Radio astronomy essentials: Pulsars and how to find them

March 2026 @ UNDARK, Annecy

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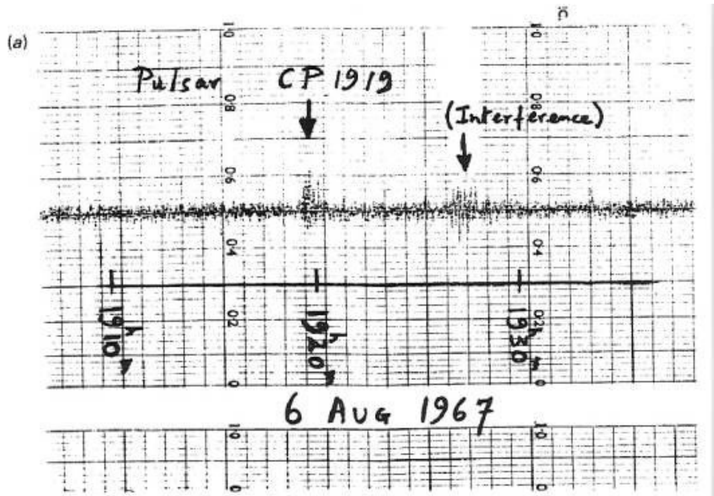
Centre National De La Researche Scientifique

LPC2E

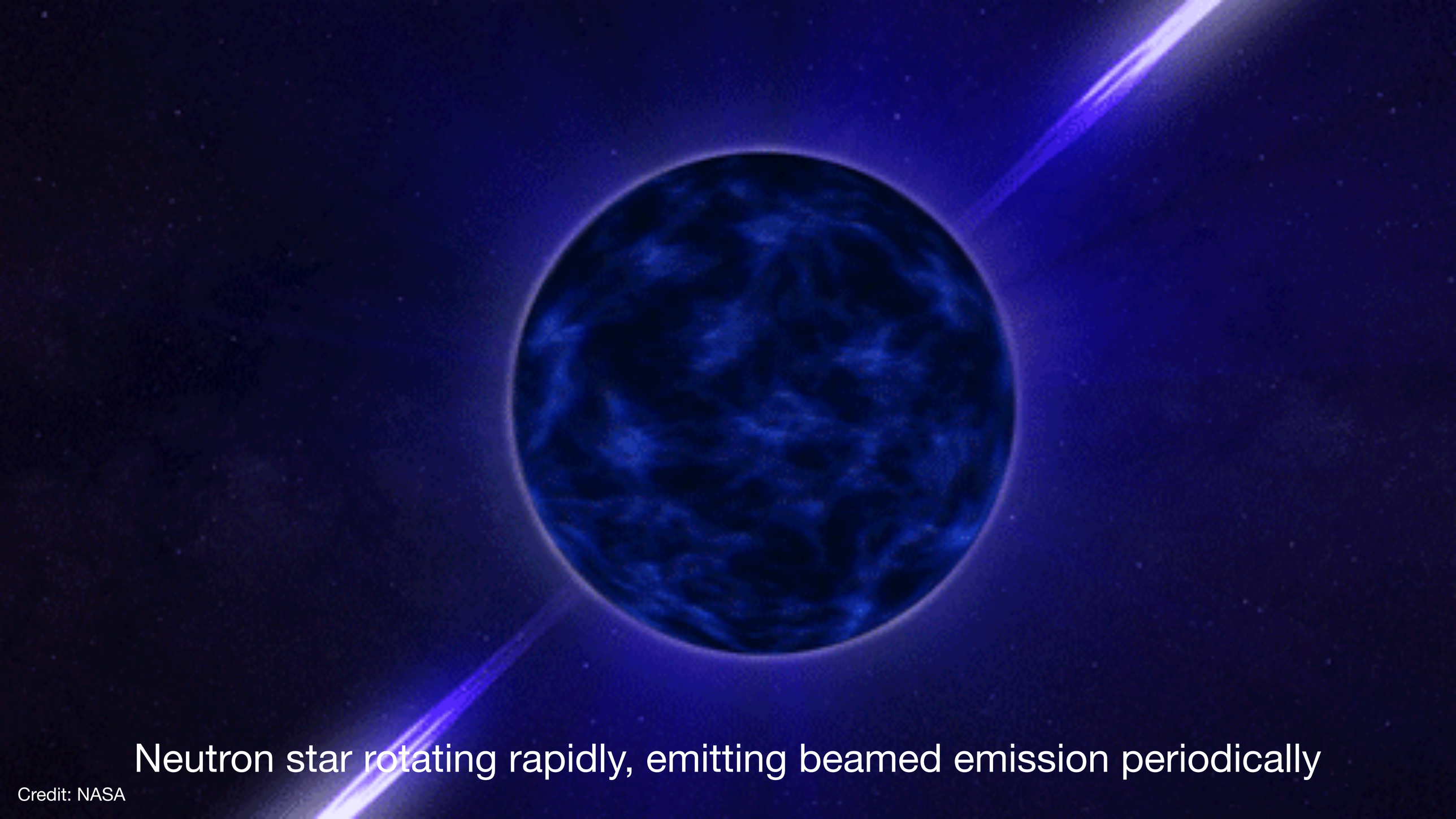
Image credit: deepai.org

Pulsar discovered by Jocelyn Bell



- Discovery in **1967** by Jocelyn Bell Burnell and Antony Hewish.
- The first pulsar: **CP 1919** (now **PSR B1919+21**).
- Initial nickname: **“LGM-1” (Little Green Men)** because of the extremely regular pulses.

Data rate: tens of meters of paper per day



Neutron star rotating rapidly, emitting beamed emission periodically

Credit: NASA

Supernova explosion at the end of life of a massive star

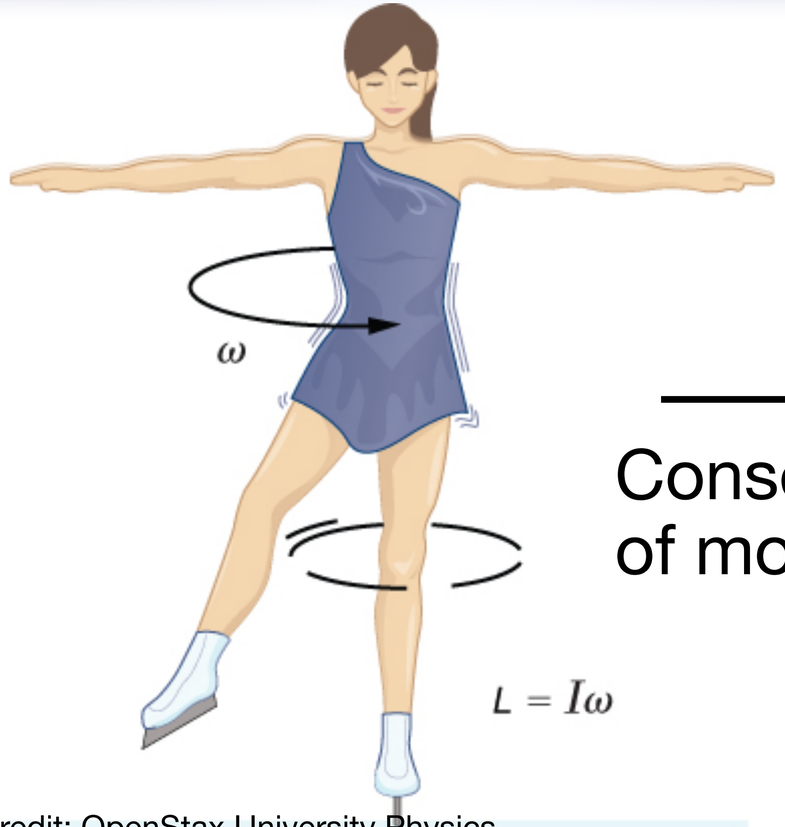
Credit: NASA

Why does it spin so fast?

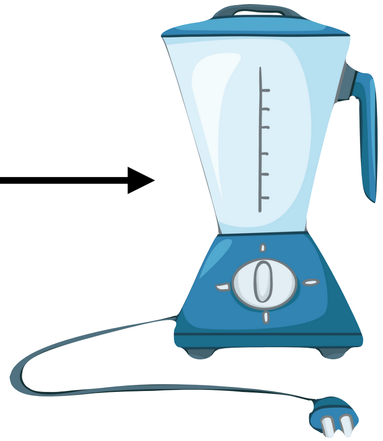
une étoile massive

l'explosion d'une supernova

Pulsar



Conservation of momentum

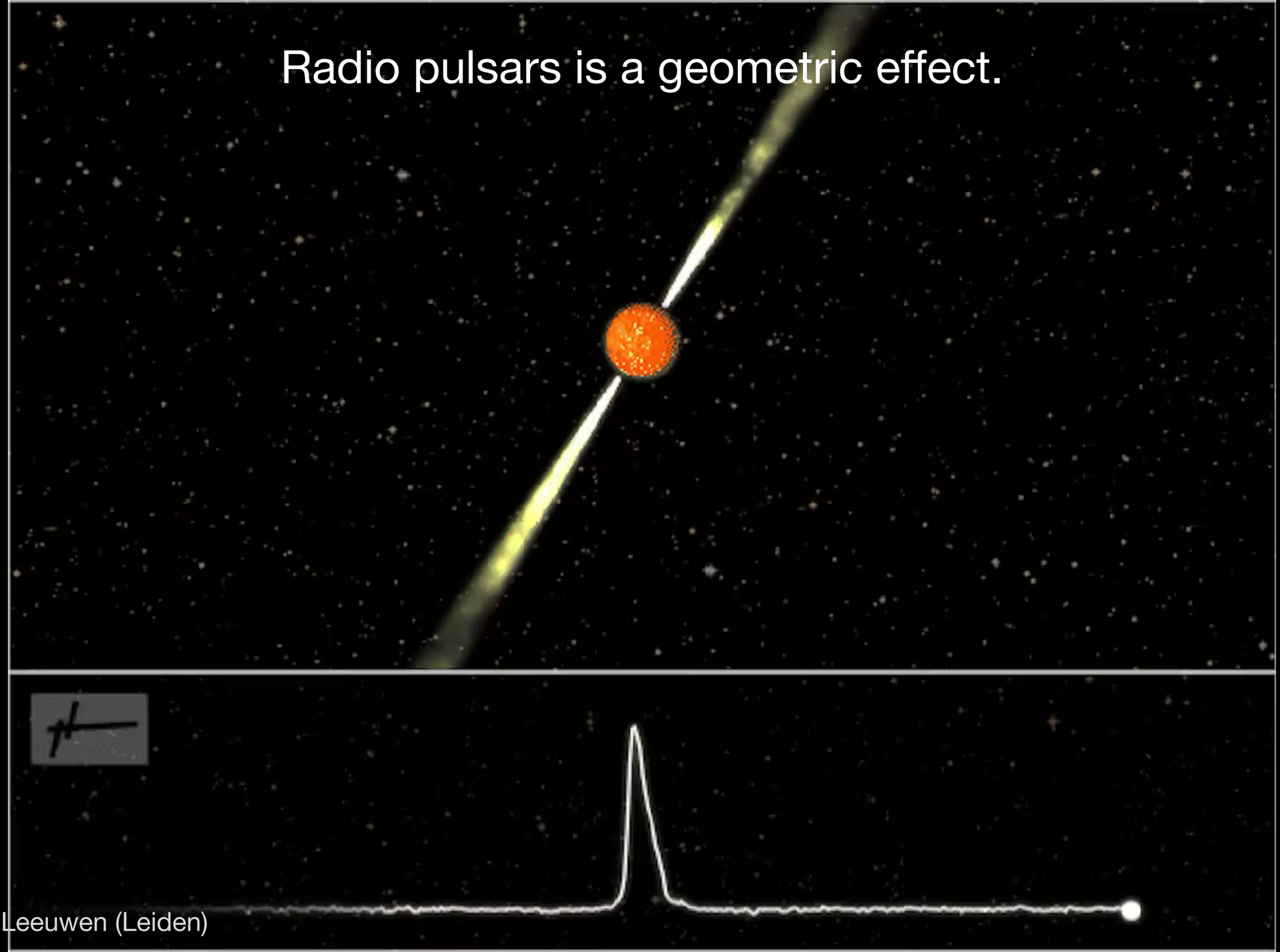


Credit: OpenStax University Physics

Credit: https://ns-in-my-city.daniel-wysocki.info/
LAPTh
Annecy

6 billion tonnes = Mount Everest = 3 million elephants

Radio pulsars is a geometric effect.



Credit: Joeri van Leeuwen (Leiden)

Pulsars in a nutshell

- Rapidly rotating Neutron Stars
- Radius ~ 10 km, mass ~ 1.4 solar mass
- → central densities: order of a billion tons / cm^3
- Highly magnetized (10^8 ~ 10^{14} Gauss)
- → emit steep spectrum radio emission aligned with β-field axis
- Misalignment of rotational and β-axes → periodic signals

Large mass → Consequent rotational stability → Accurate clocks
→ Many astrophysical applications

Light cylinder

- Radio emission comes from **magnetic polar regions**
  - enormous electric fields accelerate particles
  - these particles produce **electron–positron pairs**
  - the plasma generates the **coherent radio emission** we observe. (c.f. yesterday's lecture)

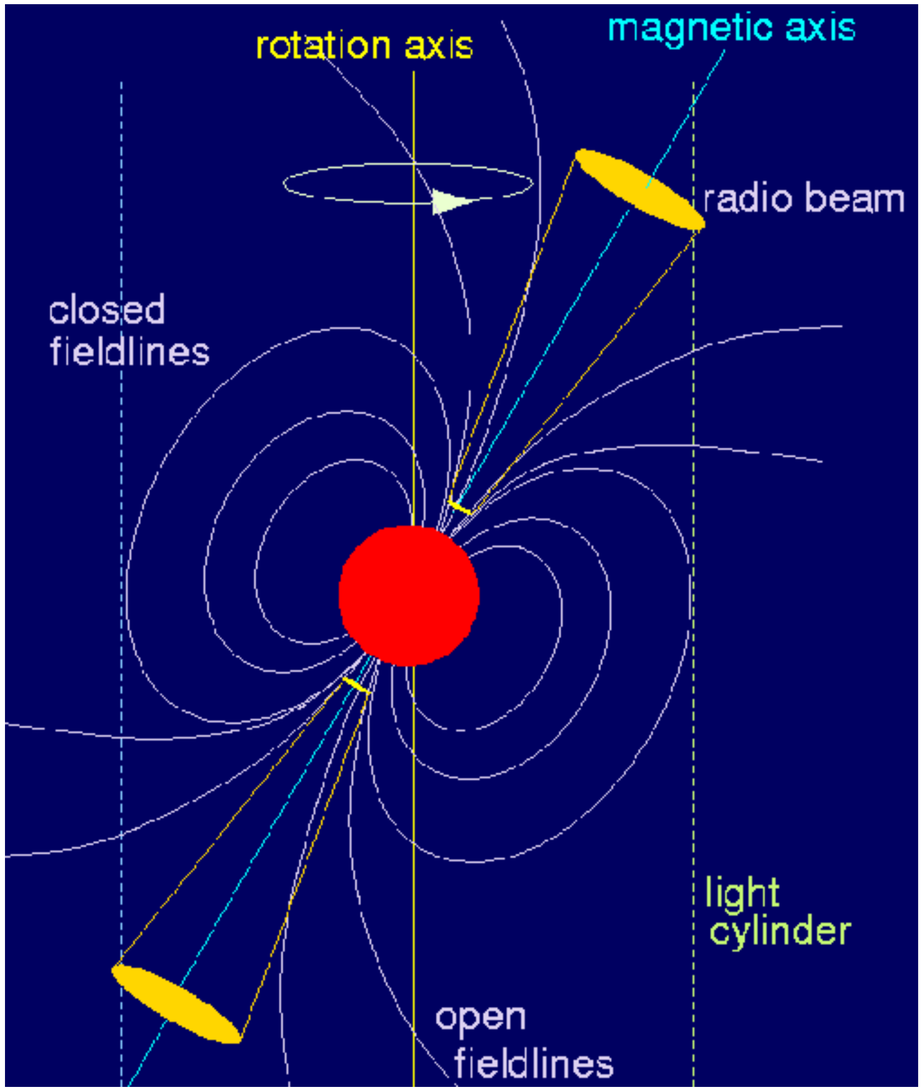
- Beam sweeps across Earth → pulses

- **light cylinder radius:** where co-rotation would require the speed of light. Outside: Open field lines and particles escape

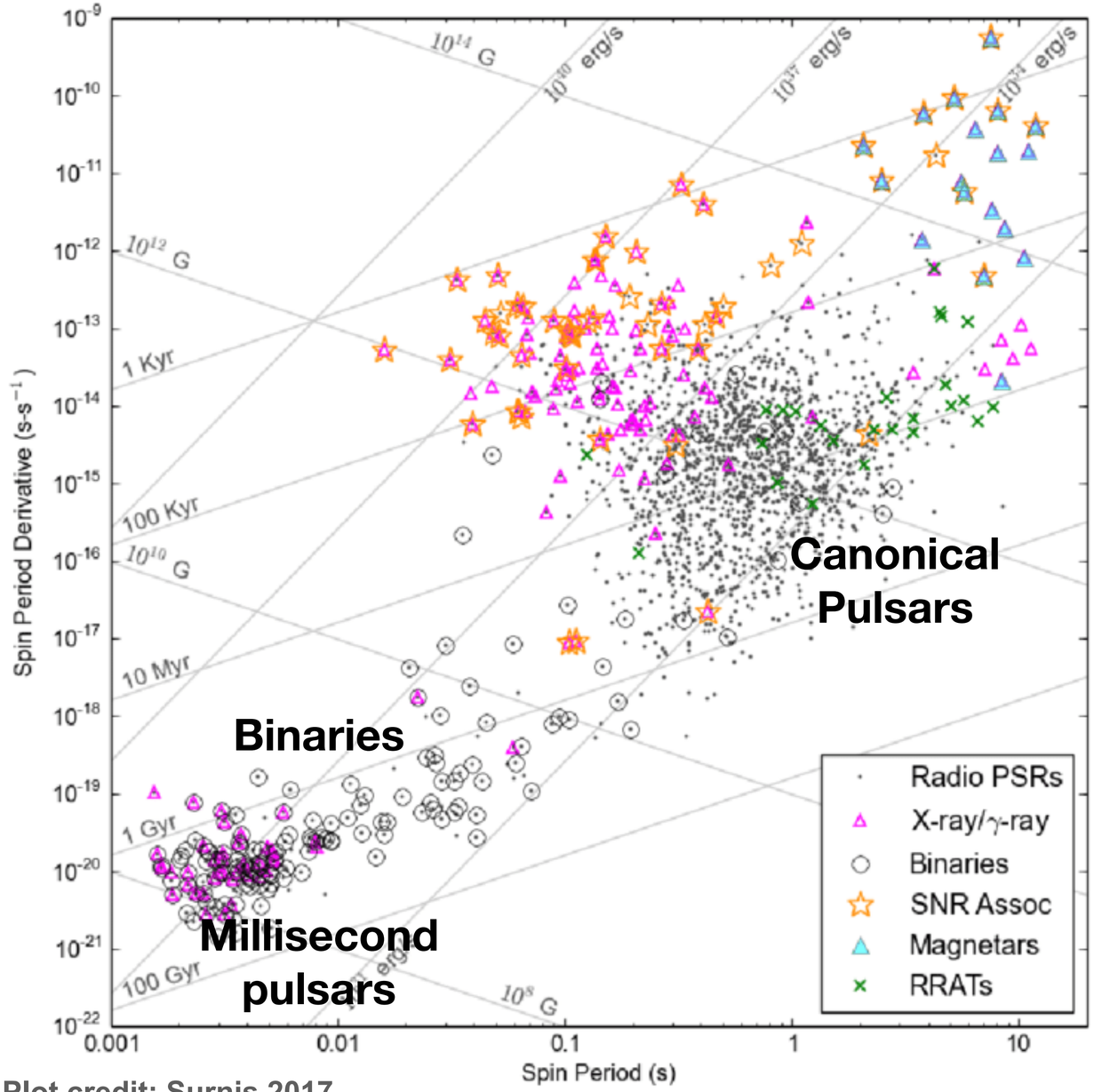
- magnetic field is not aligned with the rotation axis, so as the star rotates, the magnetic field structure is **continually changing in time** —> radiates energy away —> **spins down**

- We know pulsars are rotation-powered because they steadily lose rotational energy, and that lost energy exactly matches the power carried away by their radiation and particle winds.

Credit: U Manchester

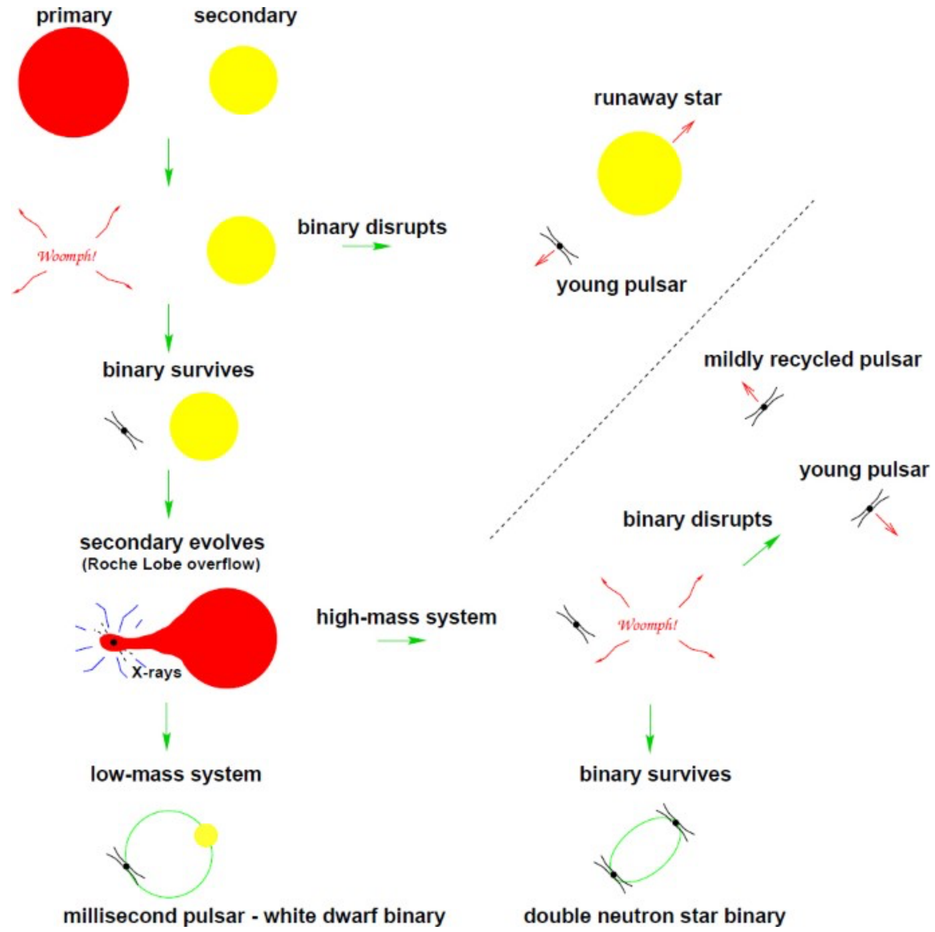


P-Pdot diagram and NS zoo



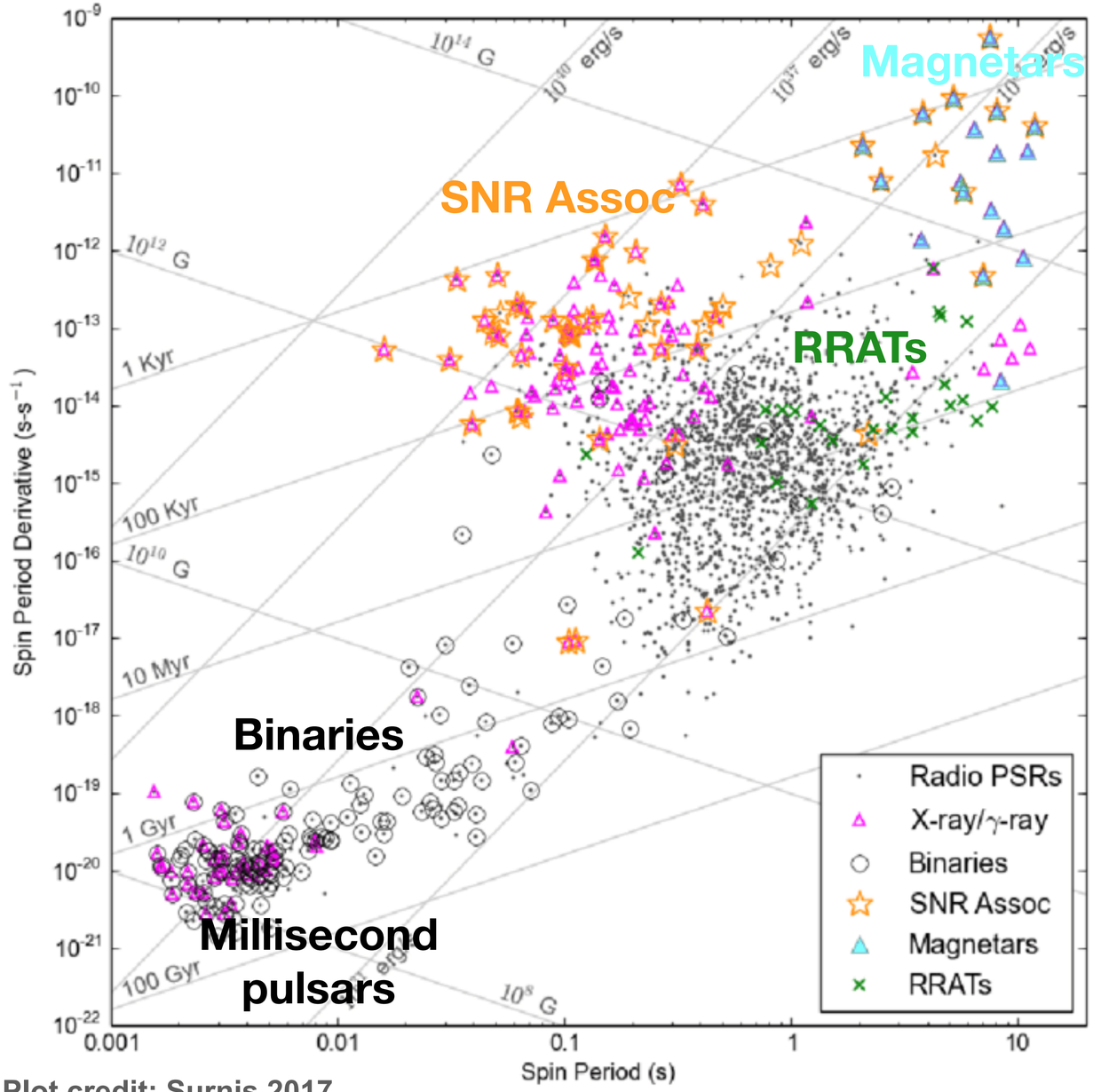
Plot credit: Surnis 2017

Plot credit: Thomas Tauris



Most MSPs in binaries — recycling

P-Pdot diagram and NS zoo



Plot credit: Surnis 2017

Characteristic ages

$$\tau_c \equiv \frac{P}{2\dot{P}} \simeq 15.8\,\mathrm{Myr}\left(\frac{P}{\mathrm{s}}\right)\left(\frac{\dot{P}}{10^{-15}}\right)^{-1}$$

If the pulsar had been slowing at the same rate its entire life, how long would it take to reach its current spin?

Surface Magnetic field strength

$$B_{\mathrm{surf}} = 3.2\times10^{19}\,\mathrm{G}\sqrt{P\dot{P}} \simeq 10^{12}\,\mathrm{G}\left(\frac{\dot{P}}{10^{-15}}\right)^{1/2}\left(\frac{P}{\mathrm{s}}\right)^{1/2}$$

Pulsars with strong magnetic fields slow down faster (stronger radiation, more outflow)

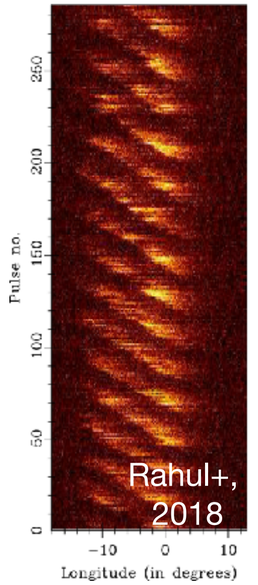
Death lines

$$B \lesssim 10^{12}\,\mathrm{G}\left(\frac{P}{1\,\mathrm{s}}\right)^{2}$$

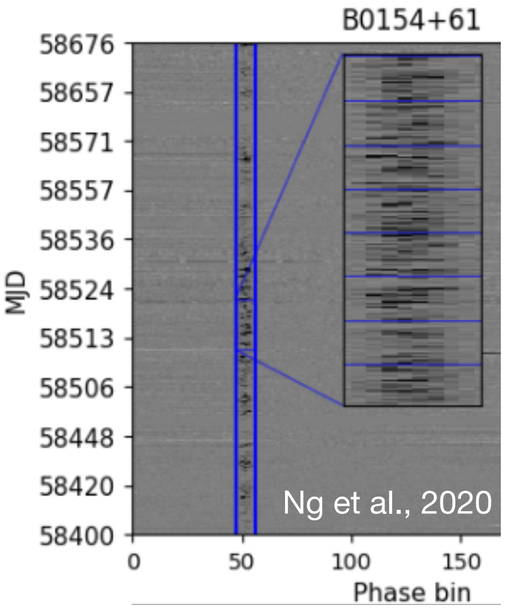
Critical value (~10^{12} G) needed to trigger pair creation, beyond that, rotation too slow to sustain the plasma needed for radio emission

Some more on emission mechanisms

- **Coherent emission**: The exact mechanism is still debated:
    - **curvature radiation from bunched particles** — Requires highly ordered bunching, hard to justify dynamically. Doesn't naturally produce the observed microstructure and subpulse variability
    - **plasma instabilities:** Explains rapid variability, Growth rates too slow to explain the brightness and short pulse widths. Difficult to produce narrow emission cones
- **Nulling:** constrains **magnetospheric models**—the engine driving the emission must be able to switch states rapidly.
- **Subpulse drifting:** components move systematically in phase. Emission comes in organized sub-beams; shows plasma circulation patterns near the polar cap.



Rahul+, 2018

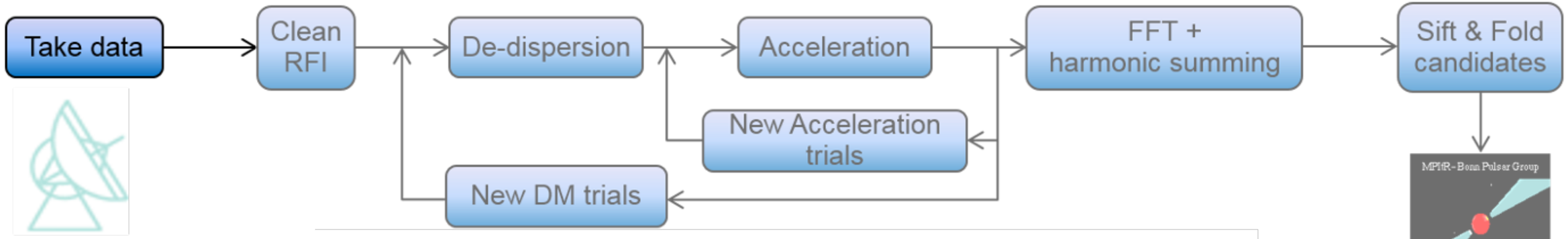


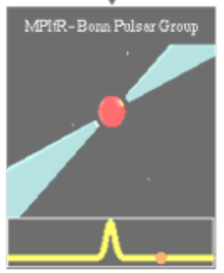
Ng et al., 2020

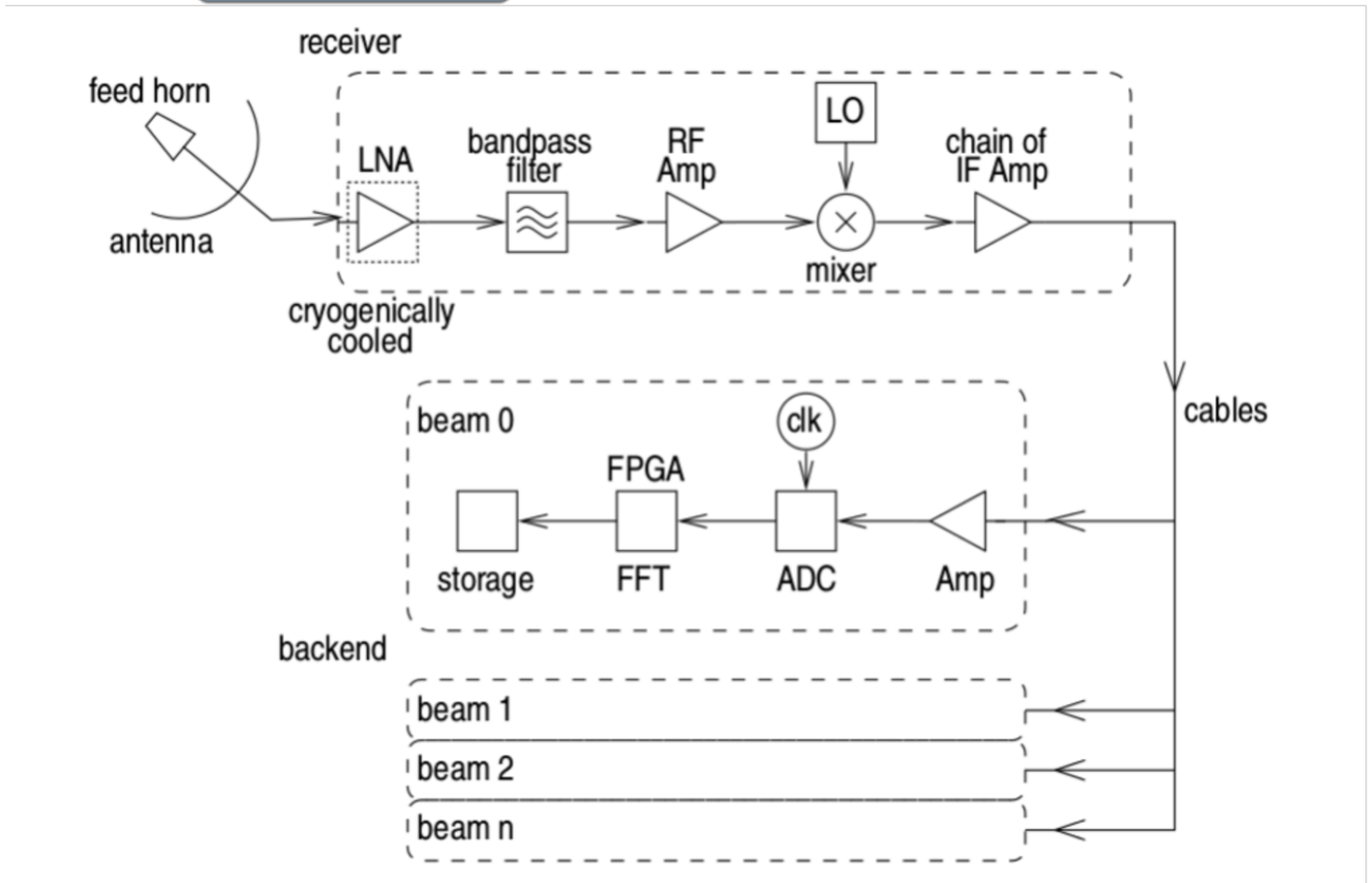
Pulsar searching

How do we find them?

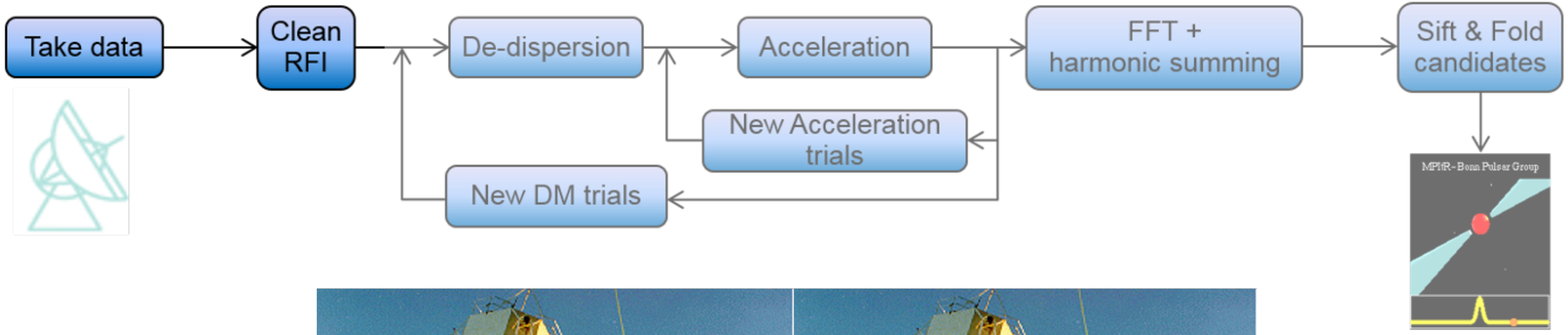
Pulsar searching by periodicity

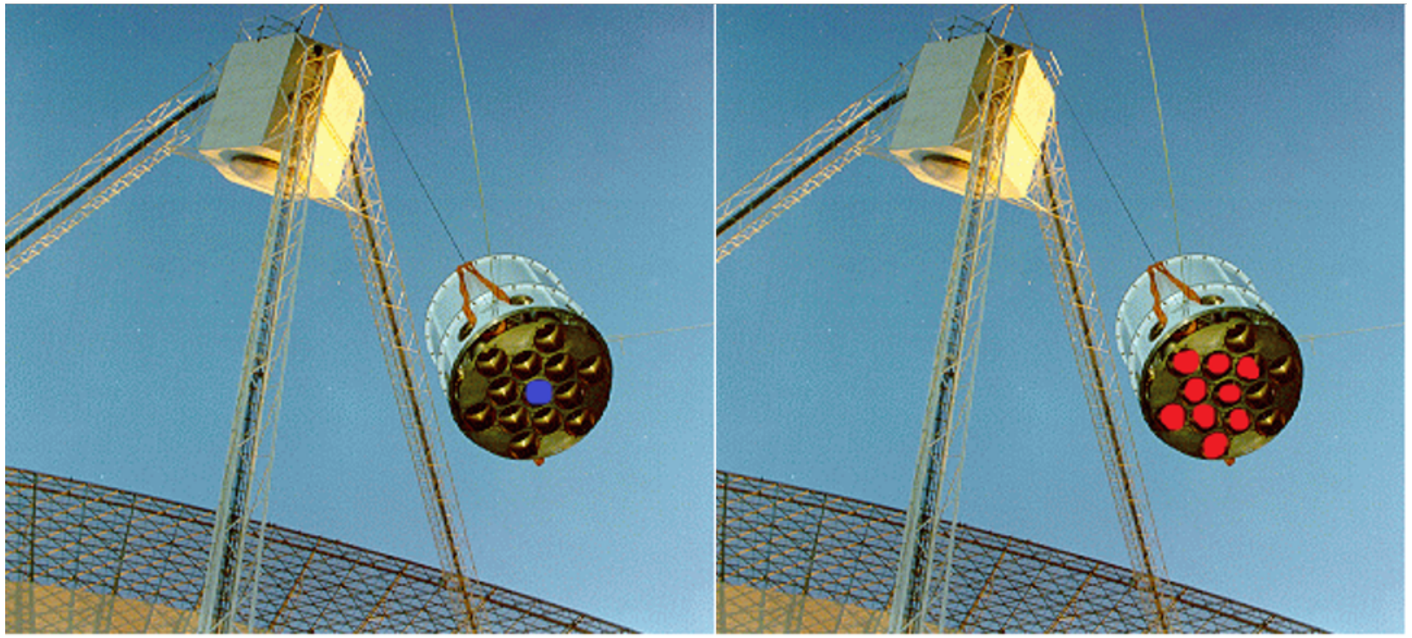






Pulsar searching by periodicity

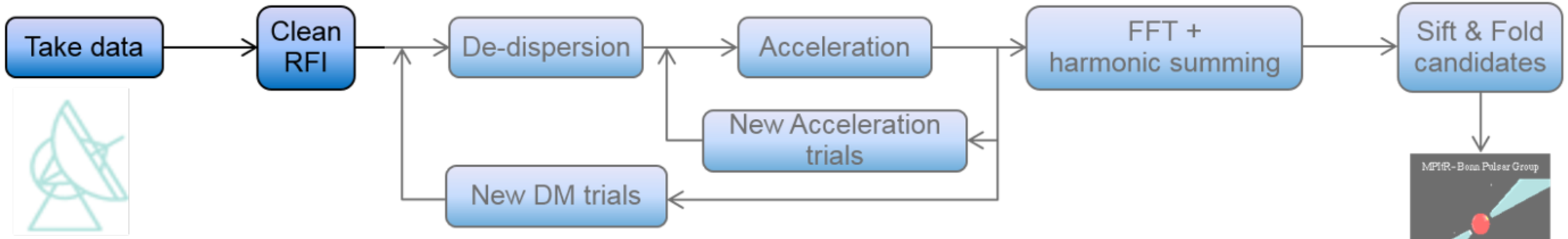


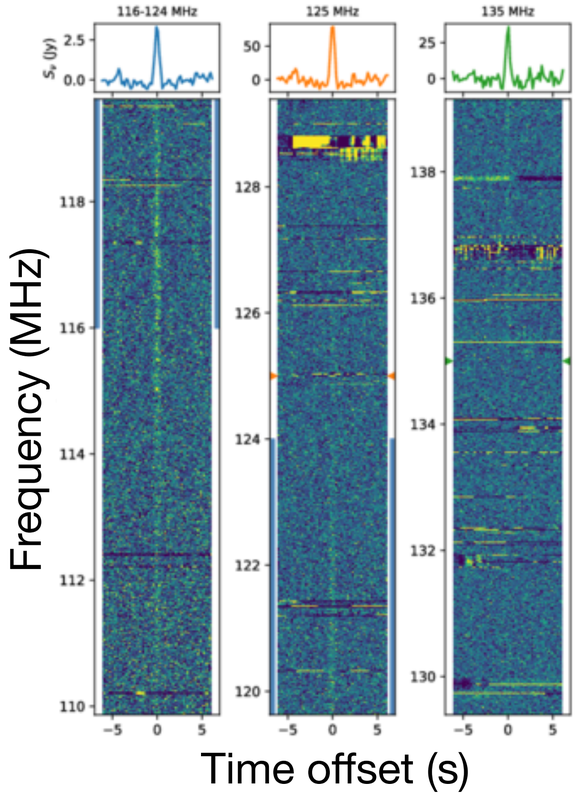


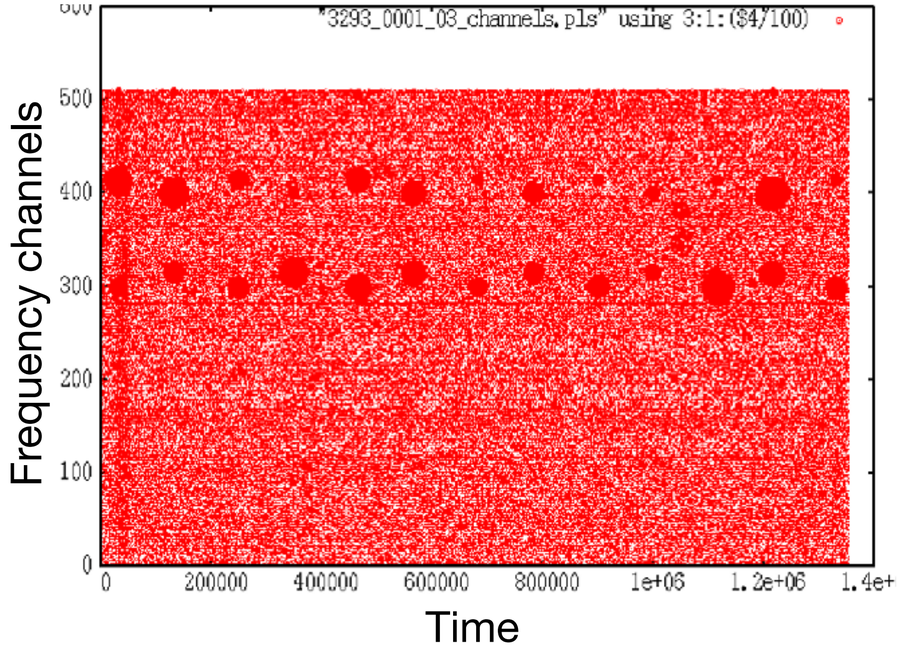
Celestial signal – single receiver beam

Terrestrial RFI – Multiple receiver beams

Pulsar searching by periodicity



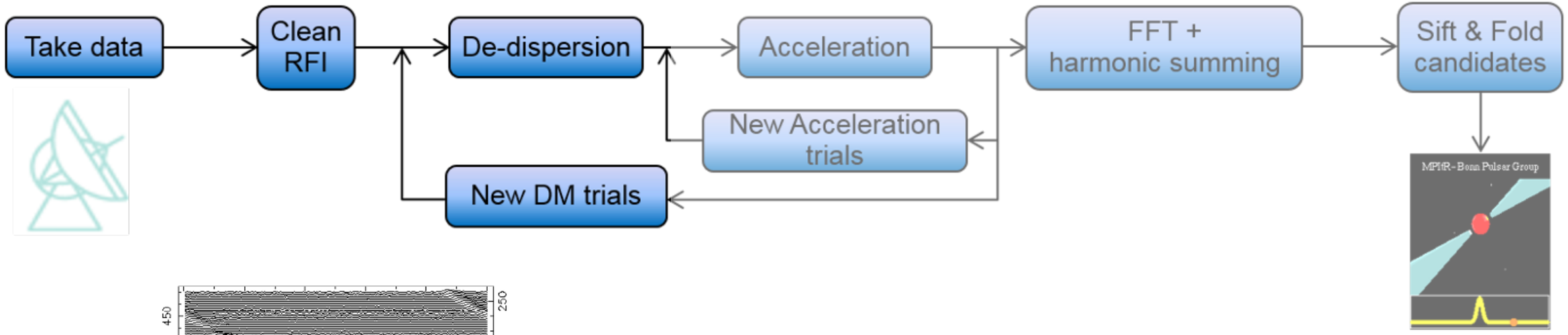


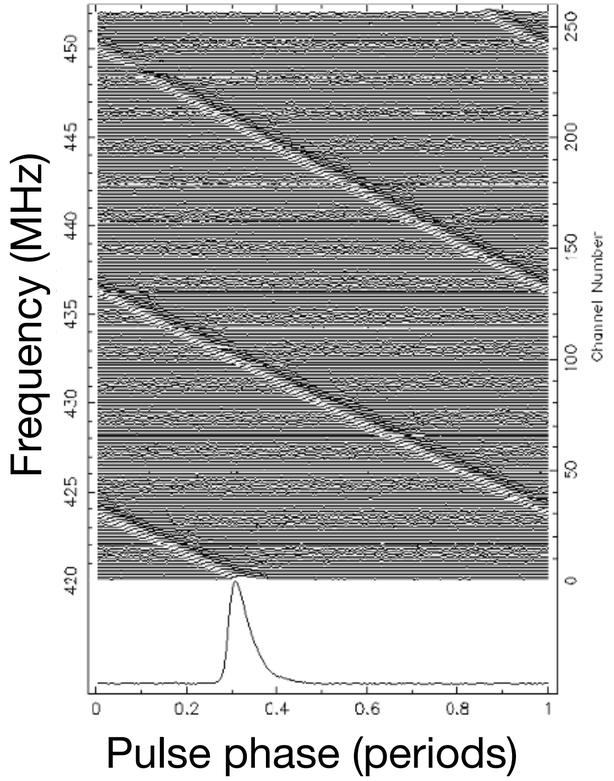


- Can be narrow band in frequency
- Time domain impulsive RFI
- Periodic RFI
- Strategy: threshold, kurtosis…
- Replace with Gaussian / running mean but be careful not to introduce artifacts

Image credit: Bassa et al 2024

Pulsar searching by periodicity



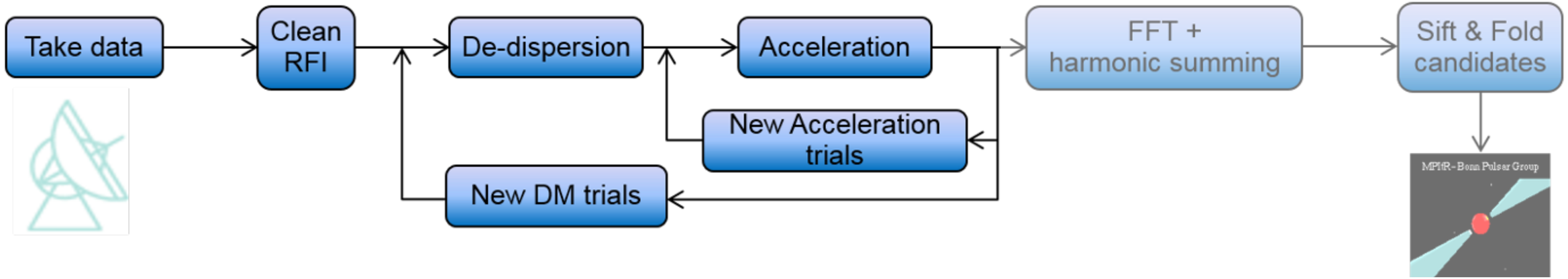


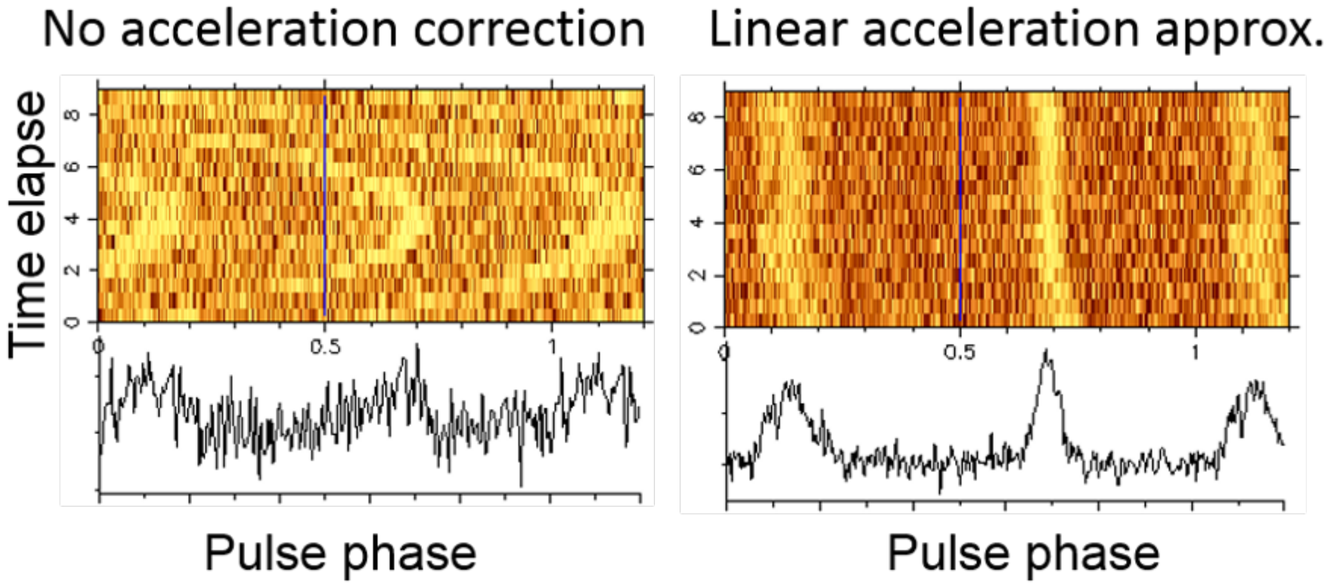
The pulse travel time (t_p) of an EM wave of freq v emitted at a distance d propagating through an electron plasma with uniform number density n_e :

Dispersion measure (DM)

$$t_p = \frac{d}{c} + \frac{e^2}{2\pi m_e c} \frac{\int_0^d n_e \, dl}{\nu^2}$$

Pulsar searching by periodicity



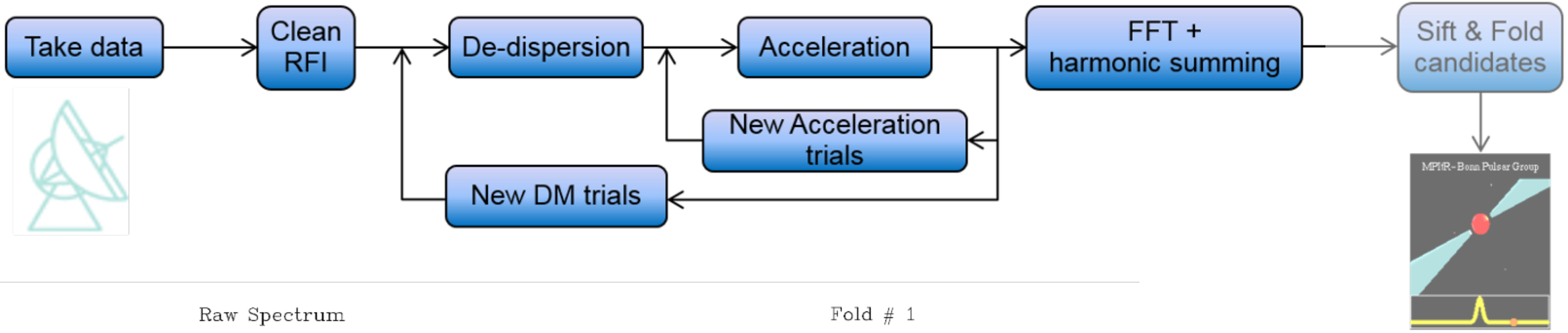


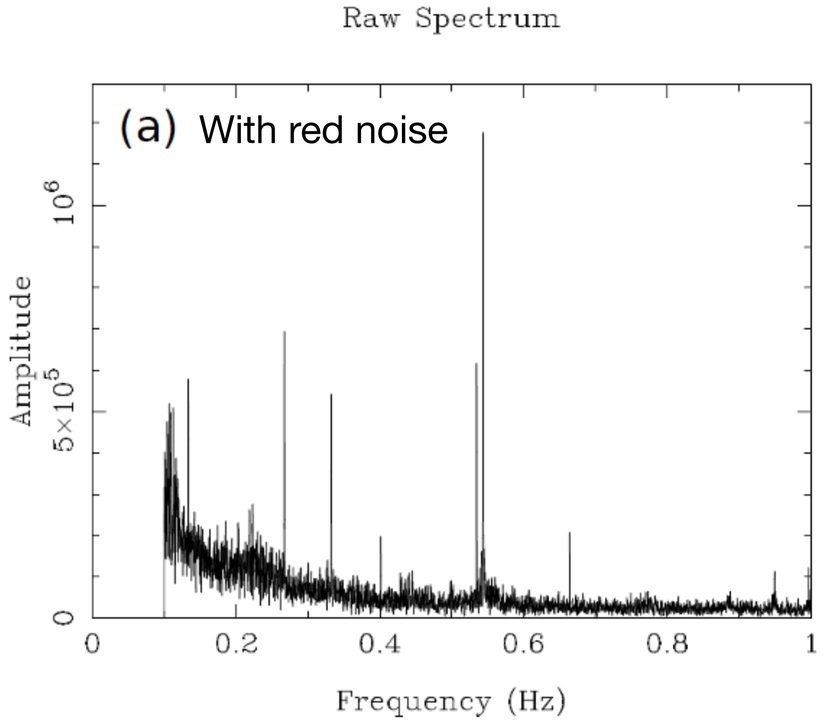
- Resampling in time to restore to rest frame of the pulsar
- Solving for full orbit too expensive —> linear acceleration approximate
- For circular orbit, timing (y(t)) is approx. a sinusoid with period equal to the orbital period (P_b) and amplitude (A) equal to the projected semi-major axis: $y(t) = A\sin(2\pi\frac{t}{P_b} + \phi) + C$

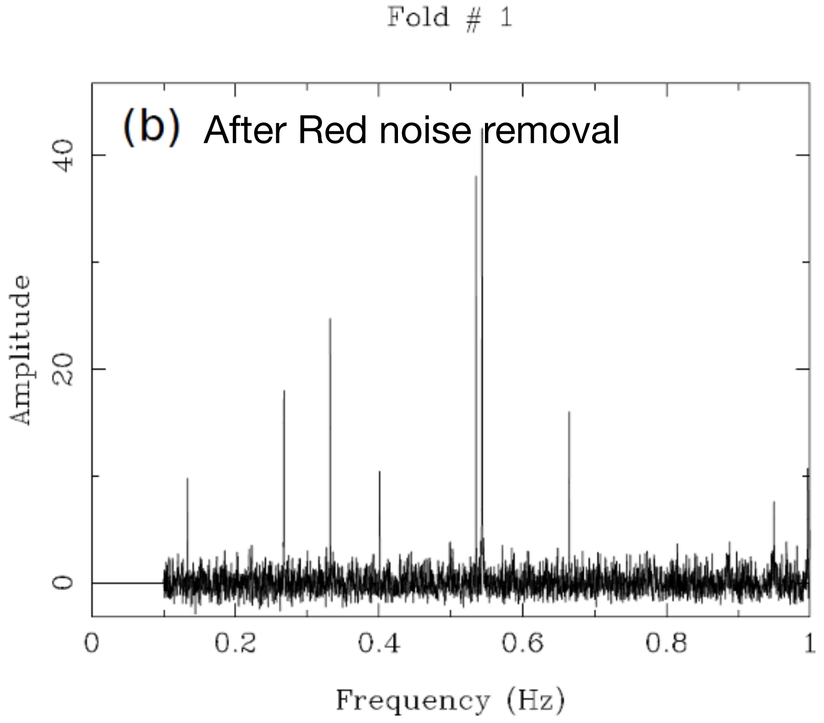
A = amp_guess
P_b = pb_guess
Phi = phase_guess
C = offset_guess

This is the 2nd exercise in the hands-on session this afternoon

Pulsar searching by periodicity







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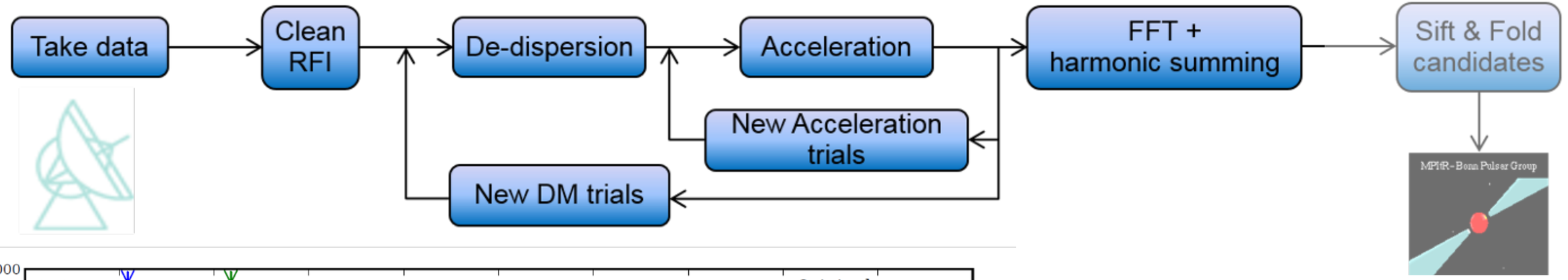
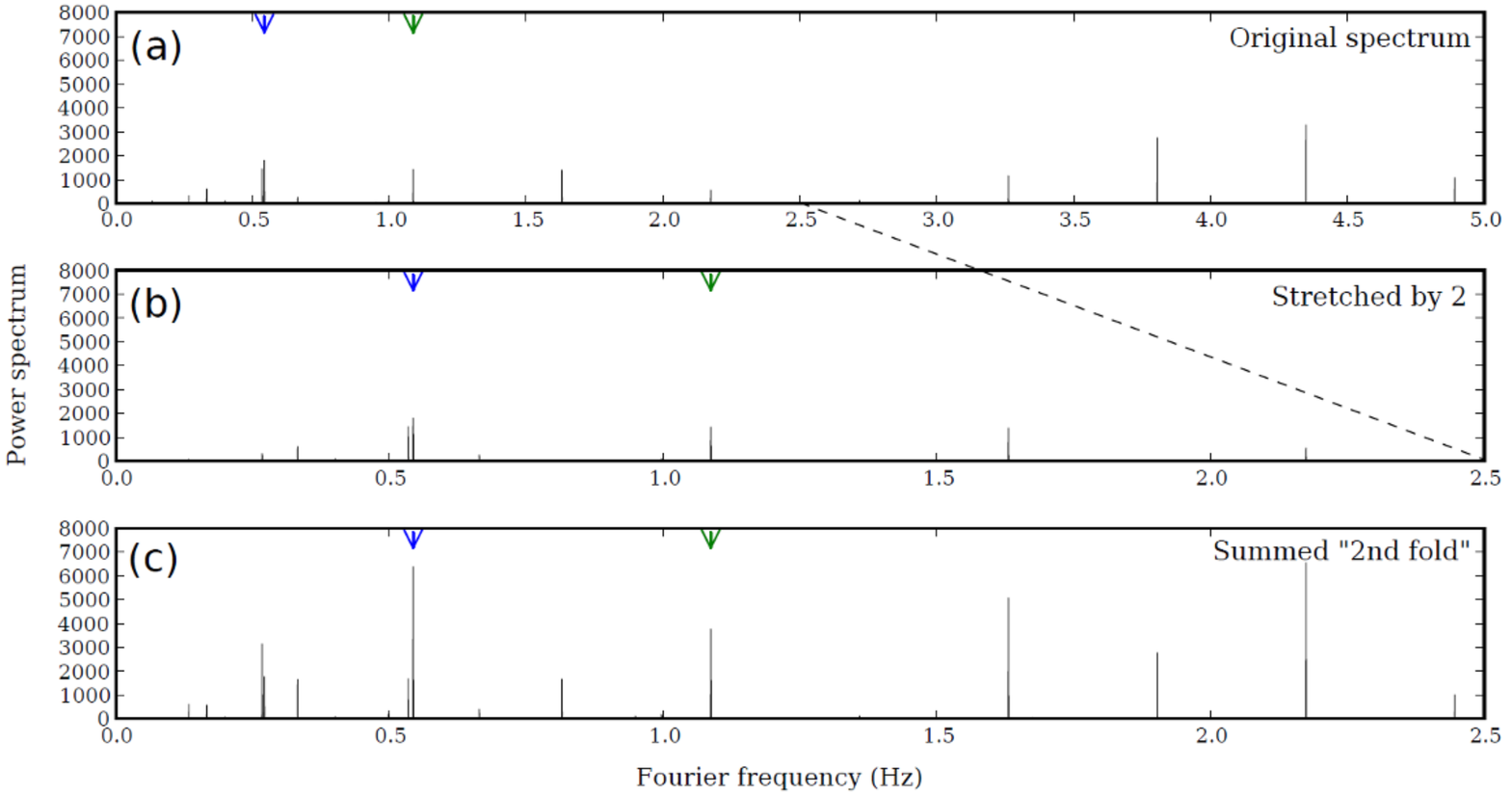
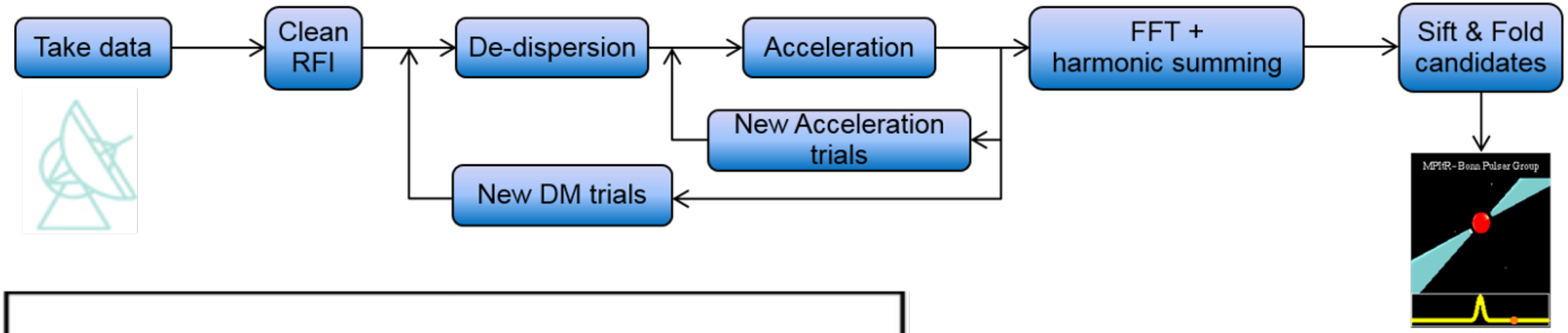




- Pulses Are narrow, Not sinusoidal
- Their power is spread over many **harmonics** in the Fourier spectrum, and incoherent harmonic summing recombines that distributed power to improve detectability.
- After rescaling, the harmonics **line up at the same frequency**, and their power can be (incoherently) summed.

Pulsar searching by periodicity



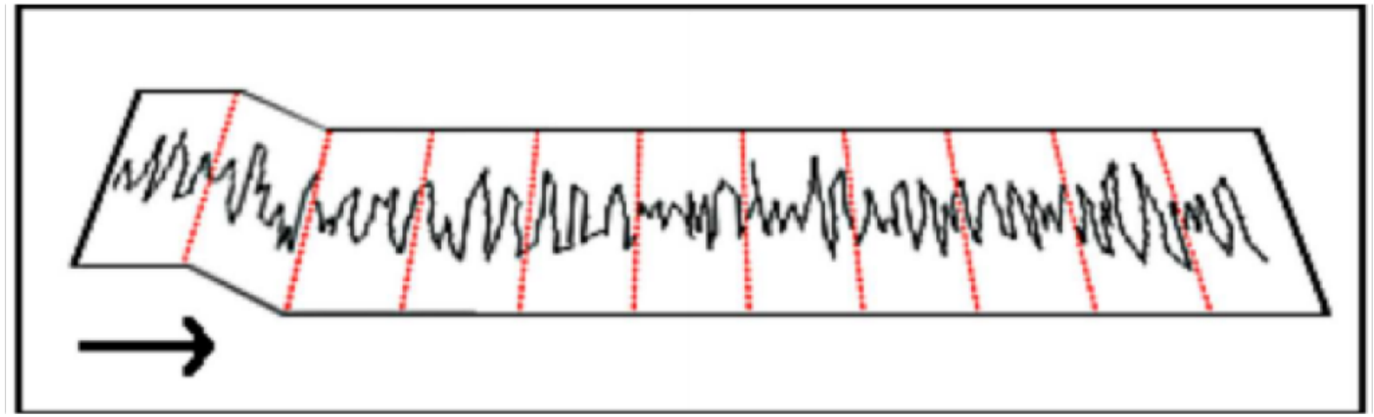
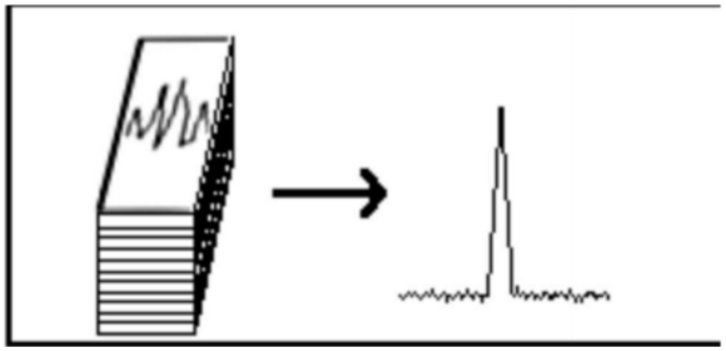


Image credit: Ryan Lynch (NRAO)



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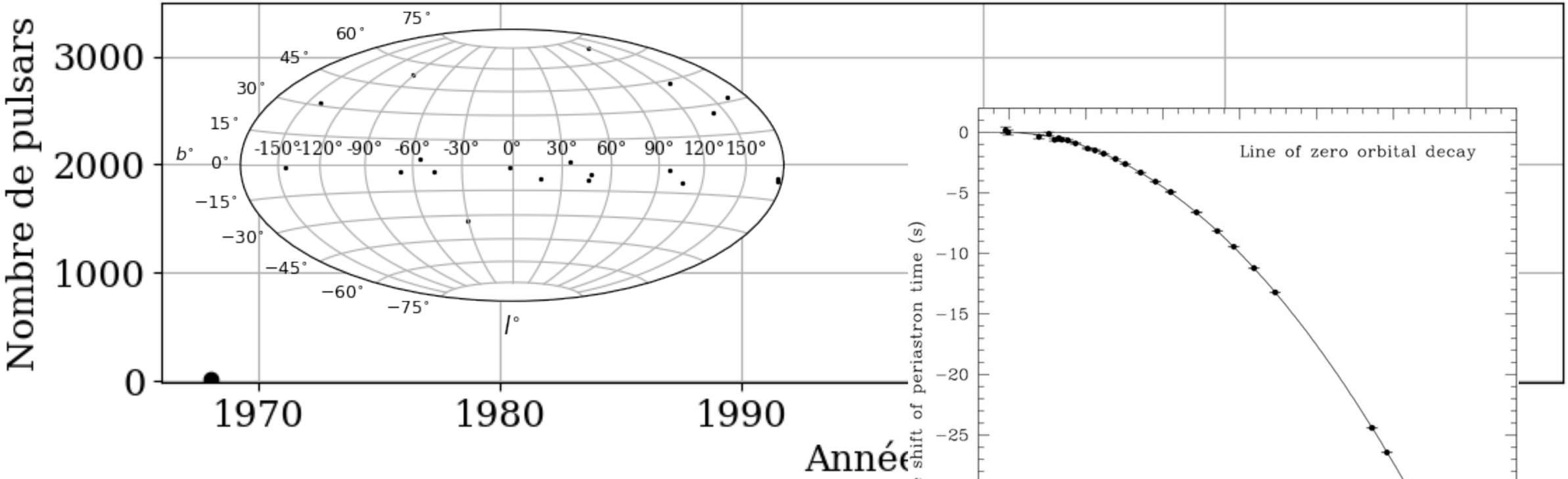
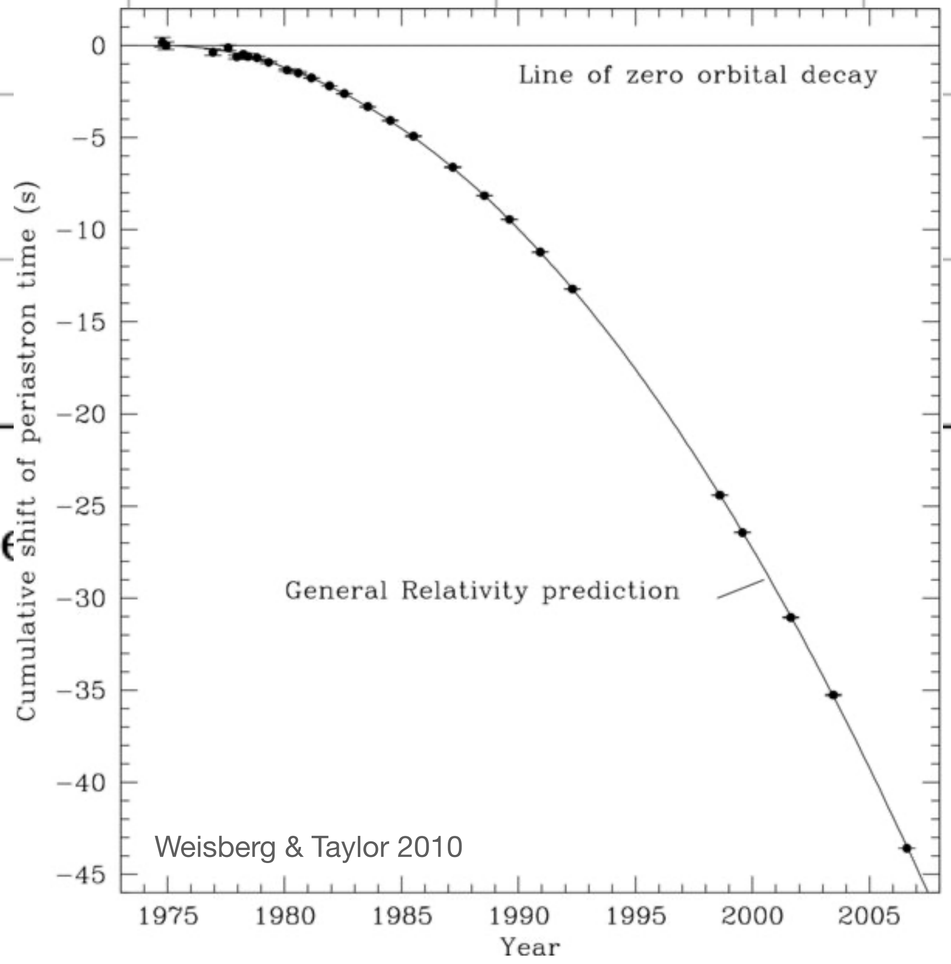
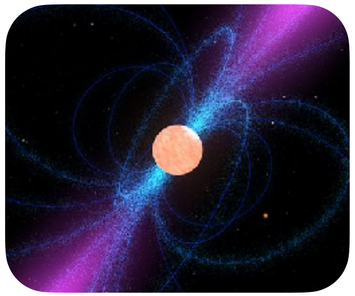
Why are pulsars important?

59 ans de découvertes de pulsars

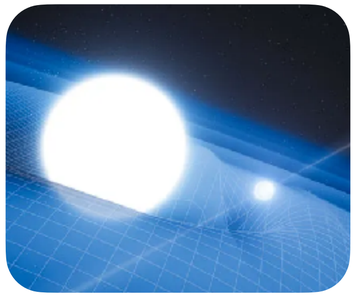




1967 (Nobel 74)
Premier pulsar

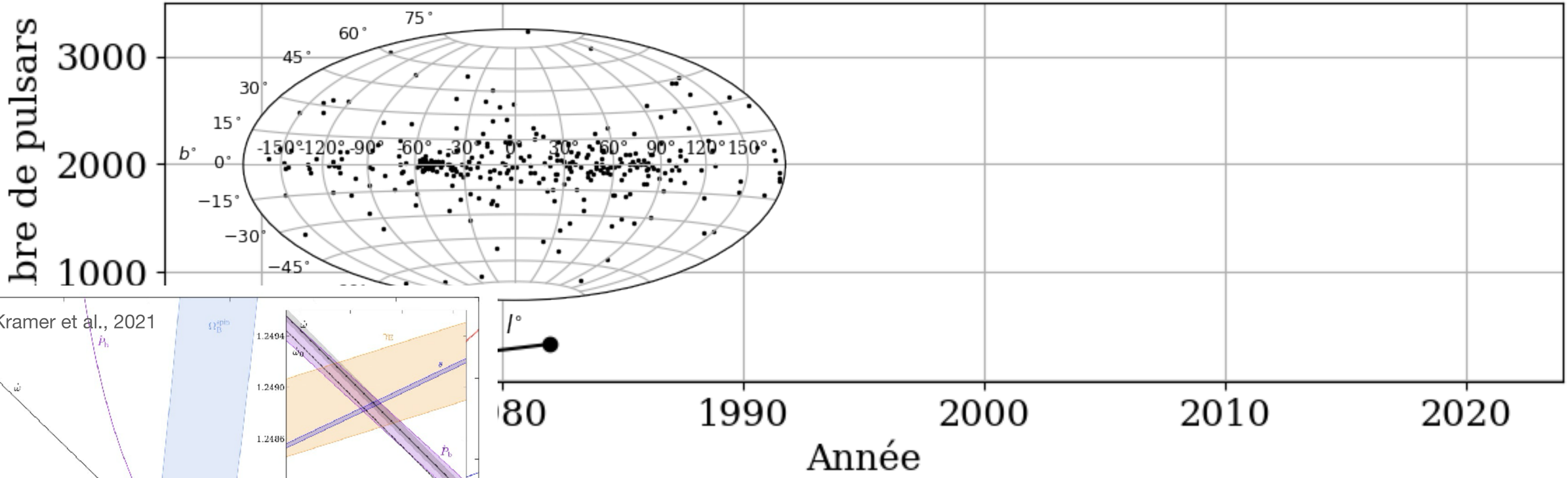


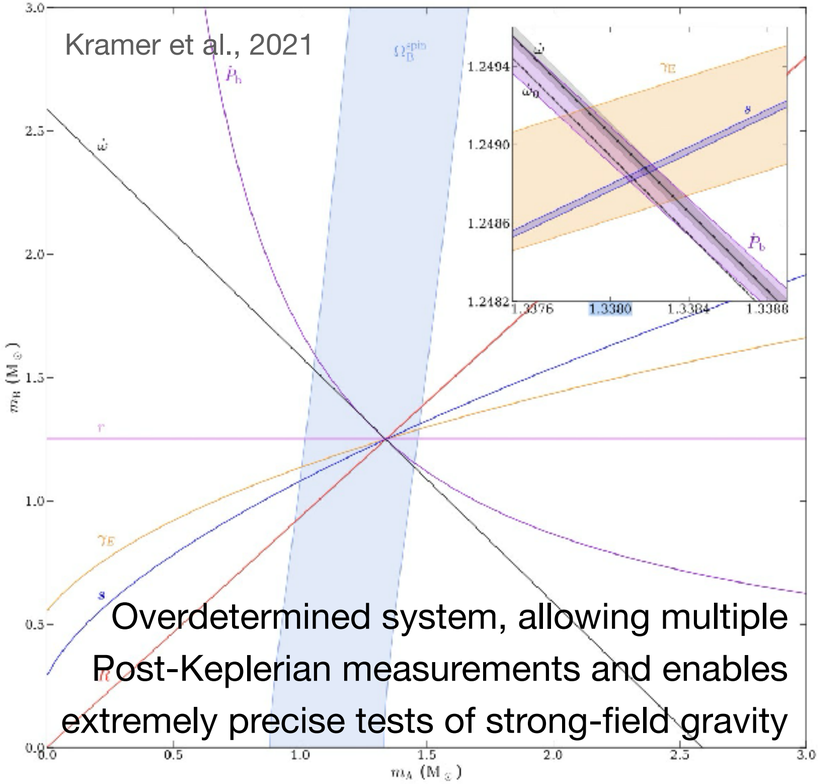
1974 (Nobel 93)
Binaire



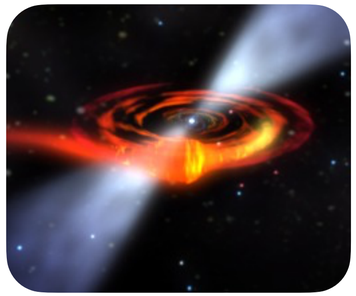
According to **GR**, accelerating massive objects should emit **GW**. Orbital period delay predicted to be ~3mm/orbit.

59 ans de découvertes de pulsars



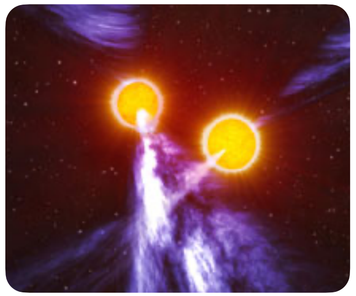


1982
Pulsar ms

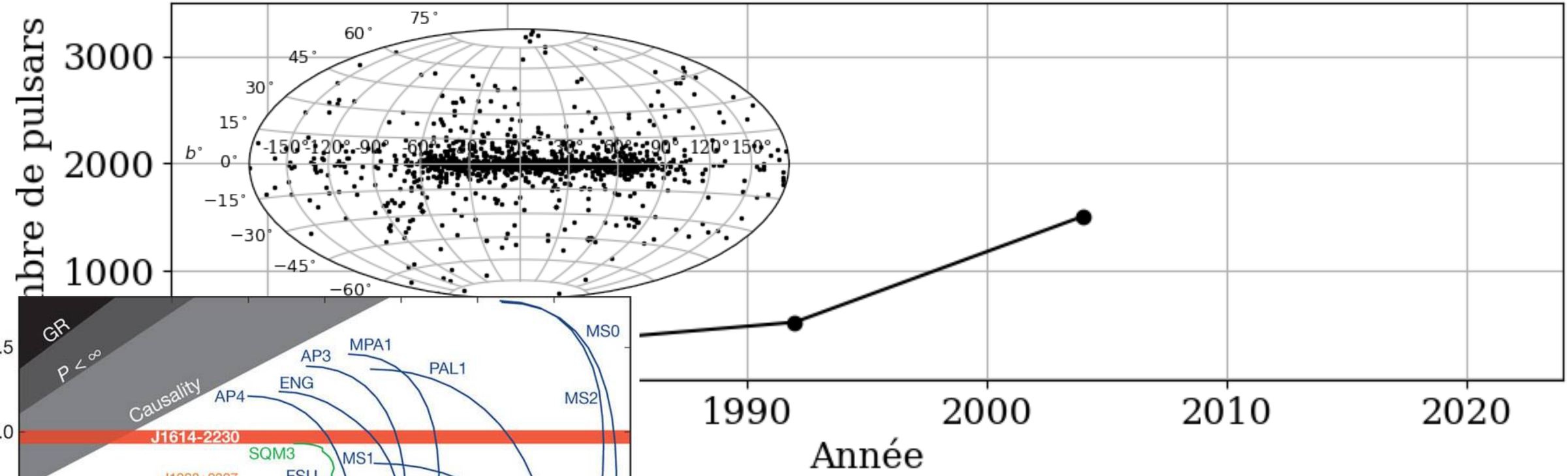


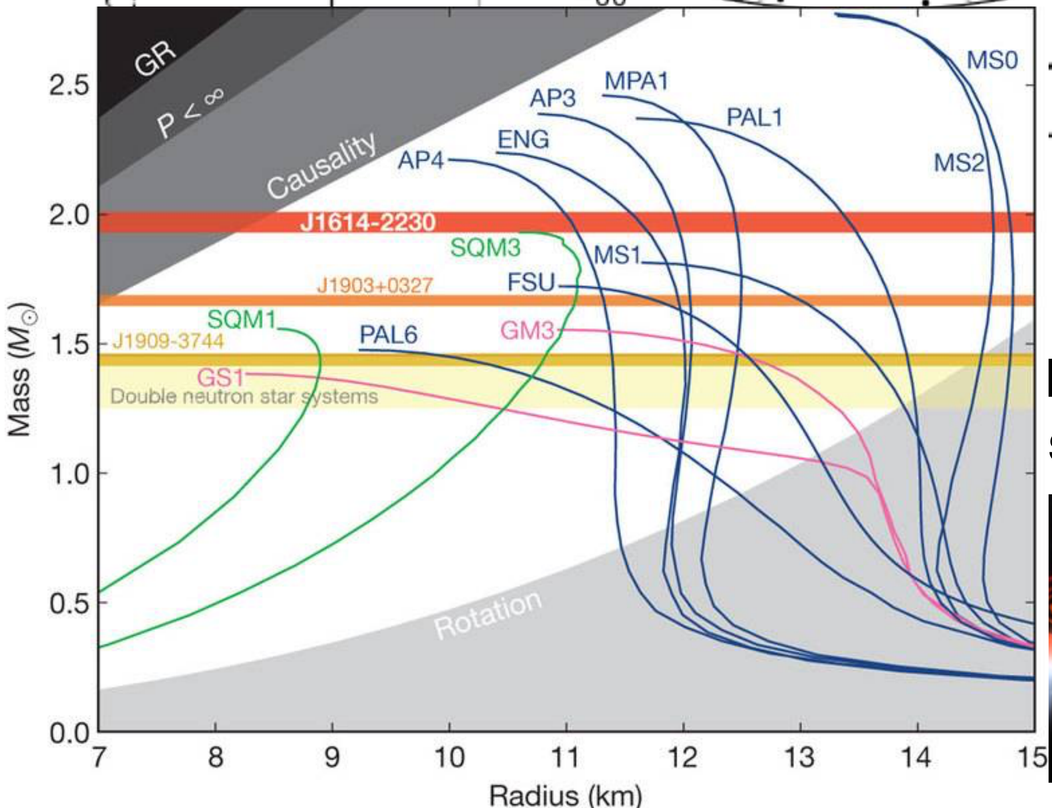
1992
Exoplanète

2004
2x pulsars

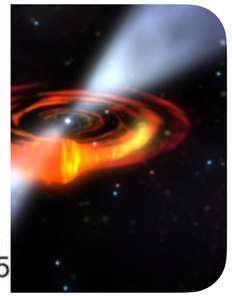


59 ans de découvertes de pulsars





1982
sar ms



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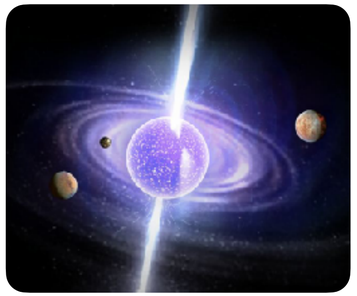
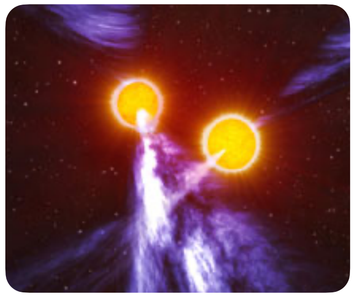


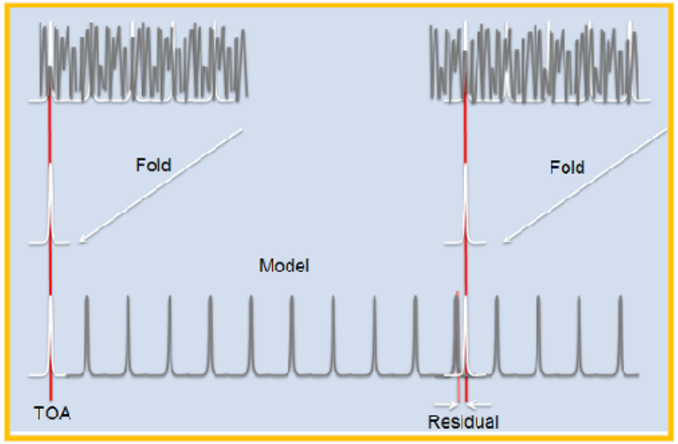
2004
2x pulsars



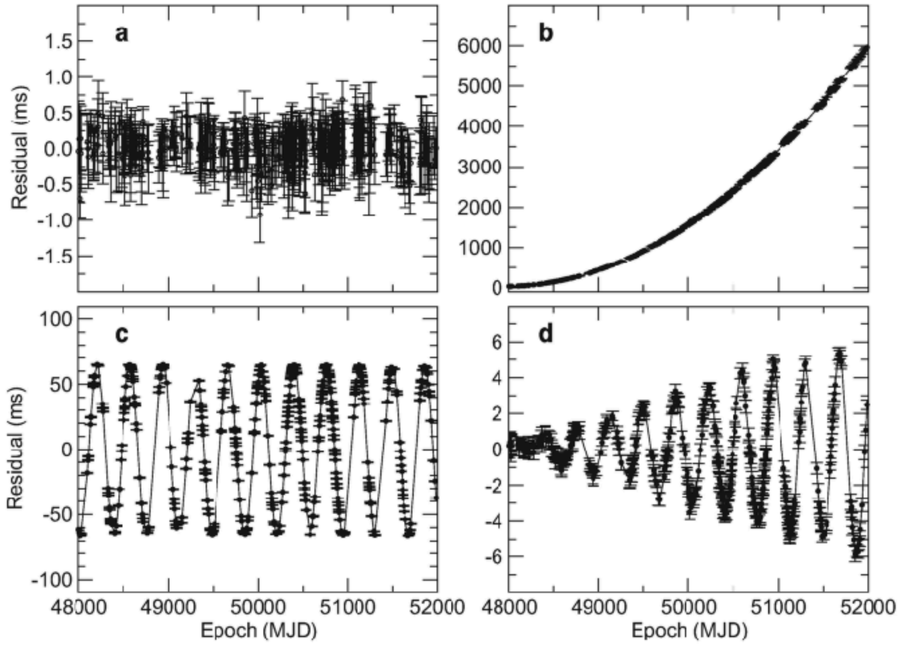
2023
Timing Array

Pulsars timing in a nutshell

- Unambiguously account for every rotation of a pulsar
- TOAs: Times of Arrival
- Measurement - Model = Timing Residuals



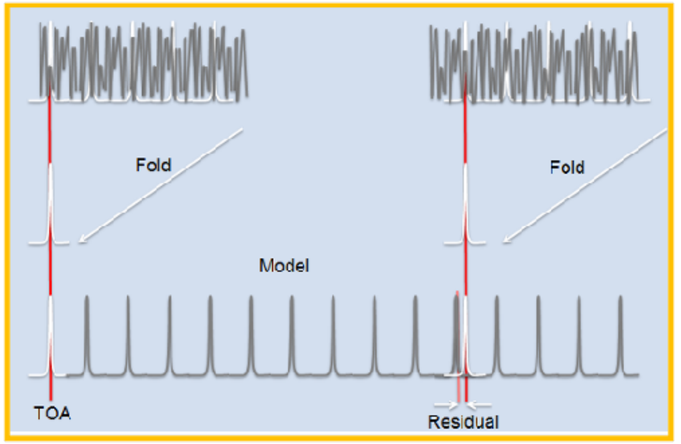
- Isolated pulsars have 4 timing parameters:
  RA, Dec, P, P-dot
- Extended timing can give Proper motion & parallax
- Binary pulsars add 5 Keplerian Orbital params:
  P_{orb}, asini/c, e, ω, T0
- Some binaries give post-Keplerian param:
  ω-dot, γ, P_{orb}-dot, r , s



Credit: Pulsar handbook by Lorimer & Kramer

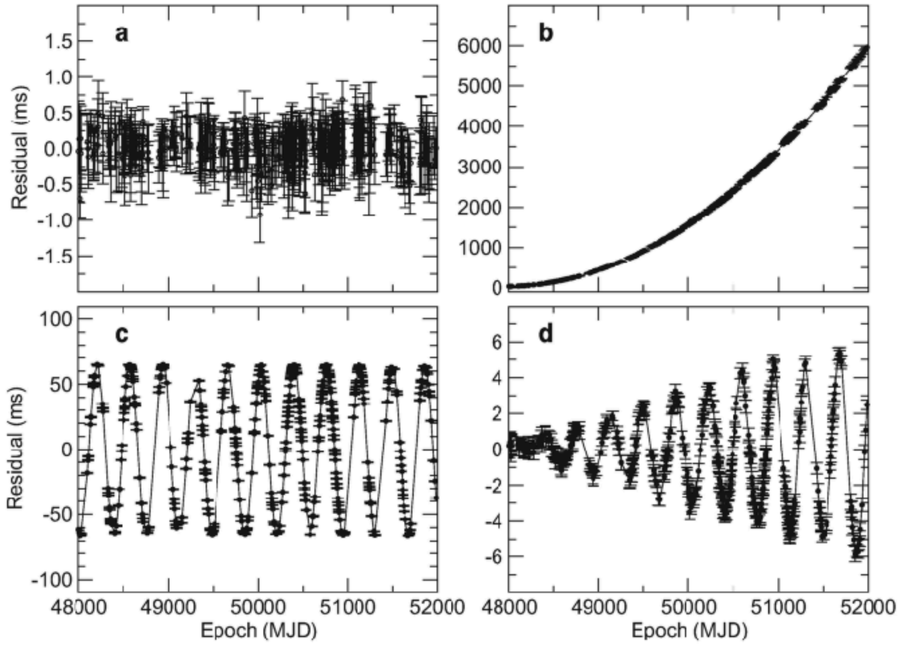
Pulsars timing in a nutshell

- Unambiguously account for every rotation of a pulsar
- TOAs: Times of Arrival
- Measurement - Model = Timing Residuals



As Michael Kramer says:

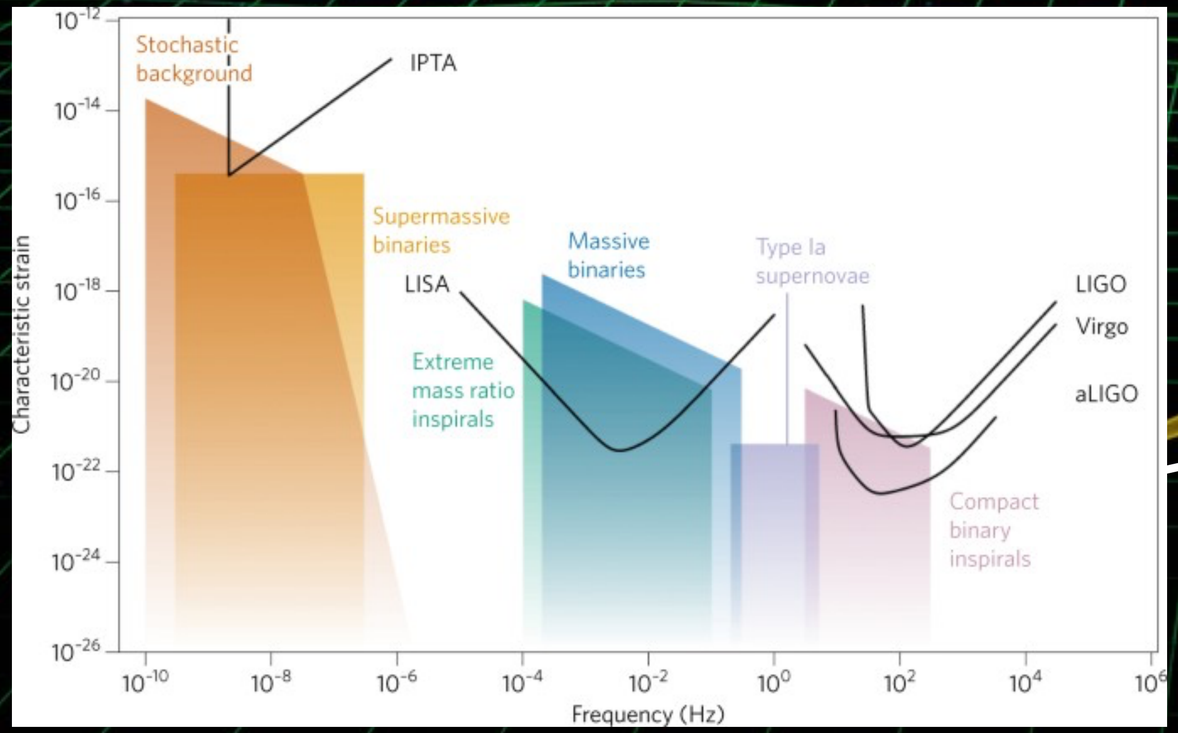
- The best pulsars keep time with an accuracy of 1 millionth of a second over 30 years (comparable to best atomic clocks)
- PSR J1012+5307: 15 years of obs with EPTA:
  P = 0.00525574901411541**0** ± 0.00000000000000015 s [Lazaridis et al. 2009]
  → 90 billion rotations since discovery, and not lost a single count!



Credit: Pulsar handbook by Lorimer & Kramer

Right size to detect GW from SMBH
c.f. 4-km arm in LIGO for stellar-mass BHs

~10,000 lightyears = few – 10s kpc



International
Pulsar
Timing
Array
Effelsberg
Lovell
Nançay
WSRT
SRT
EPTA
GBT
Arecibo
VLA
CHIME
NANOGrav
FAST
CPTA
PPTA
Parkes
InPTA
GMRT
MPTA
MeerKAT
H. Thankful Cromartie

Effelsberg Lovell Nançay WSRT SRT

EPTA

GBT

Arecibo

VLA

CHIME

NANOGrav

FAST

Parkes

GMRT

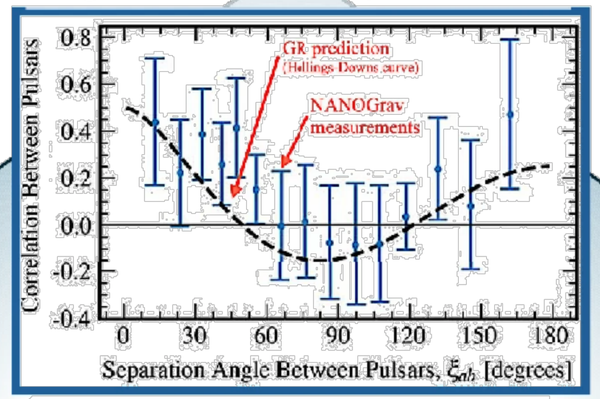
MeerKAT

H. Thankful Cromartie

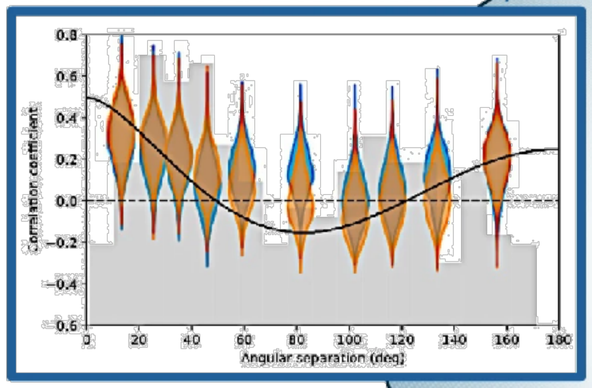
Credit: Steve Taylor (2025)

The **Hellings–Downs curve:** predicted **correlation pattern** between timing signals from different pulsars in a PTA when the timing fluctuations are caused by a **stochastic GW background**

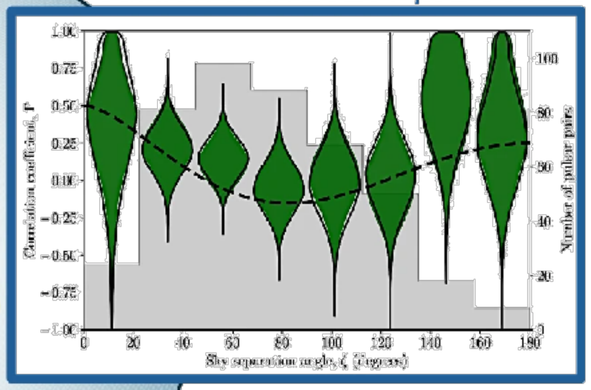
Agazie *et al* 2023 *ApJL* 951 L8



Antoniadis et al 2023 A&A 678, A50



Reardon *et al* 2023 *ApJL* 951 L6



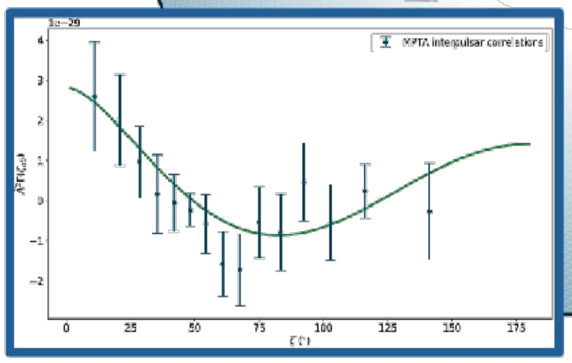
NANOGrav

EPTA
InPTA
Indian Pulsar Timing Array

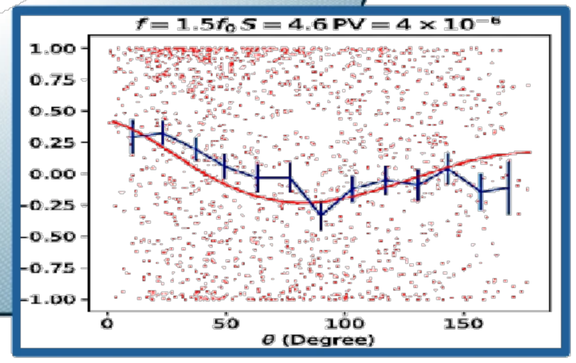
PPTA

MPTA

CPTA



Miles et al 2025 MNRAS 536 2

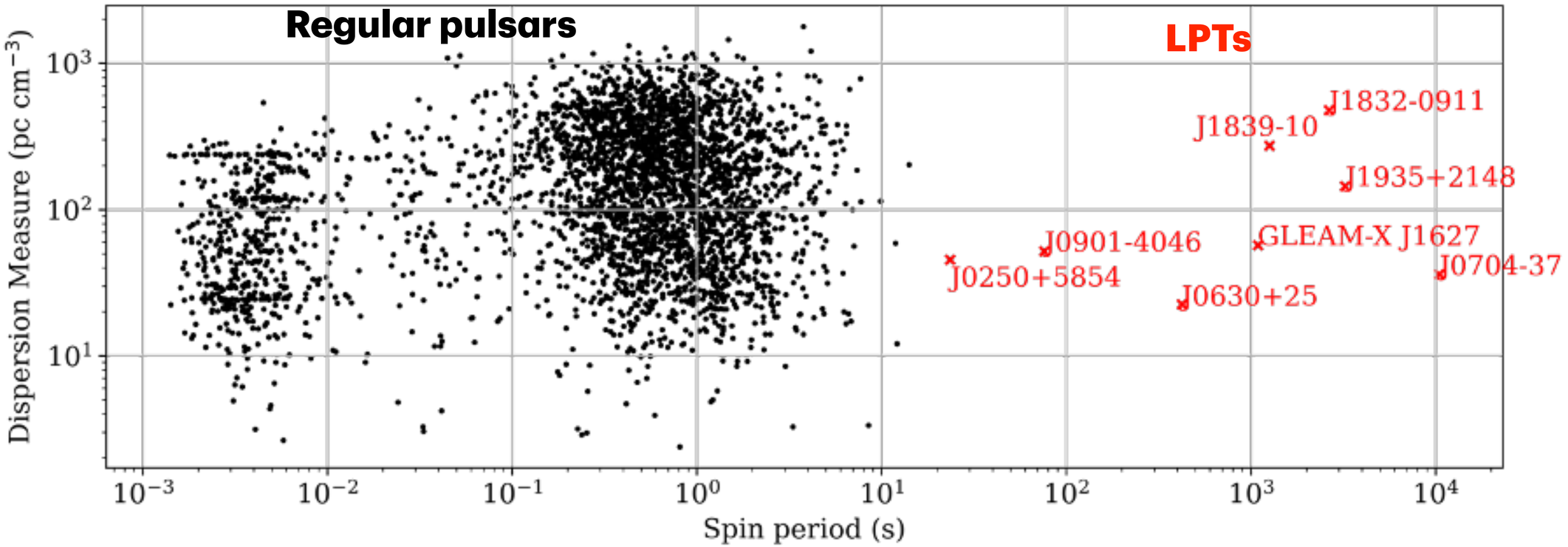


Xu et al 2023 RAA 23 075024

- Strong positive correlation when pulsars are close together
- Correlation decreases as separation increases
- Slightly negative near ~90°
- Rises again slightly toward 180°
- GW distort ST in a quadrupolar pattern —> asymmetric shape

What else are new?

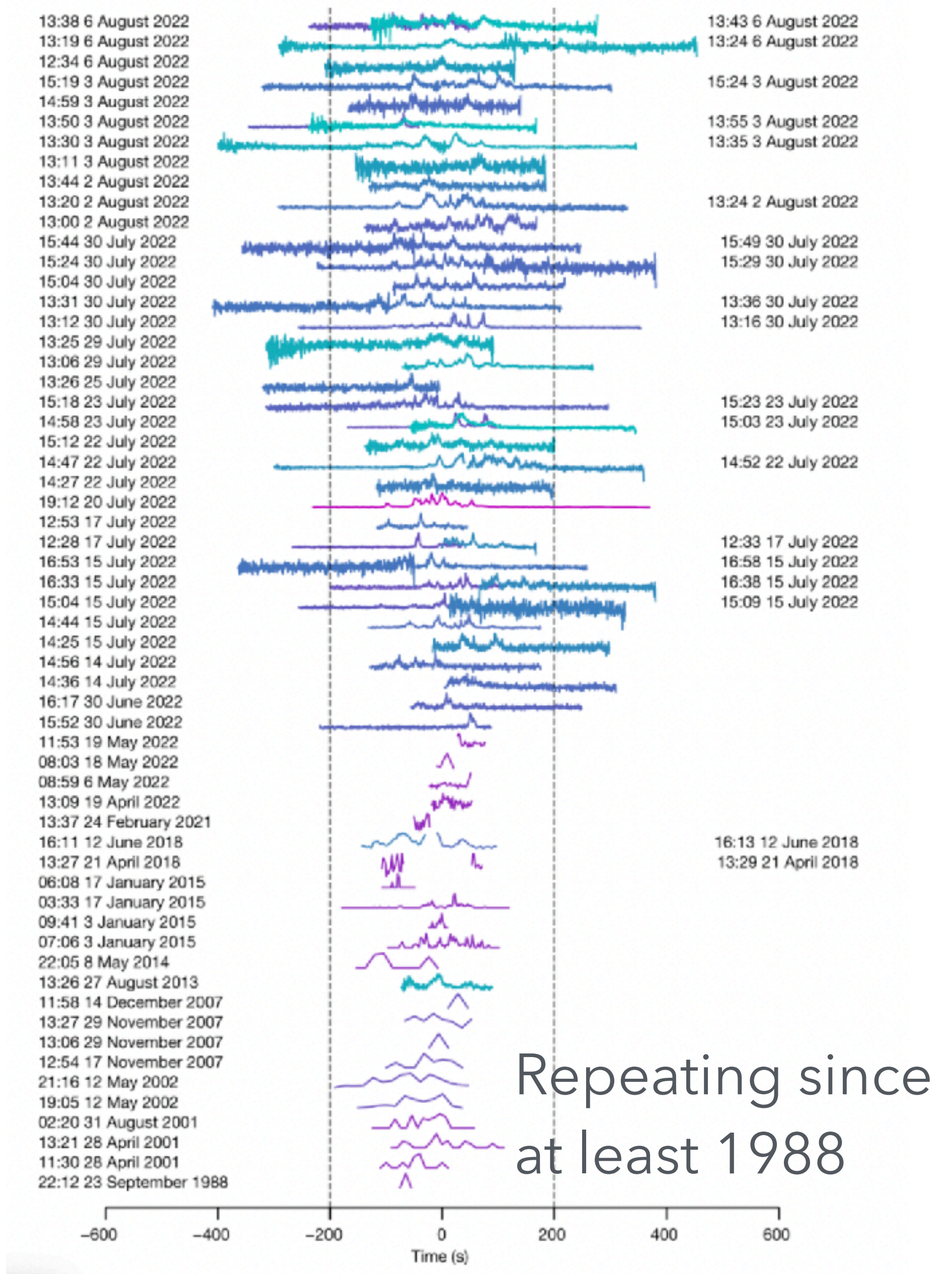
Long period transients



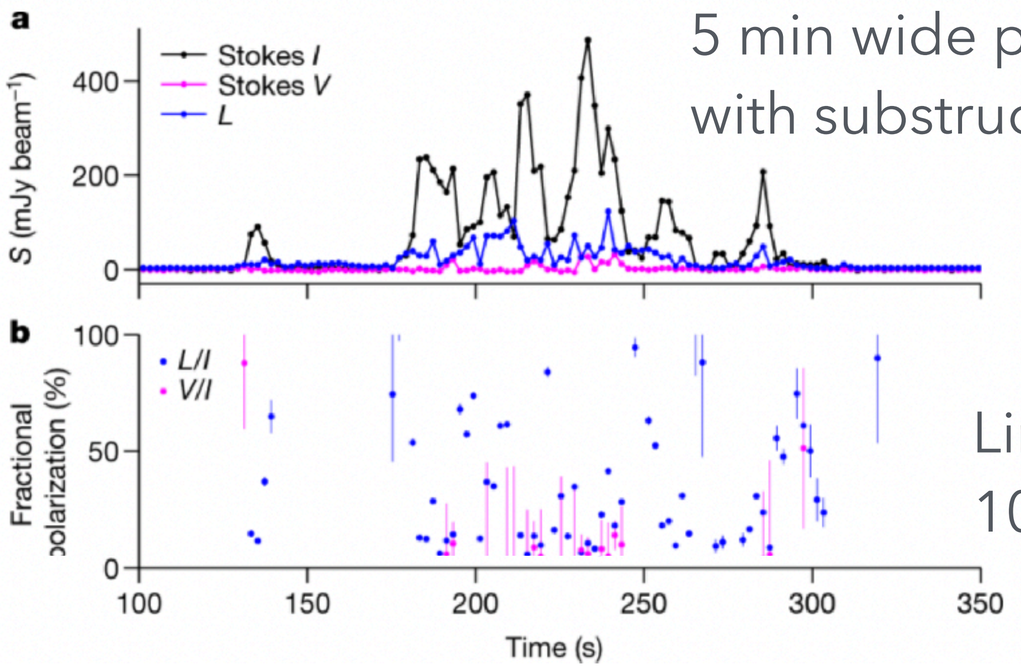
- LPTs: Periods > 10s, slowest is ~6 hours
- First noticed in around 2022 (N. Hurley-Walker+2022)
- Rotational-powered pulsar spins down —> **electric potential** no longer accelerates enough charged particles to create **electron–positron pairs** —> Death lines

GPM J1839-10

Hurley-Walker et al. 2023



Repeating since at least 1988



5 min wide pulses with substructure

Linear pol: 10%–100%

- Strict periodicity (P~22min) + long-term stability
- Defies what we thought was physically possible for pulsars or magnetars
- Twisted magnetosphere — magnetically powered, ultra-slow pulsar?

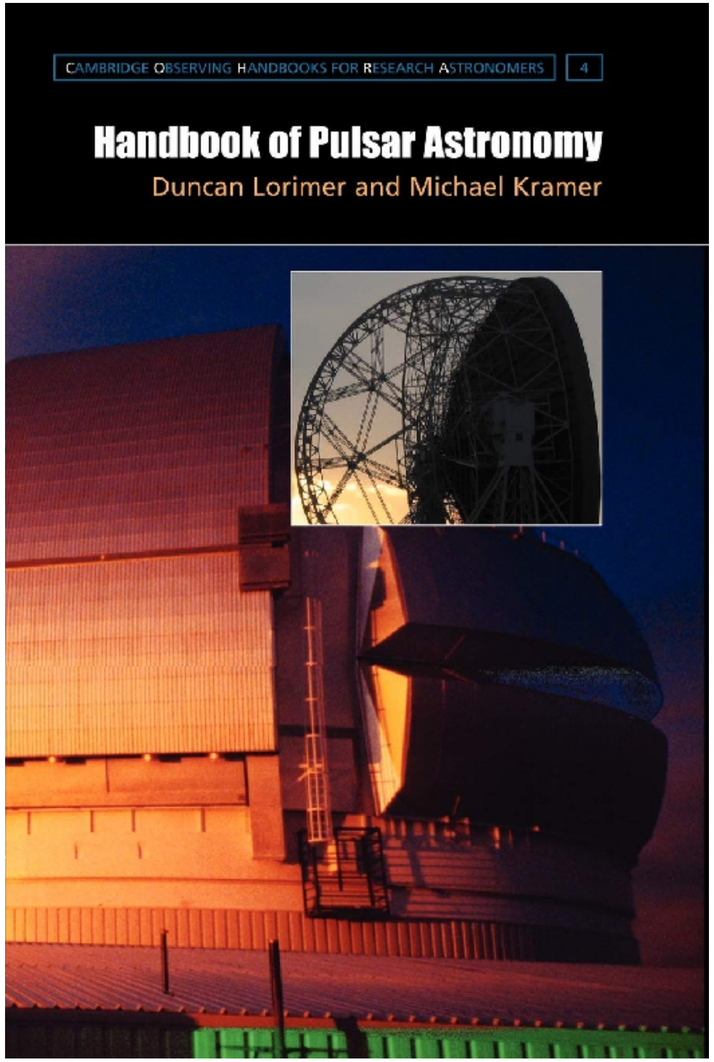
Current Open Questions

- What is the exact radio emission mechanism?
- Why do pulsars **null** or switch modes?
- What determines the **death line**? (c.f. what are LPTs?)
- How are **fast radio bursts** related to neutron stars? (See next class)
- What can PTAs tell us about the **gravitational-wave background**?

Entretiens 2026 sur les pulsars et les étoiles à neutrons

June 1-2, 2026, at the APC, Paris

- provide a regular platform for the French pulsar community to meet, exchange ideas, and collectively advance the study of pulsars, neutron stars, and FRBs.
- not a traditional conference with strictly timed presentations, but rather a series of working sessions designed to encourage discussion (advances, challenges)
- participation of doctoral students is encouraged
- Registration is free

https://indico.in2p3.fr/event/38846/overview

- Pulsars and Neutron stars
- Emission mechanism
- Pulsar searching by periodicity
- Pulsar Timing and Pulsar Timing Array (PTA)
- Notable pulsar results
- Current questions