Time-Domain Astronomy

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Pulsars

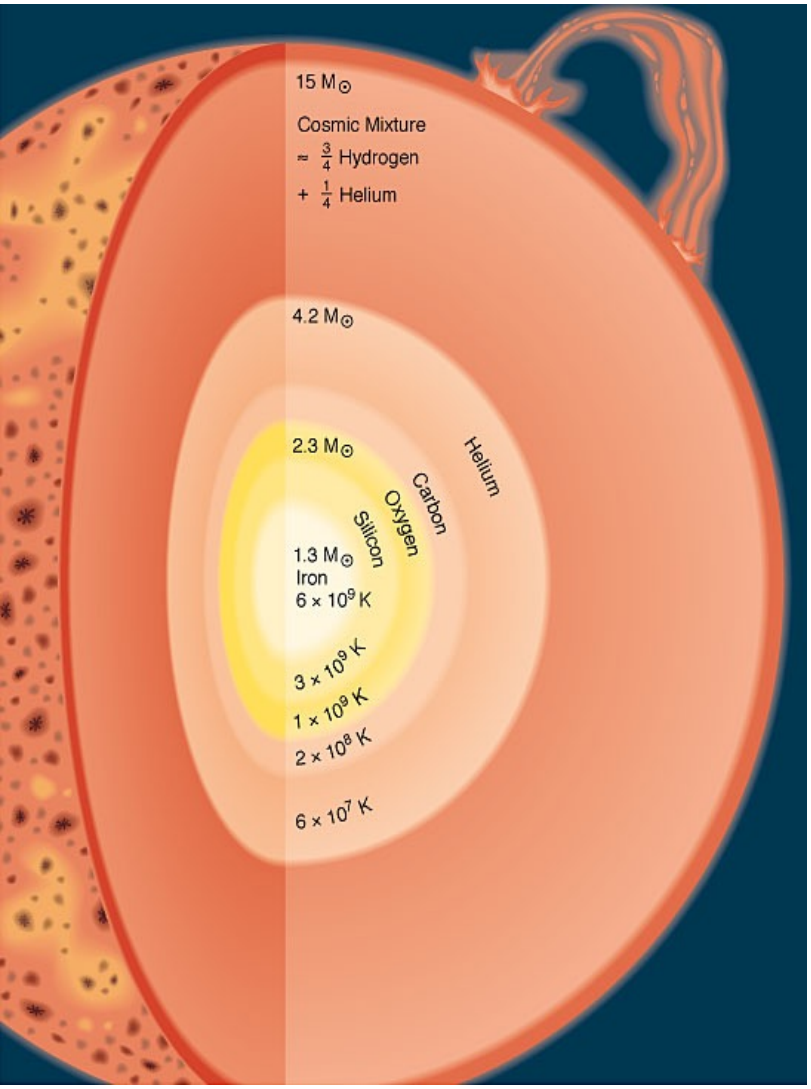
A pulsar is the final evolutionary stage of a star that was initially at least eight times more massive than the Sun. As the star evolves, it builds up an iron core, and when nuclear fusion can no longer generate pressure to support it, the core collapses, leading to the collapse of the outer layers of the star.

This collapse, in an eye blink turns into an explosion – falling outer layers of the star ignite and explode. From outside one can see a spectacular event: the explosion of a

SUPERNOVA

After the explosion sometimes the core of the star survives, as a very dense ball of collapsed matter – which due to transformation during the explosion is almost purely neutrons. It's a NEUTRON STAR

Birth of a Neutron Star



What actually happens in the centre of a supernova?

• stars live their lives in an equilibrium between the gravity and radiation pressure. But to have this presure one needs constant supply of radiation – on case of regular stars it is coming from the thermonuclear reactions in a stellar core.

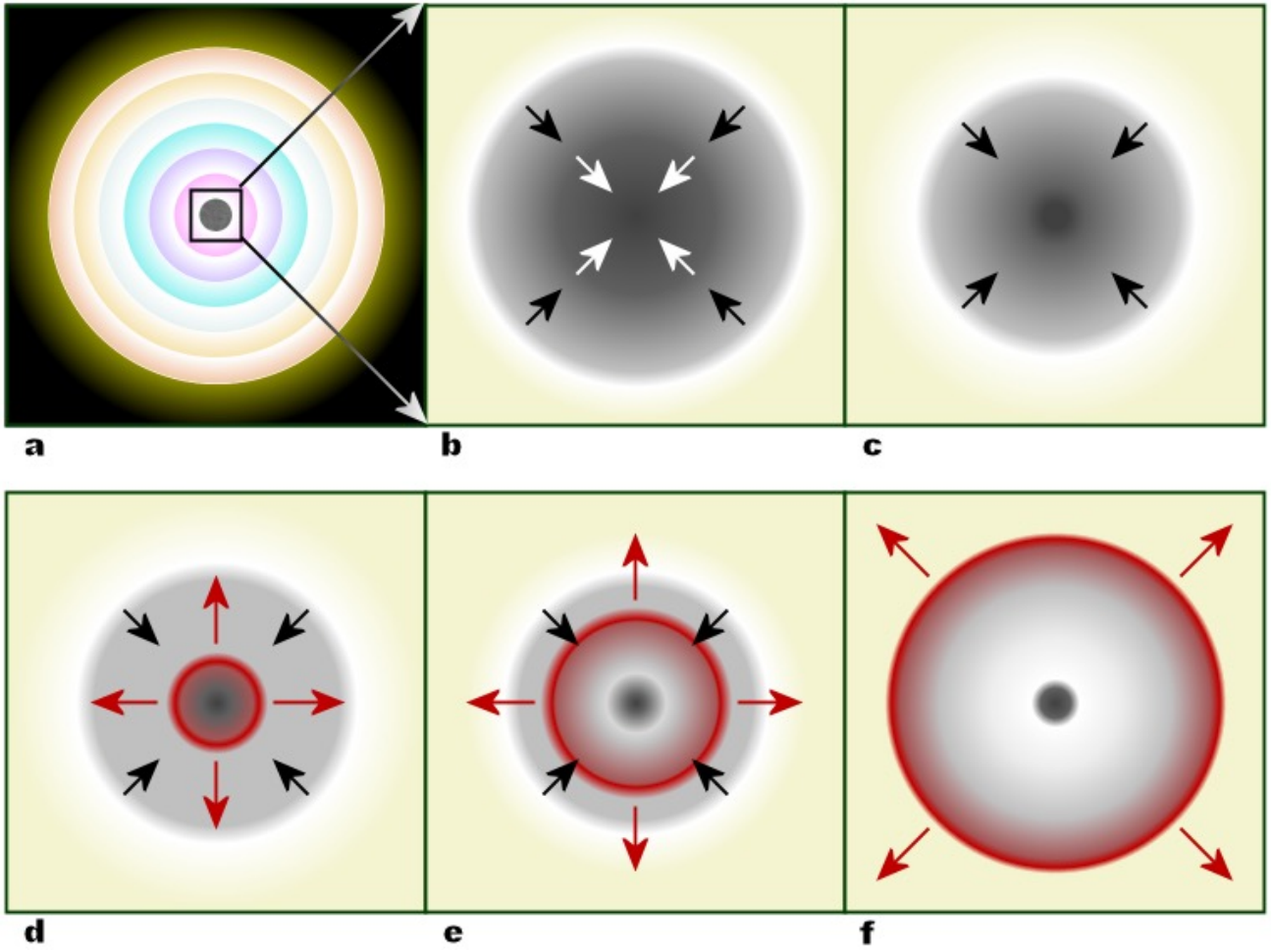
• iron is the last element which synthesis produces energy surplus. The synthesis of elements heavier than iron requires supplying energy.

• this causes the accumulation of iron in the core. The star just before the explosion resembles an onion – it has many layers consisting of various elements. The deeper you go into a star, the heavier atoms you see

Birth of a Neutron Star

At one point it gets so high, that virtually all the electrons are pressed into protons, and the neutronization of matter occurs:

$$p^+ + e^- \longrightarrow n + \nu$$



All the matter is converted into neutrons. The neutrinos created on this process help to repell the falling outer layers of the star, causing the supernova explosion.

Birth of a Neutron Star

But in the very core – a neutron star is born. If the pre-supernova star around ~ 15 solar masses – the neutron pressure in it is big enough to halt the collapse.

This scenario explains how the neutron stars get their basic properties:

• for the neutron pressure to be able to stop the collapse the neutron star has to shrink to the size of ~10 kilometers

• rapid spin is the result of the conservation of angular momentum

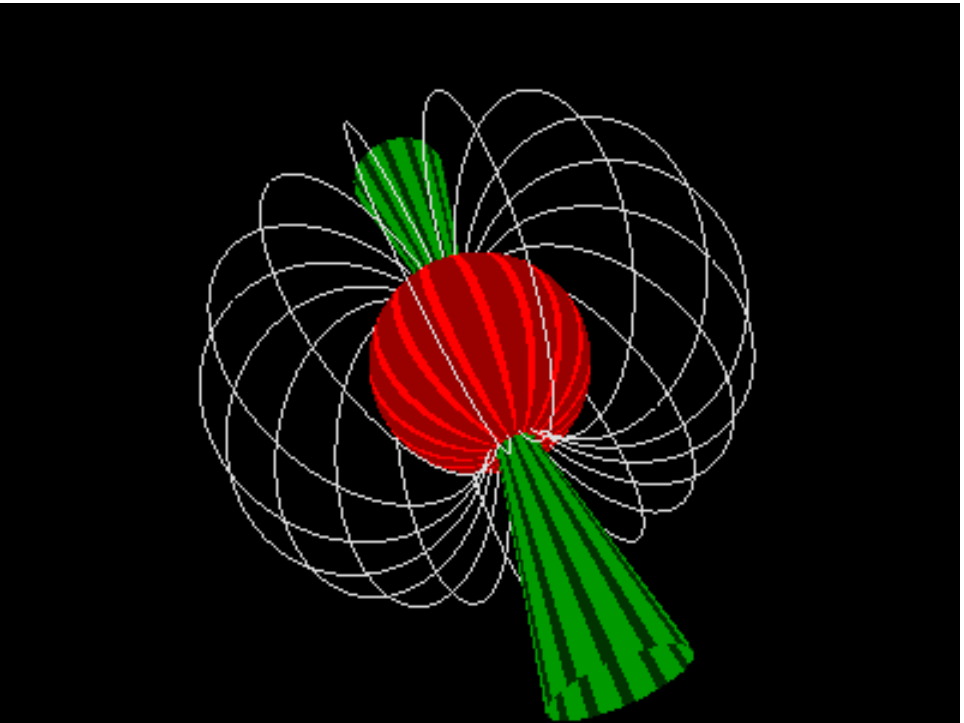
• strong magnetic field is the efect of its compression (i.e. conservation of magnetic flux)

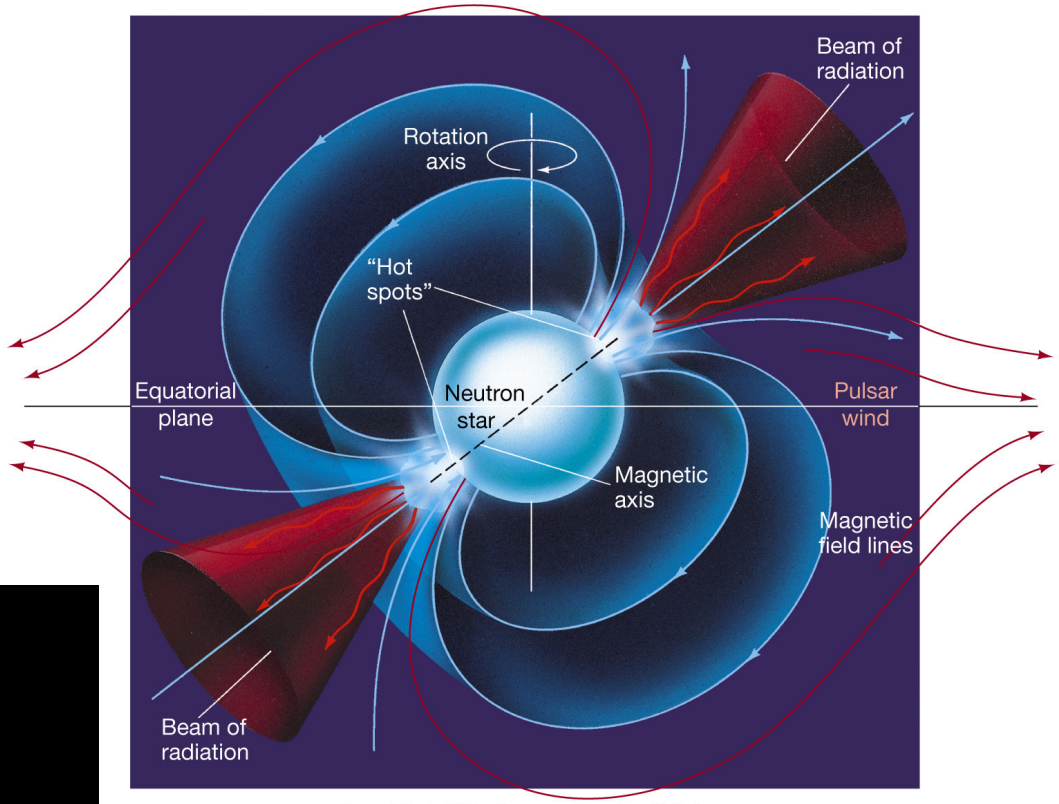
• the density in the neutron star is comparable to the atomic nucleus density (10^{15} g/cm^3) – a teaspoon of it would weigh as much as thousands of oil tankers on Earth.

Birth of a Neutron Star

So the pulsar is just a "ball" of very dense matter, which is rotating very fast.

It has very strong magnetic fields, roughly dipole in structure





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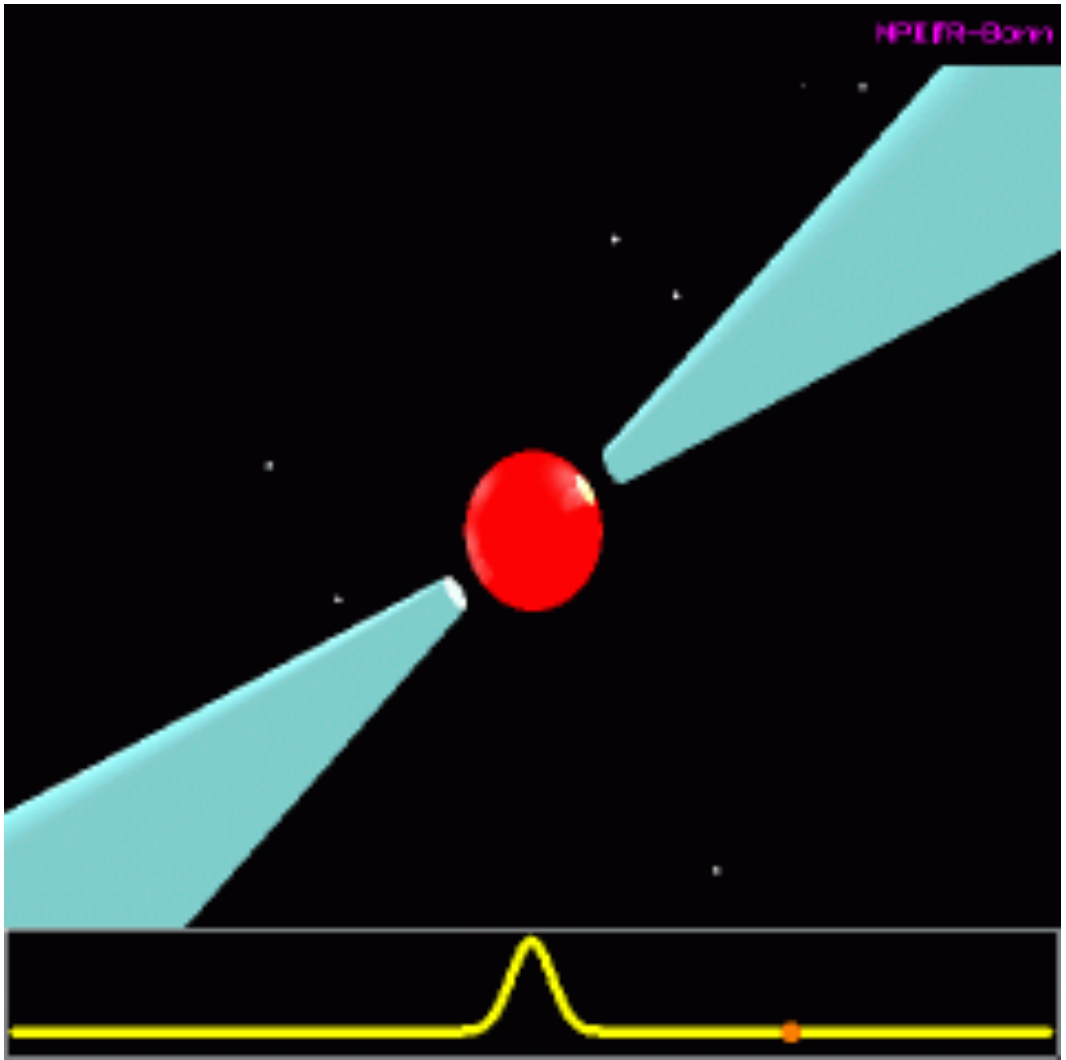
Of course the rotation axis, and the magnetic axis do not have to coincide.

The magnetosphere is rotating rigidly with the pulsar, up to a distance of the light cylinder

Birth of a Neutron Star

Pulsars emit radiation in a way very similar to the "lighthouse" – two radiation beams, originating near polar caps sweep the Universe. An observer sees a pulse of this radiation once (or, possibly twice) per pulsar rotation



The radiation is comming from the relativistic electrons, moving along the open field lines.

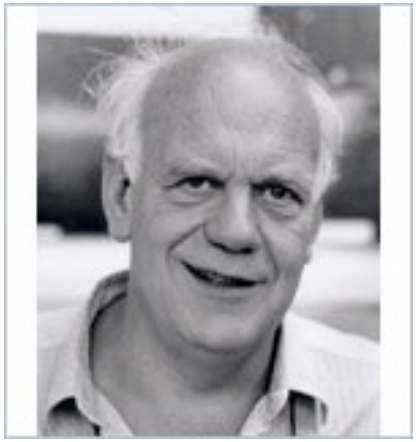
It is called the curvature radiation, and forms two oposite beams.

Neutron Stars and Pulsars – Early History
Time line : 1930 - 1970

Neutron Stars and Pulsars – Early History

Walter Baade & Fritz Zwicky 1934

Proposed existence of a new form of star : **neutron star**

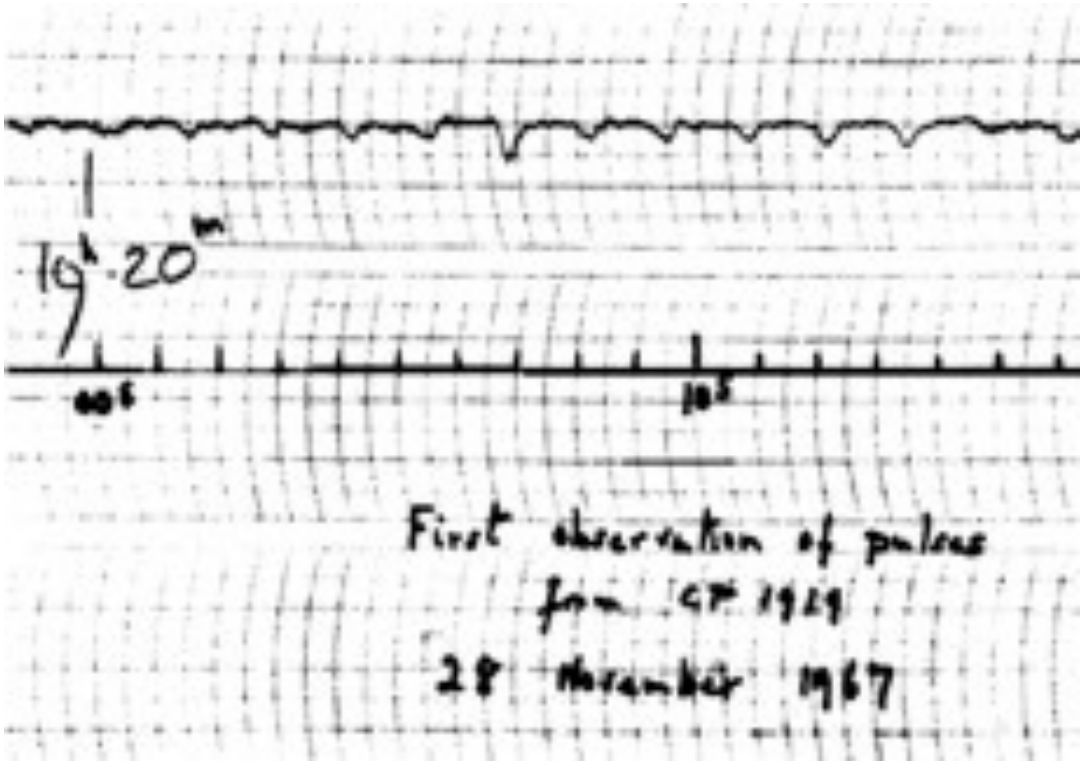


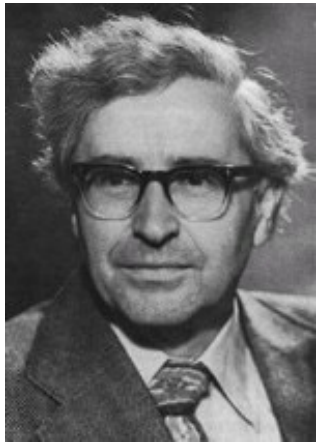
Franco Pacini 1967

Rapid rotation of highly magnetised neutron star as the energy source

Neutron Stars and Pulsars – Early History

Jocelyn Bell (graduate student), Antony Hewish et al. 1967



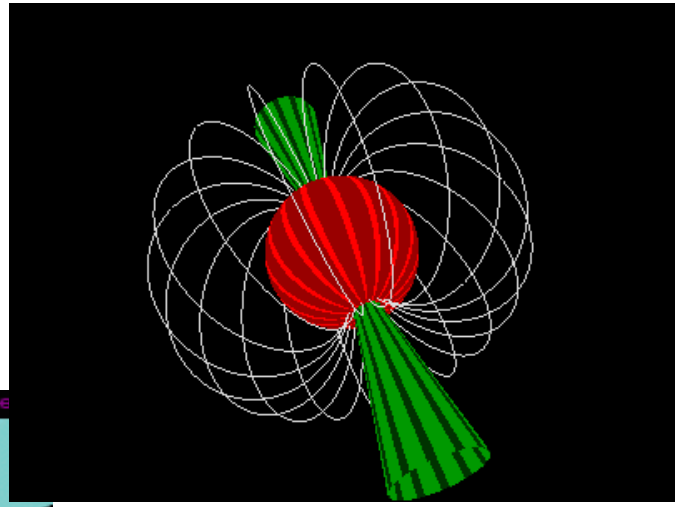


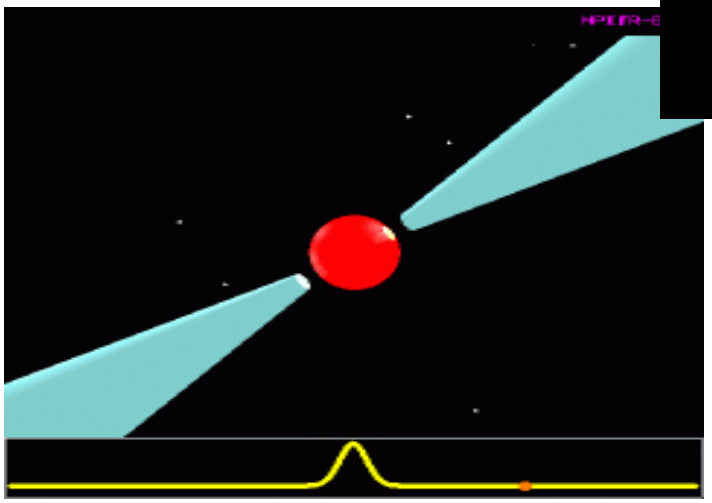
Discovery of radio pulsars → **Nobel Prize in 1974**

Neutron Stars and Pulsars – Early History

Tommy Gold 1968
: Pulsars are rotating neutron stars

Lighthouse model of pulsations





Pulsar Research last 50 years

Discovery of pulsars :
Hewish, Bell et al. 1968, Nature, 217, 709

Vacuum Gap model pulsar radio radiation:
Ruderman & Sutherland 1975, ApJ, 196,51

Discovery of pulsar in a binary system:
Hulse & Taylor, 1975, ApJ, L51

Discovery of the 1st Millisecond pulsar:
Becker, Kulkarni et al., 1982, Nature, 300, 615

Discovery of the 1st extrasolar planet around PSR J1257+12:
Wolszczan, Frail, 1992, Nature, 355, 145

Discovery of the double pulsar system:
Burgay et al. 2004, Science, 303, 1153

A millisecond pulsar in a stellar triple system:
Ransom et al. 2014

Pulsar research in different directions :
2 Nobel prizes : 1 on discovery of pulsars(1974), 1 on discovery of Hulse-Taylor binary (1993)

TOP 10 !

B1919+21 : First pulsar discovered in 1967

B1913+16 : The first binary pulsar (Hulse-Taylor binary pulsar)
Orbit is decaying at the exact rate predicted due to emission of gravitational radiation by general relativity

B1937+21 : The first millisecond pulsar

J0437-4715 : The brightest millisecond pulsar, with very stable period

B1257+12 : First millisecond pulsar with planets

J0737-3039 : Double pulsar system

B1748-2446 : Pulsar with shortest period, 716 Hz

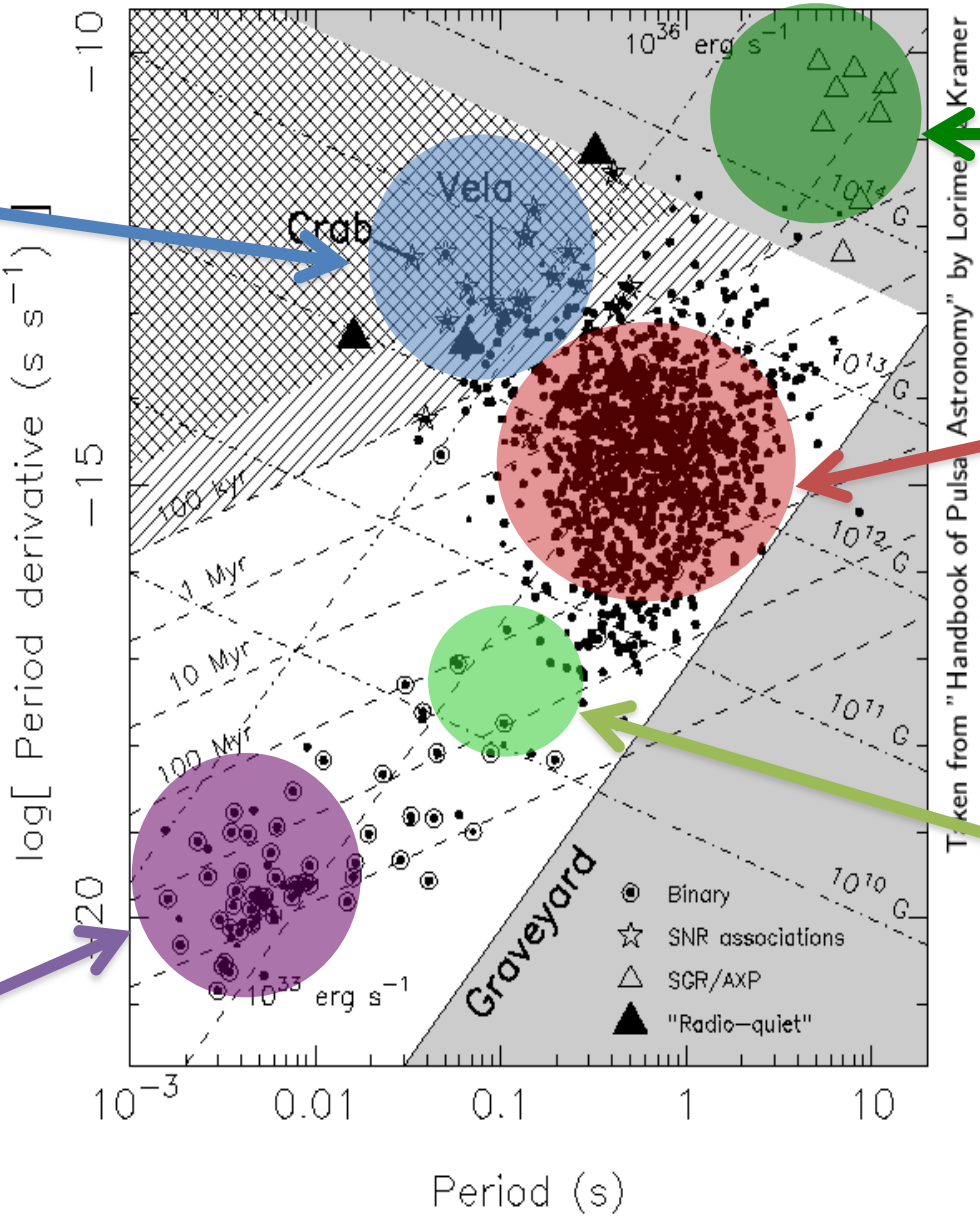
J0337+1715 : Tripple system, a millisecond pulsar with two white dwarf companions

J1023+0038 : Transition between the LMXB and MSP state

P-Pdot diagram of Neutron stars

Young Pulsars
– Energetic, with significant spin-down noise, glitches, SNRs associations

Millisecond Pulsars
– Faster, Most in binaries, stable rotators



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

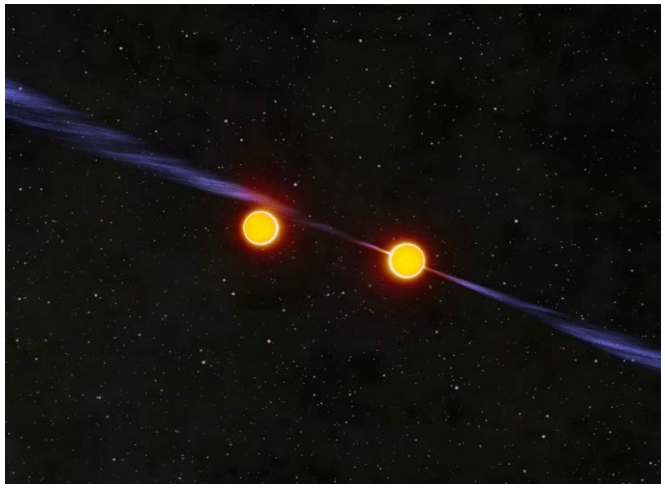
Magnetars
– High B, few in radio

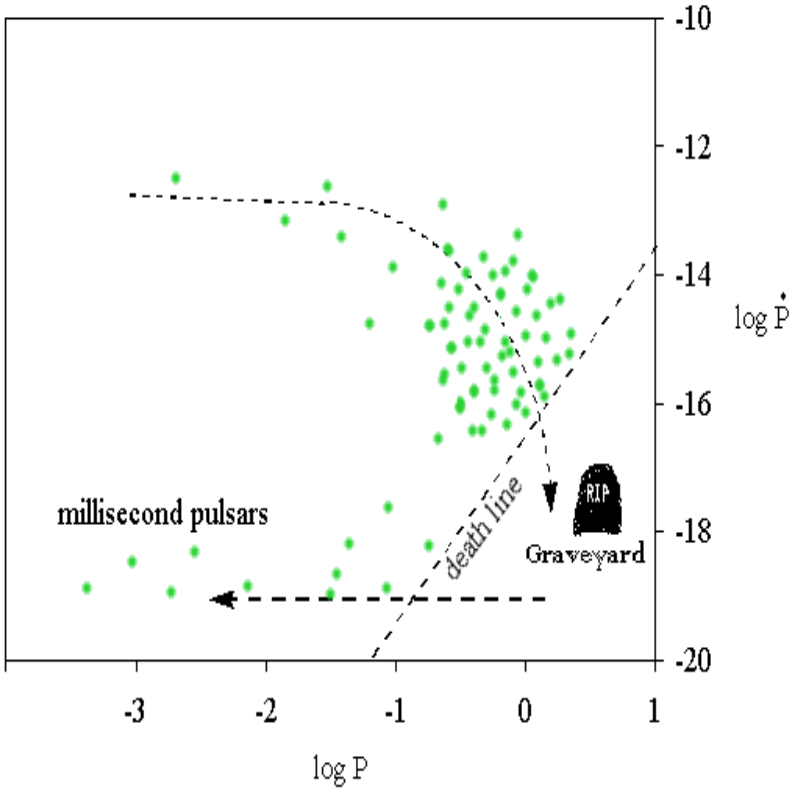
Normal Pulsars
– slower, mostly isolated, bulk of them, good for PSR studies

Double Neutron stars
– spin fast, double pulsars, good for GR tests

4000 known radio Pulsars in our galaxy

Millisecond pulsars :back from Dead





- ✓ Millisecond pulsars are a small population compared to the normal pulsars with period ~ millisecond, magnetic Field ~10^9G

- ✓ Majority of MSPs are in binary MSPs are detected in the radio, x-ray and gamma-rays

- ✓ Origin of millisecond pulsars is yet not pinned down.

Leading theory :

MSPs begin their life as longer period pulsar but are spun up or recycled through accretion

thus millisecond pulsars are often called recycled pulsars.

MSPs considered as Celestial GPS

Dispersion

Radio waves propagate through **free electrons** in the interstellar medium (ISM). The key result from plasma physics:

$$v_g = c\sqrt{1 - \frac{\nu_p^2}{\nu^2}}$$

v_g = group velocity
ν_p = plasma frequency
ν = observing frequency

The arrival time delay between two frequencies is:

$$\Delta t \propto \frac{\mathrm{DM}}{\nu^2}$$

Dispersion Measure (DM)

$$\mathrm{DM} = \int_0^d n_e \; dl$$

De-dispersion

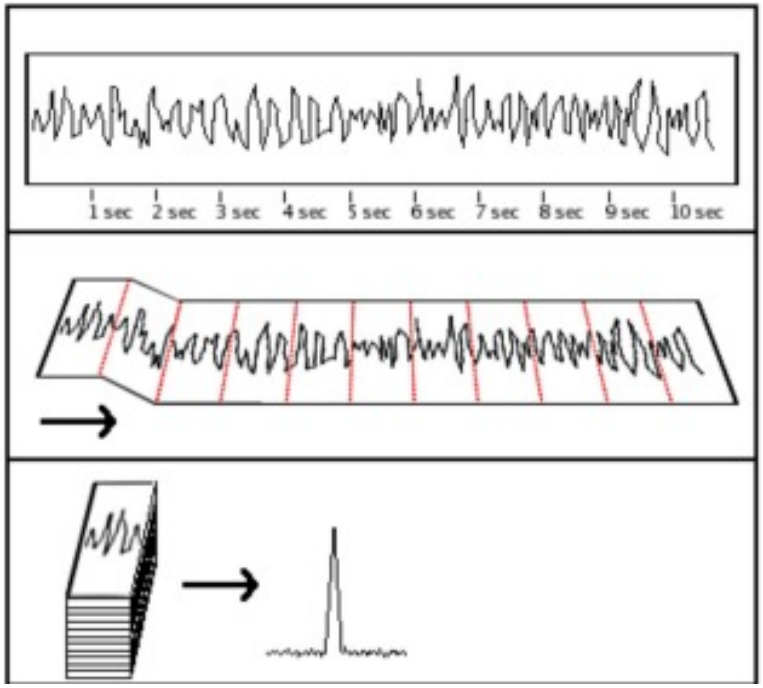
Correction of dispersion effect

$$\Delta t = \frac{\mathrm{DM}}{2.41 \times 10^{-4}} \left(\frac{1}{\nu_{\mathrm{low}}^2} - \frac{1}{\nu_{\mathrm{high}}^2} \right)$$

Input: raw data
Output: de-dispersed time series

Folding

Combine many pulses together
to build up detectable signals

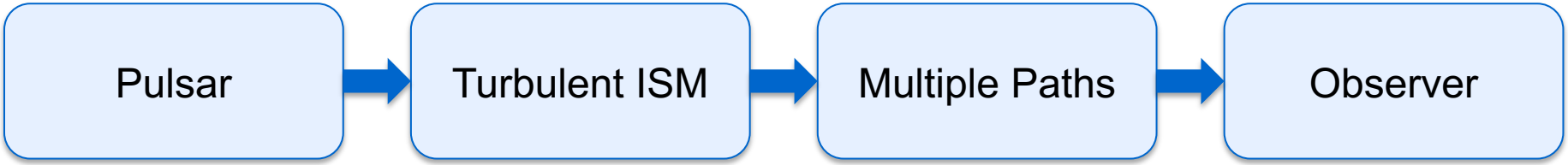


Input: de-dispersed time series
Output: average profile

Credit : http://pulsarsearchcollaboratory.com/wp-content/uploads/2016/01 PSC_search_guide.pdf

Scattering

Scattering is caused by small-scale density fluctuations in the ionized interstellar medium which make radio waves take multiple paths to the observer.



Observed pulse = intrinsic pulse ⊗ scattering response

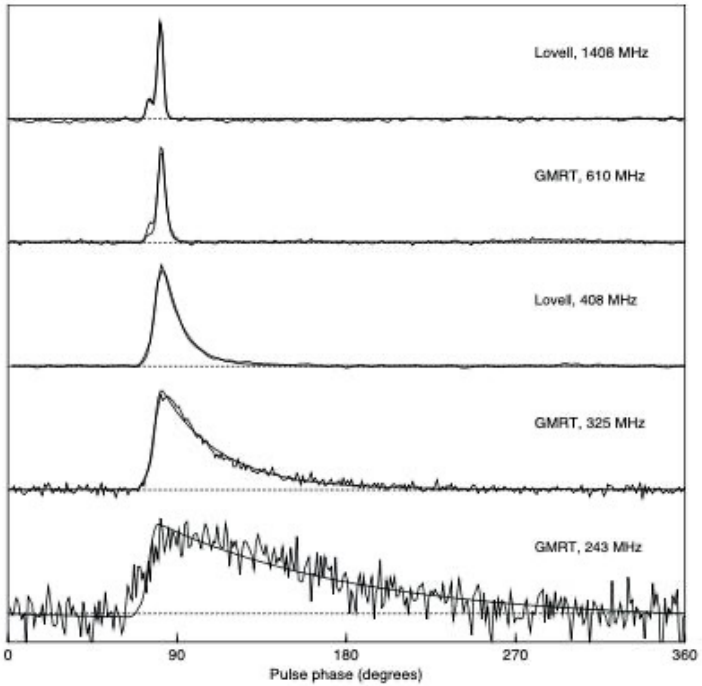
$$P_{\mathrm{obs}}(t) = P_{\mathrm{int}}(t) * h(t)$$

For thin-screen scattering:

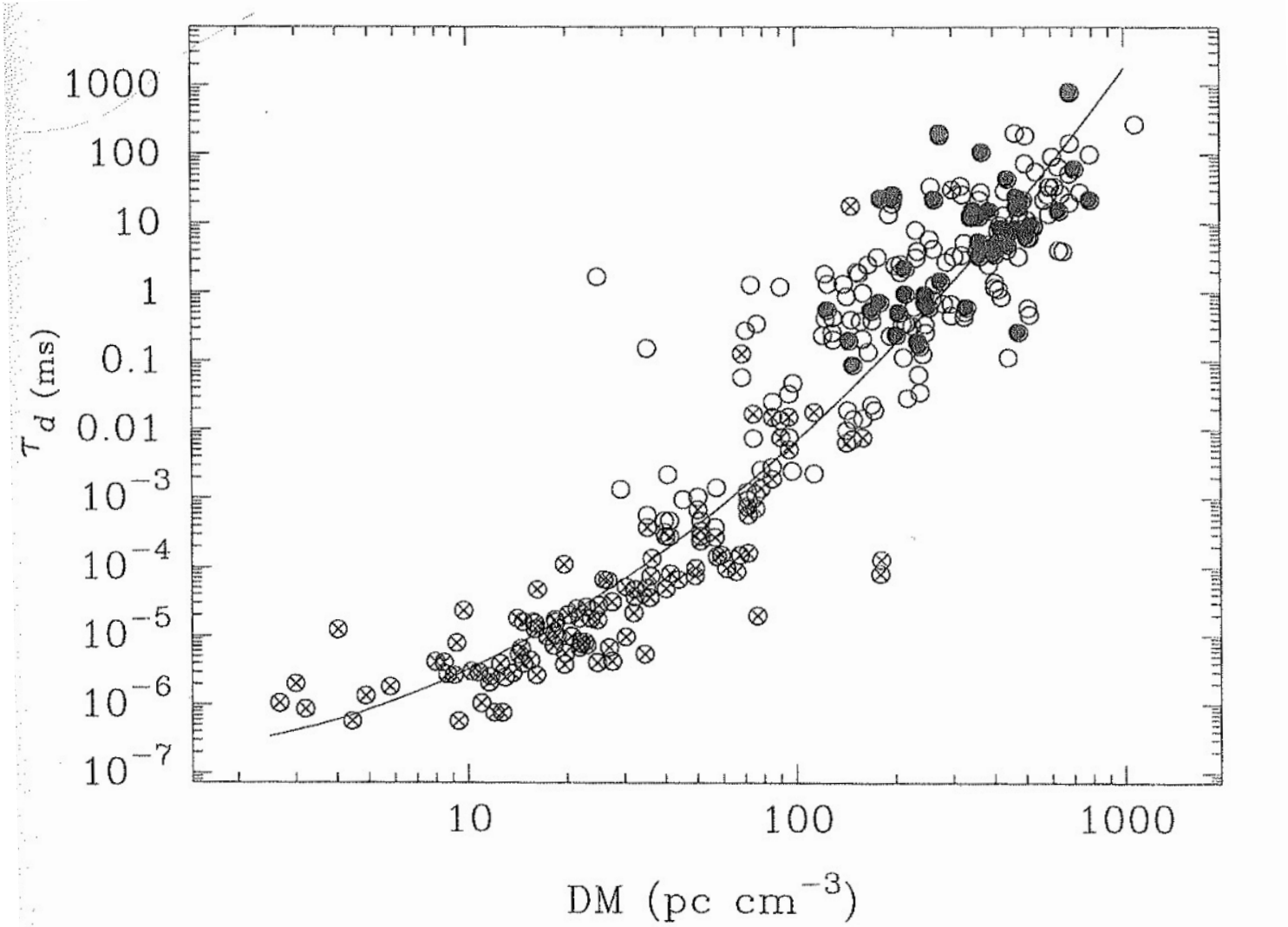
$$h(t) \propto e^{-t/\tau_s} \; (t > 0)$$

Frequency dependence

$$\tau_s \propto \nu^{-4}$$



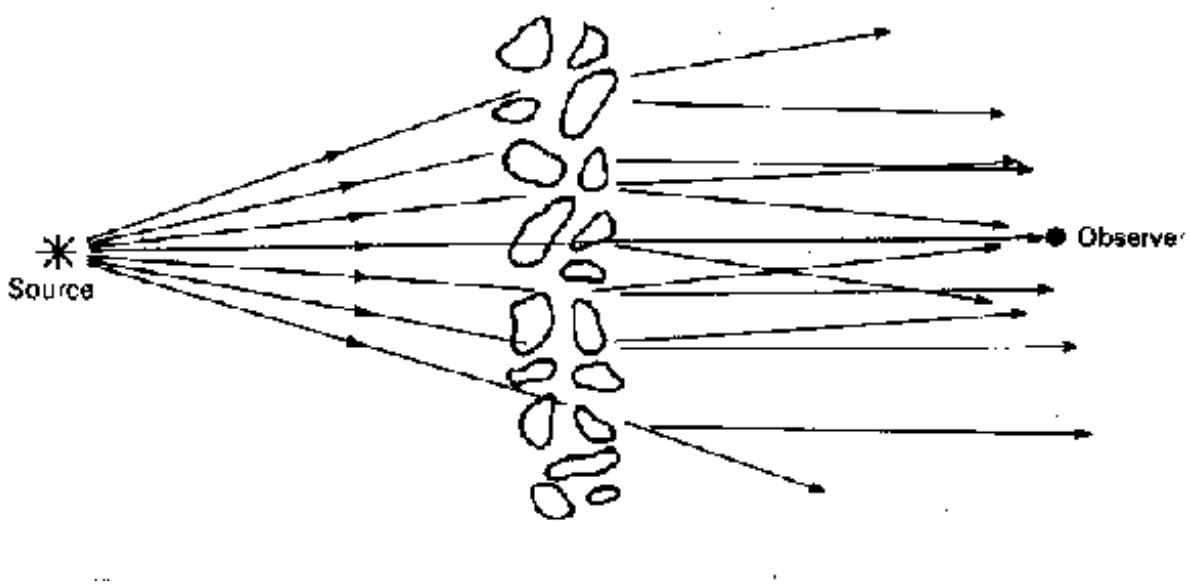
DM and Scattering



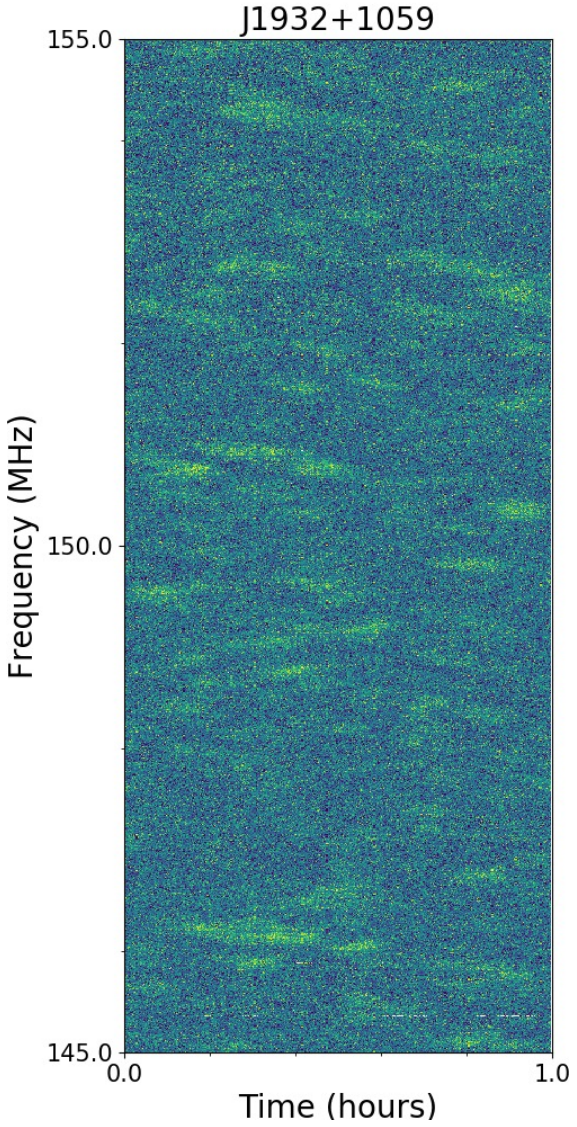
$$\log \tau_s = -6.46 + 0.154 \log(\mathrm{DM}) + 1.07(\log \mathrm{DM})^2 - 3.86 \log f,$$

Scintillation

Scintillation is the intensity modulation of a pulsar signal caused by interference between multiple scattered wave paths in the turbulent interstellar medium



Different paths → different phase → constructive/destructive interference



Scintillation

Diffractive Interstellar Scintillation (DISS):
Small-scale turbulence; Rapid variations; Narrow bandwidth

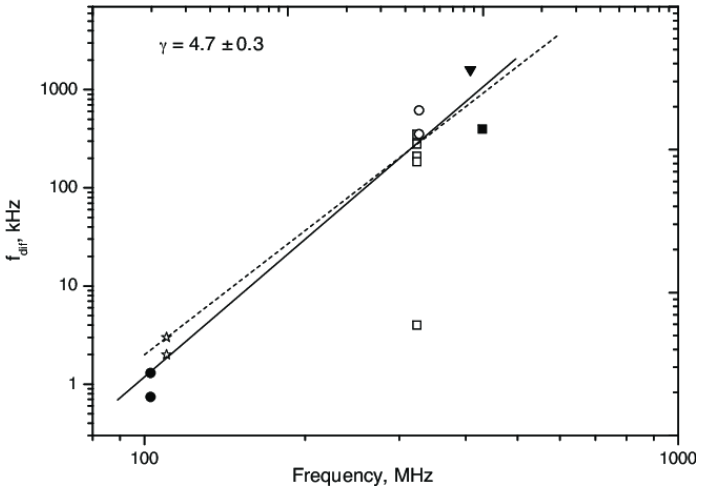
Timescale:
$t_{\mathrm{d}} \sim minutes\text{–}hours$

Bandwidth:
$\Delta\nu_{\mathrm{d}} \sim kHz\text{–}MHz$

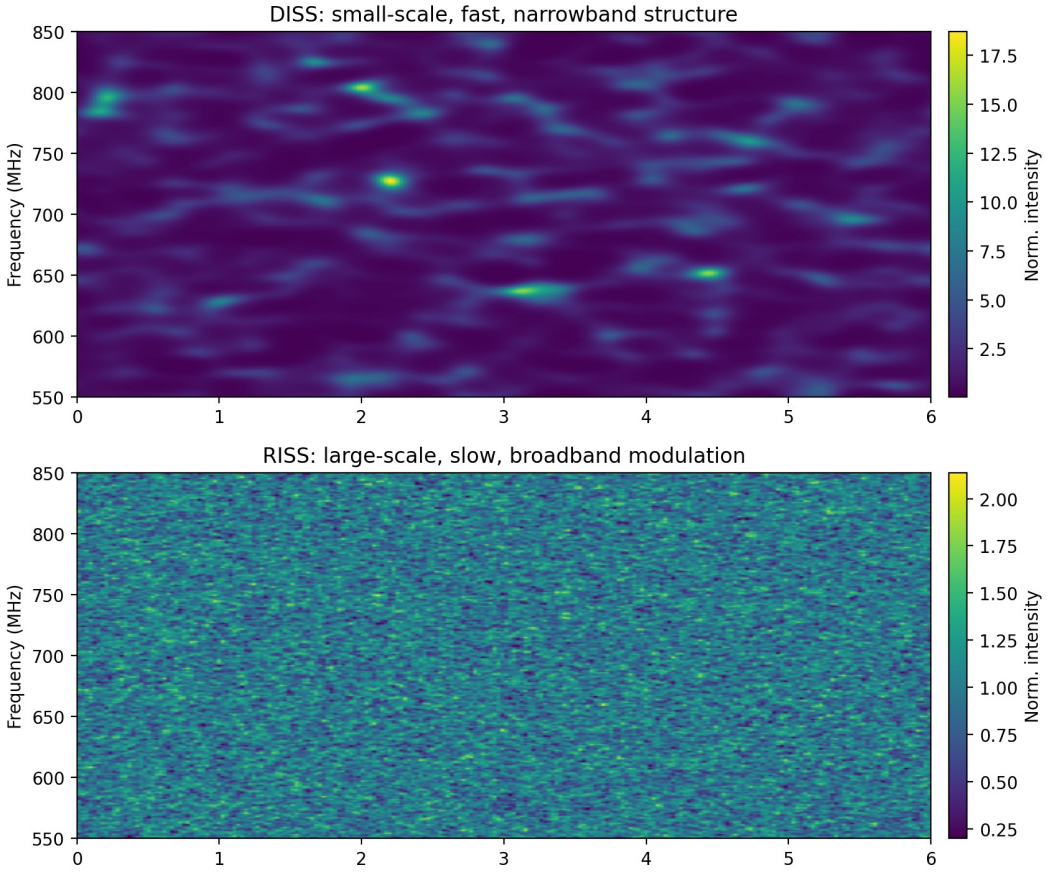
Refractive Interstellar Scintillation (RISS)
Large-scale density fluctuations; Slow variations; Broad bandwidth

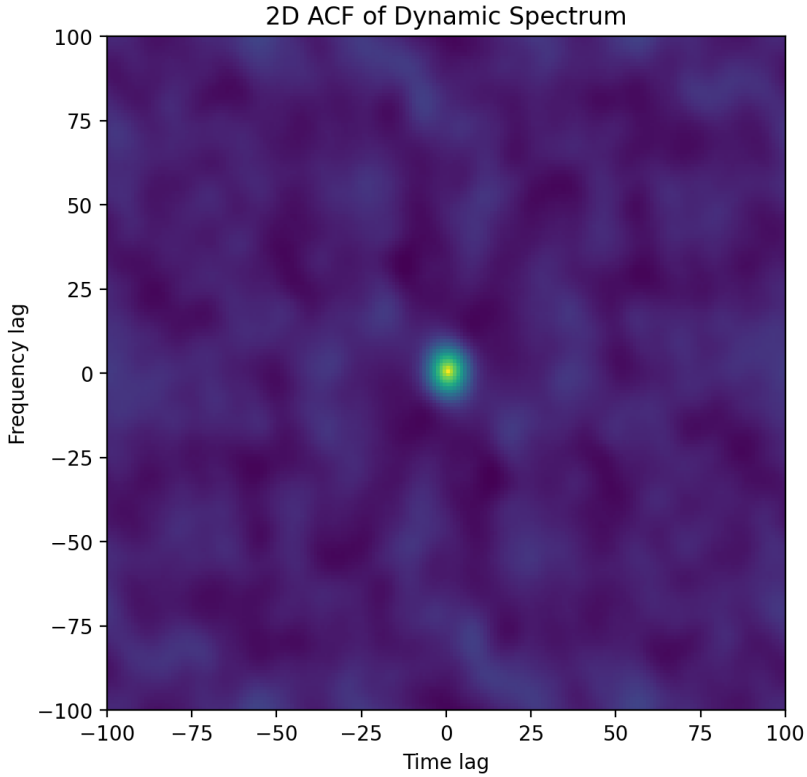
Timescale:
$t_{\mathrm{r}} \sim days\text{–}weeks$

Decorrelation/Scintillation bandwidth
$$\Delta\nu_d \sim \frac{1}{2\pi\tau_s}$$

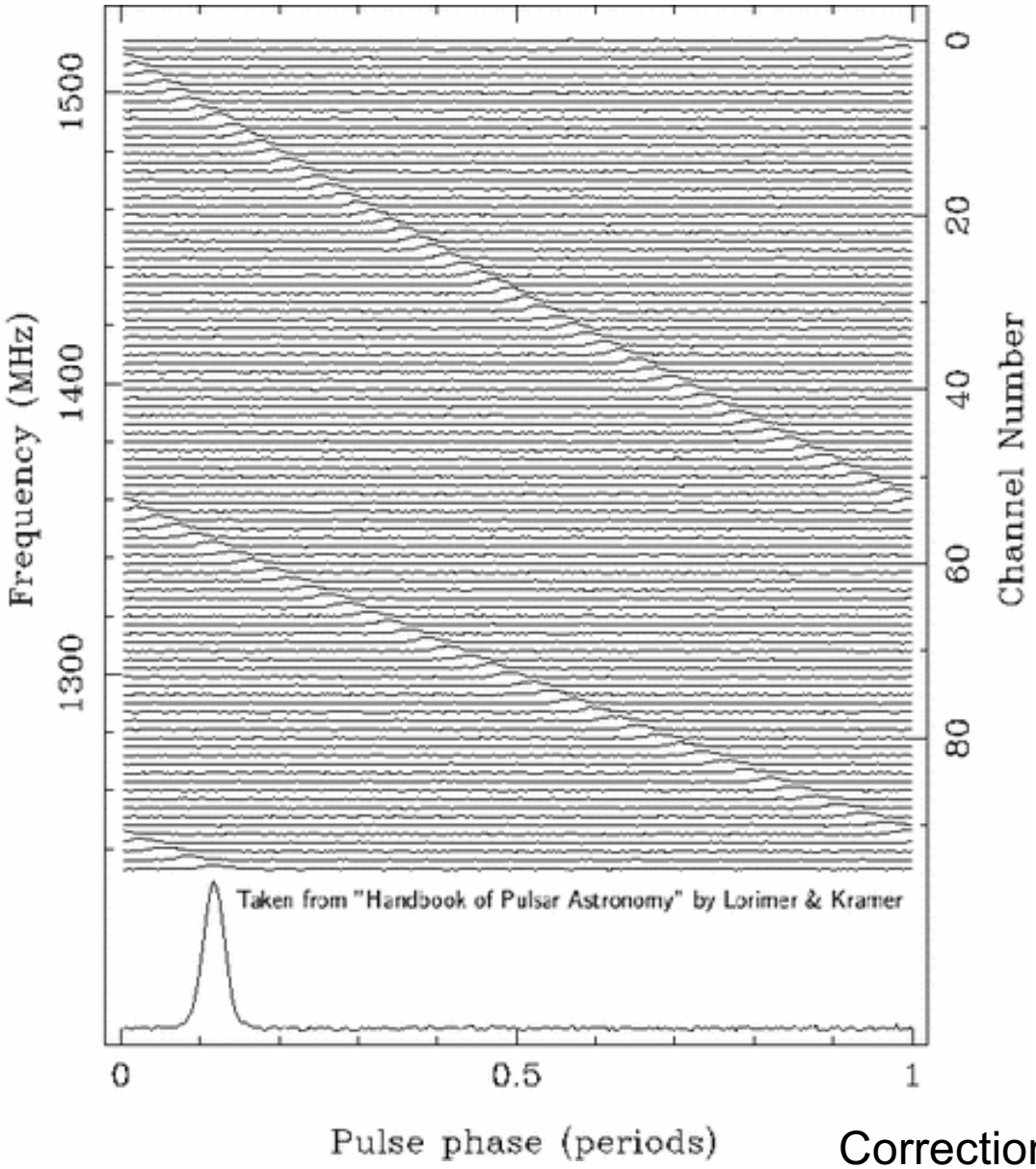


Scintillation





Interstellar dispersion effect:



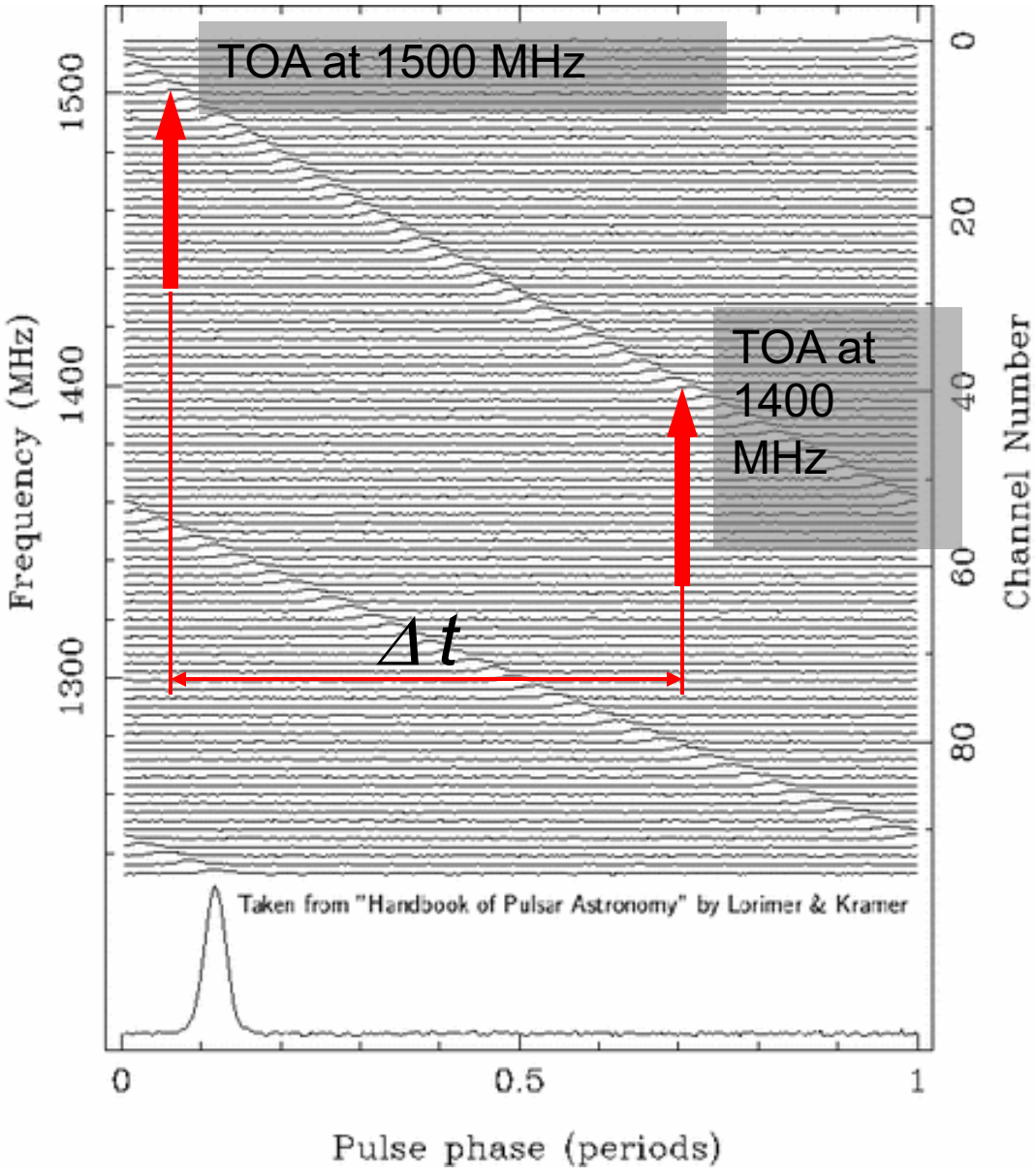
Interstellar medium (in fact the free electrons in it) is a dispersive medium for radio waves.

Radio waves of different frequencies have different speeds, while traveling through such medium

The effect is such, that the pulse comes at higher frequencies first (the speed of its travel is higher), and at lower frequencies later.

Correction of this effect is called **de-dispersion**

Interstellar dispersion effect:



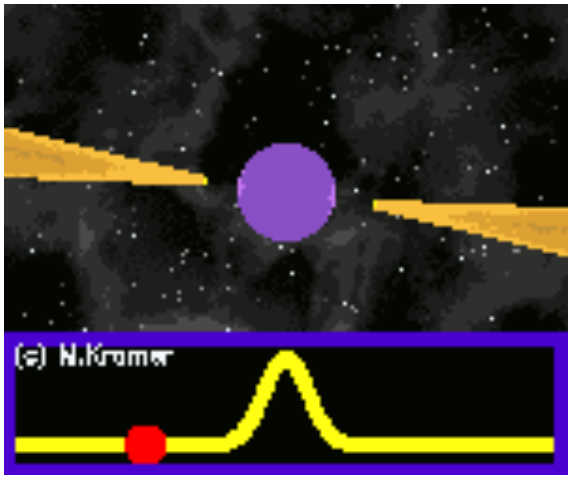
This difference between the arrival times will be solely due to the $1 / f^2$ term.

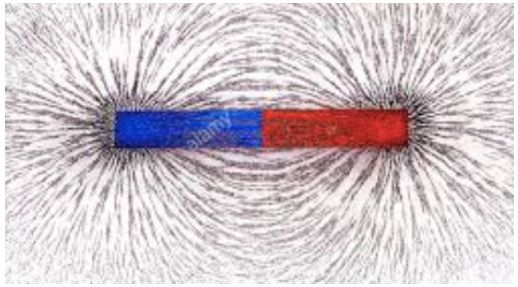
If that is so, then - by measuring the time difference, and knowing our frequencies, we can calculate the disspersion measure (*DM).*

So, we have the *DM* value. If we could only know the free electron distribution in our galaxy...

Pulsars :

Rapidly rotating strongly magnetized neutron stars





Magnetic field of refrigerator = ?

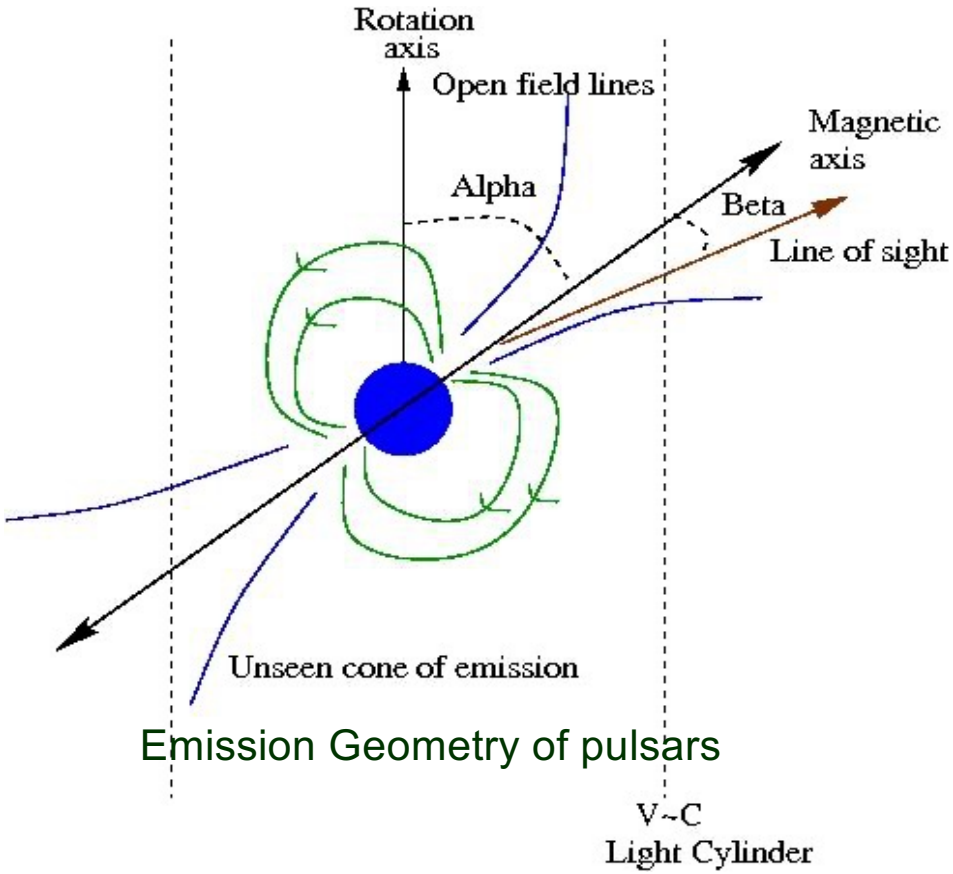
Magnetic filed of typical bar magnet = ?

Magnetic field of Earth = ?

Magnetic field of Sun = ?

Strongest magnet in Earth = ?

Magnetic field of Neutron star 10^8 to 10^{15} G



Emission Geometry of pulsars

Young pulsars are born with periods of order of 10 milliseconds.

As they age - they loose angular momentum, which is carried away by the electrons that are producing the radiation when traveling along the open field lines.

This loss is directly connected to magnetic field strength. By just measuring the period and its derivative, we can calculate (assuming dipole model) the magnetic field strength:

$$\dot{E} \simeq 3.95 \times 10^{31} \text{ erg s}^{-1} \left(\frac{\dot{P}}{10^{-15}} \right) \left(\frac{P}{\text{s}} \right)^{-3} .$$

$$B = 3.2 \times 10^{19} \text{G} \sqrt{P\dot{P}} \simeq 10^{12} \text{G} \left(\frac{\dot{P}}{10^{-15}} \right)^{1/2} \left(\frac{P}{sec.} \right)^{1/2} ,$$

We can also calculate the characteristic age of the pulsar, which is a good estimate of the real pulsar age in most cases:

$$\tau \equiv \frac{P}{2\dot{P}} = 15.8 \text{ Myr} \left(\frac{P}{s}\right) \left(\frac{\dot{P}}{10^{-15}}\right)^{-1}$$

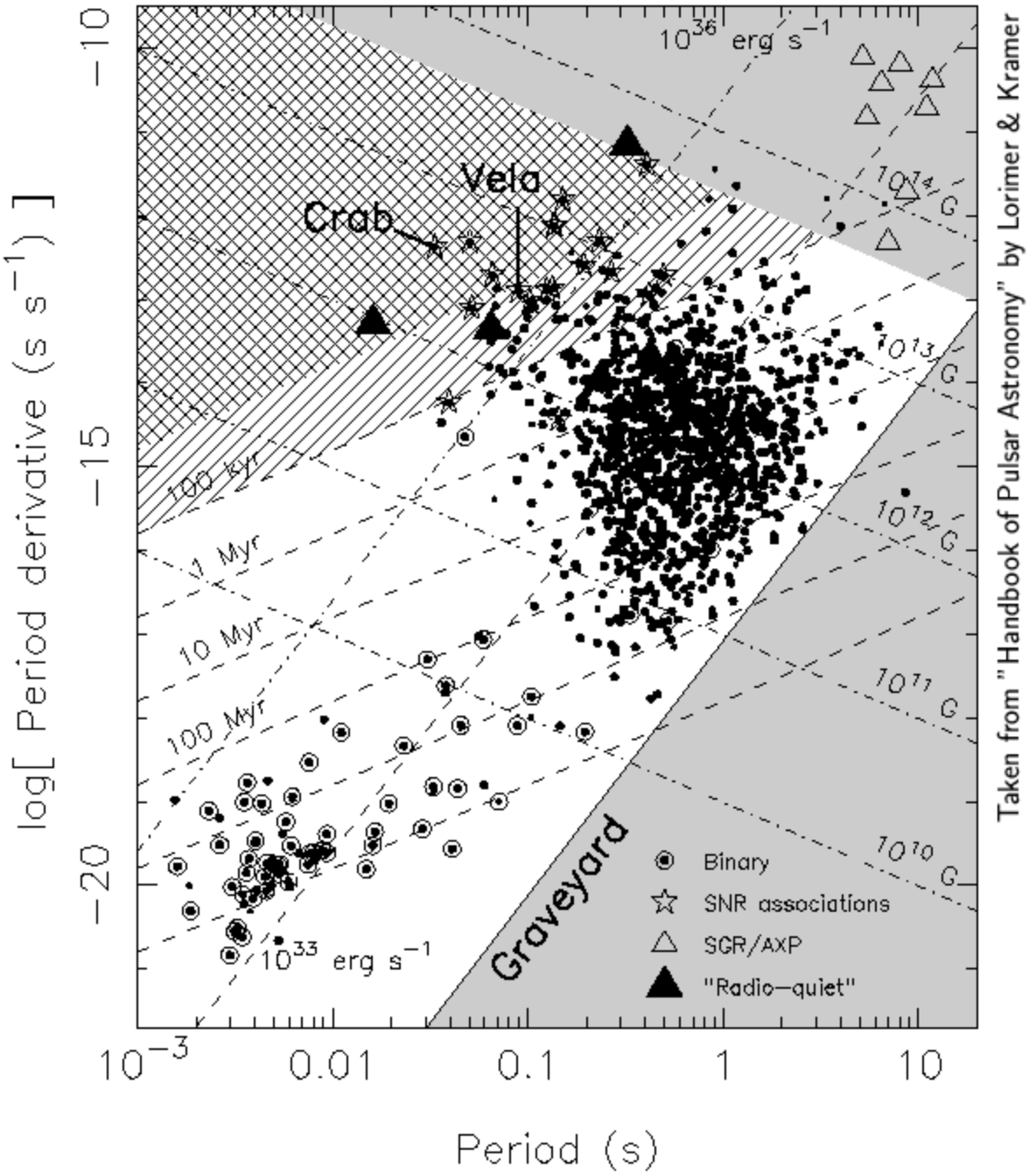
To calculate the real age one needs to measure the second period derivative (needed to ascertain the braking index *n*):

$$n = \frac{\nu\ddot{\nu}}{\dot{\nu}^2} = 2 - \frac{P\ddot{P}}{\dot{P}^2}$$

Value of braking index for pure magnetic dipole radiation = 3

If you are lucky to know the initial spin period, then the age of the pulsar is:

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



One can plot equal magnetic field lines, and equal age lines on the P-P diagram, which can give an idea, about the pulsar evolution.