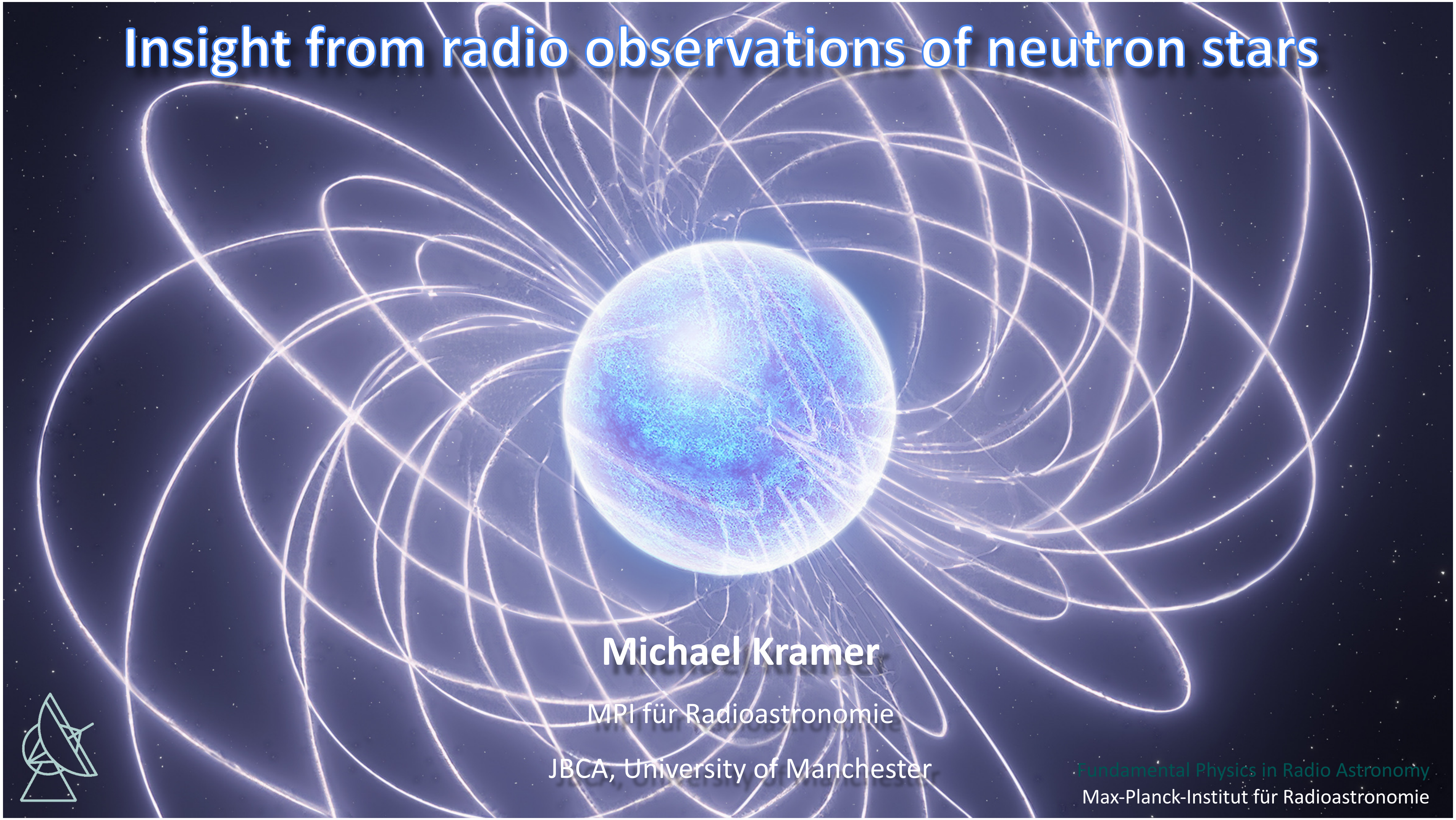
Insight from radio observations of neutron stars



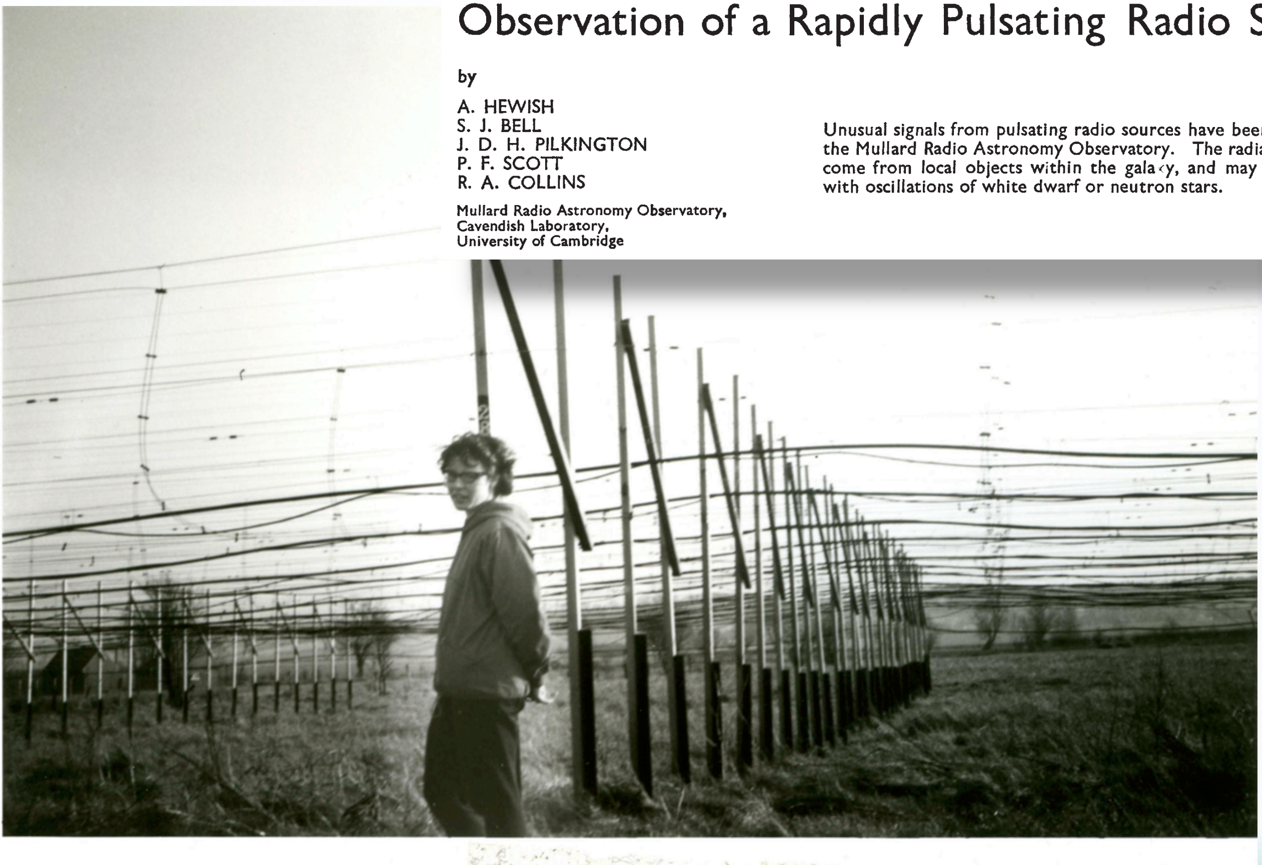
Michael Kramer

MPI für Radioastronomie

JBCA, University of Manchester

This talk is not about searching for pulsars

Pulsars turned from a theoretical construct into reality with the unexpected discovery of pulsars in Cambridge in late 1967:



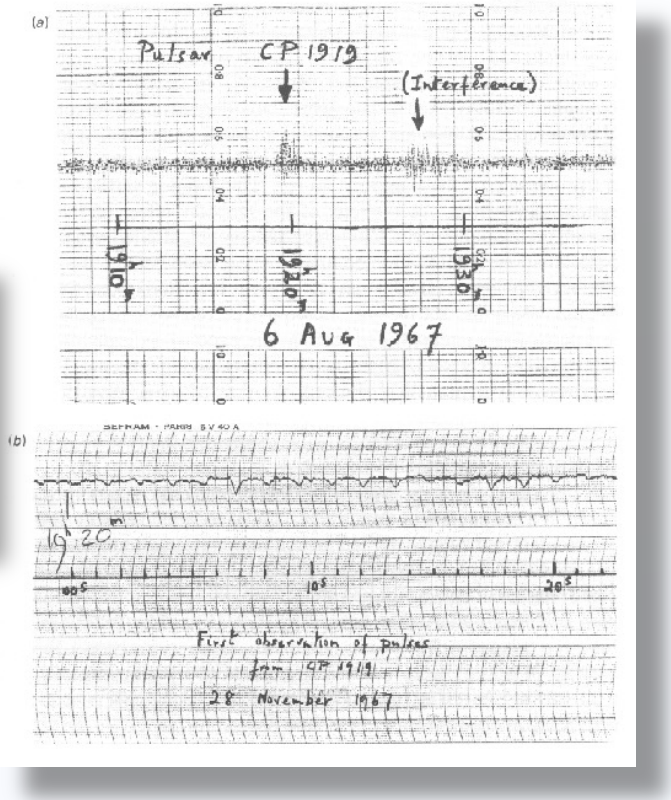
Observation of a Rapidly Pulsating Radio Source

by

A. HEWISH
S. J. BELL
J. D. H. PILKINGTON
P. F. SCOTT
R. A. COLLINS

Mullard Radio Astronomy Observatory,
Cavendish Laboratory,
University of Cambridge

Unusual signals from pulsating radio sources have been recorded at the Mullard Radio Astronomy Observatory. The radiation seems to come from local objects within the galaxy, and may be associated with oscillations of white dwarf or neutron stars.



Today we know more than 3000 pulsars

What are their properties – at birth and while they age?

We would like to know: Population, types, evolution....

Masses

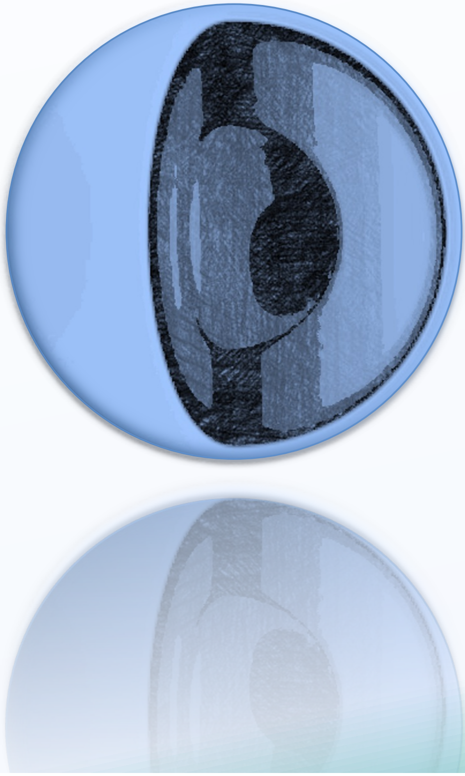
Radius

Moment-of-inertia

Ages

Velocities

Geometries



Spin frequencies

Magnetic fields

Temperatures

Density

Structure

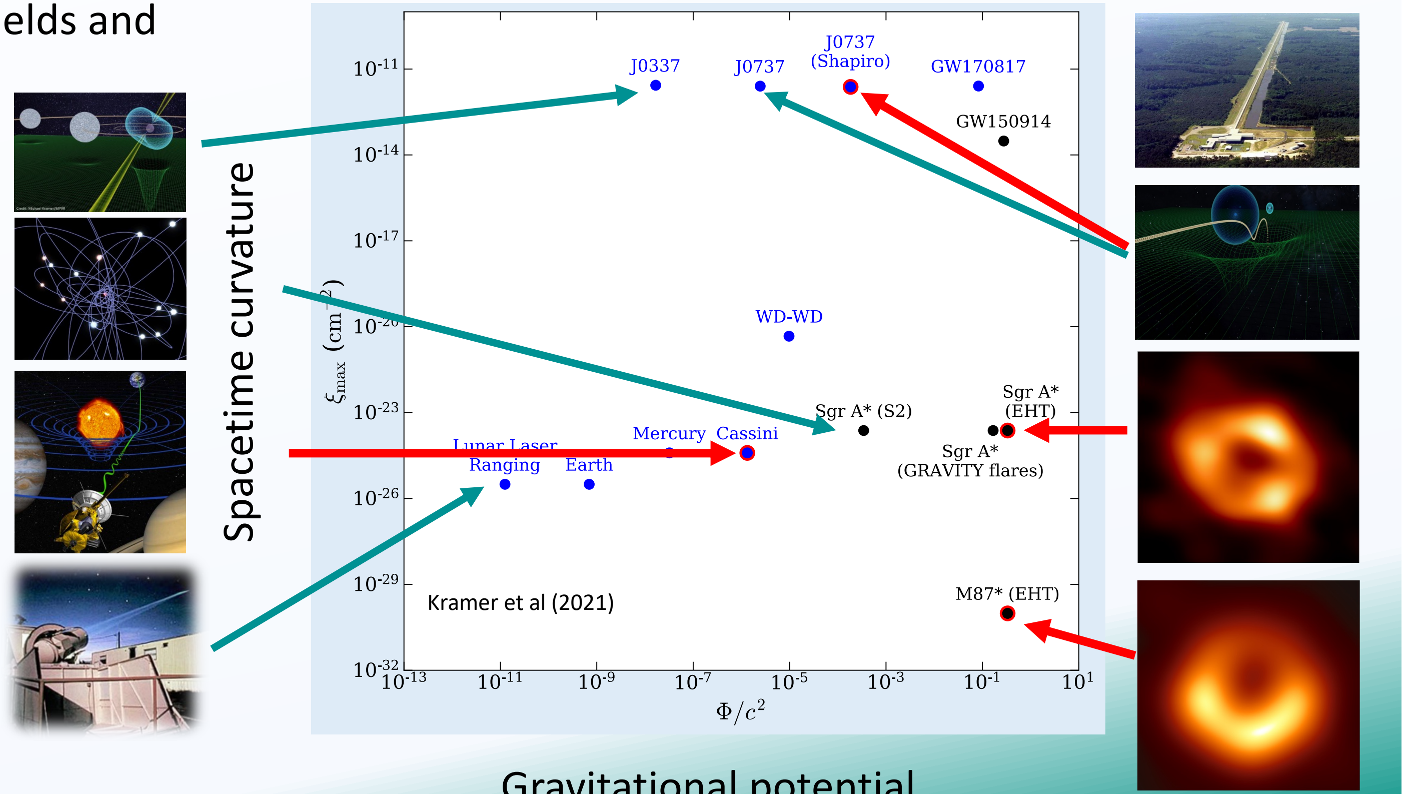
Equation of state

Why would we like to know this?

Neutron stars probe a wide range of fundamental physics:

- Properties of ultra-dense matter (nuclear physics: equation-of-State, super-fluidity, structure)
- Interaction of matter, plasma and EM radiation in ultra-strong magnetic fields (pulsars, magnetars)
- Physics in strong gravitational fields and in extremely curved space-time

Space-time tested around our pulsars is about 20 orders of magnitude more curved than for our M87* BH image experiment



Kramer et al (2021)

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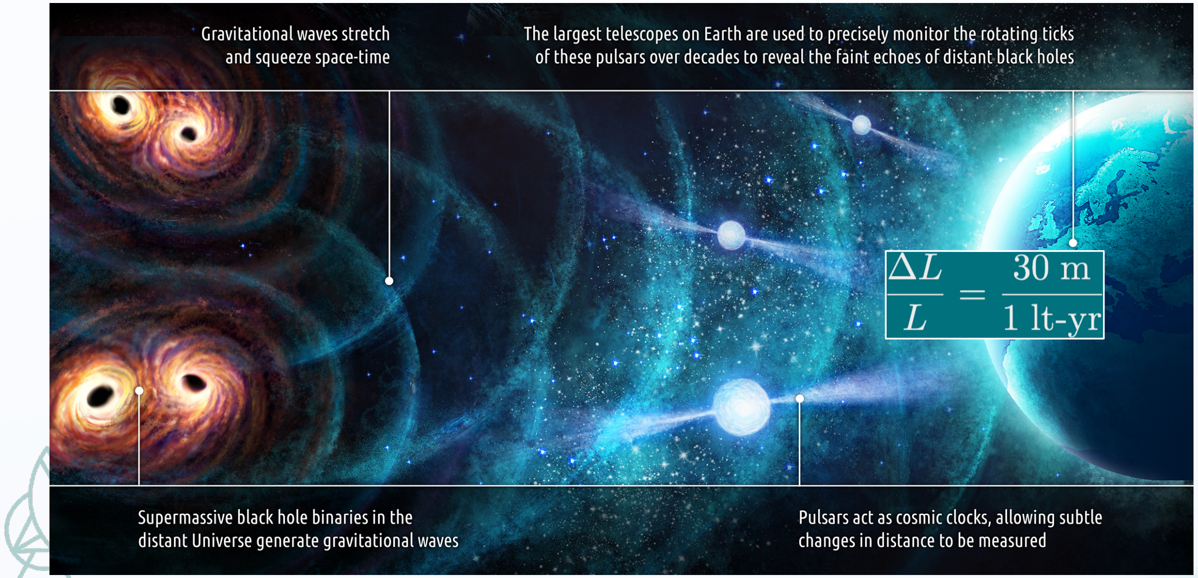
- Interaction of matter, plasma and EM radiation in ultra-strong magnetic fields (pulsars, magnetars)
- Physics in strong gravitational fields and in extremely curved space-time
- Pulsars as tools, e.g gravity tests & gravitational wave detection:
  NS properties as limiting factor (origin of red timing noise)



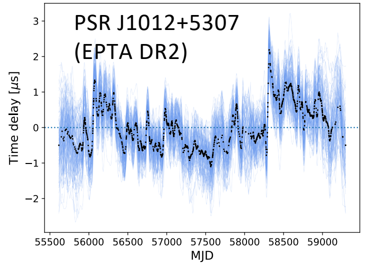
Gravitational waves stretch and squeeze space-time

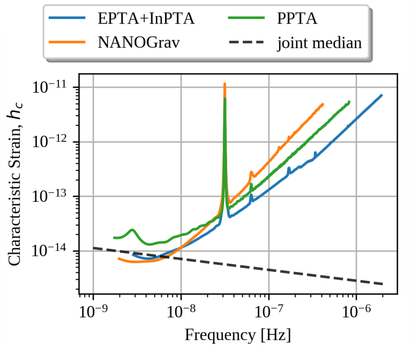
The largest telescopes on Earth are used to precisely monitor the rotating ticks of these pulsars over decades to reveal the faint echoes of distant black holes

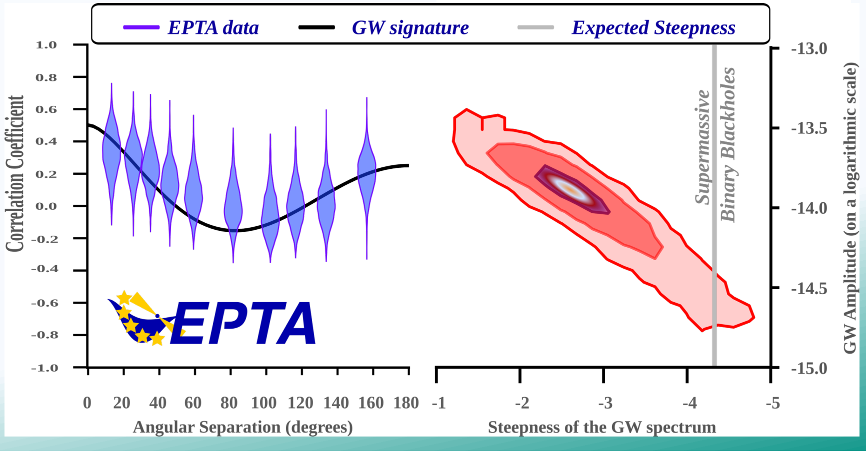
$$\frac{\Delta L}{L} = \frac{30\ \text{m}}{1\ \text{lt-yr}}$$

Supermassive black hole binaries in the distant Universe generate gravitational waves

Pulsars act as cosmic clocks, allowing subtle changes in distance to be measured







What are their properties – at birth and while they age?

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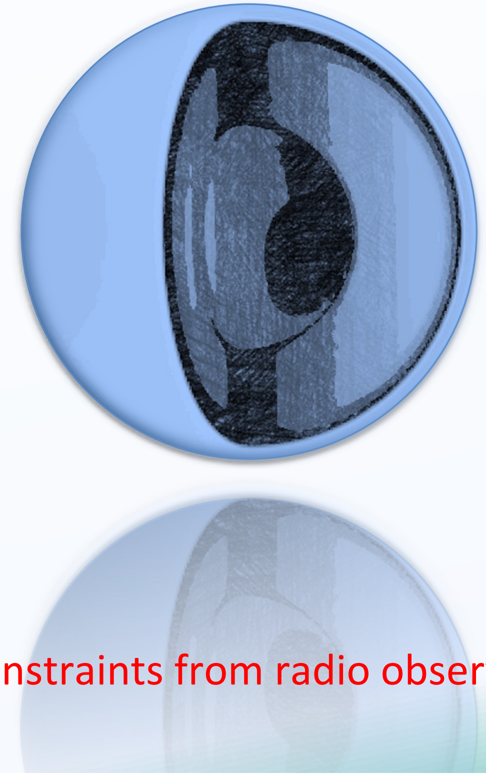

Masses

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Spin frequencies

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Temperatures

Density

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Equation of state

*Measurements and/or constraints from radio observations (for X-rays see Wednesday)

Information from radio observations

- From pulsar timing:

  - measuring pulse arrival times and tracking the rotation of the neutron star with high precision

- From emission properties:

  - full polarisation measurements from 10s MHz to 100s GHz

  - high time resolution observations down to nanosecond timescales

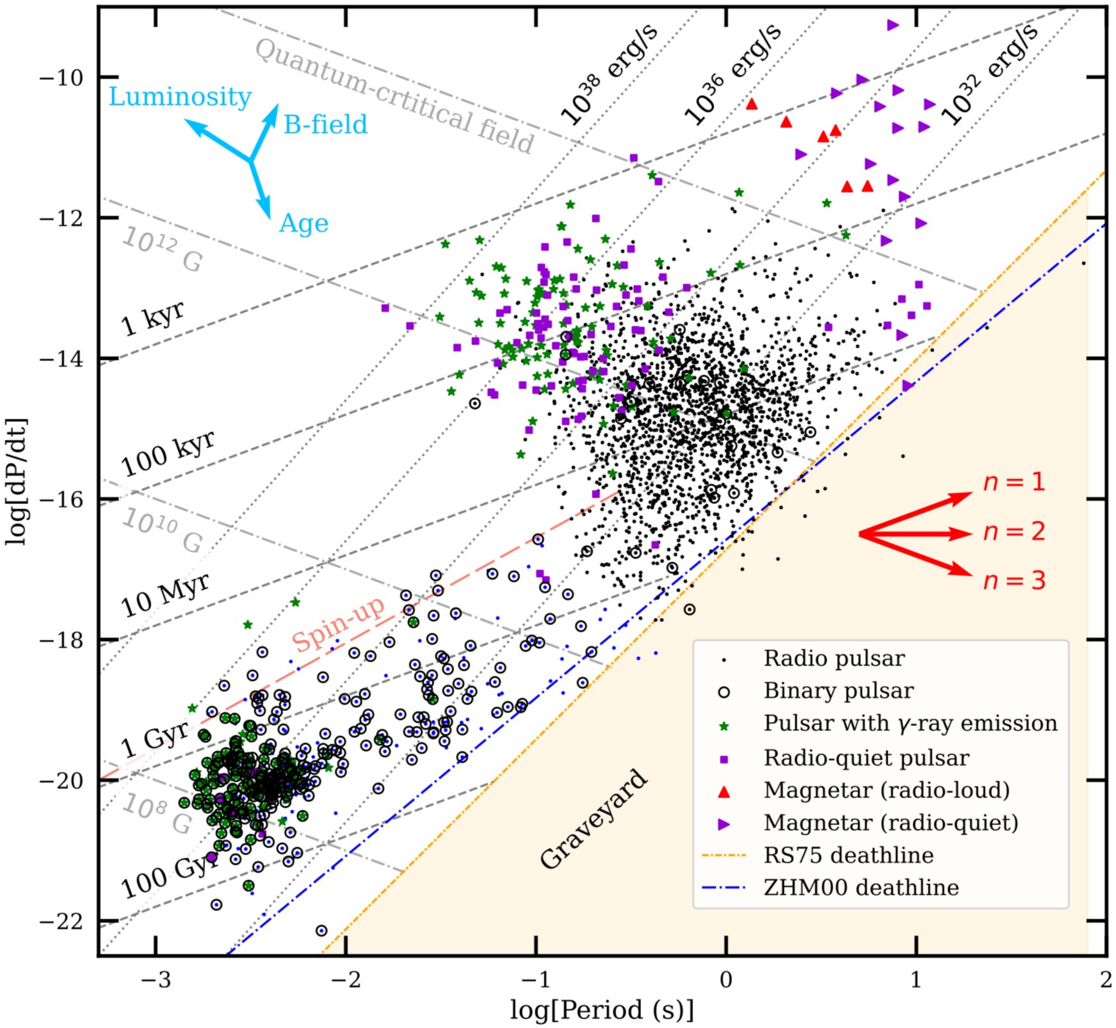
  - long-term monitoring lasting half a century (>10^9 rotations)

- From simultaneous multi-messenger observations

- From combination of particularly interesting pulsars vs bulk properties

The life of a neutron star$^{(*)}$

Lorimer & Kramer (2025)



- Young pulsars (energetic)
- Ordinary rotation-powered pulsars
- Recycled pulsars
- Magnetars
- Ultra long-period pulsars (?)

Immediate estimates: (note assumptions!)

Age:

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

B-field:

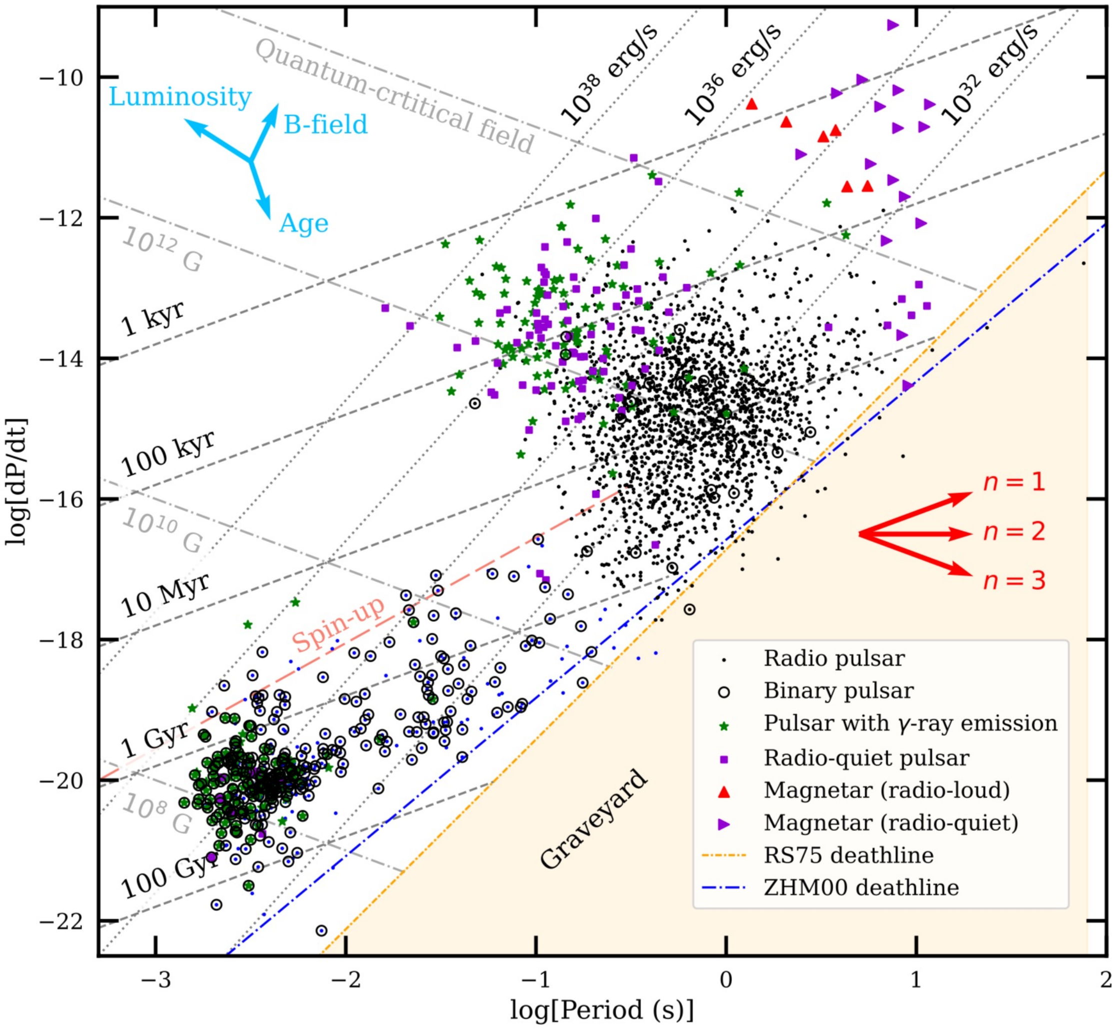
$$B_S = 3.2 \times 10^{19}\mathrm{G}\ \sqrt{P\dot{P}} \simeq 10^{12}\ \mathrm{G}\left(\frac{\dot{P}}{10^{-15}}\right)^{1/2}\left(\frac{P}{\mathrm{s}}\right)^{1/2}.$$

Energetics:

$$\dot{E} = 4\pi^2 I \dot{P} P^{-3} \simeq 3.95 \times 10^{31}\ \mathrm{erg\ s^{-1}}\left(\frac{\dot{P}}{10^{-15}}\right)\left(\frac{P}{\mathrm{s}}\right)^{-3}$$

(*) Mostly radio emitting neutron stars

The life of a neutron star$^{(*)}$



Lorimer & Kramer (2025)

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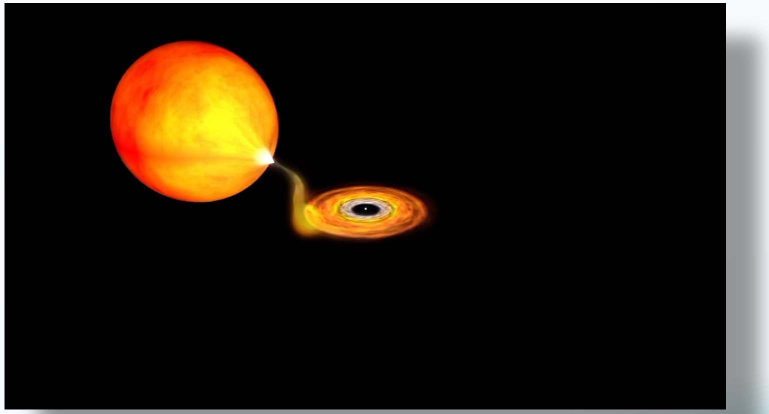
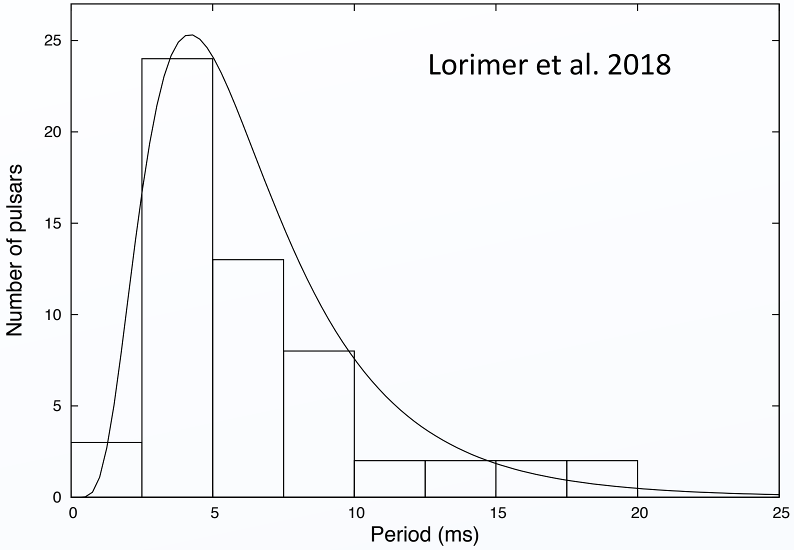
Recycling of dead pulsars in X-ray binary phase

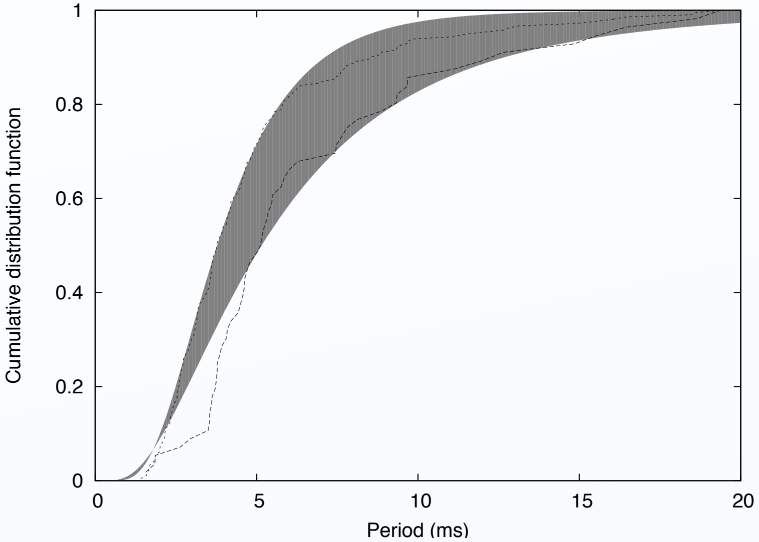


(NASA)

(*) Mostly radio emitting neutron stars

What is the shortest period?





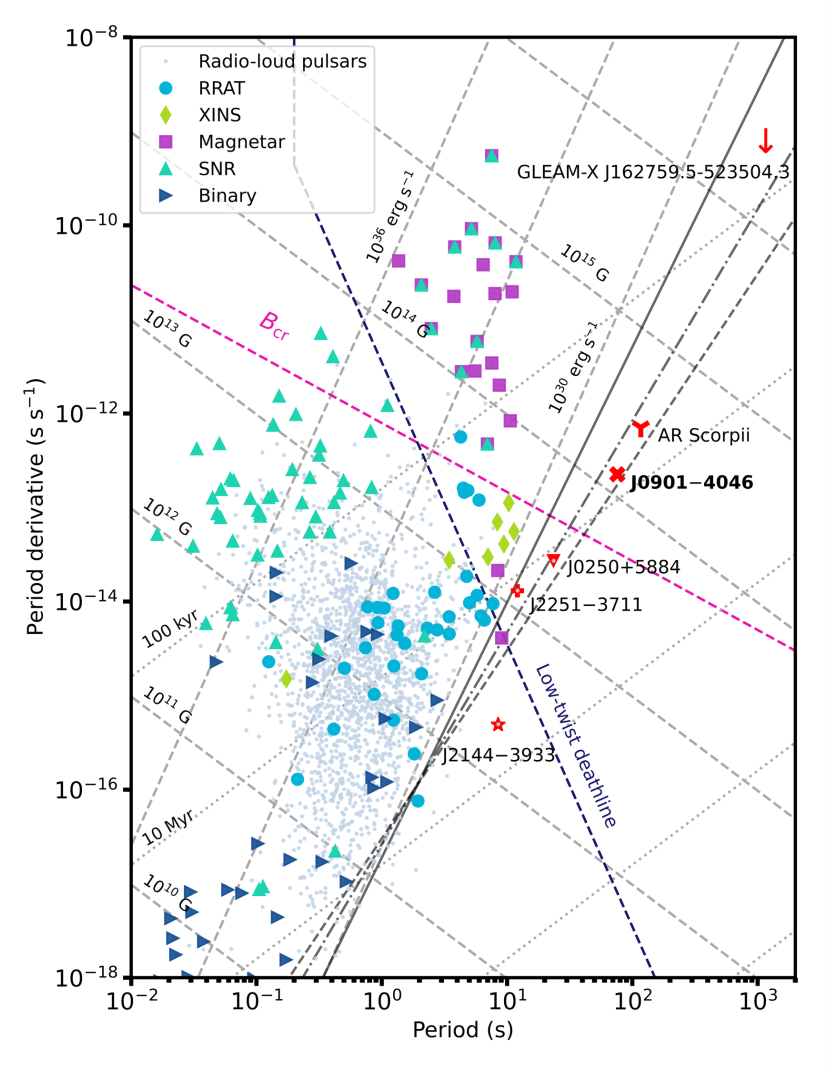
- Only ~3% of all MSP (defined here as P<20ms) have P < 1.5 ms?
- Recently, we knew 355 such MSPs, hence, expect about 10 with P < 1. 5ms. We know three…
- Our MeerKAT survey has added 200+ more MSPs..! See trapum.org

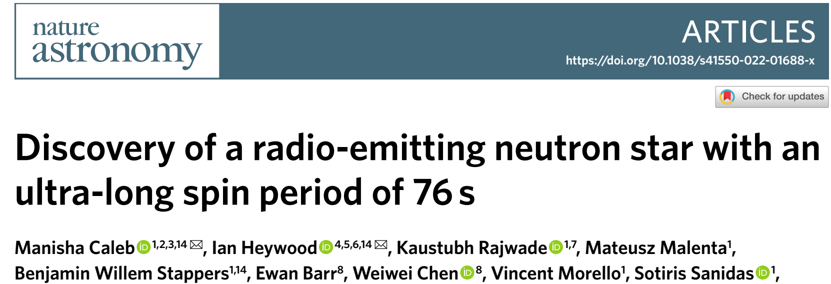
Expect a few more, but still only three... (We know selection effects...)

What about the longest period...? And why should we bother?

The boundaries are blurring....

A peculiar 76-s pulsar




nature astronomy

ARTICLES

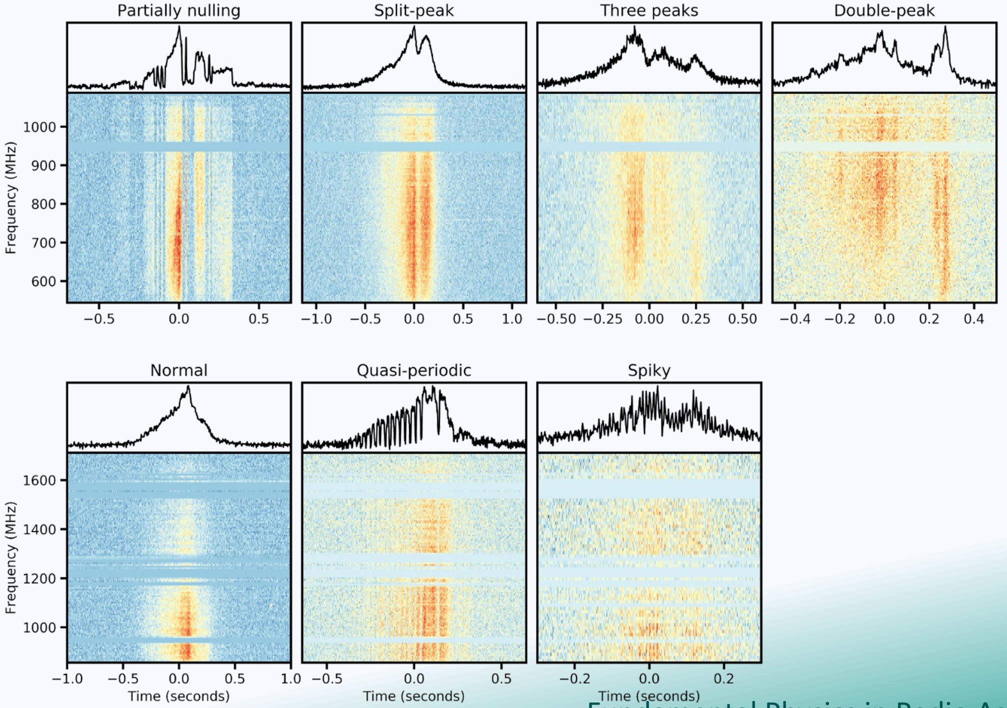
https://doi.org/10.1038/s41550-022-01688-x

Check for updates

Discovery of a radio-emitting neutron star with an ultra-long spin period of 76 s

Manisha Caleb[1,2,3,14], Ian Heywood[4,5,6,14], Kaustubh Rajwade[1,7], Mateusz Malenta[1], Benjamin Willem Stappers[1,14], Ewan Barr[8], Weiwei Chen[8], Vincent Morello[1], Sotiris Sanidas[1],

- A discovery by MeerTRAP (PI Stappers)
- Very peculiar single pulse shapes - is this a neutron star?
- Seven types:



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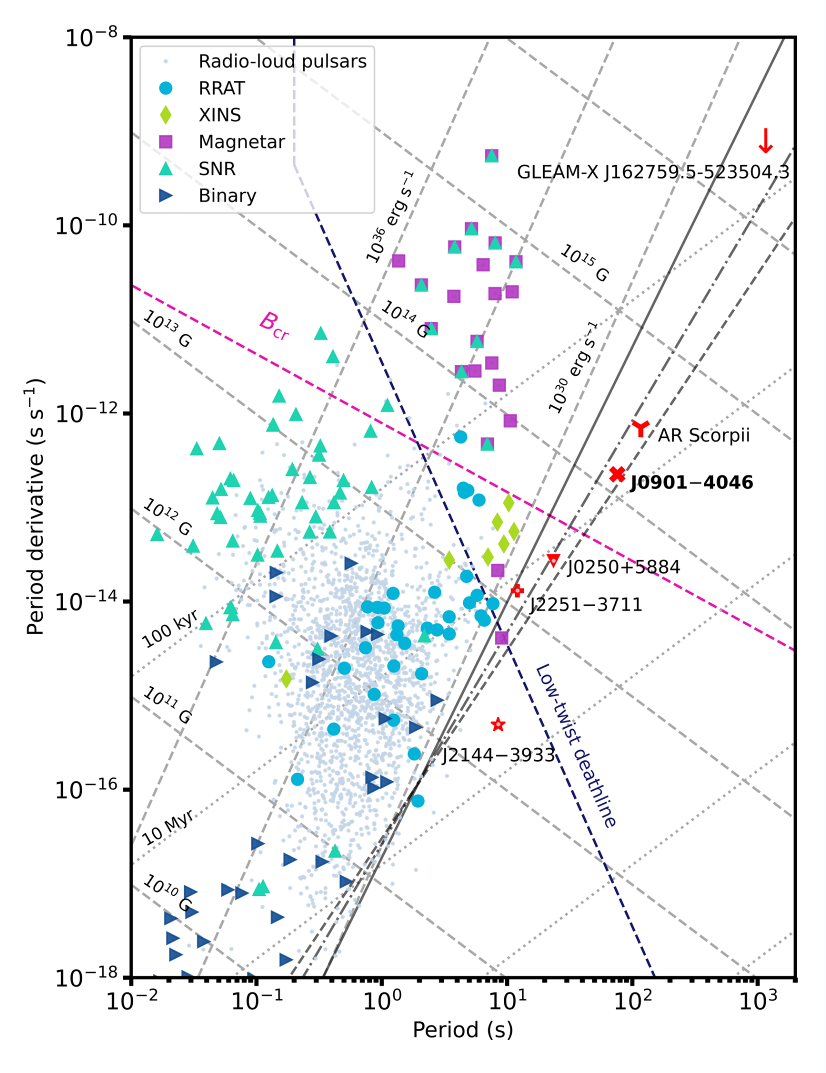

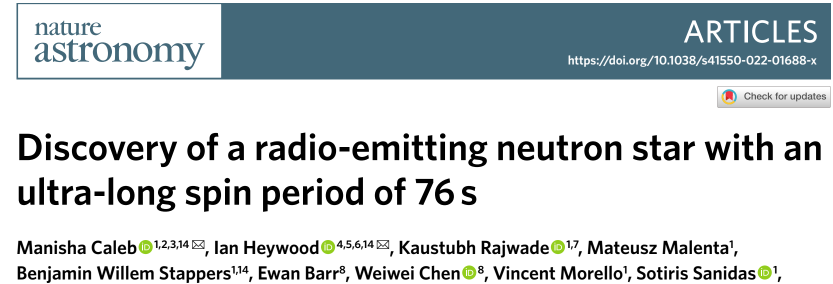

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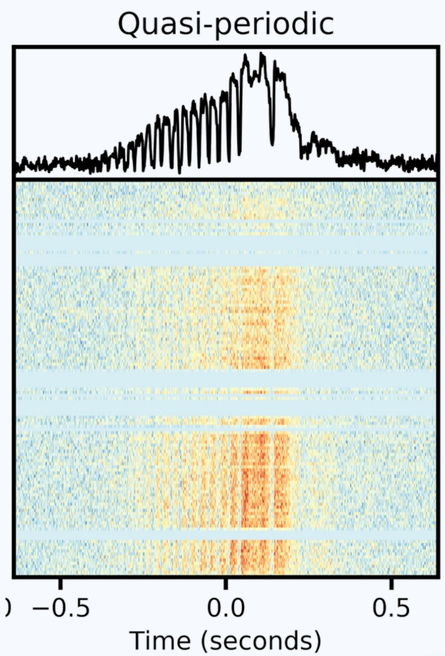
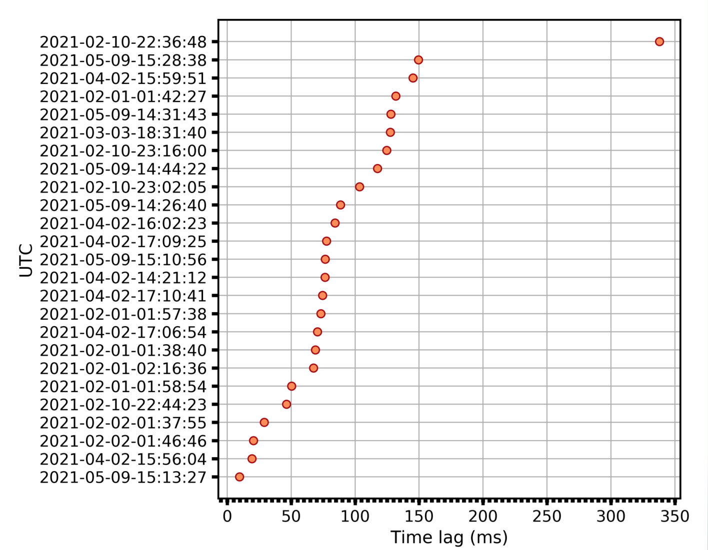
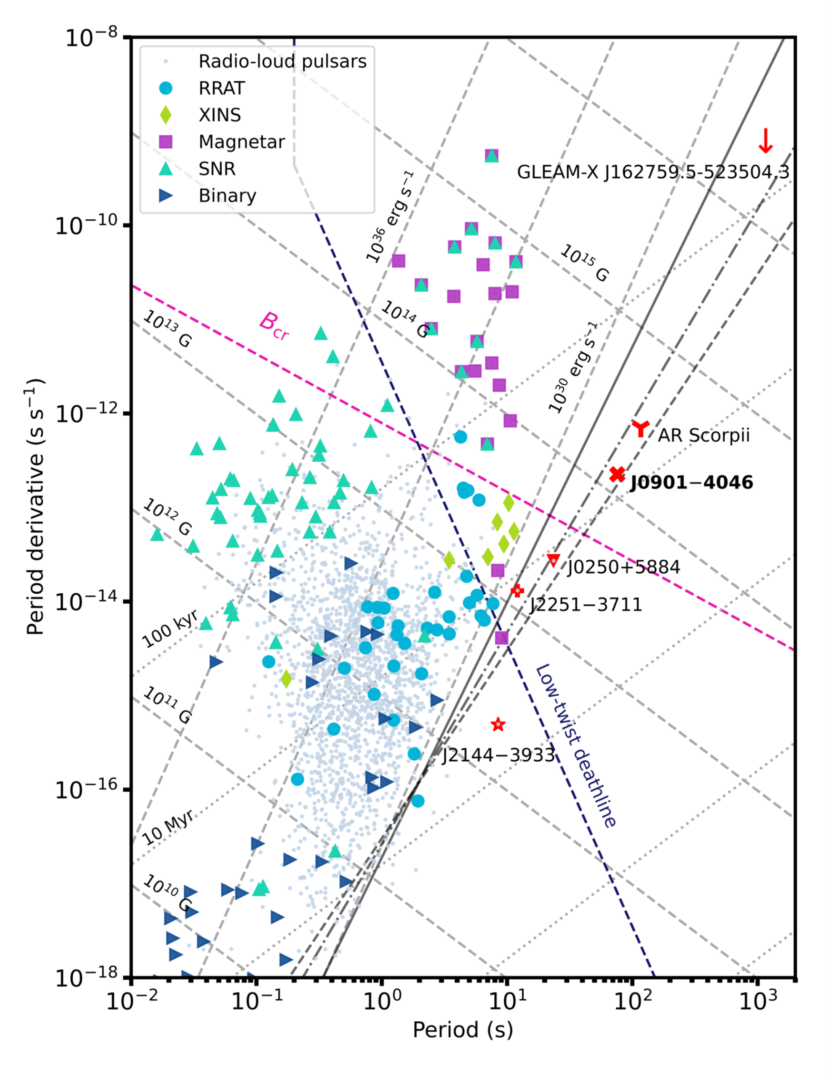




A peculiar 1090-s source



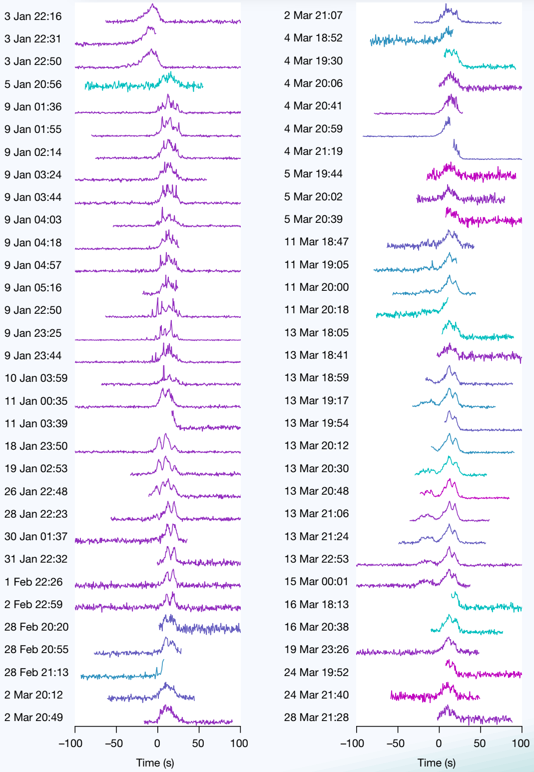
Article

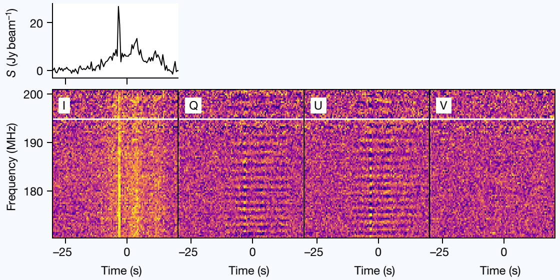
A radio transient with unusually slow periodic emission

https://doi.org/10.1038/s41586-021-04272-x

Received: 30 July 2021

N. Hurley-Walker[1✉], X. Zhang[2,3], A. Bahramian[1], S. J. McSweeney[1], T. N. O'Doherty[1], P. J. Hancock[1], J. S. Morgan[1], G. E. Anderson[1], G. H. Heald[2] & T. J. Galvin[1]



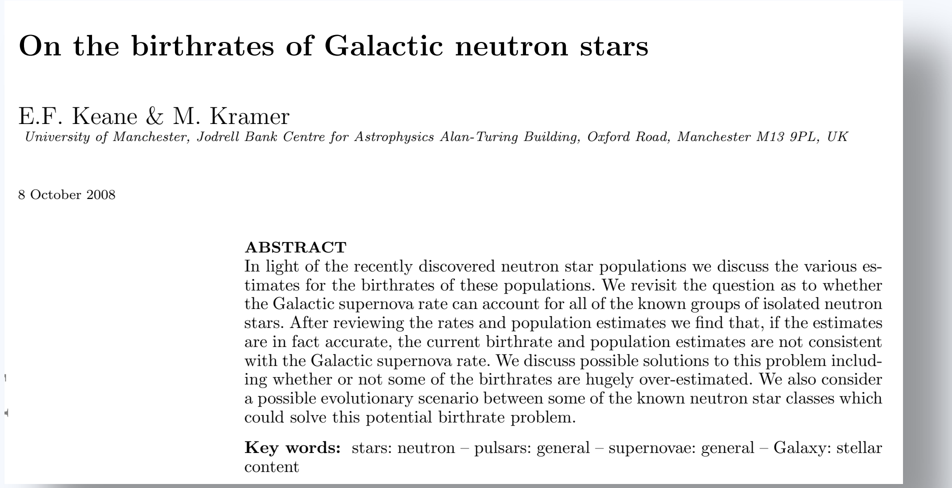


Is this really a neutron star?

We will get back to that later

Do we see too many neutron stars?

Keane & Kramer (2008)



On the birthrates of Galactic neutron stars

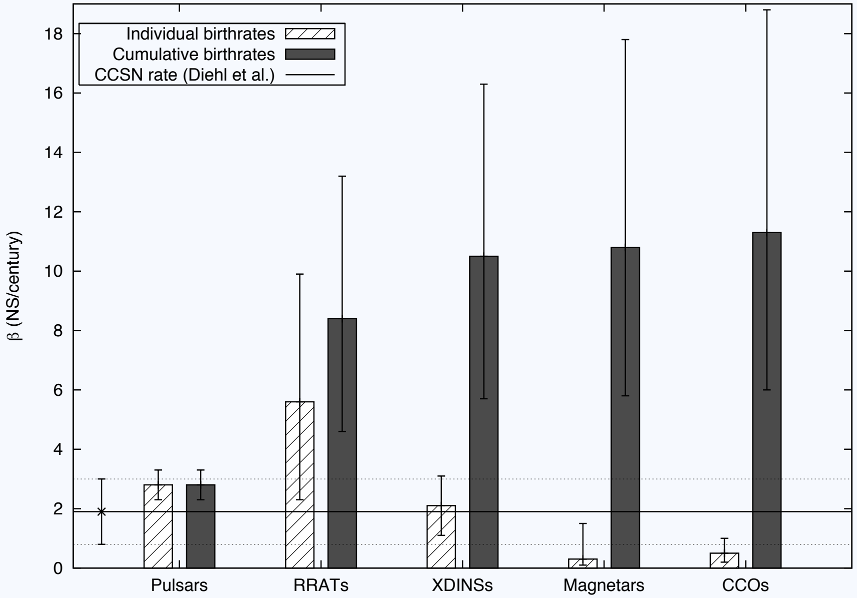
E.F. Keane & M. Kramer
University of Manchester, Jodrell Bank Centre for Astrophysics Alan-Turing Building, Oxford Road, Manchester M13 9PL, UK

8 October 2008

ABSTRACT
In light of the recently discovered neutron star populations we discuss the various estimates for the birthrates of these populations. We revisit the question as to whether the Galactic supernova rate can account for all of the known groups of isolated neutron stars. After reviewing the rates and population estimates we find that, if the estimates are in fact accurate, the current birthrate and population estimates are not consistent with the Galactic supernova rate. We discuss possible solutions to this problem including whether or not some of the birthrates are hugely over-estimated. We also consider a possible evolutionary scenario between some of the known neutron star classes which could solve this potential birthrate problem.

Key words: stars: neutron – pulsars: general – supernovae: general – Galaxy: stellar content

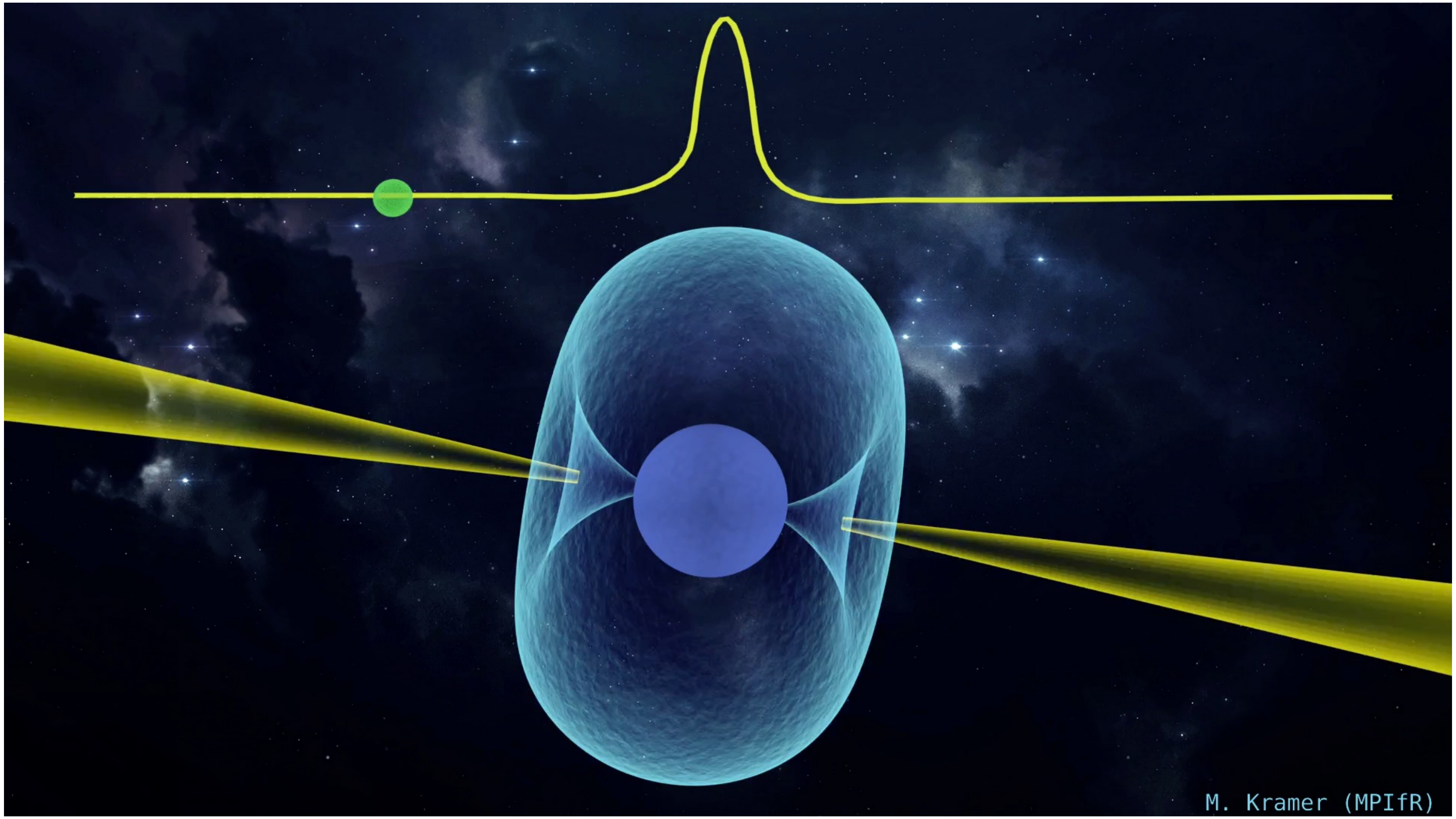
Keane & Kramer (2008)



"After reviewing the rates and population estimates we find that, if the estimates are in fact accurate, the current birthrate and population estimates are not consistent with the Galactic supernova rate."

The problem hasn't really gone away: evolutionary links or additional birth channel(s)?

Pulsar Timing Observations: cosmic lighthouses

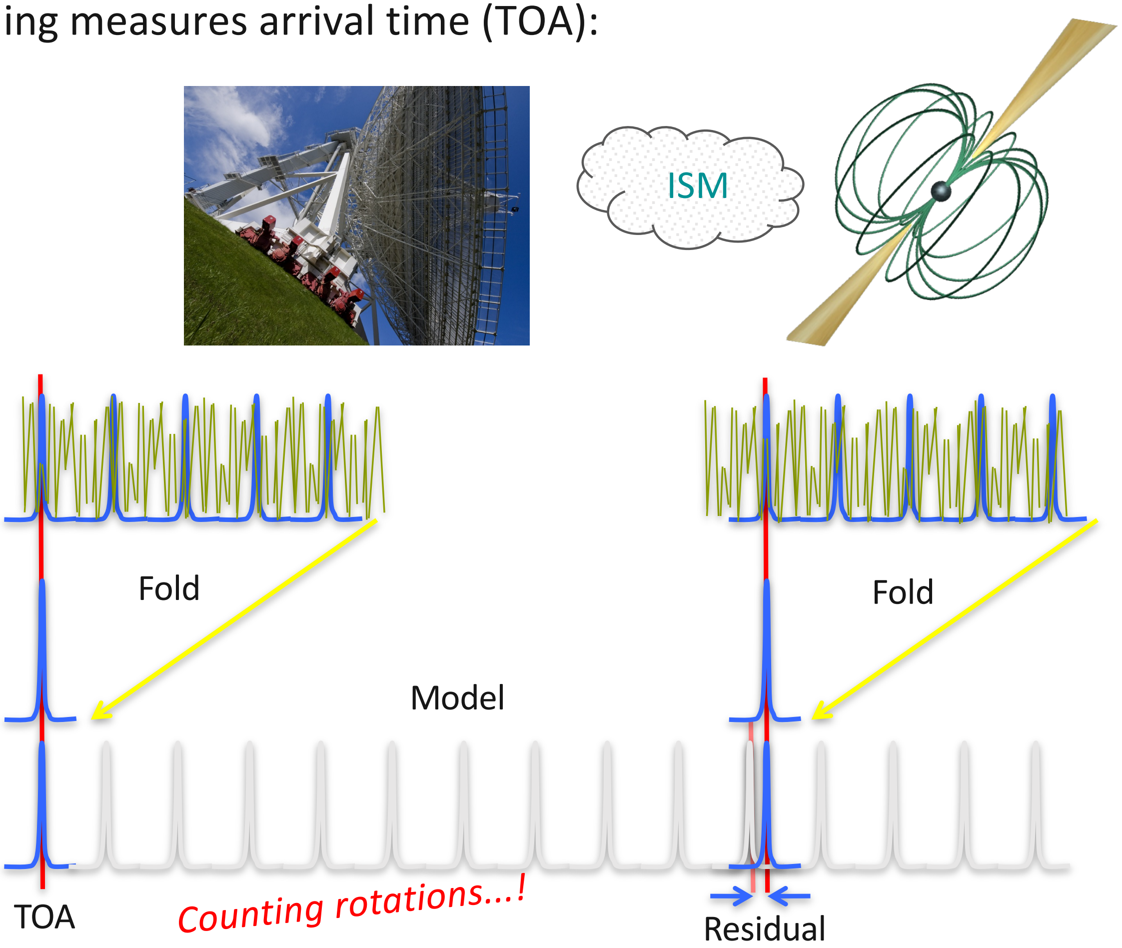


Pulsar Timing Observations: using pulsars as clocks

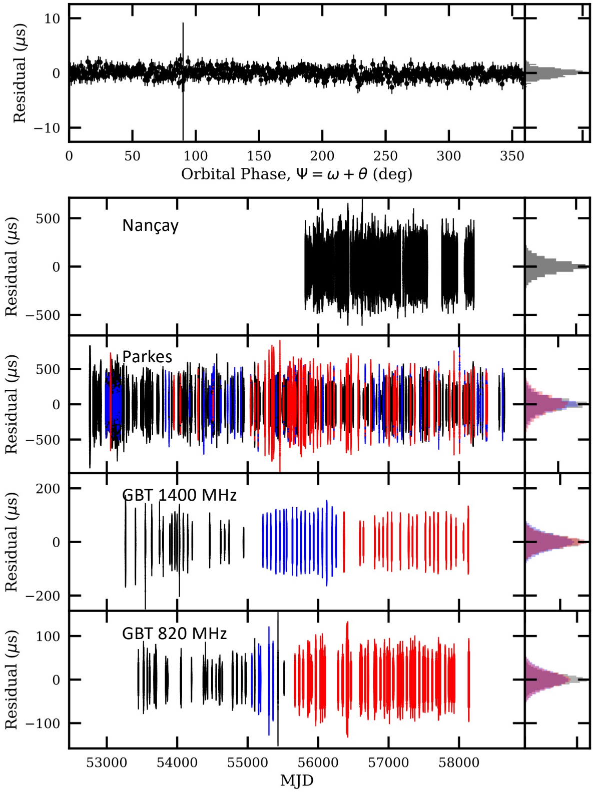
- We observe extreme and energetic processes and objects → Neutron stars & black holes
- We get lots of photons that are easy to copy and multiply → high precision
- We can build or synthesize huge telescopes → high (spatial) resolution
- We can probe the complete Universe, undisturbed from dust etc.→ see the Galactic Centre and more
- We can get polarization (magn. fields!) and dynamic information (pulses!) → clean experiments

Pulsar Timing Observations

Pulsar timing measures arrival time (TOA):



Example: Double Pulsar



Kramer et al. (2021)

Coherent timing solution about 1,000,000 more precise than Doppler method!

High precision measurements – What's possible today…

Spin parameters:

● Period:	2.947108069160717(3) ms	(Reardon et al. 2015) Note: 3 atto seconds uncertainty!

Orbital parameters:

● Period:	0.1022515592973(10) day	(Kramer et al. 2021)
● Projected semi-major axis:	424 214 903(27) m	(Kramer et al. 2021)
● Eccentricity:	0.087 777 023(61)	(Kramer et al. 2021)

Masses:

● Masses of neutron stars:	1.33819(2) / 1.24887(1) $M_\odot$	(Kramer et al. 2021)
● Mass of WD companion:	0.19730(4) $M_\odot$	(Archibald et al. 2018)
● Mass of millisecond pulsar:	1.4359(3) $M_\odot$	(Archibald et al. 2018)
● Mass of Ceres:	4.8(4) x 10^{-10} $M_\odot$	(Caballero et al. 2018)

Relativistic effects:

● Periastron advance:	16.89932(1) deg/yr	(Kramer et al. 2021)
● Einstein delay:	4.2992(8) ms	(Weisberg et al. 2010)
● Orbital GW damping:	7.152(1) mm/day	(Kramer et al. 2021)

Fundamental constants:

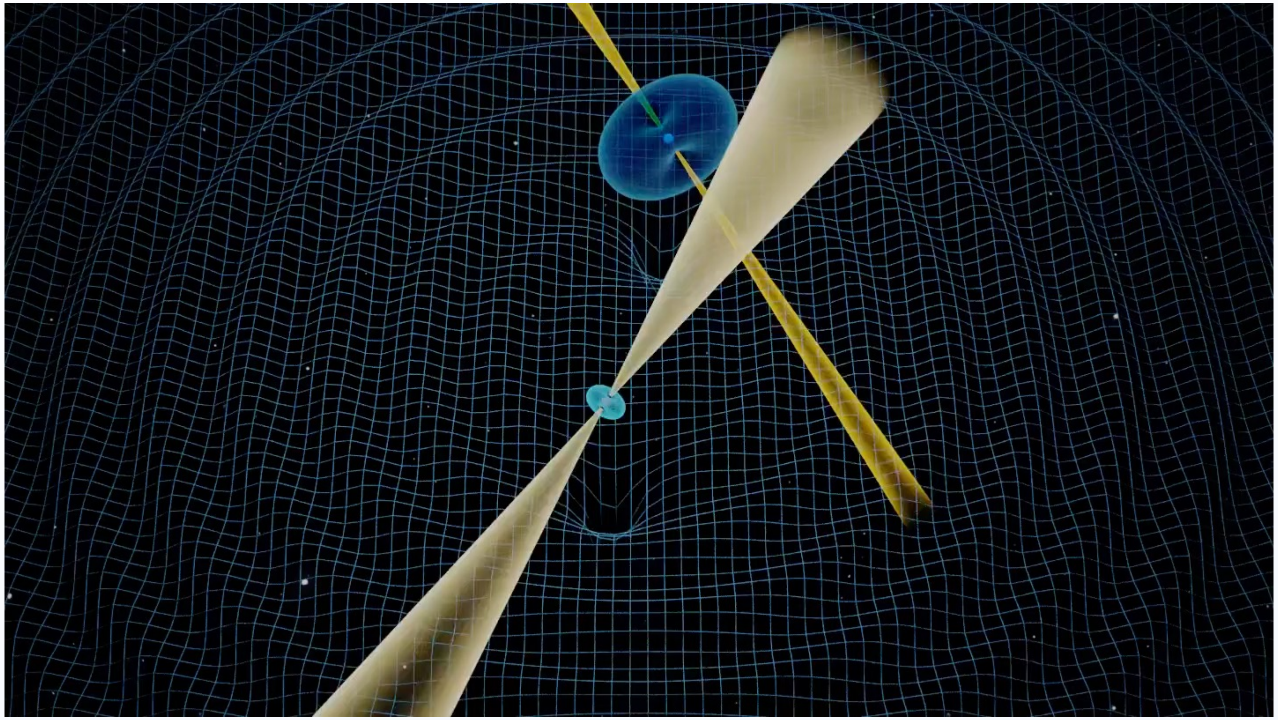
● Change in (dG/dt)/G:	$(-0.1 \pm 0.9) \times 10^{-12}\ \mathrm{yr}^{-1}$	(Zhu et al. 2018)

Gravitational wave detection:

● Change in relative distance:	30m / 1 lightyear	(EPTA, NANOGrav, PPTA)

The Double Pulsar (Burgay et al. 2003, Lyne et al. 2004)

- Mildly recycled 23-ms pulsar in a 147-min orbit with young 2.8-s pulsar - orbital velocities of 300 km/s
- Eclipsing binary in compact (3-lts), slightly eccentric (e=0.088) and edge-on orbit (tilt only 0.65 deg!)
- Ideal laboratory for gravitational physics with high precision (e.g. Rot. freq. = 44.05406864196281(17) Hz)



Relativistic effects measured:

- Orbital precession
- Time dilation
- Shapiro delay (incl. next-to-leading order)
- Aberrational light bending
- Spin precession
- Relativistic deformation of orbit
- GW emission

Plus theory-independent mass-ratio

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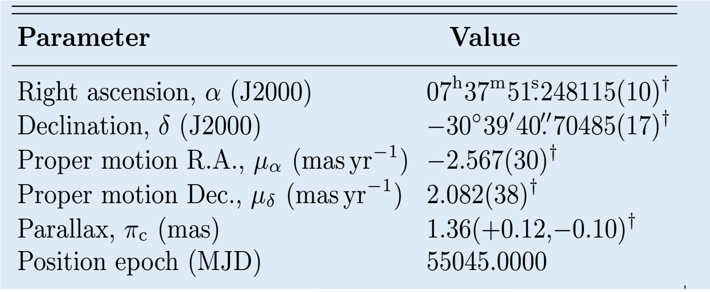
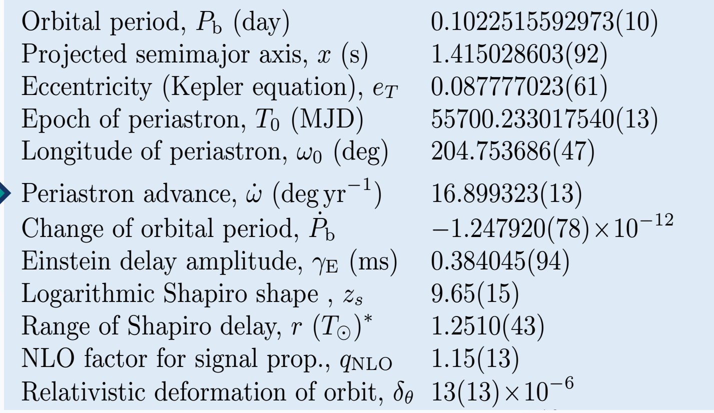
Most recent results:

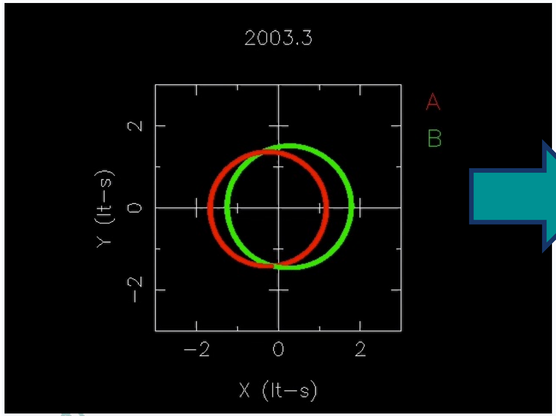
(Kramer et al 2021)



Parameter	Value
Right ascension, α (J2000)	$07^{\mathrm{h}}37^{\mathrm{m}}51\overset{\mathrm{s}}{.}248115(10)^{\dagger}$
Declination, δ (J2000)	$-30^{\circ}39'40\overset{\prime\prime}{.}70485(17)^{\dagger}$
Proper motion R.A., μ_{α} (mas yr^{-1})	$-2.567(30)^{\dagger}$
Proper motion Dec., μ_{δ} (mas yr^{-1})	$2.082(38)^{\dagger}$
Parallax, π_{c} (mas)	$1.36(+0.12,-0.10)^{\dagger}$
Position epoch (MJD)	55045.0000



Orbital period, P_{b} (day)	0.1022515592973(10)
Projected semimajor axis, x (s)	1.415028603(92)
Eccentricity (Kepler equation), e_T	0.087777023(61)
Epoch of periastron, T_0 (MJD)	55700.233017540(13)
Longitude of periastron, ω_0 (deg)	204.753686(47)
Periastron advance, $\dot{\omega}$ (deg yr^{-1})	16.899323(13)
Change of orbital period, $\dot{P}_{\mathrm{b}}$	$-1.247920(78)\times 10^{-12}$
Einstein delay amplitude, γ_{E} (ms)	0.384045(94)
Logarithmic Shapiro shape , z_s	9.65(15)
Range of Shapiro delay, r ($T_{\odot}$)*	1.2510(43)
NLO factor for signal prop., q_{NLO}	1.15(13)
Relativistic deformation of orbit, δ_{θ}	$13(13)\times 10^{-6}$



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- GW emission

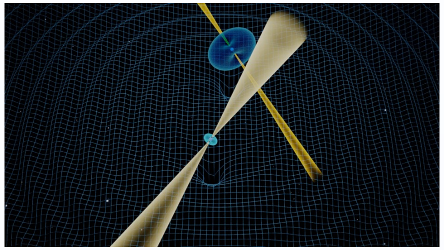
Plus theory-independent mass-ratio

Based on about 1 Million Times of Arrival measurements
“Average cadence” < 10 min

Gravitational wave emission

- Shrinkage of orbit due to GW emission:

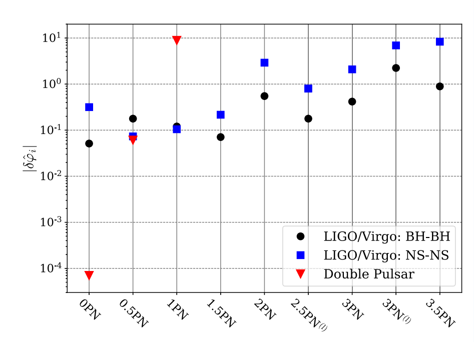
  $\Delta P_b = 107{,}820 \pm 7$ ps/day



- Pulsars approach each other by 7mm/day
- Merger in 85 M years
- Precision will still improve with time - and new telescopes

Most precise test of GR's quadrupole formula:

Kramer et al. (2021)



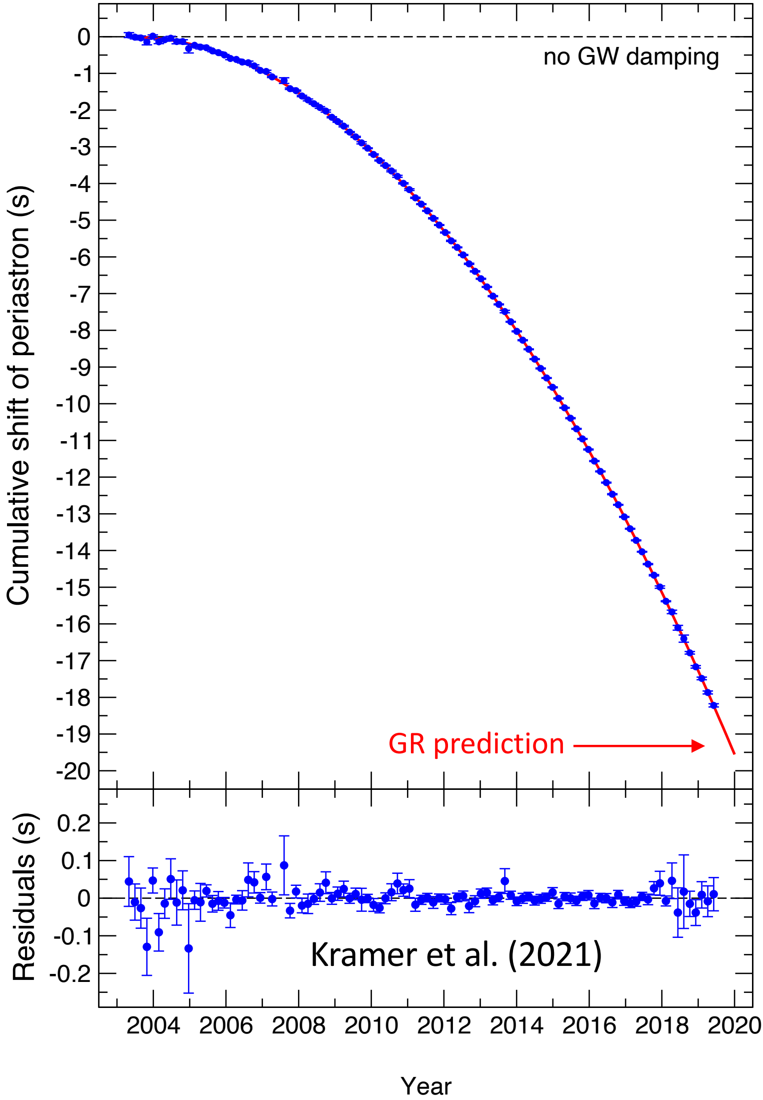
Observed/Expected = 0.99996 ±0.00006

validating at 1.3×10^{-4} (95% c.l.)

Precision is so high that we need to take mass loss due to rotational spin-down into account:

Pulsar loses rotational energy & $E = mc^2$,

i.e. 8.4 Million tons/second = 3.2×10^{-21} M_A per second



Kramer et al. (2021)

Post Keplerian (PK) - Parameters

- Theory-independent strong-field analogue of PPN formalism: "parametrized post-Keplerian" approach (Damour & Deruelle ’86, Damour & Taylor ’92)
- Theory independent, but given theory makes specific prediction for values as functions of Keplerian parameters and (a priori) unknown masses of pulsar and companion
- Simultaneous measurement of n PK parameters allows (n-2) independent tests of given theory

Post-Keplerian Parameters in GR (leading order)

Periastron advance

$$\dot{\omega} = 3T_\odot^{2/3}\left(\frac{P_b}{2\pi}\right)^{-5/3}\frac{(m_p+m_c)^{2/3}}{1-e}$$

Gravitational wave damping

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

Time dilation

$$\gamma = T_\odot^{2/3}\left(\frac{P_b}{2\pi}\right)^{1/3} e\,\frac{m_c(m_p+2m_c)}{(m_p+m_c)^{4/3}}$$

Shapiro delay (range, shape)

$$r = T_\odot m_c \qquad s = T_\odot^{-1/3}\left(\frac{P_b}{2\pi}\right)^{-2/3} x\,\frac{(m_p+m_c)^{2/3}}{m_c}$$

where $T_\odot = GM_\odot/c^3 \simeq 4.92549\,\mu s$

Total system mass (in GR)

Periastron advance

$$\dot{\omega} = 3T_\odot^{2/3}\left(\frac{P_b}{2\pi}\right)^{-5/3}\frac{(m_p+m_c)^{2/3}}{1-e}$$

Companion mass (in GR)

Shapiro delay (range, shape)

$$r = T_\odot m_c \qquad s = T_\odot^{-1/3}\left(\frac{P_b}{2\pi}\right)^{-2/3} x\,\frac{(m_p+m_c)^{2/3}}{m_c}$$

Post Keplerian (PK) - Parameters

- Theory-independent strong-field analogue of PPN formalism: "parametrized post-Keplerian" approach (Damour & Deruelle ’86, Damour & Taylor ’92)
- Theory independent, but given theory makes specific prediction for values as functions of Keplerian parameters and (a priori) unknown masses of pulsar and companion
- Simultaneous measurement of n PK parameters allows (n-2) independent tests of given theory

Post-Keplerian Parameters in GR (leading order)

Periastron advance

$$\dot{\omega} = 3T_\odot^{2/3} \left(\frac{P_b}{2\pi}\right)^{-5/3} \frac{(m_p + m_c)^{2/3}}{1-e}$$

Gravitational wave damping

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

Time dilation

$$\gamma = T_\odot^{2/3} \left(\frac{P_b}{2\pi}\right)^{1/3} e \frac{m_c(m_p + 2m_c)}{(m_p + m_c)^{4/3}}$$

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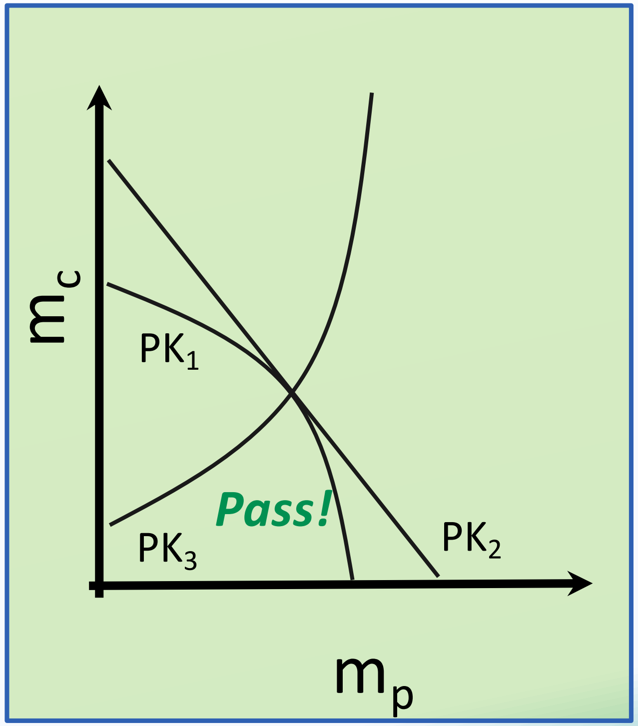
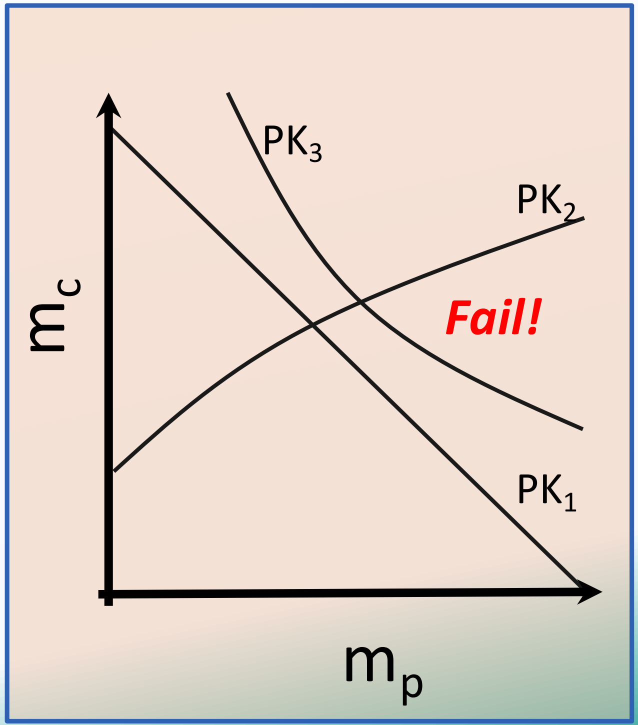
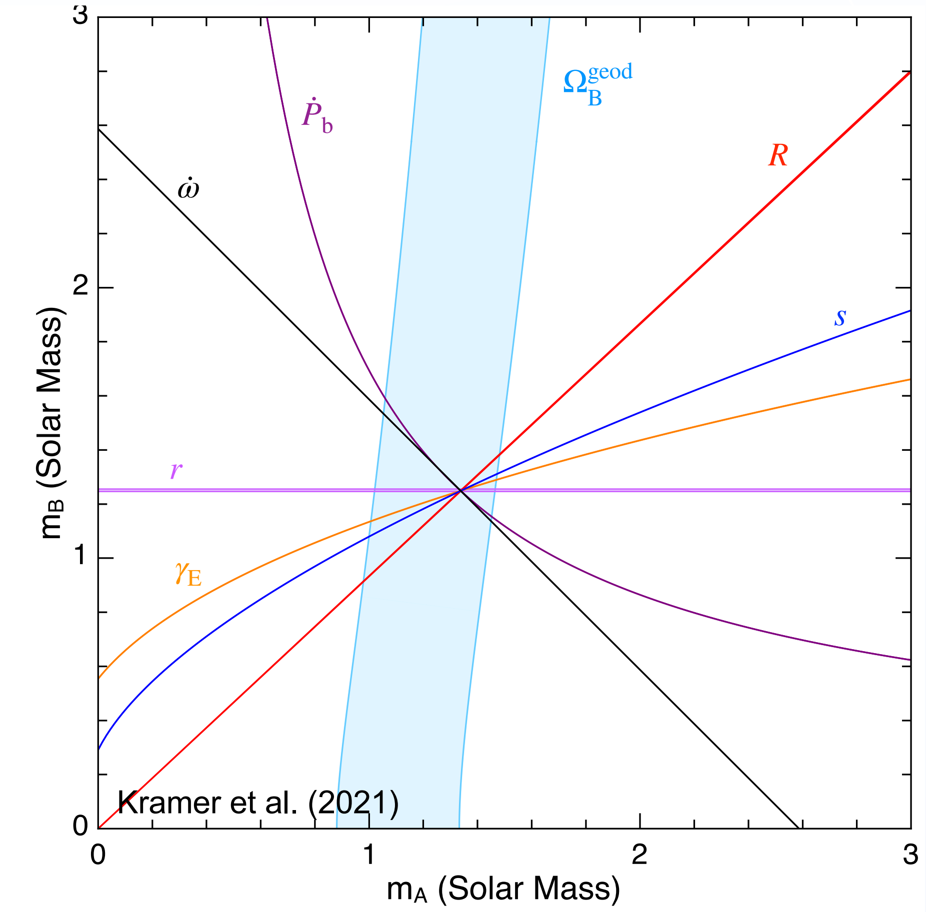
where $T_\odot = GM_\odot / c^3 \simeq 4.92549\,\mu s$





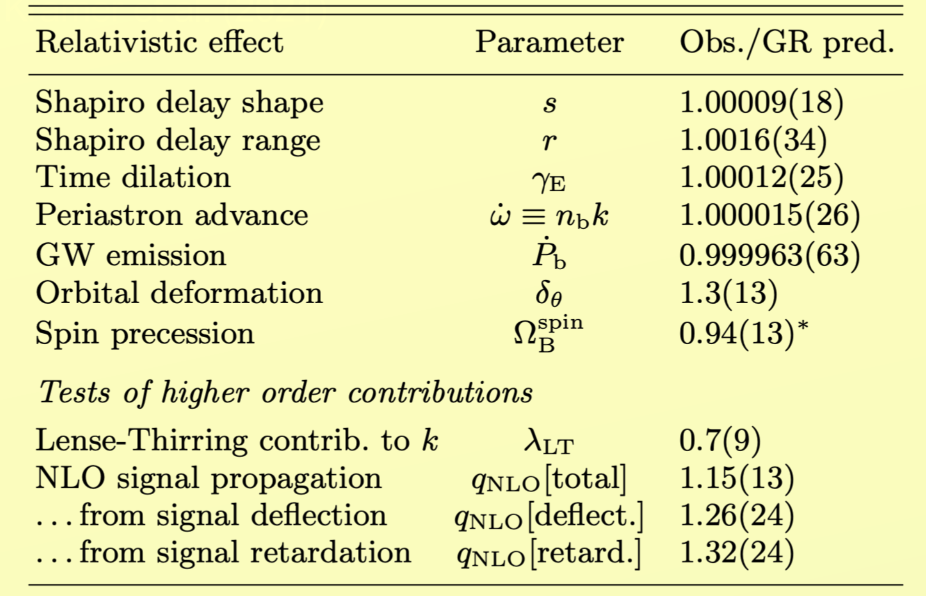
Masses via relativistic effects

Mass-mass diagram:



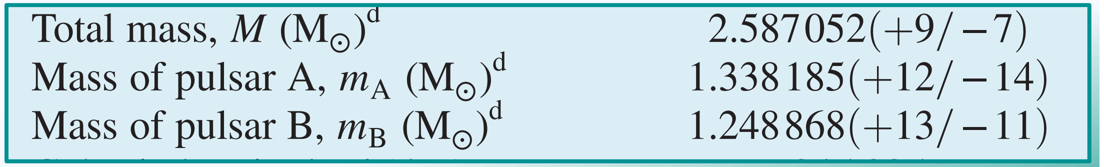
Kramer et al. (2021)

Kramer et al. (2021)



Relativistic effect	Parameter	Obs./GR pred.
Shapiro delay shape	s	1.00009(18)
Shapiro delay range	r	1.0016(34)
Time dilation	γ_E	1.00012(25)
Periastron advance	$\dot{\omega} \equiv n_\mathrm{b} k$	1.000015(26)
GW emission	$\dot{P}_\mathrm{b}$	0.999963(63)
Orbital deformation	δ_θ	1.3(13)
Spin precession	$\Omega_\mathrm{B}^\mathrm{spin}$	0.94(13)*
Tests of higher order contributions		
Lense-Thirring contrib. to k	λ_LT	0.7(9)
NLO signal propagation	q_NLO[total]	1.15(13)
. . . from signal deflection	q_NLO[deflect.]	1.26(24)
. . . from signal retardation	q_NLO[retard.]	1.32(24)

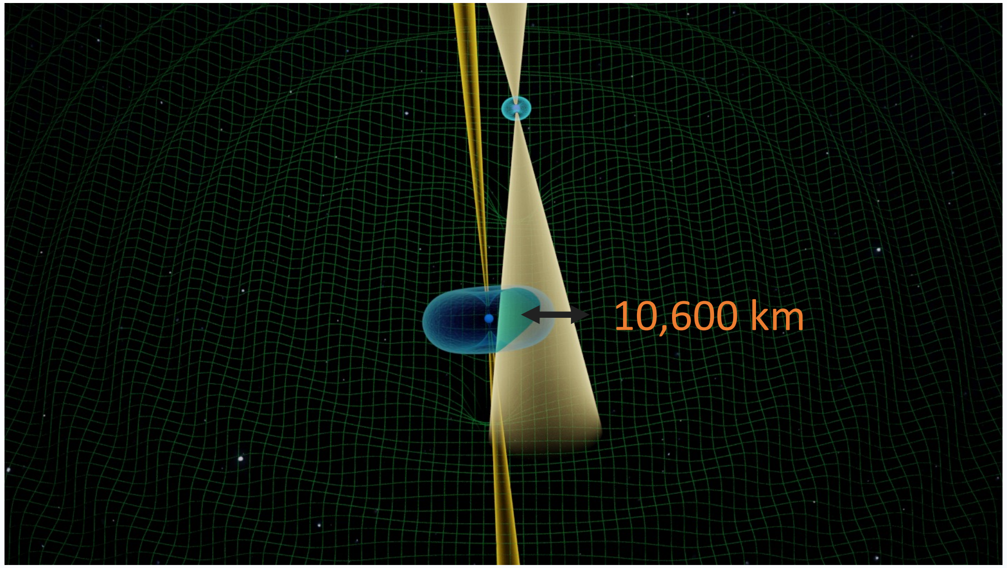
- 7 Post-Keplerian parameters
- Next-to-leading order in signal propagation
- Most precise strong-field test of GR
- MeerKAT improves timing by factor 2-3!

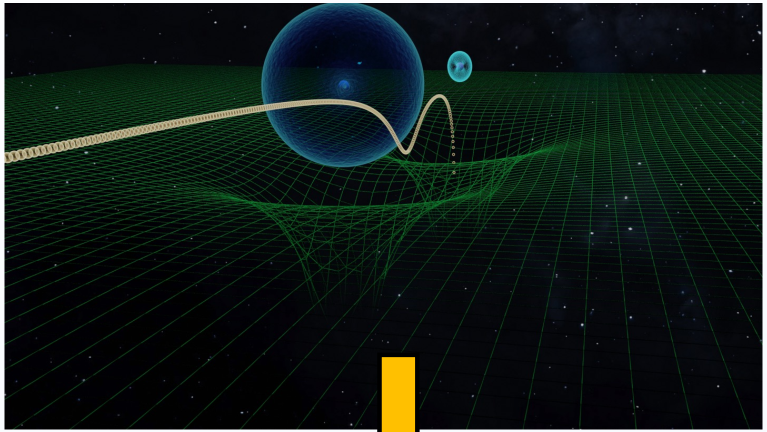


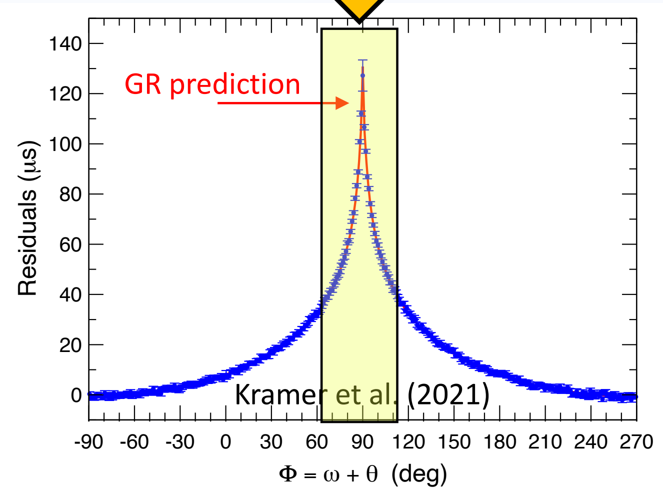
Total mass, M $(\mathrm{M}_\odot)^\mathrm{d}$	2.587052(+9/−7)
Mass of pulsar A, m_A $(\mathrm{M}_\odot)^\mathrm{d}$	1.338185(+12/−14)
Mass of pulsar B, m_B $(\mathrm{M}_\odot)^\mathrm{d}$	1.248868(+13/−11)

Light-propagation in strong gravitational fields: Shapiro Delay

Shapiro delay in edge-on orbit: $s = \sin i = 0.99994 \pm 0.00001$ - Orbital inclination angle: I = 89.35(5) deg



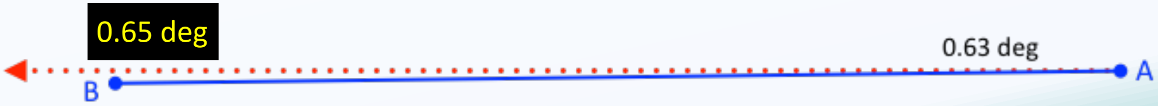




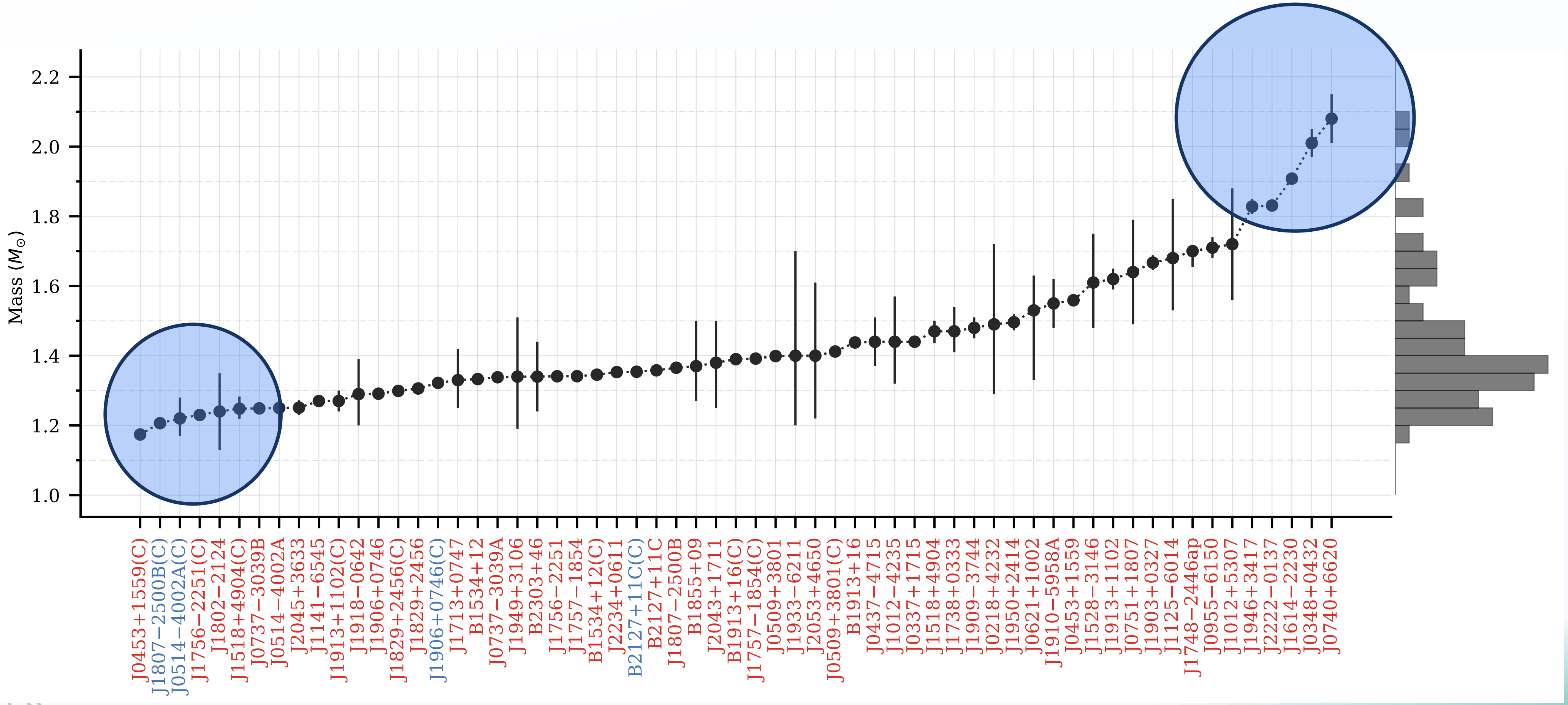
Two tests of GR:

"Shape" Obs./Exp. = 1.00009(18)

"Range" Obs./Exp. = 1.0016(34)

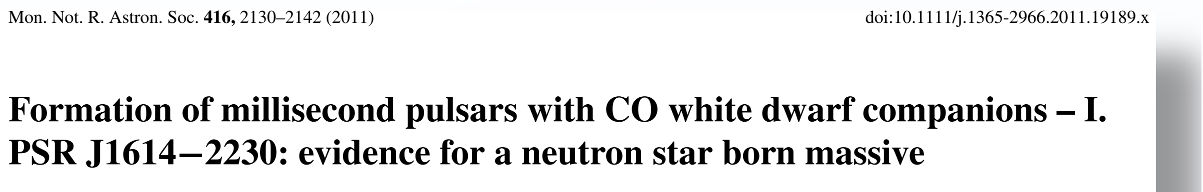


Precision mass measurements



https://www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html

Constraints on the EOS



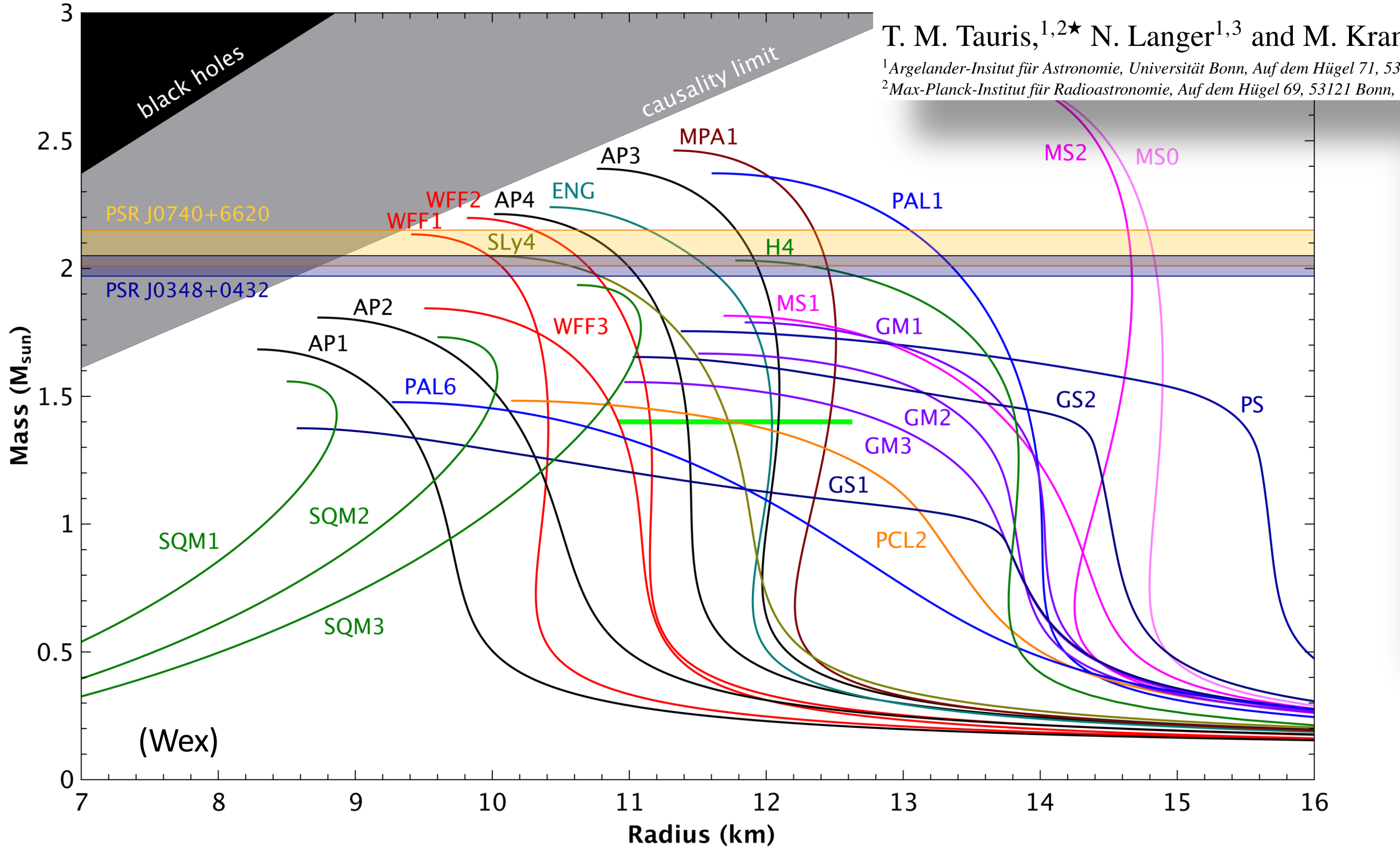
Mon. Not. R. Astron. Soc. **416,** 2130–2142 (2011) doi:10.1111/j.1365-2966.2011.19189.x

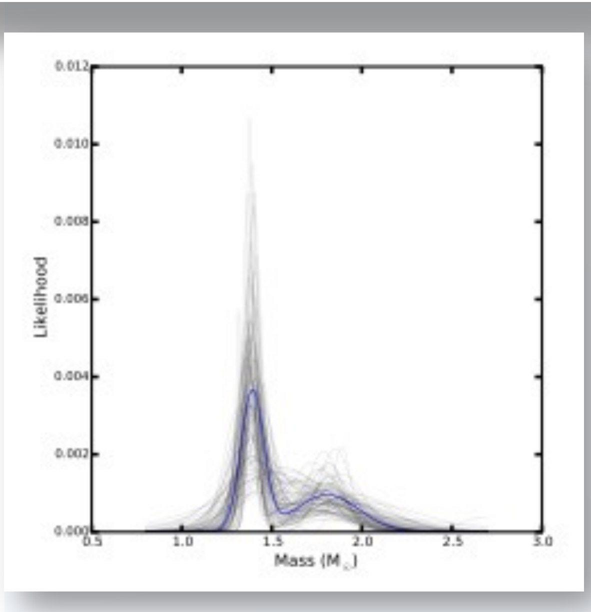
Formation of millisecond pulsars with CO white dwarf companions – I. PSR J1614−2230: evidence for a neutron star born massive

T. M. Tauris,[1,2★] N. Langer[1,3] and M. Kramer[2,4]

[1] *Argelander-Institut für Astronomie, Universität Bonn, Auf dem Hügel 71, 53121 Bonn, Germany*

[2] *Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany*





Best description by bi-modal distribution??

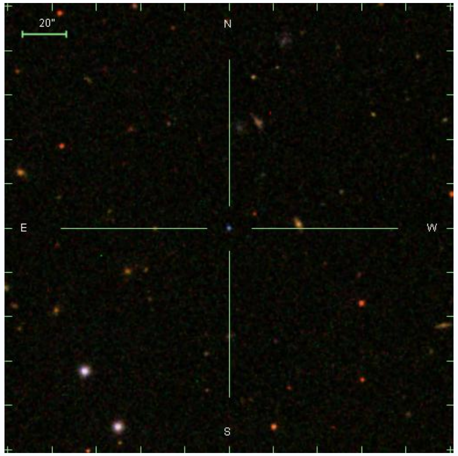
See Antoniadis et al. (2016)

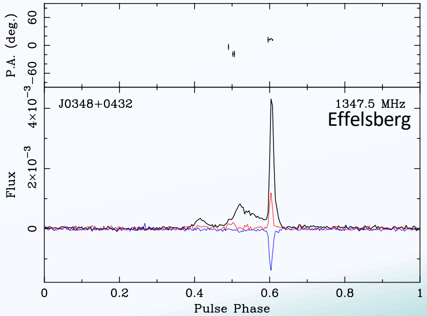
Results of phase transitions?

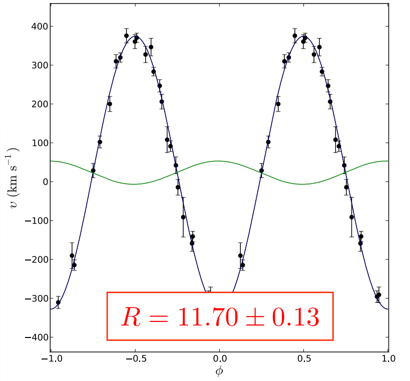
A different way to measure masses

- PSR J0348+0432 has been the first massive NS in relativistic orbit (Lynch et al. 2013) but mass measurement could be achieved via a different method
- Combining VLT, Effelsberg, Arecibo & GBT data, record mass: M=2.01±0.04 $M_\odot$ (Antoniadis et al., 2013)

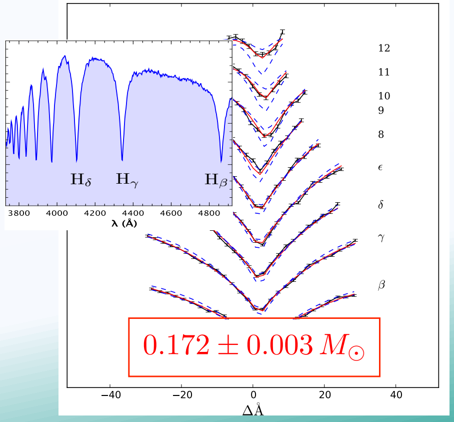
$$\begin{aligned} P &= 39.1226569017806(5)\,\mathrm{ms} \\ P_\mathrm{b} &= 2.45817750533(2)\,\mathrm{h} \\ e &\lesssim 10^{-6} \end{aligned}$$





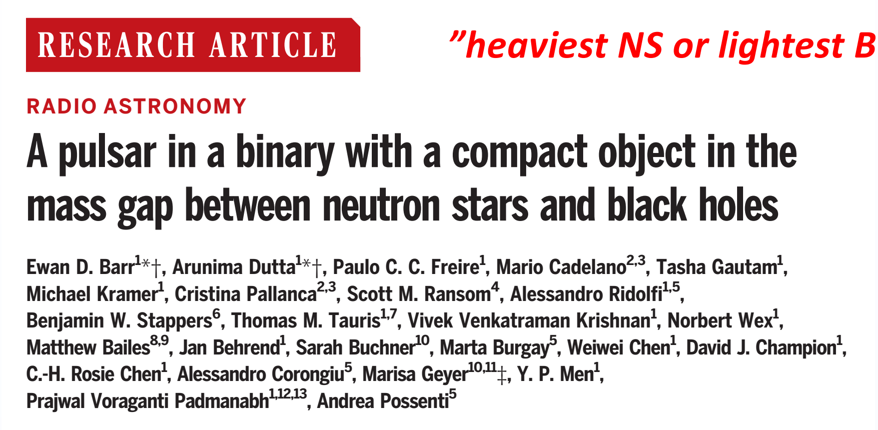


$R = 11.70 \pm 0.13$



$0.172 \pm 0.003\ M_\odot$

This could be the record holder...



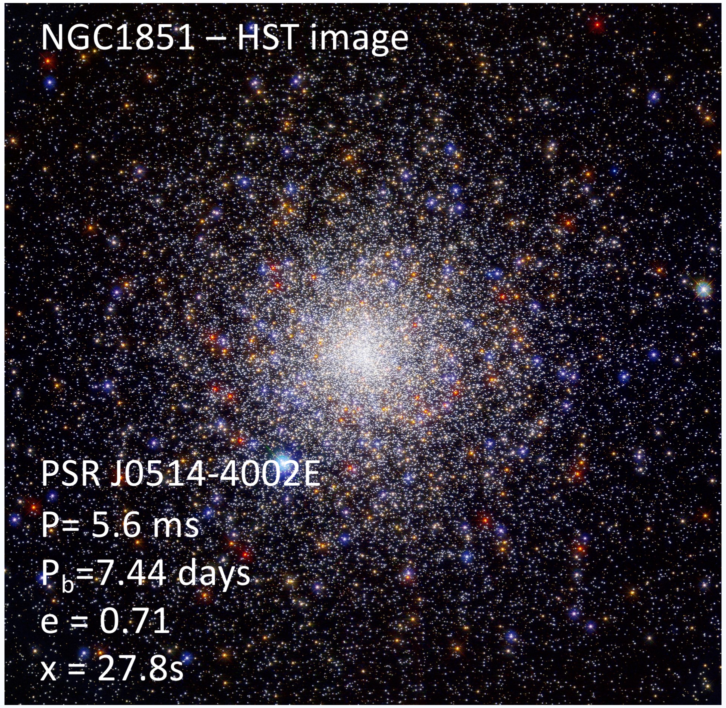
RESEARCH ARTICLE

RADIO ASTRONOMY

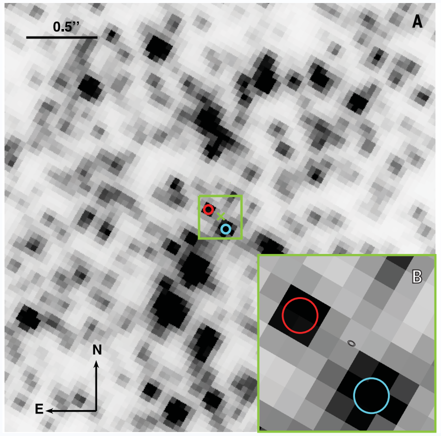
A pulsar in a binary with a compact object in the mass gap between neutron stars and black holes

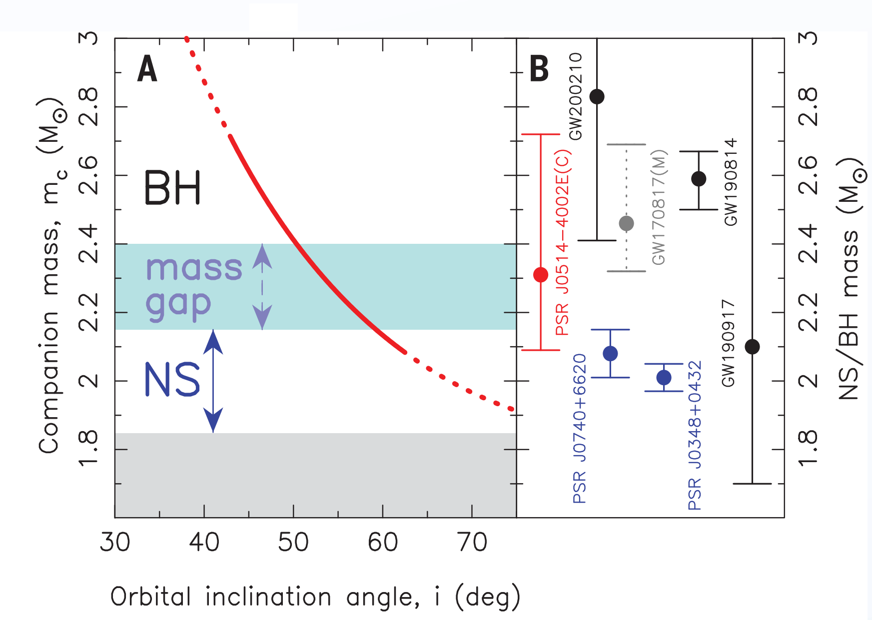
Ewan D. Barr[1]*†, Arunima Dutta[1]*†, Paulo C. C. Freire[1], Mario Cadelano[2,3], Tasha Gautam[1], Michael Kramer[1], Cristina Pallanca[2,3], Scott M. Ransom[4], Alessandro Ridolfi[1,5], Benjamin W. Stappers[6], Thomas M. Tauris[1,7], Vivek Venkatraman Krishnan[1], Norbert Wex[1], Matthew Bailes[8,9], Jan Behrend[1], Sarah Buchner[10], Marta Burgay[5], Weiwei Chen[1], David J. Champion[1], C.-H. Rosie Chen[1], Alessandro Corongiu[5], Marisa Geyer[10,11]‡, Y. P. Men[1], Prajwal Voraganti Padmanabh[1,12,13], Andrea Possenti[5]

"heaviest NS or lightest BH?"



PSR J0514-4002E
P= 5.6 ms
P_b=7.44 days
e = 0.71
x = 27.8s





m_p = 1.53 (2) $M_\odot$
m_c = 2.35 (2) $M_\odot$
i = 52 (6) deg

$$f(m_p, m_c) \equiv \frac{(m_c \sin i)^3}{(m_p + m_c)^2} =$$

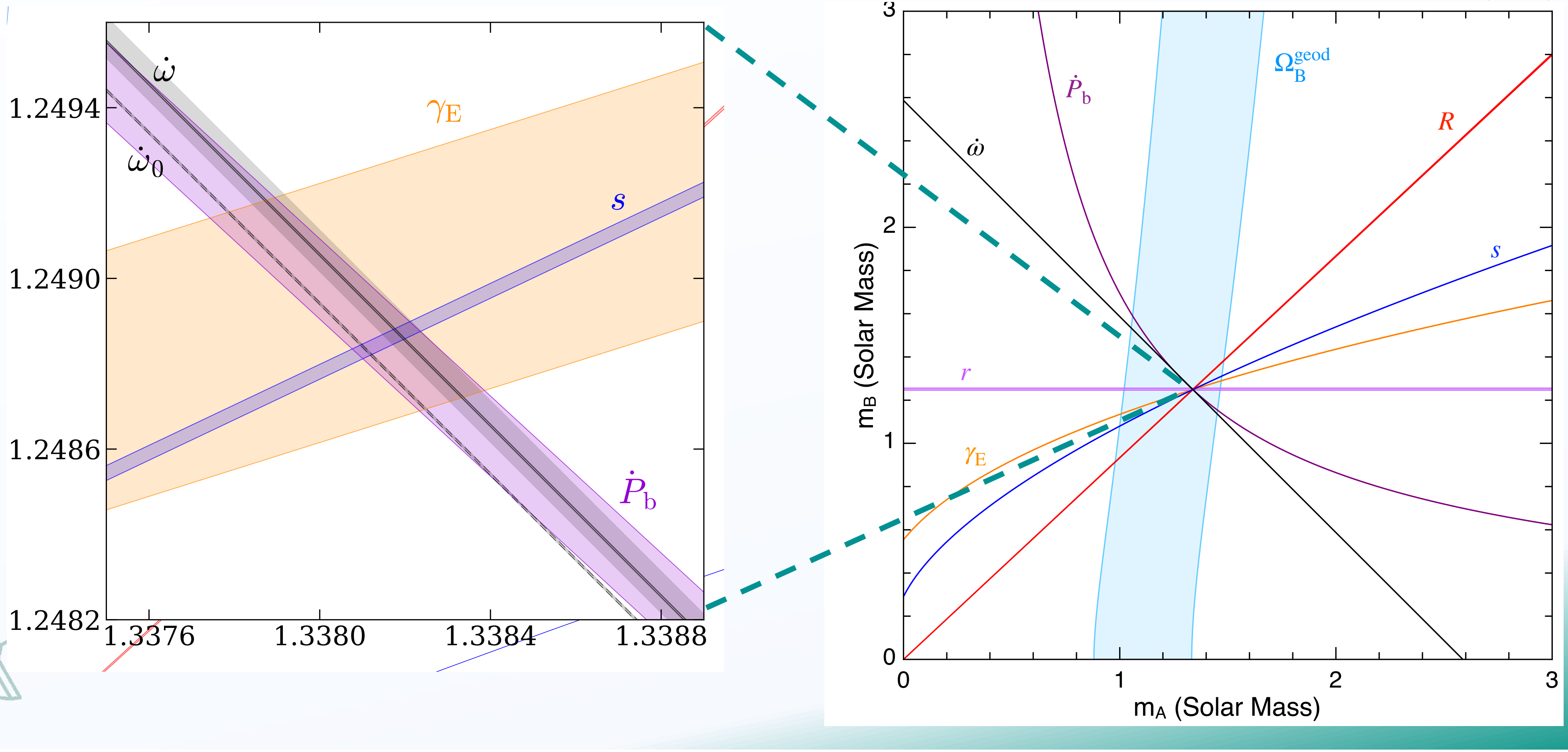
$$4\pi^2 \frac{c^3}{G}\frac{x^3}{{P_b}^2} = 0.41672 \pm 0.00022\ M_\odot$$

Fom orbital precession: total mass
M_{tot} = 3.8870 ± 0.0045 $M_\odot$

Constraints on Shapiro & Einstein

Lense-Thirring as means to determine Moment-of-Inertia

Mass-mass diagram:

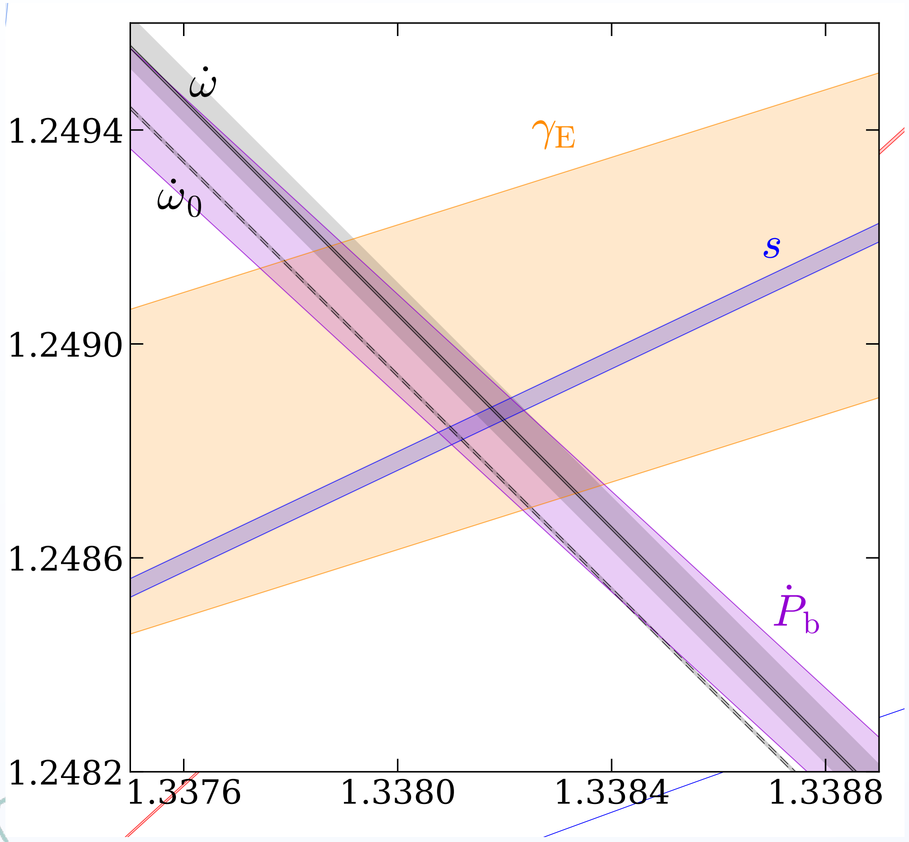


Kramer et al. (2021)

Lense-Thirring as means to determine Moment-of-Inertia

Mass-mass diagram:

Kramer et al. (2021)



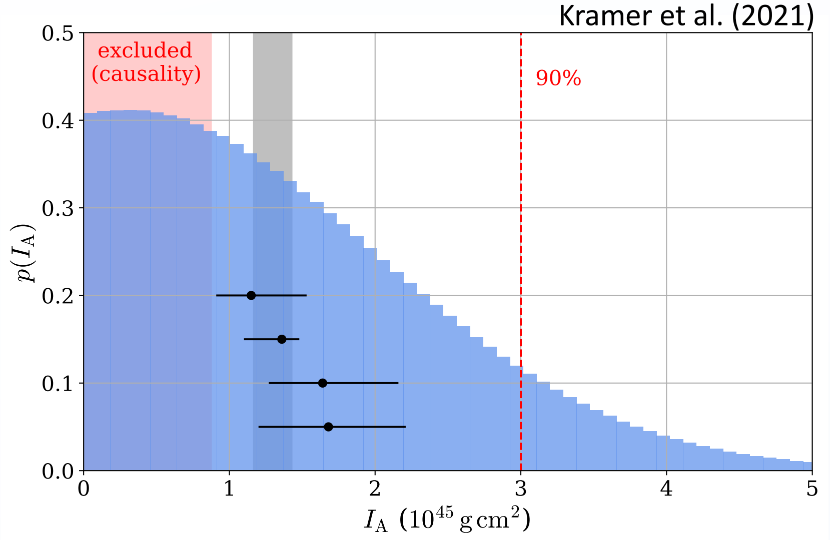
$$\dot{\omega} = \dot{\omega}^{\rm 1PN} + \dot{\omega}^{\rm 2PN} + \dot{\omega}^{\rm LT,A}$$

= 16.899323(13) deg/yr

Whereas: $\dot{\omega}^{\rm LT,A} \simeq -3.77 \times 10^{-4} \times I_{\rm A}^{(45)} \, {\rm deg\,yr}^{-1}$

Moment of inertia

Lense-Thirring as means to determine Moment-of-Inertia

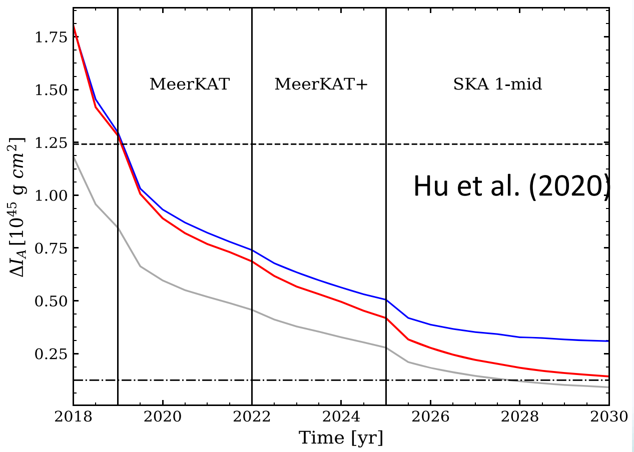

Kramer et al. (2021)

limit on R_A is < 22 km at 90% confidence.

$$\dot\omega = \dot\omega^{1\mathrm{PN}} + \dot\omega^{2\mathrm{PN}} + \dot\omega^{\mathrm{LT,A}}$$

= 16.899323(13) deg/yr

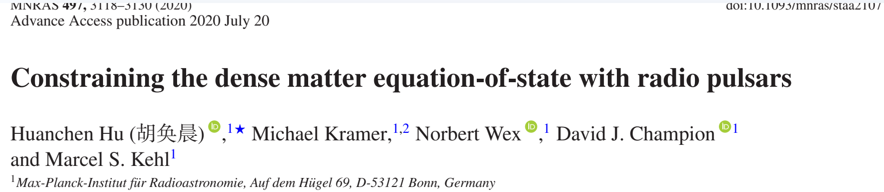
This will improve with time!



Whereas:

$$\dot\omega^{\mathrm{LT,A}} \simeq -3.77 \times 10^{-4} \times I_A^{(45)}\ \mathrm{deg\,yr^{-1}}$$

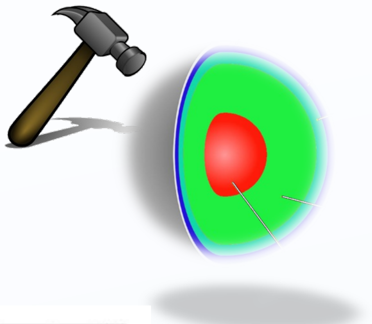
Moment of inertia


MNRAS 497, 3118–3130 (2020) doi:10.1093/mnras/staa2107
Advance Access publication 2020 July 20

Constraining the dense matter equation-of-state with radio pulsars

Huanchen Hu (胡奂晨)[1★], Michael Kramer,[1,2] Norbert Wex,[1] David J. Champion[1]
and Marcel S. Kehl[1]
[1] *Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany*
[2] *Jodrell Bank Centre for Astrophysics, The University of Manchester, Oxford Road, Manchester M13 9PL, UK*

Interior of neutron stars from glitches



Constraints on structure come from rotational glitches of pulsars:

Example: Vela

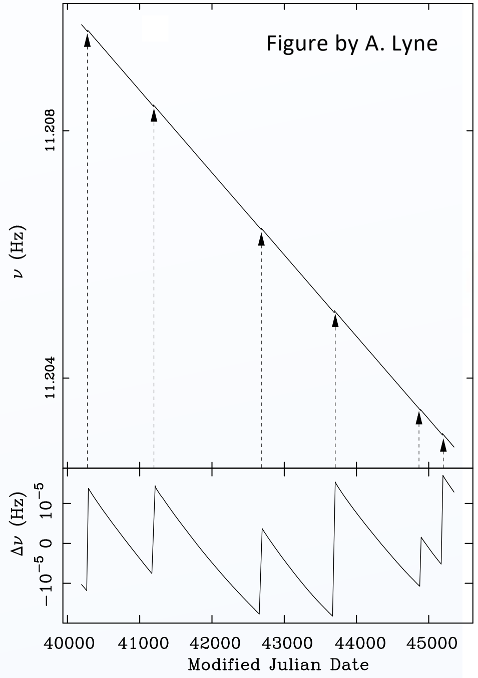
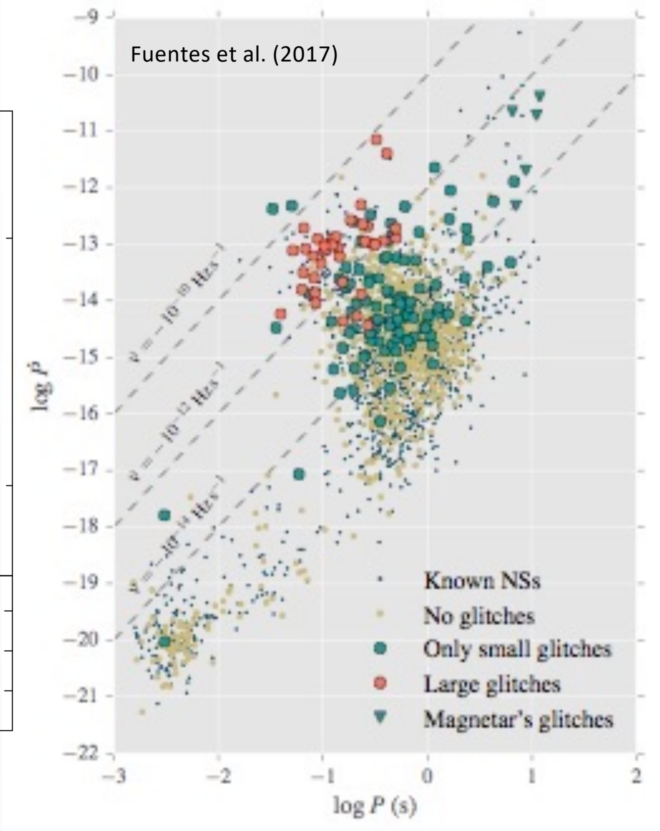
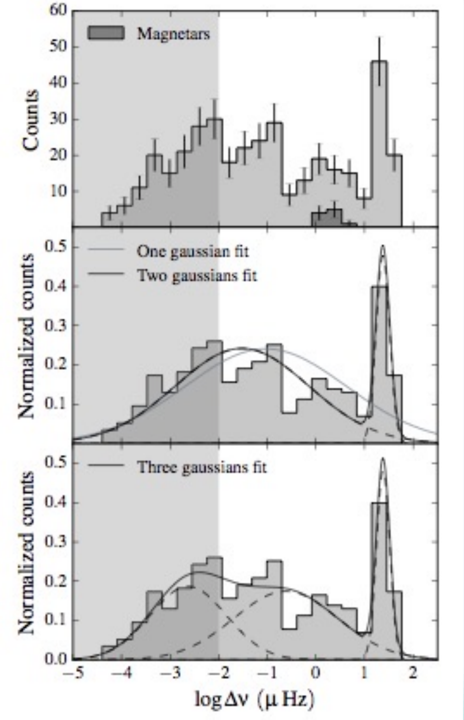


Figure by A. Lyne



Fuentes et al. (2017)

Fuentes et al. (2017)

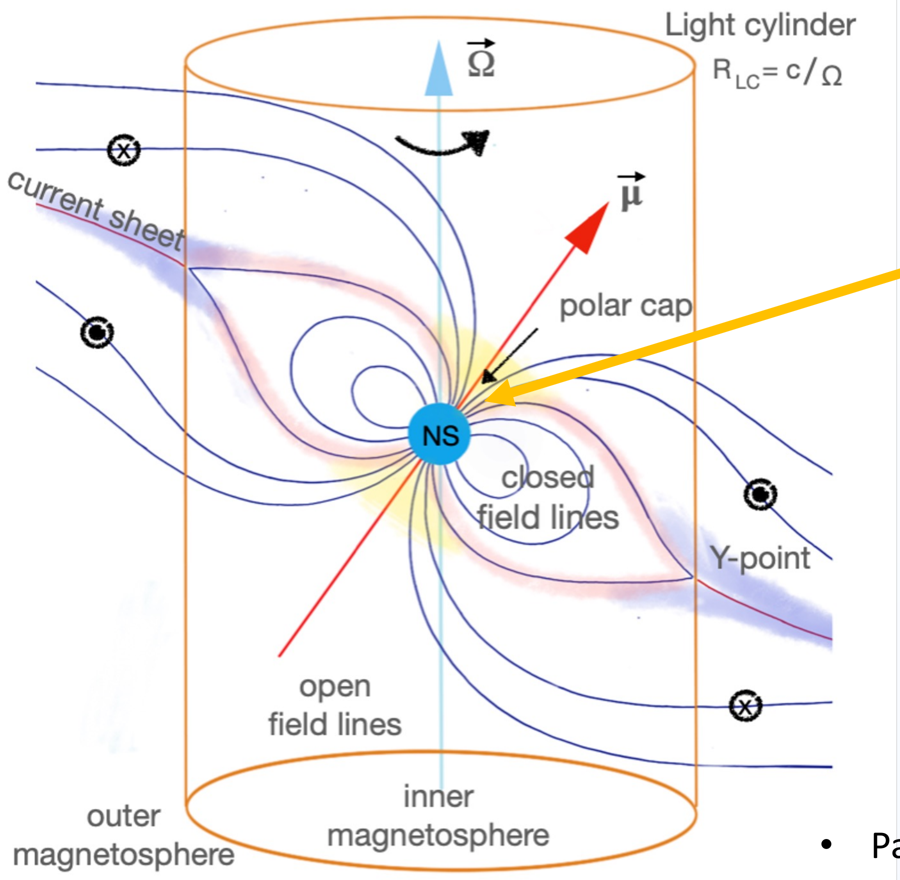


- Generally consistent with rearrangement of superfluid interior – one can try to relate this to MoI...
- See major update by Basu et al. (2022) with 106 new glitches – similar conclusions.

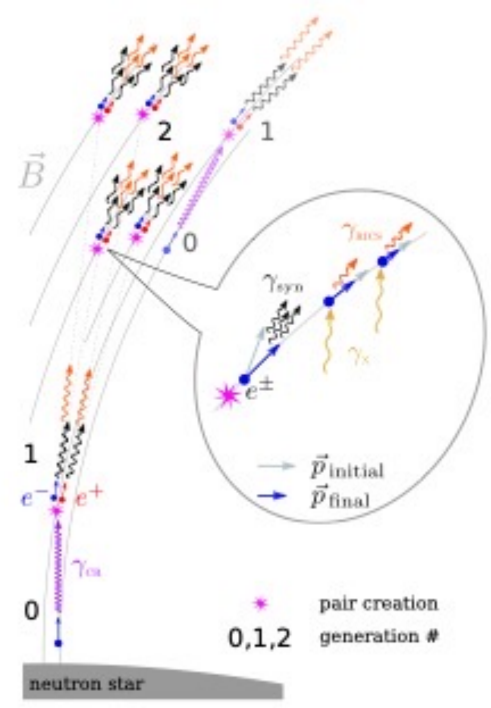
Information from Radio Observations

- From pulsar timing:
  - measuring pulse arrival times and tracking the rotation of the neutron star with high precision
- From emission properties:
  - full polarisation measurements from 10s MHz to 100s GHz
  - high time resolution up to nanosecond timescales
  - long-term monitoring lasting half a century (>10^9 rotations)
- From simultaneous multi-messenger observations
- From particularly interesting pulsars vs bulk properties

The radio emission of pulsars



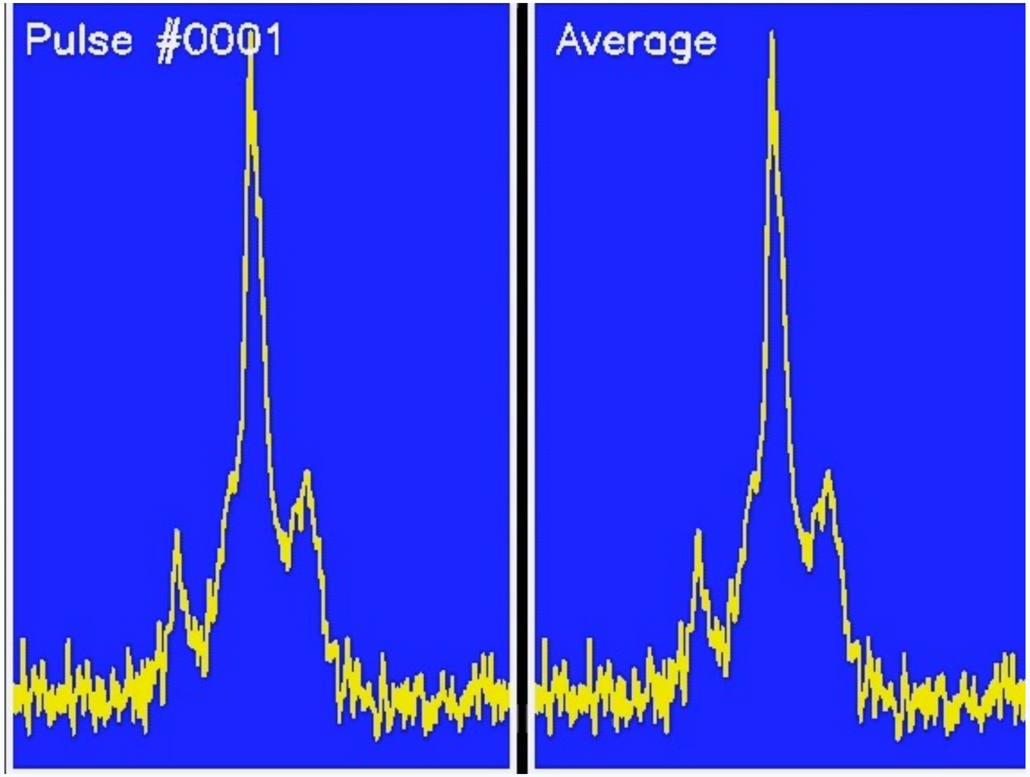
Philippov & Kramer (2022)



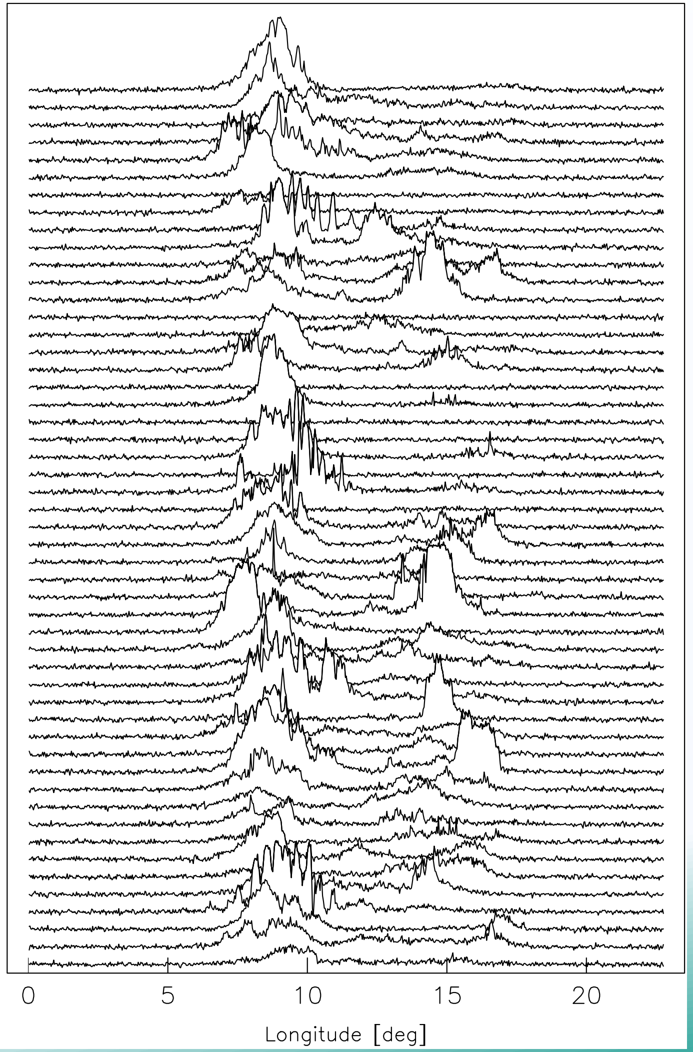
Timokhin & Harding (2019)

- Pair production above polar cap is needed for radio emission
- Initial charges available from gaseous atmosphere
- Can radio emission can tell us about the NS surface?

Pulsar emission weather and climate



Kramer

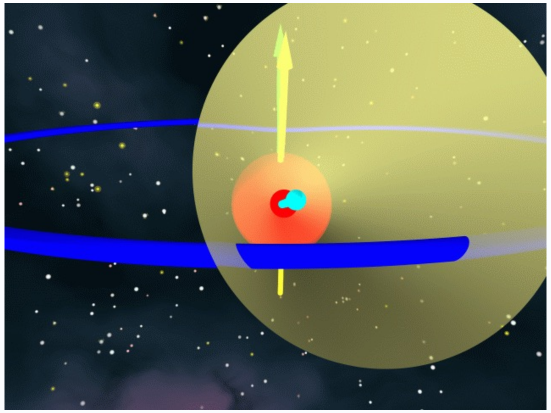


Philippov & Kramer (2022)

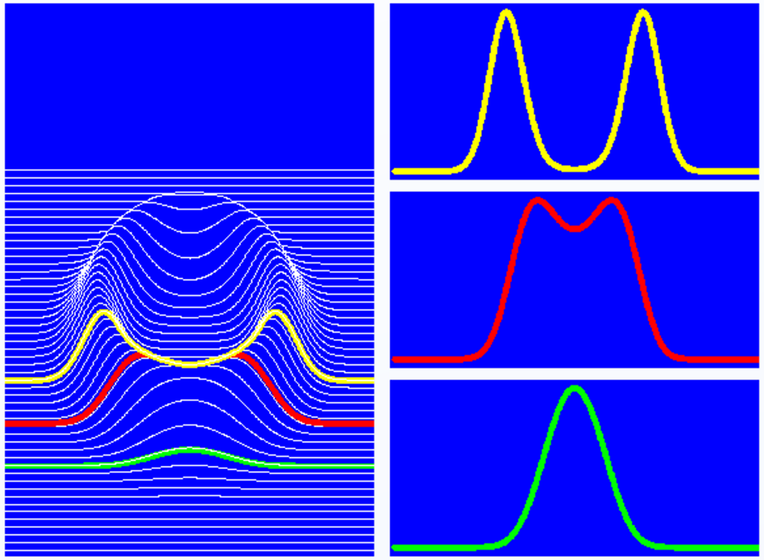
Higher time resolution can reveal “microstructure” – more later!

Average pulse shape models

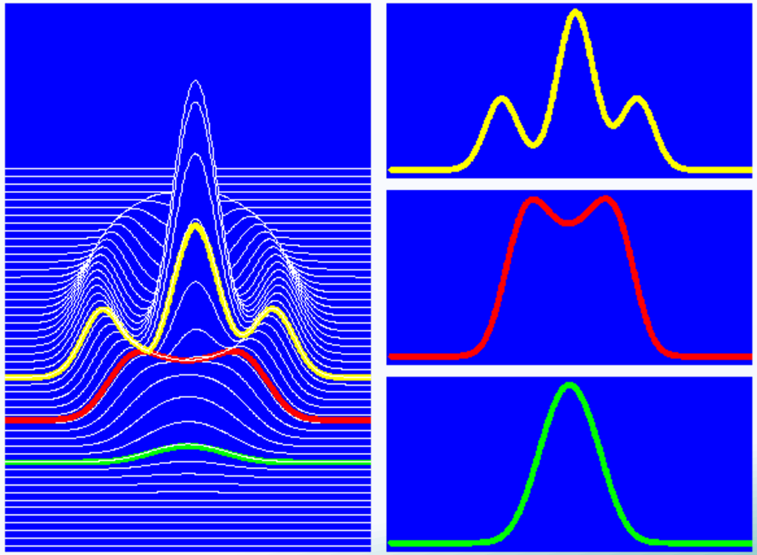
Observed pulse determined by 1-d cut through non-uniform 3D beam:



Simple phenomenological models in the past – but are they real?



“Cones”



“Cores”

REPORT

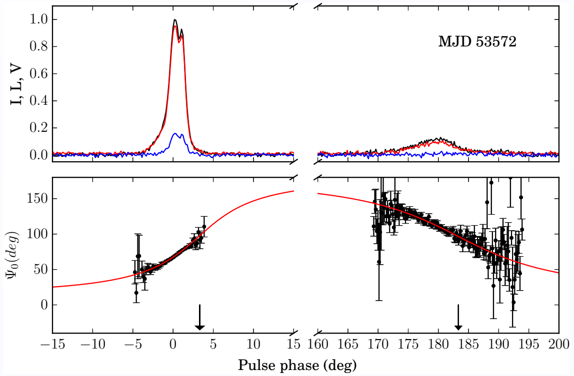
RADIO ASTRONOMY

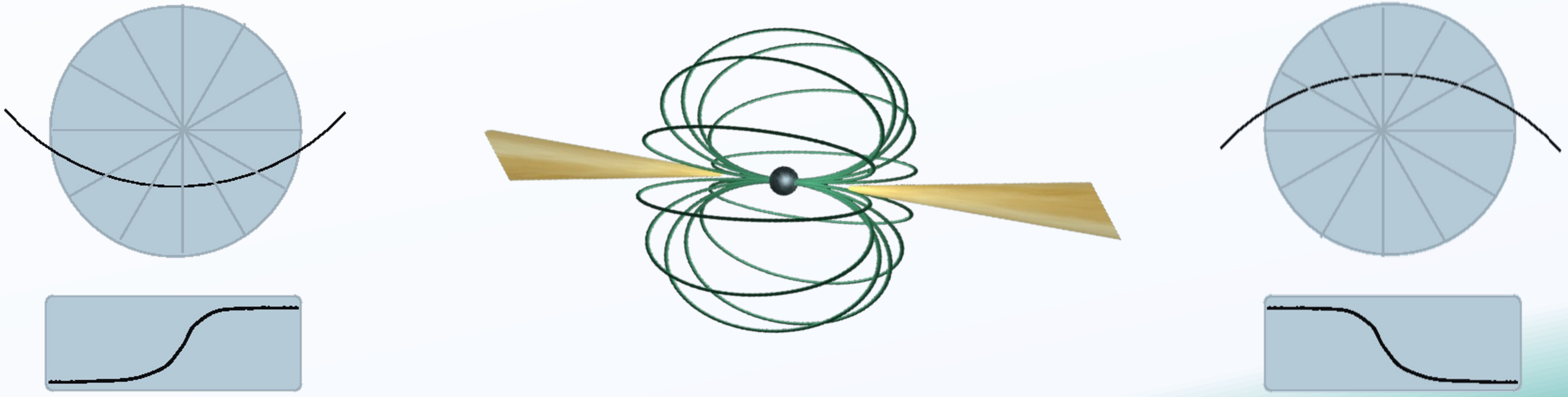
Radio emission from a pulsar's magnetic pole revealed by general relativity

Gregory Desvignes[1,2]*, Michael Kramer[1,3], Kejia Lee[4], Joeri van Leeuwen[5,6],
Ingrid Stairs[7], Axel Jessner[1], Ismaël Cognard[8,9], Laura Kasian[7],
Andrew Lyne[3], Ben W. Stappers[3]

Pulsar beam tomography: 1D ➔ 2D

Relativistic binary PSR J1906+0746 (Desvignes, et al. 2019):
- Relativistic spin-precession moves our line-of-sight through the beam
- Precise geometry and test of general relativity
- Our line-of-sight has crossed the pole of interpulse!
- Tomography of a pulsar beam
- North- and South poles are different
- Asymmetric and inhomogeneous beams





Desvignes

REPORT

RADIO ASTRONOMY

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Pulsar beam tomography: 1D → 2D

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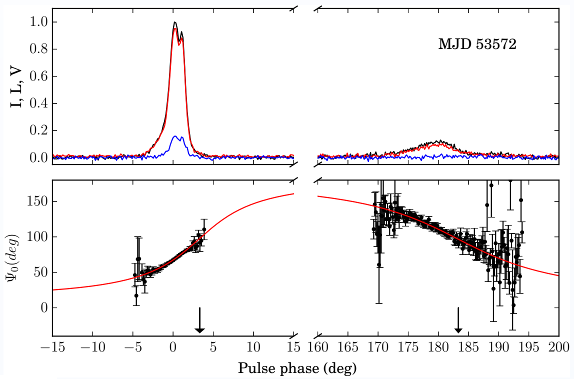
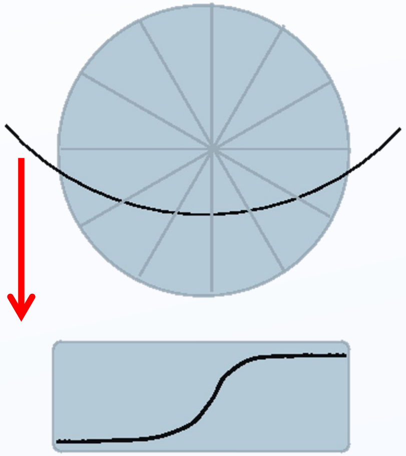
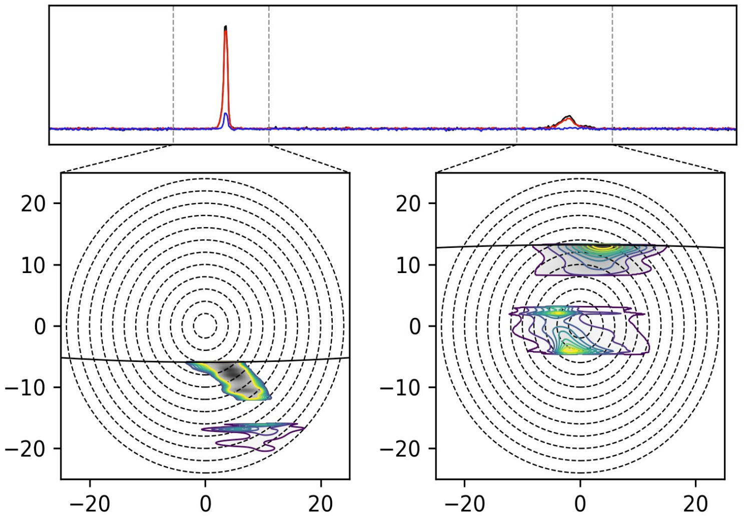
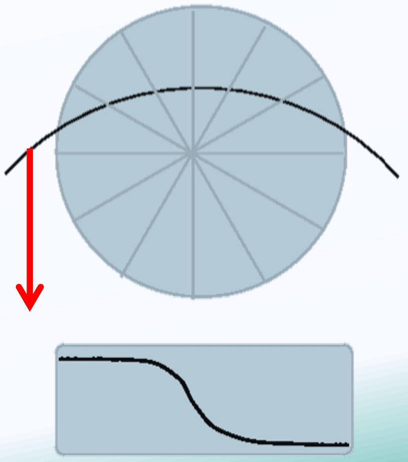




20 Jul 2005

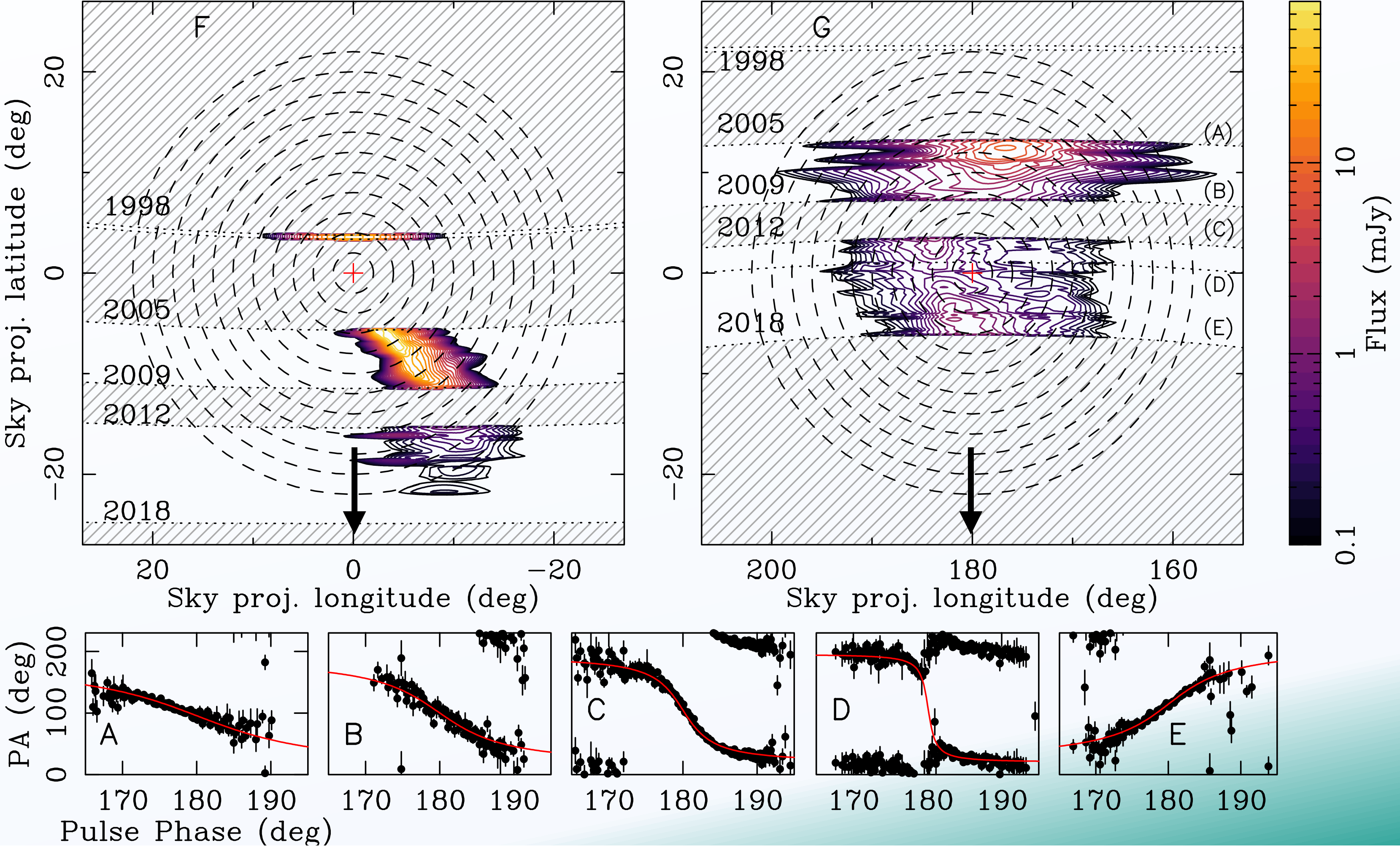


Desvignes



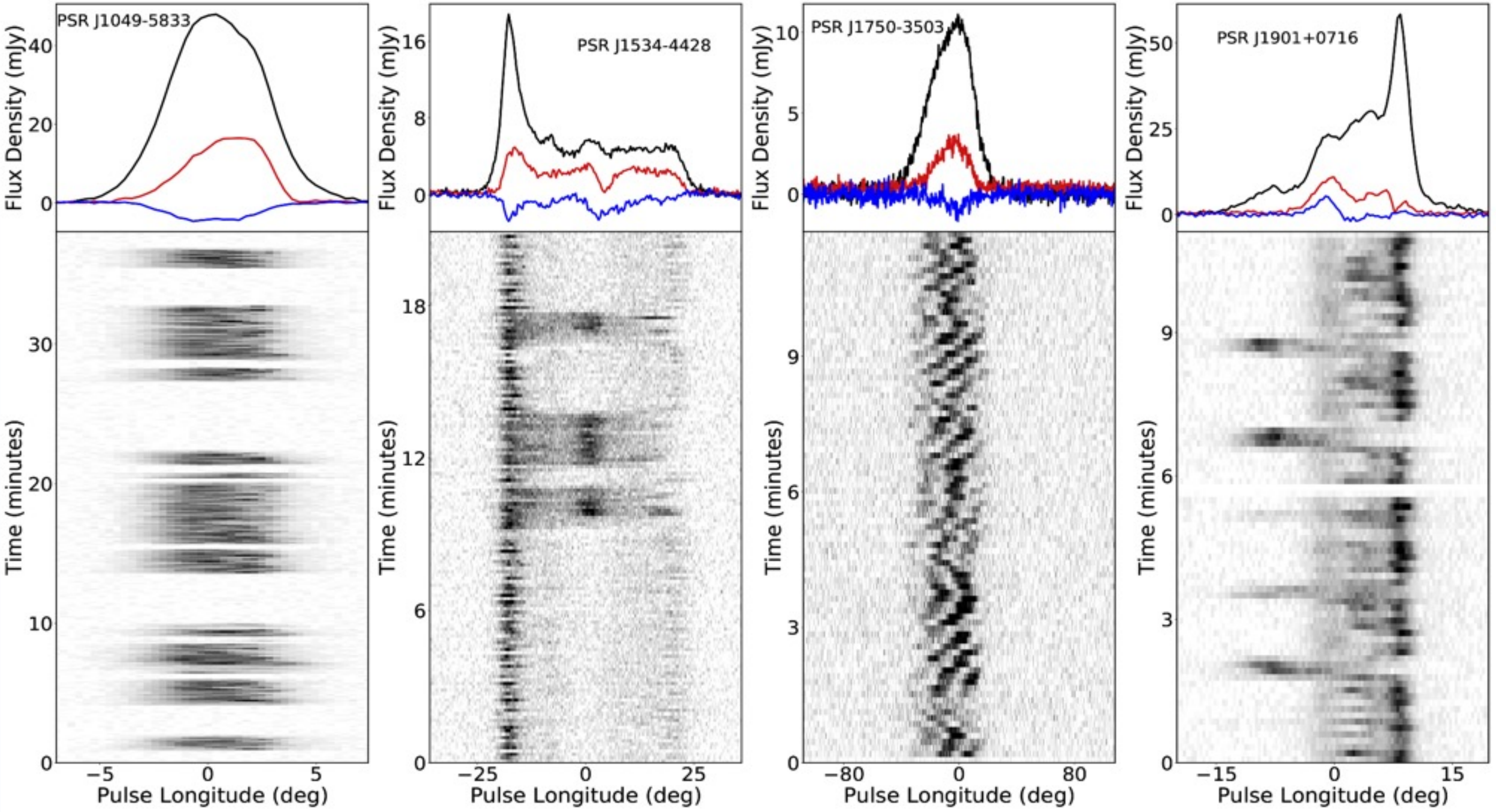
Pulsar beam tomography: 1D ➔ 2D

Beam structure as projected on the sky:



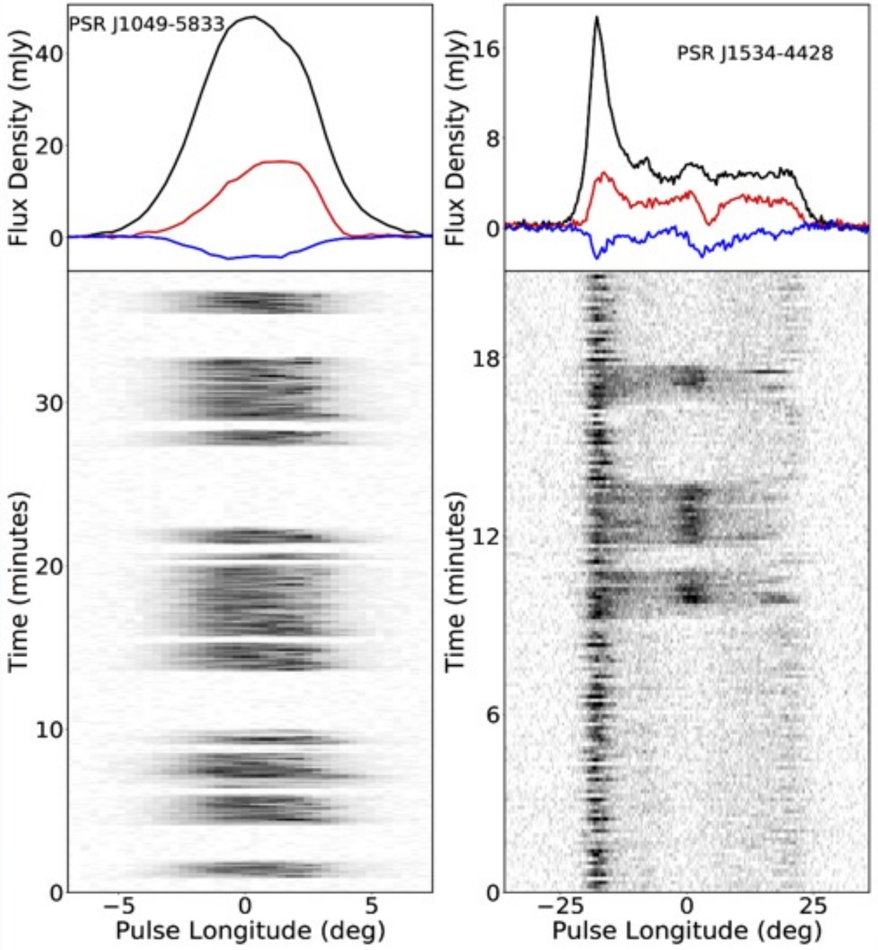
Desvignes et al. (2019)

Using time variable features in single pulses

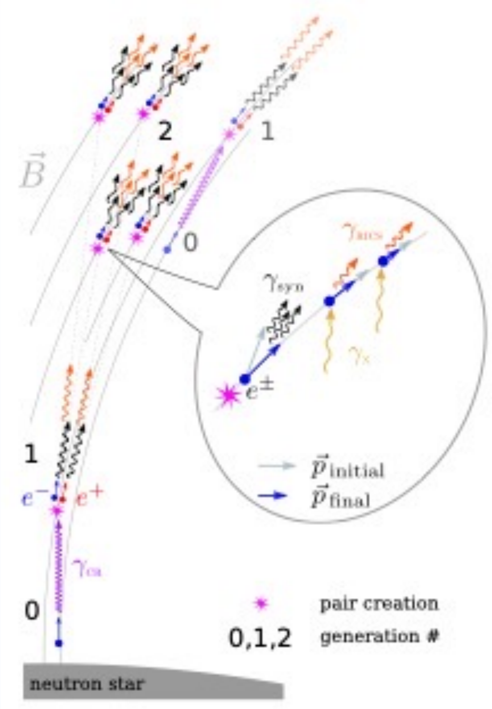


MeerKAT TPA project – Parthasarathy et al. in prep.

Using time variable features in single pulses



“Nulling” - ”Moding”
Does the pair production stop or change?



Timokhin & Harding (2019)

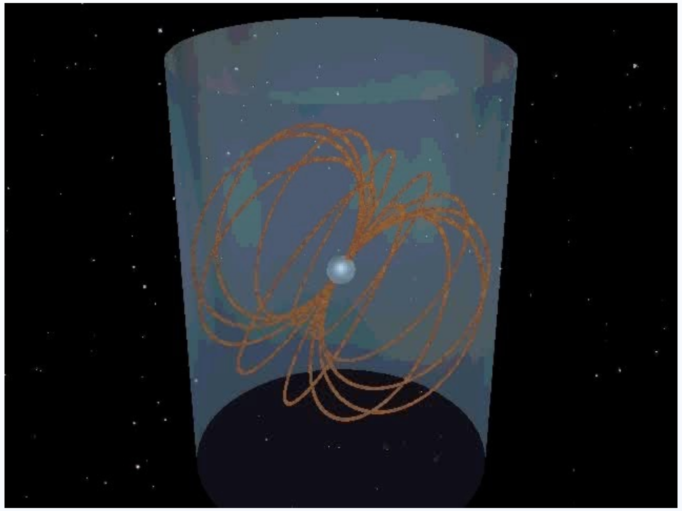
Can we see a change in the heated polar cap?

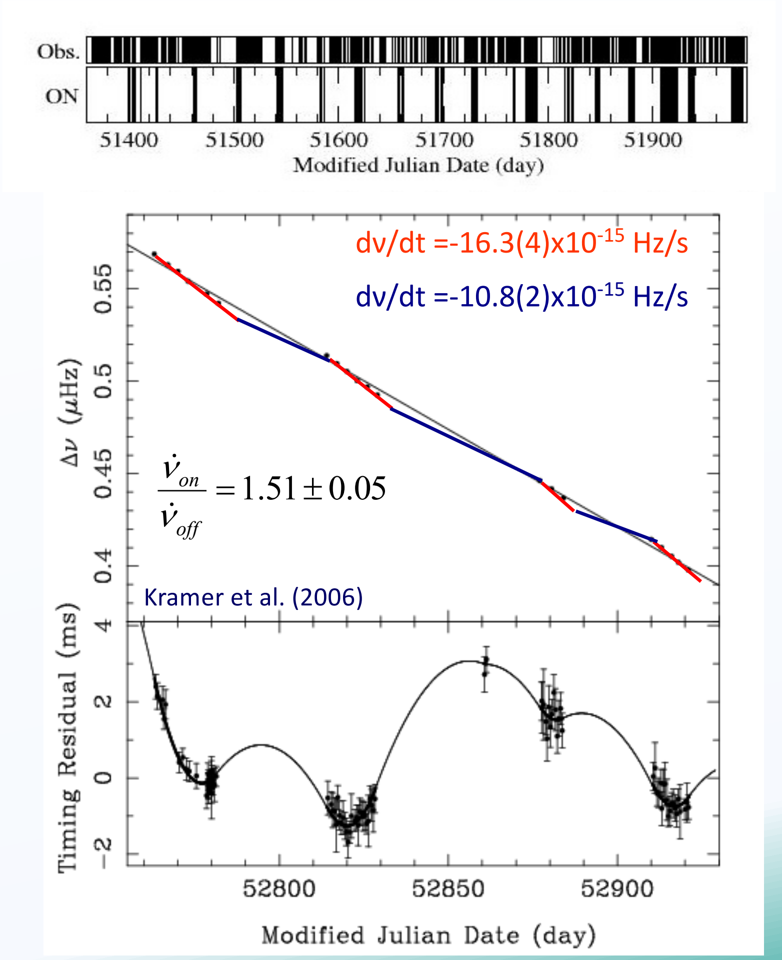
Information from Radio Observations

- From pulsar timing:
  - measuring pulse arrival times and tracking the rotation of the neutron star with high precision
- From emission properties:
  - full polarisation measurements from 10s MHz to 100s GHz
  - high time resolution up to nanosecond timescales
  - long-term monitoring lasting half a century (>10^9 rotations)
- From simultaneous multi-messenger observations
- From particularly interesting pulsars vs bulk properties

The extreme case: Intermittent pulsars

- Distinct phases of radio silence, up to few years!
- First, B1931+24, week/month timescale
- Spin-down changes with changing plasma
- Unique insight into magnetosphere
- Several more now known
- Difficult to find (and confirm)
- Significant fraction of population?
- What causes the timescales & quasi-periodicities?



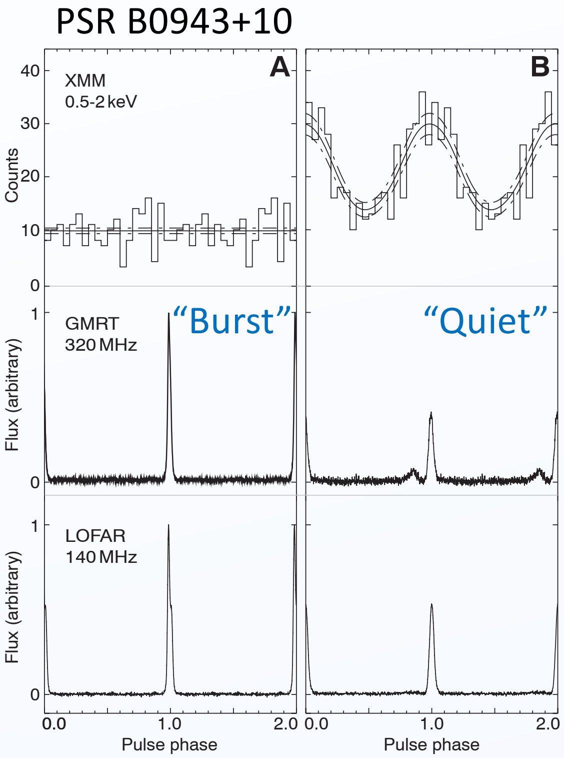


Kramer et al. (2006)

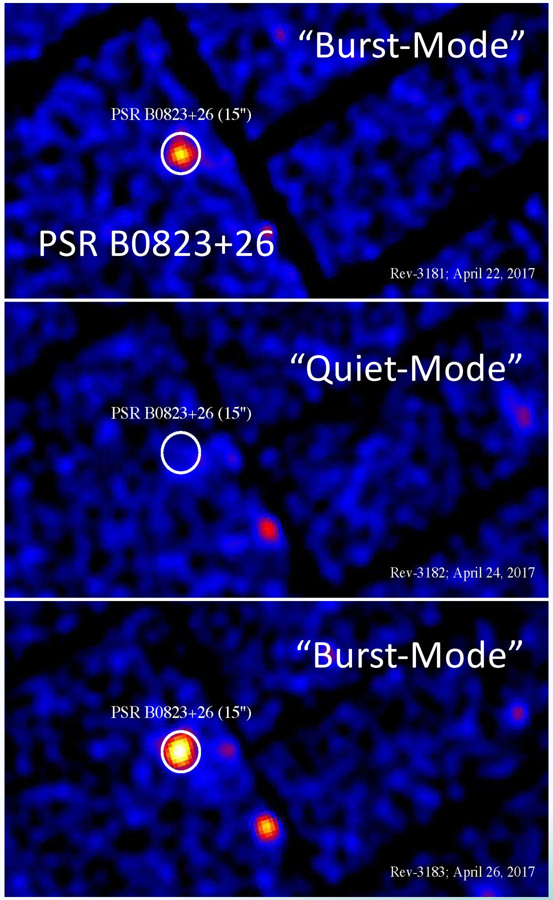
Note: implications for B-field estimates!

Seeing the heated polar cap? – Maybe.

Simultaneous radio-X-ray observations for moding pulsars:



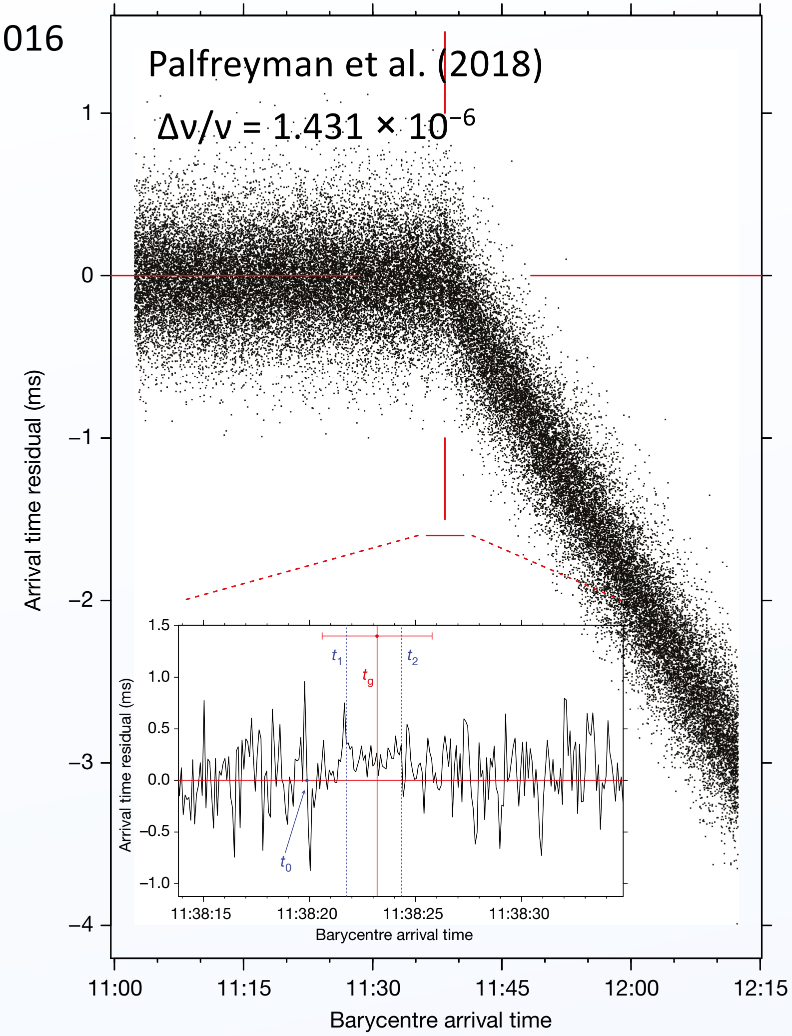
Hermsen et al. (2013)



Hermsen et al. (2018)

What causes nulling? – A peculiar Vela glitch

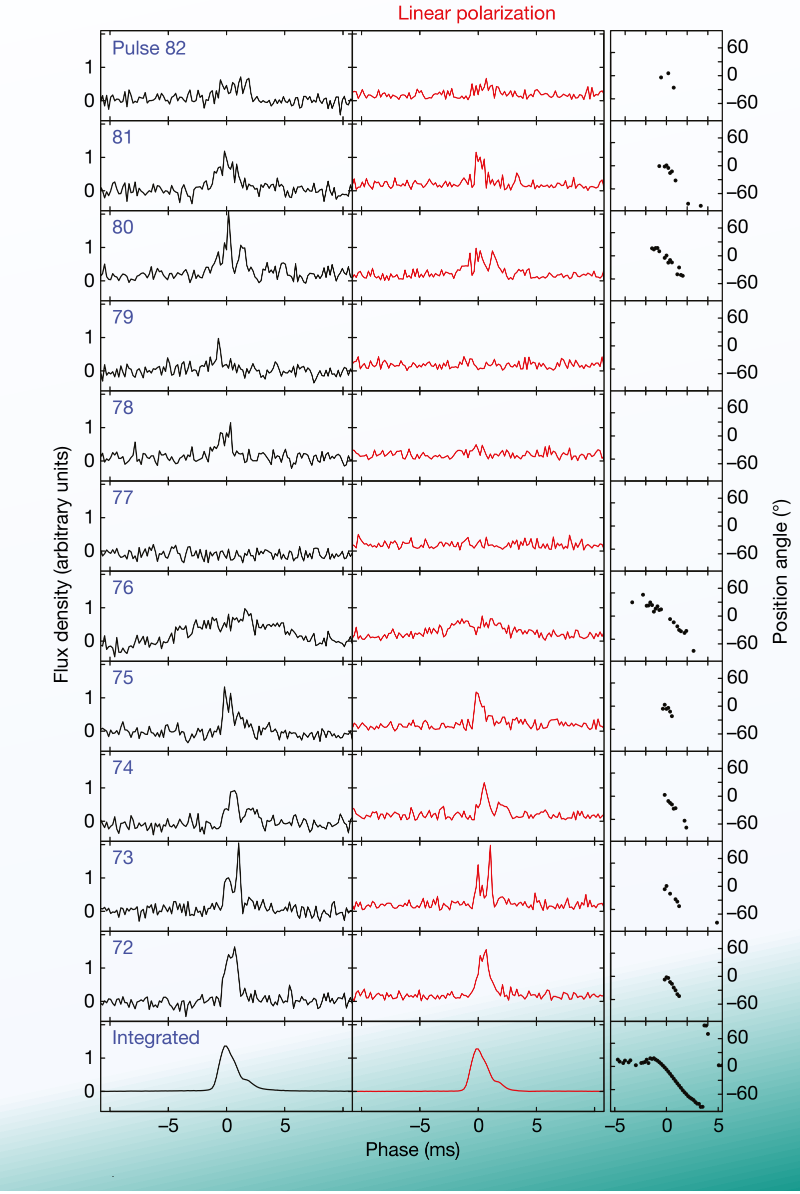
Dec 12, 2016



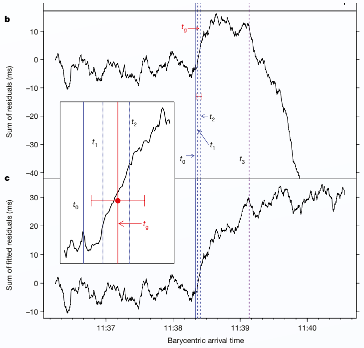
Palfreyman et al. (2018)

$\Delta\nu/\nu = 1.431 \times 10^{-6}$

Time



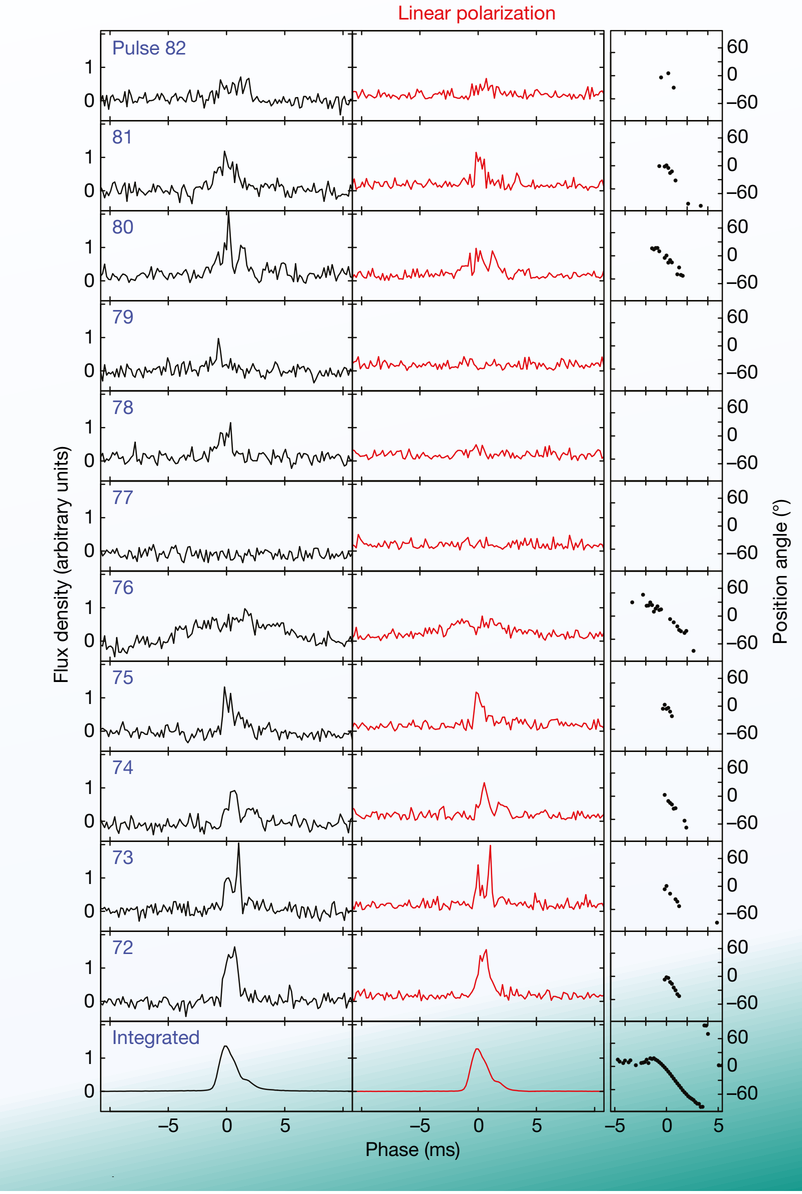
What causes nulling? – A peculiar Vela glitch



Palfreyman et al. (2018) – observations:

- Broadening of a pulse
- A null for one period
- Low linear polarisation for two further pulses
- For about 30 rotations, the pulses arrived later than expected
- Then an increase in spin-frequency became apparent.

Compare to previous cases of profile changes during glitches:
see Weltevrede et al. (2011), Keith, Shannon & Johnston (2013)



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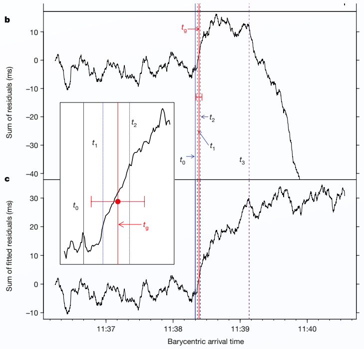

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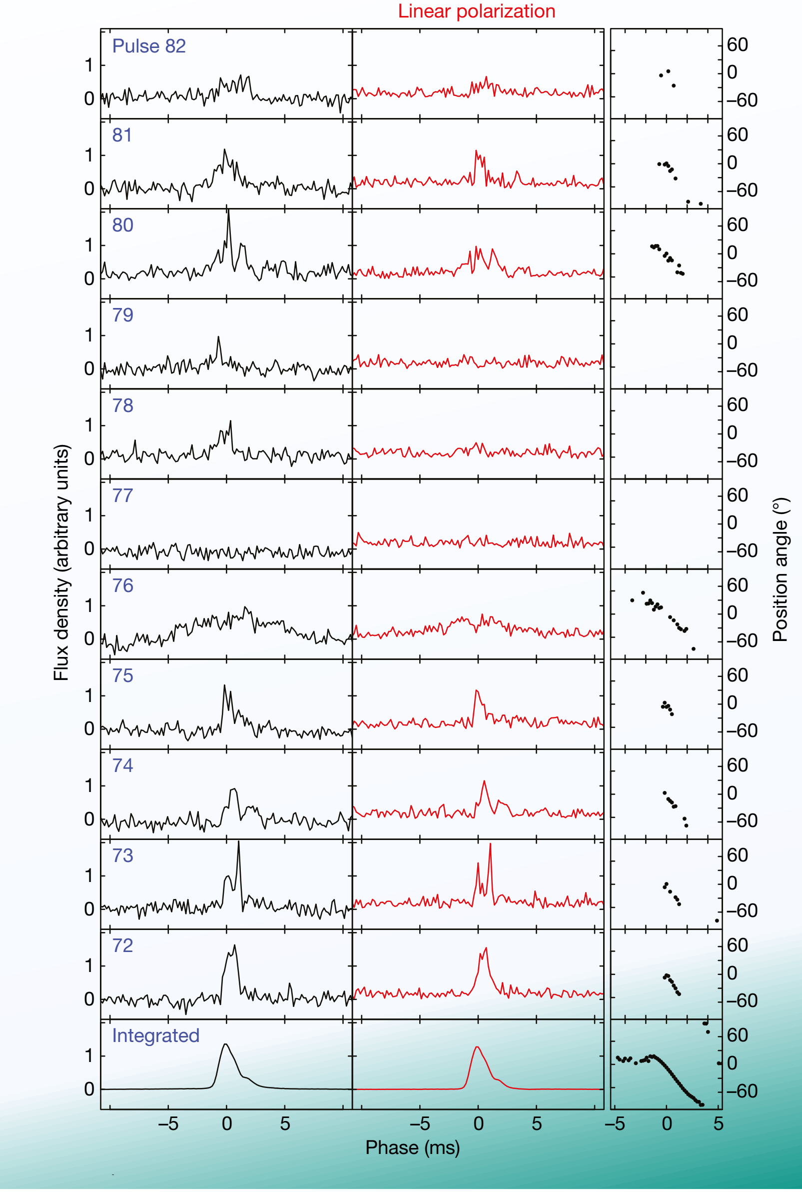
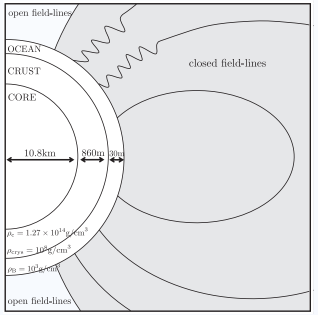
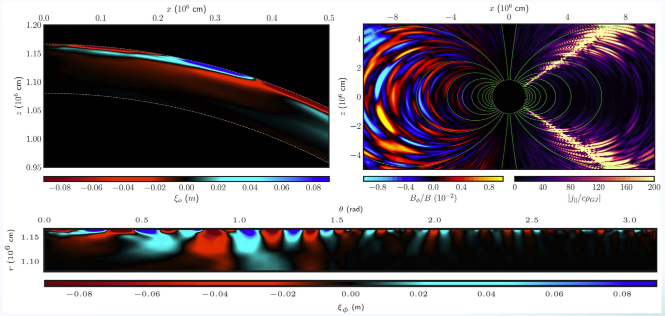


Compare to previous cases of profile changes during glitches:
see Weltevrede et al. (2011), Keith, Shannon & Johnston (2013)

Did a star-quake disturb the magnetosphere (e.g. via Alfvén waves)?
See e.g. Bransgrove et al. (2020) or Yuan et al. (2021).





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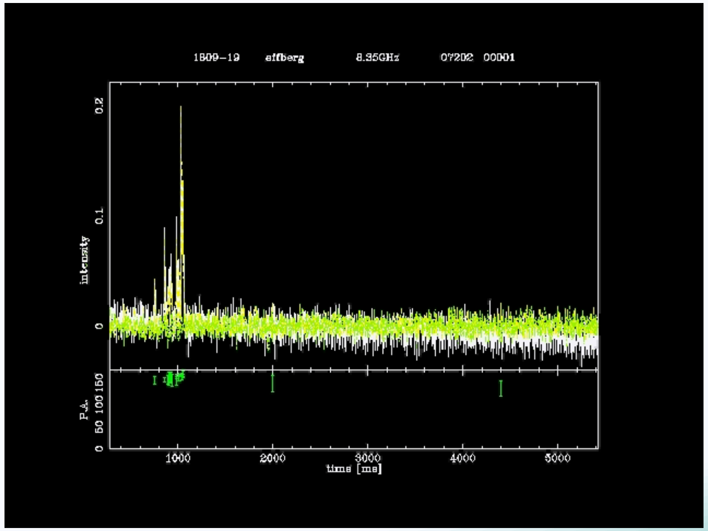
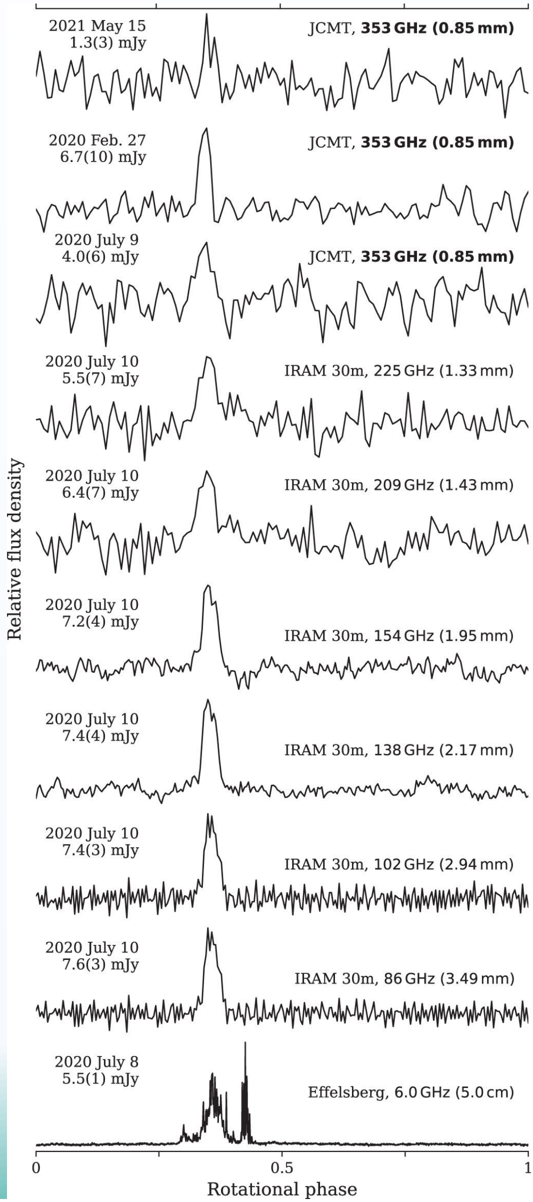
Magnetars

- Some magnetars visible as transient radio sources
- Radio triggered by outburst? – Pulsed emission detected up to 360 GHz!
- Emission properties with similarities to pulsars but also different
- Complementary information to high energies
- First discovery of magnetar in radio blind search (Levin et al. 2010)
- Handful of radio-loud magnetars known, one in Galactic Centre (Eatough et al. 2013, Torne et al. 2015, 2016)
- Timing very noisy

Kramer et al. (2007)

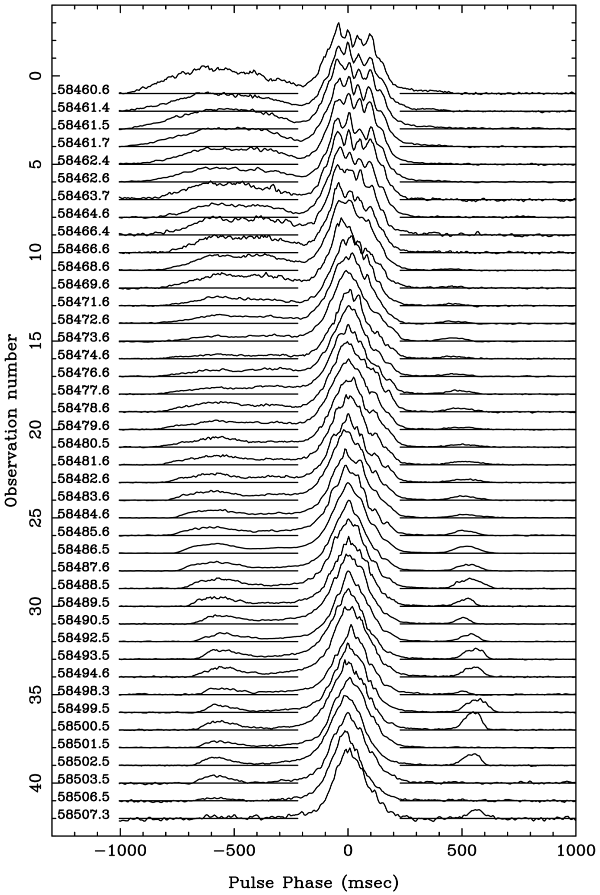


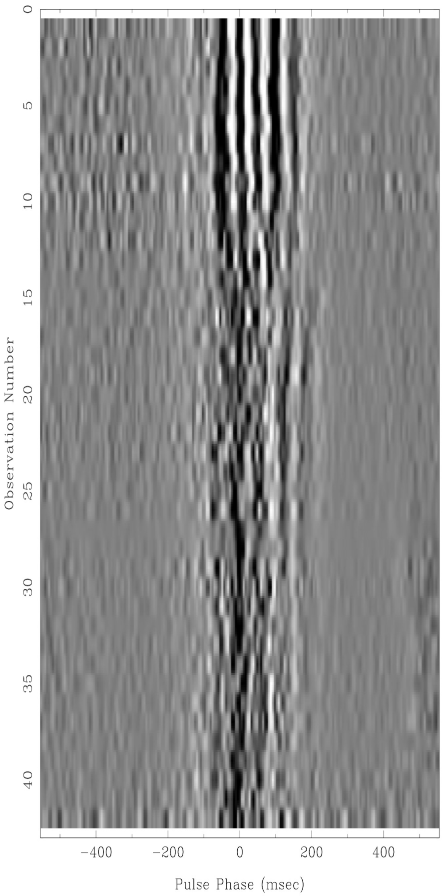
Torne et al. (2022)

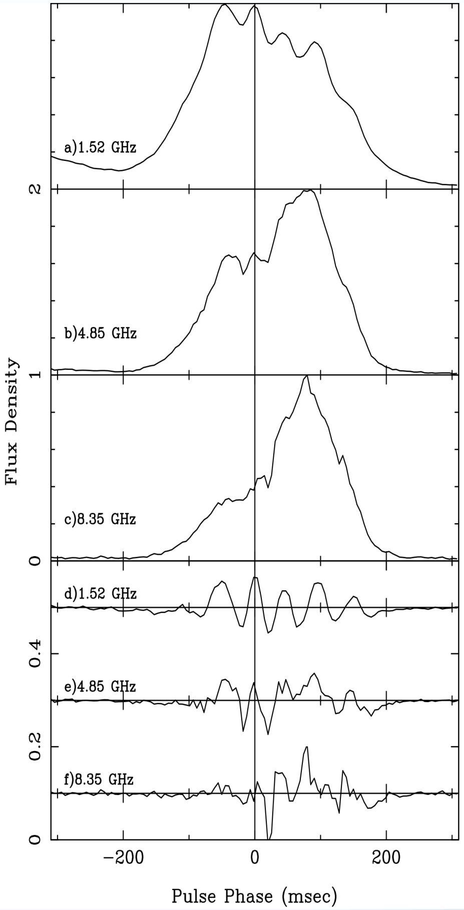


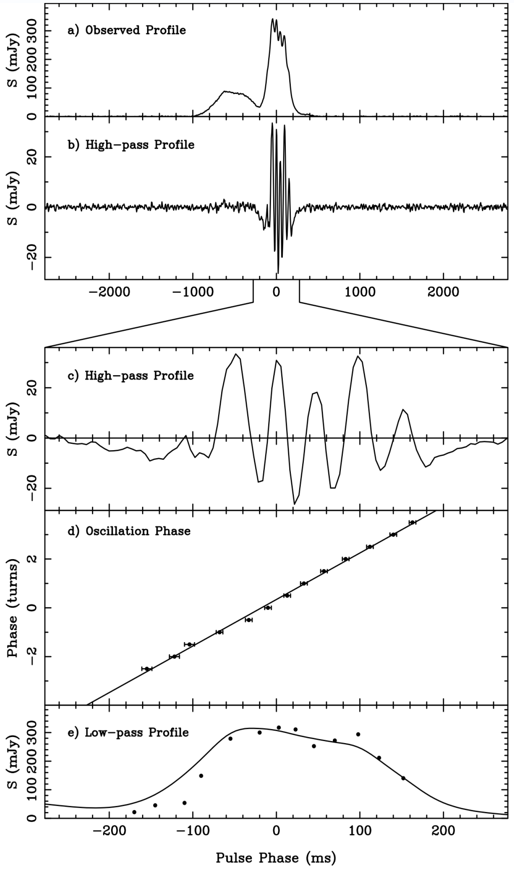
Persistent rotational stable 20 Hz-feature in XTE J1810–197 - (Levin et al. 2019)

On the surface of the neutron star at the base of the magnetic field lines hosting the radio emitting particles for ~10 days



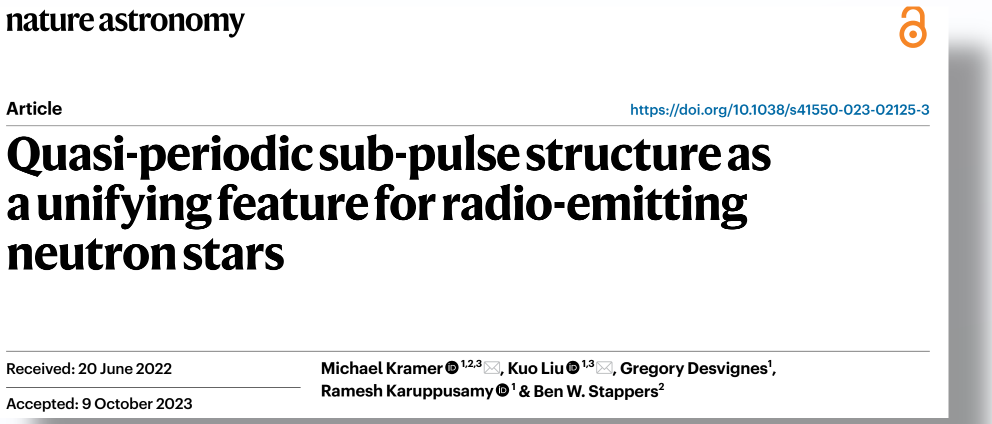






Reminiscent of surface waves in the neutron star crust (Piro & Bildsten 2004), perhaps produced as high-spherical-degree non-radial oscillations (Clemens & Rosen 2004)?

A universal law for microstructure



nature astronomy

Article

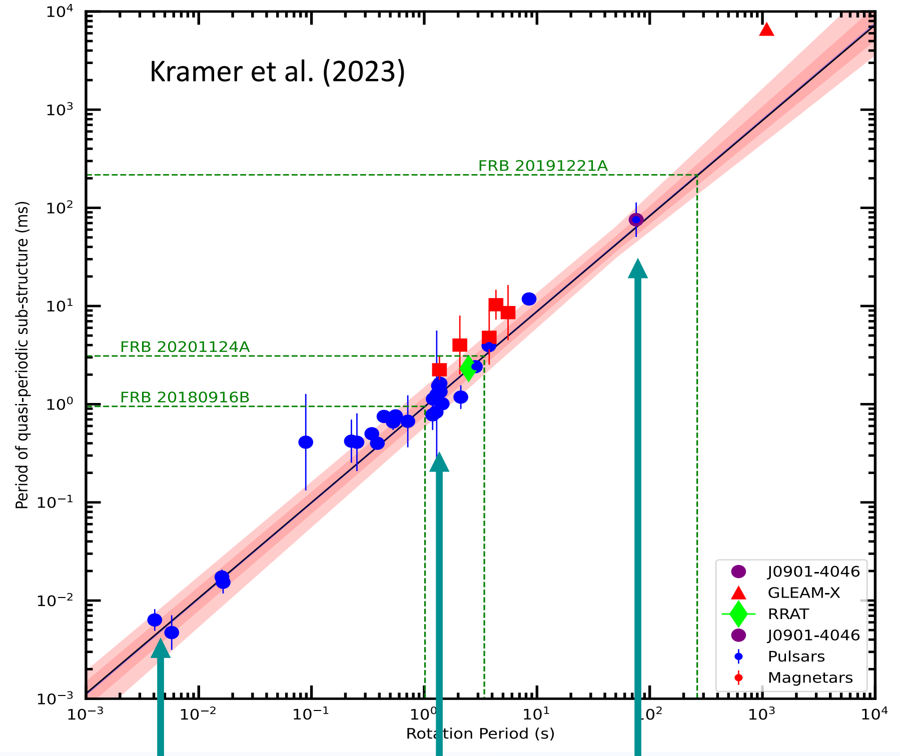
https://doi.org/10.1038/s41550-023-02125-3

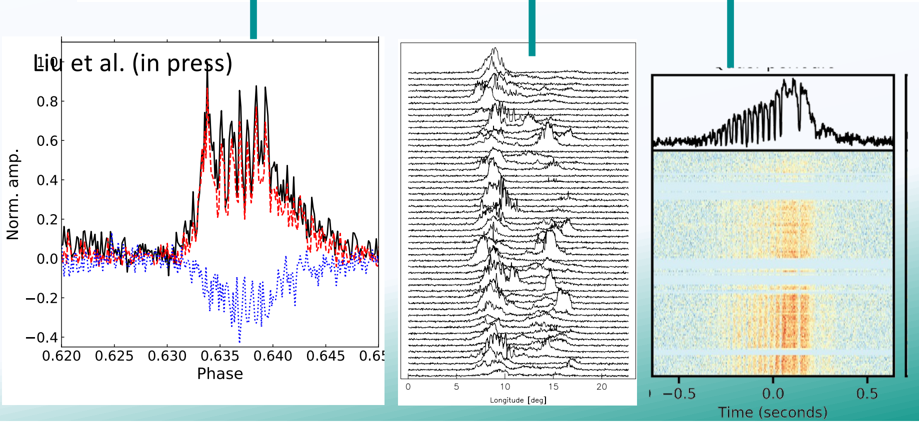
Quasi-periodic sub-pulse structure as a unifying feature for radio-emitting neutron stars

Received: 20 June 2022

Accepted: 9 October 2023

Michael Kramer[1,2,3], Kuo Liu[1,3], Gregory Desvignes[1], Ramesh Karuppusamy[1] & Ben W. Stappers[2]



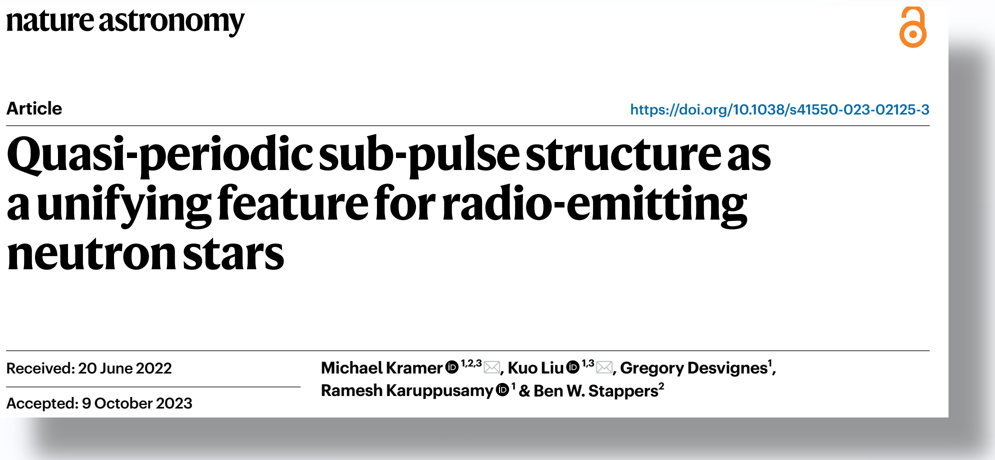


- Linear relationship over 5 orders of magnitude
- Valid also for millisecond pulsars (e.g. Liu et al. in press)
- Result of quasi-periodic beamlets?
- What causes them?
- Imprint from the neutron star surface?

Probably not! – It seems related to emission process

Possibly way to identify NS origin – also for FRBs!

A universal law for microstructure



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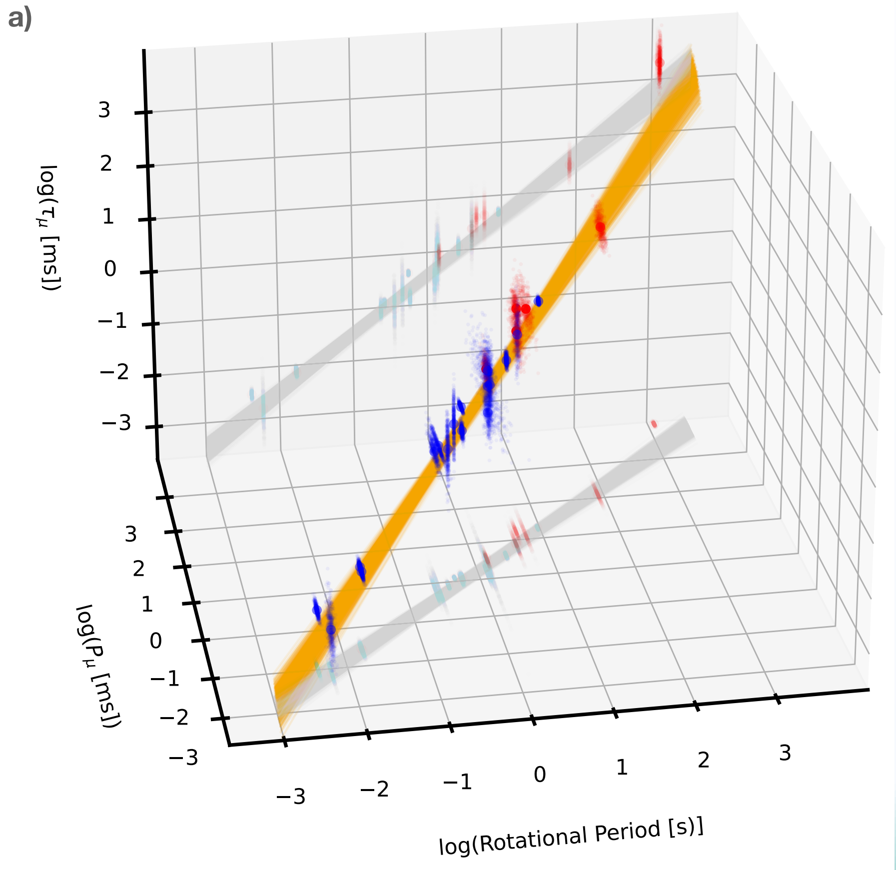

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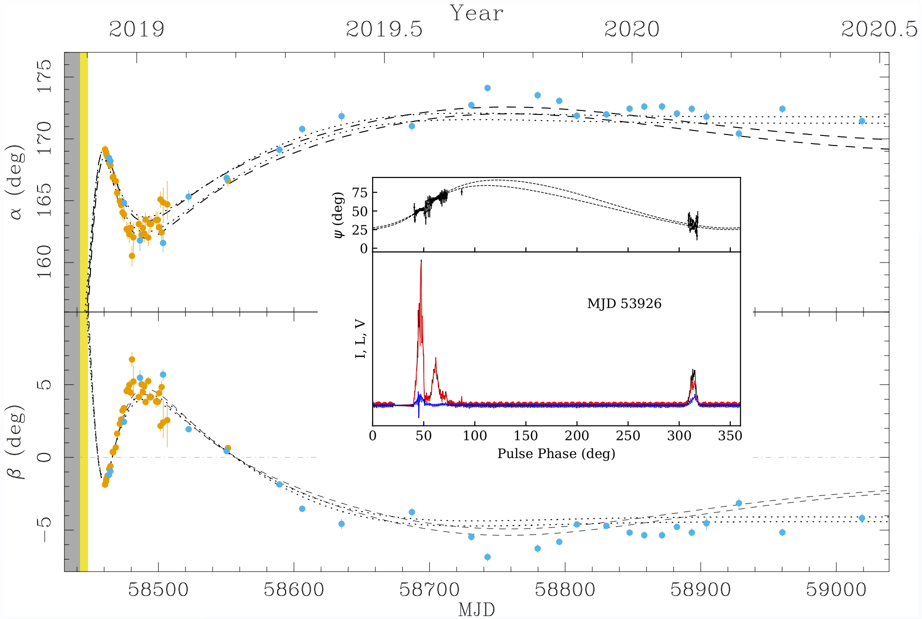
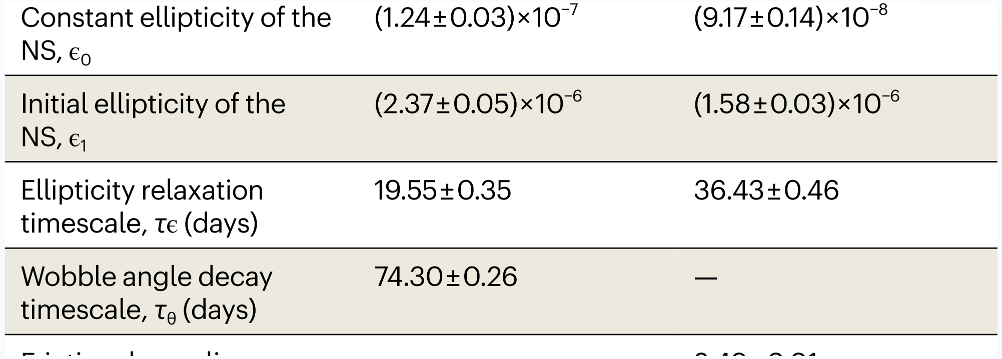
A freely precession magnetar





Constant ellipticity of the NS, ϵ_0	$(1.24\pm0.03)\times10^{-7}$	$(9.17\pm0.14)\times10^{-8}$
Initial ellipticity of the NS, ϵ_1	$(2.37\pm0.05)\times10^{-6}$	$(1.58\pm0.03)\times10^{-6}$
Ellipticity relaxation timescale, τ_ϵ (days)	19.55±0.35	36.43±0.46
Wobble angle decay timescale, τ_θ (days)	74.30±0.26	—

nature astronomy

Article

https://doi.org/10.1038/s41550-024-02226-7

A freely precessing magnetar following an X-ray outburst

Received: 16 November 2022

Accepted: 15 February 2024

[redacted]

Gregory Desvignes[1,2], Patrick Weltevrede[3], Yong Gao[4,5], David Ian Jones[6], Michael Kramer[1,3], Manisha Caleb[7,8], Ramesh Karuppusamy[1], Lina Levin[3], Kuo Liu[1], Andrew G. Lyne[3], Lijing Shao[1,5,9], Ben Stappers[3] & Jérôme Pétri[10]

- High-cadence radio observations of XTE J1810–197 shortly after an X-ray outburst in 2018
- Systematic polarization variations provide evidence for free precession following the outburst
- Precession is damped on a timescale of months
- Using free-precession models based on relaxing ellipticity, the magnetar ellipticity is in good agreement with theoretical predictions from nuclear physics.
- Precise measurement of the magnetar’s geometry can help in refining the modelling of X-ray light curves and constrain the star’s compactness.

Summary

- Radio observations not only discover pulsars but they reveal their properties

  (Note, I have not talked about birth properties. Interesting connection to CC SN)
- Precision mass measurements providing important constraints
- Moment-of-inertia can soon be determined purely from timing
- Emission properties providing complementary information, e.g. geometry
- Connection between interior and magnetosphere?
- Future observations will push constraints further (population, periods, masses, types, links)
- Application of pulsars (e.g. gravity tests, gravitational wave detection) requires improved understanding – something to work on together!
- Golden era: combination of GW and EM observations