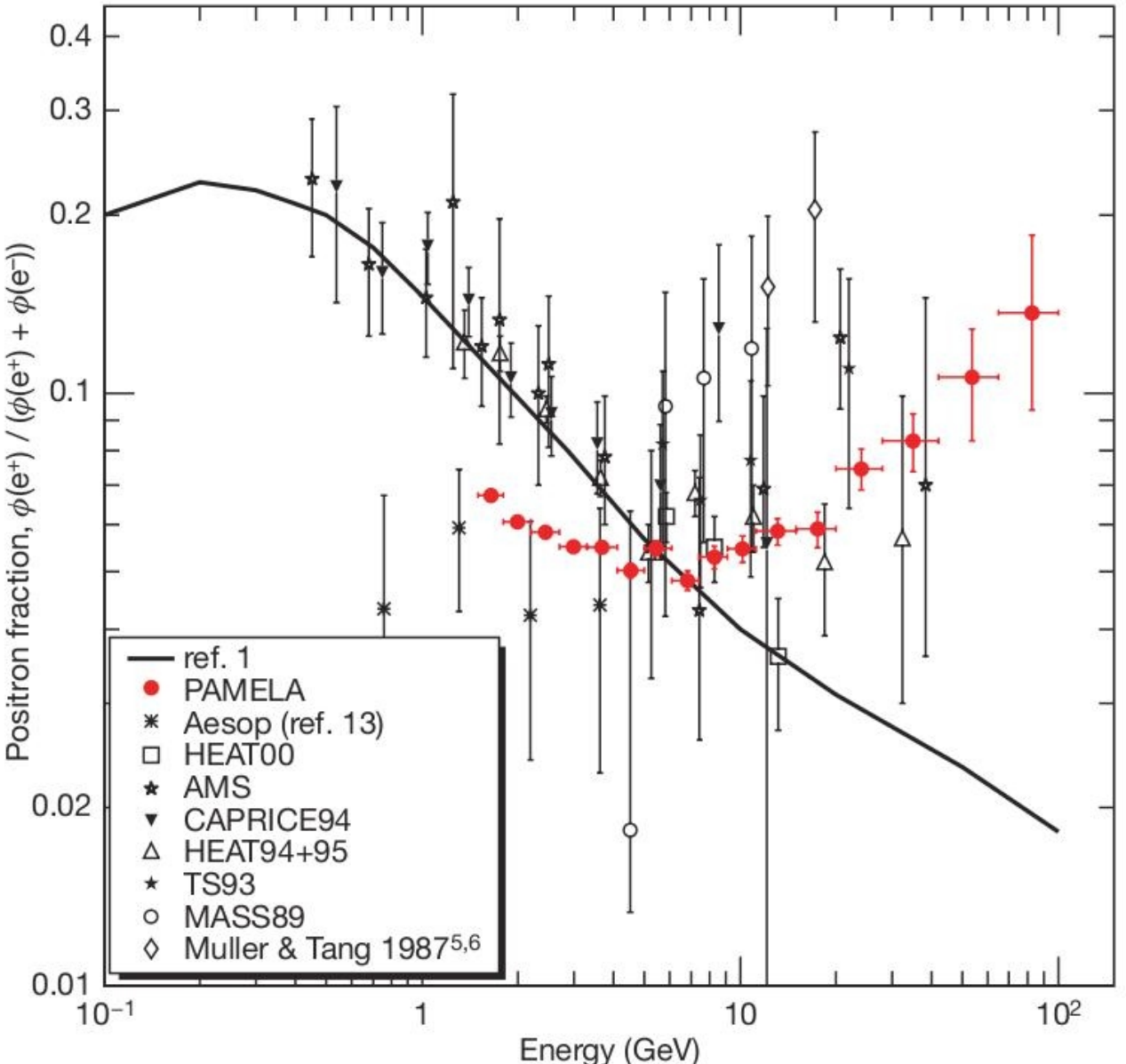
[Majorana particle]

small effect of “Cusp” on total luminosity





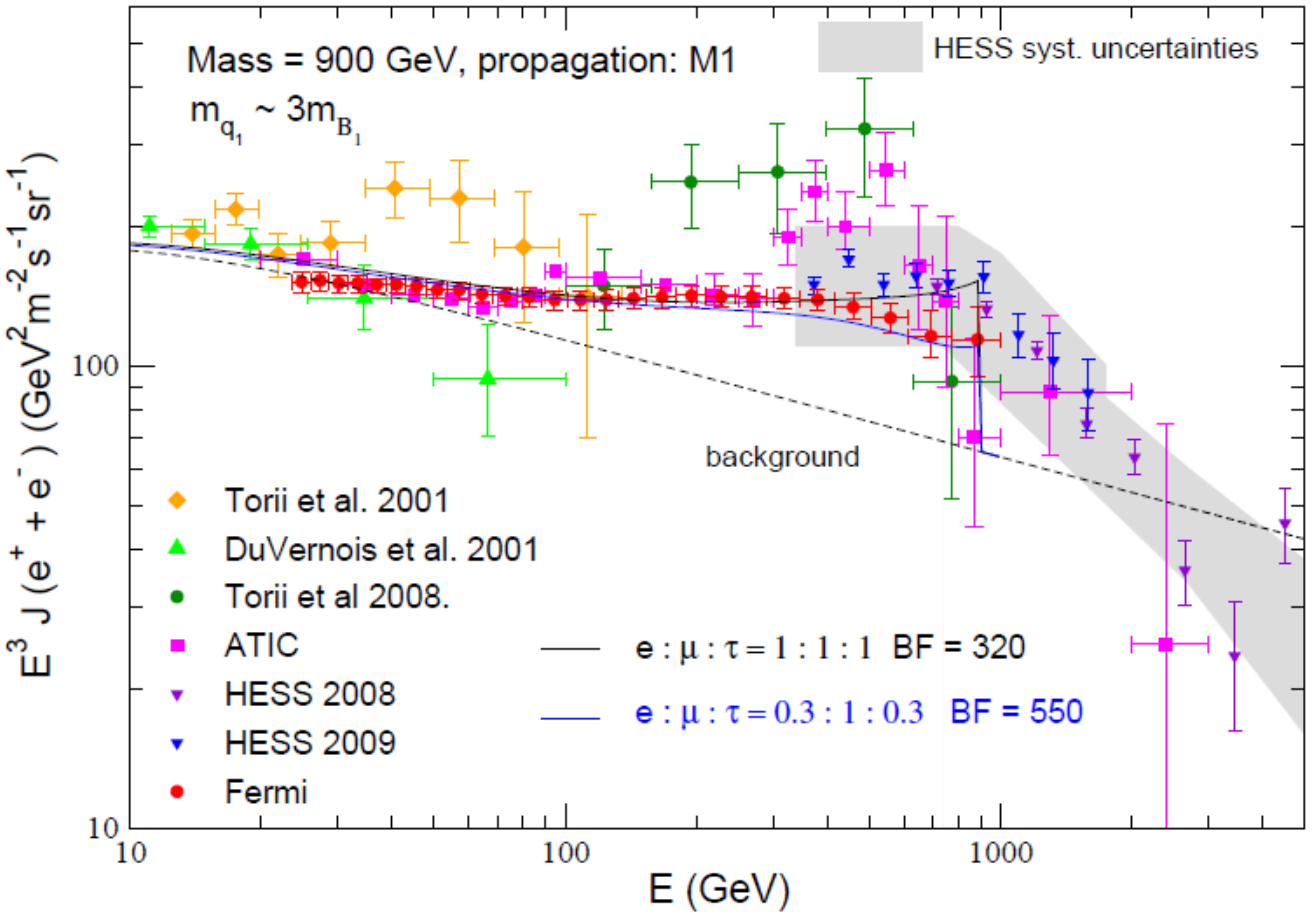
PAMELA
“anomalous positron abundance”
E = [3 - 100 GeV]



Existence of a "new, hard source of positrons" is a robust conclusion (very broad consensus).

Do we have also an “electron excess” ?

Very likely the “new source”
is approximately equal for e- and e+
and visible also in the (e- + e+) spectrum.
This allows to extend the observations to higher energy
(with FERMI + HESS)



New source energy spectrum extends up to (and not beyond) 1 TeV.

Can the PAMELA “positron excess”
be explained by Dark Matter annihilation?

.... yes, ... but not “naturally” ....

[No anti-proton excess!]

[very large $\langle \sigma\, v \rangle$ required]

Set of important upper limits
from gamma rays observations

“Positron anomaly” Interpretation

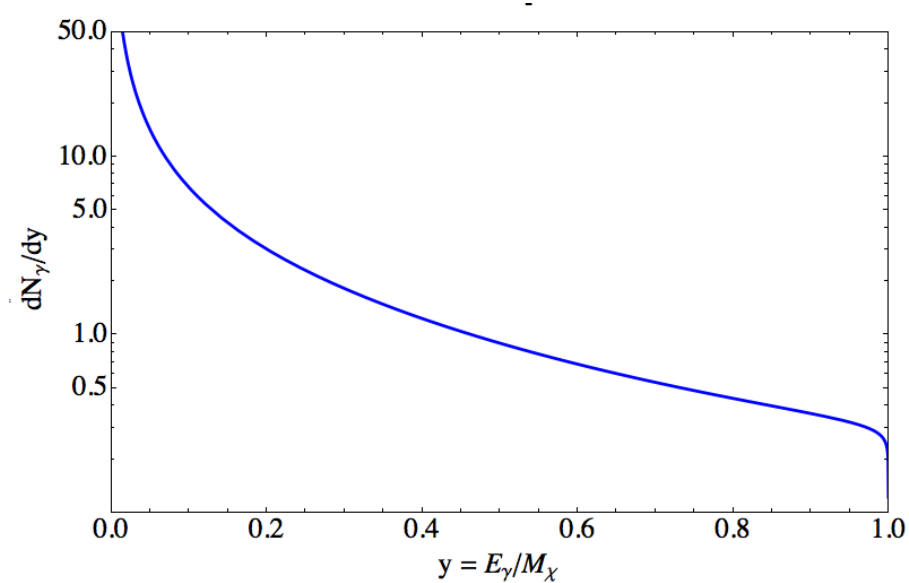
The positron emission MUST be accompanied by a significant emission of photons.

[No “ad hoc hypothesis”
such as “leptophilic, photon-hating” DM is possible.....]

Positrons (and electrons) generate
Gamma rays by Inverse Compton scattering on the
Radiation fields of the Milky Way.

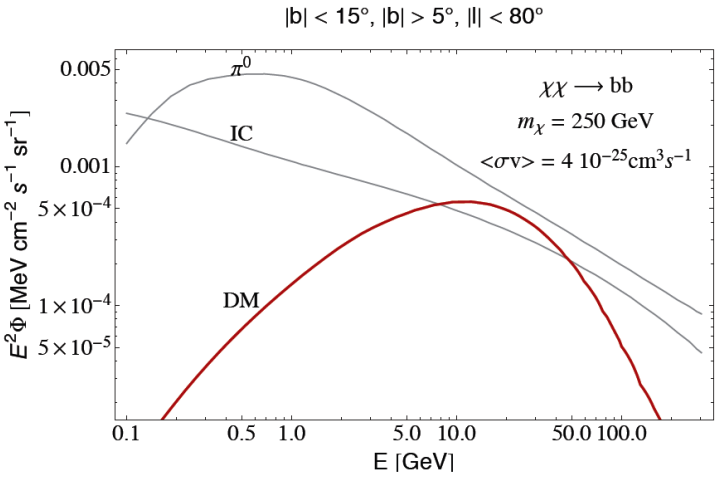
Photon emission by radiative corrections
(at level of 1%)
during annihilation

$$\frac{dN_\gamma}{dy} = \frac{\alpha}{\pi}\left(\frac{1+(1-y)^2}{y}\right)\left(\ln\left(\frac{s(1-y)}{m_\ell^2}\right)|-1\right)$$



GAMMA astronomy experimental study of the hypothesis that the DM is made of Thermal Relics.

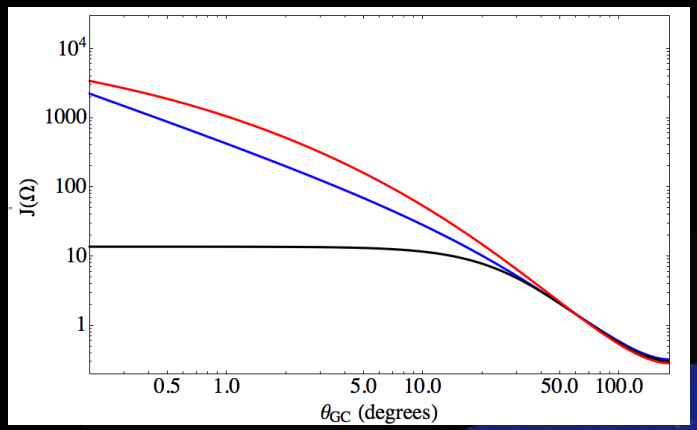
1. Energy Spectrum signatures
2. Angular distribution signatures

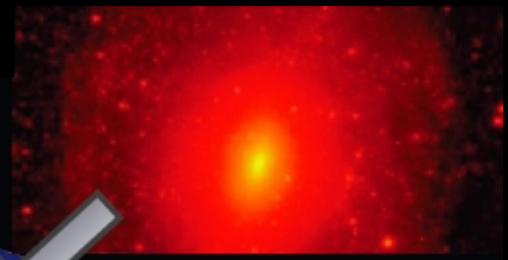


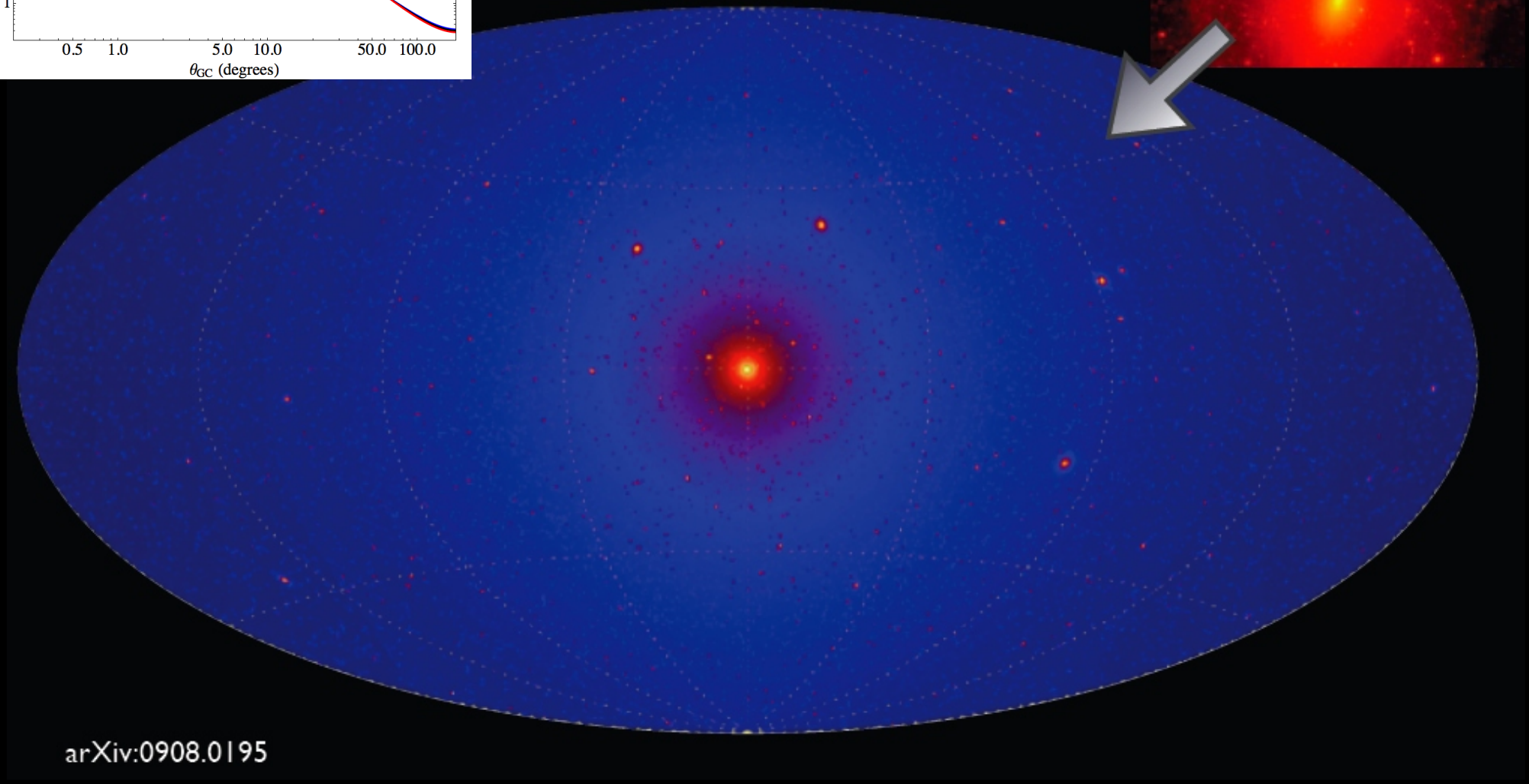
Goal B: Verify/Falsify the hypothesis that the "Pamela anomaly" is due to WIMP annihilation

Goal A: Verify/Falsify the hypothesis that the DM is made of WIMP's

Dark Matter Gamma Sky

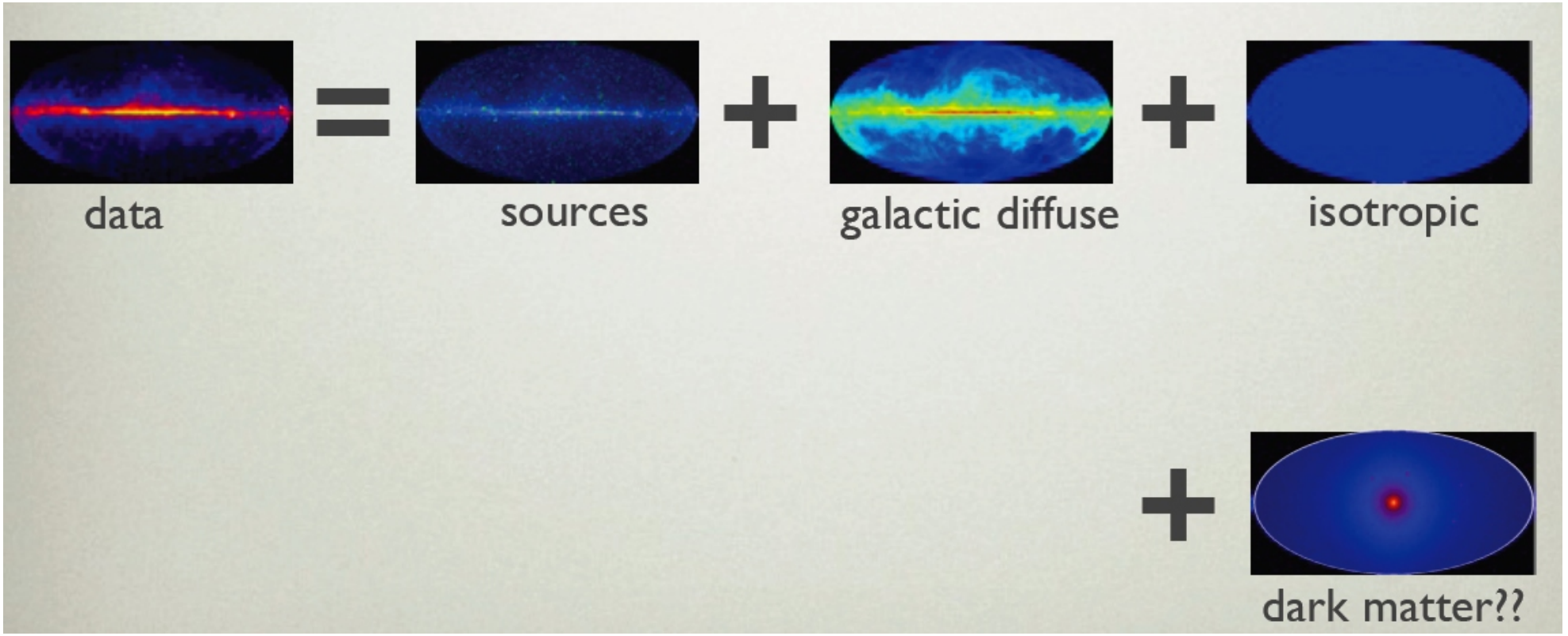


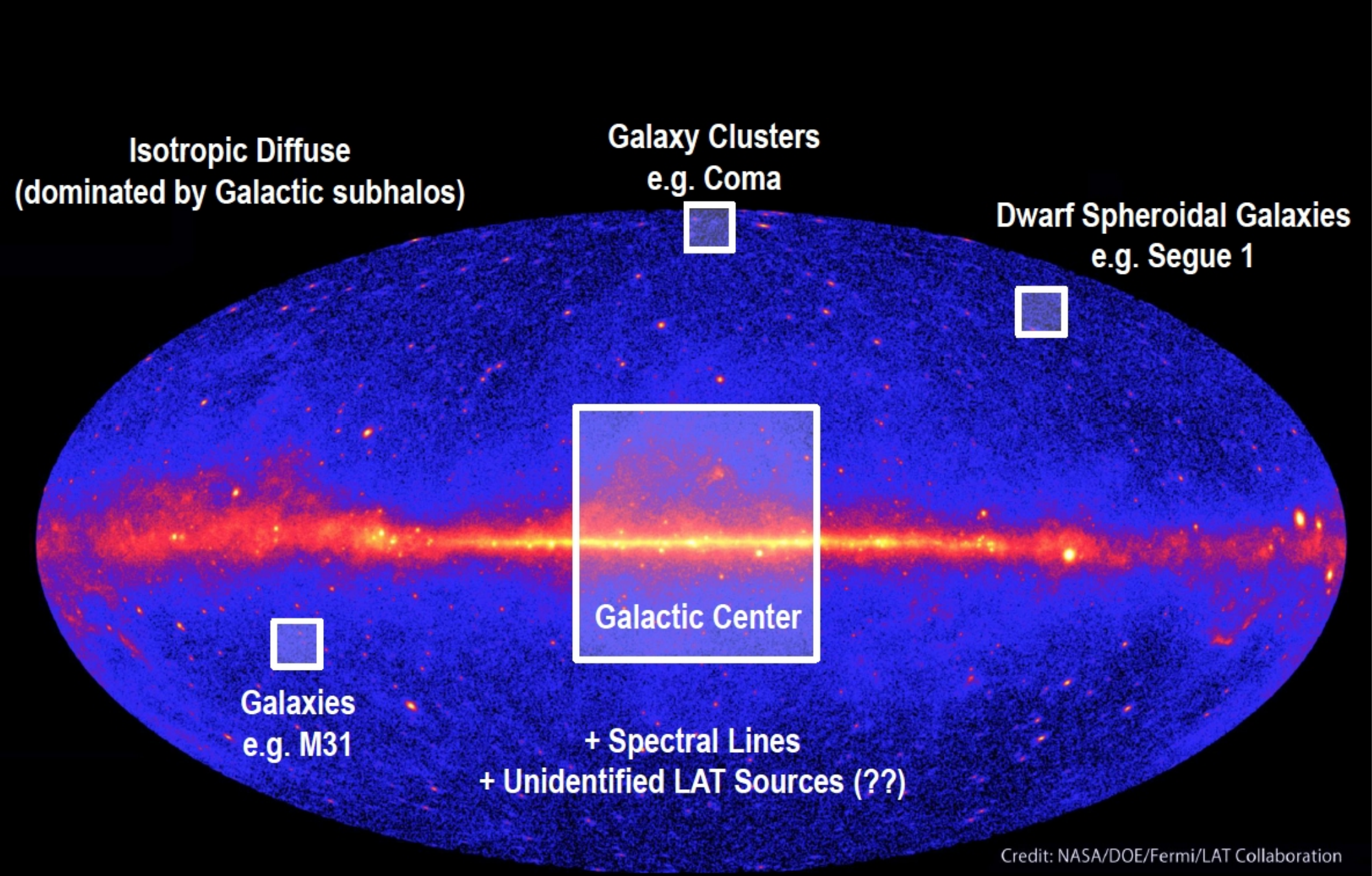




arXiv:0908.0195

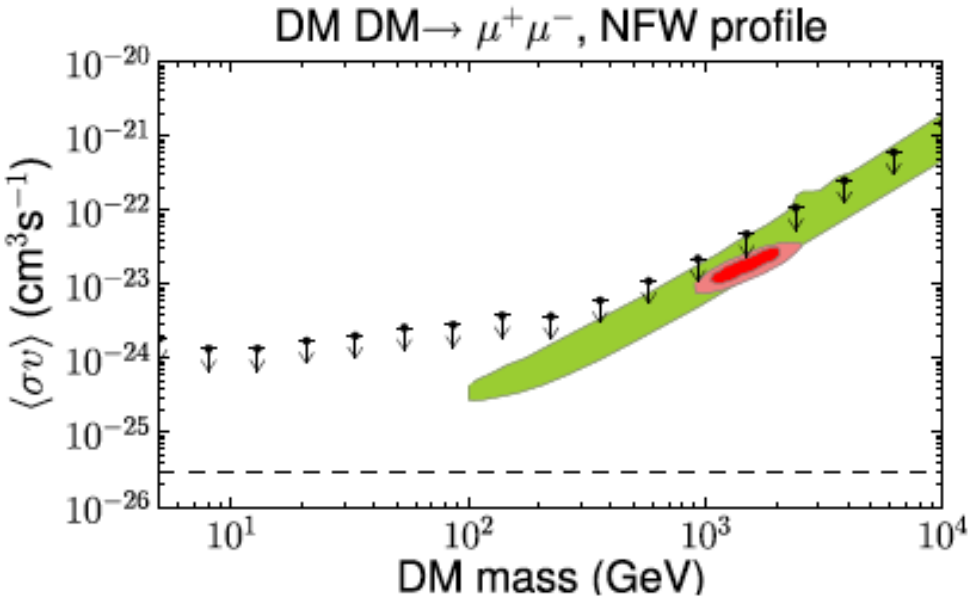
GAMMA RAY SKY

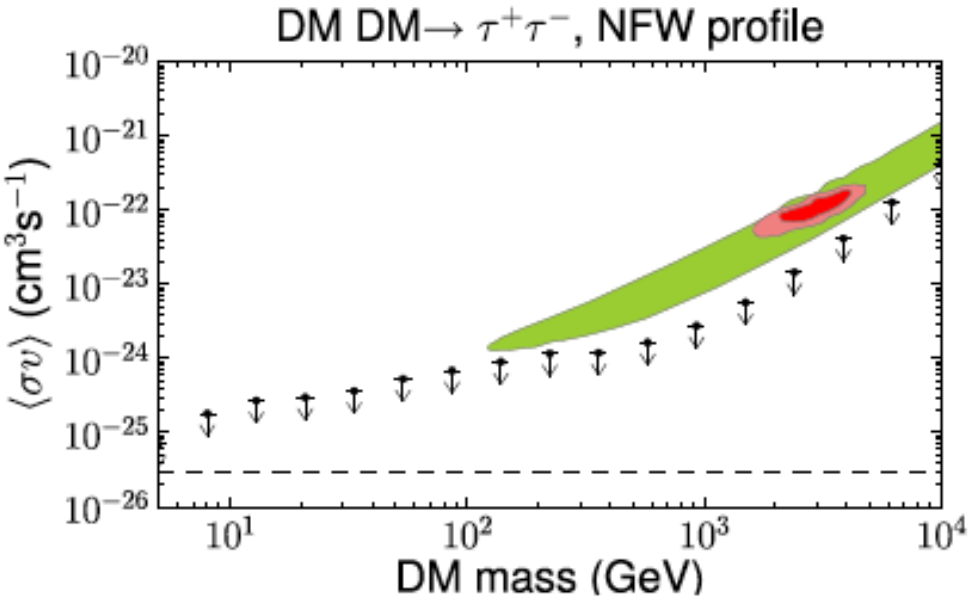


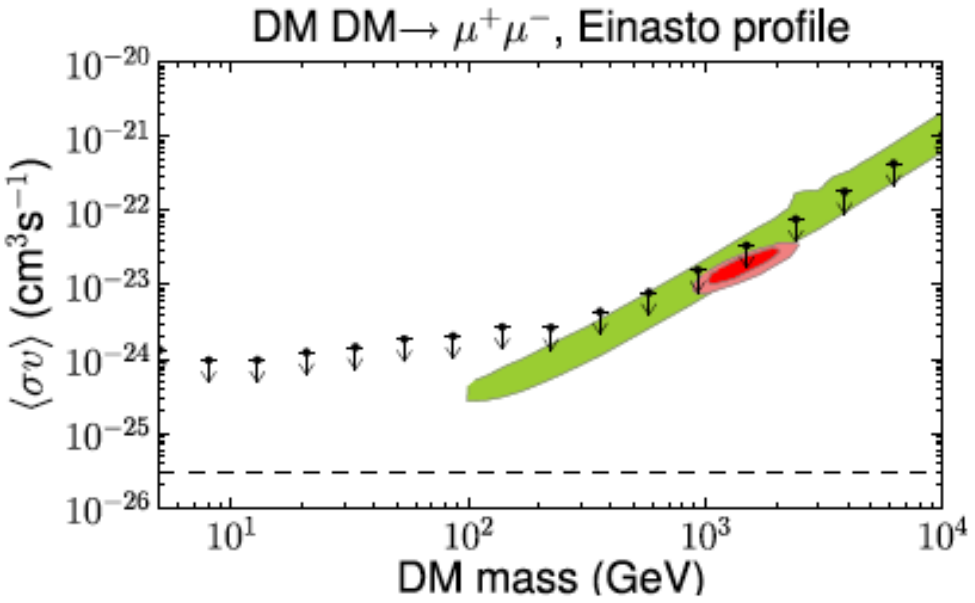


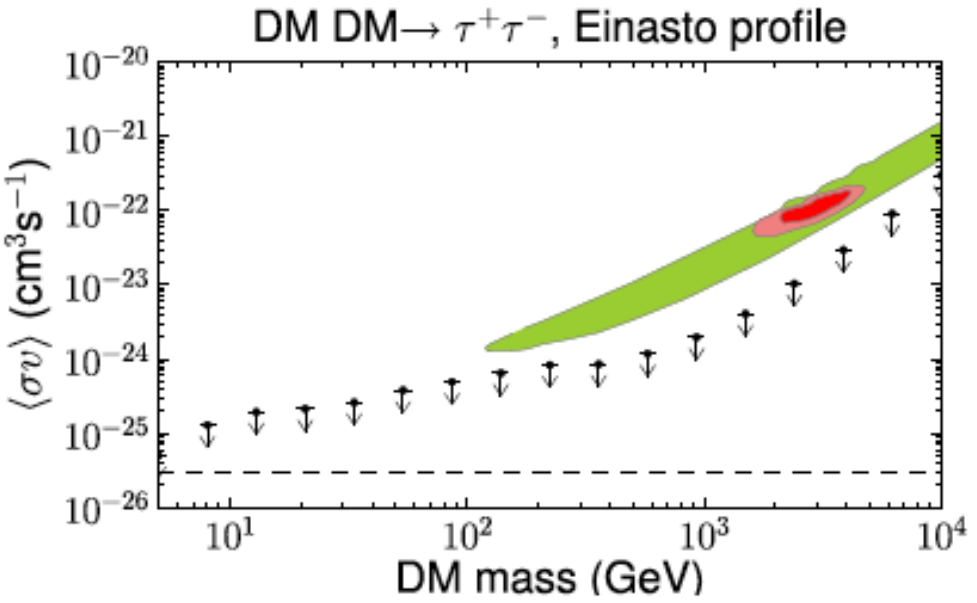
Trade-off between signal strength versus astrophysical background

P. Meade, M. Papucci, A. Strumia, and T. Volansky,
Nucl. Phys. B831, 178 (2010),









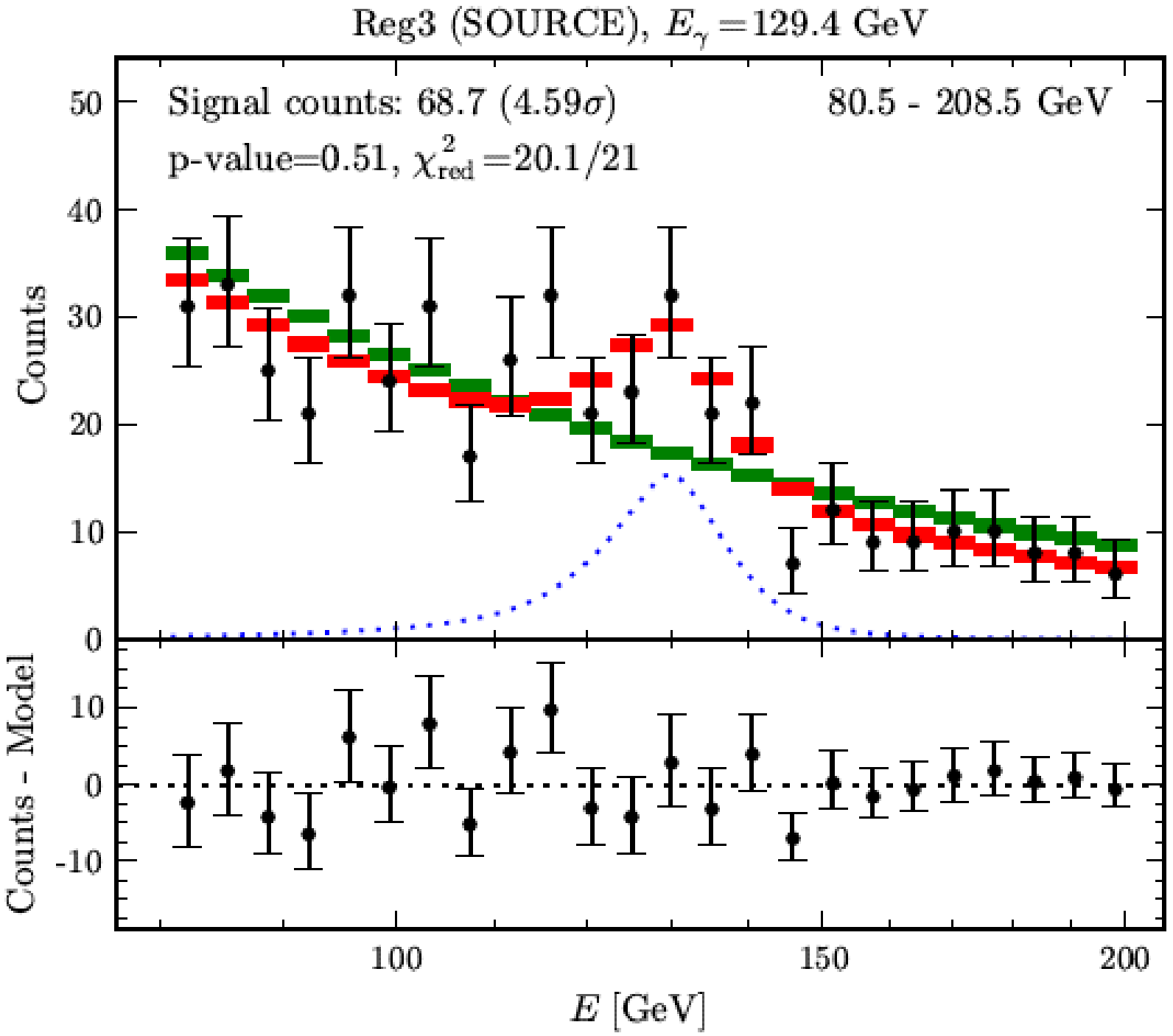
The limit of the gamma ray observations are
In serious tension with the DM interpretations
Of the PAMELA anomaly.

and start to explore the “orthodox range”
of annihilation cross sections.

What about the PAMELA anomaly then....

Pulsars ?
Other acceleration sites ?

Weniger et al. (evidence for spectral line !!?)



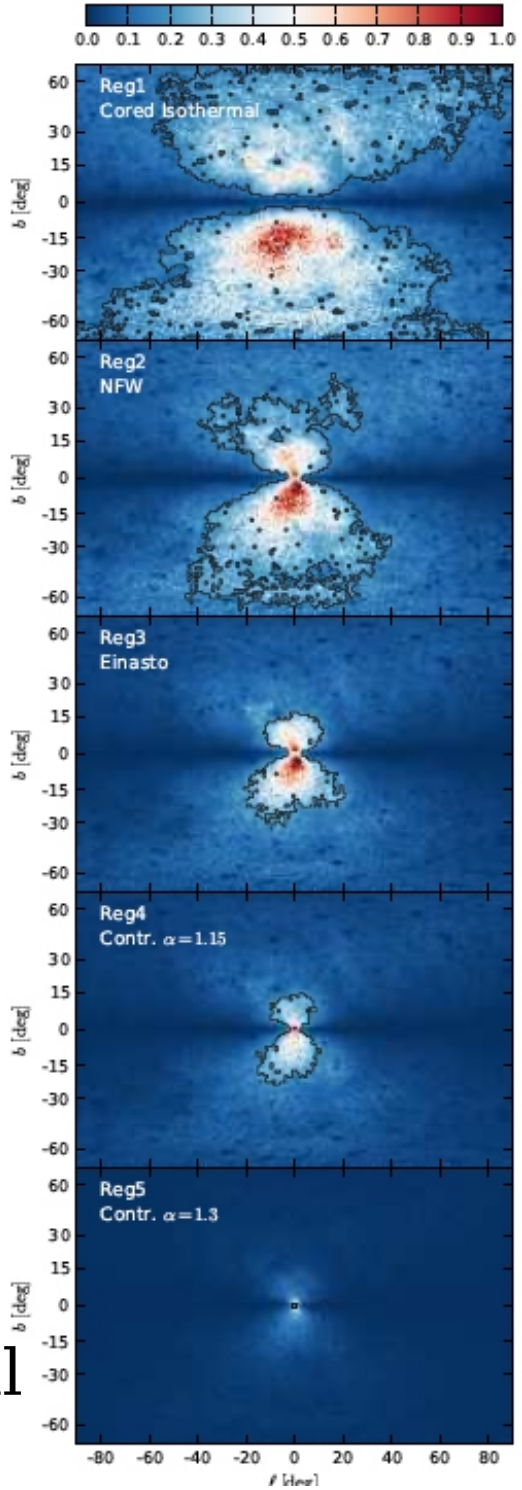
Determine angular region to optimize signal/noise

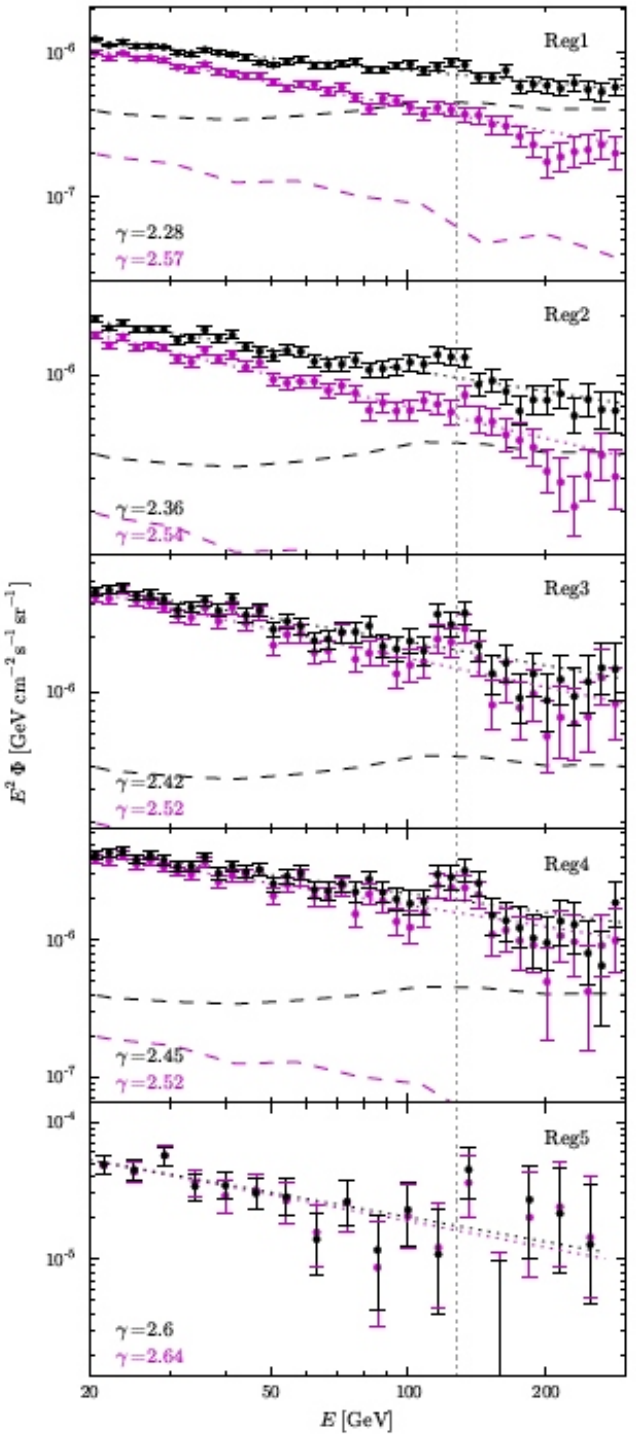
Region depends on assumptions about DM distribution

Claim of a 4.6 effect

hundreds of papers

Perhaps instrumental effect





ASTROPARTICLE Physics and SPACE

Free ourselves from the veil of the atmosphere
to study the universe.

Use relativistic particles to study SPACE
and the different fields (electromagnetic, matter)
that are filling it.

INFN and ASTROPARTICLE Physics

“Just Astronomy”

“Fundamental Physics”

INFN and ASTROPARTICLE Physics

"Just Astronomy"

"Fundamental Physics"

[Dark Matter]
[AGNs]
[GRBs]

Protons, electrons,...
Photons
Neutrinos
Gaviational Waves

Problems are intimately related
the study of extreme environments
is a natural field of research for INFN

Final Remarks

The efforts to understand the objects and the mechanisms that generate high energy relativistic particles in our Galaxy and in the universe form a vibrant field with continuous surprises and new discoveries.
[Multi-Messenger studies are essential]

The “Dark Matter problem” is one of the deepest and most fundamental questions in physics.

The “WIMP” (thermal relic) paradigm can be explored in depth with a “3-roads” approach [LHC/Direct/Indirect methods].

[Perhaps Nature is more “subtle”
“Dark Matter” could be something else
(Axions, super-massive particles, ...)
we should also be ready for alternative paradigms.]