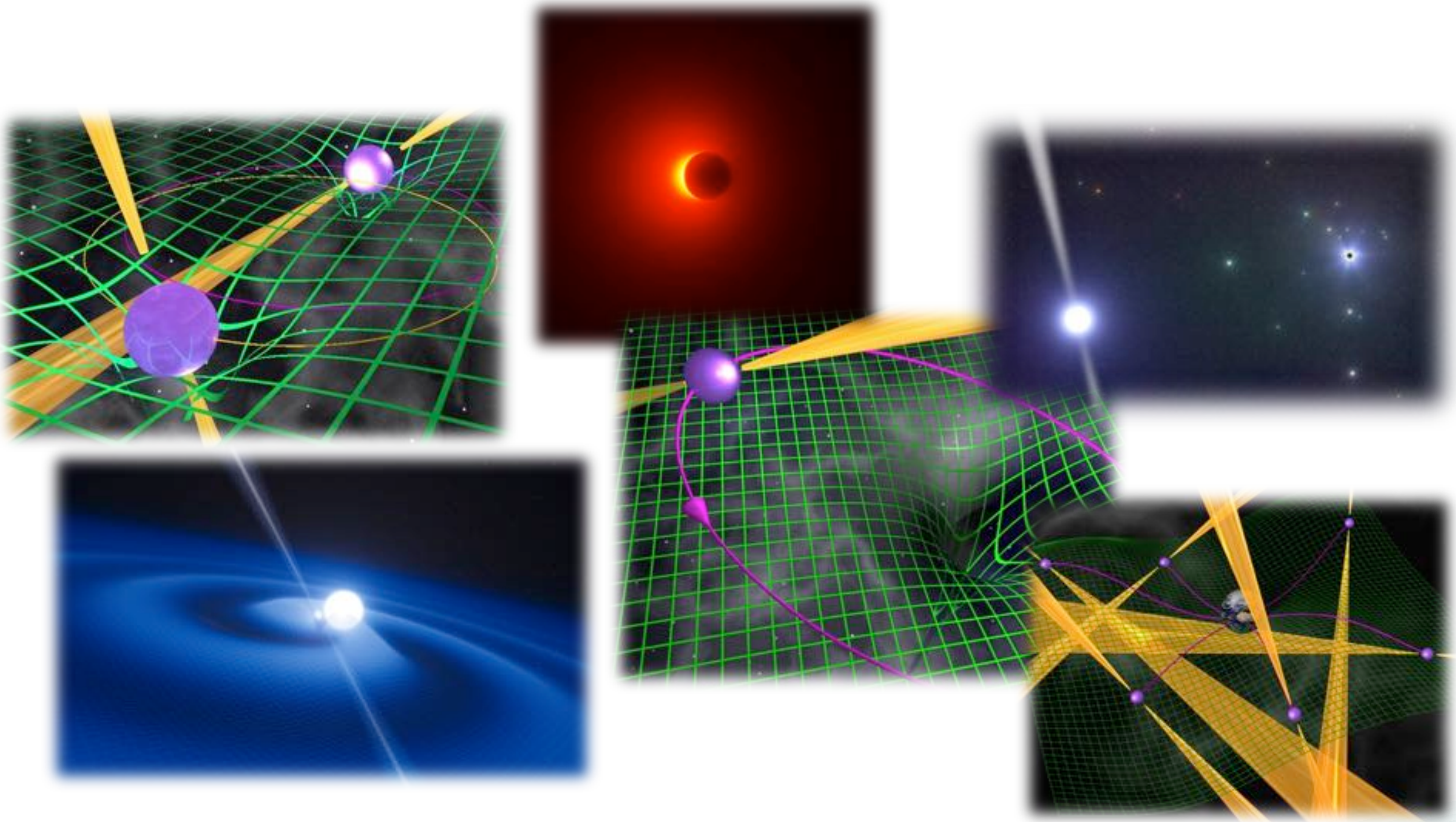
Testing theories of gravity with pulsars and binary systems



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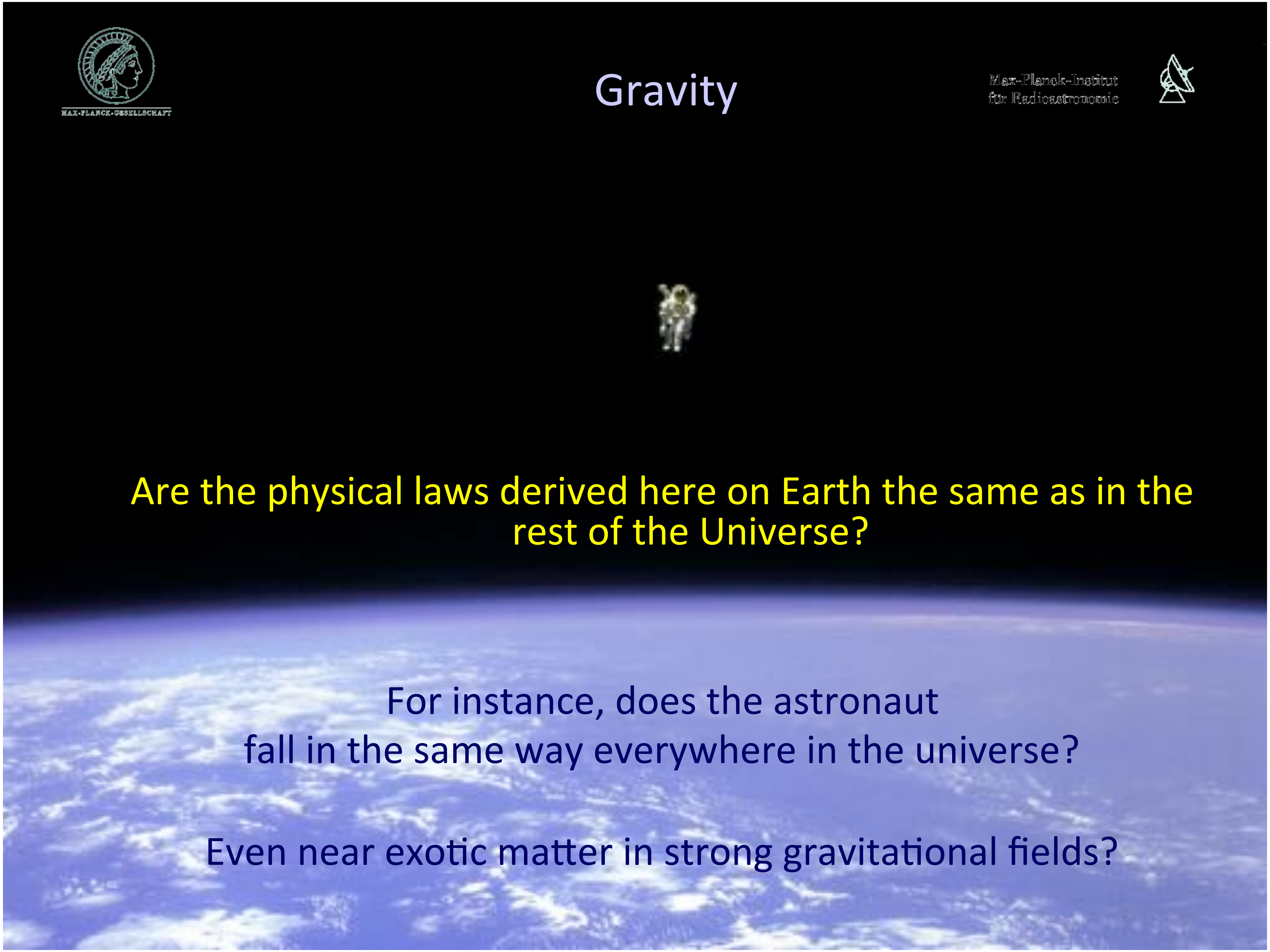
Jodrell Bank Centre for Astrophysics, University of Manchester

Gravity



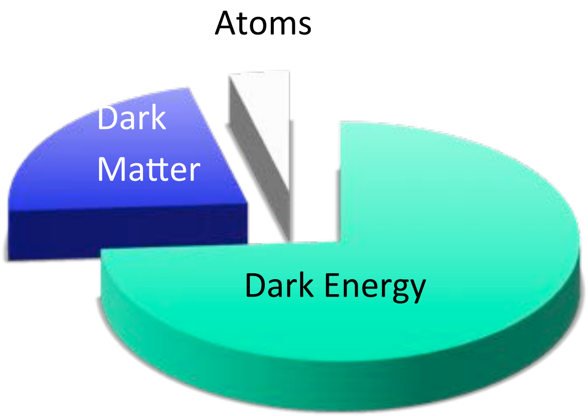
Are the physical laws derived here on Earth the same as in the rest of the Universe?

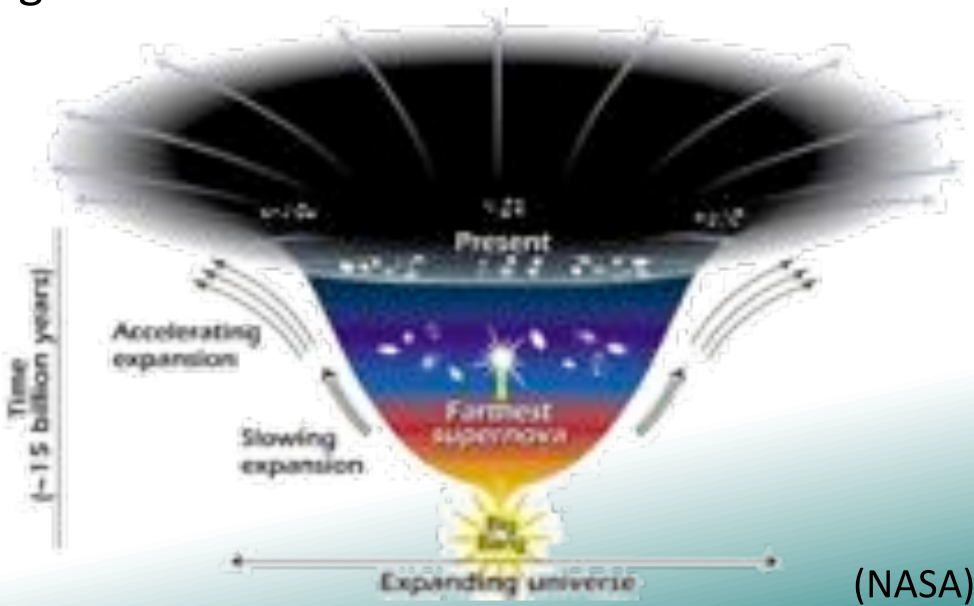
For instance, does the astronaut
fall in the same way everywhere in the universe?

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?



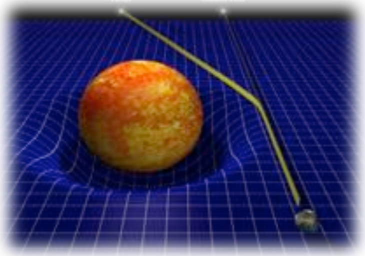


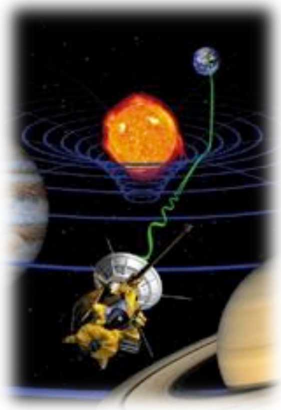
(NASA)

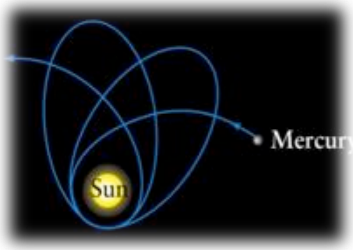
100+ years of General Relativity and Testing it

- 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

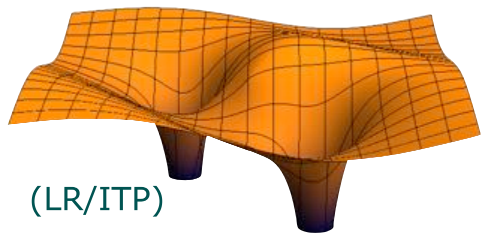


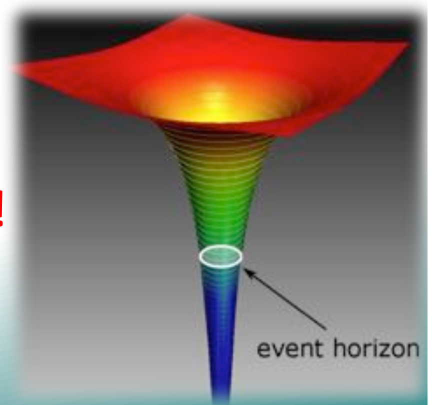




- Modern tests in solar system,

  - 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!

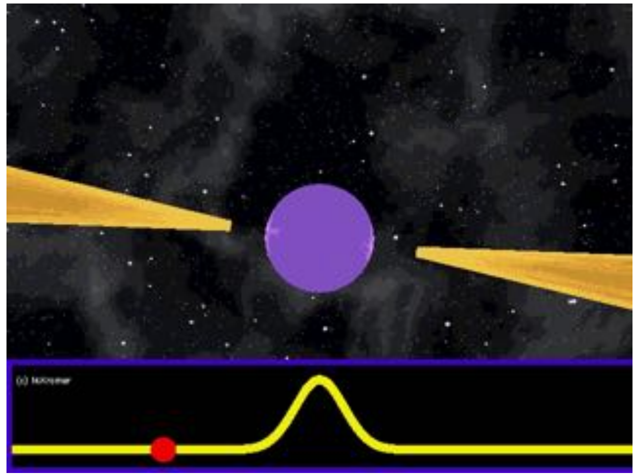
What are the properties of black holes & gravitational waves?

Using techniques and methods not known to Einstein...

Outline

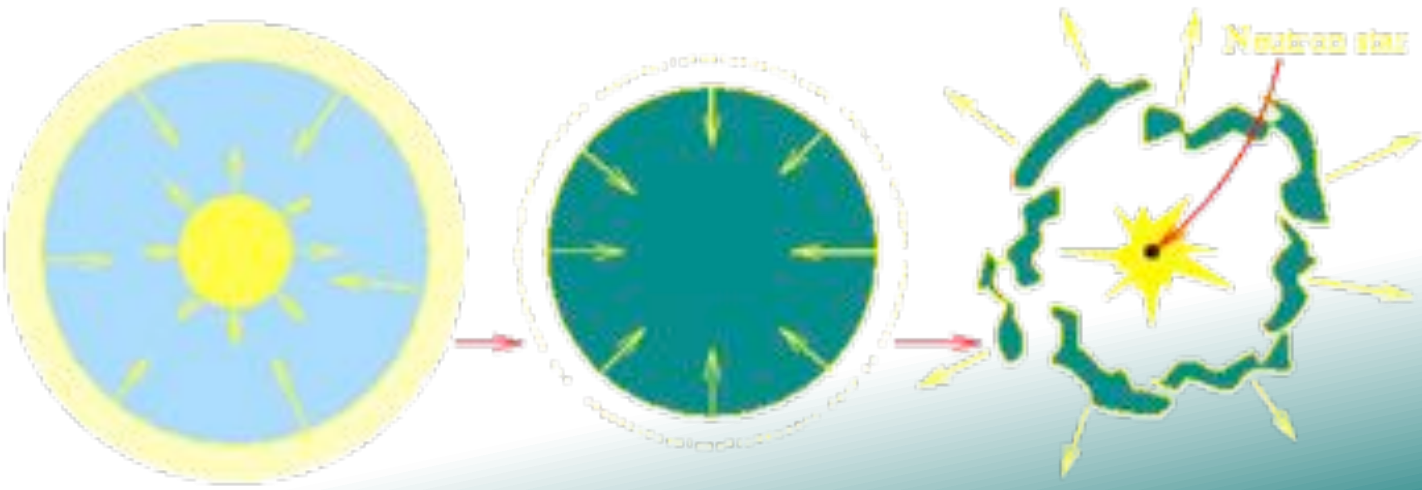
- Introduction
- Pulsars & binaries: testing GR and its alternatives
- Pulsar Timing Arrays (PTAs): detecting GWs
- The (far & near) future: SKA + EHT/BHC
- Conclusions

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!

…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

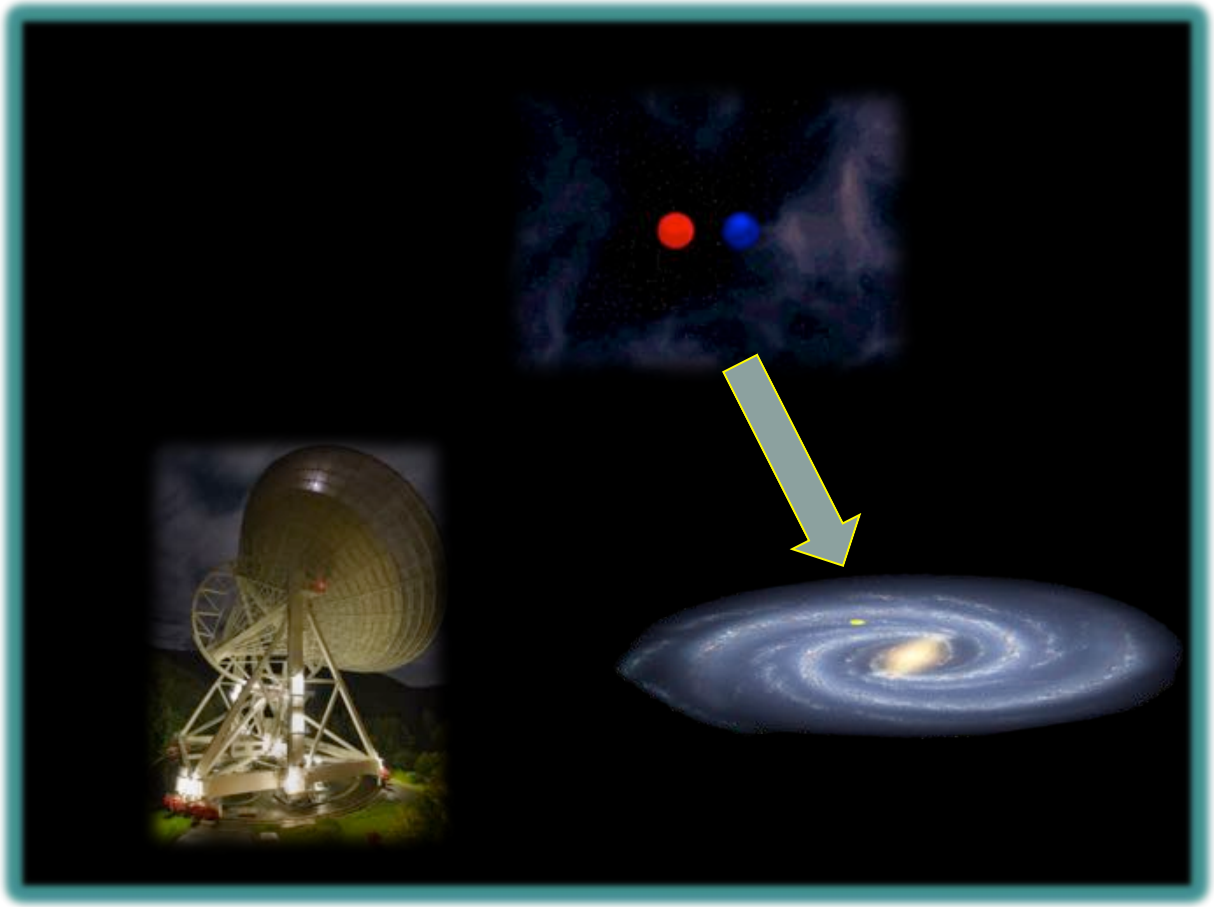
Orbital period range

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

Companions

MSS, WD, NS, planets

Wanted: PSR-BH!

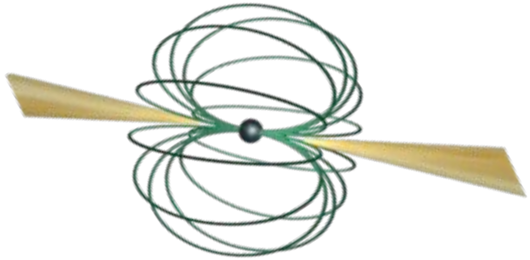


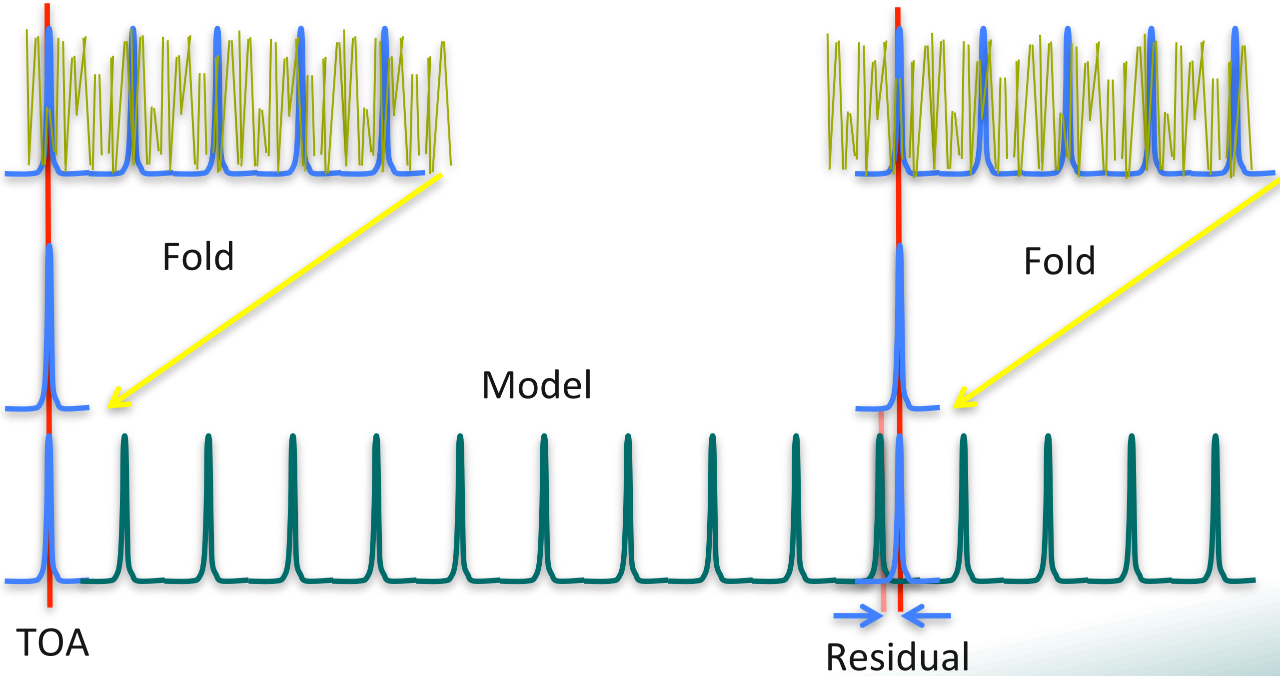
Simple experiment:

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!

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: $3.5\ (1.1) \times 10^{-7}$ (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)

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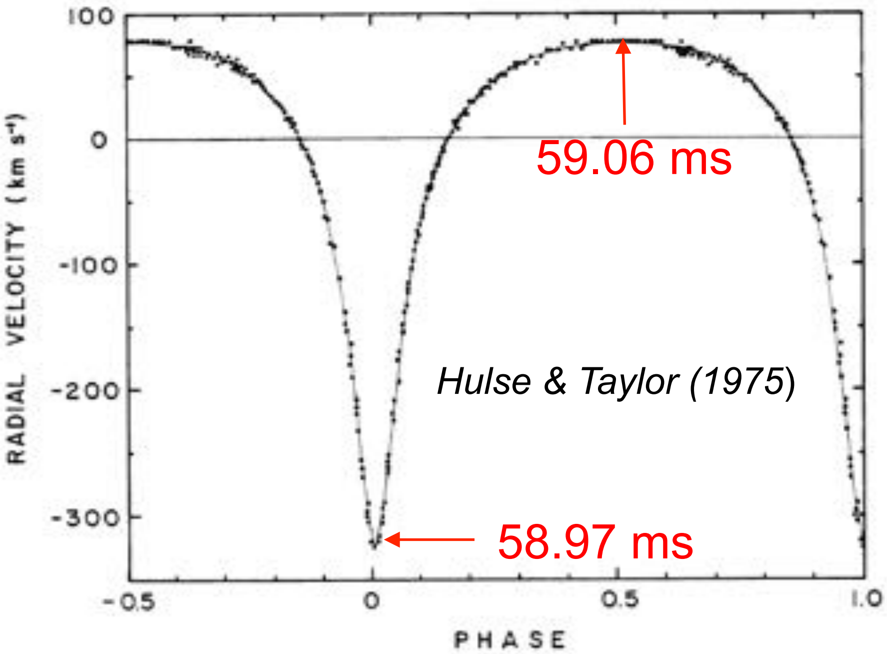
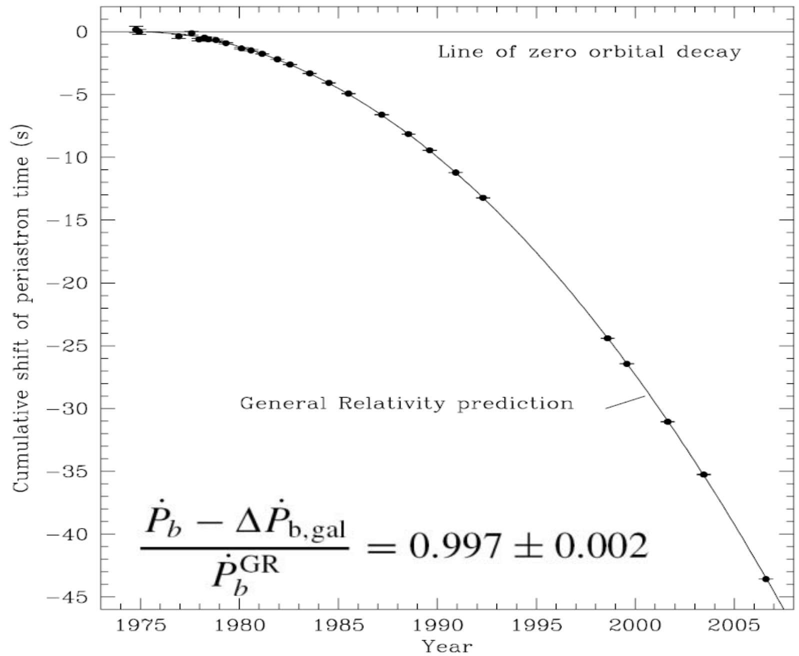
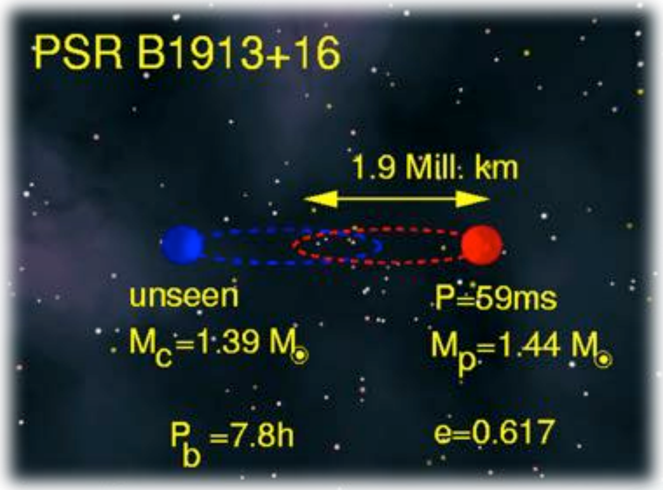
The first binary pulsar – the first DNS: Hulse-Taylor pulsar

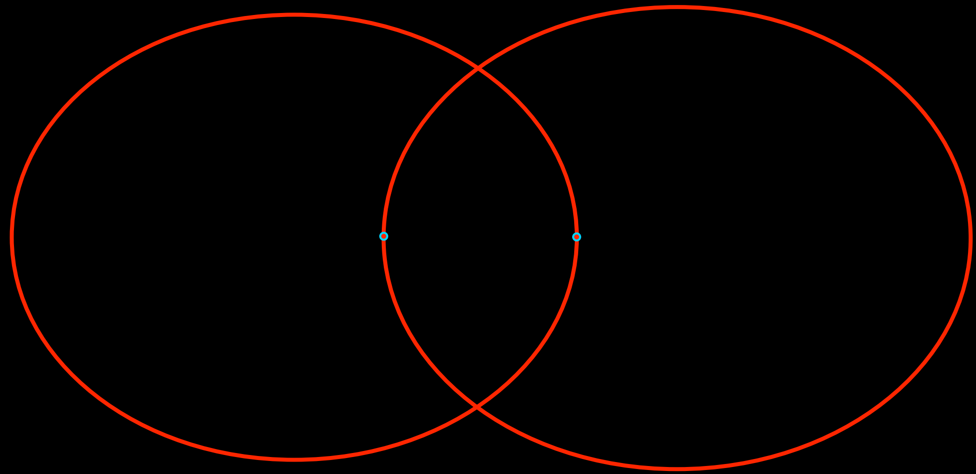




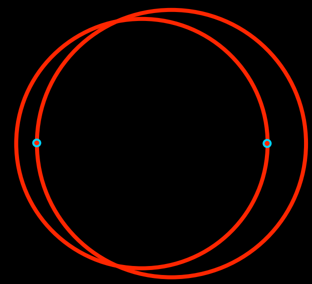


Comparison Hulse-Taylor vs Double Pulsar

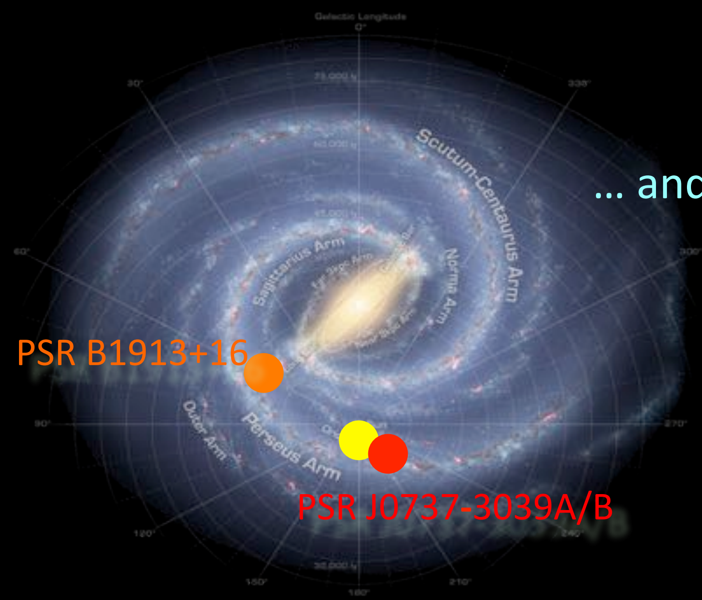
PSR B1913+16



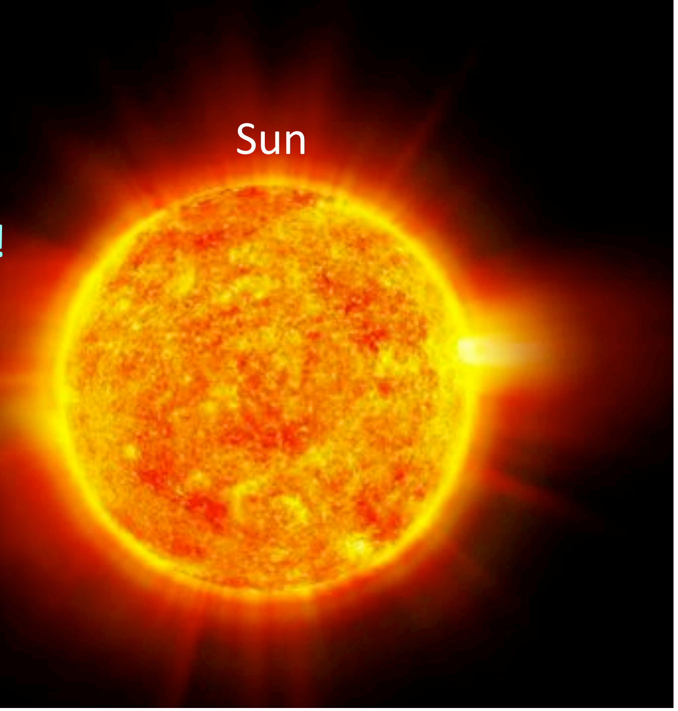
PSR J0737-3039A/B



More compact…



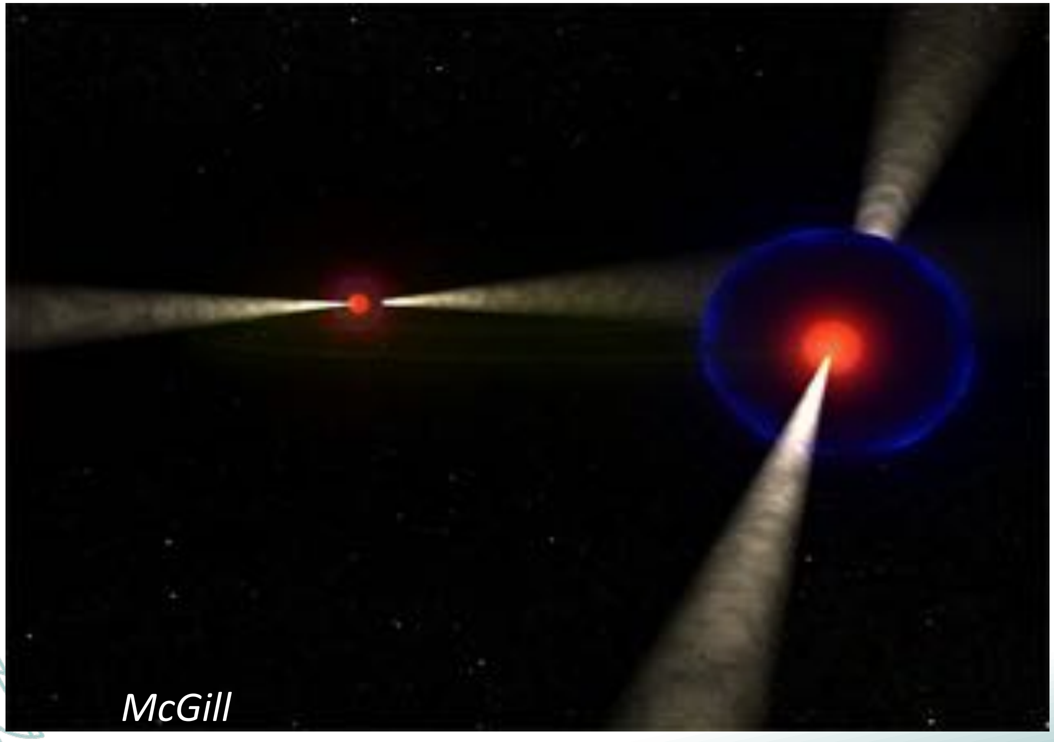
… and much closer!



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.)

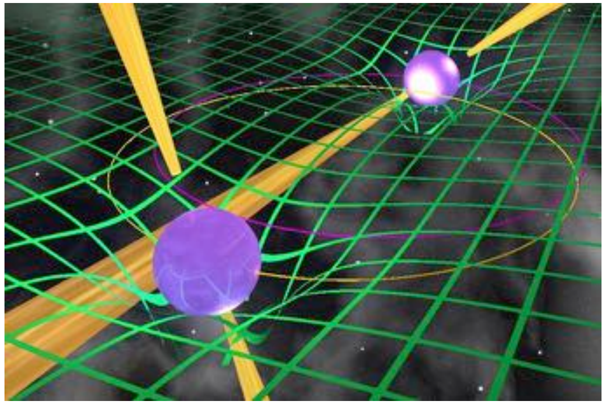


Collaborators:

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

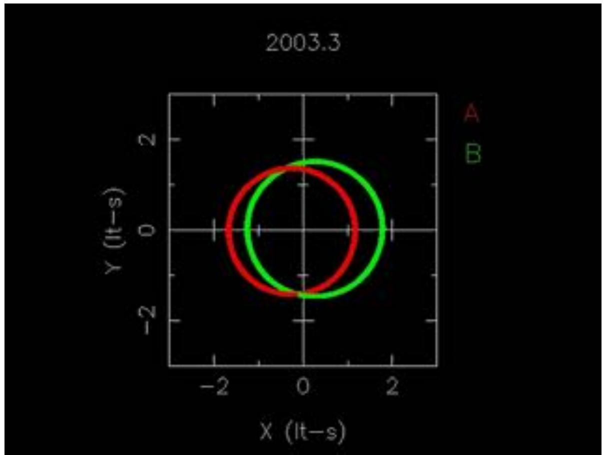
- We can measure two orbits ➔ mass ratio



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

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

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

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

Combined (GR):

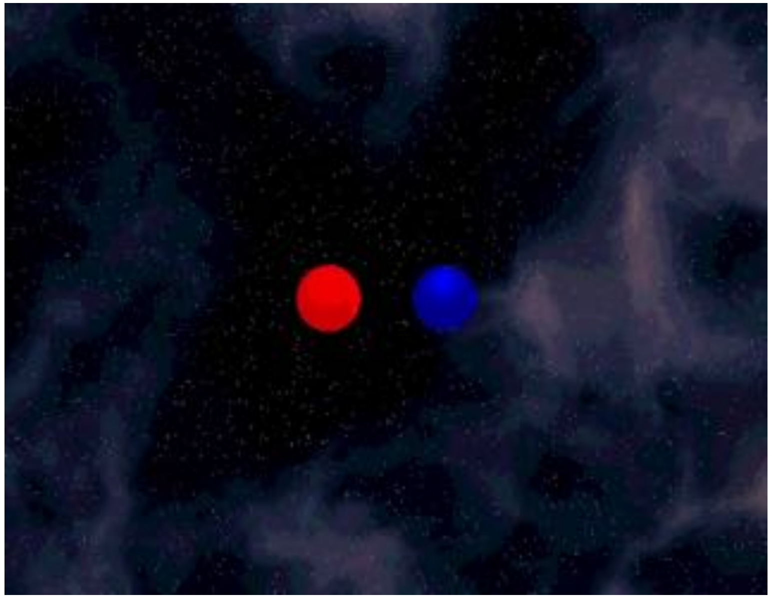
m_A= (1.3381±0.0007) $M_\odot$
& m_B= (1.2489±0.0007) $M_\odot$

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

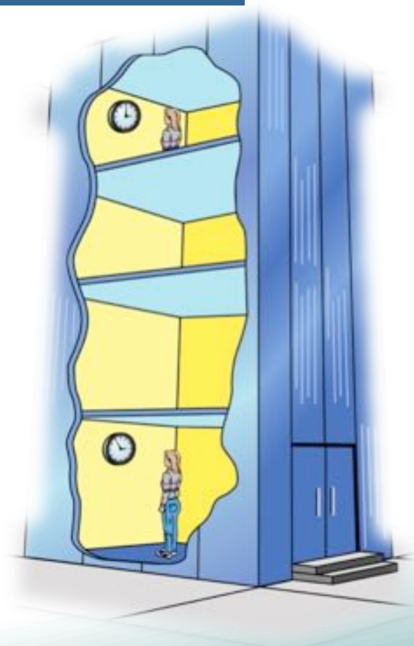
Double Pulsar: five tests in one system!

- 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!)



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



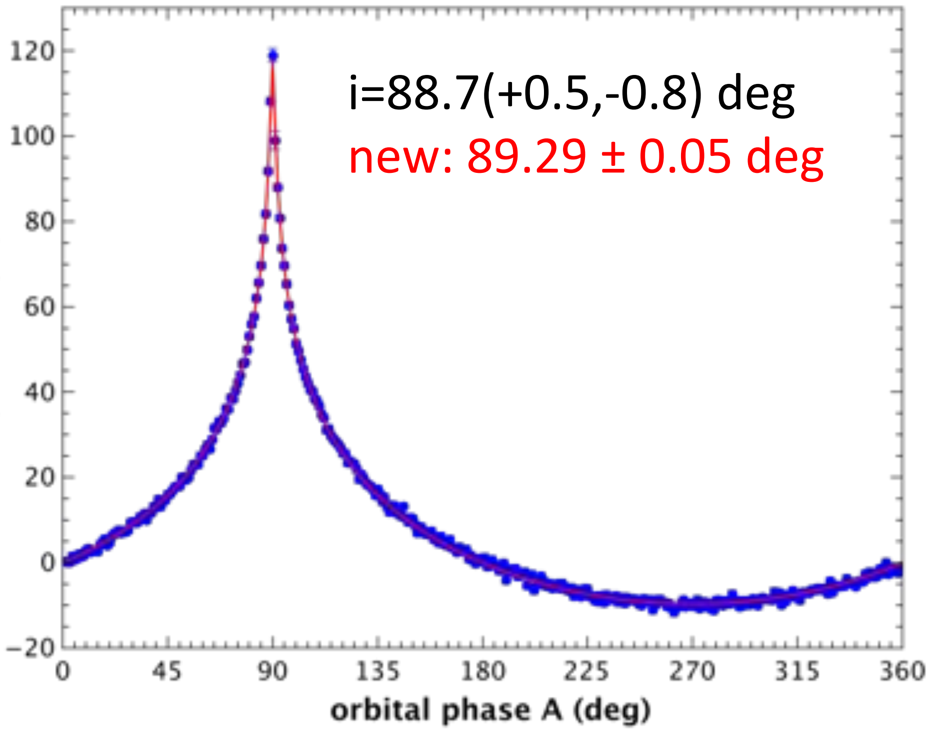
- As other clocks, pulsars run slower in deep gravitational potentials

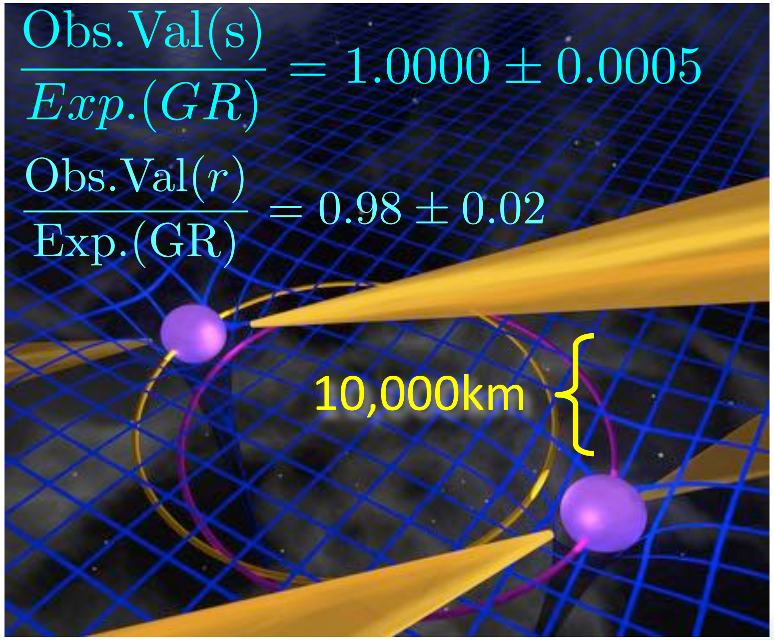
- Changing distance to companion (and felt grav. potential) during elliptical orbit

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 ± 0.000012
- 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

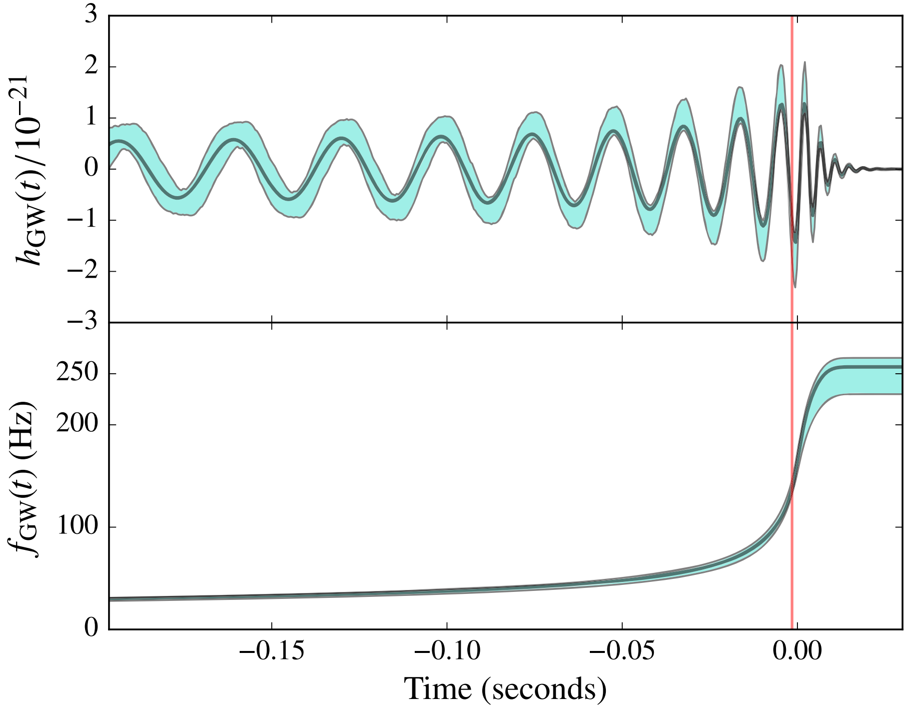
Animation by NASA/Rezzolla/AEI

Precision will improve with time: superseding solar system tests soon

How do pulsars compare to LIGO?

GW150914:

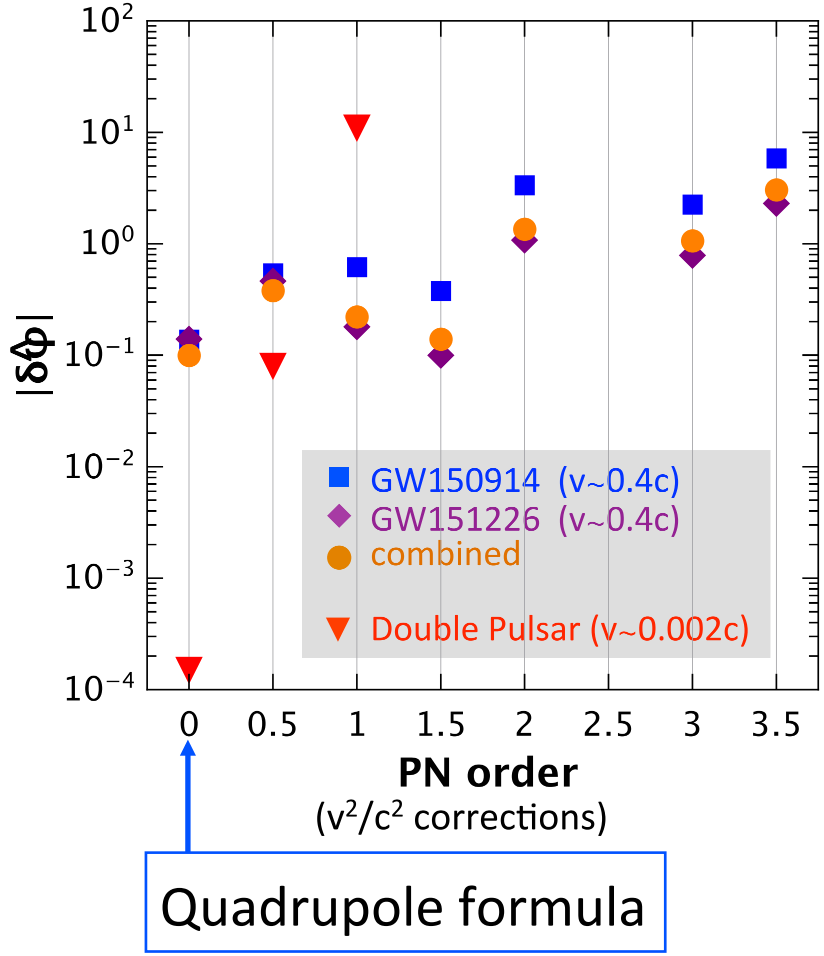
90% credible regions for the waveform and the GW frequency



GR violations are limited to less than 4% (for effects that cannot be reabsorbed in a redefinition of parameters)

[LSC/Virgo 2016]

Testing post-Newtonian corrections in the orbital phase evolution due to GW damping



[LSC/Virgo 2016, Kramer et al. in prep.]

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)

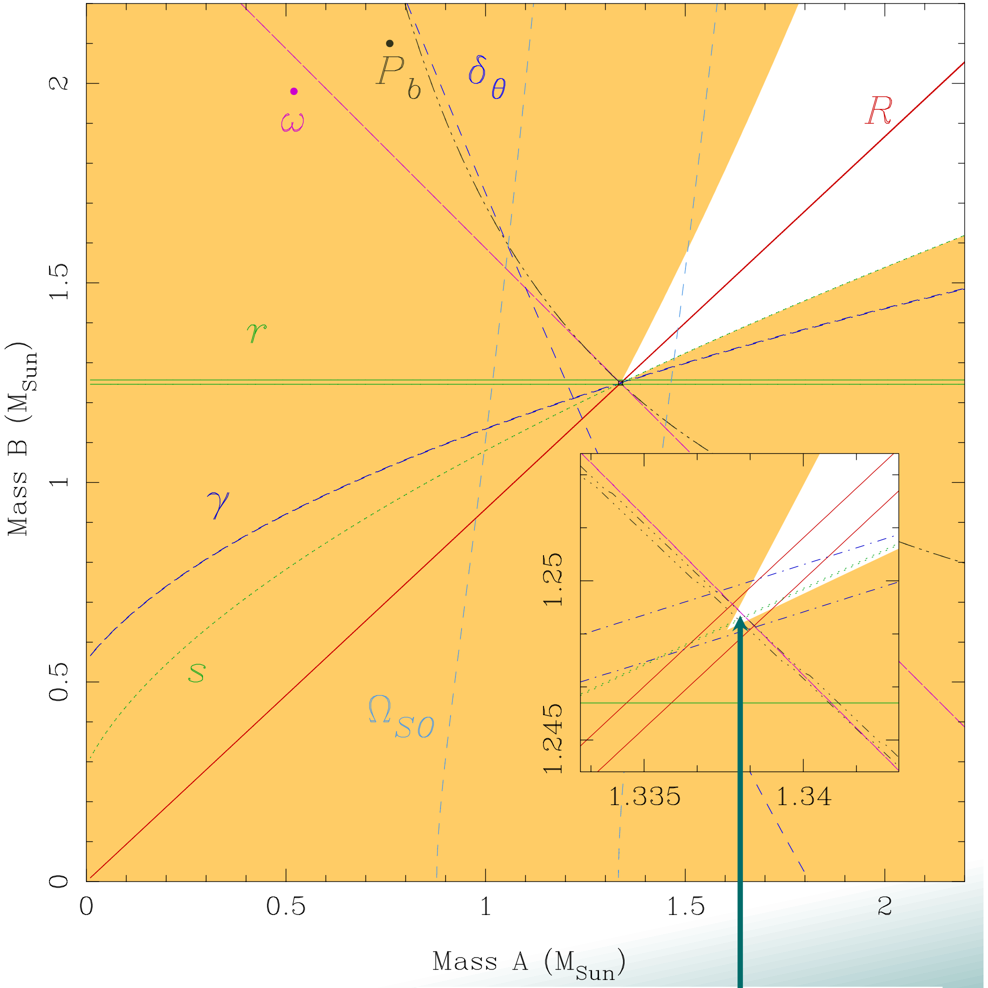
Orbital period decay (-39 μs/yr)

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

Mass ratio (1.07)

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

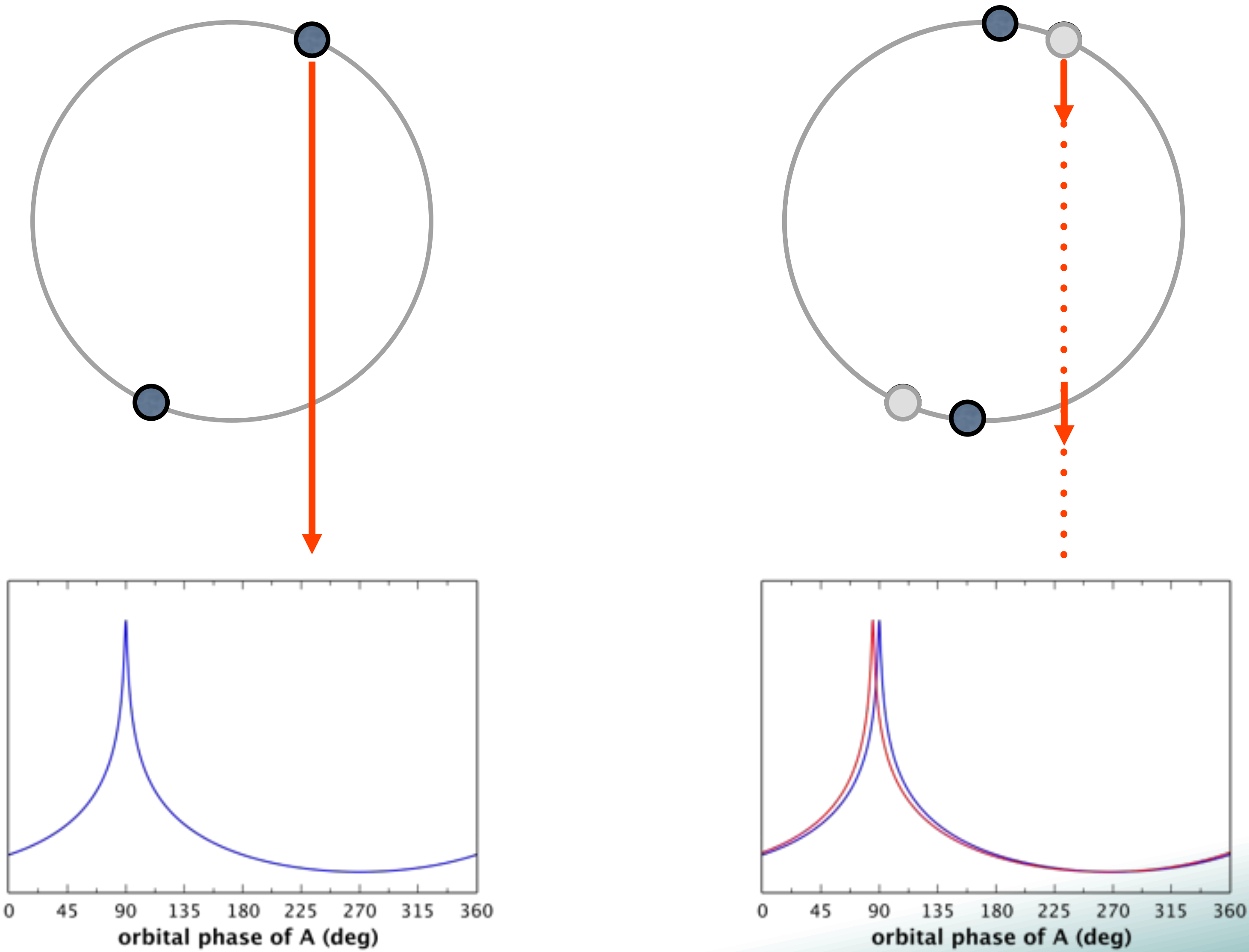
7 - 2 = 5 tests of GR plus 1 emerging one



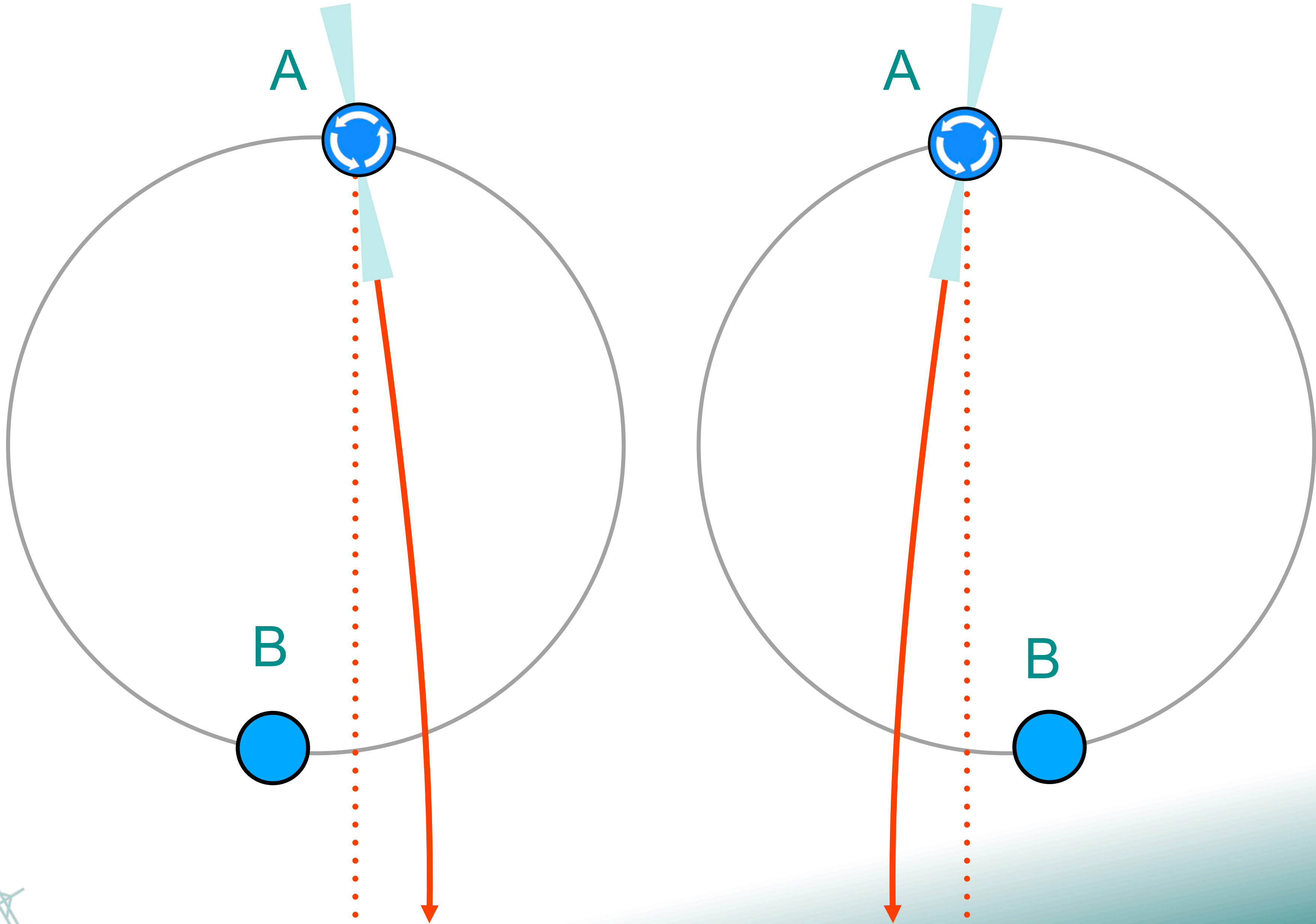
$$m_A = 1.33816 \pm 0.00002\,M_\odot$$
$$m_B = 1.24891 \pm 0.00002\,M_\odot$$

Higher order light propagation: Effect of moving lens

1.5PN Shapiro Effect:



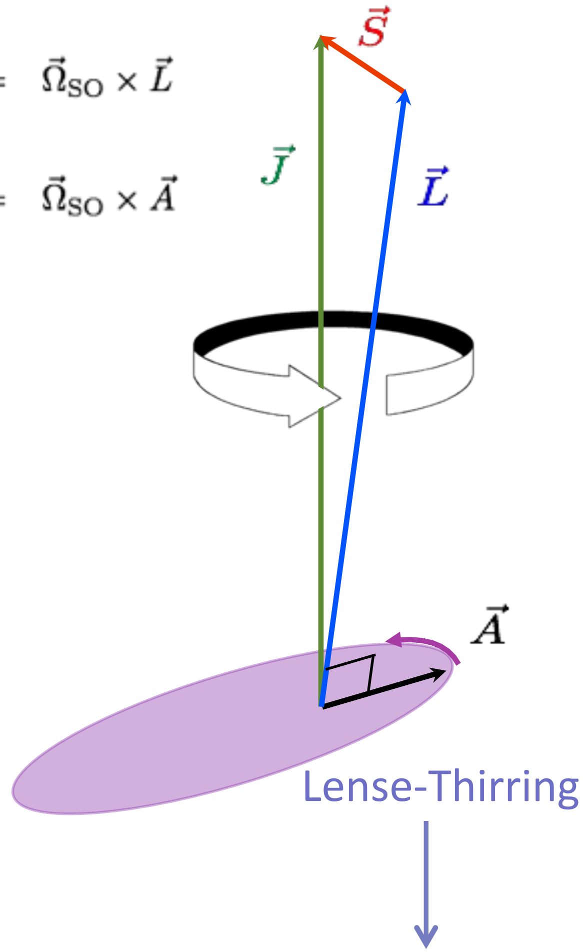
Higher order light propagation: Effect of light bending



Equation-of-State Dependence of Periastron Advance

$$\left\langle \frac{d\vec{L}}{dt} \right\rangle = \vec{\Omega}_{SO} \times \vec{L}$$

$$\left\langle \frac{d\vec{A}}{dt} \right\rangle = \vec{\Omega}_{SO} \times \vec{A}$$



$$\dot{\omega} = \dot{\omega}_{1pN} + \dot{\omega}_{2pN} + \dot{\omega}_{SO}$$

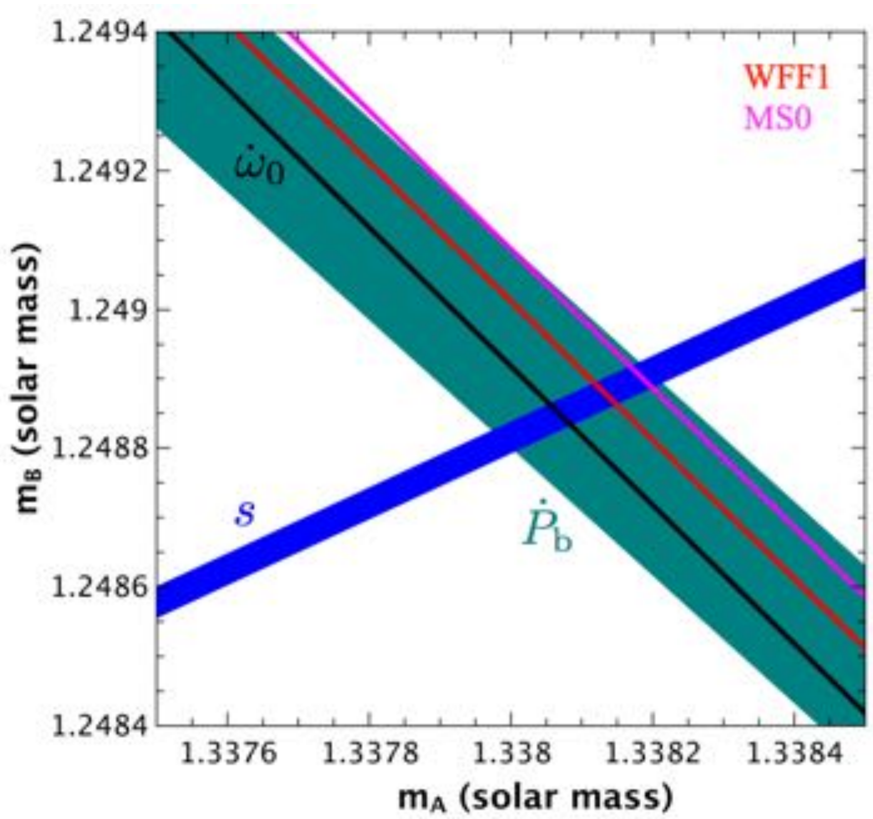
[Damour & Schäfer (1988)]

➔ Moment-of-inertia!

$$S_A \gg S_B\,, \quad \vec{S}_A \parallel \vec{L}$$

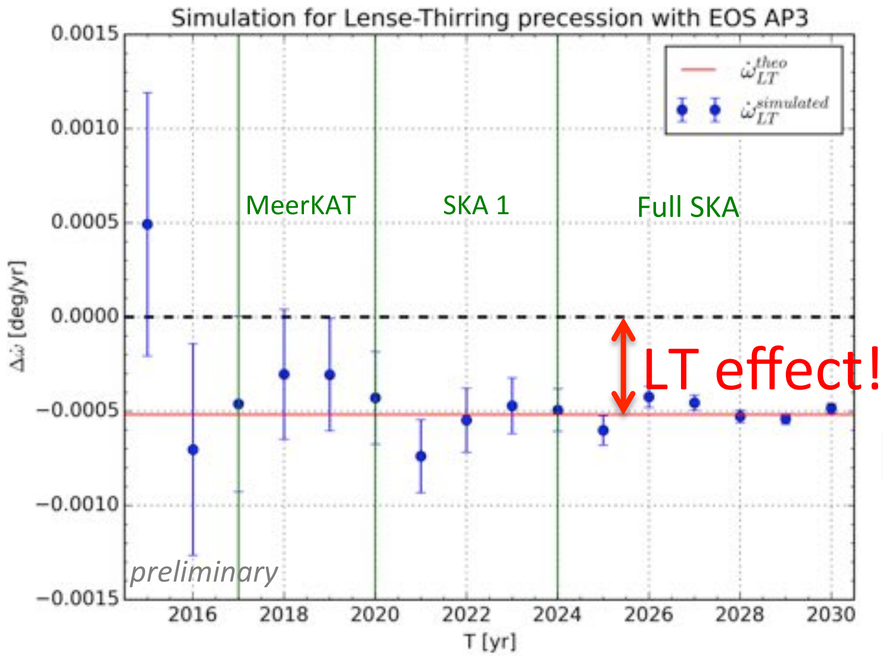
$\dot{\omega}_{1pN}$	=	16.89...	deg/yr
$\dot{\omega}_{2pN}$	=	0.00044	deg/yr
$\dot{\omega}_{SO}$	=	$-0.00038\, I_A/(10^{45}\,\mathrm{g\,cm^2})$	deg/yr
$\delta\dot{\omega}_{obs}$	=	0.00002	deg/yr

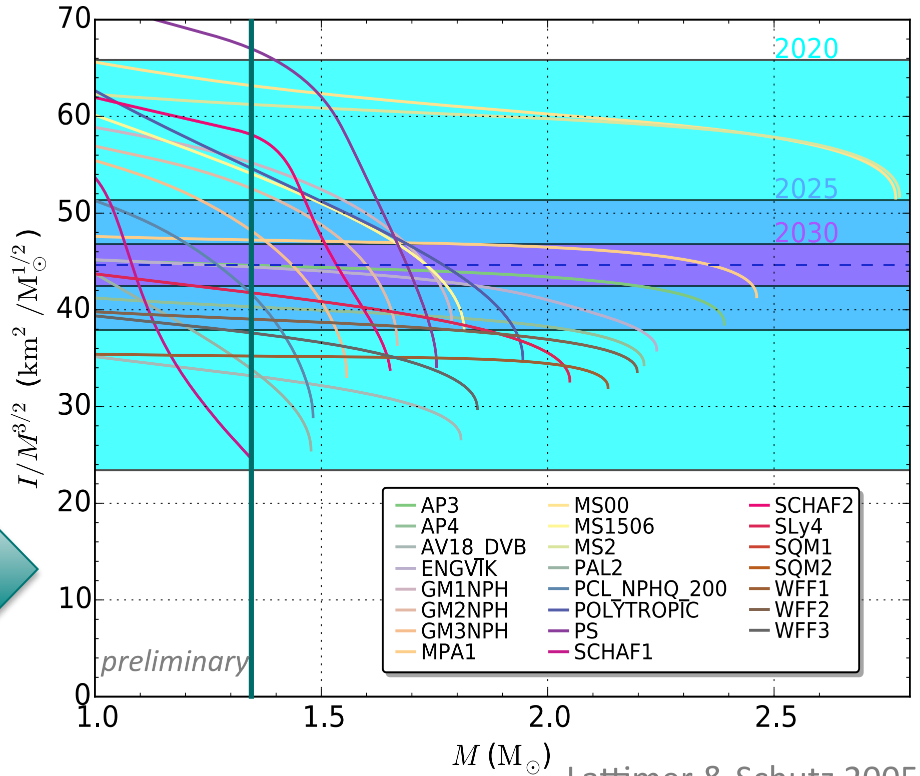
[Kramer *et al.* (in prep.)]



Future Constrains on the EOS with the Double Pulsar

MOCK data simulations of future pulsar signals (Kehl MSc thesis, 2015).





Lattimer & Schutz 2005

Lense-Thirring precession will be qualitatively measureable with SKA1

Restrict the EOS by measuring Lense-Thirring precession with future telescopes (SKA)

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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)

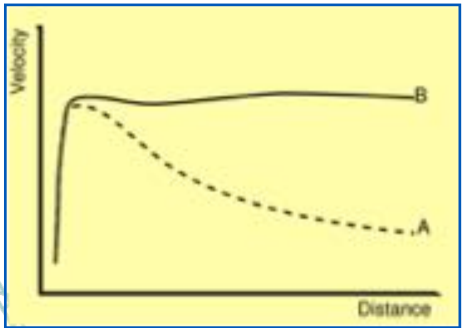
Bekenstein's TeVeS and the Double Pulsar

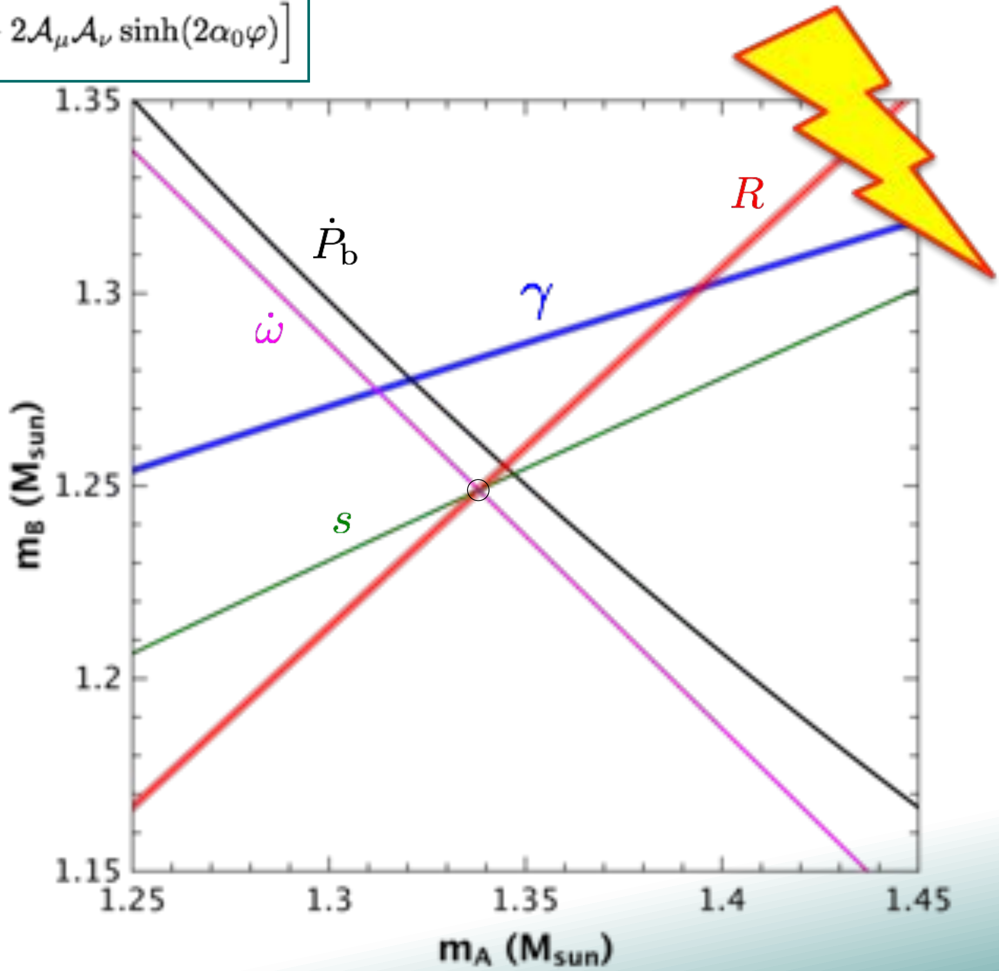
$$S = \frac{c^3}{16\pi G_*}\int d^4x\sqrt{-g^*}\Big(R^* - 2\mathcal{F}(g^*_{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi)\Big)$$
$$+ S_{\rm vector}\Big[\mathcal{A}_\mu; g^*_{\mu\nu}\Big]$$
$$+ S_{\rm matter}\Big[\psi; \tilde{g}_{\mu\nu} \equiv g^*_{\mu\nu}\exp(-2\alpha_0\varphi) - 2\mathcal{A}_\mu\mathcal{A}_\nu\sinh(2\alpha_0\varphi)\Big]$$

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?

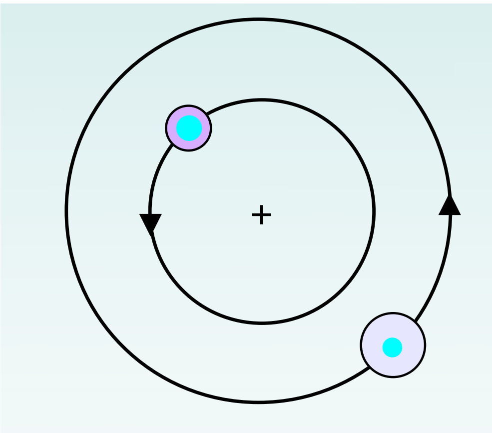
Unlike GR, most alternative theories of gravity – including tensor-scalar theories – predict dipole radiation that dominates the energy loss of the orbital dynamics:

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

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

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

Hence, visible in orbital decay:



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

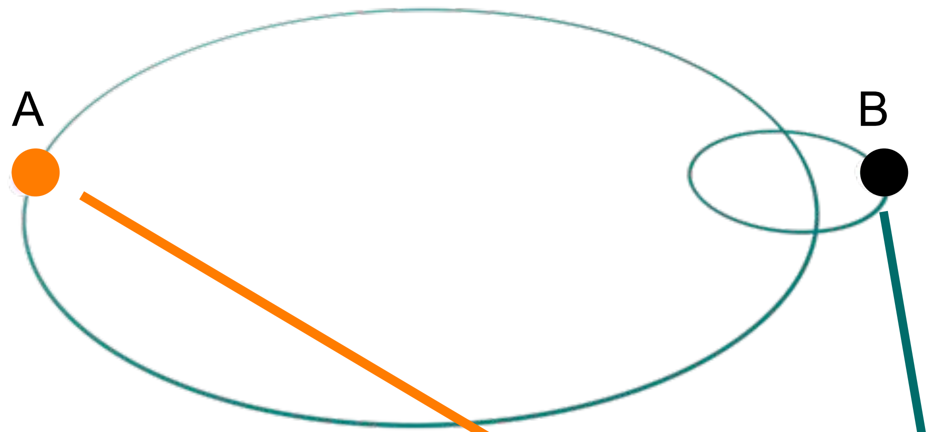
$$\dot{P}_{\rm b}^{\rm dipole} \propto \left(\frac{v}{c}\right)^3 (\alpha_A - \alpha_B)^2$$

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

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

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

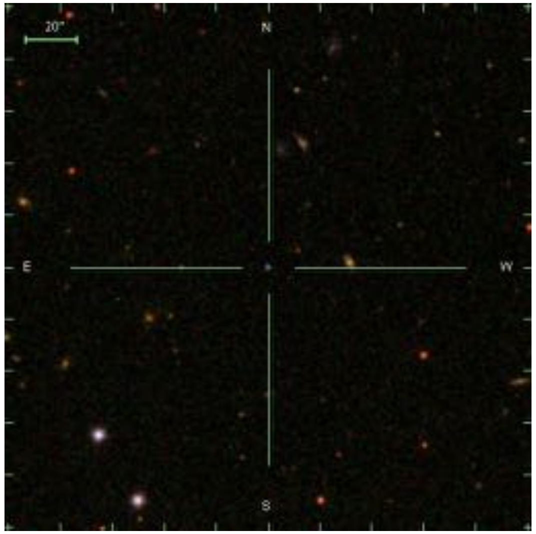
But PSR – WD system also effective lab – in particular if PSR is massive!

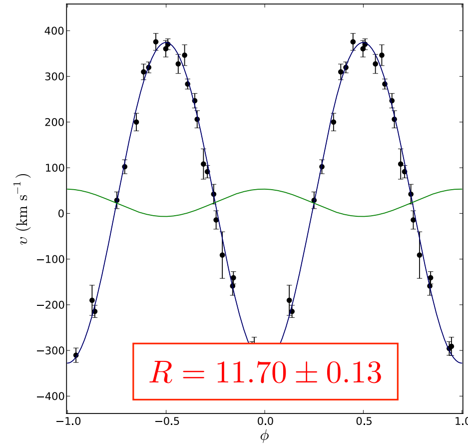
Next best thing: a PSR-WD system

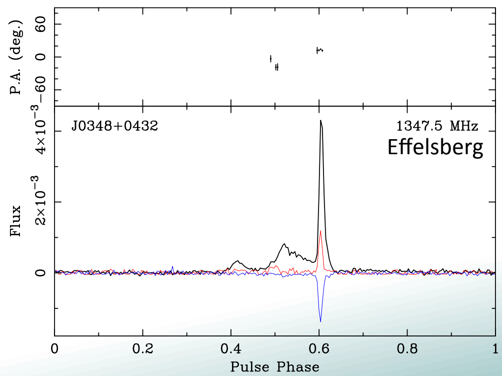
- PSR J0348+0432: first massive NS in relativistic orbit (Lynch et al. 2013)
- Combining VLT, Effelsberg, Arecibo & GBT data, new record mass measured:

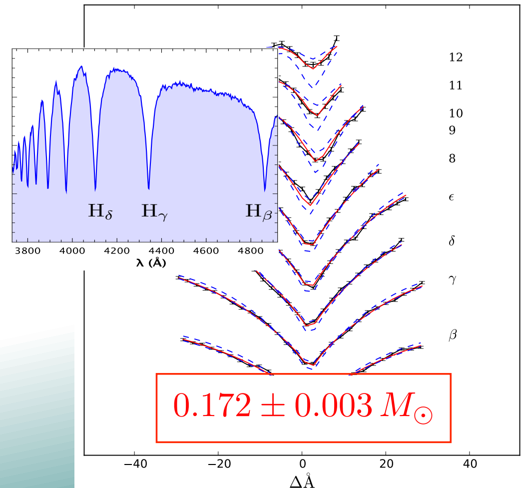
  M=2.01±0.04 $M_\odot$ (Antoniadis et al., 2013)

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









Testing a new gravity regime

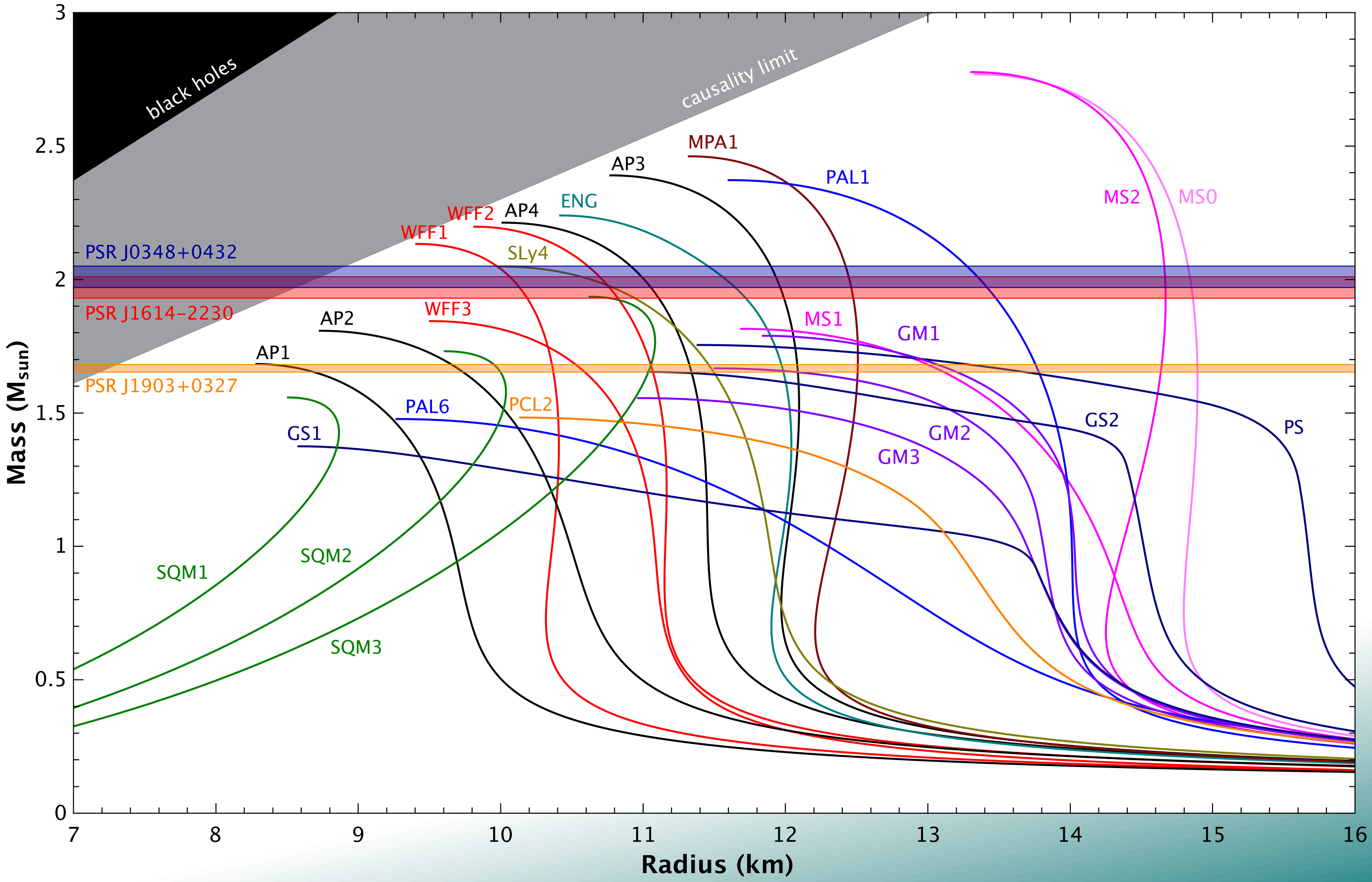
- PSR J0348+0432: first massive NS in relativistic orbit (Lynch et al. 2013)
- Combining VLT, Effelsberg, Arecibo & GBT data, new record mass measured:

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

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)

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

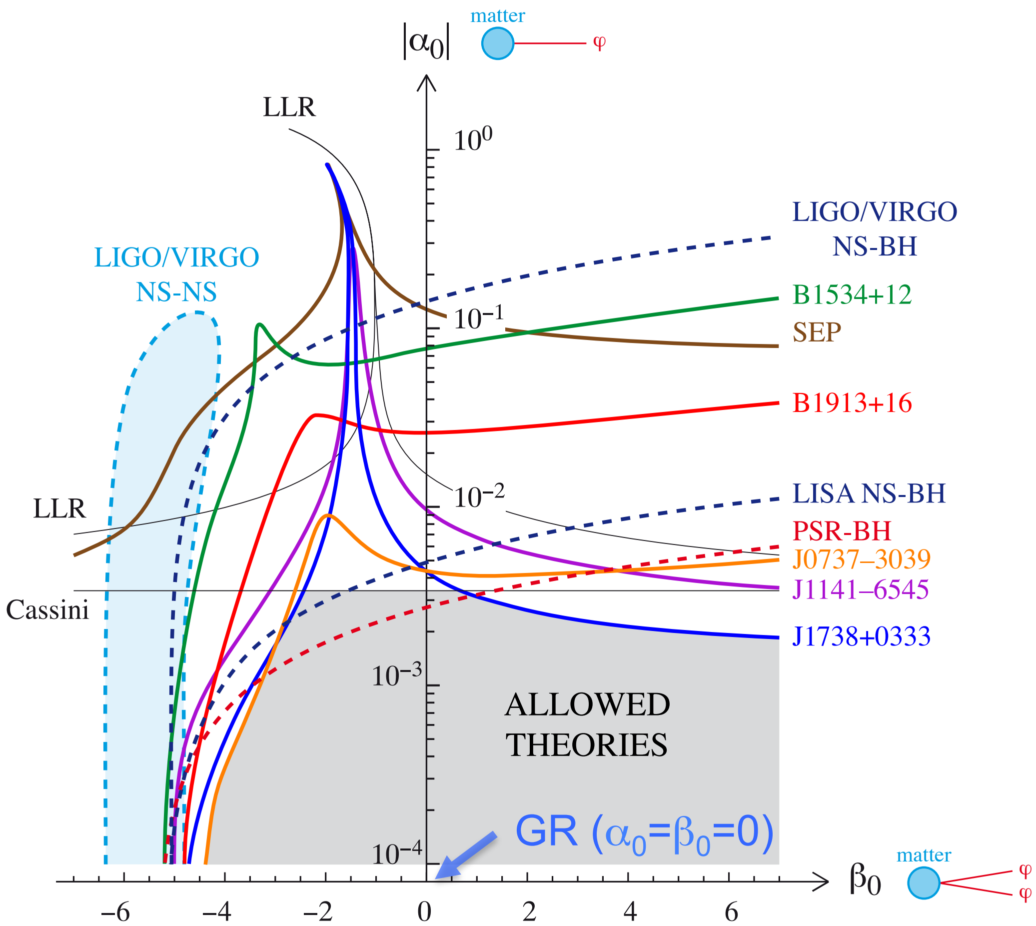
No indication of dipolar radiation!

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

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

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:



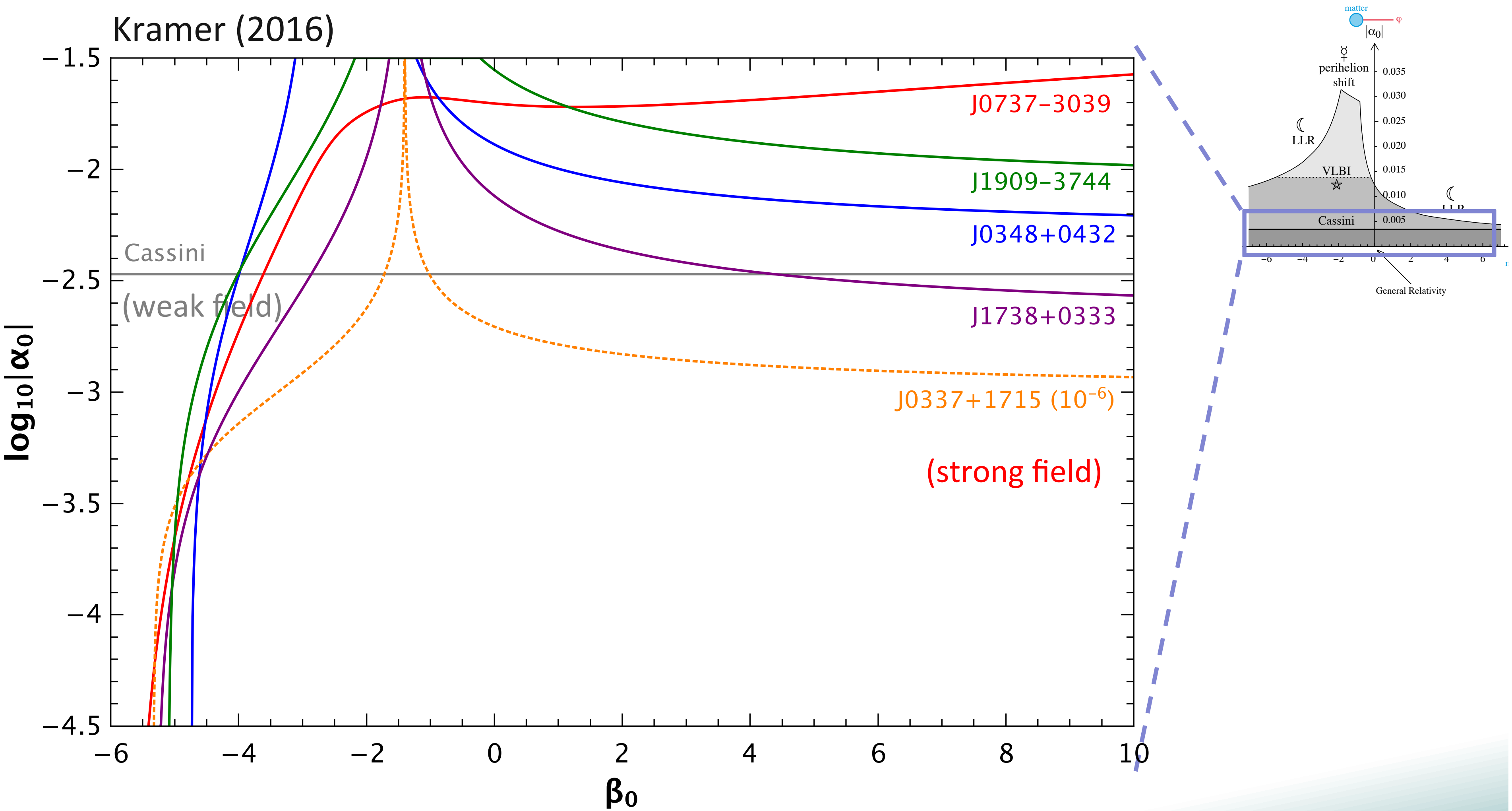
Note:

- In GR, α_0 and $\beta_0 = 0$
- Jordan-Fierz-Brans-Dicke: on axis of β_0=0

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

Figure by Esposito-Farese

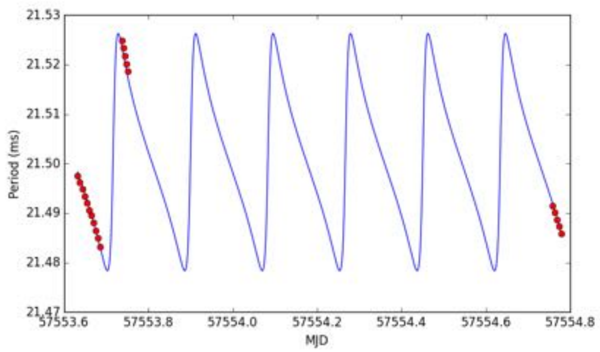
Constraining tensor-scalar gravity

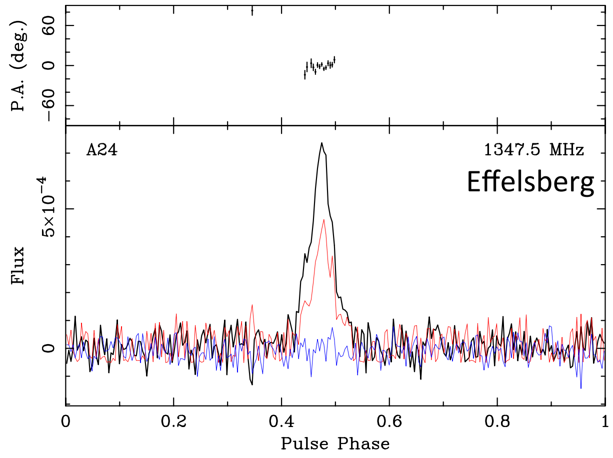


GR ($\alpha_0=\beta_0=0$)

The new "most relativistic binary"...

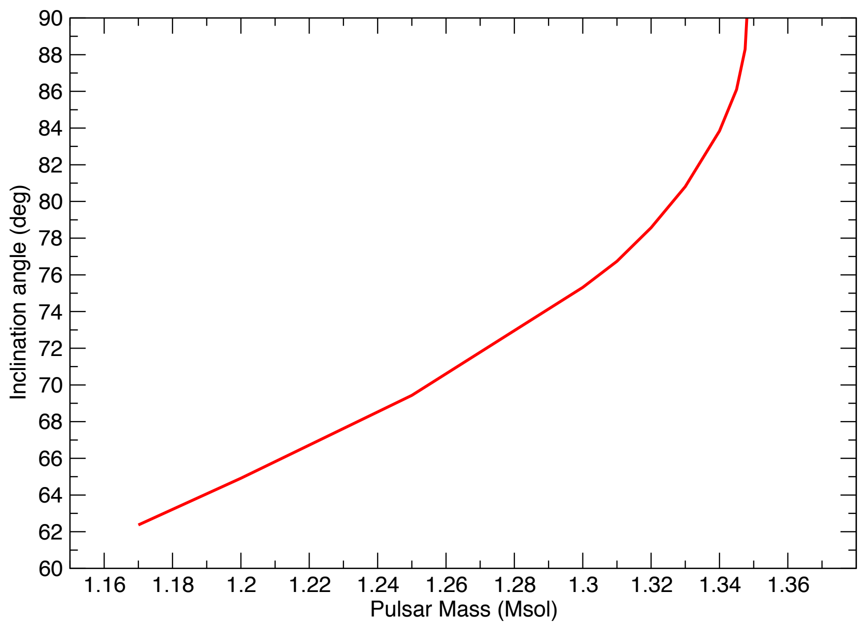
- New discovery from HTRU-S Low-lat (Cameron, Ng et al. in prep.)
- A new 4.4-h binary at about 6 kpc distance:
  - P_0 = 21.5 ms
  - P_b = 0.184 d
  - x = 2.24 lt-s
  - e = 0.61 (!)
  - $d\omega/dt$ = 10.38 deg/yr
  - max. acc > 600 m/s^2
  - $M_{tot} = 2.74 M_\odot$, $M_c > 1.39 M_\odot$





Expected:

  - γ = 3.58 ms
  - $dP_b/dt = 5.3 \times 10^{-12}$ s/s
  - $\Omega_{precess}$ = 3.1 deg/yr
  - Merger < 80 Myr – record!



The new "most relativistic binary"...

- Largest orbital precession/orbit & largest GW luminosity