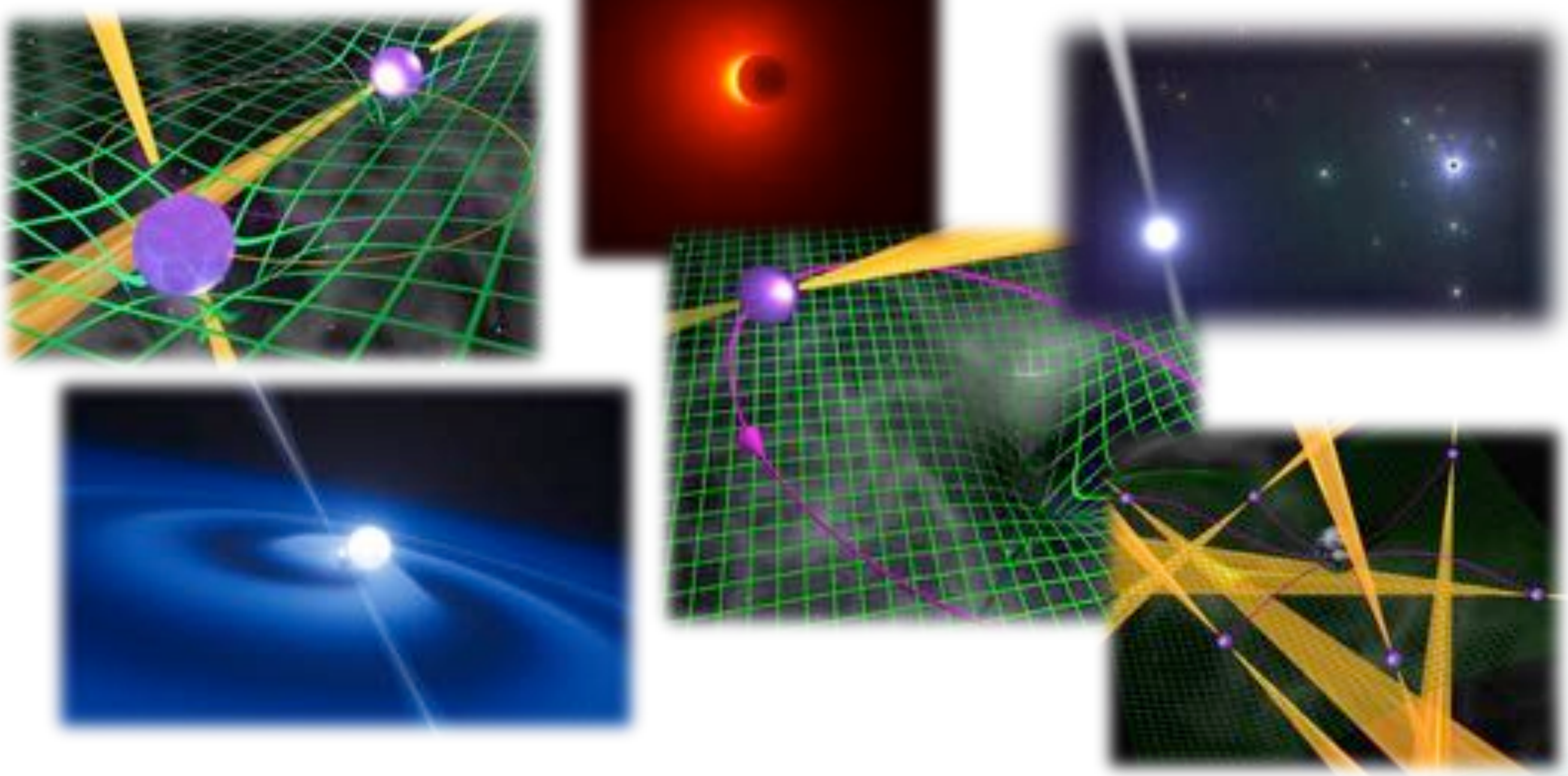
Probing gravity with radio astronomy



Michael Kramer

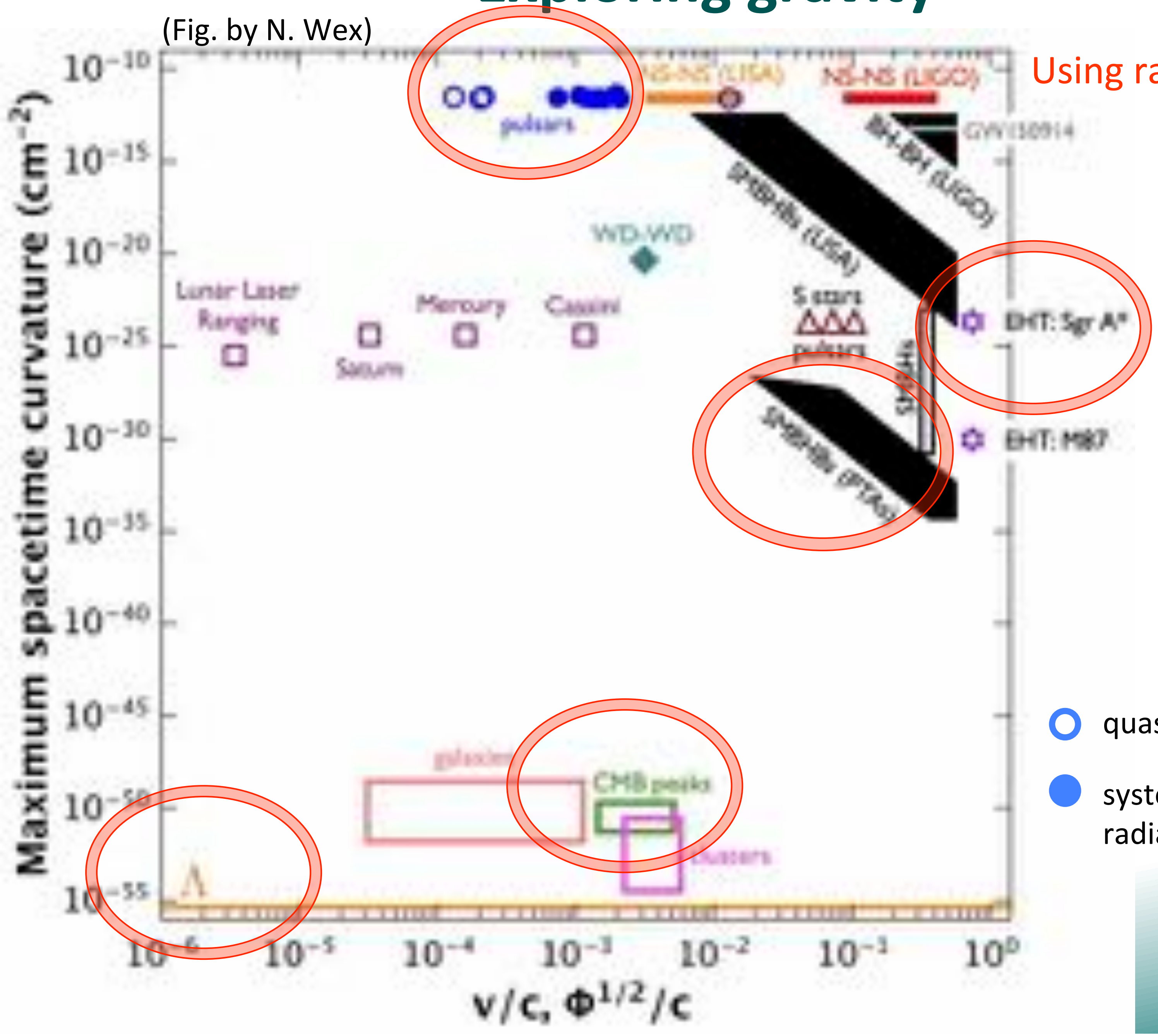
Max-Planck-Institut für Radioastronomie
Jodrell Bank Centre for Astrophysics, University of Manchester

GW detectors listen – radio telescope also…

Radio astronomy is ideal to study fundamental physics as

- we observe extreme and energetic processes and objects
- get lots of photons that are easy to copy and multiply
- can probe the complete Universe, undisturbed from dust etc.
- can get polarization (magn. fields!) and dynamic information (pulses!)

Exploring gravity



(Fig. by N. Wex)

Using radio astronomy

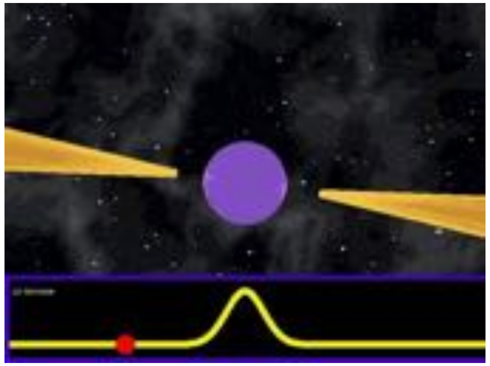
○ quasi-stationary tests

● system provides (also) a radiative test

Exploring gravity – with radio astronomy

- Introduction
- Pulsars & binaries: testing GR and its alternatives
- Pulsar Timing Arrays (PTAs): detecting GWs
- Event Horizon Telescope/BlackHoleCam: imaging a BH
- Conclusions

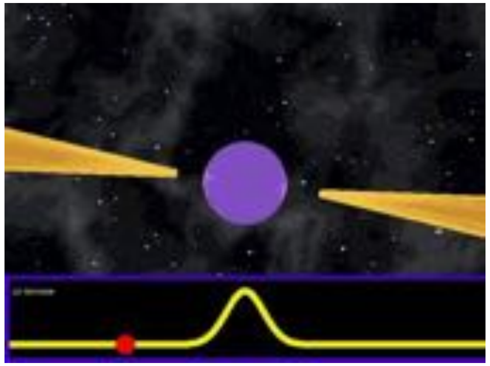
Pulsars…

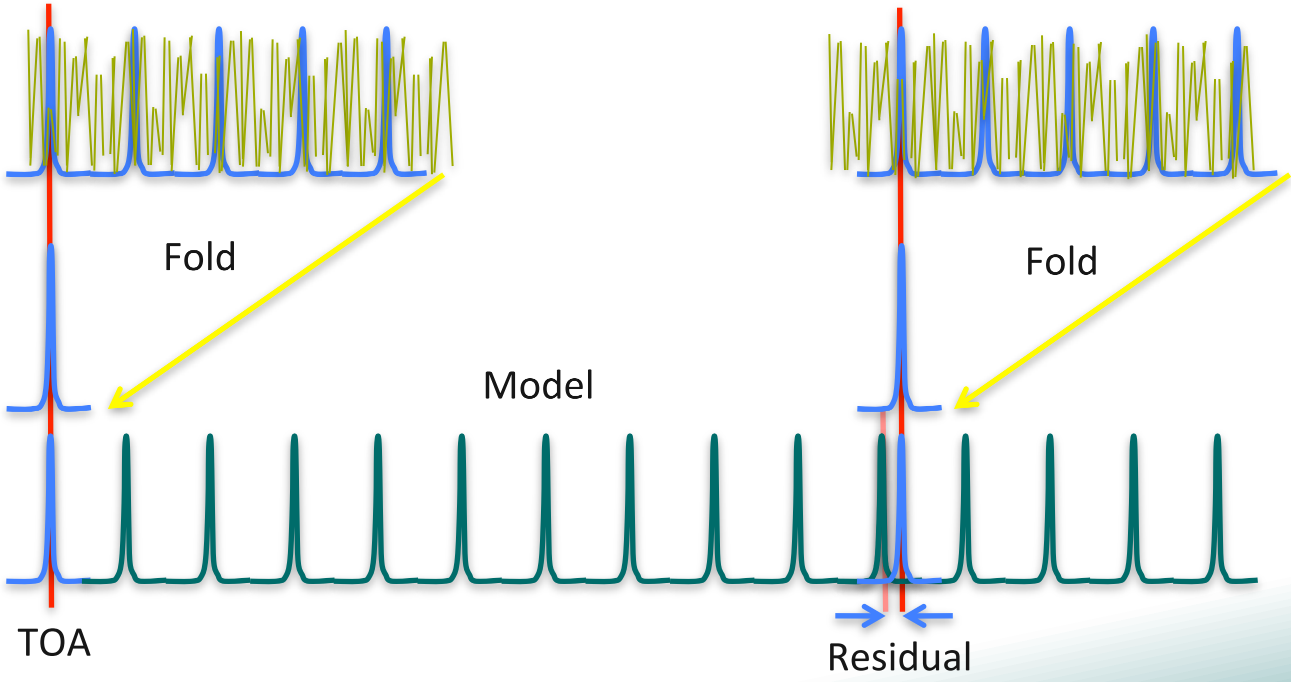


- …almost black holes
- …objects of extreme matter:
  - 10 x nuclear density
  - $B \sim B_{cr} = 4.4 \times 10^9$ Tesla
  - Electr. fields ~ 10^{12} Volt
  - $F_{EM} = 10^{11} F_{gravitation}$
  - high-temperature superfluid superconductor
  - Very stable rotators
  - Excellent clocks!

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!

Our (usual) laboratories: 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)

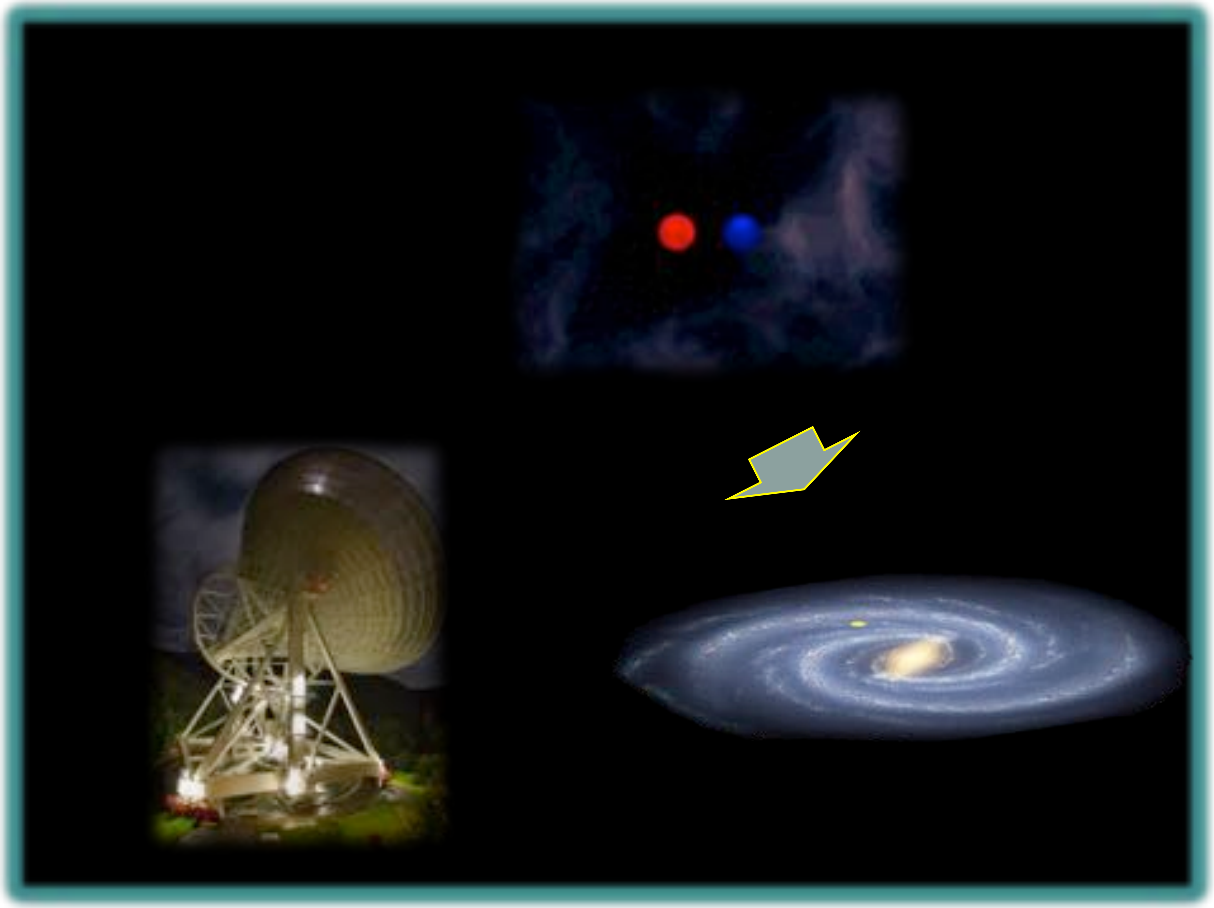
Companions

MSS, WD, NS, planets

plus **1 Double Pulsar,**

1 PSR-WD-WD

still missing: **PSR-BH**



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 very high precision!

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(1) mm/day (Kramer et al. in prep)

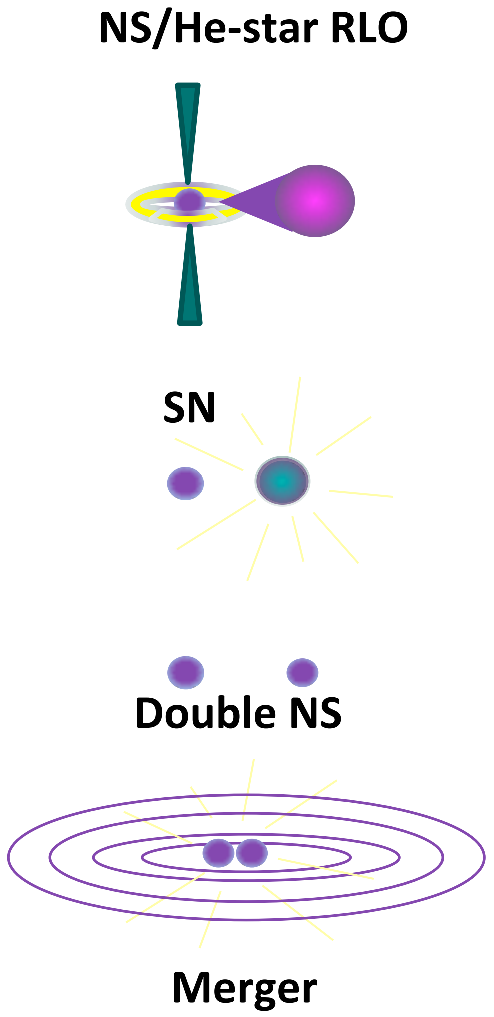
Fundamental constants:

- Change in (dG/dt)/G: $(-0.6 \pm 1.1) \times 10^{-12}\ \mathrm{yr}^{-1}$ (Zhu et al. 2015)

Gravitational wave detection:

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

Usually best: Double Neutron Star Systems



Recycled NS spin periods?
Amounts of mass accreted?

Pre-SN stellar structure?
Explosion, NS mass, kick?

Observational properties?
New DNS discoveries?

LIGO/Virgo merger rates?

Expect exciting synergies with LSC results.

Exploring gravity – with radio astronomy

- Introduction
- Pulsars & binaries: testing GR and its alternatives
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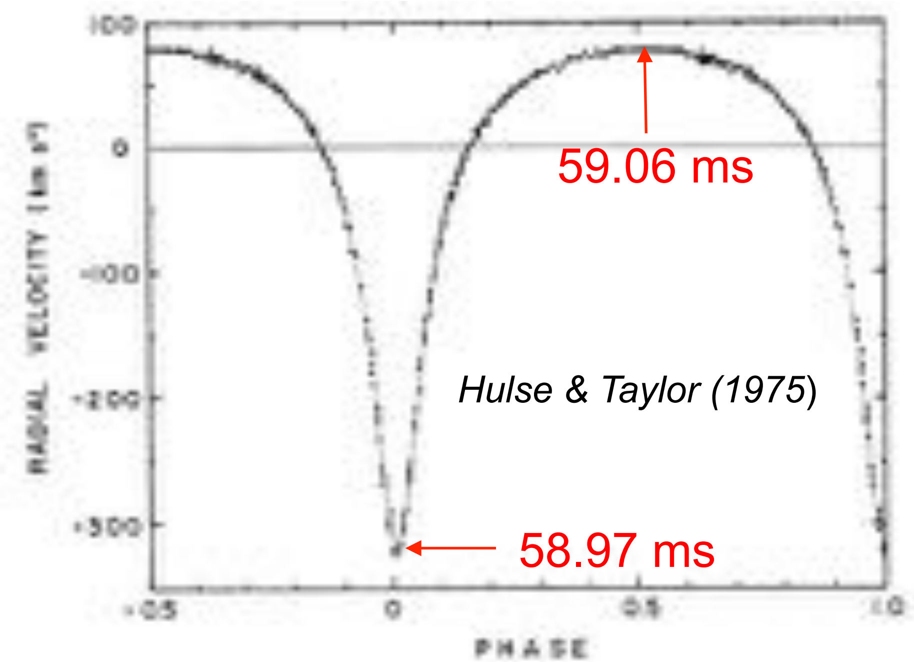
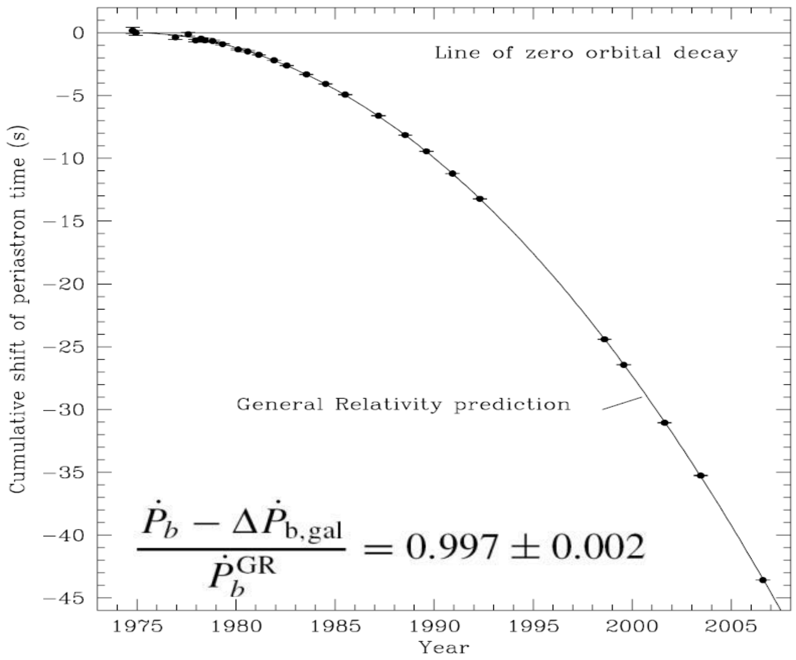
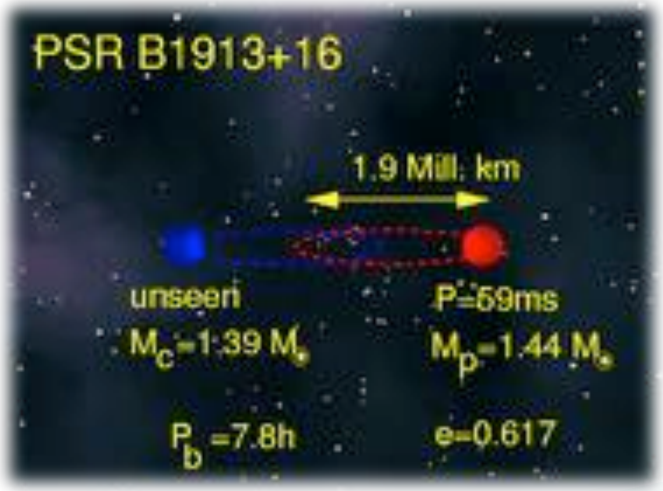
The first binary pulsar – the first DNS: Hulse-Taylor pulsar



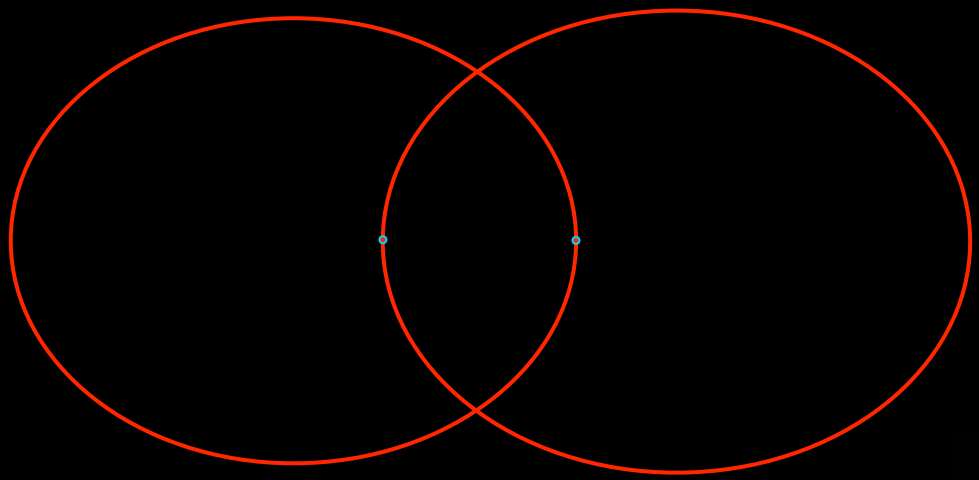


$$\frac{\dot{P}_b - \Delta\dot{P}_{\mathrm{b,gal}}}{\dot{P}_b^{\mathrm{GR}}} = 0.997 \pm 0.002$$

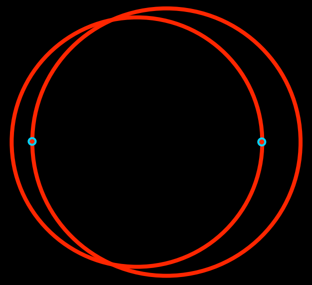


Comparison Hulse-Taylor vs Double Pulsar

PSR B1913+16

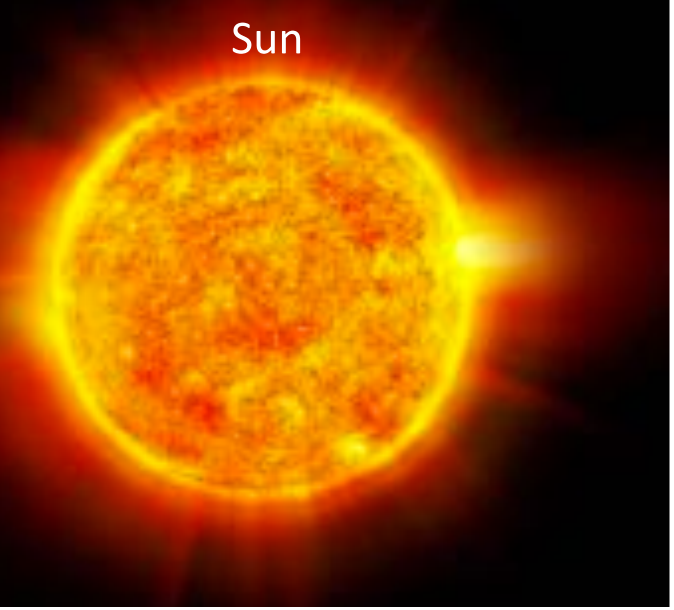


PSR J0737-3039A/B



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, Kramer et al. in prep., Wex et al. in prep.)

McGill

Collaborators:

C. Bassa, R. Brenton, M. Burgay,

I. Cognard, N., G. Desvignes,

R. Ferdman, P. Freire, L. Guillemot,
G. Hobbs, G. Janssen, P. Lazarus, D.
Lorimer, A. Lyne, R. Manchester, M.
McLaughlin, B. Perera, A. Possenti,

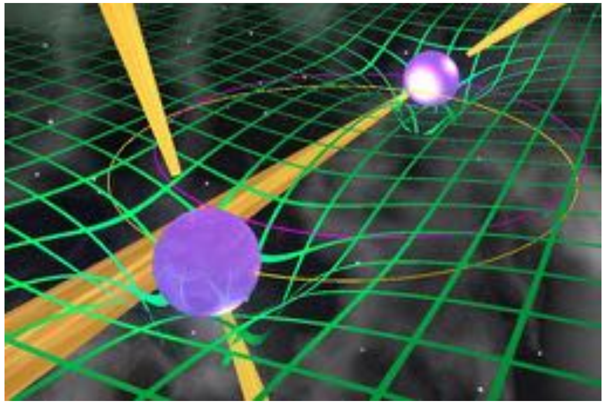
J. Reynolds, J. Sarkissian, I. Stairs,

B. Stappers, G. Thereau, N. Wex

and more

Double Pulsar: a unique relativistic double-line system

- We can measure two orbits ➔ mass ratio

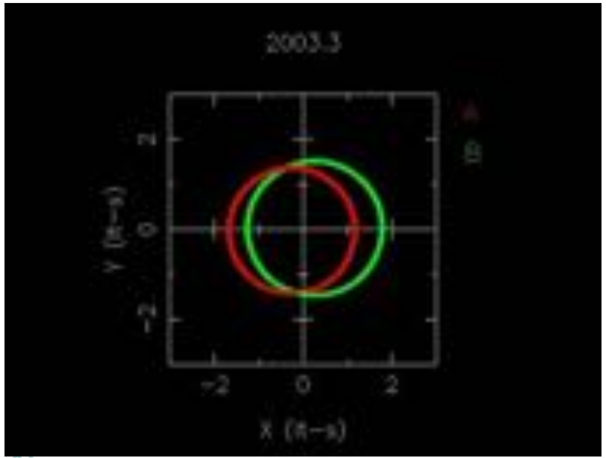


$$R \equiv \frac{x_B}{x_A} = \frac{m_A}{m_B} = 1.0714 \pm 0.0011$$

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)



Compare to Mercury:

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

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

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

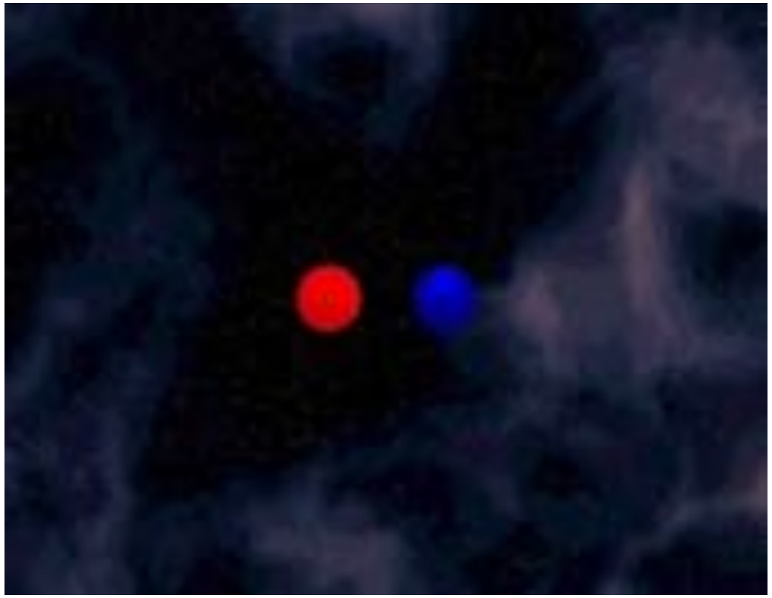
Combined (GR):

$m_A = (1.3381 \pm 0.0007)\ M_\odot$

& $m_B = (1.2489 \pm 0.0007)\ M_\odot$

Double Pulsar: five tests in one system!

- Huge orbital precession
- Clock variation due to gravitational redshift: 385.6 ± 2.6 µs!



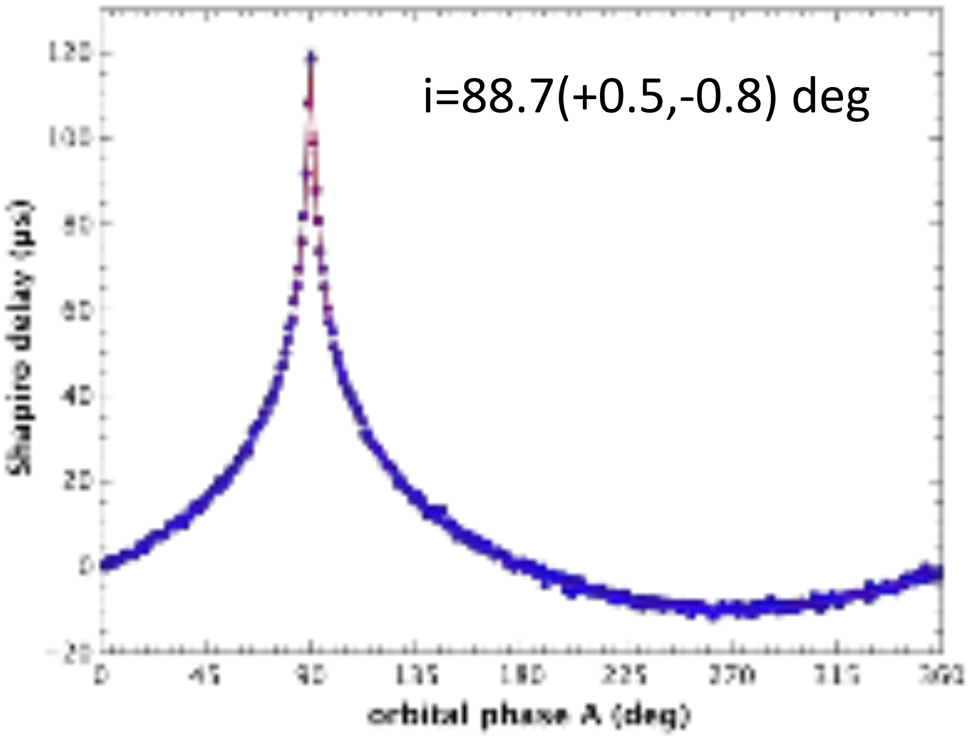
$$\frac{\text{Obs.Val.}}{\text{Exp.(GR)}} = 1.000 \pm 0.002$$

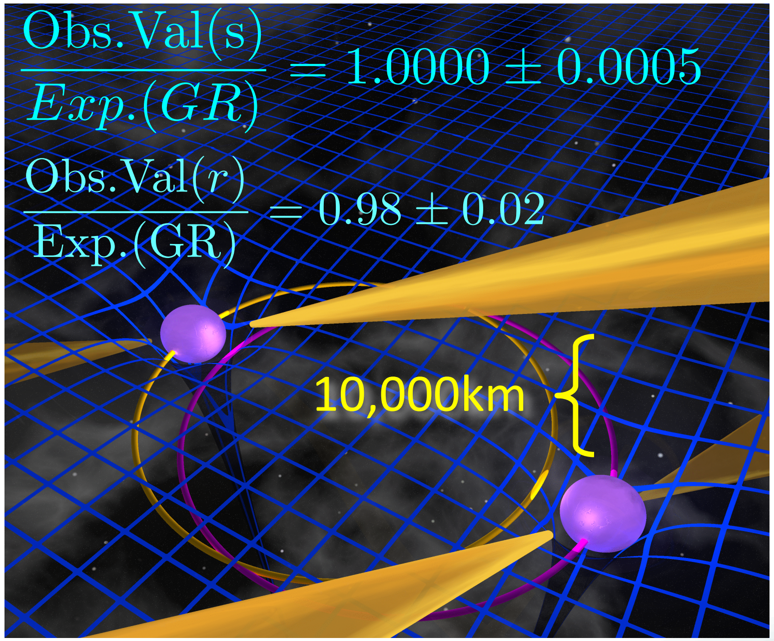
- As other clocks, pulsars run slower in deep gravitational potentials

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

Double Pulsar: five tests in one system!

- Huge orbital precession
- Clock variation due to gravitational redshift
- Shapiro delay in edge-on orbit: s = sin(i)=0.99974 (-0.00039,+0.00016)





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

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

- 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
- Clock variation due to gravitational redshif
- Shapiro delay in edge-on orbit
- Relativistic spin precession: Ω_B=4.8(7) deg yr^{-1}
- Shrinkage of orbit due to GW emission: ΔP_b=107.79 ± 0.11 ns/day!

- Pulsars approach each other by 7.152 ± 0.001 mm/day

$$\frac{\mathrm{Obs.Val}}{\mathrm{Exp.(GR)}} = 1.0000 \pm 0.0002$$

- Merger in 85 Million years

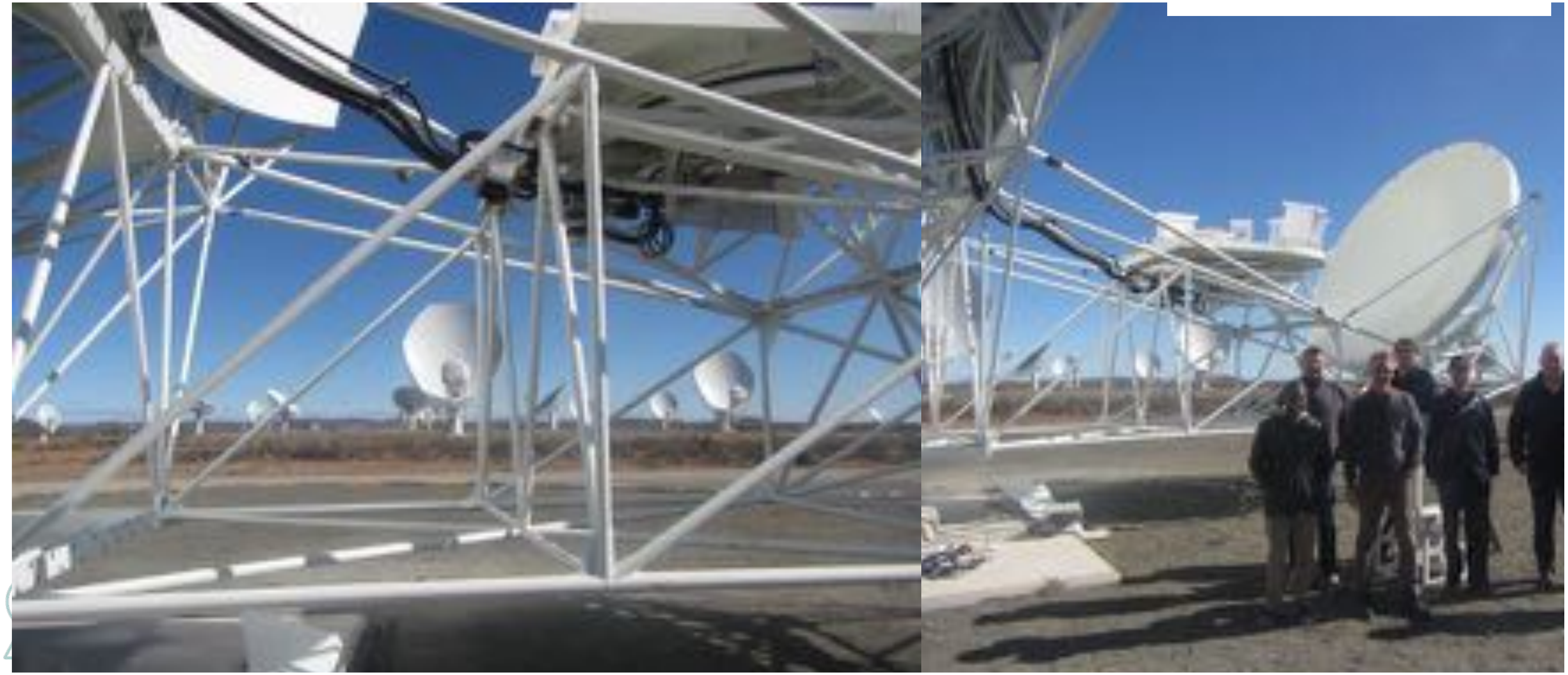
Animation by NASA/Rezzolla/AEI

Precision will improve with time: superseding solar system tests soon

MeerKAT – first step towards SKA

It will find pulsars – and will time all Southern ones with unprecedented sensitivity

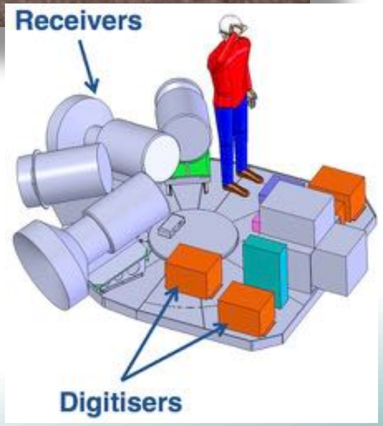
- MeerKAT – first light based on 16 dishes – completed in 2017
  - Increases sensitivity in Southern hemisphere by factor ~5
  - More sensitive than Effelsberg or GBT and similar to VLA
  - MeerTime (PI Bailes, TRAPUM (PIs Stappers/Kramer)



The MPIfR MeerKAT S-band system

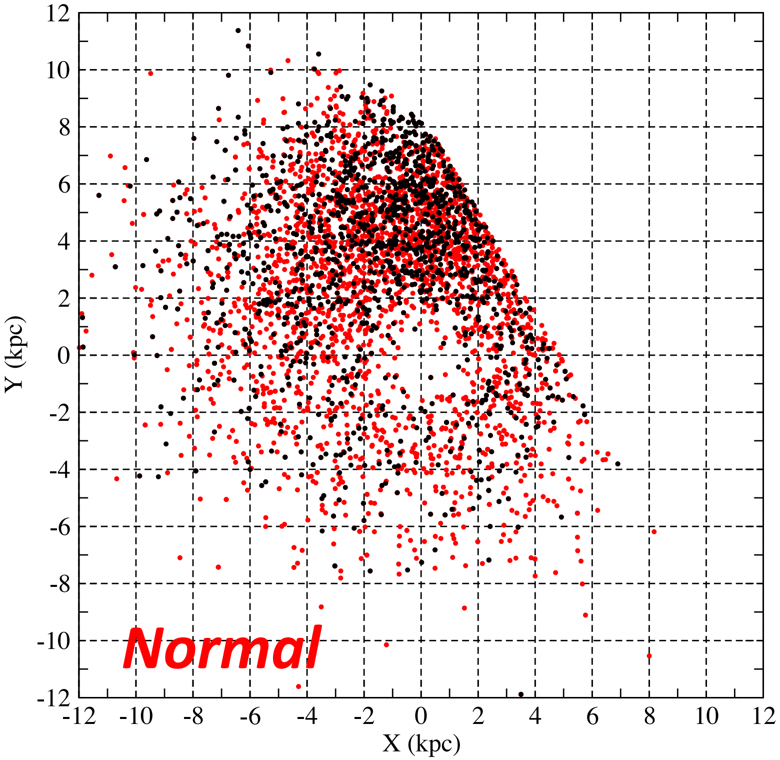
Frequency band	1.75 – 3.5 GHz
Polarisation	Dual
Digitzed band:	1.75 – 3.5 GHz
Digitzer resolution	12bits direct sampling
Bandwidth	initially: 875 MHz Full: 1.750 MHz
Tsys	~20 K

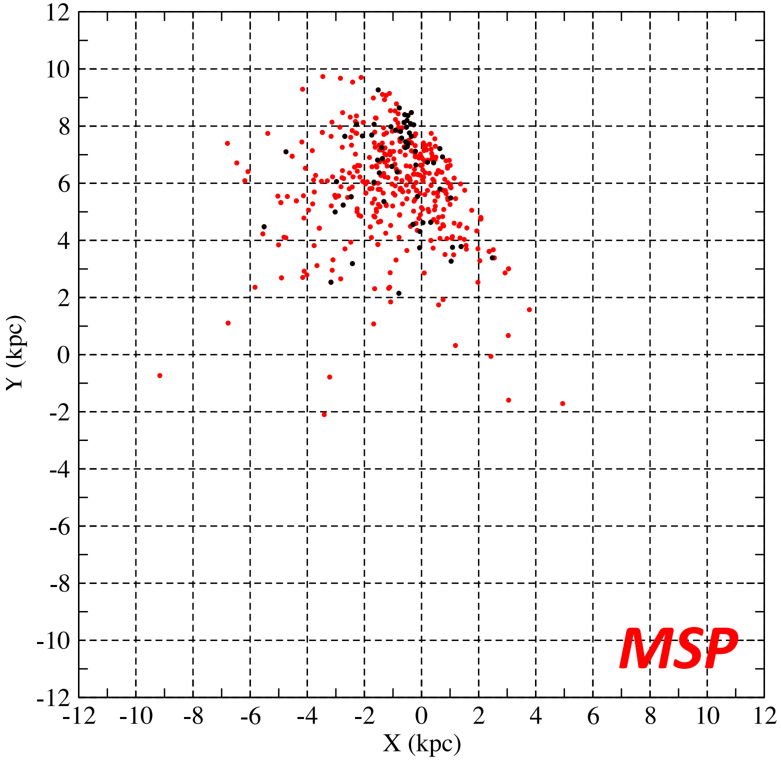
- 64 receivers + new data transport + 200 beams beam-former + cluster – extended to 400 beams by MeerTRAP
- Collaboration with UMAN & Oxford
- Main science drivers:
  - Pulsars: searching & timing
  - Transients
- Funded by MPG/MPIfR



TRAPUM+

- Deep high frequency S-band of Galactic Plane to target DNS & PSR-BH
- Larger gain of MeerKAT (~2 K/Jy) offsets decreased flux density
- Perfect combination: (here: for T_{int} and BW = HTRU-LowLat)



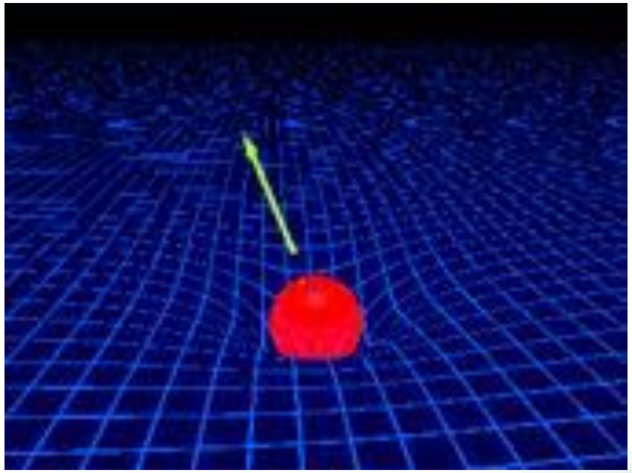


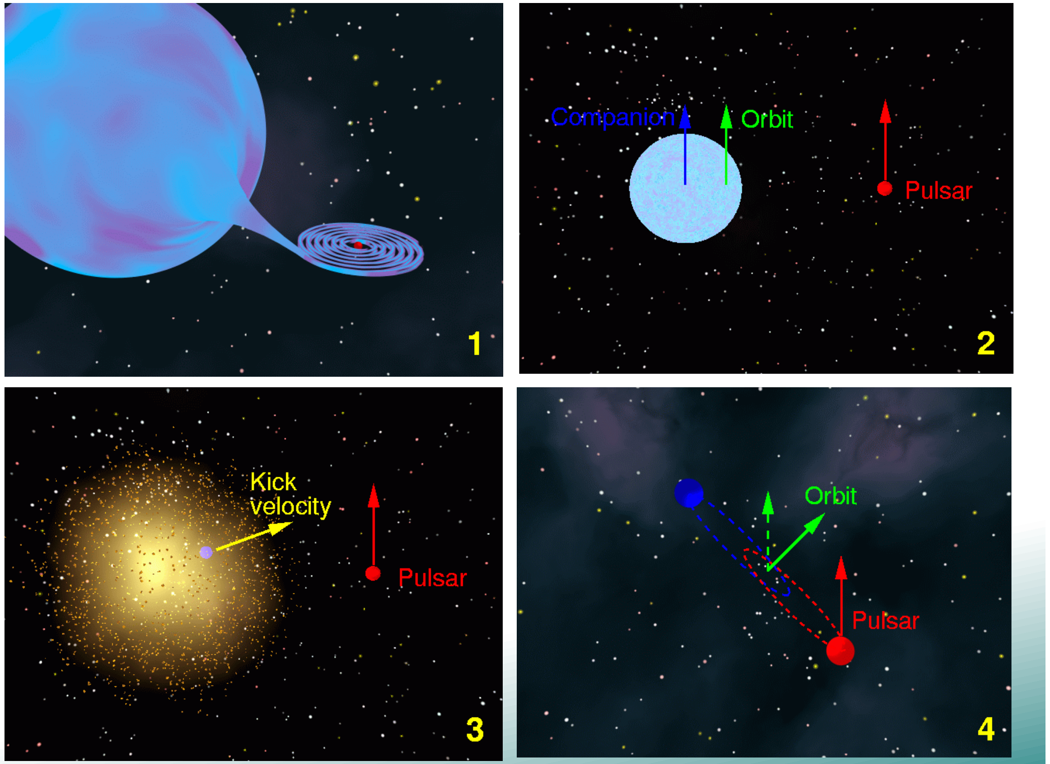
- Avoiding scattering to probe the inner Galaxy
- >1500 new normal, > 300 new MSPs – optimistic, but exciting...

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 stronglyself-gravitating bodies in HT-Pulsar (Weisberg et al. '89, Kramer’98) and PSR B1534+12 (Stairs et al. '04, Fonseca et al. '15) but no firm quantitative test until DPSR...





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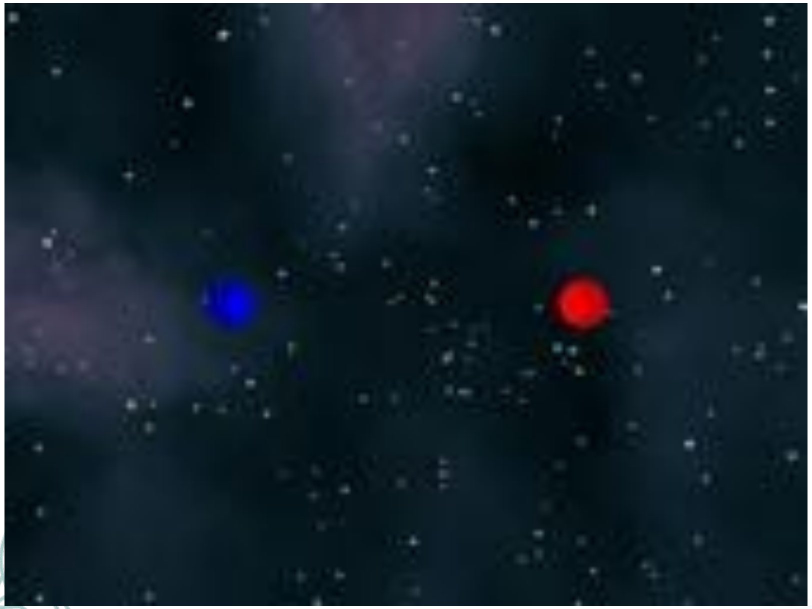
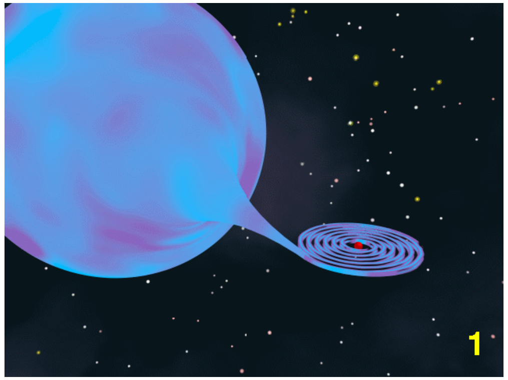
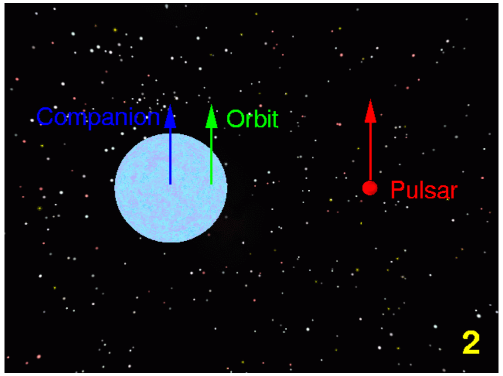
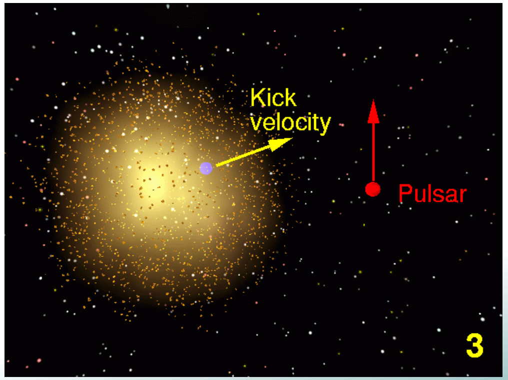
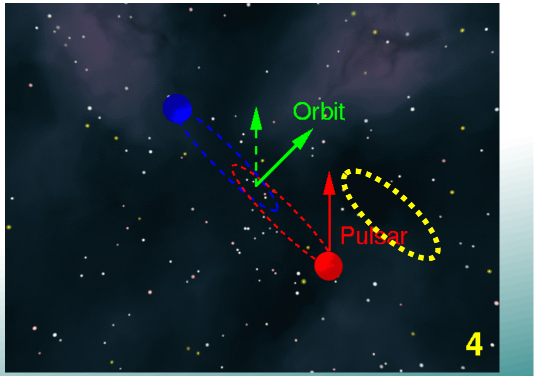
$$\Omega^p = \left(\frac{2\pi}{P_b}\right)^{5/3} T_\odot^{2/3} \frac{m_c(4m_p+3m_c)}{2(m_p+m_c)^{4/3}} \frac{1}{1-e^2}, \quad T_\odot = GM_\odot c^{-3}$$





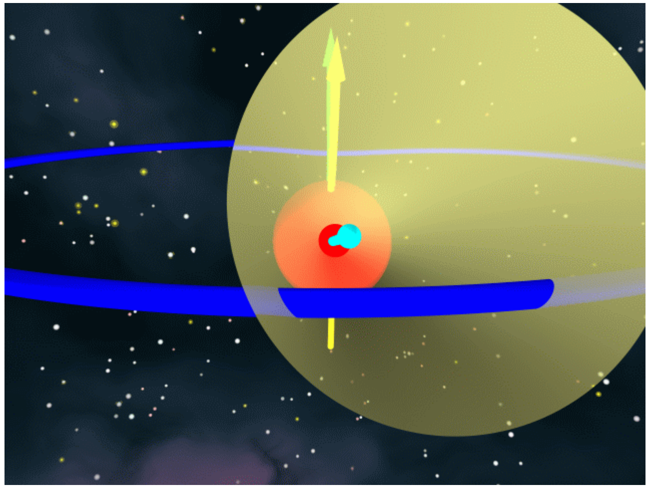




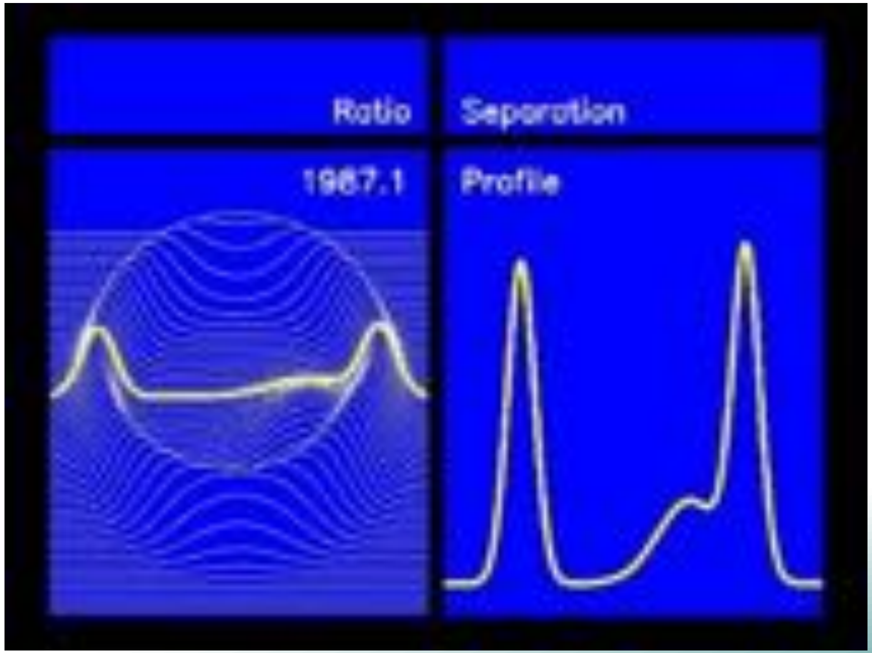


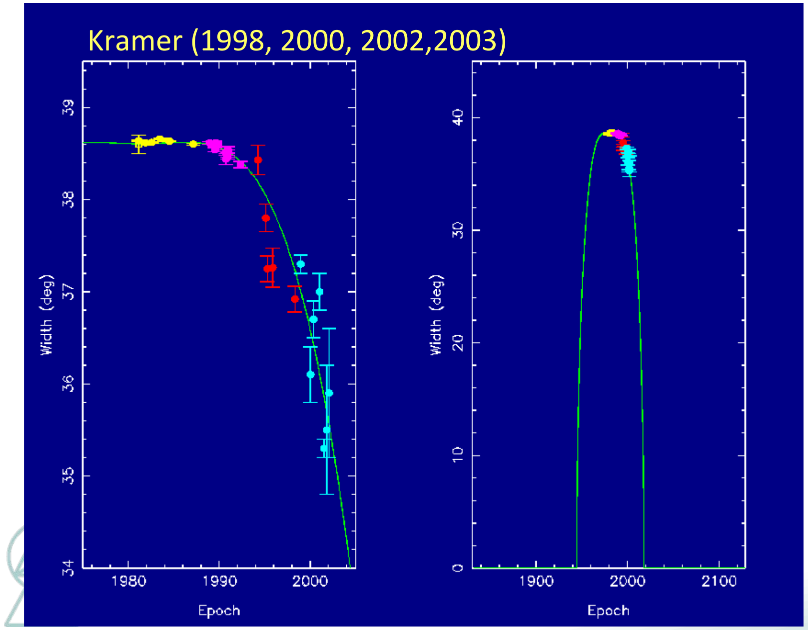
Relativistic spin precession

Changes to the pulse shape and visibility are expected (Ruffini & Damour 1974)



Kramer (2000)



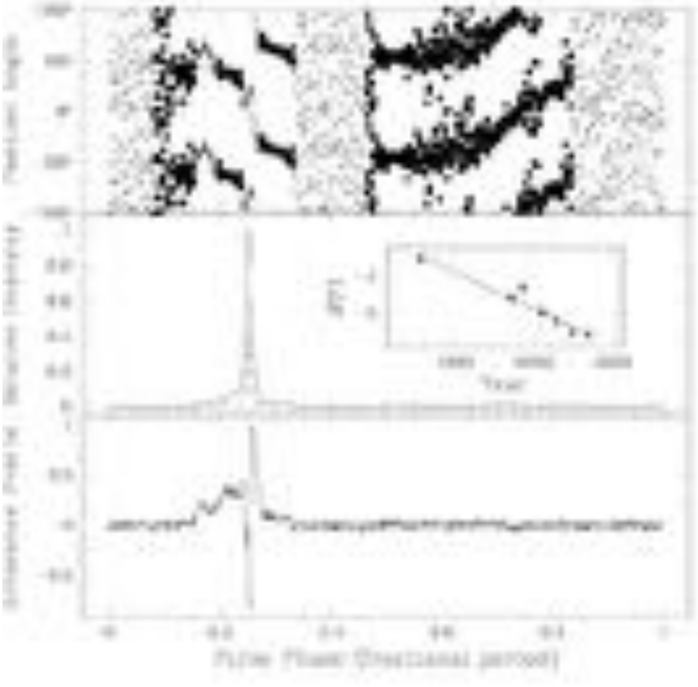

Kramer (1998, 2000, 2002,2003)

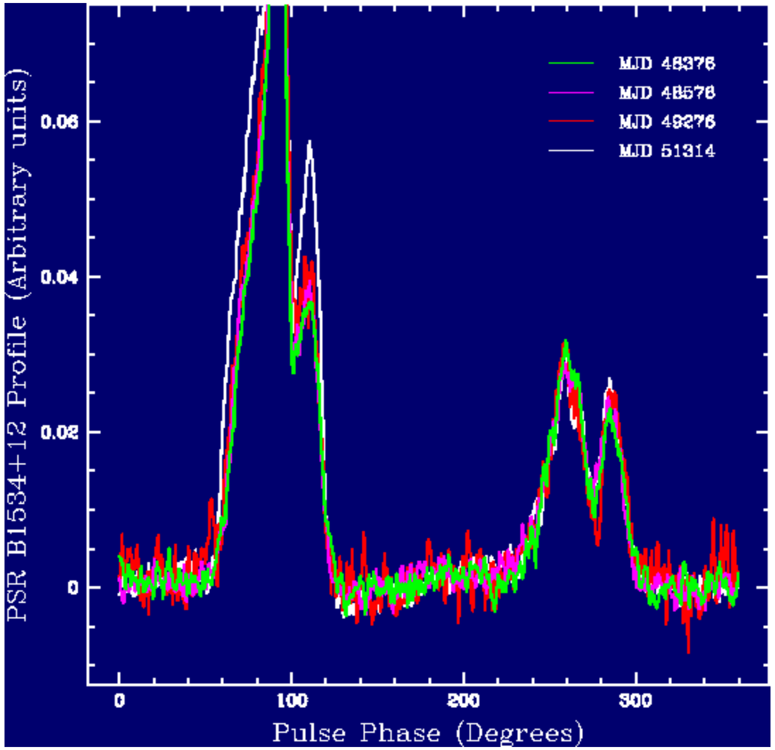
See also change of amplitude ratio by Weisberg et al. (1989)

Relativistic spin precession

Second DNS also showed this effect: PSR B1534+12

Stairs et al. (2000, 2004), , Fonseca et al. (2015)





- First time to measure changing geometry from polarization
- Combination of aberration and precession effect detected
- First attempt to derive quantitative test of precession rate

Relativistic spin precession

Changes to the pulse shape and visibility are expected (Ruffini & Damour 1974)
Seen in all pulsars where we expect it (Kramer 2012)...

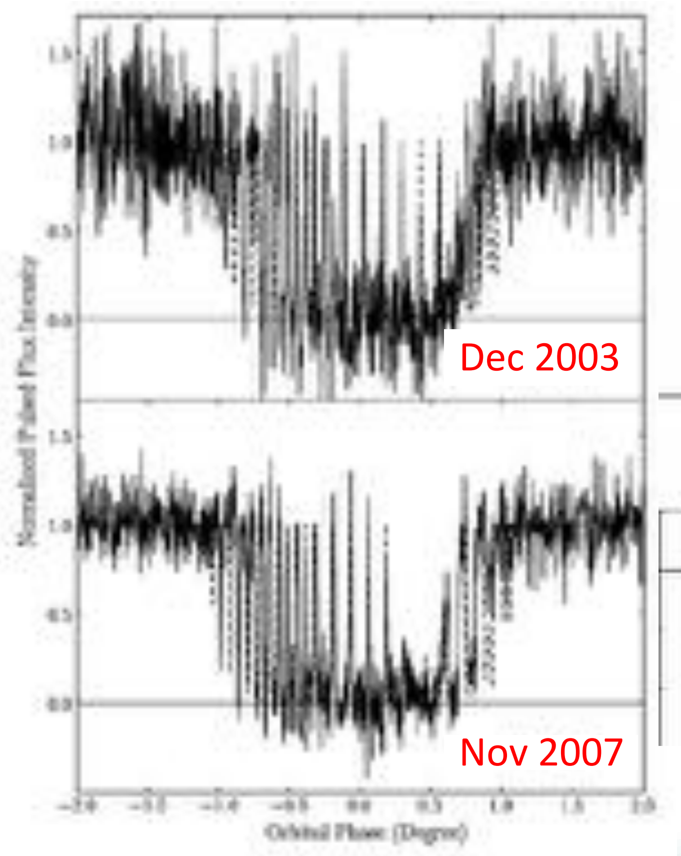
		P(ms)	P_b(d)	x(lt-s)	e	Ω(º/yr)
DNS	J0737-3039	22.7/2770	0.10	1.42/1.51	0.09	4.8/5.1
	B1534+12	37.9	0.42	3.73	0.27	0.5
	J1518+4904	40.9	8.64	20.0	0.25	-
	J1756-2251	28.5	0.32	2.76	0.18	0.76
	J1753-2240	95.1	13.63	18.1	0.30	-
	J1811-1736	104.2	18.8	34.8	0.83	-
	J1829+2456	41.0	1.18	7.24	0.14	0.08
	J1906+0746	144.1	0.17	1.42	0.09	2.2
	B1913+16	59.0	0.33	2.34	0.62	1.2
	B2127+11C	30.5	0.34	2.52	0.68	1.9
PSR-WD	J1141-6545	394.0	0.20	1.86	0.17	1.4

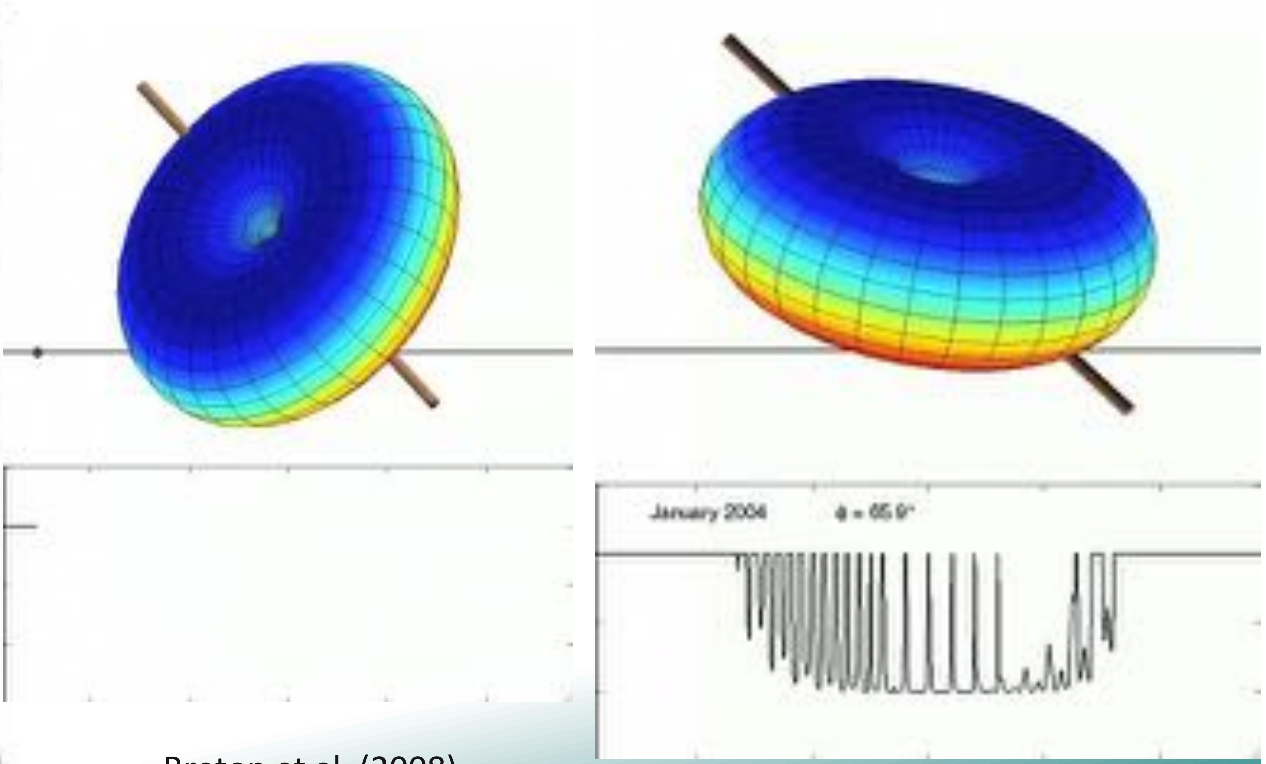
red= preecession observed

Relativistic Spin Precession in the Double Pulsar

- Not seen in pulsar A ➔ low kick supernova forming pulsar B (Ferdman et al. 2013)
- But seen in pulsar B in two ways:
  - pulsar B has disappeared in March 2008 (Perera et al. 2010)
  - precession changes eclipse pattern (Breton et al. 2008)

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



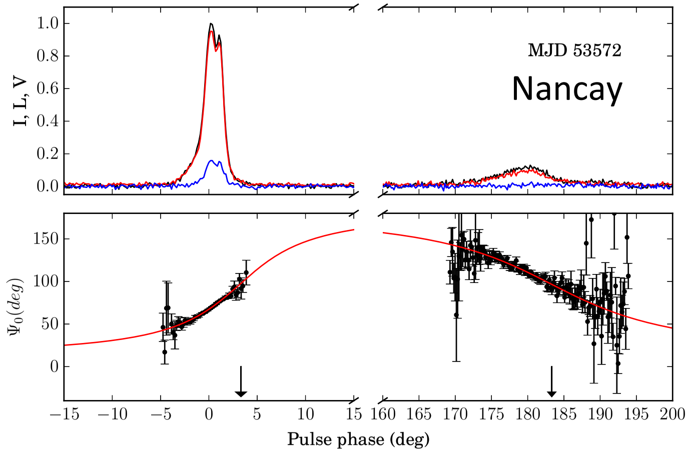


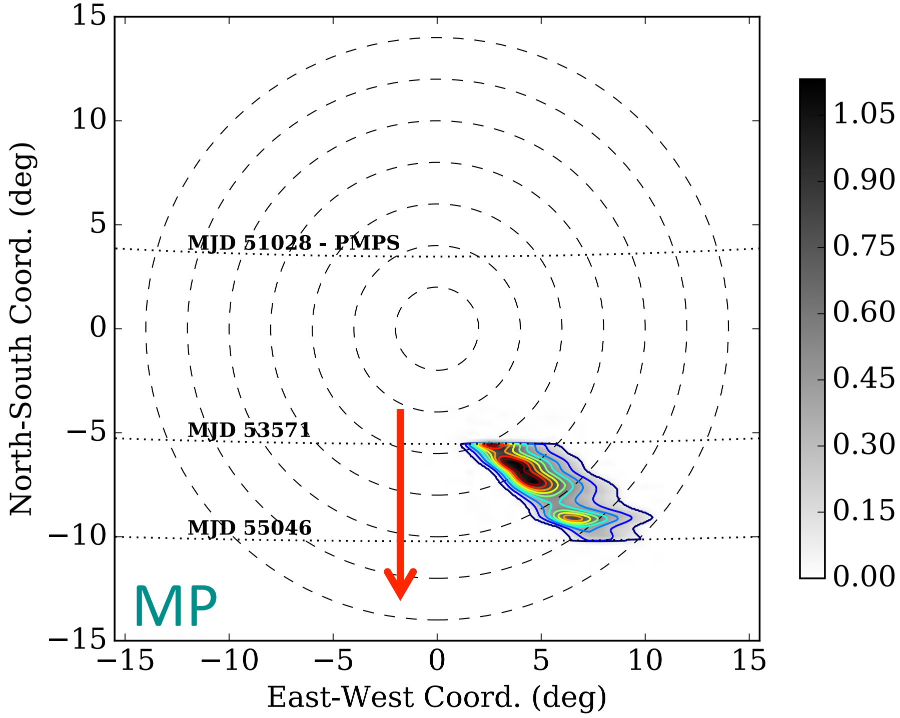
Breton et al. (2008)

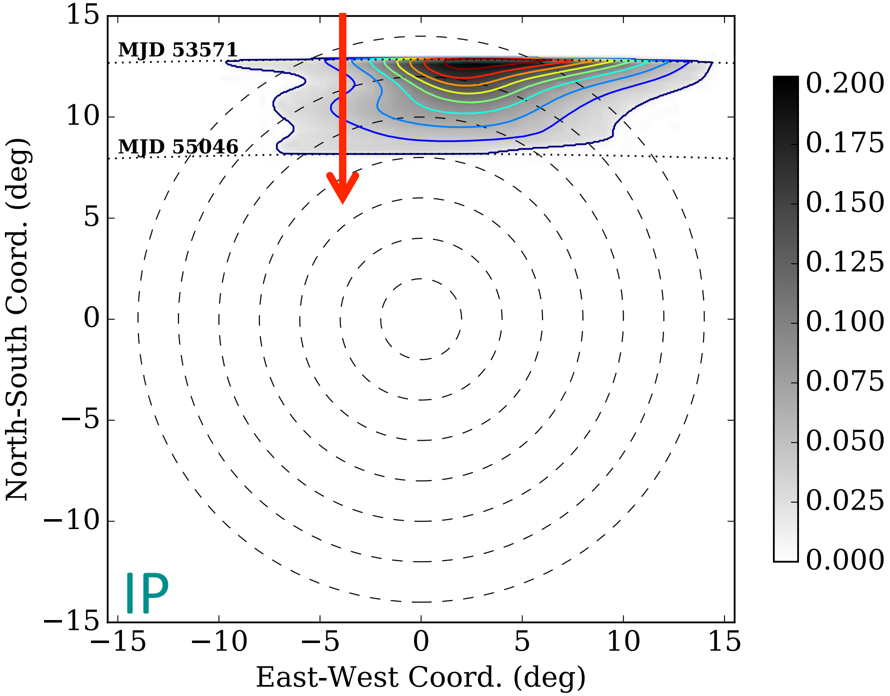
PSR J1906+0746: New best case

New results (Desvignes et al. in prep.)

- highly polarized pulsar with interpulse allowing <u>precise</u> RVM fit to trace geometry
- fit for precession rate possible
- beam maps possible (preliminary but exciting!)
- We crossed the pole! – Stay tuned..!







Constraining alternative theories – some examples...

Scalar-tensor gravity

Jordan-Fierz-Brans-Dicke	PSR J1738+0338, PSR J0348+0432 (Freire et al. 2012, Antoniadis et al. '13)
Quadratic scalar-tensor gravity (see work by Damour & Esposito-Farese)	PSR-WDs, PSR J1738+0338, PSR J0348+0432 (Freire et al. 2012, Antoniadis et al. '13)
Massive Brans-Dicke	PSR J1141-6545 (Alsing et al. 2012)

Vector-tensor gravity

Einstein-Æther Hořava gravity	Various binary pulsars (Yagi et al. 2014)

TeVeS & TeVeS-like theories

Bekenstein's TeVeS	Double Pulsar (Kramer et al. in prep, Wex et al., in prep)
TeVeS-like	PSR J1738+0338 (Freire et al. 2012)

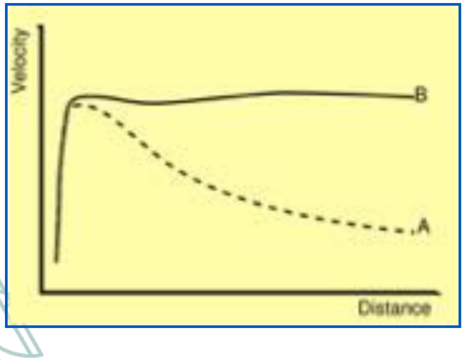
Bekenstein’s TeVeS and the Double Pulsar

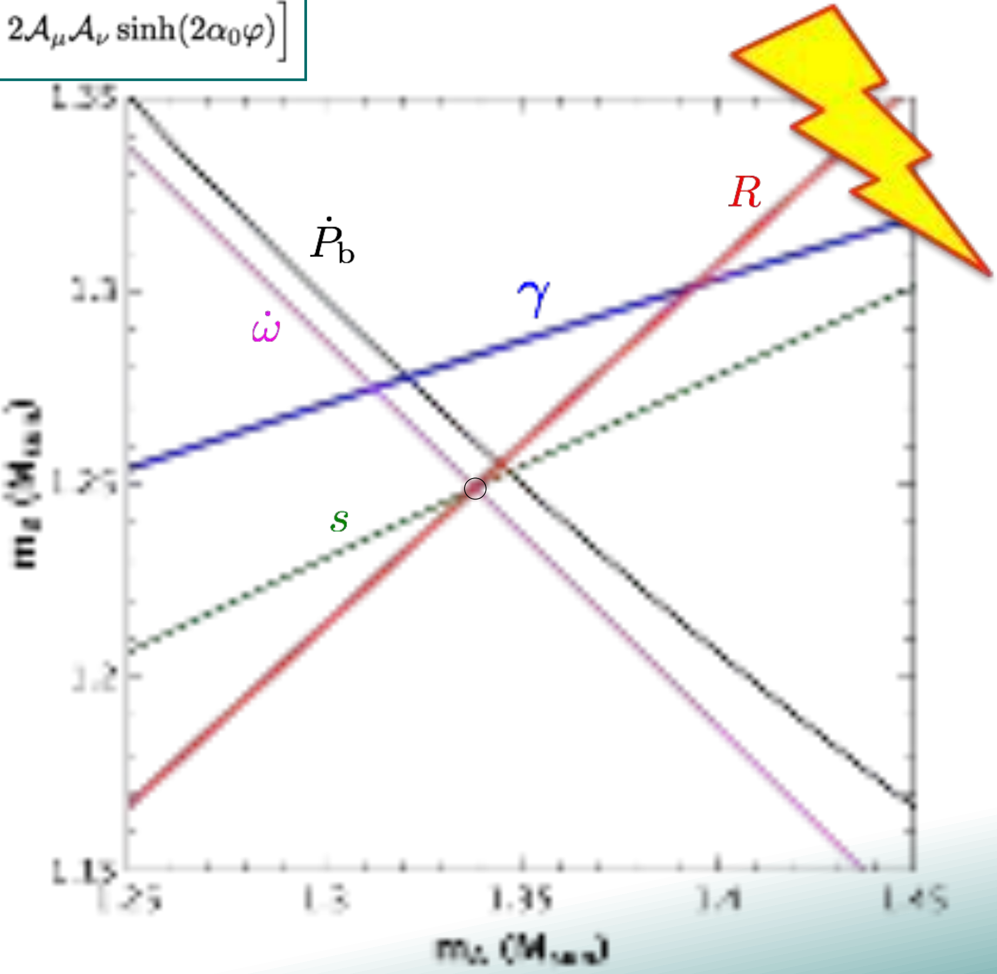
$$
\begin{aligned}
S &= \frac{c^3}{16\pi G_*}\int d^4x\sqrt{-g^*}\Big(R^* - 2\mathcal{F}(g^*_{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi)\Big)\\
&\quad + S_{\text{vector}}\Big[\mathcal{A}_\mu; g^*_{\mu\nu}\Big]\\
&\quad + S_{\text{matter}}\Big[\psi; \tilde{g}_{\mu\nu} \equiv g^*_{\mu\nu}\exp(-2\alpha_0\varphi) - 2\mathcal{A}_\mu\mathcal{A}_\nu\sinh(2\alpha_0\varphi)\Big]
\end{aligned}
$$

It doesn't pass.

➜ Scalar-vector-tensor theory with aquadratic kinetic term and disformal coupling

Scalar coupling strength $\alpha_0 \gtrsim 0.05$





[Kramer *et al.*, in prep.; Wex, Esposito-Farèse et al., in prep.]

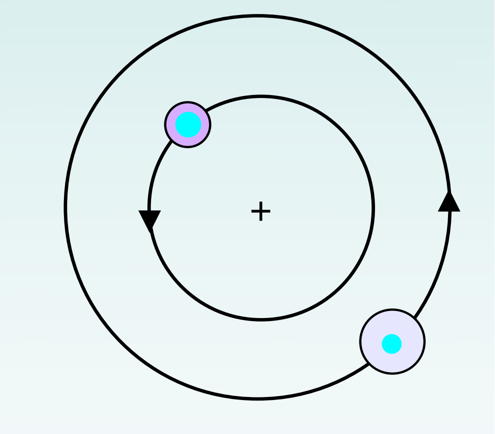
Dipolar Gravitational Radiation in Binary Systems?

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

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

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

Hence, visible in orbital decay:

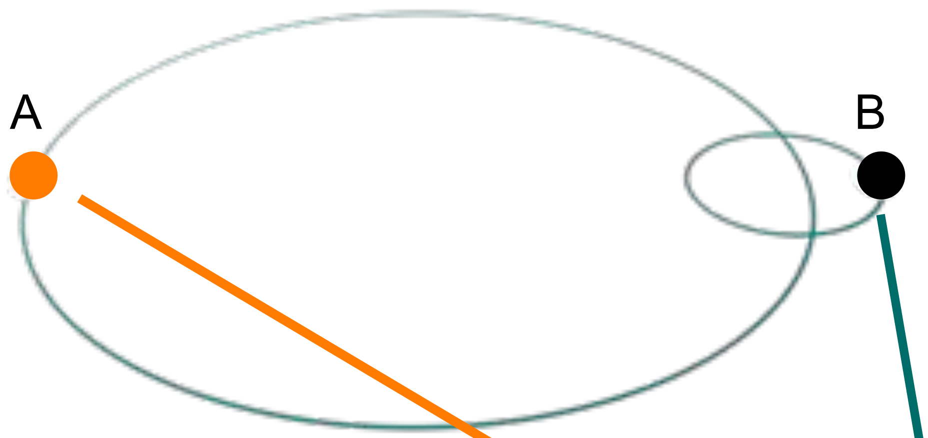


$$\dot{P}_\mathrm{b}^\mathrm{quadrupole} \propto \left(\frac{v}{c}\right)^5$$

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

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:

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

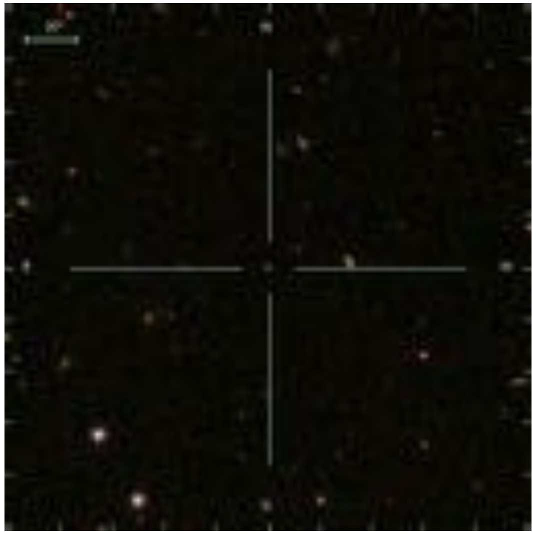
PSR-BH system would be best as BH would have zero scalar charge

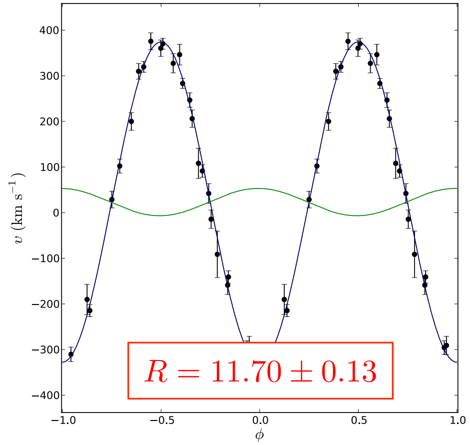
But PSR – WD system also effective lab – in particular if PSR is massive!

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)

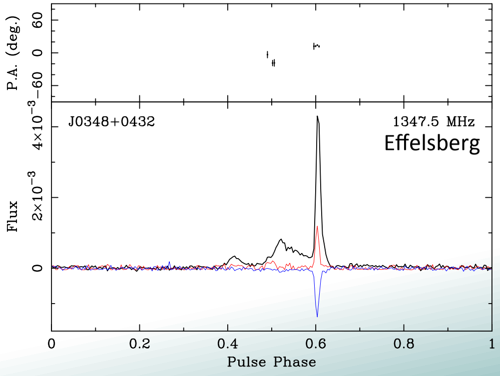


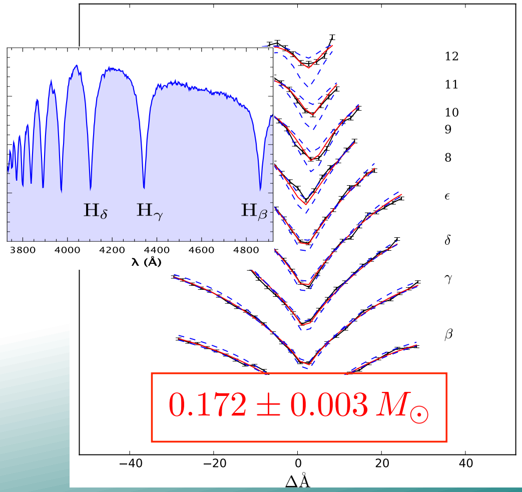


$P \;=\; 39.1226569017806(5)$ ms

$P_b \;=\; 2.45817750533(2)$ h

$e \;\lesssim\; 10^{-6}$





Testing a new gravity regime

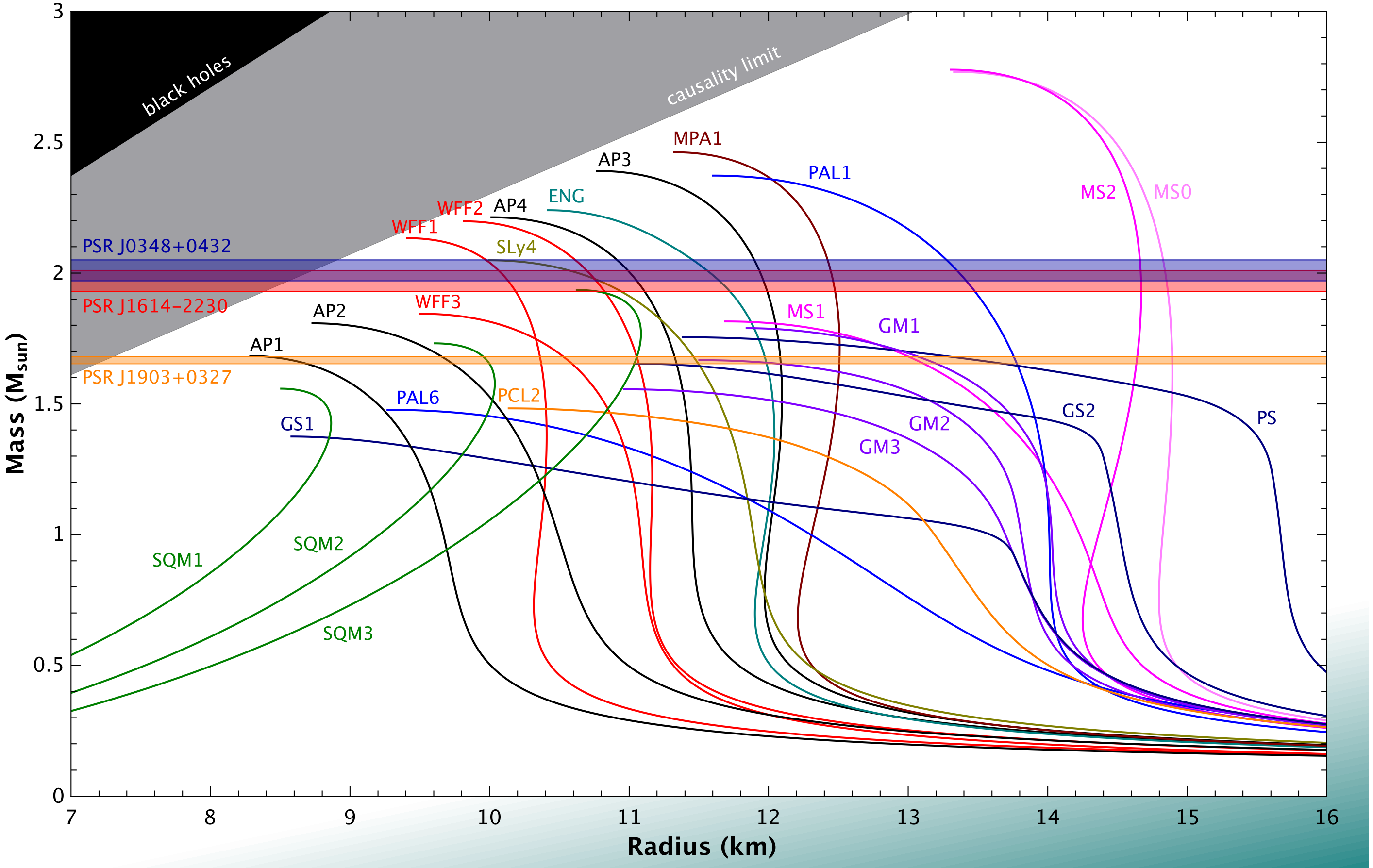
- PSR J0348+0432: first massive NS in relativistic orbit (Lynch et al. 2013)
- Combining VLT, Effelsberg, Arecibo & GBT data, new record mass measured:

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

Combine with moment-of-inertia from Double Pulsar.

Are they born massive?

See earlier…



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)

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

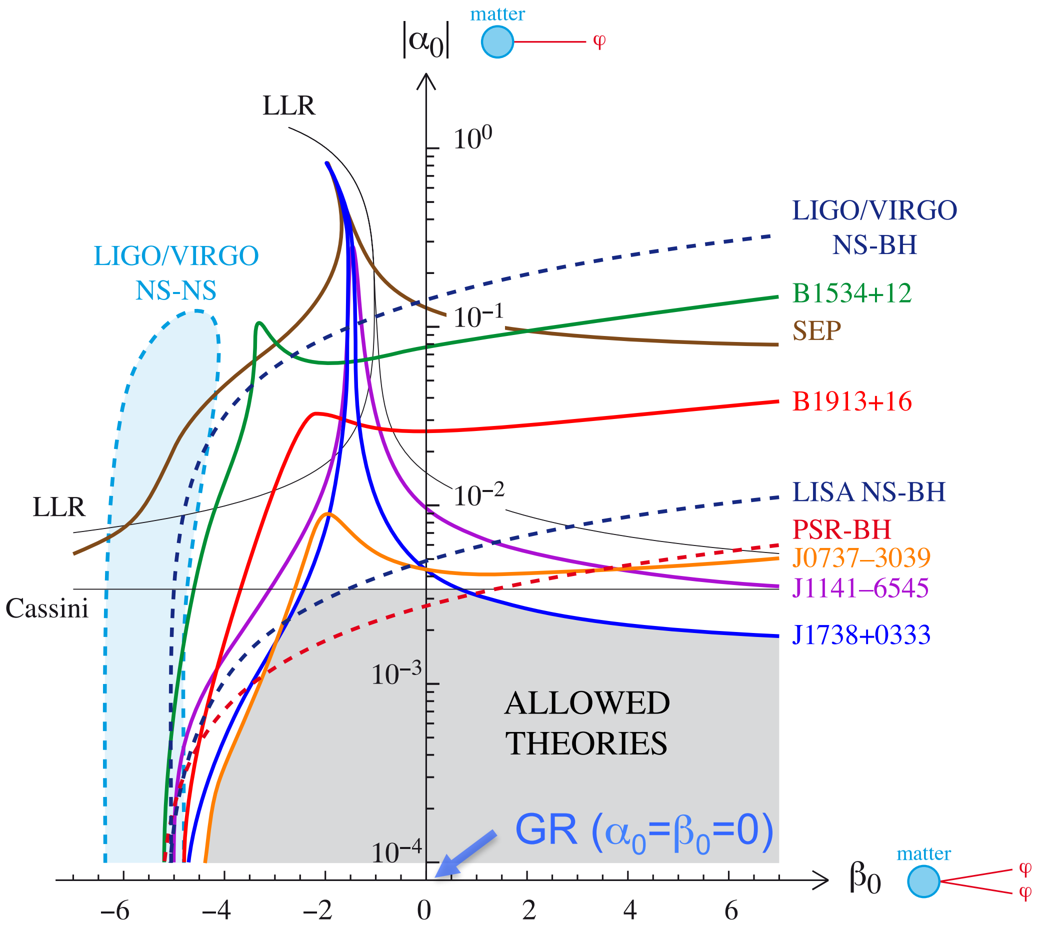
No indication of dipolar radiation!

$$\alpha_\mathrm{p} = 1 \quad \Longrightarrow \quad \dot{P}_\mathrm{b} = -110\,000 \quad \mu\mathrm{s/yr}$$

$$\mathrm{GR} \quad \Longrightarrow \quad \dot{P}_\mathrm{b} = -8.2 \quad \mu\mathrm{s/yr}$$

Limits on Tensor-scalar theories

Limits better than solar system limits for most of the parameter space, e.g. in framework by Damour & Esposito-Farese:



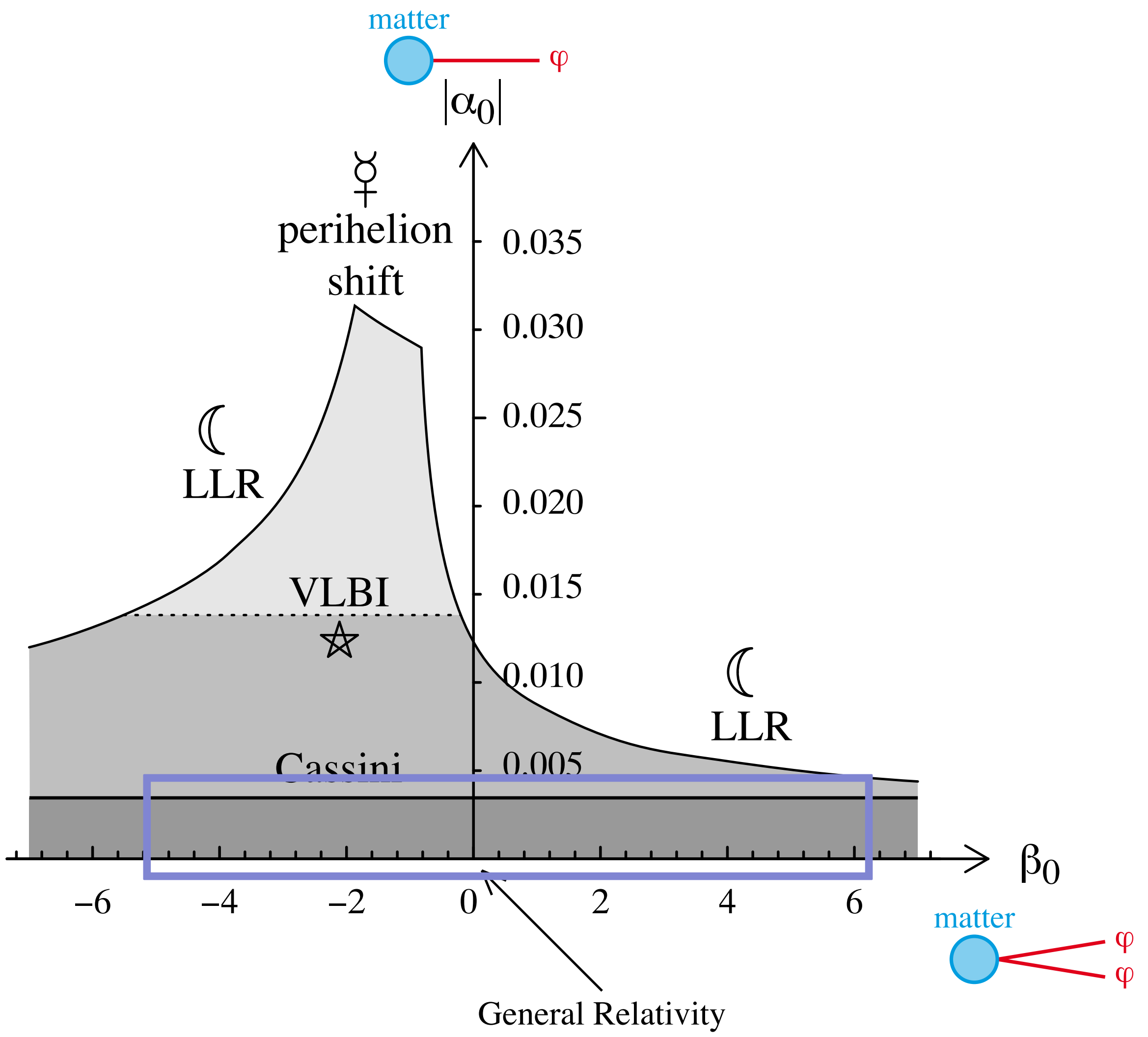
Note:

- In GR, α_0 and β_0 = 0
- Jordan-Fierz-Brans-Dicke: on axis of β_0=0

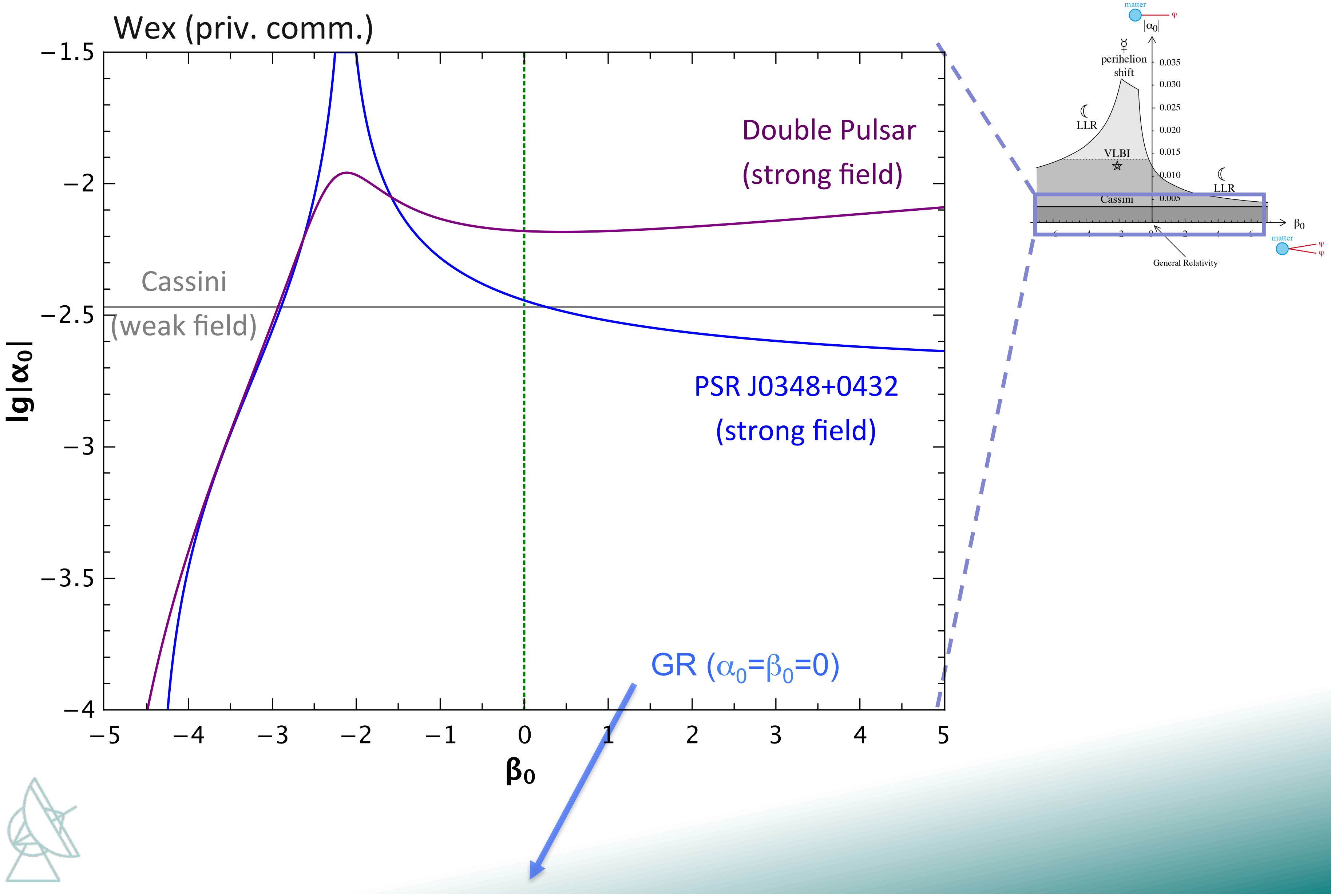
Double Pulsar closes the “gap” left by PSR-WD systems.

Figure by Esposito-Farese

Constraining tensor-scalar gravity



Constraining tensor-scalar gravity



Future SEP test: The Triple-System PSR J0337+1715

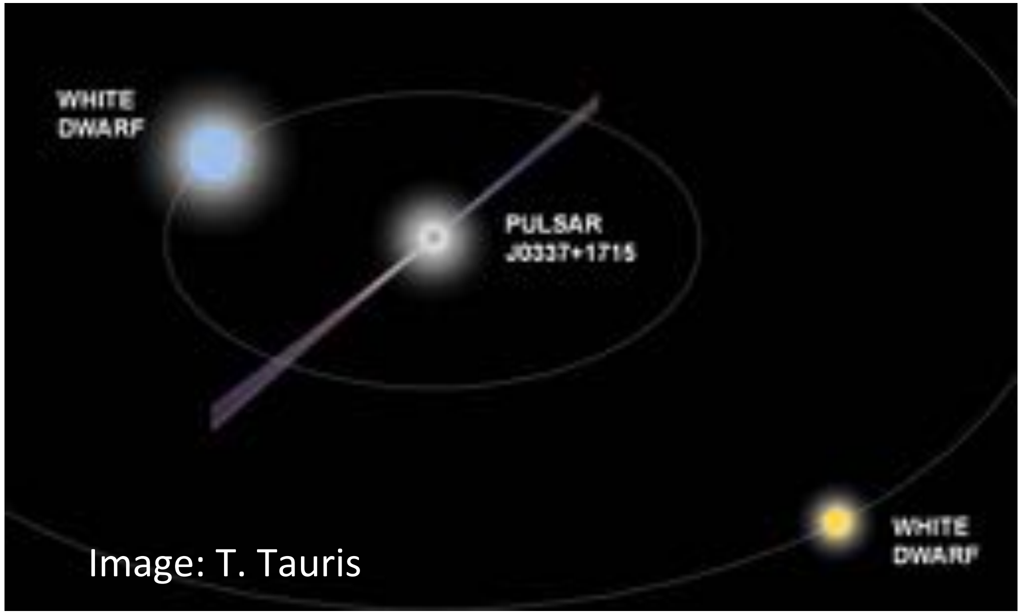


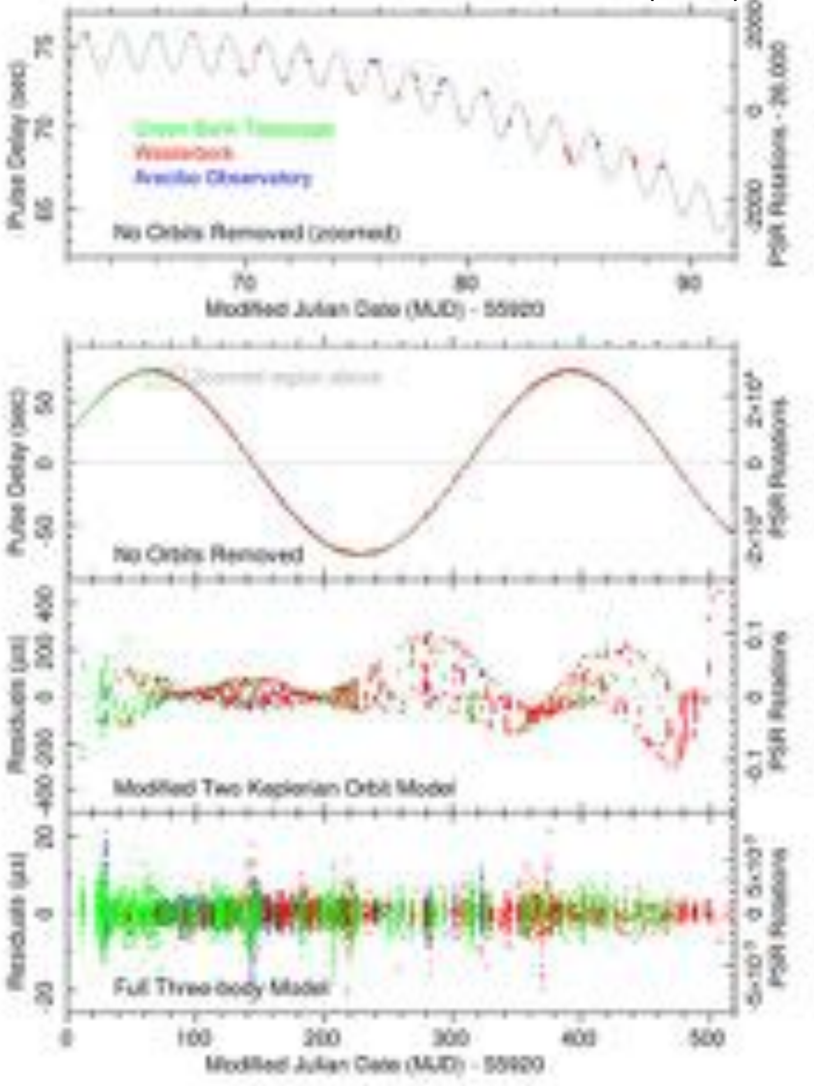
Image: T. Tauris

(Pulsar-WD)-WD system: P_b = 1.6/327 days

M = 1.44/0.2/0.4 $M_\odot$

- Pulsar and inner WD fall in external field of outer WD
- Expected improvement of current best pulsar limit ~ 10^4 (see Freire, Wex, MK 2013)

Ransom et al. (2014)



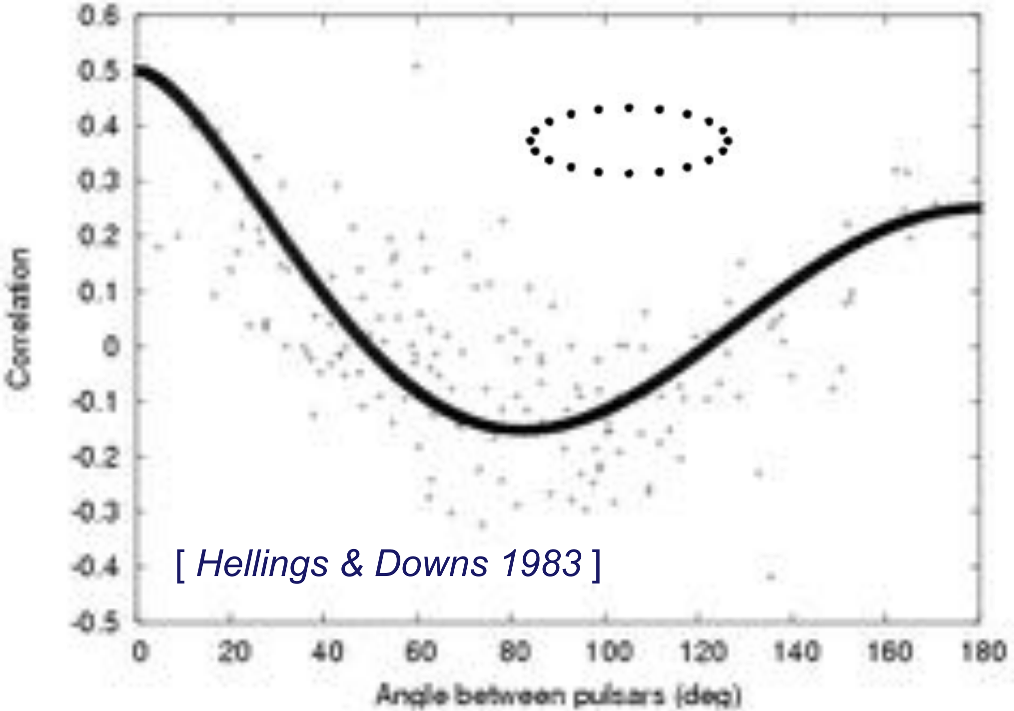
Exploring gravity – with radio astronomy

- Introduction
- Pulsars & binaries: testing GR and its alternatives
- Pulsar Timing Arrays (PTAs): detecting GWs
- Event Horizon Telescope/BlackHoleCam: imaging a BH
- Conclusions

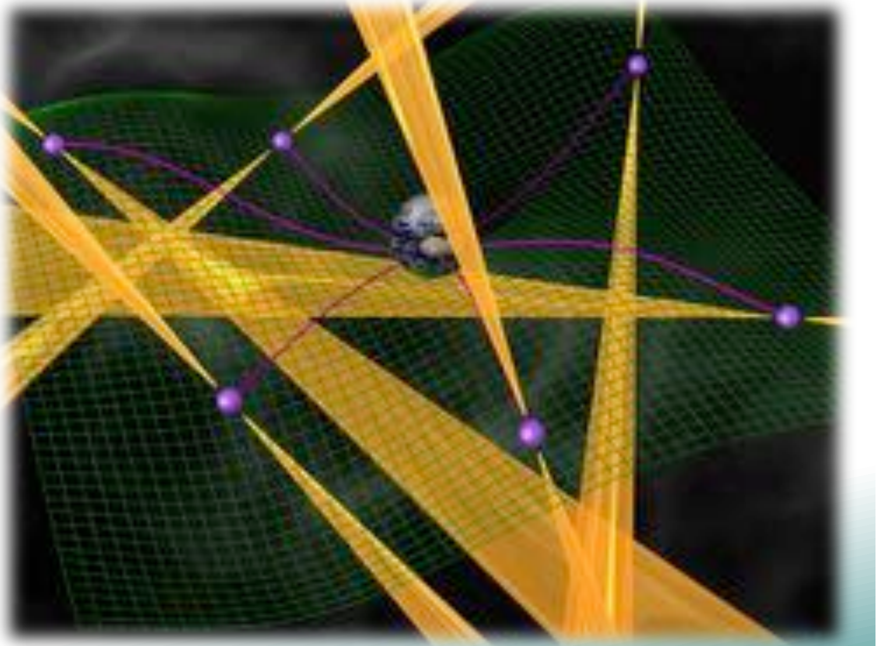
Pulsars as Gravitational Wave Detectors

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 low-frequency GWs

- Earliest signal expected from binary super-massive black holes in early galaxy evolution (PTA only way to detect $M > 10^7 M_\odot$ $P_{orb} \sim 10\text{-}20\text{yr}$)
- Amplitude depends on merger rate, galaxy evolution and cosmology but could be detectable (when? – see talks by Alberto, Lindley, Stas, Vikram and others....)

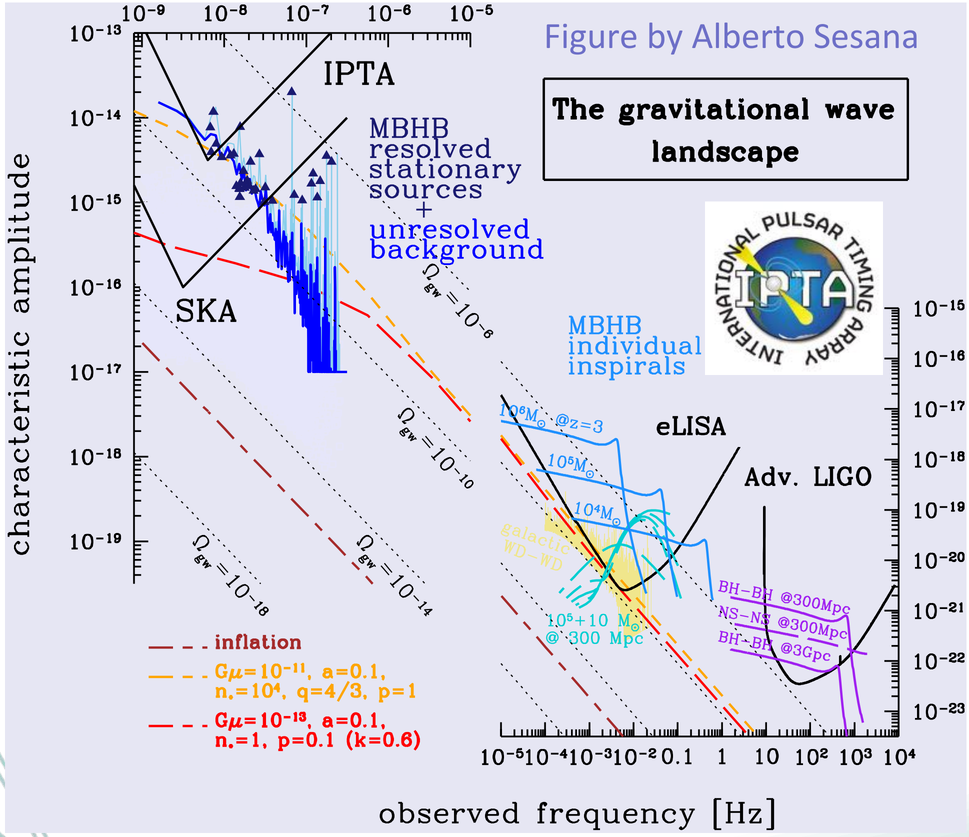


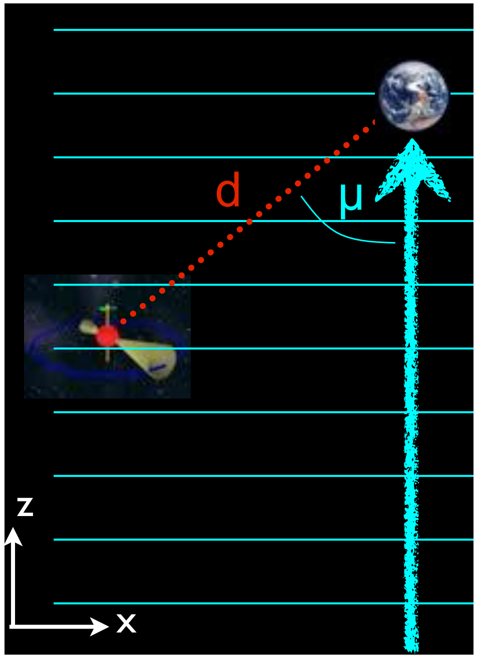
Figure by Alberto Sesana

The gravitational wave landscape

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

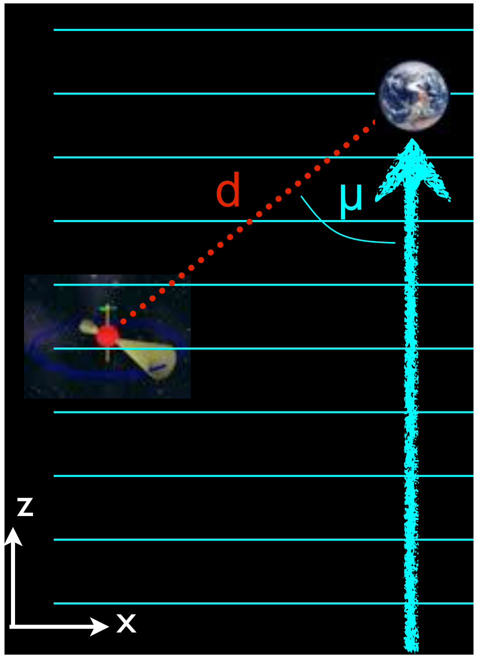
$$\frac{\delta\nu}{\nu} = H^{ij}(h^e_{ij} - h^p_{ij})$$

geometry Earth pulsar

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

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:



$$R(t) = \frac{1}{2}(1 + \cos\mu)[r_+(t)\cos(2\psi) + r_\times(t)\sin(2\psi)],$$

$$r_{+,\times}(t) = r^e_{+,\times}(t) - r^p_{+,\times}(t),$$

$$r^e_{+,\times}(t) = \int_0^t h^e_{+,\times}(\tau)\,d\tau,$$

"Earth term"

Retardation

$$r^p_{+,\times}(t) = \int_0^t h^p_{+,\times}\left[\tau - \frac{d}{c}(1 - \cos\mu)\right]d\tau,$$

"pulsar term"

[Detweiler 1979, Jenet et al. 2004]

Expected amplitudes & sources

- Highest frequency is given by cadence: ~1 per month => ~400 nHz
- Lowest frequency is given by observing length: ~10 years => ~3 nHz
- Timing residuals for a monochromatic GW (i.e. $h = h_0 \cos(2\pi ft)$)

$$r(t) = \int_0^t h(\tau)\, d\tau = \frac{h_0}{2\pi f} \sin(2\pi f t)$$

- In order to get residuals of 100 ns, on needs:

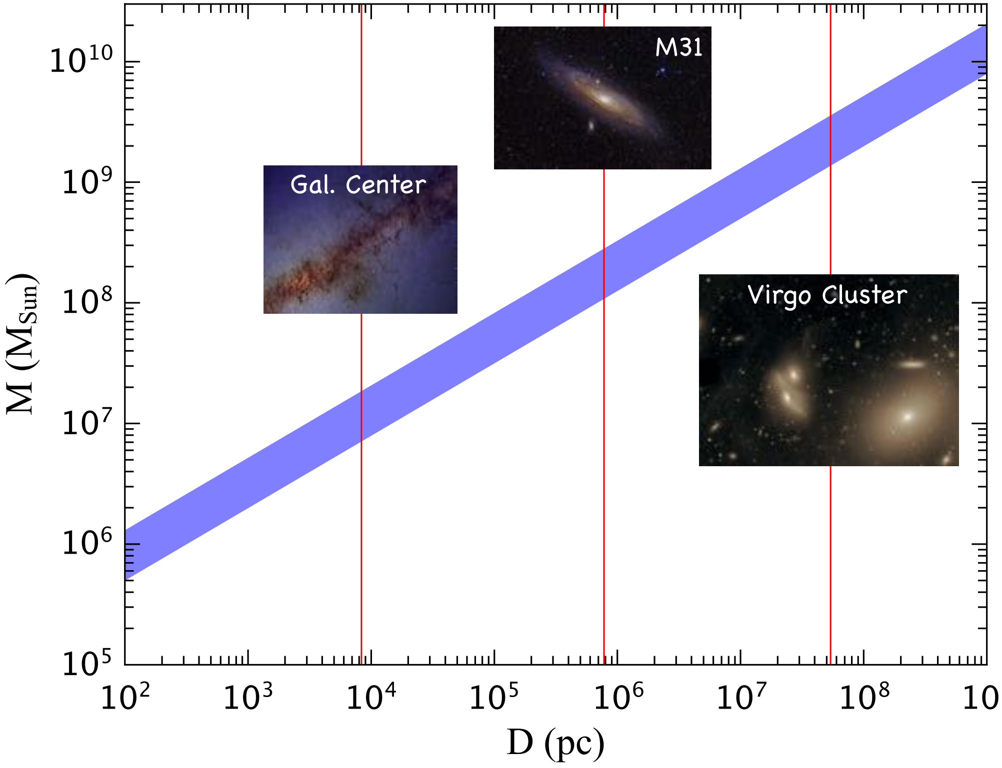
  $h_0 = 1.9 \times 10^{-15}$ at 3 nHz
  $h_0 = 2.5 \times 10^{-15}$ at 400 nHz

What sources can produce those?

Binary system (m_1=m_2):

$$h_0 = \frac{c}{D}\left(\frac{GM}{c^3}\right)^{5/3} (\pi f)^{2/3}$$

$$r_0 = \frac{c}{2D}\left(\frac{GM}{c^3}\right)^{5/3} (\pi f)^{-1},$$



Slide courtesy N. Wex

Retardation & Source evolution

Like in binary pulsars, GW damping will cause the BH binary to shrink, leading to increase in GW frequency. For a circular orbit one has:

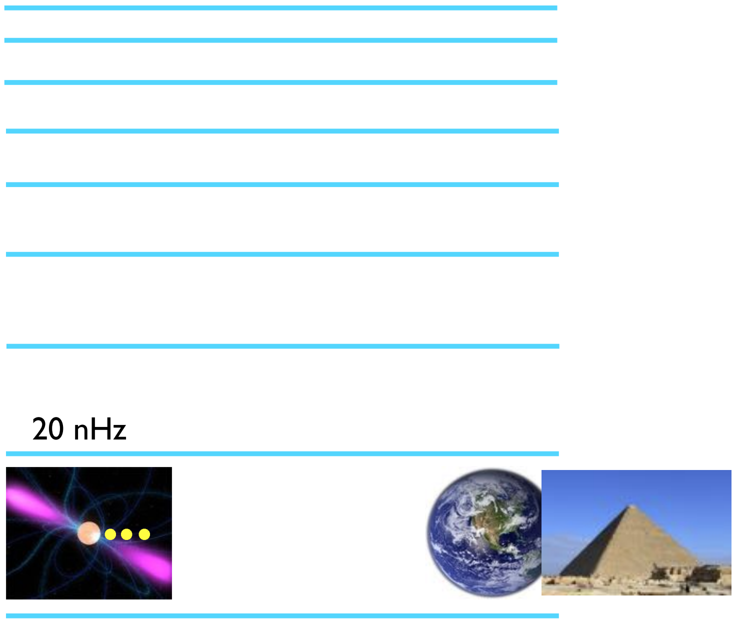
$$\frac{\dot{f}}{f} = \frac{96}{5}\left(\frac{G\mathcal{M}_c}{c^3}\right)^{5/3}(\pi f)^{8/3}$$

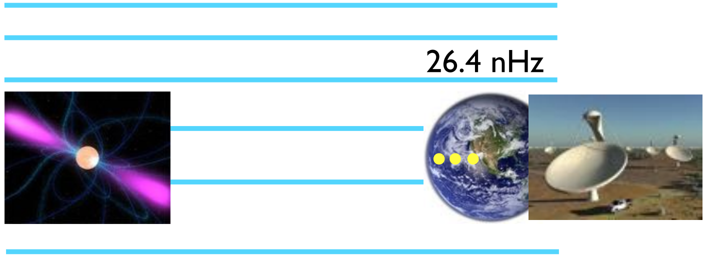
"chirp mass" $\mathcal{M}_c \equiv \frac{(m_1 m_2)^{3/5}}{M^{1/5}}$

Frequency evolution during Tobs generally negligible, but some sources could have significant frequency evolution between pulsar term and Earth term.

Example: pulsar at 1.4 kpc distance and a SMBH binary (m_1=m_2=$10^9 M_\odot$) in the Virgo cluster:

(Wex priv. comm.)





Stochastic background

For an isotropic, stochastic GW background (GWB) of cosmological (or astro-physical) origin (e.g. Maggiore 2000):

$$\Omega_{\rm gw}(f) = \frac{1}{\rho_c}\frac{{\rm d}\rho_{\rm gw}}{{\rm d}\ln f} = \frac{2\pi^2}{3H_0^2}f^2h_c^2(f)$$

with:

ρ_{GW} = GW energy density per unit logarithmic frequency

$\rho_c = 8\pi/(3H_0^2)$ = critical energy density to close the Universe

H_0 = 100h km/s/Mpc = Hubble expansion rate

As approximation (most likely not correct – see later talks!), we expect the char. strain to follow a power law:

$$h_c = A\left(\frac{f}{{\rm yr}^{-1}}\right)^{\alpha}$$

A = amplitude for f=1/1yr – related to "one-sided power spectral density":

$$S(f) = \frac{1}{12\pi^2}\frac{1}{f^3}h_c(f)^2 = \frac{A^2}{12\pi^2}\left(\frac{f}{{\rm yr}^{-1}}\right)^{-\gamma}{\rm yr}^3 \qquad \gamma \equiv 3 - 2\alpha$$

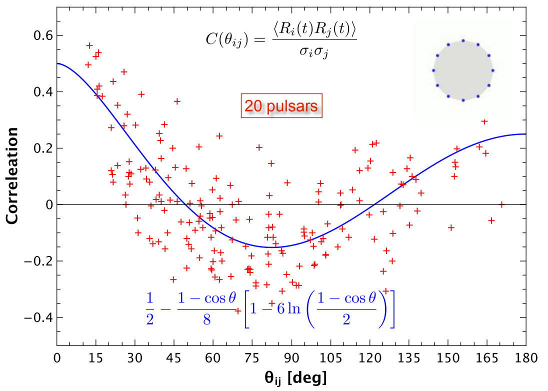
For GWB from SMBHBs, we expect $h_c(f) \alpha f^{-2/3}$ and $\gamma=13/3$

Searching for a stochastic GWB

- We are looking for a "red noise" signal with a period comparable to the length of the data set, using frequentist and Bayesian methods – see e.g. Lindley's talk
- Competing noise sources:
    - pulsar deterministic "noise" (orbital motion, spin-down etc.)
    - pulsar intrinsic white noise + instrumental (thermal) white noise
    - pulsar intrinsic red noise (pulse jitter, timing irregularities)
    - variation in the interstellar medium ("Weather", DM variation, scattering)
    - "common noise": planetary ephemeris errors, clock errors
    - stochastic noise due to GWB

- In order to extract GWB signal, a number of pulsars need to be observed
- Note that adding more pulsars should improve signals (α N) but can also add additional noise:

  fewer good pulsars may be better than
  many less good ones
  but: perhaps only way to find common noise



The International Pulsar Timing Array (IPTA)

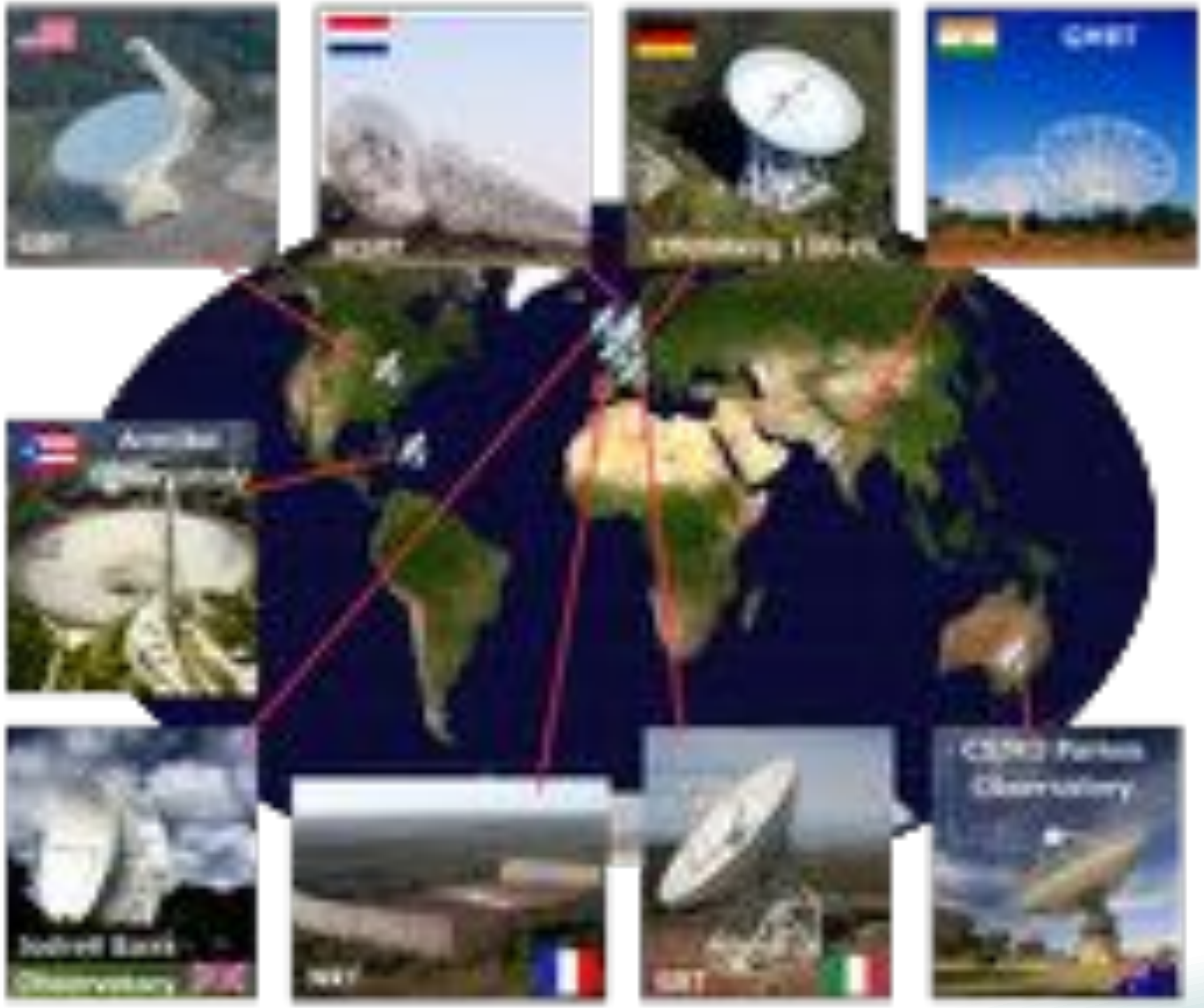
INTERNATIONAL PULSAR TIMING ARRAY

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

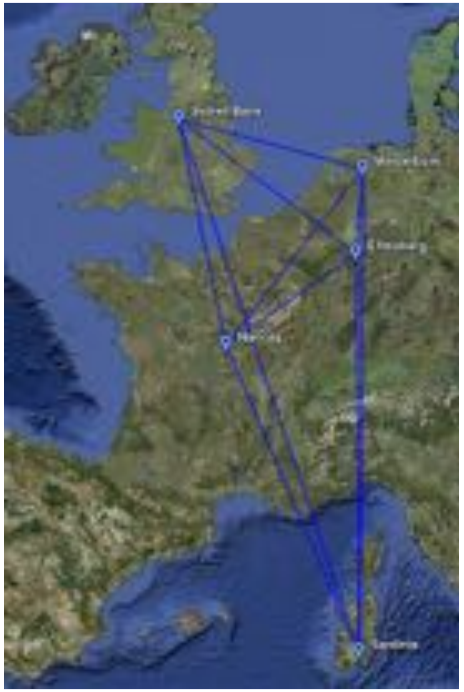

NRT, Nancay, France


WSRT, Westerbork, NL

Plus theory:

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

A Large European Array for Pulsars = a LEAP!



Coherently add pulsar observations from 5 of the largest telescopes in Europe (and the world!) to obtain most precise TOA's for GW detection.

Combine telescopes to form a phased array, a telescope with equivalent size of SKA – Phase 1!

"The best, most sensitive pulsar instrument at the moment"

A LEAP in collecting area: timing,imaging & searching.
(Kramer & Stappers 2010, Bassa et al. 2016)
Established by ERC Advanced Grant.

Telescope	Diameter (m)	ϵ	T_{sys}	Alloc. time (h/mo)	Dec. range (deg)
Effelsberg	100	0.54	24	24	> -30
Lovell	76.2	0.55	30	48	> -35
Nançay	94	0.48	35	250	> -39
Sardinia	64	0.6	25	30	> -46
WSRT	96	0.54	29	32	> -30
LEAP	**200**	**0.54**	**30**	**24**	**> -39**

from Ferdman et al. 2010, Class. Quantum Grav. 27, 084014

A Large European Array for Pulsars = a LEAP!

LEAP: the large European array for pulsars

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K. J. Lee[4,3,2], K. Liu[5,2], J. McKee[2], D. Perrodin[7,2], M. Purver[2],
S. Sanidas[8,2], R. Smits[1,2], B. W. Stappers[2]

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The beamformer and correlator for the Large European Array for Pulsars

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Variability, polarimetry, and timing properties of single pulses from PSR J1713+0747 using the Large European Array for Pulsars

K. Liu,[1,2*] C. G. Bassa,[3] G. H. Janssen,[3] R. Karuppusamy,[1] J. McKee,[4] M. Kramer,[1,4]
K. J. Lee,[5] D. Perrodin,[6] M. Purver,[4] S. Sanidas,[7,3] R. Smits,[3] B. W. Stappers,[4]
P. Weltevrede[4] and W. W. Zhu,[1]

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[3] *ASTRON, the Netherlands Institute for Radio Astronomy, Postbus 2, NL-7990 AA, Dwingeloo, The Netherlands*
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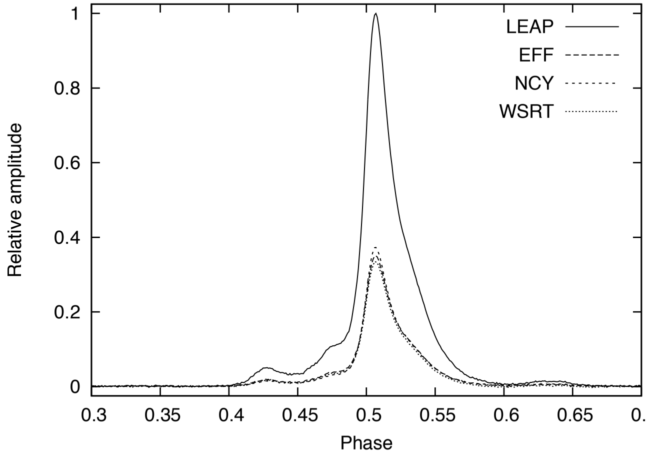
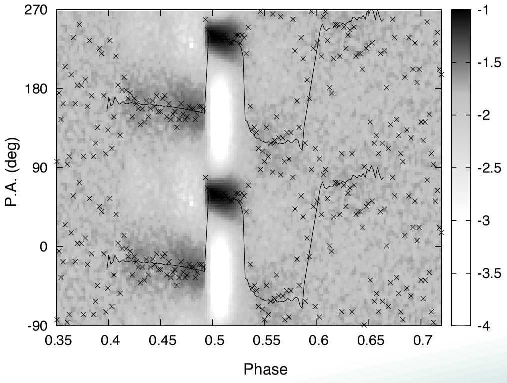
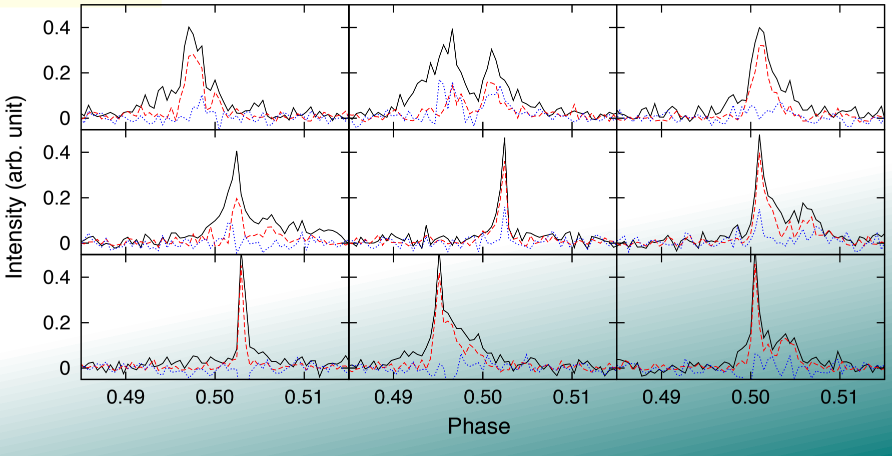
[7] *Anton Pannekoek Institute for Astronomy, University of Amsterdam, Science Park 904, NL-1098 XH Amsterdam, The Netherlands*



Stay tuned for new LEAP/EPTA TOAs.

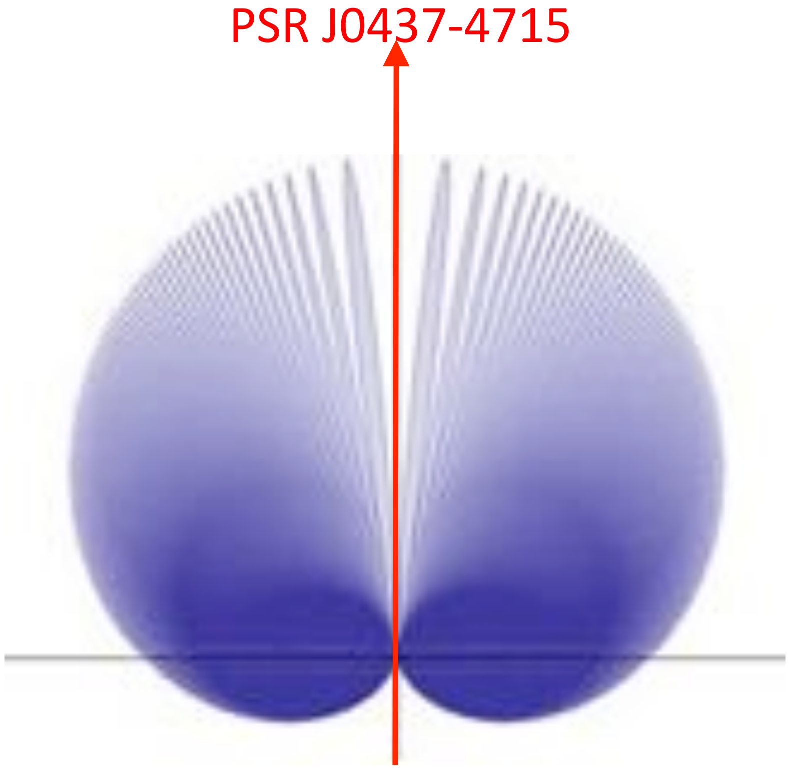




Locating a (non-evolving) single source with the SKA-PTA

Response pattern for PSR J0437-4715

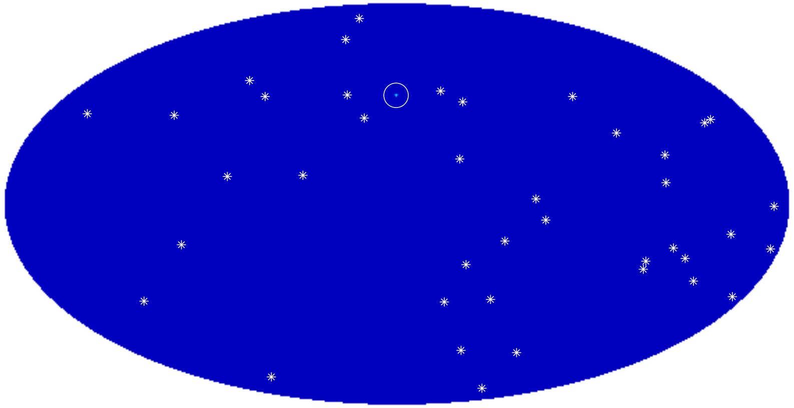
for a 6.3 nHz gravitational wave

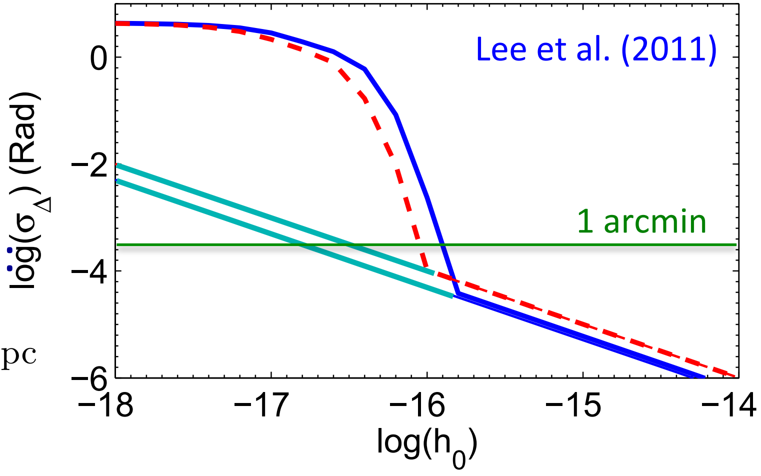


With a SKA-PTA, we can locate the binary SMBH in the sky:

40 millisecond pulsars at ~2 kpc distance

One 15 ns TOA every two weeks for 5 years





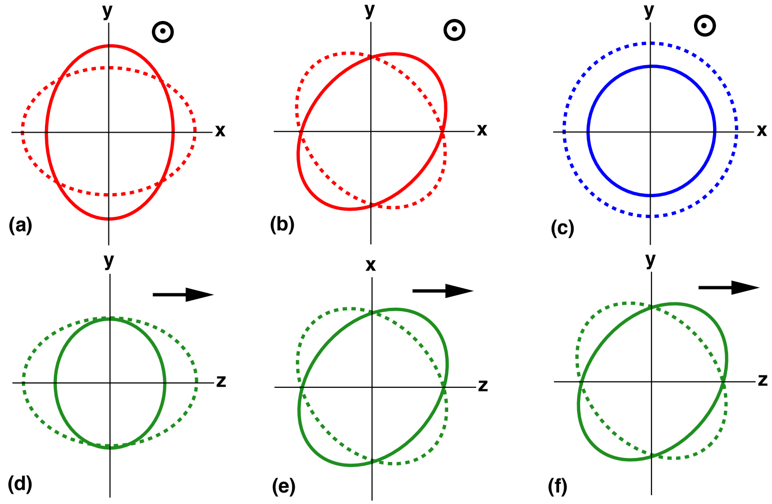
Enabling by spectacular SKA distance measurements:

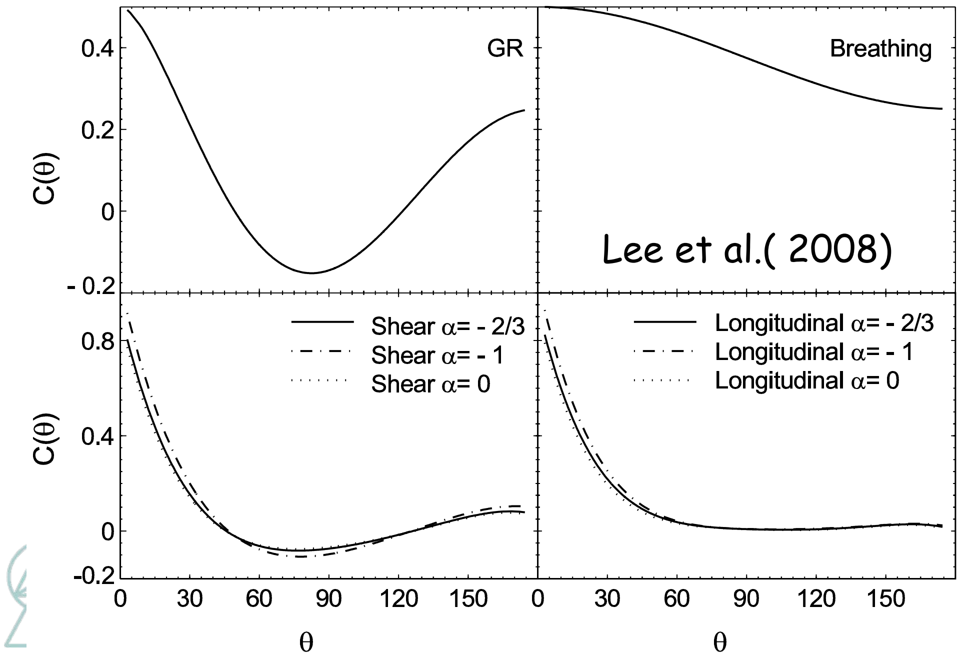
$$\sigma_{D_{\rm psr}} = \frac{4\sqrt{2}\,\sigma_{\rm n} D_{\rm psr}^2}{\sqrt{N_{\rm obs}}\, r_\oplus^2 \cos^2\beta_{\rm psr}} \simeq \frac{2.34}{\cos^2\beta_{\rm psr}} \left(\frac{N_{\rm obs}}{100}\right)^{-\frac{1}{2}} \left(\frac{D_{\rm psr}}{1\,{\rm kpc}}\right)^2 \left(\frac{\sigma_{\rm n}}{10\,{\rm ns}}\right) {\rm pc}$$

Allowing EM follow-up of GW sources!

Testing the properties of gravitons with the SKA-PTA

Polarization modes – Spin 2?



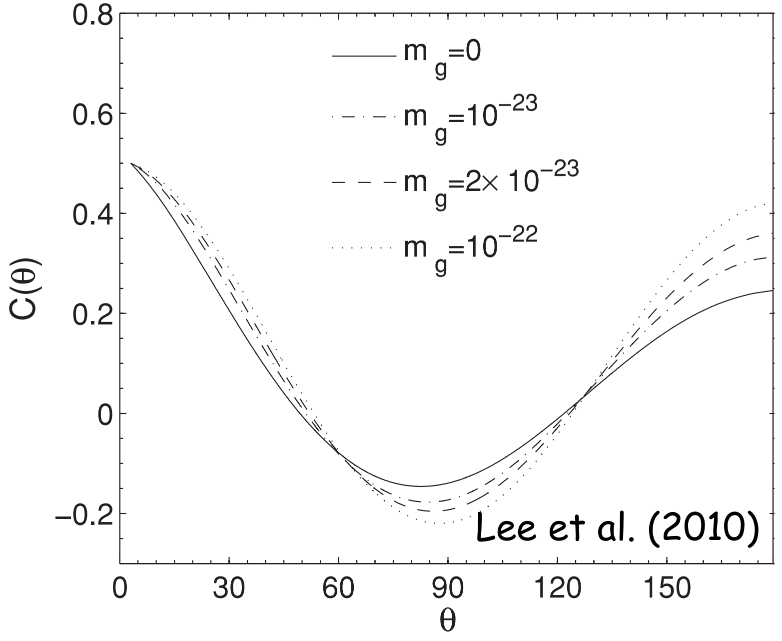


Lee et al.(2008)

Dispersion relation: massive graviton?

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

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



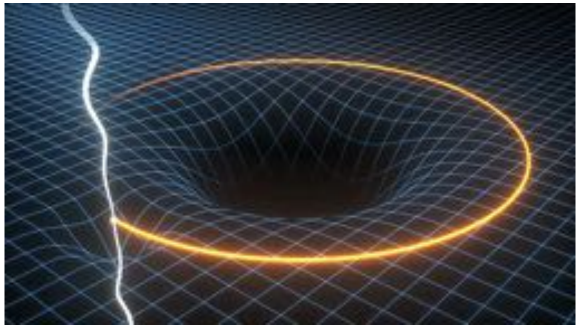
Lee et al. (2010)

Exploring gravity – with radio astronomy

- Introduction
- Pulsars & binaries: testing GR and its alternatives
- Pulsar Timing Arrays (PTAs): detecting GWs
- Event Horizon Telescope/BlackHoleCam: imaging a BH
- Conclusions

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:

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

[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%

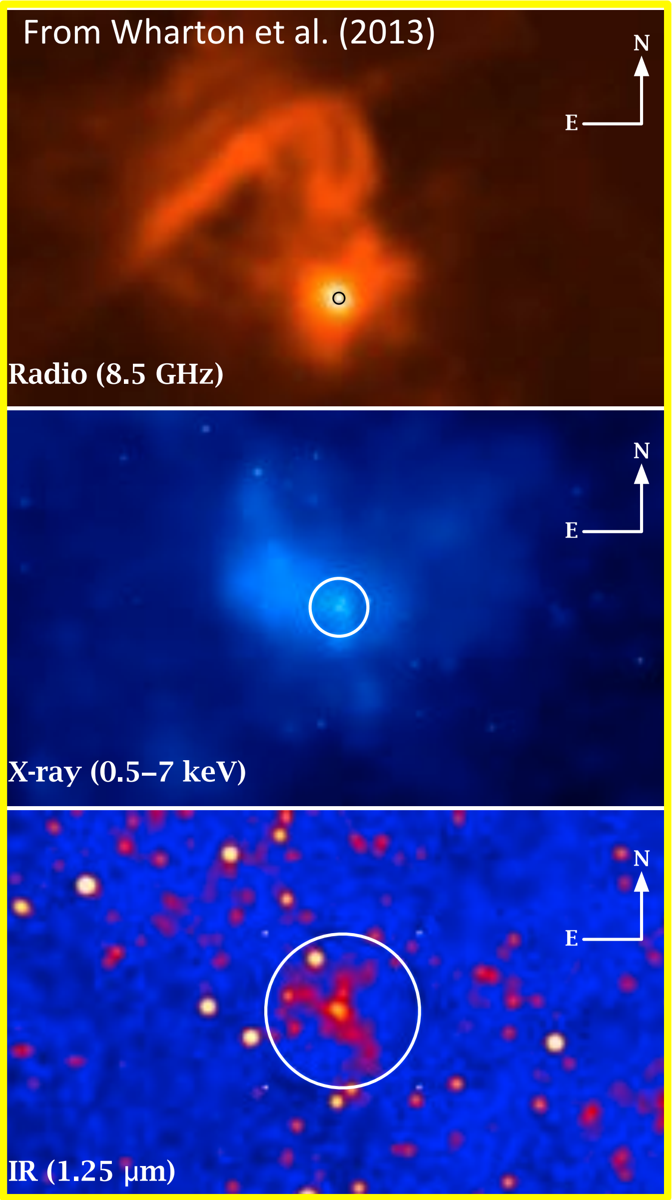
BH spin with precision < 1%

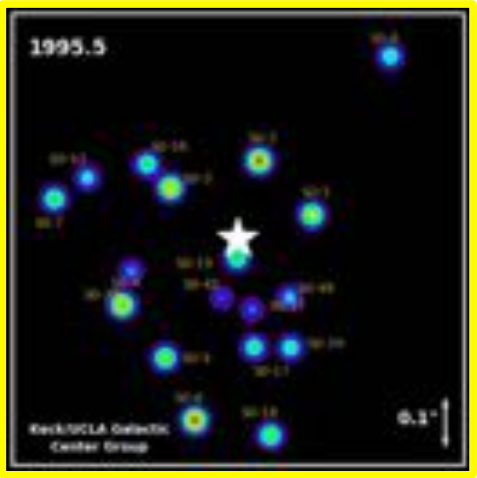
Cosmic Censorship: $S < GM^2/c$

Where or how do we find one?

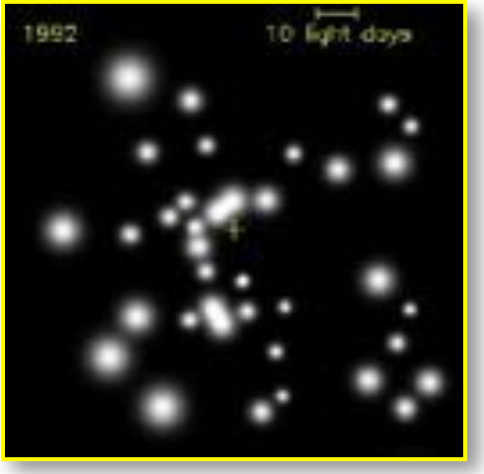
- Find "all" pulsars with the SKA
- or look where you know a black hole to be...

A well-known super-massive Black Hole





UCLA



MPE/Cologne

From astrometry of orbiting stars::

[Gillesen et al. 2008]

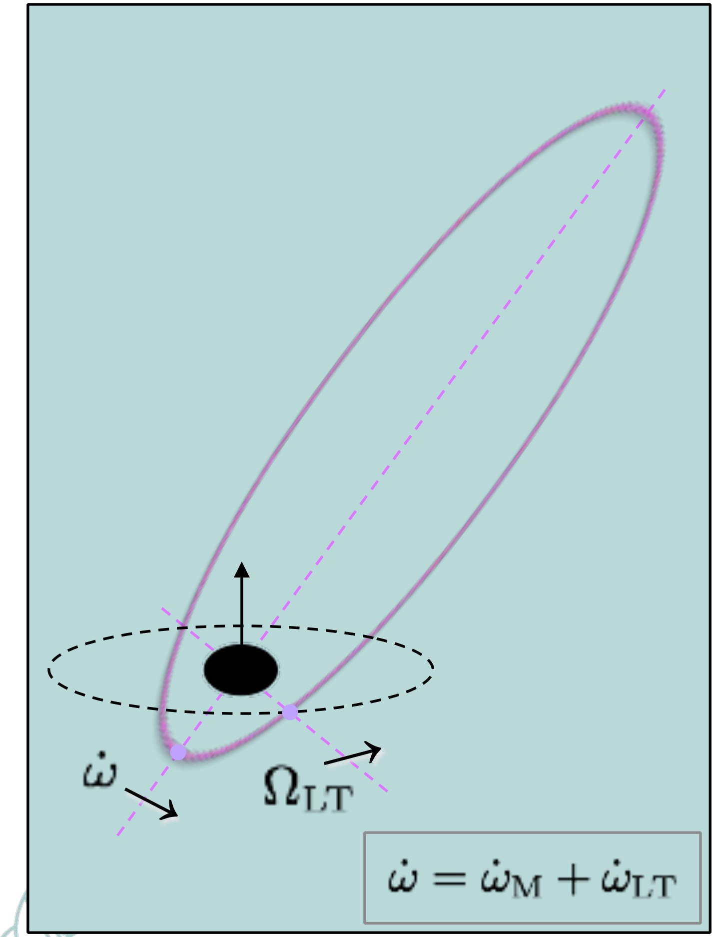
Mass: $\left(4.3 \pm 0.2_{(\mathrm{stat})} \pm 0.3_{(\mathrm{sys})}\right) \times 10^6\, M_\odot$

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, $\Delta L \sim 1.8$ AU/yr
2pN: 0.014 deg/yr, $\Delta L \sim 1{,}400{,}000$ km/yr

Einstein delay:
1pN: 15 min
2pN: 1.6 s

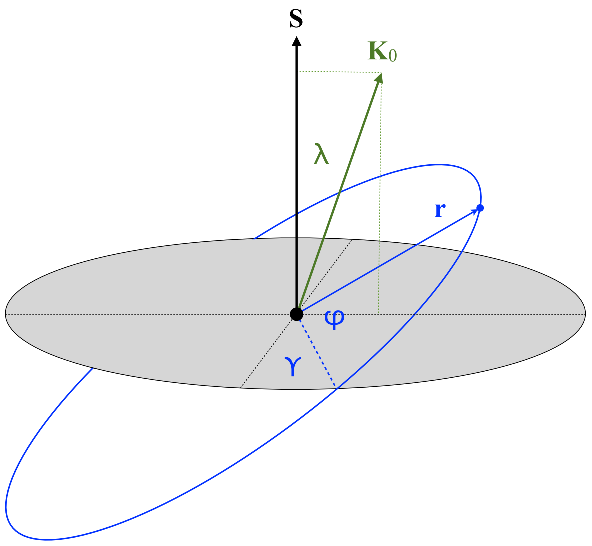
Propagation delay ($i = 0° / i = 80°$):
Shapiro 1pN: 46.4 s / 246.9 s
Shapiro 2pN: 0.2 s / 8.0 s
Frame dragging: 0.1 s / 6.5 s
Bending delay (P = 1s): 0.2 ms / 4.2 ms

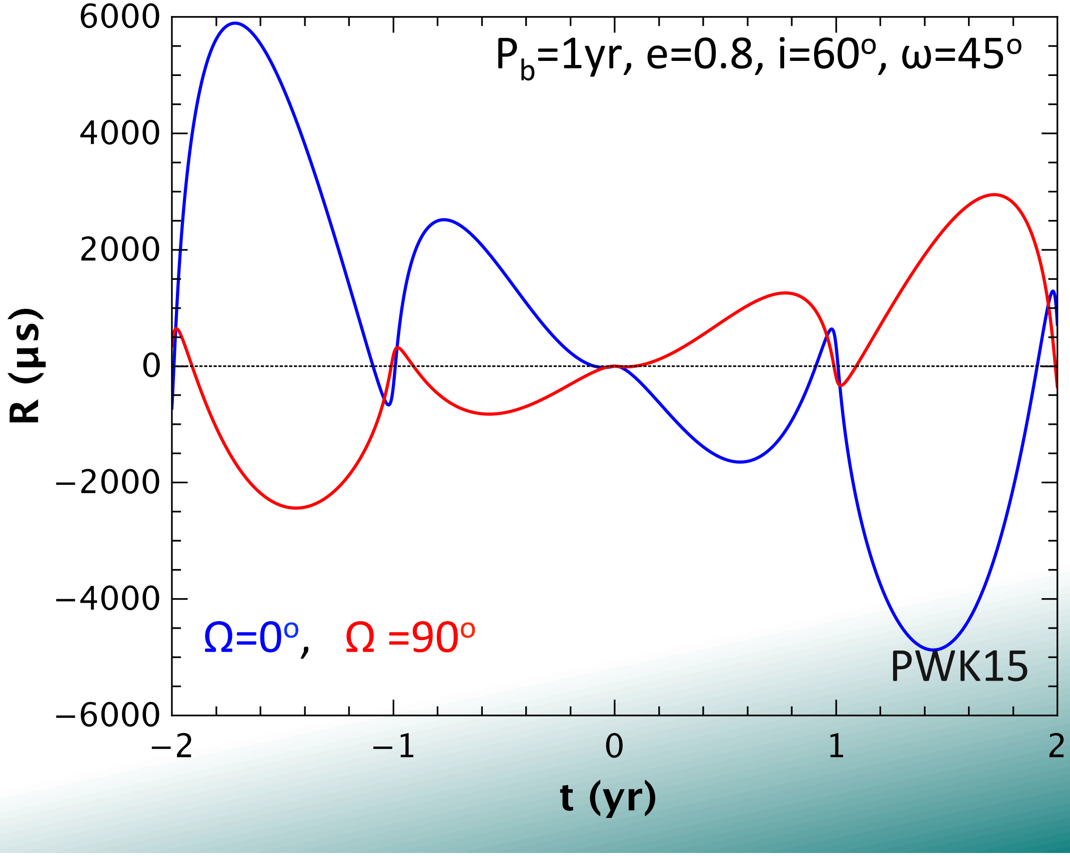
Lense-Thirring precession:
Orbital plane Ω_{LT} : 0.052 deg/yr, $\Delta L \sim 10^7$ km/yr
Similar contribution to $\dot{\omega}$
Geod. precession 1.4 deg/yr

Full 3D-direction of BH spin from pulsar orbit

- We can measure the mass of Sgr A* to precision of ~ $1M_\odot$
- 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 3-D orientation plus magnitude to about ~0.1%.



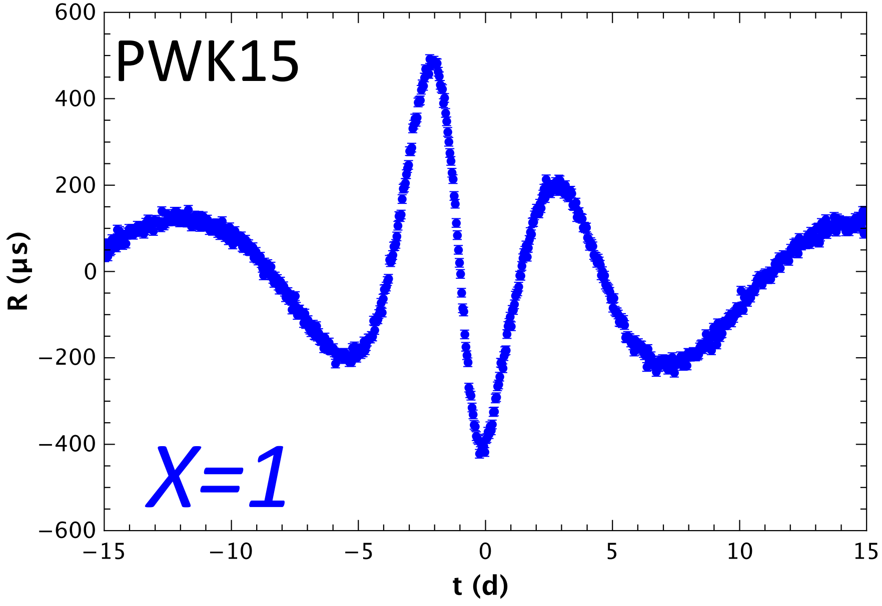


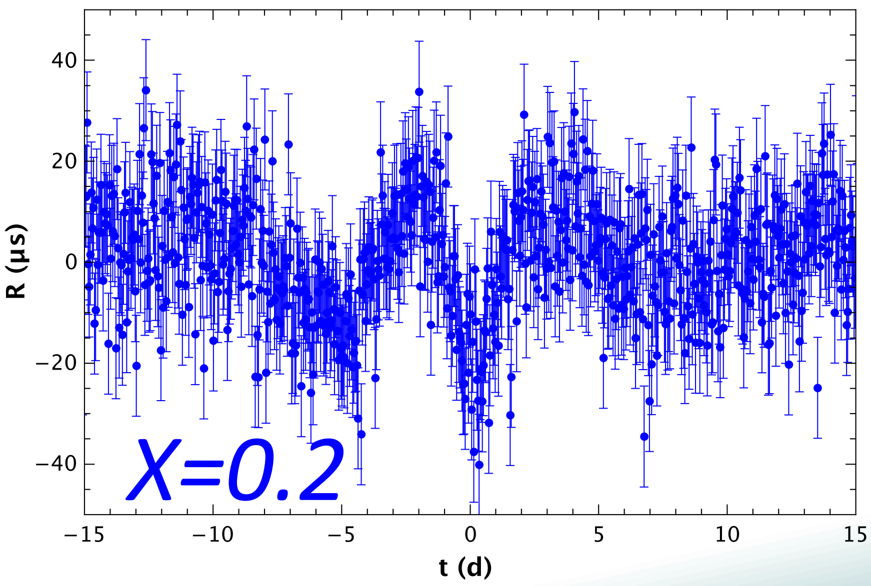
Testing the no-hair theorem

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, but it is not separable from frame-dragging
- Fortunately, quadrupole leads to *characteristic periodic residuals* ➔ Q to about 1%

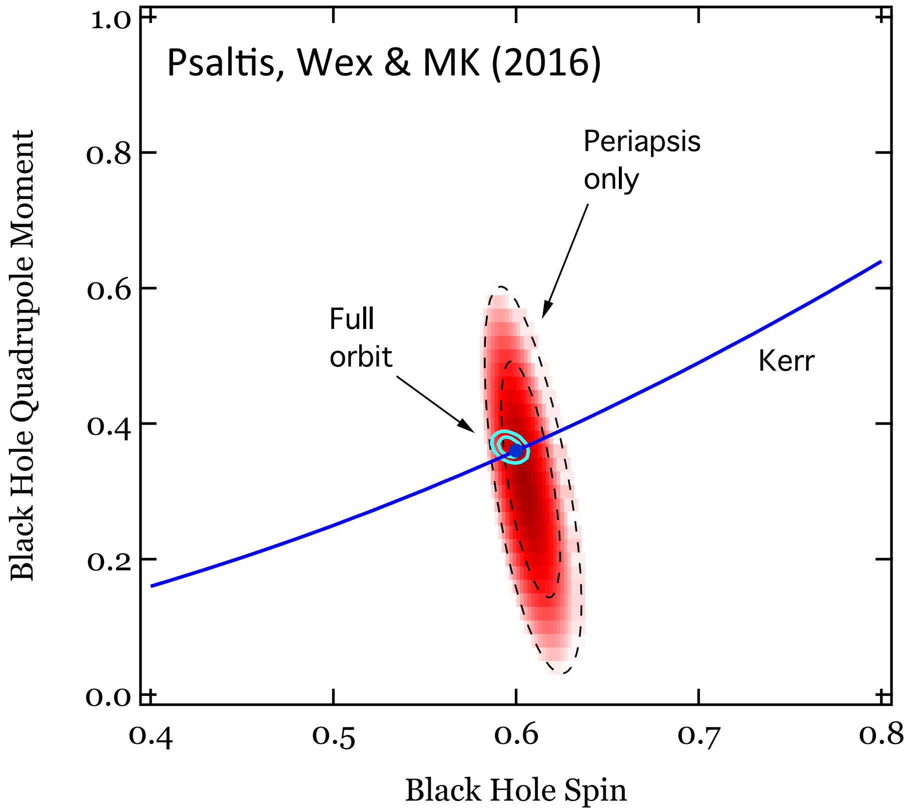




A single (even normal) pulsar is sufficient!

Partial visibility & External perturbations

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



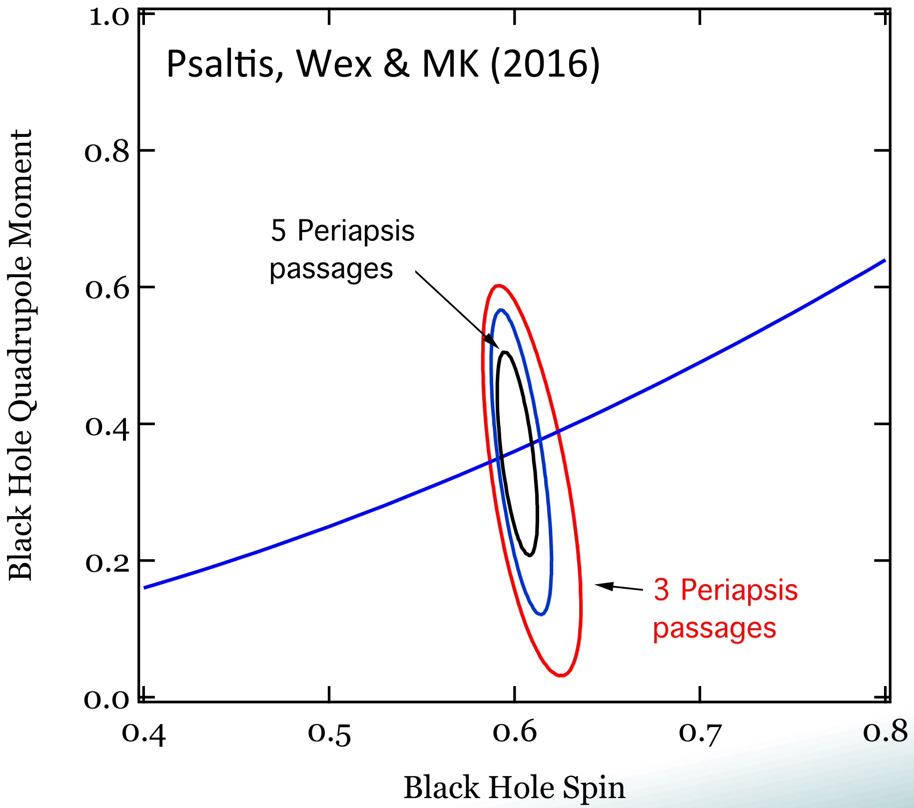
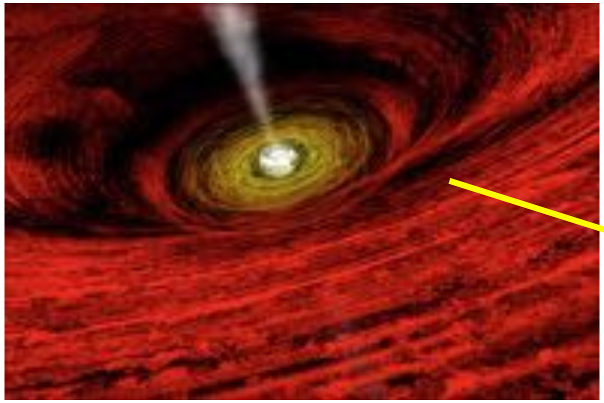


Image of the shadow of the event horizon



HOW TO See May's Western US Solar Eclipse

THE ESSENTIAL MAGAZINE OF ASTRONOMY

SKY & TELESCOPE

The Discovery Channel's Big Eye on the Sky

Einstein's Shadow

The quest for the first black hole image

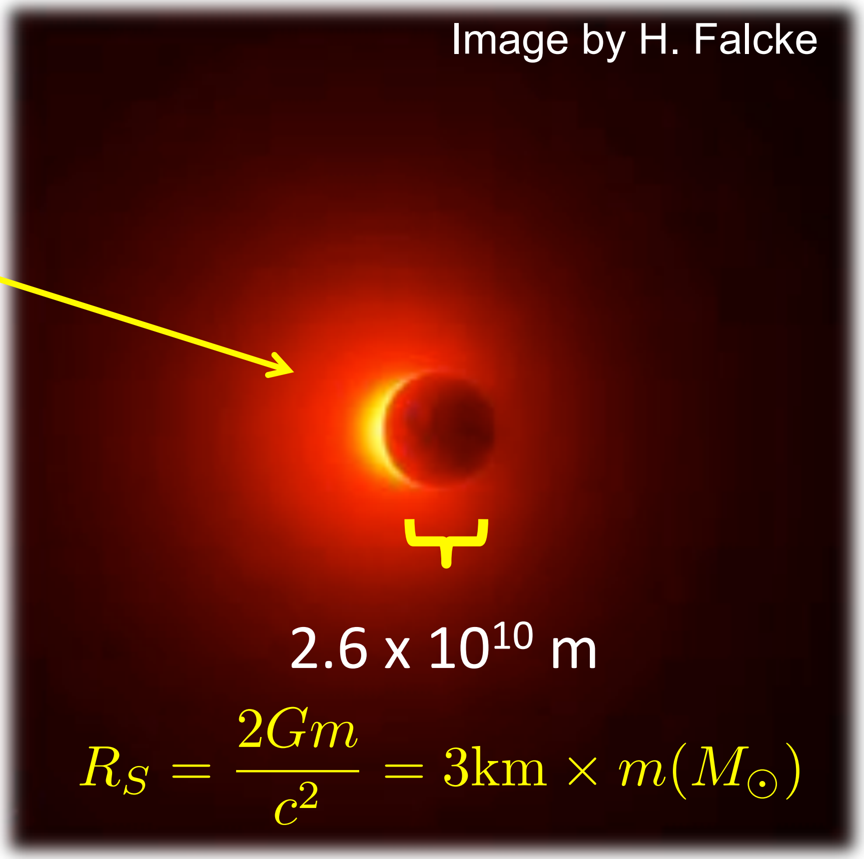


Image by H. Falcke

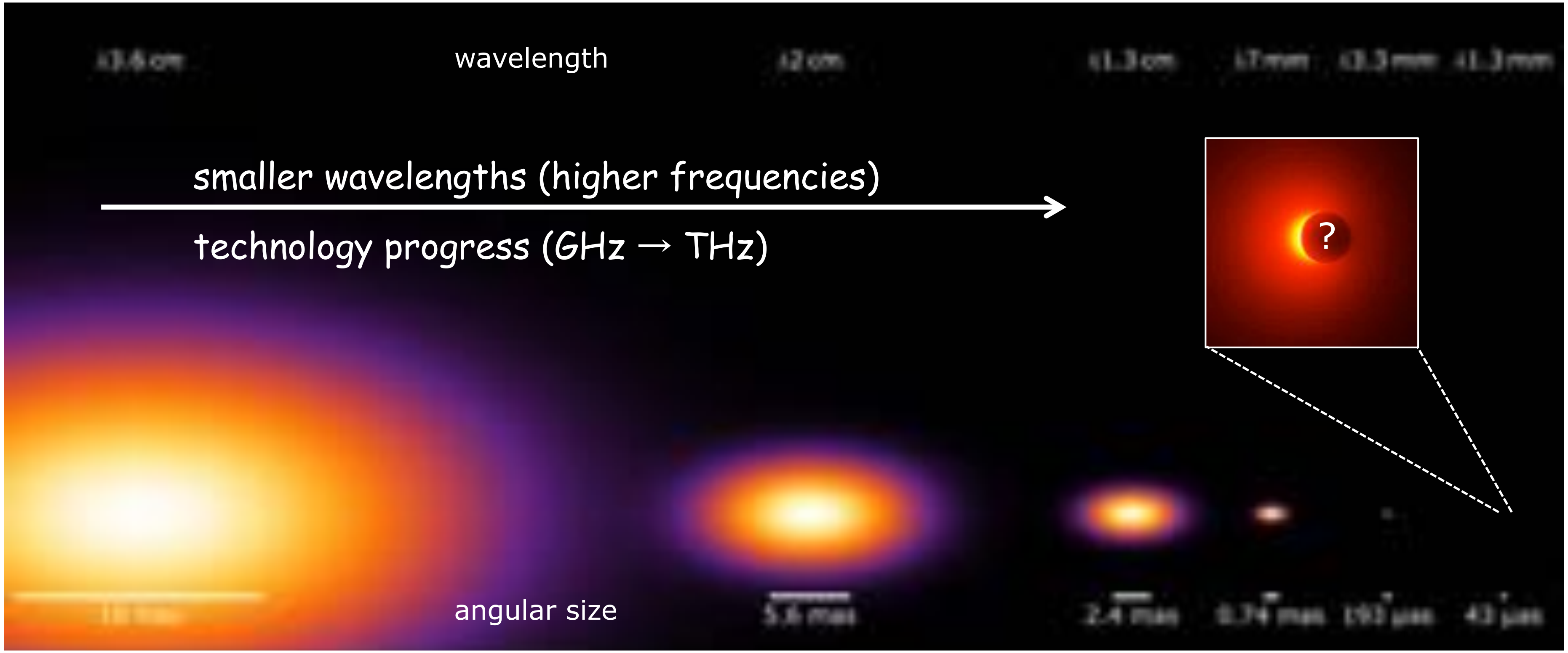
2.6 x 10^{10} m

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

Blocked in the optical – but visible at radio frequencies!

See Falcke et al. (2000) for the initial idea how,we could see the „shadow“

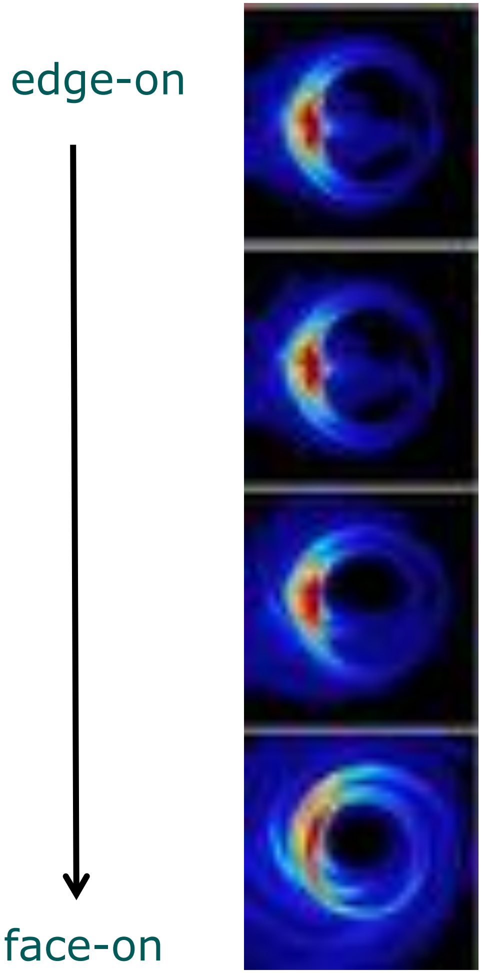
Image of the shadow of the event horizon



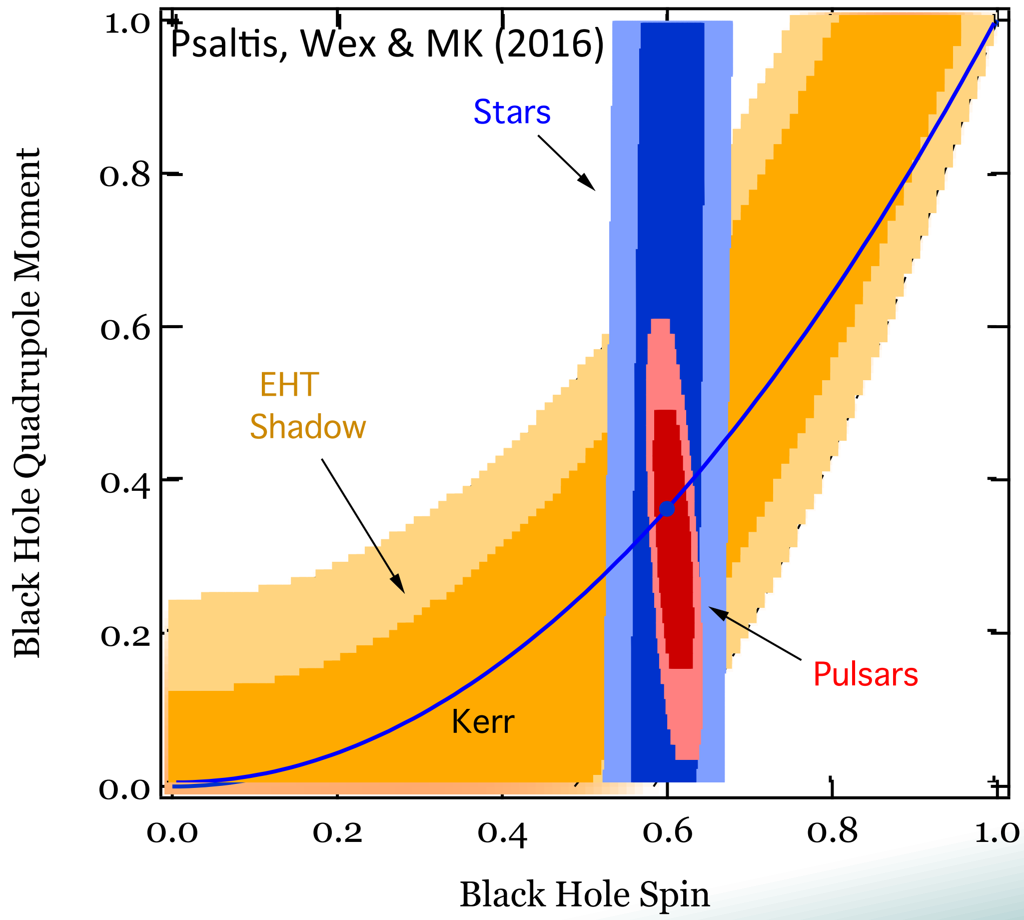
- the shorter the wavelength, the smaller the radio source (scattering!)
- at λ=1.3 mm the radio source becomes the size of the event horizon:
- the event horizon shadow should be 50 µas in diameter
- global mm-wave VLBI (EHT) with ALMA has the resolution to study it
- see Dimitiris talk!

Combining pulsars with other methods

From Event Horizon Telescope/BlackHoleCam imaging observations:



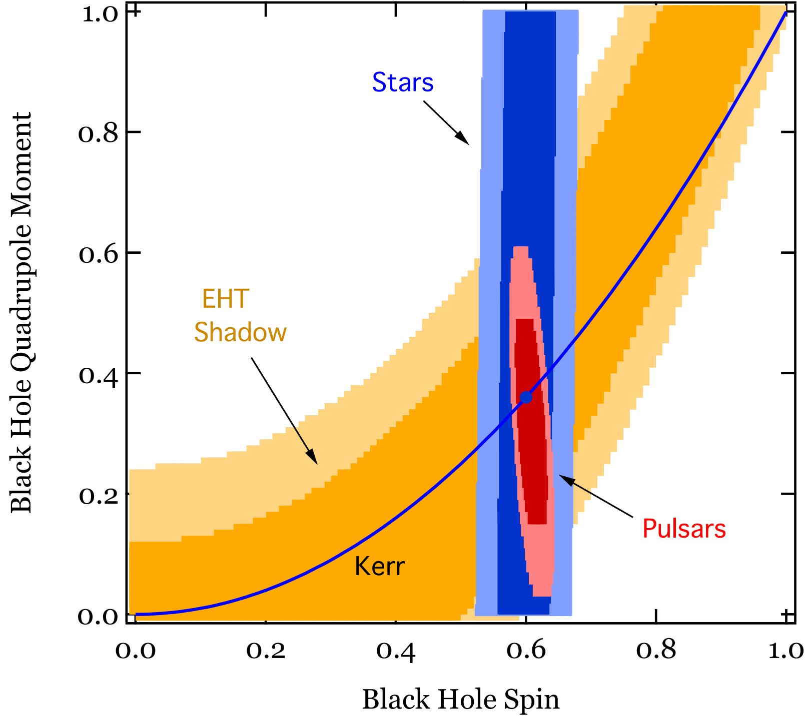
Moscibrodzka et al. (2014)

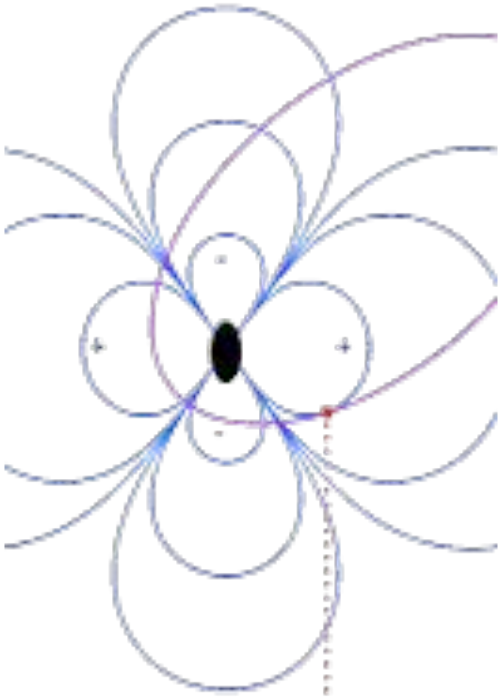


BHC funded by ERC Synergy Grant:

PIs Falcke, Kramer, Rezzolla

Combining image and pulsars


Psaltis, Wex & MK (2016)

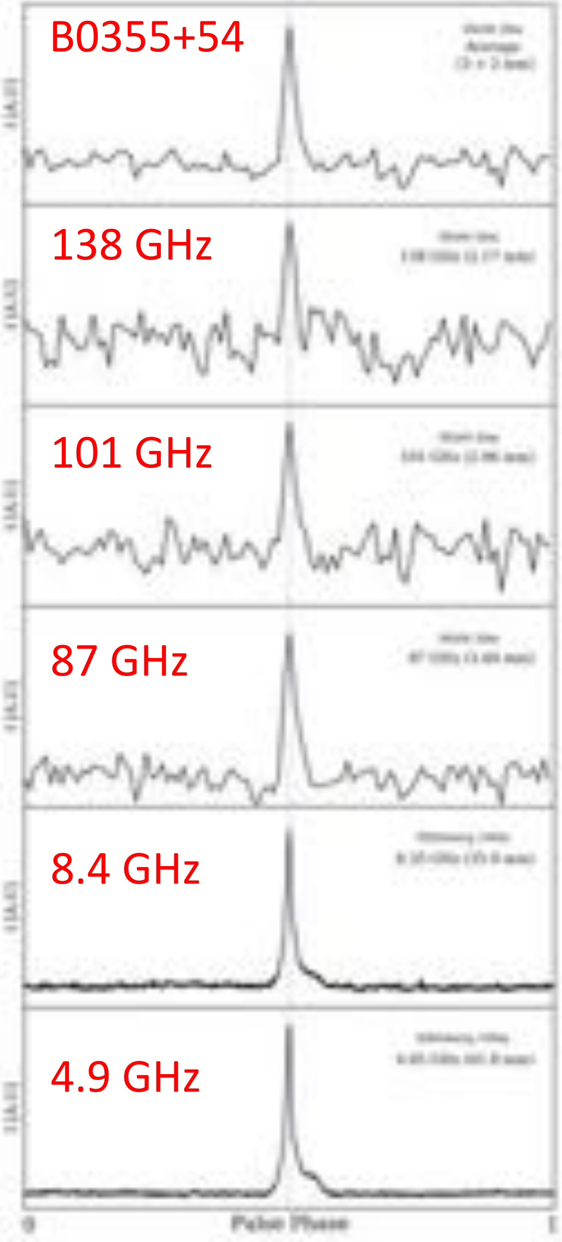


- Space time is probed at different distances (far-field & near-field)
- Impact of possible dark matter near BH will be seen.
- Different systematic uncertainties (and degeneracies):
  - \- Stars + pulsar orbit precession give spin
  - \- Pulsar timing gives quadrupole moment
  - \- EHT shadow may reveal deviation from Kerr value

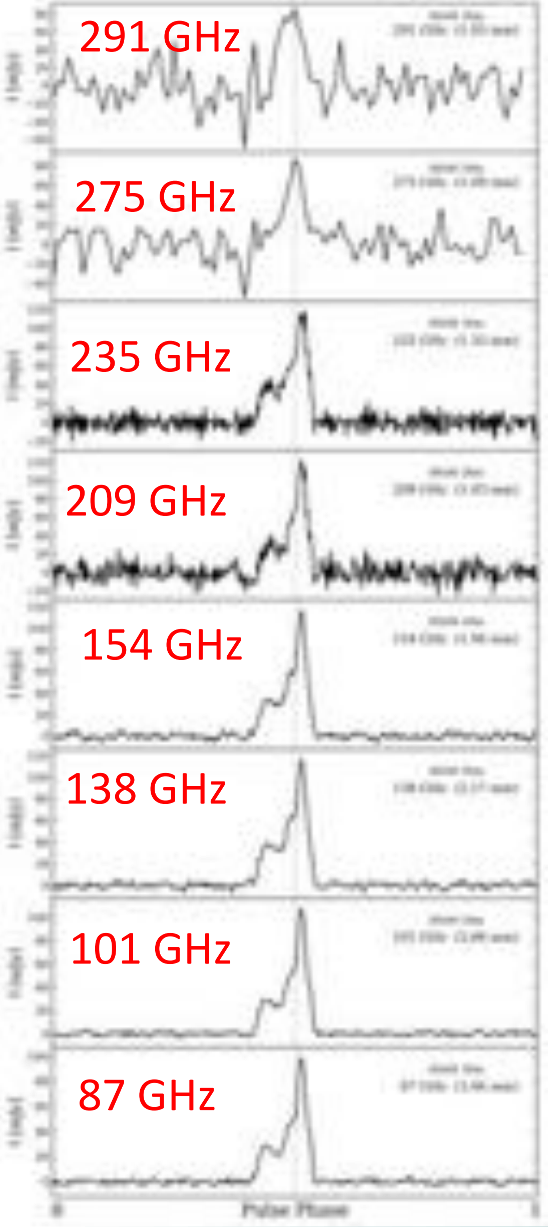
Combination will lead to uncorrelated measurement of spin and quadrupole moment

Pulsars at high frequencies and the Galactic Centre

Torne et al. (2015, 2016)



GC Magnetar



Working on ALMA:

Summary

- Unfortunately, Einstein did not live to see discovery of pulsars – and their usage
- Pulsars probe gravity for strongly self-gravitating bodies providing unique tests
- Measurements are usually clean and precise – confirming GR so far
- Tight constraints on alternative theories which need to pass binary pulsar tests
- We have seen new never-seen-before relativistic effects in the Double Pulsar
- New "most-relativistic" binary pulsar discovered – stay tuned
- Beautiful new results for relativistic spin-precession – stay tuned
- 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 MeerKAT & SKA - will allow so much more!