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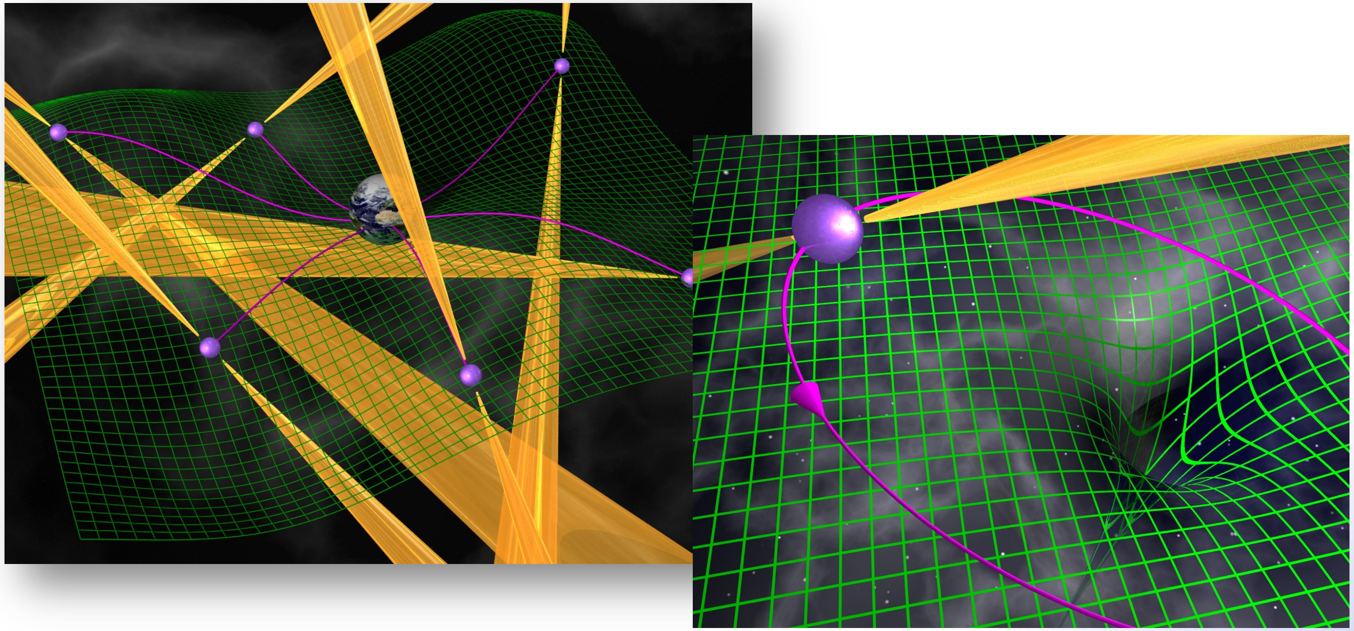
Pulsars and General Relativity



Michael Kramer

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Jodrell Bank Centre for Astrophysics, Univeristy of Manchester

Bonn, September 15th 2010

Fundamental physics with the SKA

Pushing the boundaries of our understanding of the physical world:

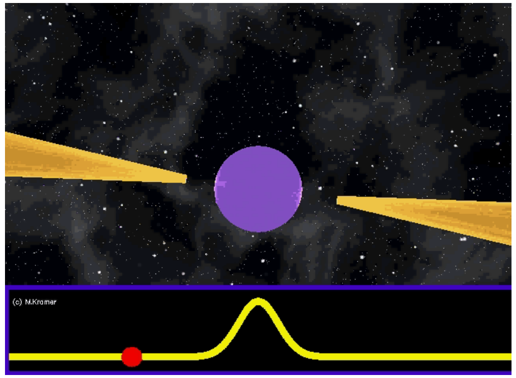
Was Einstein right? - Physics in strong gravitational fields

- Nature of gravity: tensor field, additional scalar field…?
- Properties of gravitational waves:
  - Polarisation properties: Spin 2?
  - Propagation speed: mass of graviton?
- Extreme curvature & singularities:

  BH properties? Event horizon & cosmic censorship? No-hair?

How do we intend to do it…?

Using nature's most accurate clocks: Pulsars!



- ...cosmic lighthouses
- ...almost Black Holes:
  mass of ~1.4 Solar Mass within 20km
- ...objects of extreme matter
  - 10x nuclear density
  - $B \sim B_{cr} = 4.4 \times 10^9$ Tesla
  - $F_{EM} = 10^{10-12} F_{gravity}$
- ...very stable clocks:

  The best pulsars keep time with an accuracy of 1 millionth of a second over 30 years (comparable to best atomic clocks)

PSR J1012+5307: 15 years of observations with EPTA:

$P = 0.00525574901411541 0 \pm 0.000000000000000015$ s

[*Lazaridis et al. 2009*]

→ 90 billion rotations since discovery, and not lost a single count!

- ...pulsar observations: high time and frequency sampling of the sky with accurate time stamping of signals

So far, we haven't done badly…

- Pulsar astrophysics has quite impressive track records of discoveries
- Large range of applications in the widest area of physics and astrophysics

  from smallest (=solid states physics) to largest scales (=grav. physics)
- Don't think that we have enough! … quite the opposite!
- Next generation telescopes are superb instruments for pulsar research:
  - large collecting area
  - large fractional bandwidth

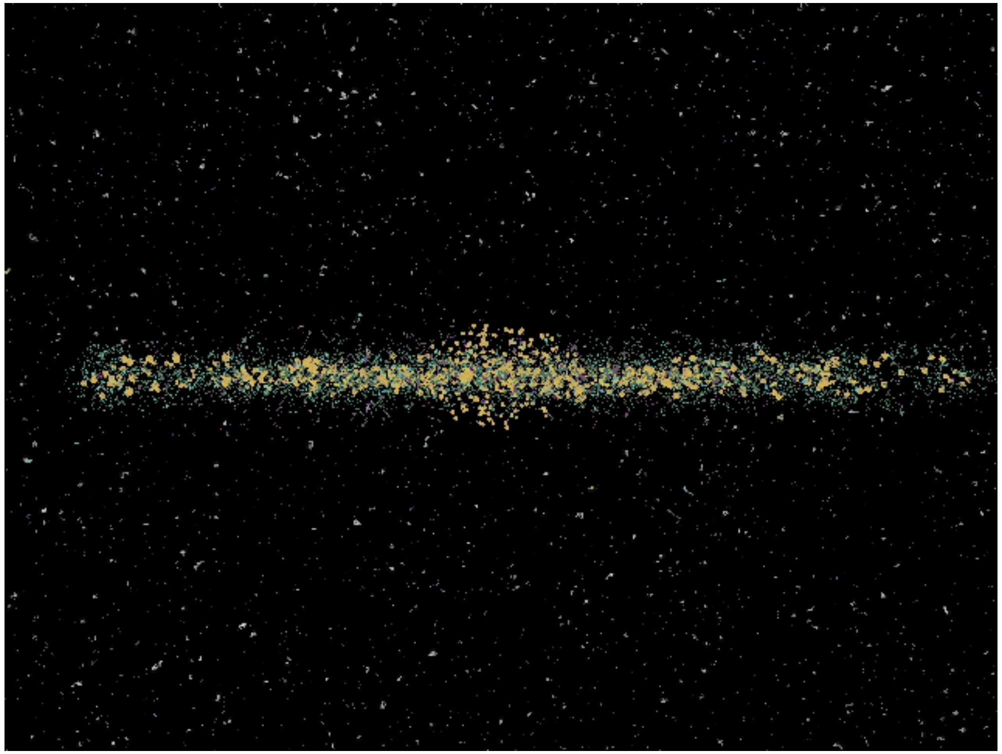
  } **Never have enough of that..!**

  - large field-of-view
  - multi-beaming capabilities

  } **Monitoring of many sources with excellent cadence**

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 rel 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!

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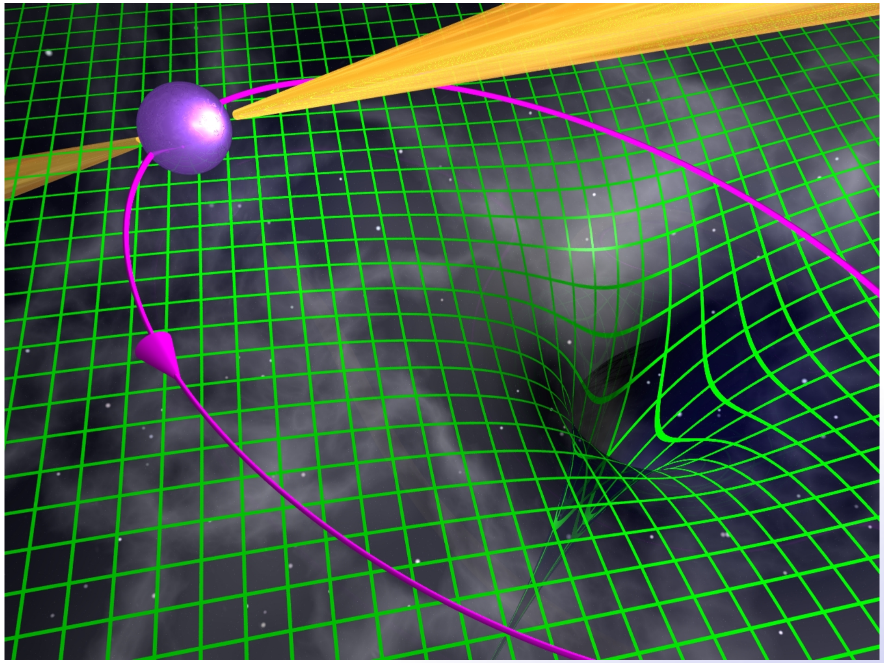
Black Hole properties

BH spin:

$$\chi \equiv \frac{c}{G}\frac{S}{M^2}$$

S = angular momentum



Relativistic spin-orbit coupling:
- Precession of the orbit
  higher order derivatives in semi-major axis and longitude of periastron

- For all compact massive, BH-like objects, we'll be able to measure spin χ very precisely
- In GR, for Kerr-BH we expect:

$$\chi \leq 1$$

"Cosmic Censorship Conjecture" (Penrose 1969)

Black Hole properties

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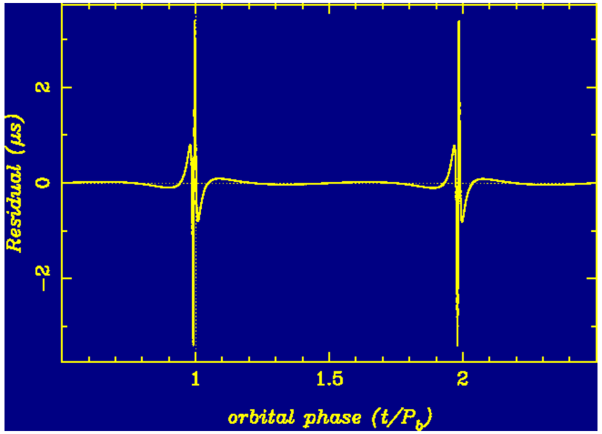


BH quadrupole moment:

$$q \equiv \frac{c^4}{G^2} \frac{Q}{M^3}$$

Q = quadrupole moment

Relativistic spin-orbit coupling:
- Precession of the orbit
  higher order derivatives in semi-major axis and longitude of periastron

Classical spin-orbit coupling:
- transient signals in timing residuals

- For Kerr-BH we expect:

$$q = -\chi^2$$

"no-hair" theorem

- For all compact massive, BH-like objects, we'll be able to measure spin χ very precisely
- In GR, for Kerr-BH we expect:

$$\chi \leq 1$$

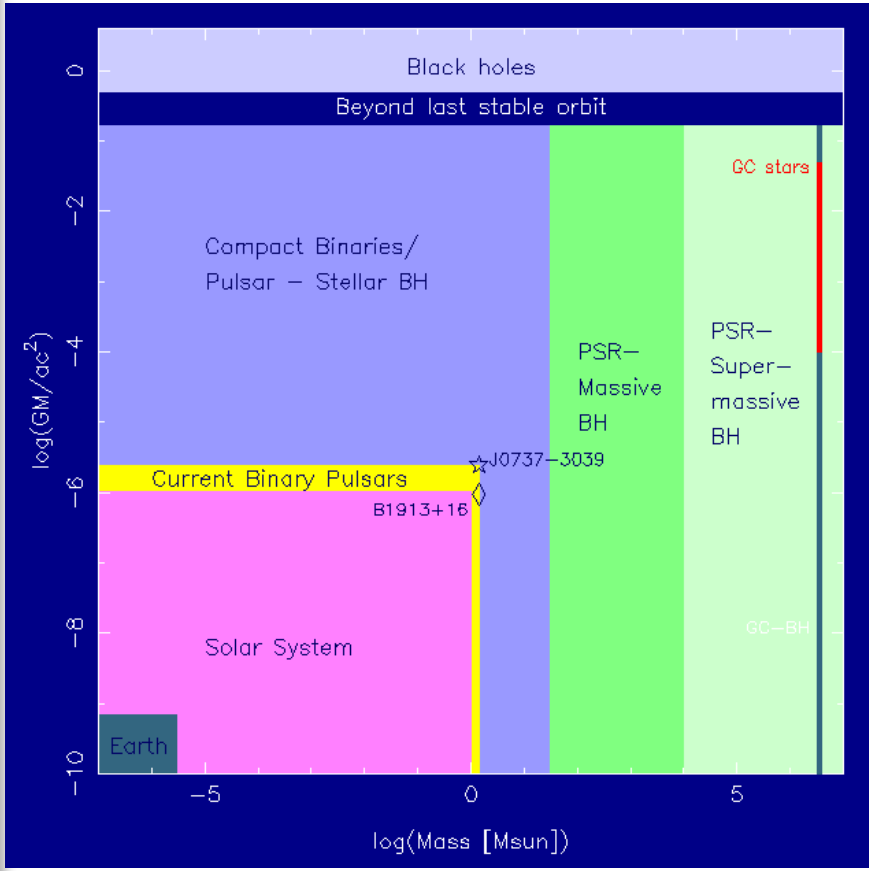
"Cosmic Censorship Conjecture" (Penrose 1969)

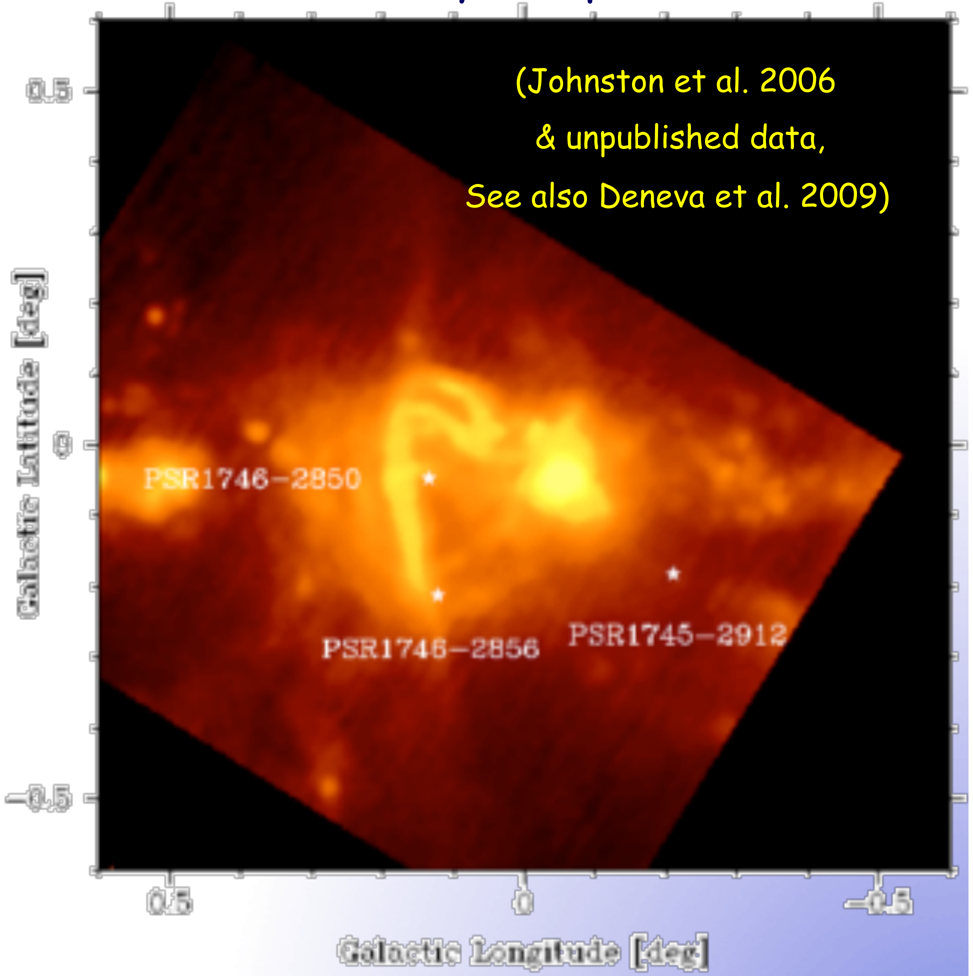
"Easy" for MBH!

… Galactic Centre!

Galactic Centre Black Hole

In principle easy to measure but ability to find and time pulsars limited due to scattering: need frequencies at 10 GHz or above – not easy but possible!





We should be able to separate orbital perturbations from BH signature.

Case Study: Pulsars in the Galactic Centre

Sgr A* black hole: $M = 4\,000\,000\, M_{\text{Sun}}$

For a pulsar in a 0.1 yr orbit with an eccentricity of 0.4

- Precession of periastron: 14.8 deg/yr
- Einstein delay: 7.7 min
- Shapiro delay: > 33 s (depends on inclination)

Simulations:

3 yr of timing observations, weekly TOA with 100 μs precision:

Precession of periastron: $d\dot{\omega}/\dot{\omega} \sim 10^{-6}$

but could have large frame dragging contribution (up to 1%)

Range of Shapiro delay allows (in most cases) a direct mass measurement:

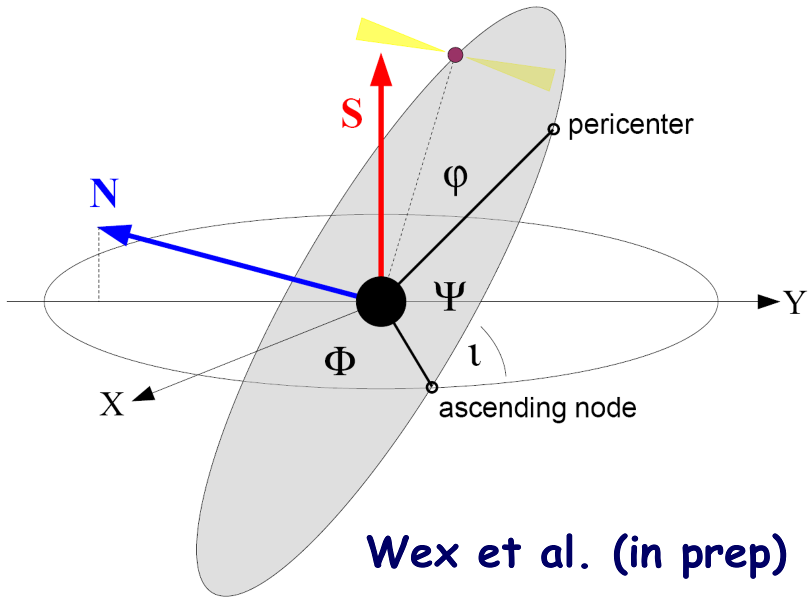
$dm/m \sim 10^{-5}$ (for low i, for high i even better)

Frame dragging contribution (up to a few 0.1%) has a characteristic signature and can be mostly removed during the fit (at the same time giving a lower limit for c)

Einstein delay: $d\gamma/\gamma \sim 10^{-5}$ $\Rightarrow$ m

(frame dragging contributions enter at about the same order)

Frame Dragging and Cosmic Censorship Test



Wex et al. (in prep)

Secular precession of the pulsar orbit

$$\dot\Phi = \Omega_{\rm LT}$$

$$\dot\Psi = \Omega_{\rm M} - 3\,\Omega_{\rm LT}\,\cos\iota$$

$$\Omega_{\rm LT} = \frac{2GS}{c^2 a^3 (1-e^2)^{3/2}}$$

~ 0.3 deg/yr
for $P_b = 0.1$ yr ($a = 34$ AU)

Observable quantities change non-linearly in time

$$x = x_0 + \dot x_{\rm LT}(t-t_0) + \tfrac{1}{2}\ddot x_{\rm LT}(t-t_0)^2 + \ldots$$

$$\omega = \omega_0 + (\dot\omega_{\rm M} + \dot\omega_{\rm LT})(t-t_0) + \tfrac{1}{2}\ddot\omega_{\rm LT})(t-t_0)^2 + \ldots$$

→ Θ_N, Φ_0, Ψ_0, ι, S

Simulations: Extreme Kerr, $P_b = 0.1$ yr, $e = 0.4$,
3 yr weekly observation, 100 μs TOAs

→ $\delta S/S \sim 10^{-4} \ldots 10^{-3}$

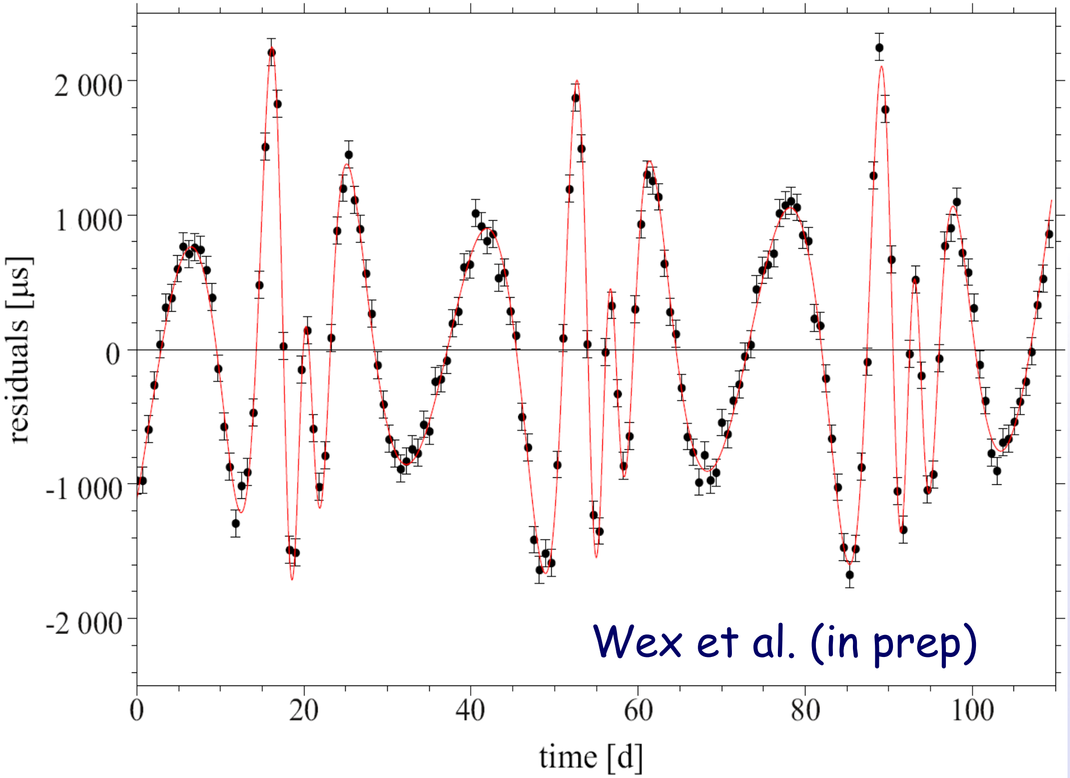
Test of *cosmic censorship*: In GR naked singularity if $cS/GM^2 > 1$

Measuring the Quadrupole Moment of the Black Hole

Pulsar in a 0.1 yr orbit around Sgr A*:

- **Secular precession caused by quadrupole is two orders of magnitude below frame dragging, and is not separable from frame-dragging**
- **Quadrupole leads to *characteristic periodic residuals* of order milliseconds**

Simulation: Extreme Kerr, 3 orbits, 160 TOAs with 100 μs error, eccentricity = 0.4



→ $\delta Q/Q = 0.008$

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Testing the No-Hair Theorem

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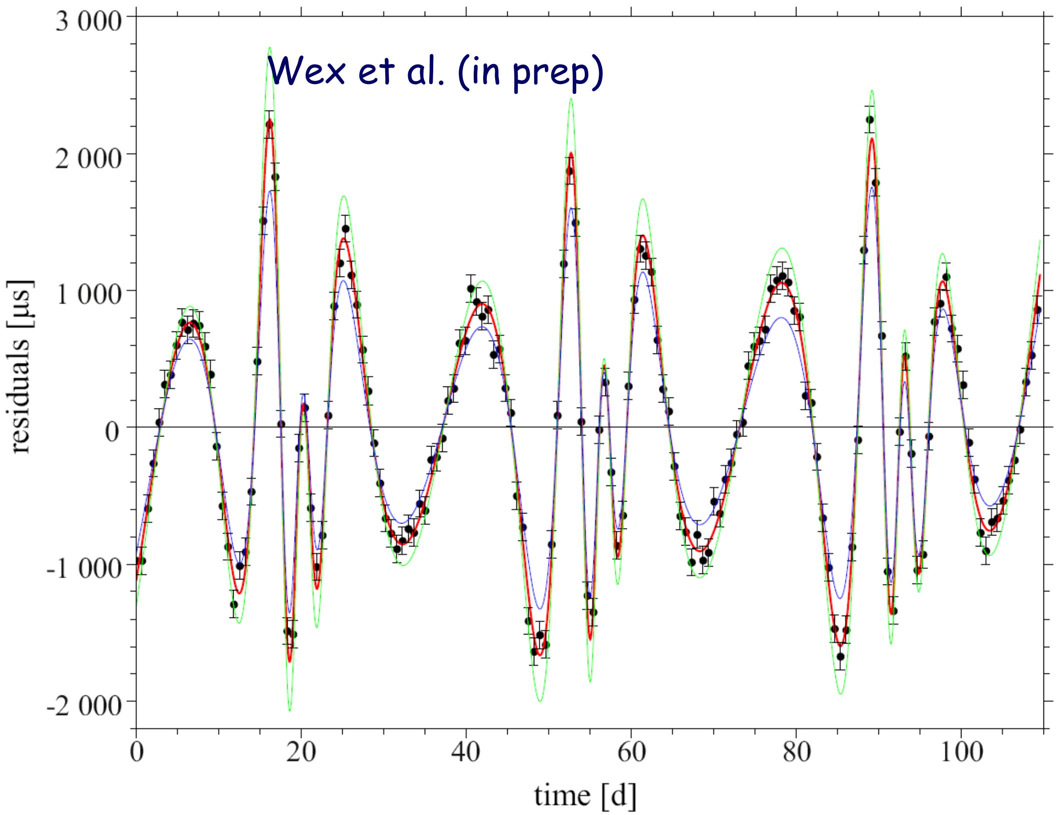
"no-hair" theorem of GR: electrically neutral black hole is completely characterized by M and S.

Quadrupole moment: $Q = -S^2/M$ (in units where $c = G = 1$)



$Q = -1.2\ S^2/M$

$Q = -1.0\ S^2/M$ (GR)

$Q = -0.8\ S^2/M$

Going to be fun!

Further PSR-BH applications

Black Hole evaporation & extra dimensions:

In a universe with large `Randall-Sundrum' extra dimensions, BHs evaporate fast due to emission of gravitons in the bulk ➔ visible in measured orbital decay!

In a BH-PSR binary, the rate of change of the orbital period due to the evaporation of the black hole may dominate that due to the emission of gravitational waves.

If we find no evidence for black-hole evaporation, then the size of the extra dimensions has to be

$$L \leq 0.1 \left(\frac{P}{2\mathrm{hr}} \right)^{4/3} \left(\frac{M_{BH}}{10 M_o} \right) \mu m$$

Psaltis & Johannsen 2010

Further PSR-BH applications

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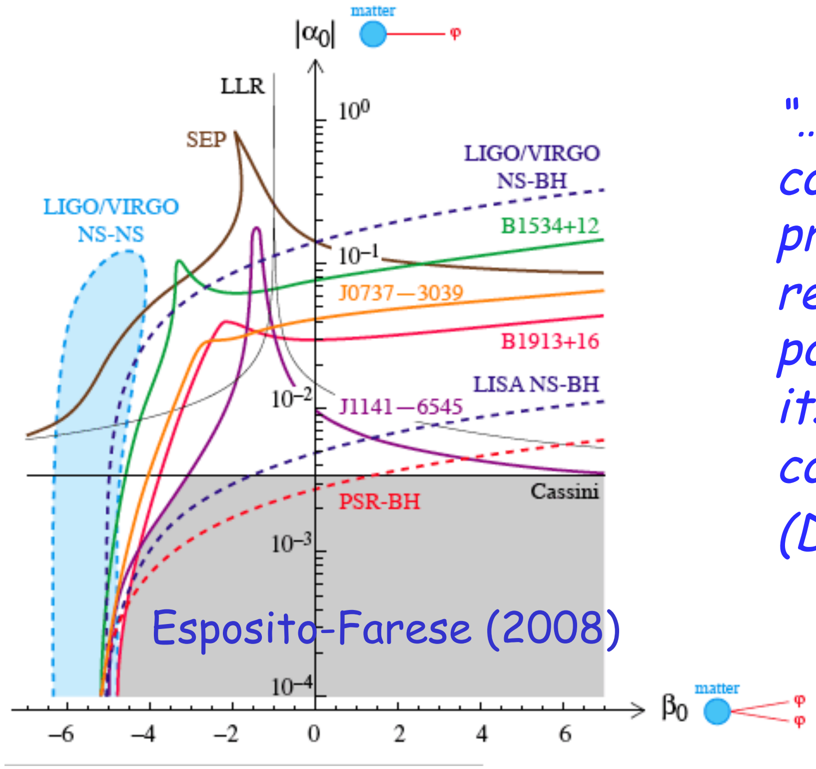
Best limit on existence of scalar field – as explanation for Dark Energy:



"…a binary pulsar with a black-hole companion has the potential of providing a superb new probe of relativistic gravity. The discriminating power of this probe might supersede all its present and foreseeable competitors…"

(Damour & Esposito-Farese 1998)

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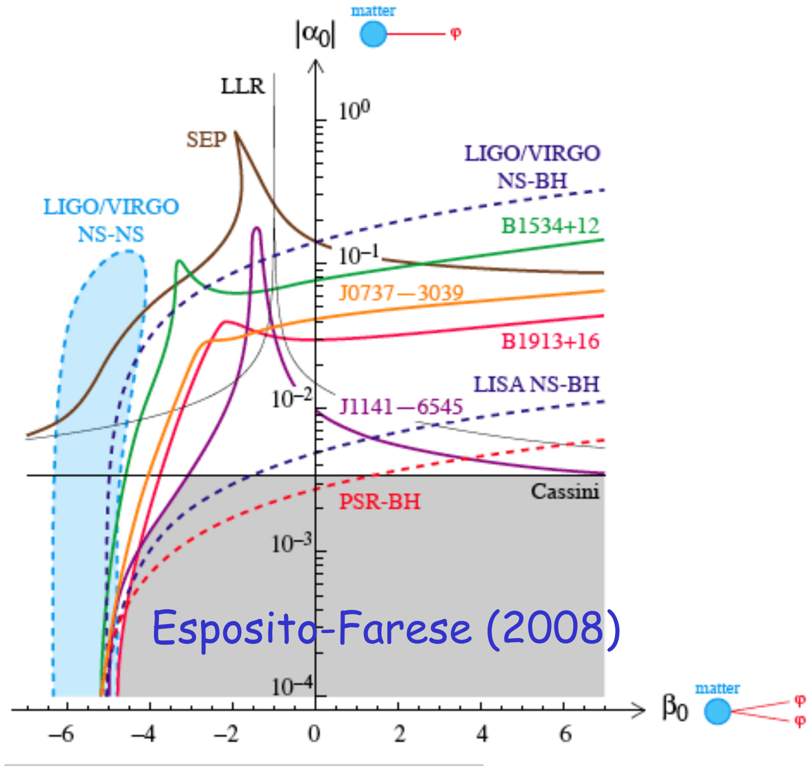
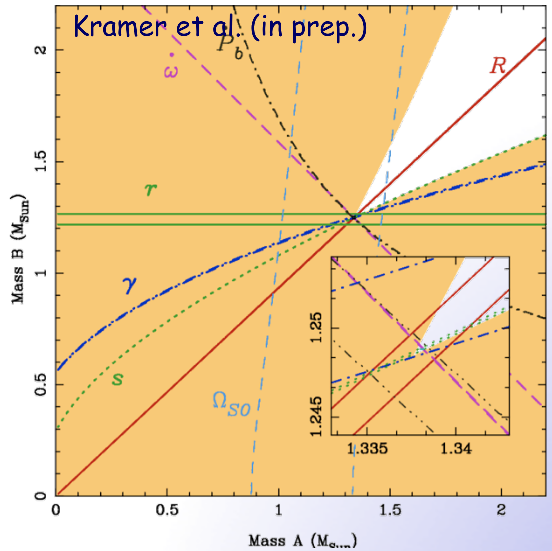


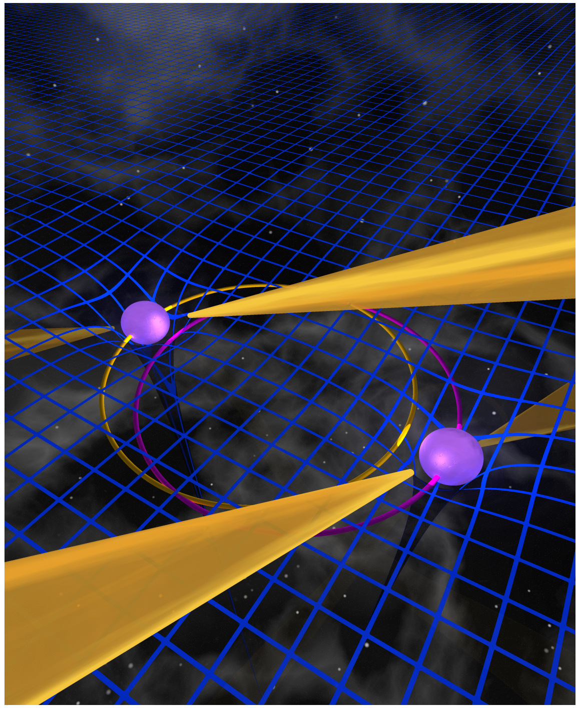


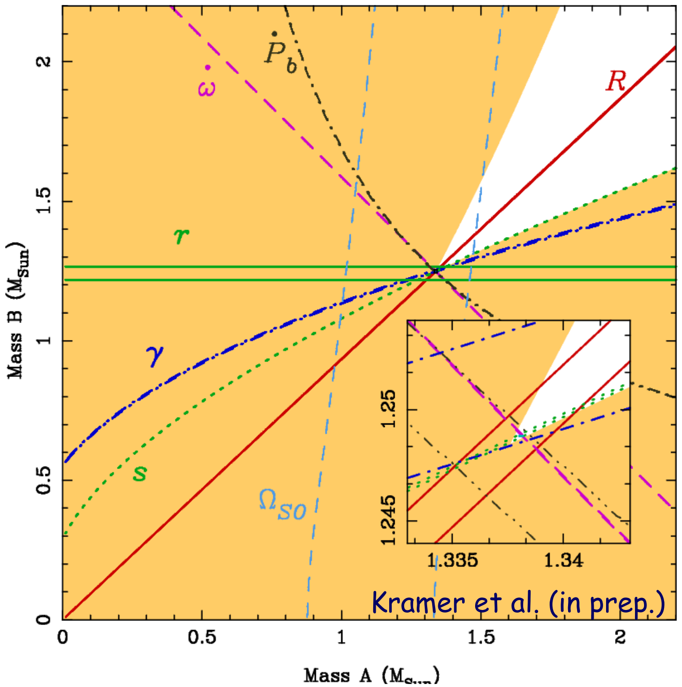
Combine with improved tests with already known pulsars, e.g. timing of double pulsar!

Double Pulsar Timing

Timing of the Double Pulsar with just SKA_1 will produce:

- Best Tests of theories of gravity in the strong-field regime
- Precision will supersede even that of weak-field solar system tests
- Measure the moment of inertia of a neutron star (pulsar A)
- Test Lorentz-invariance in strong fields

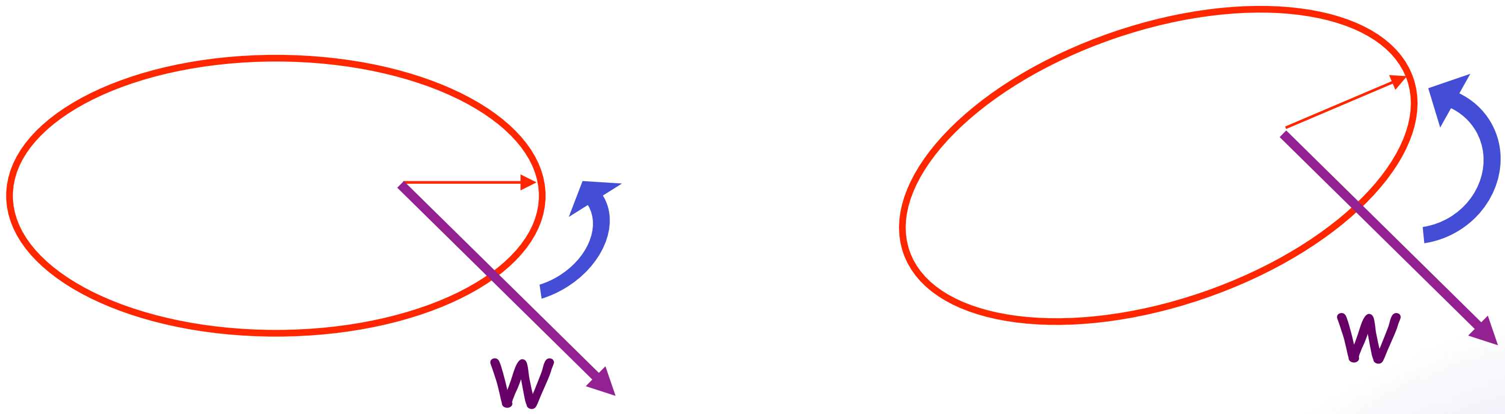




Existence of a Preferred Frame?

(Wex & Kramer 2007, 2010)

If Lorentz-invariance is violated in strong gravity fields…

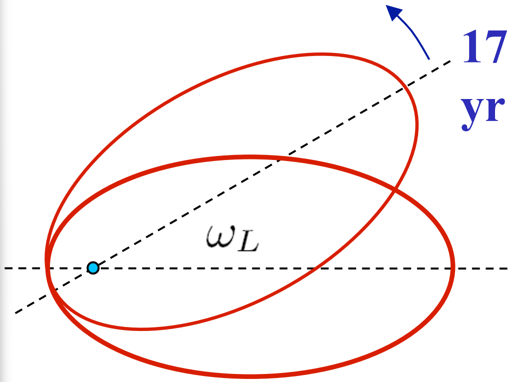


…a preferred frame would exist and the orbital orientation relative to it would change due to orbital prcession

As the angle relative to this frame changes with time, we should see a time-varying orbital parameters!

For double pulsar and other new systems, precession is huge! We should see it!

Existence of a Preferred Frame?



→ In DPSR distinct signatures in timing observations with periods of 10.7 and 21.3 years

$$\Delta\omega^{(w)}(T) = \eta_1^{(\omega)} \cos(\omega_L - \tilde{\chi}_0) - \eta_2^{(\omega)} \sin 2(\omega_L - \tilde{\chi}_0)$$

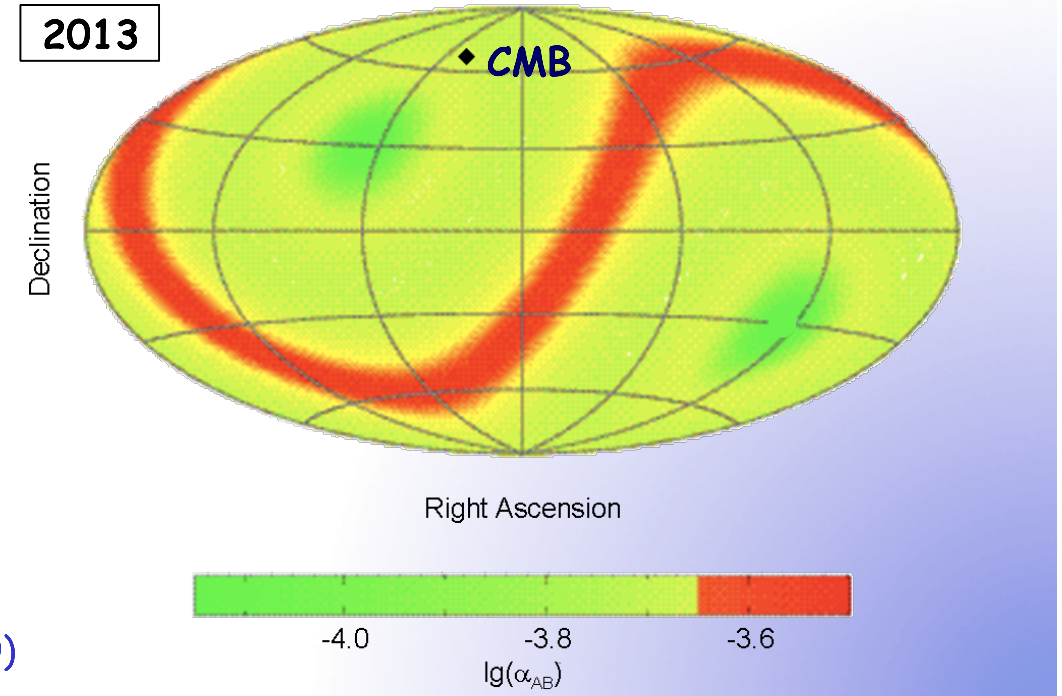
$$\Delta e^{(w)}(T) = \eta_1^{(e)} \sin(\omega_L - \tilde{\chi}_0) + \eta_2^{(e)} \cos 2(\omega_L - \tilde{\chi}_0)$$

preferred frame fingerprint

$$\eta_1^{(\omega)}/\eta_1^{(e)} = 11.262$$

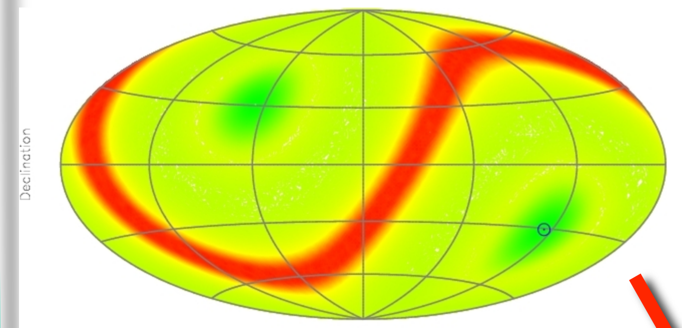
$$\eta_2^{(\omega)}/\eta_2^{(e)} = 5.642\ .$$

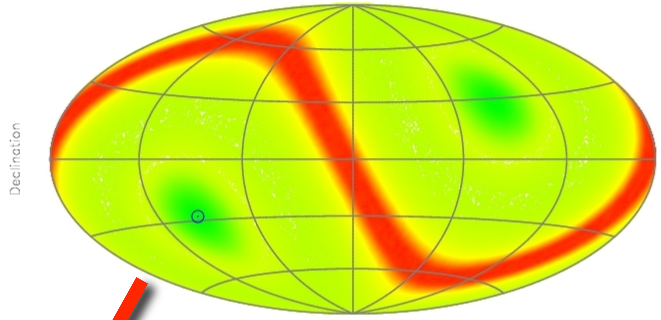
preferred frame limit



(Wex & Kramer 2007, 2010)

A PFE Antennae Array

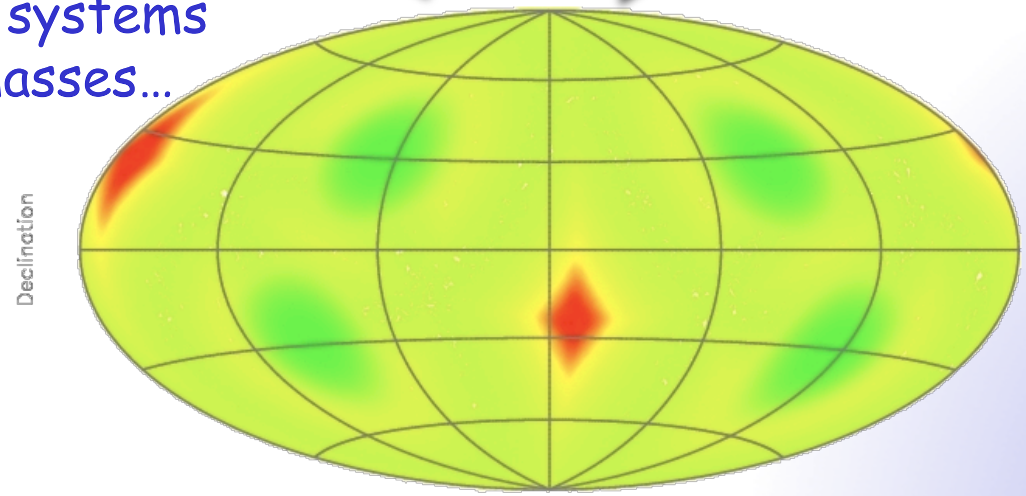




Double Pulsar system...

2nd system...

Combined for systems
with similar masses...

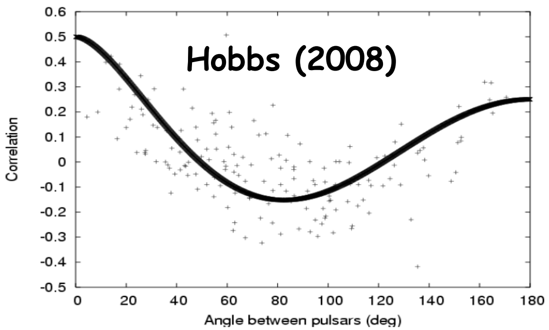


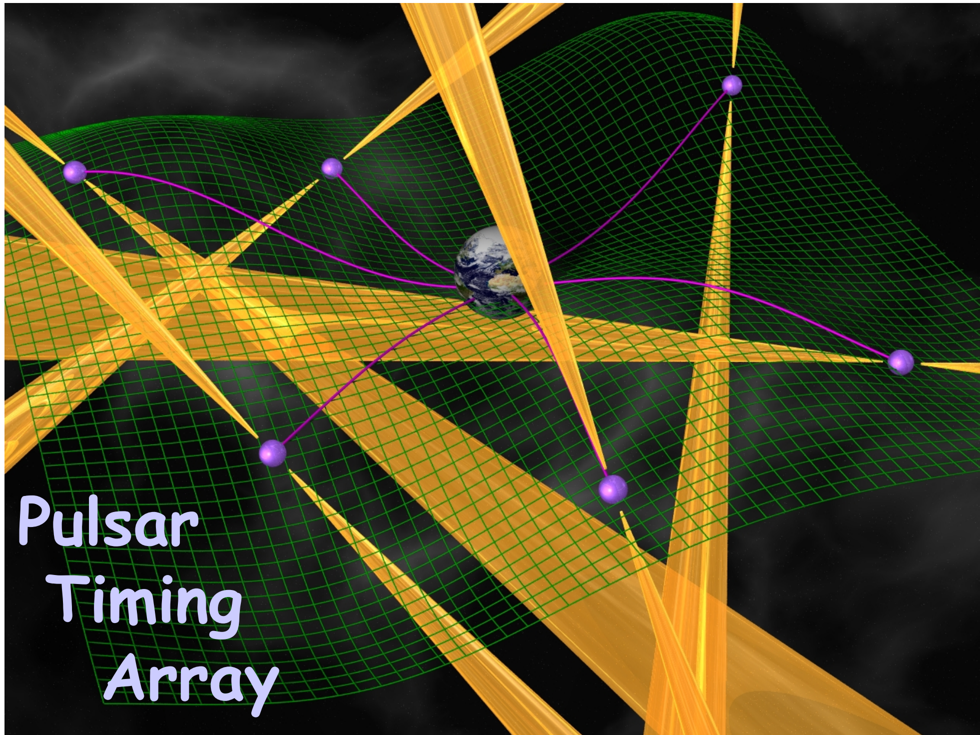
Direction can be determined also – should PFEs exist!

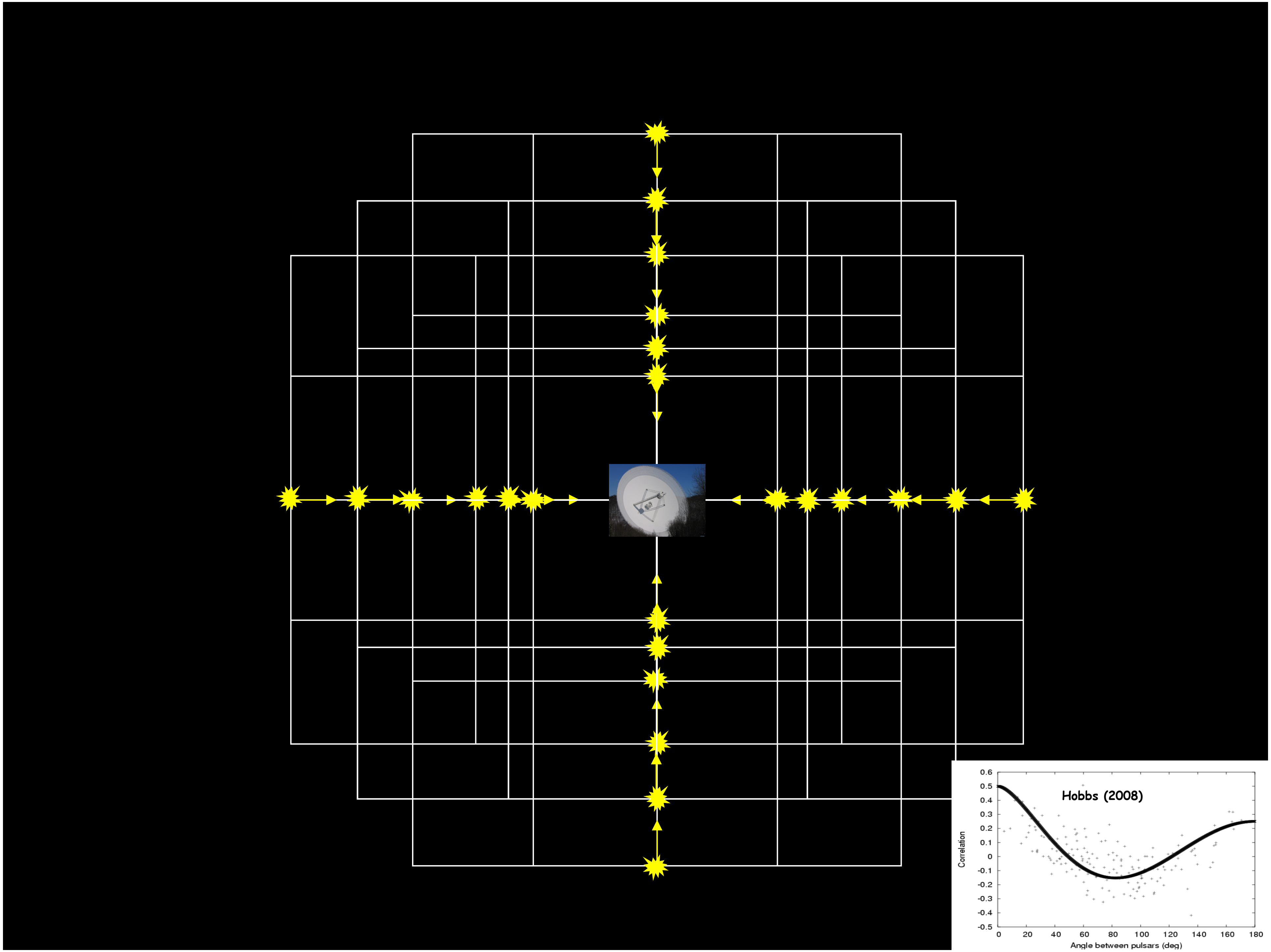
Pulsars as gravitational wave detectors

Pulse arrival times will be affected by low-frequency gravitational waves

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






Hobbs (2008)
Correlation
Angle between pulsars (deg)
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
20
40
60
80
100
120
140
160
180

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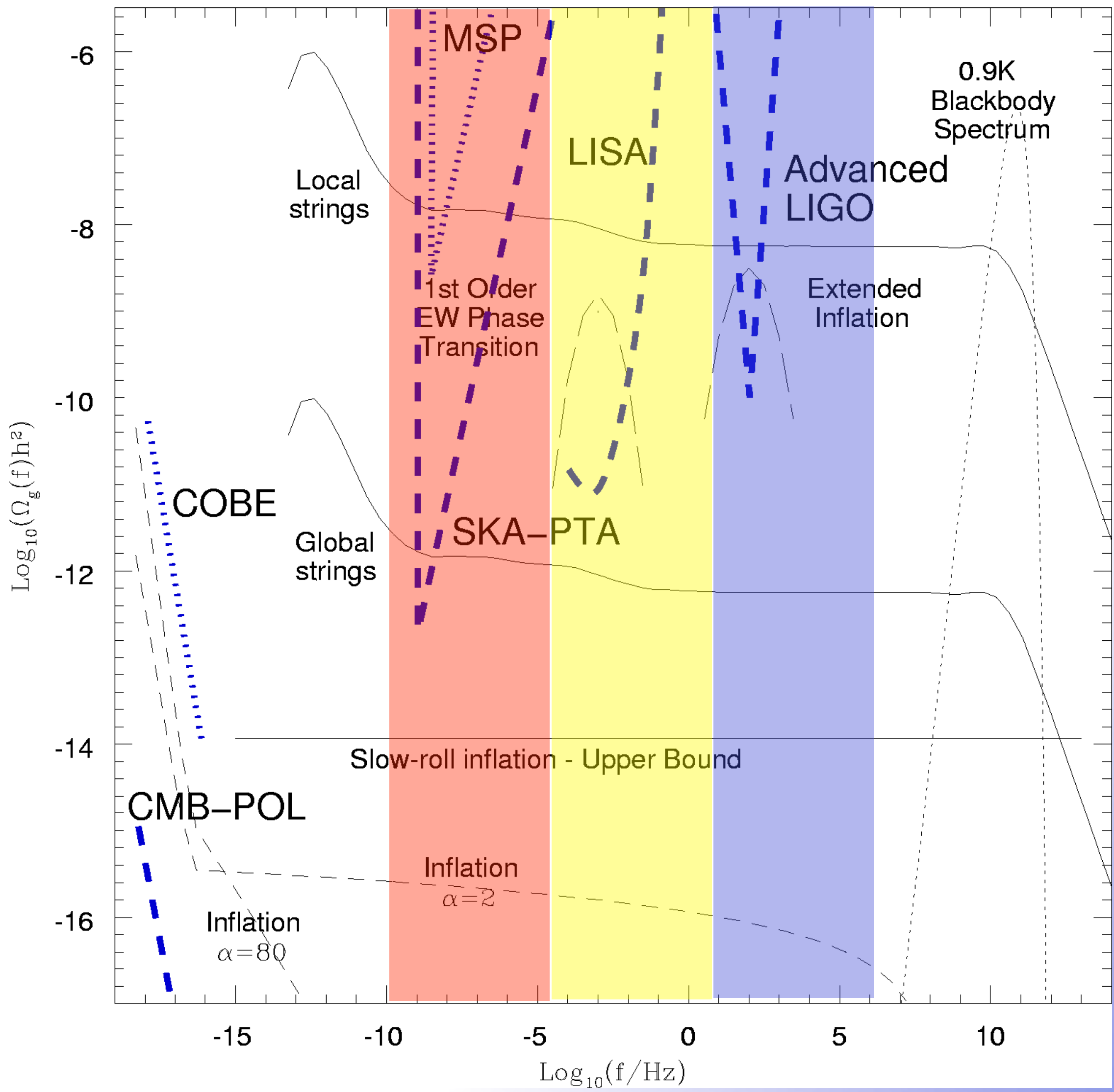
Pulsars as Gravitational Wave Detectors

(Kramer et al. 2004)

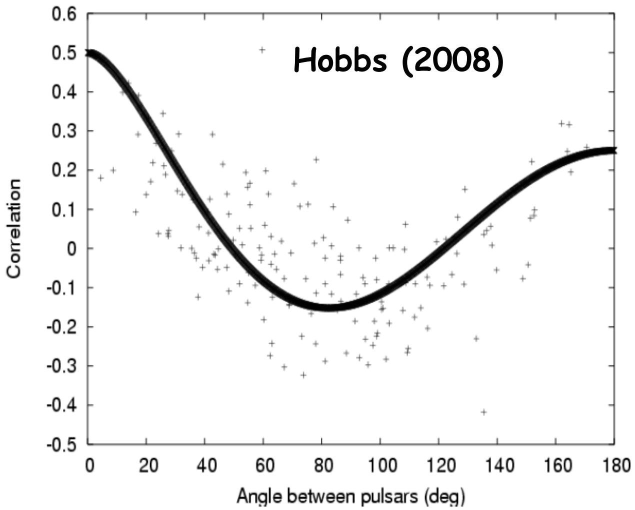
- PTA is sensitive to nHz gravitational waves
- Complementary to LISA, LIGO and CMB-pol band
- Expected sources:
  - binary super-massive black holes in early Galaxy evolution
  - Cosmic strings
  - Cosmological sources
- Types of signals:
  - stochastic (multiple)
  - periodic (single)
  - burst (single)



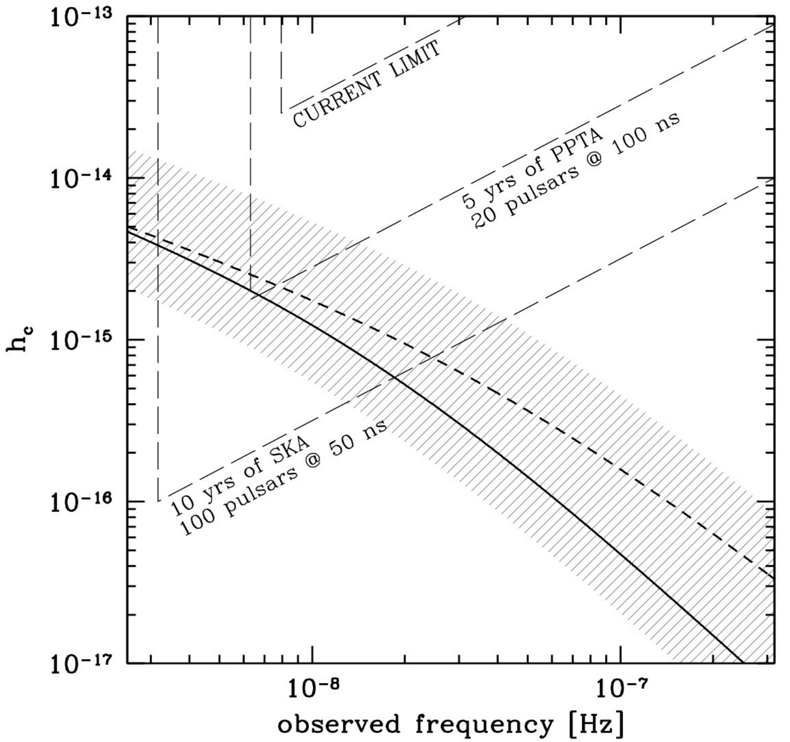
Stochastic background

- Strongest signal expected from binary super-massive black holes in early galaxy evolution (PTA only way to detect $M>10^7 M_\odot$, P_{orb}~10-20yr)
- Amplitude depends on merger rate, galaxy evolution and cosmology but could be "soon" detectable (e.g. Sesana et al. 2008)
- Ideally, want to sample correlation curve as best as possible (large PTA!)
- Current best result (Jenet et al. 2006)

  $\Omega_g < 2.0 \times 10^{-8}$
- New methods offer alternative ways to detect signal (e.g. van Haasteren et al 2009)



Sesana et al. (2008), Sesana & Vecchio (2009)



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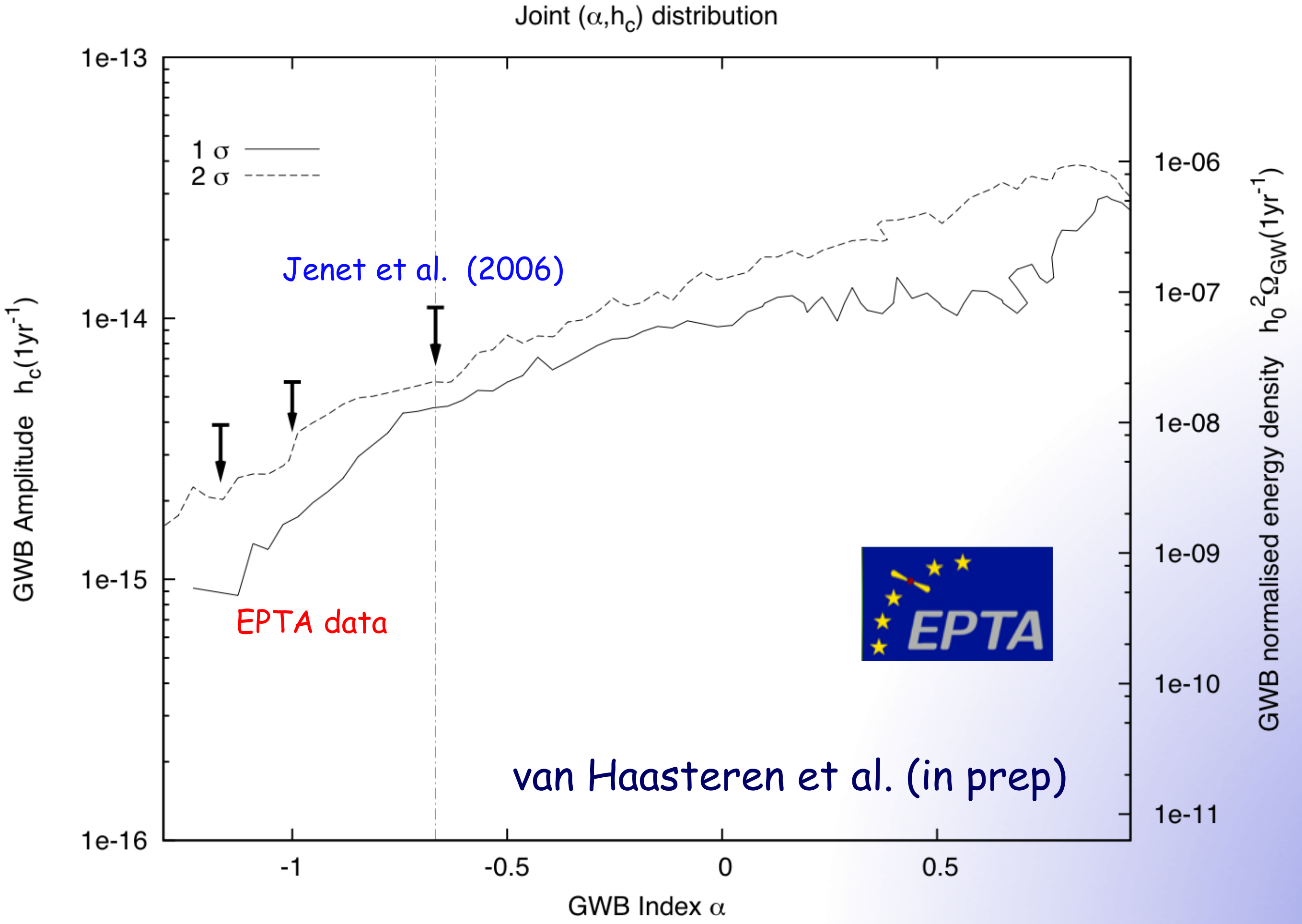
Current EPTA Limit

- European Pulsar Timing Array (ASTRON, INAF, MAN, MPIfR, Nancay, Leiden)
- Excellent test bed to investigate instrumental & systematic effects
- But we are also getting excellent results for GW studies already:



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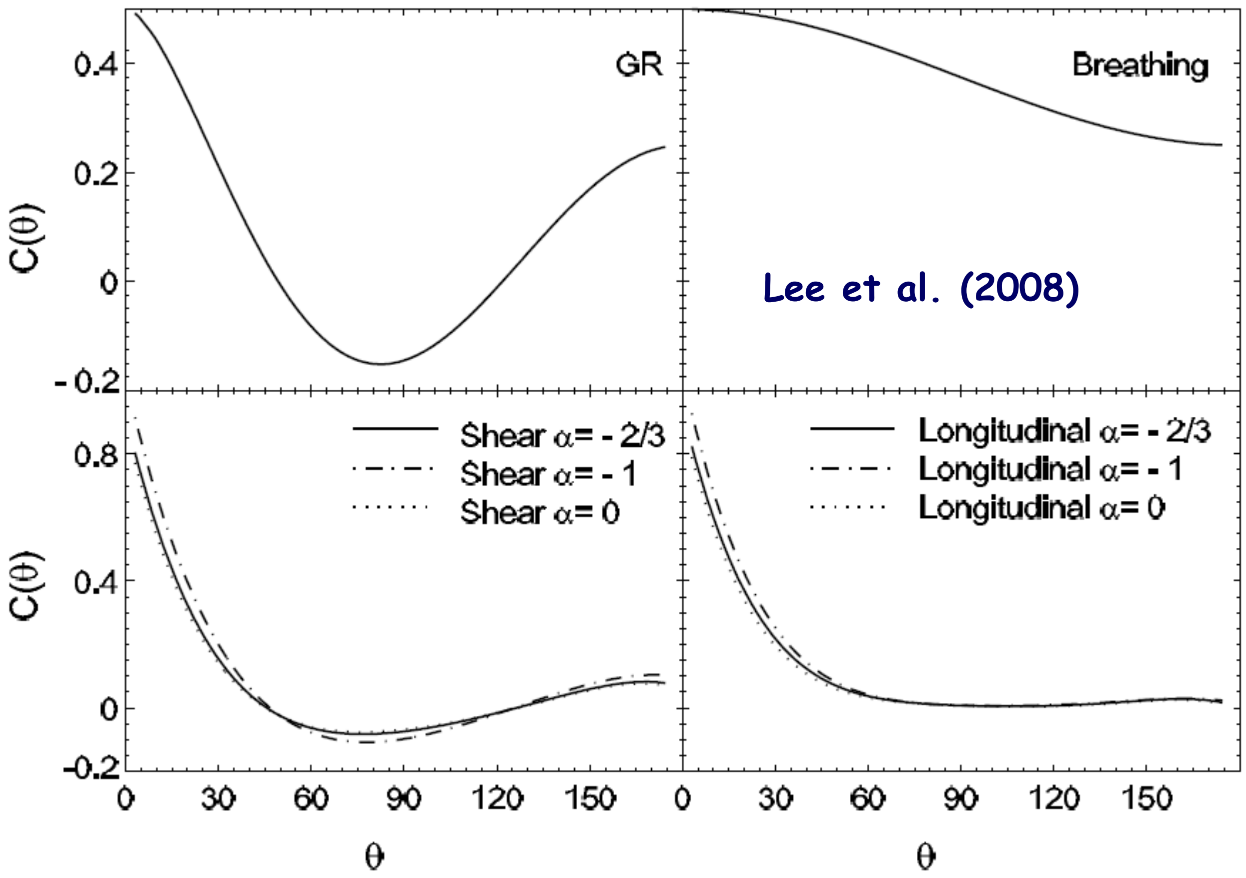
Gravitational wave physics

- We can do more than "only" detect gravitational waves
- With SKA we can study their properties: polarisation & graviton mass

GW polarisation



Lee et al. (2008)

Gravitational wave physics

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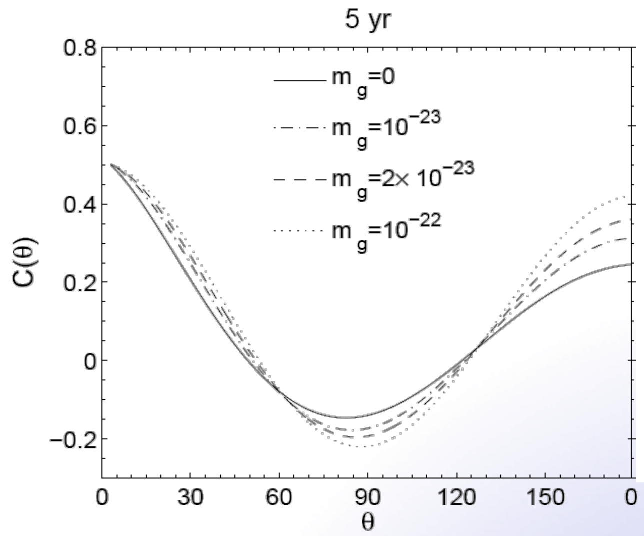
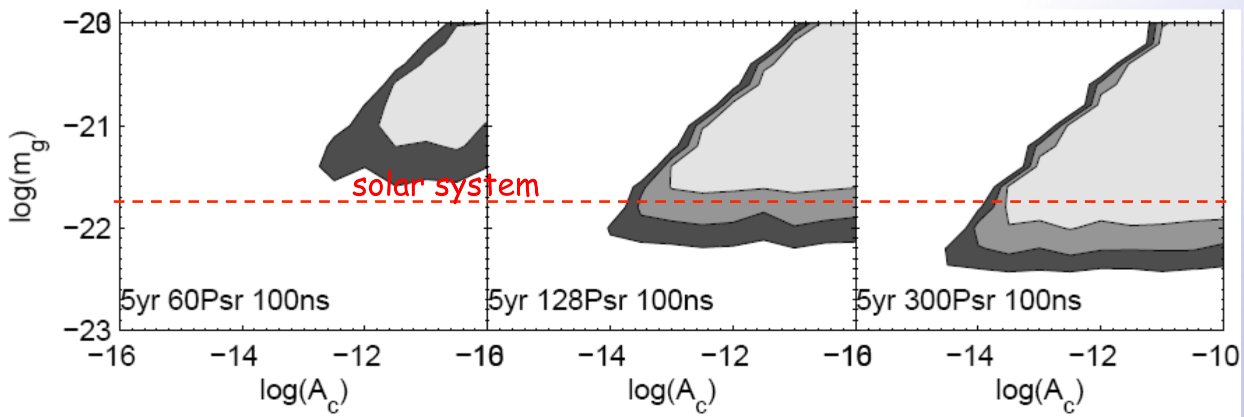
Graviton mass

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

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

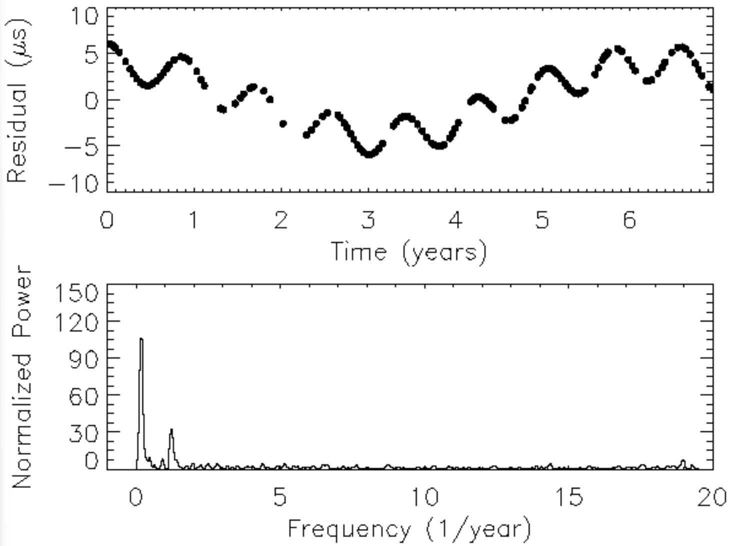


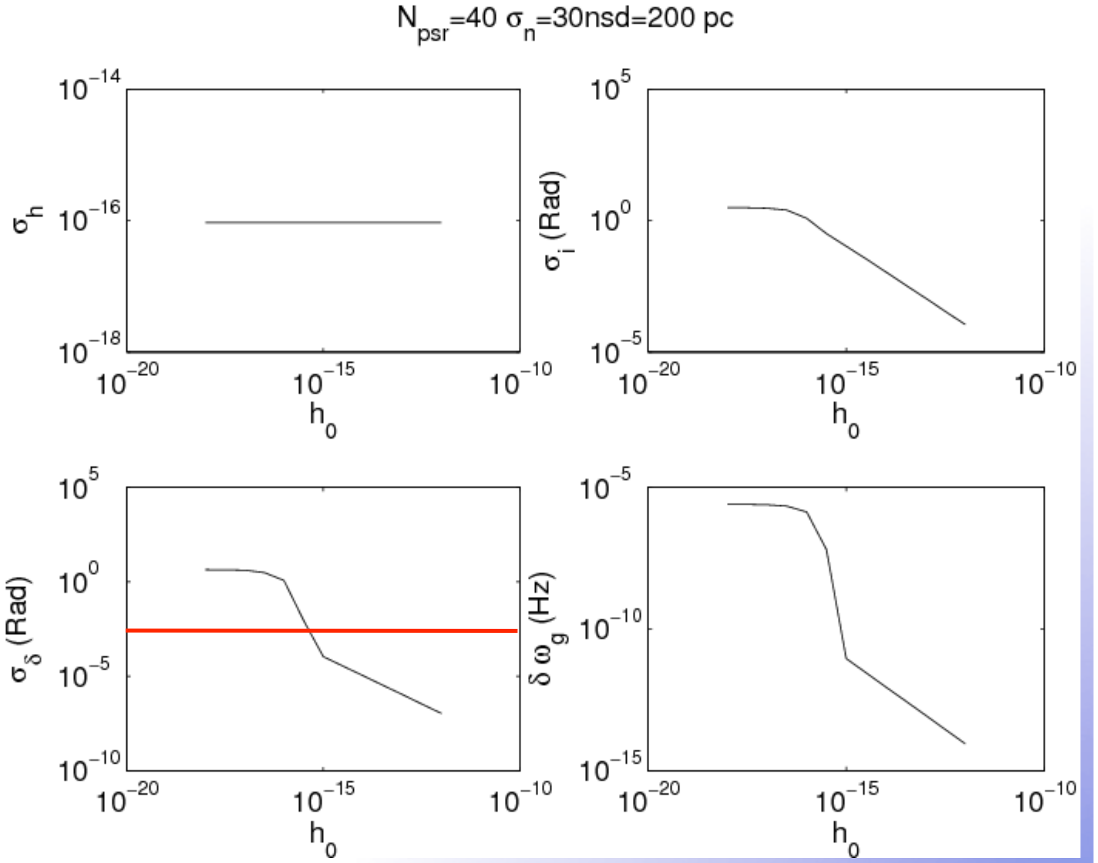
Lee et al. (2010)



Gravitational wave physics

- We can do more than “only” detect gravitational waves
- With SKA we can study their properties: polarisation & graviton mass
- …and pinpoint single GW sources, e.g. for EM identification!





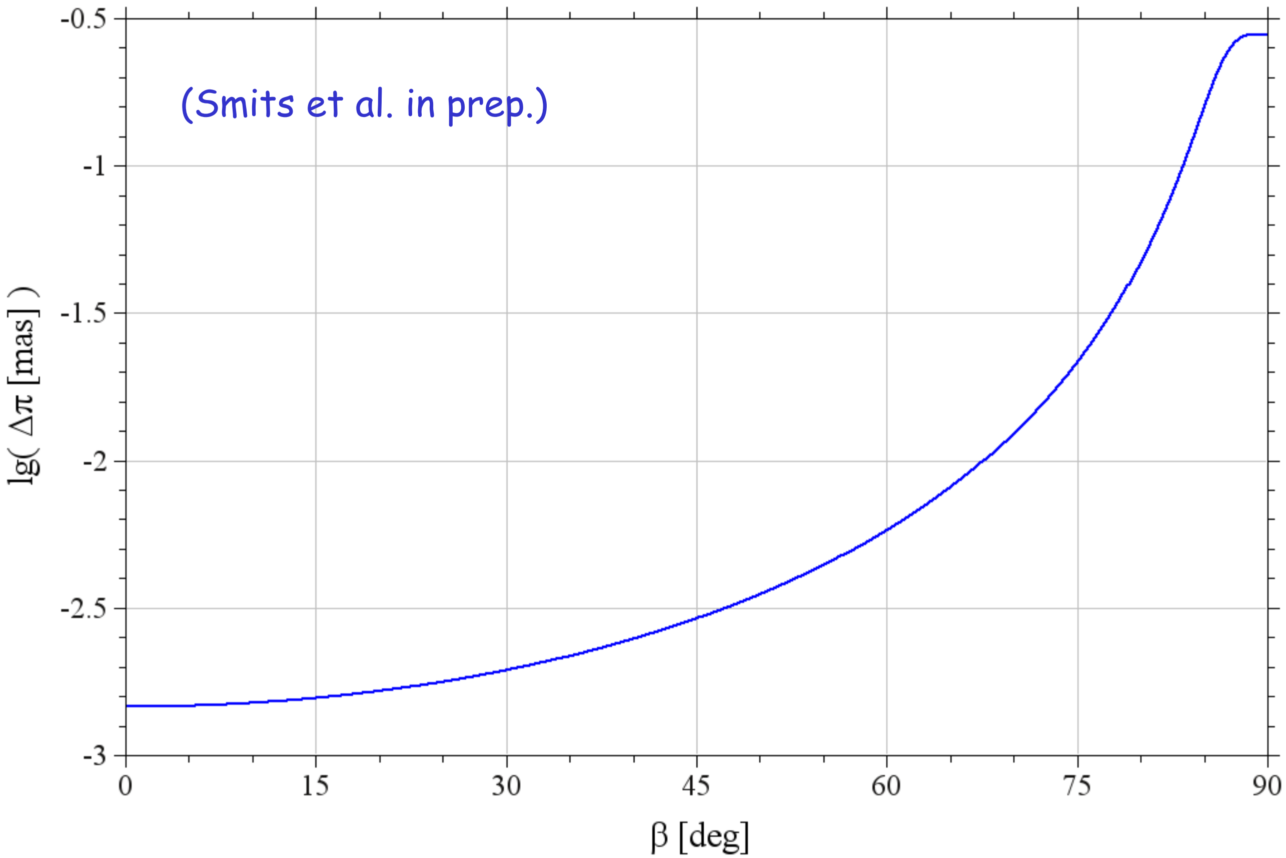
Possible by amazing astrometry of SKA!

Lee, Wex et al. (submitted)

Astrometry with the SKA

Independent and complementary ways to measure proper motions and parallax:

- interferometric (for all types of pulsars, comparable to current precision)
- timing parallax (very useful for MSPs)



- secular acceleration measurement (only MSP, GR to be assumed, need GAIA!)

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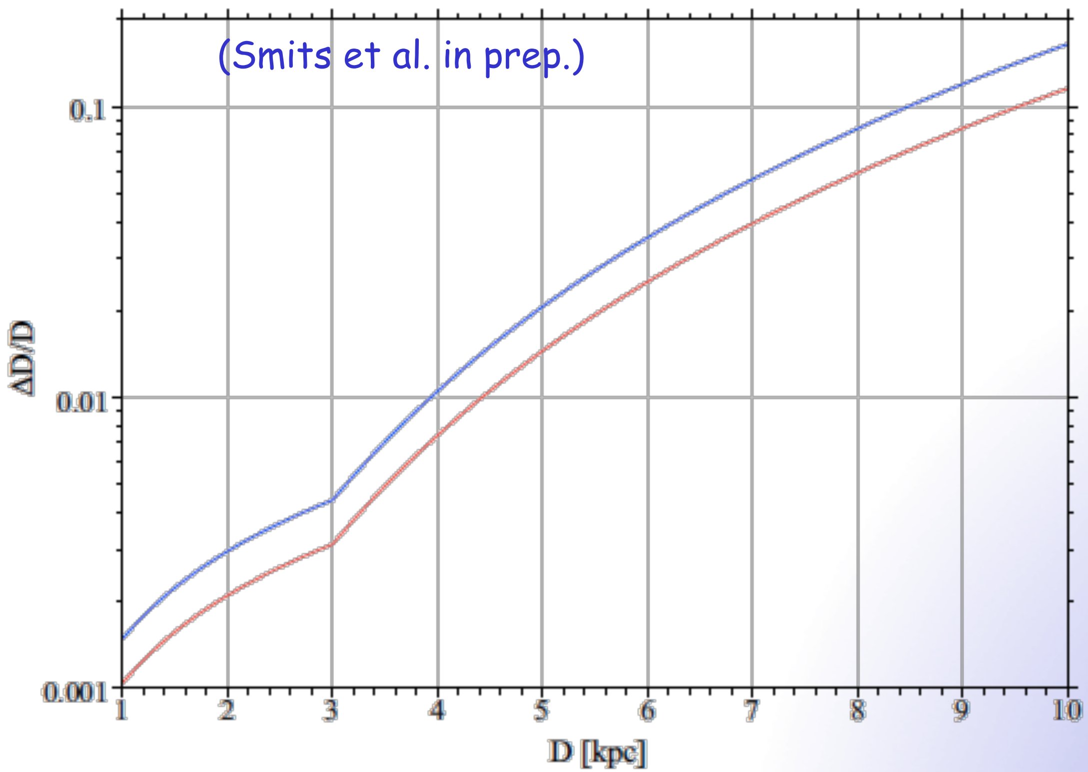
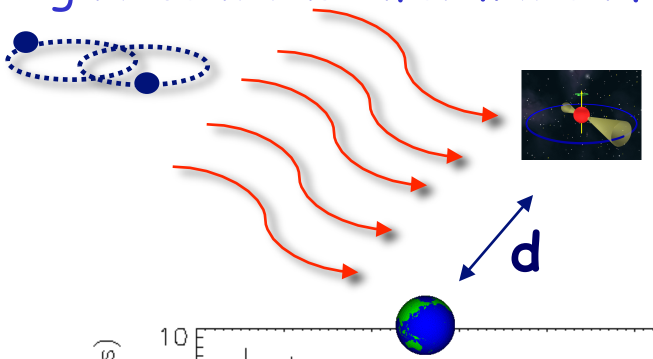


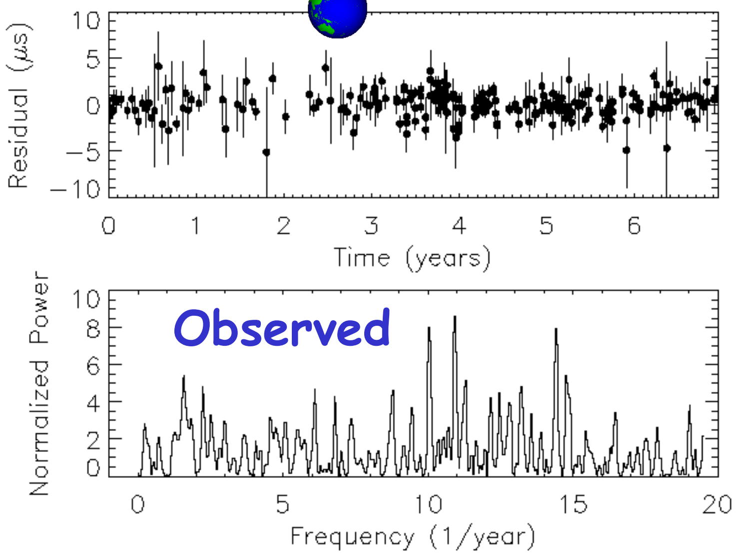
- secular acceleration measurement (only MSP, GR to be assumed, need GAIA!)

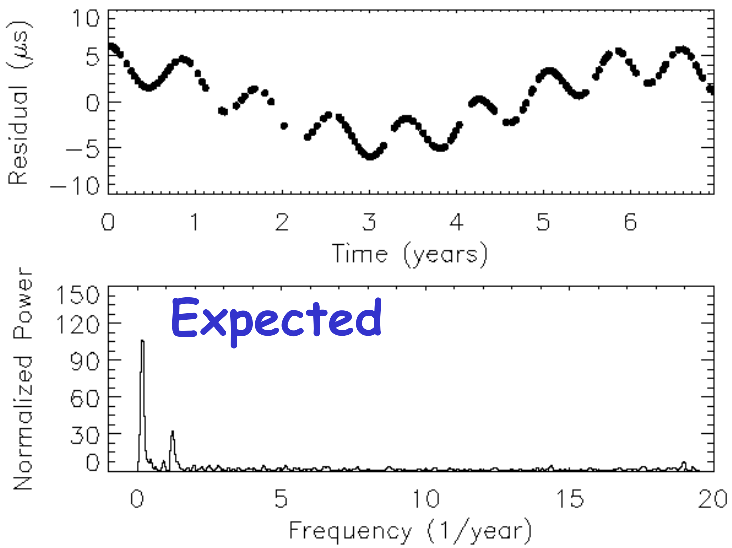
Single source detection

- Single binary super-massive black hole produces periodic signal
- Perhaps rare but complementary in mass range to LISA (Sesana et al. 2009, Sesana & Vecchio 2010)
- If SNR is high (or source and orbital period known!) we can search for signature
- Expect periodic signal but also dc-term due to memory effect (van Haasteren & Levin 2010)
- Signal contains information from two distinct epochs: t and t-d/c

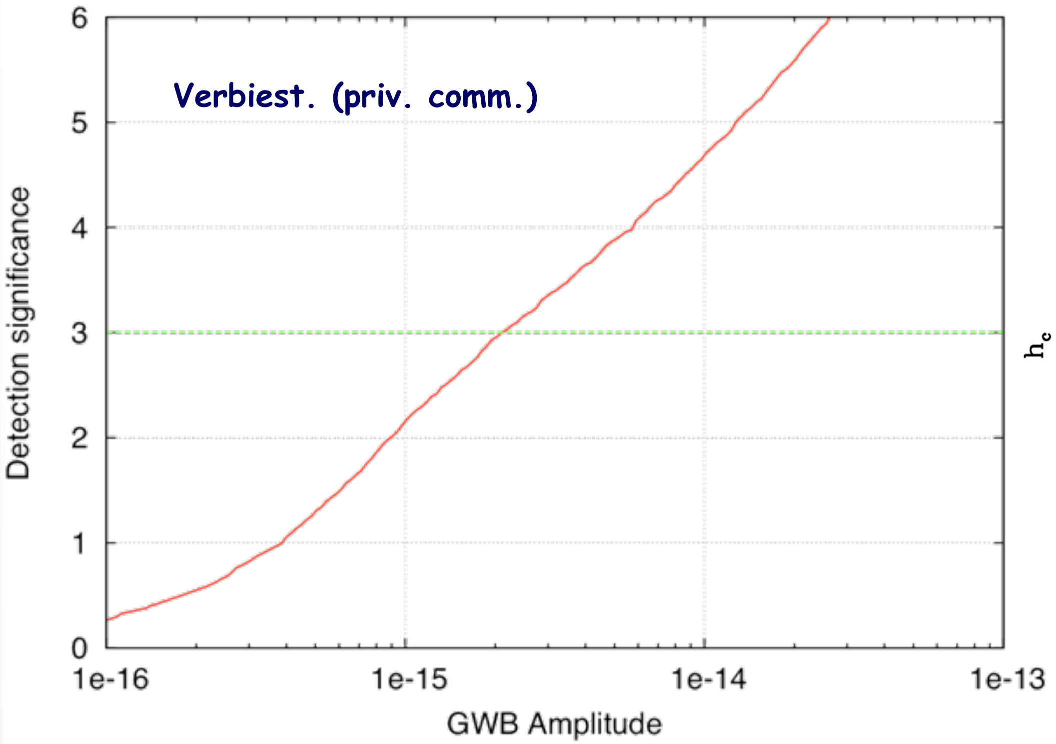


Example: if binary super-massive BH exists in 3C66B, we expected signature in timing data of PSR B1855+09 (Jenet et al 2003):

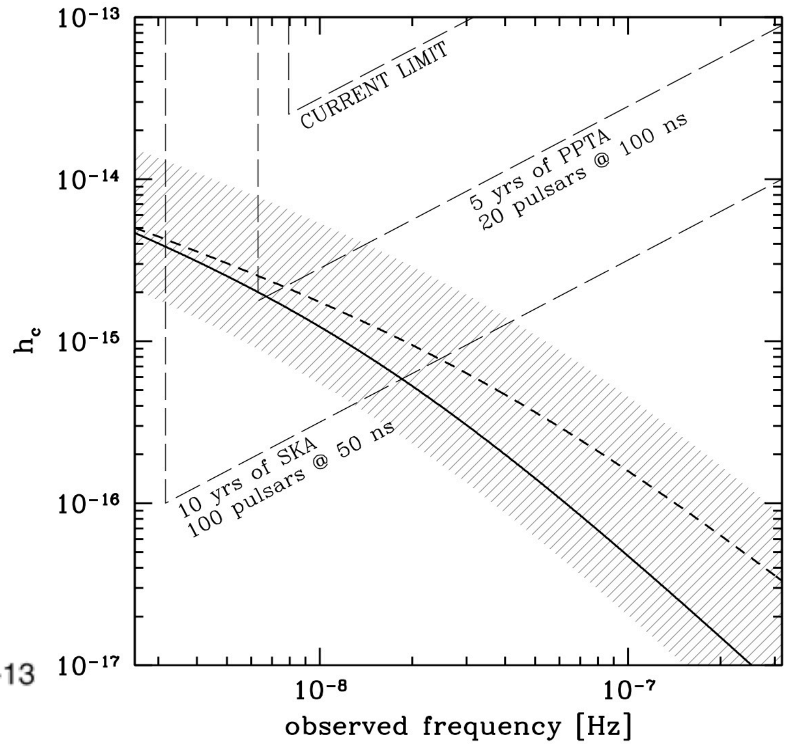




Already detection with SKA_1



Sesana et al. (2008), Sesana & Vecchio (2009)



Phase 1 should make a detection – can also make use of IPTA.

With the full SKA we can study GW properties and sources!

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The road to the full SKA: SKA_1

Phase 1 will be also an exciting search machine:

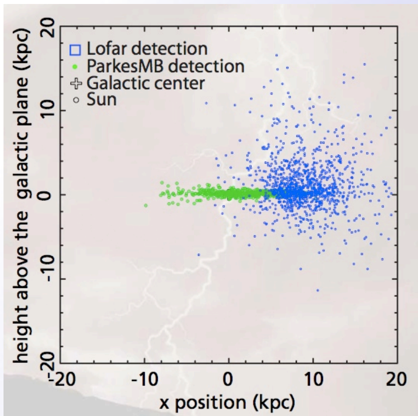
- Low-frequency array (AA, 400 MHz): 7800/950 PSRs/MSPs (Galactic)

  1-month only! 2200/750 (rest of sky)

- Dishes allow to probe further into Galaxy

- Note that full SKA cannot use full area for searching (initially) due to processing requirements – will already discover interesting sources

- Complementing the on-going HRTU all-sky survey, P-ALFA… and LOFAR!



Van Leeuwen & Stappers (2006)

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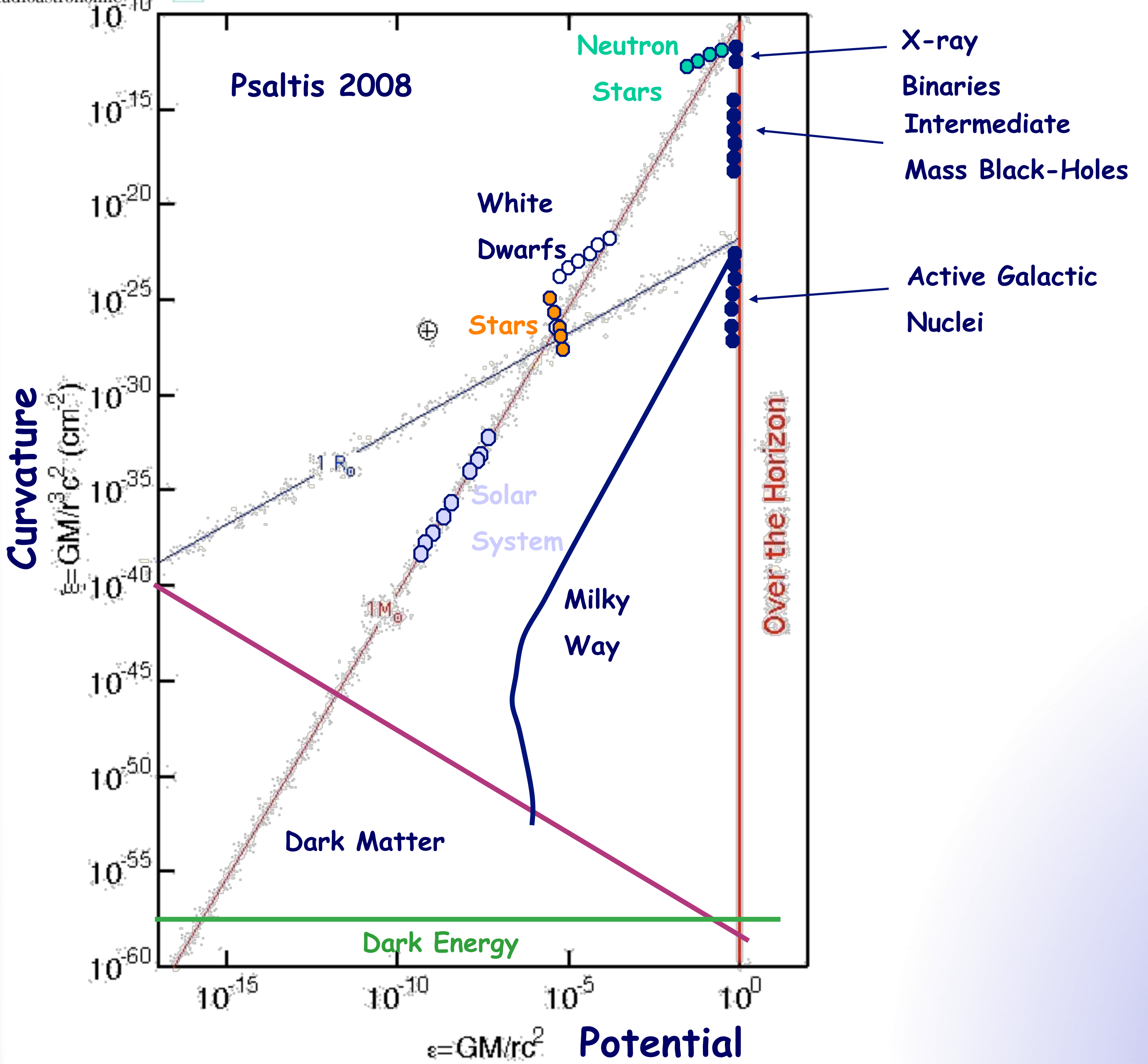

Synergy & Uniqueness

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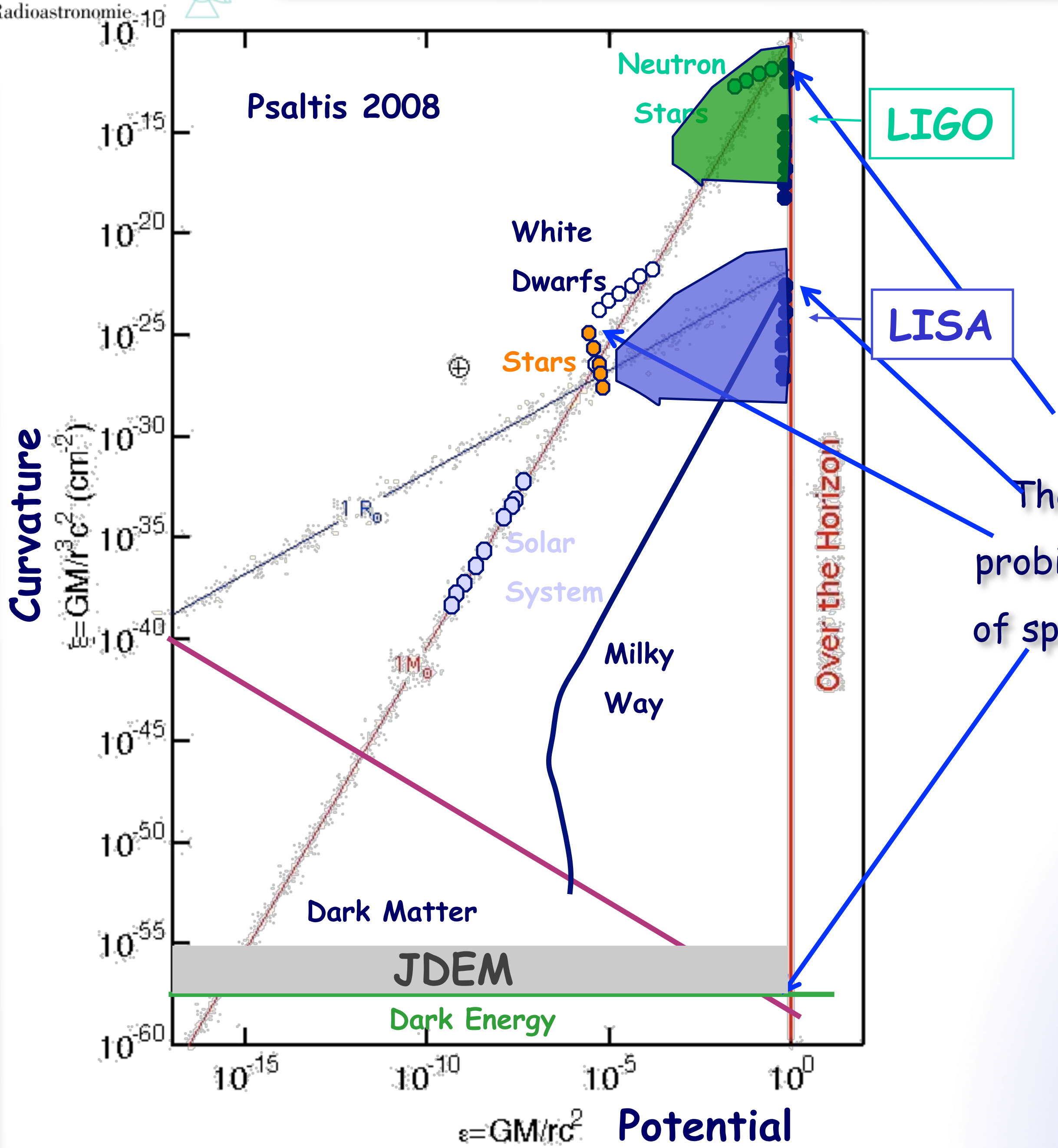

The SKA is unique in probing the entire range of spacetime curvatures!

Synergy & Uniqueness

Conclusions

- The SKA will be an amazing instrument to test fundamental physics at the edge of our current understanding including
  - study of gravitational wave properties and source
  - probing the description of black holes in theories of gravity, including testing the no-hair theorem for the GC to a few%.
- Phase 1 will already be a superb world-class facility on the way to the full SKA:
  - detection of gravitational wave background
  - discovery of thousands of pulsars
  - best tests of gravity in strong-field regime
- SKA will be – in all phases – a unique instrument with a lot of synergies and complementarities with other facilities