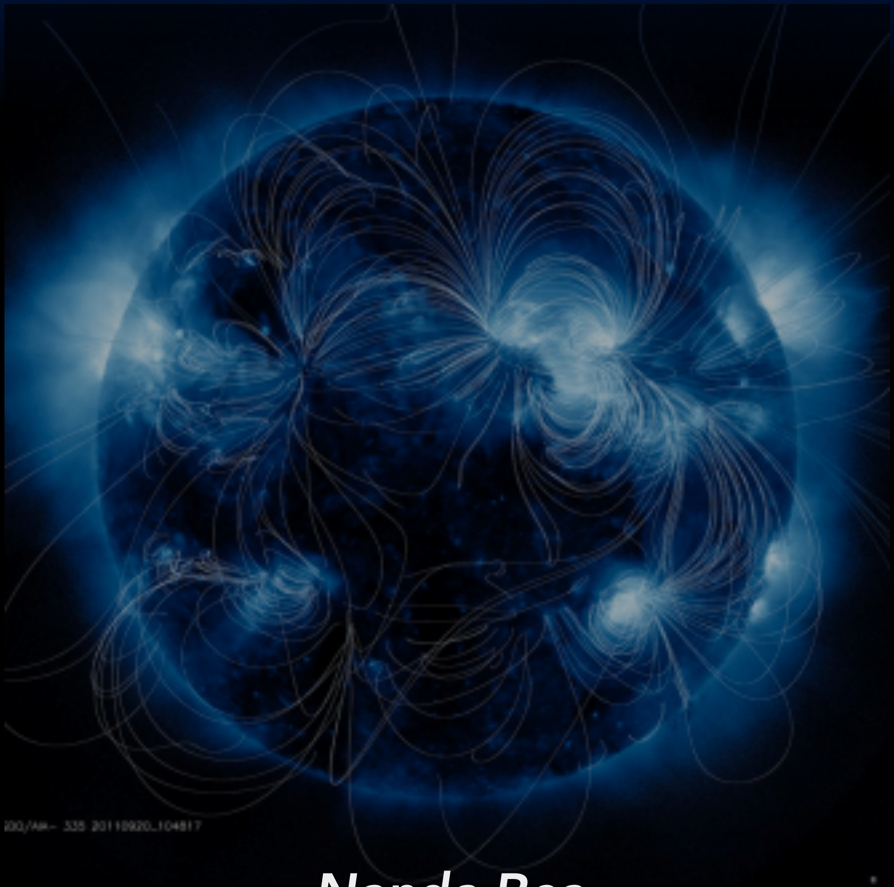
# Neutron Stars

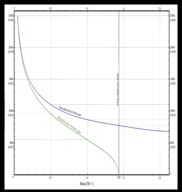


***Nanda Rea***

*Institute for Space Sciences (ICE), CSIC-IEEC, Barcelona, ES*
*Anton Pannekoek Institute, University of Amsterdam, NL*

# Early history

- 1931 Chandrasekhar argued that WDs collapse at masses > 1.4 $M_\odot$. (Chandrasekhar 1931, ApJ)



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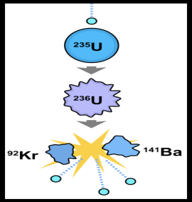


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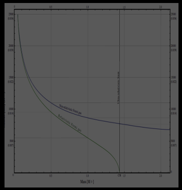

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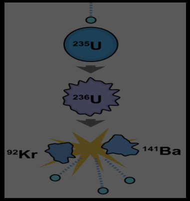


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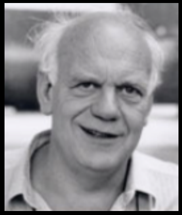

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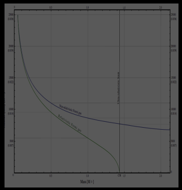

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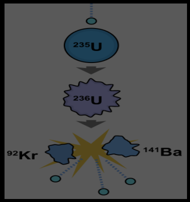


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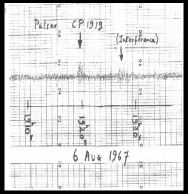
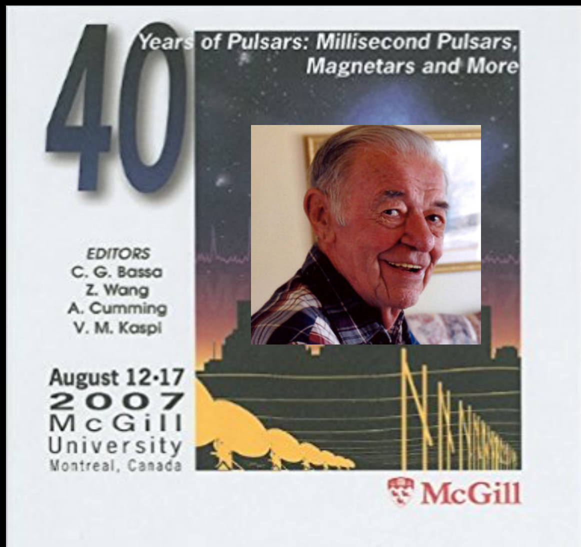
•1968 Hewish & Bell studing interplanetary scintillation observed a periodicity of 1.337s, discovering the first pulsar: PSR 1919+21. (Hewish et al. 1968, Nature)




# Curiosity…



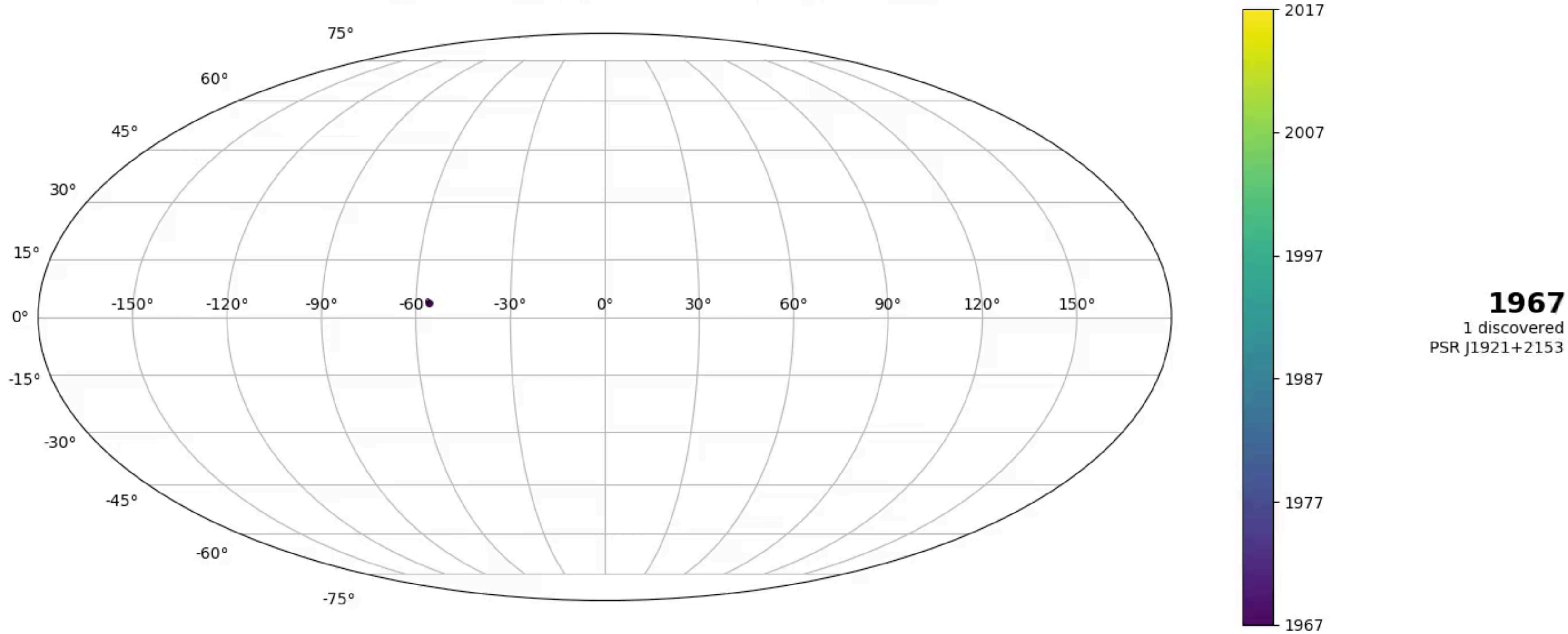

Charles Schisler 1931 – 2011
(Bluffon, South Carolina)

Independent US Navy discovery of pulsars in August 1967, and the first discovery of the Crab pulsar, with the Clear Antenna in Alaska.

FAN PASSAGE TABLE (C…

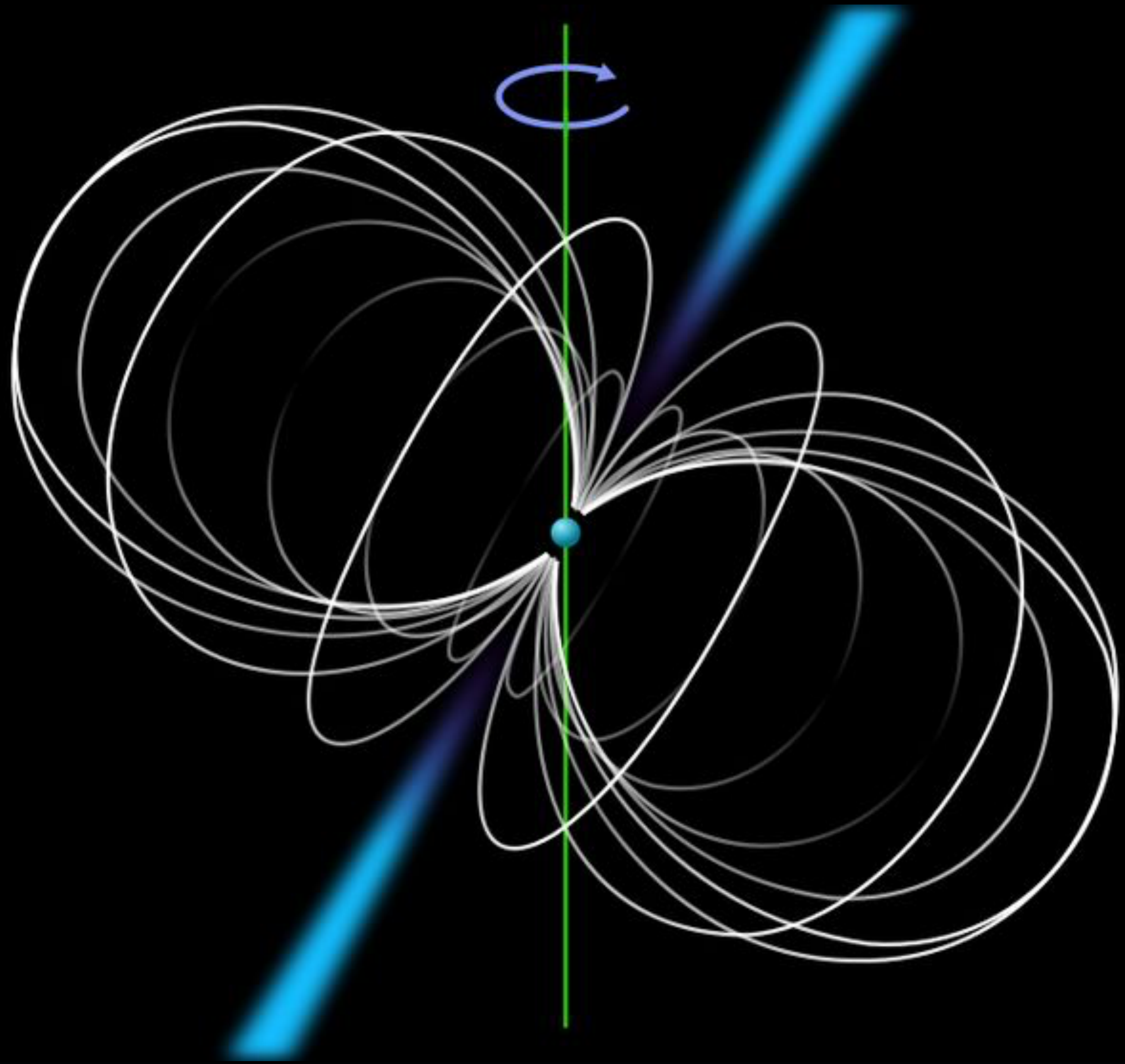
| Declin. | UPPER FAN Azim. | UPPER FAN fan GHA | GHA deg. diff. | LOWER FAN Azim. | LOWER FAN fan GHA | Time difference between fan… |
|---|---|---|---|---|---|---|
| + 30.5° | 360.0 | 329.18° | | No Show in lower fan | | — |
| + 30 | 335.8 | 301.17° | 5.09° | | | — |
| + 29 | 331.2 | 296.08° | 4.38° | | | — |
| + 28 | 327.2 | 291.70° | 1.97° | 358.0 | 327.18° | — |
| + 27.5 | 325.4 | 289.73° | 1.95° | 344.6 | 310.68° | — |
| + 27 | 323.6 | 287.78° | 3.56 | 338.6 | 303.00° | — |
| + 26 | 320.3 | 284.22° | 3.34 | 333.3 | 299.48° | 61 min |
| + 25 | 317.1 | 280.88° | 3.16 | 329.4 | 294.28° | 53 min |
| + 24 | 314.0 | 277.78° | 2.93 | 325.2 | 290.68° | 51 min |
| + 23 | 311.2 | 274.85° | 2.78 | 321.8 | 287°00′ | 48 min |
| + 22 | 308.4 | 272.07° | 2.69 | 318.4 | 283.58° | 46 min |
| + 21 | 305.6 | 269.38° | 2.58 | 315.1 | 280.28° | 44 min |
| + 20 | 303.0 | 266.80° | 2.50 | 312.1 | 277.28° | 42 min |
| + 19 | 300.5 | 264.30° | 2.42 | 309.2 | 274.38° | 40 min |
| + 18 | 297.9 | 261.43° | 2.36 | 306.5 | 271.68° | 39 min |
| + 17 | 295.5 | 259.52° | 2.30 | 303.9 | 269.08° | 38 min |
| 16 | 293.0 | 257.22° | 2.25 | 301.4 | 266.58° | 37 min |
| + 15 | 290.6 | 254.97° | 2.22 | 298.9 | 264.08° | 36 min |
| + 14 | 288.2 | 252.75° | 2.19 | 296.4 | 261.68° | 36 min |
| + 13 | 285.8 | 250.57° | 2.15 | 293.3 | 259.33° | 35 min |
| + 12 | 283.5 | 248.42° | 2.14 | 291.0 | 257.18° | 35 min |
| + 11 | 281.2 | 246.28° | 2.10 | 288.7 | 254.88° | 34 min |
| + 10 | 278.9 | 244.18° | 2.10 | 286.5 | 252.68° | 34 min |
| + 9 | 276.5 | 242.08° | 2.08 | 284.4 | 250.58° | 34 min |
| + 8 | 274.2 | 240.00° | 2.08 | 282.0 | 248.48° | 34 min |
| + 7 | 271.9 | 237.92° | 2.08 | 279.1 | 246.23° | 33 min |
| + 6 | 269.6 | 235.84° | 2.07 | 277.0 | 244.18° | 33 min |
| + 5 | 267.3 | 233.77° | 2.09 | 274.9 | 242.05° | 33 min |
| + 4 | 265.0 | 231.68° | 2.10 | 272.8 | 240.00° | 33 min |
| + 3 | 262.6 | 229.58° | 2.10 | 269.9 | 237.88° | 33 min |
| + 2 | 260.3 | 227.48° | 2.11 | 267.7 | 235.38° | 33 min |
| + 1 | 257.9 | 225.37° | 2.15 | 265.5 | 233.63° | 33 min |
| 0 | 255.5 | 223.22° | 2.19 | 263.5 | 231.68° | 34 min |
| − 1 | 253.1 | 221.03° | [illegible] | 260.7 | 229.58° | 34 min |
| − 2 | 250.7 | 218.83° | [illegible] | 258.2 | 227.38° | 34 min |
| − 3 | 248.2 | 216.58° | 2.30 | 256.1 | 225.28° | 35 min |
| − 4 | 245.7 | 214.28° | 2.35 | 254.0 | 223.18° | 36 min |
| − 5 | [redacted] | | | | | 36 min |
| − 6 | | | | | | 37 min |
| − 7 | (237.8) | 207.02° | | 246.2 | 216.38° | 37 min |
| − 8 | No Show in upper | | | 243.9 | 214.08° | — |
| − 9 | | | | 241.5 | 211.68° | — |

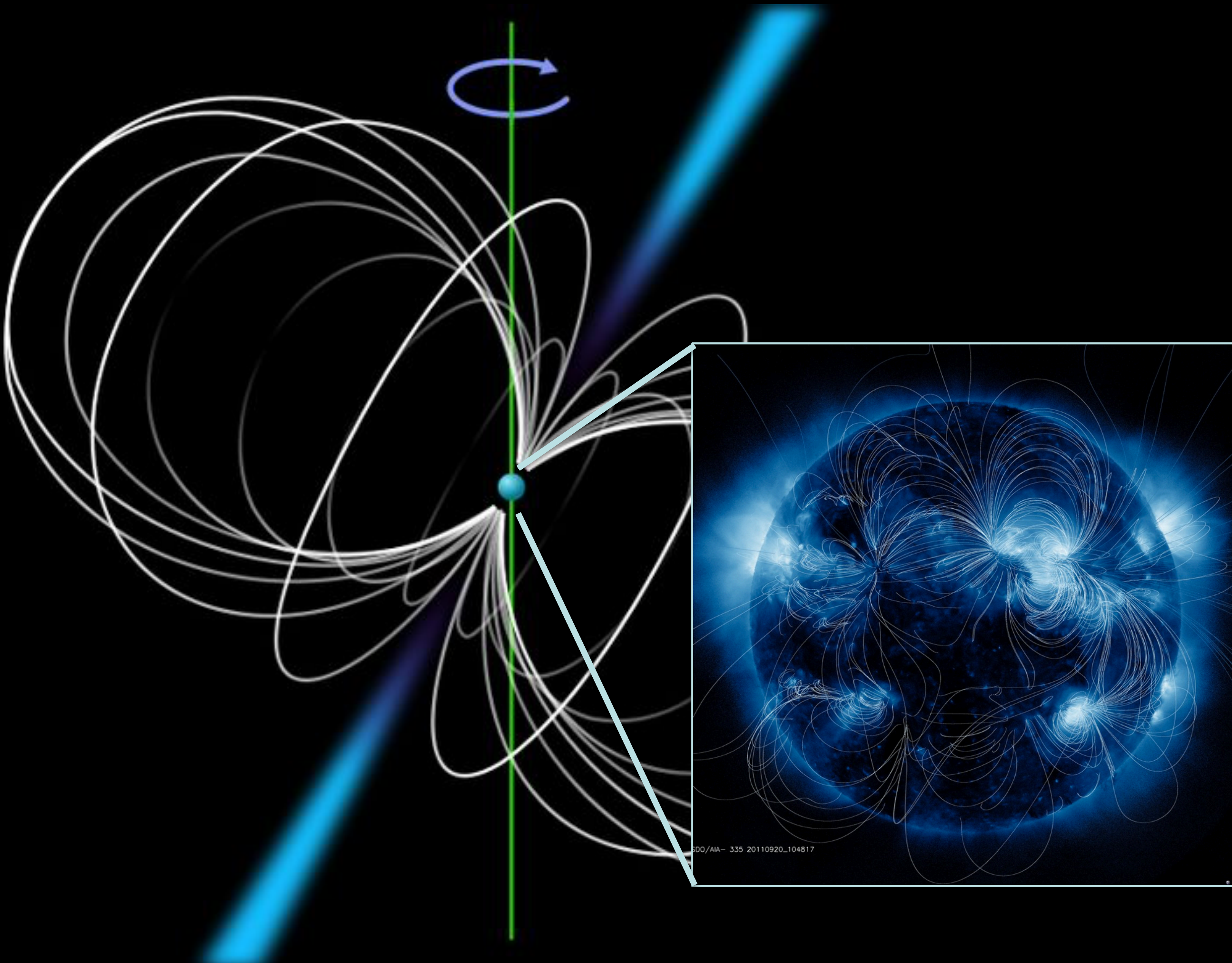
# 50 years of pulsars



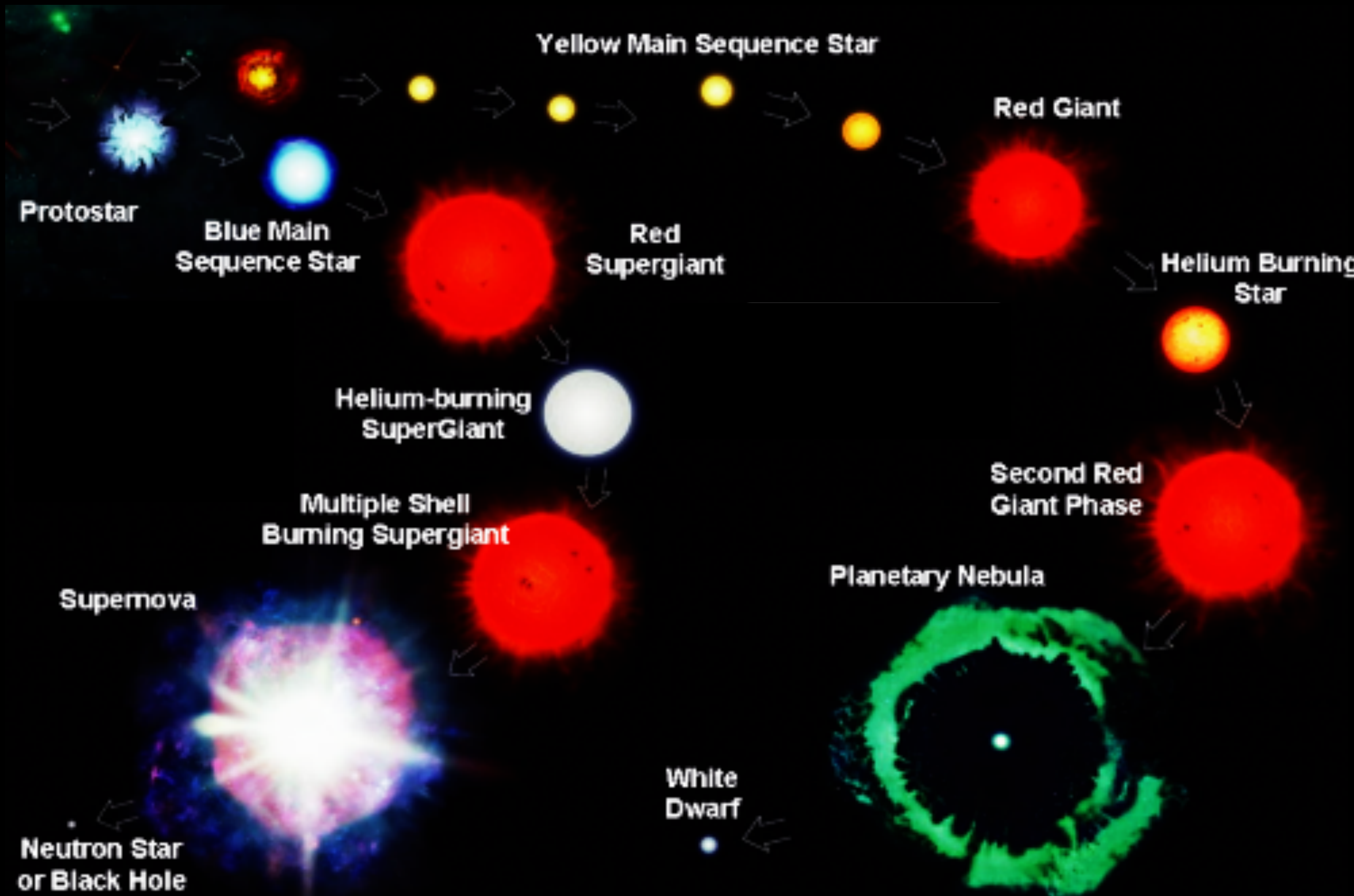

Credit: S. Serrano Elorduy N. Rea (ICE, CSIC-IEEC)

Rea 2017, Nature Astronomy, Vol. 1 p 827



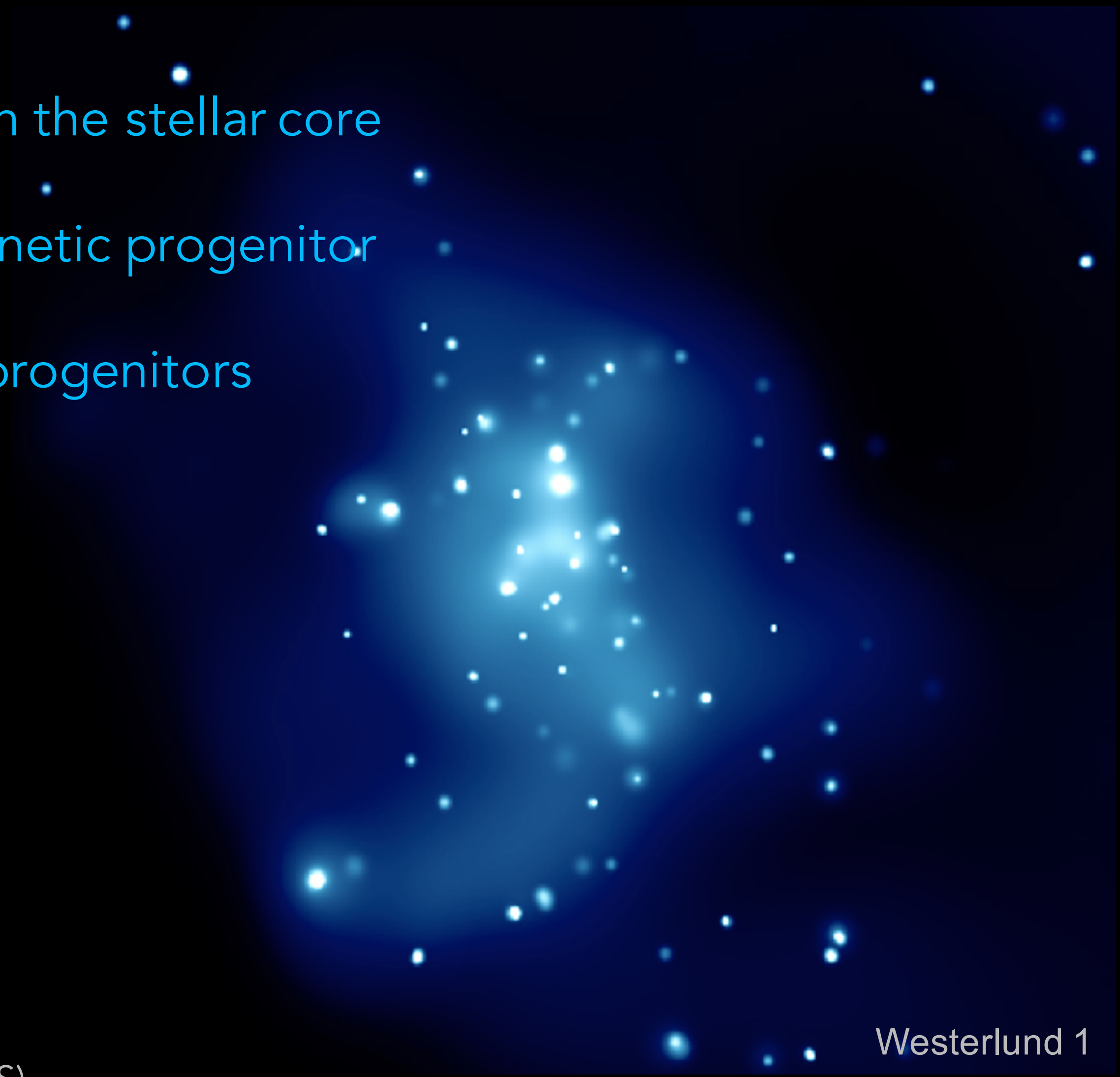

SDO/AIA- 335 20110920_104817

# Birth of a neutron star



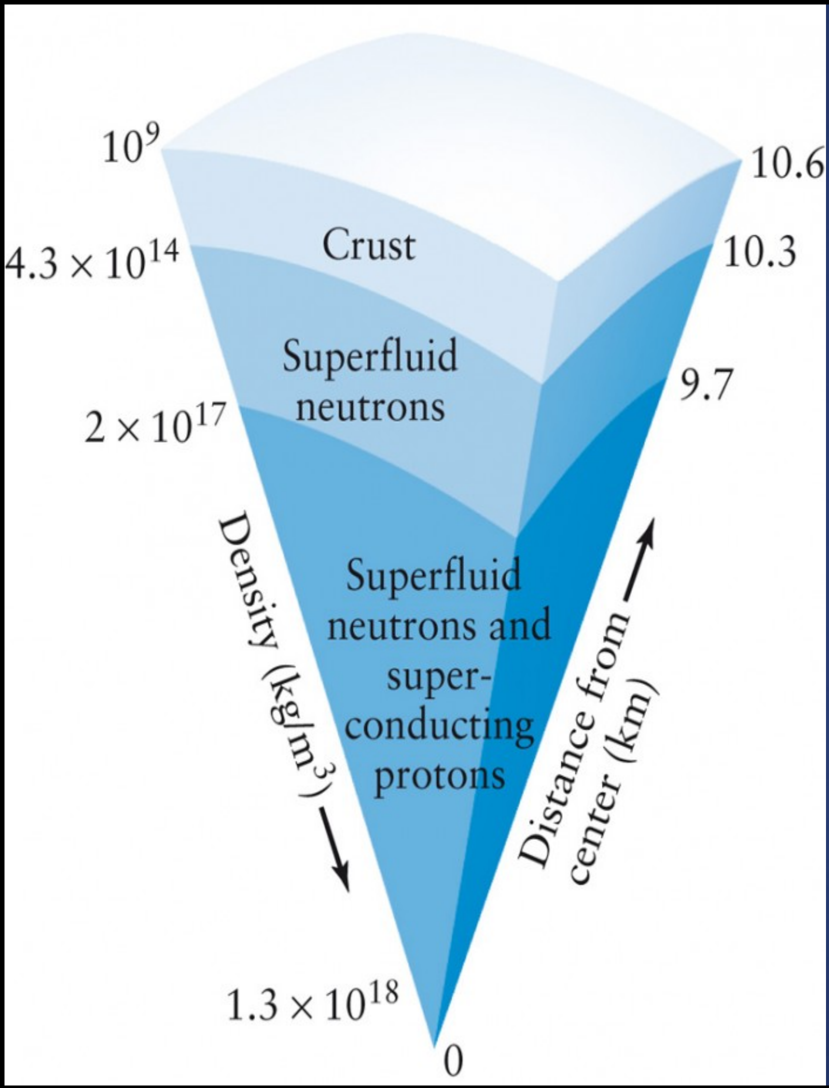
# Magnetic field formation in neutron stars

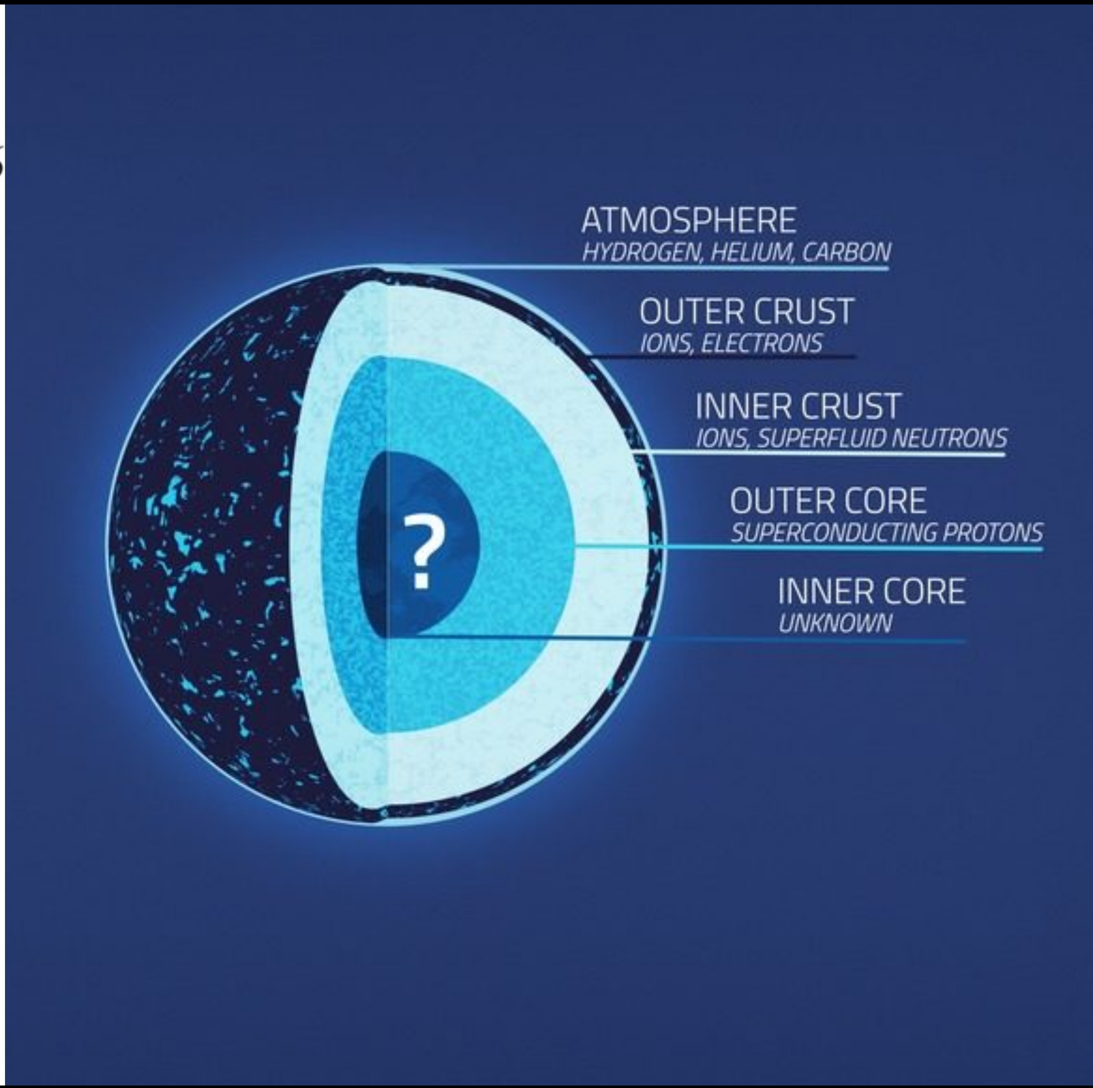
- Via dynamos/instabilities in the stellar core
- As fossil fields from a magnetic progenitor
- From massive star binary progenitors



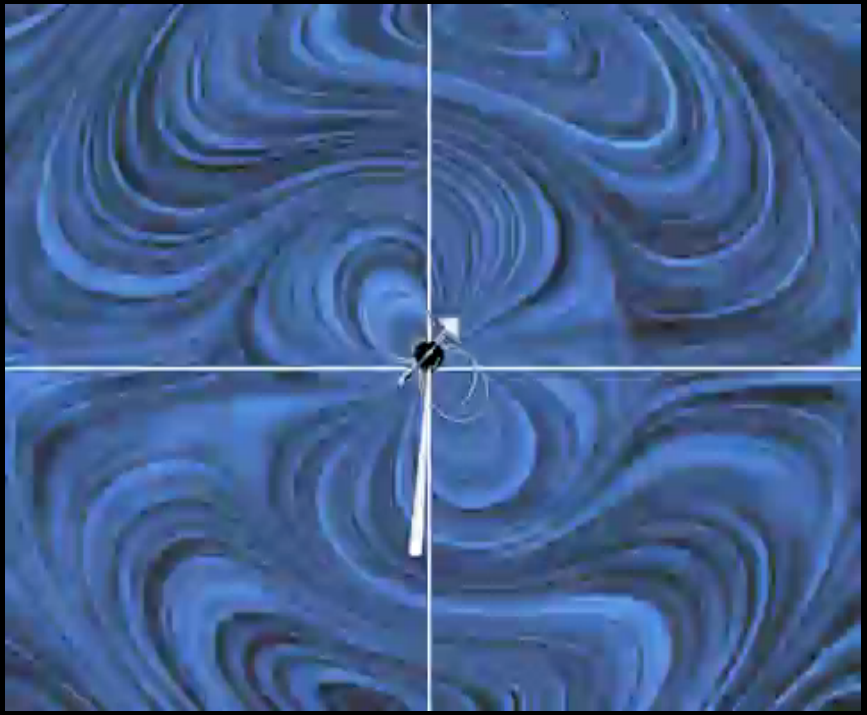

(Obergaulinger, Janka & Aloy 2015, MNRAS)

# Neutron star composition



# Magnetic field estimate



Rotating magnetic dipole

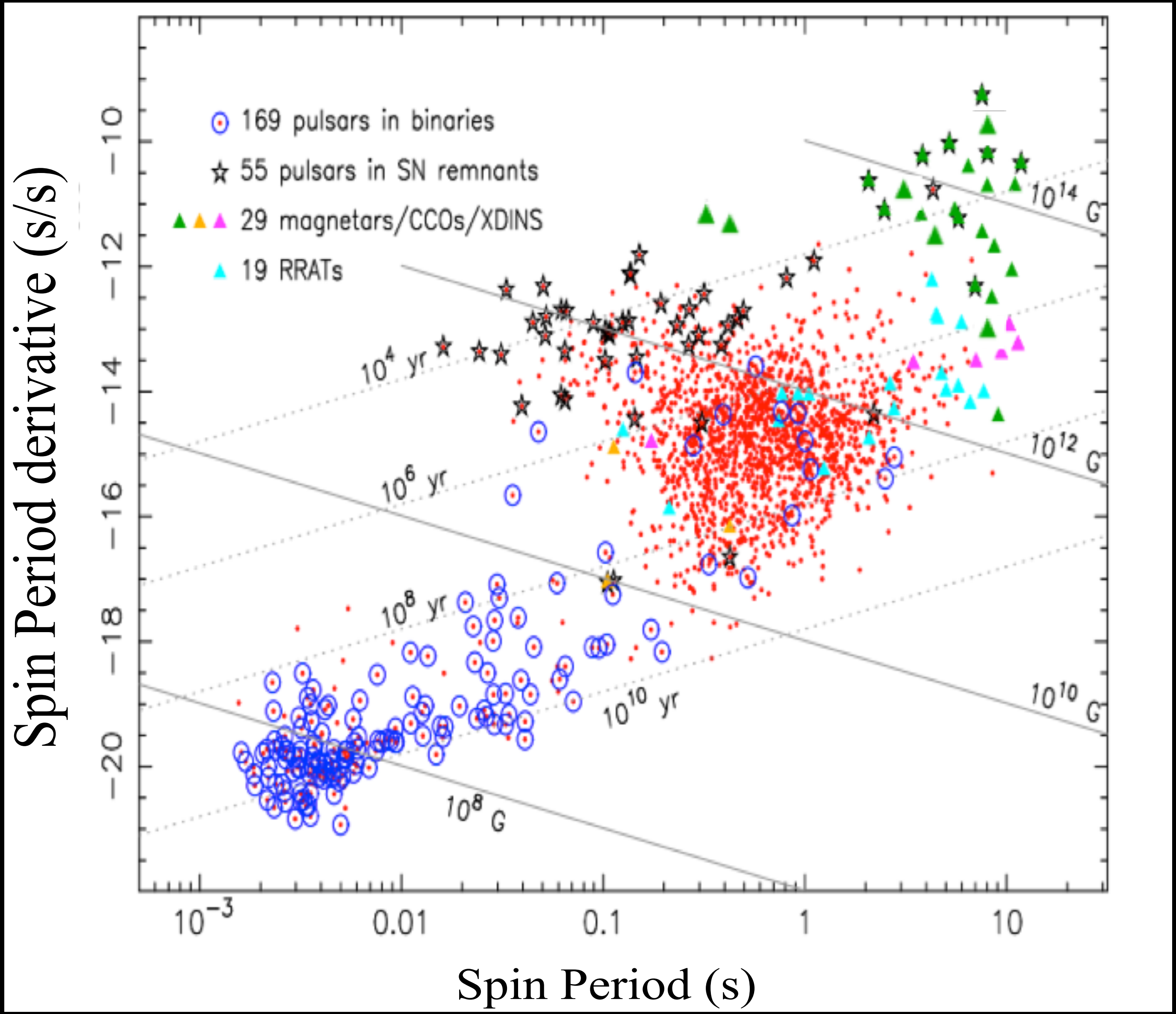
$$\dot{E}_{rot} = I_{ns}\Omega_s\dot{\Omega}_s = -\frac{4\pi^2 I_{ns}\dot{P}_s}{P_s^3}$$

$$P_{dip-rad} = -\frac{2}{3c^3}|\ddot{\mu}_d|^2 = -\frac{2(B_d R_{ns}^3 \sin(1+\alpha))^2}{3c^3}\left(\frac{4\pi^2}{P_s^2}\right)^2$$

$$B = 3.2 \cdot 10^{19}\sqrt{P\dot{P}} \text{ Gauss.}$$

$$\tau = \frac{P}{2\dot{P}}$$

# Pulsar Bestiary




Nanda Rea - Institute of Space Sciences, Barcelona, Spain

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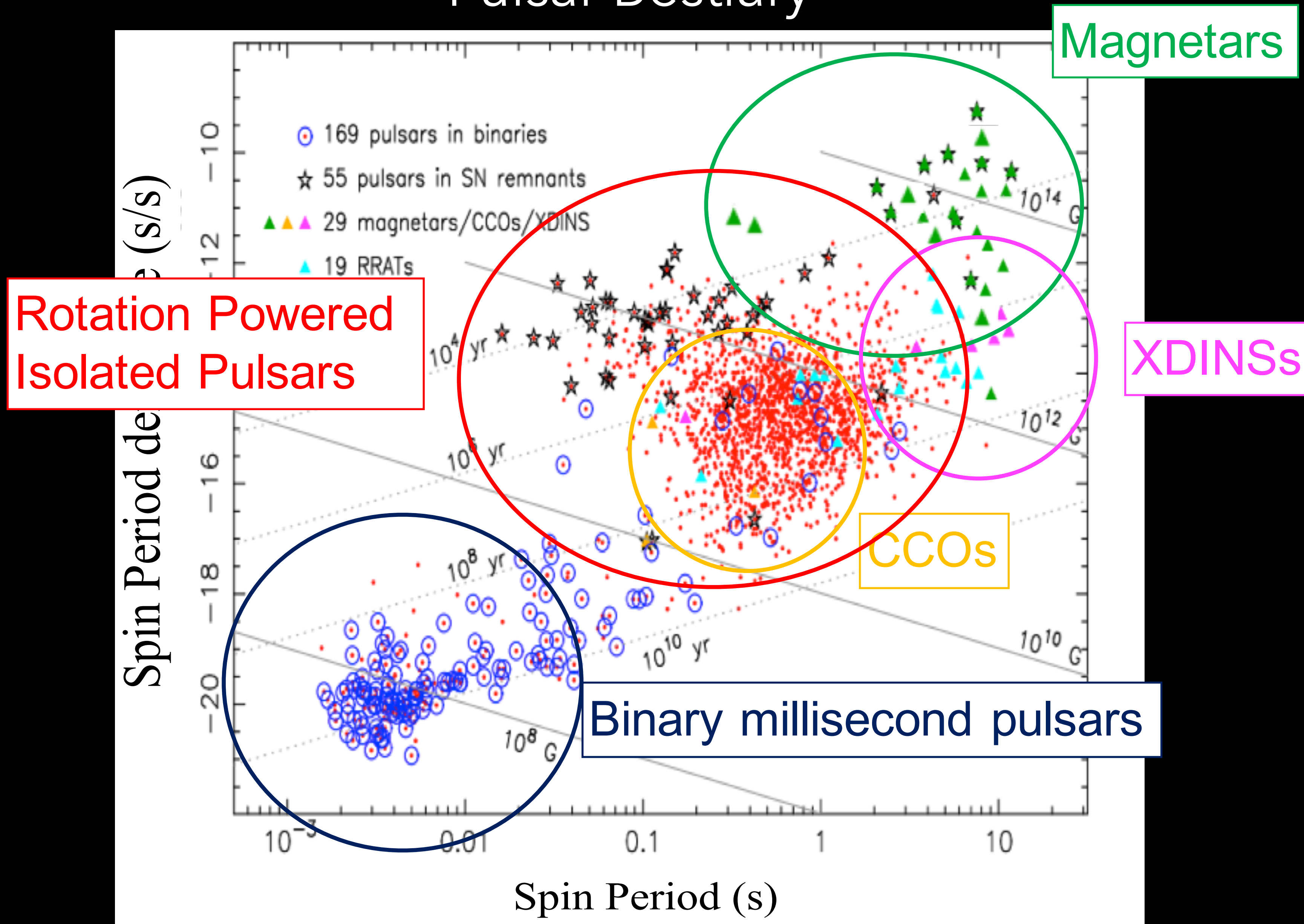
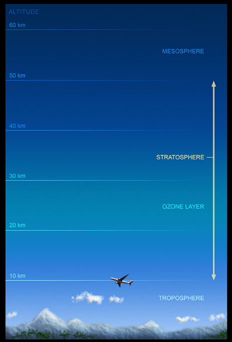
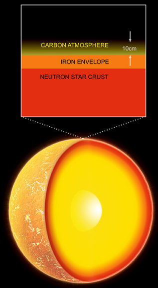


## The most dense rigid body known to date:

As dense as a nucleus, with a central pressure 10000000000000000000000000000 times the atmospheric pressure on Earth.



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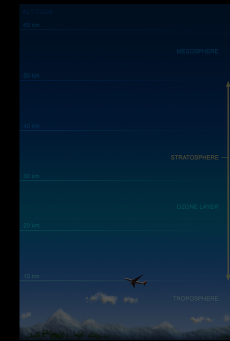
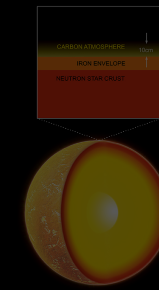
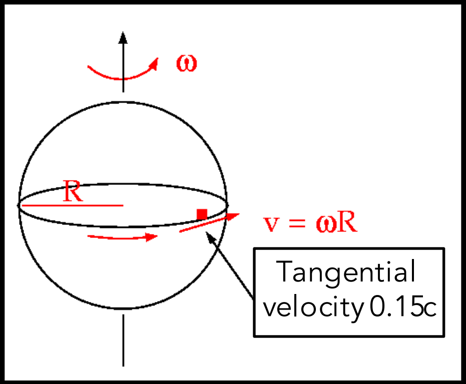




The fastest known rotating body in the Universe:
1.3959546744700354+/-0.0000000000000003ms



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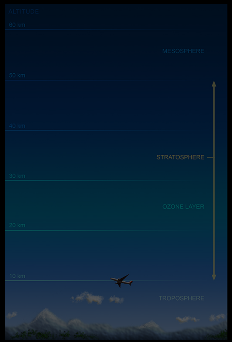

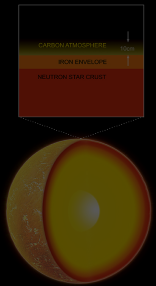

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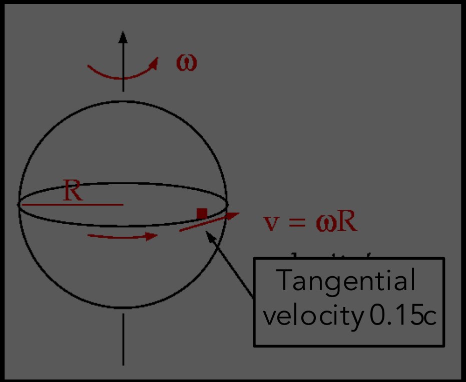
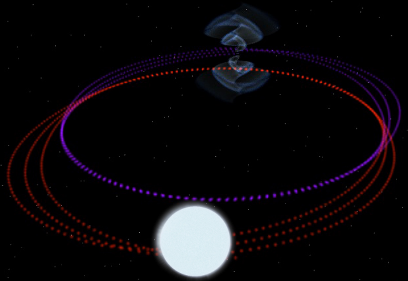
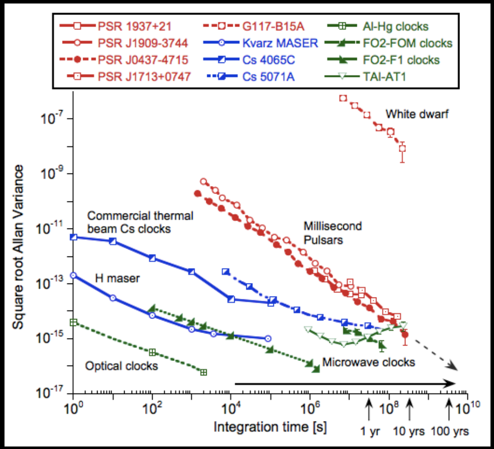



## The roundest known circle in the Universe:

Is the orbit of a pulsar around a normal star: PSR J1909-3744’s orbit it is round to 5micron (1/10 of a human hair) to 567000km.



The most stable clocks in the Universe:
Pulsar arrivals are so precise and stable that beats atomic and quantum optical clocks.



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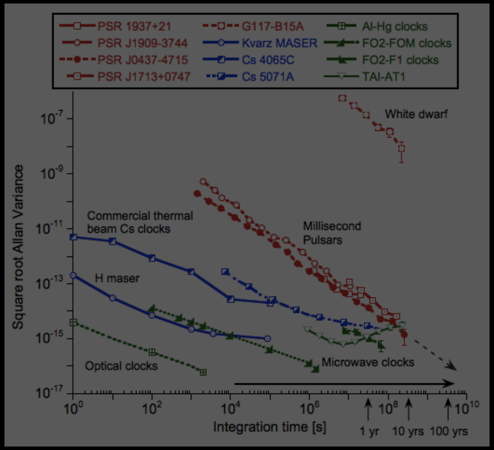
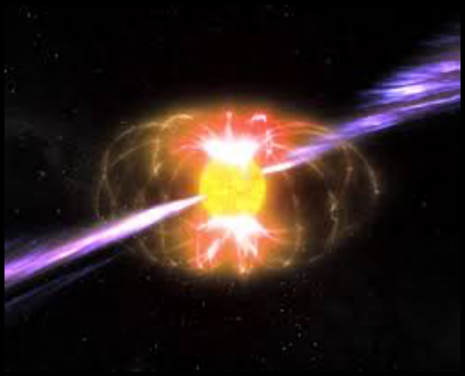



## The most magnetic objects in the Universe:

The magnetar: SGR 1806-20 has a magnetic field is 100000000 times larger than the highest B-field we can reproduce on Earth.



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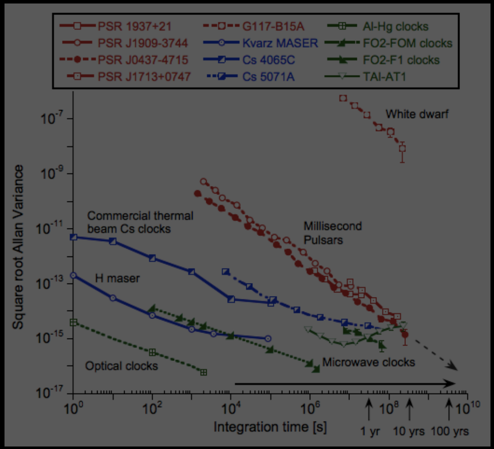


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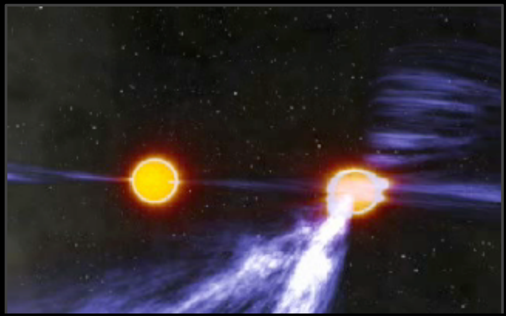
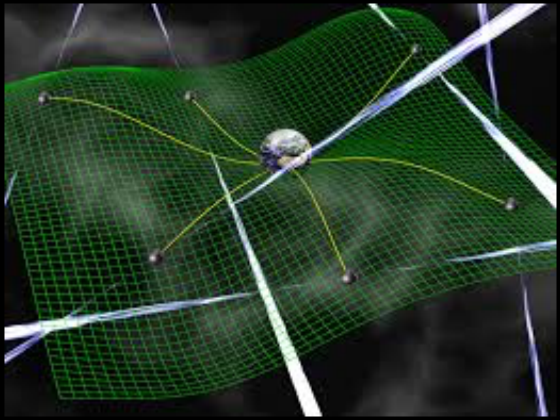
## The most precise tests of General Relativity:

Binary pulsar systems holds the Guiness for having tested GR at 0.05% confidence level. Einstein is right so far…



The least expensive Gravitation Waves detector:
Observing regularly millisecond pulsars we might detect GWs (International Pulsar Timing Array).



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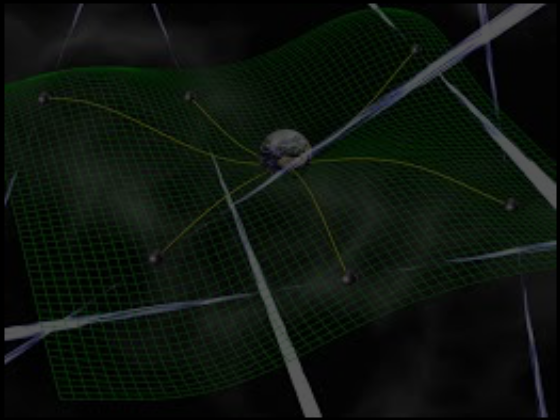
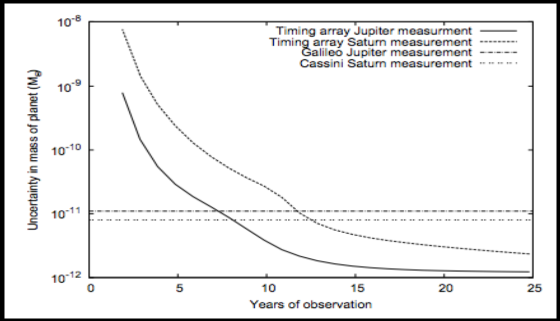


## The least expensive Solar System planet mass determination:

Observing pulsars systematically planet masses are measured as precisely as dedicated satellites.



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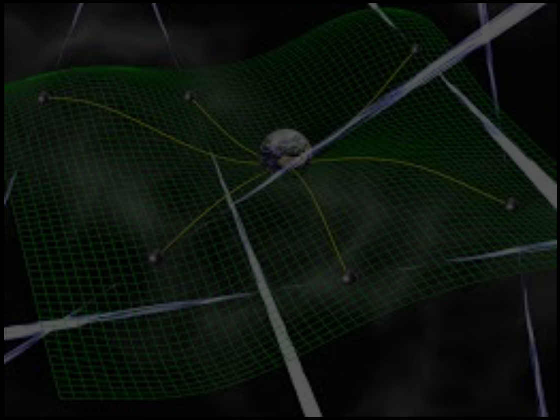

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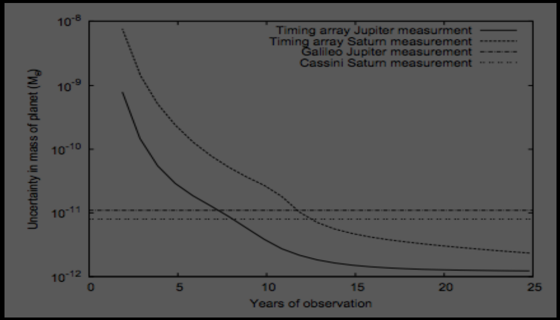
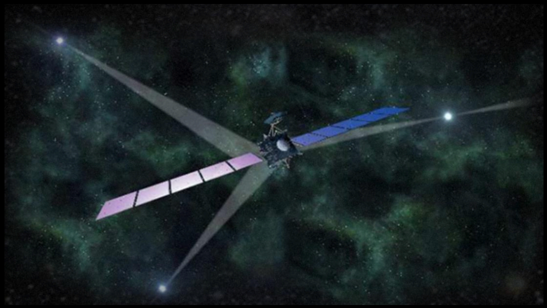



## Our future GPS in space:

Pulsar clocks are so precise that will be our unique GPS system when travelling in space with no connection with Earth.



# Pulsar Timing Technique

# The great potential of pulsar timing

1) Pulsar periods can be measured with extraordinary precision:

e.g. PSR J0437-4715 has a period of :

0.005757451924362 38 ± 0.000000000000000005 s

$\boxed{\text{17 significant digits!}}$

2) Exploiting an event which repeats a huge number of times in a reasonable time-span $T_{obs}$

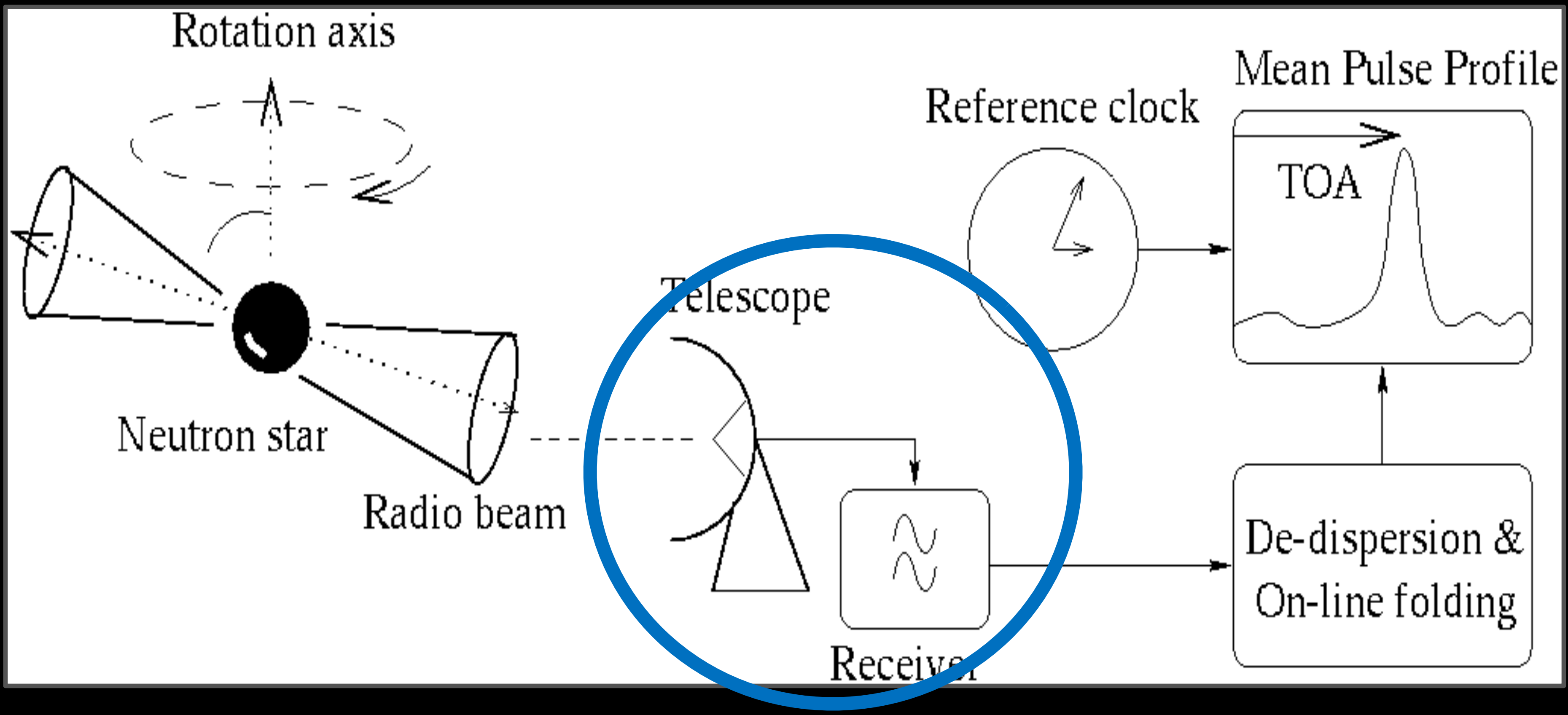
a 3-ms pulsar performs $T_{obs}/P_{spin} \sim 10^{10}$ cycles a year

by coherently counting all of them, one gets an accuracy after 1 YEAR of obs

$$\Delta P_{error}/P_{spin} = \Delta t_{error}/\ T_{obs} = 0.01\ P_{spin} / T_{obs} = 10^{-12}$$

3) Rotational stability of some pulsars is comparable to the best artificial clocks

# The great potential of pulsar timing



# Acquisition of the pulsar time series


digitization @ 1 or 2 or 4 or 8 or 16 bits

07346100374221775320153201532110233030367162

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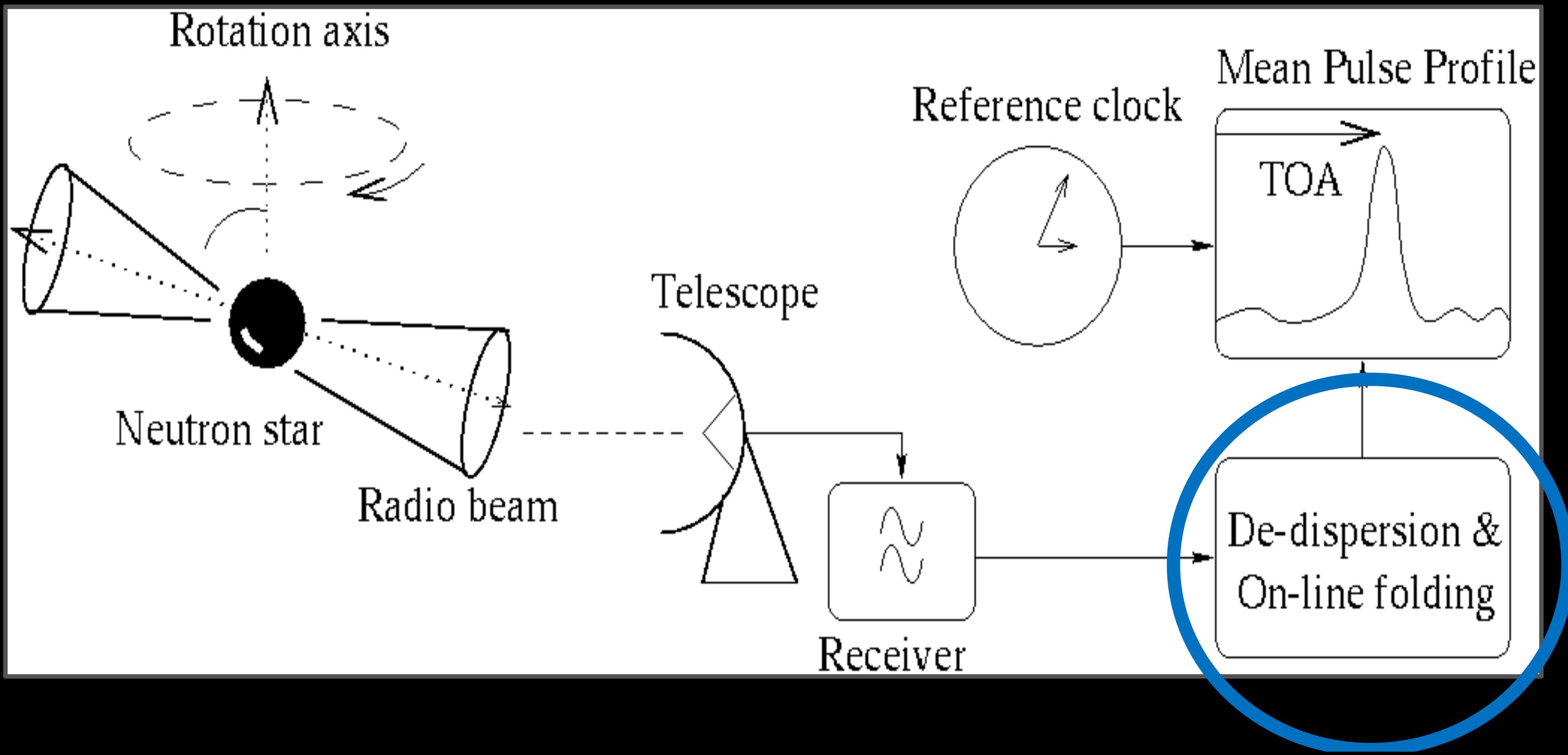
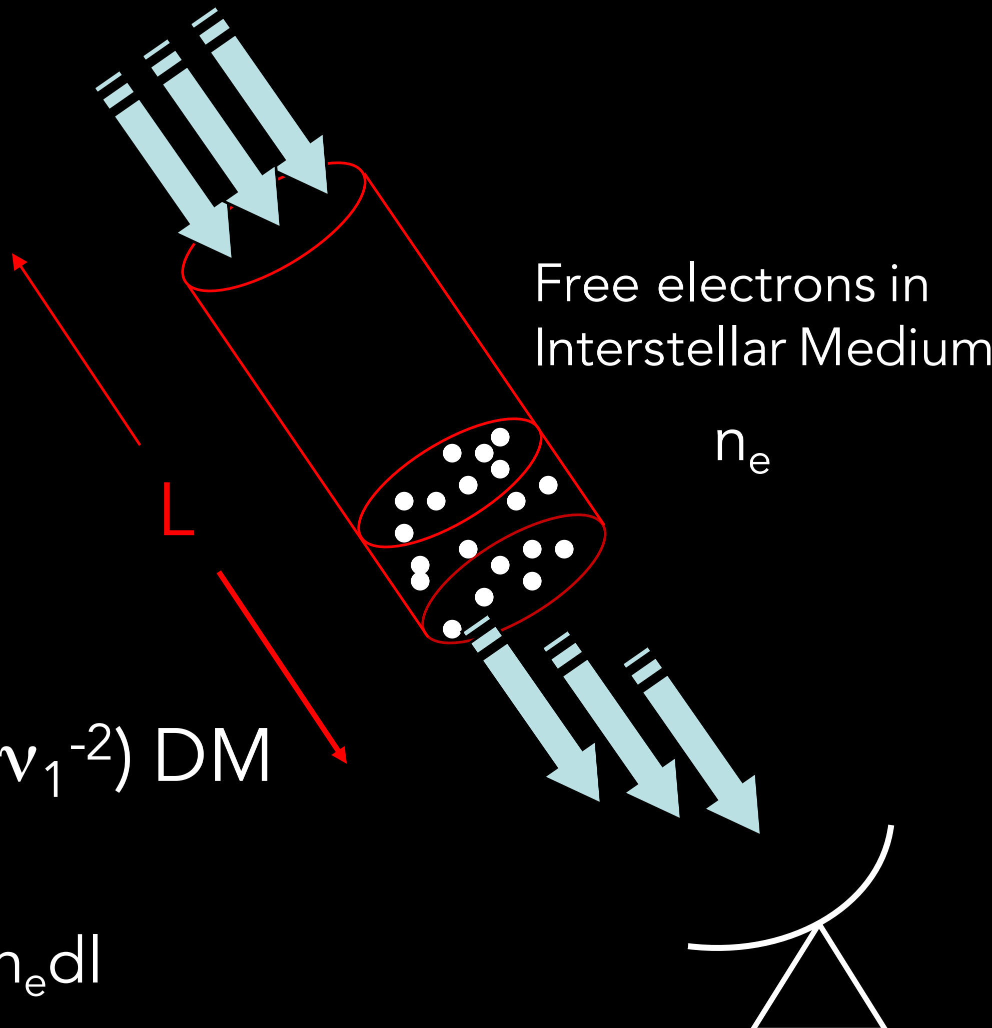
# The great potential of pulsar timing



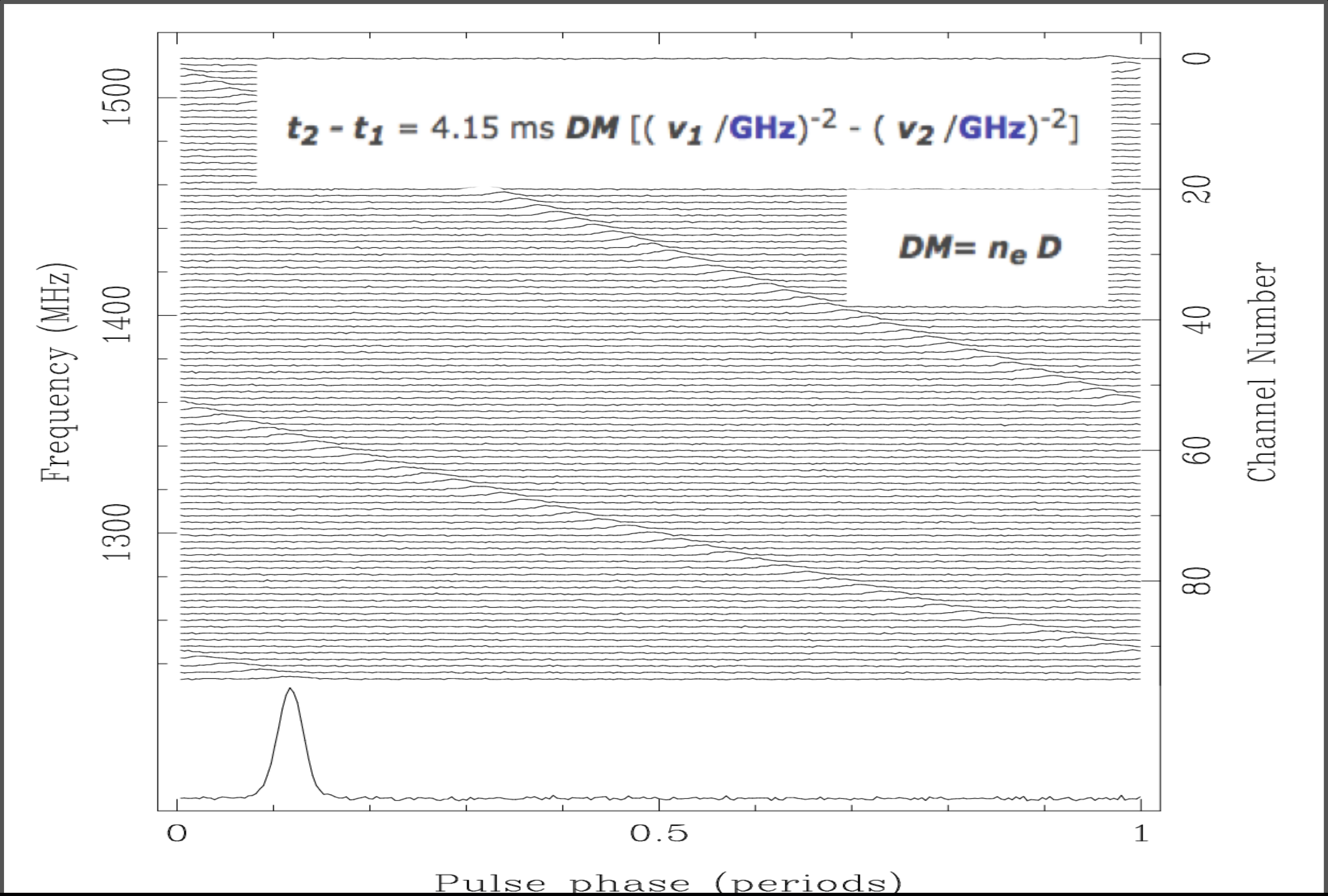
# Dispersion of the radio waves due to scattering




$$t_2 - t_1 \propto (\nu_2^{-2} - \nu_1^{-2})\ \mathrm{DM}$$

$$\mathrm{DM} = \int_0^L n_e \, dl$$

# De-dispersion of the pulsar time series



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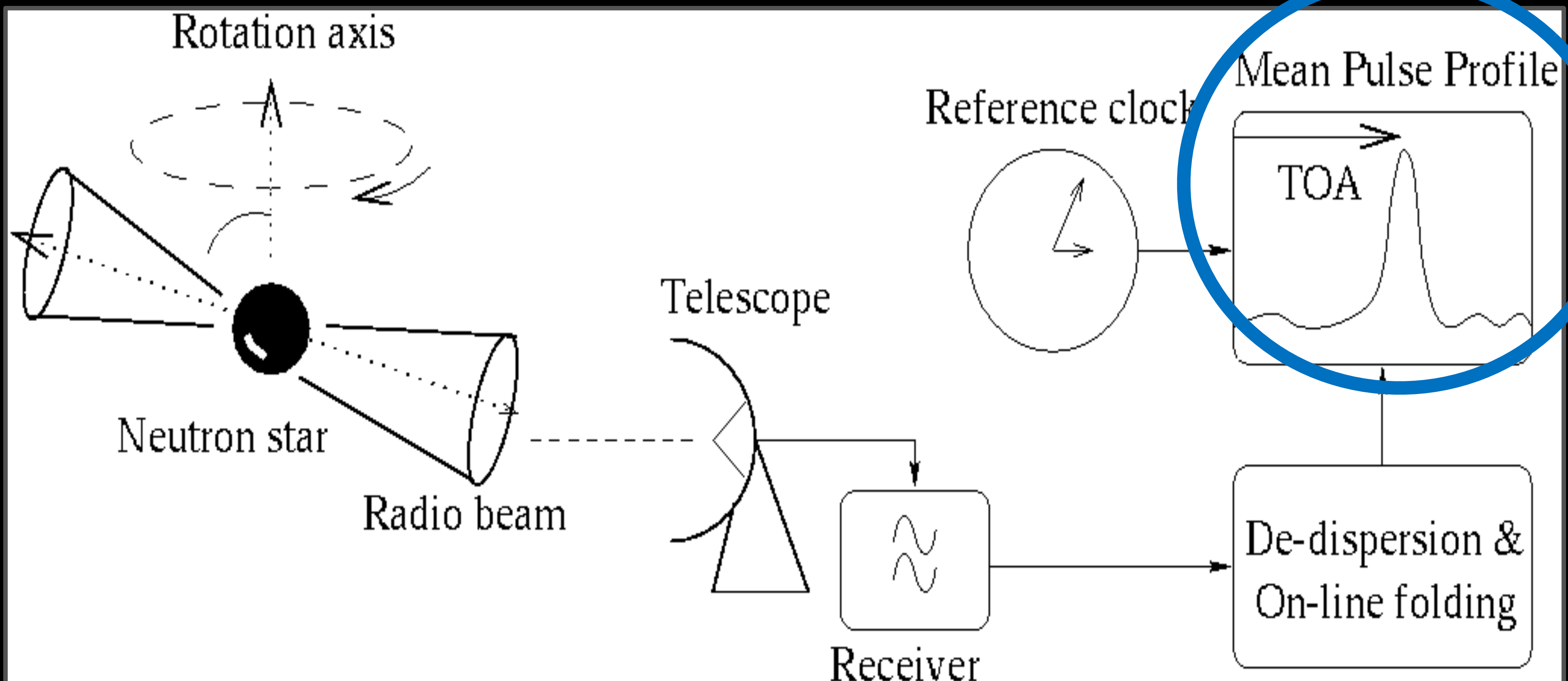
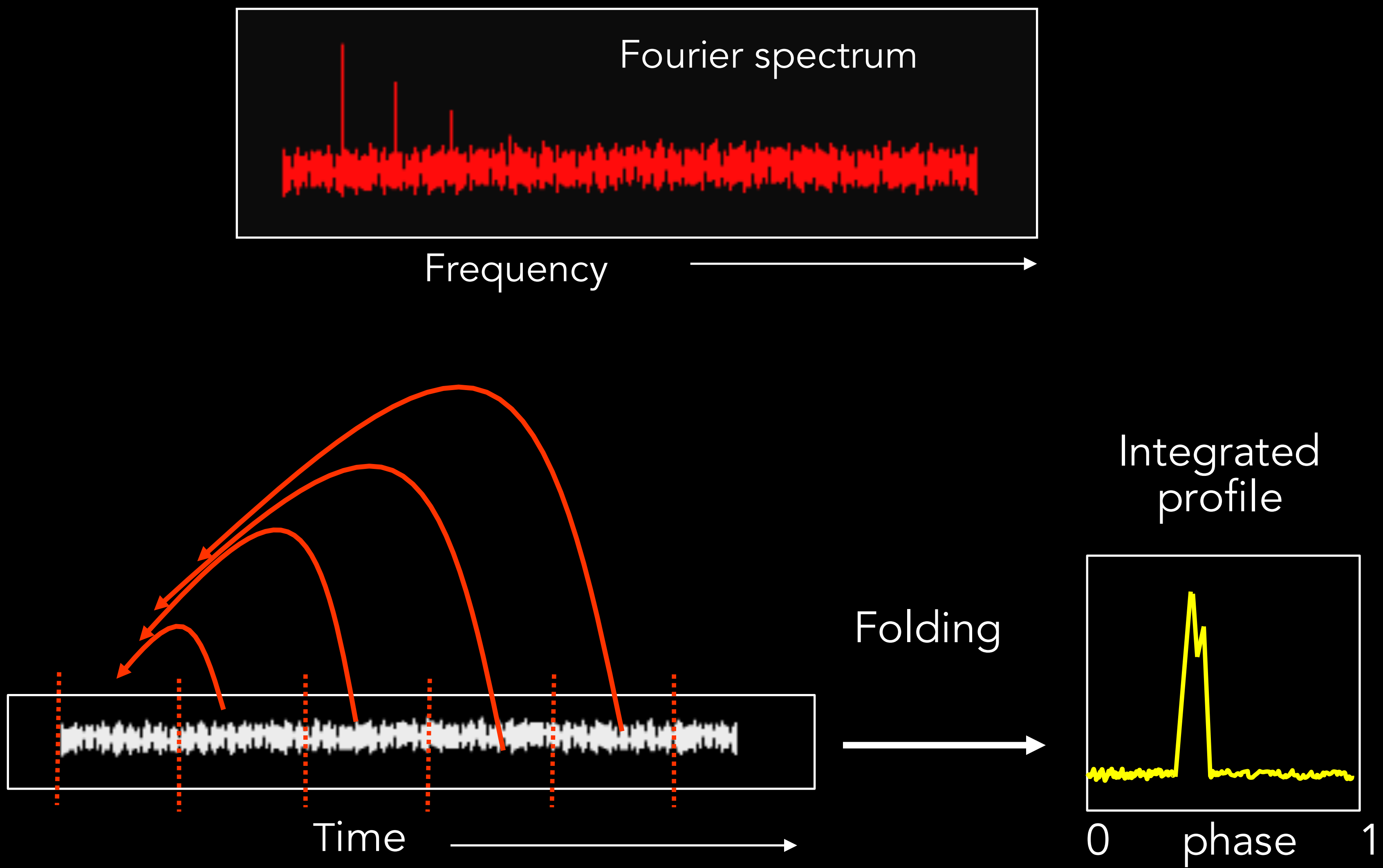
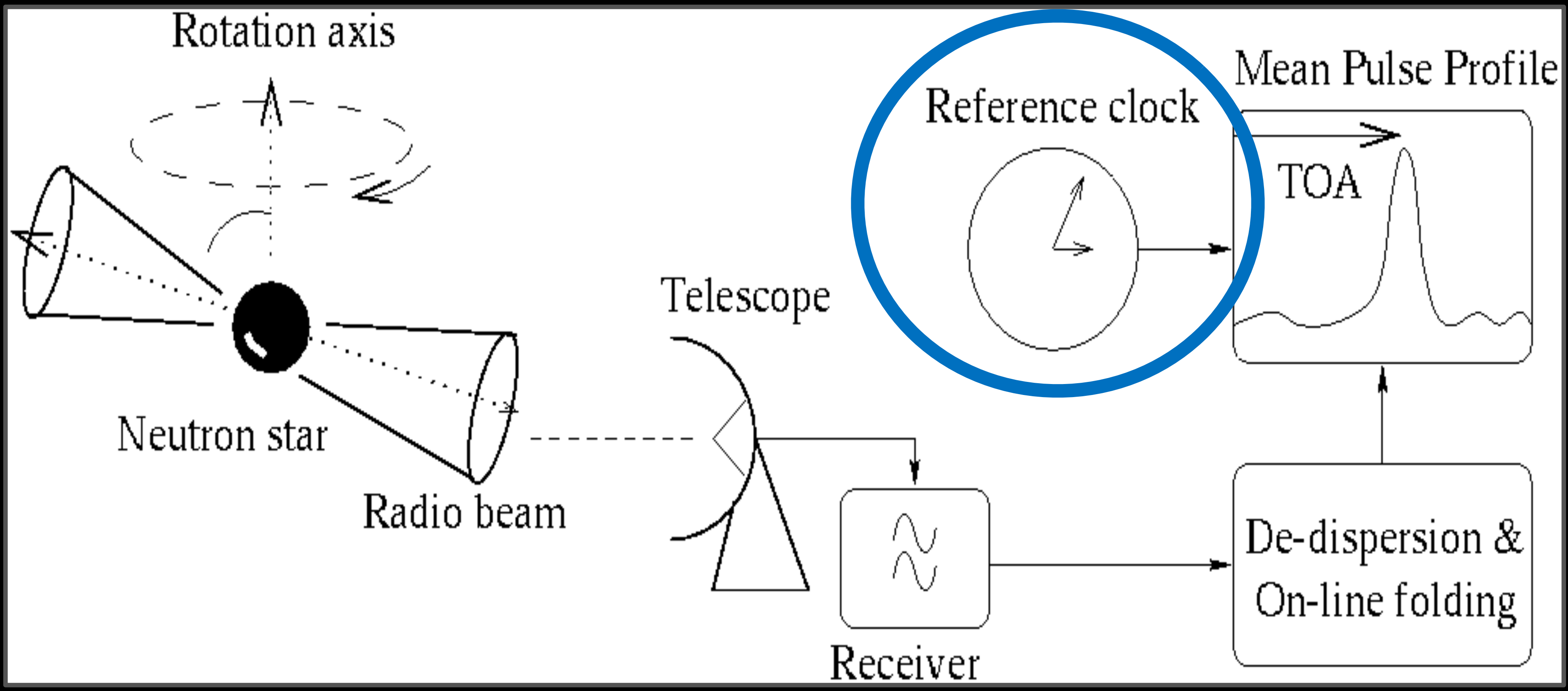


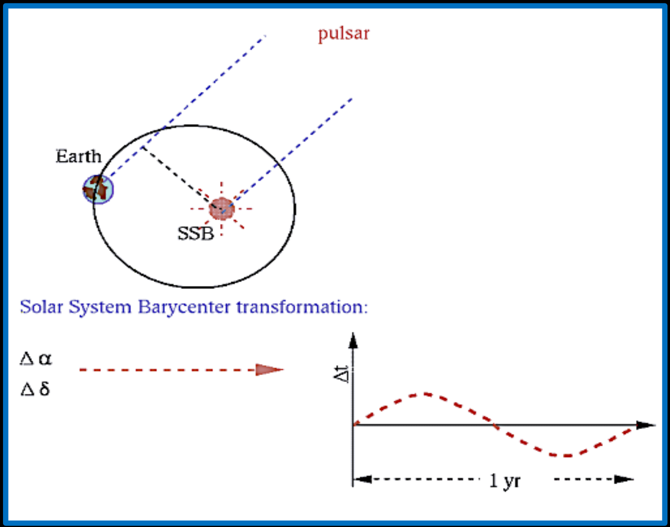
# Period search and folding of the pulsar time series



# The great potential of pulsar timing



# Pulsar times should be reported to a stable reference clock: the Solar System Barycenter (SSB)




- $t_{SSB}$ : Time calculated at the Solar System Barycenter
- $t_{obs}$ : Time measure at the Radio Antenna
- $t_{clk}$ : Observatory clock correction, usually via GPS
- $D/f^2$ : Dispersion Measure term
- $\Delta_R$ : Roemer delay (propagation) to SSB
- $\Delta_S$ : Shapiro delay in Solar-System
- $\Delta_E$ : Einstein delay at Earth

$$t_{\rm SSB} = t_{\rm obs} + t_{\rm clk} - D/f^2 + \Delta_R + \Delta_S + \Delta_E$$

# Pulsar times should be reported to a stable reference clock: the Solar System Barycenter (SSB)

$$t_{\mathrm{SSB}} = t_{\mathrm{obs}} + t_{\mathrm{clk}} - D/f^2 + \Delta_R + \Delta_S + \Delta_E$$

$$D / f^2 = [\,\mathrm{DM} \;/\; (2.41 \cdot 10^{-16})\ \mathrm{s}\,] / f^2$$

Dispersion measure correction

$$\Delta_R = \frac{(\vec{r} \cdot \vec{n})}{c} + \frac{(\vec{r} \cdot \vec{n})^2 - |\vec{r}|^2}{2\,c\,d}$$

Earth path around the Sun wit h respect to the pulsar

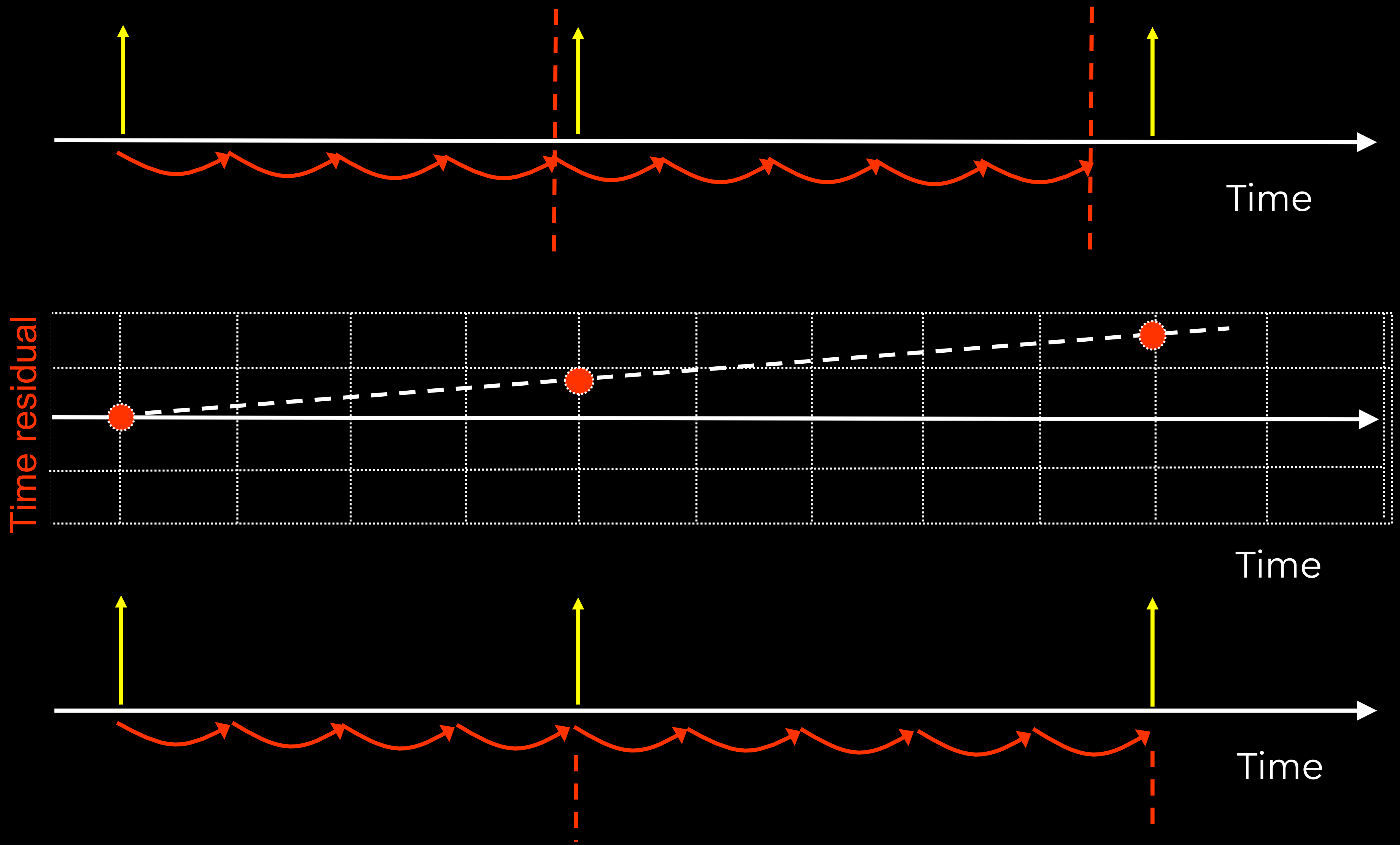
$$\Delta_S = -\,2\,T_{\mathrm{sun}}\ \log_{10}(1 + \cos\theta)$$

Solar gravitational dwell changes wave paths.

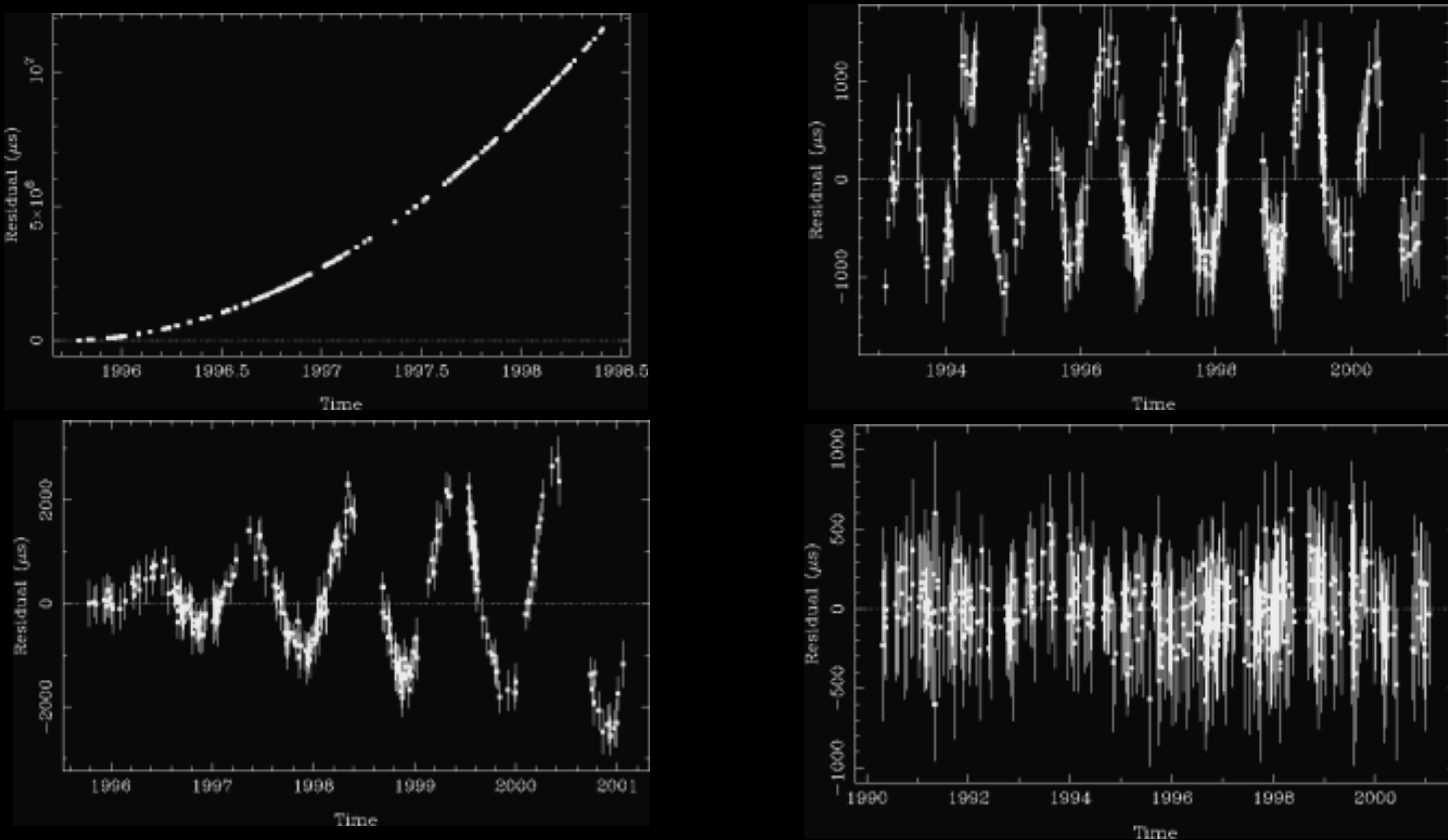
$$\frac{d\Delta_E}{dt} = \Sigma_i \left(\frac{G\,m_i}{c^2\,r_i}\right) + \frac{(v_{\mathrm{Earth\text{-}SSB}})^2}{2c^2}$$

Gravity of other planets.
This is where we can measure planet masses.

# Pulsar Timing modelling can now start…



# Pulsar Timing modelling can now start…




- Spin parameters: period, first derivative, second derivative…
- Astrometric parameters: position, proper motion, parallax

# Pulsar Sound

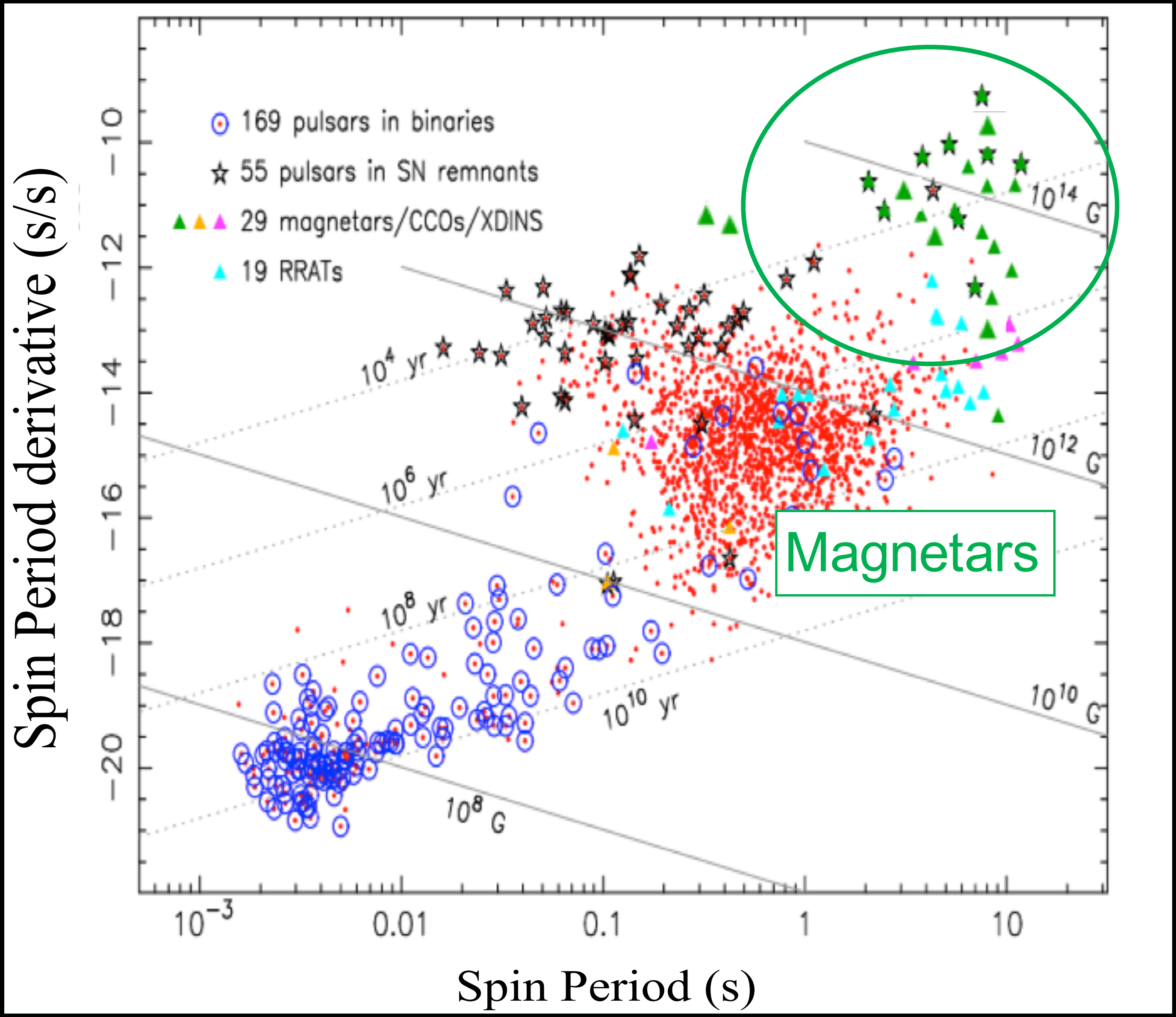
PSR B0833-45 (Vela Pulsar): rotating with a period of 89 millisec onds or about 11 times a second

PSR B0531+21(Crab Pulsar): rotating with a period of 33 millisec onds or about 30 times a second

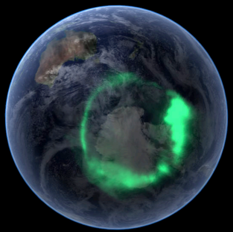
PSR J0437-4715: binary system with a pulsar rotating about 174 times a second

PSR B1937+21 (the F flat pulsar): rotating at 0.0015578064487275 seconds, or about 642 times a second

# Pulsar Bestiary



# Magnetars



1 G – The Earth magnetic field measured at the North pole

100 G – A common hand-held magnet like used to stick papers on a refrigerator

$10^4$ G – The magnetic field used for an MRI in the hospitals

$10^7$ G – The strongest man-made field ever achieved, made using focussed explosive charges, lasting only 4-8 s

$10^{12}$ G – Typical neutron star magnetic fields

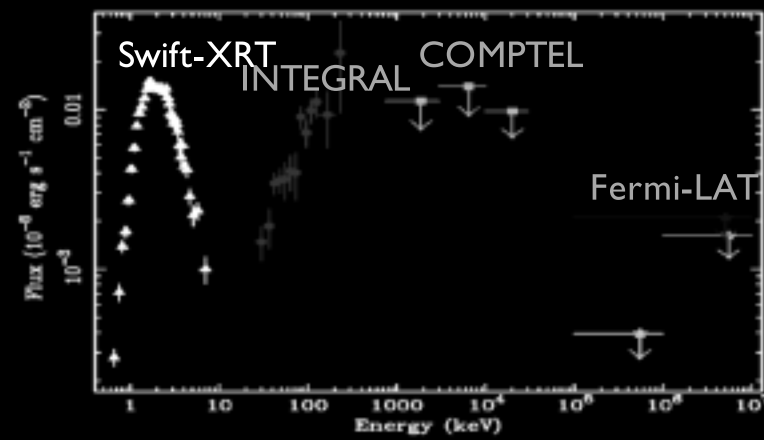
$4.4 \times 10^{13}$ G – Electron critical magnetic field

$10^{14}$-$10^{15}$ G: Magnetars overtake this limit…

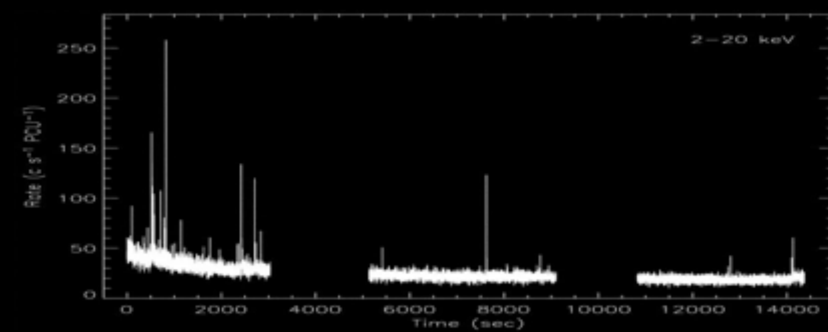
# Magnetars

- About 25 X-ray pulsars with $L_X \sim 10^{33}$-$10^{36}$ erg s$^{-1}$
- X-ray luminosity generally larger than the rotational energy loss rate
- soft and hard X-ray emission (0.5-200 keV); thermal + non-thermal spectrum
- persistent or transients
- rotating with $P \sim 0.3$-$12$ s
- magnetic fields of $B \sim 10^{13}$-$10^{15}$ Gauss
- flaring activity in soft gamma-rays ($0.01$-$10^{2}$ s; $L_X \sim 10^{39}$-$10^{47}$ erg s$^{-1}$)
- faint infrared/optical emission
- transient radio emission (in 4 cases)

Abdo et al. 2010

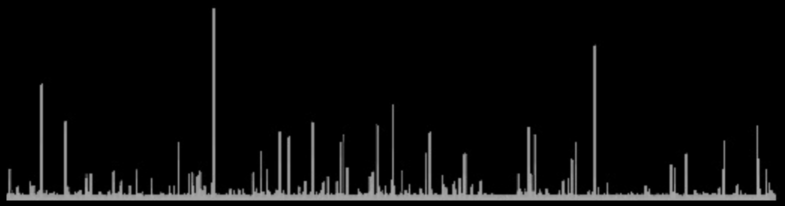



Kaspi et al. 2003



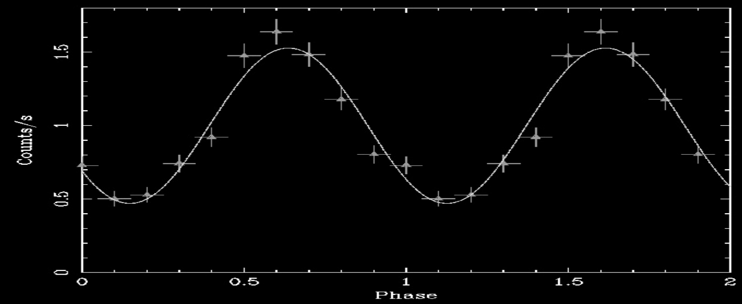
# How do we discover new magnetars?

Short X/gamma-ray bursts (at the beginning thought to be GRBs)



Soft Gamma Repeaters

Bright X-ray pulsars with 0.5-10keV spectra modelled by a thermal plus a non-thermal component



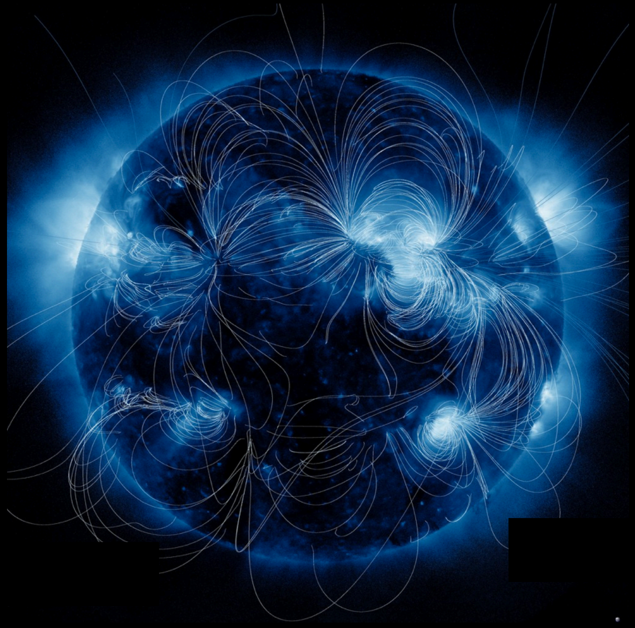

Anomalous X-ray Pulsars

Bright X-ray transients!

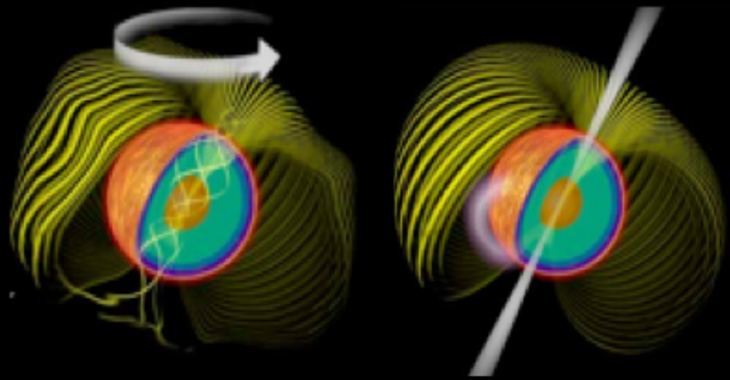
Transients magnetars

# Magnetars

- magnetars have highly twisted and complex magnetic field morphologies, both inside and outside the star.
- magnetar magnetospheres are filled by charged particles trapped in the twisted field lines, interacting with the surface thermal emission through resonant cyclotron scattering.
- twisted magnetic fields might locally (or globally) stress the crust (either from the inside or from the outside). Plastic motions and/or returning currents convert into crustal heating causing large outbursts.

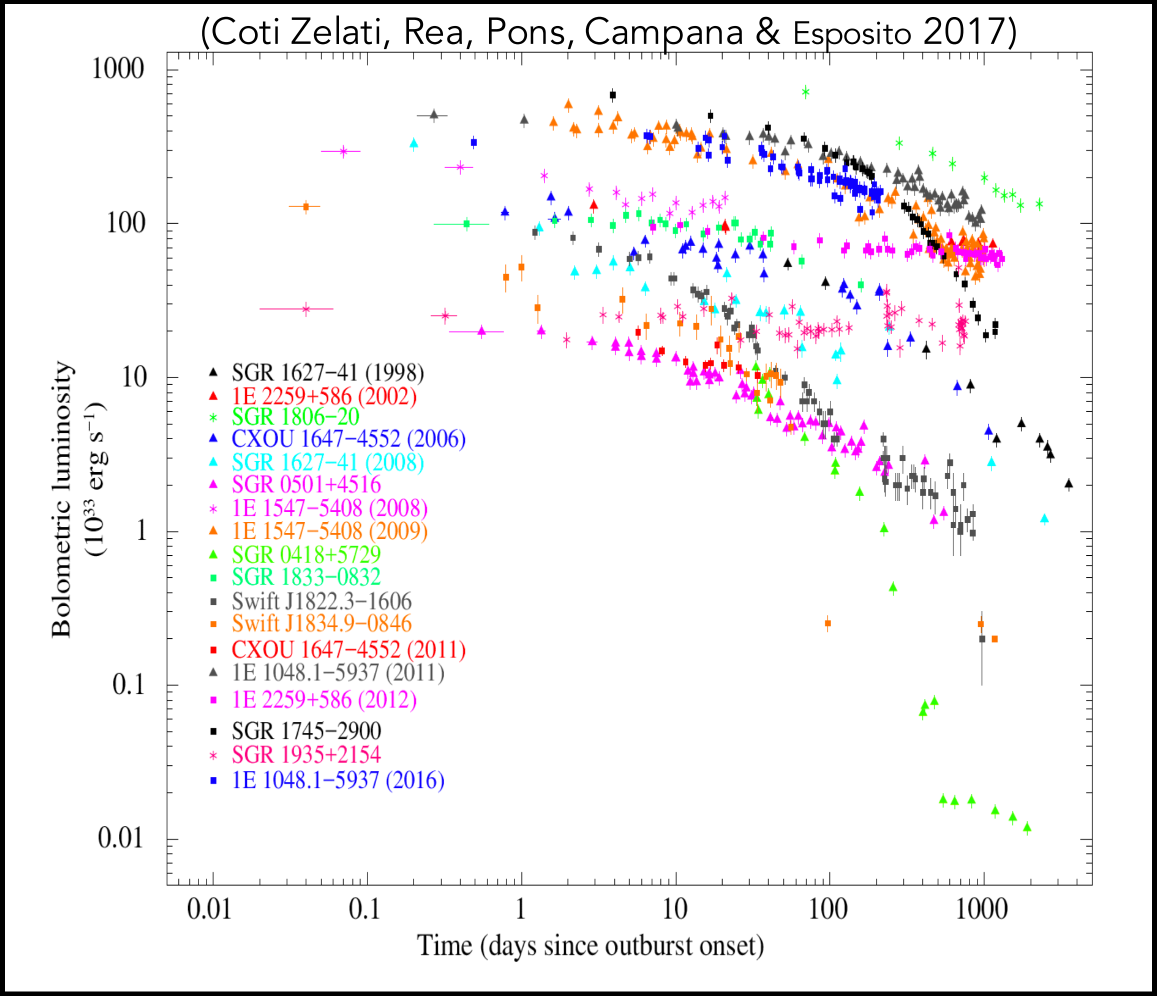


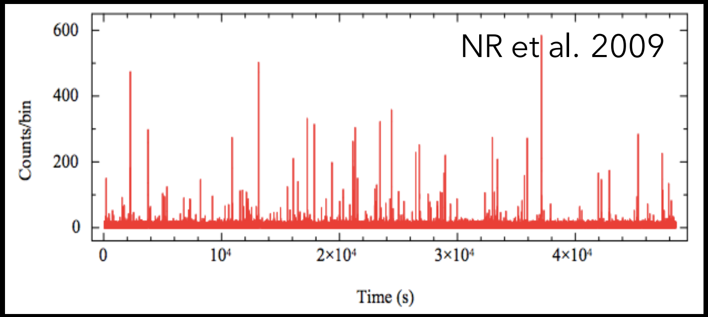
Magnetars Normal Pulsars

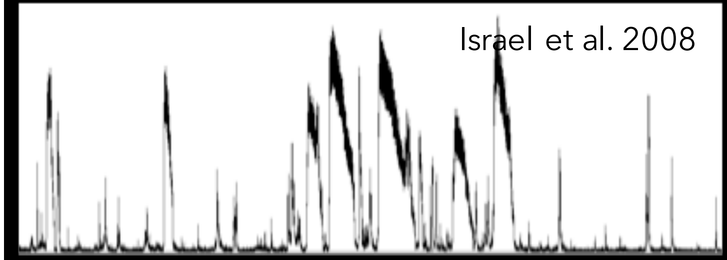


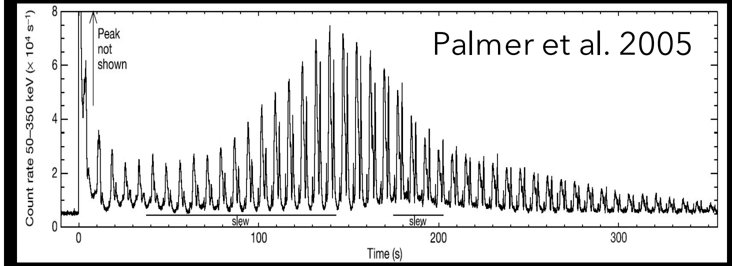
(Rea & Esposito 2011; Kaspi & Beloborodov 2017)

# Magnetars' flaring activity

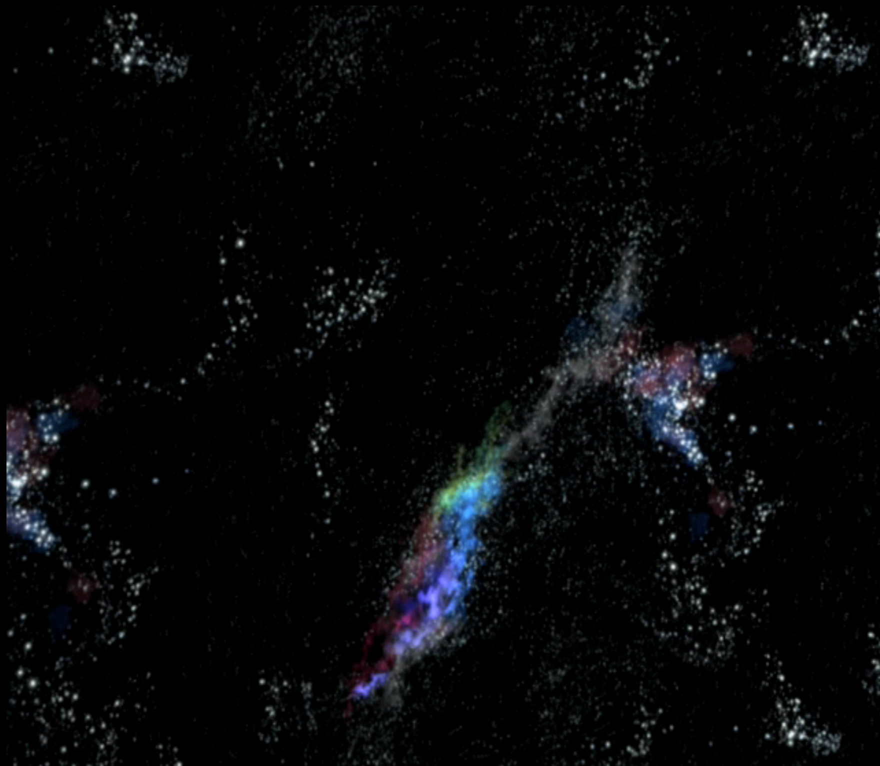


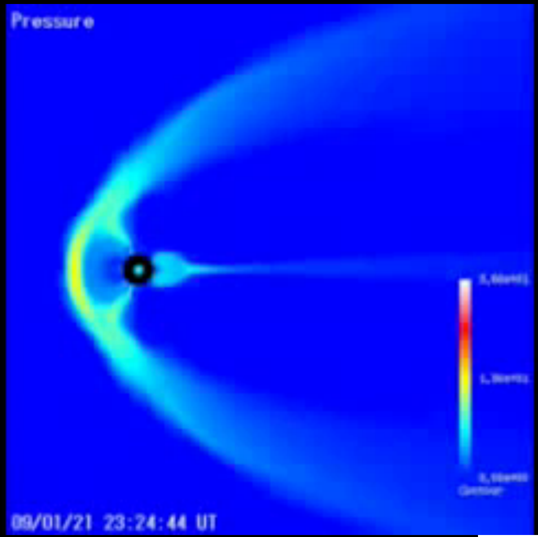



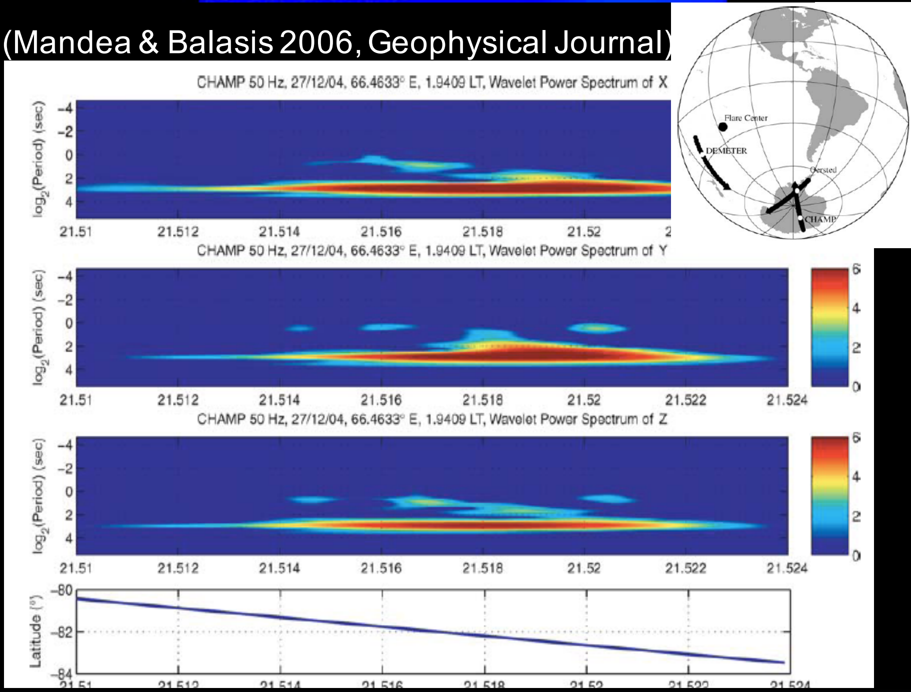



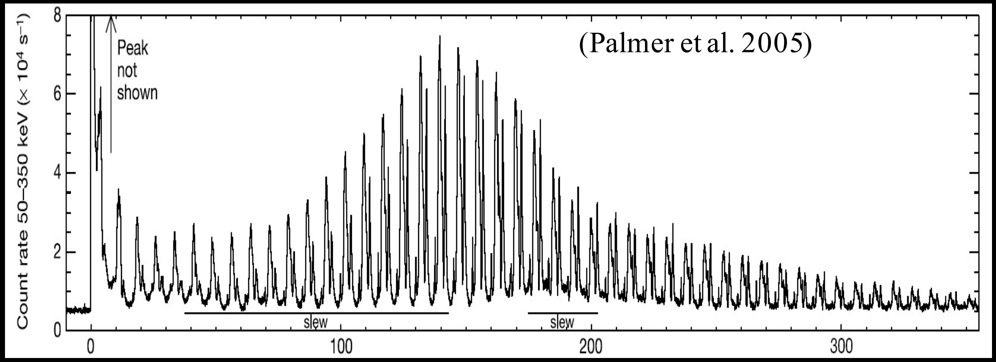
# Magnetar giant flares: the Earth perspective





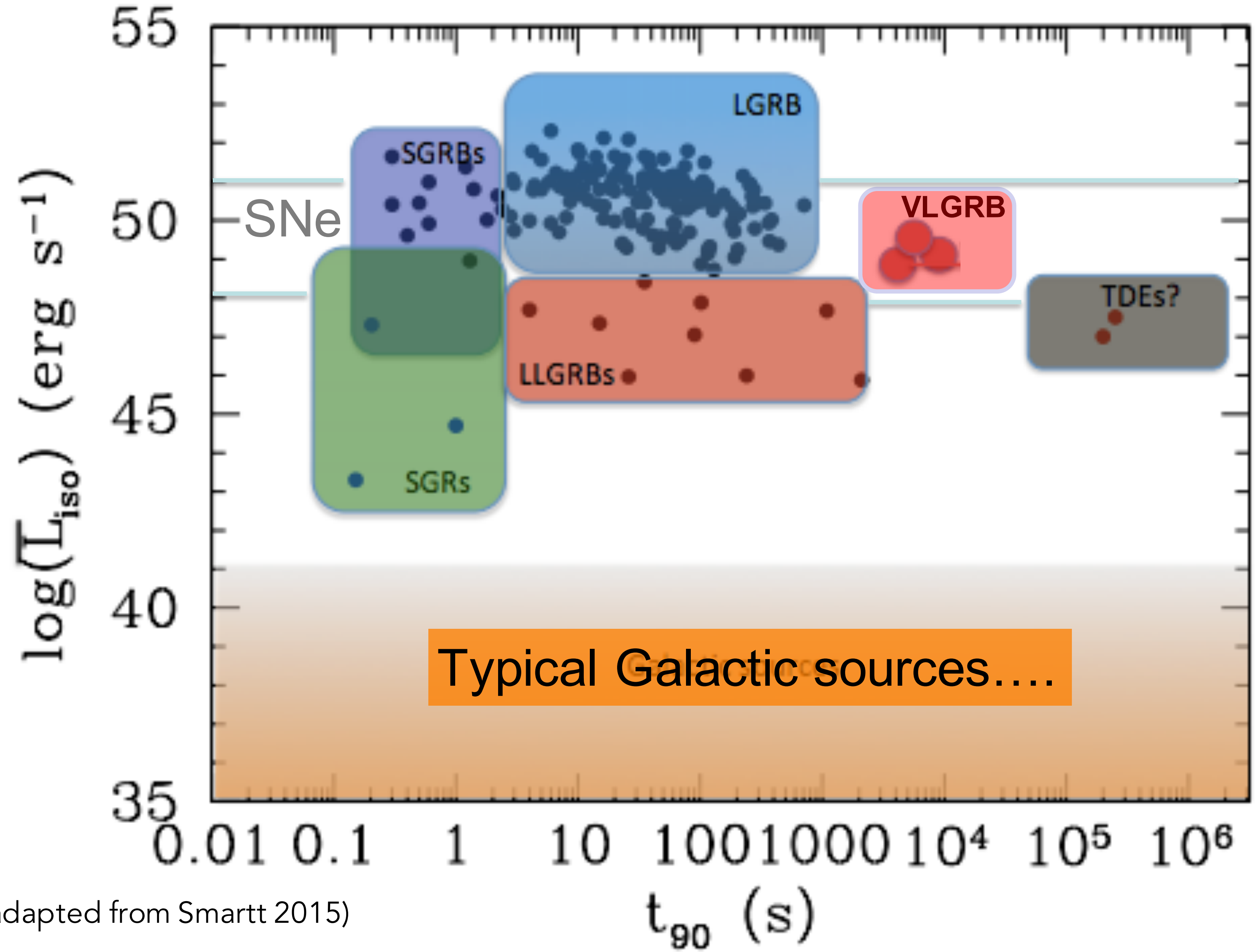

(Mandea & Balasis 2006, Geophysical Journal)



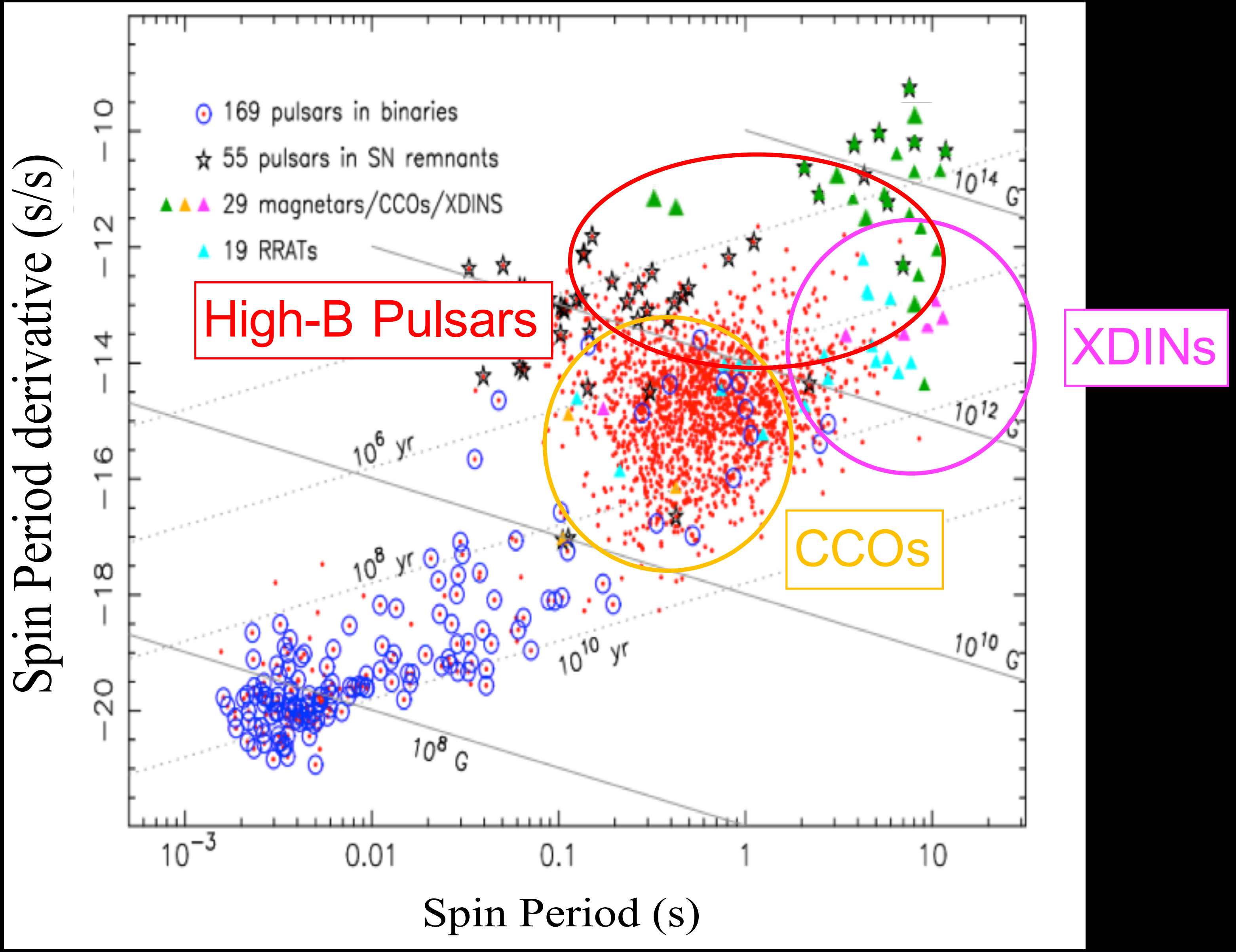

(Palmer et al. 2005)

# Comparison with other energetic transients

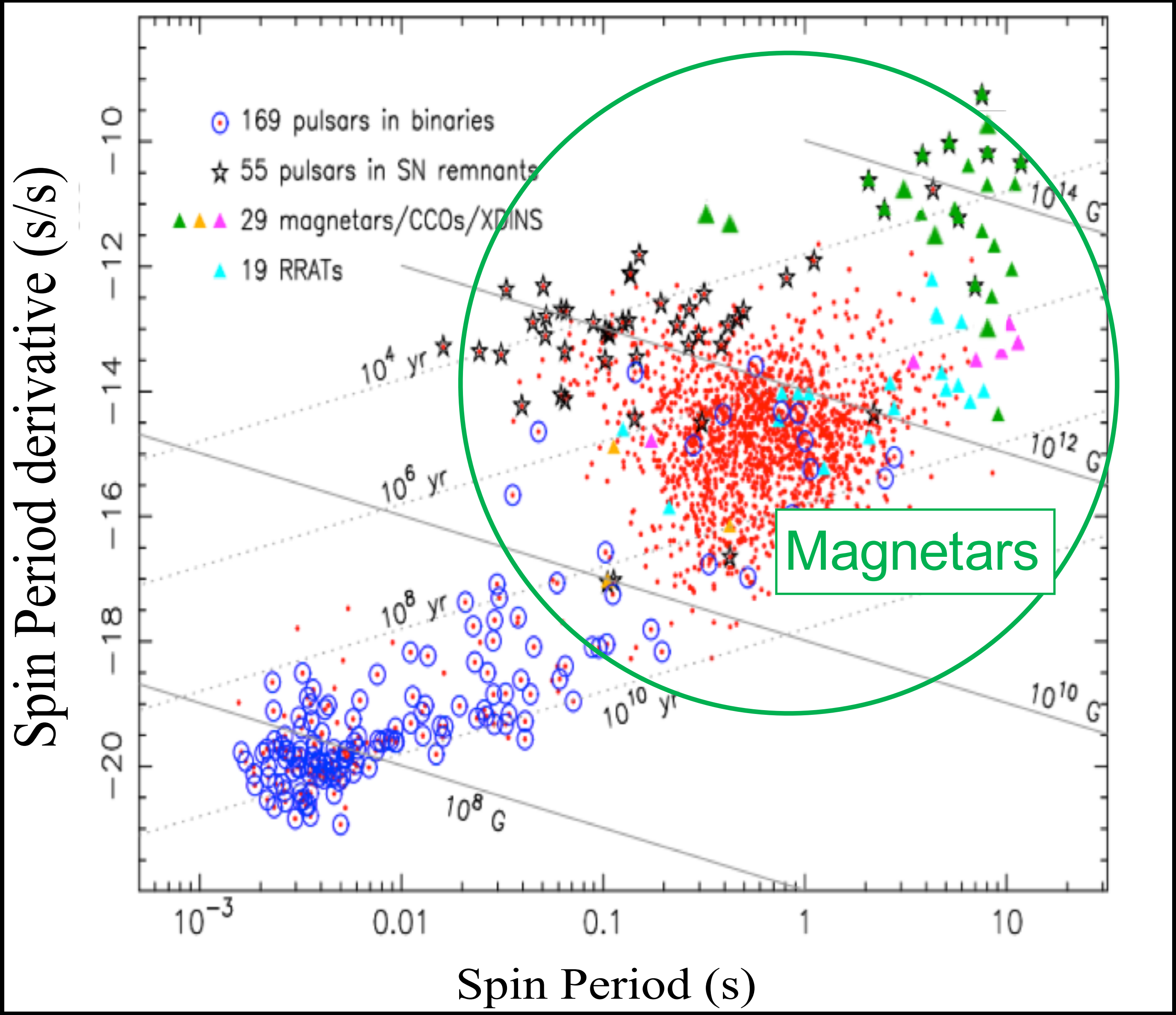



(adapted from Smartt 2015)

# Pulsar Bestiary



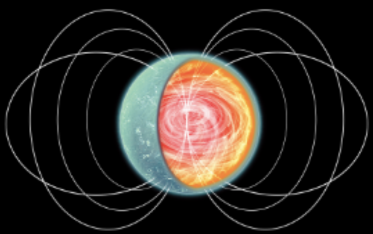
# Pulsar Bestiary



# Other Magnetar-like sources

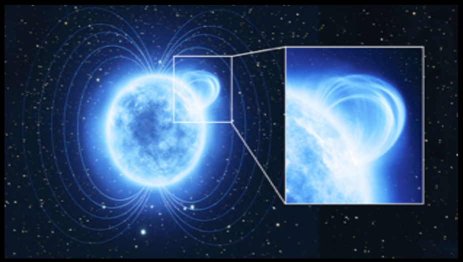
1. Magnetars were discovered having also low dipolar B-fiels and strong magnetic structures.

   (Rea et al. 2010, 2012, 2014, Tiengo et al. 2013)



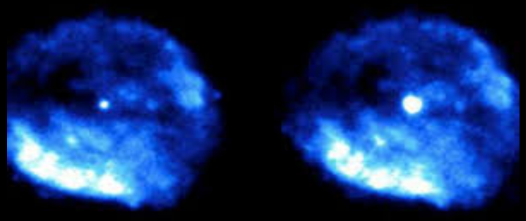
2. Two X-ray Dim Isolated NSs show evidence of strong magnetic structures

   (Borghese et al. 2015, 2017)



3. A central compact object (CCO) with a 6.4hr period showed magnetar-like activity.

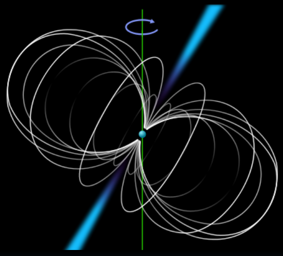
   (Rea et al. 2016; D'Ai et al. 2016)



quiescence outburst

4. Two young rotational powered pulsars showed magnetar activity.

   (Gavriil et al. 2008; Kumar & Safi-Harb, 2008; Archibald et al. 2016, Gogus et al. 2016)



# Magnetic field evolution in neutron stars

We need to solve the thermal and magnetic evolution of a neutron star over > Myr timescales…

Thermal evolution: energy balance equation

Specific heat

Thermal conductivity

Neutrino emissivity

$$C_v e^{\Phi(r)} \frac{\partial T}{\partial t} + \vec{\nabla} \cdot (-\hat{\kappa} \cdot \vec{\nabla}(e^{\Phi(r)} T)) = e^{2\Phi(r)} Q$$

Magnetic evolution: Hall induction equation

$$\frac{\partial \boldsymbol{B}}{\partial t} = -\boldsymbol{\nabla} \times \left\{ \eta \boldsymbol{\nabla} \times (e^{\nu} \boldsymbol{B}) + \boxed{\frac{c}{4\pi e n_e}} [\boldsymbol{\nabla} \times (e^{\nu} \boldsymbol{B})] \times \boldsymbol{B} \right\}$$

Hall induction

Electrical resistivity: strongly depends on T

(Aguilera et al. 2008; Pons et al. 2009; Vigano', NR, Pons, Perna, Aguilera & Miralles 2013)

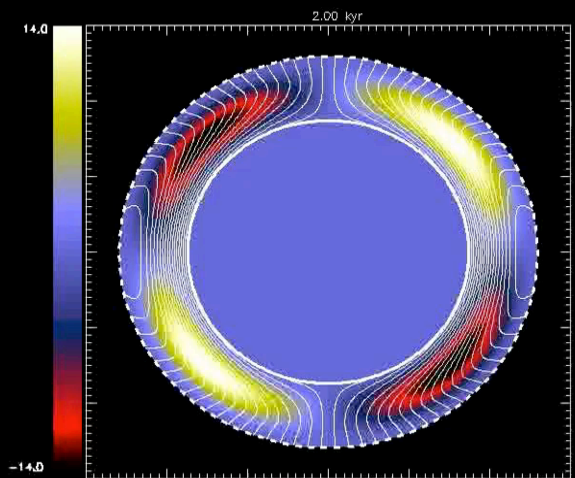
# Strong non-dipolar fields are expected in all NSs

Relatively Magnetic Pulsar

Intial conditions:

$B_{dip}\sim 10^{13}$ G (white lines)

$B_{int}\sim 10^{14}$ G (colors)

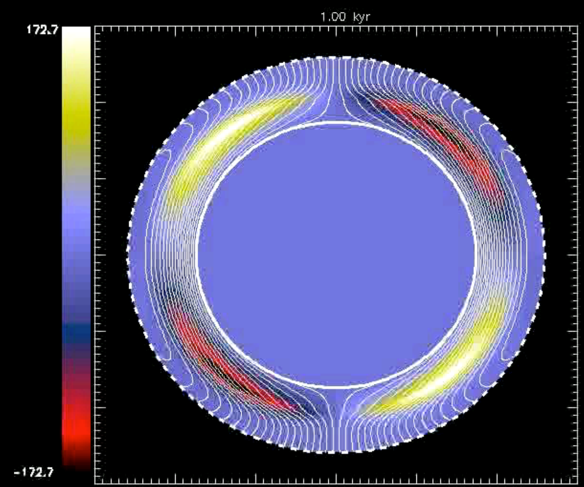



Very Magnetic Pulsar

Initial conditions:

$B_{dip}\sim 10^{14}$ G (white lines)

$B_{int}\sim 10^{15}$ G (colors)

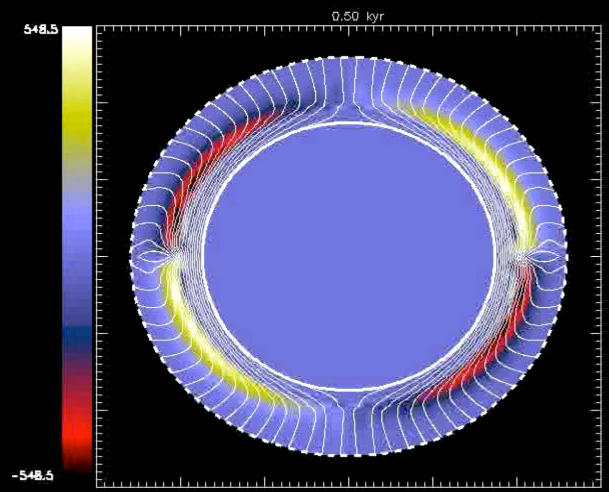



Extremely Magnetic Pulsar

Intial conditions:

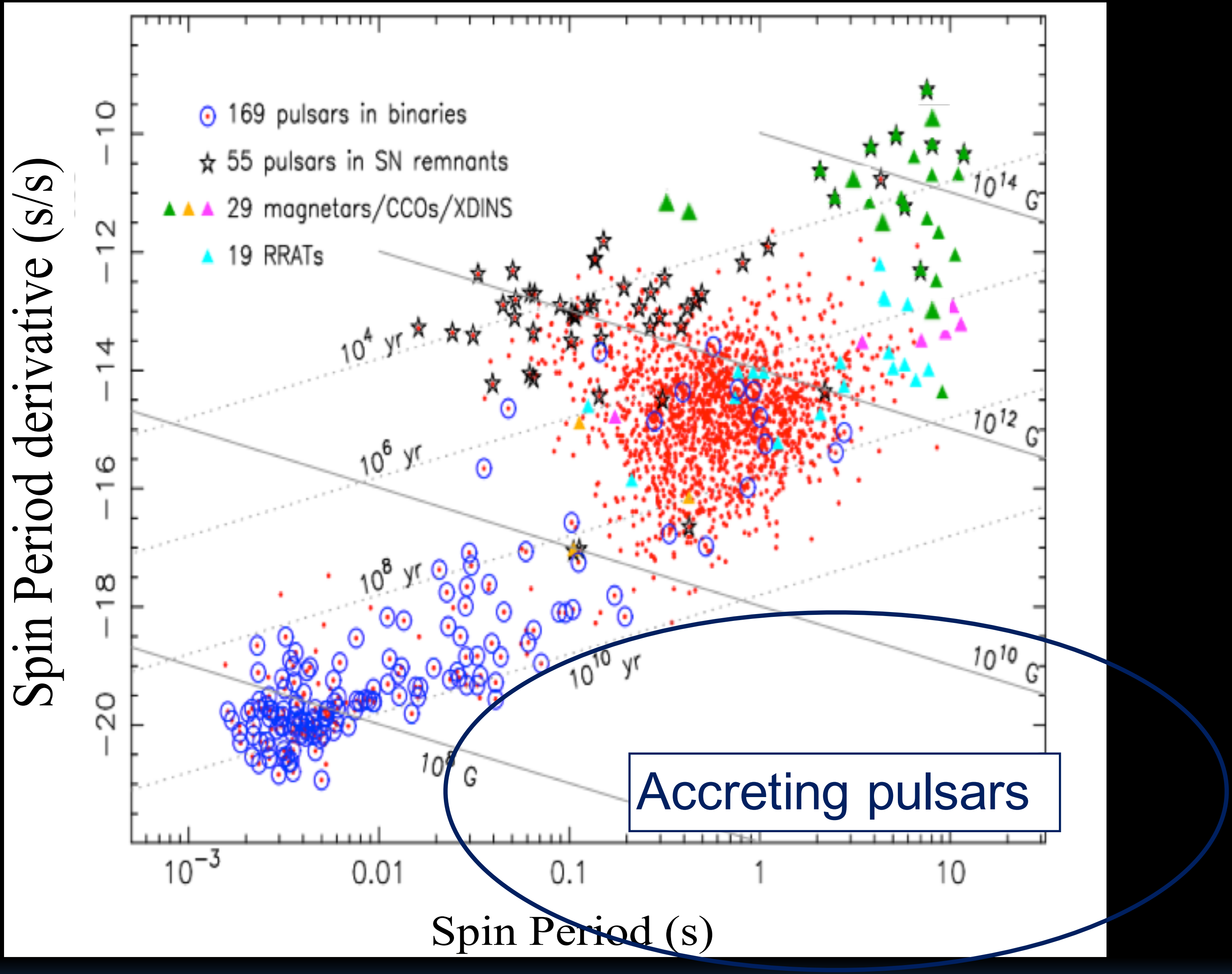
$B_{dip}\sim 10^{15}$ G (white lines)

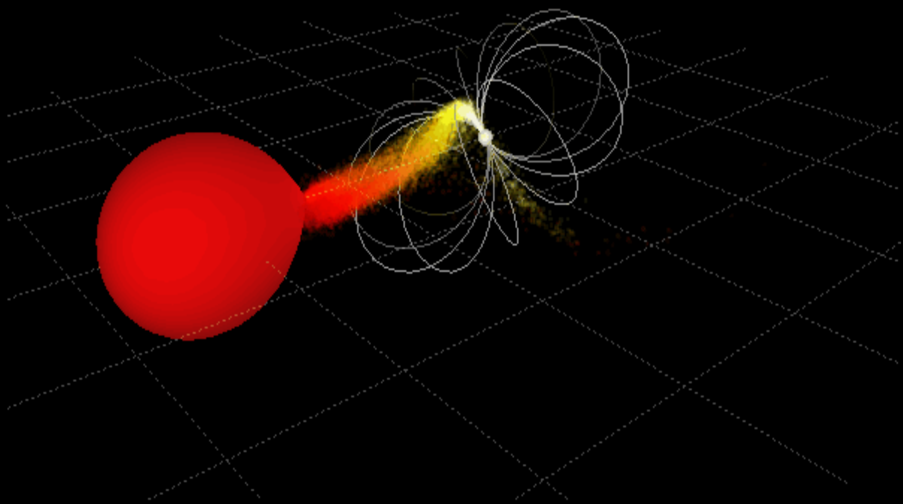
$B_{int}\sim 10^{16}$ G (colors)



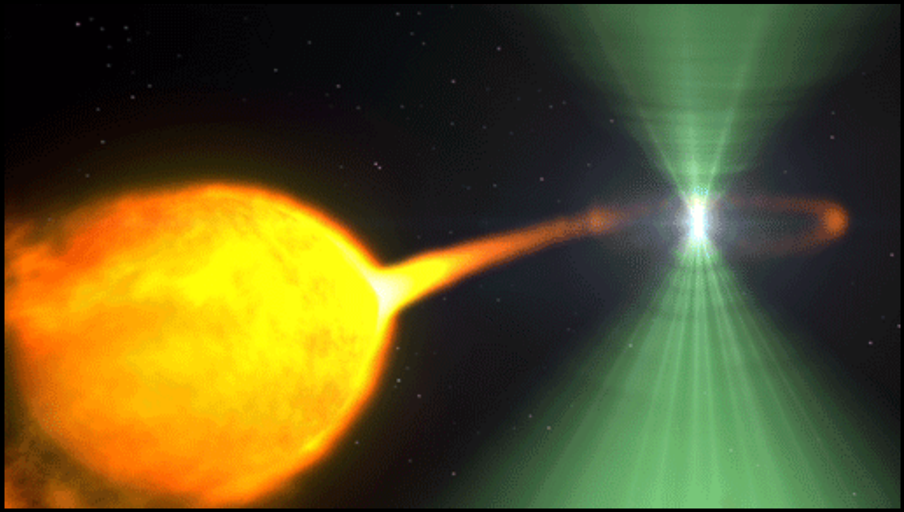

(Vigano', Rea, Pons, Perna, & Miralles 2013; Elfritz, Pons, Rea & Glampedakis 2017)

# Pulsar Bestiary





Accreting neutron stars



Transitional systems

# Pulsar accretion phases

Roughly speaking, X-rays arise from the release of gravitational potential energy as the accreting gas falls into the deep gravitational potential of the NS. e.g. A proton dropped radially onto a NS with $M=1.4M_{\odot}$ and $R=10km$, loses potential energy equal to:

$$\Delta U = \frac{GM_{ns}m_p}{R} = 195 MeV \approx 0.21 m_p c^2$$

The energy released by the gas infalling onto the NS surface goes in part to heat the stellar surface, and in part is re-emitted in the X-ray band.

# Pulsar accretion phases

Neutron Star →

- Magnetic pressure: repulsive
- Gravitational force: attractive
- Centrifugal force: repulsive

$$P_{magn} \propto \frac{B(r)^2}{8\pi}$$

$$F_{grav} \propto \frac{GMm}{r^2}$$

$$F_{cen} \propto m\Omega^2 r$$

Infalling matter →

- Ram pressure: Depends on the density of the matter falling down onto the neutron star

$$P_{ram} \propto \rho(r) v^2_{ff}(r)$$

# Pulsar accretion phases

**Magnetospheric radius:** The magnetic pressure of the neutron star equals the ram pressure of the infalling material:

$$R_{magn} = \left( \frac{\mu^4}{2GM\dot{M}^2} \right)^{1/7} \qquad \frac{B(r_m)^2}{8\pi} = \rho v_{ff}^{\,2}(r_m)$$

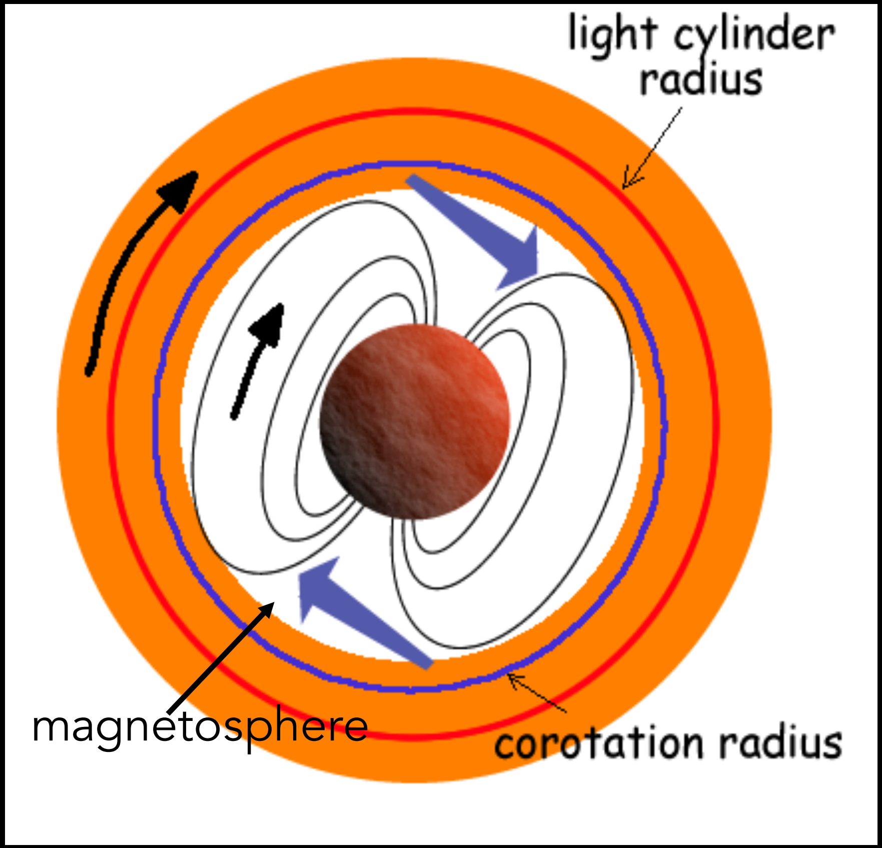
**Corotation radius:** At this radius the matter corotates with the star in keplerian motion: inside win the gravitational force and outside win the centrifugal repulsion:

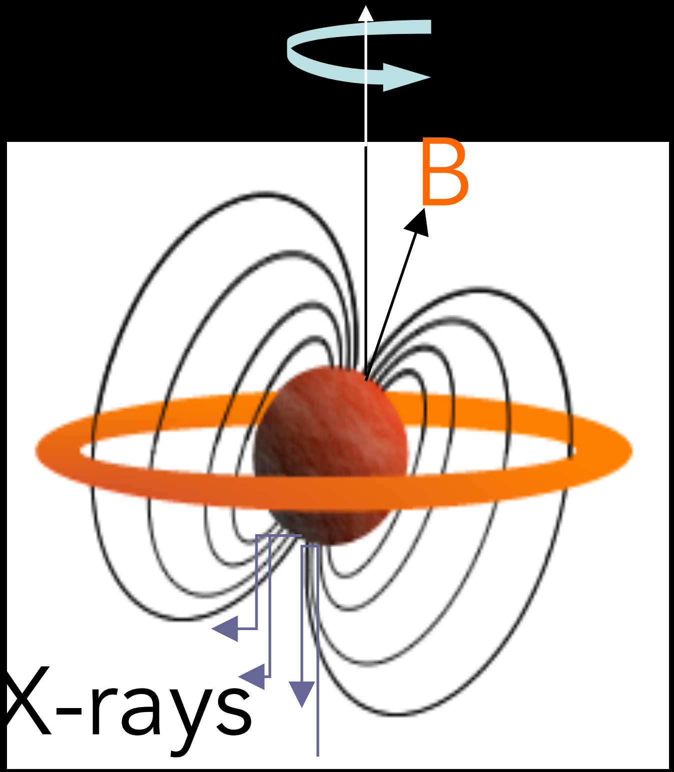
$$R_{cor} = \left( \frac{GMP^2}{4\pi^2} \right)^{1/3} \qquad \frac{GMm}{r_{co}^{\,2}} = m\Omega^2 r_{co}$$

**Light cylinder radius:** The magnetic field lines break because the tangential velocity become greater than c:

$$R_{lc} = \frac{cP}{2\pi} \qquad v_t = \Omega r_{lc} = c$$

# Pulsar accretion phases




Part of the X-ray emission is modulated by the spin period: lighthouse effect

$R(m)<R(cor)<R(lc)$

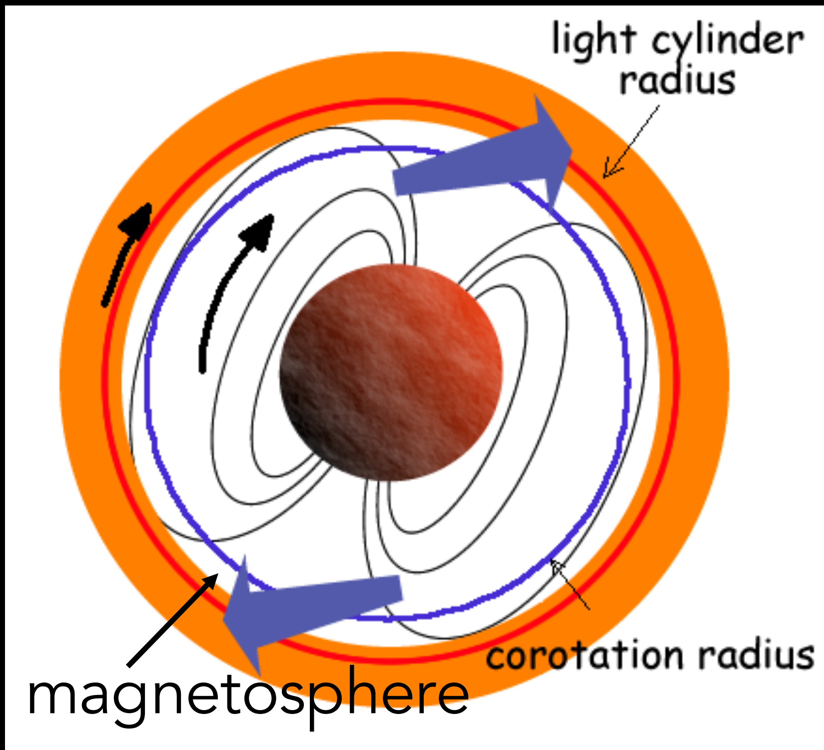
$$L_{acc} = \frac{GM\dot{M}}{R_*}$$

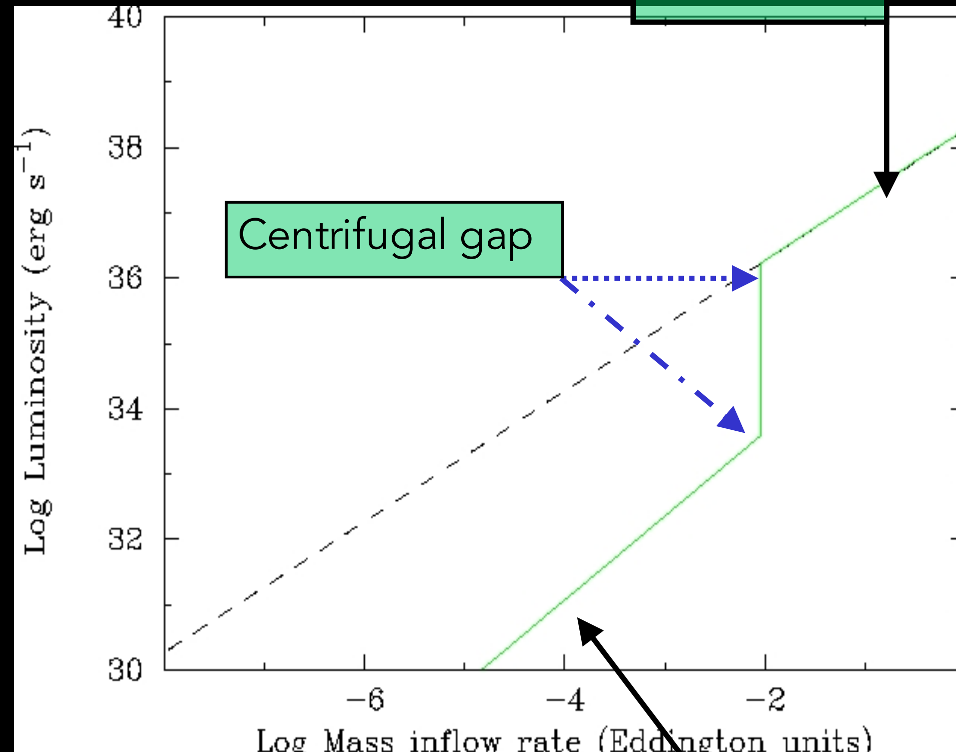
$High\ \dot{M}$

# Pulsar accretion phases

Accretion

$L = GM\dot{M}/R$



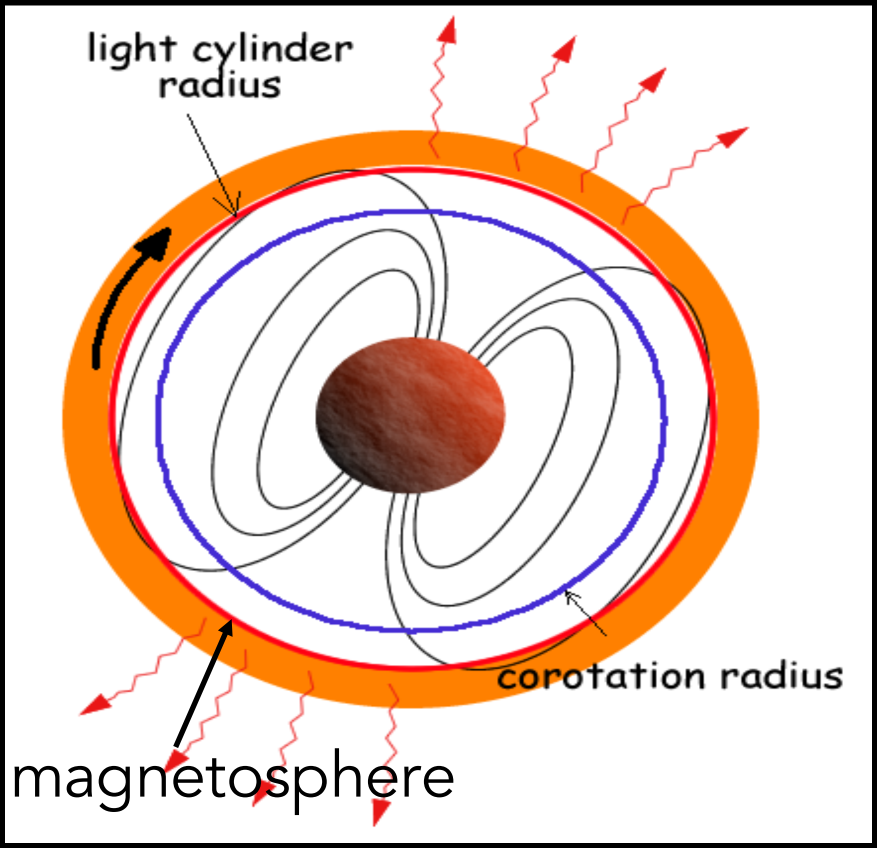

R(cor)<R(m)<R(lc)

*decrease* $\dot{M}$

Propeller

$L = GM\dot{M}/r_m \propto \dot{M}^{9/7}$

# Pulsar accretion phases

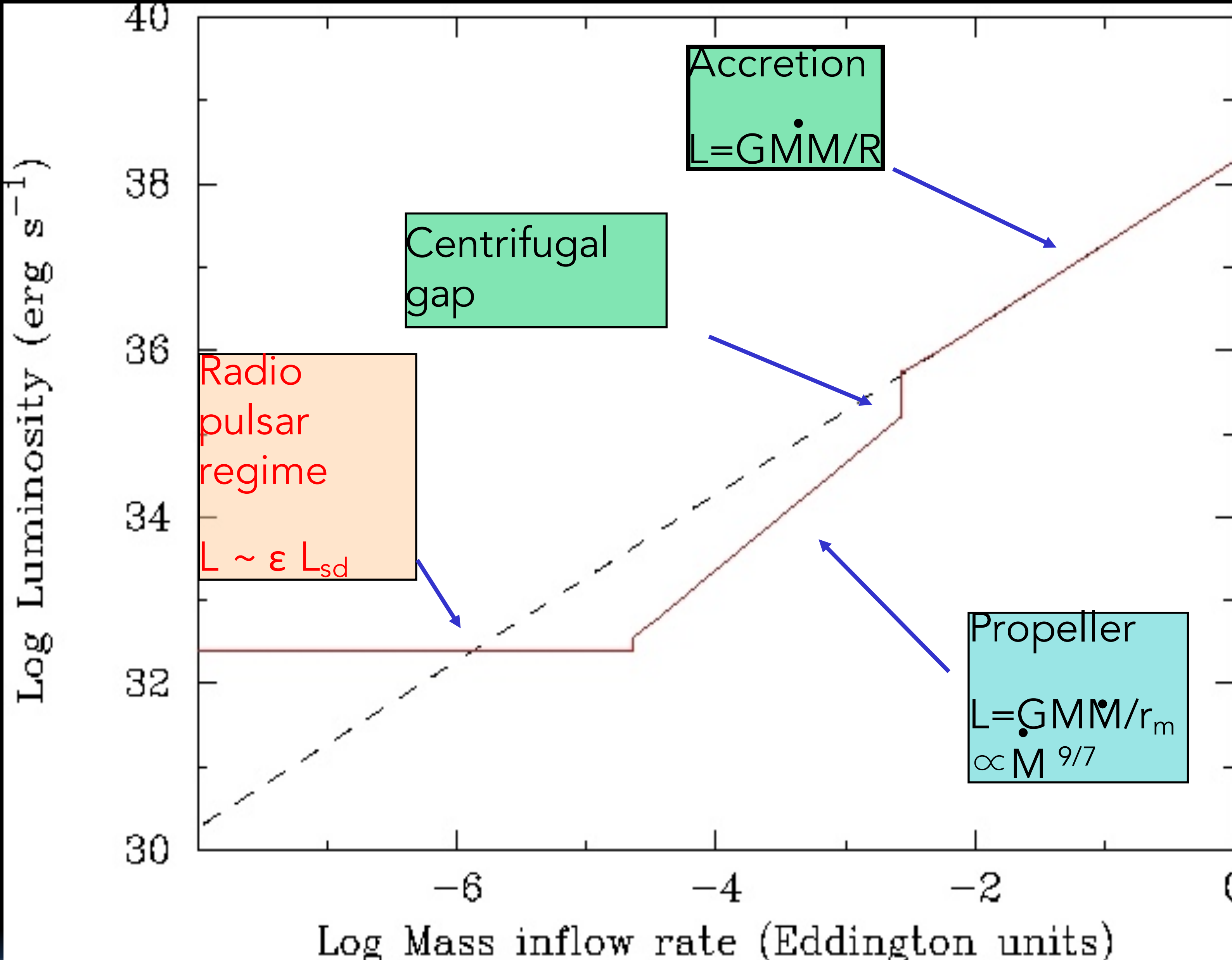



The centrifugal barrier is closed. The matter cannot reach the NS surface.

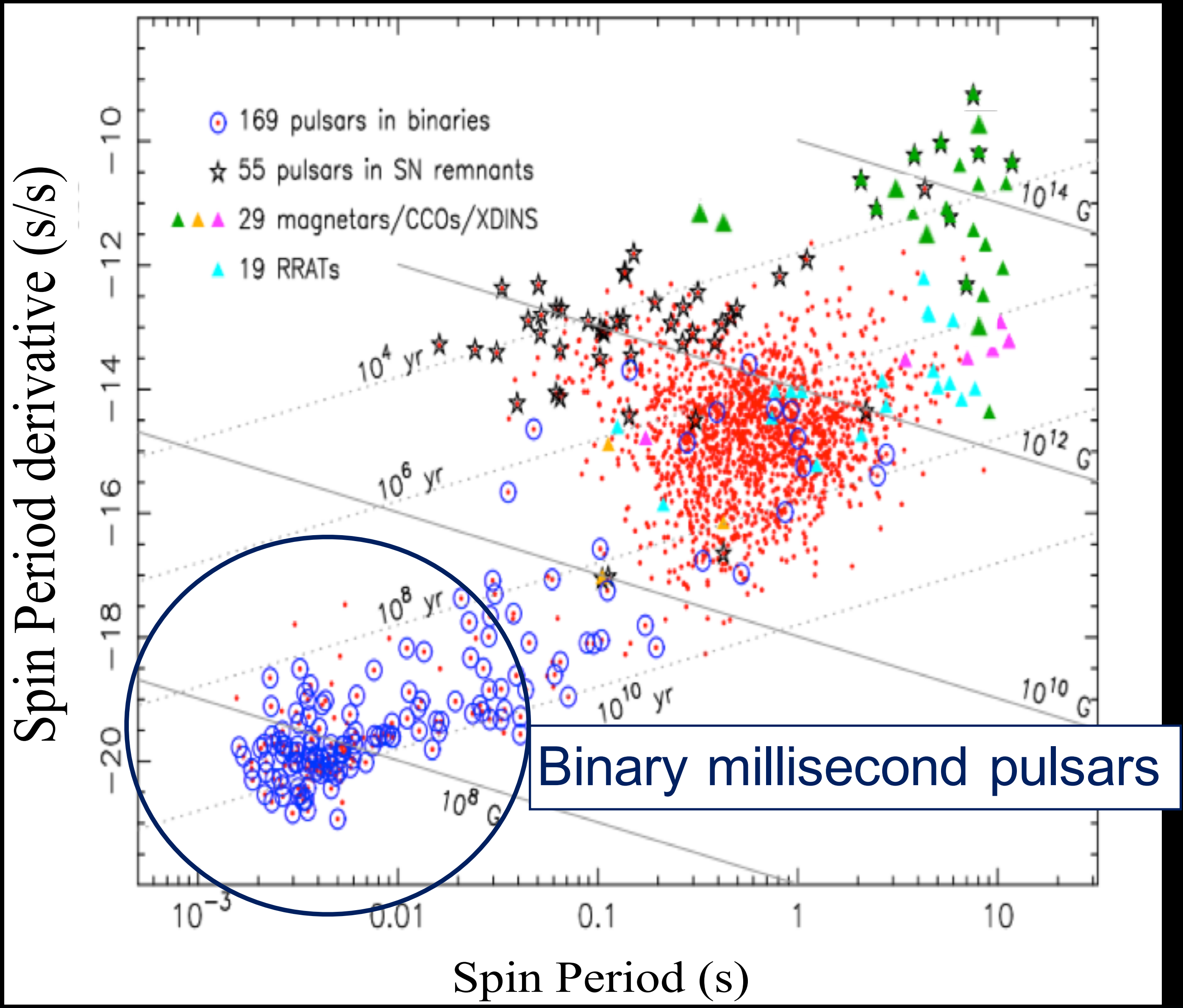
Pulsations might appear in Radio due to particles emission, not due anymore to the shock caused by the matter falling onto the magnetic poles.

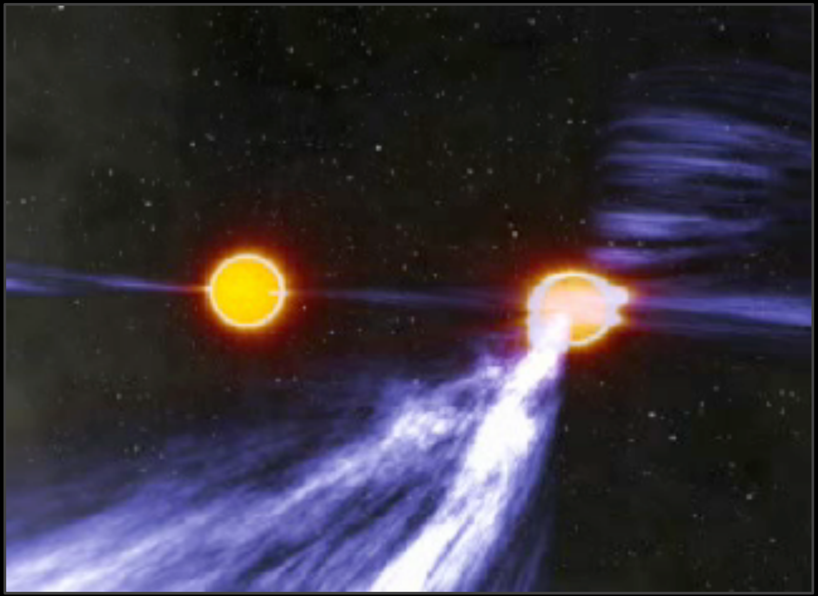
$R(cor) < R(lc) < R(m)$

# Pulsar accretion phases



# Pulsar Bestiary

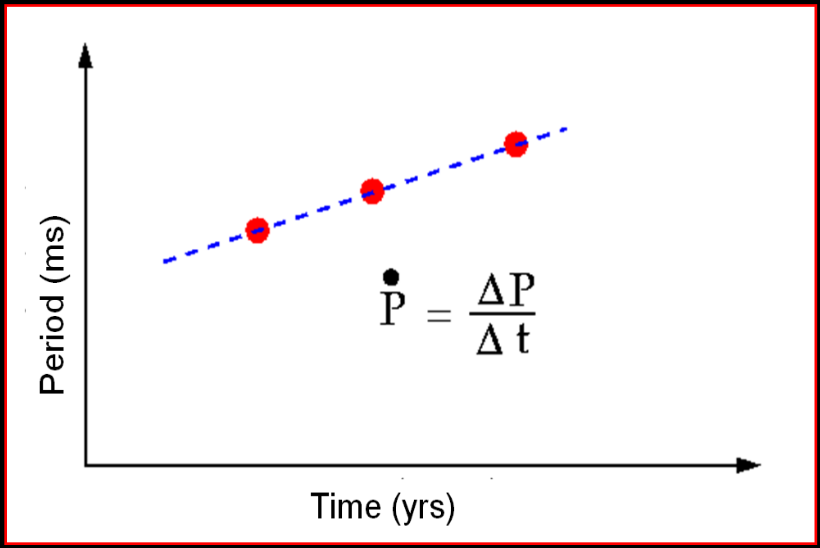


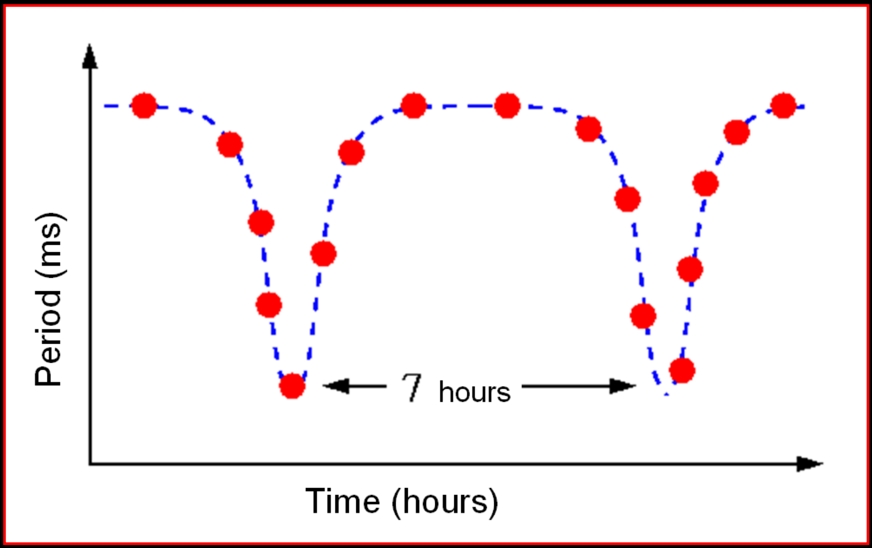


Double neutron stars

Neutron star plus a low mass companion star

# Binary millisecond pulsars

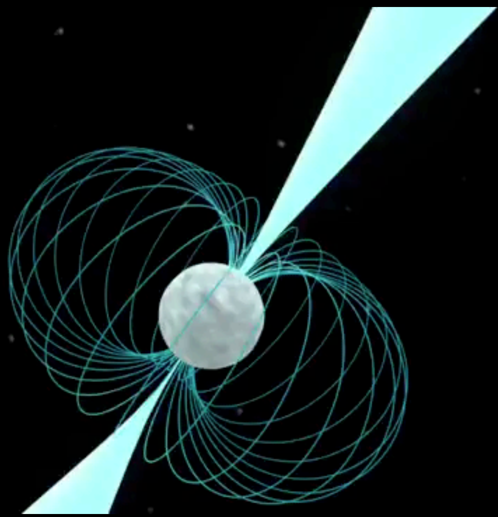


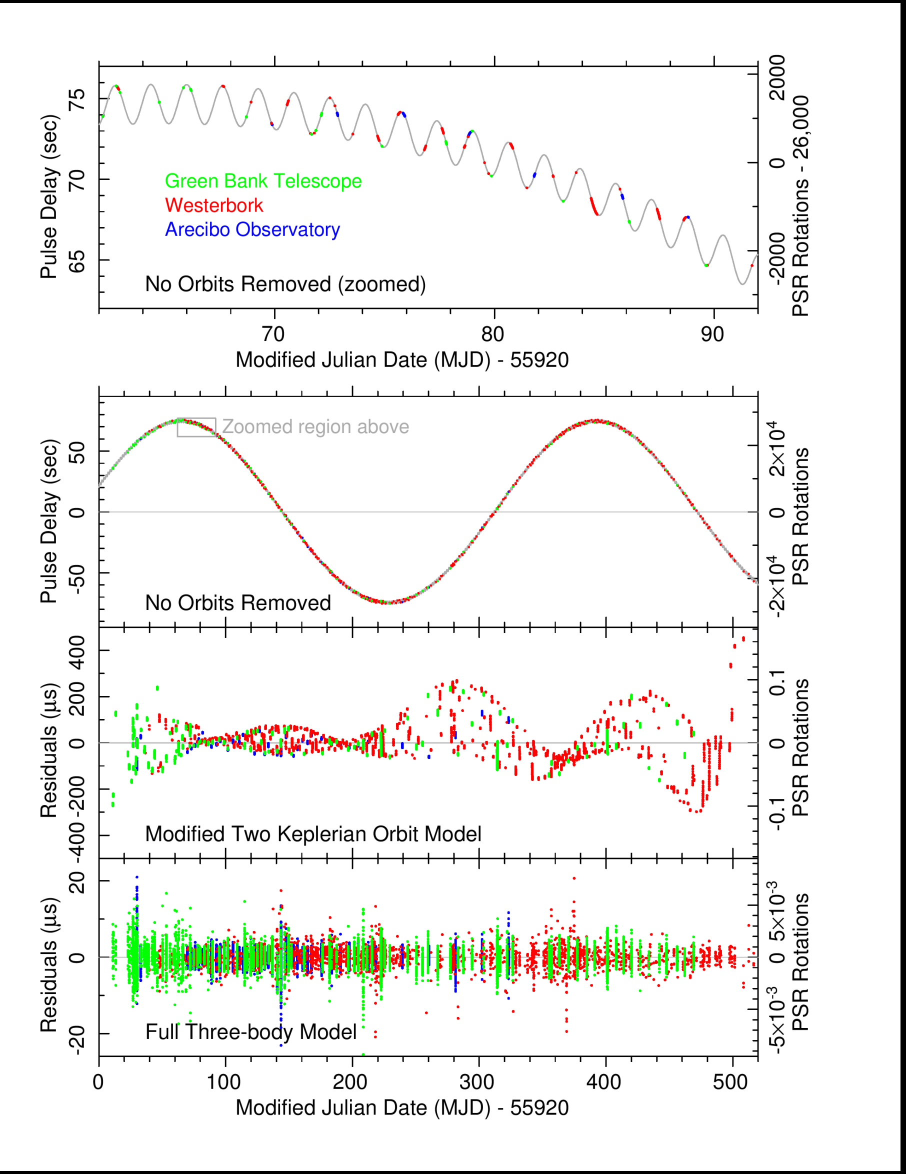




The discovery of the binary pulsar PSR B1913+16 with a period of 59ms and an orbit of 7hr (Hulse & Taylor 1979)

$$t_{PSR\text{-}BARY} = T_{psr} + \Delta_R + \Delta_E + \Delta_S + \Delta_A$$

# Triple System: PSR J0337+1715



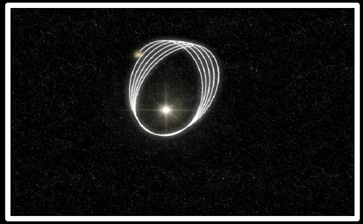



(Ransom et al. 2014, Nature)

# Binary millisecond pulsars and GR tests

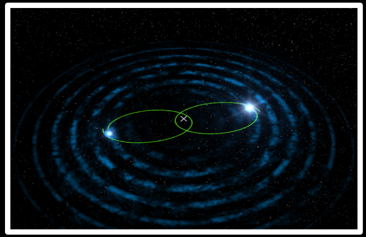
periastron precession

The modification in the shape of the orbit



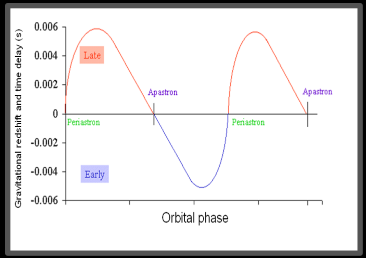
orbital decay

The modification in the shape of the orbit



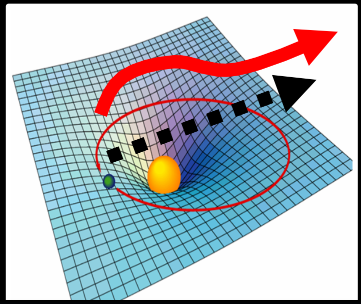
gravitational redshift and time dilation

The modification in the time of arrival of the pulses




Shapiro delay

The modification in the time of arrival of the pulses



# Binary millisecond pulsars and GR tests

$$\dot{\omega} = 3\left(\frac{P_b}{2\pi}\right)^{-5/3}(T_\odot M)^{2/3}(1-e^2)^{-1},$$ Periastron precession

$$\gamma = e\left(\frac{P_b}{2\pi}\right)^{1/3} T_\odot^{2/3} M^{-4/3} m_c (m_p + 2m_c),$$ Time dilation & gravitational redshift

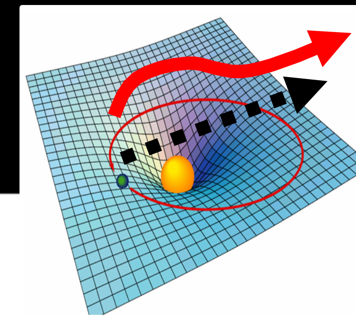
$$\dot{P}_b = -\frac{192\pi}{5}\left(\frac{P_b}{2\pi}\right)^{-5/3}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)(1-e^2)^{-7/2} T_\odot^{5/3} m_p m_c M^{-1/3},$$ Orbital period decay

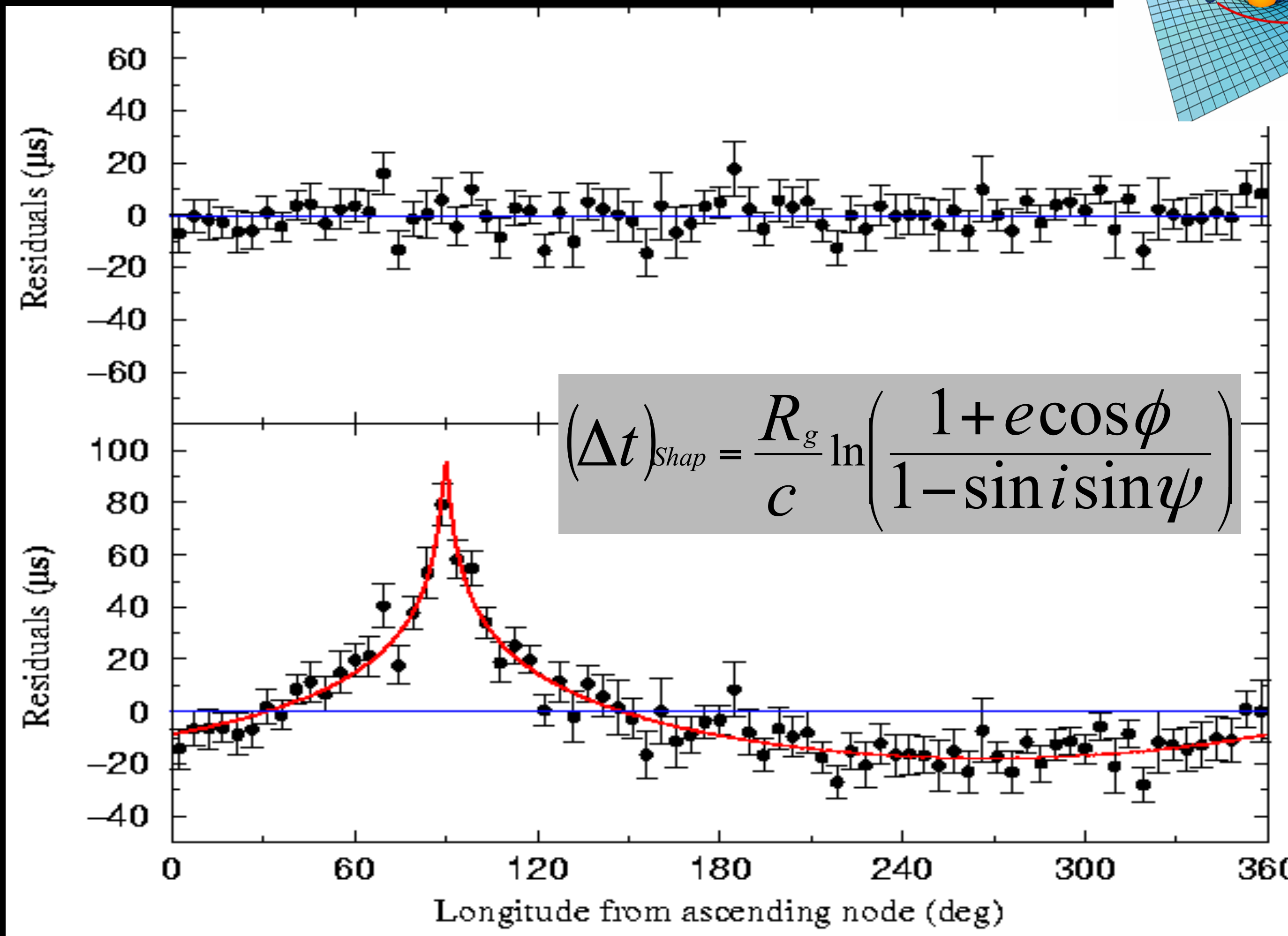
$$r = T_\odot m_c,$$ Shapiro delay (amplitude)

$$s = x\left(\frac{P_b}{2\pi}\right)^{-2/3} T_\odot^{-1/3} M^{2/3} m_c^{-1}.$$ Shapiro delay (shape)

GR tests!

# Shapiro delay in the data of a binary pulsar



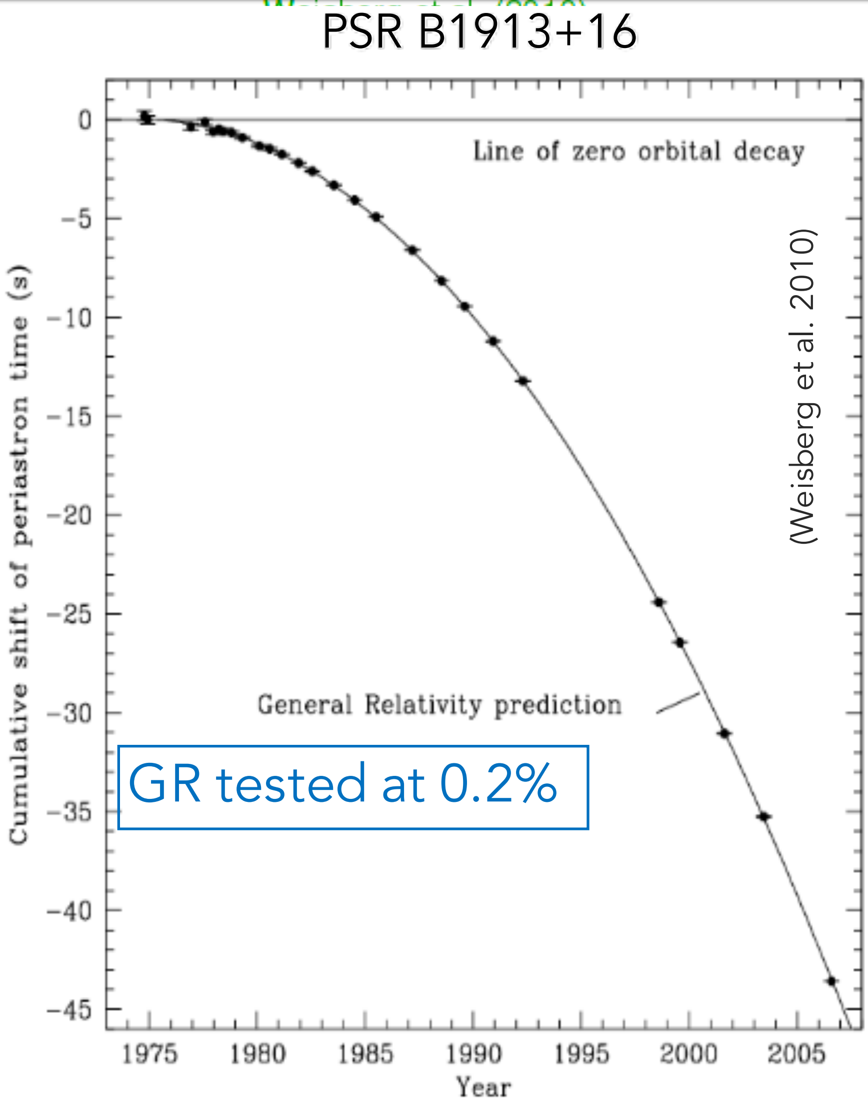


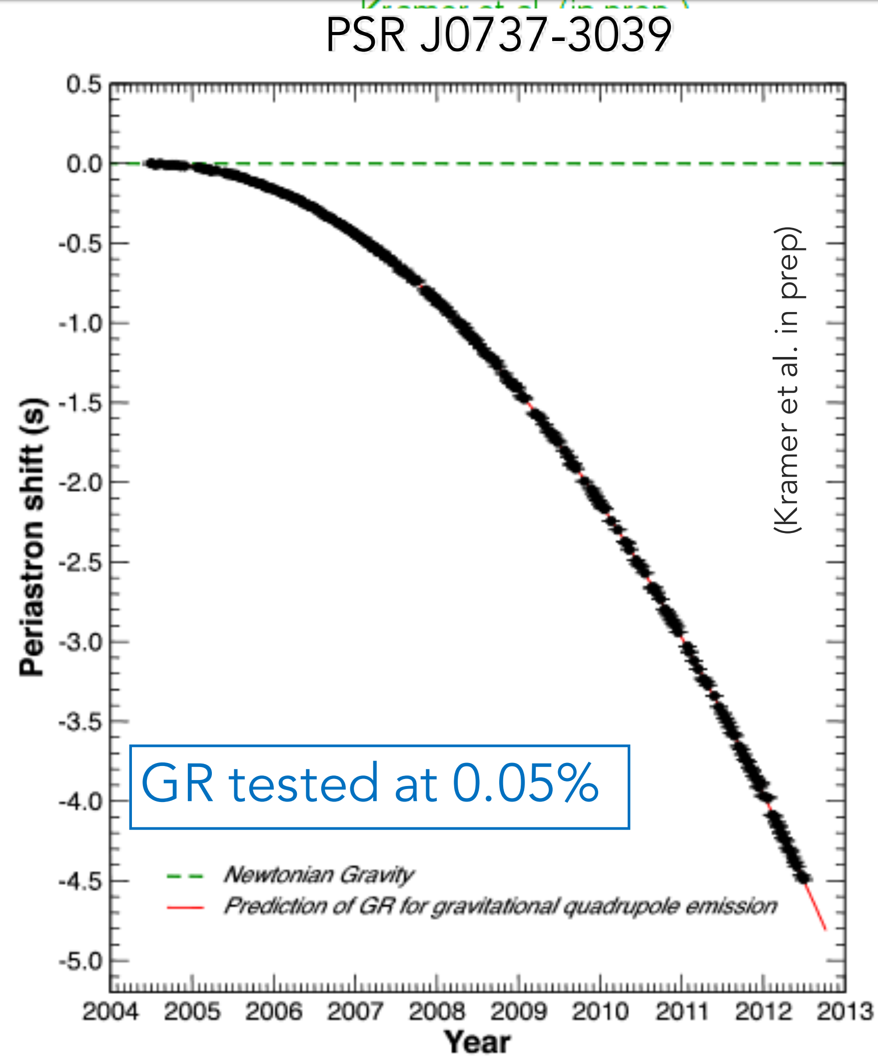

$$\left(\Delta t\right)_{Shap} = \frac{R_g}{c}\ln\left(\frac{1+e\cos\phi}{1-\sin i\sin\psi}\right)$$

[ Lyne, Burgay, Kramer, Possenti et al. 2004]

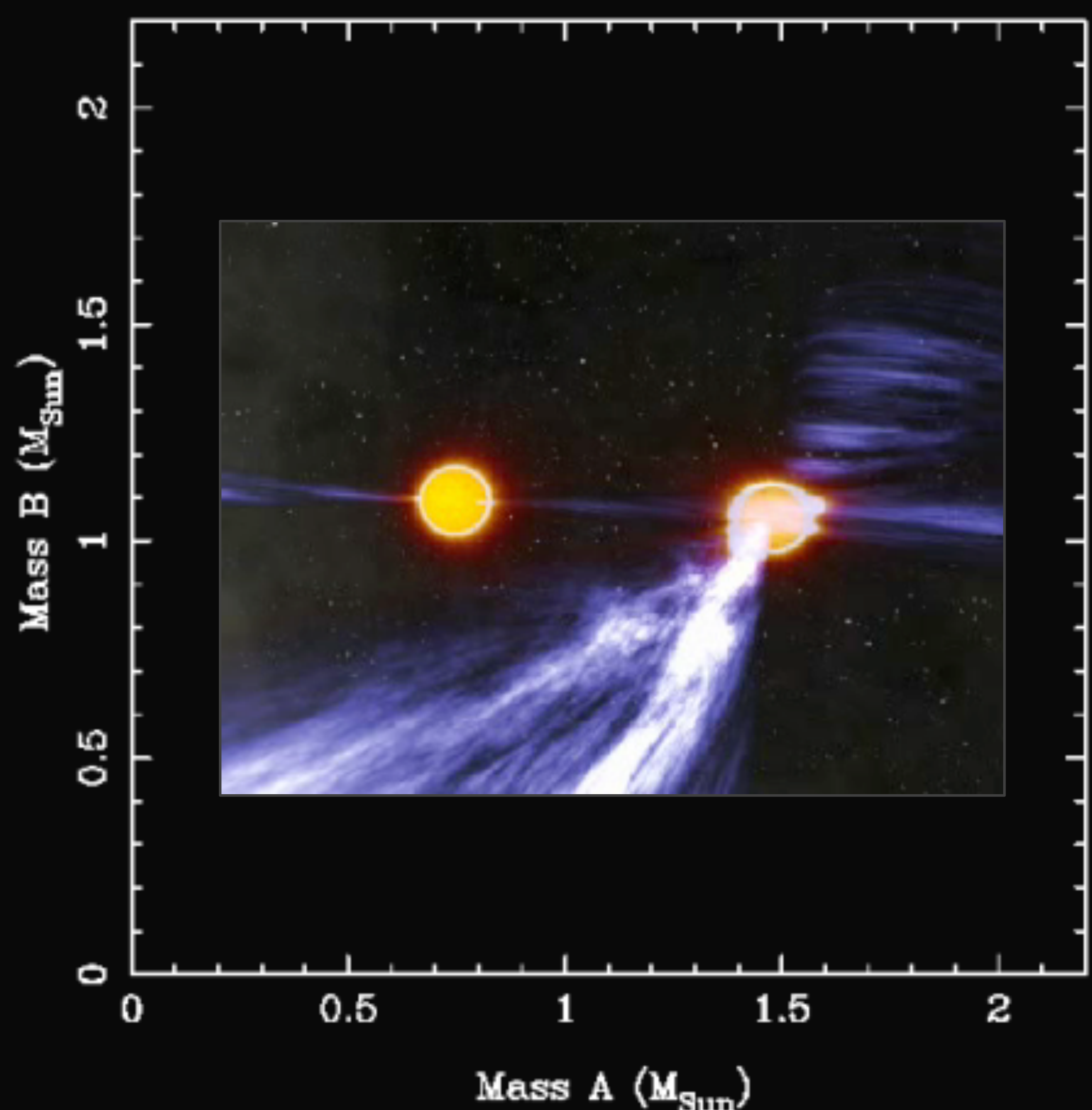
# Binary millisecond pulsars and GR tests

Nobel Prize 1993 to Hulse & Taylor!



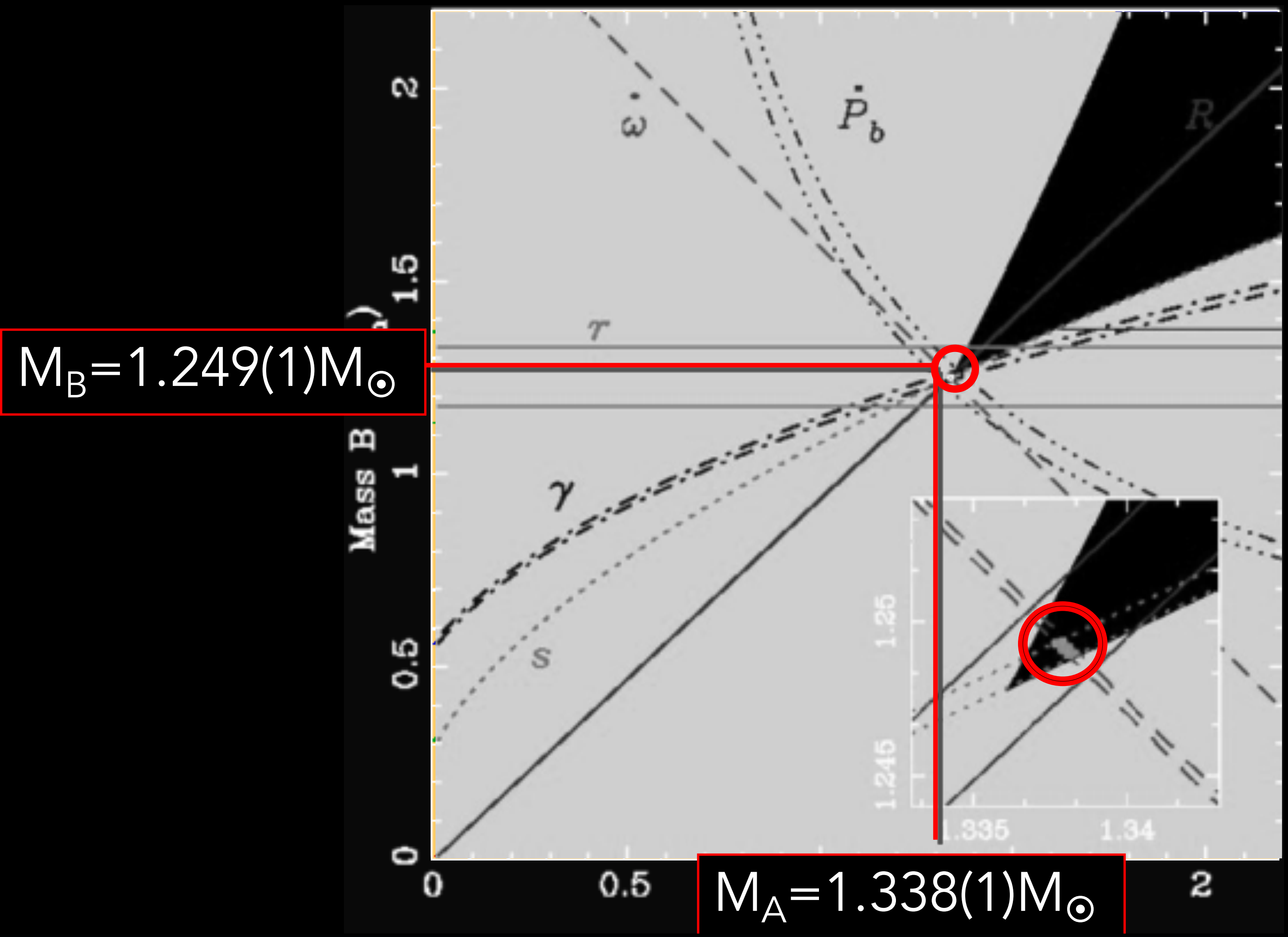
# The masses of the double pulsar PSR J0737-3039




(Burgay et al. 2003; Lyne et al. 2004)

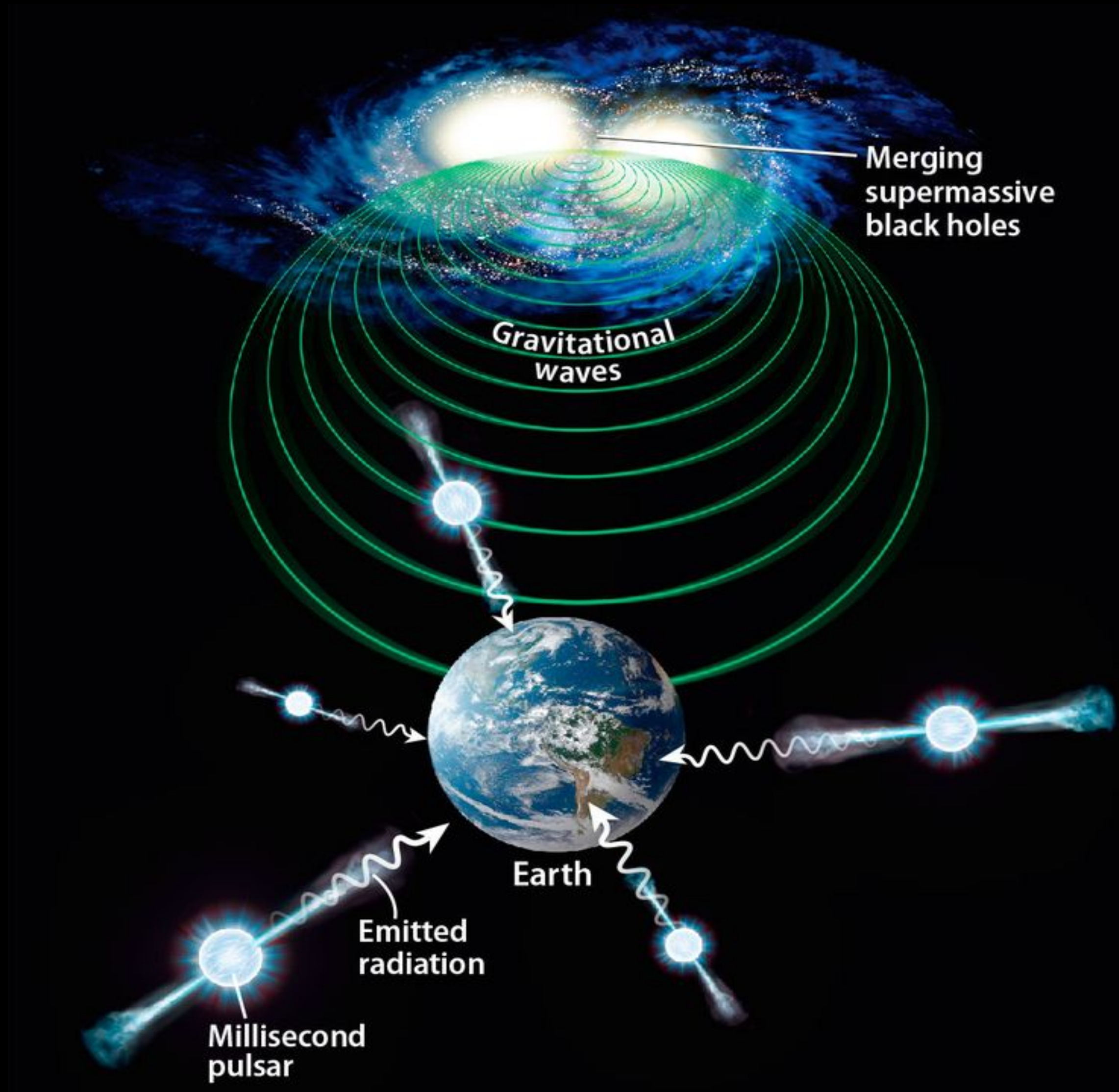
# The masses of the double pulsar PSR J0737-3039

4 independent tests of GR!



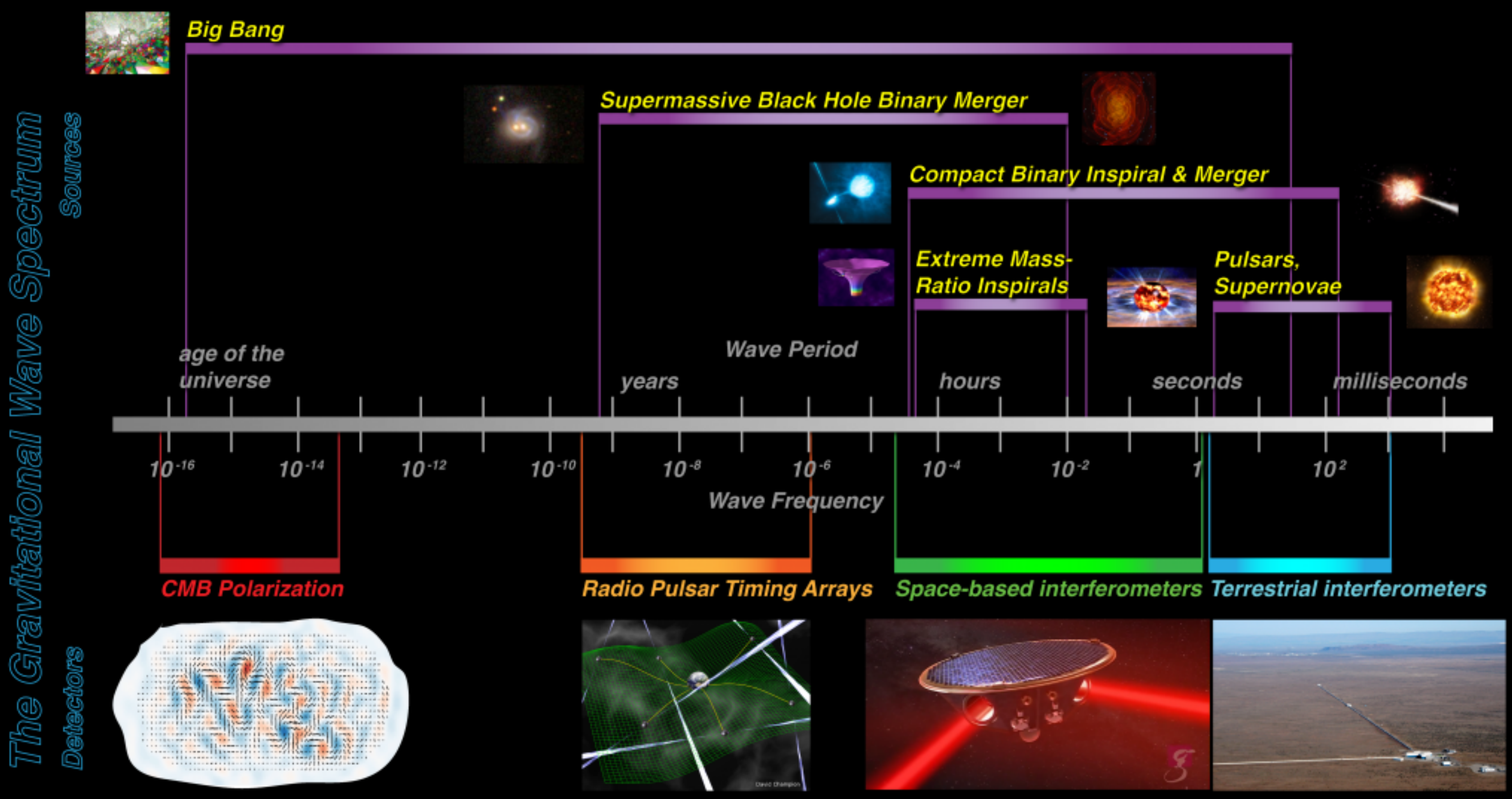

(Kramer et al 2006; Stairs et al. 2010)

# The International Pulsar Timing Array
(PTA, EPTA, NanoGRAV)

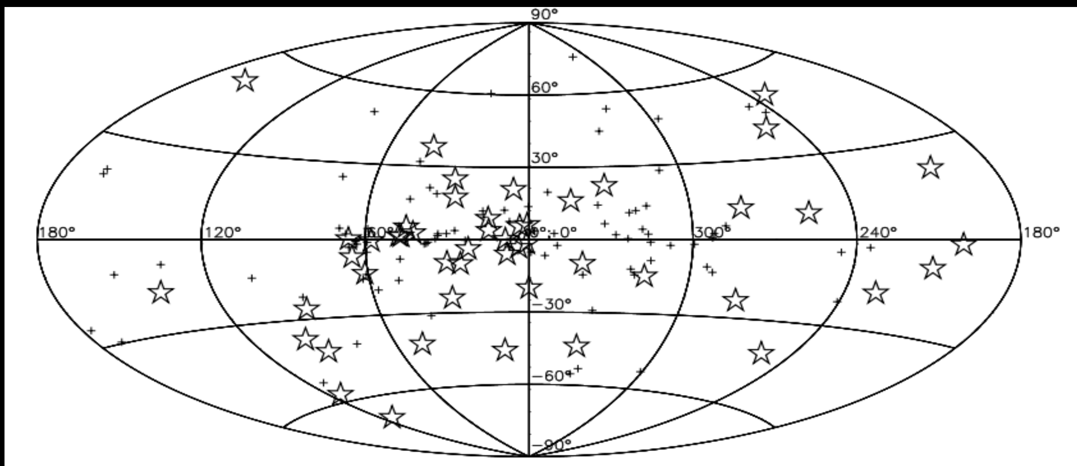


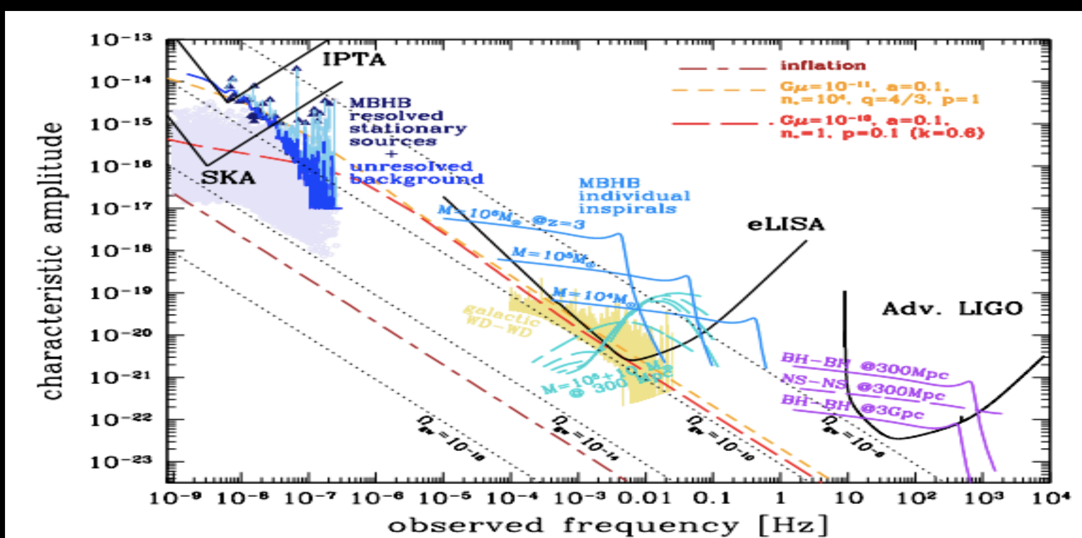
# The International Pulsar Timing Array

## (PTA, EPTA, NanoGRAV)



# The International Pulsar Timing Array
## (PPTA, EPTA, NanoGRAV)




EPTA: Effelsberg, Nancay, Jodrell, Westerborg: 42 millisecond pulsar for 7-18 years (Desvignes et al. 2016)

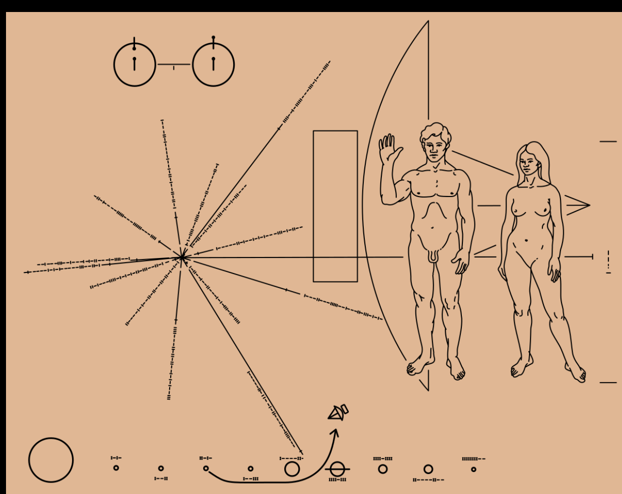
PPTA : Parkes: 24 millisecond pulsar for 8-25 years (Reardon et al. 2016)

NanoGRAV : Arecibo, GBT, VLA: 59 millisecond pulsar for 9 years (Arzoumanian et al. 2016)

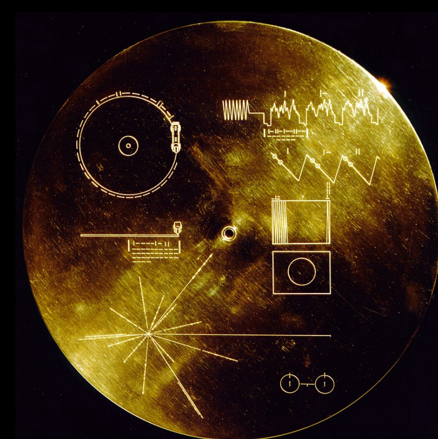
# Pulsars as deep space GPS


# Pulsars GPS idea already flying…

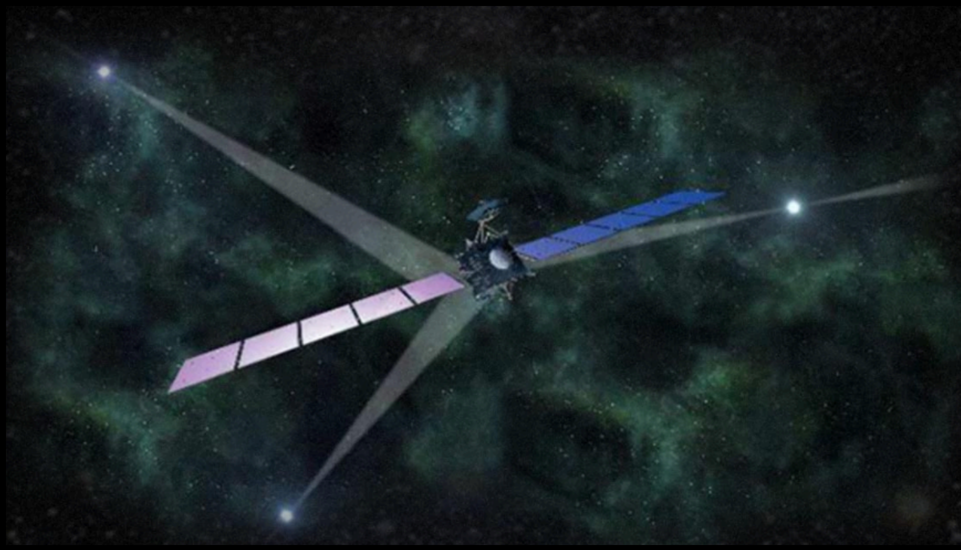
The Pioneer plaques are a pair of aluminium plaques which were placed on board the 1972 Pioneer 10, 1973 *Pioneer 11 spacecrefts*, featuring a pictoral image in case either *Pioneer 10* or *11* is intercepted by extraterrestrial life.



NASA's Voyager 1, launched 35 years ago with various messages from the Earth, is on the verge of moving into interstellar space. It has a Golden Record on-boad in case it will intercepted by extraterrestrial life



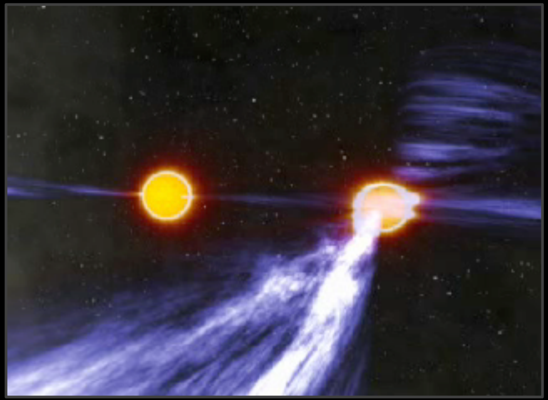
# Pulsars as deep space GPS

On January 2018 the first test of this pulsar GPS system has been successfully performed using the SEXTANT instrument onboard NICER, hosted by the International Space Station that orbits around Earth at slightly more than 17,500 mph. Within eight hours of starting the X-ray pulsar timing experiment, via timing 14 X-ray millisecond pulsars, the algorithm converged on a location with an error of 10 miles.

(NICER collaboration, Nature 2018)

# Pulsars are Cosmic gifts.



Taking their beats we can probe:
- Dense matter within the neutron stars
- The most extreme magnetic fields
- The electron density in the Galaxy
- Plasma studies at high densities and gravity in accreting systems
- General Relativity and test alternative theories
- Use them as Gravitational Wave Detectors
- Use them as GPS for deep space travels