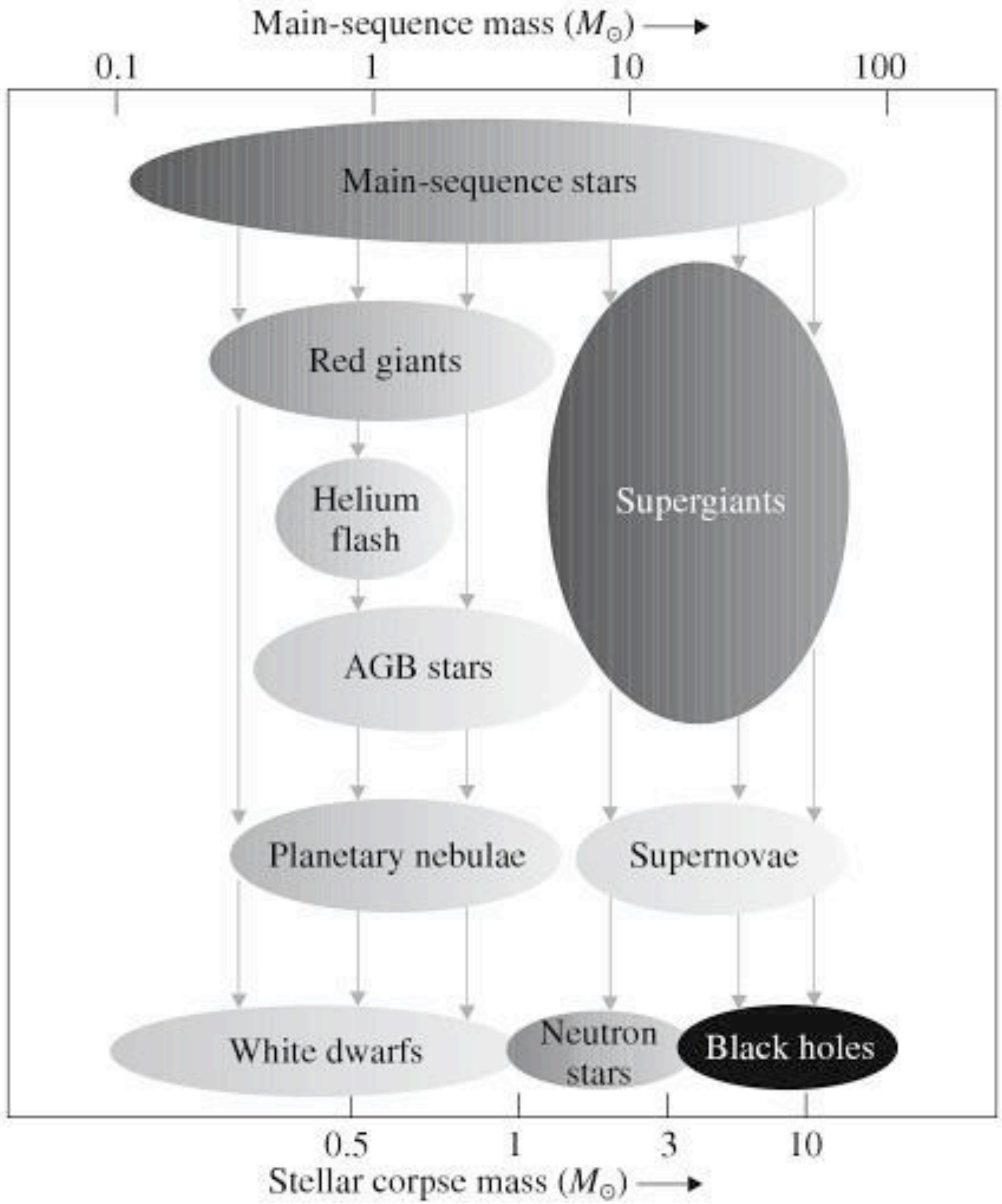
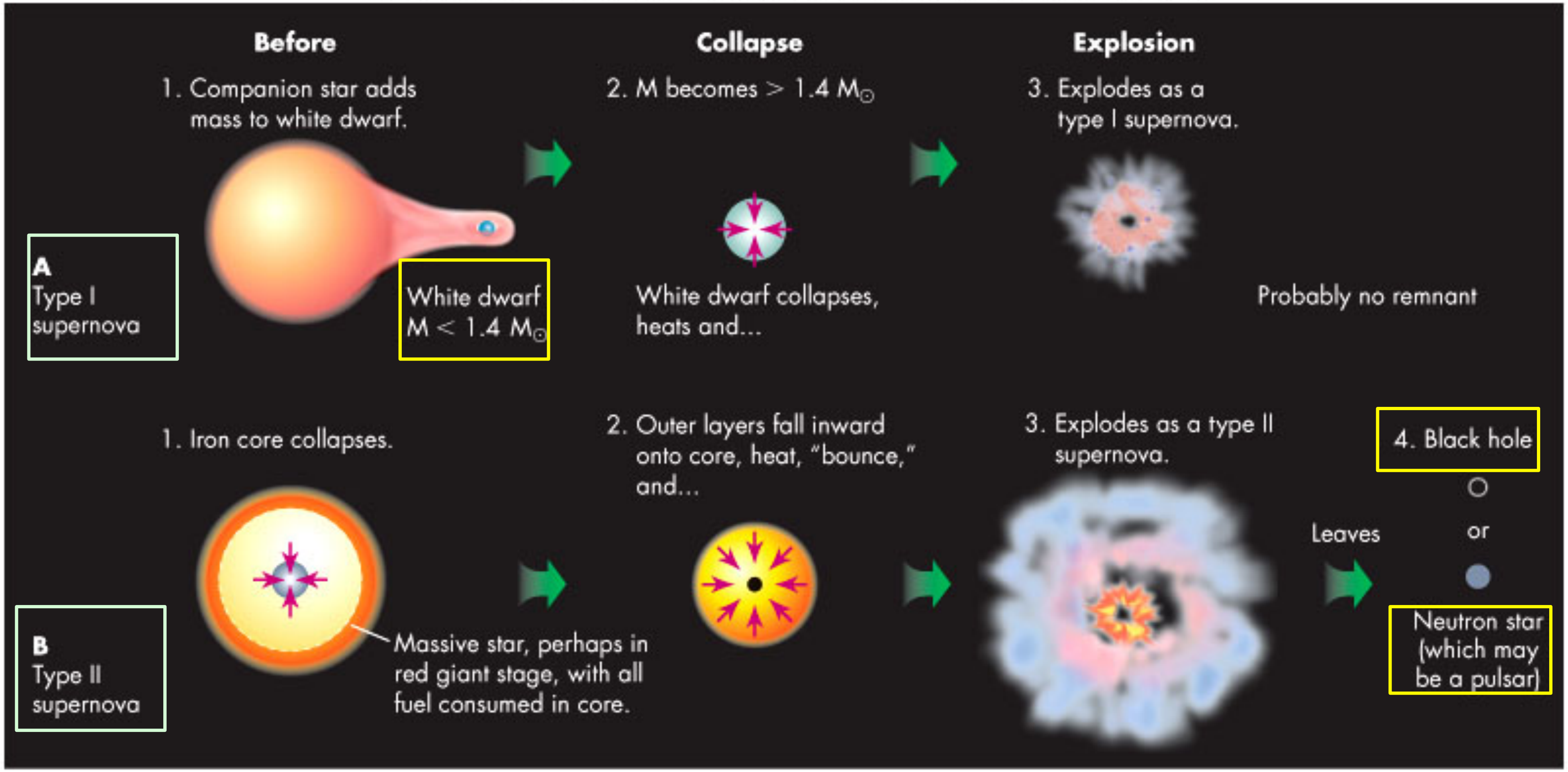
Pulsars and isolated neutron stars


Main-sequence mass ($M_\odot$)
0.1
1
10
100
Main-sequence stars
Red giants
Supergiants
Helium flash
AGB stars
Planetary nebulae
Supernovae
White dwarfs
Neutron stars
Black holes
0.5
1
3
10
Stellar corpse mass ($M_\odot$)



Postulated since 30' (Chandrasekhar), suggested link with Sne explosion (Baade & Zwicky):
"*With all reserve we advance the view that supernova represents the transition of an ordinary star into a new form of star, the **neutron star**, which would be the end point of stellar evolution. Such a star possess a very small radius and an extremely high density*"

About 2200 PSR now detected

Table 1. Pulsar varieties

Category	Count	Sub-count	Fraction
Known rotation-powered pulsars (RPPs)[a]	2286		
RPPs with measured $\dot{P} > 0$		1944	
RPPs with measured $\dot{E} > 3 \times 10^{33}$ erg s^{-1}		552	
Millisecond pulsars (MSPs, $P < 16$ ms)	292		
Field MSPs		169	
MSPs in globular clusters		123	
Field MSPs with measured $\dot{E} > 3 \times 10^{33}$ erg s^{-1}		96	
Globular cluster MSPs with measured $\dot{E} > 3 \times 10^{33}$ erg s^{-1}		25	
Gamma-ray pulsars in this catalog	117	Largely undetected before *Fermi*	
Young or middle-aged		77	
Radio-loud gamma-ray[b]		42	36%
Radio-quiet gamma-ray		35	30%
Gamma-ray MSPs (isolated + binary)		(10+30) = 40	34%
Radio MSPs discovered in LAT sources	46		
with gamma-ray pulsations[c]		34	

Abdo et al. (2014) compilation

Neutron stars: main properties

- At large densities, neutrons become degenerate, which means that Neutron Degeneracy Pressure can hold the star from gravitational collapse. A stable Neutron Star is formed.

- The diameter of a neutron star is from 10 km to 20 km.

- Neutron stars have enormous gravity, 10^{11} g, one hundred billion times the gravity on the surface of the Earth. The surface of a neutron star would be very smooth. Escape velocity would be about 80% the speed of light.

- Maximum mass that Neutron Degeneracy Pressure can hold up is between 2 and 3 solar masses.

- Remember a Neutron star, like a White Dwarf is a dead star, no fusion.

- Fast rotators (Period ≈ 0.03 to 4 sec) and huge B (up to 10^{14} G).

Some calculations on the density of NS

$$a_{rot} < a_{grav} \rightarrow \Omega^2 R < \frac{GM}{R^2} \rightarrow \frac{4\pi^2}{P^2} R < \frac{GM}{R^2} \rightarrow P^2 > \frac{4\pi^2}{GM} R^3$$

Centripetal acceleration < gravitational acceleration (otherwise: "disgregation" of the star)

$$\rho = \frac{M}{V} = \frac{M}{\left(\frac{4}{3}\pi R^3\right)}$$

$$P > \sqrt{\frac{3\pi}{G\rho}} \leftrightarrow \rho > \frac{3\pi}{GP^2}$$

Assuming: $M=1M_{\odot}$, R=10 km
First PSR discovered: P=1.3 s ➔ $\rho>10^8$ g/cm^3
Crab: P=0.033 s ➔ $\rho\approx1.3\times10^{11}$ g/cm^3

➔ $\rho_{NS}>>\rho_{WD}$

Some calculations on neutron degeneracy pressure

$$P_e \approx \hbar^2 \frac{n_e^{5/3}}{m_e}$$

Electron degeneracy pressure

$$P_n \approx \hbar^2 \frac{n_n^{5/3}}{m_n} = \hbar^2 \frac{\rho_n^{5/3}}{m_n^{8/3}}$$

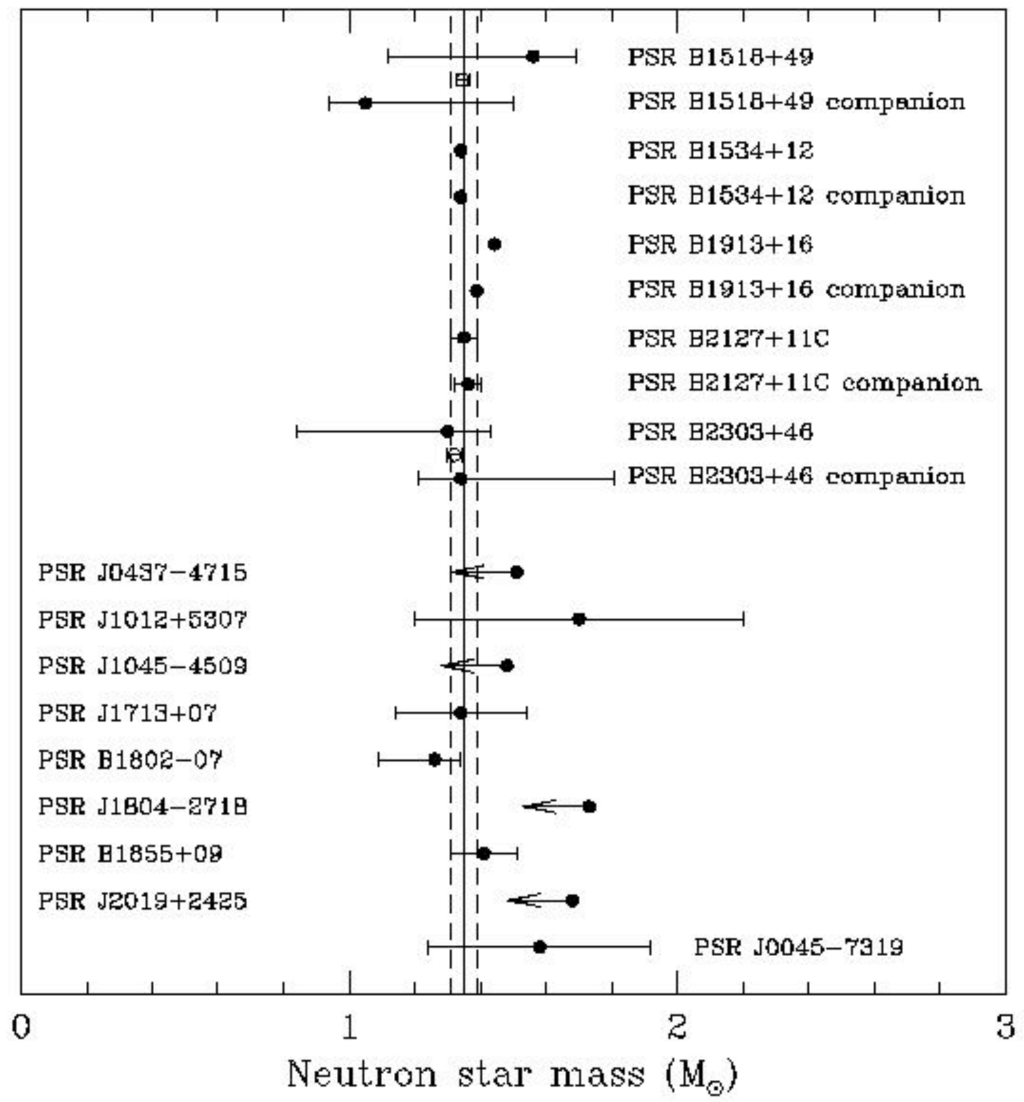
$\rho_n = n_n \times m_n$ (all star made of neutrons)
Neutron degeneracy pressure
Pauli exclusion principle still holds (for neutrons)

$$\boxed{\frac{P_n}{P_e} \approx \left(\frac{n_n}{n_e}\right)^{5/3} \times \frac{m_e}{m_n} \approx \frac{1}{2000} \times \left(\frac{n_n}{n_e}\right)^{5/3}}$$

Since the density of a neutron star is much higher than that of a WD, the neutron degeneracy pressure is able to prevent the dead star from collapsing

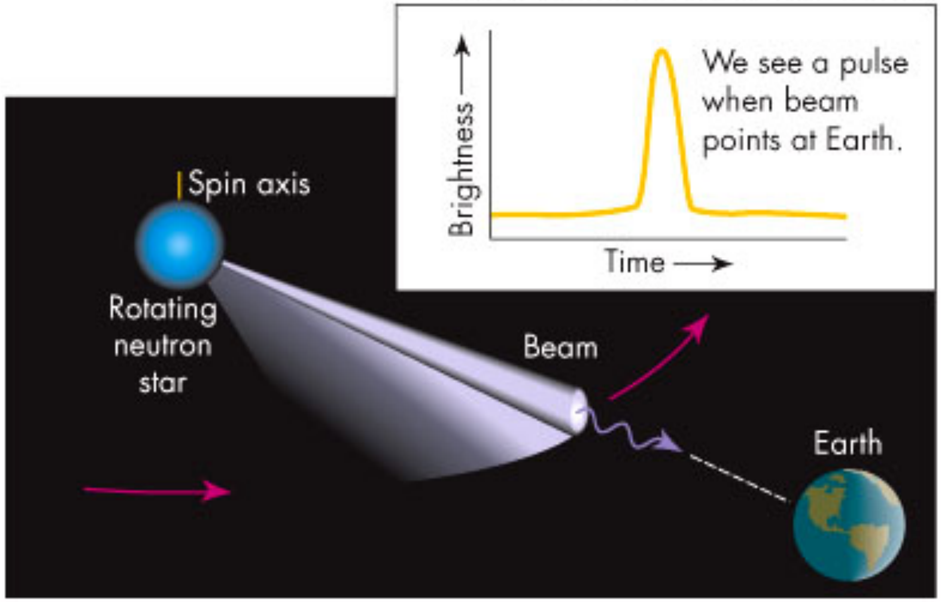
Typical mass for a NS ≈ $1.4M_\odot$
$\rho_{NS} \approx$ up to a few × 10^{12} g/cm^3
[$\rho_{WD} \approx$ up to a few × 10^6 g/cm^3]

Mass distribution of neutron stars

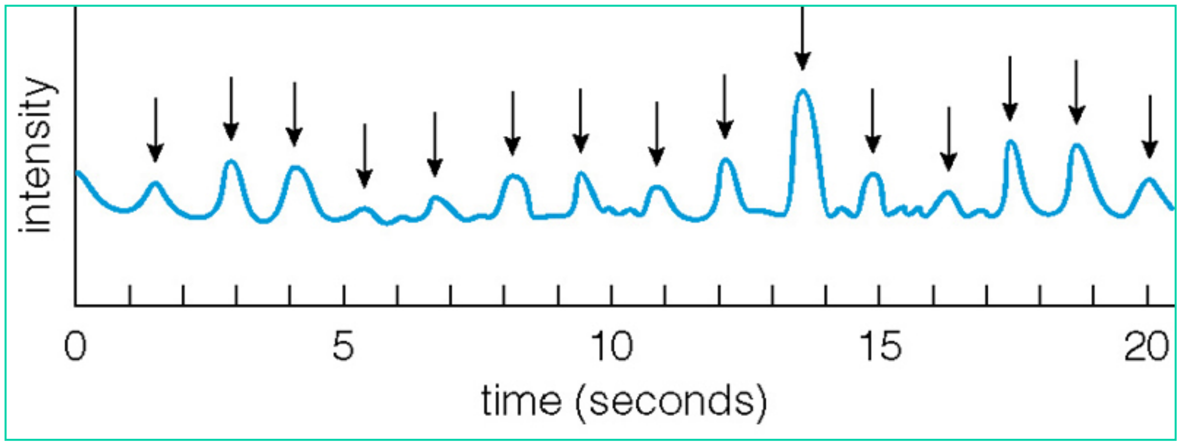


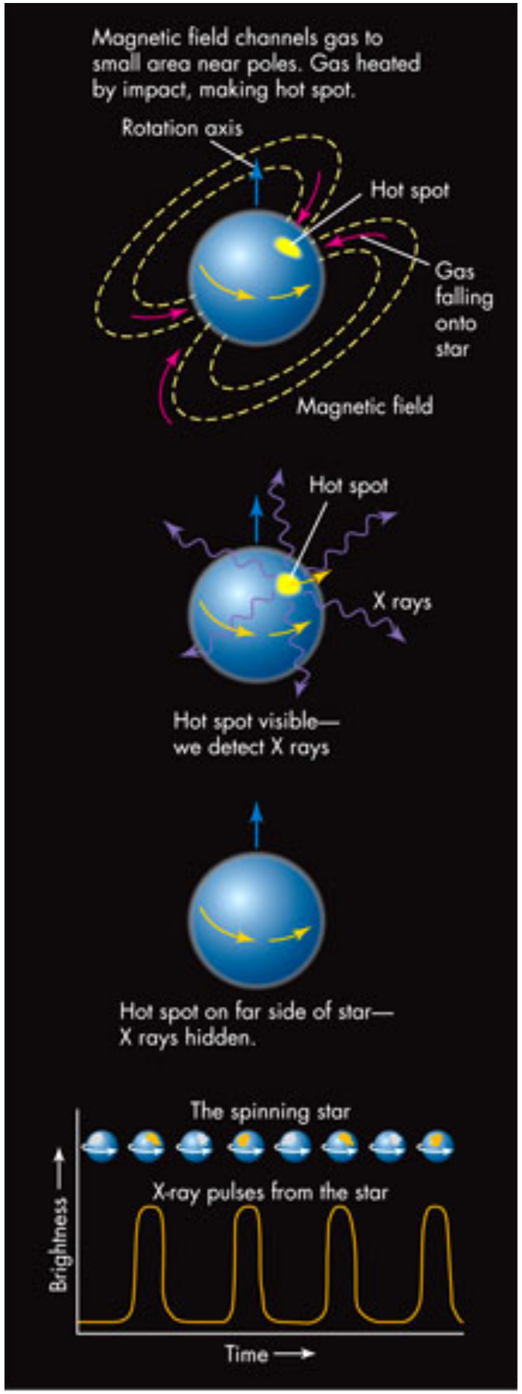
Pulsars and neutron stars

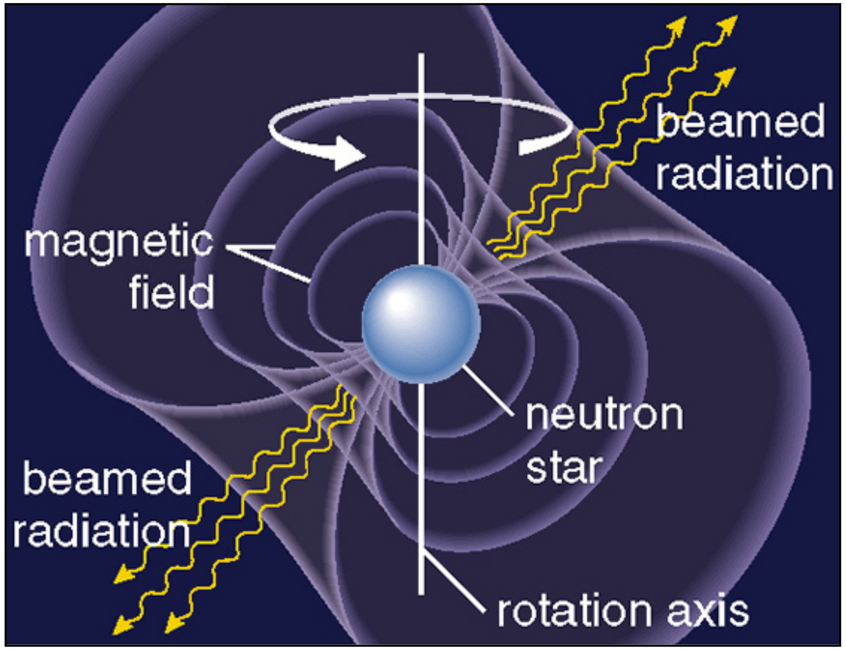
- All pulsars are neutron stars, but all neutron stars are *not* pulsars.
- Emission (mostly radio) is concentrated at the magnetic poles and focused into a beam.
- Whether we see a pulsar depends on the geometry.
  - if the polar beam sweeps by Earth's direction once each rotation, the neutron star appears to be a pulsar.
  - if the polar beam is always pointing toward or always pointing away from Earth, we do not see a pulsar



Light Curve of Jocelyn Bell's Pulsar, 1967




Magnetic field channels gas to small area near poles. Gas heated by impact, making hot spot.
Rotation axis
Hot spot
Gas falling onto star
Magnetic field
Hot spot
X rays
Hot spot visible—we detect X rays
Hot spot on far side of star—X rays hidden.
The spinning star
X-ray pulses from the star
Brightness
Time


beamed radiation
magnetic field
neutron star
beamed radiation
rotation axis

Rotation-powered Pulsars

Not to be confused with accretion-powered pulsars

Rotation-powered Pulsars

- Rapidly spinning and strongly magnetized NS
- Emitted energy coming the rotational energy: the spin period increases with time ➔ spin-down of a pulsar

$$E_{rot} = \frac{1}{2} I\omega^2$$

E_{rot}=rotational energy
I=moment of inertia=(2/5)MR^2 for a sphere
ω=angular velocity=2π/P

$$E_{rot} = \frac{1}{5} MR^2\omega^2 = \frac{4}{5}\pi^2 \frac{MR^2}{P^2} = 2\pi^2 \frac{I}{P^2}$$

$$\frac{dE_{rot}}{dt} = \dot{E}_{rot} = -4\pi^2 I P^{-3} \dot{P}$$

For the Crab PSR
(assuming M=1.4 $M_{\odot}$
and R=10 km)

$$E_{rot} \approx 2\times10^{49}\,\mathrm{erg}$$
$$P = 33\ \mathrm{ms}$$
$$\dot{P} = 4.2\times10^{-13}\,\mathrm{s\,s^{-1}}$$
$$\frac{dE_{rot}}{dt} \approx 4.5\times10^{38}\ \mathrm{erg/s}$$

→ Energy released in thermonuclear burning by a usual star in its life

Over one year, the spin rate changes only by ≈0.04%

Ostriker & Gunn 1969: pulsar slow-down due to the braking torque exerted on the NS by its magneto-dipole radiation

$$\dot{E}_{brake} = -(32\pi^4/3c^3)B_\perp^2 R^6 P^{-4}$$

B_{perp}=component of B perp. to the rotation axis

$$\dot{E}_{brake} = \dot{E}_{rot} \rightarrow B_\perp = 3.2\times10^{19}\sqrt{P\dot{P}}$$

→ $B_{perp}=3.8\times10^{12}$ G for Crab

$$P\dot{P} = \frac{8\pi^2}{3c^3}\frac{B_\perp^2 R^6}{I} = \mathrm{cons}$$

→ $\dot{P} \propto P^{2-n}$

n=braking index
(=3 in case of magneto-dipole braking)

P_0 at $t=t_0$
$t=t_0+\tau$
τ=characteristic age=
spin-down age=
time required to lose $E_{rot}(t_0)-E_{rot}(t)$ via magneto-dipole radiation

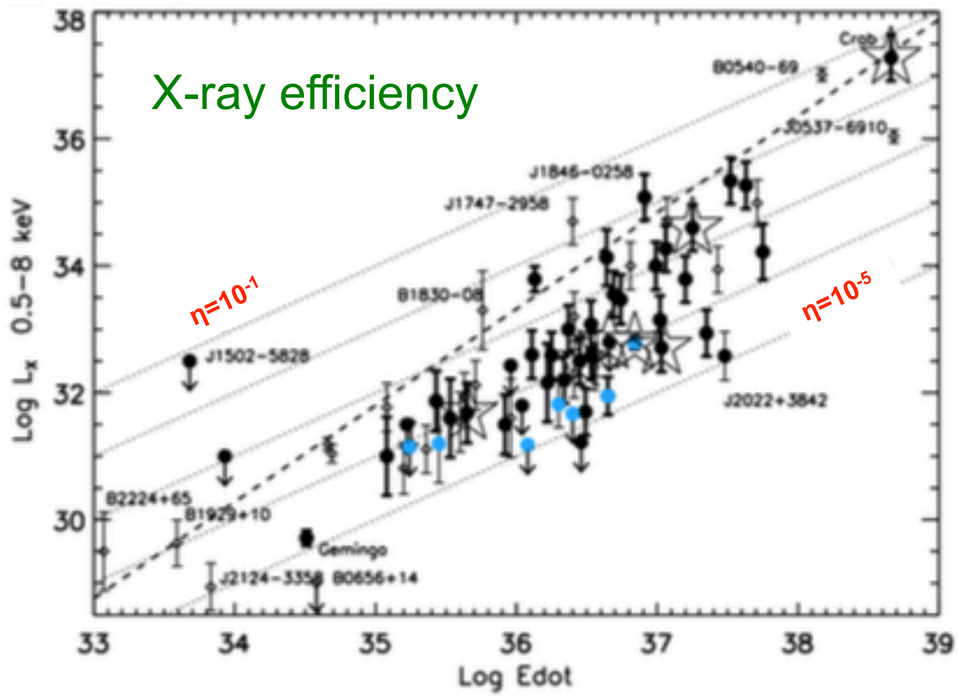
$$\tau = \frac{P}{(n-1)\dot{P}}\left[1-\left(\frac{P_0}{P}\right)^{n-1}\right] \underset{P_0 << P}{\overset{n=3}{=}} \frac{P}{2\dot{P}}$$

t=1260 yr for the Crab PSR while real t=960 yr

Magnetic braking model generally accepted but the spin-down model is found to account only for a fraction of $\dot{E}$ (E_{dot})
Efficiency (i.e., conversion of rotational energy into radiation): $\eta=L/\dot{E}=$
= 10^{-7}-10^{-5} radio/optical
= 10^{-4}-10^{-3} X-rays
= 10^{-2}-10^{-1} γ-rays
Further support comes from observed $n\neq3$ (which is expected in case of pure dipole radiation)

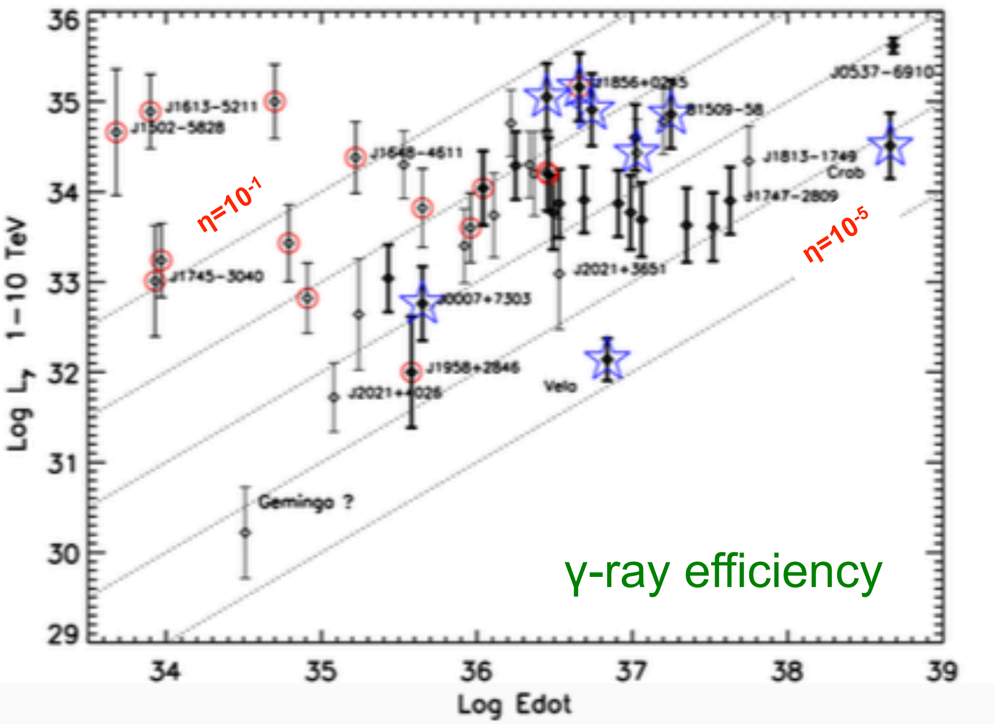
➔A significant fraction of the PSR rotational energy carried out by a PSR wind [**pulsar-wind nebula** (aka plerion or synchrotron nebula)], common for fast pulsars with strong magnetic field. Short life unless continuously replenished

X-ray



Stars: Fermi
Circles: no X-ray detection
Dashed line: theoretical upper boundary

γ-ray



Kargaltsev et al. (2015) review

Are all pulsars observed in all bands?

• Not so many pulsars are observed in more than one bands

Reasons

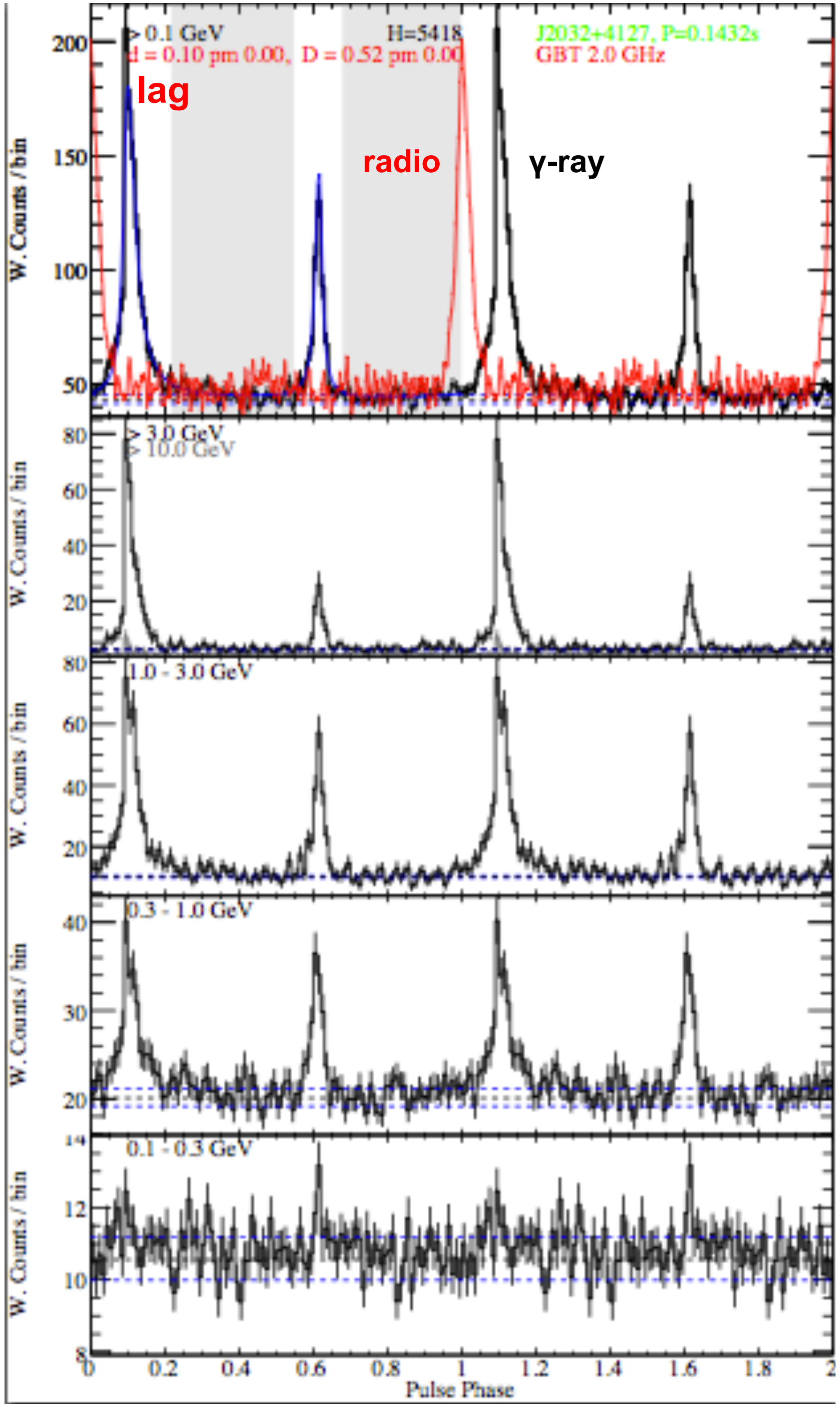
(a) observational biases (linked to sensitivity)

- radio is the most effective band for pulsar detection, as clearly indicated by the numbers (≈2000 so far)
- Pulsars have very faint magnitudes in the optical ➔ hard to pick up these pulsars besides in deep (and time-consuming) surveys. Crab and Vela pulsars are quite unusual (because bright) among pulsars with optical counterparts
- <10 pulsars in the infrared
- 117 in the *Fermi* PSR catalog (as July 2013): dozens of radio-quiet PSR + new MSPs

(b) geometrical/physical explanation

• beams at different wavelengths can be non-linear (pointing towards different directions, hence line-of-sights) or simply can be characterized by different widths

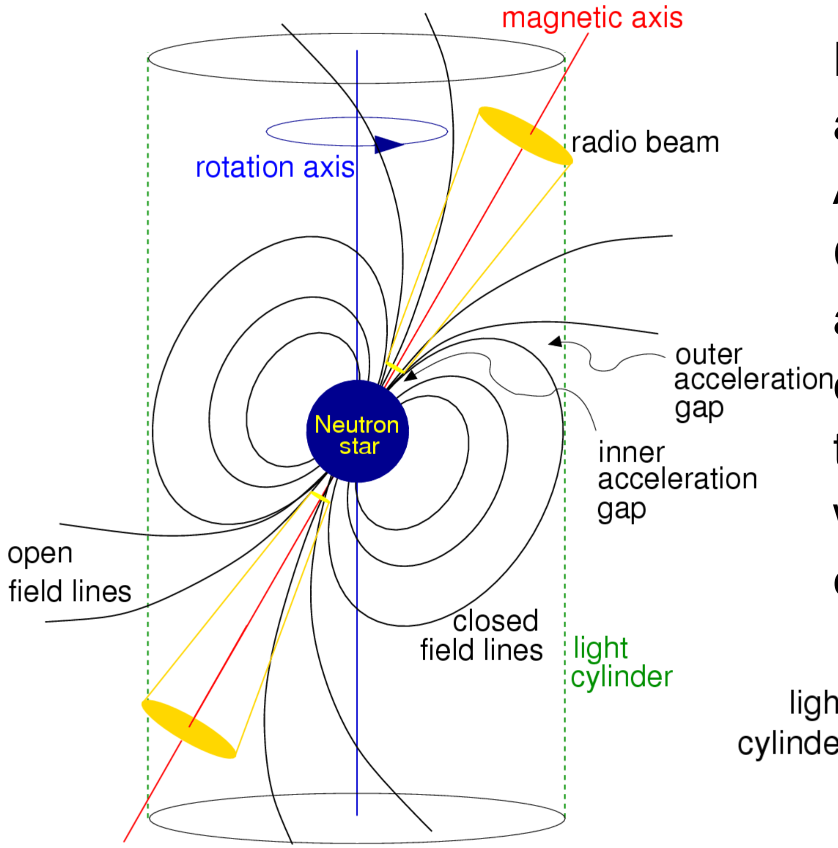
• possible link with the region where particles are extracted from the NS and accelerated



From the

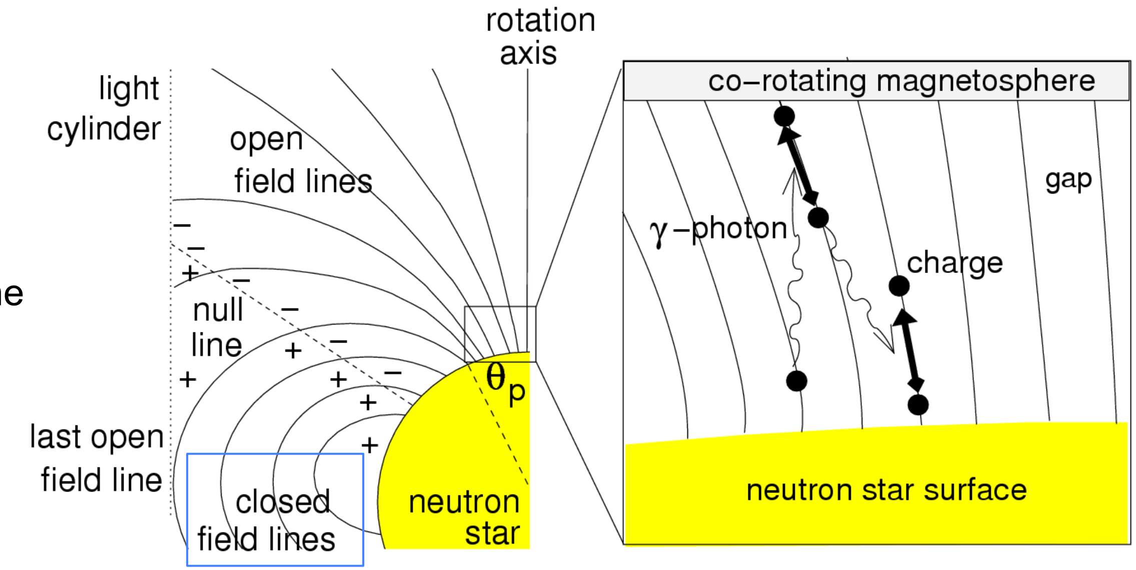
LAT second pulsar catalog

Some notations about pulsars



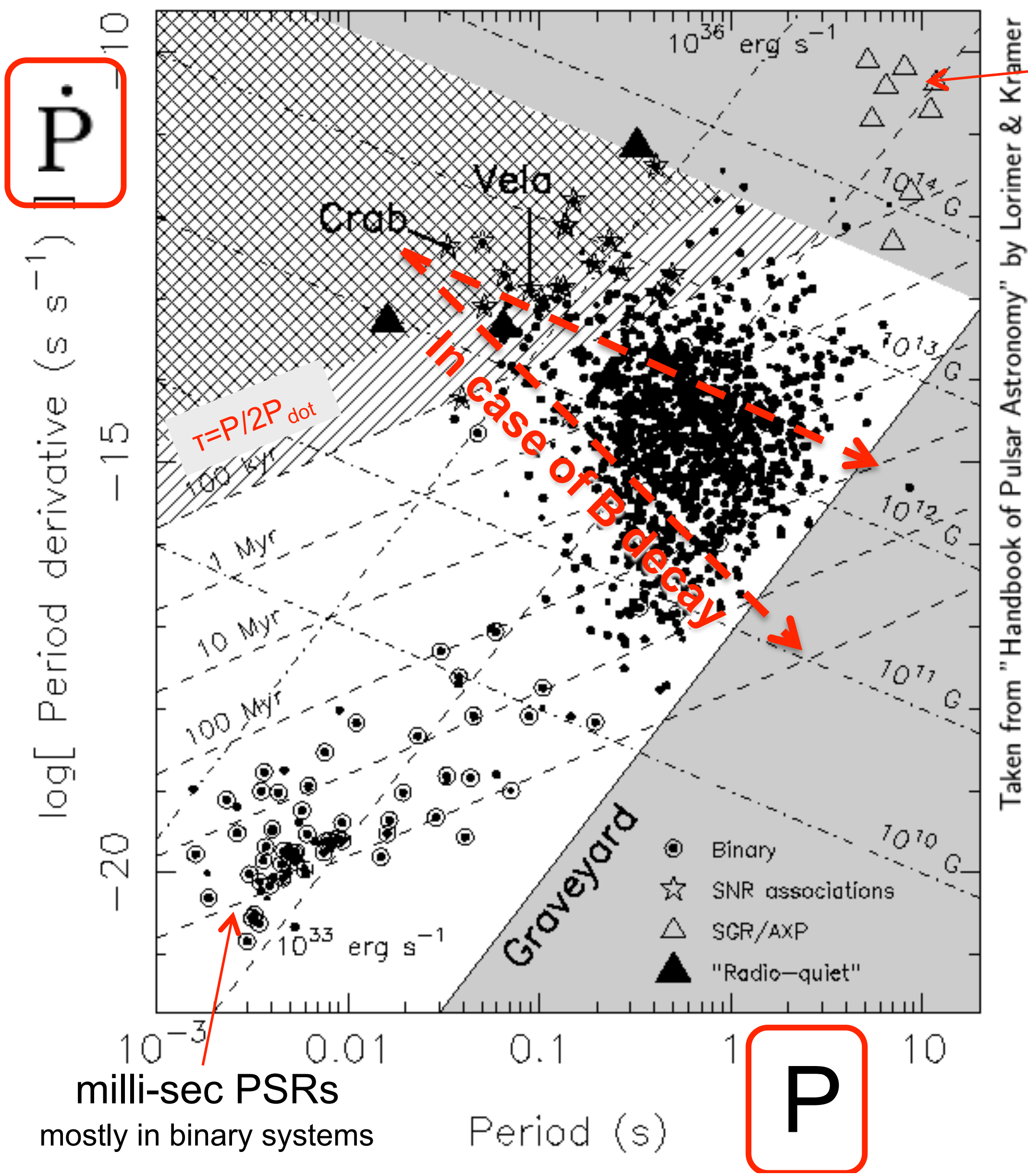
Light cylinder: cylinder centered on the PSR and aligned with the rotational axis: R_{LC}=cP/2π At its radius, v(co-rotation, B field lines)=c

Curvature radiation: *electrons* in the polar cap are *magnetically accelerated* along the open curved lines. Emission polarized in the plane of the curvature. The high-energy photons interact with B and lower-energy photons to produce e^-/ e^+ pairs in a cascade process



At the radius of the light cylinder (R_{LC}), the velocity of a plasma rotating with the neutron star would equal the velocity of light at the surface of the cylinder. At $R>R_{LC}$, the velocity of the particles would exceed c (co-rotation is not possible any further), hence field line might be open ➔ Observed emission from the PSR

P-Pdot diagram



milli-sec PSRs

mostly in binary systems

SGR: soft γ-ray repeaters magnetars

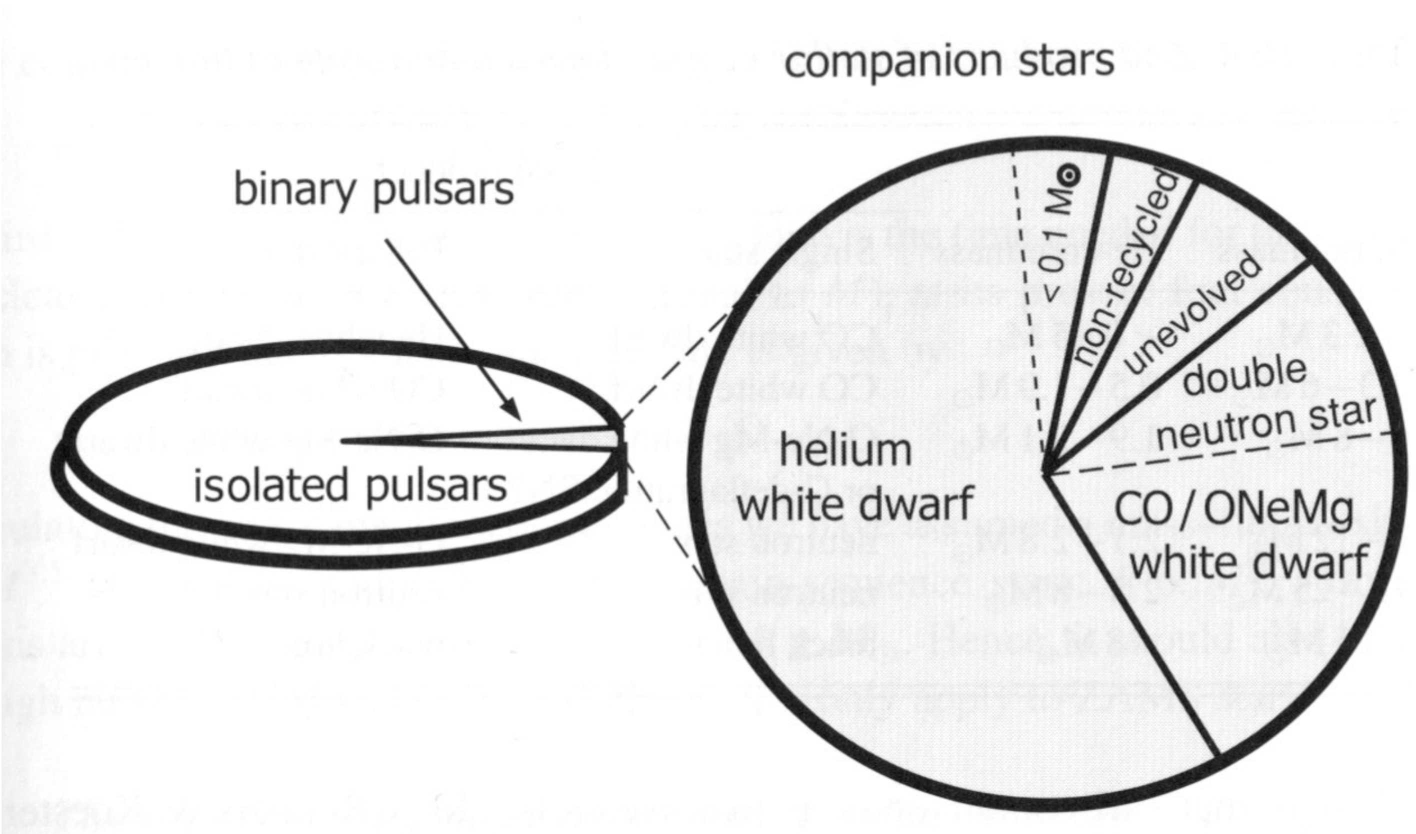
AXP: anomalous X-ray pulsars

Both are not rotation-powered (decay of B, dynamo, magnetic reconnection), young, mostly associated to SNRs, due to collapse of massive stars

Steady + bursty emission, isolated

P-Pdot diagram

- Sort of cycle of life for pulsars
- PSRs from SNeII, in the upper left corner of the diagram
- Then they gradually move to the right and down, along lines of constant B (unless B field decays)
- Young PSRs often found near recognized SN
- Finally, PSRs fall in the graveyard
- Possibility for PSRs to spin-up: “recycled pulsars” via accretion and angular momentum transfer: milli-second PSRs with B≈10^8 G



Approx. 4% of pulsars are members of a binary system (the companion being a WD, a NS, an unevolved star, etc.)

High-energy emission models

Radio emission from a coherent process (curvature radiation: relativistic electrons spiraling along the field lines). Electrons do not radiate as independent charges

Optical, X-ray and γ-ray emission from incoherent process: fluxes proportional to the densities of high-energy electrons

✓ Non-thermal emission from charged relativistic particles in the PSR magnetosphere ➔ powerlaw emission (energy particle distribution), optical to X-rays
✓ Extended emission from PSR-driven synchrotron nebulae (radio through X/γ-rays)
✓ Photospheric emission from the hot surface of a cooling NS ➔ modified BB, optical to soft X-rays
✓ Thermal soft X-ray emission from the NS polar caps, heated by the falling relativistic particles streaming back to the surface from the PSR magnetosphere

Location of the high-energy emission
Magnetospheric emission models (I)

Polar-cap model

Acceleration and radiation near the magnetic poles

The γ-ray emission forms a hollow cone centered on the magnetic pole, producing single/double pulses ➔ **radiation from "pencil" beams**

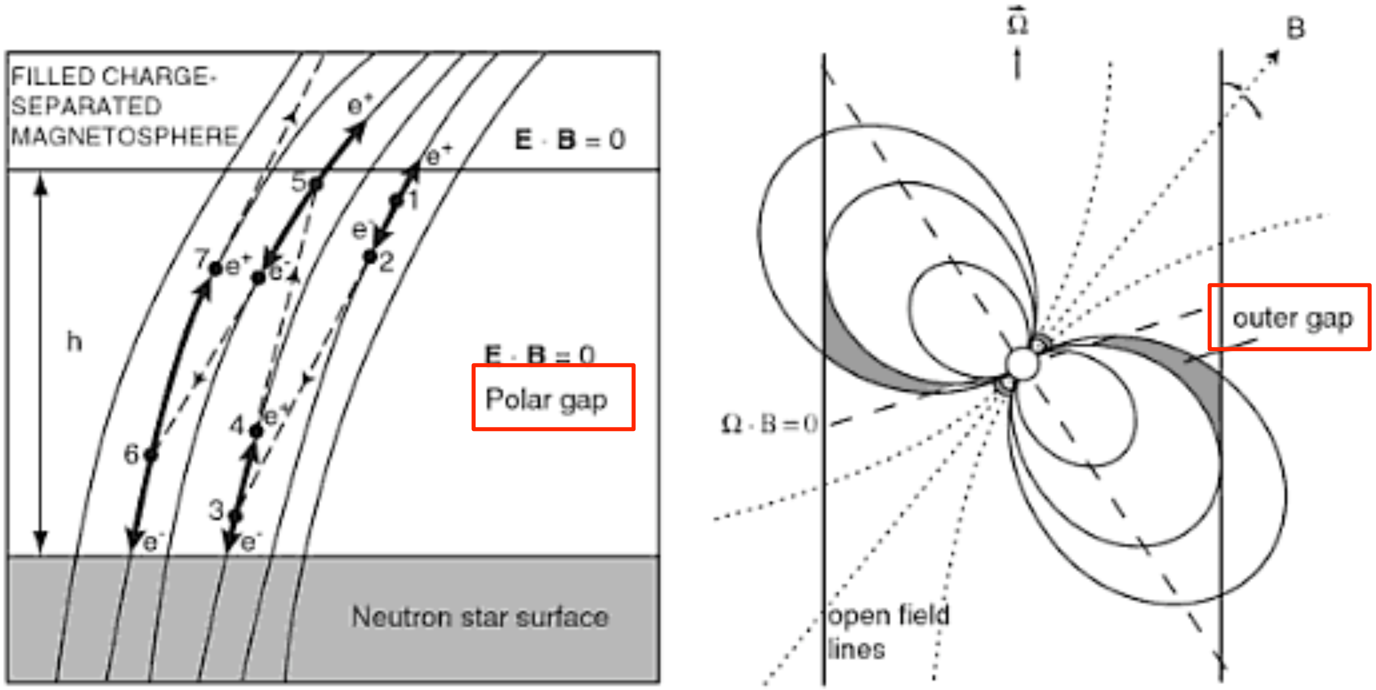
Outer-gap model

Emission zone close to the PSR light cylinder (outer magnetosphere)

Radiation emitted in "fan" beams
Easier explanation of double-pulses
Related to regions of lower B and associated to larger γ-ray emissivities
"Gaps" because charges escape and are not refilled

Common property: relativistic particles accelerated by strong electric field, generated by the magnetic field co-rotating with the NS.
Particles generated in cascade processes in charge-free gaps, located above the magnetic poles or at the light cylinder.
Main photon emission: synchrotron/curvature radiation + inverse Compton of the soft thermal X-ray photons emitted from the hot NS surface + photon-photon pairs

Magnetospheric emission models (II)

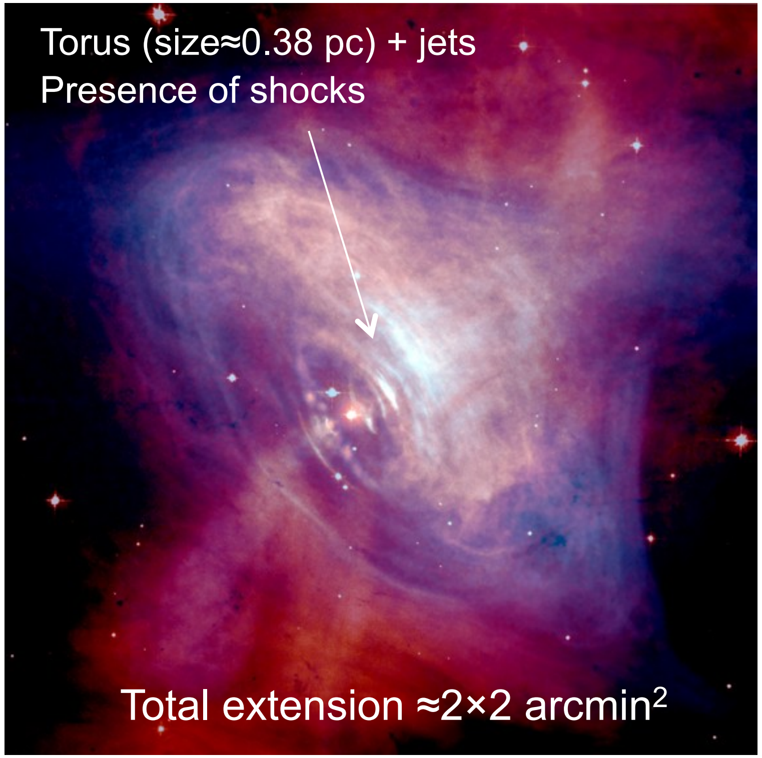


An “historical” overview of rotation-powered Pulsars

Pulsar age (years)	Pulsar category	Einstein	ROSAT ASCA	XMM-Newton Chandra
$\leq 10^4$	Crab-like	3	5	9
$10^4 - 10^5$	Vela-like	1	9	15
$10^5 - 10^6$	Cooling NS		5	6
$10^6 - 10^8$	Old and nearby	1	3	8
	binary		1	3
$\geq 10^8$	ms-Pulsar		11	39
	Σ detected:	5	33	80

Situation in 2006

Nowadays, X-rays are able to detect also radio-quiet (silent) pulsars

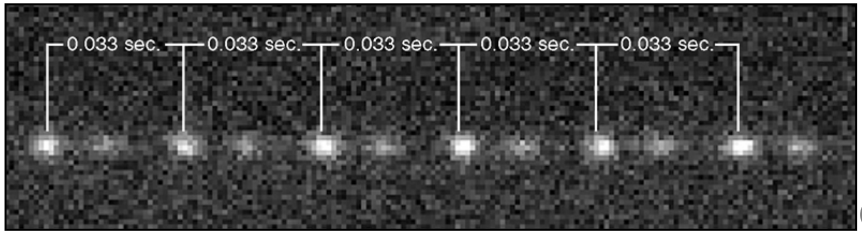


Crab nebula: t≤10^4 yr

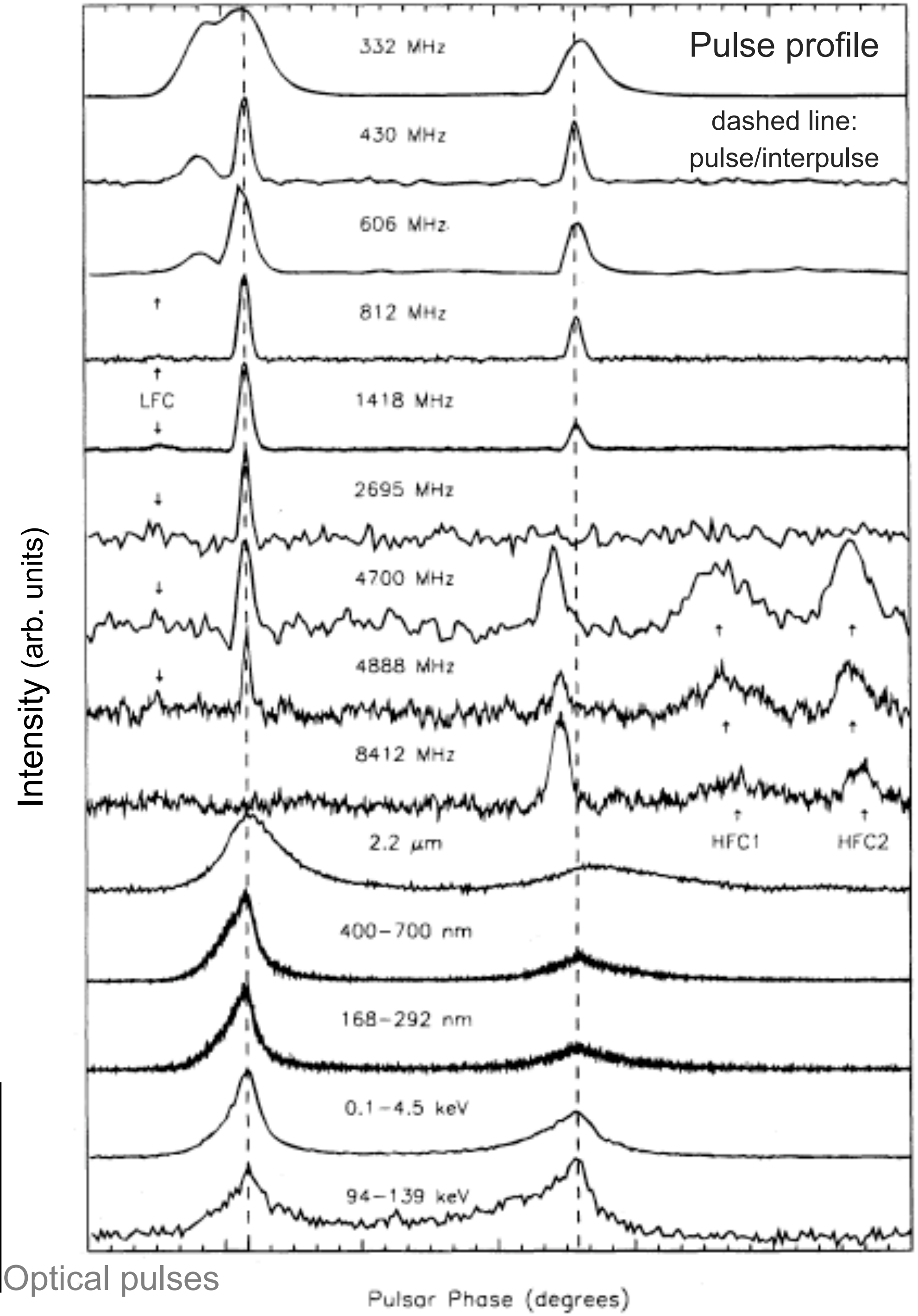
First rotation-powered PSR

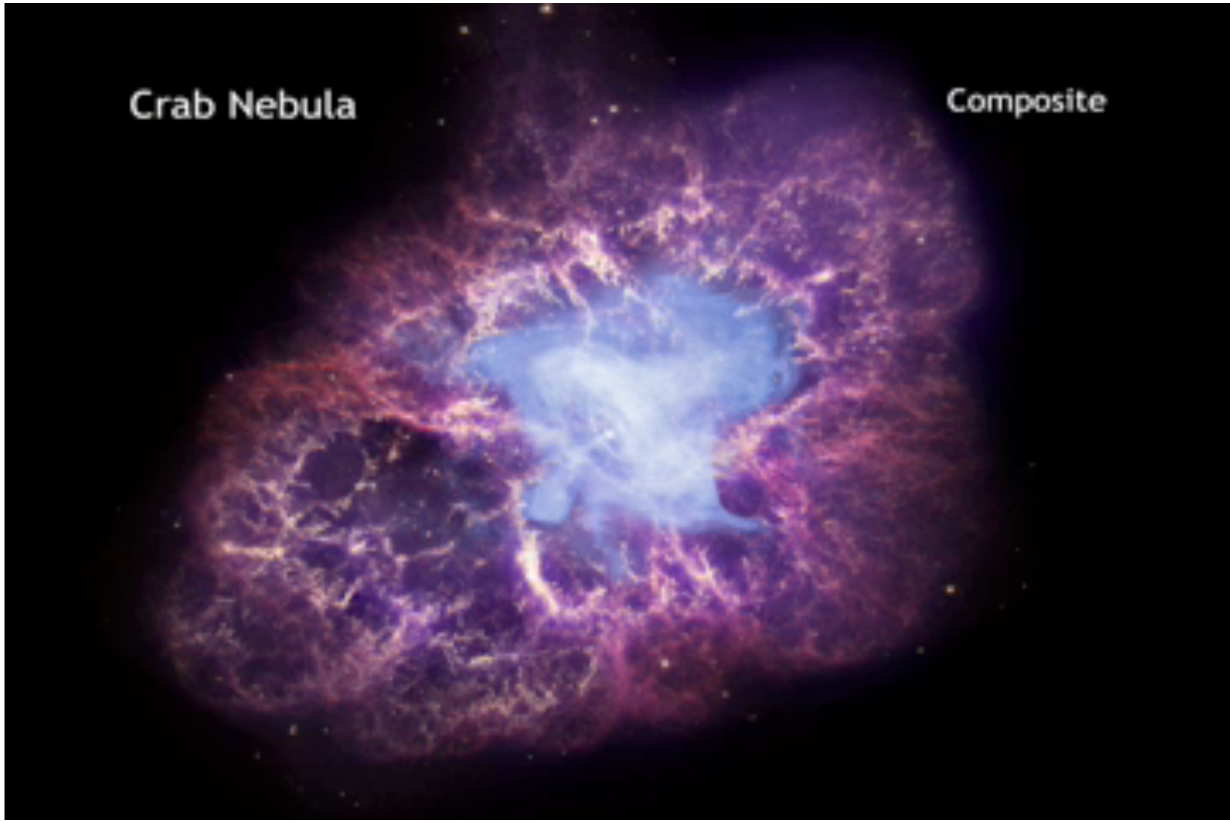
with a high-energy detection

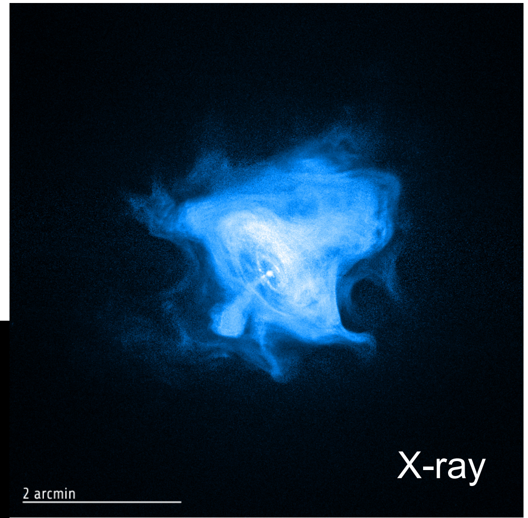
Pulse delays indicate that X-ray
pulses come from the PSR magnetosphere
closer to the NS surface wrt. radio pulses

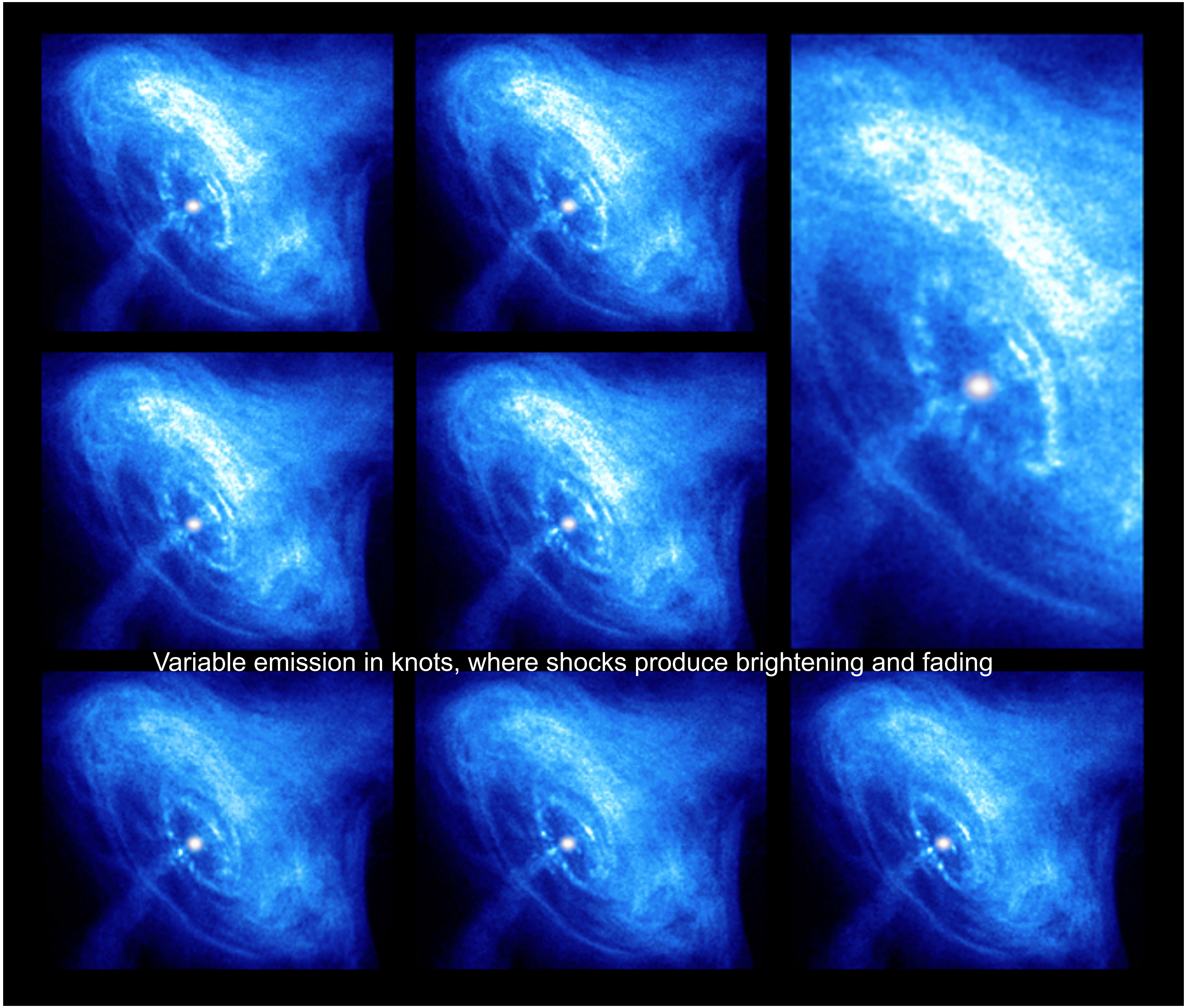


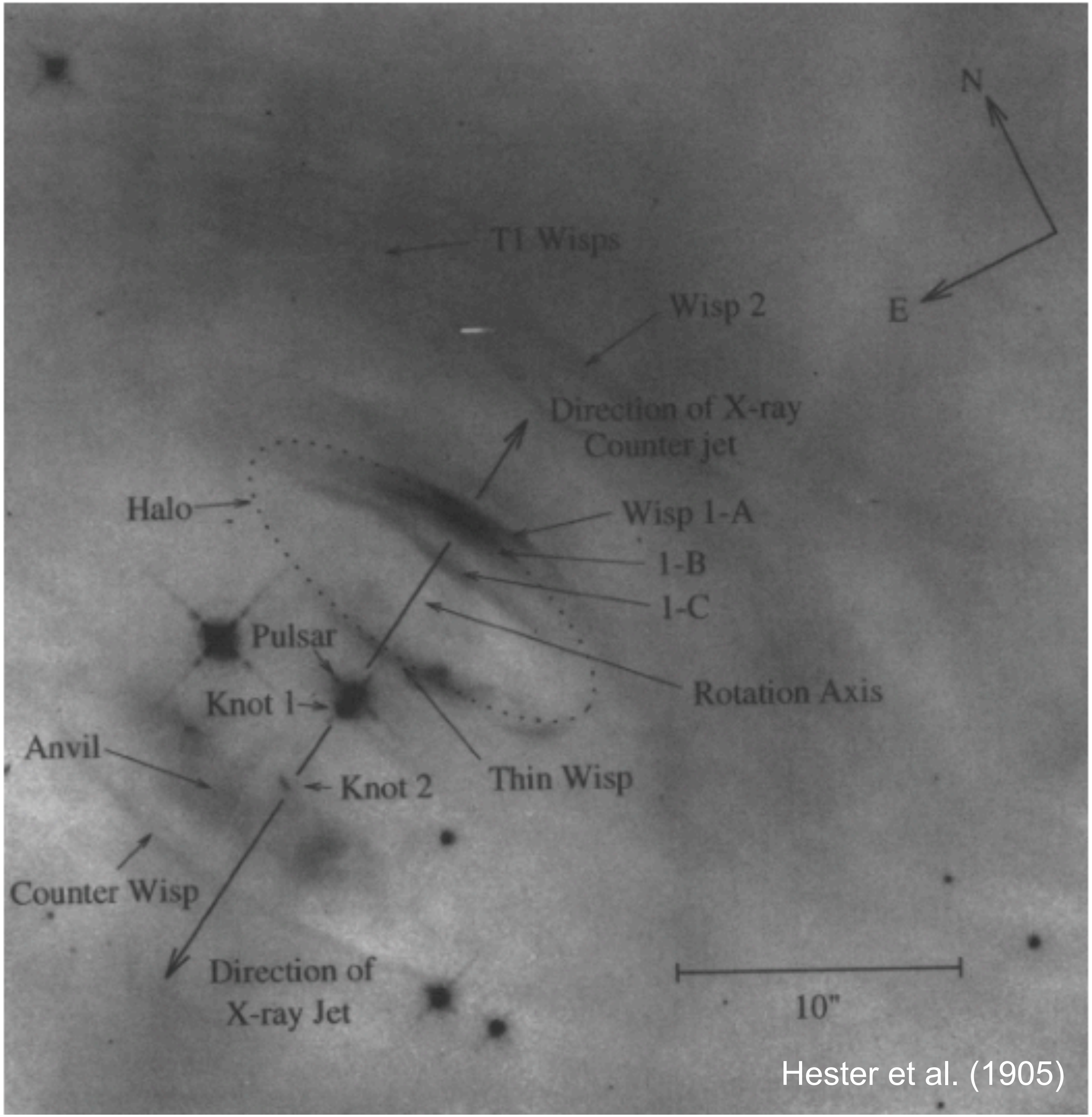
Optical pulses



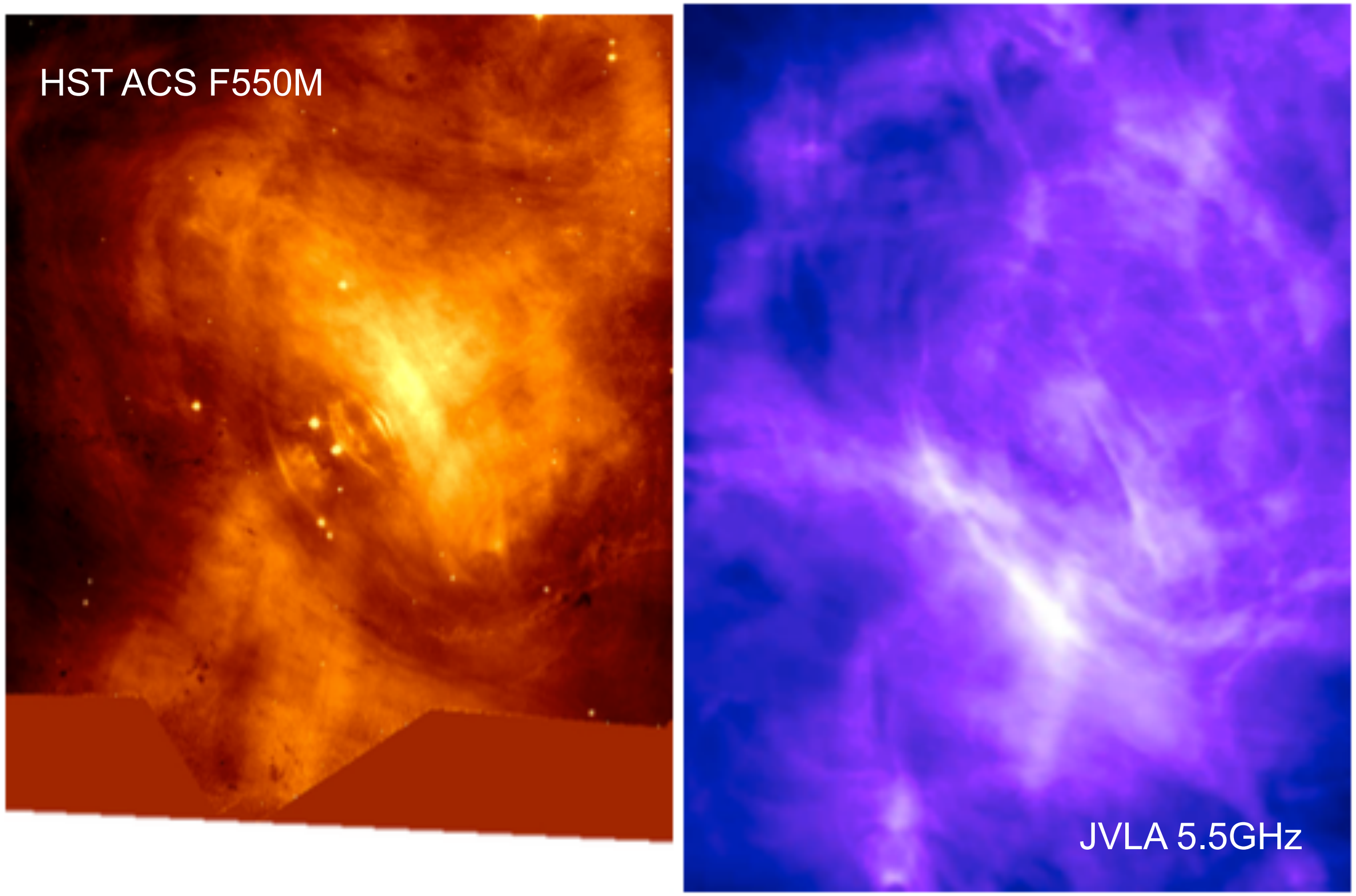

Crab Nebula
Composite


X-ray
2 arcmin

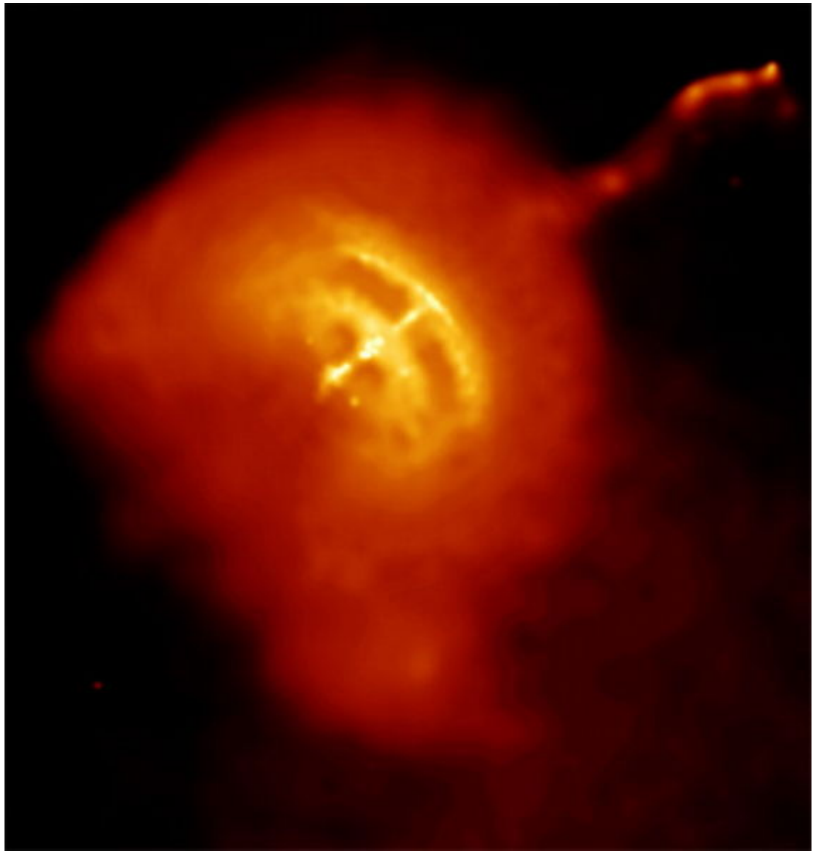

Variable emission in knots, where shocks produce brightening and fading



T1 Wisps
Wisp 2
N
E
Direction of X-ray
Counter jet
Halo
Wisp 1-A
1-B
1-C
Pulsar
Rotation Axis
Knot 1
Anvil
Knot 2
Thin Wisp
Counter Wisp
Direction of
X-ray Jet
10"
Hester et al. (1905)



see Kargaltsev et al. (2015) review



Vela nebula: $t=10^4$-10^5 yr

One of the few with optical emission in this class of age

$L_{opt,\ Vela} \approx 10^{-4}\ L_{opt,\ Crab}$
$\dot{E}_{Vela} \approx 65\%$ lower than Crab

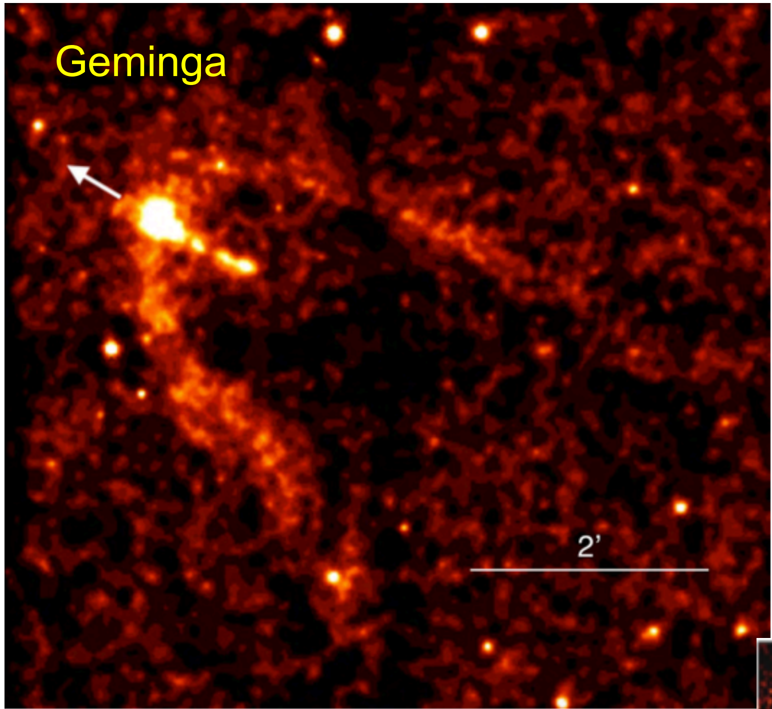
Soft X-ray emission substantially thermal

Similar plerion

Torus from shock-confined **PSR wind**: strong synchrotron emission where B is compressed and amplified due to the interaction of the post-shock plasma with the ambient medium

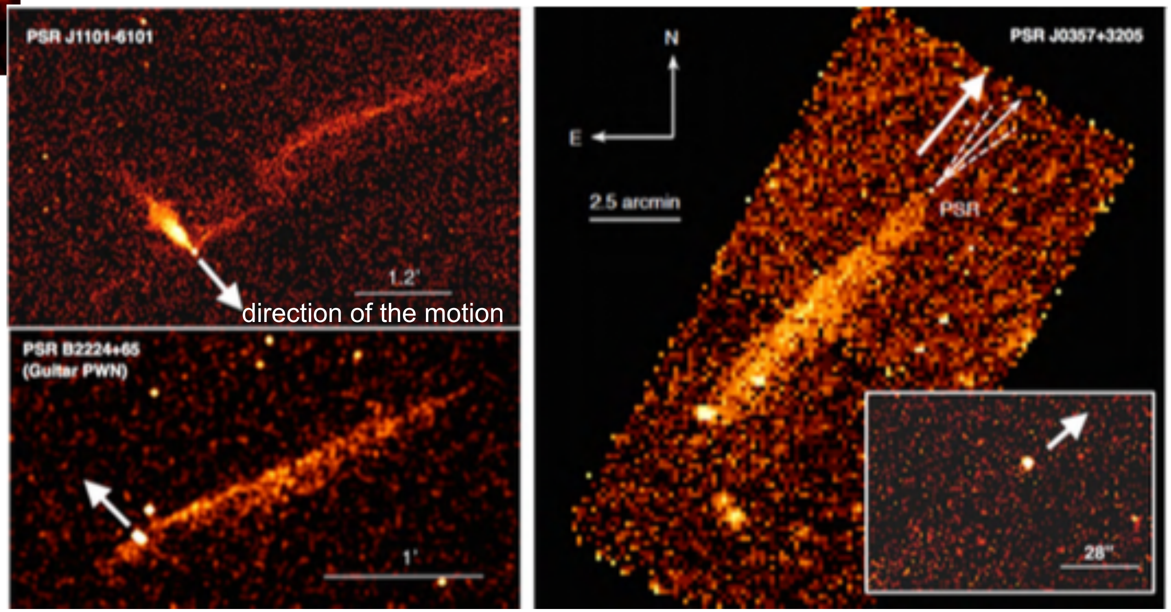
In the Crab plerion:
torus: $\alpha \approx 1.8$
jet: $\alpha \approx 2.1$ (due to intrinsic steeper electron spectrum)
outer regions: $\alpha \approx 2.3$ (due to radiative losses)

Bow shocks and tails



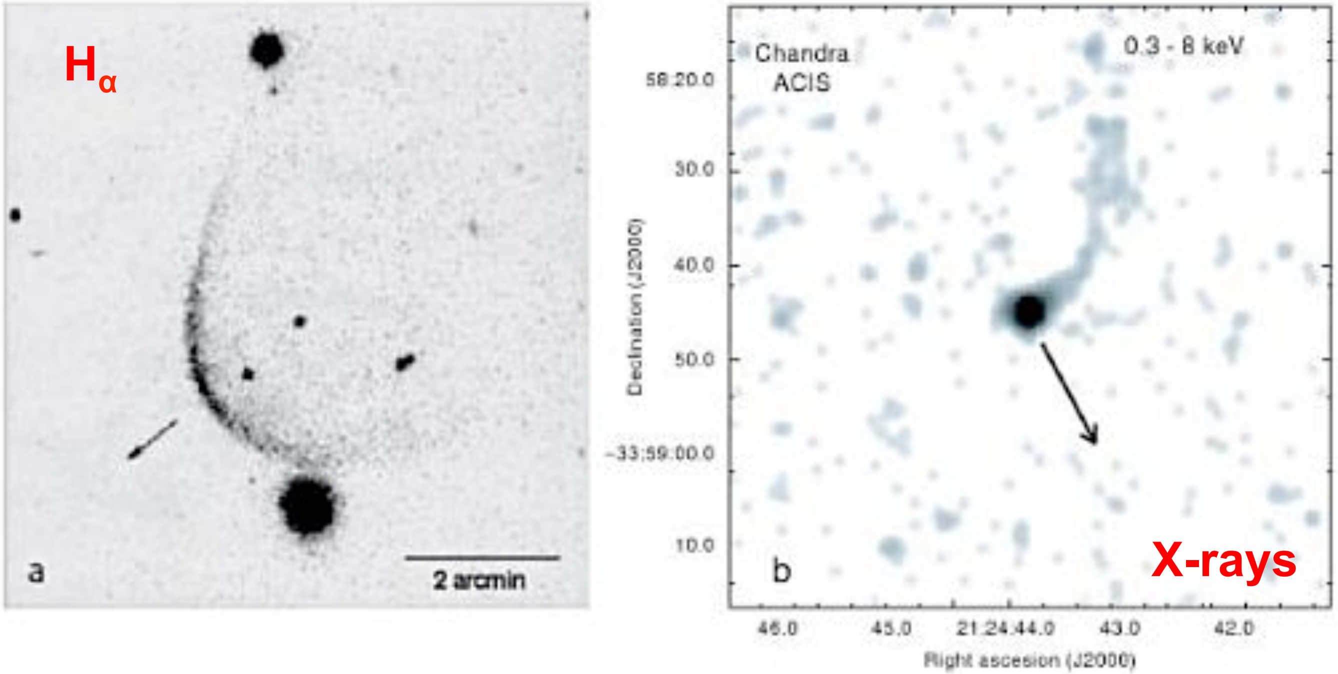
Mostly synchrotron up to MeV, then IC (CMB, NIR backgs) in the GeV

High-velocity PSRs with PWN



2/3 have tails orthogonal to proper motion direction. In one case the extended X-ray emission brightens further away from the PSR while it is very dim in its vicinity

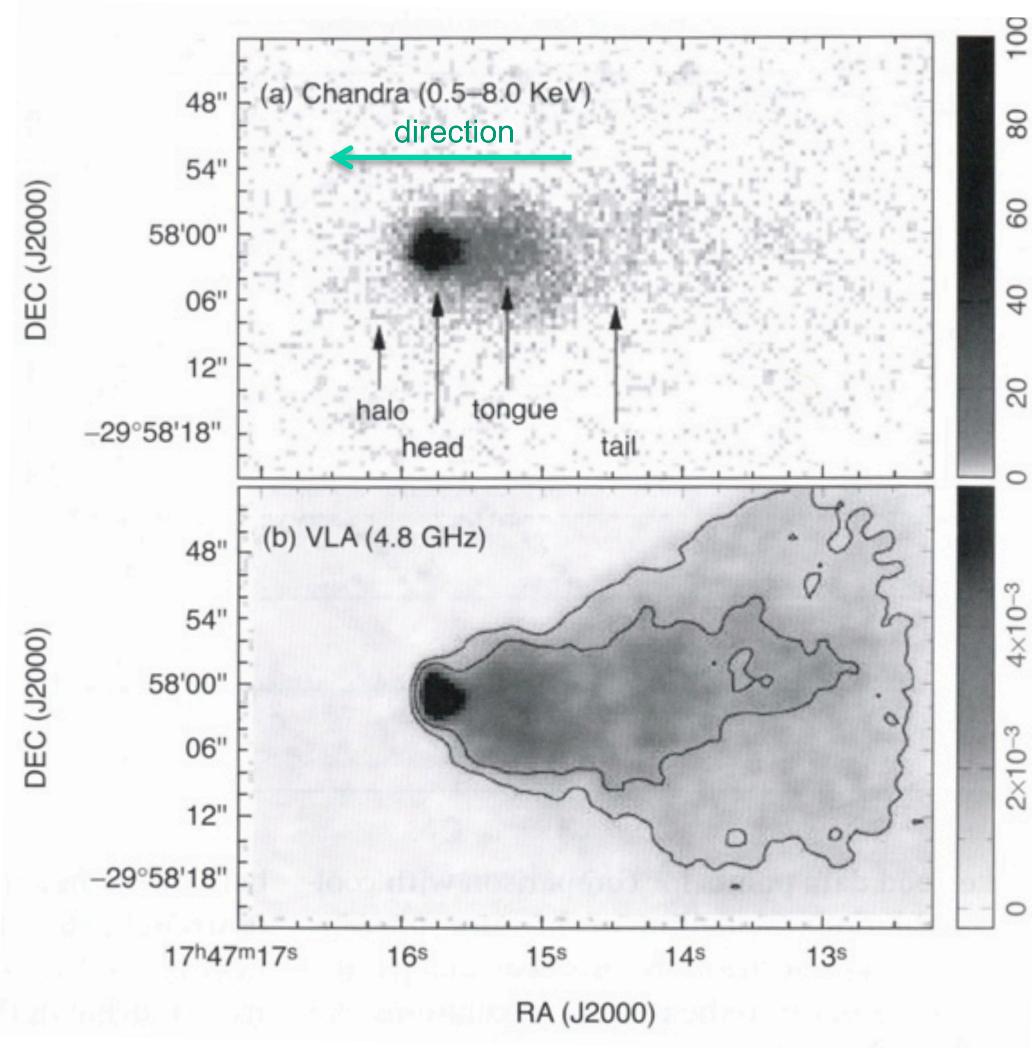
Bow-shock nebulae in PSR winds



Interaction between relativistic PSR winds (carrying out the rotational energy of the PSR) and the surrounding interstellar medium produce diffuse emission (sometimes in the form of a PSR bow-shock nebula, detected also in X-rays).

Electrons must be replenished continuously.

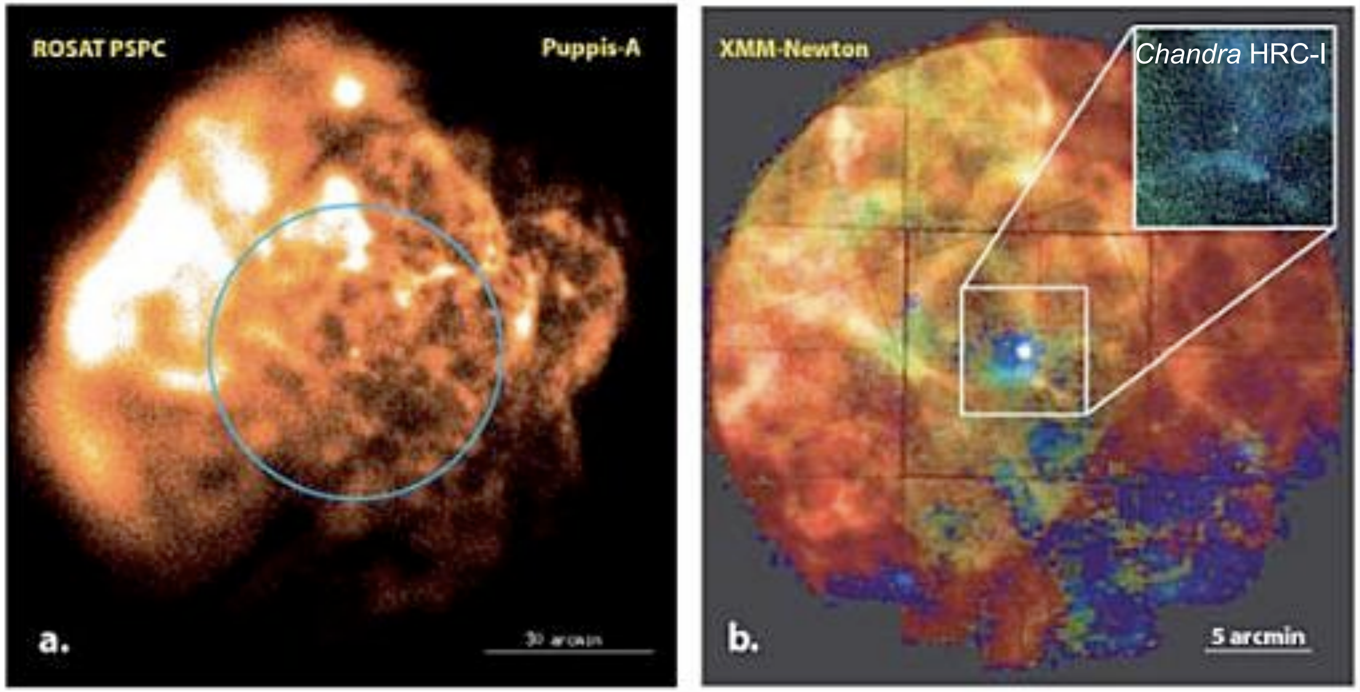
Emission from accelerated particles in the post-shock flow.



PSR J1747-2958

Gaensler et al. 2004

Central compact objects (CCOs) in SNR



T_{bb}≈a few 10^6 K
R_{bb}≈a few (0.3−5) km
L_X≈10^{32-34} erg/s

Different properties wrt young rotation-powered PSRs

Small spin-down rates

Long P (from X-rays)
Low B (≈10^{10} G; "anti-magnetars")

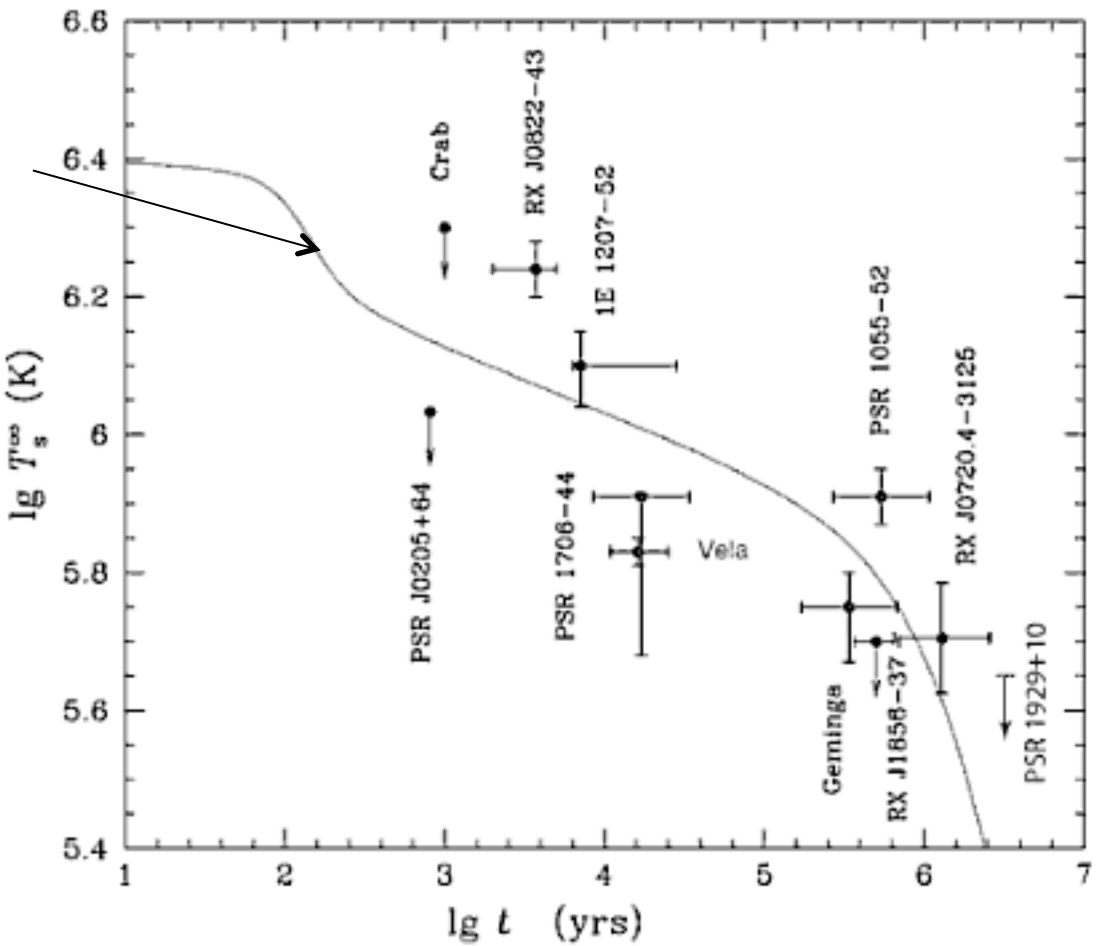
CCO: central compact objects in SNR

radio silent and optical dim, but moderately X-ray bright; no evidence for winds/companion star

- SNR with $t<10^4$ yr
- no plerionic X-ray nebula, limited evidence for pulsations
- no radio counterpart, dim optical counterparts (if any) ➔ high X/optical
- small R (not compatible with EoS of a NS) and high T_{eff} (not compatible with NS cooling models)
- **spin-down ages >> that of SNR ➔** probably born with spin periods close to the current ones

X-ray dim isolated neutron stars (XDINS) − Cooling neutron stars (I)

Theoretical cooling curve



Lack of radio emission: unfavourable orientation?

Pulsations in X-rays

X-rays unlikely due to accretion from ISM

Long spin P (≈3−11s)

(Residual) thermal radiation from isolated NS surface – T≈10^6 K (40−100 eV), L_x≈10^{31} erg/s

Radio-quiet NS, L_{opt}≈5-10 higher than expected from extrapolation of the X-ray spectrum via BB emission ➔ Possibly: (a) X-rays from hot spots at the magnetic poles, while optical emission from the cooler and larger NS surface; (b) different emission mechanism (where optical linked to particle acceleration close to the NS).

Old magnetars where most of the energy has been already dissipated?

Cooling neutron stars (II)

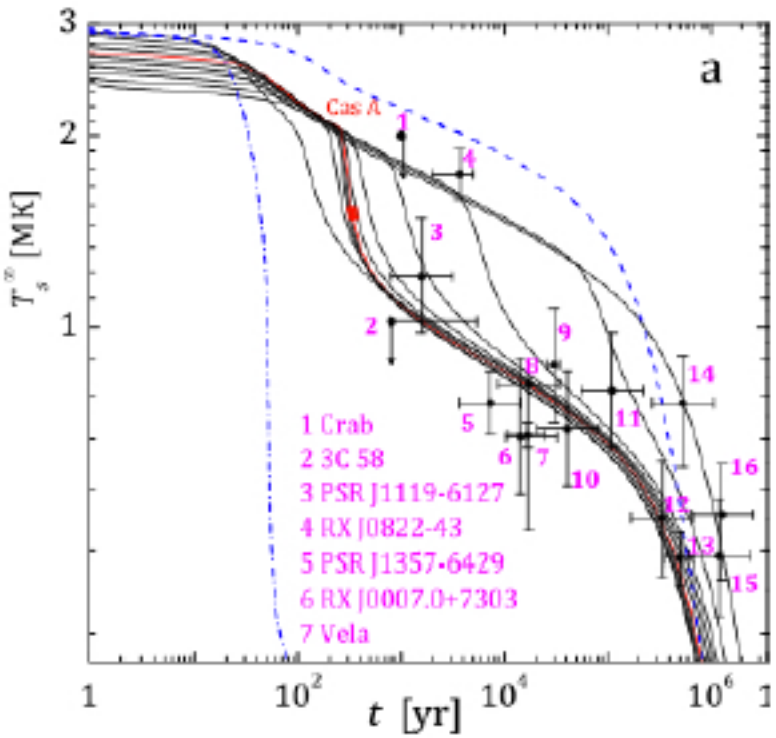


Figure 8. Cooling curves (solid lines) for NSs with a range of masses (varying other parameters can reach the blue dashed lines), compared with observations (crosses) of the temperatures of young NSs of different ages. The drop in model curves at around 100 years is due to the neutron superfluid transition. The slope of the model curve passing through the Cas A NS data point (red) also matches the observed temperature drop of the Cas A NS [85].

- Characteristic age≈1-4 Myr
- B≈1−3 10^{13} G

Rotation-powered PSRs viewed well off their radio beam?

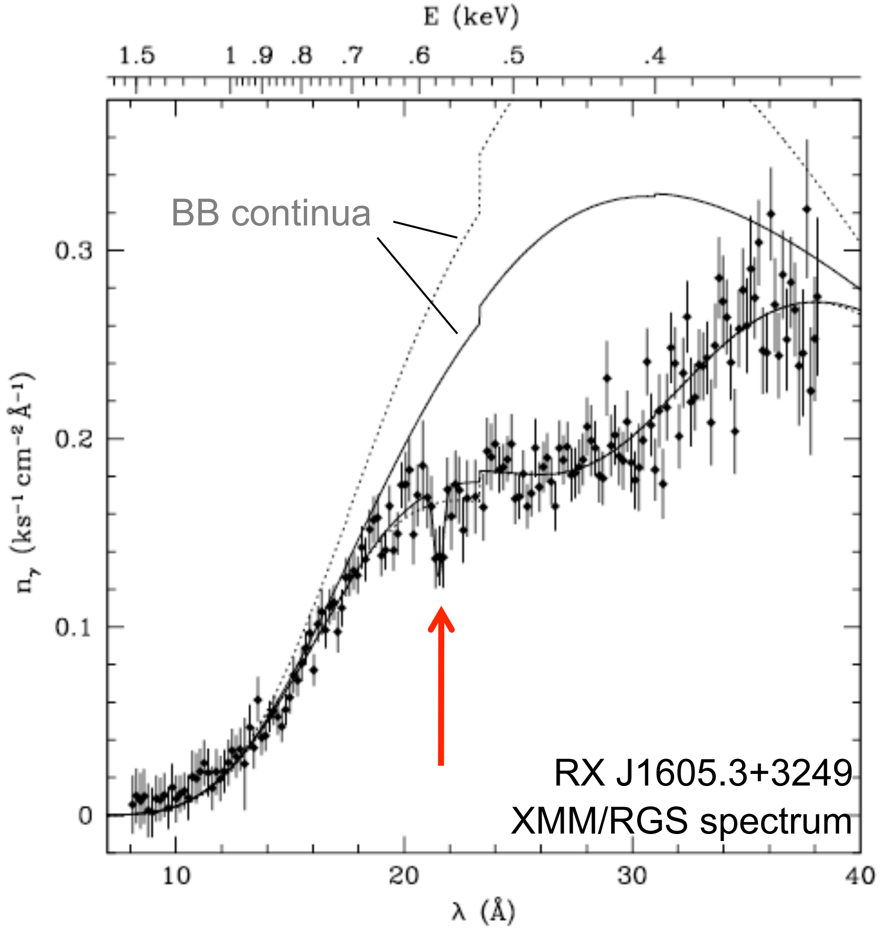
X-rays from initial cooling + additional source of heating (B decay?)

Cooling neutron stars (III)

Strong magnetic fields (B up to a few $\times 10^{13}$ G) from modeling

Observational support from cyclotron absorption line from protons/heavy nuclei

(proton-electron scattering, trapped in the dense plasma)

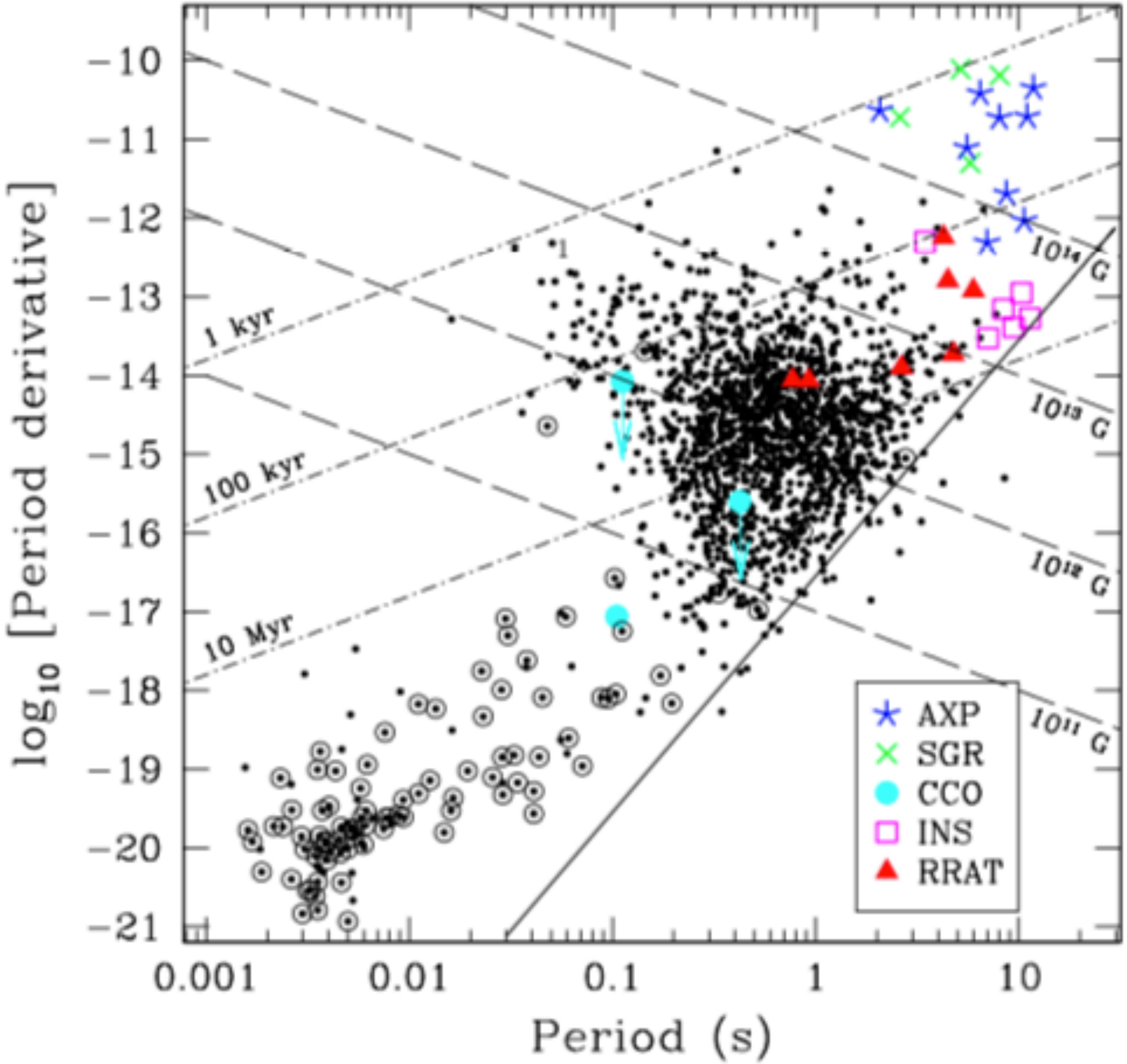


$$B = 1.6\times10^{11}\ E(\mathrm{eV})/(1-2GM/c^2R)^{1/2}\ \mathrm{G}$$

B higher by $A/Z \approx 2$ for heavy elements

One of the “Magnificent seven” isolated NS with BB emission only and cyclotron absorption lines

$kT \approx$ 40-120 eV and $L_X \approx 10^{30-32}$ erg/s

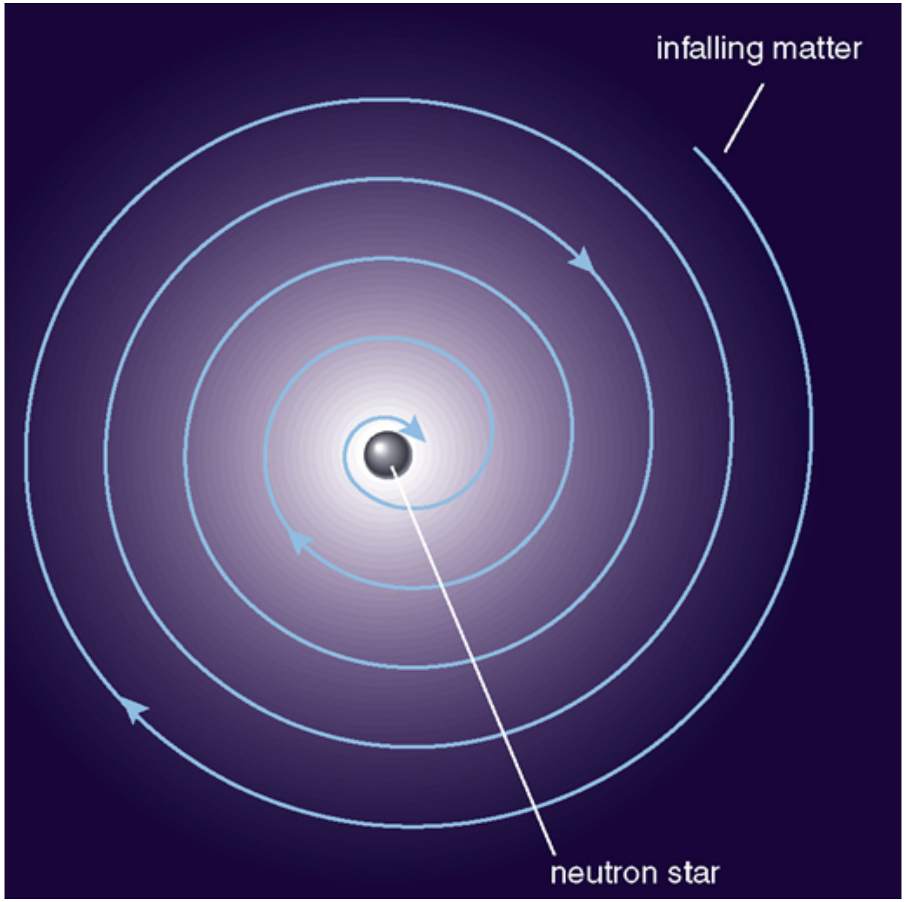


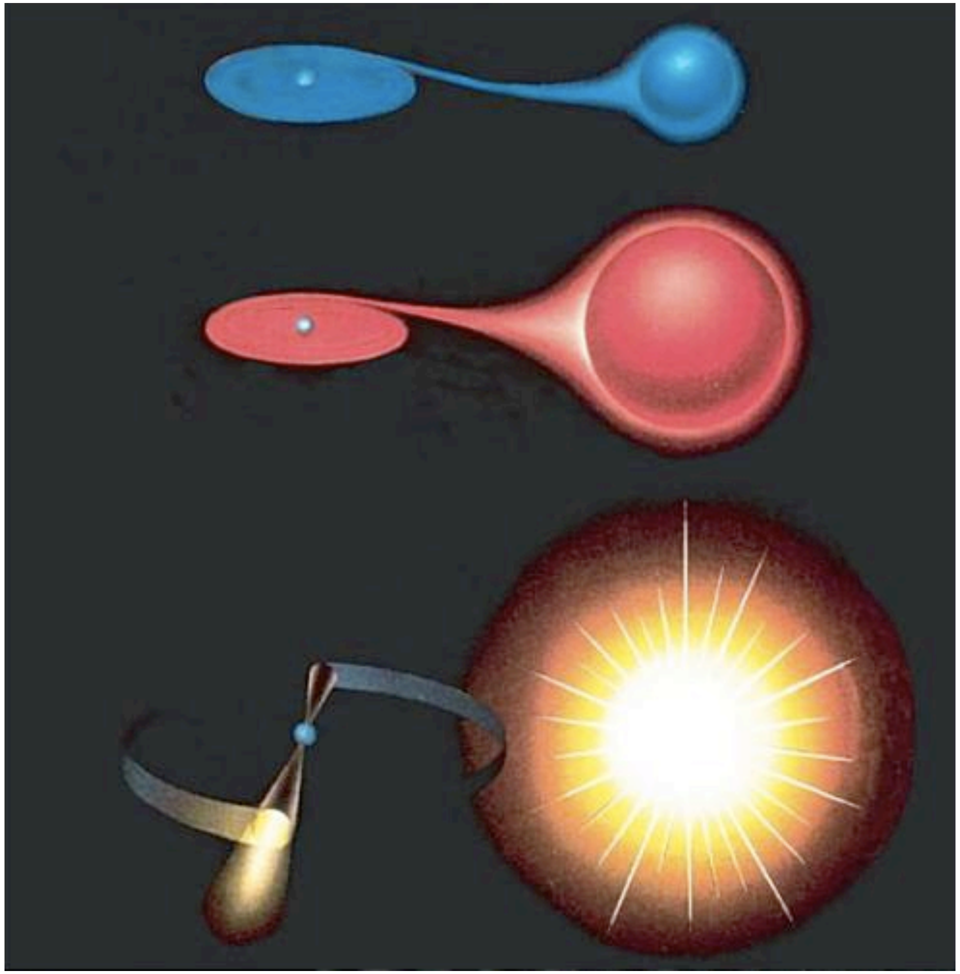
Kaspi 2010 review

Milli-second Pulsars
(recycled pulsars)

Birth of a milli-second pulsars

- Progenitors of “recycled” pulsars
- Mass transfer onto a neutron star in a binary system will spin the pulsar up faster.
  - to almost 1,000 times per sec
- Like white dwarf binaries, an accretion disk will form around the neutron star.
  - the disk gets much hotter
  - hot enough to emit X-rays





- Old, low magnetic fields
- $P \leq 20$ ms, $P_{dot} \approx 10^{-18 \div -21}$
- $\geq$ 75% of ms-PSR in binary systems (WD usually) vs. 1% ordinary PSRs
- $\approx$10% overall population, mostly in GC
- Solitary recycled PSRs: evaporated companion or disrupted system

$E_{dot} \geq 10^{35}$ erg/s: non-thermal processes dominate, mostly hard X-rays
$P \geq 4$ ms + $E_{dot} \geq 10^{34\text{-}35}$ erg/s: softer X-rays (BB+PL)
➔ *Thermal emission (BB) from polar caps, PL from accelerated particles in the co-rotating magnetosphere*

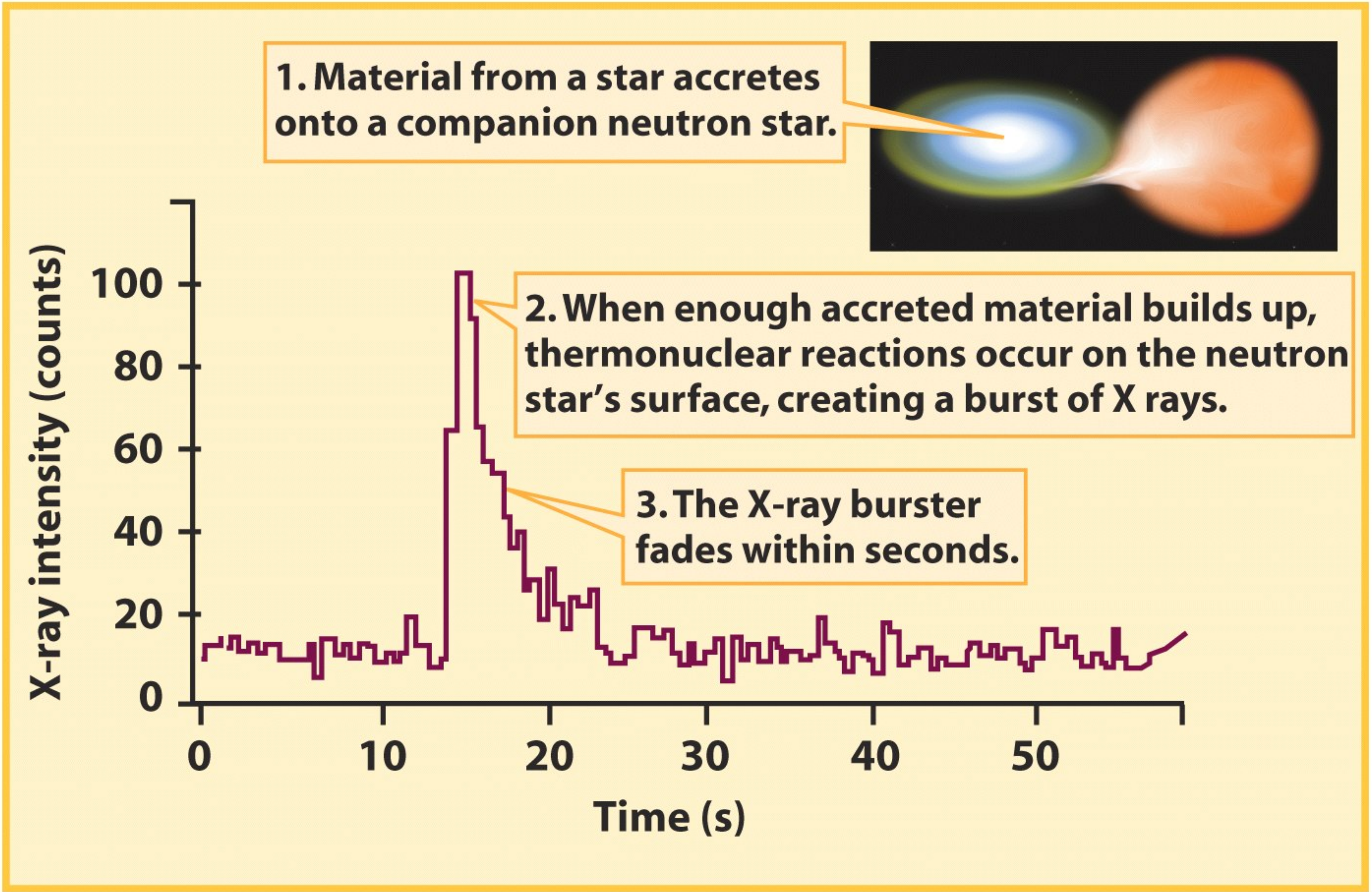
X-ray bursters

Just as is the case with novae, hydrogen gas will accrete onto the surface of the neutron star.

- a shell of Hydrogen, 1 meter thick, forms on the star
- pressure is high enough for hydrogen to fuse steadily on the neutron star surface
- a layer of helium forms underneath
- when temperatures reach 10^8 K, the Helium fuses instantly and emits a burst of energy

These neutron star “novae” are called X-ray bursters.

- a burst of X-rays, lasting a few seconds, is emitted
- each burst has the luminosity of 10^5 Suns
- the bursts repeat every few hours to every few days


1. Material from a star accretes onto a companion neutron star.
2. When enough accreted material builds up, thermonuclear reactions occur on the neutron star's surface, creating a burst of X rays.
3. The X-ray burster fades within seconds.
X-ray intensity (counts)
0
20
40
60
80
100
0
10
20
30
40
50
Time (s)