First European Physical Society Conference on Gravitation

GWs and Pulsar Timing with PTA/SKA

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La Sapienza – Rome - 21 February 2019

SKA organization and funds

[© SKA organization 2019]

Assuming a cost ceiling for SKA1 capital expenditures of:

€ 650 Million [2013 value] → €150 Million design effort – fully funded

Signature for the IGO (inter-governmental organisation) responsible for delivering the construction and operation of the SKA is due for 12th March 2019 here in Rome

SKA: a transformational instruments

Element	SKA1 scale	SKA2 scale
Dishes, feeds, receivers	~200	~2500
Aperture arrays	~130,000	~1,000,000
Signal transport	~1 Pb/s	~10 Pb/s
Signal processing	~exa-MACs	~exa-MACs
High performance computing	~100s tera-flops	~exa-flops
Data storage	Exa-byte capacity	Exa-byte
Power requirements	~10MW	~50MW

[© R. Braun 2015]

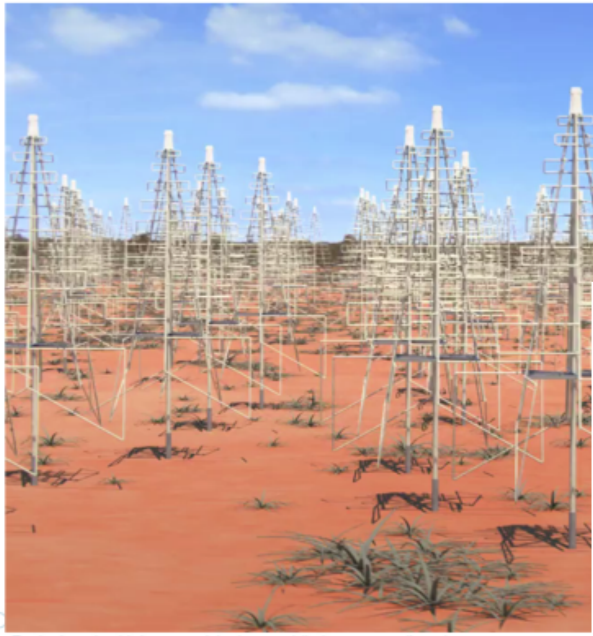
SQUARE KILOMETRE ARRAY

Exploring the Universe with the world's largest radio telescope

SKA: the two sites

SKA1-LOW, Murchison, Australia:

130,000 dipoles (512 stations x 256 antennas); 50–350 MHz
~80km baselines; large areal concentration in core



[© R. Braun 2015]

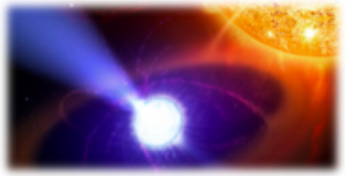
SKA1-MID, Karoo, South Africa:

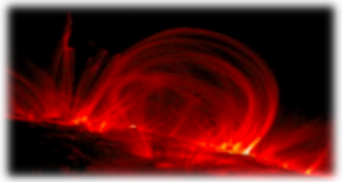
133 SKA1 + 64 MeerKAT dishes. Max baseline ~150km
Bands: 2 (0.95–1.76 GHz), 5 (4.6–14(24) GHz), 1 (0.35–1.1 GHz)

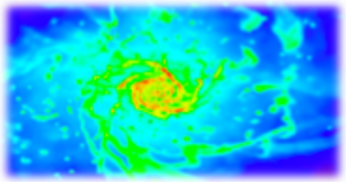
[© R. Braun 2015]

Flagship science

	SKA1	SKA2
The Cradle of Life & Astrobiology	Proto-planetary disks; imaging inside the snow/ice line (@ < 100pc), Searches for amino acids.	Proto-planetary disks; sub-AU imaging (@ < 150 pc), Studies of amino acids.
	Targeted SETI: airport radar 10^4 nearby stars.	Ultra-sensitive SETI: airport radar 10^5 nearby star, TV ~10 stars.
Strong-field Tests of Gravity with Pulsars and Black Holes	1st detection of nHz-stochastic gravitational wave background.	Gravitational wave astronomy of discrete sources: constraining galaxy evolution, cosmological GWs and cosmic strings.
	Discover and use NS-NS and PSR-BH binaries to provide the best tests of gravity theories and General Relativity.	Find all ~40,000 visible pulsars in the Galaxy, use the most relativistic systems to test cosmic censorship and the no-hair theorem.
The Origin and Evolution of Cosmic Magnetism	The role of magnetism from sub-galactic to Cosmic Web scales, the RM-grid @ 300/deg2.	The origin and amplification of cosmic magnetic fields, the RM-grid @ 5000/deg2.
	Faraday tomography of extended sources, 100pc resolution at 14Mpc, 1 kpc @ z ≈ 0.04.	Faraday tomography of extended sources, 100pc resolution at 50Mpc, 1 kpc @ z ≈ 0.13.
Galaxy Evolution probed by Neutral Hydrogen	Gas properties of 10^7 galaxies, <z> ≈ 0.3, evolution to z ≈ 1, BAO complement to Euclid.	Gas properties of 10^9 galaxies, <z> ≈ 1, evolution to z ≈ 5, world-class precision cosmology.
	Detailed interstellar medium of nearby galaxies (3 Mpc) at 50pc resolution, diffuse IGM down to N_H < 10^17 at 1 kpc.	Detailed interstellar medium of nearby galaxies (10 Mpc) at 50pc resolution, diffuse IGM down to N_H < 10^17 at 1 kpc.







[© R. Braun 2015]

The role of SKA

Challenging Einstein:

Increasing the sample of test-objects

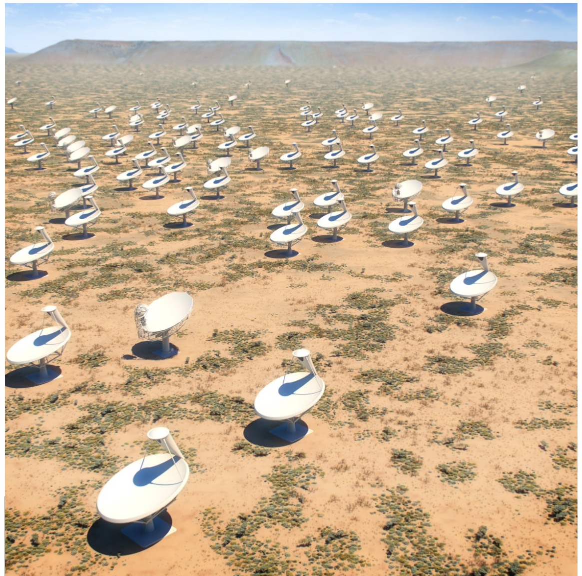
[Keane et al 2015]

Search speed ≈ $(A_{eff}/T_{sys})^2\ \Omega$

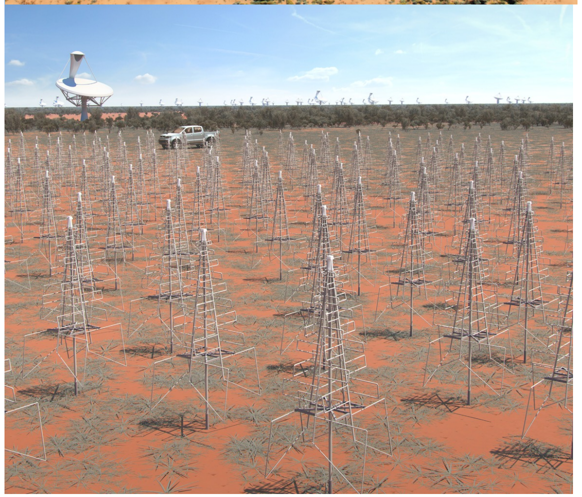
SKA1: Multiplying a factor ≈ 3-4 the known population

SKA2: Multiplying a factor ≈ 10-12 the known population

The impact of SKA1 on pulsar population



The current pulsar population ≈ 2600 (with ≈ 300 MSPs)



The post-SKA1-searches pulsar population ≈ 12000
and in particular a population of Millisecond pulsars ≈ 1500

[Keane et al 2015]

The role of SKA

Challenging Einstein:

tests of General Relativity and fundamental physics in pulsar binary systems

Timing quality $\sigma_{ToA} \approx T_{sys}/A_{eff}$

[Shao et al 2015]

SKA1: Timing most of the targets a factor 5-10 better than now

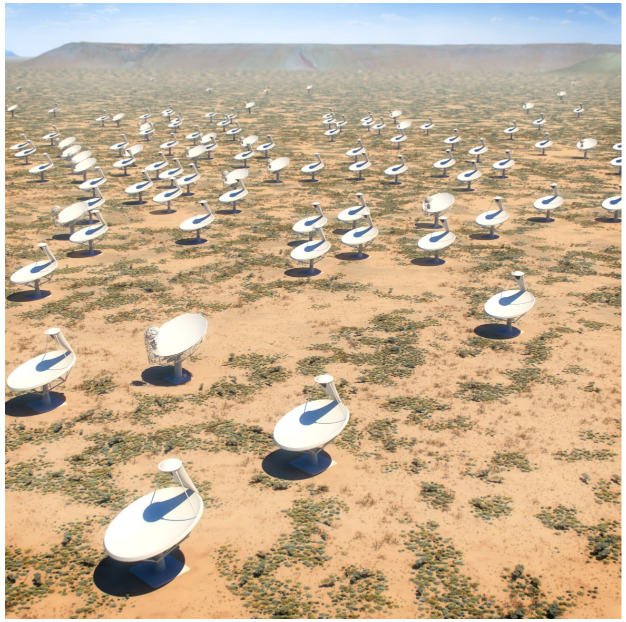
SKA2: Timing the targets a factor 10-100 better than now

The impact of SKA1 on gravity theories studies

The current relativistic pulsars population ≈ 20-30

[Keane et al 2015; Shao et al 2015]

The SKA1 relativistic pulsar population ≈ 100-200 and a timing precision better by a factor ≈ 5-10



The currently best laboratory: Double Pulsar

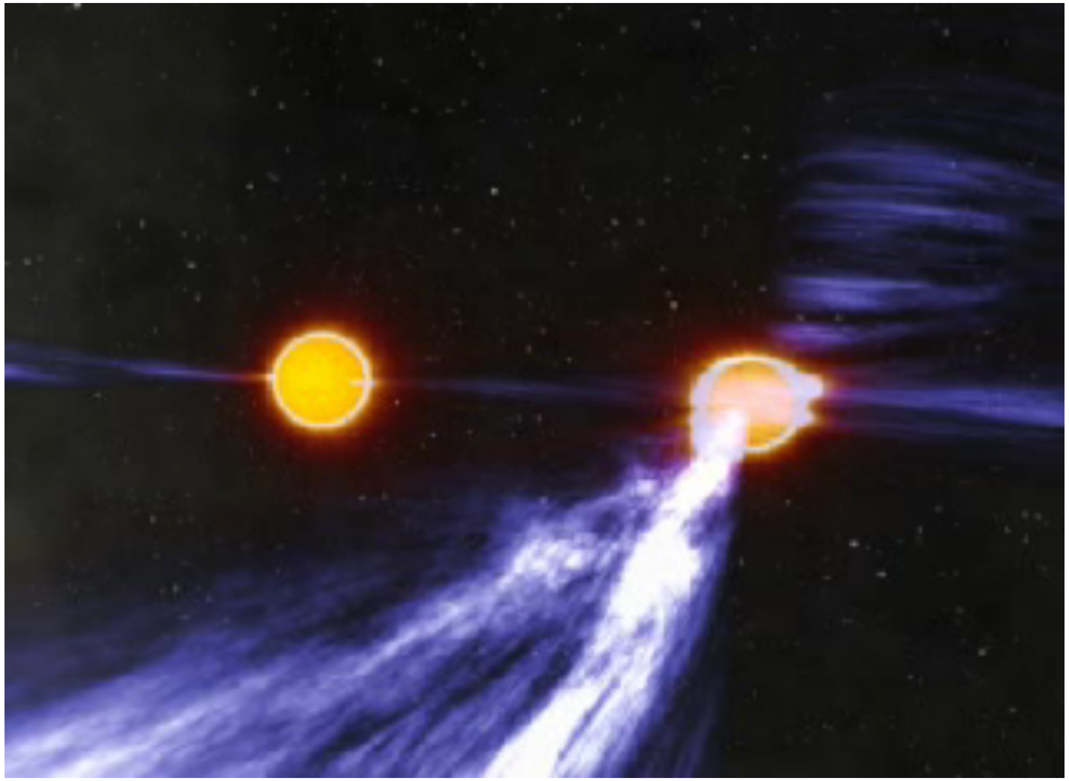
Old 23-ms pulsar in a 147-min orbit with young 2.77-s pulsar

[Burgay et al. 2003, Lyne et al. 2004]

Eclipsing binary in compact, slightly eccentric (e=0.088) and edge-on orbit

System showing the largest numbers of relativistic effects

[Kramer et al. 2006, Breton et al. 2008, Kramer et al. 2019 in prep., Wex et al. in prep, +....]



[Animation by Rowe - CASS_ATNF]

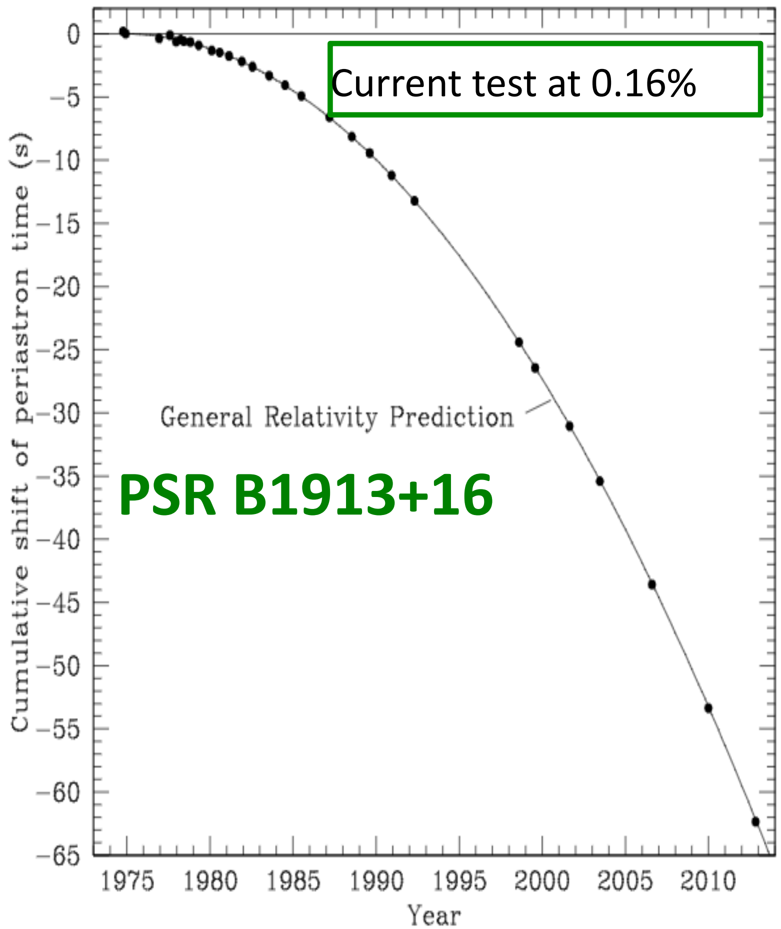
Collaborators (alphabetical):

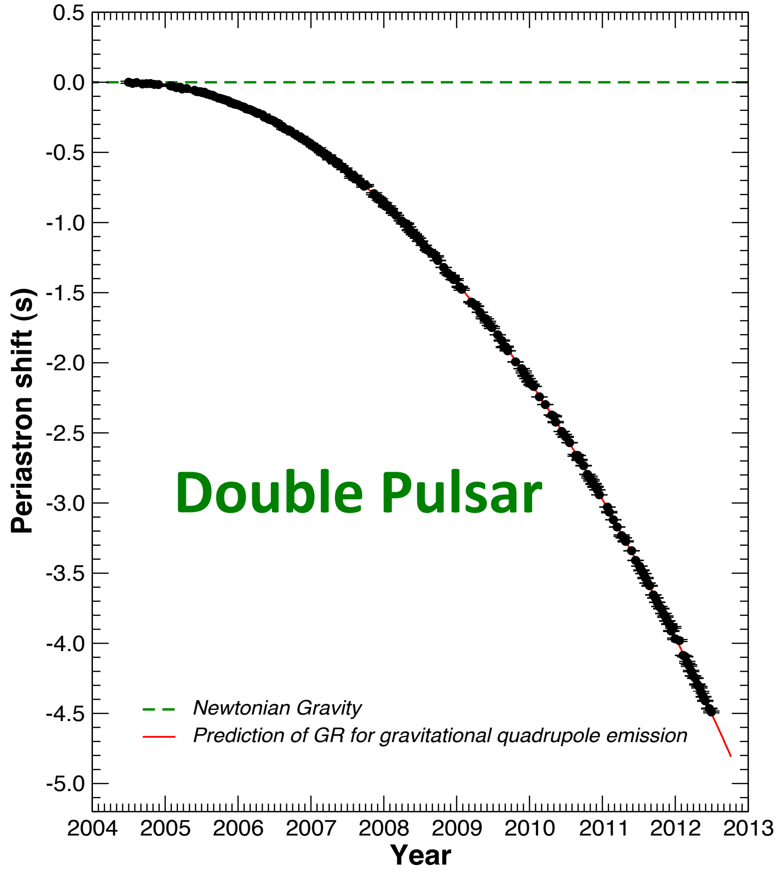
C. Bassa, R. Breton, M. Burgay, I. Cognard, N., G. Desvignes, R. Ferdman, P. Freire, L. Guillemot, G. Hobbs, G. Janssen, P. Lazarus, D. Lorimer, A. Lyne, R. Manchester, M. McLaughlin, A. Noutsos, B. Perera, A. Possenti, J. Reynolds, J. Sarkissian, I. Stairs, B. Stappers, G. Thereau, N. Wex .... and a few more

The famous orbital damping test:

from now on limited by Galactic potential

[Weisberg, Nice & Taylor 2010; Weisberg & Huang 2016]



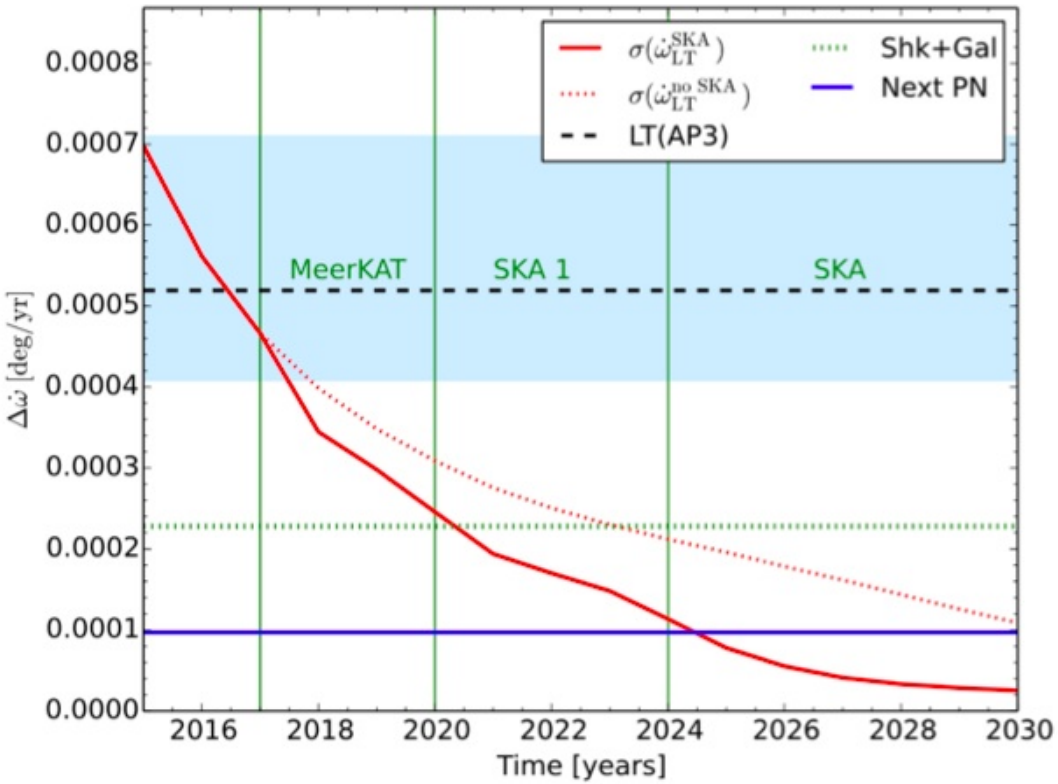


[Kramer et al 2019 in prep.)]

Testing the radiative predictions of GR with much improved precision wrt the Hulse-Taylor system...

Relativistic binaries and gravity theories tests

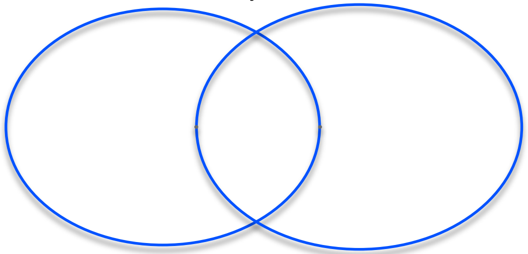
- Relativistic binaries will keep doing better at constraining the radiative terms at the leading 2.5 PN order and also at the 3.0 PN order
- the Lense-Thirring effect in the Double pulsar system will be measurable with SKA1. Subsequent monitoring of the binary could also finally lead to constraints on the moment of inertia for the pulsar down to 10% accuracy



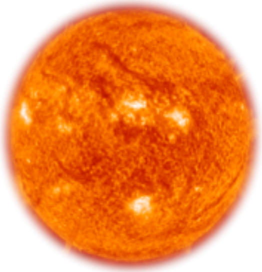
[Kehl et al. 16]

PSR J1757-1854 and PSR J1946+2052: the new frontiers

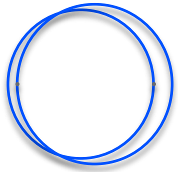
Hulse-Taylor Pulsar



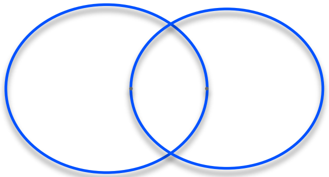
Sun



Double Pulsar



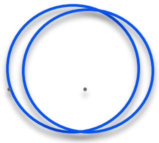
J1757-1854



21 ms
4.39 hrs
0.61
≈ 7 kpc

[Cameron et al. 2017]

J1946+2052

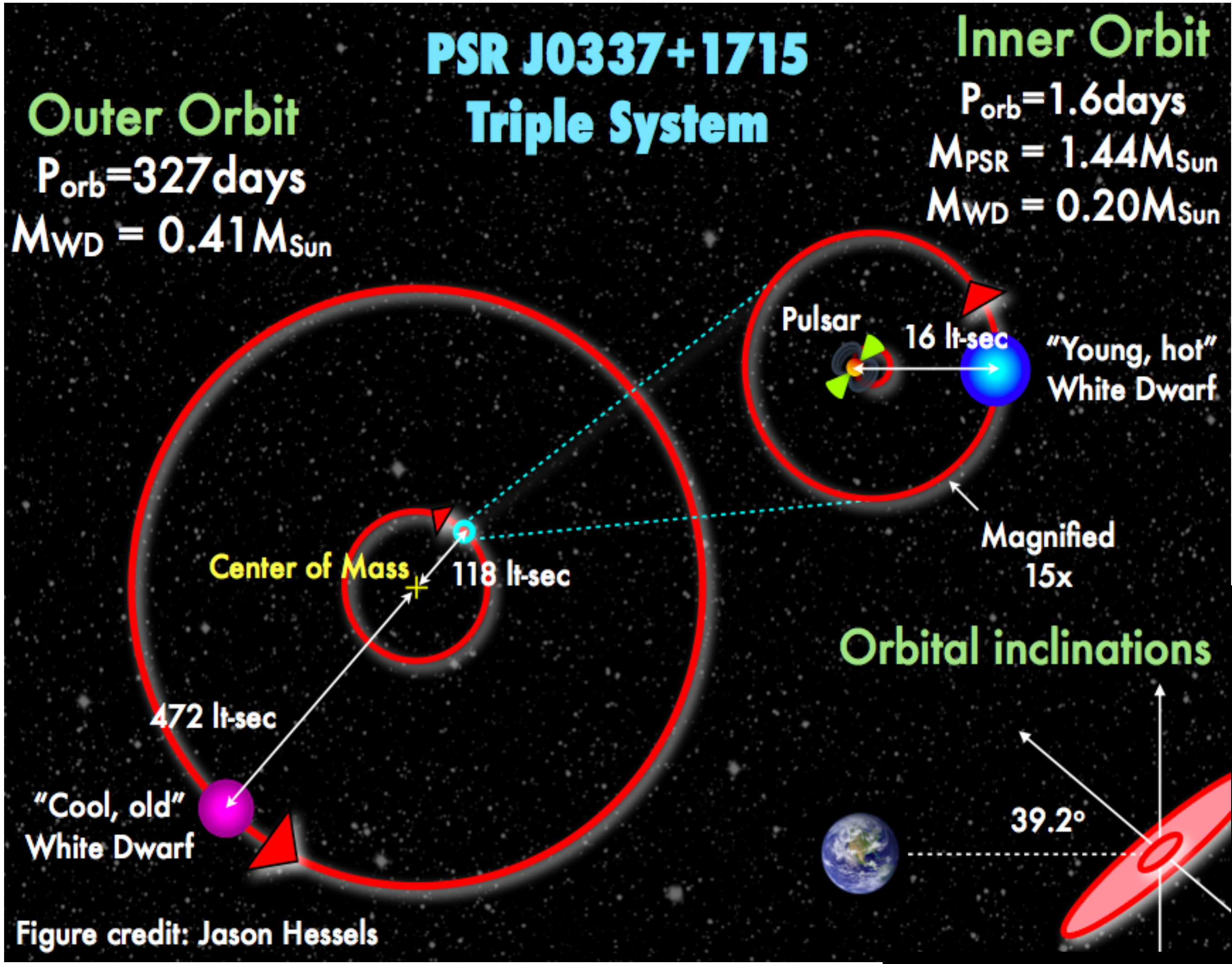


17 ms
1.88 hrs
0.06
≈ 4 kpc

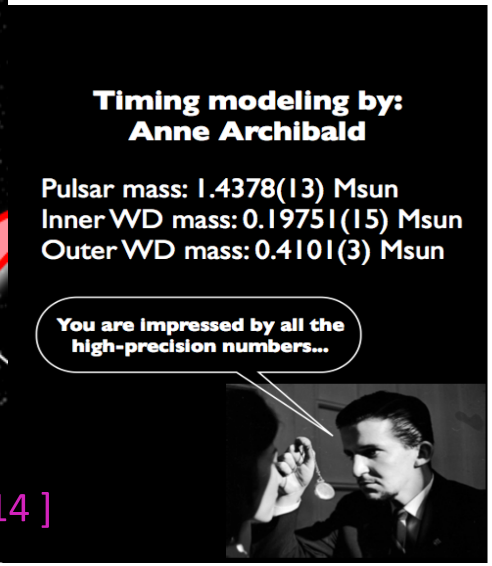
[Stovall et al. 2018]

[© adapted from A. Cameron 2017]

The triple system J0337+1715: NS + WD + WD



[Ransom et al 2014]



[Archibald et al 2014]

[© Hessels 2014]

The triple system: SEP and EEP tests

Strong Equivalence Principle (SEP): all freely falling objects, regardless of how strong their gravity, experience the same acceleration in the same gravitational field

$\Delta = m_G/m_I - 1$ the fractional difference between the pulsar's inertial (m_I) and gravitational (m_G) masses. The SEP is satisfied only if $\Delta = 0$ [Damour & Schafer 1991]

Description of fit	$\Delta \pm$ unc. $\times 10^{-6}$	stat. unc. $\times 10^{-6}$	ampl. sign.Δ (ns)	syst.unc (ns)
	Primary fit:			
Observatories: AO, GBT, WSRT Frequency band: $\nu_c \sim 1400\,\mathrm{MHz}$ DM fit interval: one year EoM: 1st order PN, $\Delta \neq 0$	-1.1 ± 0.7	0.2	33	22

[Archibald et al 2018]

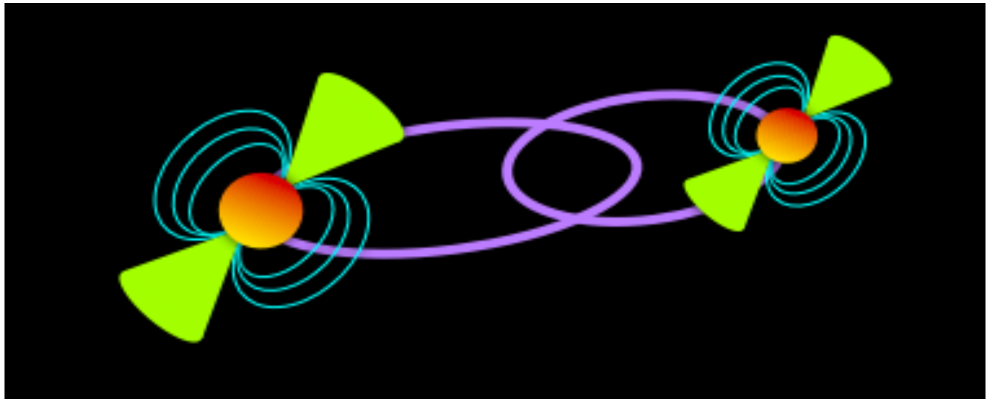
in spite of the pulsar's strong gravity, the accelerations experienced by the pulsar and the inner white dwarf differ by a fraction **$\Delta < 2.6 \times 10^{-6}$** (95% confidence level)

The constraints on the strong-field Nordtvedt parameter η_N are about 10 times smaller than that obtained from (weak-field) Solar-System SEP tests [Hofmann & Muller 2018] , and a factor of almost a thousand smaller than that obtained from other strong-field SEP tests [Zhu et al 2018]

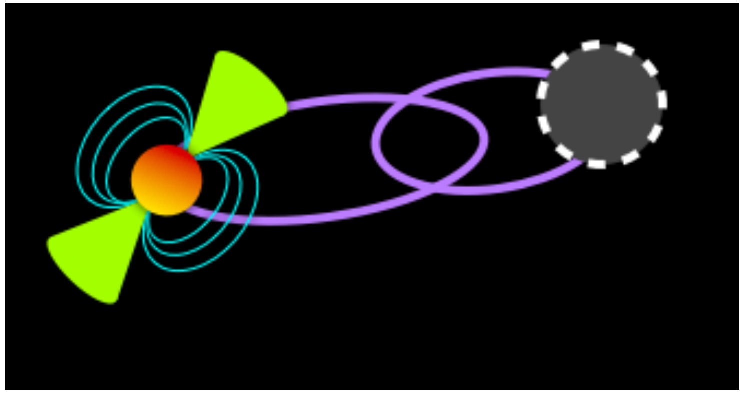
New unprecedented tests with ...

Provided the timing capabilities of SKA will be kept at the nominal capabilities of the instrument, a wealth of new unique test will stem from ....

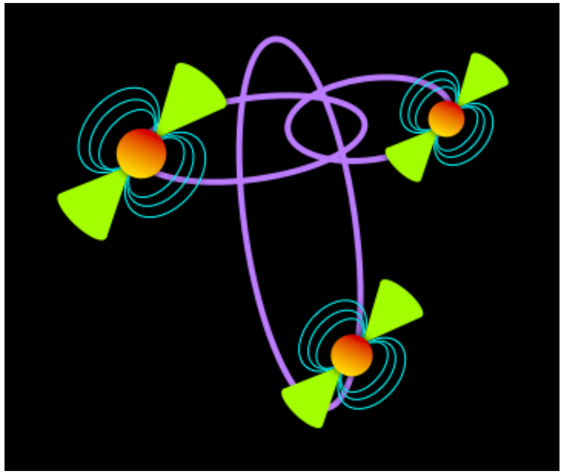
Potentially testing dark matter
[e.g. Kavic et al 2017]



MSP+MSP binary



MSP+BH binary or MSP+IMBH/SMBH



Triple MSP system

Providing tests of contributions from spin(s)

[Images: edited from Hessels 2014]

The role of SKA

Challenging Einstein:

Test basic principles of Black-Hole physics

Open the parameter space for discovering the "expectedly very rare" PSR+BH binary

Giving the chance to discover a PSR orbiting Sgr A*

The exciting perspectives of a PSR+BH ...

FINDING AND TIMING A PSR-BH BINARY (AND MAYBE A PSR-MSP BINARY IN A GLOBULAR CLUSTER [Clausen et al. 2014])

[Liu et al. 2013]

From the ordinary PK parameters — *BH mass with precision < 0.1%*

From precessional effects on semi-major axis and longitude of periastron — *BH spin S with precision < 1%*

From M & S $\chi \equiv \frac{c}{G}\frac{S}{M^2}$ — $\chi \leq 1$ *Test of* Cosmic Censorship Conjecture" [Penrose 1969]

FINDING AND TIMING A PSR CLOSELY ORBITING SGR A*

[Liu et al. 2013]

From only 1 PK parameter — *BH mass with precision < 0.001%*

From BH oblateness — *BH quadrupole moment Q with precision ~ 1%*

From M & Q $q \equiv \frac{c^4}{G^2}\frac{Q}{M^3}$ — $q = -\chi^2$ *Test of* No Hair theorem"

The role of SKA

Gravitational Wave Astrophysics in the nano-Hertz frequency band

≈ 100 usable clocks to be timed with < 100 ns accuracy

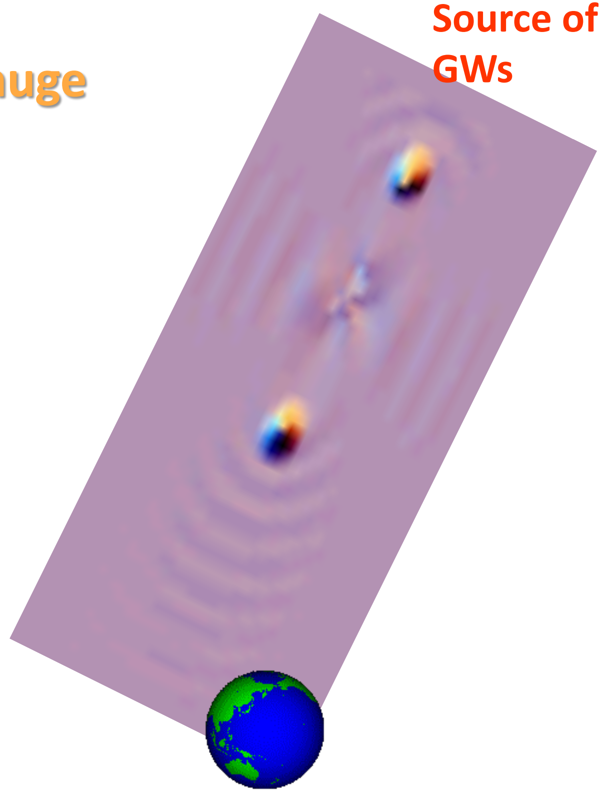
Pulsars as GW detectors

The Pulsar-Earth path can be used as the arm of a huge cosmic gravitational wave detector

Perturbation in space-time can be detected in timing residuals over a suitable long observation time span

Radio Pulsar

Source of GWs



Earth

Sensitivity (rule of thumb):

$$h_c(f) \sim \frac{\sigma_{TOA}}{T}$$

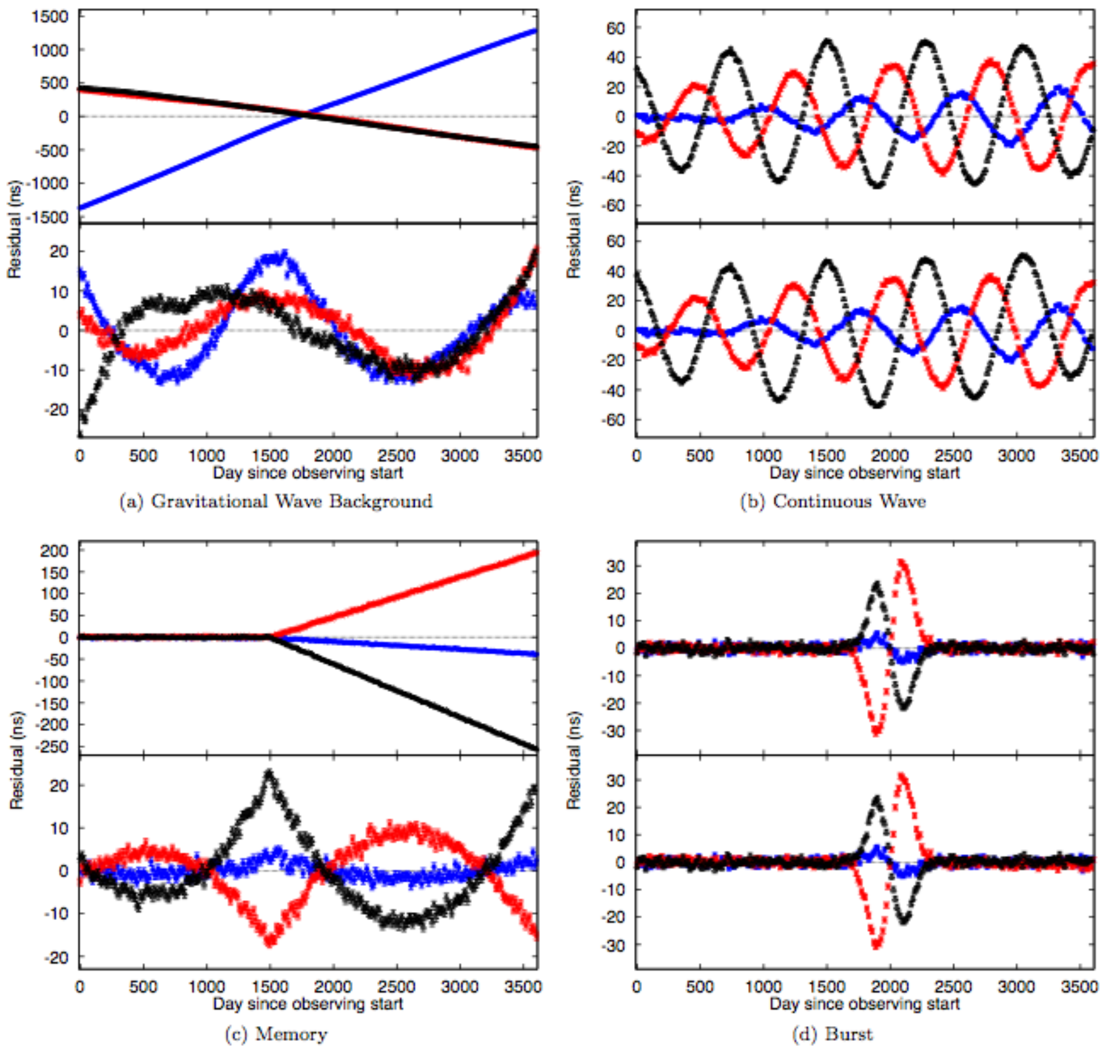
where

$h_c(f)$ is the dimensionless strain at freq f

σ_{TOA} is the rms uncertainty in Time of Arrival

T is the duration of the dataspan

The theoretical "clean" signals in the residuals



[Burke-Spolaor 2016]

Upper panels: trends without fitting for P and dP/dt

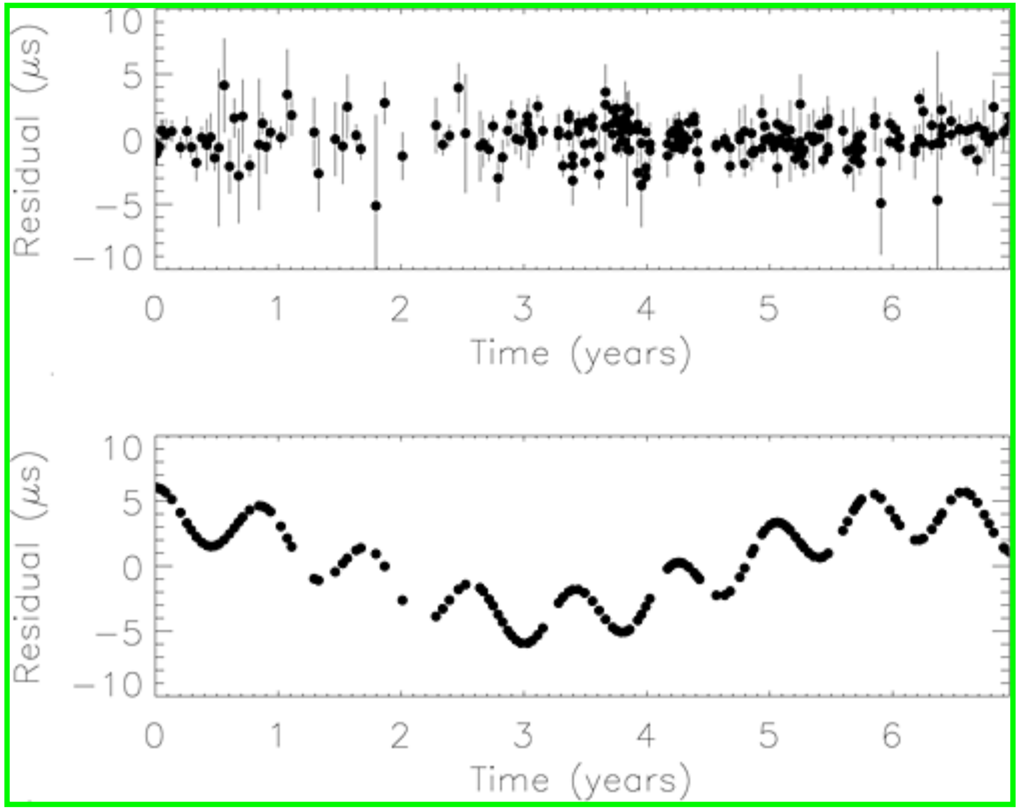
Lower panels: trends after fitting for P and Pd/dt for 3 reference pulsars*:*

PSR J0437–4715,
PSR J1012+5307
PSR J1713+0747

An instructive application (using 1 pulsar)

The radio galaxy 3C66 (at $z = 0.02$) was claimed to harbour a double SMBH with a total mass of $5.4 \cdot 10^{10}$ M_{sun} and an orbital period of order ~yr

[Sudou et al 2003]

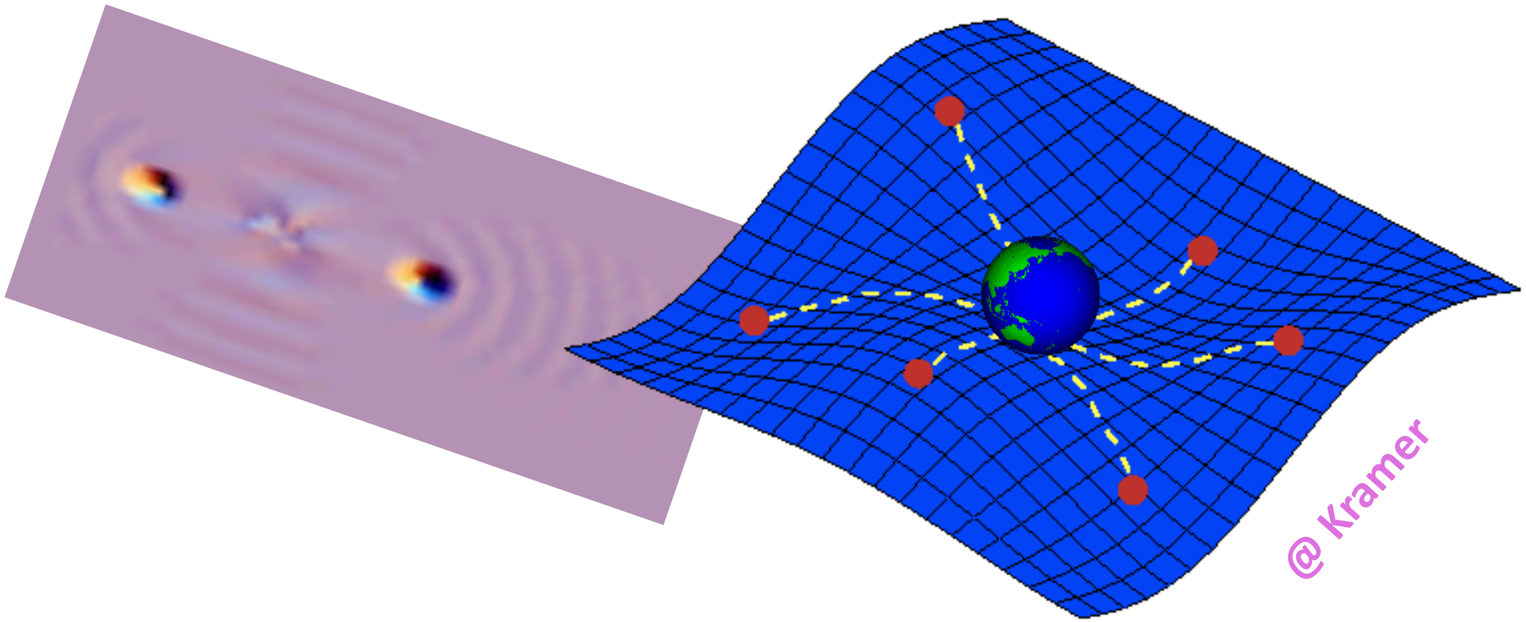


[Jenet et al 2004]

Timing residuals from PSR B1855+09 excluded such a massive double BH at 95 c.l.

A pulsar timing array (PTA)

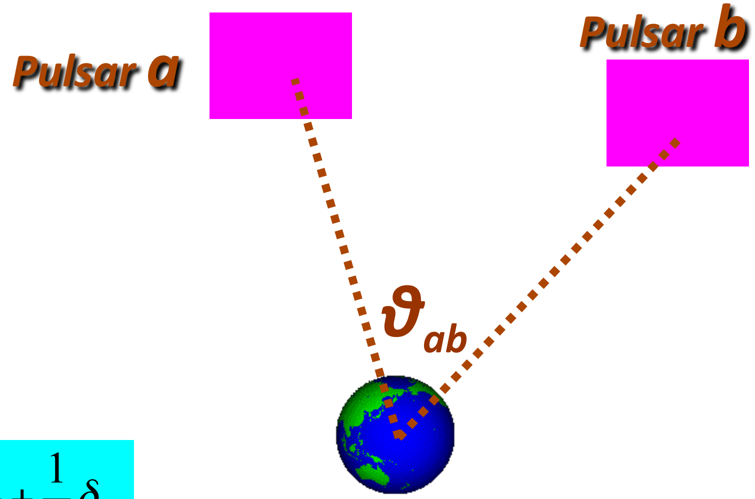
Using a number of pulsars distributed across the sky it is possible to separate the timing noise contribution from each pulsar from the signature of the GW background, which manifests as a local (at Earth) distortion in the times of arrival of the pulses which is common to the signal from all pulsars



Searching for a GW background using 2+ pulsars

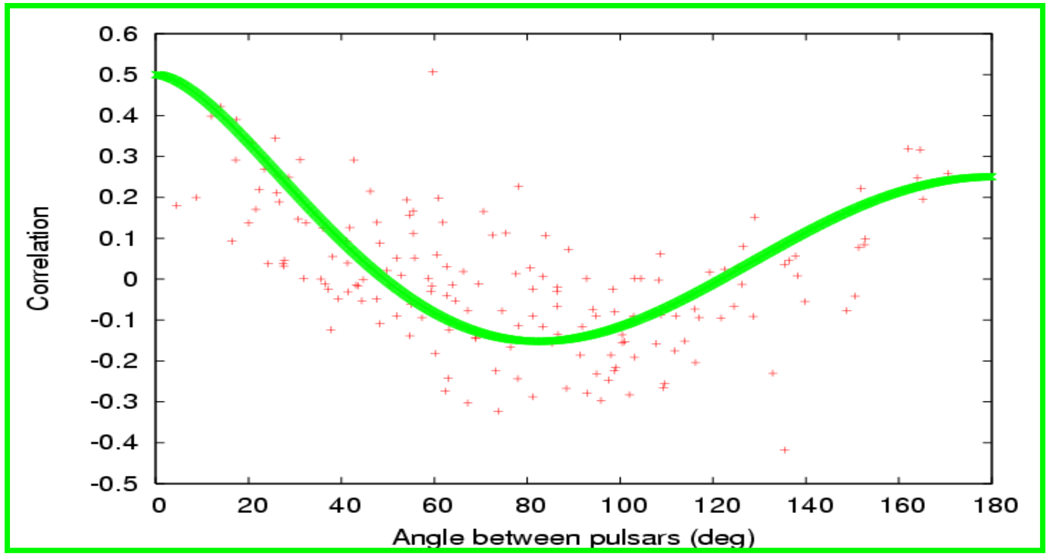
Idea first discussed by Romani [1989] and Foster & Backer [1990]

- **Clock errors**
  All pulsars have the same TOA variations:
  Monopole signature
- **Solar-System ephemeris errors**
  Dipole signature
- **Gravitational waves background**
  Quadrupole signature



$$\zeta(\theta_{ab}) = \frac{3}{2}\left(\frac{1-\cos\vartheta_{ab}}{2}\right)\log\left(\frac{1-\cos\vartheta_{ab}}{2}\right) - \frac{1}{4}\left(\frac{1-\cos\vartheta_{ab}}{2}\right) + \frac{1}{2} + \frac{1}{2}\delta_{ab}$$

[slide adapted from Manchester 11]



Hellings & Downs [1983]: correlation that an **isotropic and stocastic GWB** leaves on the timing residuals of 2 pulsars *a* and *b* separeted by an angle ϑ_{ab} in sky

The PTA collaborations

Current best limits on amplitude of the GW background from SMBH binaries (with a GW spectral idx -2/3 at fg_{GW}=2.8 nHz (i.e. P_{GW}=1 yr) for H_o = 73 km s^{-1} Mpc^{-1})

NANOGrav — **Arzoumanian et al., 2015: A < 1.5 x 10^{-15}**

EPTA — **Lentati et al., 2015: A < 3 x 10^{-15}**

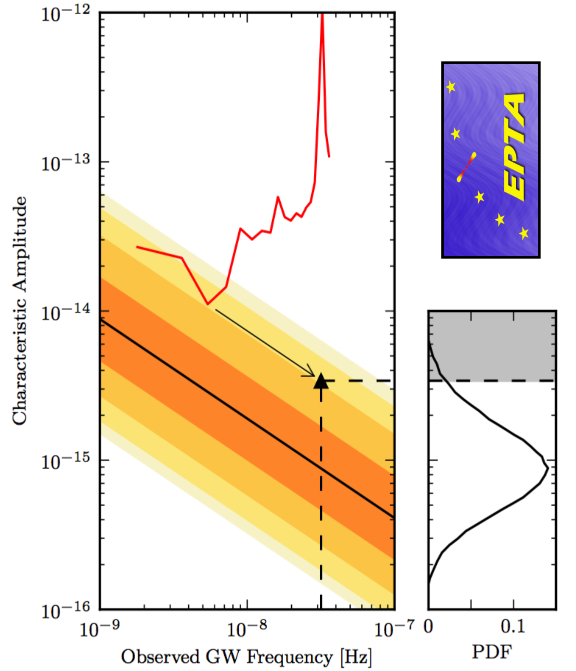
(robust limit including additional effects)

PPTA — **Shannon et al., 2015:**

A < 1.0 x 10^{-15} [Ω_{GW} < 2.3 x 10^{-10}]

IPTA — **Verbiest et al., 2016: A < 1.7 x 10^{-15}**

(based on relatively old data only)

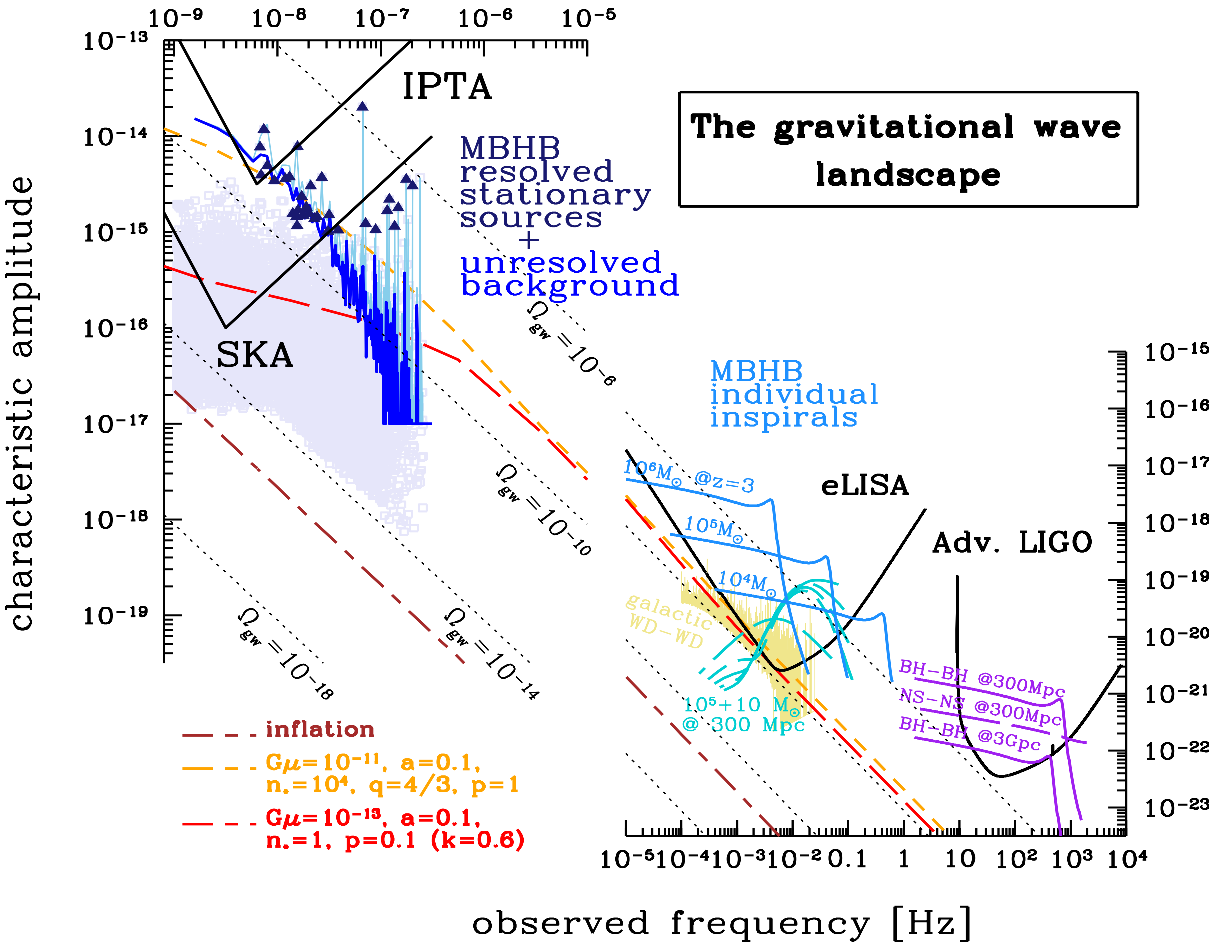


[Lentati et al. 15]

Pulsar Timing array(s): the frequency space

Note the complementarity in explored frequencies with respect to the current and the future GW observatories, like advLIGO, advVIRGO and eLISA

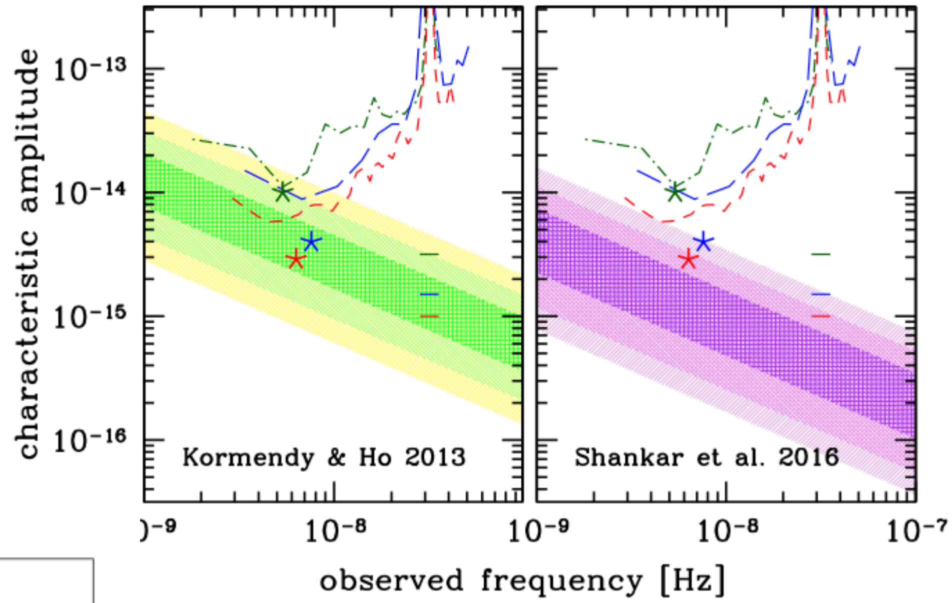
- **Expected sources:**
  - binary super-massive black holes in early Galaxy evolution
  - cosmic strings
  - cosmological sources
- **Types of signals:**
  - stochastic (multiple)
  - periodic (single)
  - burst (single)



[Janssen et al 15]

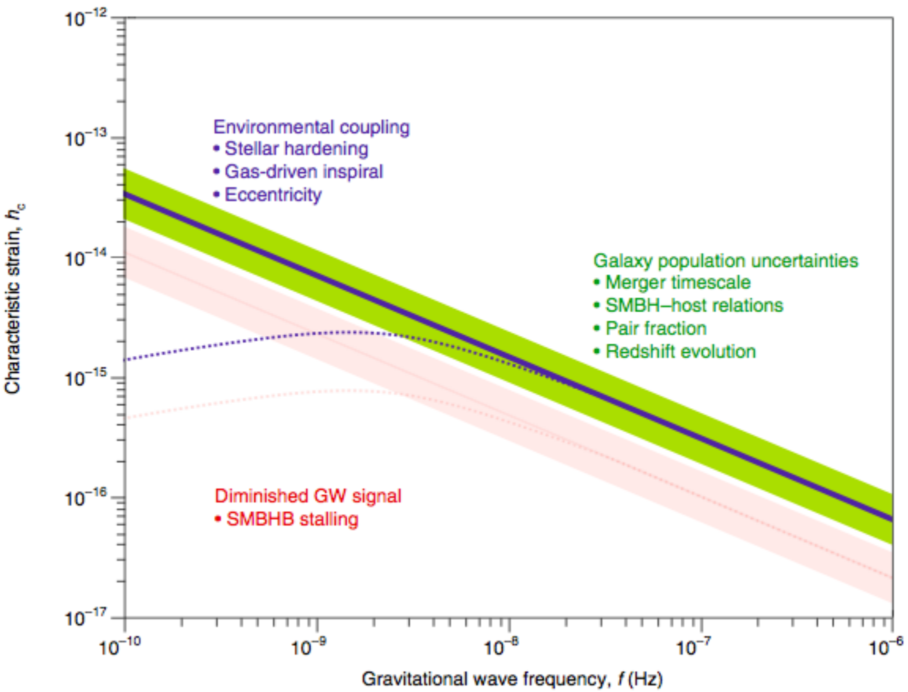
GWB amplitude predictions

- Already ruling out most generous theoretical models for stochastic GWB



[Sesana et al. 16, Kelly et al. 17]

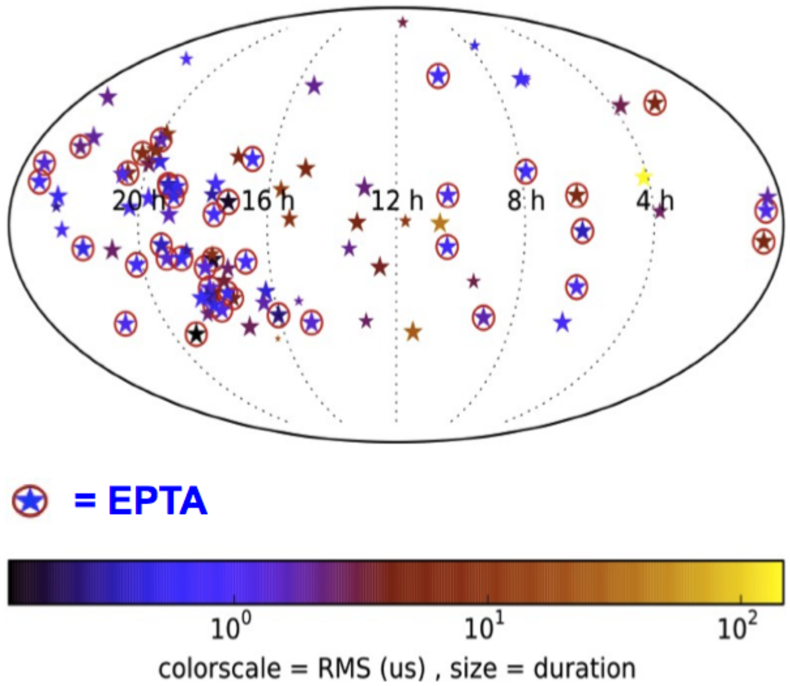
[@ Burke-Spolaor ; Mingarelli 19]



- Newer model predictions (including more physics, accounting for biases)
  - Expected GWB slightly lower
  - Still large range allowed

for a detection one needs a ...

Pulsar timing array (PTA)



The current sample of MSP of IPTA ≈ 40, of which only a handful with precision < 100 ns

IPTA (International Pulsar Timing Array)

SKA1 will provide ≈ 100 MSPs with timing precision < 100 ns

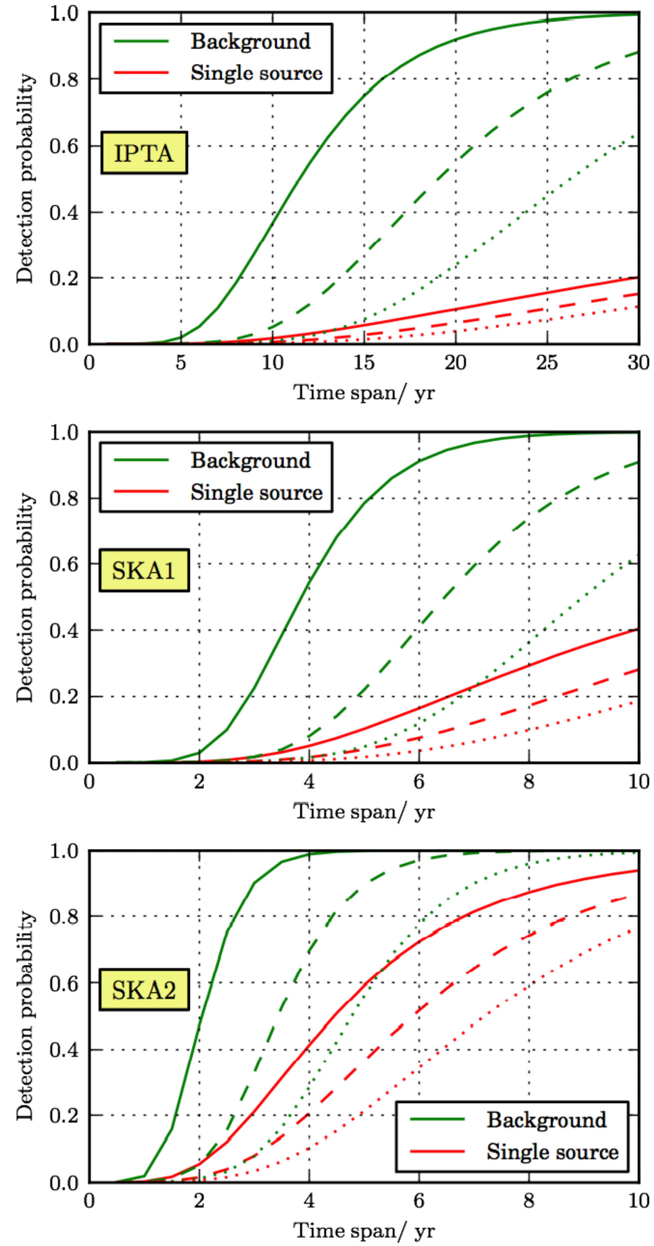
[Shao et al 2015]

Timing array(s): from limits to GWBs detection

Current projects are evolving in pace with predictions. Then at least very significant limits (and hopefully a detection) should be achieved within few years by IPTA

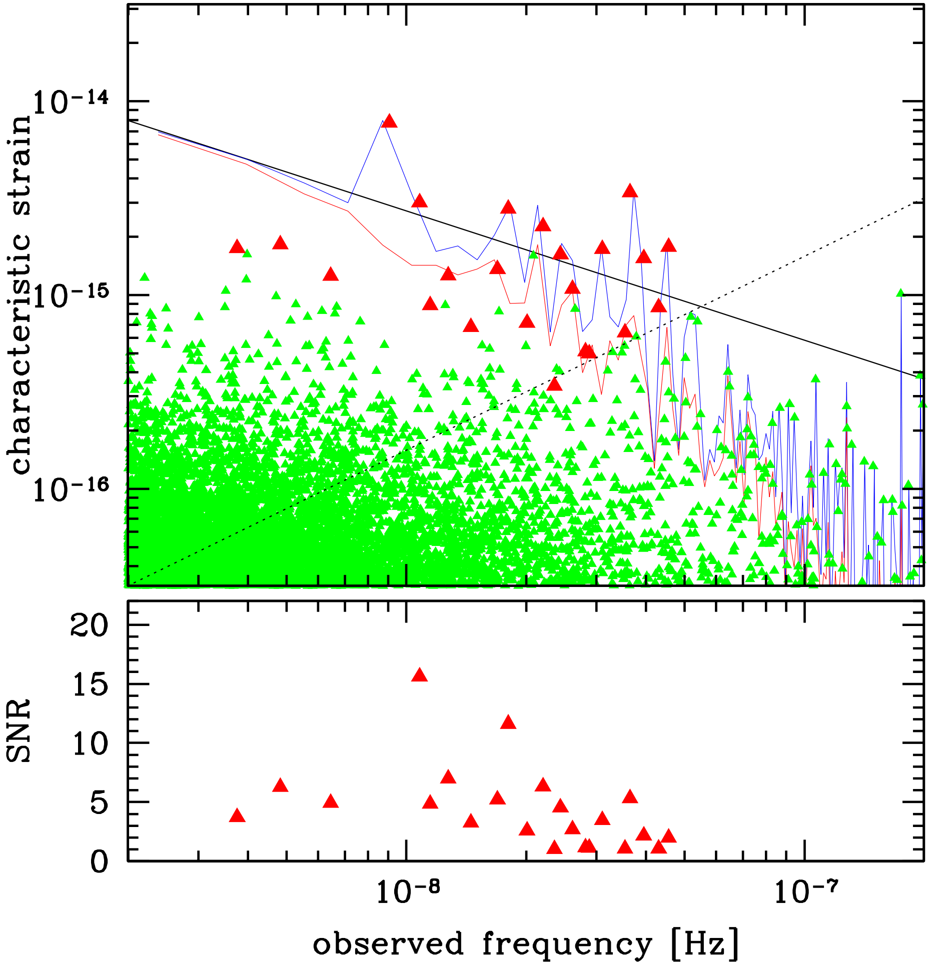
Unless the galaxy assembling model has to be rewritten, the detection and a basic studies of the GWB [spectrum, anisotropy] and of many single sources is warranted with phase 1 of SKA

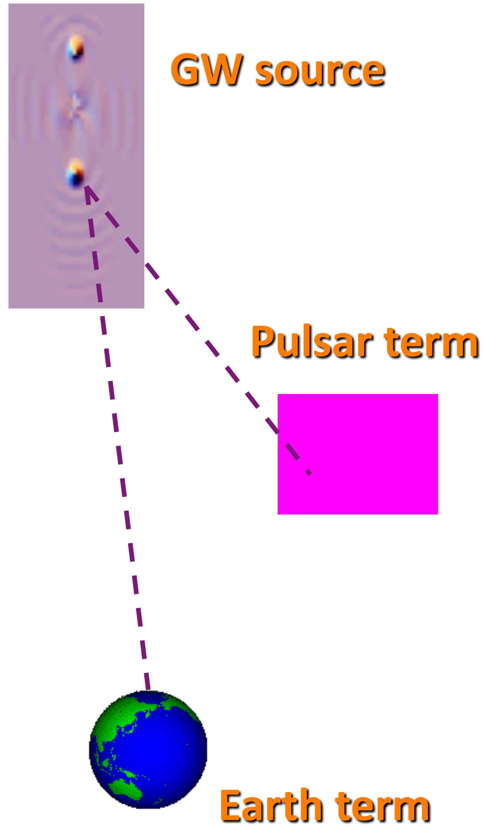
Full nanoHz-GW astronomy and implied fundamental physics tests will take place with phase 2 of SKA



[Rosado, Sesana & Gair 15]

Detection & localization of an in-spiral binary



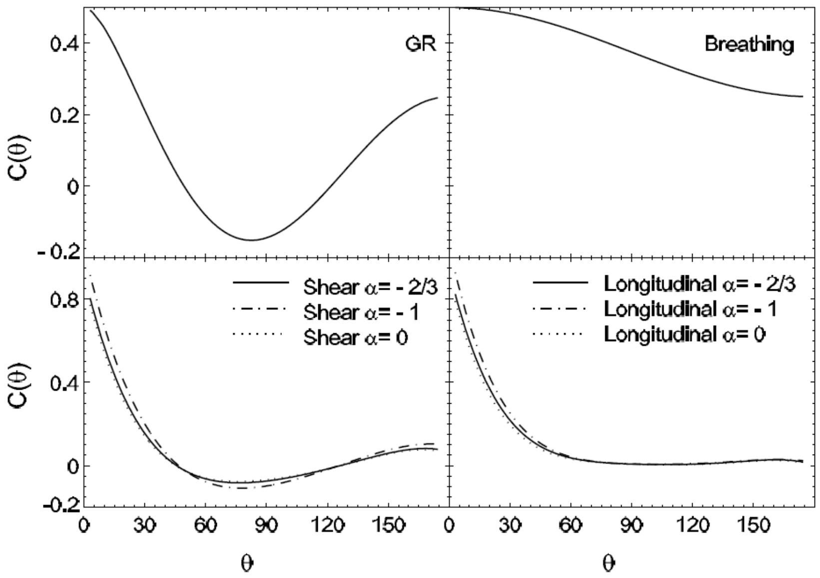


At least one SMBH+SMBH will induce timing residual of order 5-50 nanosec
[Sesana et al 2013]

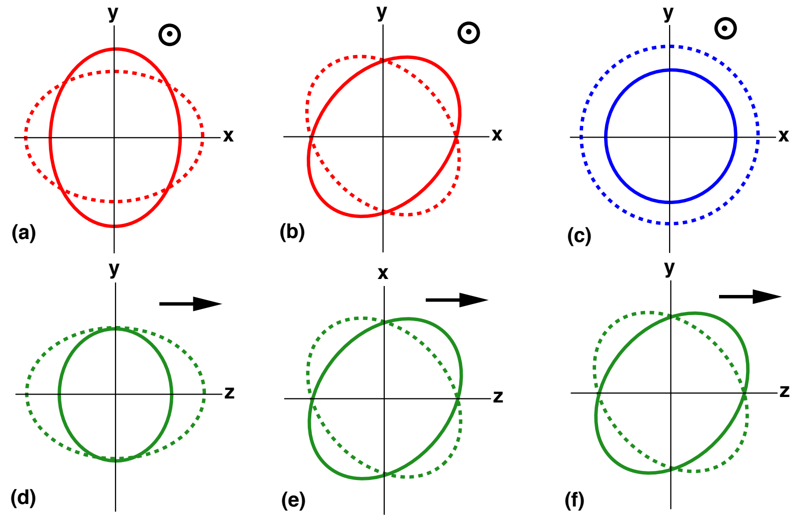
Signal contains information from two distinct epochs!

Fundamental physics tests

[Lee et al. 2009]



Tests of the polarization "modes" of the GWs

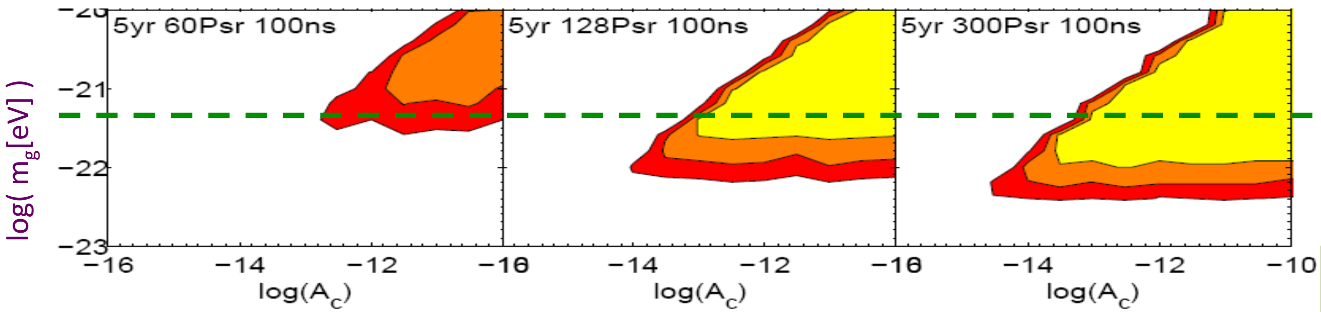


[Chamberlin & Siemens 2012]

Graviton mass

- - - - = present solar system limit

[Lee et al. 2010]



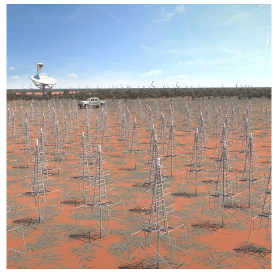
$$\mathbf{k}_{\rm g}(\omega_{\rm g}) = \frac{(\omega_{\rm g}{}^2 - \omega_{\rm cut}{}^2)^{\frac{1}{2}}}{c}\,\hat{\mathbf{e}}$$

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

Summary

- The SKA will provide the best tests of GR & complement GW detectors
- Properties of black holes will be determined: cosmic censorship, no-hair theorem
- Low-frequency gravitational waves will be detected and used for: GW astronomy, cosmology & galaxy evolution, graviton properties
- Using pulsars, the SKA will probe science from gravitation to solid-states physics

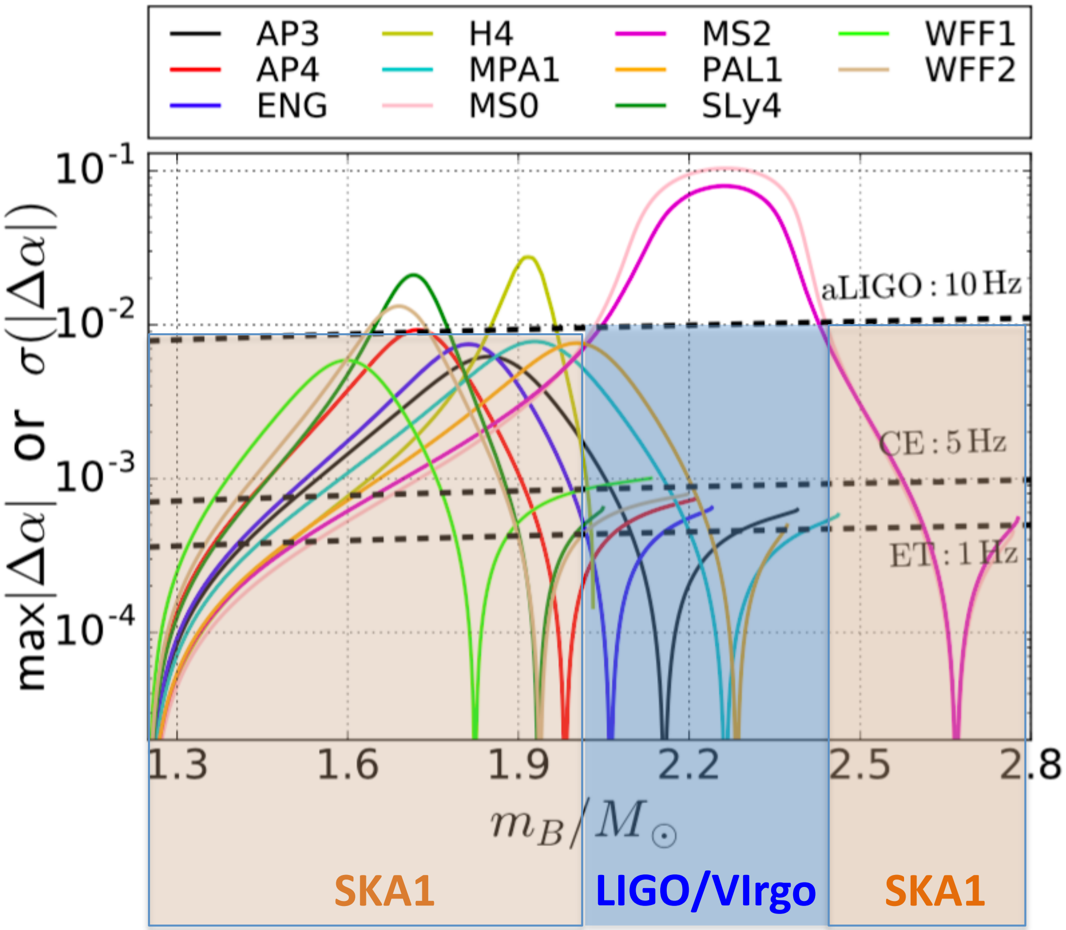
There will be superb synergies with GAIA, ELTs, LSST, CTA, AdvLIGO, AdvVIRGO, LISA etc



Thanks

Complementarity with aLIGO/advVirgo

GW detectors and the pulsar timing will really be complementary in testing the radiative predictions of GR, doing their best for different ranges for the masses of the involved neutron star



[Shao et al., 2017]