Gamma-ray experiments in space

M. Tavani

(INAF and University Tor Vergata)

100 Years of Cosmic Rays
Anniversary of their Discovery by V.F. Hess
Bad Saarow/Pieskow, August 7, 2012

- Thanks to contributions by
  - D. Thompson (NASA GSFC)
  - G. Kanbach (MPE, Garching)

- Material also from the book *Gamma-Ray Astrophysics* by C.E. Fichtel and J.I. Trombka (1997).

Gamma-ray astrophysics above 30 MeV…difficult !

- Gamma-ray astrophysics was the last to be developed, starting in the 1960's.

  – need to put instruments above the atmosphere.
  – relatively small photon intensity above 10 MeV compared with the cosmic-ray flux.
  – large background of charged particles.

Theoretical expectations and anticipations in the 60's

- Several theoretical papers in the 50-60's anticipated the gamma-ray astrophysics developments:
  - neutral pion gamma-ray emission from CRs and ISM (Hayakawa S.,1952, Progr. Theor. Phys. 8, 571).
  - Bremmstrahlung emission by CRs (Hutchinson G.W., 1952, Phil. Mag. 43, 847).
  - inverse Compton effect and CR electrons (Feenberg E. & Primakoff H., 1948, Phys. Rev. 73, 449).
  - Radiative processes (Morrison P., 1958, Nuovo Cimento 7, 858; Pollack & Fazio, 1963, Phys.Rev. 131, 2684).

Speculations on cosmic gamma-ray sources

(adapted from G. Kanbach)

P. Morrison (Nuovo Cimento, 7, 858, 1958)

(1) synchrotron emission: $E_\gamma > 1\text{MeV} \rightarrow (E_e/mc^2)\, B_{Gauss} > 10^{14}$
'magnetic variable stars'

(2) electron Bremsstrahlung: solar flares

(3) decay of neutral π mesons

(4) de-excitation of nuclei: solar flares; radioactive debris in Crab nebula (SNRs)

(5) electron-positron annihilation: baryon symmetric universe

Pollack & Fazio (Phys.Rev., 131, 2684, 1963):

…the most probable sources of gamma rays of energy > 1 MeV are:

(1) decay of neutral π mesons: high-energy nuclear interactions or antiparticle annihilations;

(2) electron-positron annihilations

(3) electron Bremsstrahlung

(4) synchrotron radiation (magnetic Bremsstrahlung);

(5) de-excitation of nuclei

(6) Inverse Compton scattering.

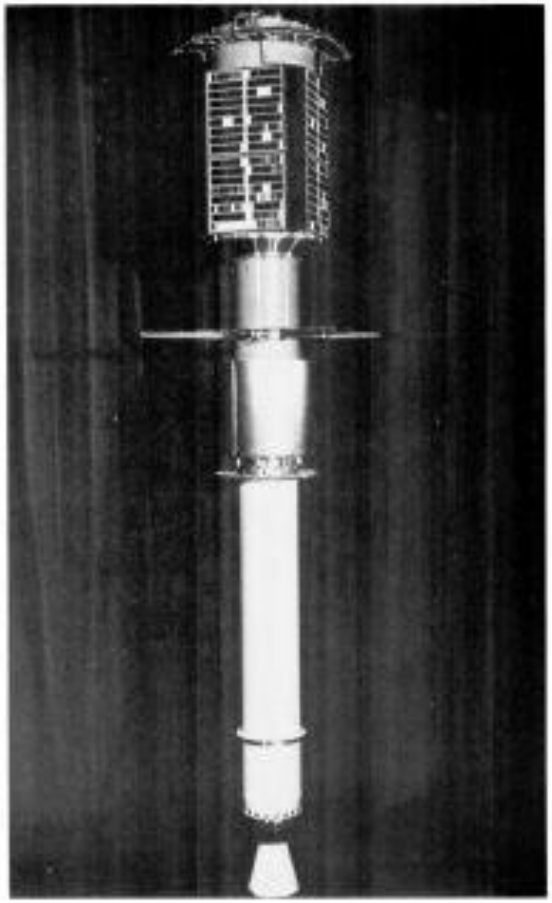
…finally, first detections in late 1960's

- First certain detection of cosmic gamma-rays above 50 MeV by a satellite experiment:
  - Third Orbiting Solar Observatory (OSO-3)
    Kraushaar W.L. et al., 1972, Astrophys. J., 177, 341.
- Positive detections by high-altitude balloon experiments:
  - detection of the Crab pulsar (Browning R., Ramdsen D. & Wright P.J., 1971, Nature, 232, 99).
  - diffuse radiation from the Galaxy central region (Kniffen, D. & Fichtel, C.E., 1970, Astrophys. J., 161, L157).

Gamma-ray (above 30 MeV) astrophysics space missions/experiments

OSO-3	NASA	Mar. 1967 – July 1968
SAS-2	NASA	Nov. 1972 – July 1973
COS–B	ESA	Aug. 1975 – Apr. 1982
CGRO	NASA	Apr. 1991 – Jun. 2000
AGILE	ASI	April 23, 2007
Fermi	NASA	June 11, 2008

(adapted from G. Kanbach)

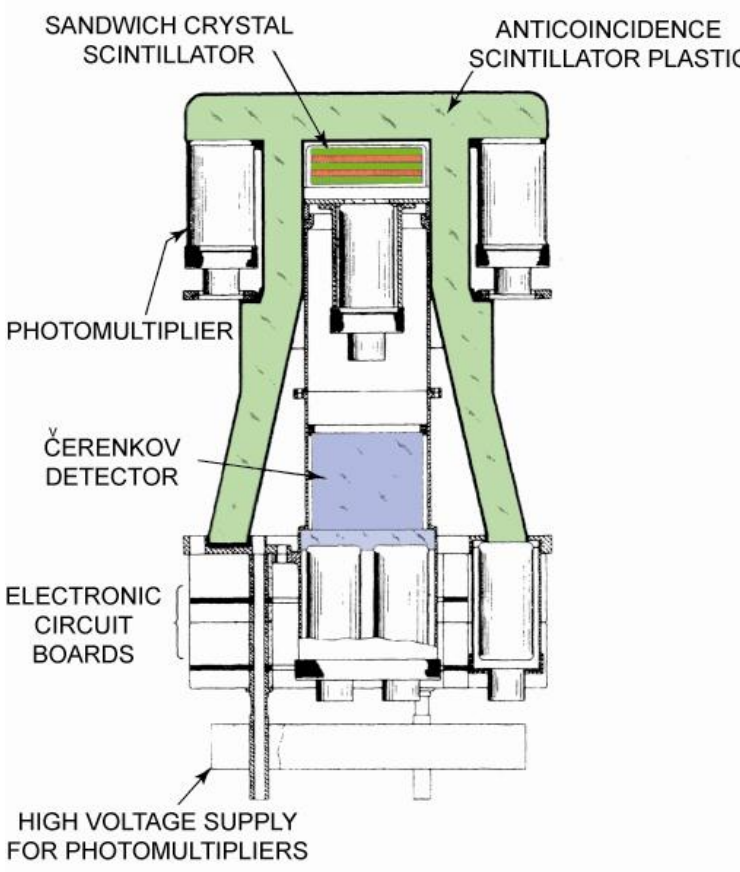


Gamma-ray detector
on **EXPLORER XI**

Kraushaar & Clark, Garmire, Helmken, Higbie, Agogino ApJ, **141**, 845, 1965.

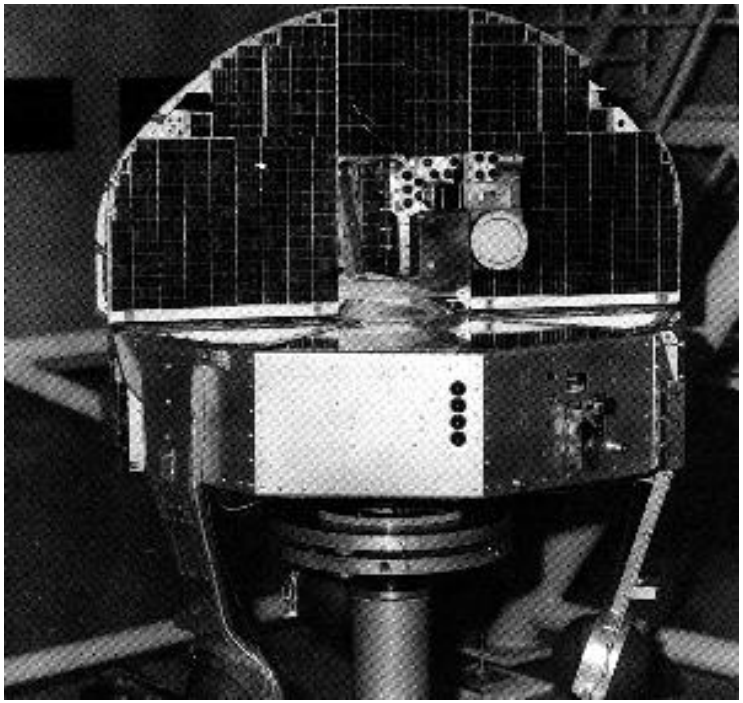
Launched on April 27, 1961, 300-1100 mile orbit, 28.8 deg.
7-month data taking.

First detection of cosmic γ-rays above 100 MeV.



the NASA Orbiting Solar Observatory (OSO-3) (March 8, 1967 – Nov. 1969)

(Peterson et al., ApJ, 145, 962, 1966)



nearly circular orbit,
H = 550 km, i = 33 degrees

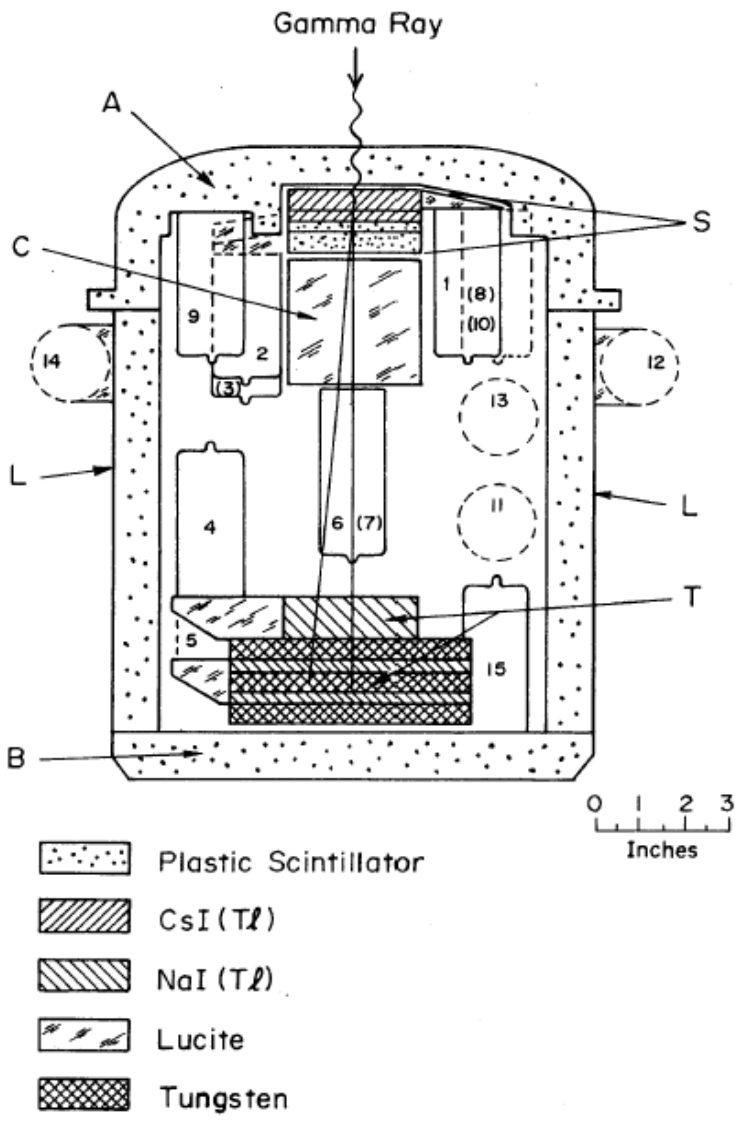
Two instruments:
X-ray telescope (7-200 keV), UCSD
Gamma-ray instrument (above 50 MeV), MIT.

Spinning (1.7 sec) with scan plane orientation within a few degrees from the Sun.

Extensive observations of many solar flares, diffuse component of X-rays, detection of an outburst from Sco X-1.

The gamma-ray detector on the Orbiting Solar Observatory (OSO-3) (March 1967 – July 1968)

(Kraushaar et al., ApJ, 177, 341, 1972)



Threshold above 50 MeV

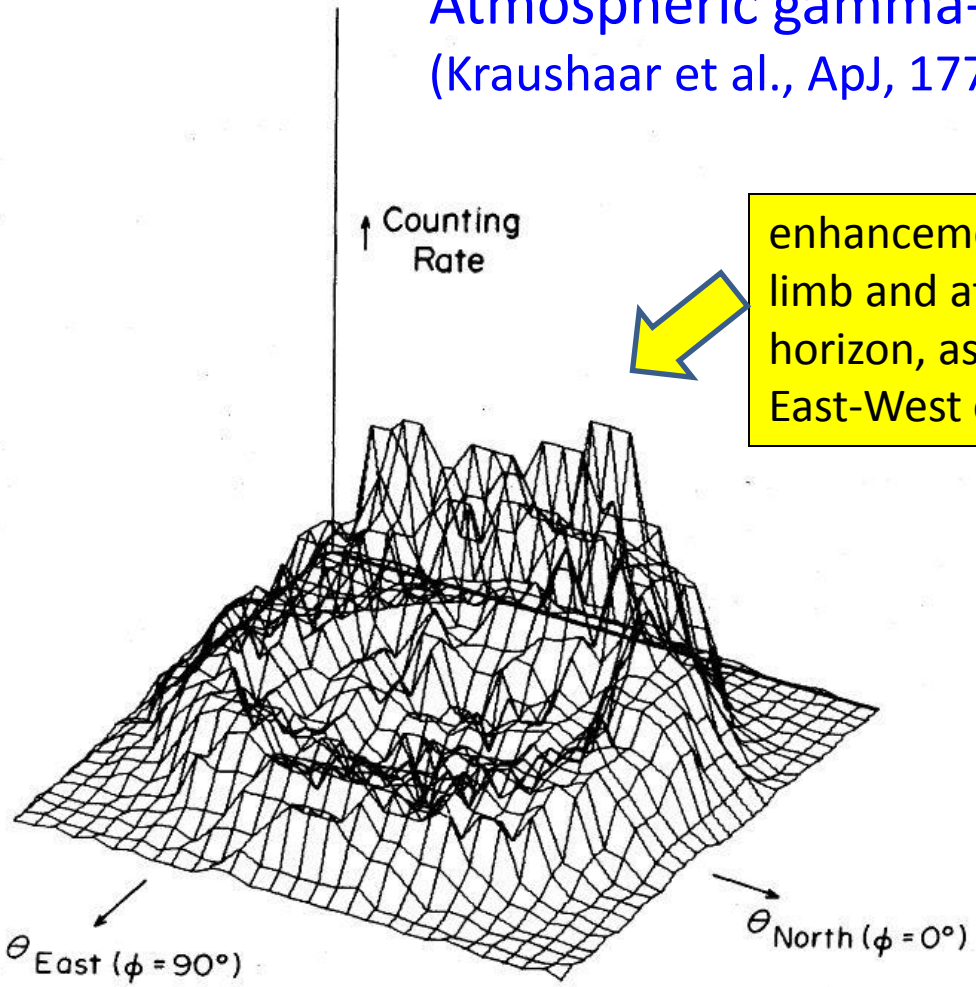
charged particle background about 10^4 times larger than gamma-ray intensity above 50 MeV

when pointed at the Earth, the gamma-ray rate is 1/200 sec; when pointing out of the Earth, the rate is 40 times less.

621 gamma-ray events collected in 16 months

Atmospheric gamma-rays (OSO-3)

(Kraushaar et al., ApJ, 177, 341, 1972)



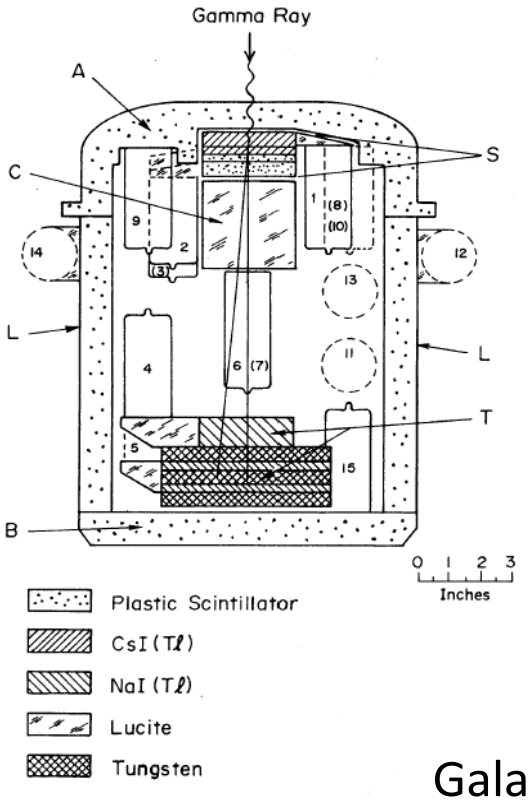
enhancement at the Earth's limb and at the Western horizon, as expected from the East-West effect.

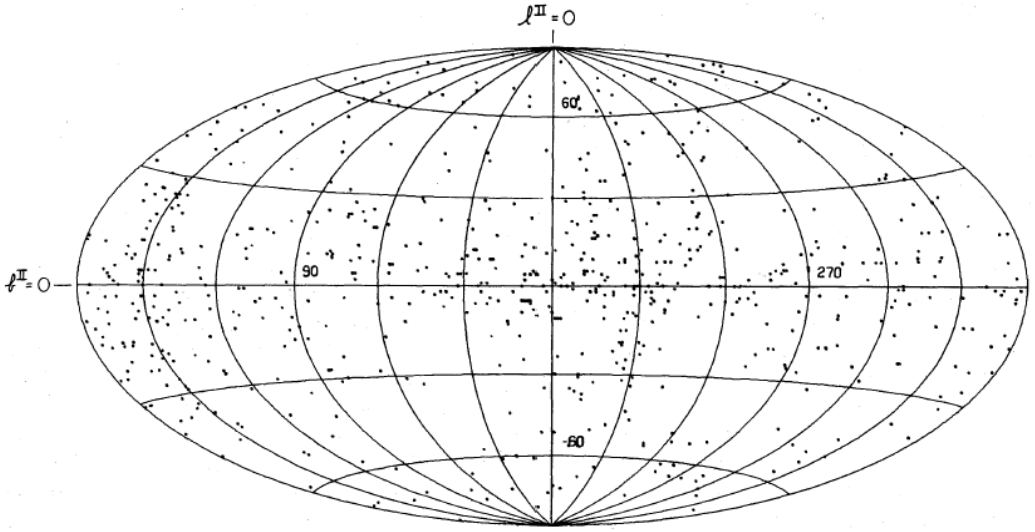
FIG. 3.—Three-dimensional plot of the counting rate in Earth-centered coordinates showing the attitude and azimuth variation of the atmospheric intensity.

OSO-3 (1967-68)

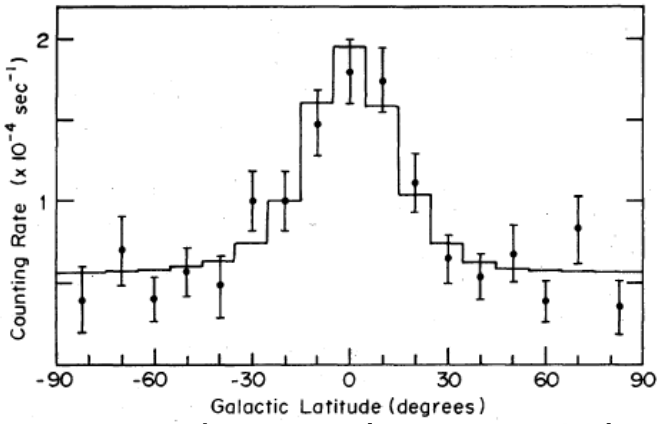
(adapted from G. Kanbach)

(Kraushaar et al., ApJ, 177, 341, 1972)

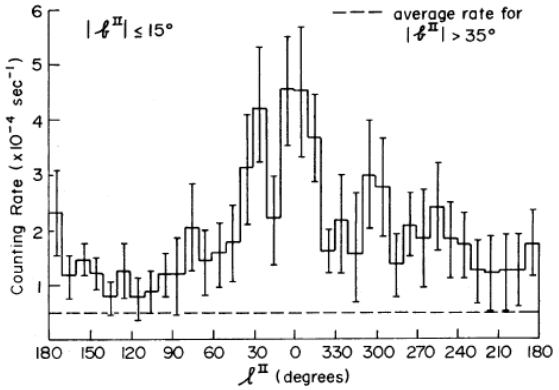




Galactic Map of 621 sky events (E>50MeV)



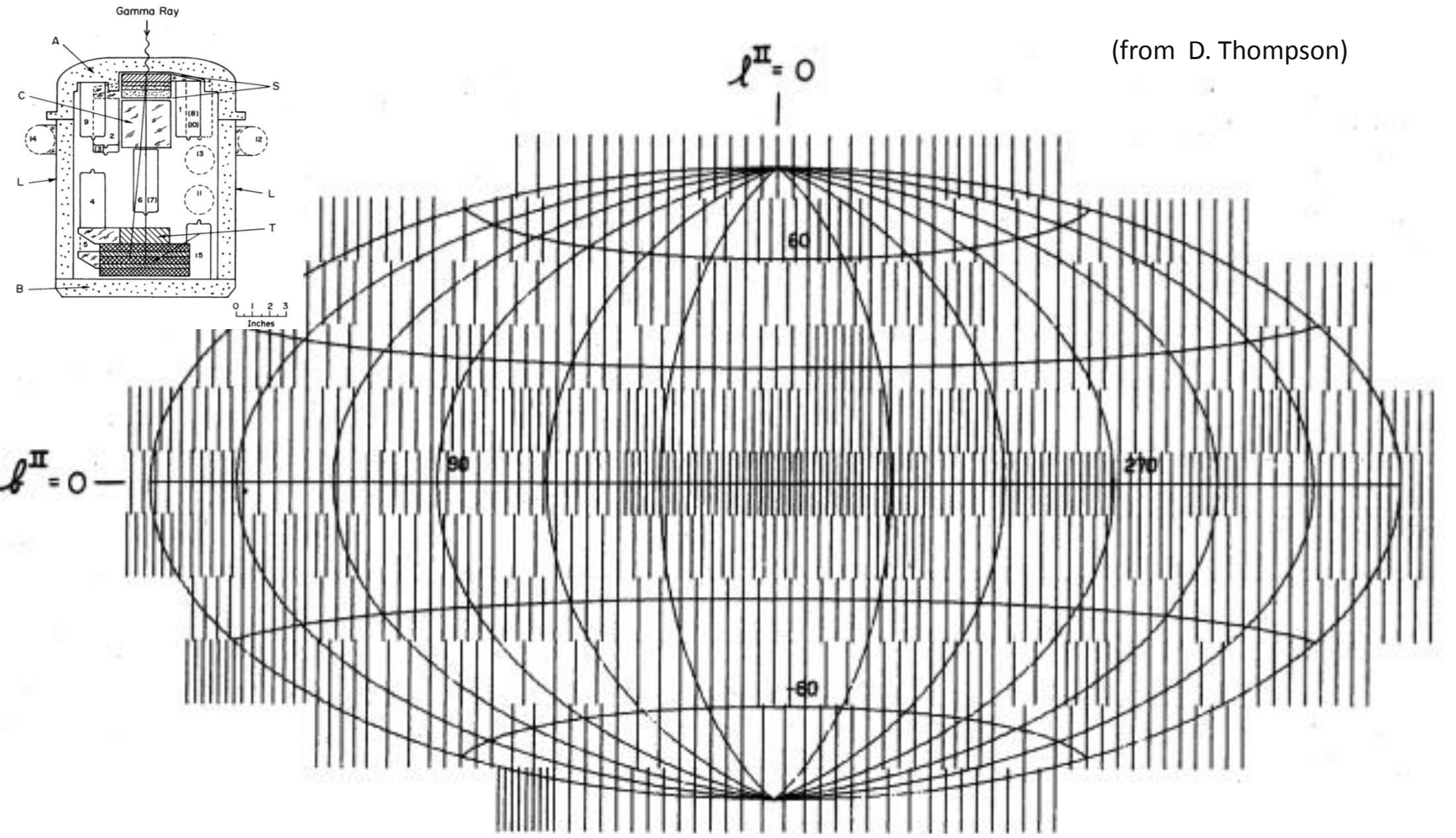
Latitude Distrib. inner Galaxy



Longitude Distrib.

Early Map of the Gamma-ray Sky – OSO-3 (1967-68)

(from D. Thompson)



621 Gamma rays

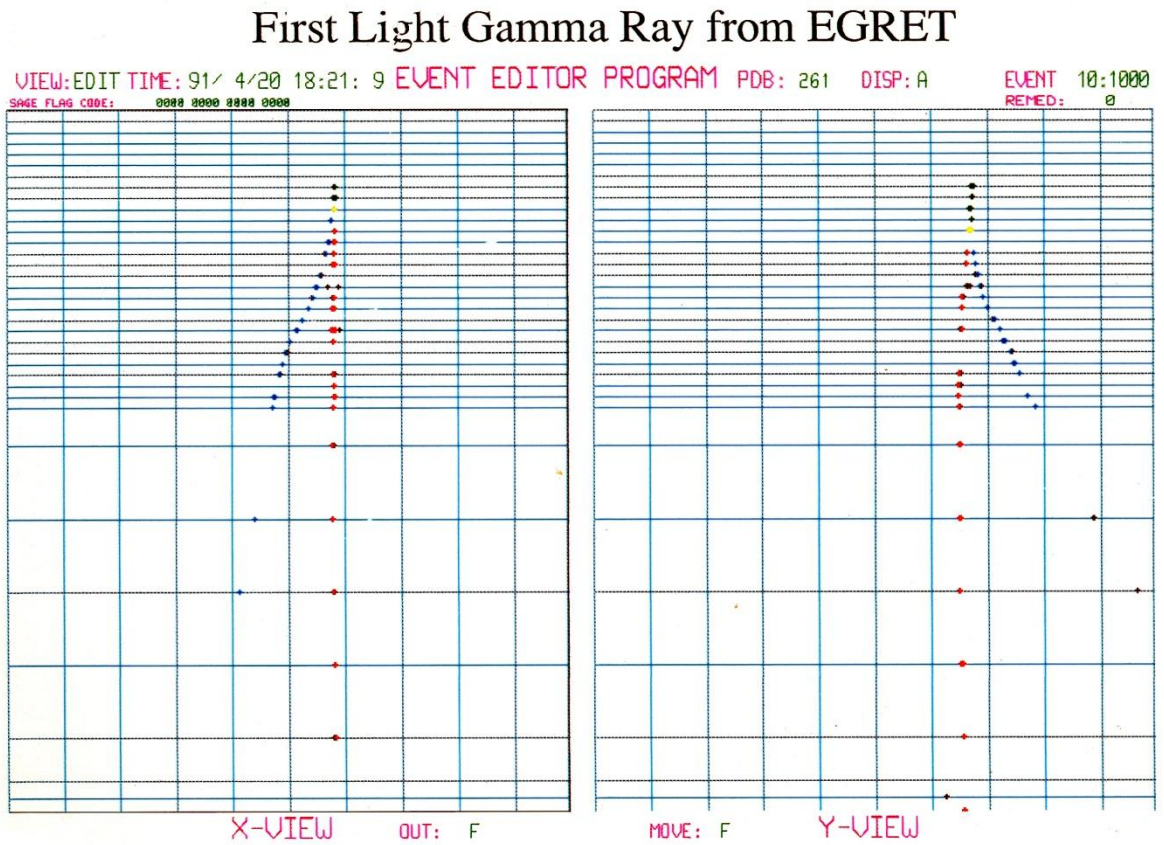
Kraushaar et al. 1972

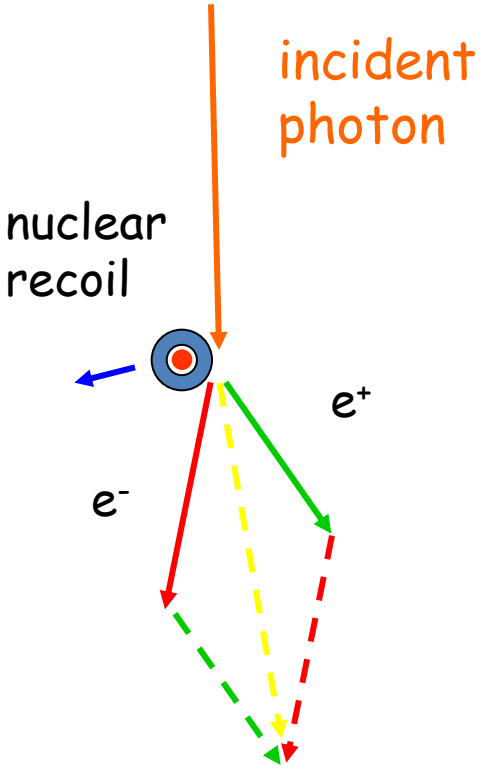
(adapted from G. Kanbach)

Imaging Pair Creation Telescopes (> 30 MeV)

Principles of imaging / spectroscopy

Angular and energy resolution





Limits to angular resol.:

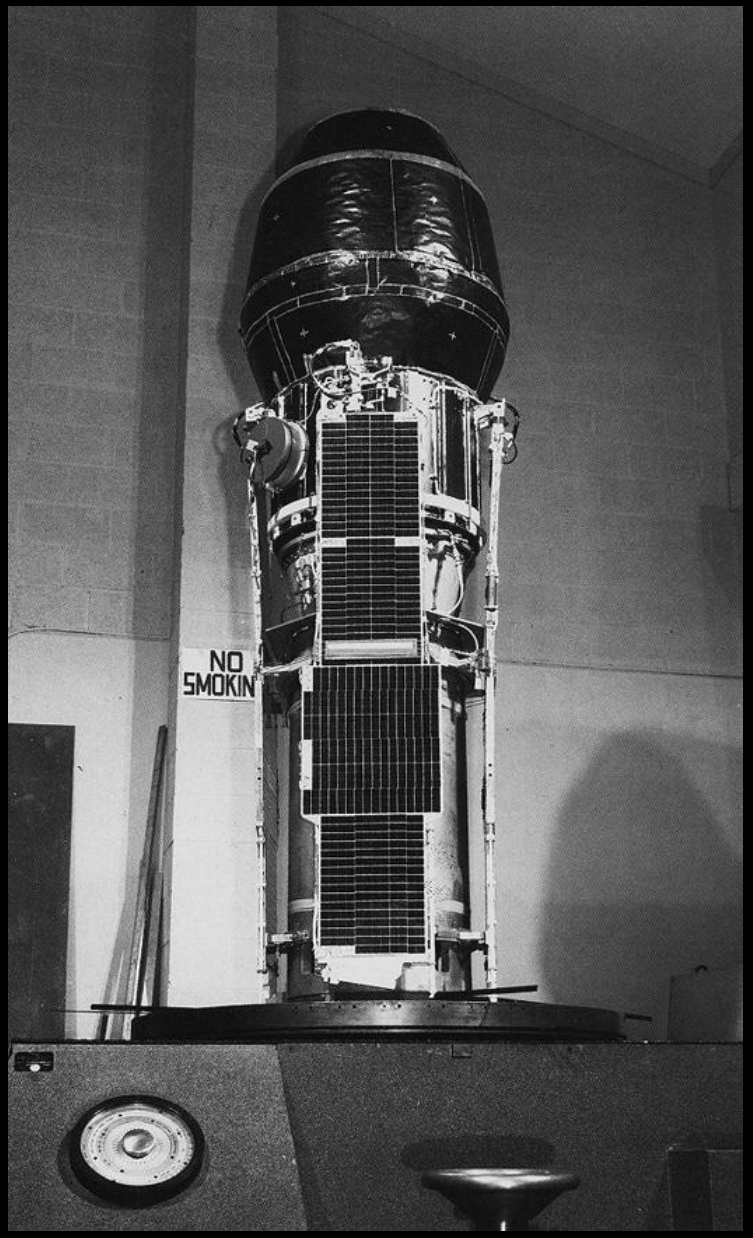
nuclear recoil

tracking of e^+/e^-

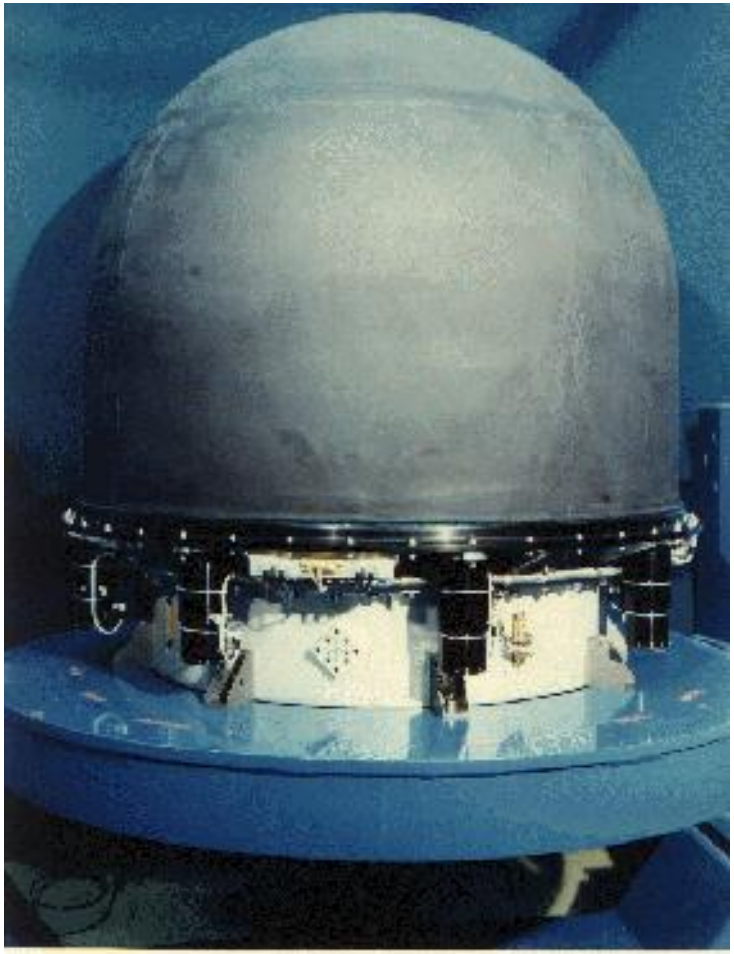
small angle scattering

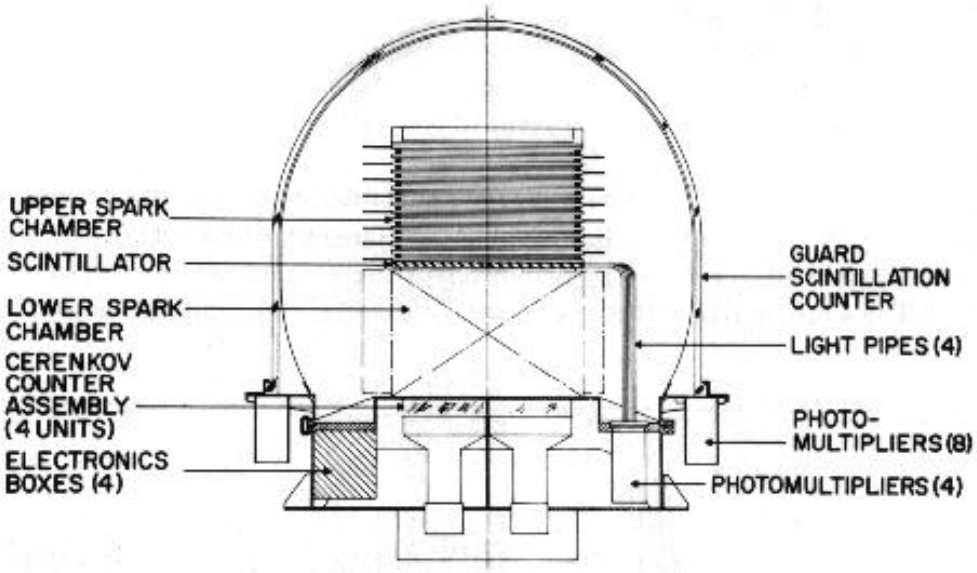
tracker accuracy

SAS-2
NASA
(1972-1973)



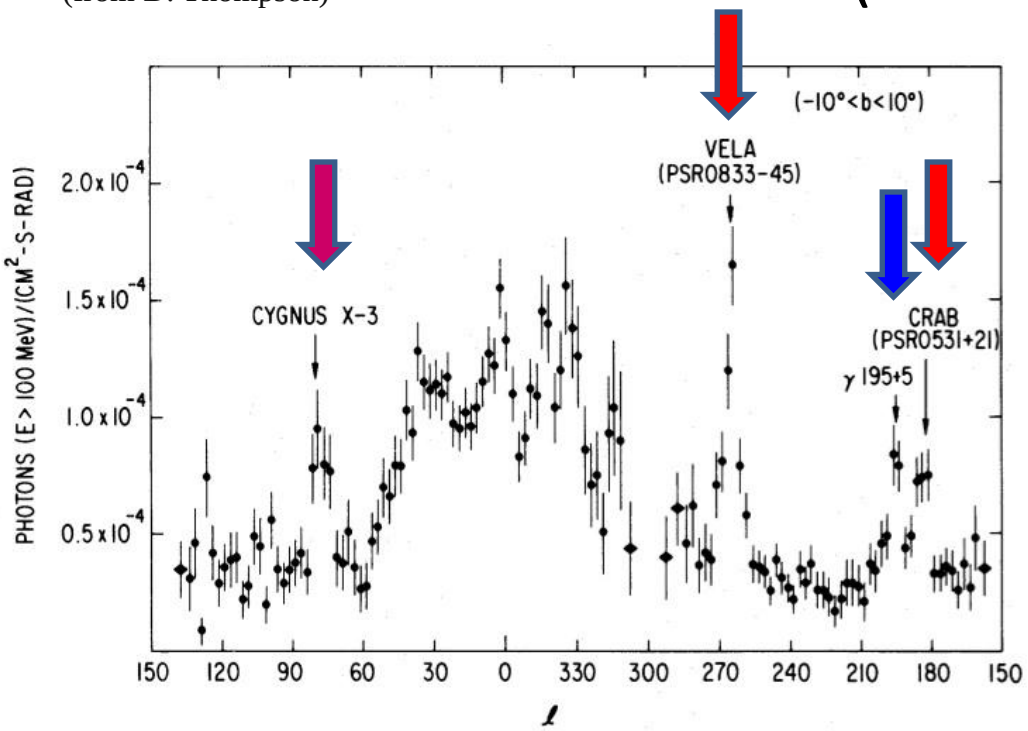
The SAS-2 gamma-ray spark chamber



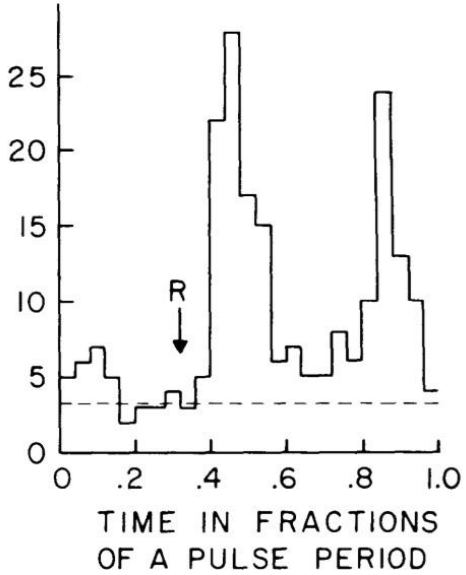


(from D. Thompson)

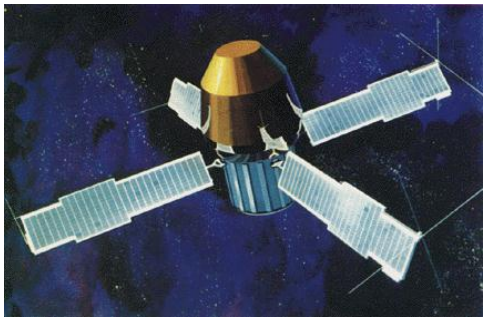
SAS-2 (1972-73)

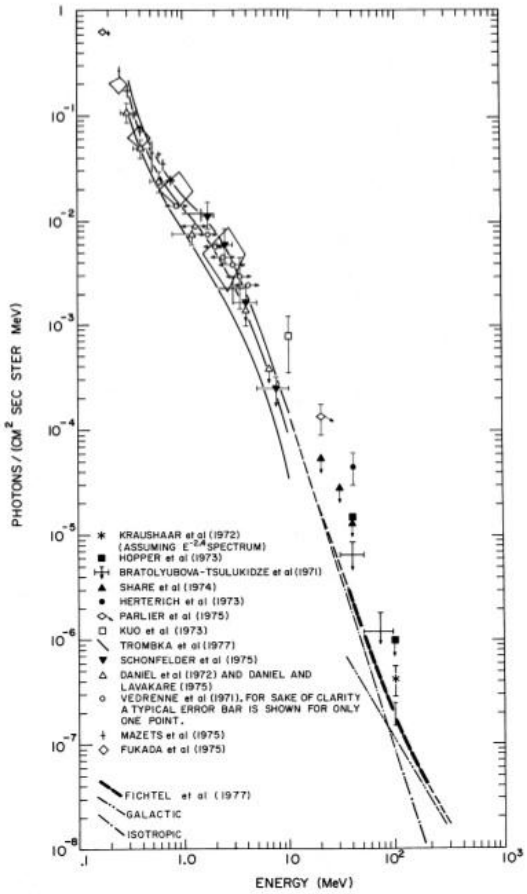


Galactic Plane (Hartman et al 1979)



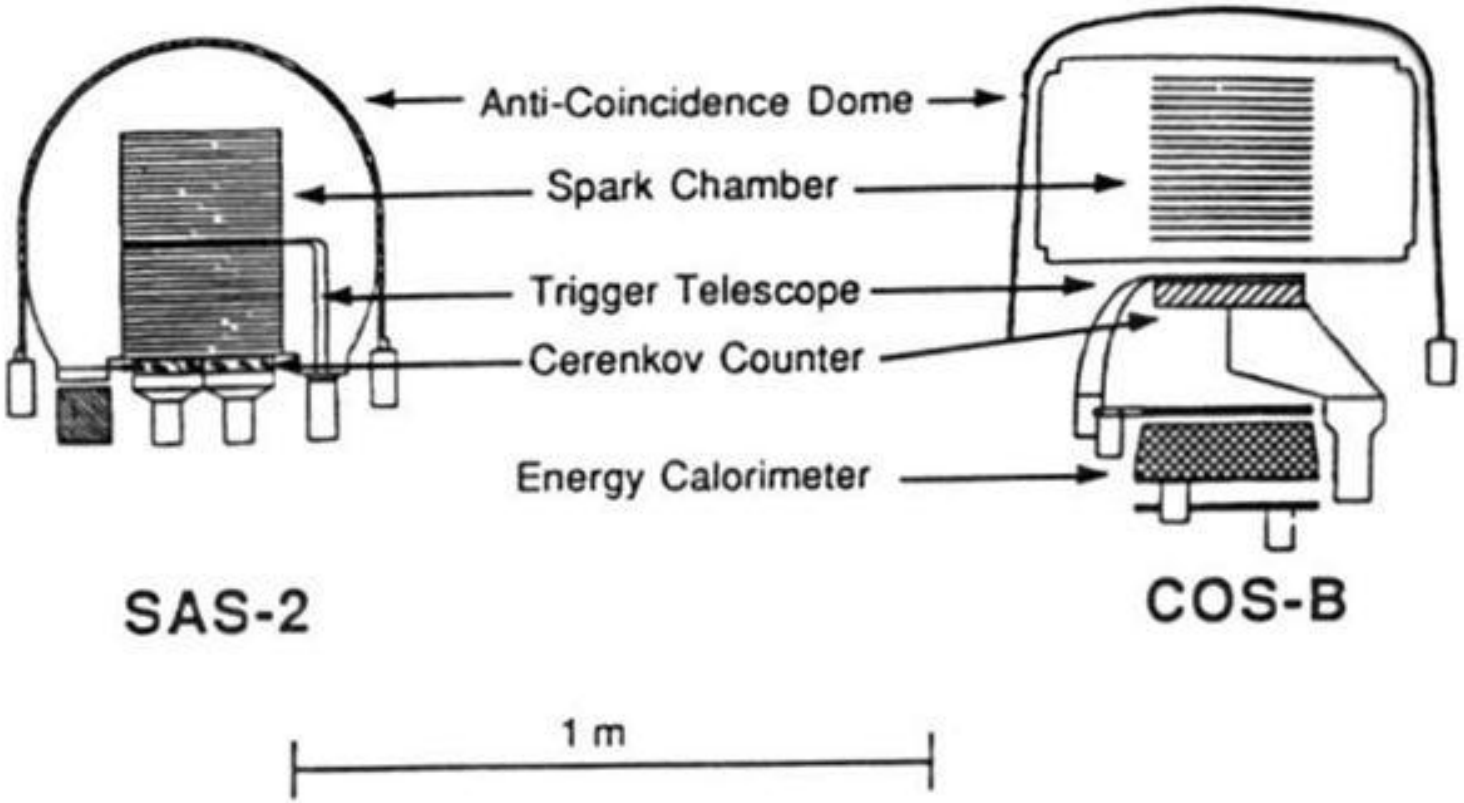
Vela Pulsar (Thompson et al 1975)



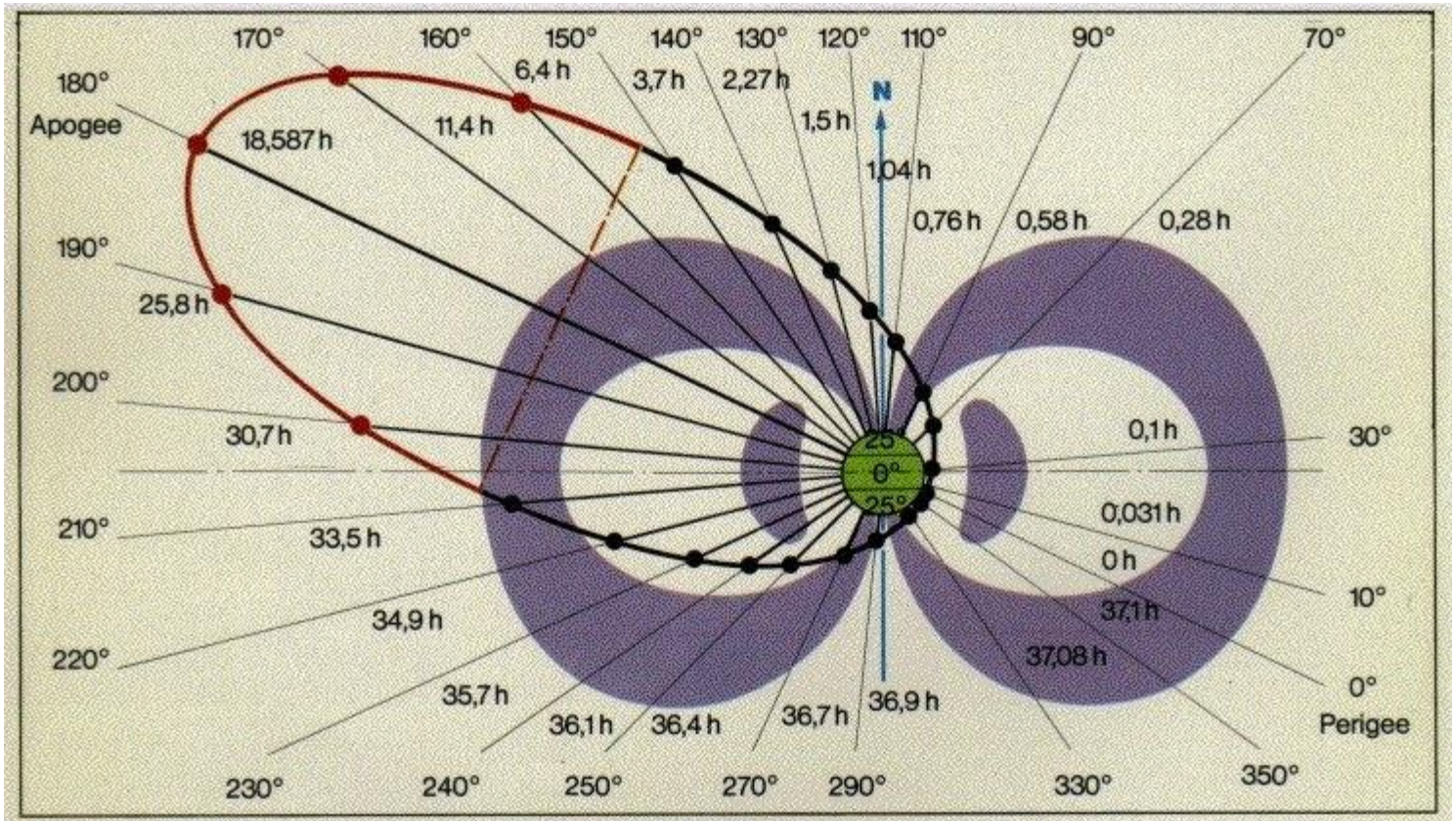


Diffuse Extragalactic (Fichtel et al 1978)

COS-B, ESA (1975-1982)

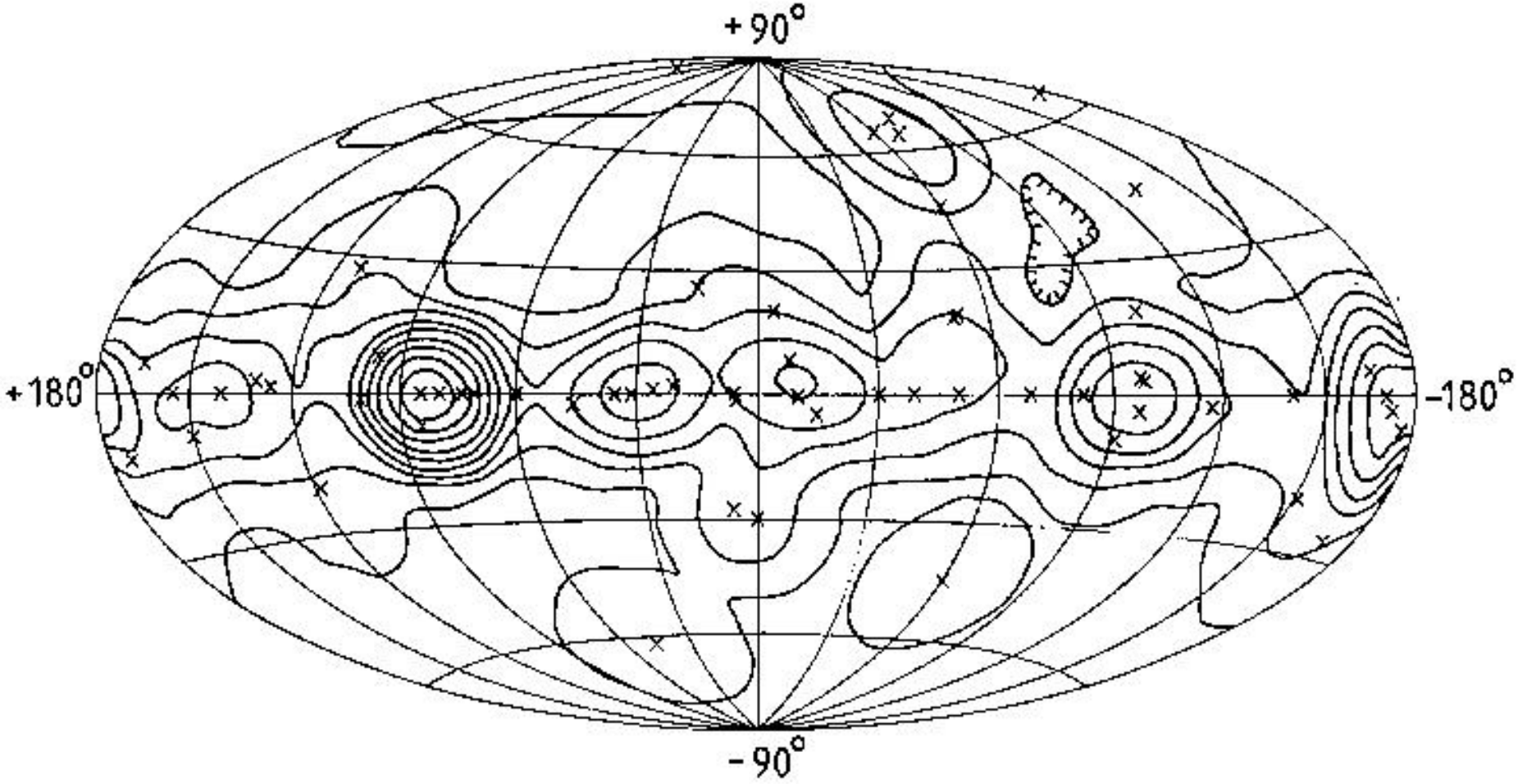

Anti-Coincidence Dome
Spark Chamber
Trigger Telescope
Cerenkov Counter
Energy Calorimeter
SAS-2
COS-B
1 m

COS-B Orbit



Perigee	350 km	Inclination to plane of equator	90°
Speed at perigee	38,200 km/h	Position of perigee	above latitude 25° S
Apogee	100,000 km		
Speed at apogee	2,410 km/h	Measuring time per period, i.e. time outside the radiation belt (red part of the orbit).	30 h
Period	37 hrs 10 min		

COS-B approximate sky coverage
01 Jun 1982



The measurements of galactic gamma-ray emission (15 Dec 1979)

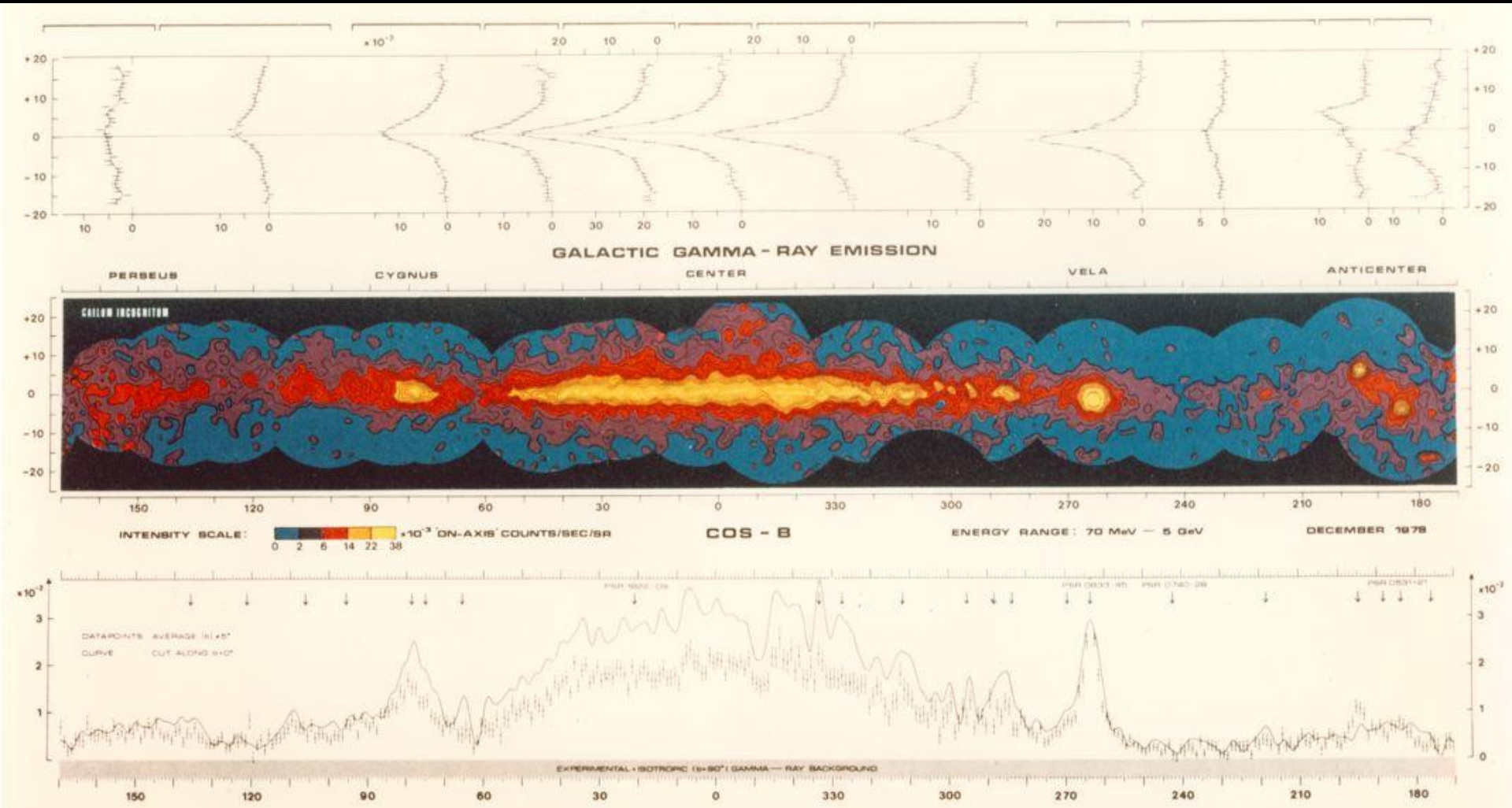


Abb. 63: Isointensitätskontourenkarte der Gammaemission der Milchstraße. Profile entlang galaktischer Länge bzw. Breite.

THE ASTROPHYSICAL JOURNAL, 243:L69–L73, 1981 January 15
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1981ApJ...

the “COS-B sources”

SECOND *COS B* CATALOG OF HIGH-ENERGY GAMMA-RAY SOURCES

B. N. SWANENBURG,[1] K. BENNETT,[2] G. F. BIGNAMI,[3] R. BUCCHERI,[4] P. CARAVEO,[3] W. HERMSEN,[1]
G. KANBACH,[5] G. G. LICHTI,[2] J. L. MASNOU,[6] H. A. MAYER-HASSELWANDER,[5] J. A. PAUL,[6]
B. SACCO,[4] L. SCARSI,[4] AND R. D. WILLS[2]

only 4 identified, L = (0.5.5) 10^{36} erg/s

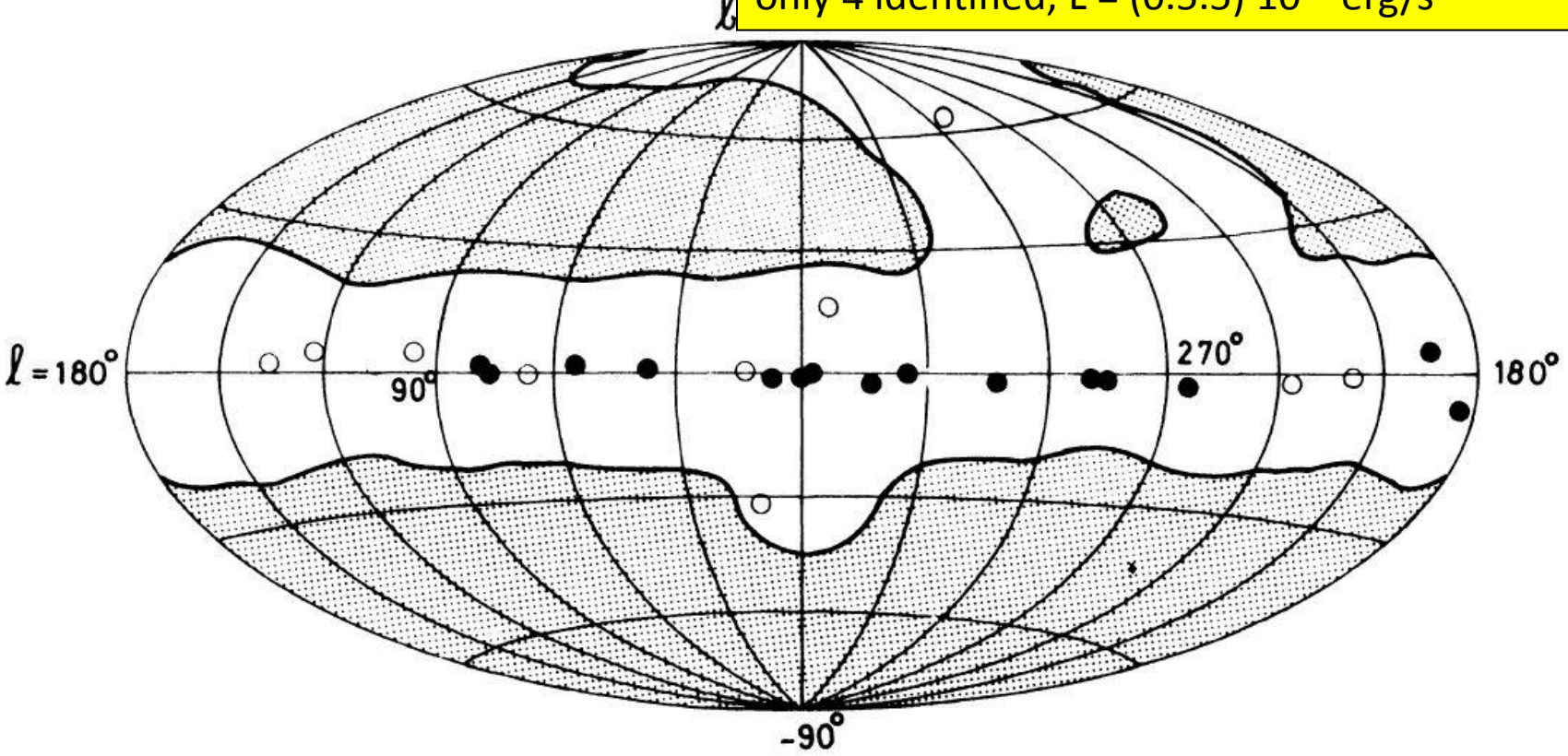
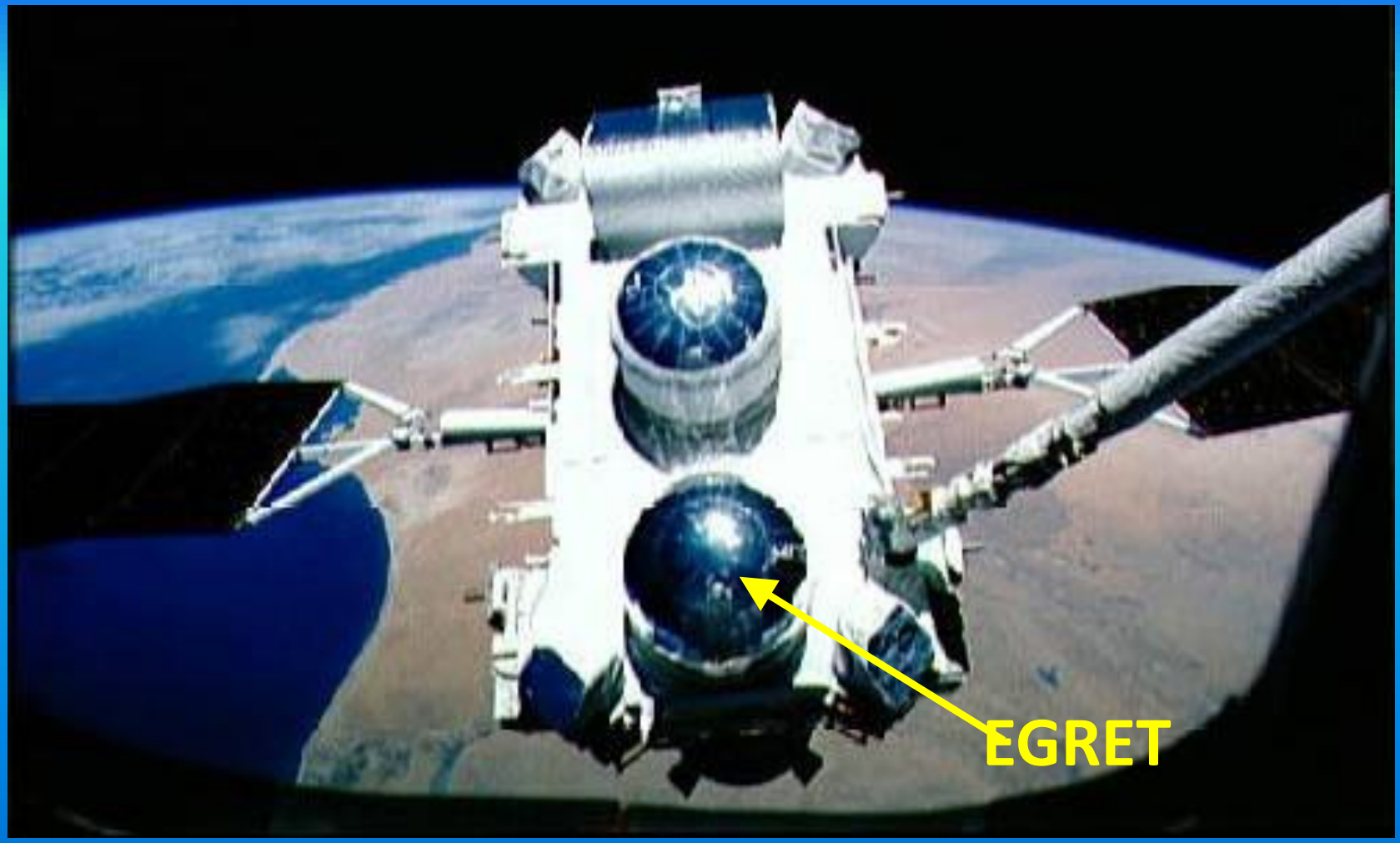


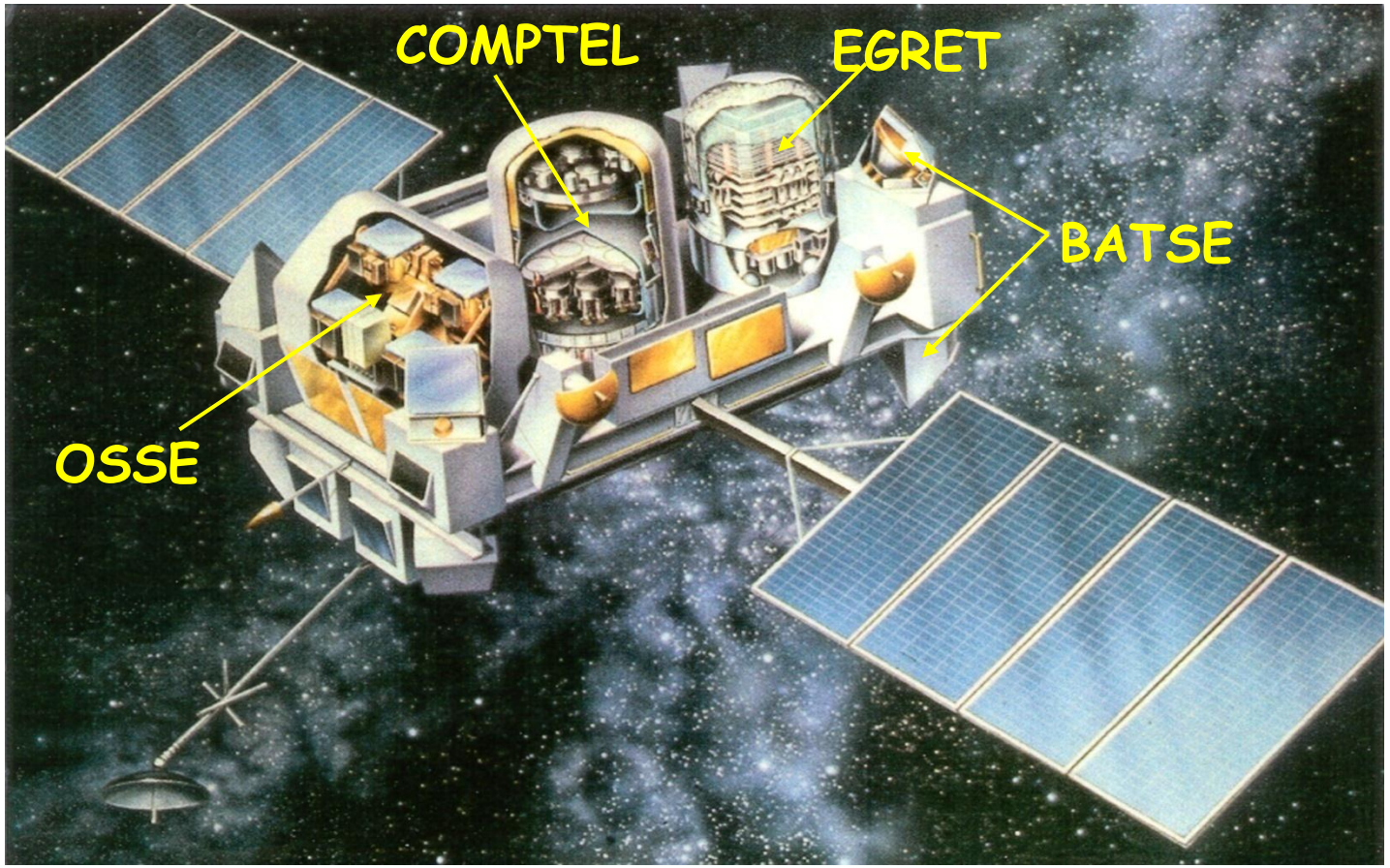
FIG. 1.—Region of the sky searched for gamma-ray sources (*unshaded*) and sources detected above 100 MeV by spatial analysis. The filled circles denote sources with measured fluxes $\geq 1.3 \times 10^{-6}$ photons cm^{-2} s^{-1}. Open circles denote sources below this threshold.

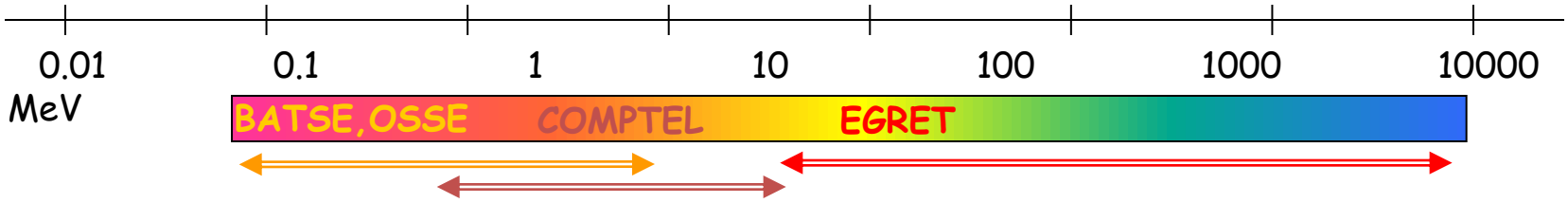
Compton Gamma Ray Observatory (1991-2000)

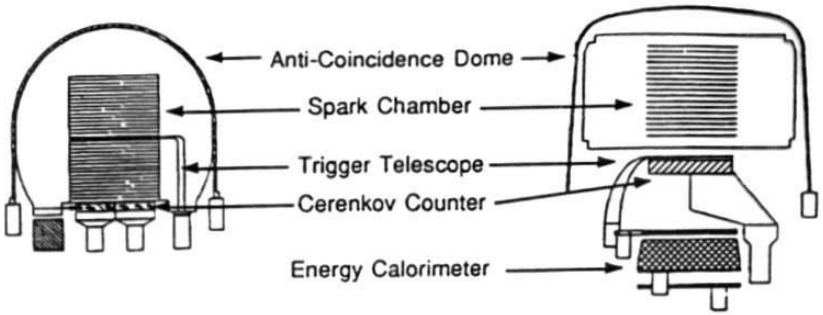


Compton Gamma-Ray Observatory (1991-2000)

from G. Kanbach

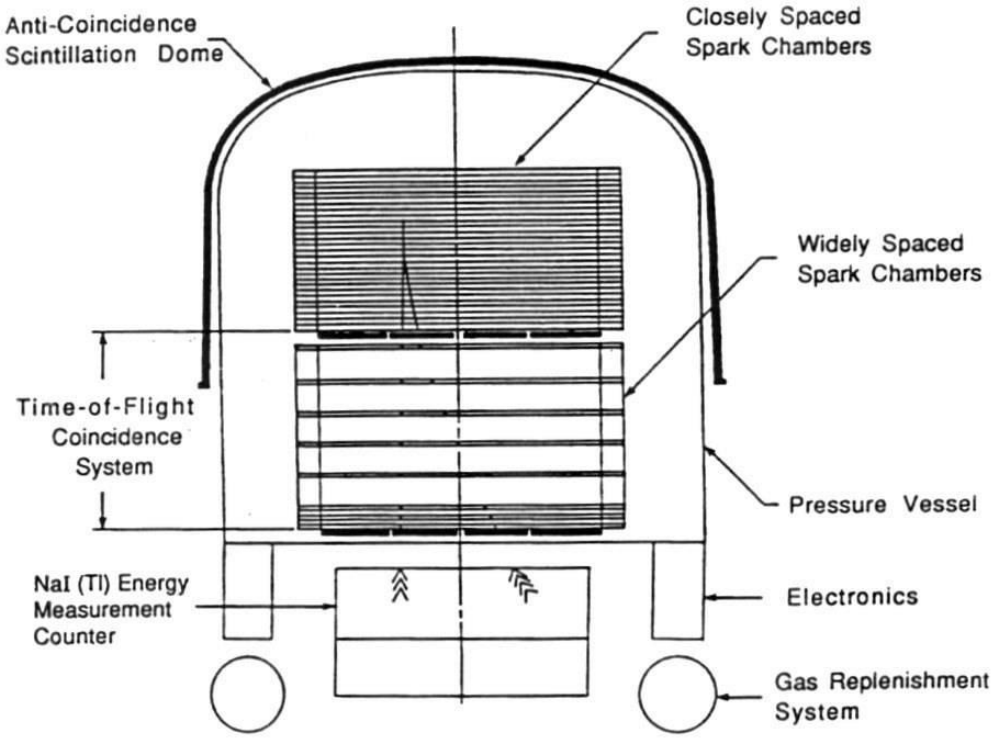






SAS-2 COS-B

1 m



EGRET

1983ICRC....8...19F

August 1983

EGRET: THE HIGH ENERGY GAMMA RAY TELESCOPE FOR NASA's GAMMA RAY OBSERVATORY

C.E. Fichtel, D.L. Bertsch, R.C. Hartman, D.A. Kniffen, D.J. Thompson
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R. Hofstadter, E.B. Hughes, L.E. Campbell-Finman
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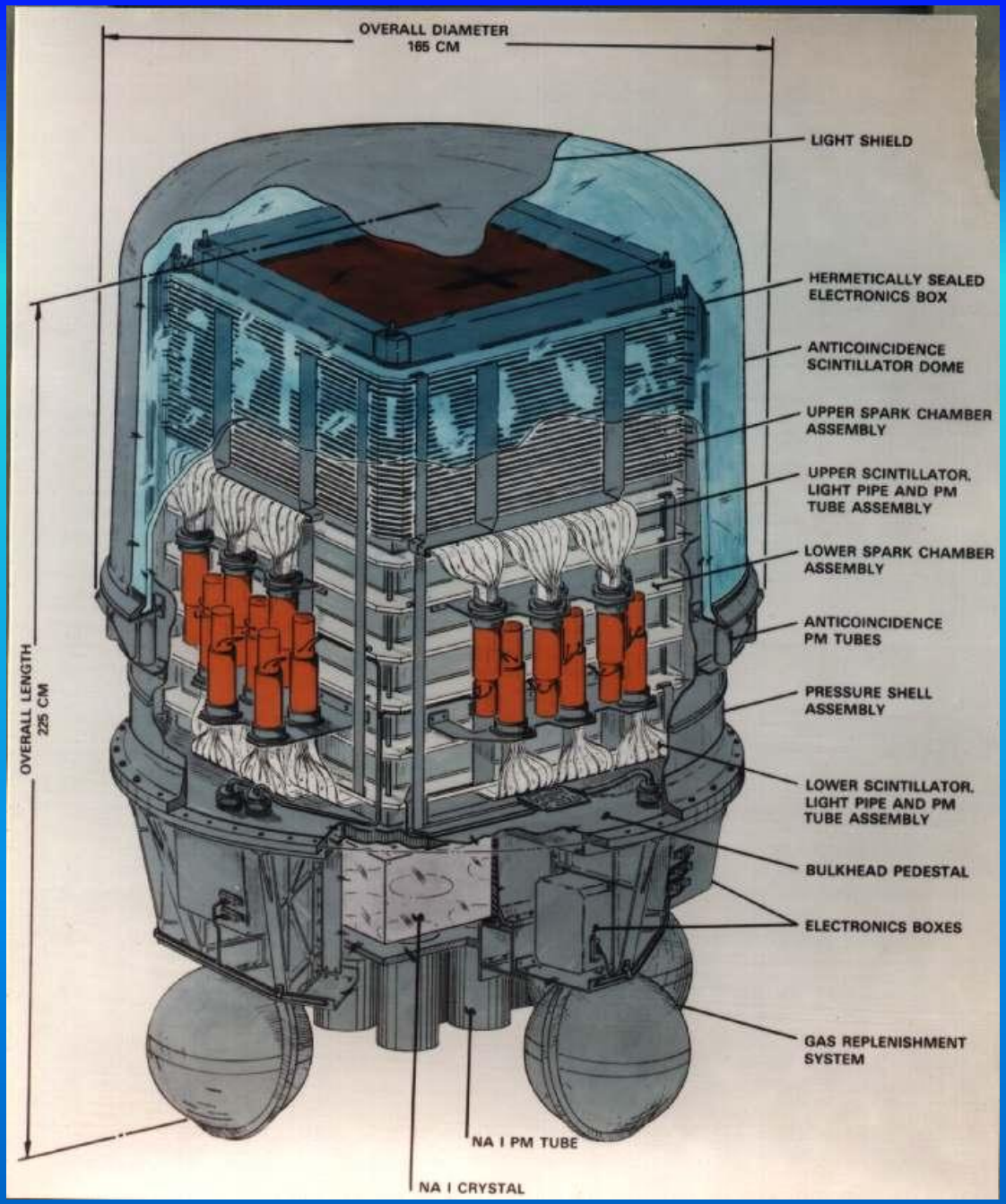
R. Hofstadter's dream…
detect "charm" in space…

ABSTRACT

The EGRET high energy γ-ray telescope under development for NASA's Gamma Ray Observatory will have an energy range of approximately 12 to 30,000 MeV, energy resolution of about 15% FWHM over most of that range, an effective area of about 2000 cm^2 at high energies, and single photon angular accuracy of ~ 2° at 100 MeV, < 0.1° above 5 GeV. This instrument can locate strong sources to an accuracy of about 5 arc min. The instrument utilizes a set of digital spark chambers interleaved with tantalum foils for detection and identification of γ-ray events, and a large NaI(Tl) scintillator for energy determination. The system is triggered



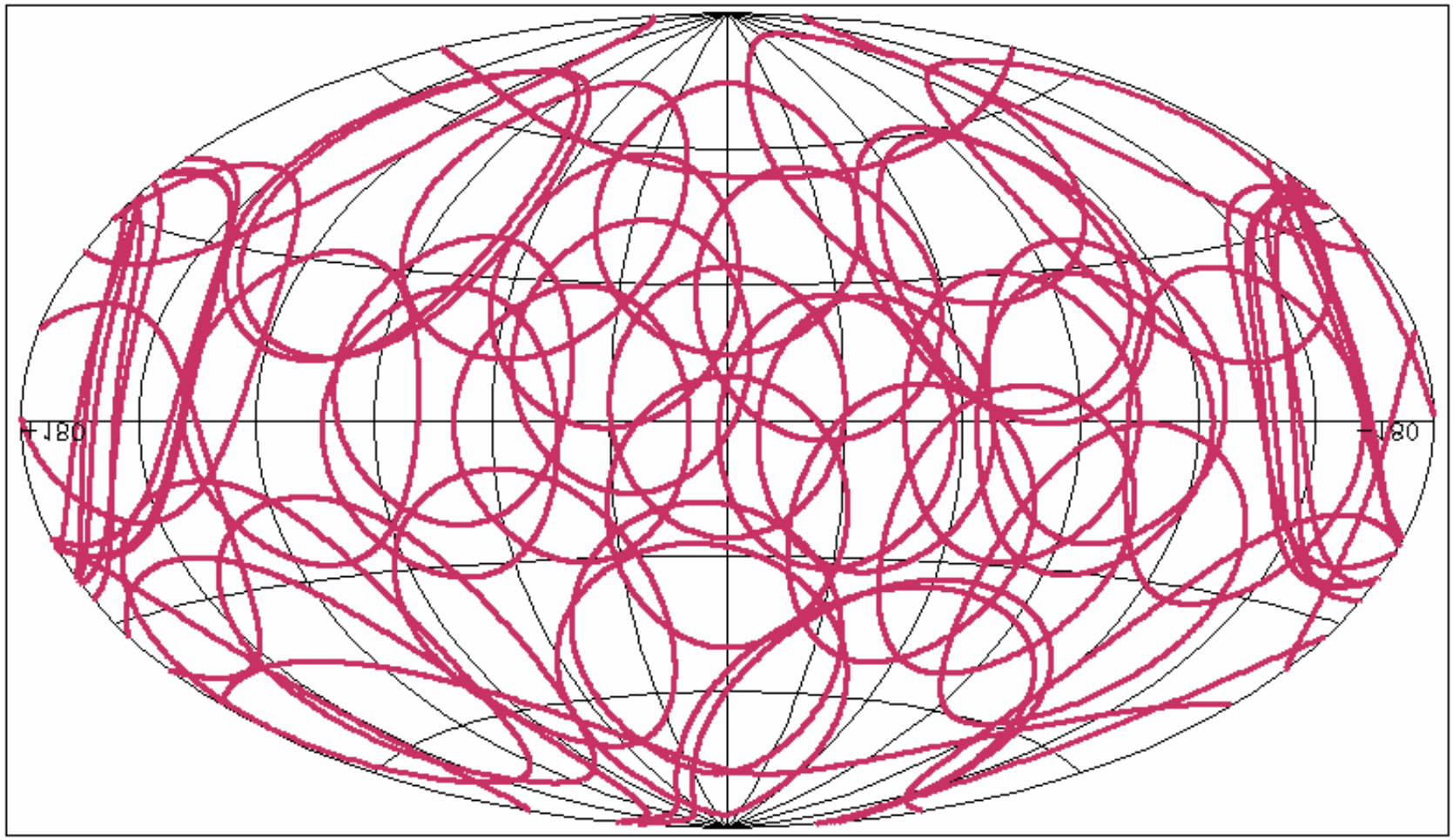
EGRET

30 MeV-30 GeV

(1.8 tons)

- Spark chamber
- TOF
- Calorimeter (NaI)

EGRET Cycle-1 pointings



(from Fichtel and Trombka, 1997)

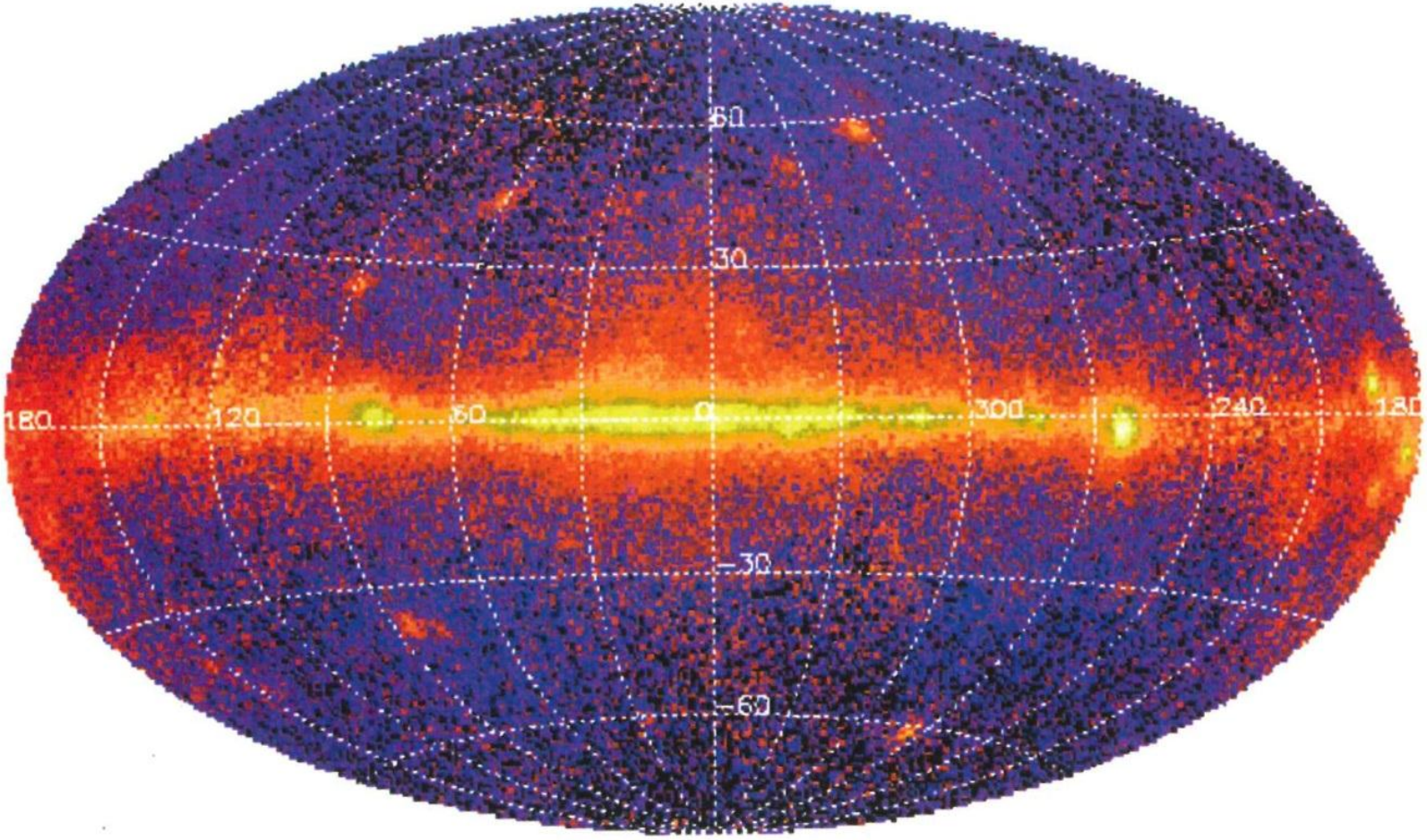


Figure 5.4. All sky intensity distribution for high-energy gamma rays (E>100MeV) determined by EGRET. (Courtesy of Carl Fichtel and the EGRET Instrument Science Team).

(from Fichtel and Trombka, 1997)

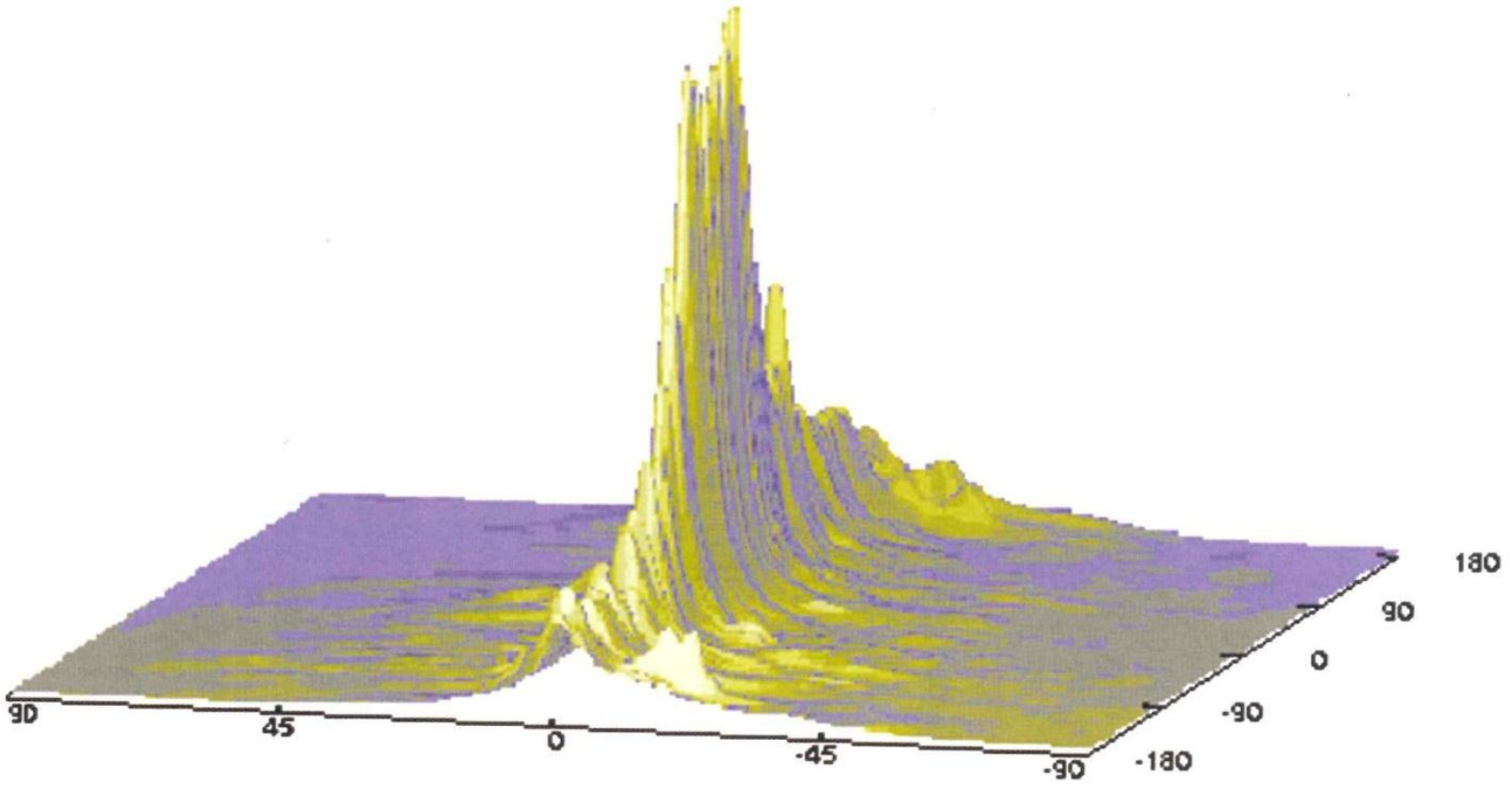
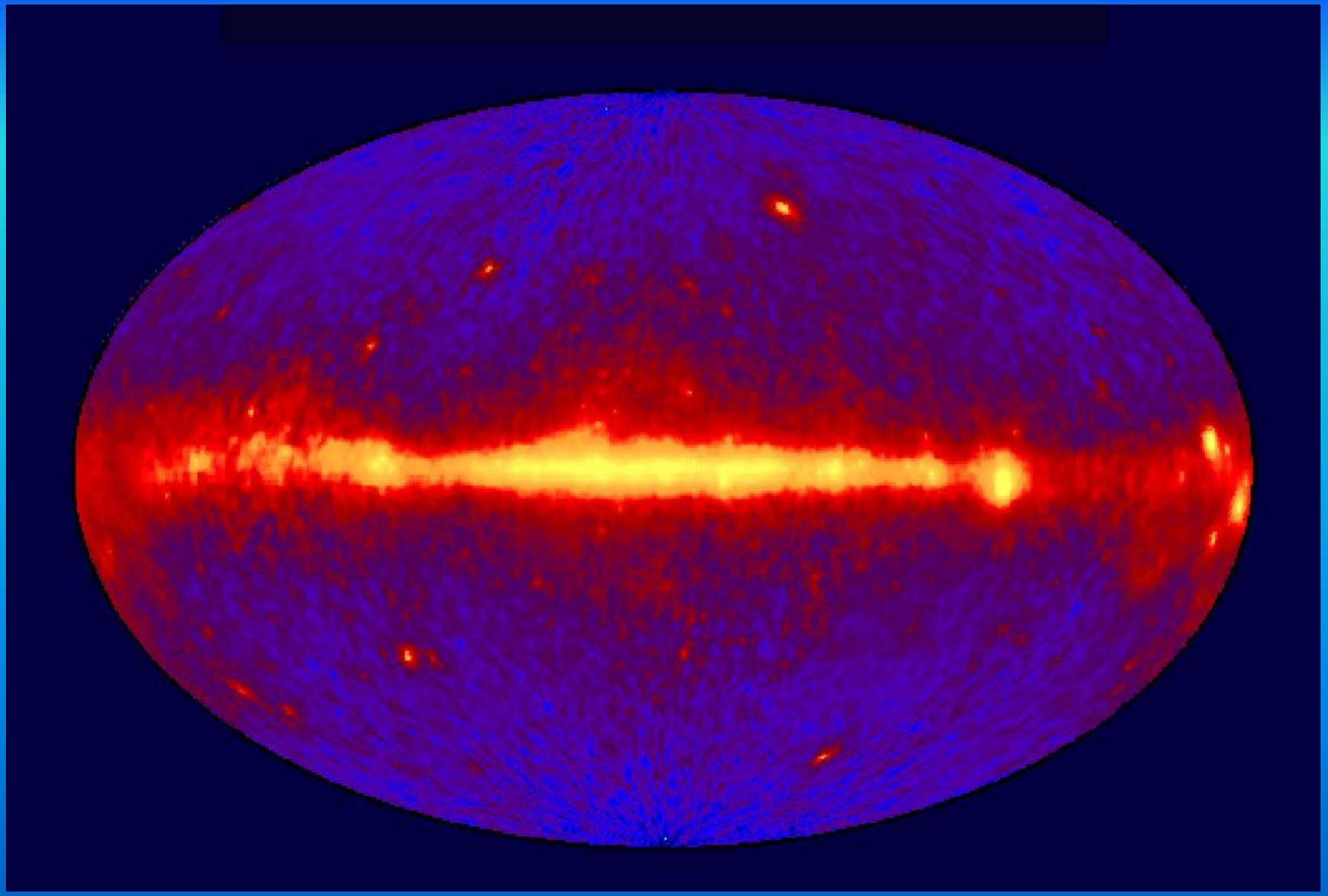


Figure 5.5. Three-dimensional portrayal of the high-energy gamma-ray intensity (E > 100 MeV) measured by EGRET. (Courtesy of Carl Fichtel and the EGRET Science Instrument Team).

EGRET/GRO gamma-ray sky map, E > 100 MeV



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May 1997

EGRET OBSERVATIONS OF THE DIFFUSE GAMMA-RAY EMISSION FROM THE GALACTIC PLANE

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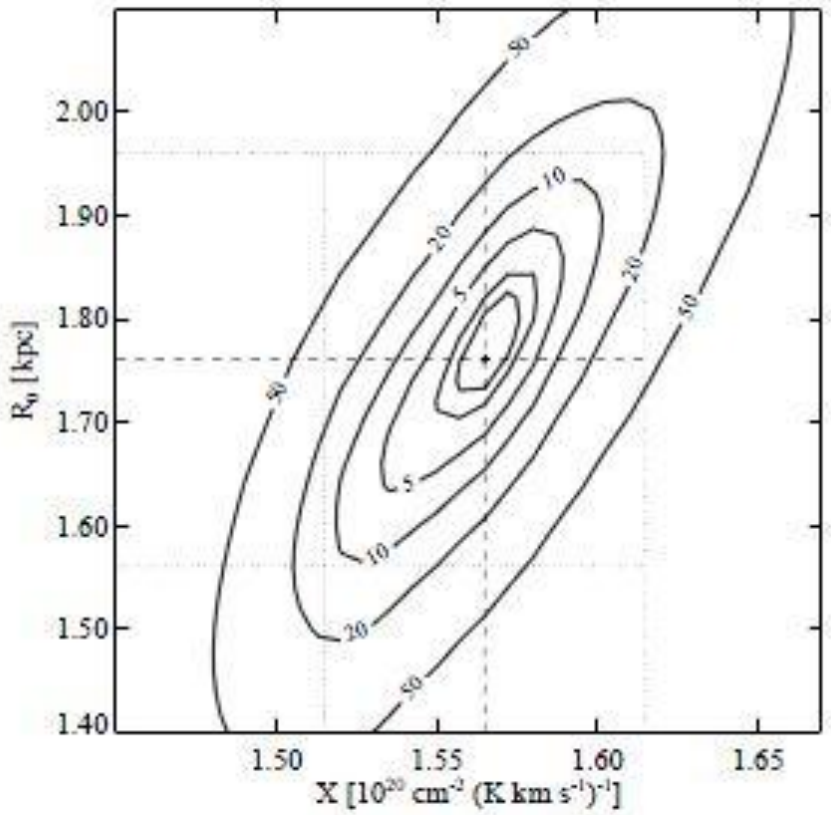
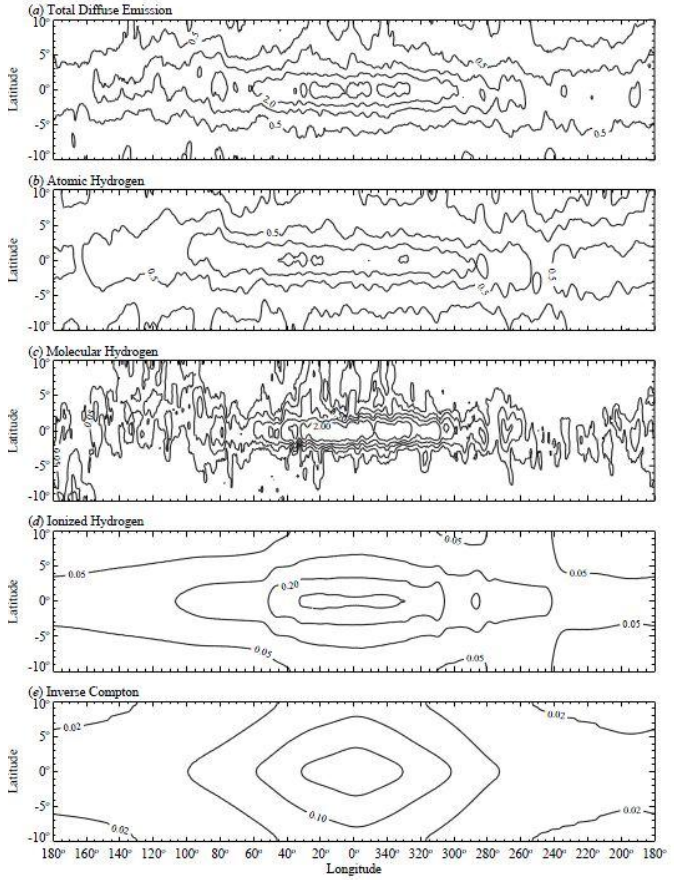
Received 1995 June 13; accepted 1996 December 5





Hunter et al., 1997

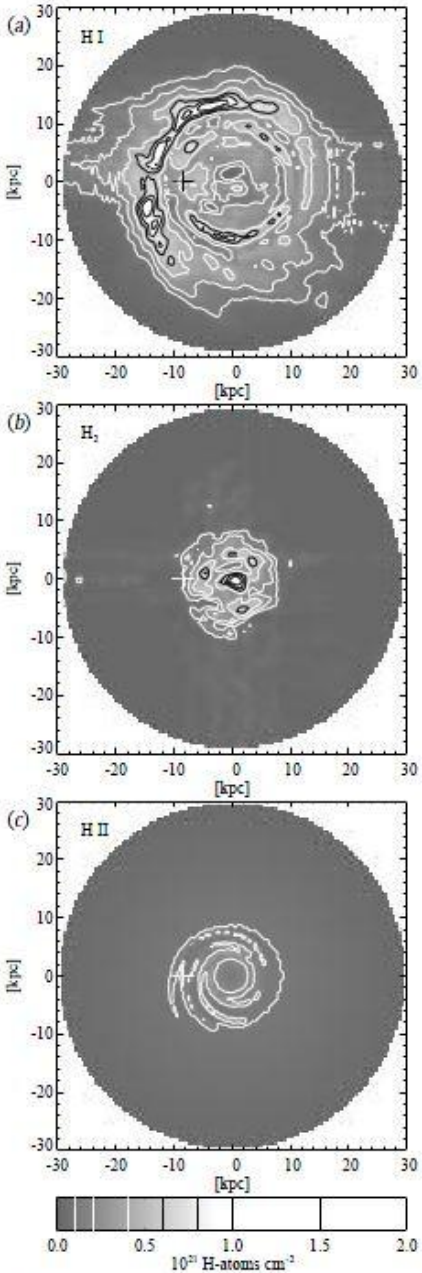


FIG. 8.—Total surface densities of (*a*) H I, (*b*) H_2, and (*c*) H II as a function of position in the Galactic plane. The H I and H_2 plots have been smoothed to 2 kpc resolution. The position of the Sun is indicated with a cross. The gas densities are assumed to be zero beyond the 30 kpc Galactic radius limit of the calculation (see § 5).

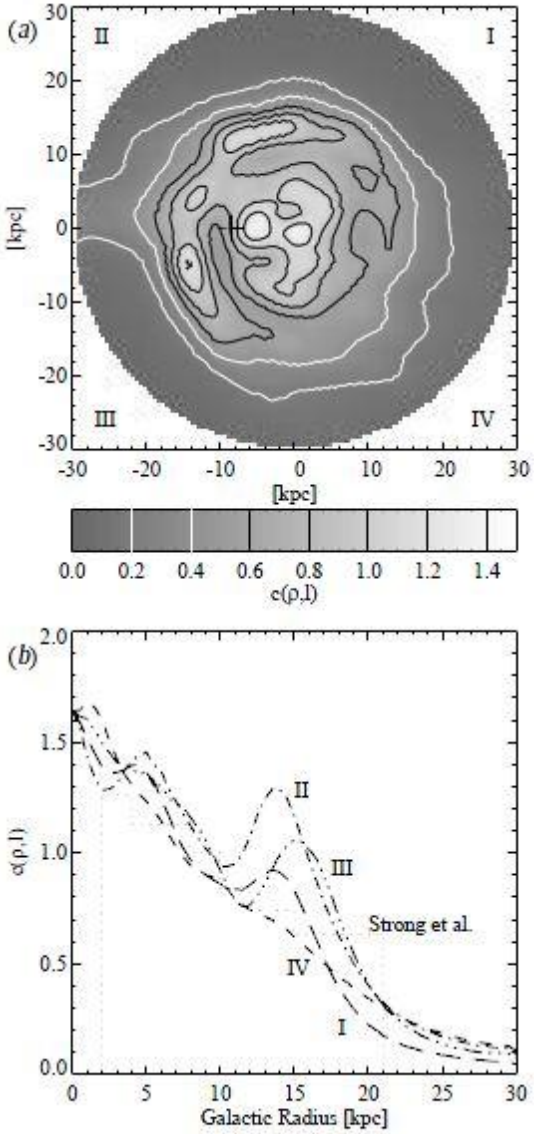
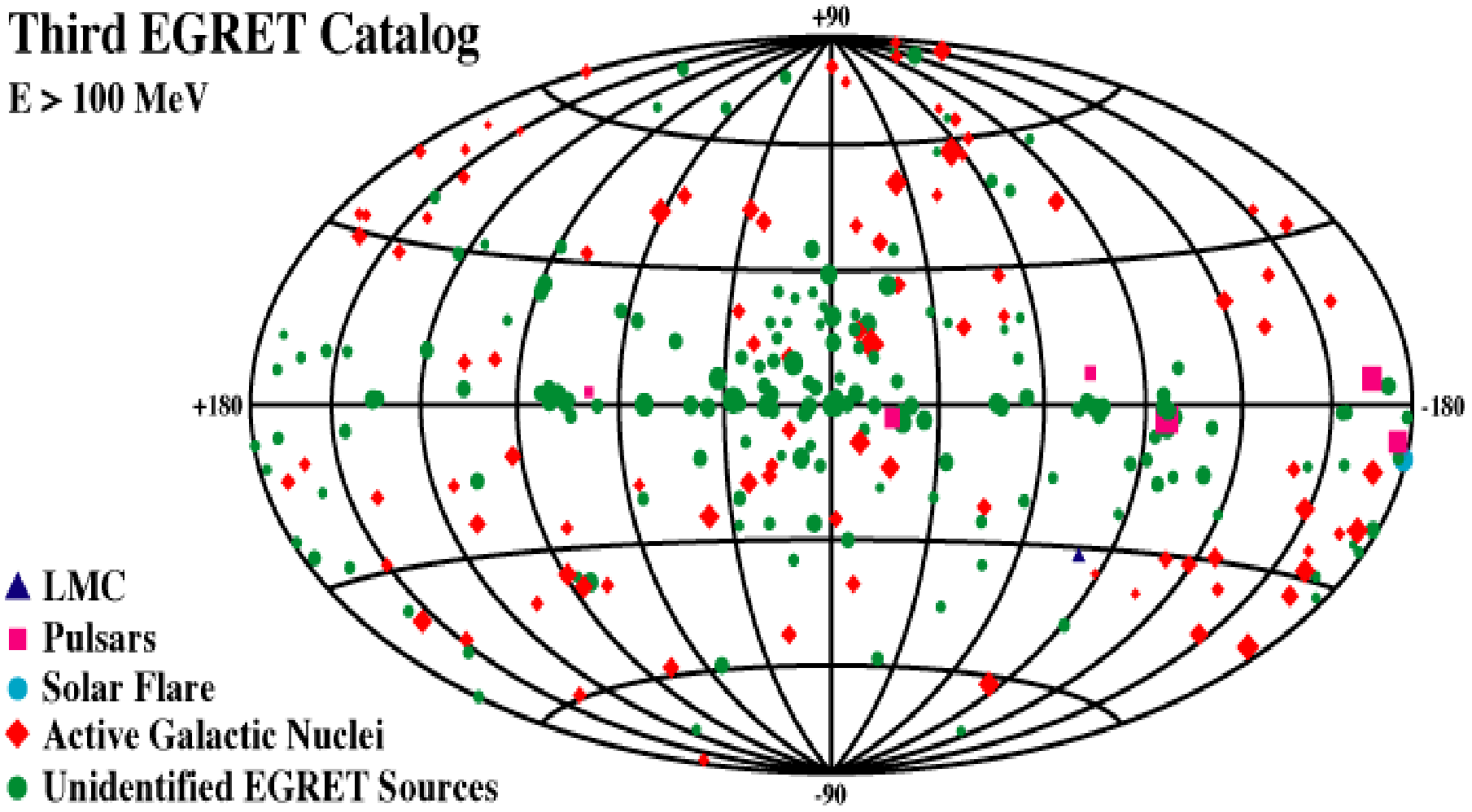
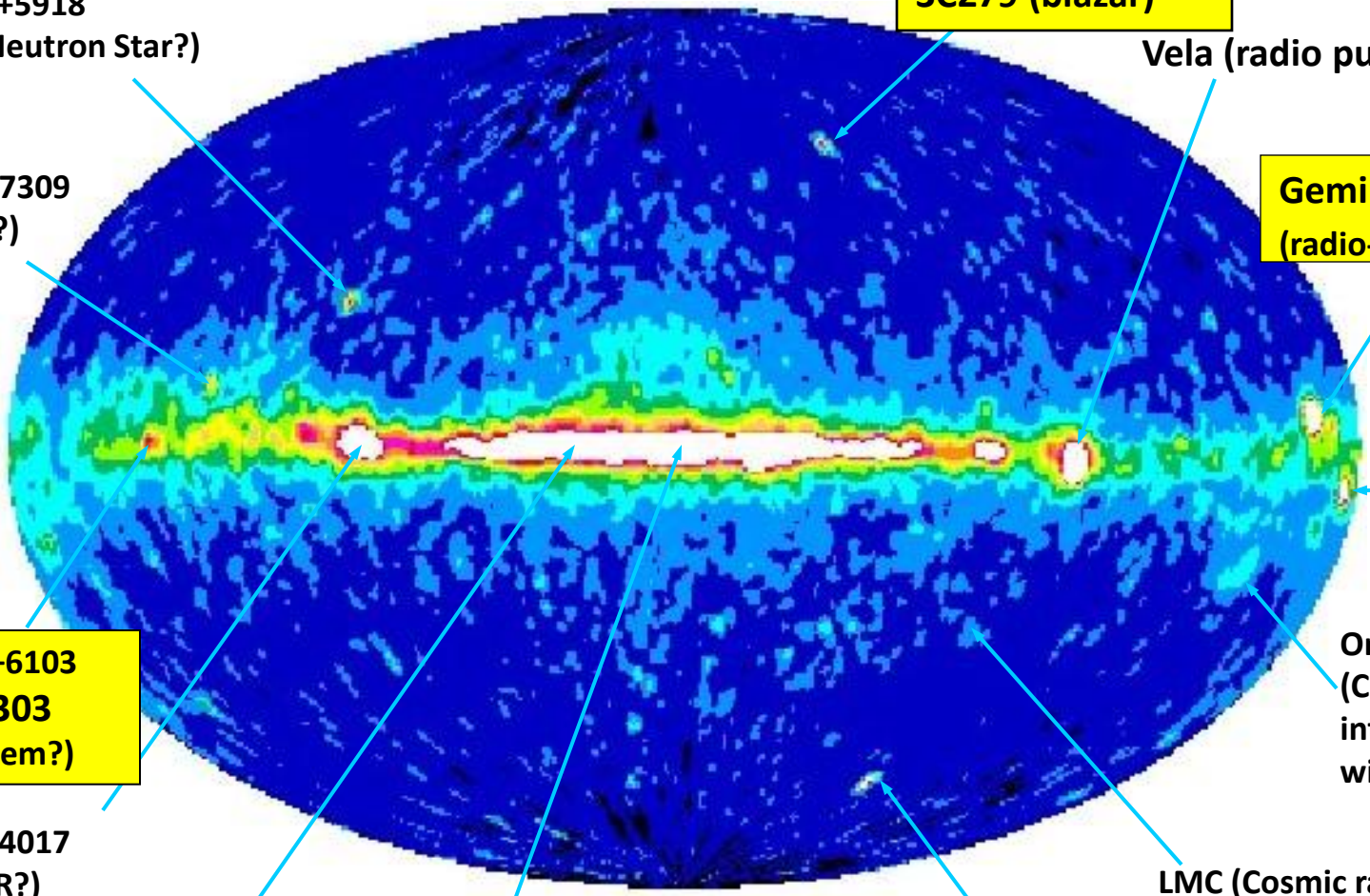


FIG. 9.—(*a*) The cosmic-ray enhancement factor $c(\rho, l)$ derived by convolving the sum of the H I, H_2, and H II surface densities from Fig. 8 with a Gaussian with FWHM equal to the best-fit value of $r_0 = 1.76$ kpc (see § 5). The enhancement factor is normalized to unity at the position of the Sun, indicated by the cross. (*b*) The azimuthal average of the cosmic-ray enhancement factor for each Galactocentric quadrant indicated in (*a*). The azimuthally symmetric gamma-ray emissivity, which is proportional to the cosmic-ray enhancement factor, determined by Strong et al. (1988, 150–300 MeV, their case 3, scaled to $R_\odot = 8.5$ kpc, and normalized to unity in the 8–10 kpc ring) is indicated by the dotted line.

R.C. Hartman et al. 1999



EGRET All Sky Map (>100 MeV)



3EG J1835+5918
(isolated Neutron Star?)

3C279 (blazar)

Vela (radio pulsar)

3EG J0010+7309
(CTA 1 SNR?)

Geminga
(radio-quiet PSR)

Crab pulsar &
Nebula

3EG J0241+6103
(LS I +61°303
Binary System?)

Orion Cloud
(Cosmic ray
interactions
with ISM)

3EG J2020+4017
(γ Cygni SNR?)

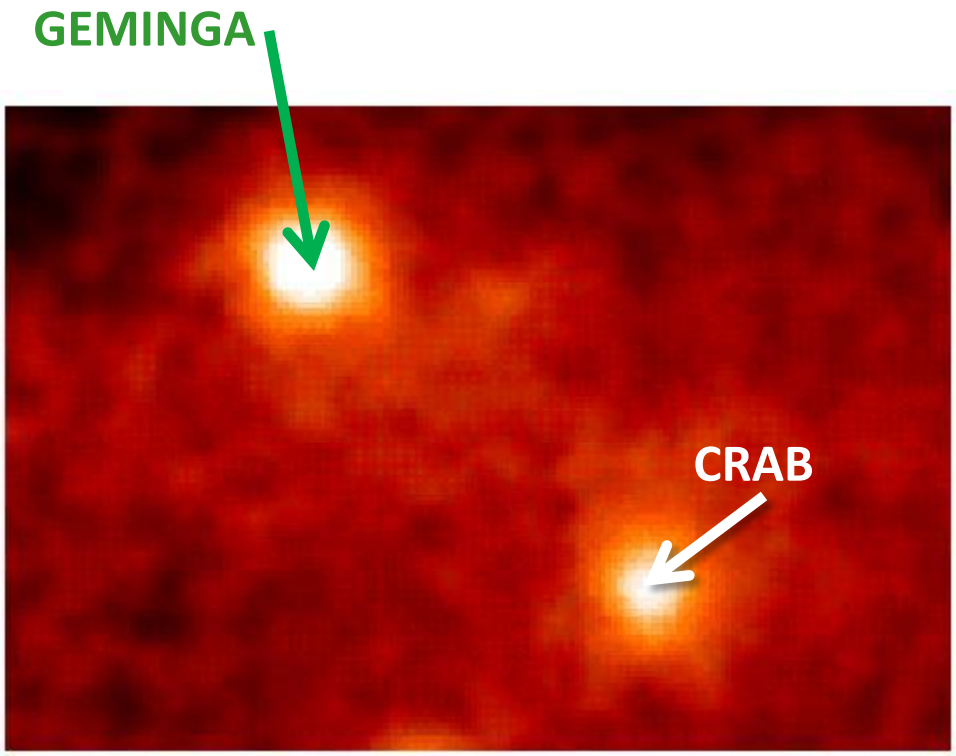
LMC (Cosmic ray
interactions with ISM)

3EG J1837-0423
(unidentified transient)

3EG J1746-2851 (Galactic
Center?)

PKS 0208-512 (blazar)

The mistery of Geminga



EGRET gamma-ray map above 100 MeV

How many Geminga-like sources (no radio pulsations, gamma-ray PSRs) are out there ???

Geminga detected by SAS-2 and COS-B, about 30% more intense than the Crab, **no obvious radio PSR or counterpart**, a mystery for many years (e.g., Bignami & Hermsen, ARAA, 21, 67,1983).

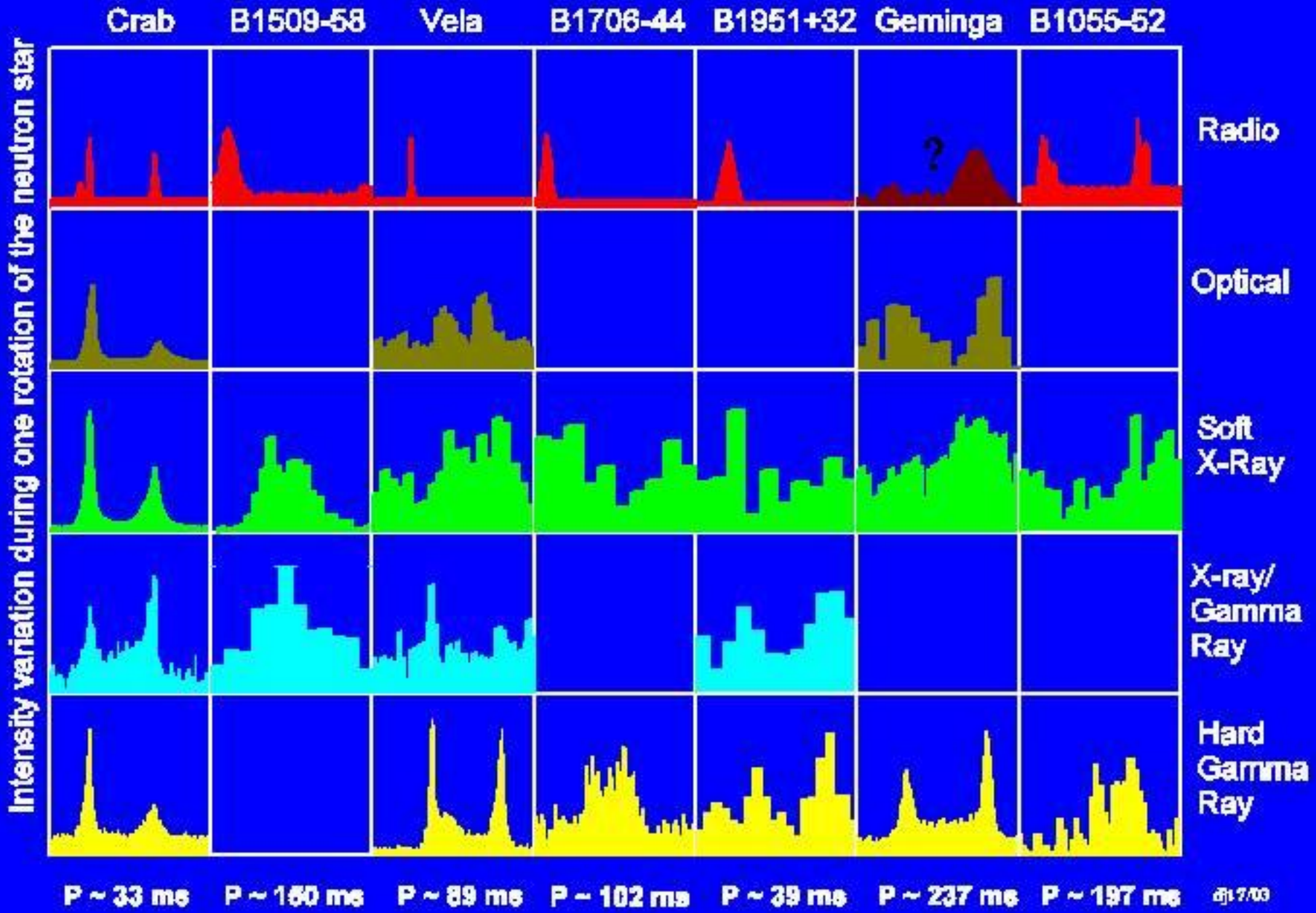
The mystery was solved by the discovery of X-ray pulsations at 237 ms with ROSAT data by Halpern & Holt, Nature, 357, 222 (1992).

Analysis of **EGRET** data immediately showed gamma-ray pulsations, **Bertsch et al., Nature, 357, 306 (1992).**

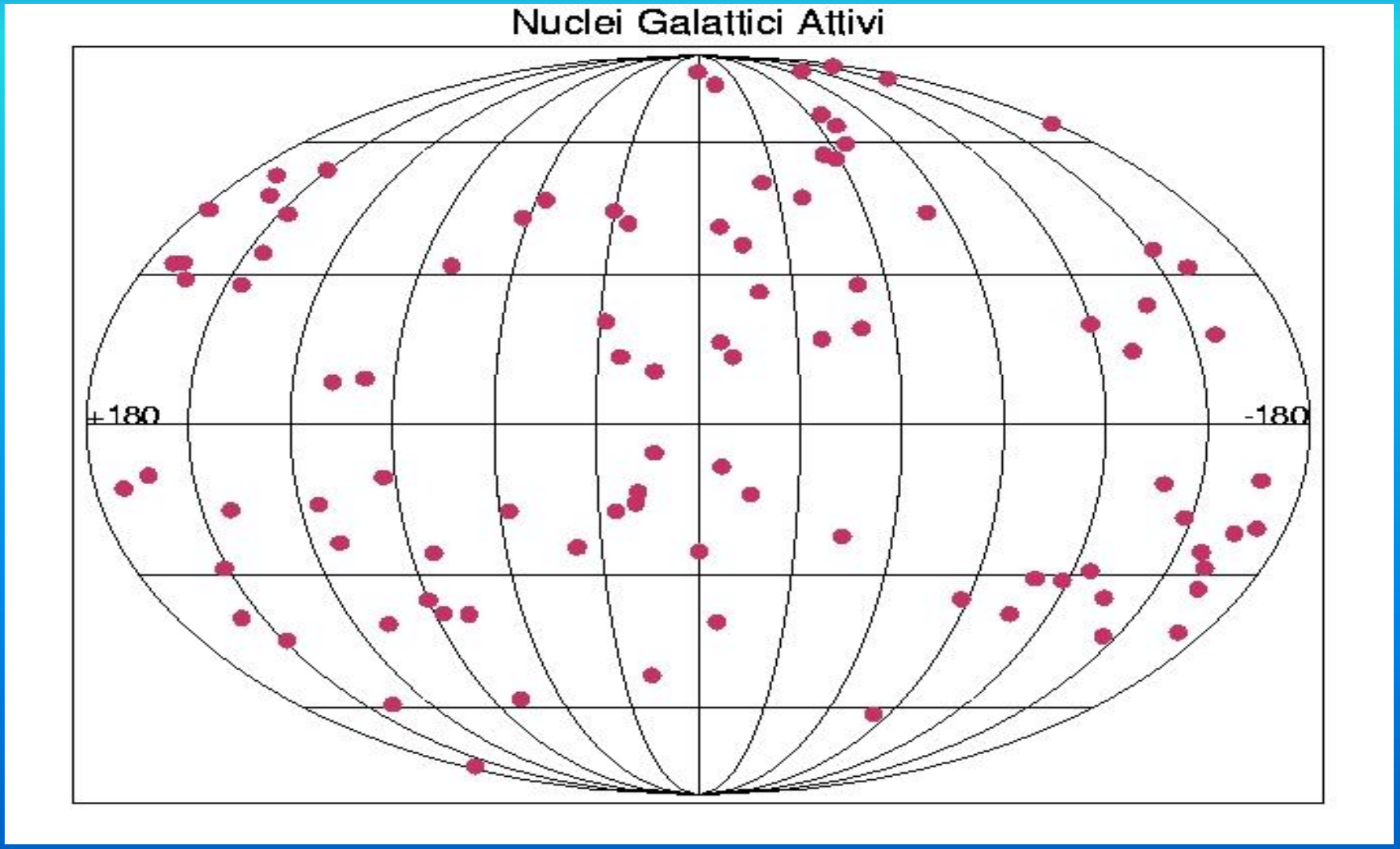
Also found in **COS-B data (Bignami & Caraveo, Nature, 357, 287, 1992)** and **SAS-2 (Mattox etal., ApJL, 401, 23L, 1992)** data.

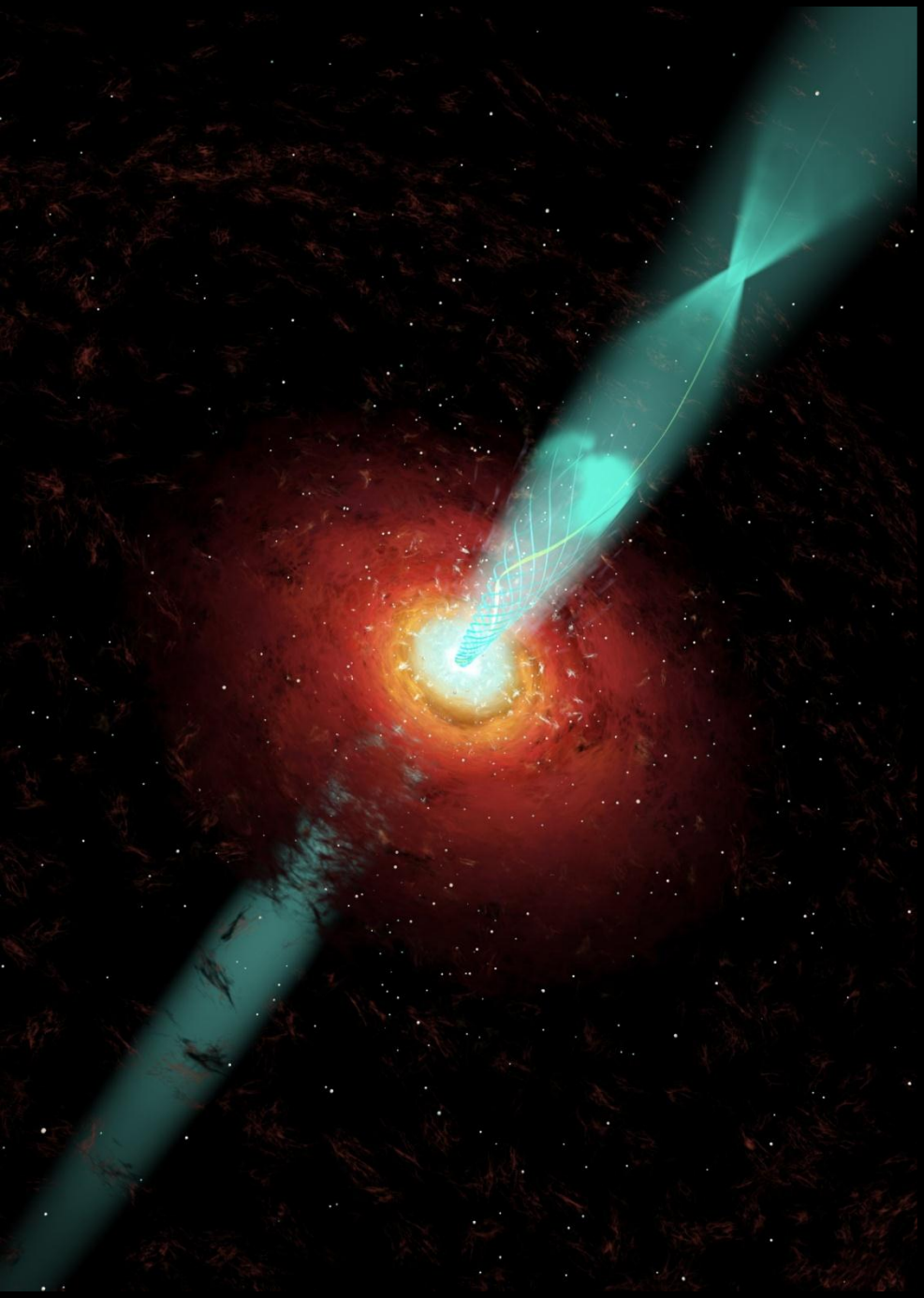
Variety in Pulsar Light Curves – A Challenge for Pulsar Models

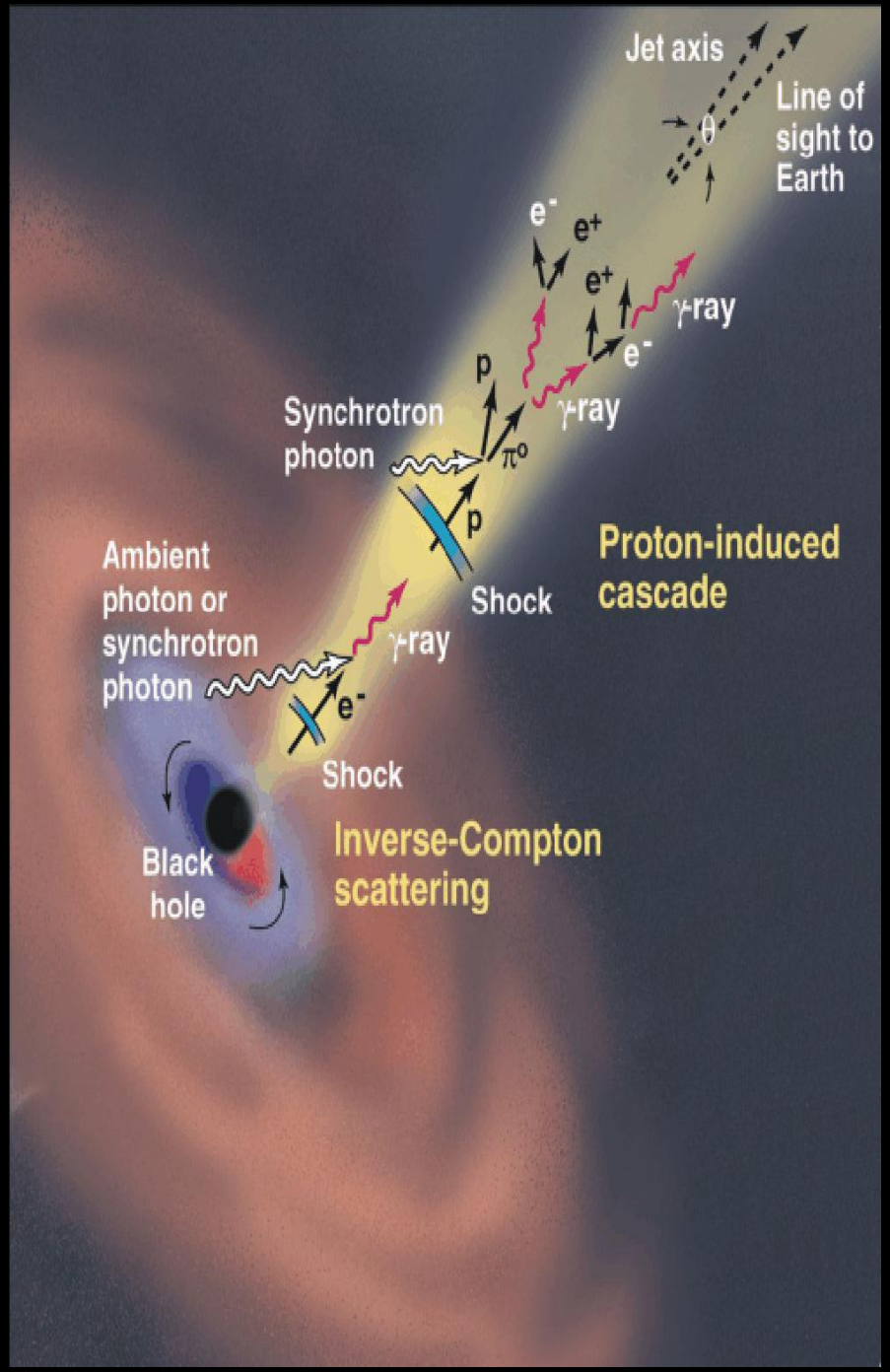
(from D.Thompson)



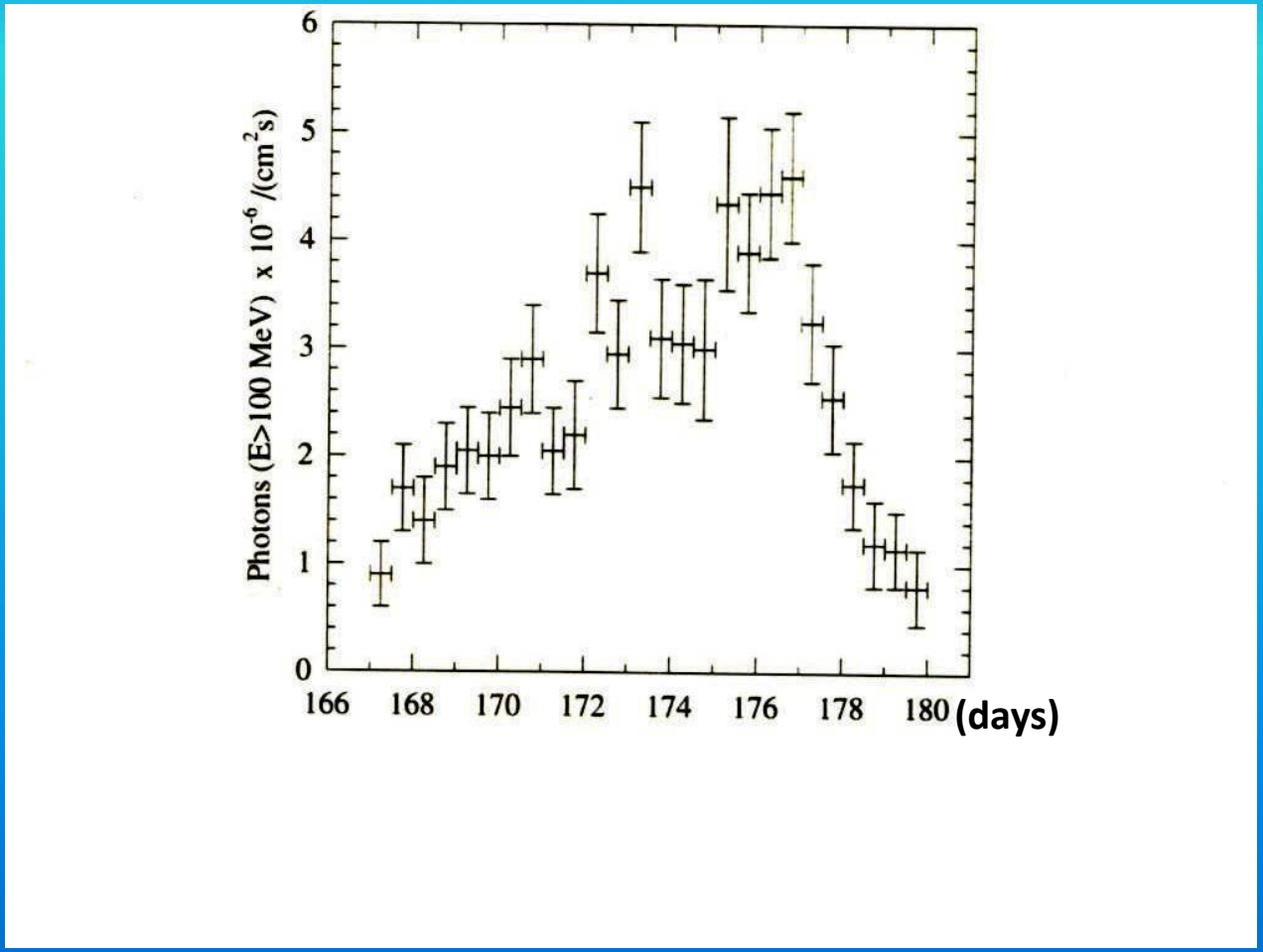
AGNs detected above 30 MeV by EGRET

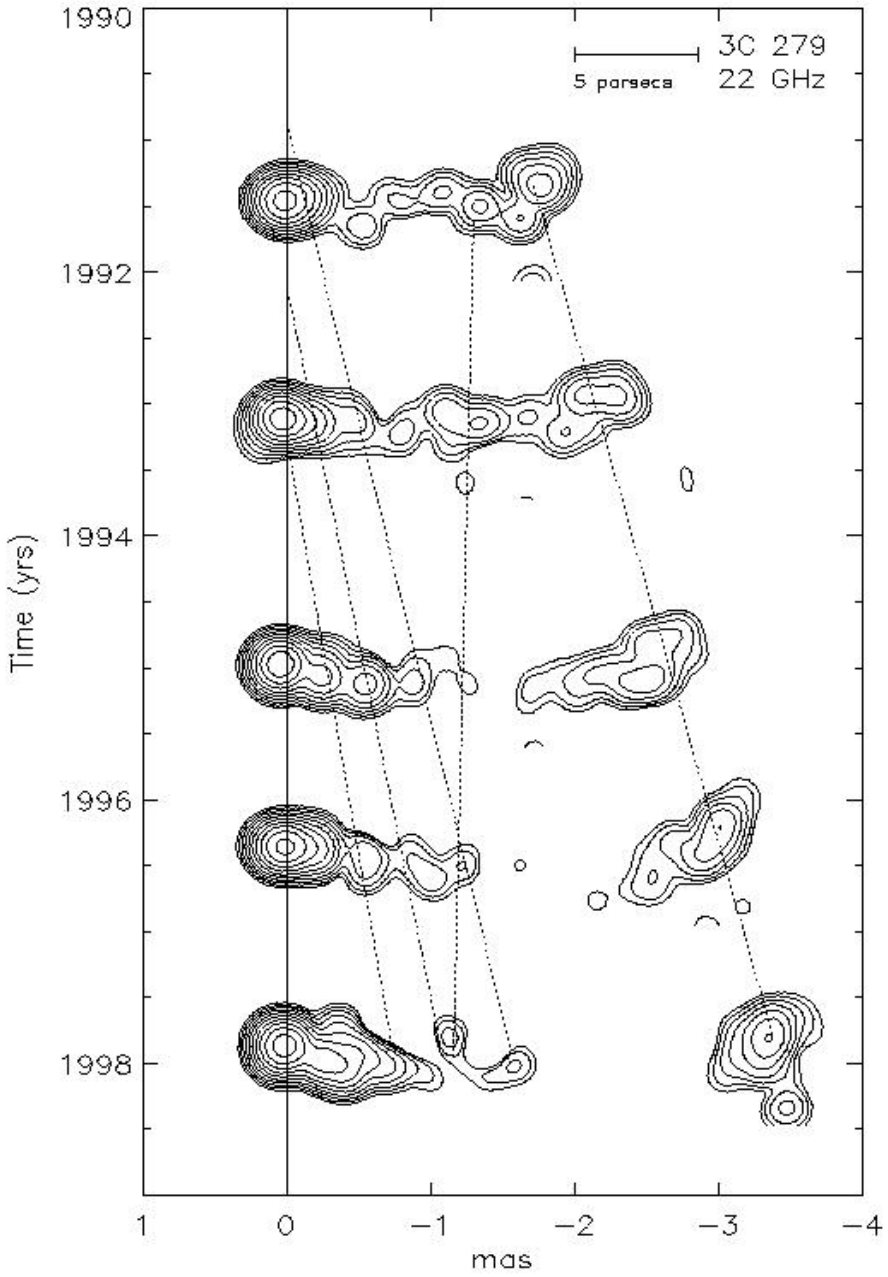





Jet axis
Line of sight to Earth
θ
e-
e+
e+
e-
γ-ray
γ-ray
p
Synchrotron photon
π0
p
Shock
Proton-induced cascade
Ambient photon or synchrotron photon
γ-ray
e-
Shock
Black hole
Inverse-Compton scattering

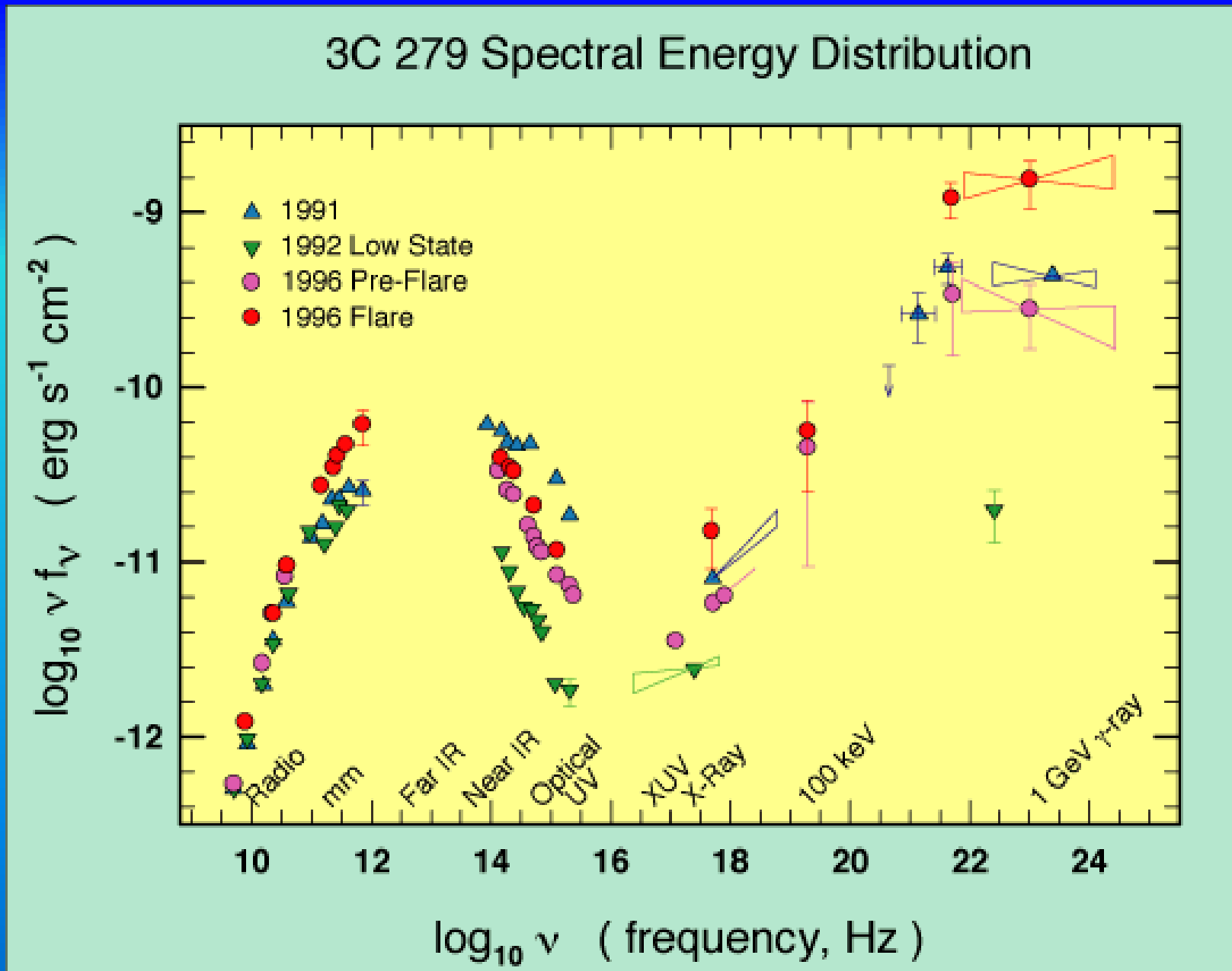
3C 279 gamma-ray flare detected by EGRET (June 1991)





3C 279 radio-plasmoid ejections

VLBI radio maps


3C 279 Spectral Energy Distribution
1991
1992 Low State
1996 Pre-Flare
1996 Flare
-9
-10
-11
-12
log10 ν fν (erg s-1 cm-2)
Radio
mm
Far IR
Near IR
Optical UV
XUV
X-Ray
100 keV
1 GeV γ-ray
10
12
14
16
18
20
22
24
log10 ν (frequency, Hz)

February 20, 1998

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EGRET OBSERVATIONS OF THE EXTRAGALACTIC GAMMA-RAY EMISSION

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D. J. THOMPSON,[1] AND T. D. WILLIS[6]
Received 1997 April 17; accepted 1997 September 29

ABSTRACT

The all-sky survey in high-energy gamma rays ($E > 30$ MeV) carried out by EGRET aboard the *Compton Gamma Ray Observatory* provides a unique opportunity to examine in detail the diffuse gamma-ray emission. The observed diffuse emission has a Galactic component arising from cosmic-ray interactions with the local interstellar gas and radiation, as well as an almost uniformly distributed component that is generally believed to originate outside the Galaxy. Through a careful study and removal of the Galactic diffuse emission, the flux, spectrum, and uniformity of the extragalactic emission are deduced. The analysis indicates that the extragalactic emission is well described by a power-law photon spectrum with an index of $-(2.10 \pm 0.03)$ in the 30 MeV to 100 GeV energy range. No large-scale spatial anisotropy or changes in the energy spectrum are observed in the deduced extragalactic emission. The most likely explanation for the origin of this extragalactic high-energy gamma-ray emission is that it arises primarily from unresolved gamma-ray–emitting blazars.

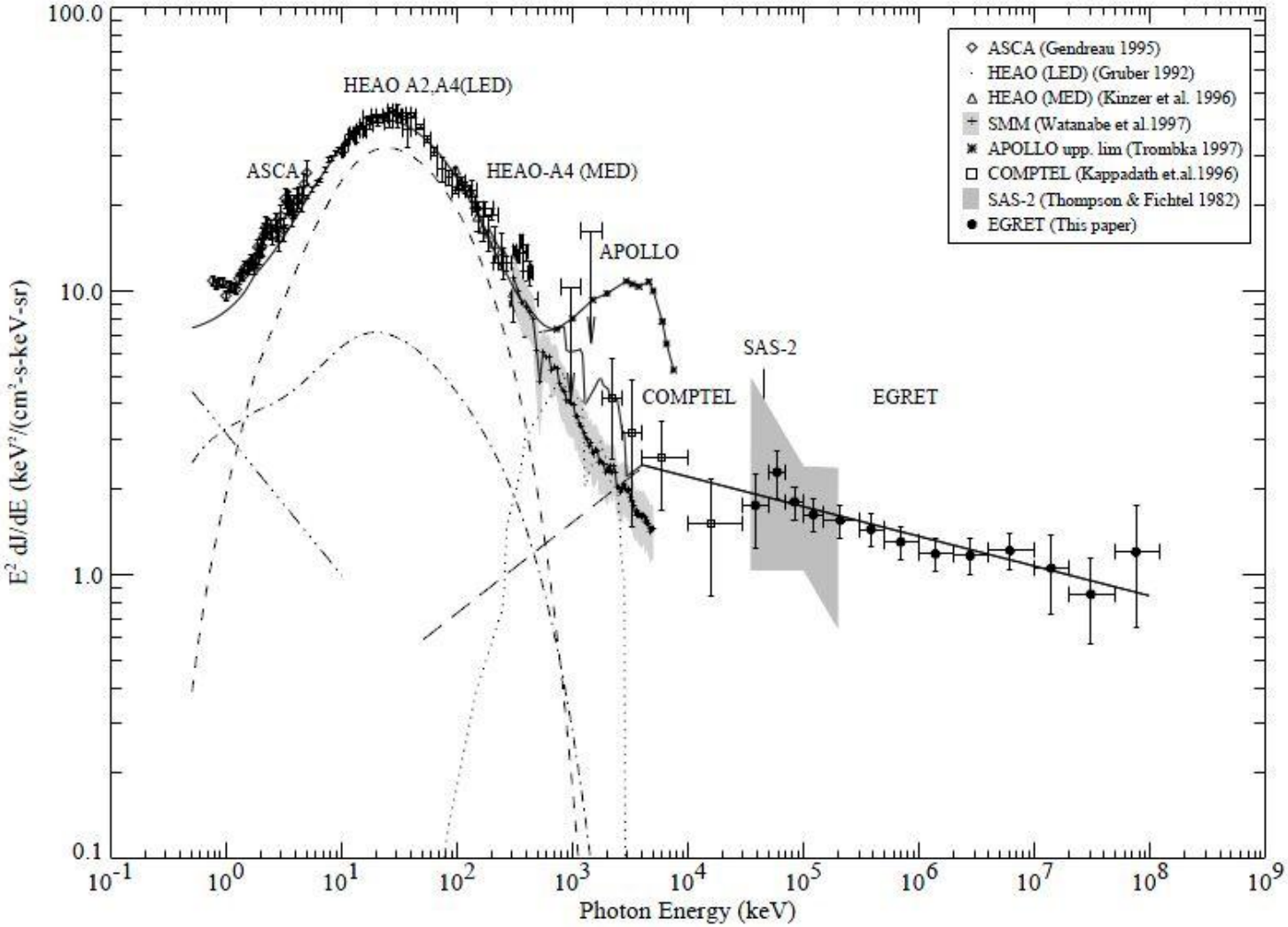
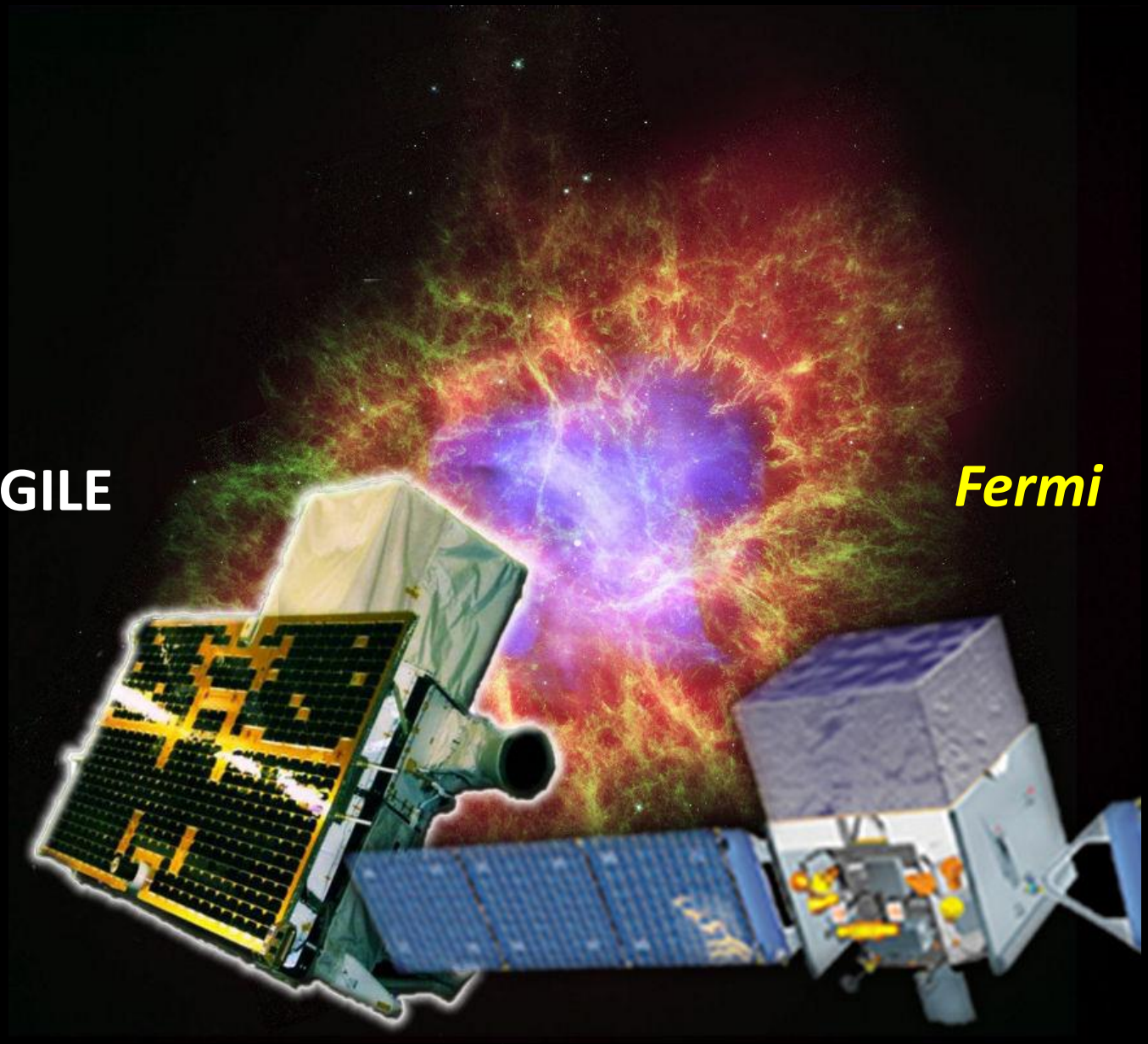


FIG. 10.—Multiwavelength spectrum of the extragalactic gamma-ray spectrum from X-rays to high-energy gamma rays. The estimated contribution from Seyfert I (*dot-dashed line*), and Seyfert II (*dashed*) are from the model of Zdziarski (1996); steep-spectrum quasar contribution (*triple-dot–dashed line*) is taken from Chen, Fabian, & Gendreau (1997); Type Ia supernovae (*dotted line*) is from The et al. (1993). The blazar contribution below 4 MeV (*long-dashed line*) is derived assuming the average blazar spectrum breaks around 4 MeV (McNaron-Brown et al. 1995) to a power law with an index of ~ -1.7. The thick solid line indicates the sum of all the components.



Picture of the day, Feb. 28, 2011, NASA-HEASARC

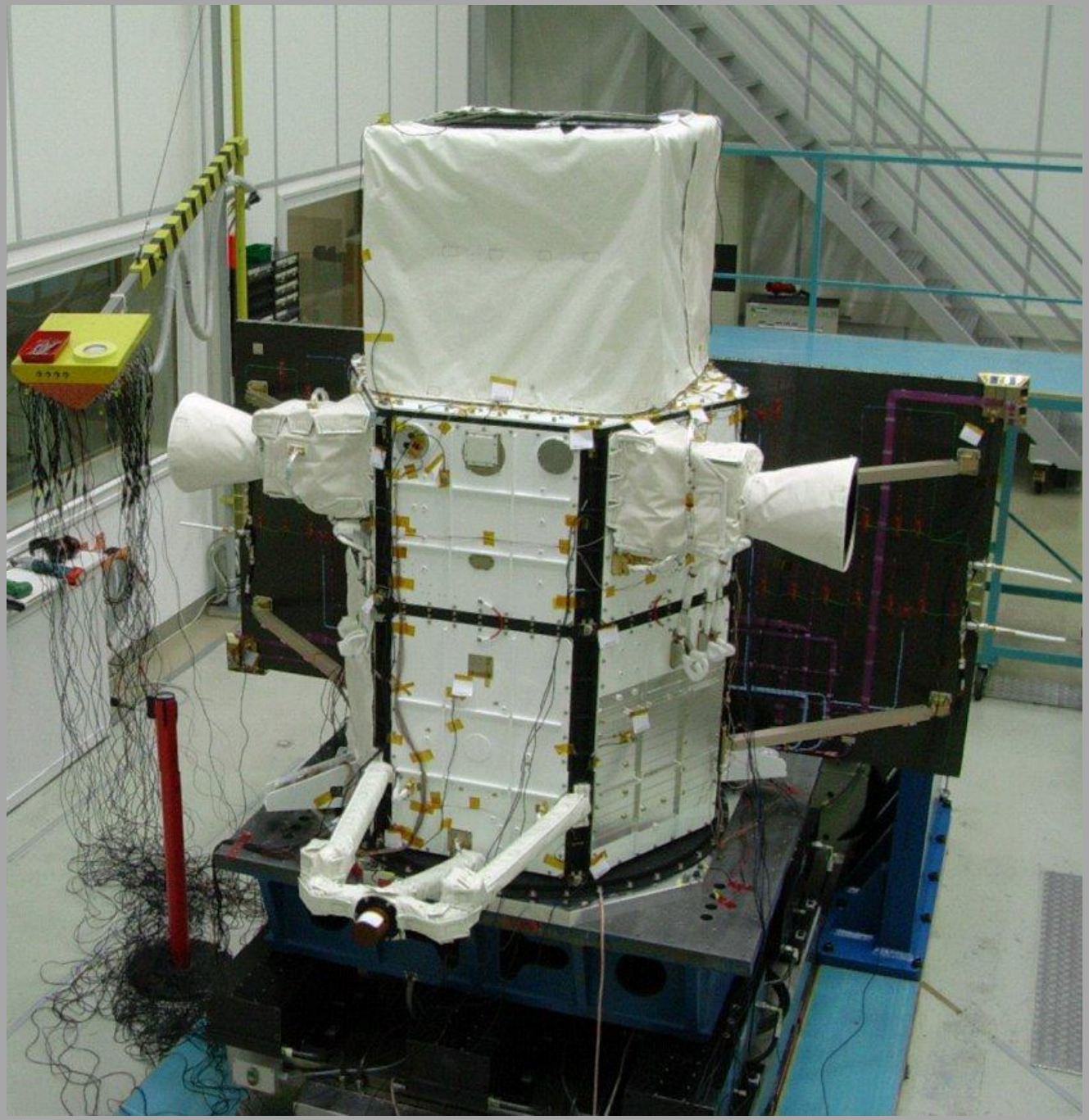
- AGILE and Fermi-LAT use Silicon detectors in very stable configurations.
- AGILE and Fermi-LAT are at the same time similar and very different !
  - very different overall weight, experiment scales
  - different gamma-ray Tracker structure
  - different readout
  - different optimal energy range
  - different pointing strategy, different sensitivity to short and long timescale transients
  - similar PSF at 100 MeV
  - similar sensitivities to transients near 400 MeV

AGILE – *Fermi*'s Smaller Cousin

(from D. Thompson)

KEY FEATURES

- **Italian gamma-ray telescope**
- **Similar to the Fermi Large Area Telescope, but about 1/16 the size**
- **Launched April 23, 2007, from ISRO facility in Sriharikota, India**
- **Indian PSLV rocket**
- **AGILE has contributed to many of the same science topics as Fermi**



AGILE Satellite (IABG, Munich 16 June, 2006)

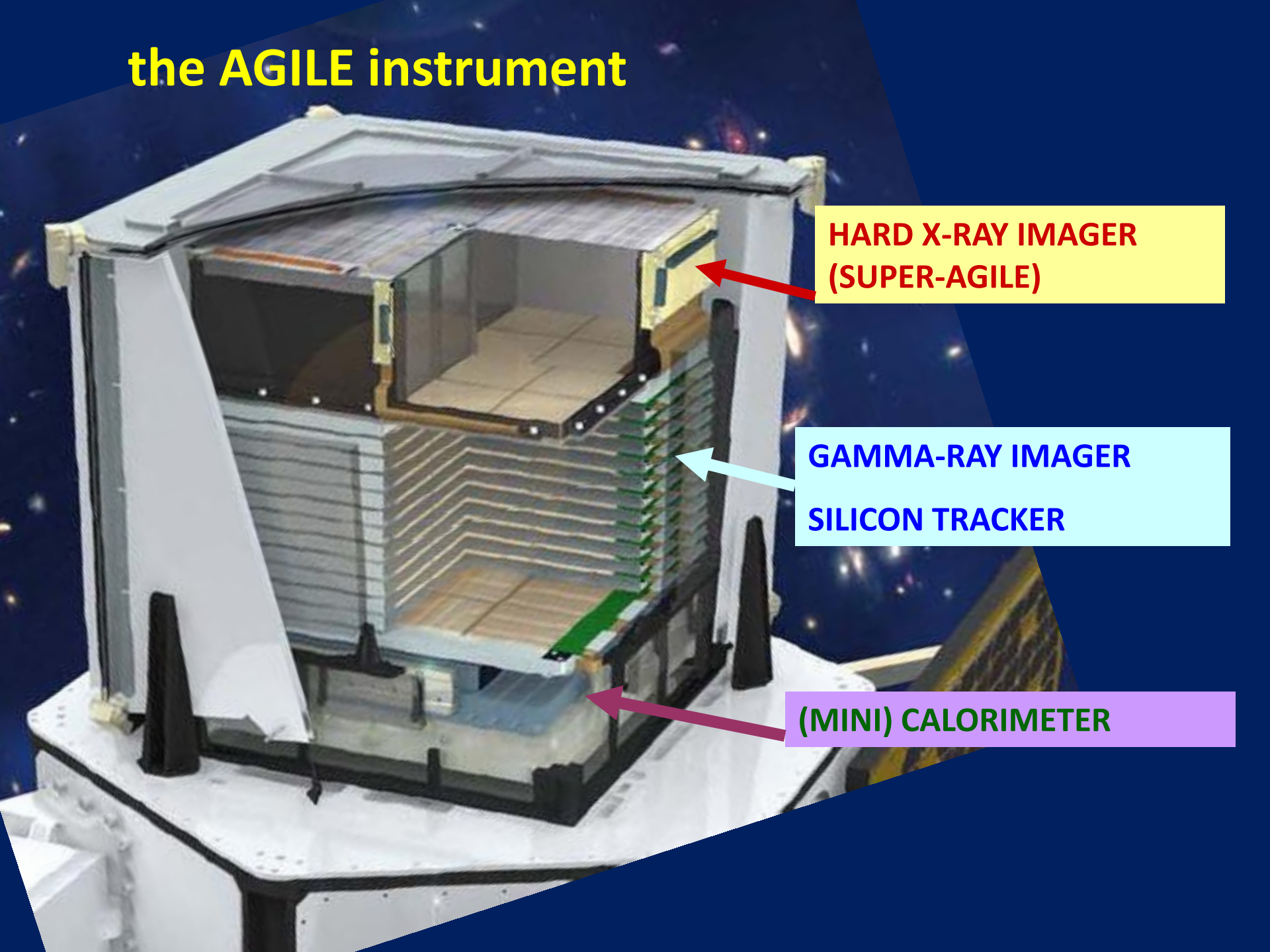
330 kg satellite

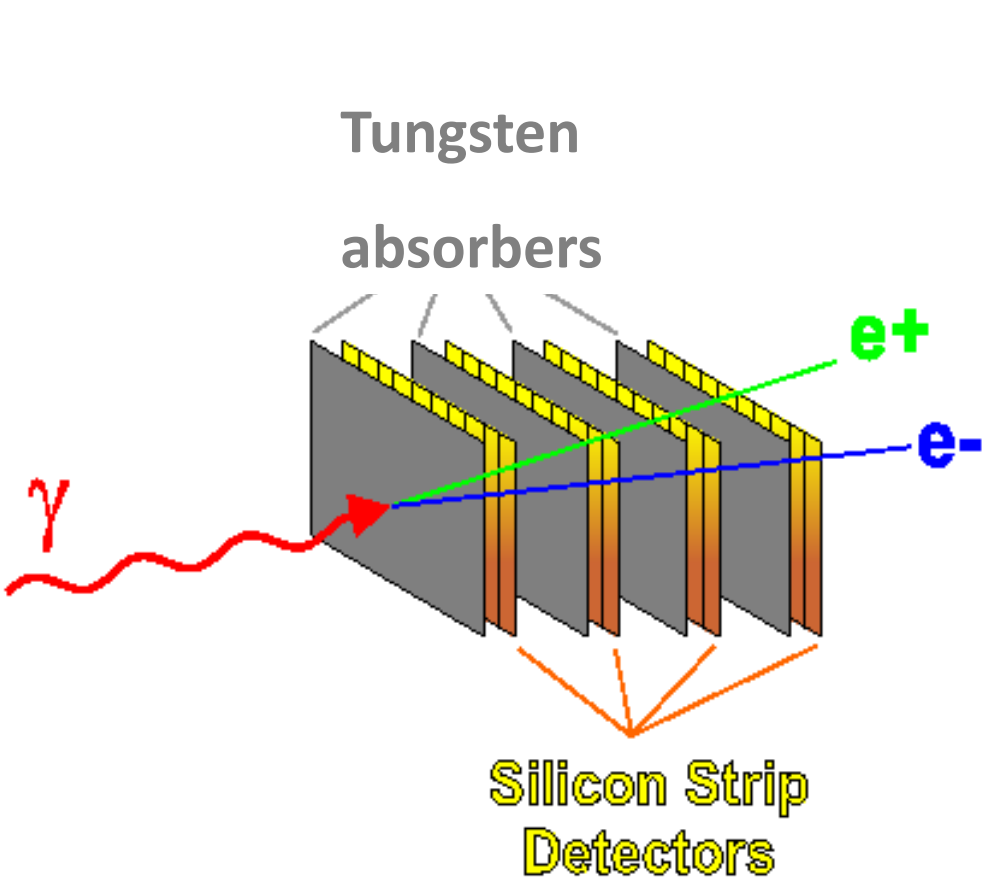
ASI

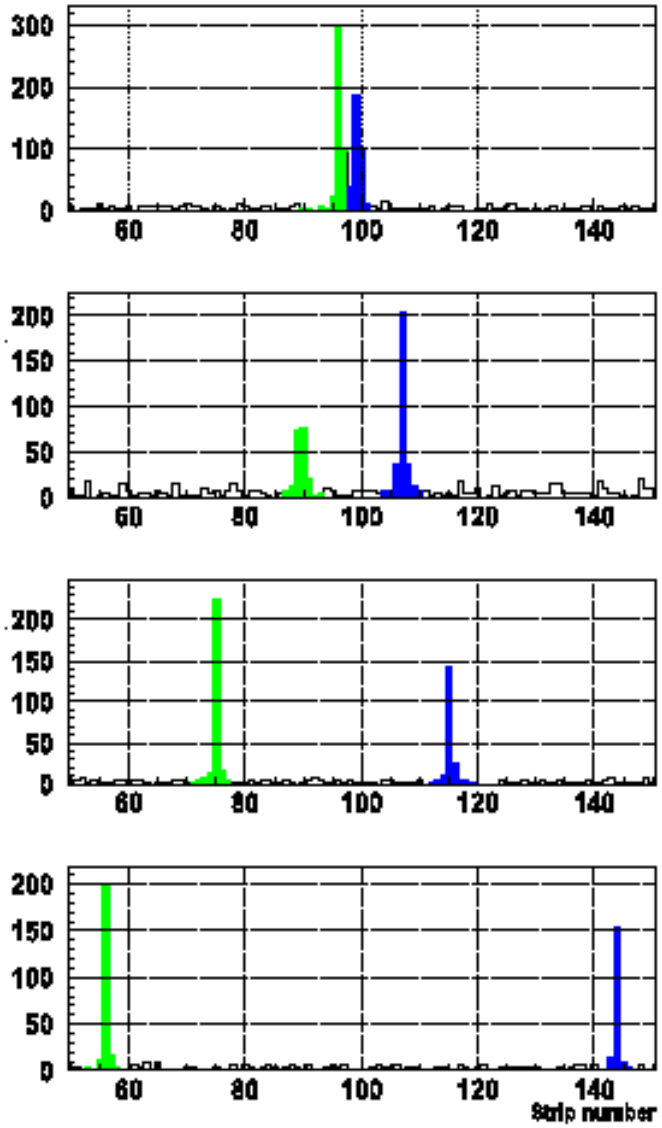
INAF

INFN

the AGILE instrument

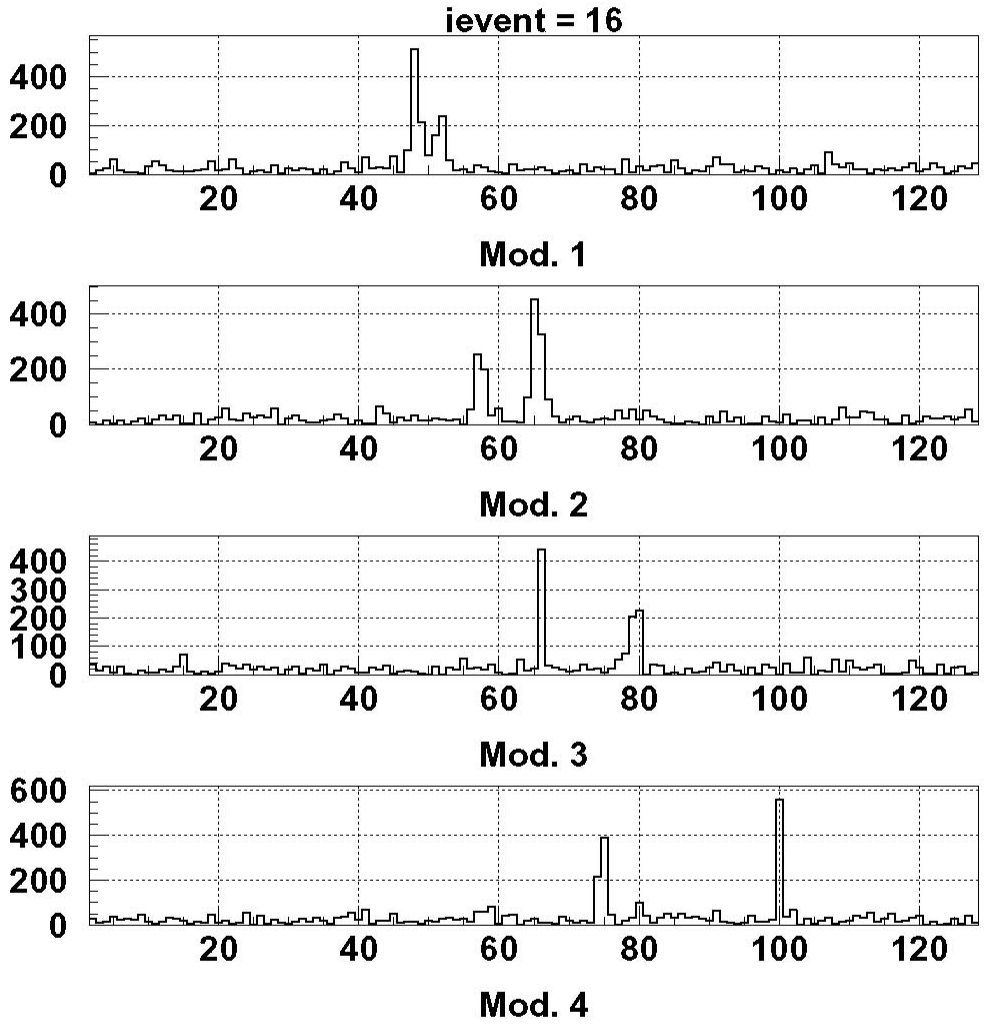






PHOTAG TESTBEAM - INFN TS/IFC MI

gamma-ray detected by the AGILE Tracker



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DOI: 10.1051/0004-6361/200810527
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Astronomy & Astrophysics

The AGILE Mission

M. Tavani[1,2,3], G. Barbiellini[3,4,5], A. Argan[1], F. Boffelli[13], A. Bulgarelli[8], P. Caraveo[6], P. W. Cattaneo[13], A. W. Chen[3,6], V. Cocco[2], E. Costa[1], F. D'Ammando[1,2], E. Del Monte[1], G. De Paris[1], G. Di Cocco[8], G. Di Persio[1], I. Donnarumma[1], Y. Evangelista[1], M. Feroci[1], A. Ferrari[3,16], M. Fiorini[6], F. Fornari[6], F. Fuschino[8], T. Froysland[3,7], M. Frutti[1], M. Galli[9], F. Gianotti[8], A. Giuliani[3,6], C. Labanti[8], I. Lapshov[1,15], F. Lazzarotto[1], F. Liello[5], P. Lipari[10,11], F. Longo[4,5], E. Mattaini[6], M. Marisaldi[8], M. Mastropietro[24], A. Mauri[8], F. Mauri[13], S. Mereghetti[6], E. Morelli[8], A. Morselli[7], L. Pacciani[1], A. Pellizzoni[6], F. Perotti[6], G. Piano[1], P. Picozza[2,7], C. Pontoni[3,5], G. Porrovecchio[1], M. Prest[5], G. Pucella[1], M. Rapisarda[12], A. Rappoldi[13], E. Rossi[8], A. Rubini[1], P. Soffitta[1], A. Traci[8], M. Trifoglio[8], A. Trois[1], E. Vallazza[5], S. Vercellone[6], V. Vittorini[1,3], A. Zambra[3,6], D. Zanello[10,11], C. Pittori[14], B. Preger[14], P. Santolamazza[14], F. Verrecchia[14], P. Giommi[14], S. Colafrancesco[14], A. Antonelli[17], S. Cutini[14], D. Gasparrini[14], S. Stellato[14], G. Fanari[14], R. Primavera[14], F. Tamburelli[14], F. Viola[18], G. Guarrera[18], L. Salotti[18], F. D'Amico[18], E. Marchetti[18], M. Crisconio[18], P. Sabatini[19], G. Annoni[19], S. Alia[19], A. Longoni[19], R. Sanquerin[19], M. Battilana[19], P. Concari[19], E. Dessimone[19], R. Grossi[19], A. Parise[19], F. Monzani[20], E. Artina[20], R. Pavesi[20], G. Marseguerra[20], L. Nicolini[20], L. Scandelli[20], L. Soli[20], V. Vettorello[20], E. Zardetto[20], A. Bonati[20], L. Maltecca[20], E. D'Alba[20], M. Patané[20], G. Babini[21], F. Onorati[21], L. Acquaroli[21], M. Angelucci[21], B. Morelli[21], C. Agostara[21], M. Cerone[22], A. Michetti[22], P. Tempesta[22], S. D'Eramo[22], F. Rocca[22], F. Giannini[22], G. Borghi[23], B. Garavelli[25], M. Conte[20], M. Balasini[20], I. Ferrario[25], M. Vanotti[25], E. Collavo[25], and M. Giacomazzo[25]

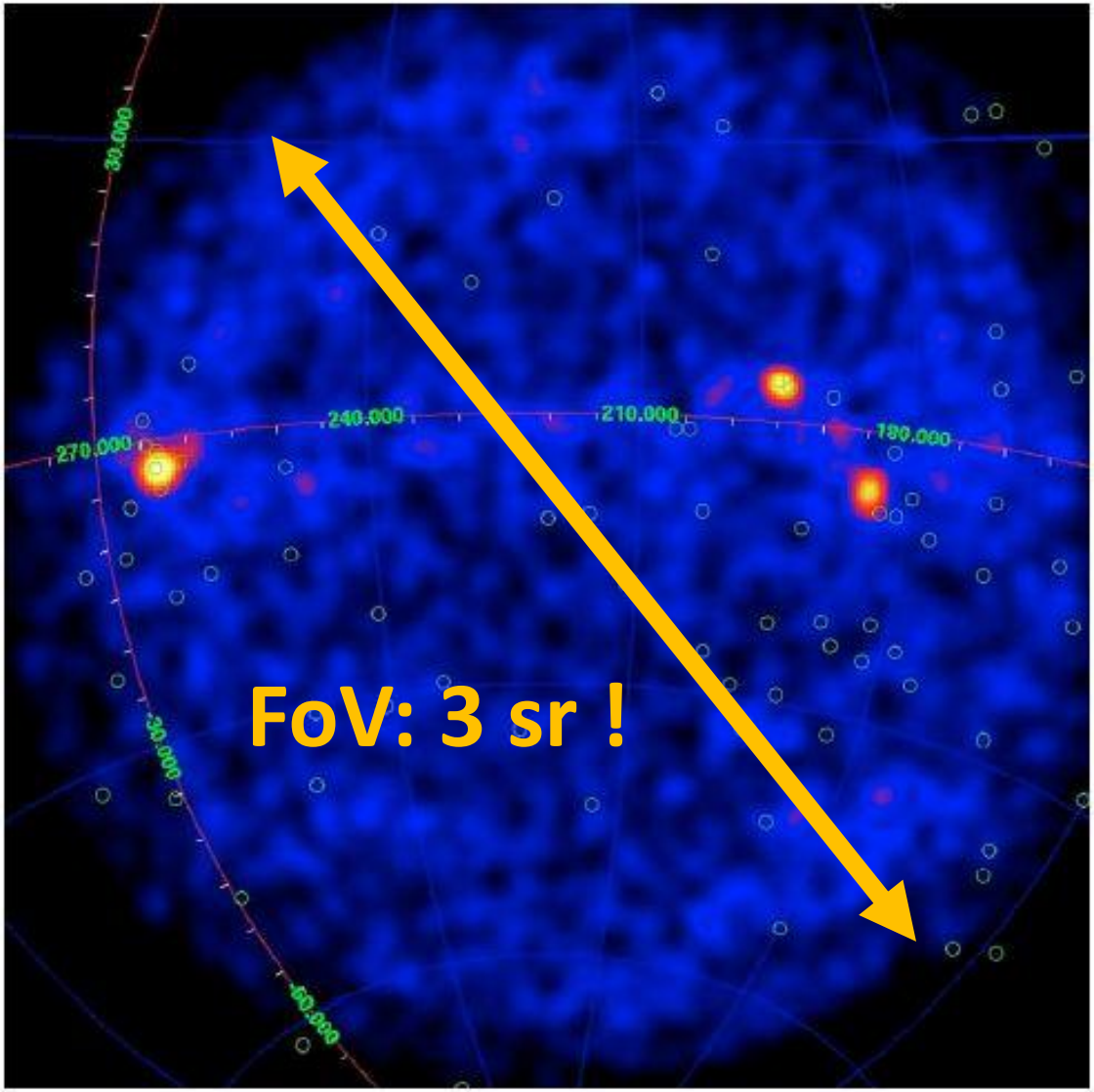
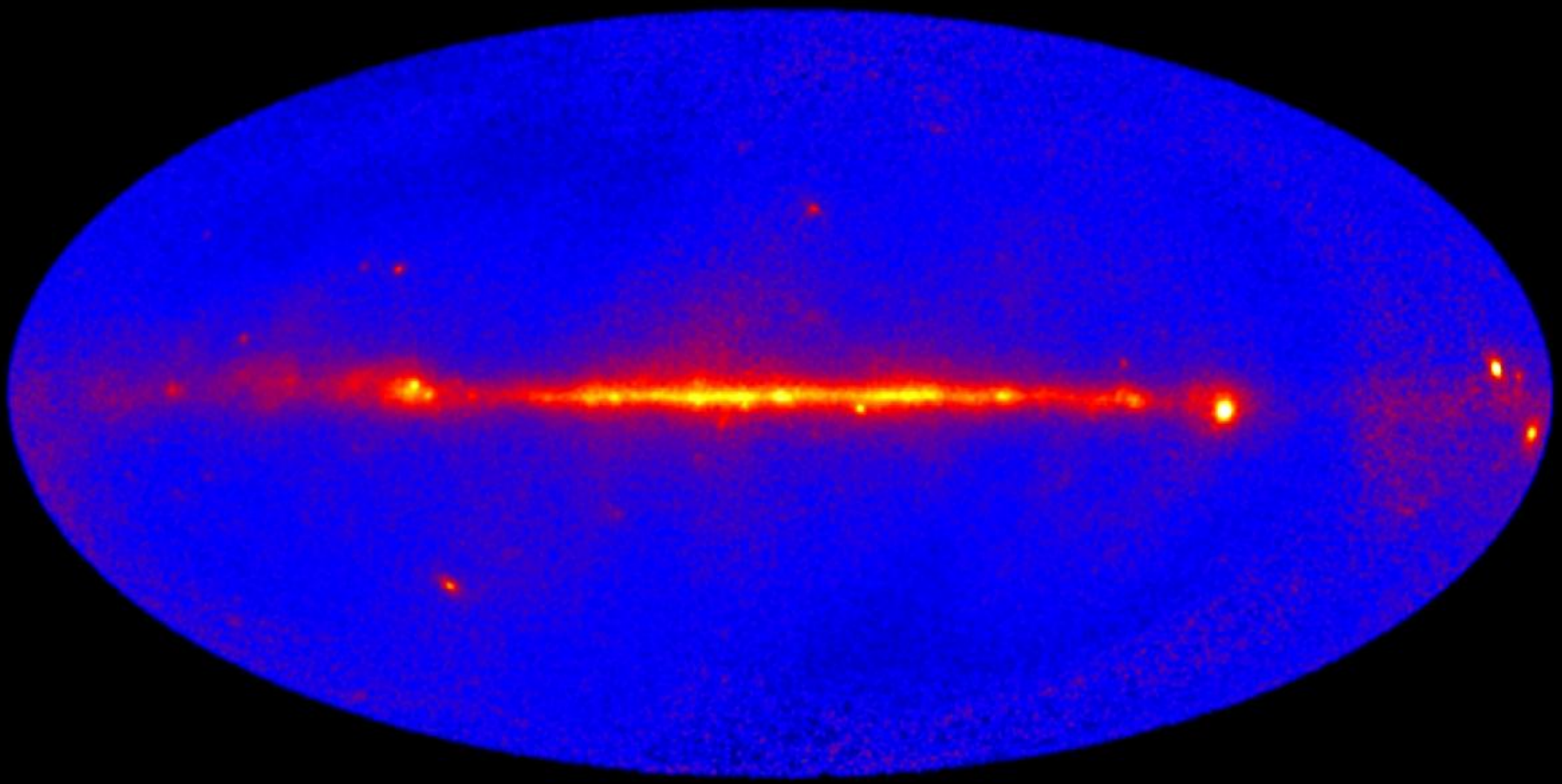


Fig. 25. The AGILE-GRID 1-day gamma-ray counts map for photons above 100 MeV obtained on 2007 September 28. The unprecedently large FOV includes for the first time in a single map all three of the most important gamma-ray pulsars: Vela, Crab, and Geminga.

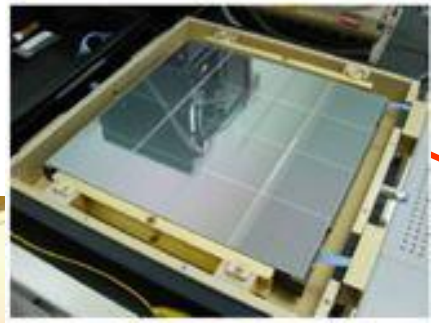
The AGILE gamma-ray sky (E > 100 MeV)
2 year exposure: July 2007 – June 2009

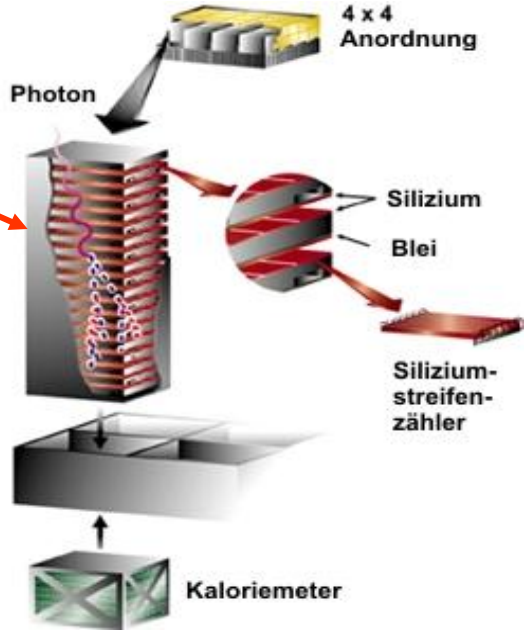


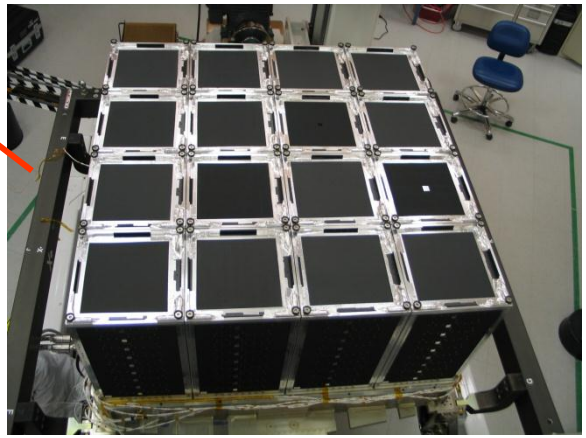
Fermi, NASA

Fermi – LAT

from G. Kanbach







… a tracker of stacked Si strip detectors

The Fermi Observatory

Large AreaTelescope (LAT)
20 MeV - >300 GeV

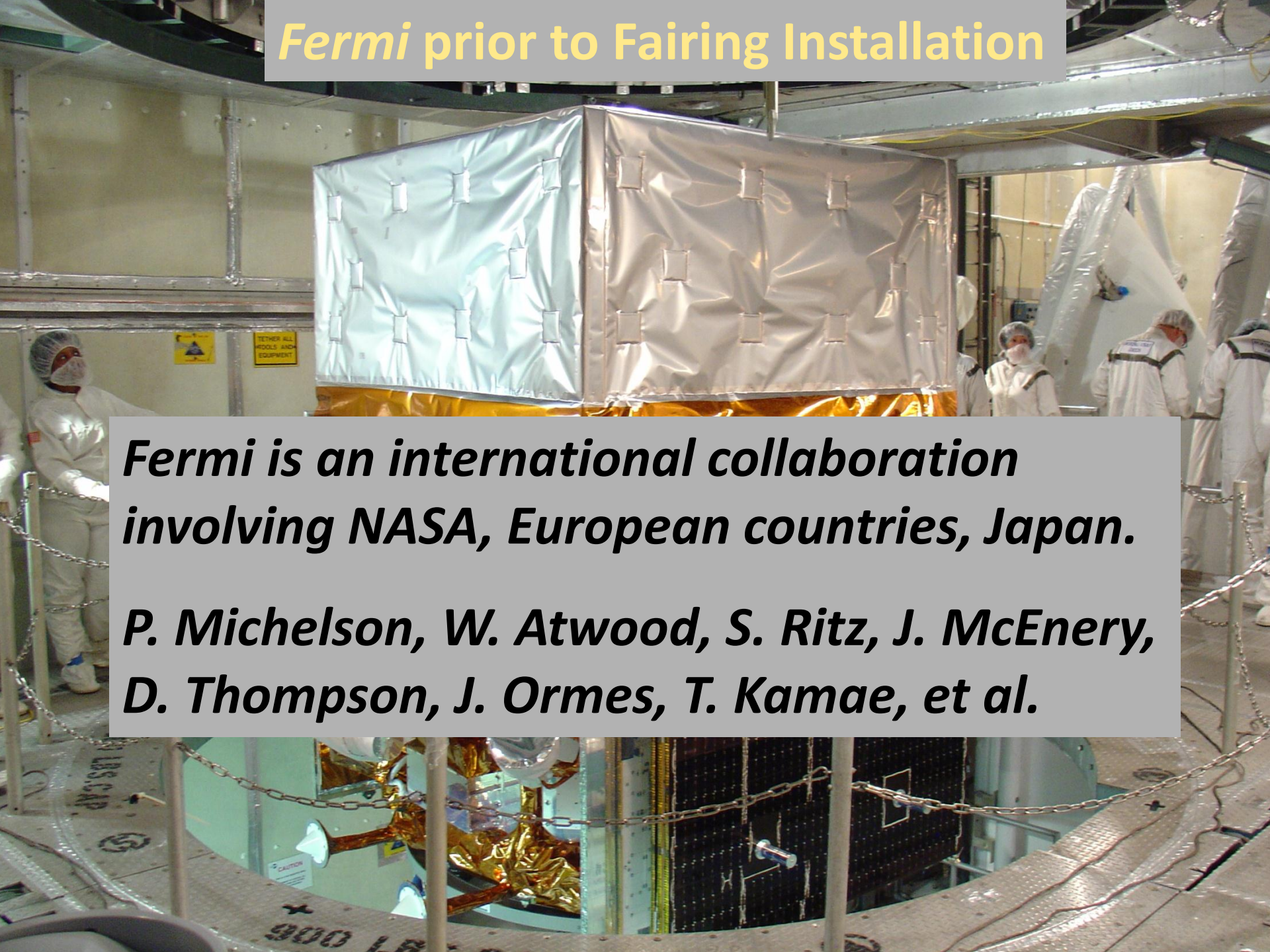
Gamma-ray Burst Monitor (GBM)
NaI and BGO Detectors
8 keV - 40 MeV

KEY FEATURES

- **Huge field of view**
  - **– LAT: 2.4 sr; 20% of the sky at any instant;**
  - **– GBM: whole unocculted sky at any time.**
- **Broad energy range.**
  - **– Total of >7 energy decades!**
- **Every photon can be time-tagged.**
  - **– 1 microsecond accuracy**

Launched June 11, 2008

Fermi prior to Fairing Installation



Fermi is an international collaboration involving NASA, European countries, Japan.

P. Michelson, W. Atwood, S. Ritz, J. McEnery, D. Thompson, J. Ormes, T. Kamae, et al.

April 2012

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FERMI LARGE AREA TELESCOPE SECOND SOURCE CATALOG*

P. L. Nolan[1,82], A. A. Abdo[2,83], M. Ackermann[3], M. Ajello[1], A. Allafort[1], E. Antolini[4,5], W. B. Atwood[6], M. Axelsson[7,8,9], L. Baldini[10], J. Ballet[11], G. Barbiellini[12,13], D. Bastieri[14,15], K. Bechtol[1], A. Belfiore[6,16,17], R. Bellazzini[10], B. Berenji[1], G. F. Bignami[18], R. D. Blandford[1], E. D. Bloom[1], E. Bonamente[4,5], J. Bonnell[19,20], A. W. Borgland[1], E. Bottacini[1], A. Bouvier[6], T. J. Brandt[21,22], J. Bregeon[10], M. Brigida[23,24], P. Bruel[25], R. Buehler[1], T. H. Burnett[26], S. Buson[14,15], G. A. Caliandro[27], R. A. Cameron[1], R. Campana[28], B. Cañadas[29,30], A. Cannon[19,31], P. A. Caraveo[17], J. M. Casandjian[11], E. Cavazzuti[32], M. Ceccanti[10], C. Cecchi[4,5], Ö. Çelik[19,33,34], E. Charles[1], A. Chekhtman[35,83], C. C. Cheung[36,83,84], J. Chiang[1], R. Chipaux[37], S. Ciprini[5,38], R. Claus[1], J. Cohen-Tanugi[39], L. R. Cominsky[40], J. Conrad[8,41,85], R. Corbet[19,34], S. Cutini[32], F. D'Ammando[28,42], D. S. Davis[19,34], A. de Angelis[43], M. E. DeCesar[19,20], M. DeKlotz[44], A. De Luca[18], P. R. den Hartog[1], F. de Palma[23,24], C. D. Dermer[45], S. W. Digel[1], E. do Couto e Silva[1], P. S. Drell[1], A. Drlica-Wagner[1], R. Dubois[1], D. Dumora[46], T. Enoto[1], L. Escande[46], D. Fabiani[10], L. Falletti[39], C. Favuzzi[23,24], S. J. Fegan[25], E. C. Ferrara[19], W. B. Focke[1], P. Fortin[25], M. Frailis[43,47], Y. Fukazawa[48], S. Funk[1], P. Fusco[23,24], F. Gargano[24], D. Gasparrini[32], N. Gehrels[19], S. Germani[4,5], B. Giebels[25], N. Giglietto[23,24], P. Giommi[32], F. Giordano[23,24], M. Giroletti[49], T. Glanzman[1], G. Godfrey[1], I. A. Grenier[11], M.-H. Grondin[50,51], J. E. Grove[45], L. Guillemot[52], S. Guiriec[53], M. Gustafsson[14], D. Hadasch[27], Y. Hanabata[48], A. K. Harding[19], M. Hayashida[1,54], E. Hays[19], A. B. Hill[55], D. Horan[25], X. Hou[56], R. E. Hughes[57], G. Iafrate[12,47], R. Itoh[48], G. Jóhannesson[58], R. P. Johnson[6], T. E. Johnson[19], A. S. Johnson[1], T. J. Johnson[36,83,84], T. Kamae[1], H. Katagiri[59], J. Kataoka[60], J. Katsuta[1], N. Kawai[61,62], M. Kerr[1], J. Knödlseder[21,22], D. Kocevski[1], M. Kuss[10], J. Lande[1], D. Landriu[11], L. Latronico[63], M. Lemoine-Goumard[46,86], A. M. Lionetto[29,30], M. Llena Garde[8,41], F. Longo[12,13], F. Loparco[23,24], B. Lott[46], M. N. Lovellette[45], P. Lubrano[4,5], G. M. Madejski[1], M. Marelli[17], E. Massaro[64], M. N. Mazziotta[24], W. McConville[19,20], J. E. McEnery[19,20], J. Mehault[39], P. F. Michelson[1], M. Minuti[10], W. Mitthumsiri[1], T. Mizuno[48], A. A. Moiseev[20,33], M. Mongelli[24], C. Monte[23,24], M. E. Monzani[1], A. Morselli[29], I. V. Moskalenko[1], S. Murgia[1], T. Nakamori[60], M. Naumann-Godo[11], J. P. Norris[65], E. Nuss[39], T. Nymark[8,9], M. Ohno[66], T. Ohsugi[67], A. Okumura[1,66], N. Omodei[1], E. Orlando[1,68], J. F. Ormes[69], M. Ozaki[66], D. Paneque[1,70], J. H. Panetta[1], D. Parent[2,83], J. S. Perkins[19,33,34,71], M. Pesce-Rollins[10], M. Pierbattista[11], M. Pinchera[10], F. Piron[39], G. Pivato[15], T. A. Porter[1], J. L. Racusin[19], S. Rainò[23,24], R. Rando[14,15], M. Razzano[6,10], S. Razzaque[2,83], A. Reimer[1,72], O. Reimer[1,72], T. Reposeur[46], S. Ritz[6], L. S. Rochester[1], R. W. Romani[1], M. Roth[26], R. Rousseau[56], F. Ryde[8,9], H. F.-W. Sadrozinski[6], D. Salvetti[17], D. A. Sanchez[50], P. M. Saz Parkinson[6], C. Sbarra[14], J. D. Scargle[73], T. L. Schalk[6], C. Sgrò[10], M. S. Shaw[1], C. Shrader[33], E. J. Siskind[74], D. A. Smith[46], G. Spandre[10], P. Spinelli[23,24], T. E. Stephens[19,75], M. S. Strickman[45], D. J. Suson[76], H. Tajima[1,77], H. Takahashi[67], T. Takahashi[66], T. Tanaka[1], J. G. Thayer[1], J. B. Thayer[1], D. J. Thompson[19], L. Tibaldo[14,15], O. Tibolla[78], F. Tinebra[64], M. Tinivella[10], D. F. Torres[27,79], G. Tosti[4,5], E. Troja[19,87], Y. Uchiyama[1], J. Vandenbroucke[1], A. Van Etten[1], B. Van Klaveren[1], V. Vasileiou[39], G. Vianello[1,80], V. Vitale[29,30], A. P. Waite[1], E. Wallace[26], P. Wang[1], M. Werner[72], B. L. Winer[57], D. L. Wood[81,83], K. S. Wood[45], M. Wood[1], Z. Yang[8,41], and S. Zimmer[8,41]

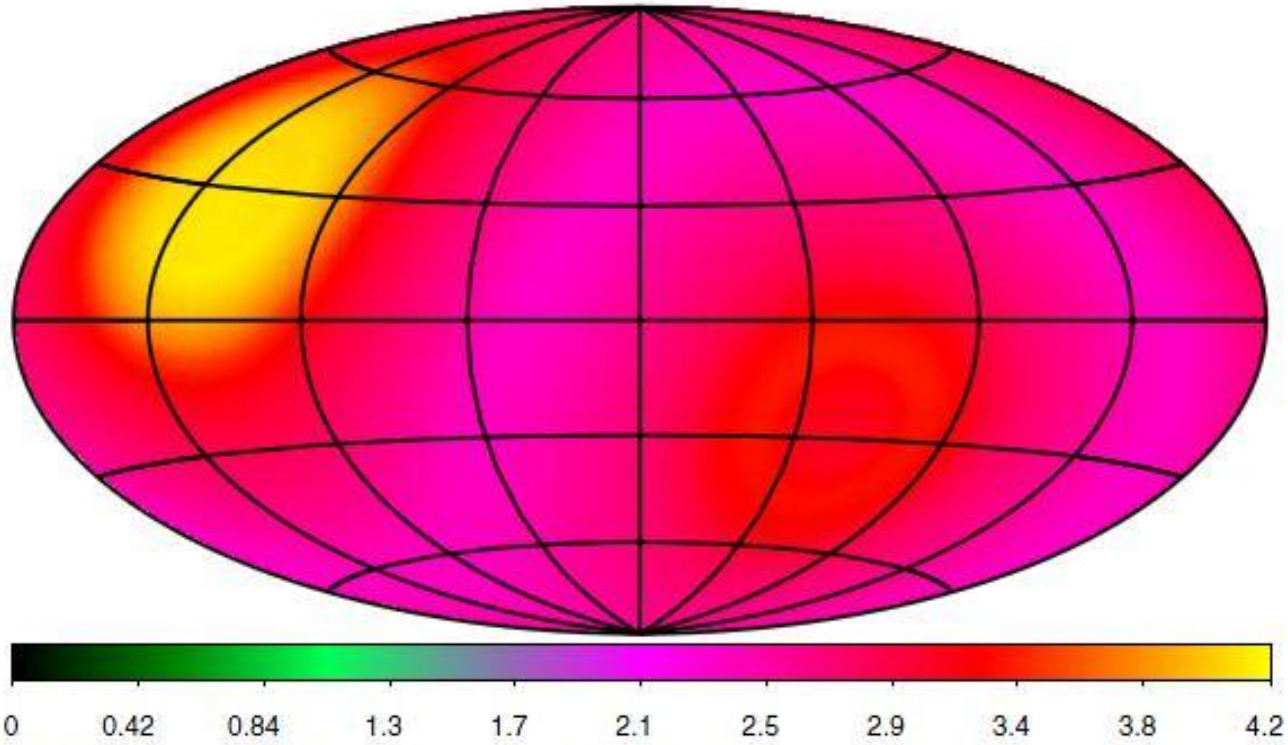
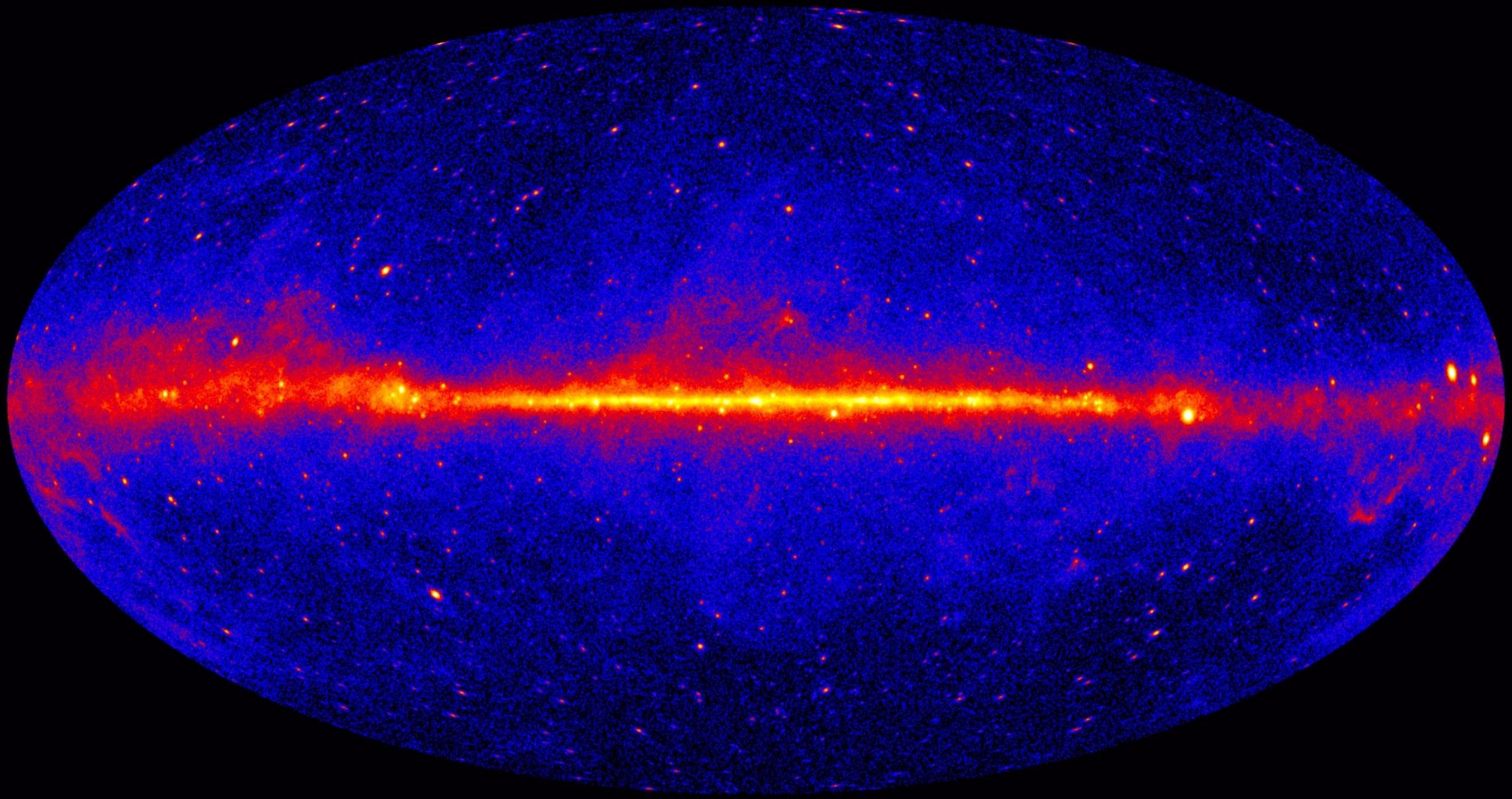


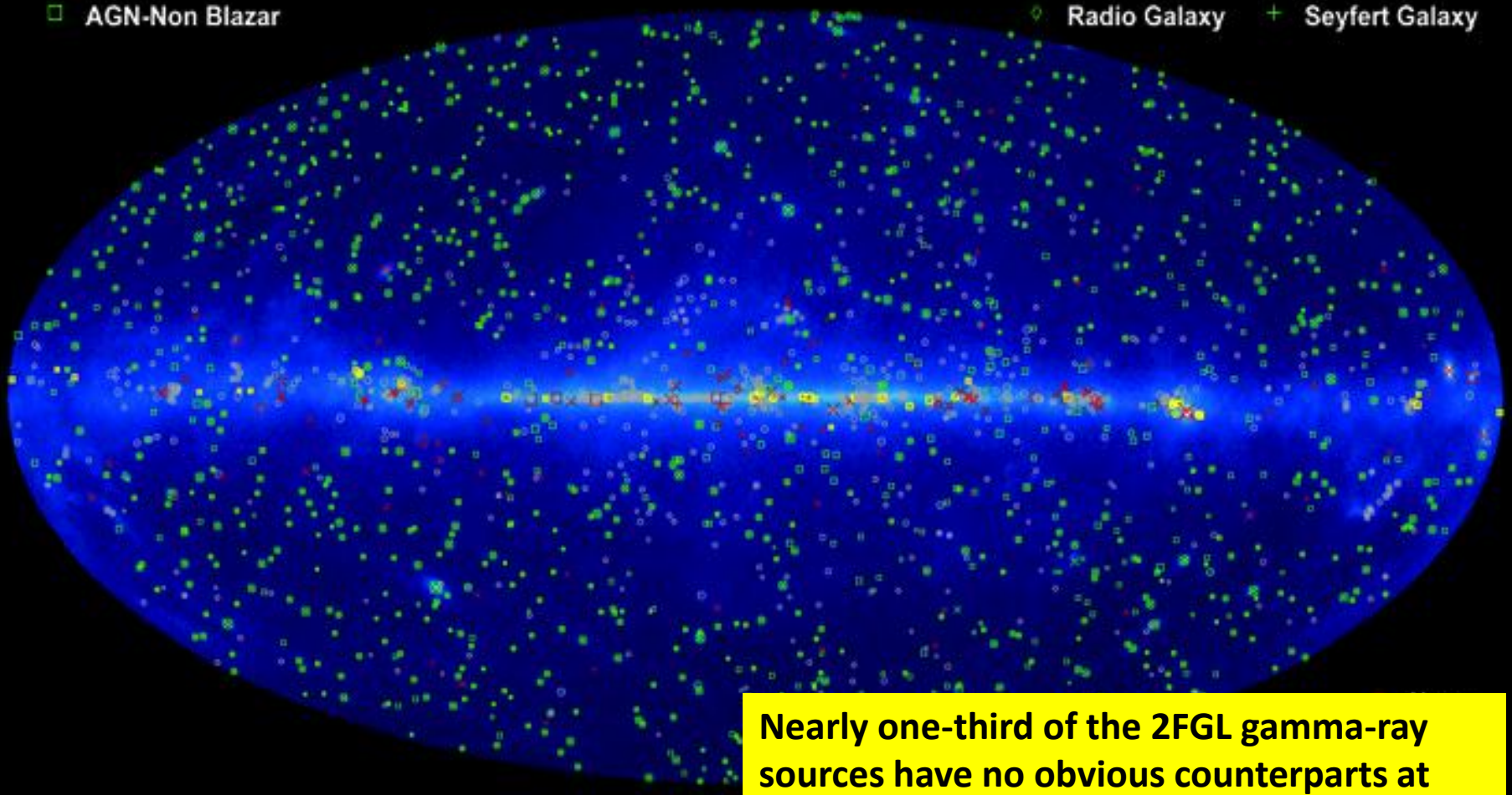
Figure 2. Exposure of the LAT for the period 2009 September to 2010 July when the rocking angle was 50°, Aitoff projection in Galactic coordinates. The units are equivalent on-axis exposure at 1 GeV in Ms.

Three years of LAT scanning data (E > 1 GeV)



Fermi Large Area Telescope 2FGL catalog

1873 Sources



Nearly one-third of the 2FGL gamma-ray sources have no obvious counterparts at other wavelengths. They are mysteries to be solved.

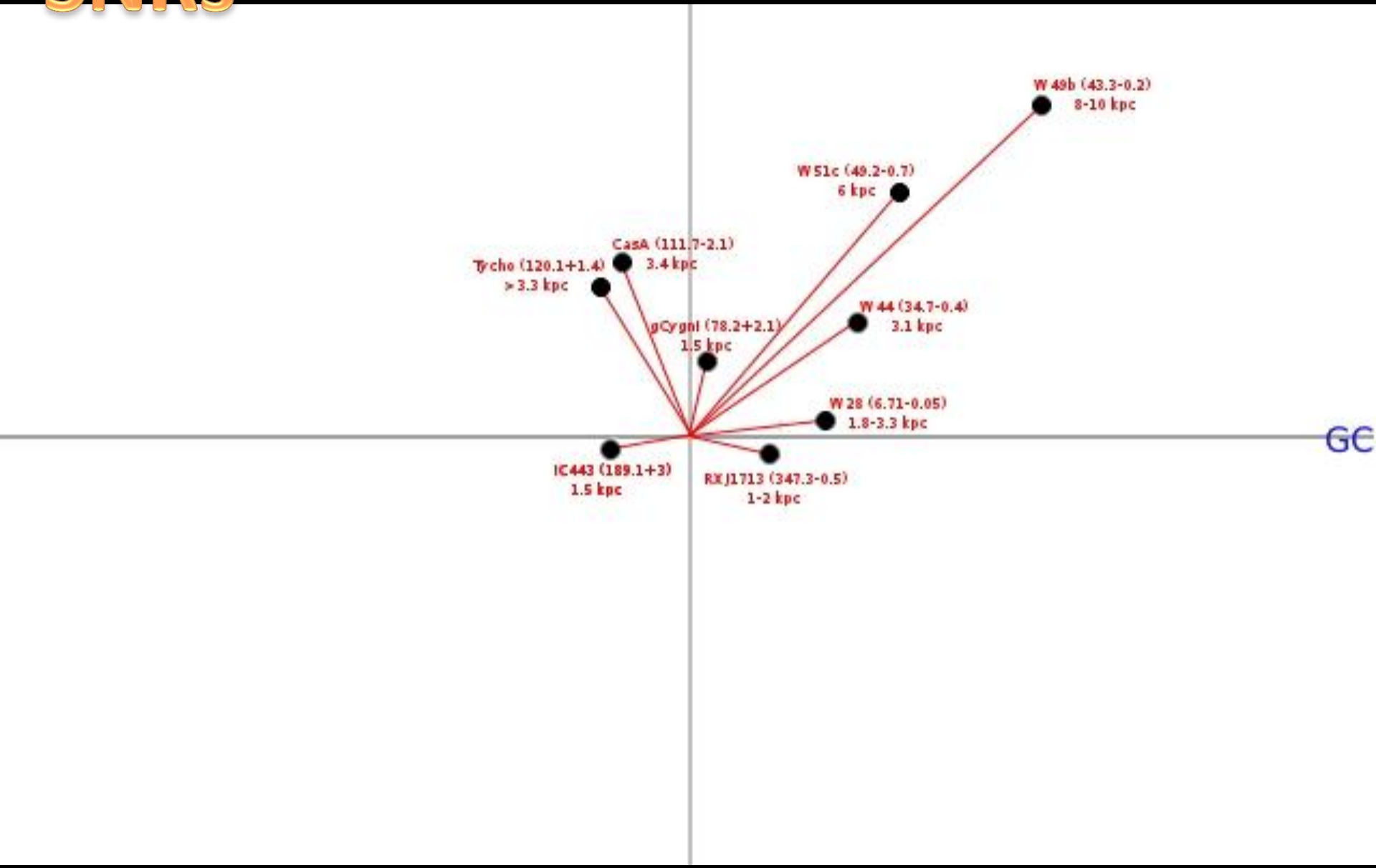
Credit: Fermi Large Area Telescope Collaboration

- **Contributions to the cosmic-ray origin problem**
- **Surprises from the Crab Nebula**
- **Relativistic jet launching**
- **“Fermi bubbles”**
- **Dark Matter searches**
- **pseudo-line near 127 GeV (probably not real, but tantalizing…)**

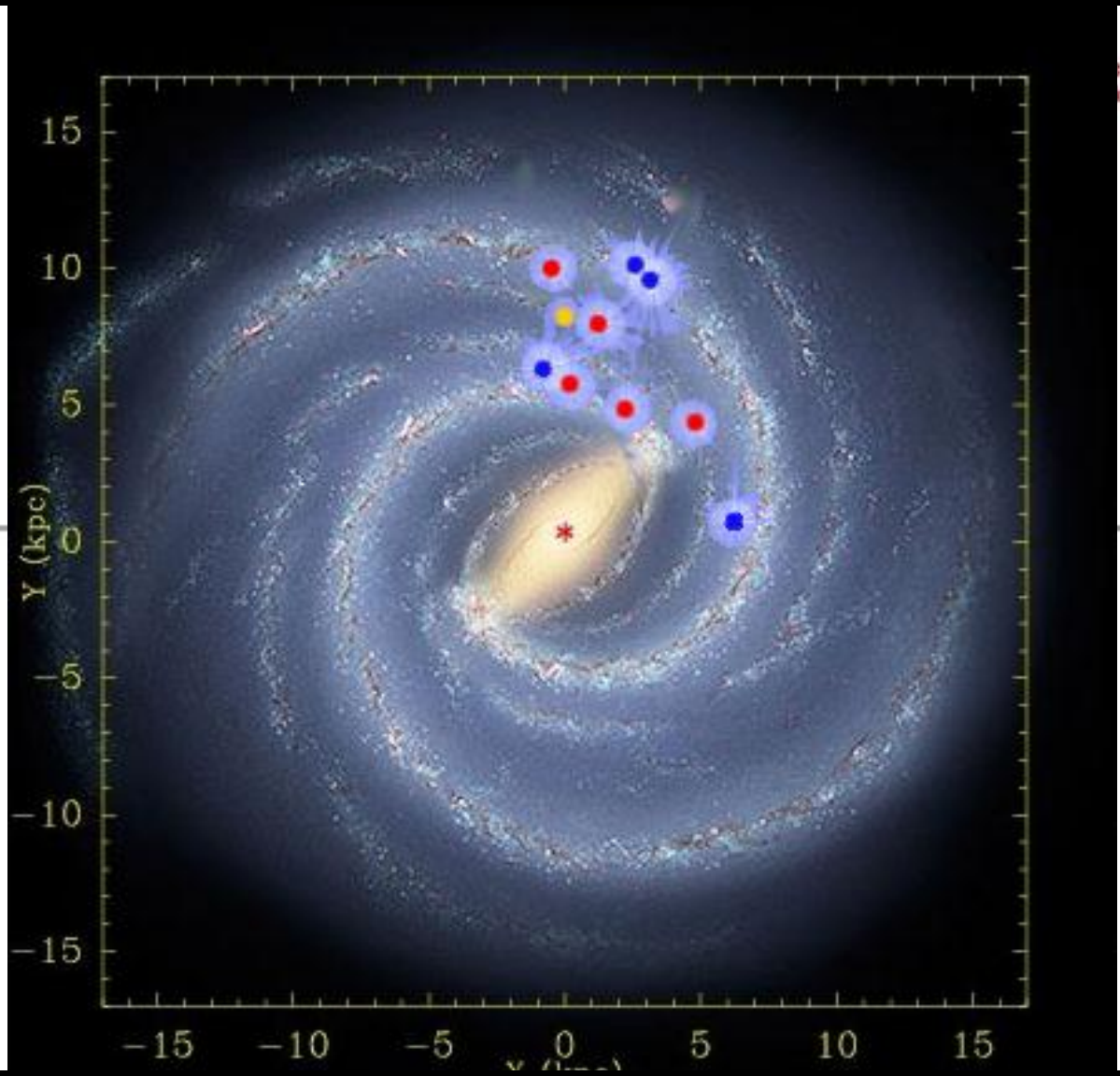
SNRs studied above 100 MeV

SNR (l,b)	distance	AGILE	Fermi-LAT	age[yrs]	MC detect.	TeV
CAS A (111.7,-2.1)	3.4 kpc	no	yes	~300	yes	Veritas, MAGIC
Tycho (120.1,+1.4)	>3.3kpc	no	yes	~440	yes	Veritas
SN 1006 (327.6,+14.6)	2.2	no	no	~1,000	-	HESS
RXJ1713 (347.3,-0.5)	1-2 kpc	no	yes	~1,600	yes	HESS
W49B (G43.3-0.2)	8-10kpc	no (we see it)	yes	1,000-4,000	no (W49a yes)	HESS
γ-Cygni (78.2,+2.1)	1.5 kpc	in prep.	no	~7,000	yes(?)	Veritas
W44 (34.7,-0.4)	3.1 kpc	yes	yes	~20,000	yes	HESS
W51 (49.2,-0.7)	6 kpc	no (we see it)	yes	>20,000	yes	MAGIC, HESS
IC443 (189.1,+3)	1.5 kpc	yes	yes	20,000-30,000	yes	Veritas, MAGIC
W28 (6.71,-0.05)	1.8 - 3.3 kpc	yes	yes	35,000-45,000	yes	HESS

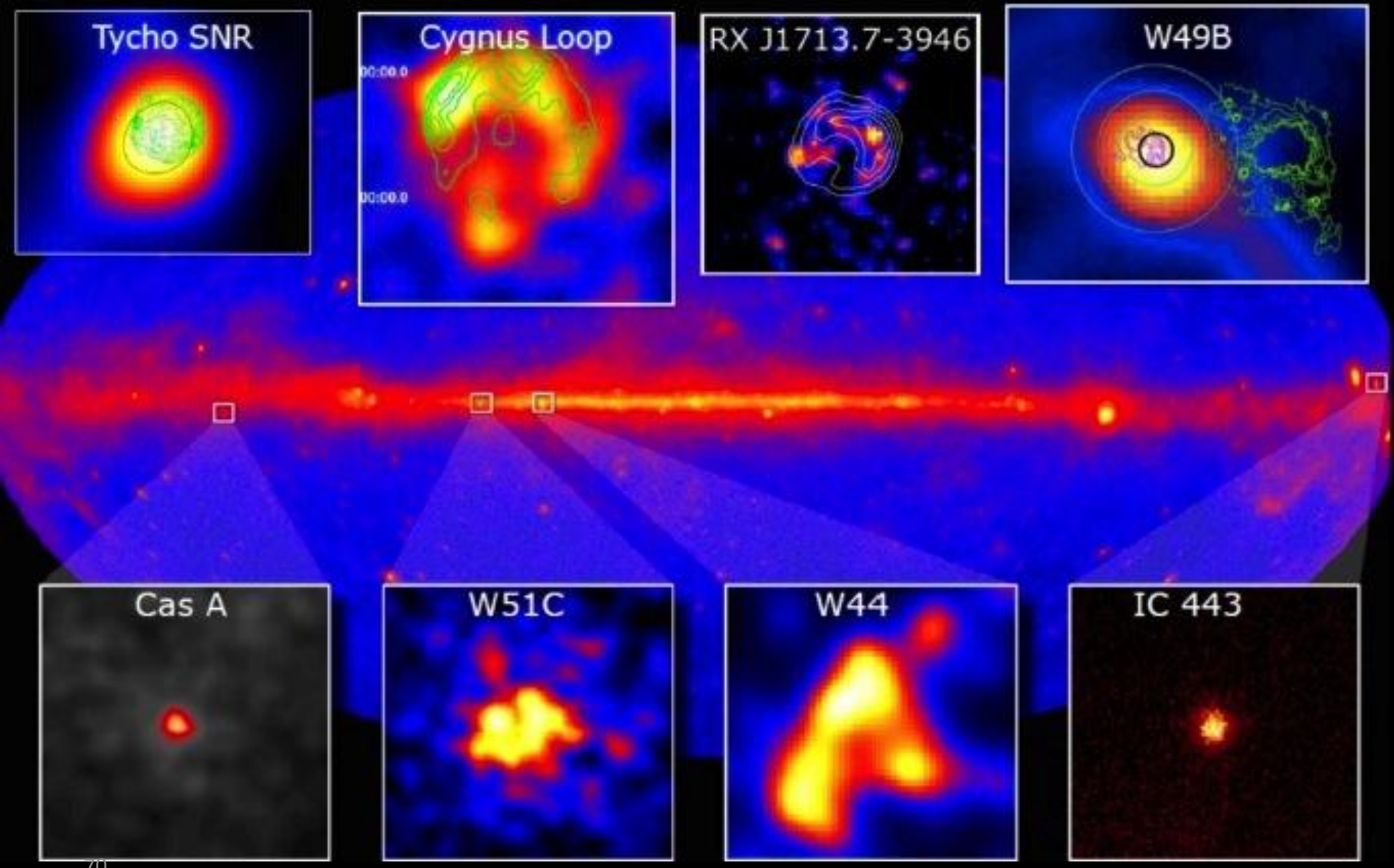
SNRs


W 49b (43.3-0.2)
8-10 kpc
W 51c (49.2-0.7)
6 kpc
CasA (111.7-2.1)
3.4 kpc
Tycho (120.1+1.4)
>3.3 kpc
W 44 (34.7-0.4)
3.1 kpc
gCygnI (78.2+2.1)
1.5 kpc
W 28 (6.71-0.05)
1.8-3.3 kpc
GC
IC443 (189.1+3)
1.5 kpc
RXJ1713 (347.3-0.5)
1-2 kpc

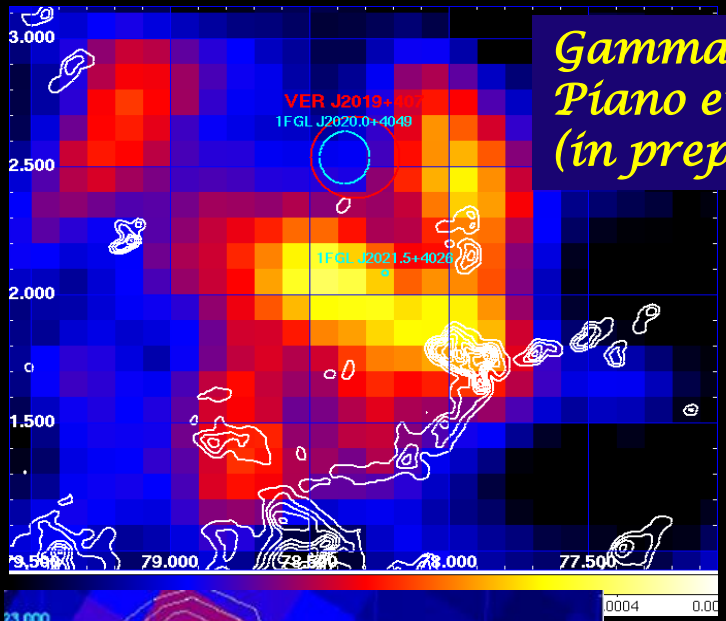
SNRs



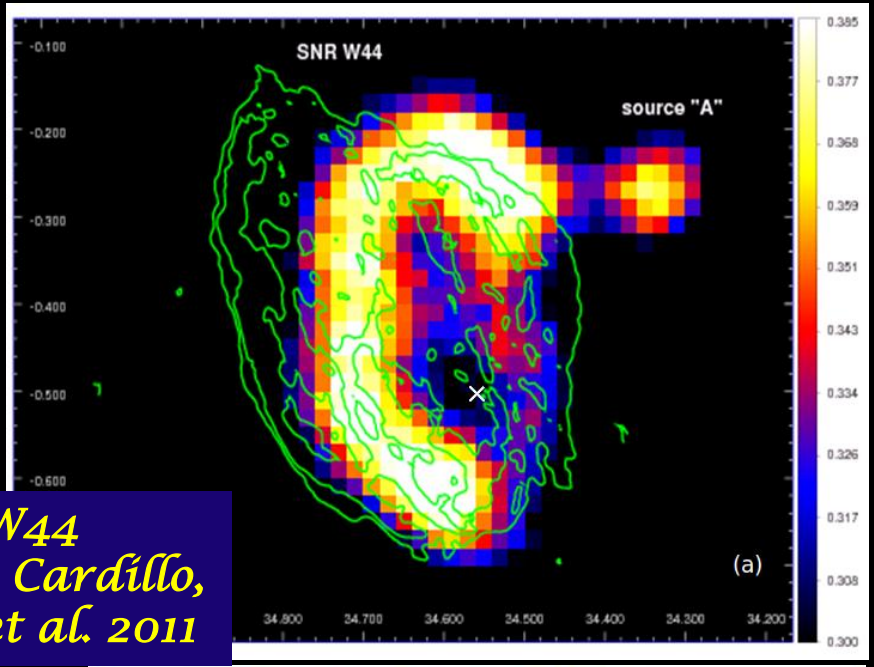
Supernova Remnants - spatially resolved by Fermi



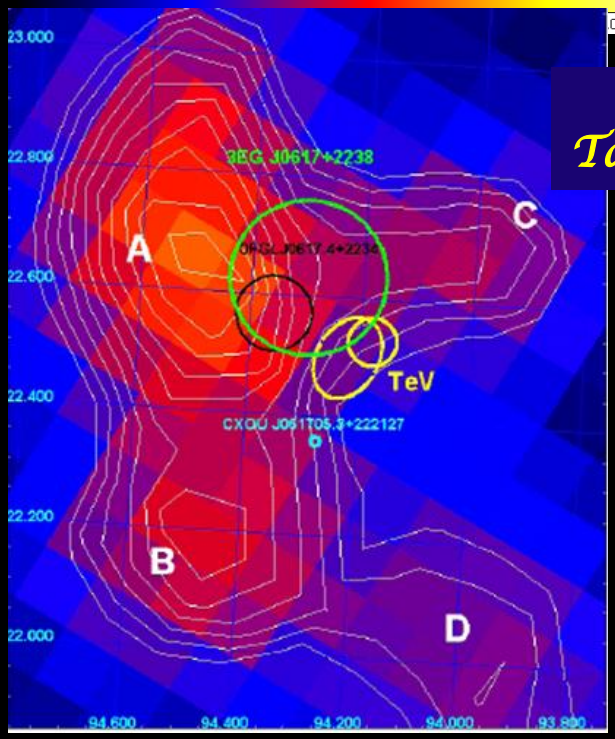
AGILE and SNRs



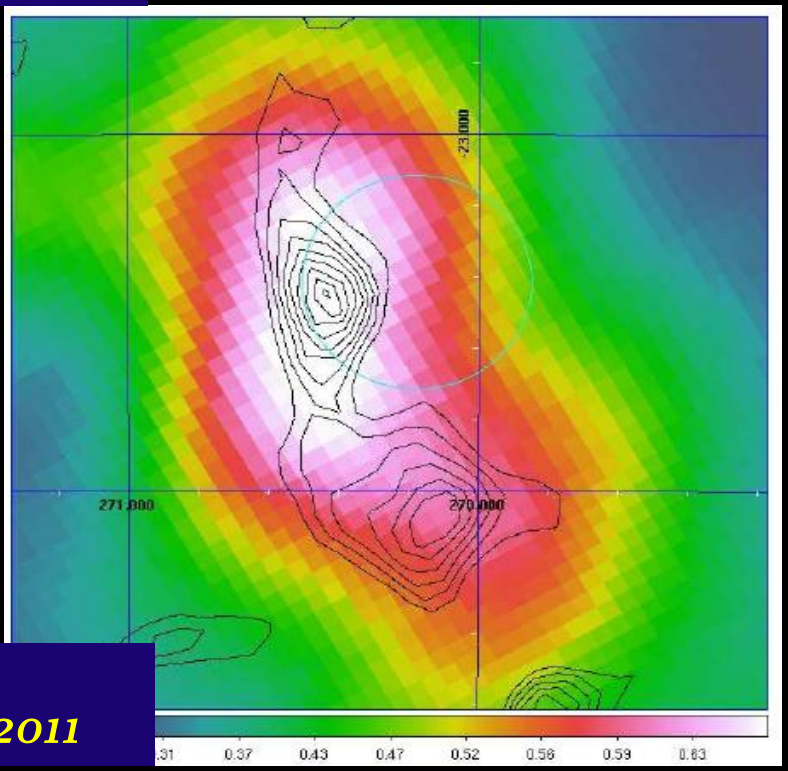
Gamma Cygni
Piano et al.
(in preparation)



W44
Giuliani, Cardillo, Tavani et al. 2011

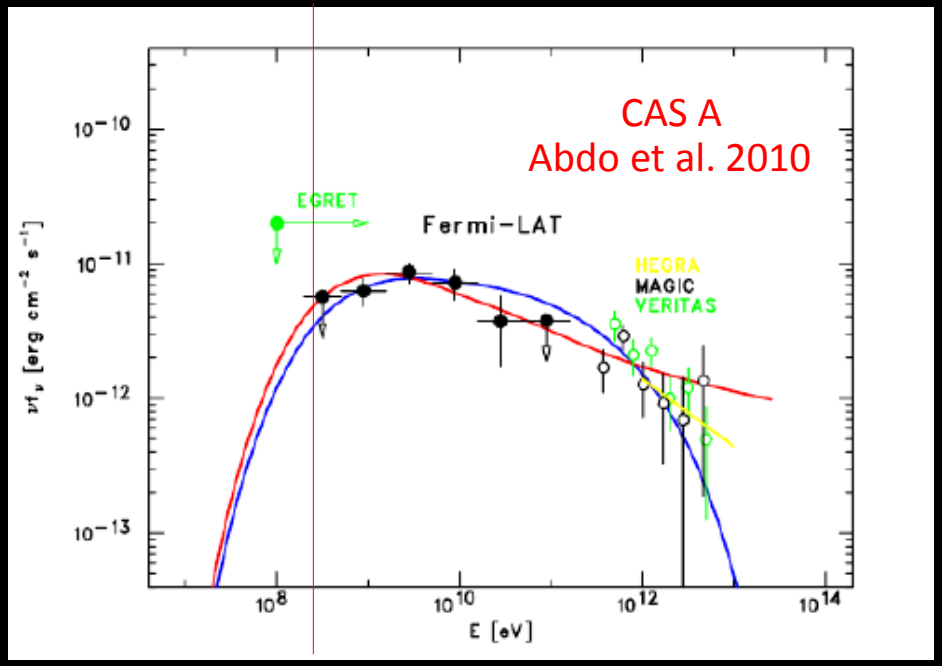


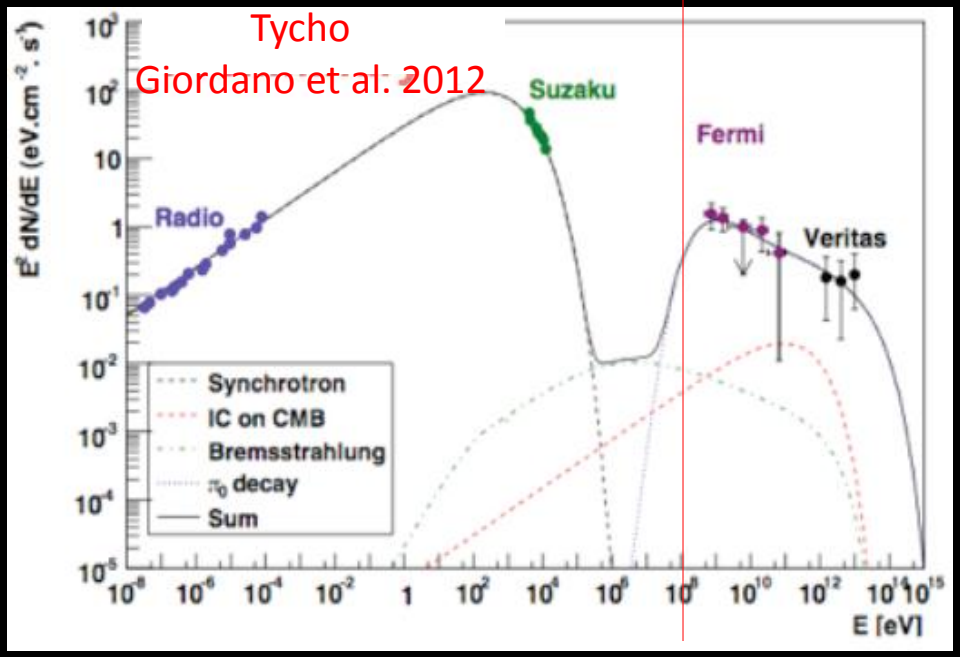
IC443
Tavani et al., 2010



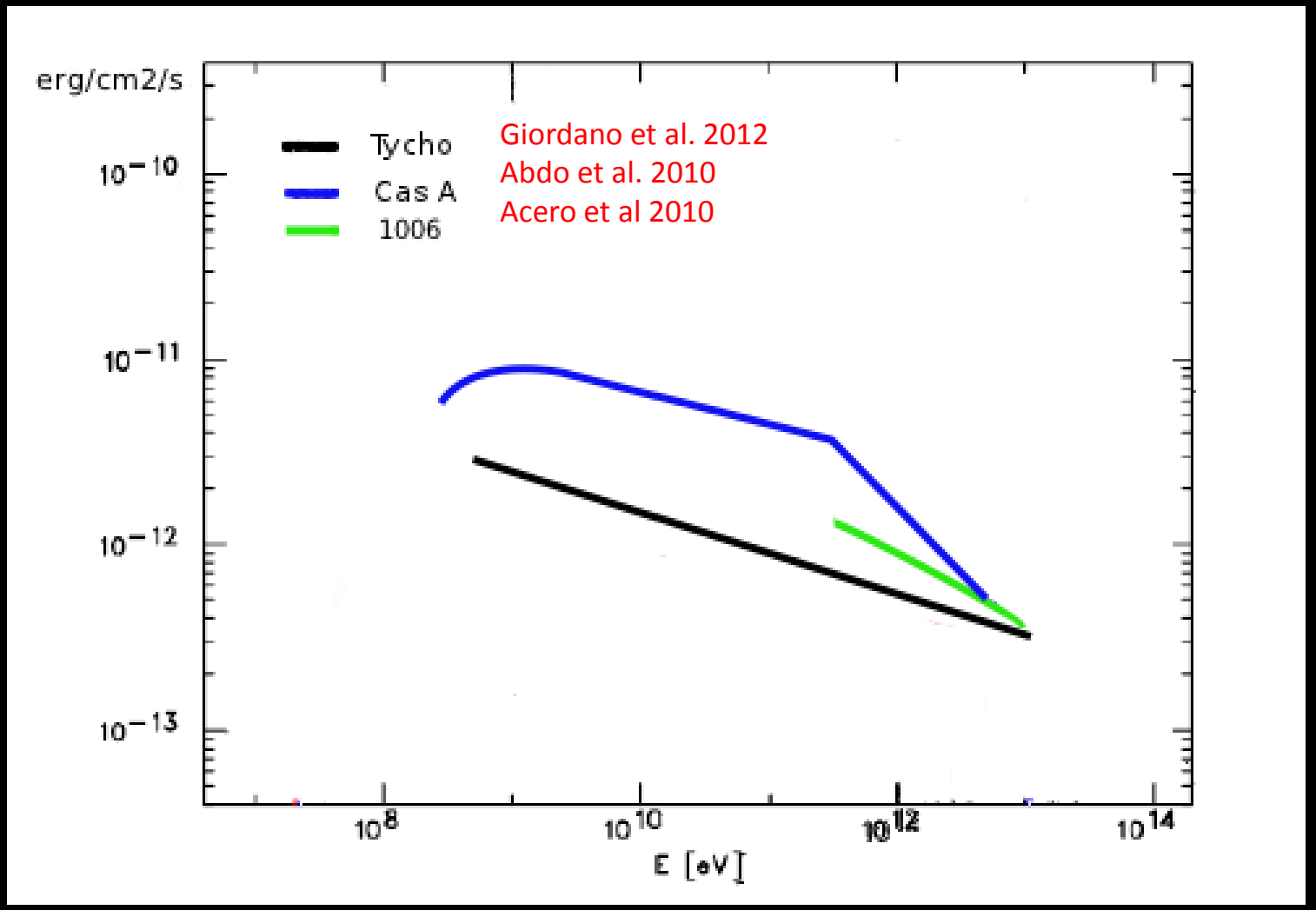
W28
Giuliani et al., 2011

young SNRs: efficient accelerators





Young SNRs: steep spectra ! (p = 2.3)
→ a problem for NLDSA



Young SNRs: steep spectra ! (p = 2.3)
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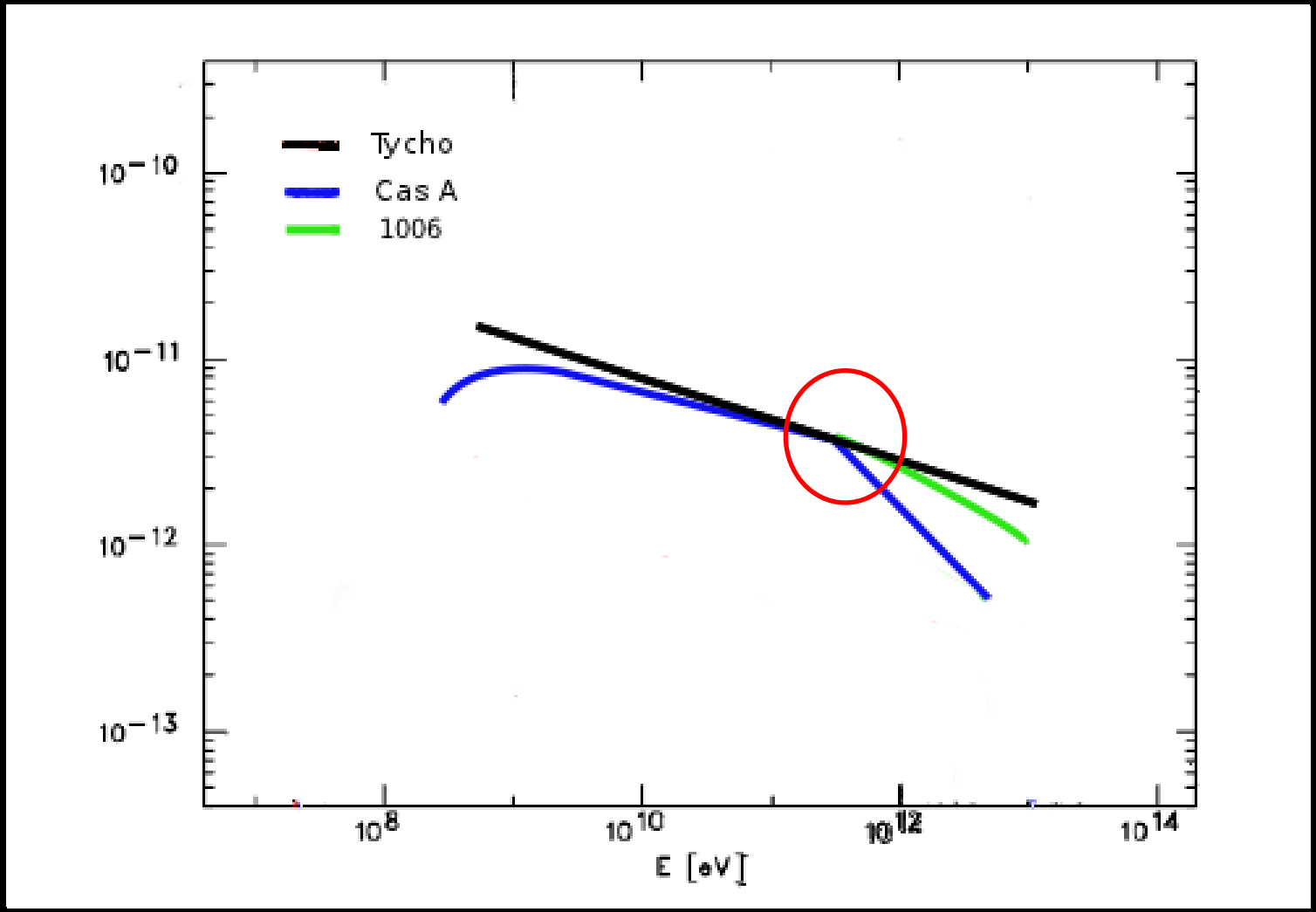


young SNRs: the steepening problem

The two young SNRs detected at GeV energies have an index steeper than 2:

$$\alpha \sim 2.3$$

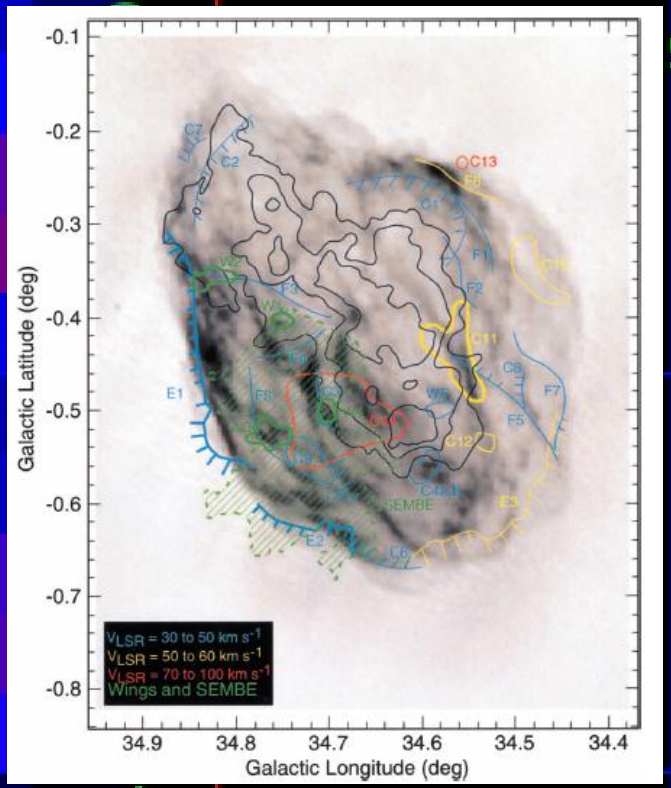
It implies a shock compression ratio "r" significantly lower than the NLDSA values (r > 4).

Several ways out are being proposed (e.g., neutrals leakage from downstream to upstream and lower "r" ,Blasi et al., 2012; Ohira et al., 2012)

SNR W44

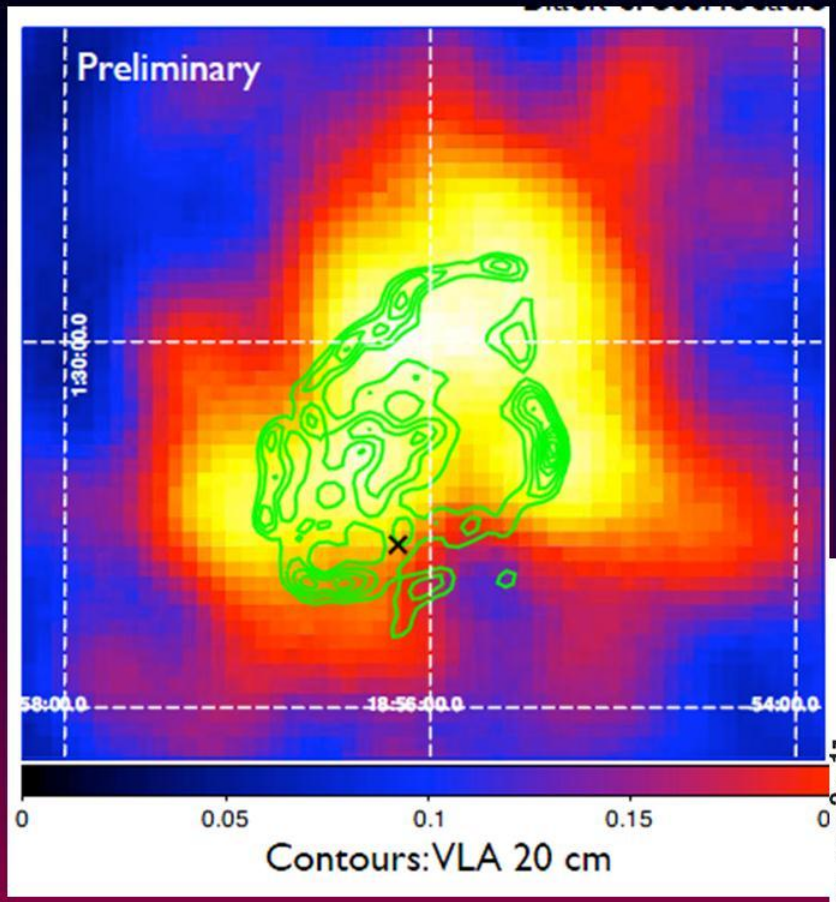
AGILE

radio

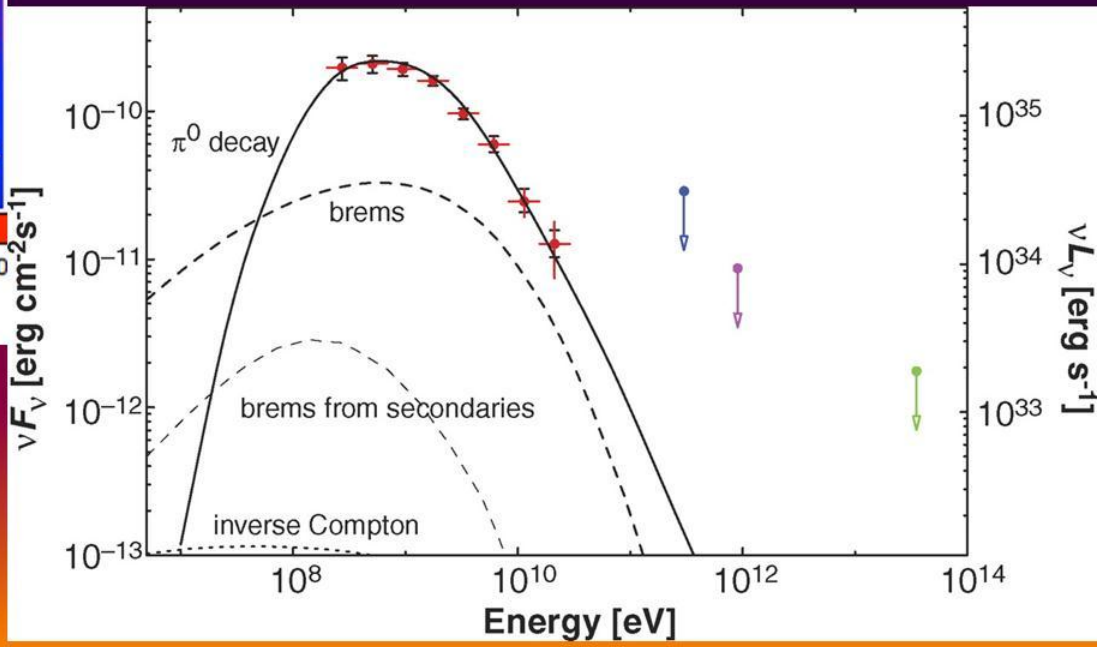


W44_AGILE_+_VLA_con

The SNR W44: Fermi-LAT

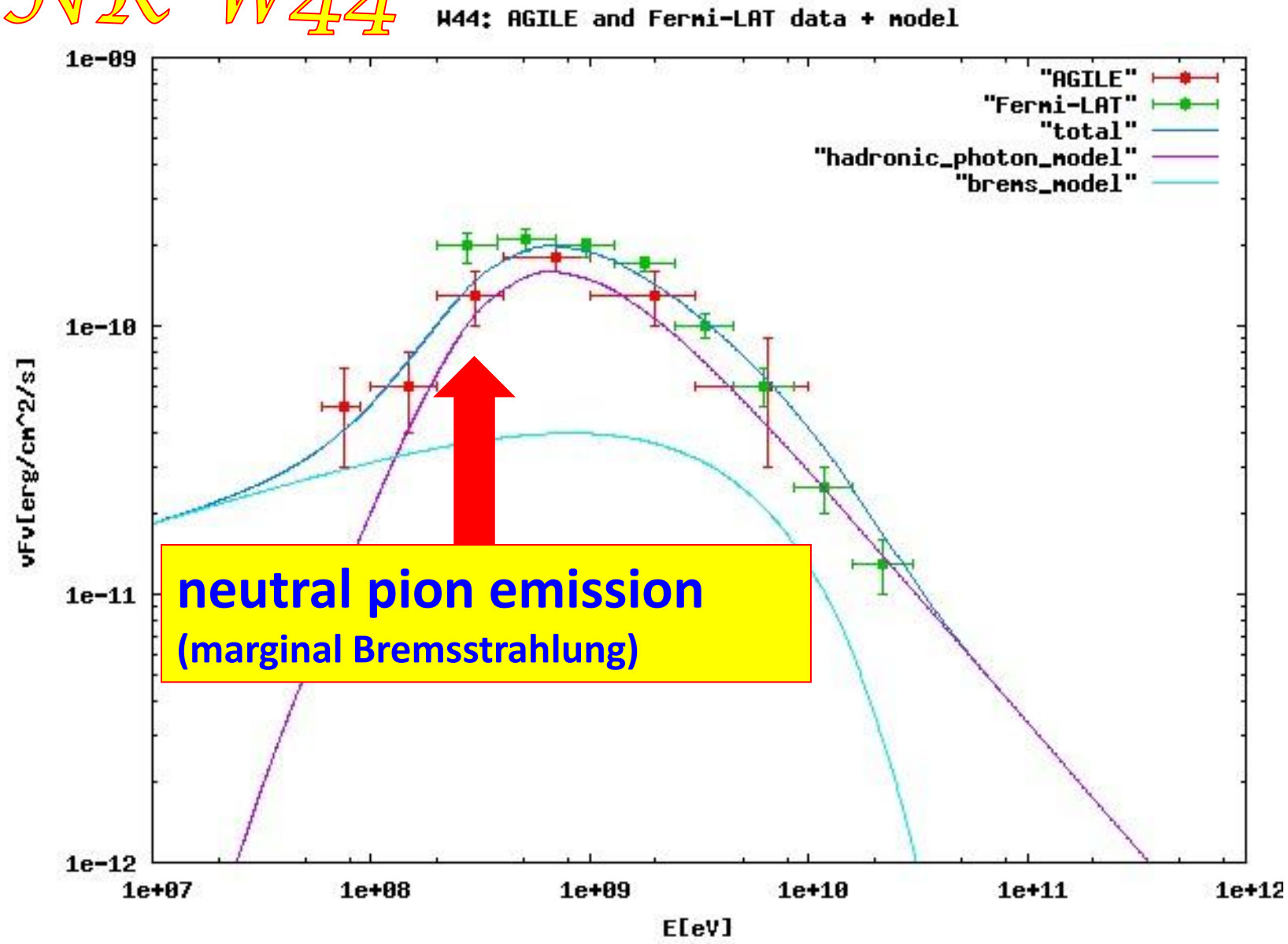


Abdo et al, 2010

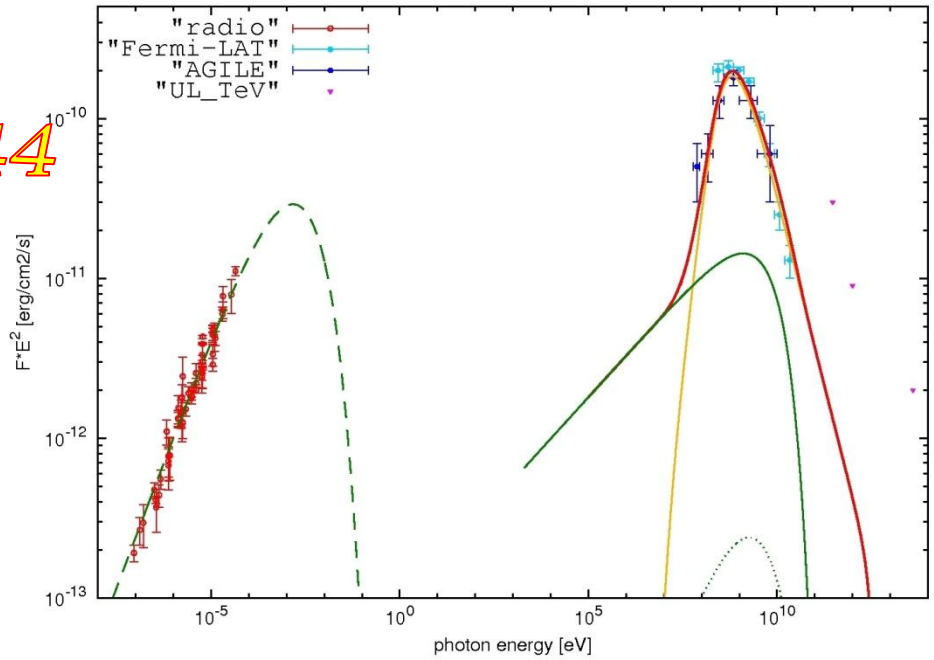


SNR W44

(Giuliani, Cardillo et al. 2011)

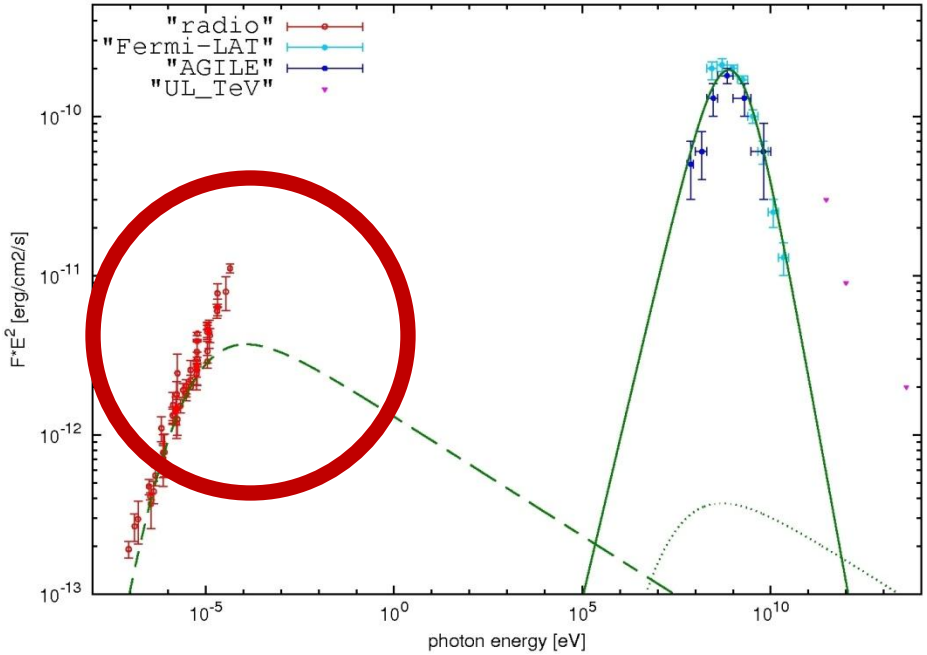


SNR W44



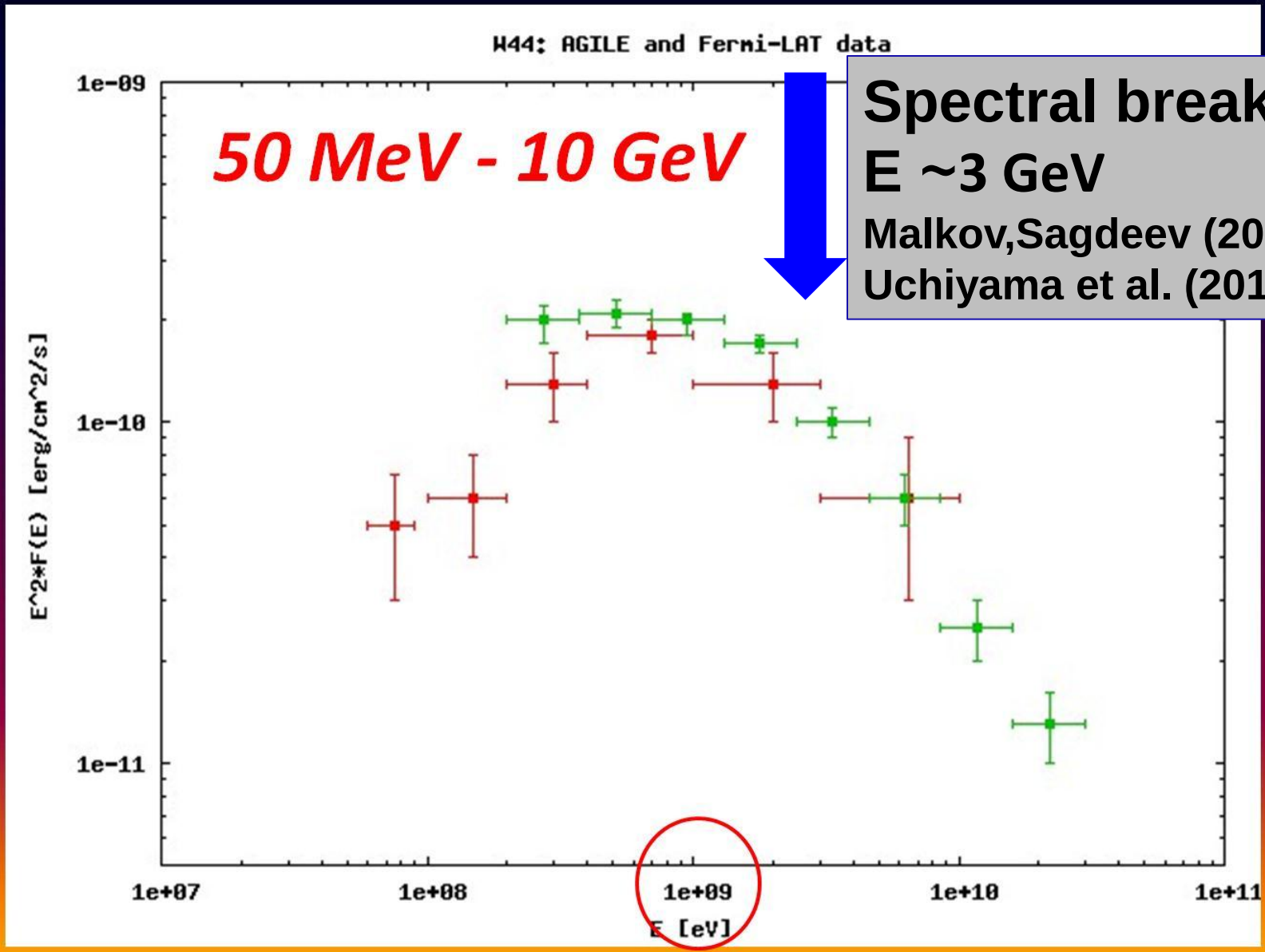
Giuliani et al, 2011

hadronic model, B = 20 μG, n = 100 cm^{-3}



"ad hoc" e- Brems. model, B = 20 μG, n = 300 cm^{-3}

SNR W44

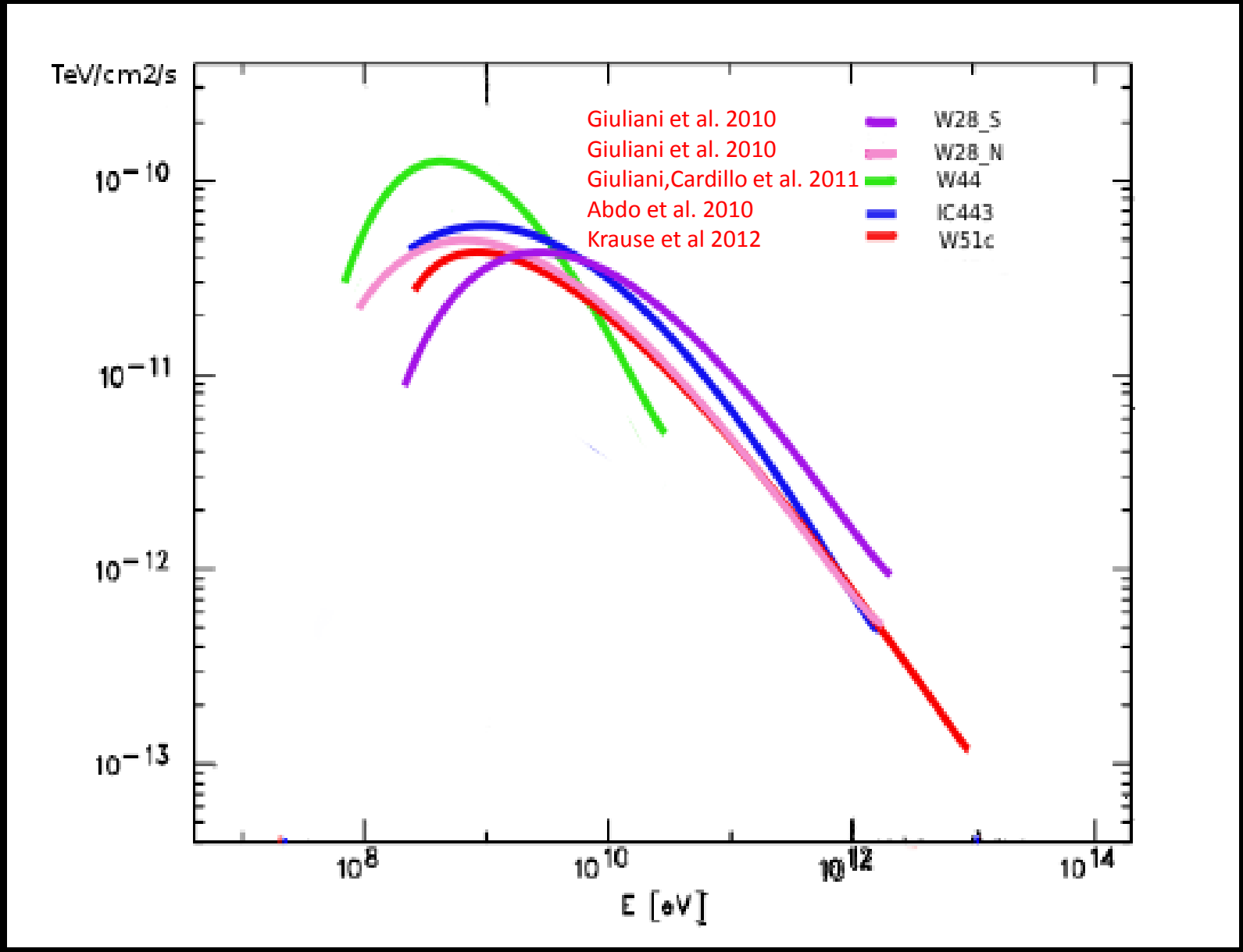


Spectral break, E ~3 GeV

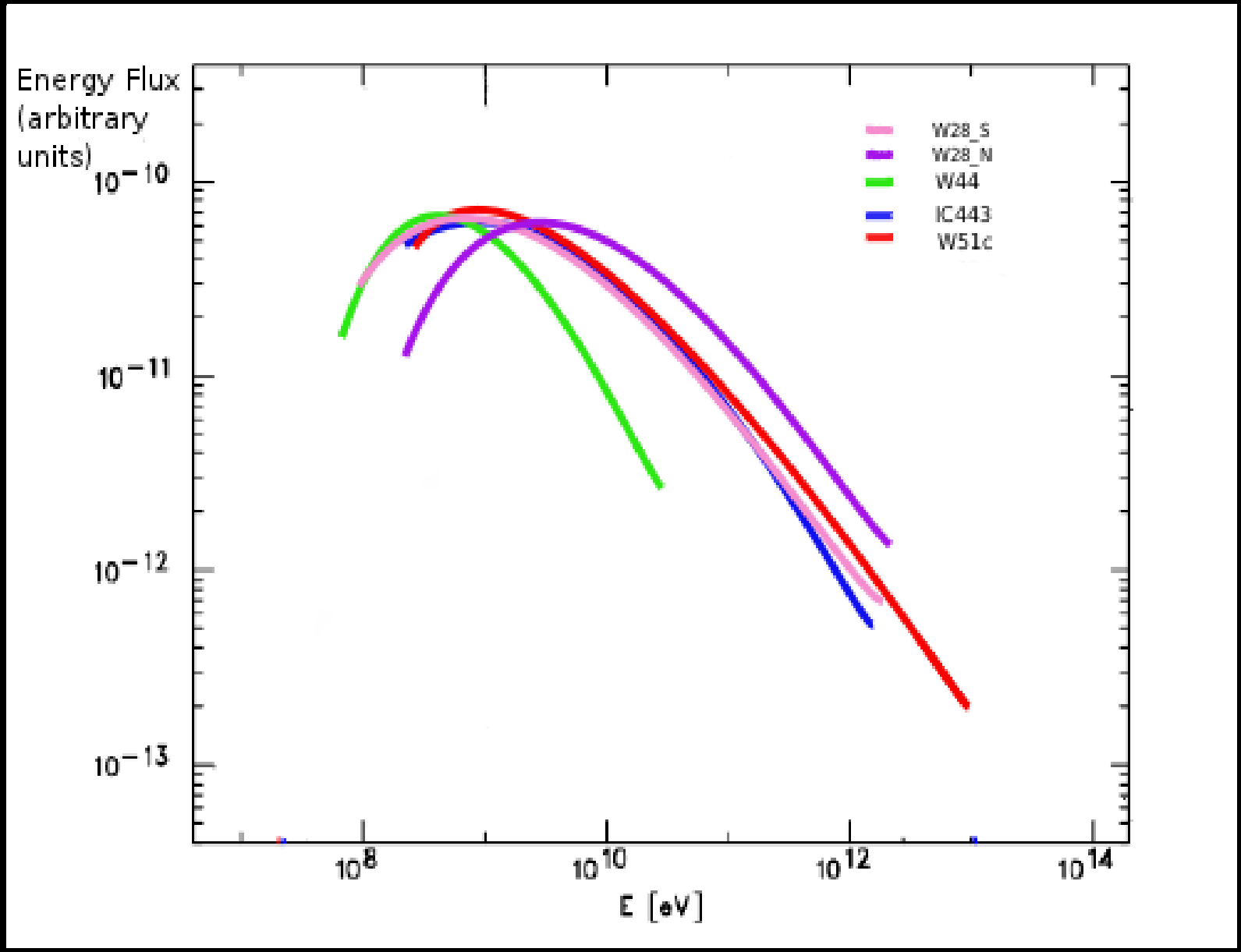
Malkov,Sagdeev (2010)

Uchiyama et al. (2010)

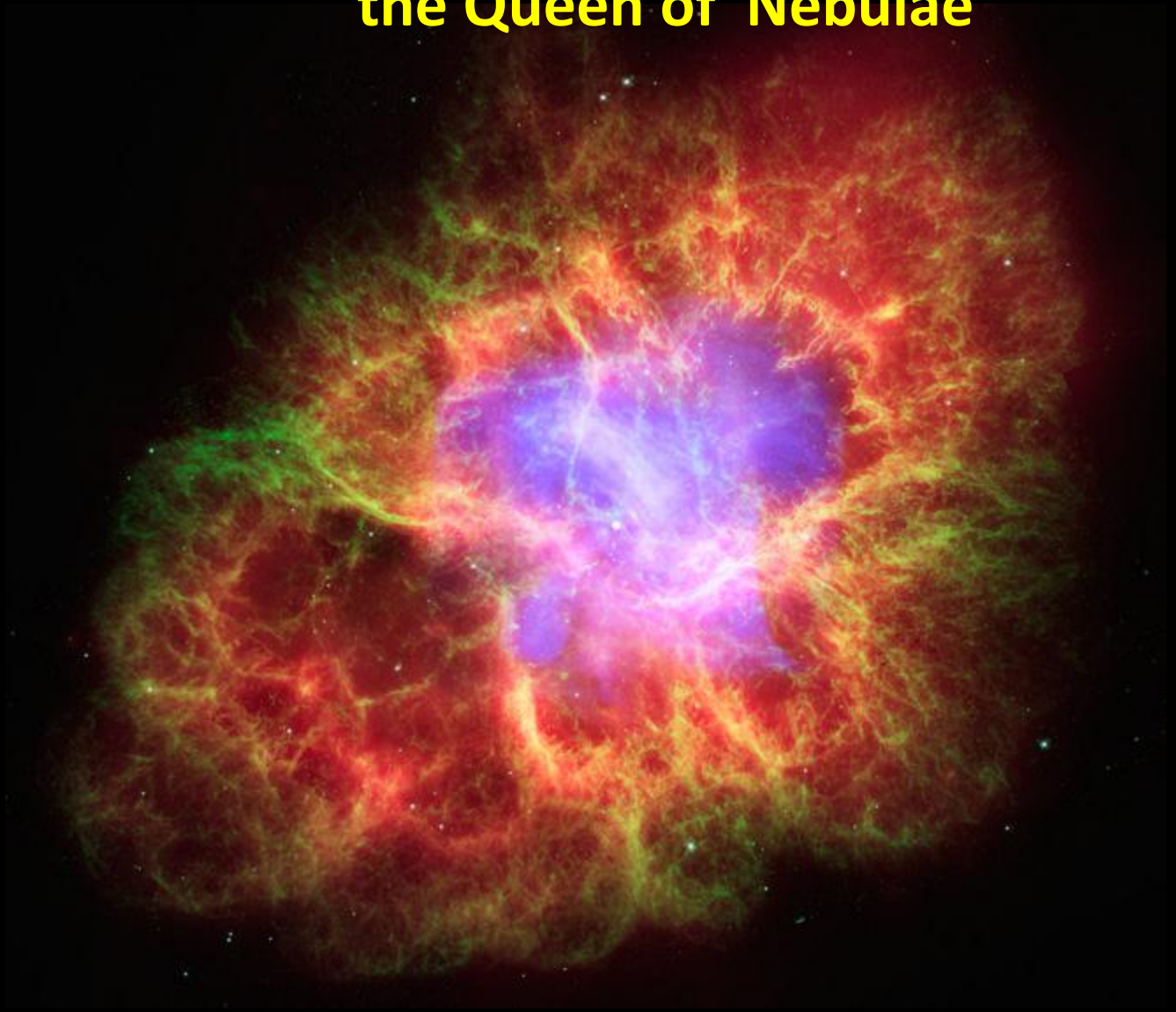
middle-aged SNRs: even more steepening !



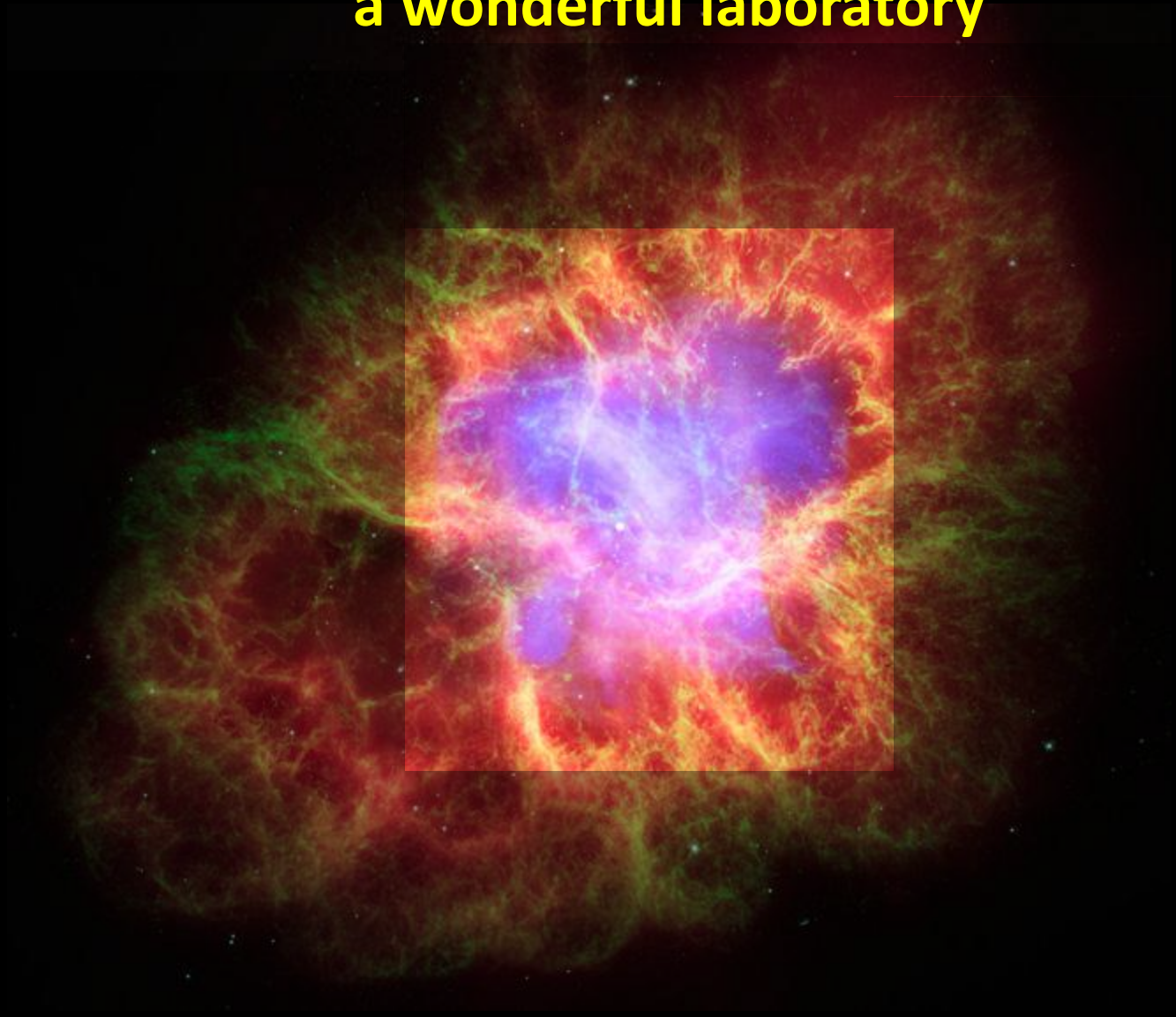
middle-aged SNRs: even more steepening !



The Crab Nebula (M1) : the Queen of Nebulae



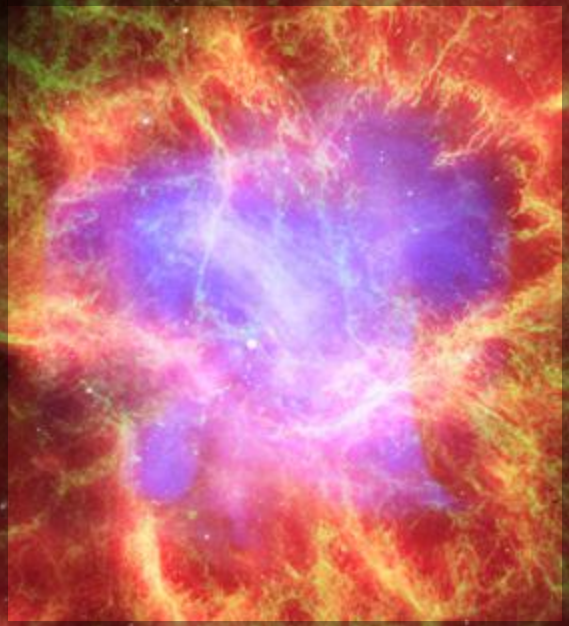
The Crab Nebula (M1) : a wonderful laboratory



The Crab Nebula (M1) : a wonderful laboratory

inner Nebula opt/X-ray (wisp) fluctuations (weeks/months)

hints of large-scale kinks in SE jet variations (5-10 years)



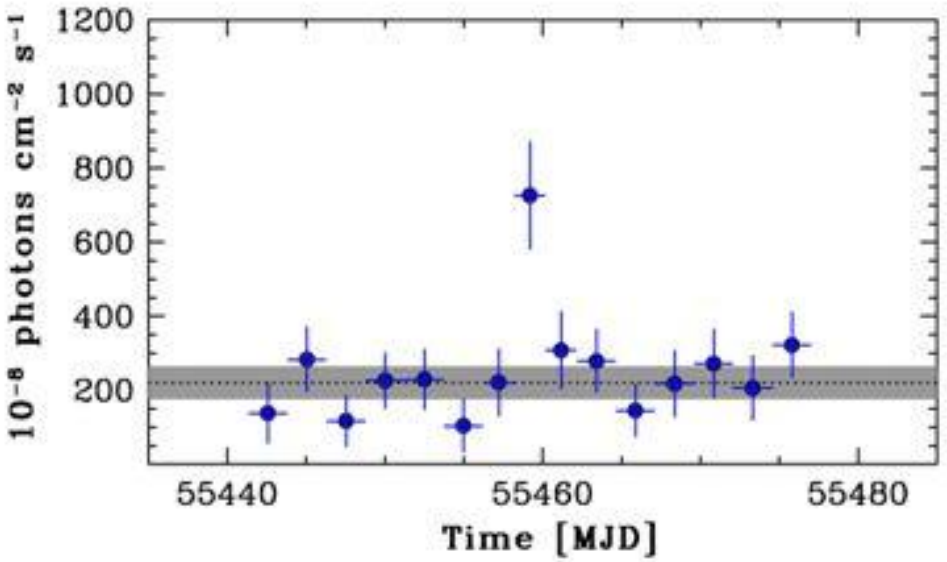
surprising gamma-ray flares (hrs/days/weeks)

secular X-ray variations (years)

the PSR appears to be “stable”

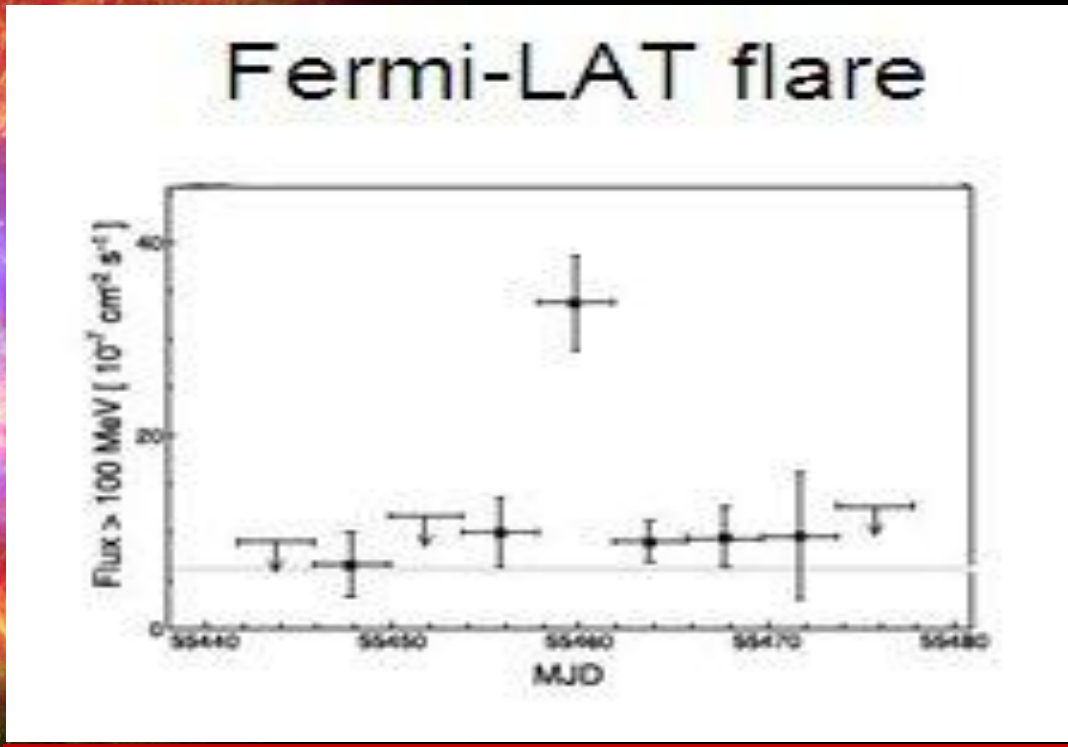
The Crab Nebula: a standard candle…?

FIRST PUBLIC ANNOUNCEMENT Sept. 22, 2010: AGILE issues the Astronomer's Telegram n. 2855



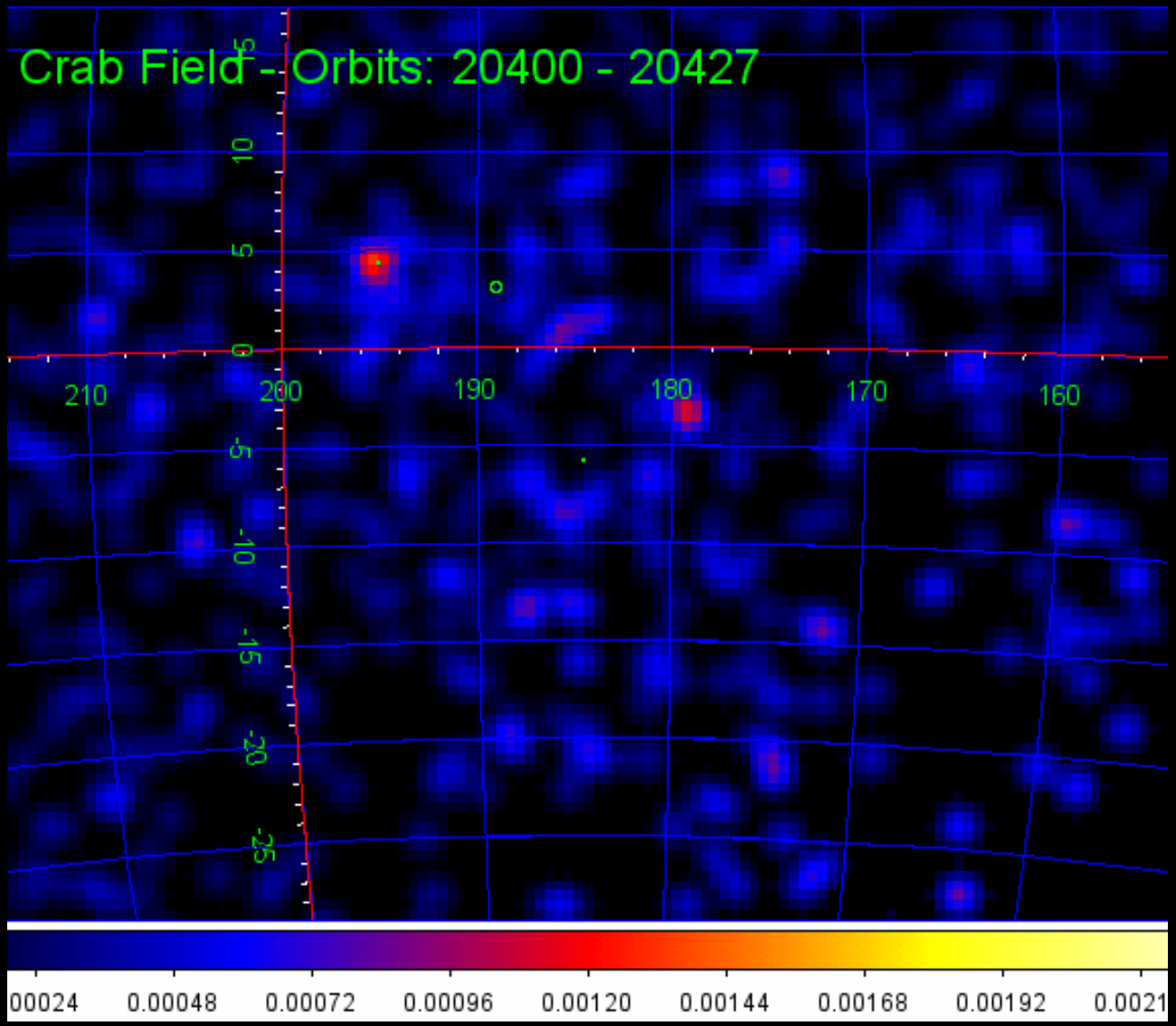
***Science Express* (6 January 2011)**

The Crab Nebula: a standard candle…?

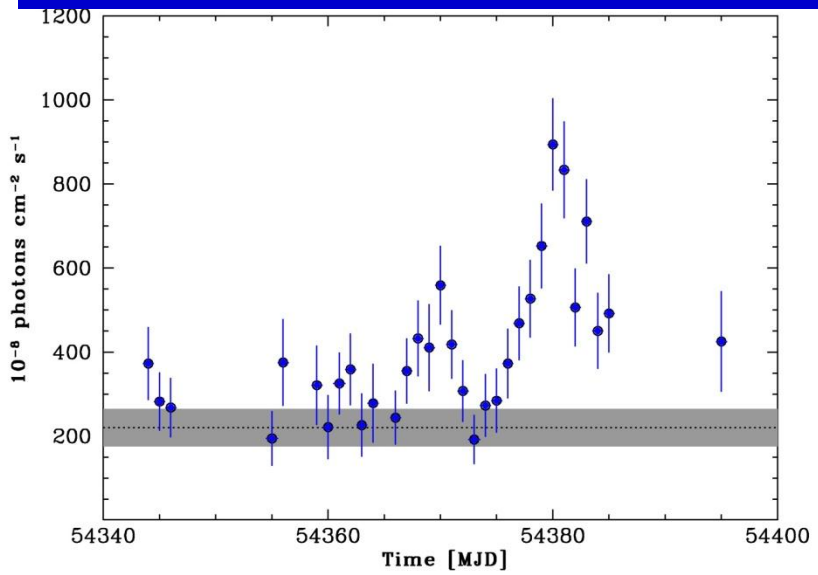


Science Express (6 January 2011)

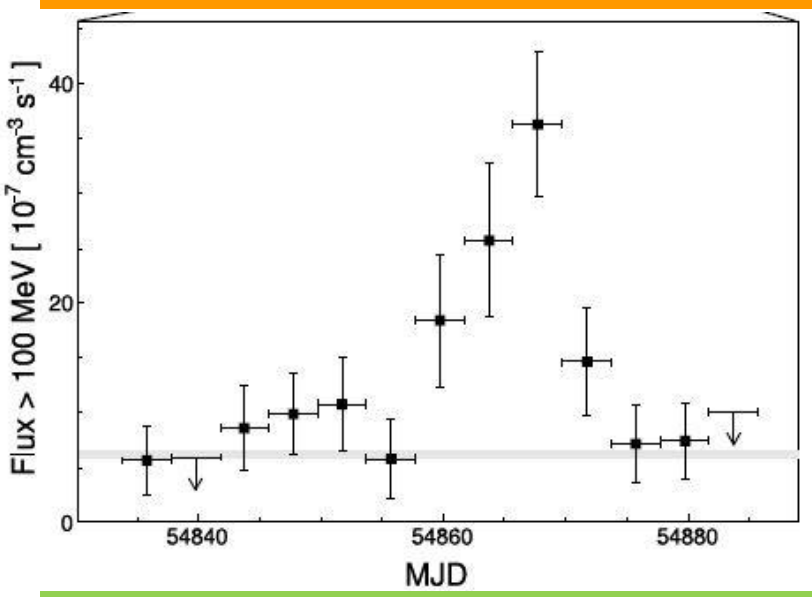
AGILE gamma-ray monitoring of the Crab (April 2011)



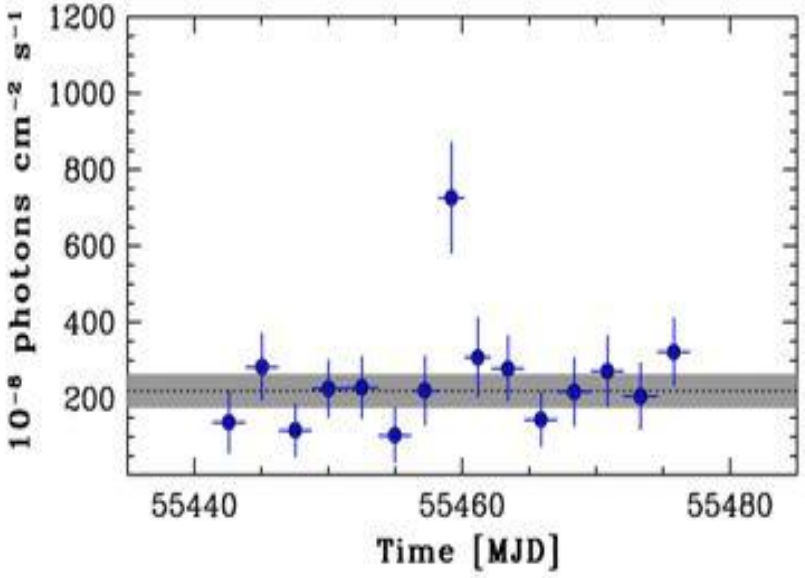
AGILE, 26 Nov. – 13 Oct. 2007



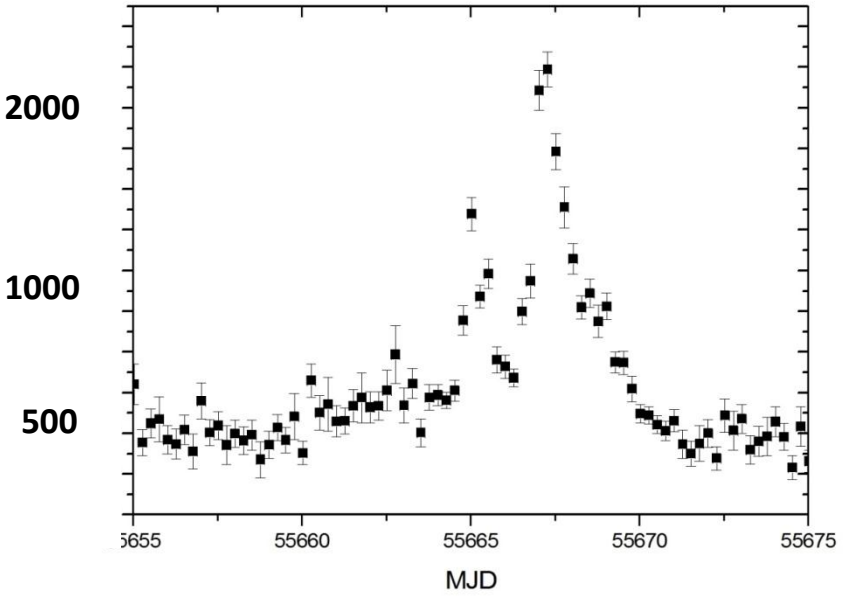
Fermi-LAT, 26 Jan. – 11 Feb. 2009



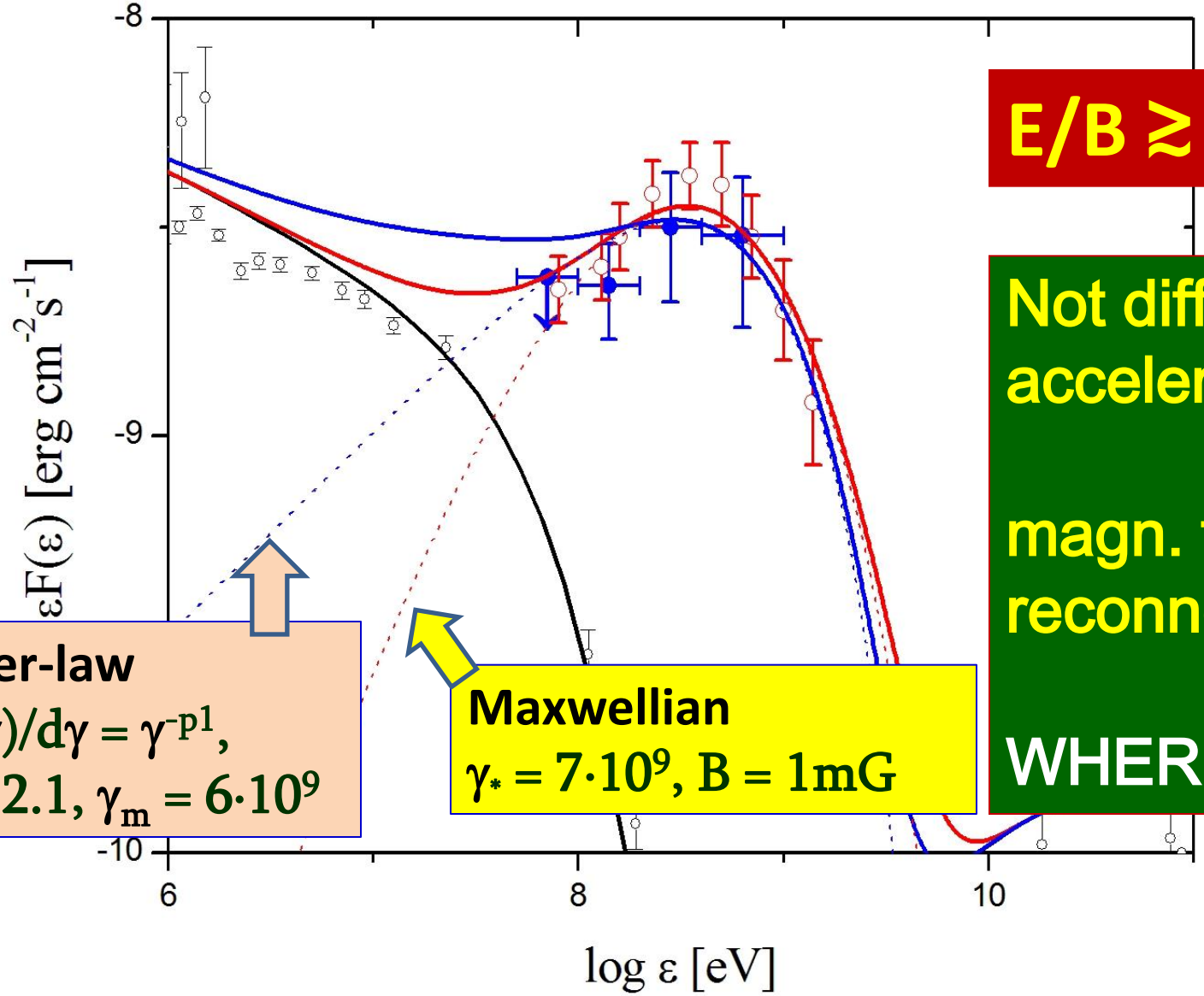
AGILE, 20-22 Sept. 2010



Fermi-AGILE, 12 – 20 Apr. 2011



modelling of the April 2012 super-flare



E/B ≳ 3 !

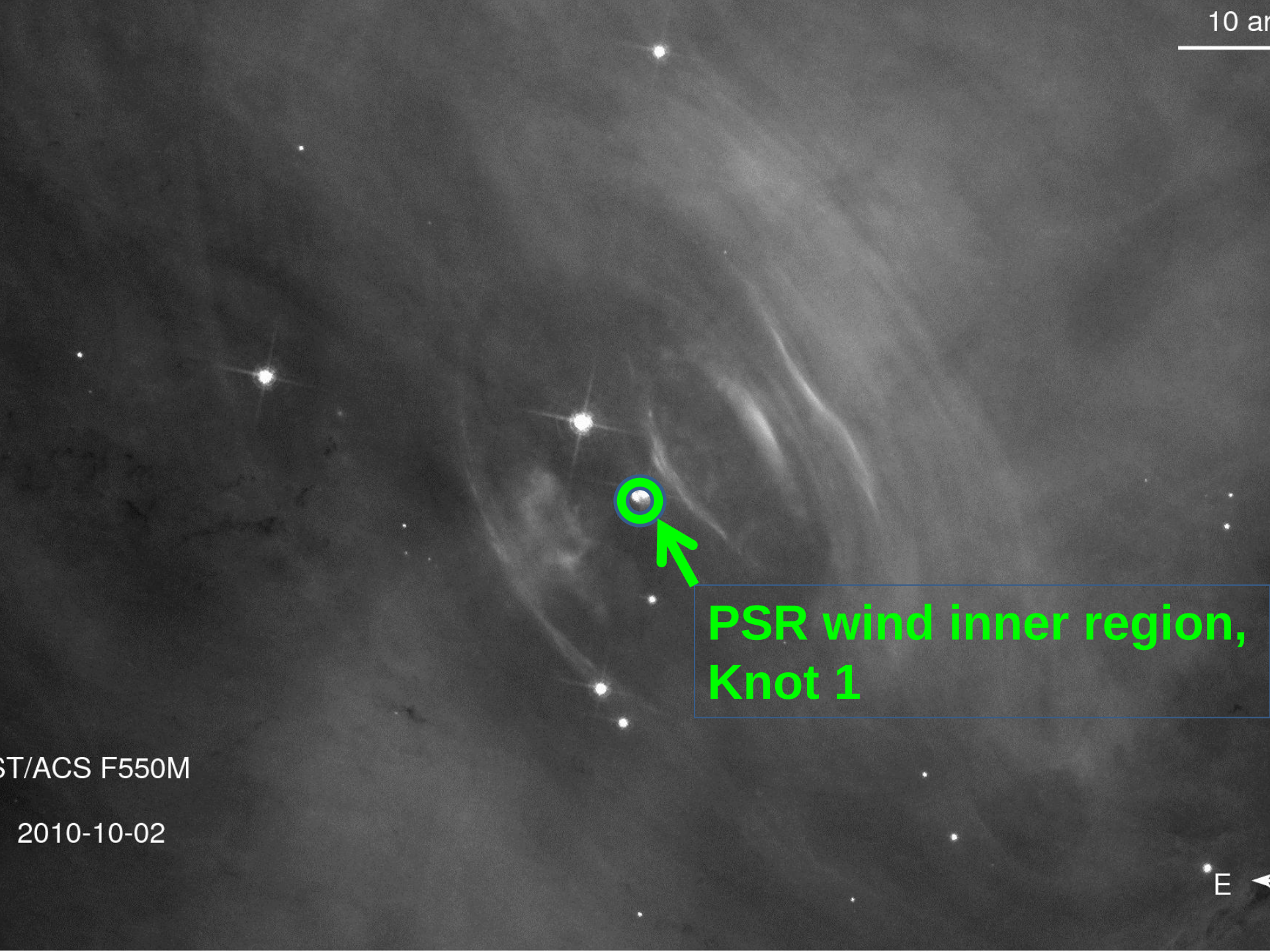
Not diffusive acceleration !

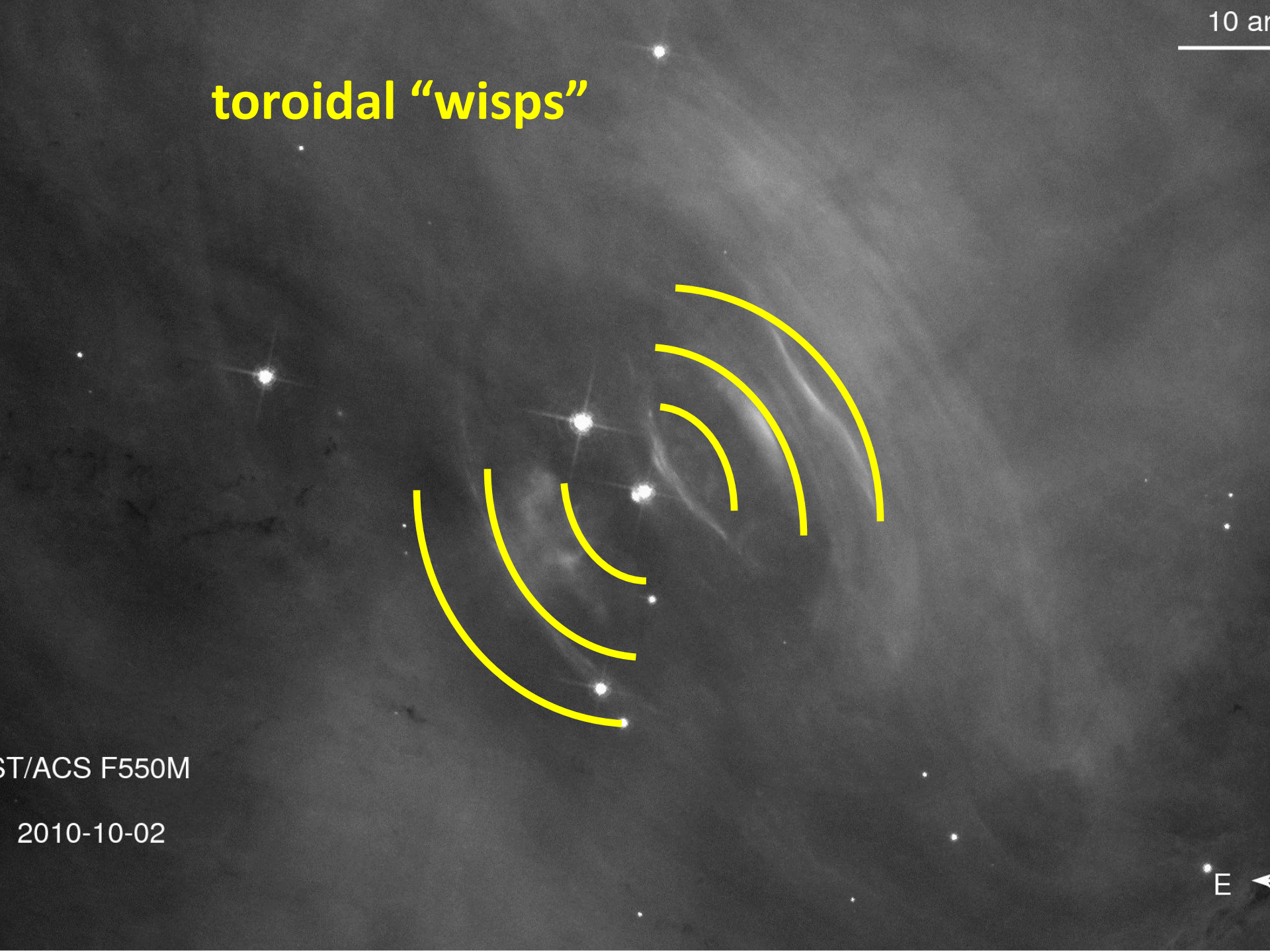
magn. field reconnection ?

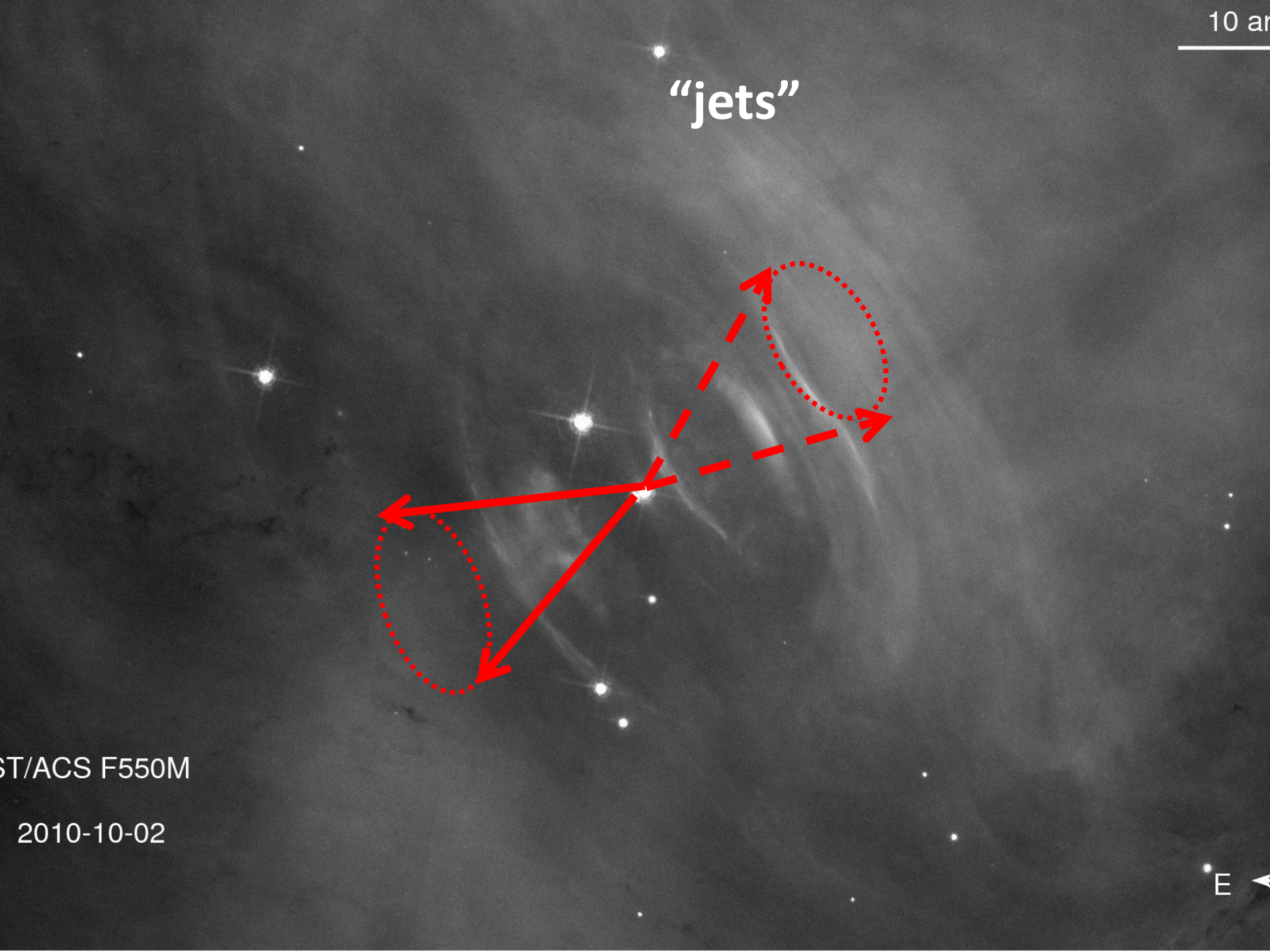
WHERE ?

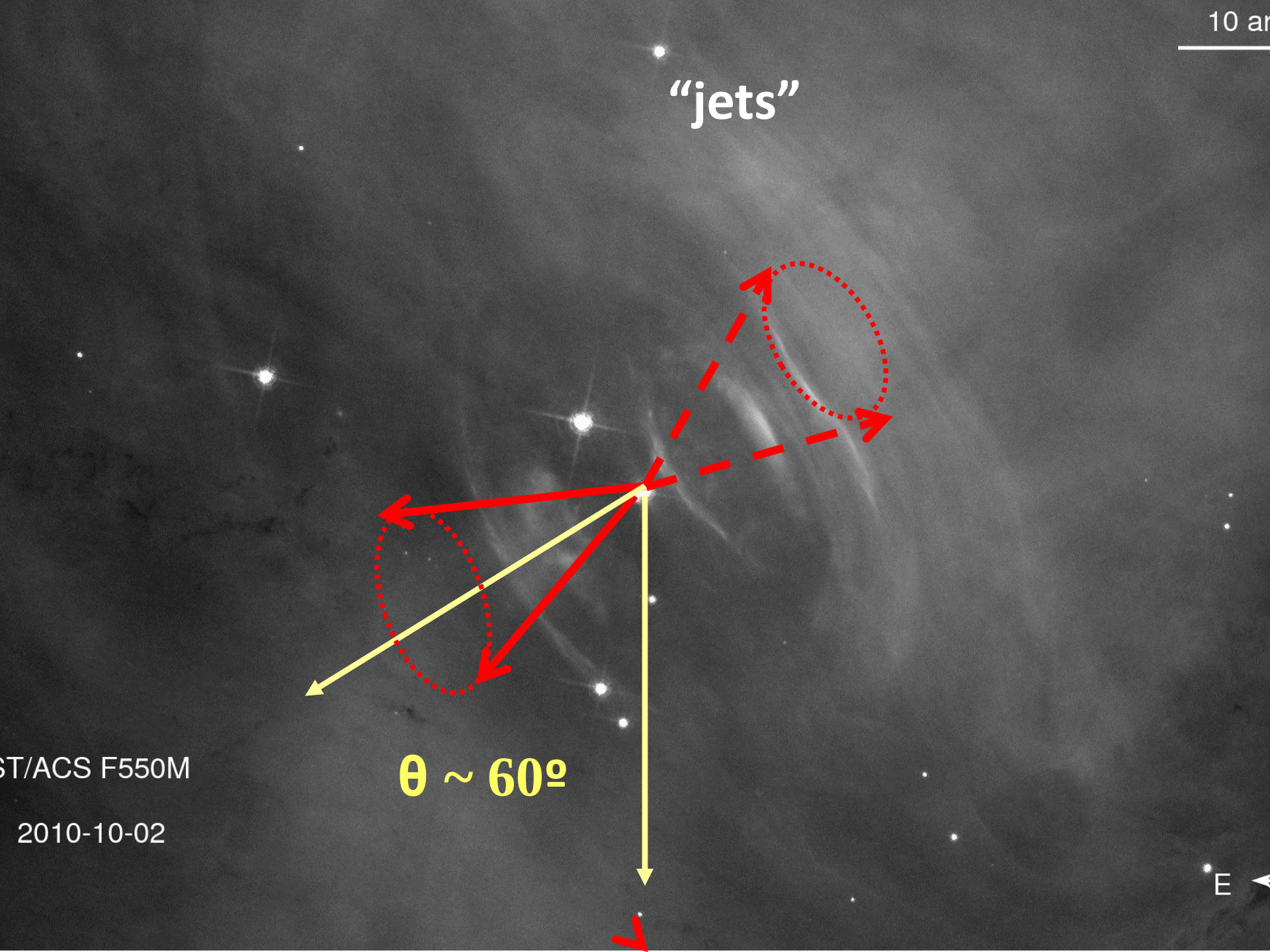
power-law
$dN(\gamma)/d\gamma = \gamma^{-p1}$,
$p1 = 2.1$, $\gamma_m = 6 \cdot 10^9$

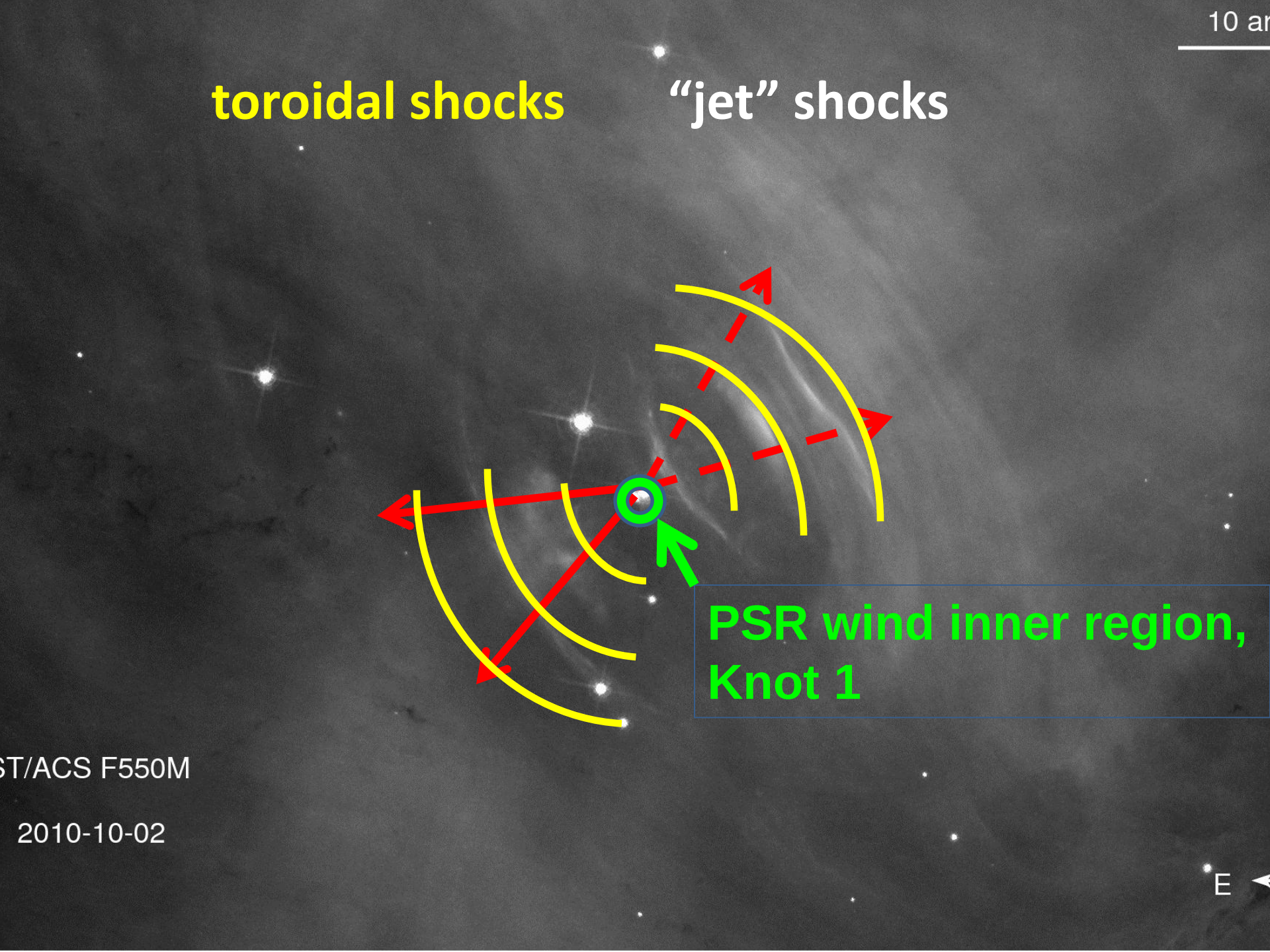
Maxwellian
$\gamma_* = 7 \cdot 10^9$, B = 1mG


10 ar
PSR wind inner region,
Knot 1
ST/ACS F550M
2010-10-02
E

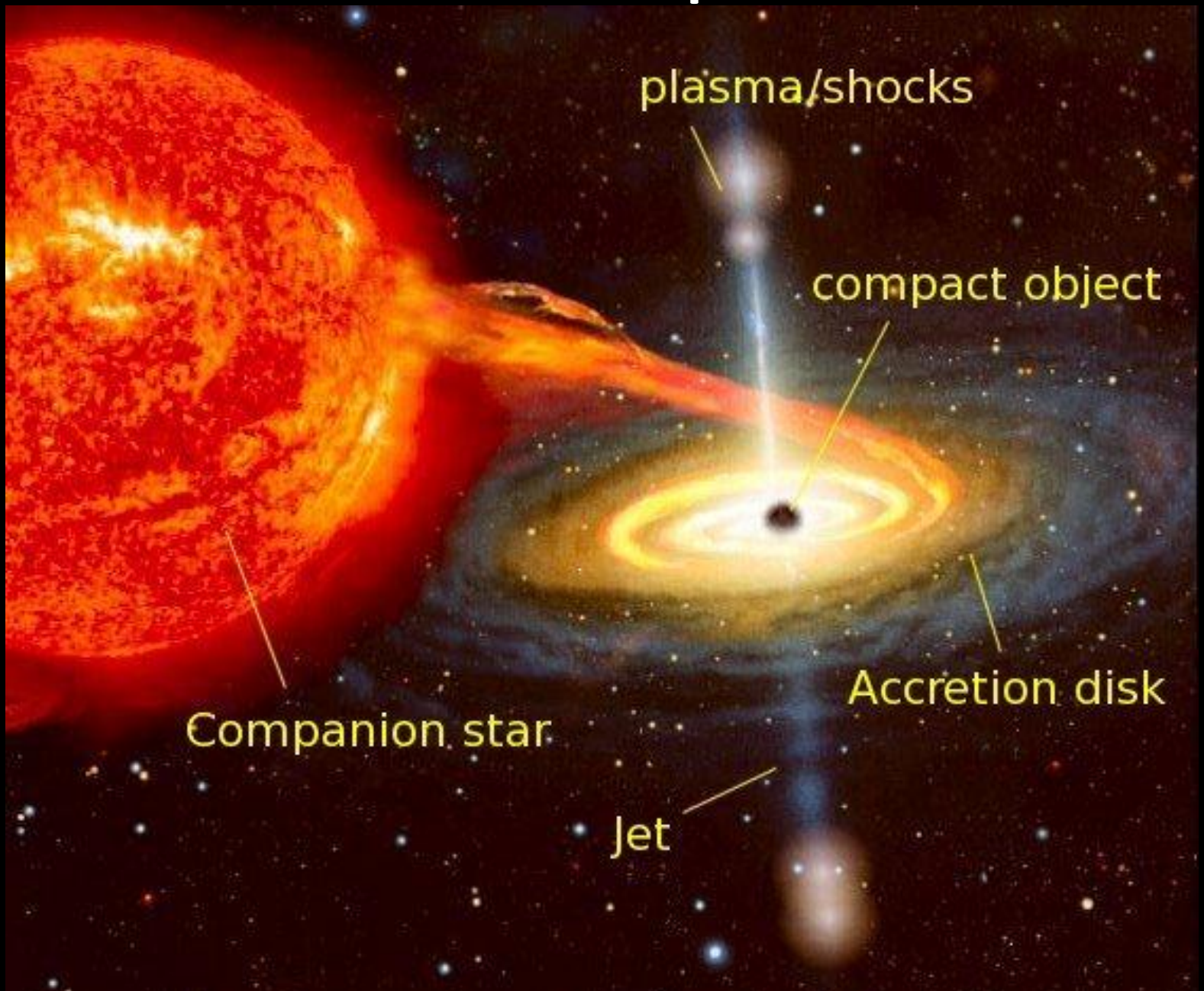

toroidal “wisps”
10 ar
ST/ACS F550M
2010-10-02
E


10 ar
“jets”
ST/ACS F550M
2010-10-02
E

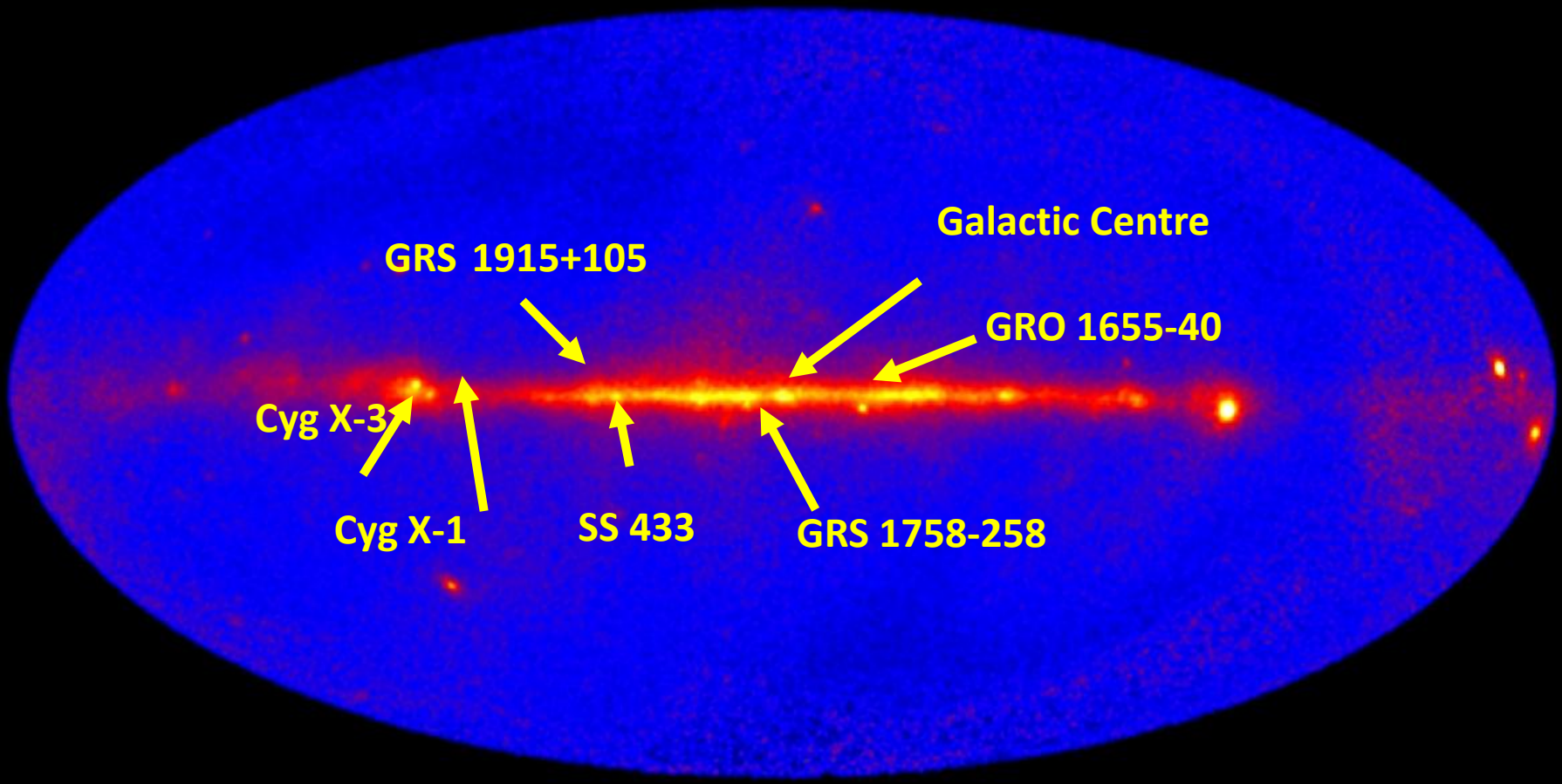

10 ar
"jets"
θ ~ 60º
ST/ACS F550M
2010-10-02
E


10 ar
toroidal shocks
“jet” shocks
PSR wind inner region,
Knot 1
ST/ACS F550M
2010-10-02
E

Galactic microquasars

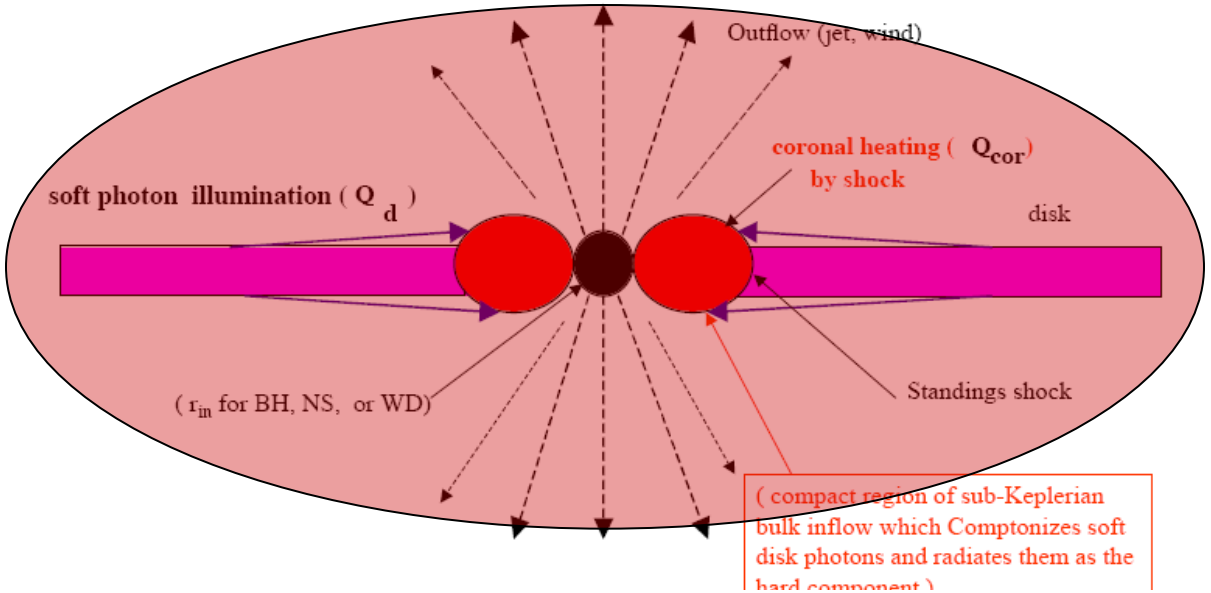


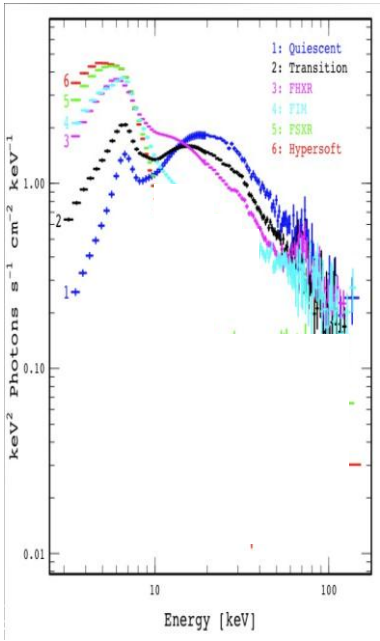
Gamma-ray exposure of Microquasars (E > 100 MeV)

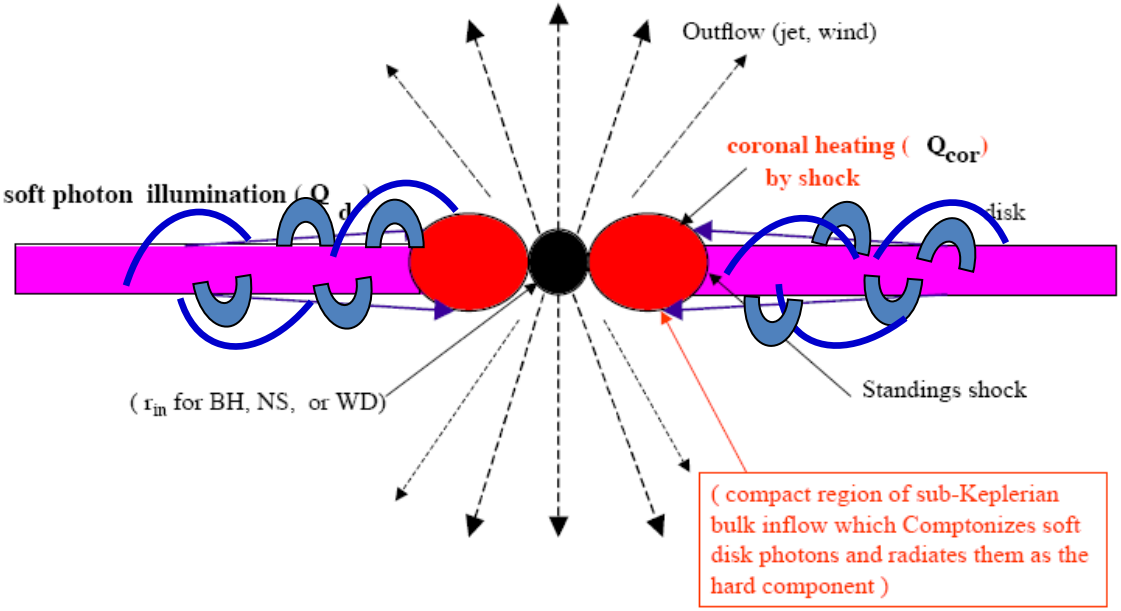


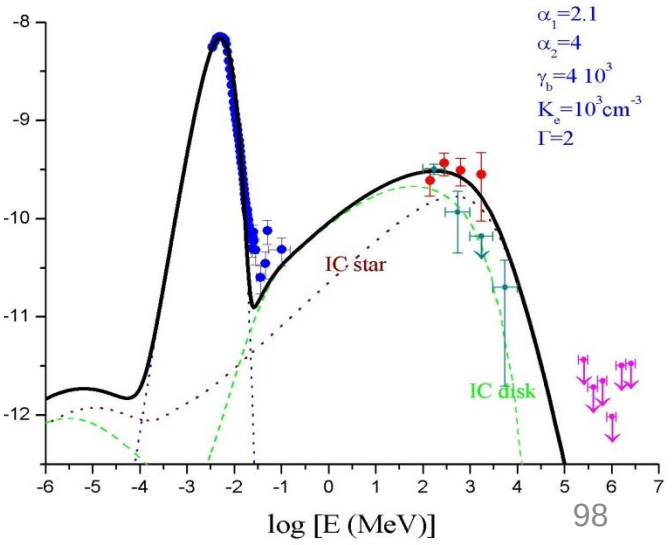
Cyg X-3: plasma diagnostics (and acceleration) around a BH or peculiar NS

Compton-thick cloud, $\tau = \sigma_T\, n\, R \sim 1\text{-}10$ $\quad n \sim (10^{15}\ \mathrm{cm}^{-3})\ R_8^{-1}$



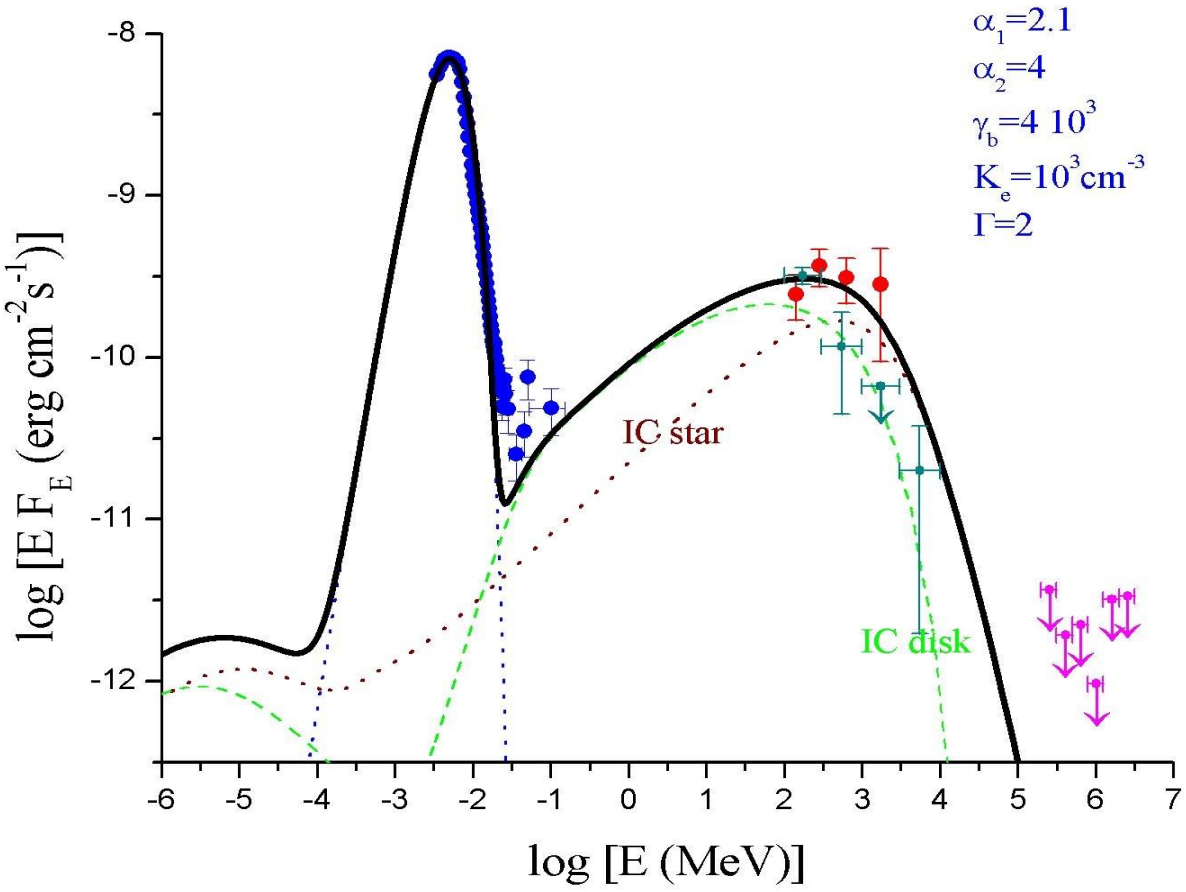






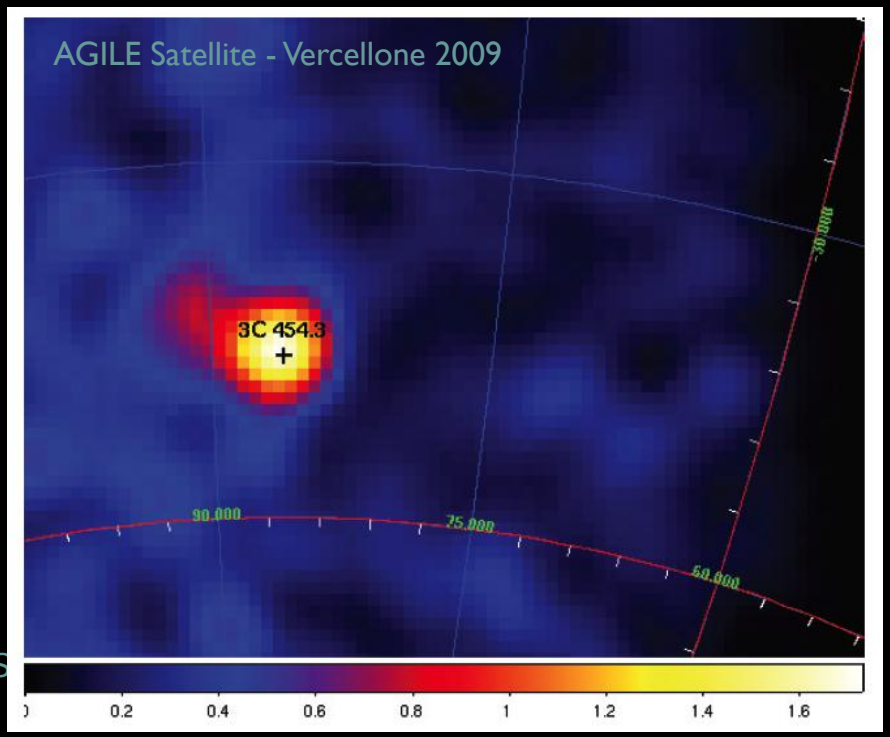
clear indication from Cyg X-3

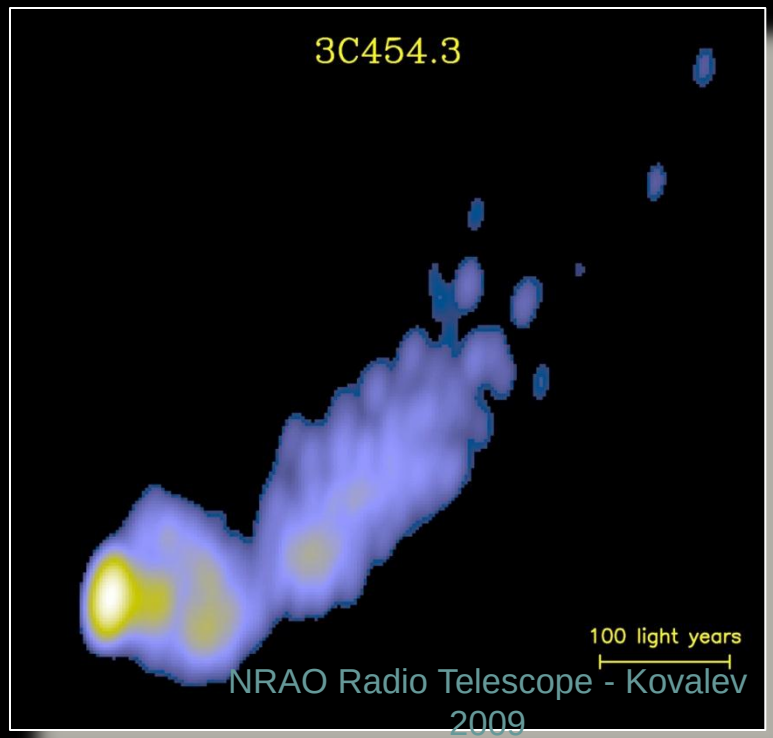
- particle acceleration (and gamma-rays detected above 100 MeV) preceding (1-2 days) jet launching



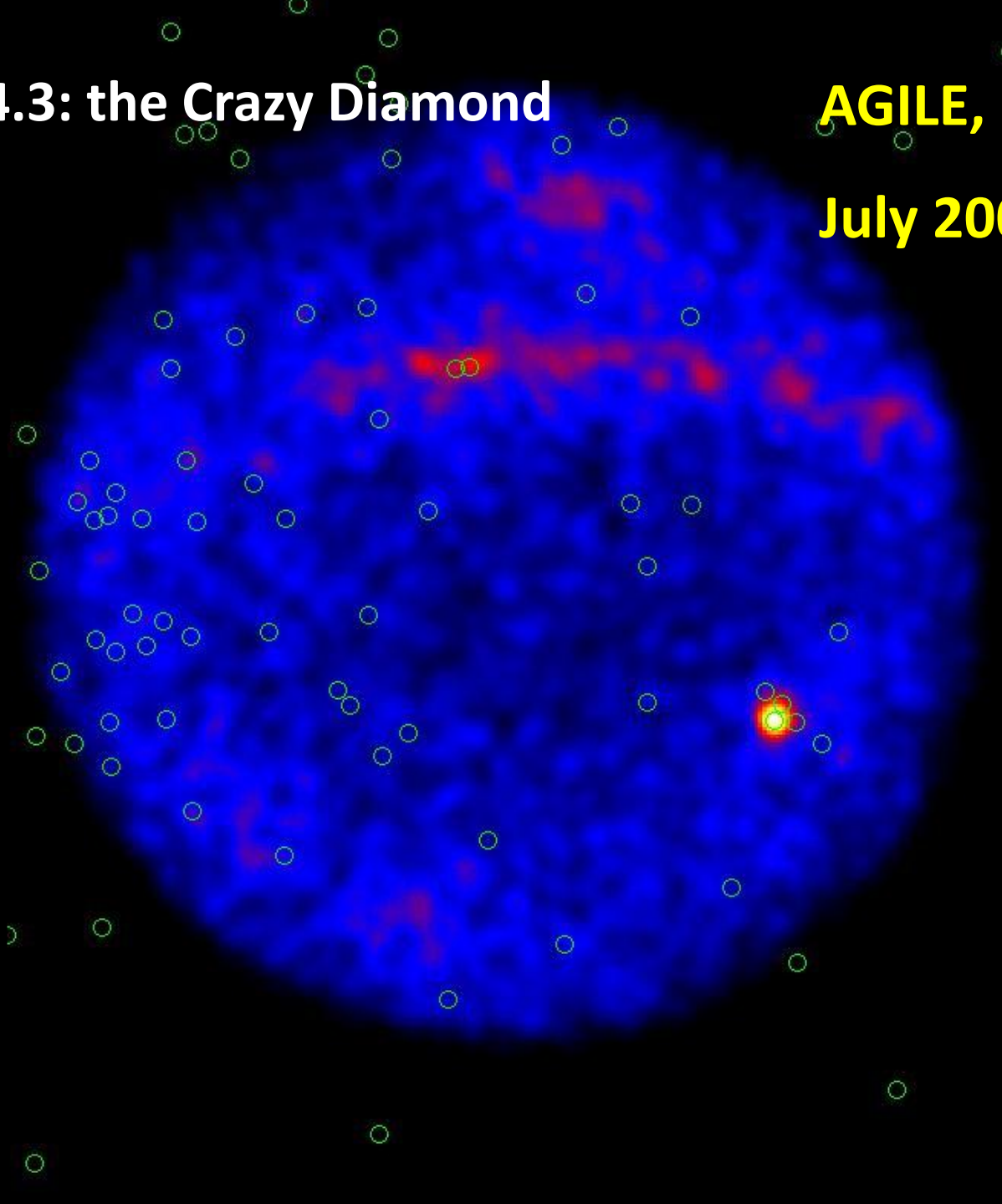
Piano, Vittorini, M.T., 2011

3C 454.3: the *Crazy Diamond*, 7 billion lightyears away…





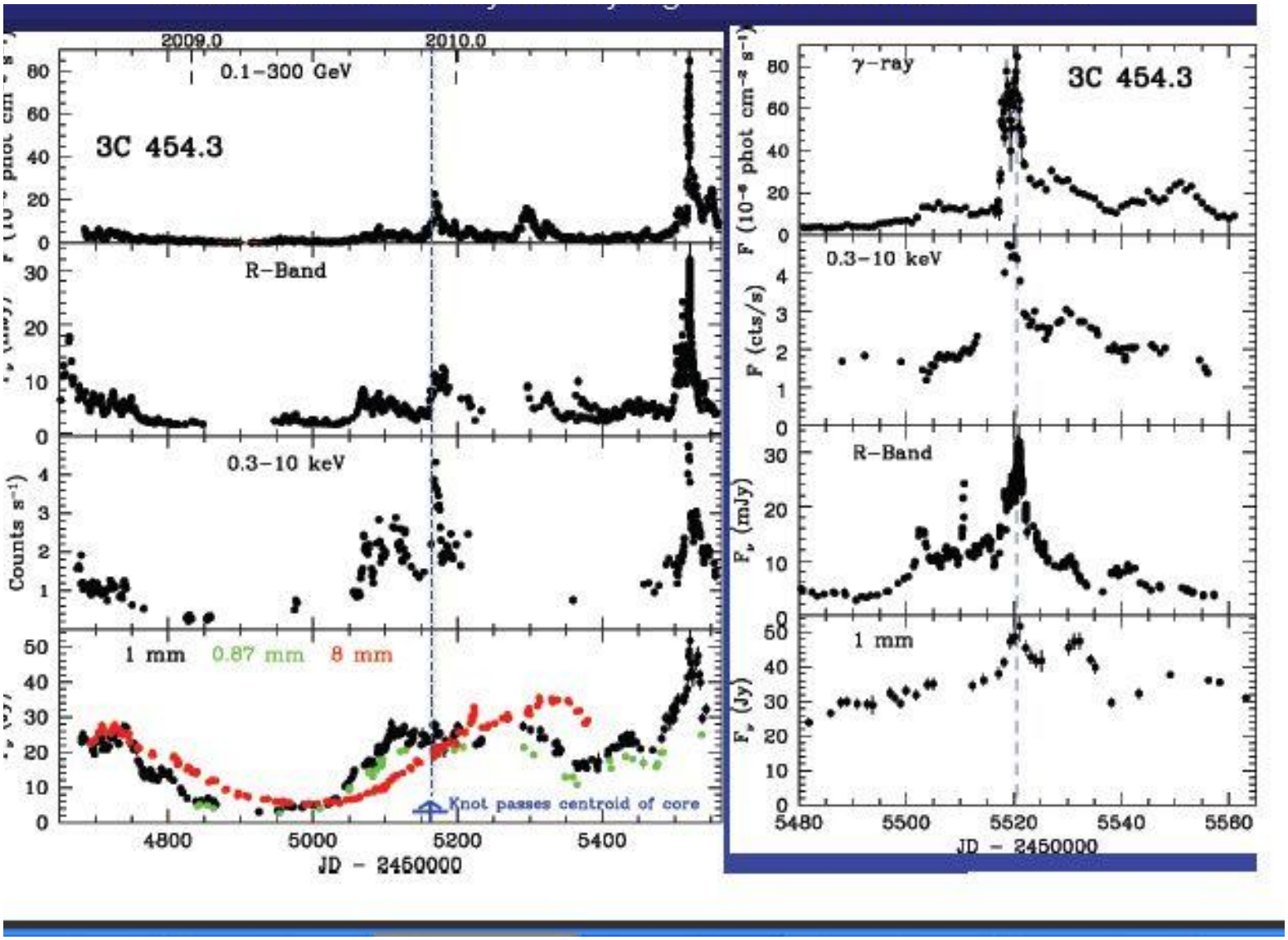
3C 454.3: the Crazy Diamond



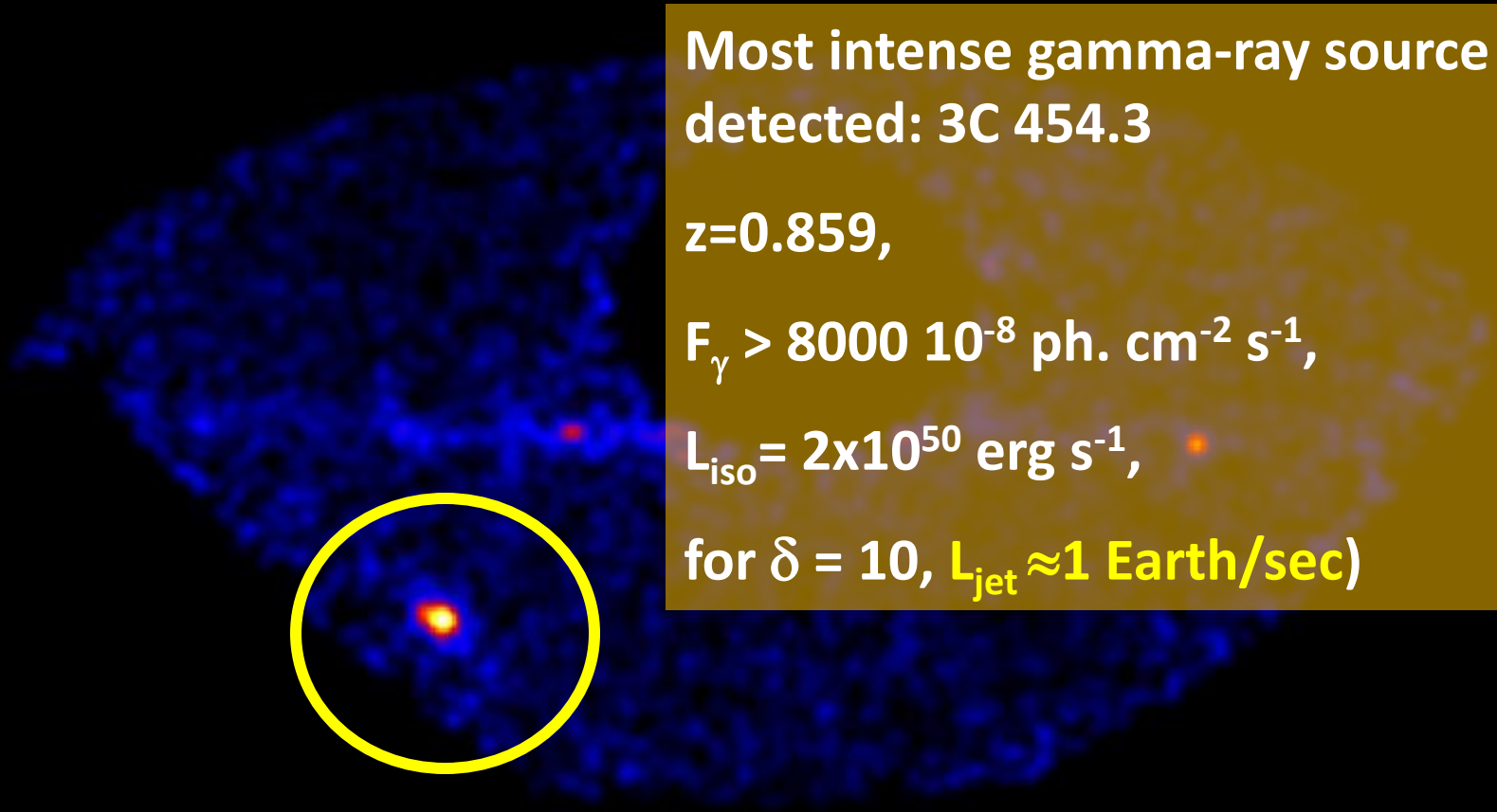
AGILE,

July 2007

(from A. Marsher, 2011)



3C 454.3 superflare (16-19 Nov. 2010)



Most intense gamma-ray source ever detected: 3C 454.3

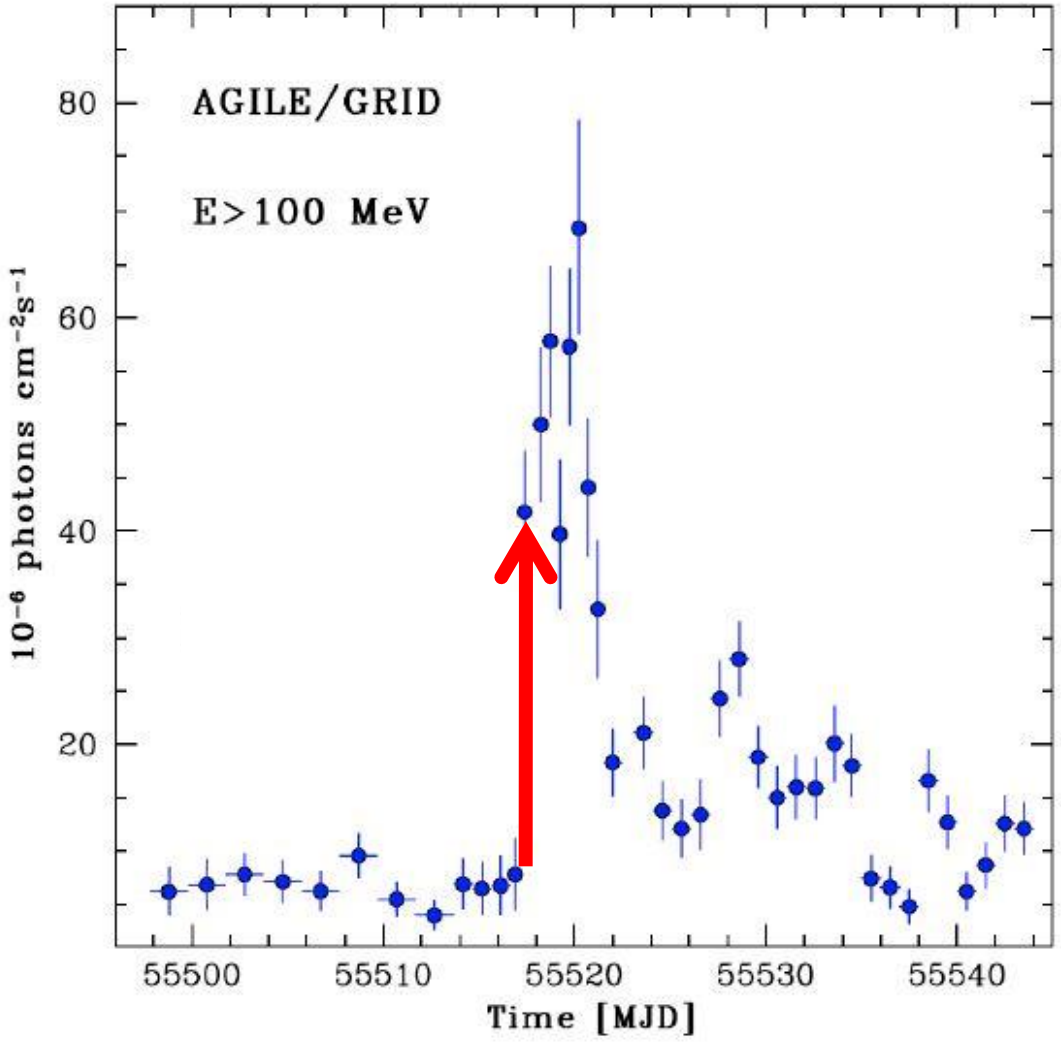
z=0.859,

$F_\gamma > 8000\ 10^{-8}$ ph. cm^{-2} s^{-1},

$L_{iso} = 2 \times 10^{50}$ erg s^{-1},

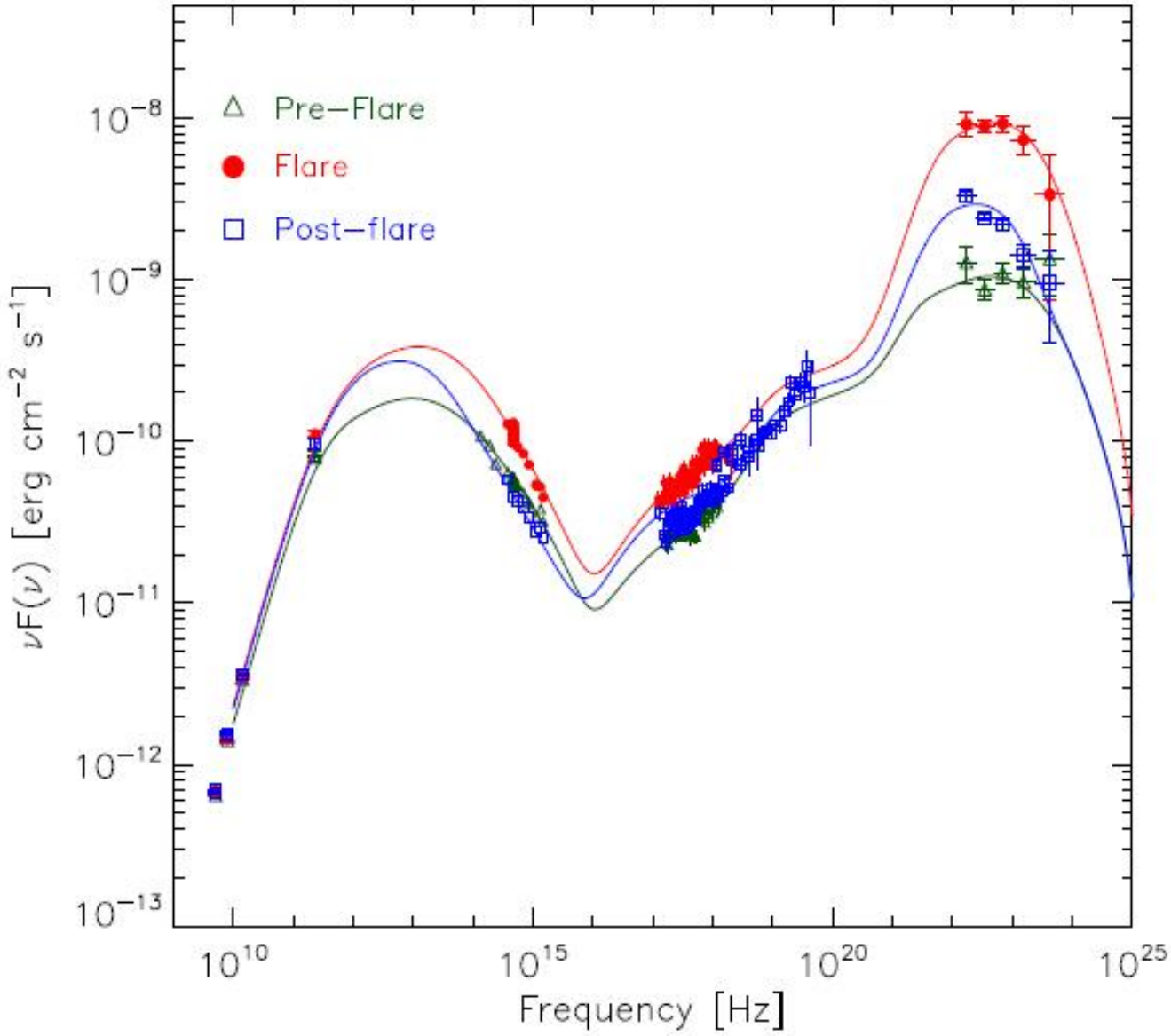
for $\delta = 10$, $L_{jet} \approx 1$ Earth/sec)

the 3C 454.3 super-flare in Nov.-Dec. 2010



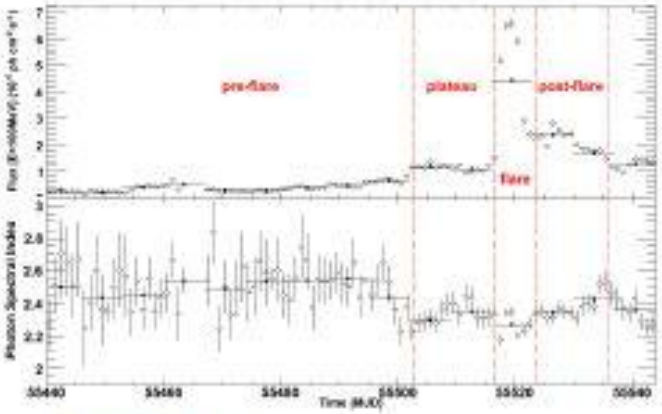
GRID light curve

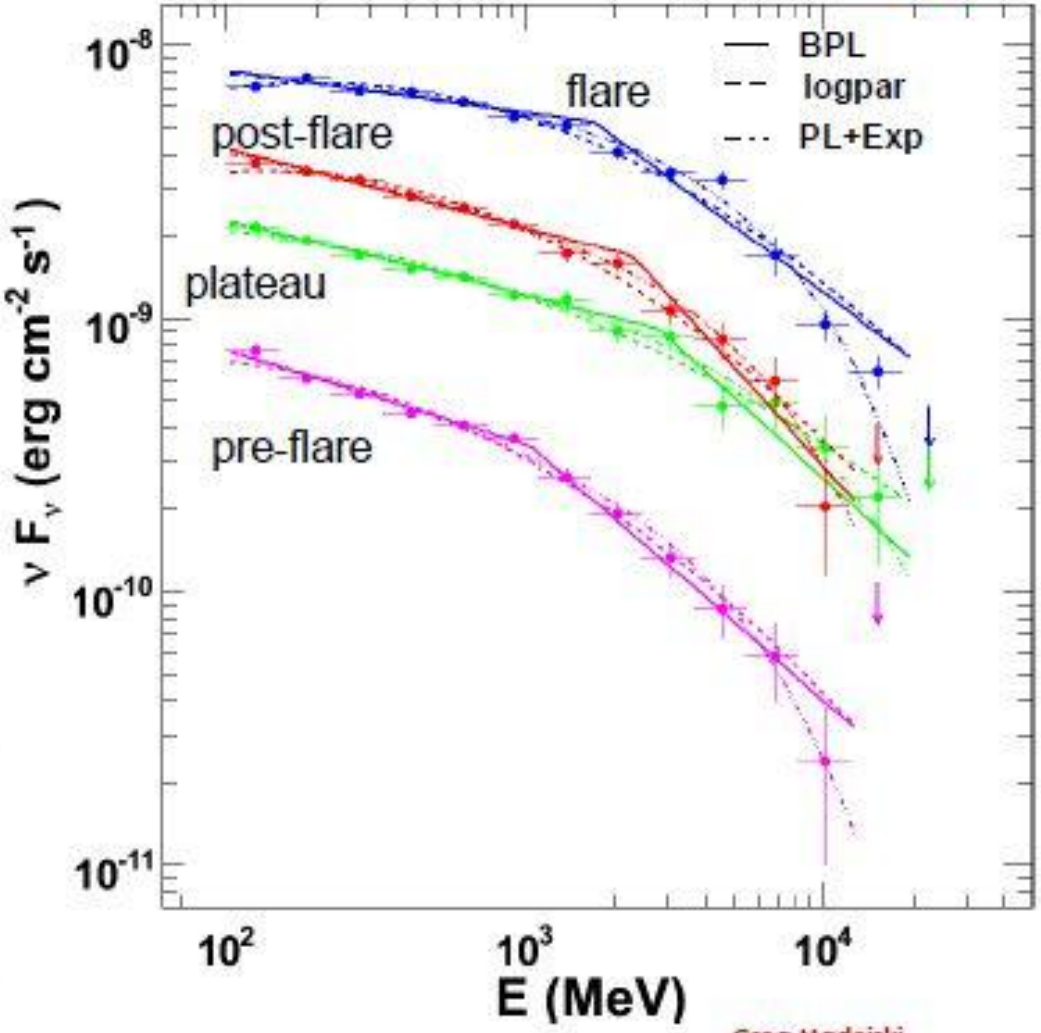
emission spectrum of 3C 454.3, November 2010 (Vercellone et al., 2011)



γ-ray νFν spectrum

- preflare and plateau: BPL and PL+expcutoff give similar quality fits, significantly better than Log-parabola
- none of tested functions gives a good fit for the flare period





Rome May 2011

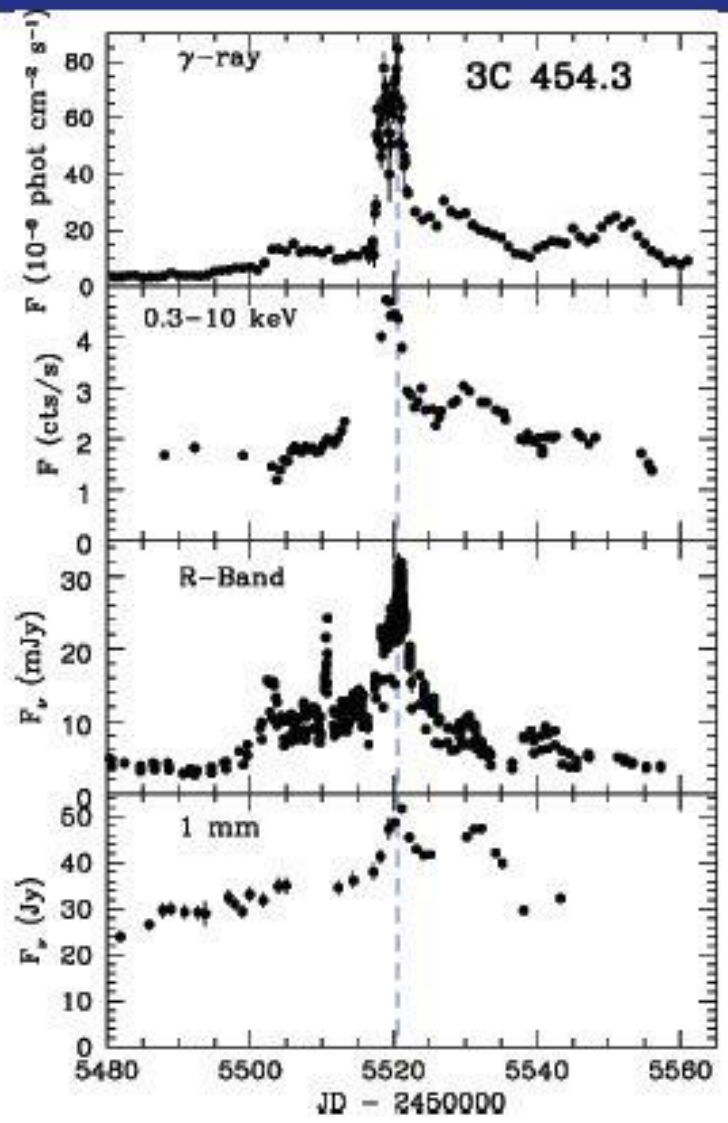
Greg Madejski

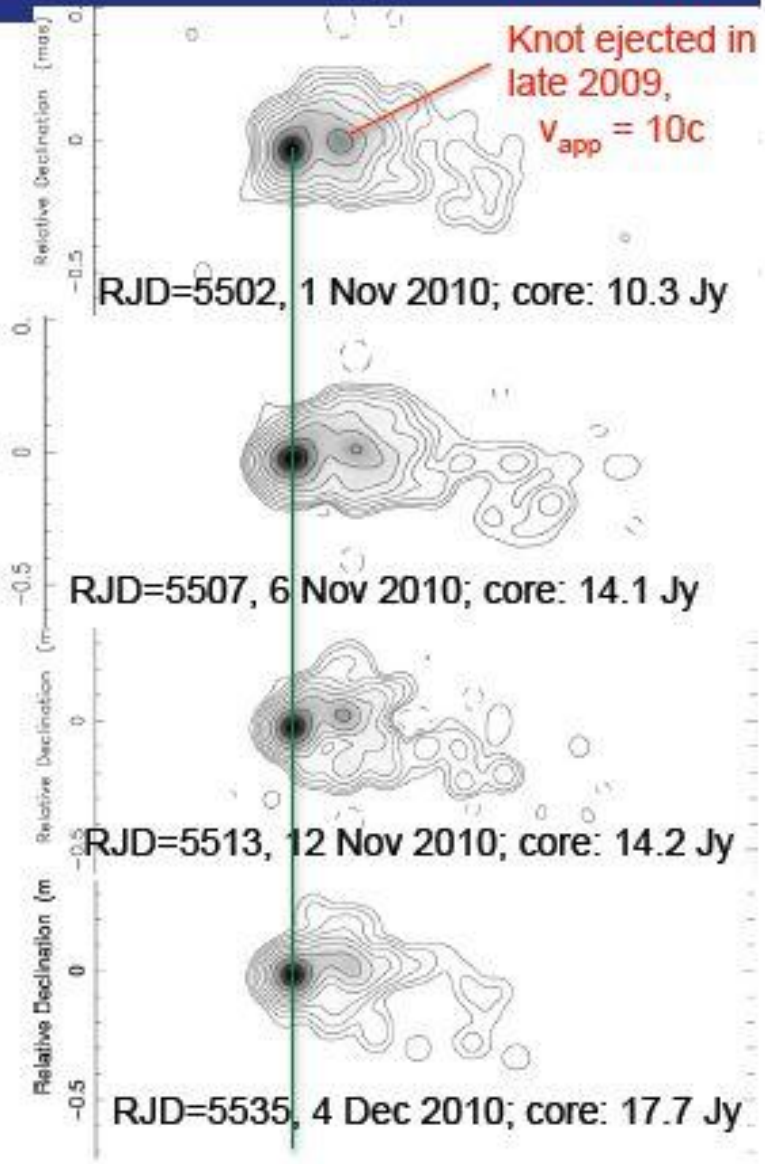
3C 454 Nov. 2010 flare

- **Energetics**
  - **dE/dt (jet kinetic energy) = M_{Earth} / 10 sec**
  - **L (gamma) = L (iso) / Γ^2 = 1.2x10^{47} erg/s**

(from A. Marsher, 2011)

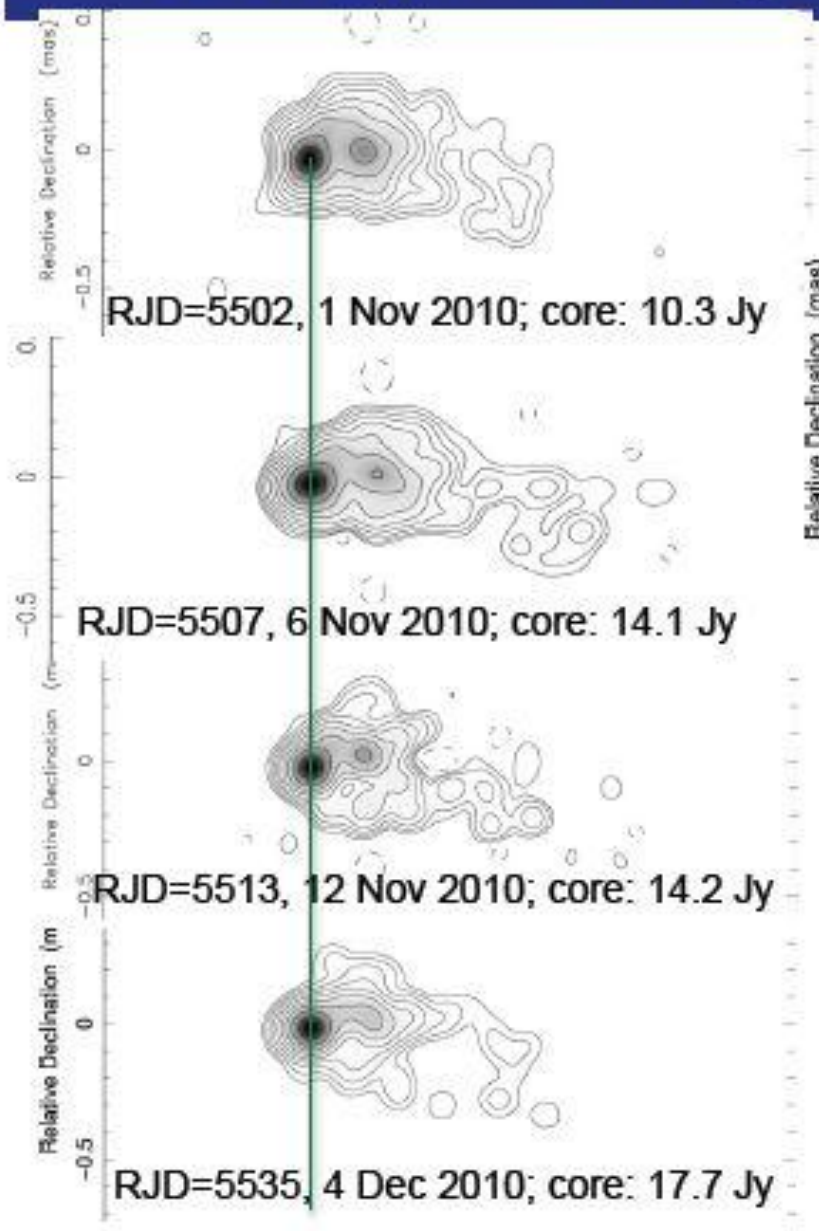
3C 454.3: 2010 super-outburst from gamma-ray to mm-wave

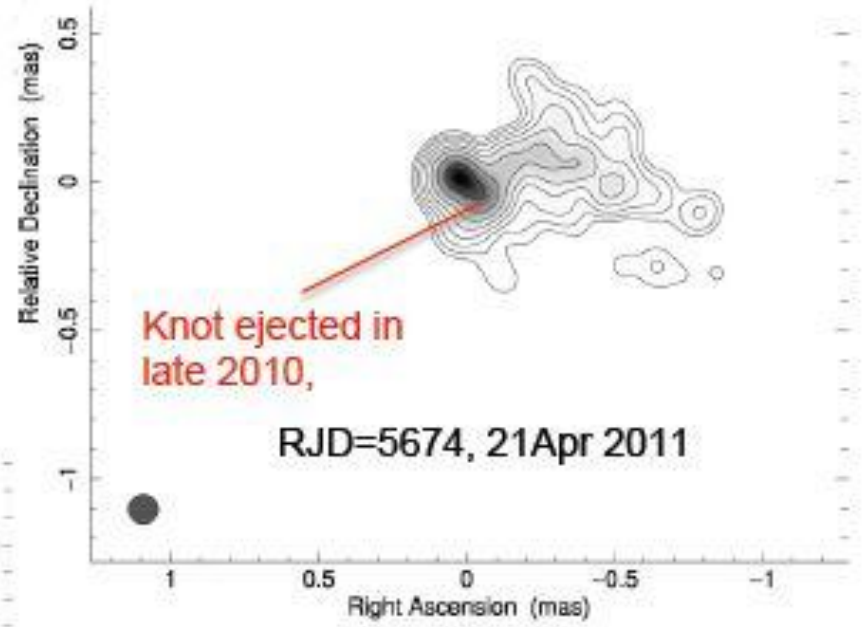




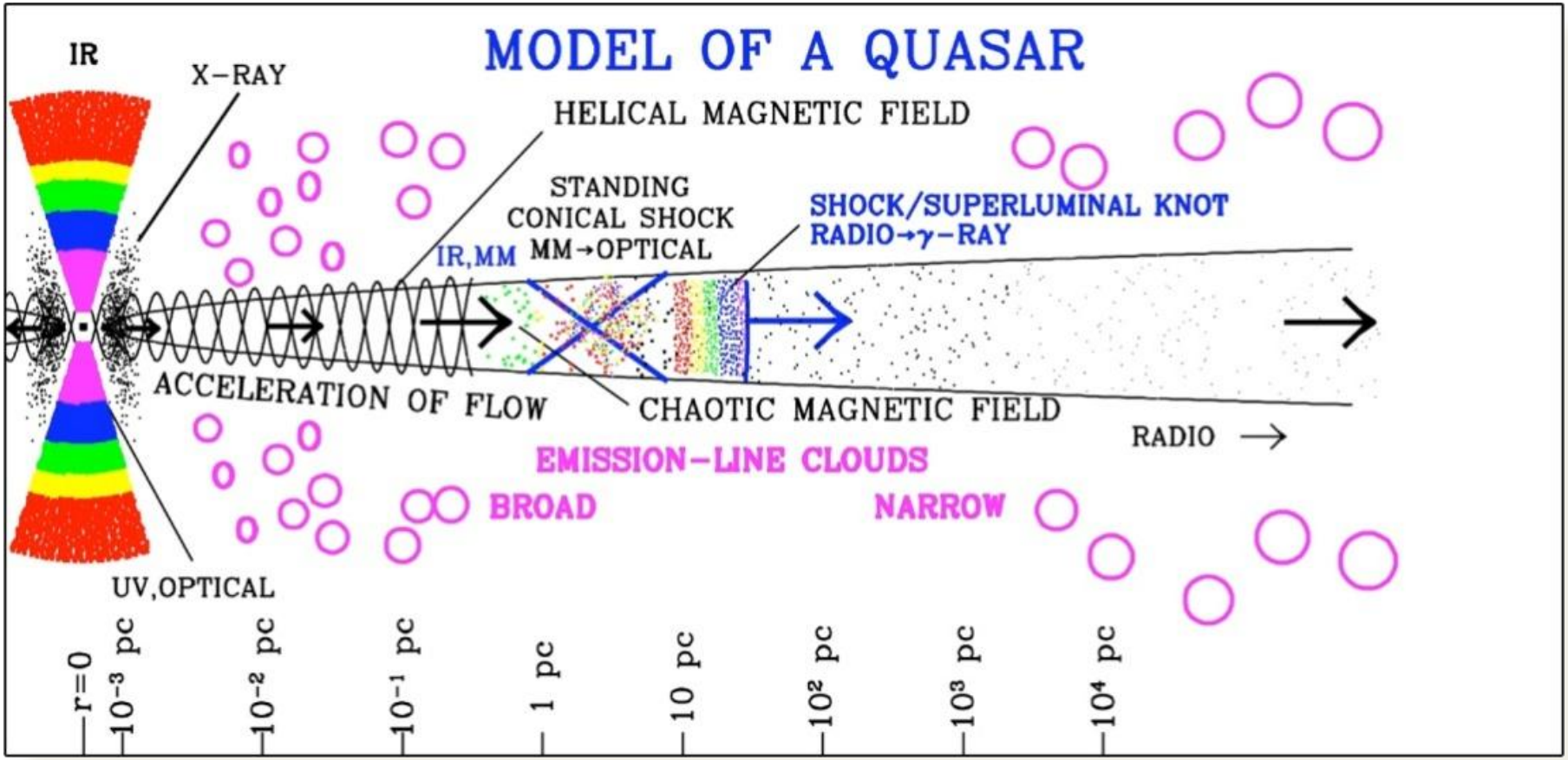
(from A. Marsher, 2011)

3C 454.3: Knot from mega-outburst moving in new direction





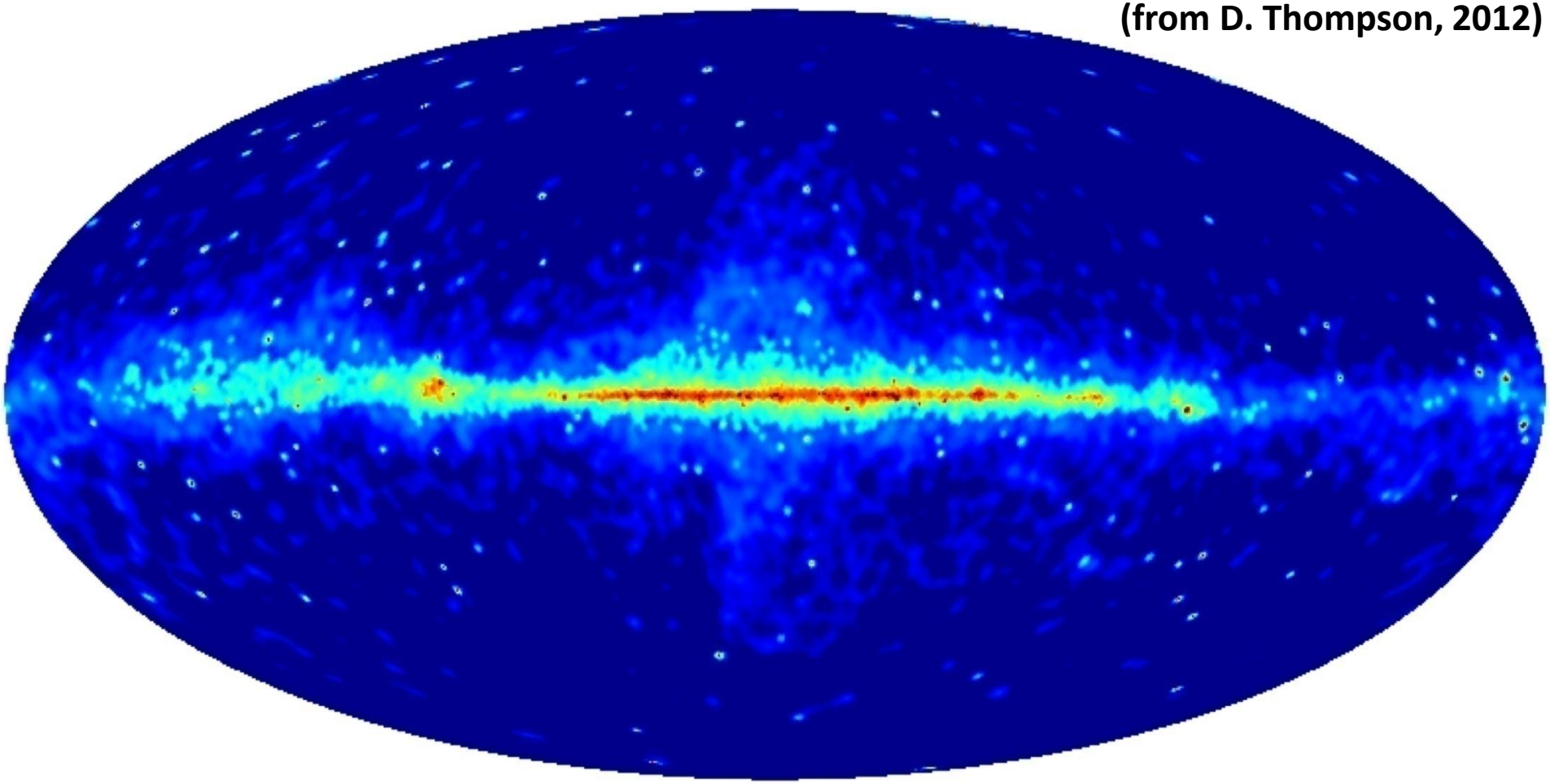
Jorstad et al. (2010 ApJ): core has triple structure, with a flare occurring as a knot passes each feature


MODEL OF A QUASAR
IR
X-RAY
HELICAL MAGNETIC FIELD
STANDING
CONICAL SHOCK
MM→OPTICAL
IR,MM
SHOCK/SUPERLUMINAL KNOT
RADIO→γ-RAY
ACCELERATION OF FLOW
CHAOTIC MAGNETIC FIELD
RADIO
EMISSION-LINE CLOUDS
BROAD
NARROW
UV,OPTICAL
r=0
10⁻³ pc
10⁻² pc
10⁻¹ pc
1 pc
10 pc
10² pc
10³ pc
10⁴ pc

The Gamma-ray Sky above 10 GeV

adaptively smoothed image, courtesy of the LAT collaboration

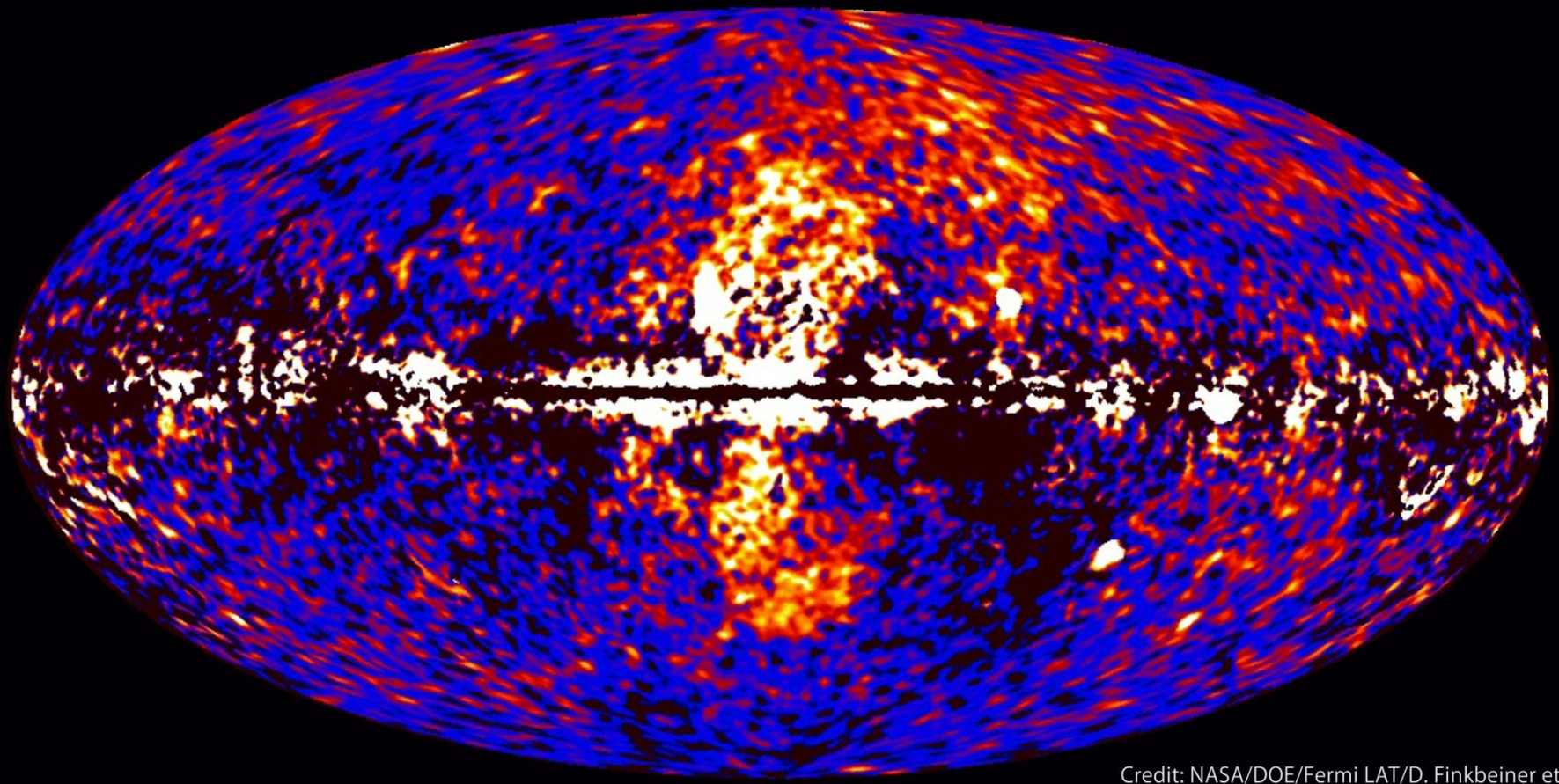
(from D. Thompson, 2012)



In addition to nearly 500 sources at these energies, the sky shows large-scale features like the previously reported “Fermi bubbles” (Su, Slatyer, Finkbeiner, 2010)

(Su, Slatyer, Finkbeiner, 2010)

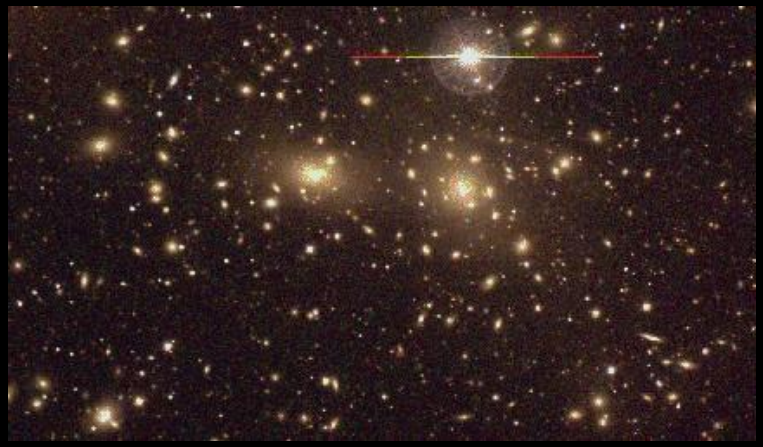
Fermi data reveal giant gamma-ray bubbles



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

What is Not Seen Can Also Be Important

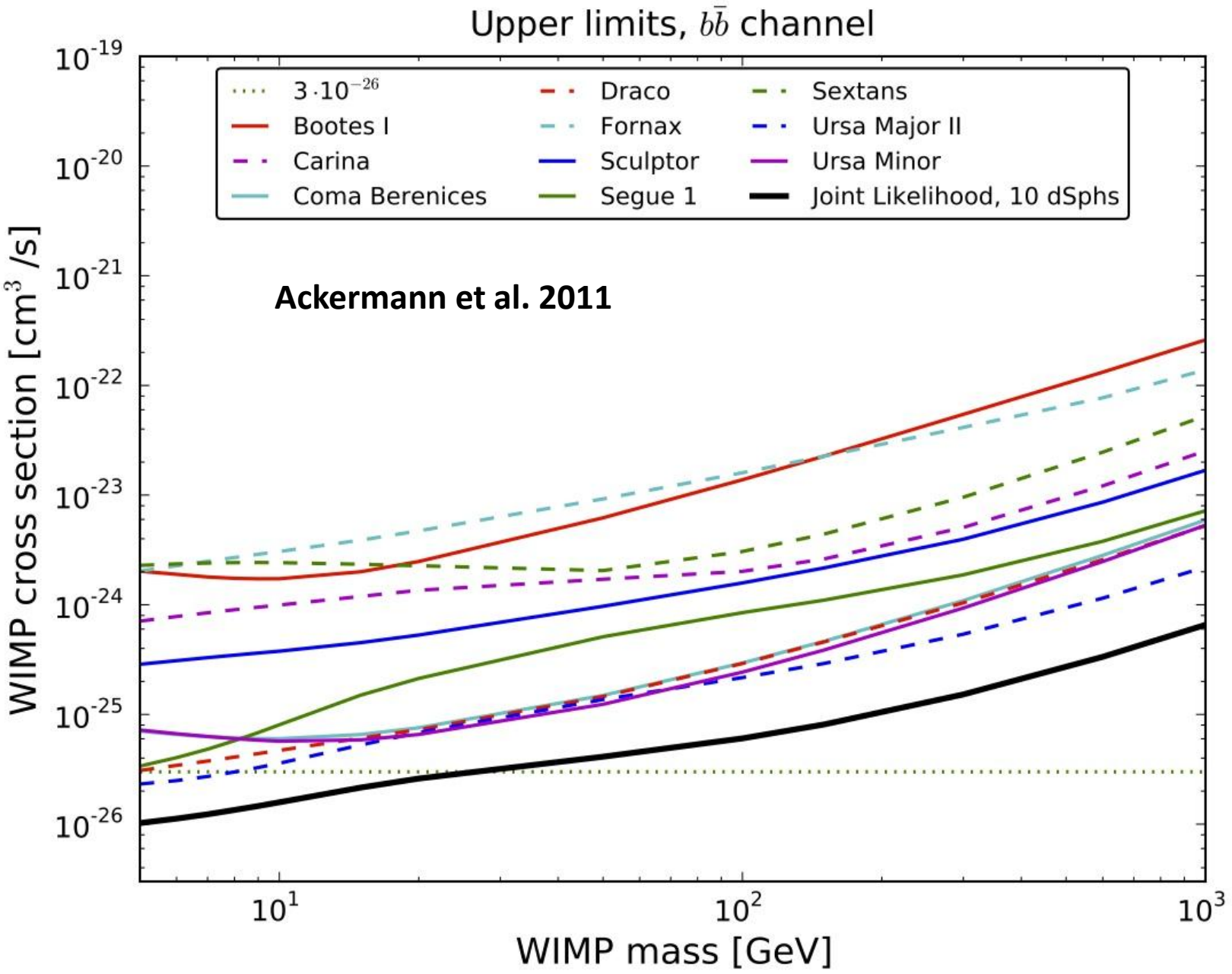
(from D. Thompson)



Some clusters of galaxies were predicted to be gamma-ray sources. None are seen in the Second LAT Catalog, indicating that the predictions were too optimistic.

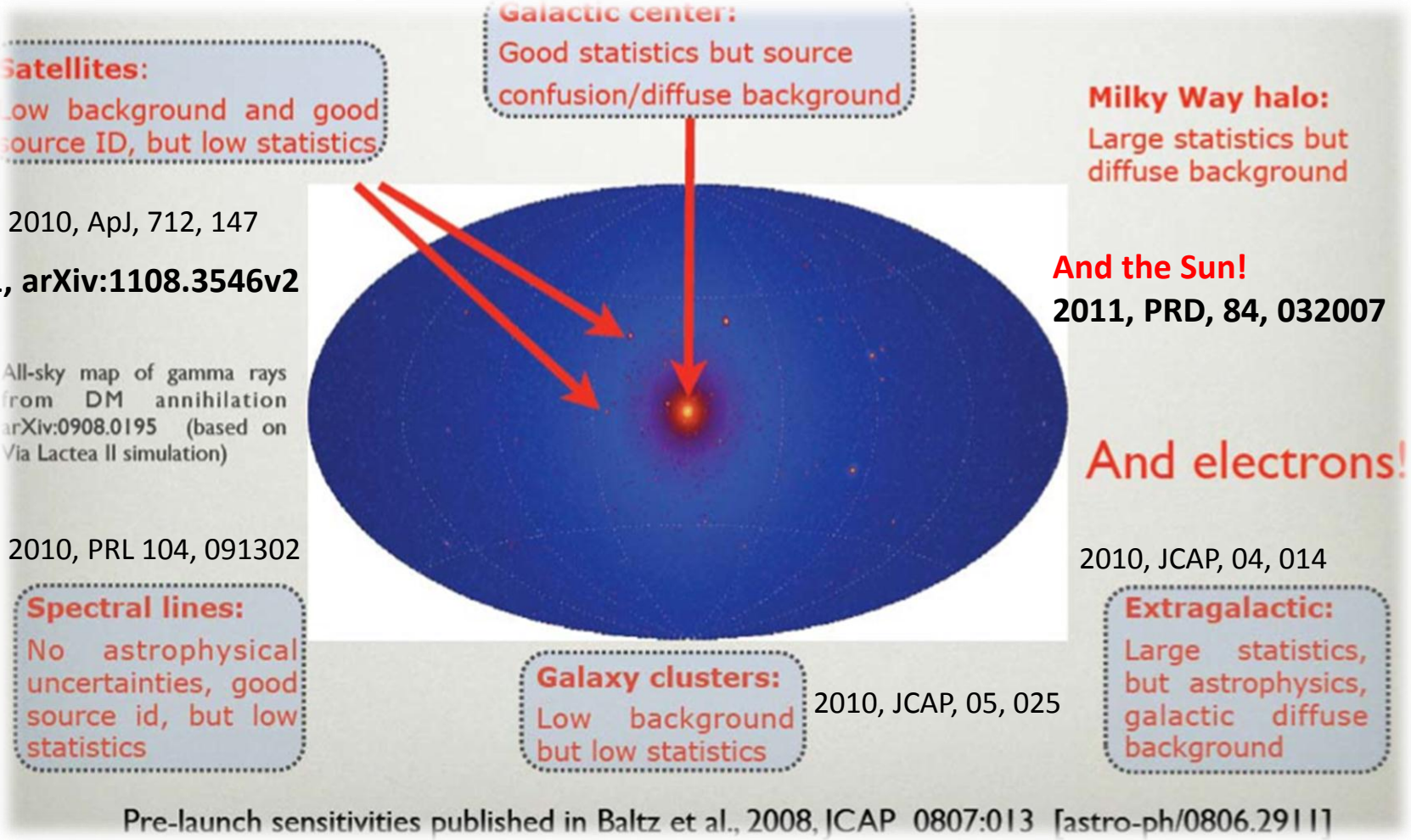
Dwarf spheroidal galaxies are thought to be largely composed of dark matter. If dark matter consists of some types of Weakly Interacting Massive Particles (WIMPs), such galaxies would be gamma-ray sources visible to Fermi LAT. Their absence puts constraints on dark matter models.

Fermi LAT Constraints on Dark Matter



Thermal limit

Dark Matter searches by *Fermi*

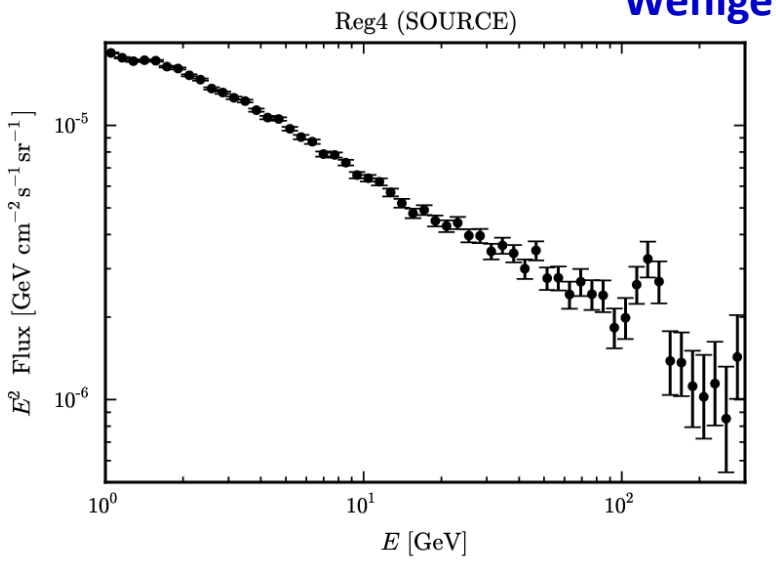


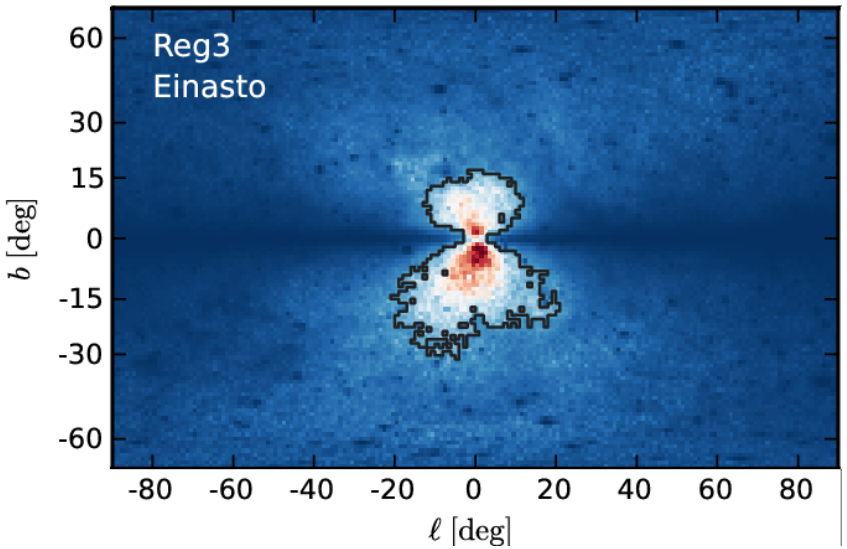
Targets → point sources, extended, all-sky

Signatures → both spectral and spatial

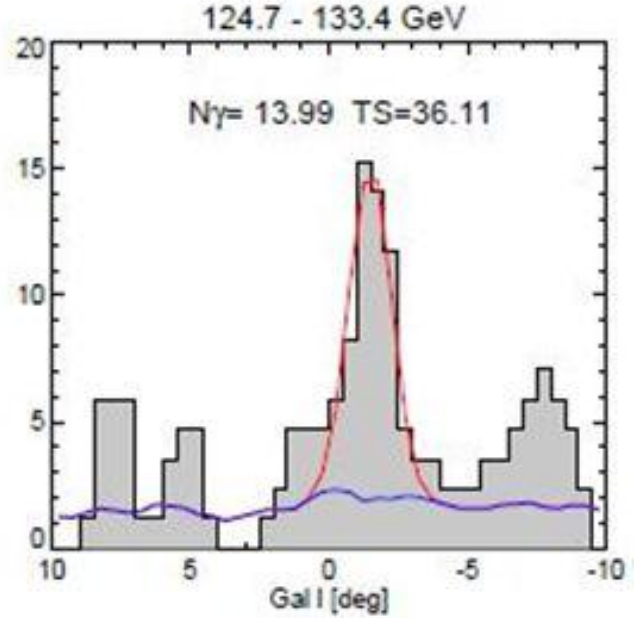
Tentative gamma-ray line near 127 GeV (???)

Weniger et al. 2012

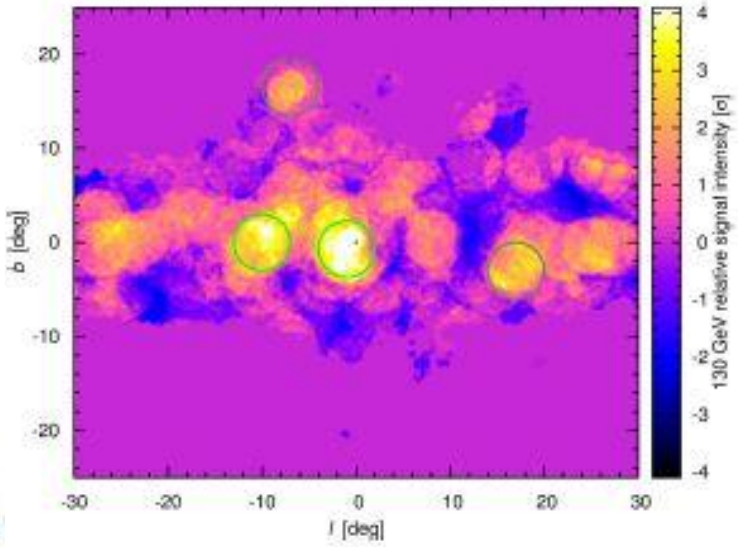




Su & Finkbeiner 2012

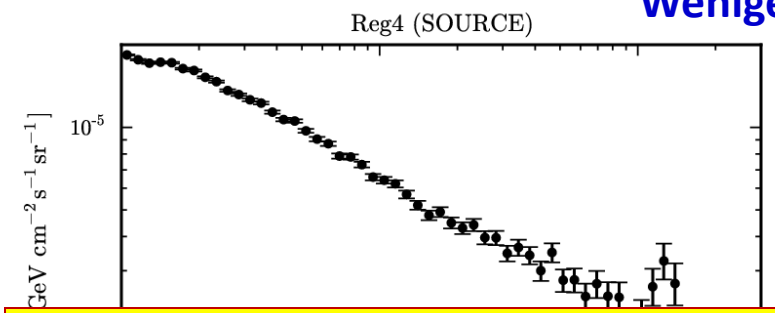


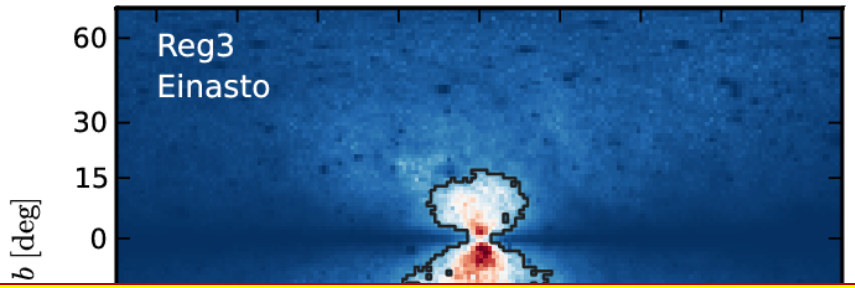
Tempel et al. 2012



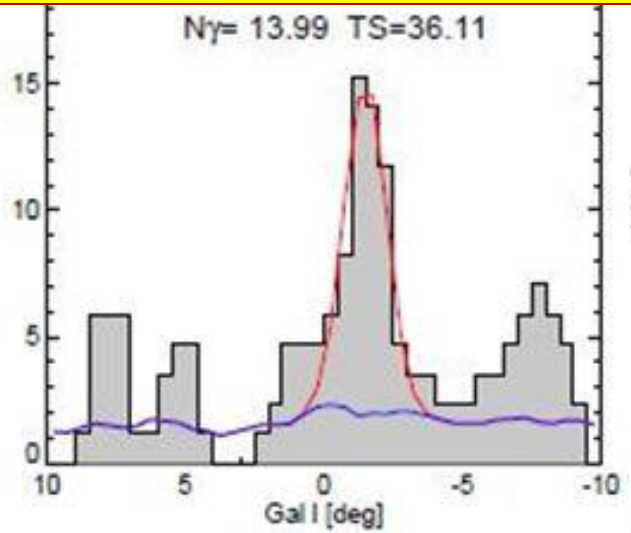
Tentative gamma-ray line near 127 GeV

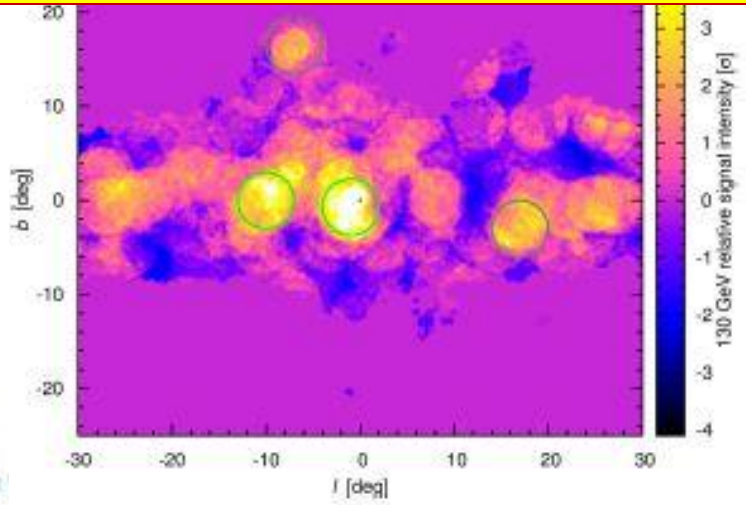
Weniger et al. 2012





But, several possible instrumental and background issues, ongoing analysis by the Fermi team, let's wait…

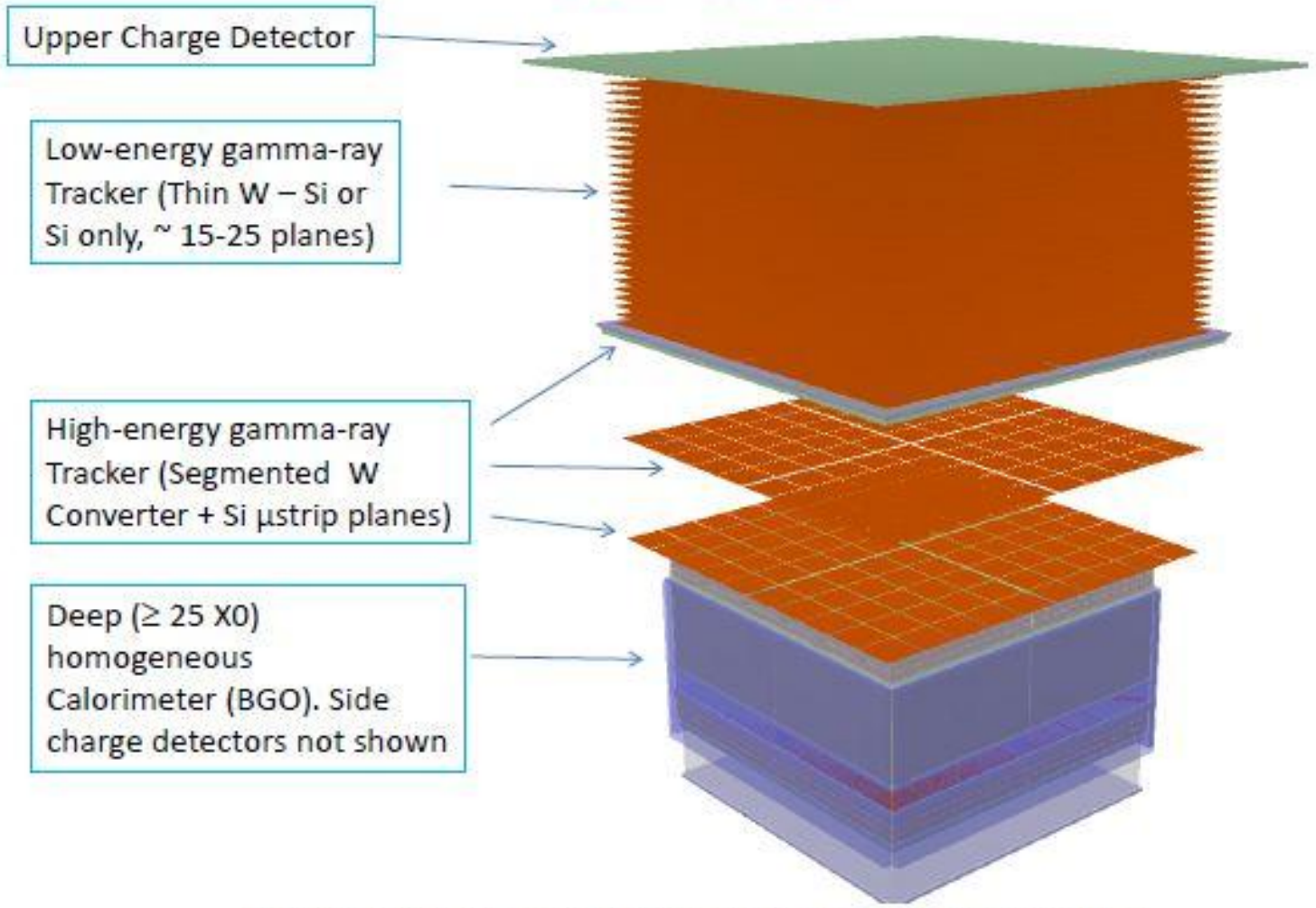




a future after Fermi and AGILE ?

- Silicon technology can be pushed to the limits.
- **Substantial PSF improvement expected by a combination of thin converter + analog readout.**
- **GAMMA-400, a new space mission concept (at the moment under study by groups in Russia, Italy, US).**
- Much improved Gamma-Ray Tracker, very deep calorimeter; a new gamma-ray and charged CR exploration.

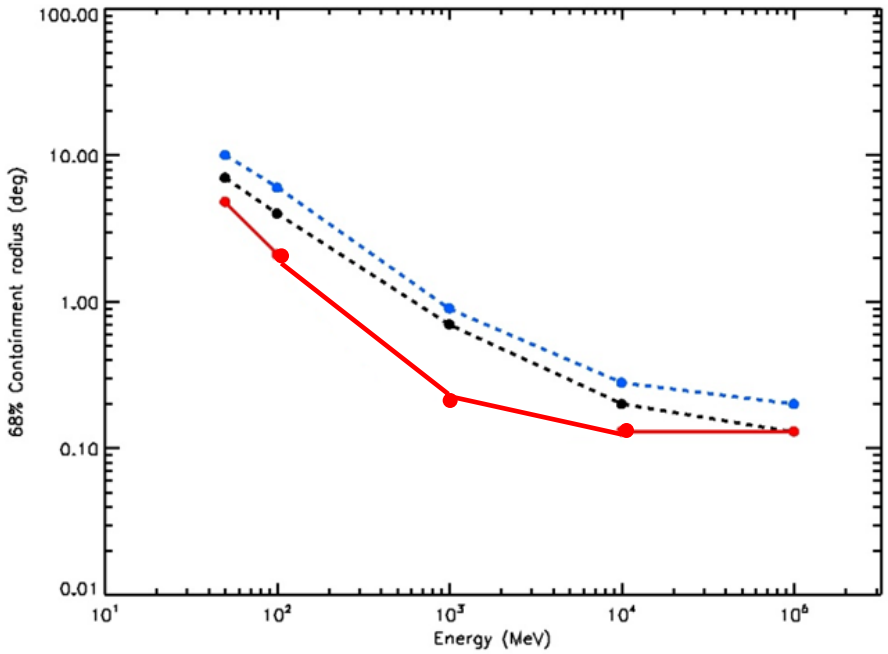
Gamma-400



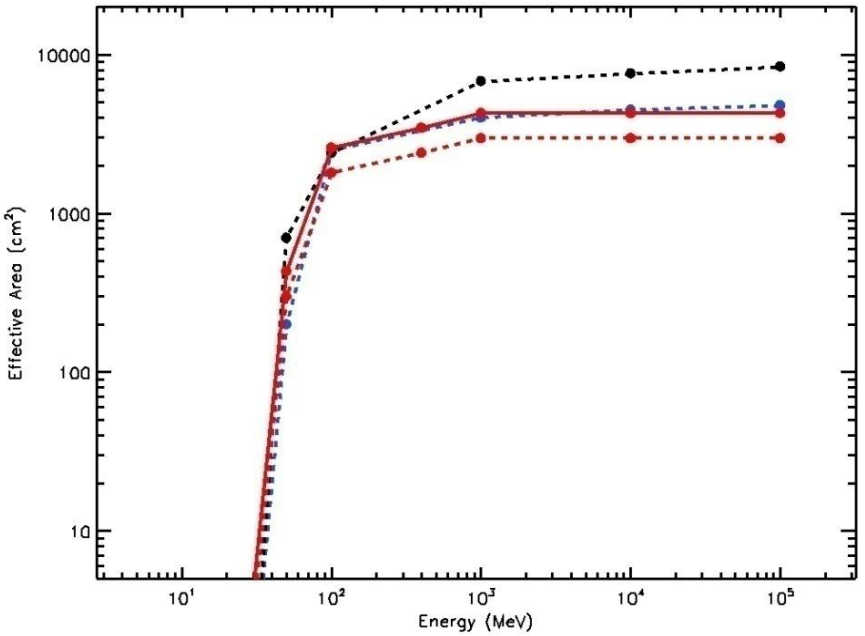
apparatus versions used in one of the preliminary simulations.

GAMMA-400 Tracker performance (preliminary)

PSF (30 degrees off-axis)



Effective Area

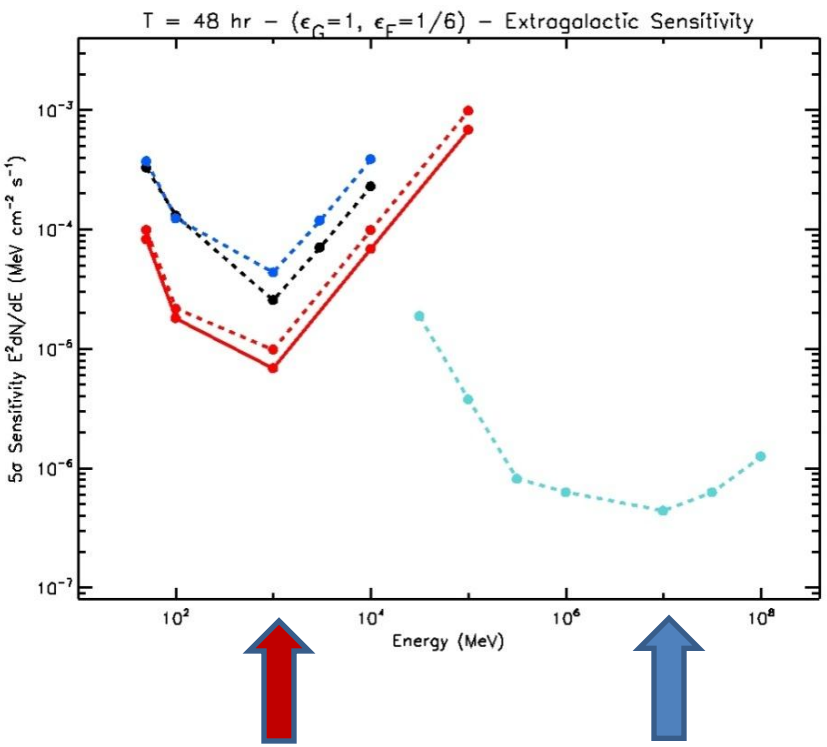


Effective area at 30 degree off-axis.
G-400: 60x60 cm2(red solid line)
G-400: 50x50 cm2 (red dotted line) .
Fermi (blue dotted: upper from PASS7)

G-400 sensitivity (extragal. pointing)

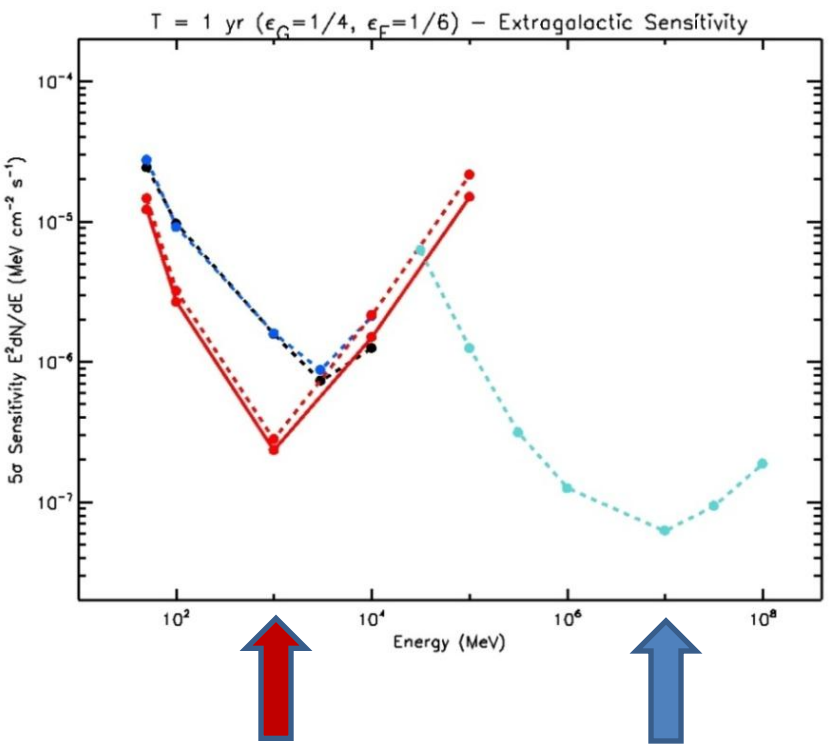
Fermi-LAT (blue), G-400 (red), CTA cyan)

G-400 48 hr, CTA 5 hr



G-400 CTA

G-400 1 yr, CTA 50 hr



G-400 CTA

Conclusions

- **A very exciting development over the years. Cosmic gamma-ray fantastic probes of our Universe.**

- **Cosmic gamma-ray data answer some questions, but also raise novel crucial issues about acceleration mechanisms in many contexts.**

- **A bright future for the GeV and TeV astrophysics.**

Back-up slides

Table: a comparison of different gamma-ray instruments

Mission	W	Pitch (micron)	Readout	D (cm)	Resolution (micron)
AGILE-GRID	0.07	120	analog	1.8	40 (3-strips)
Fermi-LAT	0.028	240	digital	3.2	200 (3-strips)
GAMMA-400	0.03	120	analog	2.8	40
GAMMA-LIGHT	0	120	analog	1.4	40

Extragalactic gamma-ray spectrum by Fermi (Abdo etal, 2010)

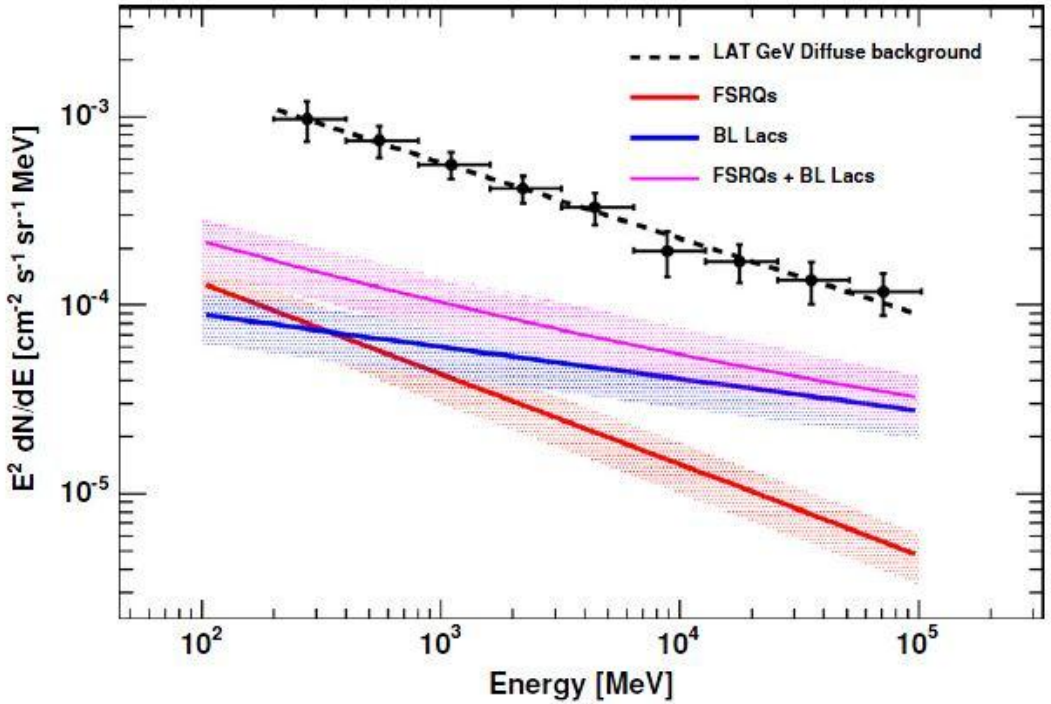
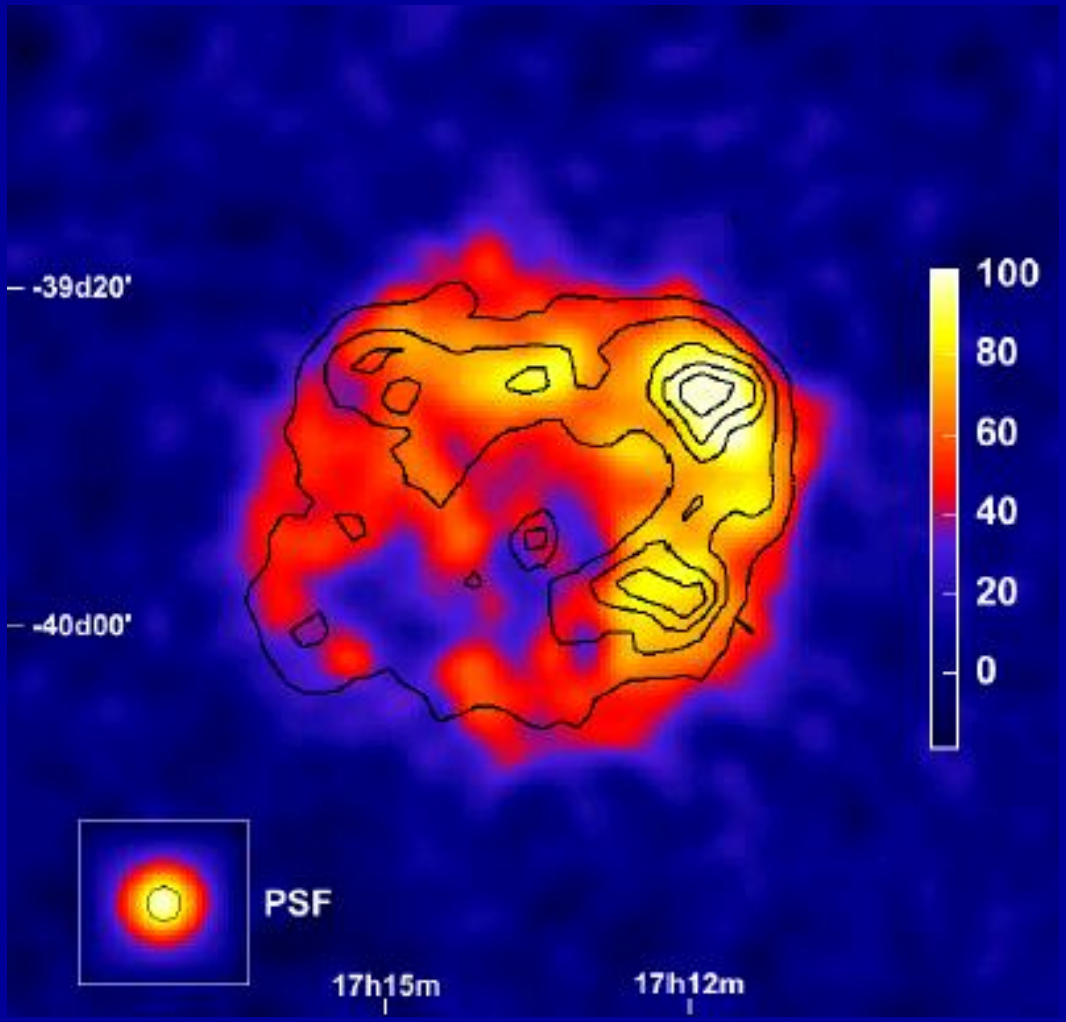
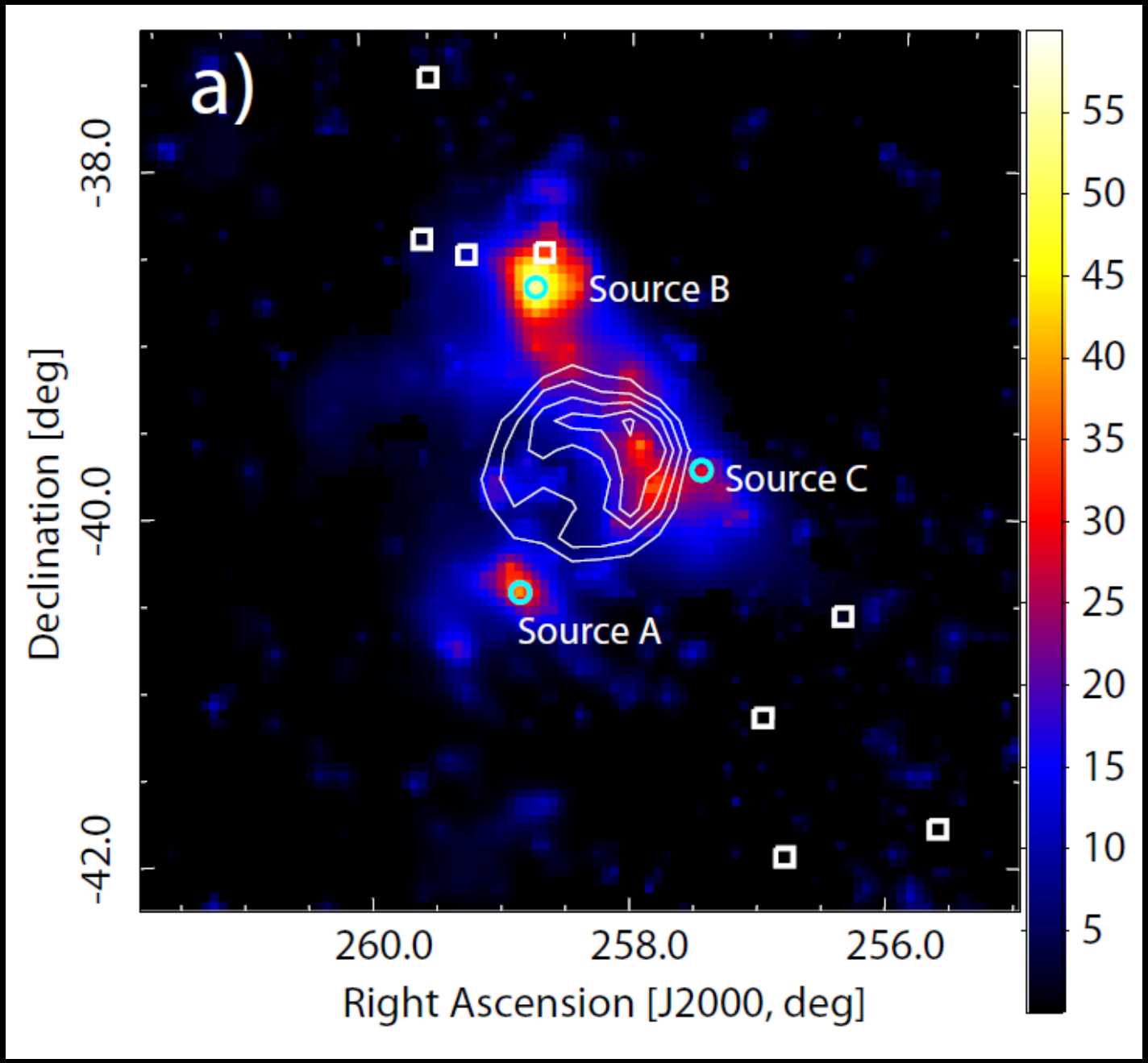


Figure 20. Contributions of different classes of blazars to the diffuse GeV background obtained by integrating the log N–log S. The red and the blue solid lines show the contribution of FSRQs and BL Lac objects, respectively, while the pink solid line shows the sum of the two. The bands around each line show the total (statistical plus systematic) uncertainty.

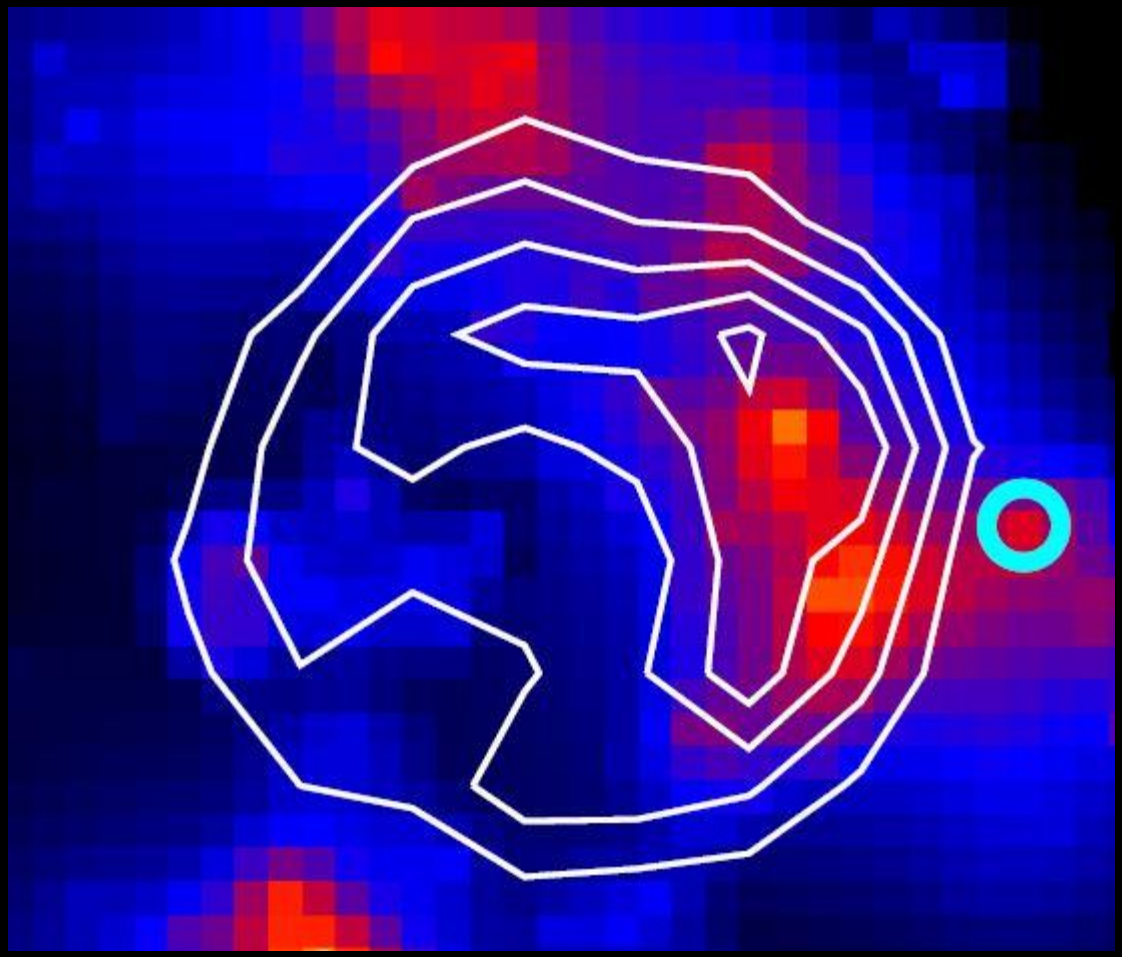
Good X-ray-TeV correlation (~80%)
ASCA-HESS data of RX 1713.7-3946 (Goumard et al. 2006)



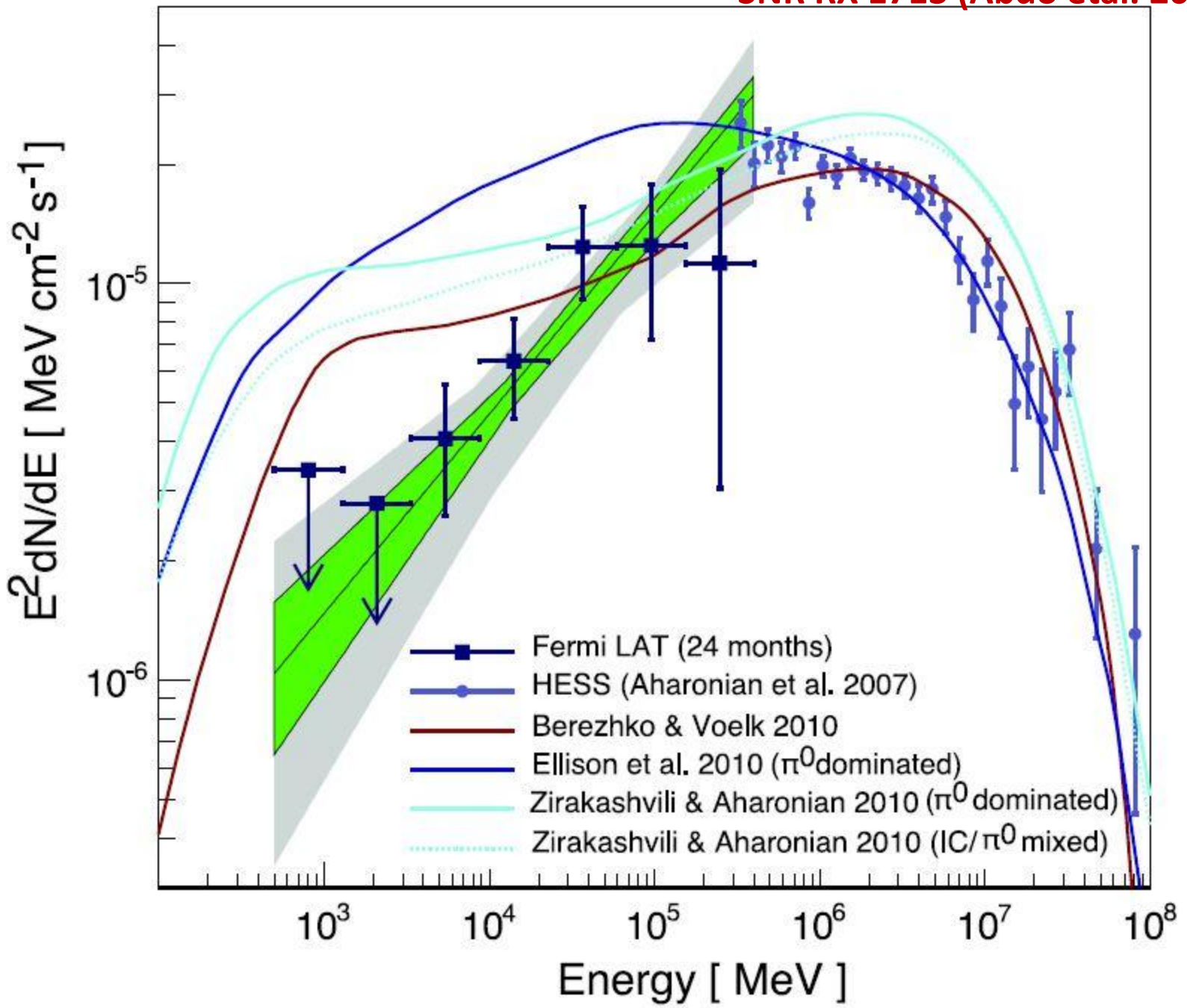
SNR RX 1713 (Abdo etal. 2011)



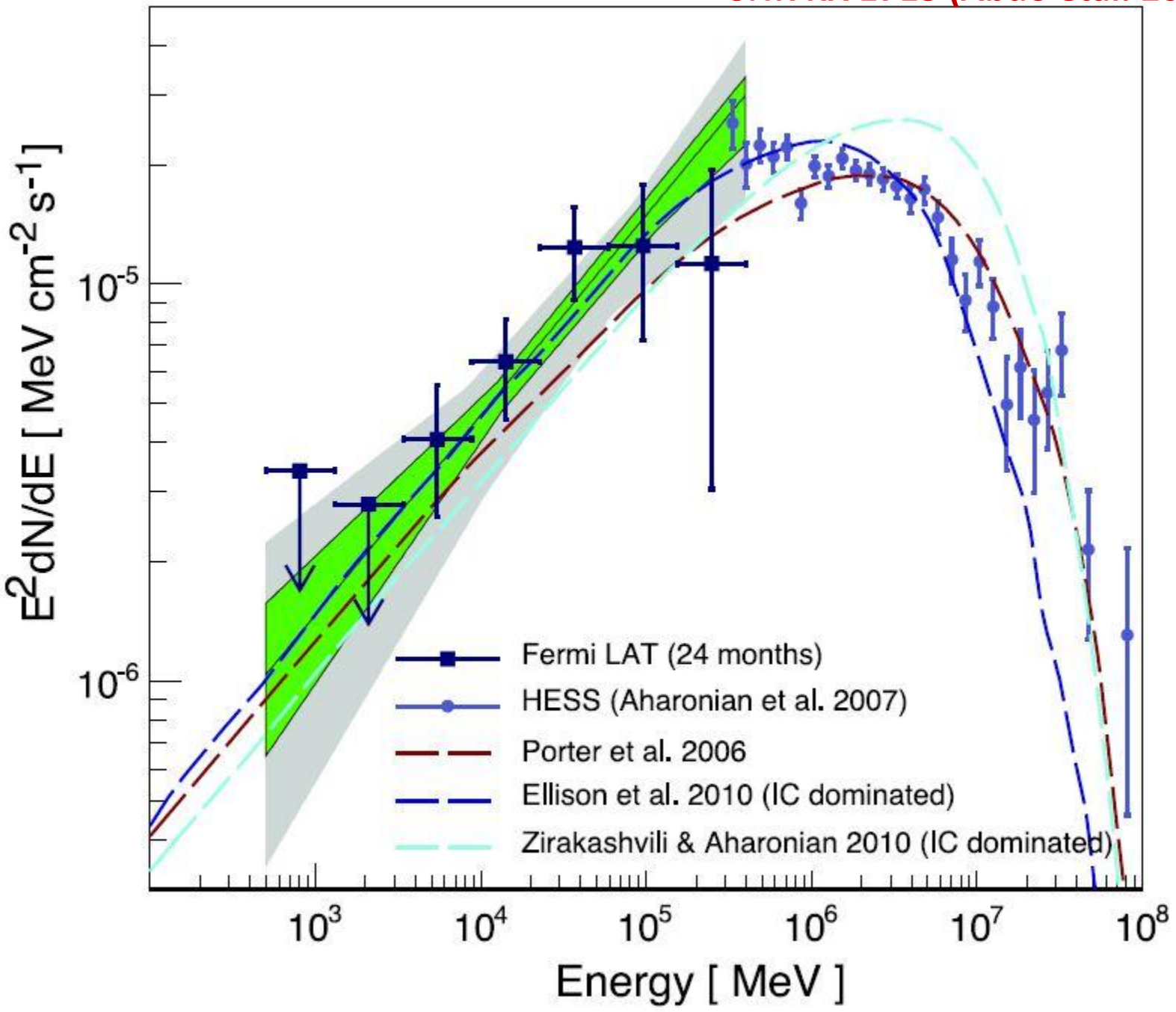
SNR RX 1713 *Fermi* 1-100 GeV (Abdo etal. 2011)



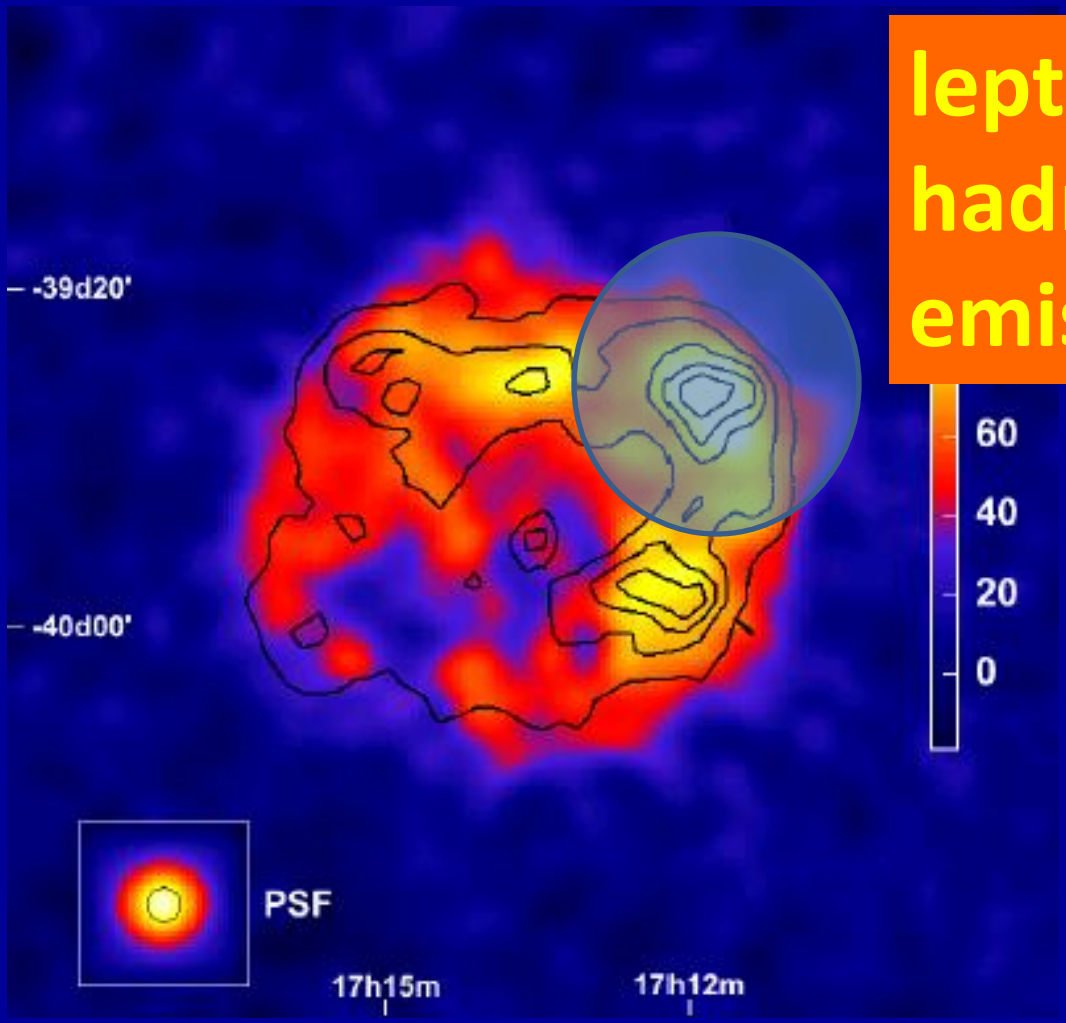
SNR RX 1713 (Abdo etal. 2011)



SNR RX 1713 (Abdo etal. 2011)

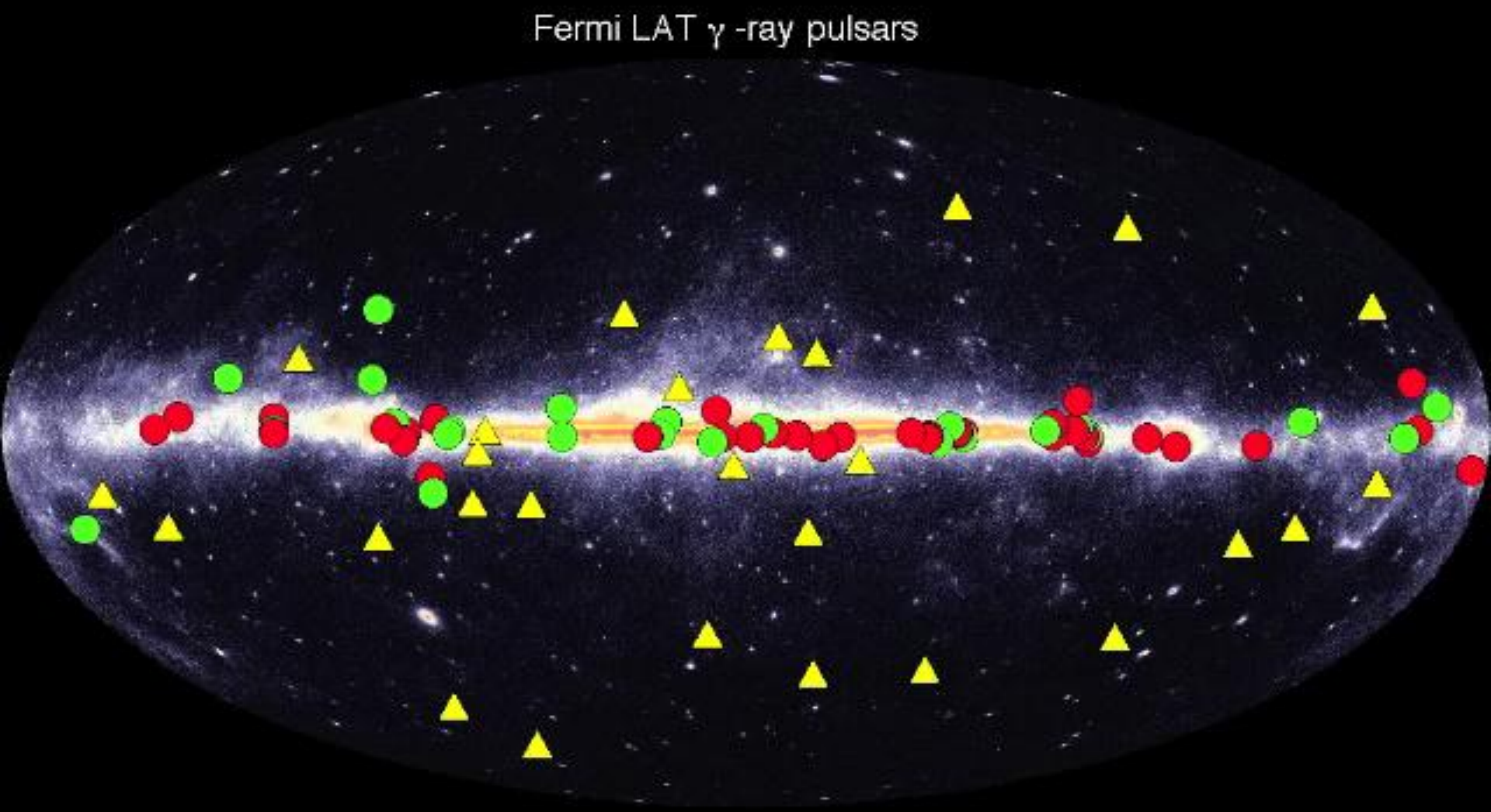


RX 1713.7-3946



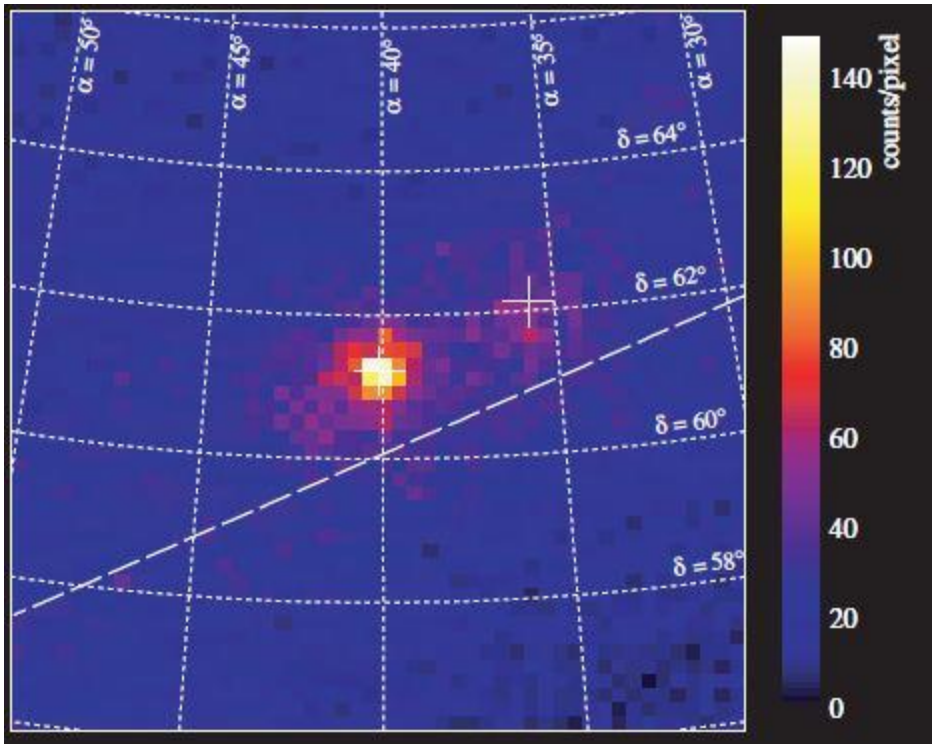
leptonic (?) or hadronic emission ?

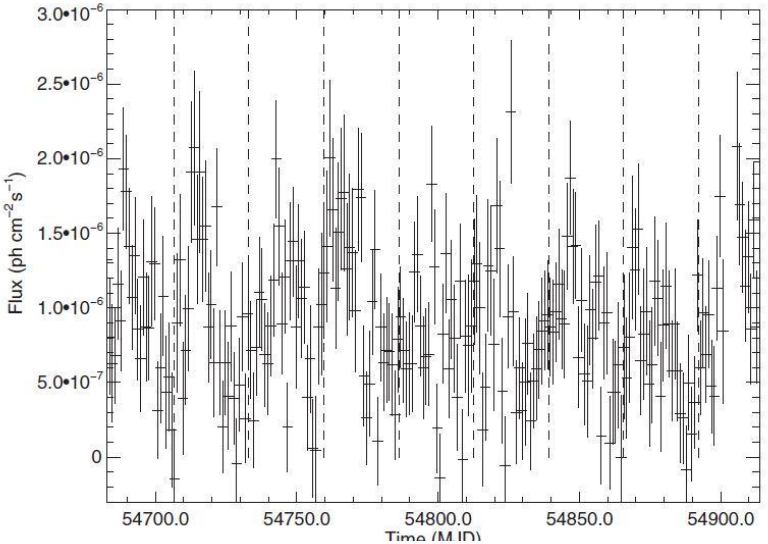
Pulsars – Rapidly Rotating Neutron Stars

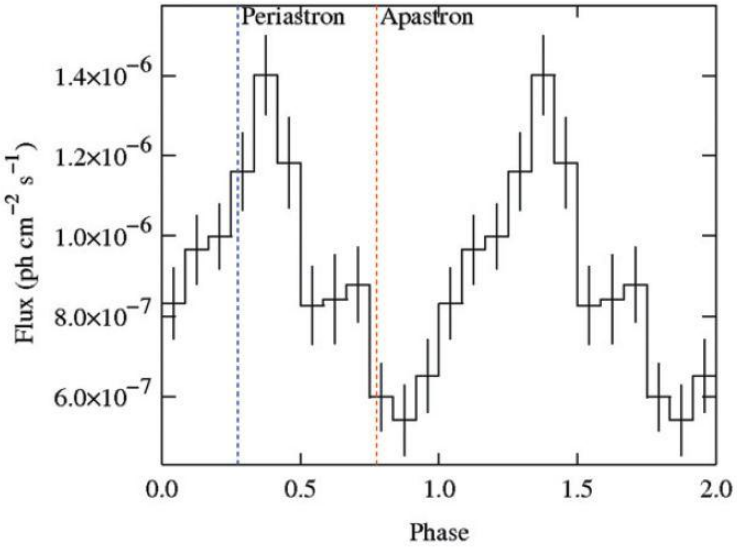


The COS-B source 2CG 135+01

(Abdo et al., 2009, ApJ, 701, L123)





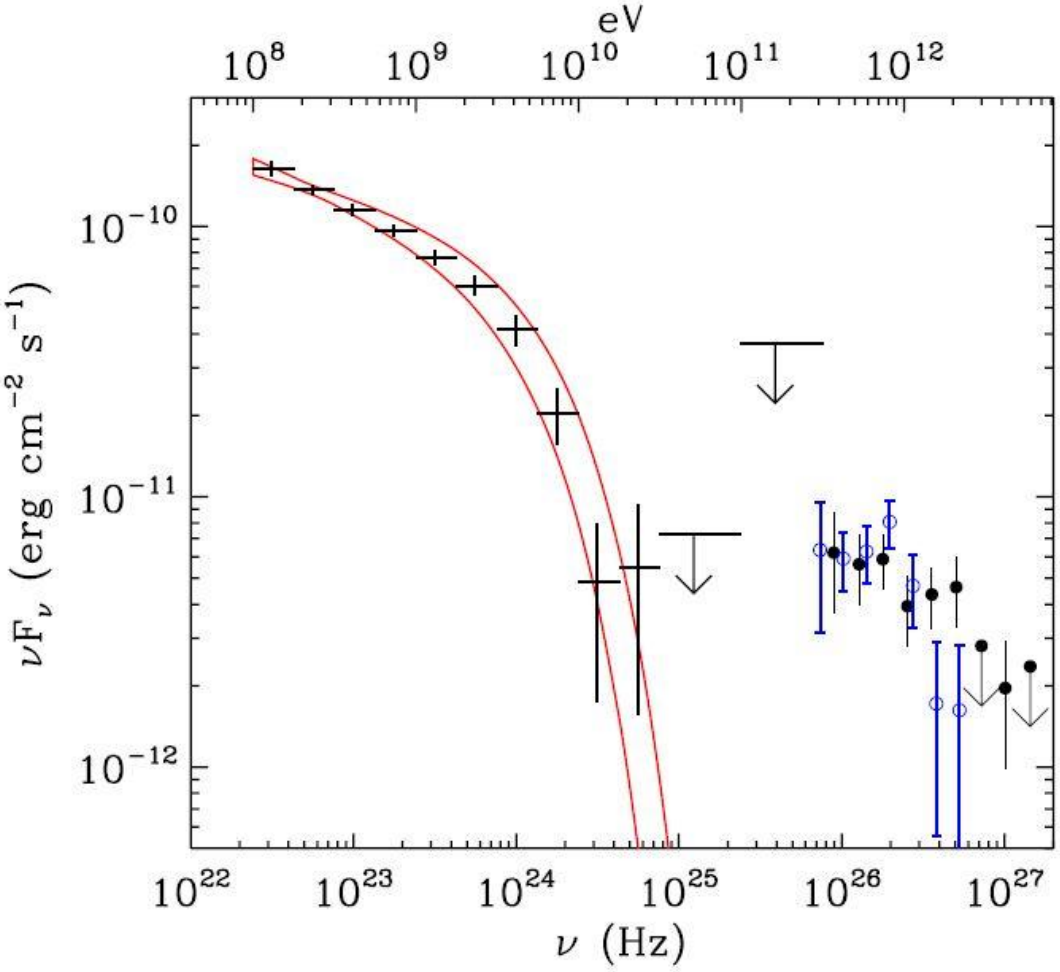


periodicity of the gamma-ray emission in agreement with the radio counterpart LS I 61 303

The COS-B source 2CG 135+01

(Abdo et al., 2009, ApJ, 701, L123)

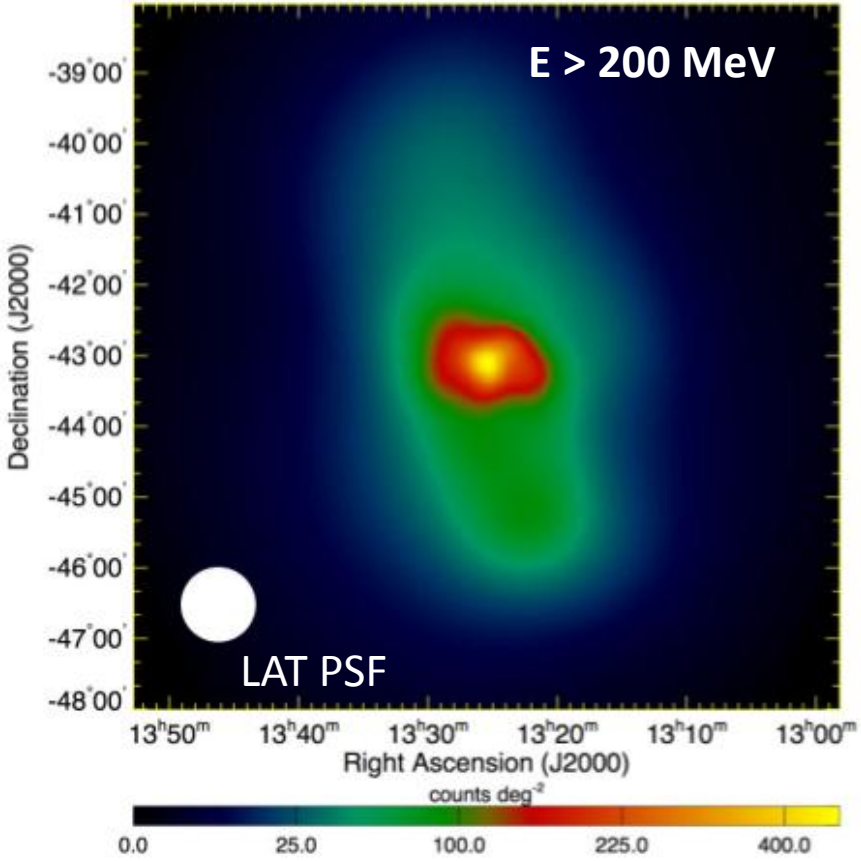
phase-averaged spectrum, GeV cutoff, non-trivial interpretation



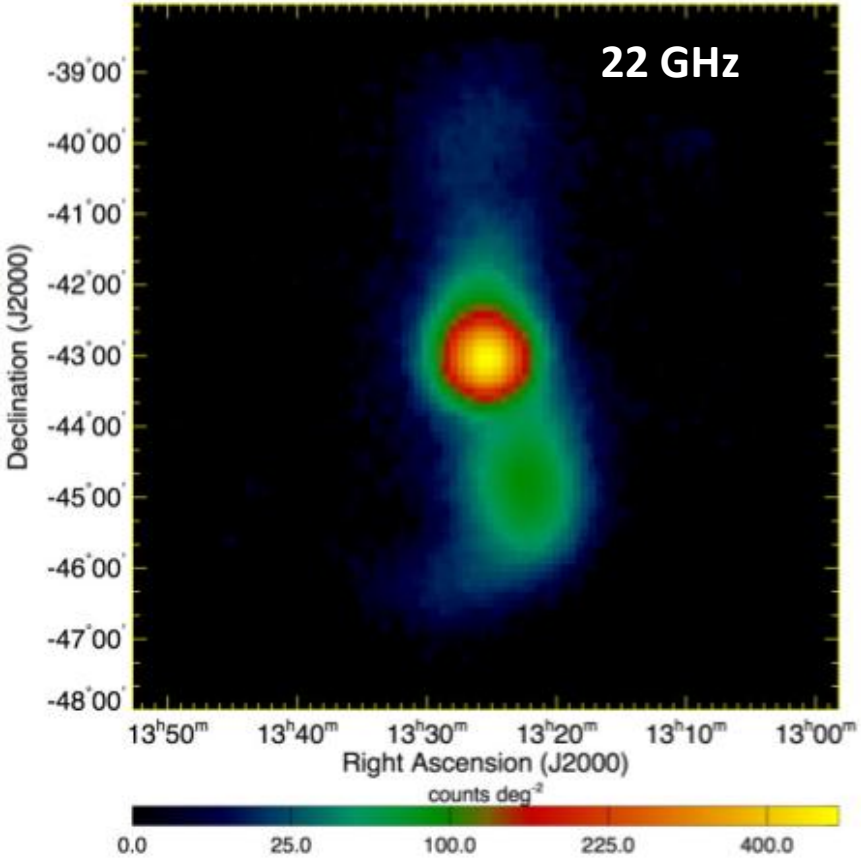
MAGIC (0.5-0.7)

VERITAS (0.5-0.8)

Centaurus A - Radio Galaxy



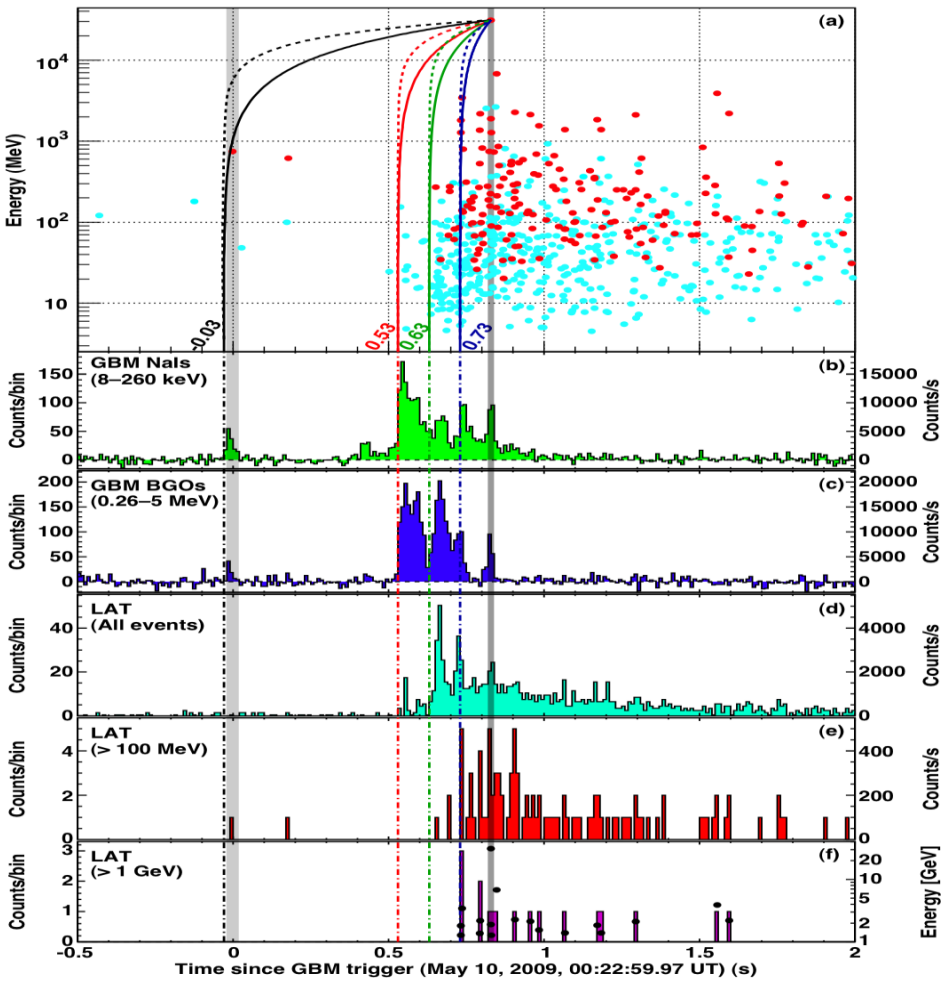
LAT counts map with background (isotropic and diffuse) and field point sources subtracted

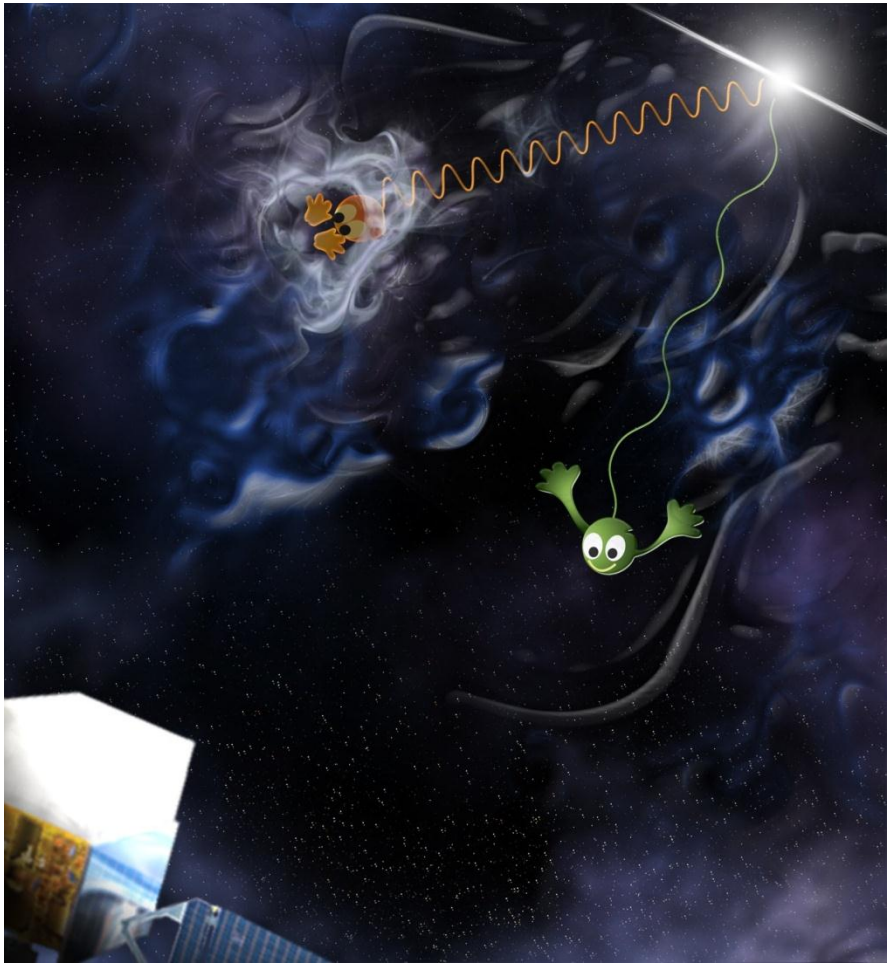


WMAP image provided by Nils Odegard (GSFC)

Requires 0.1-1 TeV electrons in giant 'relic' lobes: accelerated in-situ or efficient transport from center

GRB 090510 - testing models of Quantum Gravity



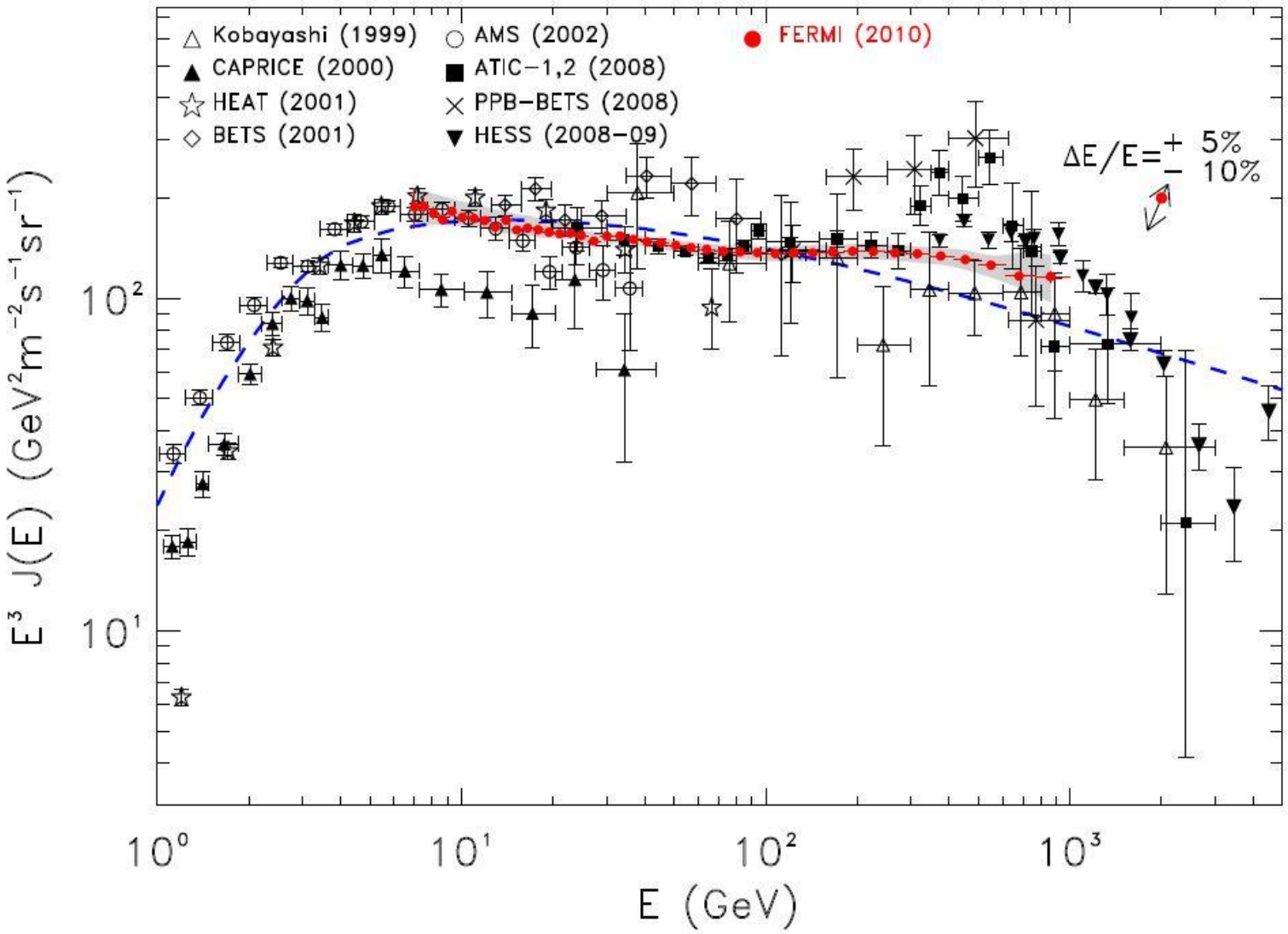


Highest energy gamma-ray arrived within 0.9s of the lower energy photons after traveling 7 billion years.

Eliminates theories of quantum gravity that predict space-time is "foamy" enough to interfere strongly with light.

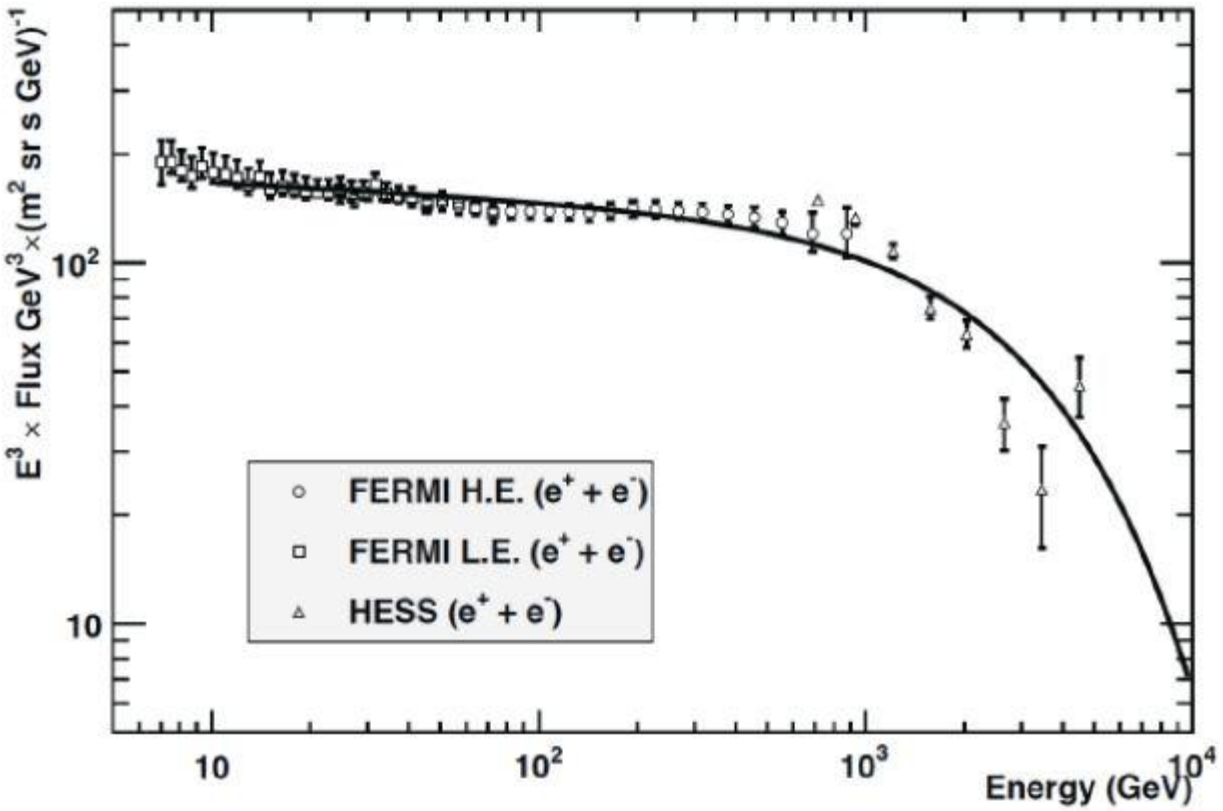
Cosmic-ray electron-positron spectrum measured by Fermi

(Ackermann M. etal. Physical Review D, vol. 82, Issue 9, id. 092004)



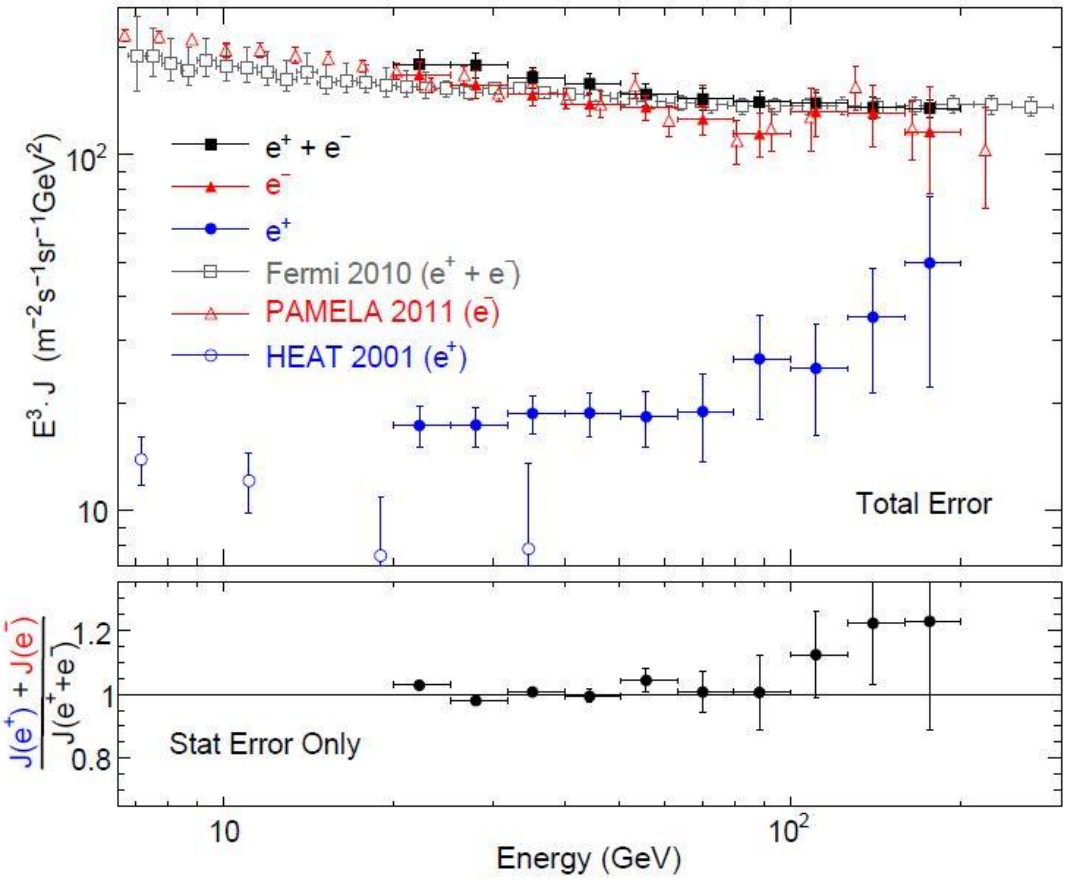
Cosmic-ray electron-positron spectrum measured by Fermi and HESS

Ackermann M. etal. Physical Review D, vol. 82, Issue 9, id. 092004
Egberts, K., et al., 38th COSPAR Scientific Assembly,18-15 July 2010, p.2



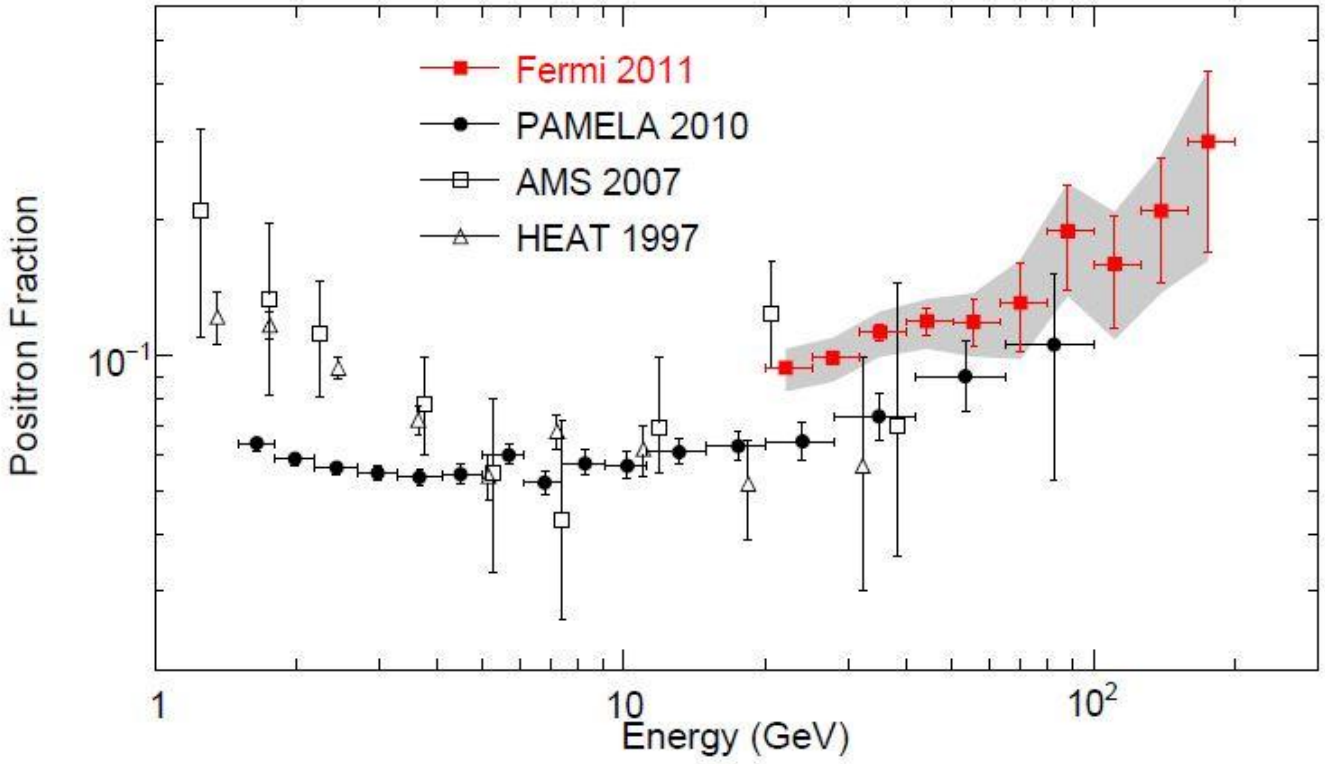
Separate electron and positron spectra measured by Fermi

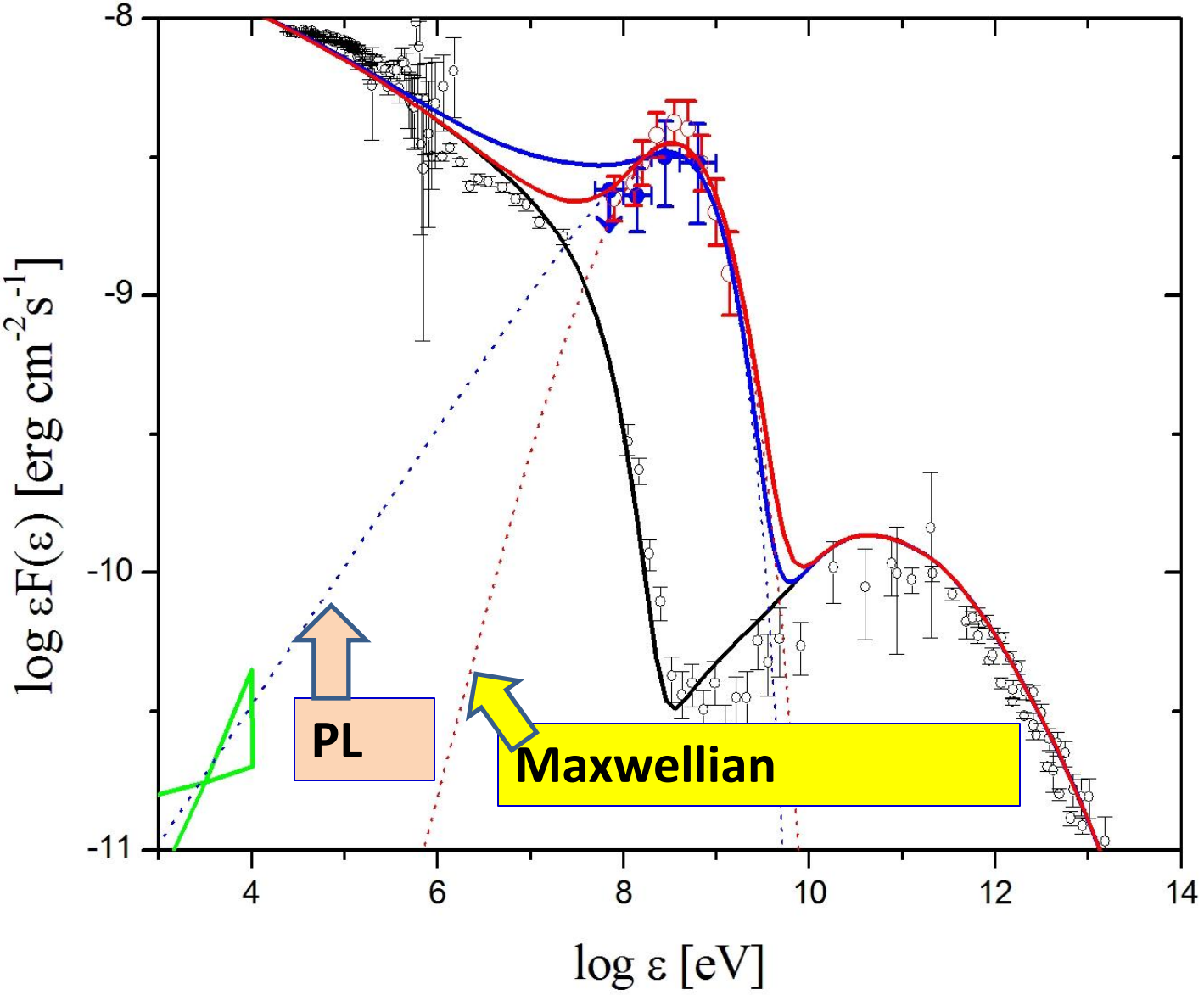
(Ackermann M. etal. Phys. Rev. Letters, 108, 011102)



Positron fraction measured by Fermi

(Ackermann M. etal. Phys. Rev. Letters, 108, 011102)




-8
-9
-10
-11
4
6
8
10
12
14
log εF(ε) [erg cm^{-2}s^{-1}]
log ε [eV]
PL
Maxwellian

→ historical flux estimates: several photons / cm^2 s
present observations: confirmed for GRBs and solar flares
but about 100 times less for cosmic sources!

→ observers, failed to see the predicted intensities!

→ after a period of disappointment the development of better and larger instruments and their use on satellites produced results after ≈1970

January 1993

1993A&AS...97...13F

ASTRONOMY & ASTROPHYSICS
SUPPLEMENT SERIES

JANUARY 1993, PAGE 13

Astron. Astrophys. Suppl. Ser. **97,** 13-16 (1993)

Overview of the first results from EGRET

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Received June 3; accepted June 5, 1992

Abstract. — The Energetic Gamma Ray Experiment Telescope (EGRET), one of four instruments carried on the Compton Gamma Ray Observatory, is capable of detecting photons in the energy range from approximately 20 MeV to 30 GeV. After a period of about one month for test and calibration, a 15-month all sky survey was begun. The June 11, 1992 solar flare was observed in gamma rays with energies from the threshold of detection to energies over 1 GeV. Detailed time histories and energy spectra have been obtained for the Crab and Vela pulsars, with one of the Vela pulses being quite sharp, approximately 2% of the total period. Several gamma ray bursts have been recorded. In particular, the one on May 3, 1991 was seen in the spark chamber system of EGRET, allowing a position to be determined. The galactic plane diffuse gamma ray emission has been observed in many regions of the plane, and the galactic center region spectrum has been compared to that expected for cosmic rays interacting with matter and photons and found to agree well. The quasar 3C 279, which has a z of 0.538, was seen in high energy gamma rays in both June and October, 1992. It is time variable on times as short as 2 days, and has a hard energy spectrum. The quasars 3C 273, PKS 0208-512, 4C 38.41, PKS 0528+134, and 0836+710 also have been tentatively identified. 4C 38.41, with a z of 1.8, has a hard gamma ray energy spectrum.

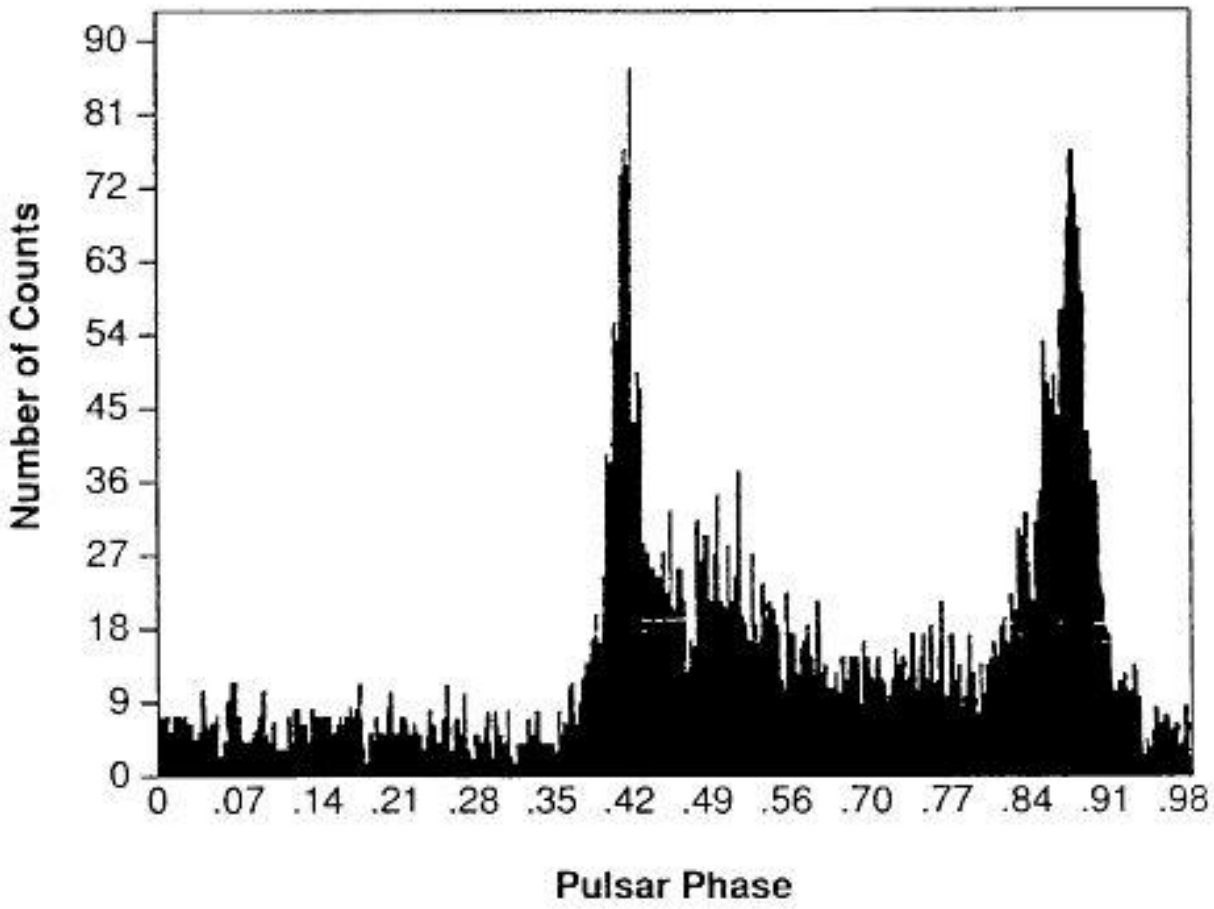

FIGURE 1. Fine time resolution phase distribution of the gamma radiation (100 MeV) from PSR 0833-45 as observed by EGRET.

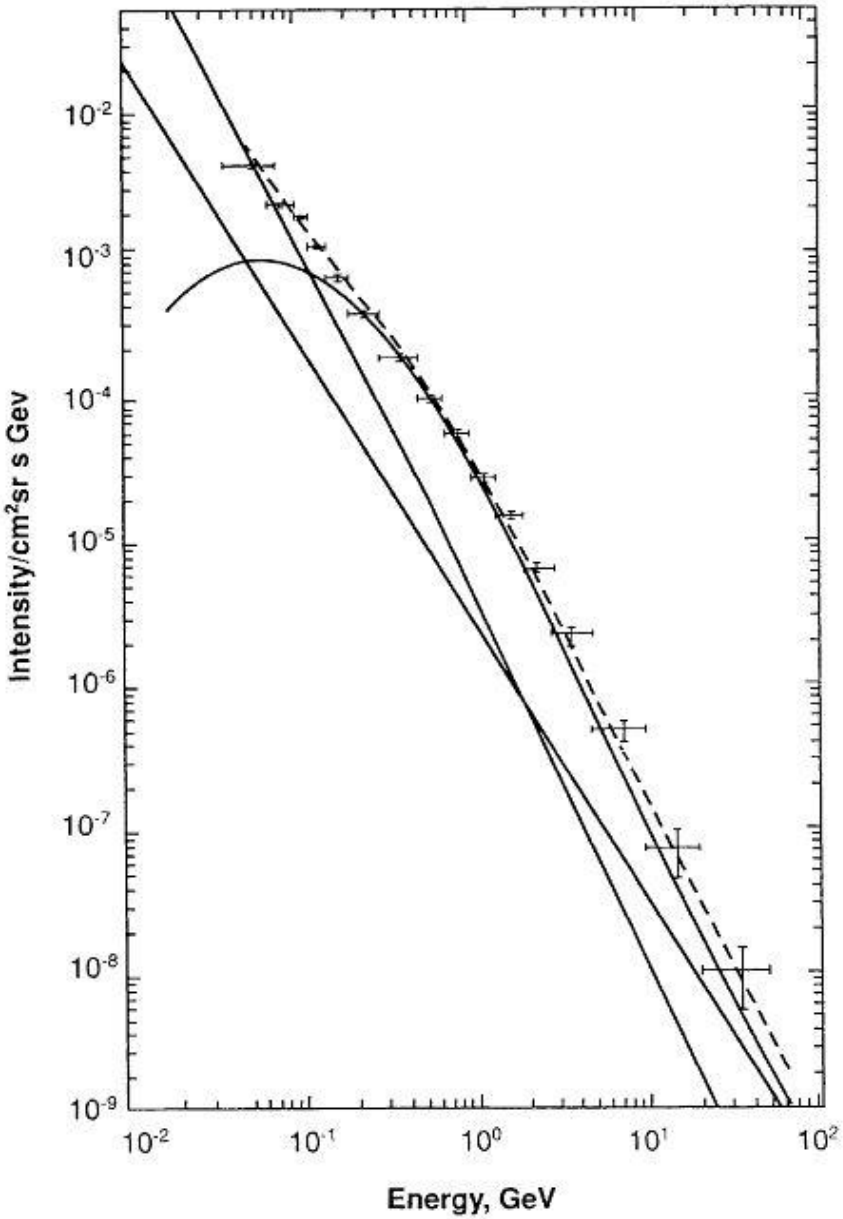

FIGURE 2. The energy spectrum for the galactic center region ($5^0 > b > -5^0, 10^0 > l > -10^0$) obained with EGRET compared to the expected energy spectrum discussed in the text.

December 1995

1995ApJS..101..259T

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THE SECOND EGRET CATALOG OF HIGH-ENERGY GAMMA-RAY SOURCES

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Received 1995 February 21; accepted 1995 May 30

ABSTRACT

The second catalog of high-energy gamma-ray observations from the Energetic Gamma-Ray Experiment Telescope (EGRET) on the *Compton Gamma Ray Observatory* includes data from phase 1 (1991 April–1992 November) and phase 2 (1992 November–1993 September) of the mission. In addition to including more data than the first EGRET catalog, this catalog uses an improved model of the diffuse Galactic gamma radiation. The 129 sources in the catalog include one solar flare bright enough to be detected as a source, the Large Magellanic Cloud, five pulsars, 40 high-confidence identifications of active galactic nuclei (AGNs), 11 AGN identifications with lower confidence, and 71 sources not yet identified with known objects. Also included are approximate upper limits for gamma-ray sources at any point in the sky and information about sources listed in the first EGRET catalog but not appearing in this one.

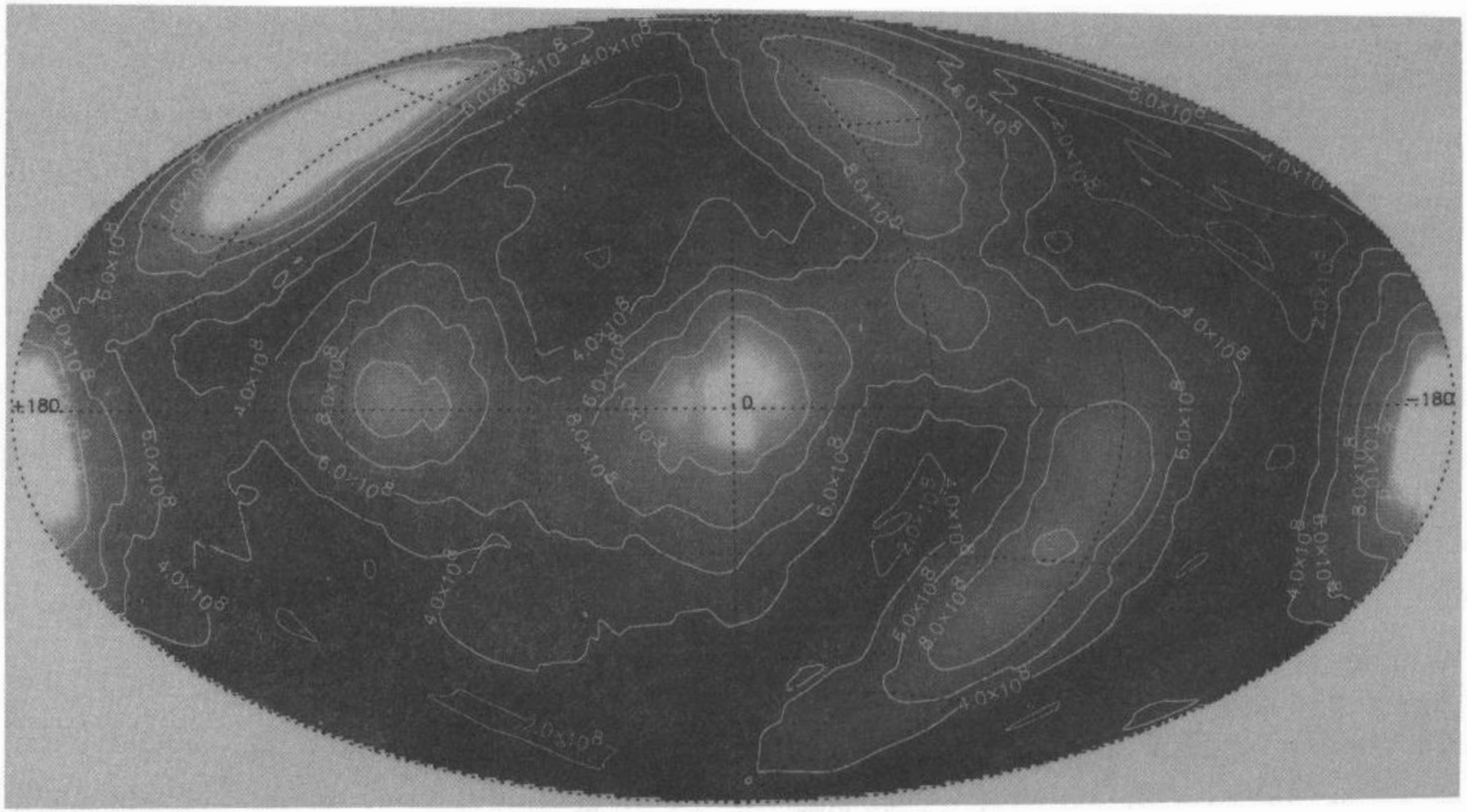

FIG. 1.—EGRET sky exposure in units of cm^2 s ($E > 100$ MeV) for *Compton Observatory* phase 1 (1991 April–1992 November) and phase 2 (1992 November–1993 September). The contours are 2.0×10^8, 4.0×10^8, 6.0×10^8, 8.0×10^8, 10×10^8, and 12×10^8.

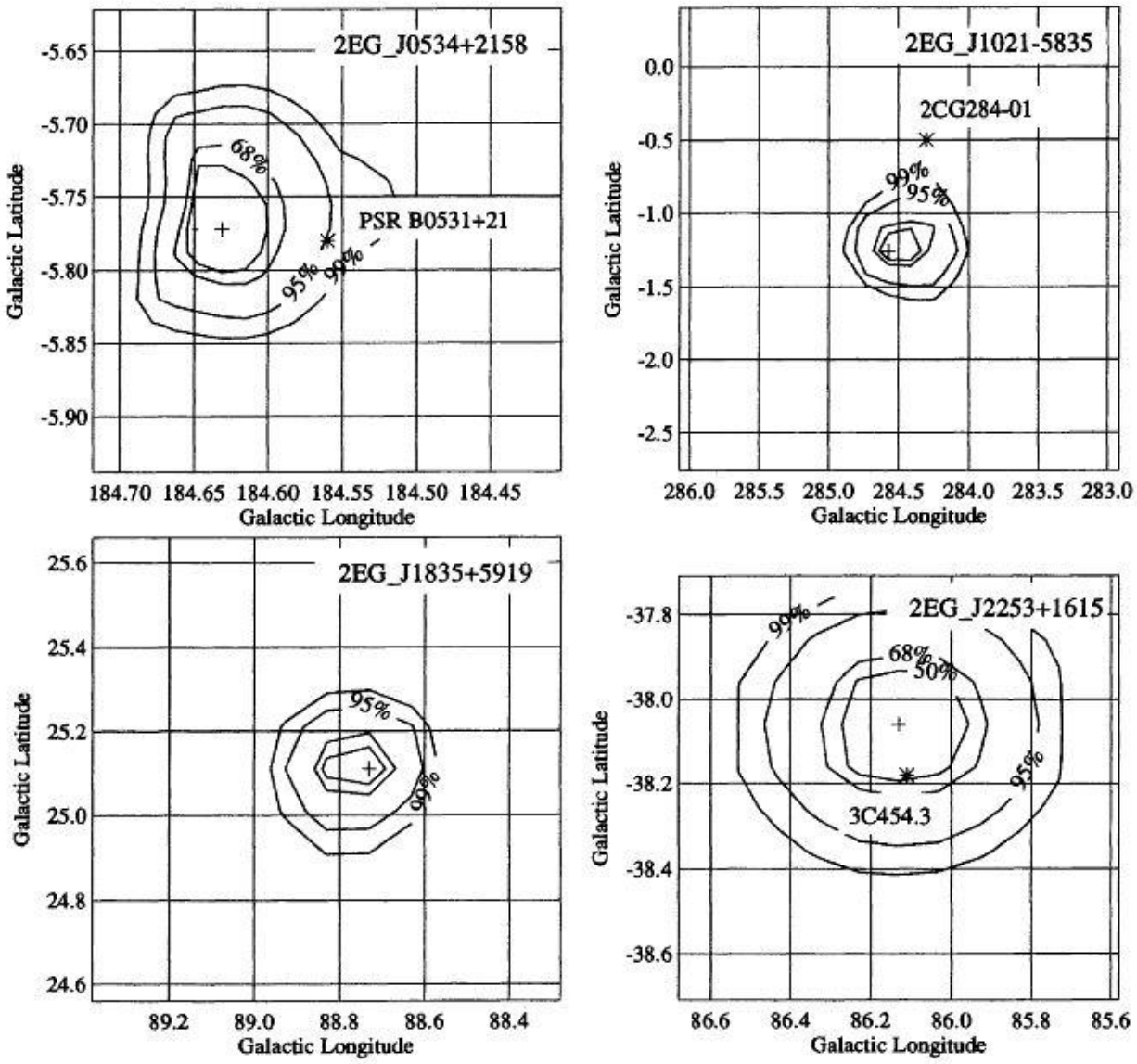

FIG. 2.—Maps of locations of four bright sources in this catalog. The contours represent the statistical probability that a single source lies within the given contour. In each map, the plus sign marks the location of the highest likelihood test statistic. An asterisk marks the location of objects seen at other wavelengths that may be related to the gamma-ray source.

December 1996

1996A&AS..120C..23F

ASTRONOMY & ASTROPHYSICS
SUPPLEMENT SERIES

Astron. Astrophys. Suppl. Ser. **120,** 23-29 (1996)

DECEMBER III **1996**, PAGE 23

EGRET overview: Achievements in the light of expectations

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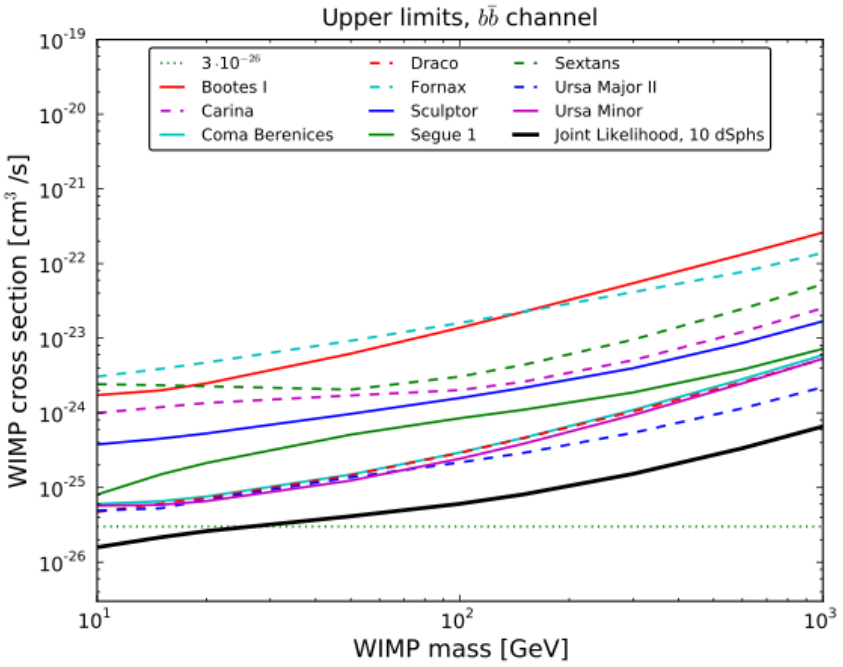
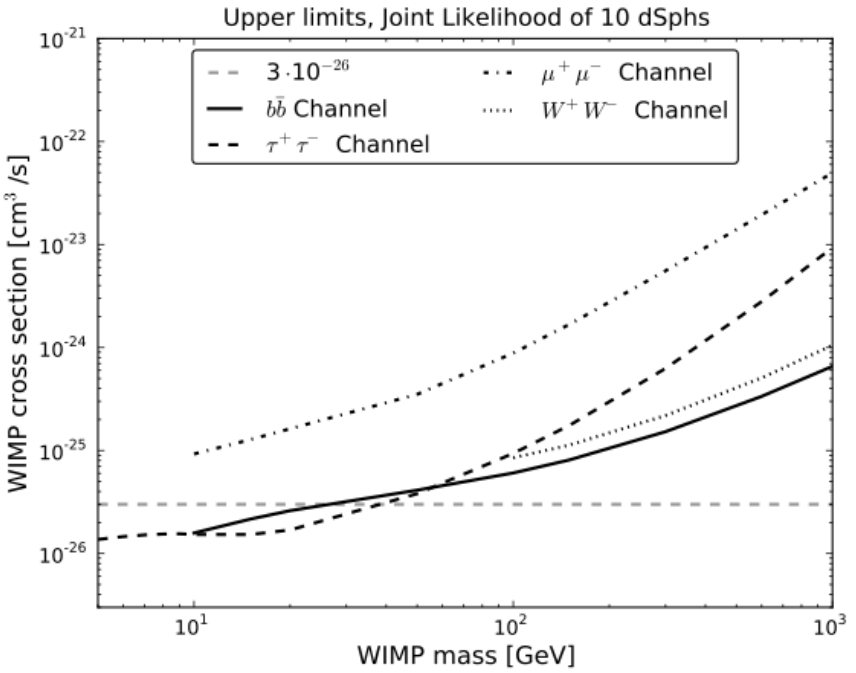
DM constraints from dwarf spheroidal galaxies (satellites)





$$L(\langle\sigma_{ann}v\rangle, m_{WIMP}; \vec{\Theta}) = \prod_{i=1}^{N} L_i(\langle\sigma_{ann}v\rangle, m_{WIMP}, C, b_i; \vec{\Theta}_i)$$

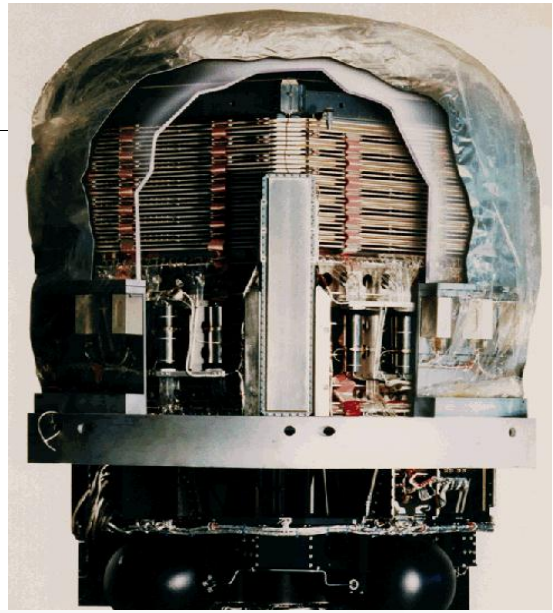
Constants (e.g. branching fraction in our case)

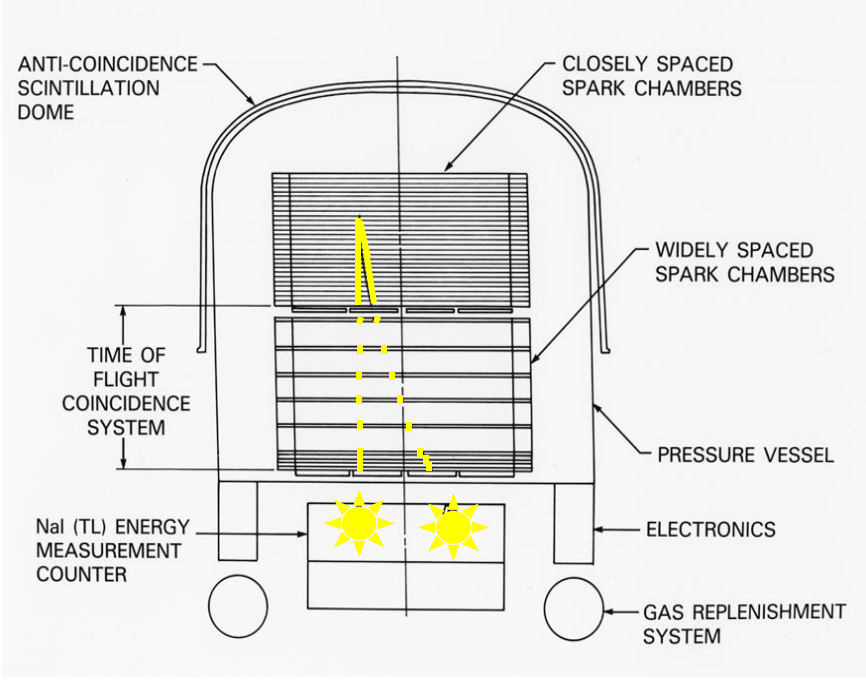
DM properties Same for all dSphs

Individual parameters (e.g. galactic diffuse normalisation..)

2011, arXiv:1108.3546v2

EGRET





EGRET Properties:

Range: 20 MeV – 30 GeV

Eff. area (on axis):~ 1000 cm^2

Angular resolution:~ 5.8° $(E/100\ MeV)^{-0.5}$

Position accuracy: ~ 5-10 arcmin

Field of view: ~0.6 sr (dia. 50°)

Energy resolution: ~ 20%

Sensitivity (>100 MeV): ~ 5 10^{-8} $cm^{-2}s^{-1}$

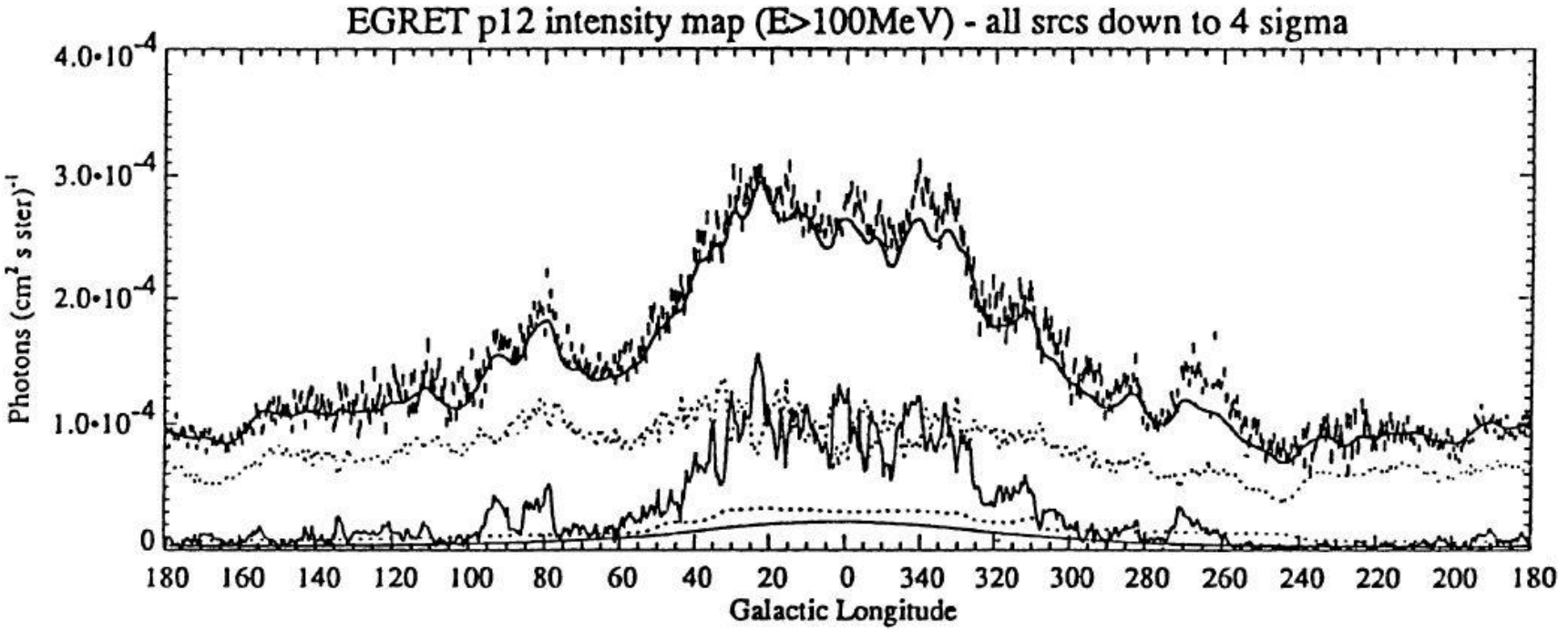


Fig. 7. The diffuse gamma-ray emission (E>100 MeV) measured by EGRET as a function of galactic longitude for the interval $-10° < b < 10°$ compared to the expected distribution. The figure is from Hunter et al. (1995)

July 1999

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 123:79–202, 1999 July
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THE THIRD EGRET CATALOG OF HIGH-ENERGY GAMMA-RAY SOURCES

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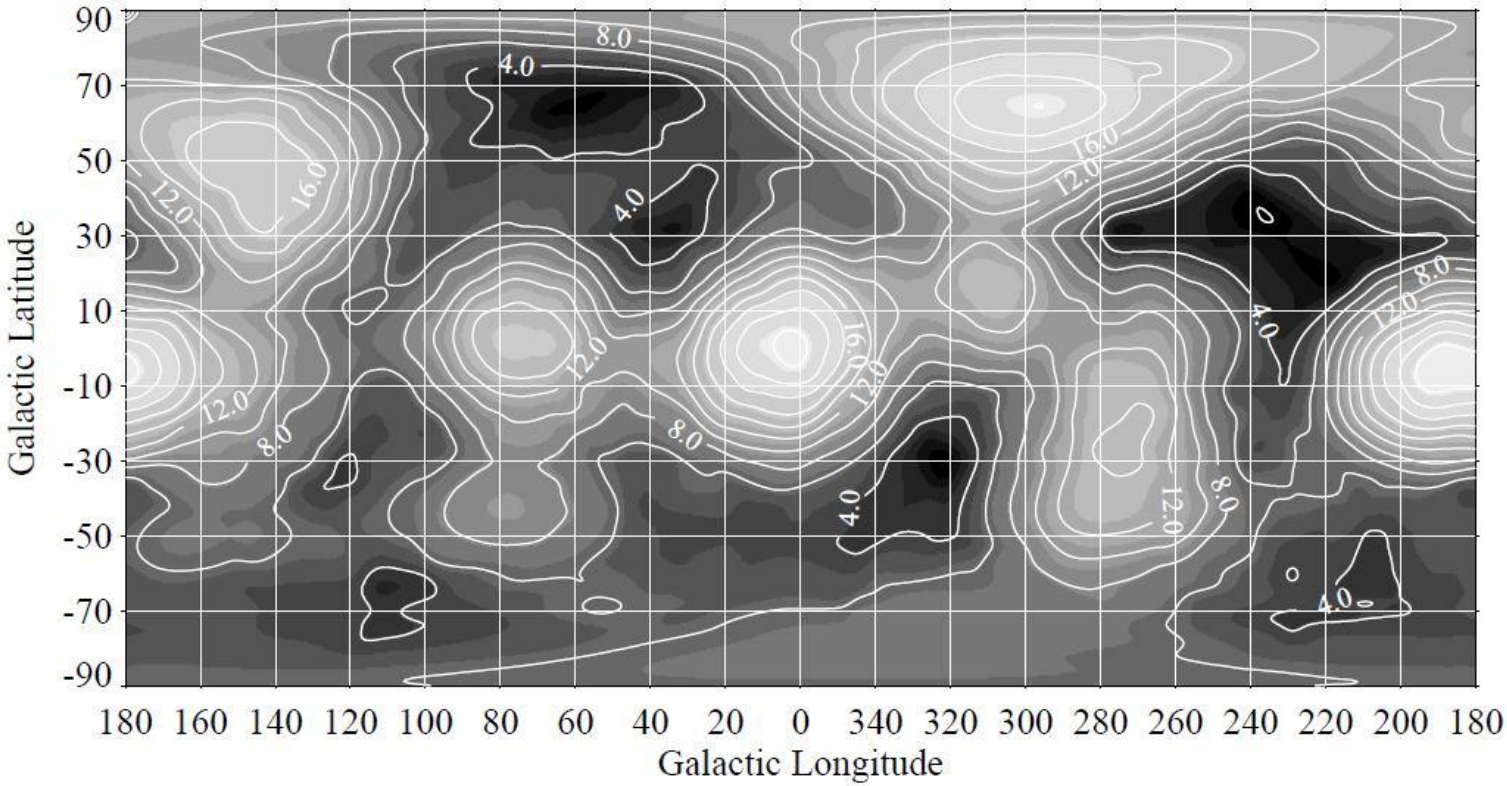
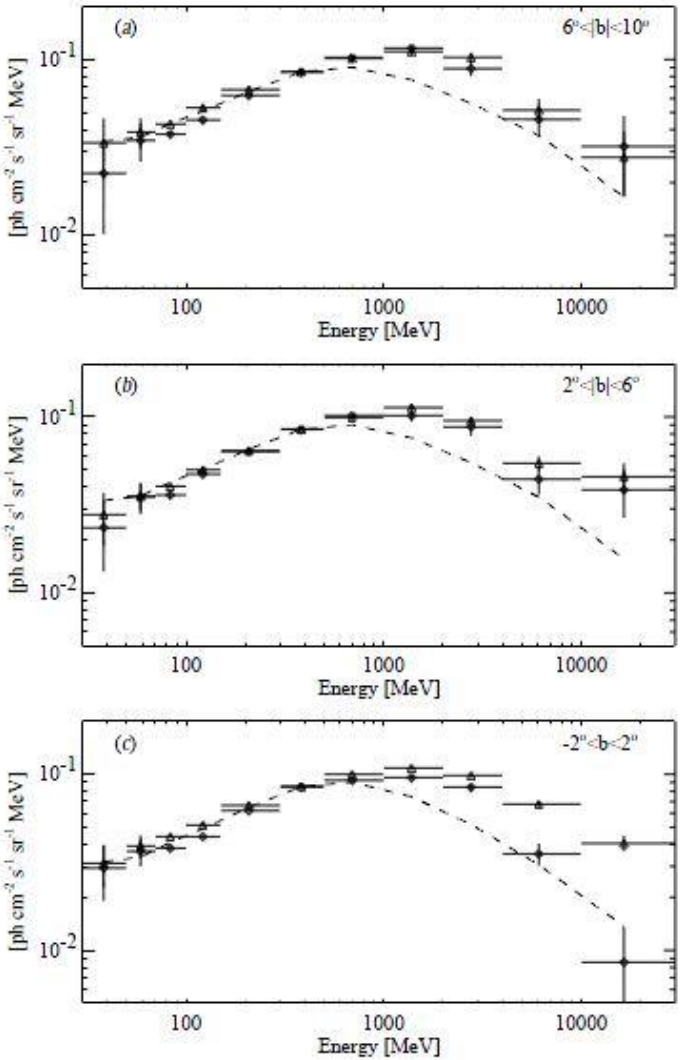
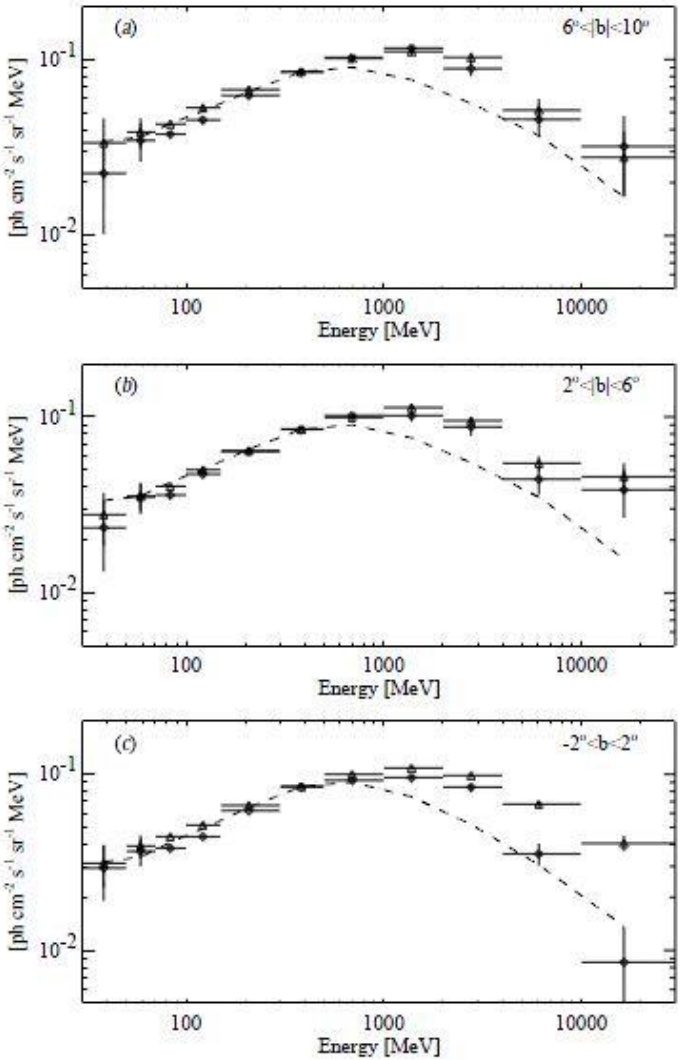


FIG. 1.—EGRET sky exposure in units of 10^8 cm^2 s (>100 MeV) for the sum of *CGRO* cycles 1, 2, 3, and 4 (1991 April 20–1995 October 3). The contours are spaced at intervals of 2×10^8.



GeV excess ?

FIG. 7.—Comparison of average spectra of the diffuse emission (the contributions from point sources detected with more than 5 σ significance and the isotropic diffuse emission have been subtracted) from the inner Galaxy ($315° < l < 45°$, *triangles*) with average spectra from the outer Galaxy ($135° < l < 225°$, *diamonds*). The medium-latitude spectra (*a*), averaged over $6° < |b| < 10°$, and (*b*), averaged over $2° < |b| < 6°$, and the low-latitude Galactic plane spectra (*c*) averaged over $|b| < 2°$, have been normalized in the 300–500 MeV energy range to the low-latitude inner-Galaxy intensity. The corresponding similarly normalized average emission from the model (see § 5) is shown as the dotted line.



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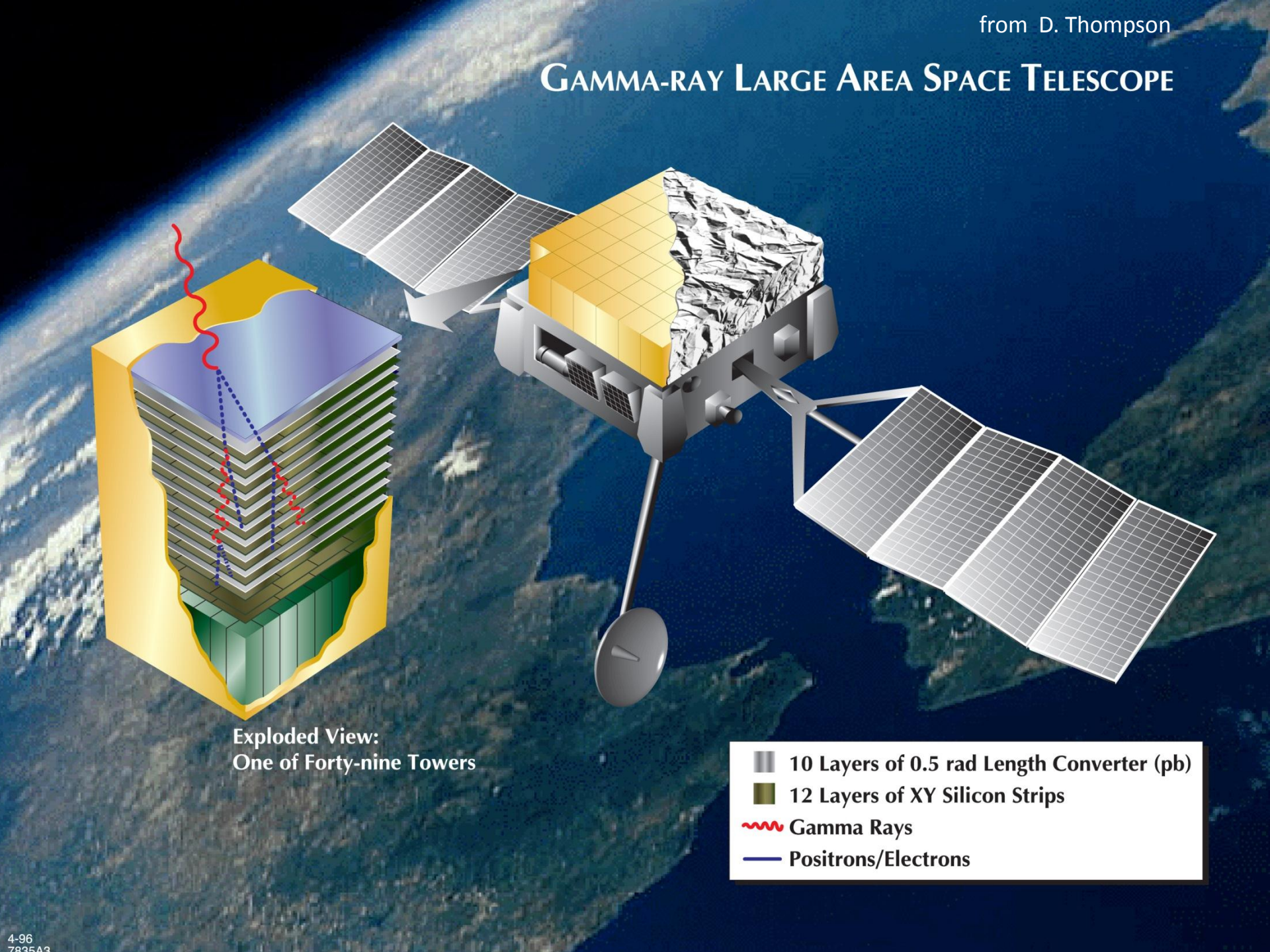
from D. Thompson

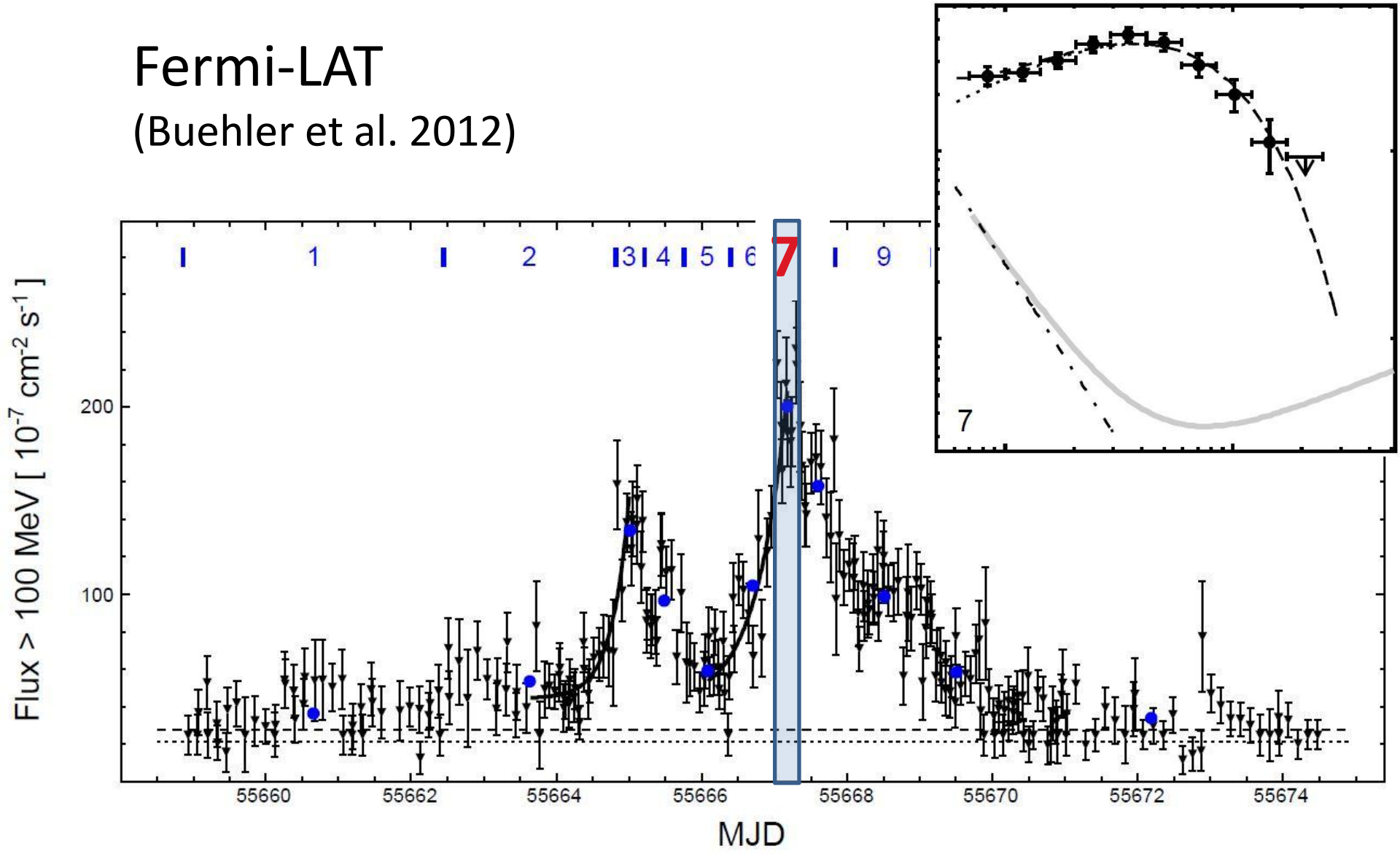
GAMMA-RAY LARGE AREA SPACE TELESCOPE



4-96

Fermi-LAT

(Buehler et al. 2012)

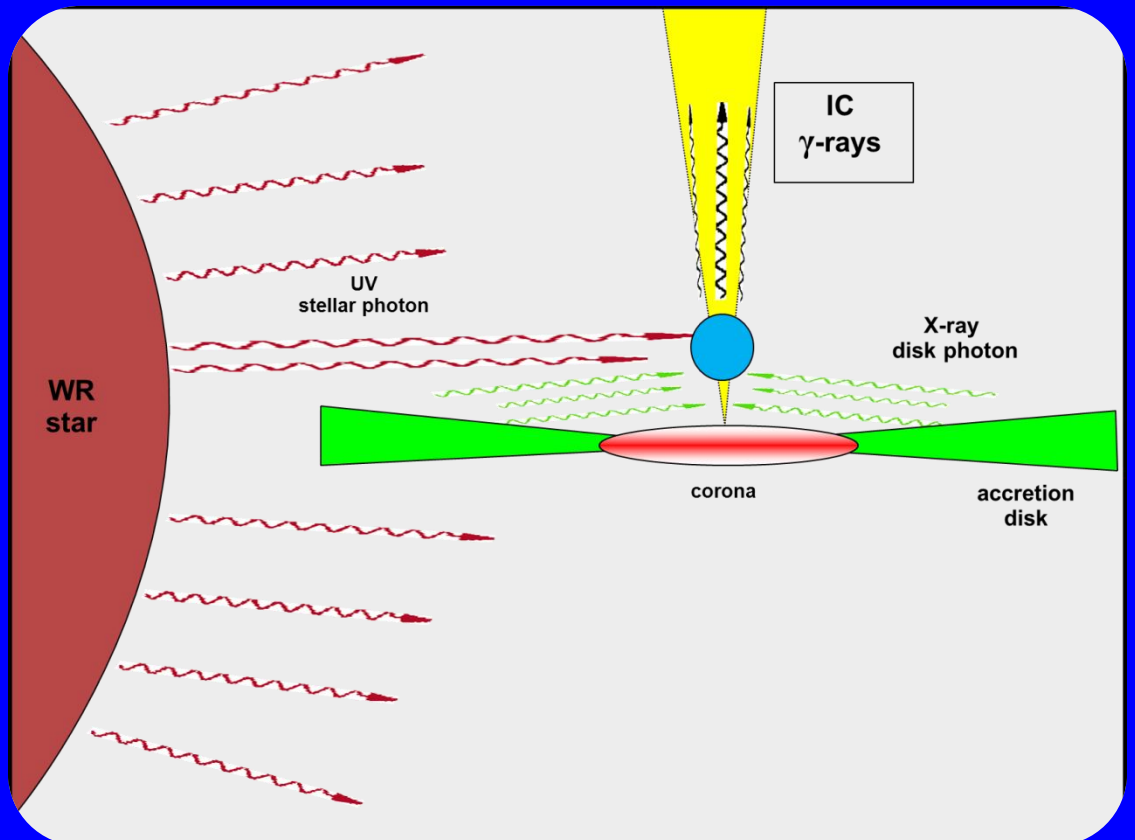


γ-ray emission from Cygnus X-3

A LEPTONIC model:

- corona "evacuation"
- injection of a spherical plasmoid of relativistic electrons/positrons scattering off soft photons from the disk and from the wind of the WR star

- γ-rays from IC processes in the jet



Cygnus X-3 multi-wavelength spectrum (model "A")

Star:

$L \sim 10^{39}$ erg/s

Disk:

$T_{bb} \sim 1.3$ keV

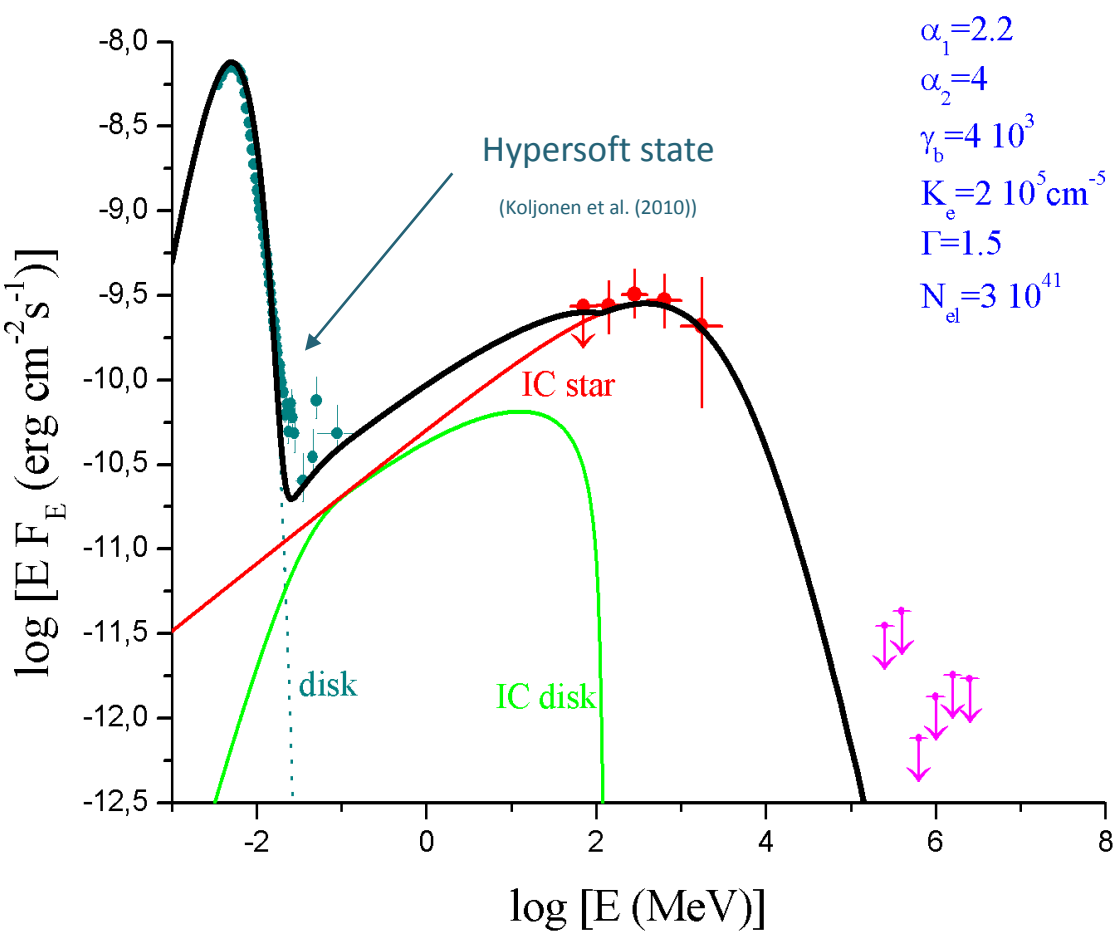
Spherical plasmoid:

$R \sim 3 \cdot 10^{10}$ cm

Broken power-law:

$$\frac{dN}{d\gamma dV} = \frac{K_e \gamma_b^{-1}}{\left(\frac{\gamma}{\gamma_b}\right)^{\alpha_1} + \left(\frac{\gamma}{\gamma_b}\right)^{\alpha_2}} \qquad [\alpha_1 < \alpha_2]$$

(Piano et al., 2012, Submitted to A&A)



Geometry of the interaction:

(d ≡ orbital distance)

(D ≡ star-blob distance)

(H ≡ disk-blob distance)

$H \sim 3 \cdot 10^{10}$ cm

$D \sim d \sim 3 \cdot 10^{11}$ cm

(plasmoid close to the disk)

electron density $\sim 3 \cdot 10^9$ cm^{-3}

Cygnus X-3 multi-wavelength spectrum (model "B")

Star:

$L \sim 10^{39}$ erg/s

Disk:

$T_{bb} \sim 1.3$ keV

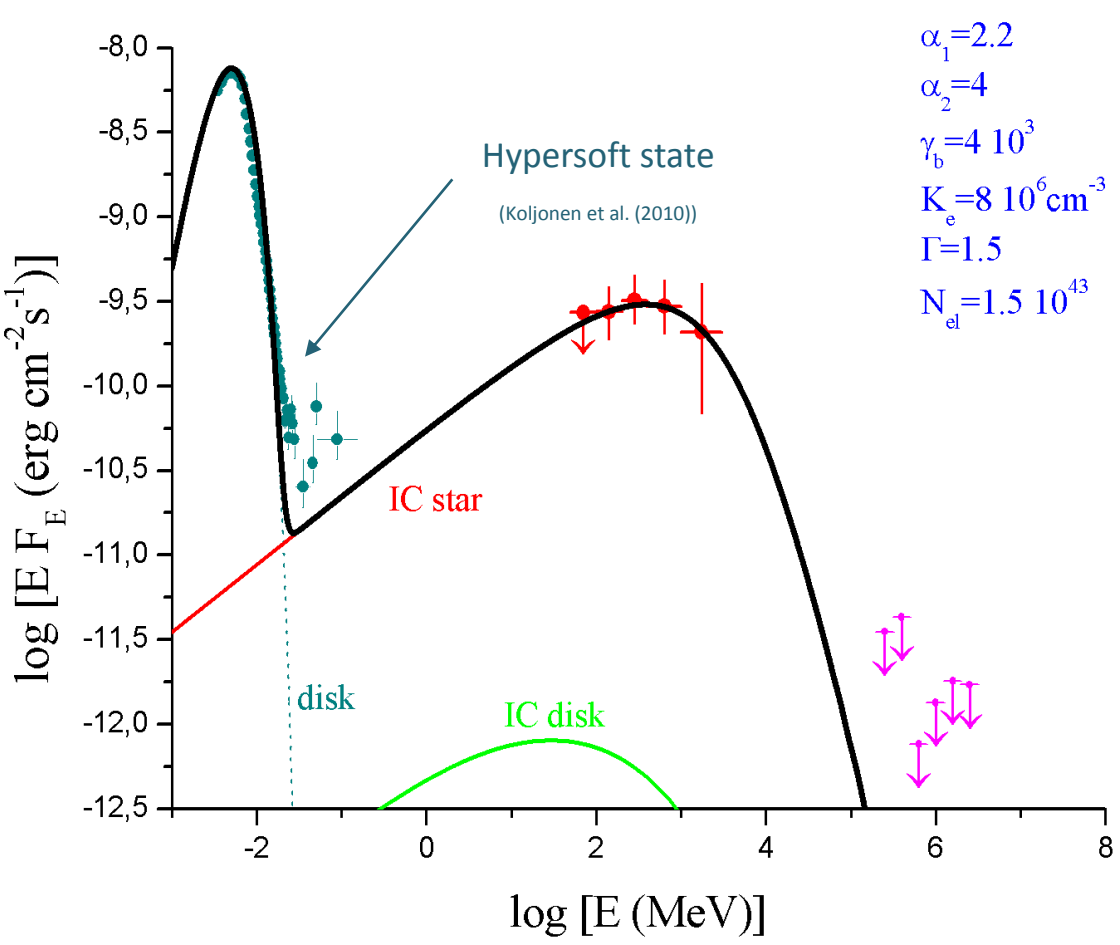
Spherical plasmoid:

$R \sim 3 \cdot 10^{10}$ cm

Broken power-law:

$$\frac{dN}{d\gamma dV} = \frac{K_e \gamma_b^{-1}}{\left(\frac{\gamma}{\gamma_b}\right)^{\alpha_1} + \left(\frac{\gamma}{\gamma_b}\right)^{\alpha_2}} \qquad [\alpha_1 < \alpha_2]$$

(Piano et al., 2012, Submitted to A&A)



Geometry of the interaction:

(d ≡ orbital distance)

(D ≡ star-blob distance)

(H ≡ disk-blob distance)

$H \sim 3 \cdot 10^{12}$ cm ~ 10 d

$D \sim H \sim 3 \cdot 10^{12}$ cm

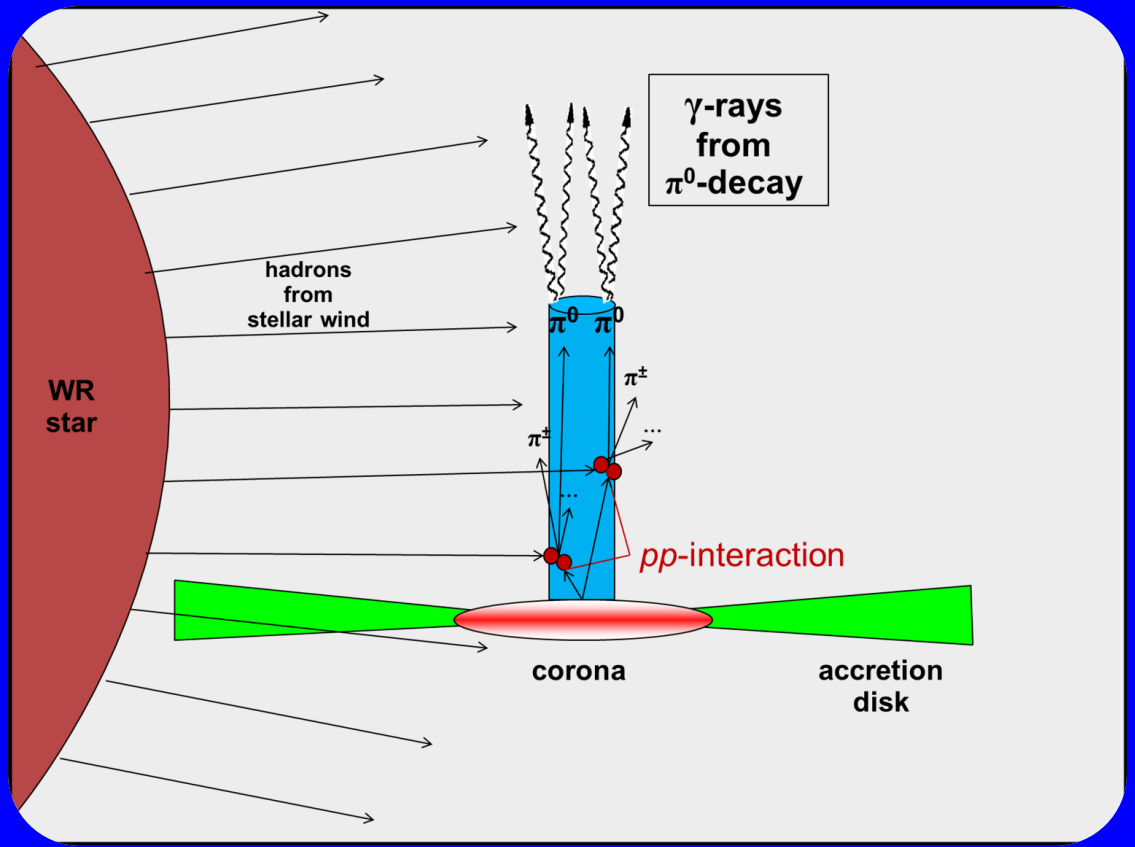
(plasmoid far away from the disk)

electron density ~ $1.5 \cdot 10^{11}$ cm^{-3}

γ-ray emission from Cygnus X-3

A HADRONIC model:

- injection of mildly relativistic protons
- interaction with the gas of the WR strong wind along a cylindrical column of matter (radius R~ $3 \cdot 10^{10}$ cm, height H ~ $3 \cdot 10^{12}$ cm)
- inelastic scatterings: $p + p \rightarrow \pi^0 + \ldots$; $\pi^0 \rightarrow \gamma + \gamma$



A hadronic model (?)

Strong stellar wind:

$v_{wind} \sim 1000 \text{ km s}^{-1}$

$\dot{M} \sim 10^{-5} M_{\odot} \text{yr}^{-1}$

Geometry of the interaction:

injected proton interact with the hadronic matter of the wind along a cylinder

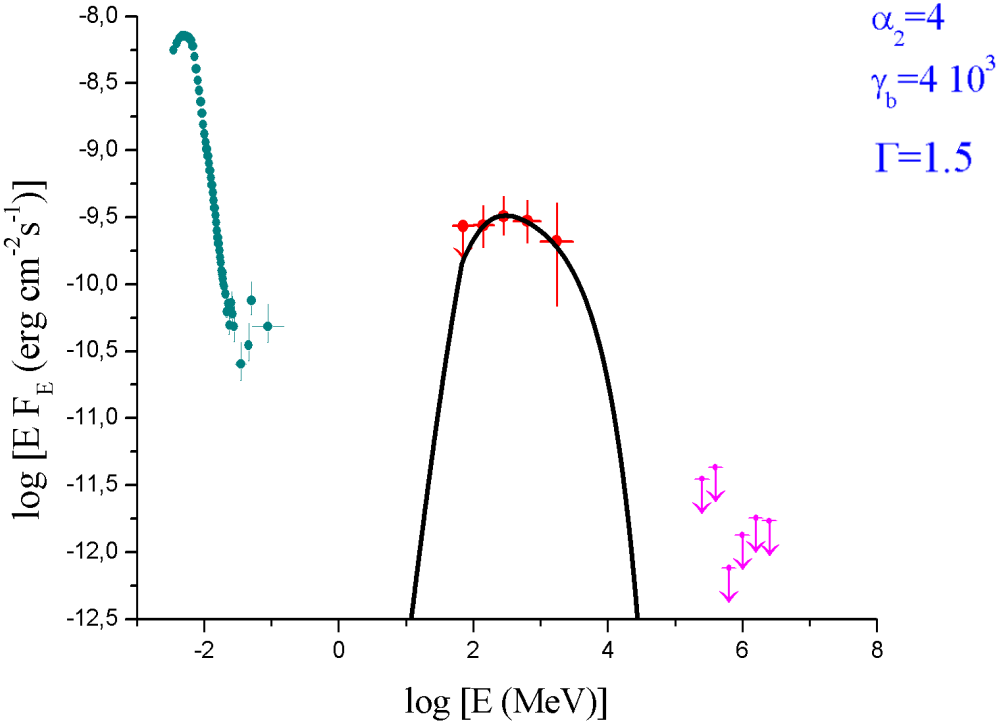
R~ $3 \cdot 10^{10}$ cm

H~ $3 \cdot 10^{12}$ cm

Broken power-law:

$$\frac{dN}{d\gamma dV} = \frac{K_e \gamma_b^{-1}}{\left(\frac{\gamma}{\gamma_b}\right)^{\alpha_1} + \left(\frac{\gamma}{\gamma_b}\right)^{\alpha_2}} \qquad [\alpha_1 < \alpha_2]$$

(Piano et al., 2012, Submitted to A&A)



Results from modeling:

$N_{p,wind} \approx 3.7 \times 10^{45}$

$N_{p,jet} \approx 2 \times 10^{45}$

$\dot{N}_{p,jet} \approx 1.4 \times 10^{43}$ protons s^{-1}

$L_{kin,\,p} \approx 3 \times 10^{40}$ erg s^{-1}

Jet kinetic luminosity exceeds:

- Disk luminosity of the Hypersoft state (L_{HYS}~10^{38} erg s^{-1})
- Eddington accretion limit (L_{Edd}~10^{39} erg s^{-1})

Spectral modeling: discussion

Both leptonic and hadronic models might account for the γ-ray flaring spectrum of Cygnus X-3 but…

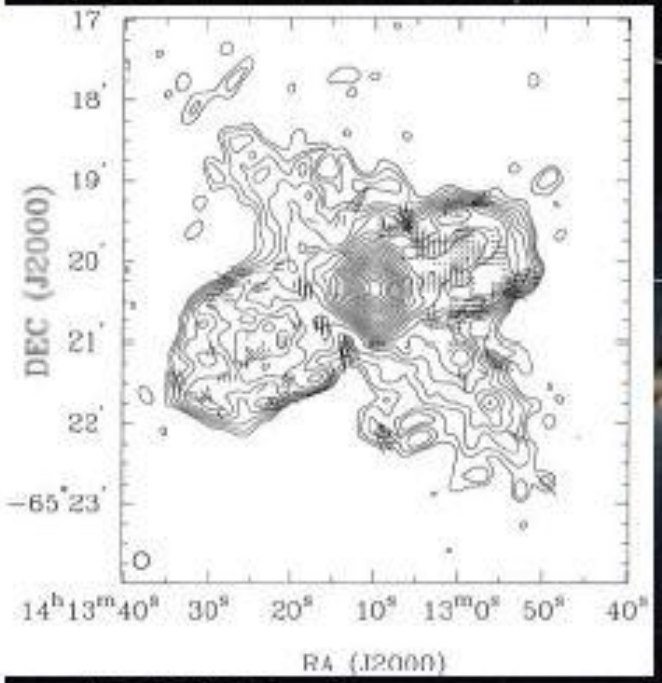
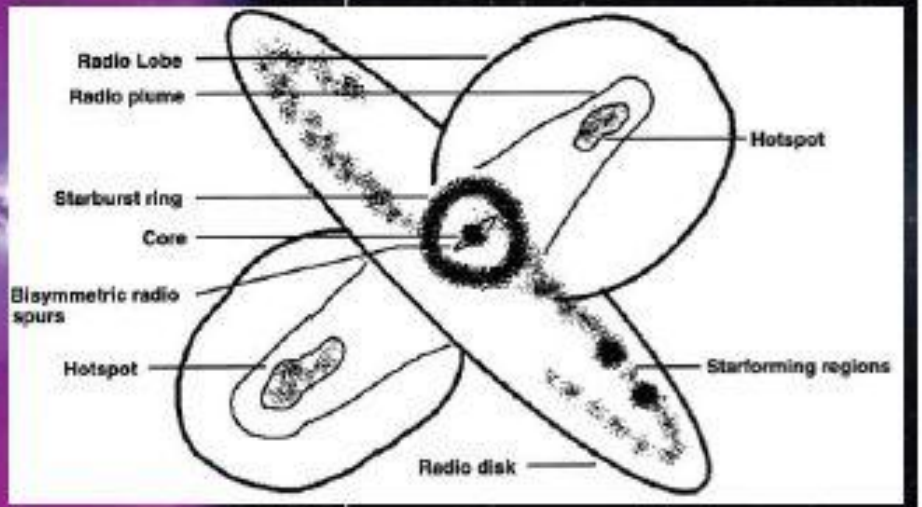
- **Hadronic models** requires very high jet kinetic power ($L_{kin,\,p} > L_{Edd}$)
  (Does Cygnus X-3 emit hadronic jet outflows in a super-Eddington regime, like SS433?)
- **Leptonic models**
  - ✓ γ-ray modulation (Dubus et al, 2010; Zdziarski et al., 2012)
  - ✓ time delay between γ-ray and radio outflows
    (Is the same population of electrons that emits in the γ-ray and in the radio band ?)
  - ✓ low jet kinetic power:

$$L^{A}_{kin,\,e} \approx 2 \times 10^{35}\ \mathrm{erg\ s^{-1}} \qquad L^{B}_{kin,\,e} \approx 10^{37}\ \mathrm{erg\ s^{-1}}$$

  - ✓ **Model "A" → spectral link between the hard X-ray tail and the γ-ray spectrum.**

Radio Jet Activity in Nearby AGN

- Circinus galaxy (D~4 Mpc)
- Radio lobes highly polarized with extent ~6 kpc
- Hosts low-luminosity AGN



ATCA λ13cm image
Elmouttie et al. (1998)