HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

Astrofísica de rayos gamma
II. La Galaxia y más allá

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INAOE

CONACYT
Consejo Nacional de Ciencia y Tecnología

Rayos gamma @ LA-CoNGA Physics - 6 julio 2021

Astrofísica de rayos gamma

1. Rayos cósmicos.
2. Rayos gamma: producción, bandas astrofísicas y observatorios.
3. Fuentes de rayos gamma en la Galaxia.
4. Intermedio.
5. Fuentes de rayos gamma más allá de la Galaxia.

La Galaxia

1. Emisión difusa Galáctica
2. Burbujas de Fermi.
3. Tipos de fuentes Galácticas.
4. Remanentes de supernova.
5. Pulsares y pulsar wind nebulae.
6. Binarias, novas…

1. Emisión difusa Galáctica

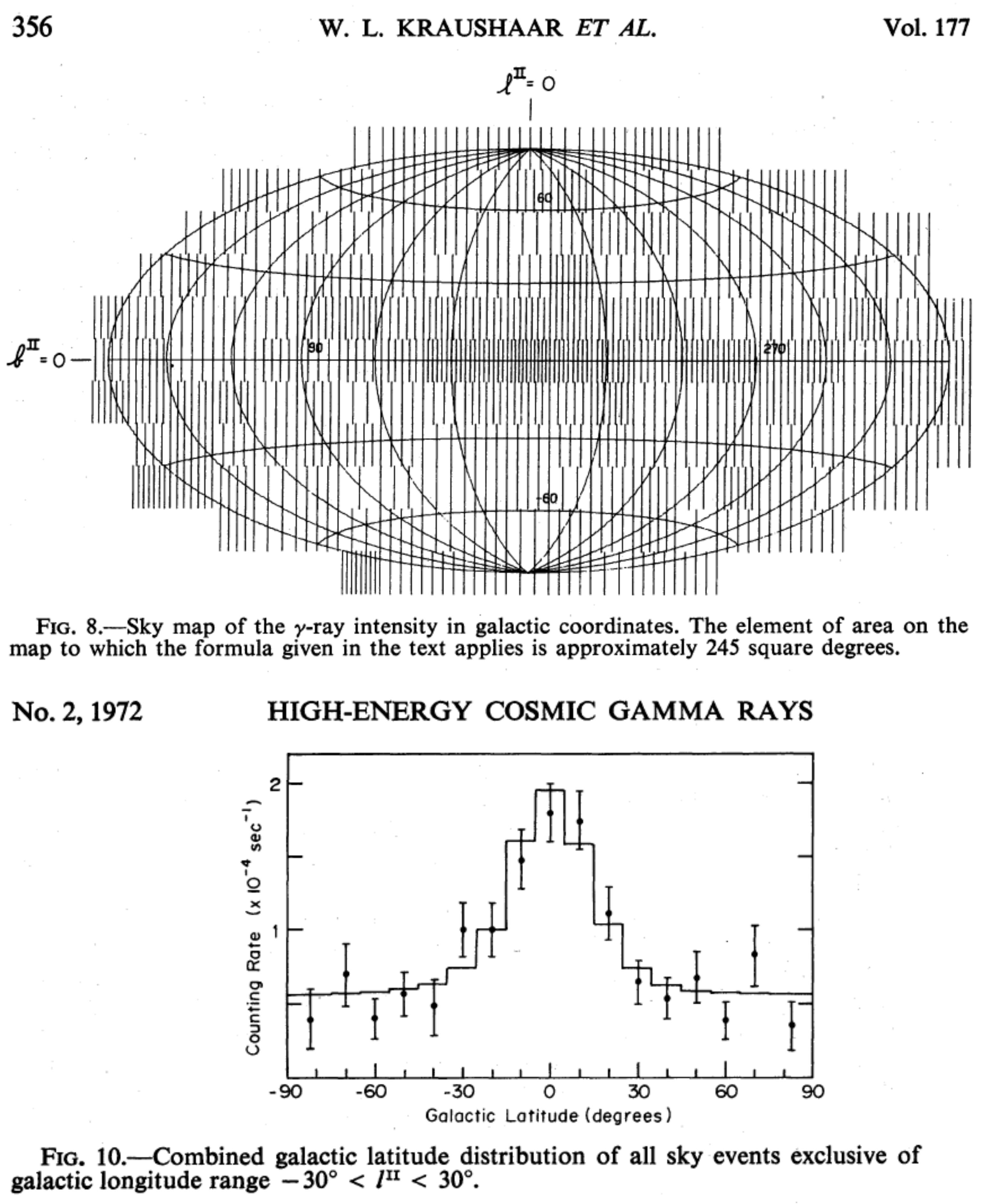
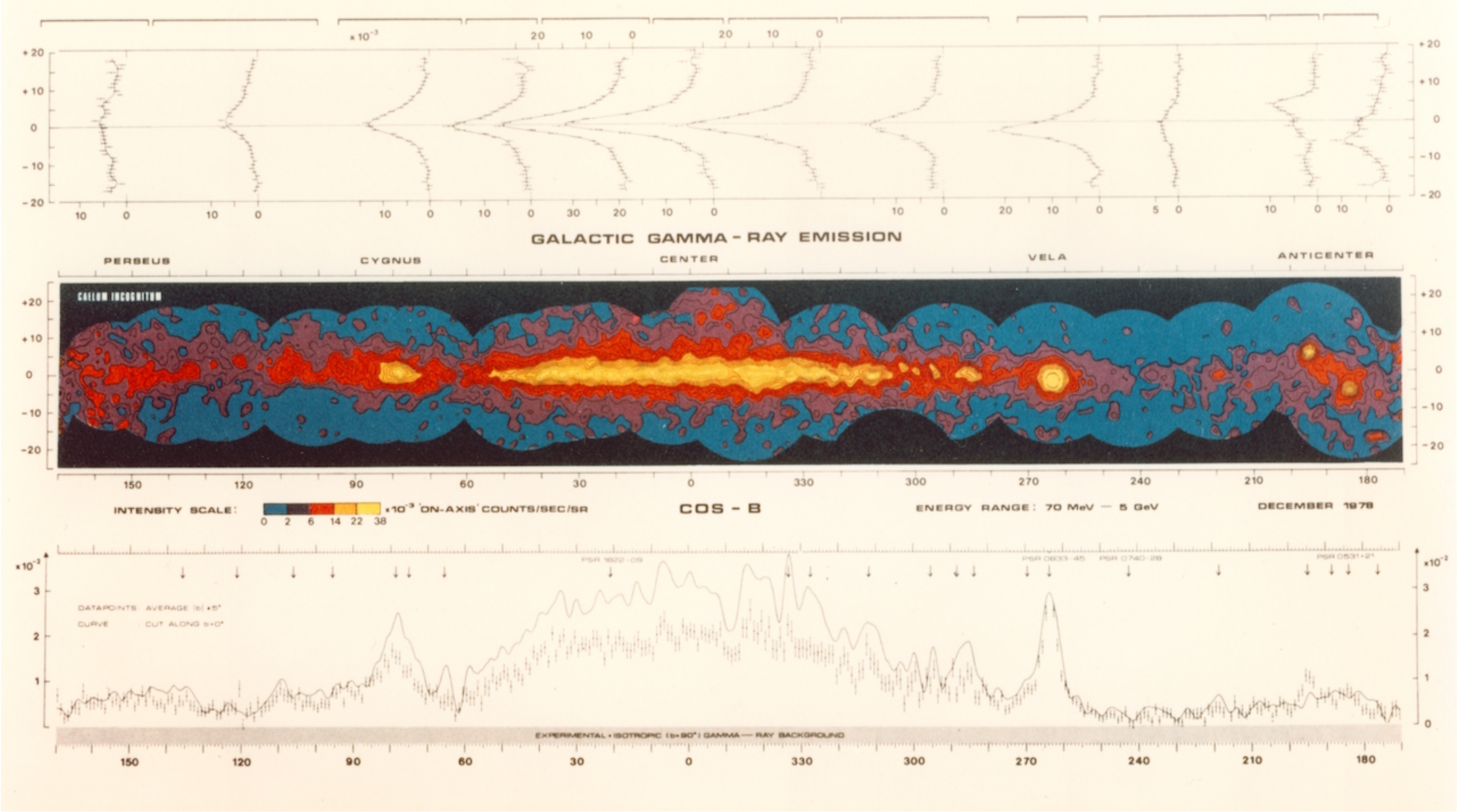

356 W. L. KRAUSHAAR *ET AL.* Vol. 177

FIG. 8.—Sky map of the γ-ray intensity in galactic coordinates. The element of area on the map to which the formula given in the text applies is approximately 245 square degrees.

No. 2, 1972 HIGH-ENERGY COSMIC GAMMA RAYS

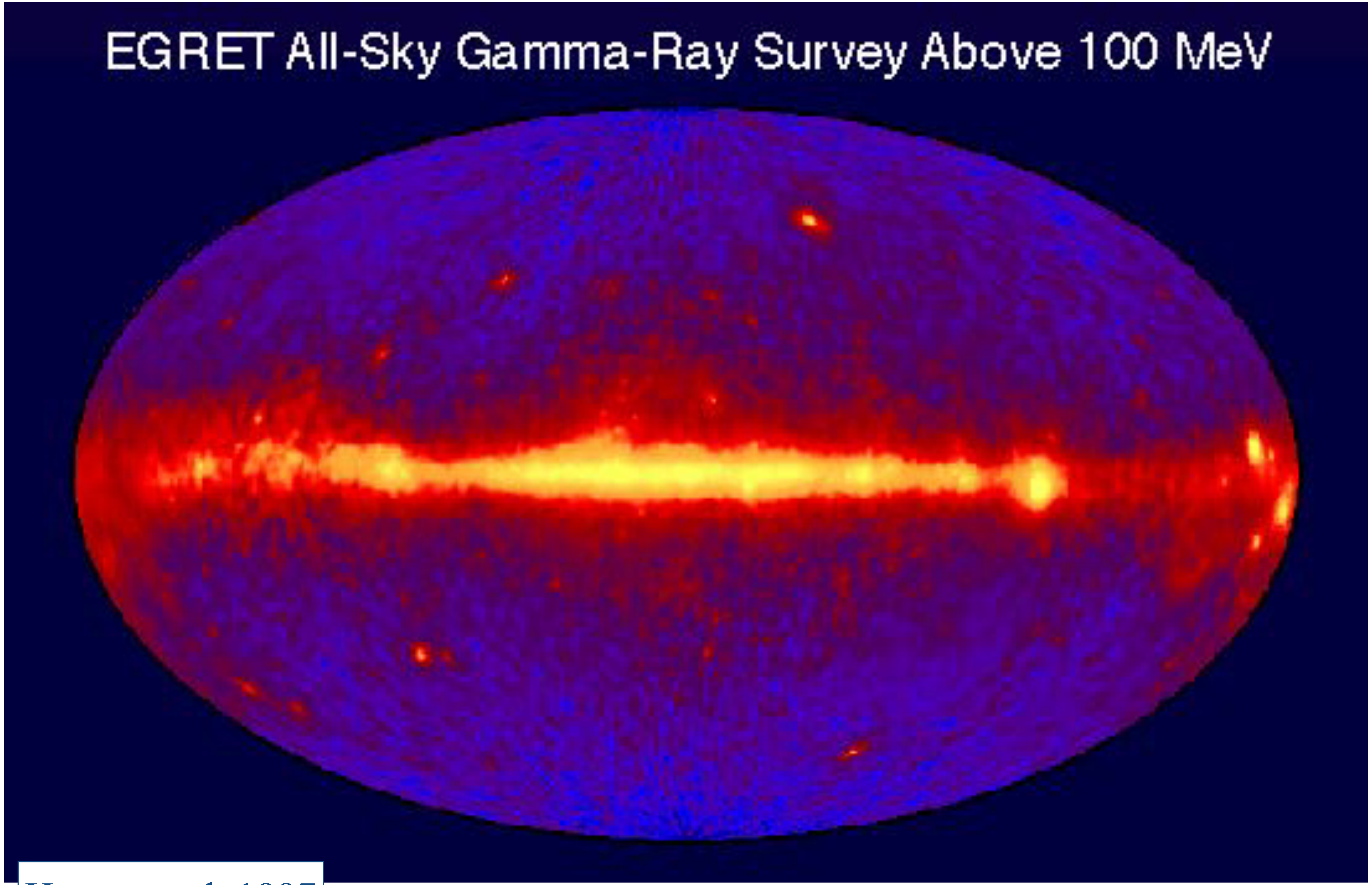
FIG. 10.—Combined galactic latitude distribution of all sky events exclusive of galactic longitude range $-30° < l^{II} < 30°$.



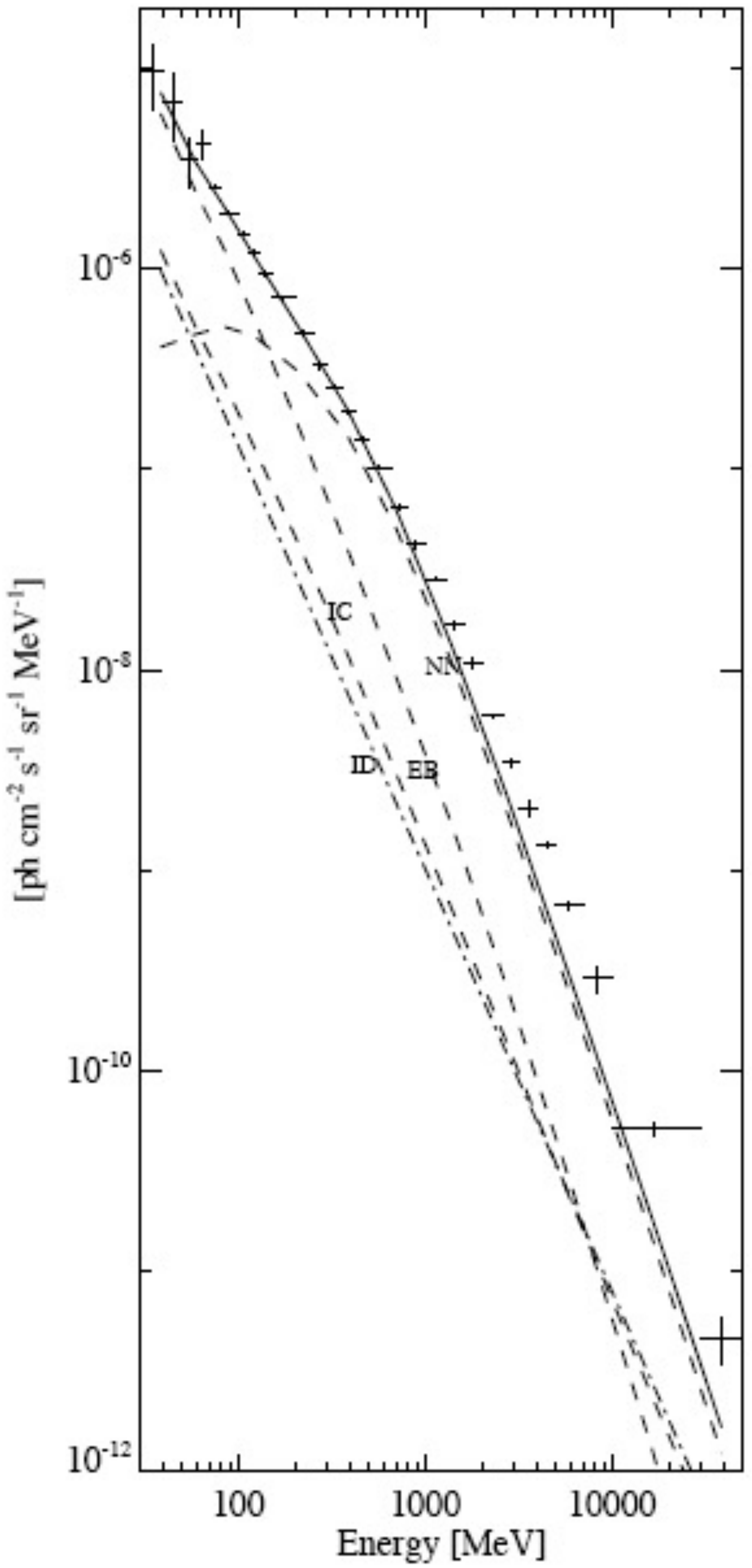
OSO-3 (1967-68): emisión difusa Galáctica y extragaláctica (621 fotones con E>50 MeV)

Kraushaar, W.L. et al. 1972, ApJ 177, 341

COS-B : Mayer-Hasselwander et al. (1982)



Hunter et al. 1997



The Astrophysical Journal Supplement Series, 232:18 (23pp), 2017 October Ajello et al.

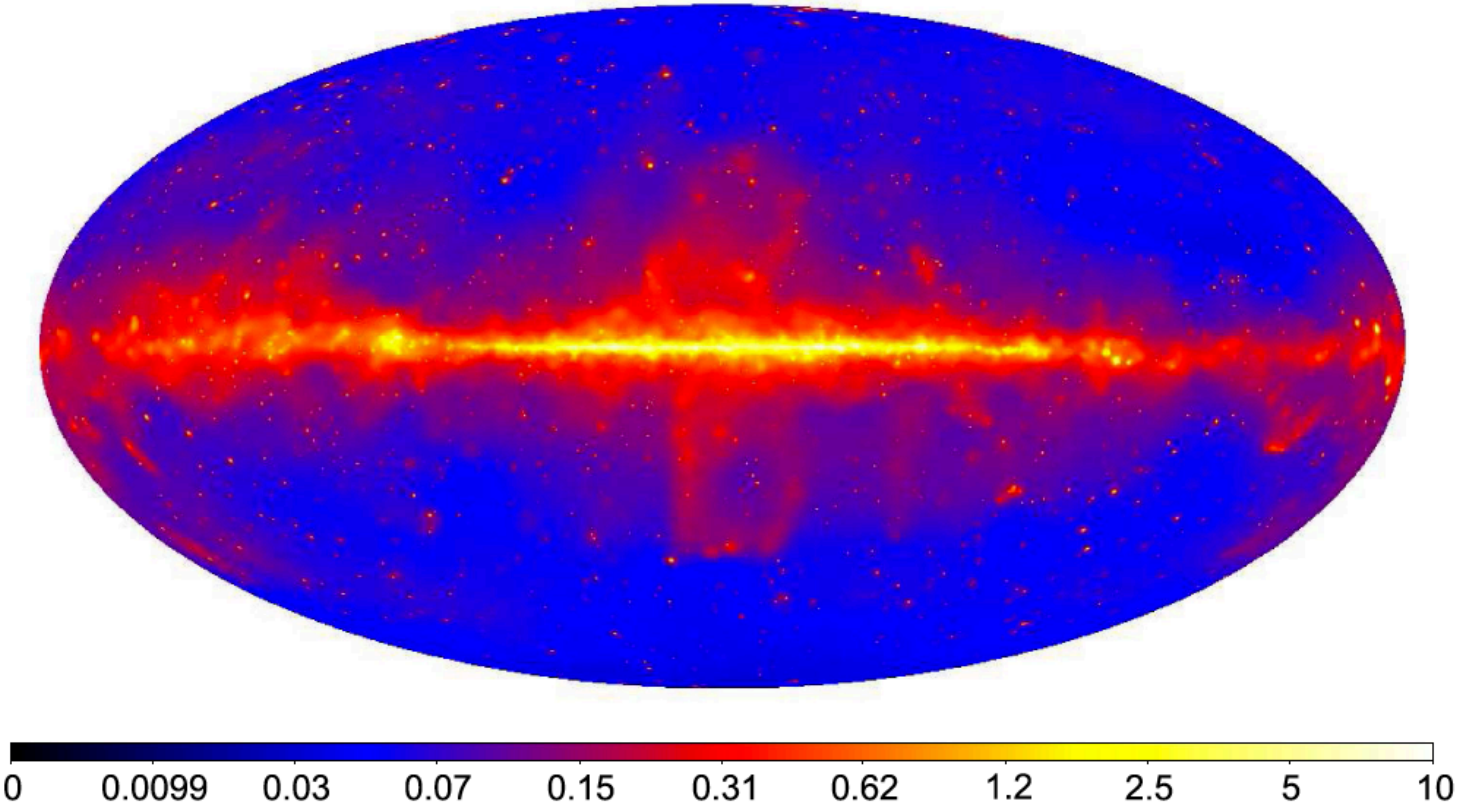
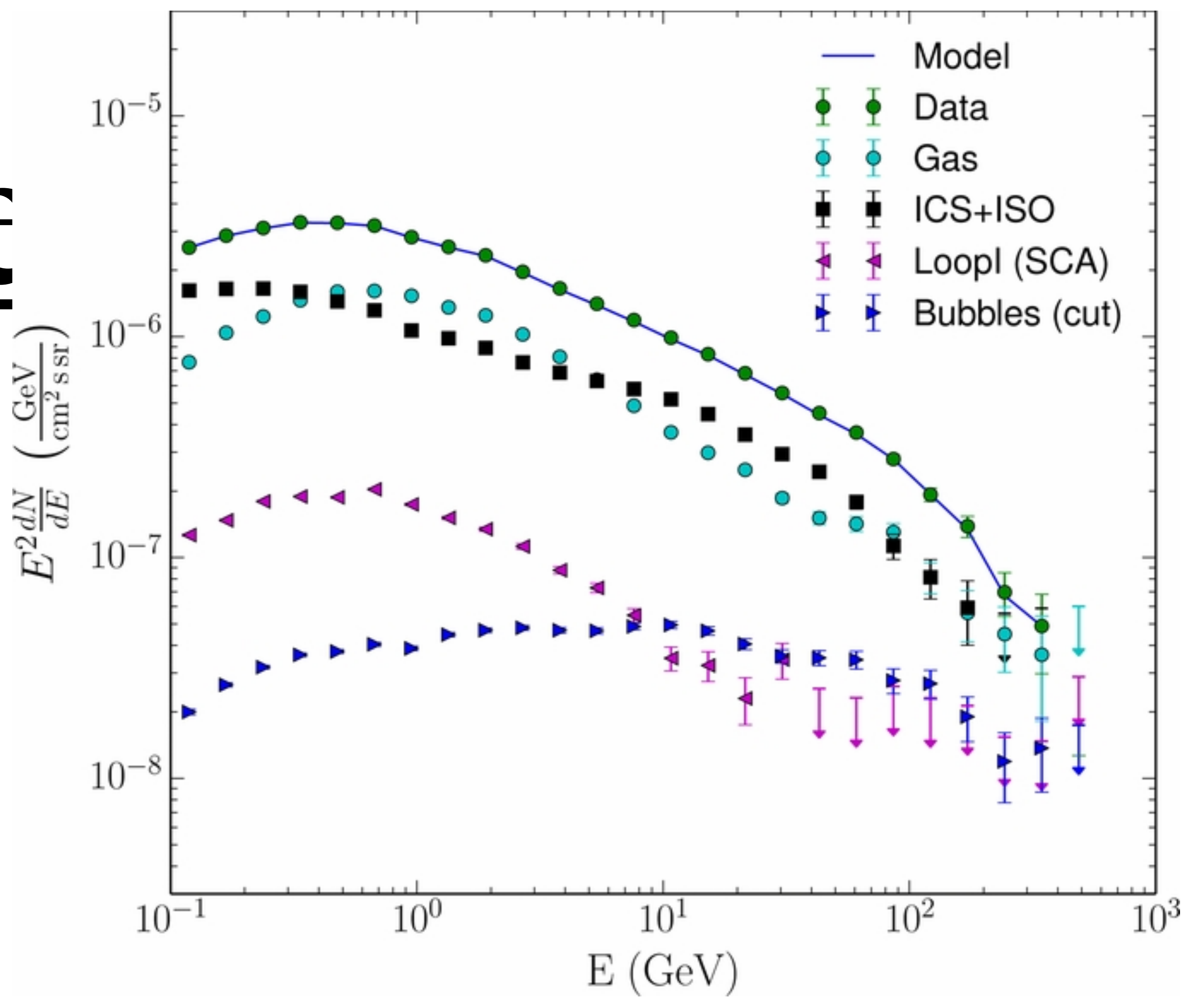


Figure 1. Adaptively smoothed *Fermi*-LAT counts map in the 10 GeV–2 TeV band represented in Galactic coordinates and Hammer–Aitoff projection. The image has been smoothed with a Gaussian kernel whose size was varied to achieve a minimum signal-to-noise ratio under the kernel of 2.3. The color scale is logarithmic and the units are counts per $(0.1\ \mathrm{deg})^2$ pixel.

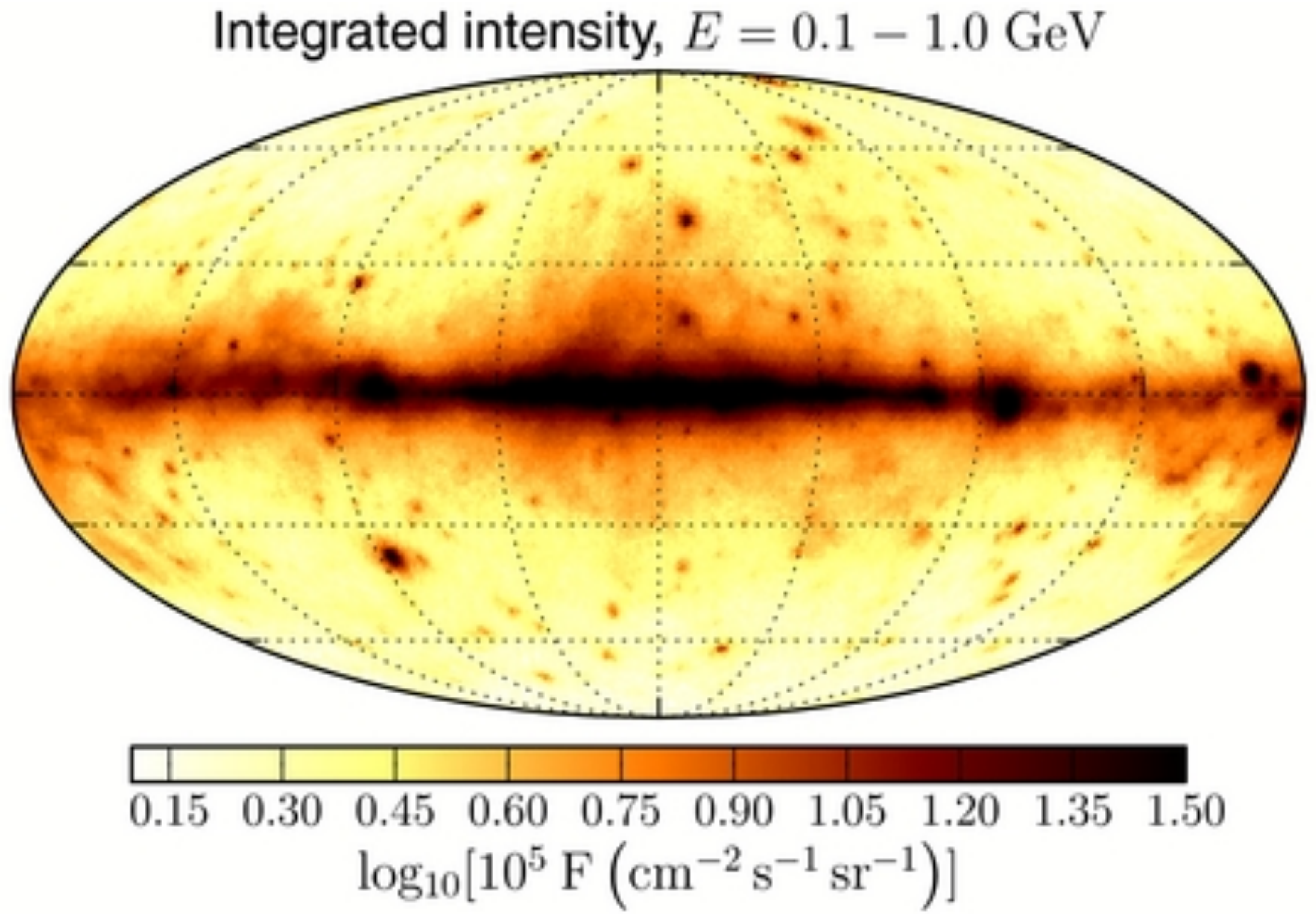
2. Burbujas de Fe

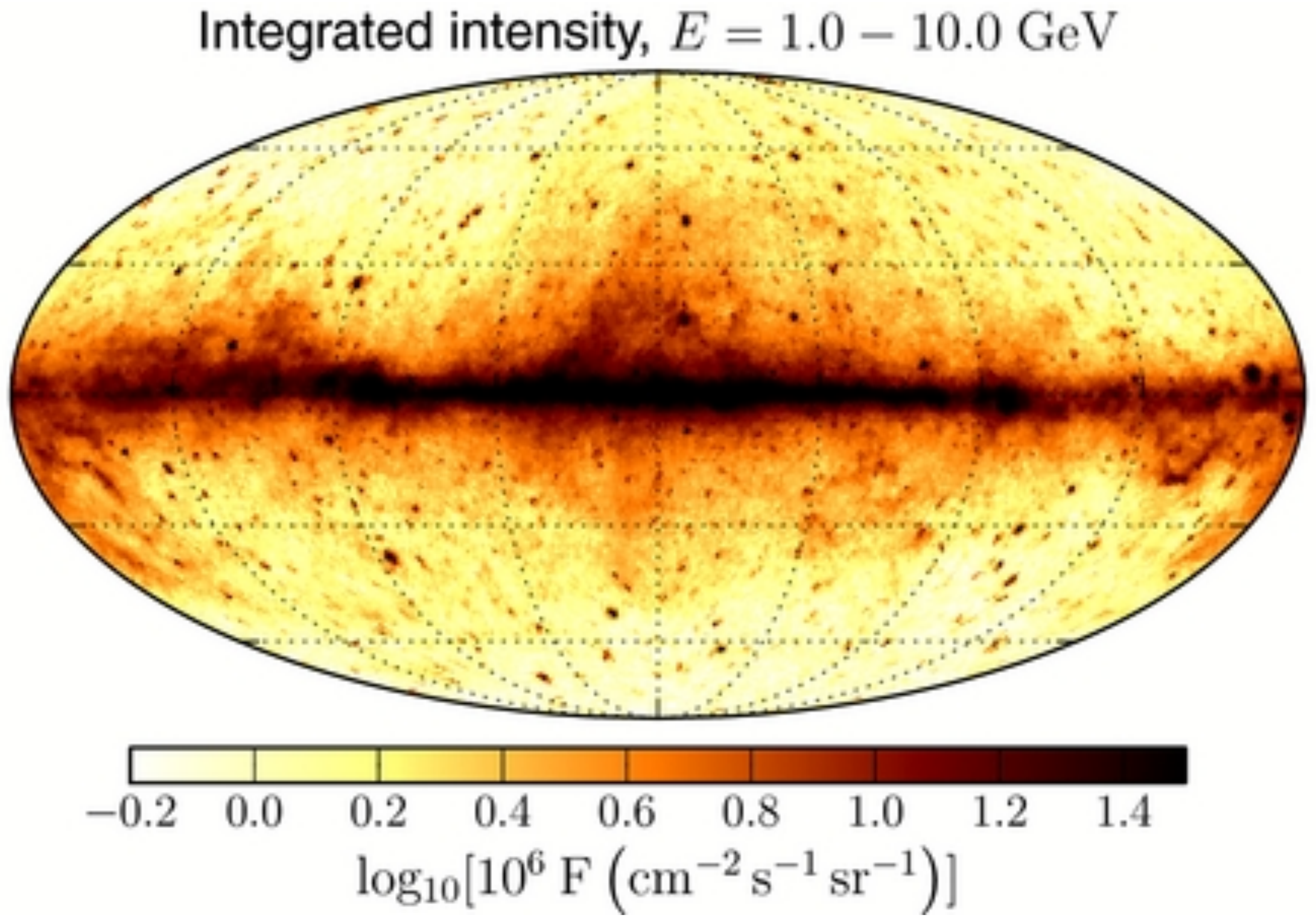


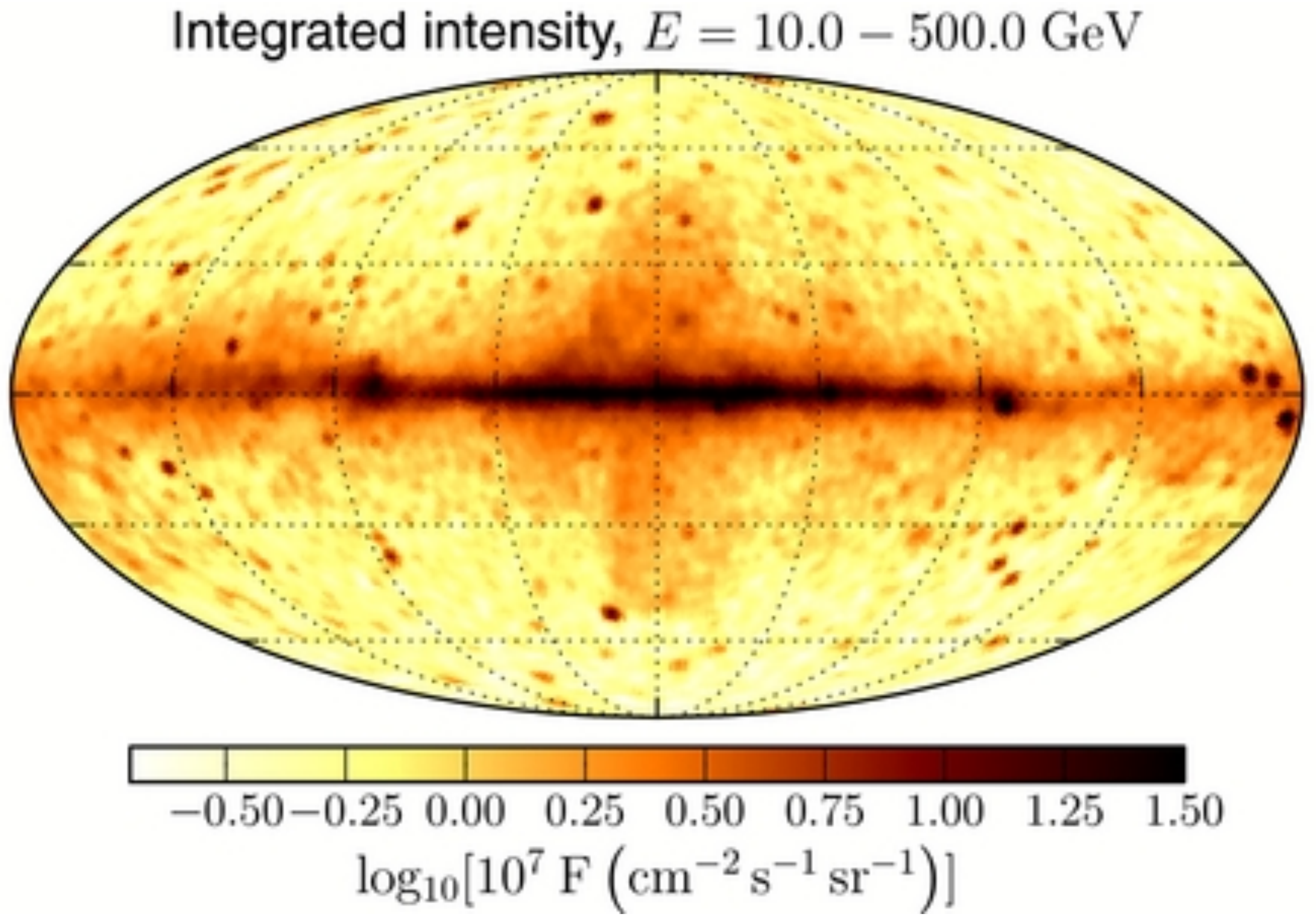
- un flujo de masa del hoyo negro Galáctico?
- evento(s) de acreción del hoyo negro Galáctico?
- vientos de supernovas?

$$L = (4.4 + 2.4 - 0.9) \times 10^{37}\ \mathrm{erg/s}$$

Ackermann et al. 2014, ApJ 793, 64







3. Fuentes Galácticas - 4FGL

Pulsares (PSR)	241	Cotejo con catálogo ATNF. Identificados por pulsaciones.
Supernova remnants (SNR)	39	24 identificadas por emisión extendida.
Pulsar wind nebulae (PWN)	18	15 tienen emisión extendida.
SNR or PWN (SPP)	92	Naturaleza indefinida al coincidir la fuente con un SNR y PWN.
Globular clusters (GLC)	30	Emisión atribuible a pulsares dentro del cúmulo
High-mass X-ray binaries (HMB)	8	LS I+61 303, LS 5039. 4FGL incluye Cygnus X-1
Star-forming regions (SFR)	3	Cygnus OB. 4FGL incluye ρ Ophiuchi
Low-mass X-ray binaries (LMB)	2	Nuevas
Binary star (BIN)	1	η Carinae
Nova (NOV)	1	V5668 Sagittarii - La señal de las novas (como V 407 Cygni) se diluyen por debajo del umbral de detección

4FGL tiene 1525 fuentes no asociadas y 118 desconocidas

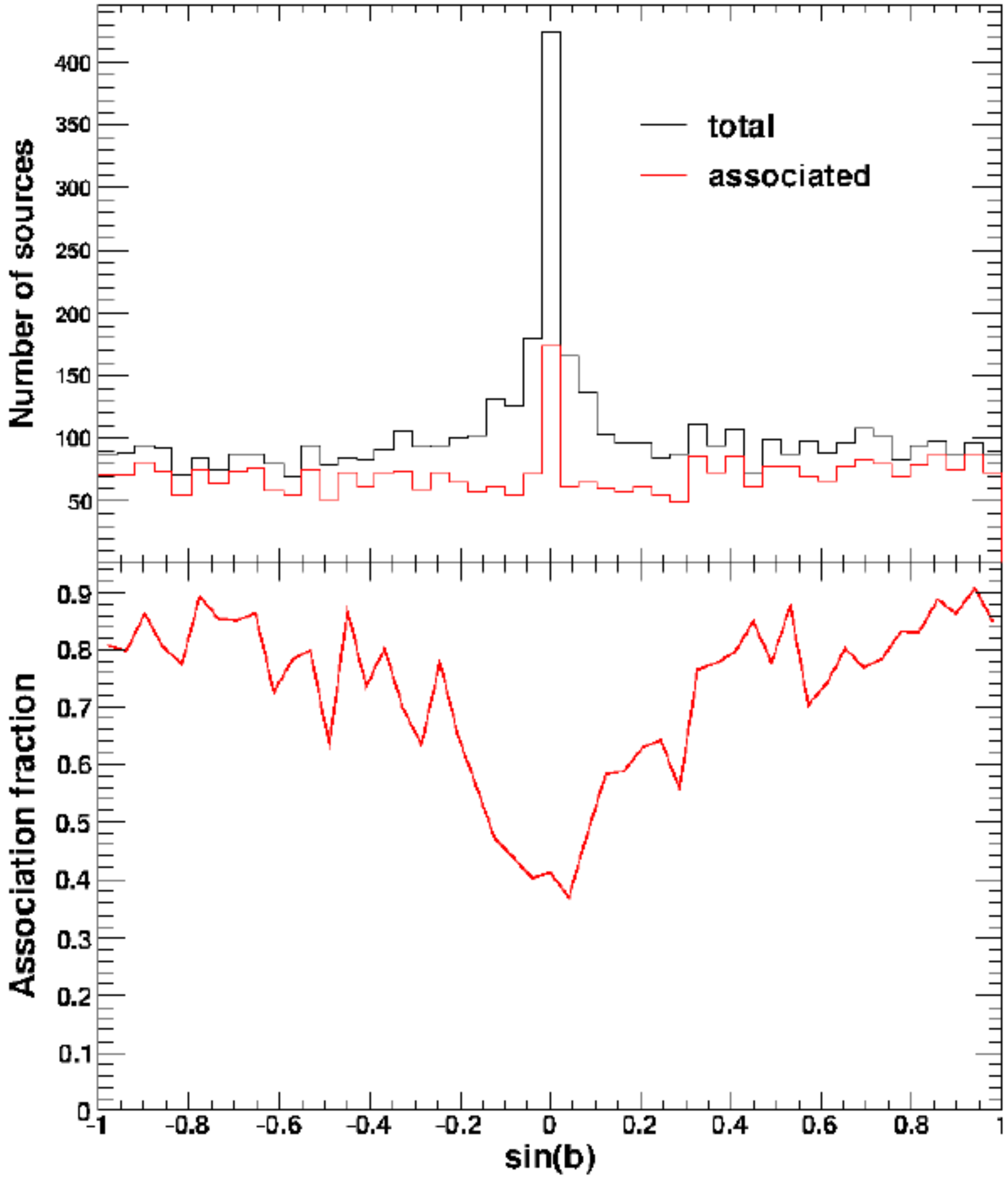
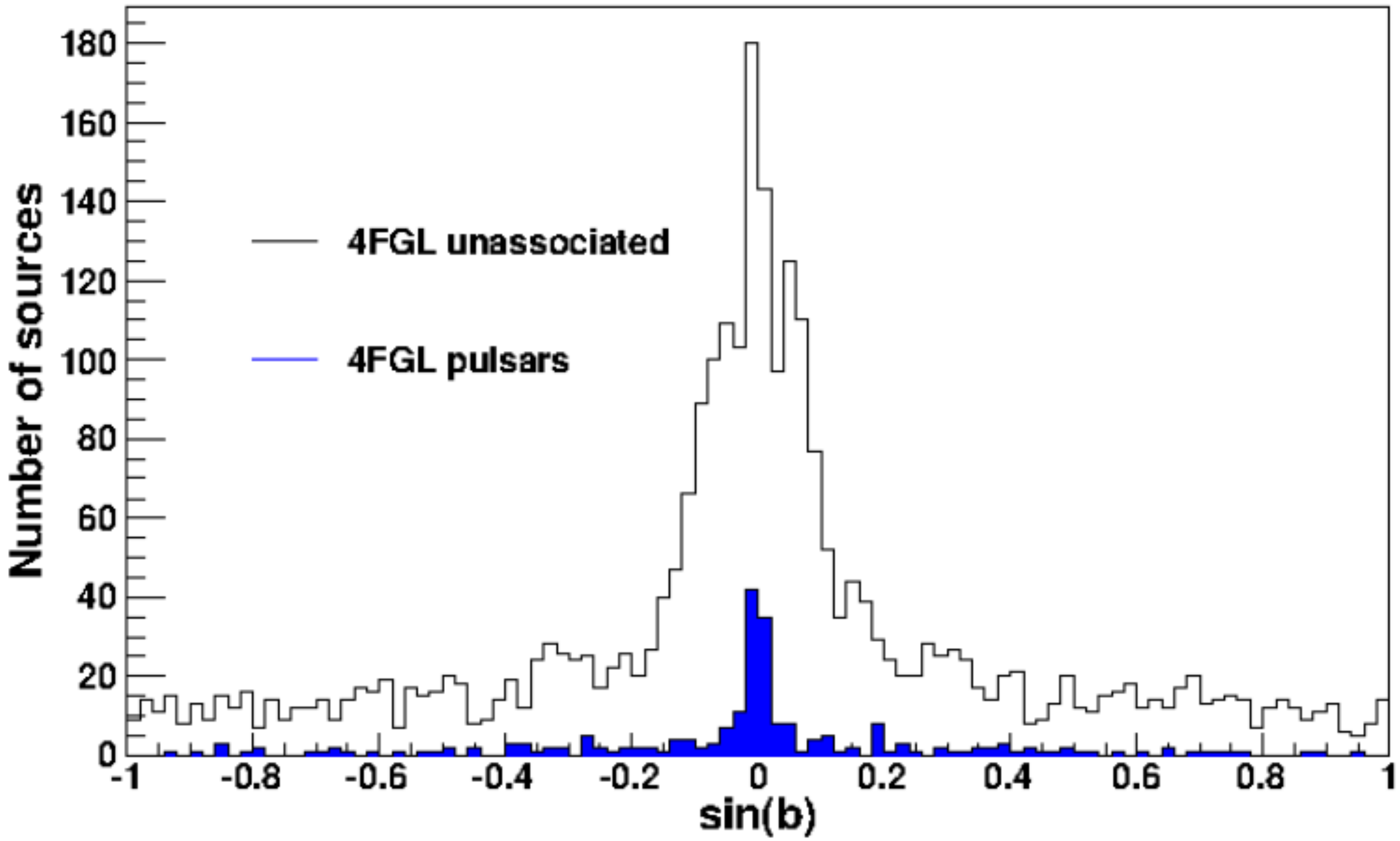


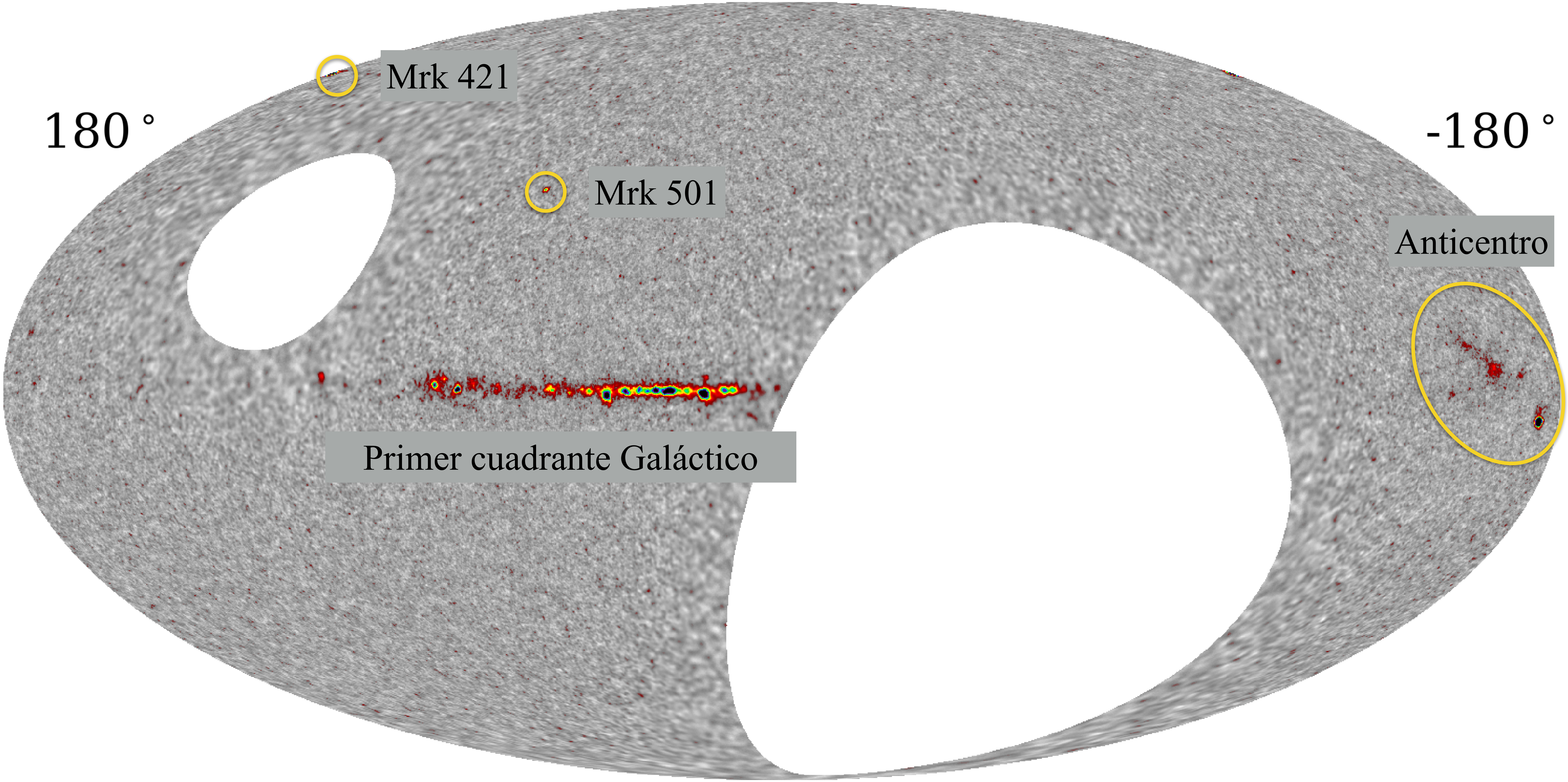
Figure 6. Upper panel: Distributions in Galactic latitude *b* of 4FGL sources (black histogram) and associated sources (blue histogram). Lower panel: Association fraction as a function of Galactic latitude.



e **7.** Distributions in Galactic latitude *b* of 4FGL unassociated sources (black histog
of LAT-detected pulsars (blue histogram).

tevcat.uchicago.edu

All-sky view; galactic coordinates; 0.0 ° ; 1523 days



Mrk 421

180 °

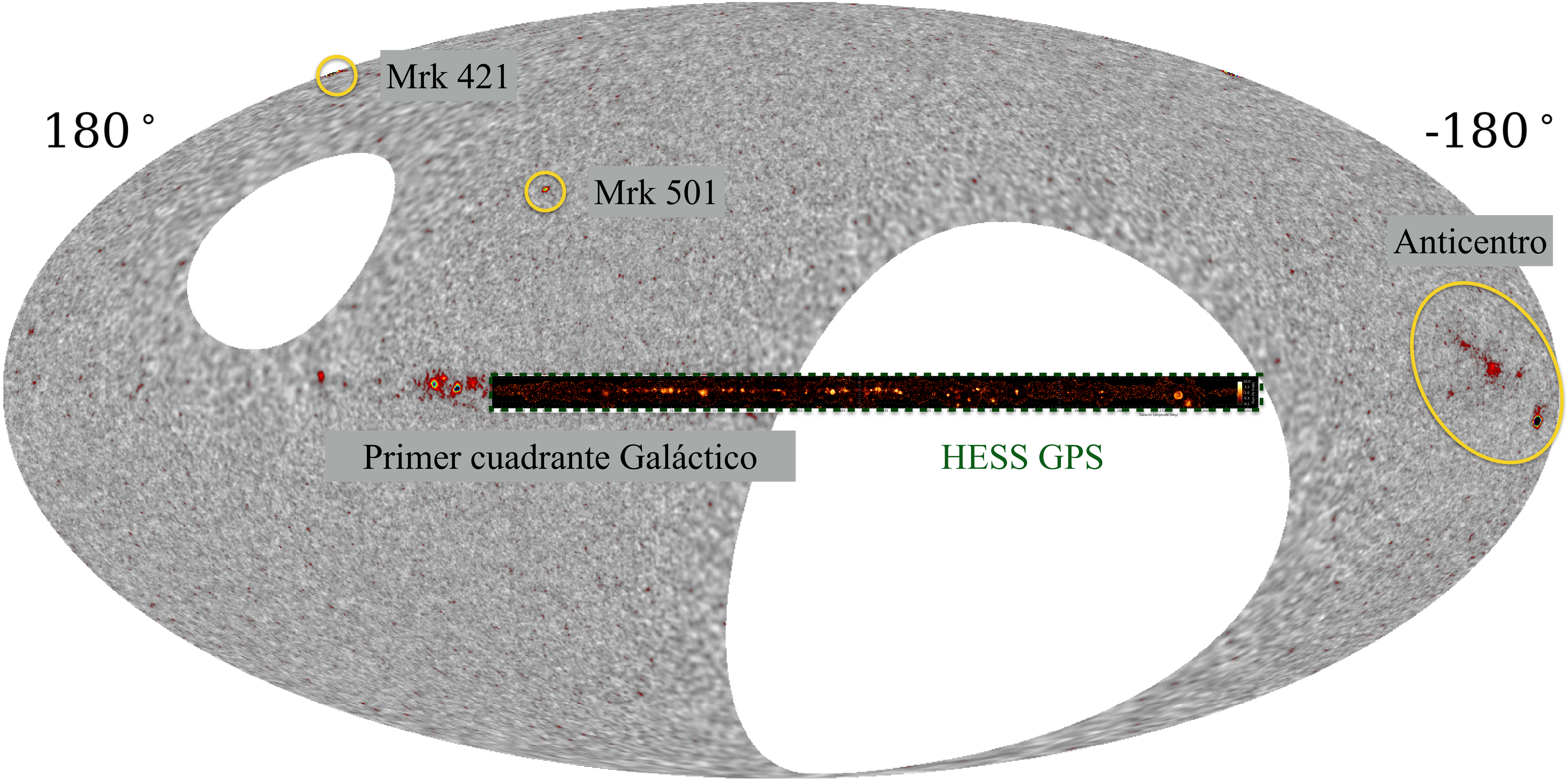
-180 °

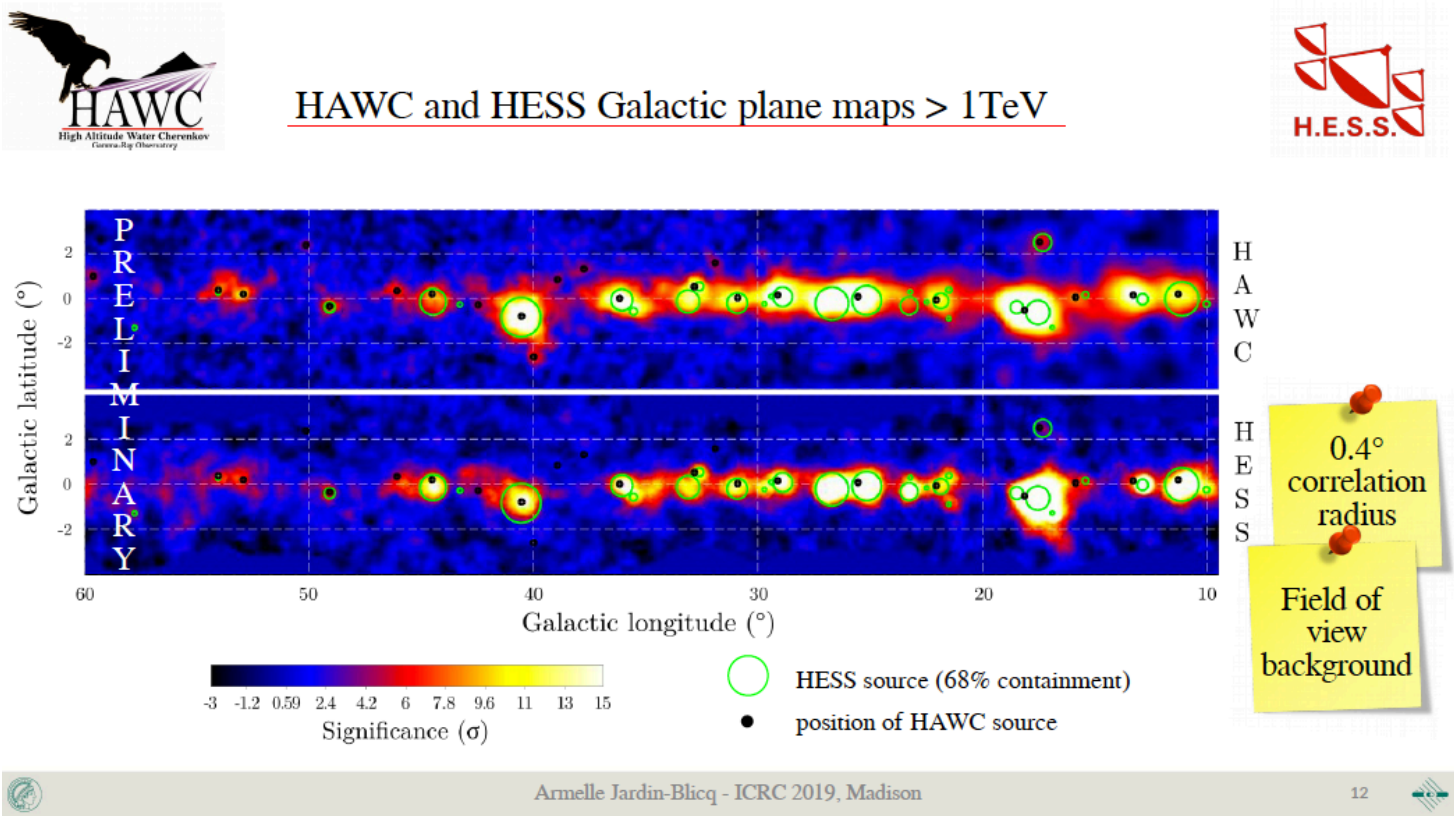
Mrk 501

Anticentro

Primer cuadrante Galáctico

All-sky view; galactic coordinates; 0.0 ° ; 1523 days





HAWC and HESS Galactic plane maps > 1TeV

0.4° correlation radius

Field of view background

Armelle Jardin-Blicq - ICRC 2019, Madison

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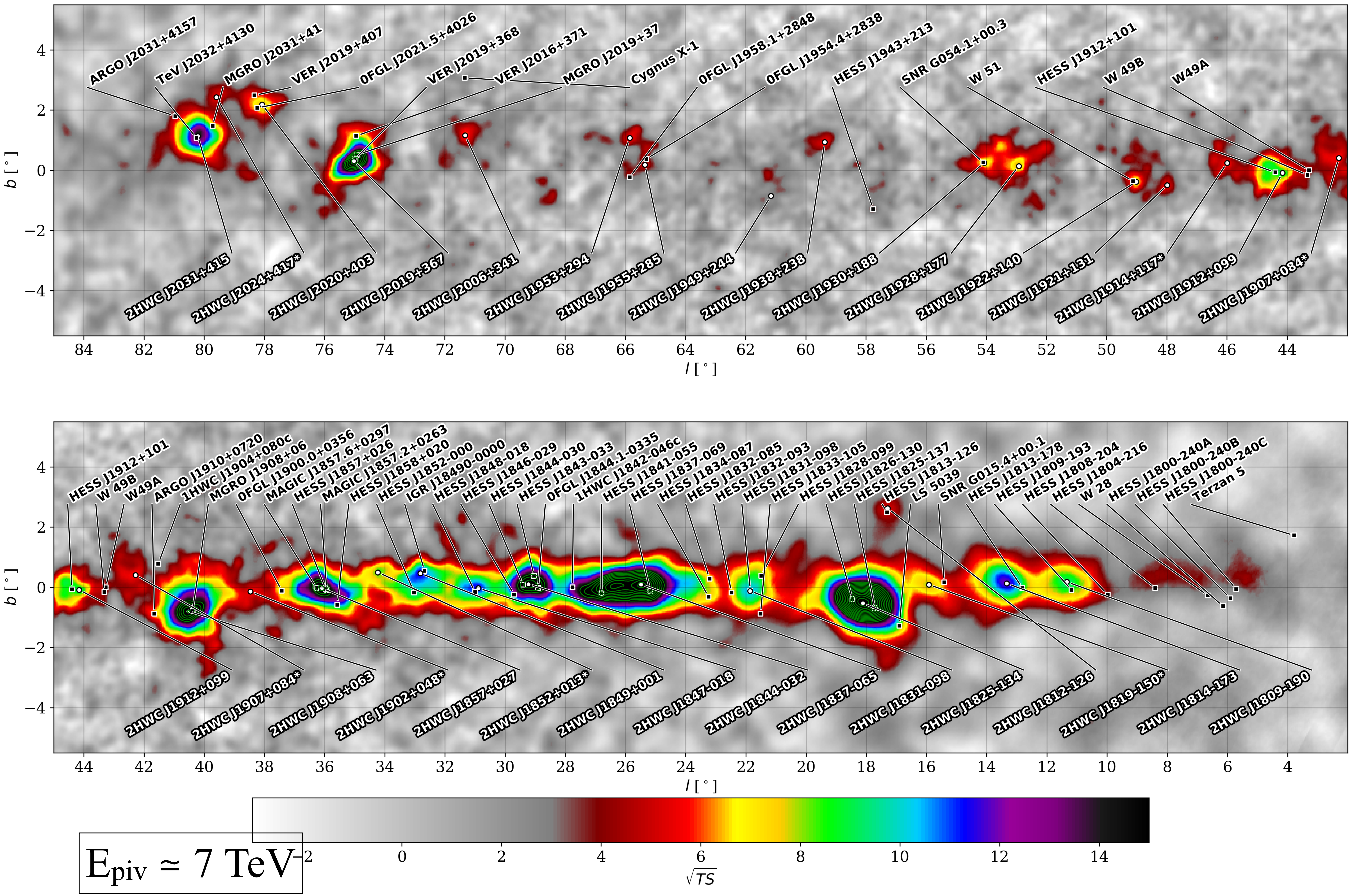
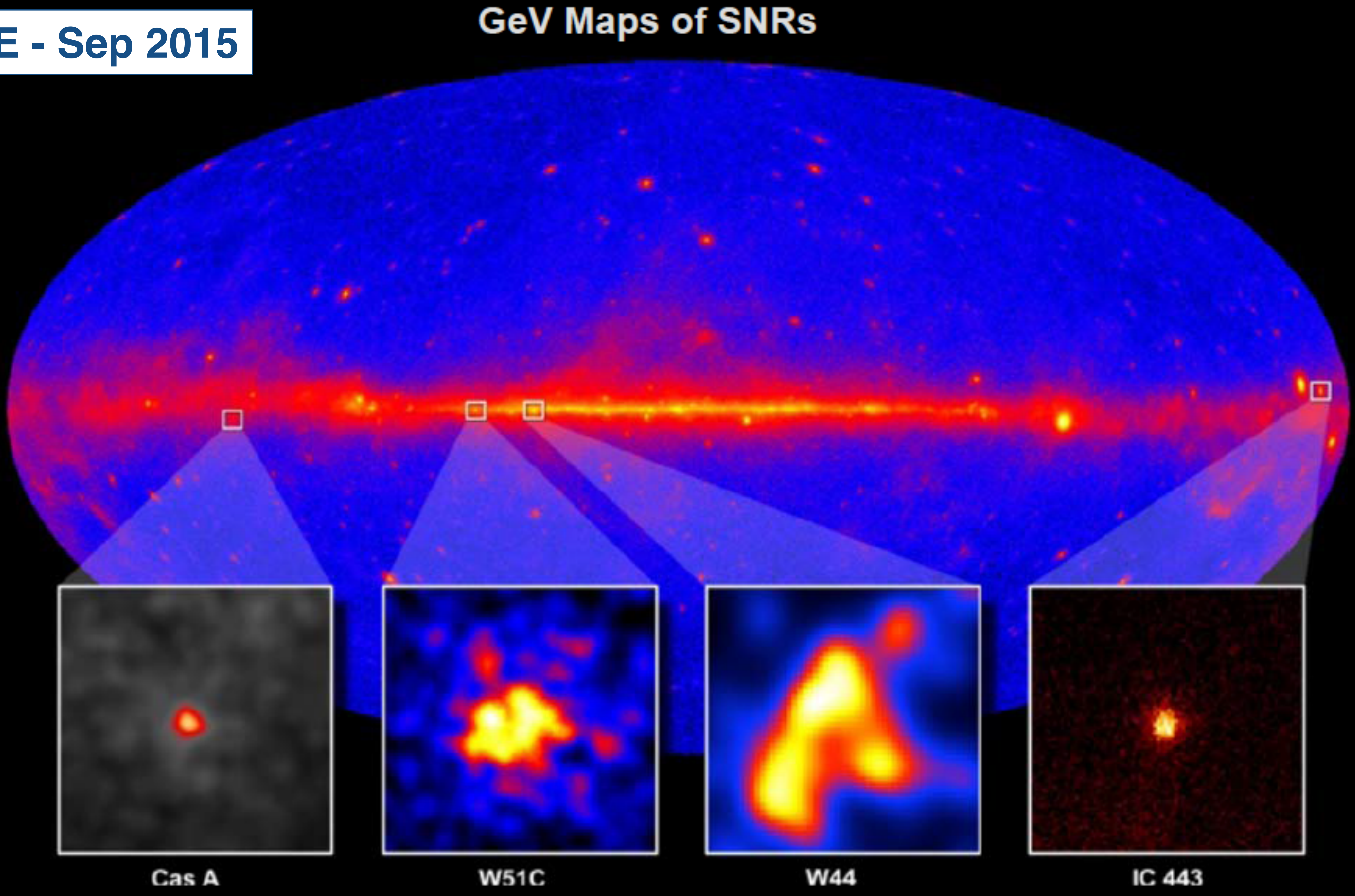


$E_{piv} \simeq 7$ TeV

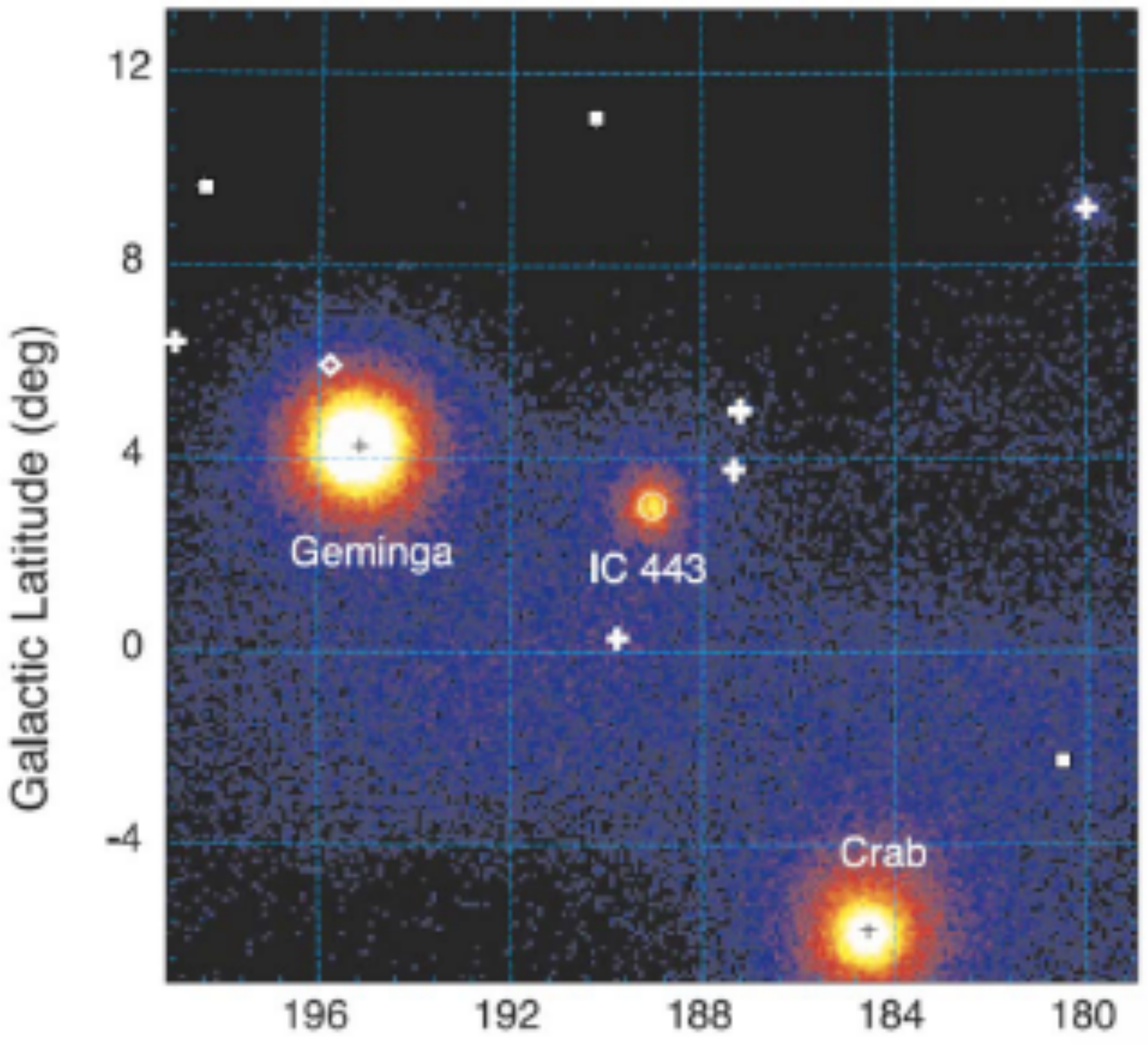
- Supernovas en expansión (varias en el Plano Galáctico)
- Pulsares con vientos (Cangrejo), y “TeV haloes” (Geminga).
- Microcuasares: SS 433
- El Centro Galáctico (H.E.S.S.)
- Cygnus: región de formación estelar.

4. Remanentes de supernova

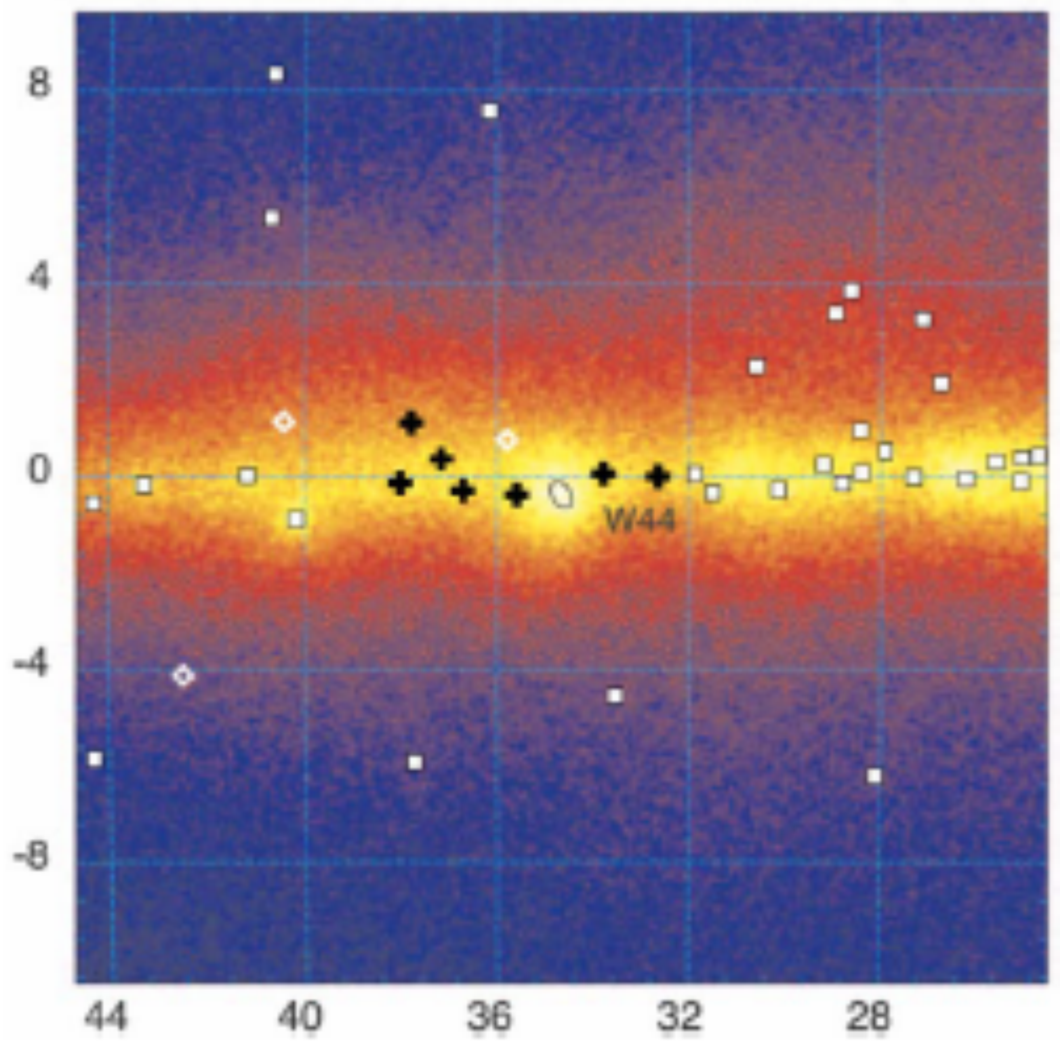
C.D. Dermer @ INAOE - Sep 2015



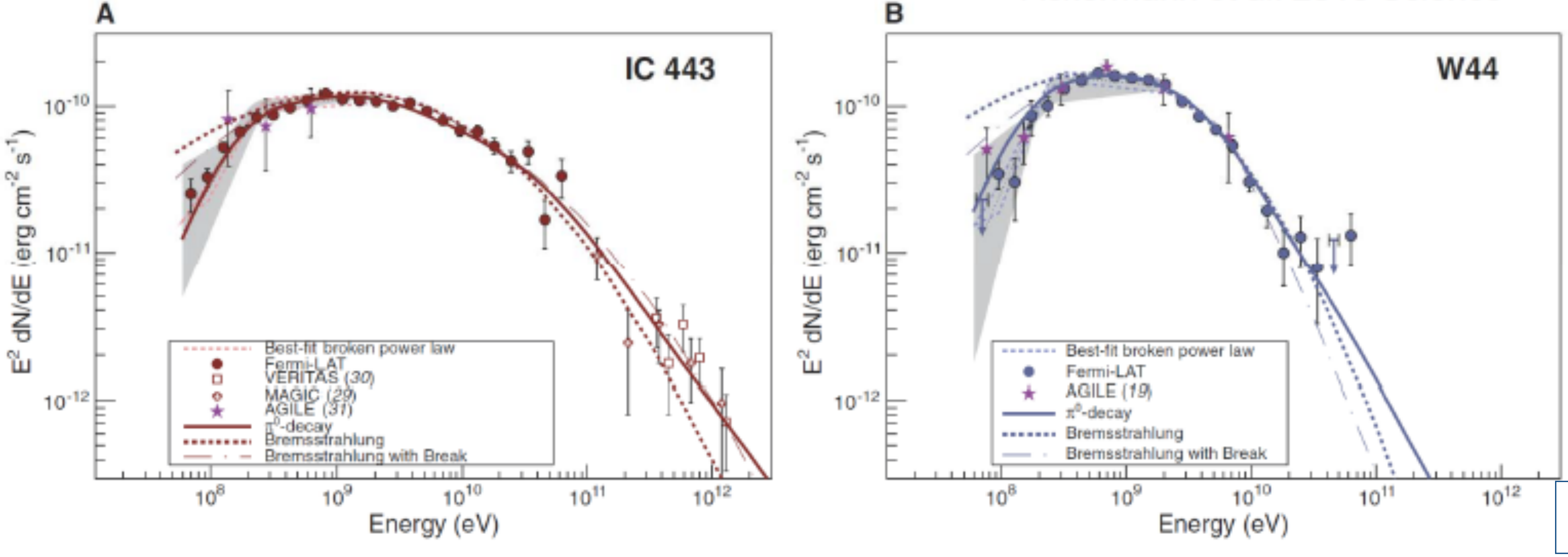
Fermi detection of π^0 bump in SNRs



- Requires good understanding of low-energy response in Fermi
- Low-energy hardening consistent with cosmic-ray origin prediction in IC 443 and W44
- However, γ-ray spectrum is soft and has cutoffs

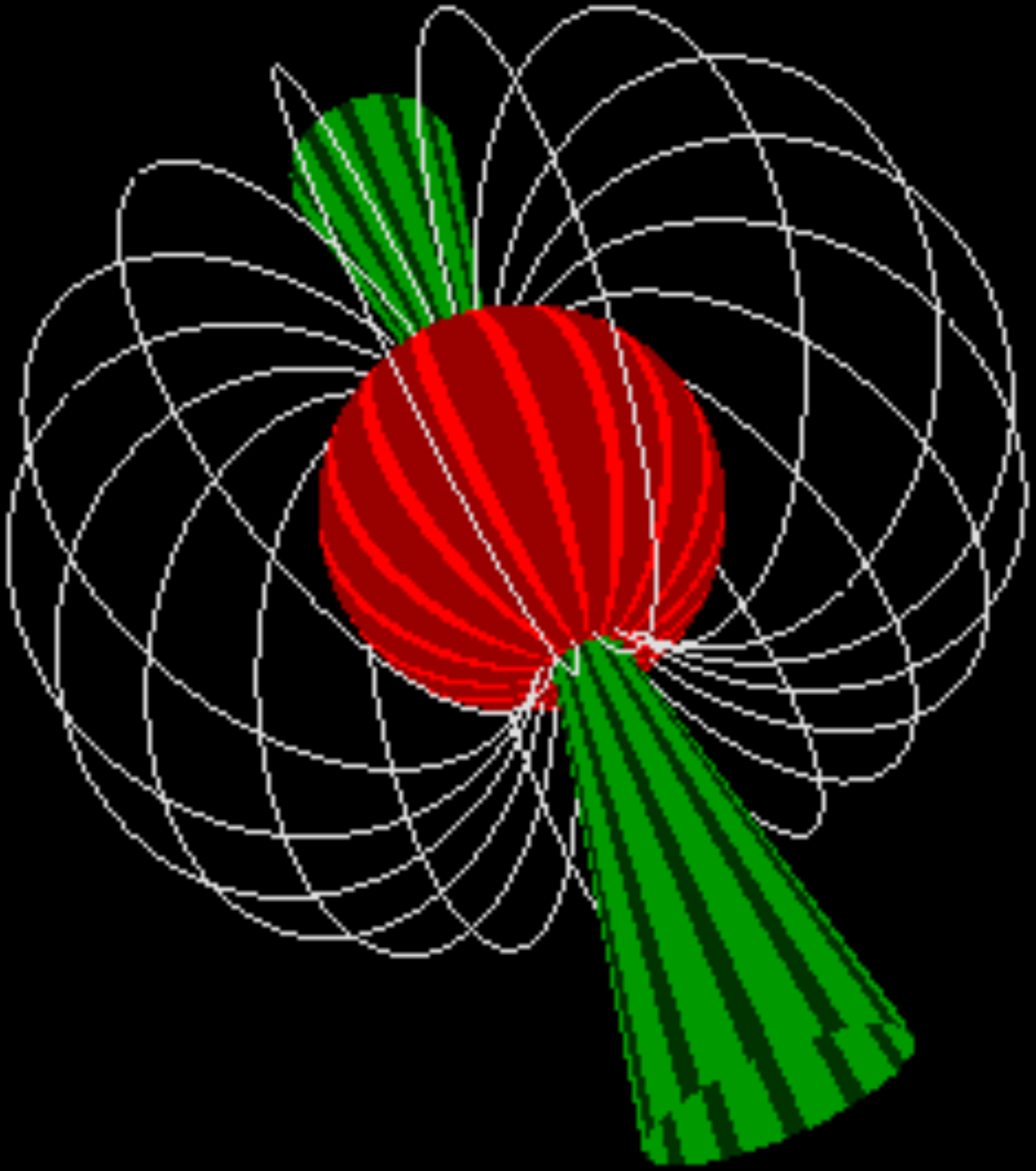


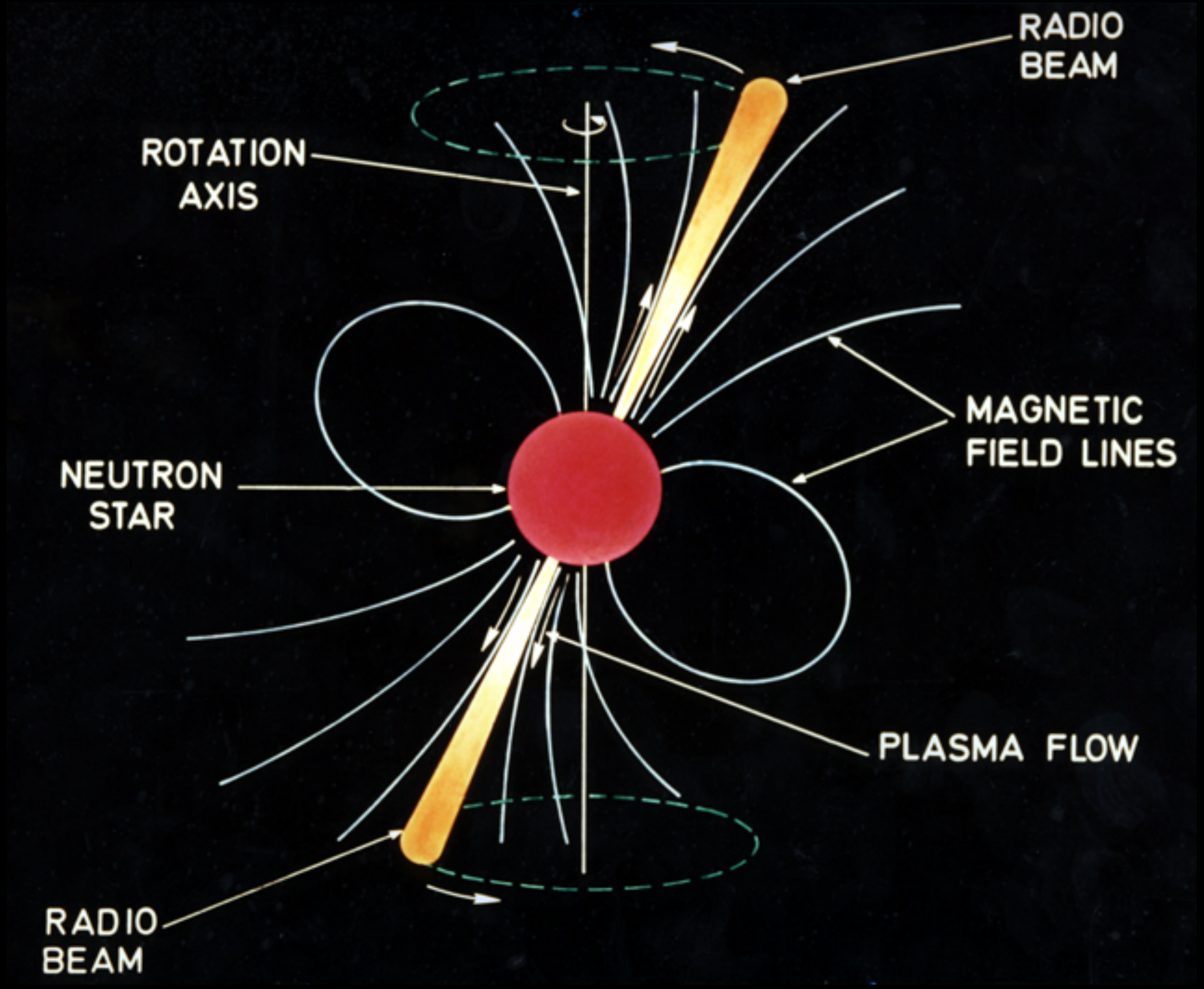
Ackermann et al. 2013 Science



C.D. Dermer @ INAOE - Sep 2015

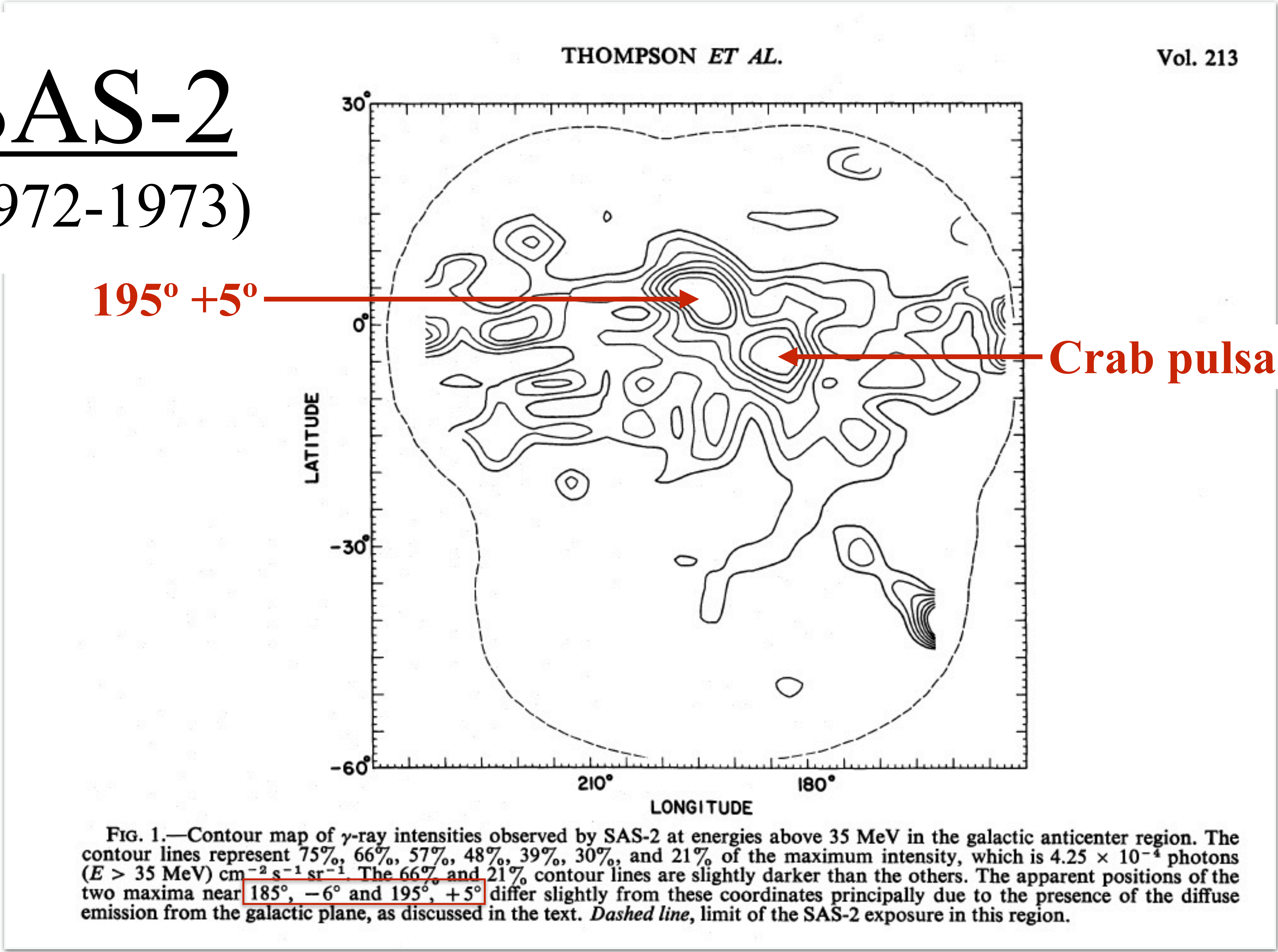
5. Pulsares y PWNe





SAS-2

(1972-1973)



THOMPSON *ET AL.* Vol. 213

195º +5º

Crab pulsar

FIG. 1.—Contour map of γ-ray intensities observed by SAS-2 at energies above 35 MeV in the galactic anticenter region. The contour lines represent 75%, 66%, 57%, 48%, 39%, 30%, and 21% of the maximum intensity, which is 4.25×10^{-4} photons ($E > 35$ MeV) $\mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$. The 66% and 21% contour lines are slightly darker than the others. The apparent positions of the two maxima near 185°, −6° and 195°, +5° differ slightly from these coordinates principally due to the presence of the diffuse emission from the galactic plane, as discussed in the text. *Dashed line*, limit of the SAS-2 exposure in this region.

Estrellas de neutrones

- Oppenheimer & Volkoff (1939) hacen el primer cálculo de la estructura de una estrella de neutrones, dando lugar a la estimación $R_\star \simeq 10\,\mathrm{km}$, $M_\star \simeq 1.4\ \mathrm{M}_\odot$.
- En un gas degenerado de neutrones el número de partículas, $N = nV$, se relaciona con el momento de Fermi, p_f de acuerdo a

$$N = 2 \int \frac{d^3r\, d^3p}{h^3} \Rightarrow p_f = h \left(\frac{3n}{8\pi} \right)^{1/3} ,$$

- La densidad de materia se estima de $p_f = mc$, con m la masa del neutrón,

$$\rho_c = \frac{8\pi m^4 c^3}{3h^3} \simeq 6 \times 10^{15}\,\mathrm{g/cm}^3 .$$

- Balanceando energía interna $u \propto \rho^\gamma/(\gamma - 1)$ con gravedad, se obtiene, para una estrella de densidad constante,

$$R = \left(\frac{3}{2\pi} \right)^{4/3} \frac{h^2 M^{-1/3}}{4 G m_N^{8/3}} \simeq 5\,\mathrm{km} \left(\frac{M}{M_\odot} \right)^{-1/3} .$$

Pulsares

Desde su descubrimiento los pulsares fueron interpretados como estrellas de neutrones en rotación[1]. A partir de estimaciones para el campo magnético de una estrella de neutrones, $B_\star \sim 10^{12}\,\mathrm{G}$, Pacini (1967) propuso un modelo de dipolo magnético rotante para la fuente de energía en M1:

$$E_{rot} = \frac{1}{2} I\Omega^2 = 2\times 10^{46}\,\mathrm{erg}\,P_{\mathrm{s}}^{-2} = 1.8\times 10^{49}\,\mathrm{erg}\left(\frac{P}{33\mathrm{ms}}\right)^{-2},$$

$$\frac{dE_{rot}}{dt} = I\Omega\dot{\Omega} \quad = \quad \frac{dE_{rad}}{dt} = -\frac{2|\ddot{\mu}|^2}{3c^3} = -\frac{2B_\perp^2 R^6 \Omega^4}{3c^3}.$$

Esta aproximación permite calcular $B_\perp$, componente perpendicular a $\vec{\Omega}$, y modelar de manera simplificada las estrellas de neutrones.

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[1] notando dos alternativas iniciales, posteriormente deshechadas

Pulsares

De los parámetros rotacionales ($I = 2M_\star R_\star^2/5$, $M_\star = 1.4 M_\odot$):
- la pérdida de energía rotacional,

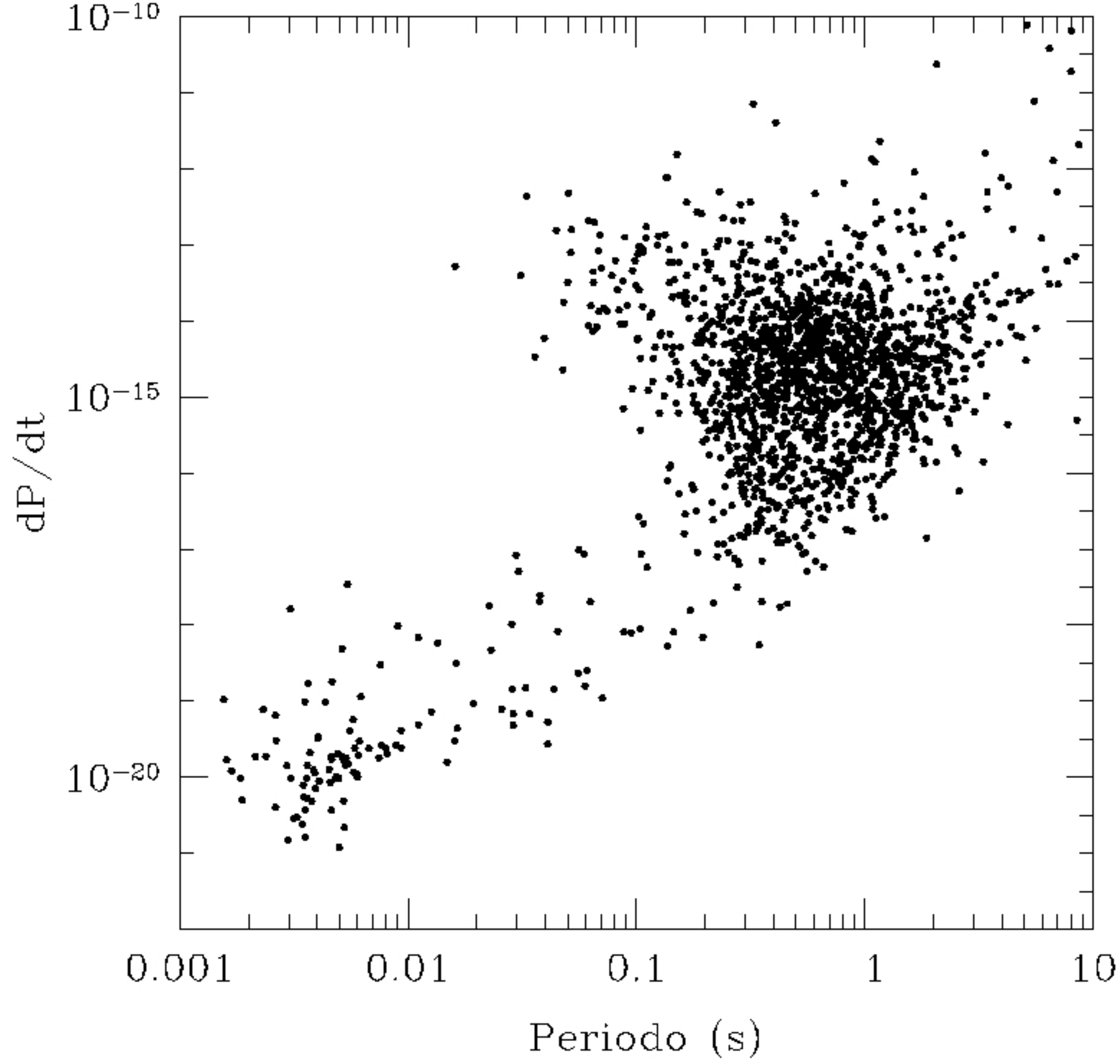
$$\frac{dE_{rot}}{dt} = 4\pi^2 I \left(\frac{\dot{P}}{P^3}\right) = 2.58 \times 10^{38} \mathrm{erg/s} \left(\frac{\dot{P}}{4.2 \times 10^{-13}}\right) \left(\frac{P}{33\,\mathrm{ms}}\right)^{-3},$$

- el campo magnético,

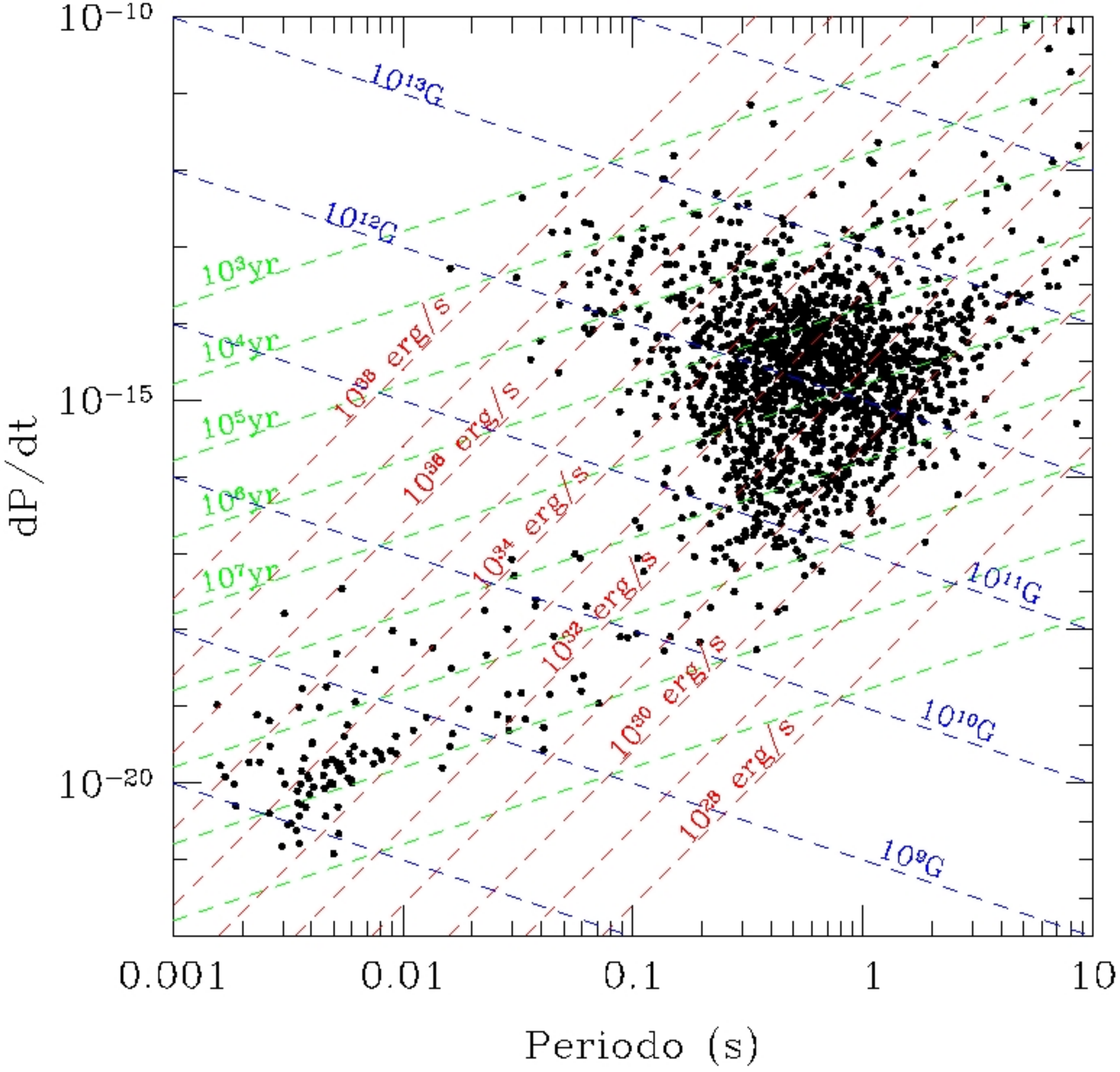
$$B = 2.38 \times 10^{19}\ \mathrm{G} \left(P\dot{P}\right)^{1/2} = 2.80 \times 10^{12}\ \mathrm{G} \left(\frac{P\dot{P}}{33\,\mathrm{ms} \cdot 4.2 \times 10^{-13}}\right)^{1/2}.$$

- la *edad dinámica*,

$$t_d = \frac{P}{2\dot{P}} = 1273\,\mathrm{años} \left(\frac{P/33\,\mathrm{ms}}{\dot{P}/4.2 \times 10^{-13}}\right).$$

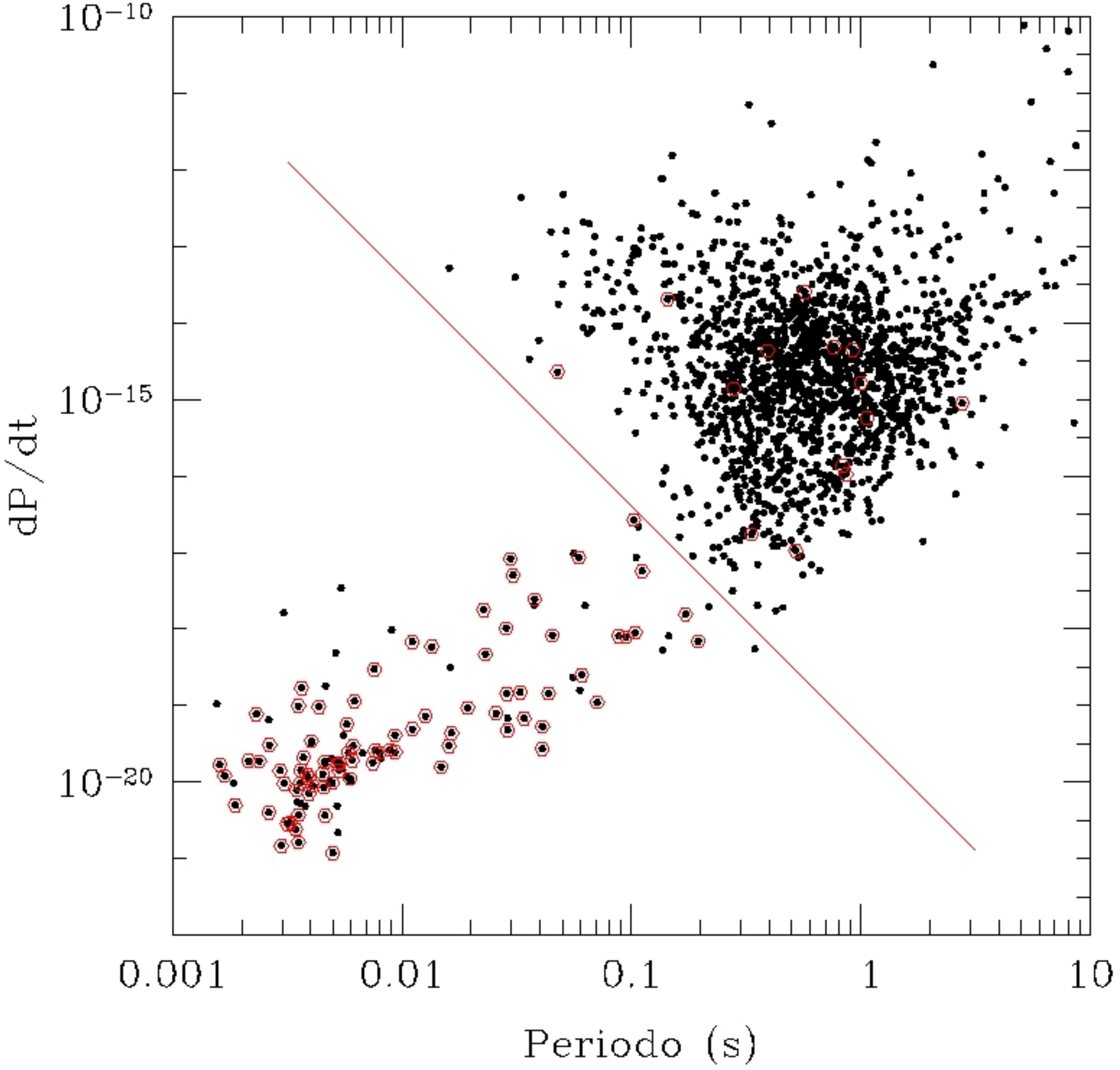


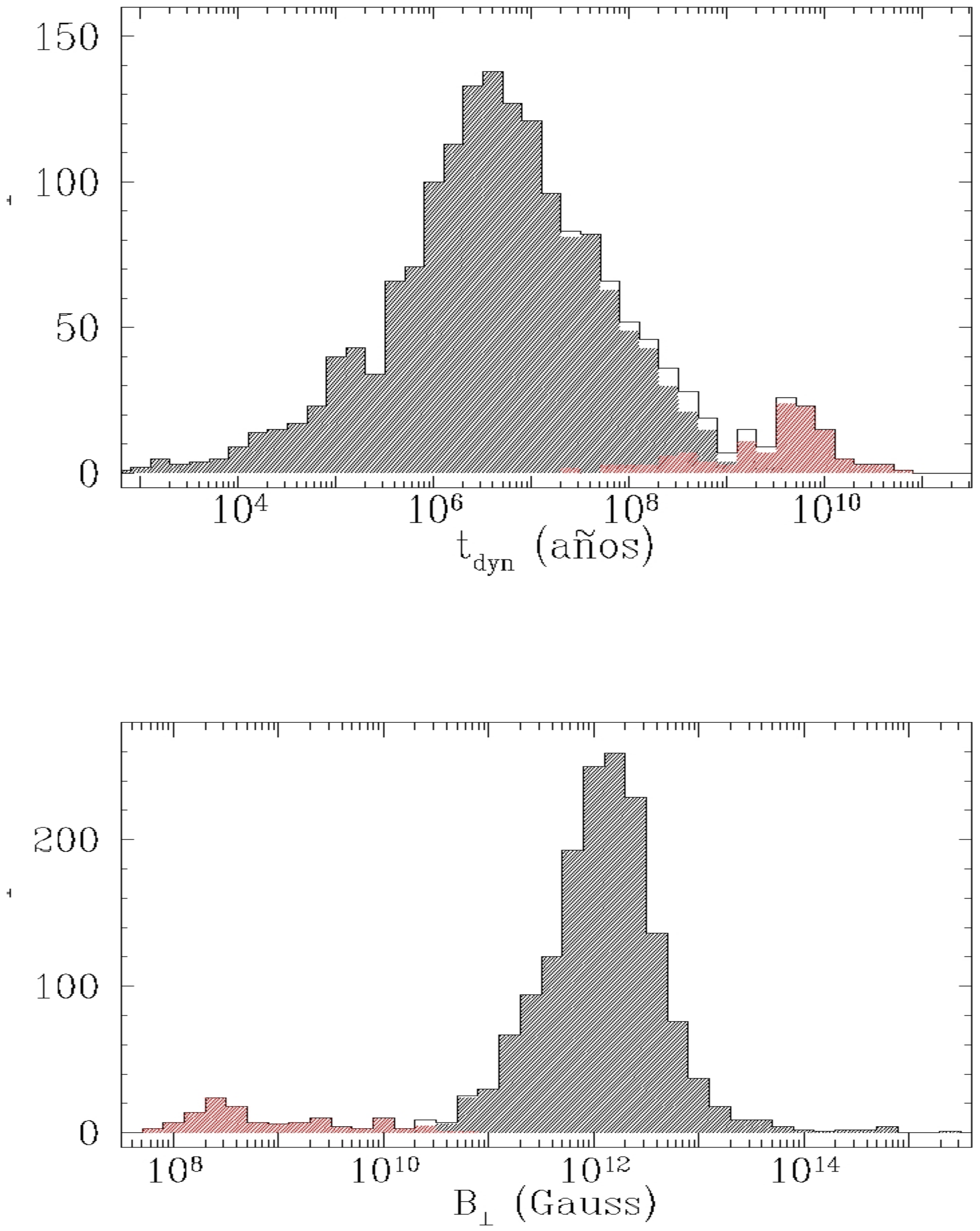
El diagrama P - Pdot permite el estudio de poblaciones de pulsares, estudiados tradicionalmente en ondas de radio



El diagrama P - Pdot permite el estudio de poblaciones de pulsares

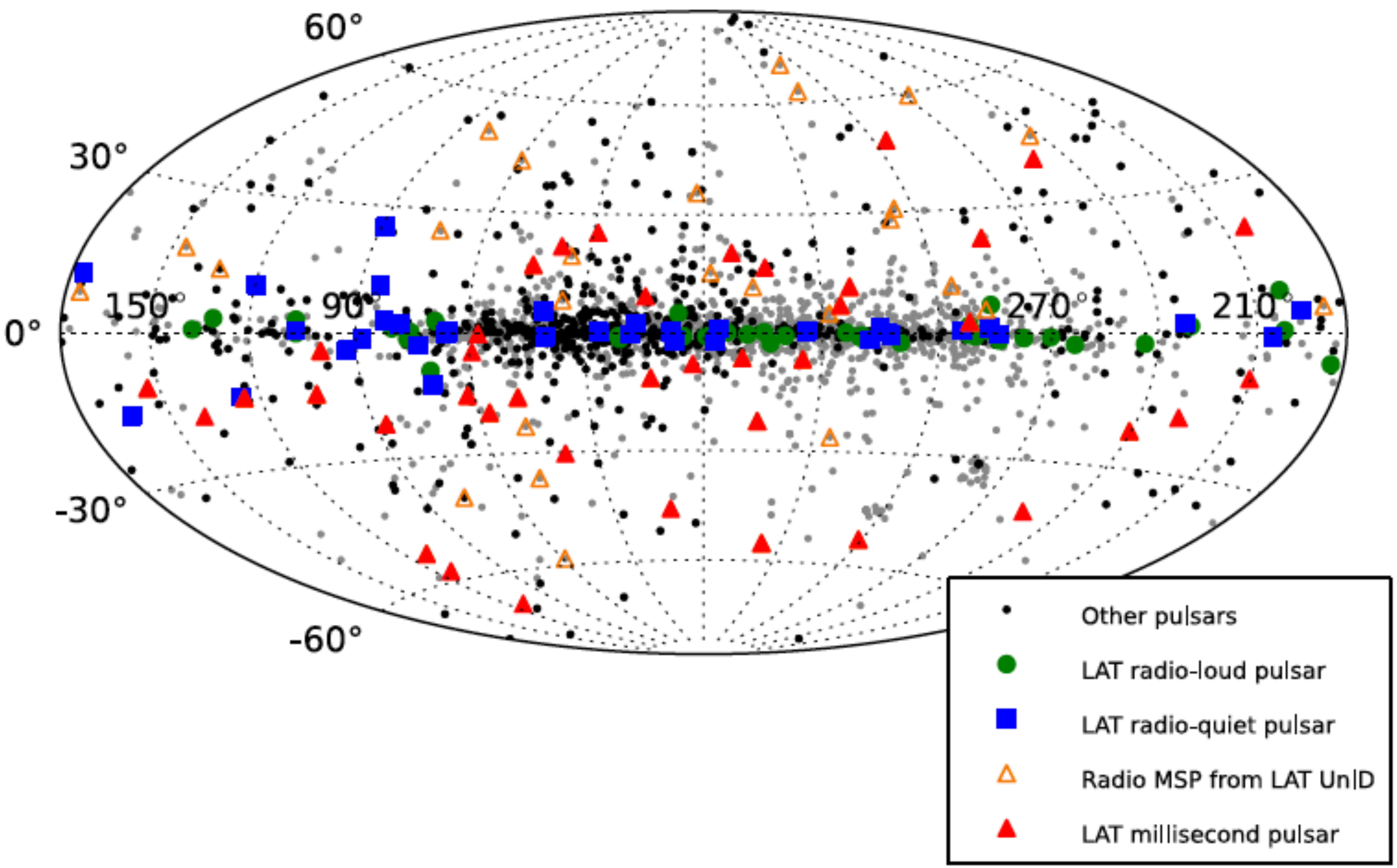
En términos de parámetros físicos

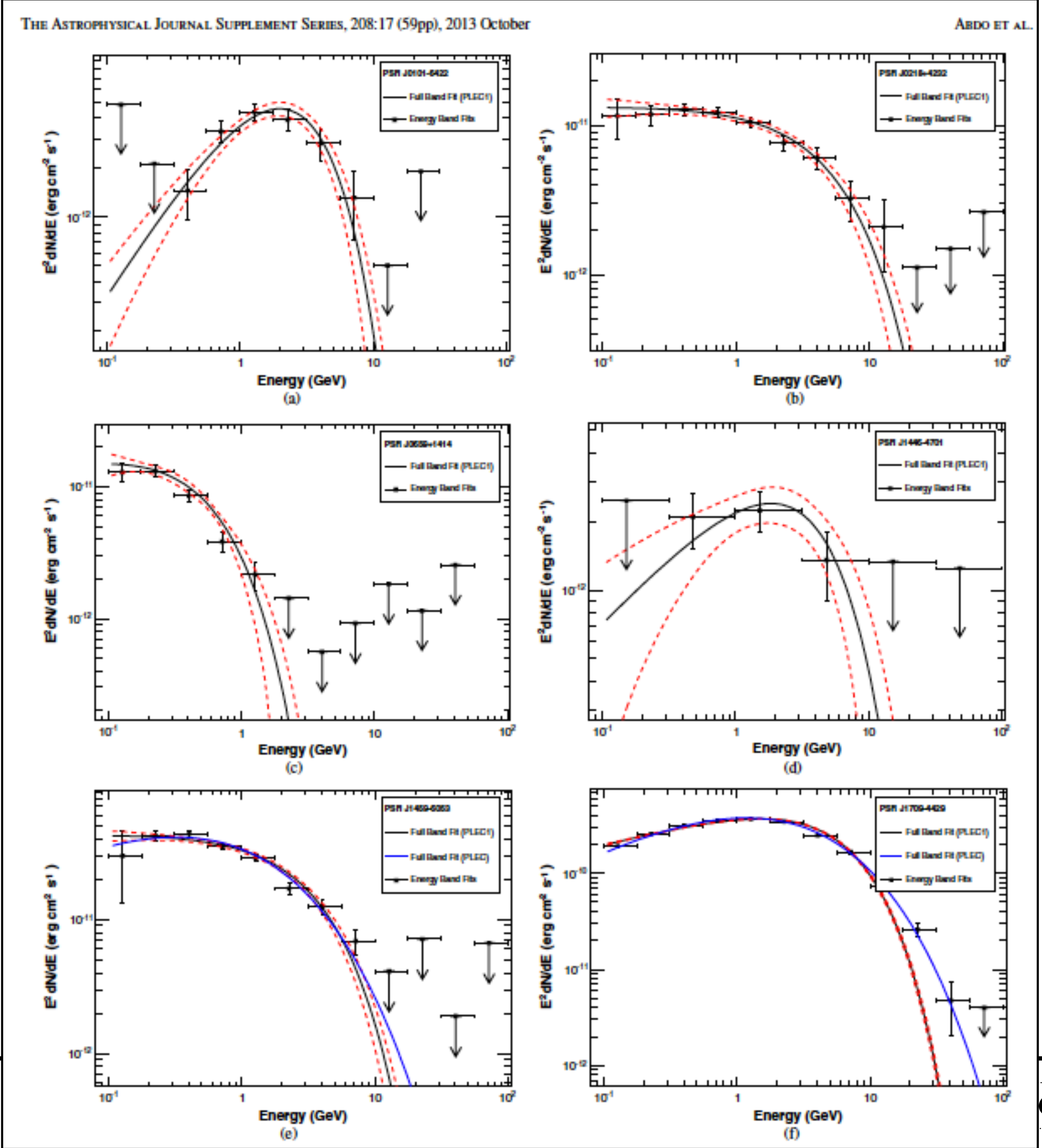


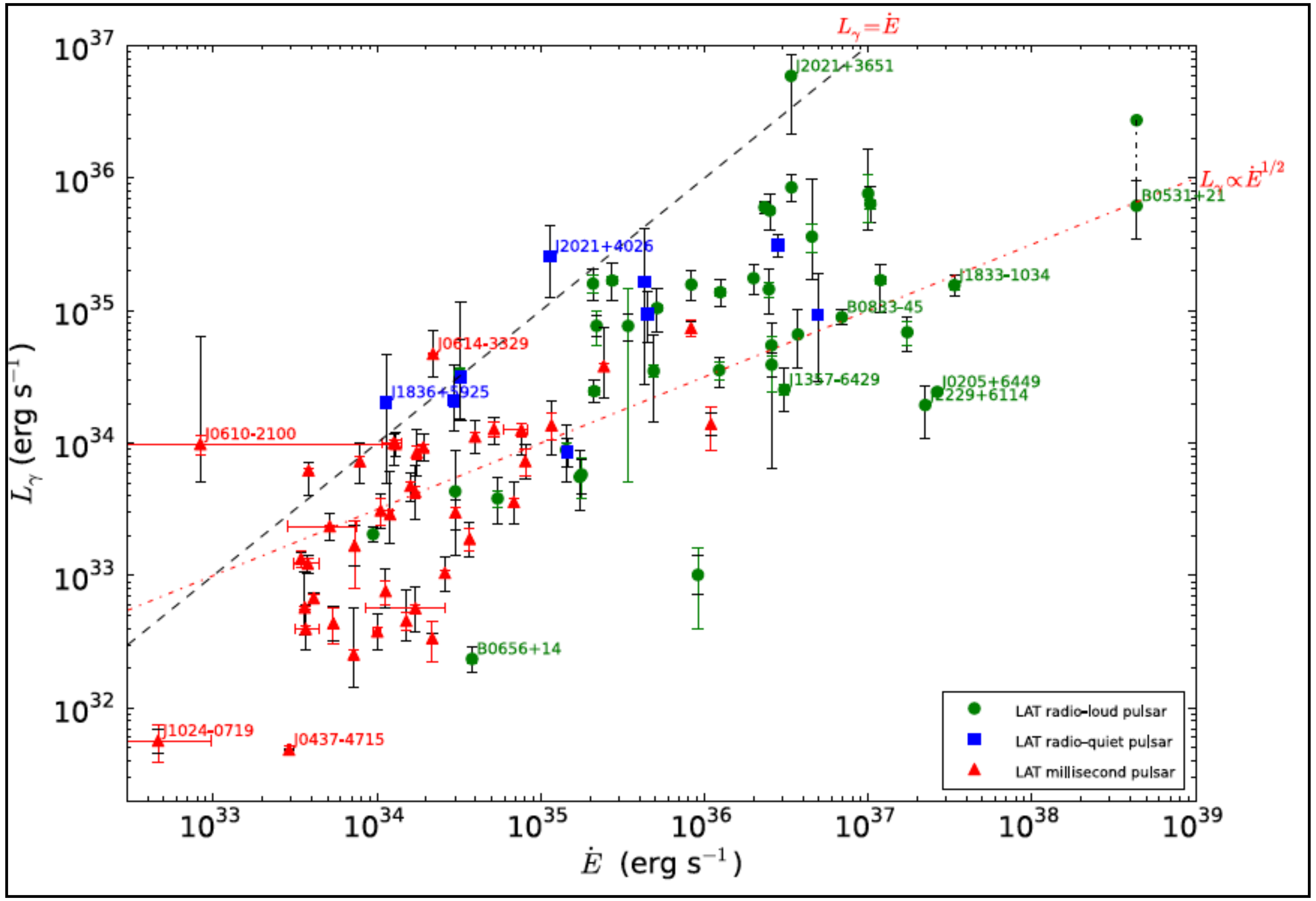


- pulsares jóvenes
- pulsares reciclados en sistemas binarios

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 208:17 (59pp), 2013 Octo




The Astrophysical Journal Supplement Series, 208:17 (59pp), 2013 October Abdo et al.



Pulsares: magnetósfera

En el vacío la rotación de la estrella induce un campo eléctrico

$$\vec{E} = -\frac{1}{c}\left(\vec{\Omega} \times \vec{r}\right) \times \vec{B}.$$

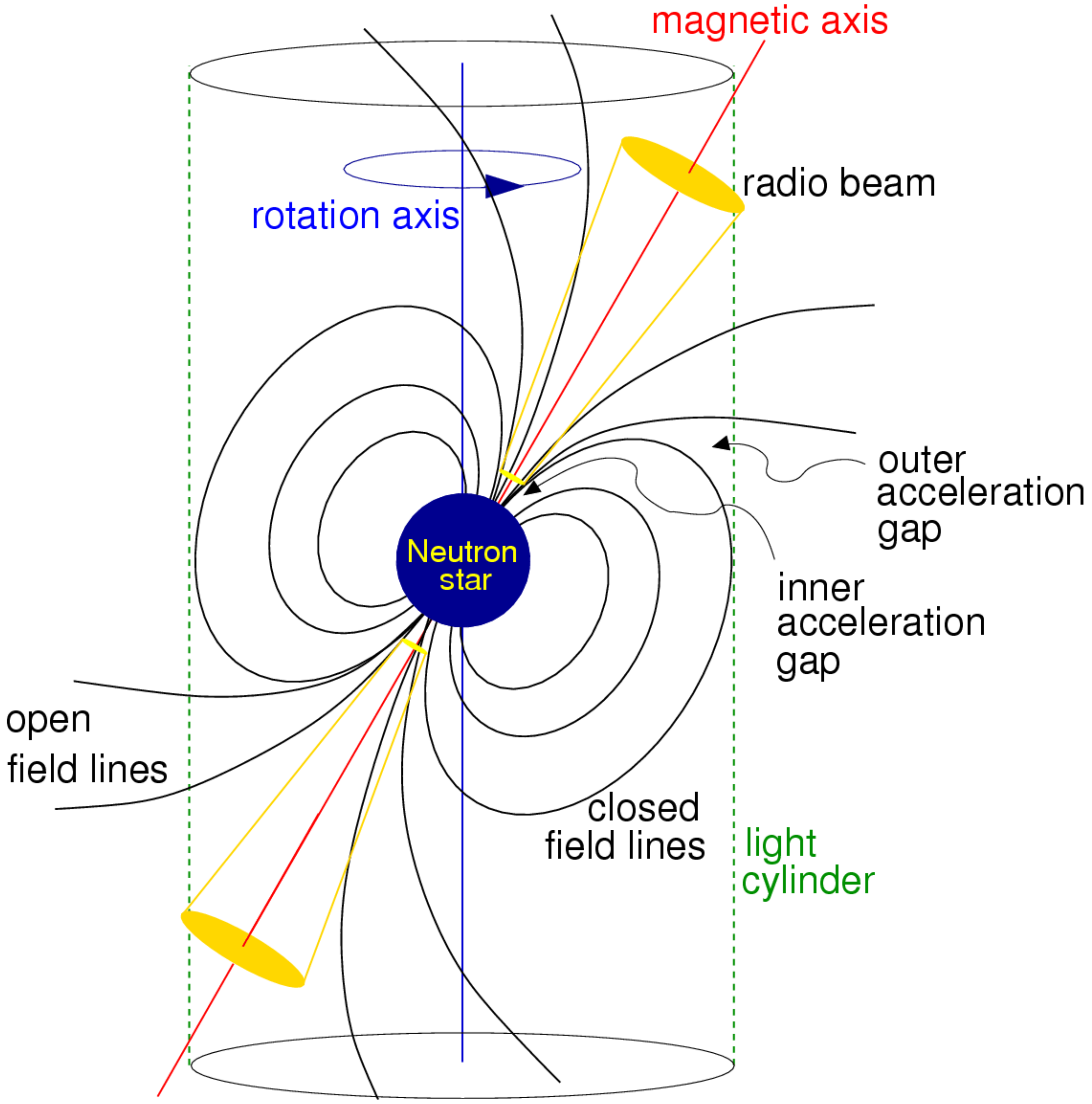
Este campo $\vec{E}$ podría acelerar cargas hasta

$$\Delta\Phi \approx \frac{\Omega^2 B_\star R_\star^3}{2c^2} \simeq 1.14 \times 10^{16}\,\mathrm{V}\left(\frac{P}{33\,\mathrm{ms}}\right)^{-3/2}\left(\frac{\dot{P}}{4.2 \times 10^{-13}}\right)^{1/2}.$$

En la práctica el campo es neutralizado por una densidad de carga (Goldreich-Julian),

$$\rho = \frac{\nabla \cdot \vec{E}}{4\pi c} = \frac{\vec{\Omega} \cdot \vec{B}}{2\pi c},$$

la cual forma una magnetósfera cargada ($\pm$) que corrota con la estrella dentro del cilindro de luz, $r_\ell = c/\Omega$.



Campo magnético crítico

En el caso relativista,

$$E = \left[m^2c^4 + p_z^2c^2 + (2n + s + 1)\, mc^2\hbar\omega_\ell\right]^{1/2} .$$

Las estrellas de neutrones tienen campos magnéticos comparables al campo crítico, $B_{cr} = m^2c^3/e\hbar = 4.413 \times 10^{12}\,\mathrm{G}$. Esto permite algunos procesos como,

- Producción de pares $\gamma \to \mathrm{e}^- + \mathrm{e}^+$, para $\hbar\omega > 2mc^2$;
- División de fotones (photon splitting) $\gamma \to \gamma\gamma$, sin umbral.

El campo mantiene la conservación de energía y momento.

Pulsares: magnetósfera y polar cap

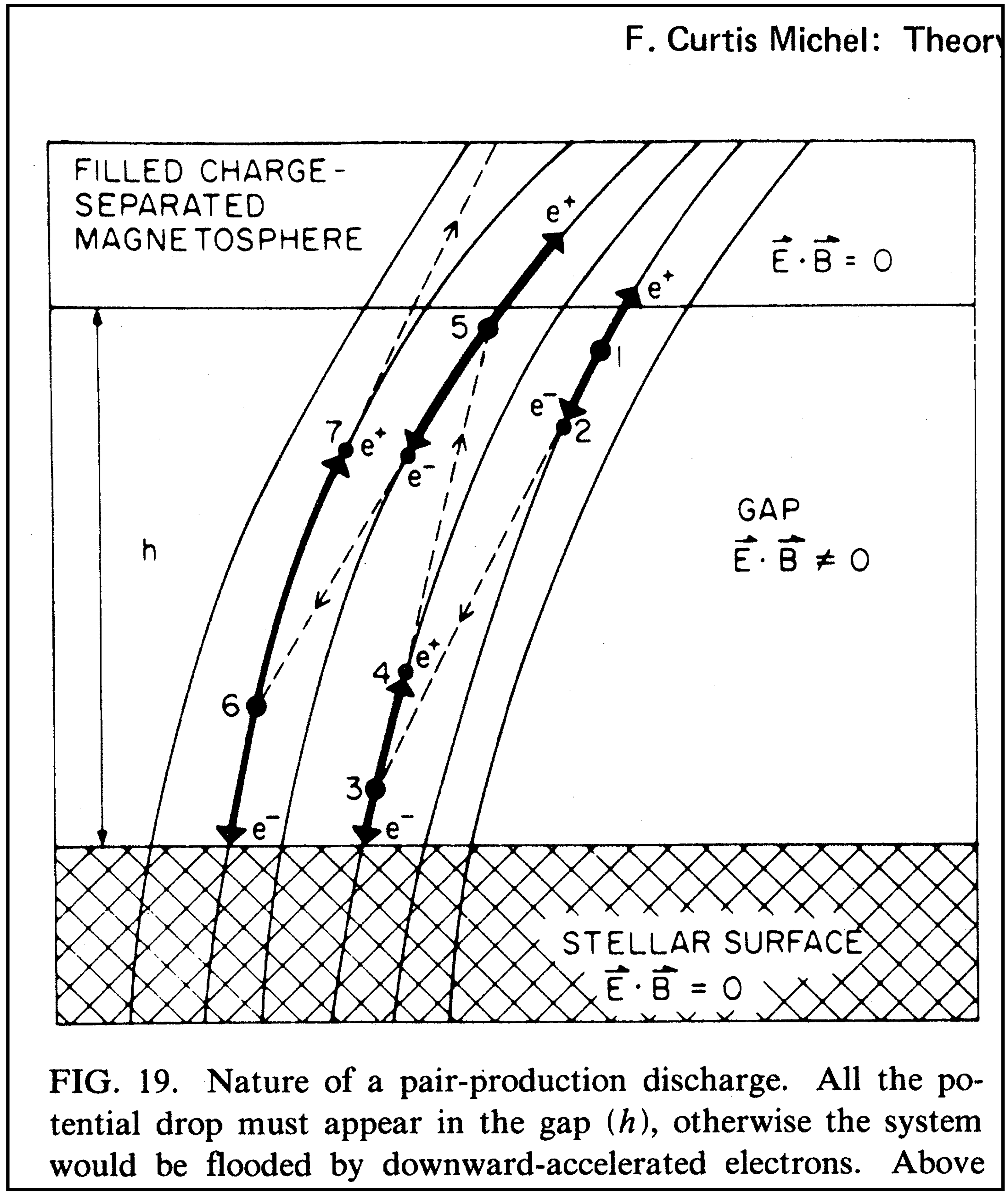
La magnetósfera permite definir el casquete polar ("polar cap"), de radio R_p, a través del ángulo de la última línea cerrada,

$$R_p = R_\star \sin\theta_p = R_\star\,(\Omega R_\star/c)^{1/2}$$

dada la forma de las líneas de campo de un dipolo, $\sin^2\theta/r = \mathrm{cte.}$
— Los modelos de "polar cap" (desde Sturrok 1971) postulan una región de aceleración de partículas de altura $h \sim R_p$ sobre el casquete polar, con un potencial

$$\Delta\Phi \sim \frac{\Omega B_\star}{2c} h^2 \sim \Omega^2 R_\star^3 B_\star/2c^2 \sim 6\times 10^{12}\mathrm{Volts}\, B_{12} P^{-2}\,.$$

Estas partículas radían fotones de alta energía y, dado un campo $B \sim B_{cr}$, estos producen pares, desencadenando una cascada. Los modelos "polar cap" tienen dificultades para reproducir la variedad de curvas de luz observadas en pulsares.



F. Curtis Michel: Theor

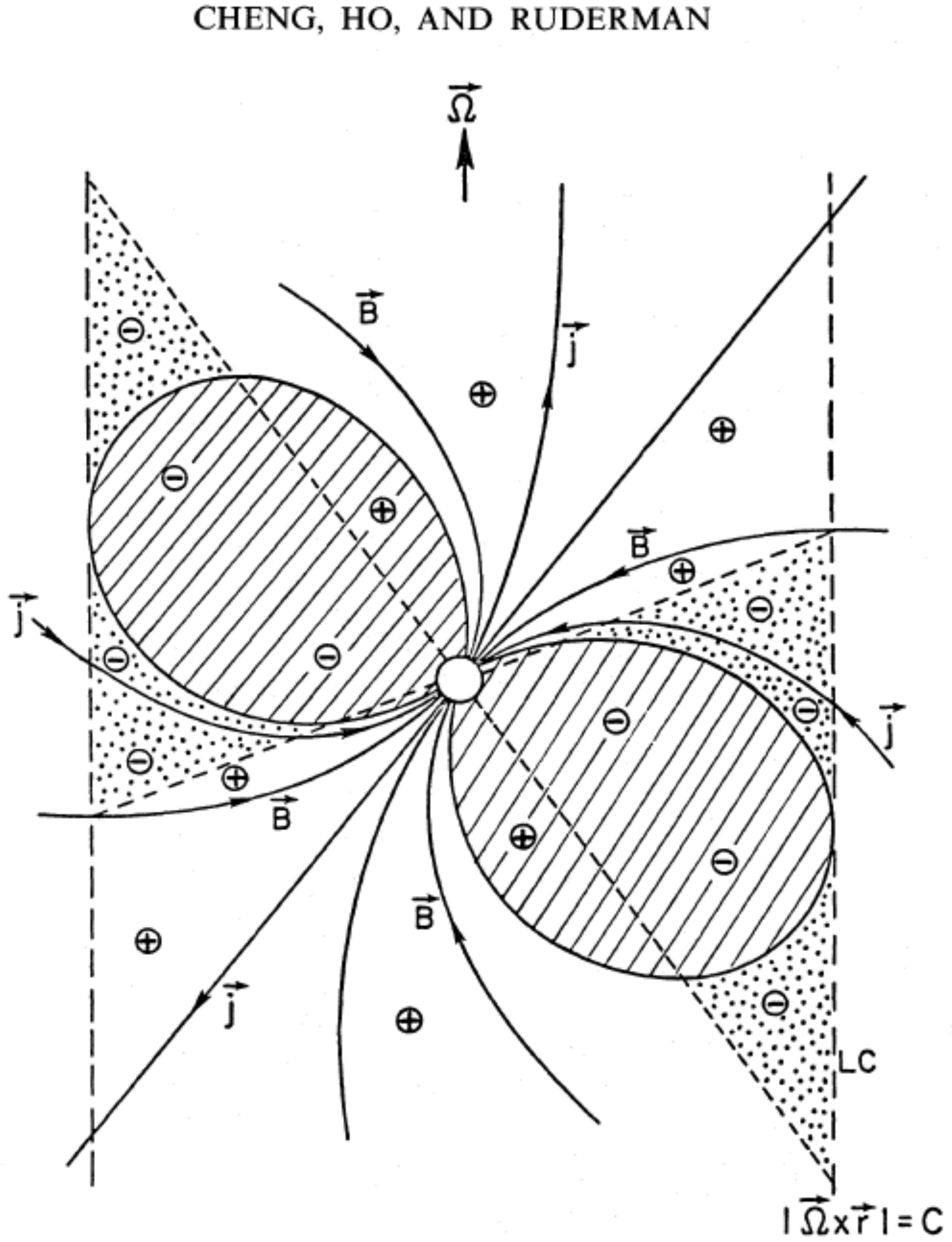
FIG. 19. Nature of a pair-production discharge. All the potential drop must appear in the gap (h), otherwise the system would be flooded by downward-accelerated electrons. Above

Magnetósfera: outer gaps

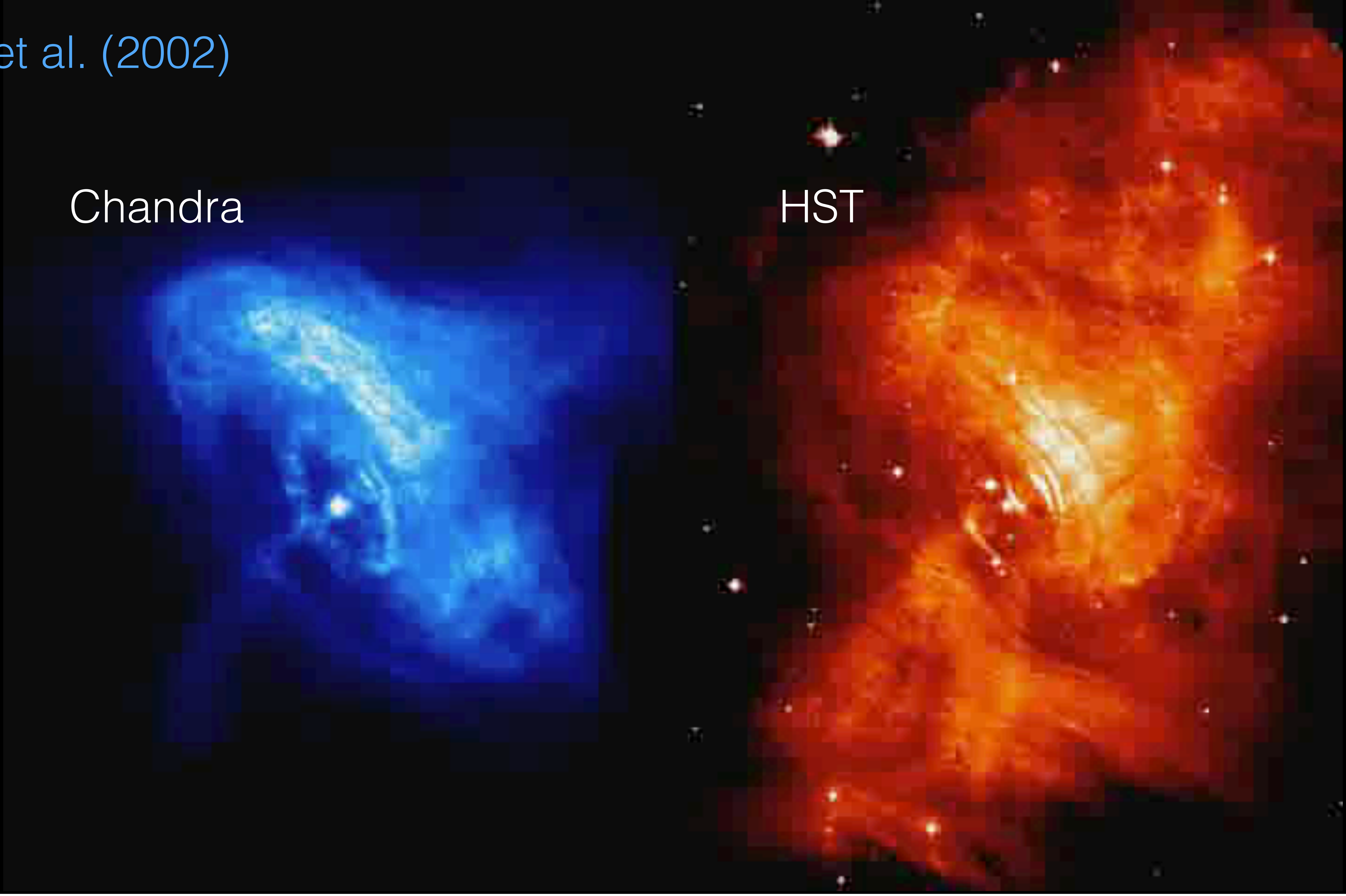
– Los modelos de "outer gap" (Cheng, Ho & Ruderman 1986) se basan en regiones de aceleración en la vecindad de regiones de carga nula ($\Omega \cdot \vec{B} = 0$). Estas partículas radian hasta energías de GeV mediante *emisión de curvatura*, donde el radio de giro es del orden de la magnetósfera,

$$\frac{dI_\omega}{d\omega} = \sqrt{3}\,\frac{e^2}{c}\gamma\, f(\omega/\omega_c),$$

con la frecuencia de corte $\omega_c = 3\gamma^3 c/2r_c$, que depende del radio de curvatura, r_c. Los fotones emitidos alcanzan energías de GeV, suficientes para producir pares en el entorno, limitando su energía. Estos modelos predicen emisión en GeV por curvatura y en TeV por Compton inverso de fotones del entorno. La evidencia observacional de esta última es limitada.

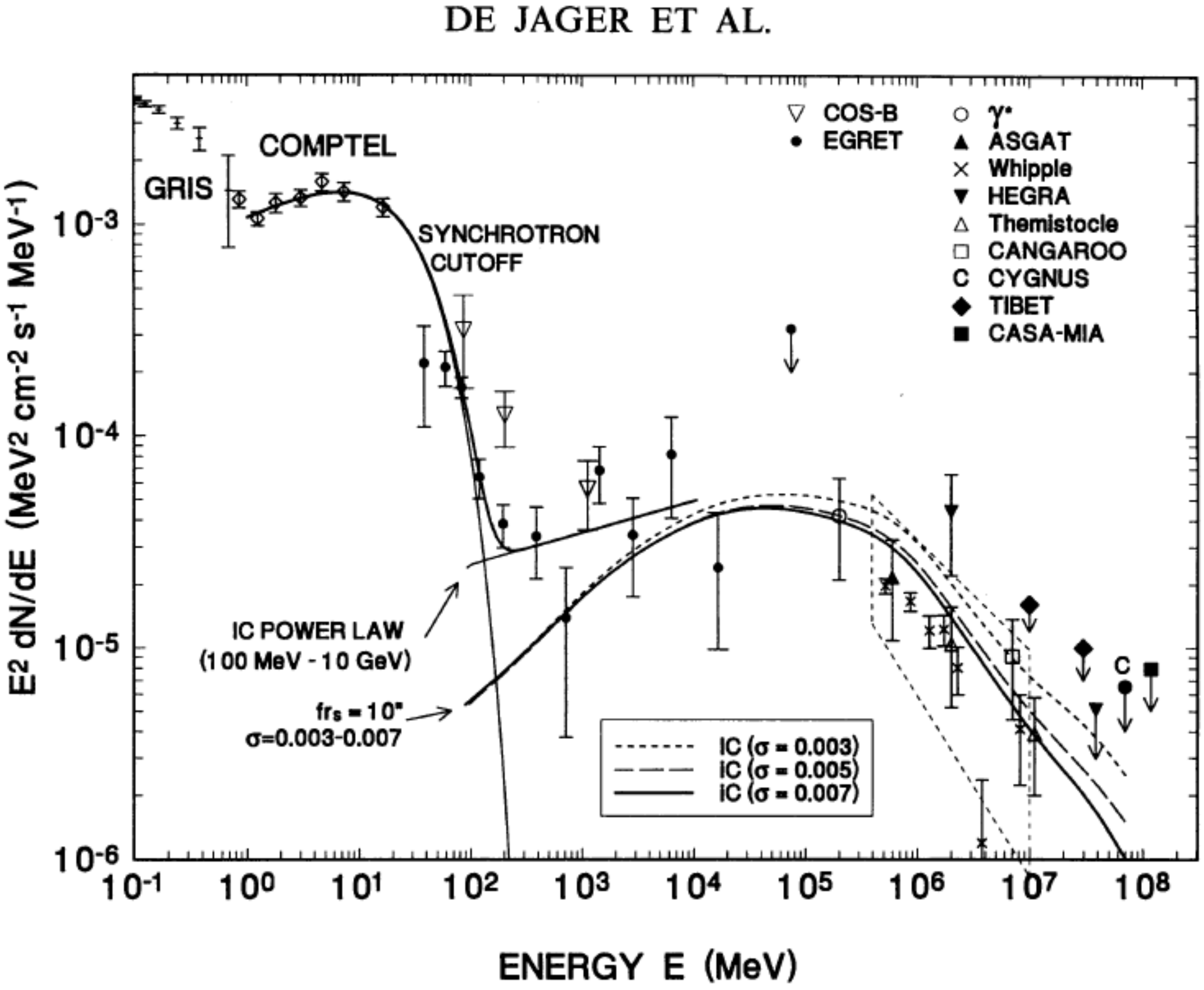


Hester et al. (2002)



5b. Vientos de pulsar

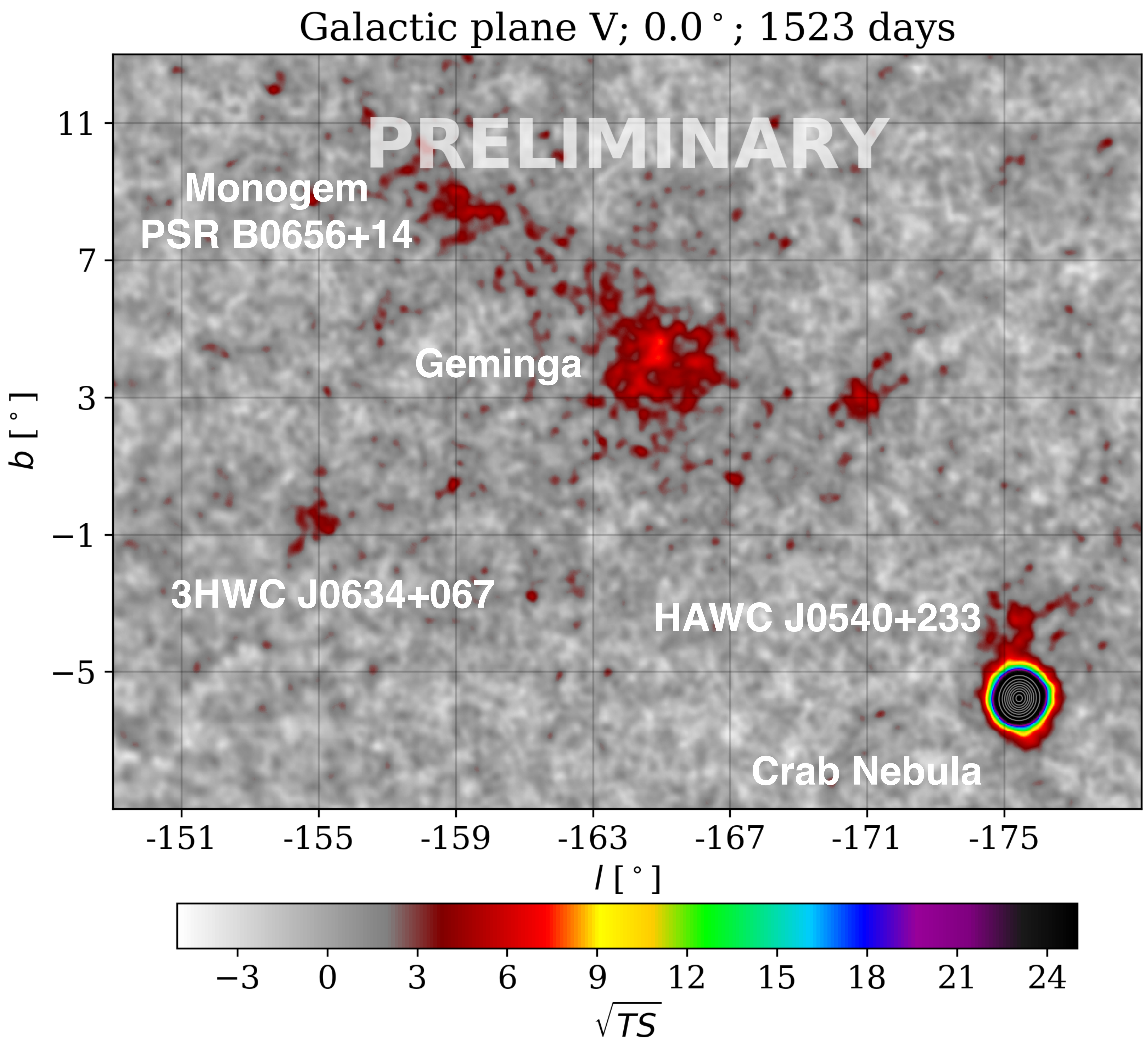
- Los pulsares producen pares $e^{\pm}$ de muy alta energía.
- Pares acelerados se mueven a lo largo de líneas de campo magnético dando lugar a un viento relativista que termina en una zona de choque.
- La interacción con los alrededores → "TeV haloes" (Linden et al. 2018).
- Proceso con escala de tiempo de varios 10^5 años.
- Puede la producción de positrones explicar el exceso observado de e^+ en los rayos cósmicos?



<u>De Jager & Harding (1992)</u>

<u>De Jager et al. (1996):</u>

Modelo SSC con B=0.3 mGauss y σ = (densidad energía magnética / partículas) como parámetro libre.



Anticentro Galáctico

Fuentes energizadas por pulsares:

- Nebulosa del Cangrejo: Pulsar Wind Nebula (PWN).
- Geminga & Monogem (PSR B0656+14): TeV halos
- HAWC J0540+233 (PSR B0540+23) y 3HWC J0634+067 (PSR J0633+0632): TeV halos?

IC 443: remanente (clásico) de supernova.

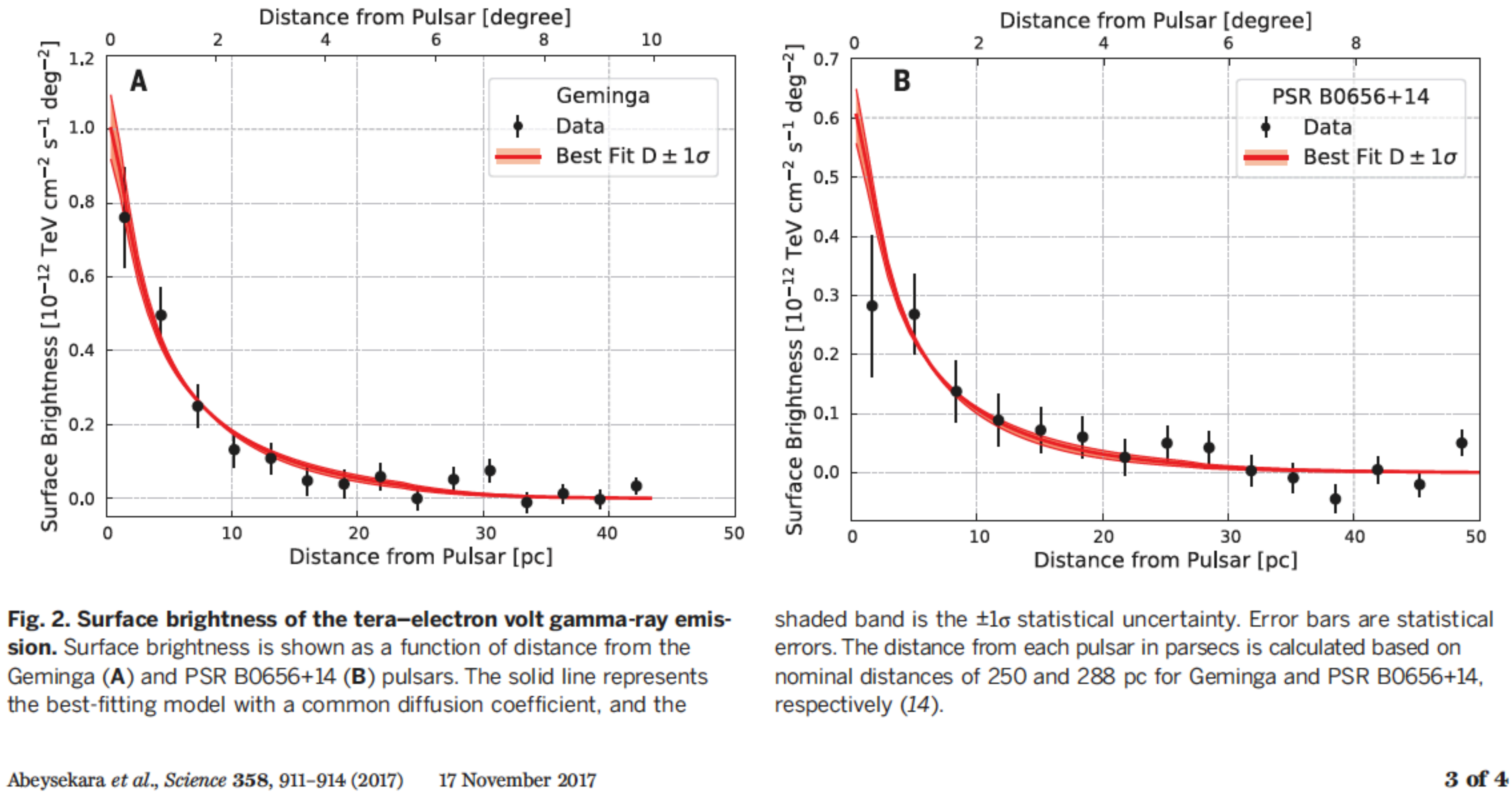
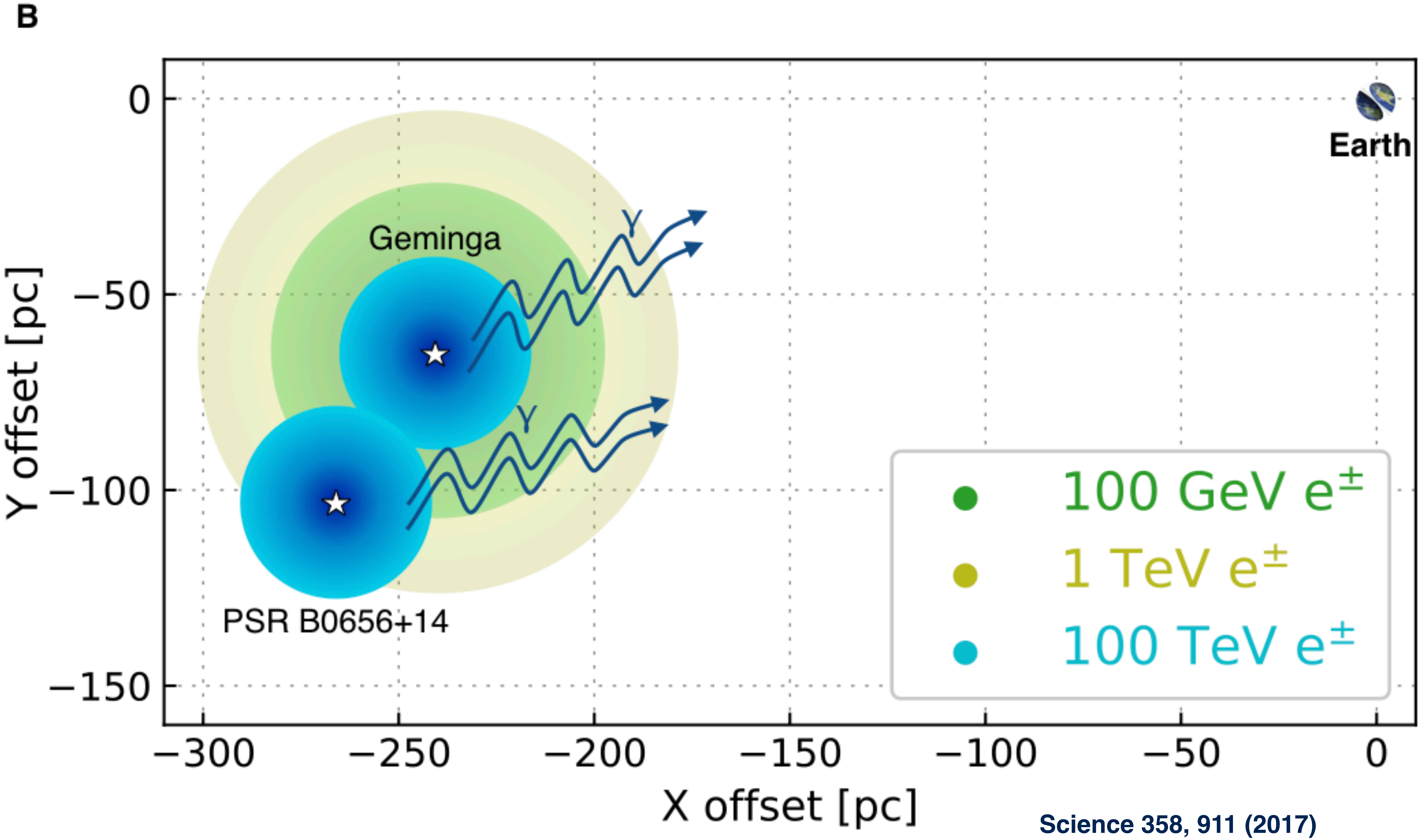


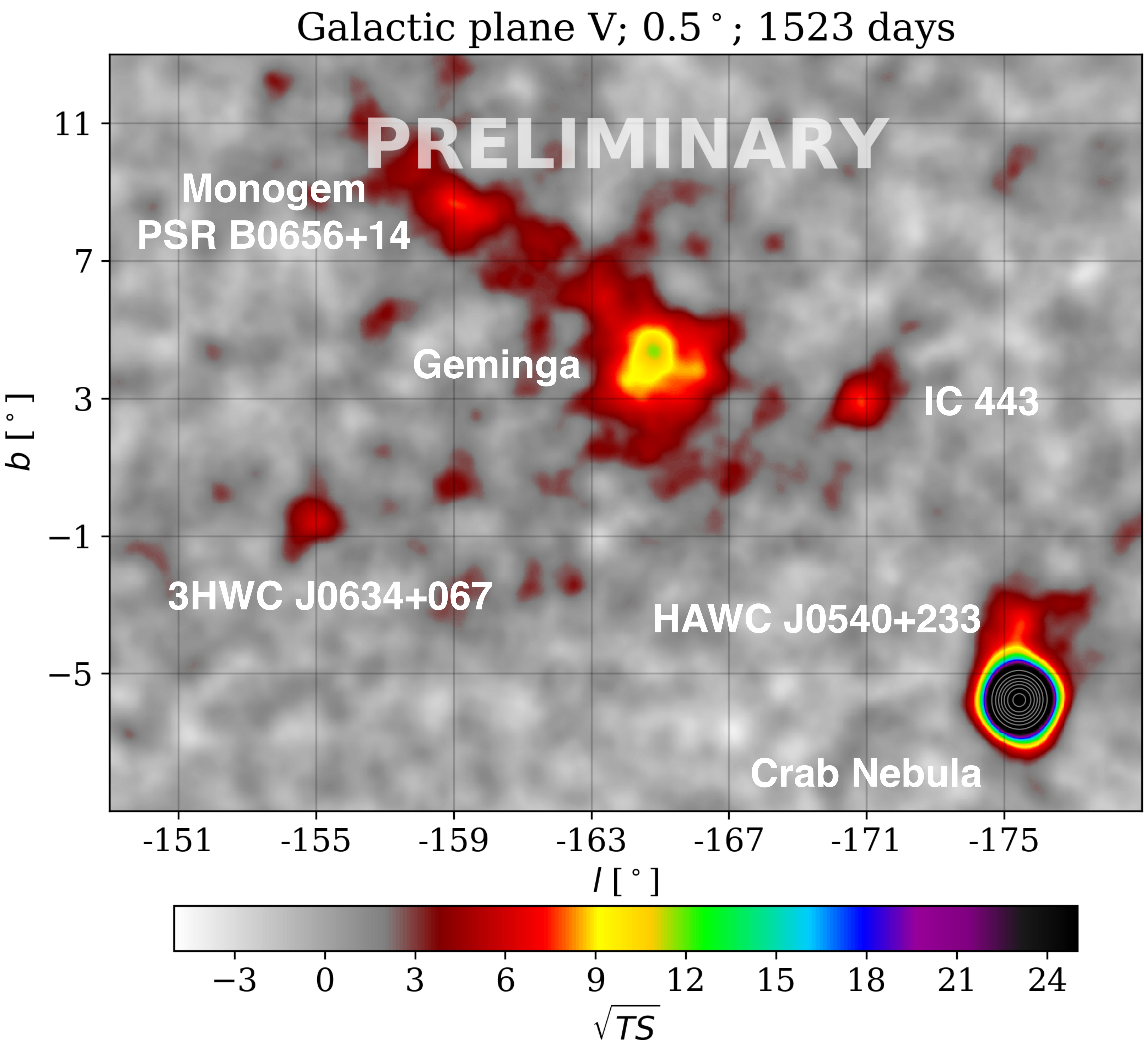
Fig. 2. Surface brightness of the tera–electron volt gamma-ray emission. Surface brightness is shown as a function of distance from the Geminga (**A**) and PSR B0656+14 (**B**) pulsars. The solid line represents the best-fitting model with a common diffusion coefficient, and the shaded band is the ±1σ statistical uncertainty. Error bars are statistical errors. The distance from each pulsar in parsecs is calculated based on nominal distances of 250 and 288 pc for Geminga and PSR B0656+14, respectively (*14*).

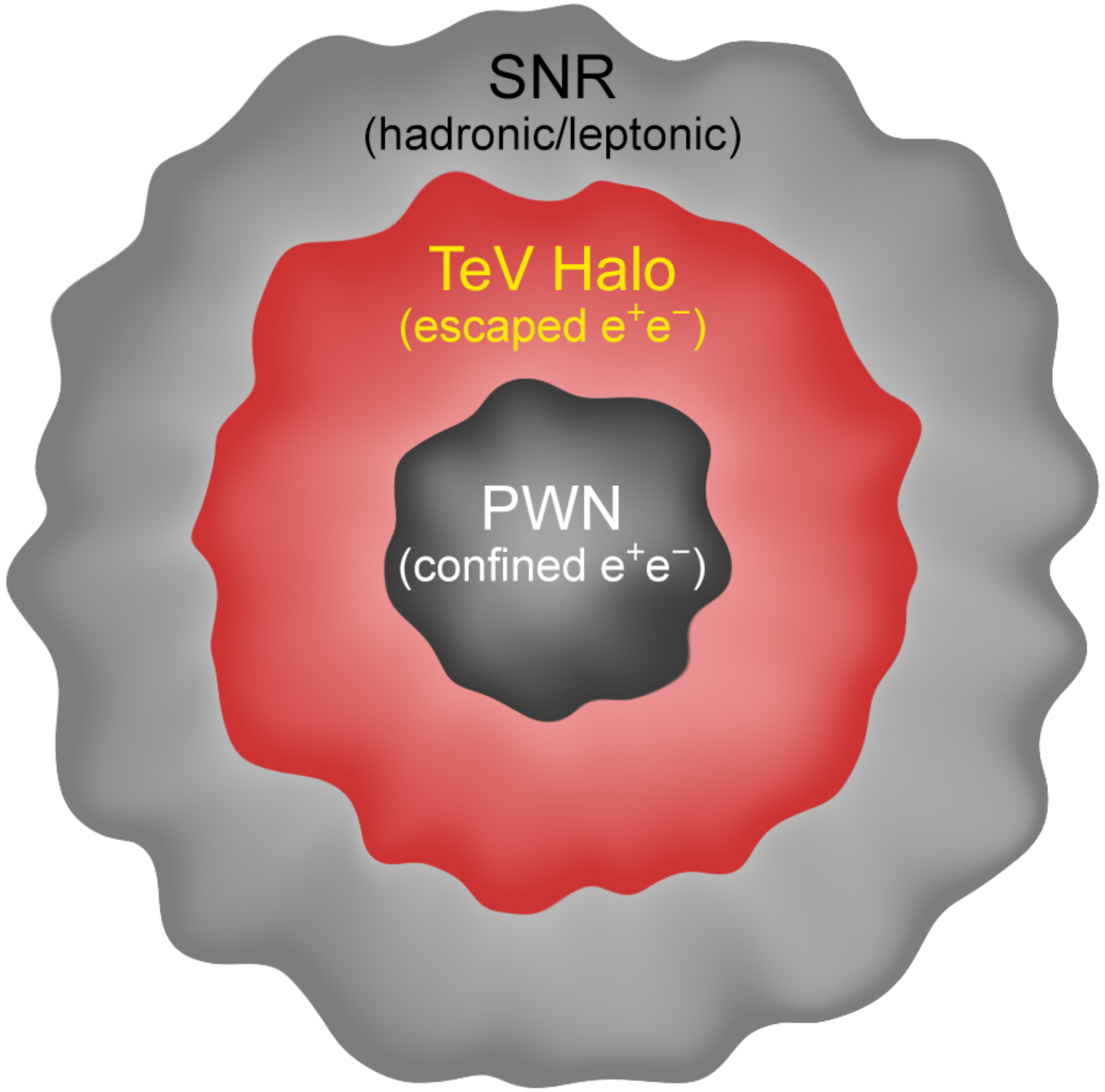
Abeysekara *et al.*, *Science* **358**, 911–914 (2017) 17 November 2017 **3 of 4**



Science 358, 911 (2017)

Sudoh, Linden & Beacom: "TeV halos are everywhere"
Phys Rew D, 100, 043016 - arxiv 1902.08203

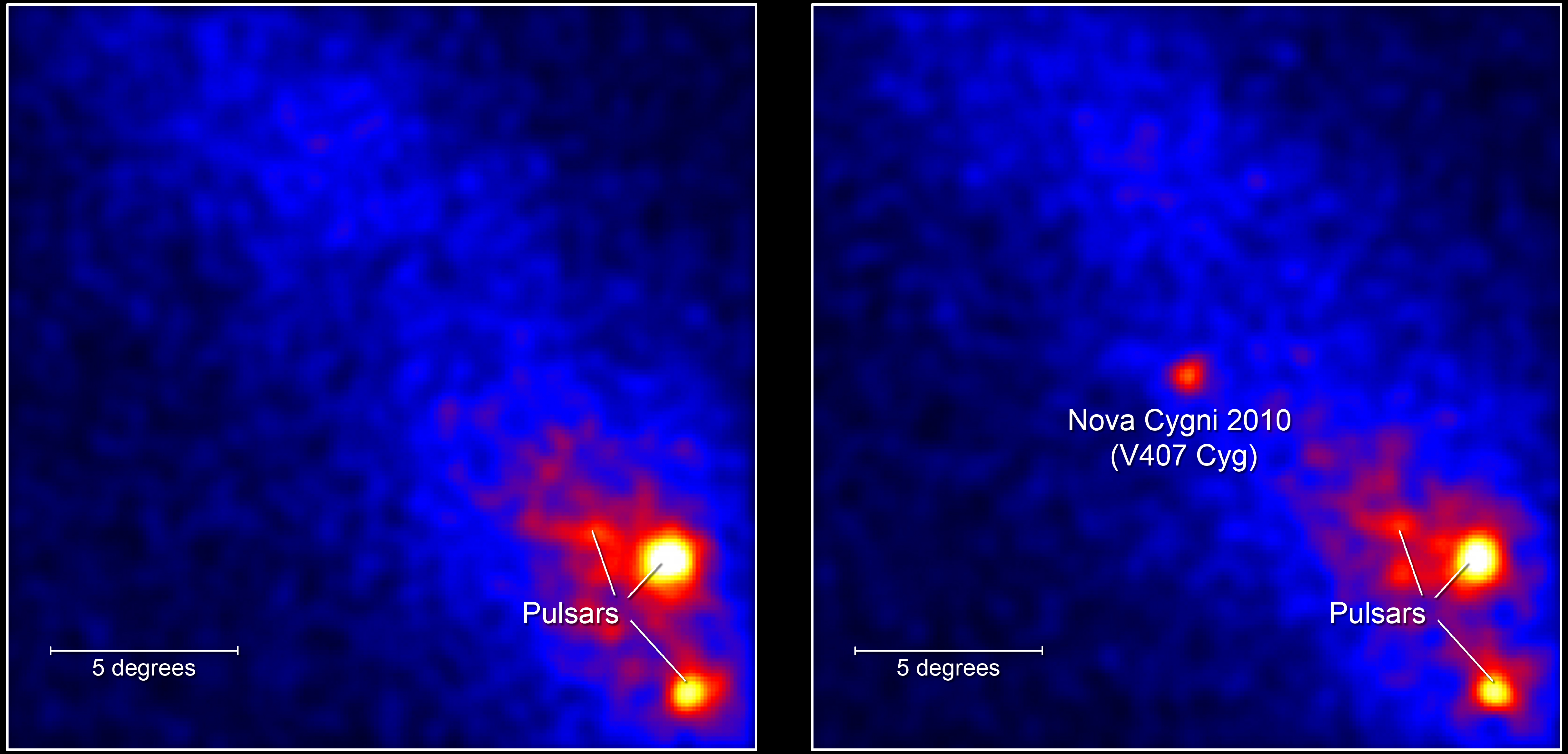




Electrones ultrarelativistas pueden producir rayos γ con energías de 100 TeV sólo por Compton scattering de fotones del CMB.

6. Binarias, novas…

Fermi Detects Gamma Rays from Nova Cygni 2010

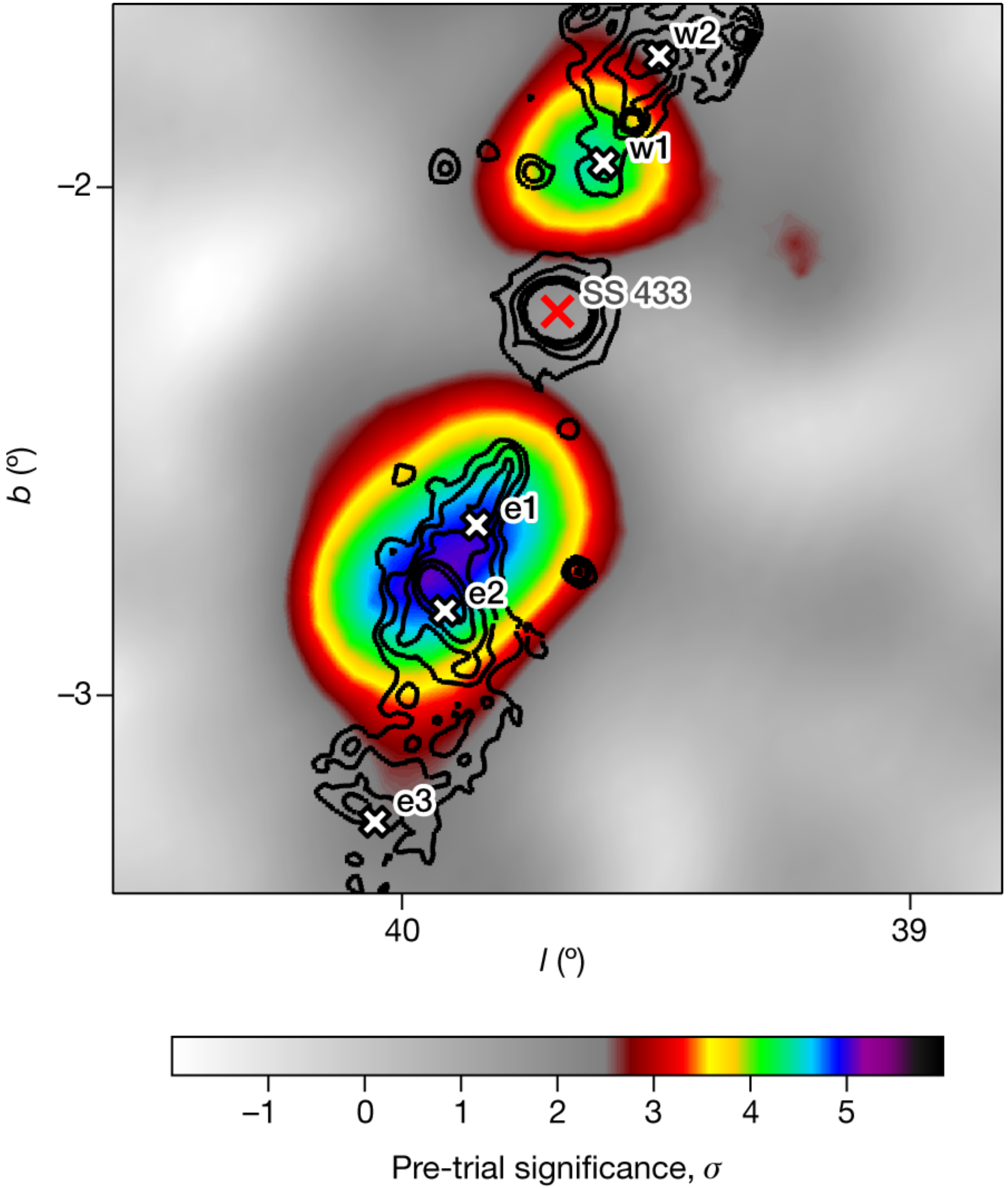


Feb. 19 to March 9, 2010

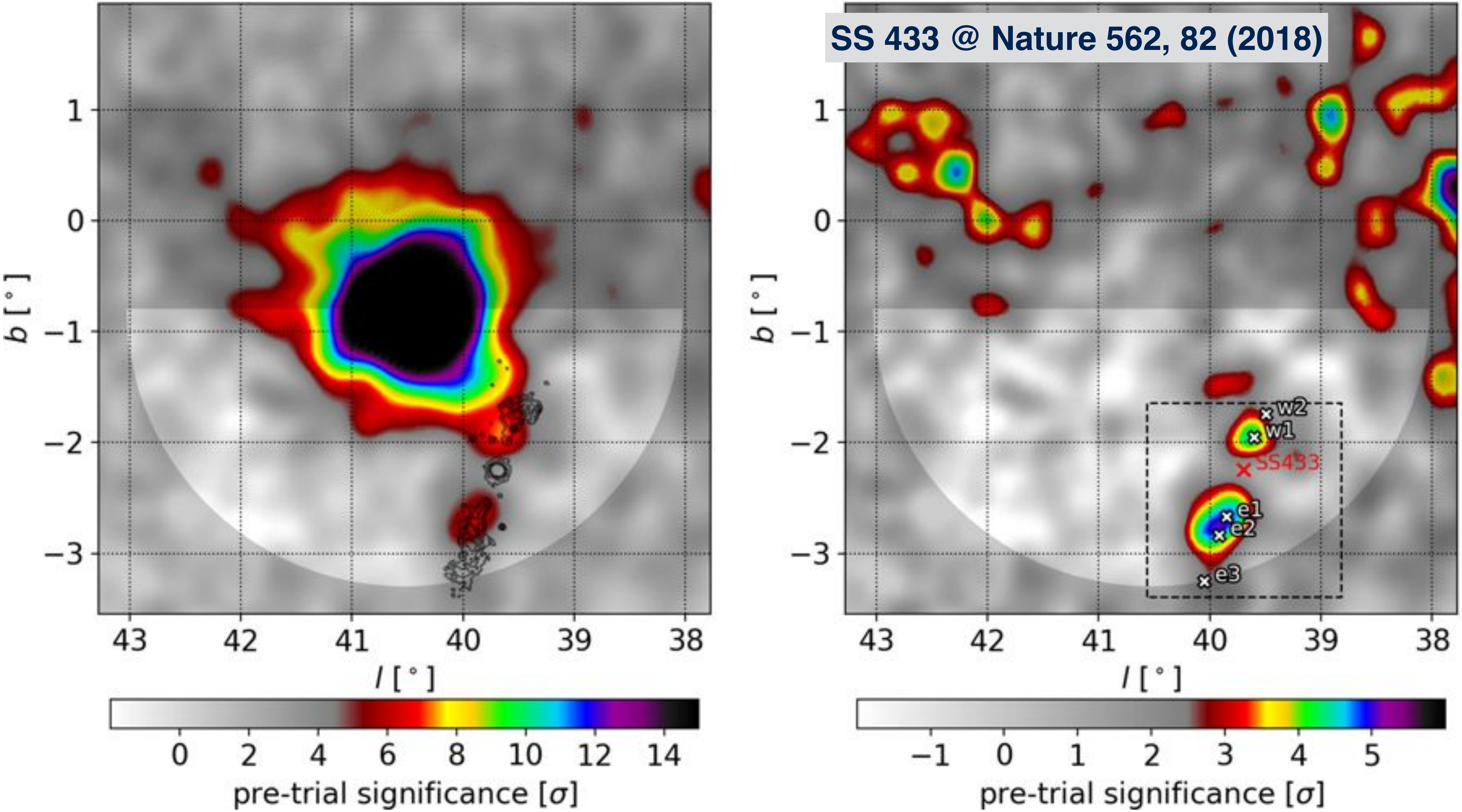
March 10 to 29, 2010

Microcuasares

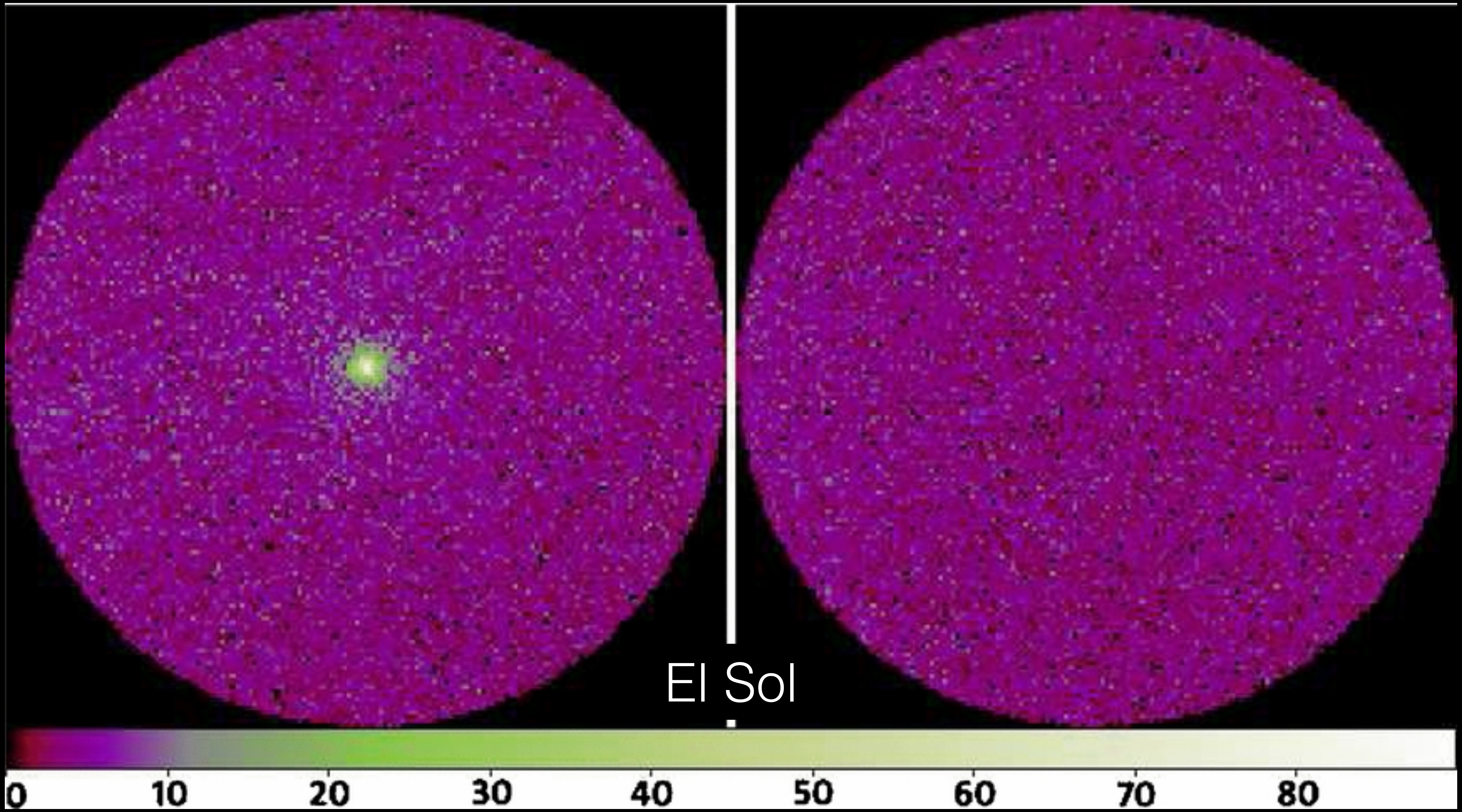
- Sistemas estelares binarios (HMXRB) Galácticos:
  - LSI +61 303, η Carinae, LS 5039

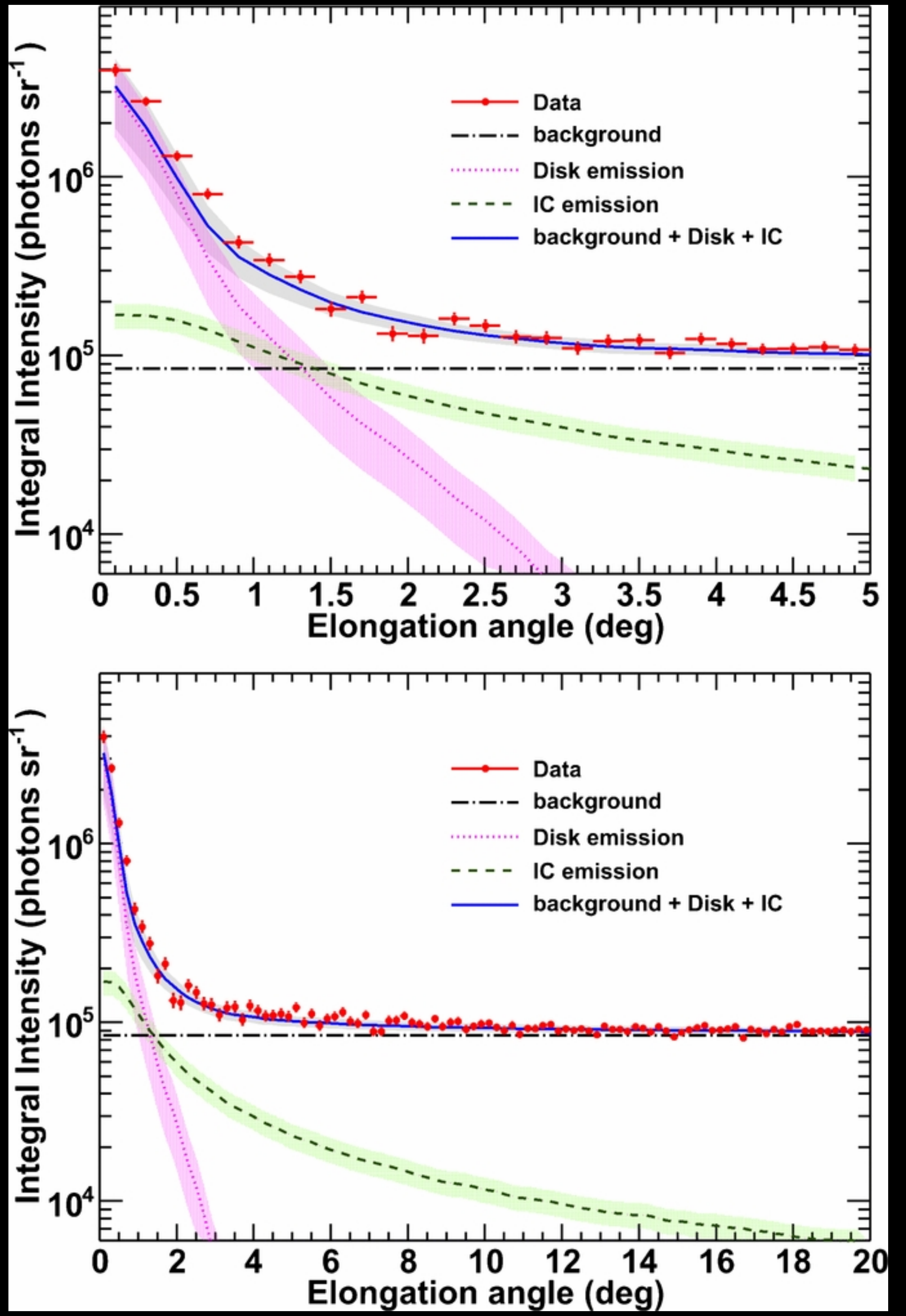


SS 433 @ Nature 562, 82 (2018)

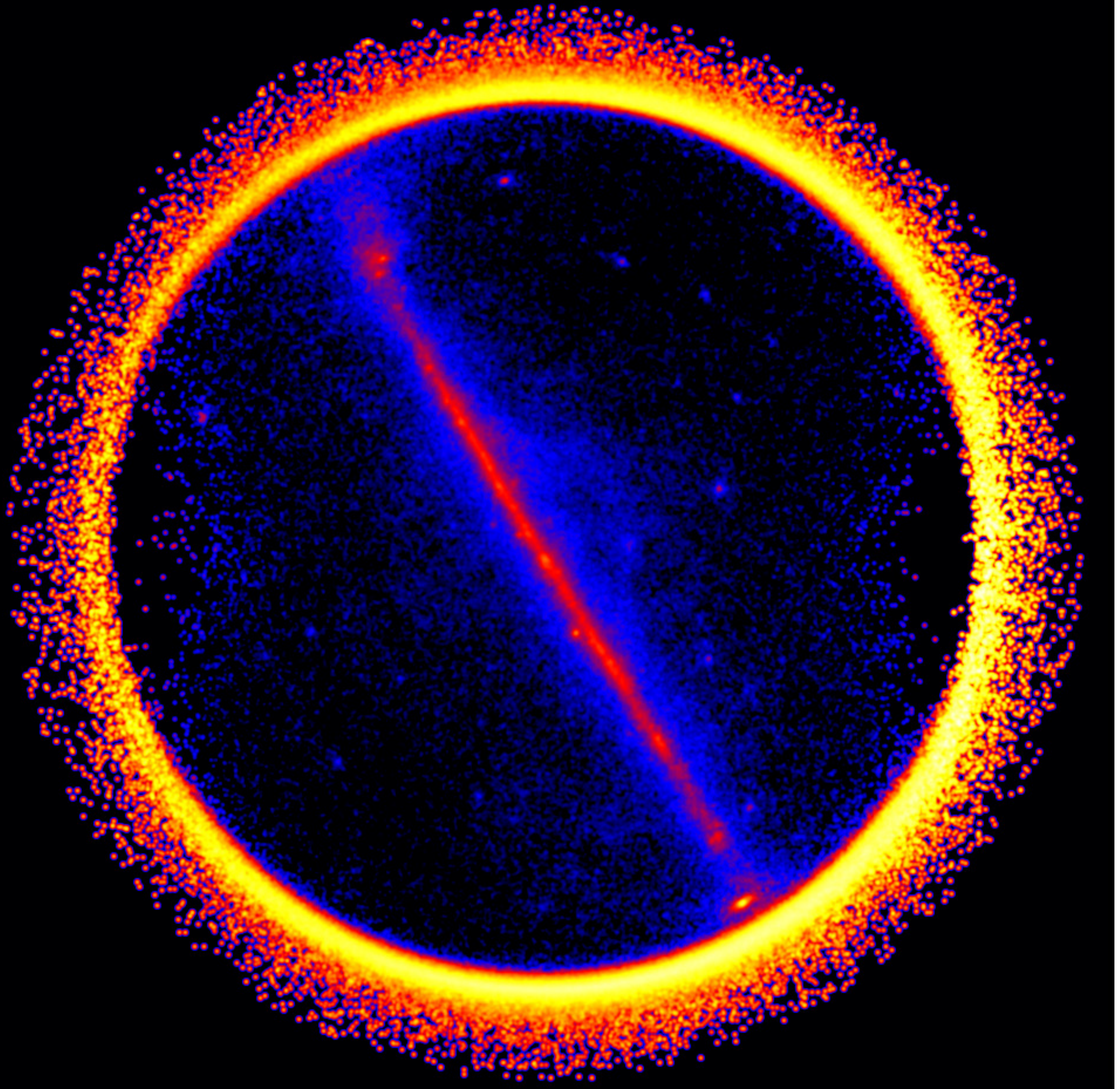


Intermedio


El Sol
0
10
20
30
40
50
60
70
80


Data
background
Disk emission
IC emission
background + Disk + IC
Integral Intensity (photons sr^{-1})
10^4
10^5
10^6
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Elongation angle (deg)
Data
background
Disk emission
IC emission
background + Disk + IC
Integral Intensity (photons sr^{-1})
10^4
10^5
10^6
0
2
4
6
8
10
12
14
16
18
20
Elongation angle (deg)

La Tierra



BRIGGS ET AL.: IMPROVED FERMI TGF OBSERVATIONS

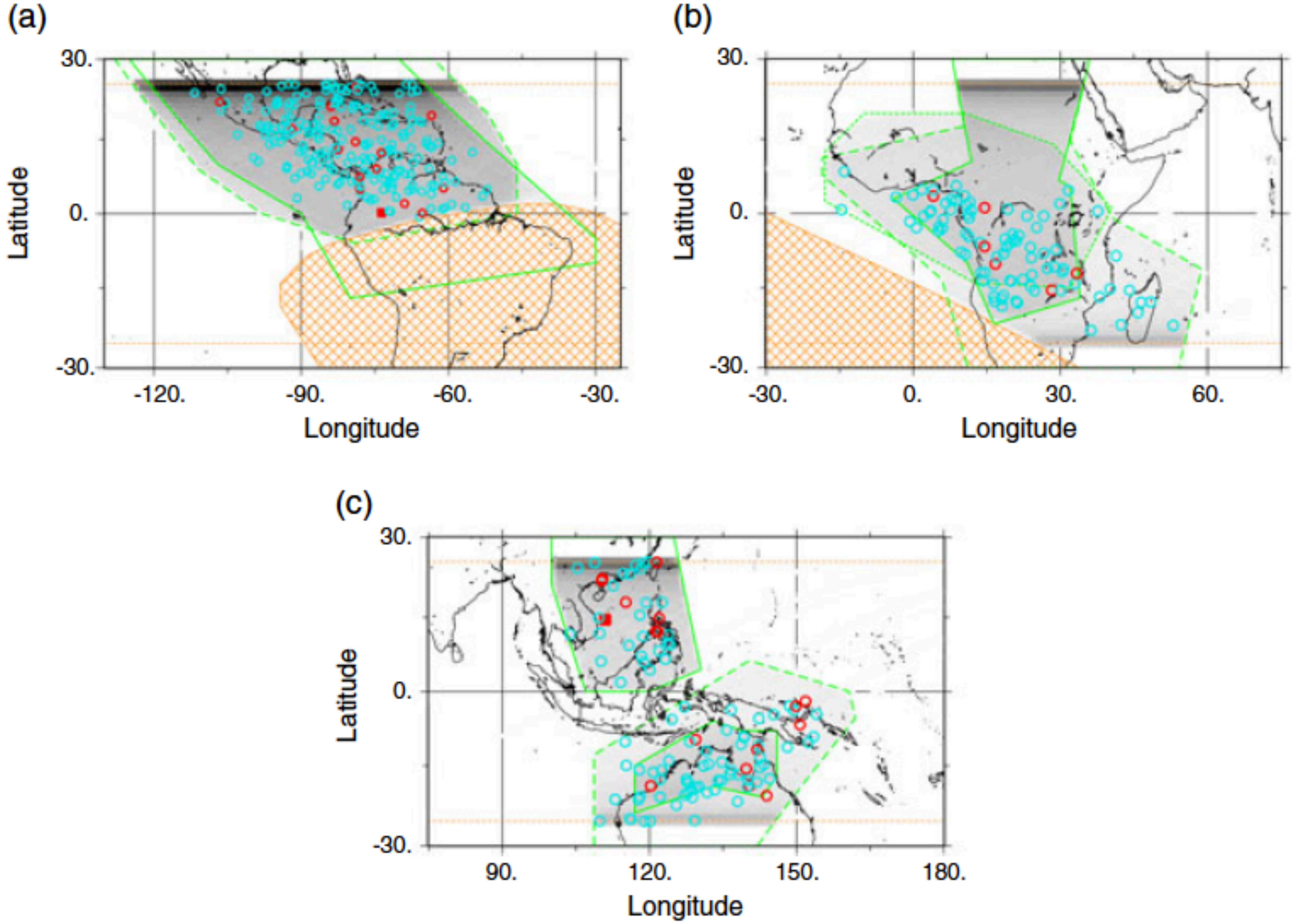
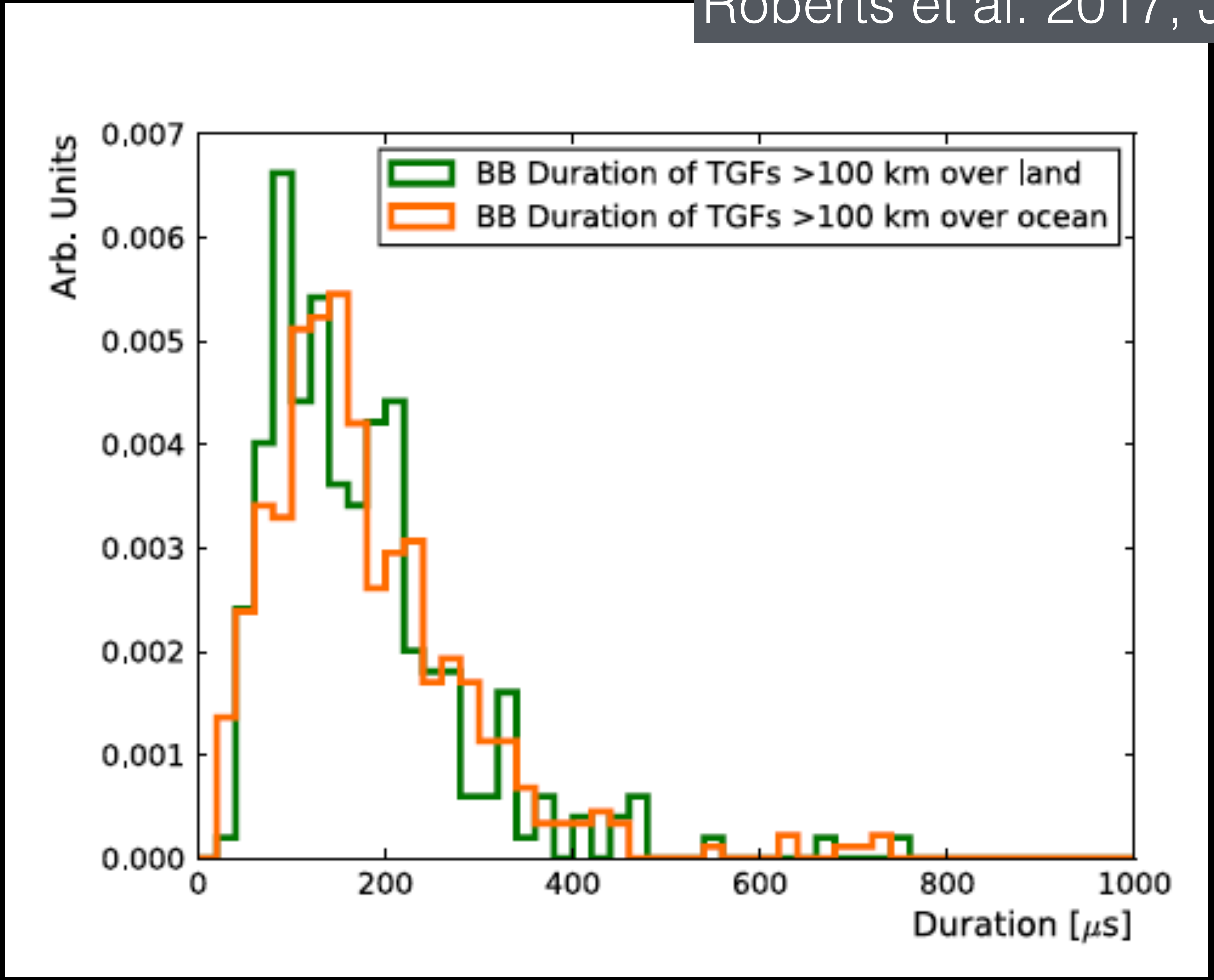
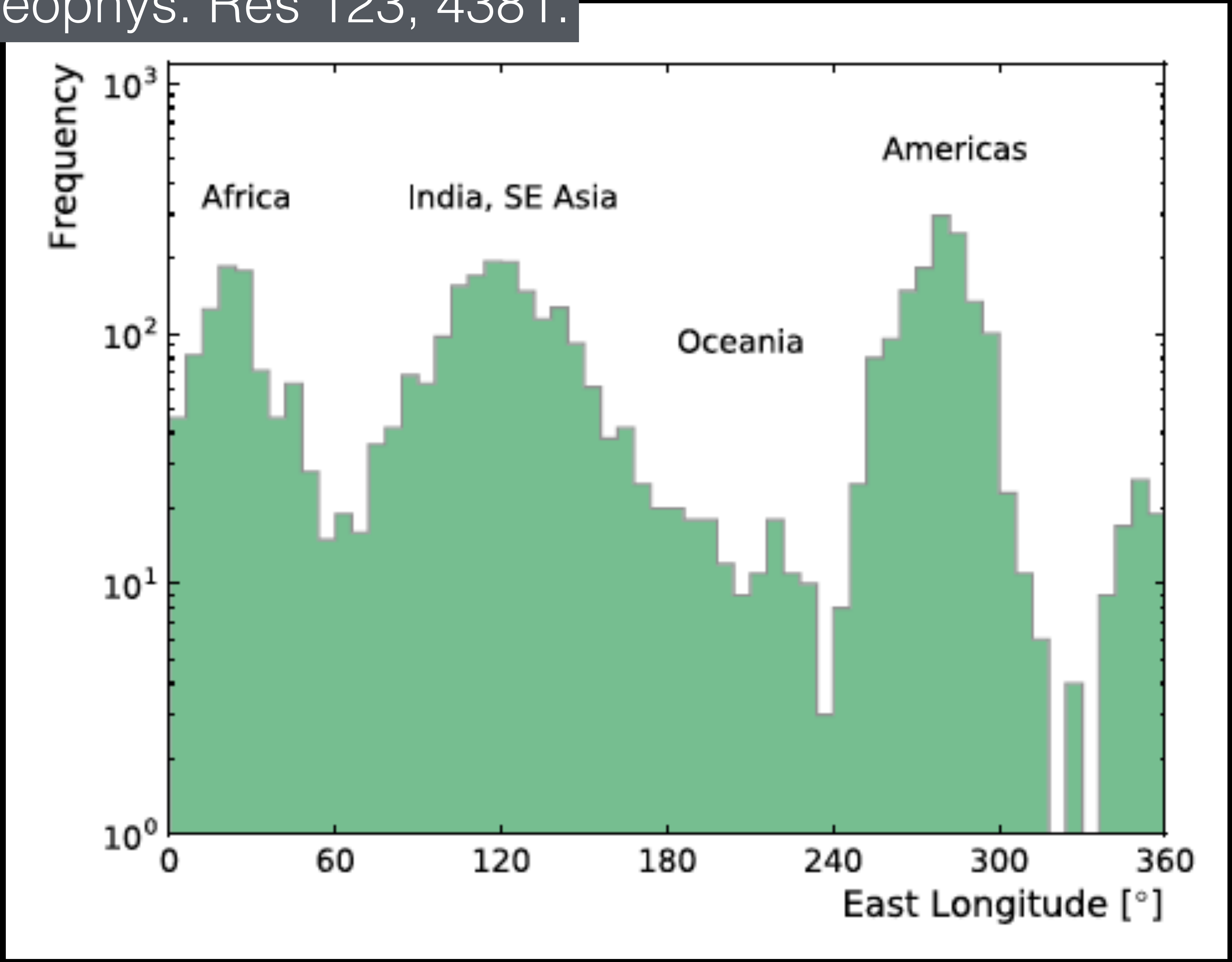


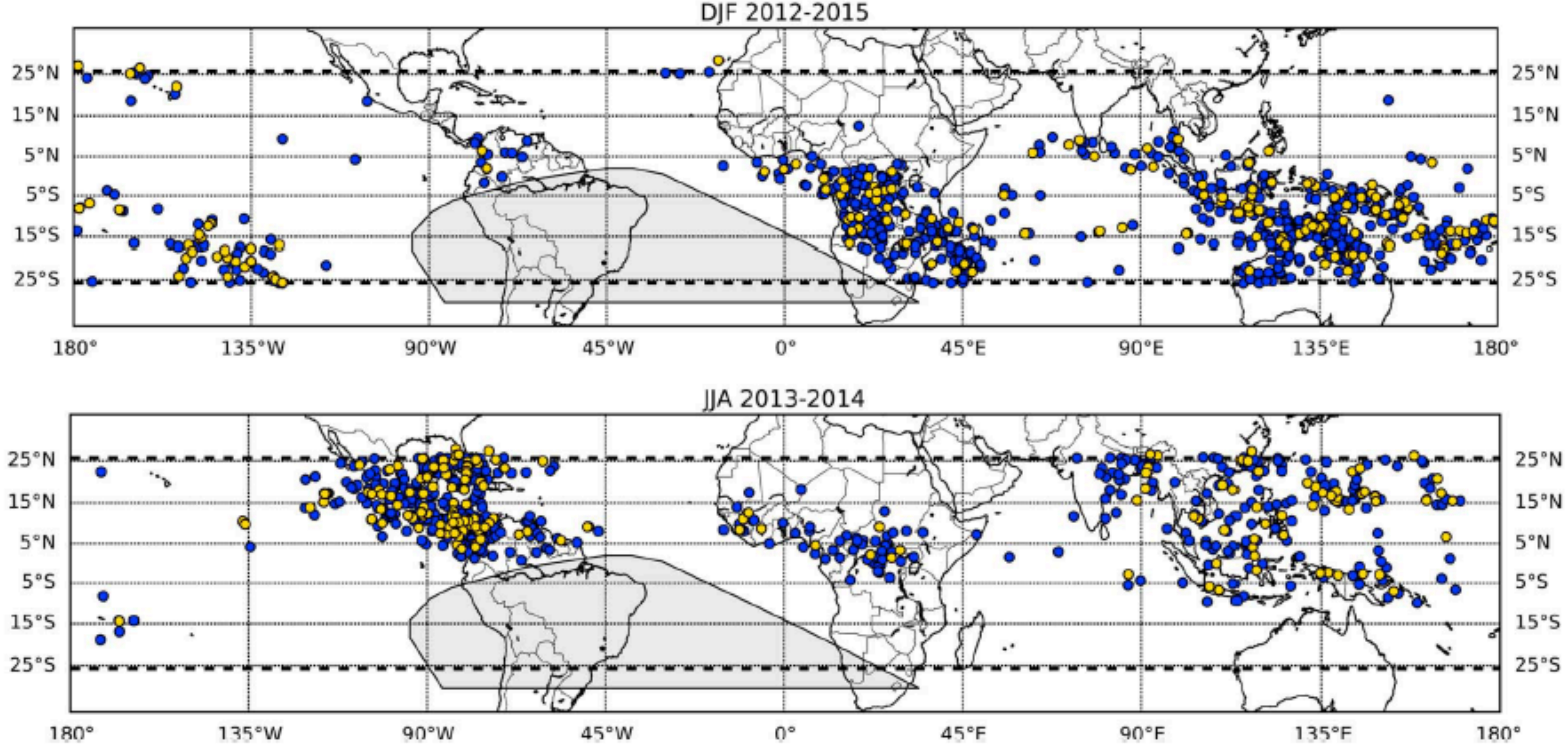
Figure 5. Locations of Fermi for the reliable sample of 425 TGFs / TEBs. The 384 TGFs found by the offline search of the continuous TTE are shown in cyan, while the 41 triggered TGFs / TEBs are shown in red. TGFs are depicted with open circles and TEBs with filled squares. There are (a) 227 TGFs and one TEB in the Americas (including 18 triggered), (b) 90 TGFs in Africa (including six triggered), and (c) 106 TGFs and one TEB in Asia and Australia (including 17 triggered).

1st Catalog of Terrestrial γ-ray Flashes

Roberts et al. 2017, J. Geophys. Res 123, 4381.

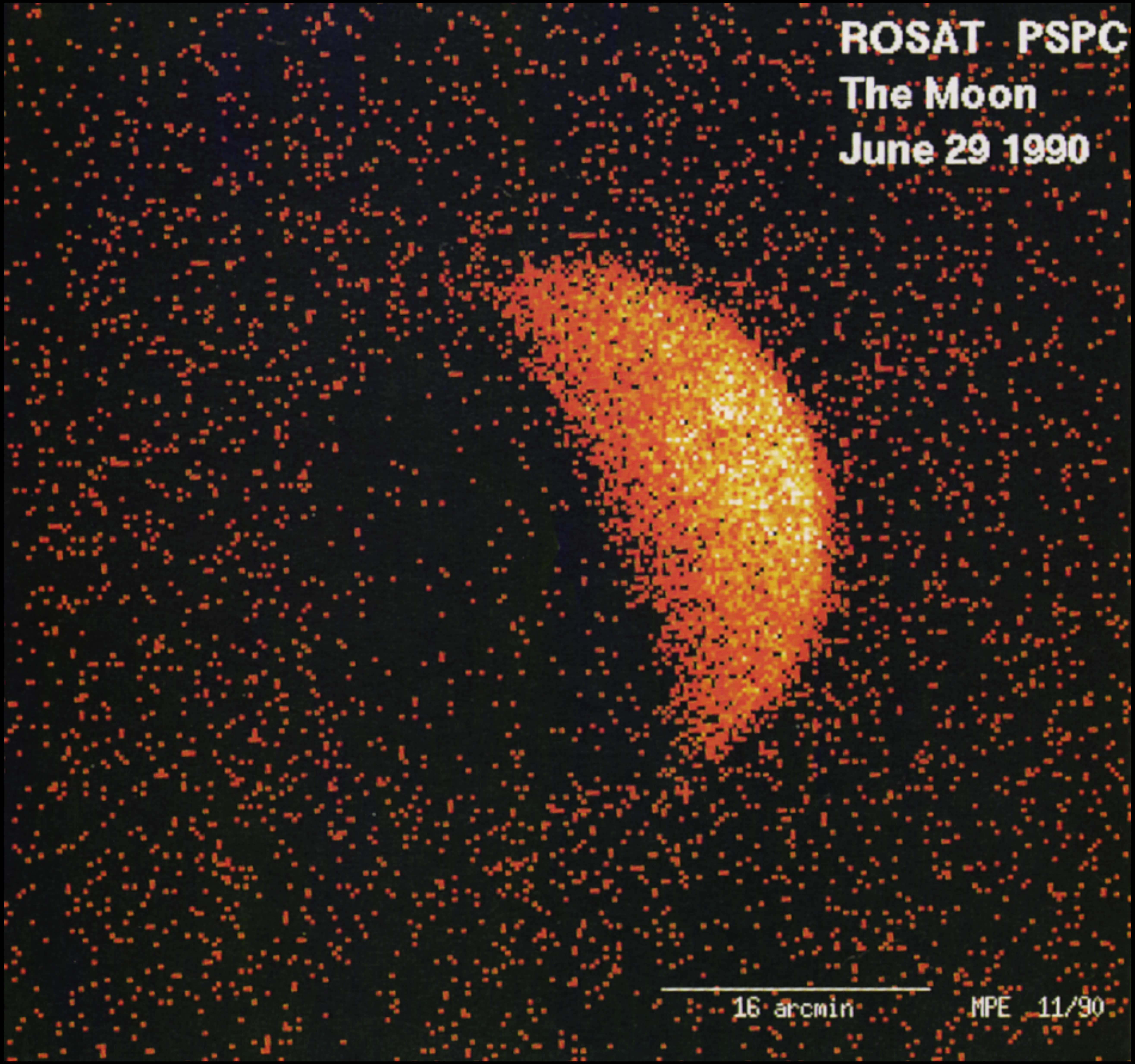


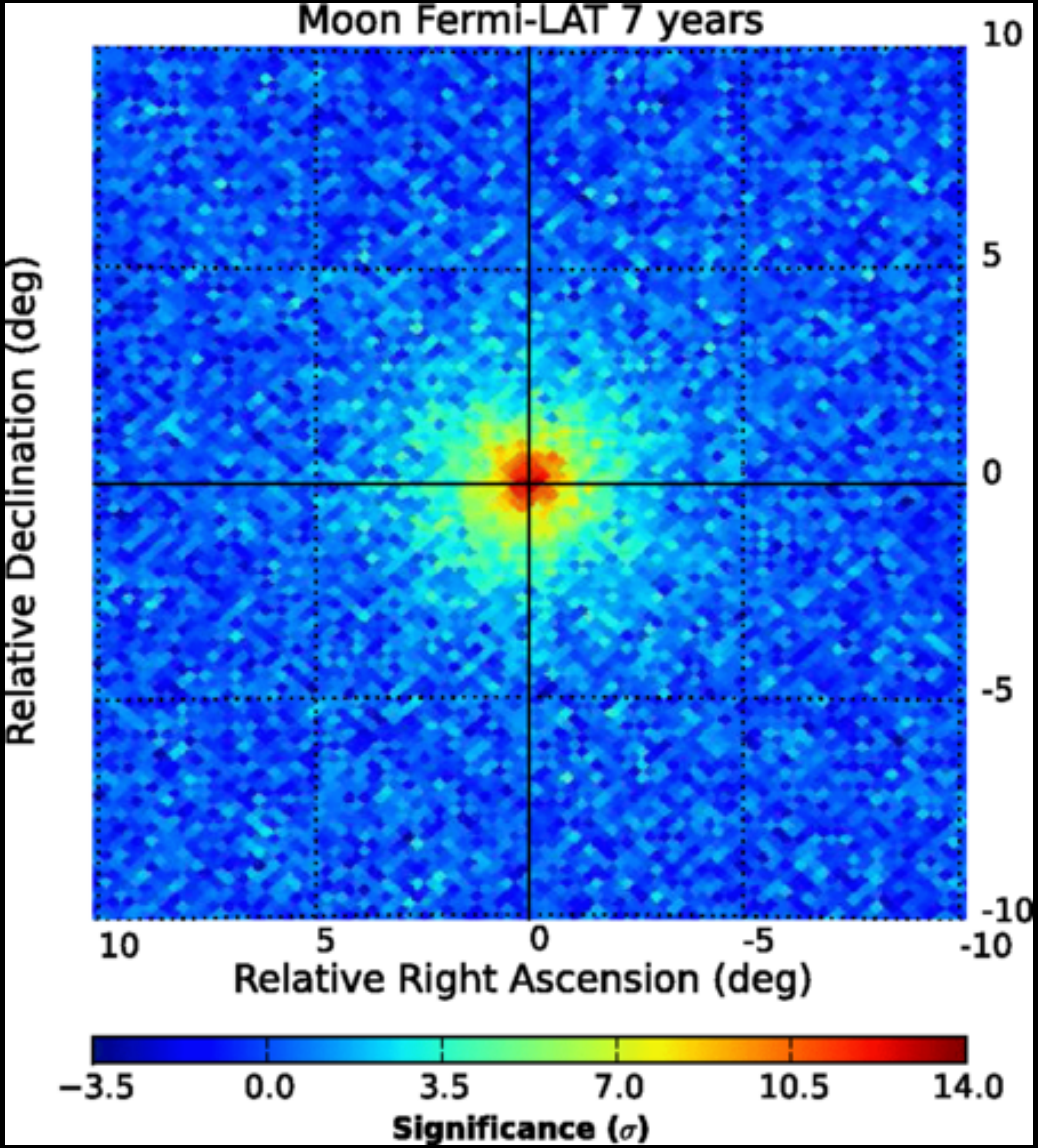



DJF 2012-2015

JJA 2013-2014

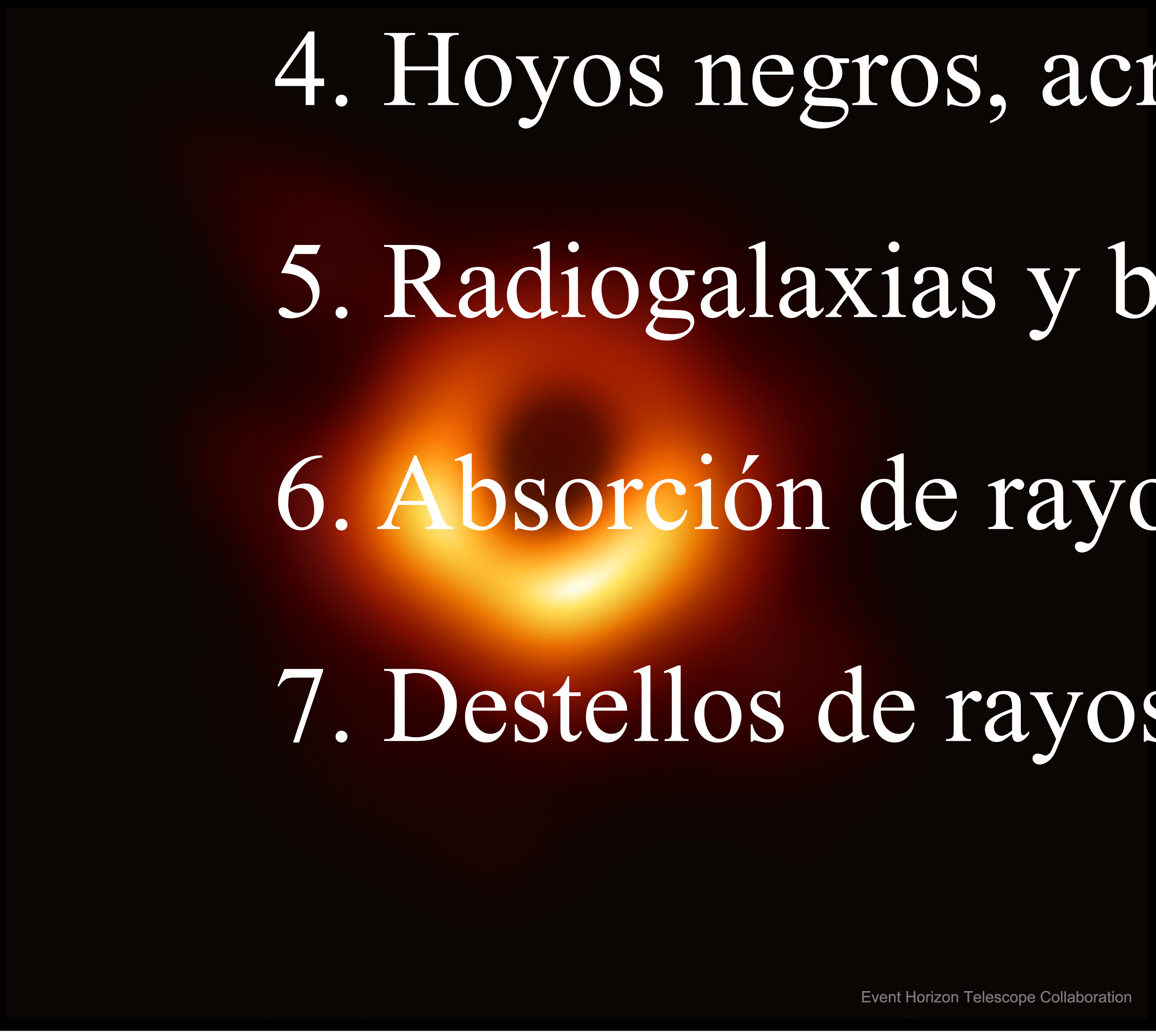
(Top) Three years of terrestrial gamma ray flash (TGF) data from the months of December, January, and February (DJF). (Bottom) Two years o


ROSAT PSPC
The Moon
June 29 1990
16 arcmin
MPE 11/90

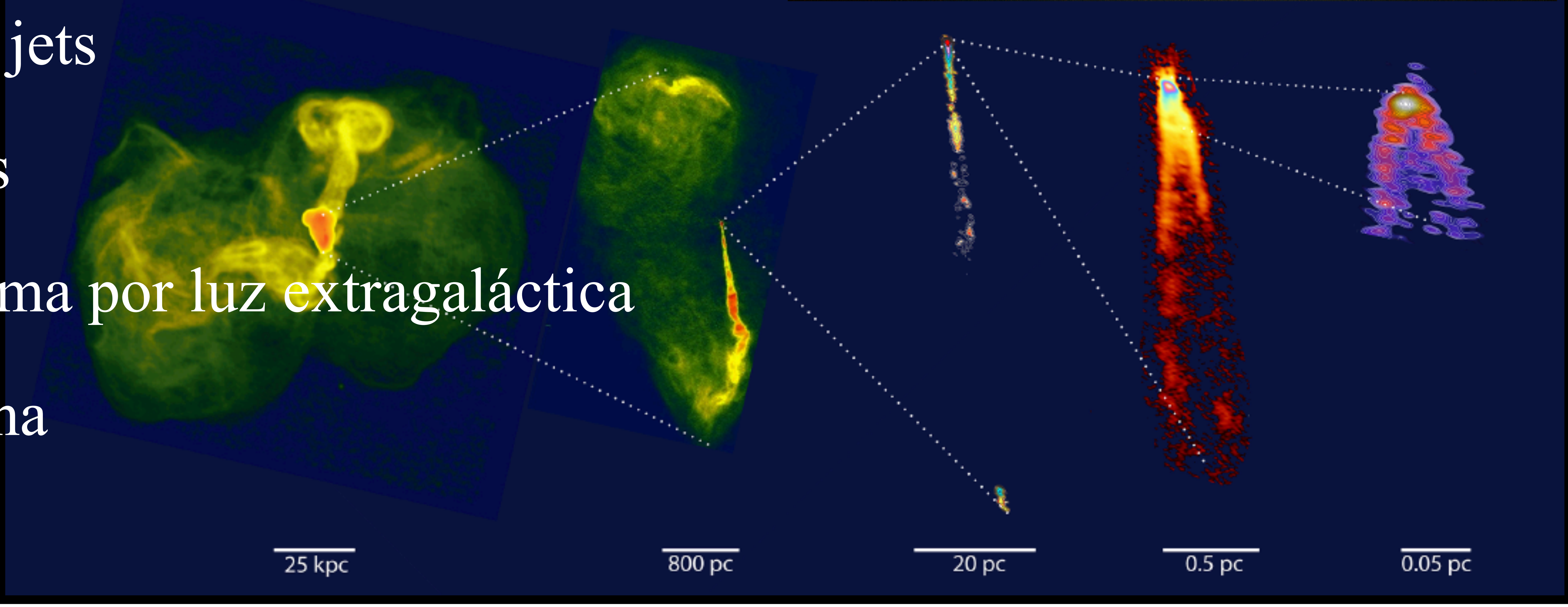

Moon Fermi-LAT 7 years
Relative Declination (deg)
Relative Right Ascension (deg)
10
5
0
-5
-10
10
5
0
-5
-10
Significance (σ)
−3.5
0.0
3.5
7.0
10.5
14.0

Fuentes extragalácticas de rayos gamma

1. Tipos de fuentes
2. Galaxias normales y starburst
3. Núcleos activos de galaxias
4. Hoyos negros, acreción, jets
5. Radiogalaxias y blazares
6. Absorción de rayos gamma por luz extragaláctica
7. Destellos de rayos gamma



Event Horizon Telescope Collaboration



COS-B (1975 - 1982)

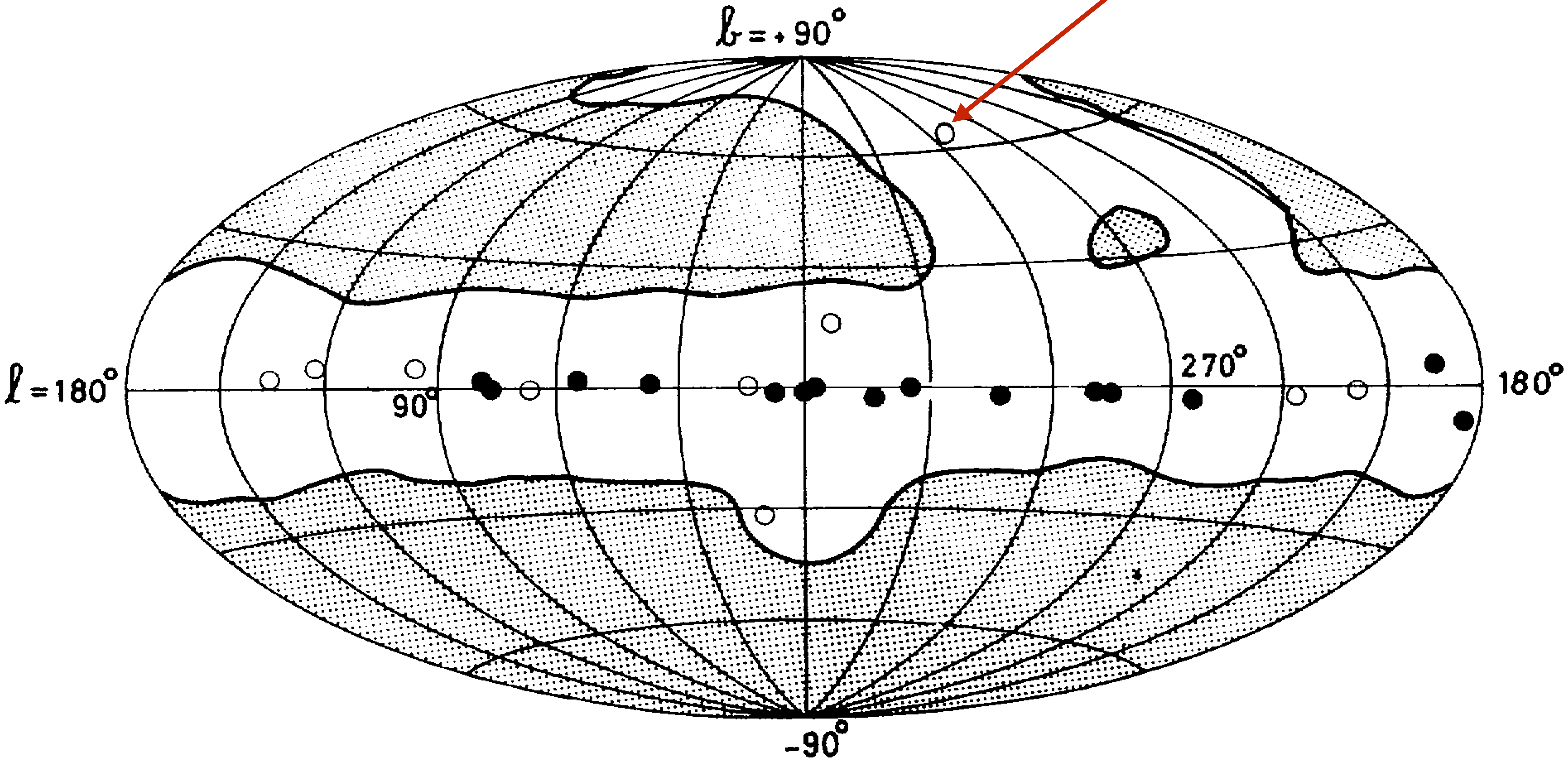
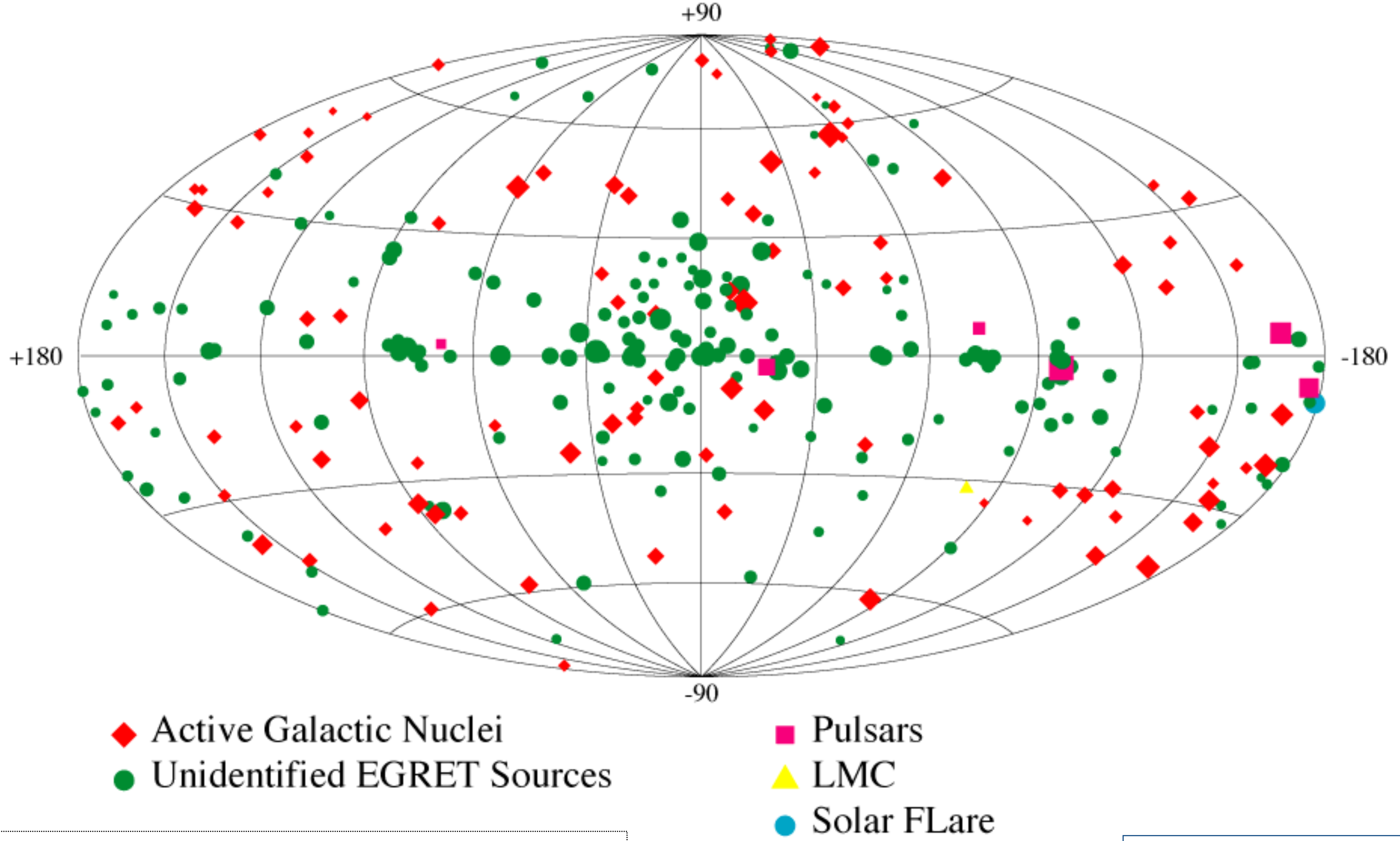


FIG. 1.—Region of the sky searched for gamma-ray sources (*unshaded*) and sources detected above 100 MeV by spatial analysis. The filled circles denote sources with measured fluxes $\geq 1.3 \times 10^{-6}$ photons cm^{-2} s^{-1}. Open circles denote sources below this threshold.

Third EGRET Catalog

E > 100 MeV



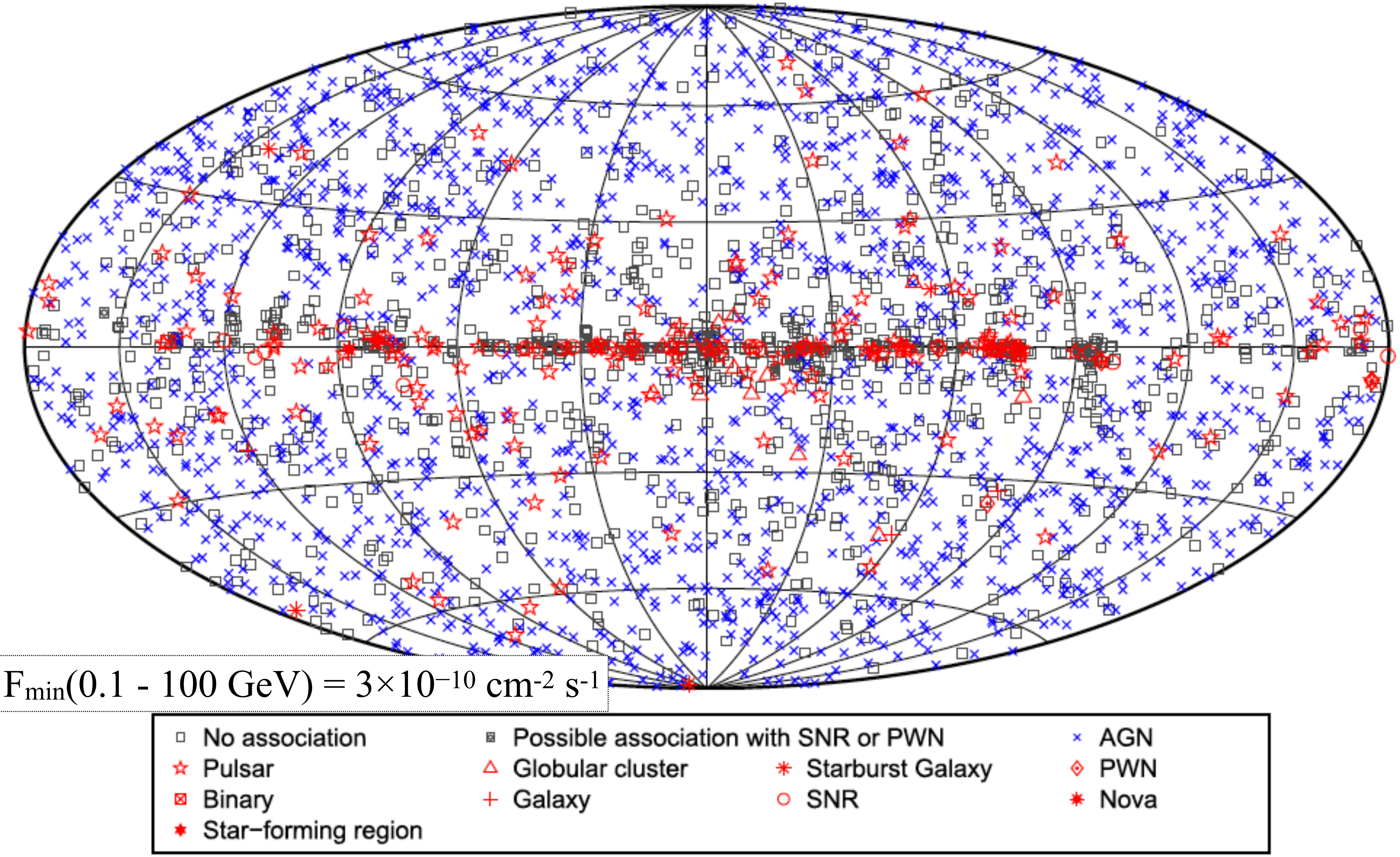
$F_{min}(E>100\ \mathrm{MeV}) = 6.2\times10^{-8}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

Hartman et al. (1999)

3FGL

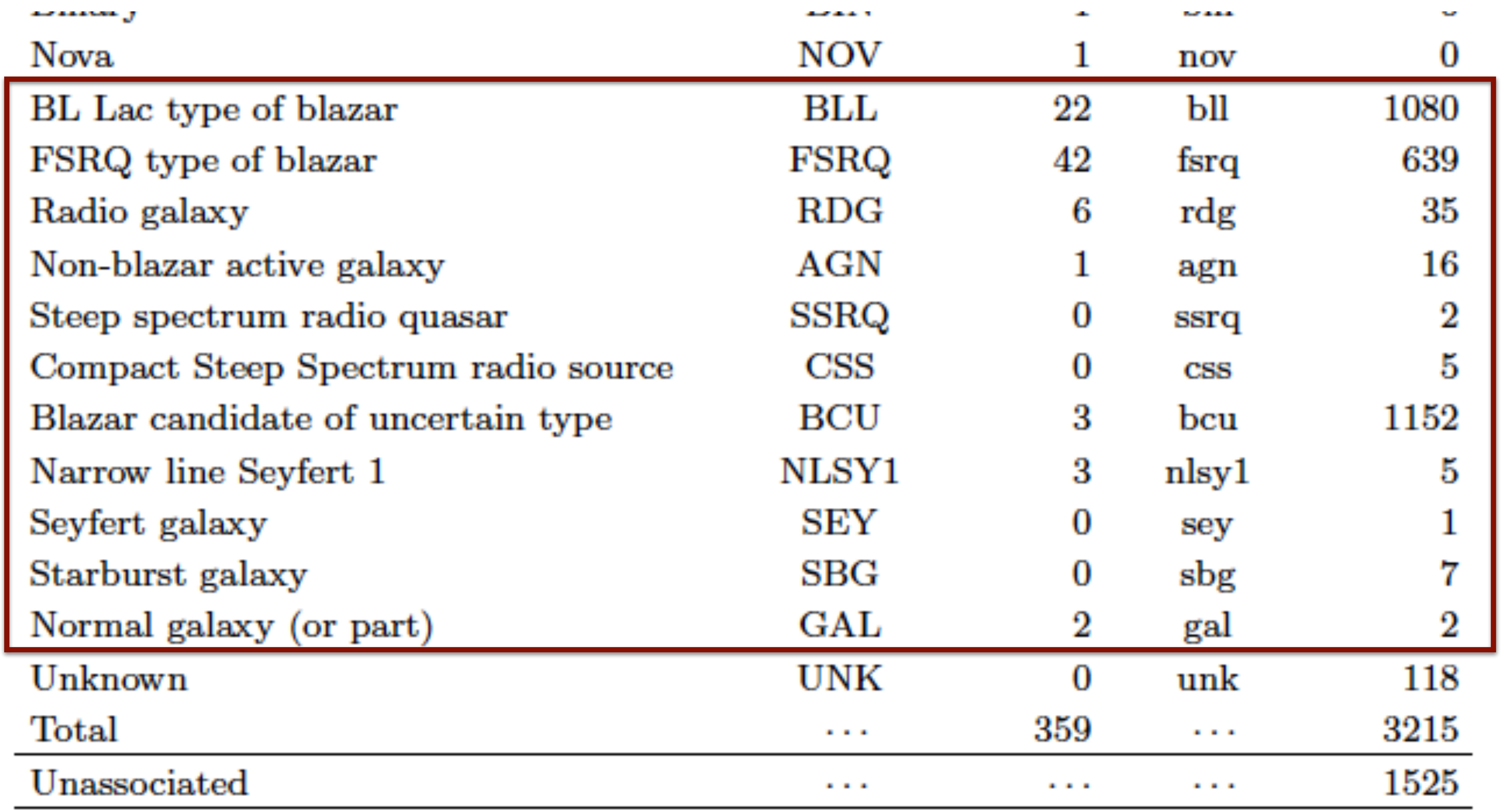
THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 218:23 (41pp), 2015 June

ACERO ET AL.



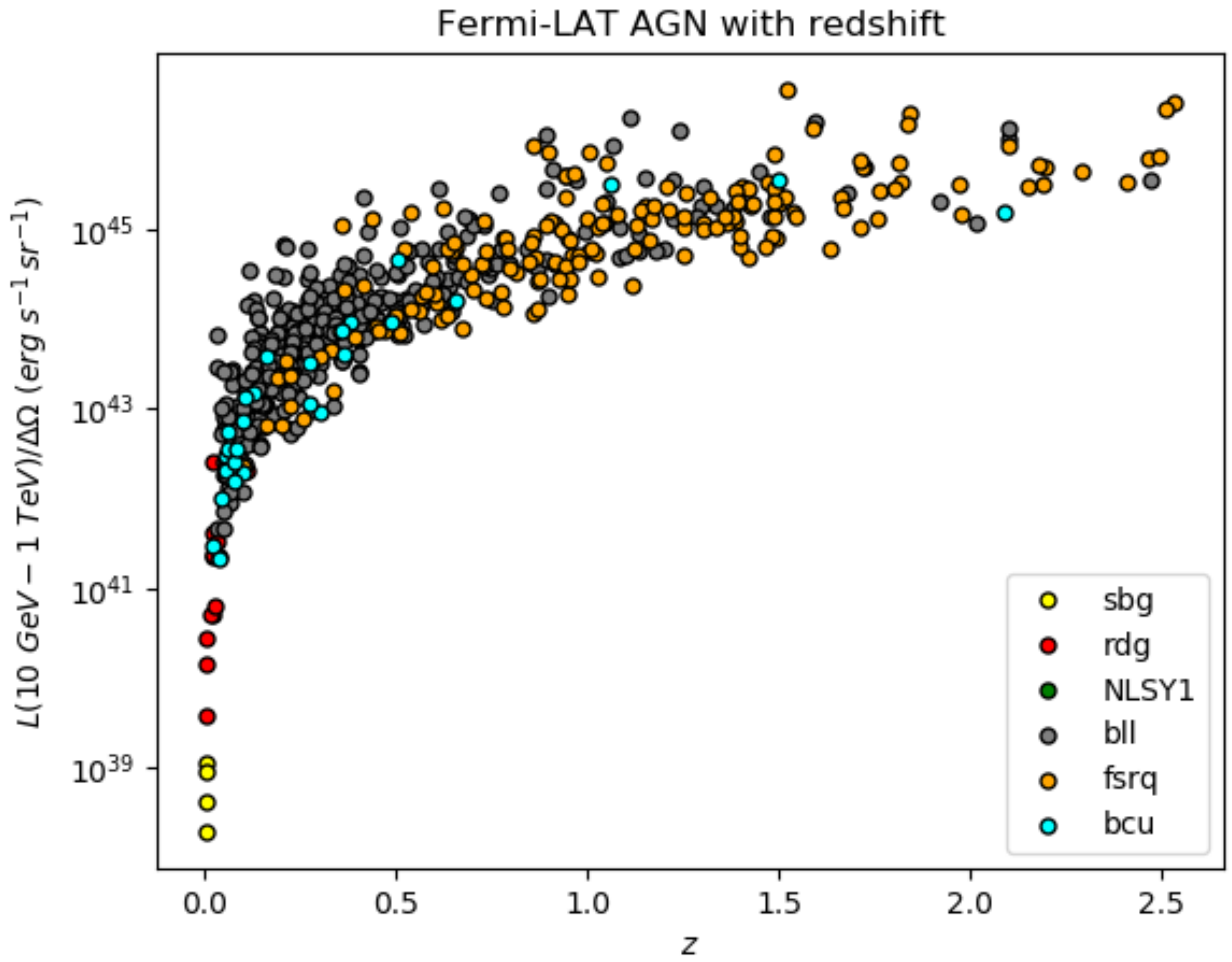
$F_{min}(0.1 - 100\ \mathrm{GeV}) = 3\times10^{-10}\ \mathrm{cm^{-2}\ s^{-1}}$

Tipos de fuentes

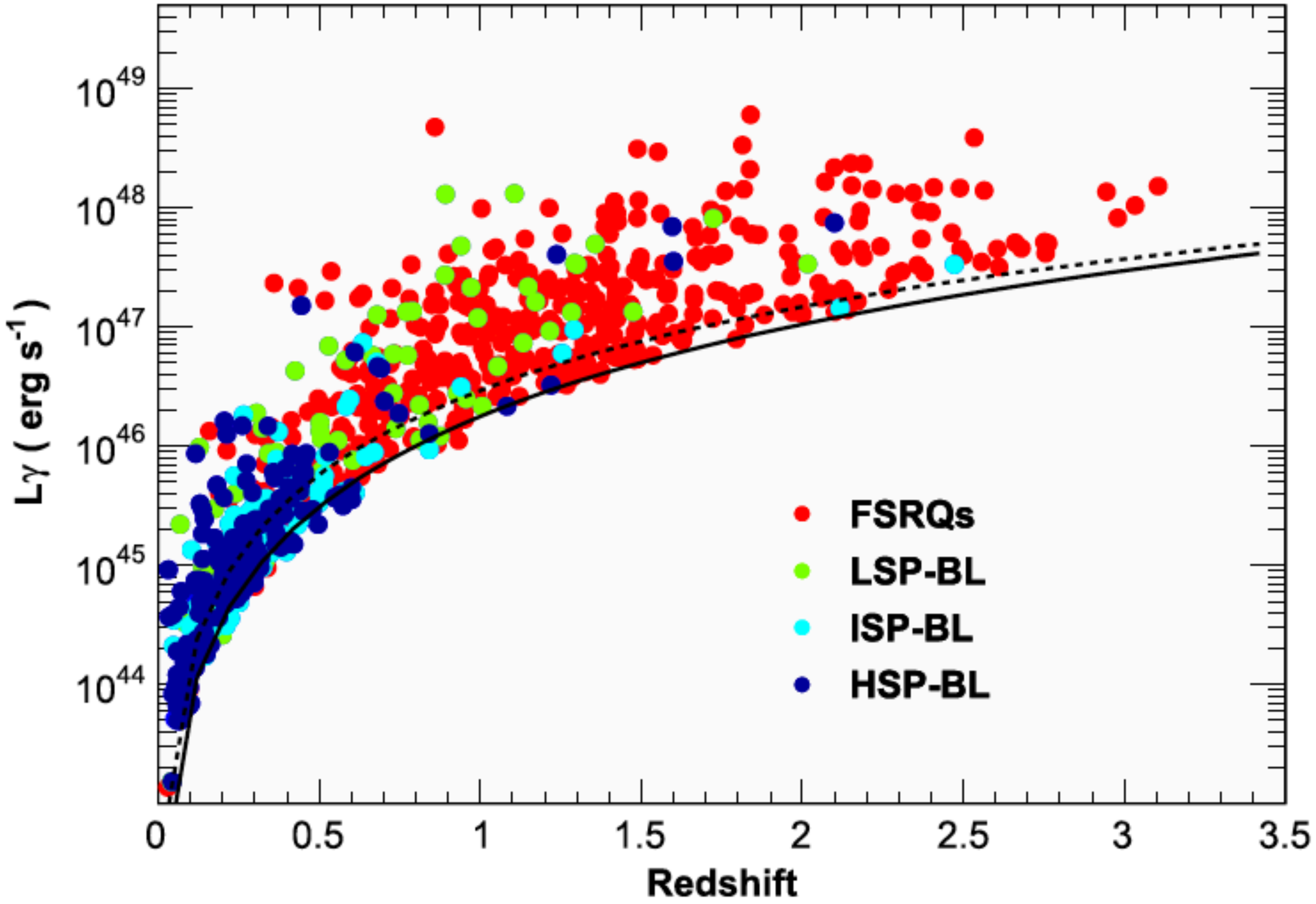


Nova	NOV	1	nov	0
BL Lac type of blazar	BLL	22	bll	1080
FSRQ type of blazar	FSRQ	42	fsrq	639
Radio galaxy	RDG	6	rdg	35
Non-blazar active galaxy	AGN	1	agn	16
Steep spectrum radio quasar	SSRQ	0	ssrq	2
Compact Steep Spectrum radio source	CSS	0	css	5
Blazar candidate of uncertain type	BCU	3	bcu	1152
Narrow line Seyfert 1	NLSY1	3	nlsy1	5
Seyfert galaxy	SEY	0	sey	1
Starburst galaxy	SBG	0	sbg	7
Normal galaxy (or part)	GAL	2	gal	2
Unknown	UNK	0	unk	118
Total	...	359	...	3215
Unassociated	...	...	...	1525

+ GRBs



THE ASTROPHYSICAL JOURNAL, 810:14 (34pp), 2015 September 1

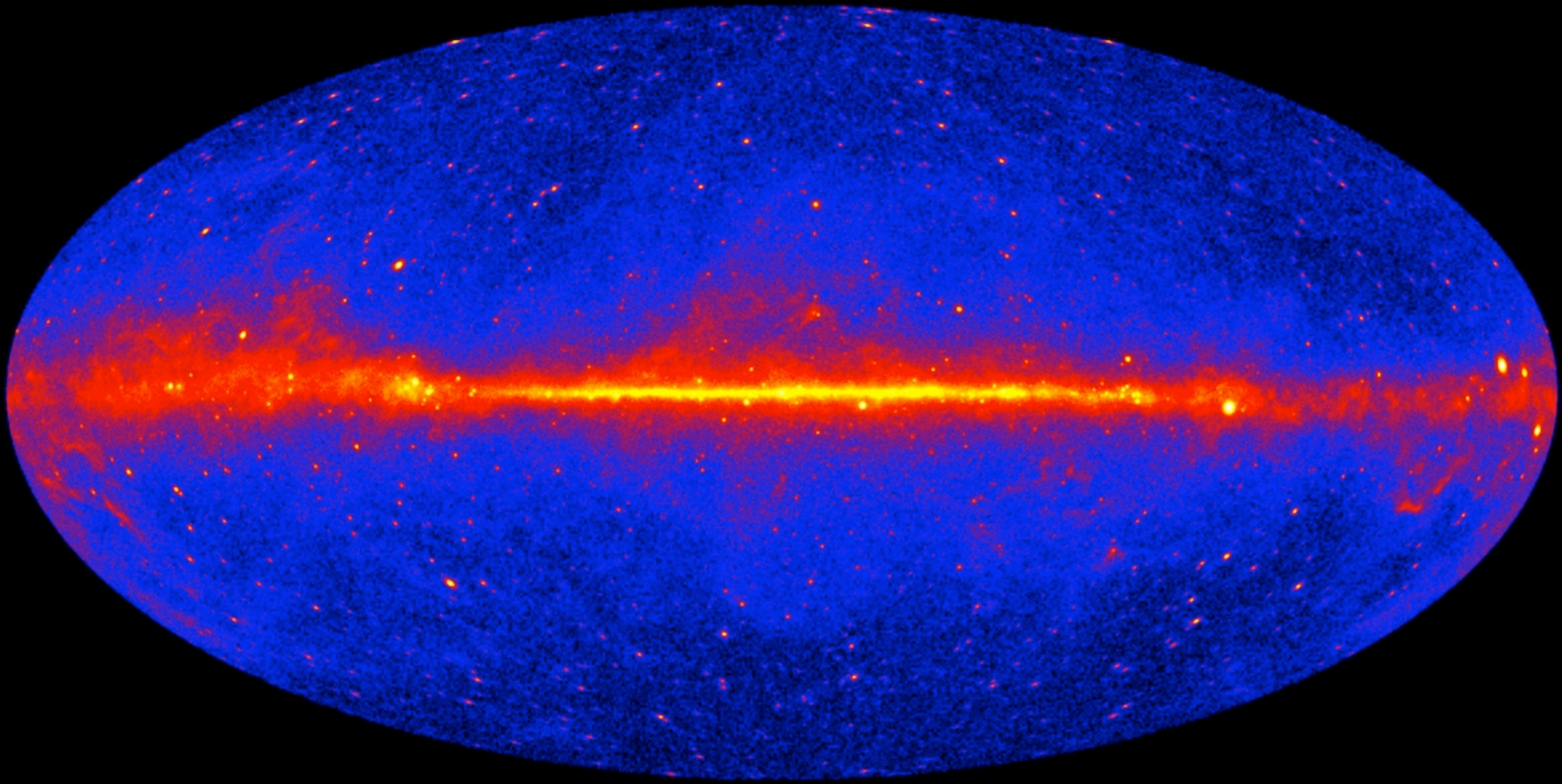


1. Tipos de fuentes

Galaxias normales	Galaxias starburst	Radio galaxias	Seyferts	FSRQ	BL Lac
MW LMC SMC M31 + M33	M82, NGC 253 NGC 4945 (Sb or Sy 2?)	M87, Cen A, NGC1275, NGC1218, NGC 6251	PMN J0948+0022, PKS 1502+036, PKS 2004-447, NGC 6951	Clásico en catálogo EGRET, 3C 454.3	EGRETs & fuentes TeV
Rayos cósmicos por formación estelar interactuando con medio interestelar	Mayor formación estelar que en galaxias normales. Sin variabilidad. AGN débil?	Variables. Aceleración de partículas en jets. AGN desalineado.	Narrow line Sy1 Sy 2 LINER Seyferts radio quiet?	Altamente variables. Aceleración en jets relativistas.	Espectro γ muy duro. Altamente variables. Aceleración en jets relativistas.

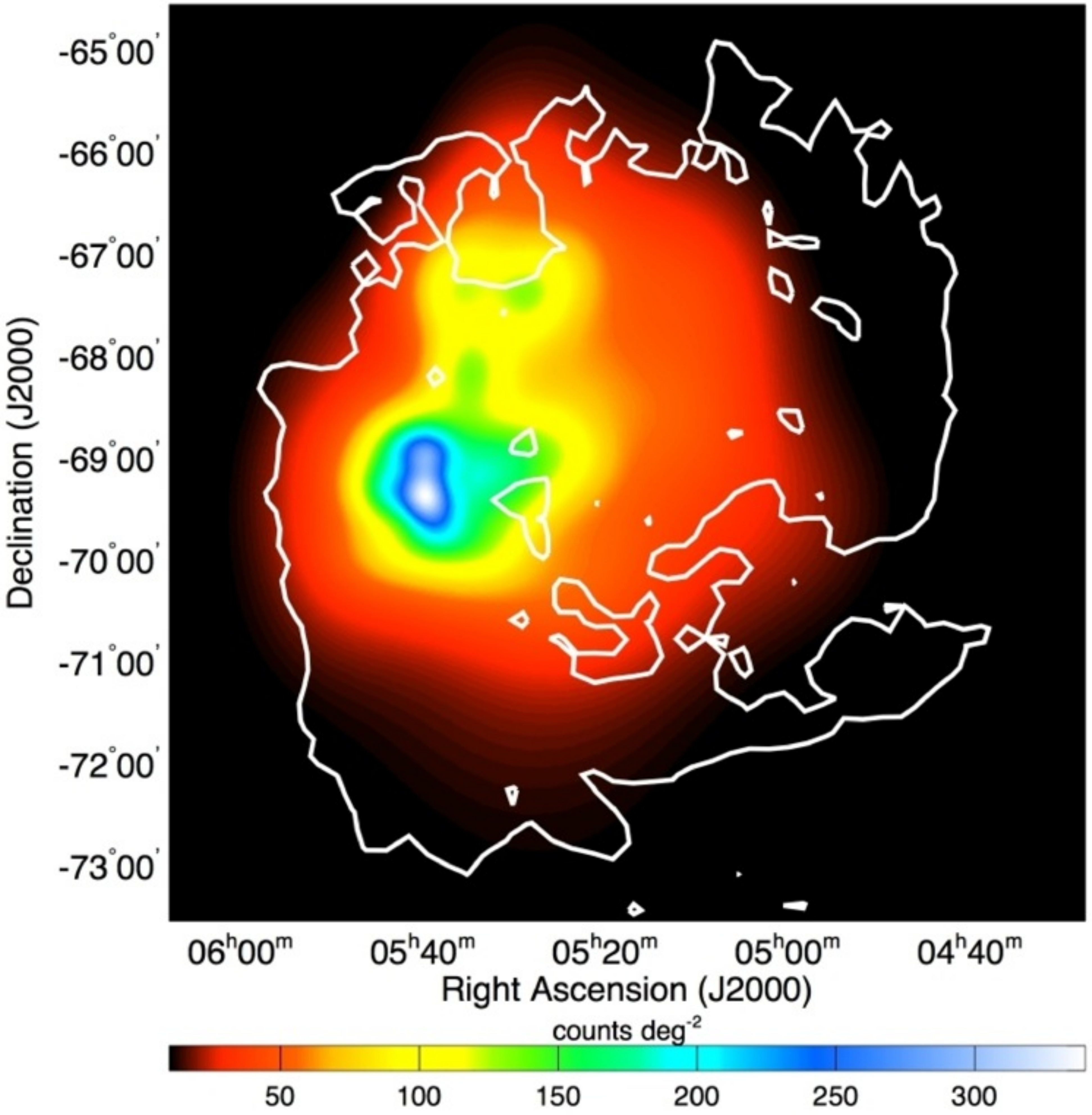
Potencia de aceleración: SF / jet / AGN →

2. Galaxias normales y starburst

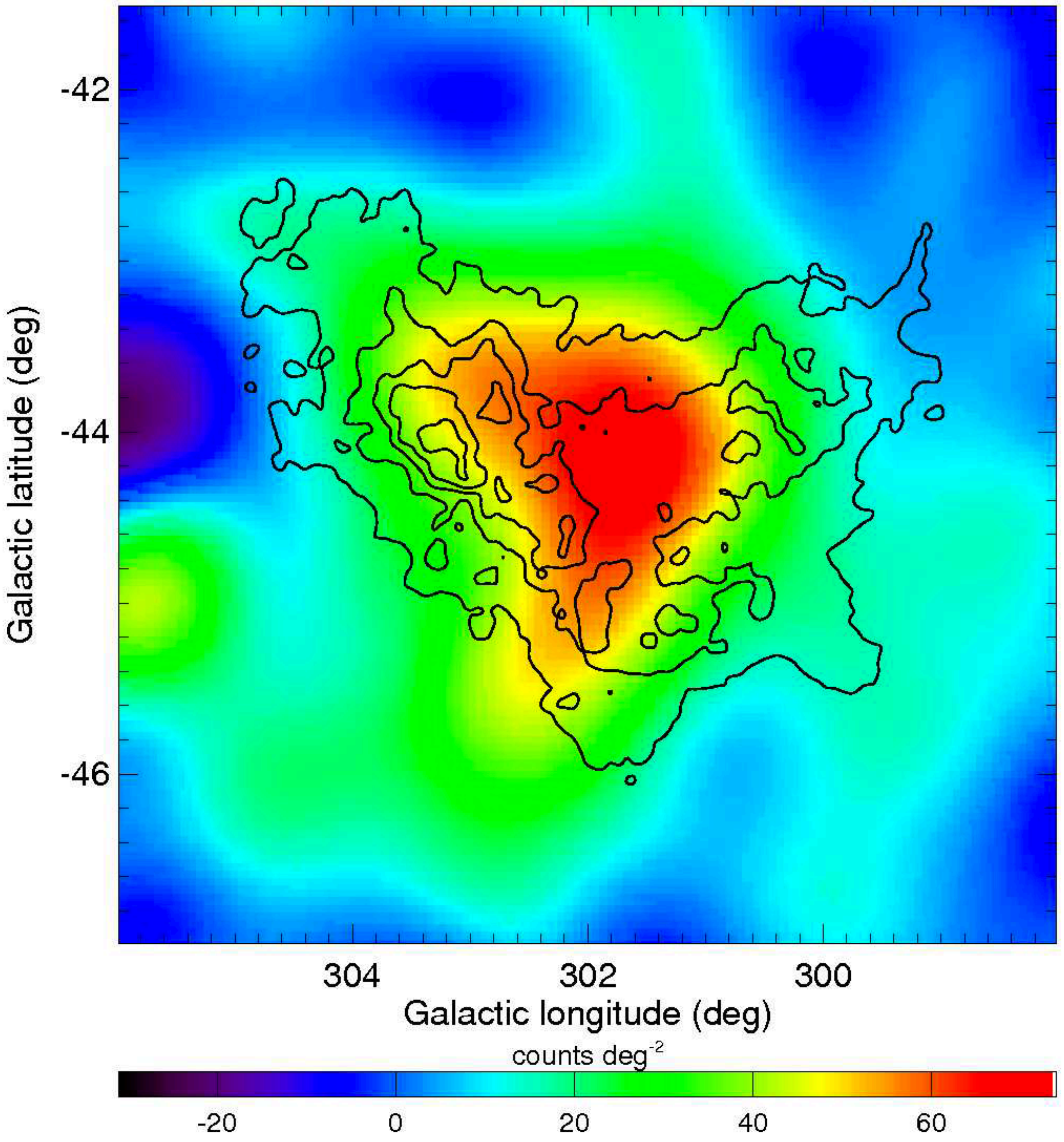


Emisión por rayos cósmicos producidos en procesos de formación estelar

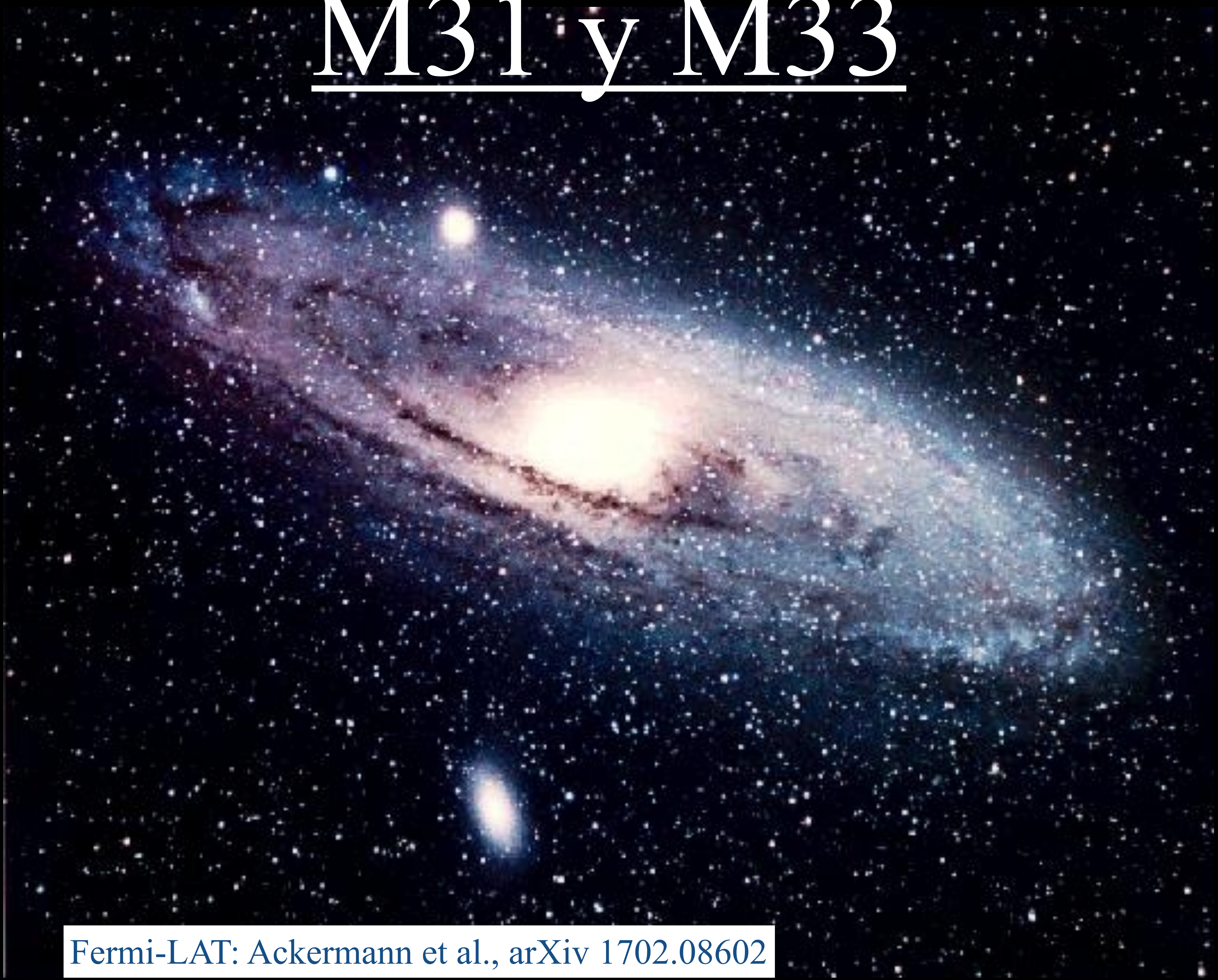
Las Nubes de Magallanes



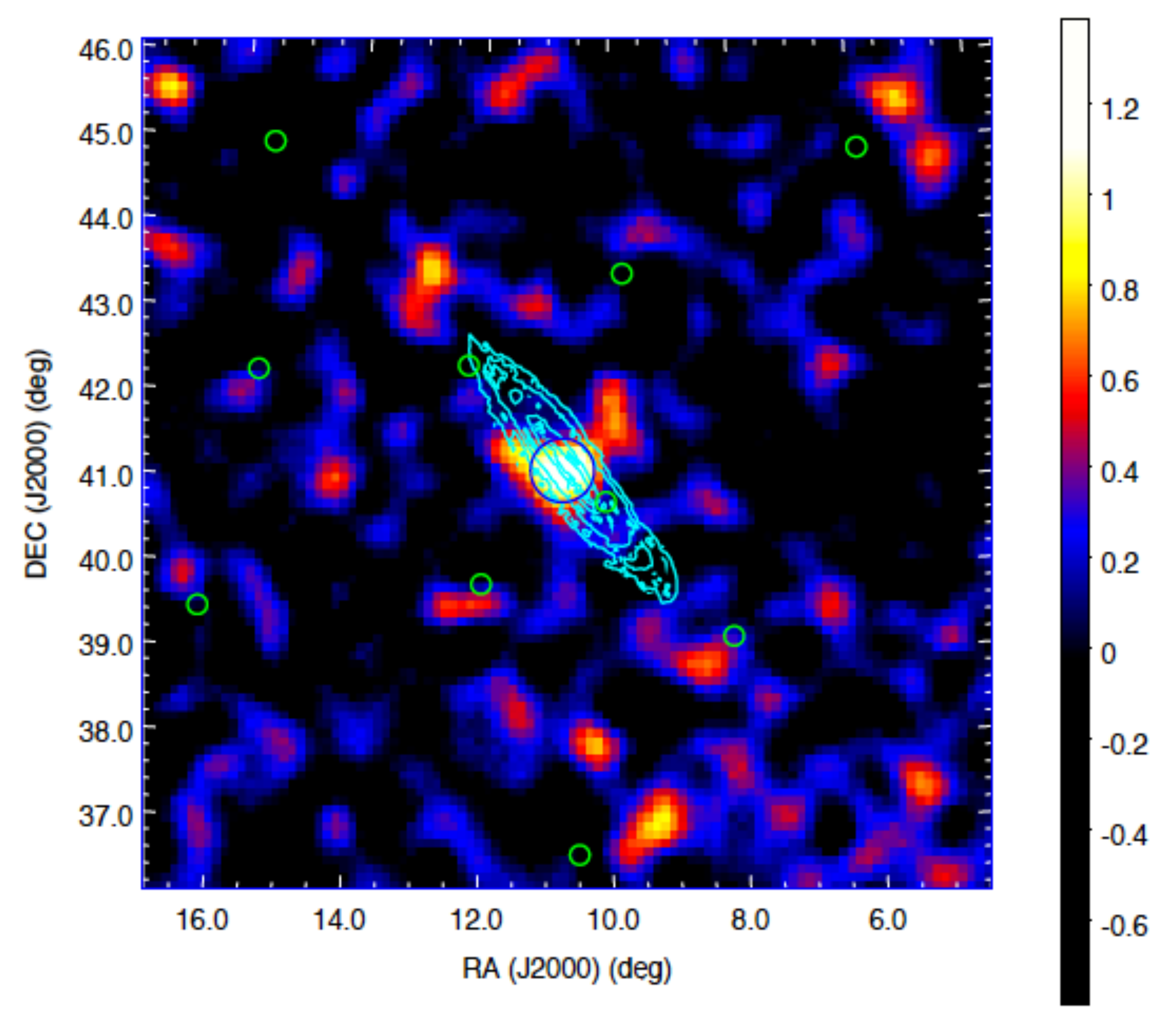
- Ambas detectadas en el rango de GeV por el satélite Fermi.
- LMC dominada por 30 Doradus
  - emisión en N 157B y PSR 0540-69
  - $u_{cr} \simeq 1/3$ Vía Láctea
- SMC: sfr ≃ 1/40 Vía Láctea

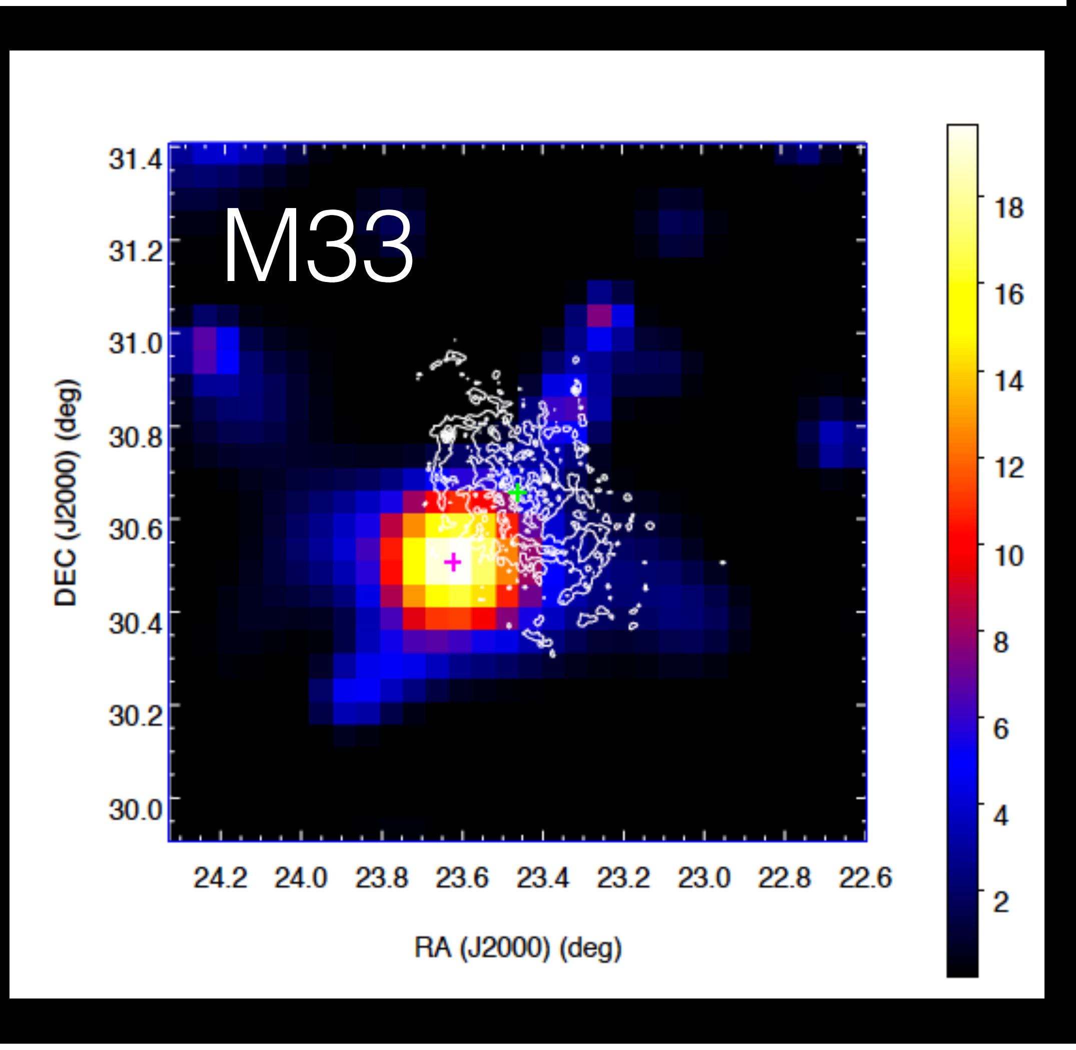


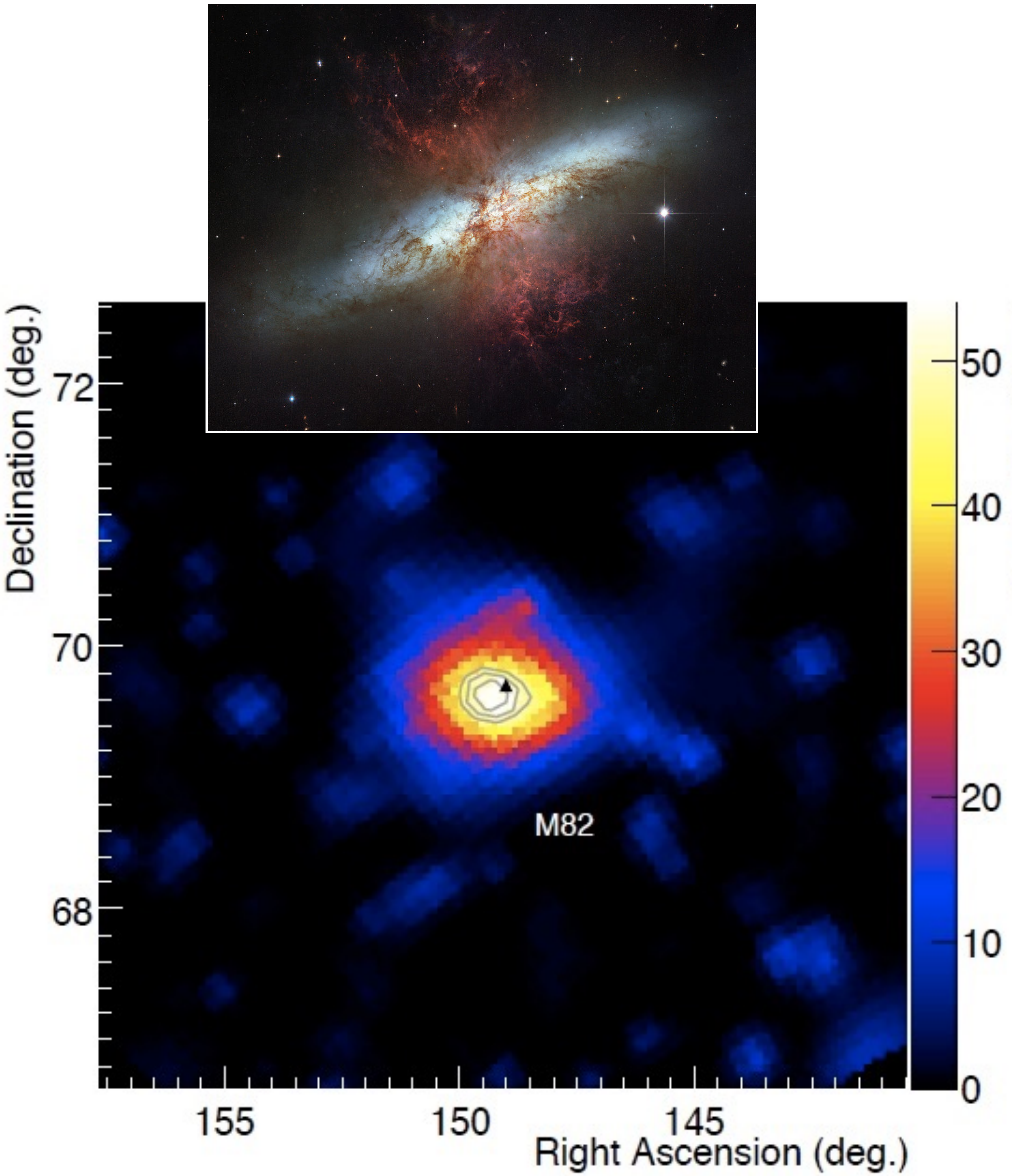
M31 y M33



Fermi-LAT: Ackermann et al., arXiv 1702.08602






Declination (deg.)
72
70
68
155
150
145
Right Ascension (deg.)
M82
0
10
20
30
40
50

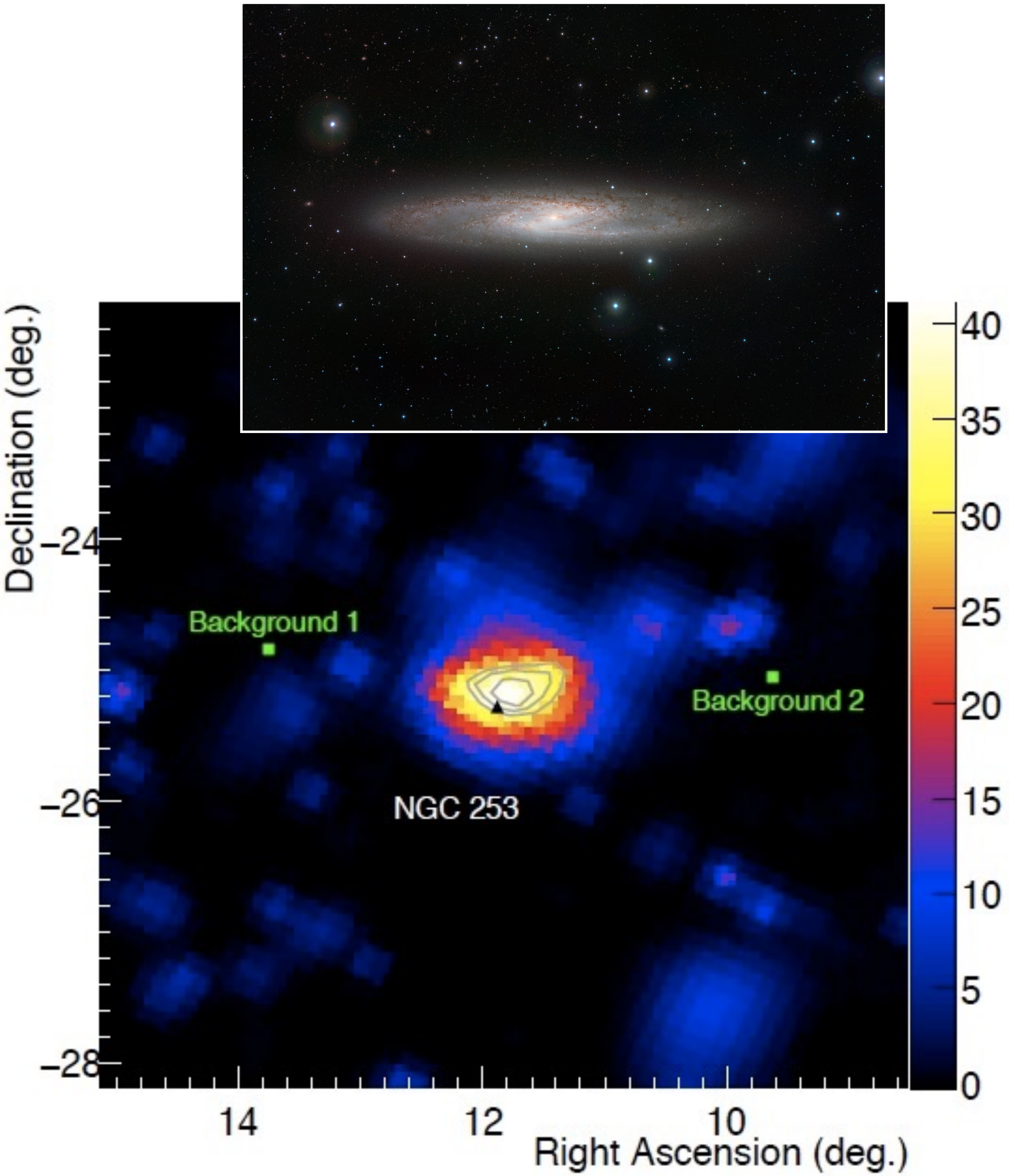
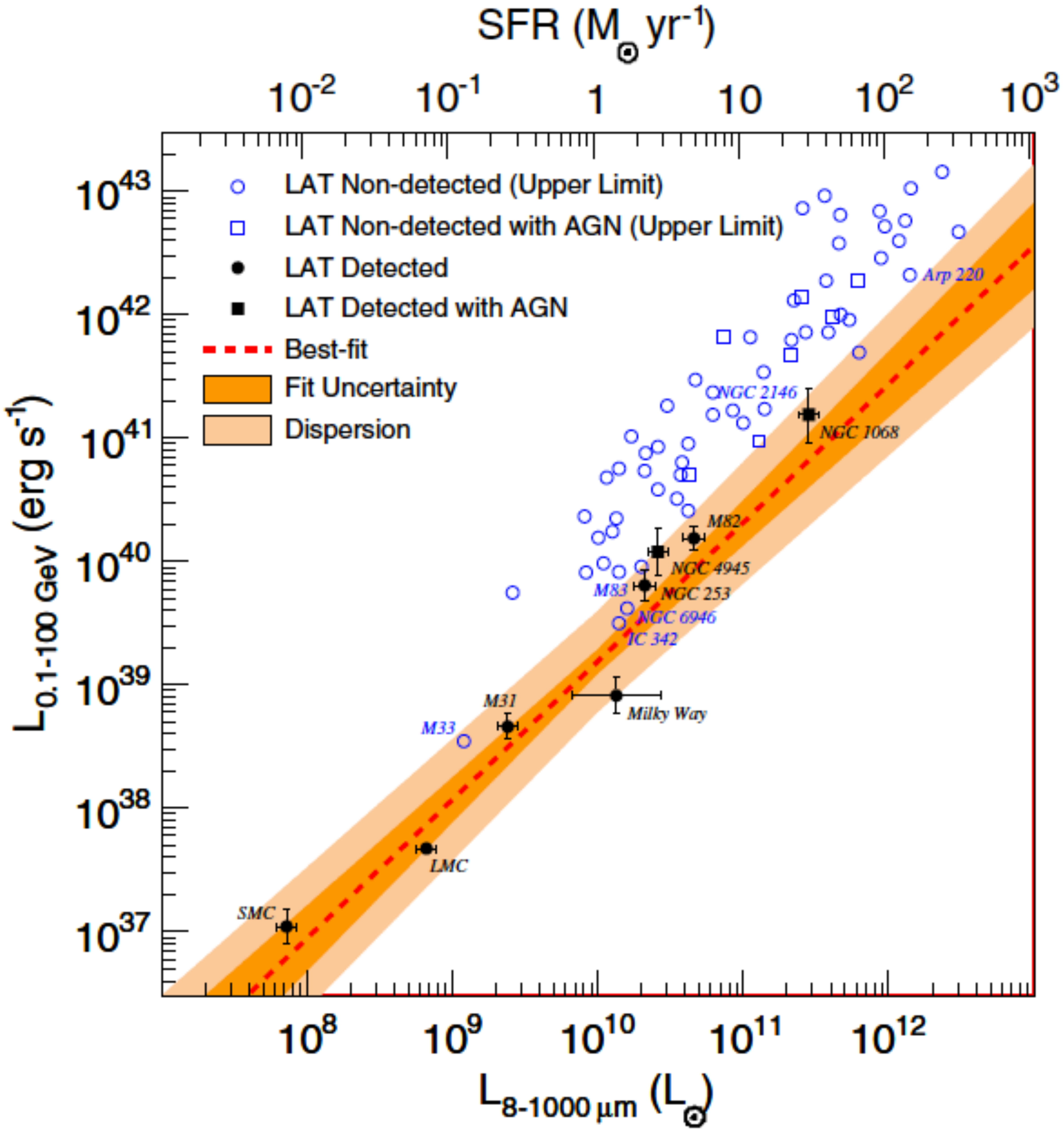

Declination (deg.)
−24
−26
−28
14
12
10
Right Ascension (deg.)
Background 1
Background 2
NGC 253
0
5
10
15
20
25
30
35
40

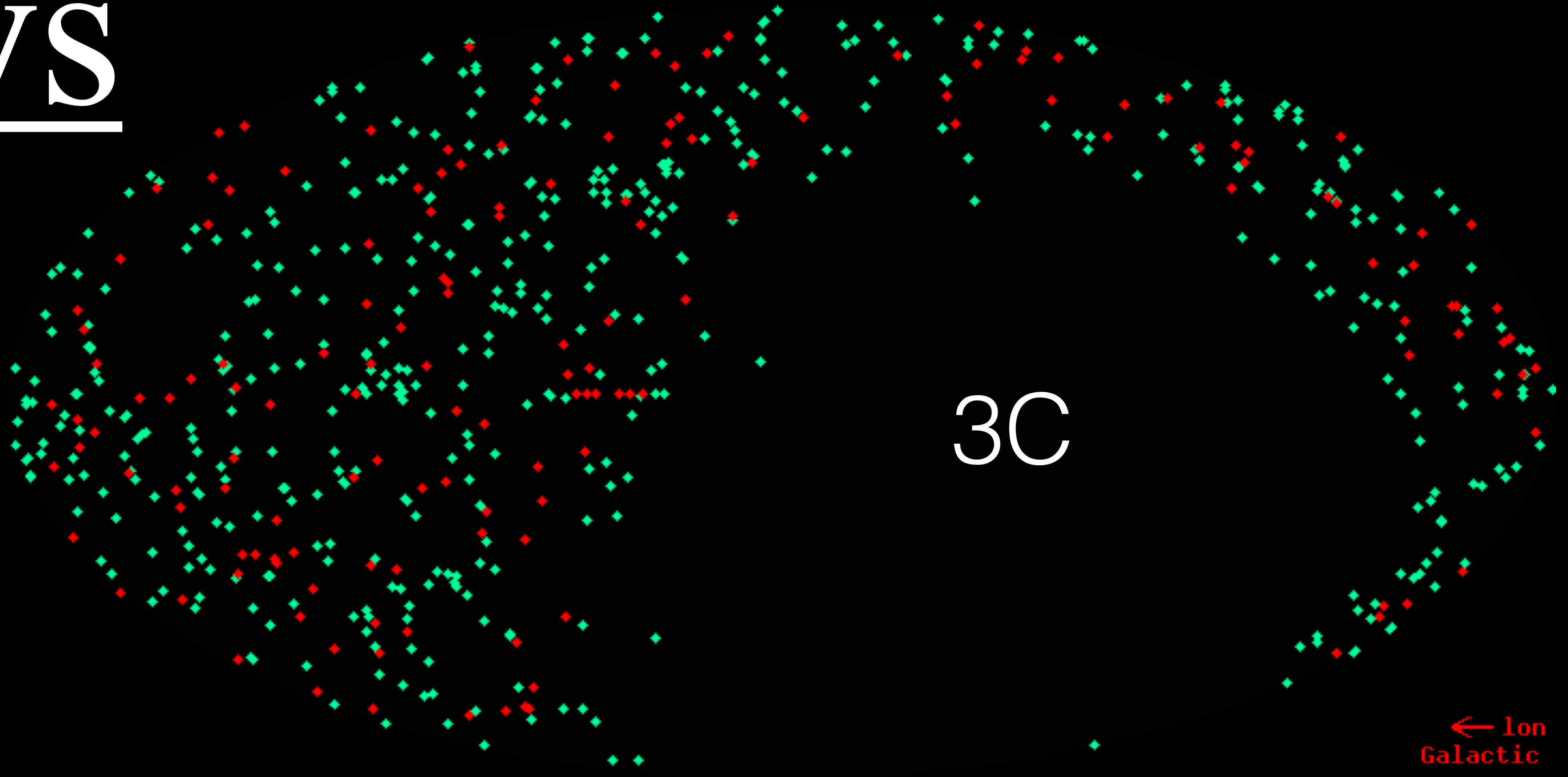
Fig. 20 Gamma-ray luminosity (0.1–100 GeV) versus total IR luminosity (8–1000 μm) for normal and starburst galaxies (Ackermann et al. 2012d). Galaxies significantly detected by the LAT are indicated with *filled symbols*, whereas galaxies with γ-ray flux upper limits (95 % confidence level) are marked with *open symbols*. Galaxies hosting *Swift*-BAT AGN are shown with *square markers*. IR luminosity uncertainties for the non-detected galaxies are omitted for clarity, but are typically ~0.06 dex. The *upper abscissa* indicates SFR estimated from the IR luminosity

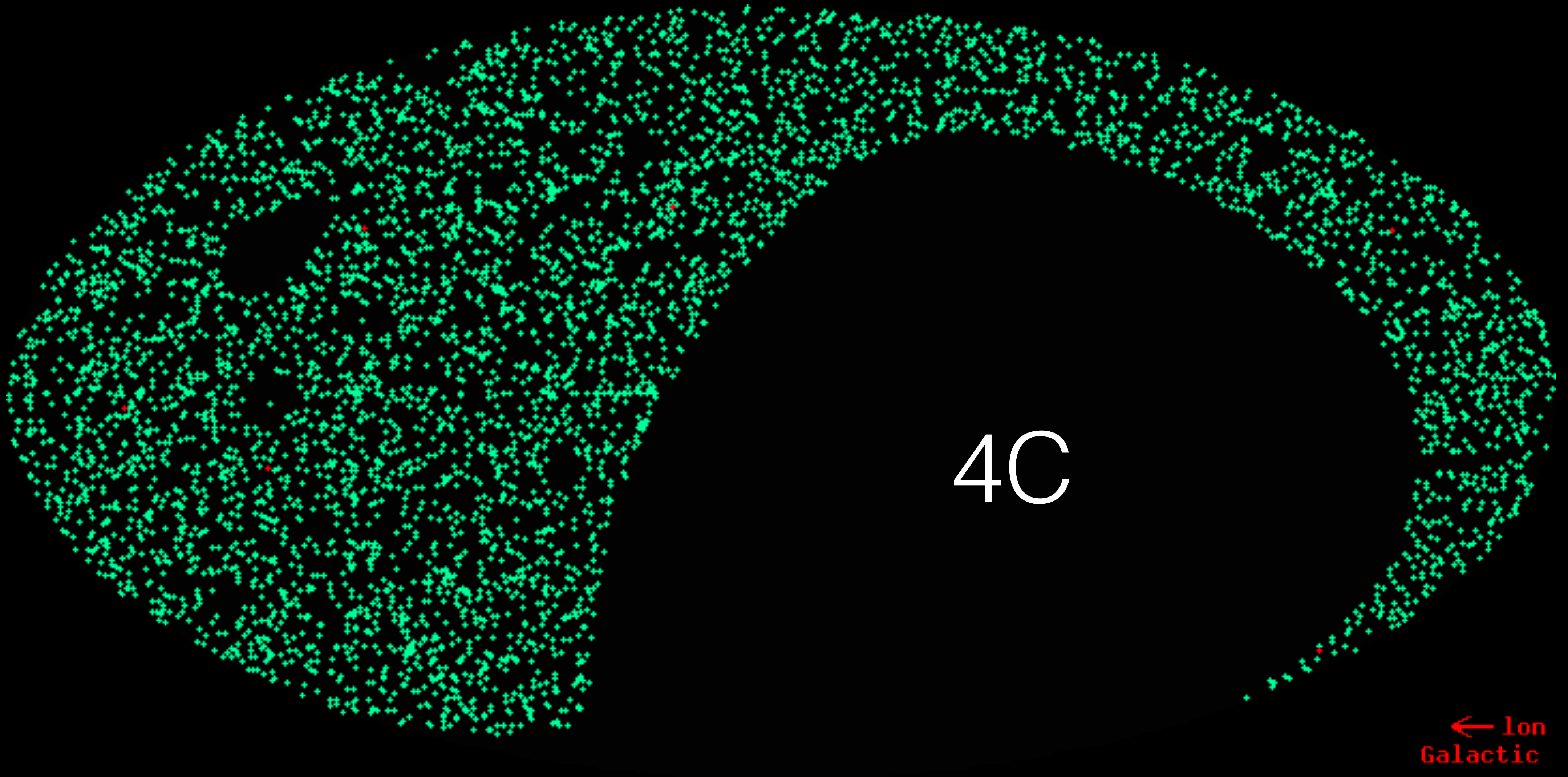


3. Núcleos activos de galaxias

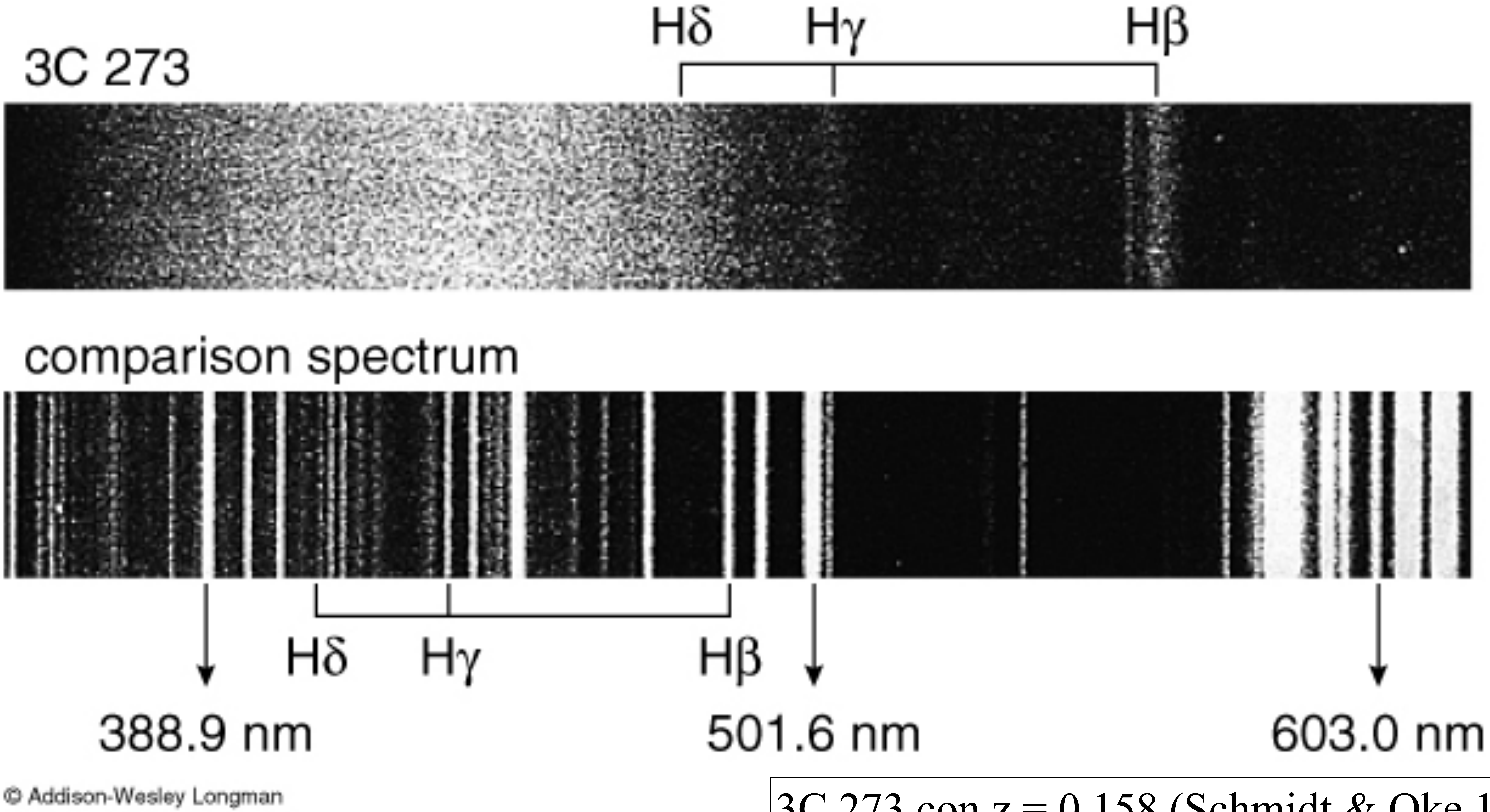
NGC 1068 (M 77) apod.nasa.gov
Parte de la muestra de Seyfert (1943)

Cambridge radio surveys





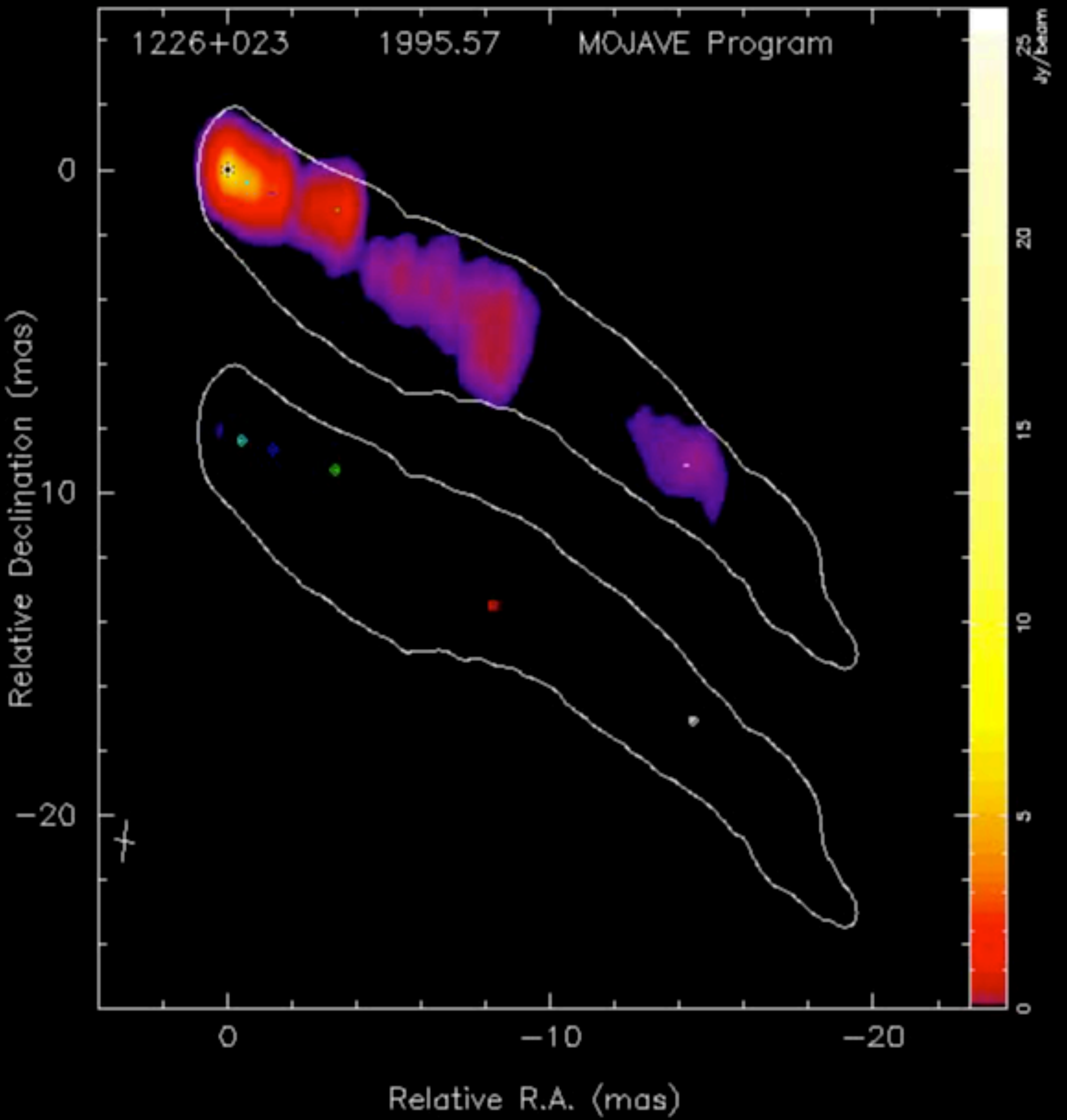
- Los surveys 3C (1959) y 4C (1965, 1967) establecieron la presencia de una población de fuentes de radio extragalácticas.



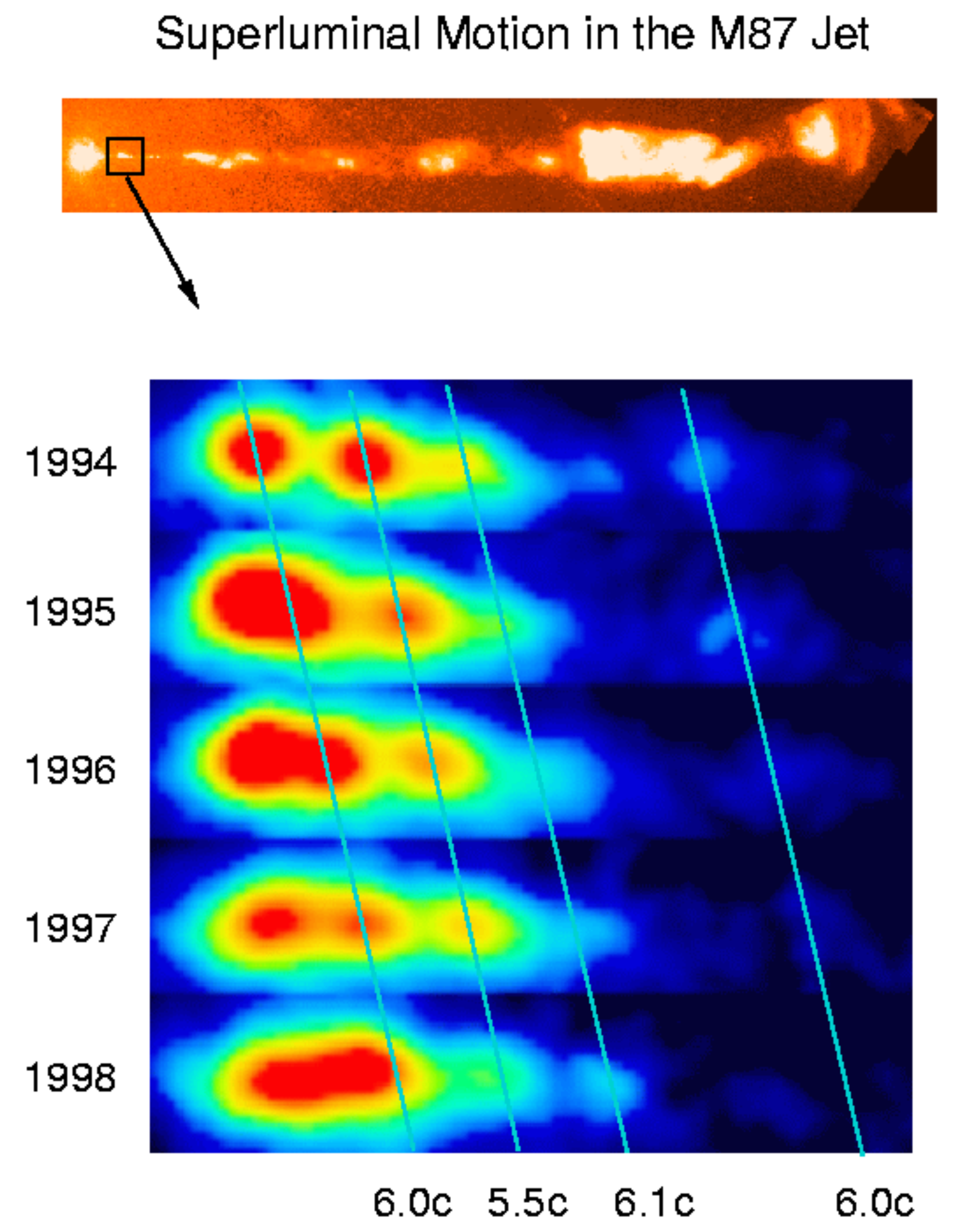
3C 273 con $z = 0.158$ (Schmidt & Oke 1963)

HST snaps optical jet of quasar 3c 273

R.C. Thomson, IoA, Cambridge, UK;C.D. Mackay, IoA, Cambridge, UK;A.E. Wright, ATNF, Parkes, Australia https://www.physics.purdue.edu/MOJAVE/movies.html



M 87 por HST


Superluminal Motion in the M87 Jet
1994
1995
1996
1997
1998
6.0c
5.5c
6.1c
6.0c


Cygnus A
50 kpc (!)

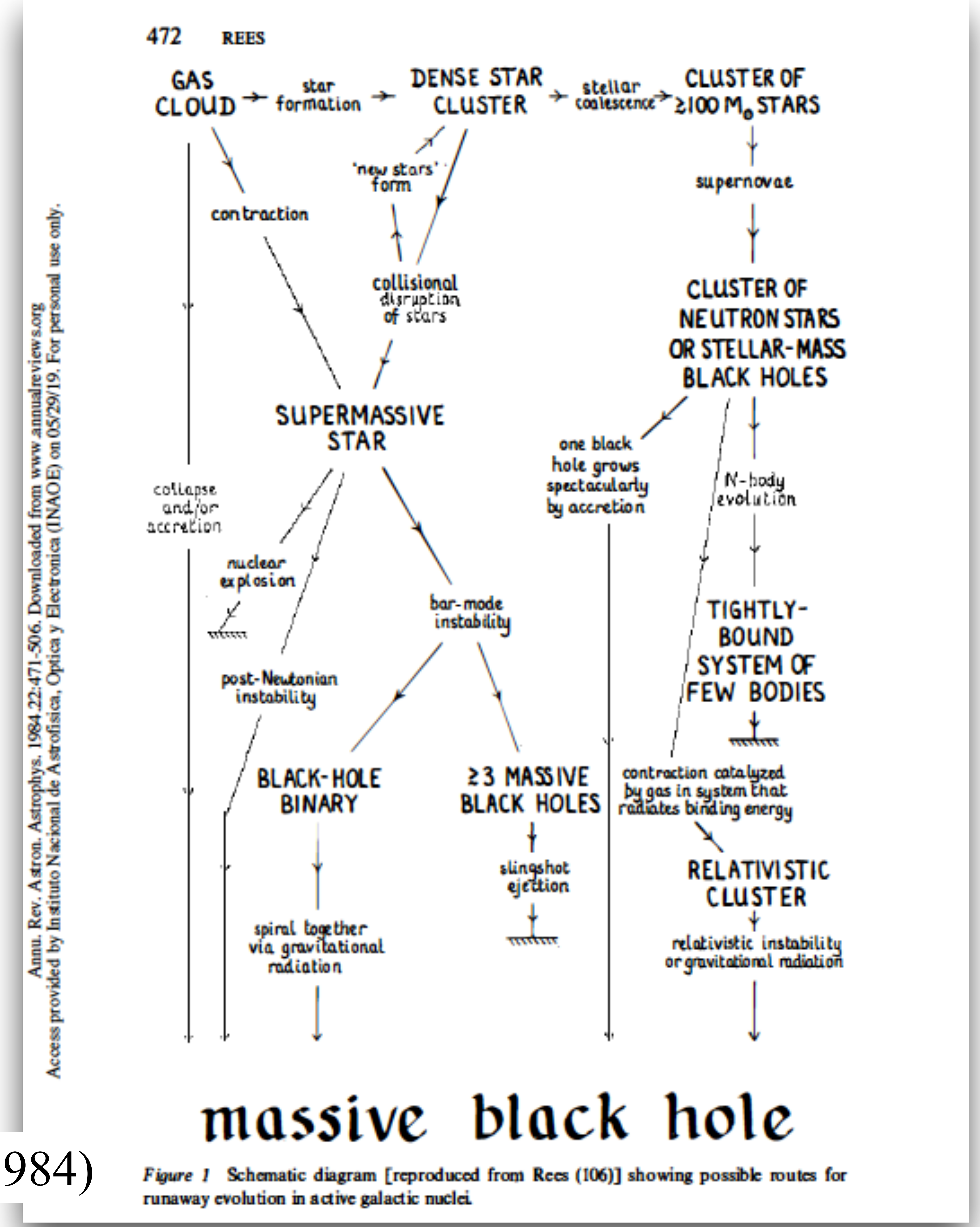
Cuasares y galaxias activas

- **Cuasares**: descubiertos como objetos aparentemente estelares por su intensa emisión en radio.
- **QSOs** (Quasi-Stellar Objects): objetos extragalácticos con propiedades similares a los cuasares, sin tener necesariamente emisión en radio.
- **Galaxias Seyfert**: Seyfert (1943) identifica varias galaxias con núcleos brillantes y exceso de emisión azul (Haro 1956, Markarian 1967).
- **Radio galaxias**: galaxias con intensa emisión de radio; mayormente elípticas.
- **Objetos BL Lacertae**: fuentes de radio quasi-estelares, sin líneas en el óptico; presentes en galaxias elípticas. Presentan variabilidad y emisión de rayos X.

Naturaleza

Emisión de radio: electrones relativistas en campos magnéticos (Shlovsky 1952).

- ~~Colisiones entre galaxias? Supernovas en cadena (Burbidge 1970s)? Formación estelar en cadena (Terlevich & Melnick 1985)? Procesos de aniquilación de materia? Evolución explosiva de una estrella supermasiva (Hoyle & Fowler 1962)?~~
- Procesos de acreción en objetos supermasivos (Hoyle & Fowler 1963; Salpeter 1964).



472 REES

Figure 1 Schematic diagram [reproduced from Rees (106)] showing possible routes for runaway evolution in active galactic nuclei.

Rees (1984)

Hoyos negros, acreción, jets

Acreción de materia

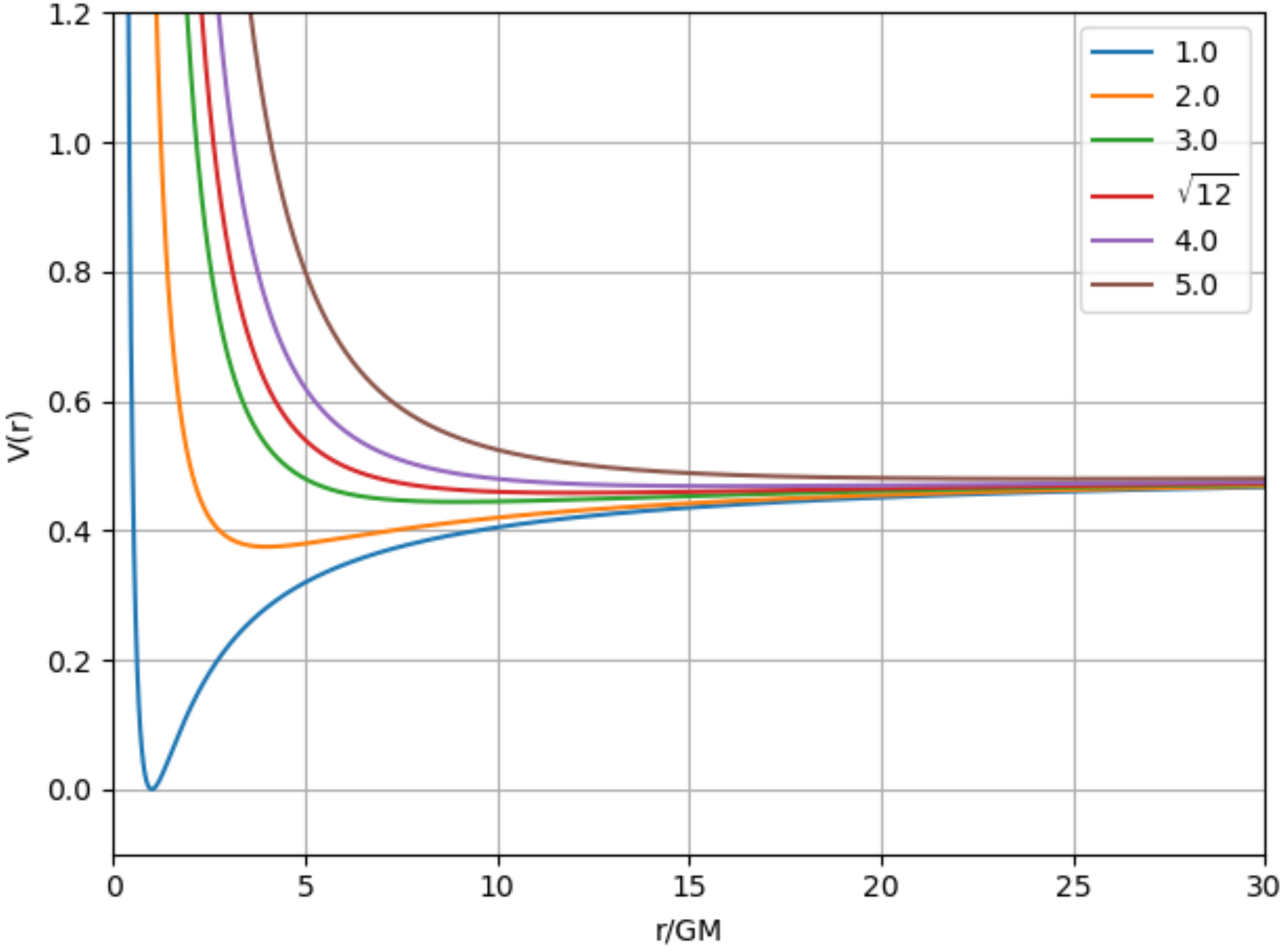
- Permite explicar luminosidades altas y escalas de tiempo pequeñas.
- La energía potencial disponible es:

$$E = \frac{GMm}{R} \quad \Rightarrow \quad L(R) = \frac{GM\dot{M}}{R}, \tag{13}$$

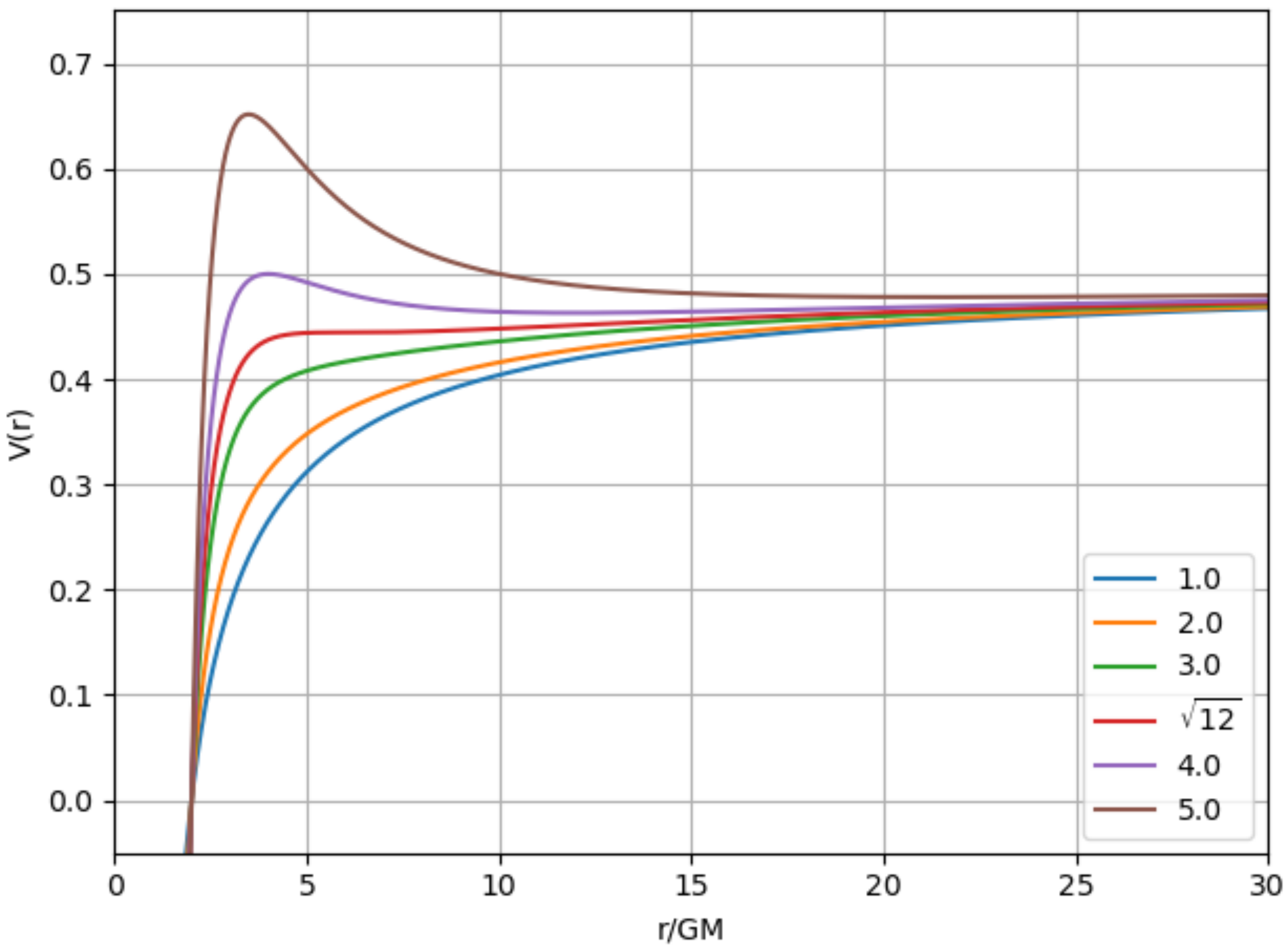
en escalas de tiempo $\Delta t \gtrsim R/c$.

- Los tres casos prototípicos:
  1. Acreción en enana blanca → variables cataclímicas, novas. $M = 0.8\ \mathrm{M}_\odot, R = 10^4\,\mathrm{km}, \dot{M} = 10^{-8}\,\mathrm{M}_\odot/\mathrm{yr}.$
  2. Acreción en estrella de neutrones u hoyo negro estelar → binarias de rayos X. $M = 1.4\ \mathrm{M}_\odot, R = 10\,\mathrm{km}, \dot{M} = 10^{-8}\,\mathrm{M}_\odot/\mathrm{yr}.$
  3. Acreción en hoyo negro supermasivo → AGN. $M \lesssim 10^9\ \mathrm{M}_\odot, R \to R_s = 2GM/c^2, \dot{M} \sim 1\,\mathrm{M}_\odot/\mathrm{yr}.$

Métrica de Schwarzschild



Órbitas clásicas



Órbitas Schwarzschild

Acreción en hoyos negros

Para un hoyo negro (un review clásico es Rees (1984)),

$$r_s = 2GM/c^2 \;\Rightarrow\; \begin{cases} L = \eta \dot{M} c^2, \quad \eta = 1/2, \\ r_s/c = 10^4 s \; (M/10^9 \mathrm{M}_\odot) \; . \end{cases}$$

Un límite teórico a la acreción es la luminosidad de Eddington; en simetría esférica,

$$L_E = \frac{4\pi G M m_p c}{\sigma_T} \simeq 1.3 \times 10^{47}\,\mathrm{erg/s}\;\; M_9 .$$

Tasa de acreción crítica, para un hoyo negro ($R = 2GM/c^2$),

$$\dot{M}_c = 4.4\,\mathrm{M}_\odot/\mathrm{yr}\; M_9\,,$$

y el tiempo característico,

$$t_E = (Mc^2/L_E) = \frac{\sigma_T c}{4\pi G m_p} \simeq 4 \times 10^8\,\mathrm{yr}.$$

La presencia de momento angular da lugar a discos de acreción.

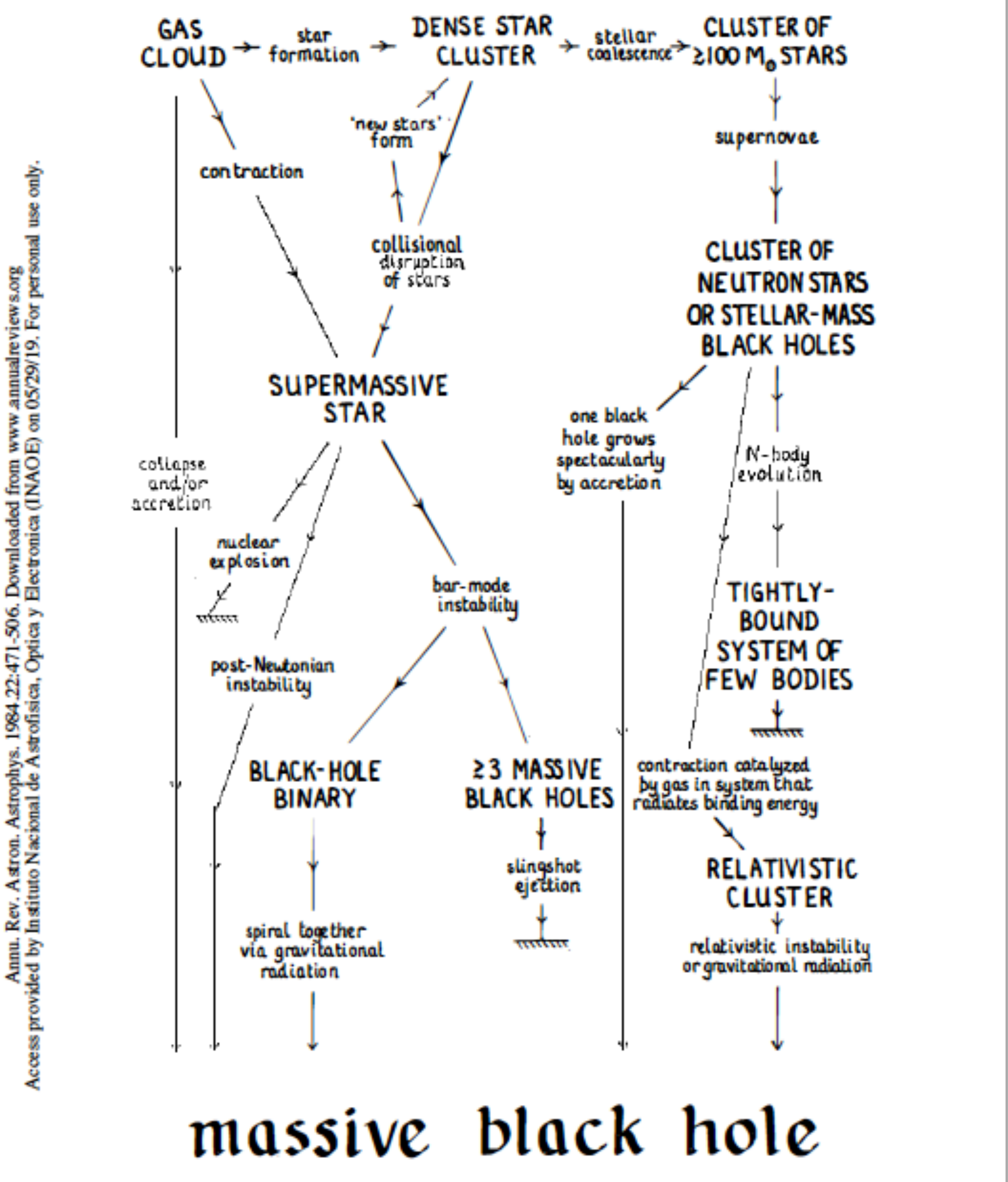


Figure 1 Schematic diagram [reproduced from Rees (106)] showing possible routes for runaway evolution in active galactic nuclei.

Discos de acreción: espectro

Shakura & Sunyaev (1973)

El espectro es una superposición de anillos emitiendo como cuerpo negro con $T(R) = T_\star (R/R_\star)^{-3/4}$ y

$$T_\star = \left(\frac{3GM\dot{M}}{8\pi\sigma_T R_\star^3} \right)^{1/4} \simeq 0.16 \times 10^6 \mathrm{K}\, \dot{M}_1 M_9^{-1/2}.$$

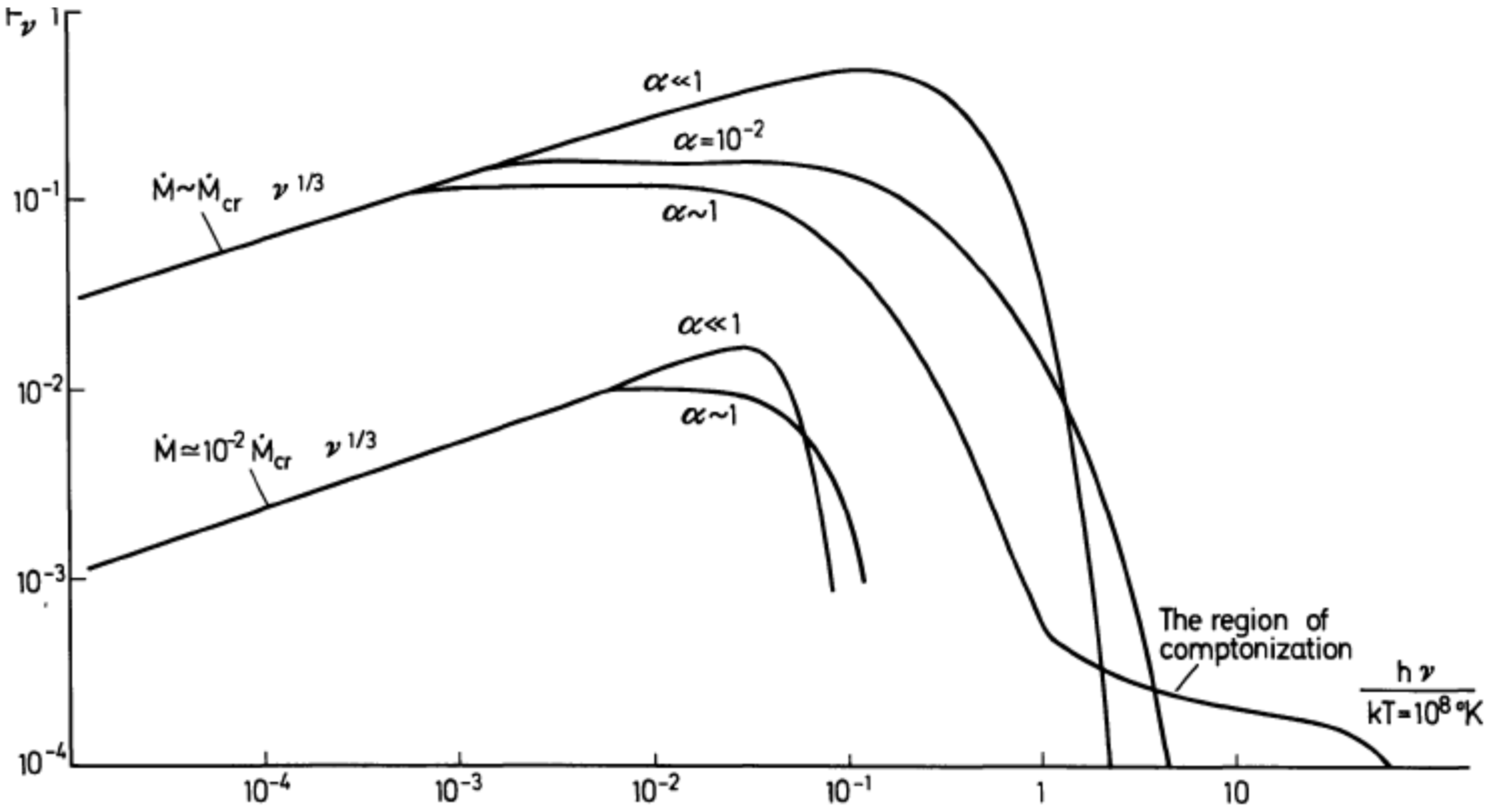


Fig. 3. The integral radiation spectrum of the disk, computed for different $\dot{M}$ and α

1973A&A....24..337S

340 N. I. Shakura a

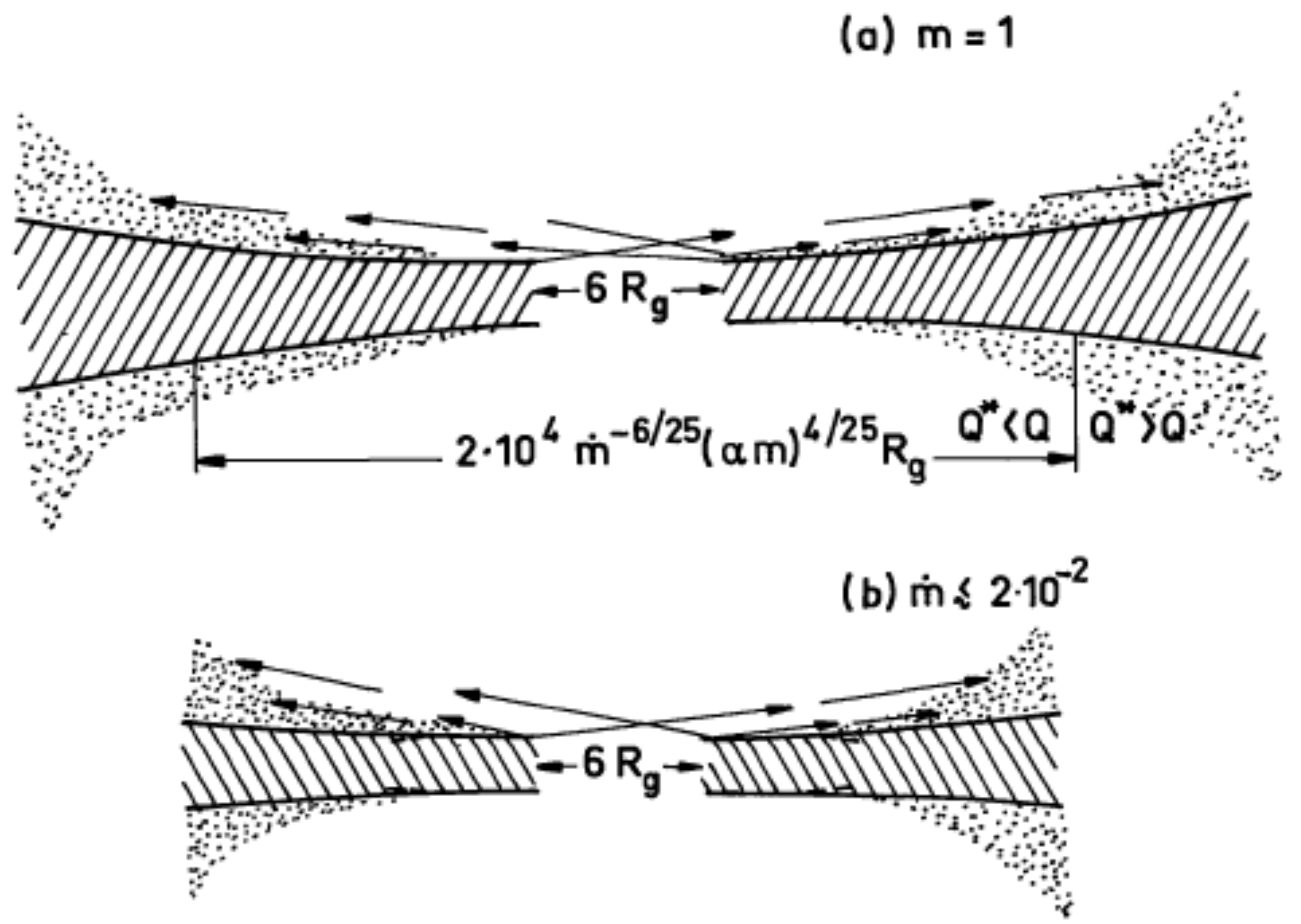


Fig. 4. The thickness of the disk as a function of the distance to the black hole: a) $\dot{M} = \dot{M}_{cr}$. b) $\dot{M} < 10^{-2} \dot{M}_{cr}$. In the central zone, $R < 3R_g$ newtonian mechanics is not applicable. Trajectories of X-ray and ultra-violet quanta which lead to evaporation and heating of the matter in the outer regions of the disk are shown by the arrows. The corona formed by the hot, evaporated matter is denoted by dots

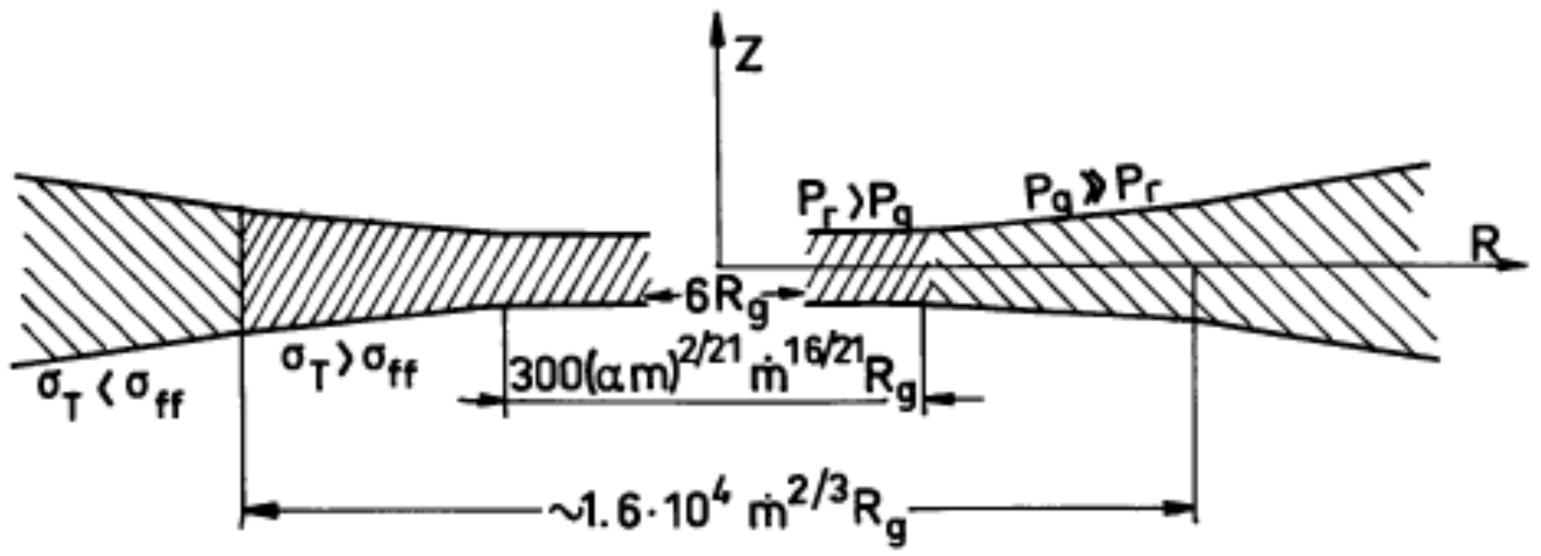


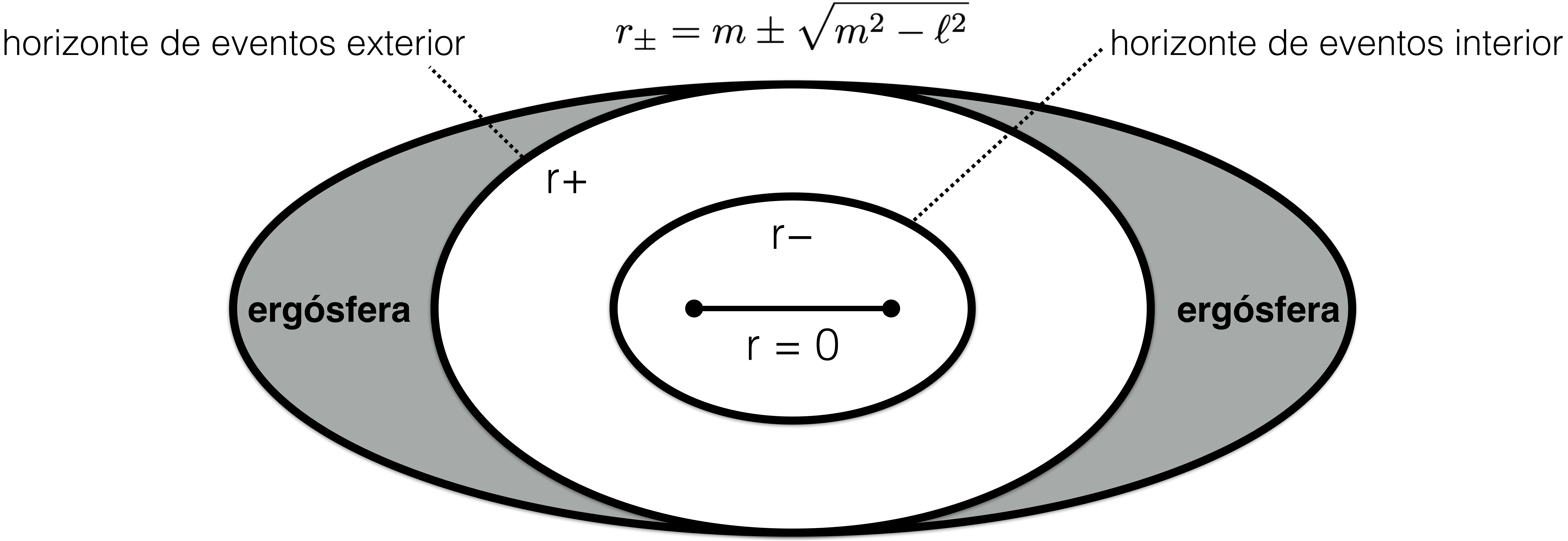
Fig. 10. The regions of disk having different physical conditions

Hoyos negros en rotación

La métrica de Kerr representa hoyos negros en rotación con momento angular parametrizado con ℓ, tal que $0 \leq \ell < m$:

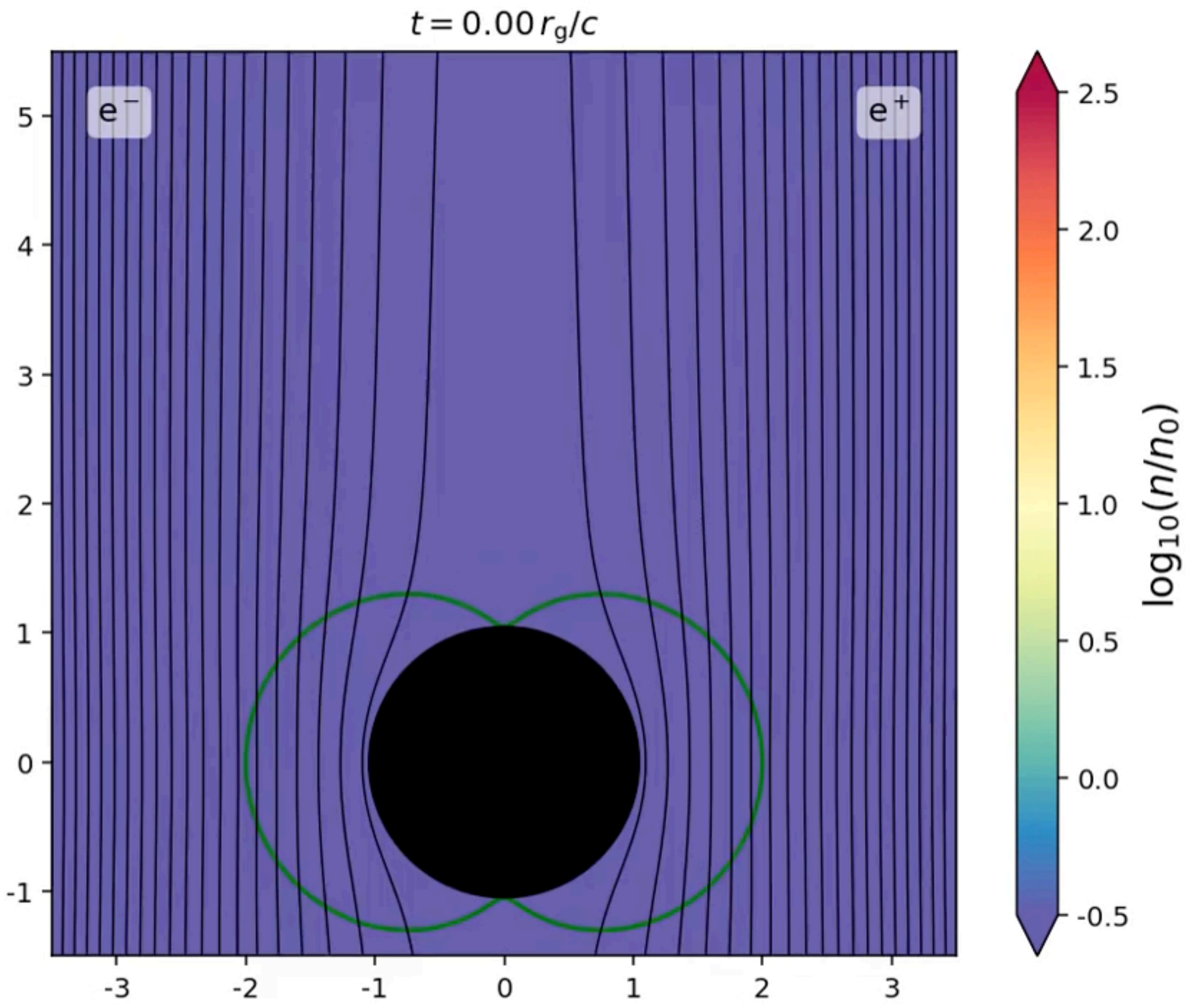
- El horizonte de eventos es más pequeño: $r_+ = m + \sqrt{m^2 - \ell^2}$.
- Las órbitas estables son más cercanas: si la materia co-rota con el hoyo, la última órbita estable tiende a $r_s/2$ para $\ell \to 1$, $\Rightarrow$ la fracción de energía extraíble a $\eta \to 1 - 1/\sqrt{3} \simeq 0.42$.
- La métrica de Kerr tiene una "ergósfera": $r_+ = m + \sqrt{m^2 - \ell^2 \cos^2 \theta}$.
- Es posible la extracción de energía del hoyo negro entrando en la ergósfera y saliendo de ella (Penrose 1969; Blandford & Znajek 1977).

$$r_{\pm} = m \pm \sqrt{m^2 - \ell^2}$$



Blandford - Znajek

- El mecanismo de Blandford - Znajek (1977) requiere un hoyo negro en rotación (métrica de Kerr).
- Dentro de la ergósfera el espacio-tiempo corrota con el hoyo negro (efecto Lense-Thirring).
- Líneas de un campo magnético externo se enredan y permiten a la materia salir en dirección axial, extrayendo energía y momento angular del hoyo negro.
- La rotación del campo magnético induce un campo electrostático que puede acelerar partículas a muy altas energías.
- De forma análoga a la magnetósfera de un pulsar, la presencia de cargas tiende a cancelar el campo, pero una cancelación imperfecta permite la aceleración.



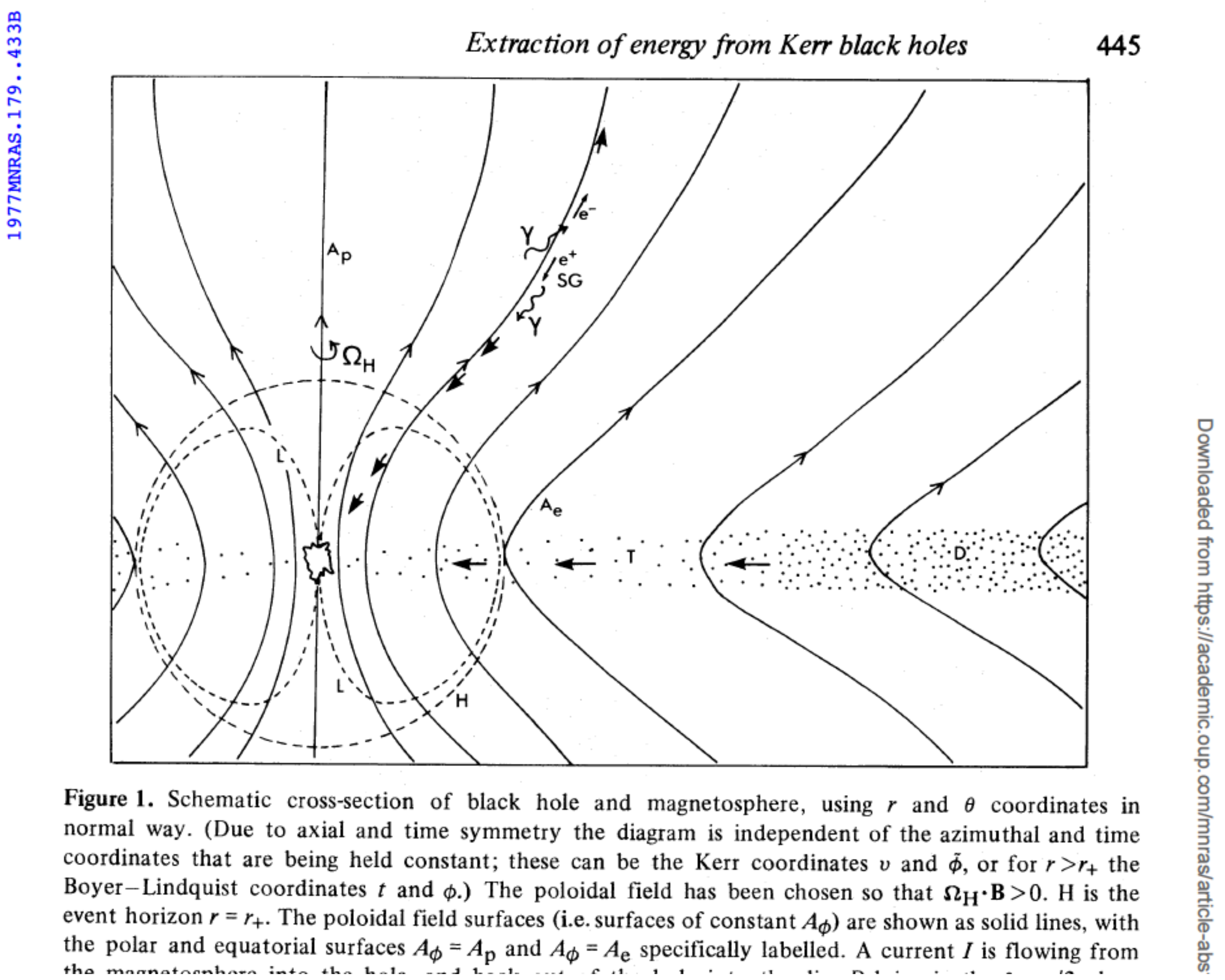

1977MNRAS.179..433B

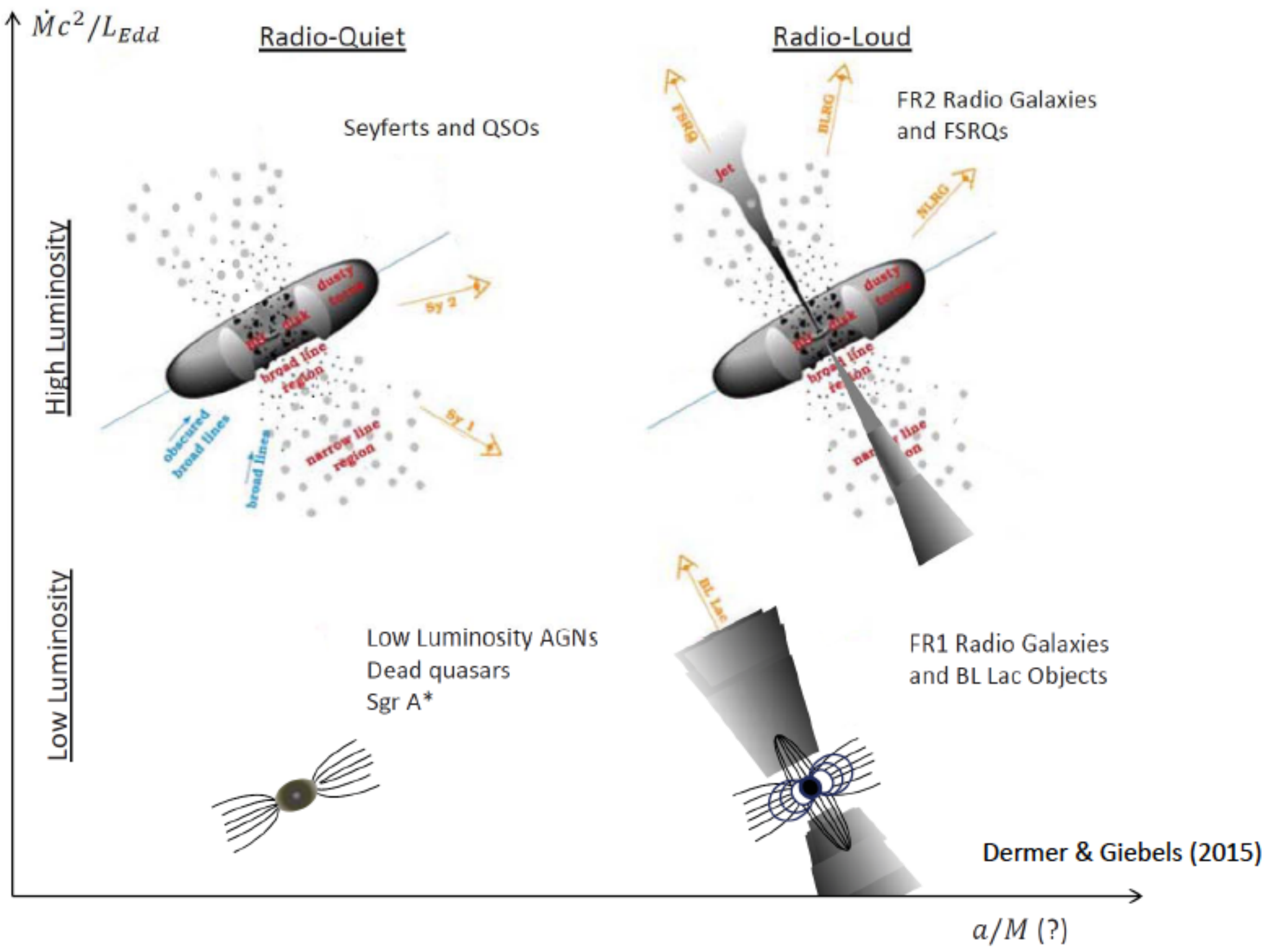
Figure 1. Schematic cross-section of black hole and magnetosphere, using r and θ coordinates in normal way. (Due to axial and time symmetry the diagram is independent of the azimuthal and time coordinates that are being held constant; these can be the Kerr coordinates v and $\tilde{\phi}$, or for $r > r_+$ the Boyer–Lindquist coordinates t and ϕ.) The poloidal field has been chosen so that $\mathbf{\Omega_H} \cdot \mathbf{B} > 0$. H is the event horizon $r = r_+$. The poloidal field surfaces (i.e. surfaces of constant A_ϕ) are shown as solid lines, with the polar and equatorial surfaces $A_\phi = A_p$ and $A_\phi = A_e$ specifically labelled. A current I is flowing from

El mecanismo de Penrose (1971)
Blandford & Znajek (1977)

Modelo unificado

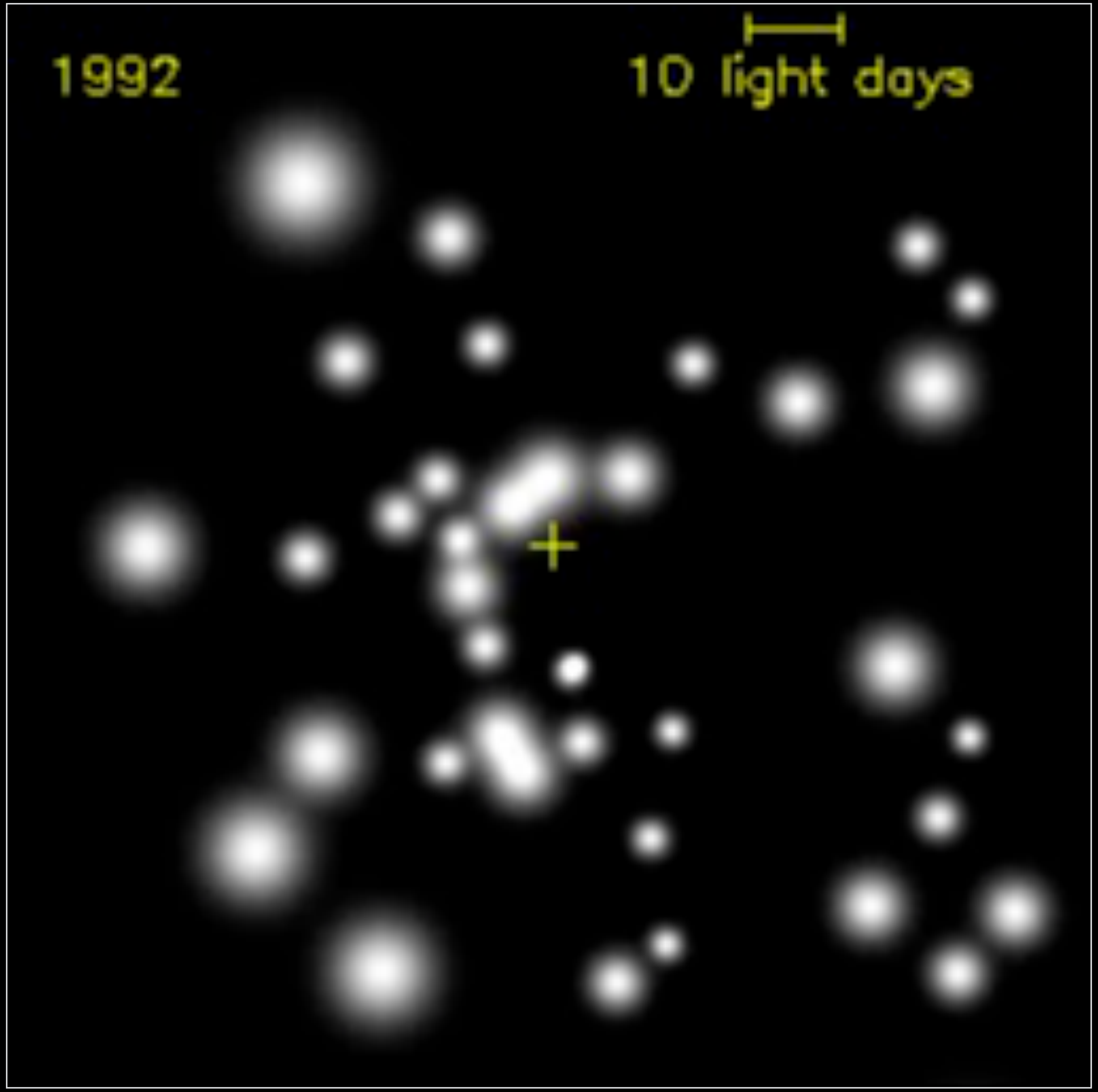
- En el modelo estándar los núcleos activos son hoyos negros supermasivos con procesos de acreción de materia.
- Un toroide de gas frío molecular rodea al sistema.
- Los jets se deben al disco o a la rotación del hoyo negro. En estos se aceleran partículas a altas energías.
- El tipo de objeto observado depende de la línea de visión.

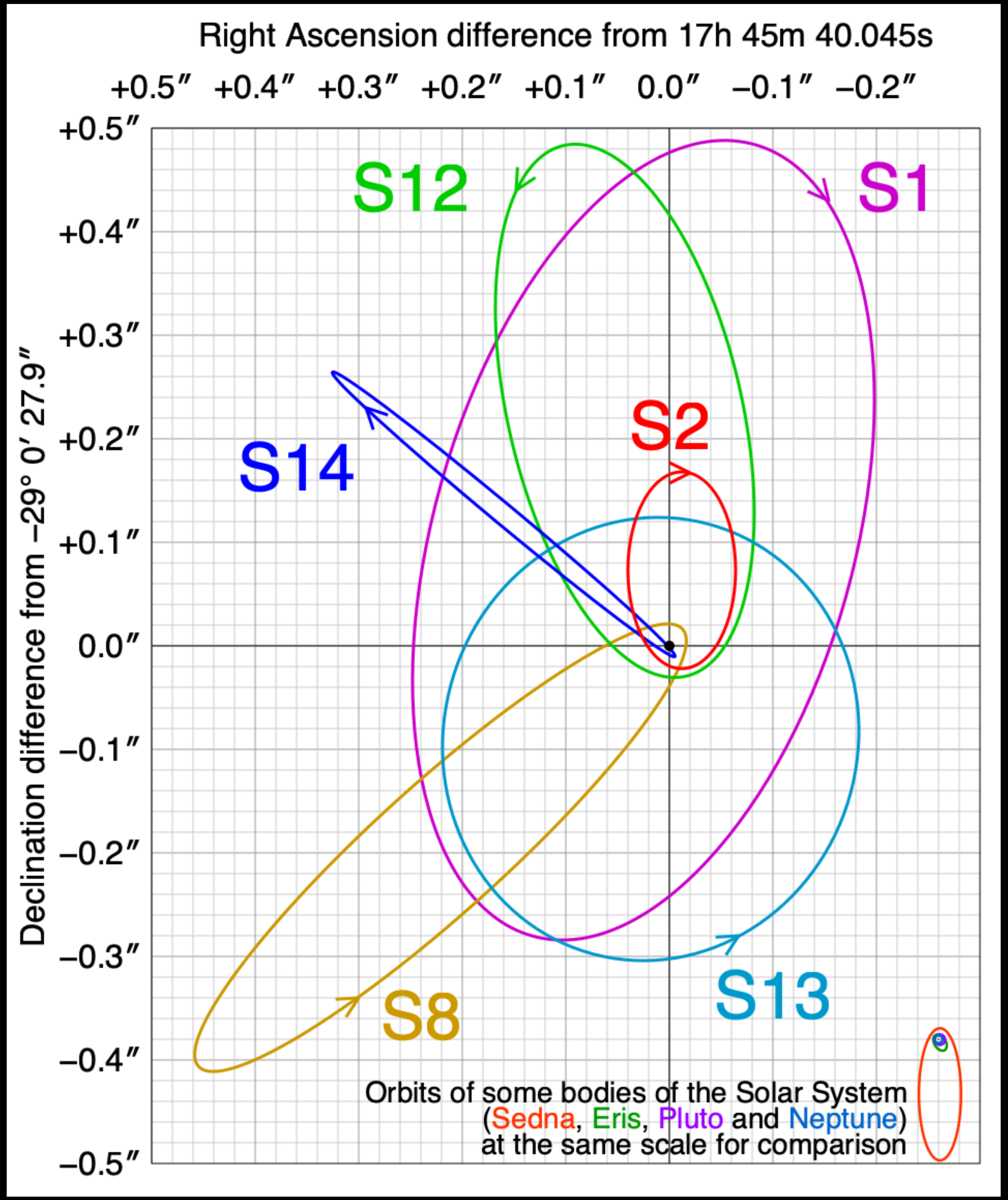
Classes of AGN and Unification



Dermer & Giebels (2015)

Hoyo negro Galáctico





Radiogalaxias

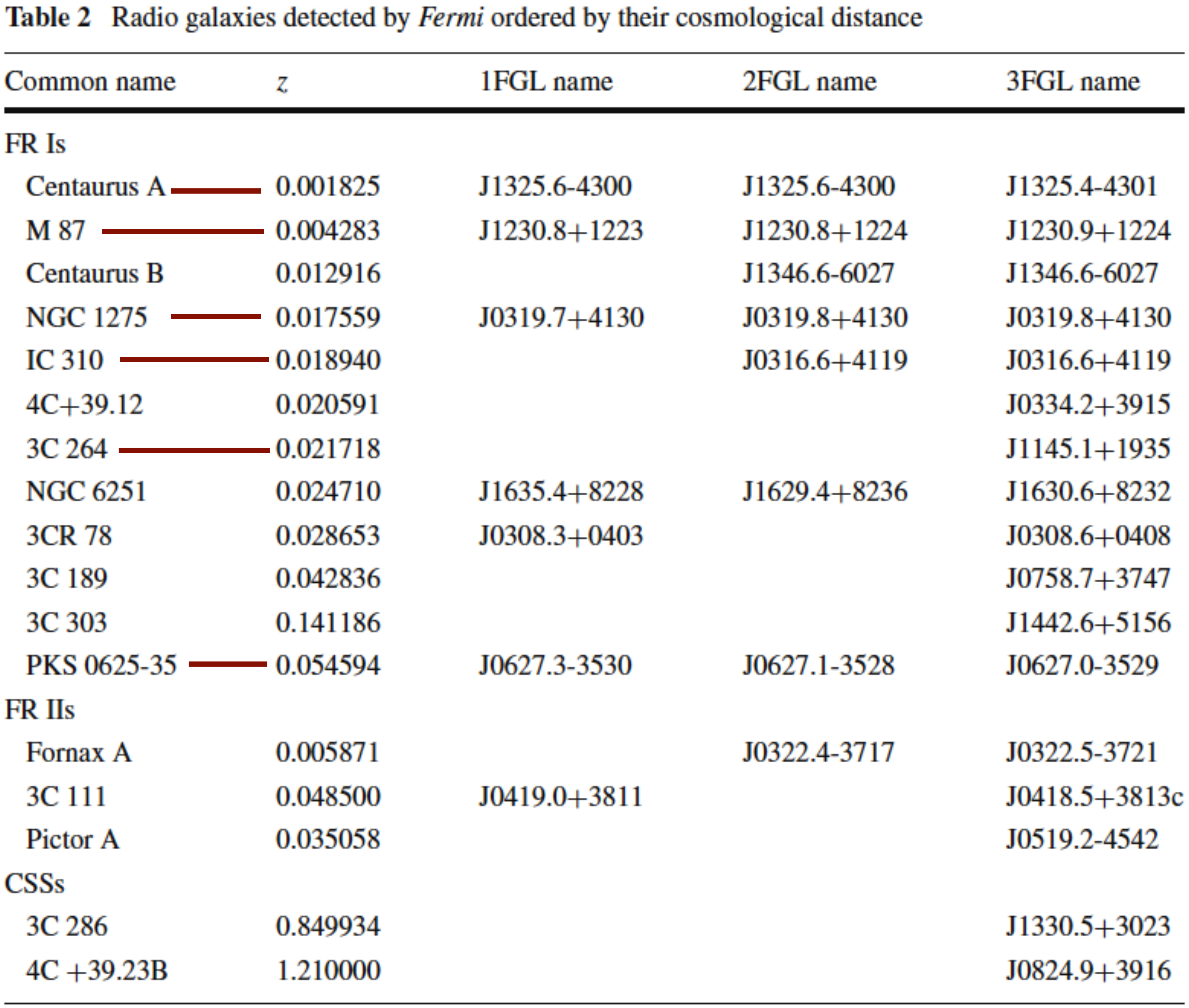


Table 2 Radio galaxies detected by *Fermi* ordered by their cosmological distance

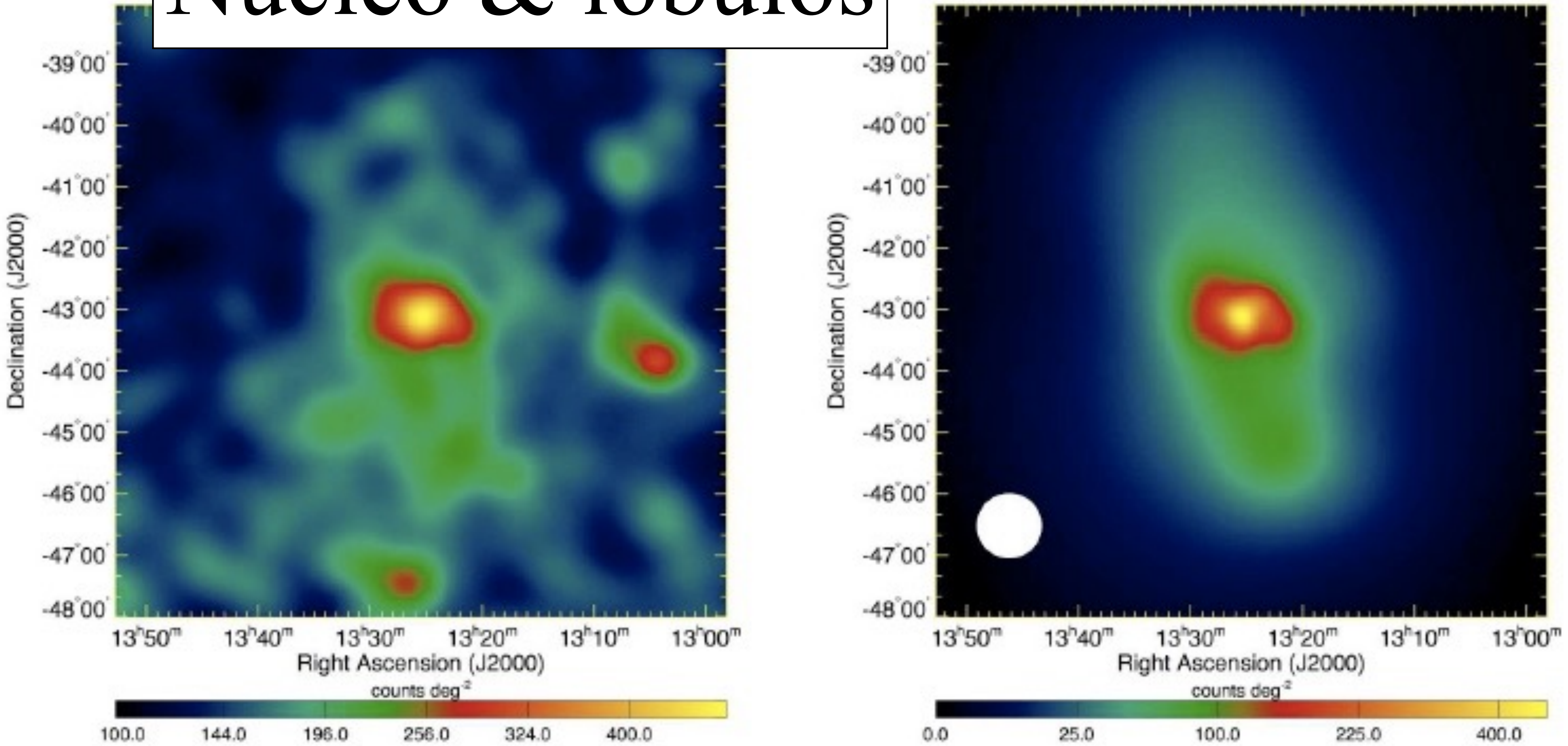
Common name	z	1FGL name	2FGL name	3FGL name
FR Is				
Centaurus A	0.001825	J1325.6-4300	J1325.6-4300	J1325.4-4301
M 87	0.004283	J1230.8+1223	J1230.8+1224	J1230.9+1224
Centaurus B	0.012916		J1346.6-6027	J1346.6-6027
NGC 1275	0.017559	J0319.7+4130	J0319.8+4130	J0319.8+4130
IC 310	0.018940		J0316.6+4119	J0316.6+4119
4C+39.12	0.020591			J0334.2+3915
3C 264	0.021718			J1145.1+1935
NGC 6251	0.024710	J1635.4+8228	J1629.4+8236	J1630.6+8232
3CR 78	0.028653	J0308.3+0403		J0308.6+0408
3C 189	0.042836			J0758.7+3747
3C 303	0.141186			J1442.6+5156
PKS 0625-35	0.054594	J0627.3-3530	J0627.1-3528	J0627.0-3529
FR IIs				
Fornax A	0.005871		J0322.4-3717	J0322.5-3721
3C 111	0.048500	J0419.0+3811		J0418.5+3813c
Pictor A	0.035058			J0519.2-4542
CSSs				
3C 286	0.849934			J1330.5+3023
4C +39.23B	1.210000			J0824.9+3916

TeVCat —

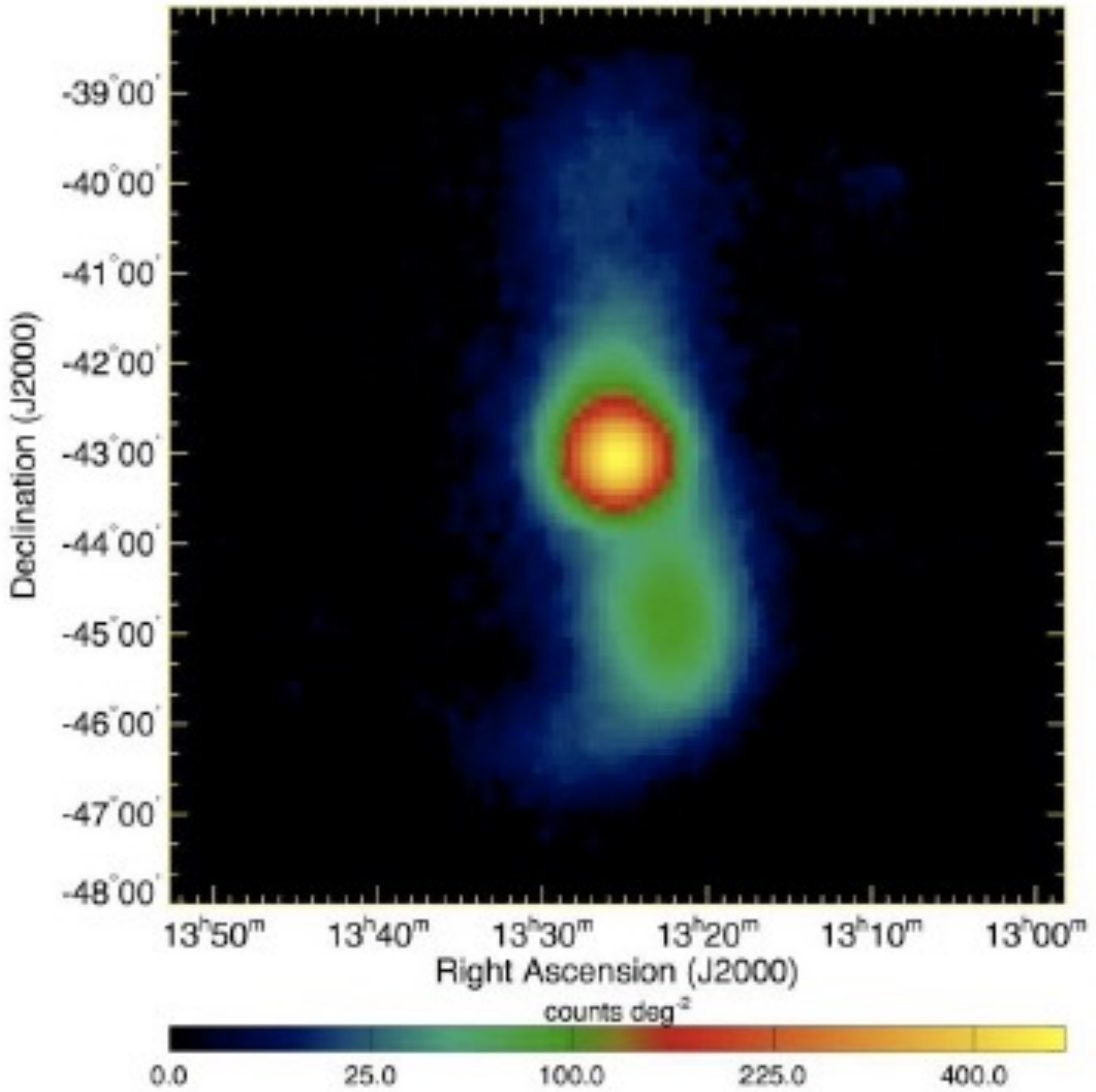
Massaro, Thompson & Ferrara (2016)

Centaurus A

Núcleo & lóbulos

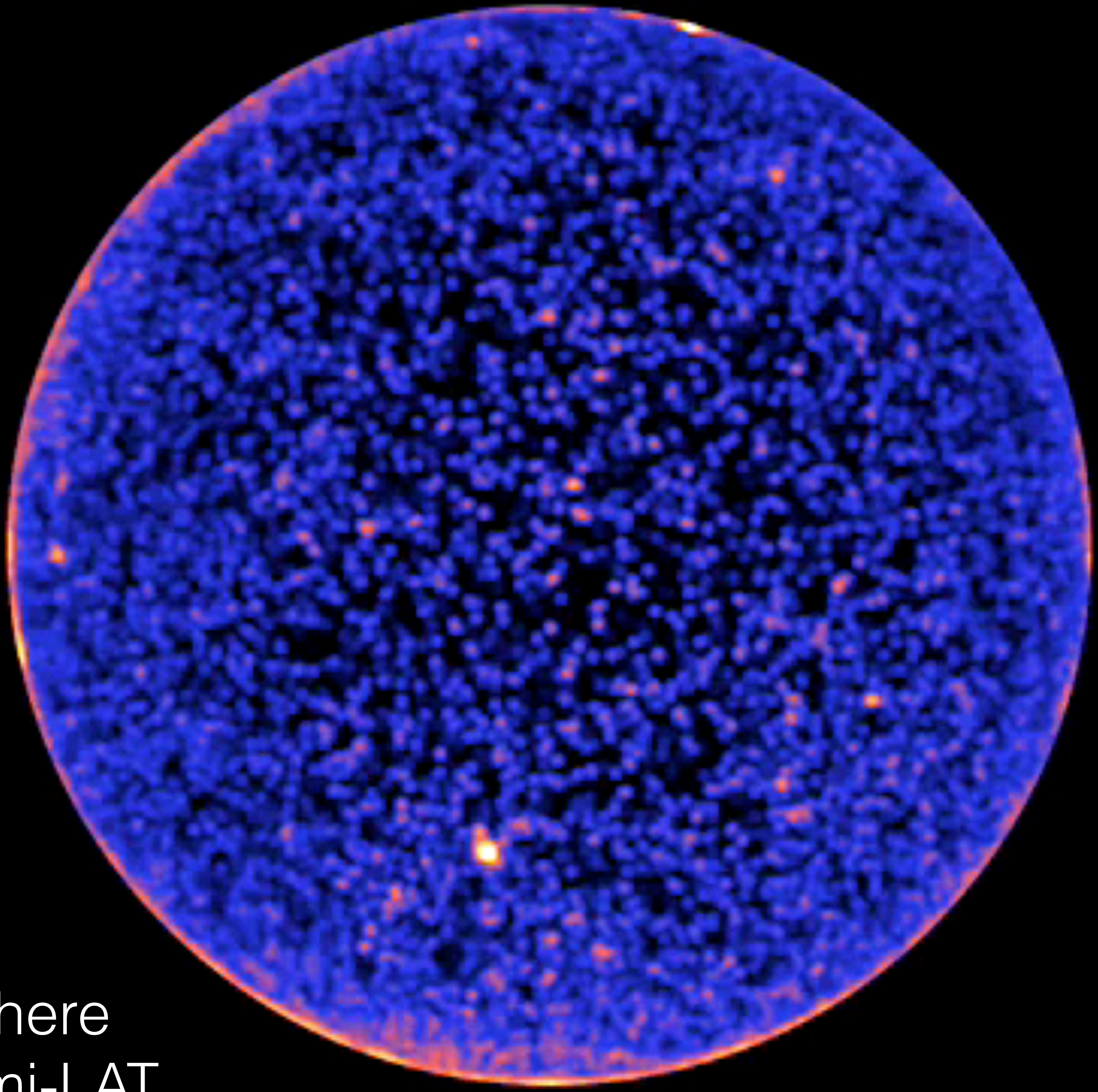


Fermi LAT - E > 200 MeV



22 GHz by WMAP

Blazares

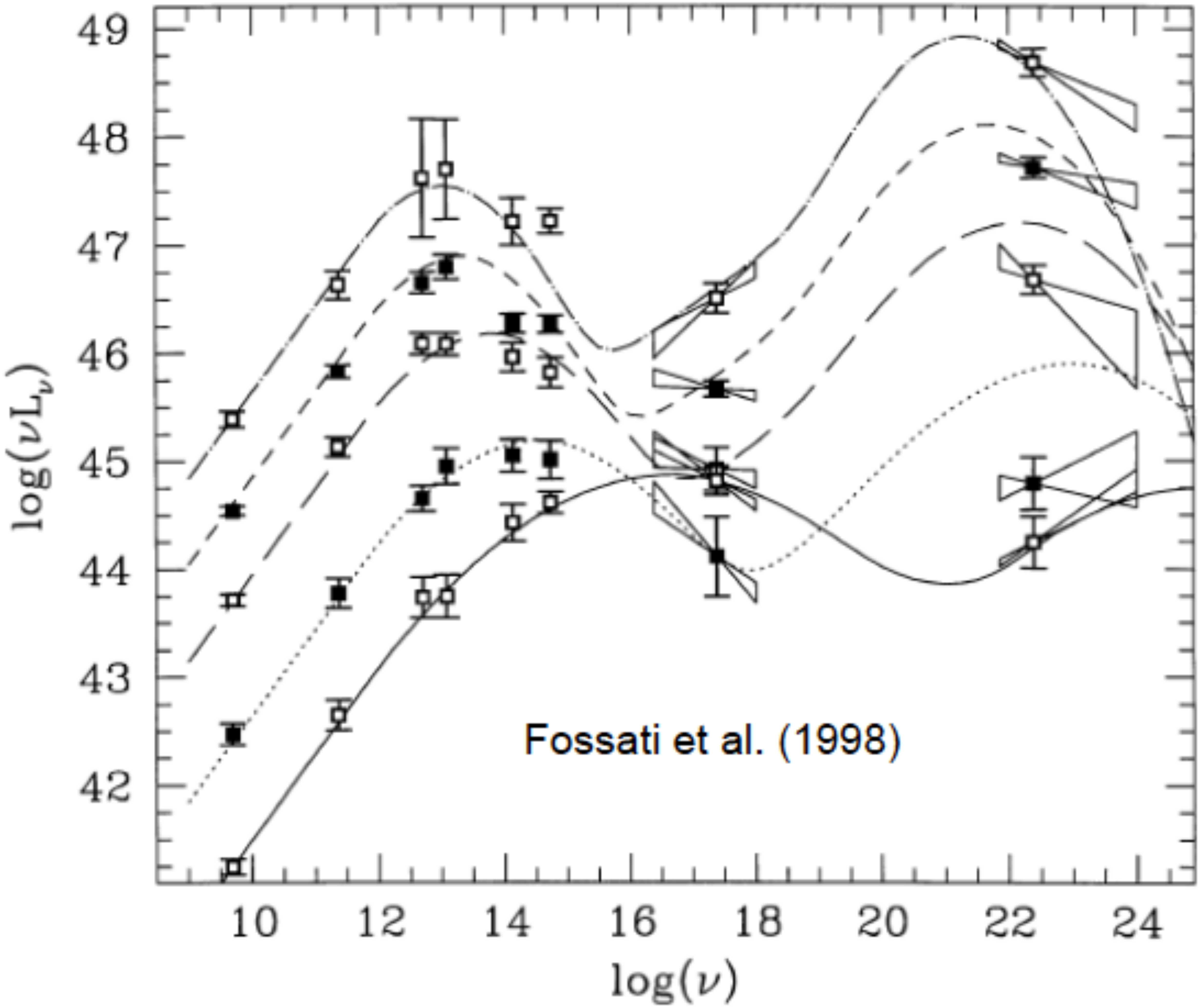


Northern Galactic hemisphere
11 month sequence by Fermi-LAT

Blazar Sequence

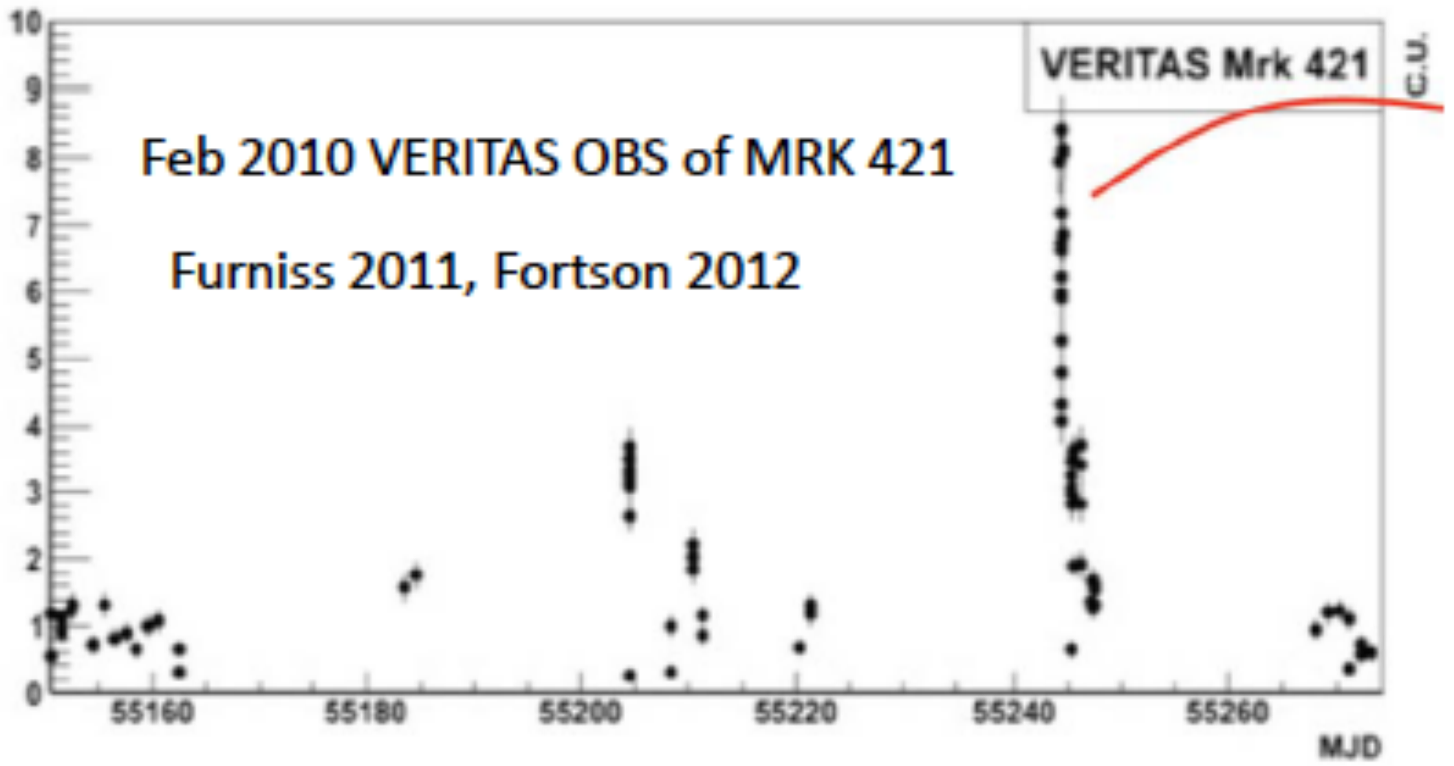
- ❑ **Searching for the Hertsprung-Russell Diagram in blazar studies**
- ❑ **Inverse correlation between E_{peak} and luminosity** (Fossati et al. 1998)
  - **LSP blazars powerful**
  - **HSP blazars weak**
- ❑ **Cooling model with external radiation for FSRQs** (Ghisellini et al. 1998)
- ❑ **Origin of the sequence**
  - **Galaxy evolution through reduction of fuel from surrounding gas and dust** (Böttcher and Dermer 2002)
  - **BZ effect**

    (Cavaliere and d'Elia 2002)



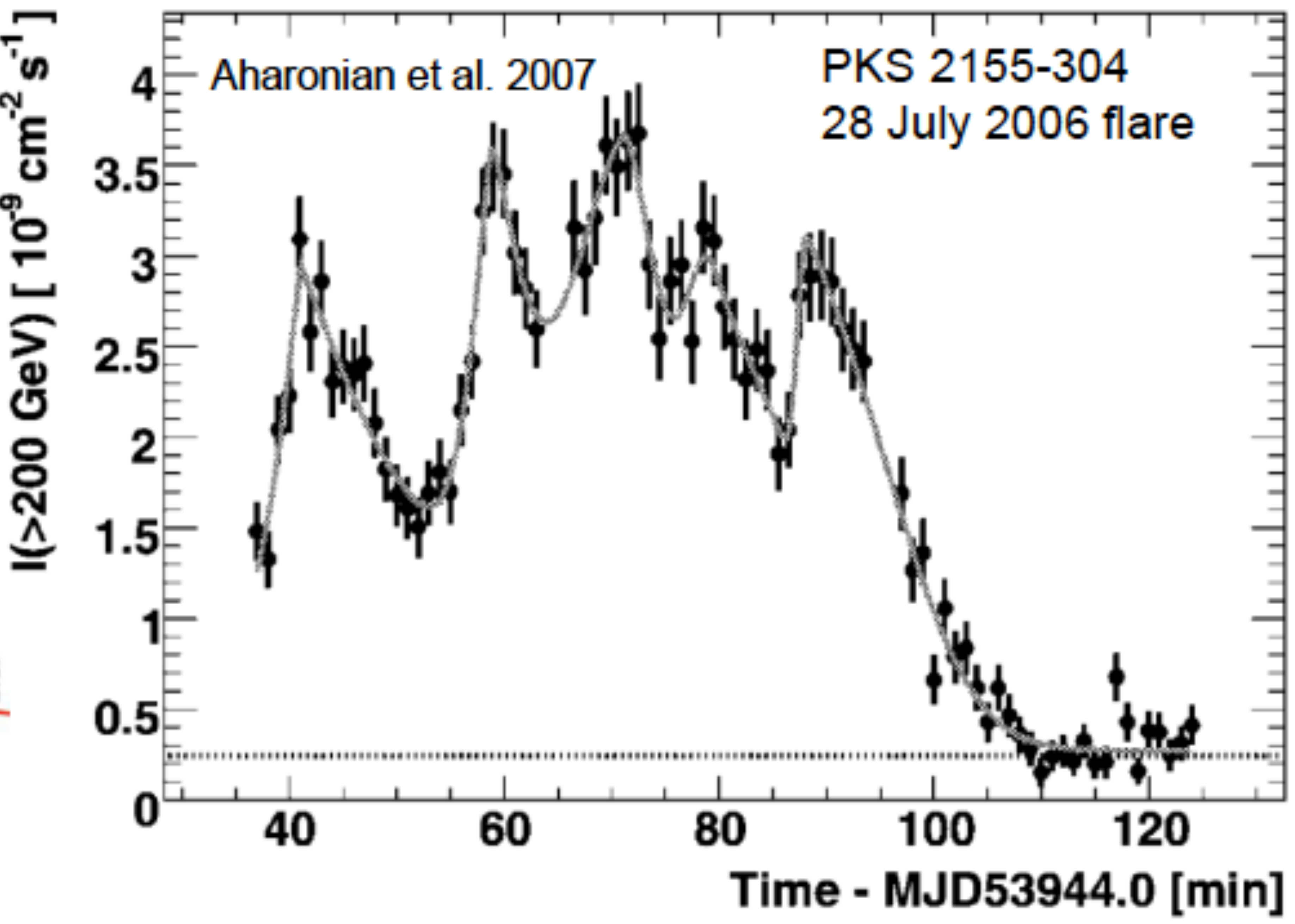
Strongly Variable Class of BL Lac Objects

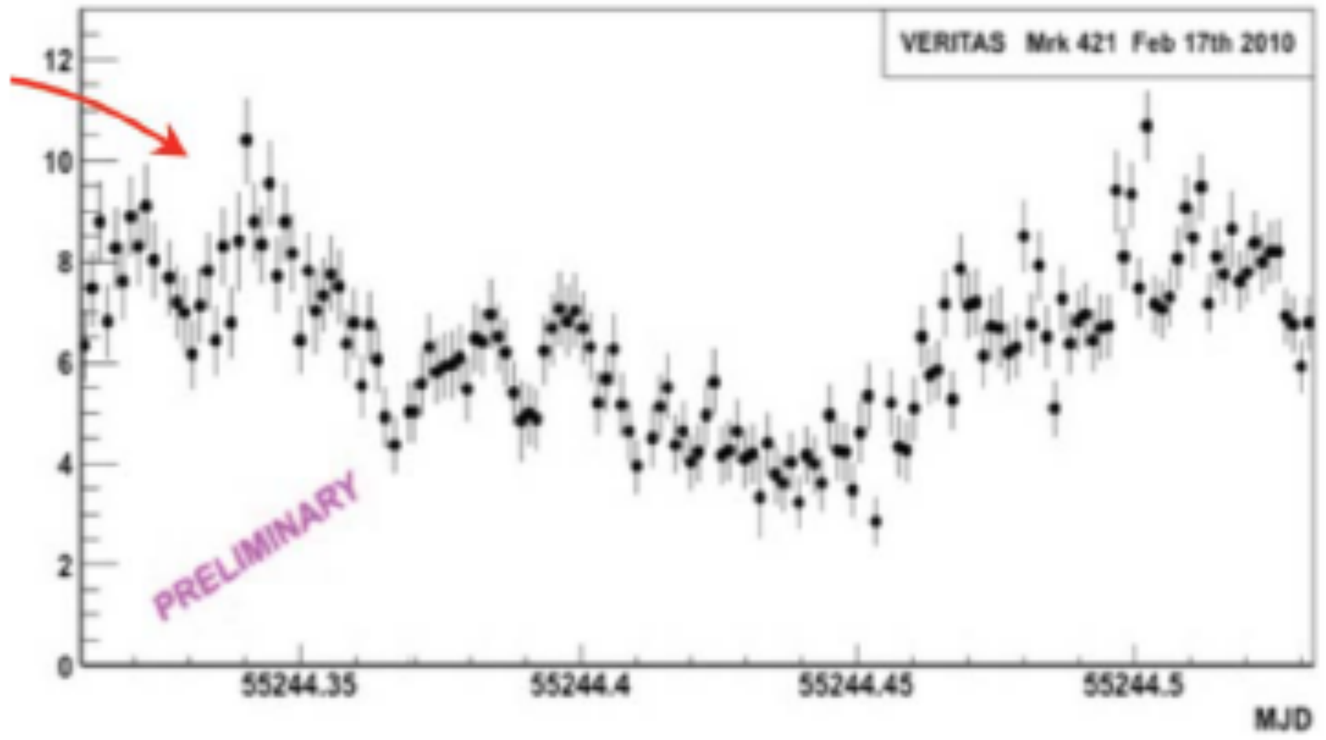
- ☐ **Strongly variable class**
  - Mrk 421, z = 0.03
  - Mrk 501, z= 0.033
  - PKS 2155-305, z = 0.116
  - – $t_{var} < R_S/c$, $L > L_{EDD}$
  - – Extreme sources



Feb 2010 VERITAS OBS of MRK 421

Furniss 2011, Fortson 2012



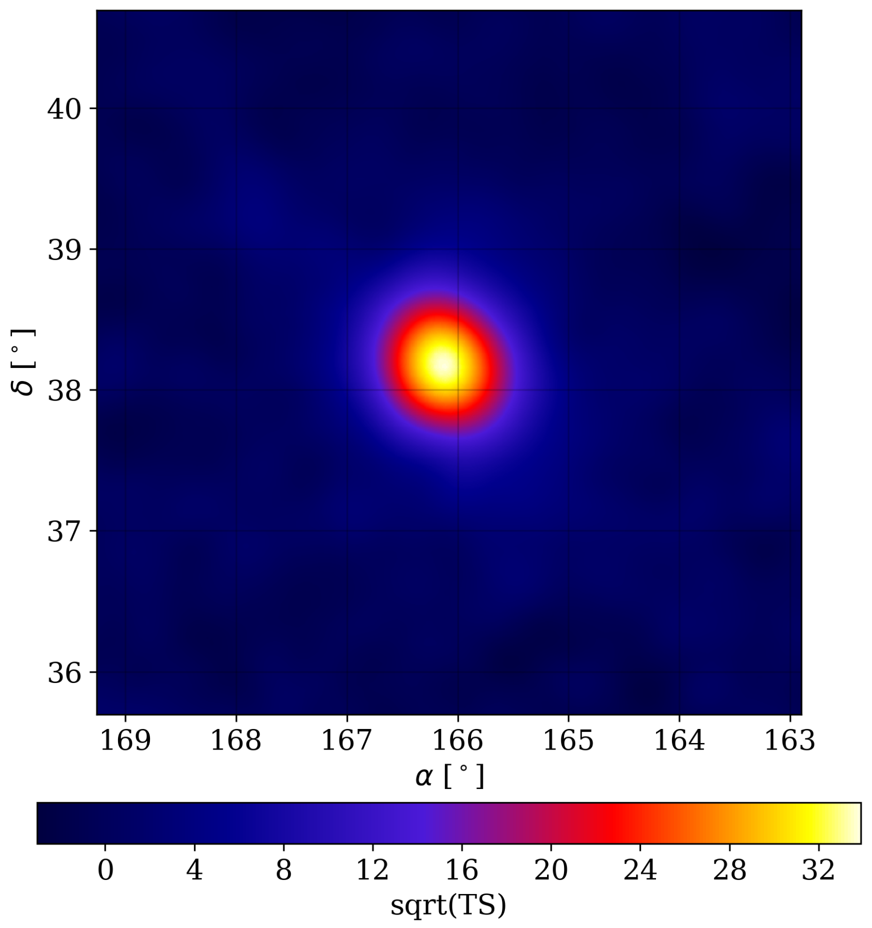


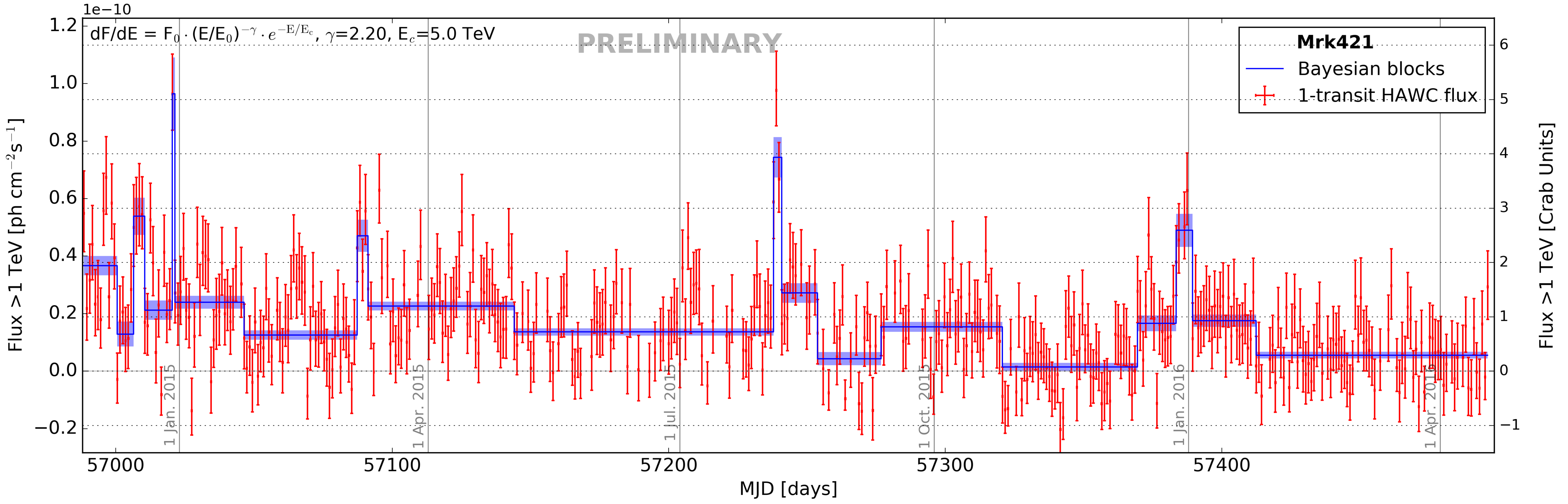
$R_S/c = 10^4 M_9$ s

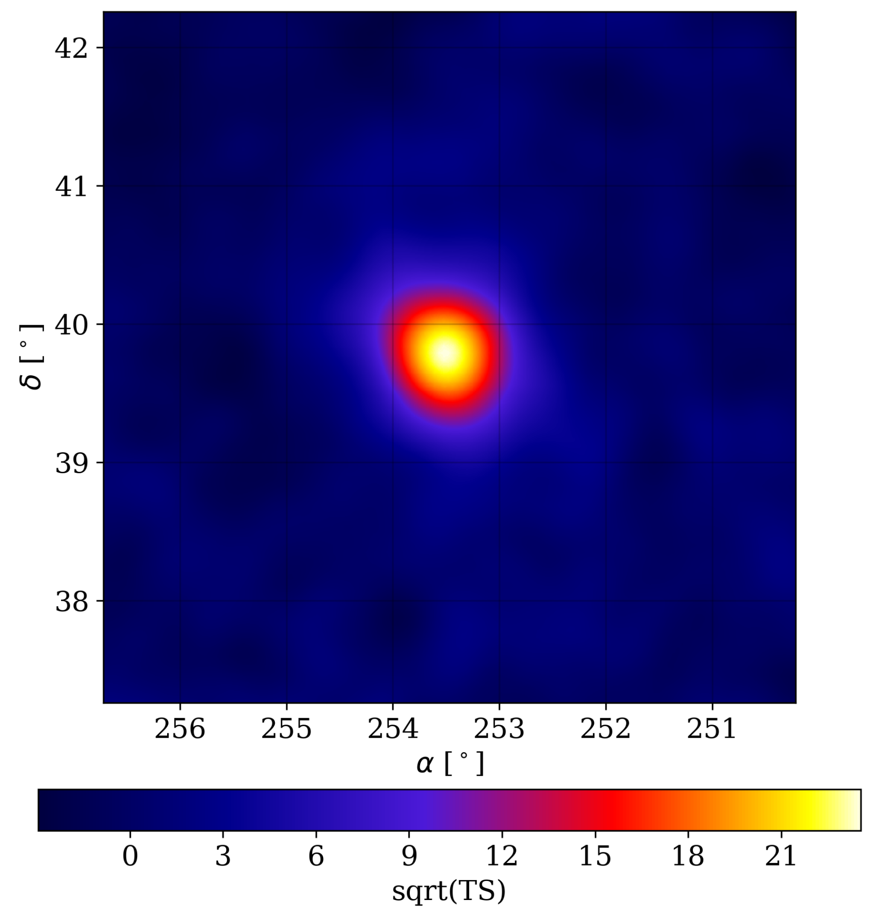
$t_{var} \sim 5$ min = 300 s

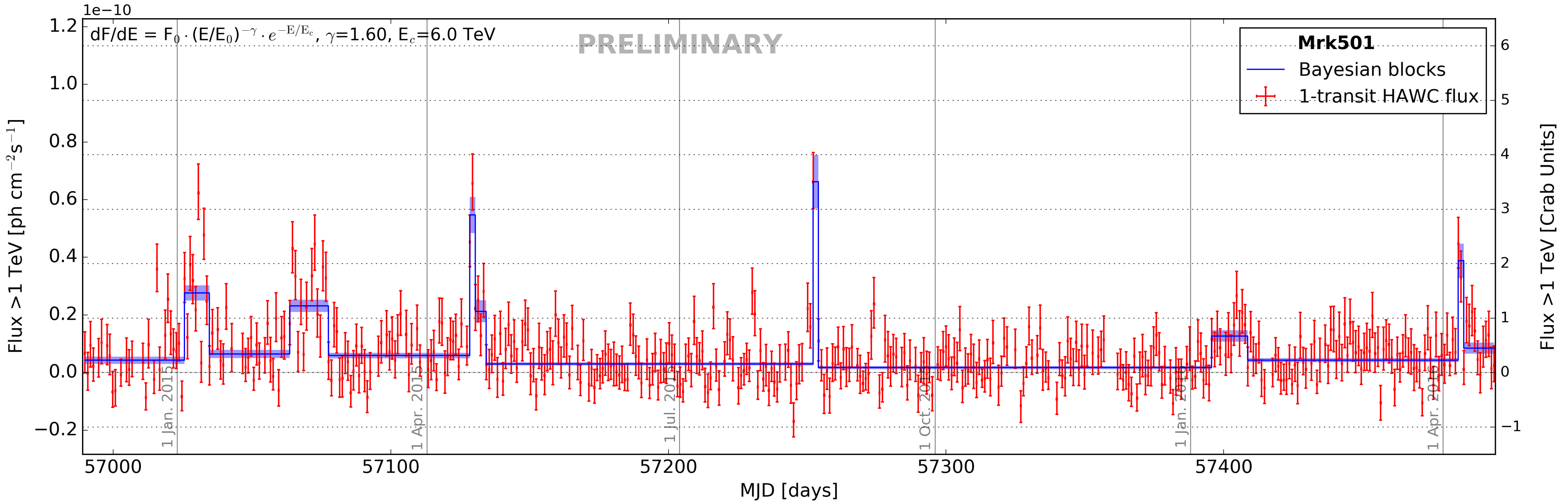
$\Rightarrow$(?) $M \ll 10^8\, M_0$

Markarian 421 y 501





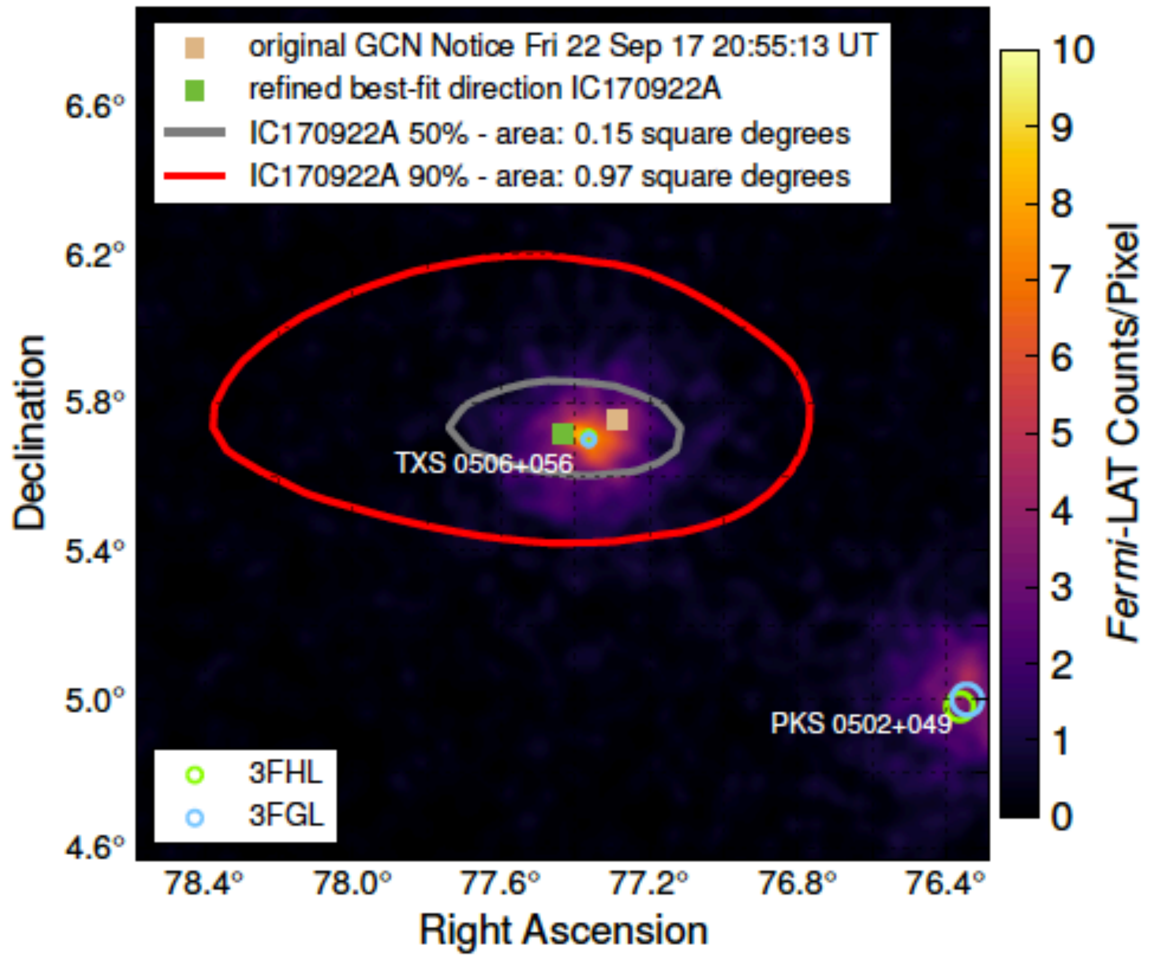




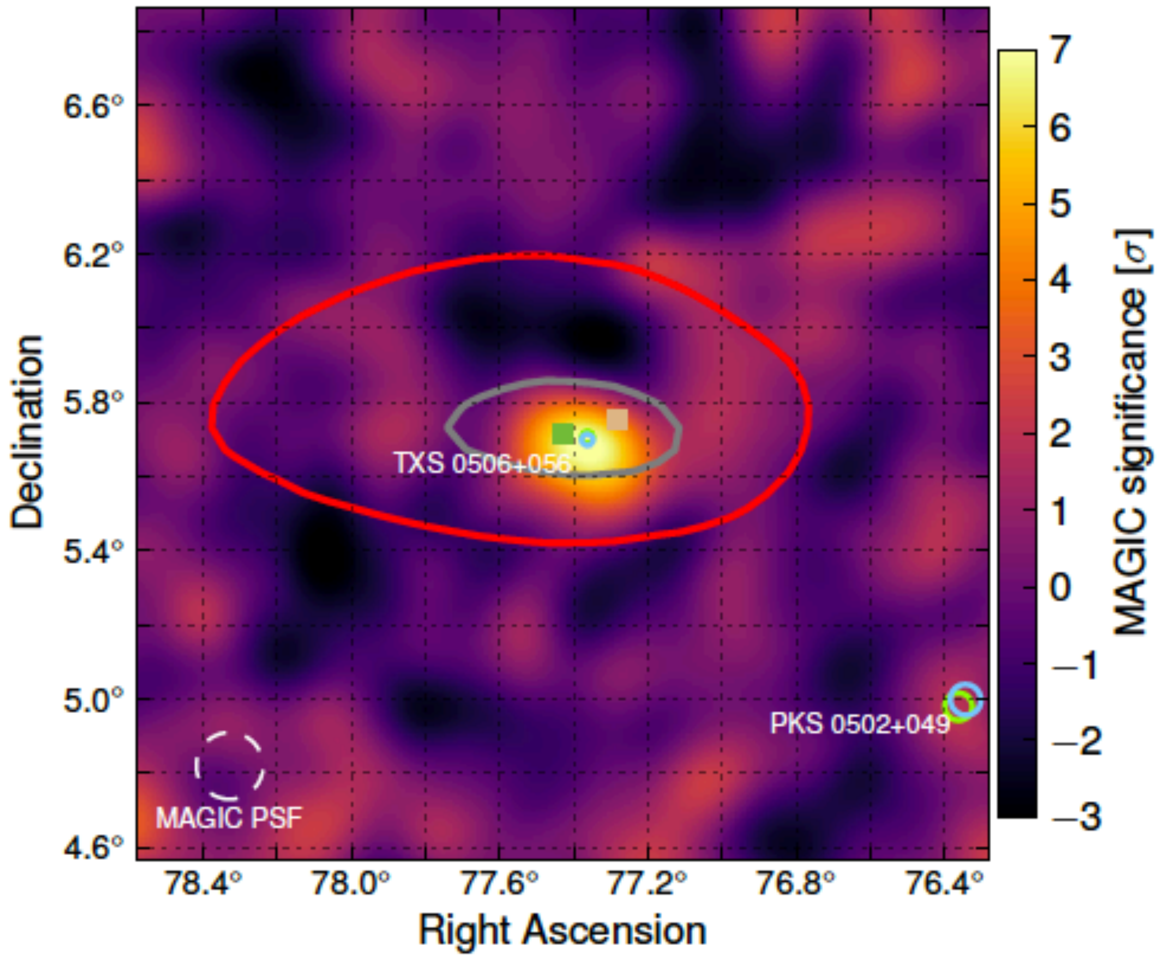
TXS 0506+056

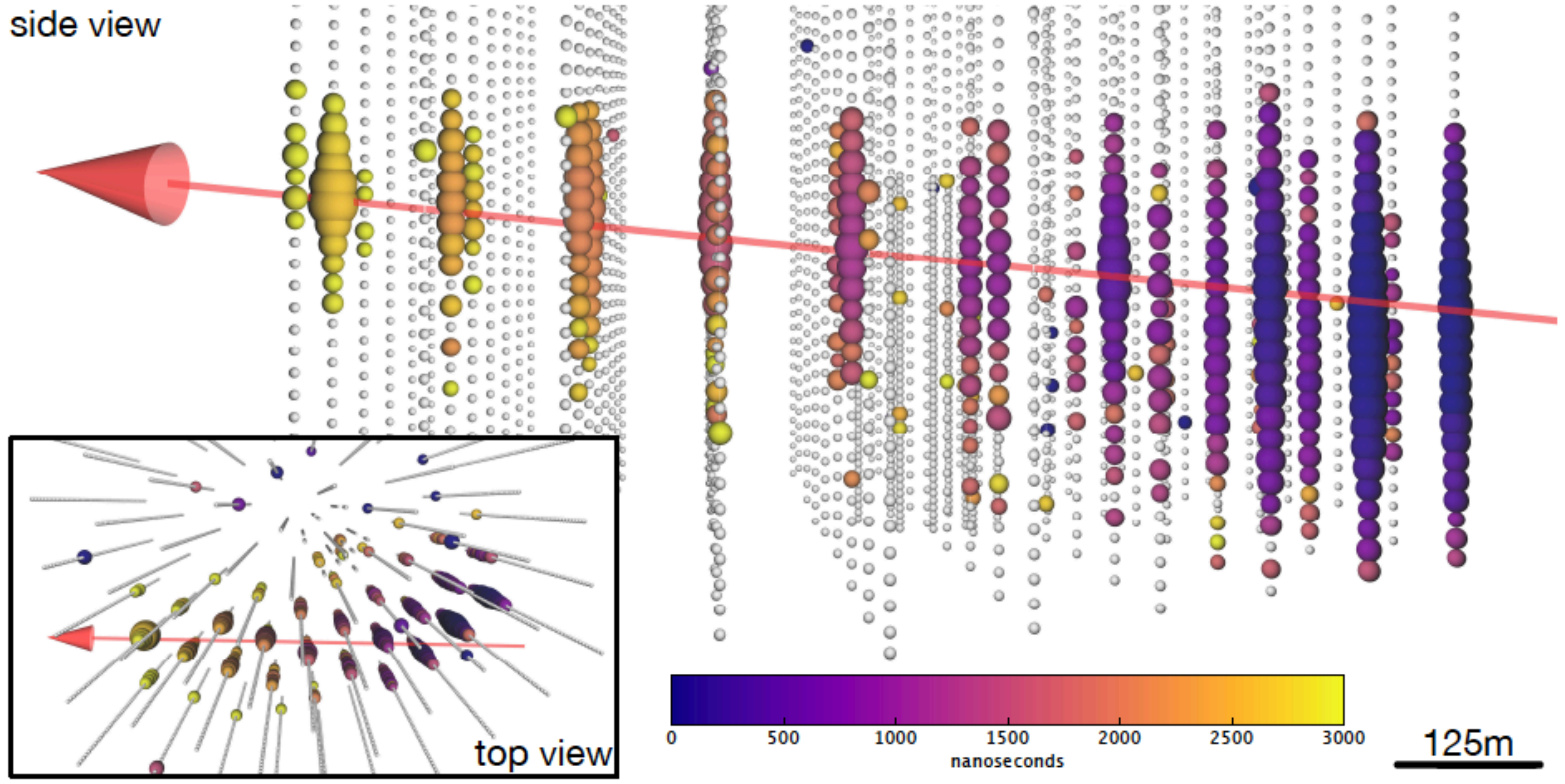
- HE (290 TeV) neutrino IceCube-170922A matching 3FHL source TXS 0506+056 @ z=0.3365 (Science 361, 2018).
- Detected by MAGIC: N(E > 90 GeV) ≃ 3.6 × 10^{-11} $cm^{-2}s^{-1}$.
- HAWC upper limits (E > 1 TeV) for emission contemporaneous to the event, and in archival data since Nov 2014 (Atel 10802, 2017).

(A)

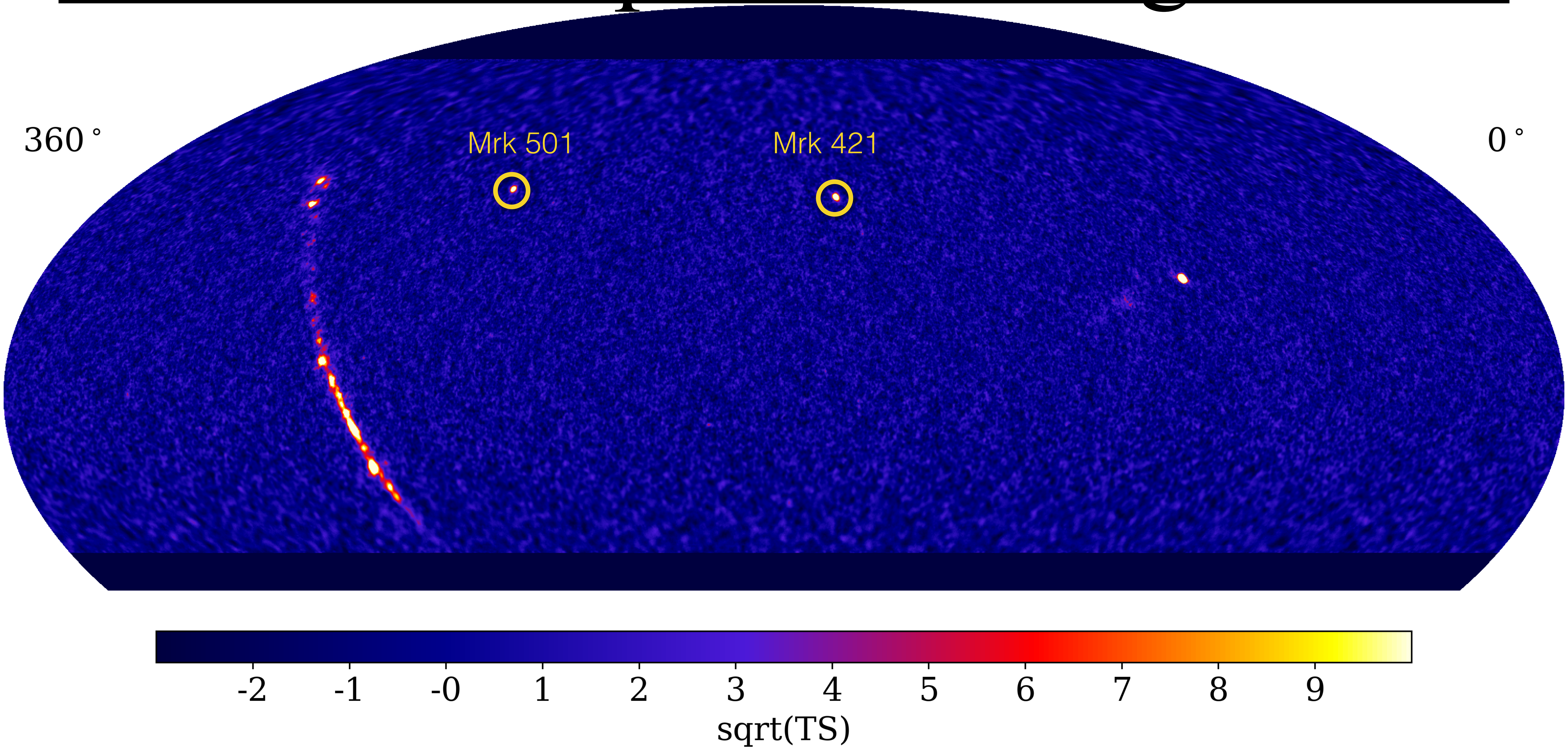


(B)





6. Absorción por luz extragaláctica



Absorción EBL - producción de pares

La producción de pares por interacción entre dos fotones

$$\gamma + \gamma \to e^+ + e^-$$

conserva energía-momento ($\hbar = 1, mc = 1$),

$$\begin{pmatrix} \omega_0 + \omega_1 \\ \omega_0 \hat{k}_0 + \omega_1 \hat{k}_1 \end{pmatrix} = \begin{pmatrix} \gamma_0 + \gamma_1 \\ \gamma_0 \vec{\beta}_0 + \gamma_1 \vec{\beta}_1 \end{pmatrix},$$

de invariante $p^\alpha_\alpha = -2\omega_0\omega_1 \left(1 - \hat{k}_0 \cdot \hat{k}_1\right) = -2 - 2\gamma_0\gamma_1 \left(1 - \vec{\beta}_0 \cdot \vec{\beta}_1\right)$ que define el umbral $\hbar\omega_1 \hbar\omega_2 \geq (mc^2)^2$.

Absorción EBL - producción de pares CM

En el CM

$$\begin{pmatrix}\omega'_0+\omega'_1\\0\end{pmatrix}=\begin{pmatrix}\gamma'_0+\gamma'_1\\0\end{pmatrix}\Rightarrow\begin{pmatrix}2\omega'\\0\end{pmatrix}=\begin{pmatrix}2\gamma'\\0\end{pmatrix},$$

con $\omega'\equiv\omega'_0=\omega'_1$, lo mismo para γ, y $\omega'=\gamma'\geq 1$. La sección eficaz es función de $\omega'=\sqrt{\omega_0\omega_1\left(1-\hat{k}_0\cdot\hat{k}_1\right)/2}$ y su máximo puede escribirse como,

$$E\,h\nu\simeq 0.35\ \mathrm{TeV\,eV}.$$

Absorción EBL - atenuación de rayos γ

Se calcula la opacidad sobre la línea de visión,

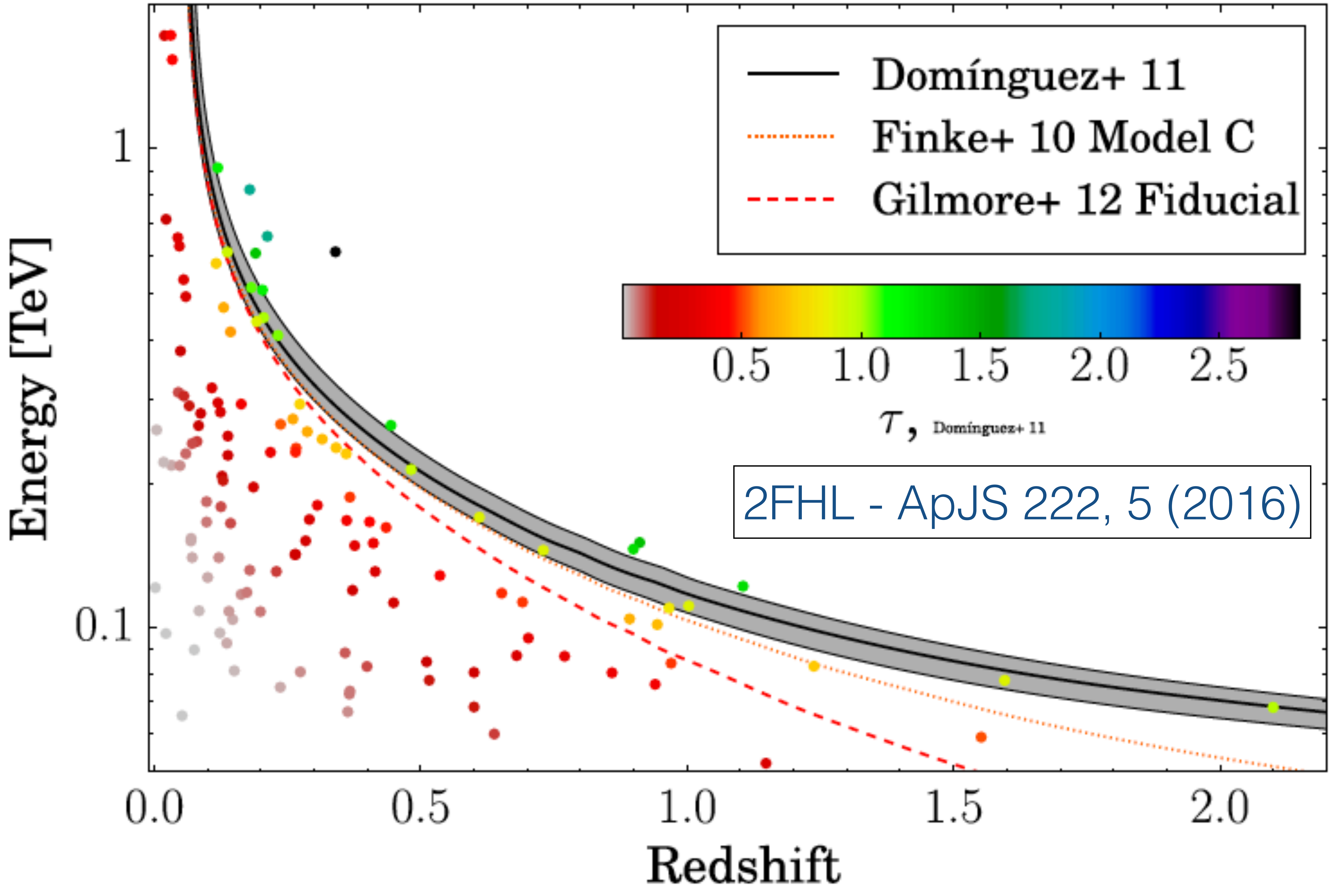
$$\tau(E,z)=\int_0^z\int_0^\infty\int_{0\star}^{\pi}\sigma(\omega)n_\nu(z')\,\frac{d\mu}{2}\,d\nu\left(\frac{d\ell}{dz'}\right)dz'$$

con $\omega=\sqrt{Eh\nu(1-\cos\theta)/2}$, $\mu=\cos\theta$, $d\ell/dz=c/H(z)(1+z)$. La integración en μ considera el umbral $\omega>mc^2$.

La distribución en frecuencias de la luz extragaláctica es incierta.

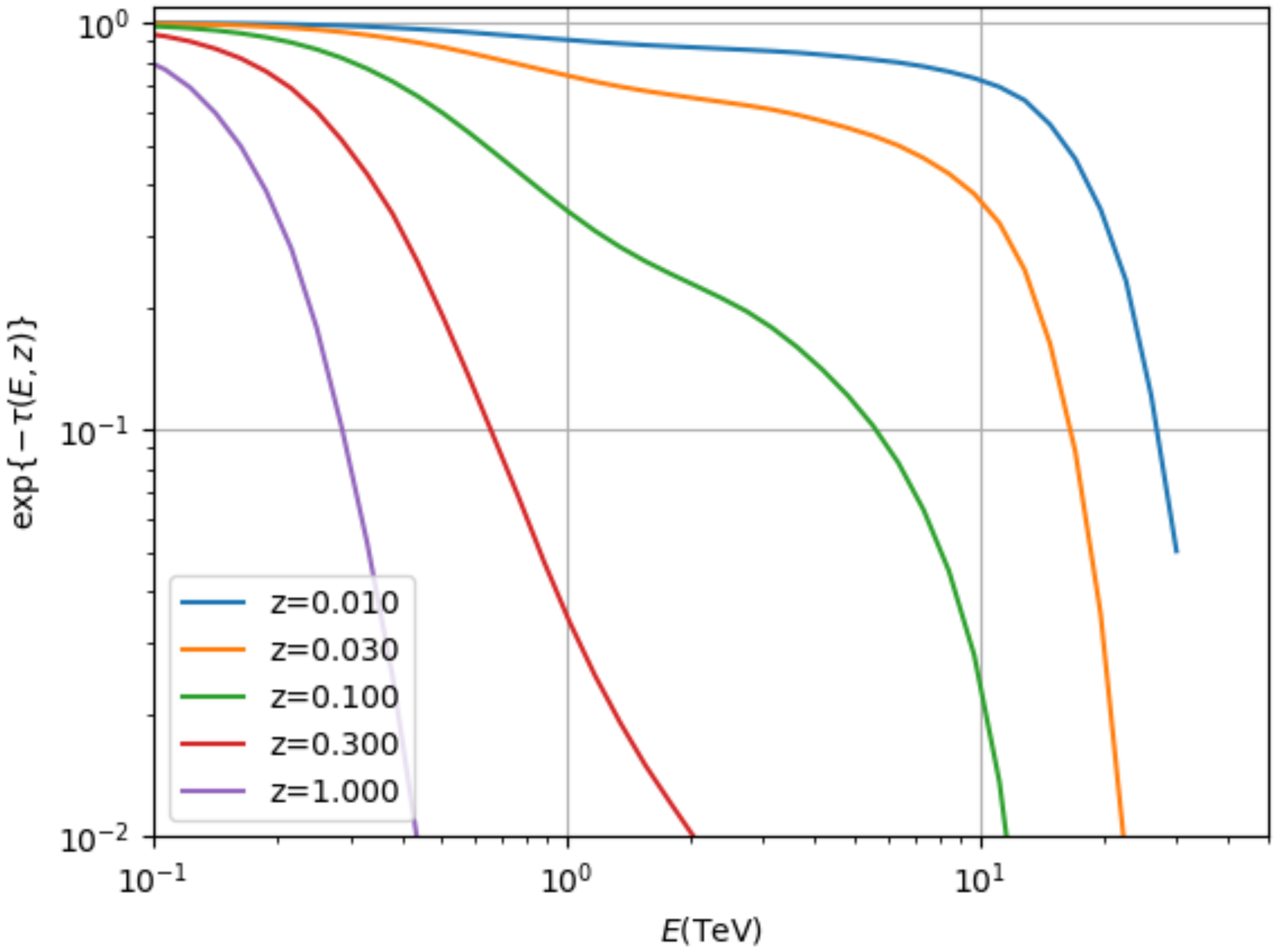
$$\boxed{E\,h\nu\simeq 0.35\ \mathrm{TeV\,eV}}$$

E (TeV)	hυ (eV)	λ (μm)
0.1	3.5	0.35
0.35	1	1.24
1	0.35	3.5
3.5	0.1	12.4
10	0.035	35
35	0.01	124
100	0.0035	350
350	0.001	1 mm

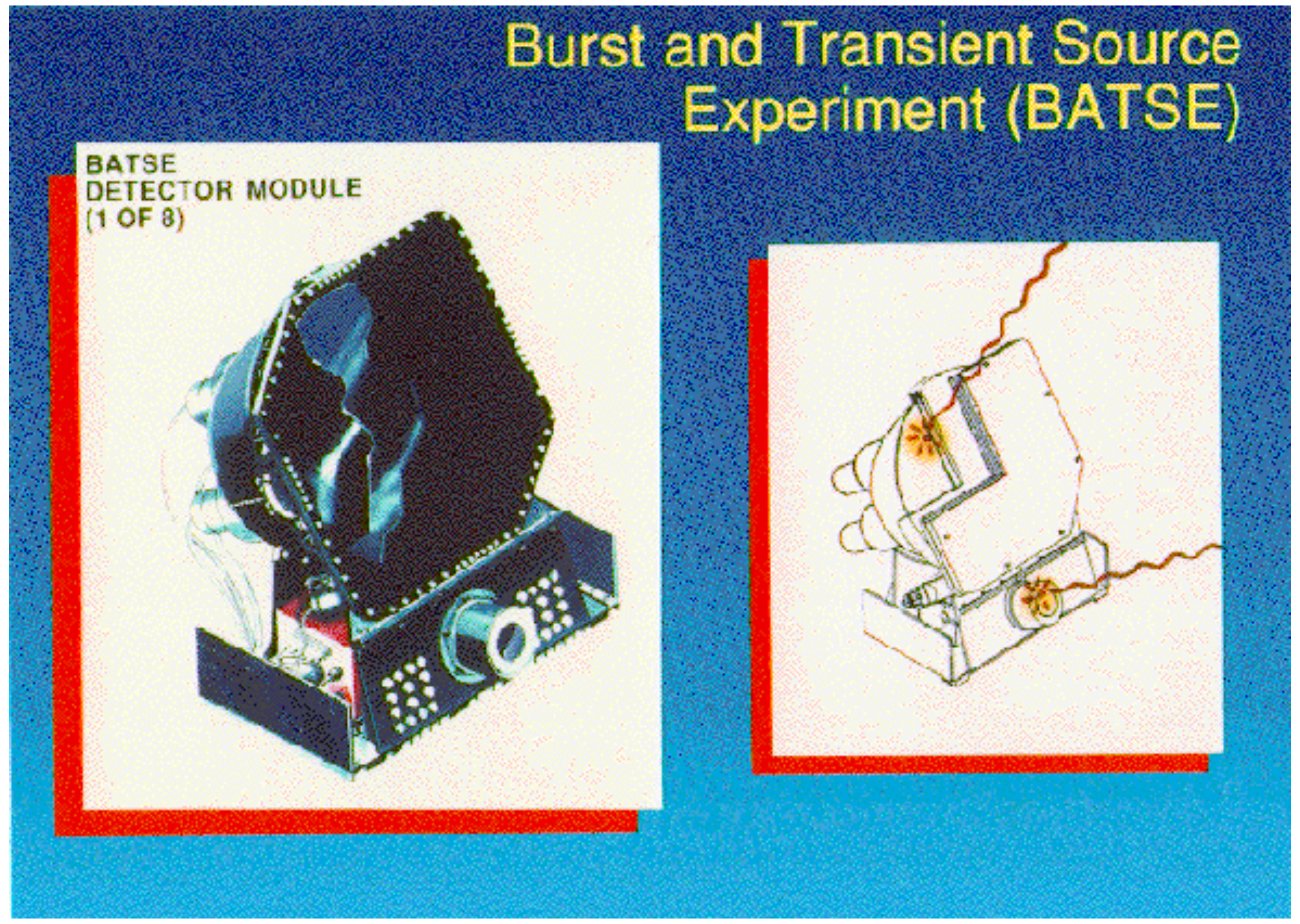


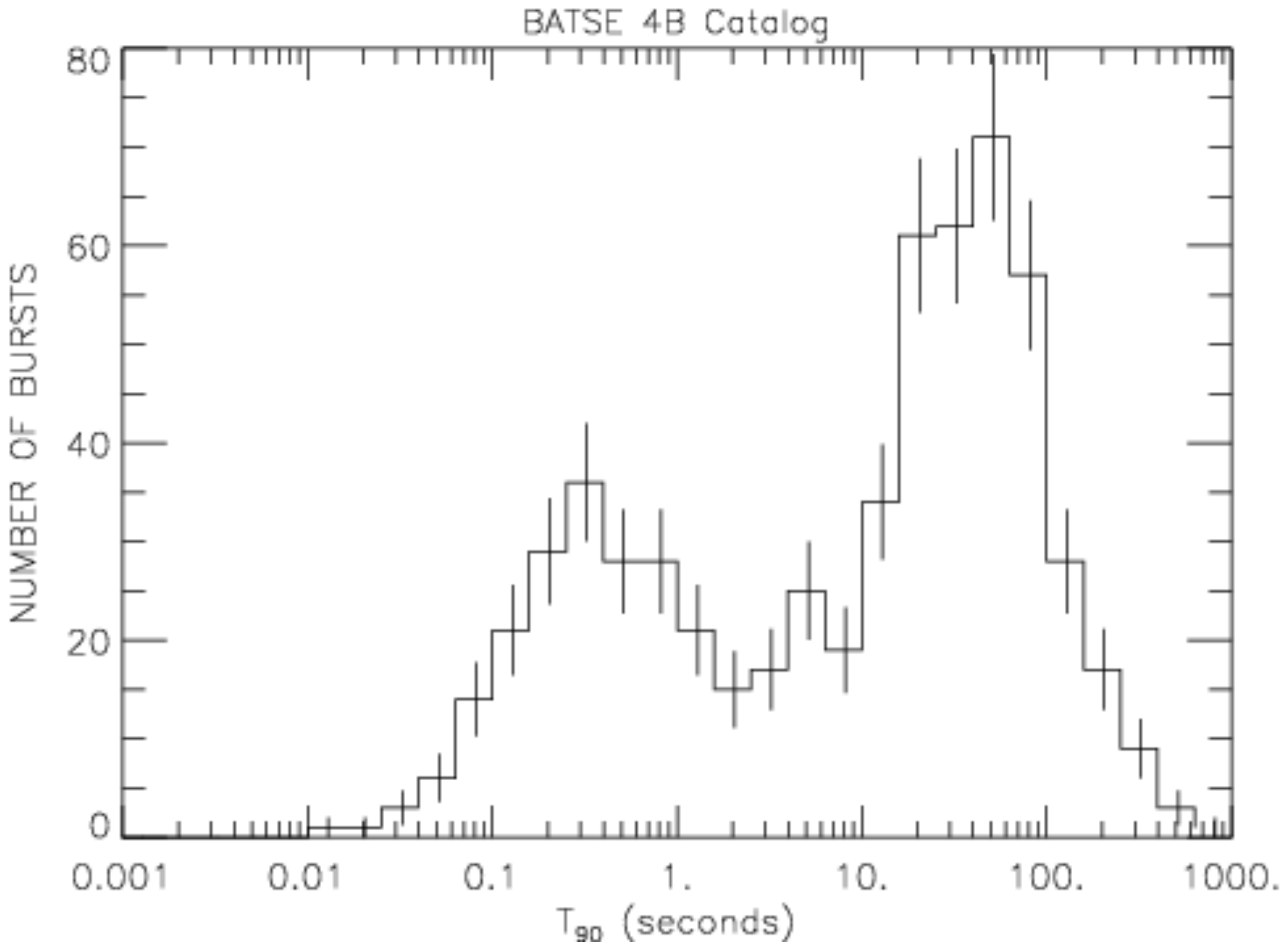
2FHL - ApJS 222, 5 (2016)

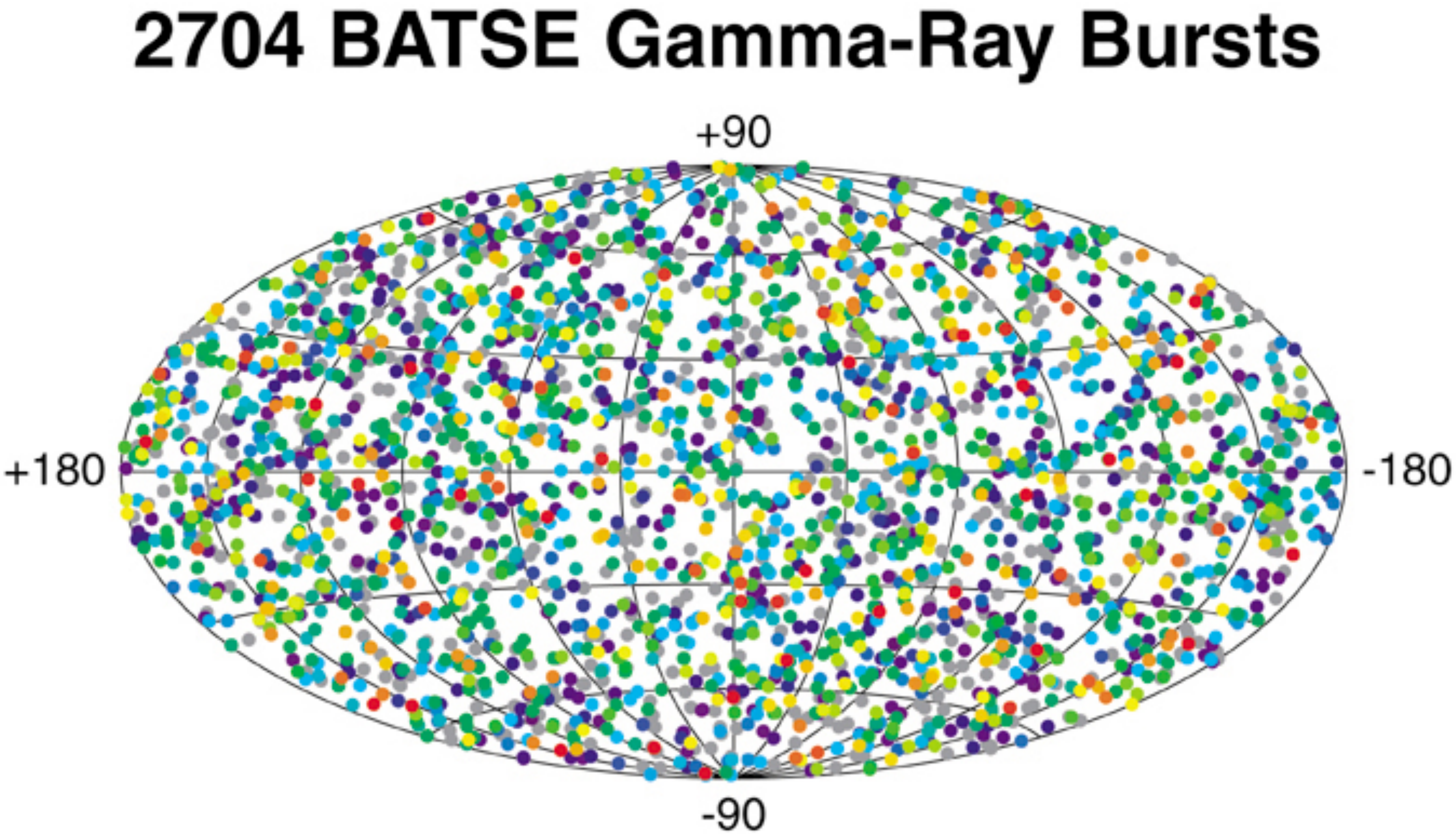
Figure 13. The highest photon energy vs. source redshift. The symbols are color coded by the optical depth, τ, estimated from the EBL model by Domínguez et al. (2011b). Different estimates of the cosmic γ-ray horizon are plotted as well, which are derived from the EBL models by Finke et al. (2010, dotted orange line), Domínguez et al. (2011b, solid black line, with its uncertainties as a shaded band) and Gilmore et al. (2012, dashed red line). We note that several photons are from near and beyond the horizon.

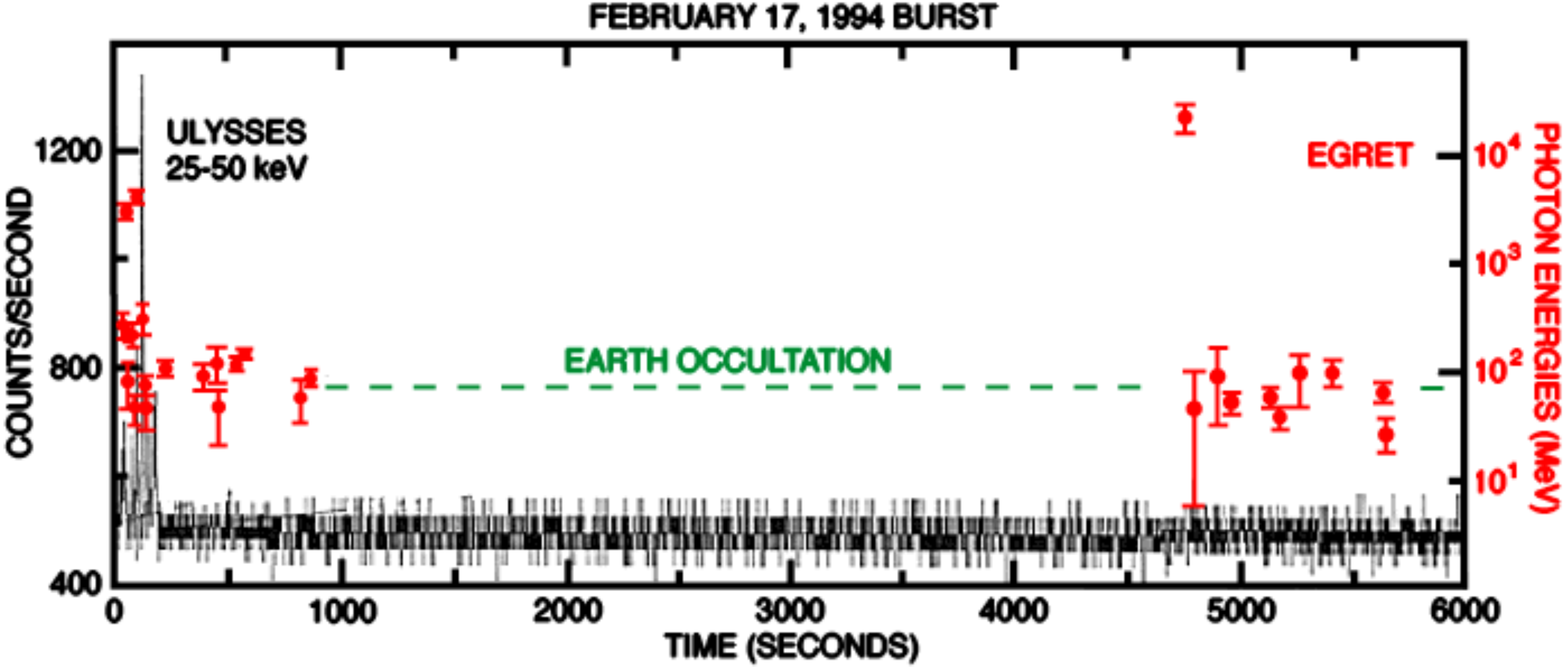


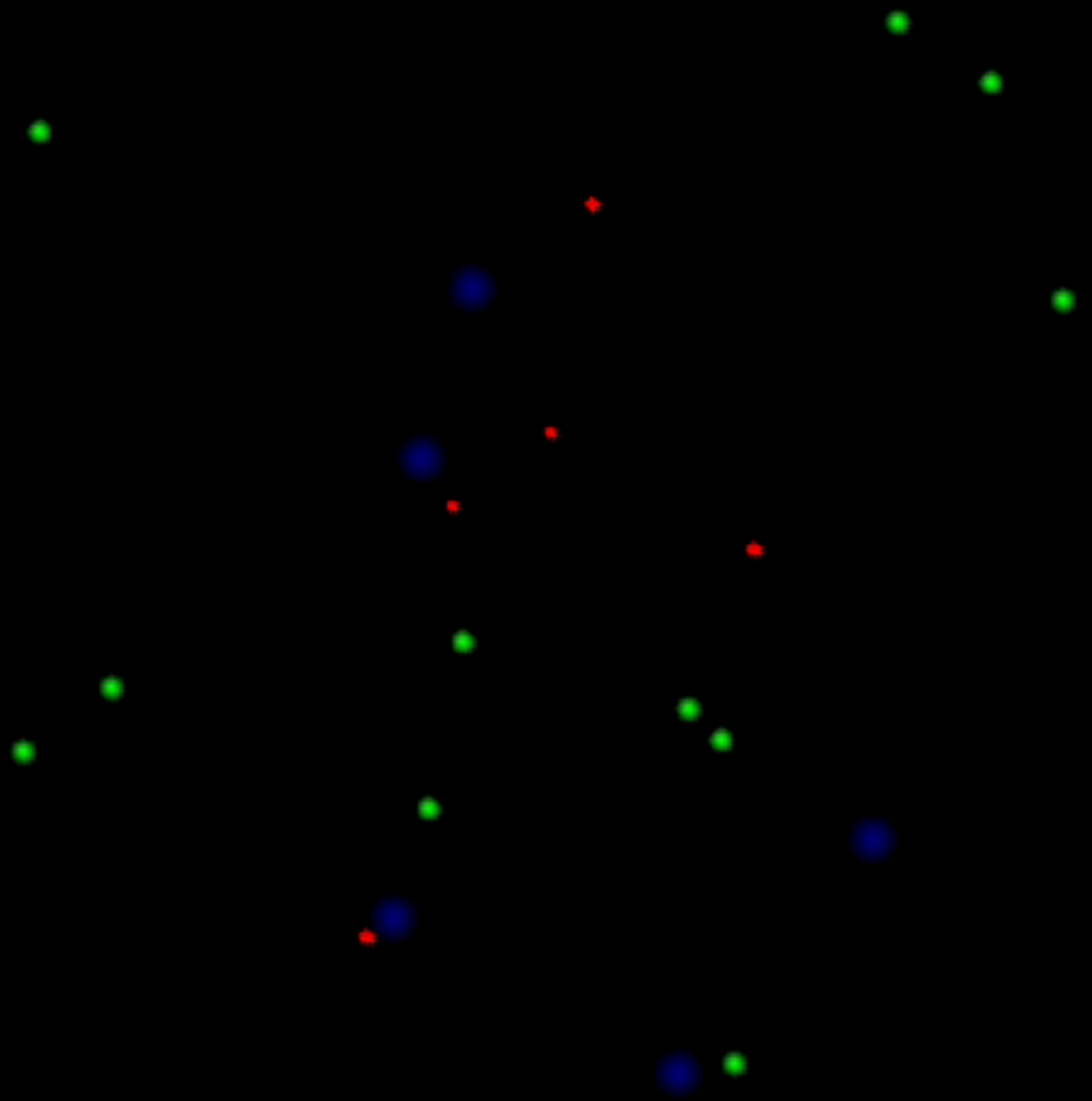
7. Destellos de rayos gamma





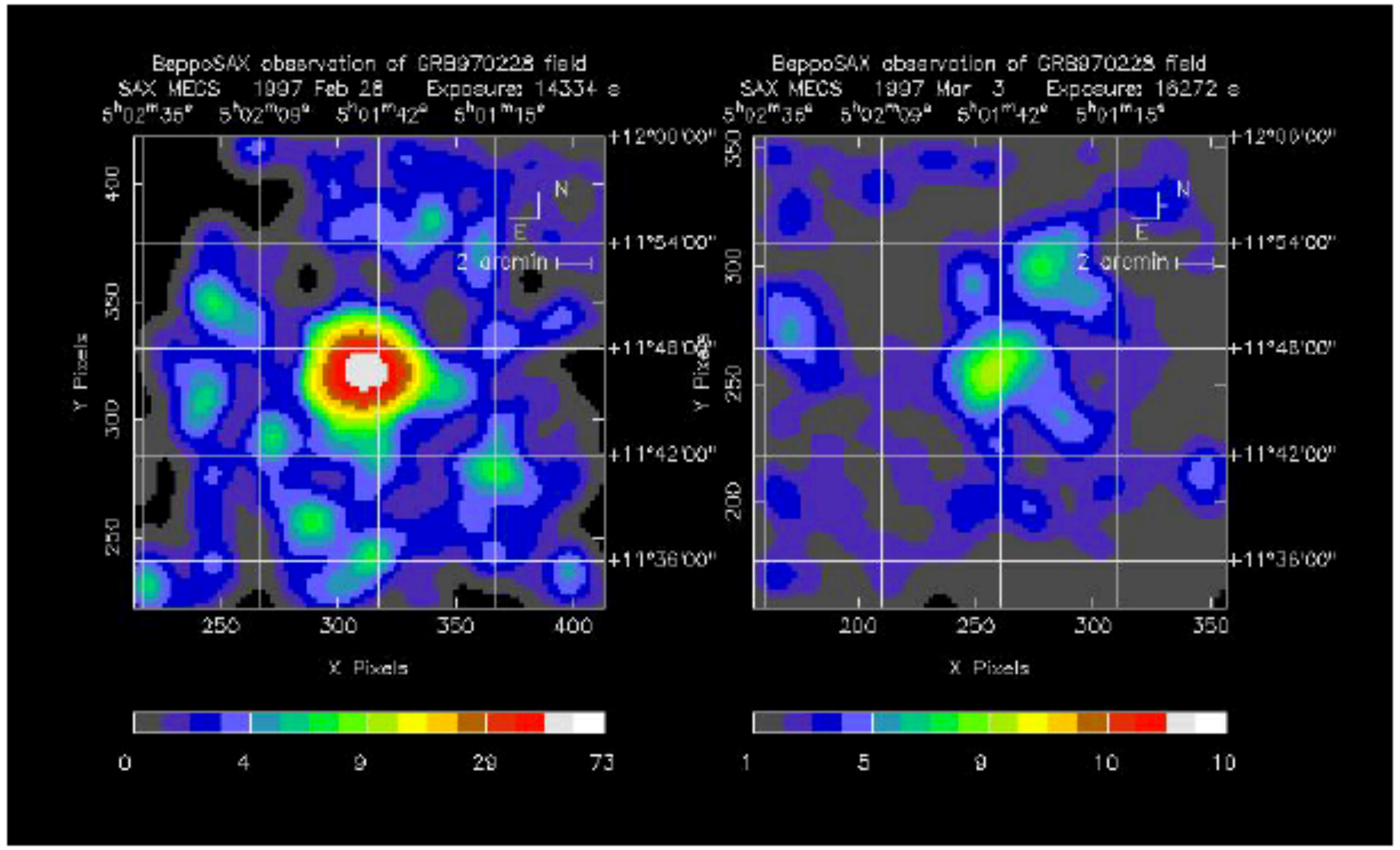



FEBRUARY 17, 1994 BURST
ULYSSES
25-50 keV
EGRET
EARTH OCCULTATION
COUNTS/SECOND
1200
800
400
PHOTON ENERGIES (MeV)
10^4
10^3
10^2
10^1
0
1000
2000
3000
4000
5000
6000
TIME (SECONDS)



GRB 080319B
Naked eye
m = 5.3
z = 0.937

Afterglows



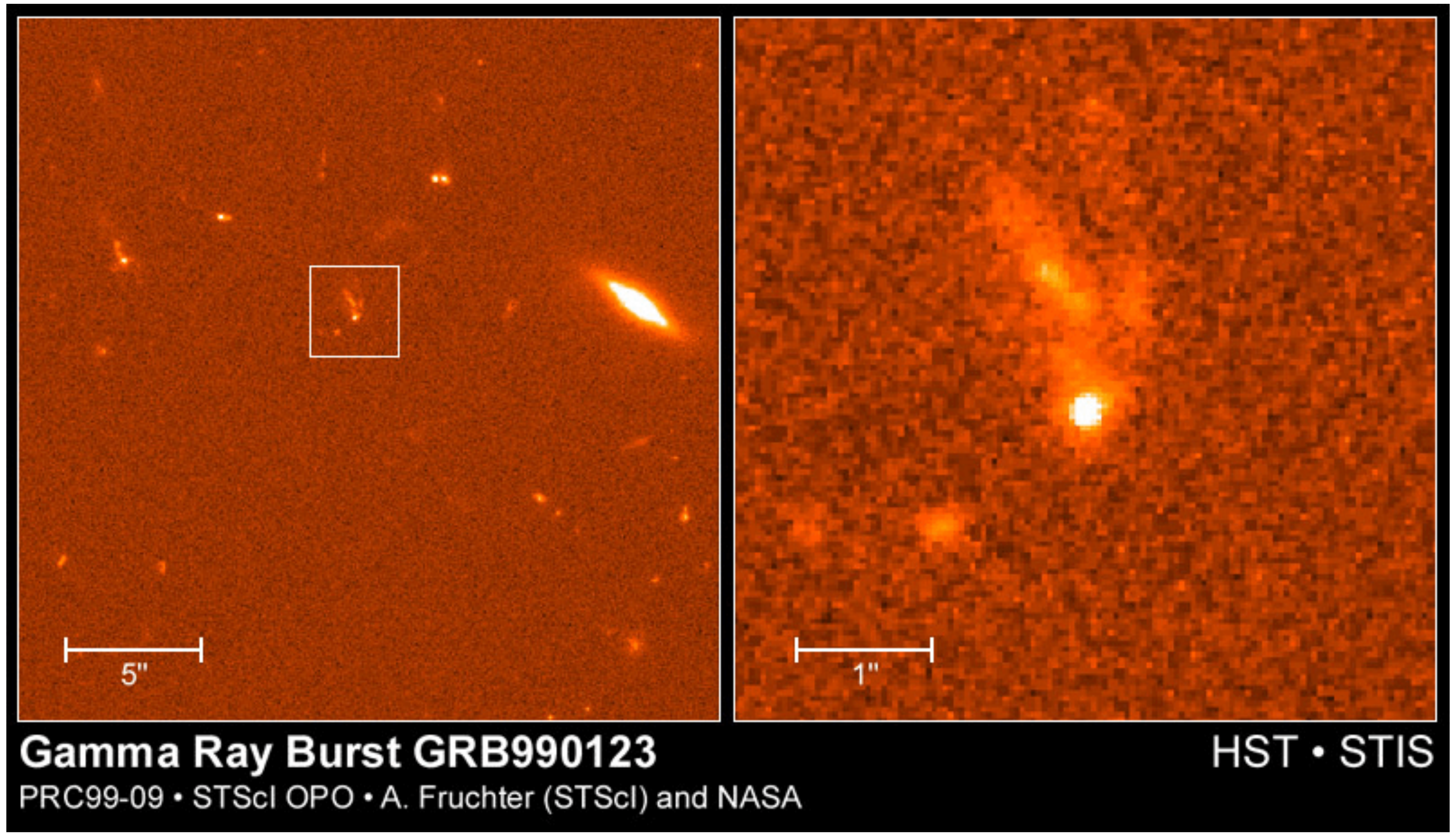


Figure 1.7: Localization of GRB 970228 observed by BeppoSAX. The left image is the X-ray emission in the γ-ray instrument error box taken $\sim$ 8 hours after trigger while the right image is taken $\sim$ 3 days after trigger. A fainting source was clearly detected at the GRB location which is the first detection of an X-ray afterglow. Through the subsequent measurement of the host galaxy redshift, this was the first conclusive evidence of the extragalactic nature of long GRBs.

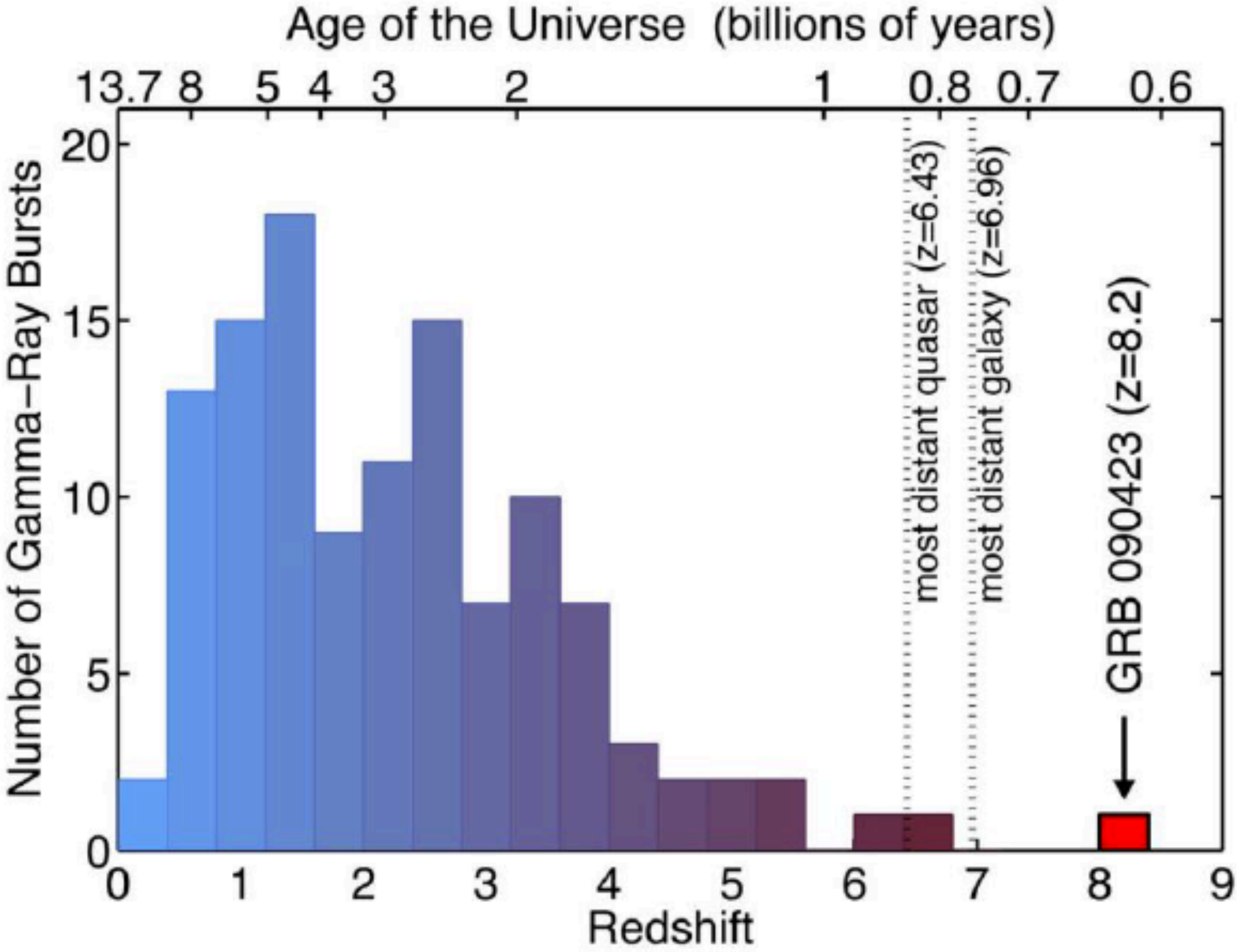
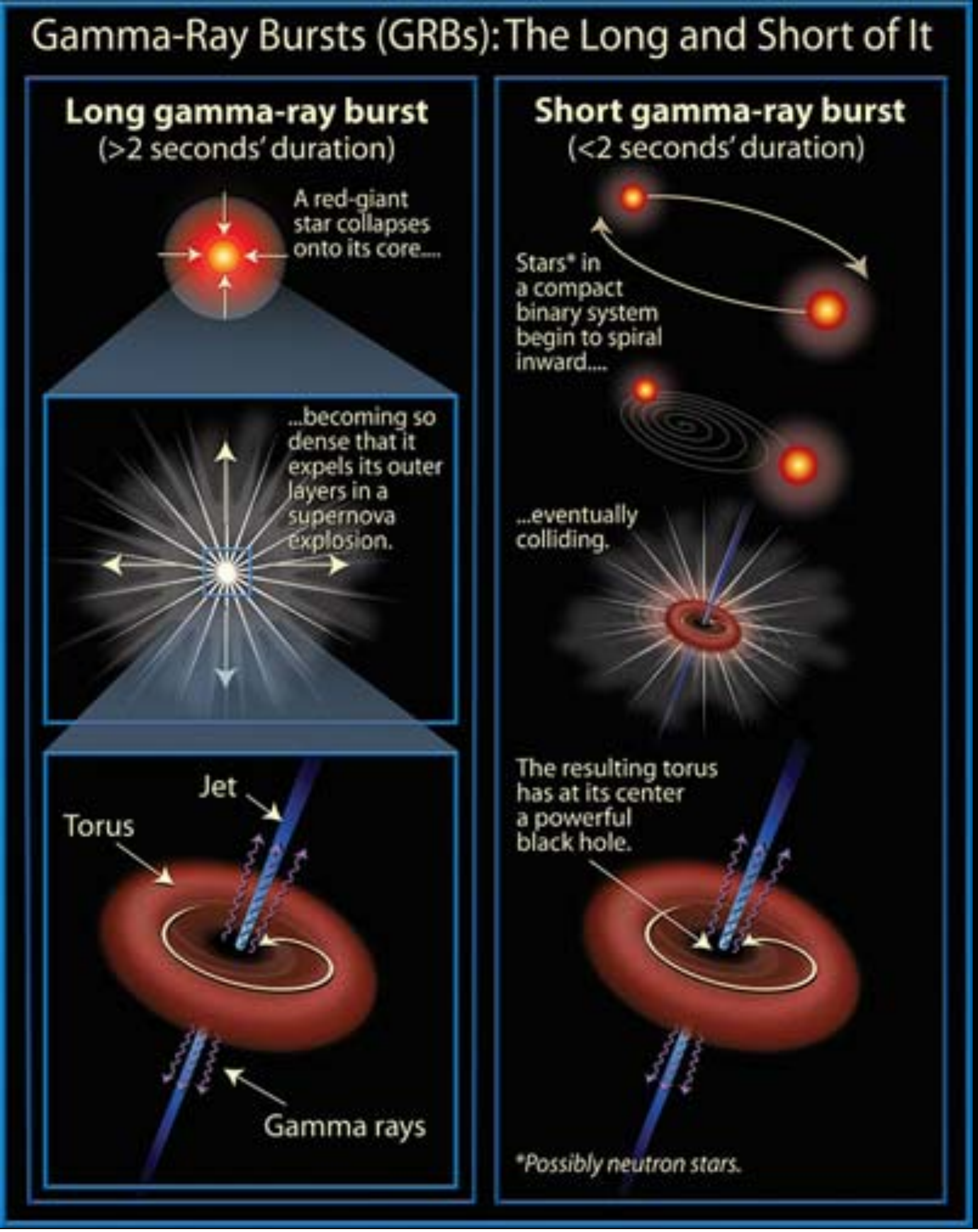
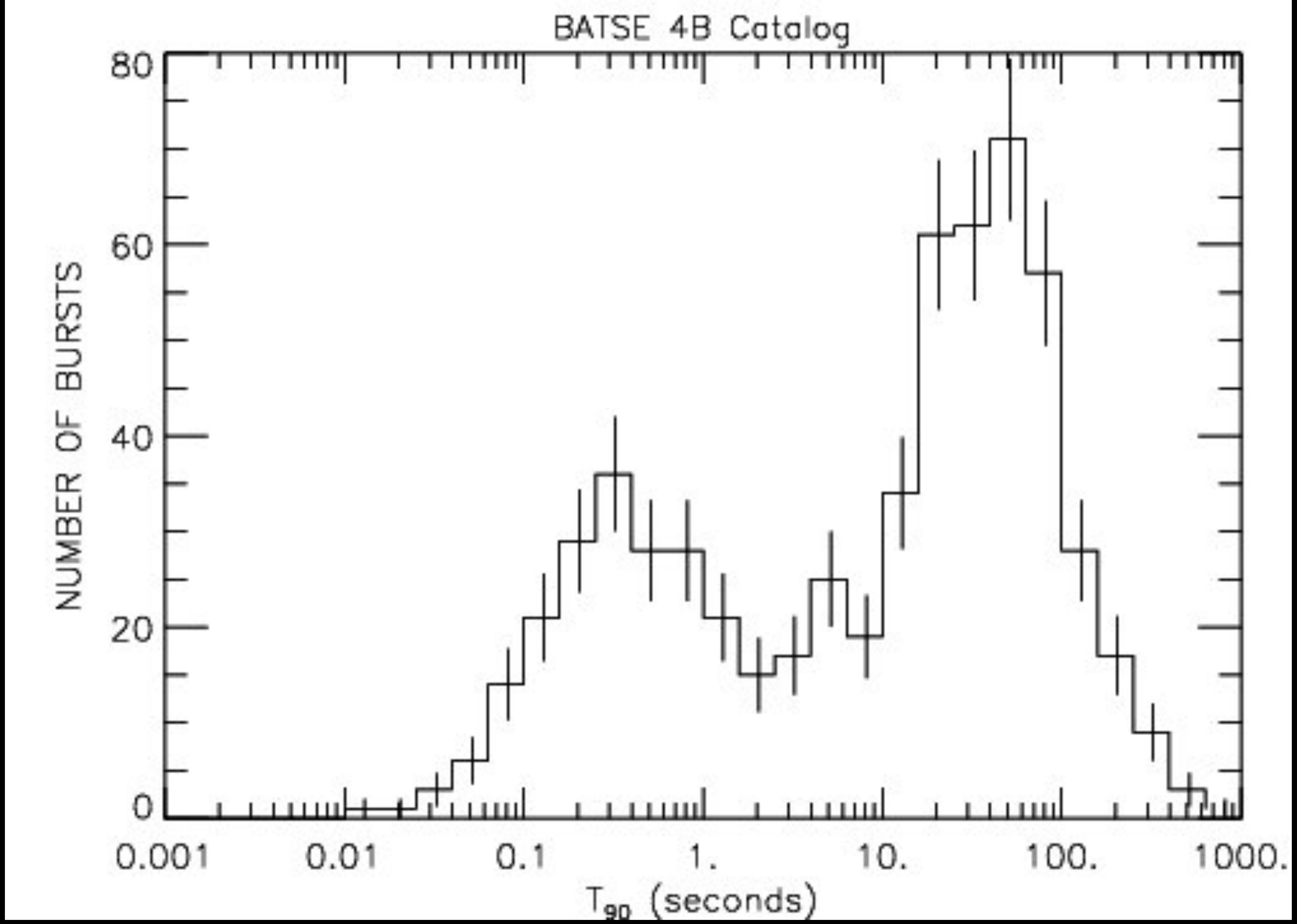
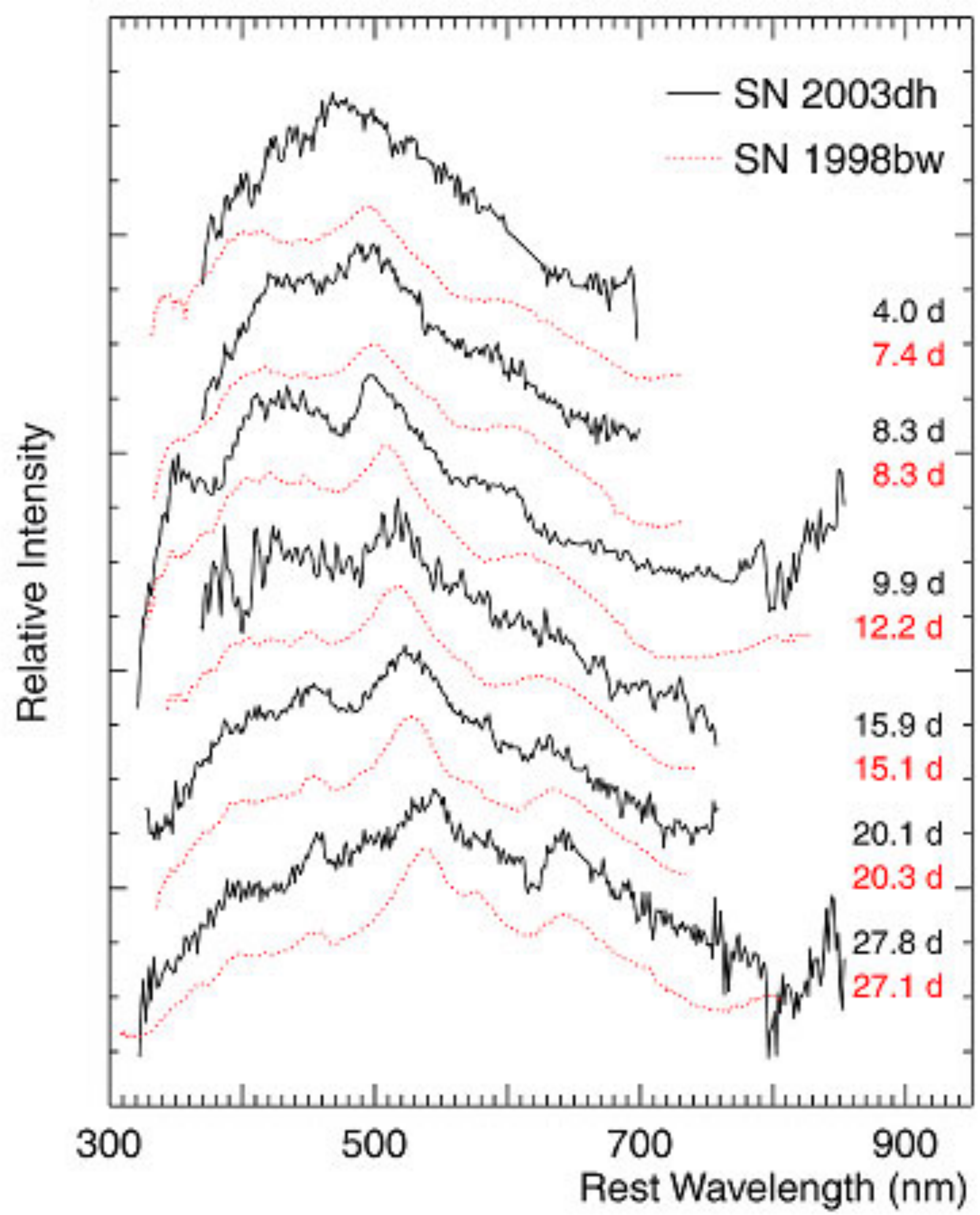


Figure 1.10: Redshif distributions of GRBs detected up to the 23^{rd} of April 2009, when the highest redshift GRBs was discovered at $z = 8.2$. Credit: Edo Berger (Harvard/CfA)


Gamma-Ray Bursts (GRBs): The Long and Short of It
Long gamma-ray burst
(>2 seconds' duration)
A red-giant star collapses onto its core....
...becoming so dense that it expels its outer layers in a supernova explosion.
Jet
Torus
Gamma rays
Short gamma-ray burst
(<2 seconds' duration)
Stars* in a compact binary system begin to spiral inward....
...eventually colliding.
The resulting torus has at its center a powerful black hole.
*Possibly neutron stars.


BATSE 4B Catalog
NUMBER OF BURSTS
0
20
40
60
80
0.001
0.01
0.1
1.
10.
100.
1000.
T90 (seconds)



Visual Spectra of Hypernova in GRB 030329
(VLT + FORS)

ESO PR Photo 17b/03 (18 June 2003)

©European Southern Observatory

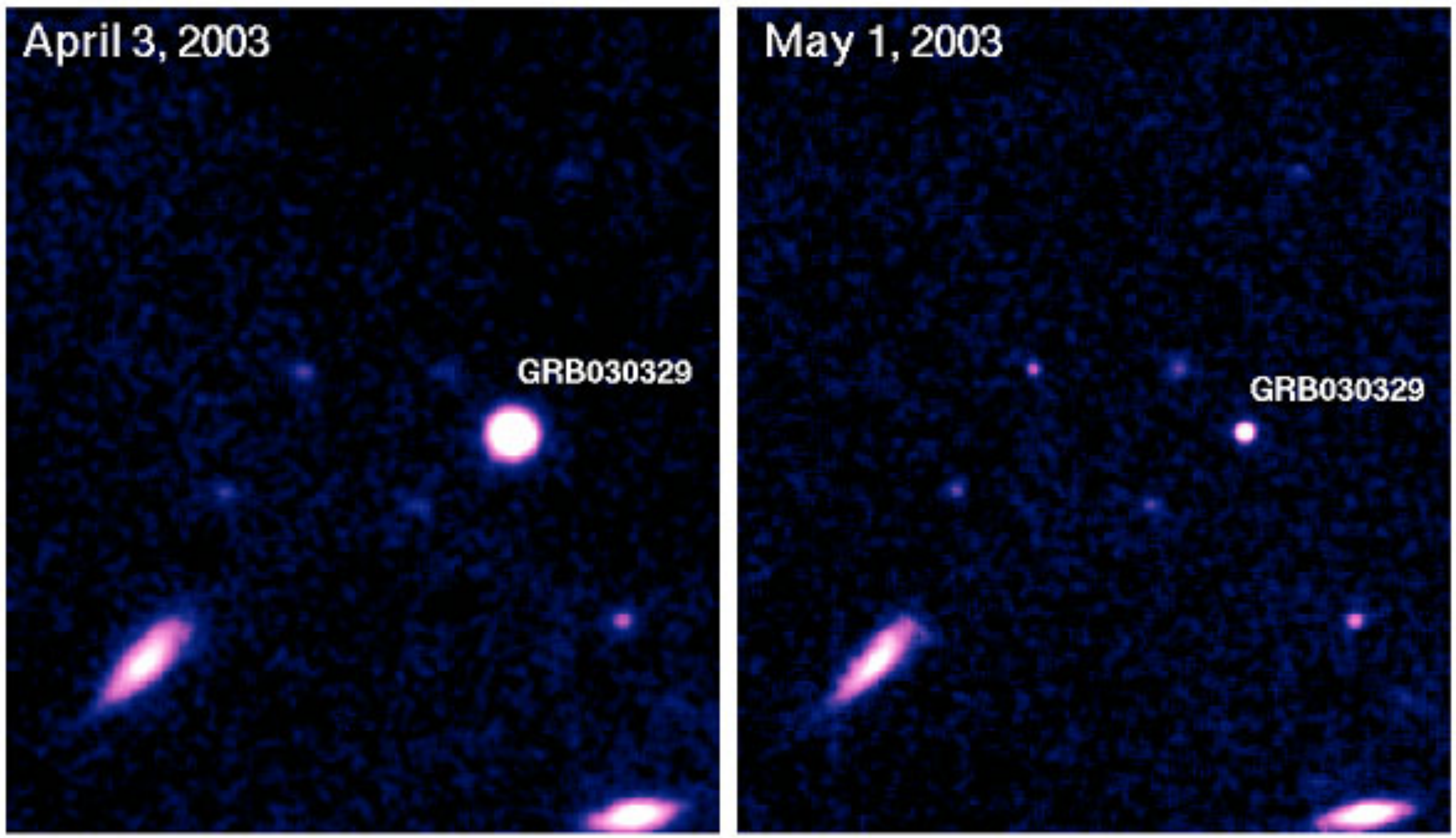
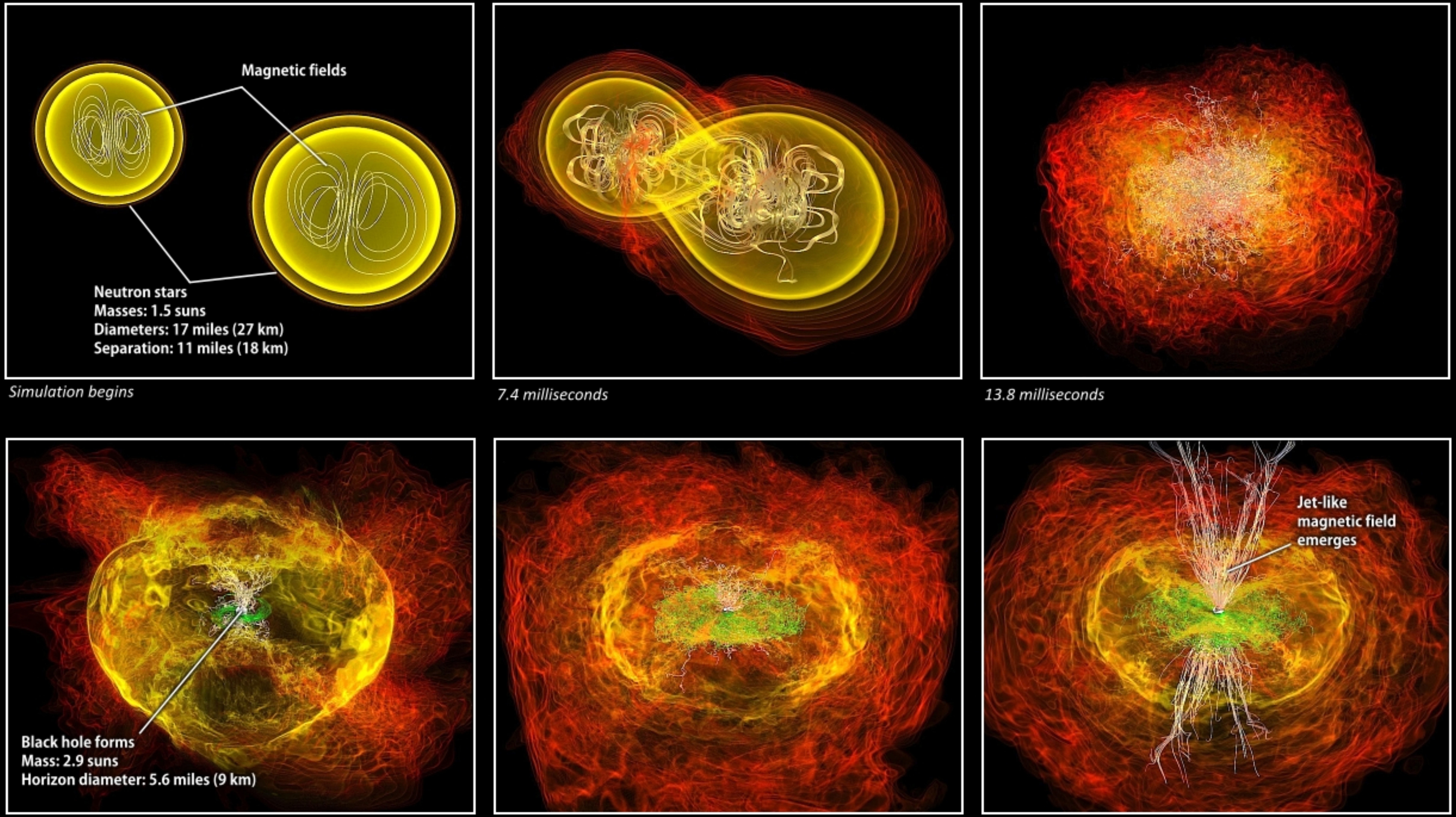


Image of Afterglow of GRB 030329
(VLT + FORS)

ESO PR Photo 17a/03 (18 June 2003)

©European Southern Observatory

Crashing neutron stars can make gamma-ray burst jets



Simulation begins

7.4 milliseconds

13.8 milliseconds

15.3 milliseconds

21.2 milliseconds

26.5 milliseconds

Credit: NASA/AEI/ZIB/M. Koppitz and L. Rezzolla

Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20