XXVII WINTER SCHOOL OF ASTROPHYSICS, Tenerife, Spain, November 9-20 2015

HIGH TIME RESOLUTION ASTROPHYSICS

09-20 November 2015 - IAC-Tenerife

# Radio Observations and Theory of pulsars and X-ray binaries

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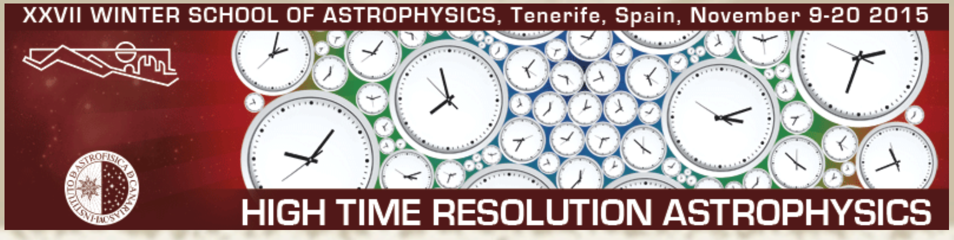
# Outline

1. Rudiments on pulsars
2. Binary pulsars and their evolution
3. Pulsar timing concepts
4. Pulsars timing as a tool for fundamental physics
5. Prospects with SKA
6. The enigma of the Fast Radio Bursts (FRBs)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HIGH TIME RESOLUTION ASTROPHYSICS

## Books

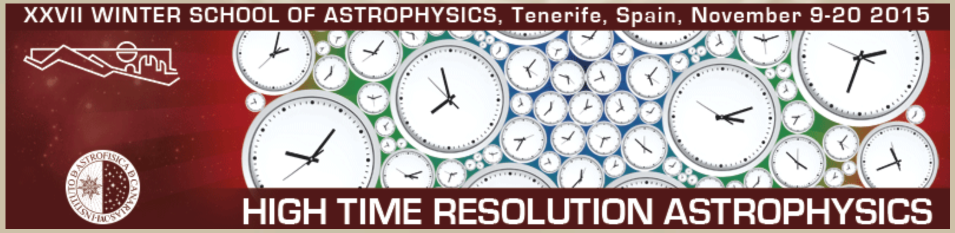
- Manchester & Taylor 1977 “Pulsars”
- Lyne & Smith 2005 “Pulsar Astronomy”
- Lorimer & Kramer 2005 “Handbook of Pulsar Astronomy”
- AA.VV. 2009 “Physics of relativistic objects in compact binaries: from birth to coalescence”, Springer

## Review Articles

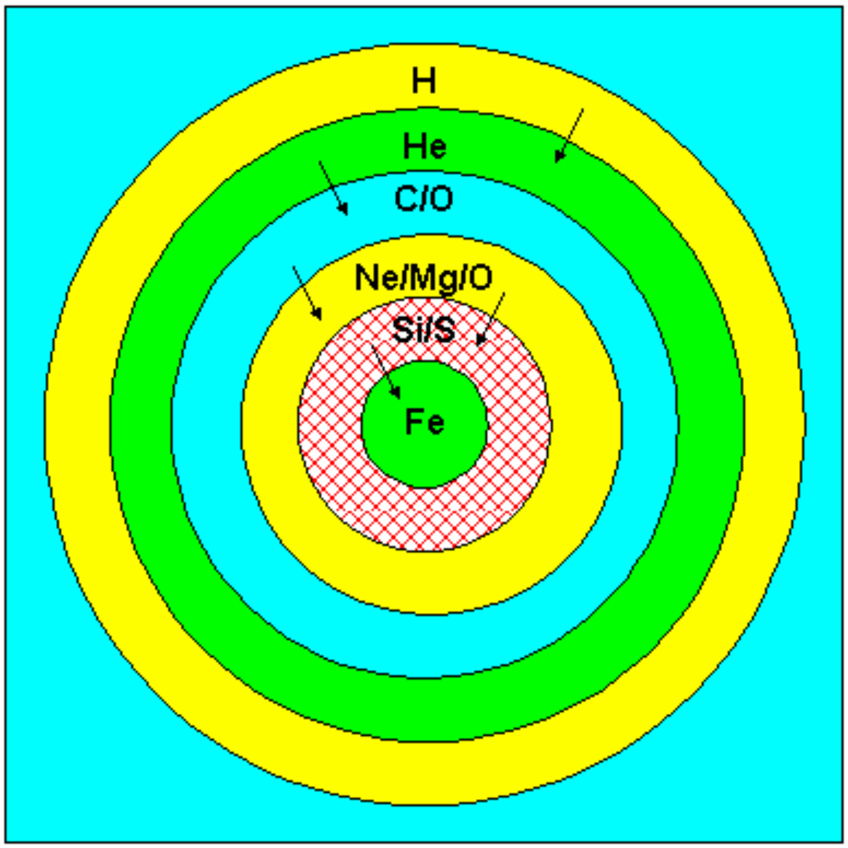
Stairs 2003: Testing General Relativity with pulsar timing
Will, 2006: The confrontation btw General Relativity and experiment
Lorimer 2008: Binary and millisecond pulsars
Kramer & Stairs 2008: The double pulsar
Camilo & Rasio 2005: Pulsars in Globular Cluster
Hessels, Possenti et al 2015: Pulsars in Globular Cluster with the SKA
Watts et al. 2015: Probing the neutron star interior and the Equation of State of cold dense matter with the SKA
Shao et al. 2015: Testing gravity with Pulsars in the SKA era
Tauris et al. 2015: Understanding the neutron star population with the SKA

# 1.

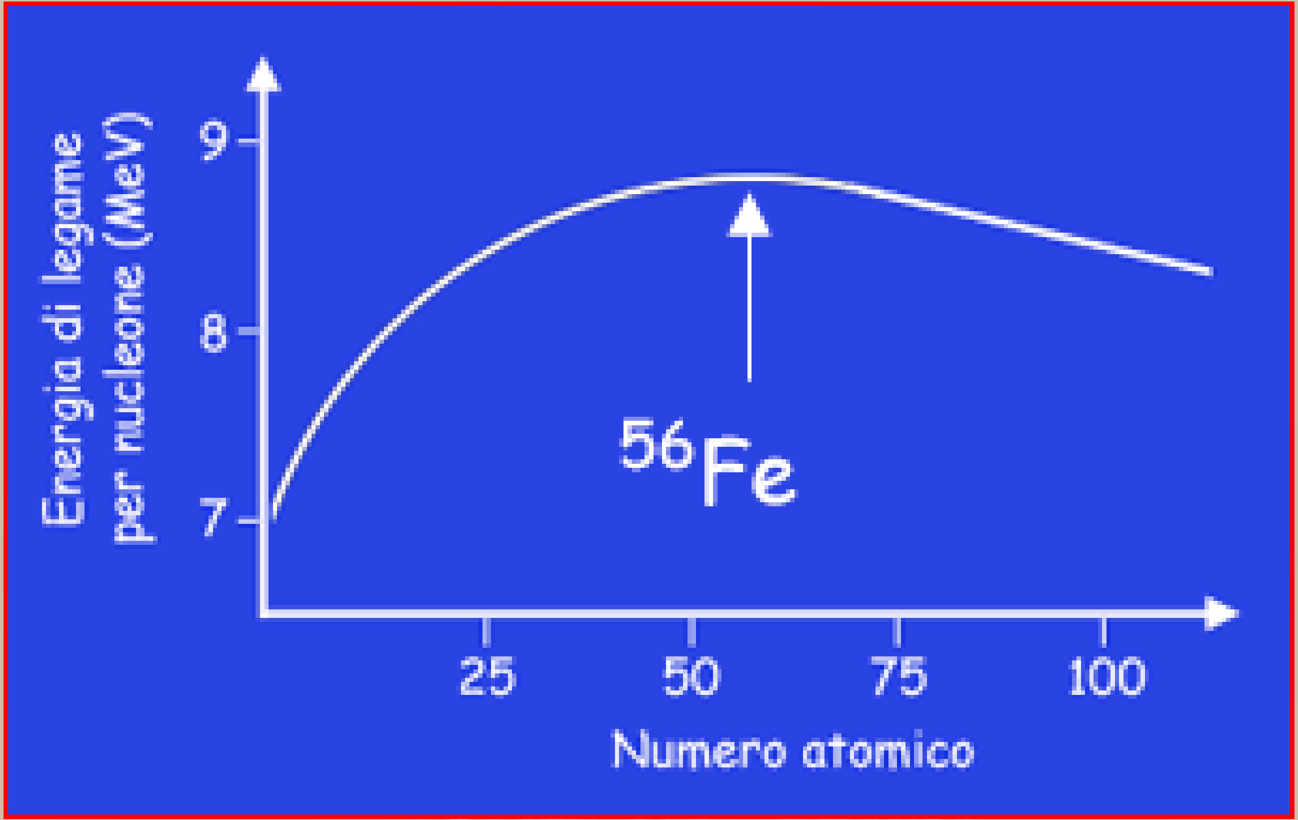
# Rudiments on Pulsars



# $8\ M_{sun} \lessapprox M_{initial} \lessapprox 19\text{–}25\ M_{sun}$

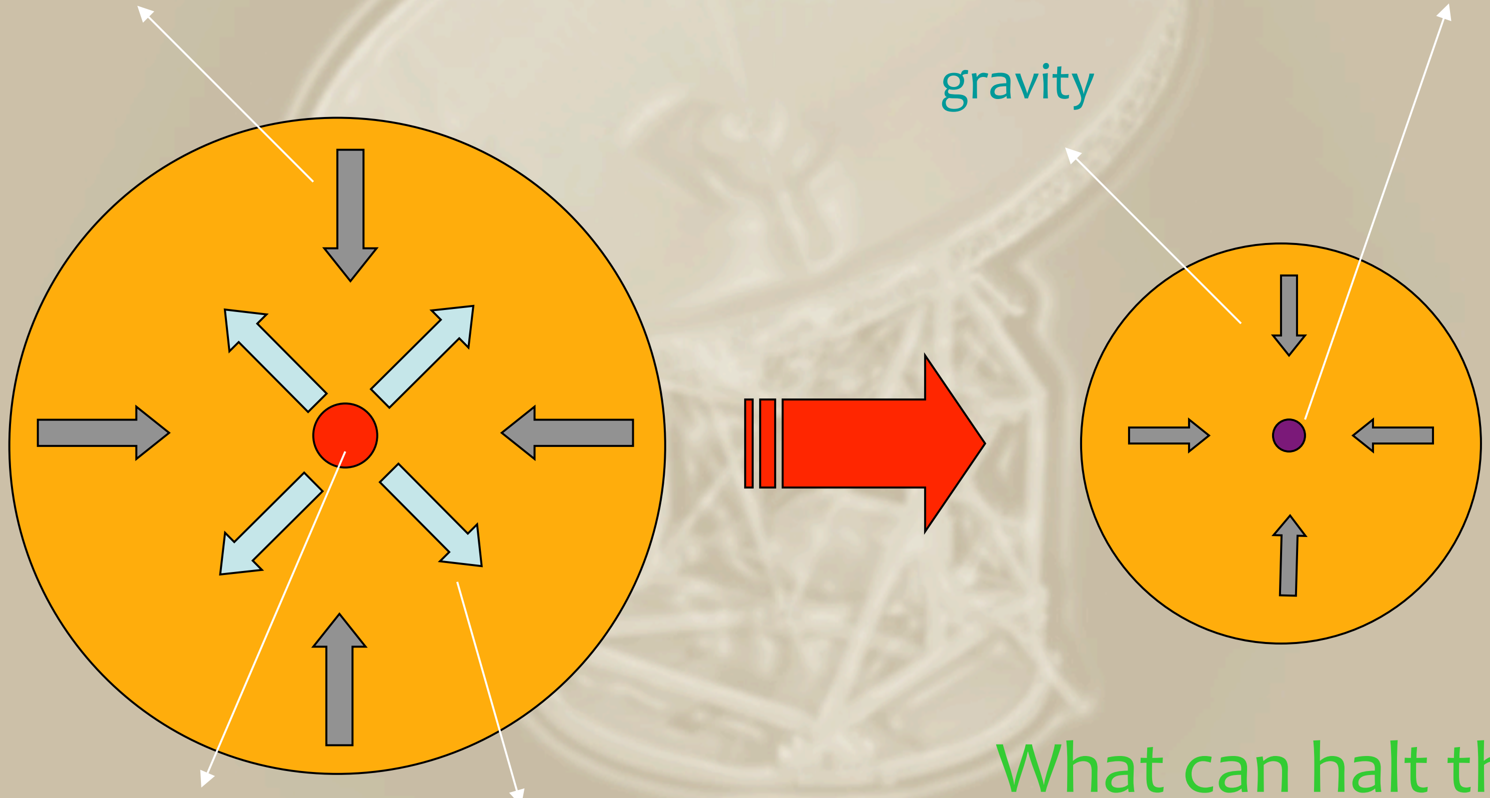


After 10-200 Myr from the birth,
the star assumes an onion structure



The nucleus of Iron 56 has the highest binding energy

# $8\ M_{sun} \approx< M_{initial} \approx< 19\text{–}25\ M_{sun}$



gravity

IRON
core

gravity

Nuclear
burning Si/S
core

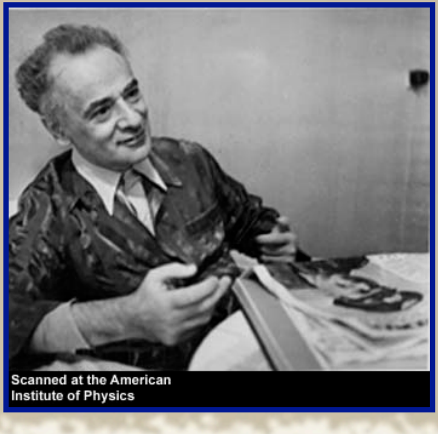
Pressure

What can halt the
collapse of the core ?

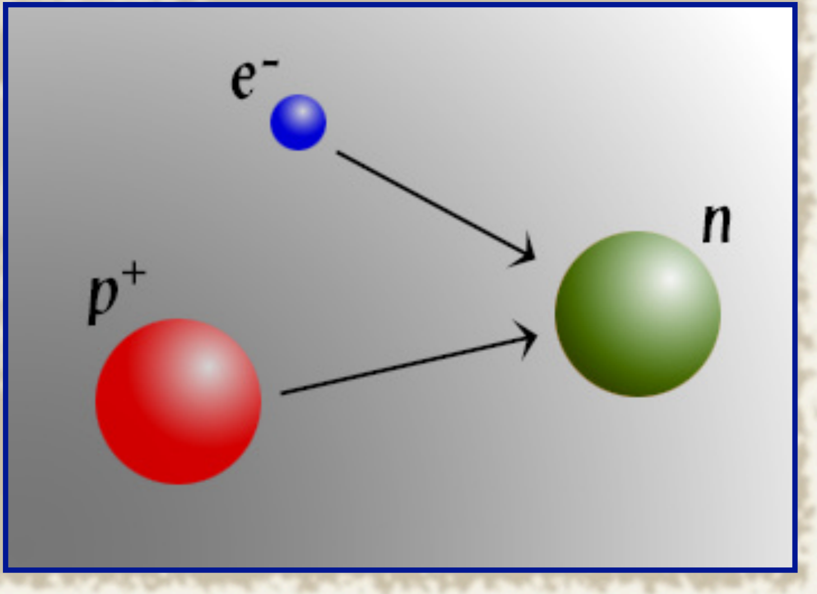
Sir James
Chadwick
(1891-1974)

(1932) Discovery
of the neutron

Lev Davidovich
Landau
(1908-1968)



(1932) ...proposes the
existence of the
NEUTRON STARS



… shown that the pressure due to a
NEUTRON DEGENERATE GAS can STOP THE COLLAPSE of the core

and

MUST EXIST A **MAXIMUM MASS** for the NEUTRON STARS

Landau reasoning (1932) leads to

$$\mathbf{M_{max} \approx M_{chandrasekhar}}$$

a more formal demonstration of the necessity of the existence of a maximum mass for **non rotating** neutron stars is from Rhoades & Ruffini (1974). Under the hypotheses:

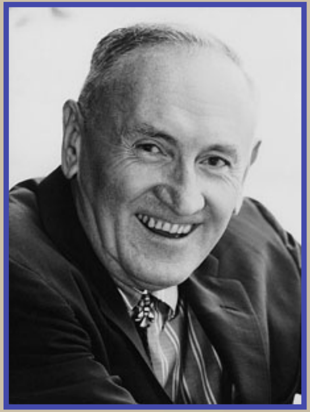
i) $dP/d\rho > 0$ (condition of microscopic stability for avoiding matter to collapse)
ii) $dP/d\rho < c^2$ (causality compliant: sound velocity cannot overcome light velocity)
iii) The equation of state of matter is known up to density $\rho_o = 4.6\ 10^{14}\ g/cm^3$

$$\mathbf{M_{max} \approx 3.2\ M_\odot\ (4.6\ 10^{14}\ g/cm^3\ /\ \rho_o)^{1/2}}$$

For **uniformly rotating** neutron stars the upper limit is [Friedman & Ipser 1987]

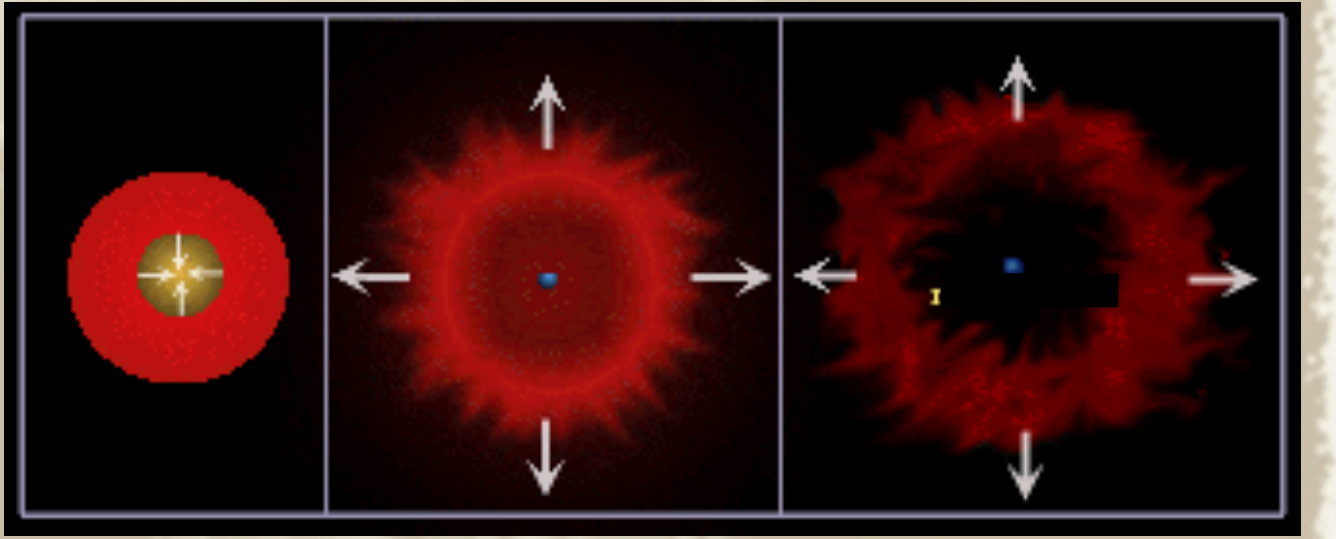
$$\mathbf{M_{max} \approx 6.1\ M_\odot\ (2\ 10^{14}\ g/cm^3\ /\ \rho_o)^{1/2}}$$

Fritz Zwicky
(1898-1974)



Walter Baade
(1893-1960)

*(1934)* … Proposed the hypothesis that the SUPERNOVA explosions rspresent the transformational event joining the Ordinary Stars with the Neutron Stars



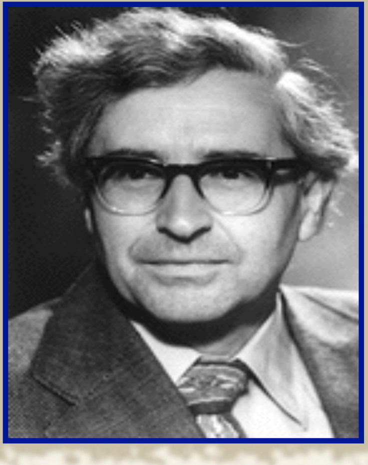
Collapse of the nucleus

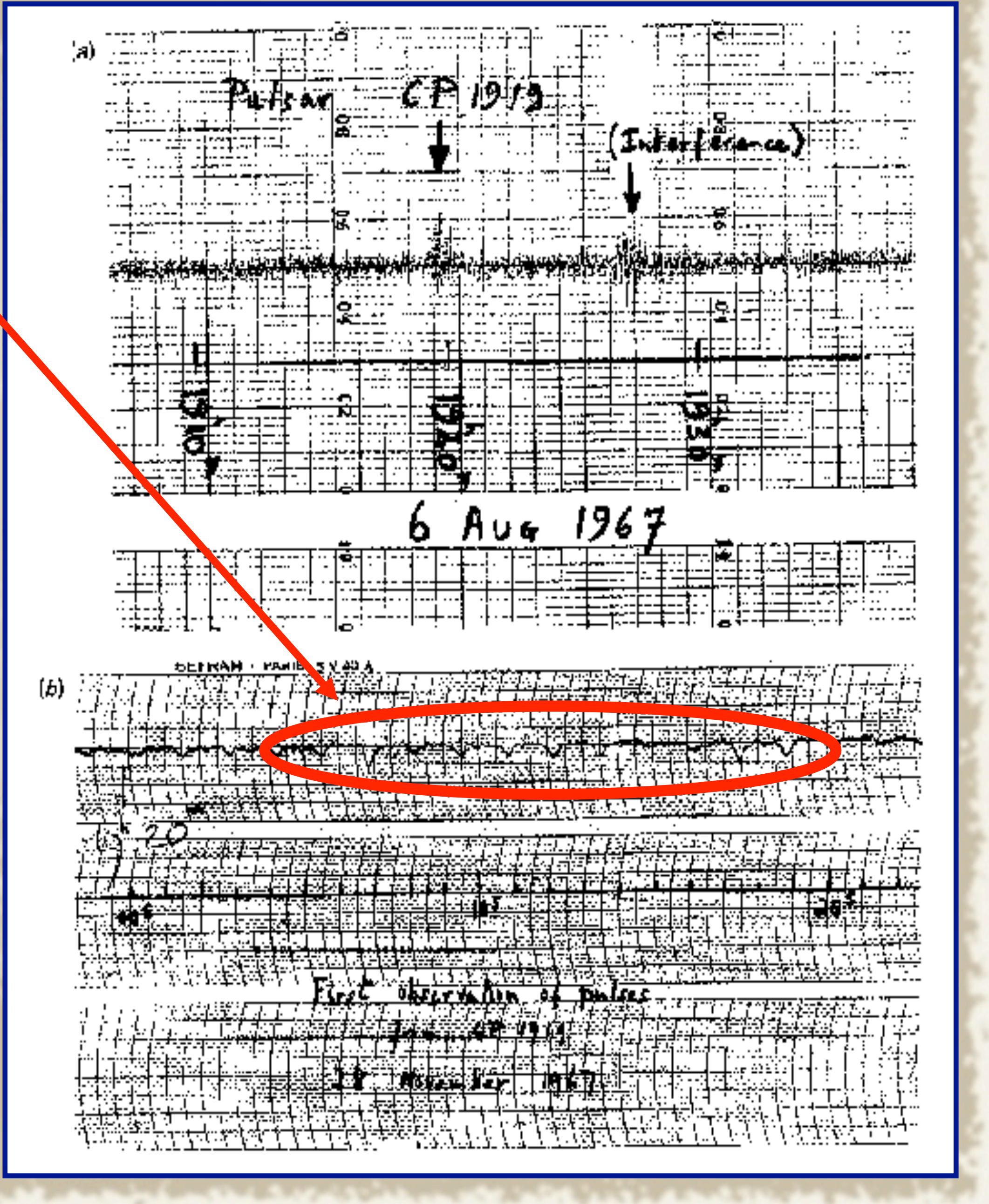
ejection of the external layers

Supernova remnant and neutroni star

(1967) … Jocelyn Bell and Antony Hewish discover celestial objects emitting regularly repeating pulsations in the radio band

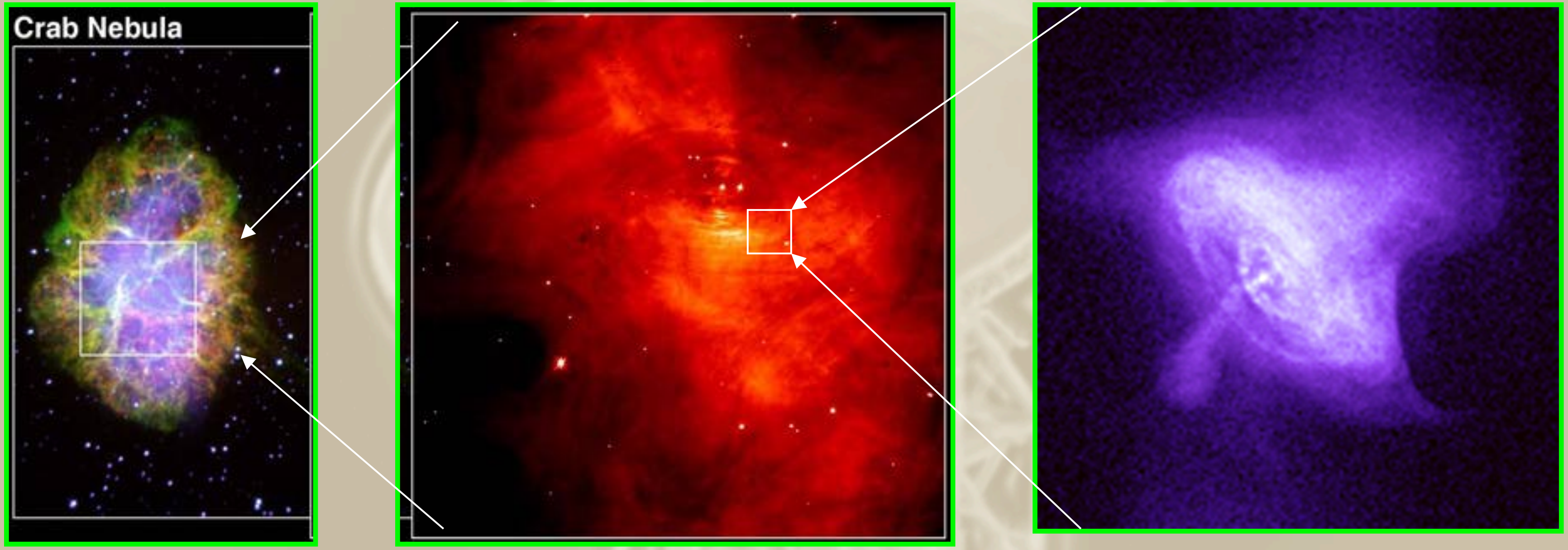
They are named **PULSAR**s by a British journalist





## (1968) ...the confirmation of the predictions of Landau and Zwicky

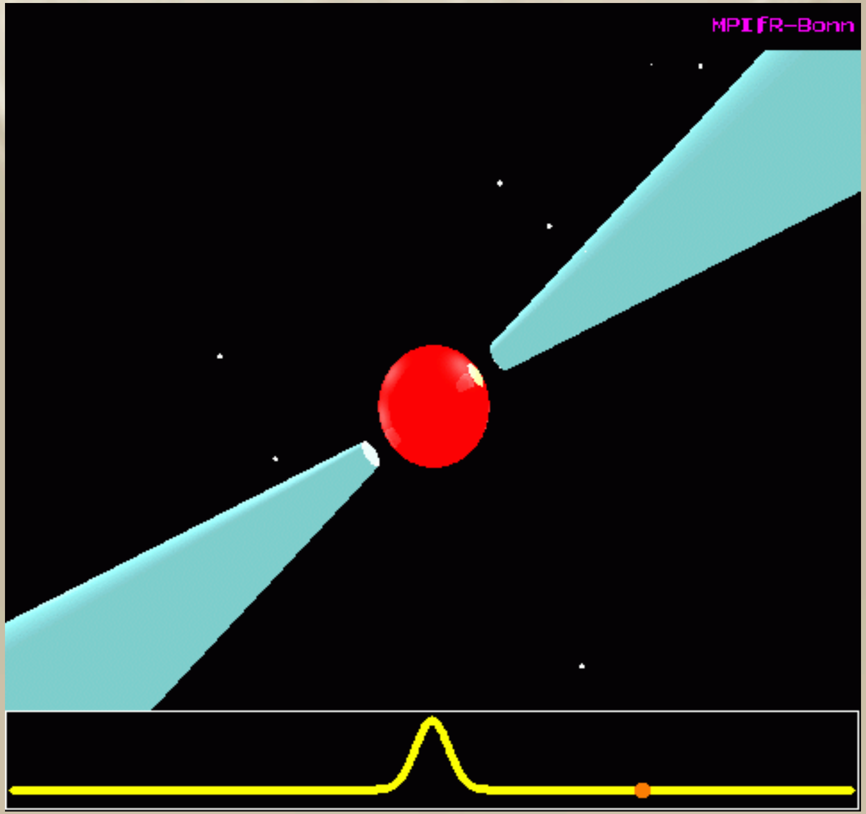
The supernova of A.D.1054… how it appears 960 yr later



a RADIO PULSAR discovered in the nebula

# *What is a Radio Pulsar*

A **PULSAR** is a rapidly **rotating** and highly **magnetized neutron star**, emitting a pulsed radio signal as a consequence of a **light-house effect**



@Kramer

**The Parkes radio telescope (in Australia) where about half of the so far known ≈ 2400 pulsars have been discovered**

PSR B0329+54 : period of 0.714 s

PSR B0833-45 : period of 0.089 s

PSR B1937+21 : period of 0.0016 s

# The rotating magnetized NS in vacuum

$\mu = \frac{1}{2} B_p R^3$
is the magnetic moment
$R$ = NS radius
$B_p$ = polar magn. field

Assuming that the rotational energy loss

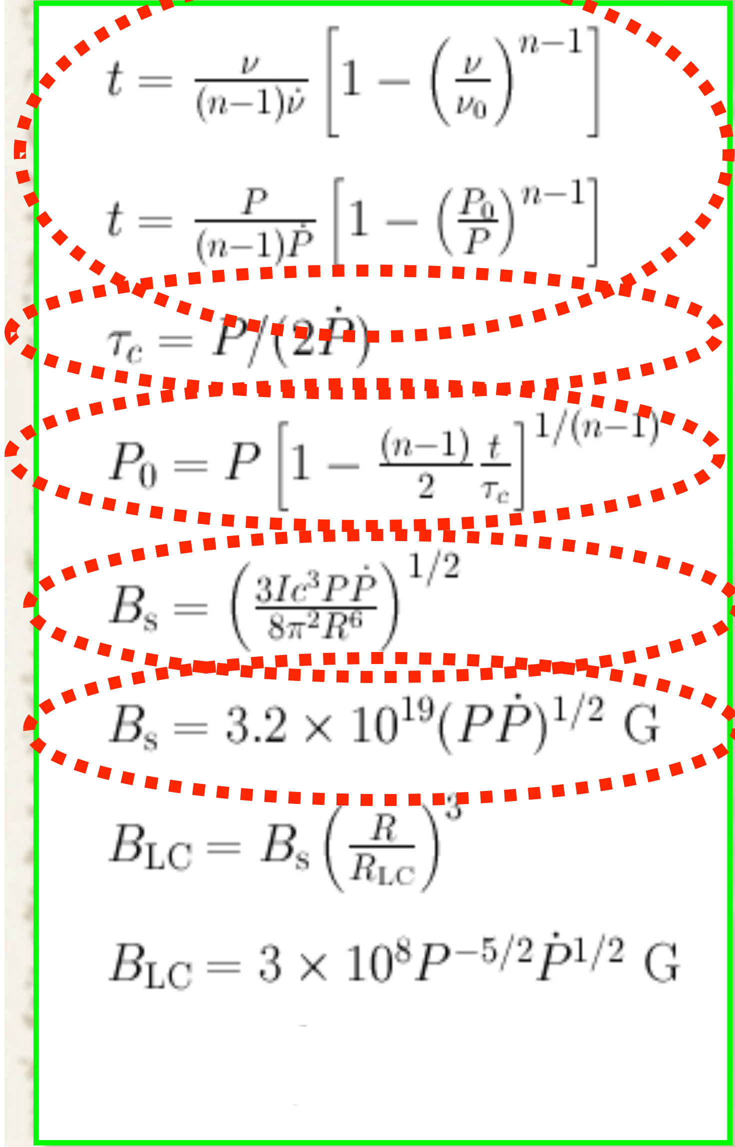
$$L_{sd} = d/dt\,(E_{rot}) = d/dt\,(I\Omega^2/2) = I\,\Omega\,\dot{\Omega}$$

matches the emitted power (derived from the basic electrodynamics Larmour formula):

$$L_{dipole} = [\,2/3c^3]\,|\,\ddot{\mu}\,|^{\,2}$$

one can infer…

# Derived parameters: age & magnetic field



$$t = \frac{\nu}{(n-1)\dot{\nu}}\left[1 - \left(\frac{\nu}{\nu_0}\right)^{n-1}\right]$$

$$t = \frac{P}{(n-1)\dot{P}}\left[1 - \left(\frac{P_0}{P}\right)^{n-1}\right]$$

$$\tau_c = P/(2\dot{P})$$

$$P_0 = P\left[1 - \frac{(n-1)}{2}\frac{t}{\tau_c}\right]^{1/(n-1)}$$

$$B_s = \left(\frac{3Ic^3 P\dot{P}}{8\pi^2 R^6}\right)^{1/2}$$

$$B_s = 3.2 \times 10^{19}(P\dot{P})^{1/2}\ \mathrm{G}$$

$$B_{\mathrm{LC}} = B_s\left(\frac{R}{R_{\mathrm{LC}}}\right)^3$$

$$B_{\mathrm{LC}} = 3 \times 10^8 P^{-5/2}\dot{P}^{1/2}\ \mathrm{G}$$

- Actual age of pulsar is function of initial period and braking index **$n=(\nu\ddot{\nu})/\dot{\nu}^2$** (assumed constant)
- For **$P_0 << P$, $n = 3$**, have **“characteristic age”**
- If true age known,one can compute initial period
- From braking equation, one can derive $B_0$ at NS equator with R = NS radius. Value **at pole is $2B_0$**
- Typically assumed **R=10 km, I=$10^{45}$ gm cm$^2$, n=3**

(from Manchester & Taylor)

# Radio pulsar basic parameters

Radio pulsars are powered by rotational energy

The observation of the spin period P and of its derivative $\dot{P}$ allows one to give an estimate of various physical quantities:

**Spin-down age:** $\tau_c = 1.6 \cdot 10^6 \; P / \dot{P}_{-14}$ yr

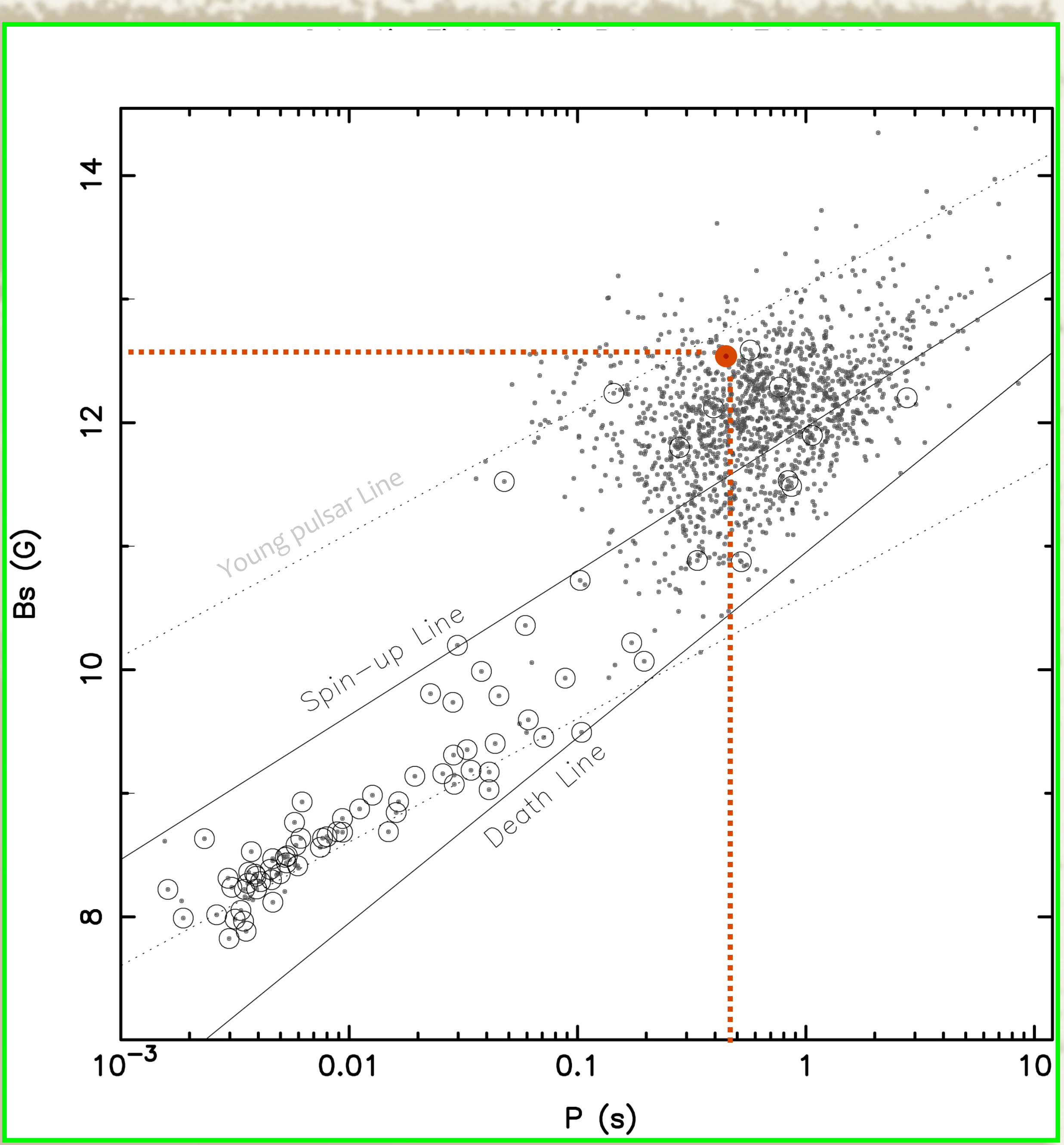
**Spin-down power:** $L_{sd} = 3.9 \cdot 10^{32} \, P^{-3} \, \dot{P}_{-14}$ erg/s

**Surface magnetic field:** $B_{surf} = 3.2 \cdot 10^{12} \, [\, P \, \dot{P}_{-14} \,]^{1/2}$ Gauss

… and allows one to place a pulsar on the basic P vs $\dot{P}$

[ or P vs $B_{surf}$ ] diagram…

# The $B_s$ vs P diagram



A pulsar is put on it once both P and dP/dt are measured, from which

$$B_s = 3.2\cdot 10^{19}\,[\,P\,\dot{P}\,]^{1/2}\ \mathrm{G}$$

ATNF Pulsar Catalogue

# Pulsar Energetics

## Spin-down Luminosity:

$L_{\mathrm{sd}} = \dot{E}_{\mathrm{sd}} = -I\Omega\dot{\Omega} = 4\pi^2 I\dot{P}P^{-3}$, where $\Omega = 2\pi/P$

For a "normal" pulsar, $I \sim 10^{45}$ g cm$^2$, $P \sim 1$ s, $\dot{P} \sim 10^{-15}$, $L_{\mathrm{sd}} \sim 10^{32}$ erg s$^{-1}$.

For an MSP, $P \sim 3$ ms, $\dot{P} \sim 10^{-20}$, $L_{\mathrm{sd}} \sim 10^{34}$ erg s$^{-1}$.

(from Manchester & Taylor)

## Radio Luminosity:

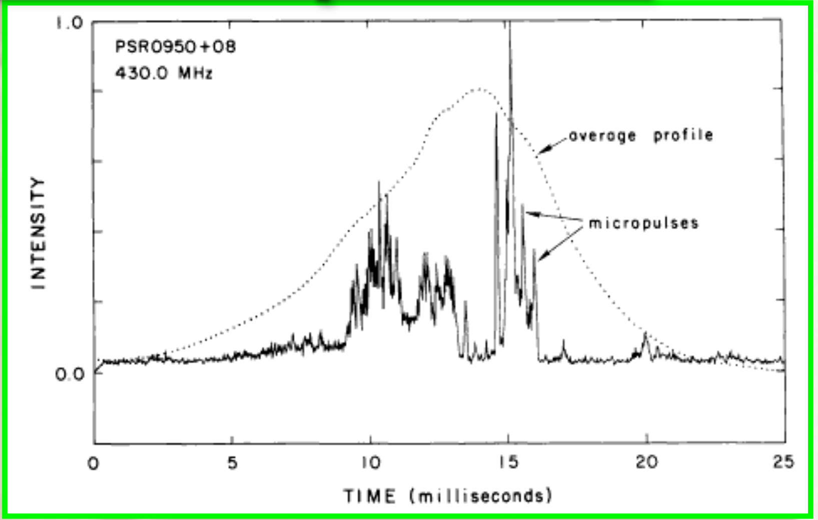
$$L_{\mathrm{rad}} = S\ 4\pi d^2\ \Delta\nu$$

For $S \sim 10$ mJy $= 10^{-28}$ W m$^{-2}$ Hz$^{-1}$ $= 10^{-25}$ erg cm$^{-2}$ Hz$^{-1}$
$d = 1$ kpc $= 3 \times 10^{21}$ cm, $\Delta\nu = 10^9$ Hz, $L_{\mathrm{rad}} \sim 10^{28}$ erg s$^{-1}$ $<< L_{\mathrm{sd}}$

(from Manchester & Taylor)

# Radio emission is a coherent process

- Source power is very large, but source area is very small
- Specific intensity is very large
- Pulse timescale gives limit on source size ~ c Δt
- Brightness temperature: equivalent black-body temperature in Rayleigh-Jeans limit



$$I_\nu = \frac{2\nu^2 k T_{\rm B}}{c^2} \ {\rm erg\ s^{-1}\ cm^{-2}\ Hz^{-1}\ sr^{-1}}$$

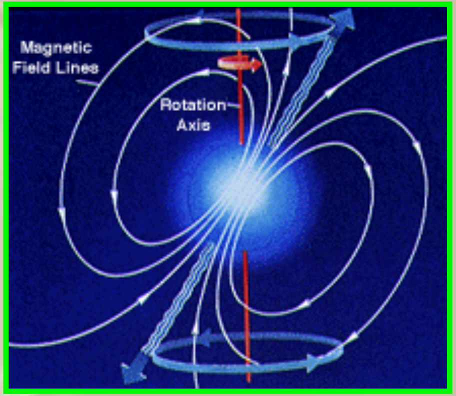
For pulse timescale $\Delta t = 1\mu$s, source area $A \sim (c\,\Delta t)^2 = 10^9$ cm$^2$ and $L_{rad} = 10^{29}$ erg s$^{-1}$:

$$I = 10^{20}\ {\rm erg\ s^{-1}\ cm^{-2}}\ (= 10^7\ {\rm MW\ cm^{-2}}!!!)$$

For solid angle $\sim 1$ sr, $\nu = 10^9$ Hz: $T_{\rm B} \sim 10^{30}$ K (!!)

**Radio emission must be from a COHERENT process!**

# The total energy budget for the Crab



Given the following parameters
at 2008 for the Crab Pulsar
$P = 33.5965$ msec
$dP/dt = 4.2 \cdot 10^{-13}$ sec/sec

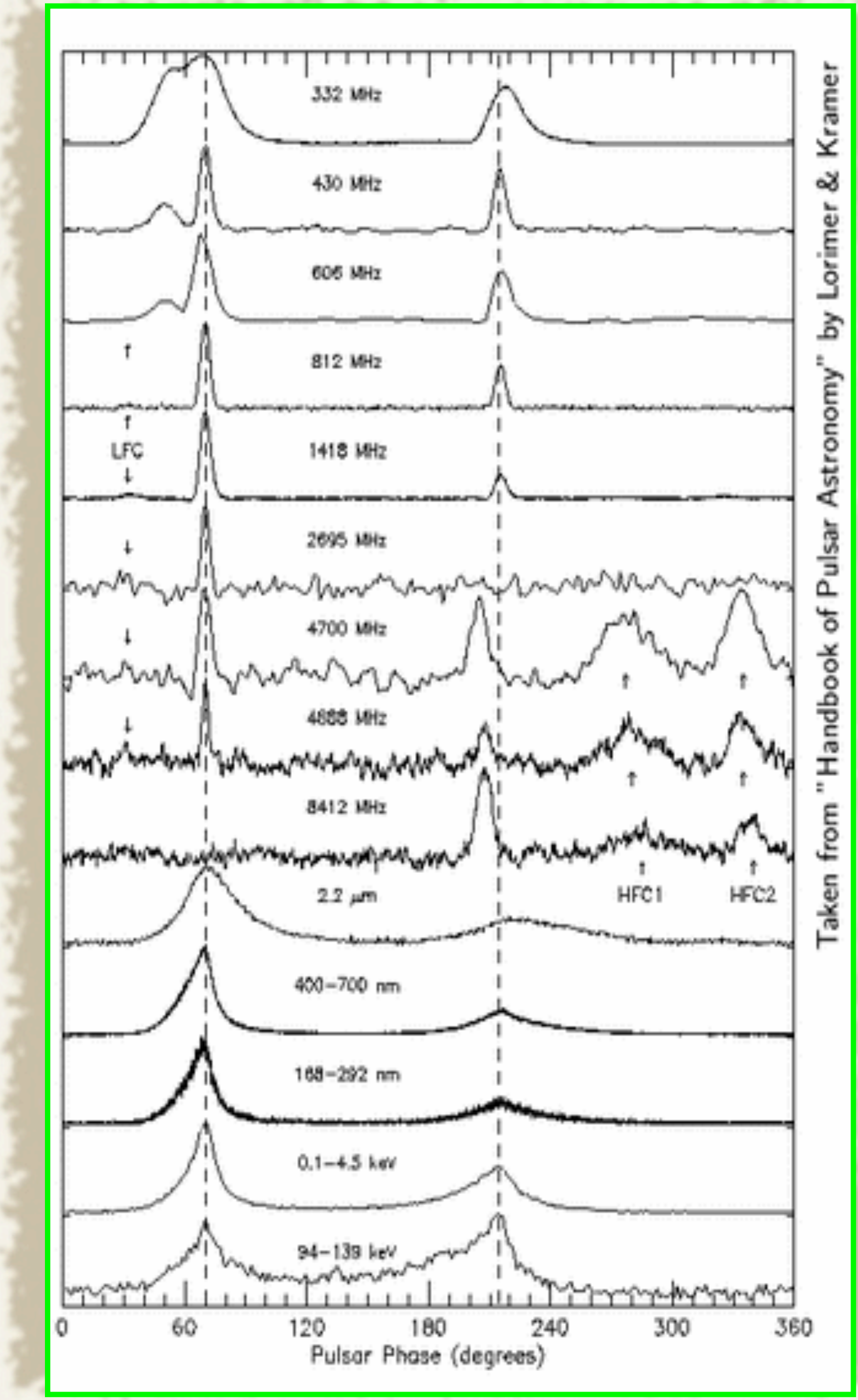
$E_{rot} = 0.5\ I\Omega^2 = 3 \cdot 10^{49}$ erg

$L_{sd} = d/dt\,(E_{rot}) = d/dt\,(0.5\ I\Omega^2) = 4.6 \cdot 10^{38}$ erg/sec

Whereas, observing the total
luminosity $L_{total}$ released from
the whole Crab Nebula

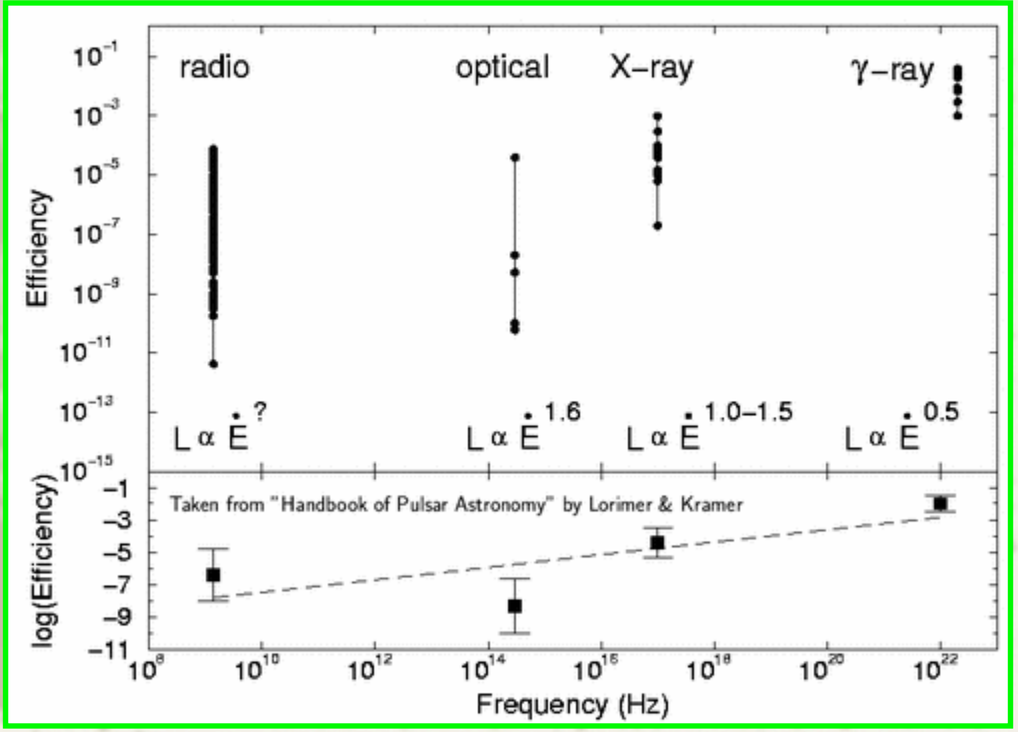
$L_{total} = L_{psr} + L_{snr} = L_{e.m.} + L_{kin\_snr} \sim 5 \cdot 10^{38}$ erg/sec

**RADIO PULSARS BELONG TO THE CATEGORY OF THE ROTATION POWERED NEUTRON STARS**



Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

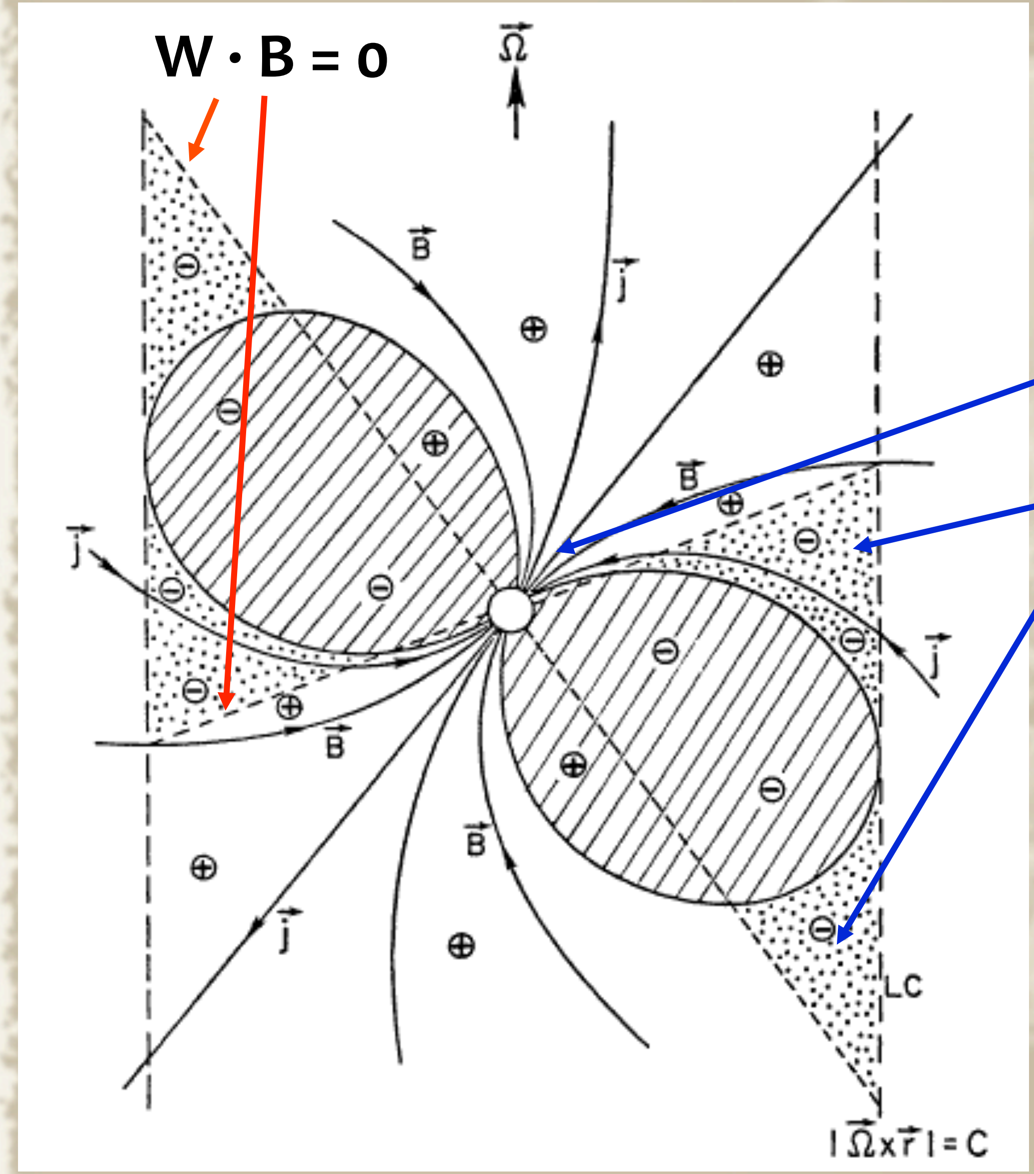
# Wide band emission and efficiency of conversion of spin down luminosity in Rotation Powered Neutron Stars



Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

# Rotating neutron-star model: magnetospheric gaps

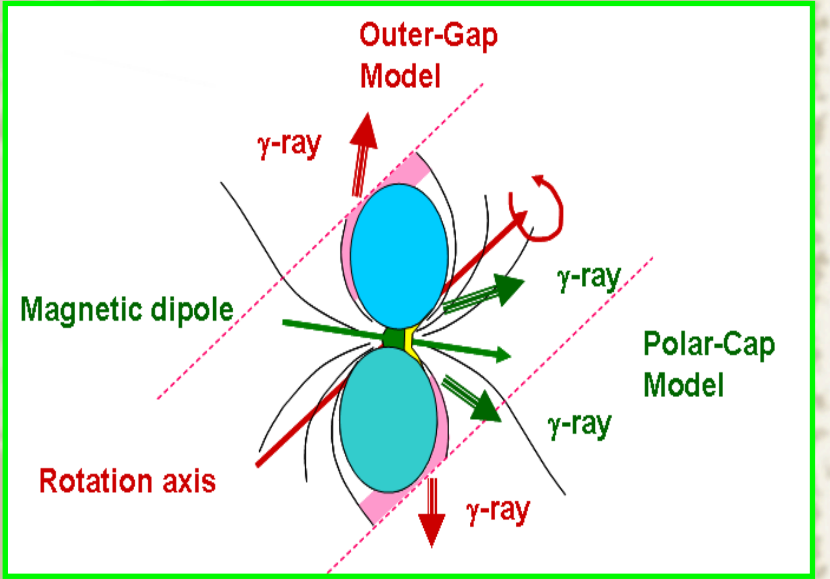
Various proposed regions of particle acceleration



Inner (polar cap) gap

Outer gaps

Cheng et al. (1986); Romani (2000)

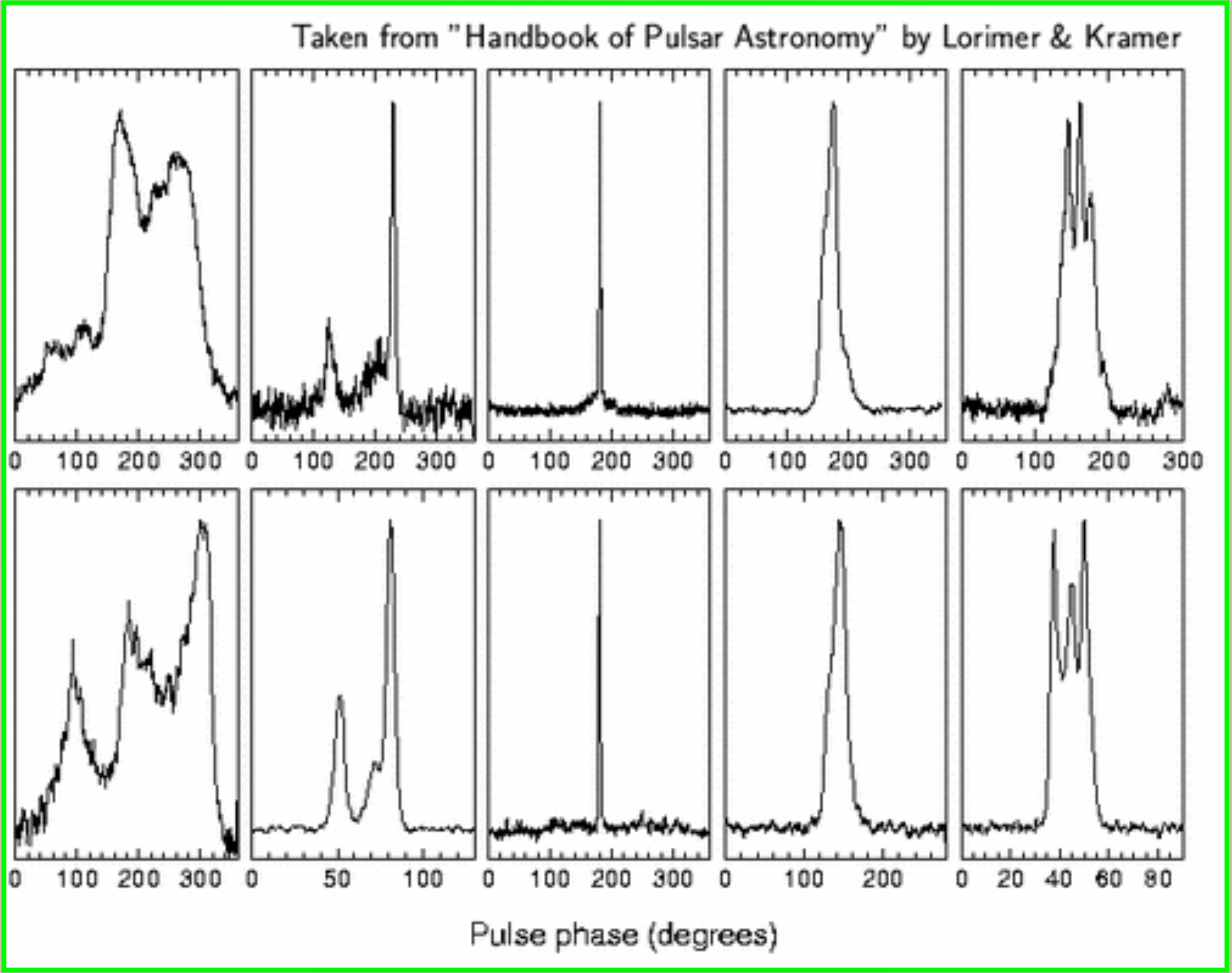


Harding (2002)

# Basic picture of pulsar electrodynamics

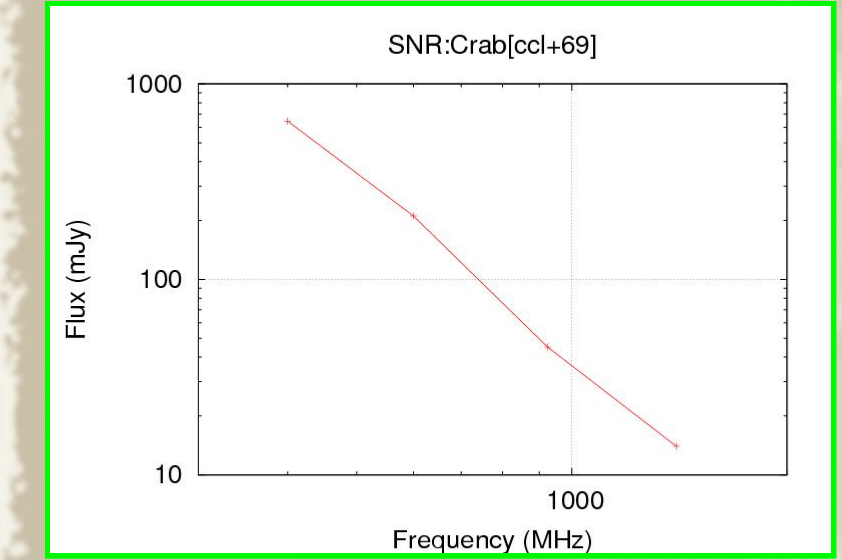
- For a typical pulsar, $P = 1$ s, $P = 10^{-15}$ s/s, $B_s \sim 10^{12}$ G
- Typical electric field at the stellar surface $E_s \sim WRB_s/c \sim 10^9$ V/cm
- $e^{\pm}$ reach ultra-relativistic energies in < 1 mm
- $e^{\pm}$ emit g-ray photons by curvature radiation. These have energy >> 1 MeV and hence decay into $e^{\pm}$ pairs in strong B field
- These in turn are accelerated to ultra-relativistic energies and in turn pair-produce, leading to a cascade of $e^+/e^-$ pairs
- Relativistic pair-plasma flows out along ‘open’ field lines
- These flows lead to generation of radiation beams at high energy via synchrotron and/or inverse Compton processes
- Additional coherent processes in the magnetosphere of (as yet) unassessed nature lead to the generation of radio beam(s)

# Mean pulse shapes



Lorimer & Kramer (2005)

# *Pulsar spectra*

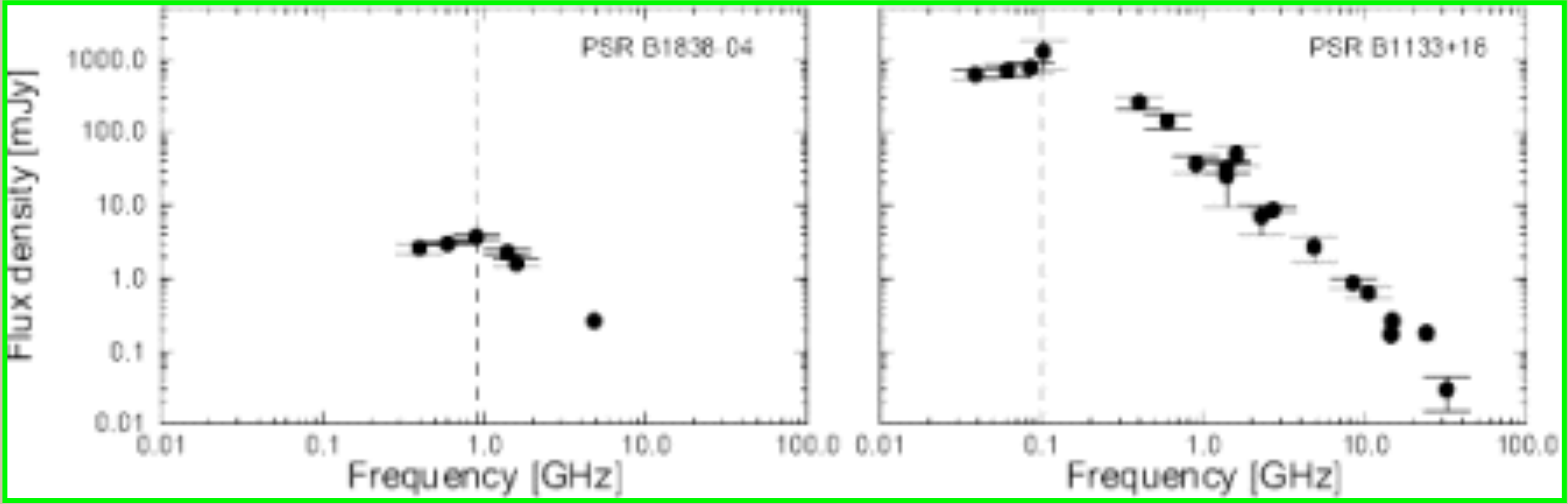


- **Pulsar spectra are typically steep**

  **Flux ~ $\nu^{-\alpha}$ $\langle\alpha\rangle \sim 1.7$**

  **but $0.0 < \alpha < 3.5$**

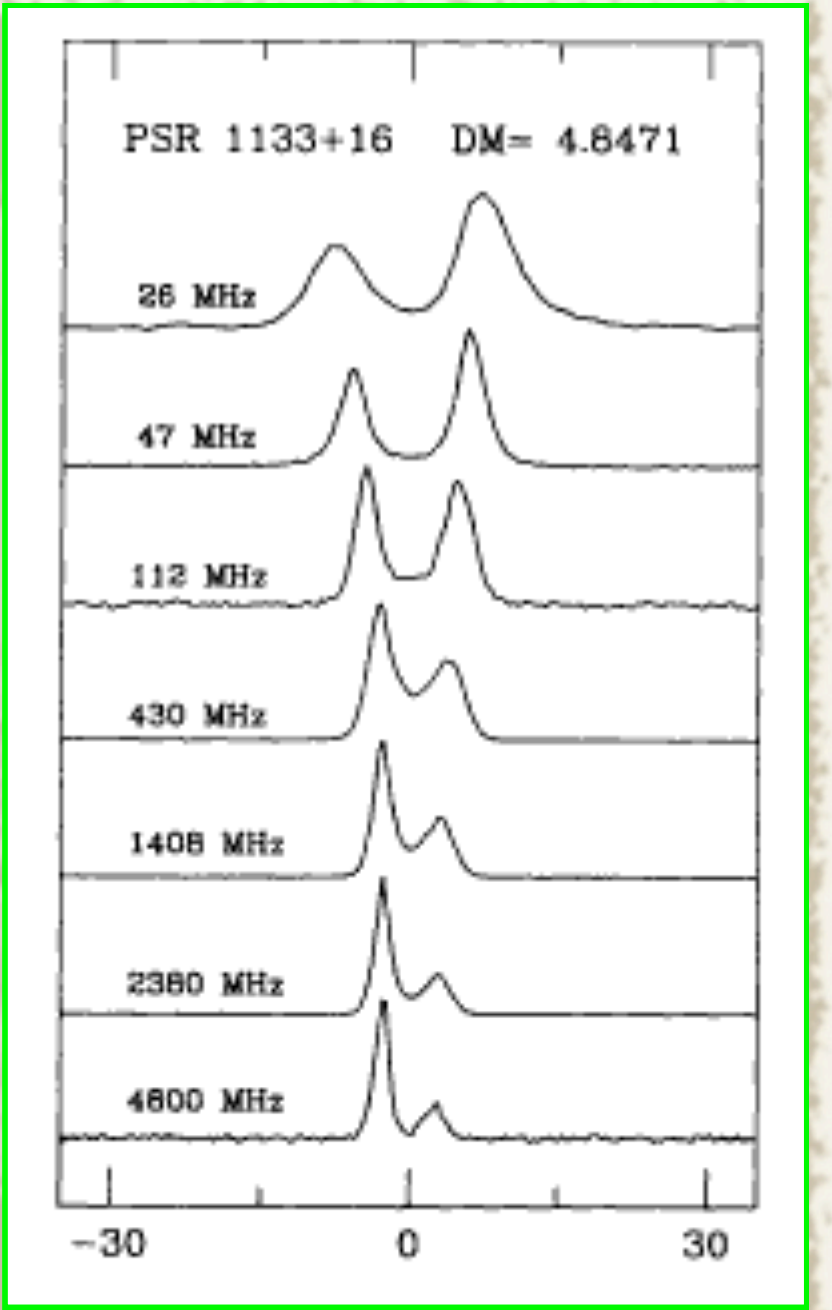
- **A turnover is tipically at $\nu \sim$ 100-200 MHz but there are exceptions**



MPIfR (2000)

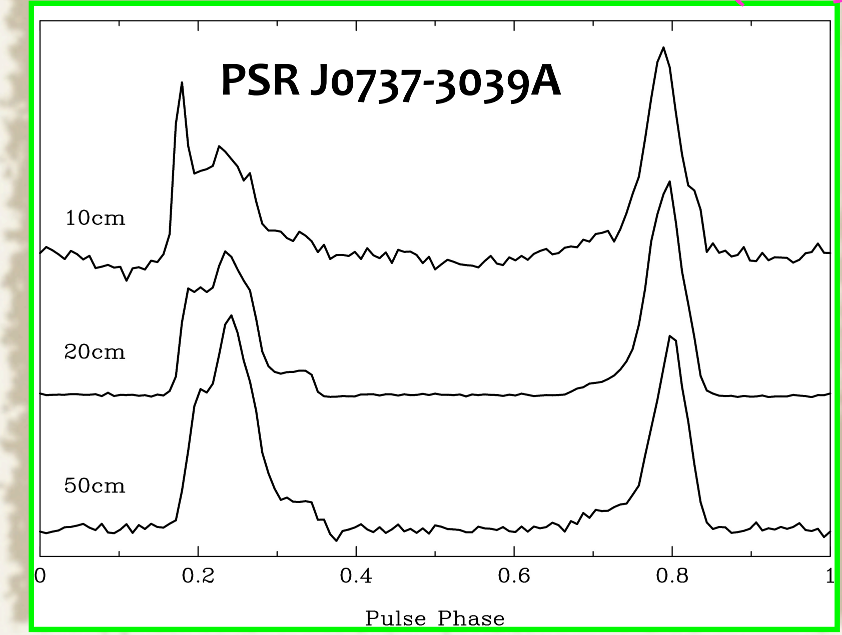
# Frequency Dependence of Mean Pulse Profile

- Pulse width generally increases with decreasing frequency.
- Consistent with 'magnetic-pole' model for pulse emission.
- Lower frequencies are emitted at higher altitudes.

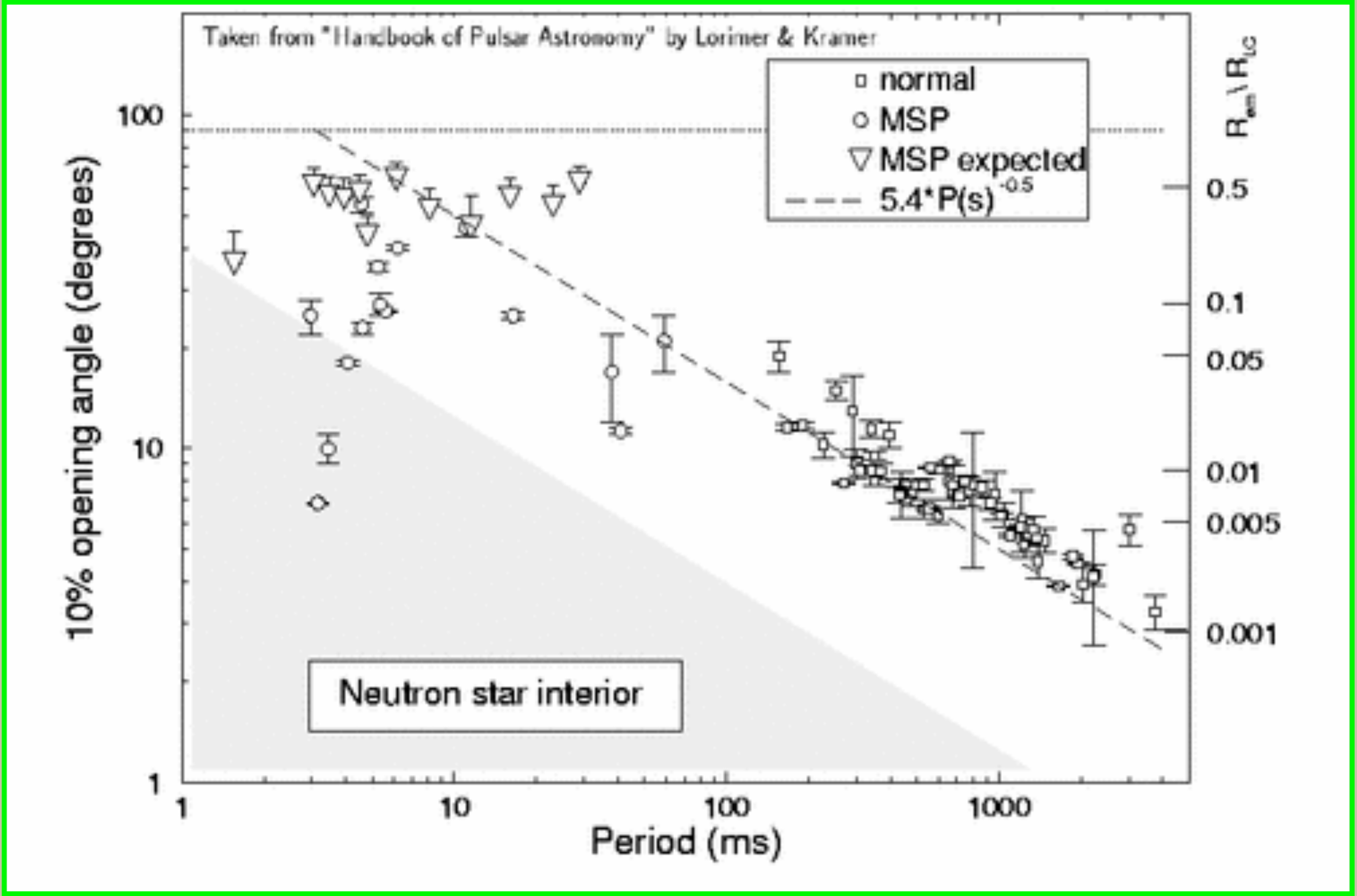


Phillips & Wolsczcan (1992)

Manchester et al. (2005)

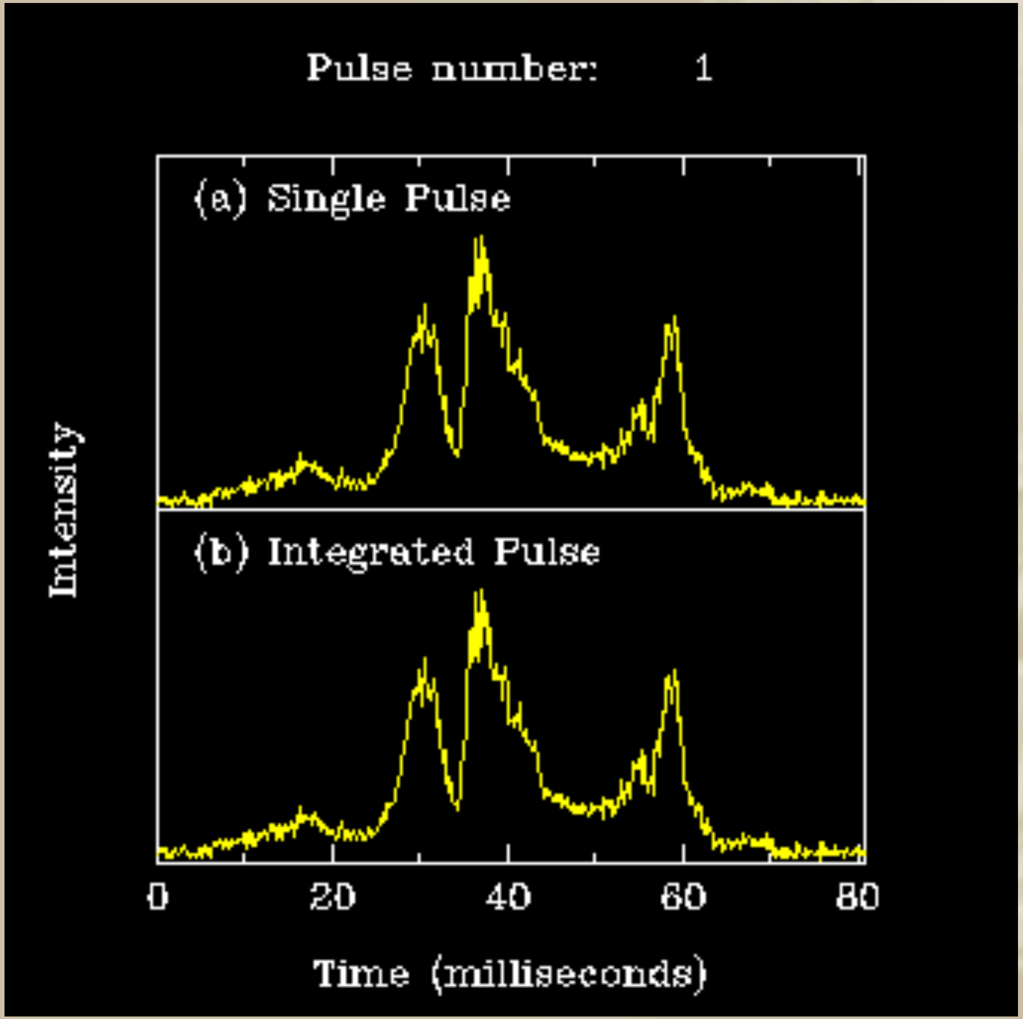


# *Width of the radio beam*



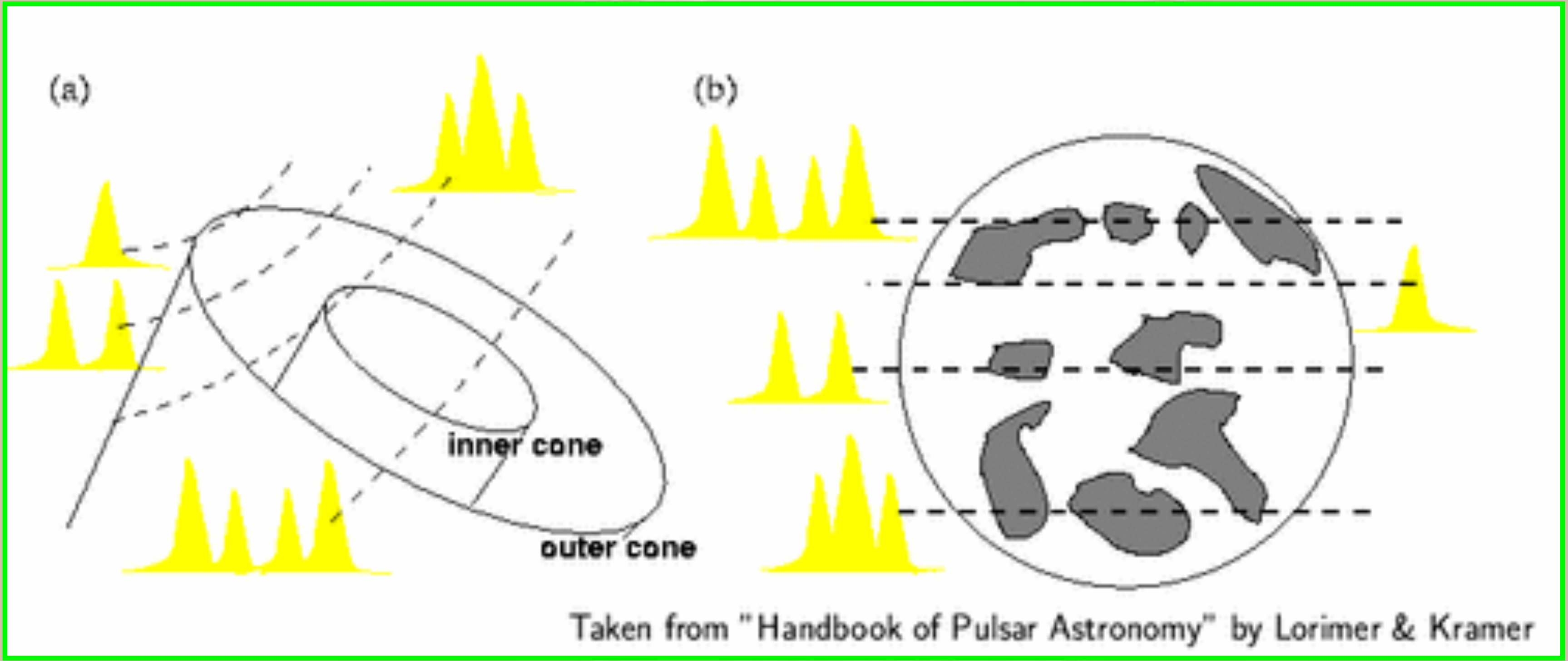
**In the subsample of pulsar with P>100 ms, there appears a tendency to present smaller beam widths for longer spin periods:** $W_{10\%} \sim 5.4^{\circ} / P(s)^{1/2}$

# Single pulse chaotic behaviour



- A stable pulse profile builds up only after summing many (typically 100-1000) pulses.

# Radio Beam structure



Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

**Core + multiple cones structure**

Rankin (1990,1995)

**Patchy structure**

Manchester & Lyne (1988)

# The many flavours of the Neutron Stars

**≈ 2400 Radio pulsars** (powered by rotational energy)

≈ **20 Rotating Radio** Transients (powered by rotational energy?)

26 Magnetars (powered by magnetic energy)

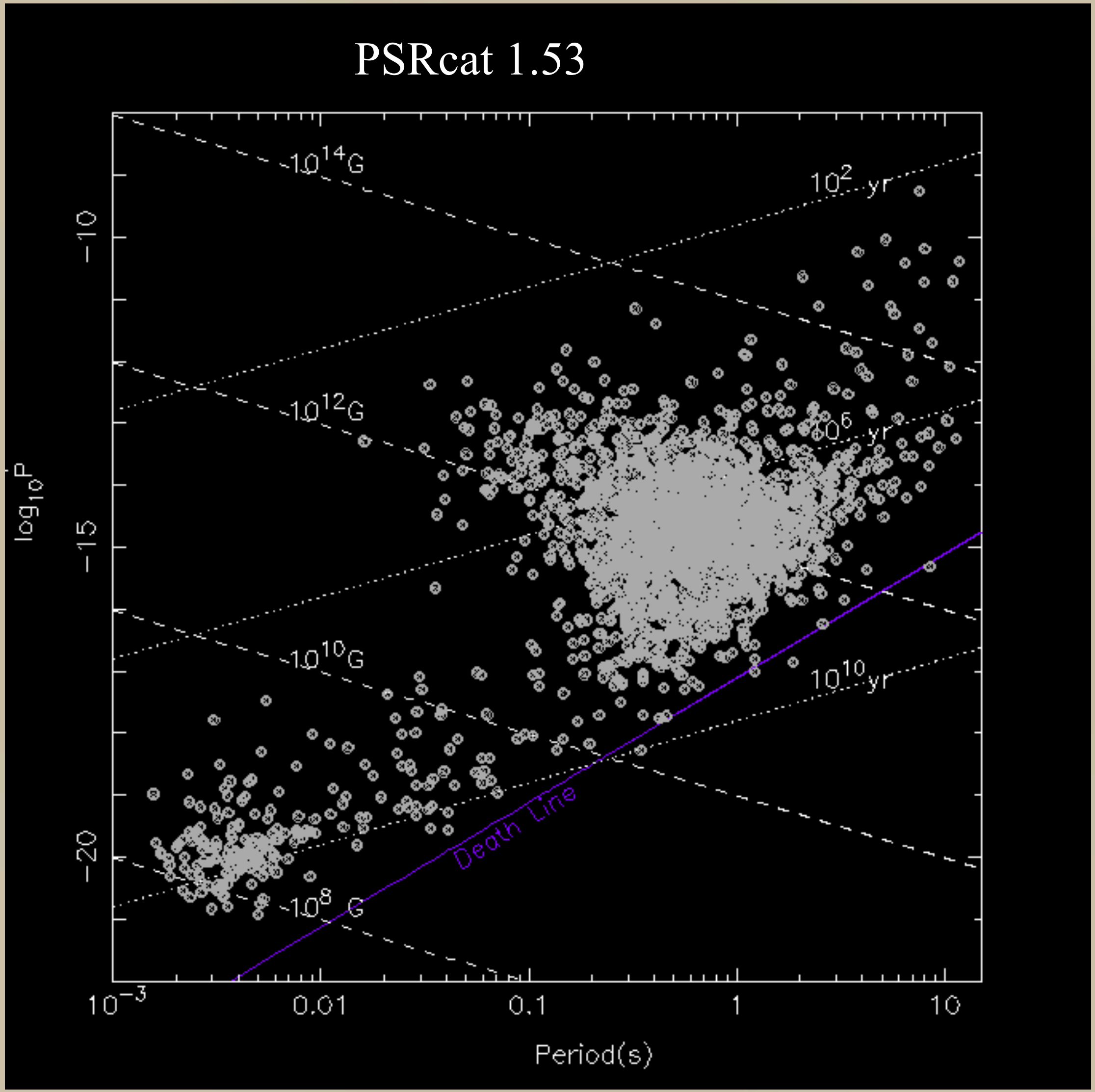
7 X-ray Dim **Isolated NS** (powered by thermal energy?)

≈ 10 Central Compact Objects **in SNR** (powered by thermal energy?)

≈ few 100s Accreting NS **in binaries** (powered by accretion energy)

# The many flavours of the Neutron Stars

The P vs $\dot{P}$ diagram



http://www.atnf.csiro.au/people/pulsar/psrcat

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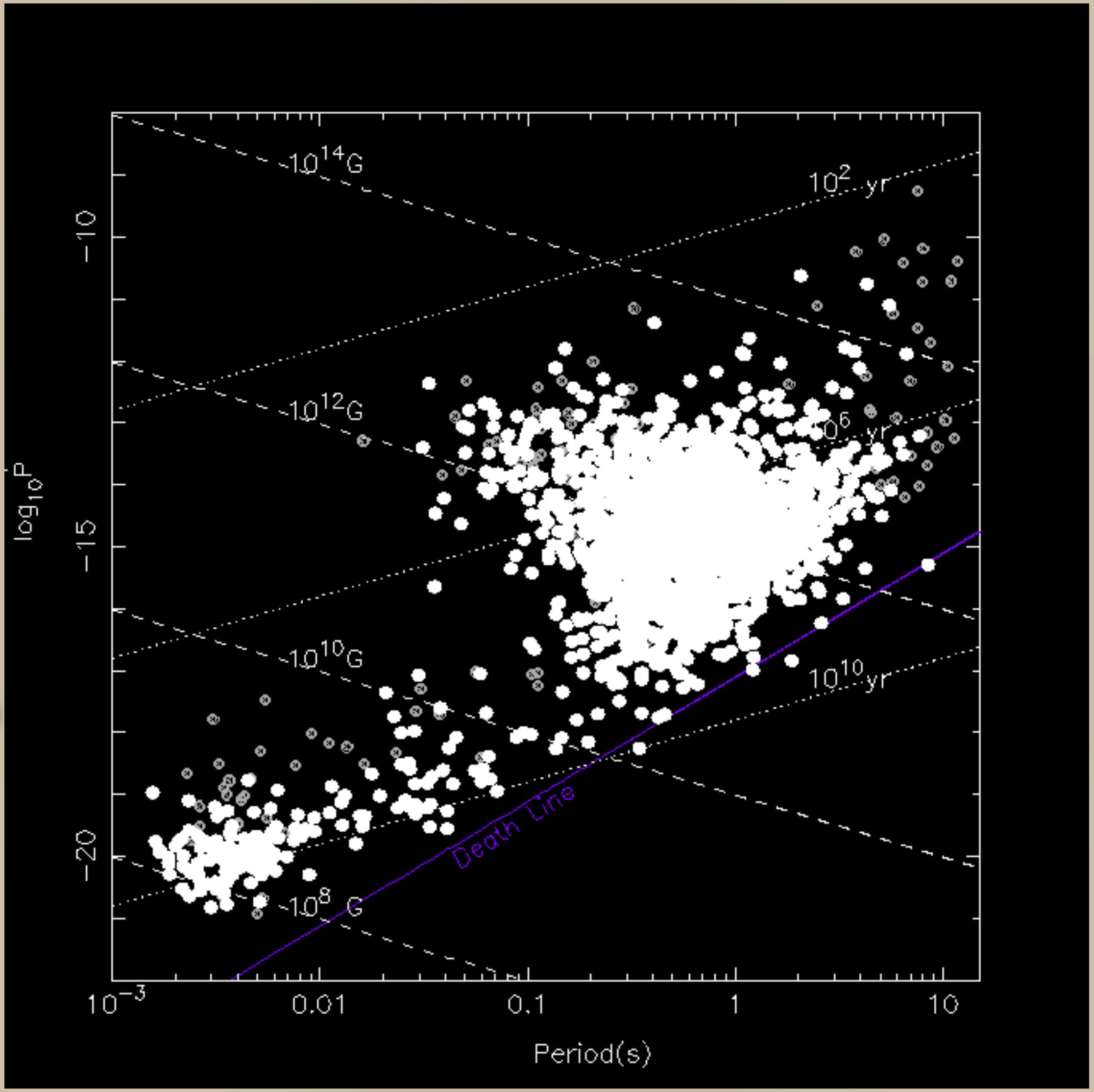
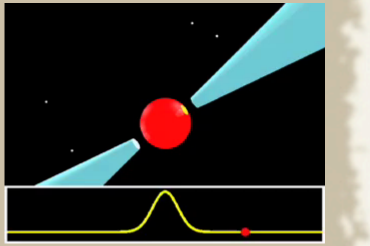
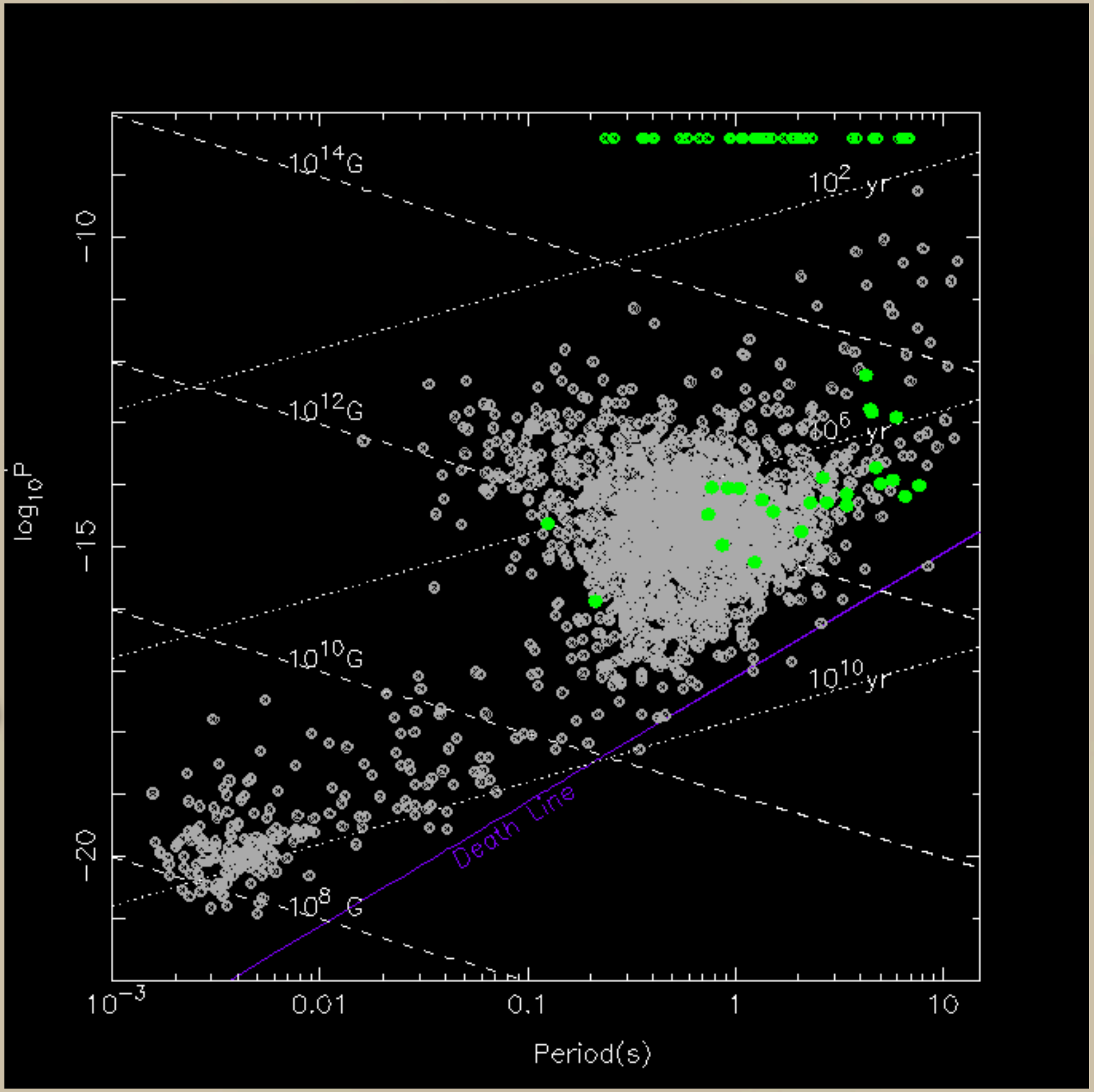
## The P vs $\dot{P}$ diagram

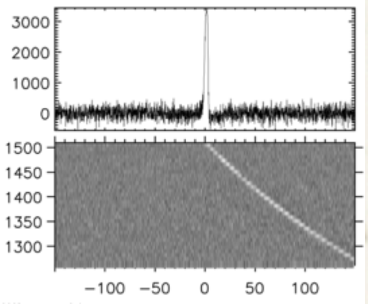


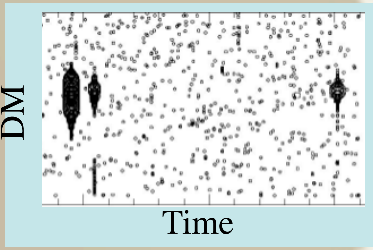


# The many flavours of the Neutron Stars

The $P$ vs $\dot{P}$ diagram







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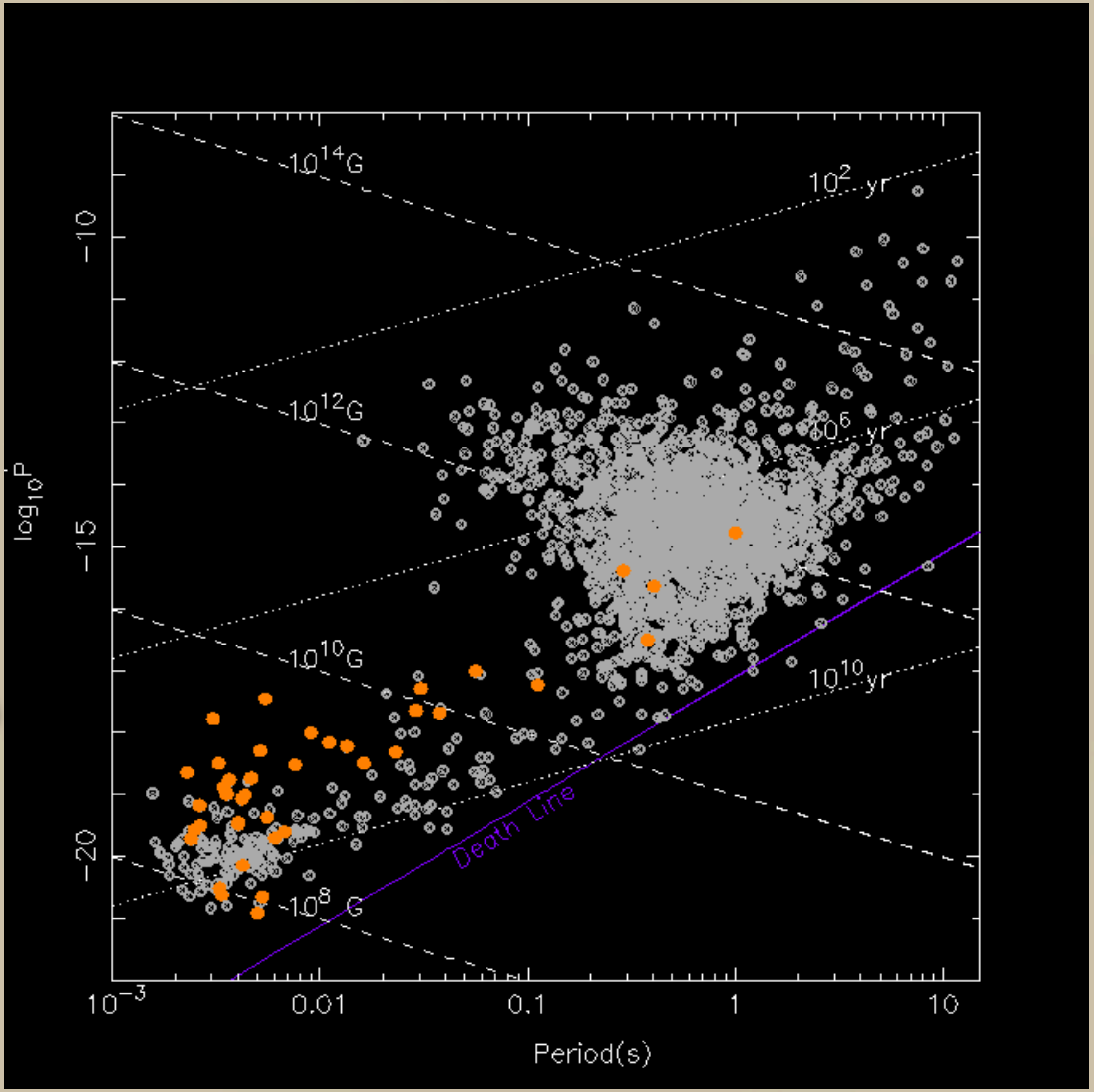

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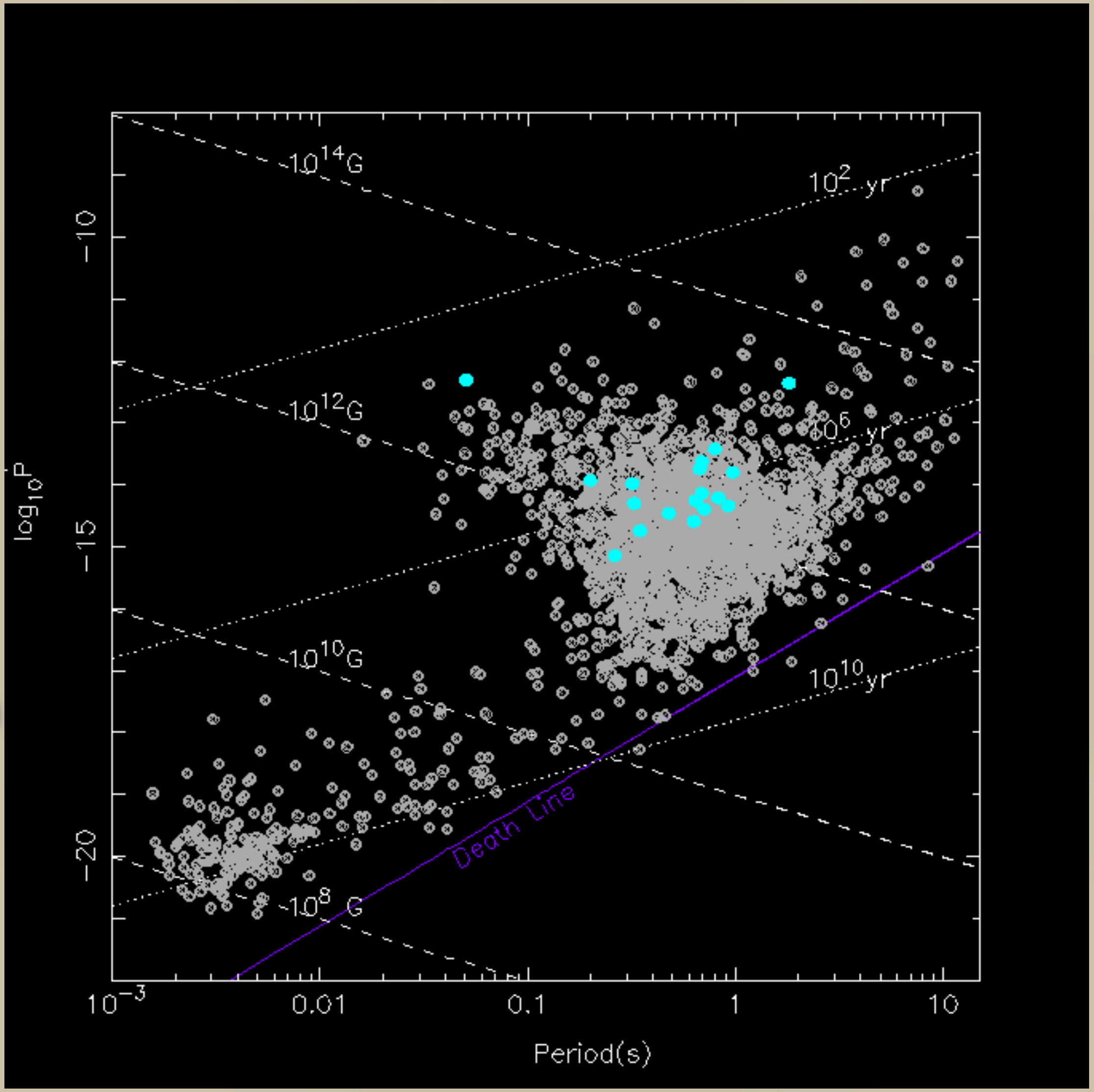

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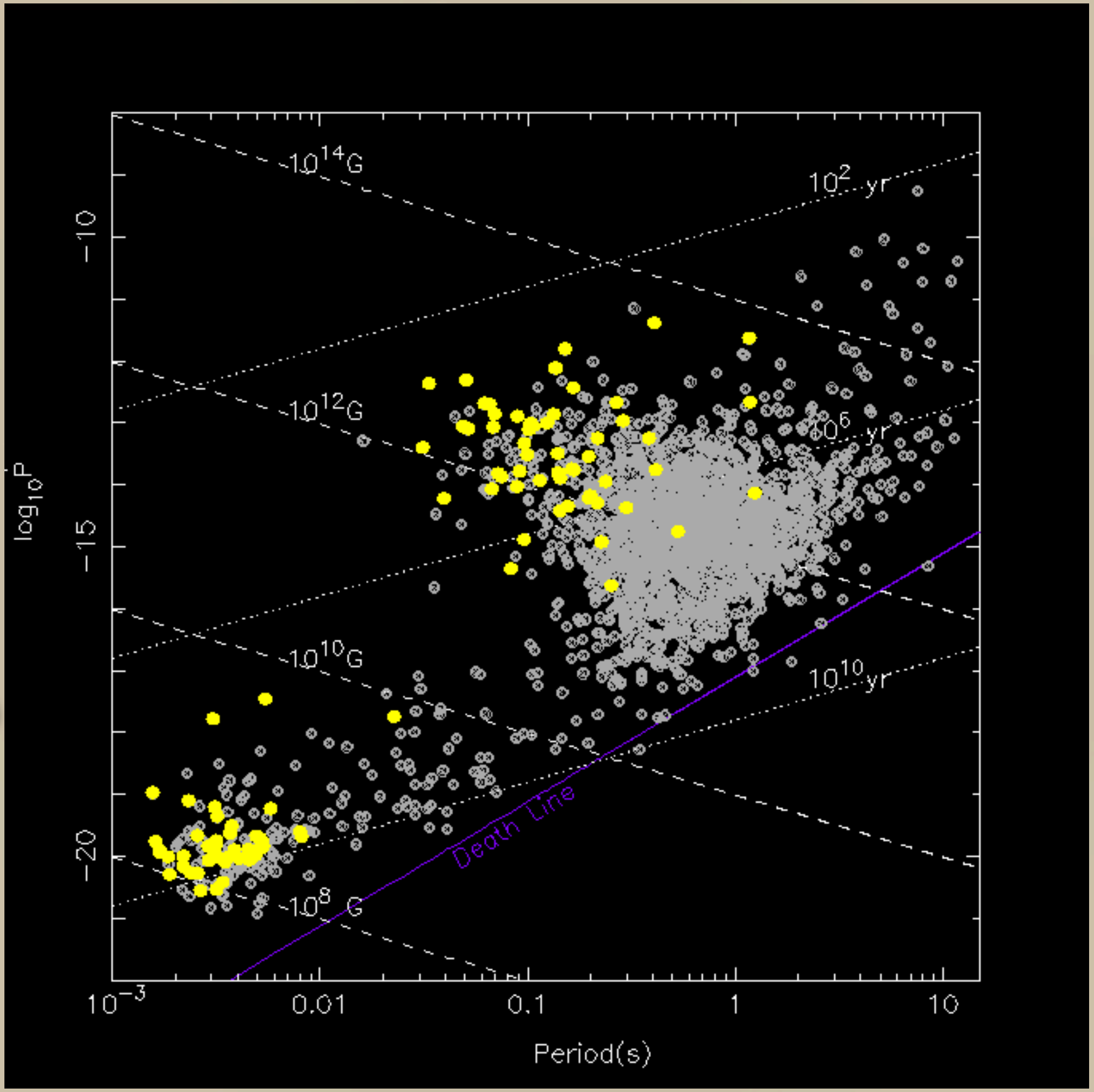

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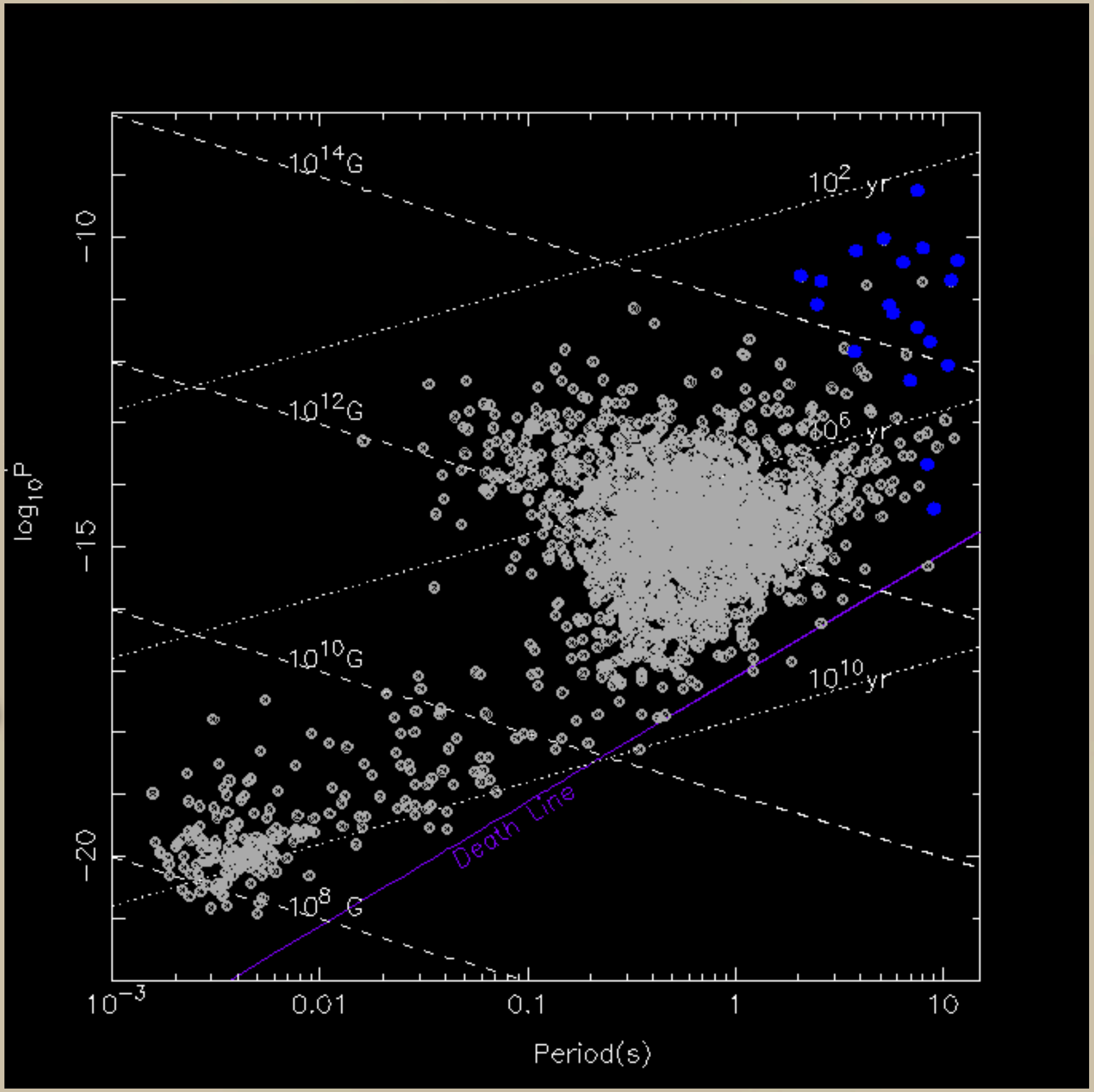
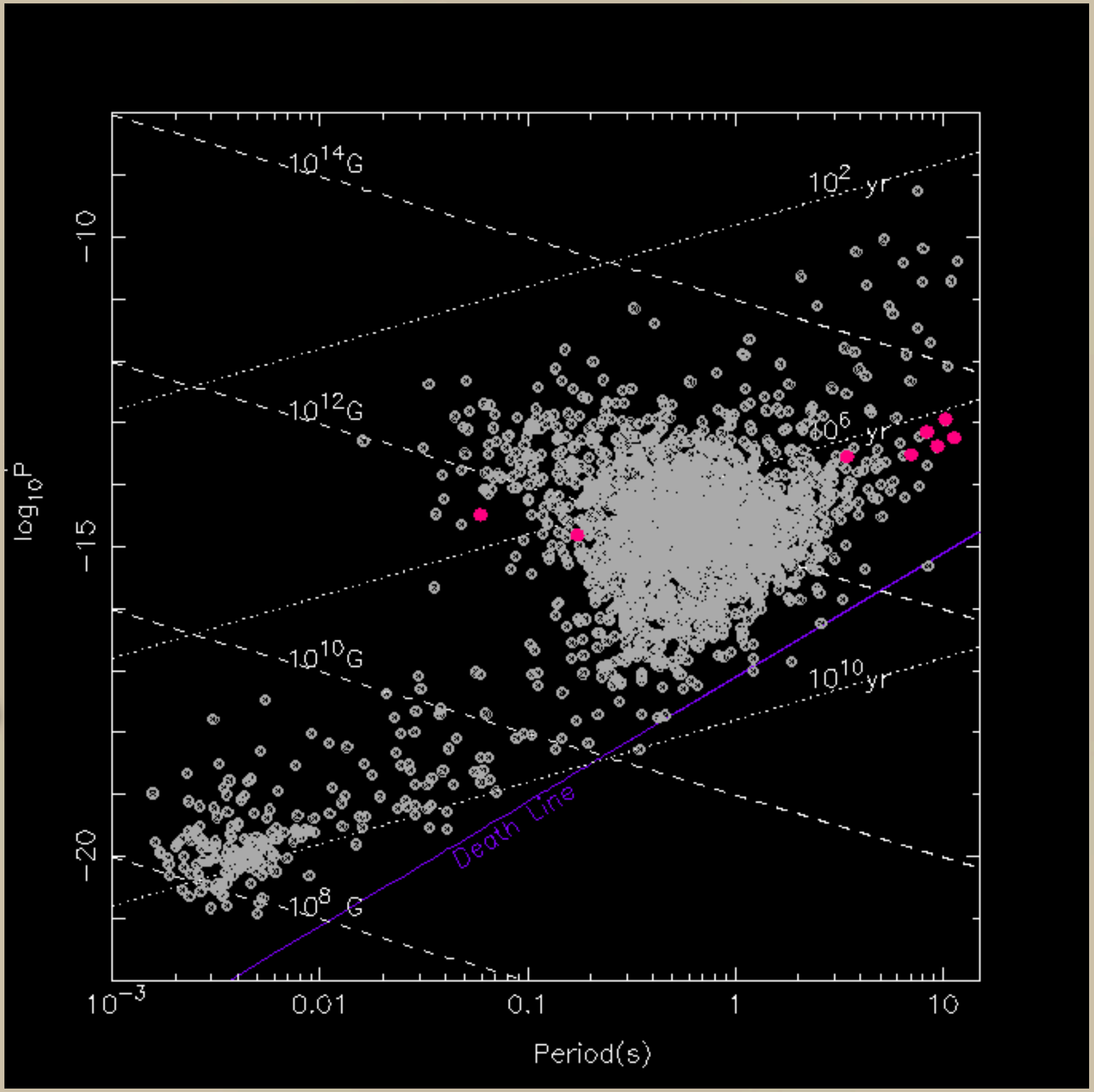


# The many flavours of the Neutron Stars

The P vs $\dot{P}$ diagram



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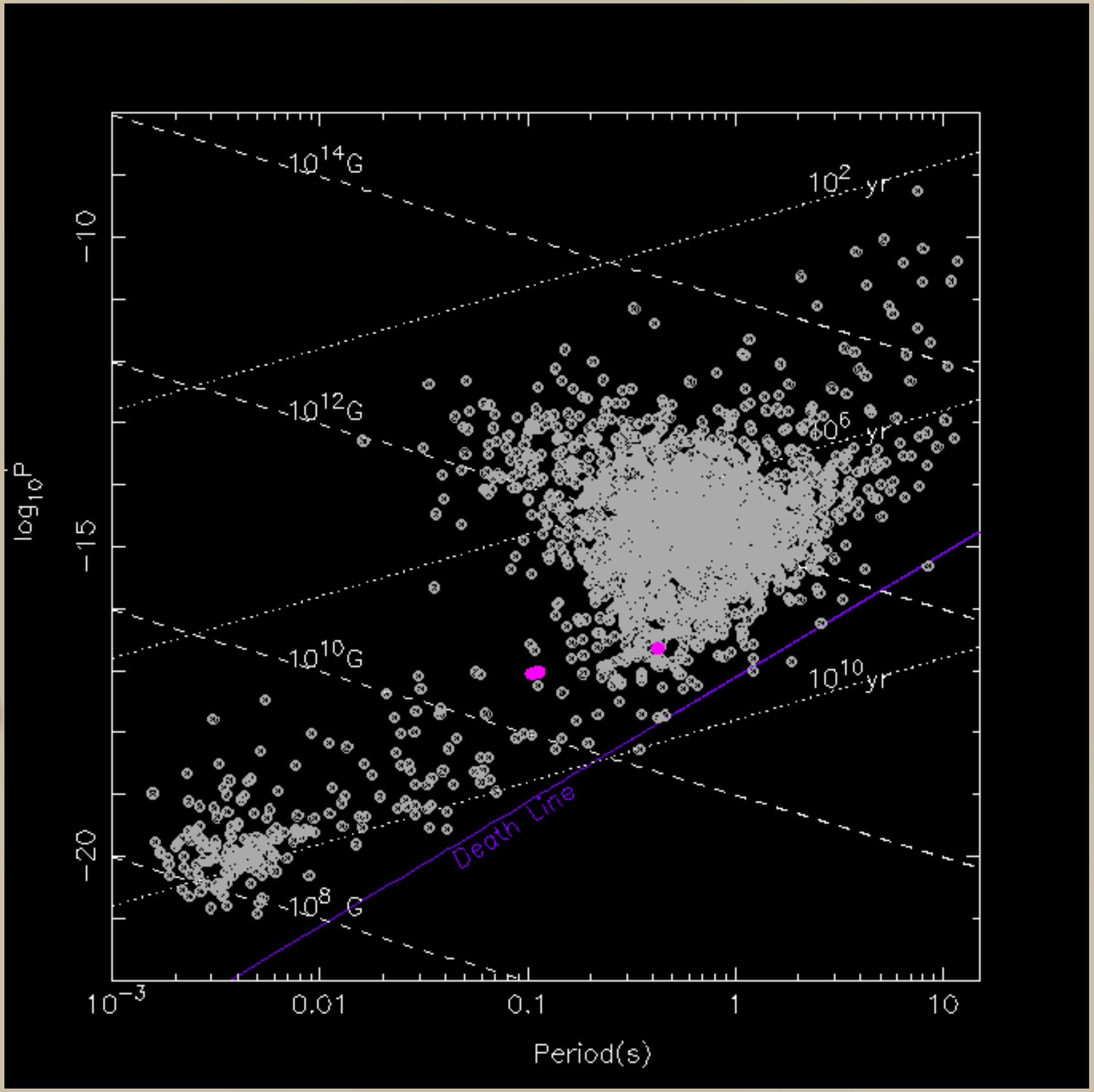

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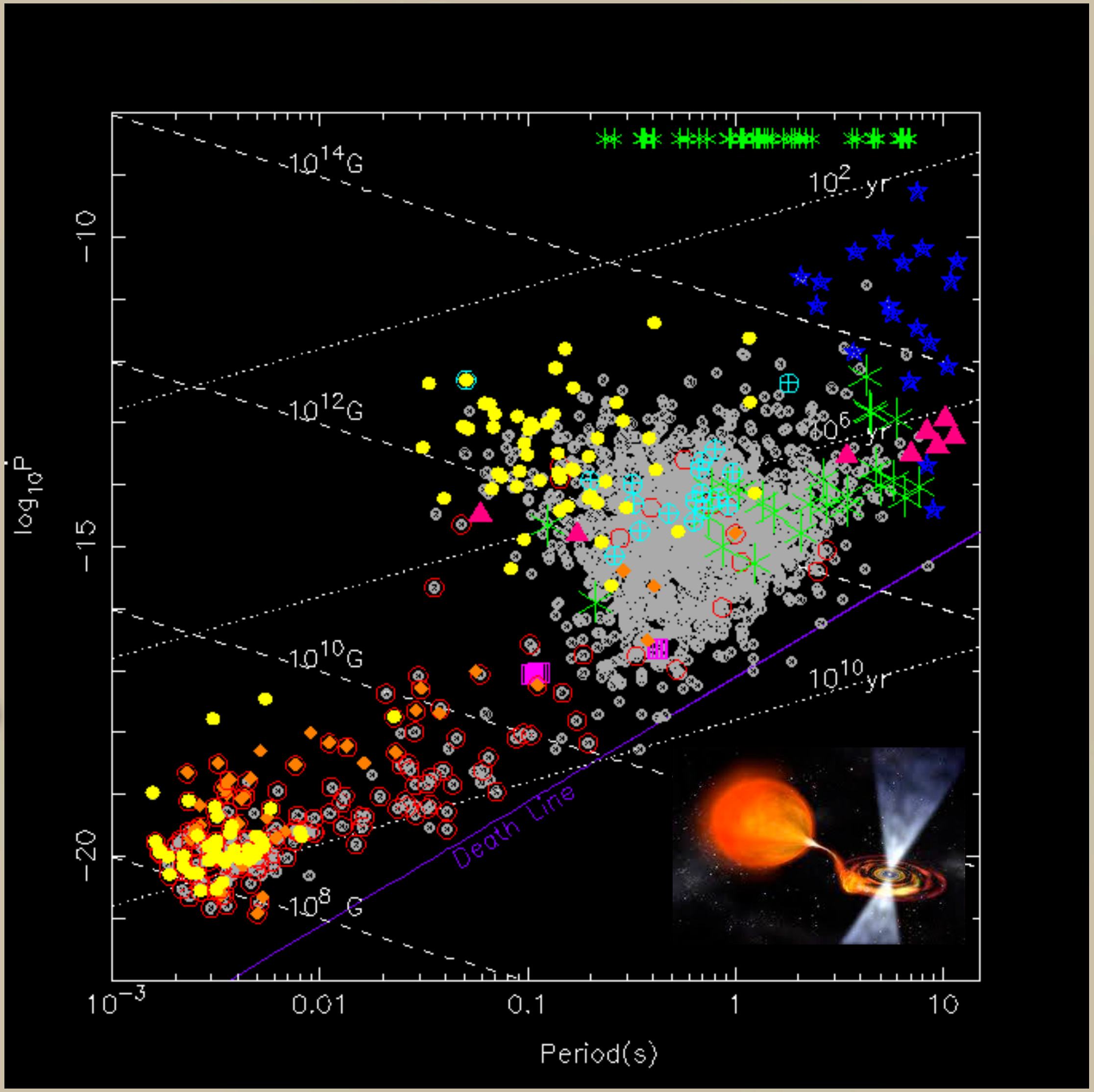

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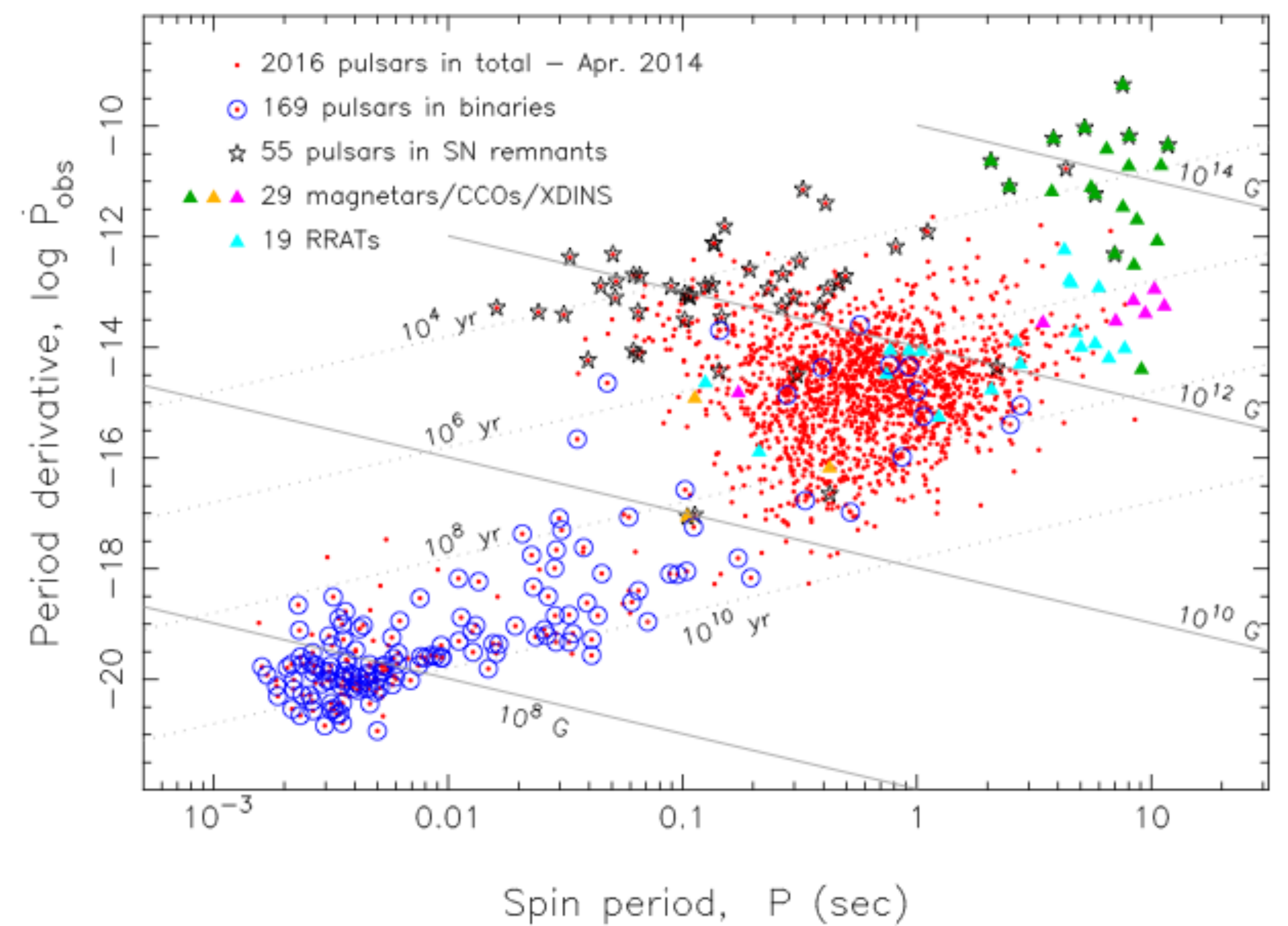
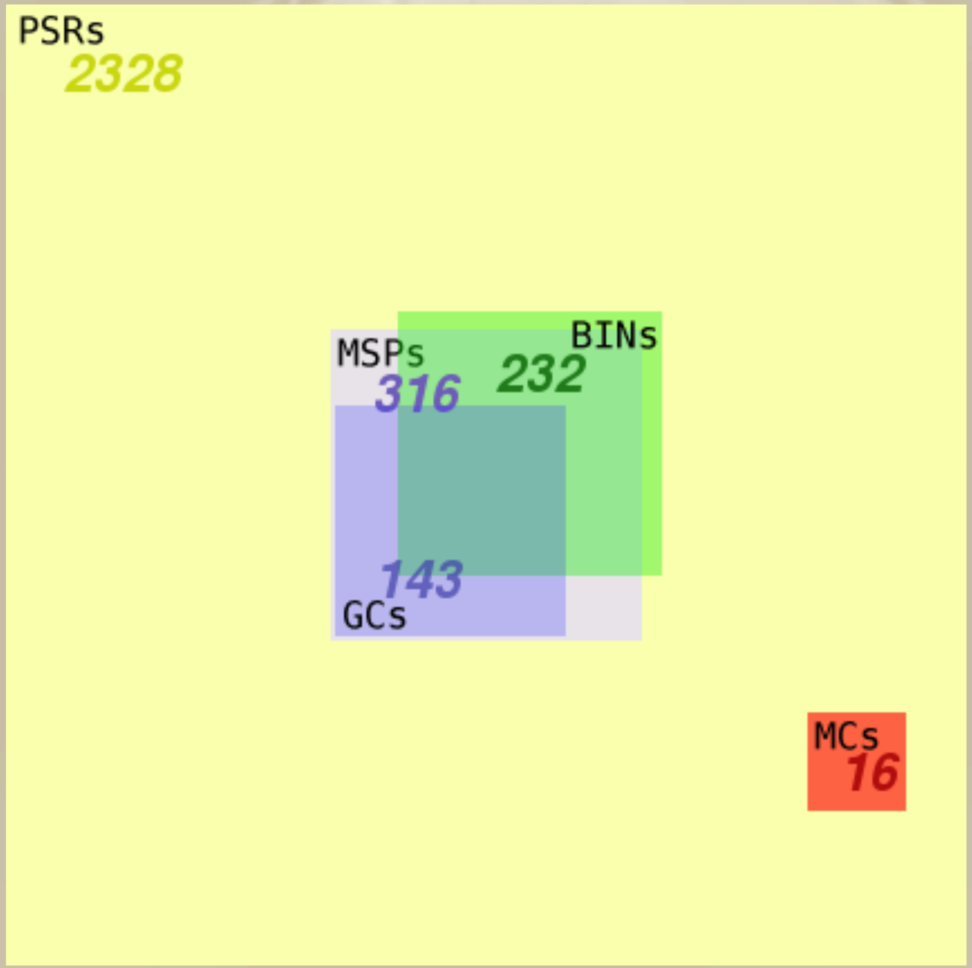


ATNF Pulsar Catalogue + [Tauris et al 2015]

# ***The current pulsar demography***



[Possenti & Burgay 2015]

≈10 % of known pulsars are in **binaries**