MAX-PLANCK-GESELLSCHAFT

Max-Planck-Institut für Radioastronomie

LOFAR

Pulsars

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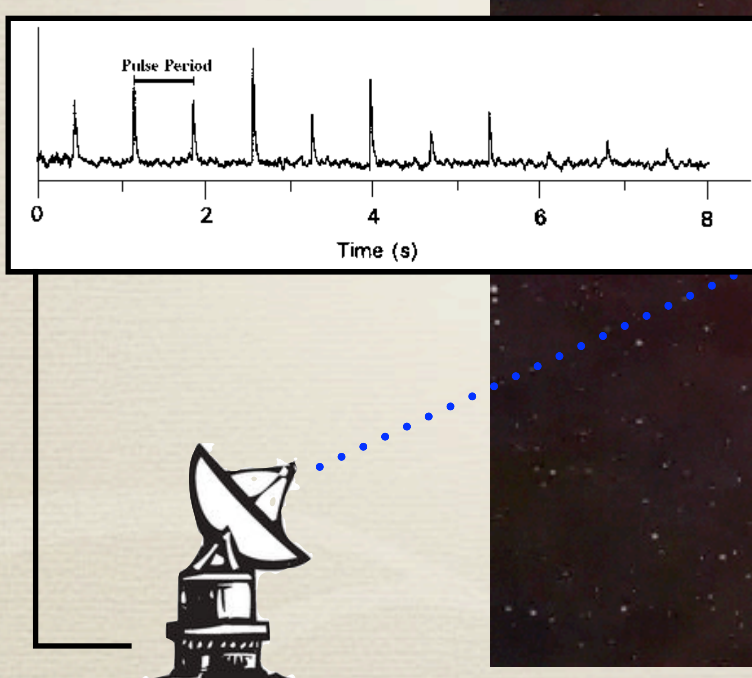
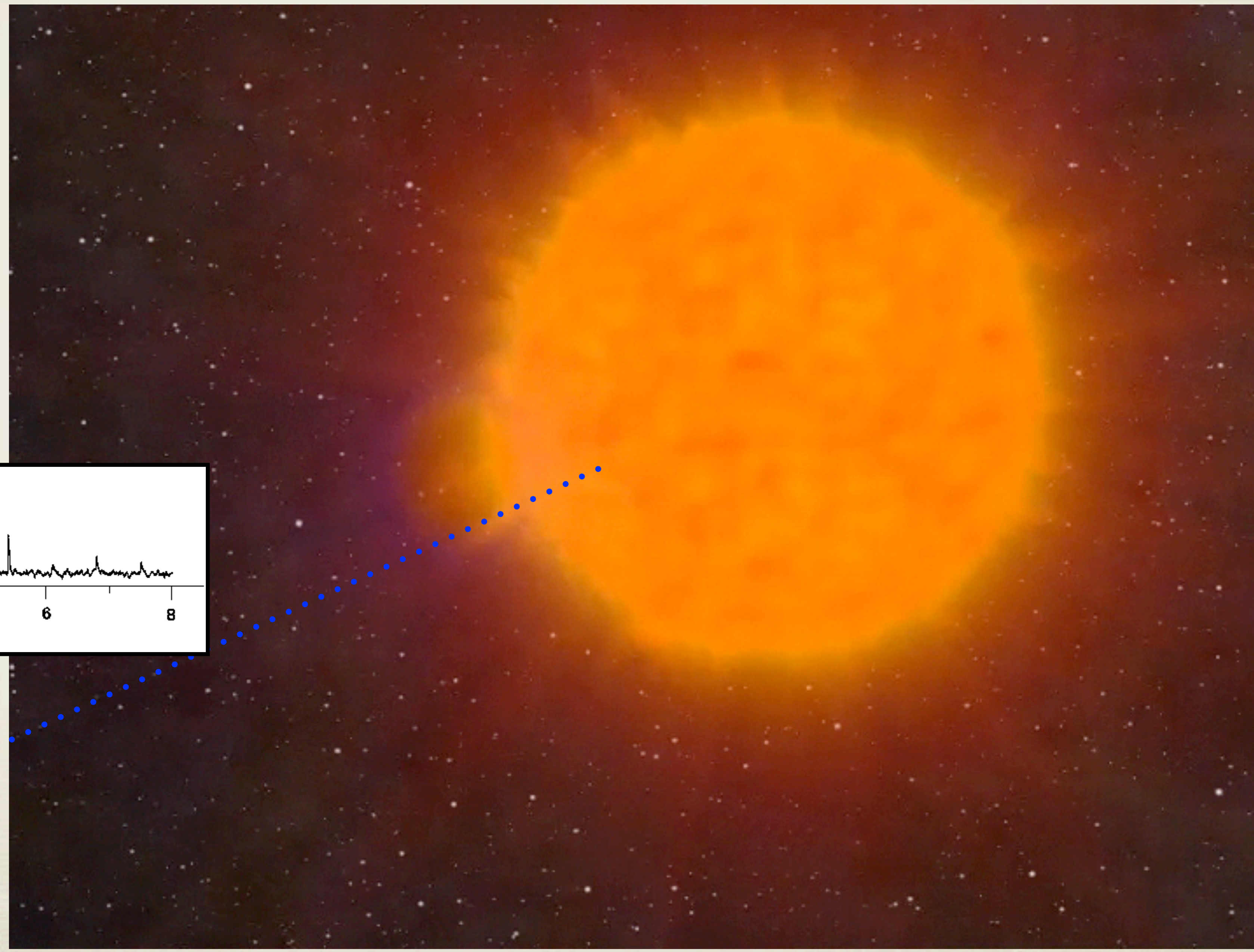
The pulsar phenomenon

Supernovae Type II mark the end of the lives of massive stars (>8$M_{\odot}$). For a brief moment the SN becomes brighter than its host galaxy and then the remnant fades away to become invisible after ~50–100 kyr.

Pulsars are cosmic lighthouses





credit: ATNF

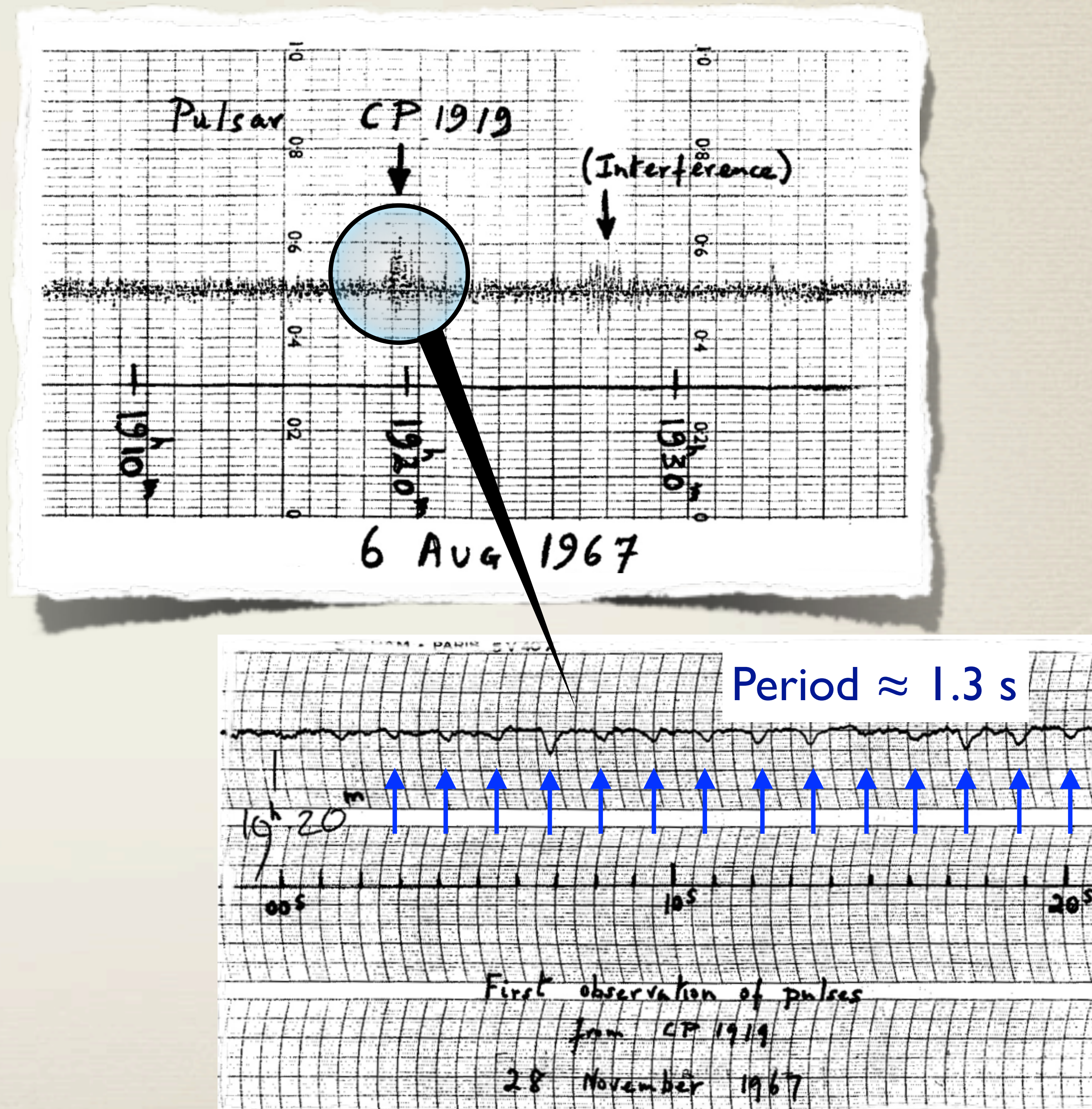
The discovery of pulsars

The transient nature of pulsars led to their discovery by Jocelyn Bell-Burnell, in 1967.

Interplanetary Scintillation Array
(frequency = **81.5 MHz**)

At the time, Hewish and Bell-Burnell were studying the intensity fluctuations of compact radio sources due to scintillation in the solar wind.

normal recording speed

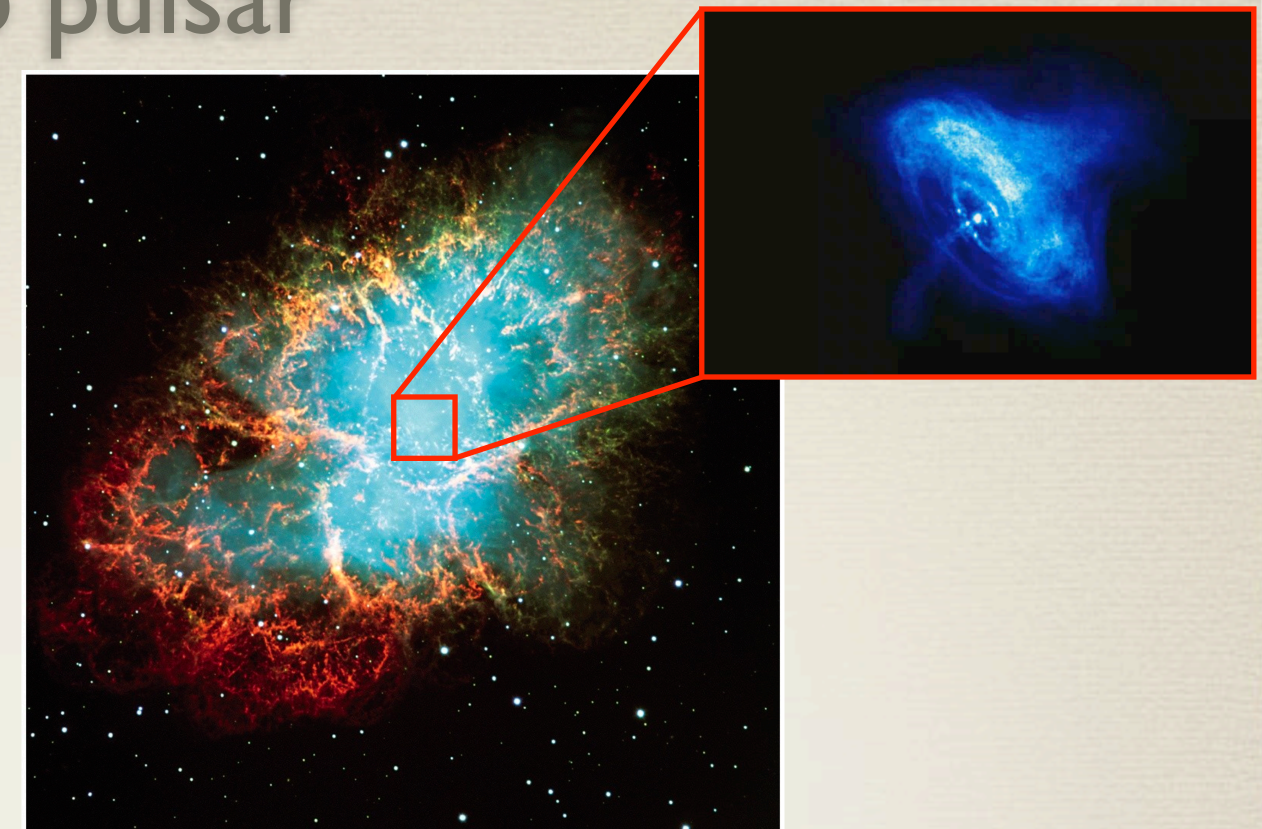


high-speed recording

Today, pulsars are regularly observed from tens of MHz to tens of GHz, but ...

it is worth remembering that the first discovery (PSR B1919+21) was made at <u>low radio frequencies</u>.

The Crab pulsar



credit: Chandra X-ray Observatory

In 1968, a 33-ms pulsar in the Crab nebula was discovered
(Staelin, Reifenstein III; Lovelace et al.)

The Crab pulsar's birth in the supernova SN1054 was witnessed on the 4 July, 1054 AD by Chinese astronomers.

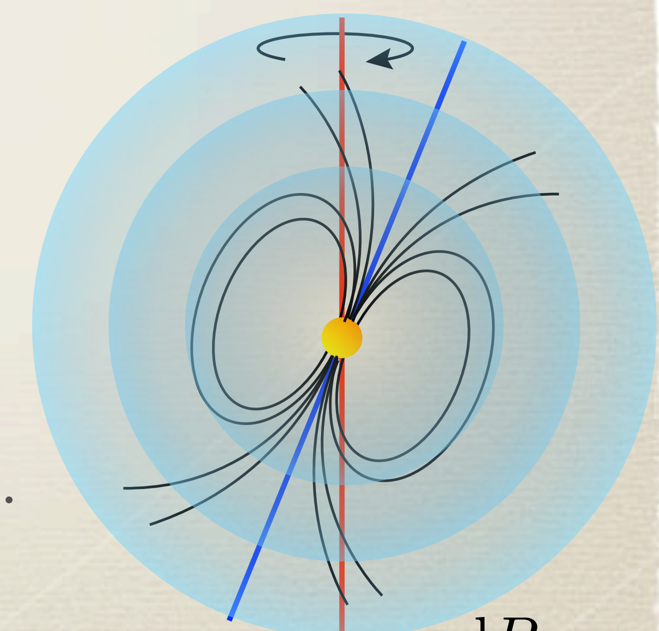
It is one of the very few pulsars whose birth has been recorded in historical documents.

The discovery of the pulsar in the Crab nebula was the pivotal moment for understanding the nature of pulsars:

- It has a period of 33 ms – it ruled out radial oscillations from white dwarfs (~1 s)
- Its density is significantly higher than that of white dwarfs:

$$m\omega^2 R = \frac{GMm}{R^2} \Rightarrow \frac{M}{R^3} = \frac{\omega^2}{G} \Rightarrow \rho \sim 4 \times 10^8 \text{ g cm}^{-3} \left(\frac{P}{\text{s}}\right)^{-2}$$

for the Crab pulsar, this gives $\rho \sim 4 \times 10^{11}$ g cm^{-3} >> ρ_{WD}.



- The Crab pulsar was the first pulsar for which the spin-down due to emission of magnetic-dipole radiation (as predicted by Gold & Pacini in 1968) was measured.

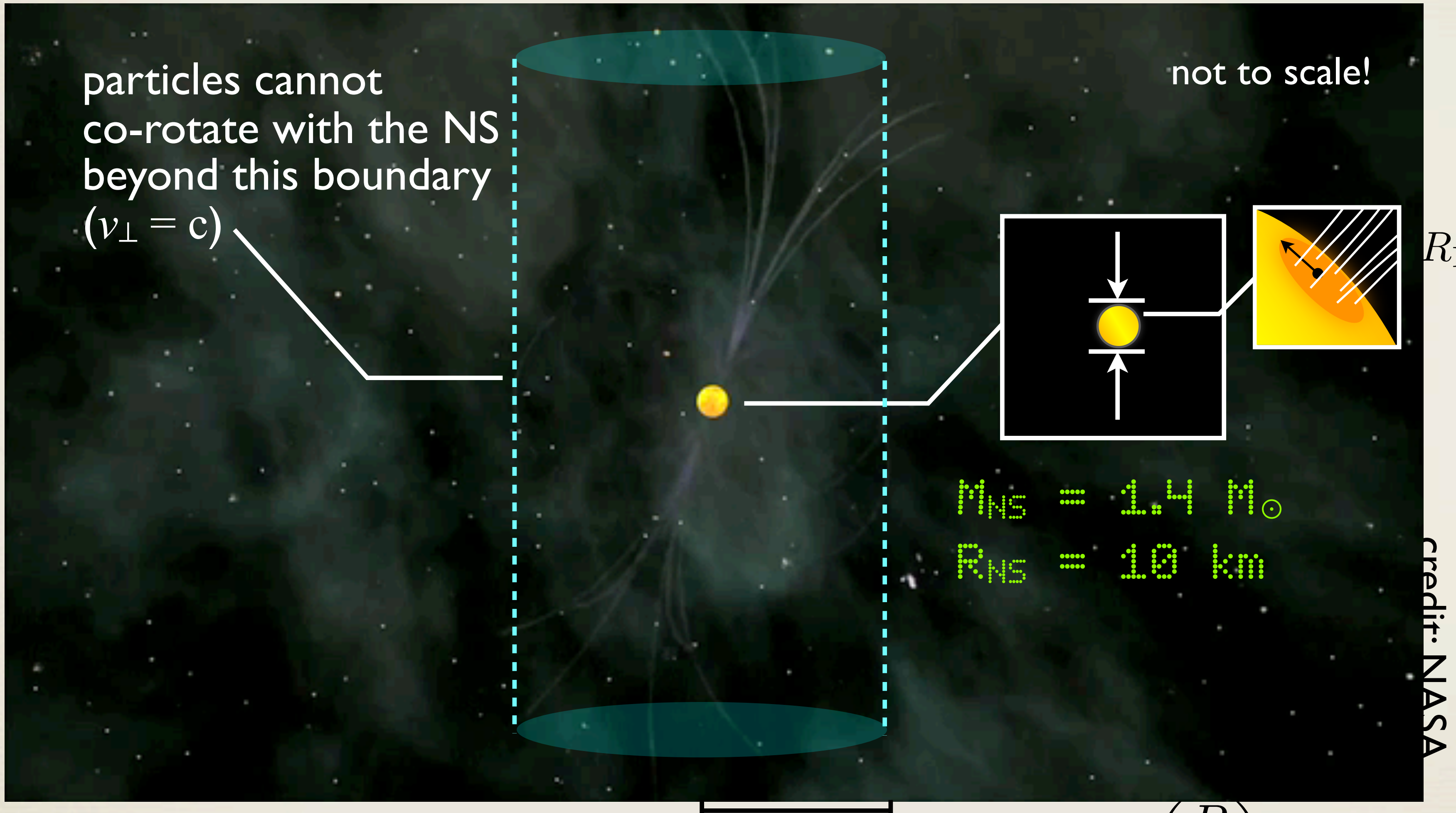
$$\dot{E}_{\text{dipole}} = -\frac{8\pi^2}{5} M R^2 \frac{\dot{P}}{P^3} \sim 10^{38} \text{ erg s}^{-1} \sim E_{\text{nebula}}$$

$$\frac{\mathrm{d}P}{\mathrm{d}t} > 0$$

The only explanation left was that pulsars are spinning neutron stars

Pulsar properties

- Highly magnetised ($B \sim 10^{12}$ G) cf. geomagnetic field ~ 0.5 G
- Rapidly spinning ($P \sim$ 1ms – 1s) cf. Terzan5ad spin frequency = 700 Hz (> F1 engine)
- Oblique rotators ($\boldsymbol{S}$^$\boldsymbol{B}$≠0) ∴ a fixed observer sees periodic pulses of radio emission
- Neutron stars ($\rho \sim 10^{17}$ kg/m^3) cf. a teaspoon of NS matter would weigh 10^{12} kg!



$R_{\rm PC} = 150 \left(\frac{P}{\rm s}\right)^{-1/2}$ m

typical size of co-rotating magnetosphere (light-cylinder): $R_{\rm LC} = 5 \times 10^4 \left(\frac{P}{\rm s}\right)$ km

Charged particles are accelerated along the magnetic field lines above the magnetic poles.

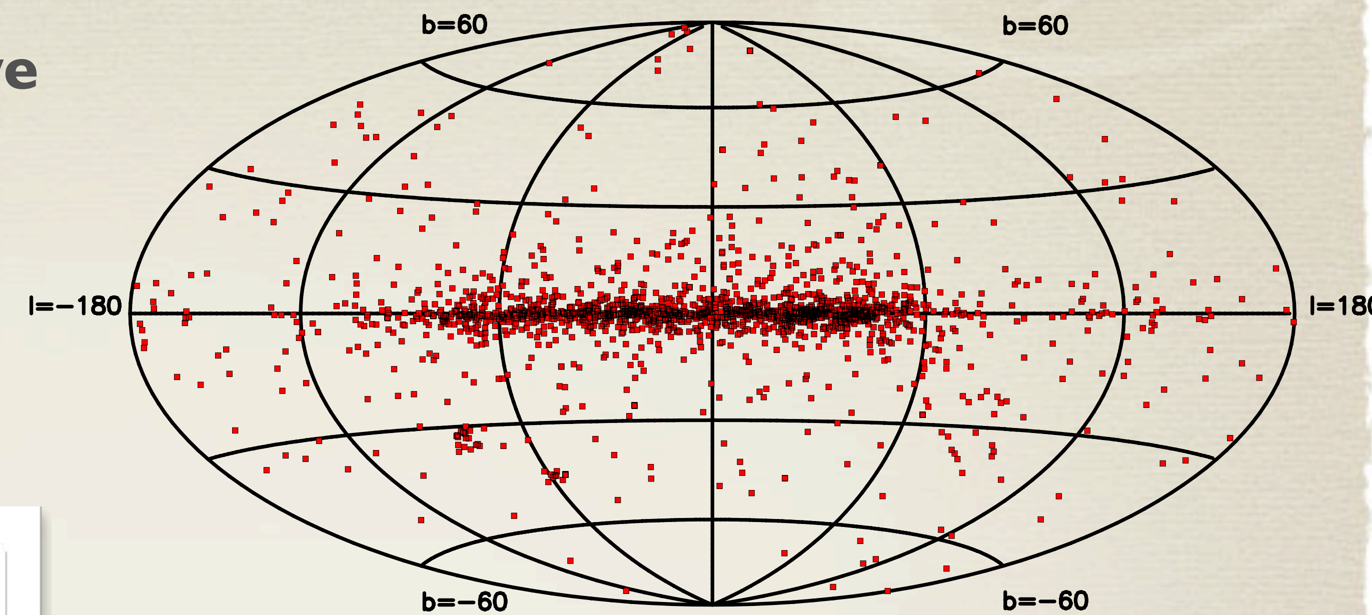
This leads to two narrow beams of coherent* radio emission.

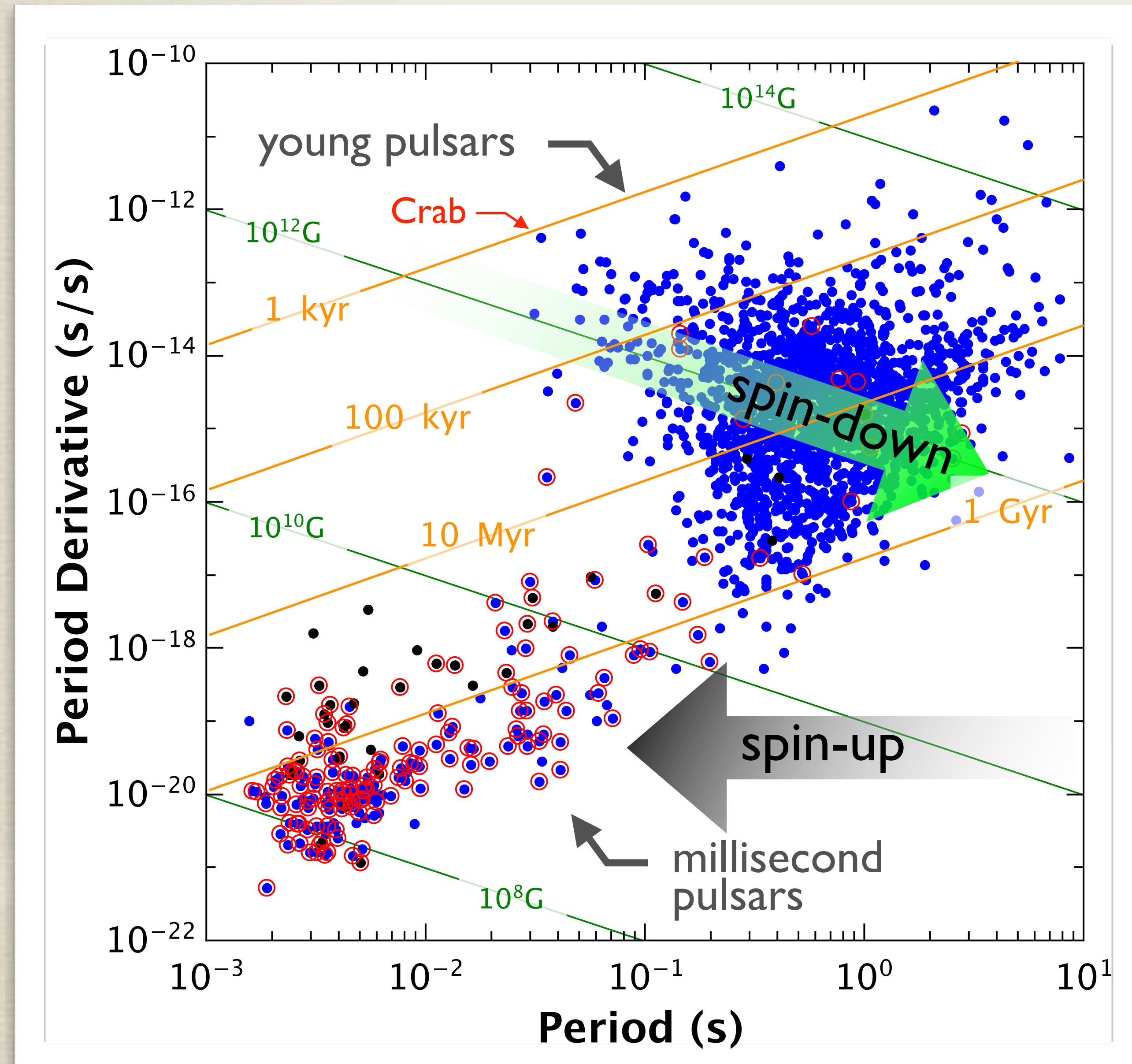
* *particles radiate in phase*

The Galactic pulsar population

Since the first pulsar discovery in 1967, we have discovered ~2,500 pulsars.

Most of them are found near the Galactic plane, coinciding with the highest density of massive OB stars, which are likely pulsar progenitors.





A very useful presentation of the pulsar population is the $P-\dot{P}$ diagram.

It shows the evolution of pulsars (equivalent to the HR diagram for main-sequence stars).

Assuming magnetic-dipole spin-down ($\dot{\nu} \propto -\nu^3$) we can estimate

$$\tau_{\rm c} = \frac{P}{2\dot{P}}$$ characteristic spin-down age

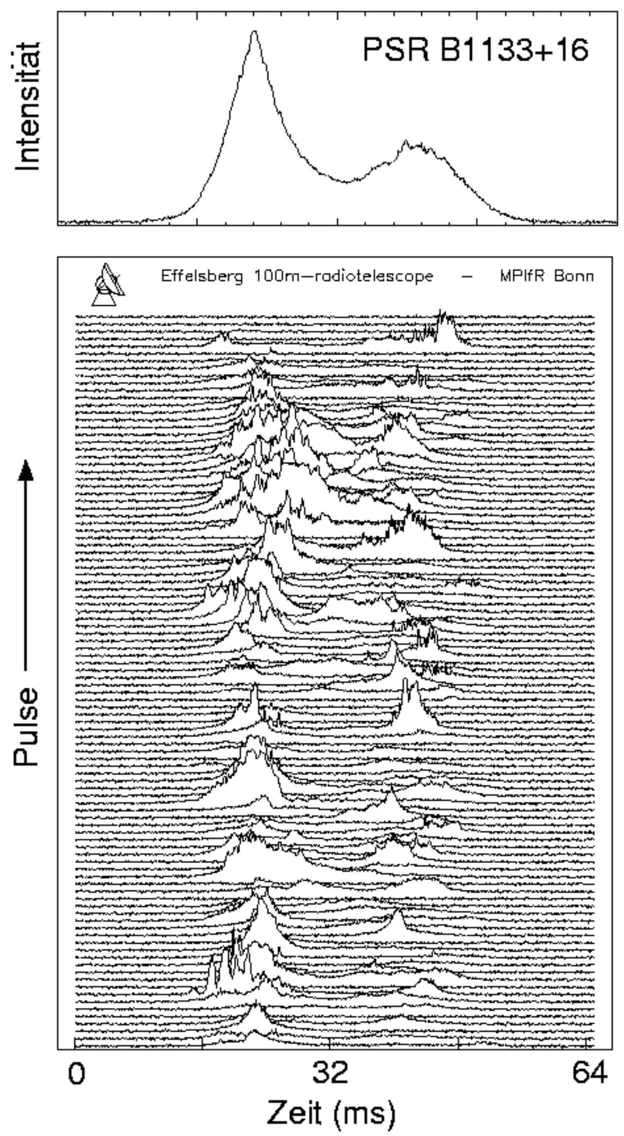
$$B_{\rm surf} = 3.2 \times 10^{19} \sqrt{P\dot{P}}$$ surface magnetic field

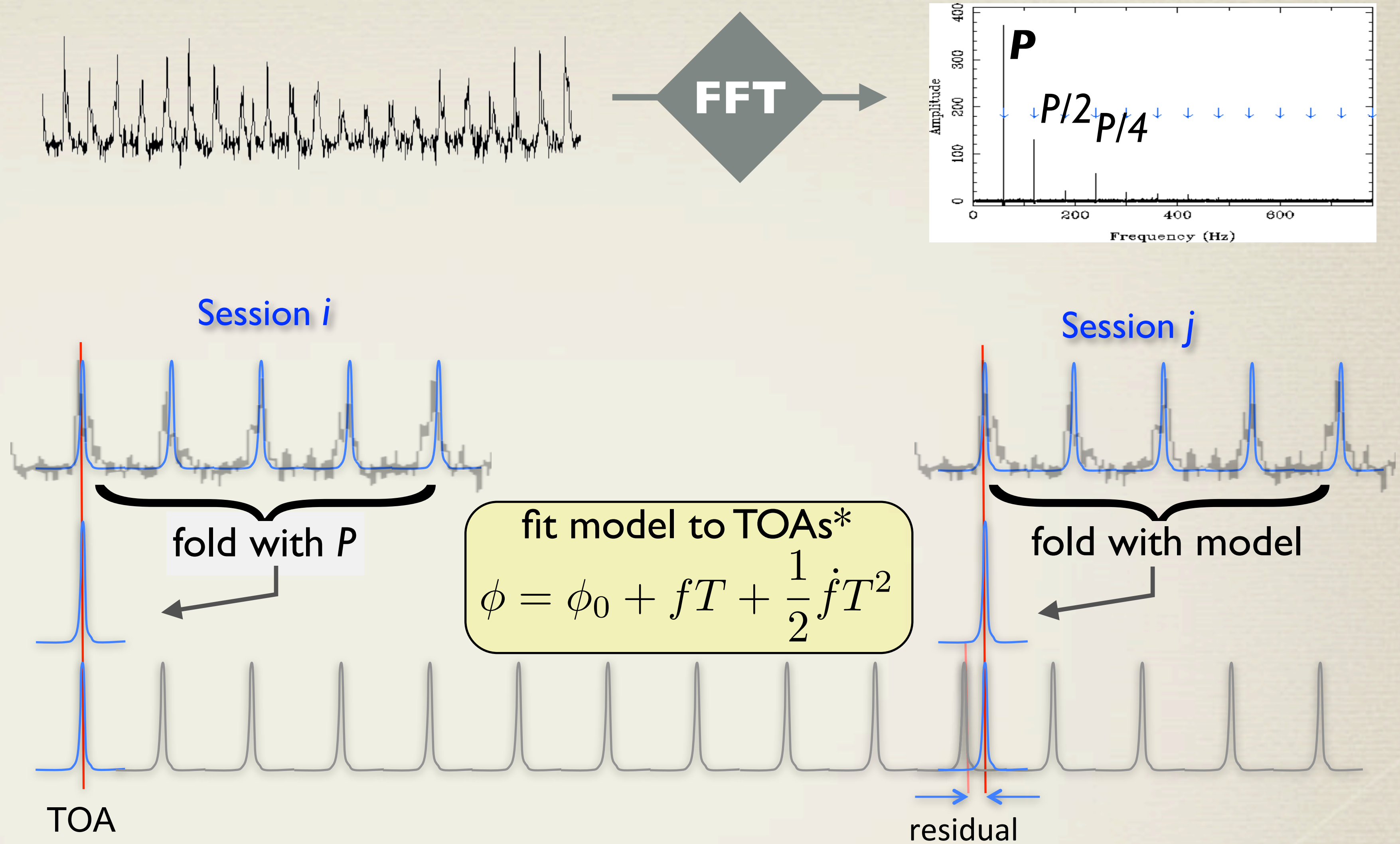
Pulsar Timing
&
Tests of GR

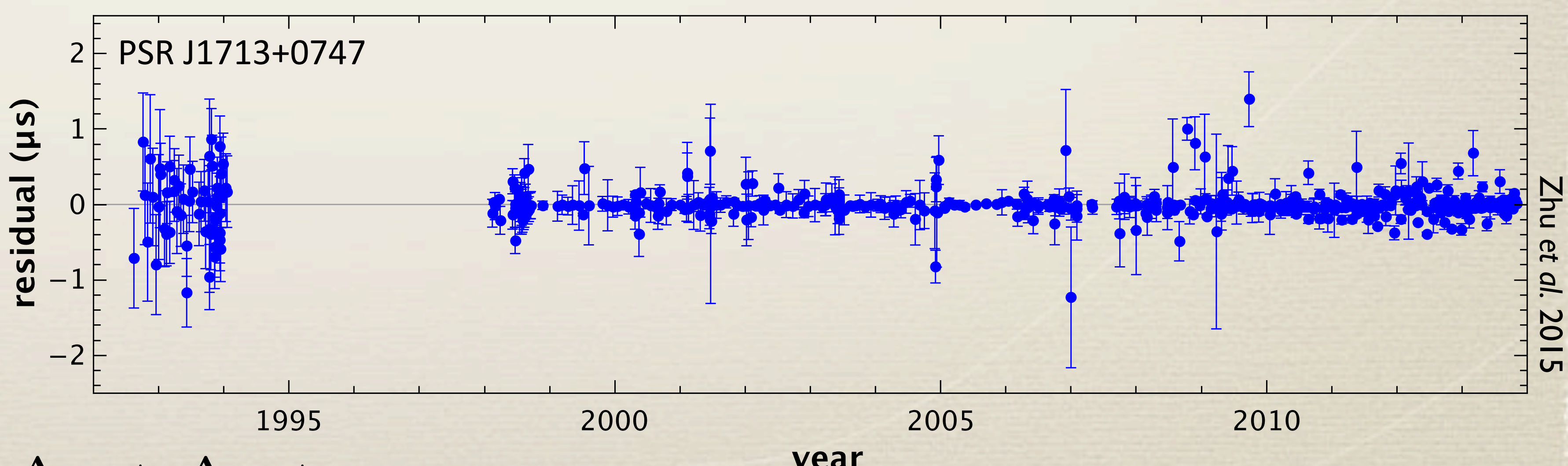
The pulsar timing technique

Perhaps the most powerful technique in pulsar astronomy is ***pulsar timing***.

Individual pulses can be weak/erratic, but the average profile of pulsars is remarkably stable







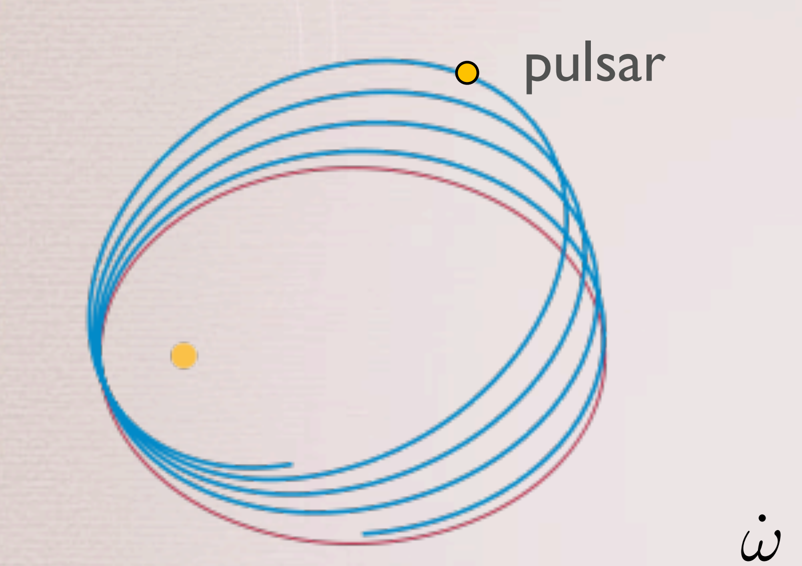
$$^*T = t + \Delta_{\rm clock} + \Delta_{\rm R\odot} + \Delta_{\rm E} + \Delta_{\rm S} + \ldots$$

Millisecond pulsar timing

Millisecond pulsars are remarkably stable rotators: on long timescales their stability rivals that of atomic clocks!

Since they are the products of accretion from a companion main-sequence star, during which they are spun up to ms periods, the vast majority are found in binary systems.

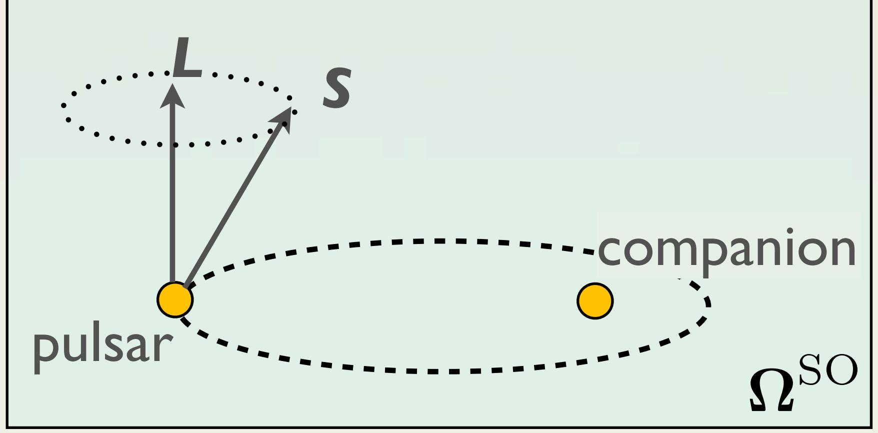
Precession of periastron



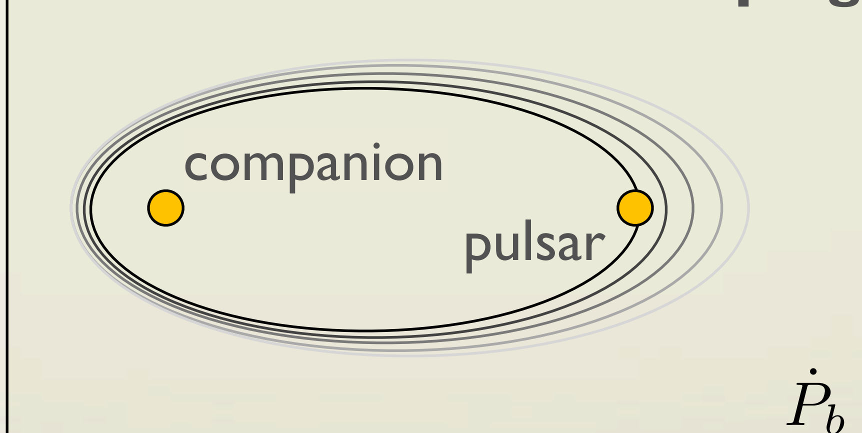
Mercury, 43″/century

double pulsar, 17°/year

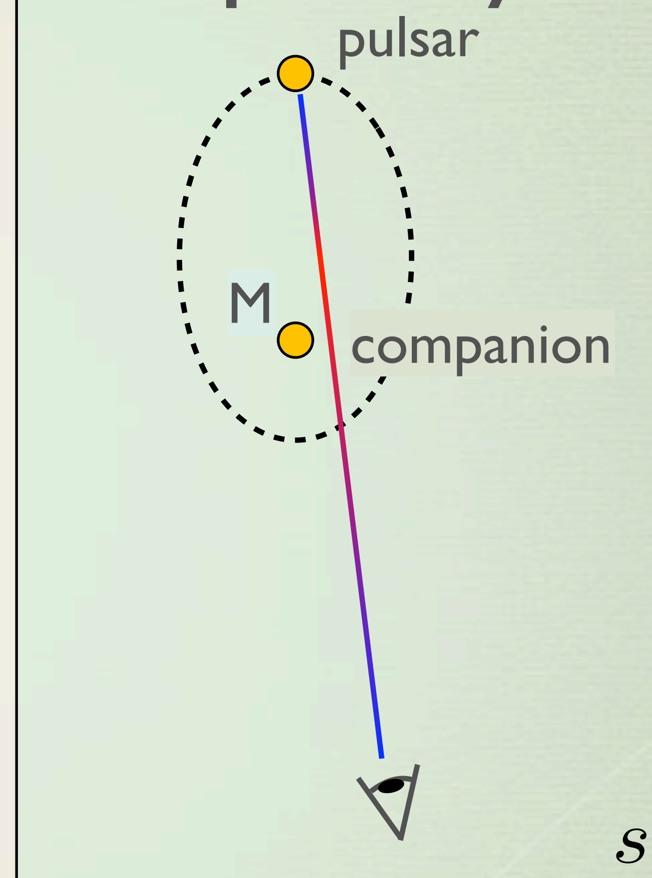
Geodetic precession



Gravitational wave damping



Shapiro delay



Pulsar timing can yield precise estimates not only of the Keplerian parameters of their binary orbits, e.g. $\omega, \;\; A\sin i, \;\; e$

but also of several post-Keplerian parameters: e.g. $\dot{\omega}$, $\dot{P}_b$, $\mathbf{\Omega}^{\rm SO}$, s

Importantly, measurement of the Shapiro delay, s, can be used to estimate the masses of the binary system.

Prime examples of timing precision

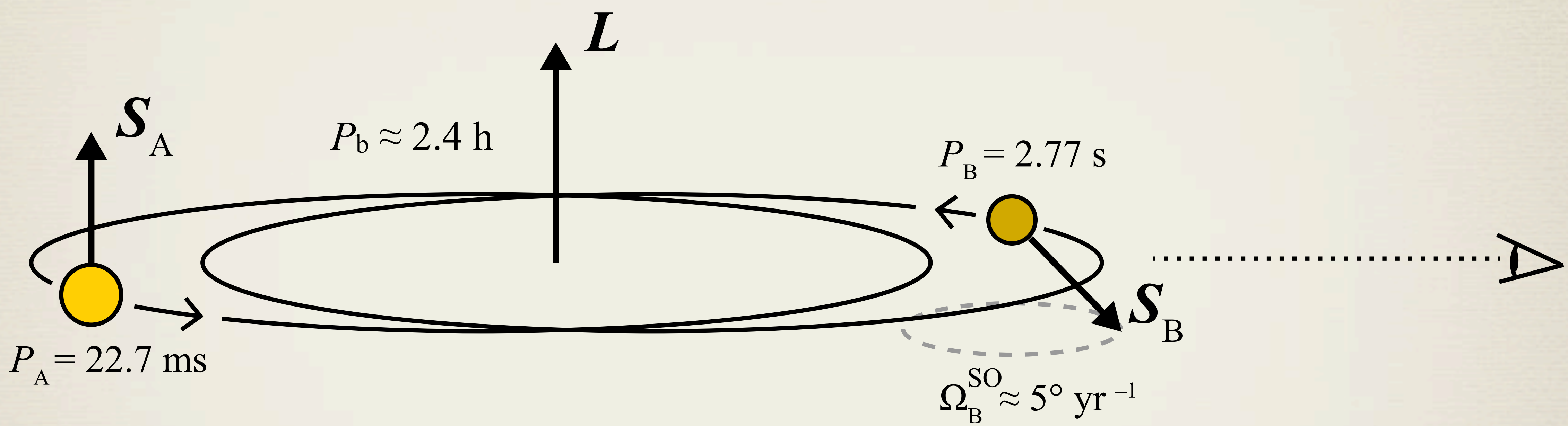
3 atto-second precision!

Spin Period	**2.947108069160717(3)** ms	(Reardon et al. 2015)
Projected semi-major axis	**31,656,123.76(15)** km	(Freire et al. 2011)
Eccentricity	**0.0000749402(6)**	(Zhu et al. 2015)
Masses	**1.3381(7)** / **1.2489(7)** $M_\odot$	(Kramer et al. 2006)
Periastron advance	**4.226598(5)** deg/yr	(Weisberg et al. 2010)
Einstein delay	**4.2992(8)** ms	(Weisberg et al. 2010)

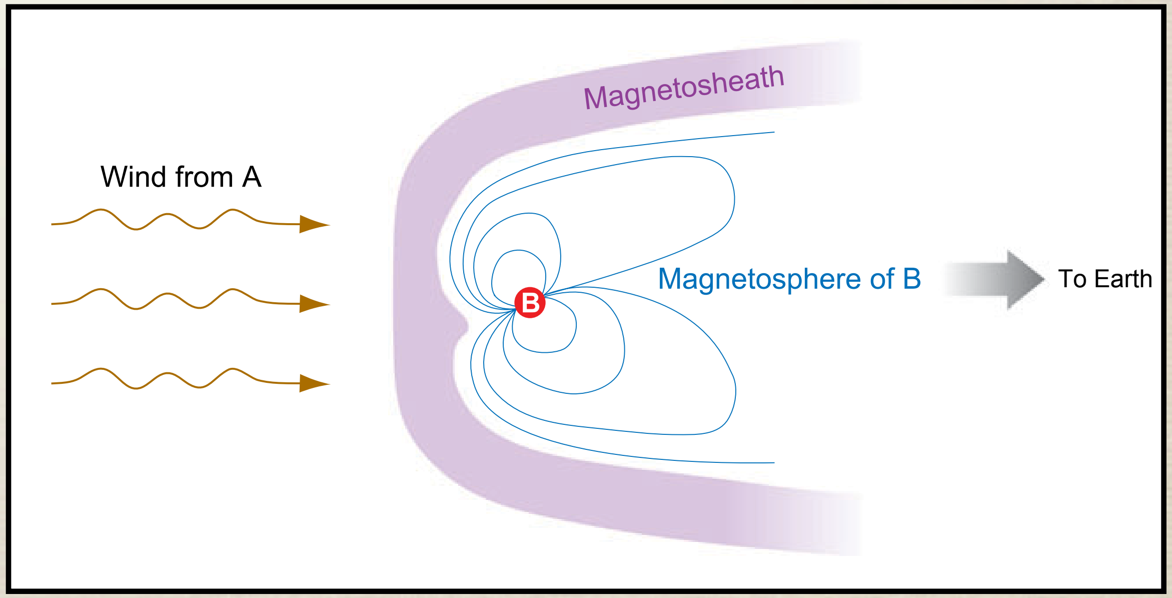
The Double Pulsar

The strong gravitational field in the vicinity of pulsars makes them ideal laboratories for tests of theories of gravity, like General Relativity (GR).

The double pulsar (PSR J0737–3039A/B) is the best system known for testing GR. It comprises a young, 2.77s pulsar (pulsar B) in an orbit around an old, 22.7ms millisecond pulsar (pulsar A).



The strong pulsar wind of A periodically distorts B's magnetosphere, causing measurable timing effects in B's emission (Kramer et al. 2006).

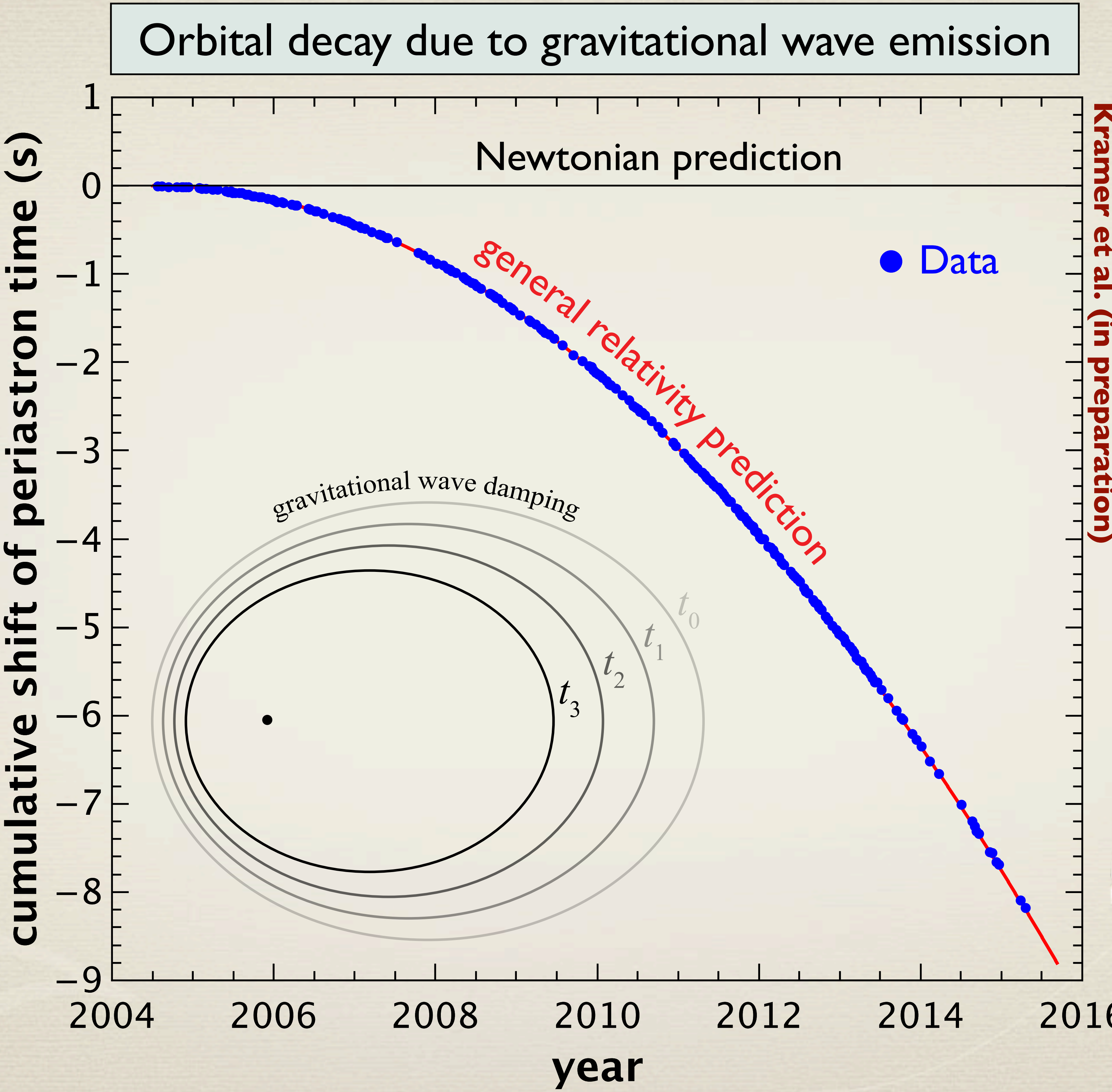


Kramer & Stairs 2008

Pulsar B exhibits geodetic precession of ~5°/year.
It precessed out of view in 2008.

Depending on B's beam pattern, it may reappear as early as this year or as late as ~2066.

Tests of General Relativity



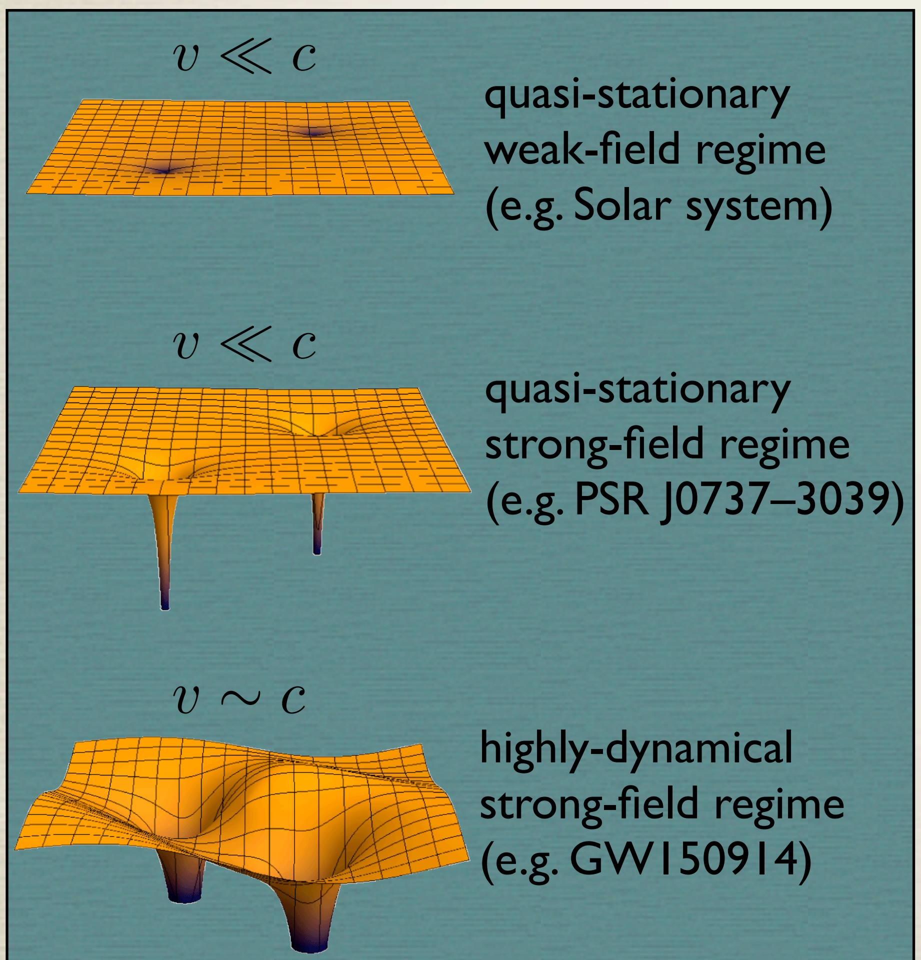
99.98% agreement

Tests of General Relativity

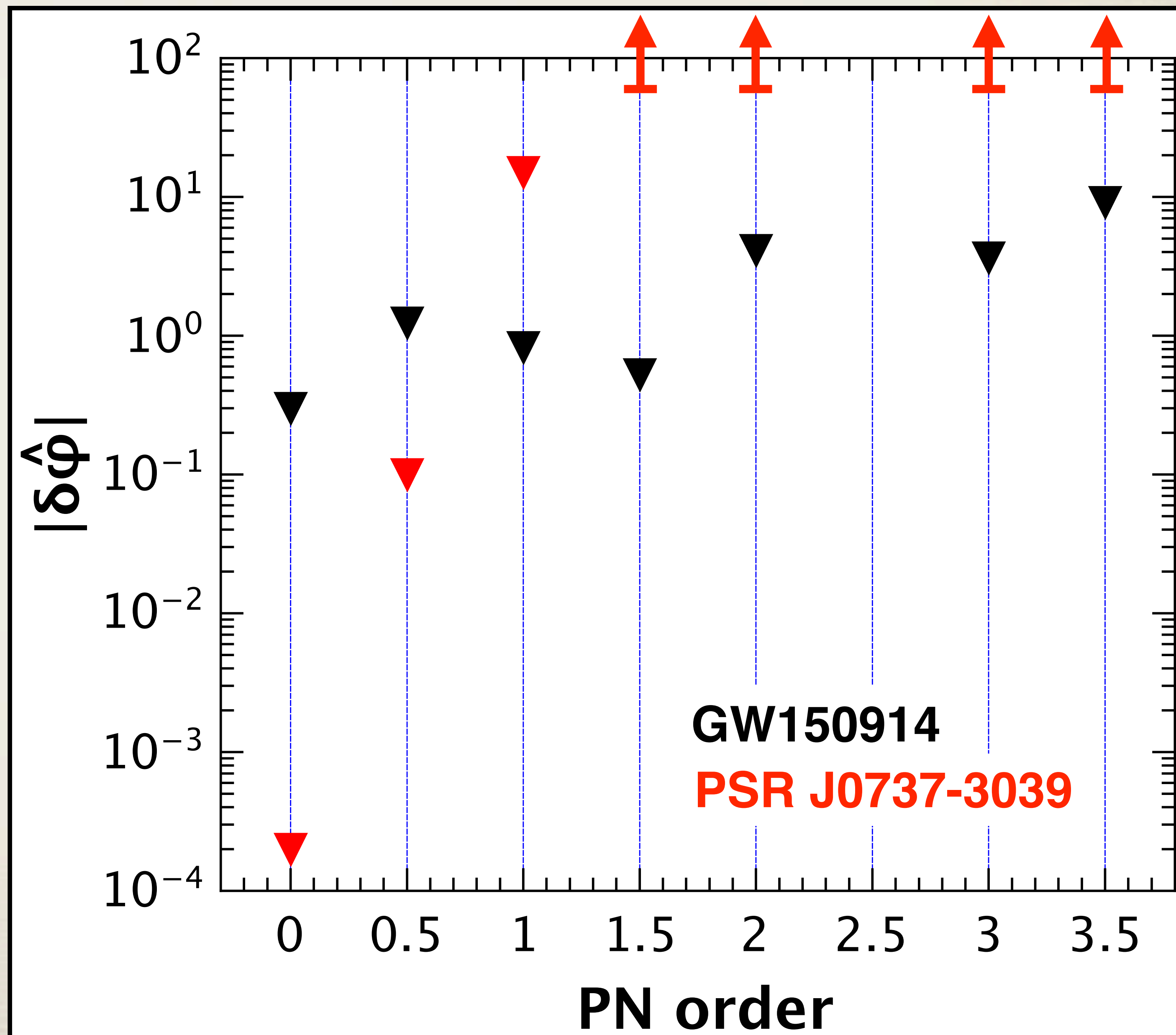
Assuming GR, we can compare the orbital-phase evolution, due to gravitational-wave emission, of the double pulsar to that of the black-hole merger detected by LIGO.

For zeroth-order post-Newtonian corrections (quadrupole formula), the constraints from 12 years of timing the double pulsar system are vastly tighter than those from the black-hole merger detection.

However, for higher-order corrections only the GW150914 event provides useful limits.



Wex (2014)



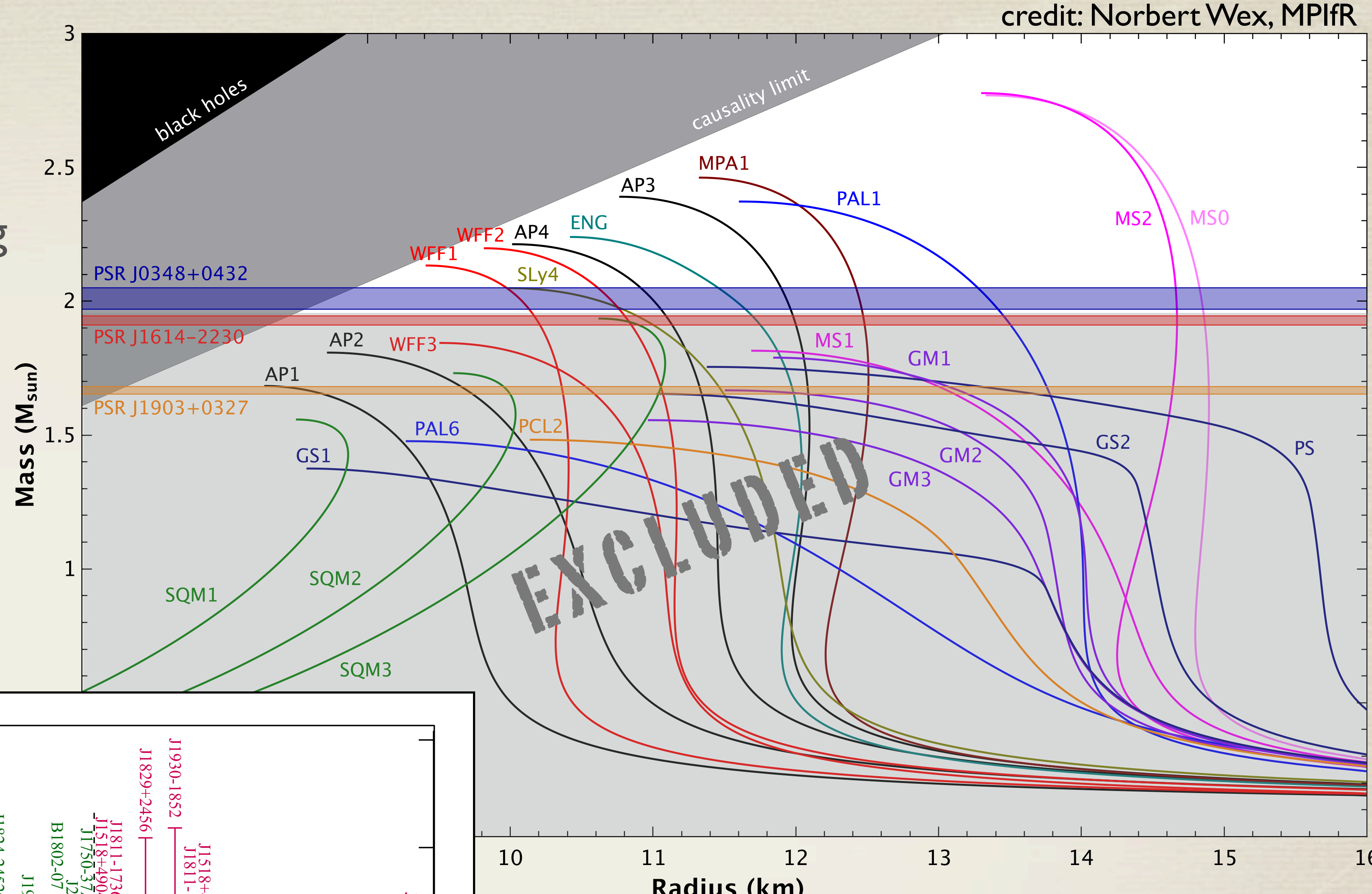
Kramer et al. (in preparation)

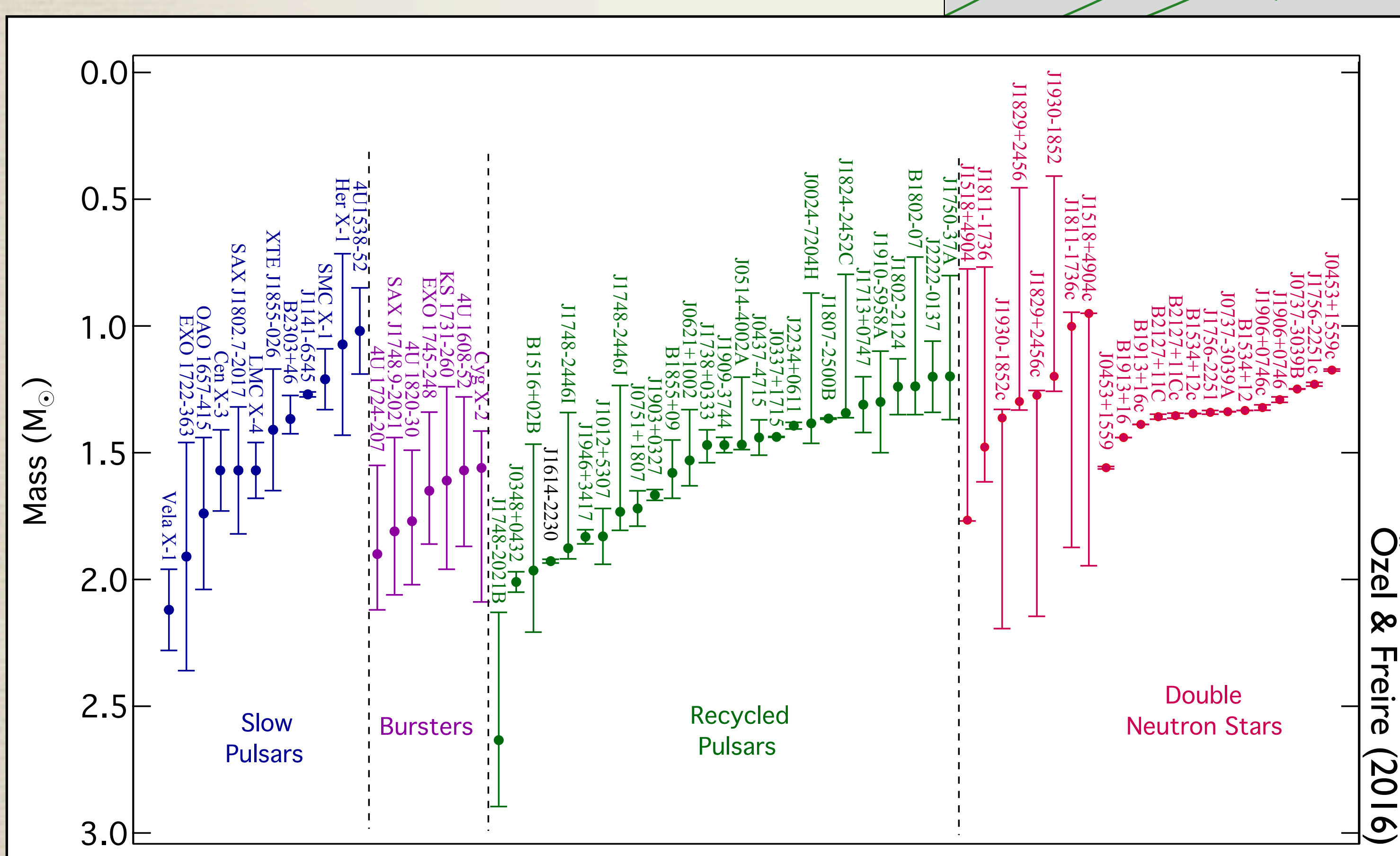
The Equation-Of-State of neutron stars

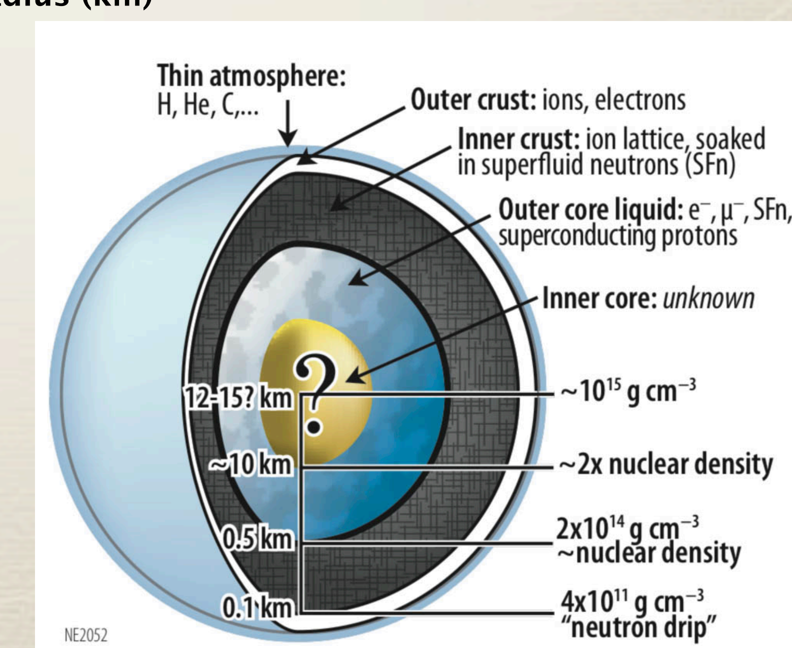
The most massive (>>1.4M☉) millisecond pulsars have also allowed us to place limits on the Equation-Of-State (EOS), describing the composition of neutron stars.

Combined with measurements of NS radii (e.g. from X-ray spectra of LMXBs; typically, $\sigma_R = \pm 5$ km), in the future we will be able to place tight constraints on the NS EOS.

credit: Norbert Wex, MPIfR



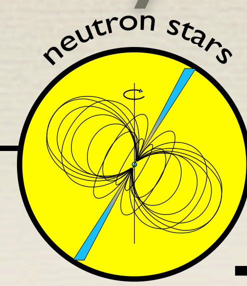




credit: NASA

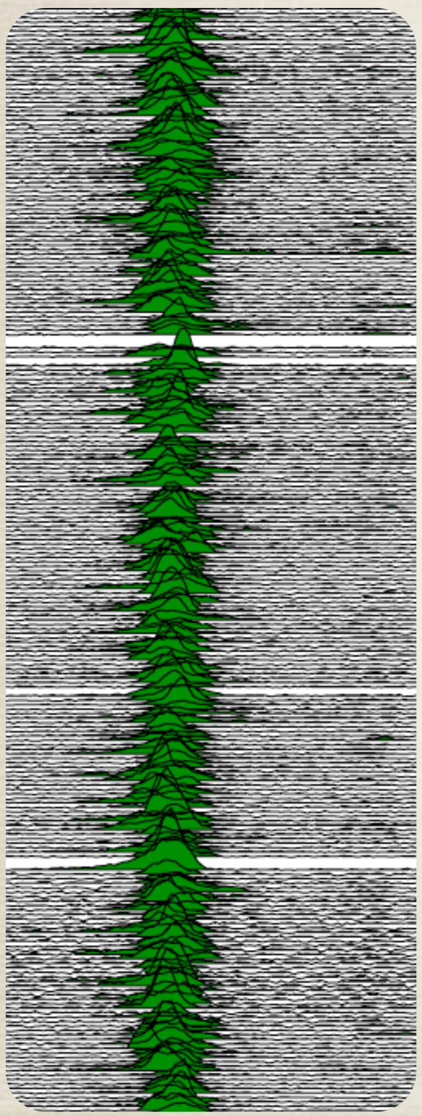
Pulsar Observations & Surveys

The many faces of neutron stars



Pulsars

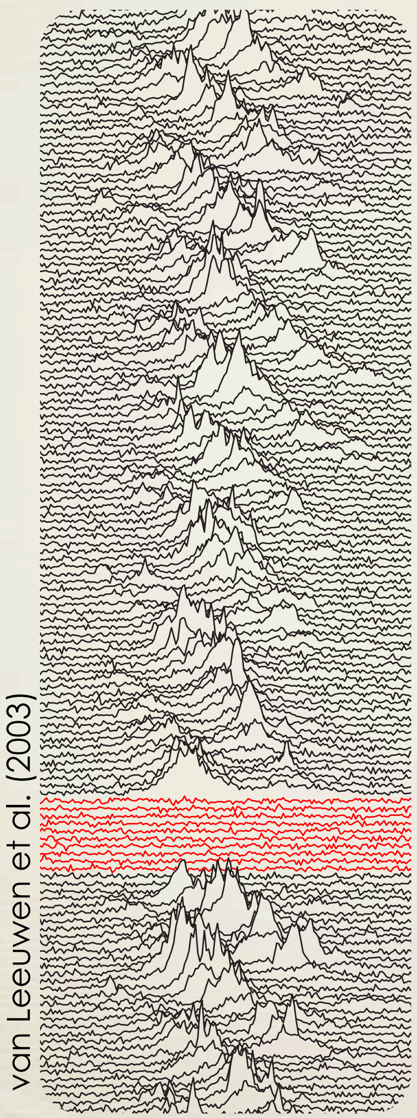
Neutron stars



Sobey (2014)

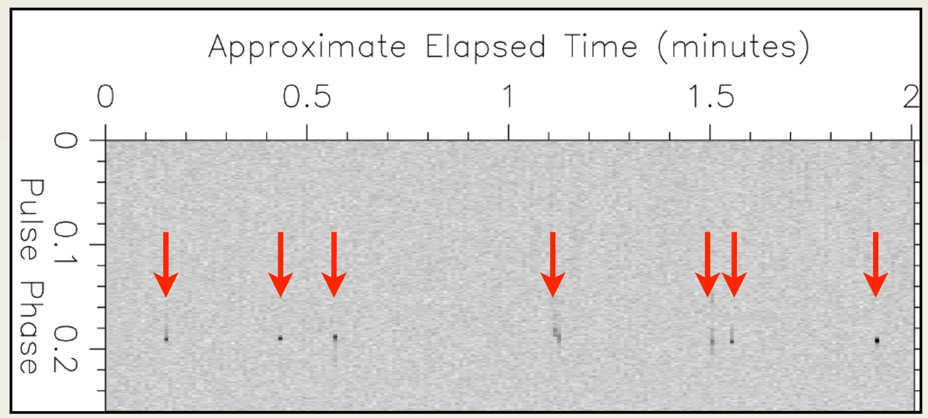
Nullers

Pulsars that occasionally stop emitting for several periods



van Leeuwen et al. (2003)

Rotating Radio Transients (RRATs)/ Intermittent pulsars/ Extreme nullers



Burke-Spolaor (2010)

RRATs:

- Sporadic emission (quiet for >99% of the time)
- Based on distance estimates, they are most likely neutron stars.

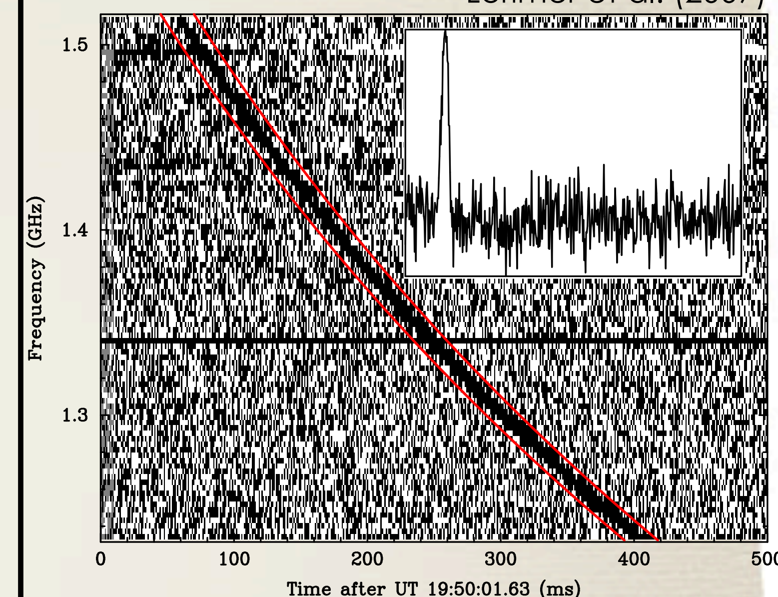
Intermittent pulsars:

- Switch between pulsar behaviour and no emission on timescales of weeks to years

?

Fast Radio Bursts (FRBs)

Lorimer et al. (2007)



- Single bursts of broadband radio emission
- Mainly from high latitudes and probably extragalactic, based on lower limits on their distance

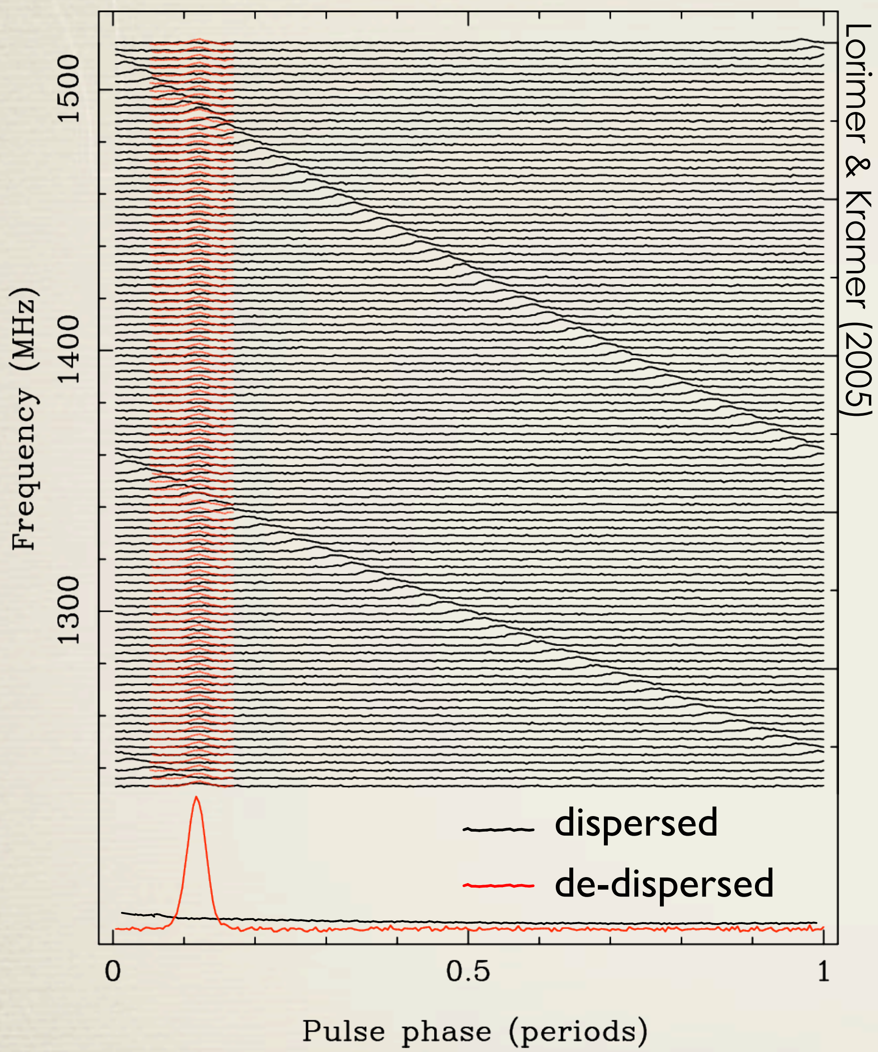
sparseness →

← knowledge

Radio-wave distortions in the interstellar medium

Dispersion

Caused by the frequency dependent refractive index of the ionised medium (n_e)

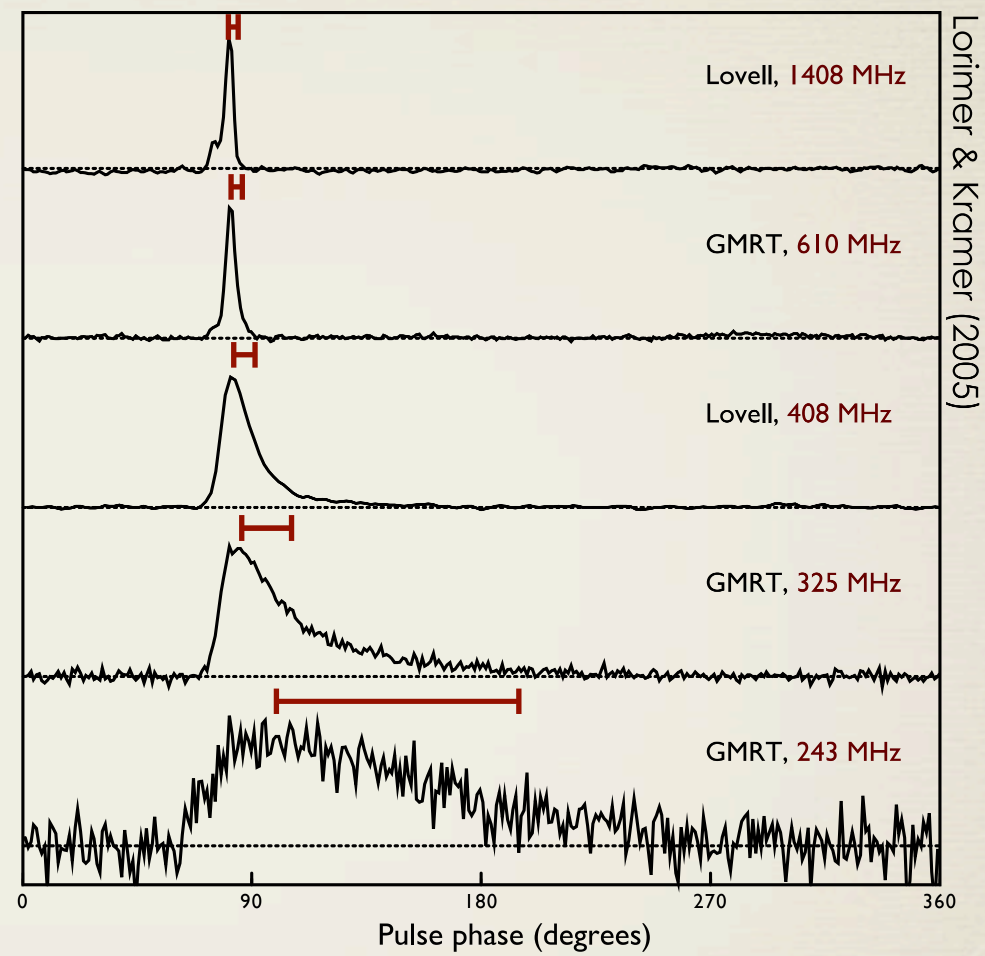


$$\Delta t \propto \frac{\mathrm{DM}}{f^2}$$

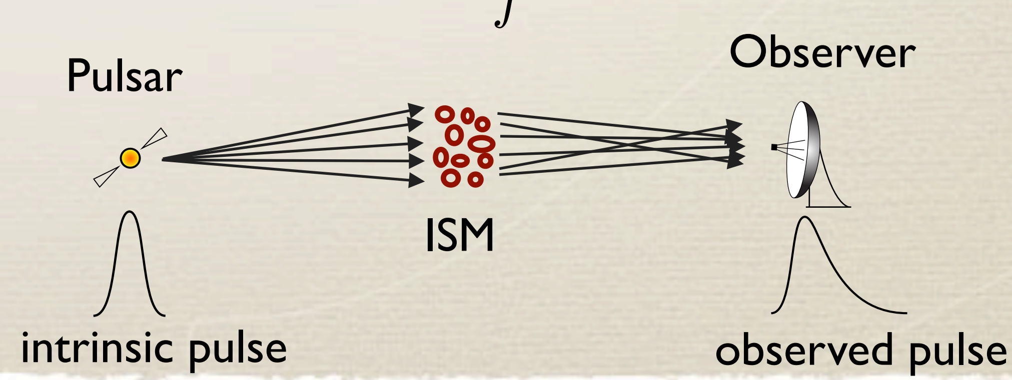
$$\mathrm{DM} = \int_{\mathrm{PSR}}^{\oplus} n_e \mathrm{d}l$$

Scattering

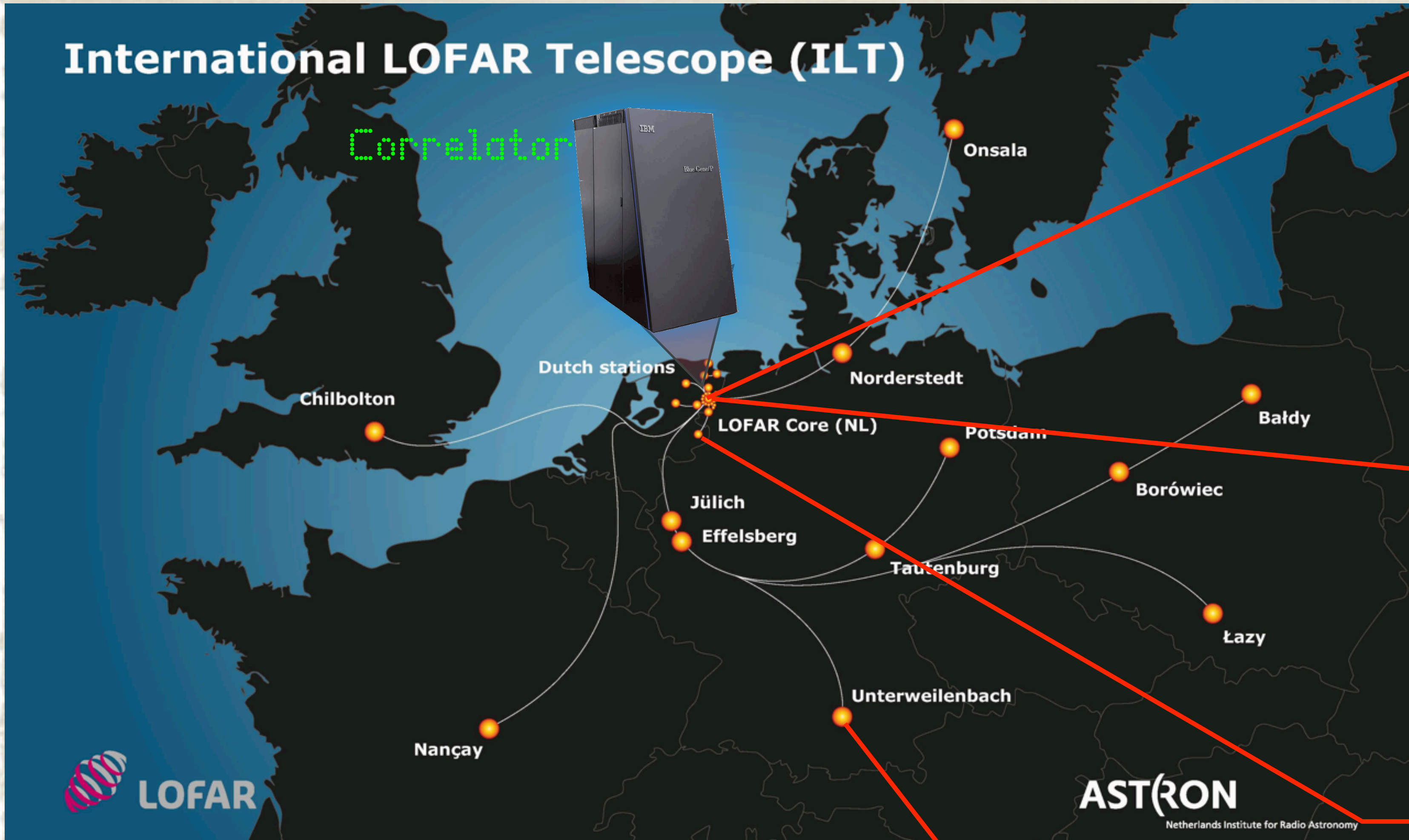
Caused by multi-path propagation of radio waves in a 'clumpy' medium



$$\tau_{\mathrm{s}} \propto \frac{1}{f^4}$$

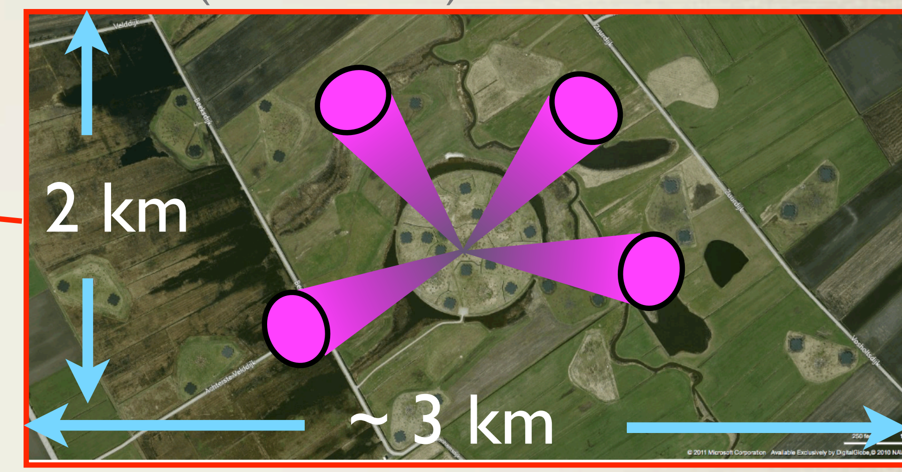


LOFAR



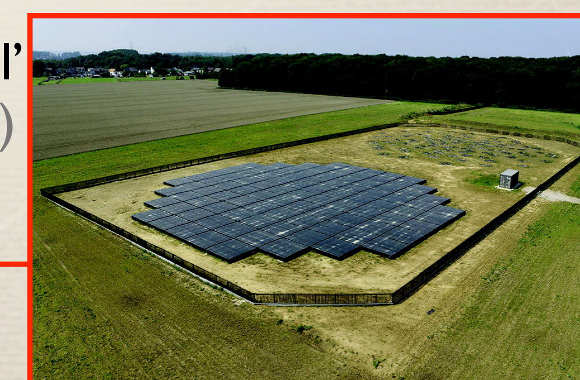
'Superterp'
(6 stations)

'Core' (24 stations)

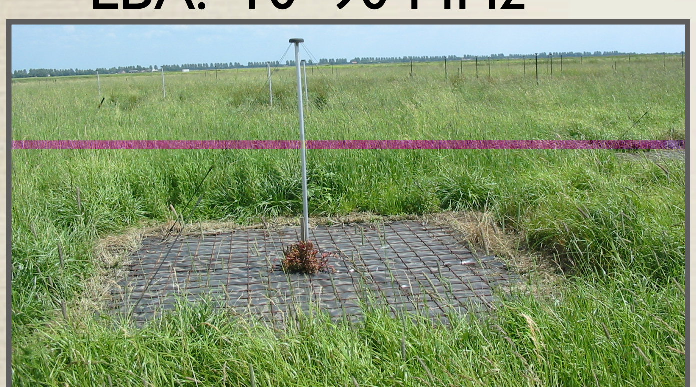


'Dutch remote'
(14 stations)

'International'
(12 stations)



LBA: 10–90 MHz



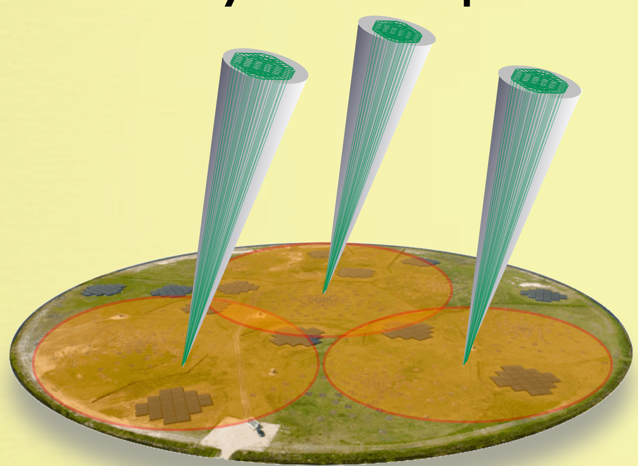
HBA: 110–240 MHz

LOFAR Tied Array All Sky Survey (LOTAAS)

A northern-sky, high-time-resolution pulsar survey at 150 MHz.

Survey specifications:

- Full northern sky
- Superterp HBA stations
- 3 sub array pointings (SAP)
- 67 tied-array beams per SAP

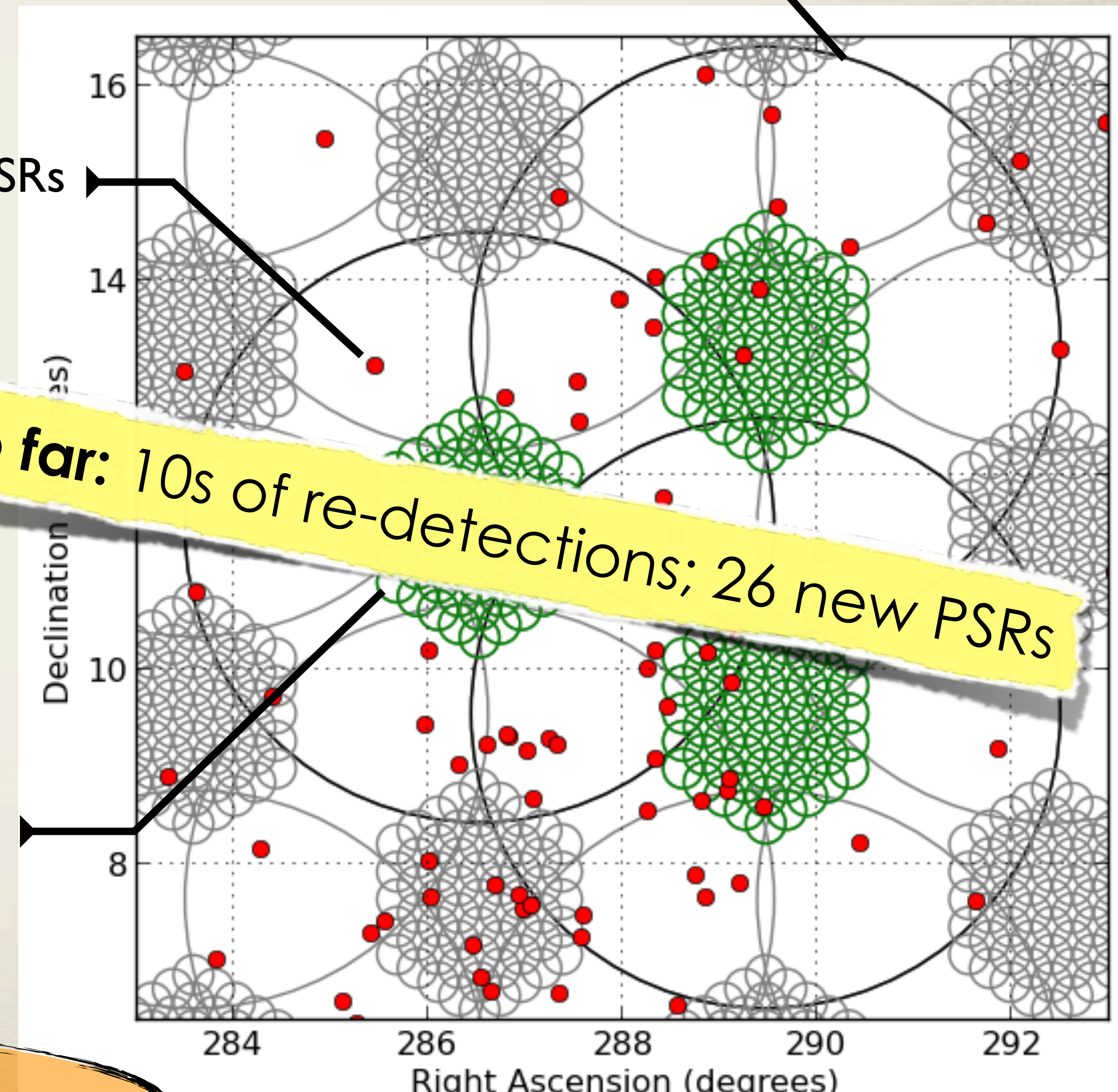


3 sub-array pointings (SAP)

Incoherently summed station beams

Known PSRs

67 tied-array beams per SAP



So far: 10s of re-detections; 26 new PSRs

This is practically the first, SKA-style pulsar survey

Credit: S. Cooper

The High Time Resolution Universe surveys

Effelsberg 100m radio telescope

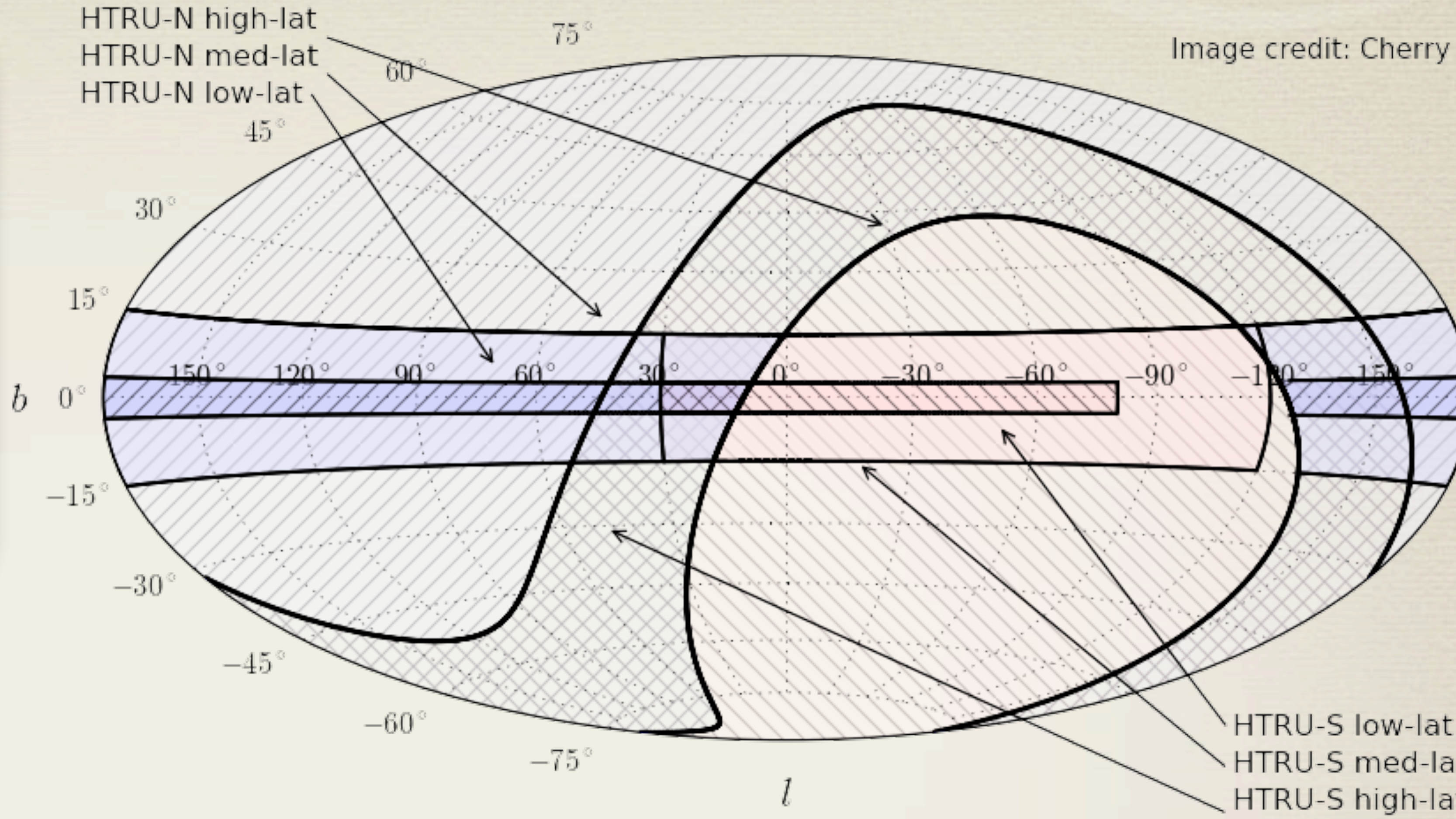
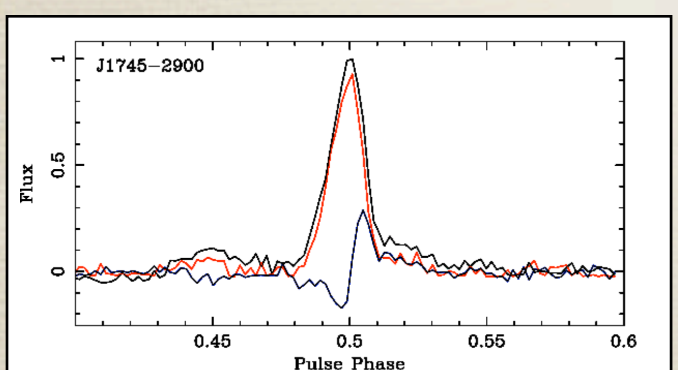


Image credit: Cherry Ng

The HTRU (High Time Resolution Universe) Northern and Southern surveys at 1.4 GHz have discovered **~ 200 new pulsars**.

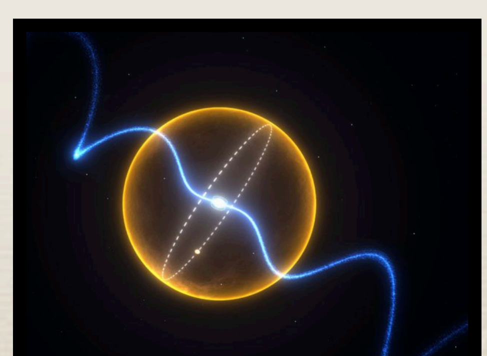
Parkes 64m radio telescope

Highlights:



Radio magnetar in the Galactic centre

'diamond planet' around a ms pulsar:
carbon WD stripped to the size of Jupiter.

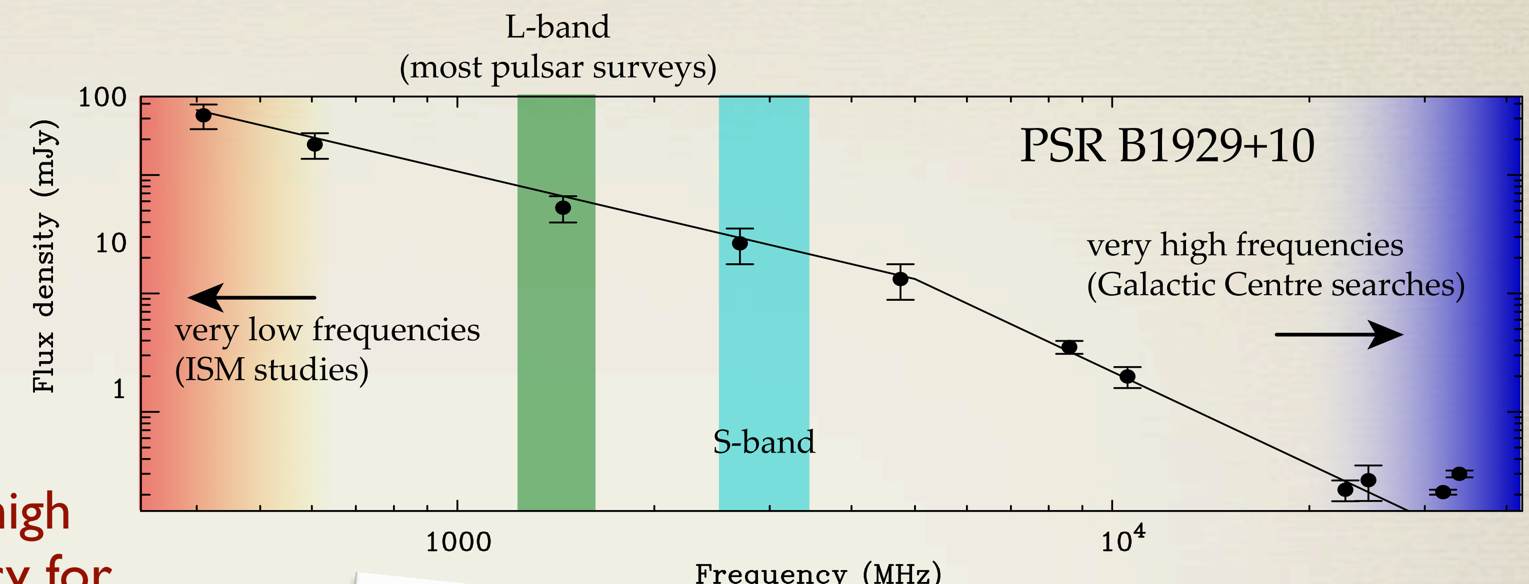


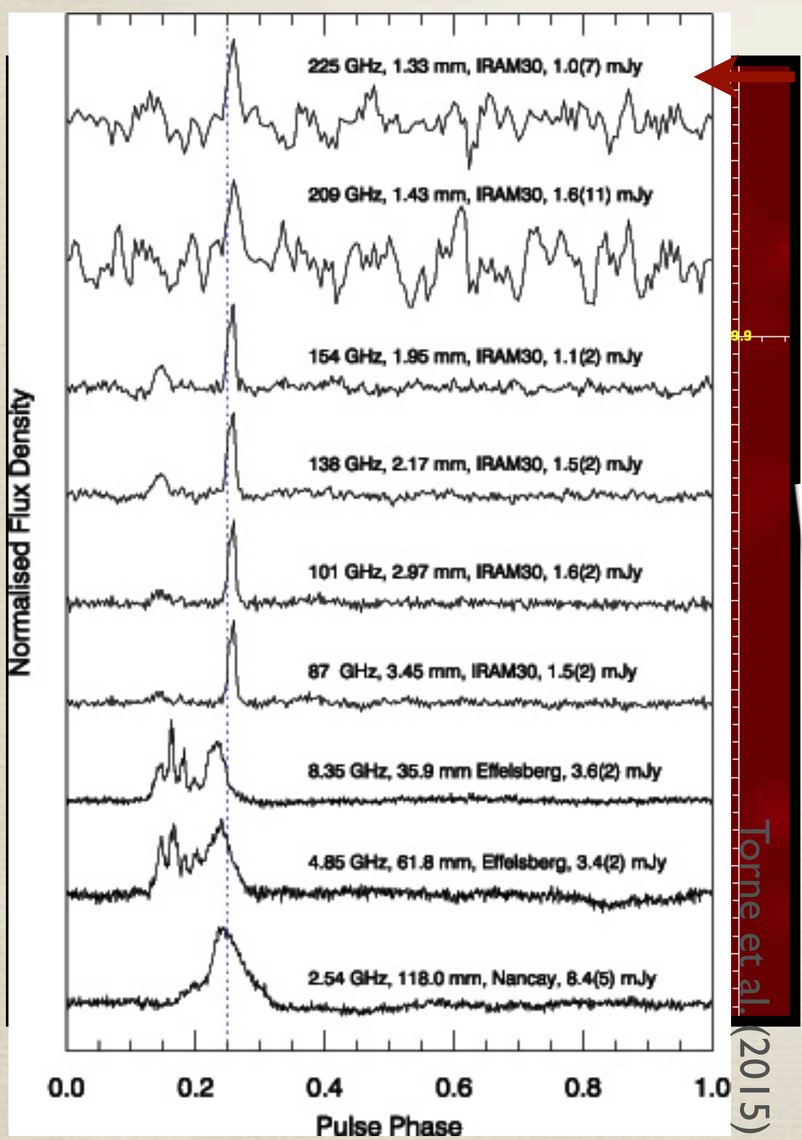
Pulsars at the Galactic Centre

Not many pulsars are known near the centre of our Galaxy. The large distance combined with interstellar scattering make pulsar detections in that region of the Galaxy exceedingly difficult.

To combat scattering, we need to observe at high radio frequencies.

But most pulsars become weak radio sources with increasing frequency.





Torne et al. (2015)

record-high frequency for radio pulsars

A special class of pulsars, *magnetars*, have strong magnetic fields and they are often detected by their high-ene... X-ray) emission.

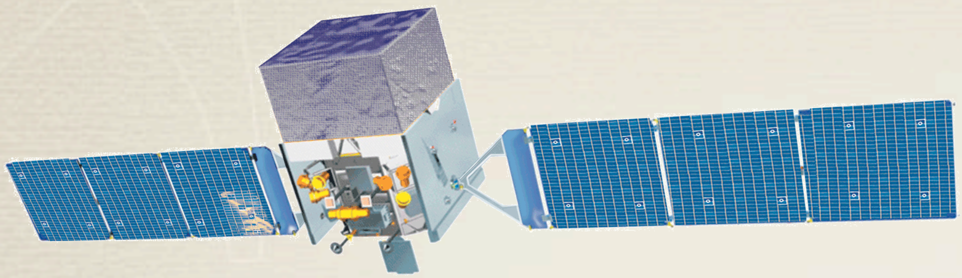
Following NuSTAR's detection of pulsed X-ray emission from the direction of Sgr A*, ... detected the ... the Effelsberg 10... radio magnetar

Its DM(=1778 pc cm^{-3}) places it within 10 pc of the Galactic Centre (Eatough et al. 2013).

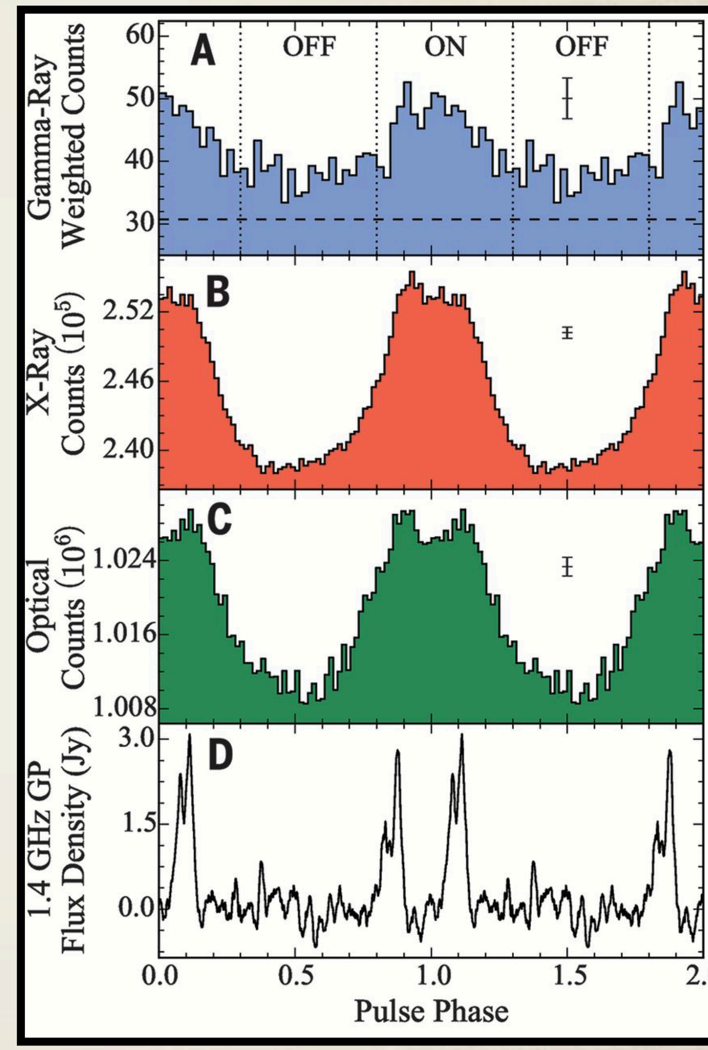
Magnetars tend to have flat spectra, meaning that they are still detectable at very high frequencies. Such high-frequency observations can help us understand how coherent, radio emission is produced.

Pulsars at high energies

The Large Area Telescope (LAT) on the *Fermi* satellite is sensitive to gamma-rays between 20 MeV and 300 GeV.



Fermi has an all-sky coverage. The collected gamma-ray photons from pulsars can be folded using a timing ephemeris to create light-curves of the periodic emission.

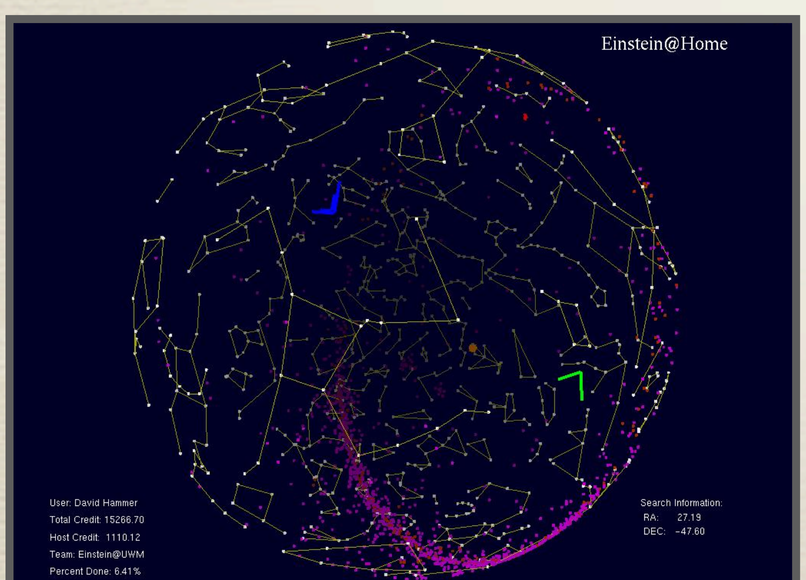


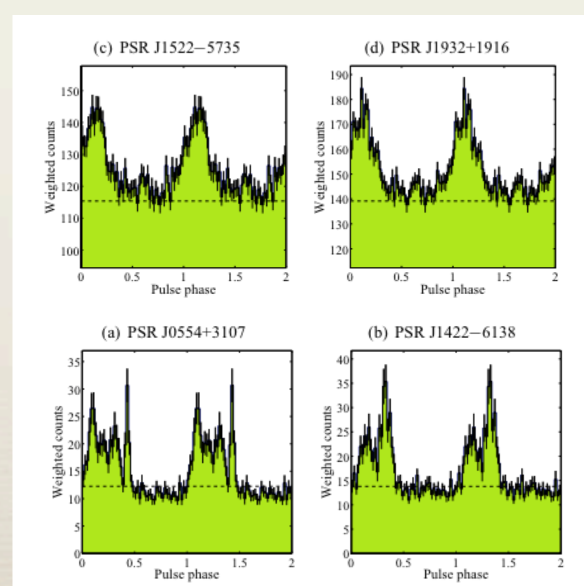
Ackermann et al. (2015)

In 3.5 years of LAT data, Fermi has detected the first extragalactic gamma-ray pulsar, PSR B0540–6919, in the Large Magellanic Cloud. It is the most luminous gamma-ray pulsar known, being 20x brighter than the Crab in gamma-rays.

The **Einstein@Home** volunteer distributed computing survey searches for astrophysical signals from neutron stars, in Fermi data.

Already, ~20 pulsars have been discovered in such "blind" searches.



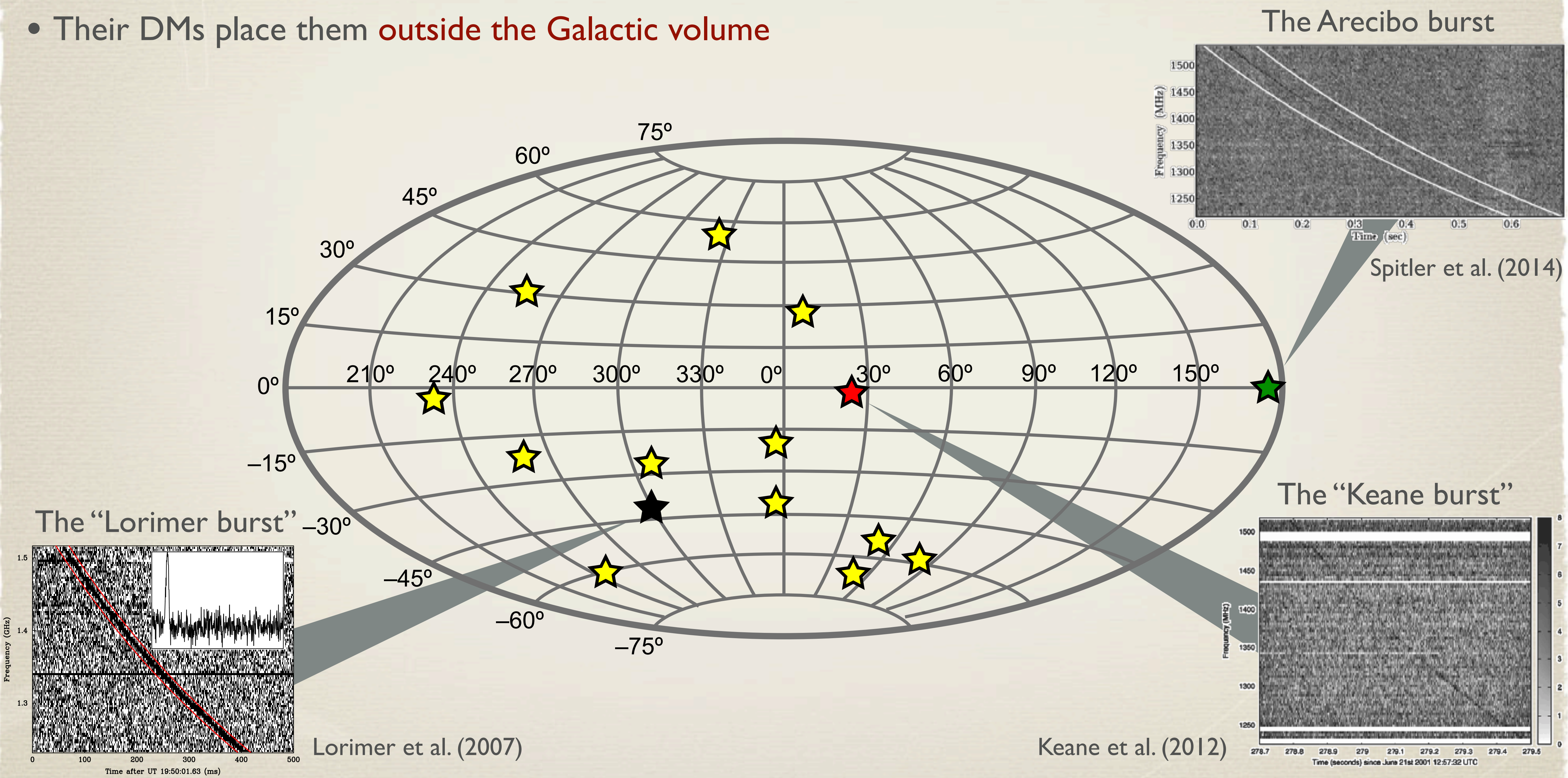


Pletsch et al. (2013)

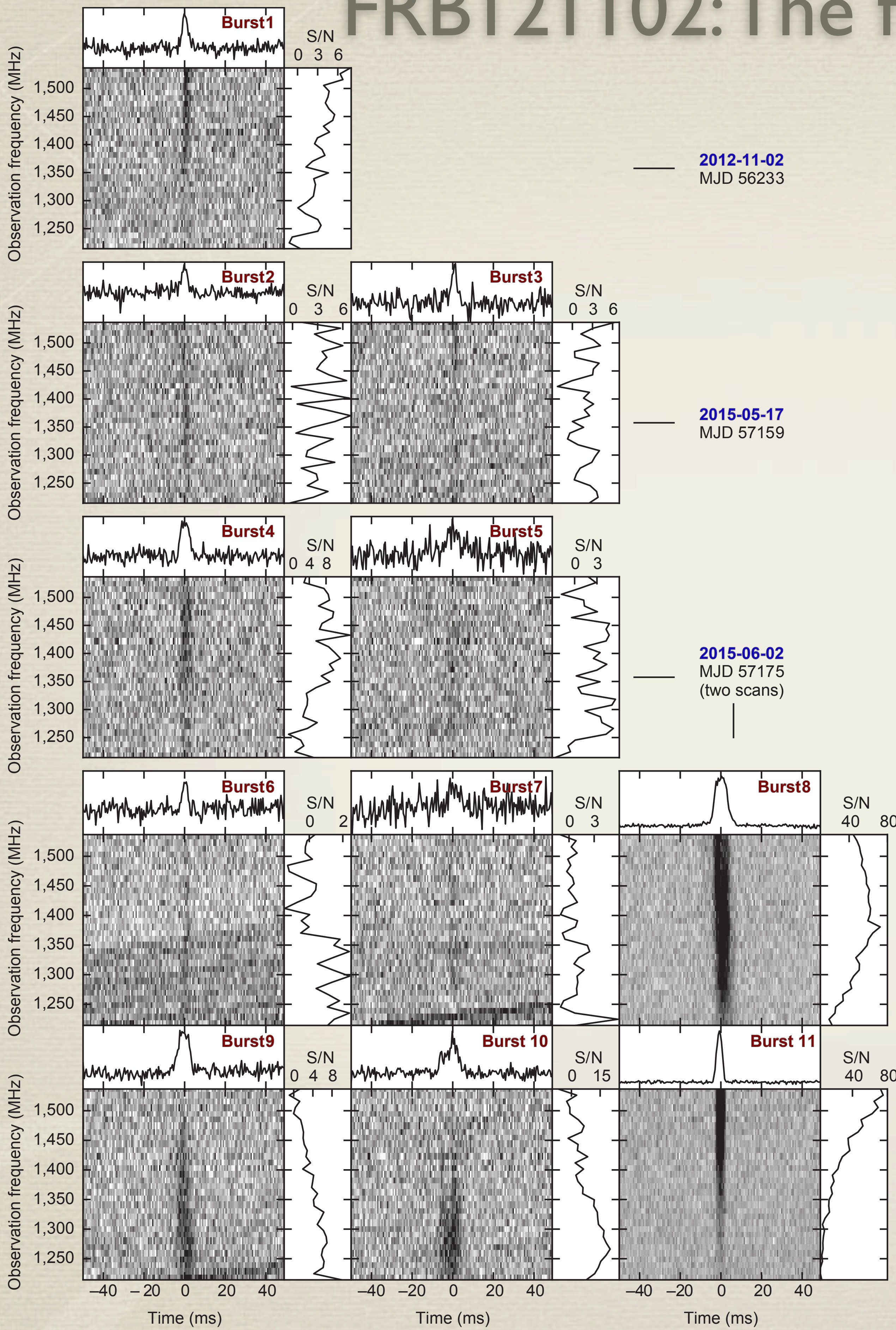
Fast Radio Bursts

Fast Radio Bursts (FRBs)

- Single, millisecond bursts of broadband radio emission
- Most of them are found at high Galactic latitudes
- FRB dispersion follows ~ f^{-2} (in agreement with cold plasma dispersion)
- Profile broadening follows ~ f^{-4} (in agreement with Kolmogorov turbulence)
- Their DMs place them outside the Galactic volume



FRB121102: The first repeating FRB



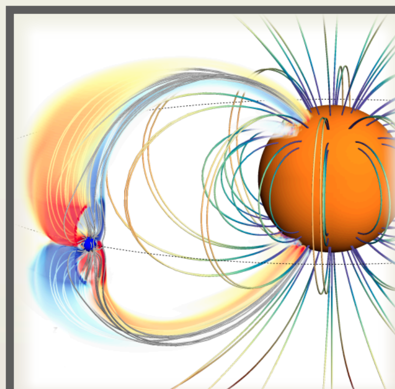
Spitler et al. (2016)

Follow-up observations of the Arecibo FRB detected more bursts from the same direction and the same DM.

No periodicity has been found yet, but ...

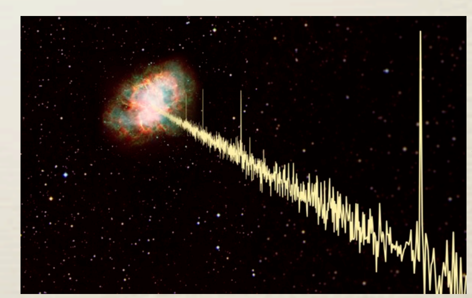
The spectral-index variation matches well that which is observed for the giant pulses of the Crab.

Based on their repetition, duration and spectral characteristics, it is deemed likely that they are produced by neutron stars.



Alfvén wings
(Mottez & Zarka)

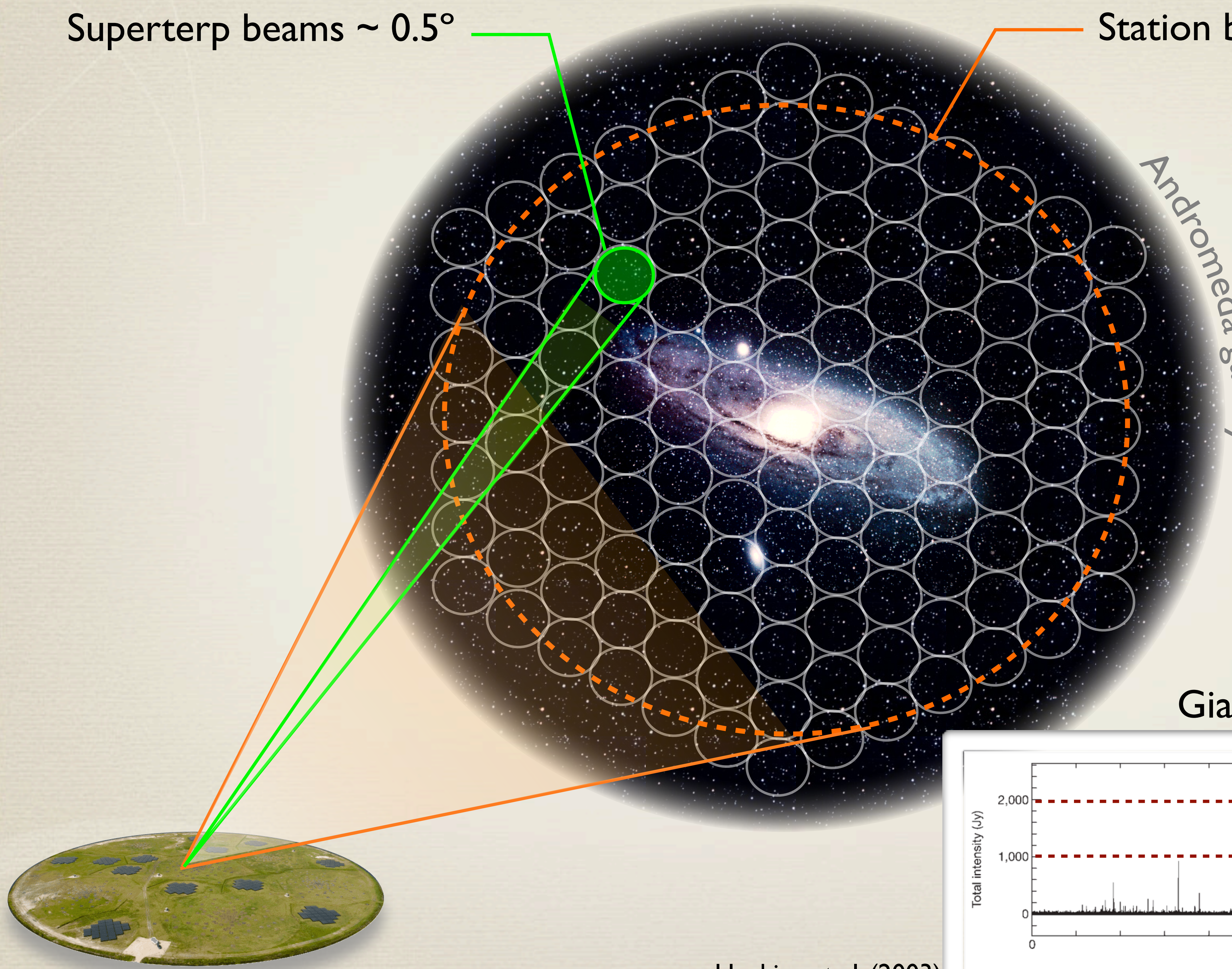
'Blitzars'
(Falcke & Rezzolla)



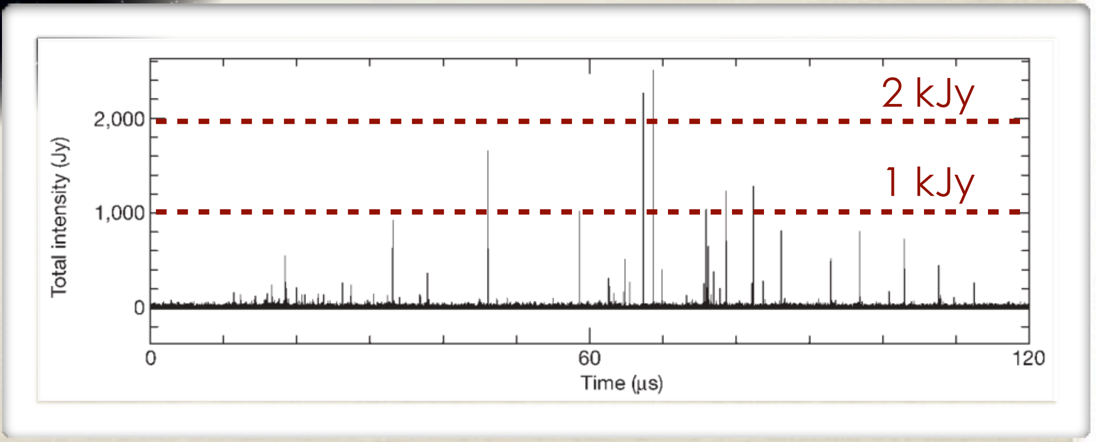
Giant pulses
(Cordes & Wasserman)

The repetitive nature precludes catastrophic events as the source of at least this type of FRBs

Searching for extragalactic pulsars with LOFAR



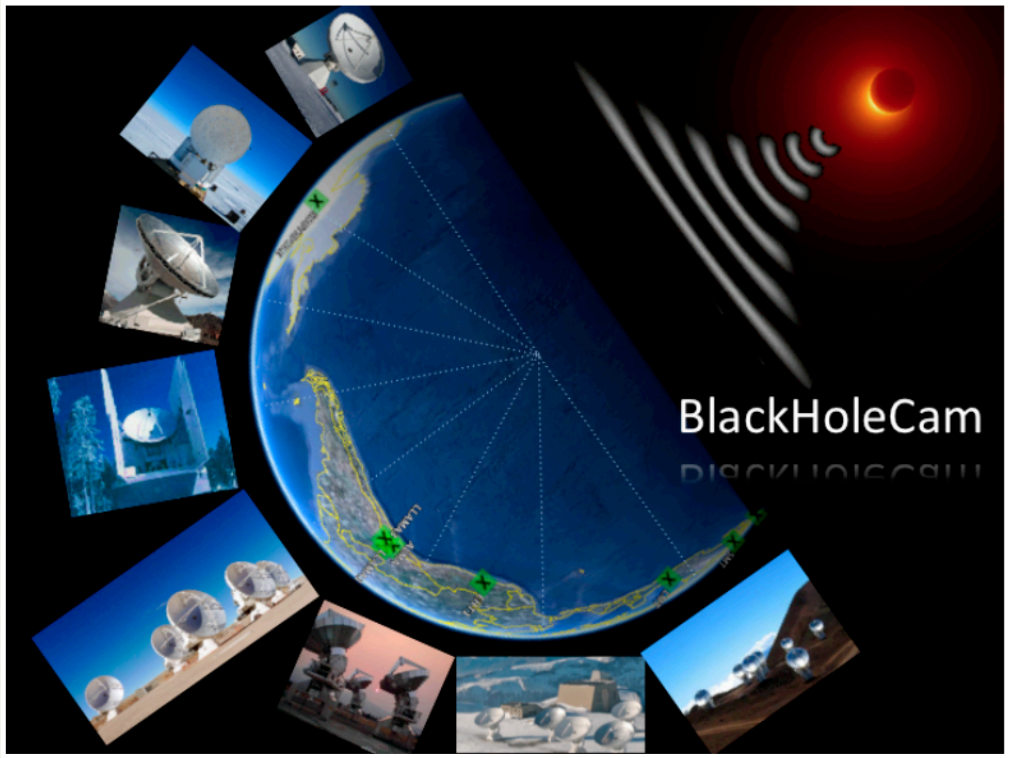
Giant pulses



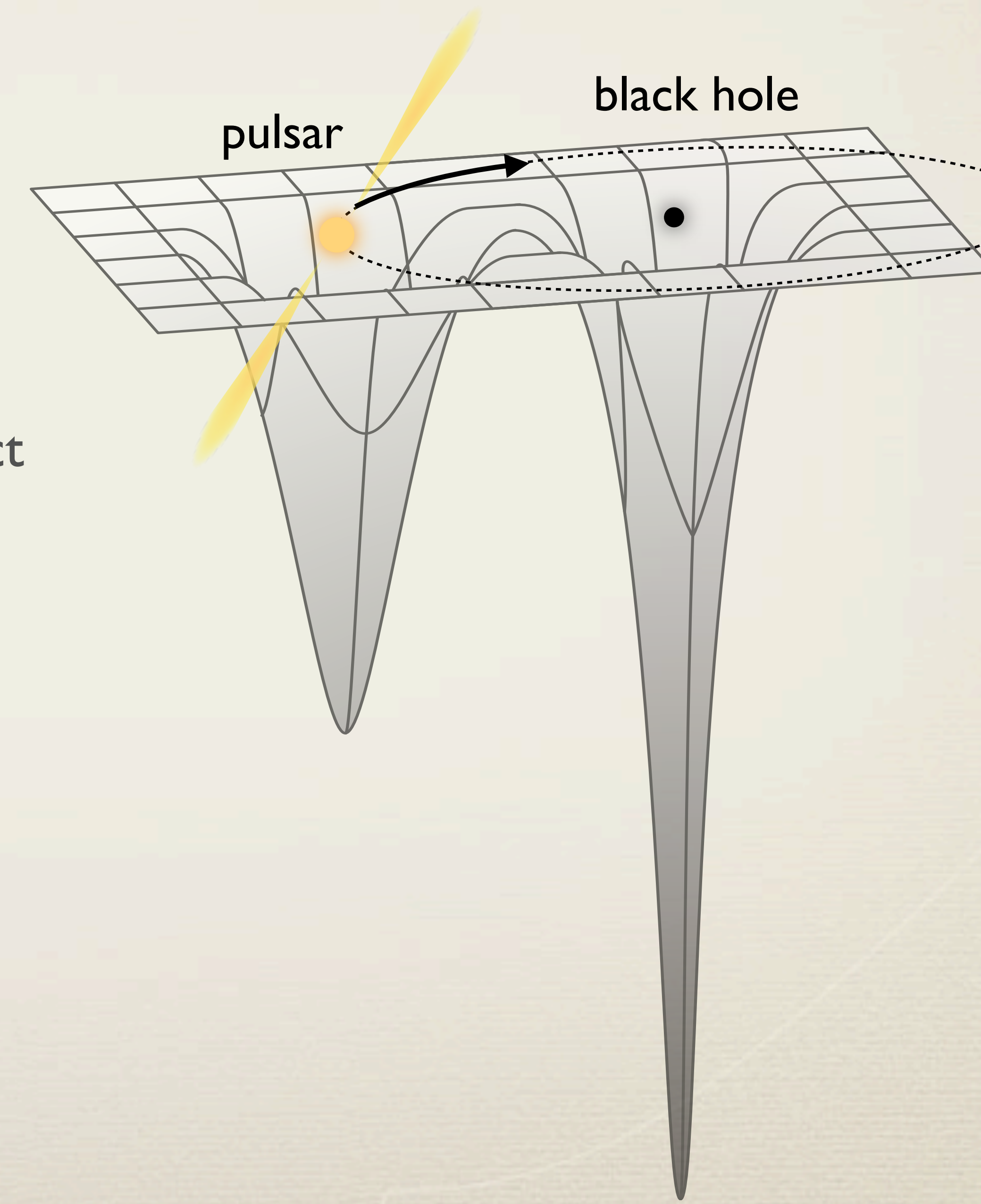
Hankins et al. (2003)

Future Instrumentation & Observations

BlackHoleCam: Imaging the central black hole



The BlackHoleCam projects aims at interferometrically combining the world's most sensitive millimetre observatories to image the event horizon of Sgr A* – the supermassive black hole at the GC.



The project also will use ALMA to try and detect the first pulsar orbiting Sgr A*.

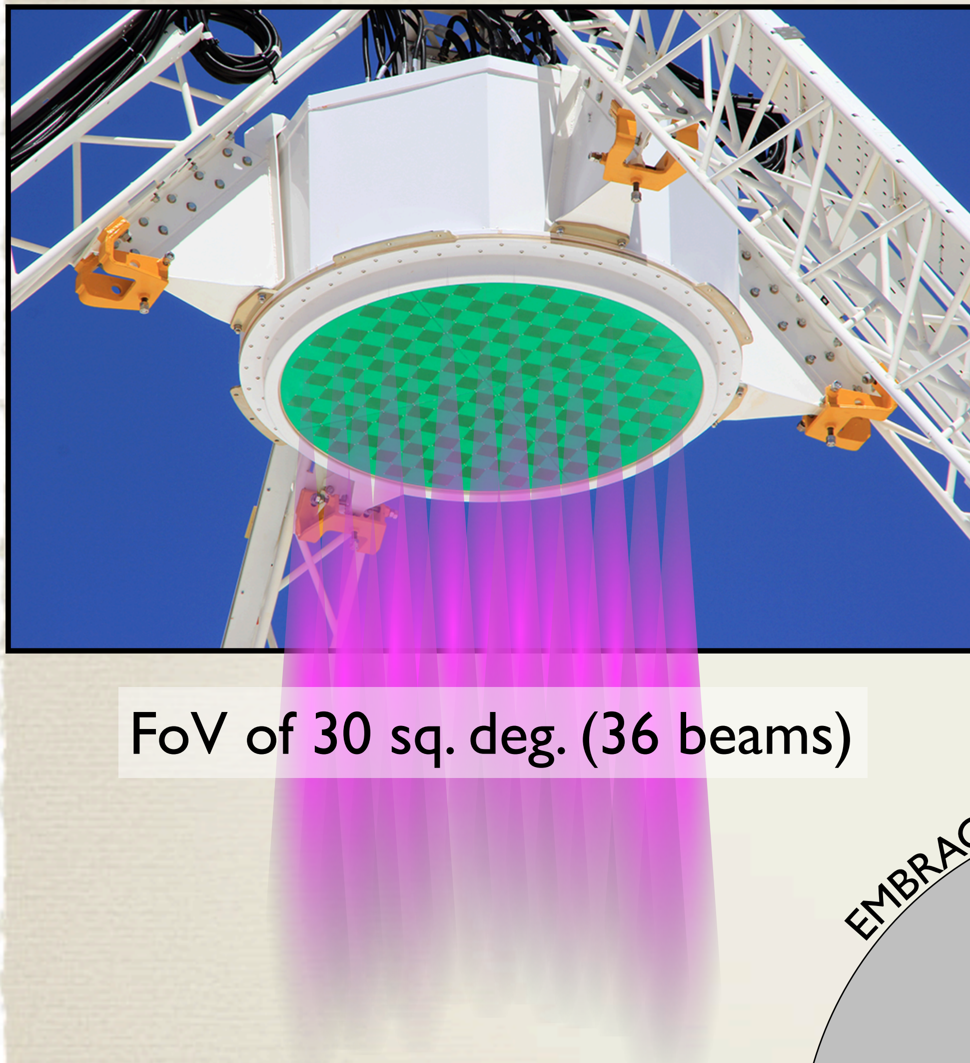
Credit: NRAO

Observations of a black-hole binary pulsar will allow not only to measure the black hole mass with 10^{-6} precision, but also the black hole spin to a few %.

New receivers for pulsar surveys

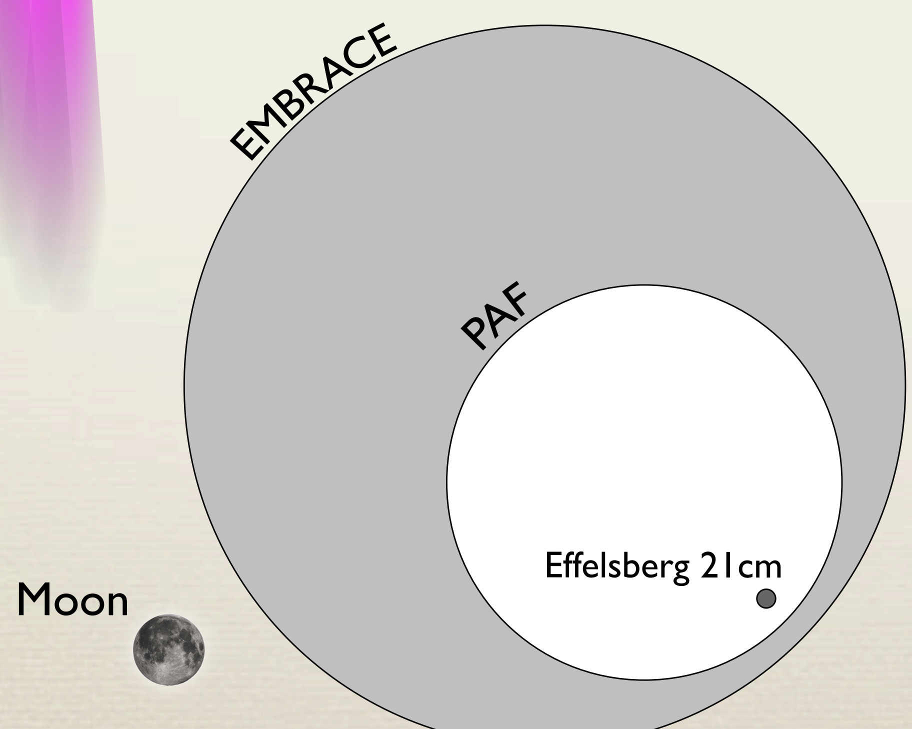
A new generation of multi-beam receivers providing large FoVs at high radio frequencies

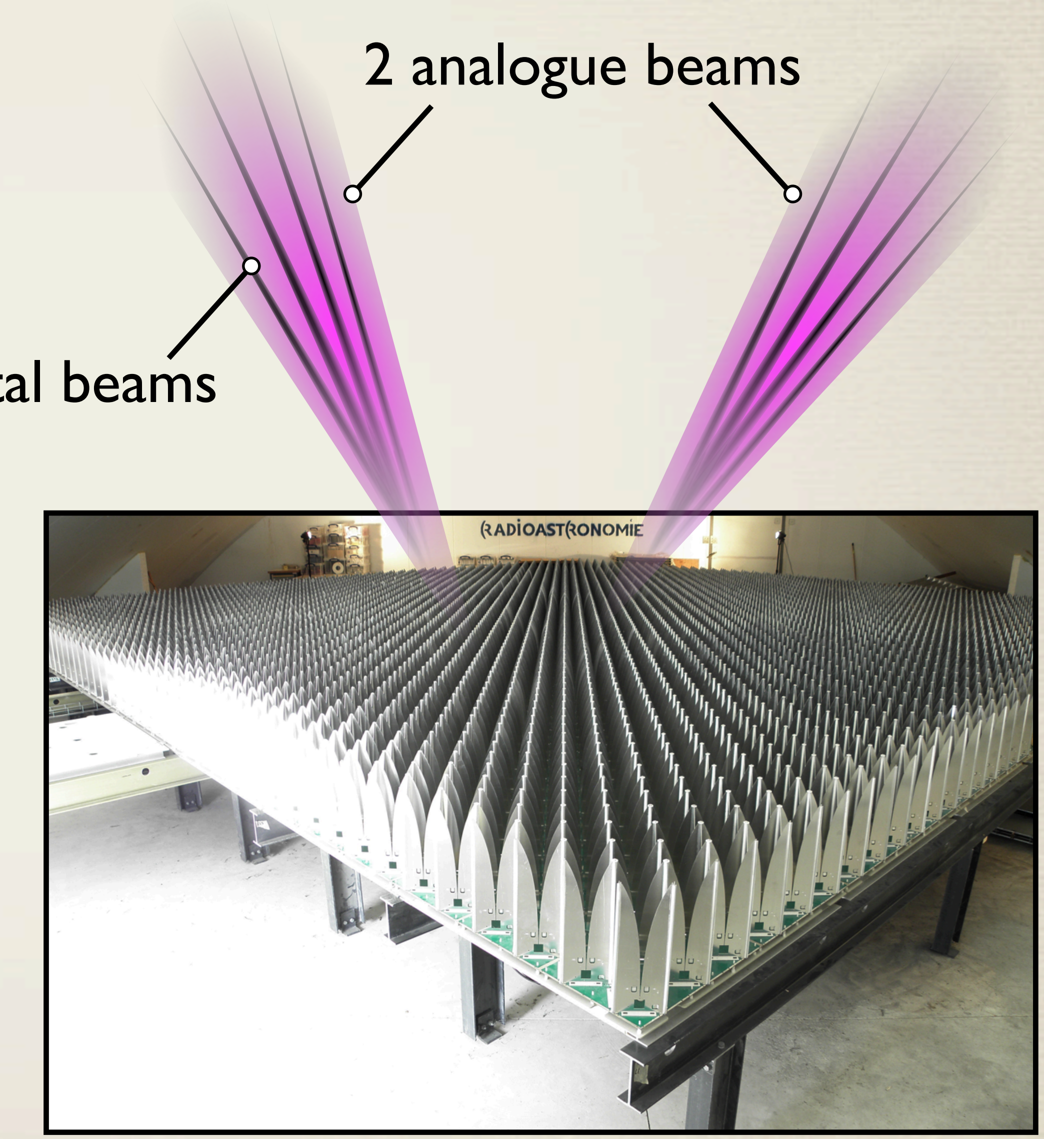
PAFs (~1 GHz)



Credit: WA Department of Commerce

FoV of 30 sq. deg. (36 beams)



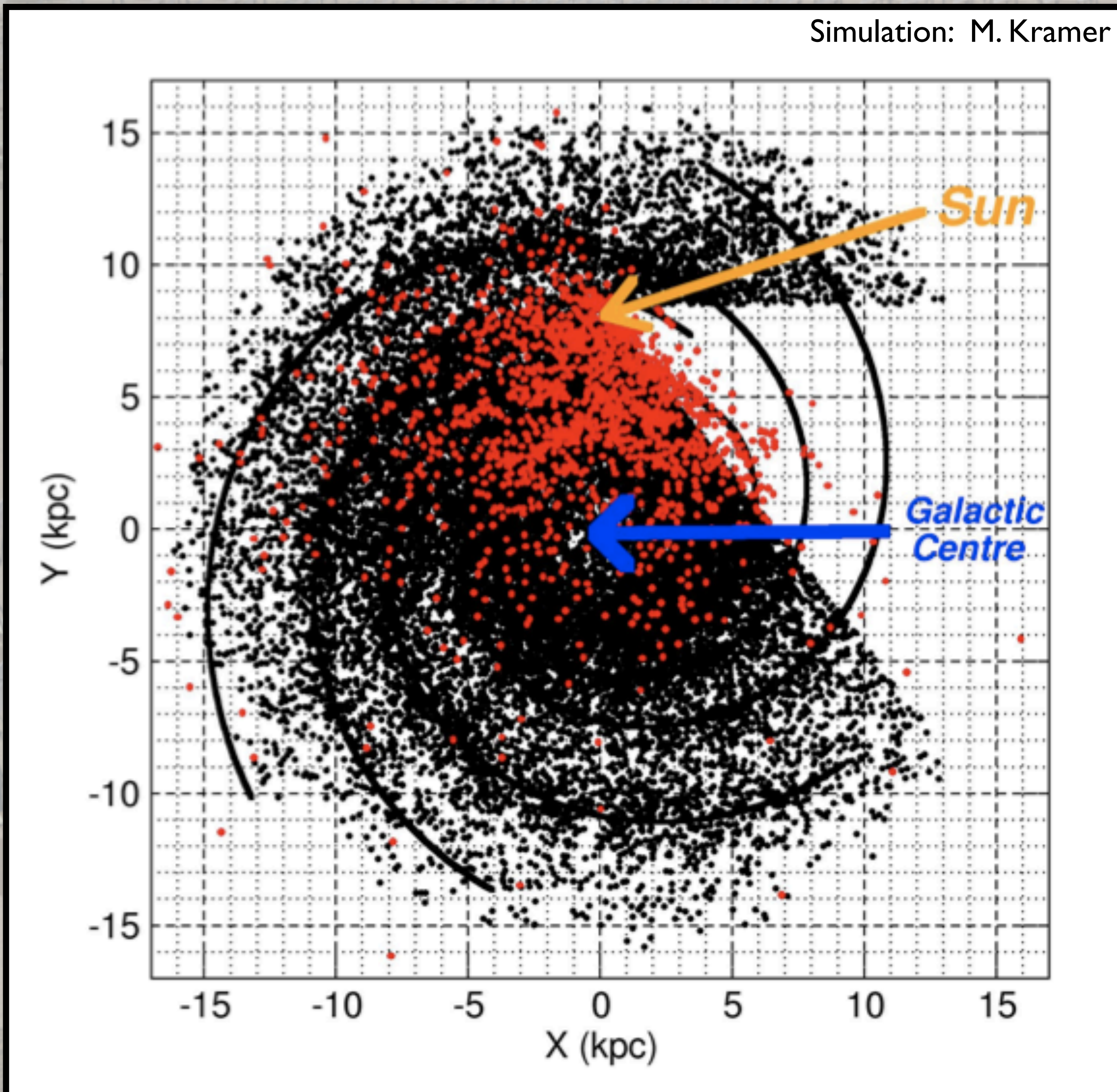


Credit: Steve Torchinsky / Nançay Observatory

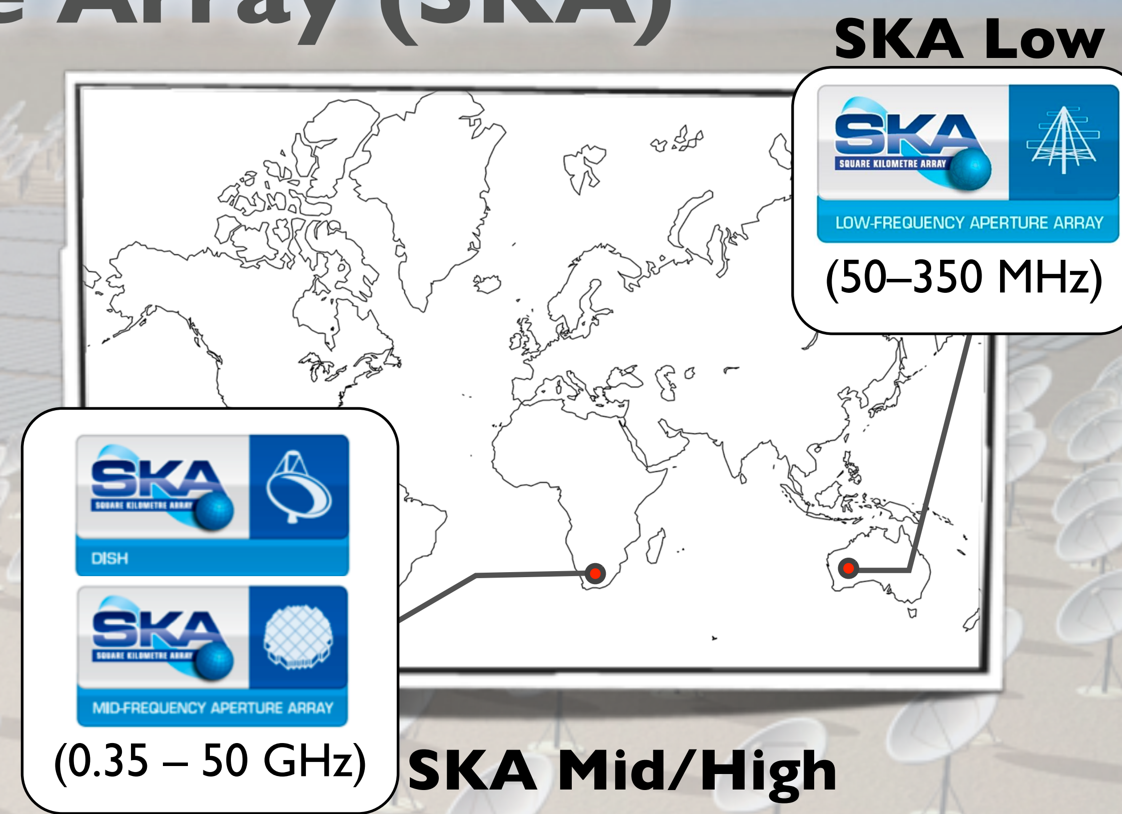
EMBRACE (1–2 GHz)

FoV up to 100 sq. deg. (~200 beams)

The Square Kilometre Array (SKA)



- known pulsars
- expected pulsars from the SKA



Upon completion, ca. 2030, the full SKA will be the most sensitive radio telescope in the world.

It will discover all the visible pulsars in the Milky Way (~20,000 – 30,000).

Given the current knowledge about FRBs and the SKA capabilities, we should expect to detect 1 FRB / day with SKA mid.

Find the first ms-pulsar orbiting a BH → measure the spin and quadrupole moment of the BH → test the 'no-hair' theorem.

Summary / Conclusions

• Pulsar astronomy offers a unique laboratory for studies of physics at extreme densities, gravitational and magnetic fields.

• Timing of millisecond pulsars provides the most stringent tests of GR in the strong gravity regime.

The decay of the of the double pulsar orbit due to gravitational wave emission is consistent with the prediction of GR at the 99.98% level.

• The serendipitous discovery of a new class of fast transient, the Fast Radio Bursts, proves that after nearly 50 years since the discovery of pulsars time-domain astronomy keeps surprising us.

The current distribution of 15 FRBs indicates that they are of extragalactic origin

The latest discovery of a repeating FRB, together with its spectral characteristics, possibly favours a connection between these haphazard events and neutron stars.

• The SKA will ultimately discover all pulsars in the Galaxy and shine light on the nature of known and yet to be discovered fast transient events. Before the SKA sees first light, the sky is being surveyed across the radio spectrum for pulsars and other transients.

The LOFAR all-sky survey at 150 MHz is the first SKA-like transient survey and has already discovered tens of pulsars.

The HTRU Northern and Southern surveys at 1.4 GHz have discovered nearly 10% of the currently know pulsars, including a number of exotic systems, showing that in the era of phased arrays single-dish surveys are still relevant.