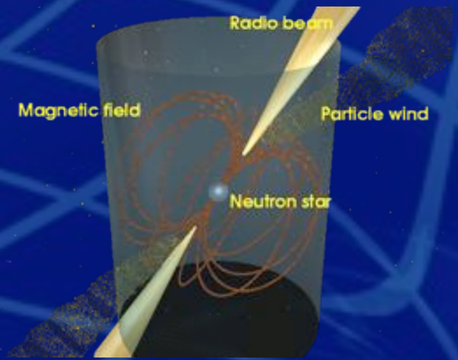
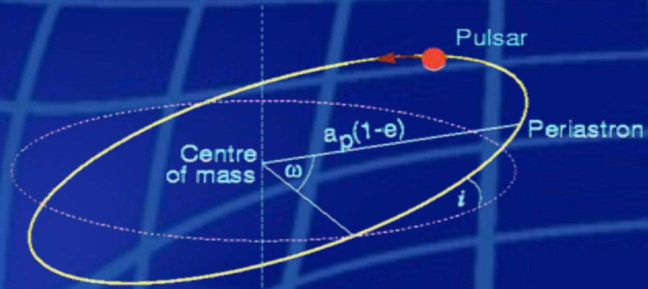
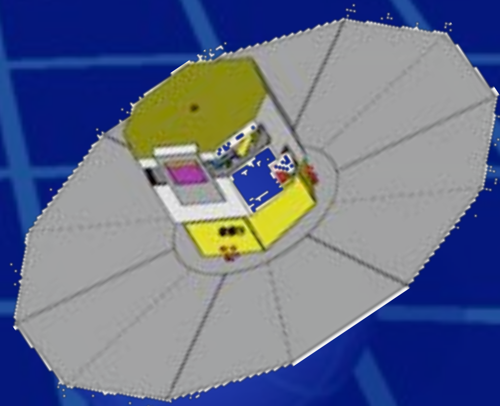
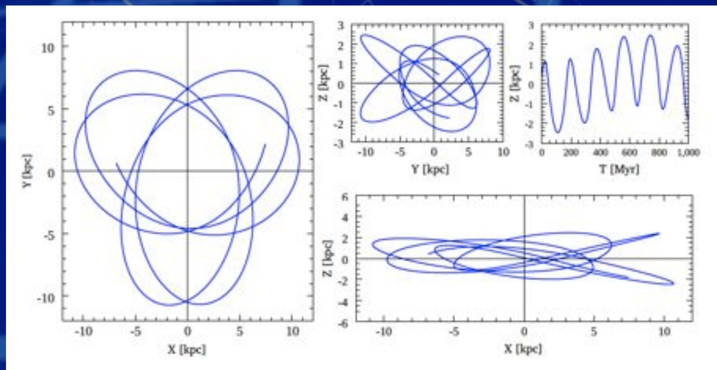
Precision measurements for binary pulsars









Michael Kramer
Max-Planck-Insitut für Radioastronomie
University of Manchester – Jodrell Bank Centre for Astrophysics

The University of Manchester Jodrell Bank Observatory

What do we mean by precision measurement? Best of…

Masses:

- Masses of neutron stars: m_1 = 1.4398(2) $M_\odot$ and m_2 = 1.3886(2) $M_\odot$ (Weisberg et al. 2010)
- Mass of WD companions: Shapiro: 0.204 (2) $M_\odot$ (Jacoby et al. 2005)
  optical: 0.181 (7) $M_\odot$ (Antoniadis et al. in prep.)
- Mass of millisecond pulsar: 1.67(2) $M_\odot$ (Freire et al. 2010)
- Main sequence star companion: 1.029(8) $M_\odot$ (Freire et al. 2010)

Spin parameters:

- Period: 5.757451924362137(2) ms (Verbiest et al. 2010) = 2 atto seconds uncertainty!

Orbital parameters:

- Period: 0.102251562479(8) days (Kramer et al. in prep.)
- Eccentricity: 3.5 (1.1) × 10^{-7} (Freire et al. in prep.)

Astrometry:

- Distance: 157(1) pc (Verbiest et al. 2010)
- Proper motion: 140.915(1) mas/yr (Verbiest e t al. 2010)

GR Test:

- Perihelion advance: 4.226598(5)deg/yr (Weisberg et al. 2010)
- Shrinkage due to GW emission: 7.152±0.008 mm/day (Kramer et al. in pep)
- GR validity (obs/exp): 1.0000(5) (Kramer et al. in prep.)

In the future…

- Measure mass of SGR A* to 10^{-6}!
- Measure spin of SGR A* to precision of 10^{-4} to 10^{-3} : Cosmic Censorship!
- Measure quadrupole moment to 10^{-3} to 10^{-2} : No hair! (Liu et al. submitted)

Outline or *How do we do it?*

Pulsar timing

- Pulsars
- Timing
- Solving pulsars & orbits
- Post-Keplerian parameters

Optical observations

- Doppler measurements
- Surface gravity

Astrometry

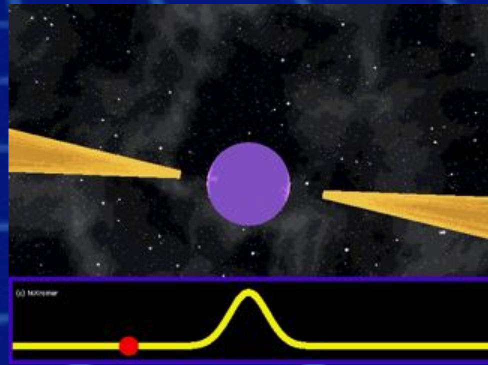
- Timing parallax
- Orbital annual parallax
- Kinetic parallax

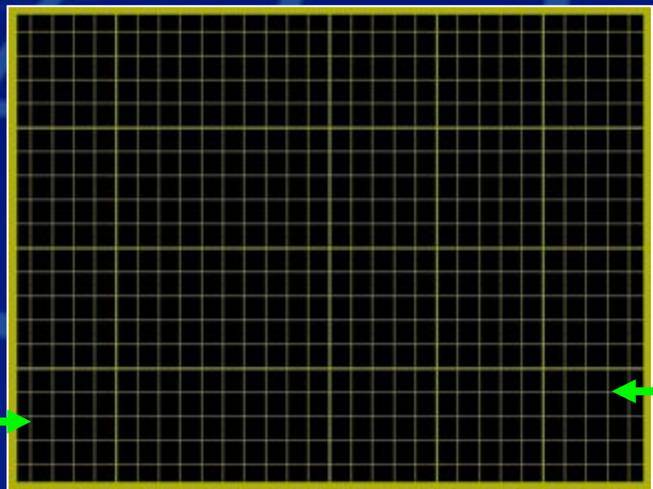
The future

A simple and clean experiment: Pulsar Timing

Pulsars are…

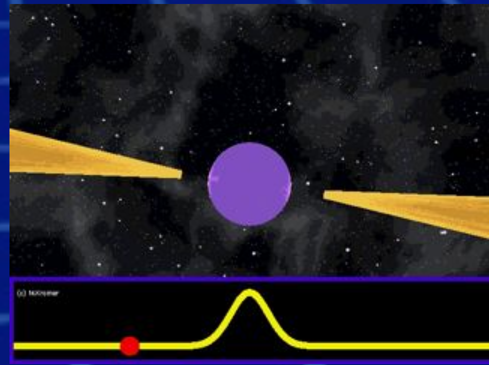
- …cosmic lighthouses
- …almost Black Holes: ~1.4 $M_{\odot}$ within 20km
- …objects of extreme matter : 10x nuclear
- …massive flywheels, hence very stable clocks
- …pulsar timing measures arrival time (TOA):



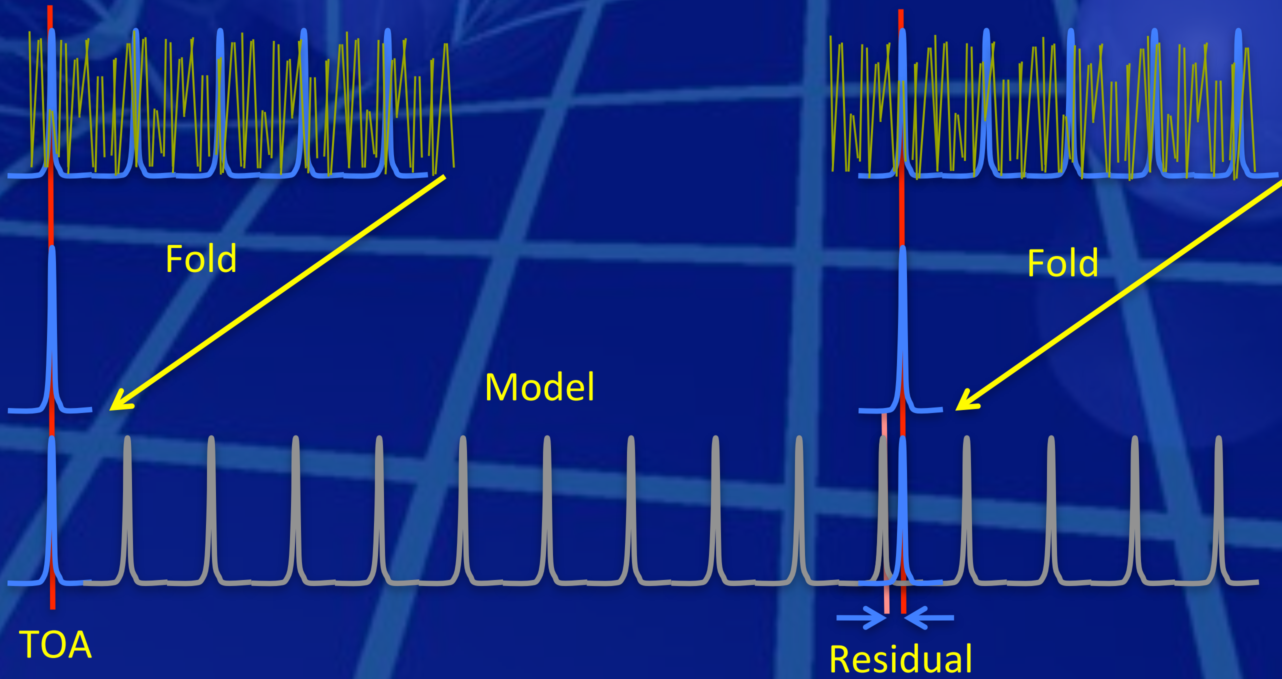


A simple and clean experiment: Pulsar Timing

Pulsars are…



- …cosmic lighthouses
- …almost Black Holes: ~1.4 $M_{\odot}$ within 20km
- …objects of extreme matter : 10x nuclear
- …massive flywheels, hence very stable clocks
- …pulsar timing measures arrival time (TOA):



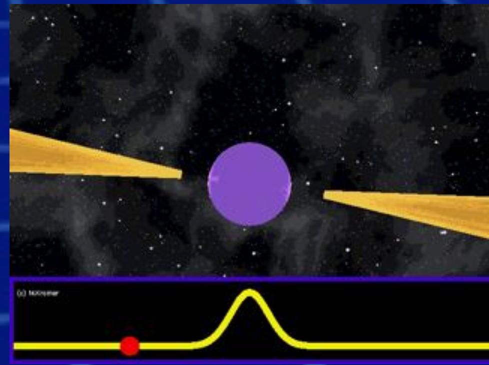
Counting rotations: about 1,000,000 more precise than Doppler method!

The University of Manchester
Jodrell Bank Observatory
MAX-PLANCK-GESELLSCHAFT

A simple and clean experiment: Pulsar Timing

Pulsars are…

- …cosmic lighthouses
- …almost Black Holes: ~1.4 $M_{\odot}$ within 20km
- …objects of extreme matter : 10x nuclear
- …massive flywheels, hence very stable clocks
- …pulsar timing measures arrival time (TOA):



PSR J1012+5307: 15 years of observations with EPTA

P = 0.005255749014115410 ± 0.000000000000000015 s

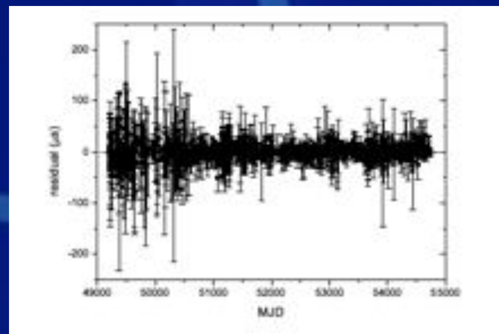
[*Lazaridis et al. 2009*]

→ 100 billion rotations since discovery & not lost a single count!

Determine all parameters by fitting TOAs to Timing model, i.e. minimizing:

$$\chi^2 = \sum_{i \in TOAs} \left(\frac{N(t_i) - n_i}{\sigma_i} \right)^2$$

where n_i is nearest integer to $N(t_i)$ for TOA t_i with uncertainty σ_i

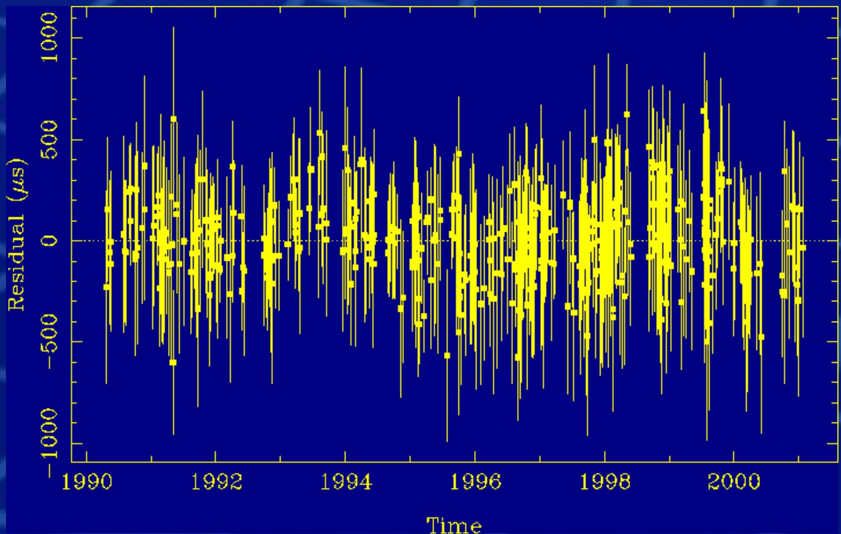


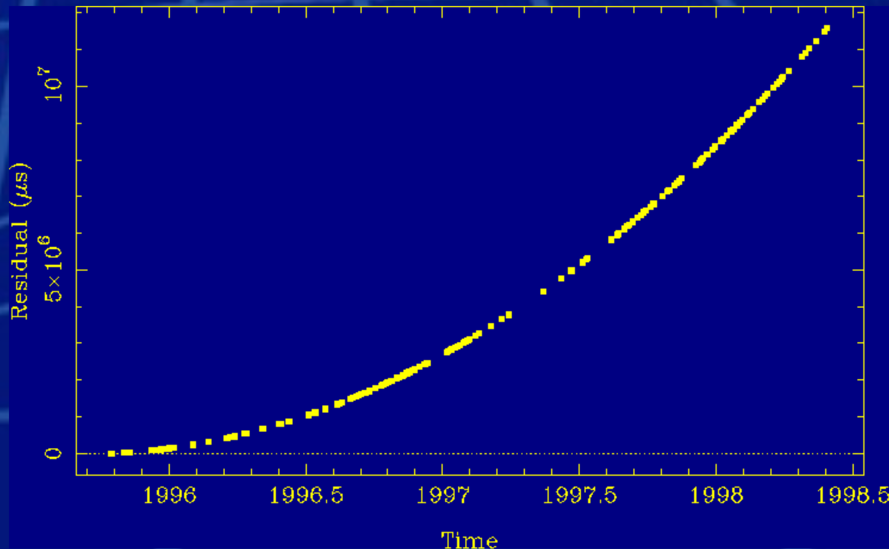
If all significant parameters determined, we expect gaussian post-fit residuals.

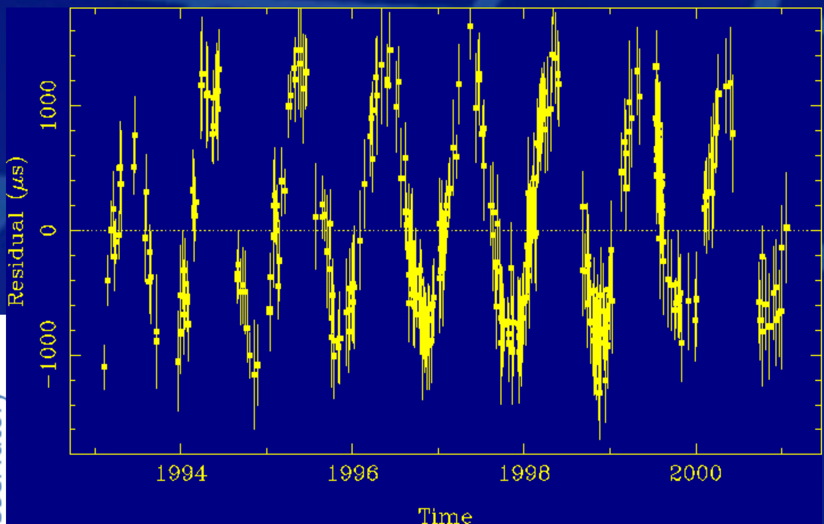
The University of Manchester Jodrell Bank Observatory

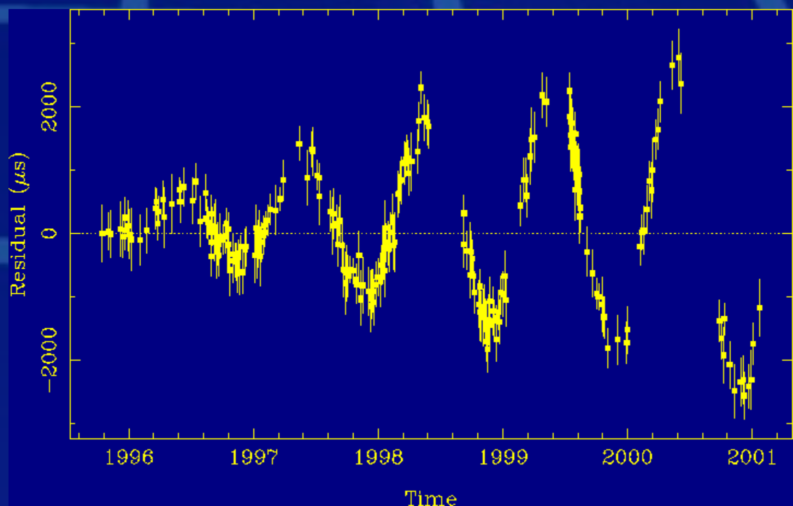
Post-fit residuals characteristics

Non-random post-fit residuals identify unmodelled effects:

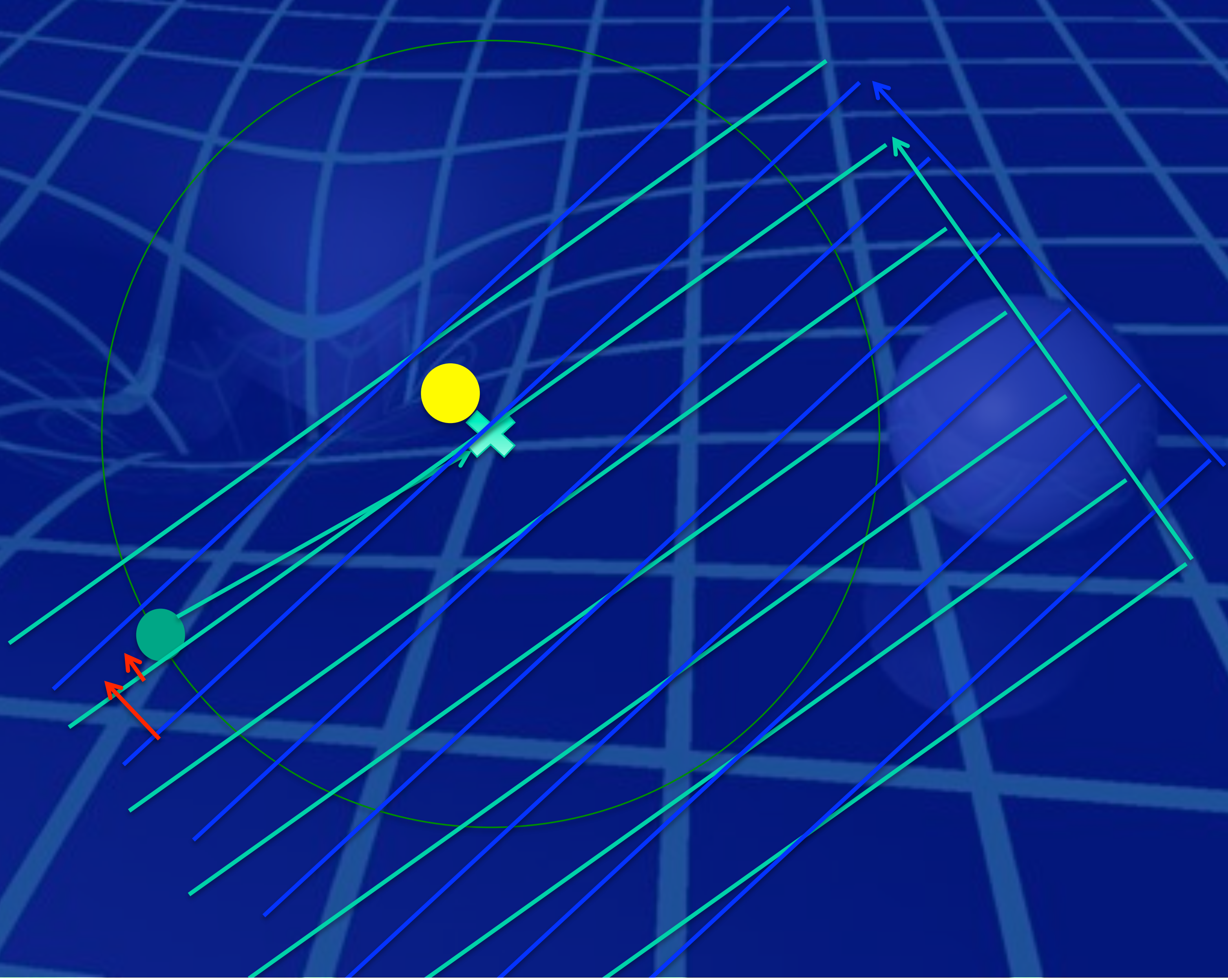








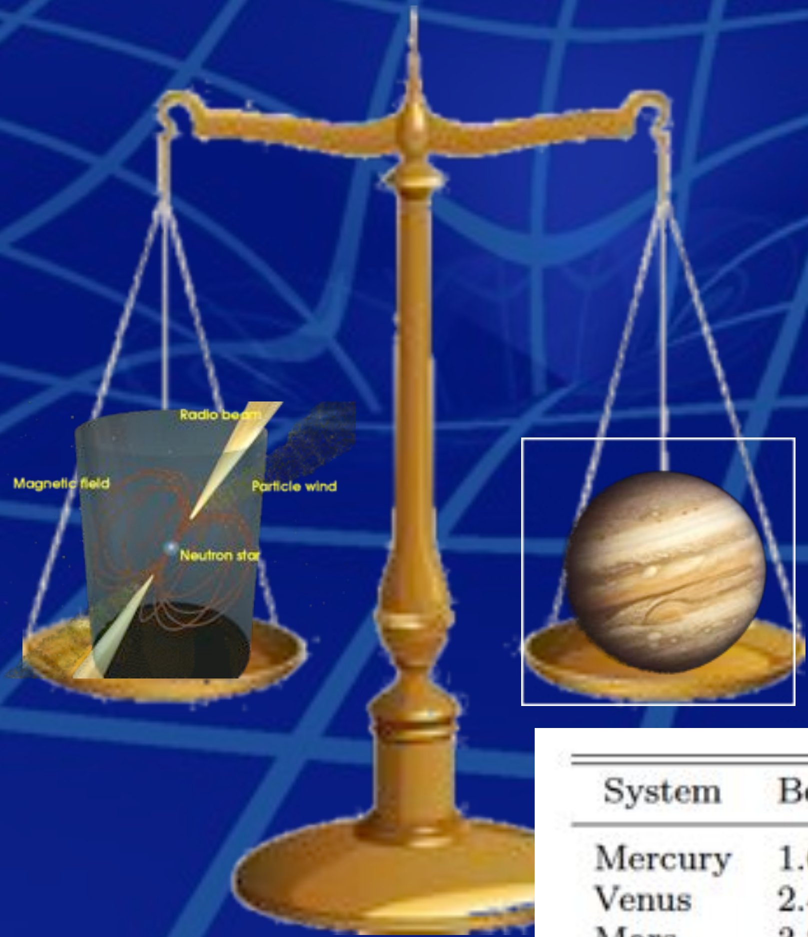
Good knowledge of Solar System Barycentre is essential

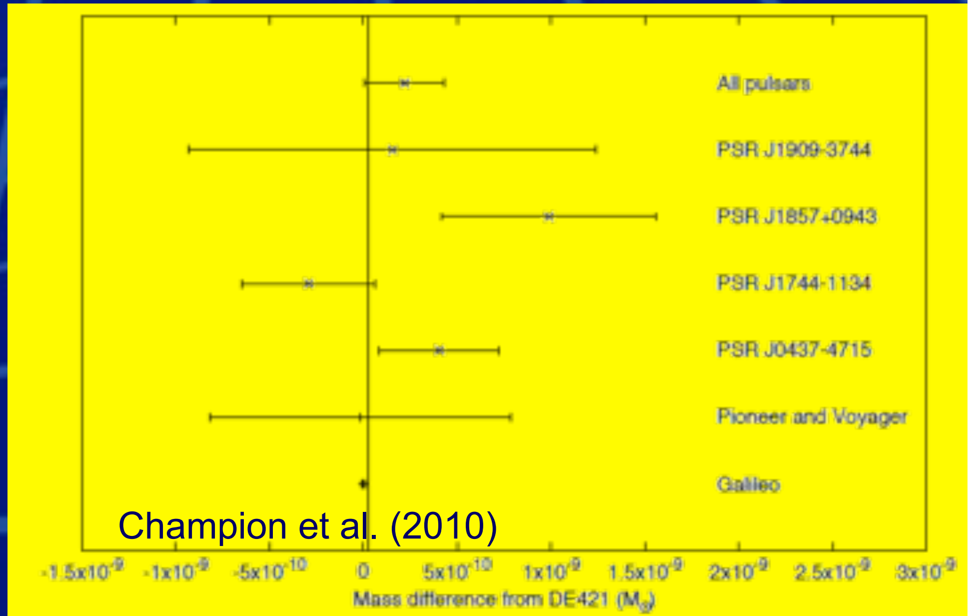


The University of Manchester
Jodrell Bank
Observatory

Putting the planets on the pulsar scale!

Measuring the Jovian system mass and other planets!





System	Best-Known Mass ($M_\odot$)	Ref.	This Work ($M_\odot$)	δ_j/σ_j
Mercury	$1.66013(7)\times10^{-7}$	1	$1.6584(17)\times10^{-7}$	1.02
Venus	$2.44783824(4)\times10^{-6}$	2	$2.44783(17)\times10^{-6}$	0.05
Mars	$3.2271560(2)\times10^{-7}$	3	$3.226(2)\times10^{-7}$	0.58
Jupiter	$9.54791898(16)\times10^{-4}$	4	$9.547921(2)\times10^{-4}$	1.01
Saturn	$2.85885670(8)\times10^{-4}$	5	$2.858872(8)\times10^{-4}$	1.91

The University of Manchester Jodrell Bank Observatory

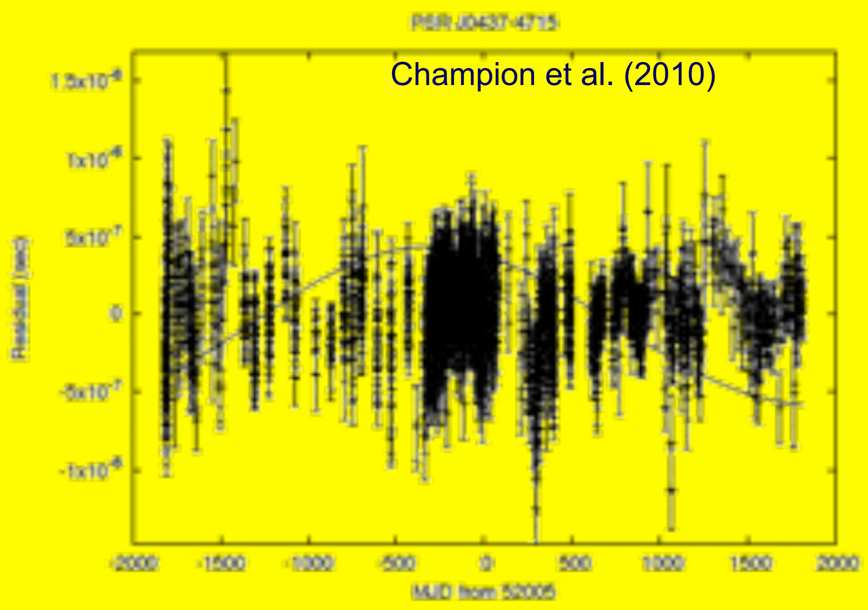
MAX-PLANCK-GESELLSCHAFT

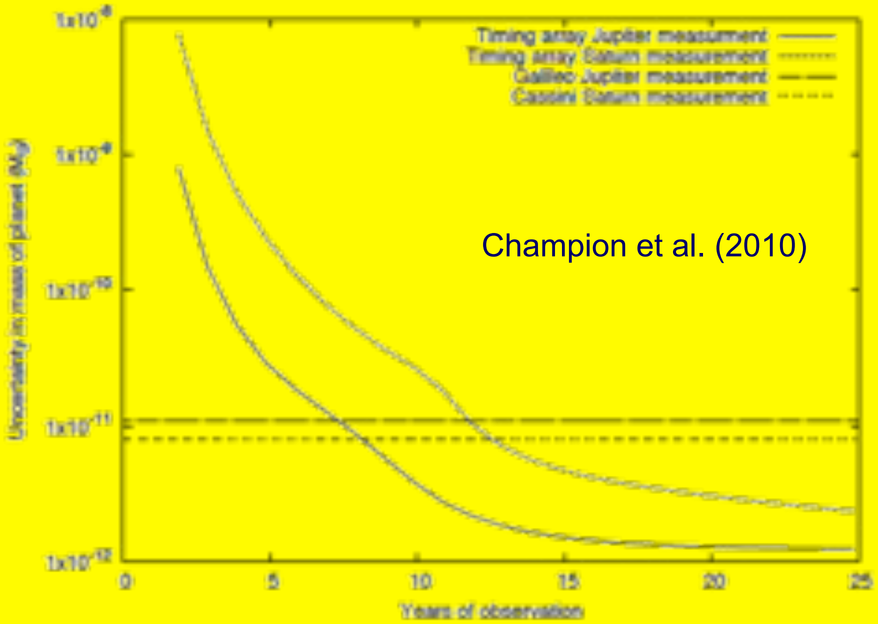
Putting the planets on the pulsar scale…

• incorrect planet masses have severe impact on our timing residuals

= measured – expected pulse times of arrival

• in the future, a PTA should measure planet masses very precisely



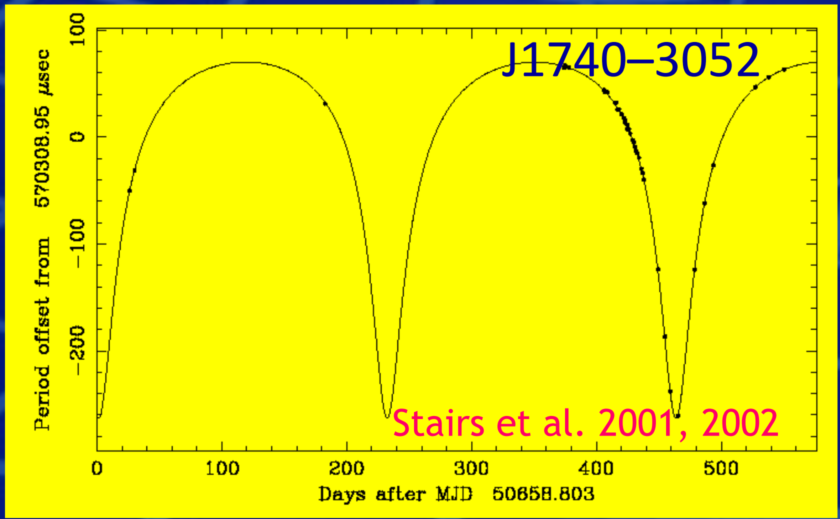


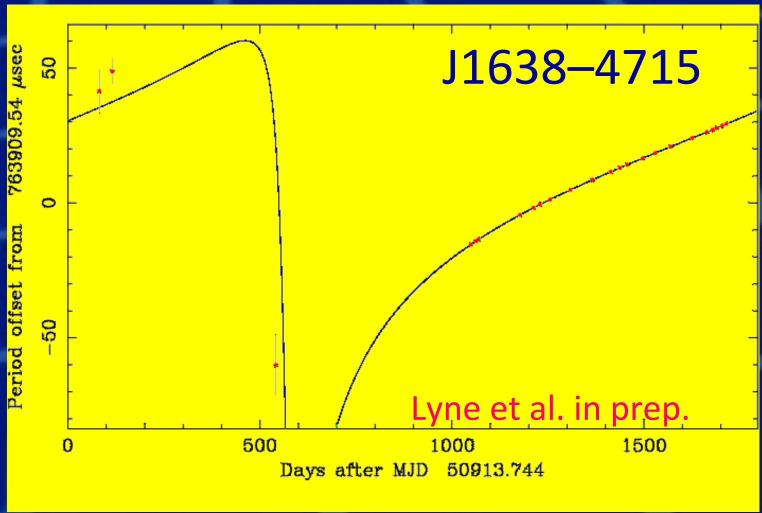
Effect of a jupiter mass modified by 5×10^{-10} M_{sun}

PTA with biweekly observations of 20 pulsars

Solving binary orbits I.

- We start with Doppler-varying pulse periods to get first guess, e.g.



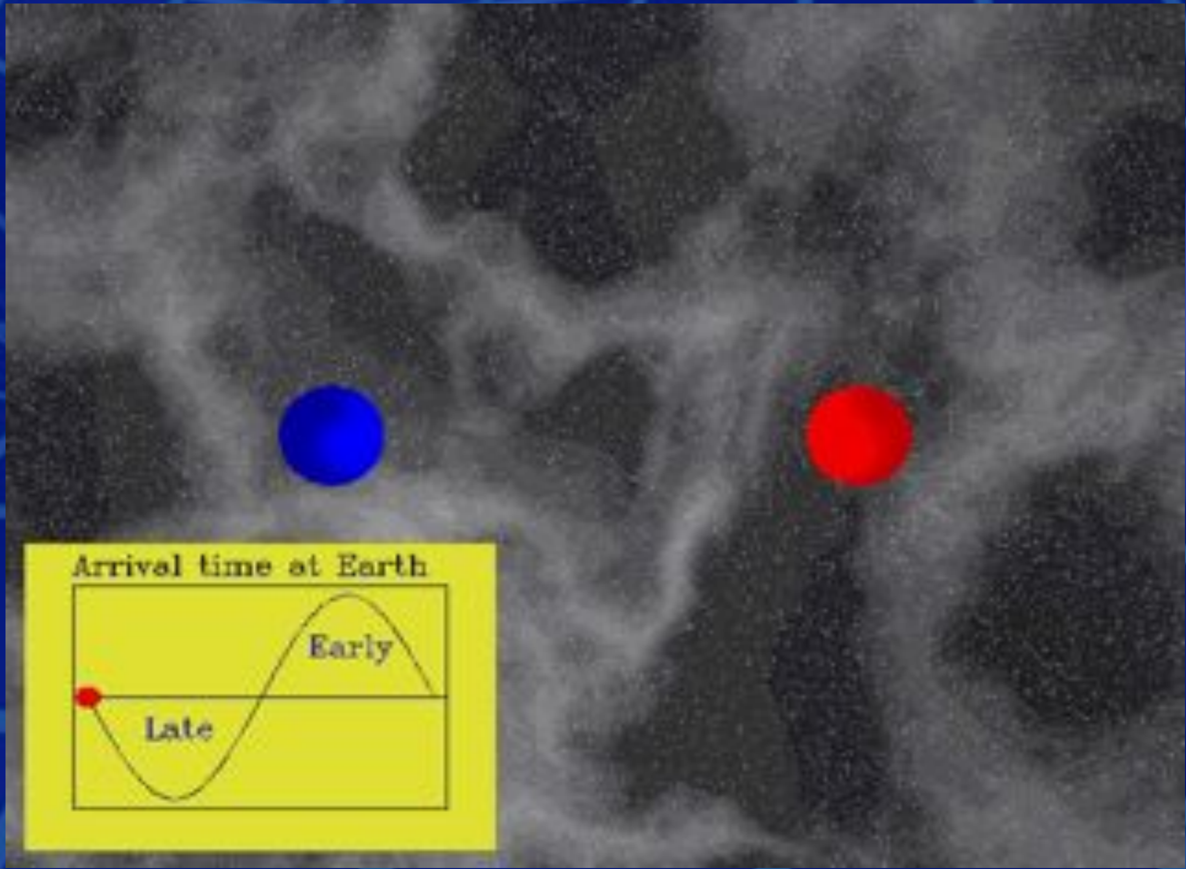


- Period = 570 ms
- P_b = 230 d
- e = 0.579
- M_c>11 M_{sun}

- Period = 764 ms
- P_b = 1744 d
- e = 0.96
- M_c>6 M_{sun}
- Eclipsing!

Solving binary orbits I.

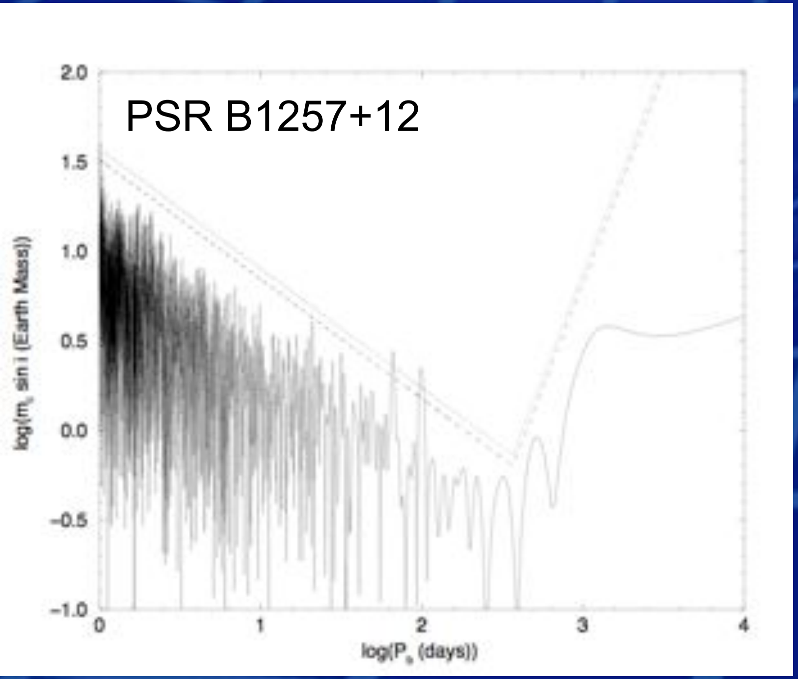
- We start with Doppler-varying pulse periods to get first guess
- After initial estimate, we switch to use arrival times:

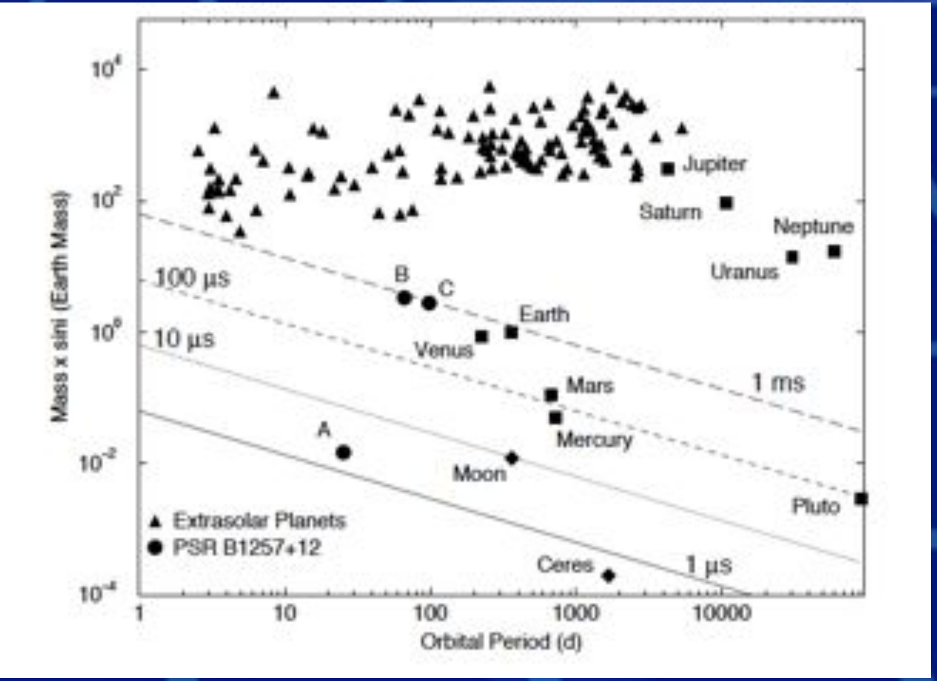


Current state-of-art locates orbital position to within 30 m!

Sensitive to asteroid-sized companions

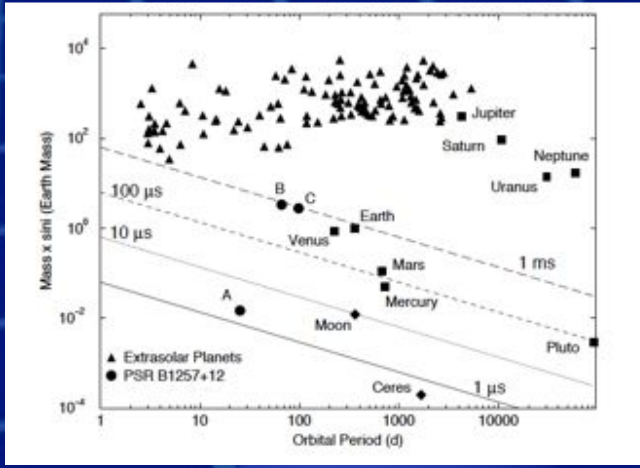
- Variation in pulse times-of-arrival very sensitive:



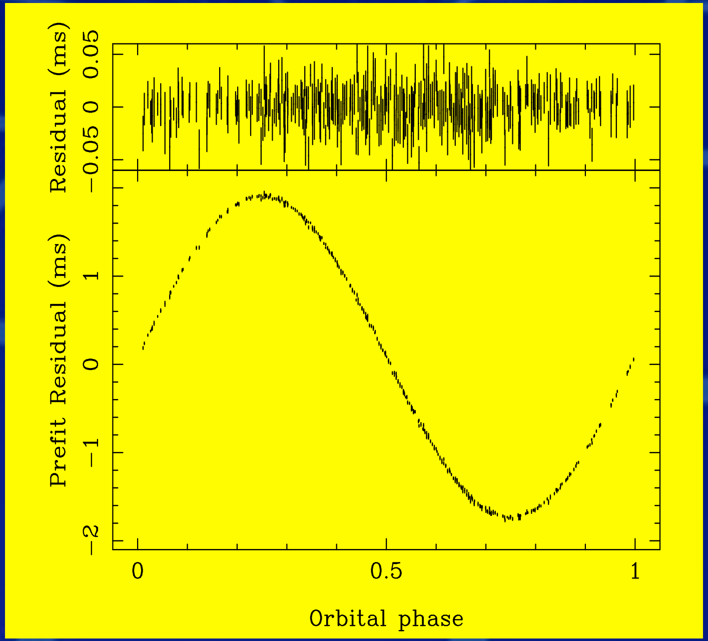


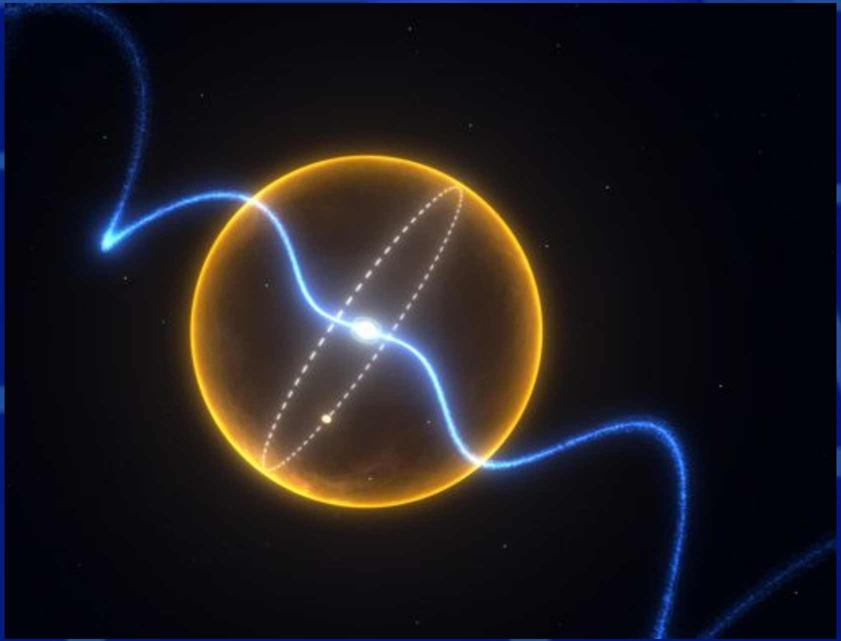
Sensitive to asteroid-sized companions

- Variation in pulse times-of-arrival very sensitive:



- Some exotic "planetary systems" – The "Diamond Planet" (Bailes et al. 2011)



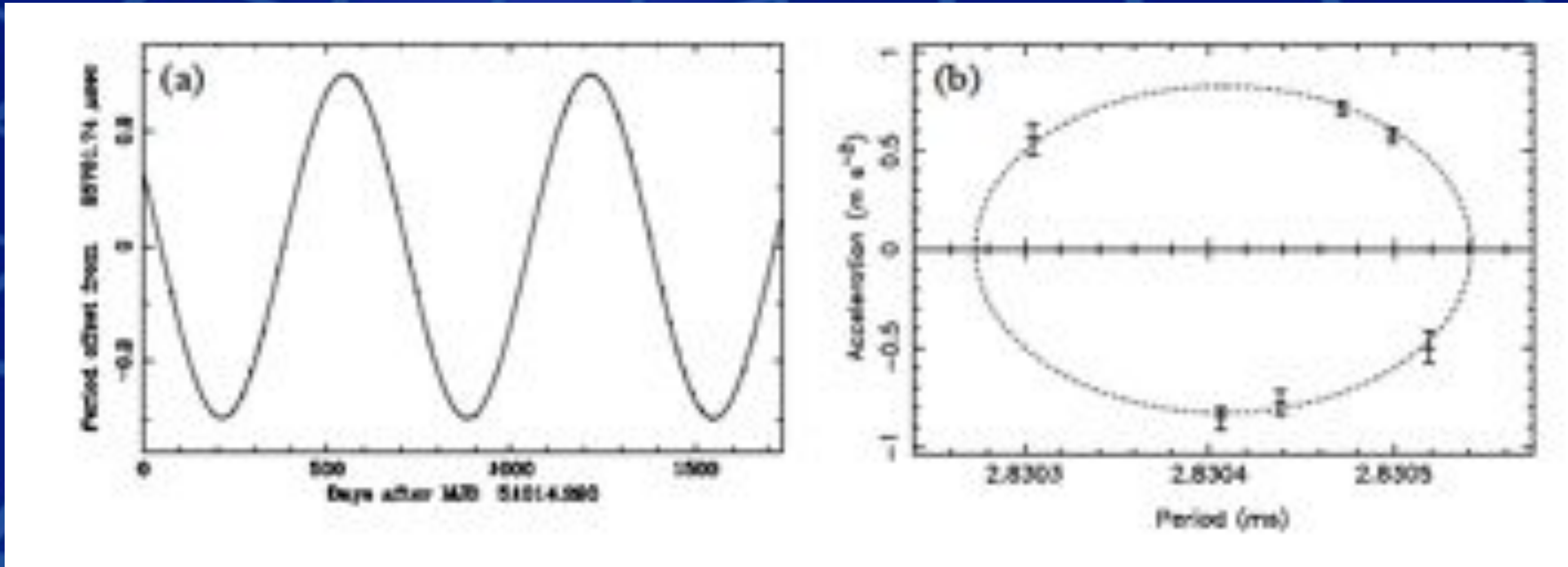


The University of Manchester
Jodrell Bank Observatory

Solving binary orbits II.

- Solving orbits is very difficult if cadence is low or large gaps in orbital coverage
- But neat method if acceleration can be measured (Freire, Kramer & Lyne 2001)

  For circular orbits, values for line-of-sight acceleration & period fall on ellipses



$$P(f) = P_0 + P_0 x \frac{2\pi}{P_B} \cos f \equiv P_0 + P_1 \cos f$$

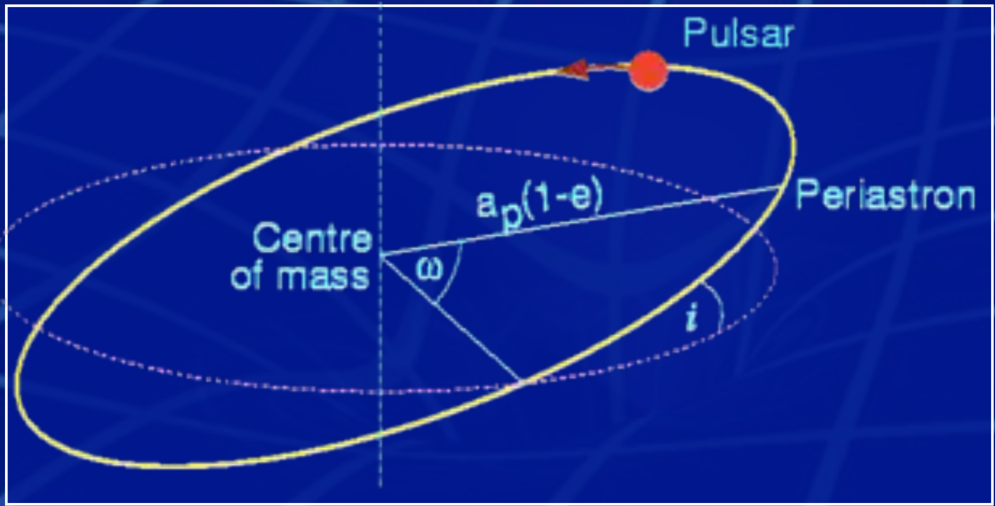
and

$$A(f) = -\frac{4\pi^2}{P_B^2} xc \sin f \equiv -A_1 \sin f.$$

Three measured pairs of (a,P) are sufficient to solve orbit and to determine main orbital parameters.

Beyond simple Keplerian Orbits

Relativistic effects measured as corrections to Keplerian orbit:



Post-Keplerian Parameters
= theory independent corrections to describe pulse arrival times

Keplerian parameter:

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

Post-Keplerian (PK) parameters:

Among others:

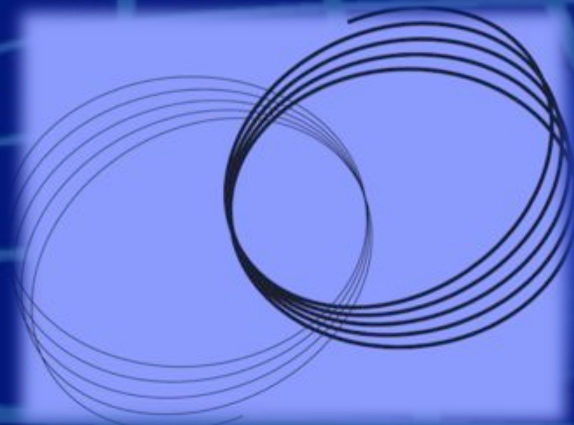
- Shapiro delay, r and s
- Gravitational redshift, γ
- Decay of orbit, dP_b/dt
- Precession of orbit, $d\omega/dt$

Post-Keplerian Parameters & Gravity Tests

Elegant method to test (falsify!) any theory of gravity
(Damour & Taylor '92)

All PK parameter can be written as function of only observed Keplerian and the masses of pulsar and companion, e.g. in GR we can write orbital precession rate as:

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



Periastron advance

For every post-Keplerian parameter, we can write:

Mass $_{\text{companion}}$ = Function $_{\text{Theory}}$ (Mass $_{\text{pulsar}}$ | Keplerian, PK paramteters)

The University of Manchester Jodrell Bank Observatory

MAX-PLANCK-GESELLSCHAFT

Strong-field tests with binary pulsars

For every post-Keplerian parameter, we can write:

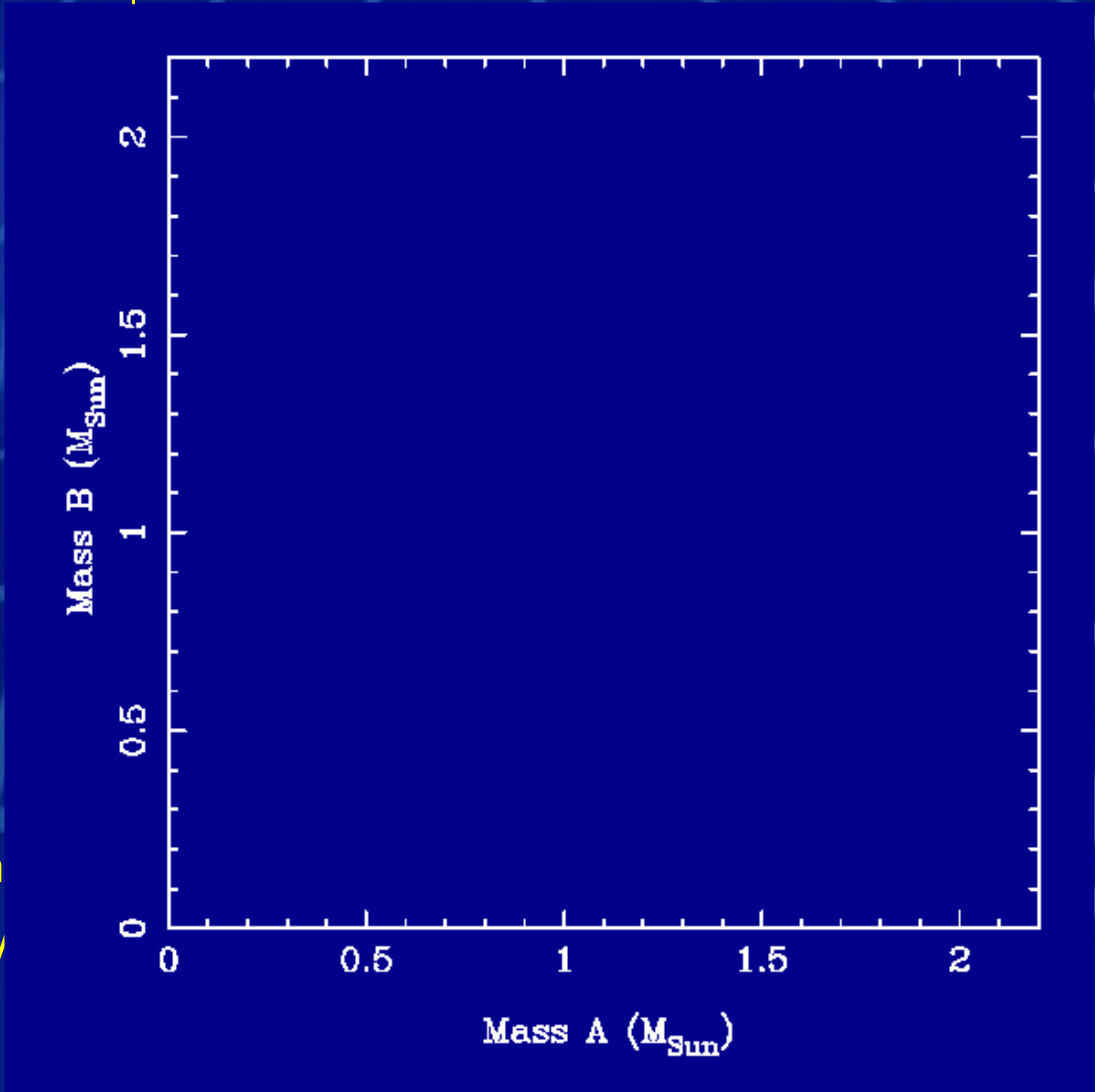
Mass $_{companion}$ = Function $_{Theory}$ (Mass $_{pulsar}$ | Keplerian, PK paramteters)

All lines given by PK measurements need to meet in a single point for theory to pass test!

We need 2 PK parameters to define intersection point.

Every additional PK-line can potentially miss this intersection point and hence tests the theory

N_{PK} – 2 tests possible



Strong-field tests with binary pulsars

For every post-Keplerian parameter, we can write:

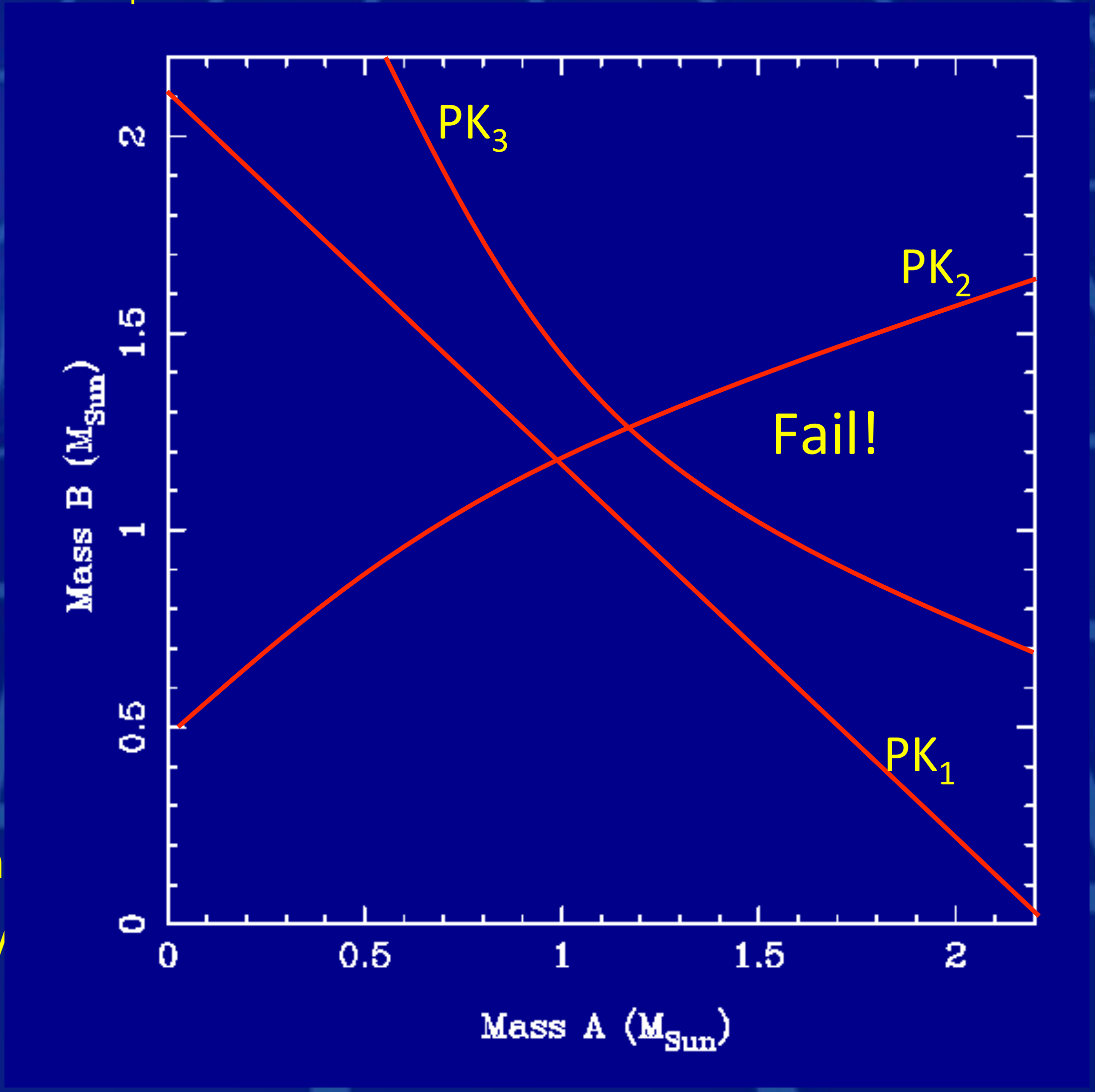
Mass $_{companion}$ = Function $_{Theory}$ (Mass $_{pulsar}$ | Keplerian, PK paramteters)

All lines given by PK measurements need to meet in a single point for theory to pass test!

We need 2 PK parameters to define intersection point.

Every additional PK-line can potentially miss this intersection point and hence tests the theory

$N_{PK} - 2$ tests possible



Strong-field tests with binary pulsars

For every post-Keplerian parameter, we can write:

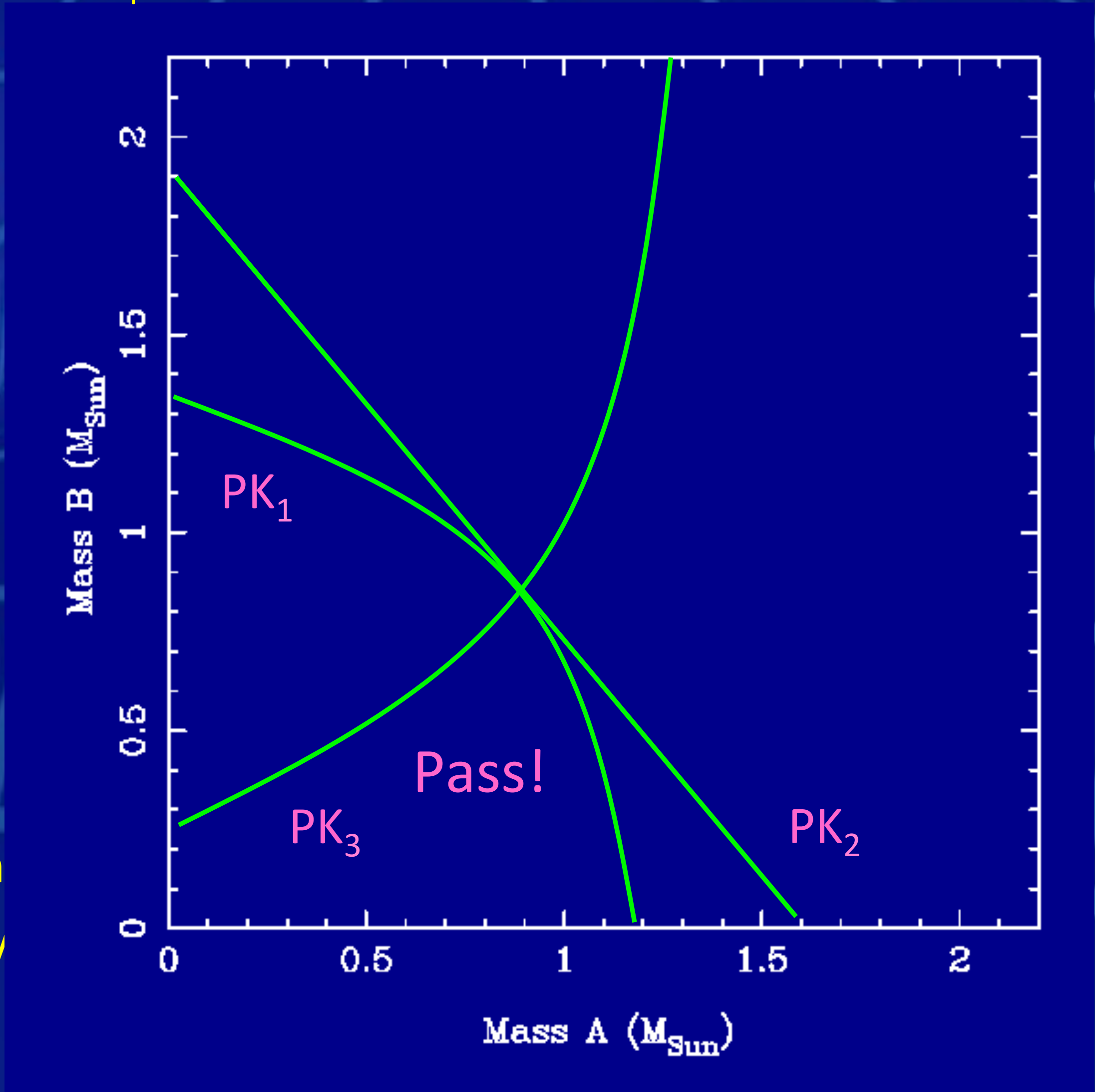
Mass $_{companion}$ = Function $_{Theory}$ (Mass $_{pulsar}$ | Keplerian, PK paramteters)

All lines given by PK measurements need to meet in a single point for theory to pass test!

We need 2 PK parameters to define intersection point.

Every additional PK-line can potentially miss this intersection point and hence tests the theory

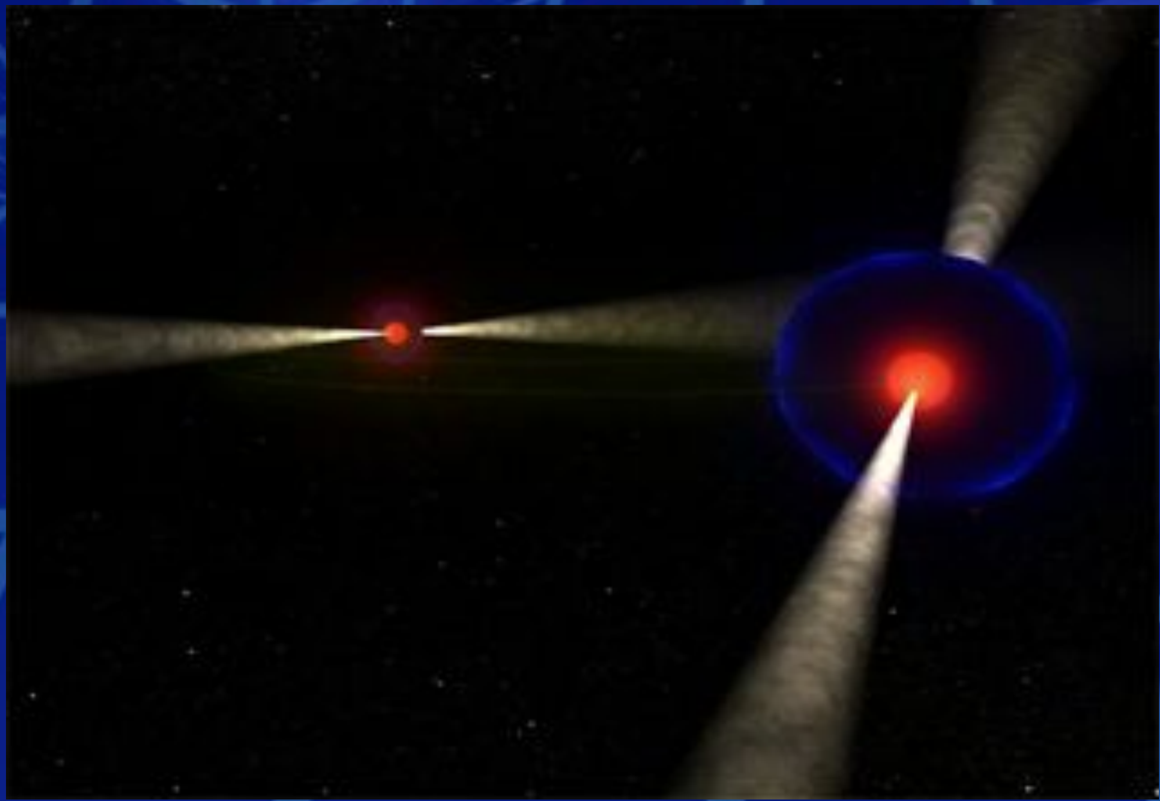
N_{PK} – 2 tests possible



GR Tests: Current State-of-Art = The Double Pulsar

Old 22-ms pulsar in a 147-min orbit with young 2.77-s pulsar (Burgay et al. 2003, Lyne et al. 2004)

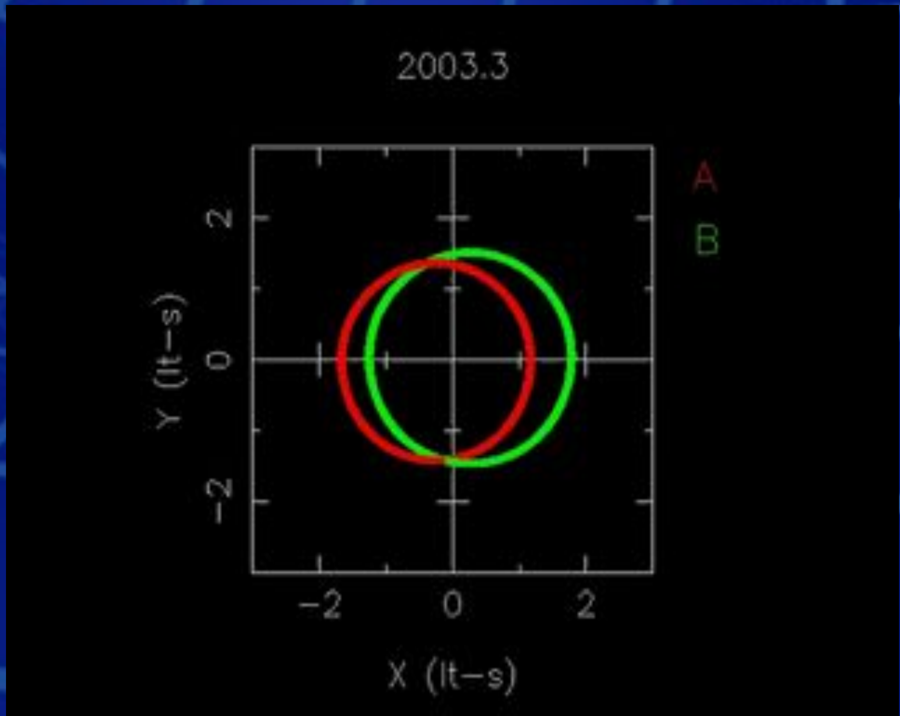
- Orbital velocities of 1 Mill. km/h
- Eclipsing binary
- Ideal laboratory for gravitational and fundamental physics (Kramer et al. 2006)
- Recent very significant improvement (Kramer et al. in prep.)



McGill

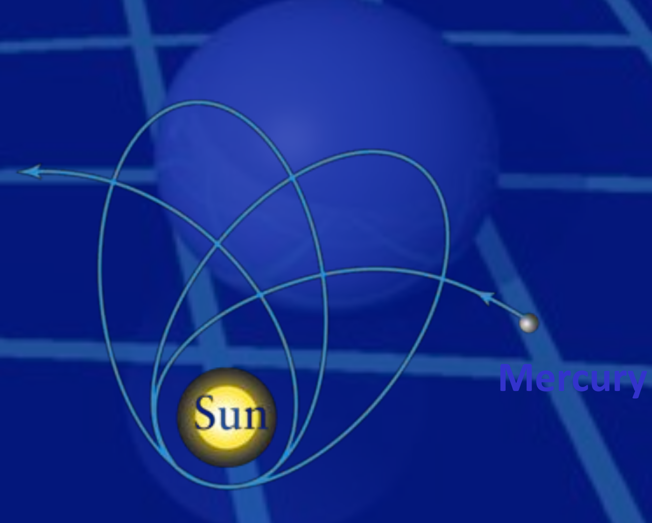
Most relativistic system: orbital precession

- Huge precession of 16.8991±0.0001 deg/yr!



Compare to Mercury:

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

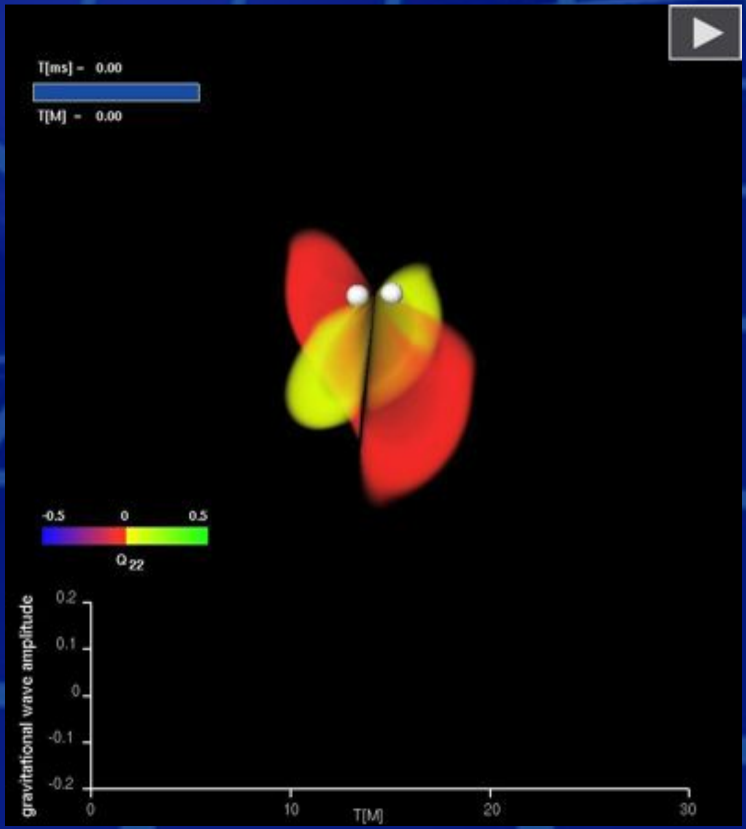


- Measured within a few days of observations!
- One full revolution in about 20 years!

(cf. to 3 Million years for Mercury's orbit)

Most relativistic system: orbital decay

- Effects of gravitational wave emission detected
- Orbit shrinks every day by 7.152±0.008 mm/day
- Merger of the two pulsars in 85 Million years



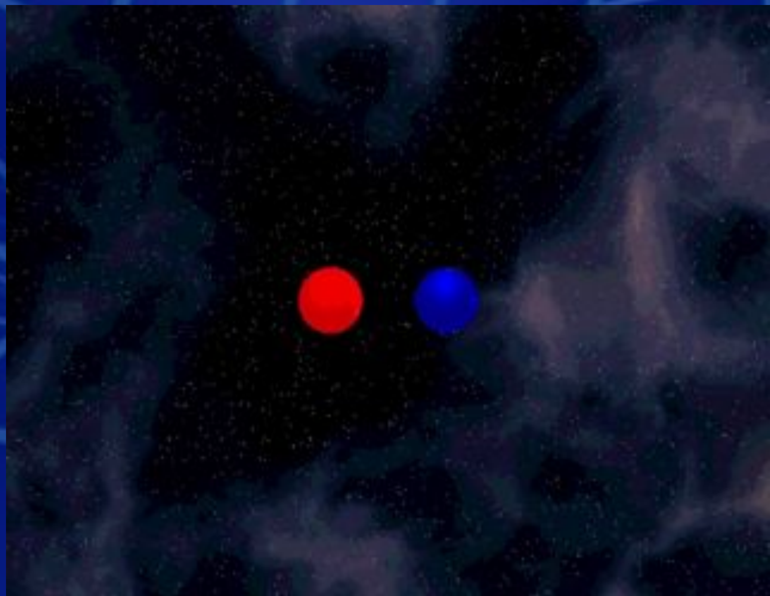
Rezzolla (AEI)

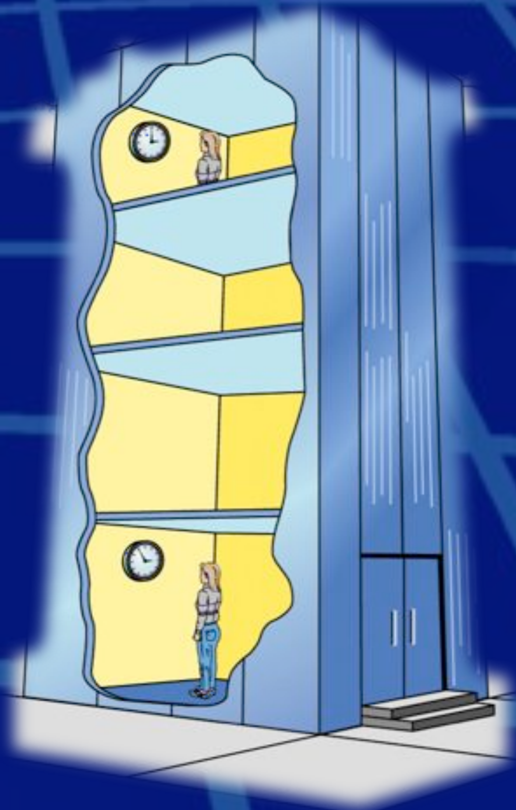
- Exactly the kind of source to be detected with GW detectors like LIGO/VIRGO/GEO

The University of Manchester Jodrell Bank Observatory

Most relativistic system: gravitational redshift

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



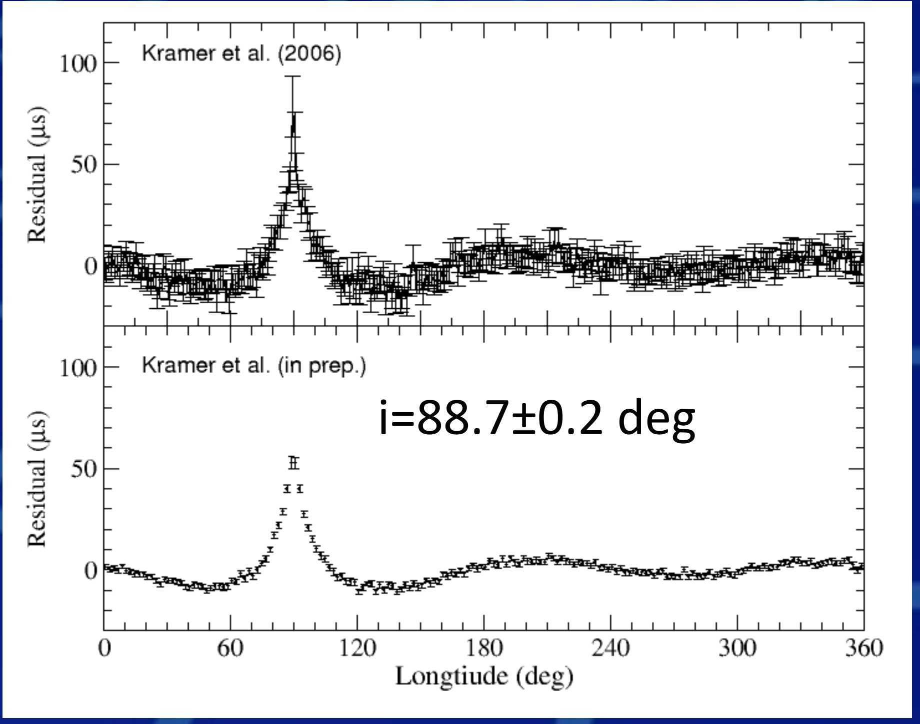


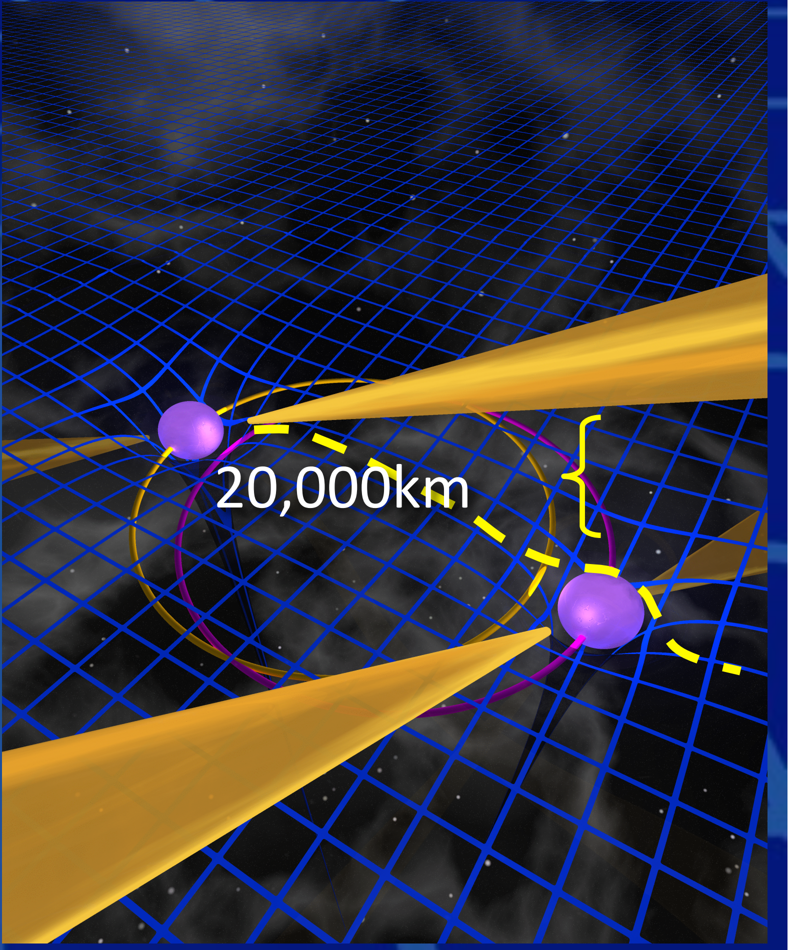
- Pulsars are running slower and faster during orbit by 383.9±0.6 microseconds!

Most relativistic system: Shapiro delay

- At superior conjunction, pulses from pulsar A pass near pulsar B
- Space-time near companion is curved
- Additional path length
- Delay in arrival time:

  s = sin(i)=0.99975±0.00009

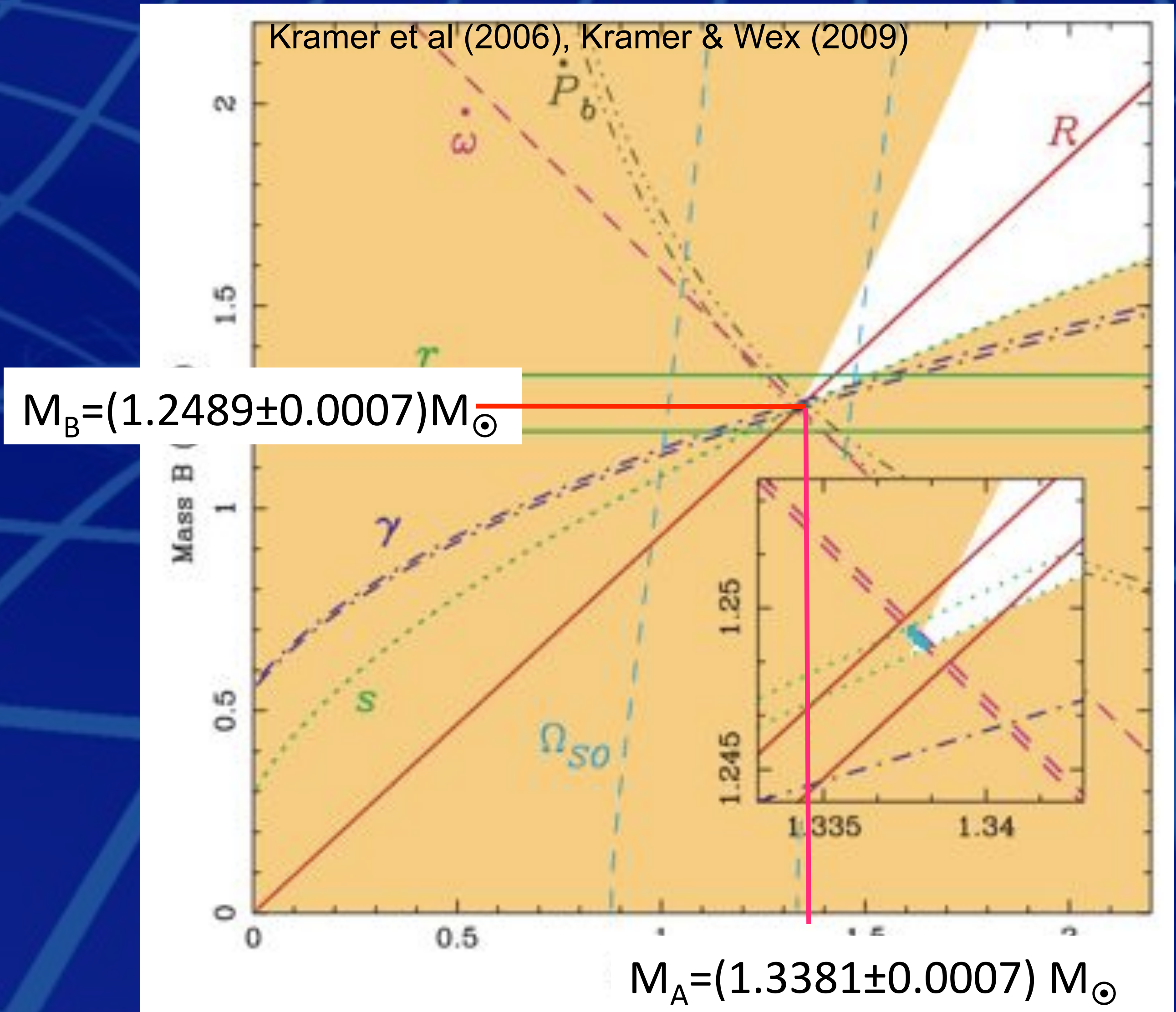




The University of Manchester Jodrell Bank Observatory

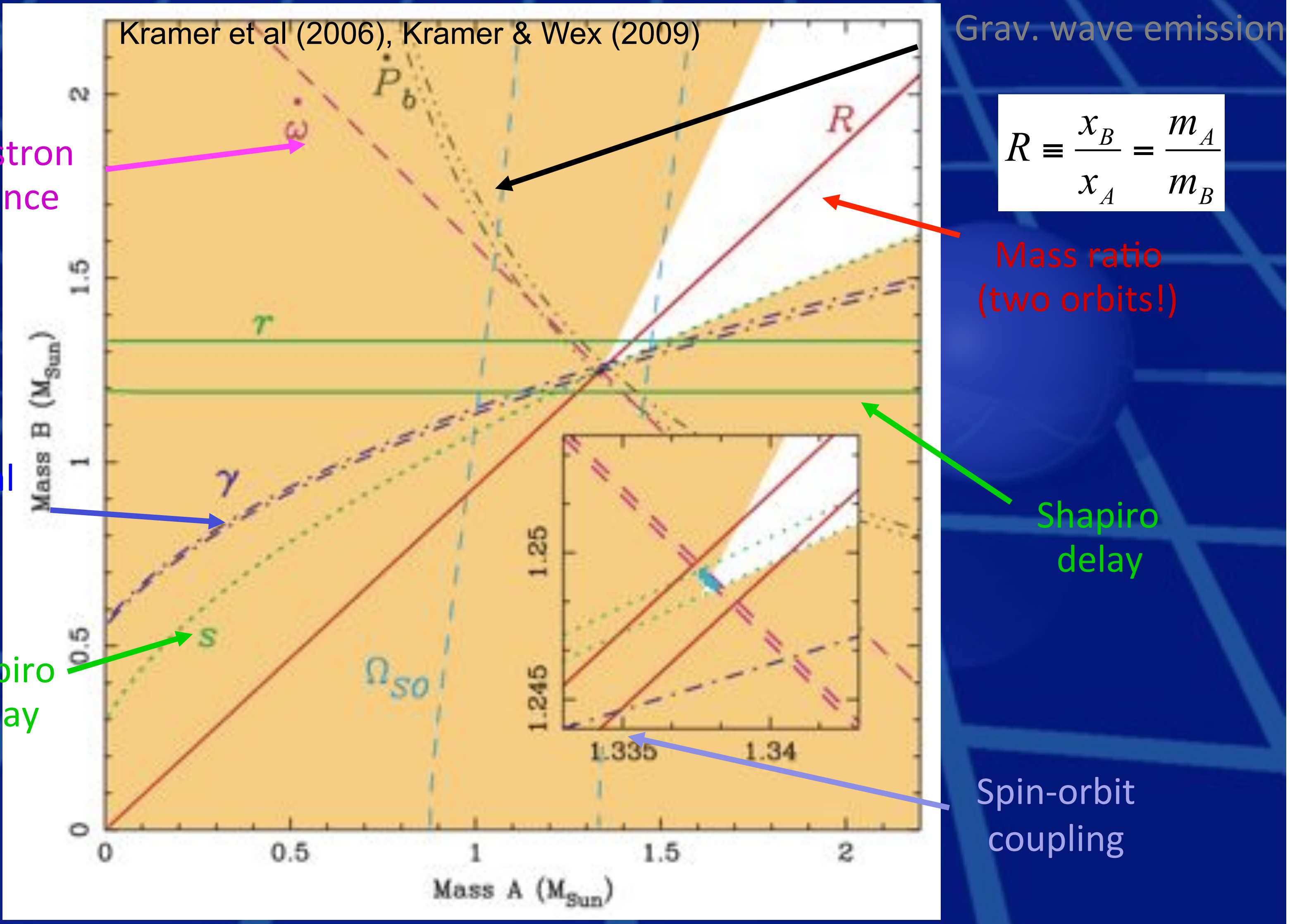
Precision mass measurements

Five(!) unique strong-field tests, represented in a single mass-mass plot



GR tests with the Double Pulsar

Five(!) unique strong-field tests, represented in a single mass-mass plot:



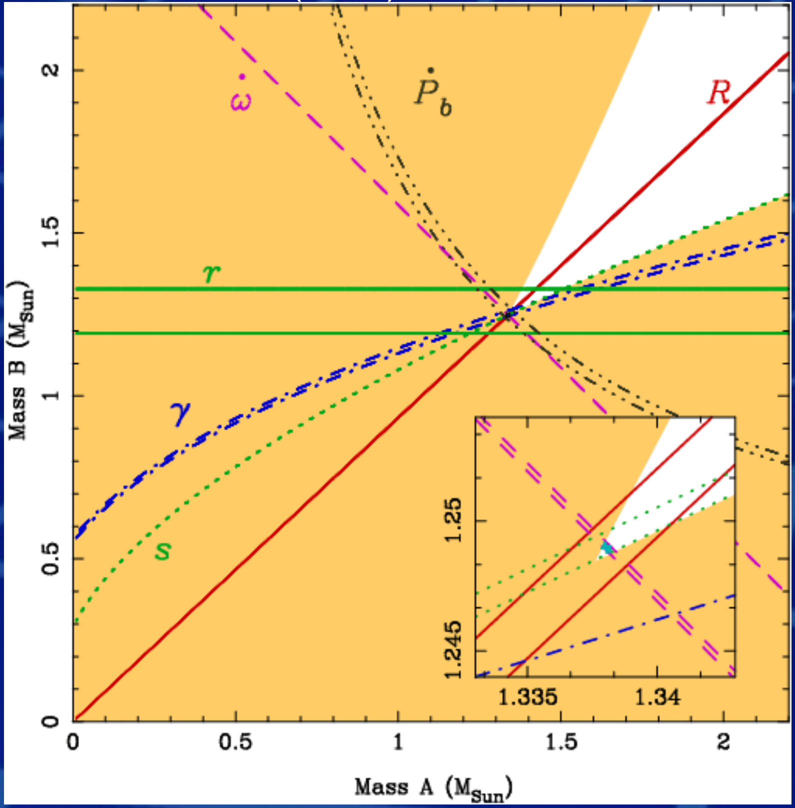
$$R \equiv \frac{x_B}{x_A} = \frac{m_A}{m_B}$$

The University of Manchester Jodrell Bank Observatory
MAX-PLANCK-GESELLSCHAFT

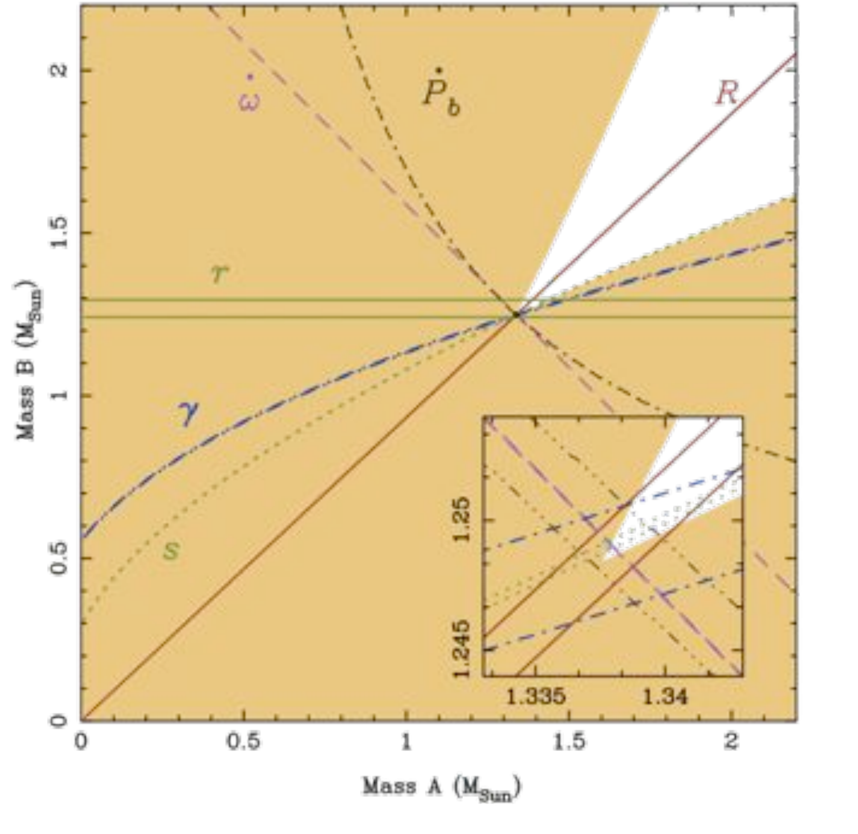
Best test of General Relativity

Recent big improvements:

Kramer et al (2006)



Kramer et al (in prep.)



Precision measurements, e.g.

P (ms) = 22.6993785996213 ± 0.0000000000002 (measured to 0.2 picoseconds!)

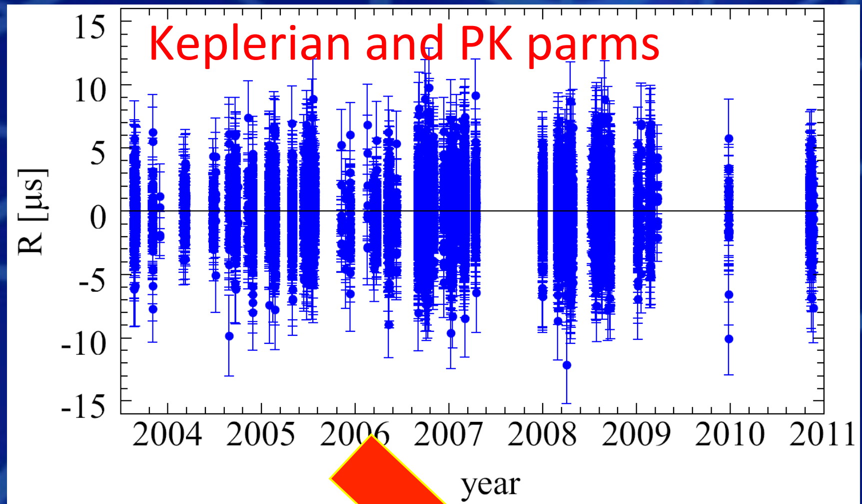
P_b (d) = 0.102251562452 ± 0.000000000008 (i.e. 2.45h measured to 691 ns!)

dP_b/dt = (-1.248±0.001) x 10^{-12} - agreement with GR at 0.1% - best radiation test!

Combining precision optical and radio data

Timing observations of PSR 1738+0333

[*Freire et al., in prep.*]



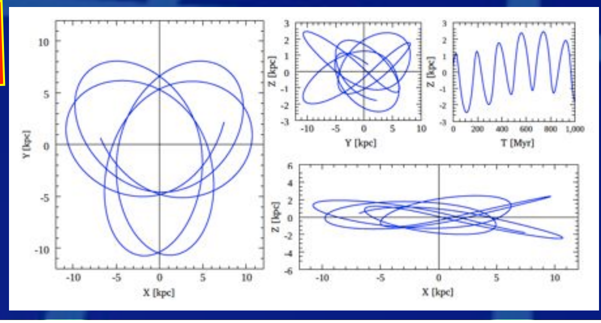
P = 5.85 ms

P_b = 8.51 h

e ~ 10^{-7}

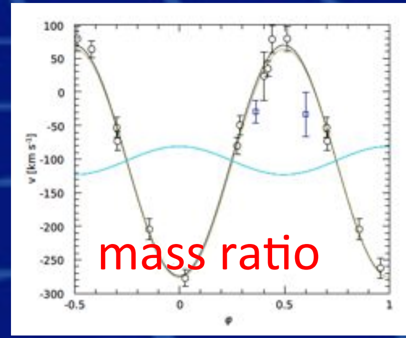
D_p = 1.4 ± 0.1 kpc

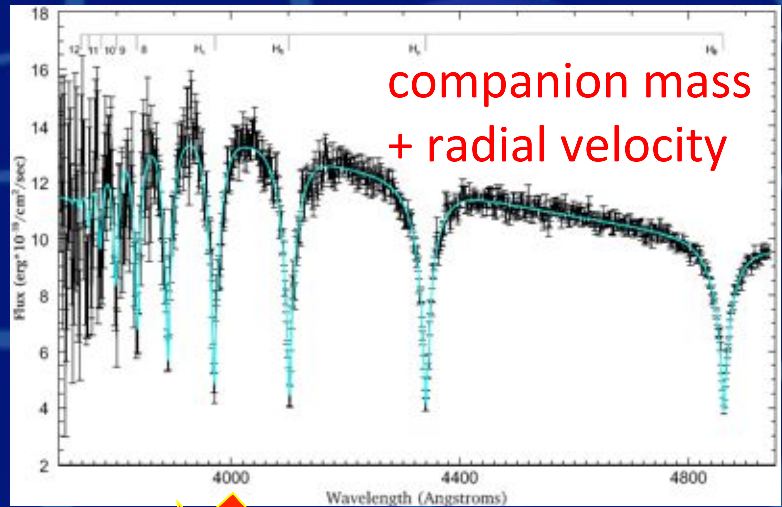
dP_b/dt = (-3 ± 1) × 10^{-14}



Optical observations of the WD companion

[*Antoniadis et al., in prep.*]





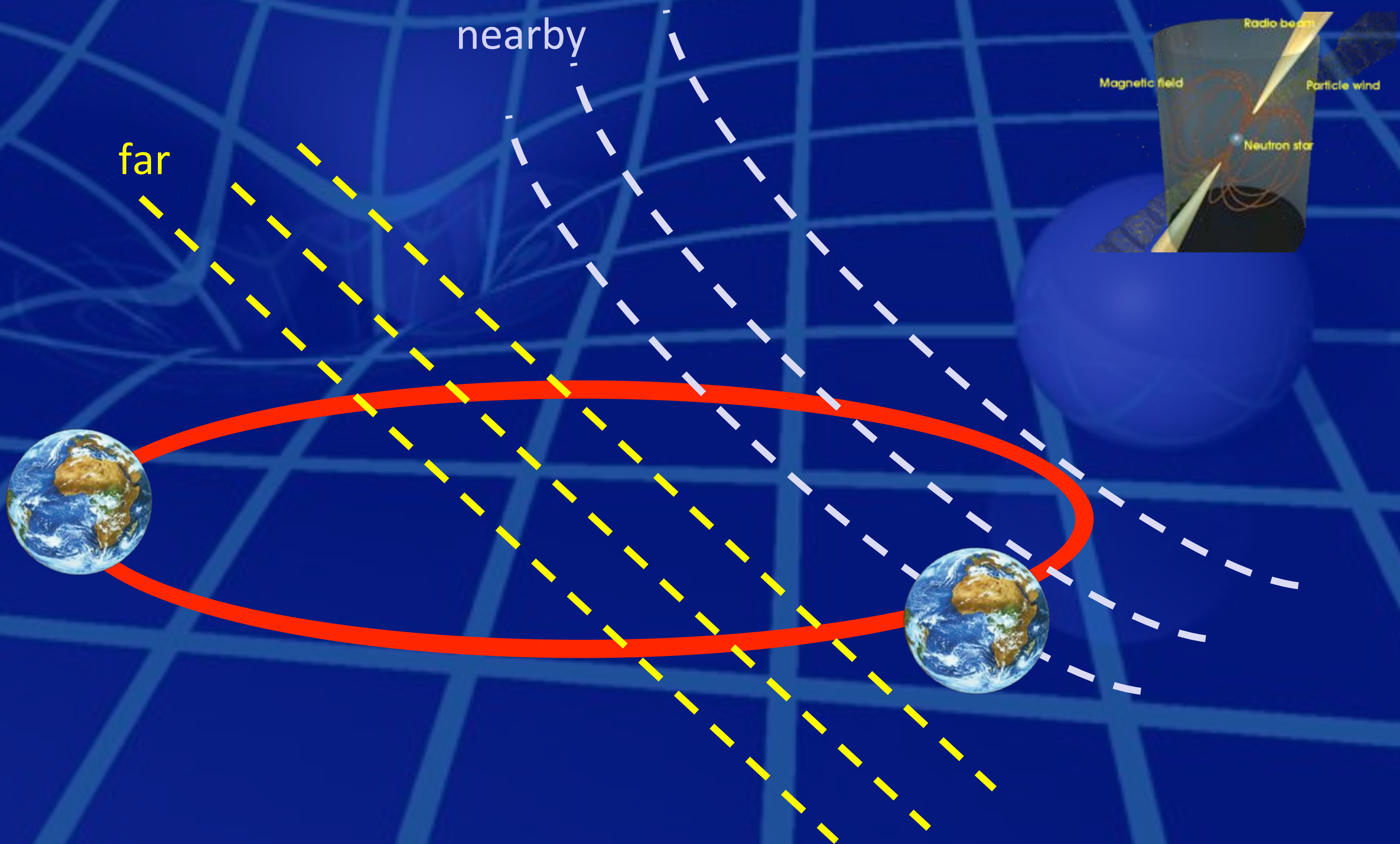
m_c = 0.178 +0.015 ± 0.009 M_{sun}

m_p/m_c = 8.20 ± 0.19

The University of Manchester
Jodrell Bank Observatory

Astrometry

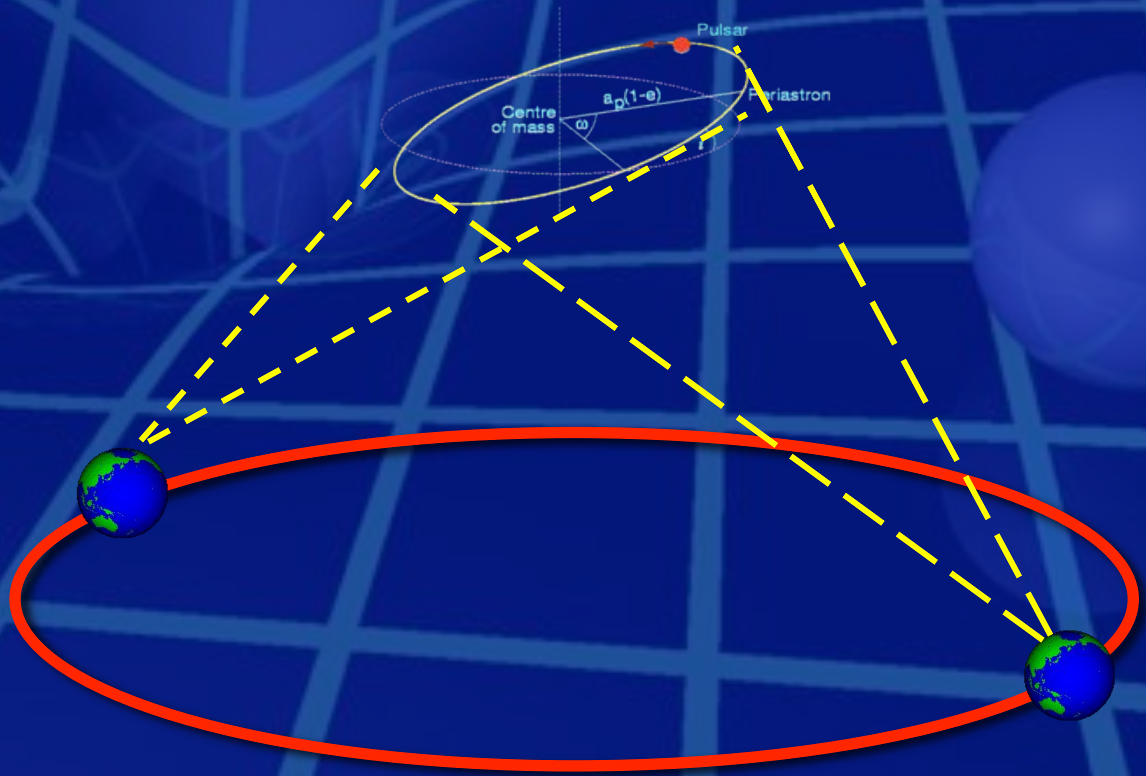
- Pulsar timing only allows the measurement of transverse velocities
- Timing parallax measurements are somewhat different than optical parallax:



Distance determined from the periodic delay due to curvature of the wavefront

Astrometry

- Pulsar timing only allows the measurement of transverse velocities
- Timing parallax measurements are somewhat different than optical parallax
- For nearby binary system we can use annual orbital parallax:



Astrometry

- Pulsar timing only allows the measurement of transverse velocities
- Timing parallax measurements are somewhat different than optical parallax
- For nearby binary system we can use annual orbital parallax
- For relativistic binaries we can use relativistic effects to determine distance

Transverse motion causes a secular acceleration ("Shklovskii term"):

$$\left(\frac{\dot{P}_b}{P_b}\right)^{obs} = \left(\frac{\dot{P}_b}{P_b}\right)^{GW} + \frac{1}{c}\vec{K}_0(\vec{a}_{PSR} - \vec{a}_{SSB}) + \frac{V_T^2}{cd}$$

By measuring transverse speed we can compare observed value with GR

This "kinematic parallax" is usually much more precise when available

Astrometry

- Pulsar timing only allows the measurement of transverse velocities
- Timing parallax measurements are somewhat different than optical parallax
- For nearby binary system we can use annual orbital parallax
- For relativistic binaries we can use relativistic effects to determine distance

Transverse motion causes a secular acceleration (“Shklovskii term”):

$$\left(\frac{\dot{P}_b}{P_b}\right)^{obs} = \left(\frac{\dot{P}_b}{P_b}\right)^{GW} + \frac{1}{c}\vec{K}_0(\vec{a}_{PSR} - \vec{a}_{SSB}) + \frac{V_T^2}{cd}$$

GAIA?!

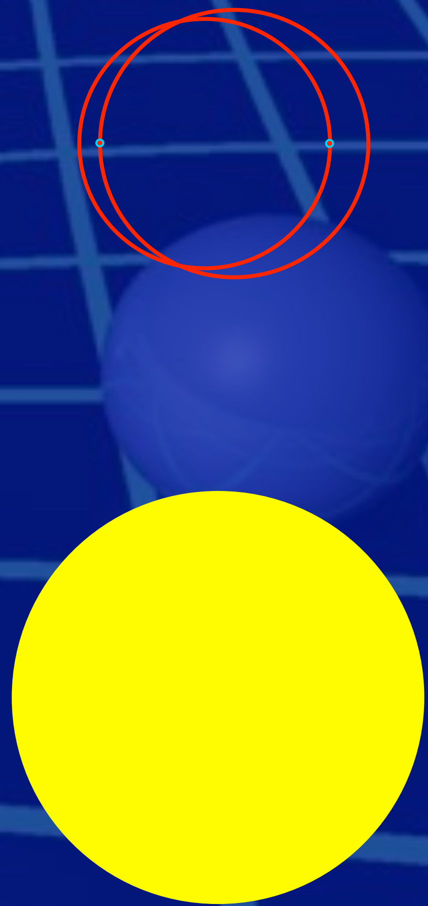
By measuring transverse speed we can compare observed value with GR

This “kinematic parallax” is usually much more precise when available

Comparison Hulse-Taylor vs Double Pulsar

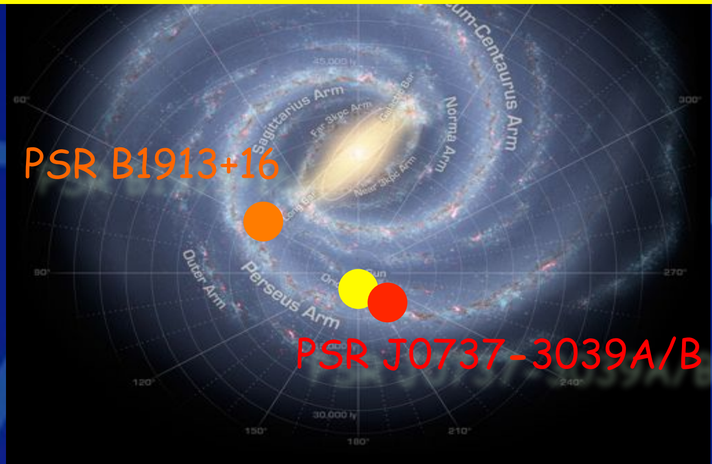
PSR B1913+16

PSR J0737-3039A/B



Sun

$$\left(\frac{\dot{P}_b}{P_b}\right)^{obs} = \left(\frac{\dot{P}_b}{P_b}\right)^{GW} + \frac{1}{c}\vec{K}_0(\vec{a}_{PSR} - \vec{a}_{SSB}) + \frac{V_T^2}{cd}$$



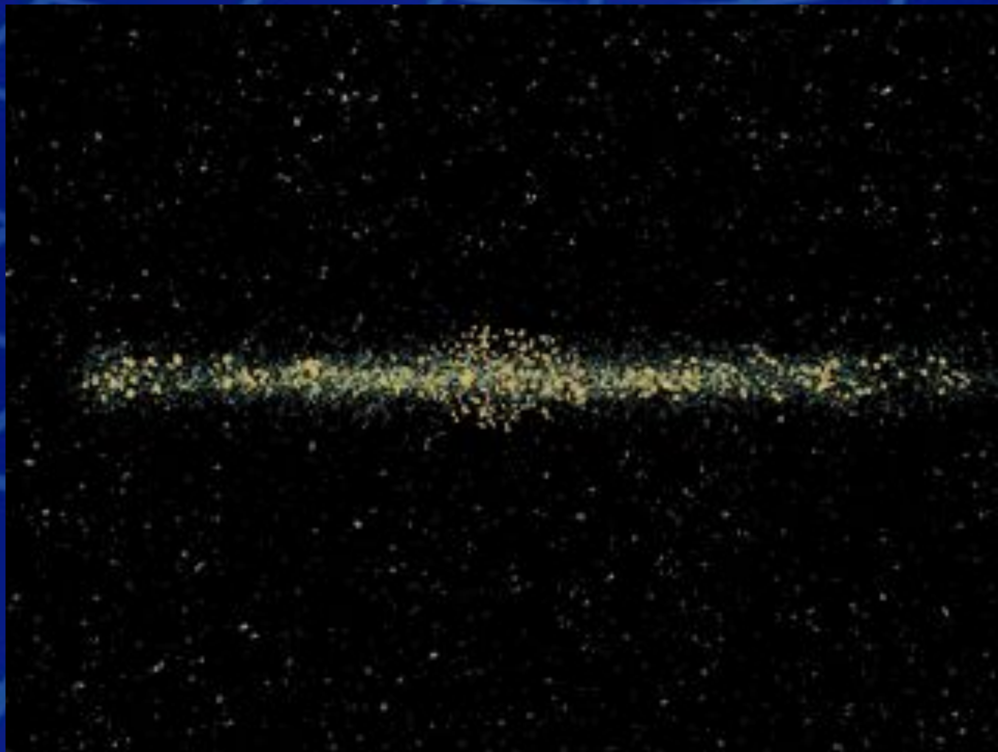
The Future: The Square-Kilometre-Array

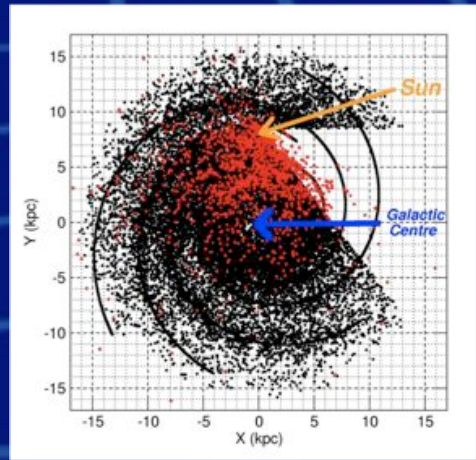
- will make detection and study of nHz gravitational waves relatively easy
- will also find the “holy grail” – a pulsar – black hole system (Kramer et al. 2004)

Galactic census with the SKA

With the SKA' S collecting area and increase in survey speed:

(Kramer et al. 2004, Smits et al. 2008)





- ~30,000 normal pulsars
- ~2,000 millisecond psrs
- ~100 relativistic binaries
- first pulsars in Galactic Centre
- first extragalactic pulsars

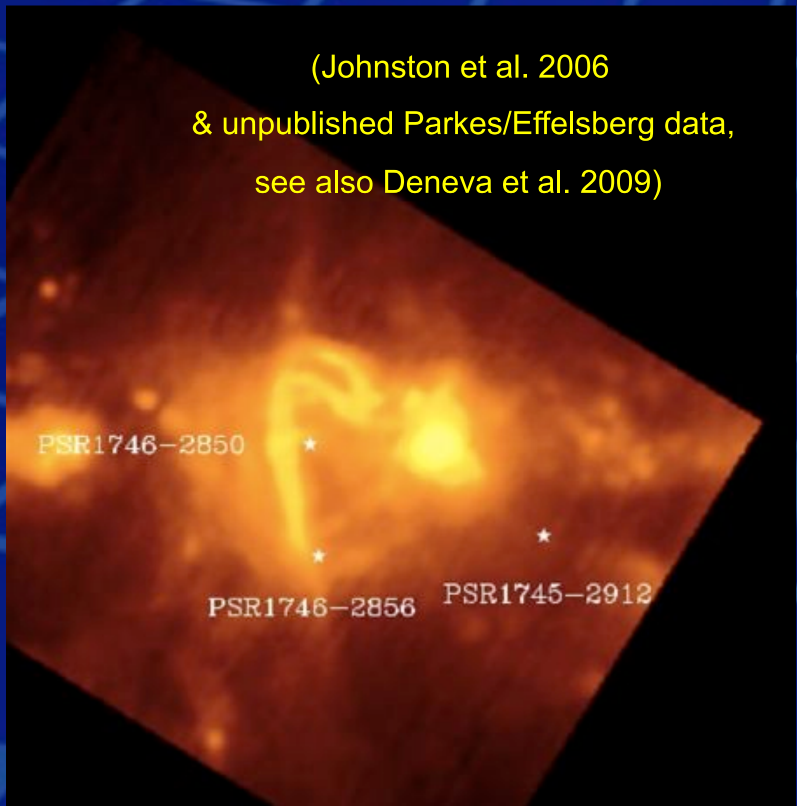
➔ with sensitivity also timing precision is expected to increase by factor ~100

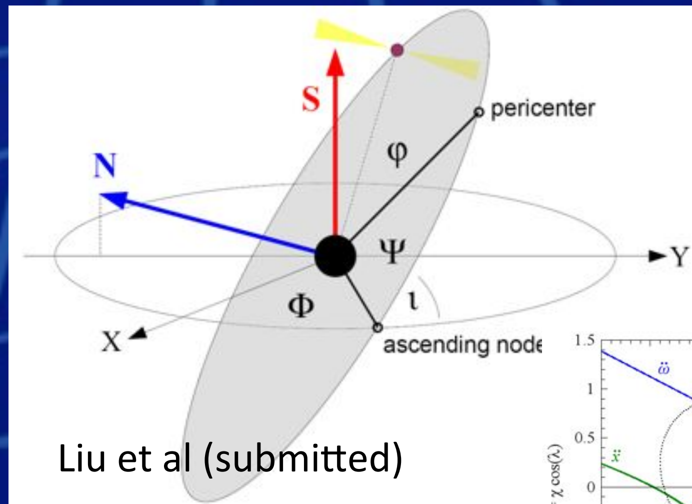
➔ rare and exotic pulsars and binary systems: including PSR-BH systems!

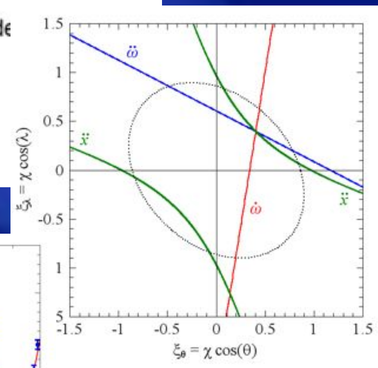
The University of Manchester Jodrell Bank Observatory
MAX-PLANCK-GESELLSCHAFT

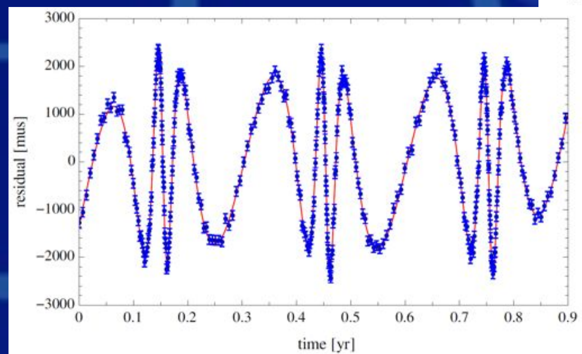
The ultimate dance: a Pulsar orbiting SGR A*

Finding even a “simple” normal slow pulsar, we can measure the BH with amazing precision:









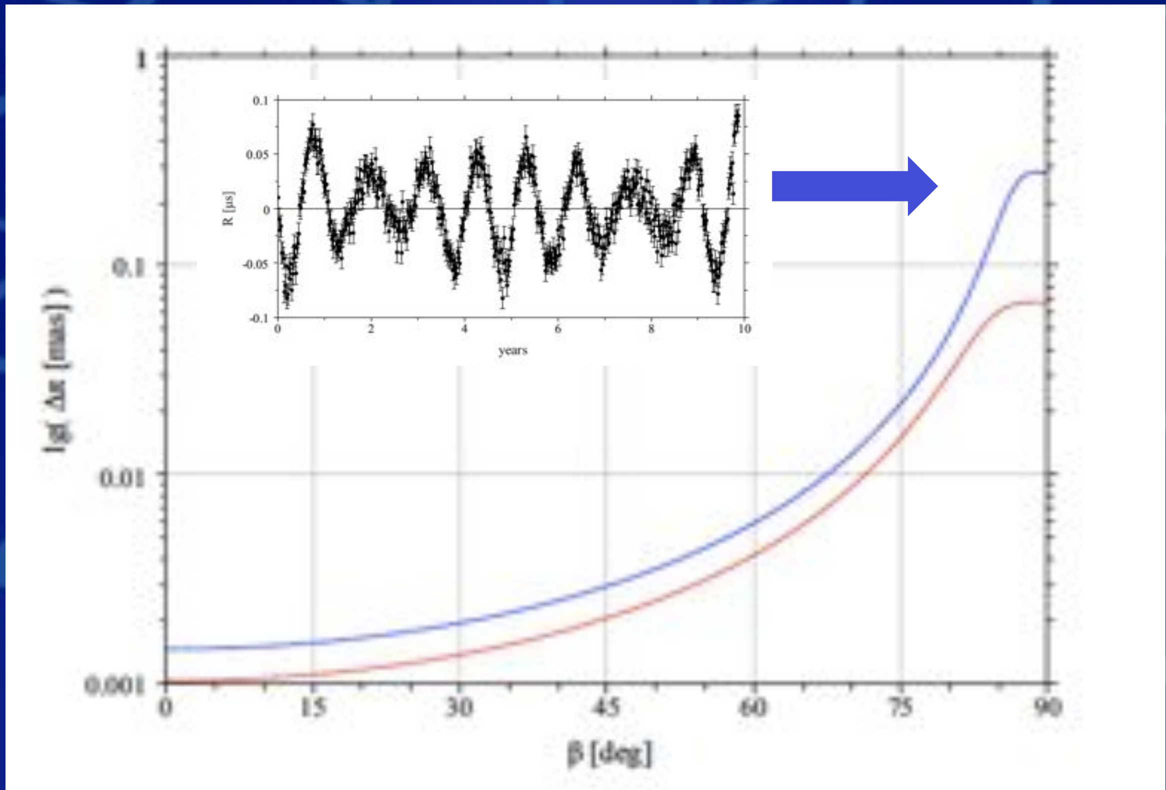
- Measure mass of SGR A* to 10^{-6}!
- Measure spin of SGR A* to precision of 10^{-4} to 10^{-3} : Cosmic Censorship!
- Measure quadrupole moment to 10^{-3} to 10^{-2} : No hair! (Liu et al. submitted)

The University of Manchester Jodrell Bank Observatory

MAX-PLANCK-GESELLSCHAFT

SKA Astrometry (Smits et al. 2011)

- Interferometric – applicable to all types of pulsars (for ~9,000 sources)
- Timing parallax – applicable to millisecond pulsars:
  As we measure the curvature of the incoming wave front, decreasing precision for higher ecliptic latitude sources!



Assuming 10ns, 5/10 yr:

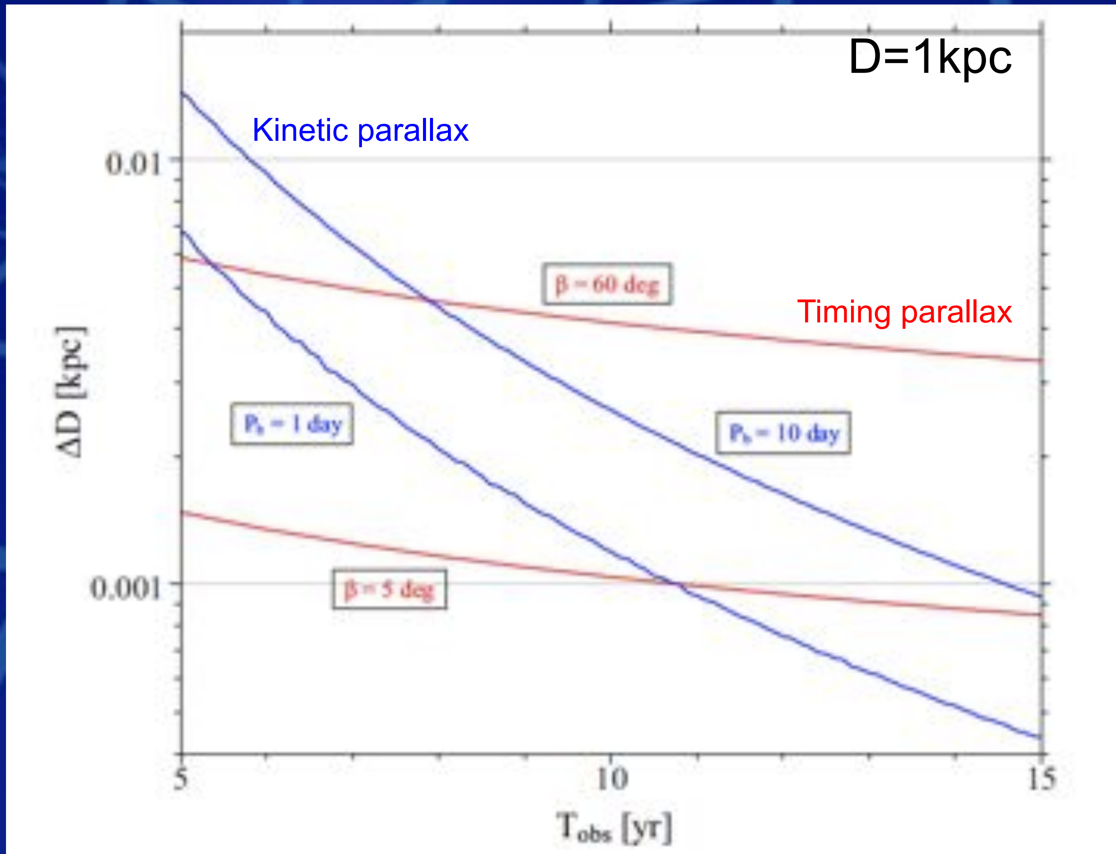
10 kpc

1000 kpc

SKA Astrometry (Smits et al. 2011)

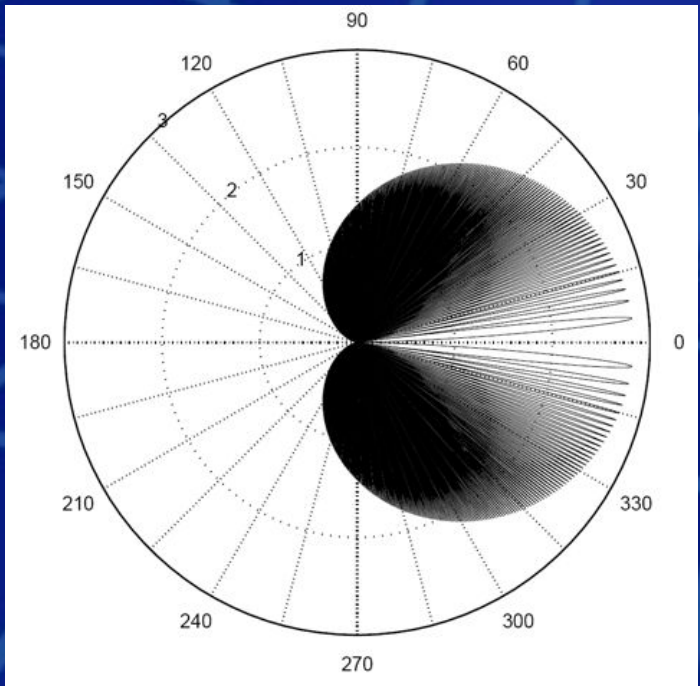
- Interferometric – applicable to all pulsars (for ~9,000 sources)
- Timing parallax – applicable to millisecond pulsars:
- "Kinetic parallax" - for binaries, we can also assume that GR is correct and attribute any deviation from GR solely to secular acceleration:

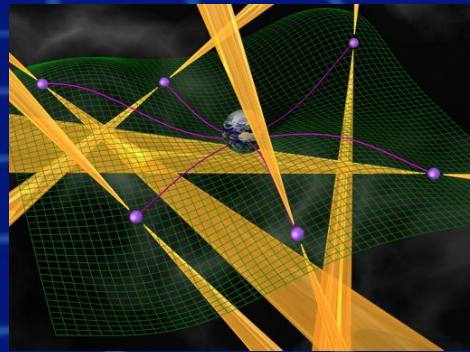
$\Delta(dP_b/dt) \rightarrow v_T \rightarrow D$

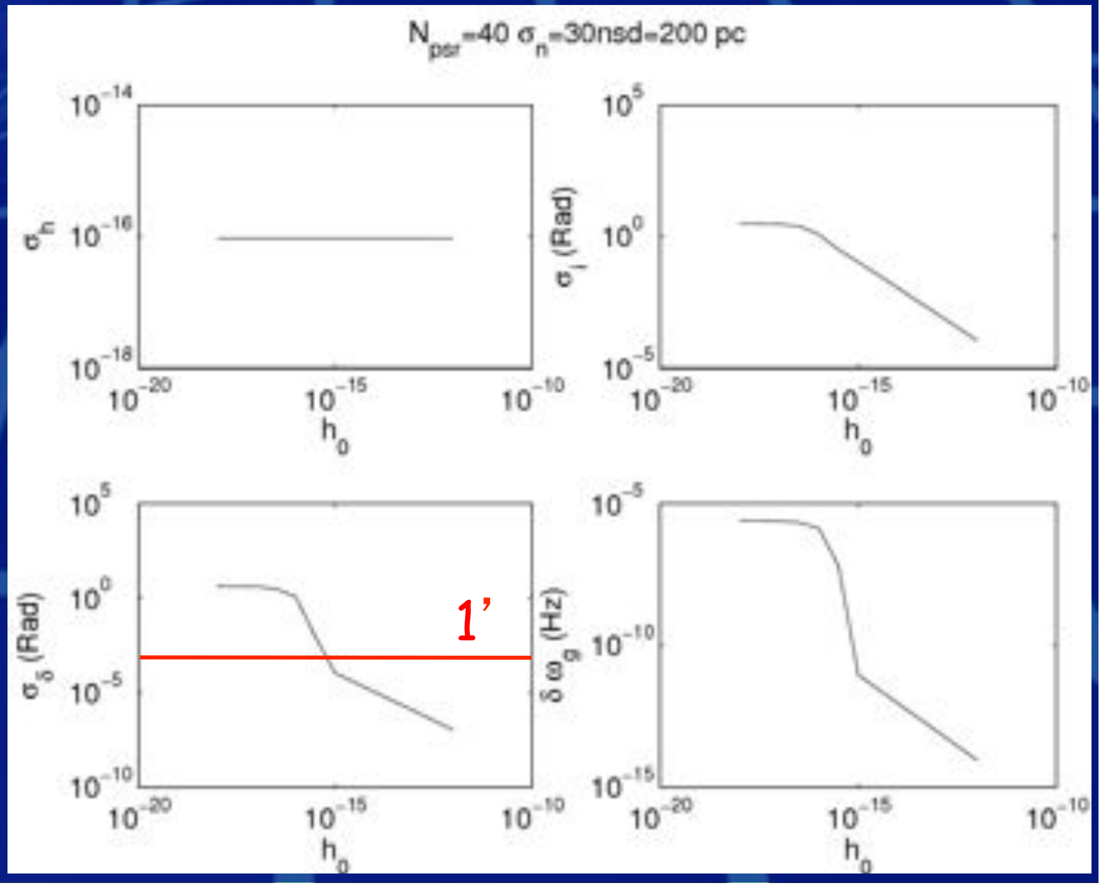


Gravitational Wave Astronomy

- With the SKA we will measure gravitational waves using pulsar timing
- We can pinpoint a single GW source:







Possible by amazing astrometry of SKA!

Lee et al. (2011)

Conclusions

- Pulsars are precision tools for a wide range of unique applications
- Good astrometry is also important for pulsar astrophysics
- Unfortunately, GAIA may not be able to detect the usual pulsar companion
- BUT GAIA will be very useful to determine the Galactic gravitational potential

  (We need acceleration measurements! Is someone working on this?)
- Also, very interesting to compare reference frames (radio, optical, planetary)
- Expect a lot of synergies between GAIA & SKA!

Masses:

- Masses of neutron stars: m_1 = 1.4398(2) $M_\odot$ and m_2 = 1.3886(2) $M_\odot$ (Weisberg et al. 2010)
- Mass of WD companions: Shapiro: 0.204 (2) $M_\odot$ (Jacoby et al. 2005)
  optical: 0.181 (7) $M_\odot$ (Antoniadis et al. in prep.)
- Mass of millisecond pulsar: 1.67(2) $M_\odot$ (Freire et al. 2010)
- Main sequence star companion: 1.029(8) $M_\odot$ (Freire et al. 2010)

Orbital parameters:

- Period: 0.102251562479(8) (Kramer et al. in prep.)
- Eccentricity: 3.5 (1.1) × 10^{-7} (Freire et al. in prep.)

Astrometry:

- Distance: 157(1) pc (Verbiest et al. 2010)
- Proper motion: 140.915(1) mas/yr (Verbiest e t al. 2010)

GR Test:

- Perihelion advance: 4.226598(5)deg/yr (Weisberg et al. 2010)
- Shrinkage due to GW emission: 7.152±0.008 mm/day (Kramer et al. in pep)
- GR validity: 1.0000(5) (Kramer et al. in prep.)

Spin parameters:

- Period: 5.757451924362137(2) ms (Verbiest et al. 2010)

In the future…

- Measure mass of SGR A* to 10^{-6}!
- Measure spin of SGR A* to precision of 10^{-4} to 10^{-3} : Cosmic Censorship!
- Measure quadrupole moment to 10^{-3} to 10^{-2} : No hair! (Liu et al. submitted)

The University of Manchester Jodrell Bank Observatory

MAX-PLANCK-GESELLSCHAFT