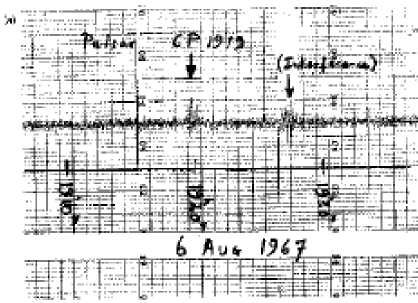
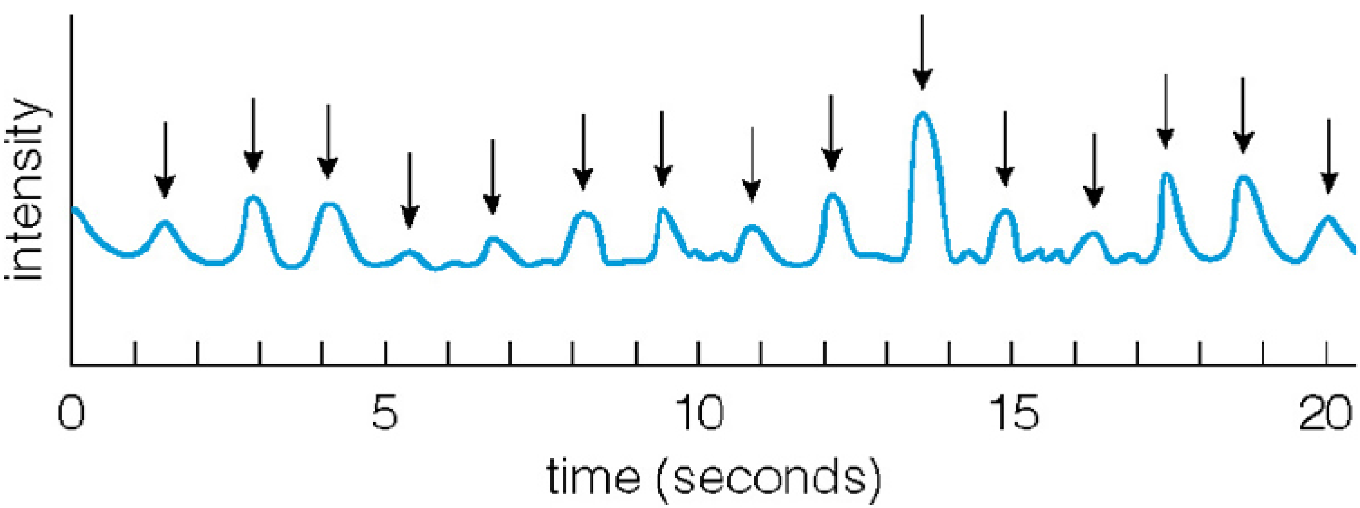
- In 1967, graduate student Jocelyn Bell and her advisor Anthony Hewish accidentally discovered a radio source in *Vulpecula* ***(LGM1)***.
- Sharp pulse recurred every 1.3 sec.
- Determined it was 300 pc away.
- They called it a "**pulsar**", but what was it?

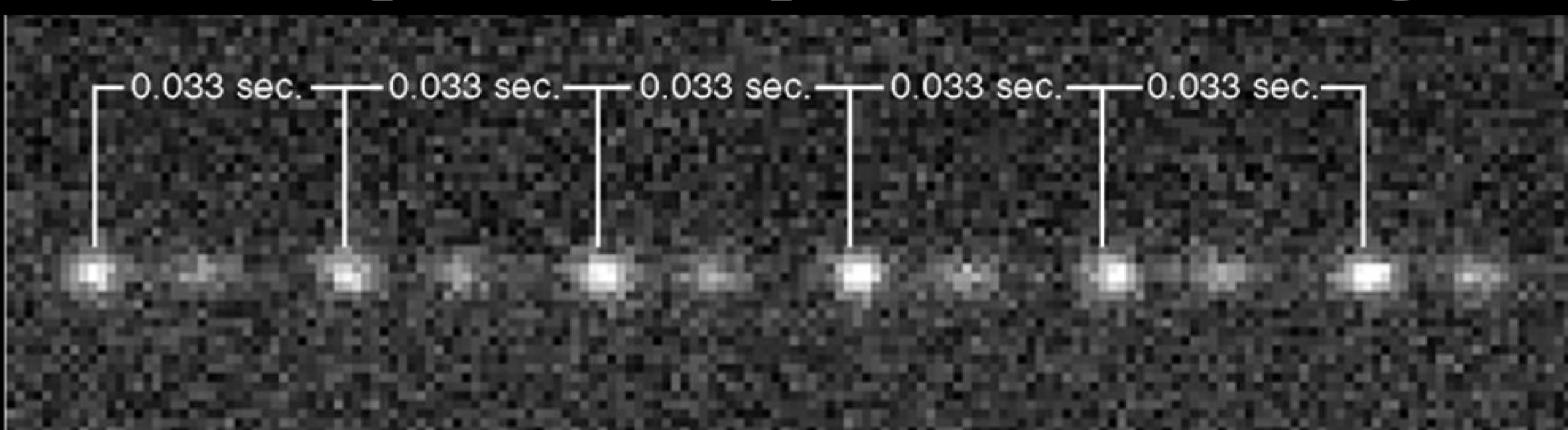




The Crab Pulsar

The mystery was solved when a pulsar was discovered in the heart of the Crab Nebula.

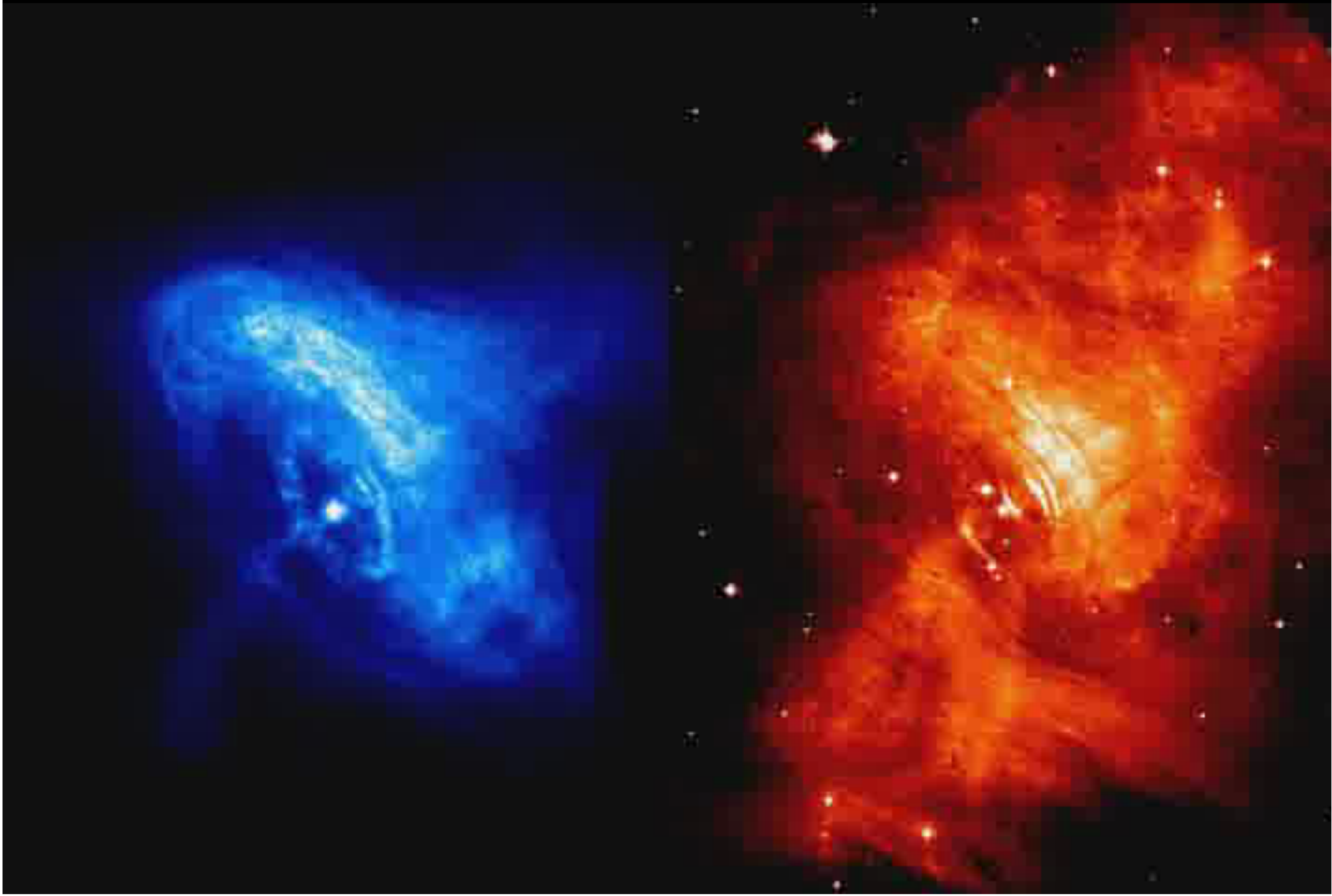
The Crab pulsar also pulses in visual light

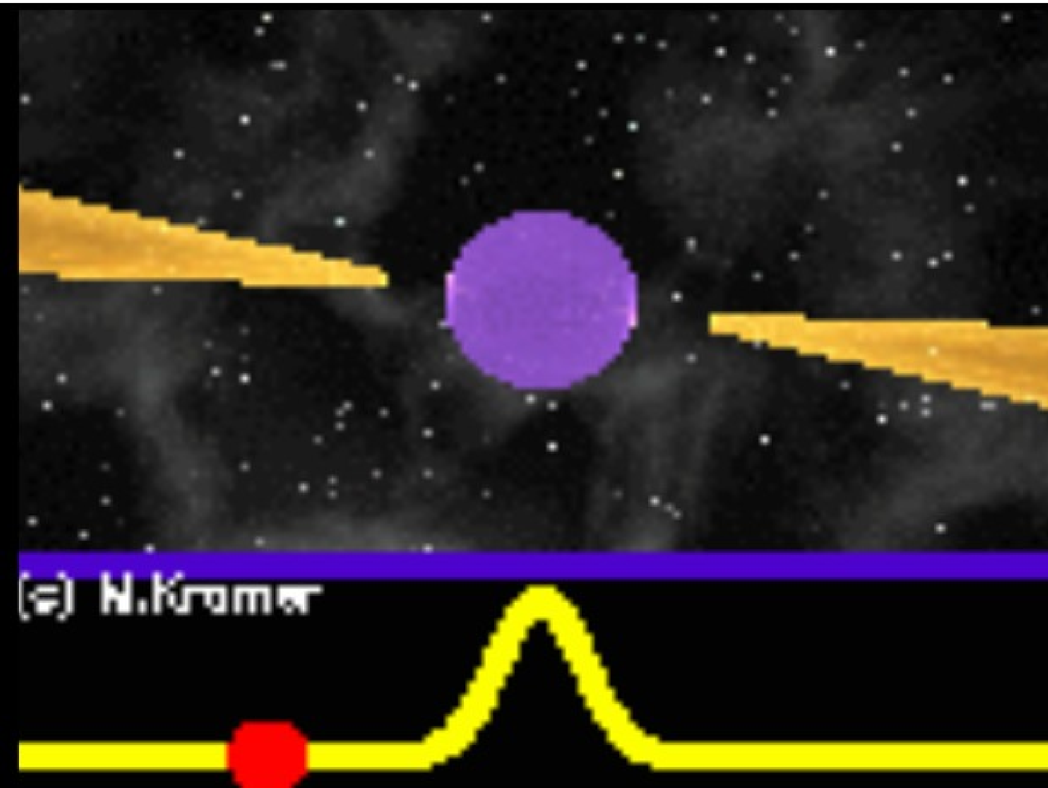


X-rays

Crab Nebula

Infrared





- PSR 0329+54 (714 ms)
- Vela Pulsar (89 ms)
- PSR 1937-21 (1.5 ms)

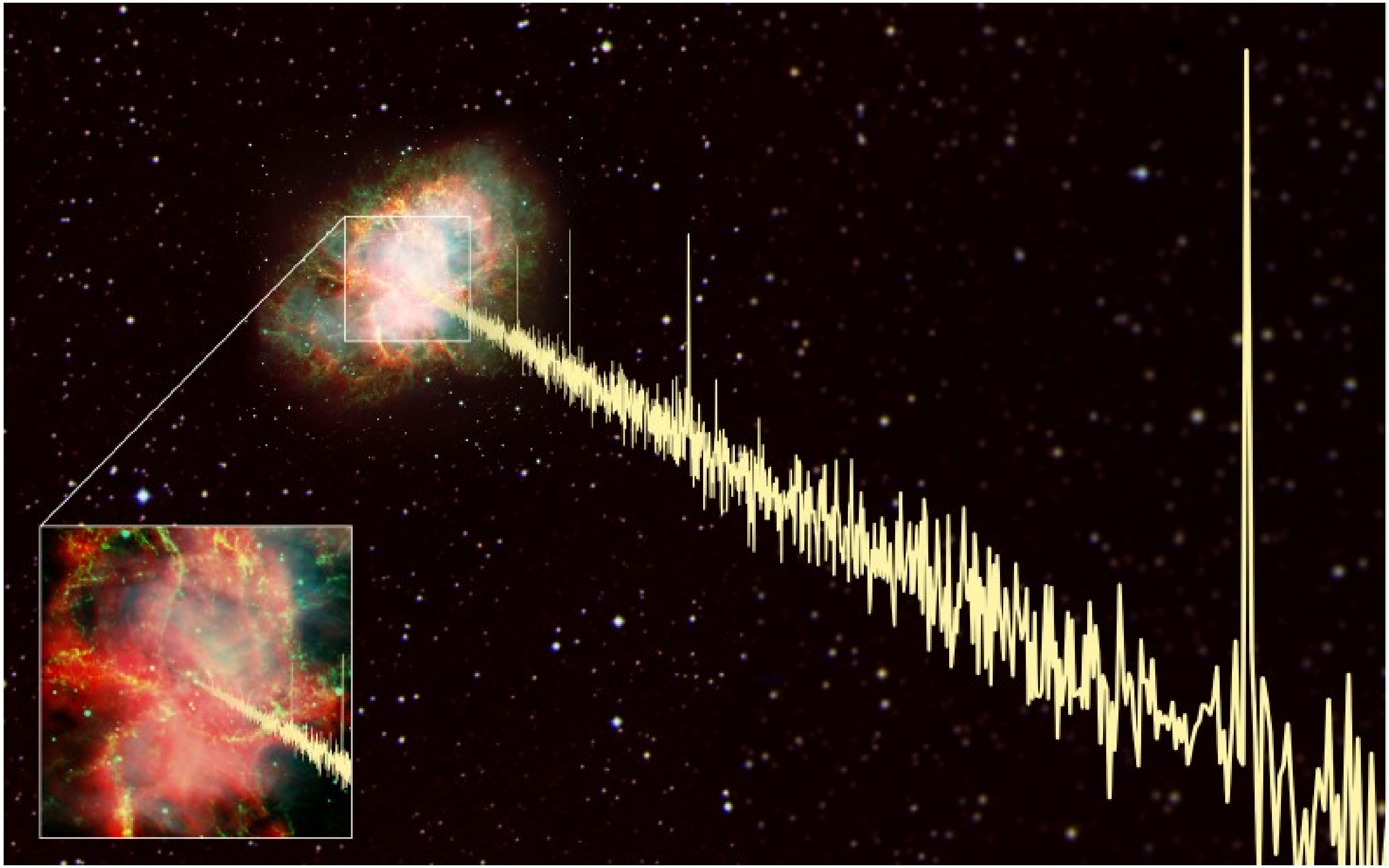
Centrifugal acceleration at equator < gravitational acceleration

$$\Omega^2 R < \frac{GM}{R^2} \Rightarrow \frac{4\pi^2}{P^2} < \frac{GM}{R^3} \Rightarrow P > 2\pi\sqrt{\frac{R^3}{GM}}$$

Minimum spin period for:

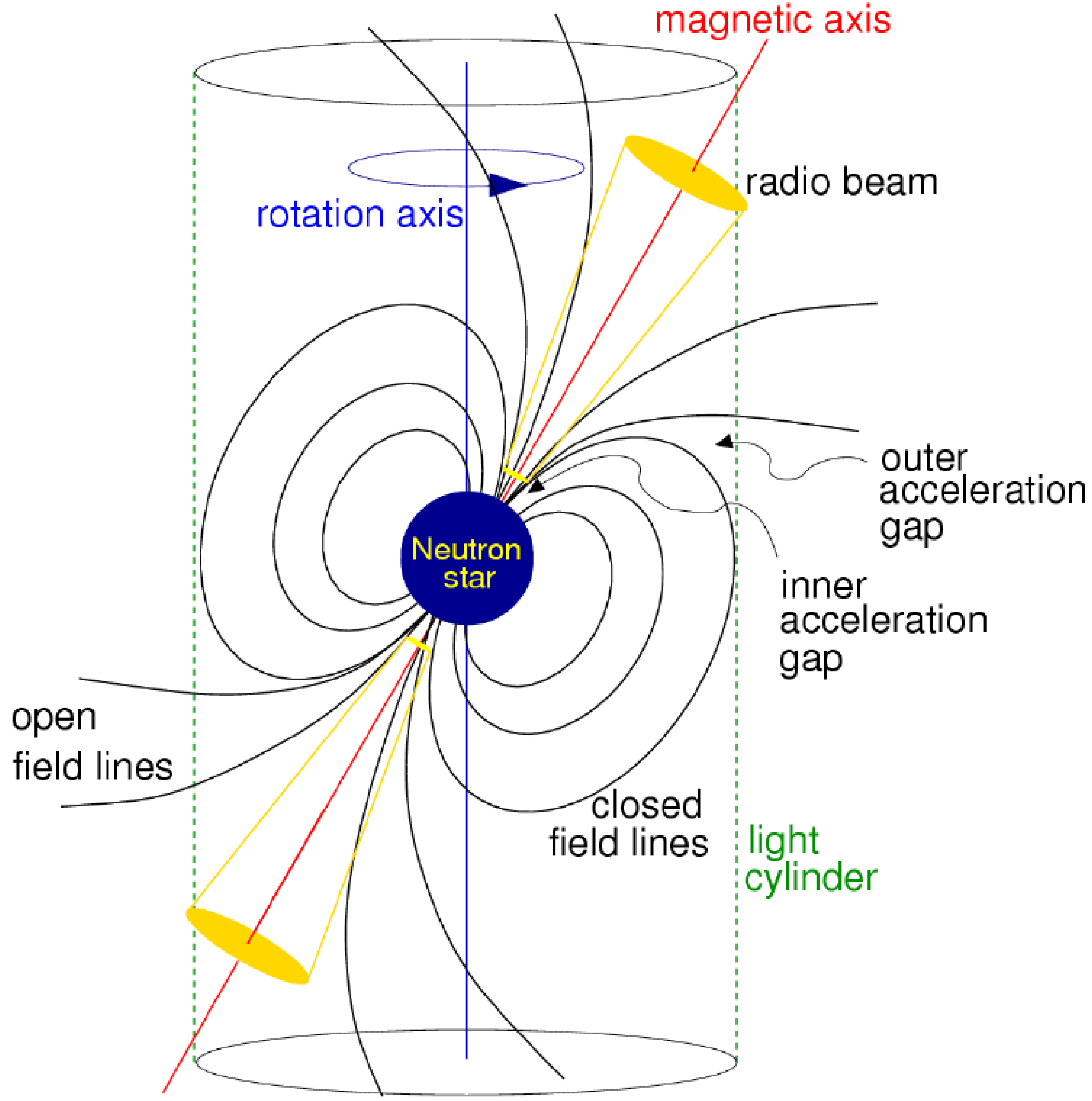
- Typical WD (R=10000 km, M=0.5 $M_\odot$) *P>24 s*
- The fastest WD (R=3000 km, M=1.3 $M_\odot$) *P>2.5 s*
- Typical NS (R=10 km, M=1.4 $M_\odot$) *P>0.5 ms*

Theory	**Observations**
Tiny	Small Pulse Width
Mass ~ 1.5 $M_\odot$	Confirmed in binaries
Supernova Corpse	Seen in SN Remnants
Rotating Fast	Short Pulse Period
High magnetic field	Synchrotron nebula and spin-down rate



- Isolated NSs are born as **fast-spinning radio pulsars**
- Pulsars **spin down** because of dipole radiation

From **young, fast and energetic** to **old, slow and faint** pulsars


magnetic axis
radio beam
rotation axis
outer
acceleration
gap
Neutron
star
inner
acceleration
gap
open
field lines
closed
field lines
light
cylinder

Crab: P=33 ms, $\dot{P}$=4.3 x 10^{-13} s s^{-1}

Rotational energy loss: $\dot{E}_{rot} = \frac{d}{dt}\left(\frac{1}{2} I\omega^2\right) = I\omega\dot{\omega} = I\frac{4\pi^2}{P}\frac{d}{dt}\left(\frac{1}{P}\right) = -4\pi^2 I\dot{P}P^{-3}$

$\Rightarrow \dot{E}_{rot,Crab} \approx 5\times 10^{38}$ erg s^{-1}

Rotating magnetic dipole in vacuum: $\dot{E} = -(32\pi^4/3c^3)B_\perp^2 R^6 P^{-4}$

$$\Rightarrow B_\perp = \sqrt{\frac{3c^3 IP\dot{P}}{8\pi^2 R^6}} \approx 3.2\times 10^{19}\left(P\dot{P}\right)^{1/2} \text{ G}$$

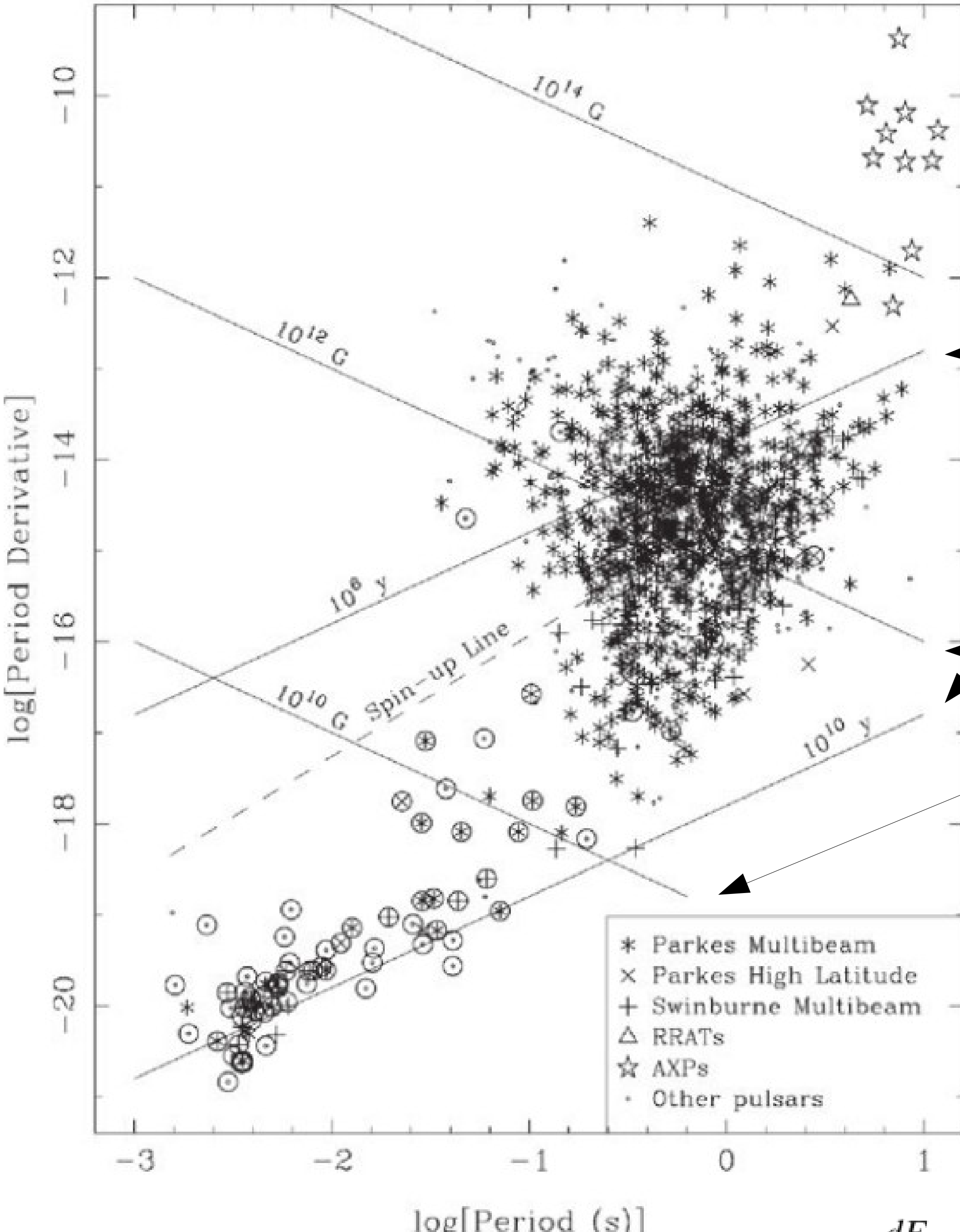
$\Rightarrow B_{Crab} \approx 4\times 10^{12}\ G$

Characteristic age: $\tau = P/2\dot{P}$

Assuming $B = const$: $P\dot{P} = const$

$$P\dot{P} = P\frac{dP}{dt} \Rightarrow \int_0^\tau PdP = \int_0^\tau P\dot{P}dt \Rightarrow \frac{1}{2}\left(P^2 - P_0^2\right) = P\dot{P}\tau \Rightarrow \tau \approx \frac{P}{2\dot{P}} \text{ if } P_0 << P$$

$\Rightarrow \tau_{Crab} \approx 1218$ yrs $\approx 2014 - 1054 = 960$ yrs



$$\tau = P/2\dot{P},$$

$$B_{NS} \propto \sqrt{P\dot{P}}.$$

$$-\frac{dE_{rot}}{dt} = \frac{d}{dt}\left(\frac{1}{2}I\Omega^2\right) = \frac{4\pi^2}{P^3}I\dot{P},$$

$$-\frac{dE_{md}}{dt} = \frac{B^2(R_{LC})}{8\pi}\left(4\pi R_{LC}^2 c\right) = \frac{1}{2}B_{NS}^2\left(\frac{R_{NS}^6}{R_{LC}^4}\right)c \propto \frac{B_{NS}^2}{P^4}.$$

- **Rotating Radio Transients (RRaTs):** discovered in 2006 as isolated radio pulses. But pulse separations are not random: regularly slowing down periods ⇒ “intermittent” radio pulsars

- **Radio-quiet gamma-ray pulsars:** only one (*Geminga*) known before 2008. Tens discovered by *Fermi* gamma-ray satellite. Why not detected in radio?

Emission beam much broader in gamma than in radio

Egret Pulsars

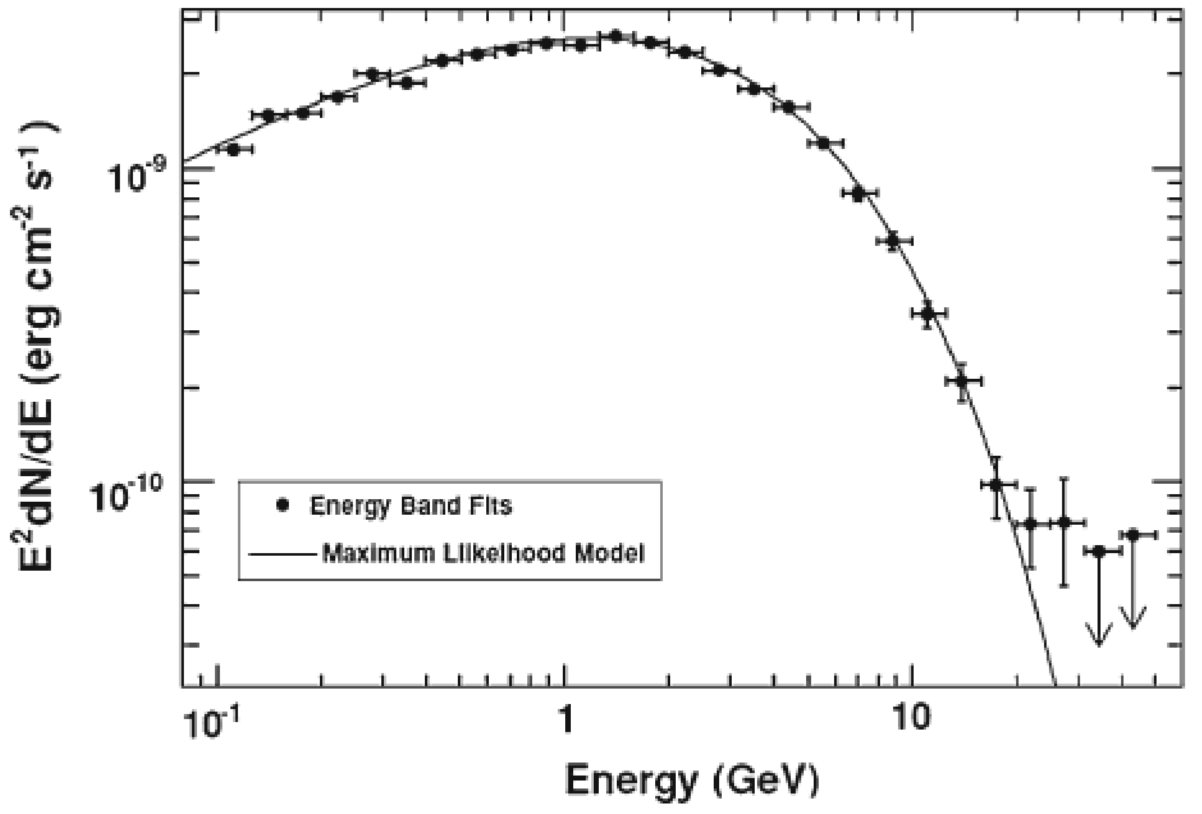
Table 3 γ-ray fluxes of EGRET pulsars [17, 44, 70]

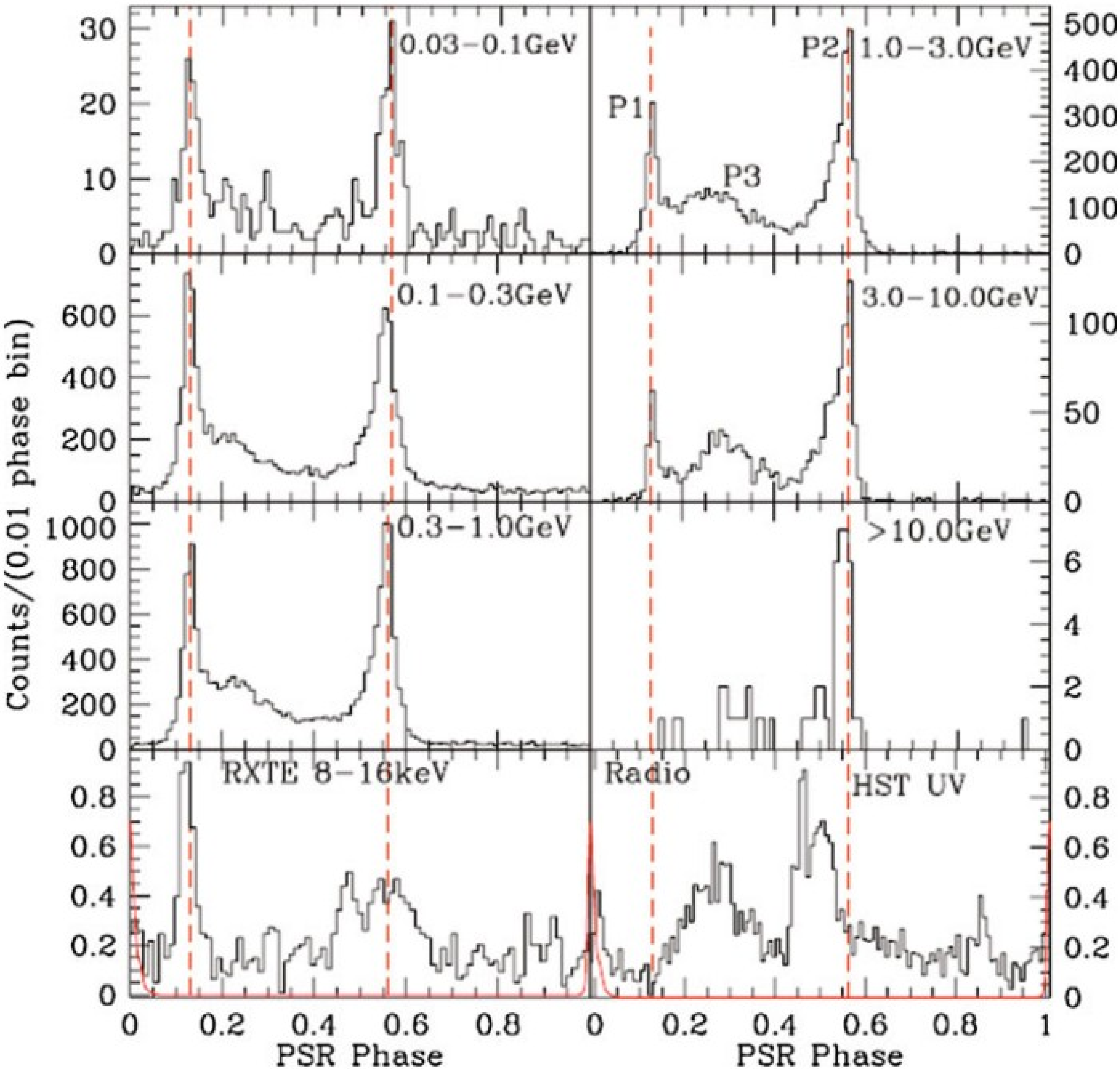
Pulsar	Period (ms) P	Age (kyr) $P/2\dot{P}$	EGRET F_{-8}	Pulsar catalog F_{-8}	2FGL F(1–100 GeV)[a]
0833-45, Vela	89.3	11.3	834.3 ± 11.2	1061 ± 7.0	135.8 ± 0.4
J0633+1746, Geminga	237	340	352.9 ± 5.7	305.3 ± 3.5	72.9 ± 0.3
0531+21,[b] Crab	33	1.25	226.2 ± 11.2	209 ± 4	18.3 ± 0.15
1706-44	102	17.6	111.2 ± 6.2	149.8 ± 4.1	19.1 ± 1.7
1055-52	197	540	33.3 ± 3.82	30.45 ± 1.7	5.0 ± 0.09
1951+32[c]	39.5	110	16 ± 2	17.6 ± 1.9	2.1 ± 0.07
1509-58,[c] Circinus	88.9	150	–	8.7 ± 1.4	1.45 ± 0.08

[a] Also in units of 10^{-8} ph cm^{-2} s^{-1}
[b] Associated with SN 1054
[c] Pulsars not reported in the 3EG [71]

Gamma-ray spectrum

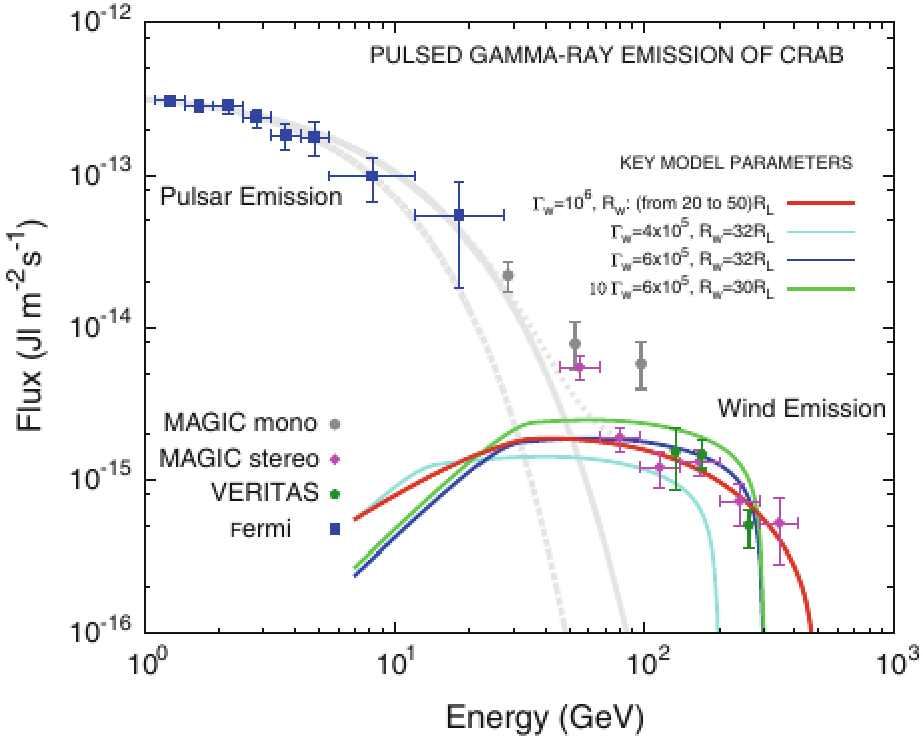
$$N(E) \propto E^{-\Gamma_\gamma} \exp[-(E/E_c)^b],$$



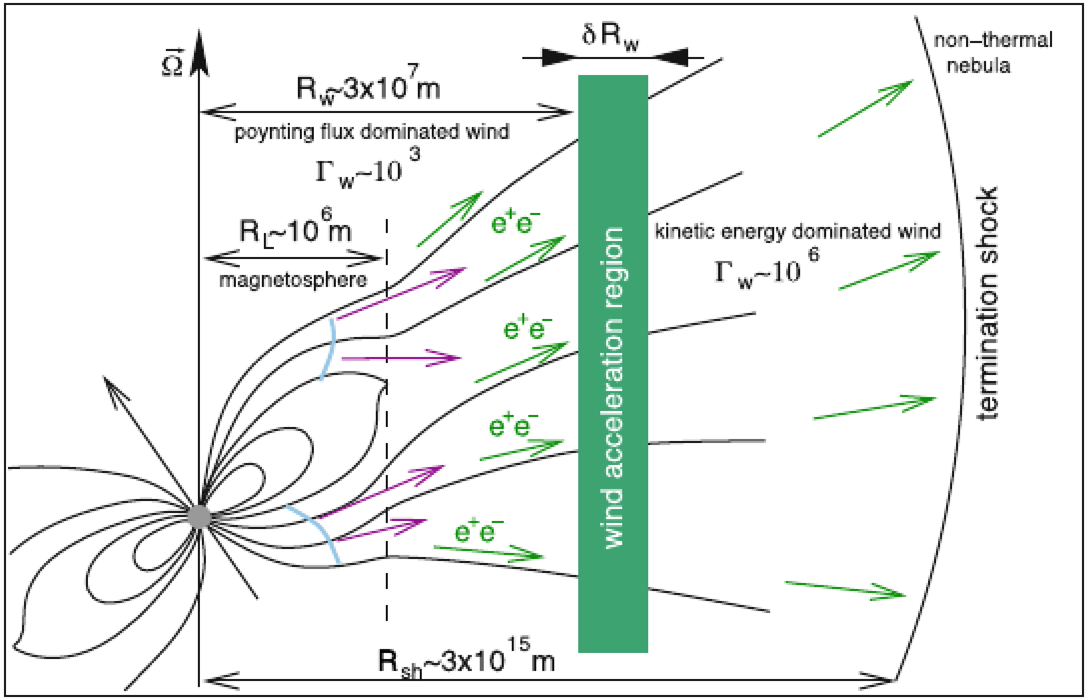


0.03–0.1GeV
P1
P2
P3
1.0–3.0GeV
0.1–0.3GeV
3.0–10.0GeV
0.3–1.0GeV
>10.0GeV
RXTE 8–16keV
Radio
HST UV
Counts/(0.01 phase bin)
PSR Phase
PSR Phase

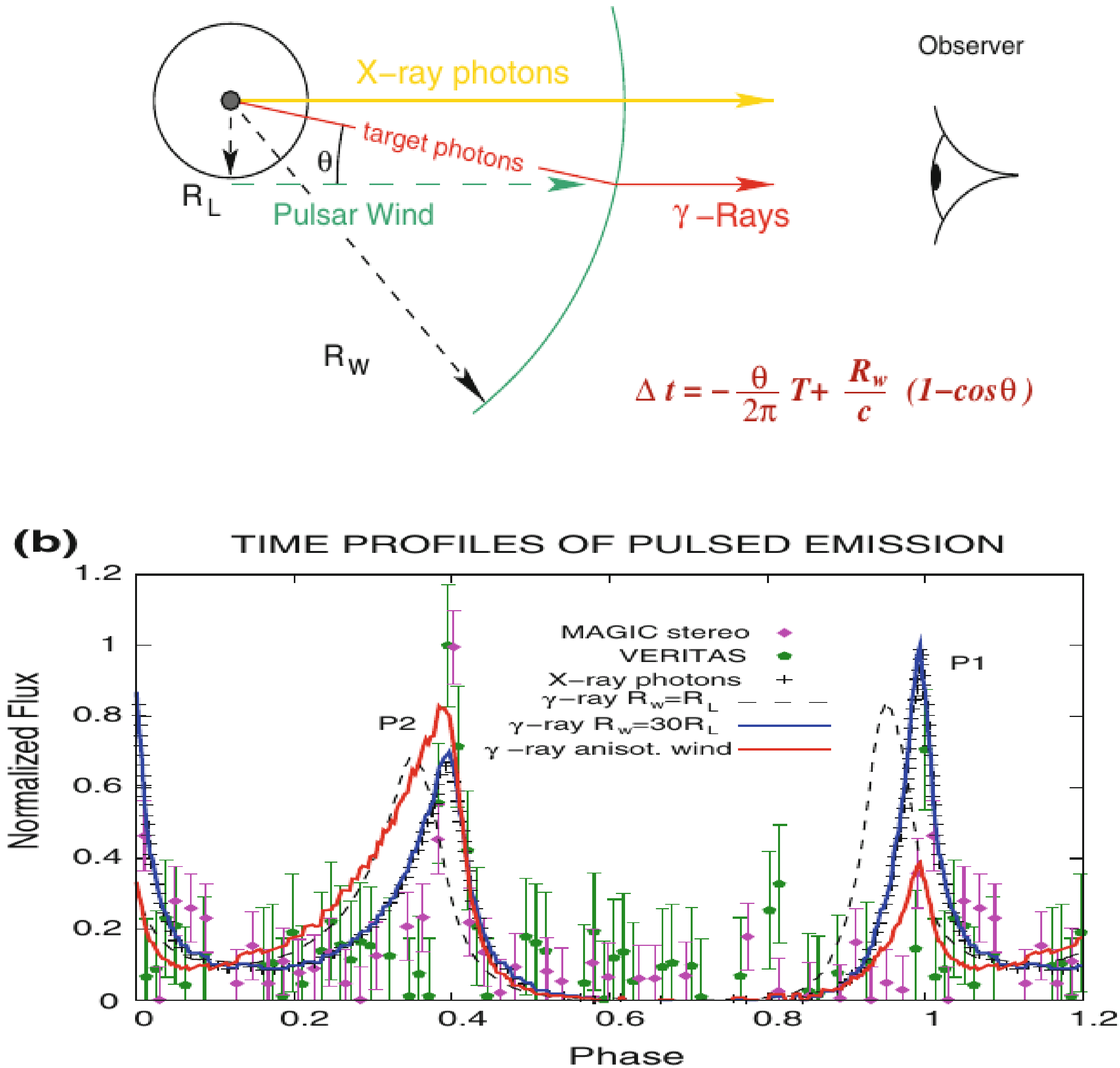
Crab Pulsed SED



Pulsar Wind

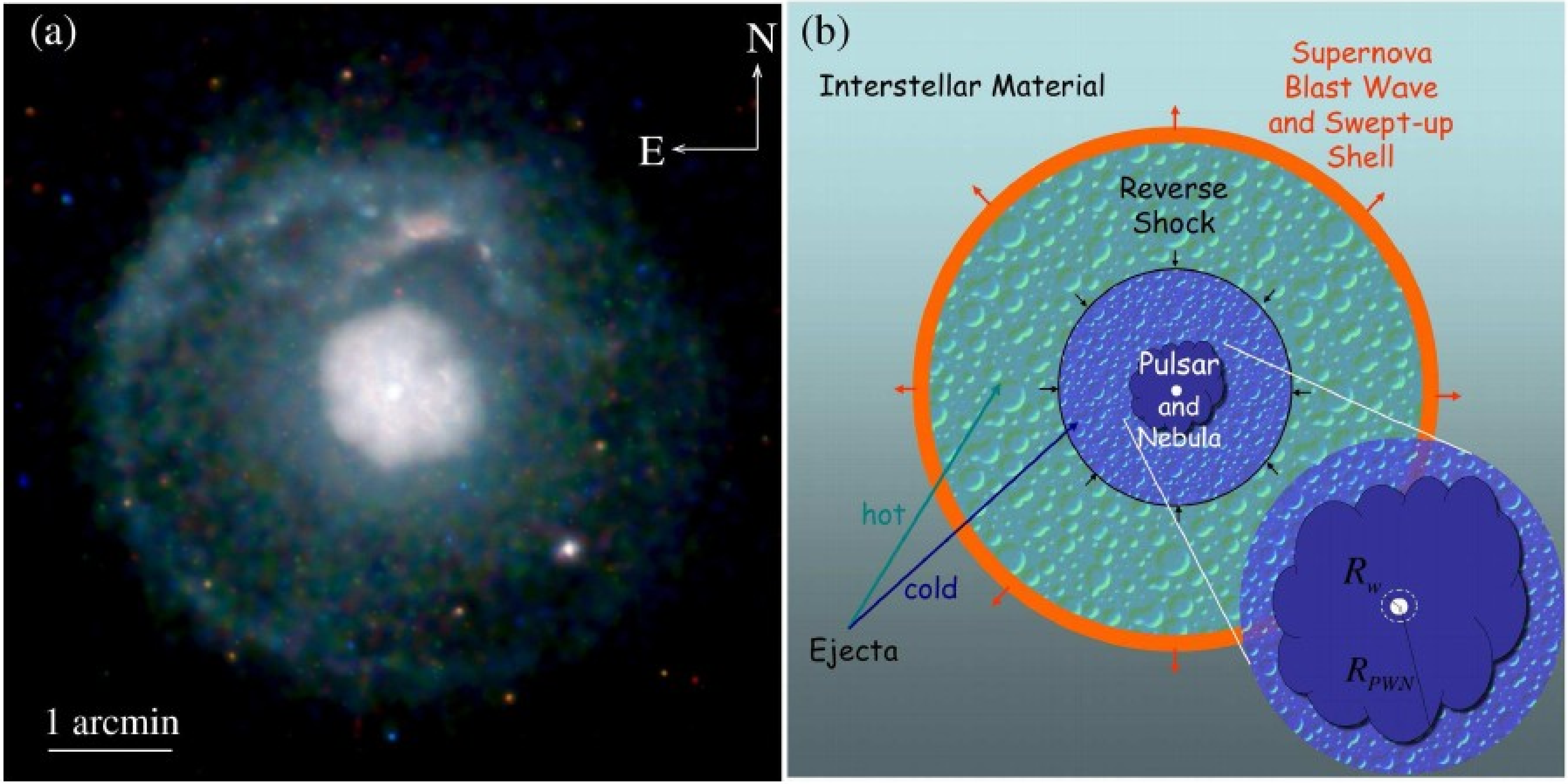


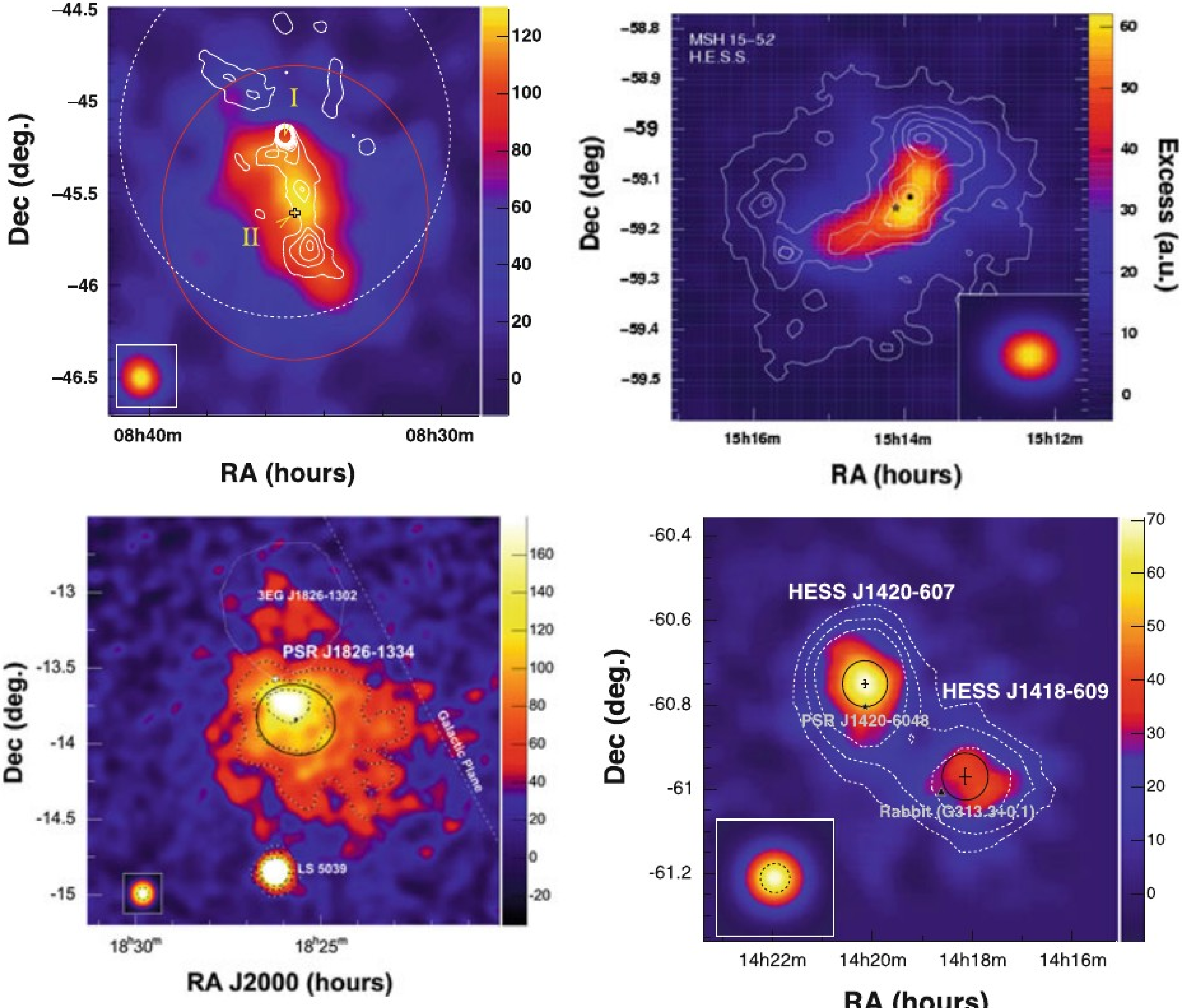
Ω
δ R_w
non−thermal nebula
R_w~3x10^7 m
poynting flux dominated wind
Γ_w~10^3
R_L~10^6 m
magnetosphere
e+e−
e+e−
e+e−
e+e−
wind acceleration region
kinetic energy dominated wind
Γ_w~10^6
termination shock
R_sh~3x10^15 m



Observer
X–ray photons
target photons
θ
R L
Pulsar Wind
γ –Rays
R W
$\Delta t = -\frac{\theta}{2\pi} T + \frac{R_w}{c} (1-\cos\theta)$
(b)
TIME PROFILES OF PULSED EMISSION
Normalized Flux
Phase
MAGIC stereo
VERITAS
X–ray photons
γ–ray R w=R L
γ–ray R w=30R L
γ –ray anisot. wind
P1
P2
0
0.2
0.4
0.6
0.8
1
1.2

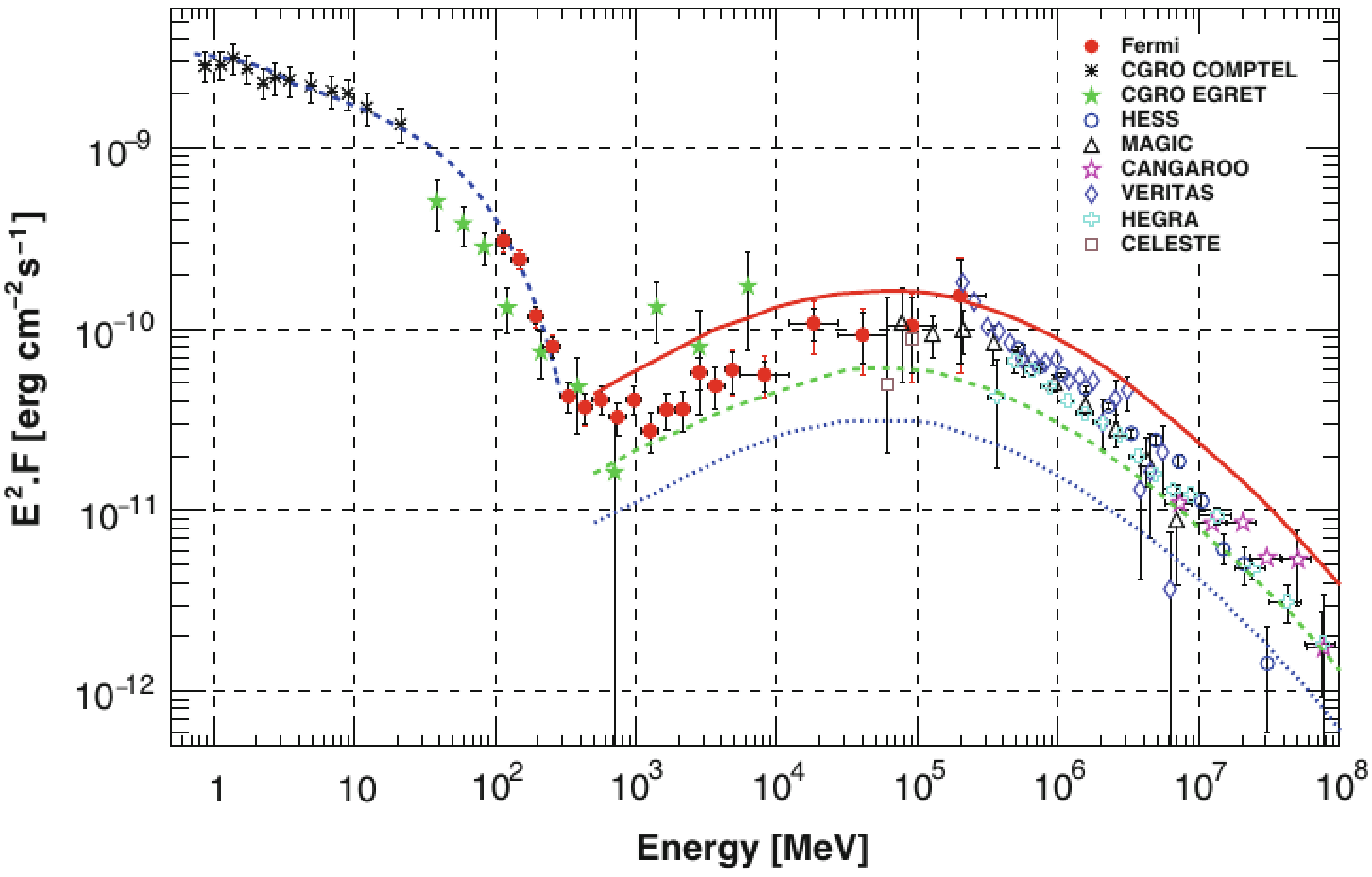
Pulsar Wind Nebulae



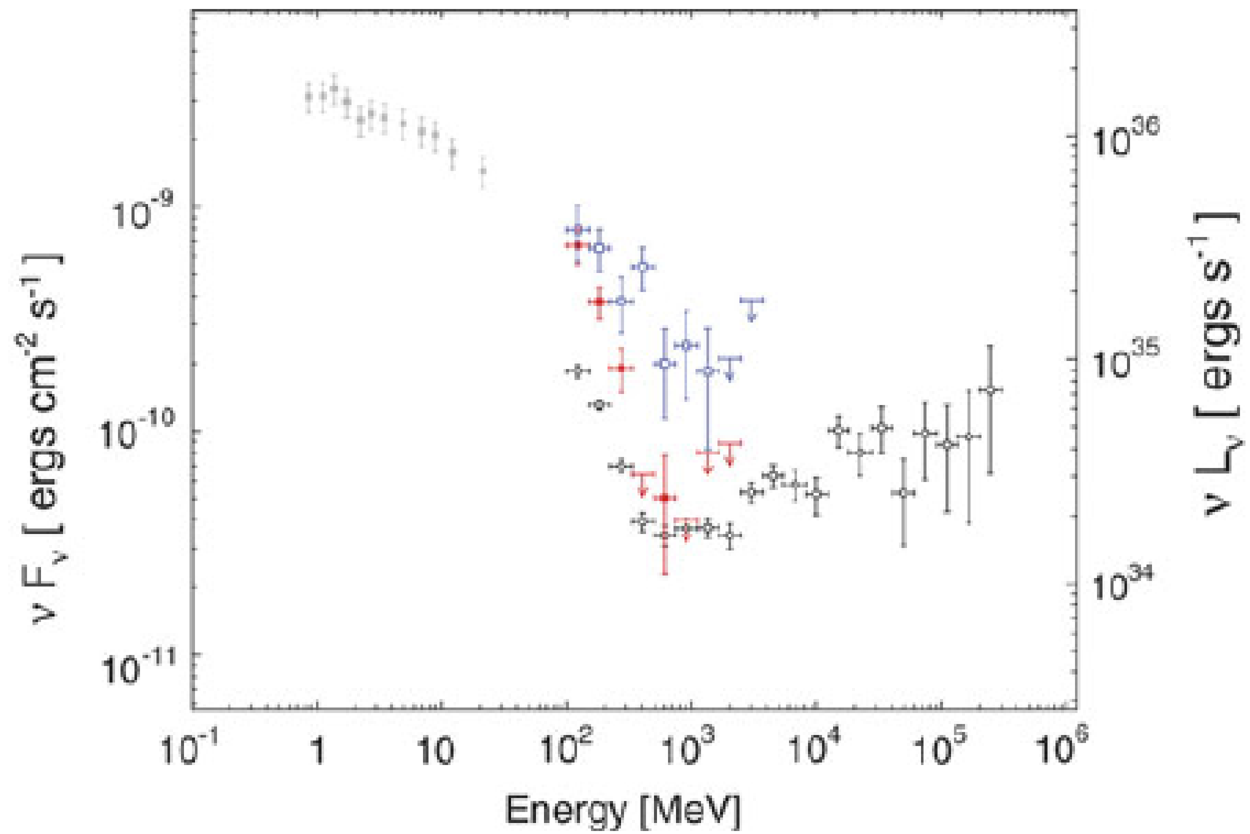


Dec (deg.)
-44.5
-45
-45.5
-46
-46.5
I
II
120
100
80
60
40
20
0
08h40m
08h30m
RA (hours)
MSH 15-52
H.E.S.S.
Dec (deg)
-58.8
-58.9
-59
-59.1
-59.2
-59.3
-59.4
-59.5
Excess (a.u.)
60
50
40
30
20
10
0
15h16m
15h14m
15h12m
RA (hours)
Dec (deg.)
-13
-13.5
-14
-14.5
-15
3EG J1826-1302
PSR J1826-1334
Galactic Plane
LS 5039
160
140
120
100
80
60
40
20
0
-20
18h30m
18h25m
RA J2000 (hours)
Dec (deg.)
-60.4
-60.6
-60.8
-61
-61.2
HESS J1420-607
HESS J1418-609
PSR J1420-6048
Rabbit (G313.3+0.1)
70
60
50
40
30
20
10
0
14h22m
14h20m
14h18m
14h16m
RA (hours)

Crab PWN SED


Fermi
CGRO COMPTEL
CGRO EGRET
HESS
MAGIC
CANGAROO
VERITAS
HEGRA
CELESTE
E^2.F [erg cm^{-2}s^{-1}]
Energy [MeV]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
1
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8

Crab Flares



10^-9
10^-10
10^-11
ν F_ν [ergs cm^-2 s^-1]
10^36
10^35
10^34
ν L_ν [ergs s^-1]
10^-1
1
10
10^2
10^3
10^4
10^5
10^6
Energy [MeV]

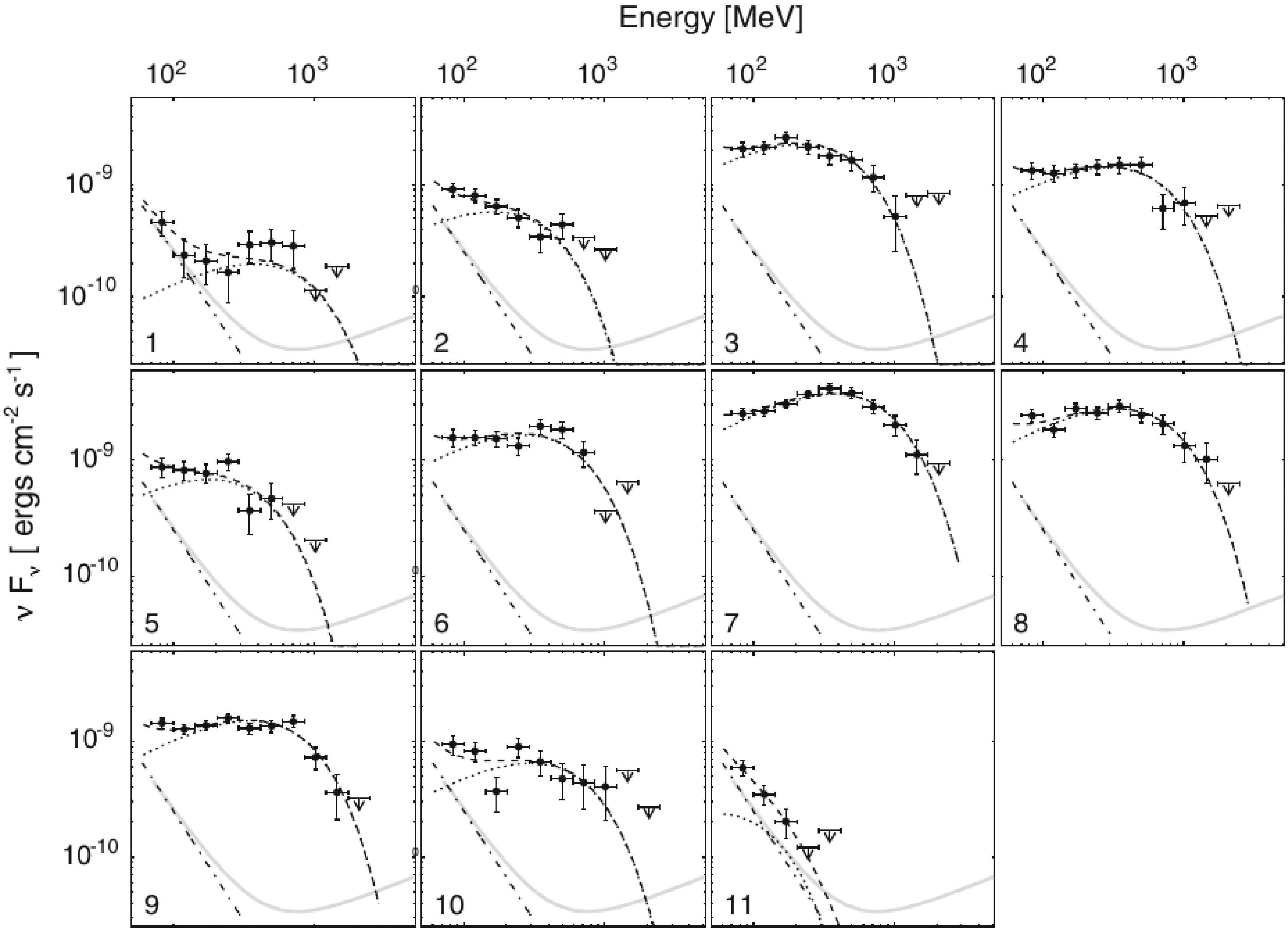
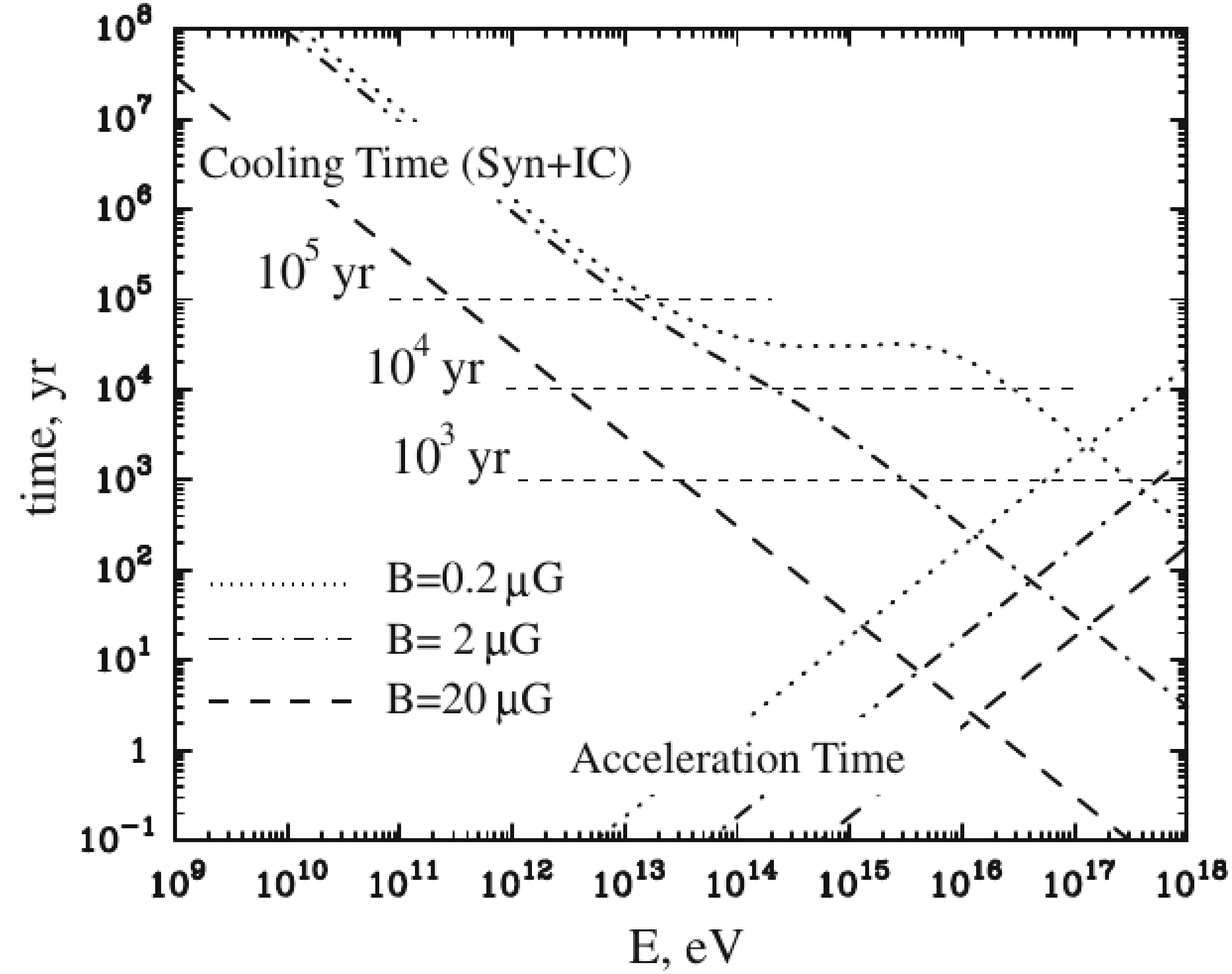
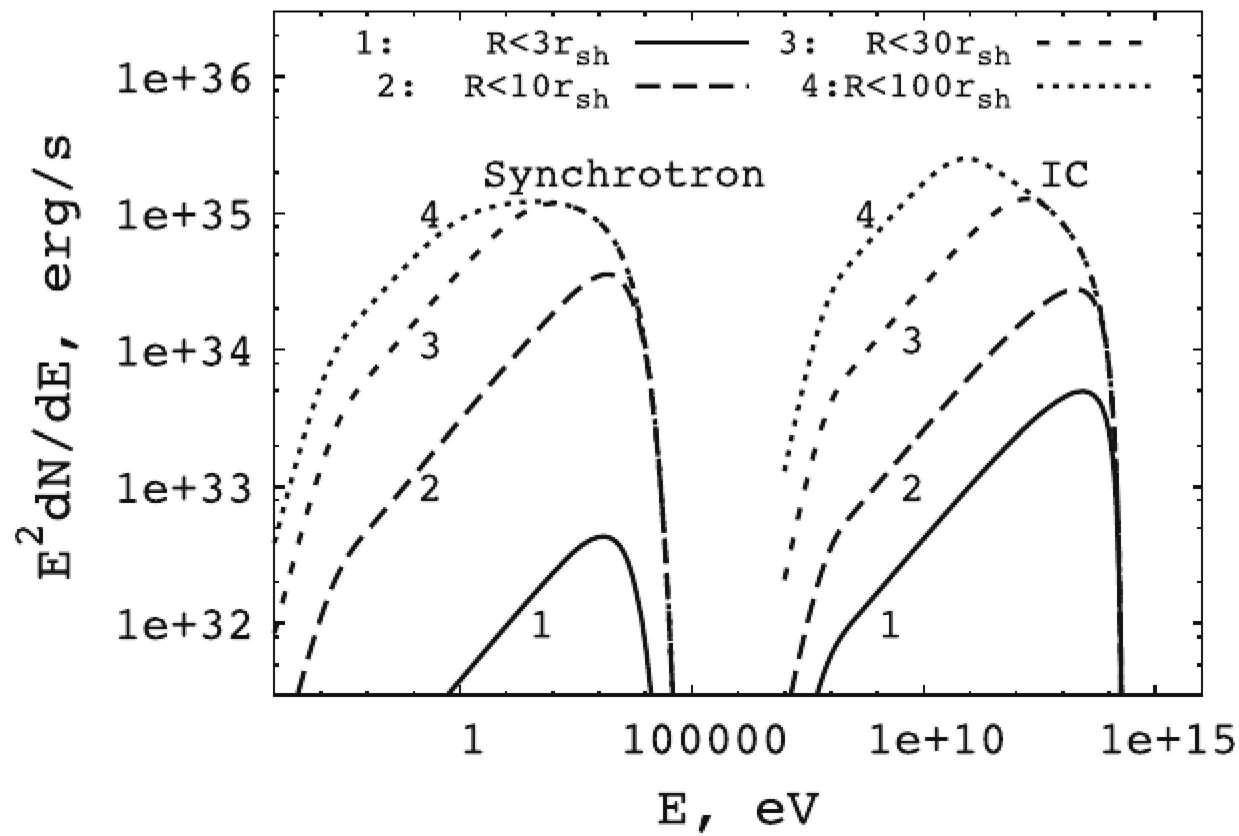


Fig. 41 Time evolution of the Crab SED during the April 2011 flare. The flare duration of approximately 9 days has been divided in 11 time windows of approximately constant flux. The *dot-dashed line* indicates the assumed constant background from the synchrotron nebula. The *dotted lines* show the flaring component, and the *dashed lines* are the sums of the background and flaring components (from Ref. [110])



Cooling Time (Syn+IC)
10^5 yr
10^4 yr
10^3 yr
B=0.2 μG
B= 2 μG
B=20 μG
Acceleration Time
time, yr
E, eV


1: R<3r_sh
3: R<30r_sh
2: R<10r_sh
4:R<100r_sh
Synchrotron
IC
4
3
2
1
4
3
2
1
1e+36
1e+35
1e+34
1e+33
1e+32
E^2dN/dE, erg/s
1
100000
1e+10
1e+15
E, eV

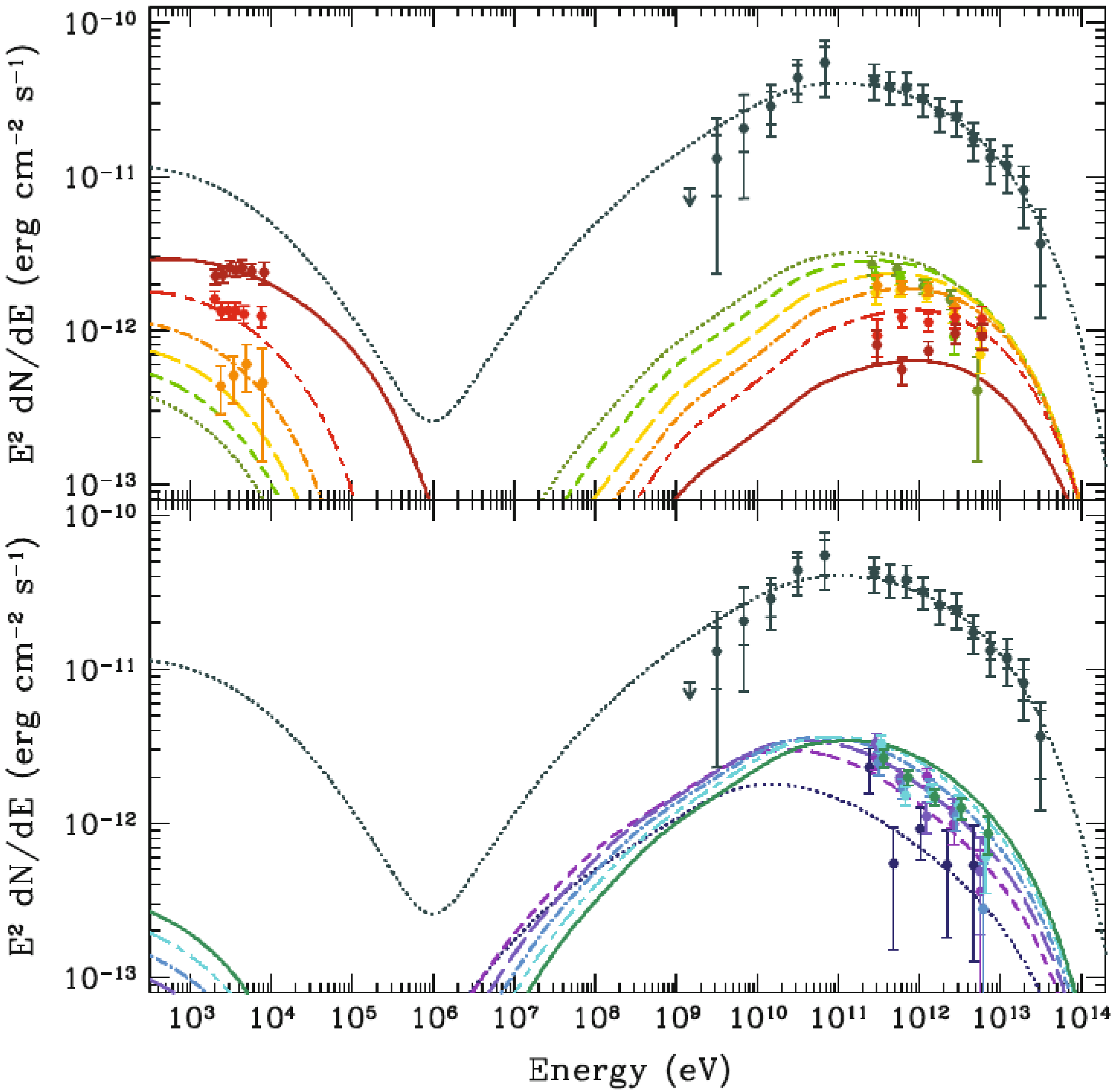


Fig. 48 SED of broad-band IC gamma-ray emission of the pulsar wind nebula HESS J1825-137 calculated for 12 zones with a constant 6 arcmin width of the zones: $0' - 6'$, $6' - 12'$, $\ldots 66' - 72'$. The *theoretical curves* are shown together with observational points obtained with the *Suzaku* (the inner 6 zones), *Fermi LAT* (the entire nebula), and HESS (all 12 zones) telescopes [242]