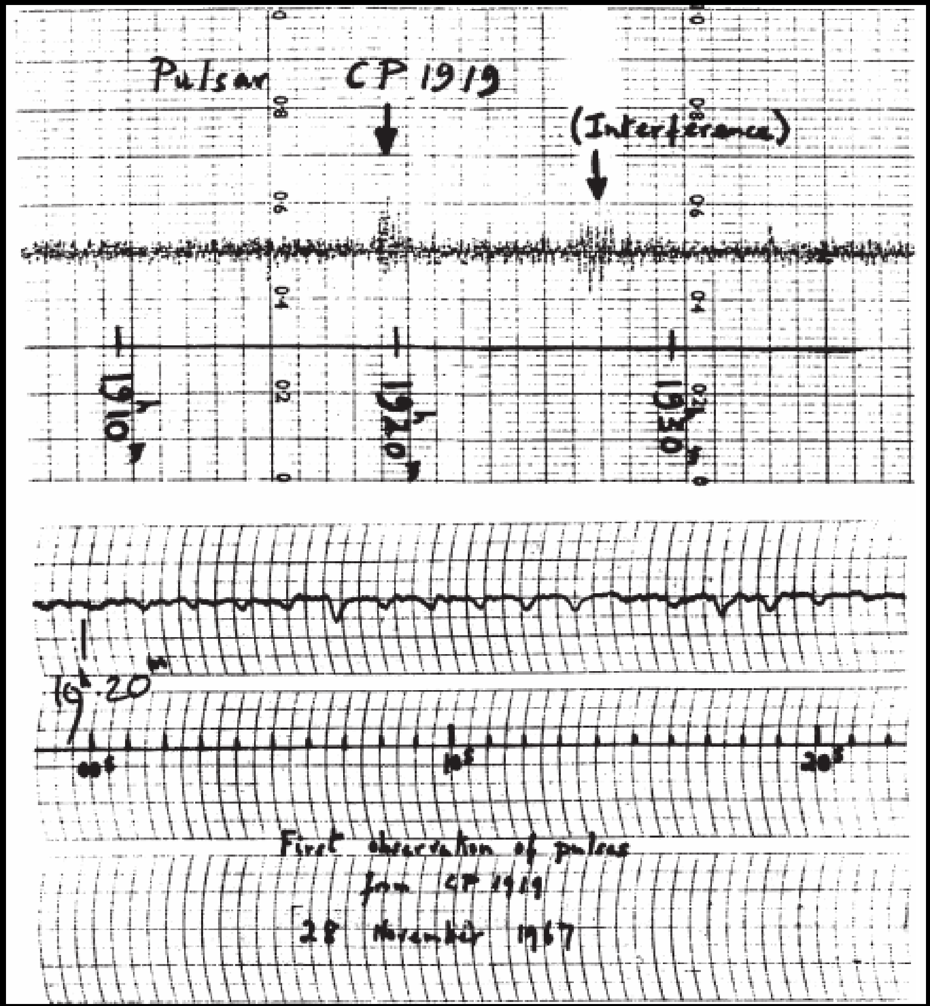
Pulsar and
Pulsar Wind Nebulae

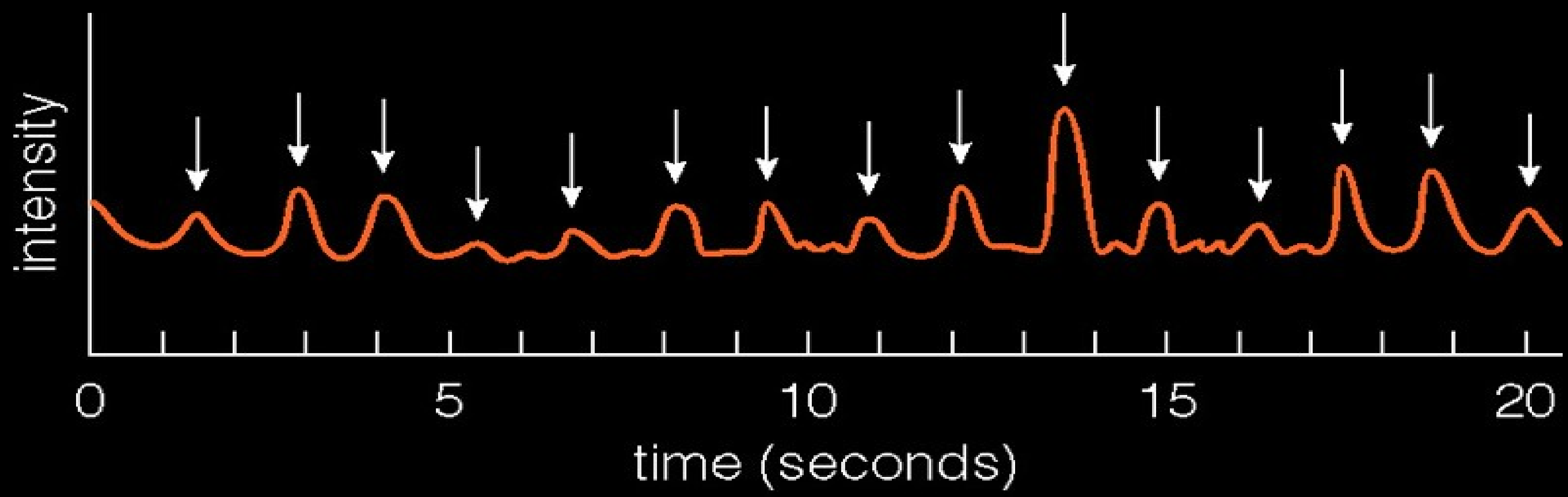
Discovery of 1st Pulsar



In 1967, graduate student Jocelyn Bell and her advisor Anthony Hewish accidentally discovered a radio source in *Vulpecula* ***(LGM1)***.

Discovery of 1st Pulsar

- Sharp pulse recurred every 1.3 sec.
- Determined it was 300 pc away.
- They called it a "**pulsar"**, but what was it?



Break-up limit for WDs and NSs

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 $M_{\odot}$)

M1 – Crab Nebula

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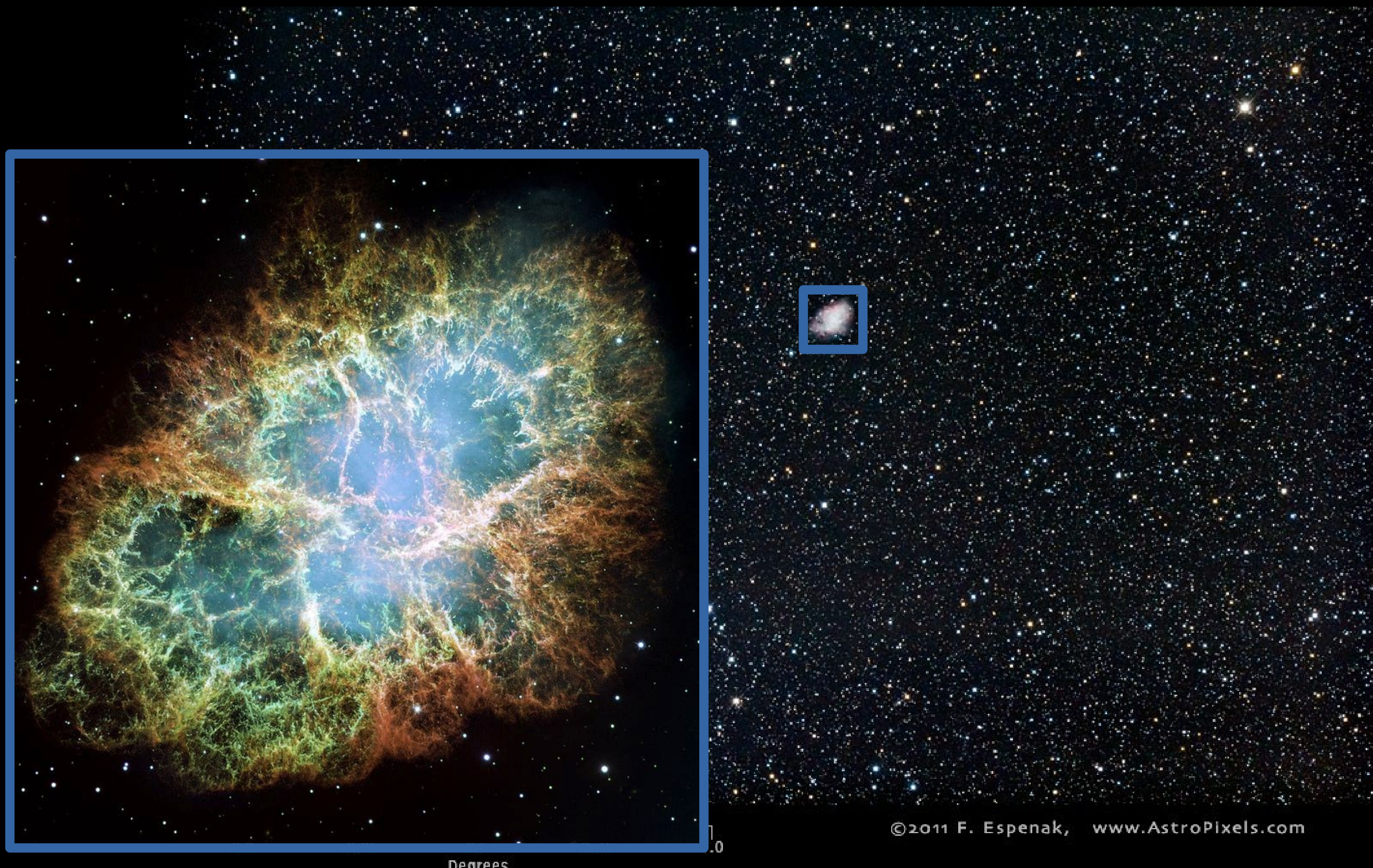
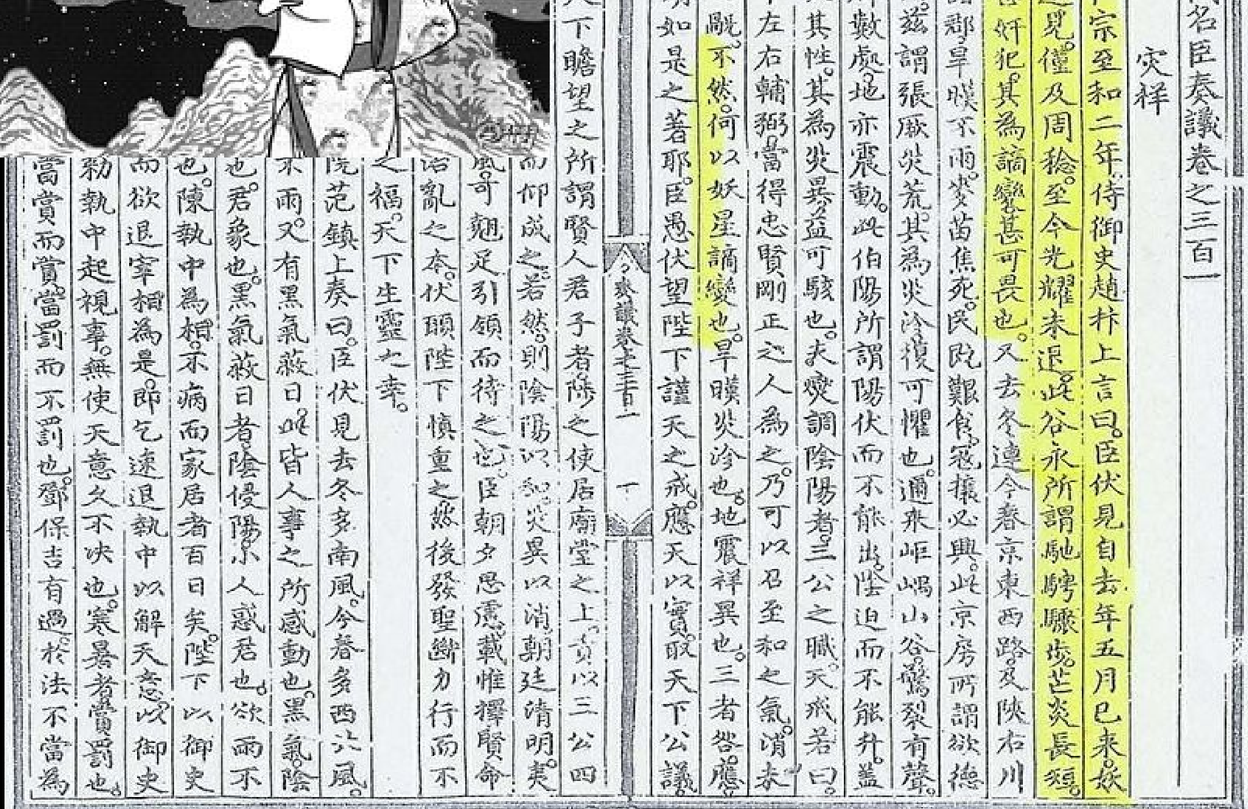


SN 1054



歷代名臣奏議卷之三百一

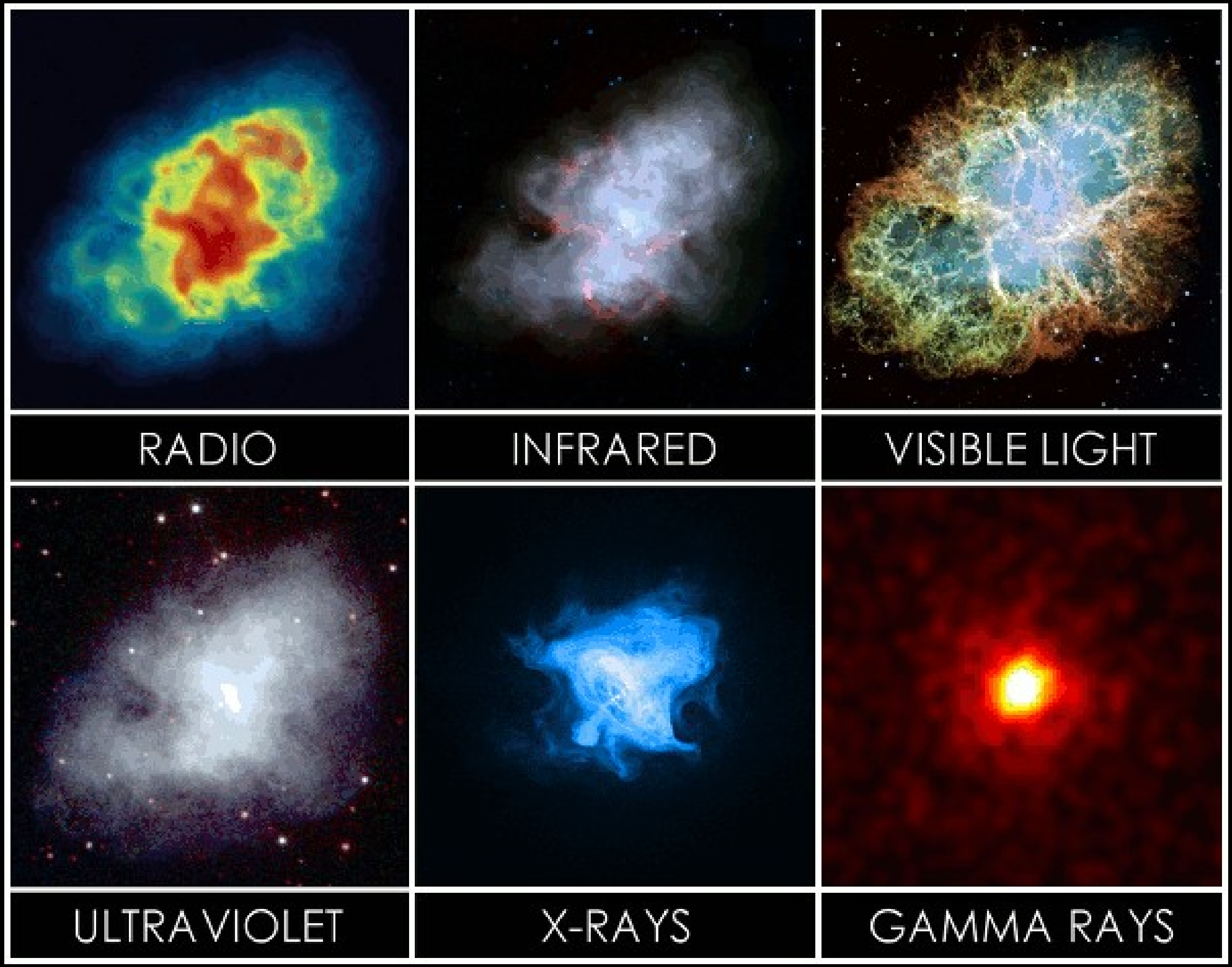
災祥

宋仁宗至和二年侍御史趙抃上言曰臣伏見自去年五月已來妖星遂見僅及周稔至今光耀未退此谷永所謂馳騁驂驪芒炎長短所懸奸犯其為謫變甚可畏也又去冬連今春京東西路及陝右川蜀諸郡旱暵不雨麥苗焦死民既艱食寇攘必興此京房所謂欲德不用茲謂張厥災荒其為災沴複可懼也邇來岷峨山谷驚裂有聲他郡數處地亦震動此伯陽所謂陽伏而不能出陰迫而不能升蓋土失其性其為災異益可駭也夫燮調陰陽者三公之職天戒若曰陛下左右輔弼當得忠賢剛正之人為之乃可以召至和之氣消去萌之亂不然何以妖星謫變也旱暵災沴也地震祥異也三者咎應燦明如是之著耶臣愚伏望陛下謹天之戒應天以實取天下公議

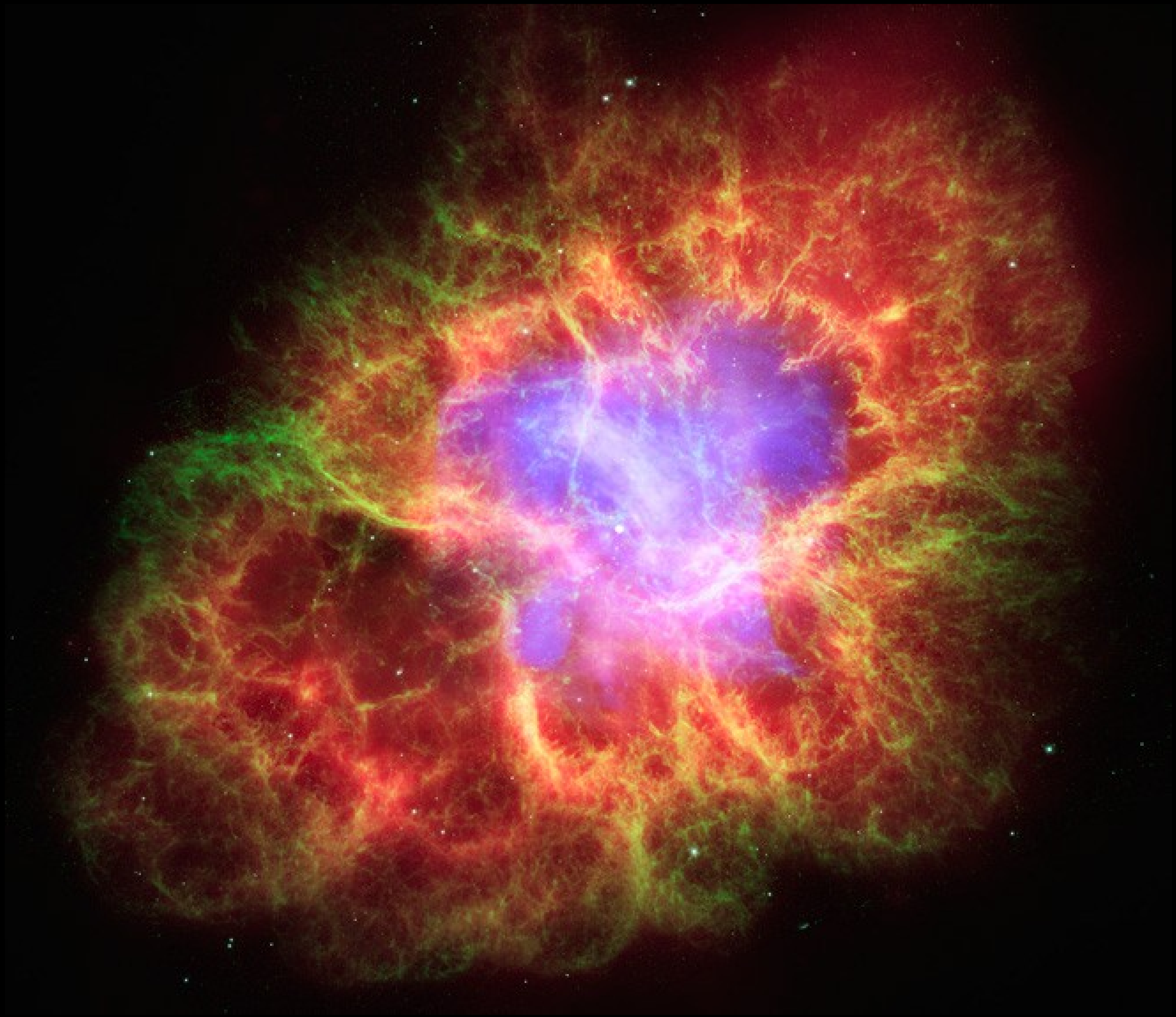
奏議卷三百一　一

與天下瞻望之所謂賢人君子者陟之使居廟堂之上貢以三公四
而仰成之若然則陰陽以和災異以消朝廷清明矣
風奇翹足引領而待之也臣朝夕思慮載惟擇賢命
治亂之本伏願陛下慎重之然後發聖斷力行而不
之福天下生靈之幸
院范鎮上奏曰臣伏見去冬多南風今春多西北風
不雨又有黑氣蔽日此皆人事之所感動也黑氣陰
也君象也黑氣蔽日者陰侵陽小人惑君也欲雨不
也陳執中為相不病而家居者百日矣陛下以御史
而欲退窜相為是郎乞速退執中以解天意以御史
勑執中起視事無使天意久不決也寒暑者賞罰也
當賞而賞當罰而不罰也鄧保吉有過於法不當為

MW Crab Nebula

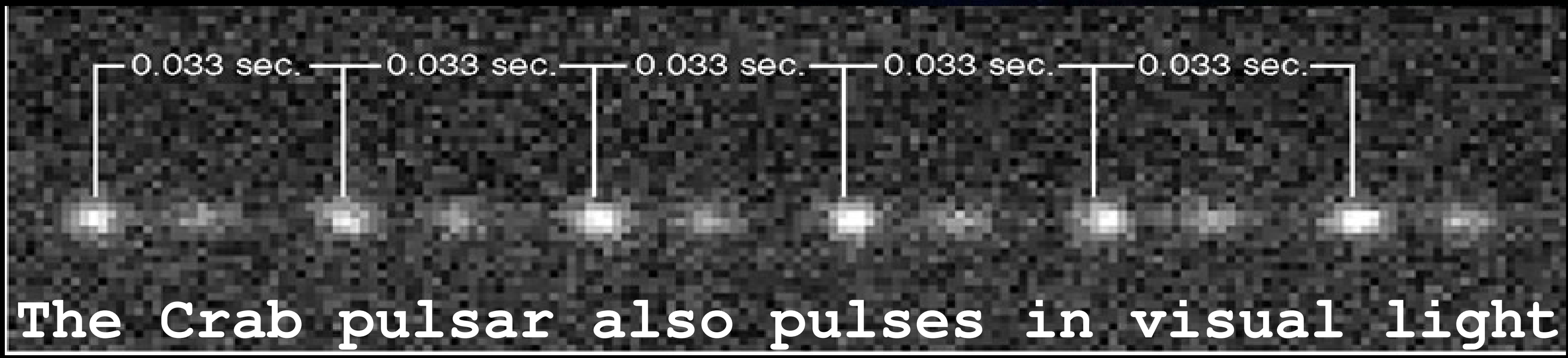


Crab



The Crab Pulsar

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



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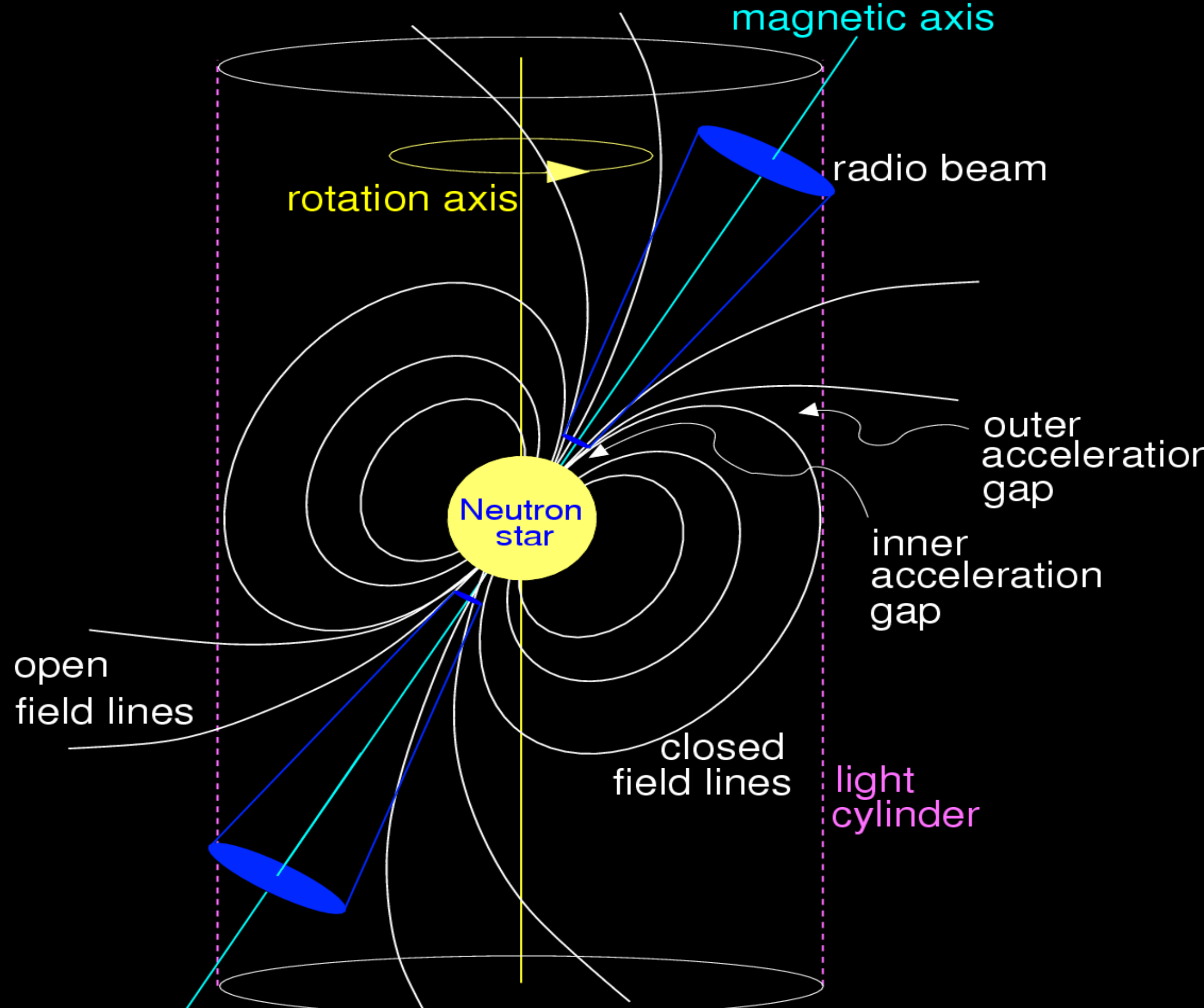
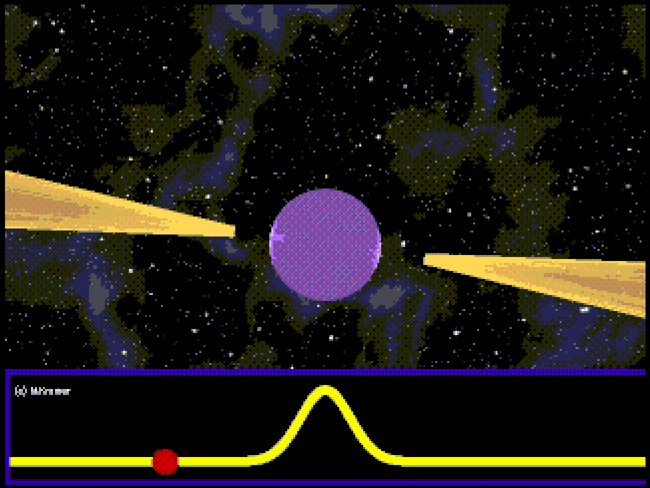
- Typical WD (R=10000 km, M=0.5 $M_\odot$) *P>24 s*
- The fastest WD (R=3000 km, M=1.3 $M_\odot$) *P>2.5 s*
- Typical NS (R=10 km, M=1.4 $M_\odot$) *P>0.5 ms*


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

Pulsar: cosmic lighthouse



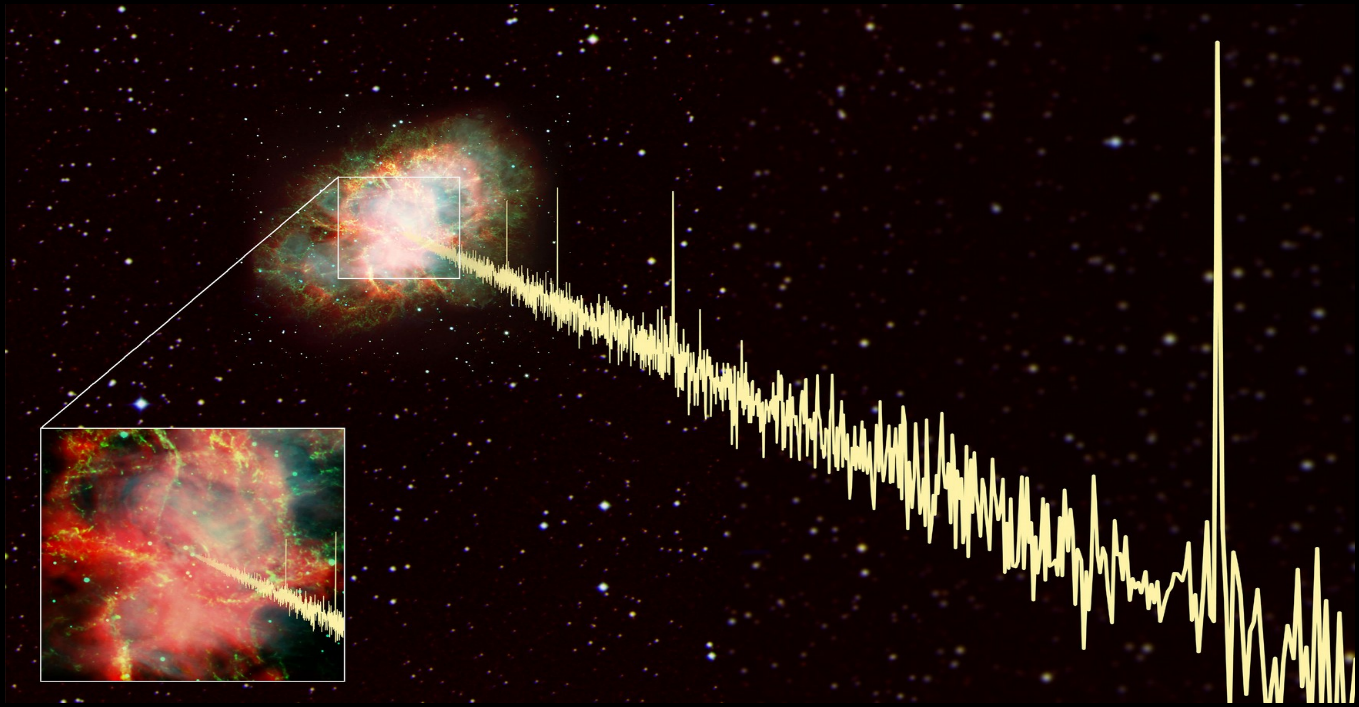
- PSR 0329+54 (714 ms)
- Vela Pulsar (89 ms)
- PSR 1937-21 (1.5 ms)

Neutron Star = Pulsar

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 and spin-down rate	Synchrotron nebula

The Crab paradigm

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



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

Crab Pulsar

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

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

$$\Rightarrow \dot{E}_{rot,Crab} \approx 5\times10^{38}\ \text{erg s}^{-1}$$

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

$$\Rightarrow B_\perp = \sqrt{\frac{3c^3 IP\dot{P}}{8\pi^2 R^6}} \approx 3.2\times10^{19}\left(P\dot{P}\right)^{1/2}\ \text{G}$$

$$\Rightarrow B_{Crab} \approx 4\times10^{12}\ G$$

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

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

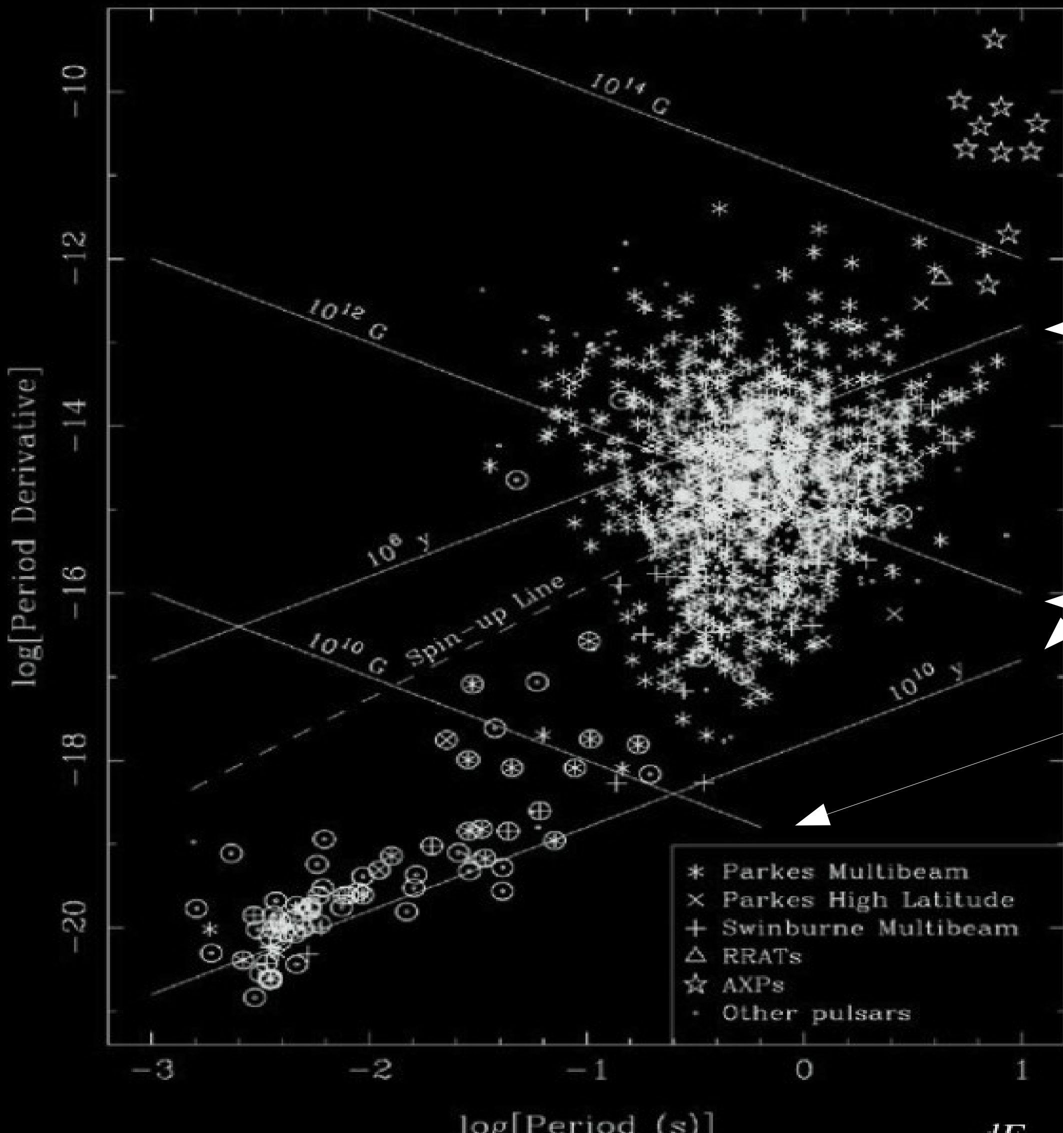
$$P\dot{P} = P\frac{dP}{dt} \Rightarrow \int_0^\tau PdP = \int_0^\tau P\dot{P}dt \Rightarrow \frac{1}{2}\left(P^2 - P_0^2\right) = P\dot{P}\tau \Rightarrow \tau \approx \frac{P}{2\dot{P}} \text{ if } P_0 << P$$

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

What is the energy source?

Rotation

Radio pulsars are rotation-powered neutron stars



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

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

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

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

Neutron Stars cooling

Originating from supernova explosions, NSs are very **hot at birth**: $T \sim 10^{11}$ K

Very **fast initial cooling**, due to neutrino emission: $T \sim 10^{9}$-10^{10} K after ~1 day

- After ~100 years, NS interior is **~isothermal**.
- Cooling: $dU/dt = - L_\nu(T_i) - L_\gamma(T_s) + \Sigma_k H_k$
  - $L_\nu = \int Q_\nu \, dV$
  - $L_\gamma = 4\pi R^2 \sigma T_s^4$
  - H_k = heating processes (esothermal reactions, viscosity, beta decay, accretion ...)

Cooling is driven by **neutrinos** for $\sim 10^5$ years, then by photons

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

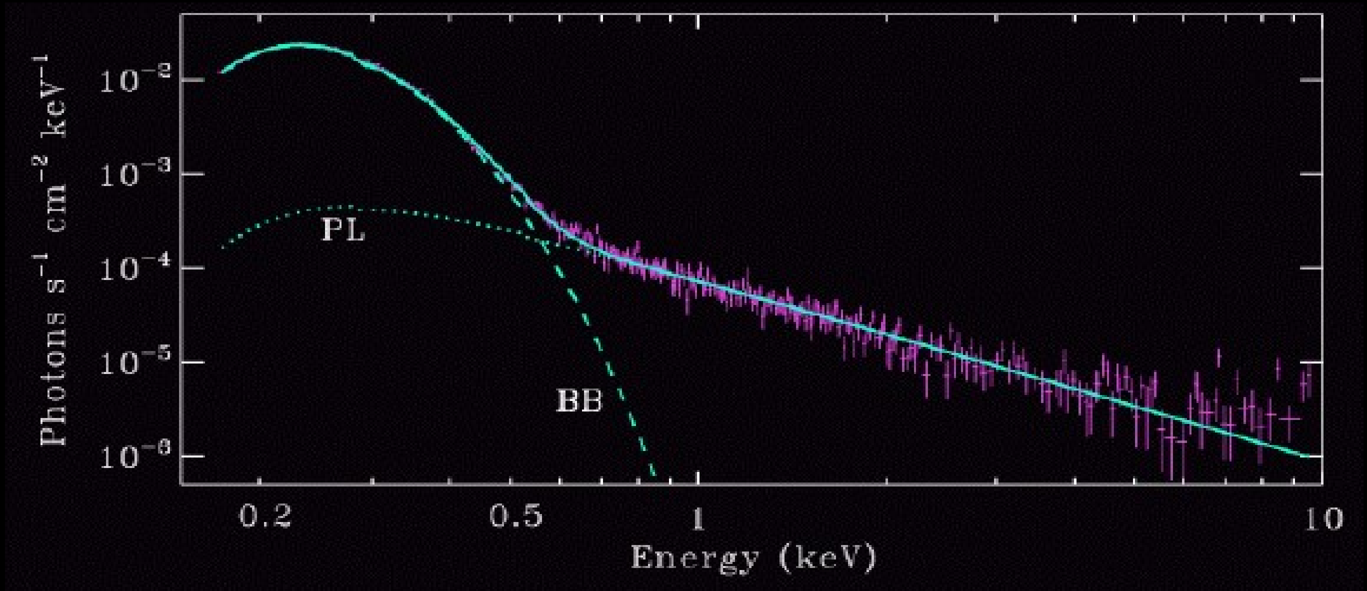
[a] Also in units of 10^{-8} ph cm^{-2} s^{-1}
[b] Associated with SN 1054
[c] Pulsars not reported in the 3EG [71]

Emission in pulsars

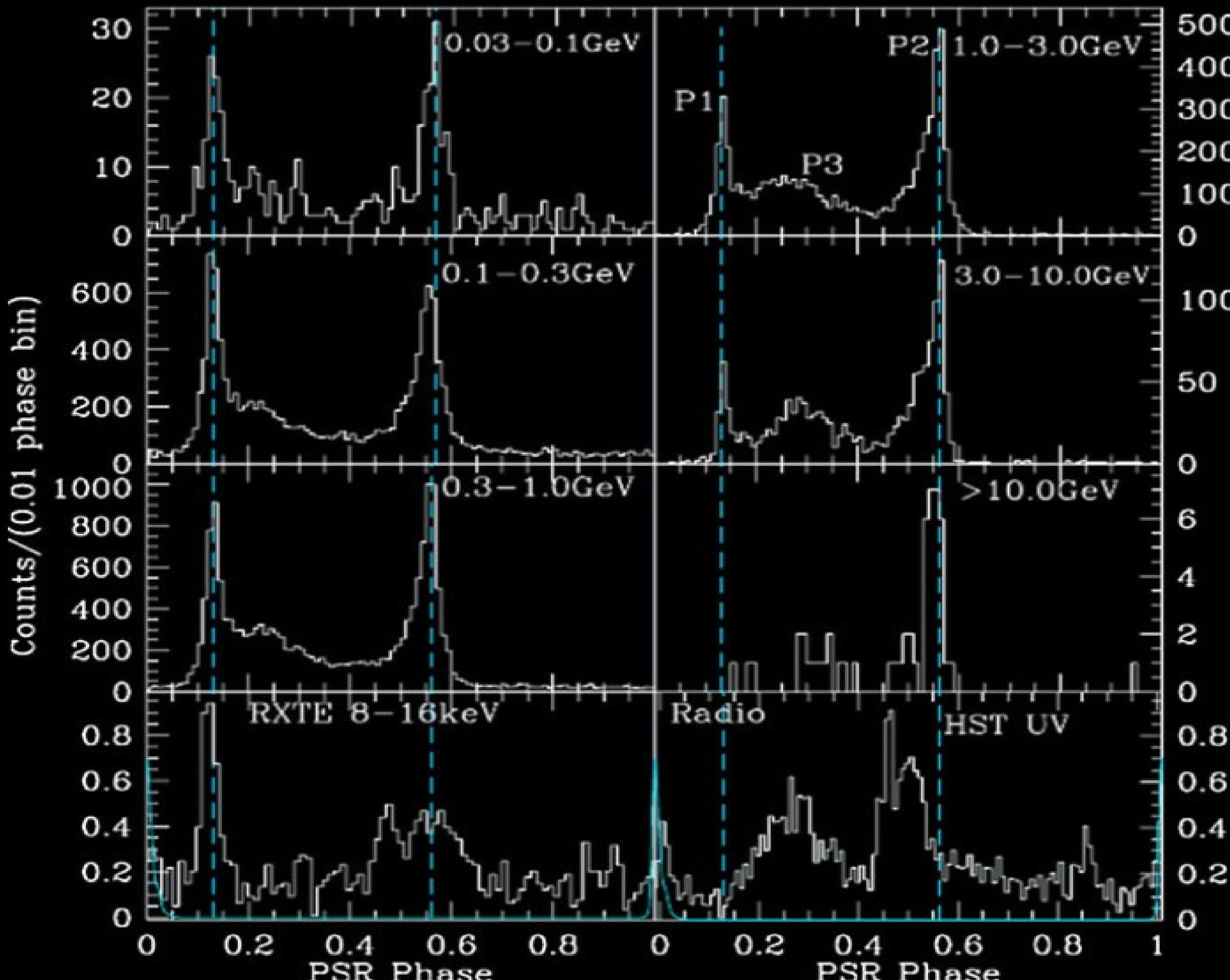
Crab-like: $\tau < 10^4$ years. In SNR and thermal emission well below non-termal PL emission (only upper limits on T)

Vela-like: $\tau \sim 10^4$-10^5 years. Thermal emission emerging from non-thermal emission ($T_\infty \sim 1$ MK)

Geminga-like: $\tau \sim 10^5$-10^6 years. At X-rays, thermal emission and non-thermal tail

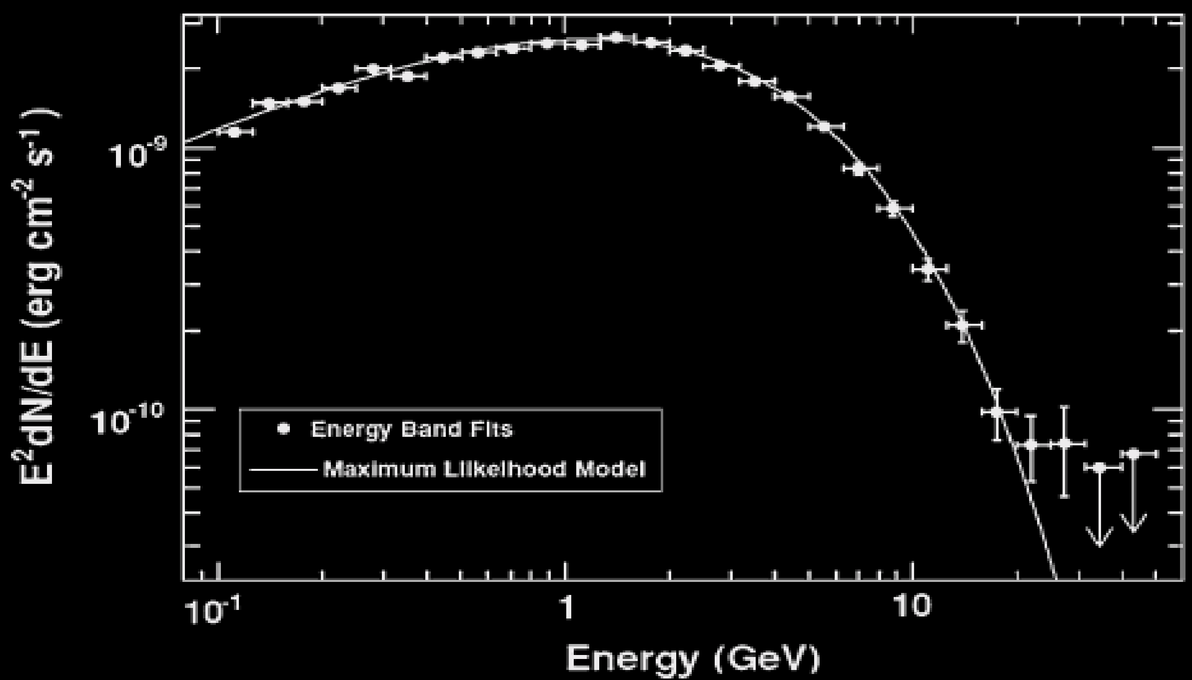


Vela pulsar light curve



Gamma-ray spectrum

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



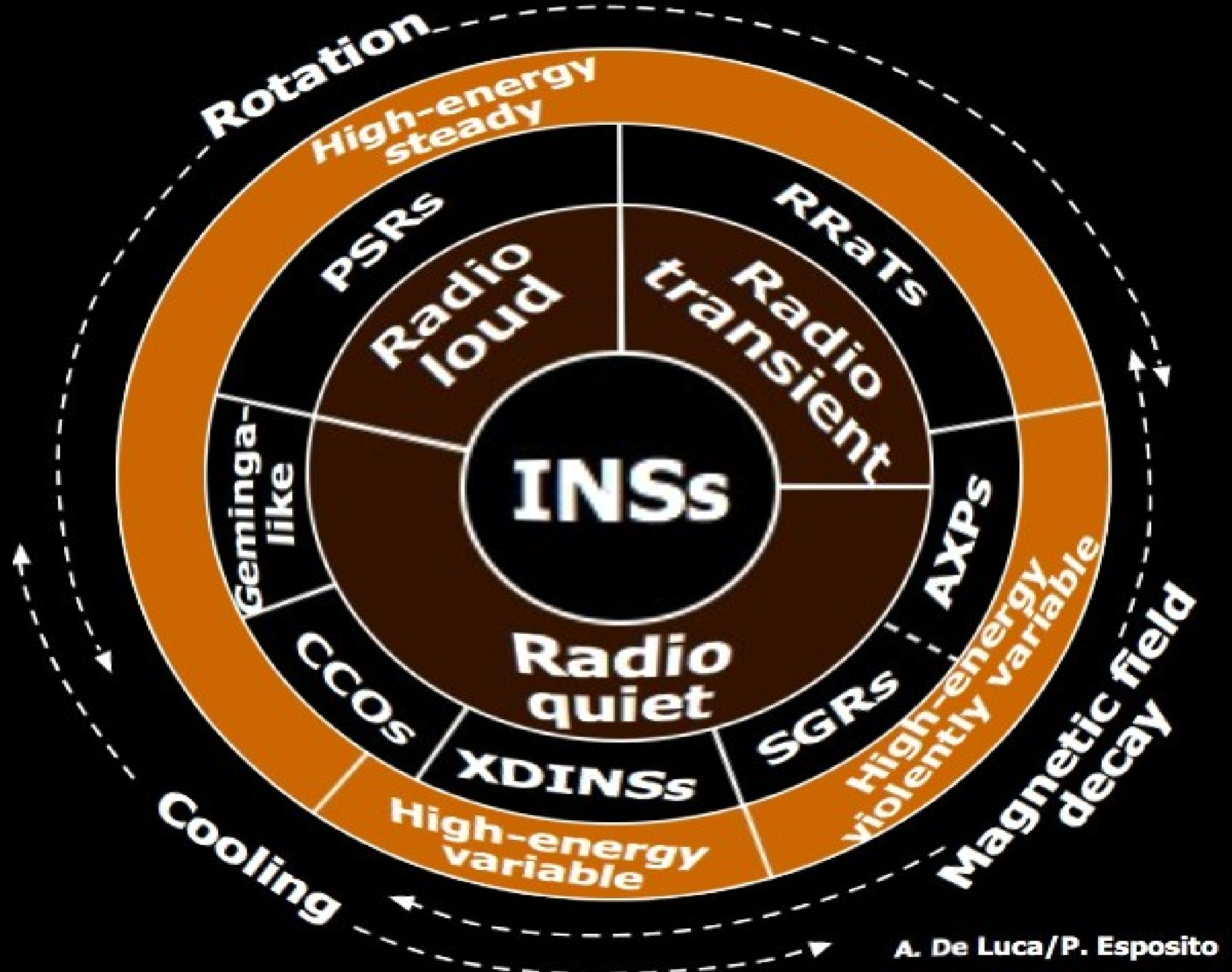
The zoo of isolated neutron stars

NSs are remains of **SNRs explosions** and *presumably* governed by a **single EoS**

Why do they exhibit so many flavours?

- Different **progenitors** or **formation** conditions?

- Does one population **evolve** into another?



Other rotation-powered NSs

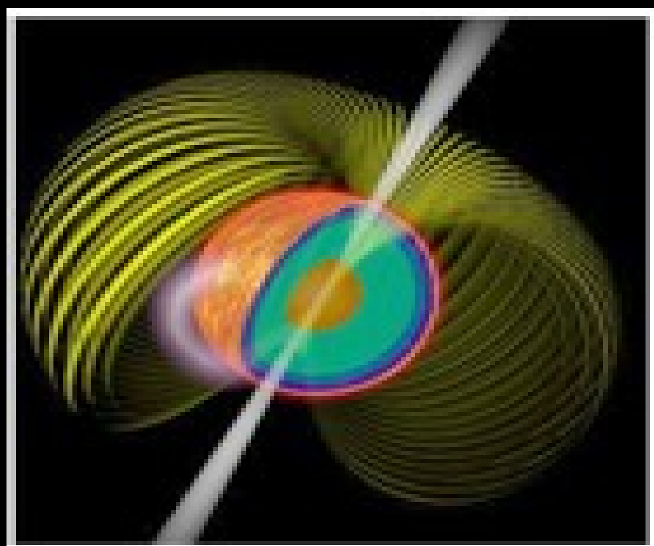
- **Rotating Radio Transients (RRaTs):** discovered in 2006 as isolated radio pulses. But pulse separations are not random: regularly slowing down periods ⇒ "intermittent" radio pulsars

- **Radio-quiet gamma-ray pulsars:** only one (*Geminga*) known before 2008. More than 150 discovered by *Fermi* gamma-ray satellite. Why not detected in radio?

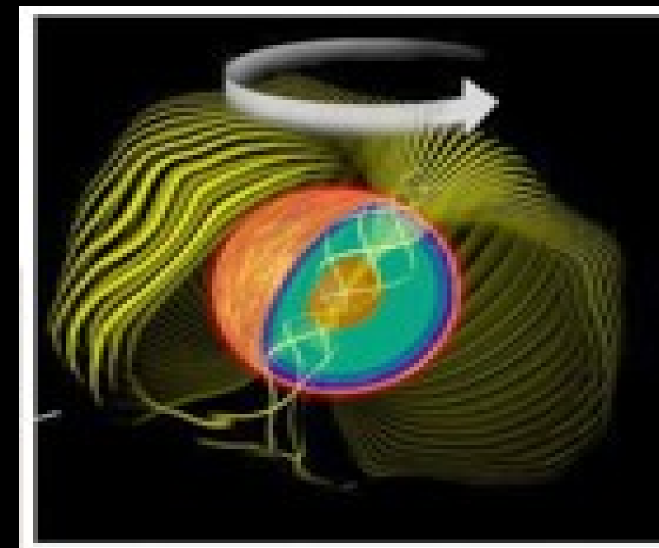
  Emission beam much broader in gamma than in radio

Magnetars and radio pulsars

High-*B* radio PSRs



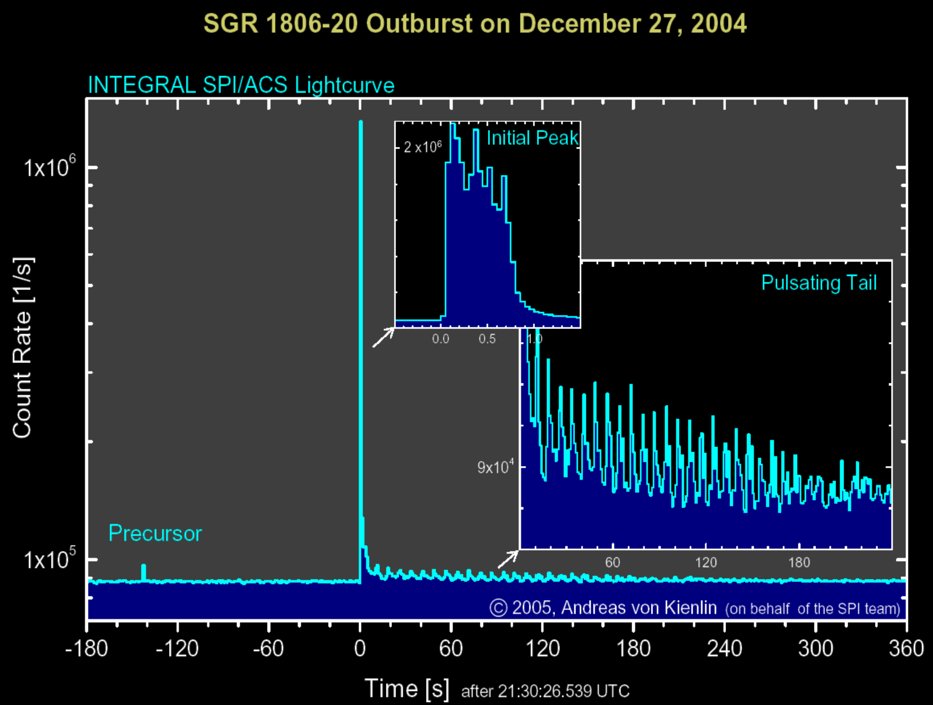
High-*B*

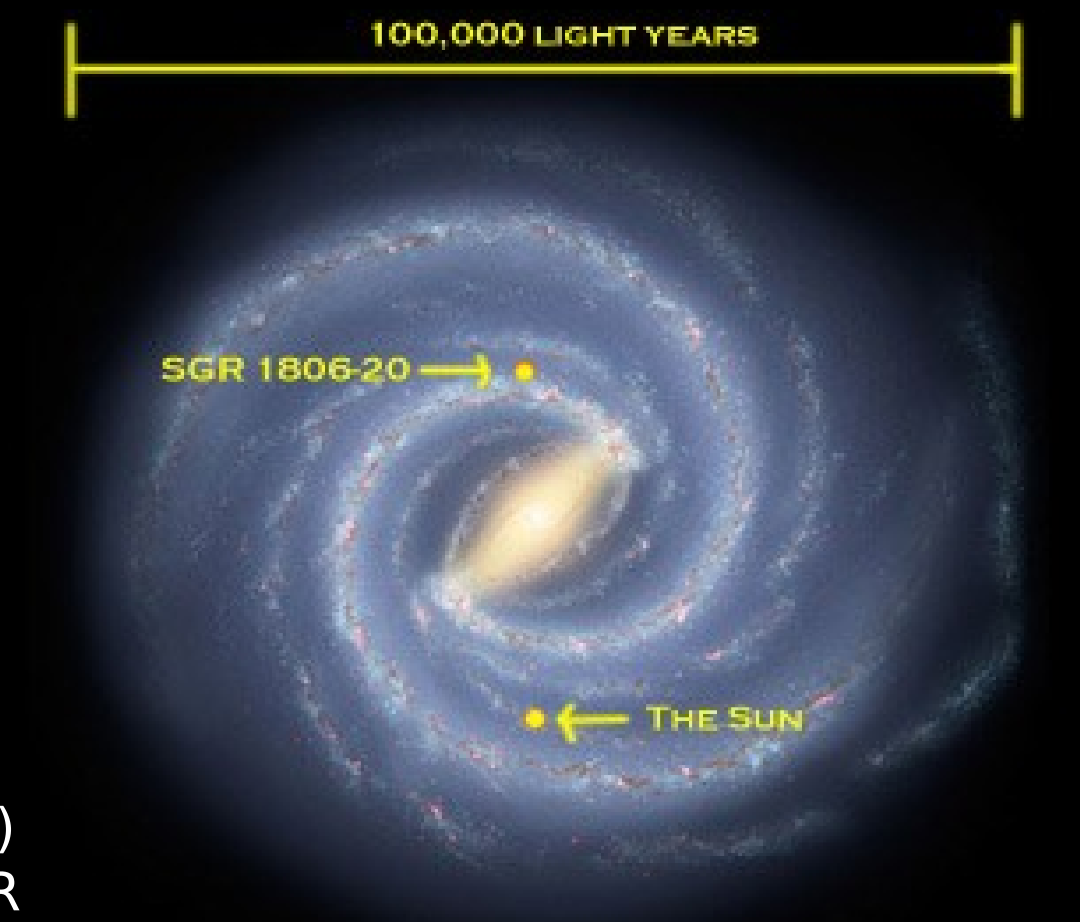


Magnetars

- In magnetars, the **internal** magnetic field is **twisted**
  field **decay** twists the **magnetosphere**
  X-rays from magnetospheric currents and bursts
  (Thompson, Lyutikov & Kulkarni 2002)

The strongest GRB is not a GRB!





Bright spike + pulsating tail (P=7.5 s)
Periodicity and position of known SGR
Although distance is rather uncertain, $E \sim 10^{46}$ - 10^{47} erg

Was it really so bright?

- Saturation of almost all scientific satellites, even if pointing to other directions
- Detected by Coronas satellite (with ~2 seconds delay), even if occulted by Earth!

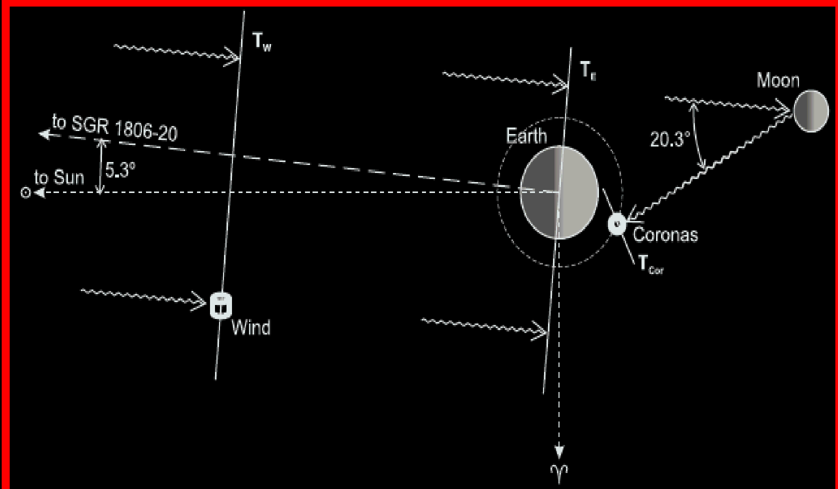
Giant Flare in SGR 1806–20 and Its Compton Reflection from the Moon

D. D. Frederiks[1], S. V. Golenetskii[1], V. D. Palshin[1], R. L. Aptekar[1*], V. N. Ilyinskii[1], F. P. Oleinik[1], E. P. Mazets[1], and T. L. Cline[2]

[1]Io e Physical–Technical Institute, Russian Academy of Sciences, ul. Politekhnicheskaya 26, St. Petersburg, 194021 Russia

[2]Goddard Space Flight Center, NASA, Greenbelt, MD 20771, USA

Received August 17, 2006



Magnetar model
(Duncan & Thompson 1992)

- Introduced to explain the first **Giant Flare** (GF, March 5, 1979) and **GRBs**
- ***Magnetars*** are defined as neutron stars powered by magnetic field (**B~10^{14}-10^{15} G**)
- The strong magnetic field is formed by dynamo processes due to fast rotation (**P~1 ms**) in proto-NS
- $E_B = \frac{4}{3}\pi R^3 \frac{B^2}{8\pi} \approx 10^{47}$ erg $\Rightarrow$ can power GF

Magnetar model
(Thompson & Duncan 1995; 1996)

- $E_B \sim 10^{47}$ erg can power **persistent X-ray** emission of AXPs and SGRs for $>10^4$ yrs
- **Bursts** generated by magnetic stresses in neutron star crust
- **Giant Flares** involve large scale magnetic field reconnection
- **Spin-down** caused by dipole radiation for $B \sim 10^{14}$-10^{15} G

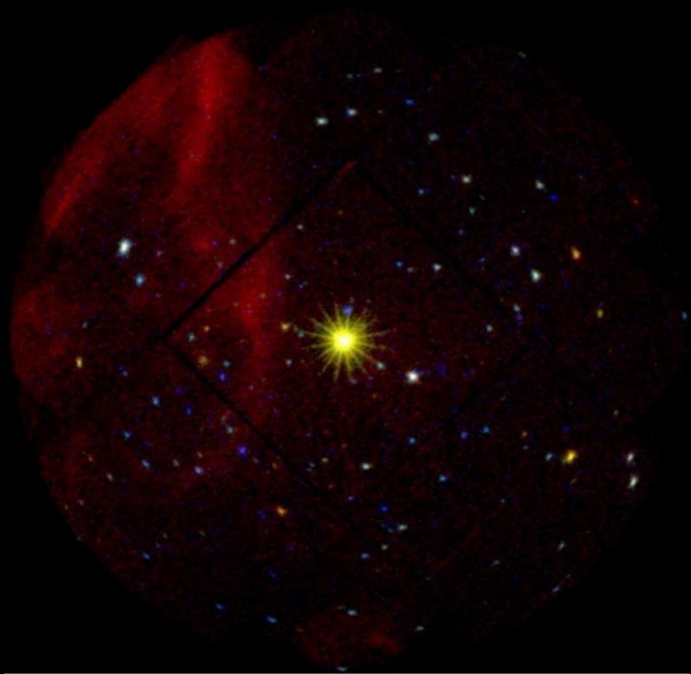
Central Compact Objects (CCOs)

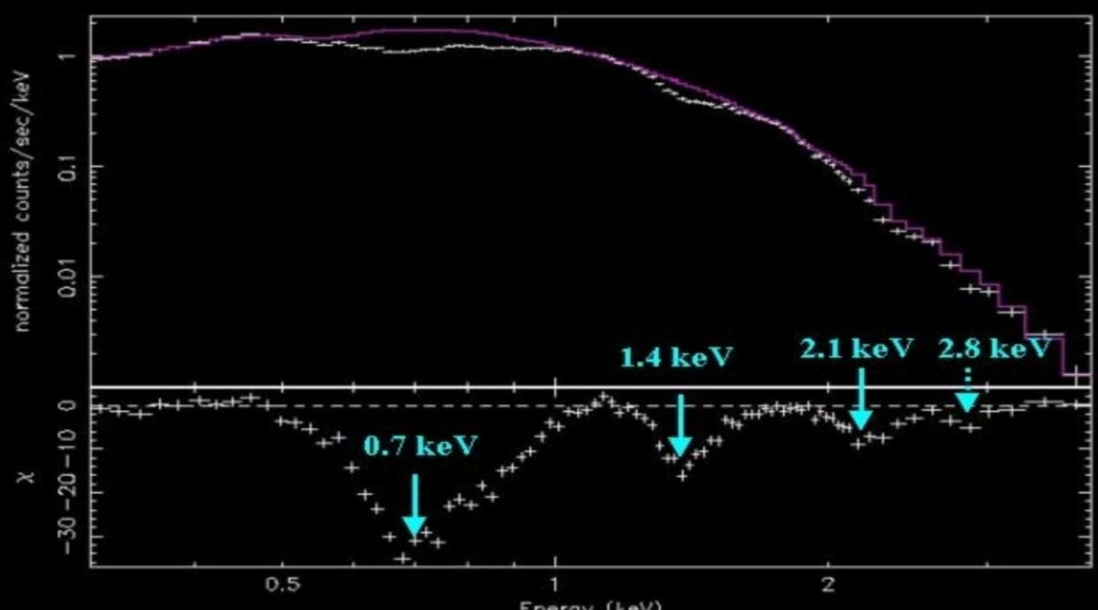
° Point-like **Xray source** in young SNR with with **no radio/gamma counterpart**

° **Thermal** X-ray spectrum (typically the sum of two BBs)

° In some cases, **pulsation** (P ≈ 0.1 s) and **low spin-down** (B<< 10^{12} G) ⇒ *anti-magnetars*

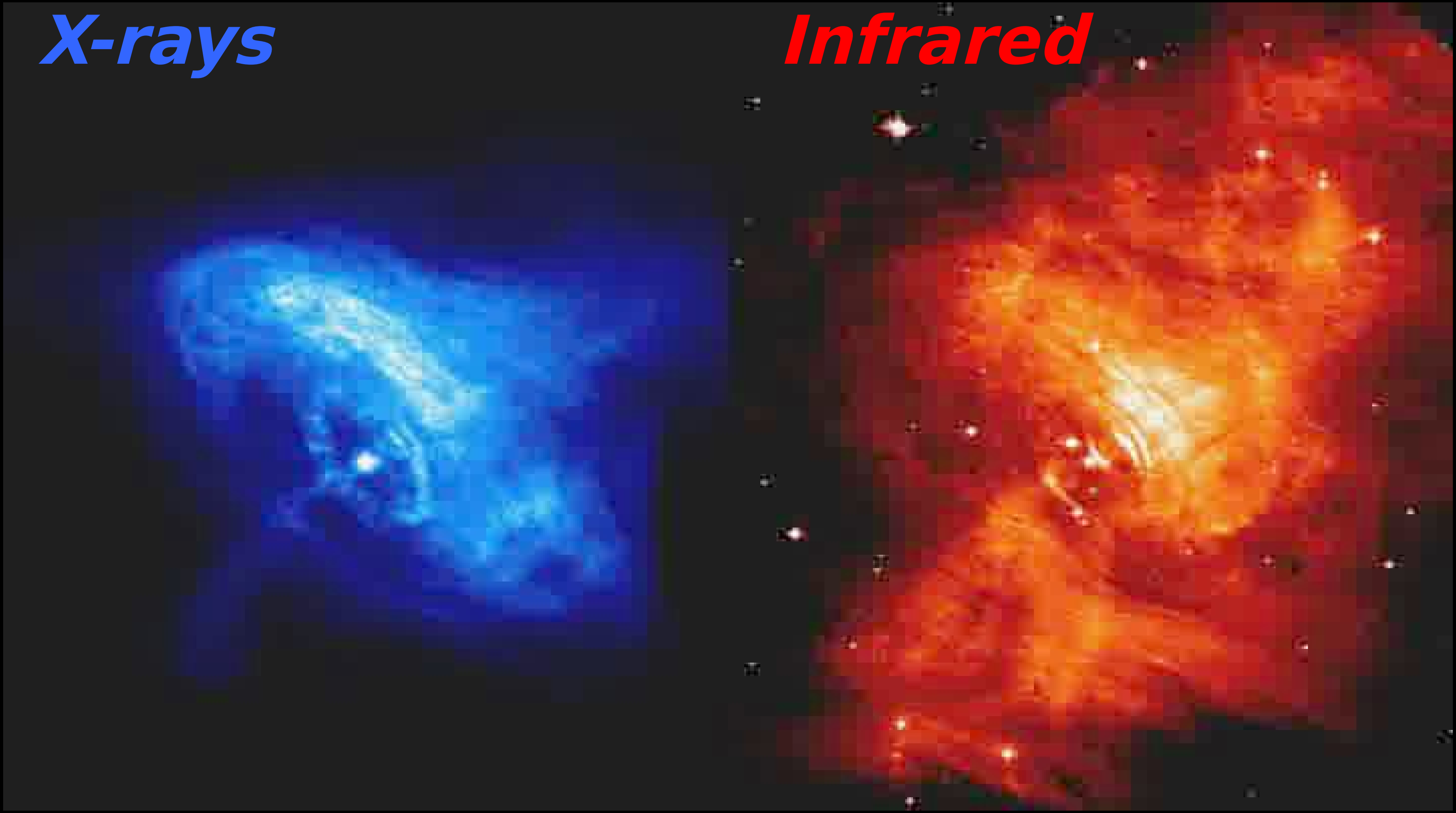
° Absorption lines in CCO **1E 1207-5209** ⇒ **electron cyclotron** features (Bignami et al. 2003)



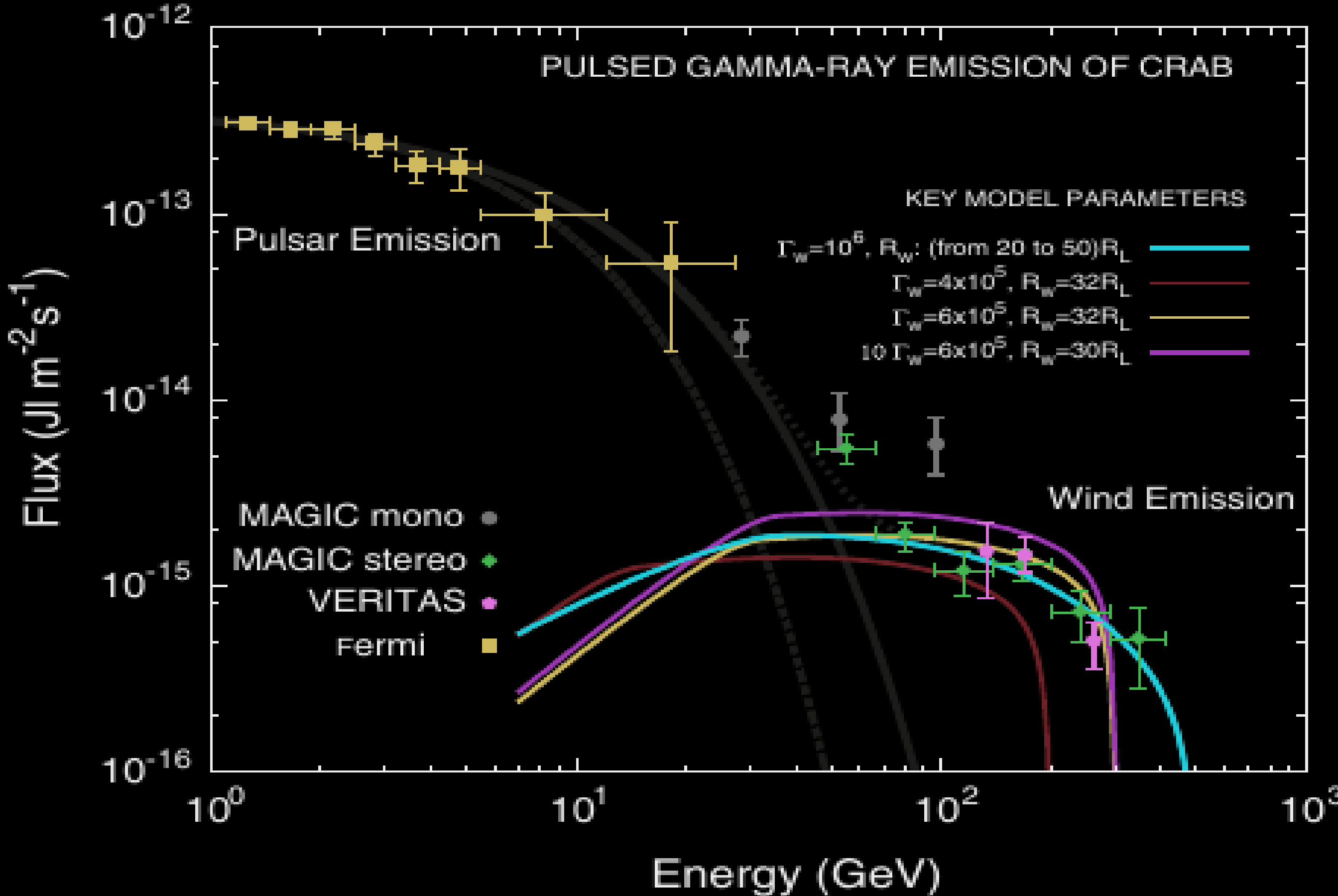


Let’s zoom out….

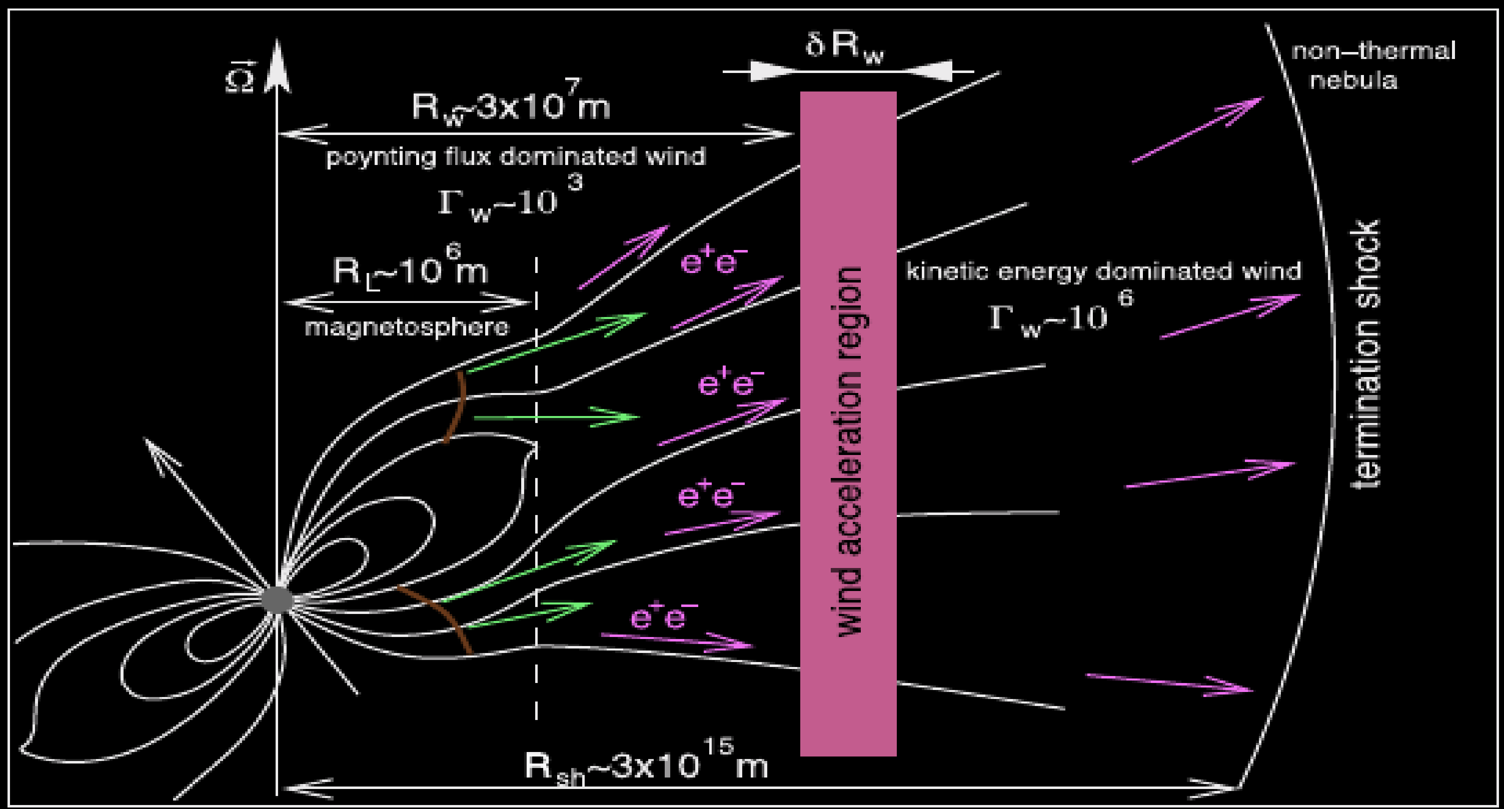
Crab Nebula



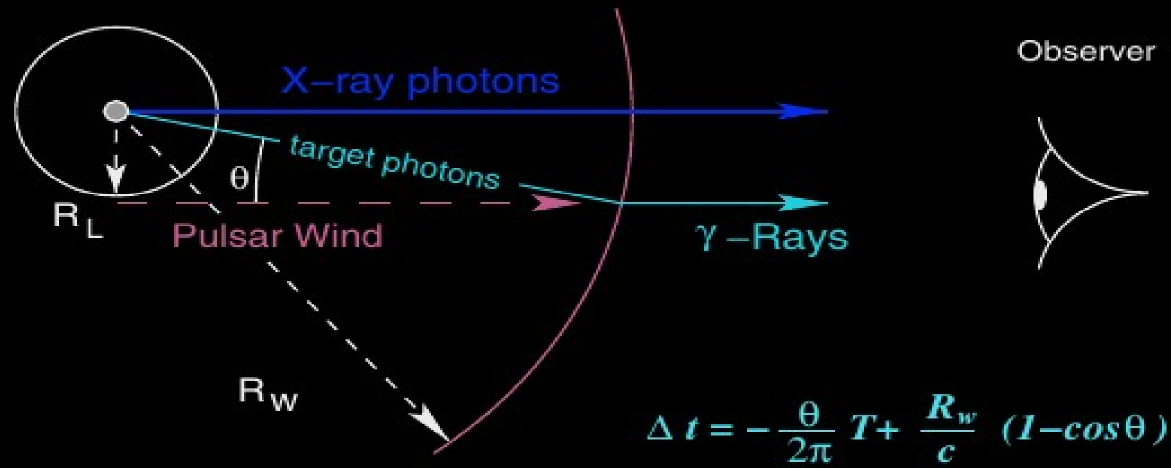
Crab Pulsed SED

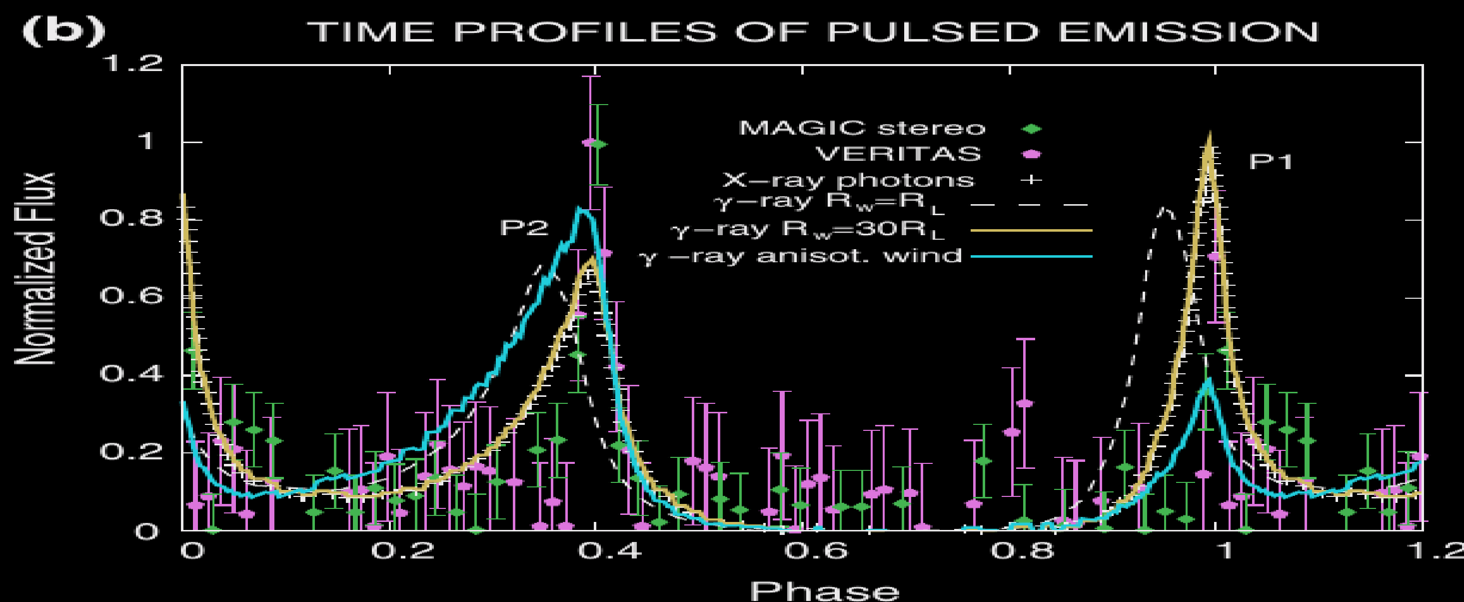


Pulsar Wind

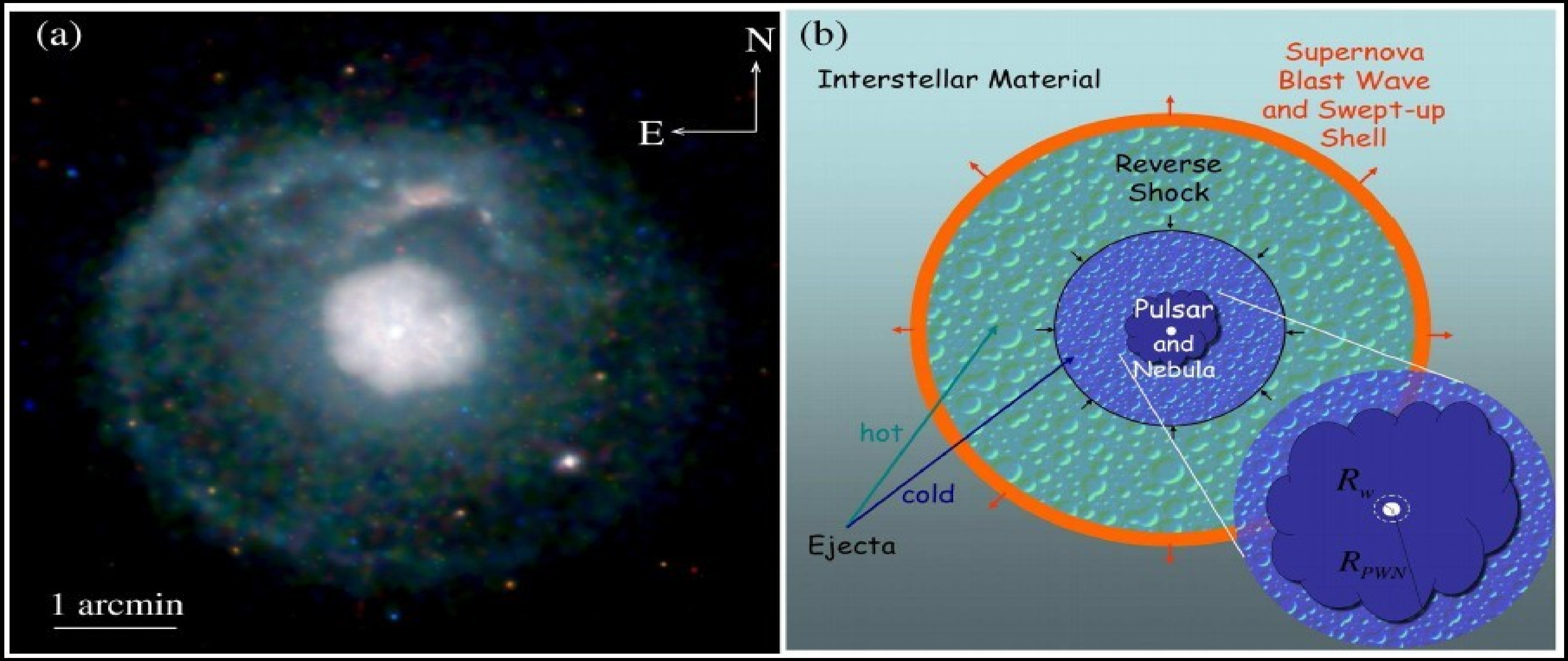


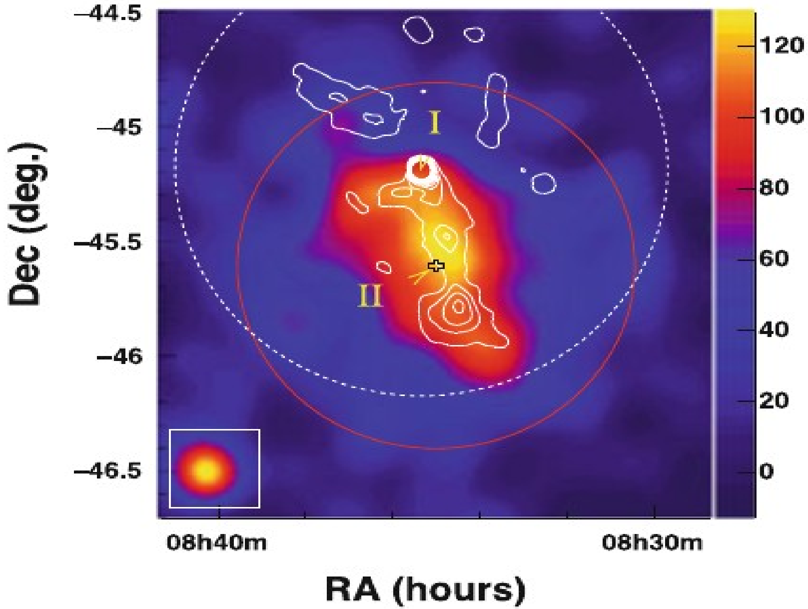
$\vec{\Omega}$
R_w~$3x10^7$m
poynting flux dominated wind
$\Gamma_w \sim 10^3$
R_L~10^6m
magnetosphere
δR_w
e^+e^-
e^+e^-
e^+e^-
e^+e^-
wind acceleration region
kinetic energy dominated wind
$\Gamma_w \sim 10^6$
non–thermal nebula
termination shock
R_{sh}~$3x10^{15}$m

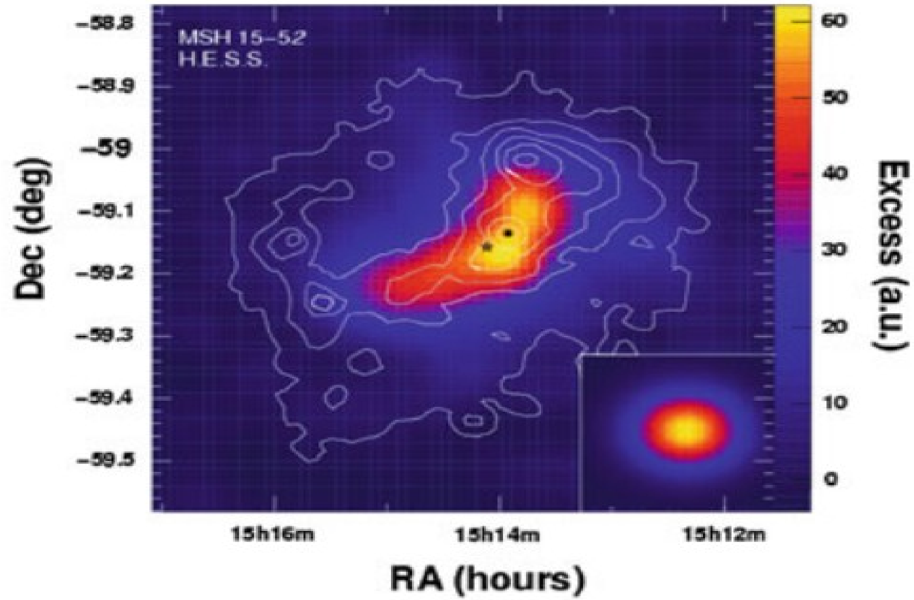

Observer
X−ray photons
target photons
θ
R_L
Pulsar Wind
γ −Rays
R_W
$\Delta t = -\frac{\theta}{2\pi}T + \frac{R_w}{c}(1-\cos\theta)$

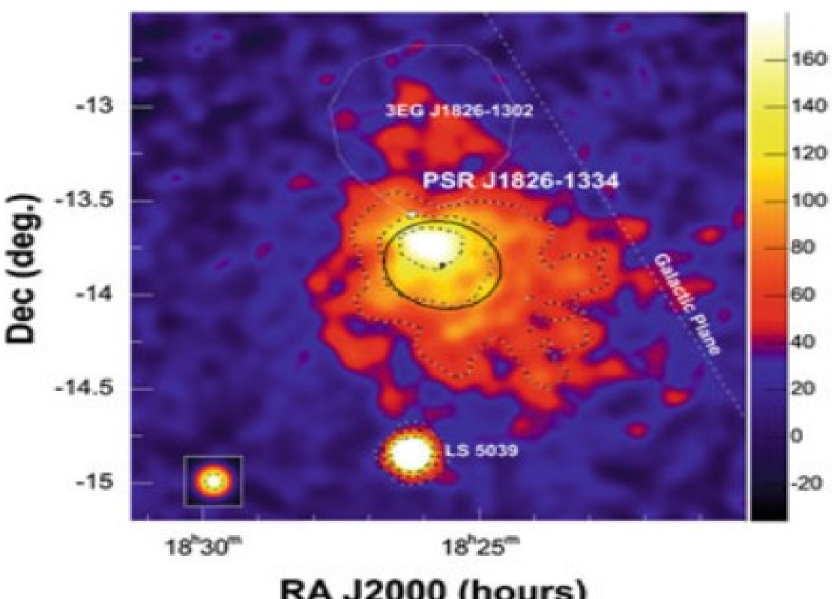

(b)
TIME PROFILES OF PULSED EMISSION
Normalized Flux
Phase
0
0.2
0.4
0.6
0.8
1
1.2
MAGIC stereo
VERITAS
X−ray photons
γ−ray R_w=R_L
γ−ray R_w=30R_L
γ −ray anisot. wind
P1
P2

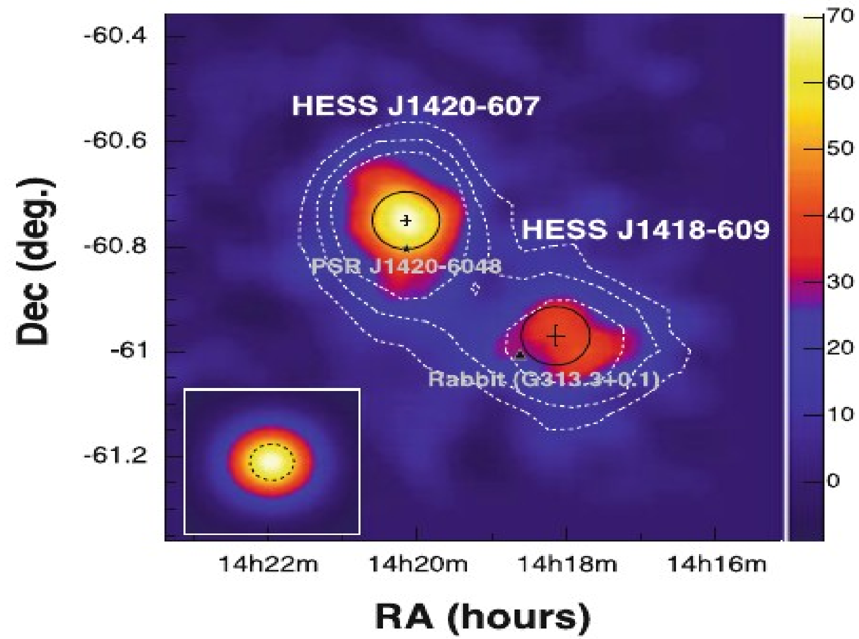
Pulsar Wind Nebulae



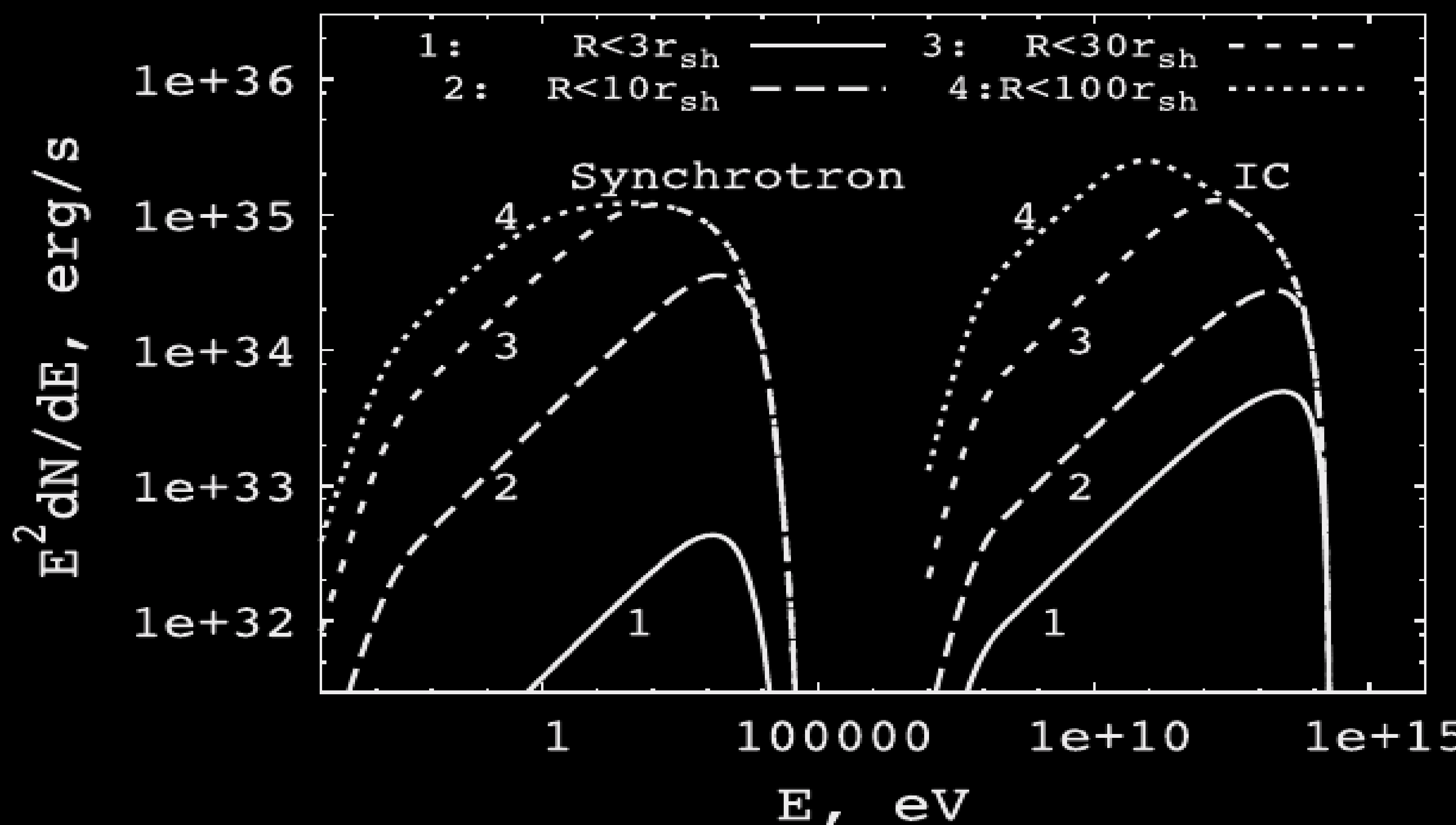

I
II
Dec (deg.)
RA (hours)
08h40m
08h30m
−44.5
−45
−45.5
−46
−46.5
120
100
80
60
40
20
0


MSH 15-52
H.E.S.S.
Dec (deg)
RA (hours)
Excess (a.u.)
15h16m
15h14m
15h12m
-58.8
-58.9
-59
-59.1
-59.2
-59.3
-59.4
-59.5
60
50
40
30
20
10
0


3EG J1826-1302
PSR J1826-1334
LS 5039
Galactic Plane
Dec (deg.)
RA J2000 (hours)
18h30m
18h25m
-13
-13.5
-14
-14.5
-15
160
140
120
100
80
60
40
20
0
-20

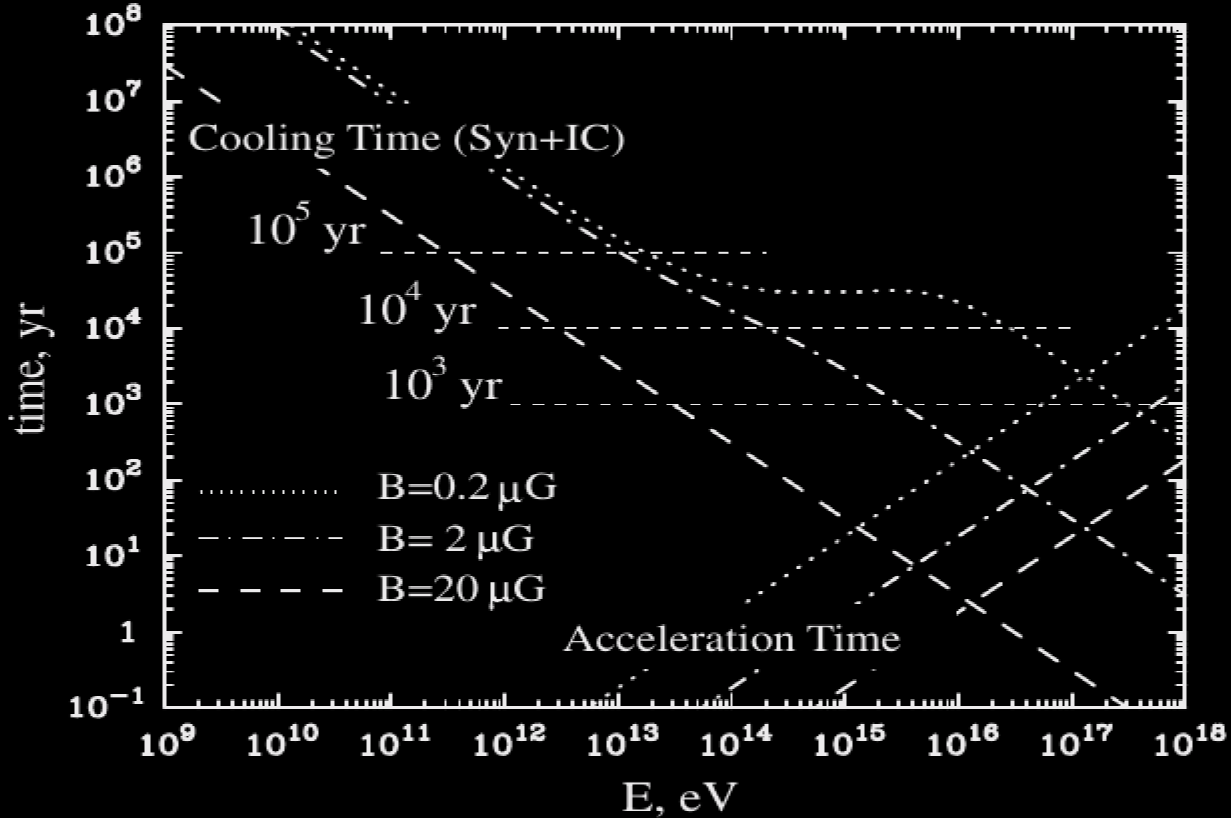

HESS J1420-607
HESS J1418-609
PSR J1420-6048
Rabbit (G313.3+0.1)
Dec (deg.)
RA (hours)
14h22m
14h20m
14h18m
14h16m
-60.4
-60.6
-60.8
-61
-61.2
70
60
50
40
30
20
10
0

PWN SED



1: R<3r_sh
2: R<10r_sh
3: R<30r_sh
4:R<100r_sh
Synchrotron
IC
1e+36
1e+35
1e+34
1e+33
1e+32
1
100000
1e+10
1e+15
E²dN/dE, erg/s
E, eV

Cooling times



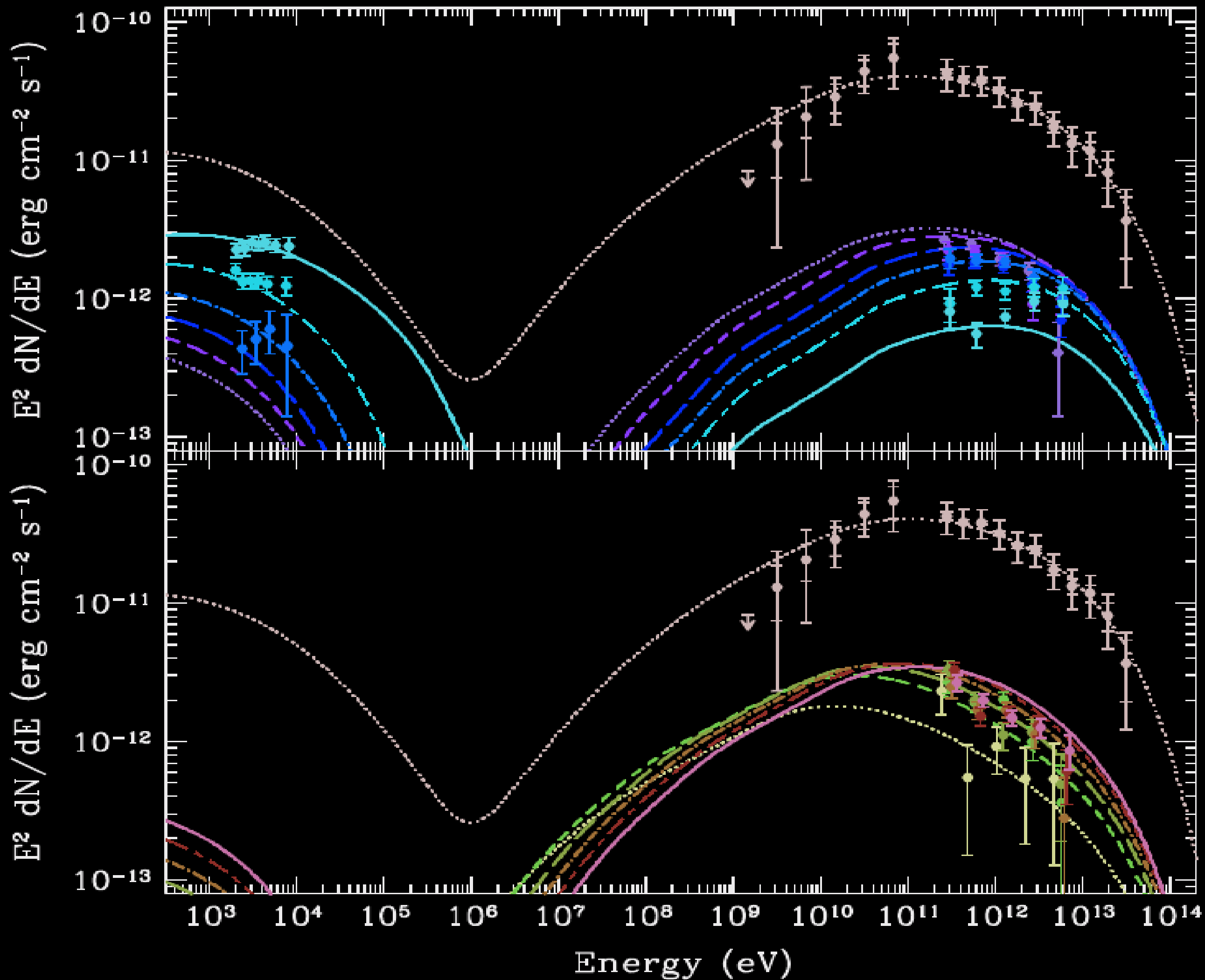
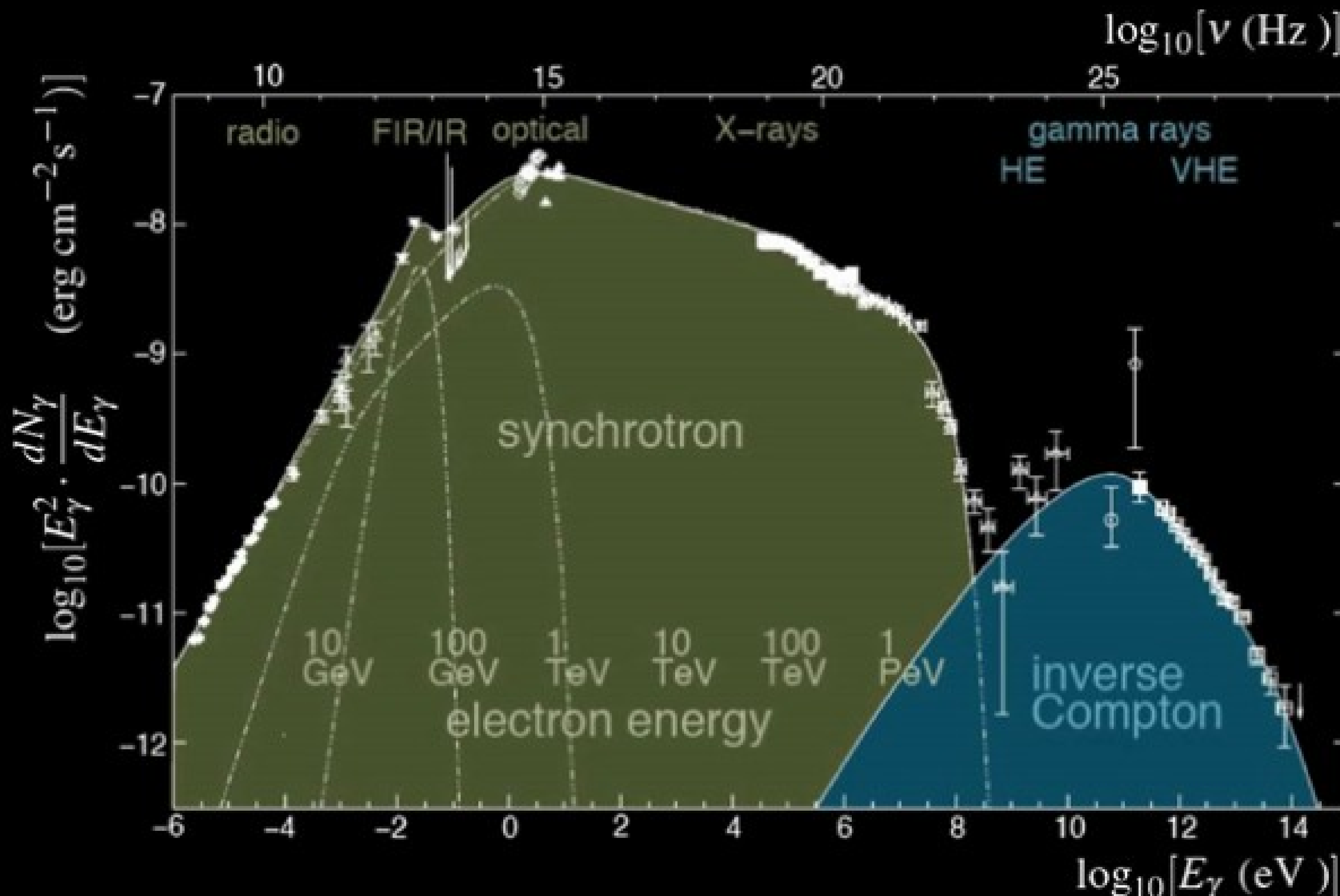


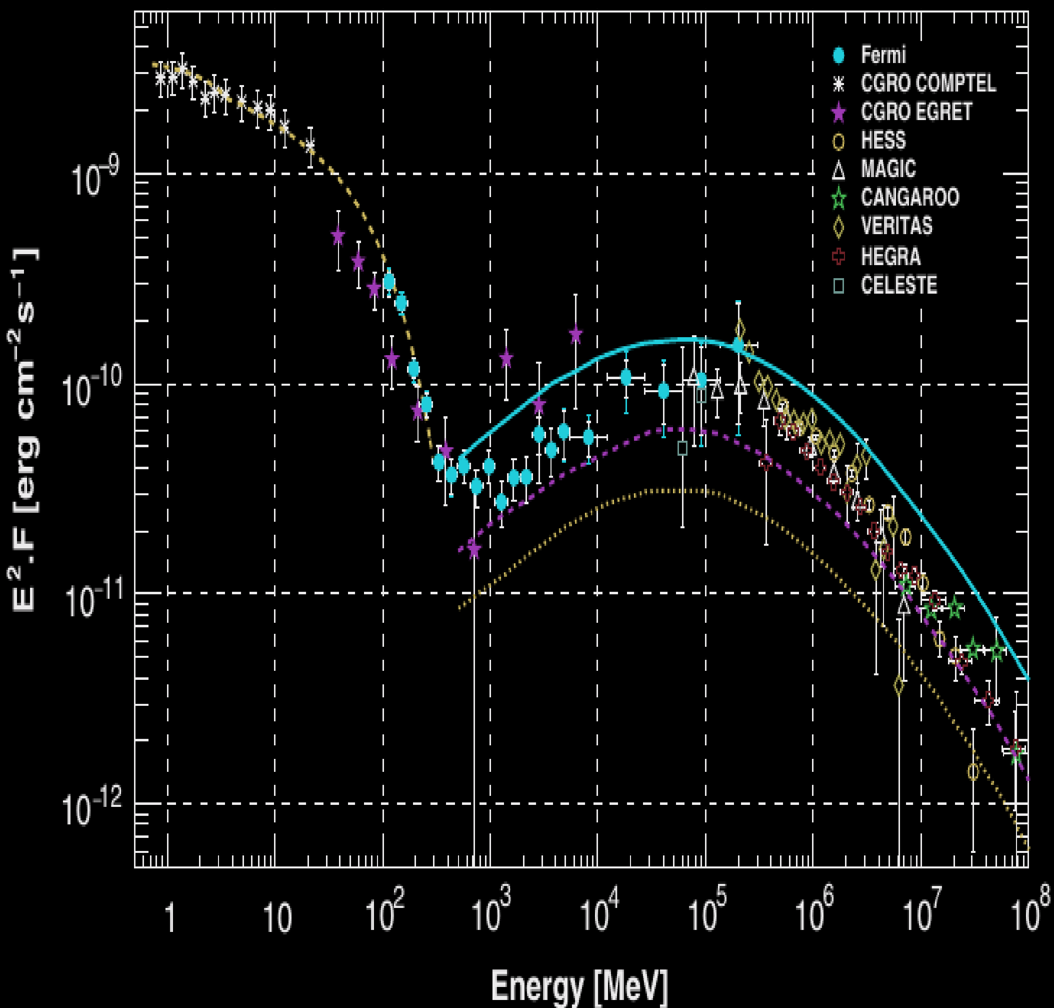
Fig. 48 SED of broad-band IC gamma-ray emission of the pulsar wind nebula HESS J1825-137 calculated for 12 zones with a constant 6 arcmin width of the zones: $0' - 6'$, $6' - 12'$, ... $66' - 72'$. The *theoretical curves* are shown together with observational points obtained with the *Suzaku* (the inner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

Crab PWN SED

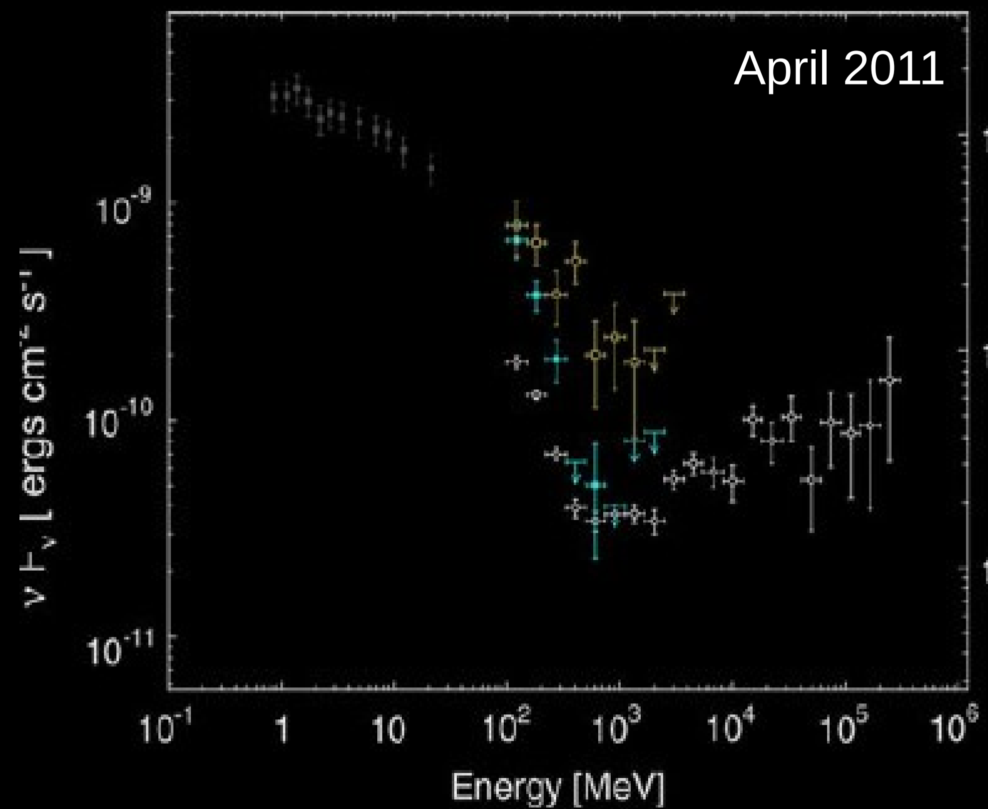


$\log_{10}[\nu\ (\mathrm{Hz})]$
10
15
20
25
radio
FIR/IR
optical
X–rays
gamma rays
HE
VHE
synchrotron
10 GeV
100 GeV
1 TeV
10 TeV
100 TeV
1 PeV
electron energy
inverse Compton
-7
-8
-9
-10
-11
-12
$\log_{10}[E_\gamma^2 \cdot \frac{dN_\gamma}{dE_\gamma}\ (\mathrm{erg\ cm^{-2} s^{-1}})]$
-6
-4
-2
0
2
4
6
8
10
12
14
$\log_{10}[E_\gamma\ (\mathrm{eV})]$

Crab Flares



Fermi
CGRO COMPTEL
CGRO EGRET
HESS
MAGIC
CANGAROO
VERITAS
HEGRA
CELESTE
$E^2.F$ [erg cm^{-2} s^{-1}]
Energy [MeV]



April 2011
Energy [MeV]

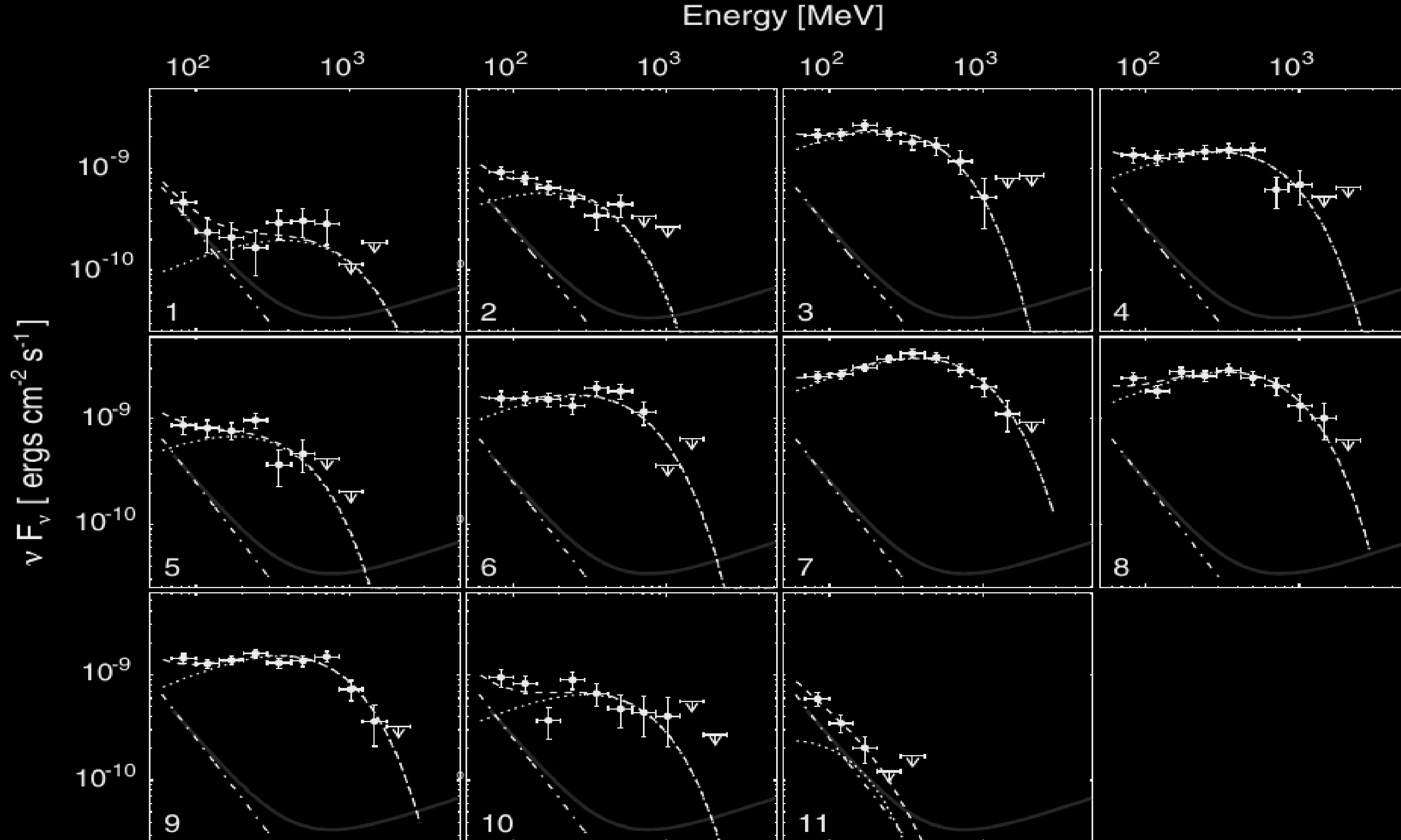


Fig. 41 Time evolution of the Crab SED during the April 2011 flare. The flare duration of approximately 9 days has been divided in 11 time windows of approximately constant flux. The *dot-dashed line* indicates the assumed constant background from the synchrotron nebula. The *dotted lines* show the flaring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

Crab Nebula Flares – Sed