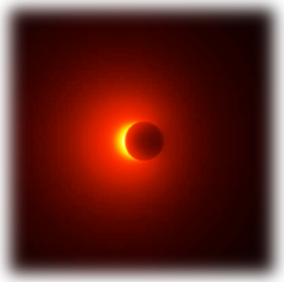
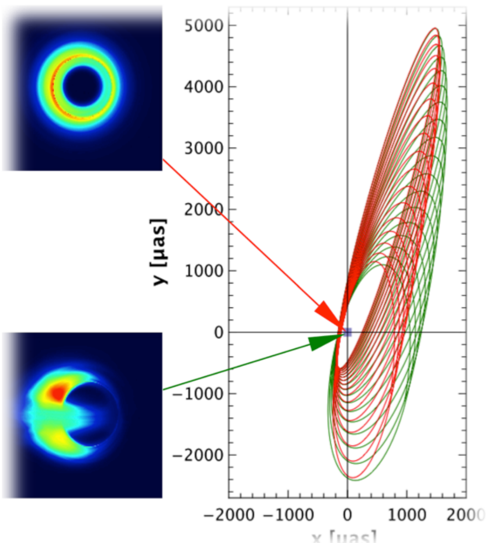
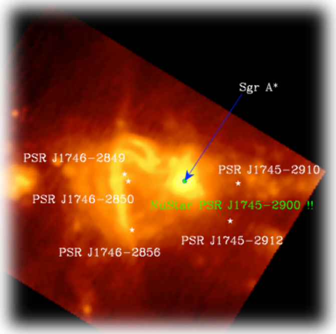
Finding and exploiting pulsars in the Galactic Centre







Michael Kramer

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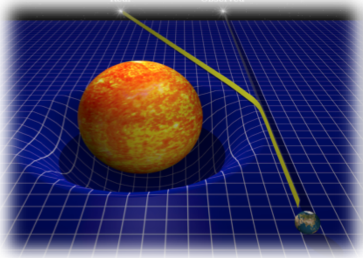
Understanding Gravity

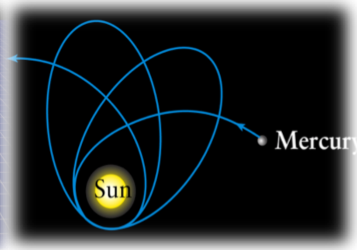
General relativity conceptually different than description of other forces

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

Classical tests:

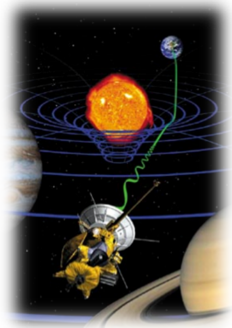
- Mercury perihelion advance
- Light-deflection at Sun
- Gravitational redshift





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)



But, is there a problem..?

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

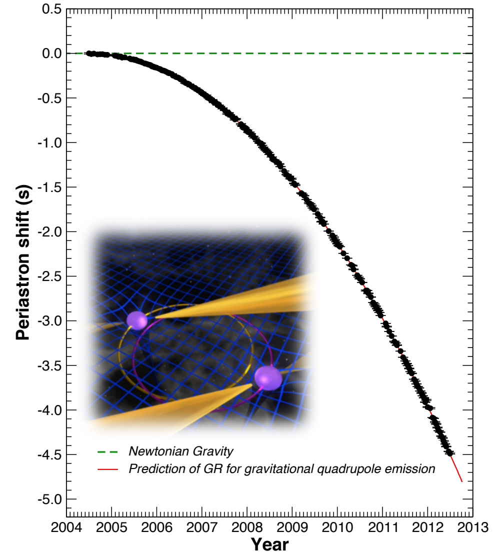
Question: Will Einstein have the last word on (macroscopic) gravity

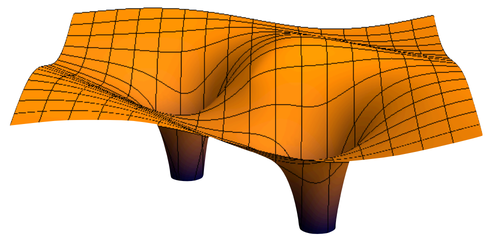
does GR fail far below the Planck energy? Alternatives?

We need to test gravity in strong, non-linear conditions.

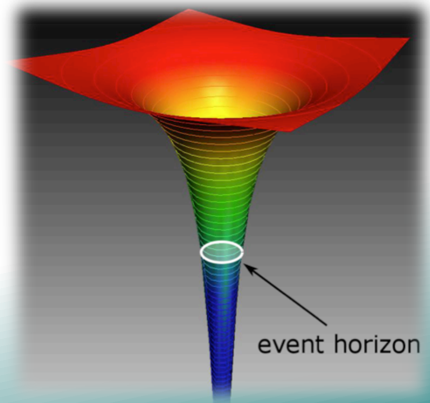
What are the properties of black holes and also gravitational waves.

Kramer et al. (2015)





(LR/ITP)



Dipolar Gravitational Radiation in Binary Systems?

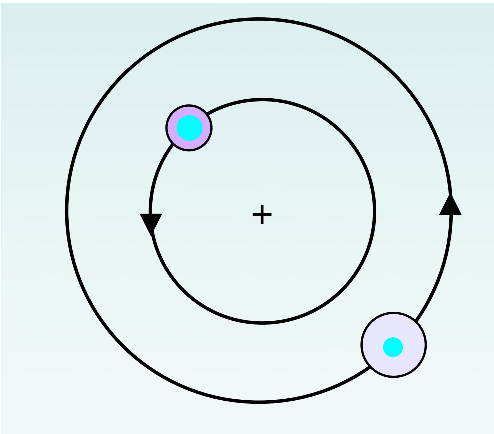
Unlike GR, most alternative theories of gravity – including tensor-scalar theories – predict other radiation multipoles that dominate the energy loss of the orbital dynamics:

$$\text{Energy flux} = \frac{\text{Quadrupole}}{c^5} + O\left(\frac{1}{c^7}\right) \quad \text{spin 2}$$

$$+ \frac{\text{Monopole}}{c}\left(0 + \frac{1}{c^2}\right)^2 + \frac{\text{Dipole}}{c^3} + \frac{\text{Quadrupole}}{c^5} + O\left(\frac{1}{c^7}\right) \quad \text{spin 0}$$

Dipole term: $\propto (\alpha_A - \alpha_B)^2$

Hence, visible in orbital decay:



$$\dot{P}_{\rm b}^{\rm quadrupole} \propto \left(\frac{v}{c}\right)^5$$

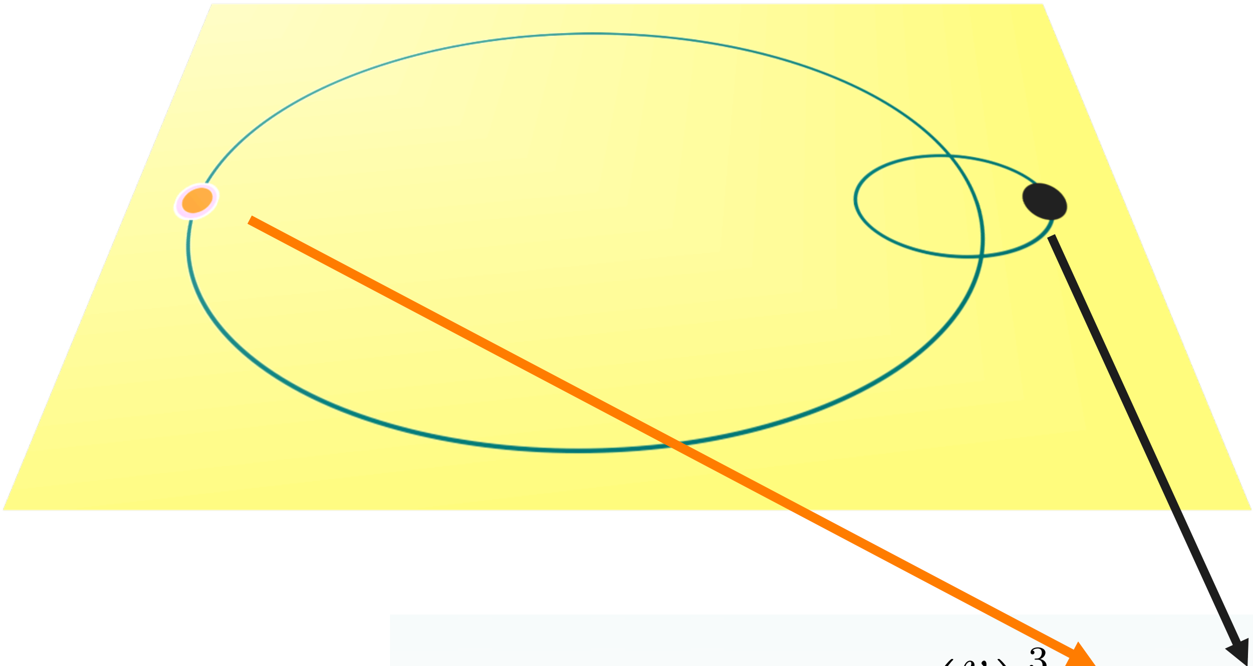
$$\dot{P}_{\rm b}^{\rm dipole} \propto \left(\frac{v}{c}\right)^3 (\alpha_A - \alpha_B)^2$$

$\dot{P}_{\rm b}^{\rm dipole}$: = 0 in GR

$(\alpha_A - \alpha_B)^2$: ~ 0 in Double Pulsar since $\alpha_A \approx \alpha_B$

<u>Dipolar</u> Gravitational Radiation in Binary Systems?

Unlike GR, most alternative theories of gravity – including tensor-scalar theories – predict other radiation multipoles that <u>dominate</u> the energy loss of the orbital dynamics:

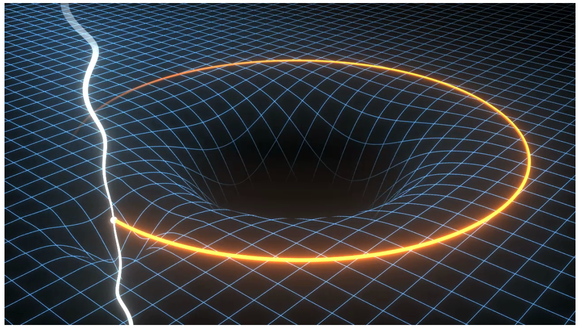


$$\dot{P}_{\mathrm{b}}^{\mathrm{dipole}} \propto \left(\frac{v}{c}\right)^3 (\alpha_A - \alpha_B)^2$$

- PSR-BH system would be best as BH would have zero scalar charge
- Hence, we can use PSR-BH system as lab for both GW and BH properties

Observations of Black Holes Properties

- We need to trace the spacetime around a black hole – ideally in a clean way!
- In a perfect world, we have a clock around it…
- …in a nearly perfect world, we have a pulsar!
- See Wex & Kopeikin (1999) for a first recipe and Liu et al. (2012) for more details



- Spin from Lense-Thirring/spin-orbit coupling ("wobble of orbit"):

$$\begin{aligned} \omega &= \omega_0 + (\dot{\omega}_{\rm PN} + \dot{\omega}_{\rm LT})(T - T_0) + \tfrac{1}{2}\ddot{\omega}_{\rm LT}(T - T_0)^2 + \ldots \\ x &= x_0 + \dot{x}_{\rm LT}(T - T_0) + \tfrac{1}{2}\ddot{x}_{\rm LT}(T - T_0)^2 + \ldots \end{aligned}$$

[Wex & Kopeikin 1999; Liu 2012; *Liu et al. 2014*]

With a fast millisecond pulsar about a 10-30 $M_\odot$ BH, we practically need the SKA:

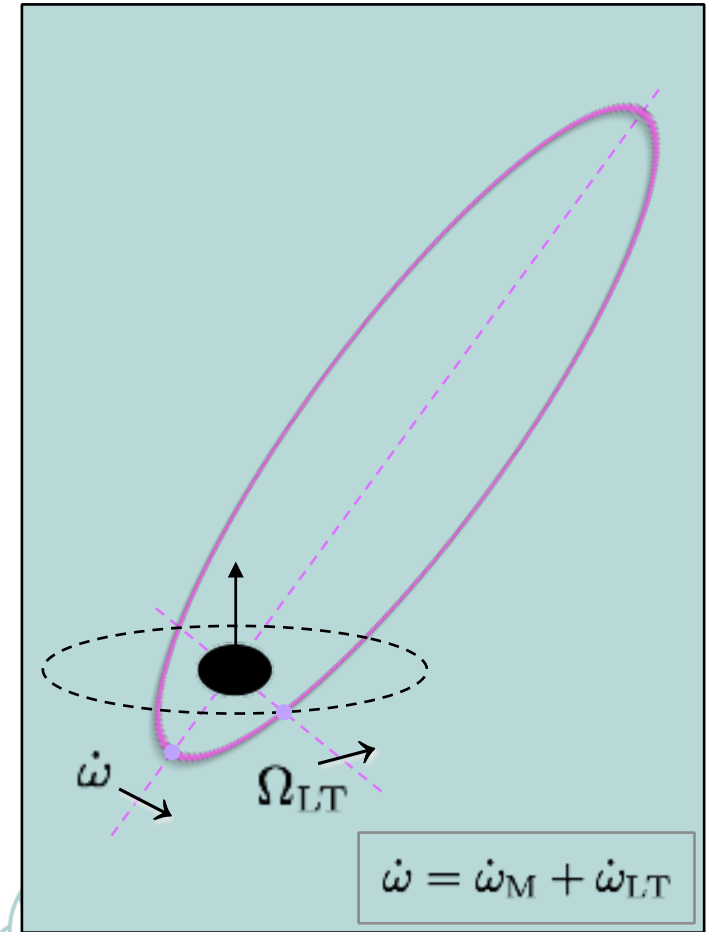
→

BH mass with precision < 0.1%
BH spin with precision < 1%
Cosmic Censorship: $S < GM^2/c$

A more massive BH with pulsars would be much easier…

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

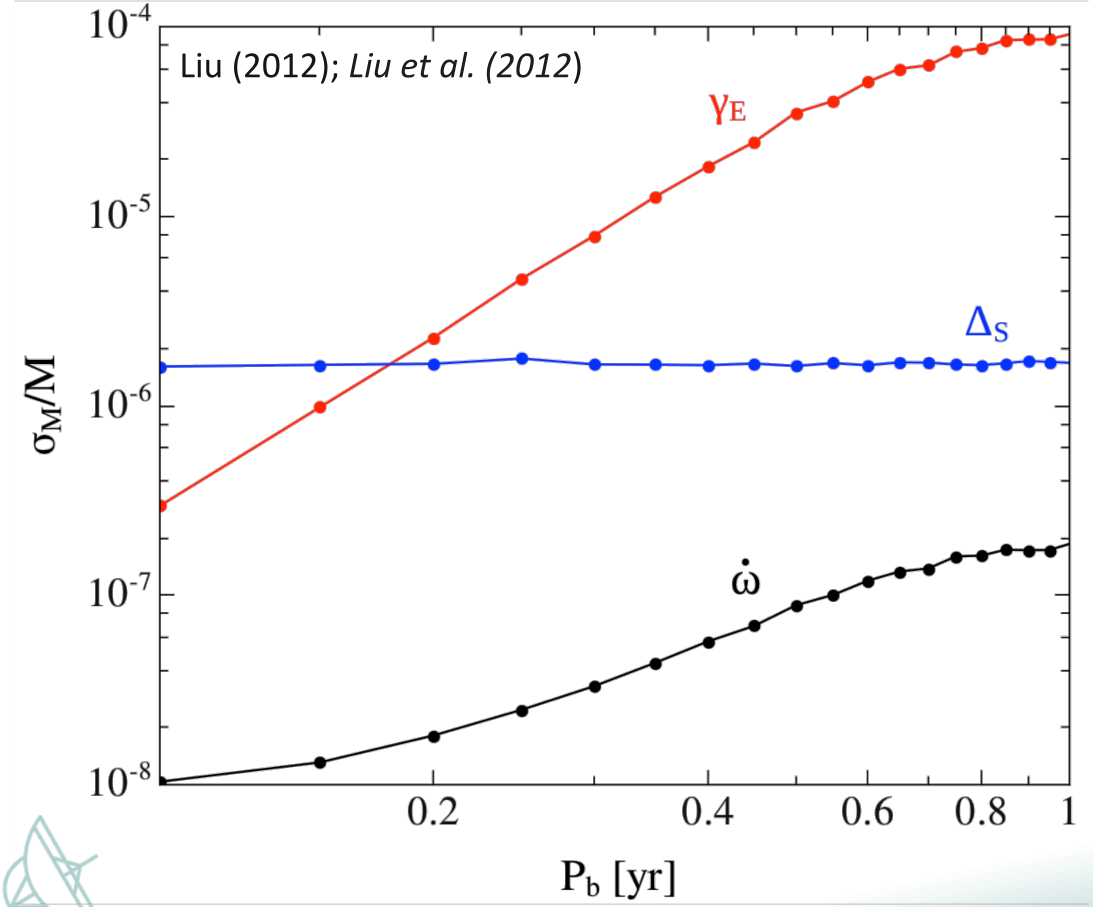
Similar contribution to $\dot{\omega}$

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!

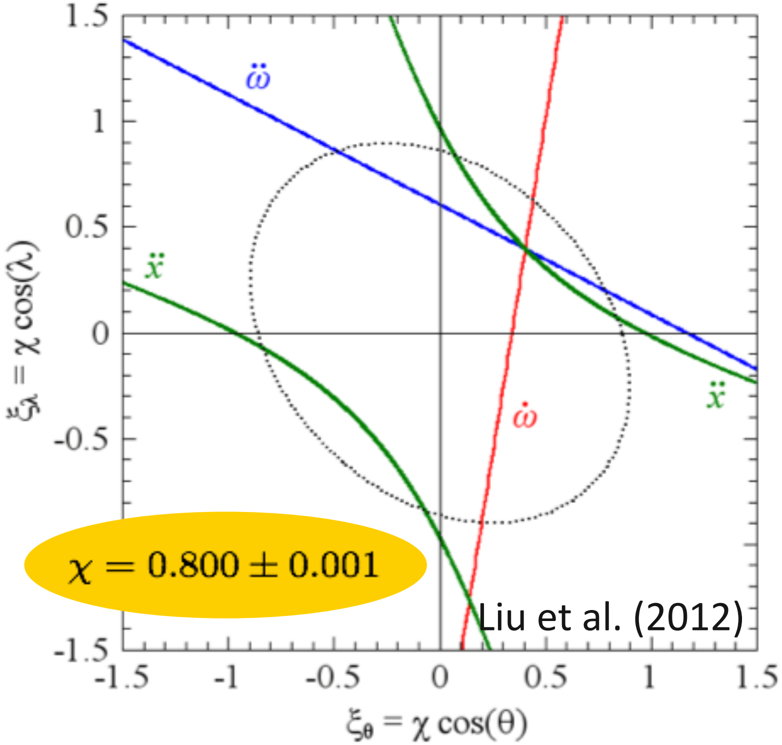
Combining with 10 µas astrometry from e.g. GRAVITY

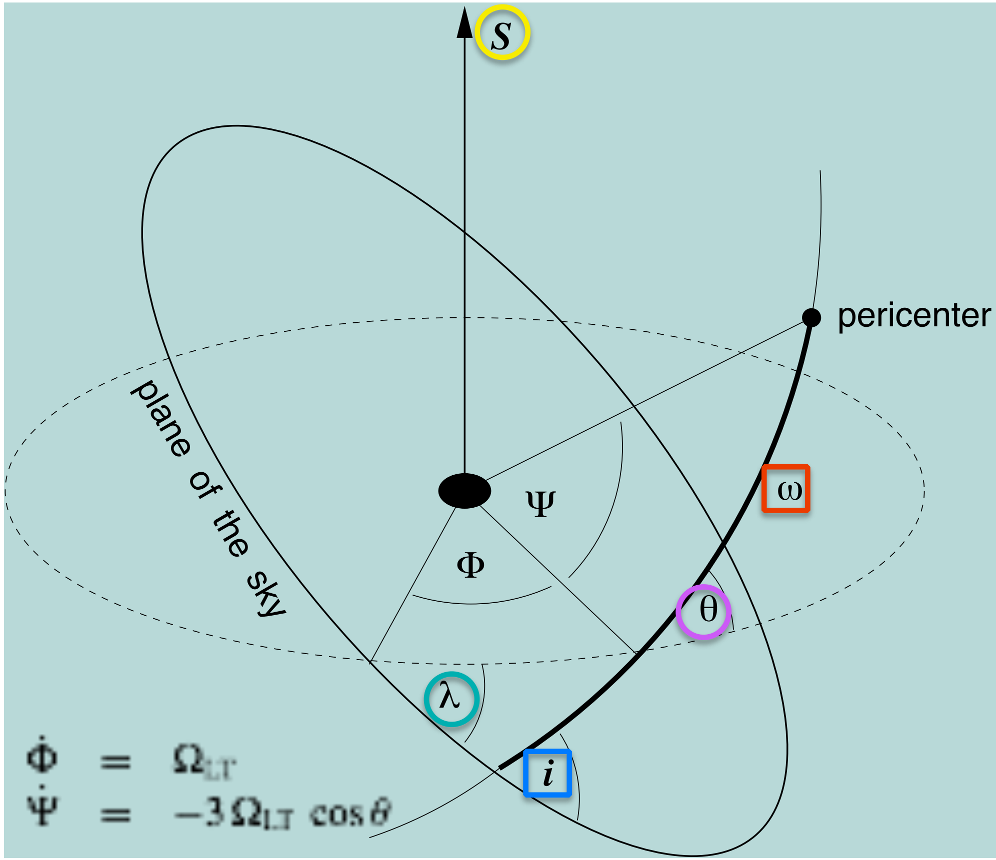
R_0 with ~1 pc uncertainty

Determining 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]

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

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

Pulsar orbit P_b= 0.3 yr, e = 0.5

Weekly TOA: 100 µs

Determining the spin of Sgr A*

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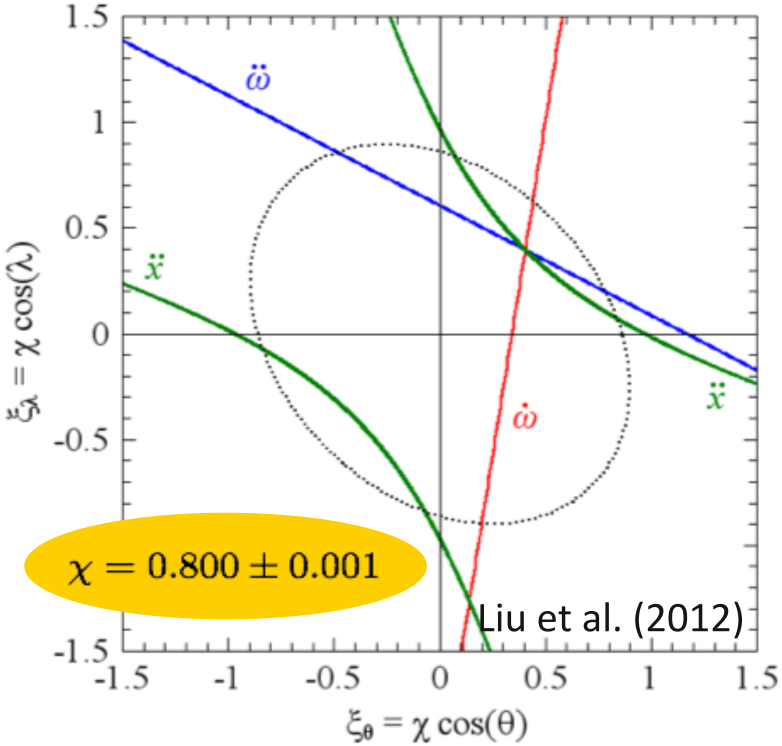
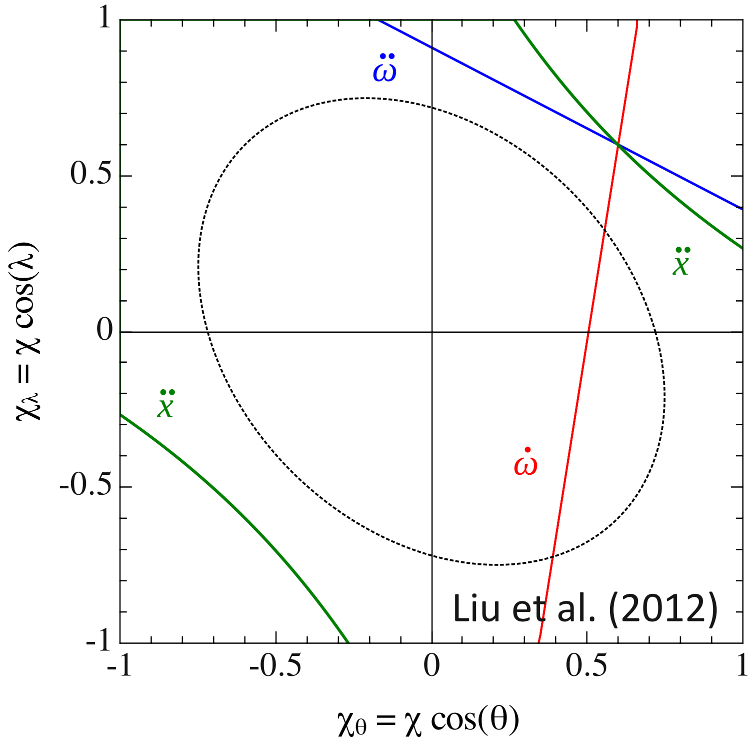


In case of a naked singularity:



[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

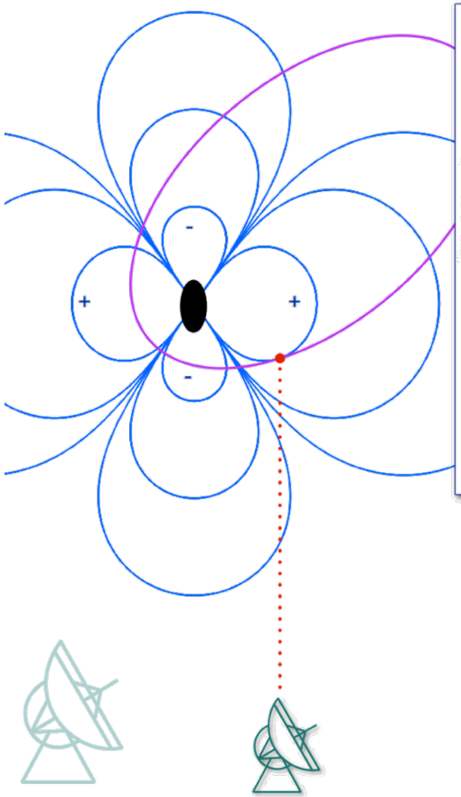
Testing the no-hair theorem

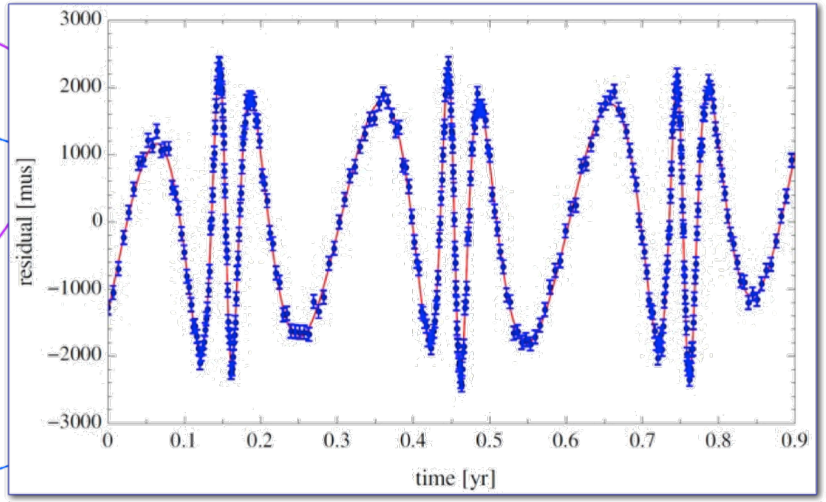
No-hair theorem $\Rightarrow$ $Q = -S^2/M$ (units where c=G=1)

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* of order msecs

Simulation: Extreme Kerr, 3 orbits, 160 TOAs with 100 µs error, e = 0.4





→ $\delta Q/Q = 0.008$

No-hair theorem to ~1%

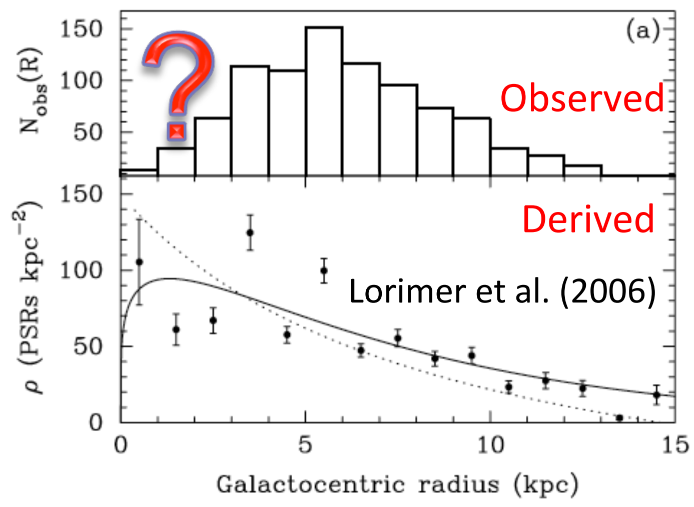
[*Liu et al. 2012*]

$$q \equiv \frac{c^4}{G^2}\frac{Q}{M^3} = -\chi^2 \quad \text{(no-hair theorem)}$$

In case of pertubations, see later...

Are there pulsars?

- 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 (in fact, already doing – see later)



- 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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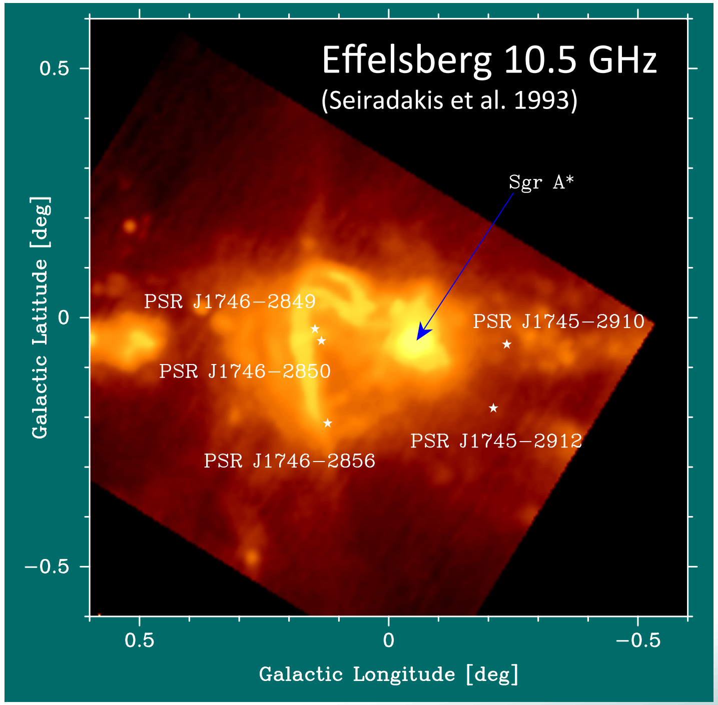
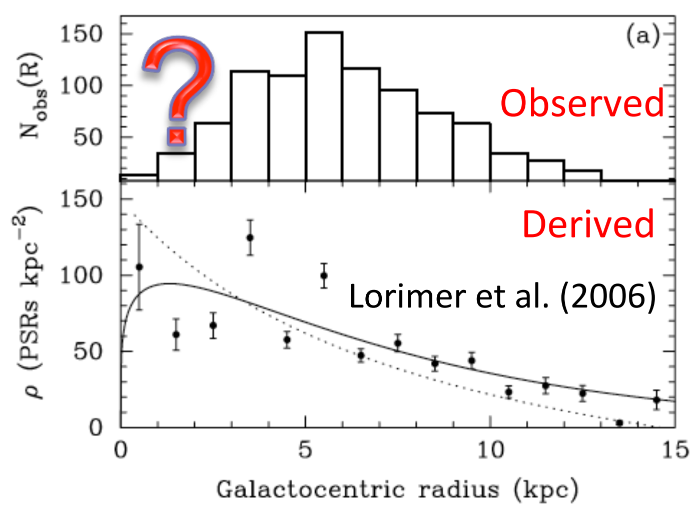
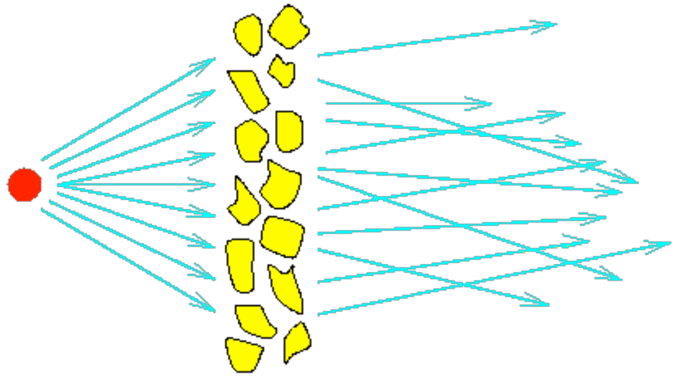
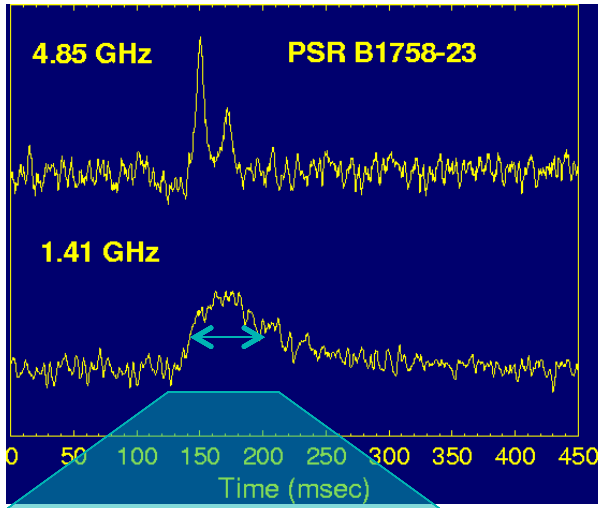




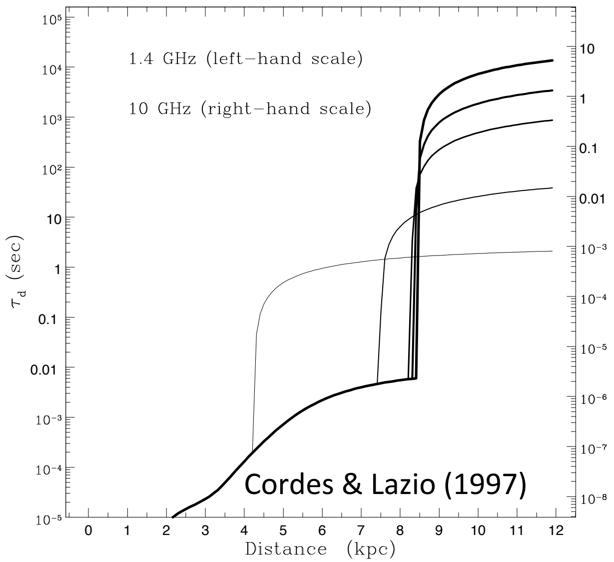
Selection effects – Why is it so hard?

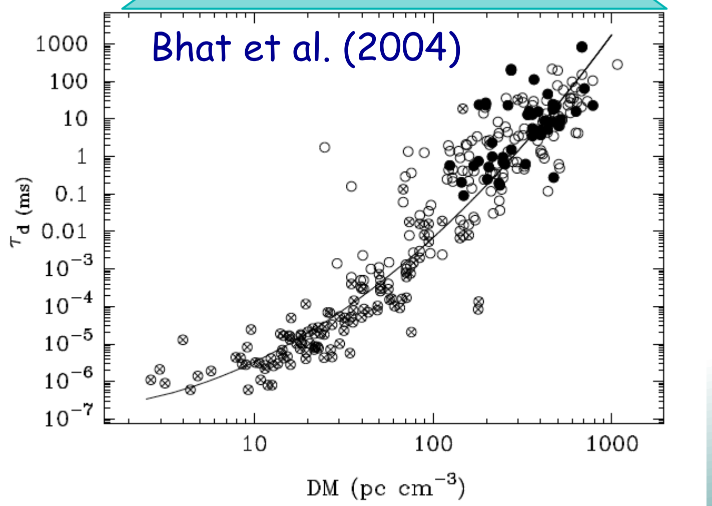
The inhomogeneous ionized ISMs smears and scatters the pulses (NB: dispersion is easy…) :





Expected scattering time may be enormous:



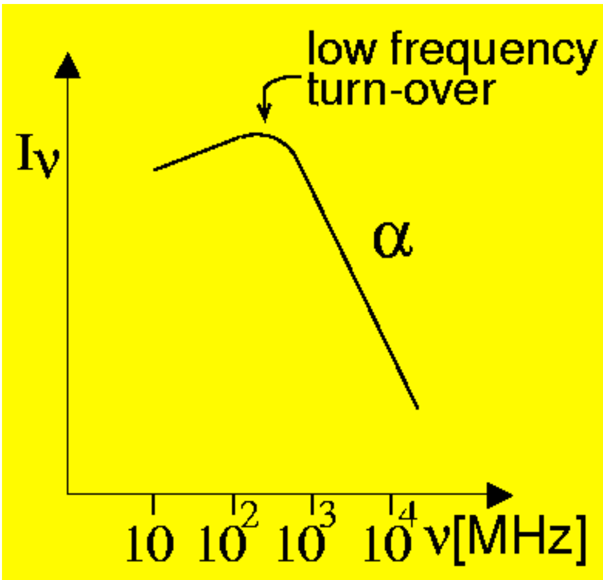


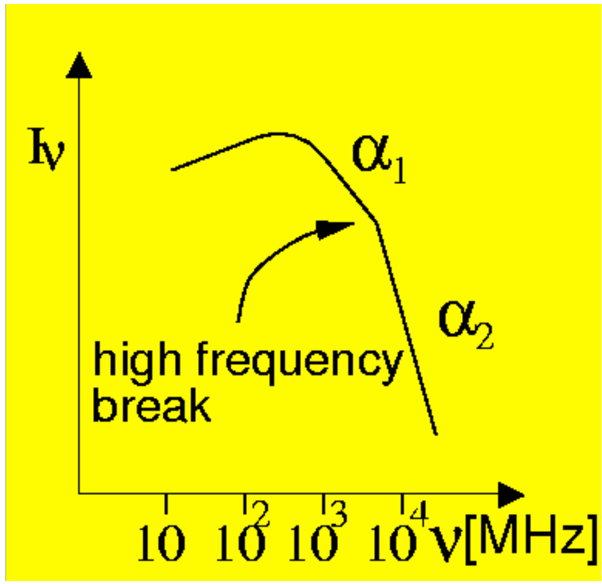
➔ In particular at the centre:

At “normal” search frequencies pulses may be undetectable!

Why not observing at very high frequencies?

- Pulsars generally have steep flux density spectra (mean spectral index of -1.7)



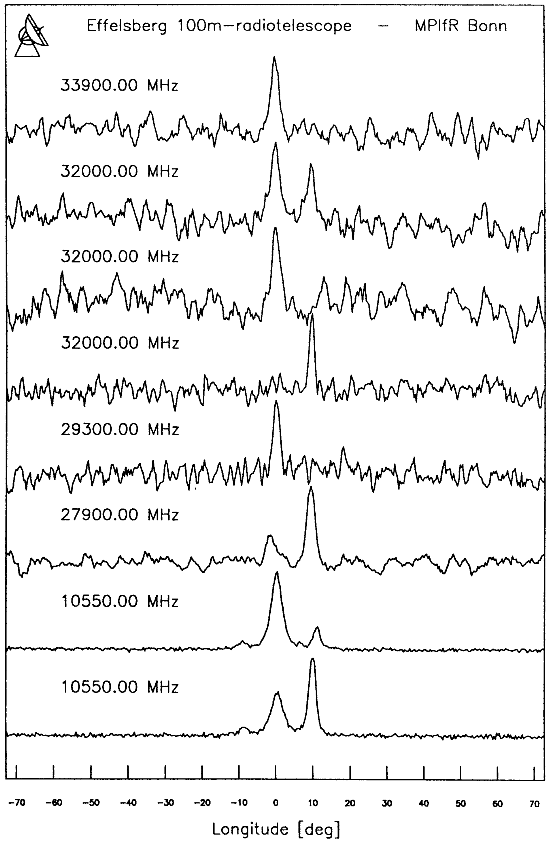


- We know most about pulsars from frequencies < 2 GHz (note: in past < 700 MHz!)
- The suitability of pulsars as clocks scales inversely with the signal-to-noise ratio
- We need sensitivity at high frequencies – for now it is difficult.

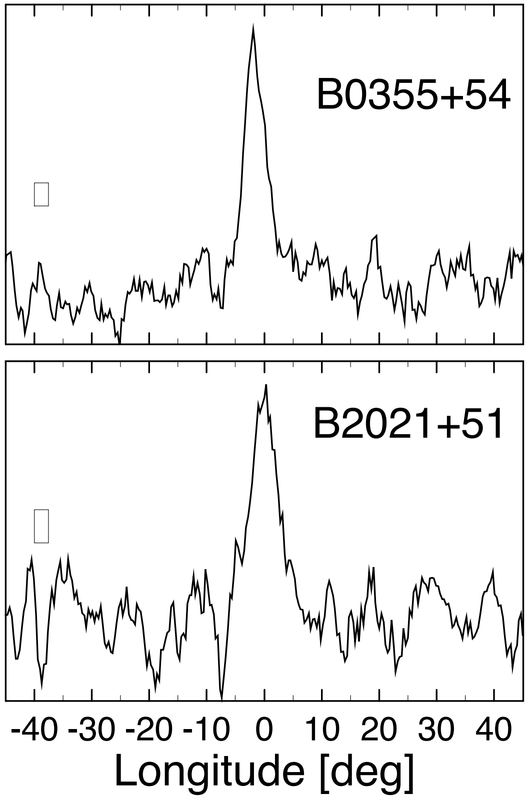
Observations at mm-wavelengths

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

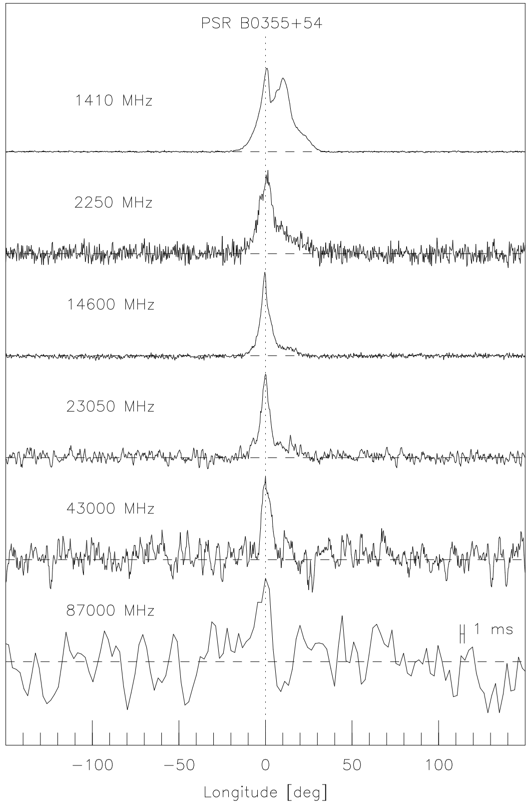
9mm



7mm



3mm



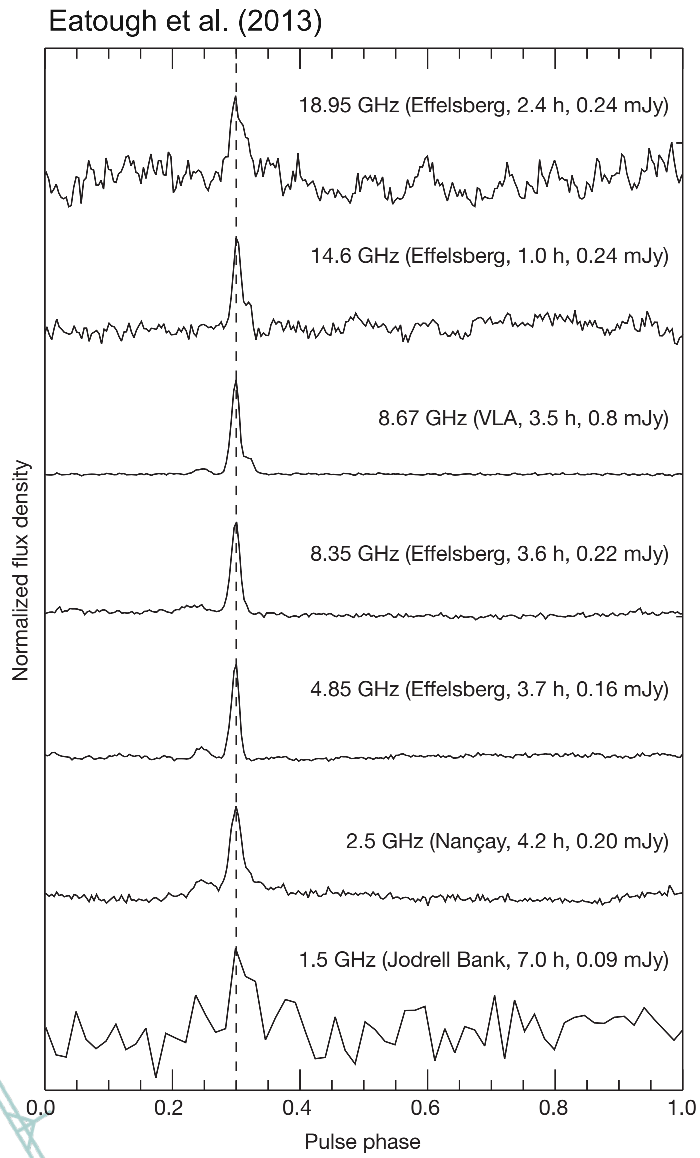
Kramer et al. (1996)

Kramer et al. (1997)

Morris et al. (1997)

But we still need more pulsars...!

The first pulsar in the Galactic Centre

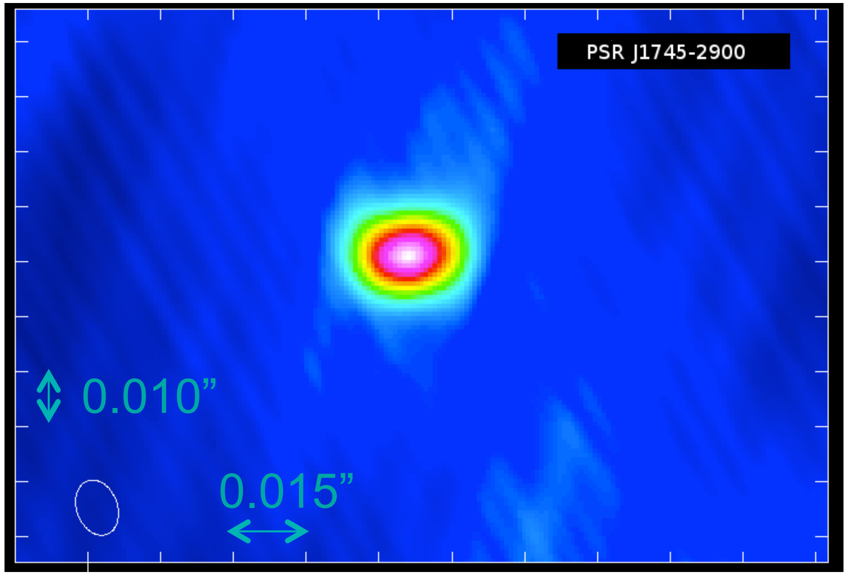


- First discovered with SWIFT (Kennea et al. ,13) and NuSTAR (Mori et al. 13)
- Pulsations at 3.76s
- Discovery by Effelsberg and later Nancay and Jodrell at radio frequencies (Eatough et al.'13)
- Observed dispersion and rotation measures place it firmly inside the Galactic Centre
- Estimated distance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

Proof that pulsars exist in Galactic Centre region!!

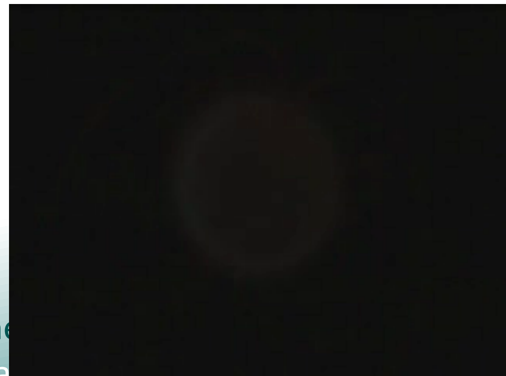
Not normal: The interesting properties of PSR J1745-2900

- 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 (Bower et al.)
- Single pulses measured – Probe of Galactic Centre scattering (Spittler et al. 2013, 2015)
- 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*, Eatough et al. 2013)
- Lets us probe the Galactic magnetic field at the boundary of the Bondi accretion zone of Sgr A* (Eatough et al. 2013)



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

We discovered very rare pulsar! There must be more!



If we had even more pulsars...

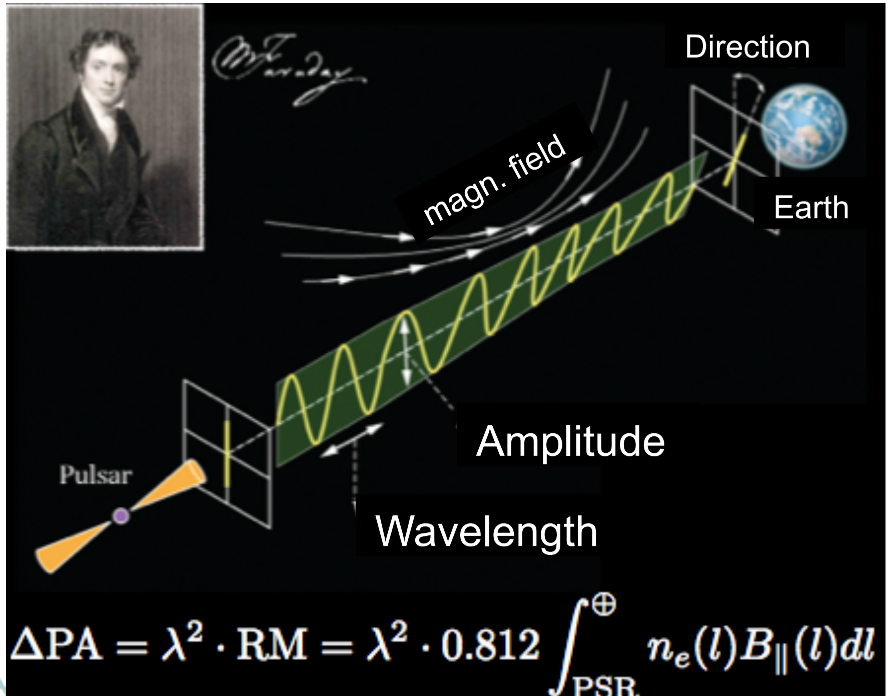
The magnetic field of Sgr A*

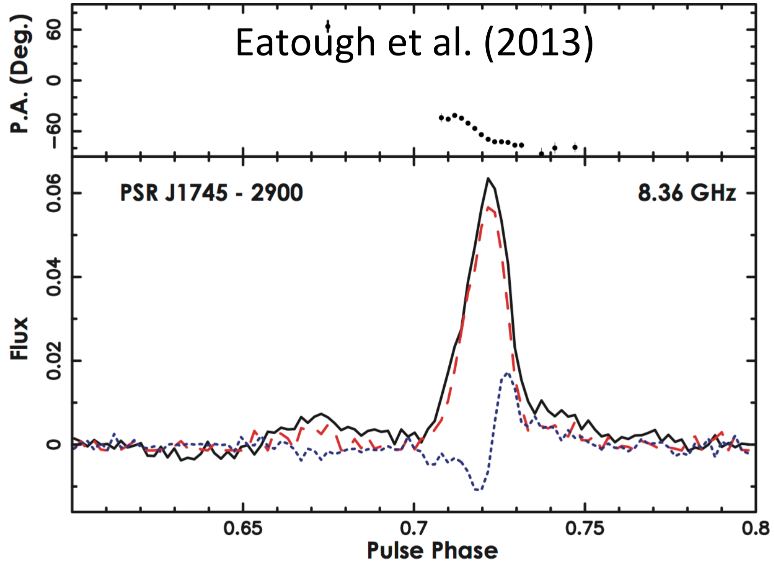
LETTER

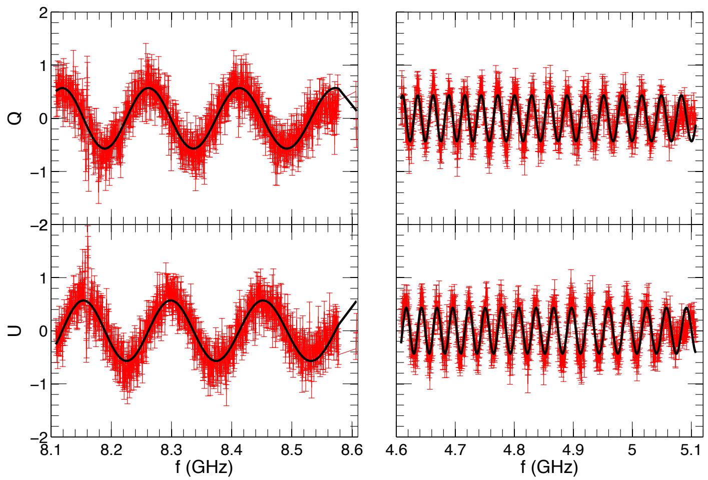
doi:10.1038/nature12499

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]

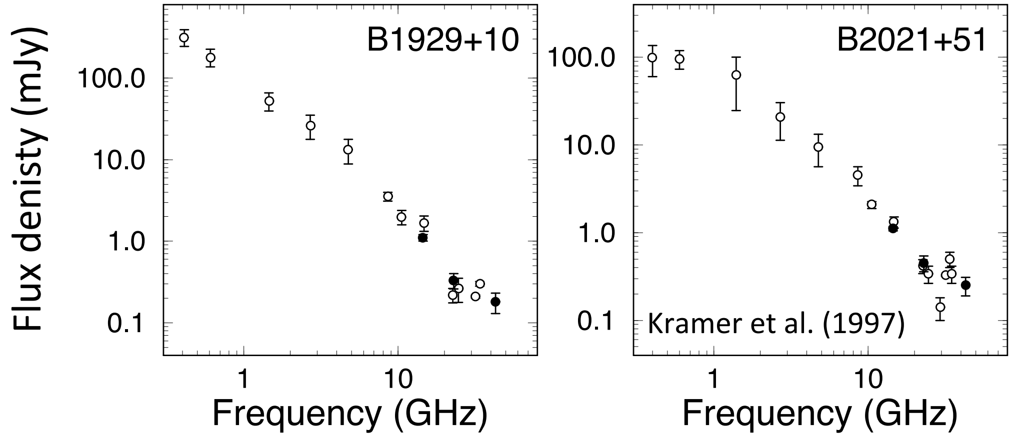




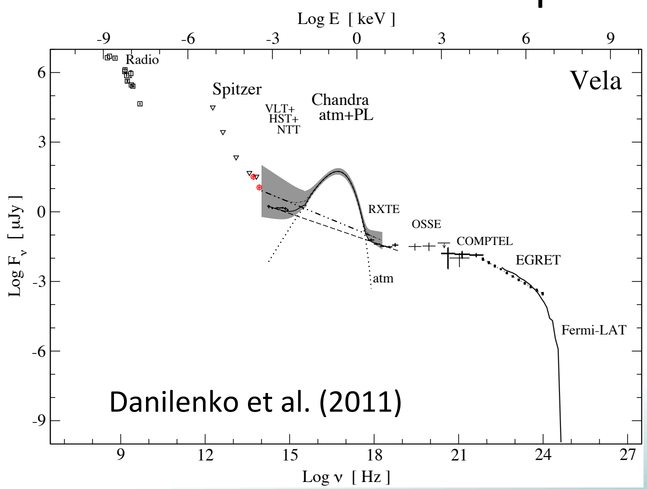


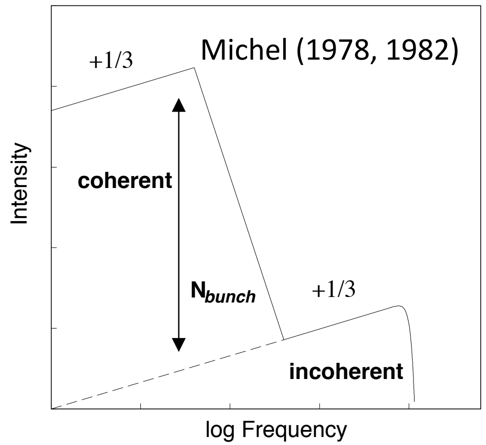
Previous indications for spectral change

- 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– and possibly expected:

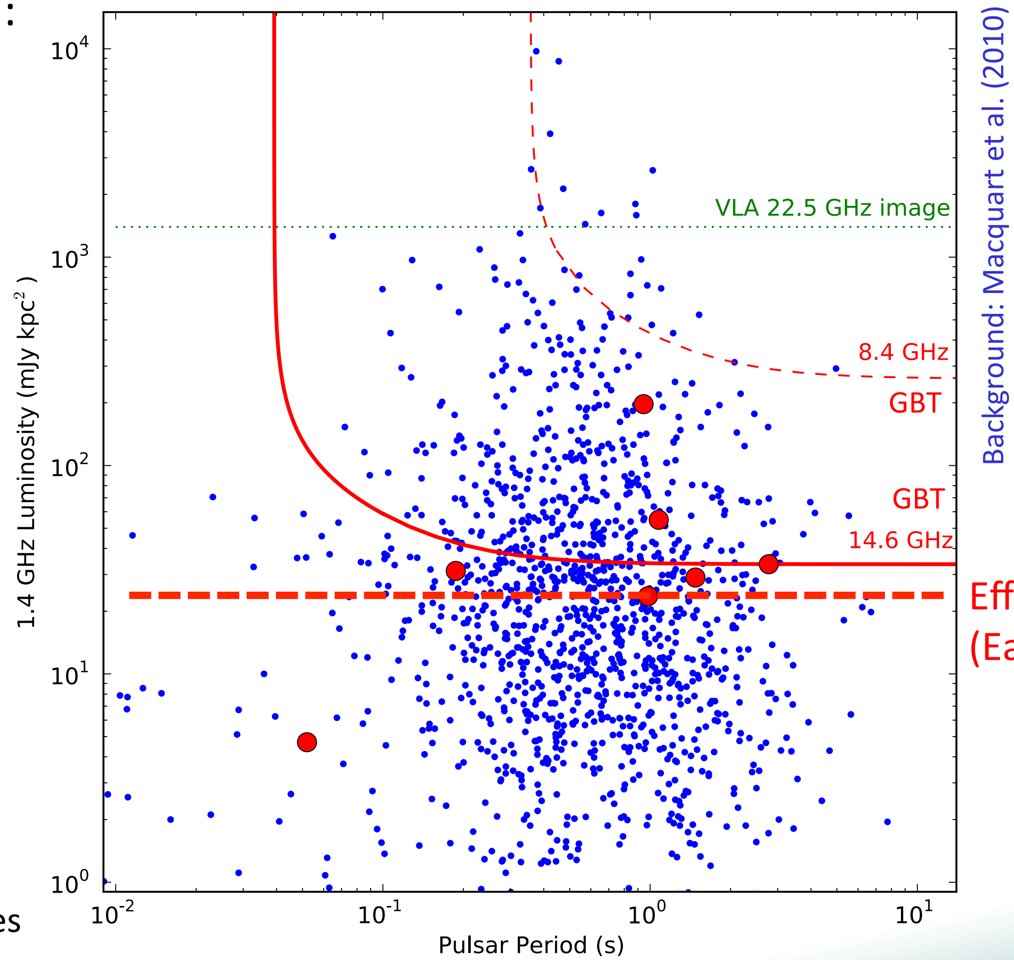




Finding pulsars with an extended VLA

- Comparing current best GBT and Effelsberg searches with that of an VLA (or SKA...) for standard spectra:

5 x VLA @ 43 GHz!

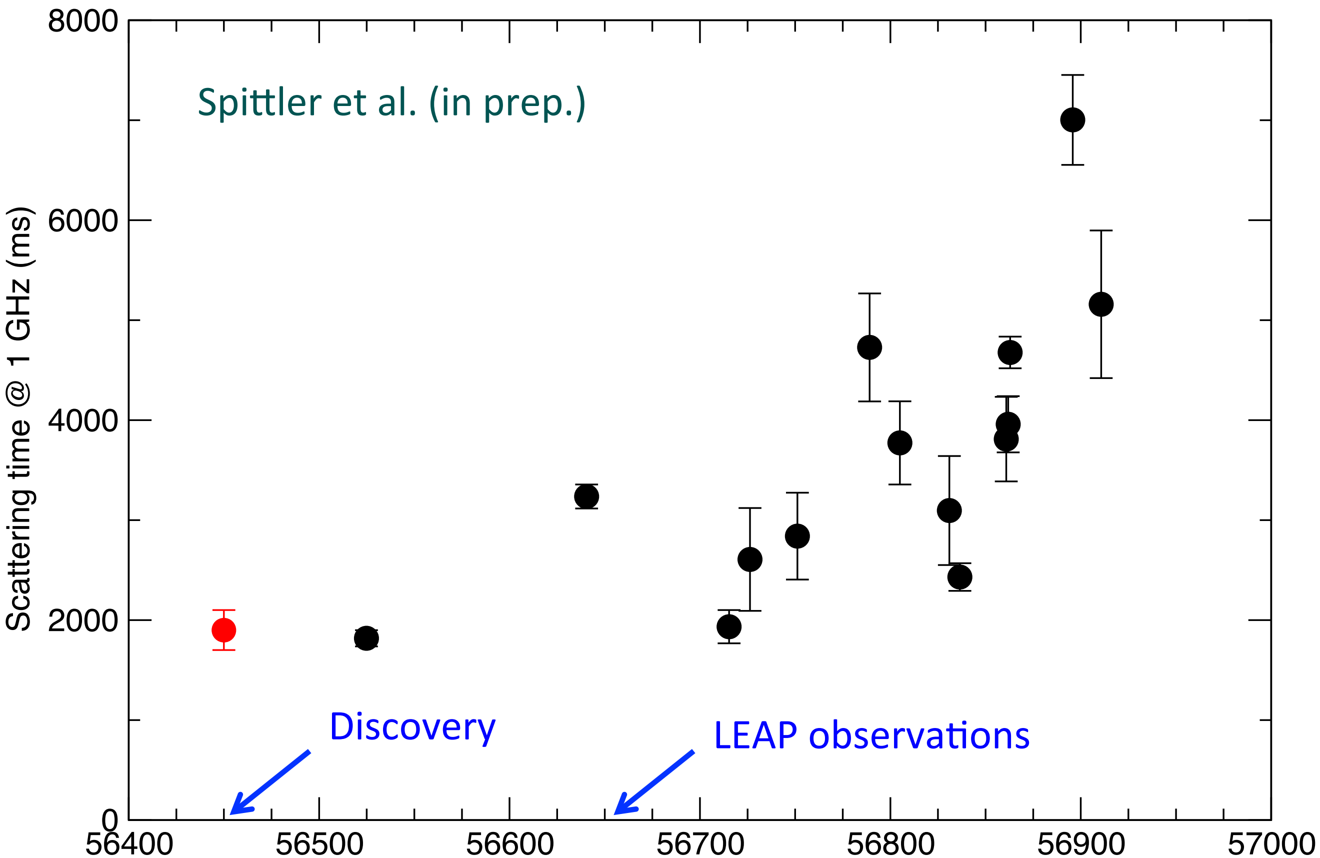


Effelsberg 18 GHz
(Eatough et al. in prep)

Note:
This diagram is biased against luminous sources

Where are the pulsars? – Scattering revisited

- Based on our measurements of the scattering for the magnetar (Spittler 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:

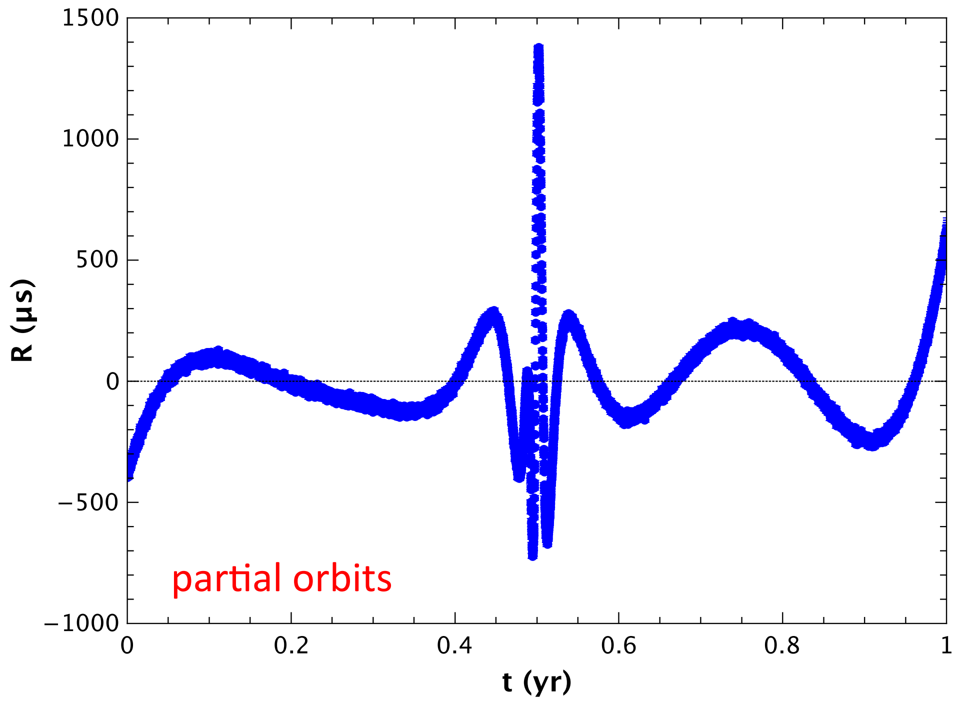


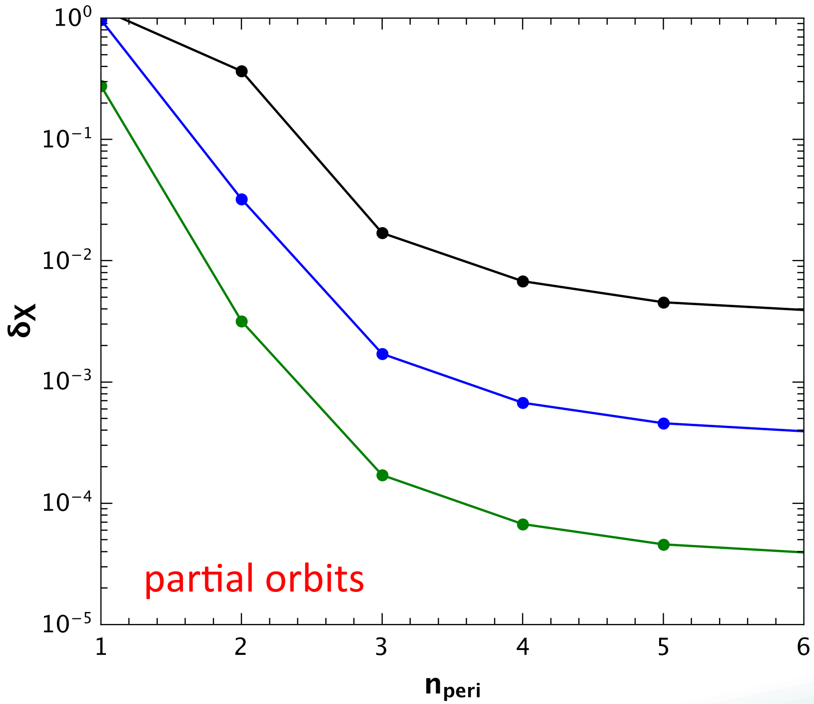
➔ Scattering material is close to source, consistent with RM change!

➔ 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
- Even only measuring part of orbit around pericentre sufficient to determine spin





Partial visibility & External perturbations

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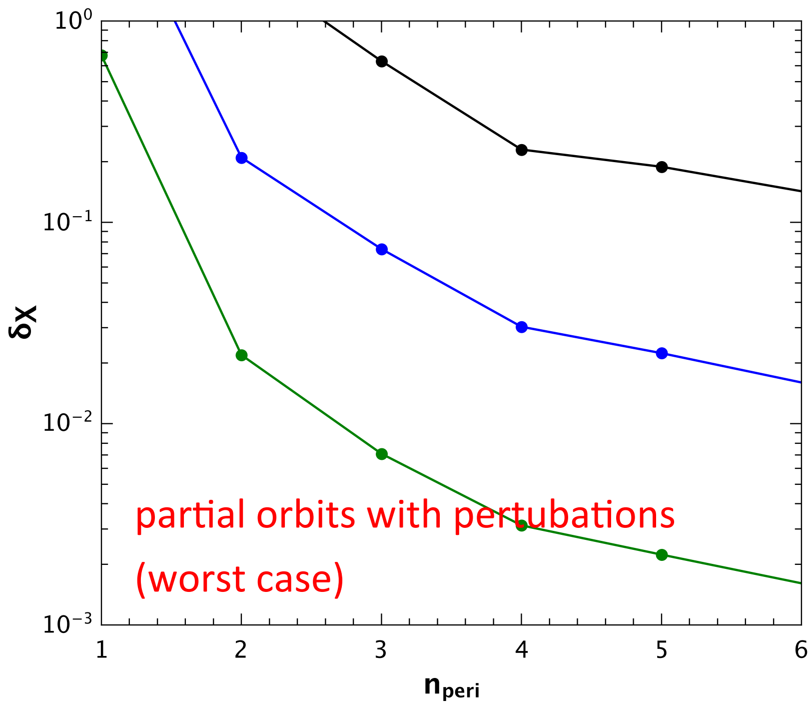
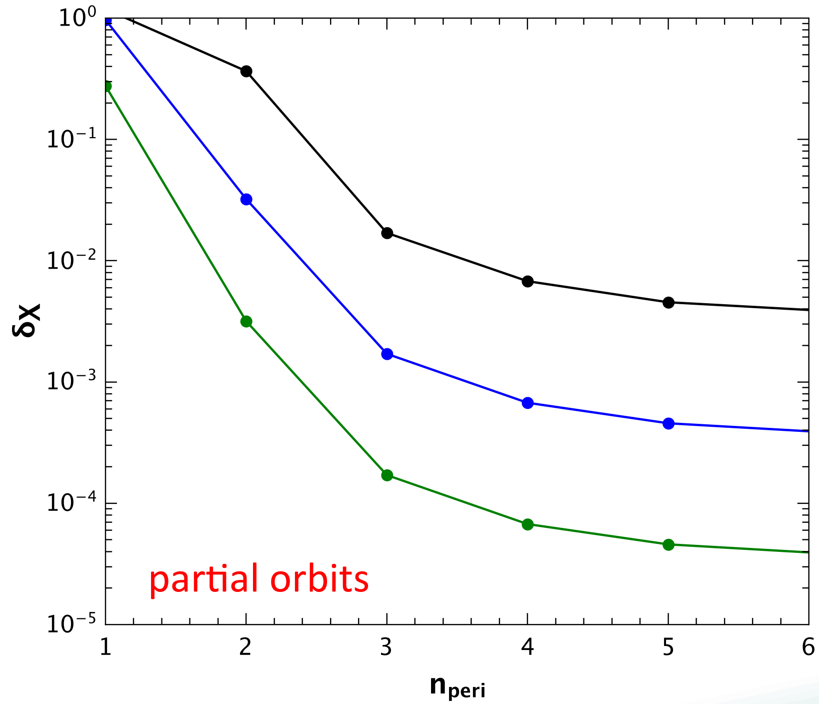
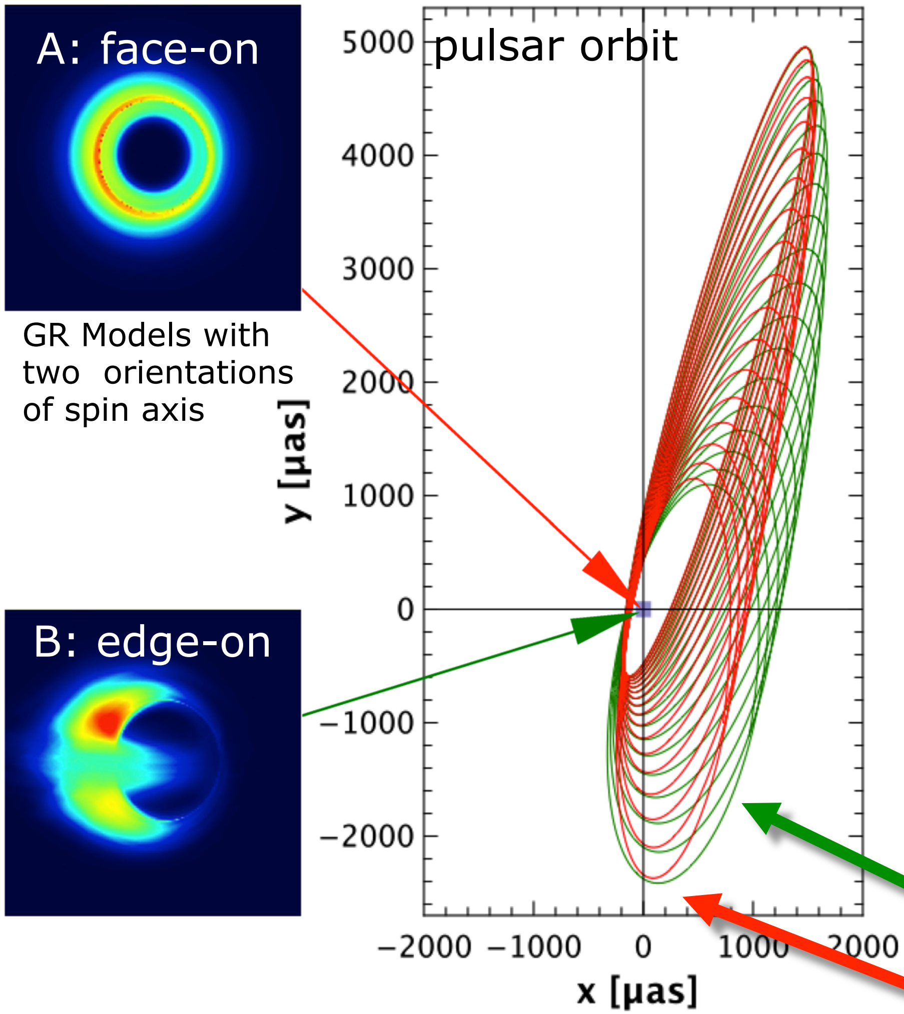




- Even in case of perturbations – which will act away from periastron – we can use partial orbit observations to measure spin!

Combining the information from 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

(see ERC BlackHolCam & Wex et al. in prep.)

Summary

- Pulsars probe GC region and wide range of fundamental physics, in particular gravity
- Eventually, a single pulsar can probe BH properties for ultimate tests of GR, precisely
- Recent results support idea to find and observe pulsars at mm-wavelengths
  although we also have great expectation for SKA as magnetar proves cm-potential
- Combination of SGR A* probes using stars, pulsars and mm-VLBI image
  will be exciting and unique!