Pulsar Science with a phased ALMA

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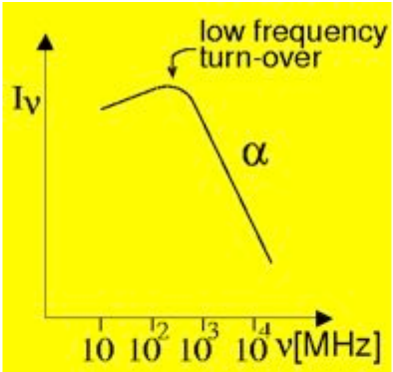
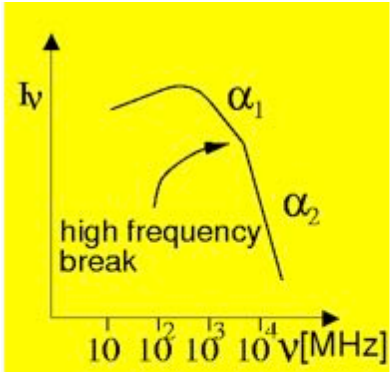
Why should you observe pulsars with ALMA?

- You may think that this is a daft idea…
- Indeed, there are several very good reasons <u>not</u> to do it:

  - Pulsars generally have steep flux density spectra





- We know most about pulsars from frequencies < 2 GHz (note: in past < 700 MHz!)

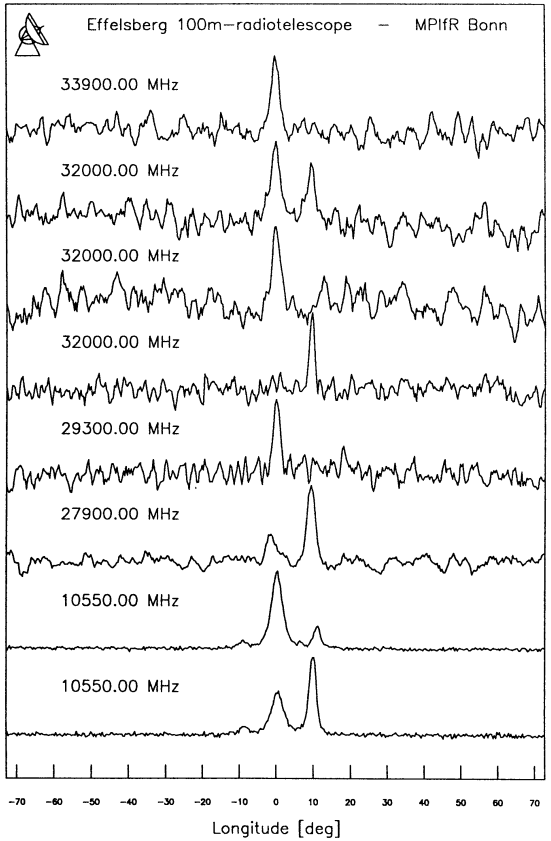
- The use of pulsars as clocks scales inversely with the signal-to-noise ratio.

Hence, using mm-wavelengths is not ideal…

But, there are also very good reasons ...

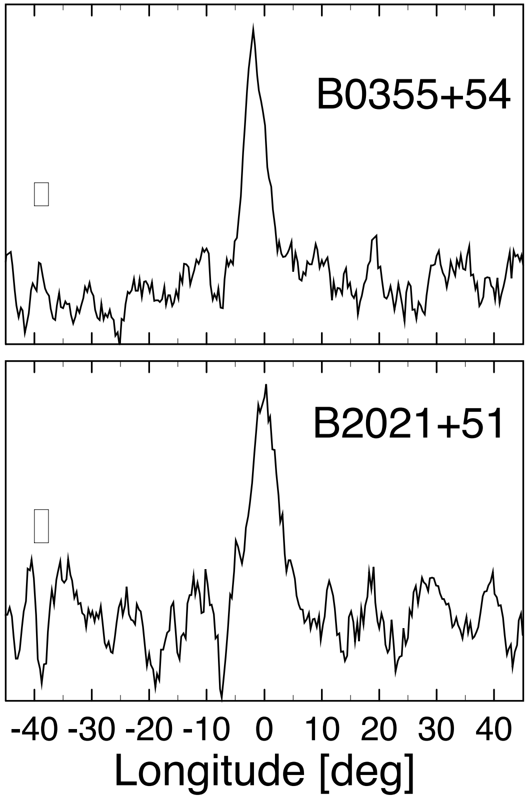
Pulsars have been detected at mm-wavelengths, e.g.:

9mm



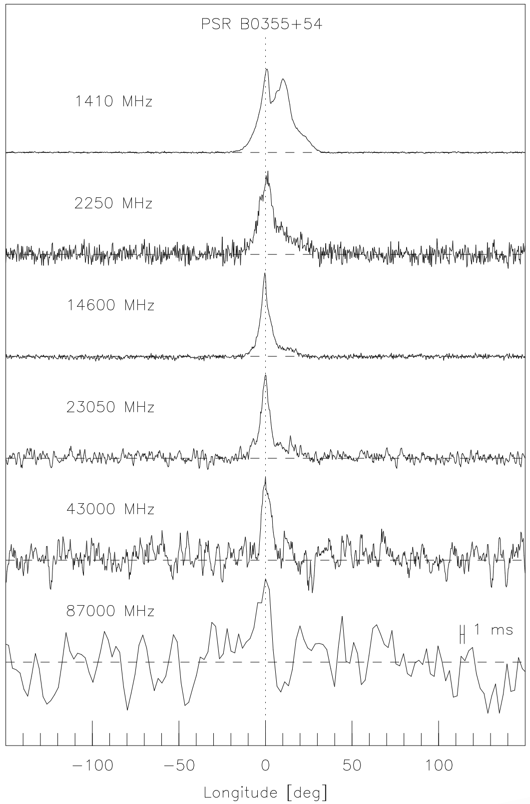
Kramer et al. (1996)

7mm



Kramer et al. (1997)

3mm



Morris et al. (1997)

But, there are also very good reasons...

- Pulsars have been detected at mm-wavelengths
- So far,

Table 1. Results of observations at 32 GHz.

PSR	Pulses total	Time (min)	Flux density (mJy)	No. of measurements
		New detections:		
B0144+59	30 552	99.8	0.062 ± 0.006	2
B0823+26	24 752	218.9	0.023 ± 0.0010	2
	12 516	111.0	<0.170	0 (K95)*
B2022+50	9720	60.4	0.046 ± 0.009	1
		Re-detections:		
B0355+54	17 480	45.6	0.76 ± 0.14	2
	57 095	148.8	0.8 ± 0.2	6 (K95)
B1133+16	2148	42.5	0.055 ± 0.06	1
	13 920	275.4	0.03 ± 0.02	2 (K95)
B1706−16	8712	94.8	0.07 ± 0.01	1
	11 154	121.2	0.06 ± 0.01	2 (K95)
B1929+10	15 708	59.3	0.19 ± 0.02	1
	13 3188	502.8	0.21 ± 0.01	6 (K95)
B2020+28	6278	35.9	0.06 ± 0.01	1
	41 065	235.2	0.09 ± 0.02	1 (K95)
B2021+51	3752	33.1	0.28 ± 0.03	1
	61096	349.8	0.323 ± 0.007	9 (K95)
		Upper flux limits:		
B0154+61	4578	179.0	<0.06	
B0611+22	32 076	179.0	<0.09	
B0628−28	2256	46.8	<0.3	
B0740−28	16 554	46.0	<0.17	
B1604−00	5460	38.4	<0.13	
B1642−03	7334	47.4	<0.3	
B1822−09	2888	37.0	<0.13	
B1935+25	6734	22.6	<0.9	
B2000+32	8946	103.9	<0.08	
B2319+60	3168	119.0	<0.3	
B2323+63	2490	59.6	<0.6	
B2334+61	4830	39.9	<0.4	

* The designation (K95) refers to earlier observations reported by Kramer (1995).

Löhmer et al. (2008)

Until recently:

9 sources @ 32 GHz

4 sources @ 43 GHz

2 sources @ 87 GHz

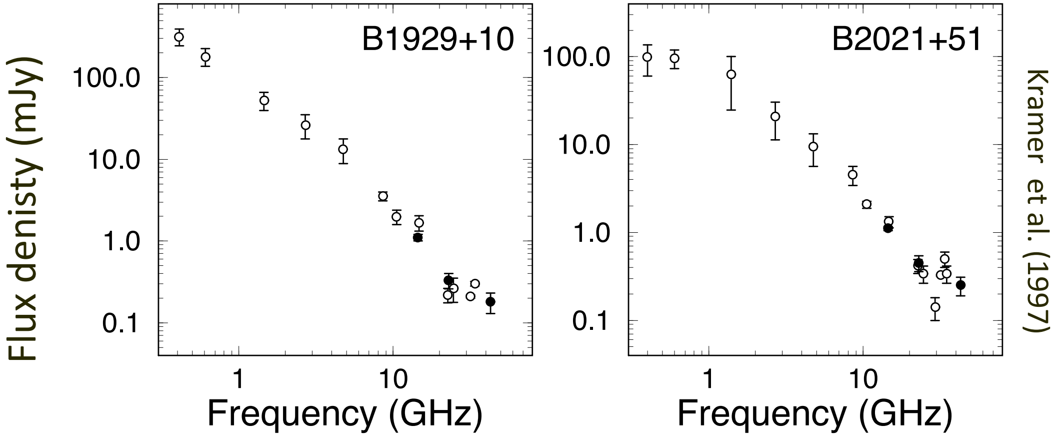
1 source @ 144 GHz

Note:

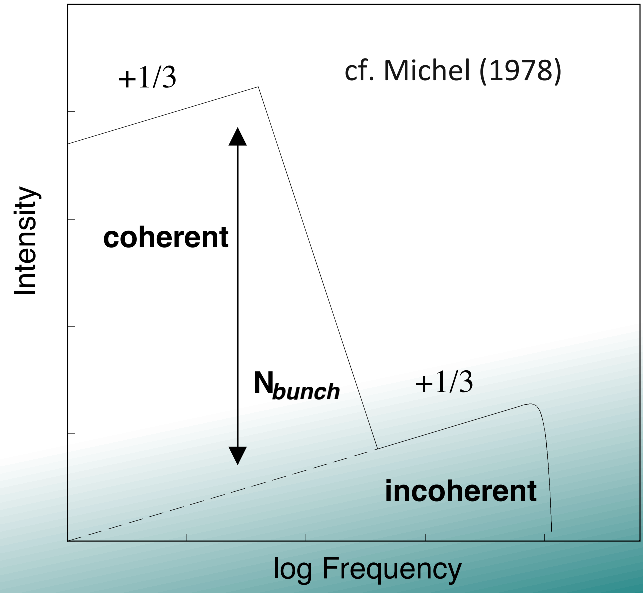
- need more sensitivity
- 72% of all pulsars $\delta < 0$ deg
- no appropriate telescope in the South – so far!

Pulsars may even become stronger

- Some pulsars observed at 9mm and 7mm seem to show a peculiar spectral change:



- This does not come totally unexpected, e.g. we know from the Crab that its infrared flux density is much higher than the high-frequency radio flux density
- Similar observations also for Vela
- Unknown emission radio is coherent, but there should be also incoherent component

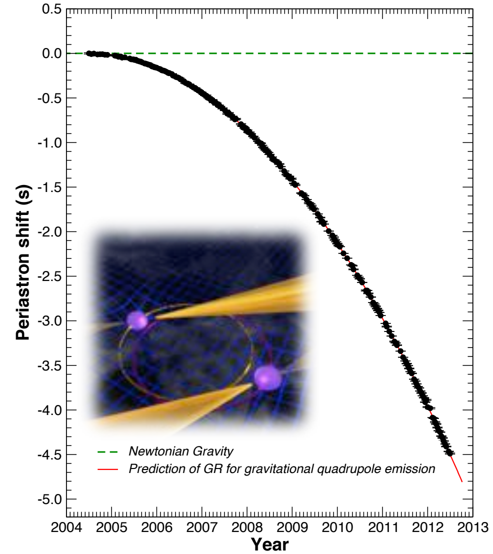


Finding the transition frequency between the coherent and incoherent part would gives us the important unknown intrinsic coherence length

➔ coherent process!?!

Use ALMA to understanding Gravity

Kramer et al. (2015)

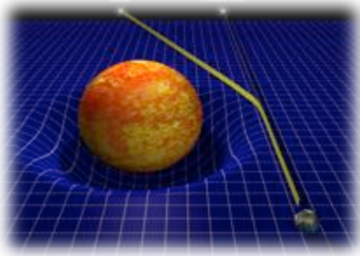


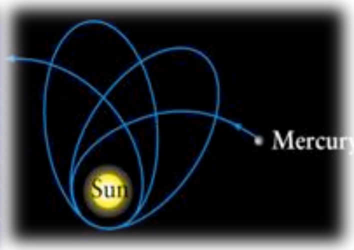
General relativity conceptually different than description of other forces

But GR has been tested precisely, e.g. in solar system

Classical tests:

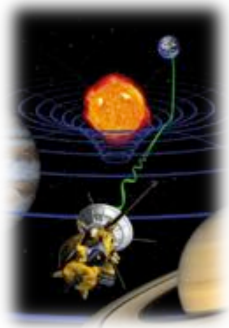
- Mercury perihelion advance
- Light-deflection at Sun
- Gravitational redshift

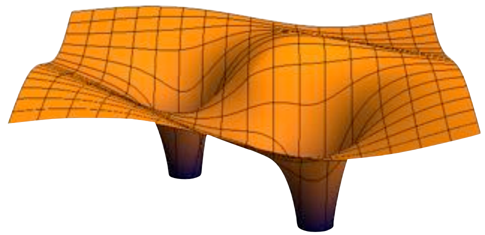




Modern tests in solar system,

- Lunar Laser Ranging (LLR)
- Radar reflection at planets, Cassini spacecraft signal
- LAGEOS & Gravity Probe B
- Binary Pulsars (Hulse-Taylor Pulsar, Double Pulsar)





(LR/ITP)

But, is there a problem..?

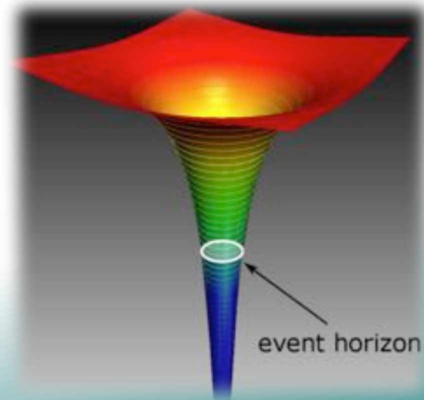
See precision cosmology: Inflation? Dark Matter? Dark Energy?

Question: Will Einstein have the last word on (macroscopic) gravity

does GR fail far below the Planck energy? Alternatives?

We need to test gravity in strong, non-linear conditions, i.e. NS,BH

What are the properties of black holes and also gravitational waves?



Can we probe Sgr A* with pulsars – are there any?

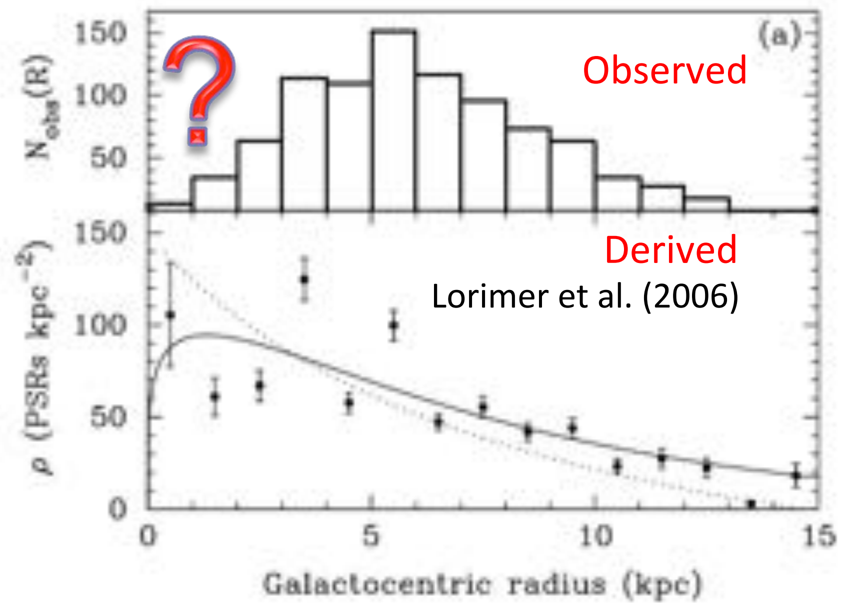
- We have evidence for past formation of massive stars in the Galactic Centre, i.e. massive stars and the remnants are being observed
- It is a region of high stellar density, so exchange interaction can produce all types of binary companions, we can expect all kinds of extreme binary systems
- …e.g. Faucher-Giguere & Loeb (2011) predict highly ecc. stellar BH-MSP systems
- We can even expect > 1000 pulsars, incl. millisecond pulsars (Wharton et al. 2013)
- We can probe:

- star formation history (from char. ages)

- local gravitational potential (from accel.)

- distribution and properties of central ISM

- properties & strength of central B-field (RM)



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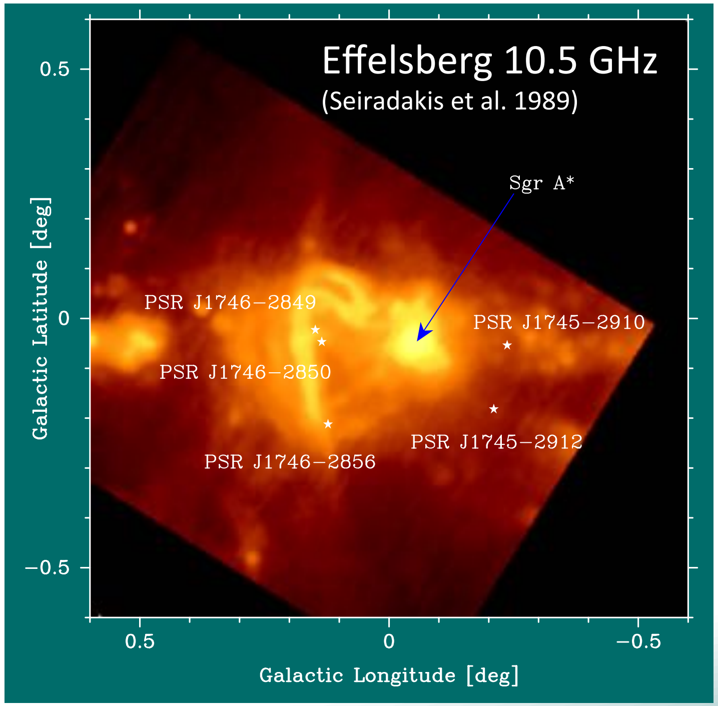

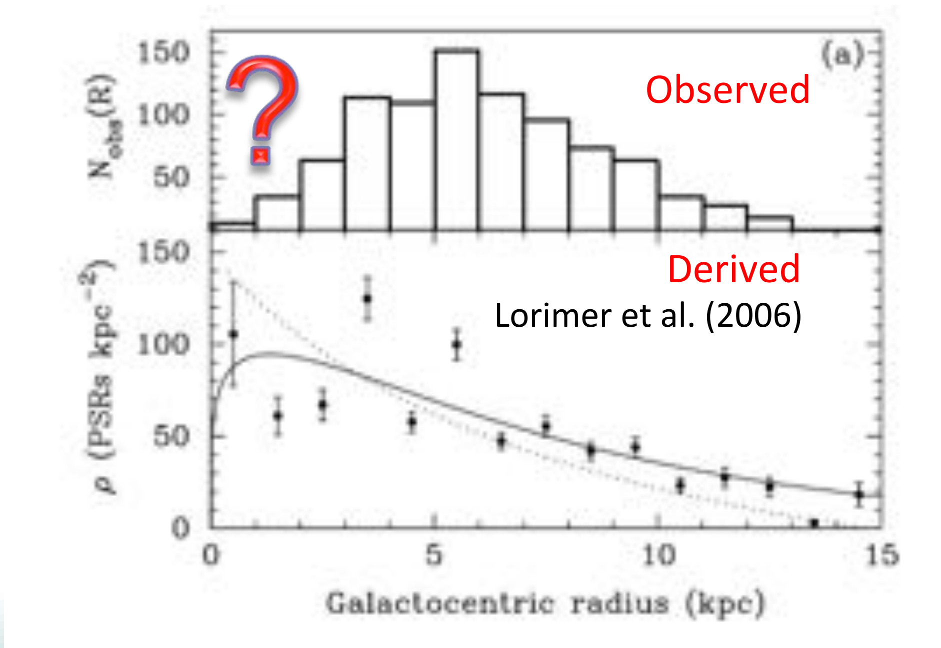

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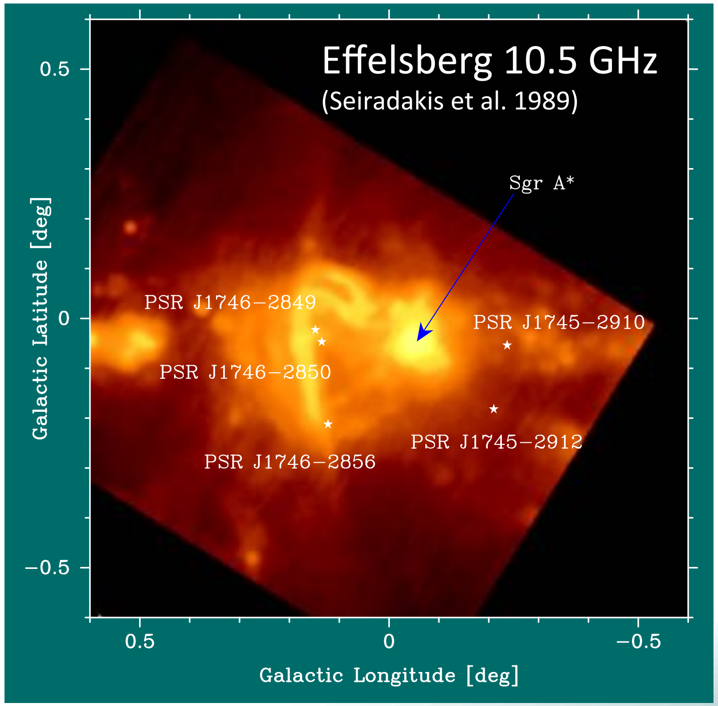
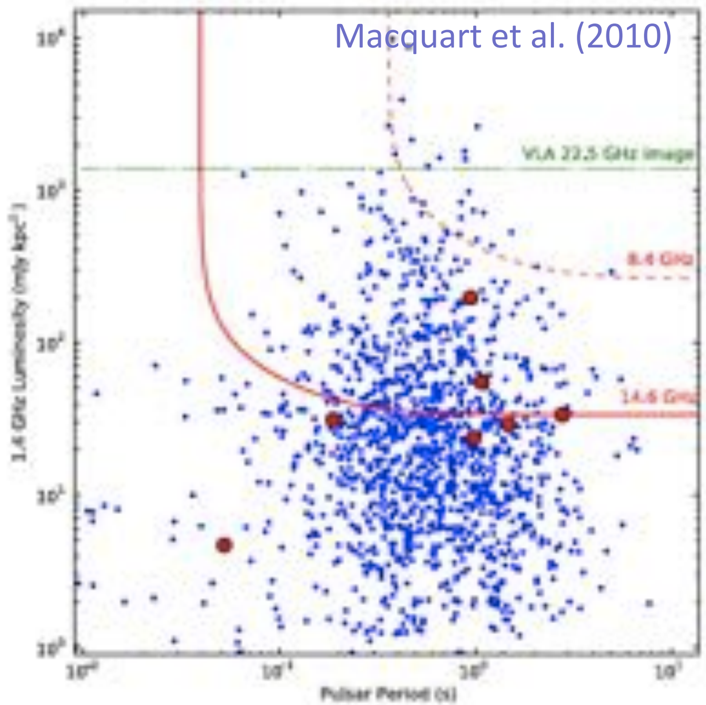
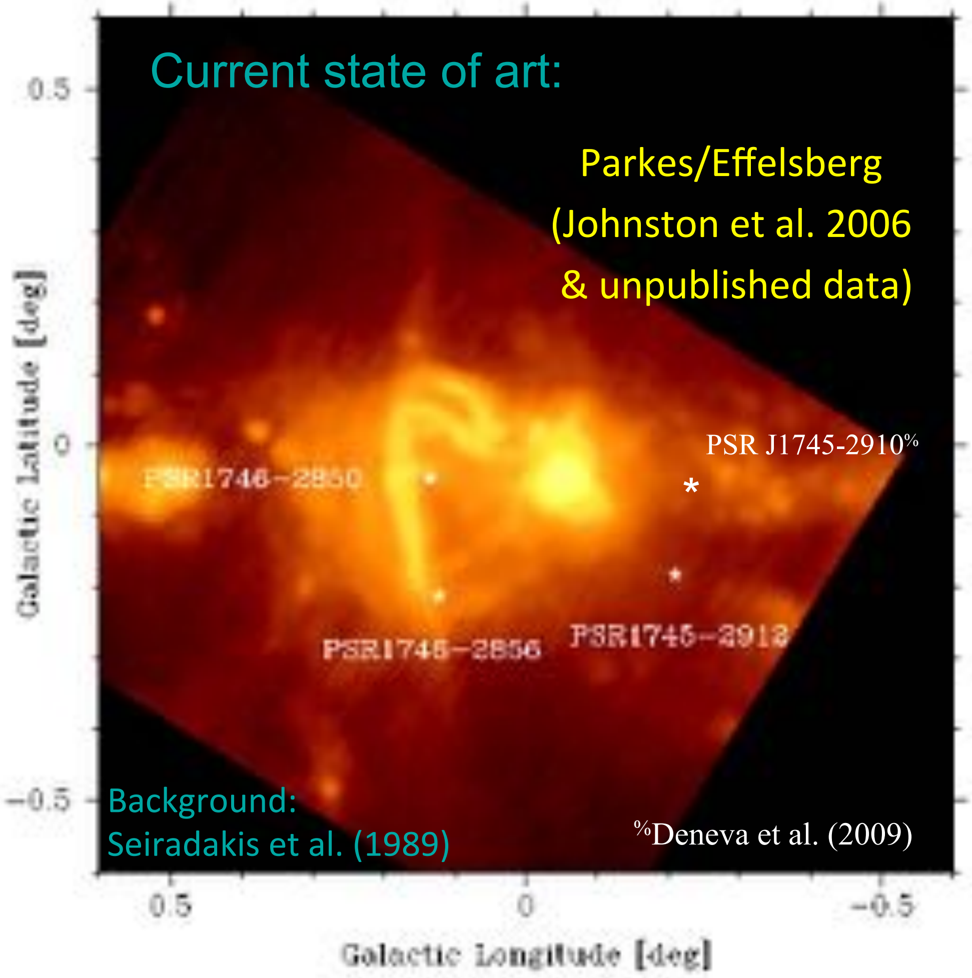


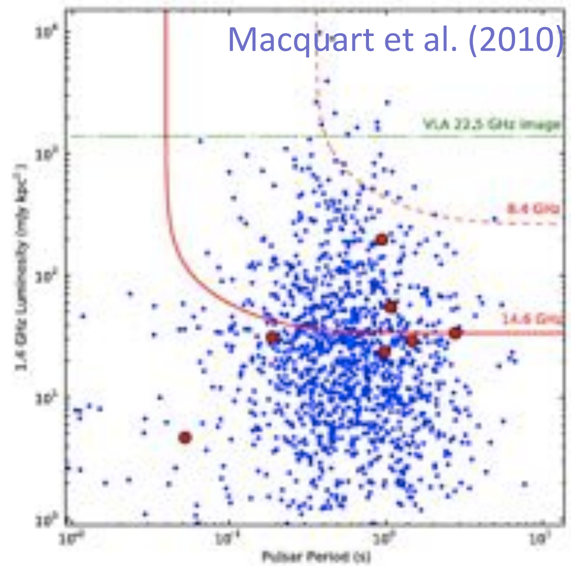


Searching for pulsars in the Galactic Centre

- We have only probed the outer layer of the Galactic centre population:
- using a nominal distance of 8.33 kpc (Gillessen et al. '09), the closest we used to get was about 20 pc!

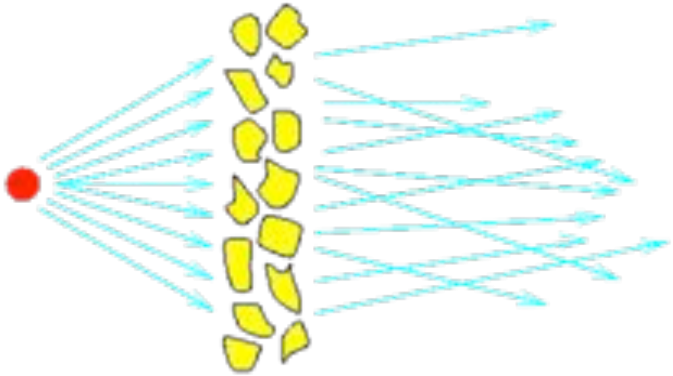


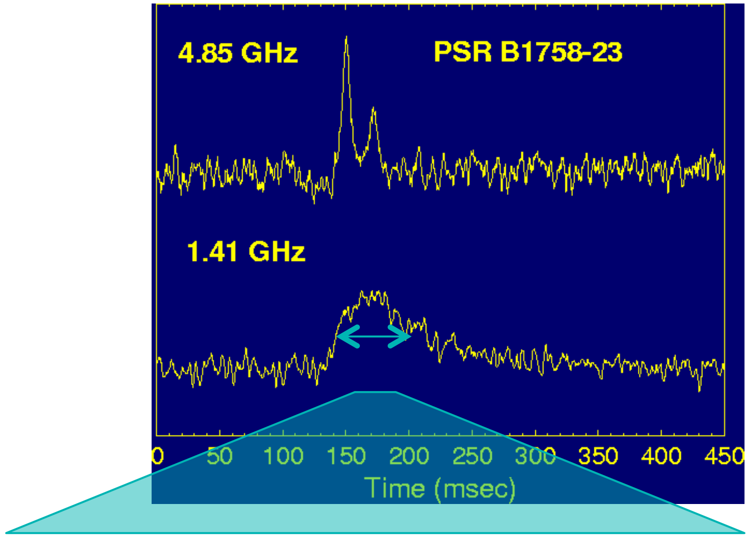
Dedicated surveys so far include:
- Effelsberg (4.9 GHz, Klein et al. '99
  19 GHz, Eatough et al.))
- GBT (1.8 GHz, Deneva et al. '09;
  14.8 GHz, Macquart et al. '10
  22 GHz, ongoing)
- Parkes (2.3/8.5 GHz, Johnston et al. '06)



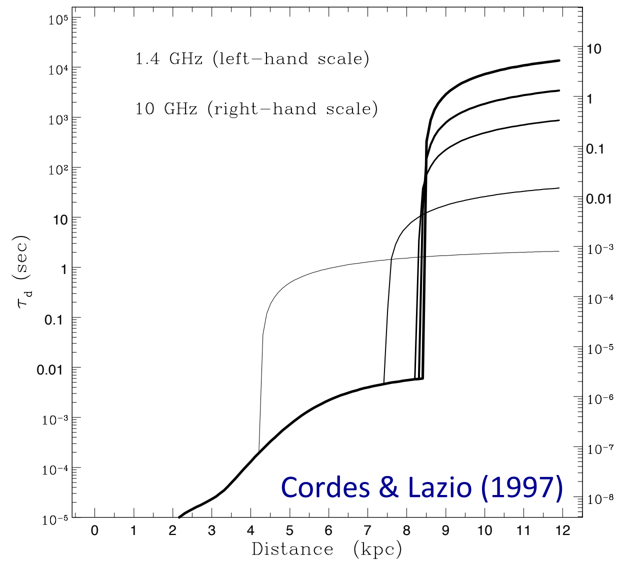
Selection effects – Why is it so hard?

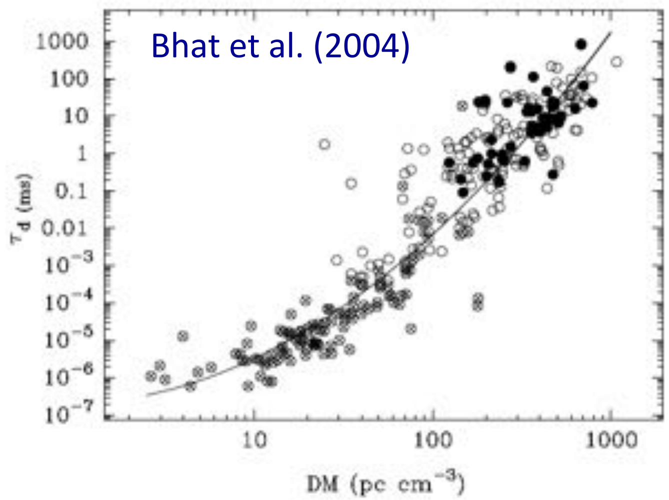
The inhomogeneous ionized ISMs smears and scatters the pulses (NB: dispersion is easy…) :





Expected scattering time is enormous:



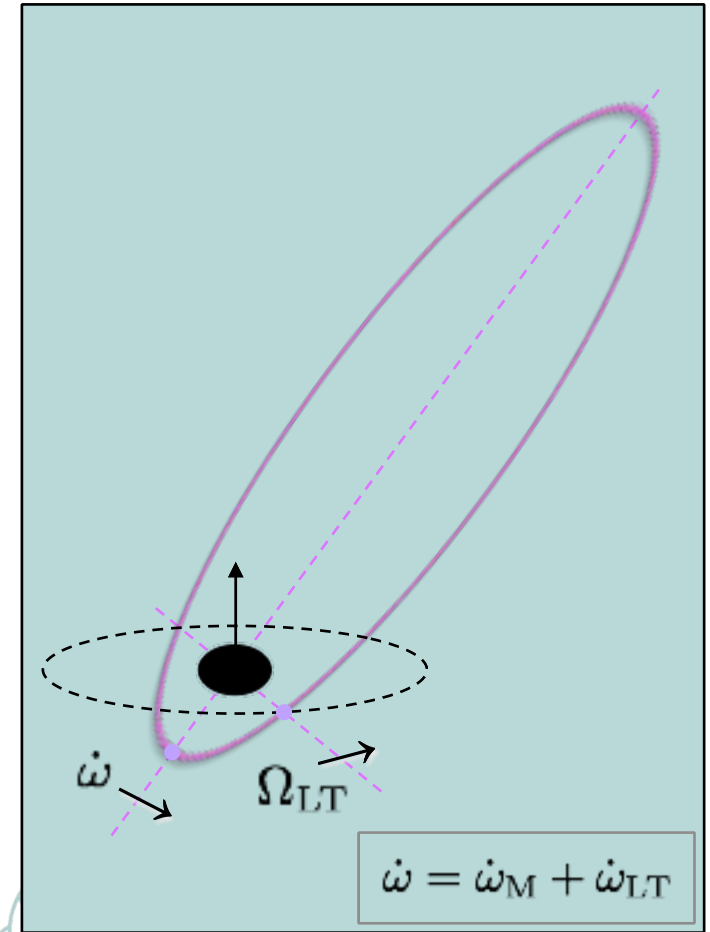


➔ In particular at the centre:

At "normal" search frequencies pulses should be undetectable!

Relativistic effects for a pulsar orbit around Sgr A*

Pulsar in a 0.3 yr eccentric (e=0.5) orbit around Sgr A*



Semi-major axis:	72 AU = 860 R_S
Pericenter distance:	36 AU = 430 R_S
Pericenter velocity:	0.042 c (~ 20 × Double Pulsar)

Pericenter advance:

1pN:	2.8 deg/yr,	ΔL ~ 1.8 AU/yr
2pN:	0.014 deg/yr,	ΔL ~ 1,400,000 km/yr

Einstein delay:

1pN:	15 min
2pN:	1.6 s

Propagation delay (i = 0° / i = 80°):

Shapiro 1pN:	46.4 s	/ 246.9 s
Shapiro 2pN:	0.2 s	/ 8.0 s
Frame dragging:	0.1 s	/ 6.5 s
Bending delay (P = 1s):	0.2 ms	/ 4.2 ms

Lense-Thirring precession:

Orbital plane Ω_{LT} : 0.052 deg/yr, ΔL ~ 10^7 km/yr

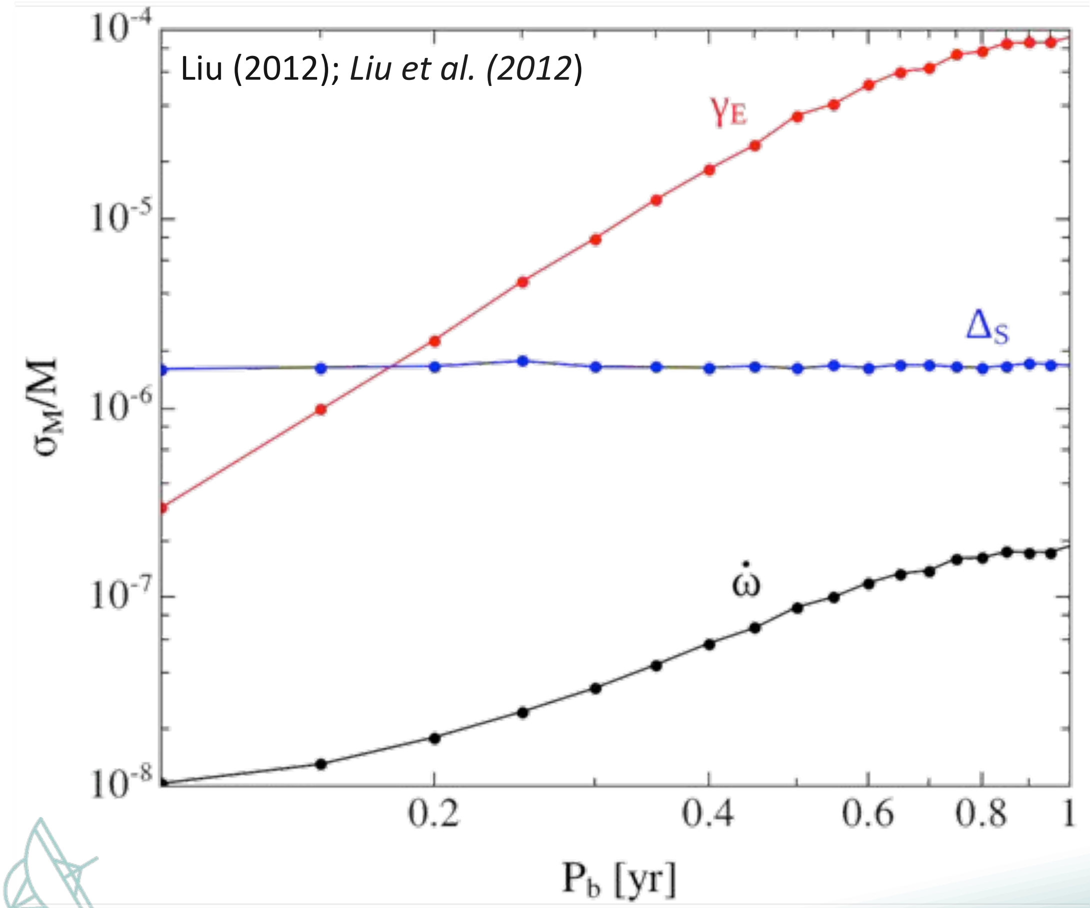
Similar contribution to $\dot{\omega}$

Geod. precession 1.4 deg/yr

Mass of Sgr A*, a first GR test & the GC distance

$M_{BH} >> m_{PSR} \Rightarrow$ only one relativistic effect needed to measure mass of Sgr A*

Simulations: 5 yr of timing, one 100 μs TOA per week: Mass precision ~ 1 $M_\odot$!



A first GR test:

$$M_{\Delta S} \stackrel{?}{=} M_{\gamma E}$$

Note: mass measurement not affected by the uncertainty in R_0!

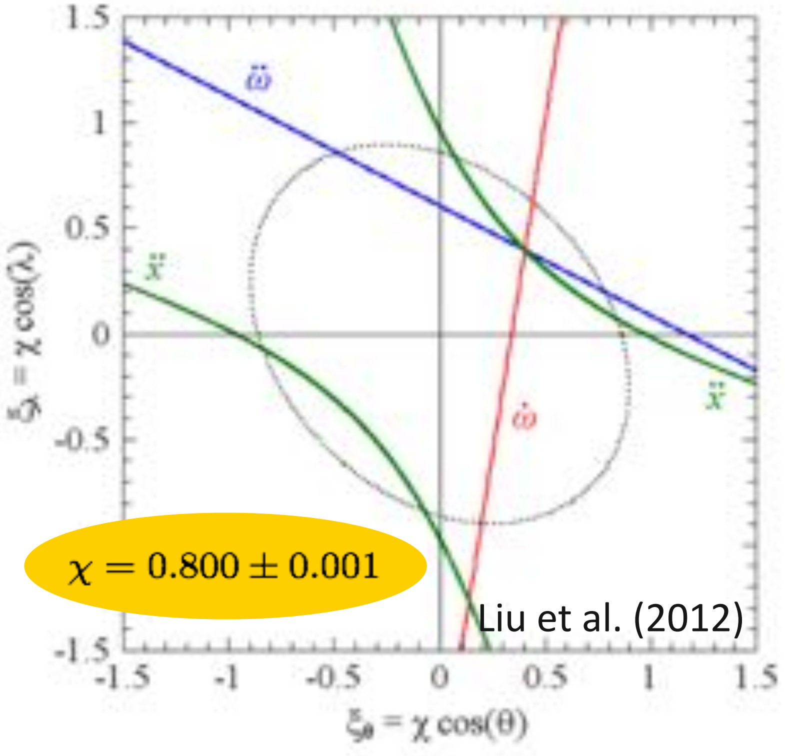
Combining with
10 μas astrometry
from e.g. GRAVITY

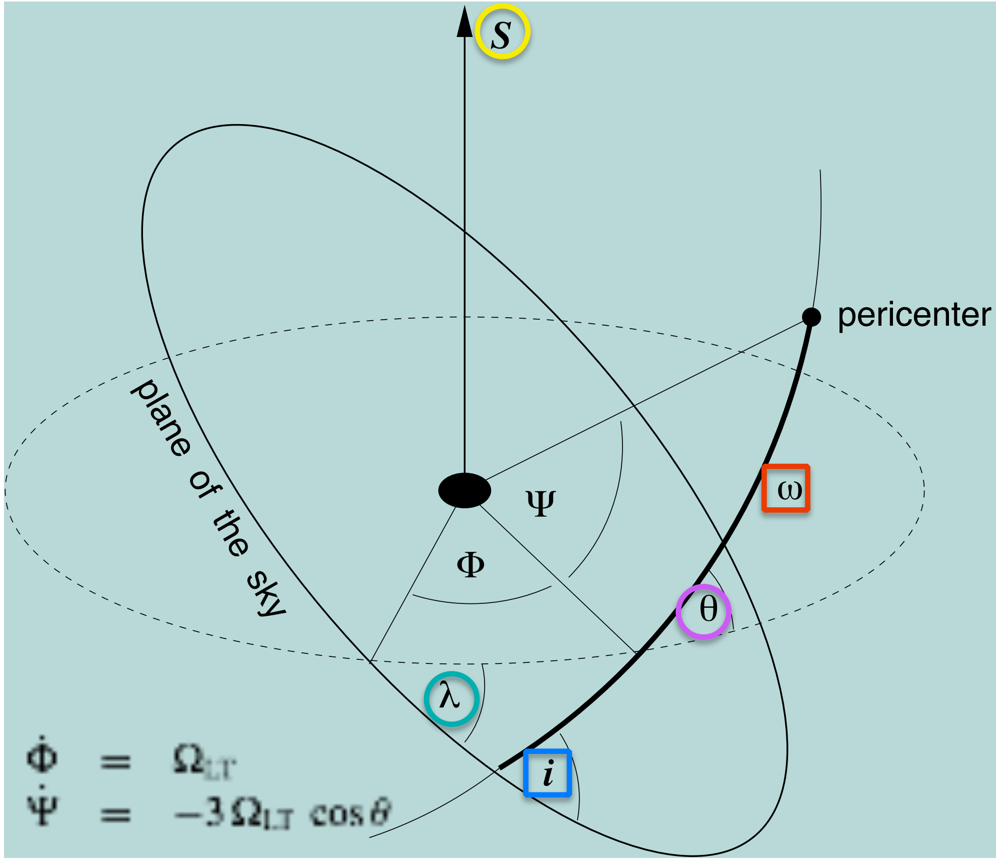
R_0 with ~1 pc uncertainty

Determining magnitude & projection of the spin of Sgr A*

Testing Cosmic Censorship Conjecture:

$$\chi \equiv \frac{c}{G}\frac{S}{M^2} \leq 1$$





[Wex & Kopeikin 1999, Liu et al. 2012]

$$\boxed{\omega} = \omega_0 + \dot{\omega}_0(T - T_0) + \tfrac{1}{2}\ddot{\omega}_0(T - T_0)^2 + \ldots$$
$$\boxed{x} = x_0 + \dot{x}_0(T - T_0) + \tfrac{1}{2}\ddot{x}_0(T - T_0)^2 + \ldots$$

Pulsar orbit P_b= 0.3 yr, e = 0.5

Weekly TOA: 100 µs

Determining magnitude & projection of the spin of Sgr A*

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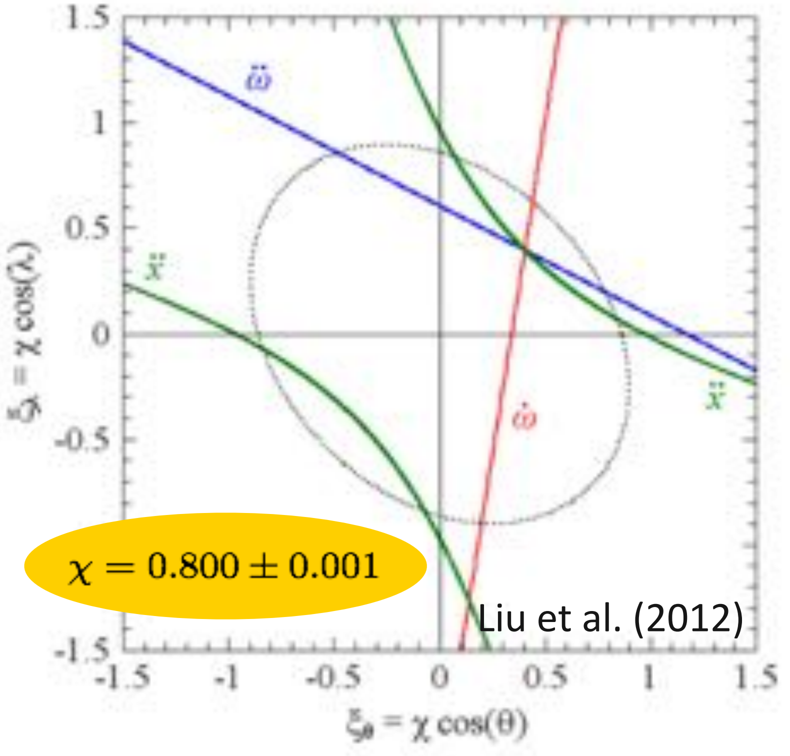
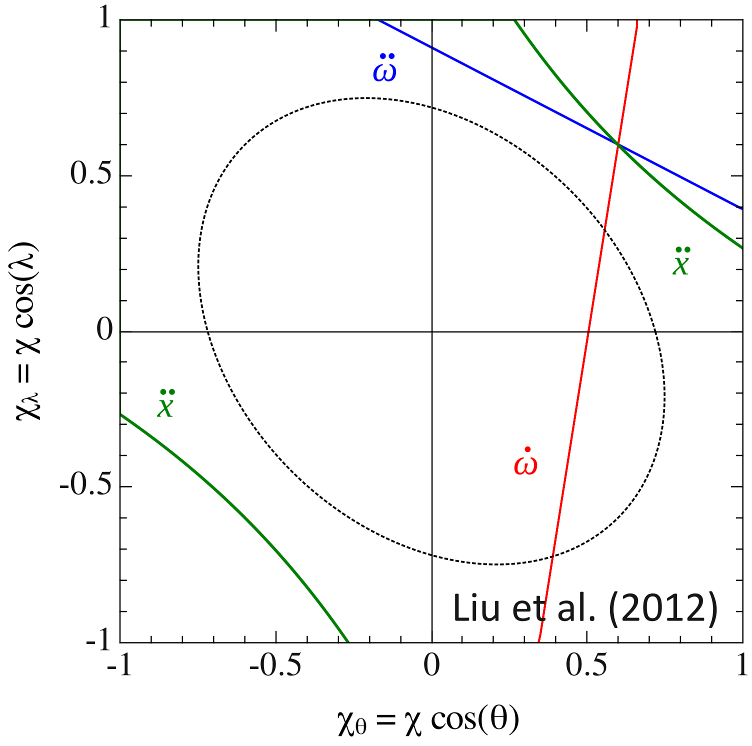


In case of a naked Kerr-singularity:



[Wex & Kopeikin 1999, Liu et al. 2012]

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Pulsar orbit P_b= 0.3 yr, e = 0.5

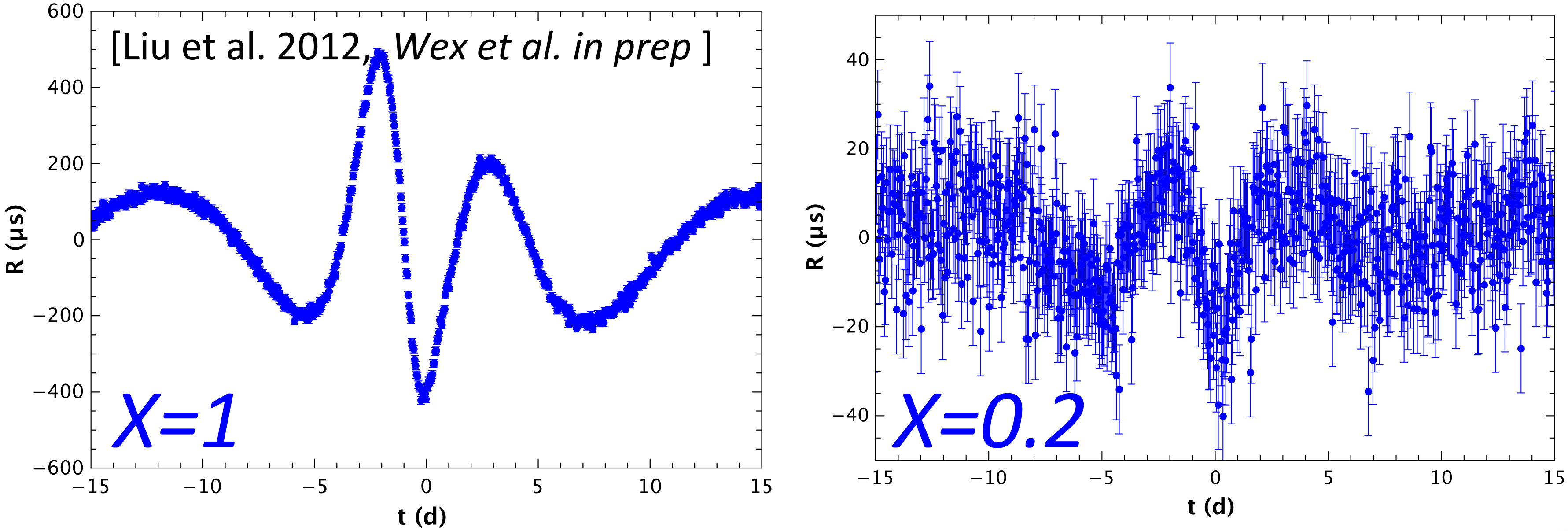
Weekly TOA: 100 μs

Testing the no-hair theorem

No-hair theorem $\Rightarrow$ $Q = -S^2/M$ (units where $c=G=1$)

Pulsar in a 0.1 yr orbit around Sgr A*:

- *Secular precession* caused by quadrupole is 2 orders of magnitude below frame dragging, and is not separable from frame-dragging
- Fortunately, quadrupole leads to *characteristic periodic residuals*

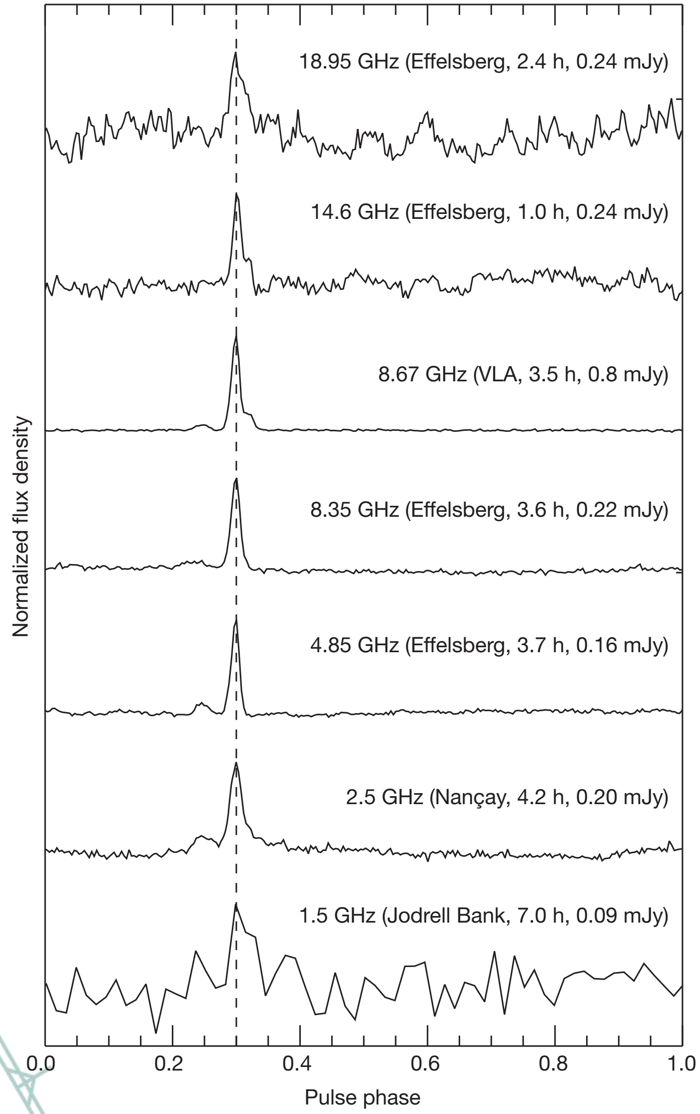


No-hair theorem testable to ~1%
(Liu et al. 2012)

In case of pertubations, see later...

The first pulsar in the Galactic Centre

Eatough et al. (2013)

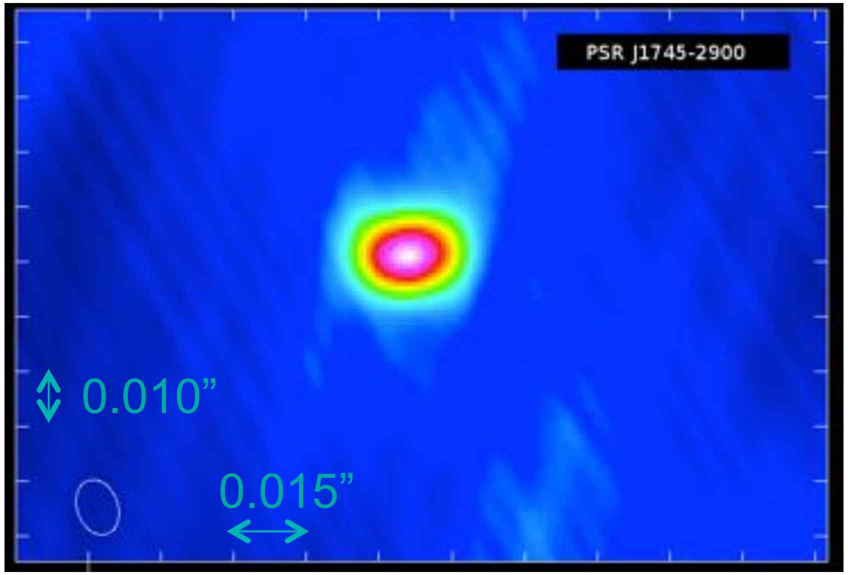


- First discovered with SWIFT (Kennea et al. ,13) and NuSTAR (Mori et al. 13)
- Pulsations at 3.76s
- Discovery by Effelsberg and later Nancay and Jodrell at radio frequencies (Eatough et al.'13)
- Observed dispersion and rotation measures place it firmly inside the Galactic Centre
- Estimated distance about 0.1pc
- It is a radio-loud magnetar = very rare NS!

Proof that pulsars exist in Galactic Centre region!!

Not normal: The interesting properties of PSR J1745-2900

- Power output from spin-down not enough to explain X-ray luminosity; likely a magnetar (Mori et al. 2013).
- Could be as close as 0.1 pc (same as S-stars). Orbital period > 500 yr – Proper motion possible with VLBI.
- Single pulses measured – Probe of Galactic Centre scattering.
- DM 1778±3 cm^{-3} pc – Highest DM known
- ~ 100% linearly polarized.
- Rotation Measure -66960±50 rad m^{-2} – Largest RM measured in the Galaxy (with exception of Sgr A*).
- Lets us probe the Galactic magnetic field at the boundary of the Bondi accretion zone of Sgr A*.



PSR J1745-2900 detection with the VLBA and JVLA. (Bower et al. 2014, 2015)

We discovered very rare pulsar! There must be more!

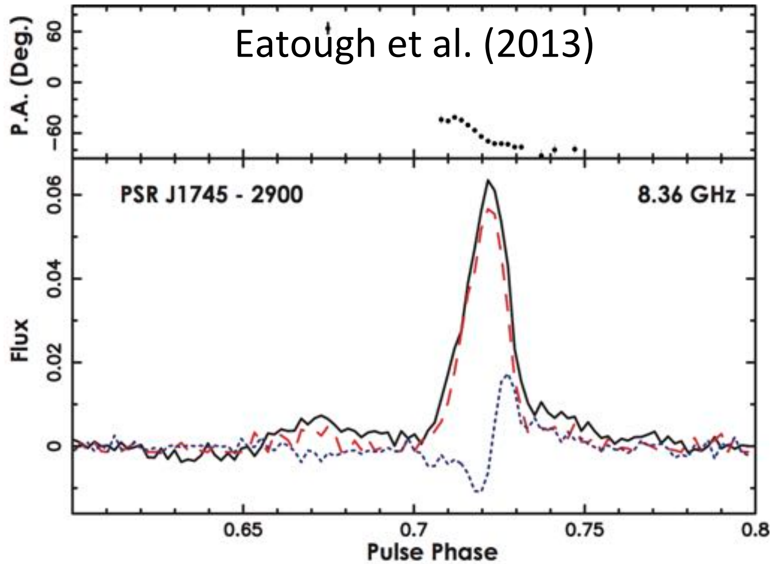
The magnetic field of Sgr A*

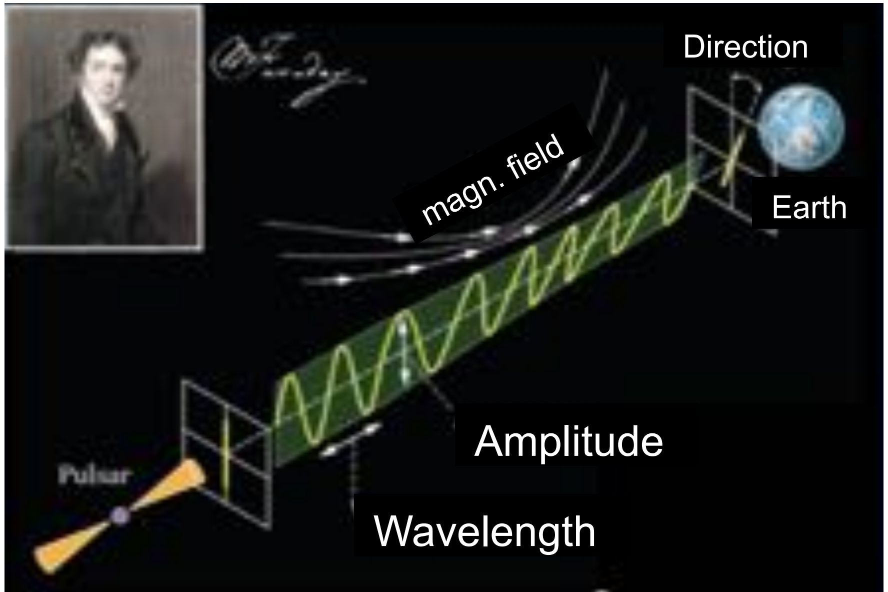
LETTER

doi:10.1038/nature12499

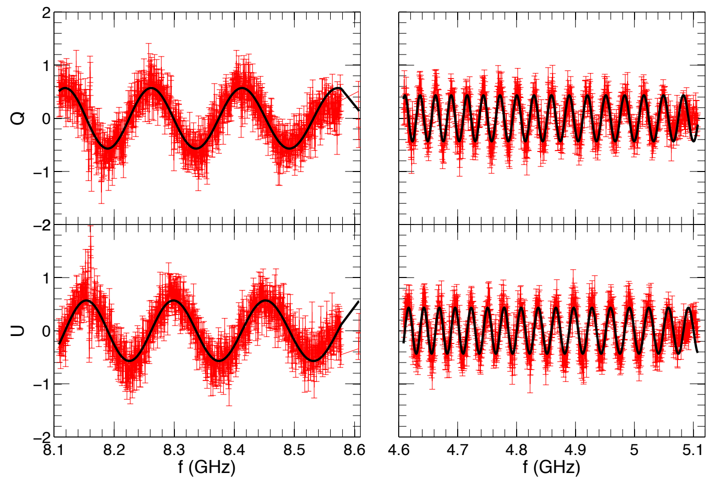
A strong magnetic field around the supermassive black hole at the centre of the Galaxy

R. P. Eatough[1], H. Falcke[1,2,3], R. Karuppusamy[1], K. J. Lee[1], D. J. Champion[1], E. F. Keane[4], G. Desvignes[1], D. H. F. M. Schnitzeler[1], L. G. Spitler[1], M. Kramer[1,4], B. Klein[1,5], C. Bassa[4], G. C. Bower[6], A. Brunthaler[1], I. Cognard[7,8], A. T. Deller[3], P. B. Demorest[9], P. C. C. Freire[1], A. Kraus[1], A. G. Lyne[4], A. Noutsos[1], B. Stappers[4] & N. Wex[1]



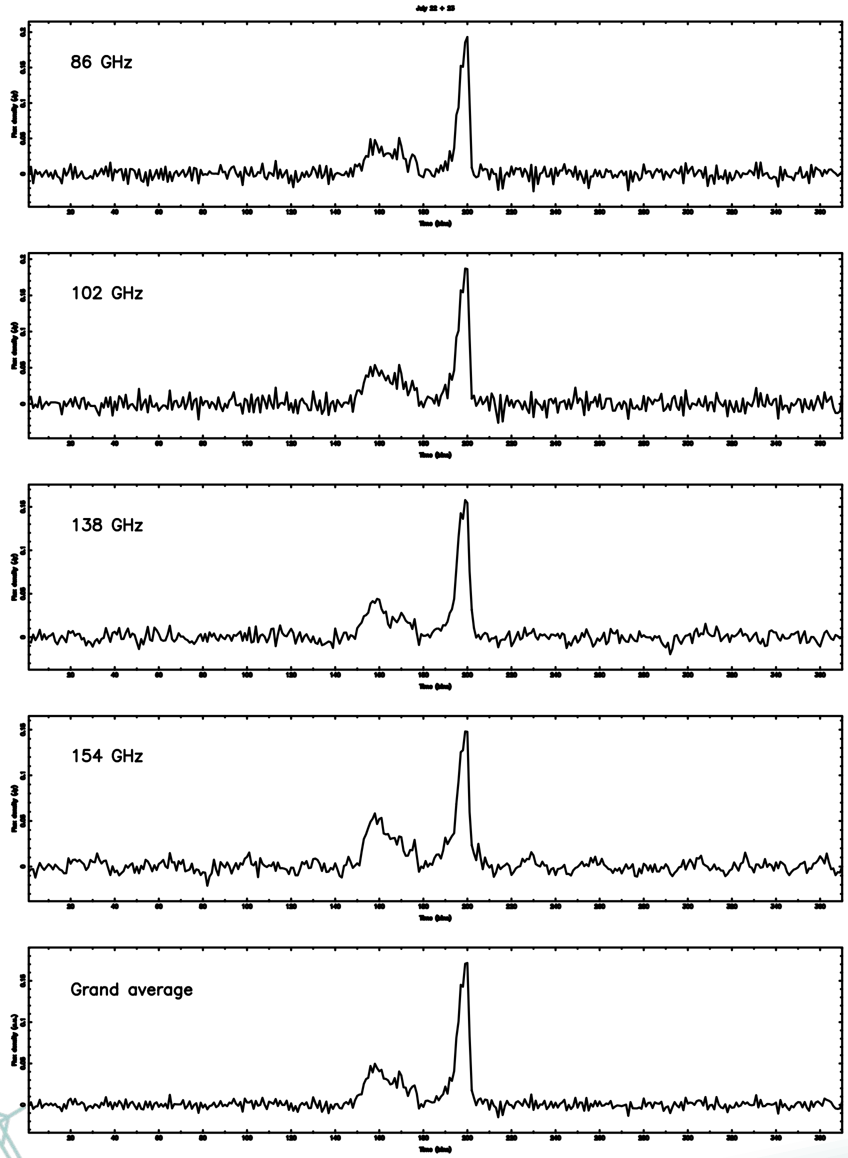


$$\Delta PA = \lambda^2 \cdot RM = \lambda^2 \cdot 0.812 \int_{PSR}^{\oplus} n_e(l) B_{\parallel}(l) dl$$

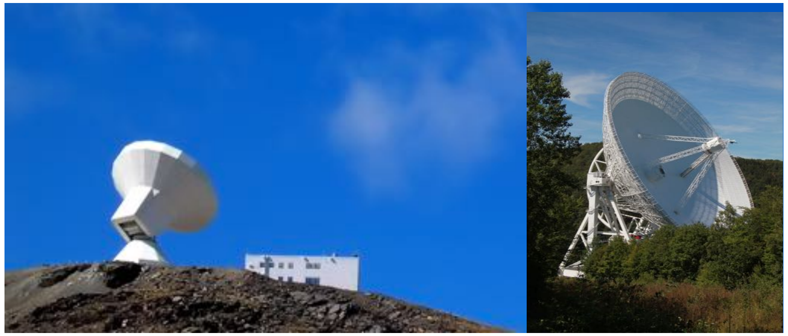


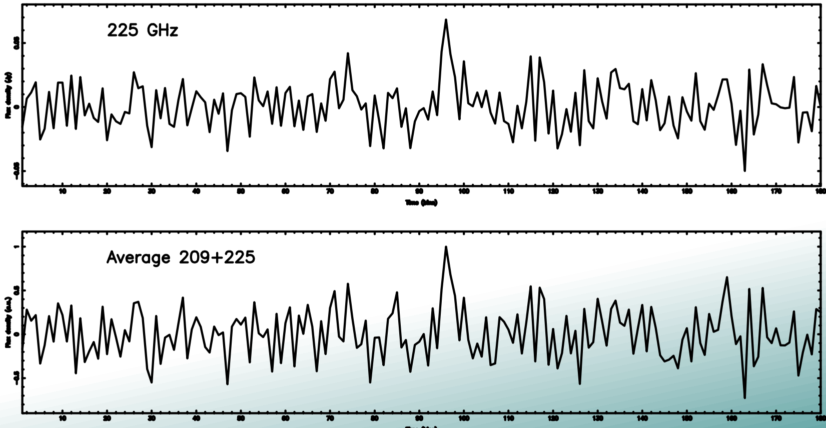
Record observations of the GC Magnetar

Torne et al. (to be submitted)

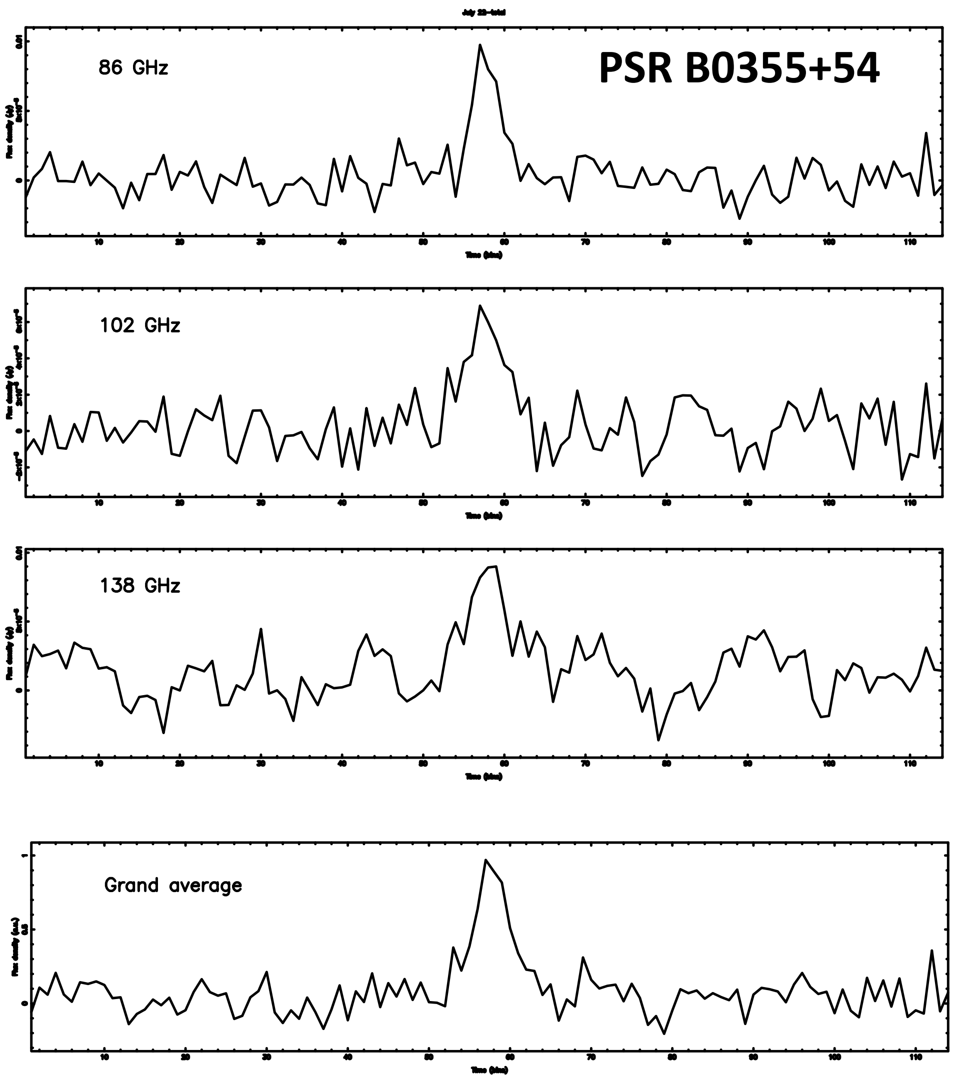


- Detection up to 154 GHz, perhaps even 225 GHz!
- Single pulses up to 154 GHz!
- Simultaneous observations with Pico Veleta and Effelsberg: 5-154 GHz





Also normal pulsars detectable!



New record!

Detection also at 102 & 134 GHz

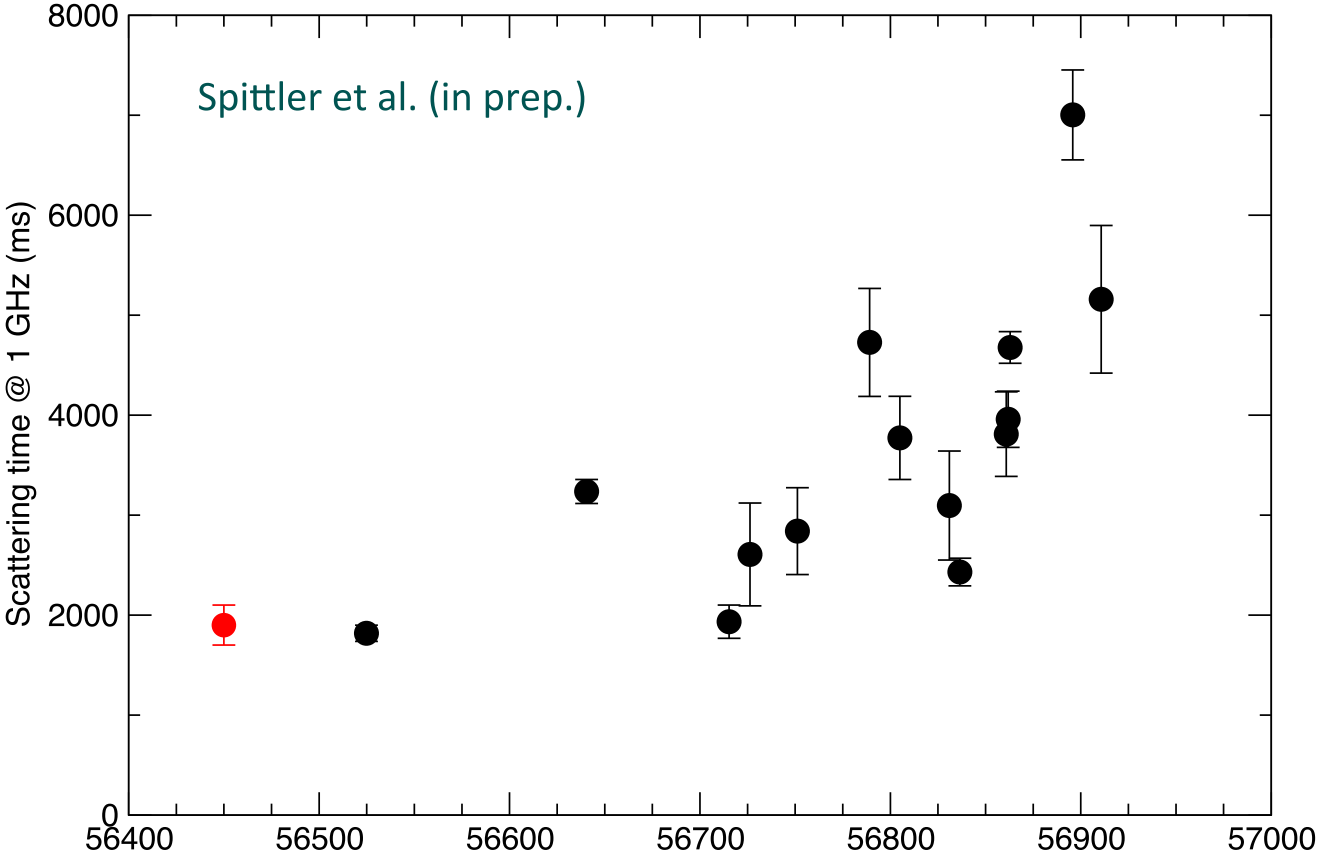
Change of spectrum?

We can detect pulsars at ALMA frequencies!

Torne et al. (to be submitted)

Where are the pulsars? – Scattering revisited

- Based on our measurements of the scattering for the magnetar (Spitler et al. 2013) lots of people have claimed that there are not any pulsars, since scattering so low
- However, medium is very turbulent and there is a lot of "weather" – new result:

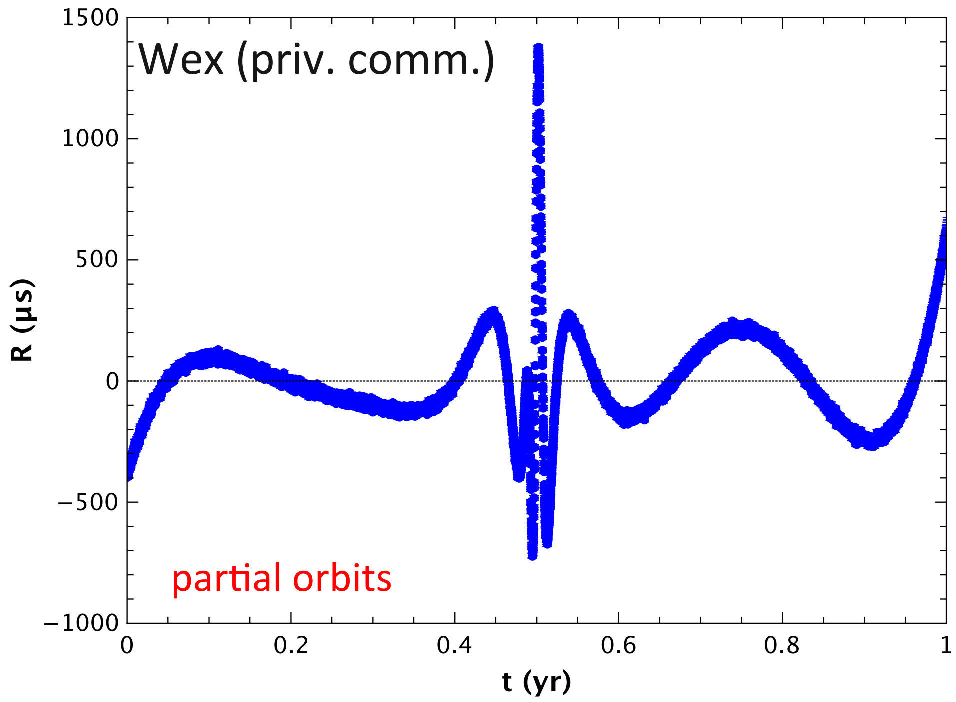


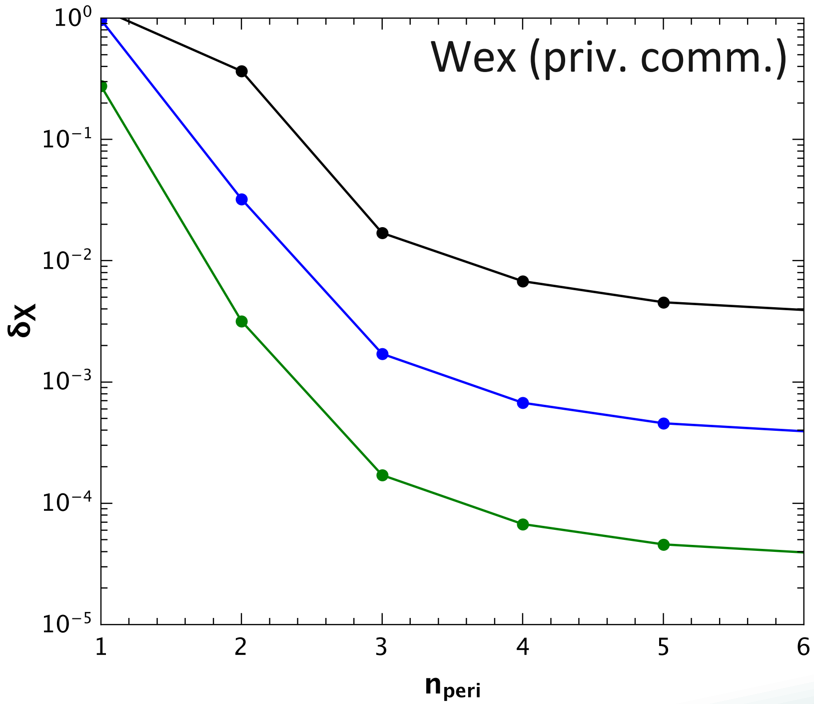
➔ Scattering material is close to source, consistent with RM change!

➔ We may not see pulsars all the time!

Partial visibility & External perturbations

- In Wex et al. (in prep.) we develop full dynamic treatment of pulsar timing about SGR A*
- We go beyond beyond Wex & Kopeikin (1999) and Liu et al. (2012) to study residuals
- Only measuring part of orbit around pericentre sufficient to determine spin





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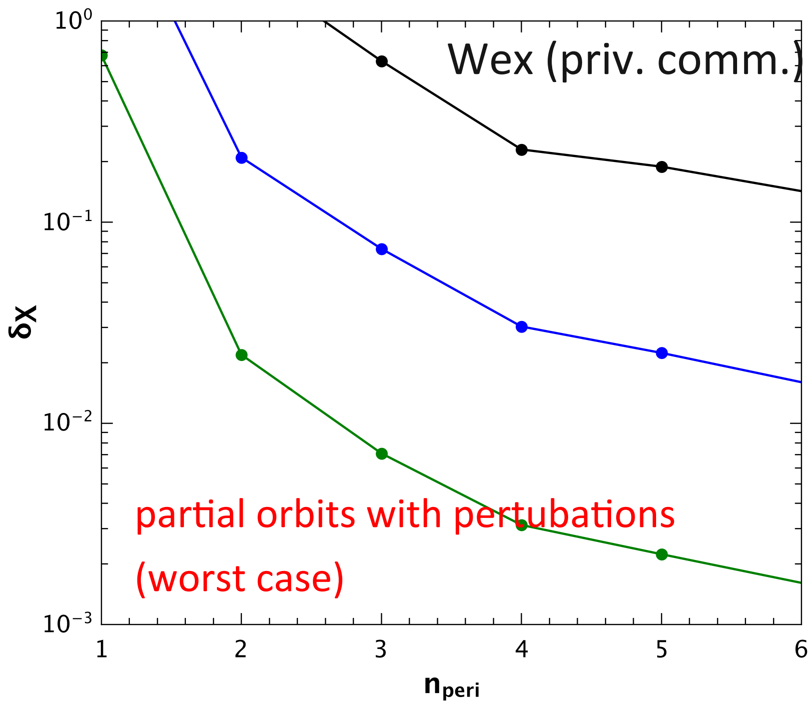
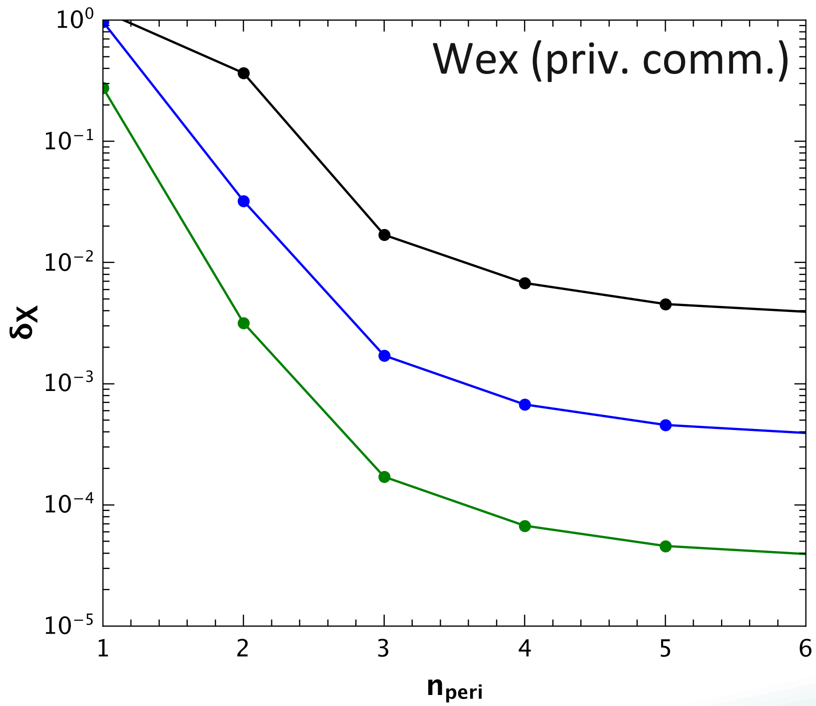
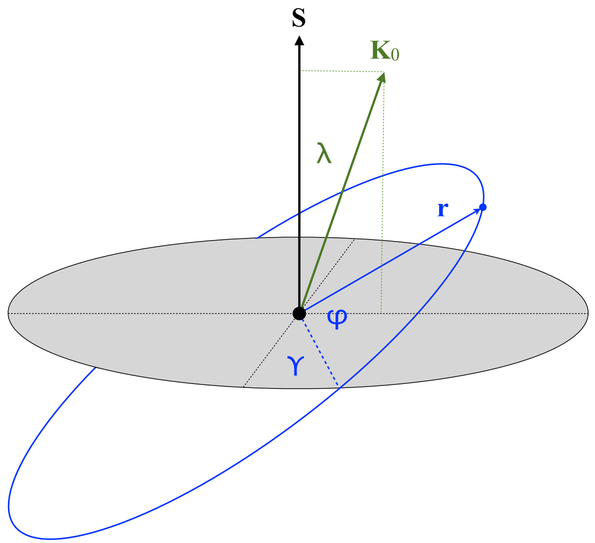


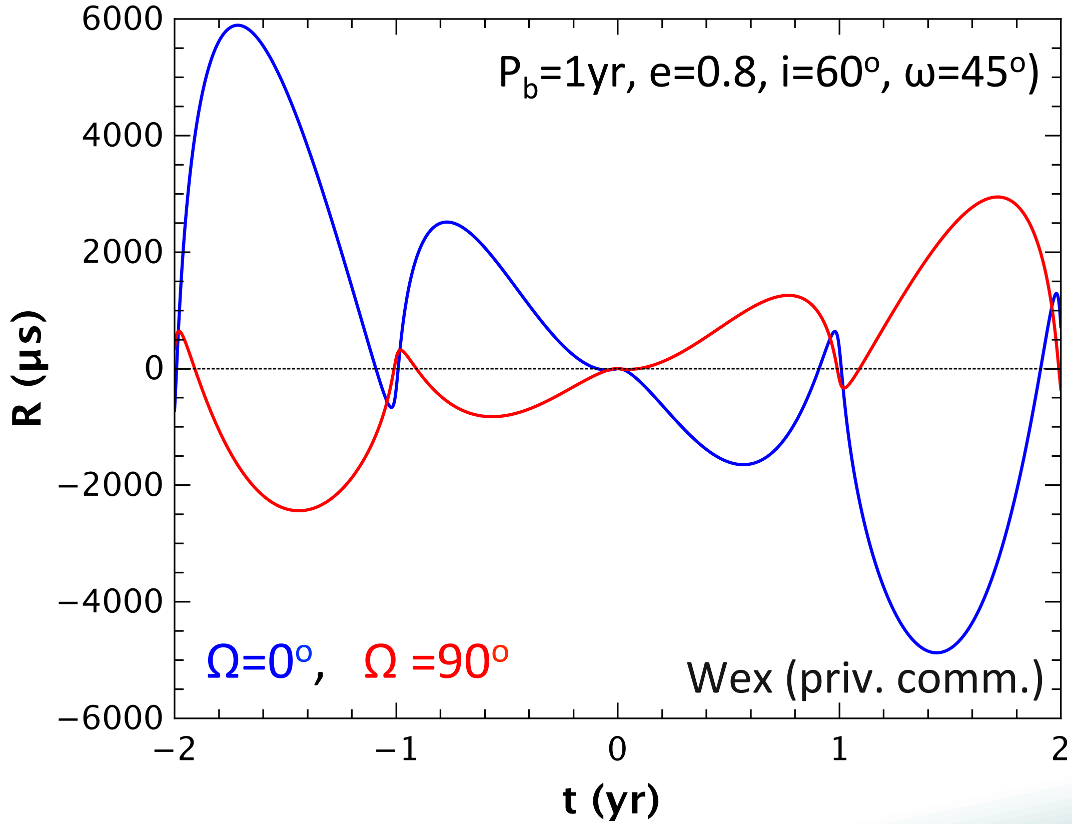


- Even in case of perturbations – which will act away from pericentre – we can use partial orbit observations to measure spin!

3D-direction of BH spin from pulsar orbit

- In Wex et al. (in prep.) we show that the relative motion of SGR A* to SSB affects <u>observed</u> pulsar orbit in a dramatic way that allows us to determine full BH spin (not only projections!):

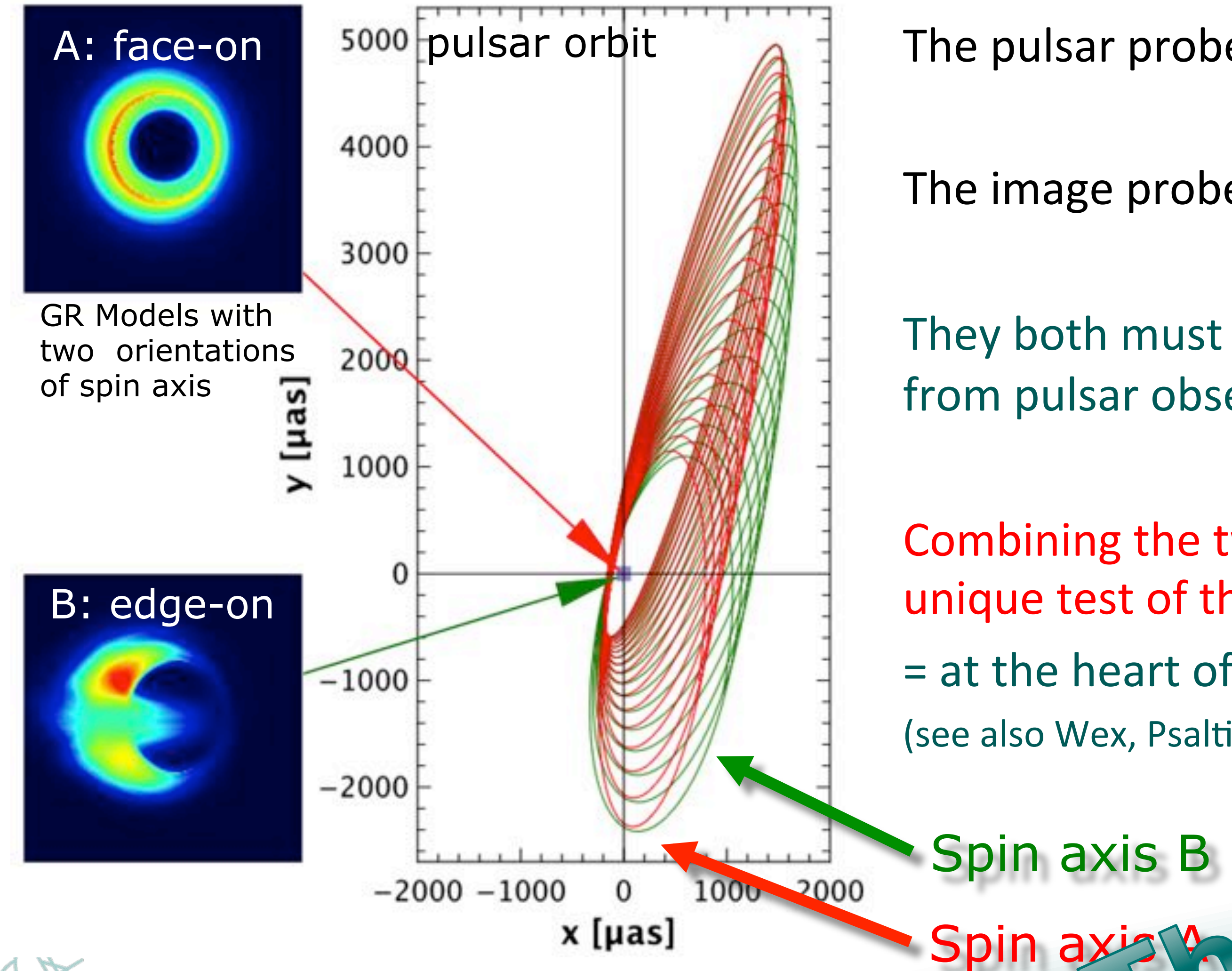




We can compare these precision measurement to EHT results...

Combining the image and pulsars

A single pulsar can give you precise spin & direction – potentially very cleanly!



The pulsar probes the far-field.

The image probes the near-field.

They both must fit, i.e. predict image from pulsar observations and compare.

Combining the two information is a unique test of theories of gravity

= at the heart of ERC BlackHoleCam

(see also Wex, Psaltis & Kramer, in prep.)

Thank you!