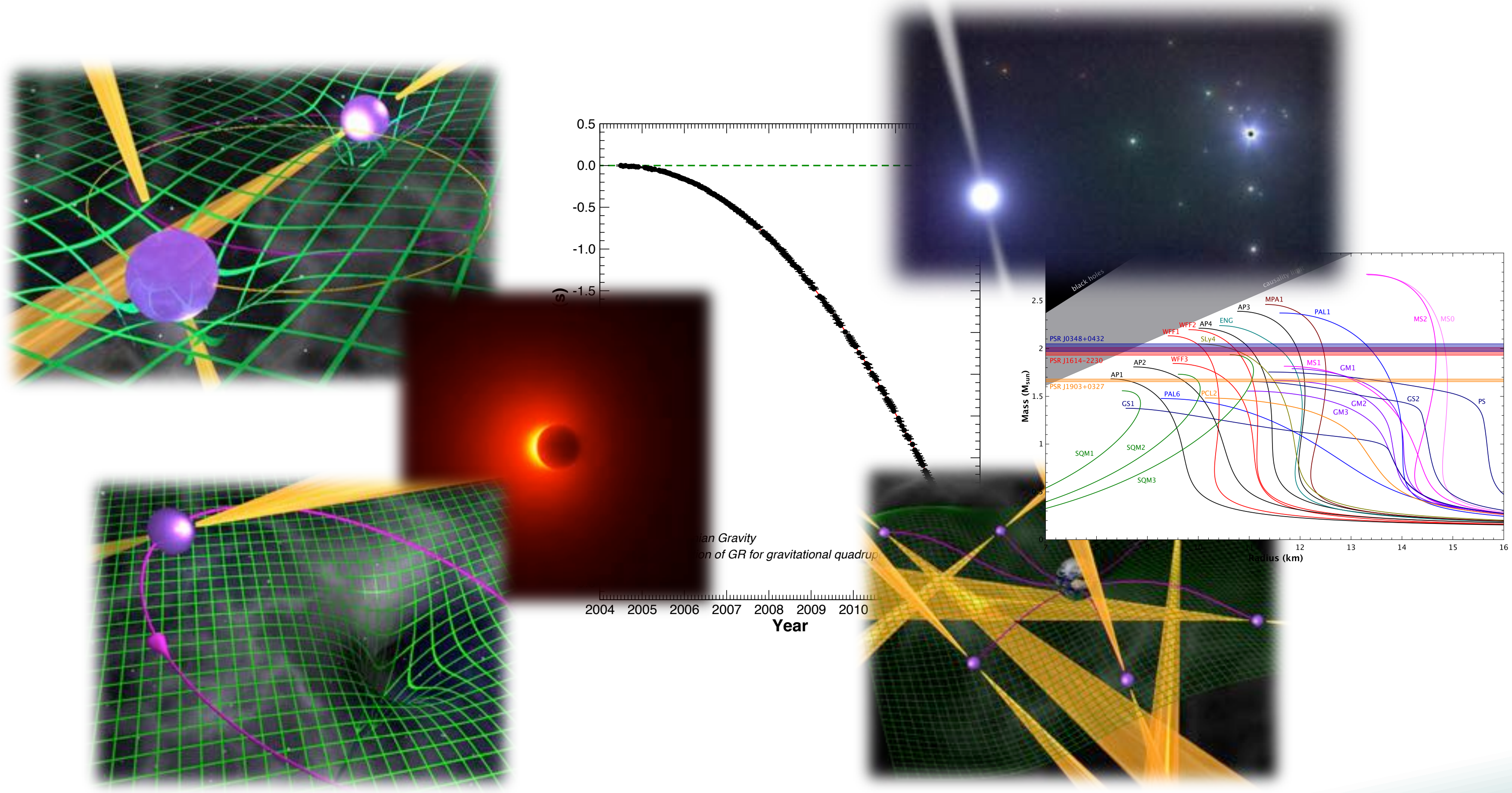
Fundamental physics, the centenary of general relativity and Big Data - or the life of a radio astronomer



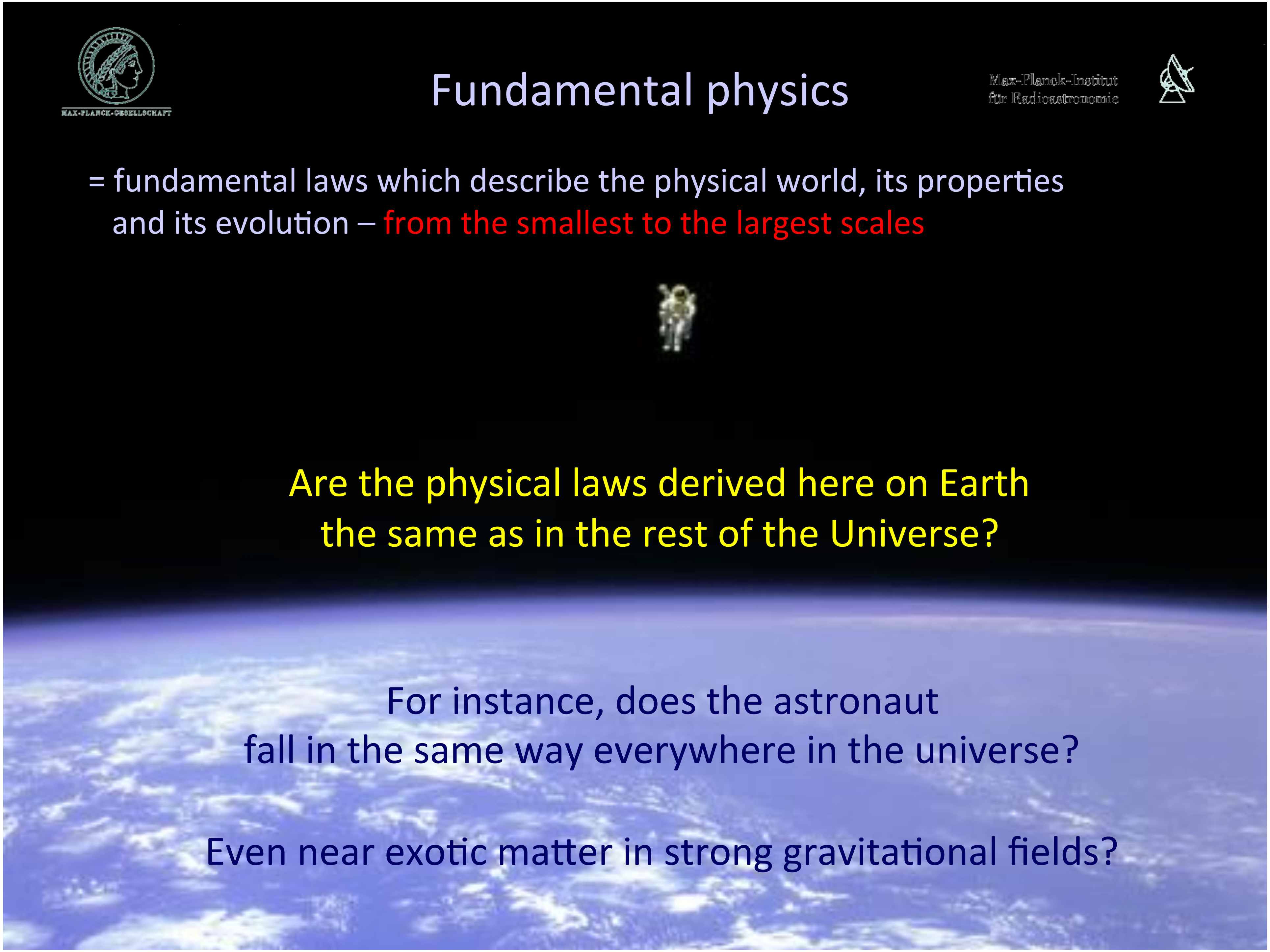
Michael Kramer

Max-Planck-Institut für Radioastronomie

Jodrell Bank Centre for Astrophysics, University of Manchester

Fundamental physics

= fundamental laws which describe the physical world, its properties and its evolution – from the smallest to the largest scales



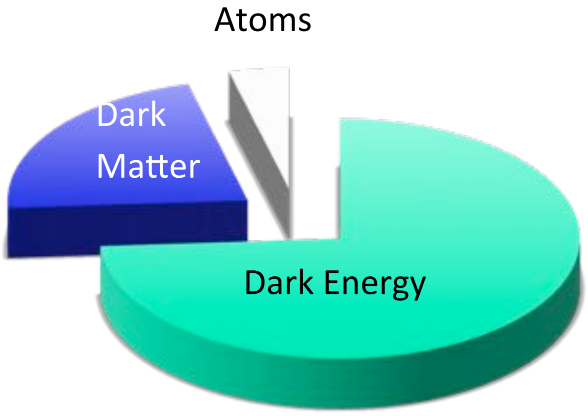
Are the physical laws derived here on Earth the same as in the rest of the Universe?

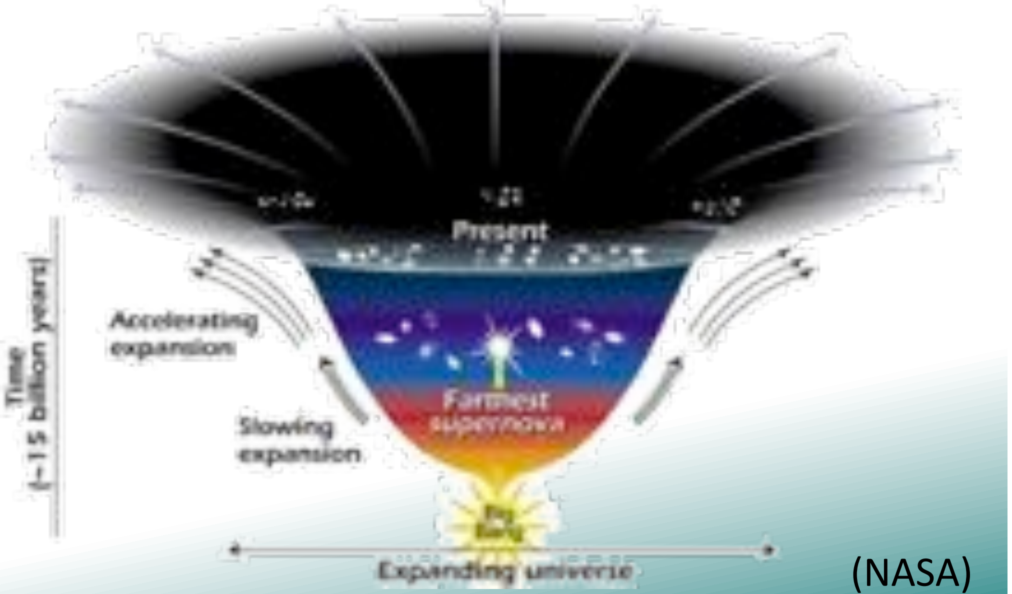
For instance, does the astronaut fall in the same way everywhere in the universe?

Even near exotic matter in strong gravitational fields?

100 years of General Relativity and Testing it

- General relativity conceptually different than description of other forces
- We expect that GR must eventually fail (incompatibility with quantum theory, singularities), but we don’t know how and where
- Will Einstein have the last word on (macroscopic) gravity or does GR fail far below the Planck energy?
- What is dark matter and dark energy?
- Do we have to modify gravity on large scales?
- How to test it?





(NASA)

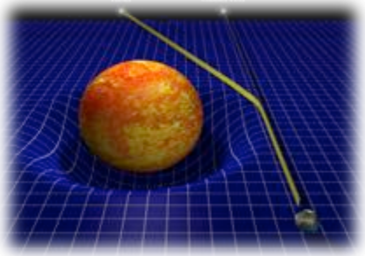
100 years of General Relativity and Testing it

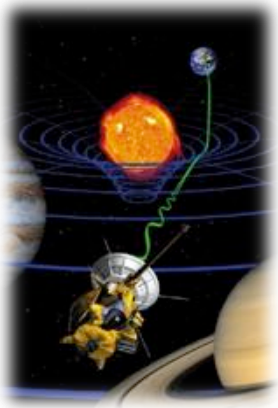
- General relativity conceptually different than description of other forces
- GR has been tested precisely, e.g. in solar system
- Classical tests:

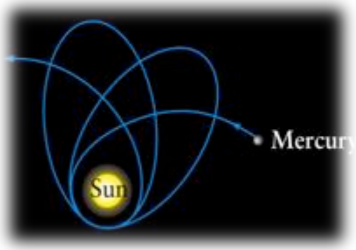
  - Mercury perihelion advance

  - Light-deflection at Sun

  - Gravitational redshift





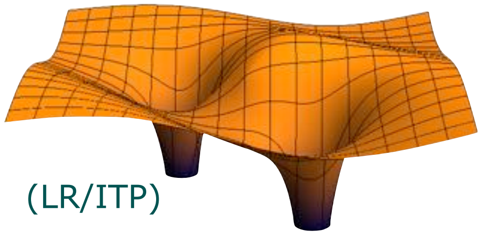


- Modern tests in solar system,

  - Lunar Laser Ranging (LLR)

  - Radar reflection at planets, Cassini spacecraft signal

  - LAGEOS & Gravity Probe B



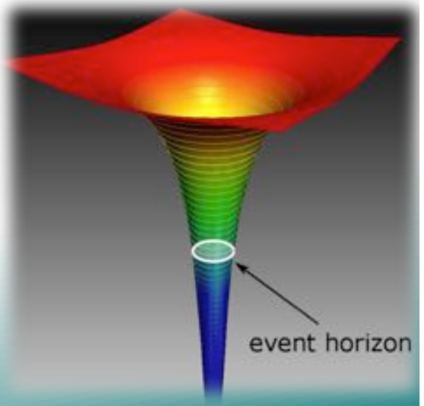
(LR/ITP)

Still...

We need to test gravity in strong, non-linear conditions: NS+BH!

What are the properties of black holes & gravitational waves?

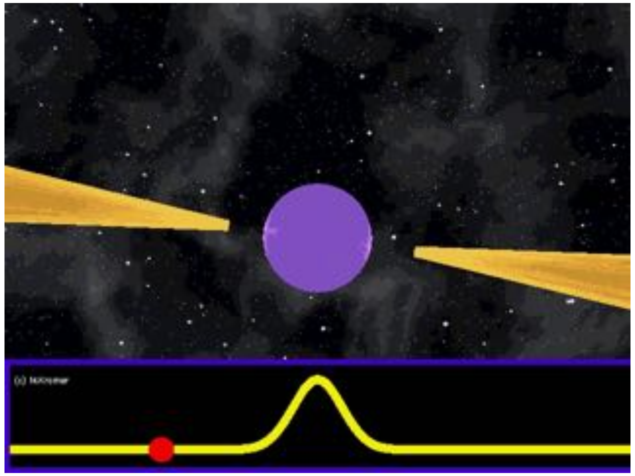
Using techniques and methods not known to Einstein...



Outline

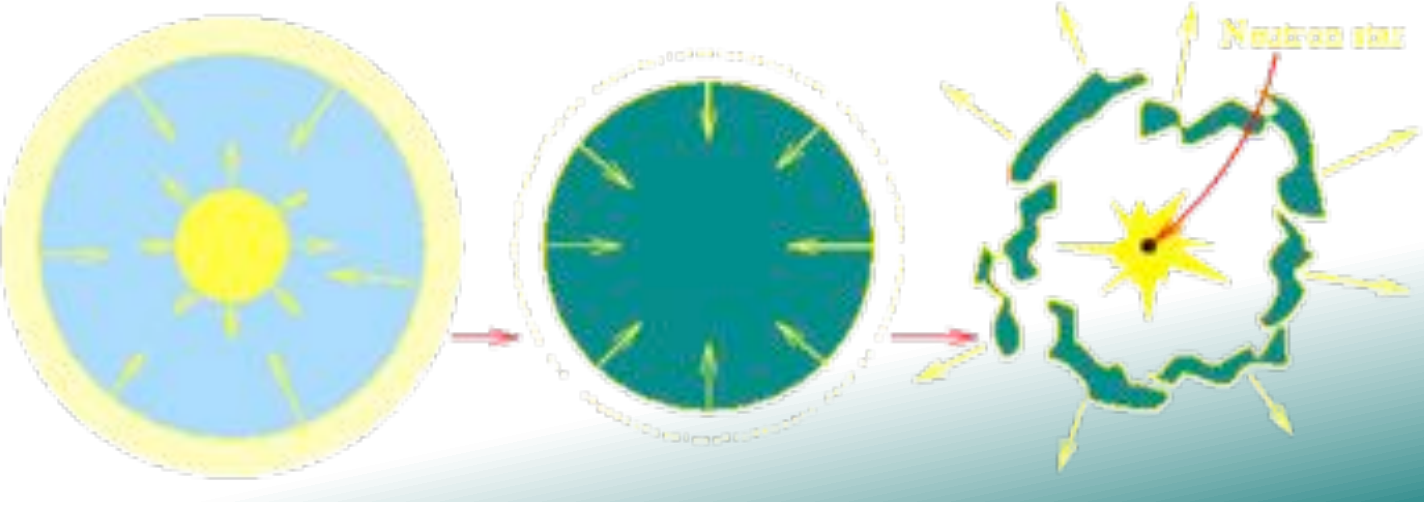
- Introduction: Pulsars & gravitational waves
- Testing general relativity with binary pulsars
- Testing alternative theories
- (Near?!) Future tests with Black Holes: Sgr A*

Pulsars…



- …almost black holes
- …Objects of extreme matter:
  - 10 x nuclear density
  - $B \sim B_{cr} = 4.4 \times 10^9$ Tesla
  - Electr. fields ~ 10^{12} Volt
  - $F_{EM} = 10^{11} F_{gravitation}$
  - High-temperature superfluid superconductor!

…born in (usually Type II) Supernova explosion:



Pulsars… rotate very fast!

J1748-2446ad

1.4 ms

Crab pulsar

33 ms

J2144-3933

8.5 s

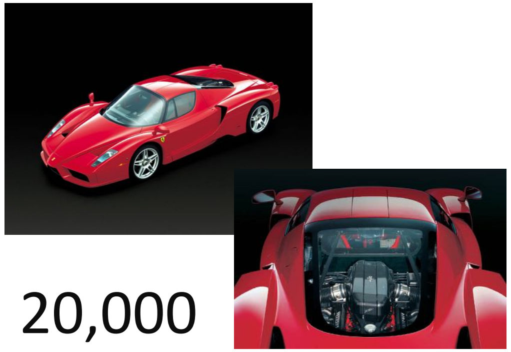
Period

Vela-Pulsar 89 ms

42,960

Rotations per minute

7



20,000

1,600

- Speed at equator: 45,000,000 m/s = 162 Million km/h!
- Centrifugal acceleration: 20 Million g!
- Pulsars are massive, fast rotating fly wheels
- Pulsars are excellent clocks

Most useful: Pulsars with companions

~ 2500 radio pulsars

1.40 ms (PSR J1748-2446ad)
8.50 s (PSR J2144-3933)

~ 10% binary pulsars

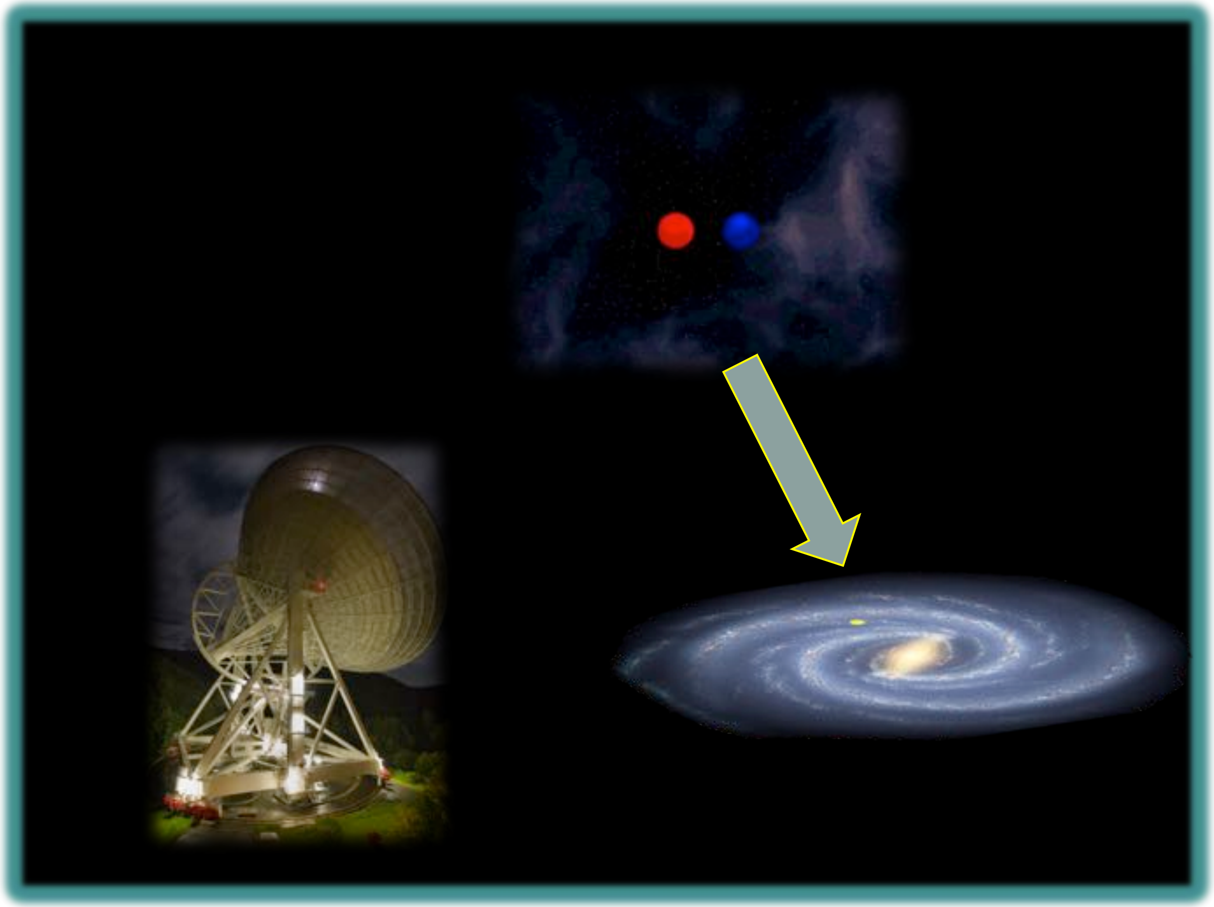
Orbital period range

94 min (PSR J1311-3430)
5.3 yr (PSR J1638-4725)

Companions

MSS, WD, NS, planets

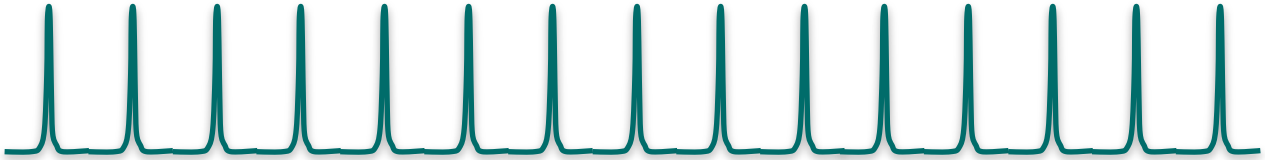
Wanted: PSR-BH!

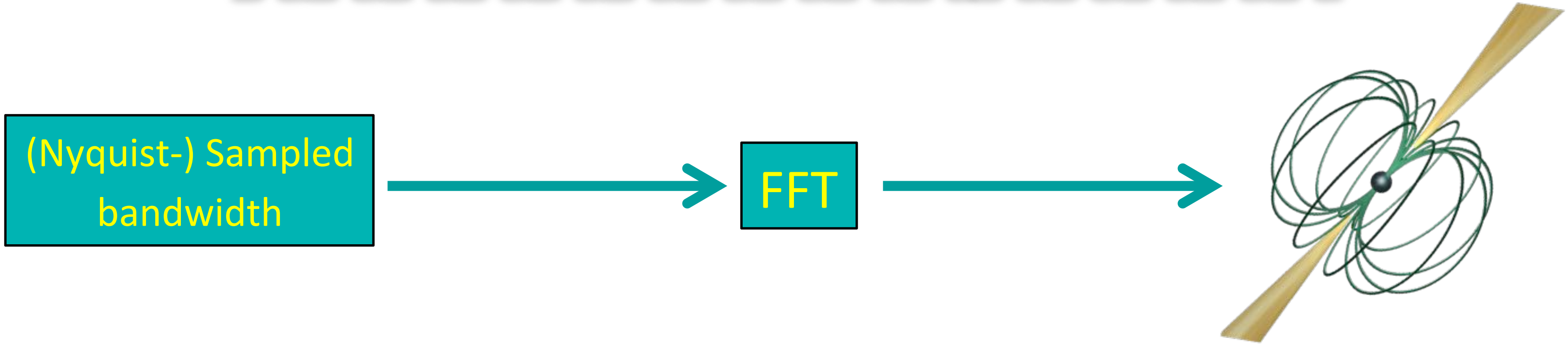


Simple recipe:
1. Find them!
2. Time them!

i.e. Measure (=time!) how a pulsar falls as a test mass in the gravitational potential of a companion (and in the Galaxy) … a clean experiment with extreme precision!

Finding (binary) Pulsars

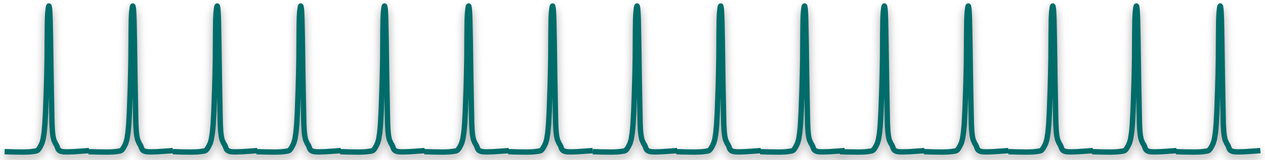


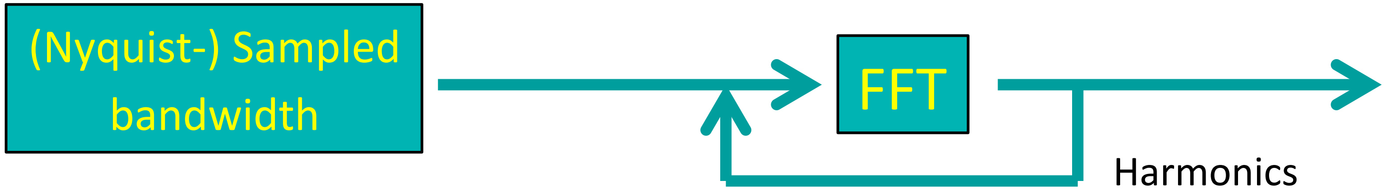


(Nyquist-) Sampled bandwidth

FFT

Finding (binary) Pulsars

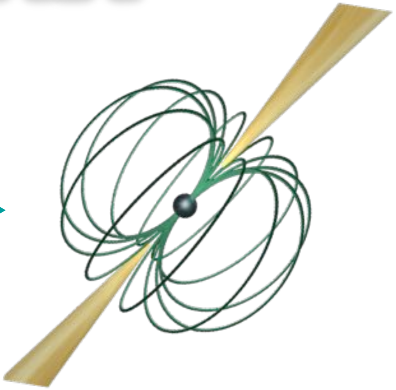


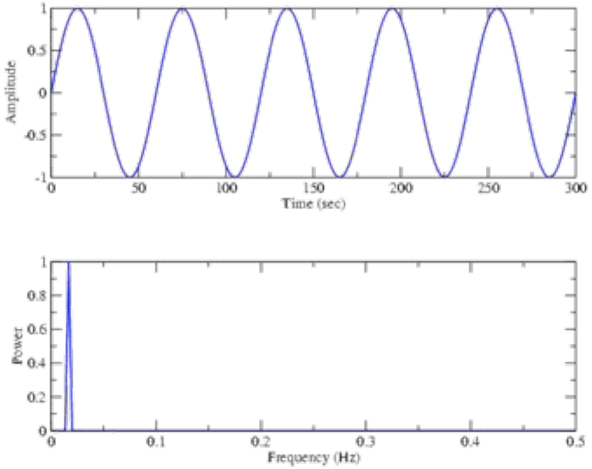


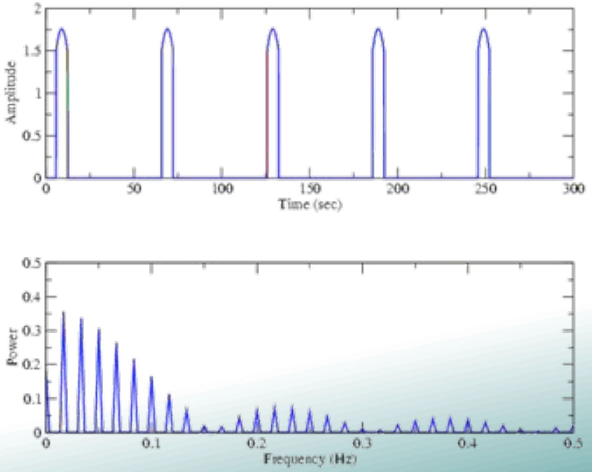
(Nyquist-) Sampled bandwidth

FFT

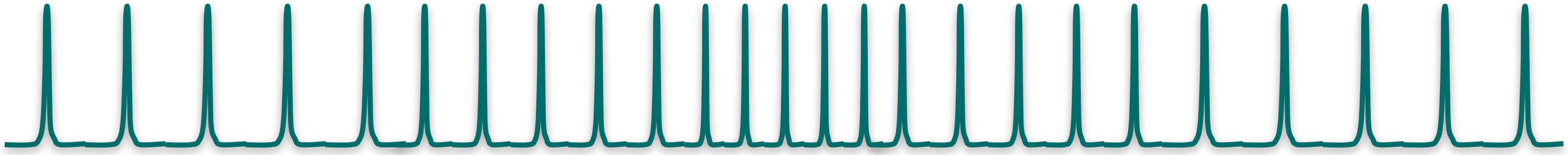
Harmonics

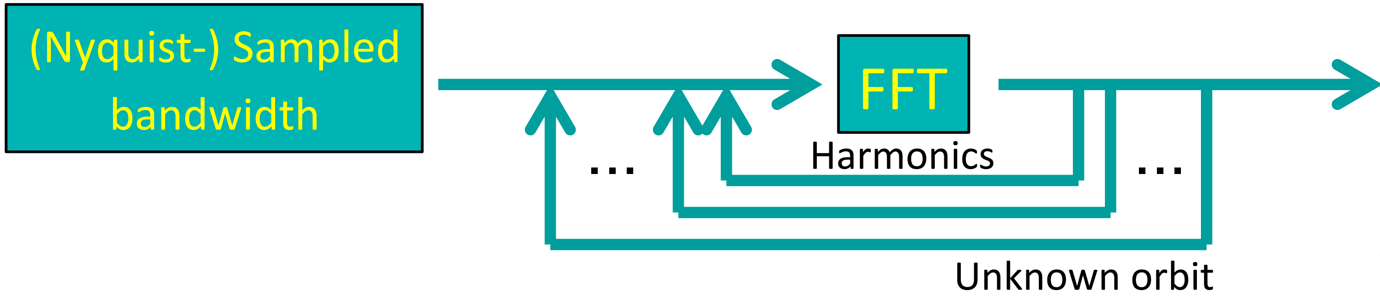






Finding (binary) Pulsars





(Nyquist-) Sampled bandwidth

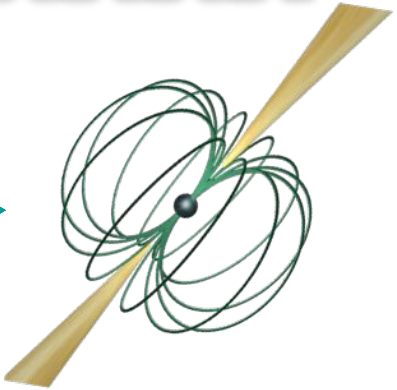
FFT

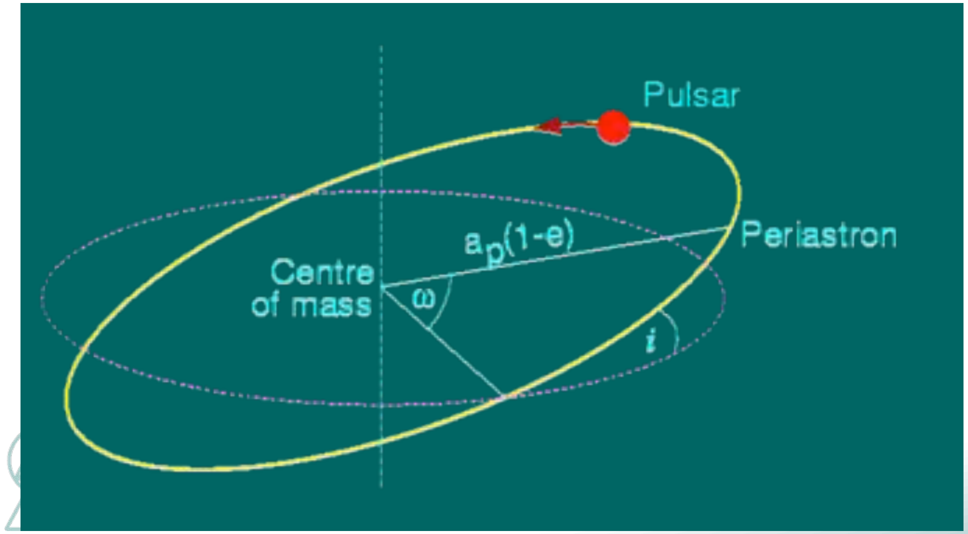
Harmonics

…

…

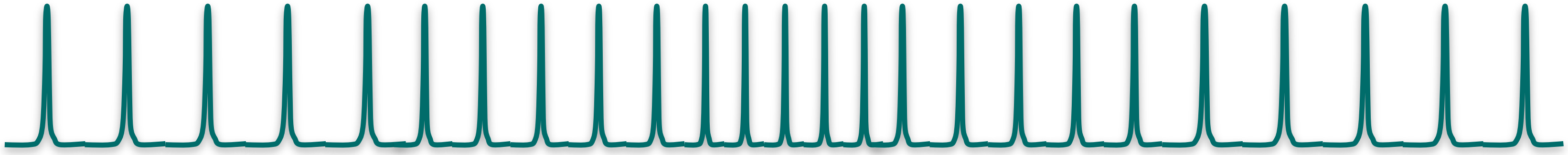
Unknown orbit



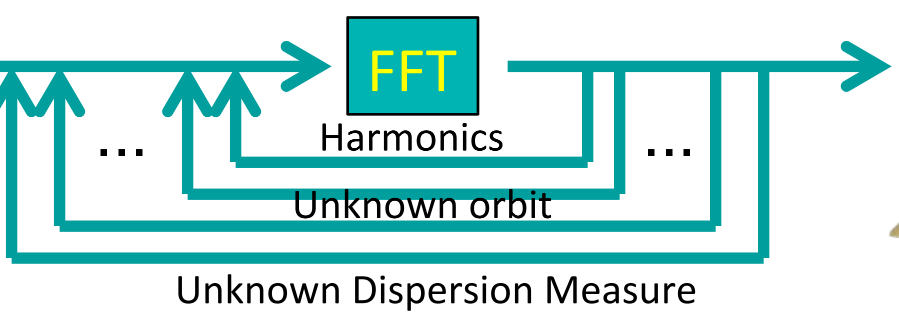


- Binary period, P_b
- Projected semi-major axis,
- $x = a_p \sin(i) / c$
- Eccentricity, e
- Longitude of periastron, ω
- Epoch periastron, T_0

Finding (binary) Pulsars



(Nyquist-) Sampled
bandwidth
and sub-banded



FFT

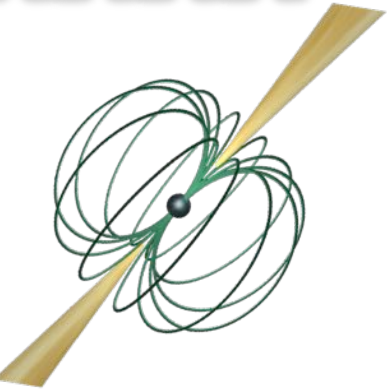
Harmonics

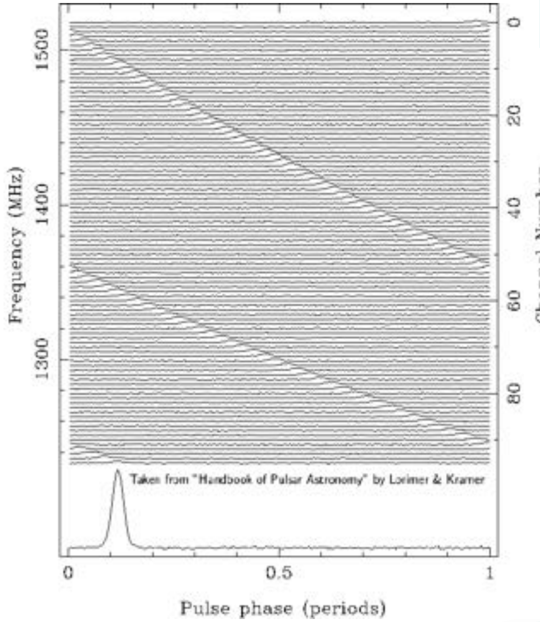
…

…

Unknown orbit

Unknown Dispersion Measure

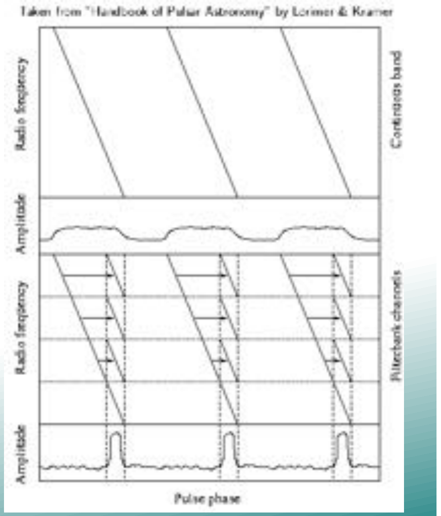




Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

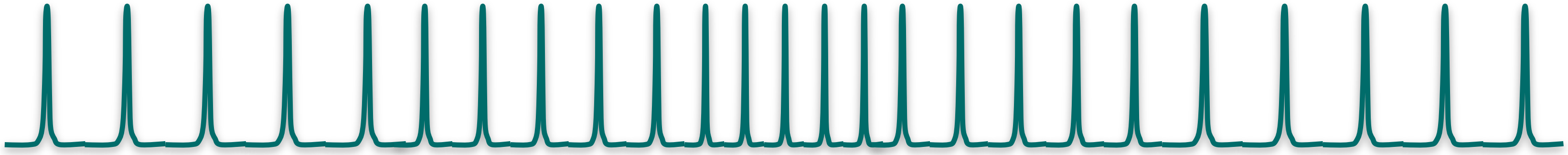
Unknown dispersion due to ionized interstellar medium.

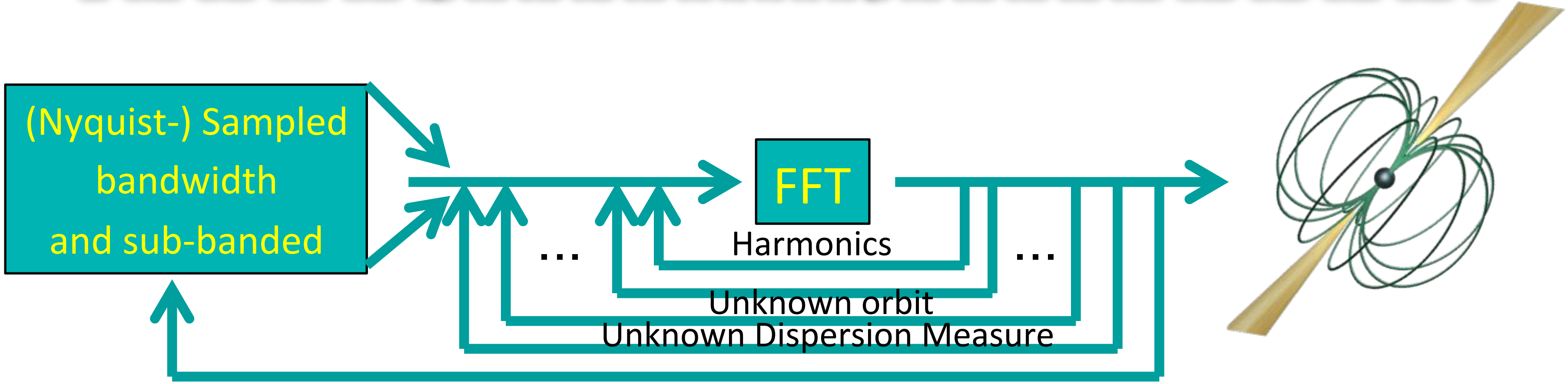
Without de-dispersion, we can not see the pulsar: search for DM



Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

Finding (binary) Pulsars





(Nyquist-) Sampled bandwidth and sub-banded

FFT

Harmonics

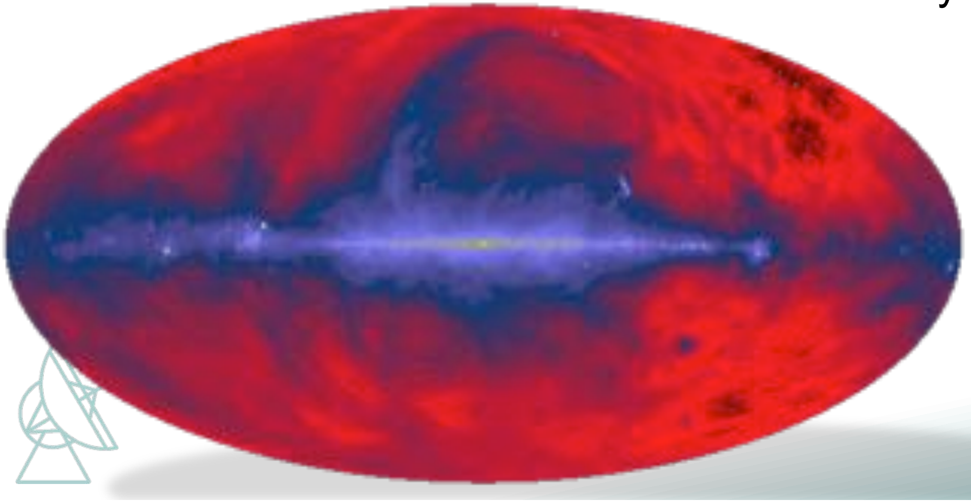
...

...

Unknown orbit

Unknown Dispersion Measure

whole sky – millions of beams

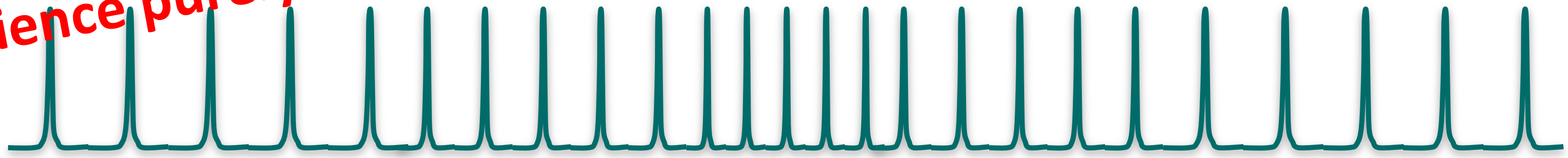


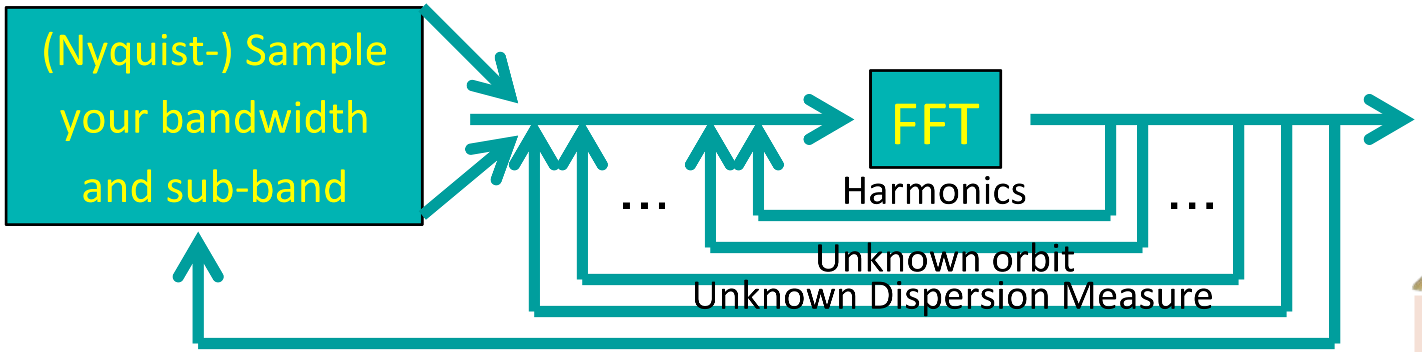
...and repeat the whole thing for
>million positions on the sky!

Today: ~50 TB/h
Soon (MeerKAT/Effelsberg PAF): 100-200 TB/h
SKA1: ~1 PB/s
Eventually need PFlops to EFlops on the fly...

Finding (binary) Pulsars

Science purely limited by compute power!





(Nyquist-) Sample your bandwidth and sub-band

FFT

Harmonics

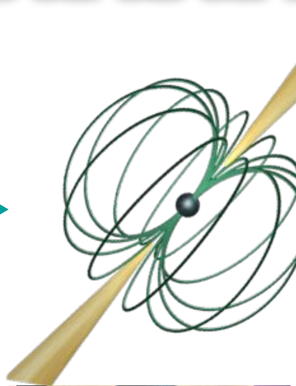
…

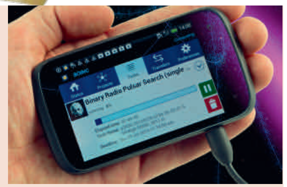
…

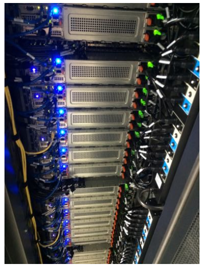
Unknown orbit

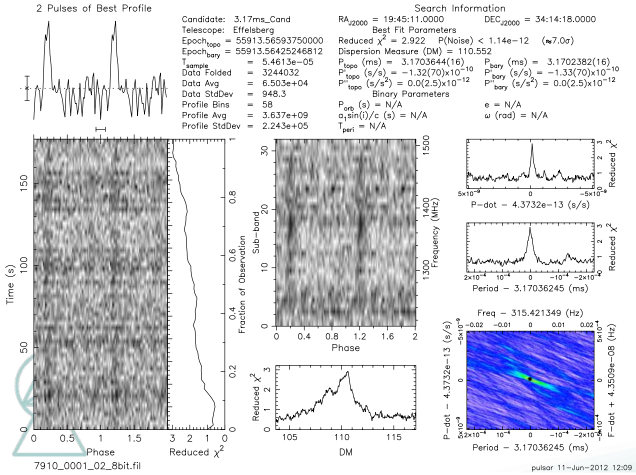
Unknown Dispersion Measure

whole sky – millions of beams









Candidate: 3.17ms_Cand
Telescope: Effelsberg
Epoch_{topo} = 55913.56593750000
Epoch_{bary} = 55913.56425246812
T_{sample} = 5.4613e−05
Data Folded = 3244032
Data Avg = 6.503e+04
Data StdDev = 948.3
Profile Bins = 58
Profile Avg = 3.637e+09
Profile StdDev = 2.243e+05

RA_{J2000} = 19:45:11.0000
DEC_{J2000} = 34:14:18.0000

Best Fit Parameters
Reduced χ^2 = 2.922 P(Noise) < 1.14e−12 (≈7.0σ)
Dispersion Measure (DM) = 110.552
P_{topo} (ms) = 3.1703644(16)
P_{bary} (ms) = 3.1702382(16)
P'_{topo} (s/s) = $-1.32(70)\times10^{-10}$
P'_{bary} (s/s) = $-1.33(70)\times10^{-10}$
P''_{topo} (s/s^2) = $0.0(2.5)\times10^{-12}$
P''_{bary} (s/s^2) = $0.0(2.5)\times10^{-12}$

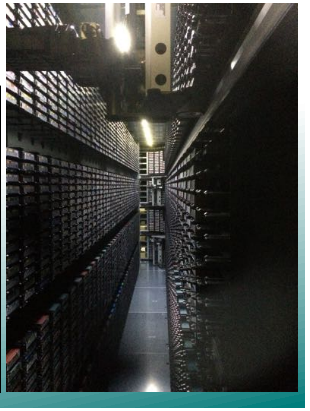
Binary Parameters
P_{orb} (s) = N/A
e = N/A
$a_1\sin(i)/c$ (s) = N/A
ω (rad) = N/A
T_{peri} = N/A

For each beam, $2^{28\text{-}30}$ samples, producing millions of candidates per beam:

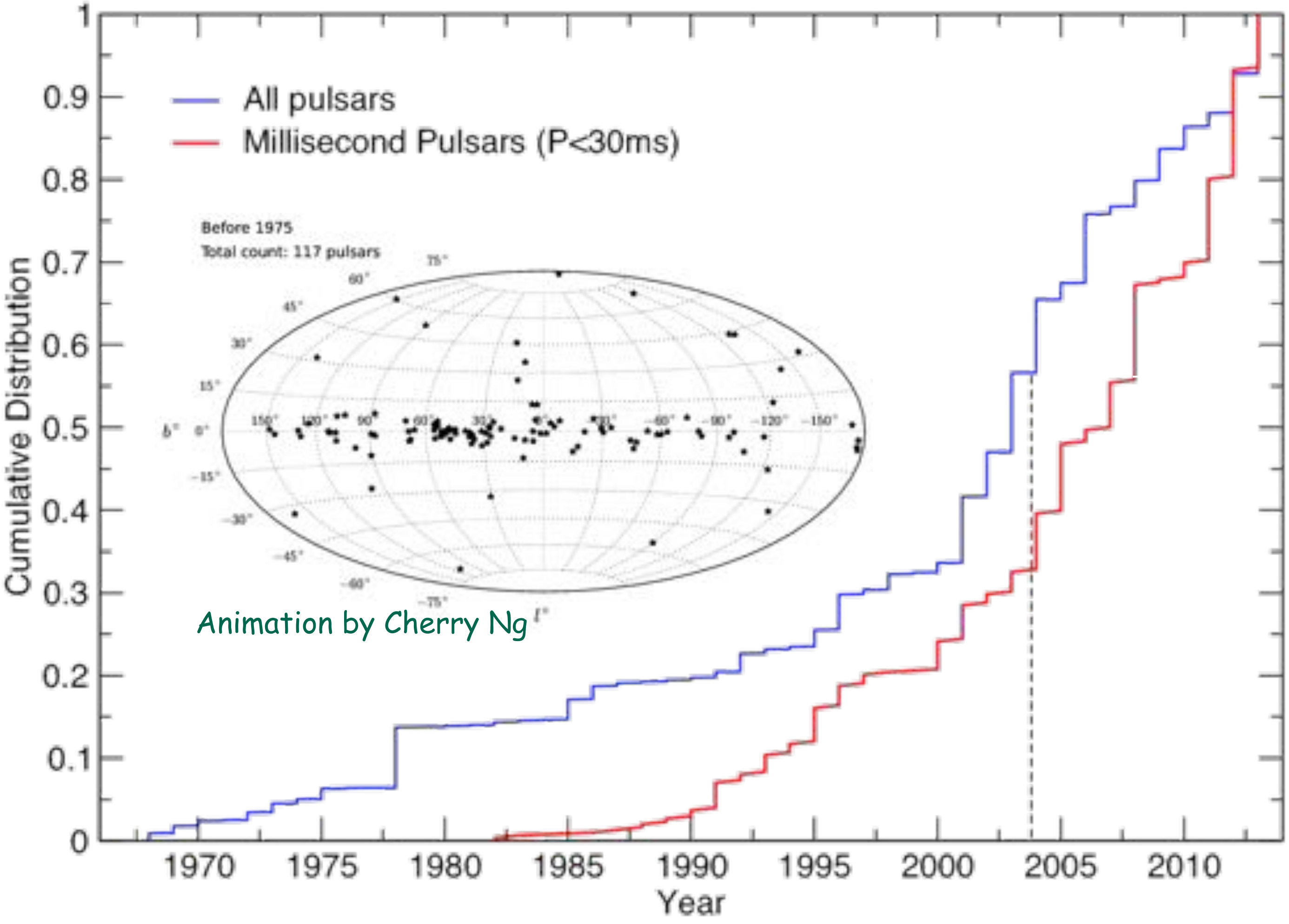
Selection of radio pulsar candidates using artificial neural networks

R. P. Eatough[1,2⋆], N. Molkenthin[1], M. Kramer[2,1], A. Noutsos[1], M. J. Keith[3,1], B. W. Stappers[1], and A. G. Lyne[1].

[1] *Jodrell Bank Centre for Astrophysics, Alan Turing Building, School of Physics and Astronomy, The University of Manchester, Manchester, M13 9PL, United Kingdom.*
[2] *Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121, Bonn, Germany.*
[3] *Australia Telescope National Facility, CSIRO, P.O. Box 76, Epping, NSW 1710, Australia.*

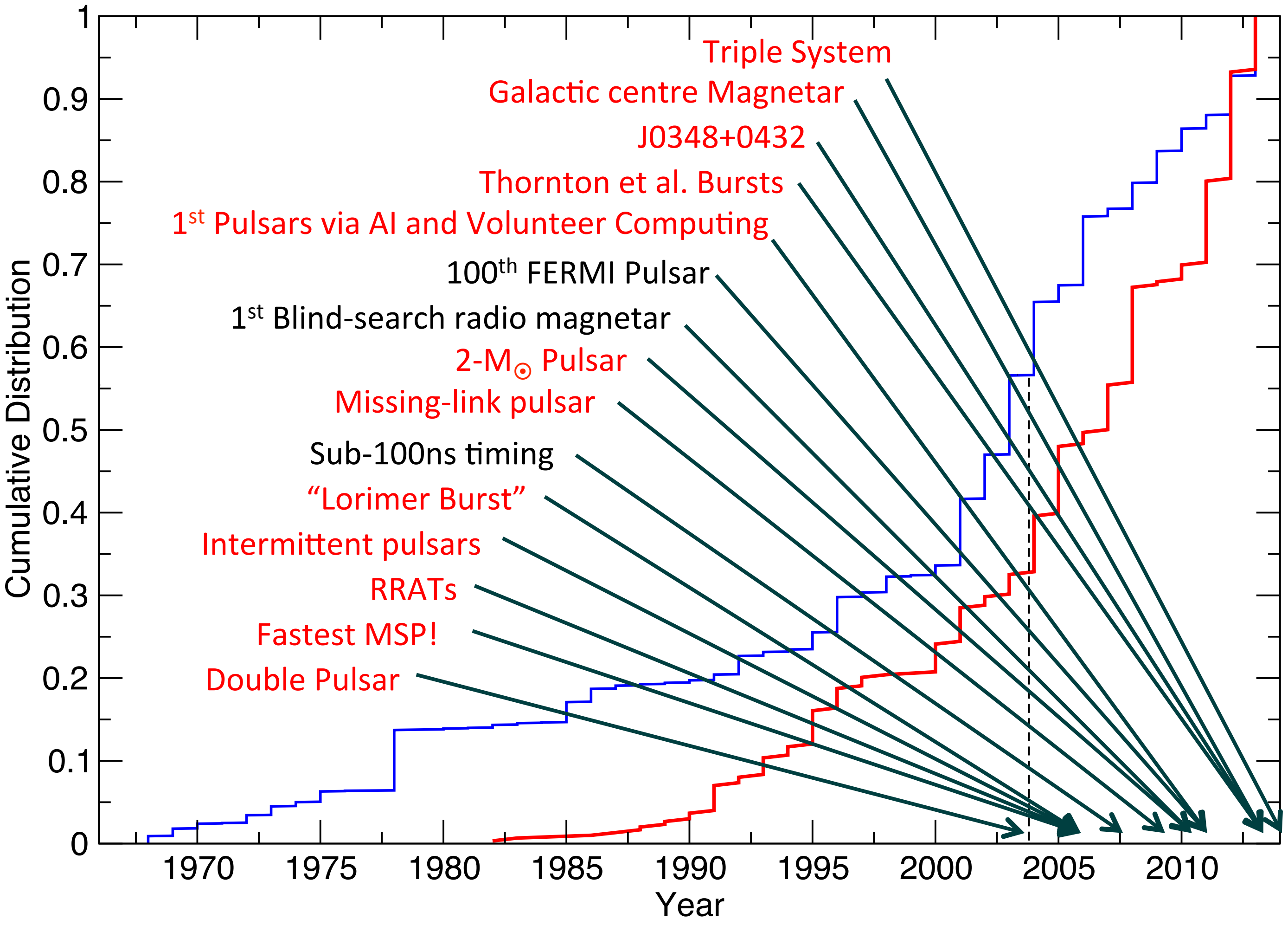


Discoveries over time



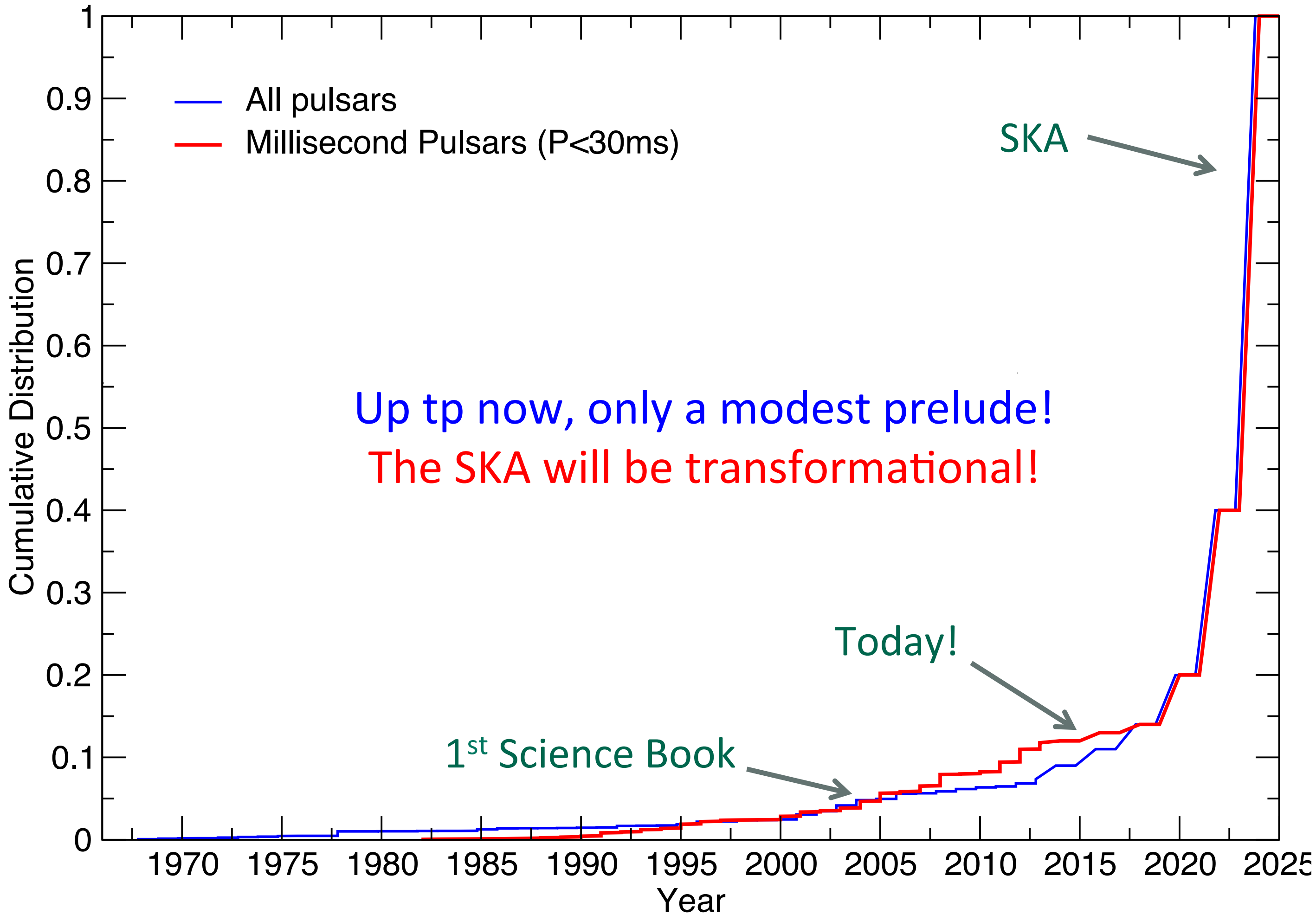
Animation by Cherry Ng

Discoveries lead to excellent science!



Exciting science ranging from solid-state physics to testing gravity.

“…but that’s only the beginning!”



SKA

Up tp now, only a modest prelude!

The SKA will be transformational!

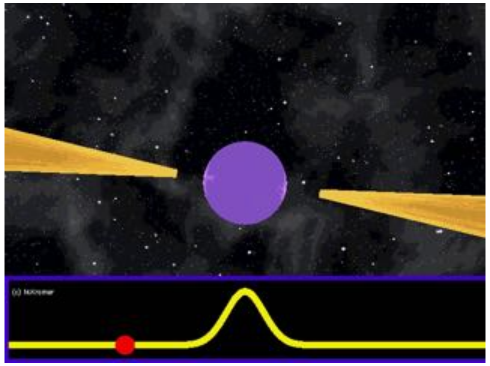
Today!

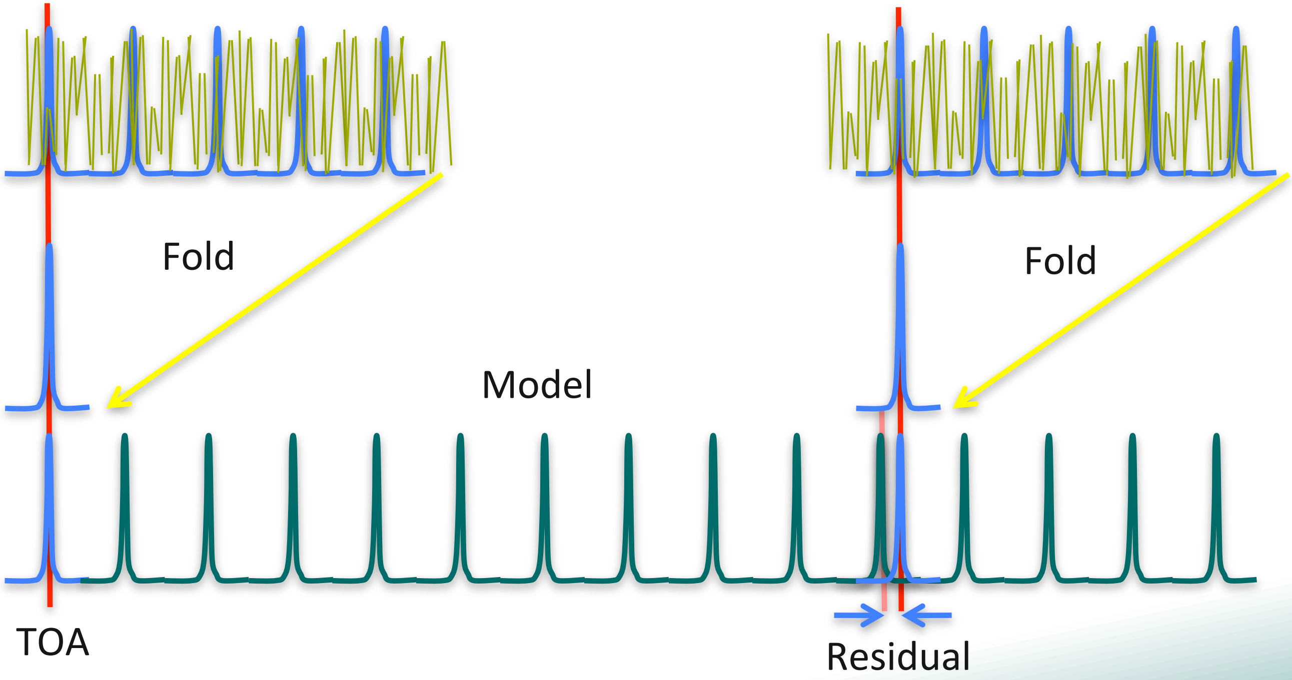
1st Science Book

- We can expect to find about 30,000 active (visible) pulsars
- Among those will be about 2000 millisecond pulsars
- A dramatic increase in the number of known sources!

A simple and clean experiment: Pulsar Timing

Pulsar timing measures arrival time (TOA):





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

High precision measurements – What's possible today…

Spin parameters:

- Period: 5.757451924362137(2) ms (Verbiest et al. 2008) Note: 2 atto seconds uncertainty!

Astrometry:

- Distance: 157(1) pc (Verbiest et al. 2008)
- Proper motion: 140.915(1) mas/yr (Verbiest e t al. 2008)

Orbital parameters:

- Period: 0.102251562479(8) day (Kramer et al. in prep.)
- Projected semi-major axis: 31,656,123.76(15) km (Freire et al. 2012)
- Eccentricity: 3.5 (1.1) × 10^{-7} (Freire et al. 2012)

Masses:

- Masses of neutron stars: 1.33816(2) / 1.24891(2) $M_\odot$ (Kramer et al. in prep.)
- Mass of WD companion: 0.207(2) $M_\odot$ (Hotan et al. 2006)
- Mass of millisecond pulsar: 1.667(7) $M_\odot$ (Freire et al. 2012)
- Main sequence star companion: 1.029(3) $M_\odot$ (Freire et al. 2012)
- Mass of Jupiter and moons: 9.547921(2) x 10^{-4} $M_\odot$ (Champion et a. 2010)

Relativistic effects:

- Periastron advance: 4.226598(5) deg/yr (Weisberg et al. 2010)
- Einstein delay: 4.2992(8) ms (Weisberg et al. 2010)
- Orbital GW damping: 7.152(8) mm/day (Kramer et al. in prep)

Fundamental constants:

- Change in (dG/dt)/G: (−0.6 ± 1.1) × 10−12 yr^{-1} (Zhu et al. 2015)

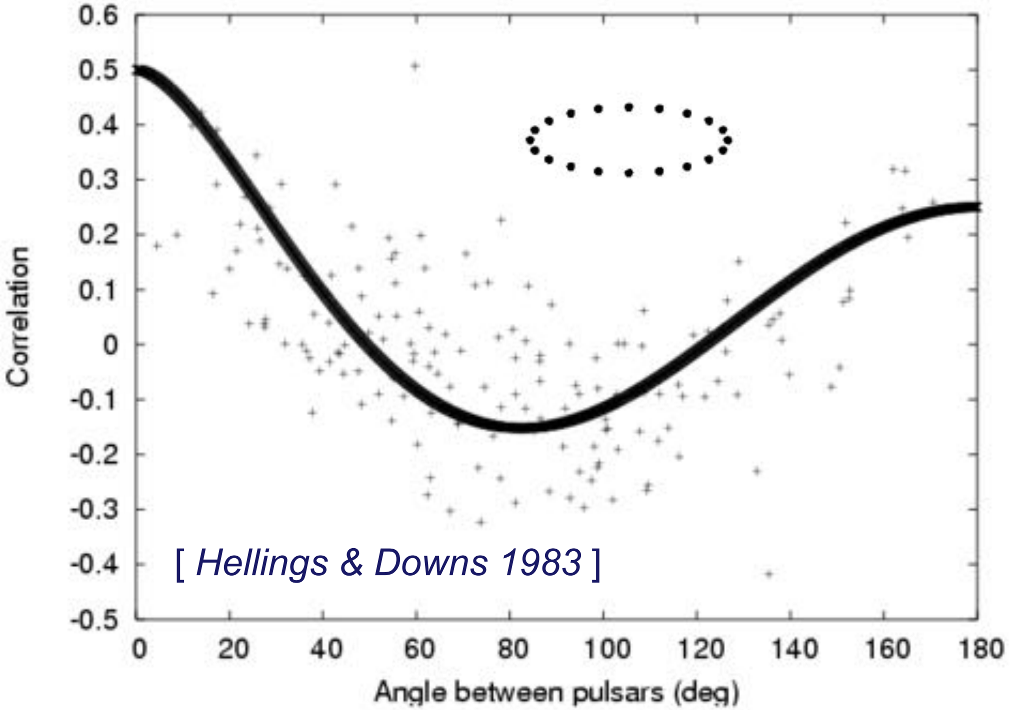
Gravitational wave detection:

- Change in relative distance: 100m / 1 lightyear (EPTA, NANOGrav, PPTA)

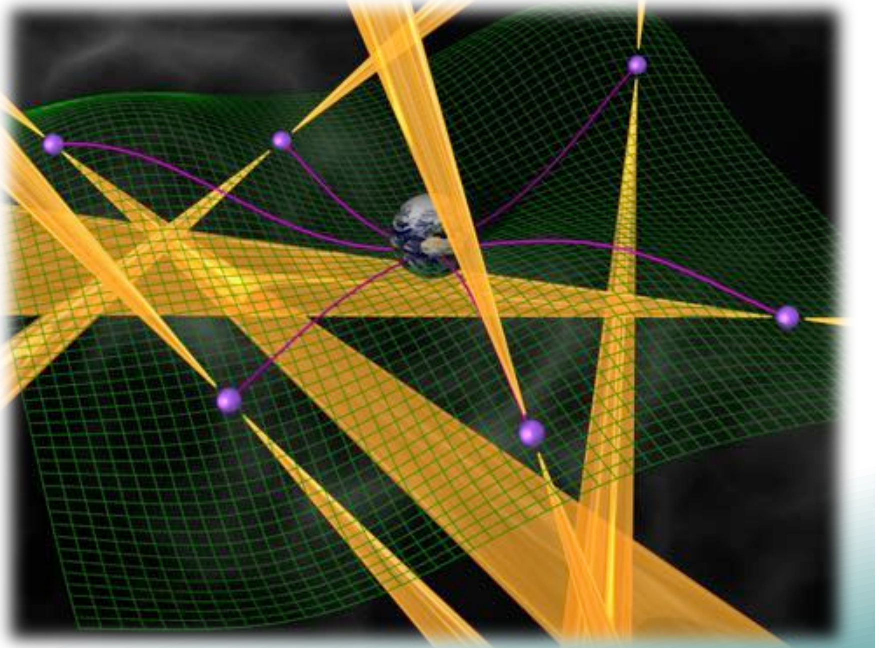
Pulsars as Gravitational Wave Detectors

Pulse arrival times will be affected by low-frequency gravitational waves – correlated across sky!

In a "Pulsar Timing Array" (PTA) pulsars act as the arms of a cosmic gravitational wave detector



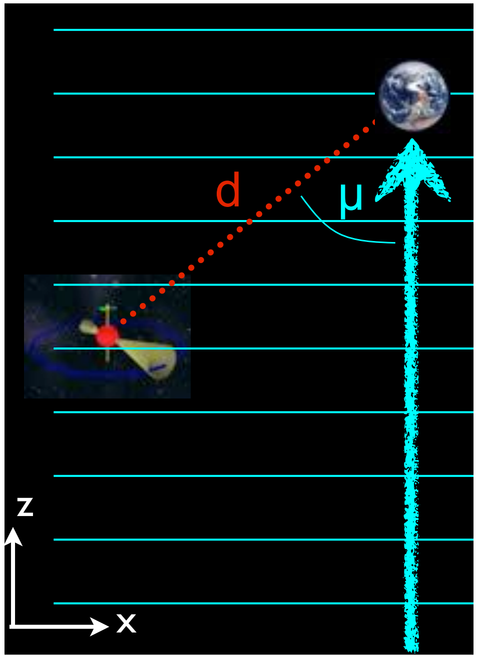
[Hellings & Downs 1983]



Detecting gravitational waves

- Sazhin (1978) and Detweiler (1979) first showed that a GW signal causes a fluctuation in the observed pulse frequency δν/ν
- The timing residual is the integral over these variation over the duration of the timing experiment:

$$R(t) = -\int_0^t \frac{\delta\nu(t)}{\nu}dt$$



With Doppler shift given by

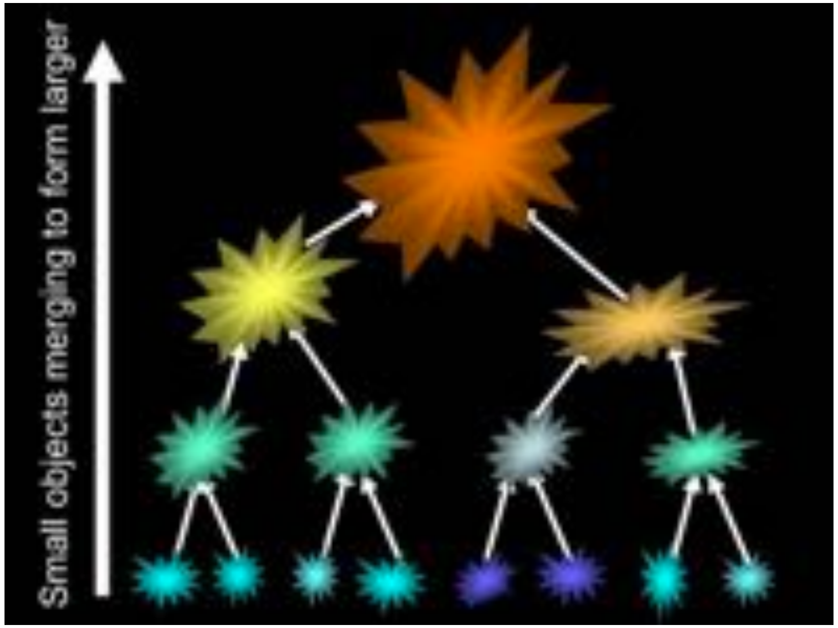
$$\frac{\delta\nu}{\nu} = H^{ij}(h^e_{ij} - h^p_{ij})$$

geometry Earth pulsar

$c T_{\rm obs} \sim \lambda \ll d$ -> short wavelength approximation

What are the sources?

- In standard model of hierarchical galaxy formation, SMBHB will form

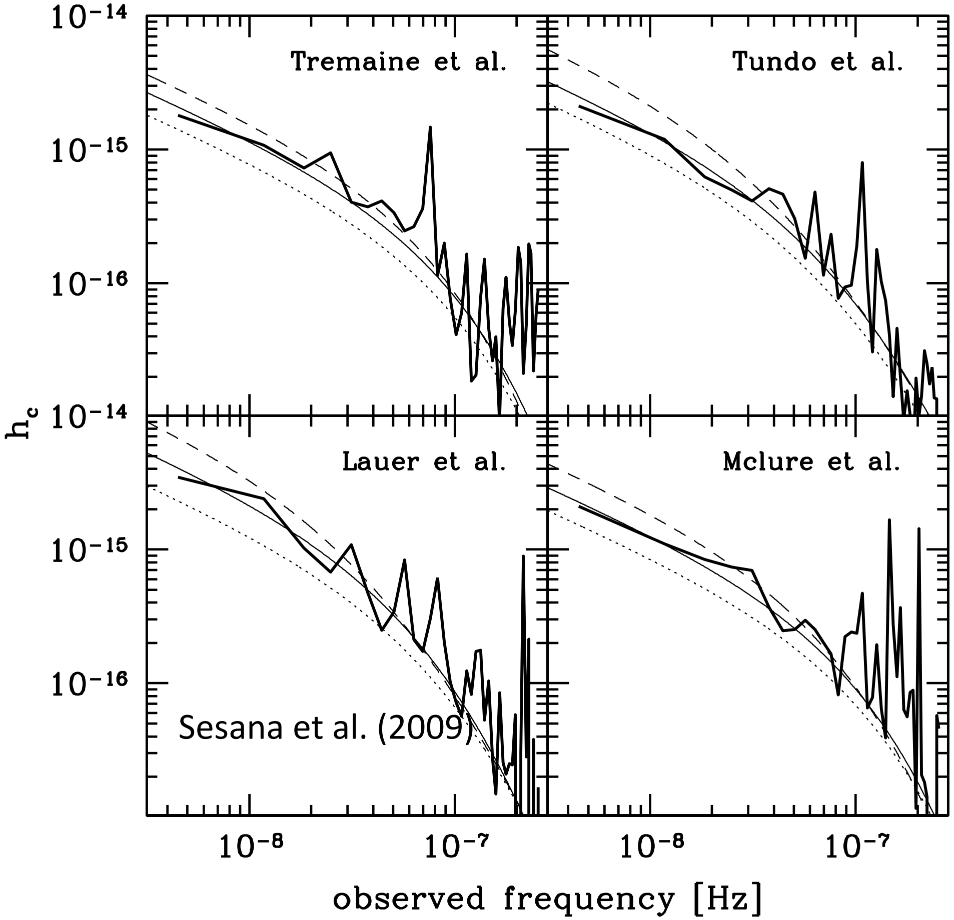


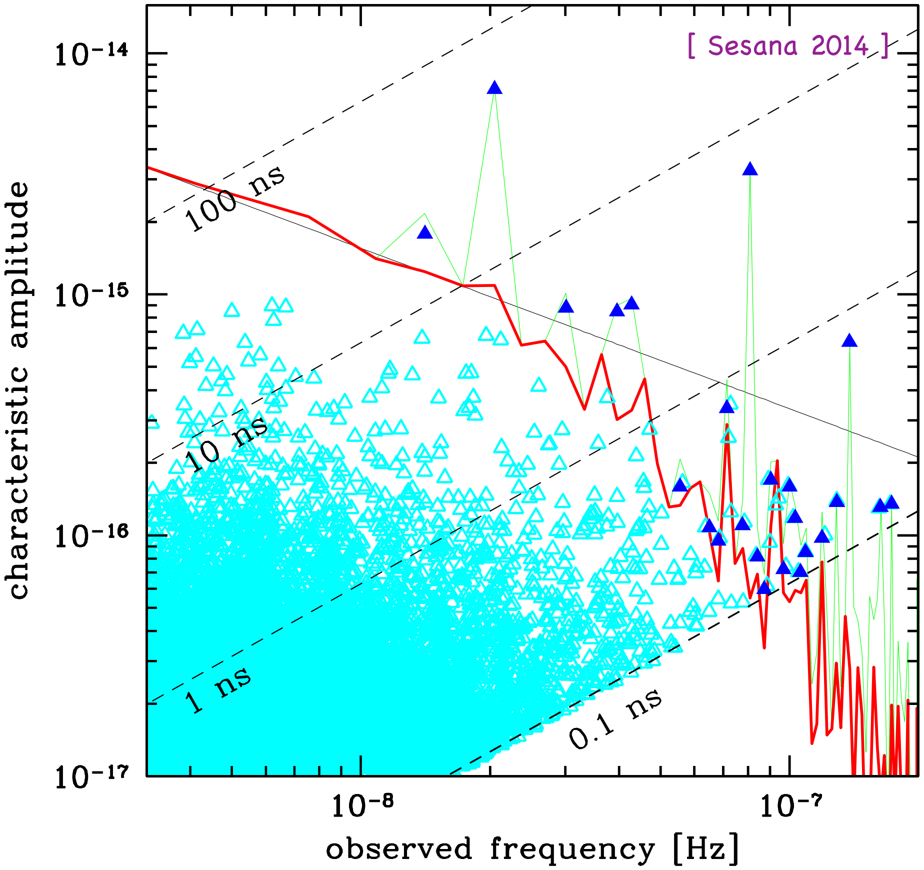
- A number of details not too well understood:

- Galaxy merger rate affects the number of sources at each frequency
- MBH mass (local dynamics) and accretion (when? how?) affect the mass of the sources
- Environment coupling (gas & stars) affects the chirping rate of the binaries

(e.g. see work by Sesana and others for details)

How common are these sources?

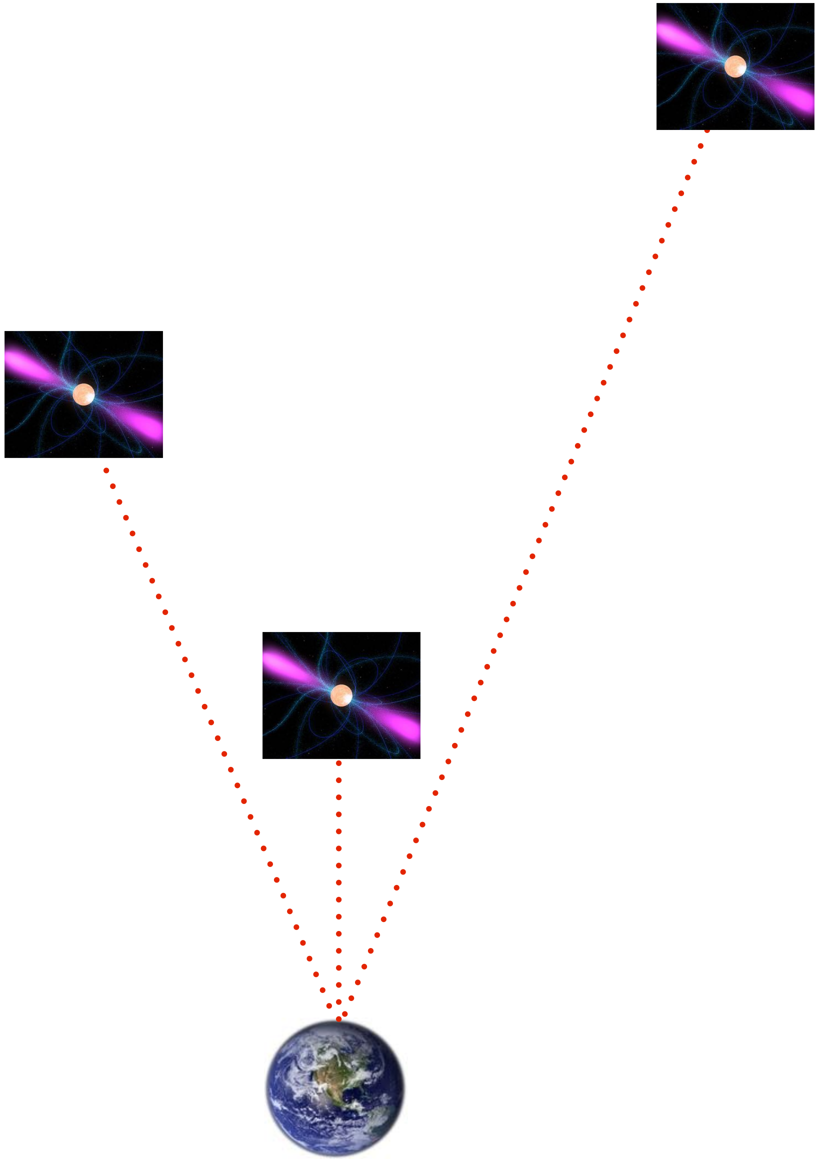


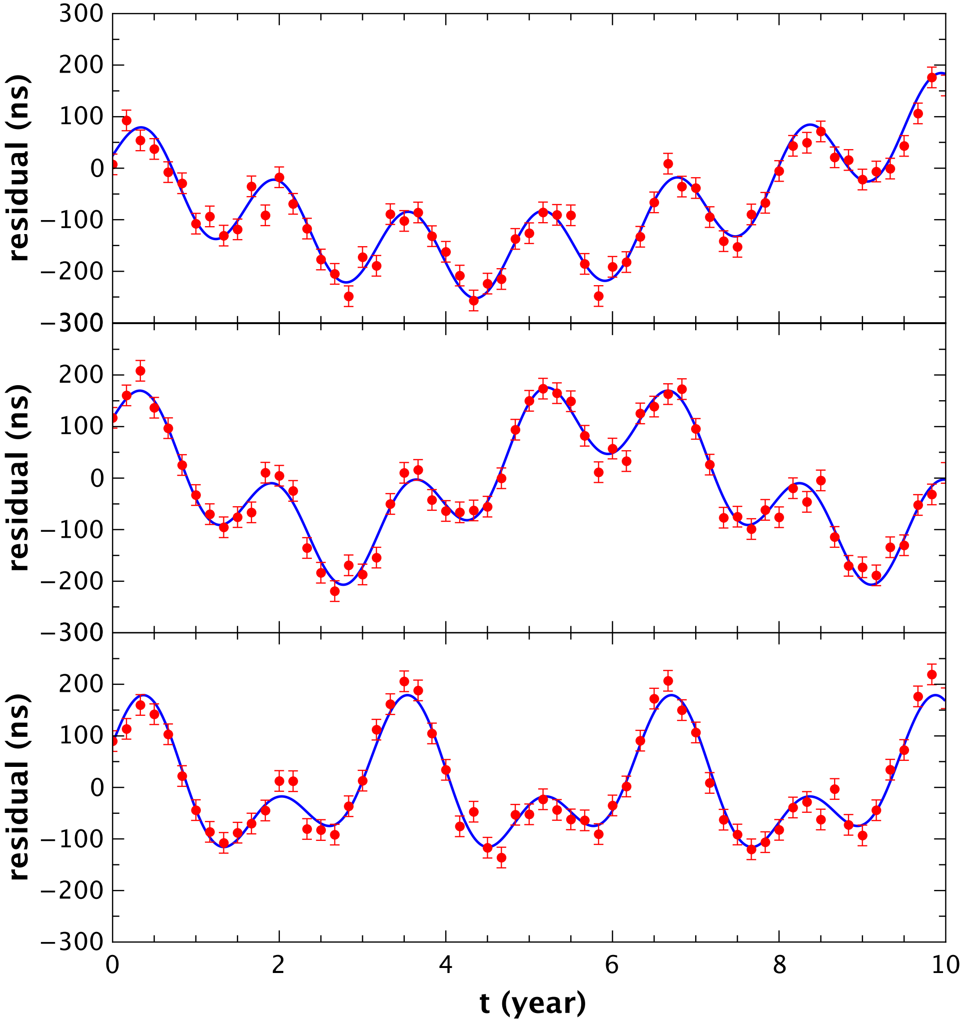


- A single source may already be detectable but it may be rare
- All them form a stochastic background of possibly unresolved sources
- Shape of the spectrum will give information about galaxy merger

Retardation & Source evolution

In principle a tool to look at past evolution of source:





(Wex priv. comm.)

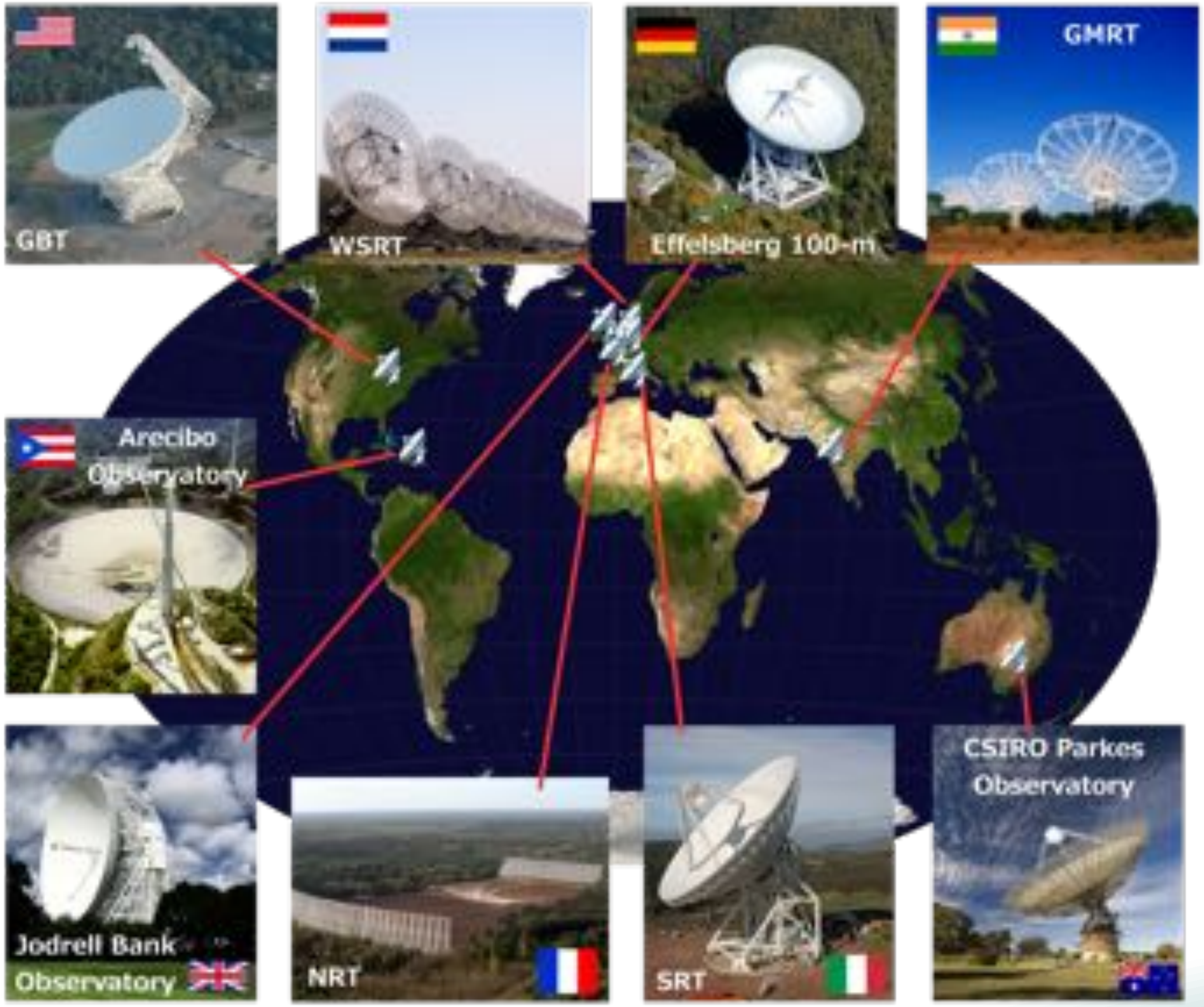
The International Pulsar Timing Array (IPTA)

INTERNATIONAL PULSAR TIMING ARRAY
IPTA

EPTA

NANOGrav

PPTA



•Brian Burt

Currently timing 50 MSPs at six radio frequencies with seven (soon nine) telescopes. There are roughly 50,000 TOAs spanning 10 years in the current IPTA data release.

The European Pulsar Timing Array (EPTA)

An array of 100-m class telescopes to form a pulsar timing array


SRT, Sardinia, Italy


Effelsberg 100-m, Germany


Lovell, Jodrell Bank, UK


NRT, Nancay, France


WSRT, Westerbork, NL

Plus theory:

and ultimately forming the Large European Array for Pulsars (LEAP)

The IPTA in the GW Landscape

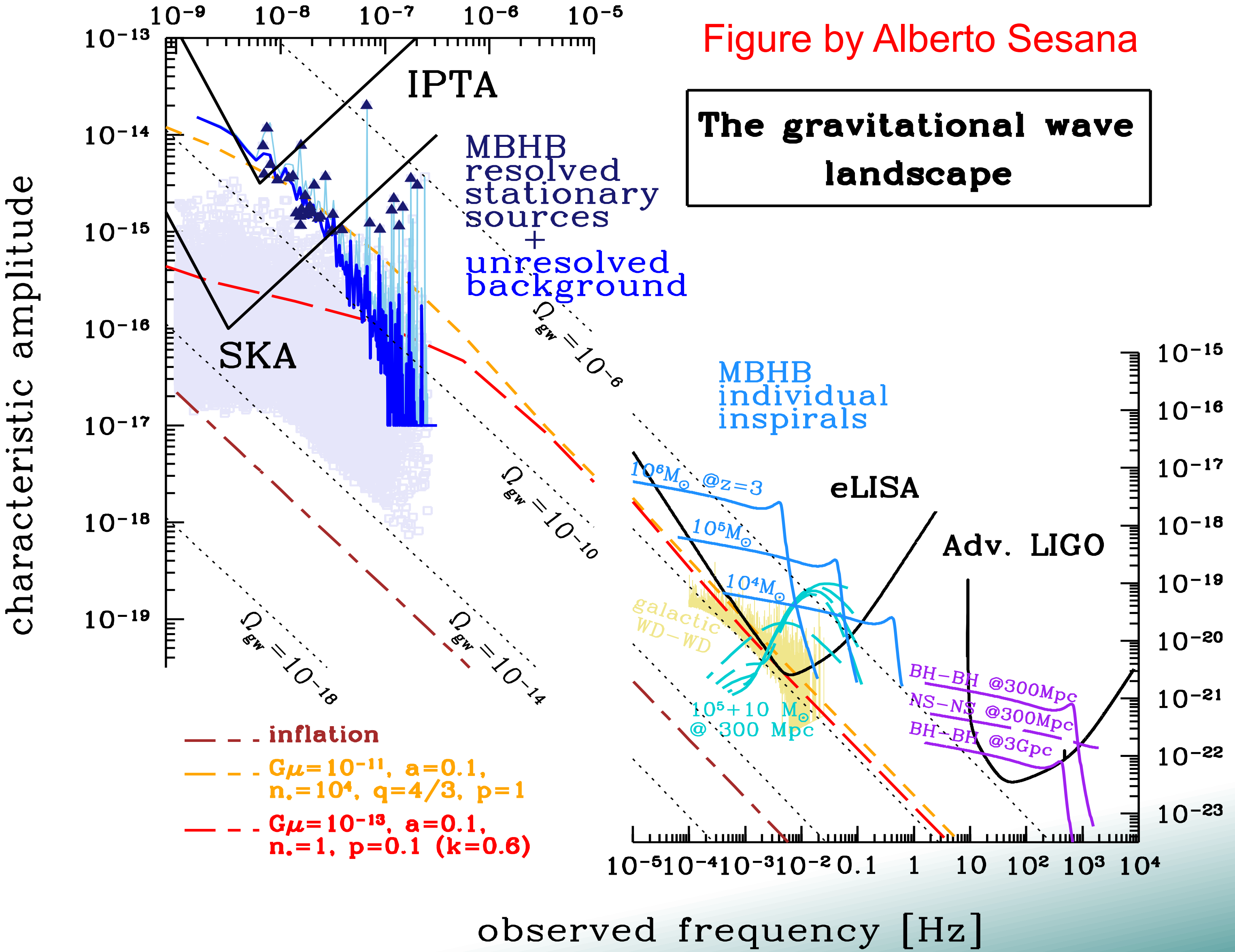
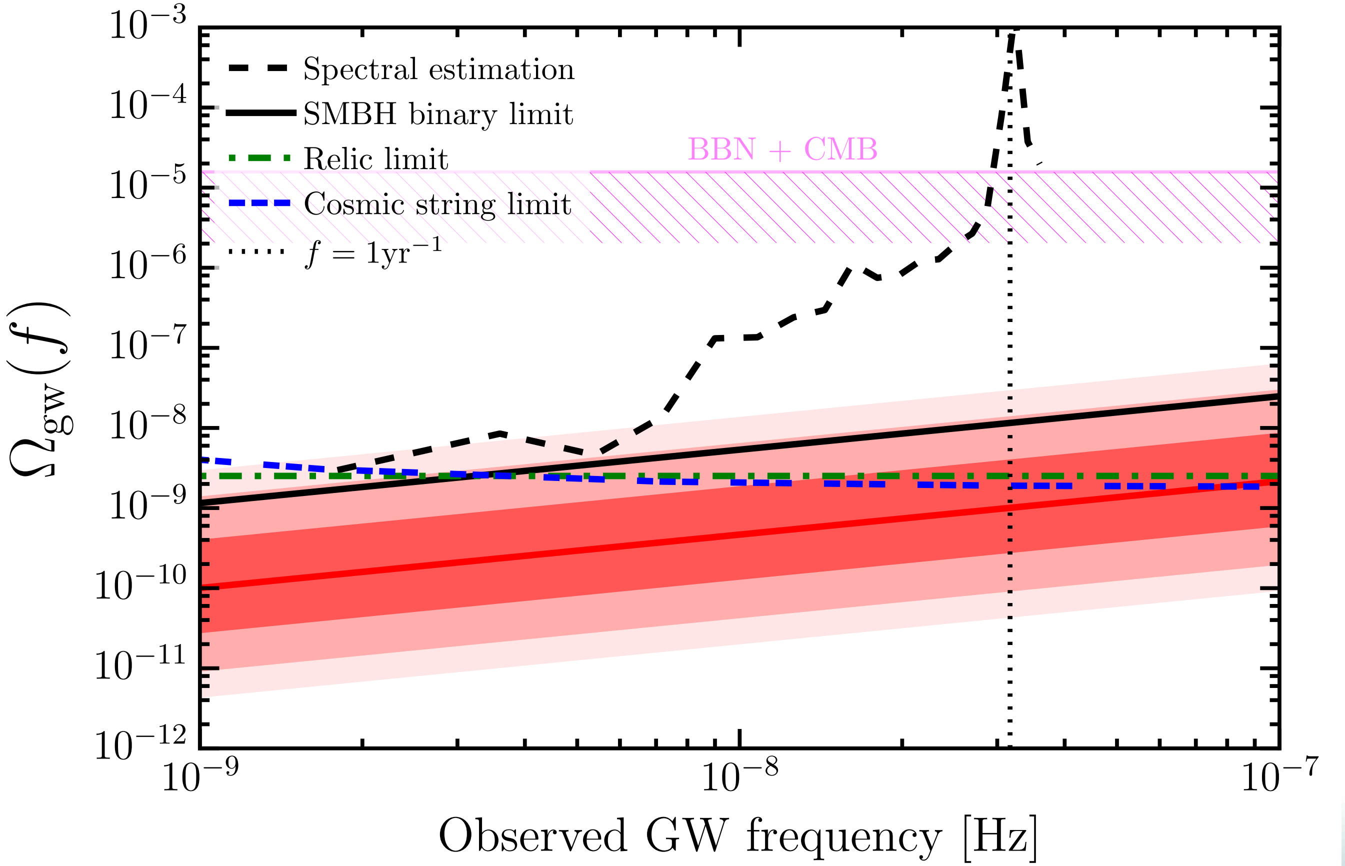


Figure by Alberto Sesana

Recent EPTA publication work

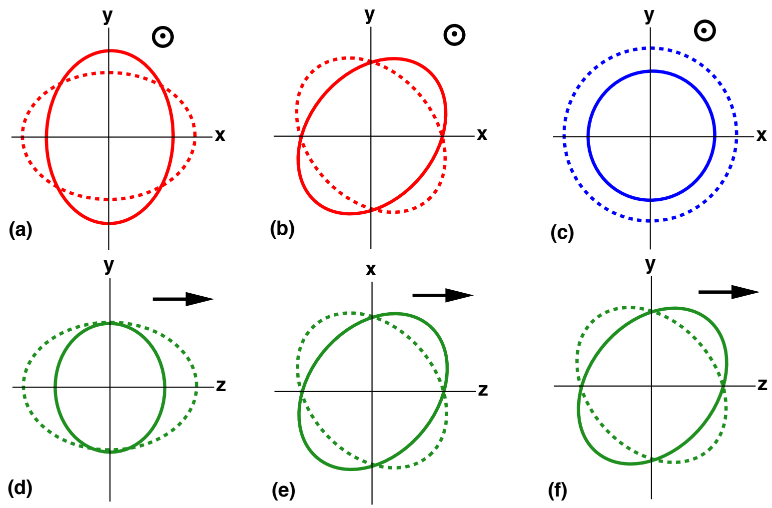
European Pulsar Timing Array Limits On An Isotropic Stochastic Gravitational-Wave Background, Lentati et al. 2015 (arXiv:1504.03692)



Also limits on string tension, $G\mu/c^2$, characterising a background from a cosmic string network for a set of possible scenarios, and for a stochastic relic GWB.

Testing the properties of gravitons with the SKA

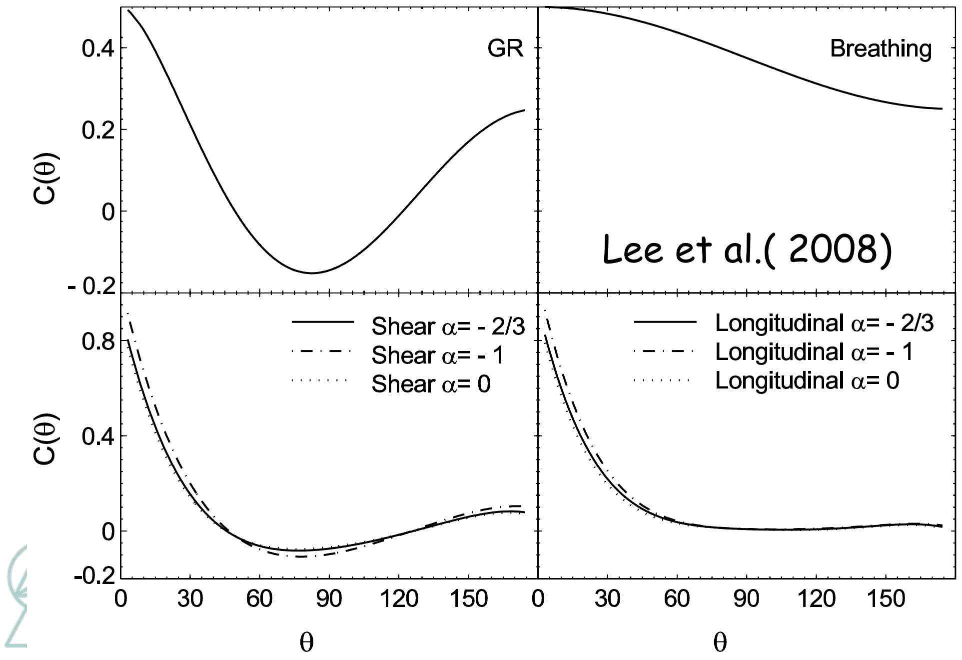
Polarization modes – Spin 2?

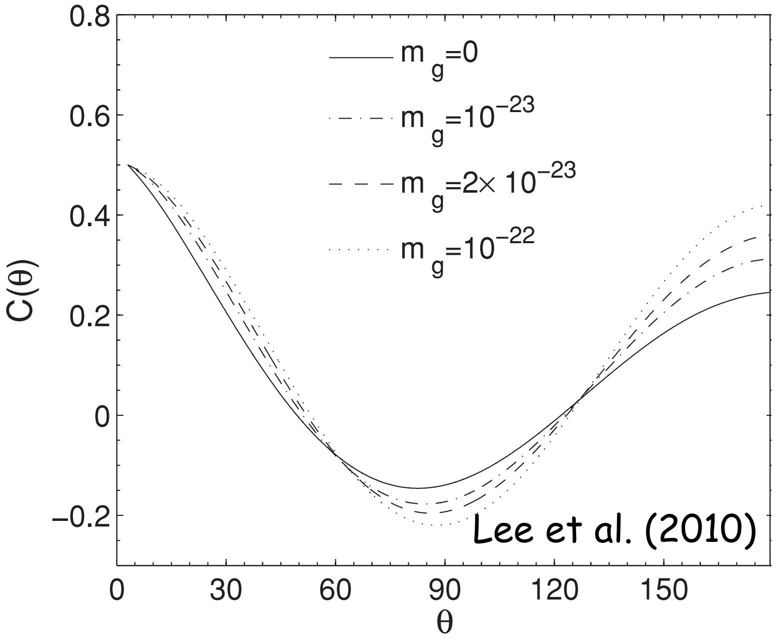


Dispersion relation: massive graviton?

$$\mathbf{k}_{\mathrm{g}}(\omega_{\mathrm{g}}) = \frac{\left(\omega_{\mathrm{g}}^2 - \omega_{\mathrm{cut}}^2\right)^{\frac{1}{2}}}{c}\,\hat{\mathbf{e}}_z$$

$$\omega_{\mathrm{cut}} \equiv m_{\mathrm{g}} c^2/\hbar$$

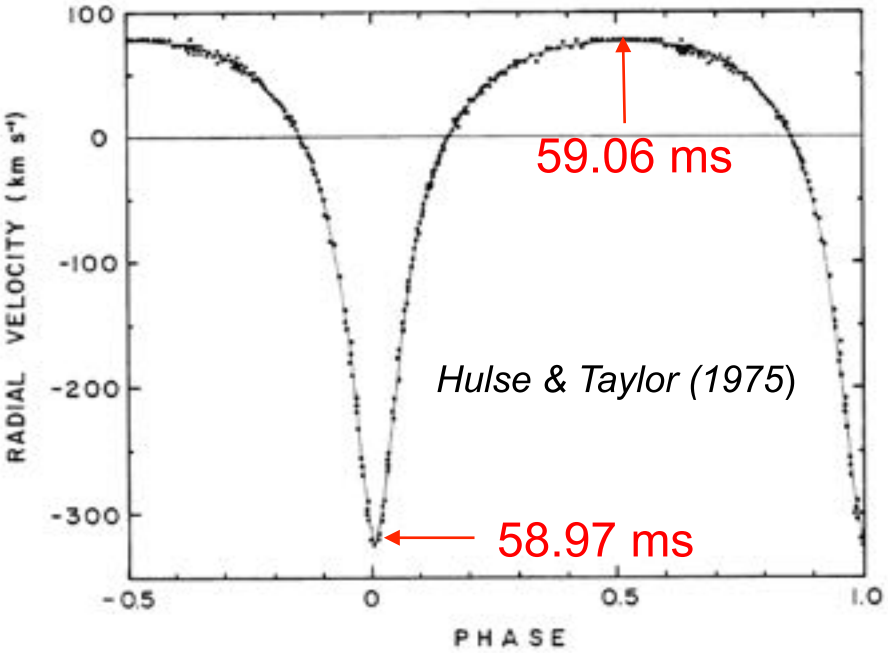


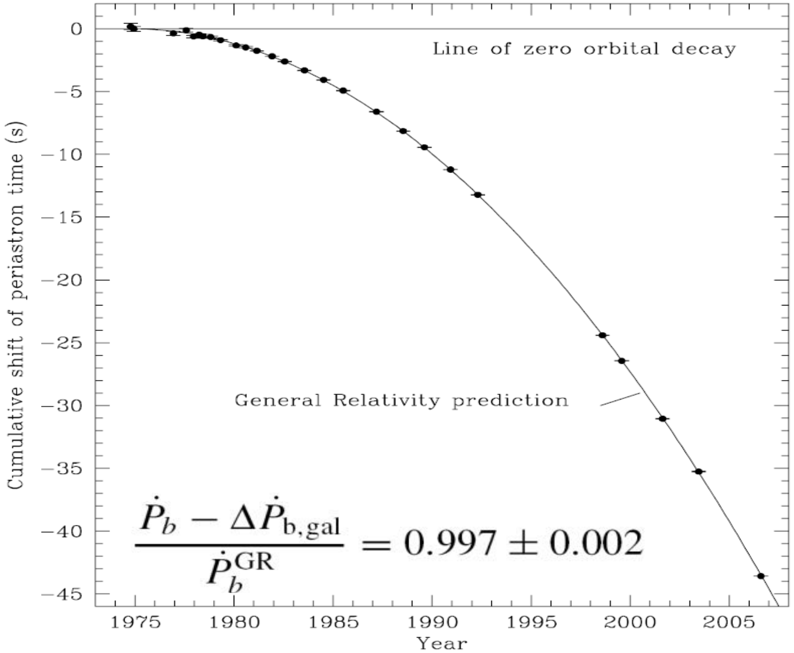


Outline

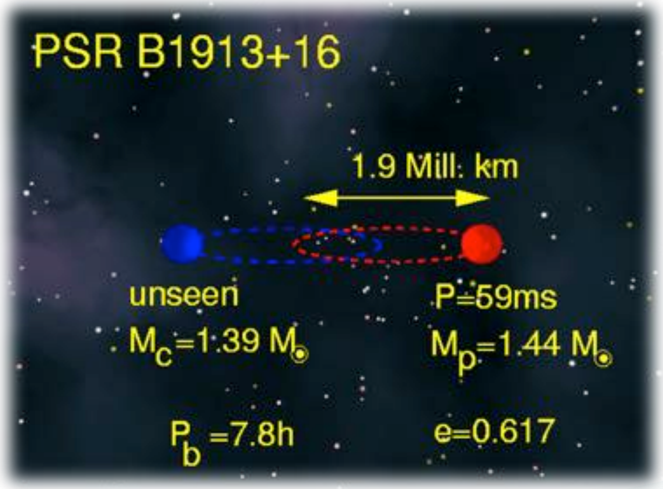
- Introduction: Pulsars & gravitational waves
- Testing general relativity with binary pulsars
- Testing alternative theories
- (Near?!) Future tests with Black Holes: Sgr A*

The first binary pulsar: Hulse-Taylor pulsar



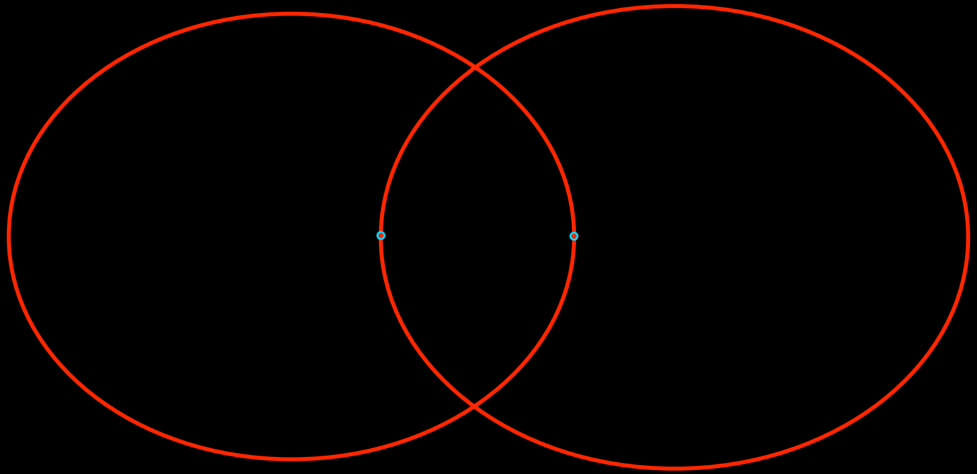


$$\frac{\dot{P}_b - \Delta\dot{P}_{\rm b,gal}}{\dot{P}_b^{\rm GR}} = 0.997 \pm 0.002$$

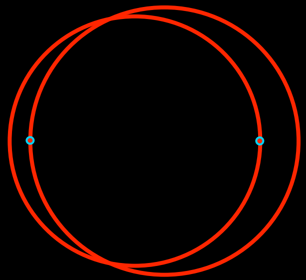


Comparison Hulse-Taylor vs Double Pulsar

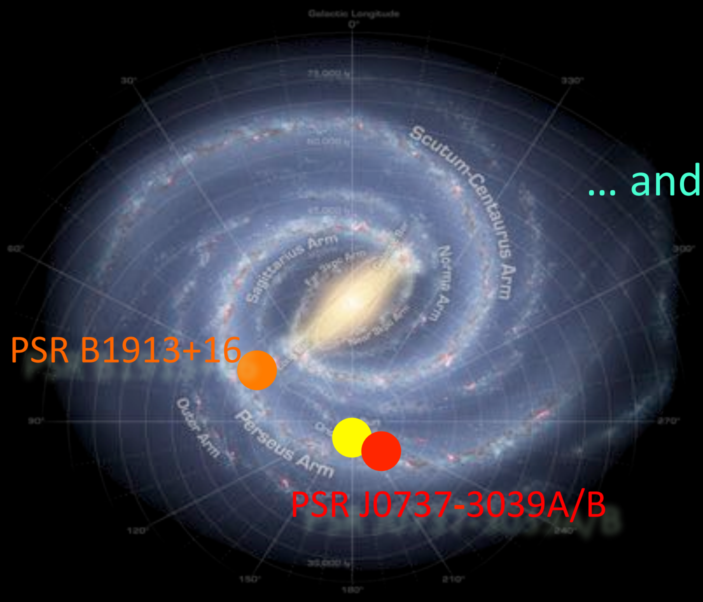
PSR B1913+16



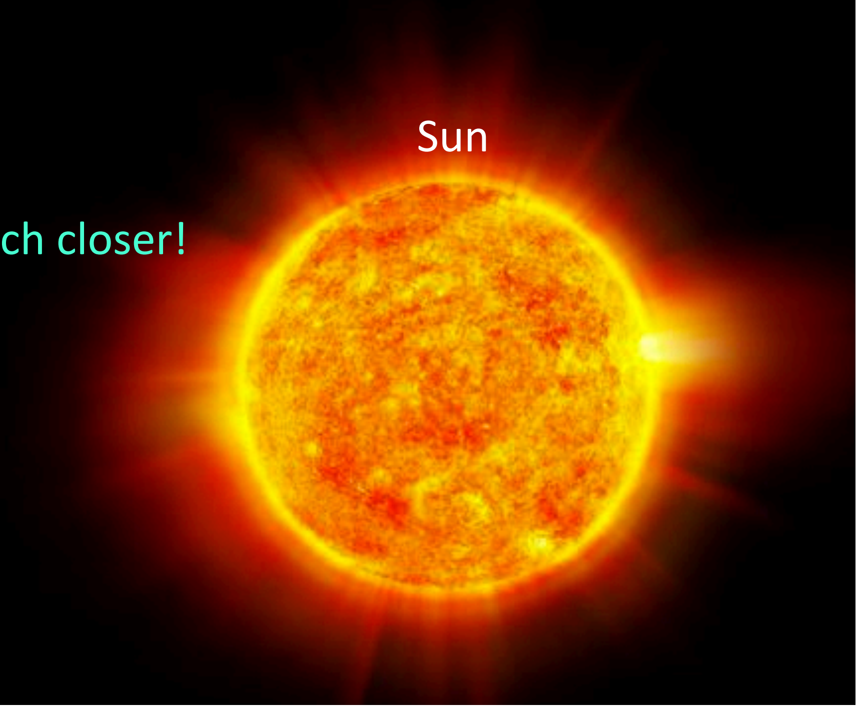
PSR J0737-3039A/B



More compact…



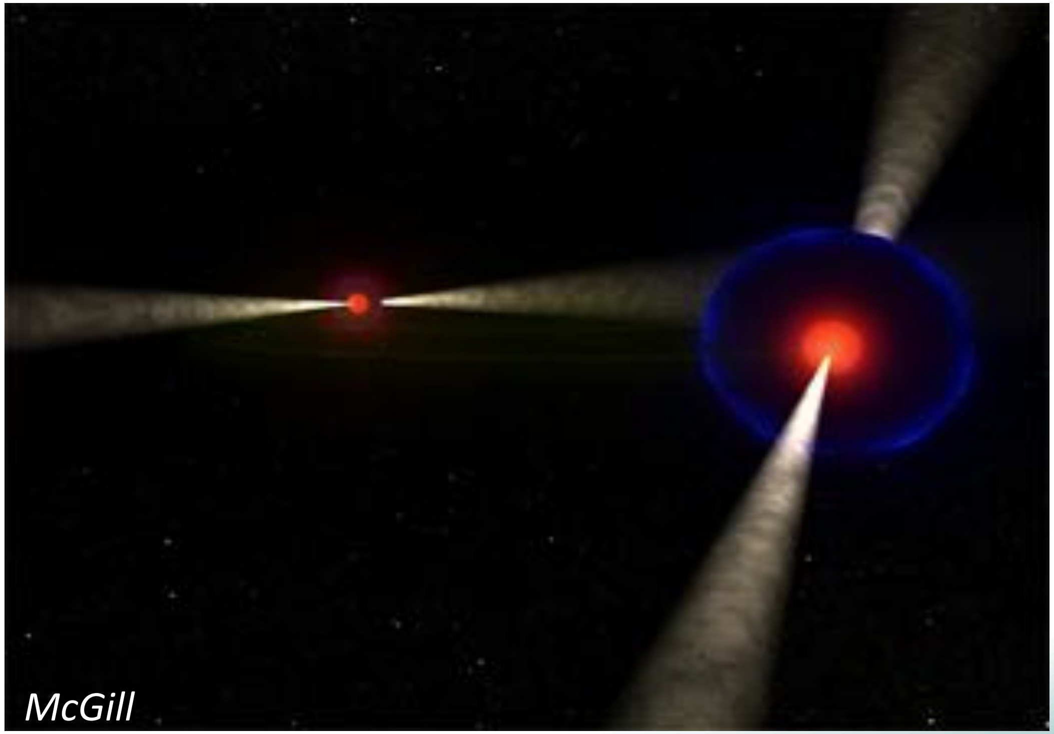
… and much closer!



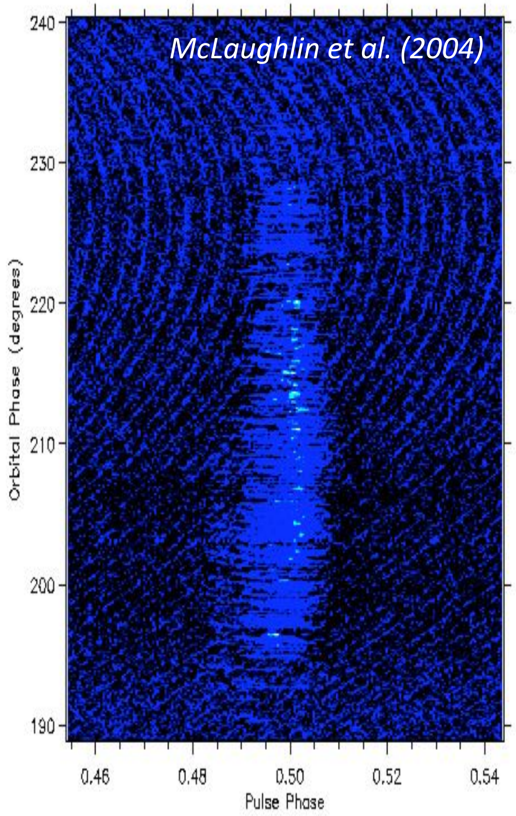
The Double Pulsar (Burgay et al. 2003, Lyne et al. 2004)

- Old 22-ms pulsar in a 147-min orbit with young 2.77-s pulsar
- Orbital velocities of 1 Mill. km/h
- Eclipsing binary in compact, slightly eccentric (e=0.088) and edge-on orbit
- Ideal laboratory for gravitational and fundamental physics
- In particular, exploitation for tests of general relativity

(Kramer et al. 2006, Breton et al. 2008)



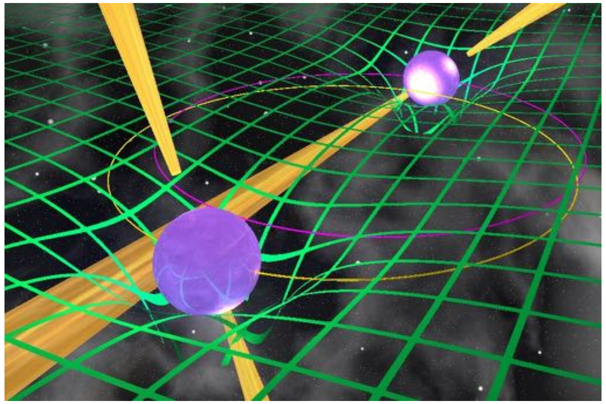
McGill



McLaughlin et al. (2004)

Double Pulsar: a unique relativistic double-line system

- We can measure two orbits ➔ mass ratio



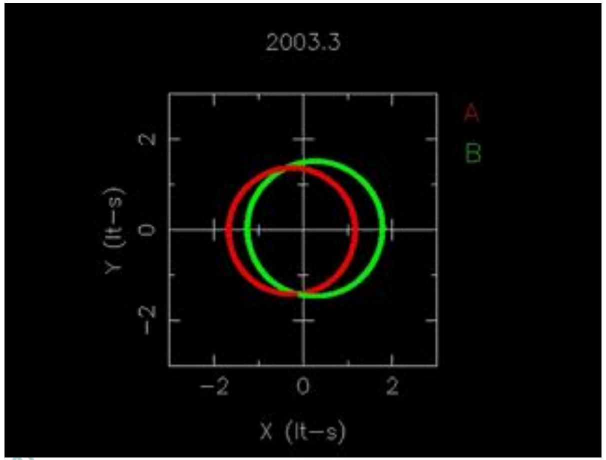
$$R \equiv \frac{x_B}{x_A} = \frac{m_A}{m_B} = 1.0714 \pm 0.0011$$

Note: theory-independent to 1PN order!

(Damour & Deruelle 1986, Damour 2005)

- Huge orbital precession of 16.8991 ± 0.0001 deg/yr!

(4 x larger than Hulse-Taylor
- already at 2PN precision!)



Compare to Mercury:

$$\dot{\omega} = 0.00012 \text{ deg/yr}$$

$$d\omega / dt = 3T_{Sun}^{2/3} \left(\frac{P_b}{2\pi}\right)^{-5/3} \frac{(m_A + m_B)^{2/3}}{1 - e^2}$$

$m_A + m_B$=(2.58706±0.00001) $M_\odot$

Combined (GR):

m_A= (1.3381±0.0007) $M_\odot$

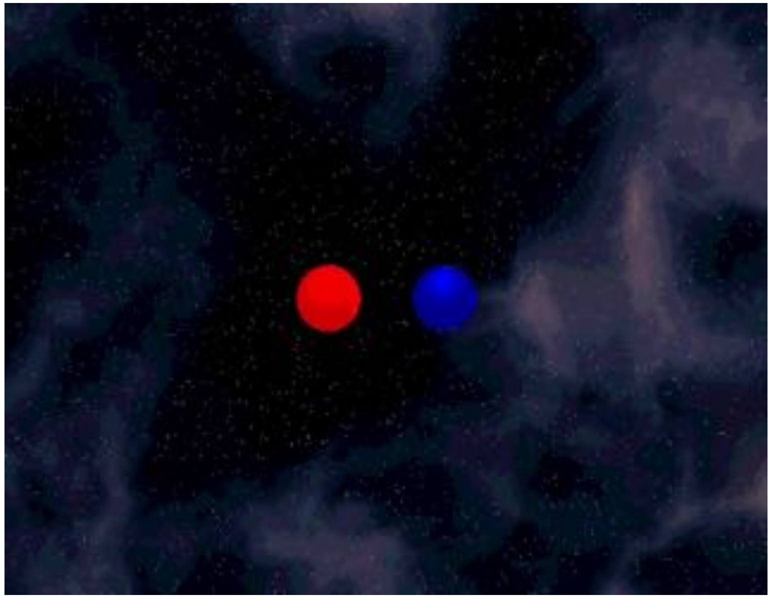
& m_B= (1.2489±0.0007) $M_\odot$

Newest measurement: dω/dt = 16.89931(2) deg/yr - error about 10 x 2PN!

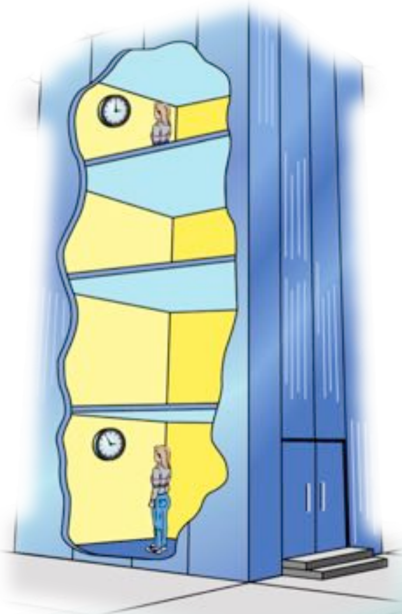
Double Pulsar: five tests in one system!

- Huge orbital precession of 16.89931(2) deg/yr!
- Clock variation due to gravitational redshift: 385.6 ± 2.6 μs!

Latest measurement: 383.9 ± 0.5 μs (improvement: x 5 – but not x 30!)



$$\frac{\text{Obs.Val.}}{\text{Exp.(GR)}} = 1.000 \pm 0.002$$



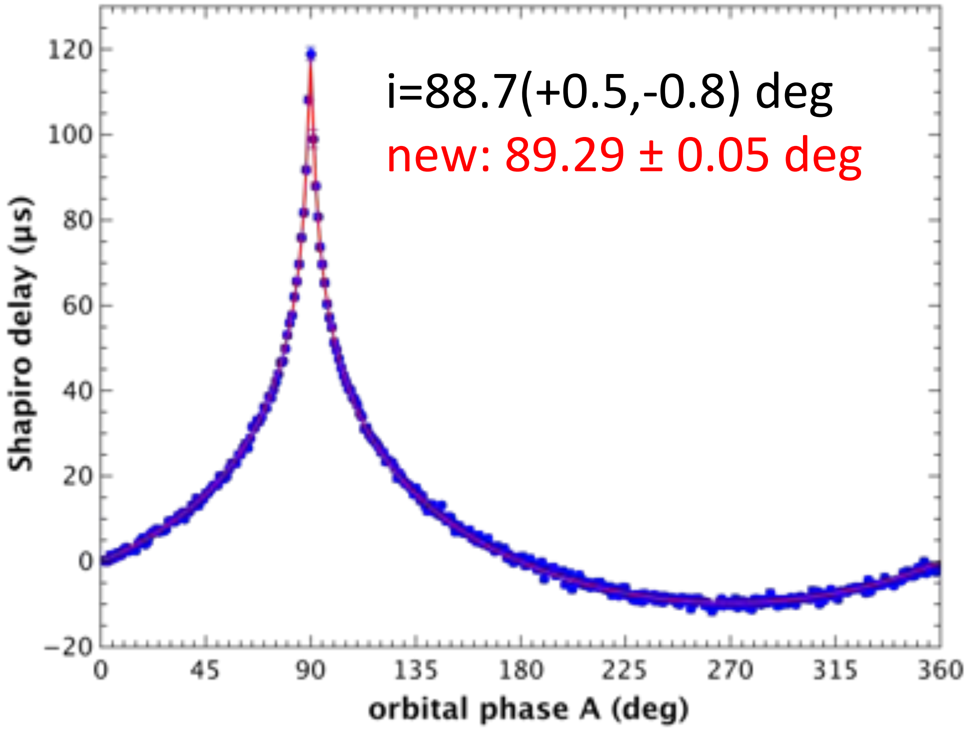
- As other clocks, pulsars run slower in deep gravitational potentials

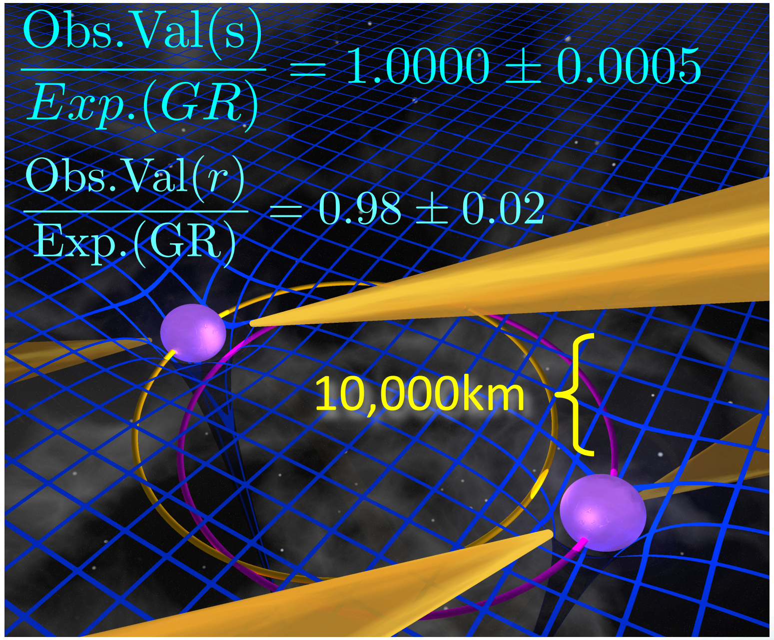
- Changing distance to companion (and felt grav. potential) during elliptical orbit

Double Pulsar: five tests in one system!

- Huge orbital precession of 16.89931(2) deg/yr!
- Clock variation due to gravitational redshift: 383.9 ± 0.5 μs !
- Shapiro delay in edge-on orbit: s = sin(i)=0.99974 (-0.00039,+0.00016)

s = sin(i)=0.999923 ± 0.000012





$$\frac{\mathrm{Obs.Val(s)}}{Exp.(GR)} = 1.0000 \pm 0.0005$$

$$\frac{\mathrm{Obs.Val}(r)}{\mathrm{Exp.(GR)}} = 0.98 \pm 0.02$$

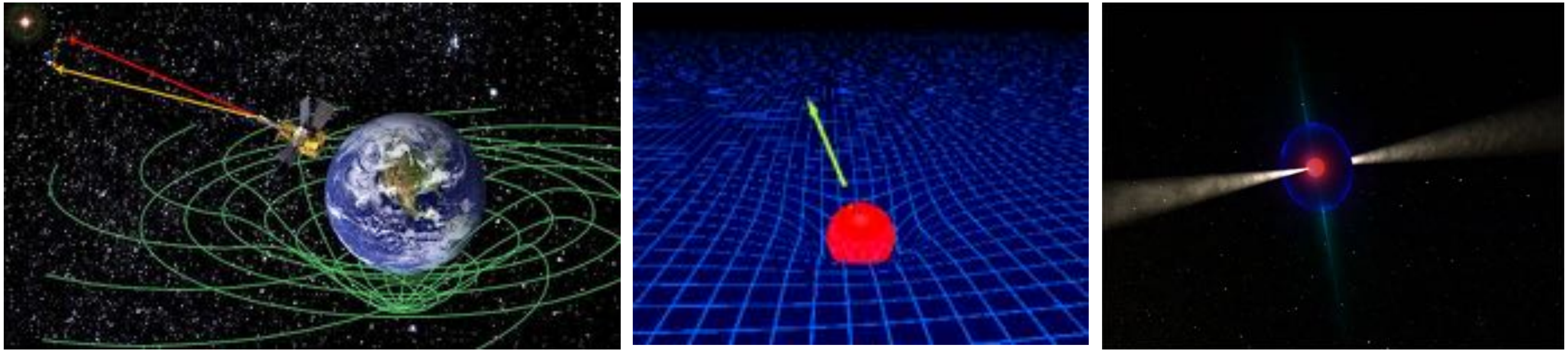
- At superior conjunction, pulses from pulsar A pass B in <10,000km distance

- Space-time near companion is curved ➔Additional path length

➔ Delay in arrival time – depending on geometry and companion mass

Double Pulsar: five tests in one system!

- Huge orbital precession of 16.89931(2) deg/yr!
- Clock variation due to gravitational redshift: 383.9 ± 0.5 μs !
- Shapiro delay in edge-on orbit: s = sin(i)=0.999923 ± 0.000012
- Relativistic spin precession



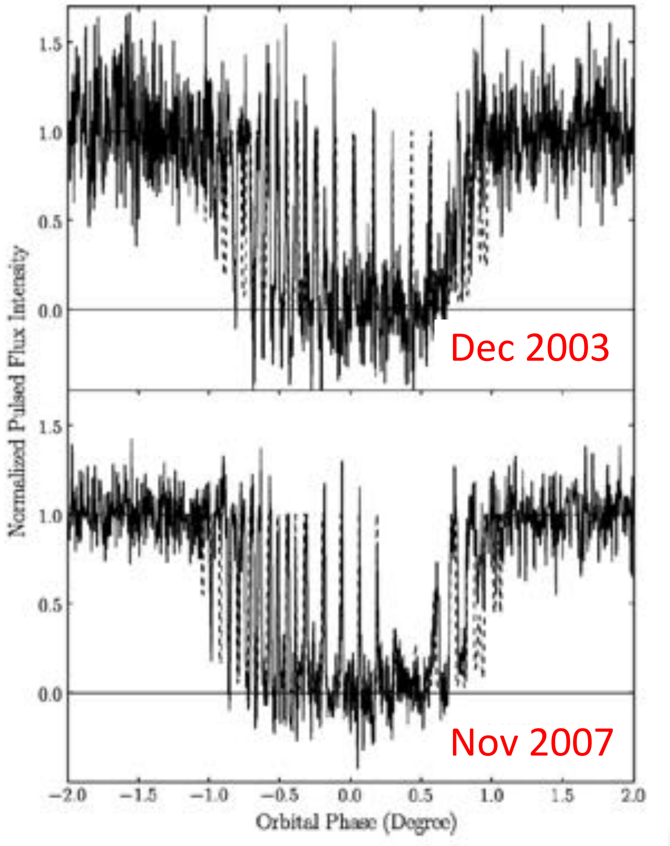
Experiments made in Solar System provide precise tests for this effect and confirm it, e.g. gyro-experiments such as Gravity-Probe B

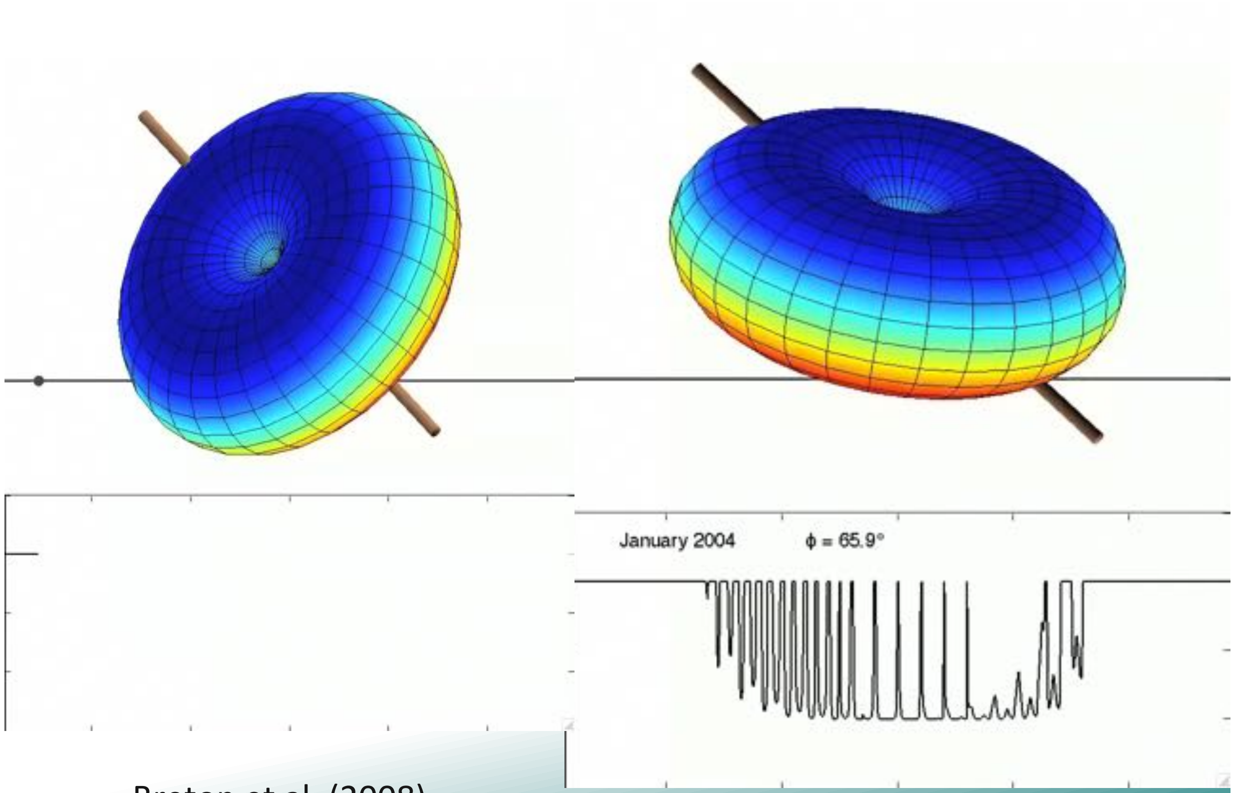
First seen for HT-Pulsar (Kramer'98) and PSR B1534+12 (Stairs et al. '04, Fonseca et al. '15),
…but no firm quantitative strong-field test until Double Pulsar

Double Pulsar: five tests in one system!

- Huge orbital precession of 16.89931(2) deg/yr!
- Clock variation due to gravitational redshift: 383.9 ± 0.5 μs !
- Shapiro delay in edge-on orbit: $s = \sin(i) = 0.999923 \pm 0.000012$
- Relativistic spin precession: $\Omega_B = 4.8(7)$ deg yr^{-1}

$$\frac{\text{Obs.Val.}}{\text{Exp.(GR)}} = 0.93 \pm 0.13$$





Breton et al. (2008)

Double Pulsar: five tests in one system!

- Huge orbital precession of 16.89931(2) deg/yr!
- Clock variation due to gravitational redshift: 383.9 ± 0.5 μs !
- Shapiro delay in edge-on orbit: $s = \sin(i) = 0.999923 \pm 0.000012$
- Relativistic spin precession: $\Omega_B = 4.8(7)$ deg yr^{-1}
- Shrinkage of orbit due to GW emission: $\Delta P_b = 107.79 \pm 0.11$ ns/day!

old: $dP_b/dt = -1.25(2) \times 10^{-12}$ s/s

- Pulsars approach each other by

7.152 ± 0.008 mm/day

$$\frac{\text{Obs.Val.}}{\text{Exp.(GR)}} = 1.000 \pm 0.001$$

- Merger in 85 Million years

Animation by NASA/Rezzolla/AEI

Precision of all tests will improve with time:
expect to supersede solar system tests

Outline

- Introduction: Pulsars & gravitational waves
- Testing general relativity with binary pulsars
- Testing alternative theories
- (Near?!) Future tests with Black Holes: Sgr A*

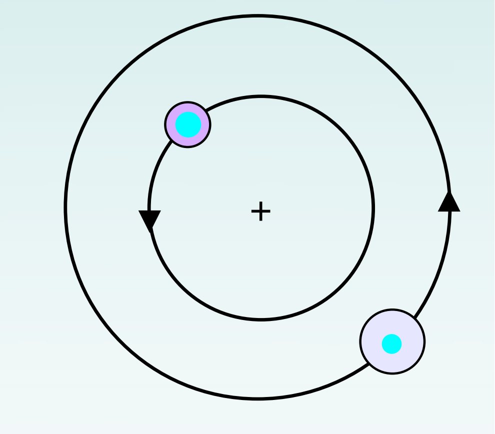
Dipolar Gravitational Radiation in Binary Systems?

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

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

$$+ \frac{\text{Monopole}}{c}\left(0+\frac{1}{c^2}\right)^2 + \underset{\overset{\uparrow}{\propto(\alpha_A-\alpha_B)^2}}{\frac{\text{Dipole}}{c^3}} + \frac{\text{Quadrupole}}{c^5} + O\left(\frac{1}{c^7}\right) \qquad \text{spin 0}$$

Hence, visible in orbital decay:

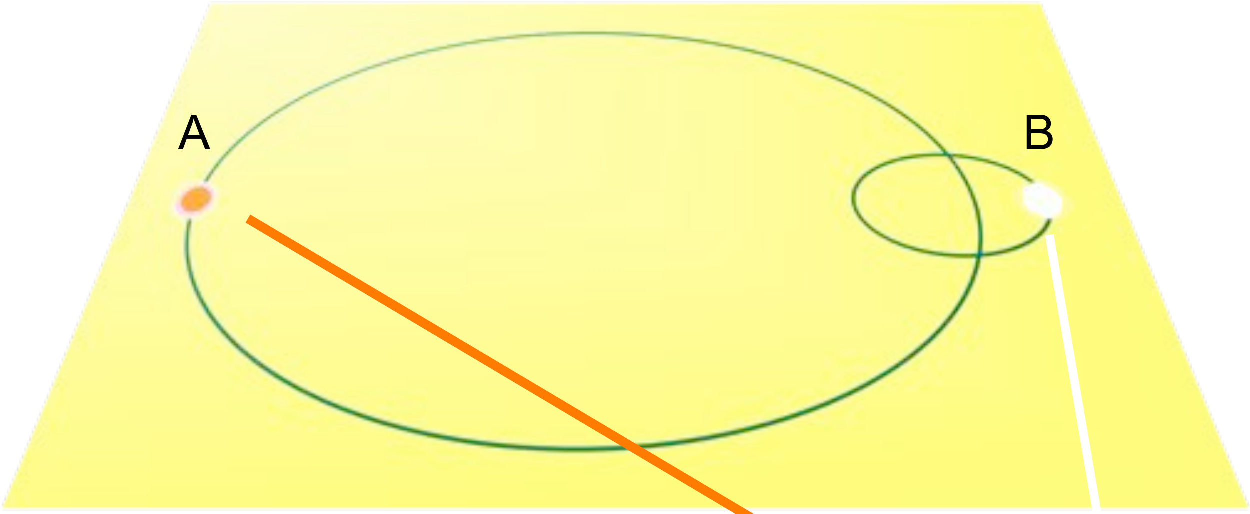


$$\dot{P}_\mathrm{b}^{\mathrm{quadrupole}} \propto \left(\frac{v}{c}\right)^5$$

$$\underset{\overset{\uparrow}{\boxed{= 0 \text{ in GR}}}}{\dot{P}_\mathrm{b}^{\mathrm{dipole}}} \propto \left(\frac{v}{c}\right)^3 \underbrace{(\alpha_A-\alpha_B)^2}_{\sim 0 \text{ in Double Pulsar since } \alpha_A \approx \alpha_B}$$

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 dynamcis (1.5 pN):



For different bodies, measurable as orbital decay from dipolar radiation:

$$\dot{P}_{\rm b}^{\rm dipole} = -\frac{4\pi^2}{P_{\rm b}} \frac{G m_{\rm A} m_{\rm B}}{c^3 (m_{\rm A} + m_{\rm B})} \frac{1 + e^2/2}{(1 - e^2)^{5/2}} (\alpha_{\rm A} - \alpha_{\rm B})^2$$

PSR-BH system would be best as BH would have zero scalar charge

But PSR – WD system also effective lab – in particular if PSR is massive!

Next best thing: a PSR-WD system

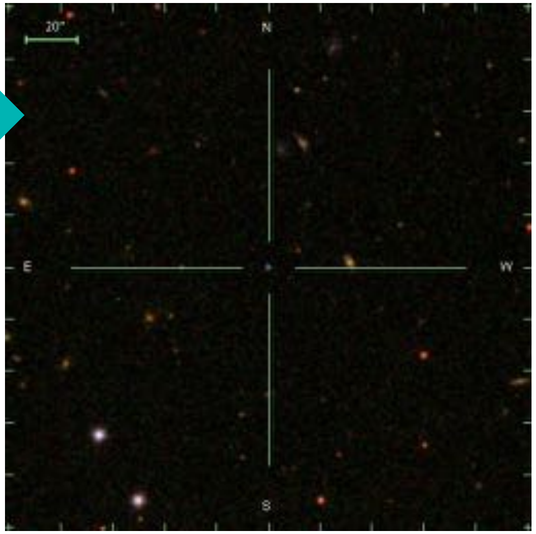
- PSR J0348+0432: first massive NS in relativistic orbit (Lynch et al. 2013)
- Combining VLT, Effelsberg, Arecibo & GBT data, new record mass measured:

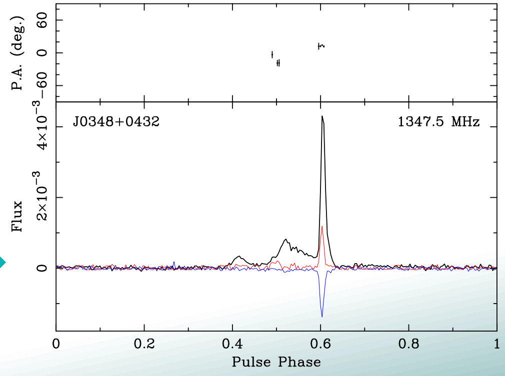
  M=2.01±0.04 $M_\odot$ (Antoniadis et al., 2013)

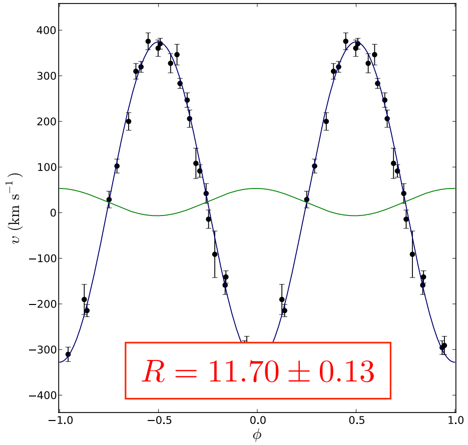
$P = 39.1226569017806(5)\,\mathrm{ms}$

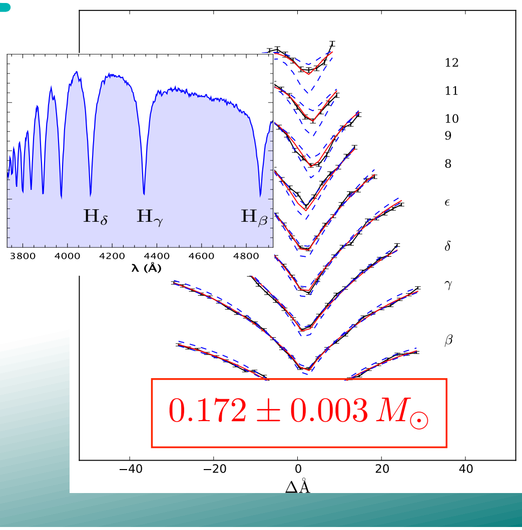
$P_\mathrm{b} = 2.45817750533(2)\,\mathrm{h}$

$e \lesssim 10^{-6}$









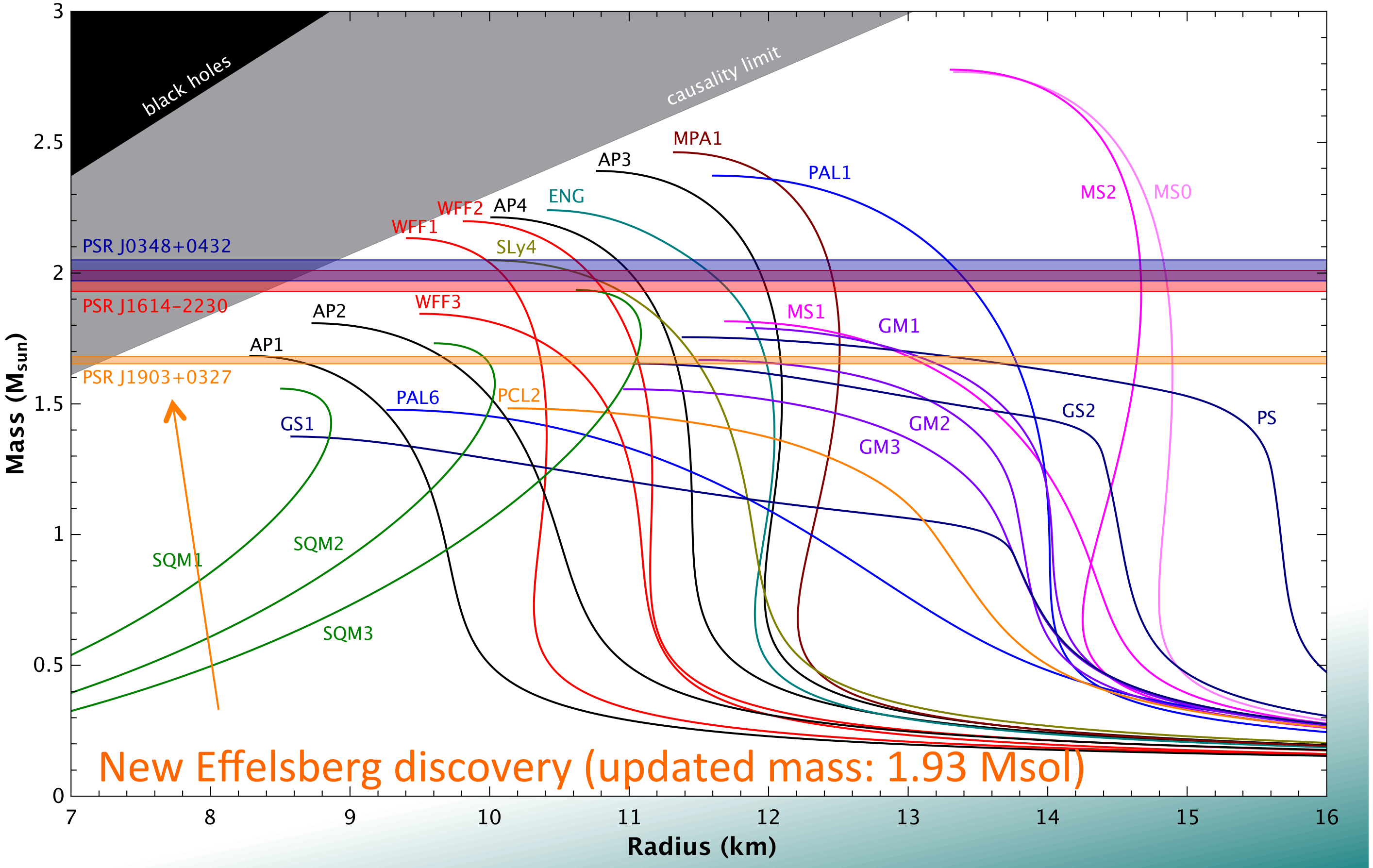
Testing a new gravity regime

- PSR J0348+0432: first massive NS in relativistic orbit (Lynch et al. 2013)
- Combining VLT, Effelsberg, Arecibo & GBT data, new record mass measured:

  M=2.01±0.04 $M_\odot$ (Antoniadis et al., 2013)
- Important for probing different grav fields but also for EoS of superdense matter fields!

Combine with moment-of-inertia from Double Pulsar.

Are they born massive?



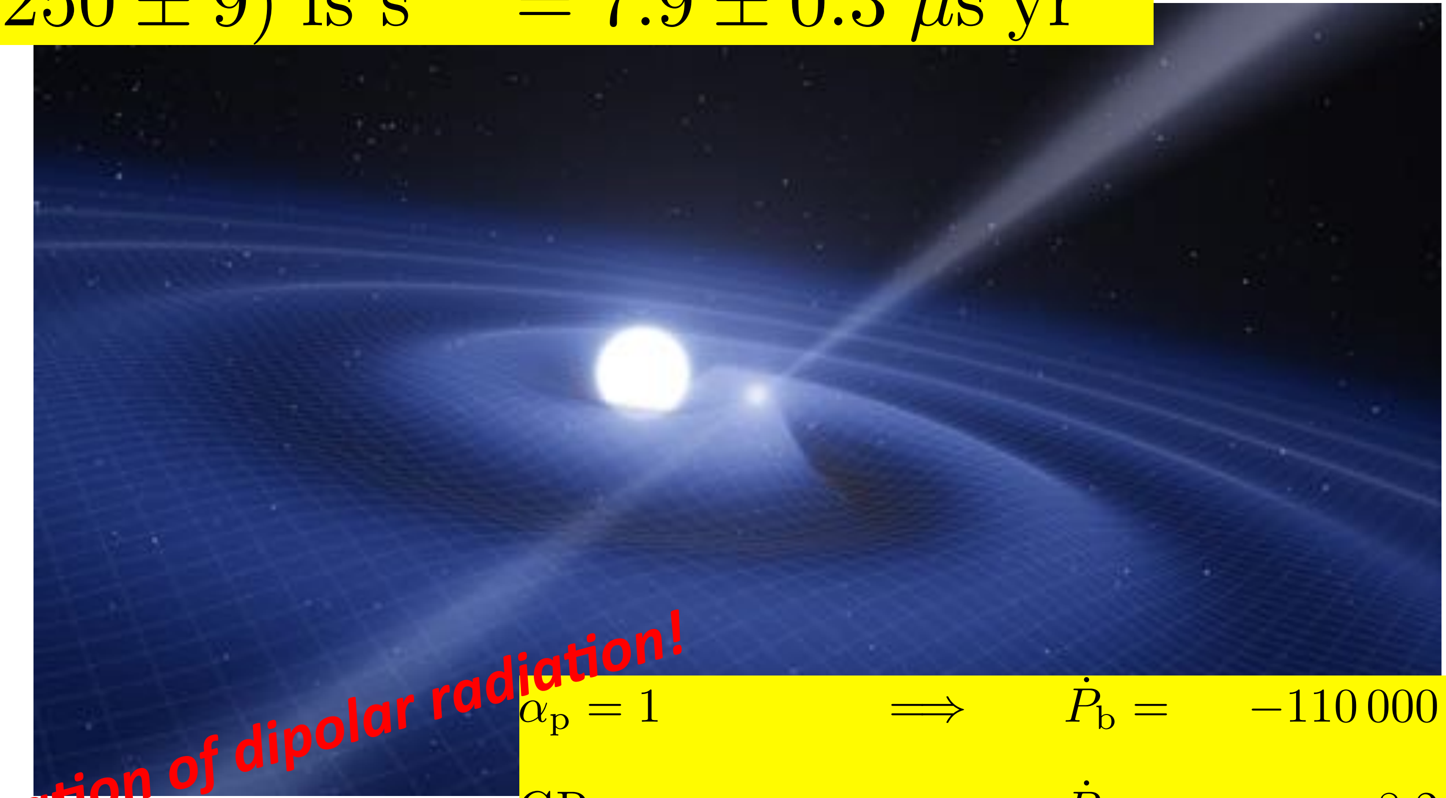
New Effelsberg discovery (updated mass: 1.93 Msol)

Next best thing: a PSR-WD system

- PSR J0348+0432: first massive NS in relativistic orbit (Lynch et al. 2013)
- Combining VLT, Effelsberg, Arecibo & GBT data, new record mass measured:

  M=2.01±0.04 $M_\odot$ (Antoniadis et al., 2013)

$$\dot{P}_b = (-250 \pm 9)\ \mathrm{fs\ s}^{-1} = 7.9 \pm 0.3\ \mu\mathrm{s\ yr}^{-1}$$



No indication of dipolar radiation!

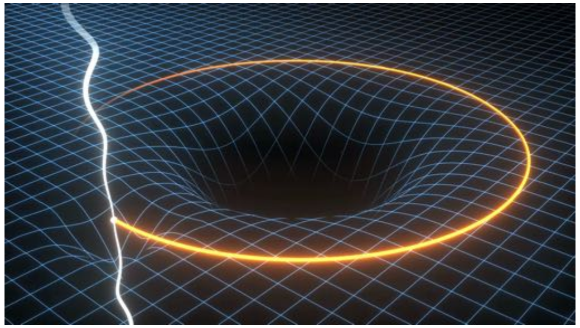
$\alpha_\mathrm{p} = 1$	$\Longrightarrow$	$\dot{P}_\mathrm{b} =$	$-110\,000$	$\mu\mathrm{s/yr}$
GR	$\Longrightarrow$	$\dot{P}_\mathrm{b} =$	-8.2	$\mu\mathrm{s/yr}$
Observations	$\Longrightarrow$	$\dot{P}_\mathrm{b} =$	-8.6 ± 1.4	$\mu\mathrm{s/yr}$

Outline

- Introduction: Pulsars & gravitational waves
- Testing general relativity with binary pulsars
- Testing alternative theories
- (Near?!) Future tests with Black Holes: Sgr A*

The ultimate system: PSR-BH

- We'd like 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!



- BH properties from spin-orbit coupling:

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

[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:

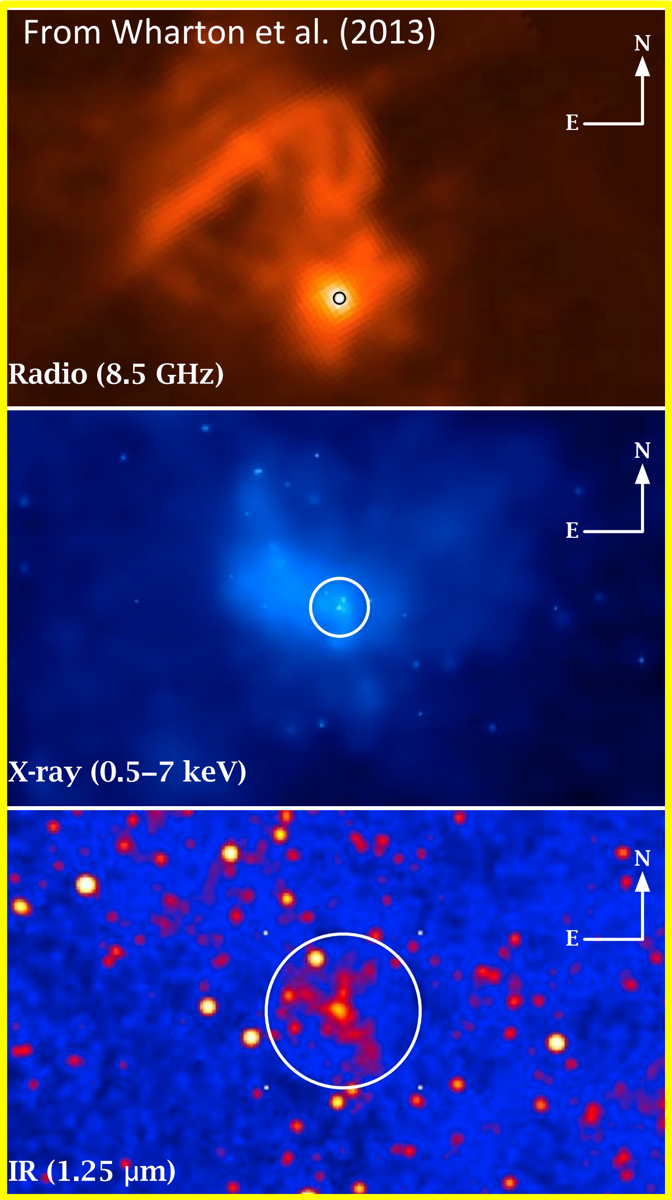
BH mass with precision < 0.1%

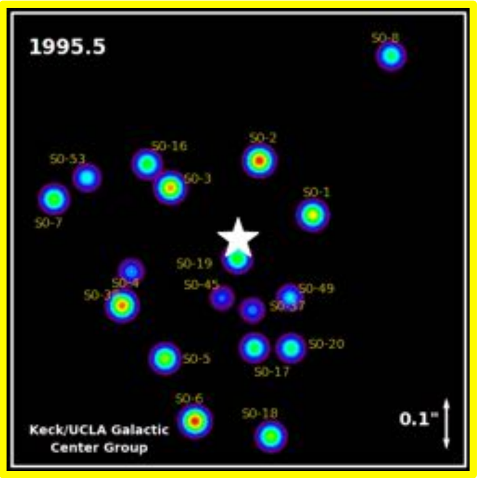
BH spin with precision < 1%

Cosmic Censorship: $S < GM^2/c$

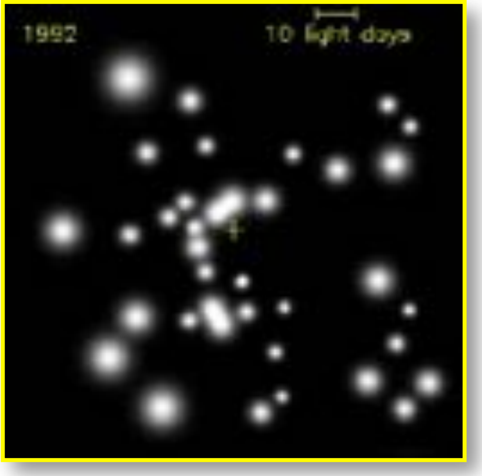
Where or how do we find one?

A well-known super-massive Black Hole





UCLA



MPE/Cologne

From astrometry of orbiting stars::

[Gillesen et al. 2008]

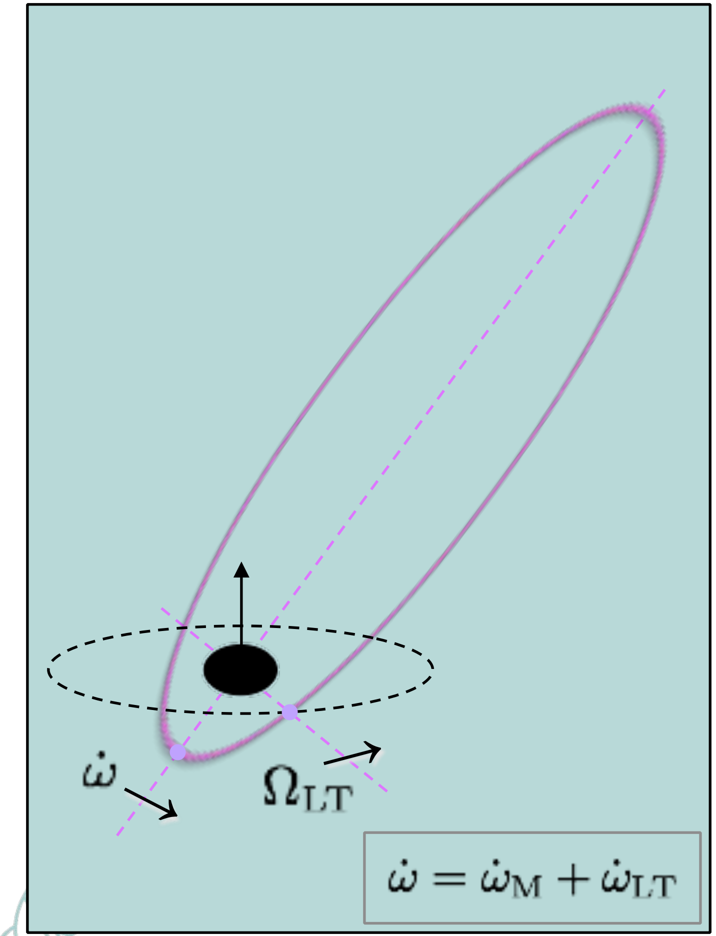
Mass: $(4.3 \pm 0.2_{(\mathrm{stat})} \pm 0.3_{(\mathrm{sys})}) \times 10^6\, M_\odot$

Spin: $\chi = 0.2 \ldots 0.99$

[Genzel et al. 2003, 2008;
Aschenbach et al. 2004;
Belanger et al. 2006;
Aschenbach 2010]

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

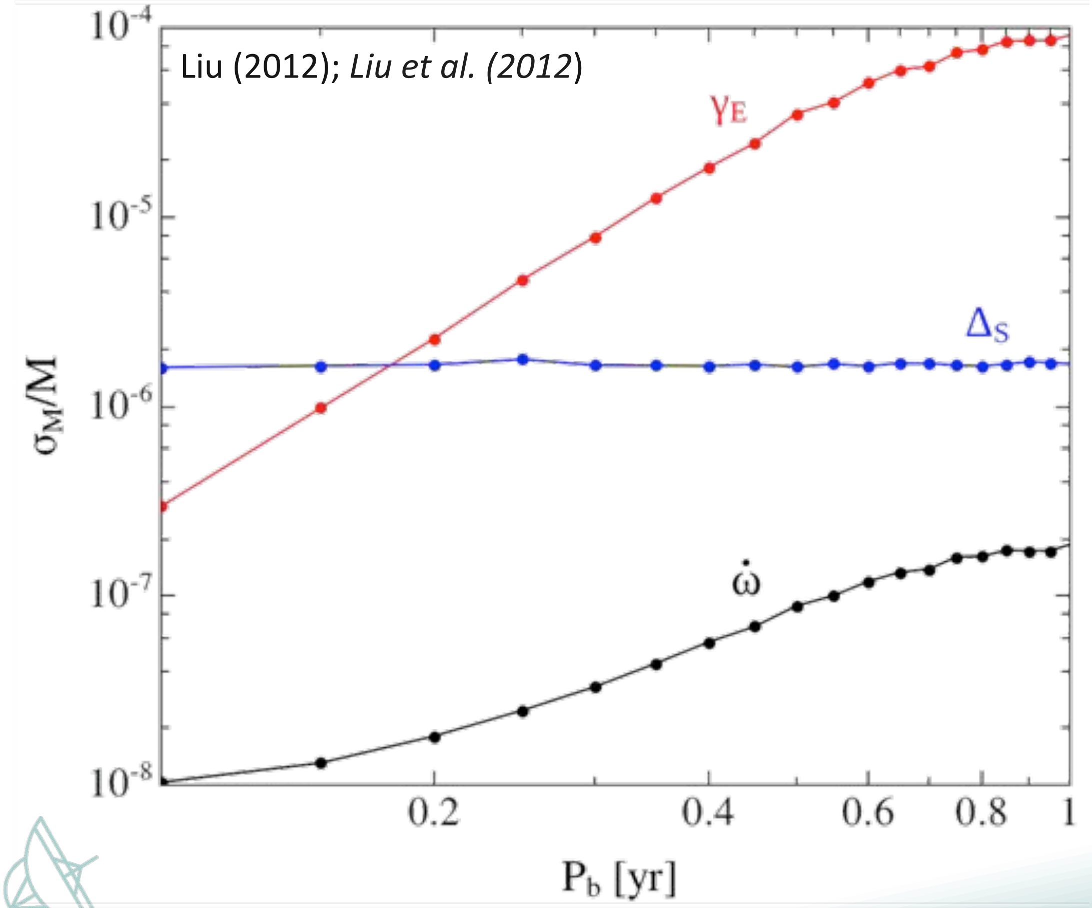
Propagation delay (i = 0° / i = 80°):
Shapiro 1pN: 46.4 s / 246.9 s
Shapiro 2pN: 0.2 s / 8.0 s
Frame dragging: 0.1 s / 6.5 s
Bending delay (P = 1s): 0.2 ms / 4.2 ms

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*-BH, a first GR test & the GC distance

$M_{BH} >> m_{PSR}$ ⇒ only one post-Keplerian parameter 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 GRAVITY

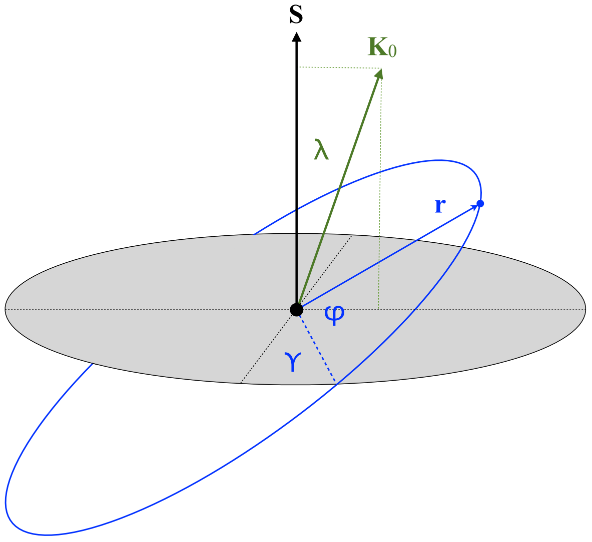
R_0 with ~1 pc uncertainty

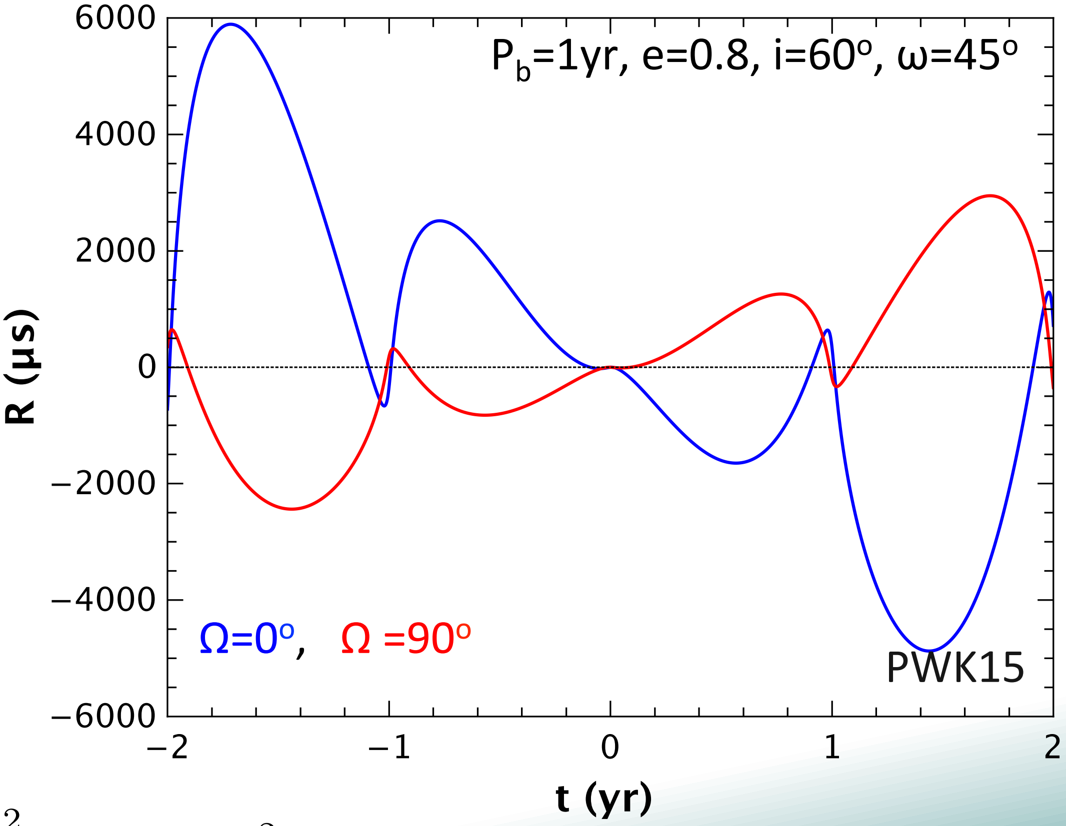
Full 3D-direction of BH spin from pulsar orbit

- Orbital variation of pulsar orbit due to Lense-Thirring gives 2-D projection (Liu et al. 2012)

- Relative motion of pulsar orbit/SGR A* to SSB gives 3rd direction (Psaltis, Wex & MK '15)

- Full orientation plus magnitude to about ~0.1%.





$$\delta D \sim 2\,\frac{c\sigma_{\rm TOA}}{\sqrt{N}}\left(\frac{D}{a}\right)^{2}$$

$$\sim 20\,{\rm pc}\left(\frac{\sigma_{\rm TOA}}{10^{2}\,\mu{\rm s}}\right)\left(\frac{N}{10^{3}}\right)^{-1/2}\left(\frac{a}{10^{2}\,{\rm au}}\right)^{-2}$$

Also provides independent distance measurement to ~20 pc precision!

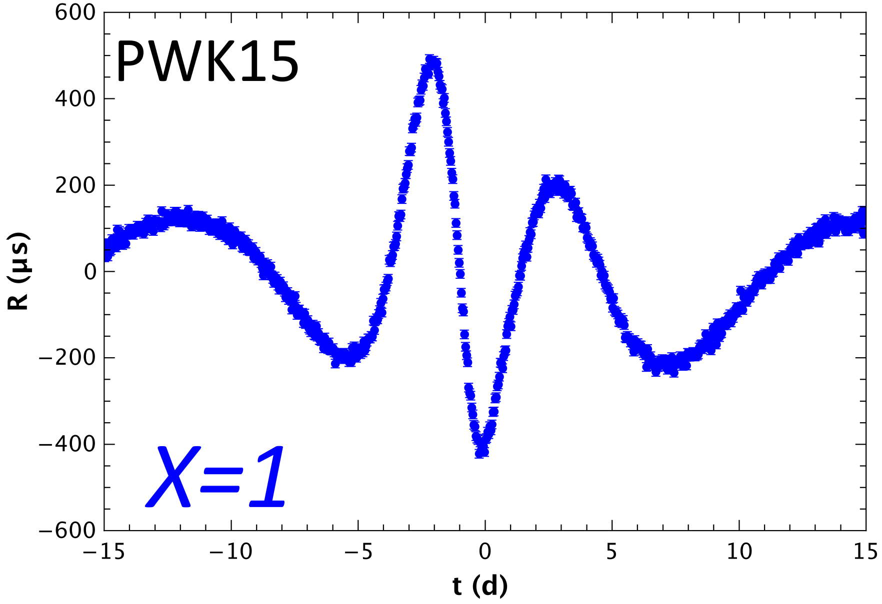
Testing the no-hair theorem

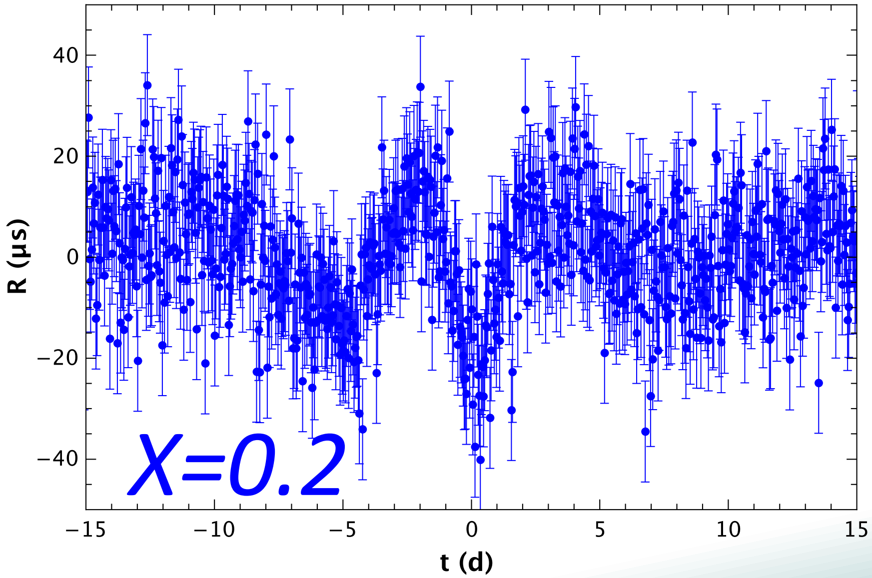
No-hair theorem $\Rightarrow$ $Q = -S^2/M$ (units where c=G=1)

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* ➔ Q to about 1%

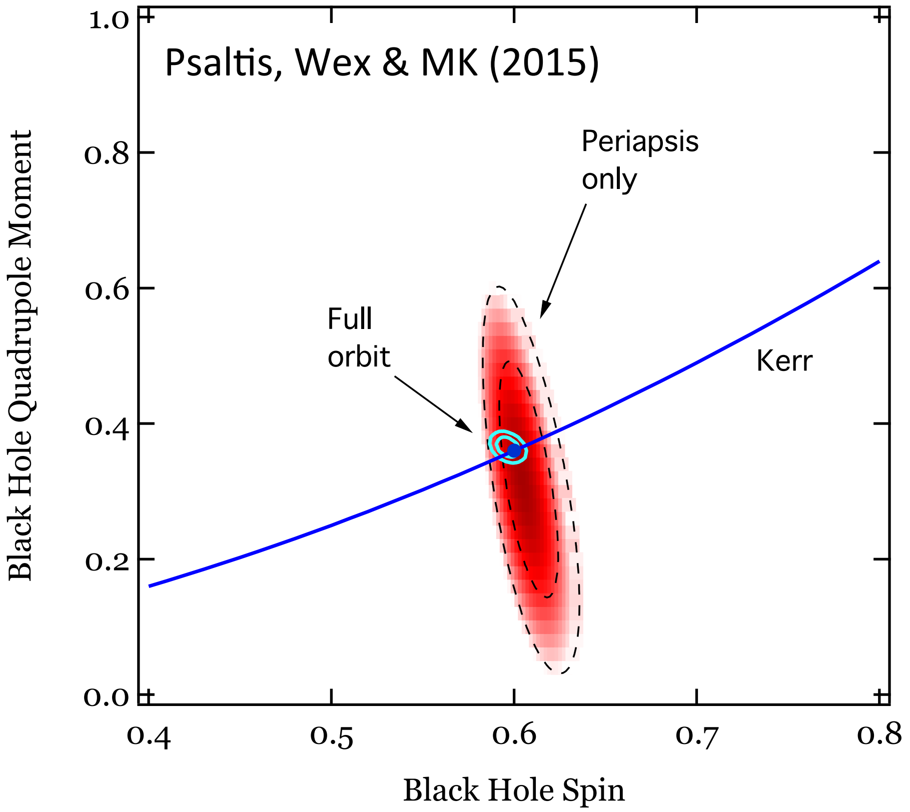


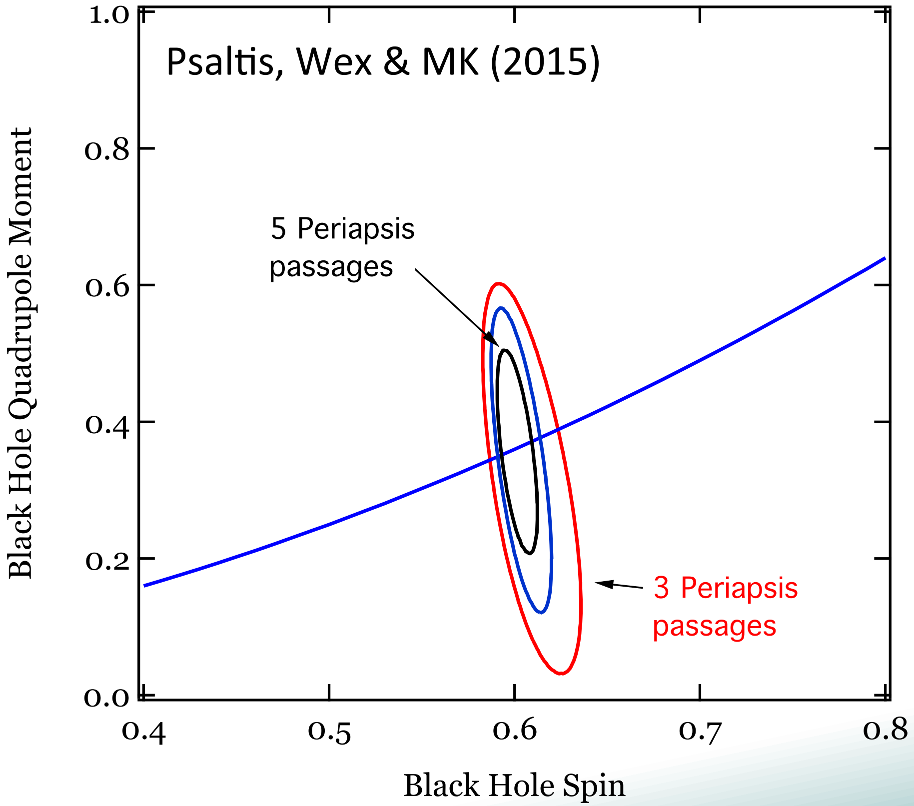


A single (even normal) pulsar is sufficient!

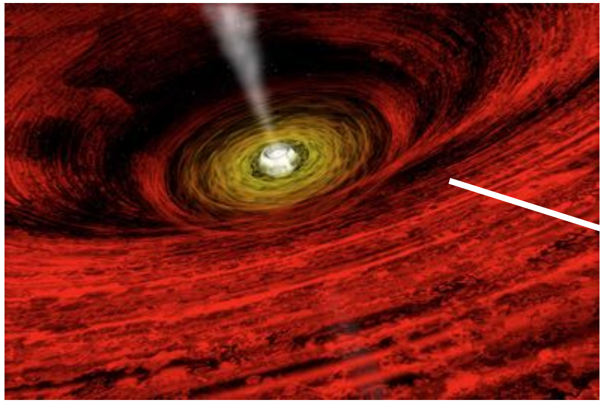
Partial visibility & External perturbations

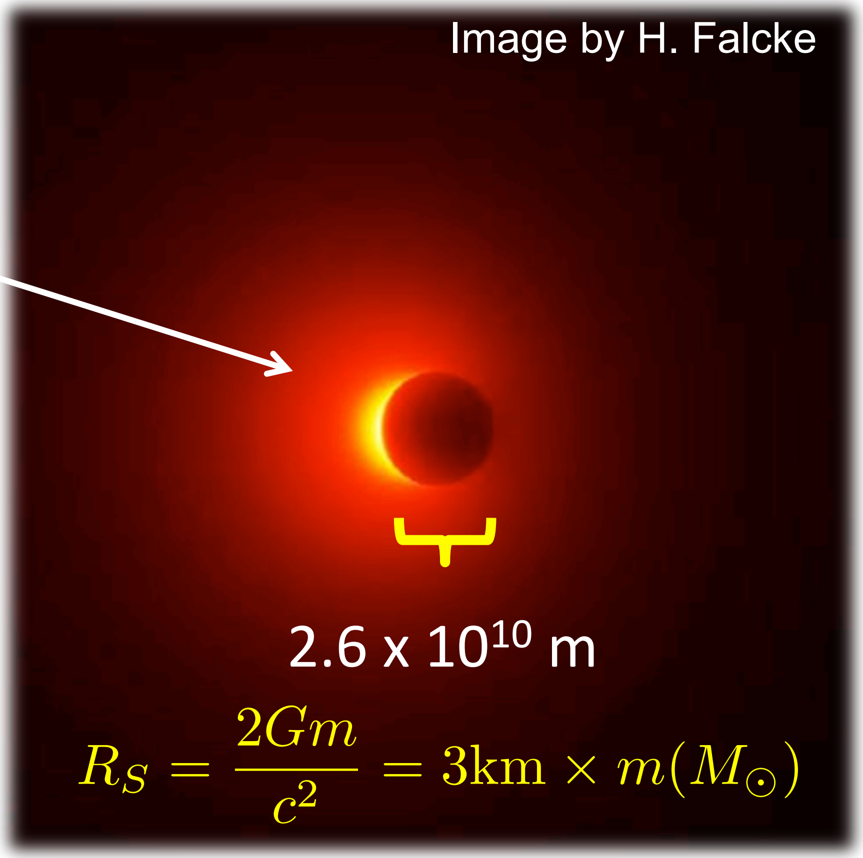
- Even in case of stellar perturbations – which will act away from periapsis – we can use partial orbit observations to measure spin!





Can we see the Galactic Centre Black Hole?





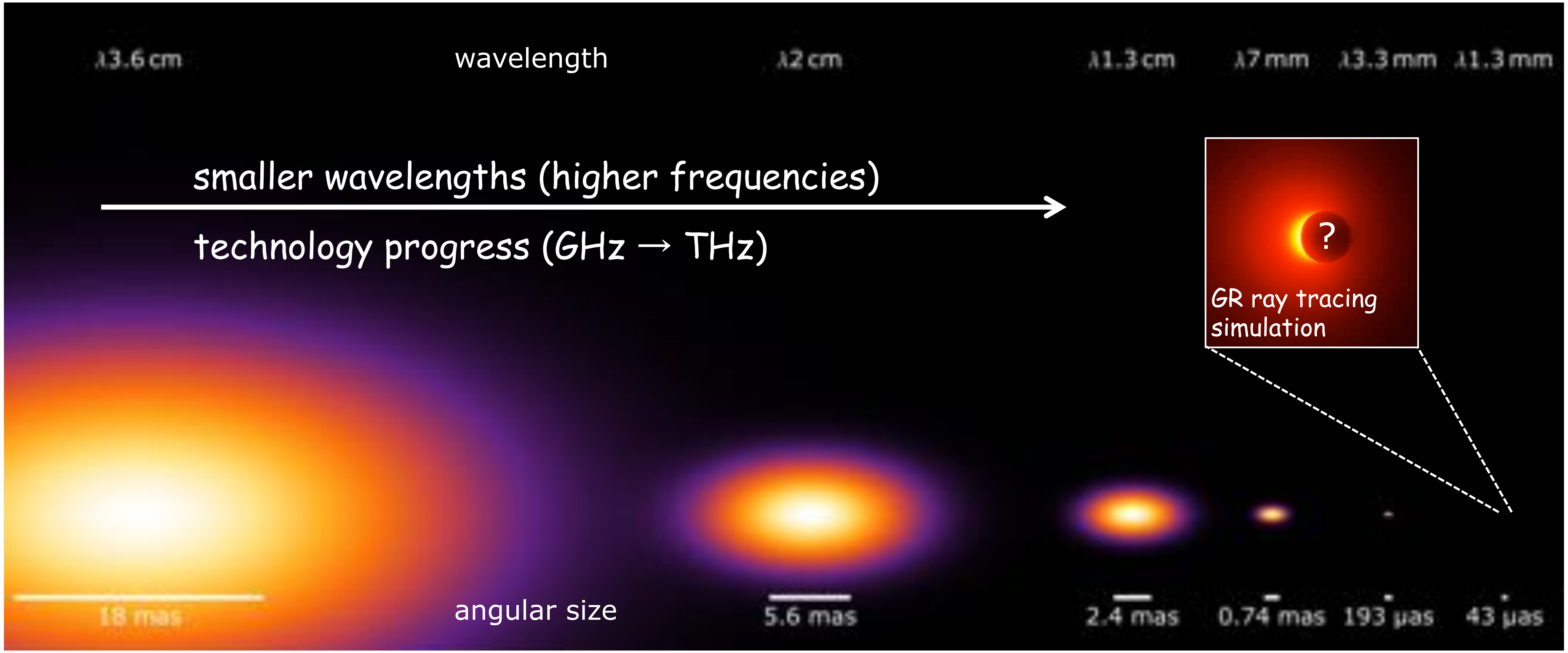
2.6×10^{10} m

$$R_S = \frac{2Gm}{c^2} = 3\mathrm{km} \times m(M_\odot)$$

Blocked in the optical – but visible at radio frequencies!

Based on an idea by Falcke et al. (2000), we could see the „shadow“!

Image of the shadow of the event horizon



The shorter the wavelength, the smaller the radio source.

At λ=1.3 mm the radio source becomes the size of the event horizon:

The event horizon shadow is 50µas in diameter –
global mm-wave VLBI has the resolution (12-20µas) to see it.

“The Event Horizon Telescoe (EHT)”

Using mm-Very Long Baseline Interferometry (Slide by H. Falcke):

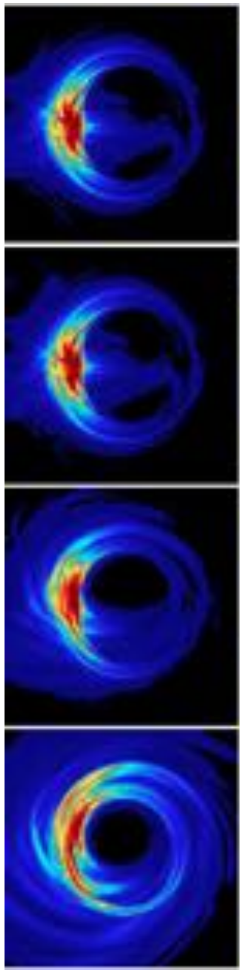
Create a virtual radio telescope the size of the earth, using the shortest wavelength.

$$\text{resolution} = \frac{\text{wavelength}}{\text{telescope separation}}$$

Combining pulsars with other methods

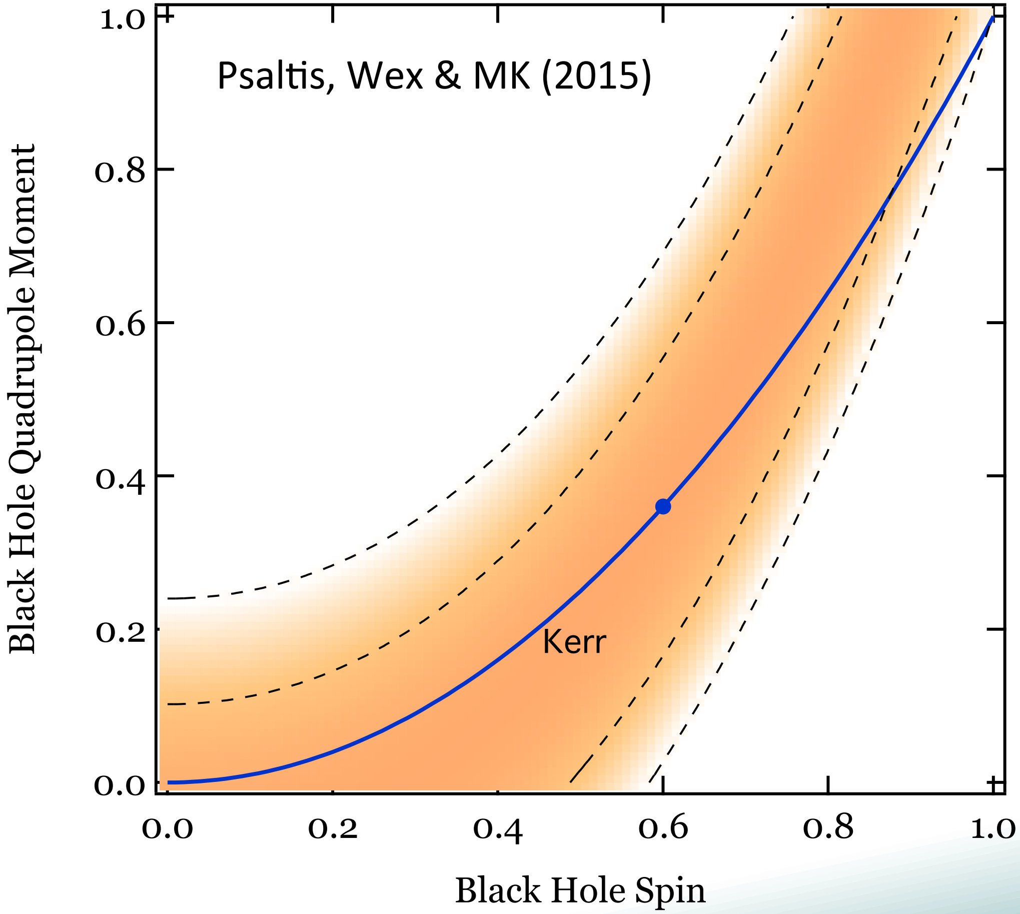
From Event Horizon Telescope/BlackHoleCam imaging observations:

edge-on



face-on

Moscibrodzka et al. (2014)



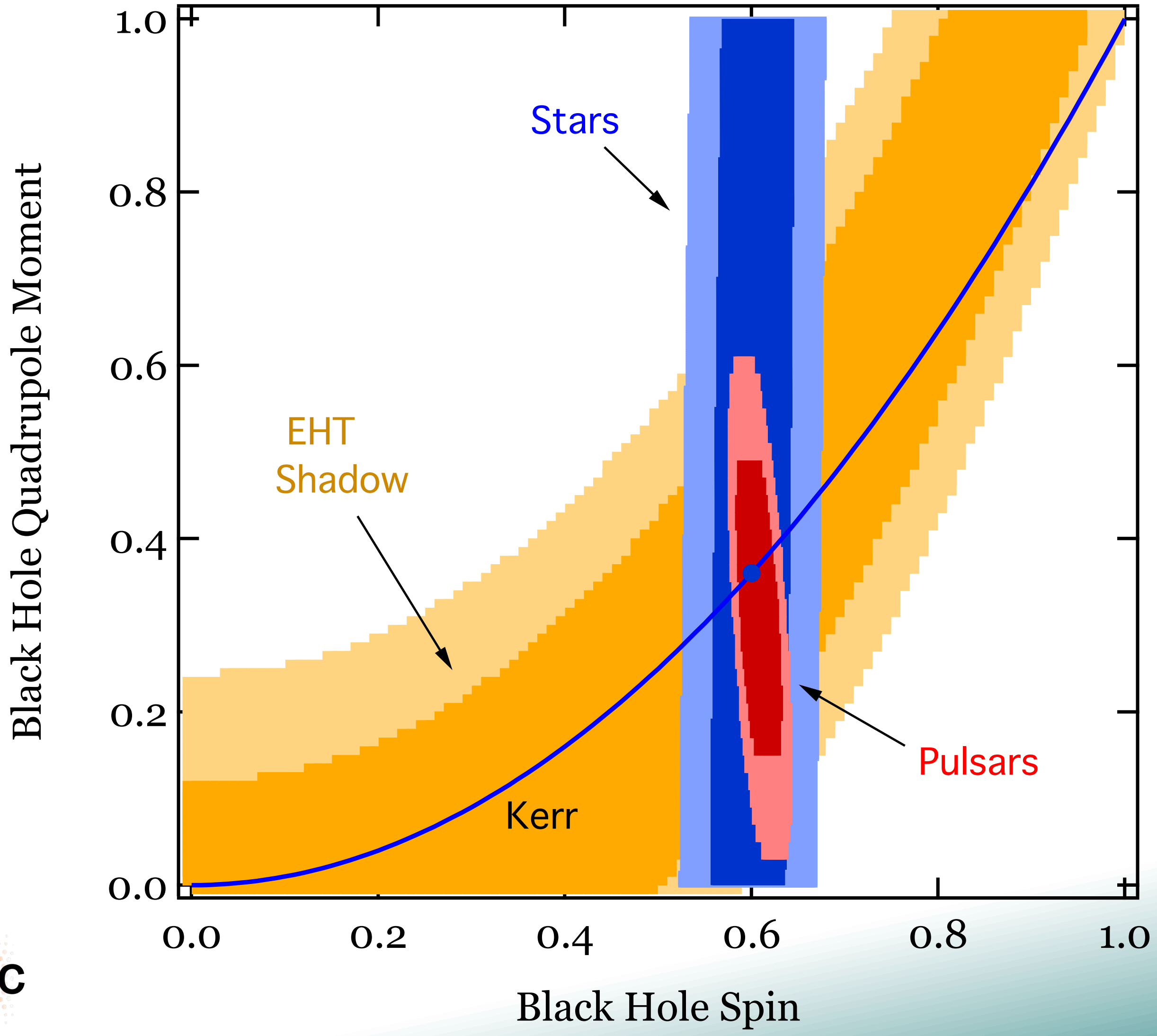
Psaltis, Wex & MK (2015)

BHC funded by ERC Synergy Grant
(PIs Falcke, Kramer, Rezzolla)

Combining pulsars with other methods

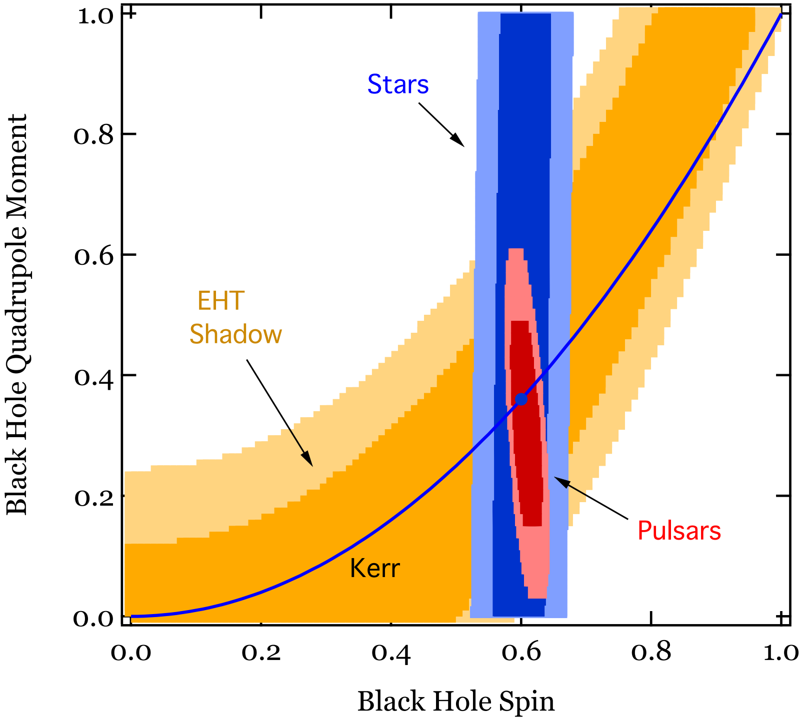
Combined:

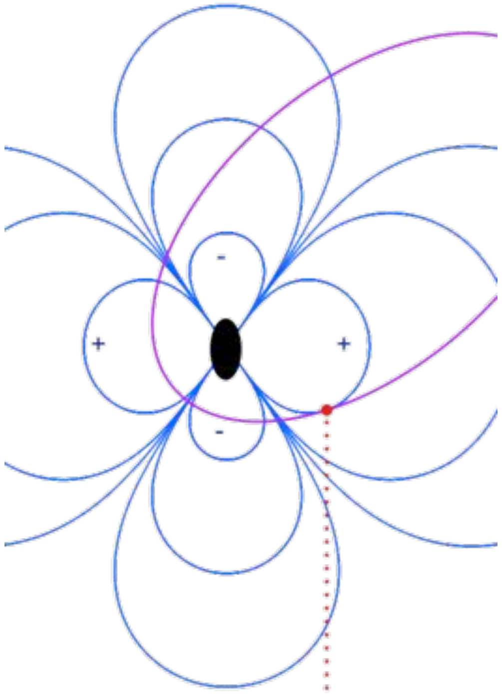
Psaltis, Wex & MK (2015)



Combining pulsars with other methods

Combined:



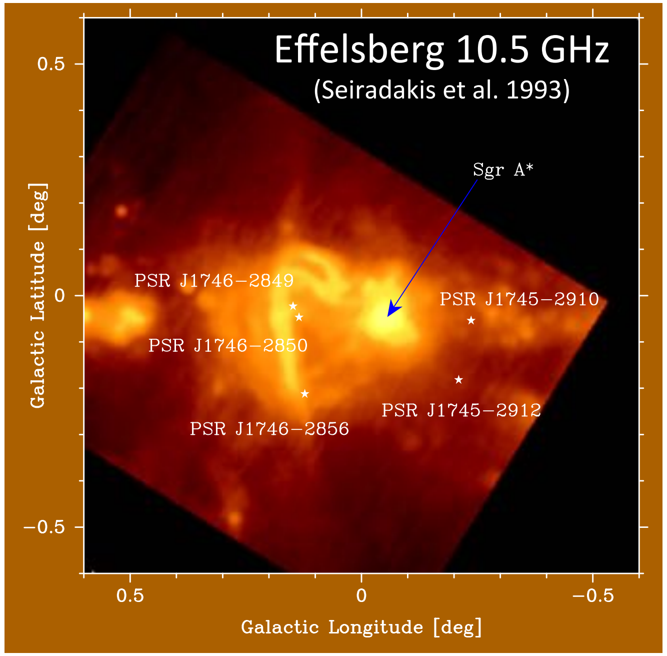


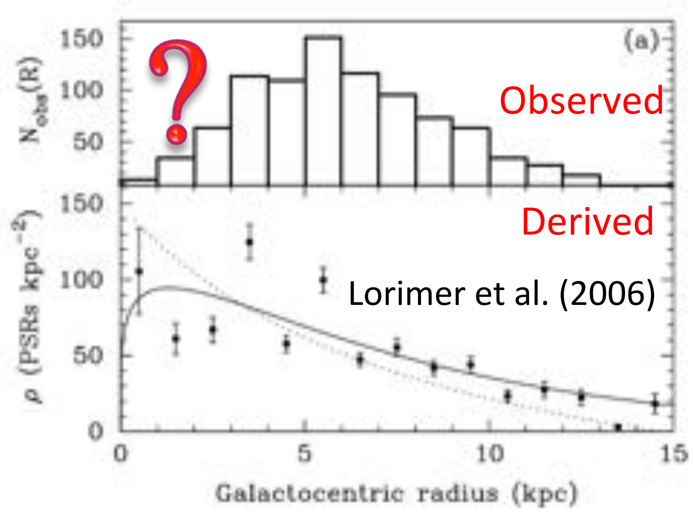
- Space time is probed at different distances, also allowing to probe mass dist.
- Impact of possible dark matter near BH willl be seen.
- Different systematic uncertainties (or degeneracies):
  - Stars + pulsar orbit precession give spin
  - Pulsar timing gives quadrupole moment
  - EHT shadow may reveal deviation from Kerr value

Combination will lead to uncorrelated measurement of spin and quadrupole moment

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)
- But see also Dexter & O'Leary (2014)

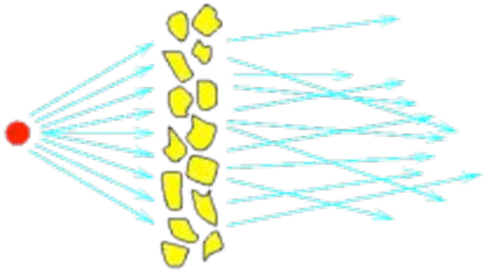


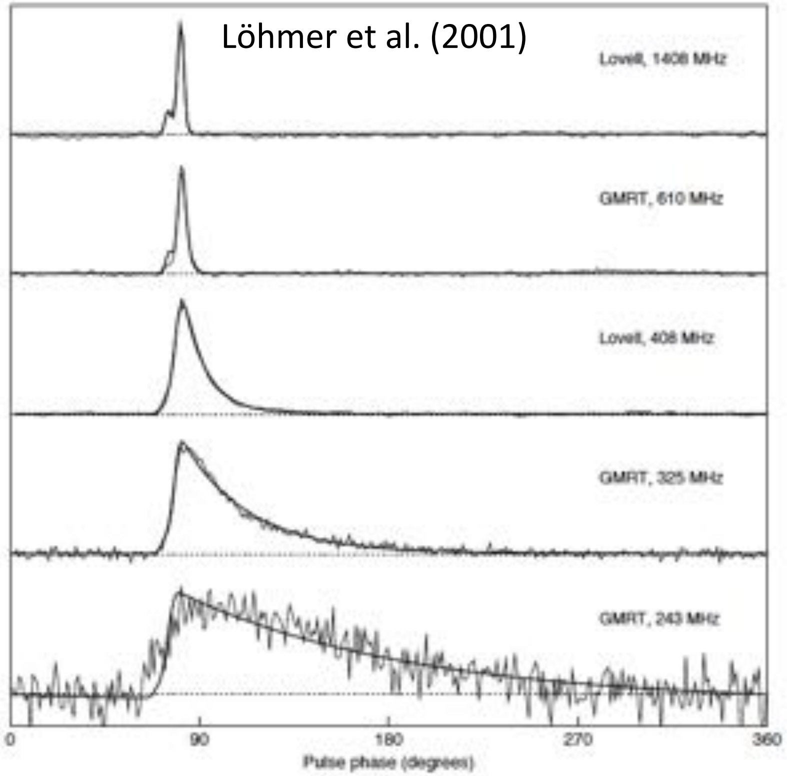


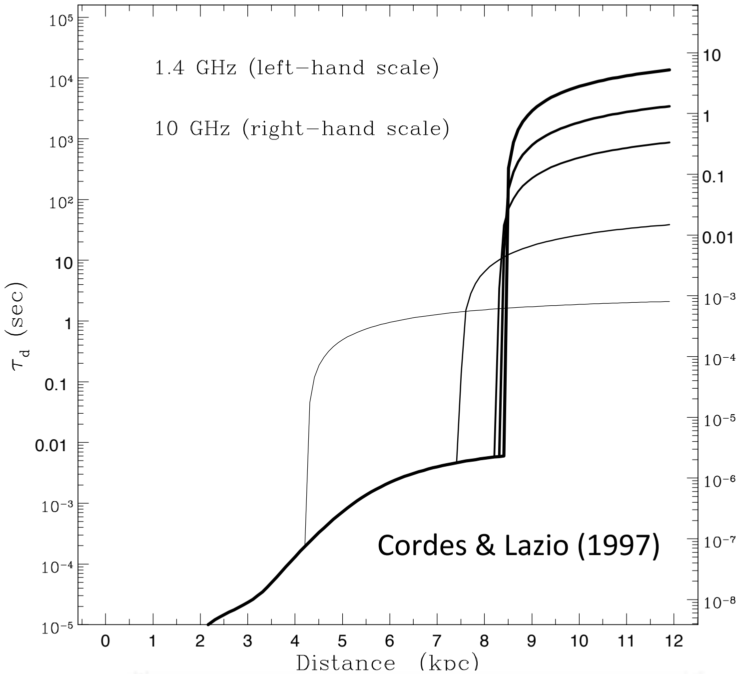
See Johnston et al. (2006)

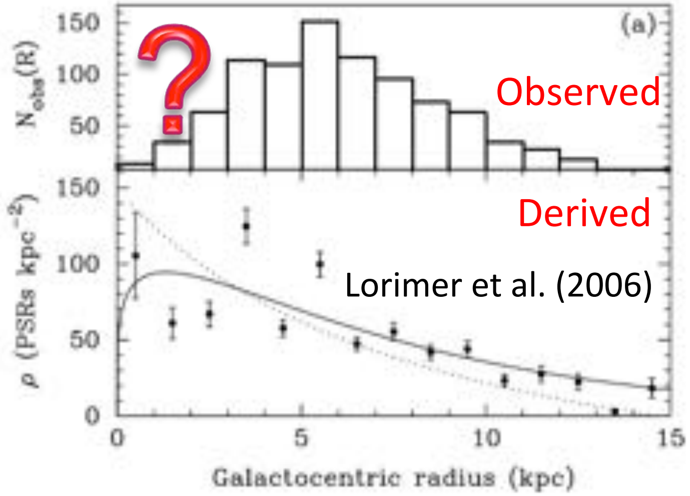
Why is it difficult to find pulsars in the GC?

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




Löhmer et al. (2001)


Cordes & Lazio (1997)

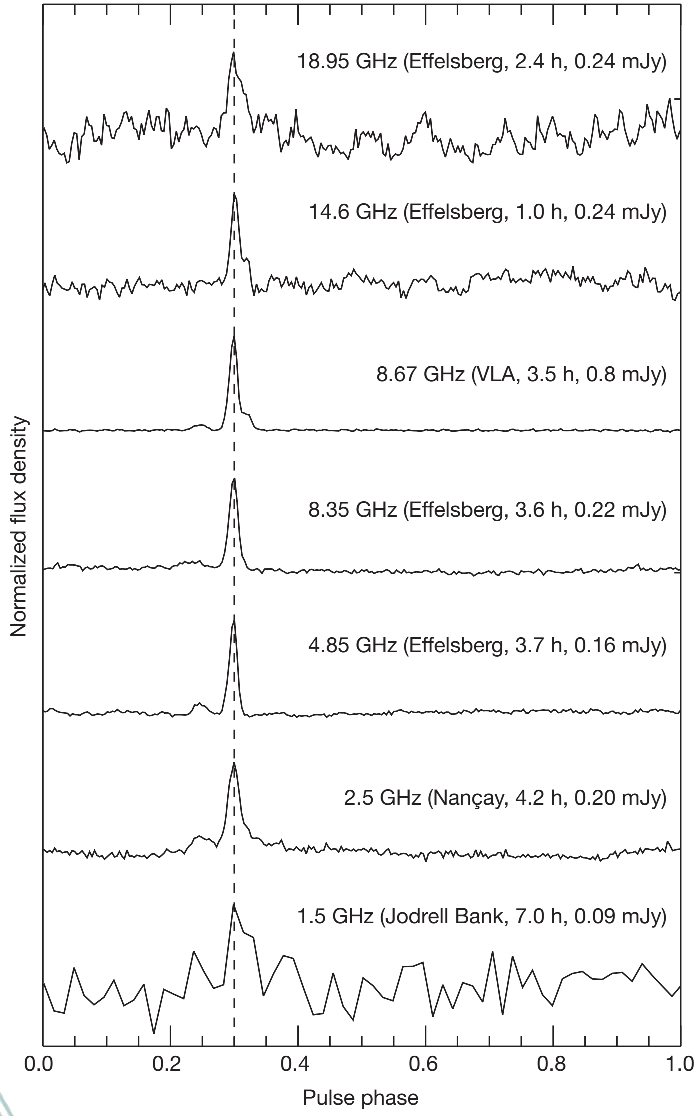

Observed

Derived

Lorimer et al. (2006)

The first pulsar in the Galactic Centre

Eatough et al. (Nature, 2013)



- First discovered with SWIFT (Kennea et al. ,13) and NuSTAR (Mori et al. 13)
- Pulsations at 3.76s
- Radio source discovered in Effelsberg (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!

- Status: - Population not yet known
  - Too many modelled unselection effects
  - Searches continue – stay tuned!

Summary

- Unfortunately, Einstein did not live to see discovery of pulsars – and their usage
- Pulsar probe gravity for strongly self-gravitating bodies providing unique tests
- Measurements are usually clean and precise – confirming GR so far
- We have seen new never-seen-before relativistic effects in the Double Pulsar
- Direct detection of gravitational waves maybe soon – also using pulsars
- Ultimately, we will probe BH properties (plus image!) for extreme tests of GR
- Future telescopes - especially the SKA - will allow so much more!
- At the end, we will always be limited by the available compute power..!

> *"Wie kommt uns da die pedantische Genauigkeit der Astronomie zu Hilfe, über die ich mich im Stillen früher oft lustig machte!"*

(Albert Einstein in letter to Arnold Sommerfeld, 9.12.1915)