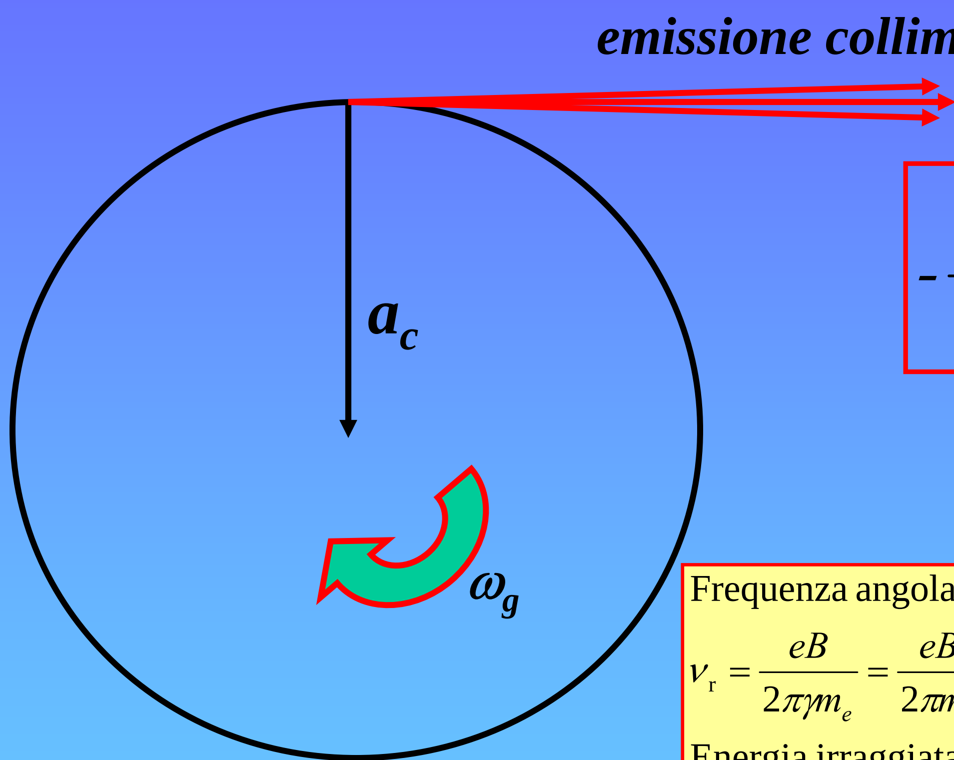
Radiazione di sincrotrone



$$\boxed{-\frac{dE}{dt}=\frac{4}{3}\sigma_T\ cU_{mag}\left(\frac{\mathrm{v}}{c}\right)^2\gamma^2}$$

Frequenza angolare:

$$\nu_{\mathrm{r}}=\frac{eB}{2\pi\gamma m_e}=\frac{eB}{2\pi m_e}\frac{1}{\gamma}=\nu_g\frac{1}{\gamma}\ ;\ \text{con}:\frac{eB}{2\pi m_e}=2.8\cdot 10^{10}=28\ GHz\quad (B=1T)$$

Energia irraggiata (non relativ.):

$$-\frac{dE}{dt}=\frac{e^2|\vec{a}|^2}{6\pi\varepsilon_0 c^3}\rightarrow_{relativ.}\frac{\gamma^4 e^2|\vec{a}|^2}{6\pi\varepsilon_0 c^3}\ \text{(nel laboratorio)}$$

Radiazione dipolare $\rightarrow \theta =$ angolo tra $\vec{a}$ e direzione di osservazione:

E $\approx \sin\theta \Rightarrow$ Potenza/unita' di angolo solido $\approx \sin^2\theta$

Radiazione polarizzata con $\vec{E}//\vec{a}$

Distribuzione spettrale della Rad. Sinc.

Massima componente di Fourier: $\nu \sim \Delta t^{-1} \sim \gamma^2 \nu_g = \gamma^3 \nu_r = \gamma^3 v/(2\pi r_g)$

Se $\beta \# 90^0 \rightarrow \nu = \gamma^2 \nu_g \sin\beta$

Per valutazioni di ordini di grandezza e' sufficiente far uso di queste relazioni per valutare le frequenze dominanti, e della →

$$-\frac{dE}{dt} = \frac{4}{3}\sigma_T \; cU_{mag}\left(\frac{v}{c}\right)^2 \gamma^2$$

per valutare l'energia irraggiata per unita' di tempo

Per calcoli piu' dettagliati e' necessario ricorrere ad una procedura di maggiore complessita', partendo dai potenziali di Lienard-Weickert

Spettro dei fotoni

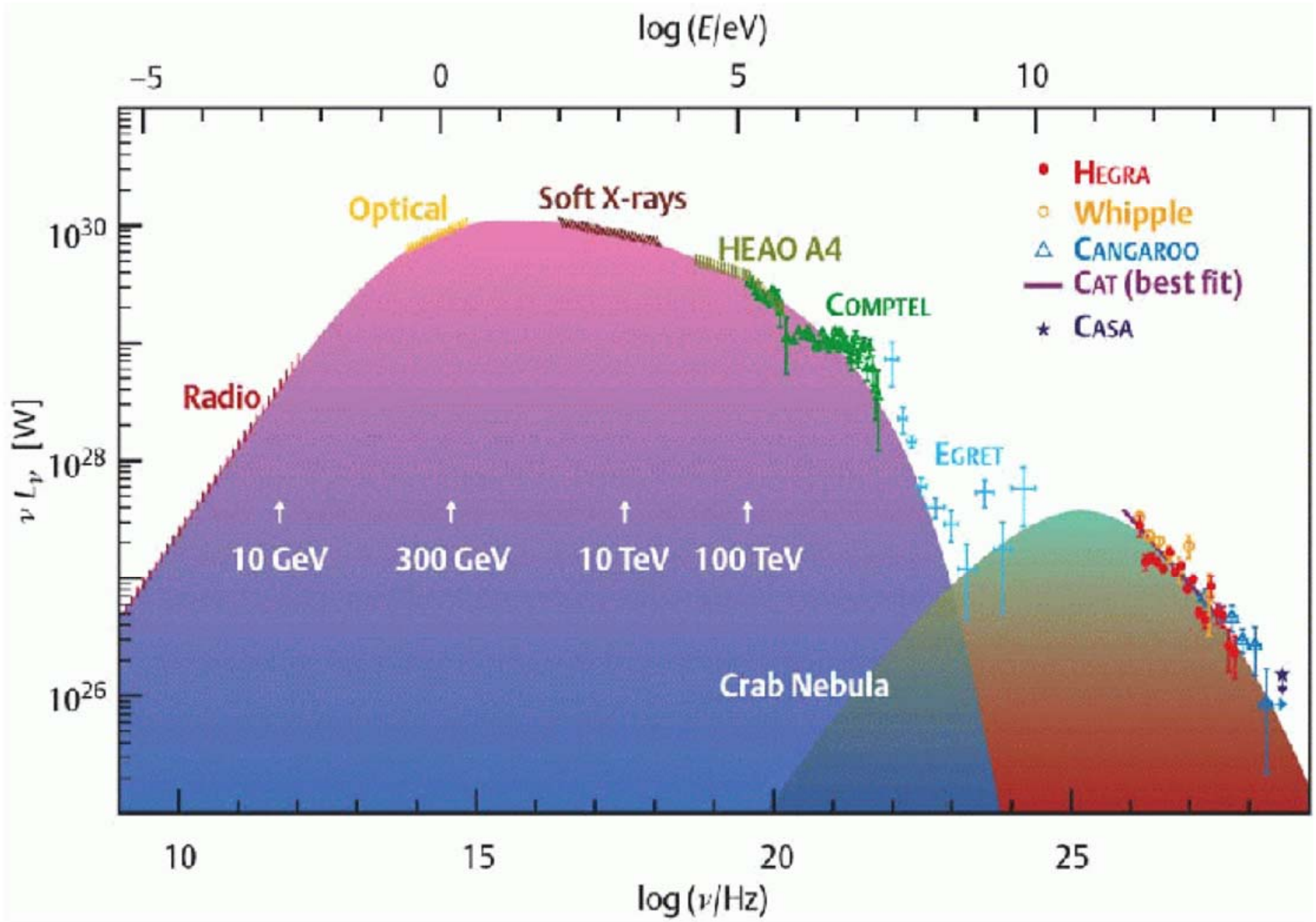


Fig. 11. Spectral energy distribution of the emission from the Crab Nebula. The electron energies producing the dominant synchrotron peak at lower energies are indicated by the arrows. The CGRO γ-telescopes COMPTEL and EGRET determine the synchrotron fall-off and the transition to the Inverse Compton peak expected at some tens of GeV, and indicated by the Cherenkov telescope measurements. (Adapted from Aharonian and Atoyan (1998); Courtesy "Sterne und Weltraum".)

Radiazione di sincrotrone

Espessioni numeriche utili[1]

Perdita d'energia:

$$-\left(\frac{\mathrm{dE}}{\mathrm{dt}}\right)=2\sigma_T c U_{mag}\gamma^2\left(\frac{\mathrm{v}}{c}\right)^2\sin^2\beta \quad\Rightarrow\quad 1.587\times10^{-14}B^2\gamma^2\left(\frac{\mathrm{v}}{c}\right)^2\sin^2\beta \quad [W] \quad (con\ B\ in\ T)$$

Mediata su β:

$$-\left(\frac{\mathrm{dE}}{\mathrm{dt}}\right)=1.058\times10^{-14}B^2\gamma^2\left(\frac{\mathrm{v}}{c}\right)^2 \quad [W] \quad (con\ B\ in\ T)$$

In GeV/s, con v = c:

$$-\left(\frac{\mathrm{dE}}{\mathrm{dt}}\right)=3.79\times10^{-6}\left(\frac{B}{Gauss}\right)^2\left(\frac{\mathrm{E}}{GeV}\right)^2 \quad [Gev/s] \quad (con\ B\ in\ T)$$

Spettro d'emissione di un singolo elettrone:

$$J(\nu)=\frac{\sqrt{3}e^3 B\sin\beta}{4\pi\varepsilon_0 c m_e}F\left(\frac{\nu}{\nu_c}\right) \quad\Rightarrow\quad 2.344\times10^{-25}B\sin\beta\ F\left(\frac{\nu}{\nu_c}\right) \quad \left[W/Hz\right]$$

$$\nu_c=\frac{3}{2}\gamma^2\frac{eB}{2\pi m_e} \quad\Rightarrow\quad 4.199\times10^{10}\gamma^2 B \quad [Hz]$$

In GeV: $\nu_c=1.61\times10^{13}\left(\frac{E}{GeV}\right)^2\left(\frac{B}{Gauss}\right) \quad [Hz]$

Lo spettro in numero di fotoni ha un picco a $0.29\,\nu_c$.

Per $\mathrm{E}=10$ GeV e $\mathrm{B}=1\mu\mathrm{G}\Rightarrow\nu_c=1.61\,GHz \quad [\lambda=0.186\,m]$

Per $\mathrm{E}=10^5$ GeV e $\mathrm{B}=1\mu\mathrm{G}\Rightarrow\nu_c=1.61\times10^{17}\ Hz \quad [\lambda=1.86\,nm]$;

Per $\mathrm{E}=10^5$ GeV e $\mathrm{B}=1\mathrm{T}\Rightarrow\nu_c=1.61\times10^{27}\ Hz \quad [\lambda=2.07\times10^{-19}\,m]$

Radiazione di sincrotrone
Espessioni numeriche utili[2]

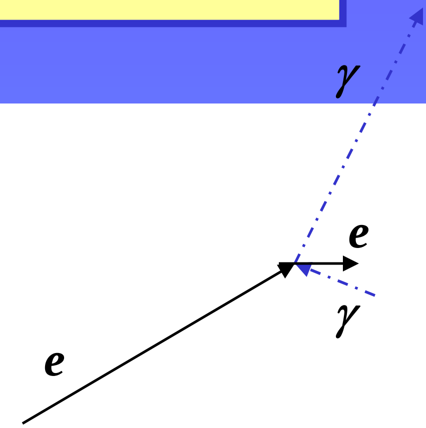
Spettro di radiazione da elettroni con distribuzione di potenza di esponente - p :

$$J(\nu) = \frac{\sqrt{3}e^3 Bk}{4\pi\varepsilon_0 c m_e}\left(\frac{3eB}{2\pi\nu m_e^3 c^4}\right)^{\left(\frac{p-1}{2}\right)} a(p); \quad \text{con :}$$

$$a(p) = \frac{\sqrt{\pi}}{2}\frac{\Gamma\left(\frac{p}{4}+\frac{19}{12}\right)\Gamma\left(\frac{p}{4}-\frac{1}{12}\right)\Gamma\left(\frac{p}{4}+\frac{5}{4}\right)}{(p+1)\Gamma\left(\frac{p}{4}+\frac{7}{4}\right)}$$

$$\text{In unita' SI} \Rightarrow J(\nu) = 2.344\times10^{-25} a(p) B^{(p+1)/2} k\left(\frac{1.253\times10^{37}}{\nu}\right)^{\left(\frac{p-1}{2}\right)} \quad \left[Wm^{-3}Hz^{-1}\right]$$

Scattering Compton inverso (IC)



Scattering di un elettrone di alta energia con fotoni ambiente di energia $\varepsilon = h\nu_0$.

N = numero di fotoni per unita' di volume $\Rightarrow$ densita' di energia dei fotoni : $\mathrm{U_{rad}} = \mathrm{Nh}\nu_0$

Energia massima che un fotone puo' acquistare in una collisione con un elettrone

di alta energia (collisione frontale) $\Rightarrow (h\nu)_{\max} = h\nu_0\gamma^2\left(1+\frac{\mathrm{v}}{c}\right)^2 \approx 4\gamma^2 h\nu_0$

(v e γ sono relativi all'elettrone)

Perdita d'energia dell'elettrone : $\frac{dE}{dt} = \frac{4}{3}\sigma_T c U_{rad}\left(\frac{\mathrm{v}^2}{c^2}\right)\gamma^2 \quad \Rightarrow_{\mathrm{v}\to c} \quad \frac{4}{3}\sigma_T c U_{rad}\gamma^2$

Spettro della radiazione diffusa : $I(\nu)d\nu = \frac{3\sigma_T c}{16\gamma^2}\frac{N(\nu_0)}{\nu_0{}^2}\nu\left[2\nu\ln\left(\frac{\nu}{4\gamma^2\nu_0}\right)+\nu+4\gamma^2\nu_0-\frac{\nu^2}{2\gamma^2\nu_0}\right]d\nu$

$N(\nu_0) =$ *densita' numerica di fotoni*

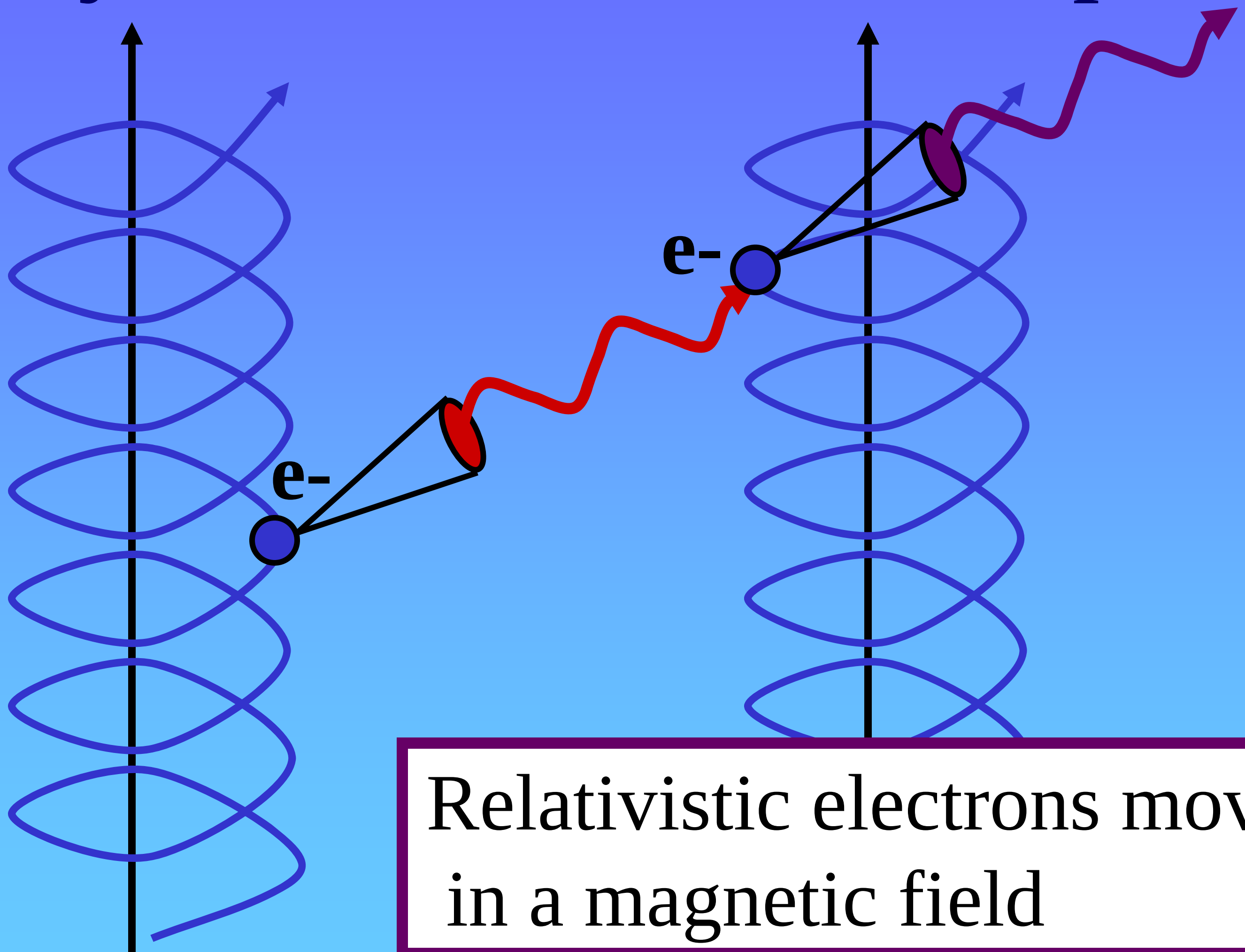
Energia media dei fotoni diffusi : $\frac{4}{3}\gamma^2 h\nu_0$

Frequenze tipiche dei fotoni prodotti (per $\gamma = 10^3 - 10^4$) :

Per scattering sui fotoni della radiazione di fondo ($\nu_0 \cong 10^{11}\ Hz$) $\Rightarrow \nu = 10^6 \times 10^{11}\ Hz = 10^{17}\ Hz \quad (0.4\ KeV = raggi\ X)$

Per scattering sui fotoni ottici ($\nu_0 \cong 10^{15}\ Hz$) $\Rightarrow \nu = 10^6 \times 10^{15}\ Hz = 10^{21}\ Hz \quad (4\ MeV = raggi\ \ \gamma)$

Synchrotron Self-Absorption



Relativistic electrons moving in a magnetic field

Perdite d'energia per IC e Sync. Rad.

$$\text{Inoltre}: \left(\frac{\mathrm{dE}}{\mathrm{dt}}\right)_{IC} \Big/ \left(\frac{\mathrm{dE}}{\mathrm{dt}}\right)_{Rad.\,Sinc.} = \frac{U_{rad}}{U_{mag}}$$

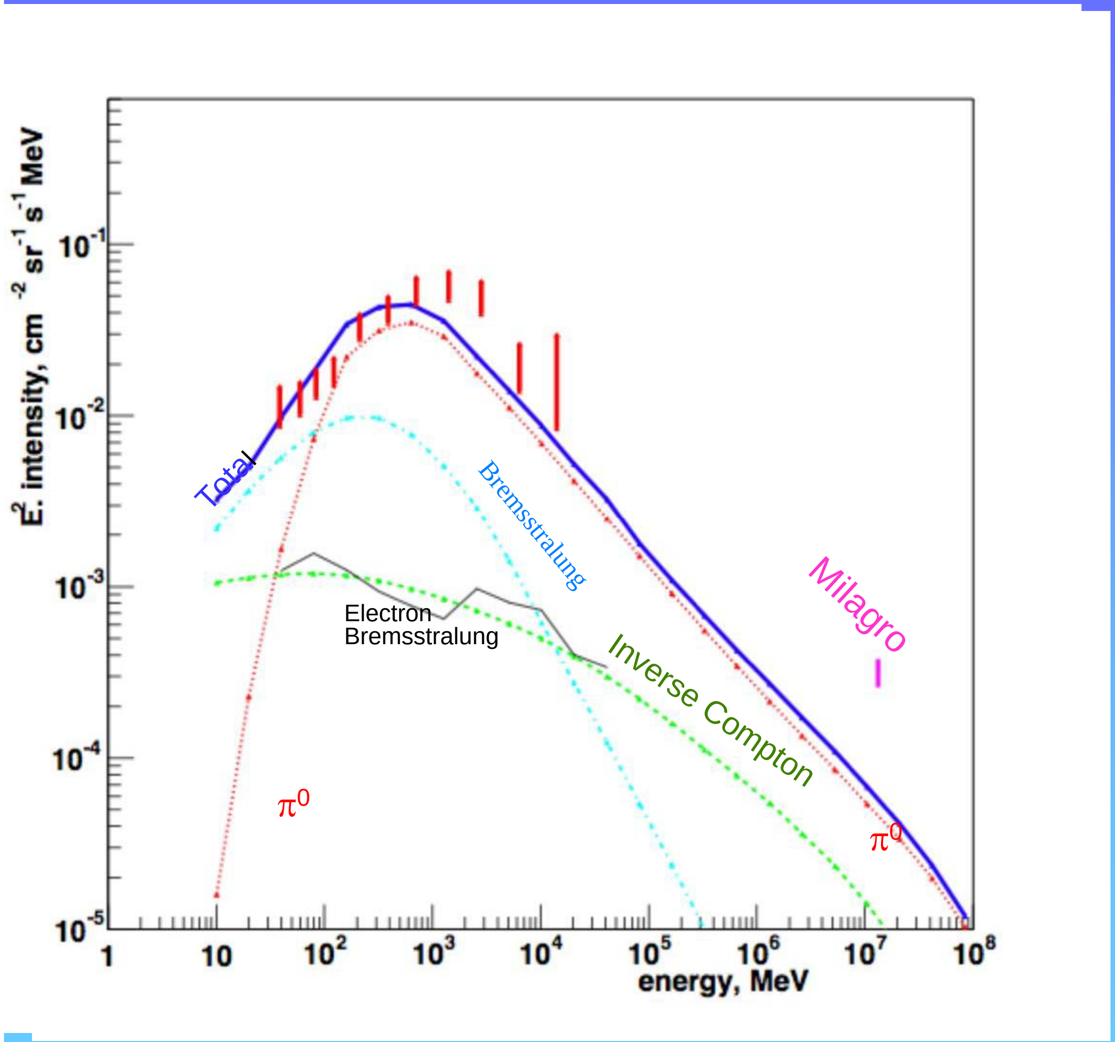
$$\text{Valori tipici}: \ \mathrm{B} = 3\times 10^{-10}\ T; \quad U_{rad} = 6\times 10^{5} \quad eV\,m^{-3} \Rightarrow U_{rad}/U_{mag} = 3$$

Massimo tempo di "vita" di un elettrone di alta energia nell'Universo:

$$\tau = \frac{\mathrm{E}}{(\mathrm{dE}/\mathrm{dt})_{IC}} = \frac{\mathrm{E}}{\frac{4}{3}\sigma_T c U_{rad}\gamma^2} = \frac{\mathrm{E}}{\frac{4}{3}\sigma_T c U_{CBR}\gamma^2} = \frac{2.3\times 10^{12}}{\gamma} \quad [anni]$$

Per $U_{CBR} = 2.62\times 10^{5} \quad eV\ m^{-3}$. Per un elettrone di 100 GeV $\Rightarrow \tau \le 10^{7}\ anni$

Diffuse Emission from Cygnus Region



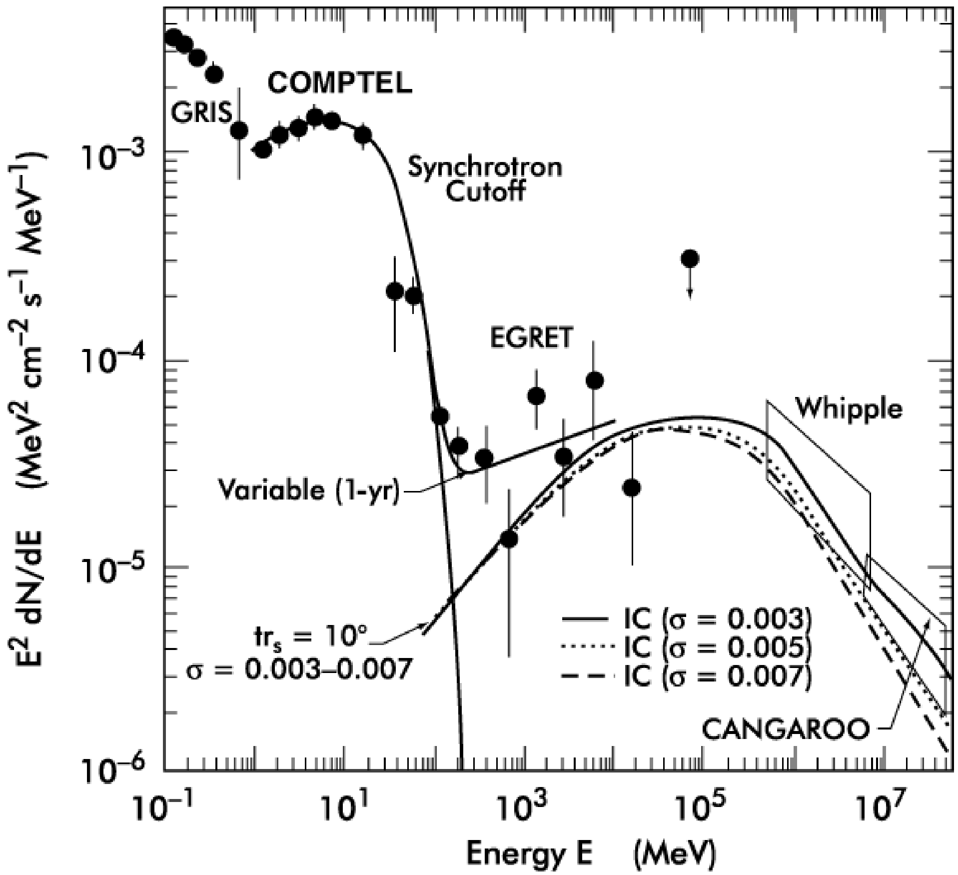
Hadronic contribution →
$\pi^0 \rightarrow \gamma\ \gamma$

- Strong & Moskalenko standard model
  - Fit to EGRET < 1 GeV
  - Increase π^0 and IC component throughout Galaxy
  - Milagro ~5x above prediction
  - Unresolved sources?
  - Proton accelerators?

Sorgenti di fotoni di alta energia

Supernovae
Pulsars
Gamma-ray-bursts

Energy Spectrum (CRAB)



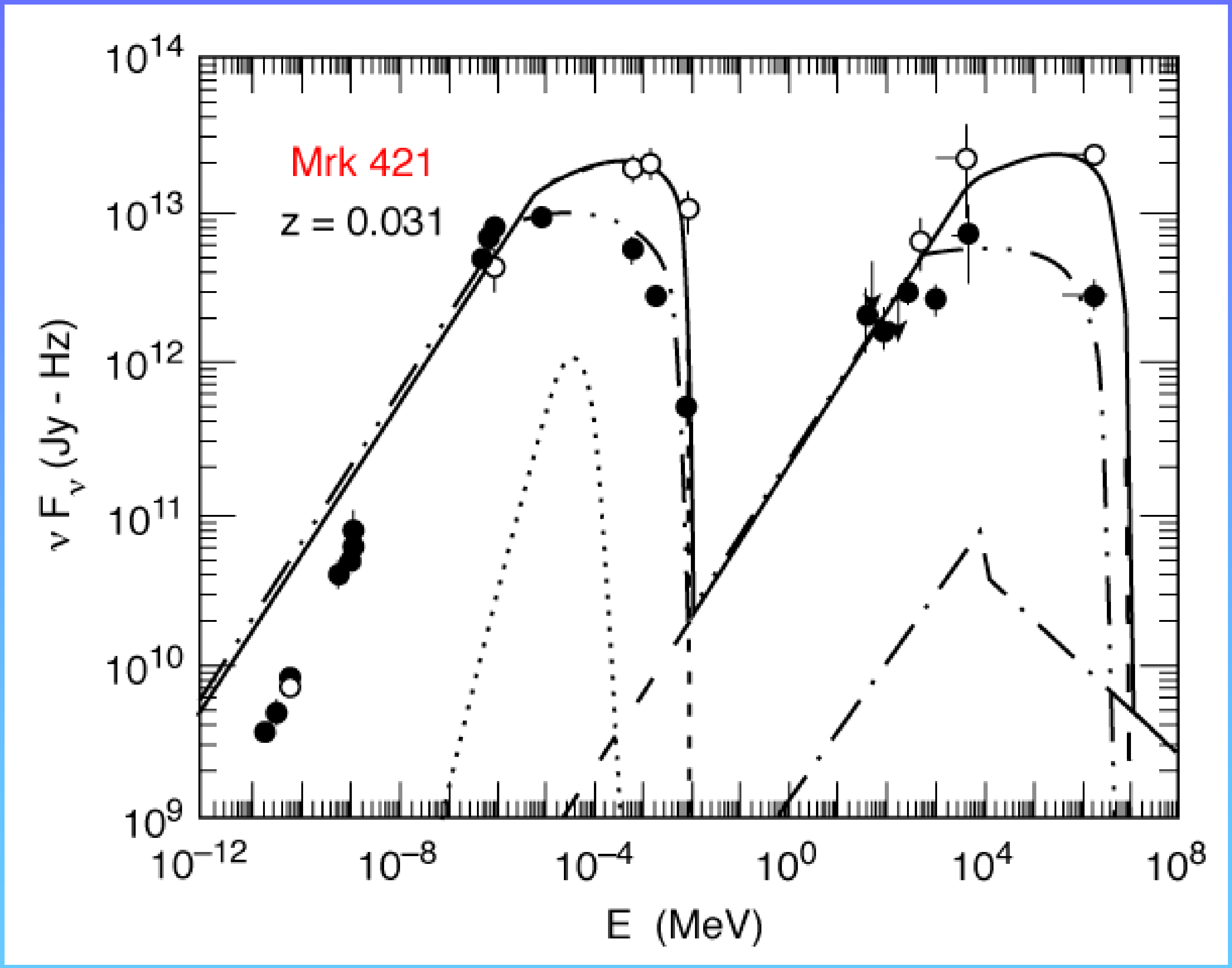
Parametrizzazione adoperata per descrivere la forma dello spettro ad alte energie:

$$\frac{dN}{dE} = KE^{-\Gamma} \times e^{-\frac{E}{E_0}}$$

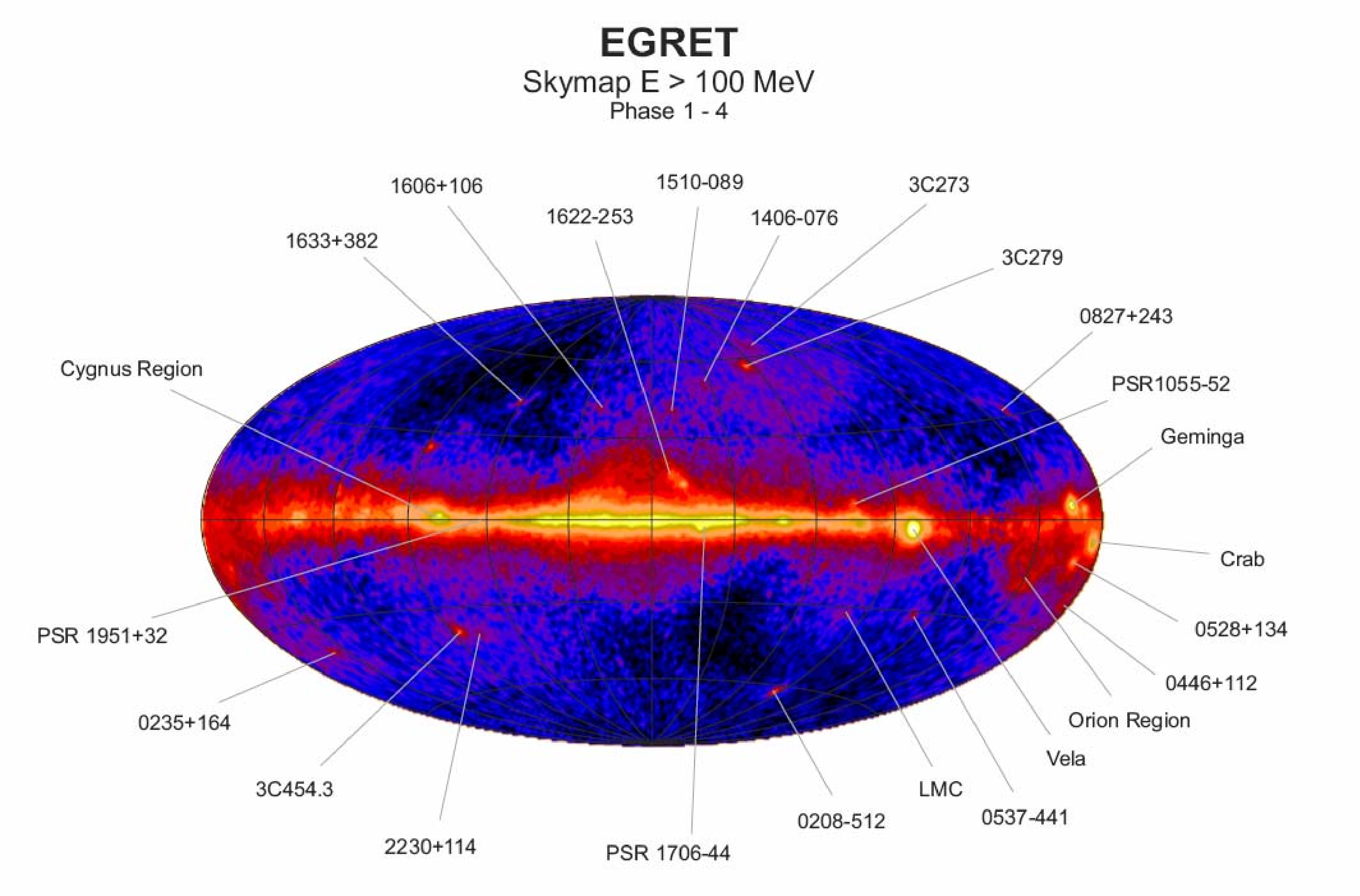
Legge di potenza con taglio esponenziale

e.g.: Mkn 501: $\Gamma = 1.92$ e $E_0 = 6.2$ TeV
Mkn 521: $\Gamma = 2.19$ e $E_0 = 3.6$ TeV

Energy Spectrum (MRK 421)



Il cielo nei γ (Egret)



Galactic Center (Egret)

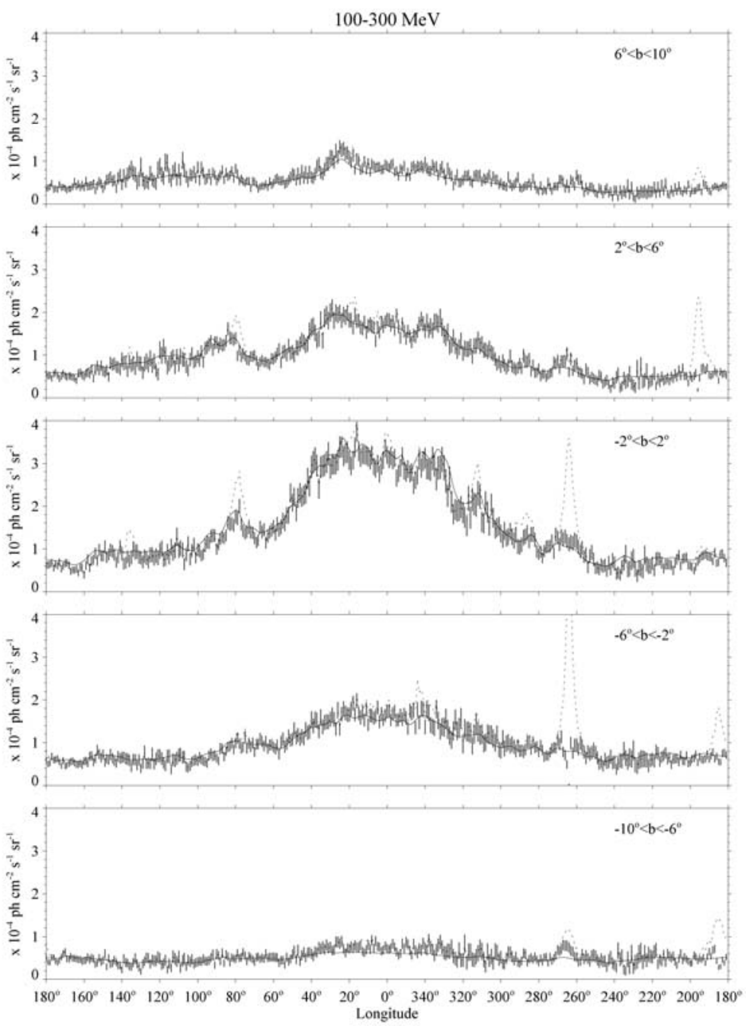


FIG. 2b

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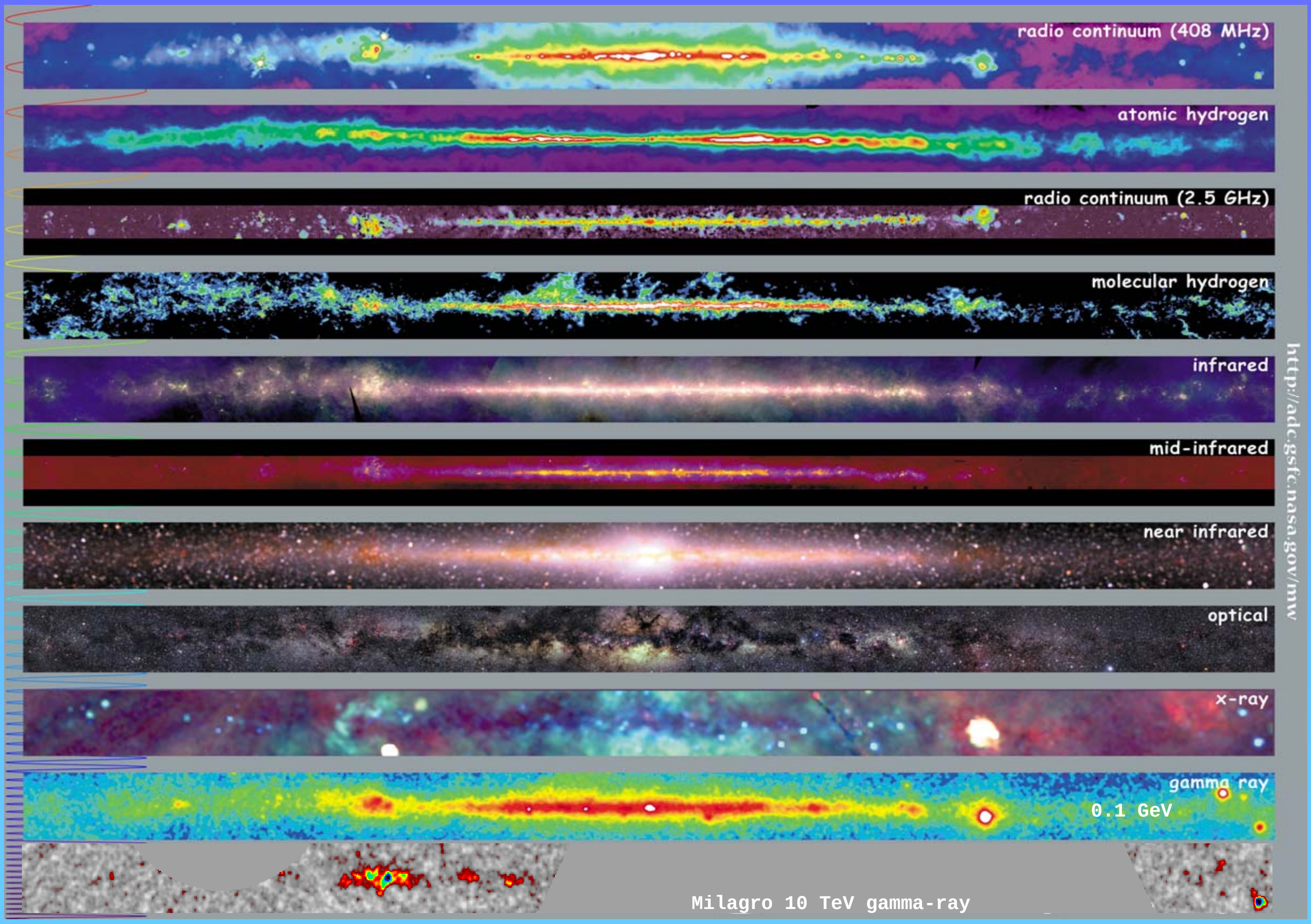
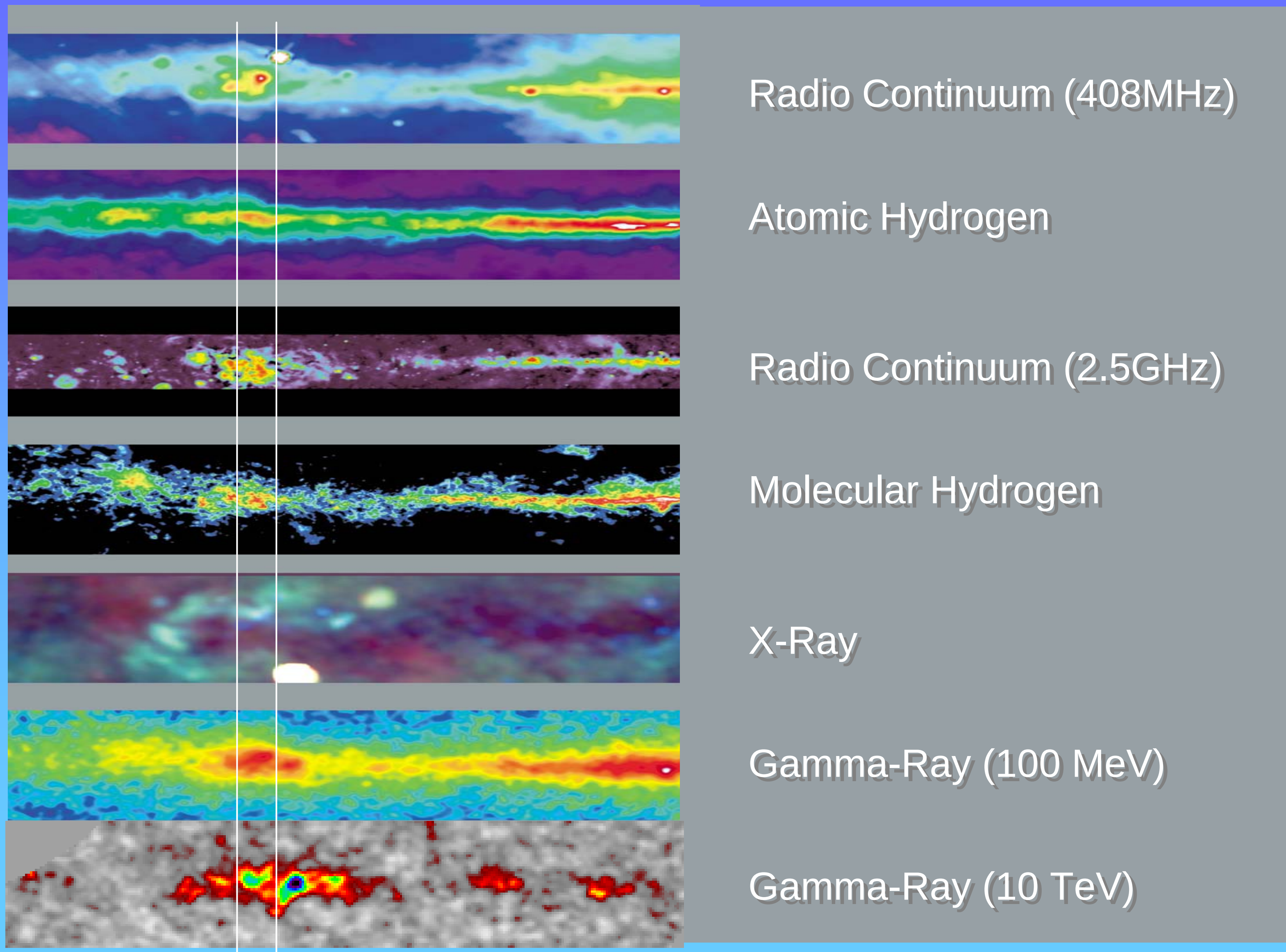
Misure dei γ visti da EGRET nel piano galattico →
Flusso in funzione della longitudine galattica per diversi valori di latitudine

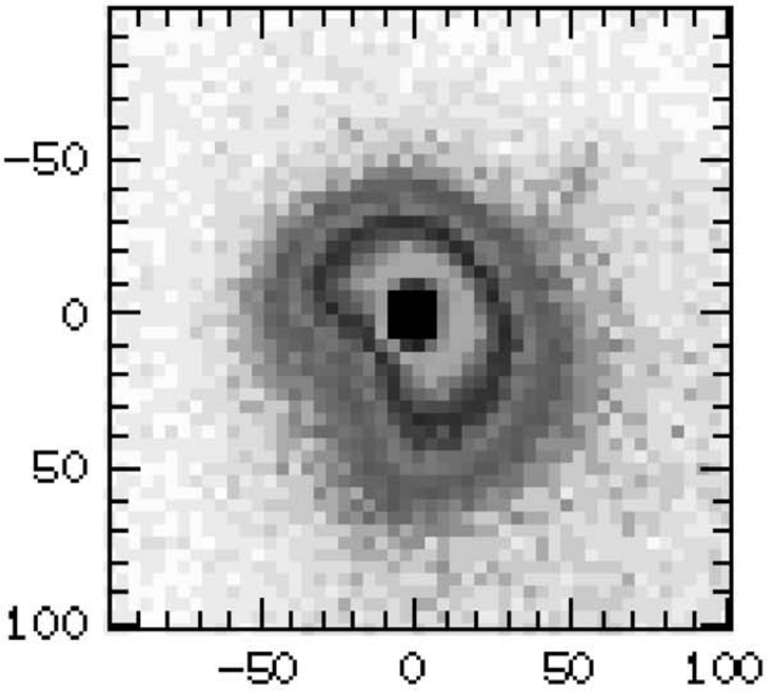
TeV: Una nuova finestra sul cielo



Cygnus Region Multi-Wavelength



Vela X nebula [1]



La Vela negli X (ROSAT)

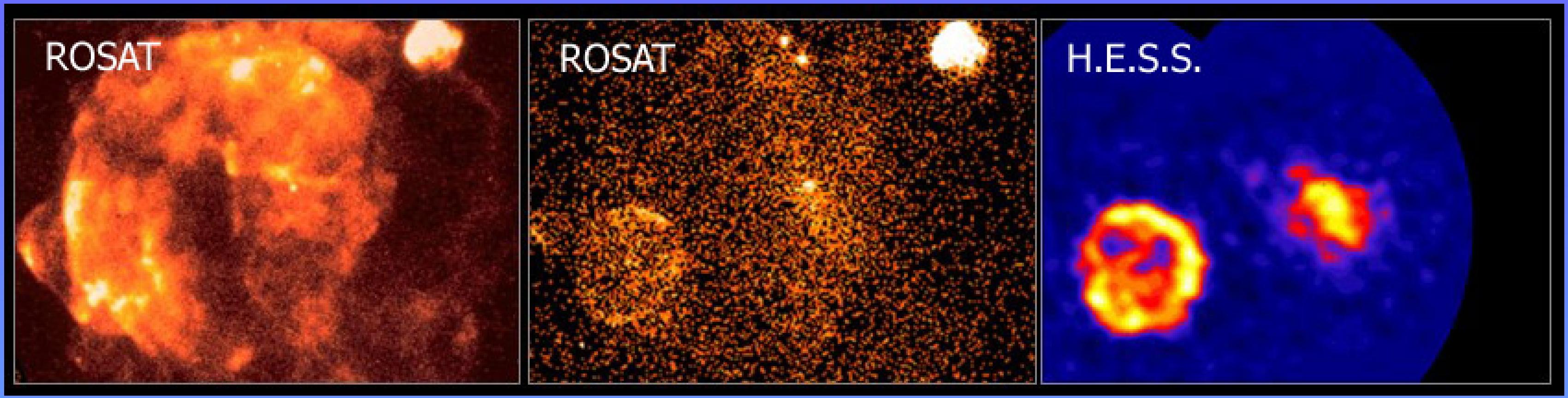
Pulsar e Supernova Remnant

Regione complessa, comprendente diverse sorgenti

Distanza ~ 290 pc

Figure 2: False greyscale *ROSAT* HRI image of the Vela pulsar and X-ray compact nebula. The nebula has the shape of a bow shock, and is consistent with the independently determined proper motion of 100 km s^{-1} to the northwest (upper right). The pulsar is at coordinate (0,0), measured in arcseconds. The false greyscale is use to increase contrast; in reality the intensity decreases monotonically from the pulsar.

Vela X nebula [1]



Tre viste della regione della Vela: a sinistra i dati di ROSAT (0.1-2.4 KeV) mostrano l'enorme supernova remnant, con la piccola supernova remnant Puppis nell'angolo in alto a destra.
Una veduta ad energie piu' alte >1.3 keV (al centro) mostra un'ulteriore supernova remnant, Vela Junior o RX J0852.0-4622, oltre alla Vela pulsar al centro dell'immagine. L'intensa emissione negli X a sud della pulsar e' nota come Vela X-nebula. L'immagine a destra e' stata presa ad energie del TeV (H.E.S.S.); La vecchia Vela supernova remnant non si vede a queste energie, ma la giovane Vela Junior remnant e' chiaramente visibile, insieme ad un'emissione estesa a sud della pulsar, coincidente con la Vela X.

La Vela Pulsar

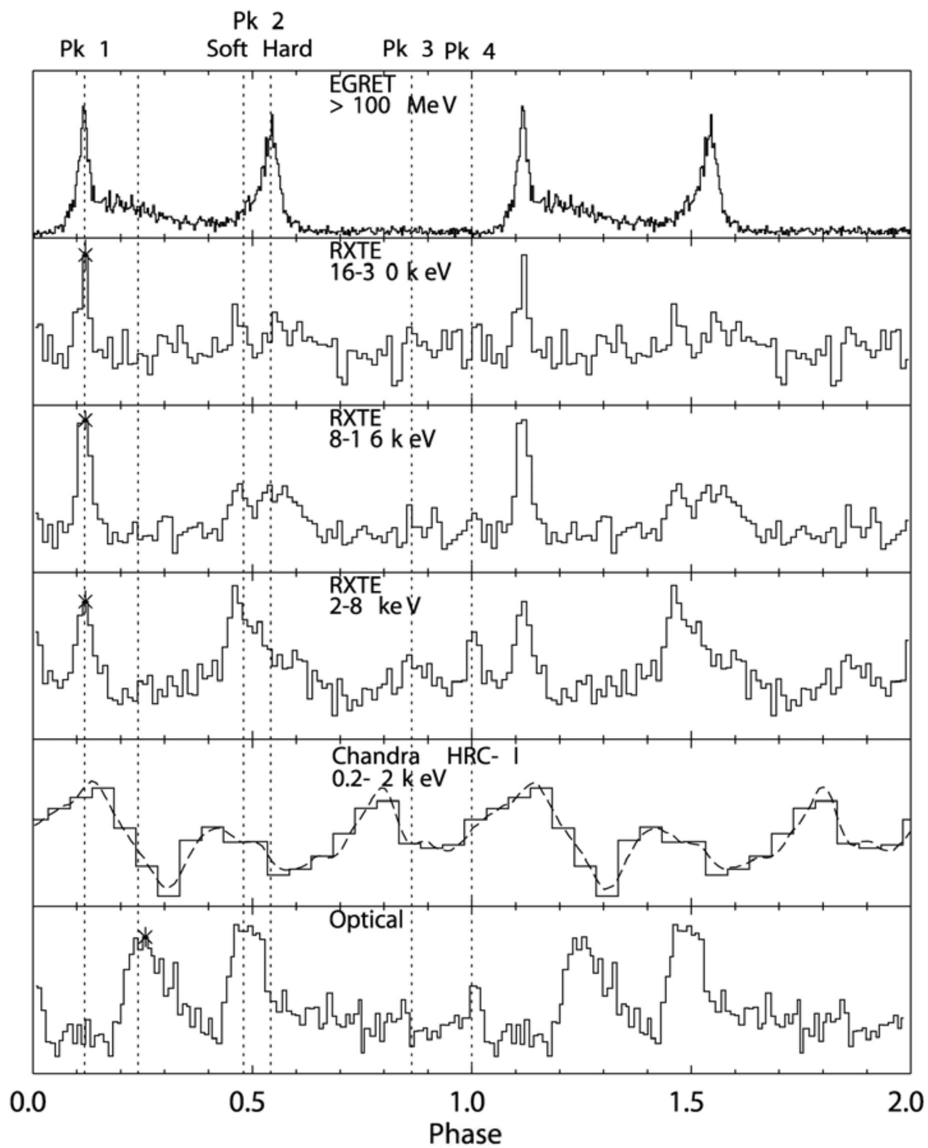
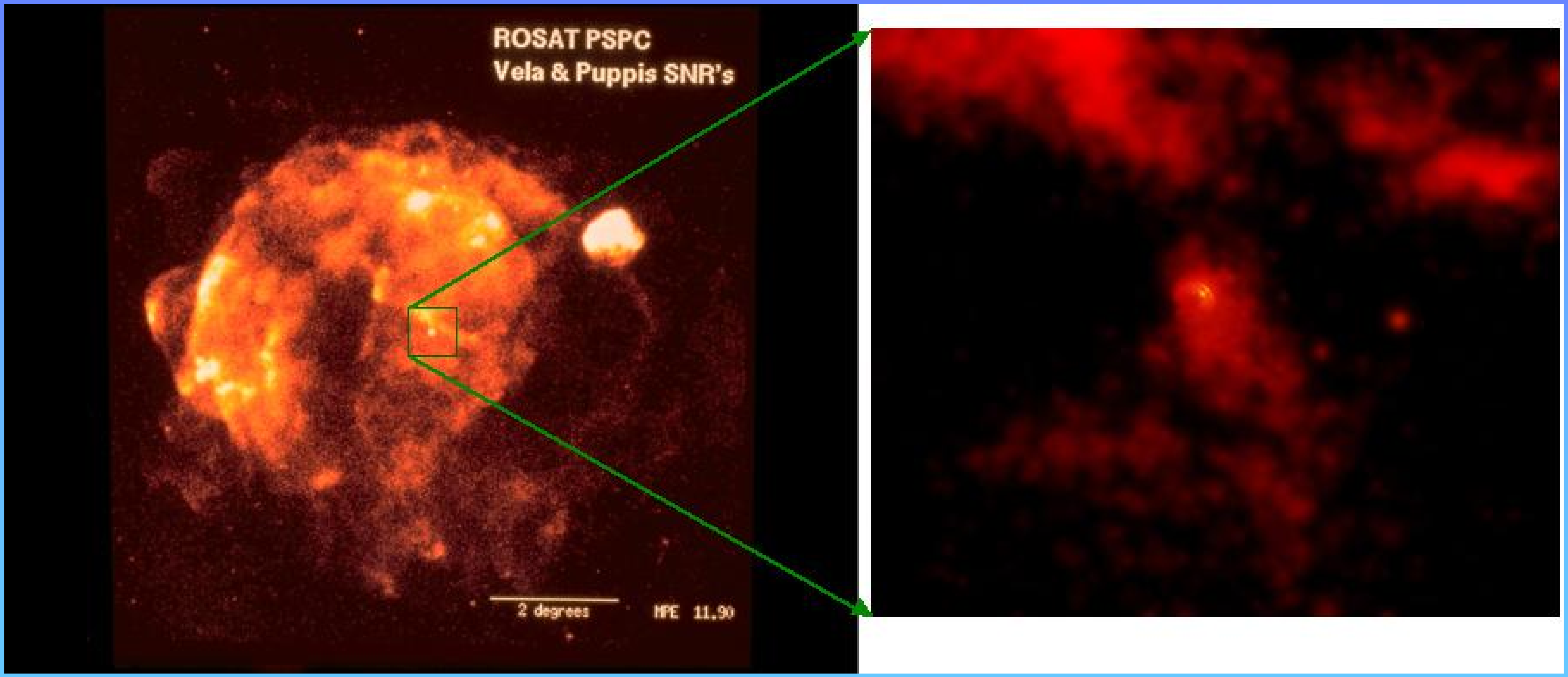


FIG. 1.—Vela Cycle 3 *RXTE* pulsed emission-phase histograms in three broad energy bands, averaged over the entire observation. Also shown are pulse profiles in EGRET (Kanbach et al. 1994), *Chandra* (Sanwal et al. 2002), and optical (Gouiffes 1998) bands.

La Vela e Puppis (negli X)



La Vela nei γ

F. Aharonian:
arXiv:astro-ph/0601575 v1 25 Jan 2006

Pulsar

Misure di Hess

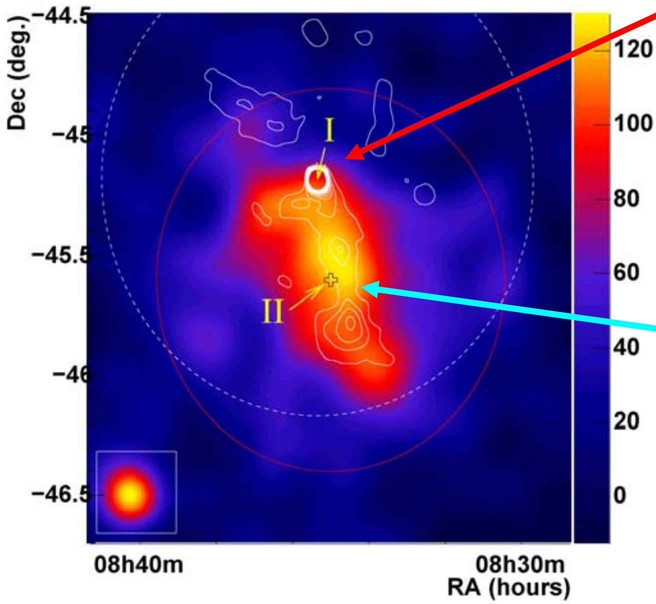


Fig. 1. Gaussian smoothed sky map of region surrounding Vela pulsar, showing significant emission to the south of the pulsar position, coincident with an X-ray feature seen by ROSAT (white contours). The smoothing width used is 0.09°. The contours corresponding to the strong emission close to the pulsar (Position I) are truncated. The image inset in the bottom left corner indicates the size of a point source as seen by H.E.S.S., for an equivalent analysis. The solid circle represents the H.E.S.S. integration region for the spectral measurement, while the dashed circle represents the field of view for the ROSAT observations. Position II is marked by a black cross.

ia-ray spectral maximum from a Cosmic source 3

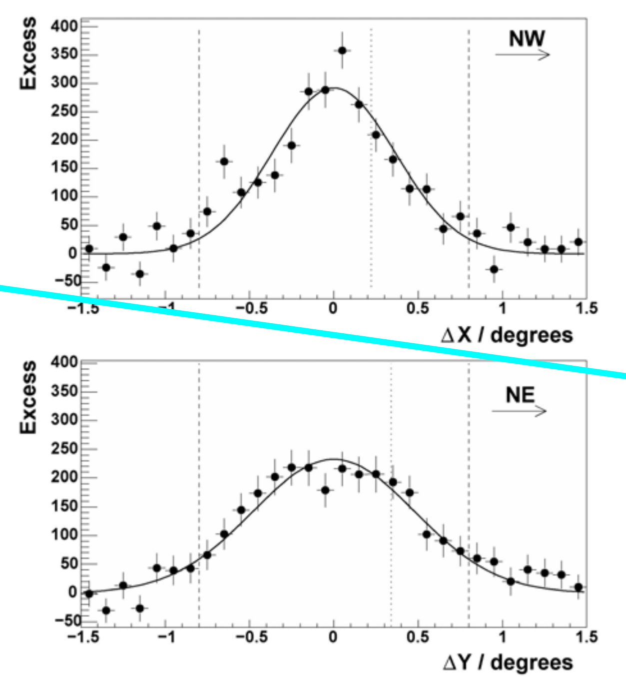


Fig. 2. Profile of the excess from the extended feature coincident with Vela X along minor axis (top) and along major axis (bottom); events within 0.8° of the axis are integrated into the profile in each case. The two dimensional fit of an elongated Gaussian convolved with the H.E.S.S. PSF is also shown as a profile for comparison. The position of the Vela pulsar is marked by a vertical dotted line in each plot for reference, while the integration region in each case for the spectral measurement is marked by dashed lines (within 0.8° of position II).

Distanza dalla pulsar ben nota (~290 pc) → possibile stimare la dimensione della Nuova sorgente: 5.1x3.8 pc

Hess J0835-455

Spazialmente coincidente con l'osservazione negli X di ROSAT (0.4-2.4 KeV)

Spettro energetico di *Hess J0835-455*

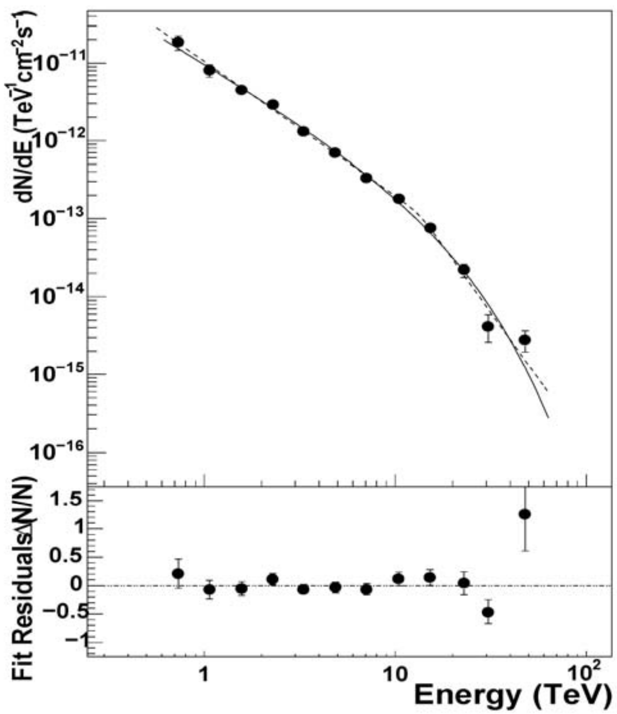


Fig. 3. Energy spectrum of γ-ray emission from the Vela X region. The solid line denotes the best fit of a power law with an exponential cutoff. The dashed line represents the best fit broken power law spectrum. The bottom panel shows the residuals to the exponential cutoff fit.

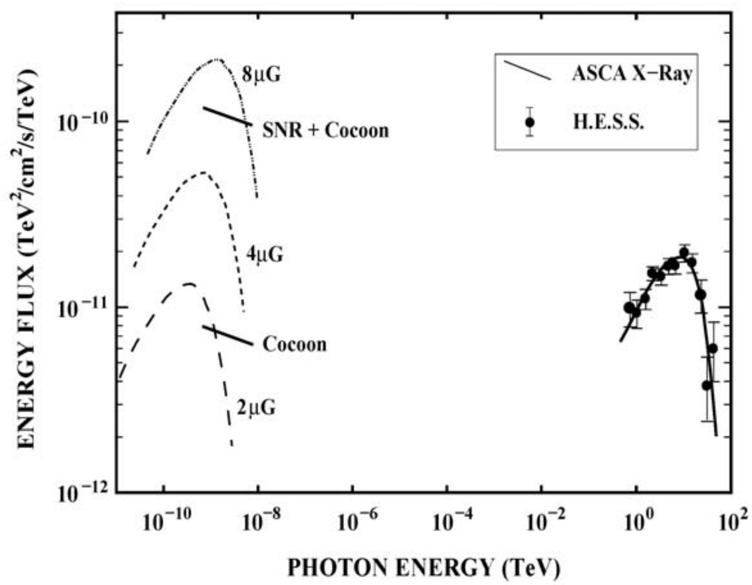


Fig. 4. Spectral energy distribution for the H.E.S.S. and ASCA spectral measurements (Markwardt & Ögelman 1997). The two alternative X-ray spectra are described in the text. The fitted inverse Compton emission (solid line) from the Vela X region is shown, given the electron energy distribution described in the text. The predicted synchrotron flux is shown for three possible magnetic field levels, between 2 μG and 8 μG.

$\Phi \sim E^{-\Gamma}$ con Γ=1.45+/- 0.09
con taglio esponenziale a 13.8 TeV

Il flusso e’ il 50% di quello della CRAB per E>1 TeV

Hess Sgr A*

Regione del centro galattico: ricca di potenziali sorgenti gamma →
Sgr A   Buco Nero Supermassivo (BH) di 2.6x10^6 masse solari*
debole emissione negli X e nell'infrarosso
Emissione legata alla caduta (accretion) di materiale (venti stellari) sul BH.
Gamma di alta energia dal centro galattico osservati in altri esperimenti

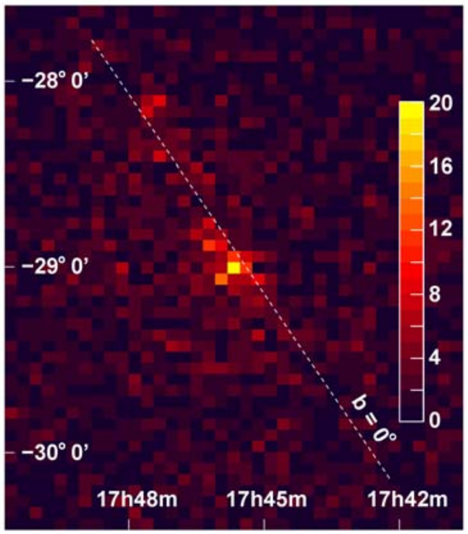


Fig. 1. Angular distribution of γ-ray candidates for a 3° field of view centred on Sgr A*. Both data sets ('June/July' and 'July/August') are combined, employing tight cuts to reduce the level of background. The significance of the feature extending along the Galactic Plane is under investigation.

γ potrebbero esser prodotti nell'accelerazione di elettroni o protoni nei relativi shocks

Hess: rivelatorCerenkov atmosferico
(4 specchi , solo due al momento della misura)

Osservazioni in una finestra di 3° attorno a Sgr A*

Eccesso di molte deviazioni standard a:
l = 359° 56′ 53″ ; b = -0° 2′ 57″ (coincidente con Sgr A*)

Hess Sgr A*

Mappa di Chandra (raggi X)

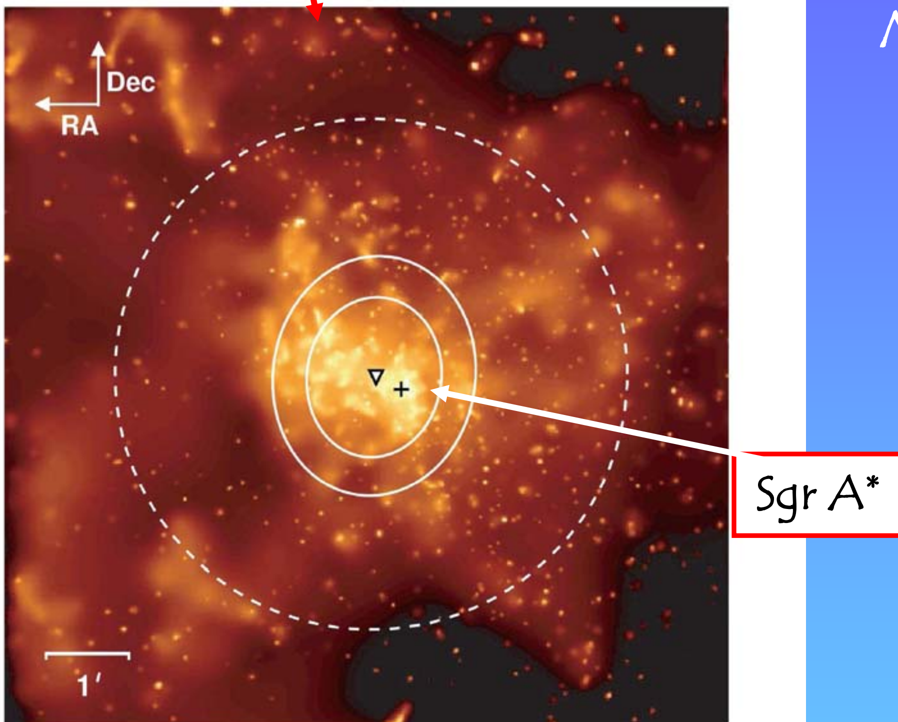


Fig. 2. Centre of gravity of the VHE signal (triangle), superimposed on a 8.5′ by 8.5′ Chandra X-ray map (Muno et al. 2003) of the GC. The location of Sgr A* is indicated by a cross. The contour lines indicate the 68% and 95% confidence regions for the source position, taking into account systematic pointing errors of 20″. The white dashed line gives the 95% confidence level upper limit on the rms source size. The resolution for individual VHE photons - as opposed to the precision for the centre of the VHE signal - is 5.8′ (50% containment radius).

Nessuna evidenza per un'estensione finita

Oggetto "puntiforme"
< 7 pc !

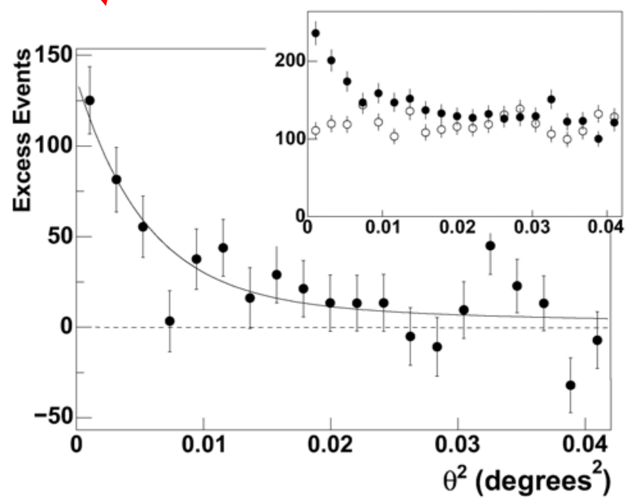


Fig. 3. Angular distribution of VHE γ-rays relative to the location of Sgr A*. Inset: distributions in θ^2 where θ is the angle between the γ-ray direction and Sgr A*; a uniform background results in a flat distribution in θ^2. Full points: signal region; open points: background region. The main figure shows background-subtracted excess counts. The solid line indicates the distribution expected for a point source of γ-rays at the position of Sgr A*.

Hess Sgr A*

Spettro energetico di Cangaroo

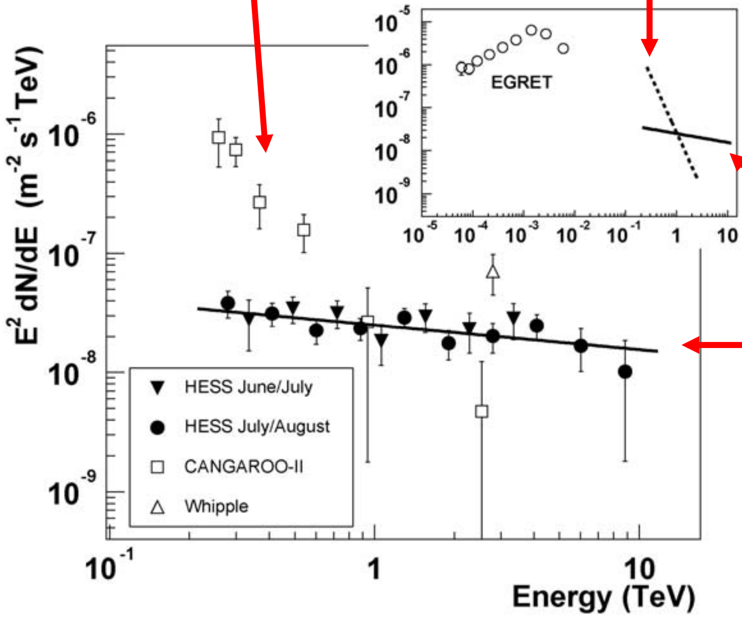


Fig. 4. Energy spectrum $E^2 dN/dE$ of γ-rays from the Galactic Centre. Full circles: H.E.S.S. 'July/August 2003' data set. Full triangles: H.E.S.S. 'June/July 2003' data set. The line indicates a power-law fit to the 'July/August' spectrum. Open squares: CANGAROO-II spectrum from Summer 2001 and 2002 (Tsuchiya et al. 2004). Open triangle: Whipple flux from 1995 through 2003 (Kosack et al. 2004), converted to a differential flux at the peak detection energy assuming a Crab-like spectrum. The inset shows the EGRET flux from 1991 to 1996 (Mayer-Hasselwander et al. 1998) (circles) compared to fits to the CANGAROO-II (dashed line) and H.E.S.S. (solid line) spectra. Due to the poor angular resolution of EGRET (1°) the flux shown may include other sources.

Spettro energetico di Hess

$F(E)=F_0\ E^{-\Gamma}$

$F_0=(2.50 +/- 0.21)\times 10^{-8}\ m^{-2}\ s^{-1}\ TeV^{-1}$

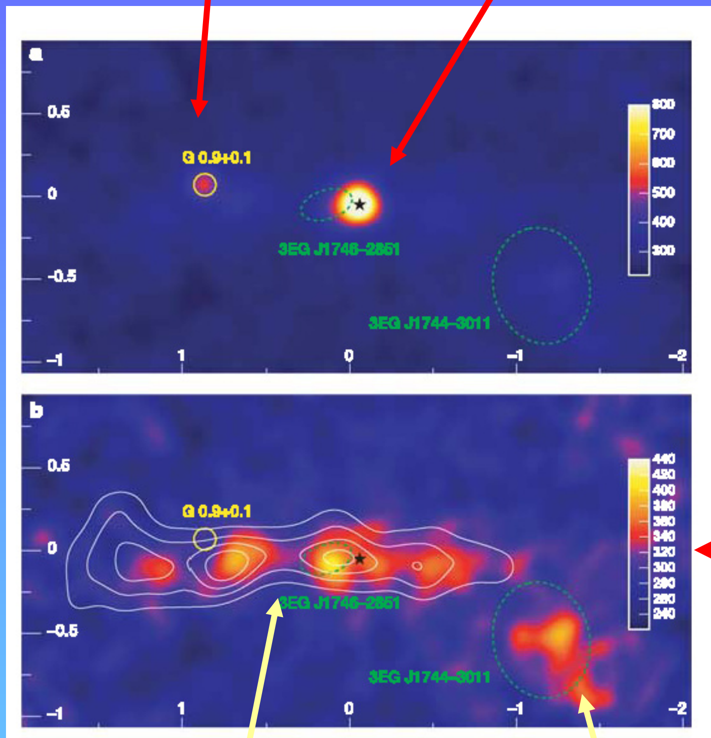
$\Gamma= 2.21 +/- 0.09$

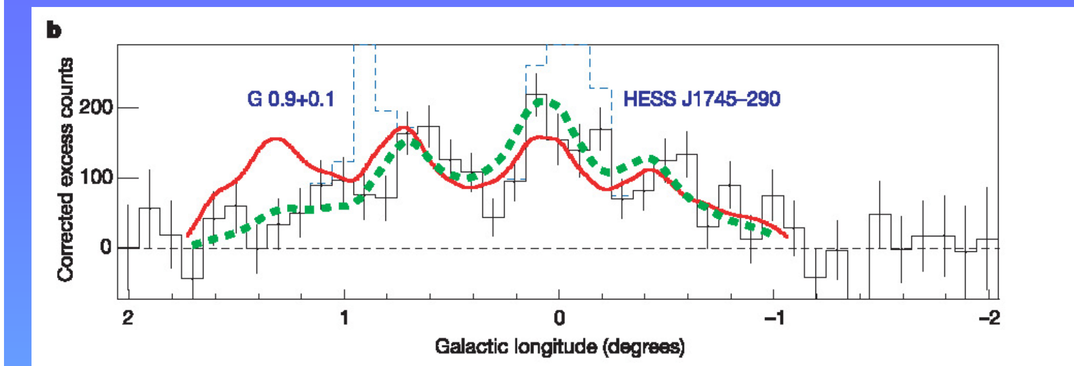
Flusso per E> 165 GeV equivalente al 5% della CRAB

Cangaroo trovava $\Gamma=4.6 +/- 0.5$

Hess GC ridge

Sorgenti intense:
G 0.9+0.1 e Sagittarius





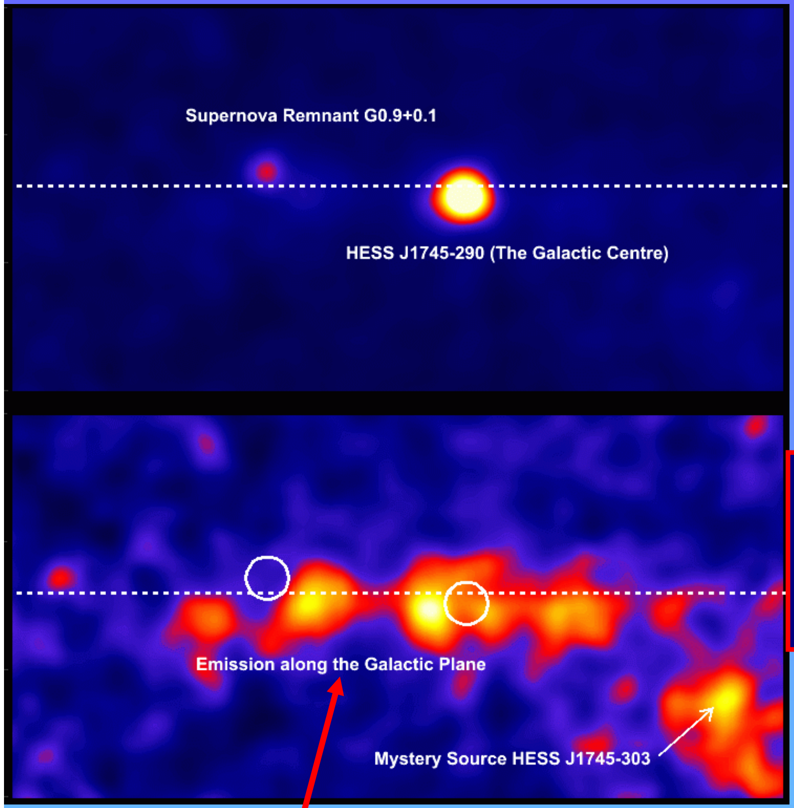
Distribuzione dopo la sottrazione delle sorgenti piu' intense: 3EG J1746-2851, G 0.9+0.1

Spettro energetico nella zona di emissione estesa → legge di potenza, con Γ = 2.29 +/- 0.07

Emissione estesa nel piano Galattico

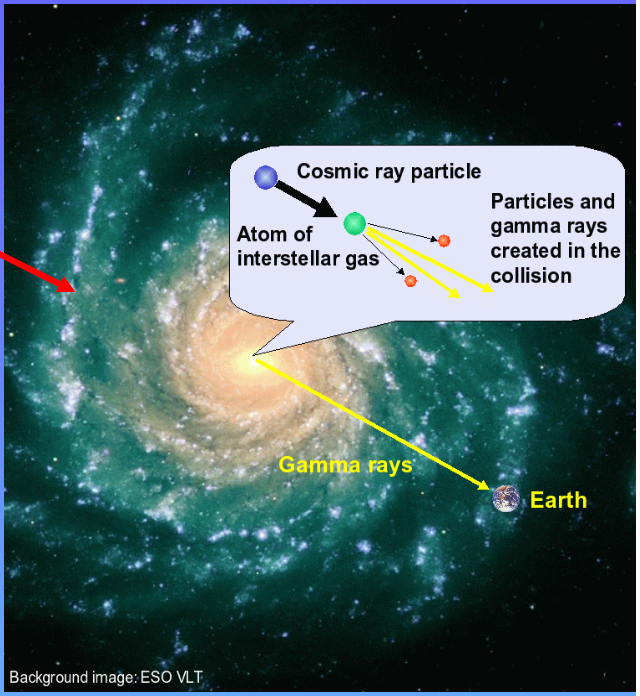
EGRET EG J1744-3011

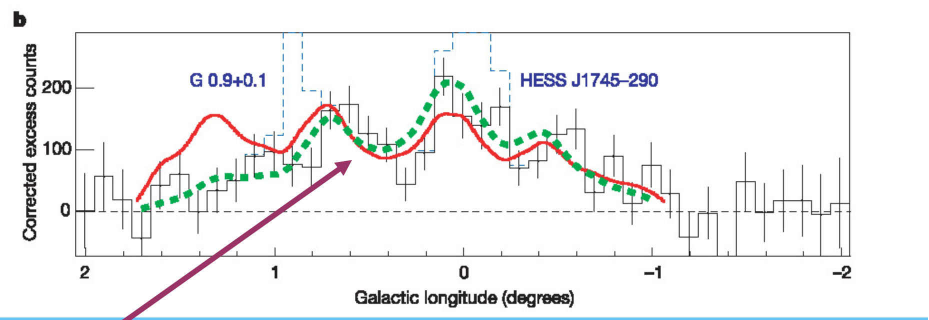
Hess GC



Interazioni di raggi cosmici con il gas → produzione di fotoni

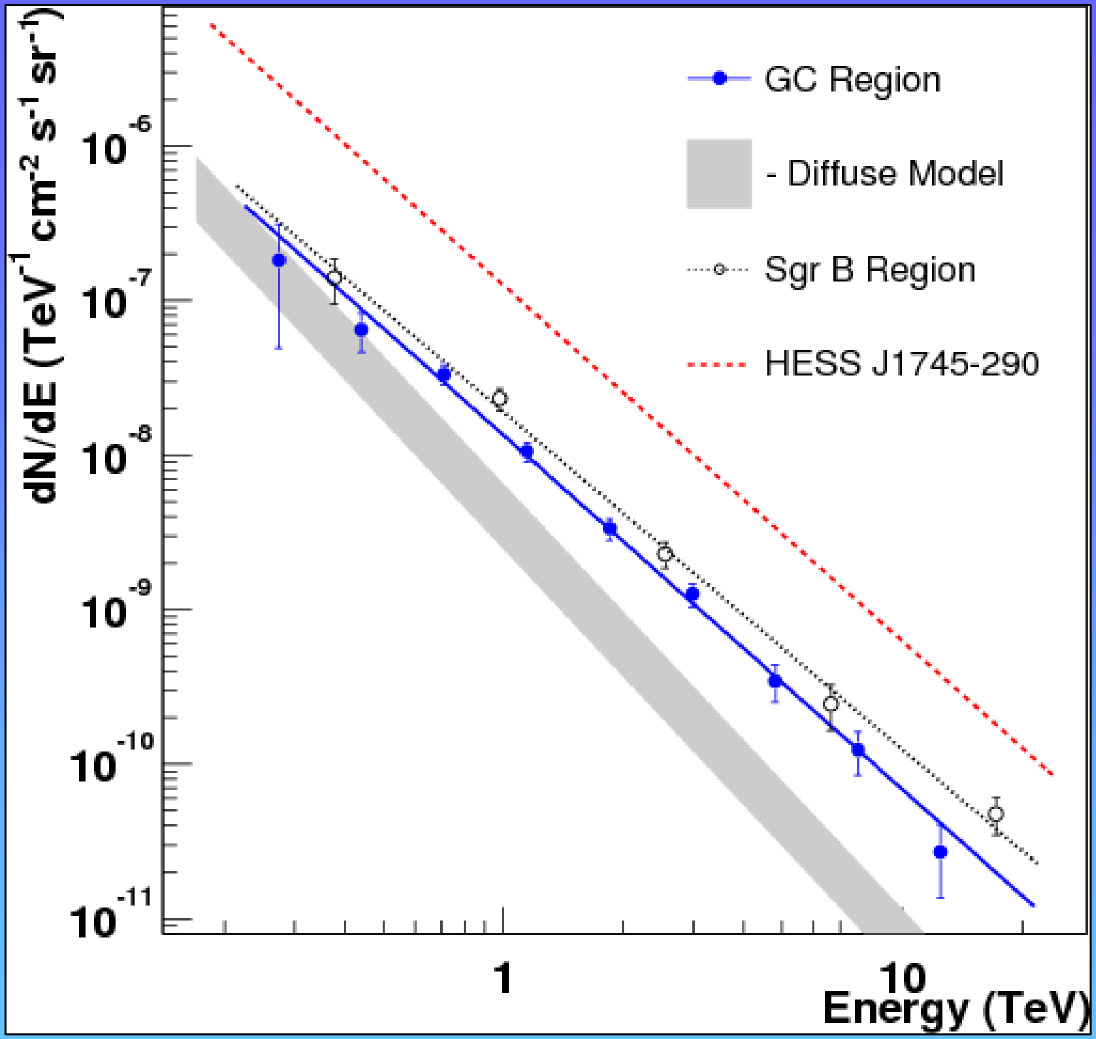
$(3\text{-}8)\times10^7$ masse solari di gas – in nubi sovrapposte





Estensione in latitudine della zona di Emissione estesa: $\Delta b = 0.2°$
Simile a quella del materiale interstellare nelle nubi molecolari giganti osservate in questa regione (curva in rosso)

Hess GC ridge



Given the observed spectrum $E^{-2.3}$, this can be interpreted as photons from π^0 decay produced in pp interactions where the TeV protons have the same spectrum and could have been produced in a SN event.

Note that this is consistent with the source spectrum both expected from shock acceleration theory and from the cosmic ray spectrum observed in the solar neighborhood, $E^{-2.7}$, corrected for diffusion in the galactic magnetic field

Hess GC ridge

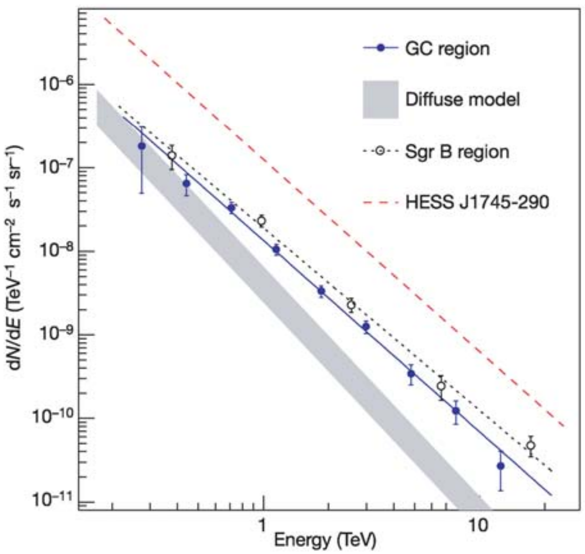


Figure 3 | Energy distribution of Galactic cosmic rays. γ-ray flux per unit angle in the Galactic Centre region (data points), compared with the expected flux, assuming a cosmic-ray spectrum as measured in the solar neighbourhood (shaded band). The spectrum of the region $|l| < 0.8°$, $|b| < 0.3°$ is shown using full circles. These data can be described by a power law: $dN/dE = k[E(\text{in TeV})]^{-\Gamma}$, with $k = (1.73 \pm 0.13_{stat} \pm 0.35_{sys}) \times 10^{-8}$ TeV^{-1} cm^{-2} s^{-1} sr^{-1} and a photon index $\Gamma = 2.29 \pm 0.07_{stat} \pm 0.02_{sys}$. The shaded box shows the range of expected π^0-decay fluxes from this region assuming a cosmic-ray spectrum identical to that found in the solar neighbourhood and a total mass of 1.7–4.4×10^7 solar masses in the region $|l| < 0.8°$, $|b| < 0.3°$ estimated from CS measurements. Above 1 TeV an enhancement by a factor of 3–9 relative to this prediction is observed. Using independent mass estimates derived from submillimetre measurements[24], $5.3 \pm 1.0 \times 10^7$ solar masses, and from $C^{18}O$ measurements[25], $3^{+2}_{-1} \times 10^7$ solar masses, results in enhancement factors of 4–6 and 5–13, respectively (see Supplementary Information). The strongest emission away from the bright central source HESS J1745–290 occurs close to the Sgr B complex of giant molecular clouds[26]. In a box covering this region ($0.3° < l < 0.8°$, $-0.3° < b < 0.2°$), integrated CS emission suggests a molecular target mass of 6–15×10^6 solar masses. The energy spectrum of this region is shown using open circles. The measured γ-ray flux (>1 TeV) implies a high-energy cosmic-ray density which is 4–10 times higher than the local value. Standard γ-ray selection cuts are applied here, yielding a spectral analysis threshold of 170 GeV. The spectrum of the central source HESS J1745−290 is shown for comparison (using an integration radius of 0.14°). All error bars show ± 1 standard deviation.

Conclusione:
la morfologia osservata e lo spettro in energia sono evidenza del fatto che uno o piu' acceleratori di raggi cosmici sono stati attivi al centro della Galassia negli ultimi 10,000 anni.
Il fatto che lo spettro energetico sia uguale a quello di HESS J1745-290 suggerisce che questa potrebbe essere la sorgente in questione.

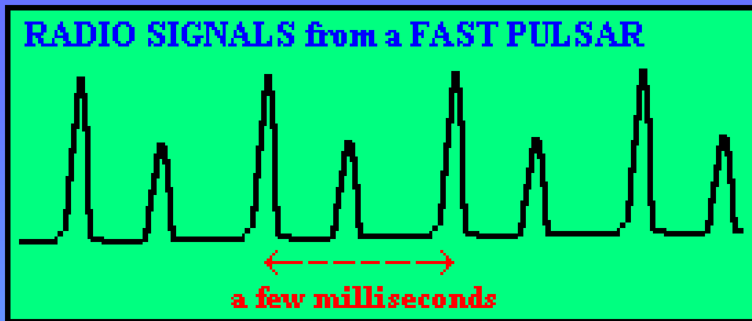
Ref.: Nature Vol. 439, 9 February 2006

Pulsars come sorgenti di γ

Estate 1967: Hewish + J. Bell (Cambridge)
Osservazioni con una radiotelescopio (81.5 MHz). Sorgente pulsante → T=1.337729 s
Cambridge Pulsar (CP1919) (Ascensione retta 19h 19m)
Centinaia di Pulsars scoperte successivamente a frequenze radio, negli X etc.

Modello: Stella di neutroni ruotante

(Radio) Pulsars



Scoperte nel 1967 da Hewish e Bell

Predette nel attorno al 1934 da Baade e Zwicky come “stelle di neutroni”

Predizione non prevedeva emissione “non termica”

Successiva predizione nel 1967 di Pacini: stelle di neutroni magnetizzate e ruotanti ➔ emissione radio

PSR B0329+54

This pulsar is a typical, normal pulsar, rotating with a period of 0.714519 seconds, i.e. close to 1.40 rotations/sec.

PSR B0833-45, The Vela Pulsar

This pulsar lies near the centre of the Vela supernova remnant, which is the debris of the explosion of a massive star about 10,000 years ago. The pulsar is the collapsed core of this star, rotating with a period of 89 milliseconds or about 11 times a second.

PSR B0531+21, The Crab Pulsar

This is the youngest known pulsar and lies at the centre of the Crab Nebula, the supernova remnant of its birth explosion, which was witnessed by Europeans and Chinese in the year 1054 A.D. as a day-time light in the sky. The pulsar rotates about 30 times a second.

PSR J0437-4715

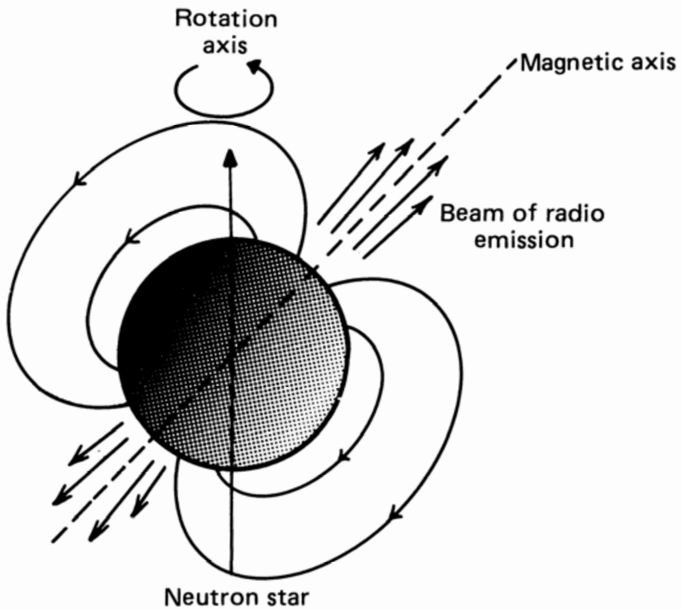
This is a recently discovered millisecond pulsar, an old pulsar which has been spun up by the accretion of material from a binary companion star as it expands in its red giant phase. The accretion process results in orbital angular momentum of the companion star being converted to rotational angular momentum of the neutron star, which is now rotating about 174 times a second.

PSR B1937+21

This is the fastest known pulsar, rotating with a period of 0.00155780644887275 seconds, or about 642 times a second. The surface of this star is moving at about 1/7 of the velocity of light and illustrates the enormous gravitational forces which prevent it flying apart due to the immense centrifugal forces

Pulsars come sorgenti di γ

Fig. 16.5. A schematic model of a pulsar as a magnetised rotating neutron star in which the magnetic and rotation axes are misaligned.



Periodo di rotazione estremamente stabile:

$P/\dot{P} \sim 10^8$ anni

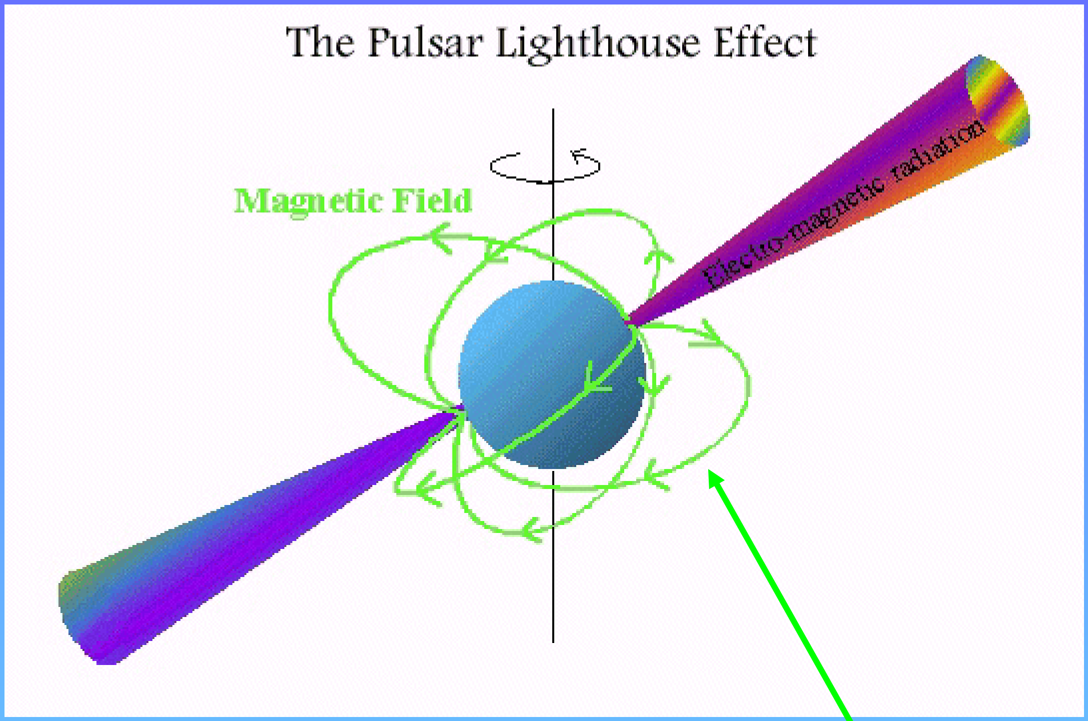
Dimensione L della regione di emissione legata alla durata dell'impulso Δt:

$L \sim c\ \Delta t$

(Vero per qualsivoglia sorgente che emetta brevi impulsi: Pulsars, Gamma Ray Bursts...)

CRAB ➔ 10000 km

Pulsars (1)

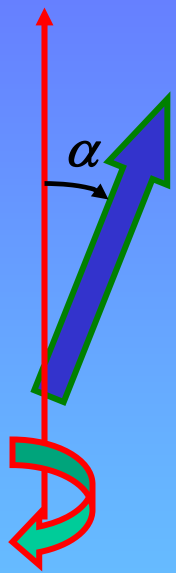


Impulsi rivelati quando uno dei jets punta verso la Terra

Elettroni che spiralizzano nel campo magnetico della stella di neutroni

Pulsars (2)

Periodi di rotazione P=(0.0015-4.0) s
Modello: NS con momento magnetico non allineato con l'asse di rotazione ⟹ emissione di dipolo magnetico



Periodo P; frequenza angolare Ω=1/P.

Fattore di qualita': $Q = \frac{1}{\dot{P}}$

$Q = \left(10^{12} \div 10^{19}\right)$; tra gli orologi piu' stabili dell'Universo!

T = periodo di osservazione: $\frac{\Delta\Omega}{\Omega} = \frac{T\dot{\Omega}}{\Omega} = \frac{T\dot{P}}{P} = \frac{T}{QP}$

$\frac{T}{P} \cong 10^{8} \div 10^{11}$

Potenza totale irraggiata da un dipolo magnetico ruotante con velocita' angolare Ω:

$$-\frac{dE}{dt} = \frac{\mu_0 \left|\ddot{\vec{p}}\right|^2}{6\pi c^3} \quad ;$$

Per un dipolo che ruoti ad un angolo α rispetto all'asse
indicando con p_0 la componente del momento perpendicolare all'asse di rotazione:
$p = p_0 \sin \Omega t$

$$-\left\langle \frac{dE}{dt} \right\rangle = \frac{\mu_0}{6\pi c^3} \left| \frac{d^2}{dt^2} \left[p_0 \sin \Omega t \right] \right|^2 = \frac{\mu_0}{6\pi c^3} p_0^{\,2}\, \Omega^4$$

Pulsars (3)

La potenza irraggiata e' estratta dall'energia cinetica di rotazione $\frac{1}{2} I\Omega^2 \Rightarrow$

$$-\frac{d}{dt}\left(\frac{1}{2} I\Omega^2\right) = -I\Omega\dot{\Omega} = \left\langle \frac{\mathrm{dE}}{\mathrm{dt}} \right\rangle = \frac{\mu_0 \Omega^4 p_0^2}{6\pi c^3}; \quad \text{da cui :}$$

$$\dot{\Omega} = -\frac{\mu_0\, p_0^2\ \Omega^3}{6\pi c^3 I} \propto -\Omega^3$$

"Braking index" n definito da : $\dot{\Omega} = \text{-}K\,\Omega^n$

Nel nostro caso quindi $n = 3$

Misura di n possibile se si misura $\ddot{\Omega}$: $\dot{\Omega} = \text{-}K\,\Omega^n \quad \Rightarrow \quad \ddot{\Omega} = -n\,K\ \Omega^{n-1}\,\dot{\Omega}$

dividendo membro a membro :

$$\frac{\ddot{\Omega}}{\dot{\Omega}} = \frac{n\ \Omega^{n-1}\,\dot{\Omega}}{\Omega^n} \quad \Rightarrow \quad n = \frac{\ddot{\Omega}\ \Omega}{\dot{\Omega}^2} = \frac{\nu\,\ddot{\nu}}{\dot{\nu}^2}$$

Periodo : $P = \frac{1}{\nu}; \quad \dot{\nu} = -\frac{1}{P^2}\dot{P}; \quad \ddot{\nu} = \frac{2\dot{P}^2}{P^3} - \frac{\ddot{P}}{P^2}$

$$n = 2 - \frac{P\,\ddot{P}}{\dot{P}^2}$$

Misure di n:
CRAB: **2.515 +/- 0.005**
PSR 1509-58: **2.8 +/- 0.2**
PSR 0540-69: **2.01 +/- 0.02**

L'eta' puo' esser stimata ammettendo che la decelerazione sia caratterizzata da un "braking index" costante

$$\dot{\Omega} = -K\Omega^n \quad ; \quad Integrando:$$

$$\int_0^\tau \frac{\dot{\Omega}}{\Omega^n} dt = -K\,\tau; \quad \int_{\Omega_0}^{\Omega} \frac{d\Omega}{\Omega^n} = -K\,\tau; \quad \frac{1}{n-1}\left[\frac{1}{\Omega_0^{n-1}} - \frac{1}{\Omega^{n-1}}\right] = -K\,\tau$$

$$Se\ n > 1\ e\ \Omega_0 >> \Omega \quad \Rightarrow \quad \tau = -\frac{\Omega^{-(n-1)}}{K(n-1)} = -\frac{\Omega^{-(n-1)}\Omega^n}{K(n-1)\Omega^n} = \frac{\Omega}{(n-1)\dot{\Omega}}$$

$$= \frac{P}{(n-1)\dot{P}};$$

$$Per \quad n = 3 \quad \Rightarrow \quad \tau = \frac{P}{2\dot{P}}$$

Grafico di $\dot{P}$ in funzione di P

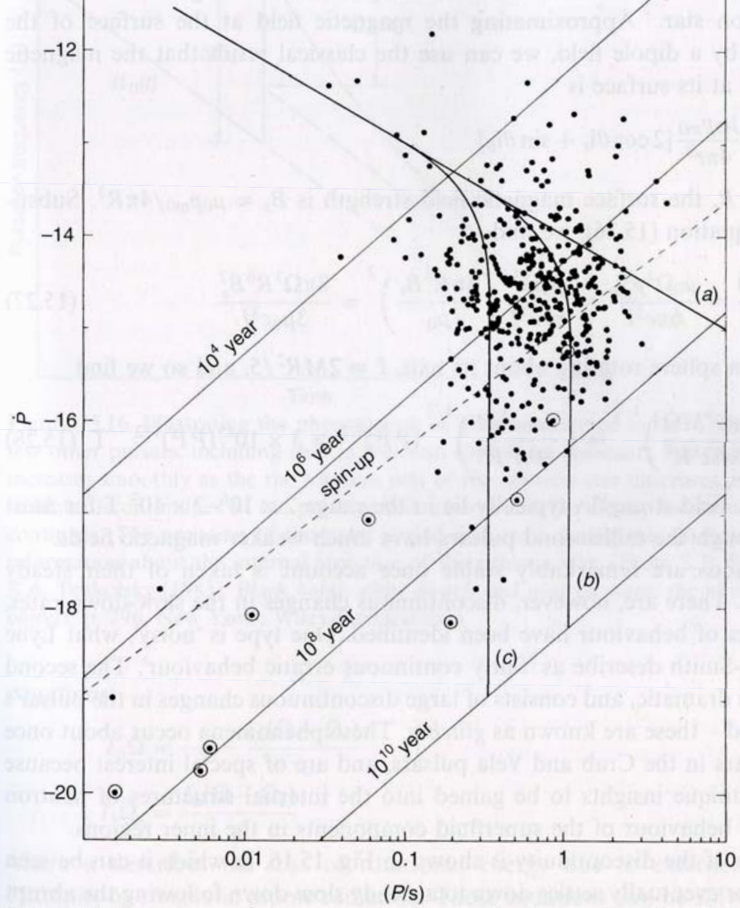
Eta' di una Pulsar (2)

Dal grafico di $\dot{P}$ *in funzione di* P *si vede che la vita media per la grande maggioranza delle pulsar e' dell'ordine di* 10^7 *anni.*

Crab Pulsar: $\tau = 1400$ *anni*

Crab Nebula (Supernova): esplosa nel 1054

$\dot{P}$



P

Figure 15.15. A plot of $\dot{P}$ versus P for pulsars. The dots enclosed in circles repres pulsars which are members of binary systems. Lines of constant age according to formula $\tau = P/2\dot{P}$ are shown. Schematic evolutionary tracks of pulsars on this dia are shown assuming (*a*) that there is no decay in the strength of the magnetic field that the timescale for decay of the magnetic fields is (*b*) 10^7 years and (*c*) 10^6 yea The upper limit to the spin-up periods for dead pulsars according to the models c van den Heuvel (1987) is also shown (see the discussion leading to expression (16.4 (After A.G. Lyne and F. Graham-Smith (1990). *Pulsar astronomy*, p. 129. Cambrid Cambridge University Press.)

Perdita d'energia delle Pulsar

Perdita d'energia per unita' di tempo $\Rightarrow$

$$\left\langle \frac{\mathrm{dE}}{\mathrm{dt}} \right\rangle = -\frac{d}{dt}\left(\frac{1}{2} I\Omega^2\right) = -I\Omega\dot{\Omega} =$$

Ammettendo che massa e raggio siano quelli tipici di una stella di neutroni:

$\mathrm{M} = 1.4\,\mathrm{M_S}$

Si puo' calcolare I $\left(\mathrm{I} = \frac{2}{5} MR^2 \right)$e, da misure di Ω ed $\dot{\Omega}$ ottenere $\left\langle \frac{\mathrm{dE}}{\mathrm{dt}} \right\rangle$

Per la Crab si trova:

$$\left\langle \frac{\mathrm{dE}}{\mathrm{dt}} \right\rangle \cong 6.4 \cdot 10^{31}\ W$$

Energia irraggiata dalla remnant + energia di espansione della remnant $\cong 5 \cdot 10^{31}\ W$

$\Rightarrow$ e' la pulsar ad "alimentare" la remnant!

Campo B delle Pulsar

Campo della Pulsar $\Rightarrow$ campo di dipolo:

$$\vec{B} = \frac{\mu_0 p_0}{4\pi r^3}\left[2\cos\vartheta\,\hat{u}_r + \sin\vartheta\,\hat{u}_\vartheta\right]$$

(dove abbiamo supposto che il modulo di p coincida con p_0)

Per $r = R \quad \Rightarrow \quad B_S \cong \dfrac{\mu_0 p_0}{4\pi R^3}$.

Ricavando p_0 e sostituendo nella:

$$-I\Omega\dot{\Omega} = \frac{\mu_0 \Omega^4 p_0^2}{6\pi c^3}; \quad \text{ovvero nella:}$$

$$-\frac{d\Omega}{dt} = \frac{\mu_0 \Omega^3 p_0^2}{6\pi c^3\, I} = \frac{\mu_0 \Omega^3}{6\pi c^3\, I}\left(\frac{4\pi R^3 B_S}{\mu_0}\right)^2 = \frac{8\pi\,\Omega^3 R^6 B_S^2}{3\mu_0 c^3\, I}$$

Per una sfera uniforme di raggio R:

$$\mathrm{I} = \frac{2}{5}MR^2; \quad \text{da cui:}$$

$$B_S = \left(\frac{3\,\mu_0\, c^3\, M\,\dot{\Omega}}{20\pi\,\Omega^3 R^4}\right)^{1/2}; \quad \text{dove: } \Omega = \frac{2\pi}{P} \quad \text{e quindi: } \quad \frac{\dot{\Omega}}{\Omega^3} = \frac{P\dot{P}}{4\pi^2} \quad \Rightarrow$$

$$B_S = \left(\frac{3\,\mu_0\, c^3\, M}{80\,\pi^3 R^4}\right)^{1/2}\left(P\,\dot{P}\right)^{1/2}$$

Campi tipici

$2 \cdot 10^6 - 2 \cdot 10^9$ T

Periodi delle Pulsar

Se il momento magnetico e' costante $\Rightarrow$

$$\frac{d\Omega}{dt} \propto -\Omega^3; \quad \text{da cui: } \quad \frac{\dot{P}}{P} \propto \text{costante} \Rightarrow$$

$$\log \dot{P} = k\text{-} \log P$$

Momento magnetico che "decade" con costante di tempo ~ 10^6-10^7 anni

Assenza di pulsar con periodo breve come quello della Crab

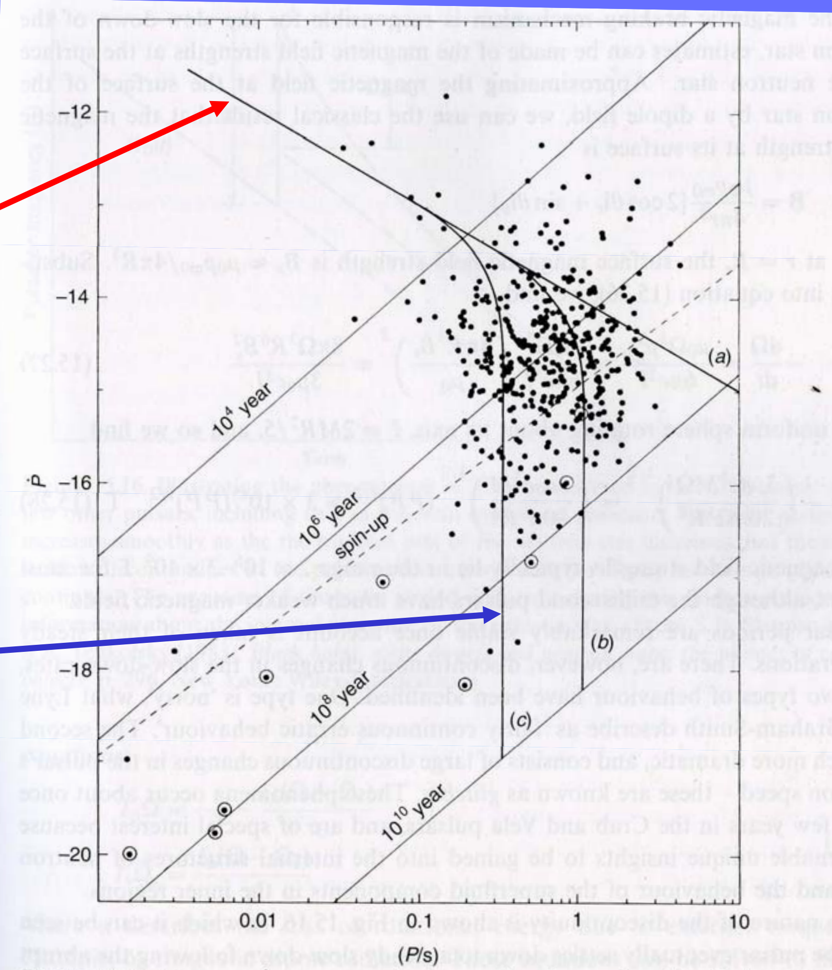
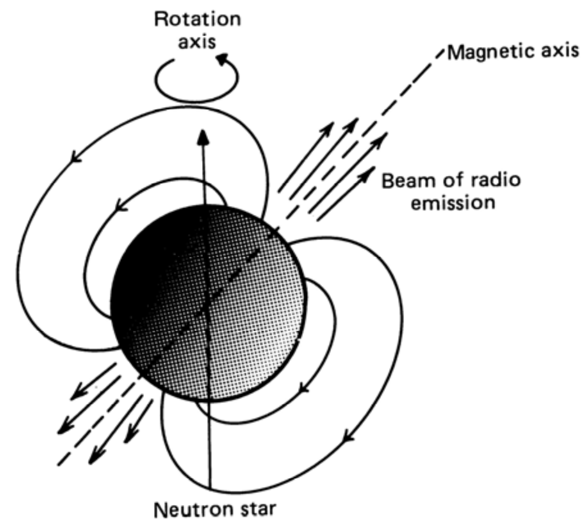


Figure 15.15. A plot of $\dot{P}$ versus P for pulsars. The dots enclosed in circles repres pulsars which are members of binary systems. Lines of constant age according to formula $\tau = P/2\dot{P}$ are shown. Schematic evolutionary tracks of pulsars on this dia are shown assuming (*a*) that there is no decay in the strength of the magnetic field that the timescale for decay of the magnetic fields is (*b*) 10^7 years and (*c*) 10^6 yea The upper limit to the spin-up periods for dead pulsars according to the models c van den Heuvel (1987) is also shown (see the discussion leading to expression (16.4 (After A.G. Lyne and F. Graham-Smith (1990). *Pulsar astronomy*, p. 129. Cambric Cambridge University Press.)

Emissione e.m. delle Pulsar

Rotazione del dipolo magnetico ➔
Campo elettrico
elettroni accelerati spiralizzano ed emettono rad. di sincrotrone
fotoni prodotti convertono in coppie elettrone-positrone
questi sono accelerati e spiralizzano
………
Radiazione (radio) coerente

Fig. 16.5. A schematic model of a pulsar as a magnetised rotating neutron star in which the magnetic and rotation axes are misaligned.



Pulsars

La pulsar fornisce energia tramite induzione e.m.:

$$\nabla \times \epsilon = -\frac{\partial B}{\partial t} \rightarrow \frac{\epsilon}{L} = B\omega_0$$

ϵ è il campo elettrico indotto su di una regione lineare L.

L'energia massima fornita ad una particella di carica Ze:

$$E_{max} = \int Ze \cdot \epsilon \cdot dx = Ze \cdot B\omega_0 L \cdot L$$

per $Z = 1$, $B = 10^8 T$, $\omega_0 = 10^3 s^-1$, $R = 10km$:

$$E_{max} = Ze \cdot B\omega_0 L^2 = 1.6 \times 10^{-19}(C) \cdot 10^8(T) \cdot 10^3(s^{-1} \cdot 10^8(m^2) = 1.6\, J = 10^{19}\, eV$$

Altre caratteristiche delle Pulsar

Rallentamento maggiore per Pulsar con campo elevato → vite piu' brevi

Bias osservazionale: vita piu' breve → minore possibilita' di osservarla

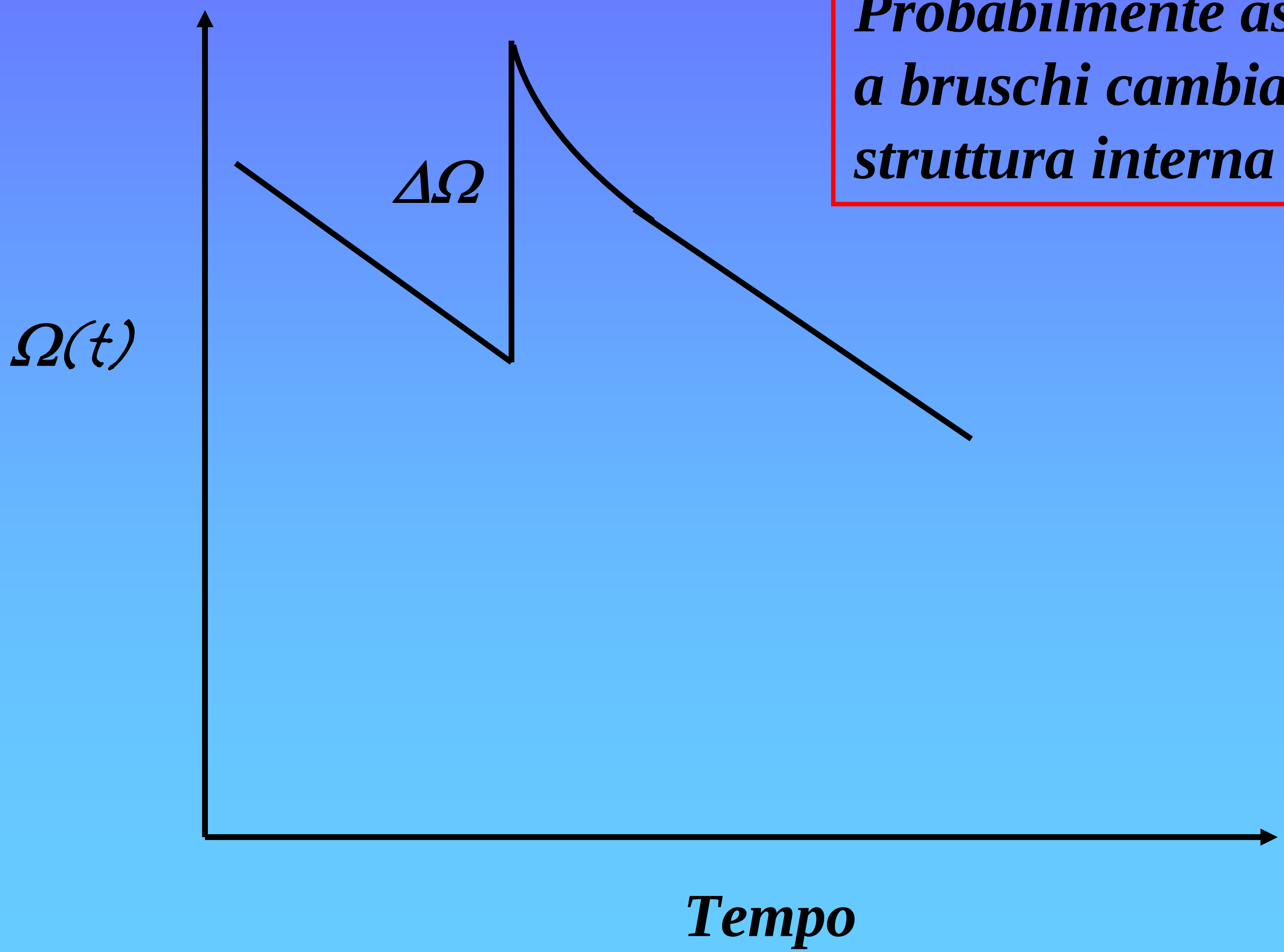
Solo poche Pulsar sono associate a Supernovae Remnants note (oltre 500 Pulsars note e 150 SN Remnants nella Galassia, ma solo 8 associazioni). Probabilmente la piu' gran parte delle Pulsar sono abbastanza "vecchie" (> 30000 anni) che una eventuale Remnant non e' piu' visibile.

Poche Pulsar (~ 1%) sono in sistemi binari (mentre il 50% di tutte le stelle sono in sistemi binari). Possibili spiegazioni:

a) Produzione in eventi di collisione con espulsione della Pulsar dal sistema binario. Compatibile con le alte velocita' osservate.
b) In un sistema binario si ha in genere "accretion" (assorbimento di materiale da parte di uno dei partner, a spese dell'altro) → produzione di materia altamente ionizzata (conduttrice) che impedisce lo sviluppo di elevati campi elettrici e quindi l'accelerazione di particelle e l'emissione.

Brusche discontinuita' in Ω (Glitches)

Probabilmente associati a bruschi cambiamenti nella struttura interna (starquake)



occasional sudden spin-up (Normally, the rotation speed of pulsar is extremely accurate)

general belief: glitches result from the sudden angular momentum transfer between internal superfluid and the solid component

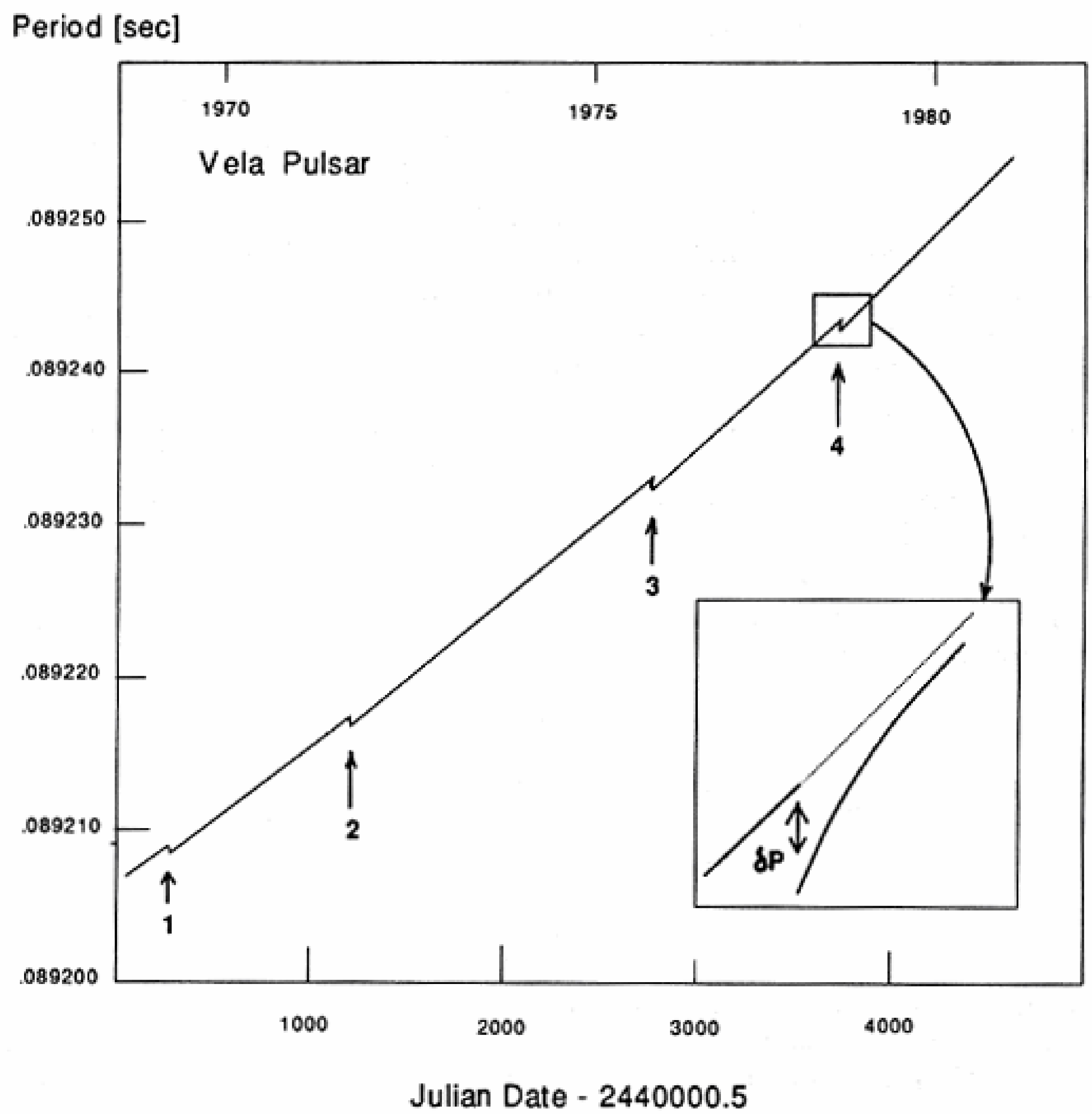


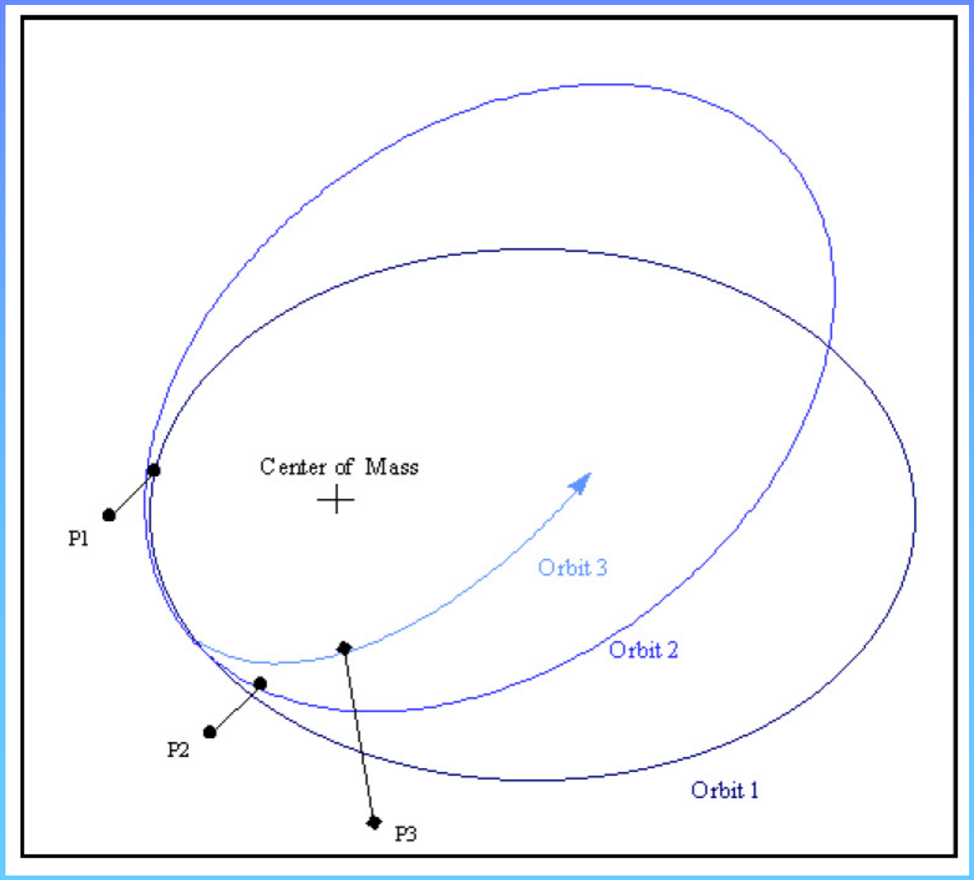
Figure 4. The first four giant glitches of Vela pulsar [from G. Downs (1981)]. The change in period due for each glitch is of order $\Delta P/P \sim 10^{-6}$, and the timescale for the recovery of the glitch is estimated to be of order $\tau \sim 1-3$ months; however, the post-glitch behavior of the period is more complicated than simple exponential recovery of the period and spin-down rate.

Pulsar Binarie (1)

Scoperte nel 1974 da Russell Hulse e Joseph Taylor dell'Universita' di Princeton

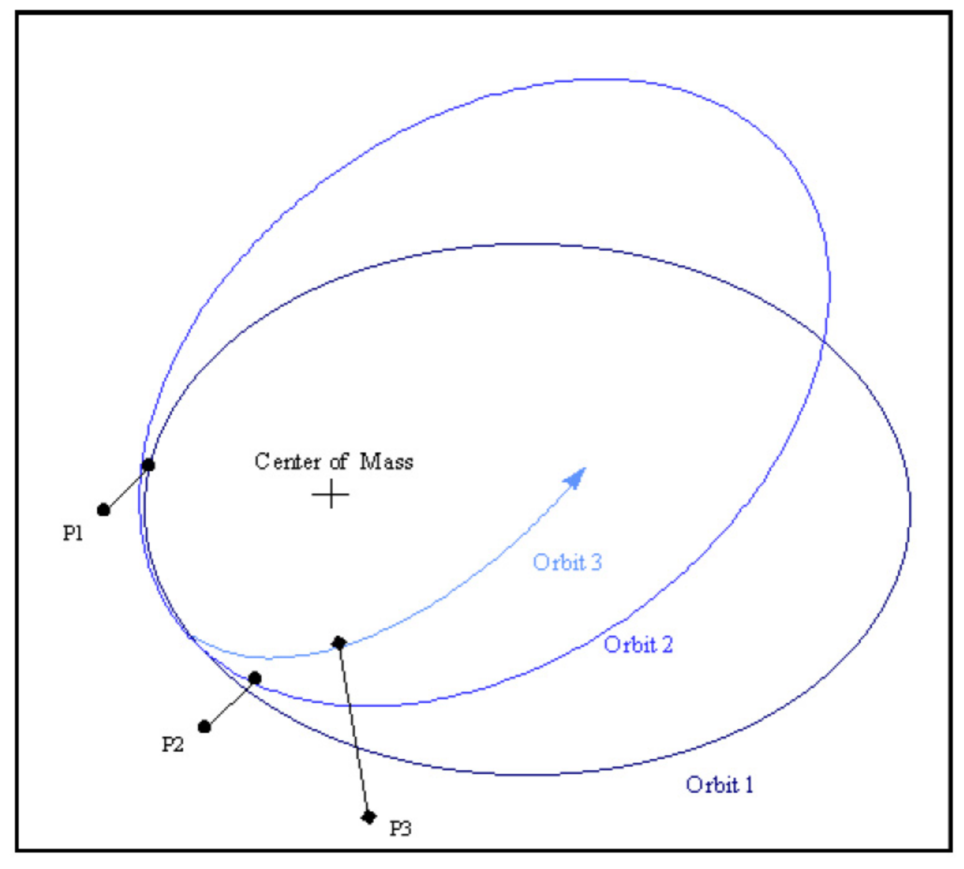
PSR1913+16

Premio Nobel per la Fisica nel 1993



Pulsar Binarie (2)

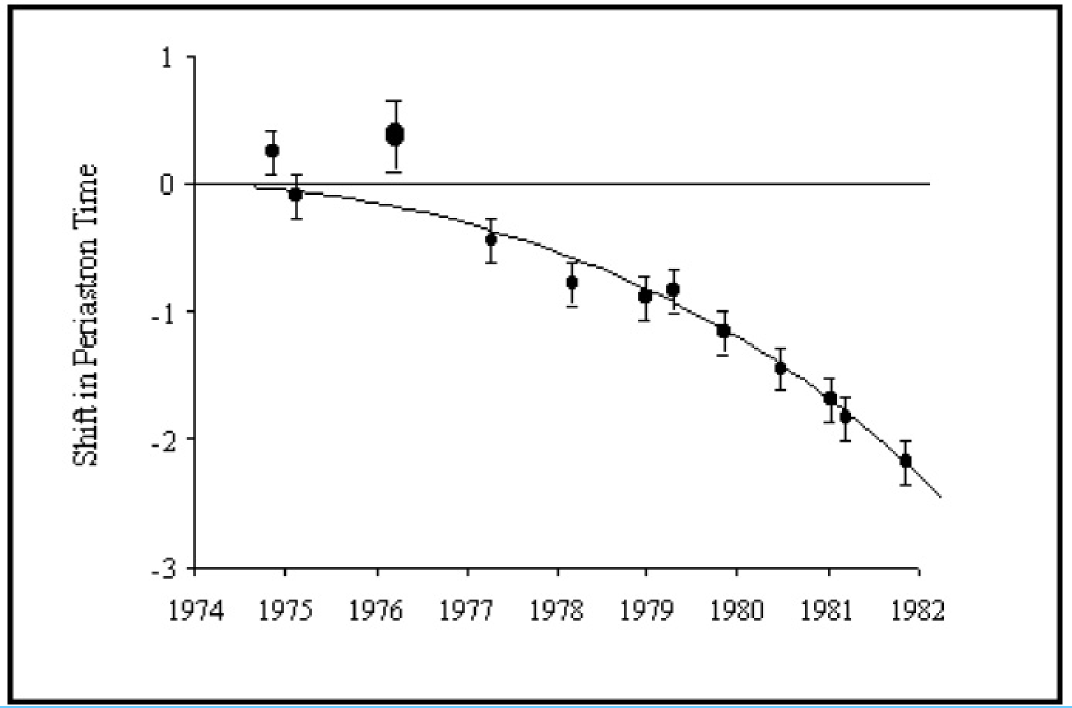
The orbit of the pulsar appears to rotate with time; in the diagram, notice that the orbit is not a closed ellipse, but a continuous elliptical arc whose point of closest approach (periastron) rotates with each orbit.
The rotation of the pulsar's periastron is analogous to the advance of the perihelion of Mercury in its orbit.
The observed advance for PSR 1913+16 is about 4.2 degrees per year; the pulsar's periastron advances in a single day by the same amount as Mercury's perihelion advances in a century.



Pulsar Binarie (3)

PSR1913+16

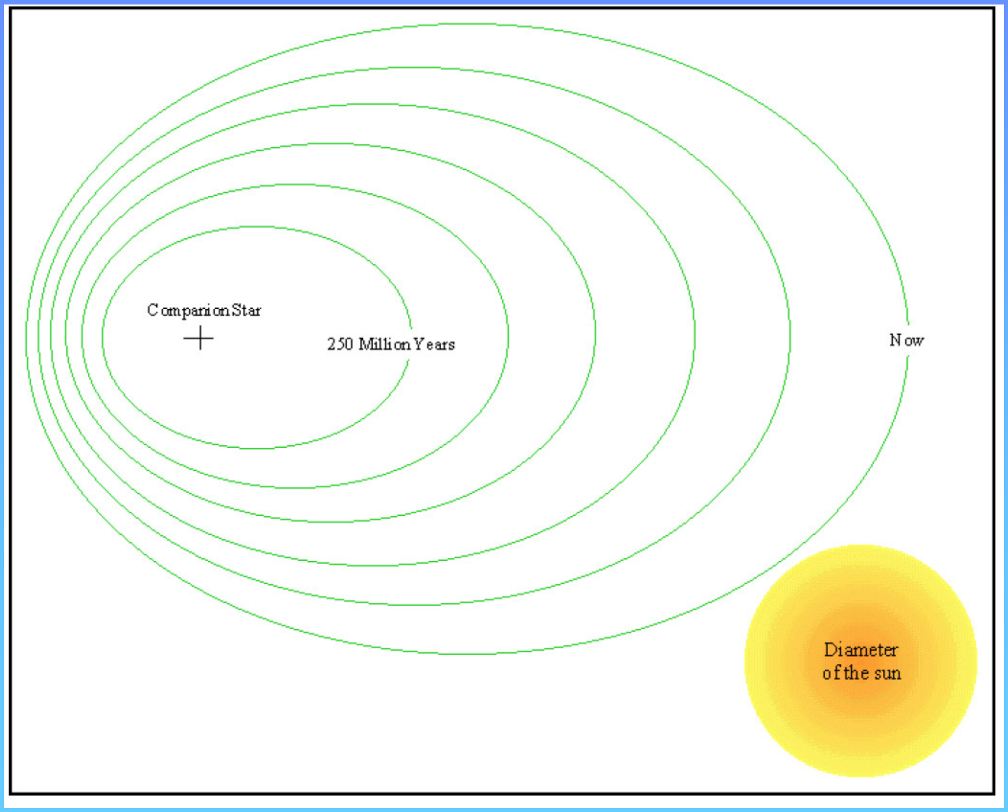
In 1983, Taylor and collaborators reported that there was a systematic shift in the observed time of periastron relative to that expected if the orbital separation remained constant. In the diagram shown here, data taken in the first decade after the discovery showed a decrease in the orbital period as reported by Taylor and his colleagues of about 76 millionths of a second per year. By 1982, the pulsar was arriving at its periastron more than a second earlier than would have been expected if the orbit had remained constant since 1974.



Pulsar Binarie (4)

PSR1913+16

The pulsar's orbit is shrinking with time as shown in this diagram; currently, the orbit shrinks by about 3.1 mm per orbit.
The two stars should merge in about 300 million years from now.



Pulsar Binarie (5)

Her X-1

Pulsar Binaria Her X-1 osservata negli X. Visibile per 34 ore ed acclisata per 6 ore.

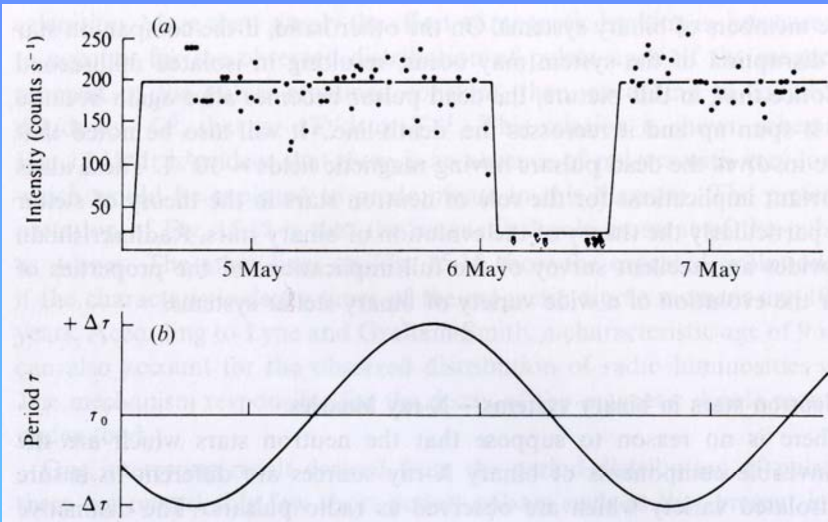


Figure 15.18. (*a*) The rate of arrival of X-ray photons from the X-ray source Hercules X-1 (Her X-1). The source is observed for about 34 hours and then is eclipsed for 6 hours. (*b*) Variations in the arrival time of pulses from Her X-1. The sinusoidal variation of the pulse arrival time is naturally attributed to orbital motion of the X-ray source in a binary system.

Pulsar Binarie: determinazione della massa

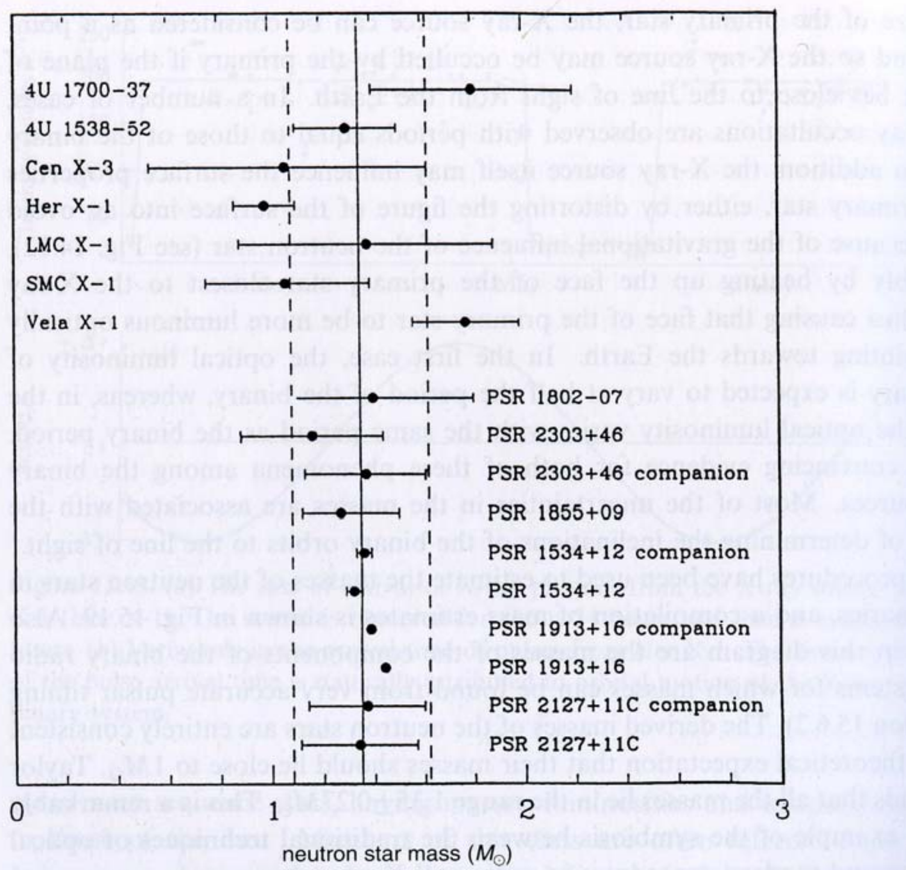
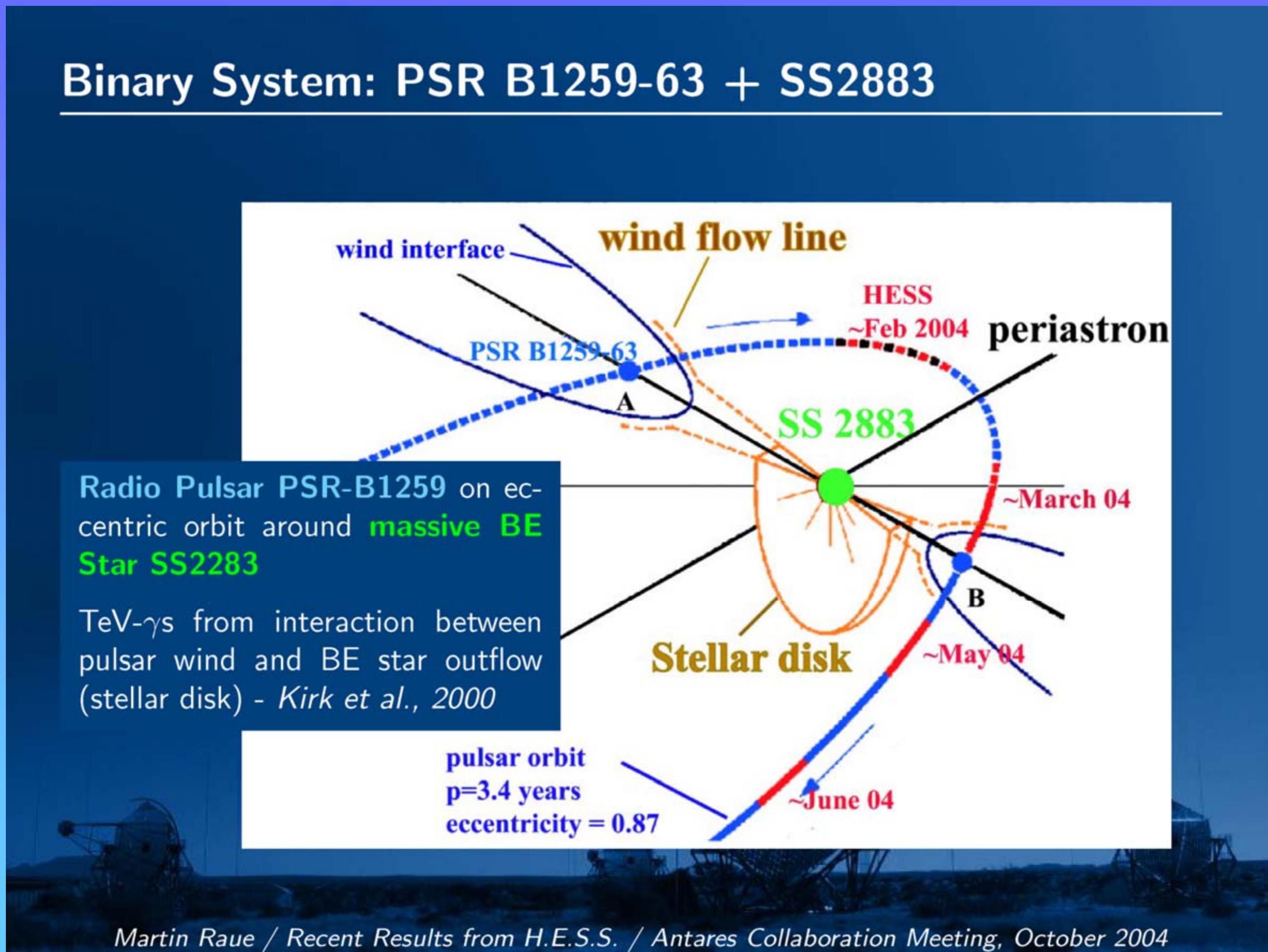
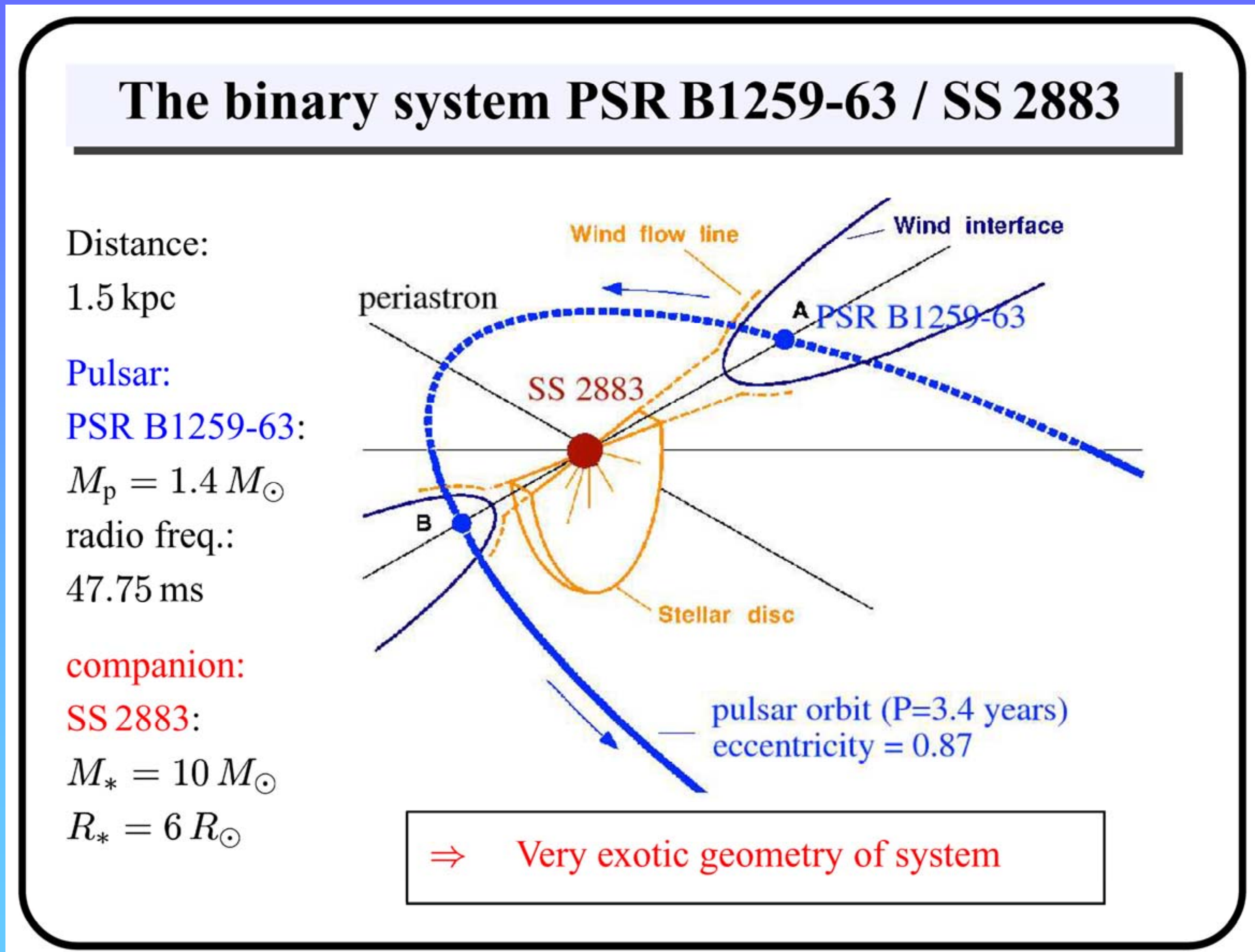


Figure 15.19. Mass estimates for the neutron stars in X-ray binary systems and t radio pulsars, for which good mass determinations are available from their veloc curves and other information. (Courtesy of Professor J. Taylor. See also S.L. Sha S.A. Teukolsky (1983). *Black holes, white dwarfs and neutron stars: the physics of objects*, p. 256, New York: Wiley-Interscience.)

Risultati di Hess



Risultati di Hess



Risultati di Hess

Previous GeV/TeV observations

- Observation with *CANGAROO-II*: (astro-ph/0402214)

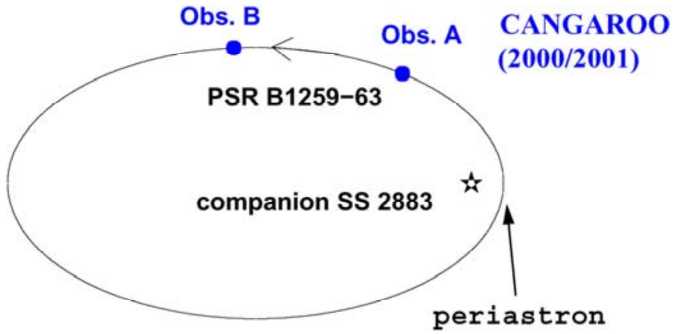
ID	time	$T - T_{\text{Periastron}}$	$E_{\text{threshold}}$
Obs. A	Dec. 2000	47 days	3.6 TeV
Obs. B	March 2001	157 days	0.78 TeV

CANGAROO results:

flux upper limits

$0.13\ \Phi_{\text{Crab}}$ (*Obs. A*)

$0.54\ \Phi_{\text{Crab}}$ (*Obs. B*)



$\Rightarrow$ no significant detection...

Risultati di Hess

Previous GeV/TeV observations

- Observation with *CANGAROO-II*: (astro-ph/0402214)

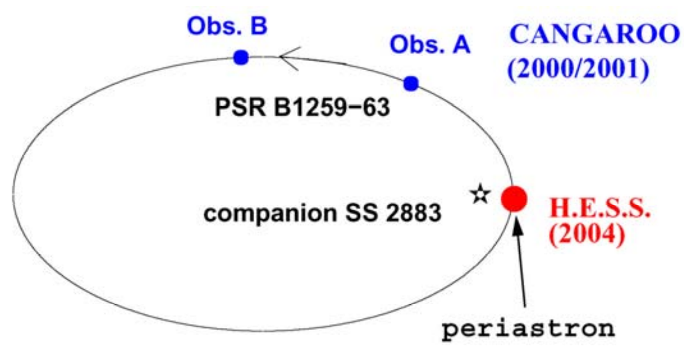
ID	time	$T - T_{\text{Periastron}}$	$E_{\text{threshold}}$
Obs. A	Dec. 2000	47 days	3.6 TeV
Obs. B	March 2001	157 days	0.78 TeV
H.E.S.S.	Feb/March 2004	~ -8 days	~ 0.2 TeV

CANGAROO results:

flux upper limits

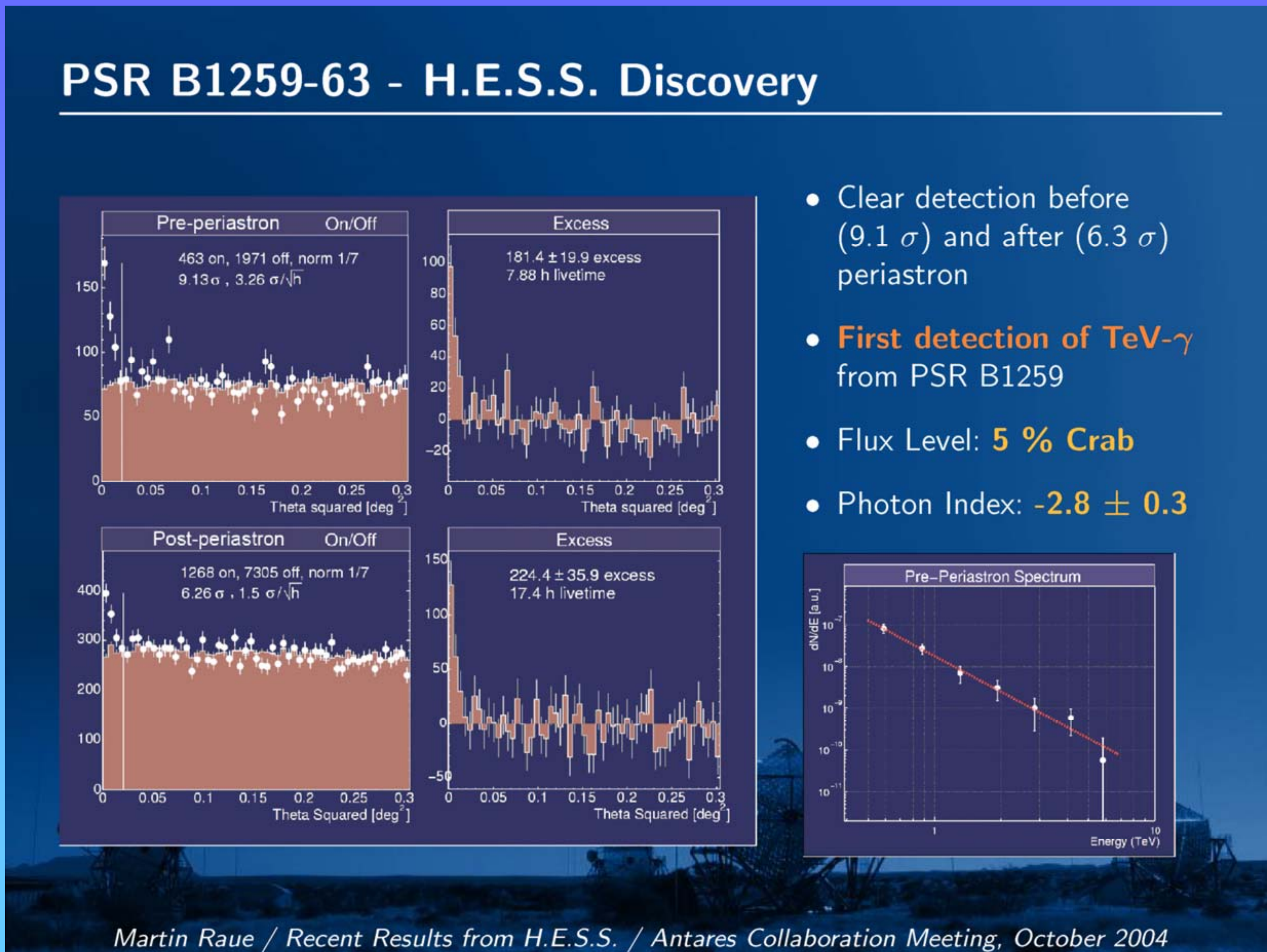
$0.13\,\Phi_{\text{Crab}}$ (*Obs. A*)

$0.54\,\Phi_{\text{Crab}}$ (*Obs. B*)



⇒ H.E.S.S.: more sensitive, observations closer to periastron

Risultati di Hess



Pulsars: animations