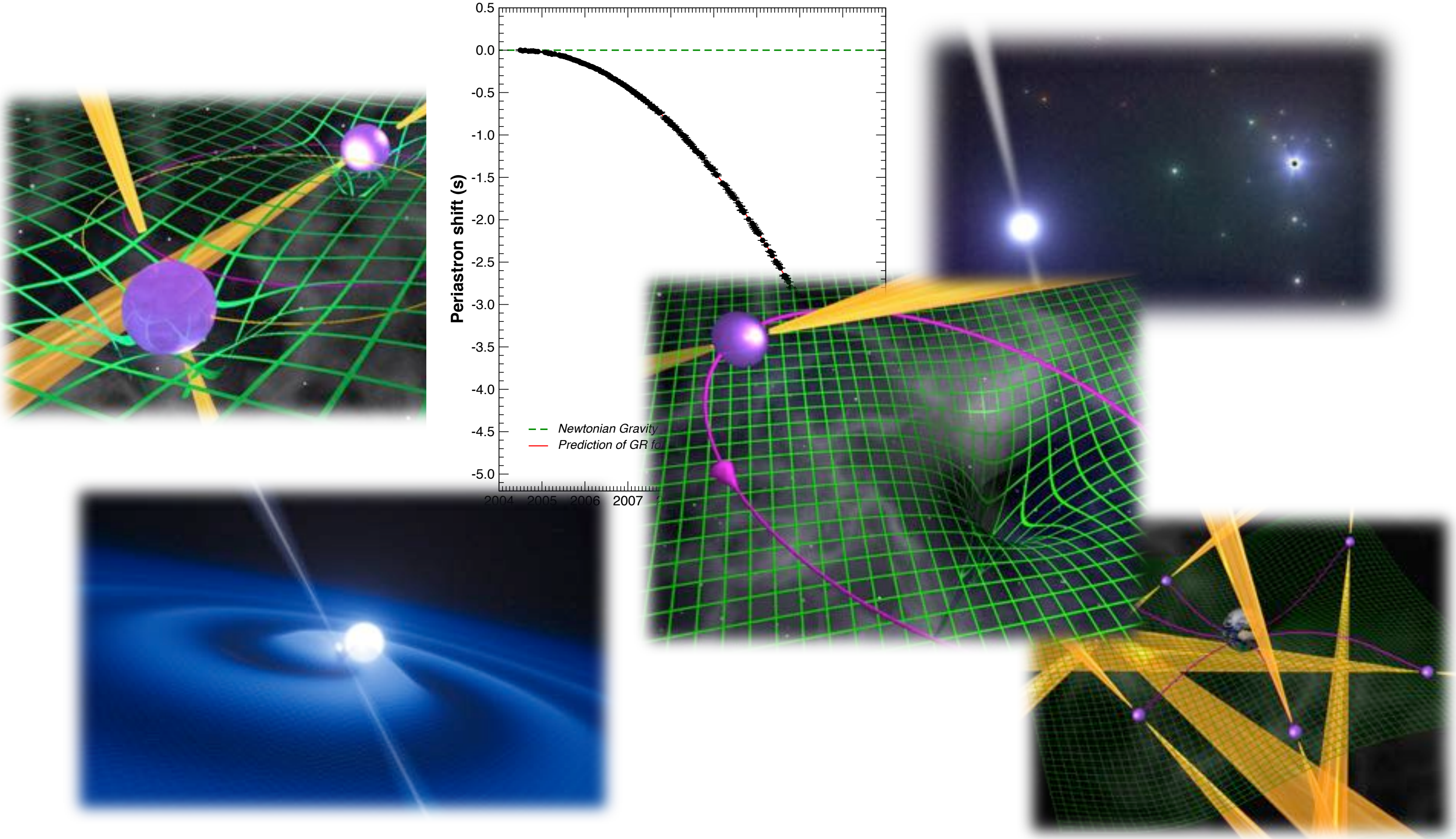
Experimental tests of general relativity in binary systems



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Outline

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

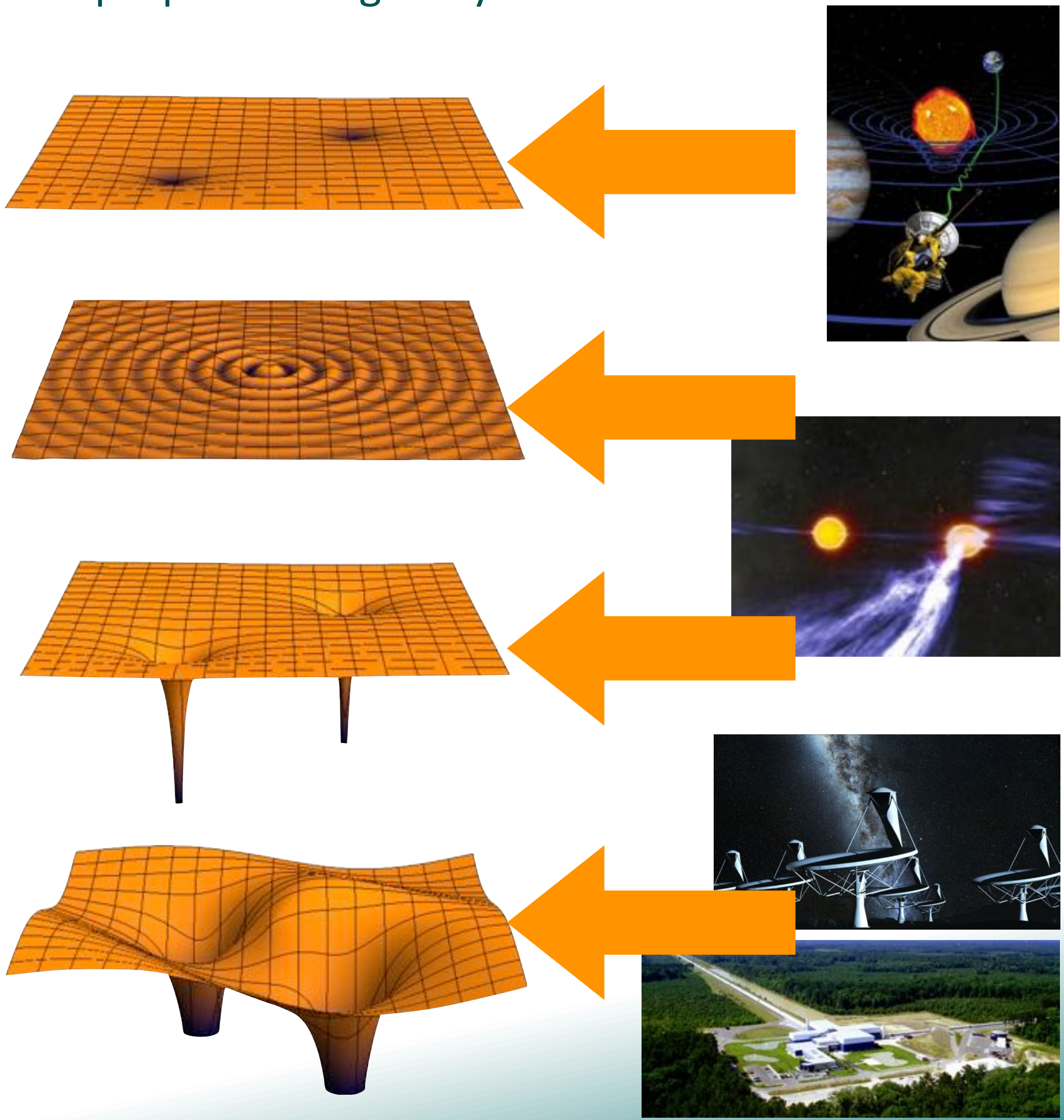
- We need clean tests where gravity is strong and non-linear.
- We must test the radiative properties of gravity.

Quasi-stationary weak-field regime

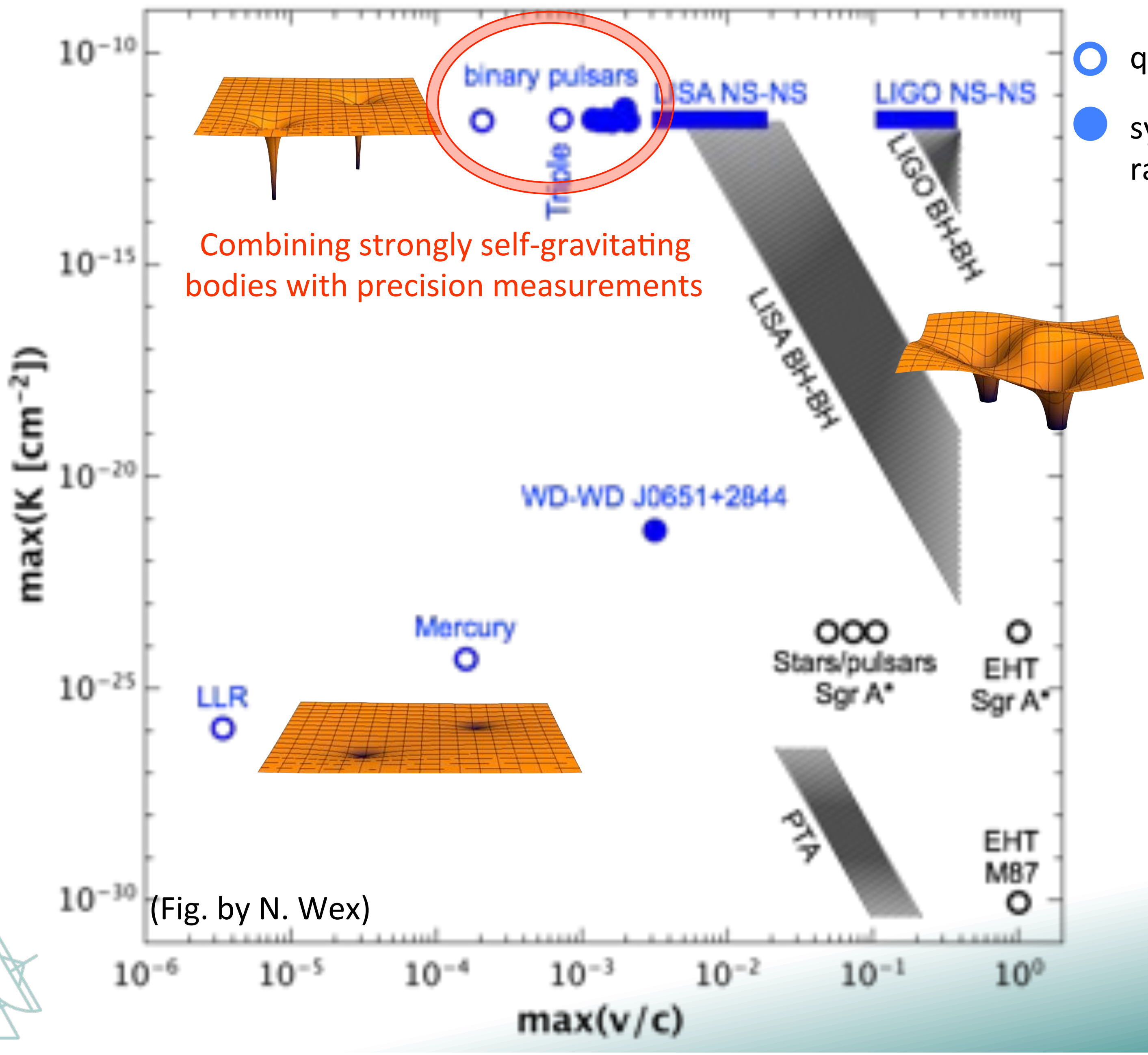
Quasi-stationary strong-field regime

Radiative regime

Highly relativistic regime



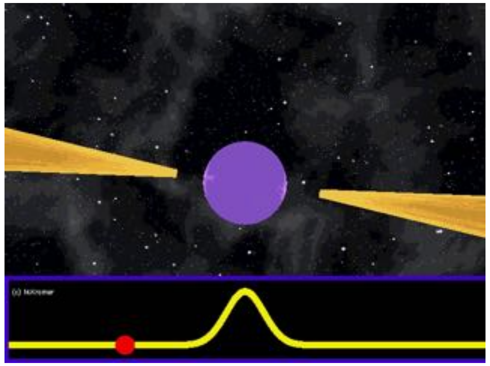
Binary system tests



quasi-stationary tests

system provides (also) a radiative test

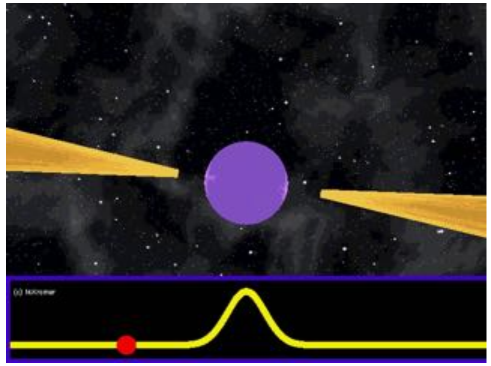
Pulsars…

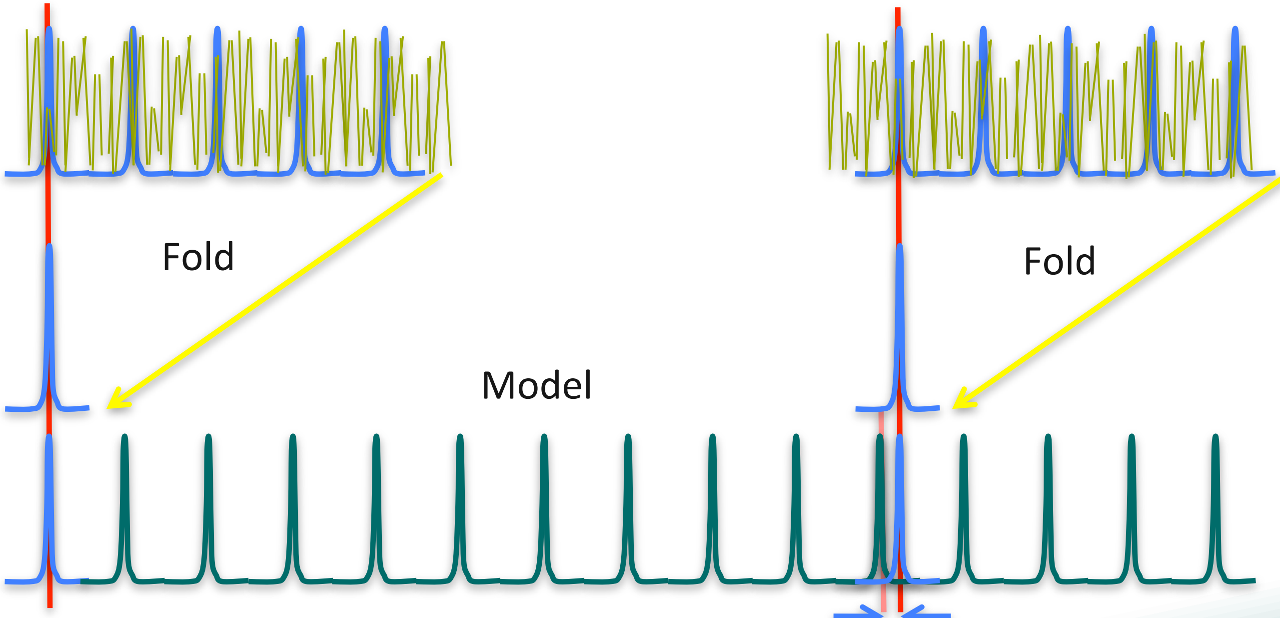


- …almost black holes
- …objects of extreme matter:
  - 10 x nuclear density
  - $B \sim B_{cr} = 4.4 \times 10^9$ Tesla
  - Electr. fields ~ 10^{12} Volt
  - $F_{EM} = 10^{11} F_{gravitation}$
  - high-temperature superfluid superconductor
  - Very stable rotators
  - Excellent clocks!

Pulsar timing: a simple and clean experiment…

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)

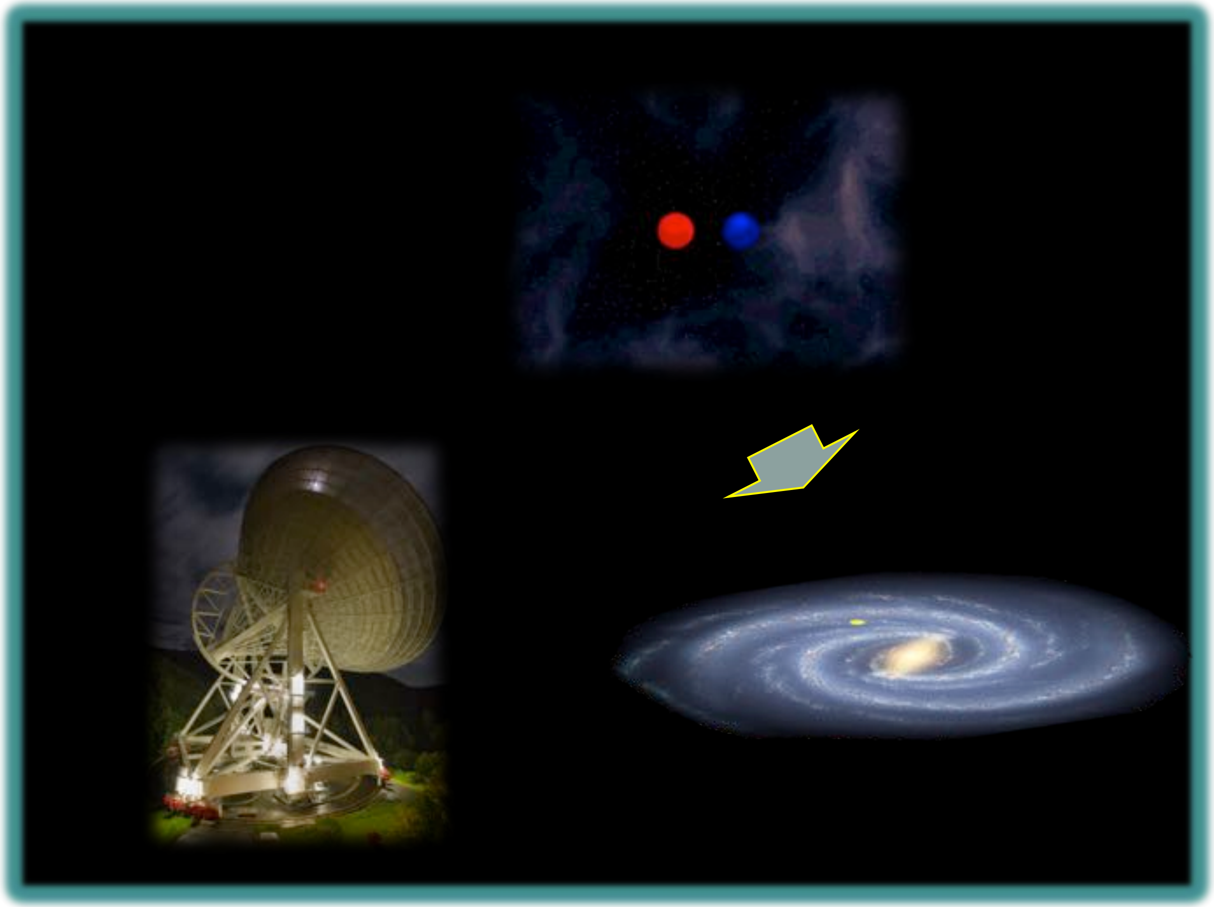
Companions

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: $3.5\ (1.1) \times 10^{-7}$ (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: $9.547921(2) \times 10^{-4}\ M_\odot$ (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: $(-0.6 \pm 1.1) \times 10^{-12}\ yr^{-1}$ (Zhu et al. 2015)

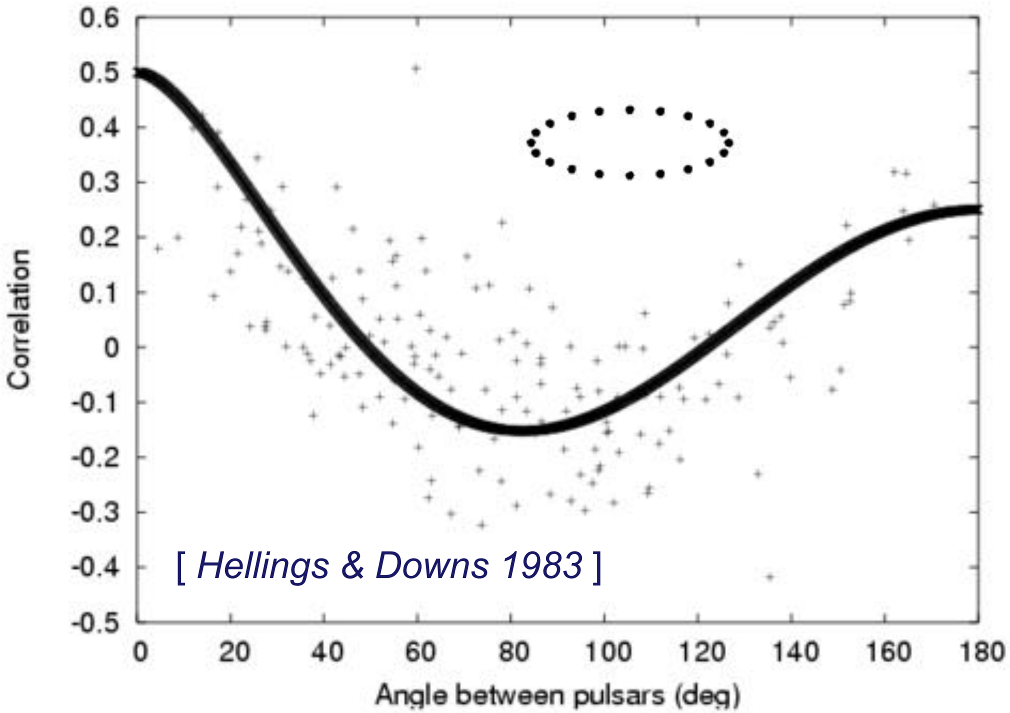
Gravitational wave detection:

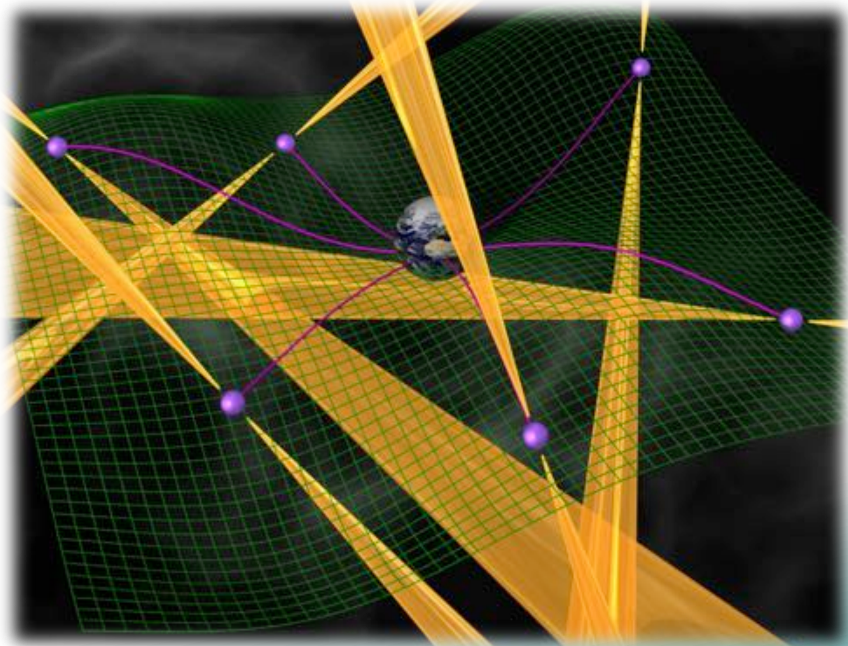
- Change in relative distance: 100m / 1 lightyear (EPTA, NANOGrav, PPTA)

Pulsars as Gravitational Wave Detectors

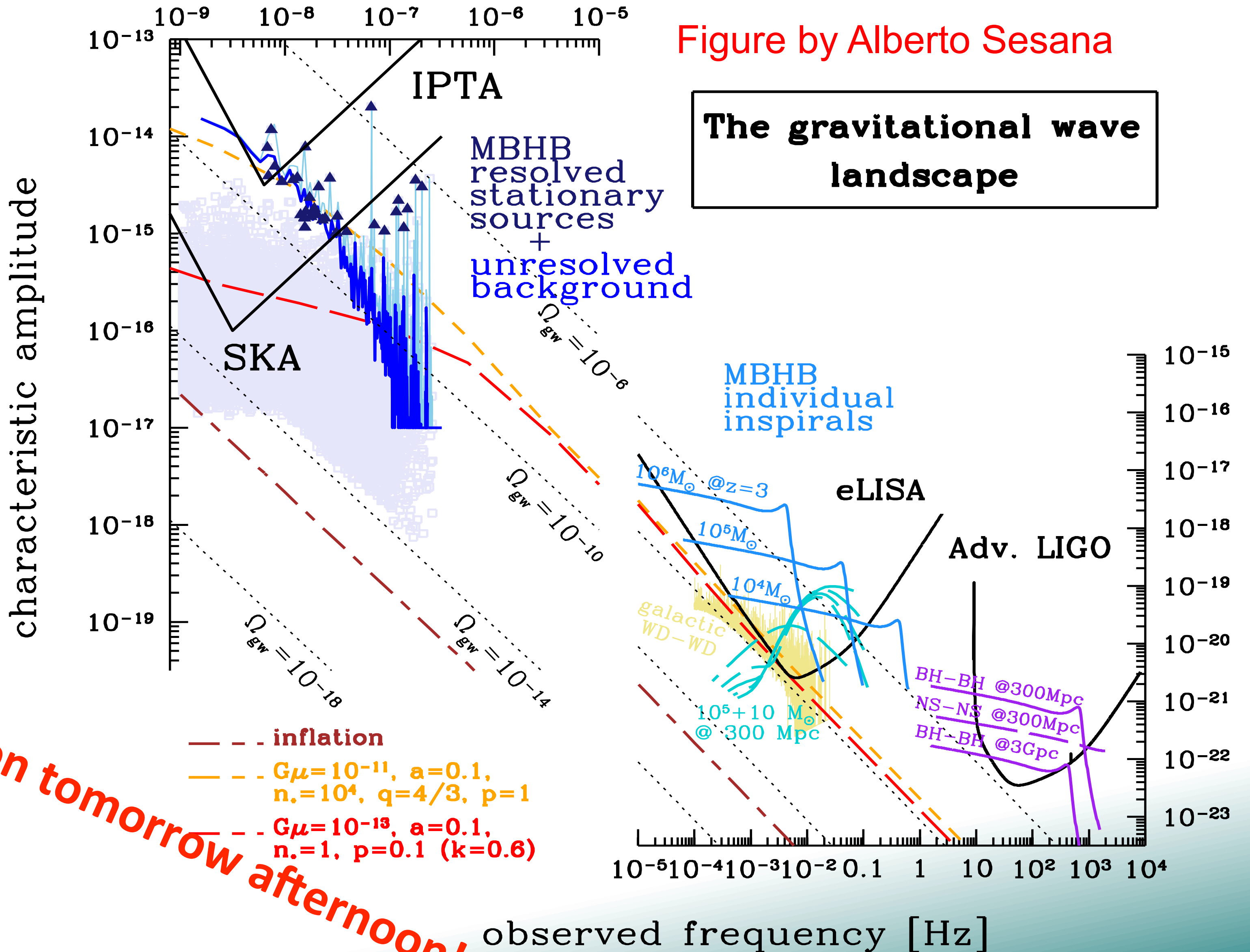
Pulse arrival times will be affected by low-frequency gravitational waves – correlated across sky!

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



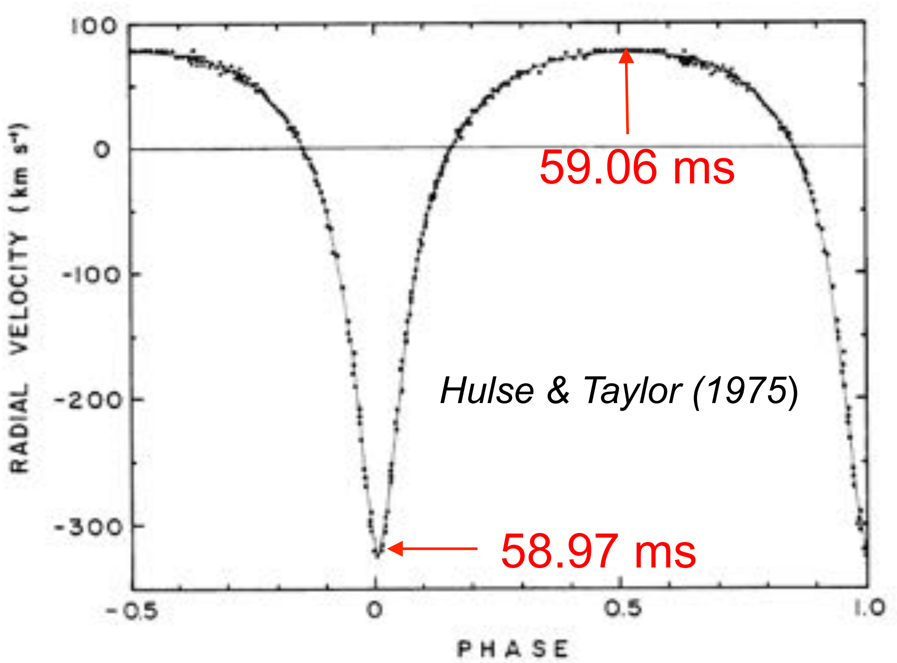


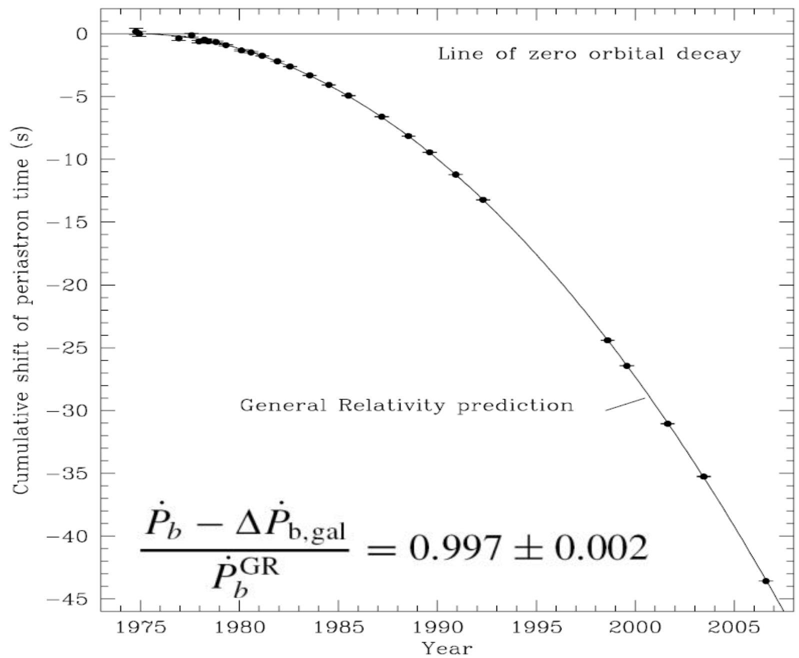
Pulsar Timing Arrays in the GW Landscape

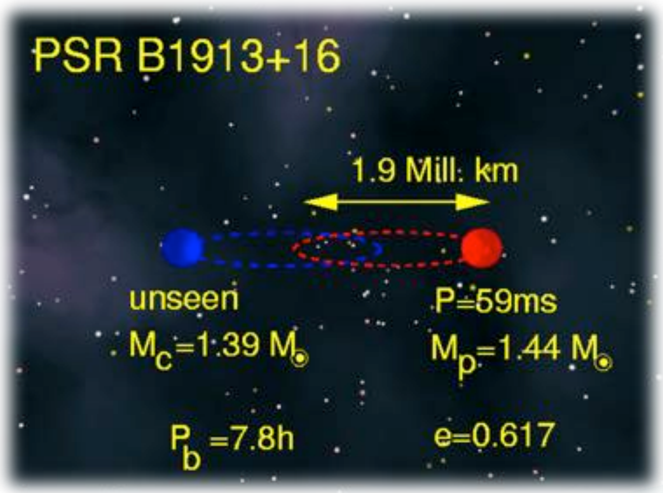


See session tomorrow afternoon!

The first binary pulsar: Hulse-Taylor pulsar

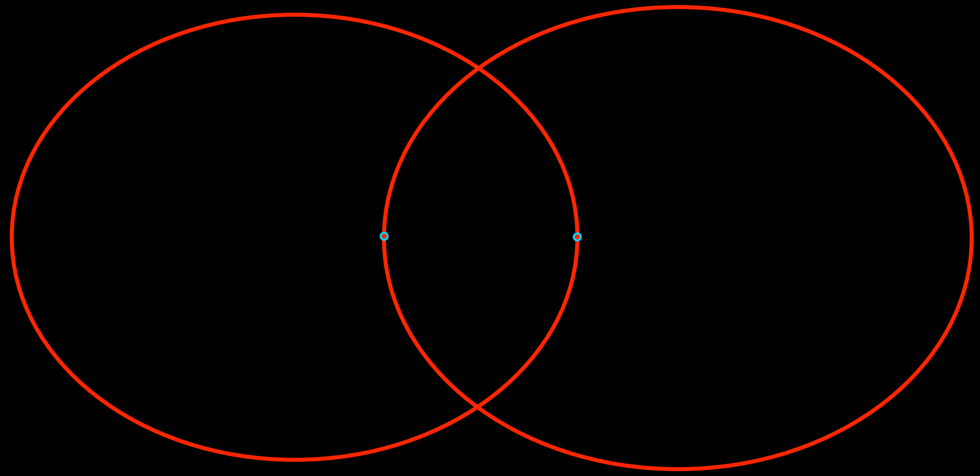




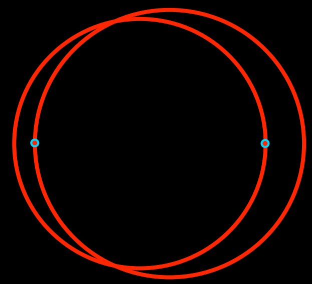


Comparison Hulse-Taylor vs Double Pulsar

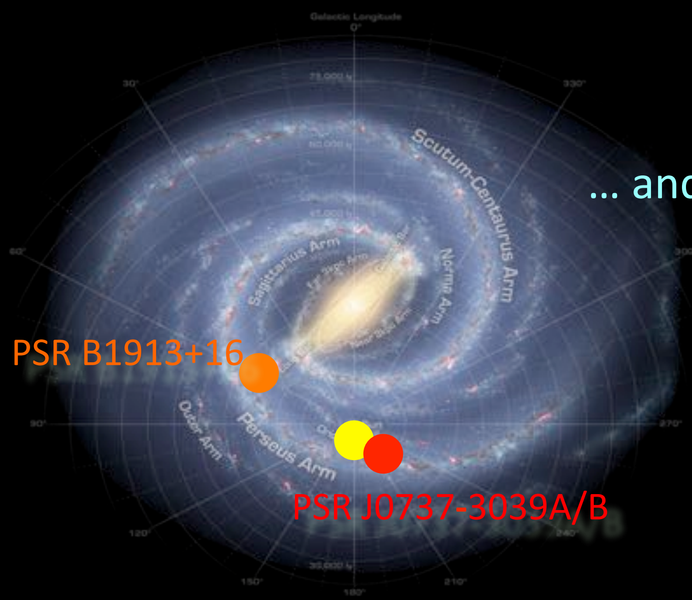
PSR B1913+16



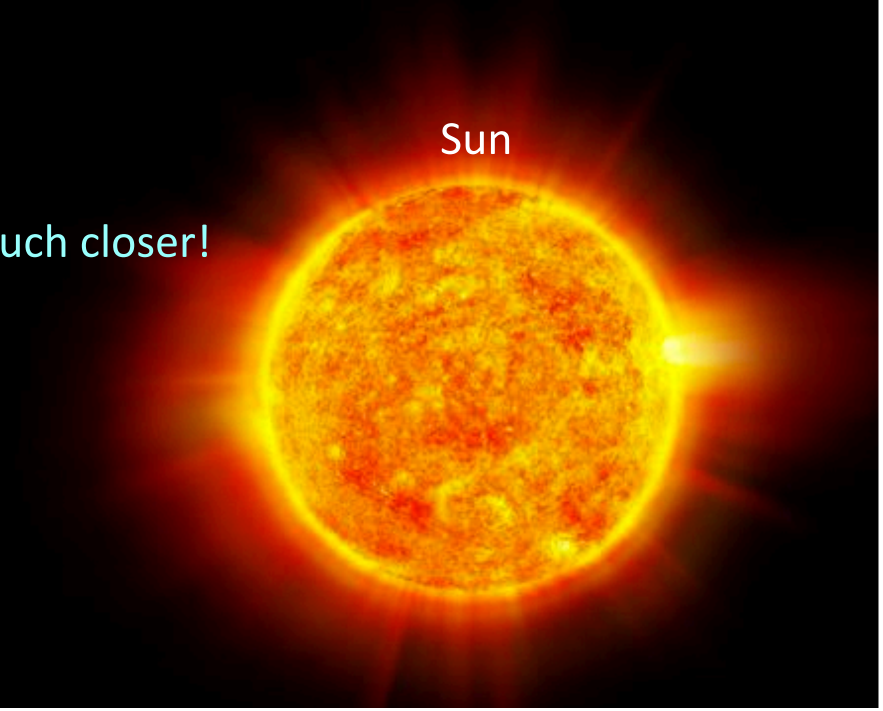
PSR J0737-3039A/B



More compact…



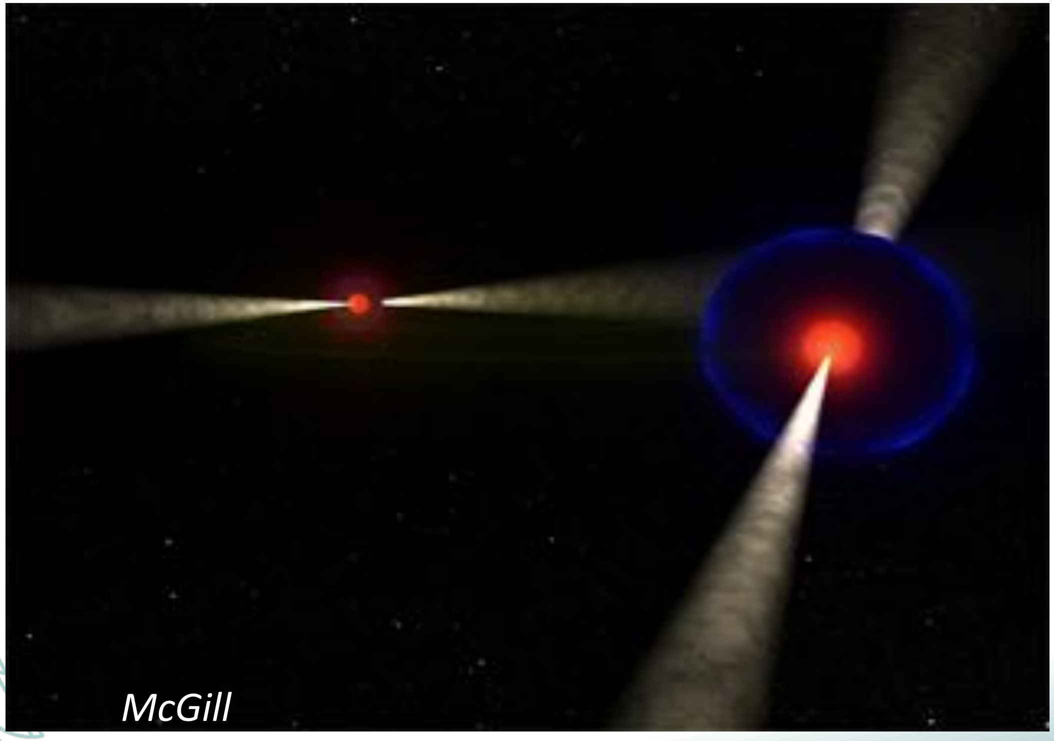
… and much closer!



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.)

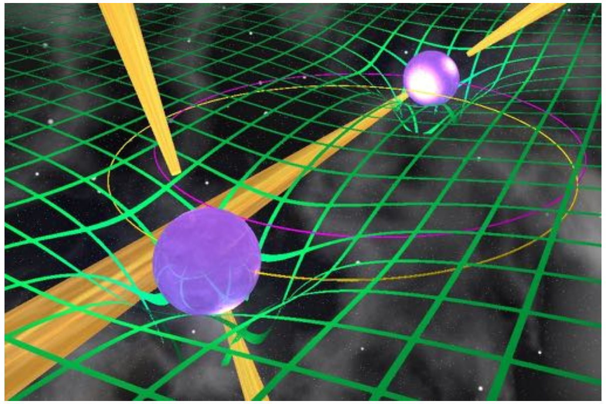


Collaborators:

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

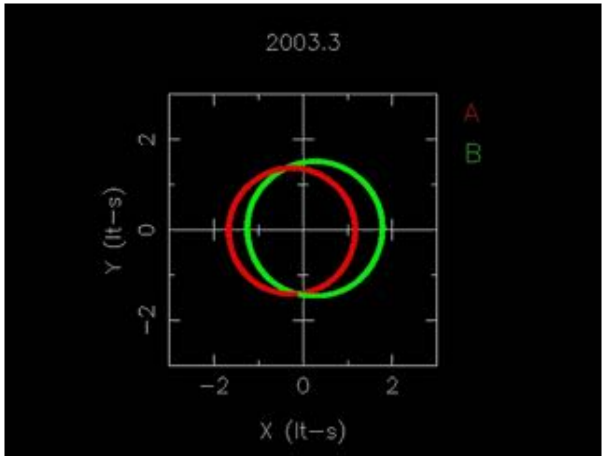
- We can measure two orbits ➔ mass ratio



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

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):

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

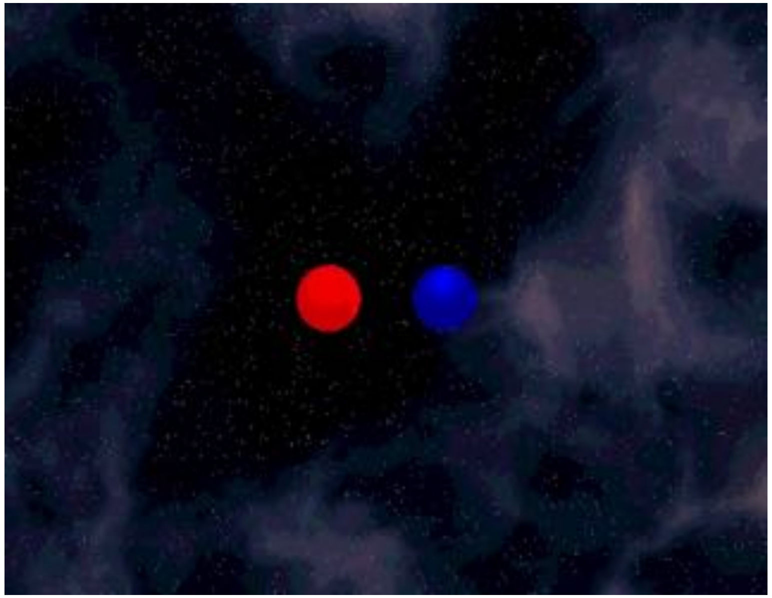
& $m_B = (1.2489 \pm 0.0007)\ M_\odot$

Newest measurement: dω/dt = 16.89931(2) deg/yr - error about 1/10 x 2PN!

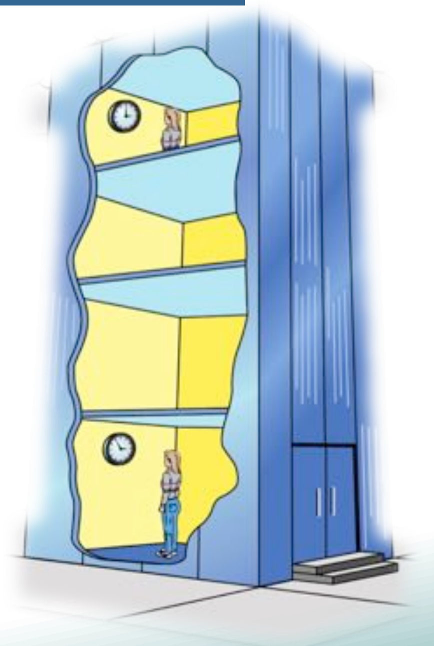
Double Pulsar: five tests in one system!

- 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!)



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

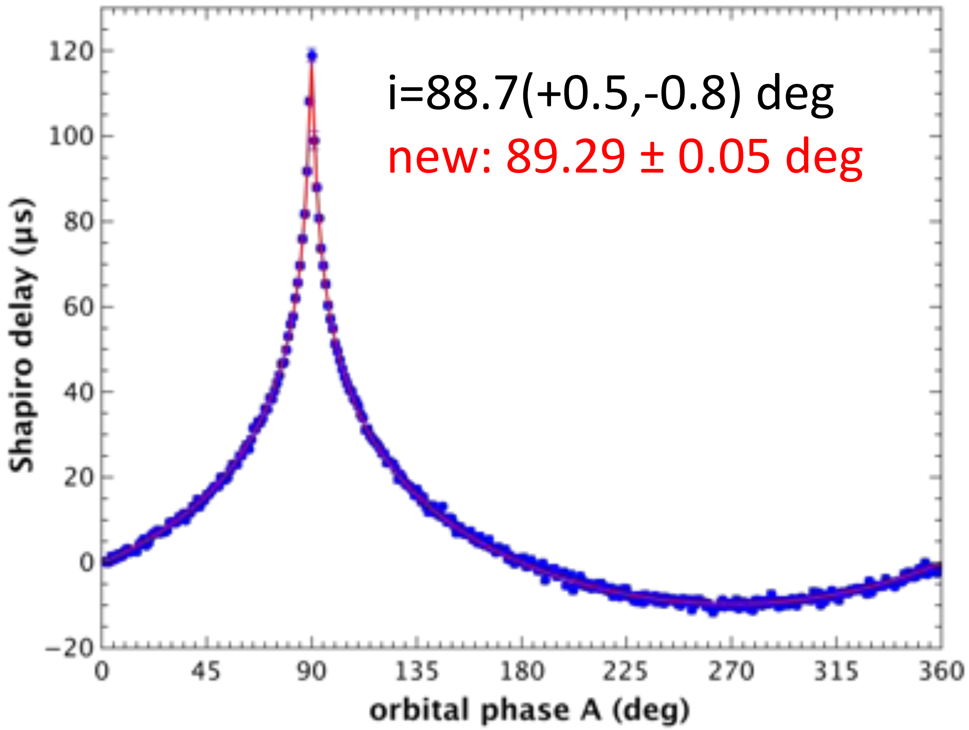


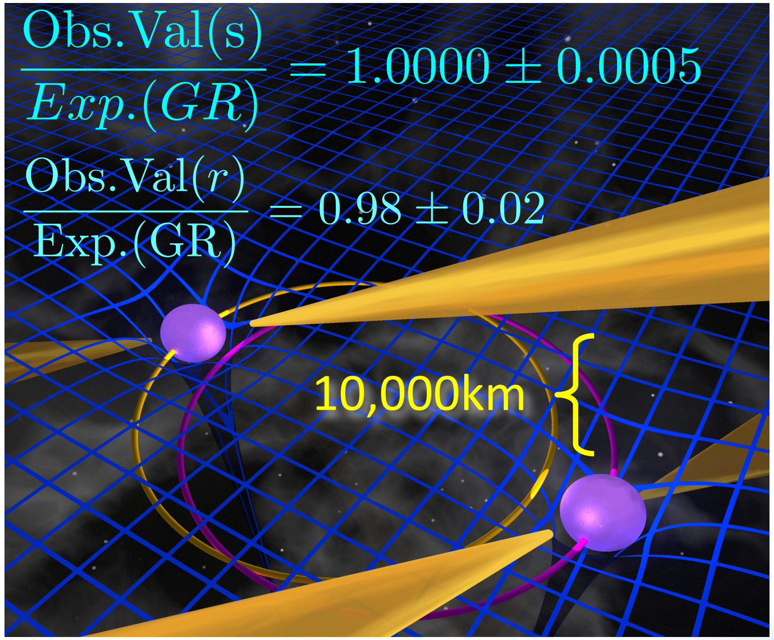
- As other clocks, pulsars run slower in deep gravitational potentials
- Changing distance to companion (and felt grav. potential) during elliptical orbit

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



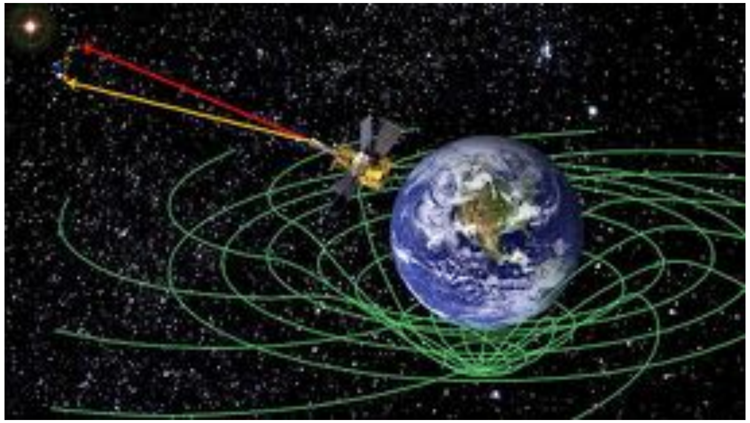


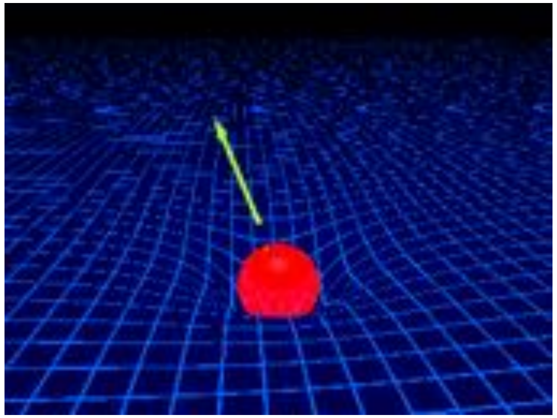
- At superior conjunction, pulses from pulsar A pass B in <10,000km distance
- Space-time near companion is curved ➔Additional path length

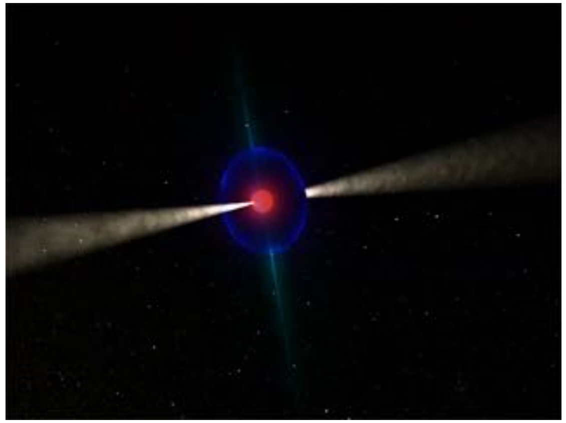
➔ Delay in arrival time – depending on geometry and companion mass

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: $s = \sin(i) = 0.999923 \pm 0.000012$
- Relativistic spin precession







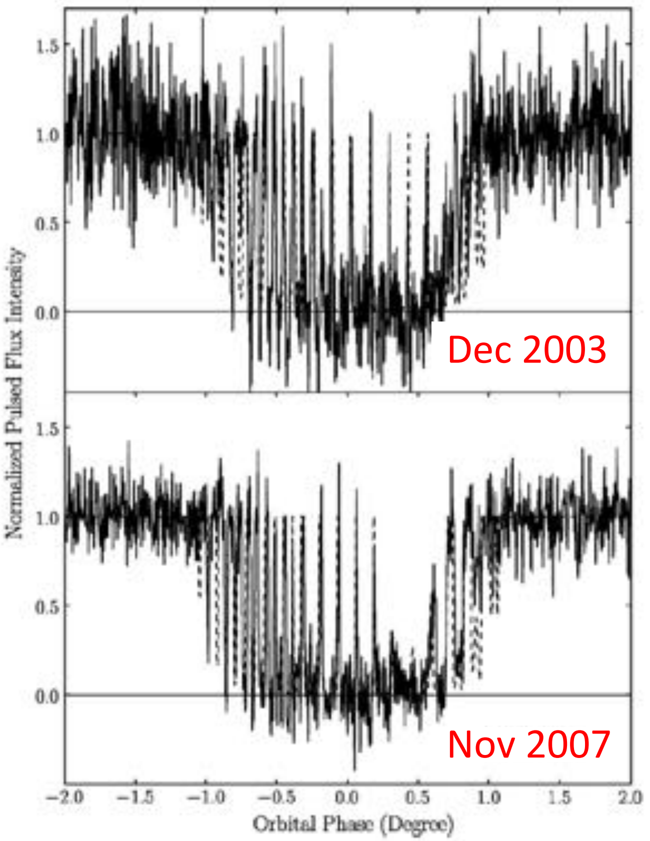
Experiments made in Solar System provide precise tests for this effect and confirm it,
e.g. gyro-experiments such as Gravity-Probe B

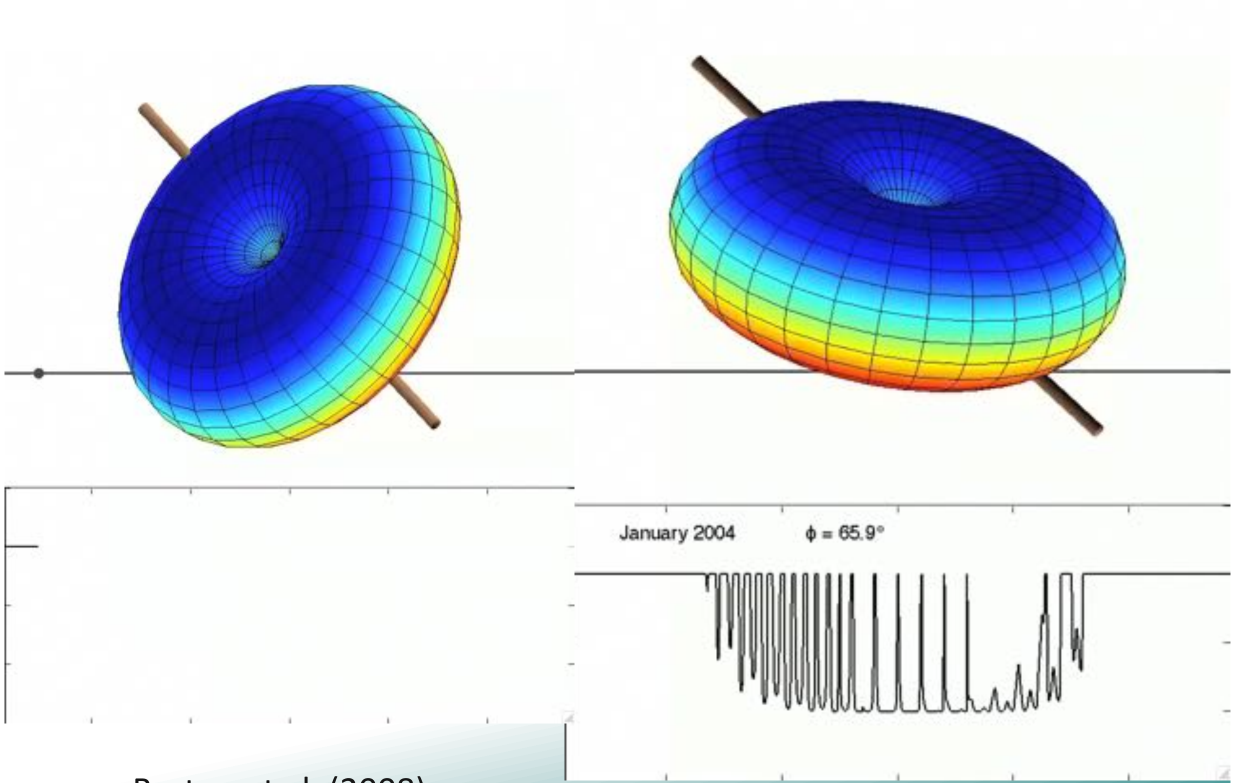
First seen for HT-Pulsar (Kramer'98) and PSR B1534+12 (Stairs et al. '04, Fonseca et al. '15),
...but no firm quantitative strong-field test until Double Pulsar

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!

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

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

- Merger in 85 Million years

Animation by NASA/Rezzolla/AEI

Precision will improve with time: superseding solar system tests soon

Combining all tests: a "mass-mass diagram"

Quasi-stationary strong field tests

Precession of periastron (17 deg/yr)

$$\dot{\omega} = 3\,\frac{G^{2/3}}{c^2}\left(\frac{2\pi}{P_b}\right)^{5/3}\frac{1}{1-e^2}\,(m_A+m_B)^{2/3}$$

Time dilation / Einstein delay (380 μs)

$$\gamma = \frac{G^{2/3}}{c^2}\left(\frac{P_b}{2\pi}\right)^{1/3} e\,\frac{m_B(m_A+2m_B)}{(m_A+m_B)^{4/3}}$$

Shapiro delay (130 μs)

$$r = \frac{G}{c^3}\,m_B \qquad s = \frac{c}{G^{1/3}}\left(\frac{2\pi}{P_b}\right)^{2/3} x_A\,\frac{(m_A+m_B)^{2/3}}{m_B}$$

Geodetic precession of B (5 deg/yr)

$$\Omega_B = \frac{G^{2/3}}{c^2}\left(\frac{2\pi}{P_b}\right)^{5/3}\frac{1}{1-e^2}\,\frac{m_A(4m_B+3m_A)}{2(m_A+m_B)^{4/3}}$$

Radiative tests (gravitational wave damping)

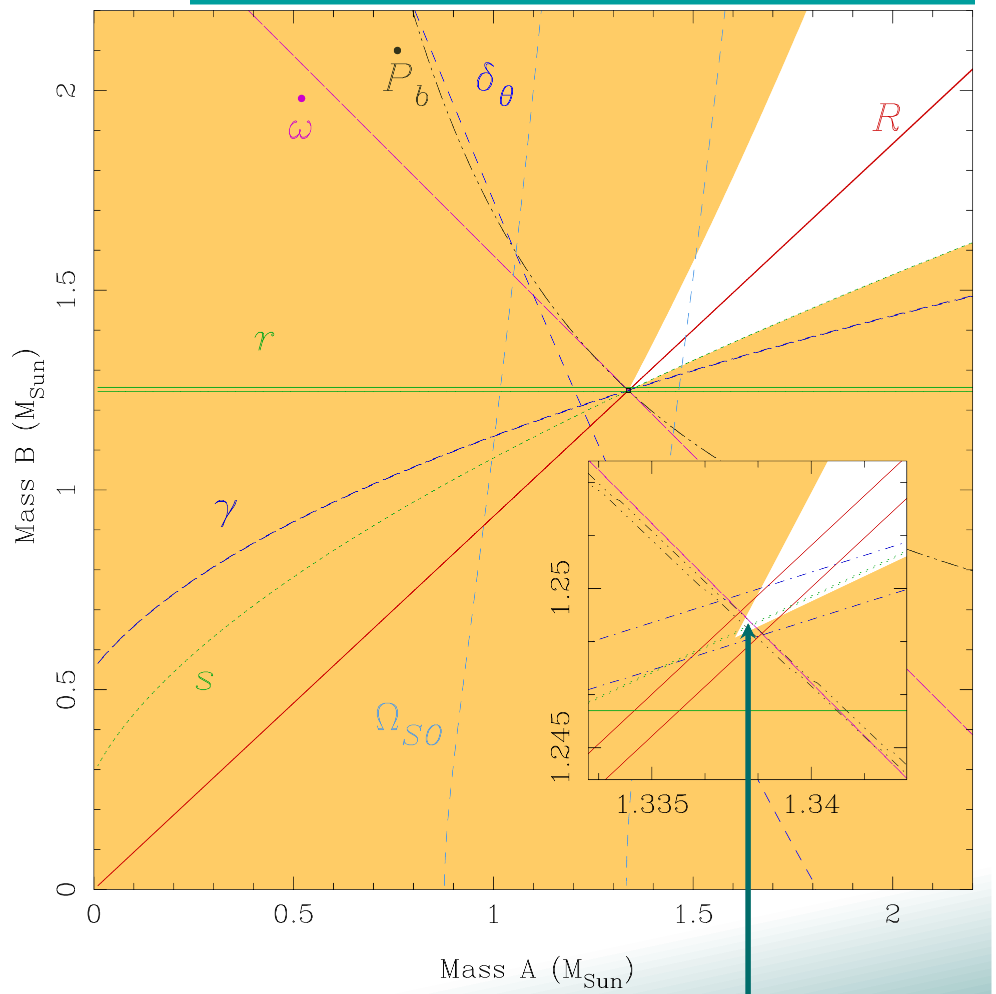
Orbital period decay (-39 μs/yr)

$$\dot{P}_b = -\frac{192\pi}{5}\,\frac{G^{5/3}}{c^5}\left(\frac{2\pi}{P_b}\right)^{5/3}\frac{1+\frac{73}{24}e^2+\frac{37}{96}e^4}{(1-e^2)^{7/2}}\,\frac{m_A m_B}{(m_A+m_B)^{1/3}}$$

Mass ratio (1.07)

$$R = x_B/x_A = m_A/m_B + \mathcal{O}(v^4/c^4)$$

7 - 2 = 5 tests of GR plus 1 emerging one



$$m_A = 1.33816 \pm 0.00002\,M_\odot$$
$$m_B = 1.24891 \pm 0.00002\,M_\odot$$

Constraining alternative theories

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)

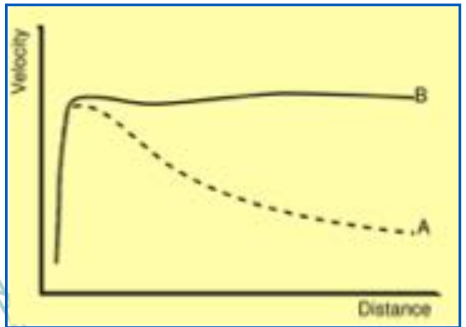
Bekenstein's TeVeS and the Double Pulsar

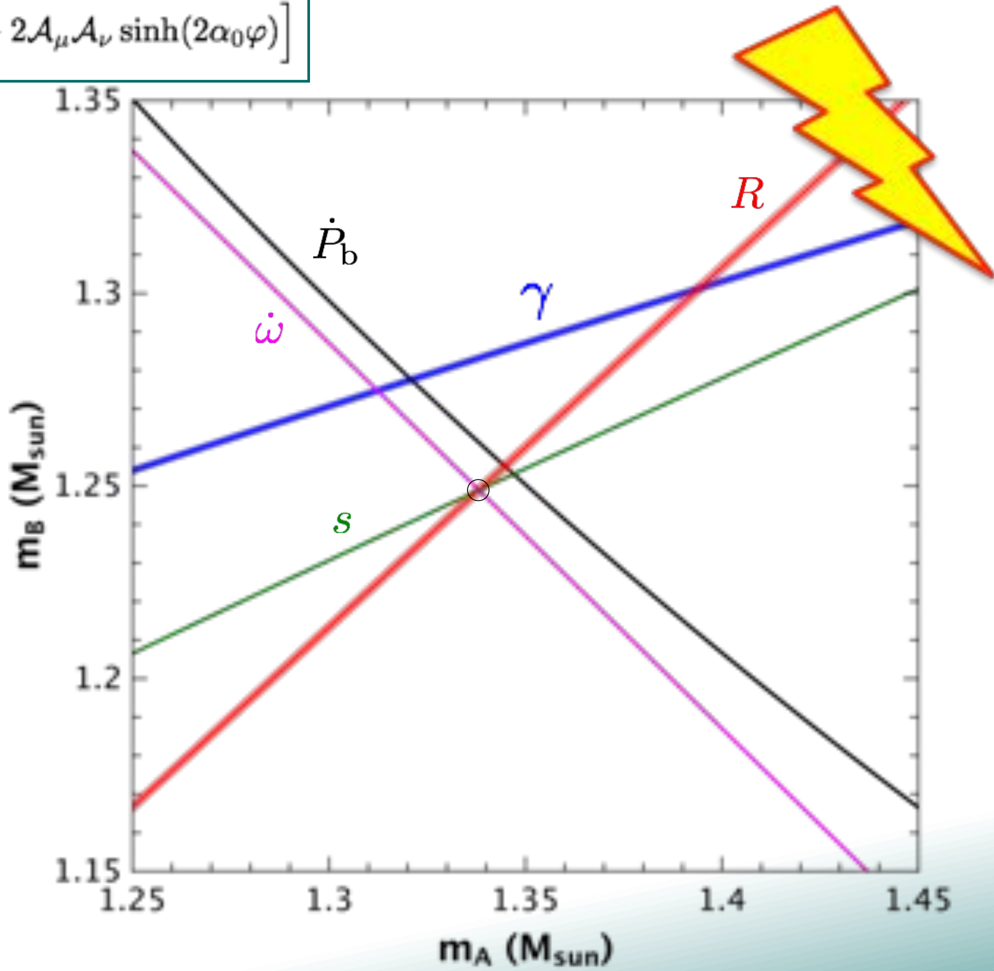
$$S = \frac{c^3}{16\pi G_*}\int d^4x\sqrt{-g^*}\Big(R^* - 2\mathcal{F}(g^{*}_{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi)\Big)$$
$$+ S_{\rm vector}\Big[\mathcal{A}_\mu; g^*_{\mu\nu}\Big]$$
$$+ S_{\rm matter}\Big[\psi; \tilde{g}_{\mu\nu} \equiv g^*_{\mu\nu}\exp(-2\alpha_0\varphi) - 2\mathcal{A}_\mu\mathcal{A}_\nu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

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?

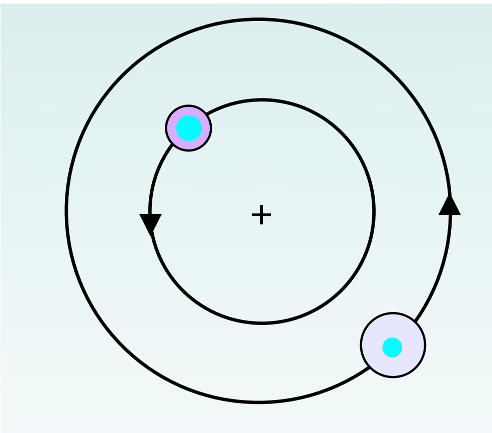
Unlike GR, most alternative theories of gravity – including tensor-scalar theories – predict dipole radiation that dominates the energy loss of the orbital dynamics:

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

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

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

Hence, visible in orbital decay:



$$\dot{P}_b^{\text{quadrupole}} \propto \left(\frac{v}{c}\right)^5$$

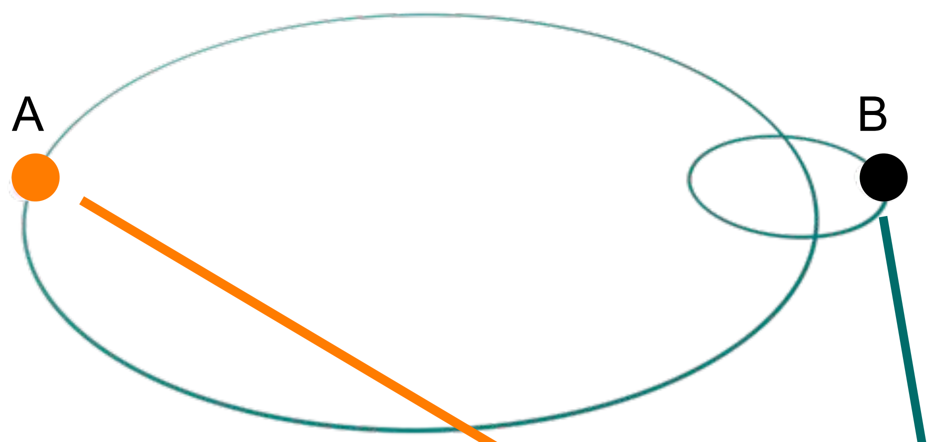
$$\dot{P}_b^{\text{dipole}} \propto \left(\frac{v}{c}\right)^3 (\alpha_A - \alpha_B)^2$$

$\dot{P}_b^{\text{dipole}}$ = 0 in GR

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

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

Unlike GR, most alternative theories of gravity – including tensor-scalar theories –predict other radiation multipoles that <u>dominate</u> the energy loss of the orbital dynamcis (1.5 pN):



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

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

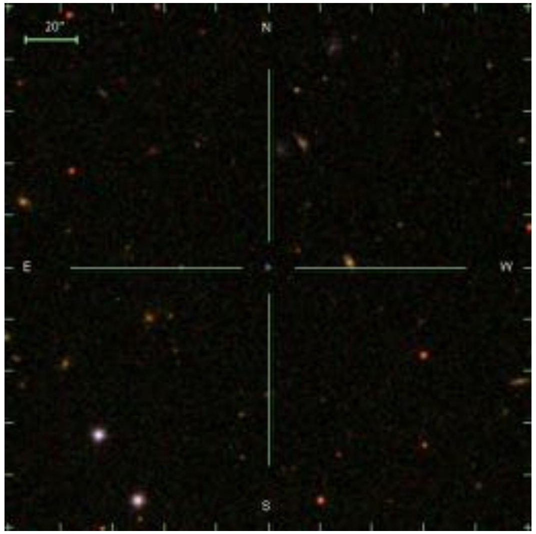
PSR-BH system would be best as BH would have zero scalar charge

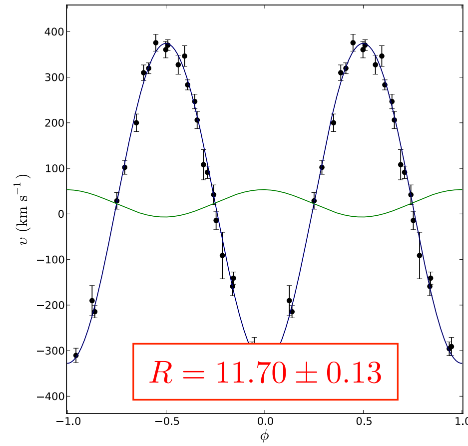
But PSR – WD system also effective lab – in particular if PSR is massive!

Next best thing: a PSR-WD system

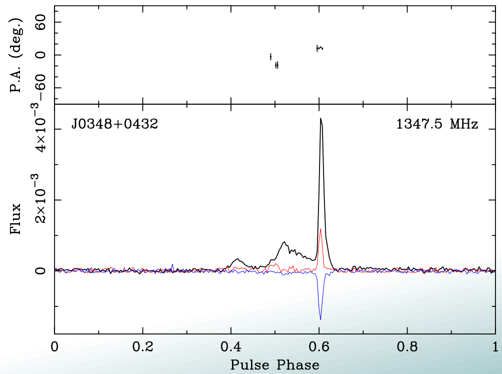
- PSR J0348+0432: first massive NS in relativistic orbit (Lynch et al. 2013)
- Combining VLT, Effelsberg, Arecibo & GBT data, new record mass measured:

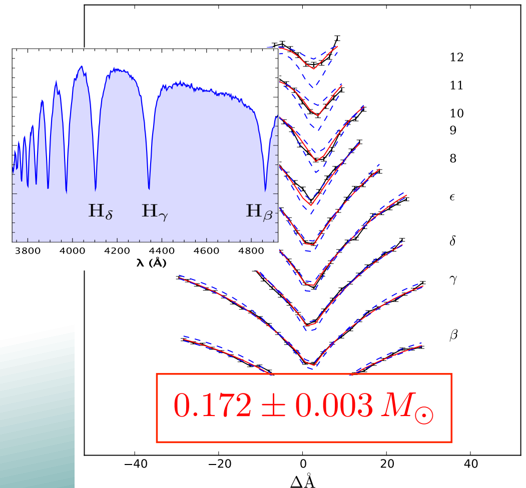
$M=2.01\pm0.04\ M_\odot$ (Antoniadis et al., 2013)





$$P = 39.1226569017806(5)\ \mathrm{ms}$$
$$P_b = 2.45817750533(2)\ \mathrm{h}$$
$$e \lesssim 10^{-6}$$





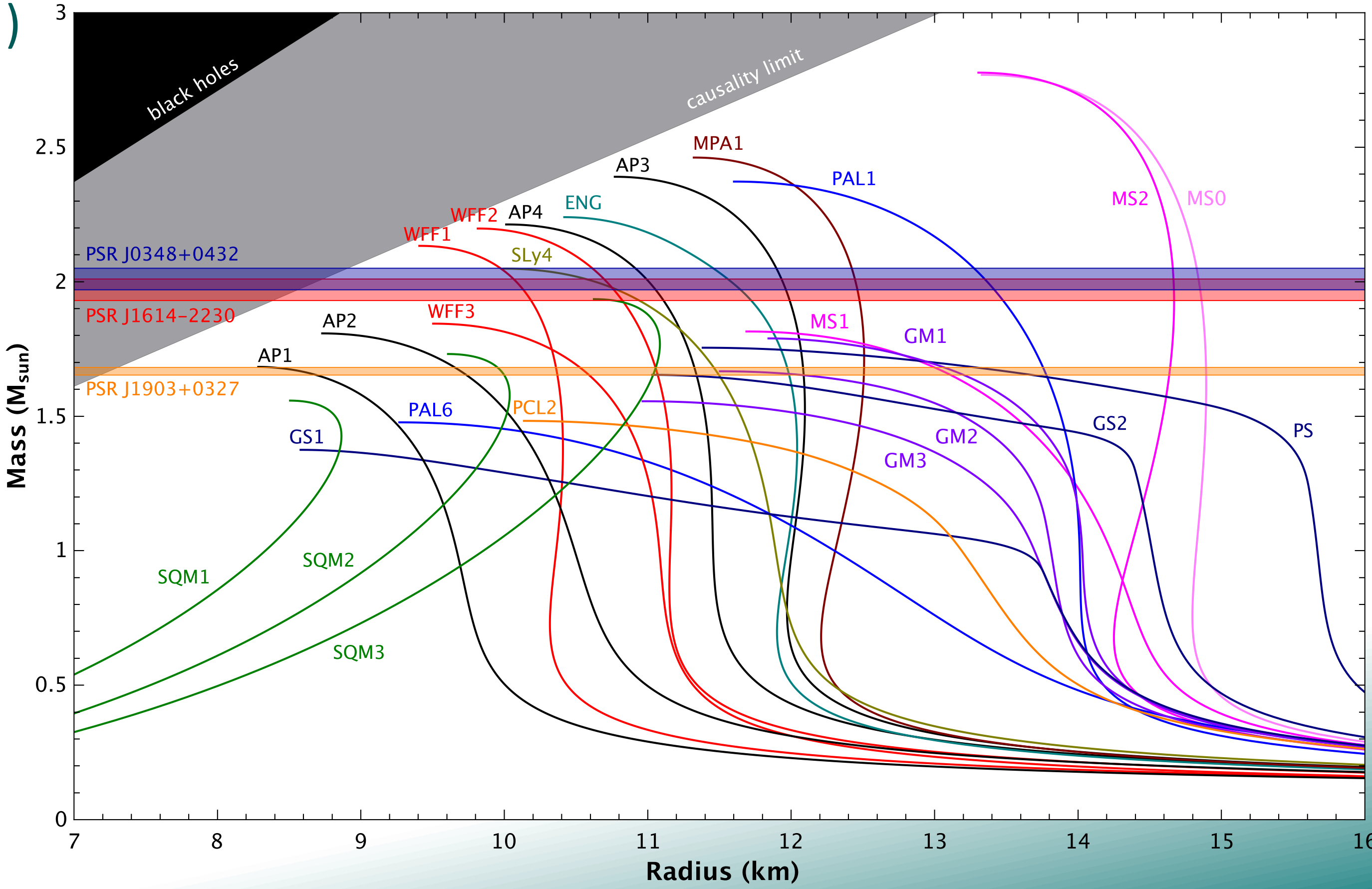
Testing a new gravity regime

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

  $M=2.01\pm0.04\ M_{\odot}$ (Antoniadis et al., 2013)
- Important for probing different grav fields but also for EoS of super-dense matter (see A. Watts' talk!)

Combine with moment-of-inertia from Double Pulsar.

Are they born 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)

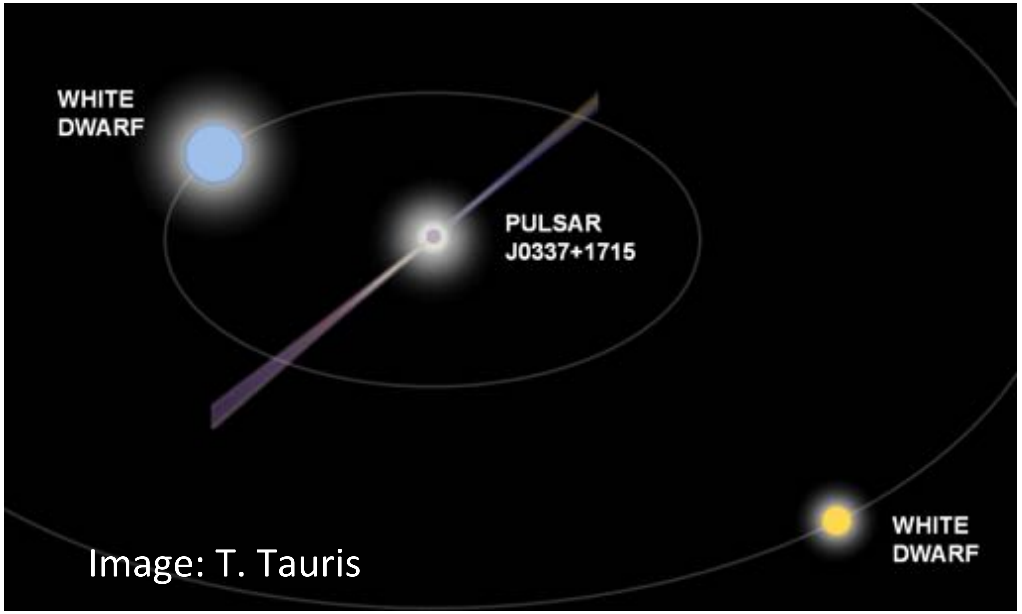
$$\dot{P}_b = (-250 \pm 9)\ \mathrm{fs\ s^{-1}} = 7.9 \pm 0.3\ \mu\mathrm{s\ yr^{-1}}$$

No indication of dipolar radiation!

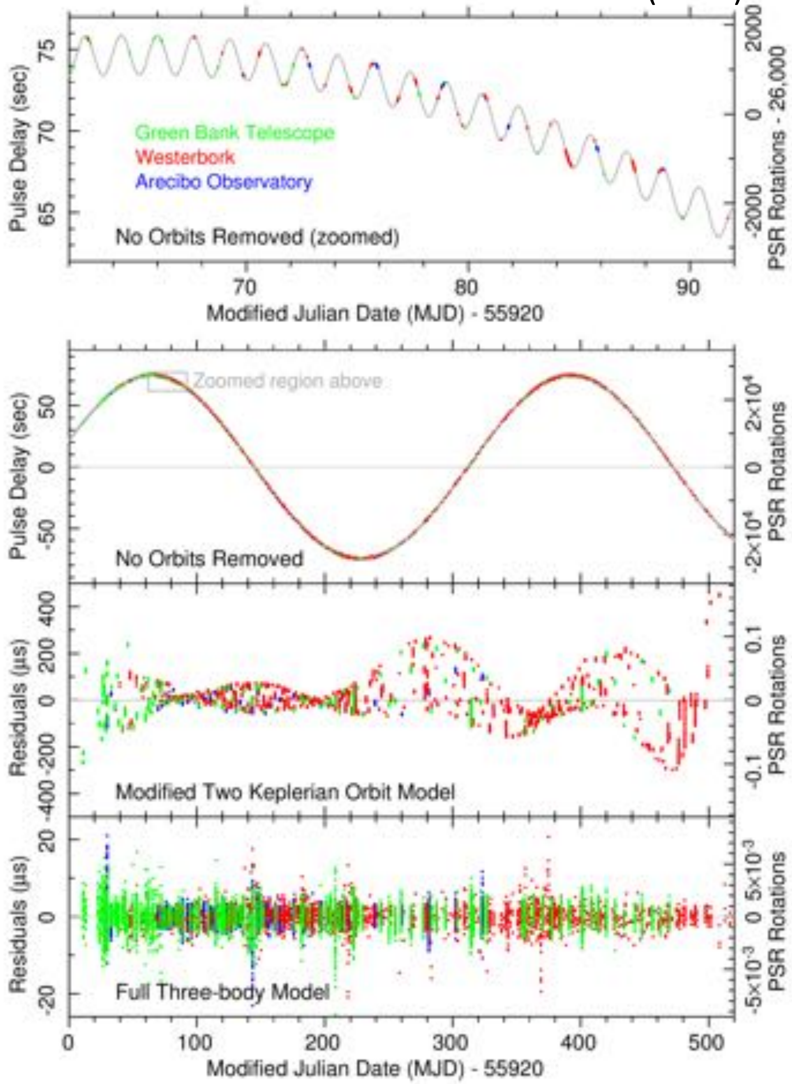
$$\alpha_\mathrm{p} = 1 \quad \Longrightarrow \quad \dot{P}_\mathrm{b} = \quad -110\,000 \quad \mu\mathrm{s/yr}$$

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

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



Ransom et al. (2014)



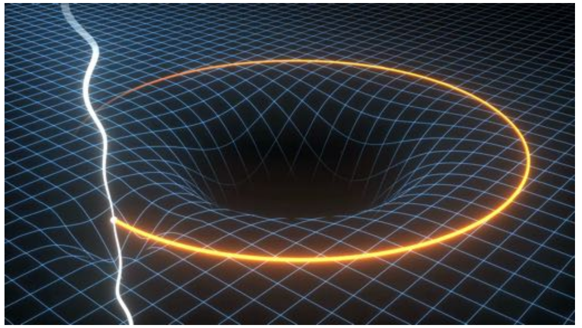
(Pulsar-WD)-WD system: P_b = 1.6/327 days

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 Jason Hessels' talk later today!

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%

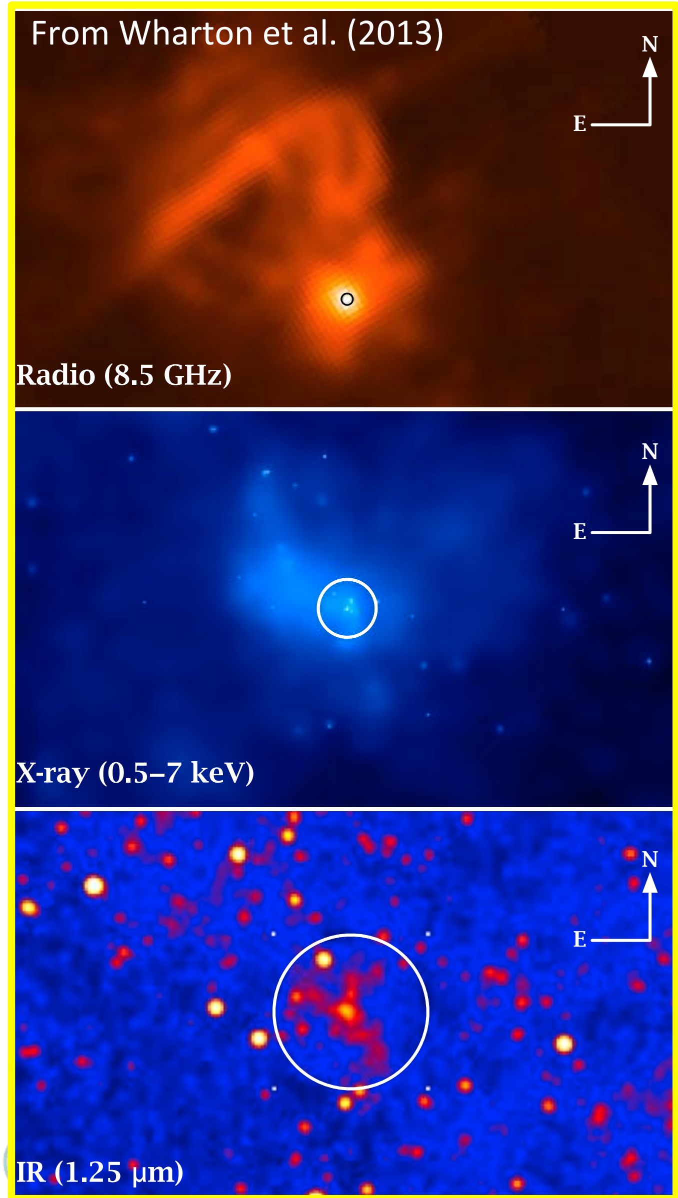
BH spin with precision < 1%

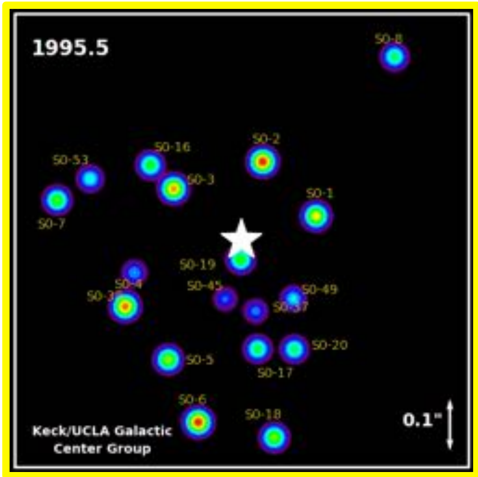
Cosmic Censorship: $S < GM^2/c$

Where or how do we find one?

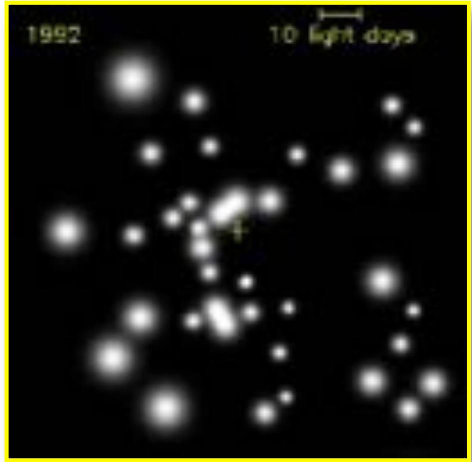
- Find "all" pulsars with the SKA
- or look where you know a black hole to be...

A well-known super-massive Black Hole





UCLA



MPE/Cologne

From astrometry of orbiting stars::

[Gillesen et al. 2008]

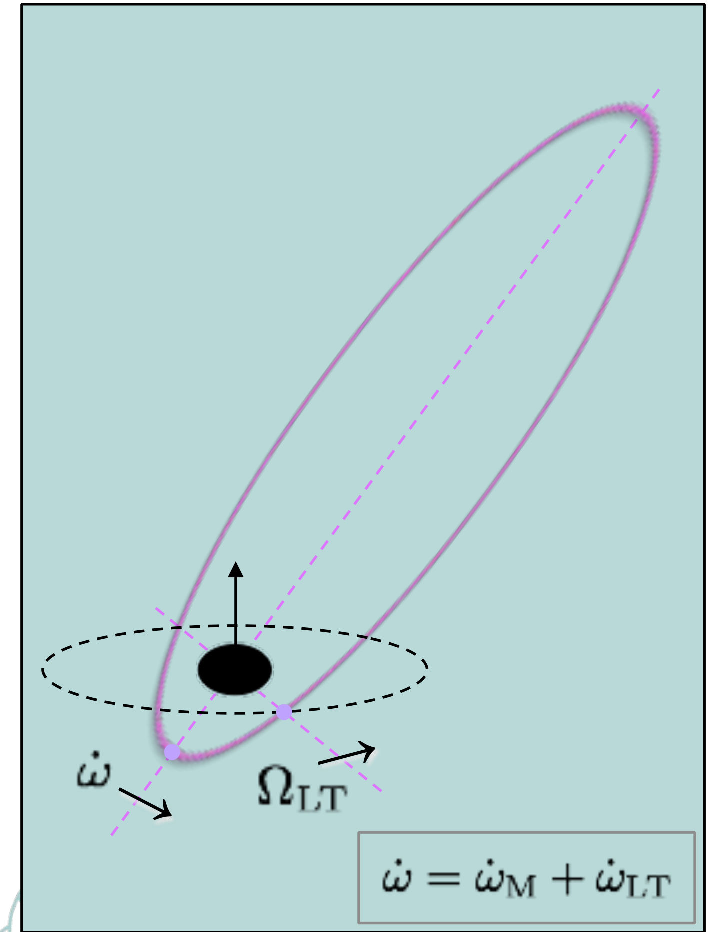
Mass: $(4.3 \pm 0.2_{(\mathrm{stat})} \pm 0.3_{(\mathrm{sys})}) \times 10^6\, M_\odot$

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

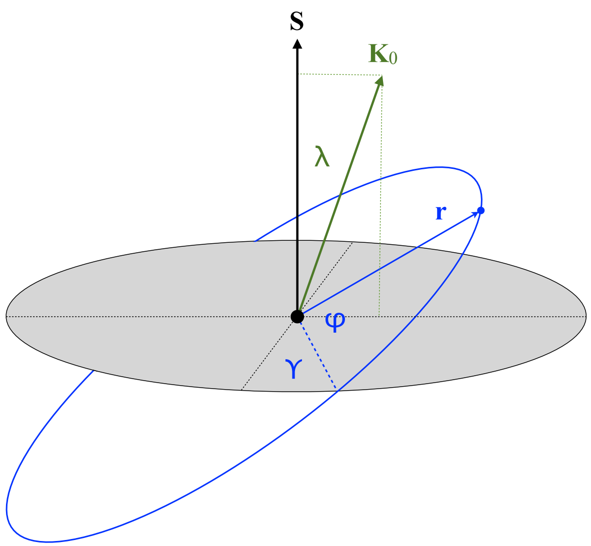
Similar contribution to $\dot{\omega}$

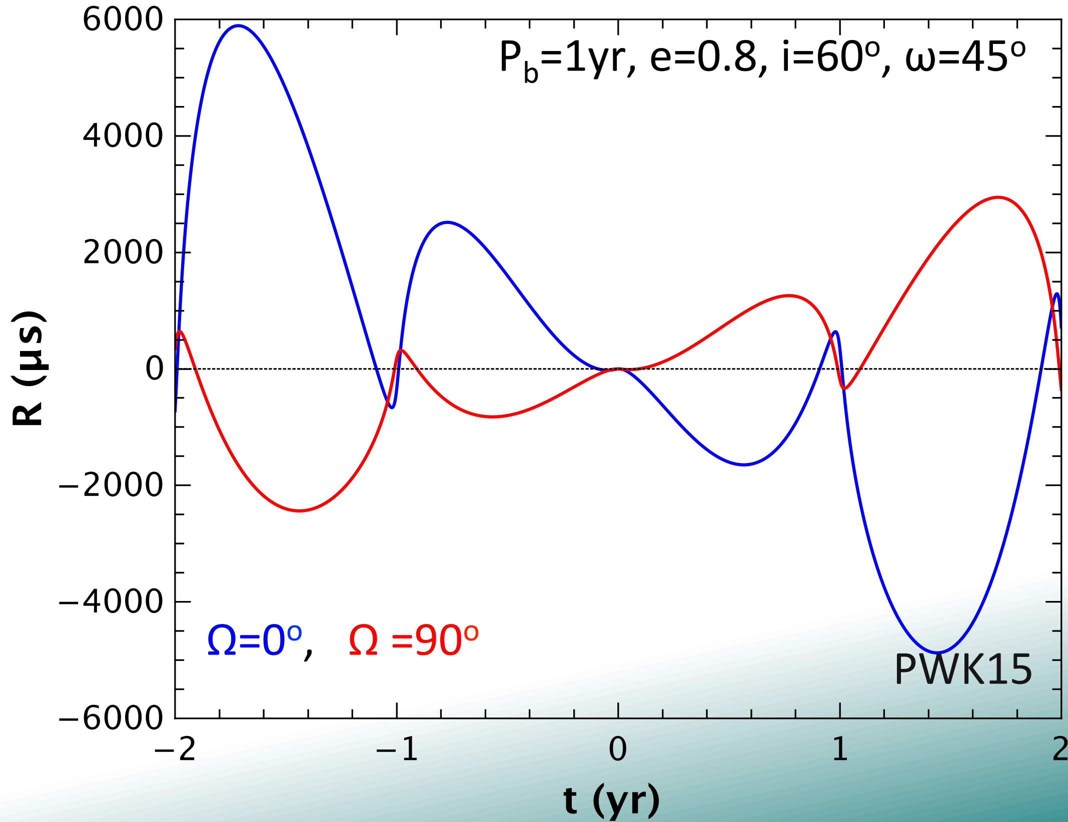
Geod. precession 1.4 deg/yr

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%.



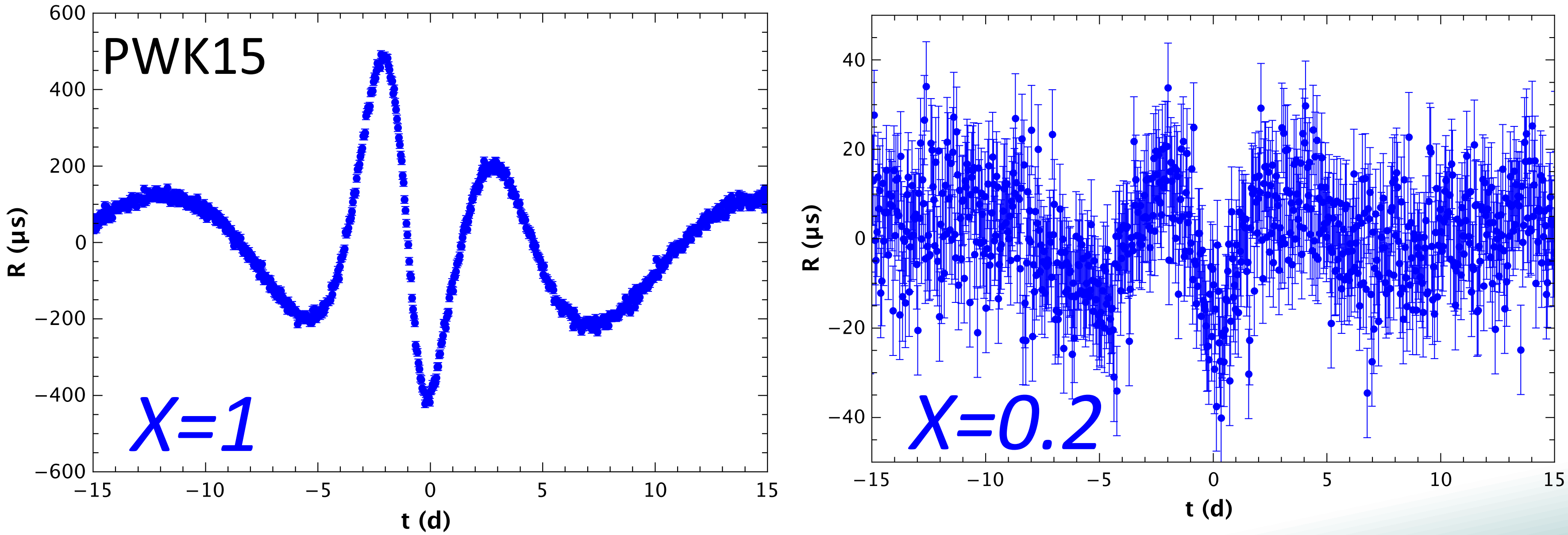


Testing the no-hair theorem

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

Pulsar in a 0.1 yr orbit around Sgr A*:

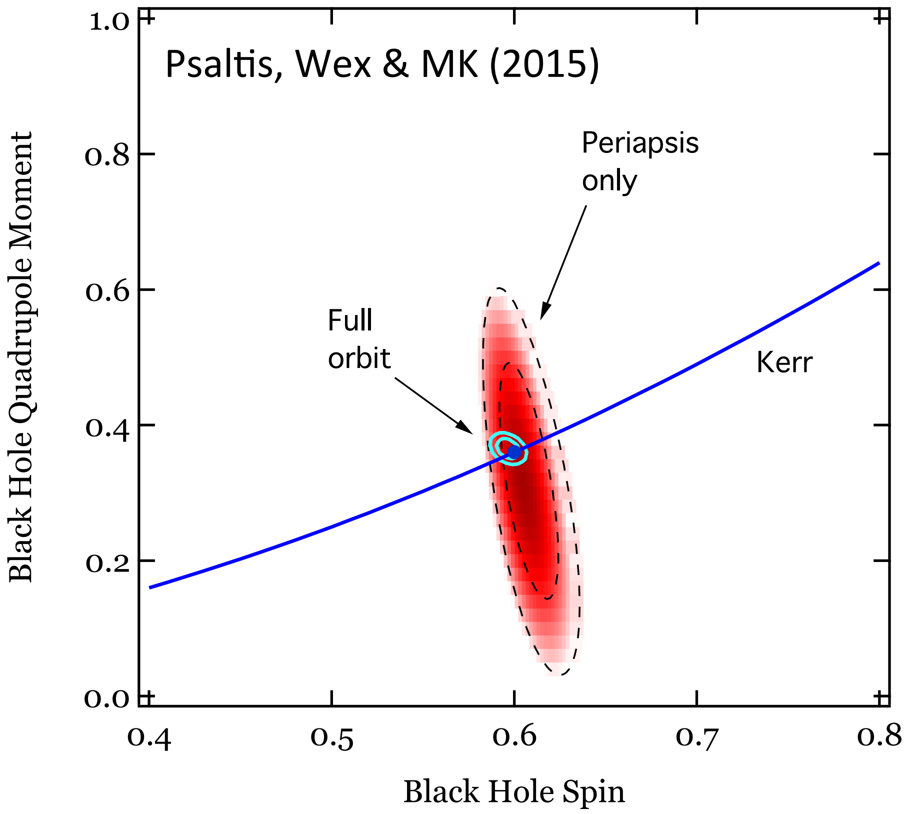
- *Secular precession* caused by quadrupole is 2 orders of magnitude below frame dragging, but it is not separable from frame-dragging
- Fortunately, quadrupole leads to *characteristic periodic residuals* ➔ Q to about 1%



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!



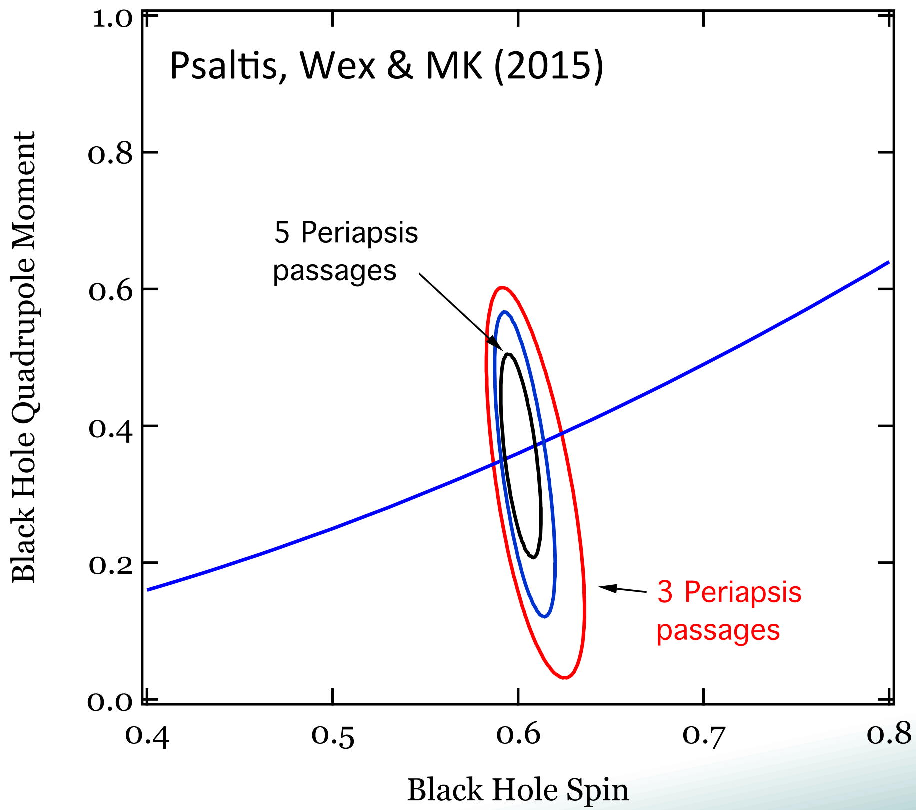
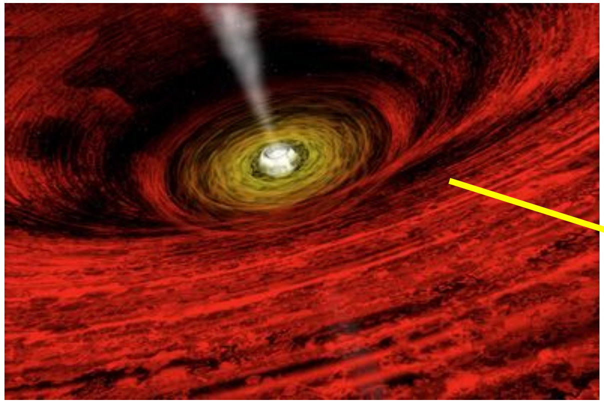
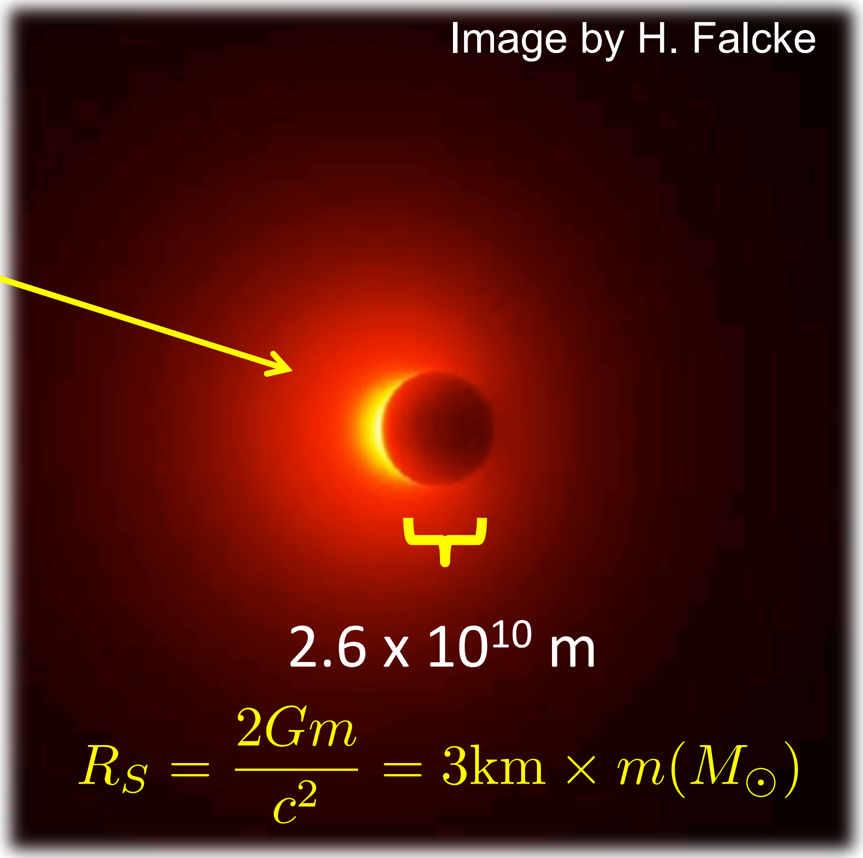


Image of the shadow of the event horizon

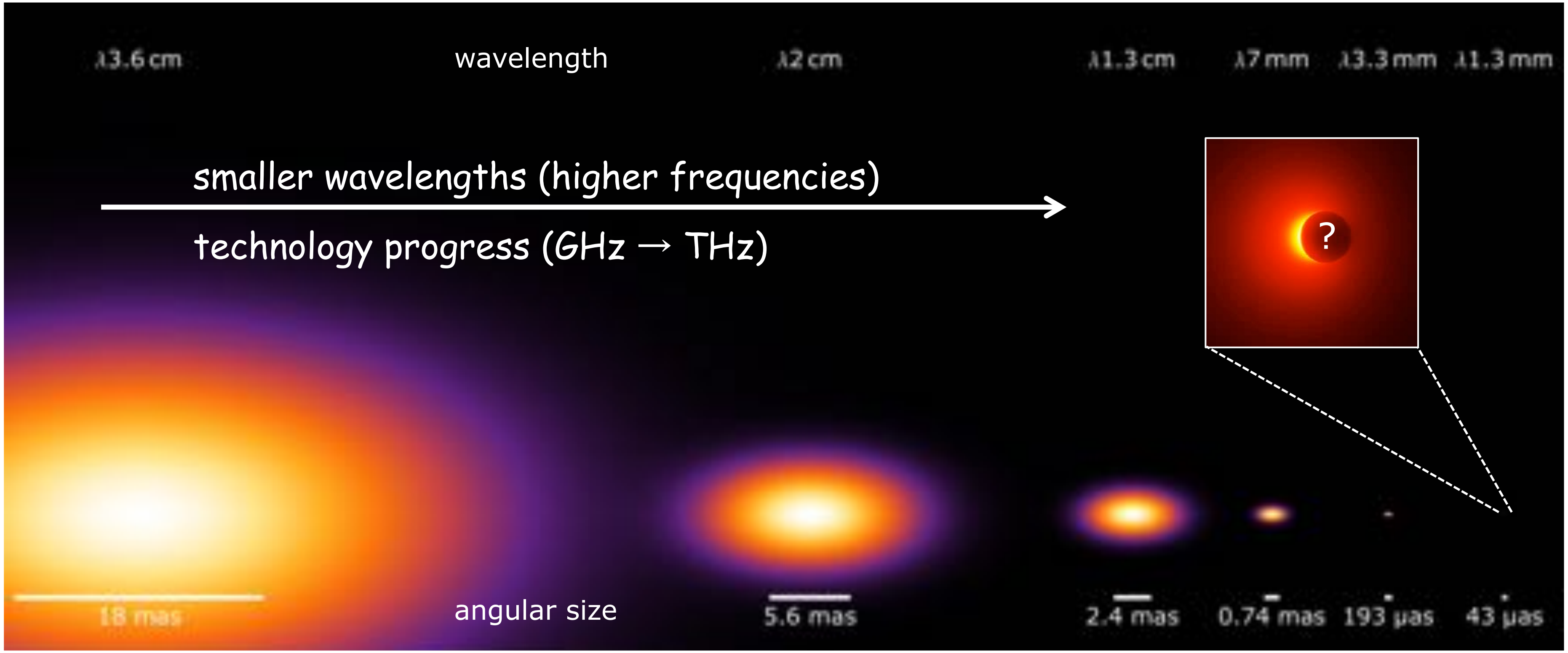




Blocked in the optical – but visible at radio frequencies!

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

Image of the shadow of the event horizon

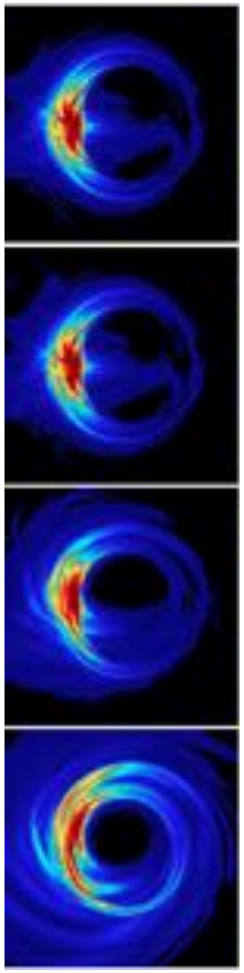


- the shorter the wavelength, the smaller the radio source (scattering!)
- at λ=1.3 mm the radio source becomes the size of the event horizon:
- the event horizon shadow should be 50 µas in diameter
- global mm-wave VLBI (EHT) with ALMA has the resolution to study it
  (see also Robert Laing's on ALMA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

Combining pulsars with other methods

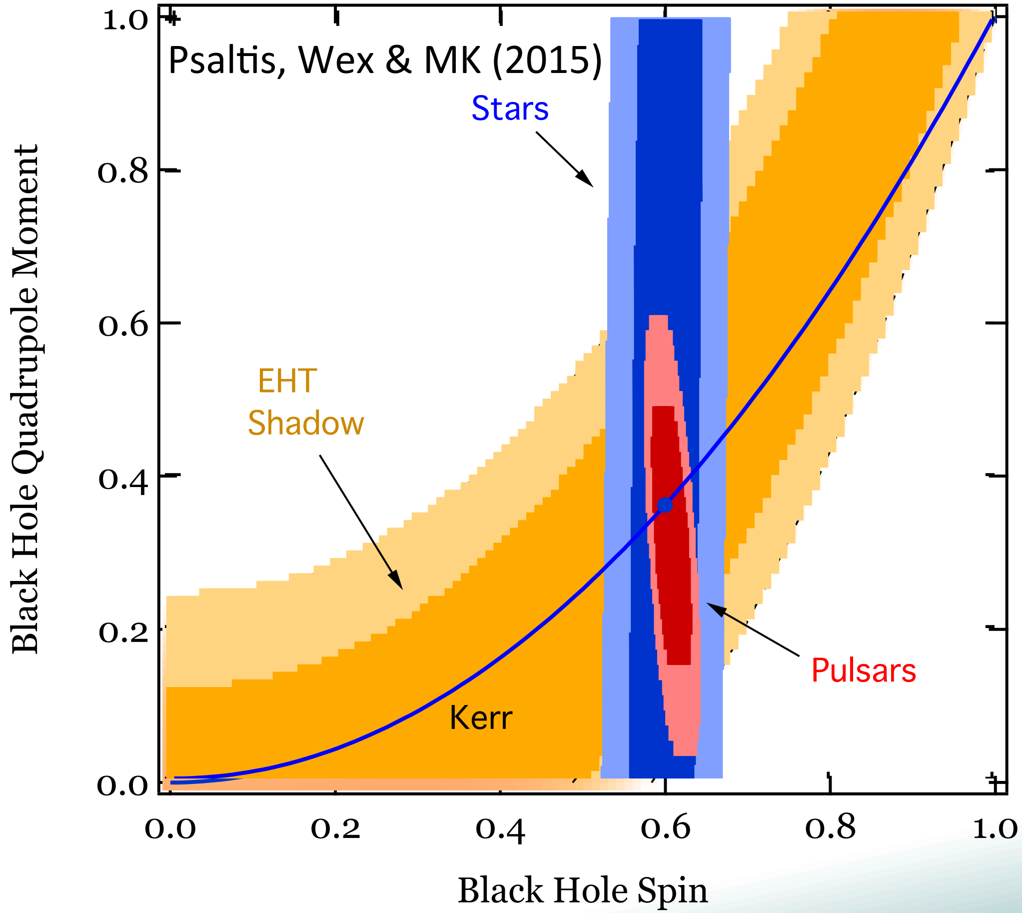
From Event Horizon Telescope/BlackHoleCam imaging observations:

edge-on



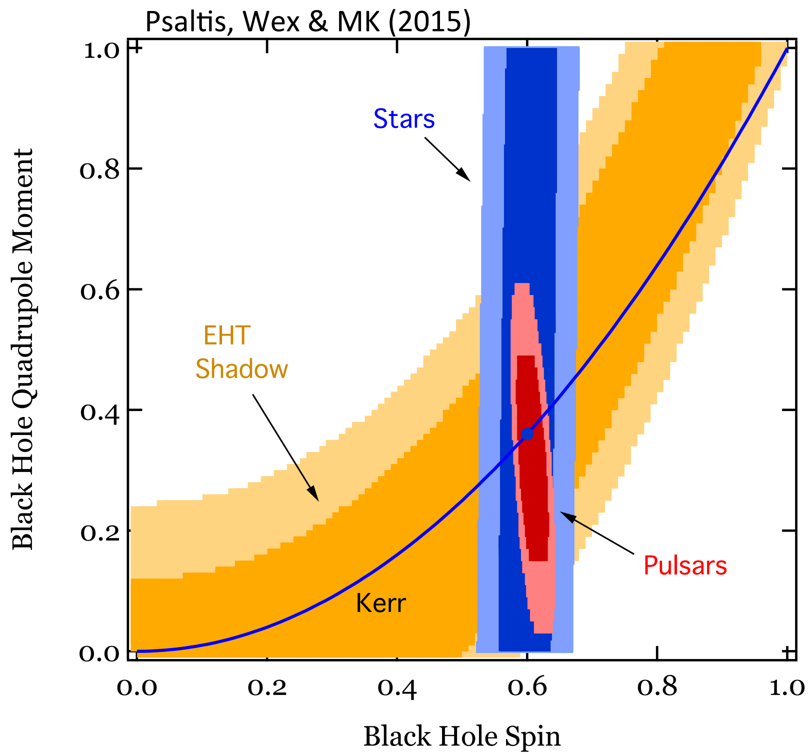
face-on

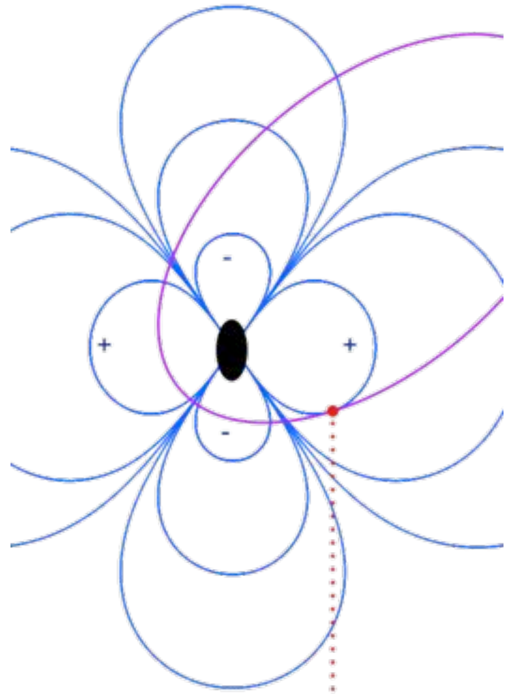
Moscibrodzka et al. (2014)



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

Combining image and pulsars





- 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

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
- The Triple System will provide interesting constraints in the future
- 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!