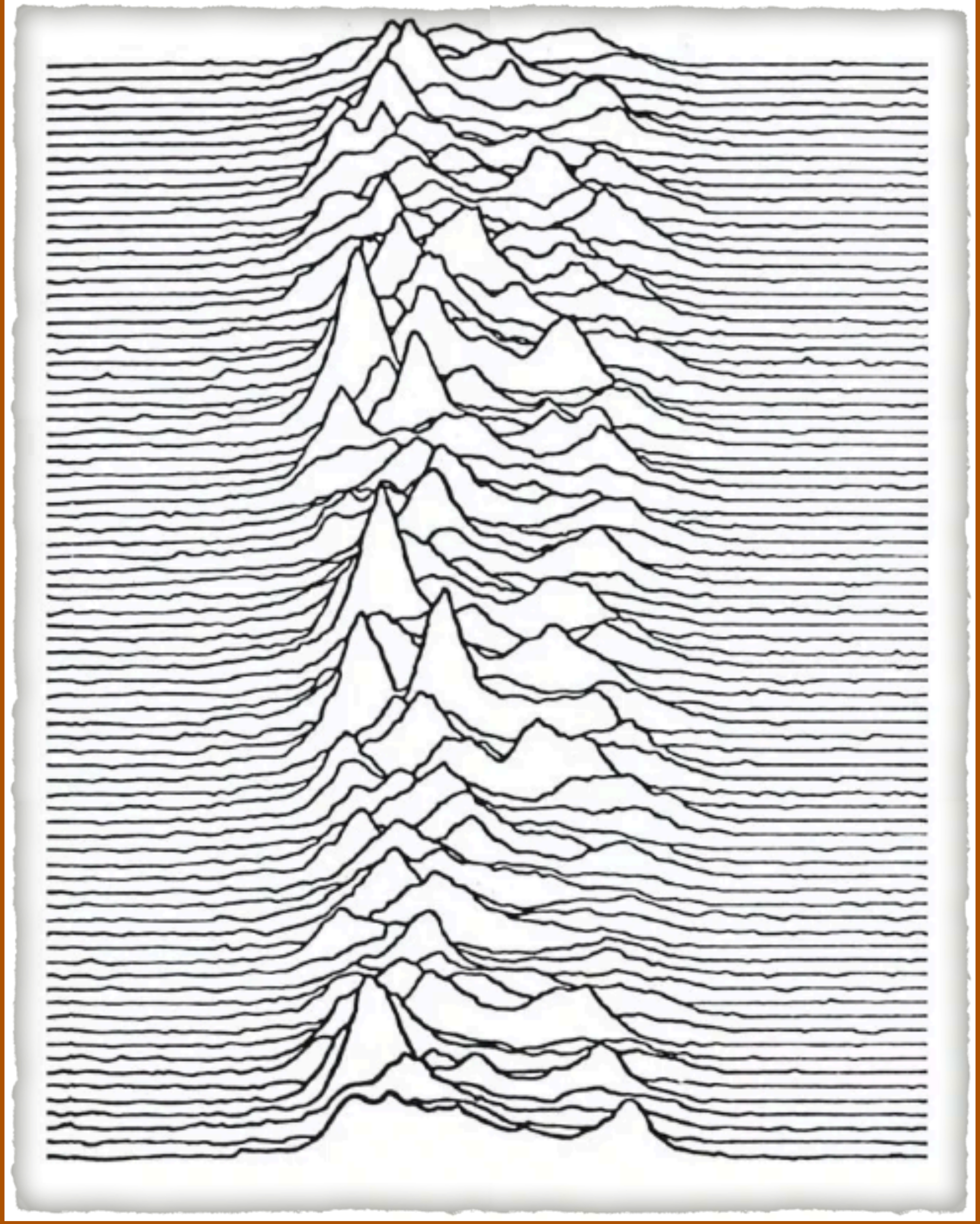
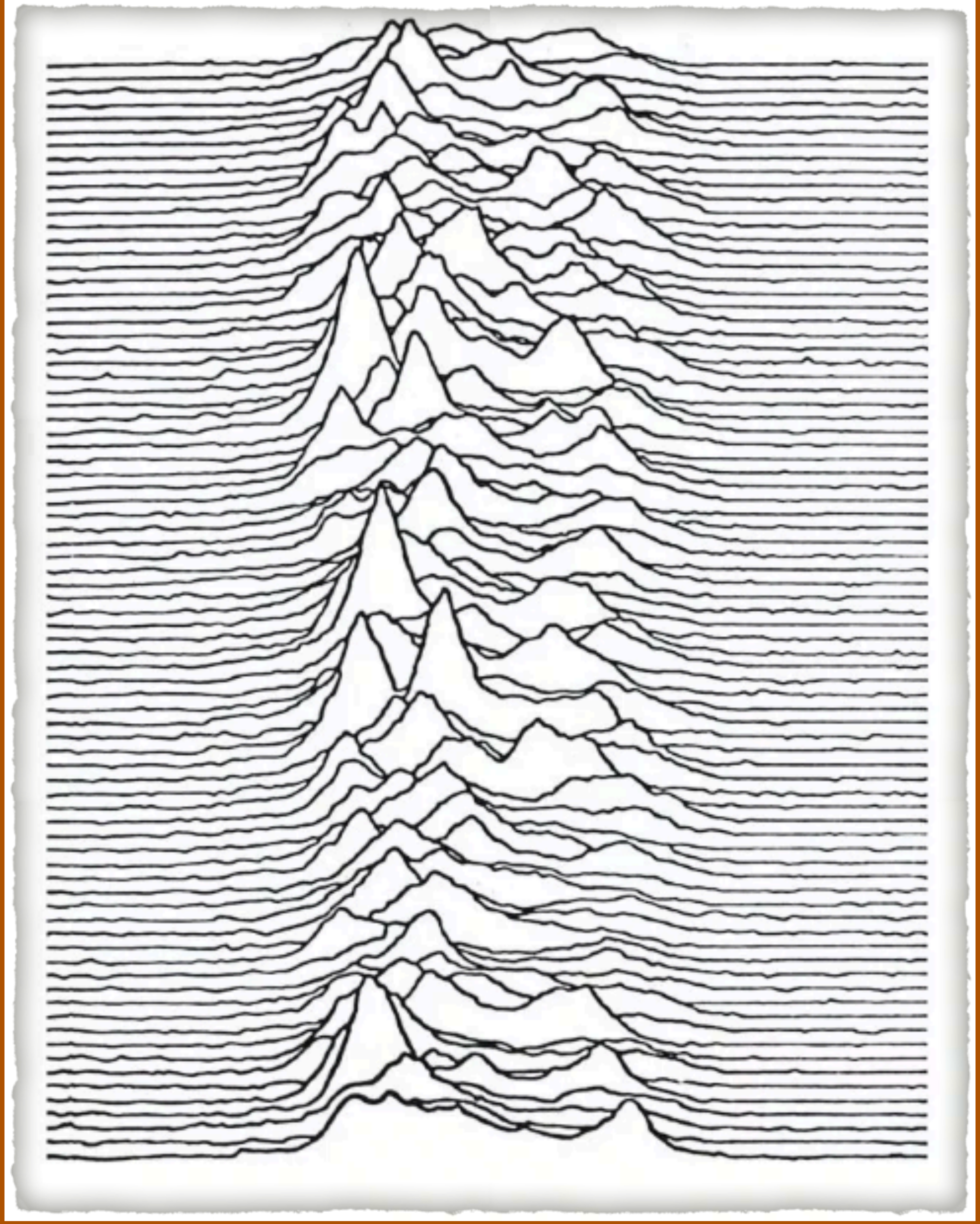
NASSP Pulsar lectures



Lecture 2: Pulsar properties

Marisa Geyer, SARAO

NASSP Pulsar lectures



Course layout:

Lecture 1: Radio pulsar observations

Lecture 2: Pulsar properties

Marisa Geyer, SARAO

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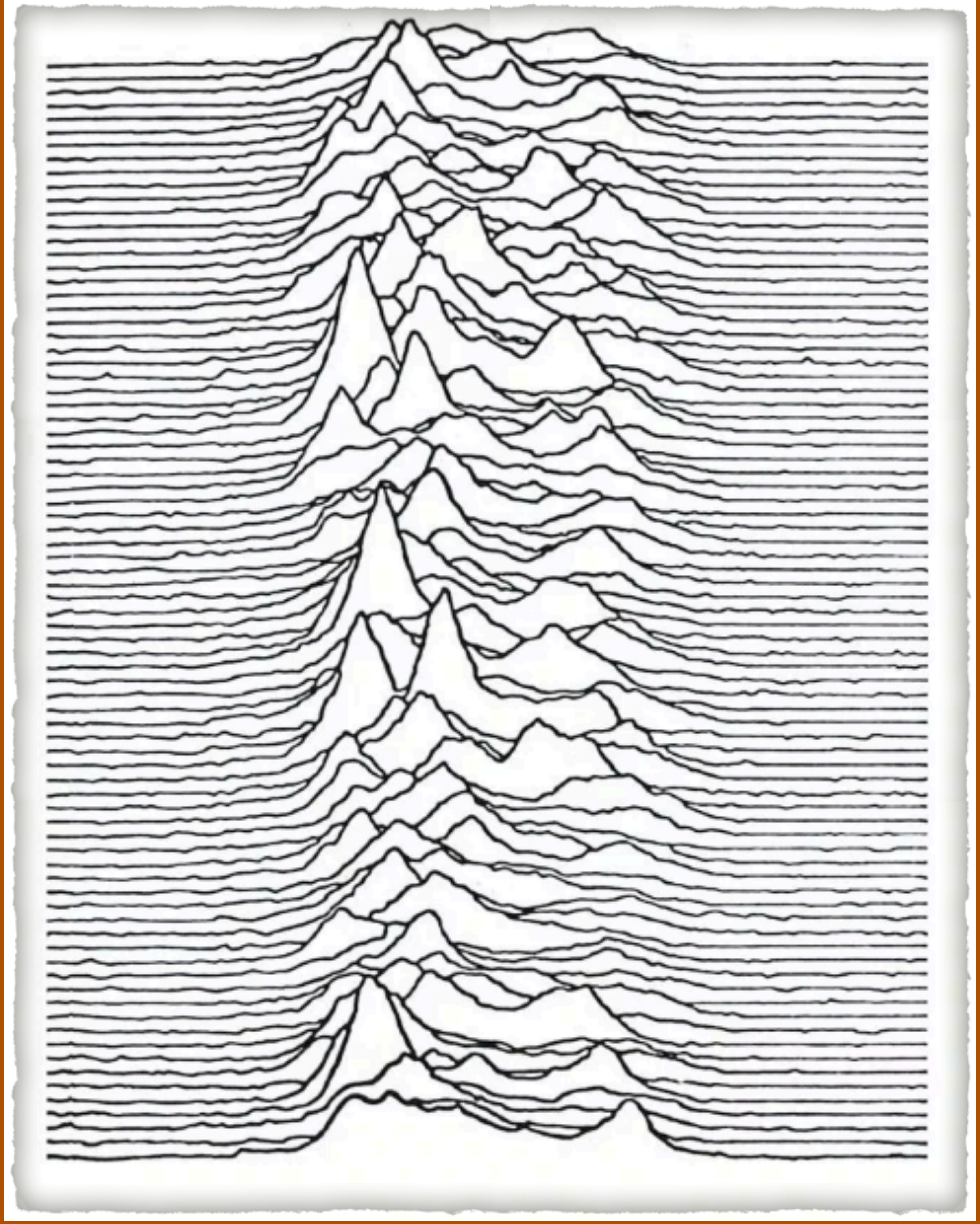


Course material

Much of what is discussed in these lectures come from

1) NRAO 'Essential Radio Astronomy' course found online at:
https://science.nrao.edu/opportunities/courses/era

2) Handbook of Pulsar Astronomy Lorimer and Kramer

Marisa Geyer, SARAO

Lecture 2. : Pulsar Properties

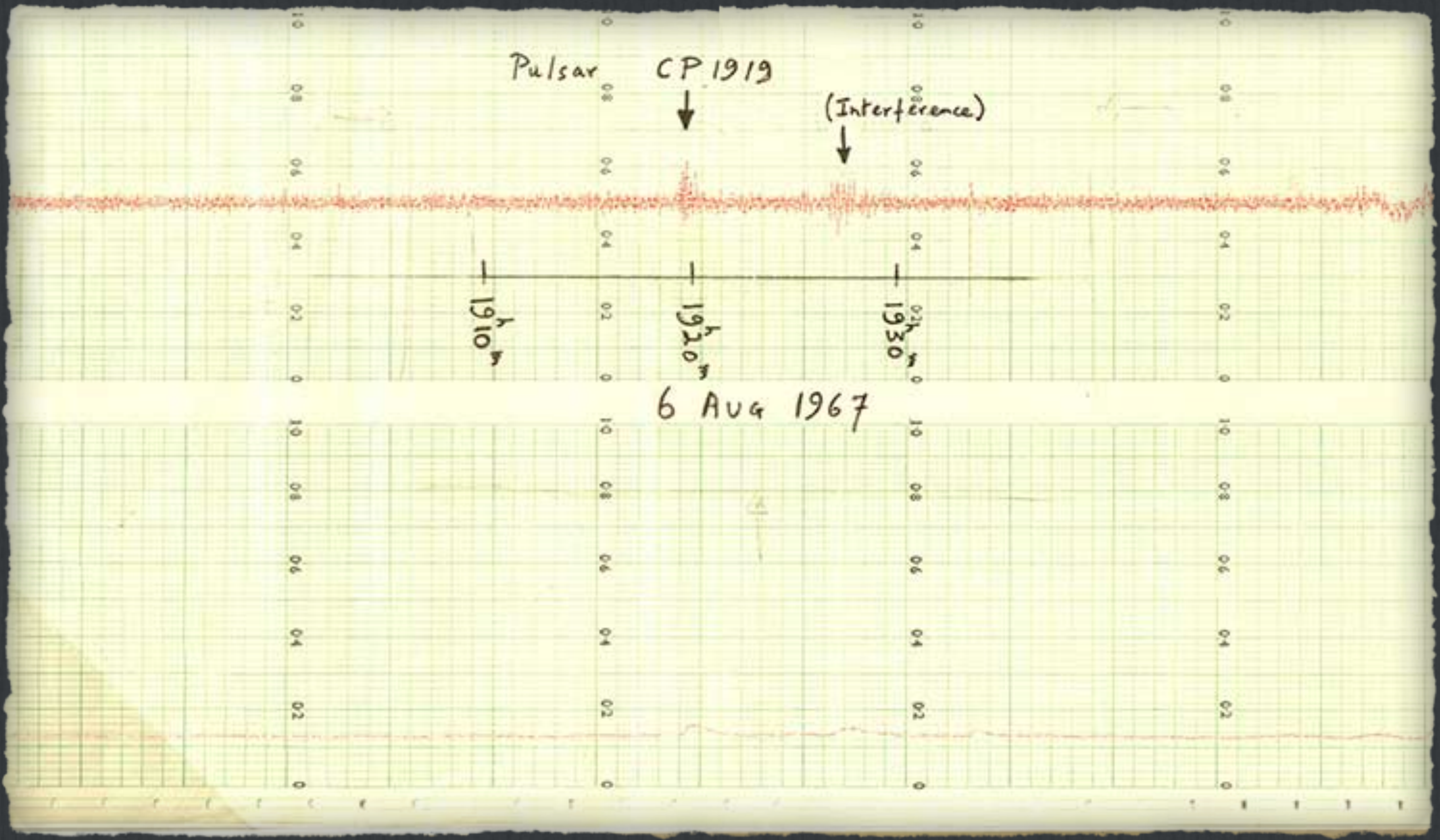
- The discovery of CP1919
- The minimum pulsar density
- The spin properties of neutron stars
- Neutron star radius and masses
- Standard pulsar model
- NS magnetic field
- Magnetic dipole radiation
- NS Rotational energy and loss of rotational energy
- Characteristic age
- The pulsar population
- The P-Pdot diagram

The Discovery of CP1919

- One of the great serendipitous discoveries in astronomy
- In the 1960s Jocelyn Bell-Burnell (then a PhD student at Cambridge Uni) was helping to build a new radio telescope in Cambridge
- The real aim of the experiment was to find extra galactic compact radio sources that scintillate in the interplanetary plasma
- In 1967 she noticed some ‘scruffy’ pulses in the chart recordings.

Image credit: University of Cambridge

The Discovery of CP1919



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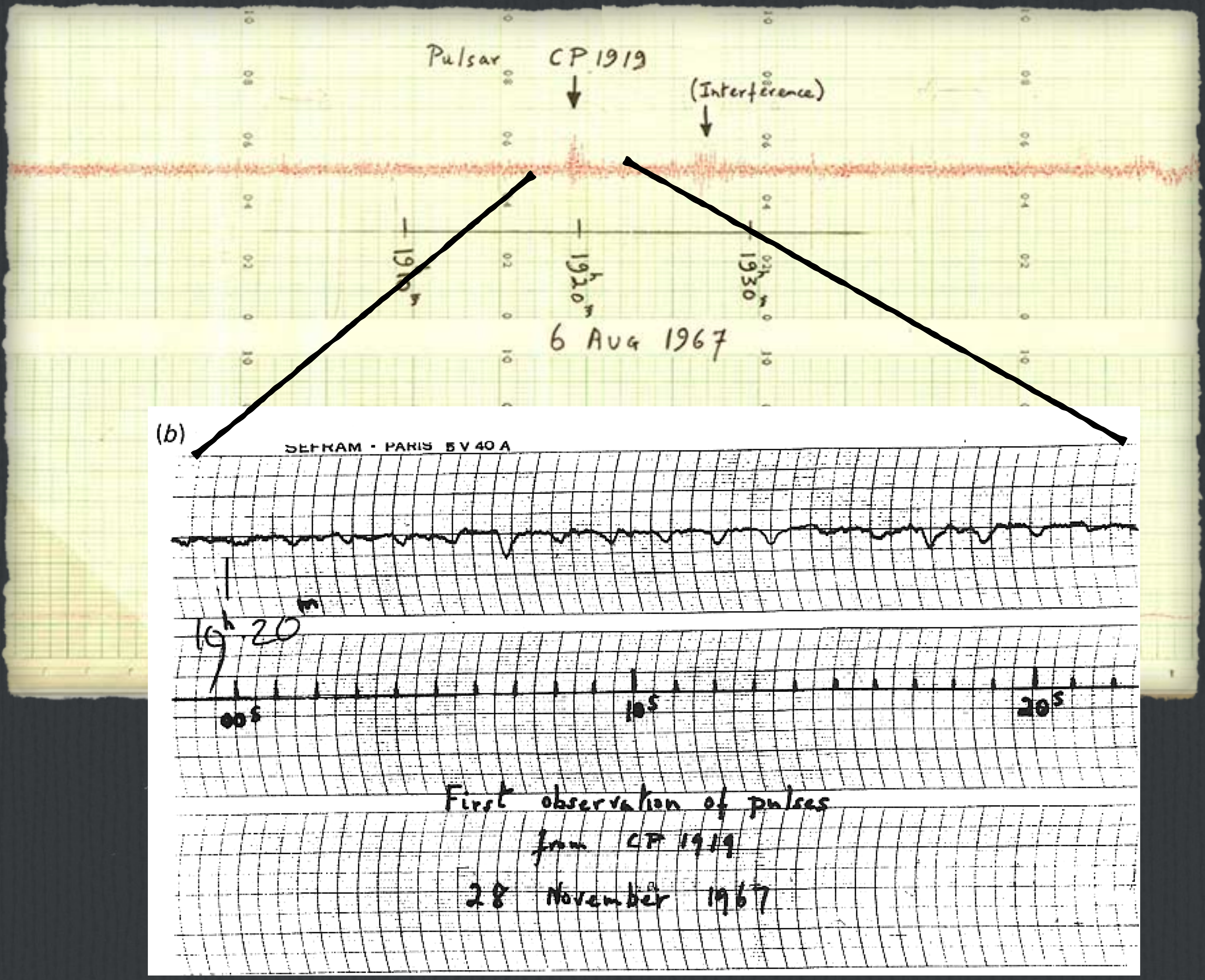


- The data were recorded using pen charts
- By running the chart recorder at a higher speed Jocelyn Bell-Burnell was able to separate the ‘scruff’ into distinguishable pulses
- The pulses appeared to have a period of 1.337s
- They seemed oddly ‘man made’ — but they appeared in the sky every … true to sidereal time, so it could not be terrestrial
- Perhaps it was signatures from ‘little green men’

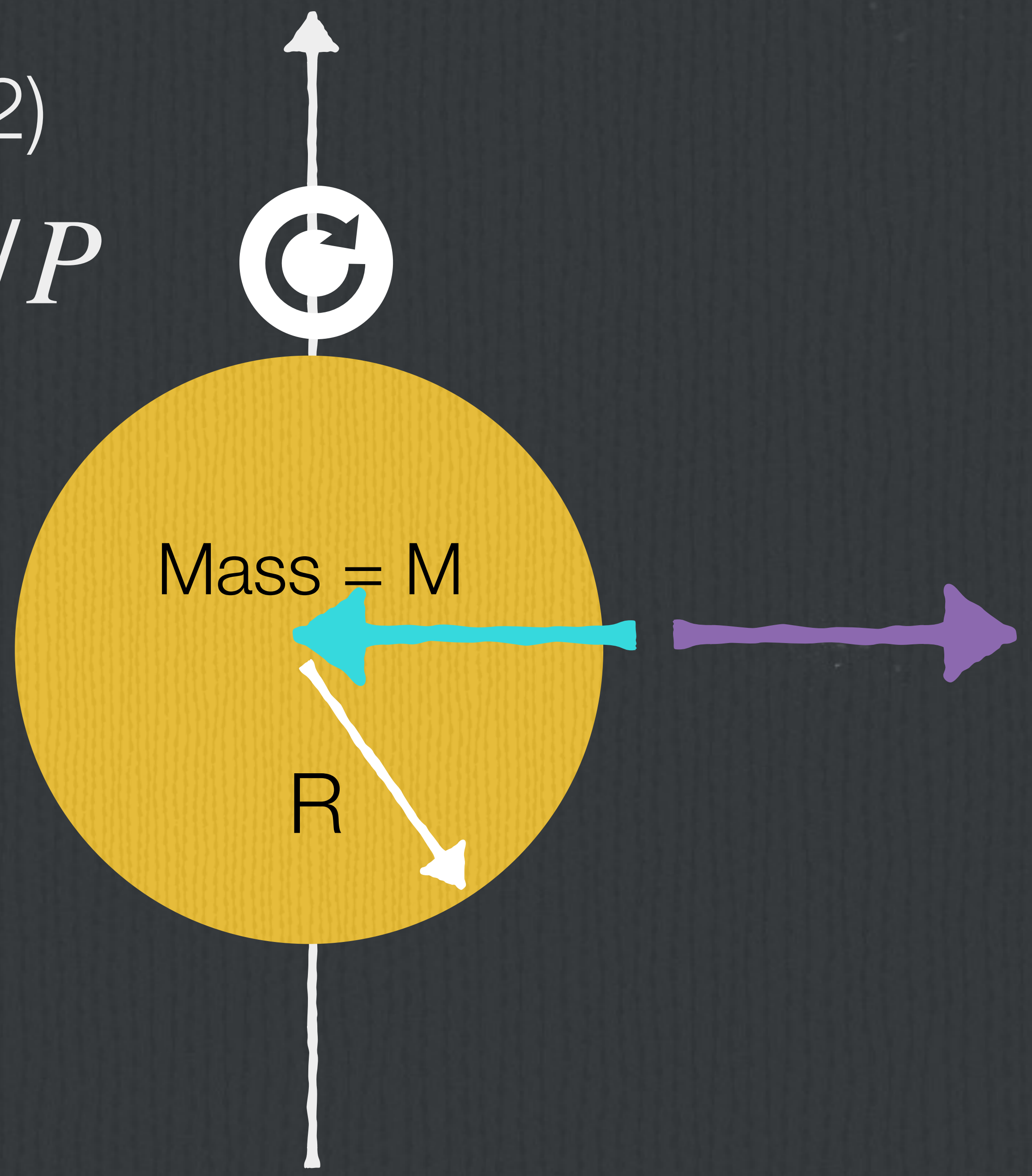
CP1919 - Can it be a spinning star?

Density of sphere — (1)

$$\rho = \frac{M}{V_{sphere}} = M\left(\frac{4}{3}\pi R^3\right)^{-1}$$

Angular velocity — (2)

$$\Omega = 2\pi/P$$



- Pulses with period P = 1.33s
- Can this be a spinning star?
- The fastest a star can spin is set by the limit that

centrifugal acceleration (at the equator) < gravitational acceleration

$$\Omega^2 R < \frac{GM}{R^2}$$

CP1919 minimum stellar density

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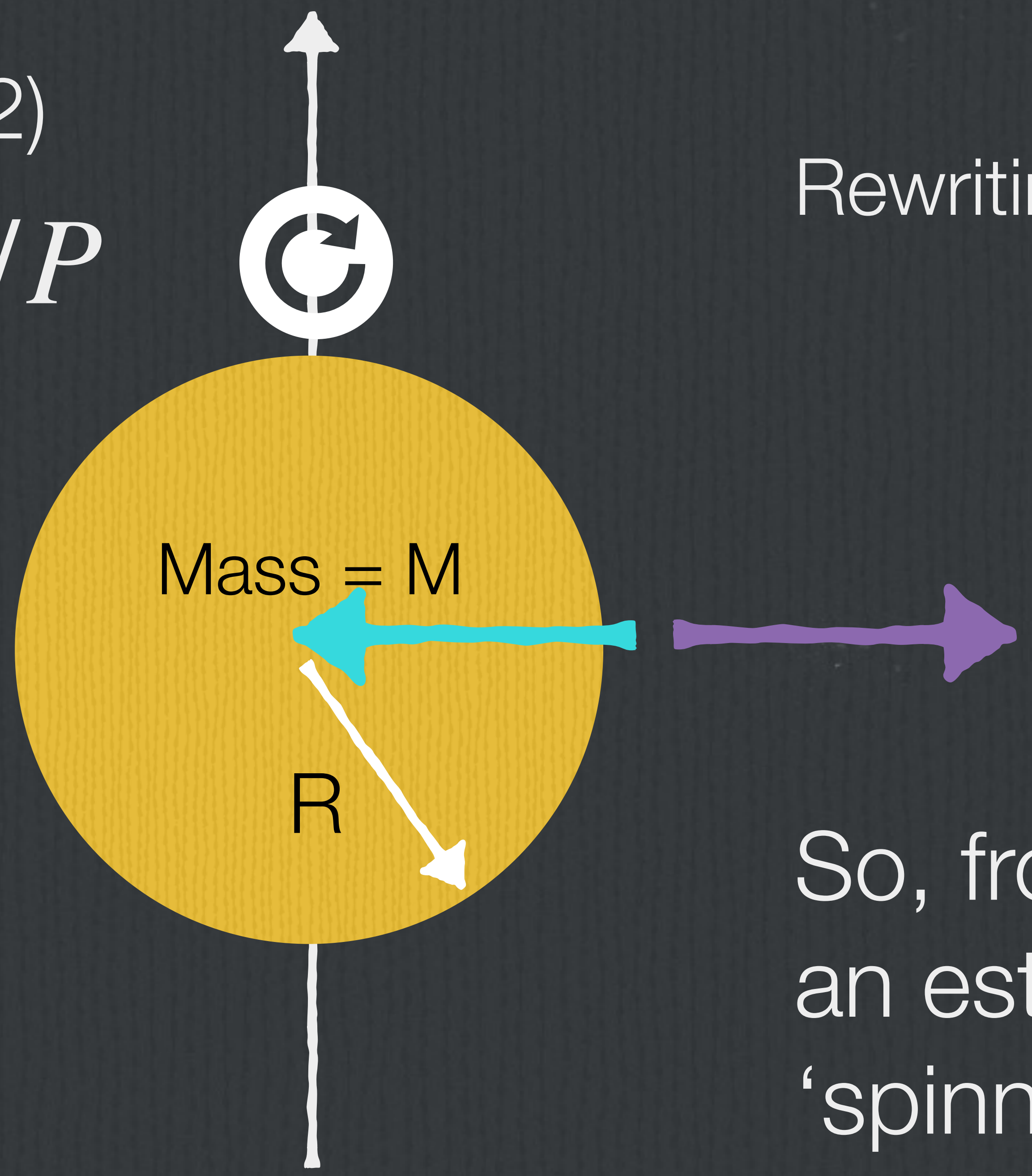


Rewriting i.t.o stellar density using (1) and (2):

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

So, from only measuring the pulse period, we already have an estimate of the lower density limit density of the ‘spinning object’

CP1919 minimum stellar density

- Pulses with period P = 1.33s
- The minimum density estimate of the spinning object:

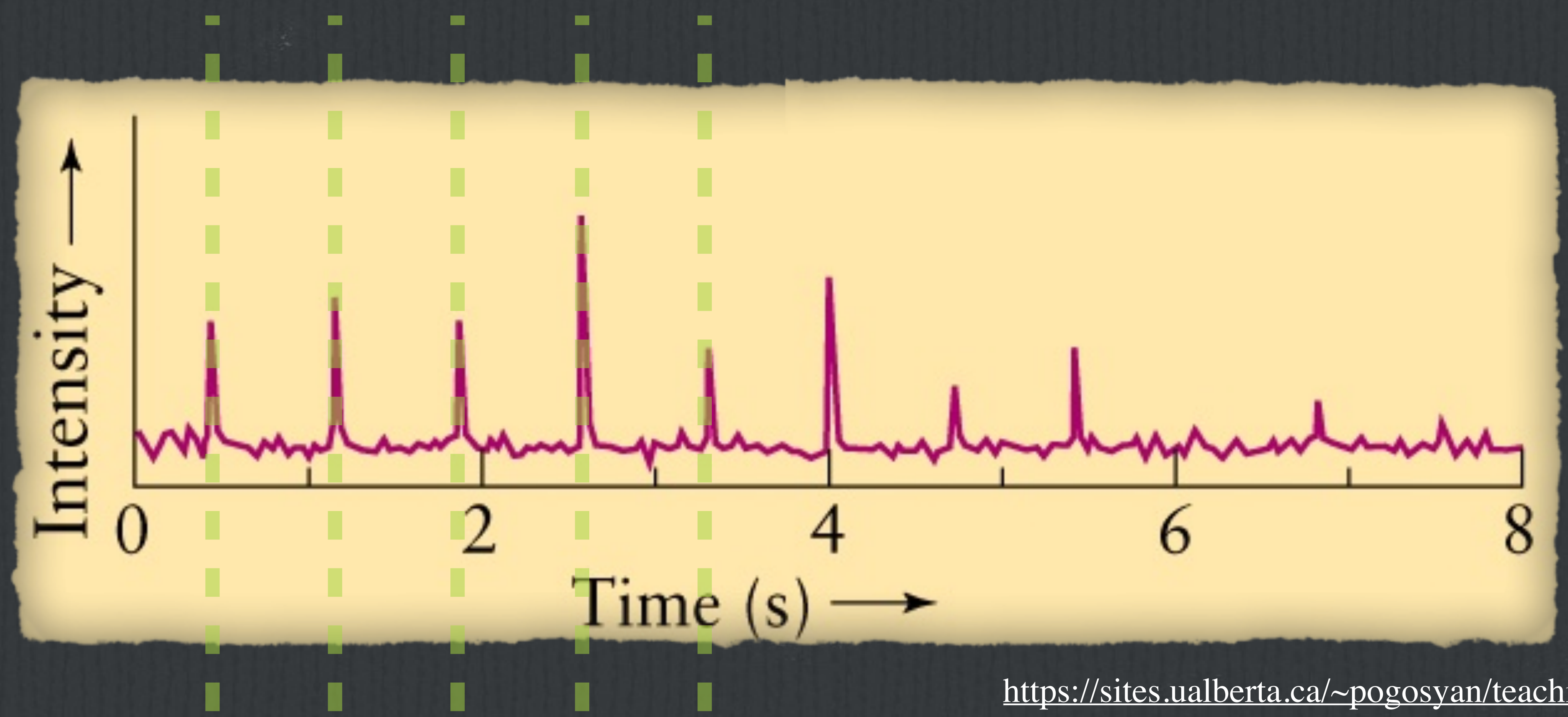
$$\rho > \frac{3\pi}{P^2 G}$$

$G \sim 6.67 \times 10^{-11}\ m^3\ kg^{-1}\ s^{-2}$

$$\rho > \frac{3\pi}{(1.33s)^2\, 6.67 \times 10^{-11} \mathrm{m}^3 \mathrm{kg}^{-1} \mathrm{s}^{-2}}$$

$$\rho \gtrsim 8 \times 10^{10}\,\mathrm{kg\,m}^{-3}$$

P = 1.33 s



https://sites.ualberta.ca/~pogosyan/teaching/ASTRO_122/lect19/lecture19.html

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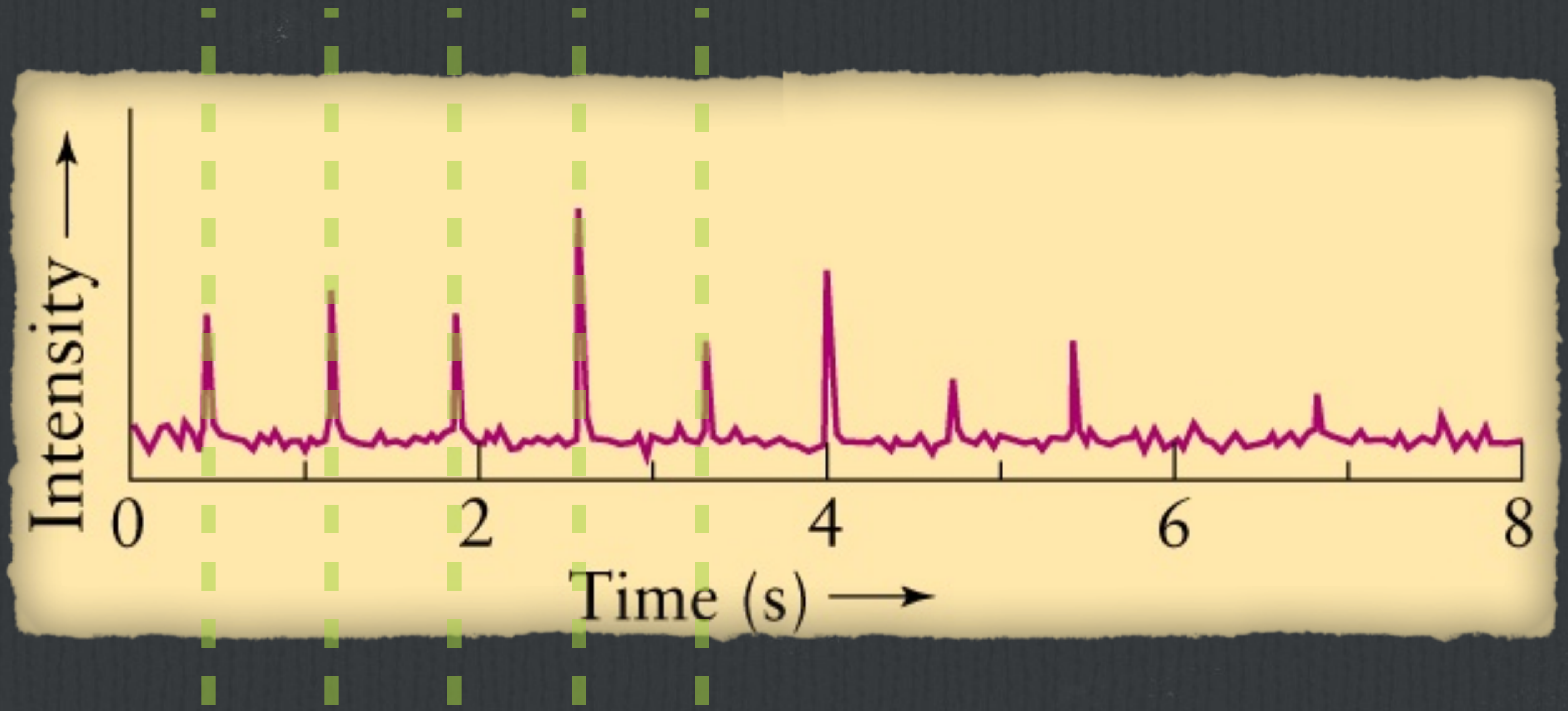
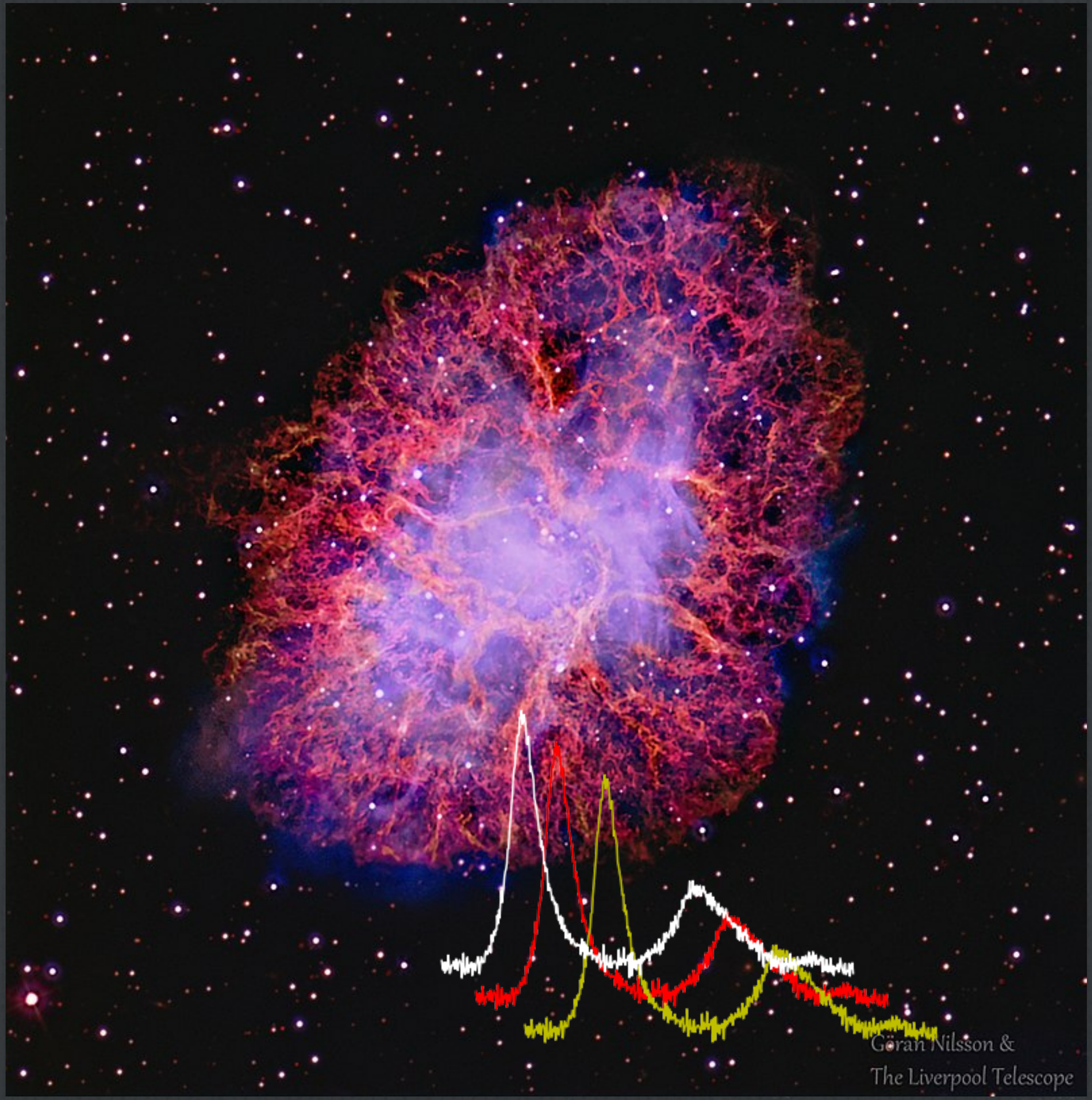
White dwarf density lies between 10^7 and 10^{11} kg m^{-3}

This means CP1919 was just within the white dwarf limit: could it be a white dwarf?

P = 1.33 s



Discovery of the Crab pulsar



- Several pulsars were discovered shortly after CP1919
- Amongst them the Crab pulsar (PSR B0531+21) in 1968, associated with the Supernova remnant SN 1054
- Crab pulsar with a spin period P = 0.033s, leading to a minimum density of

$$\rho > \frac{3\pi}{(0.033s)^2\, 6.67 \times 10^{-11}\mathrm{m}^3\mathrm{kg}^{-1}\mathrm{s}^{-2}}$$

$$\rho \gtrsim 1.3 \times 10^{13}\,\mathrm{kg\,m}^{-3}$$

TOO dense for a white dwarf, but …

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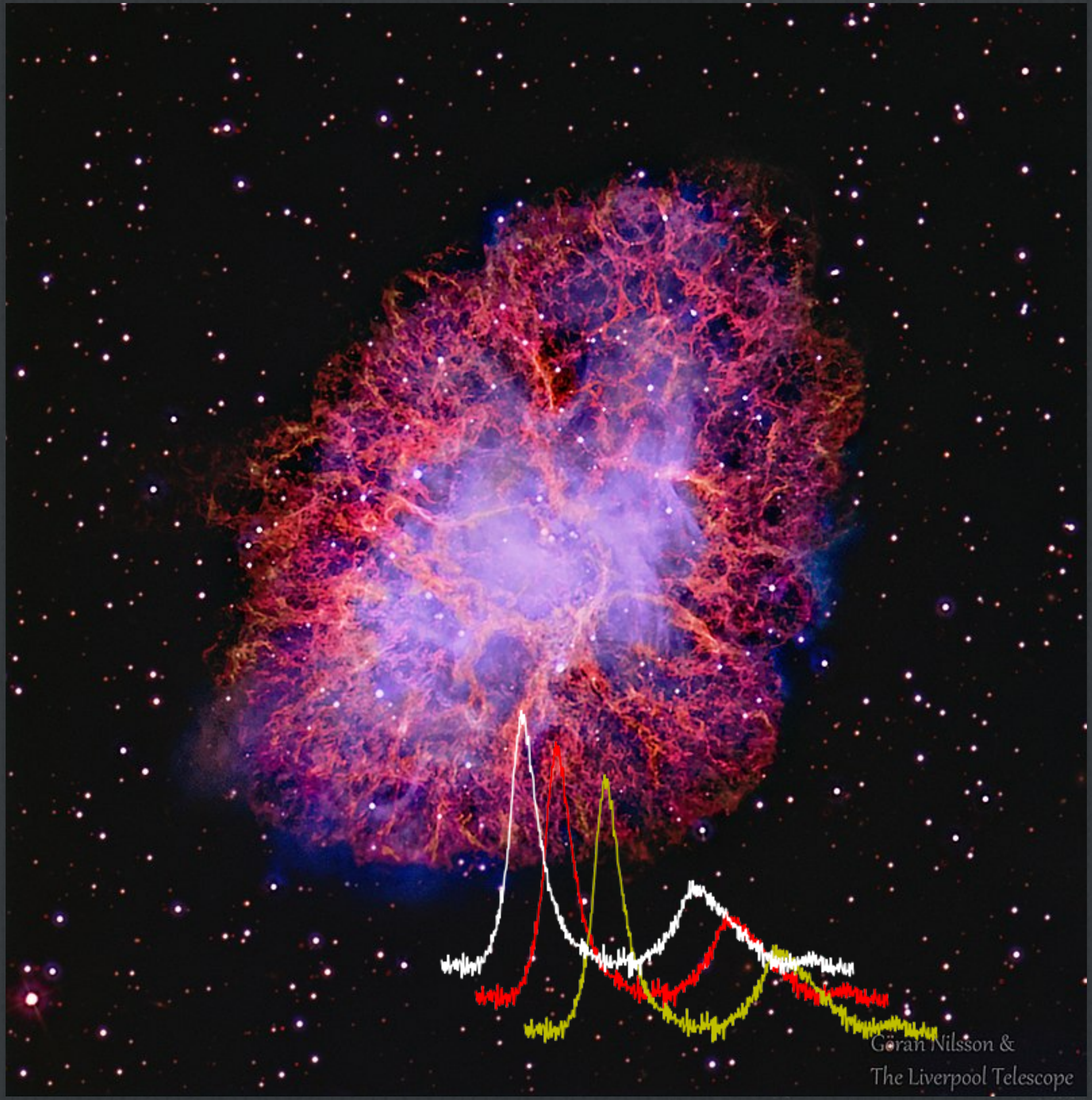

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TOO dense for a white dwarf, but … fitted the theoretical description proposed by Baade and Zwicky 1934

A ‘neutron star’

Baade and Zwicky 1934

Baade and Zwicky published two papers in 1934 - back to back in PNAS (Proceedings of National Academy of Sciences):

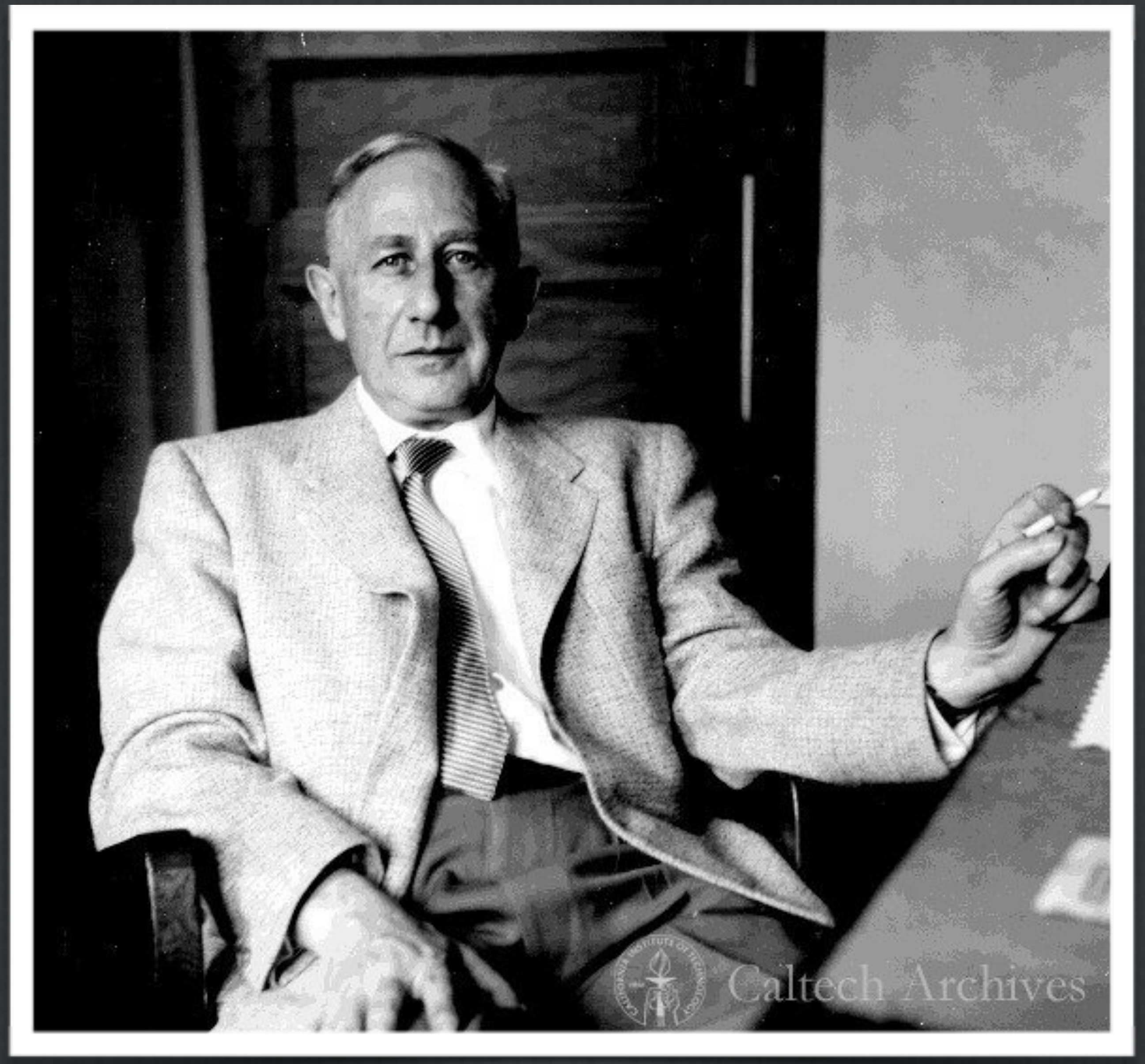
“On Super-novae” and “Cosmic Rays from Super-novae”, in which they

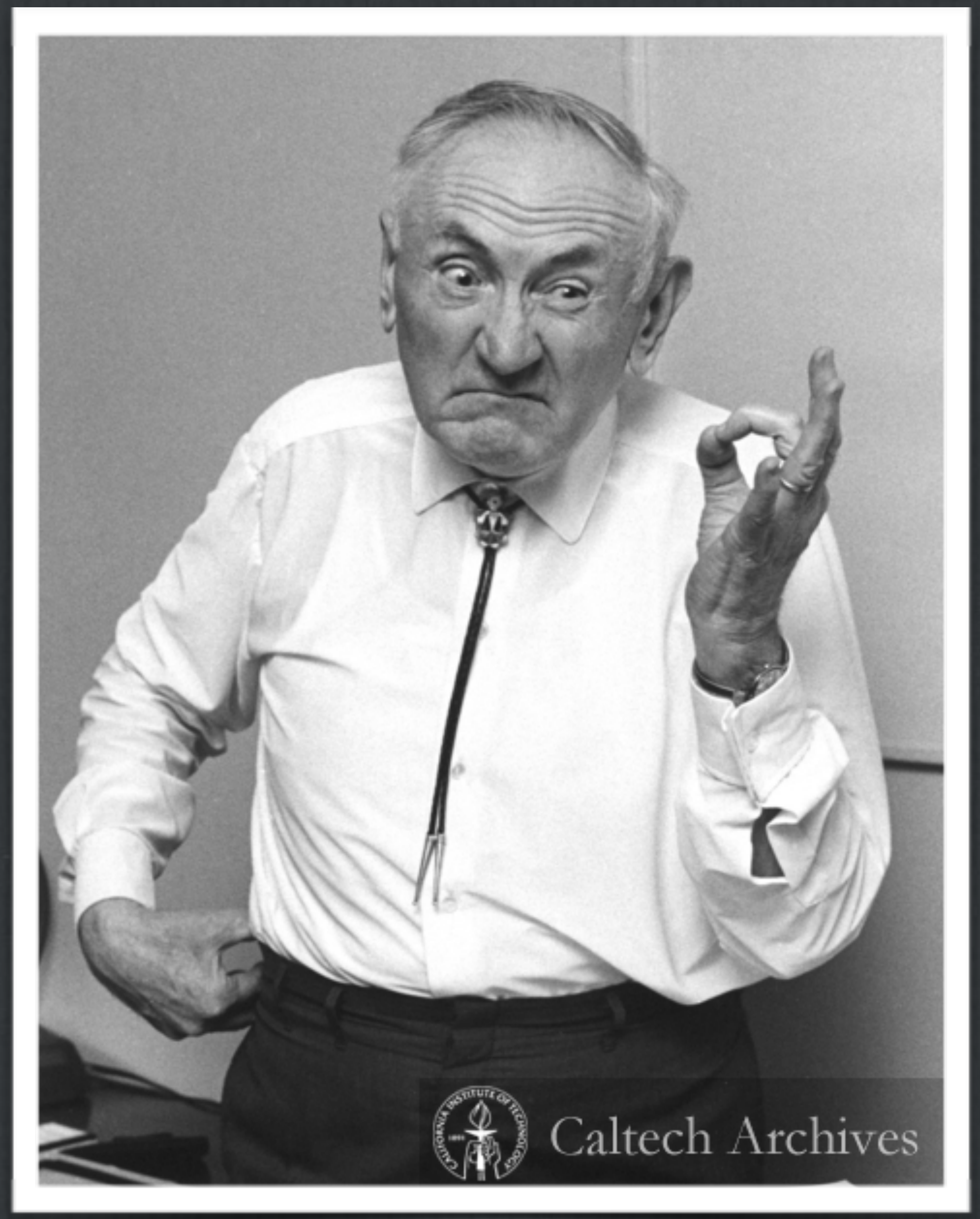
1) compute the mass radiated away during a SNe:

“therefore it becomes evident that the phenomenon of a super-nova represents the transition of an ordinary star into a body of considerably smaller mass.”

2) and in the “additional remarks” section propose

"With all reserve we advance the view that a super-nova represents the transition of an ordinary star into a **neutron star**, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density”





Today: Pulsars are NS and come from SNe

- Depending on a star's mass, it will end its life differently — the most massive ones (> 60 M_{sun}) will collapse to black holes,

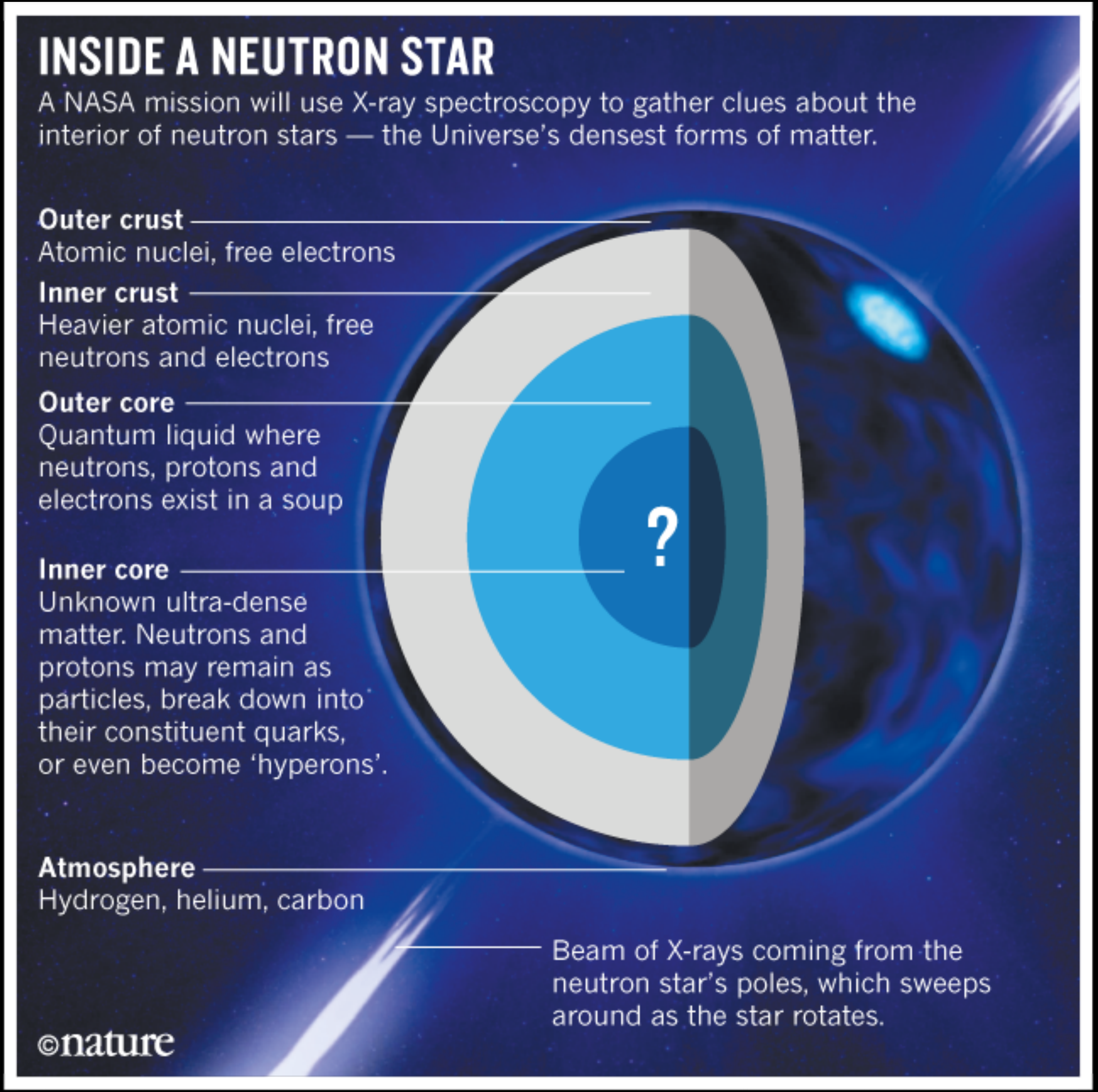
- While the intermediate ones (10 - 40 M_{sun}) will end their lives collapsing to a dense core, stopped only by neutron degeneracy pressure.

- In the rebound shock the outer gas shells are flung out in a spectacular supernova explosion

- The NS that remains is typically an order of magnitude more dense than nuclear matter. This provides a highly exotic environment beyond the scope of lab experiments on Earth.

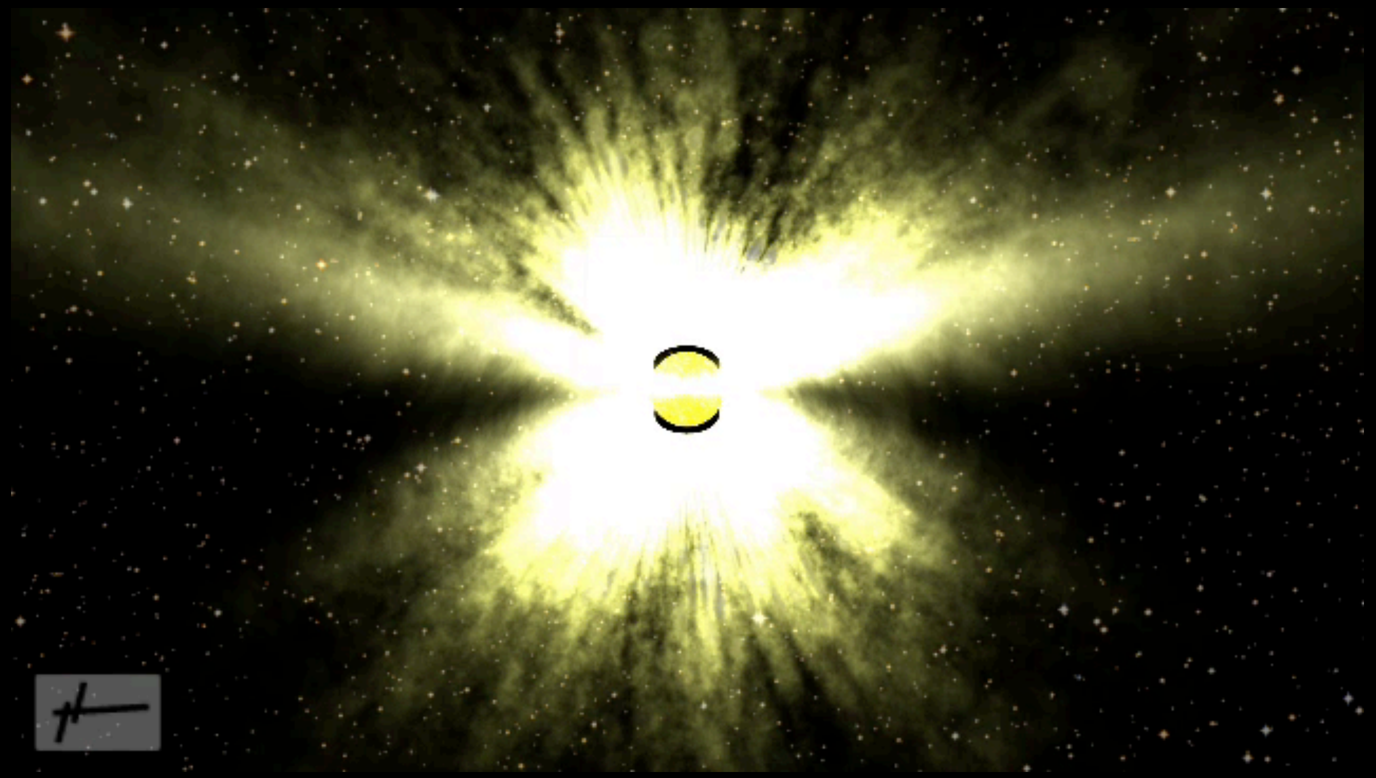
- Various models exist for what exactly the core of the NS is made of including hyperon or boson condensates or free quarks. Many of these models are struggling to explain observations of NS > 2 M_{sun}.

- An exact model for the equation of state (that relates the density, mass and radius of neutron stars) remains an area of intensive research



Today: the fastest known pulsar

Credit: Joeri van Leeuwen



- The fastest known pulsar was discovered in 2004 in the globular cluster known as Terzan 5
- PSRJ1748-2446ad spins at 716 Hz!
- Q: what is it's minimum density?

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

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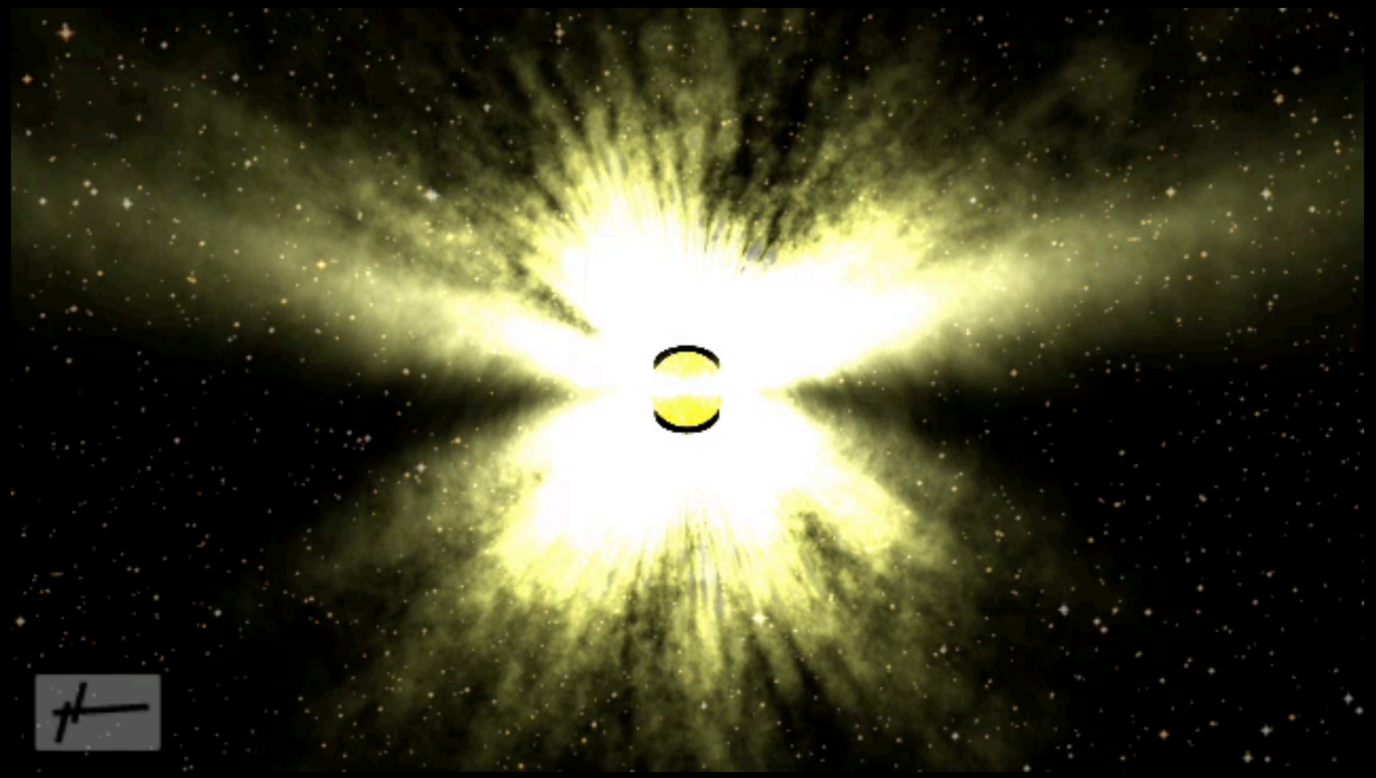

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$$\sim 7.2 \times 10^{16}\,\mathrm{kg\ m^{-3}}$$

Neutron star radius

The largest mass at which a white dwarf can be stable is the Chandrasekhar limit.

At this limit the star is supported by outward electron degeneracy pressure

$$M_{\mathrm{Ch}} \sim \left(\frac{\hbar c}{G}\right)^{3/2} \frac{1}{m_{\mathrm{p}}^2} \approx 1.4 M_{\odot}$$

A more massive star will collapse to a neutron star — supported through neutron degeneracy pressure

From the definition of density:

$$\rho = \frac{M}{V_{sphere}} = M\left(\frac{4}{3}\pi R^3\right)^{-1} \rightarrow R < \left(\frac{3\,M}{4\,\pi\rho}\right)^{1/3}$$

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Est. mass

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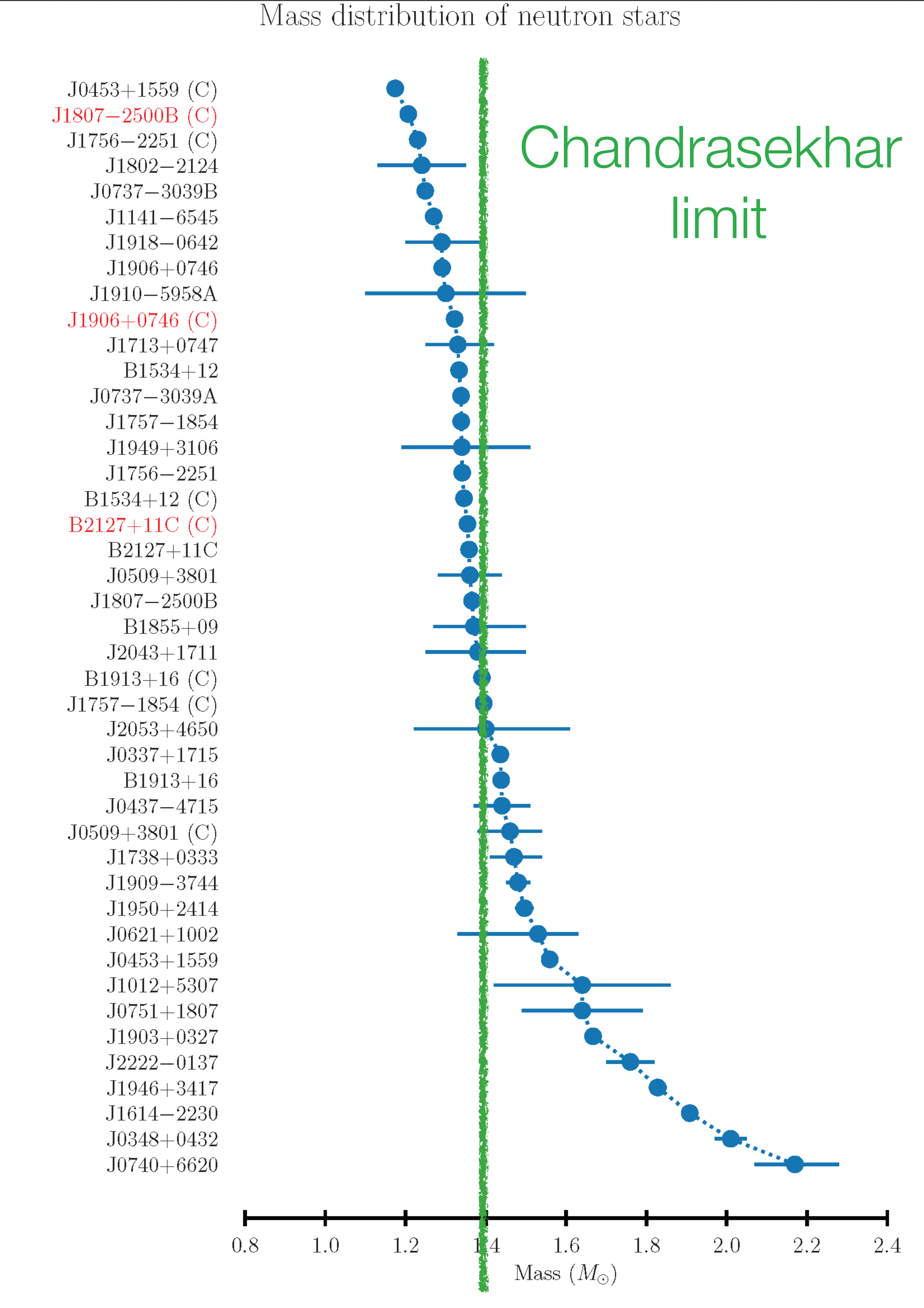
$$\rho = \frac{M}{V_{sphere}} = M\left(\frac{4}{3}\pi R^3\right)^{-1} \rightarrow R < \left(\frac{3\,M}{4\,\pi\rho}\right)^{1/3} \lesssim 20\,\mathrm{km}$$

Highest est. density

$$\sim 7.2 \times 10^{16}\,\mathrm{kg\ m^{-3}}$$

Standard pulsar parameters are often considered to be R ~ 10km and mass ~ 1.4 Msun, though as detections of these parameters improve larger deviations are measured.



Measured masses

- Wide distribution of masses measured
- Continuous updates in the literature on finding more/the most massive neutron star
- Website that keeps good track of these: https://www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html
- We are currently doing a campaign with MeerKAT to investigate the mass of J1748-2021B - it may well turn out to be the record breaker!

April 2019: https://arxiv.org/abs/1904.06759

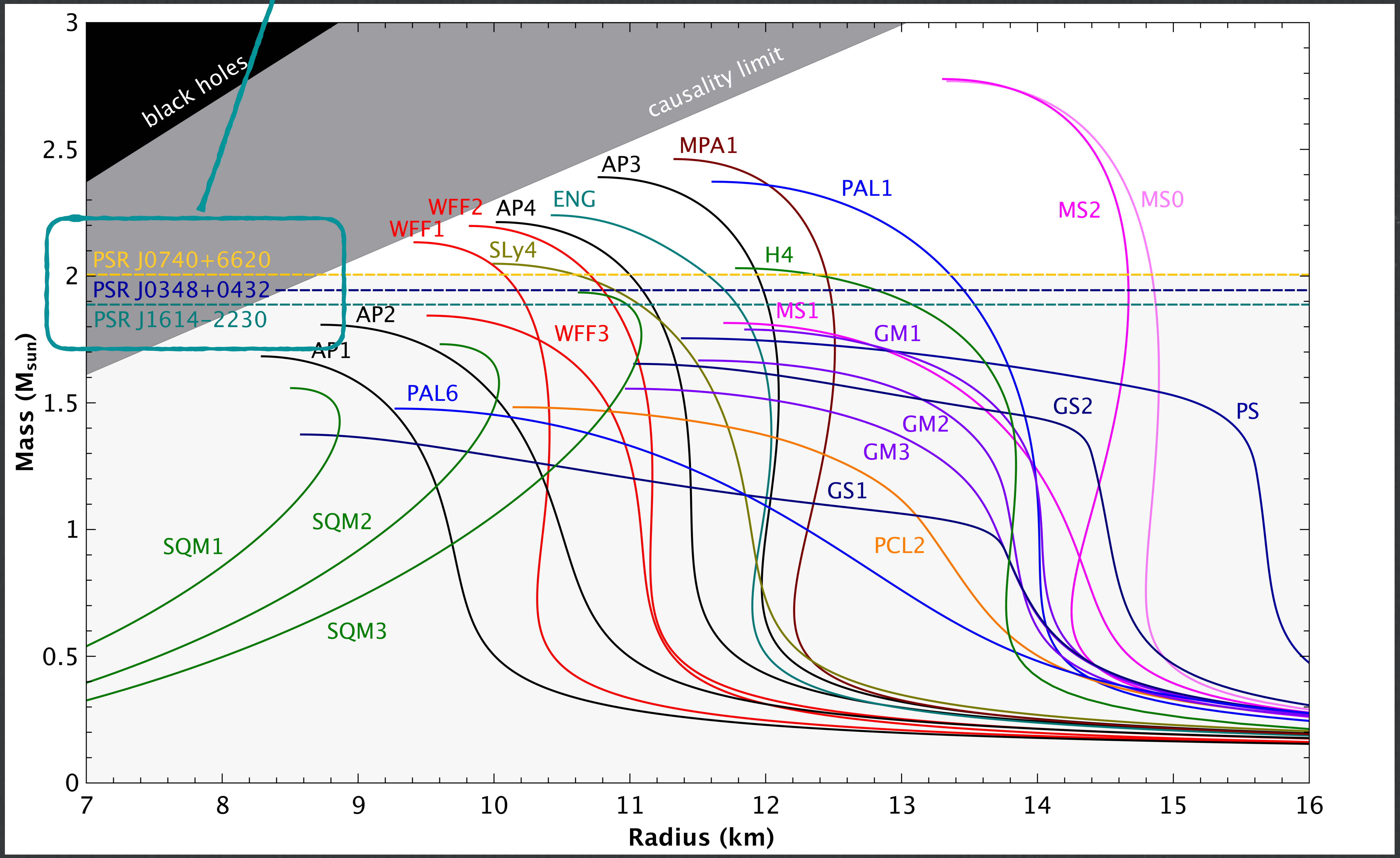
From a timing experiment using Green Bank Telescope a team have measured the mass of the MSP J0740+6620 to be 2.17 +/− 0.11. solar masses.

It may therefore be the most massive neutron star yet observed, and would serve as a strong constraint on the neutron star interior EoS.

Credit: Venkatraman Krishnan

Constraining the EOS

Mass measurements of these 3 pulsars have already ruled out many of the EOS models that lie beneath its mass values.



- The NS “equation of state”, which relates the density, mass and radius of neutron stars in a mathematical description, remains an area of ongoing research
- With each new observation one more theoretical model could potentially be ruled out, leaving only a last few standing
- This is partly why pulsar astronomers are so keen on accurate new massive NS mass measurements

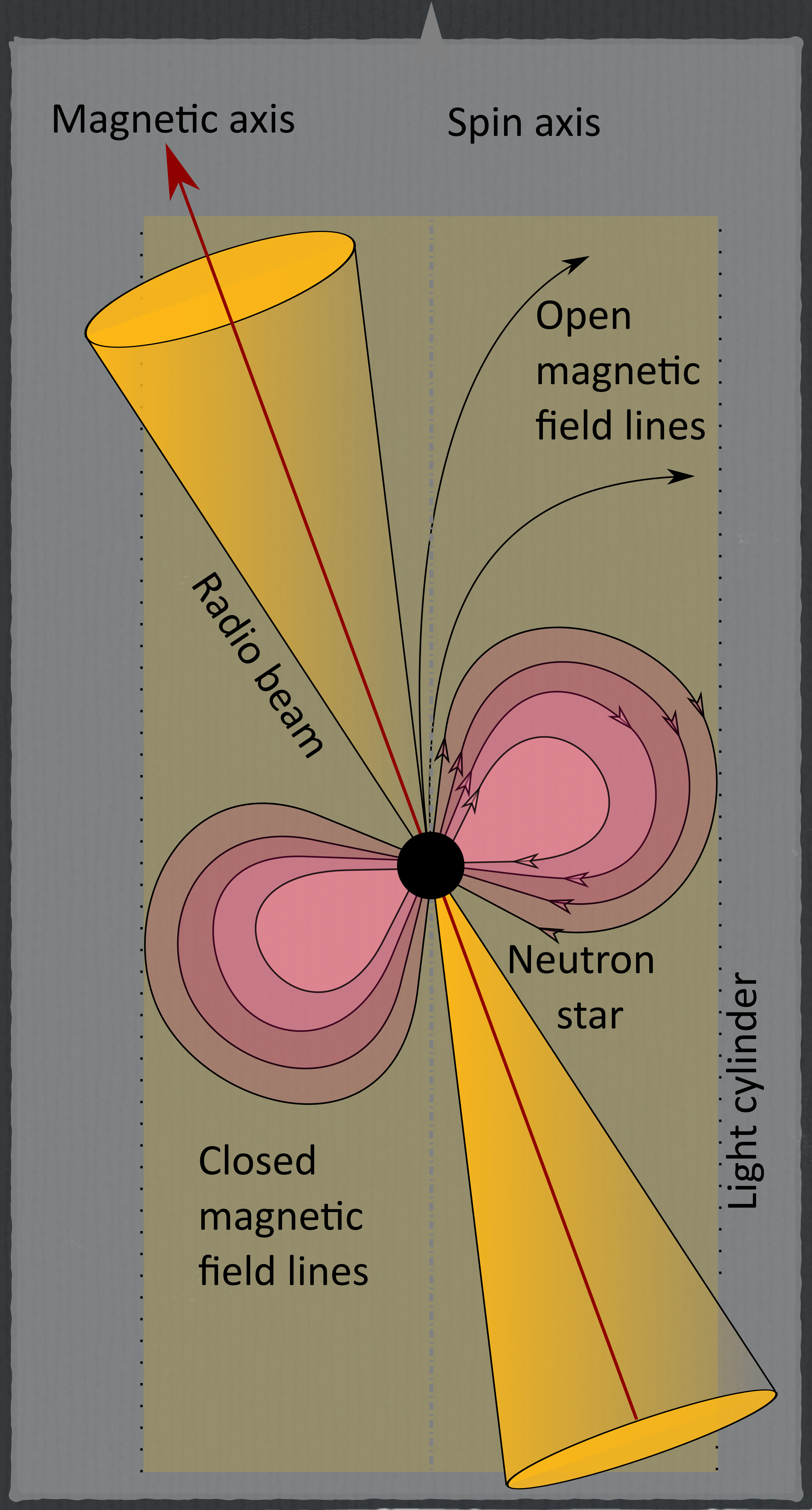
Neutron star magnetic fields

NS progenitor stars (like most stars) possess dipolar magnetic fields

Let the progenitor star have a radius ~ 10^6 km. When it collapses to NS with R ~ 10 km, it means the surface is shrinking by a factor of ~ $(10^5)^2 = 10^{10}$

During the collapse the magnetic flux is conserved, and since the magnetic field scales with surface area, that means the magnetic field increases by a factor of 10^{10}!

Q: what are typical magnetic fields of massive stars?



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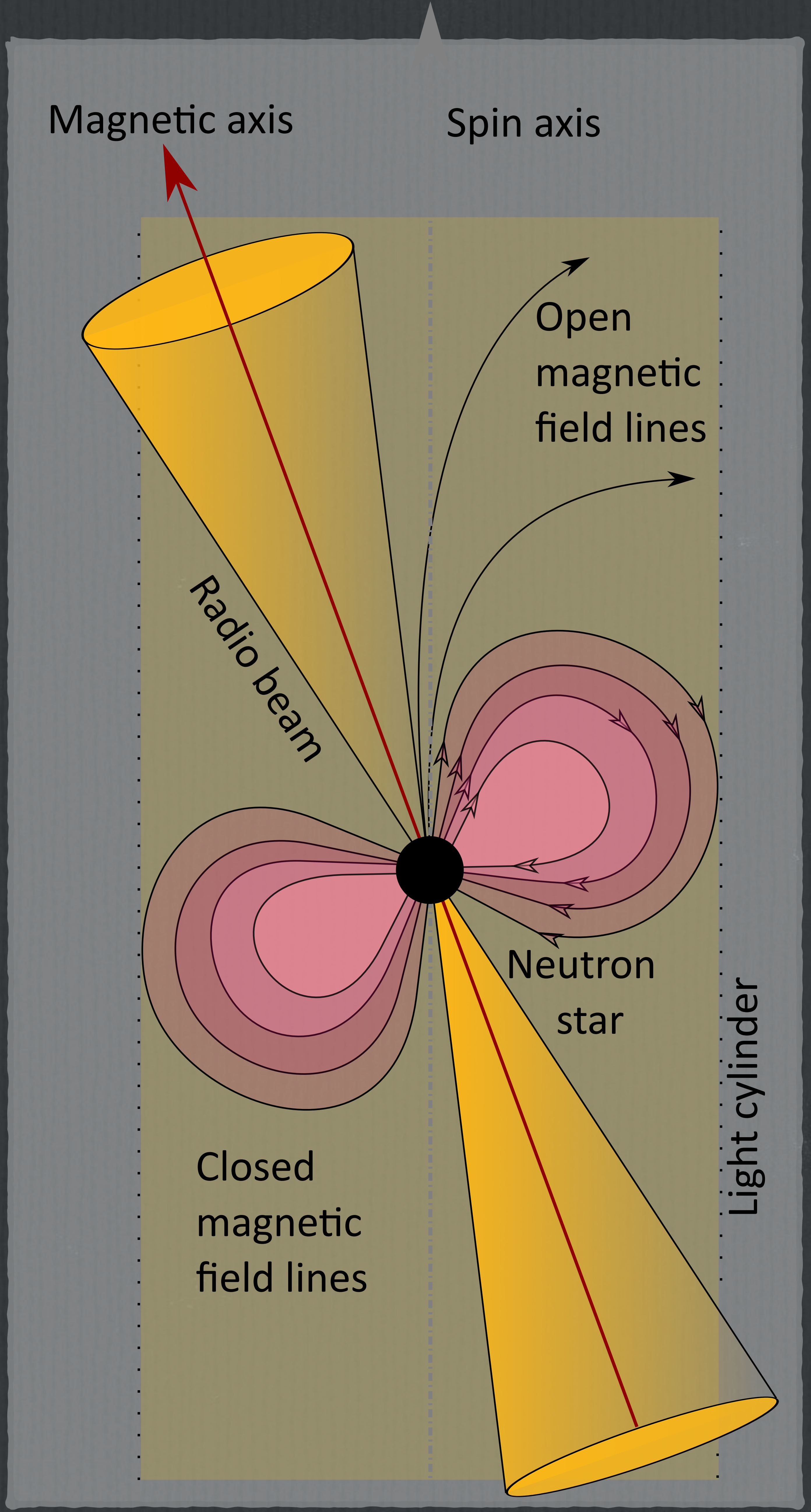
Q: what are typical magnetic fields of massive stars?

The initial 100 Gauss magnetic field is scaled to become a NS field of 10^{12} G during collapse.

These strong NS magnetic fields accelerate particle cascades away from the NS surface at relativistic speeds, leading to coherent radio emission along the open magnetic field lines (the north and south pole of the pulsar)



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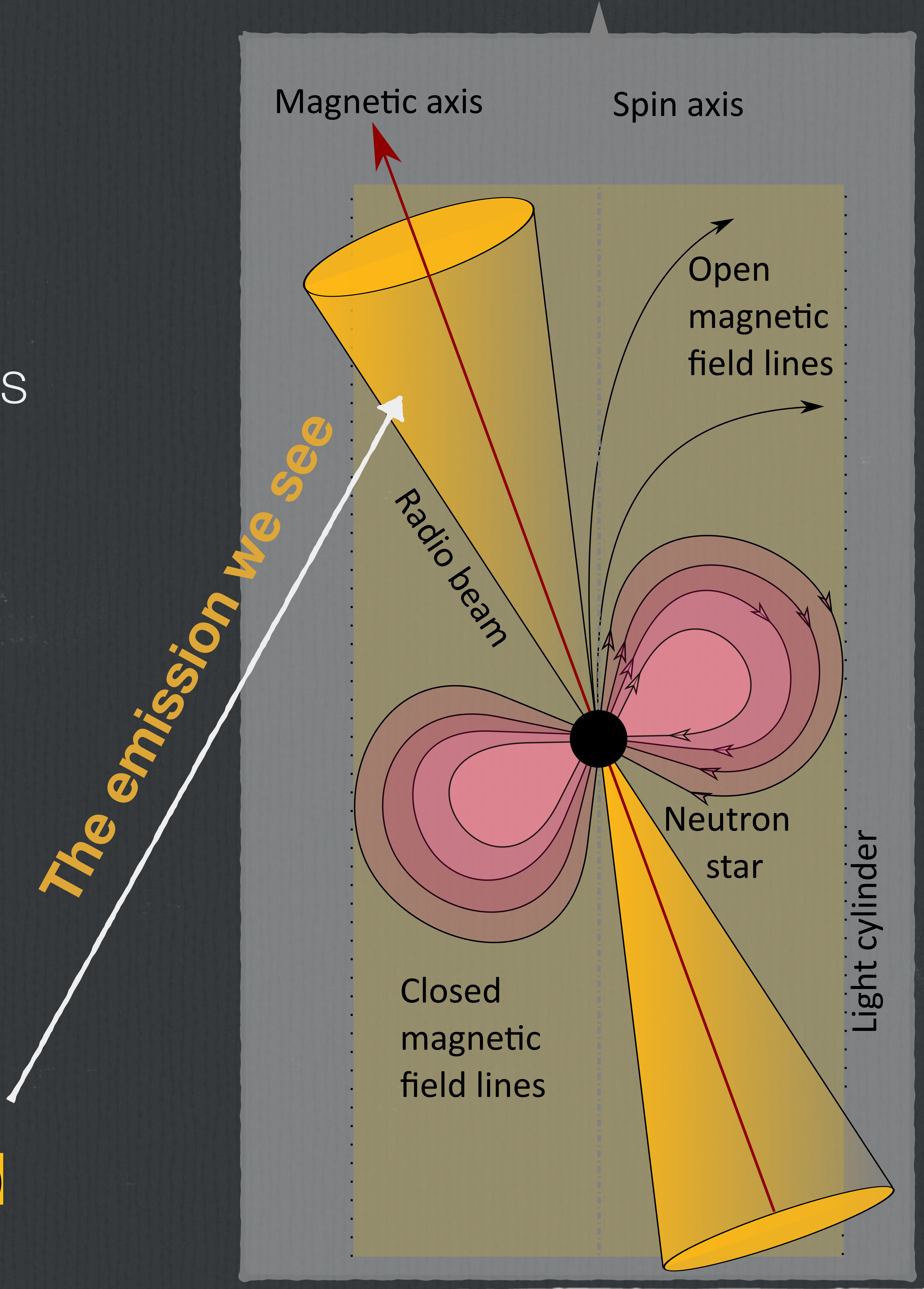


Standard pulsar model

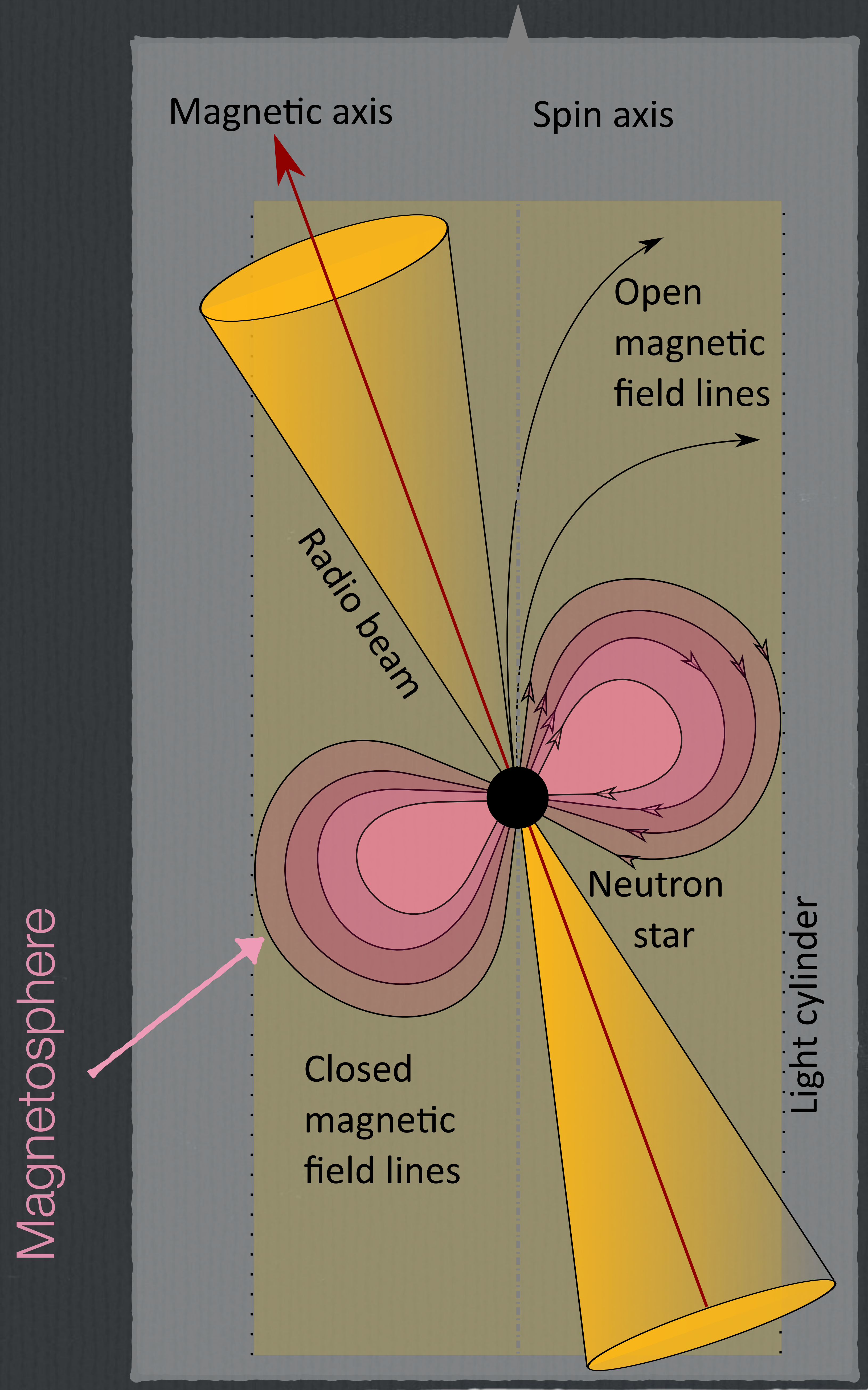
The misalignment between the spin axis and the magnetic axis allow us to see the pulses sweep across our line of sight (like a lighthouse).

Radio emission streams along the open magnetic field lines, in the standard pulsar model the beam is considered to be cone-shaped.
This standard model fits many pulsar observations well, however the details of the emission mechanism itself and the beam shape is not yet well understood for all pulsars

The magnetic field lines transition from closed field lines to open field lines at the pulsar's "light cylinder radius". This is the radius beyond which the magnetosphere (associated with the closed field lines) would have to travel faster than the speed of light to co-rotate with the pulsar.

We call neutron stars from which we observe radio pulses "pulsars".

We can only see the pulsars for which the emission cuts our line of sight. This is greatly dependent on the orientation of the pulsar in the sky. From geometry arguments we estimate that approximately 10% of all pulsars are beamed in Earth's direction and therefore observable to us.



Spinning down: magnetic dipolar radiation

- Pulsars are observed to spin down, in other words the period P is seen to slowly increase with time

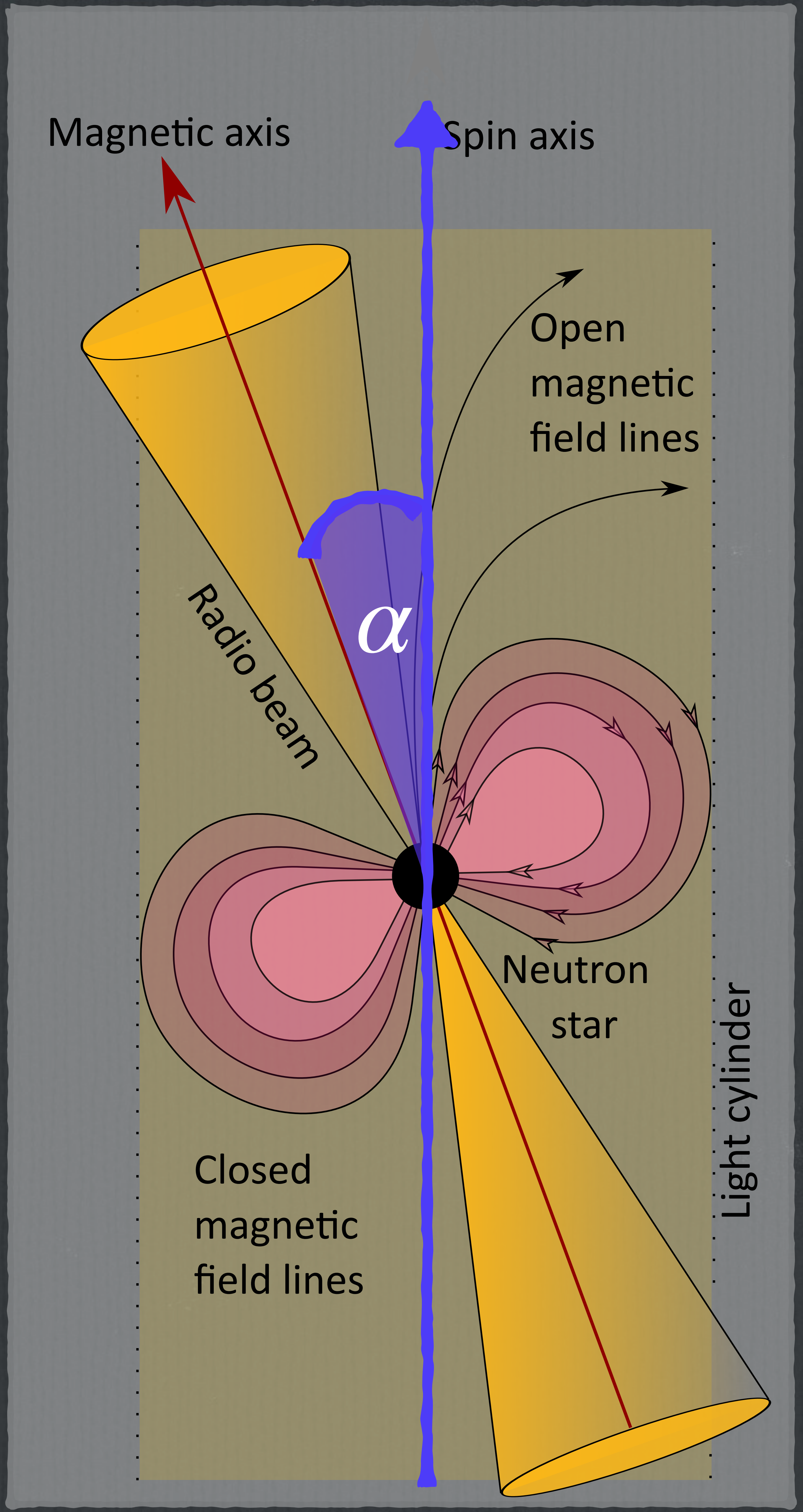
$$\dot{P} = \frac{dP}{dt} > 0$$

- What causes it to slow down?

- A rotating magnetic dipole (inclined w.r.t, the spin axis) emits radiation at the rotational frequency of the system. This radiation extracts from the rotational energy of NS causing it to slow down.

$$P_{\rm rad} = \frac{2}{3c^3}(BR^3 \sin\alpha)^2\left(\frac{2\pi}{P}\right)^4 \lesssim \frac{32\,B^2\,R^6\,\pi^4}{3c^3\,P^4}$$

- Q: What frequency is this magnetic dipole radiation?
- Q: Think back to Lecture 1: does this emission propagate through the ISM?



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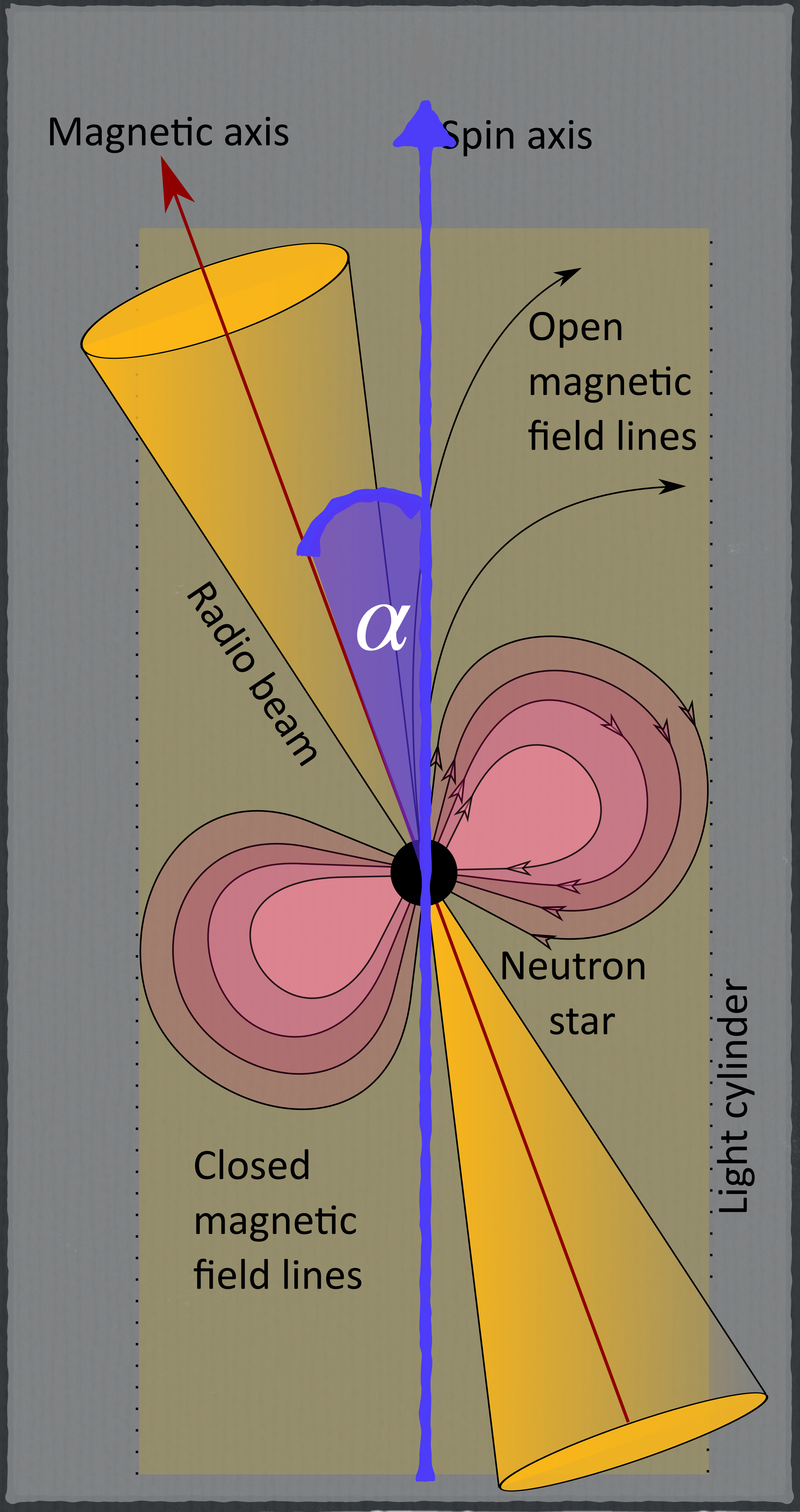
Frequency = 1/P < 1 kHz .. it does not propagate through the ISM.



Rotational energy

- Pulsars are observed to be spinning down with time —losing rotational energy
- We can estimate this rotational energy, and how it changes

- Rotational kinetic energy, E:

$$E = \frac{I\Omega^2}{2} = \frac{2\pi^2 I}{P^2}$$

Moment of inertia

$$I = \frac{2MR^2}{5}$$

$$= \frac{2 \times 1.4 \times 1.98 \times 10^{30}\,\mathrm{kg} \times (10^4\mathrm{m})^2}{5}$$

$$= 1.1 \times 10^{38}\,\mathrm{kg\,m^2}$$

- For a young pulsar like the Crab (in SN 1054) with P = 0.033 s, the rotational energy is:

$$E = \frac{2\pi^2 \times 1.1 \times 10^{38}\,\mathrm{kg\,m^2}}{(0.033\,\mathrm{s})^2} = 1.99 \times 10^{42}\,\mathrm{J}$$

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1Joule = 1N .m = 1 kg m^2 s^{-2}

Losing Rotational Energy

- From the observed changes in P we can estimate the loss in rotational energy.

$$\dot{\Omega} = -\frac{2\pi\dot{P}}{P^2}$$

$$\Omega = 2\pi/P$$

From: $$E = \frac{I\Omega^2}{2}$$

$$\dot{E} = \frac{d}{dt}\left(\frac{1}{2}I\Omega^2\right) = I\Omega\dot{\Omega}$$

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

Observables

Losing Rotational Energy: Crab pulsar

Solar Luminosity

$$L_\odot = 3.83 \times 10^{26}\, W$$

$$\dot{E}_{\text{Crab}} = -\frac{4\pi^2 I\dot{P}}{P^3}$$

$$= \frac{4\,\pi^2 \times 1.1 \times 10^{38} \times 4.2 \times 10^{-13}}{(0.033)^3} W = 5 \times 10^{31} W \approx 10^5 L_\odot$$

The luminosity of this low frequency (1/P ~ 30 MHz, in wavelength ~ 10^7 m) magnetic dipole radiation is comparable with the entire output of the Galaxy!

The radiation is absolved by and heats up the surrounding Crab Nebula.

Composite image of the Crab Nebula. Blue indicates X-rays (from Chandra), green is optical (from the HST), and red is radio (from the VLA).
Image credit: J. Hester (ASU), CXC, HST, NRAO, NSF, NASA.

Estimating Magnetic Field

- Assuming the loss rotational energy is entirely due to the magnetic field (magnetic dipole radiation), we can estimate the magnetic field of a pulsar

$$-\dot{E} = P_{\rm rad}$$

$$\frac{4\pi^2 I\dot{P}}{P^3} \lesssim \frac{32\, B^2\, R^6\, \pi^4}{3c^3\, P^4} \qquad B^2 \geq \frac{3\, I\, c^3}{8\, \pi^2\, R^6}\, \frac{P}{\dot{P}}$$

Q: What is the minimum magnetic field of the Crab pulsar?

‘Characteristic Age’

First order differential Eq.

$$-\dot{E} = P_{\rm rad}$$

$$\frac{4\pi^2 I\dot{P}}{P^3} = \frac{32\,B^2\,R^6\,\sin^2\alpha\,\pi^4}{3c^3\,P^4}$$

$$\boxed{\dot{P} = KP^{-1}}$$

Notice K is a constant, so that

$$\dot{P}P = K = \text{const}$$

$$\frac{dP}{dt} = \frac{K}{P}$$

$$\int_{P_0}^{P} P\,dP = K\int_0^{\tau_c} dt = \dot{P}P\int_0^{\tau} dt$$

‘Characteristic Age’

$$K = \frac{8\,B^2R^6\sin^2\alpha\,\pi^2}{3Ic^3}$$

First order differential Eq.

$$-\dot{E} = P_{\mathrm{rad}}$$

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Solving the integrals

$$\frac{1}{2}\left[P^2 - P_0^2\right] = \dot{P}P\,\tau_c$$

'Characteristic Age'

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Solving the integrals

$$\frac{1}{2}\left[P^2 - P_0^2\right] = \dot{P}P\,\tau_c$$

Rewriting i.t.o τ_c the "characteristic age"

$$\tau_c = \frac{P}{2\dot{P}}\left[1 - \left(\frac{P_0}{P}\right)^2\right] \approx \frac{P}{2\dot{P}}$$

$$P_0 \ll P$$

Birth period P_0 much less than current P

'Characteristic Age'

An assumption!

$$-\dot{E} = P_{\rm rad}$$

$$\frac{4\pi^2 I\dot{P}}{P^3} = \frac{32\,B^2\,R^6\,\sin^2\alpha\,\pi^4}{3c^3\,P^4}$$

First order differential Eq.

$$\boxed{\dot{P} = KP^{-1}}$$

Notice K is a constant, so that

$$\dot{P}P = K = \text{const}$$

$$\frac{dP}{dt} = \frac{K}{P}$$

$$\int_{P_0}^{P} P\,dP = K\int_0^{\tau_c} dt = \dot{P}P\int_0^{\tau} dt$$

Solving the integrals

$$\frac{1}{2}\left[P^2 - P_0^2\right] = \dot{P}P\,\tau_c$$

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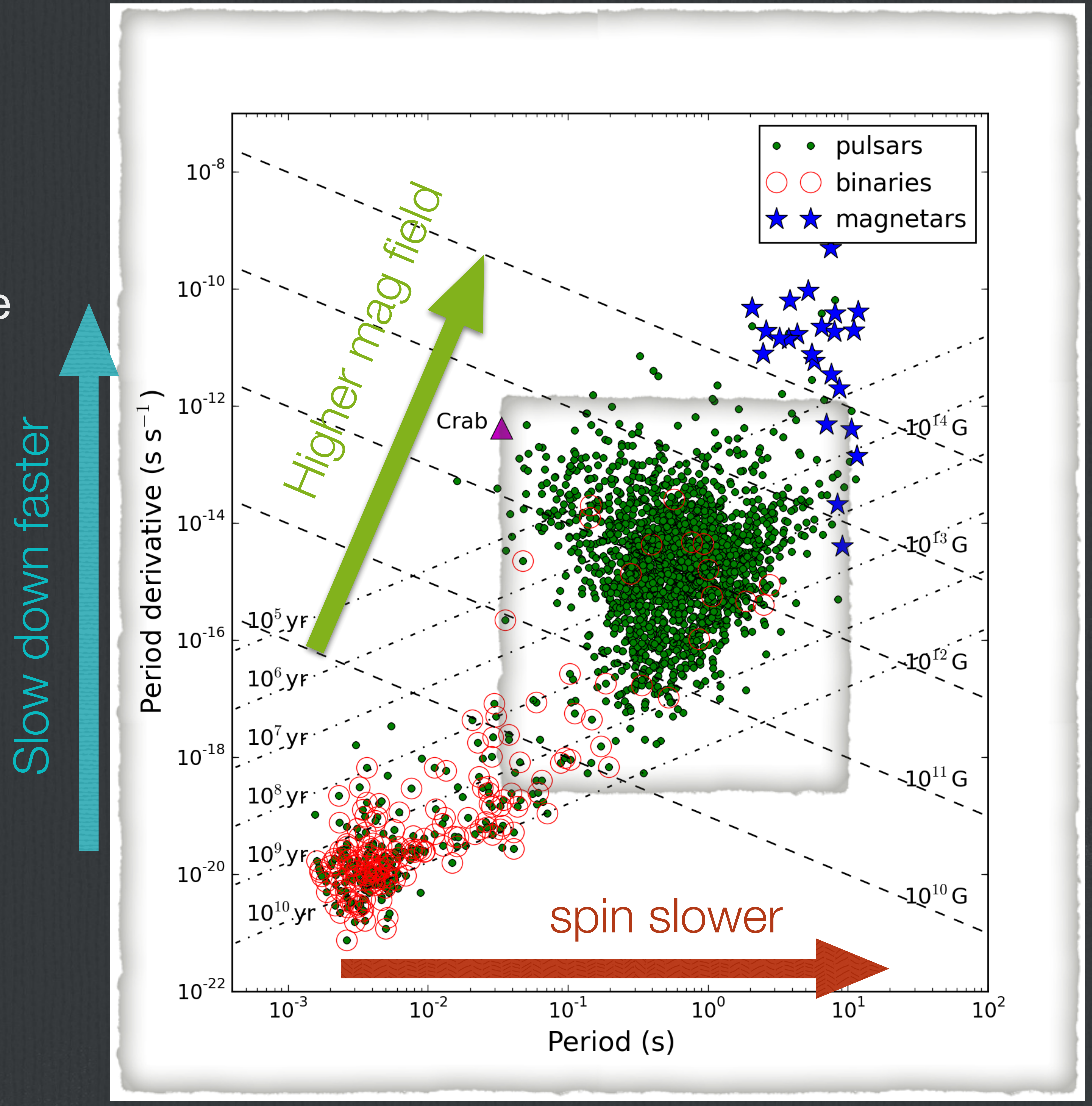
$$P_0 \ll P$$

Birth period P_0 much less than current P

Adding P, P-dot, magnetic field and characteristic age to one diagram!

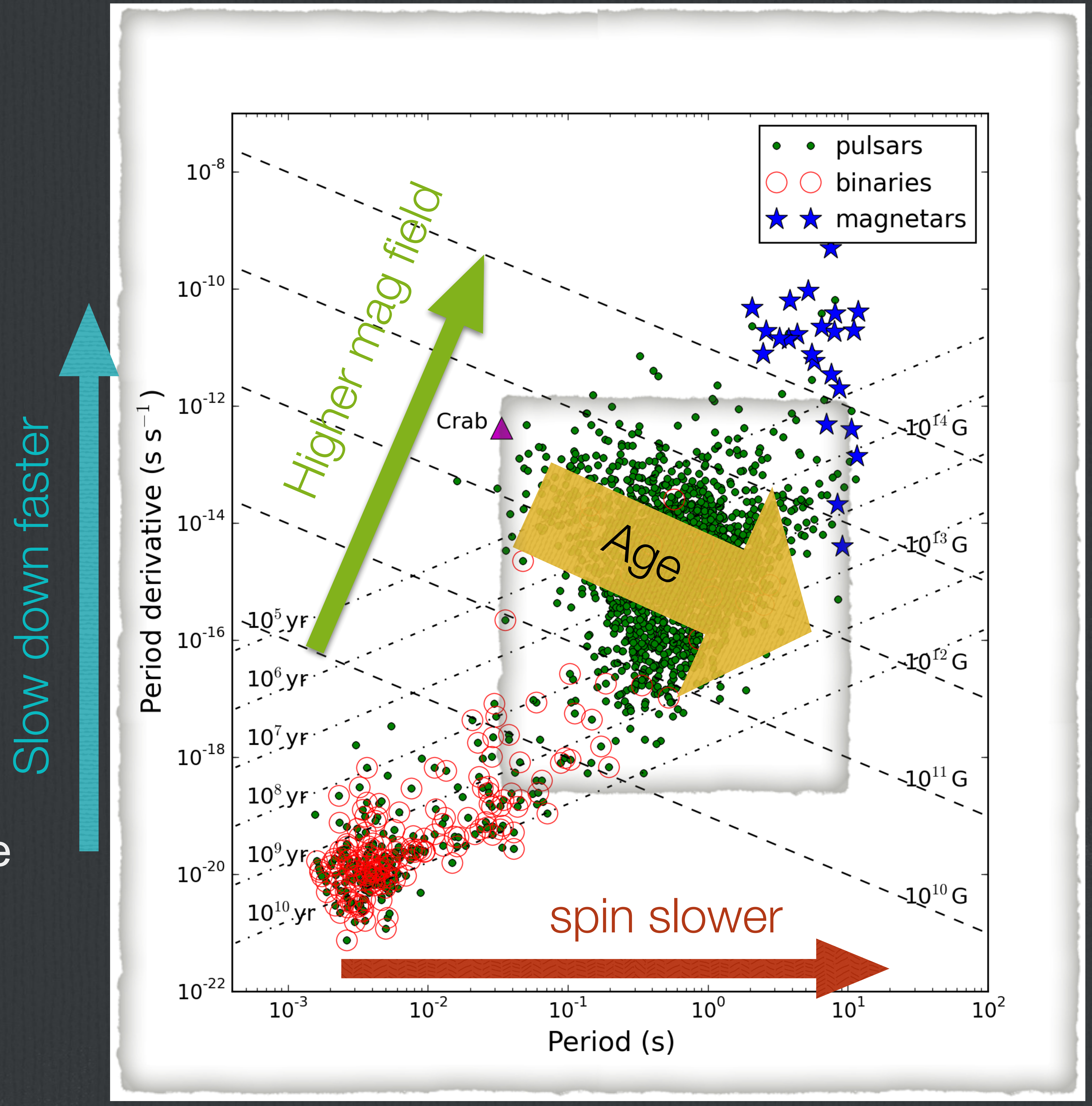
P-Pdot diagram

- The P-Pdot diagram gives an overview of the pulsar population.
- Over 3000 pulsars discovered to date (Do we see them outside the MW?)
- 'Norma/isolated' pulsars (green point without red circle around) evolve over the course of their lives:
  younger pulsars spin faster, but are more erratic, older ones slower, but more stable
- As they age the isolated pulsars slow down. When their spin rate is too slow to produce radio emission, they shut off



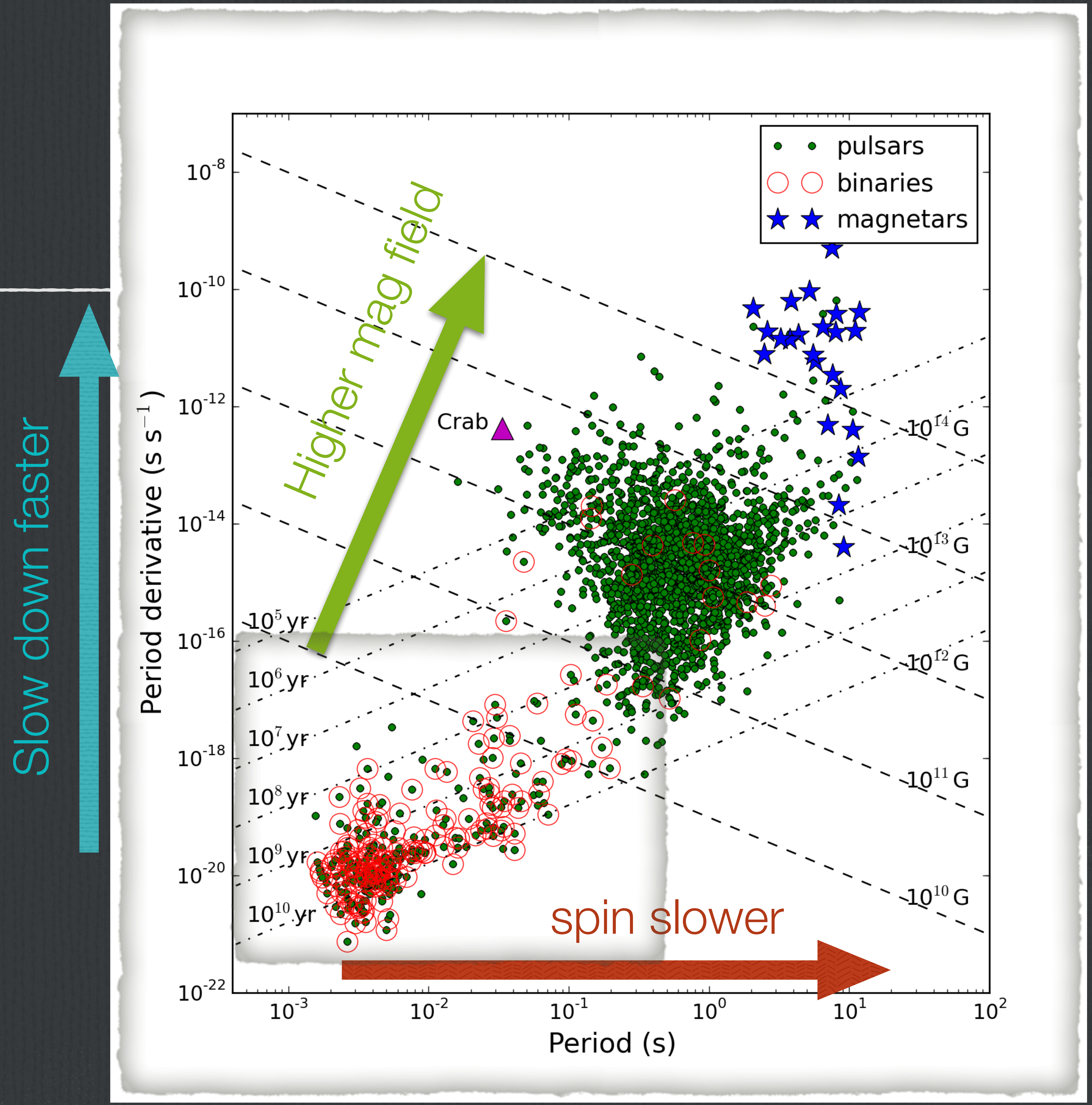
P-Pdot diagram

- As they age the isolated pulsars slow down. When their spin rate is too slow to produce radio emission, they shut off
- In the computation of characteristic age we have assumed that the magnetic field stays constant, that's why the "age arrow" is along a constant magnetic field size, but across the characteristic age lines.



MSP population

- Two main pulsar groups: ‘normal/isolated’ pulsars and the millisecond pulsars (MSP, red circles)
- Approximately 10% of the pulsar population are MSPs
- MSPs are most often in binary systems, and have been spun up through accretion to incredible rotations of a few ms!
- MSPs are used for high precision pulsar timing experiments



MSPs are 'recycled pulsars'

- Binary star system with massive stars
- The most massive star goes SNe & creates pulsar
- Companion star goes through red giant phase
- Strong gravitational pull from MSP accretes material from the red giant companion, spinning the pulsar up, to higher spin rates than before.

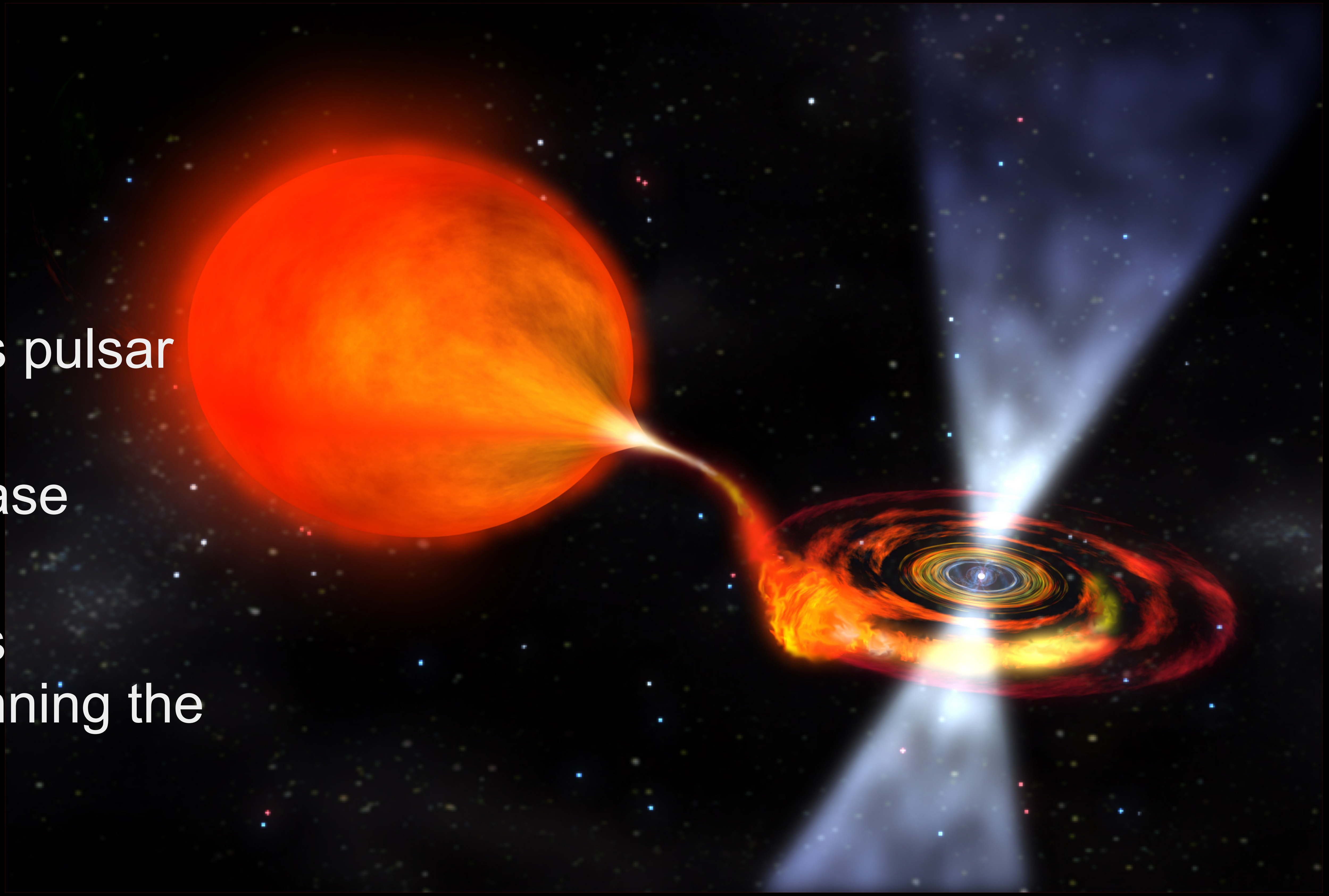


Image credit: Nasa/Dana Berry

The End of Lecture 2

Extra slides on pulsar timing for fun… not for class

How do we time them?

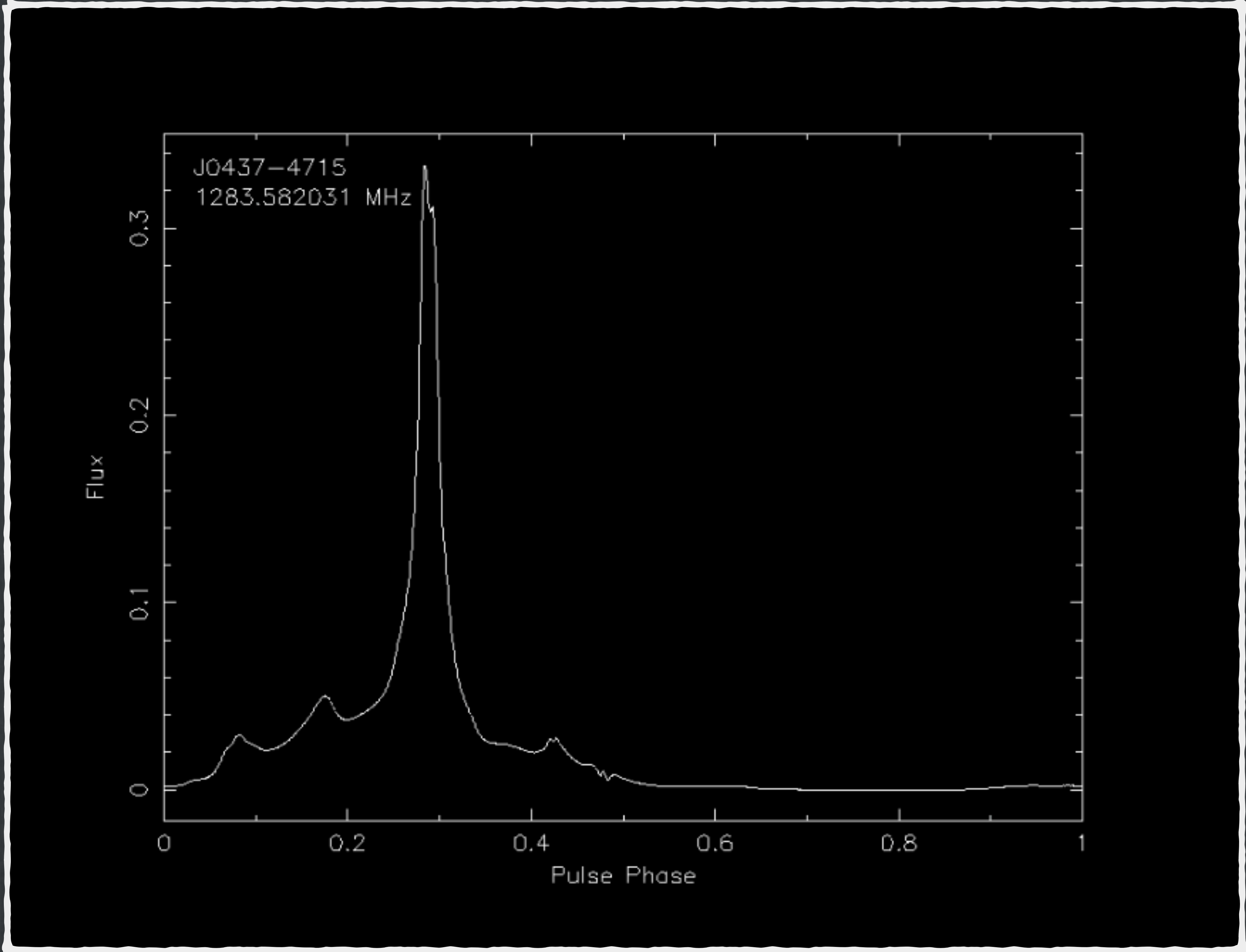
— The main idea in pulsar timing is that you can account for every single pulse the pulsar emits …

… over long timescales (months to years)

— We create a model to predict when a next pulse should arrive

— And then compare the model prediction to the outcome of an observation

Ave profile of PSR J0437-4715



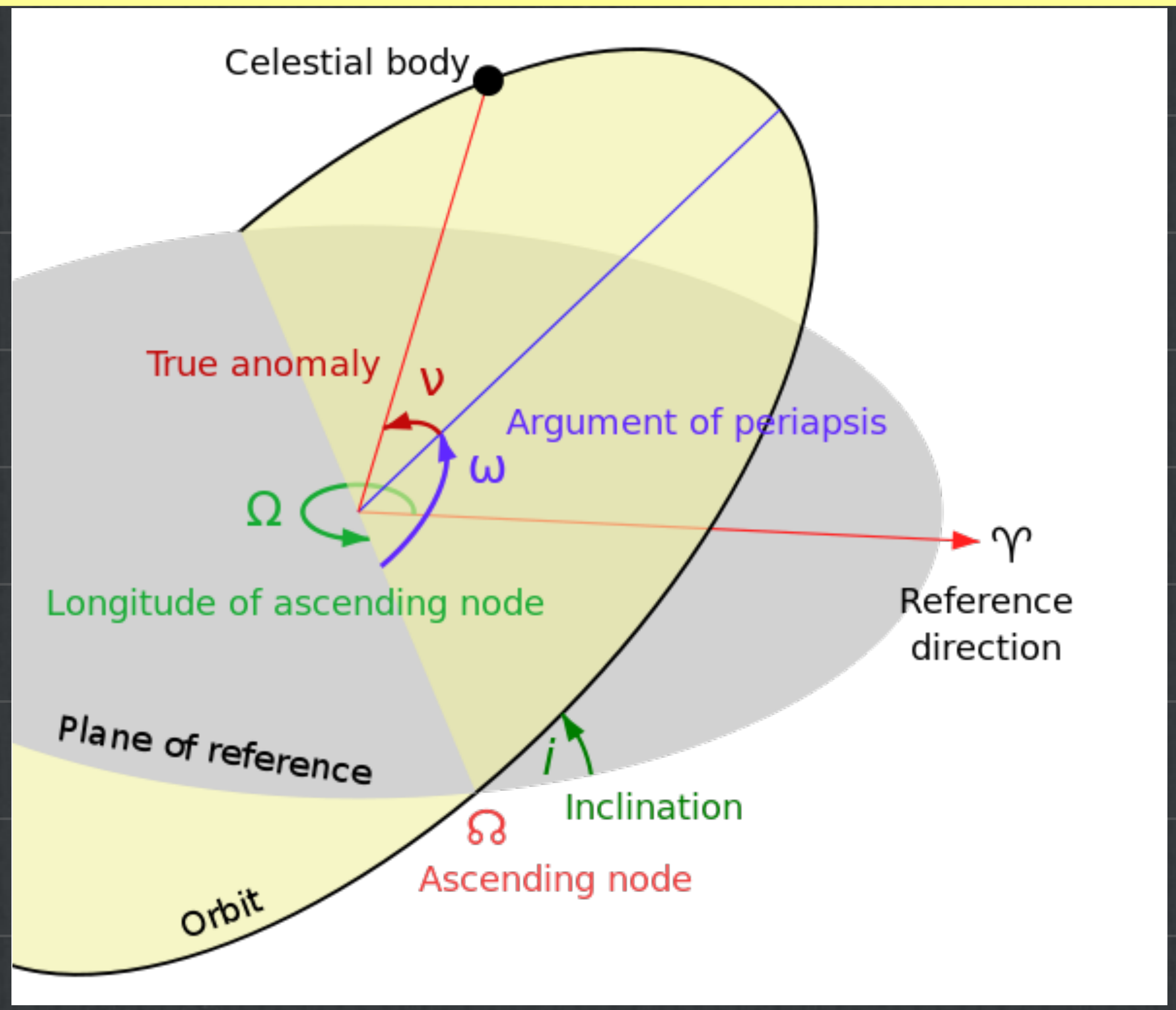
Pulse period: 5.75745195692365 +/- 5.72921315987526e-17 ms

Only changes every 500 years

Changes every 30 min

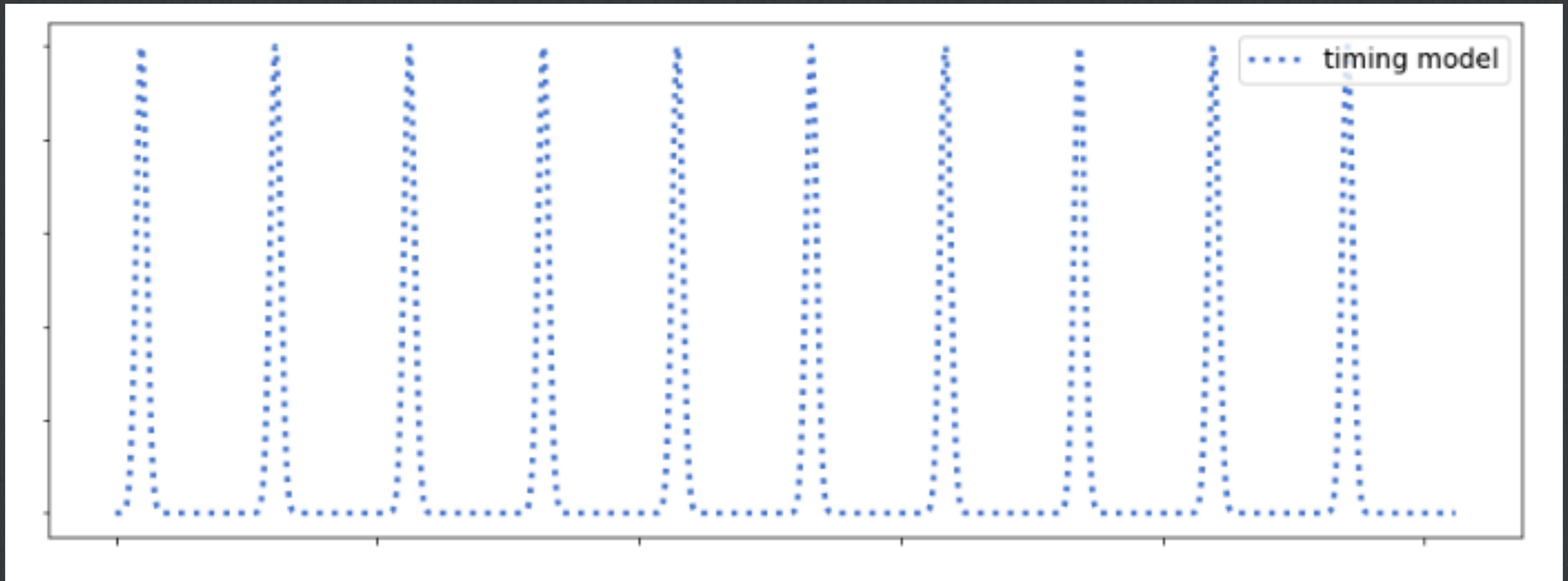
Timing model for PSR J0437-4715 – many parameters required!

PSRJ	J0437-4715		Description
RAJ	04:37:15.8961737	0.00000059222328833097	Position RA, DEC in J2000
DECJ	-47:15:09.11071	0.00000626551891151144	
F0	173.68794581218427973	4.6845149140224002772e-13	Pulse frequency (1/P)
F1	-1.7283605122731730757e-15	4.1071593643911663336e-21	Pulse frequency derivative
DM	2.6449834563206059848	0.00008653635874335857	Dispersion measure (~ distance)
PMRA	121.43854597164442692	0.00191452076416571883	Proper motion (pulsars move fast!)
PMDEC	-71.47543404131 2093429	0.00195429949160796880	
SINI	0.67486415393420895459		Measure of inclination
PB	5.7410459155735336523	0.00000032533158441279	Orbital period
T0	54501.467101261028311	0.00026804860643427281	Epoch of periastron
A1	3.3667144446637437 45	0.00000004747802657046	Projected semi-mayor axis
OM	1.3633107005337778062	0.01680834622164296271	Long. periastron
ECC	1.9181125869312663381e-05	0.00000000147116125760	Eccentricity
PBDOT	3.7275957595519669874e-12	5.7550064565980936078e-15	Derivative of orbital period
OMDOT	0.013787042894548421 77	0.00129789329107361513	Epoch of periastron
M2	0.22397223617905254602	0.00623027717171982780	Mass of companion



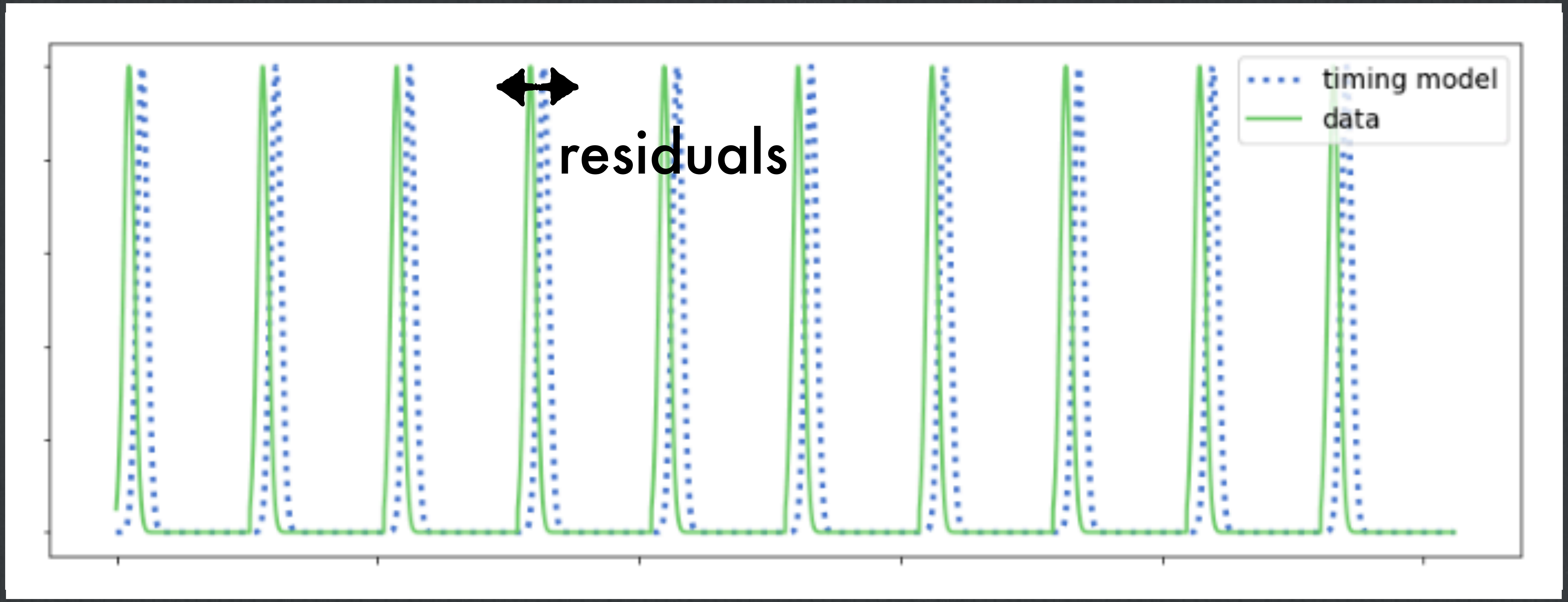
Getting the timing residuals low!

Time pulses are predicted to arrive at the Sun:

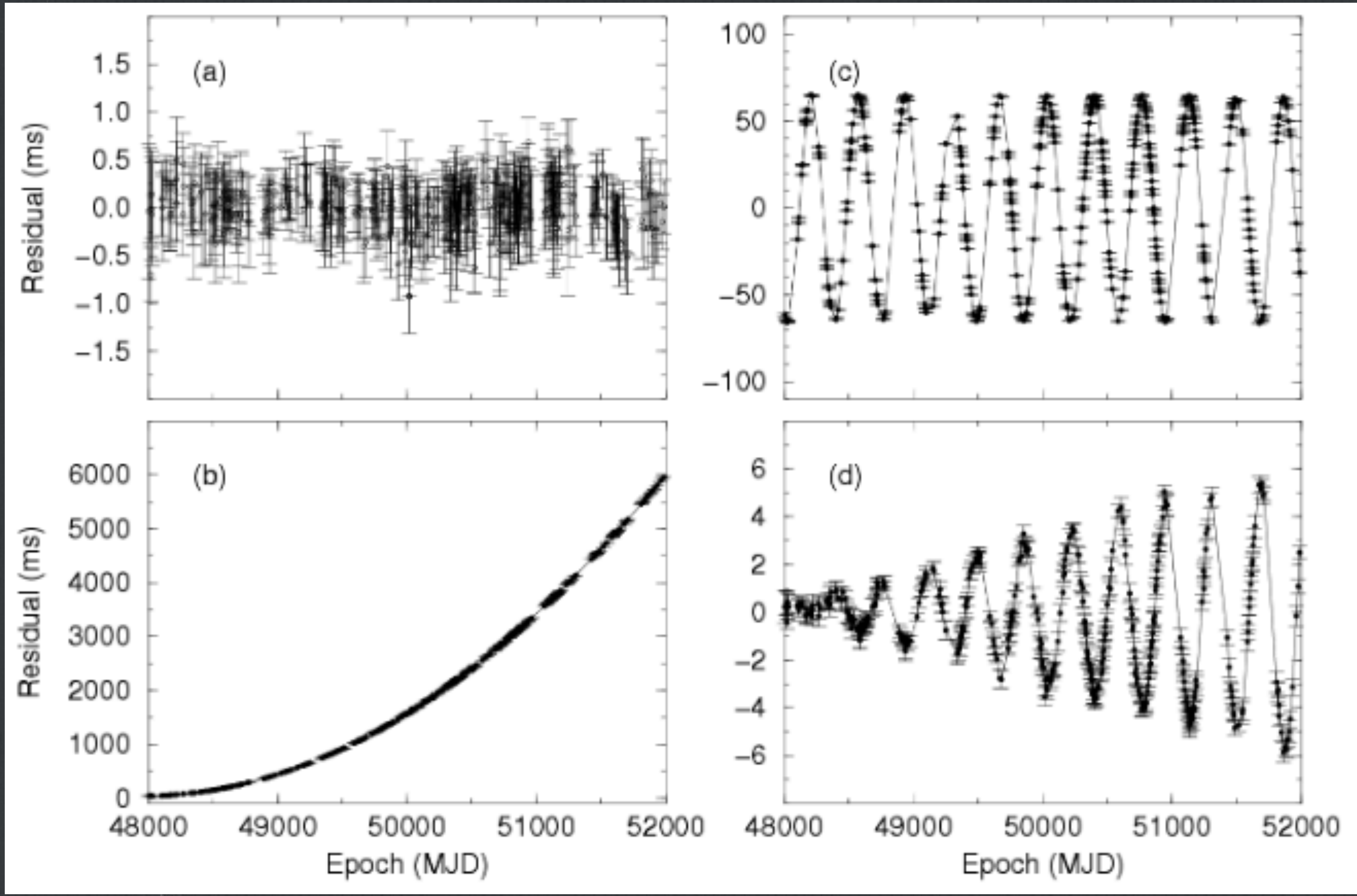


Getting the timing residuals low!

Measure difference between model and data



Guess the problem!



1. Wrong pulsar position

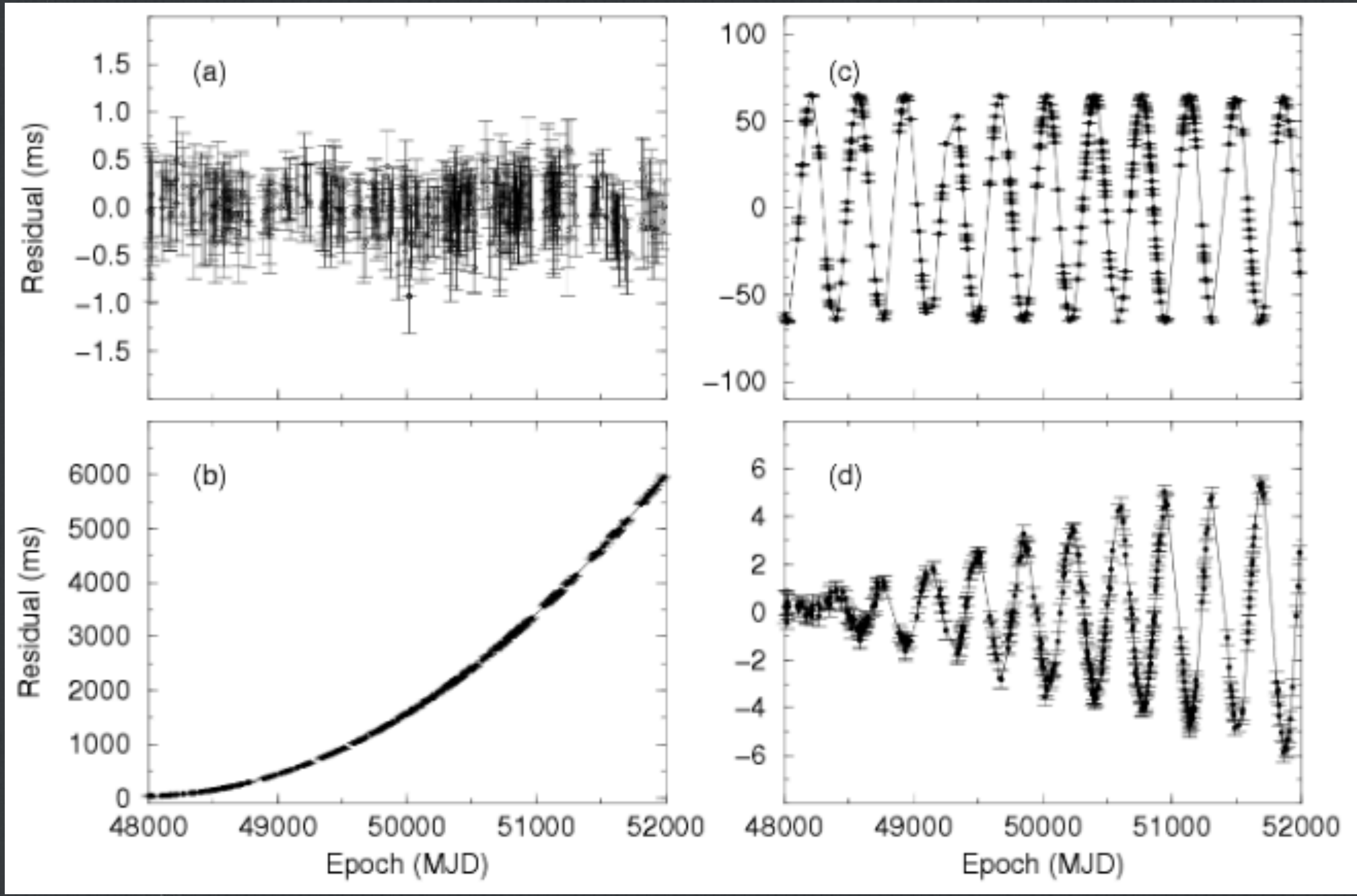
2. Good timing model

3. Period derivative (slow down rate) is wrong

4. Proper motion not modelled

5. Mass of companion is wrong

Guess the problem!



1. Wrong pulsar position
2. Good timing model
3. Period derivative (slow down rate) is wrong
4. Proper motion not modelled
5. Mass of companion is wrong

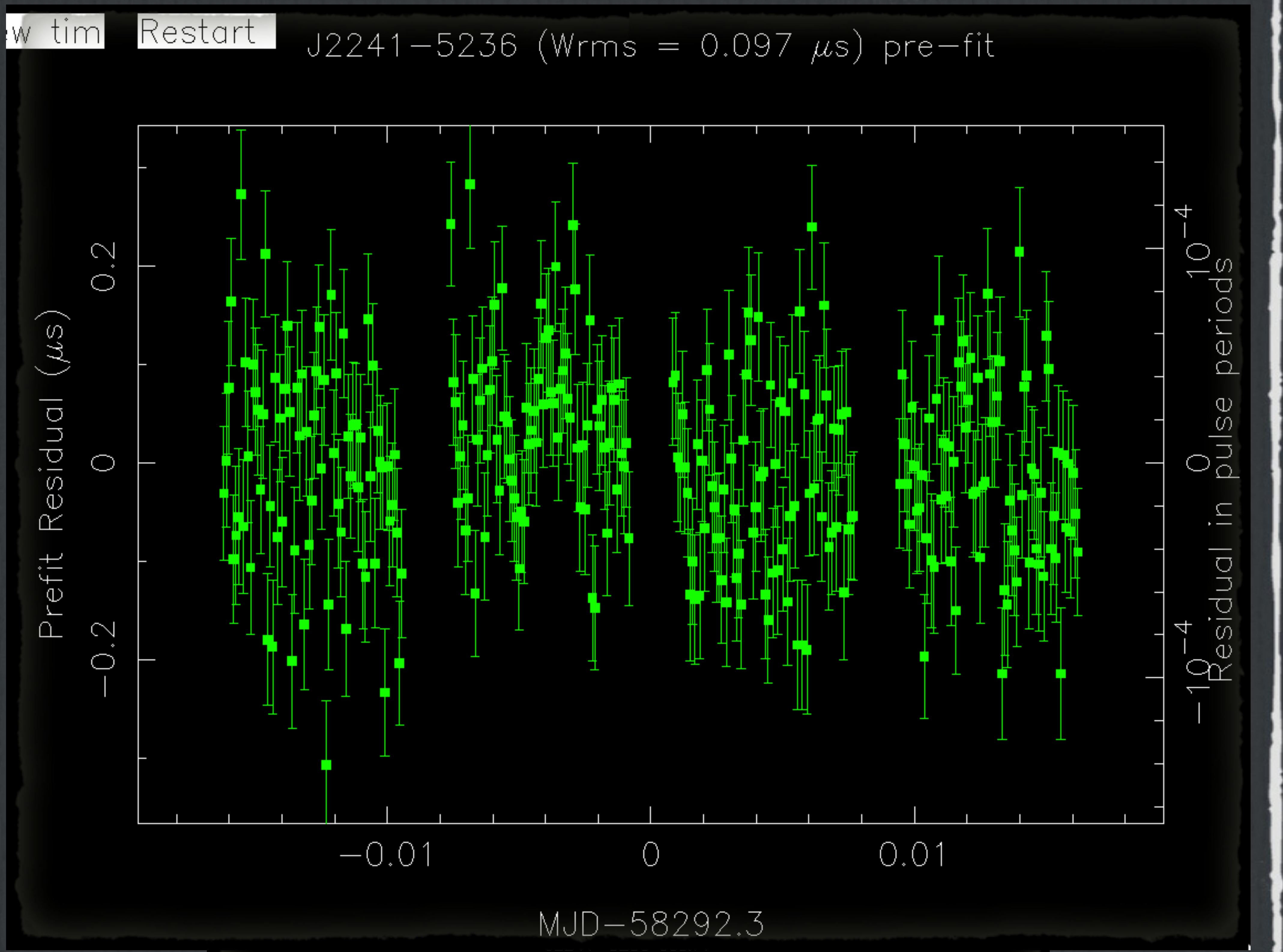
Answers: (a) -> 2, (b) -> 3, (c) -> 1, (d) -> 4
5. I'll show you soon

Pulsar Timing with MeerKAT

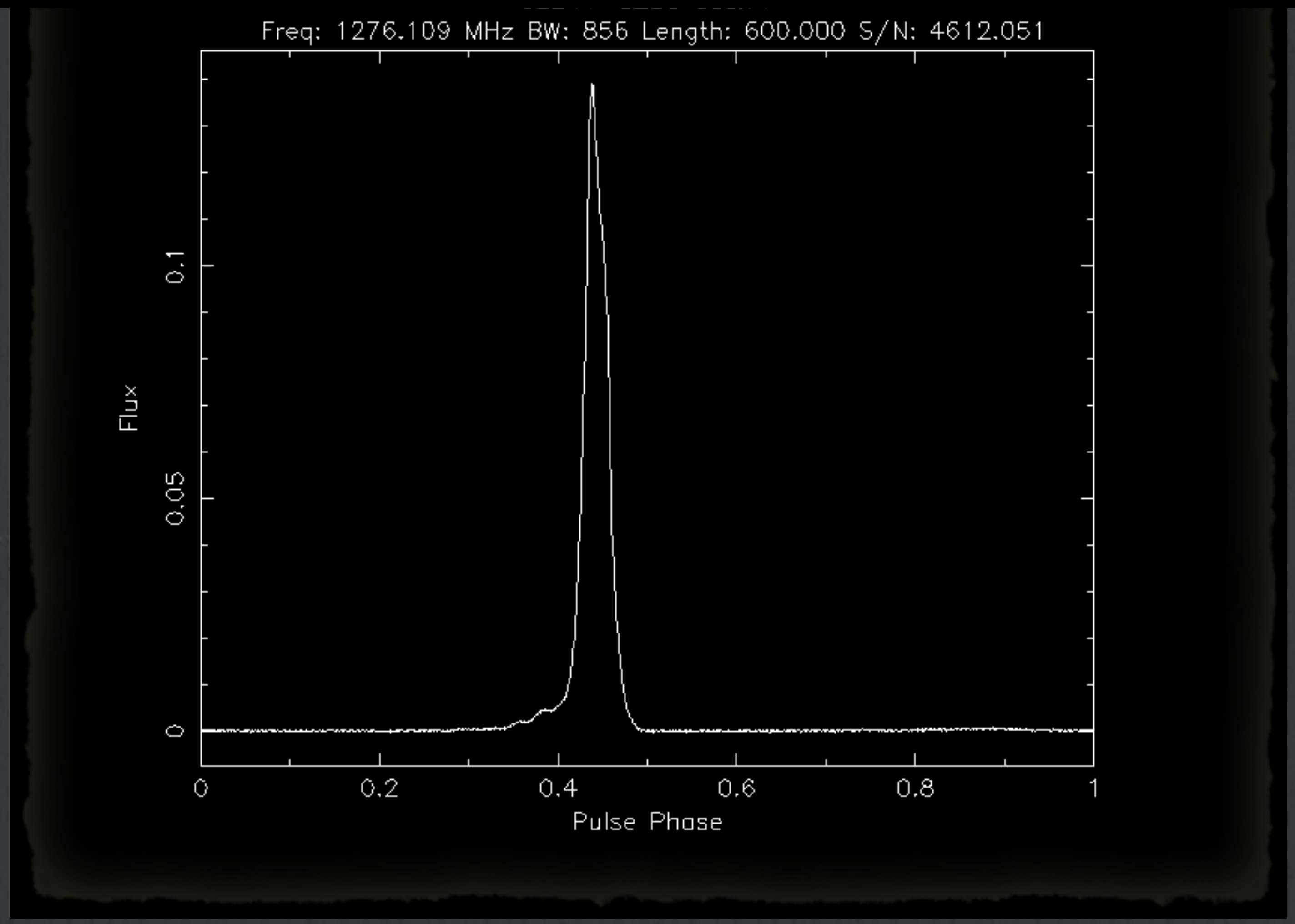
MeerTIME: Big involvement of Melbourne group at Swinburne Uni of Technology (www.meertime.org)

Using just four incredibly bright (S/N >3000) observations of 10 min each,

RMS error in the measured TOAs for PSR J2241-5236 **was just 97 ns!**

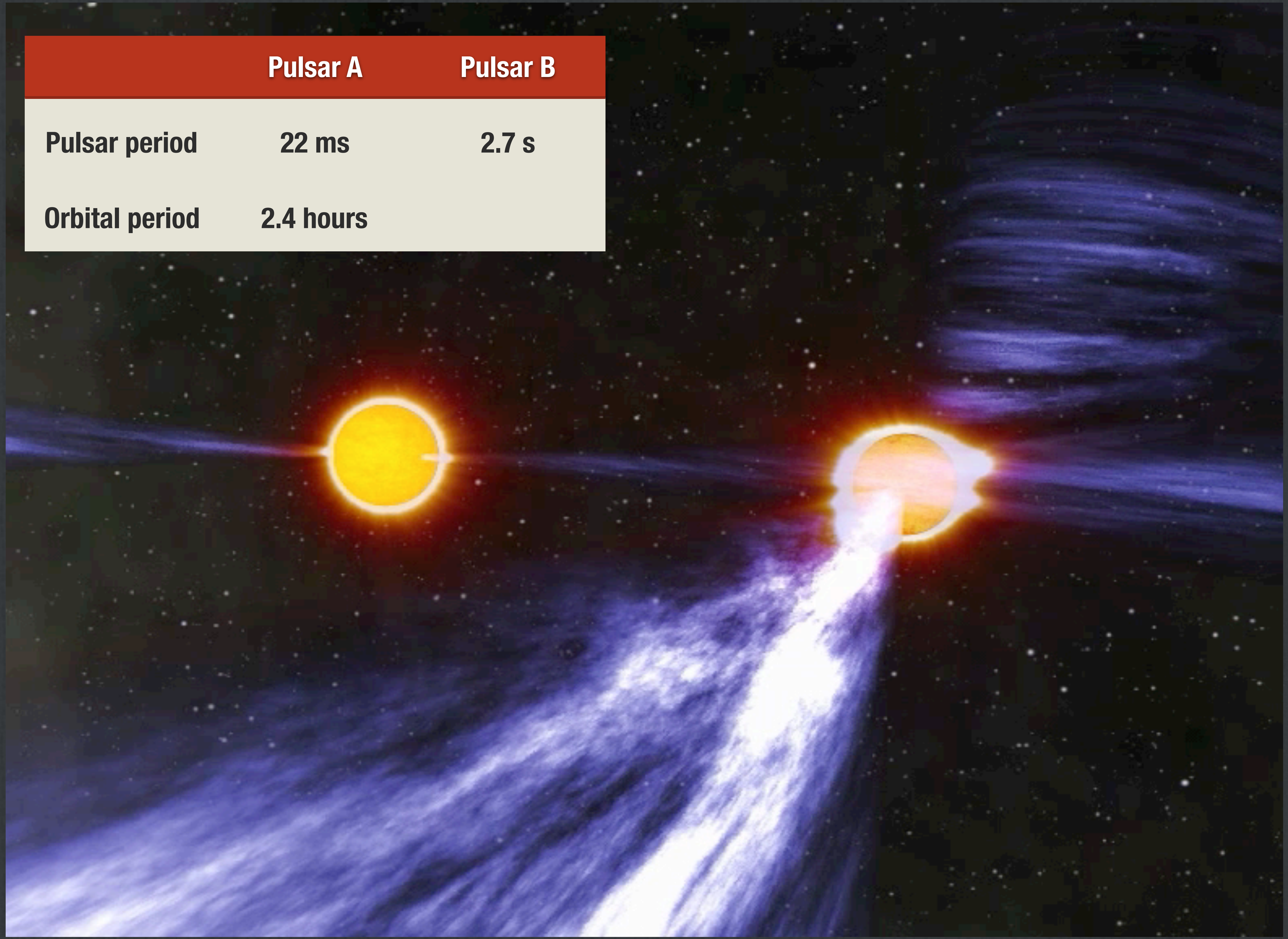


Pulsar	Parkes	MeerKAT
	S/N (Dai et al, 2015)	S/N
J2241-5236	3500 in 6.4 days	4600 in 10 min
J1744-1134	4500 in 5.4 days	10 400 in 30min

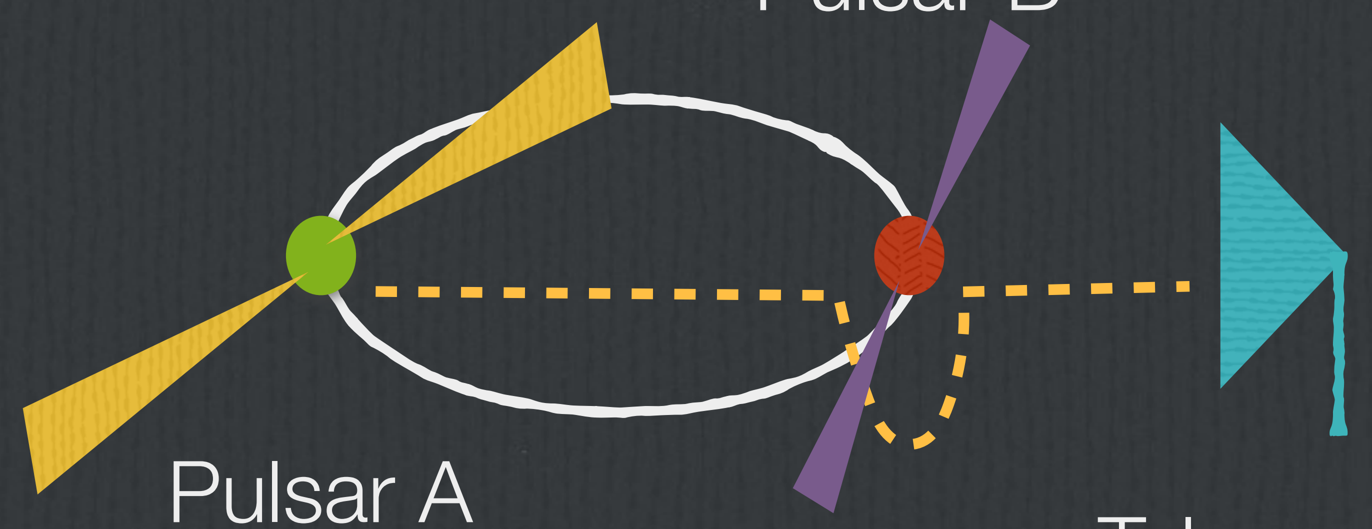


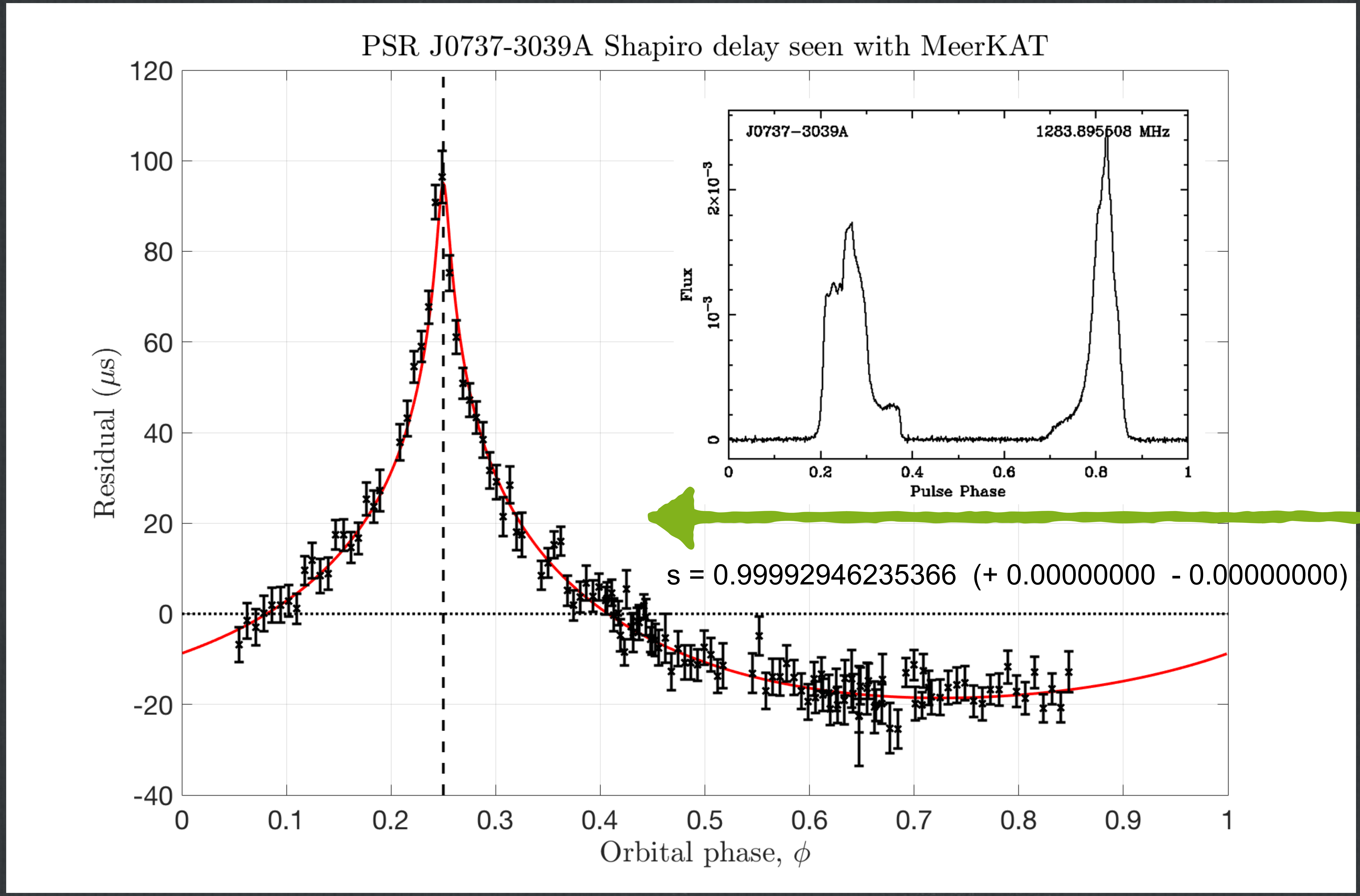
Testing GR with pulsars: The double pulsar J0737-3039A and B

- Discovered pulsar A at Parkes 2003, (Burgay et al, *Nature*)
- Found the orbit's orientation was changing rapidly: $d\omega/dt = 17°/yr$, suggesting a companion
- Companion turned out to be pulsar too!
- Great candidate for strong field tests of GR
- Orbit shrinks by 7mm per day
- GR prediction of orbital parameters agree to within 0.05% of measured orbital parameters
- Great example is the Shapiro delay, the gravitational delay as the pulses from the one pulse pass through the gravitational potential of the other

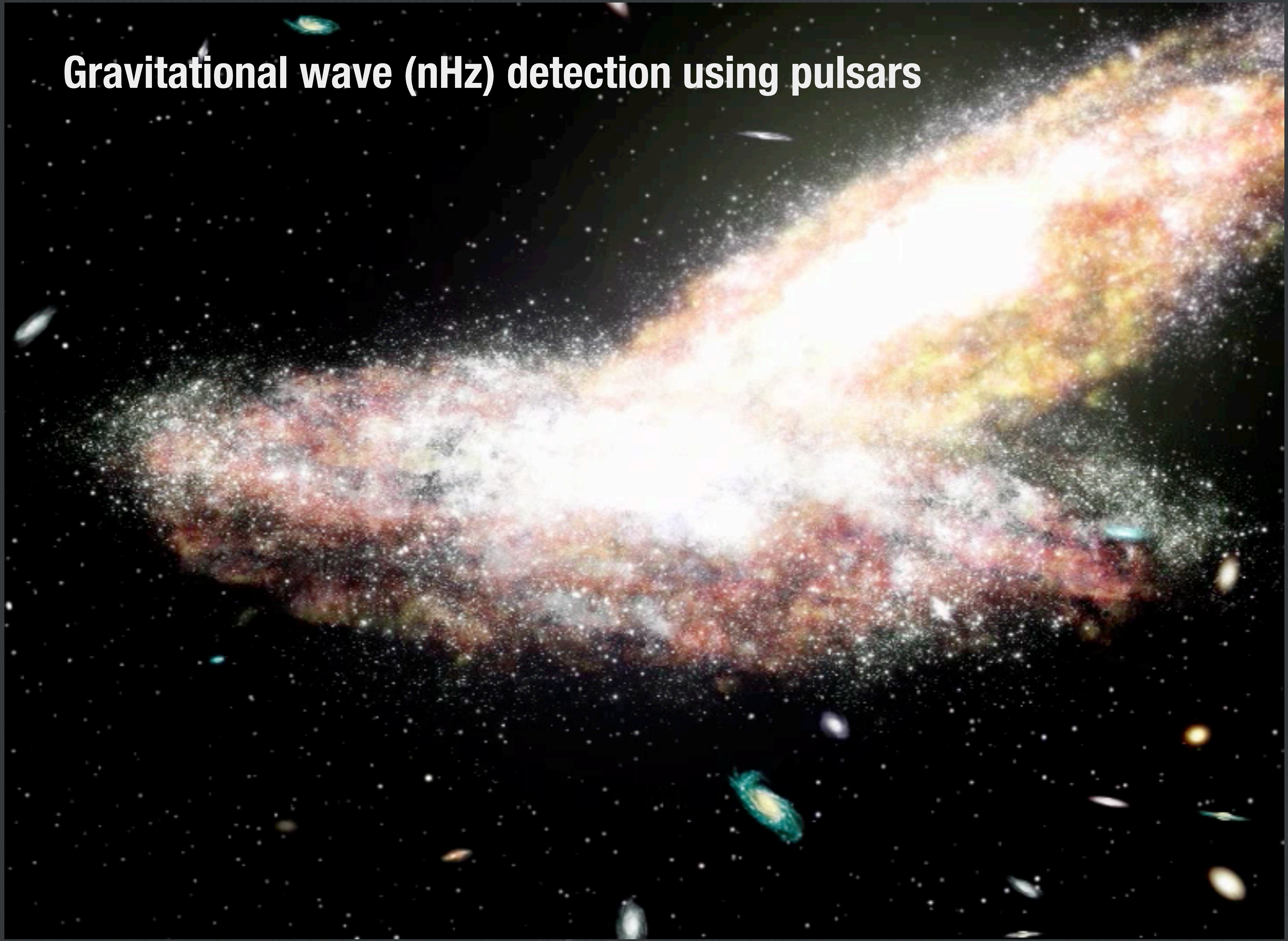


Shapiro delay of double pulsar with MeerKAT





- During the orbit of the double pulsar system, pulsar A will at some point be behind pulsar B
- The pulses of pulsar A will travel through the gravitational field of pulsar B before it is detected at the telescope
- The measured delay of pulses from pulsar A as it passes through the gravitational well of the companion pulsar B is measured via the Shapiro s-parameter


Gravitational wave (nHz) detection using pulsars