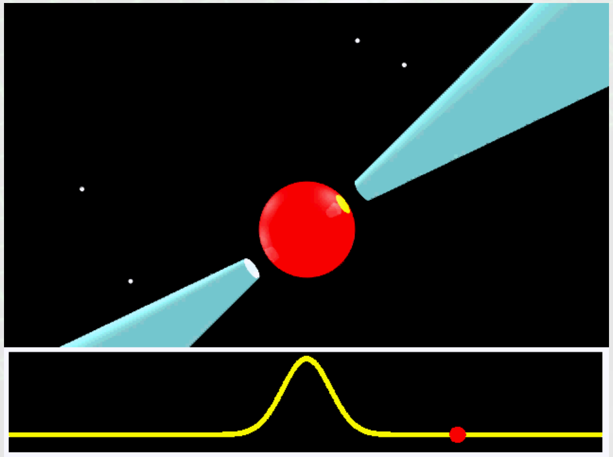
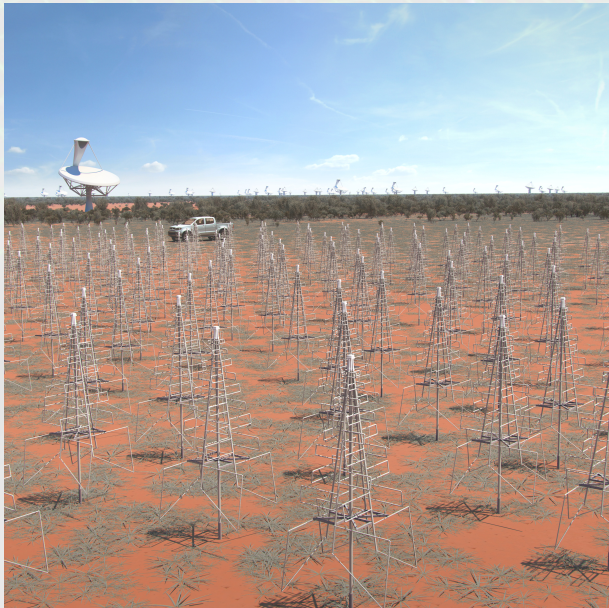
Pulsar science with the SKA

probes of extreme physics

Gemma Janssen for the PSWG





SKA Pulsar science

SKA PSWG top priorities

- Revealing the pulsar population
- High precision timing for testing gravity and GW detection

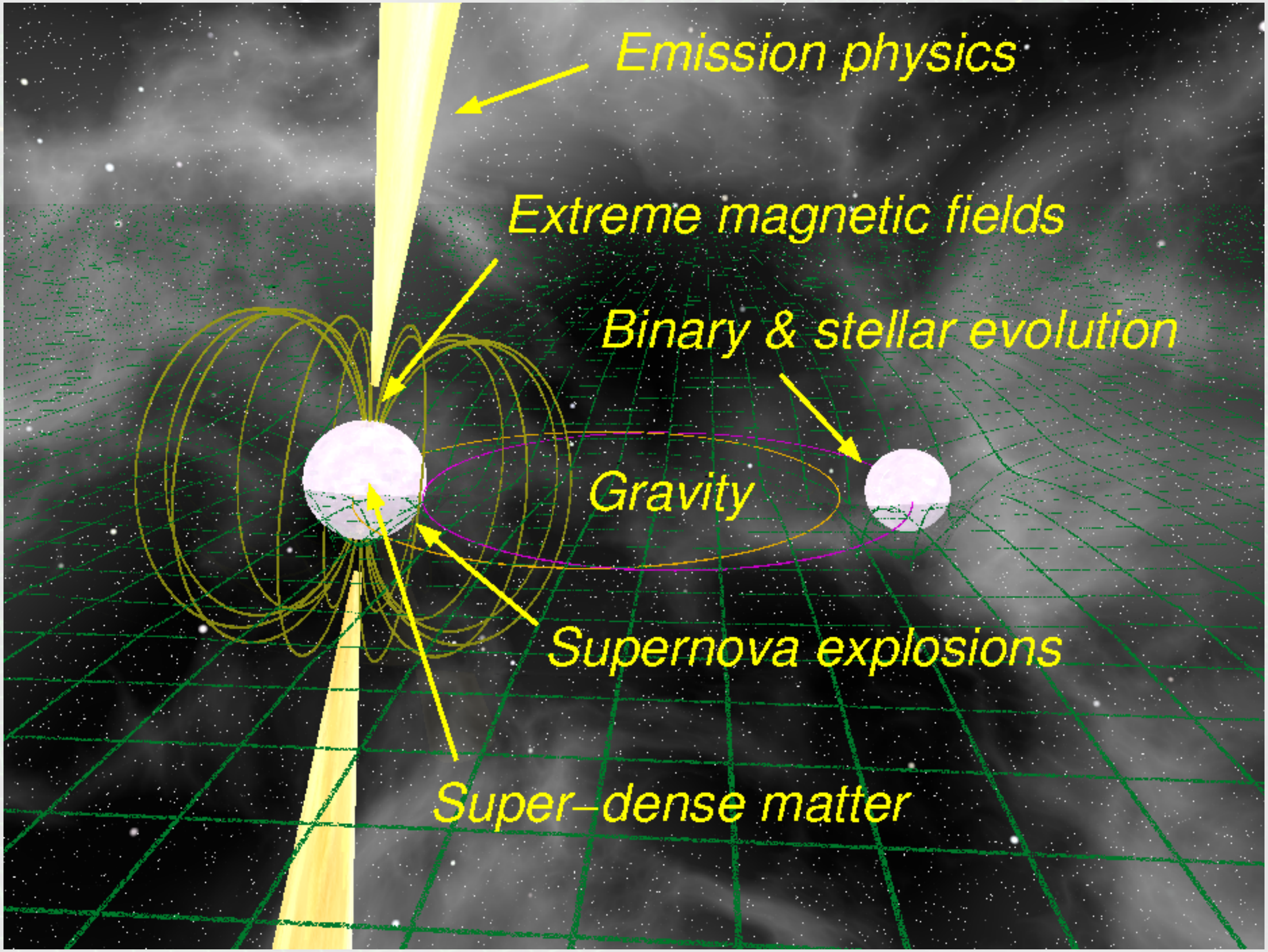
High priority

- Characterising the pulsar population
- Finding and using (millisecond) pulsars in globular clusters and external galaxies
- Finding pulsars in the Galactic Centre
- Astrometric measurements of pulsars to enable improved tests of GR

Medium priority

- Mapping the pulsar beam
- Understanding pulsars and their environments through their interactions
- Mapping the galactic structure

Observations of pulsars have wide scientific impact



See overview chapter by Kramer & Stappers (2015)

SKA Pulsar science

SKA pulsar science– from SKA Science book (Sicily 2014)

- Cosmic census (Keane et al. 1501.00056)
- Testing Gravity (Shao et al. 1501.00058)
- GW astronomy (Janssen et al. 1501.00127)
- Understanding PSR Magnetospheres (Karastergiou et al. 1501.00126)
- Understanding NS population (Tauris et al. 1501.00005)
- Galactic & Intergalactic medium (Han et al. 1412.8749)
- NS Equation of State (Watts et al. 1501.00042)
- Pulsars in the Galactic centre (Eatough et al. 1501.00281)
- Pulsars in Globular clusters (Hessels et al. 1501.00086)
- Pulsar wind nebulae (Gelfand et al. 1501.00364)

- Overview (Kramer & Stappers 1507.04423)

Synergy with

- Transients
- VLBI
- Computing

How do we reach our (top) goals?

Cosmic Census: Reveal the pulsar population

- Blind searches
- Targeted searches
- (Extra-galactic searches)

Testing Gravity and Gravitational wave astronomy

- Long-term of stable millisecond pulsars
- High-cadence timing of exotic pulsar systems
- Follow-up timing of newly found pulsars

Cosmic census of pulsars

Blind searches

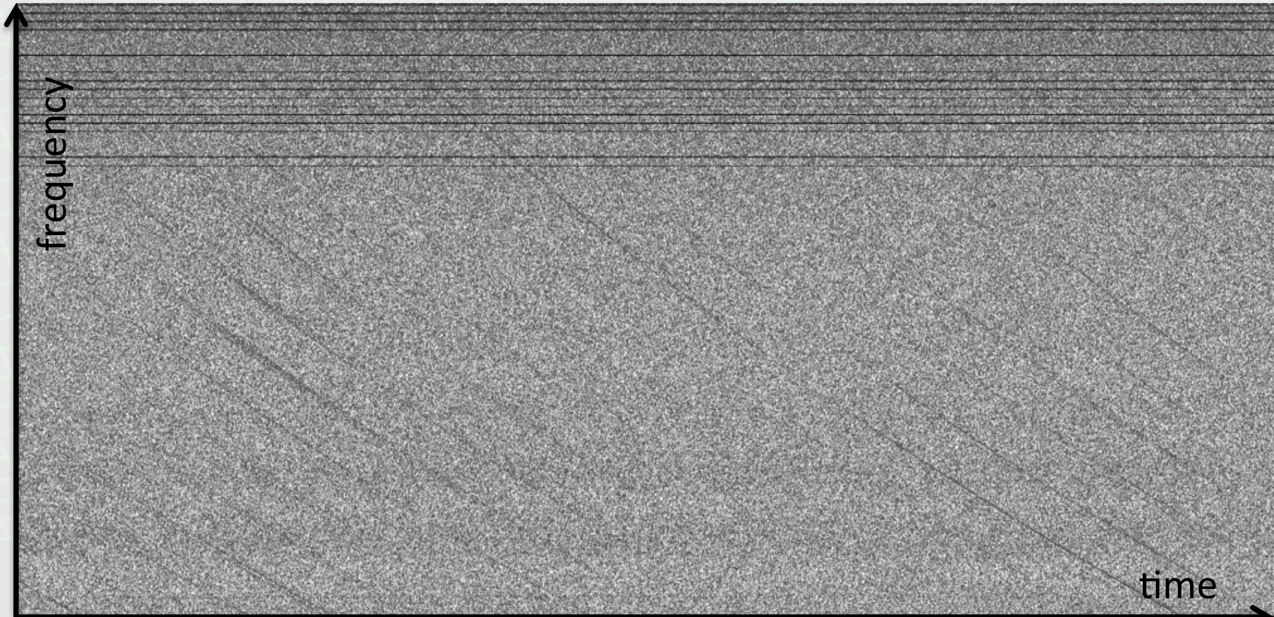
-PSRs of interest could be anywhere in our Galaxy or beyond

-'Blind search' of a large parameter space over entire visible sky required

-Impractical to find PSRs in images

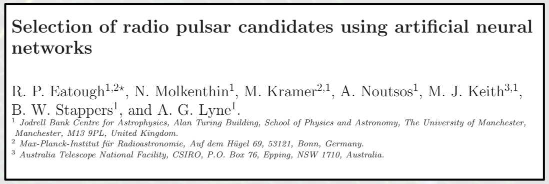
  -high time resolution (fast orbits, narrow duty cycles)

  -high frequency resolution required (dedispersion)



Searching for Pulsars: The challenges of “non-imaging processing”

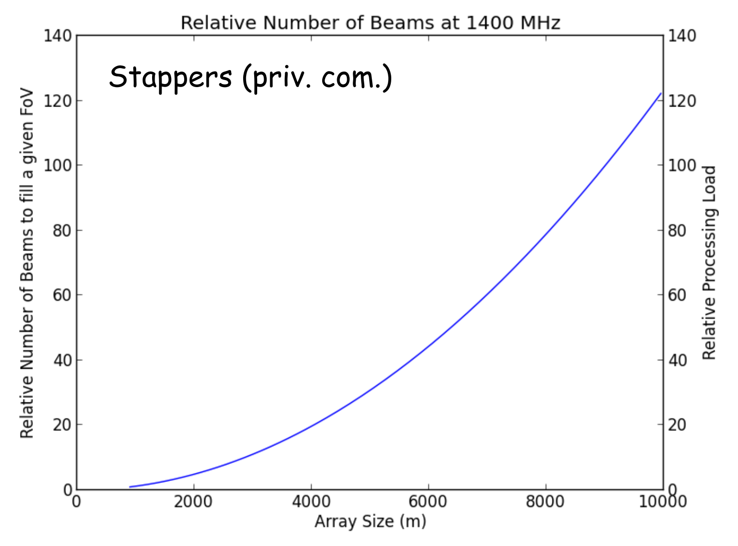
- Blind survey over the FoV requires beam forming, $N_{beam} \sim (b_{max}/D)^2$
- Design 1500 beams (limited by compute power!)
- Each beam has to be processed - on the fly!
- Essentially: de-dispersion + Fourier transform + RFI excision + Candidate selection
- No-human involvement: machine learning & artificial intelligence
- Big challenge: acceleration search for unknown orbits: $N_{ops} \sim T_{obs}^3$

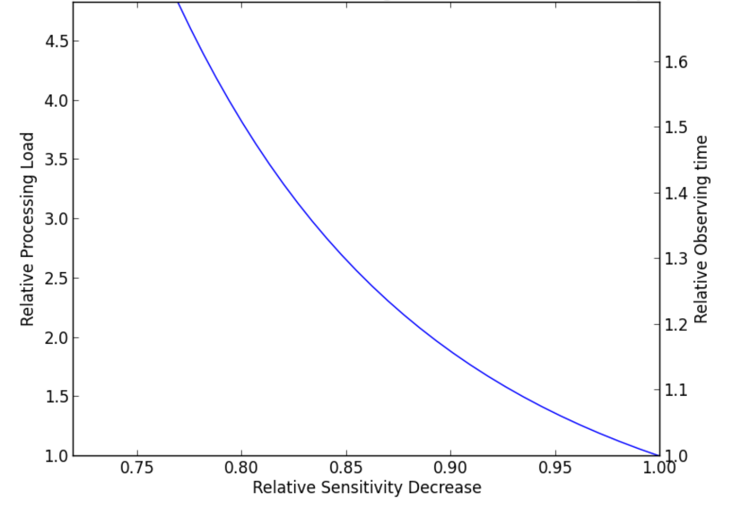


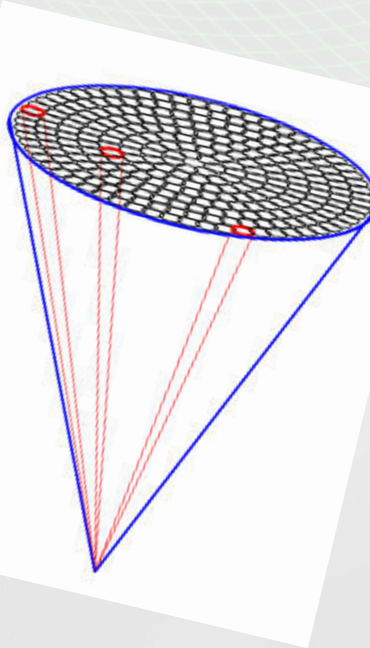
Selection of radio pulsar candidates using artificial neural networks

R. P. Eatough[1,2★], N. Molkenthin[1], M. Kramer[2,1], A. Noutsos[1], M. J. Keith[3,1], B. W. Stappers[1], and A. G. Lyne[1].

[1] *Jodrell Bank Centre for Astrophysics, Alan Turing Building, School of Physics and Astronomy, The University of Manchester, Manchester, M13 9PL, United Kingdom.*
[2] *Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121, Bonn, Germany.*
[3] *Australia Telescope National Facility, CSIRO, P.O. Box 76, Epping, NSW 1710, Australia.*







Note: We cannot trade sensitivity for observing time!

Reason: For searching, computing; for timing, science!

Cosmic census of pulsars

Blind searches

-PSRs of interest could be anywhere in our Galaxy or beyond
-'Blind search' of a large parameter space over entire visible sky required
-Impractical to find PSRs in images
  -high time resolution (fast orbits, narrow duty cycles)
  -high frequency resolution required (dedispersion)

Requirements:
Sensitivity -> add many elements in coherent beams
FoV small -> many beams to increase survey speed
  Nbeams: SKA1-Mid: 1500; SKA1-Low: 500   (SKA2: 10000)
Tobs increase can't compensate for loss in sensitivity
  -computing time for binary search: T_{obs}^3
  -instantaneous sensitivity required

Cosmic census of pulsars

Targeted searches

- deep search on selected sky positions
    - Galactic Centre (Eatough et al. 2015)
    - Extragalactic, e.g. M31, Radio bursts
    - Globular Clusters (Hessels et al. 2015)
    - High-energy PSRs (e.g. Fermi targets) and multi-λ synergy (Antoniadis et al. 2015)

Cosmic census of pulsars

Finding pulsars == Enabling Science!

- Full census: understanding the NS population (Tauris et al. 2015)
- Full census: studying the ISM and mitigating its effects (Han et al. 2015)
- Relativistic binaries & BH psrs: Gravity tests (Shao et al. 2015)
- Census and rotation: NS Equation of state (Watts et al. 2015)
- Emission and rotation: NS magnetosphere (Karastergiou et al. 2015)
- Stable MSPs: GW detection (Janssen et al. 2015)

Follow-up timing required: first weeks/months require more observations

-characterise pulsars and find interesting/stable sources

-different strategy for different types of sources

SKA1-Mid vs SKA1-Low search

SKA1-Mid search:
+ improved sensitivity
+ multiple bands
- miss steep-spectrum PSRs
- small FoV -> needs lots of beams

+- dispersion
+ Tsky not an issue
+ scattering not a problem

Will find MSPs for PTA, gravity tests
PSRs with high DM, in Galactic plane

SKA1-Low search:
+ improved sensitivity
+ large fractional bandwidth
+ can find steepest spectrum PSRs
+ large FoV -> high survey speed

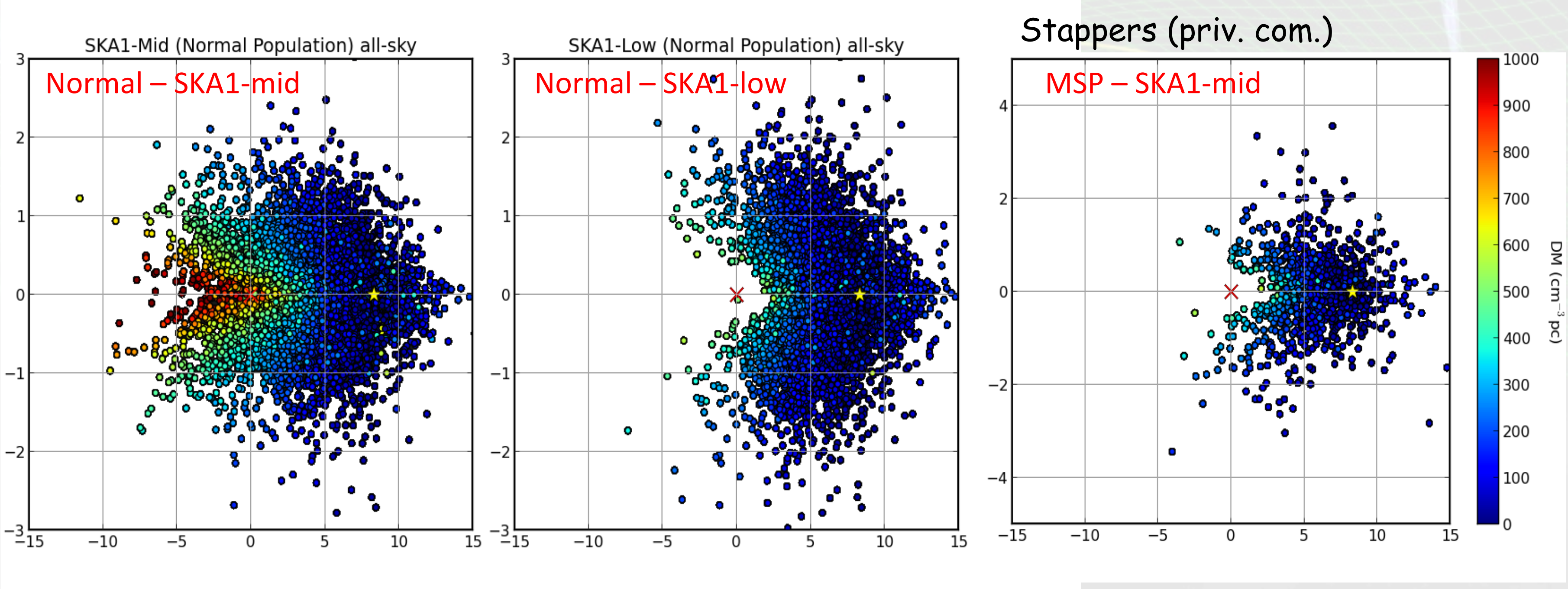
- dispersion (but can be solved)
- Tsky high in plane
- scattering can be a problem

Will find local population (low DM),
steep-spectrum, high Galactic latitude

Combination of Low & Mid required to **find** all the pulsars
In particular MSPs and exotic systems

Phase I will already be an excellent search machine

- Excellent lessons from SKA Pathfinders, in particular LOFAR
- We can find nearly 50% of all pulsars with Phase I already – in combination of SKA-low and SKA-mid:



Stappers (priv. com.)

Note: - Phase I will be great for searching: expect 9000 normal and 1500 MSPs

- We need to time all of these pulsars…at least for a while…

SKA Timing

Science goals requires different observing modes
(timing, searching, single pulses, emission studies)

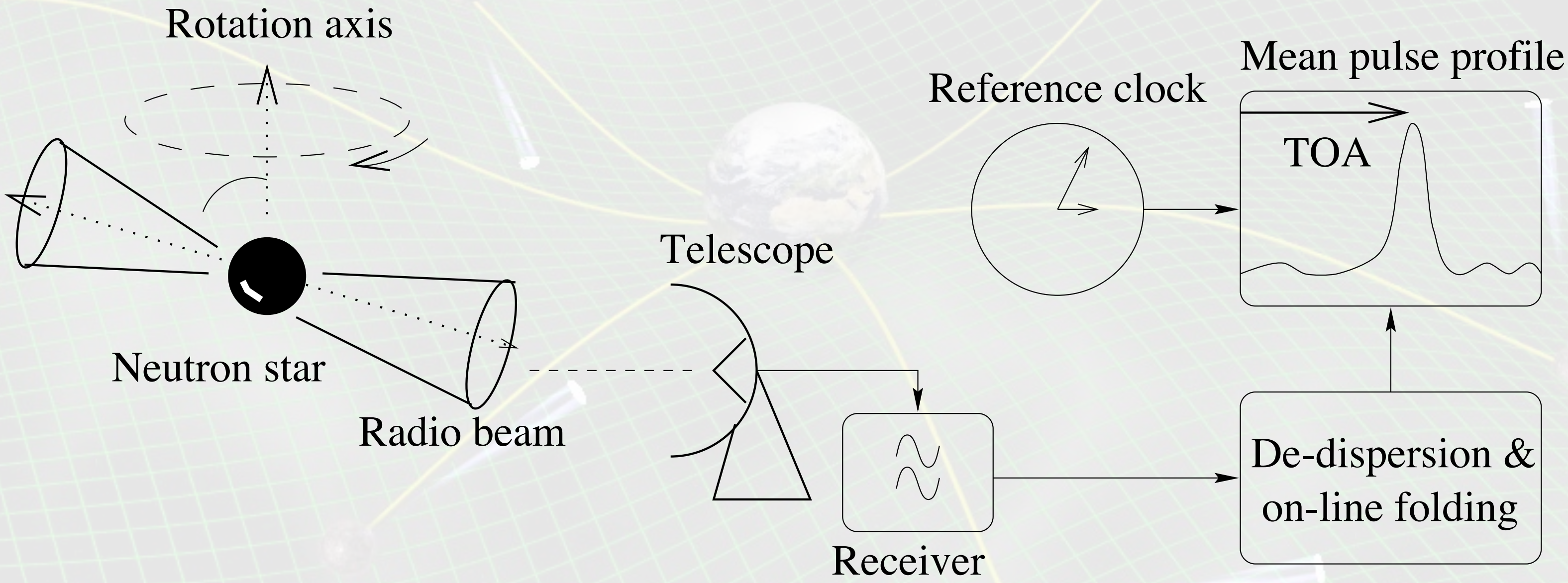
Timing strategies are different for different classes of pulsars
(long-term, high-cadence/full-orbit, follow-up, multifrequency)

Pulsar selection/observing is different for different goals
(Npsr, rms, cadence, Tspan, frequency coverage)

A	Amplitude
N_p	# of pulsars
c	cadence
σ	pulsar RMS
T	obs time

Pulsar Timing

Pulsars are very stable rotators, use as cosmic clocks



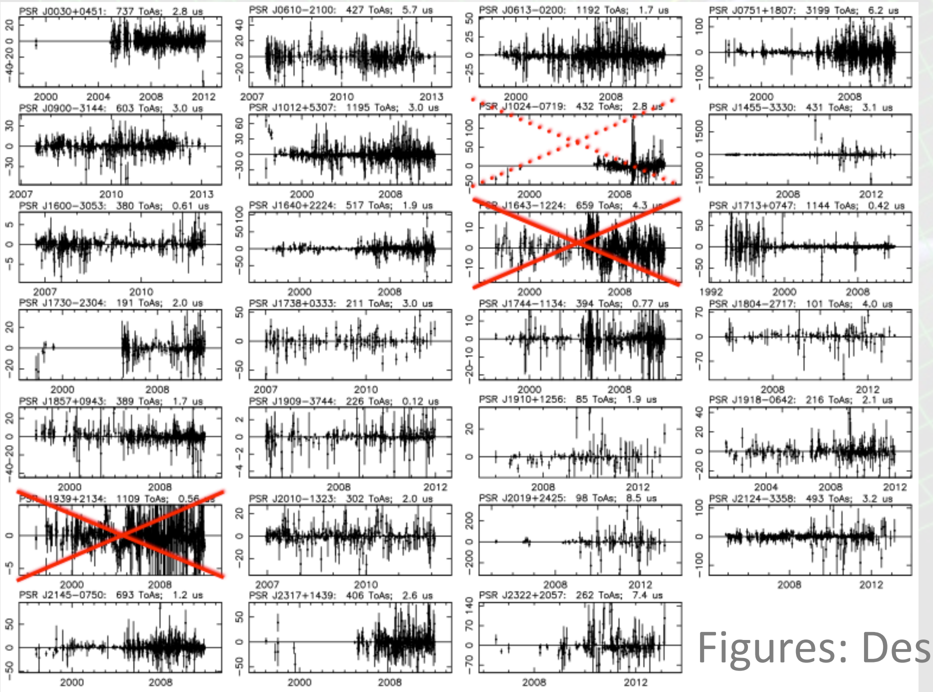
- Pulsar parameters
- Binary parameters
- Astrometry VLBI
- ISM studies Han
- Gravity tests (GR) Shao

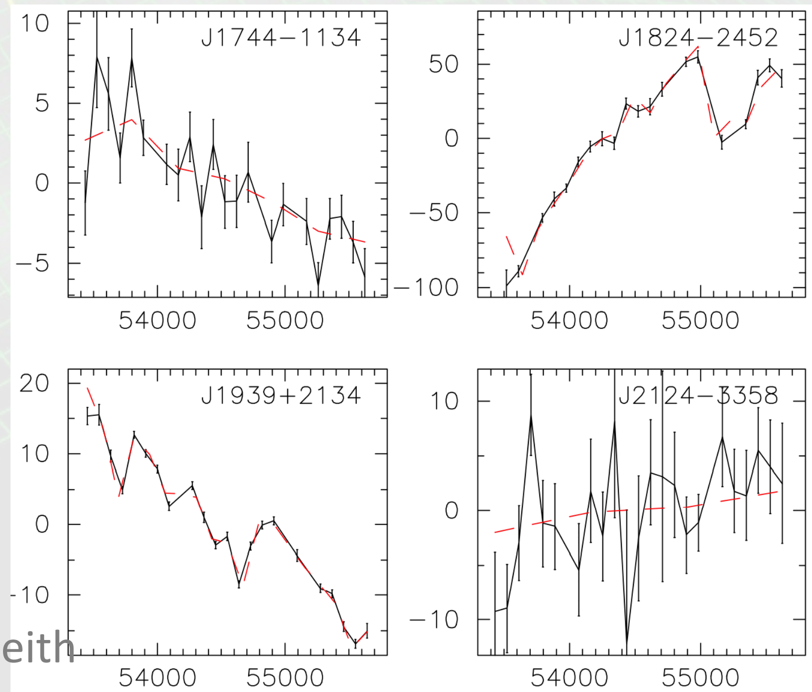
- Equation of state Watts
- Emission mechanism Karastergiou
- Solar system ephemerides
- Clock offsets
- Gravitational wave astronomy Janssen

Figure: Pulsar Handbook (Lorimer & Kramer)

Pulsar timing limitations: red noise effects

- Pulse jitter: limits the ultimate timing precision; short timescales
- Timing noise: long-term pulsar-intrinsic irregularities: unpredictable
- Interstellar medium effects
  - Dispersive delays:
    - need multiple observing freqs (SKA$_1$-mid)
    - Need low freqs (SKA$_1$-low)
  - Scattering: requires higher (>2-3 GHz observing freqs)

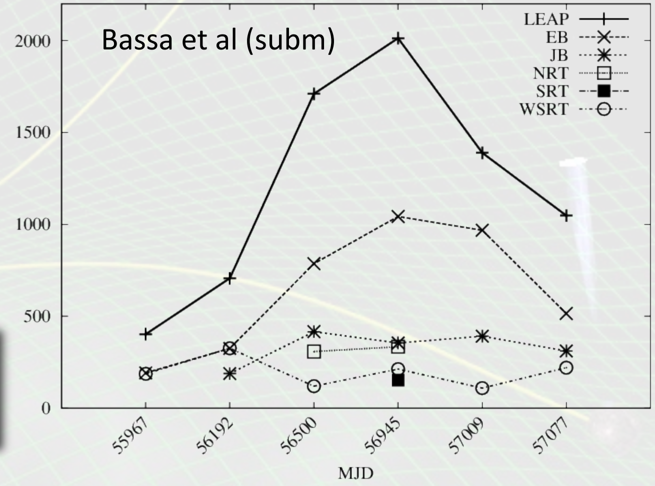


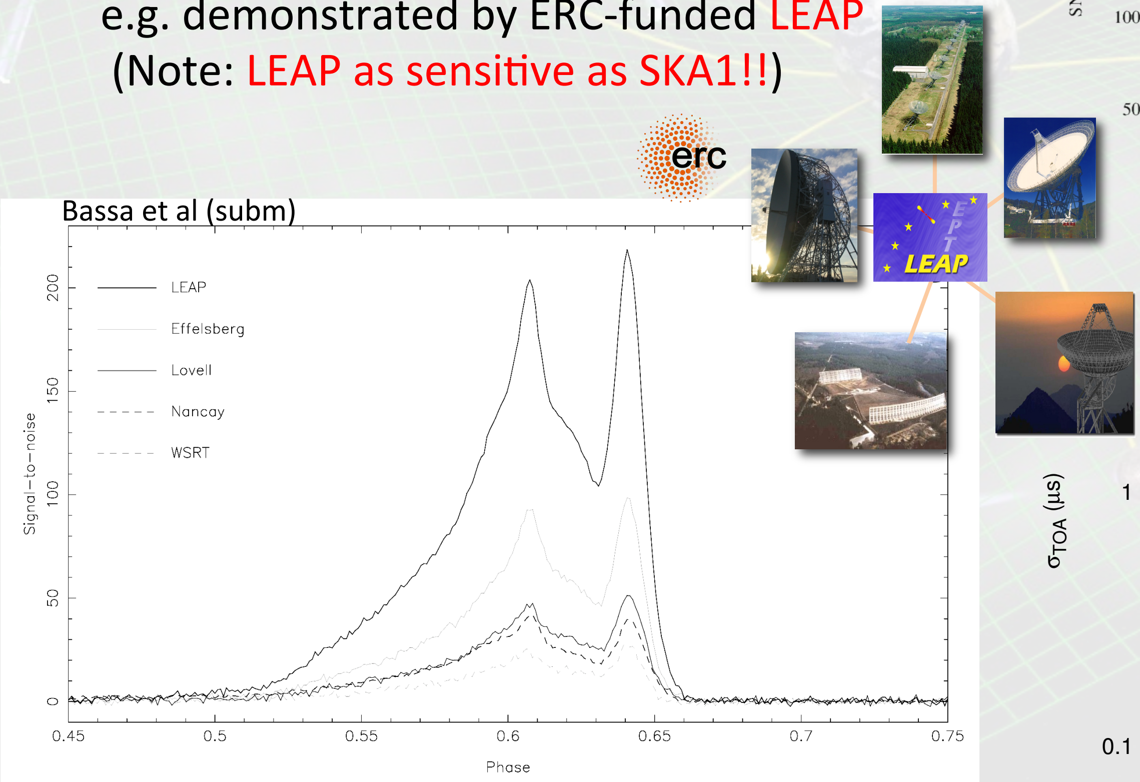


Figures: Desvignes/Keith

Requirement: Timing precision

- All pulses are different ("pulse jitter"), so that we need minimum integration time to obtain a stable pulsar profile.
- Beyond pulse jitter (and calibration & ISM), timing precision scales with Signal-to-Noise, e.g. demonstrated by ERC-funded LEAP (Note: LEAP as sensitive as SKA1!!)


Bassa et al (subm)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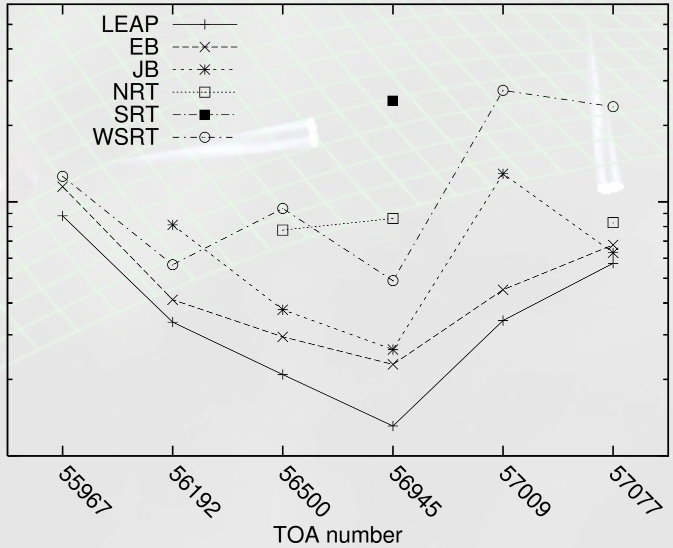
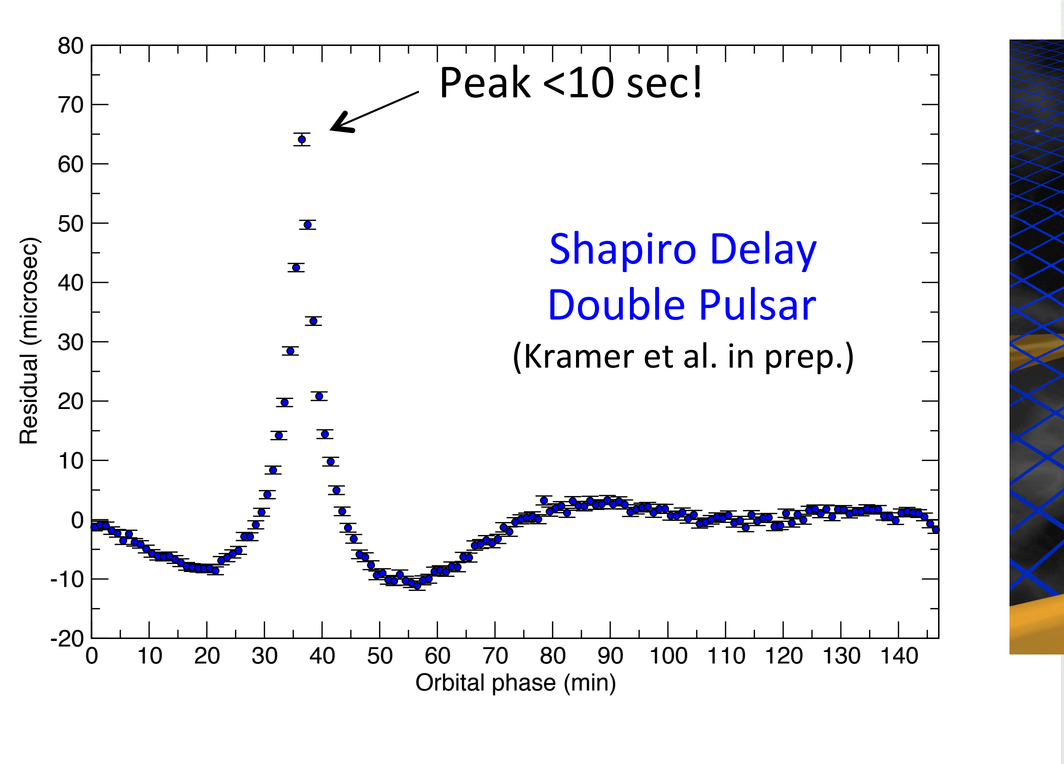
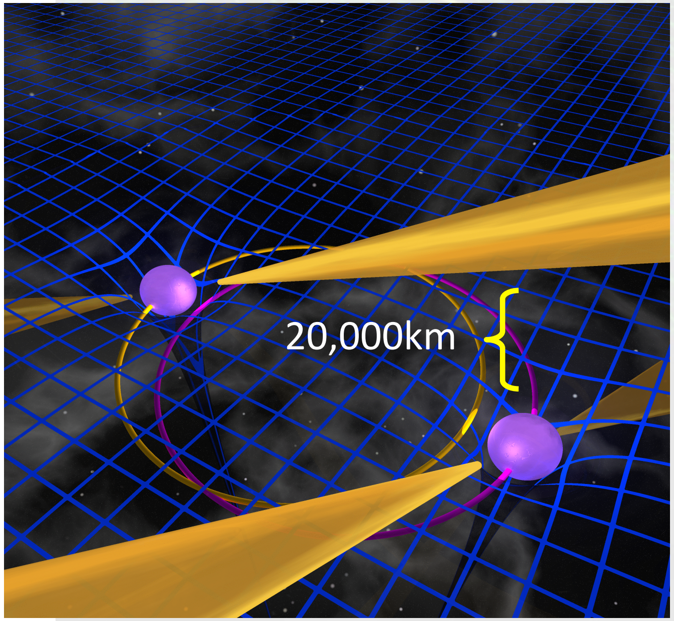


Careful polarisation calibration essential to obtain full precision!

Requirement: Timing precision

- All pulses are different ("pulse jitter"), so that we need minimum integration time to obtain a stable pulsar profile.
- Beyond pulse jitter (and calibration & ISM), timing precision scales with Signal-to-Noise, e.g. demonstrated by LEAP
- To resolve orbits, we cannot compensate loss in sensitivity with observing time

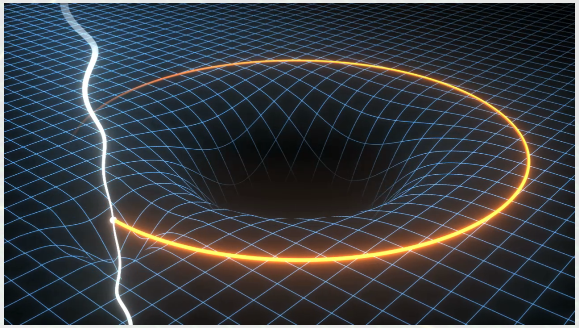




$m_A = 1.338148 \pm 0.000008\ M_\odot$ and $m_B = 1.248915 \pm 0.000008\ M_\odot$

Goal: Observations of Black Holes Properties

- We need to trace the spacetime around a black hole – ideally in a clean way!
- In a perfect world, we have a clock around it…
- …in a nearly perfect world, we have a pulsar!
- See Wex & Kopeikin (1999) for a first recipe and Liu et al. (2012, 2014) for more details
- Spin from Lense-Thirring/spin-orbit coupling:



$$
\begin{aligned}
\omega &= \omega_0 + (\dot{\omega}_{\rm PN} + \dot{\omega}_{\rm LT})(T - T_0) + \tfrac{1}{2}\ddot{\omega}_{\rm LT}(T - T_0)^2 + \ldots \\
x &= x_0 + \dot{x}_{\rm LT}(T - T_0) + \tfrac{1}{2}\ddot{x}_{\rm LT}(T - T_0)^2 + \ldots
\end{aligned}
$$

[Wex & Kopeikin 1999; Liu 2012; Liu et al. 2014]

With a fast millisecond pulsar about a 10-30 $M_\odot$BH, the SKA could measure the quadrupole:

⇨

BH mass with precision < 0.1%
BH spin with precision < 1%
Cosmic Censorship: $S < GM^2/c$

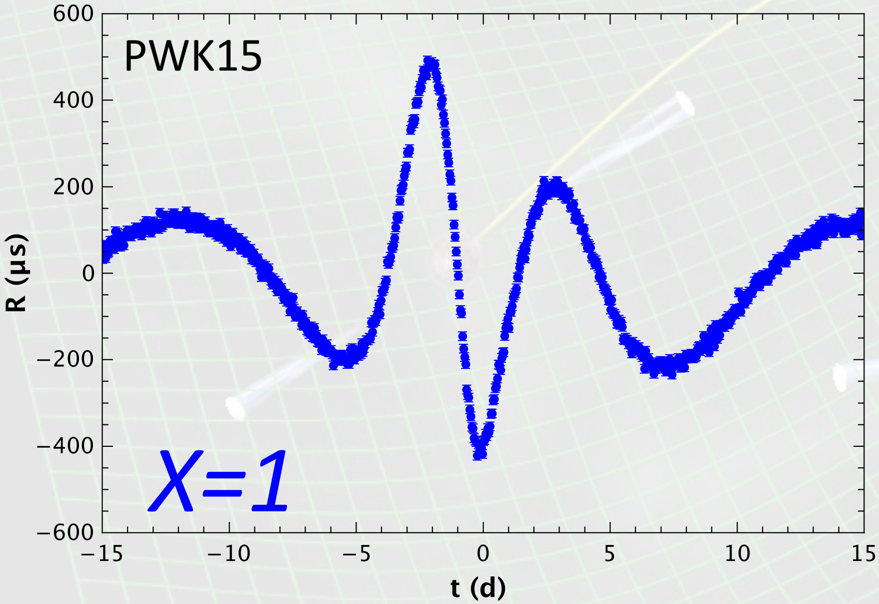
A more massive BH with pulsars would be much easier…

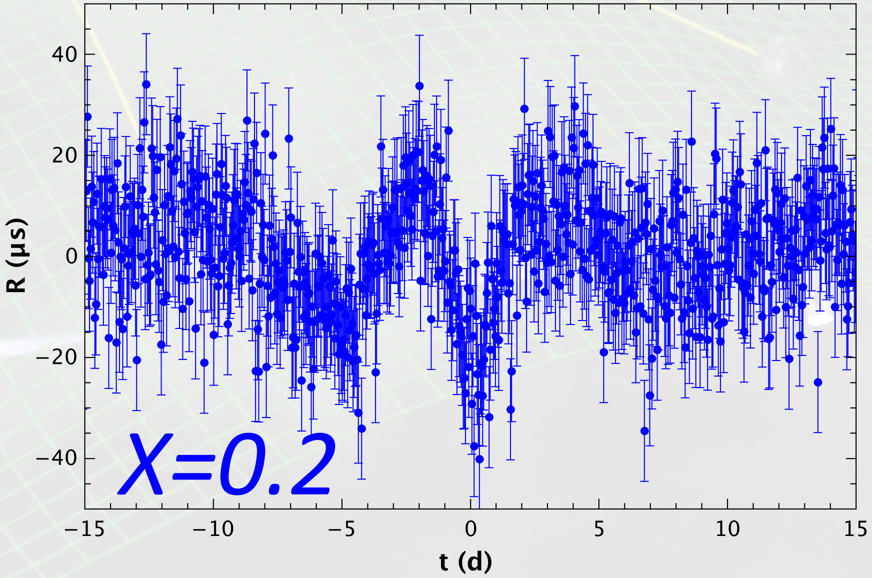
Goal: Testing the no-hair theorem

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

Pulsar in a 0.1 yr orbit around Sgr A*:

- *Secular precession* caused by quadrupole is 2 orders of magnitude below frame dragging, and is not separable from frame-dragging
- Fortunately, quadrupole leads to *characteristic periodic residuals* of order **msecs**

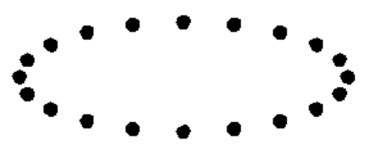




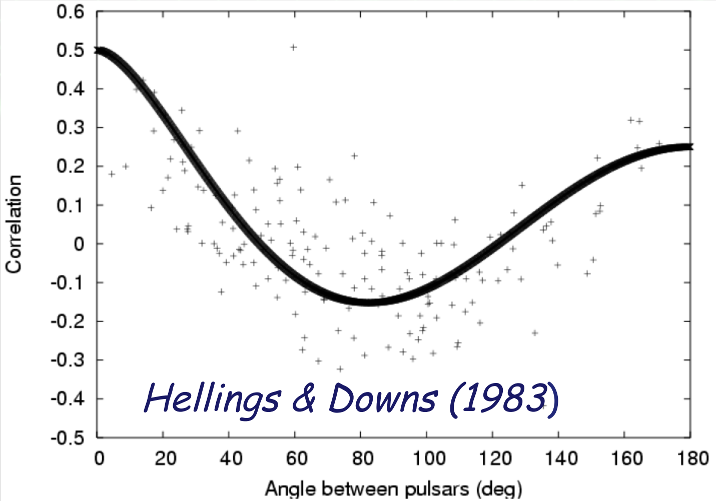
We can test the no-hair theorem to about 1% precision!

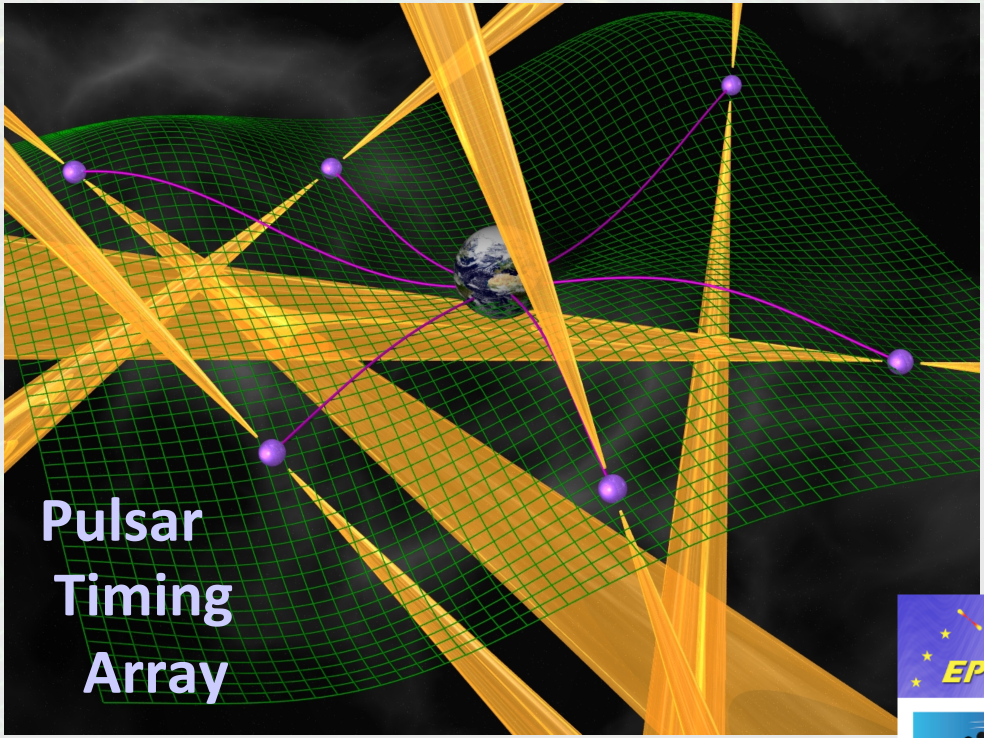
Pulsars as gravitational wave detectors

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



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





Probe of fundamental physics and more…

EPTA

NANOGrav

PPTA

The International Pulsar Timing Array

Three collaborations:
EPTA http://www.epta.eu.org
PPTA http://www.atnf.csiro.au/research/pulsar/ppta/
NANOGrav http:nanograv.org

forming the

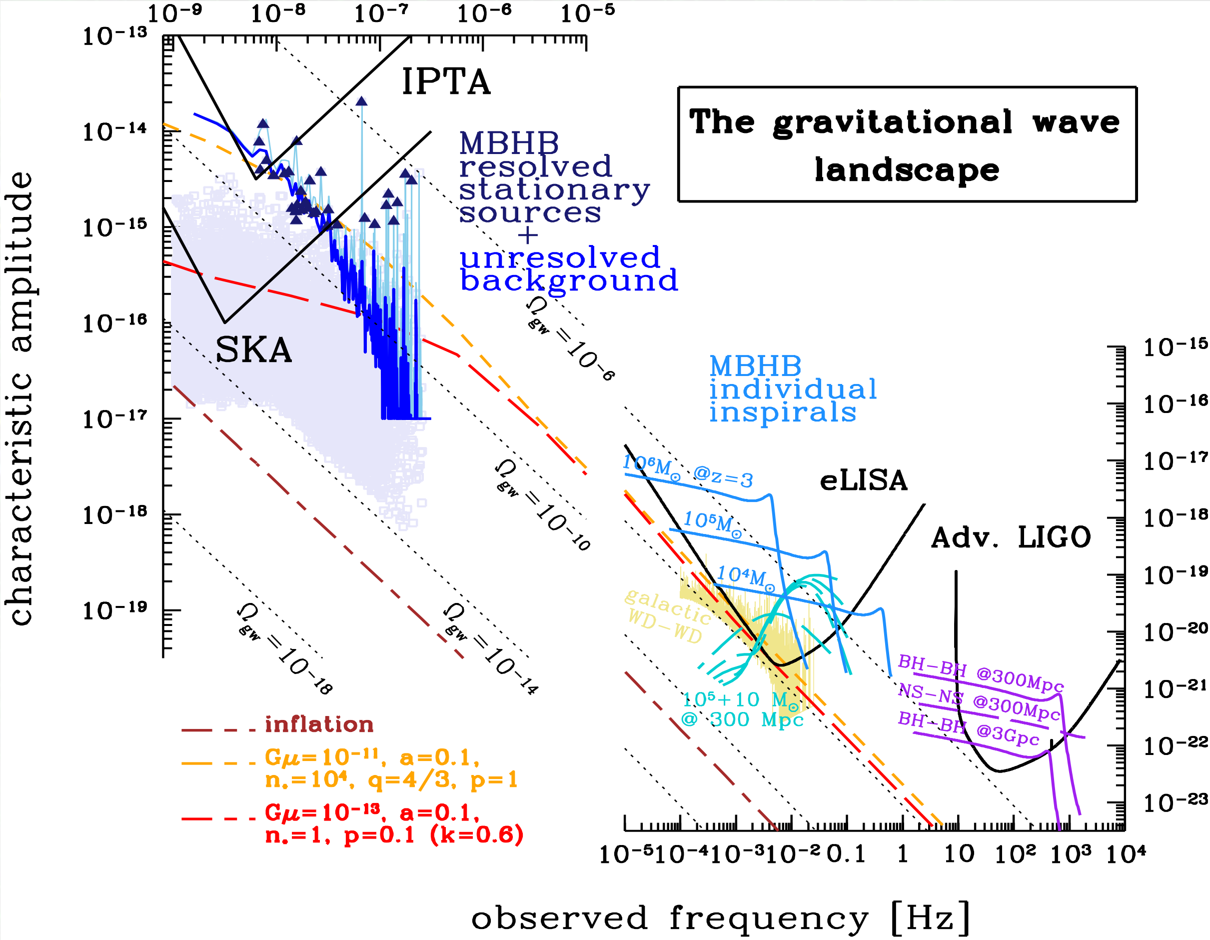
IPTA http://www.ipta4gw.org

Pulsar timing programmes on all major radio telescopes,
Plans for future facilities and pathfinders

8 large radio telescopes
All have unique strengths
Interesting limits,
but no detection yet -> SKA sensitivity required

The SKA as a Gravitational Wave Detector

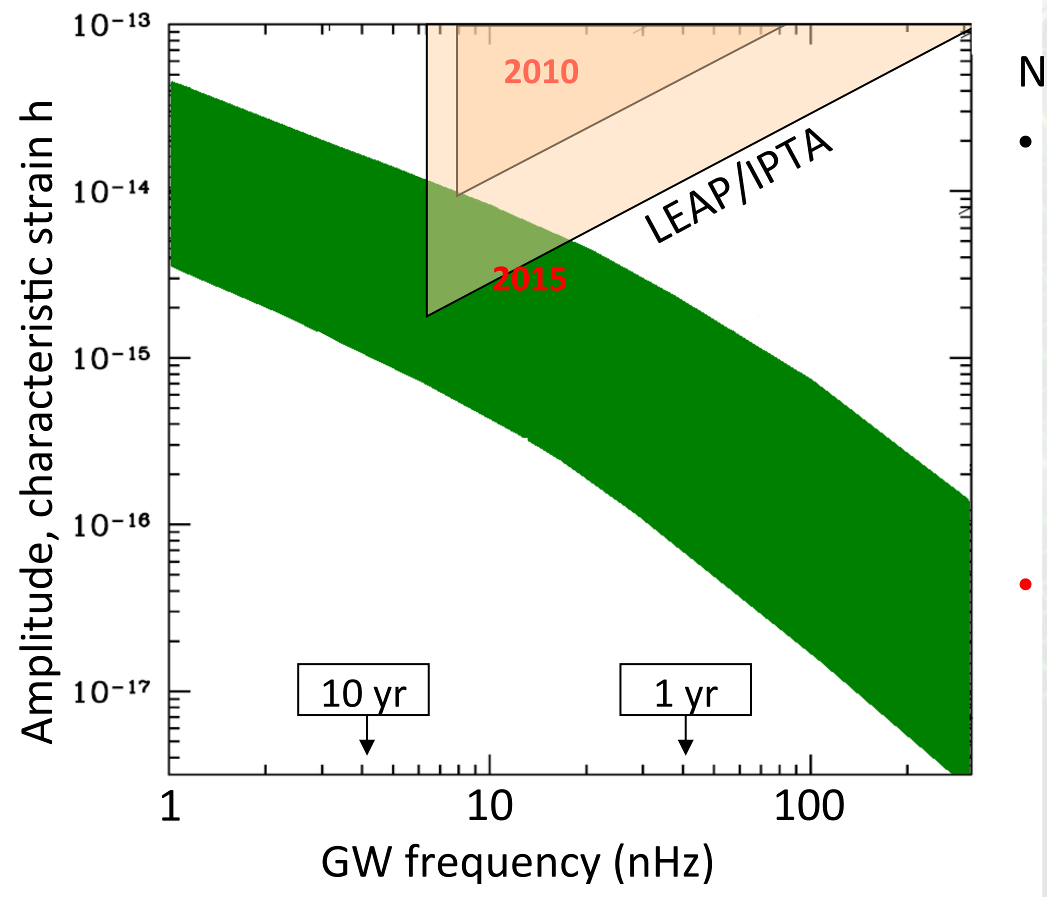
- SKA-PTA is sensitive to nHz gravitational waves
- Complementary to LISA, LIGO and CMB-pol band
- Expected sources:
  - binary super-massive black holes in early Galaxy evolution
  - Cosmic strings
  - Cosmological sources
- Types of signals:
  - stochastic (multiple)
  - periodic (single)
  - burst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



(Janssen et al. 2015)

Stochastic GW background

- Earliest 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)



Note:

- Current best limits from European, North-American, Australian timing array are all very similar:

  EPTA: Lentati et al. (2015)

  NanoGrav: Arzoumanian et al. (2015)

  PPTA: Shannon et al. (2013)
- All are tantalizingly close to expected detection limit!

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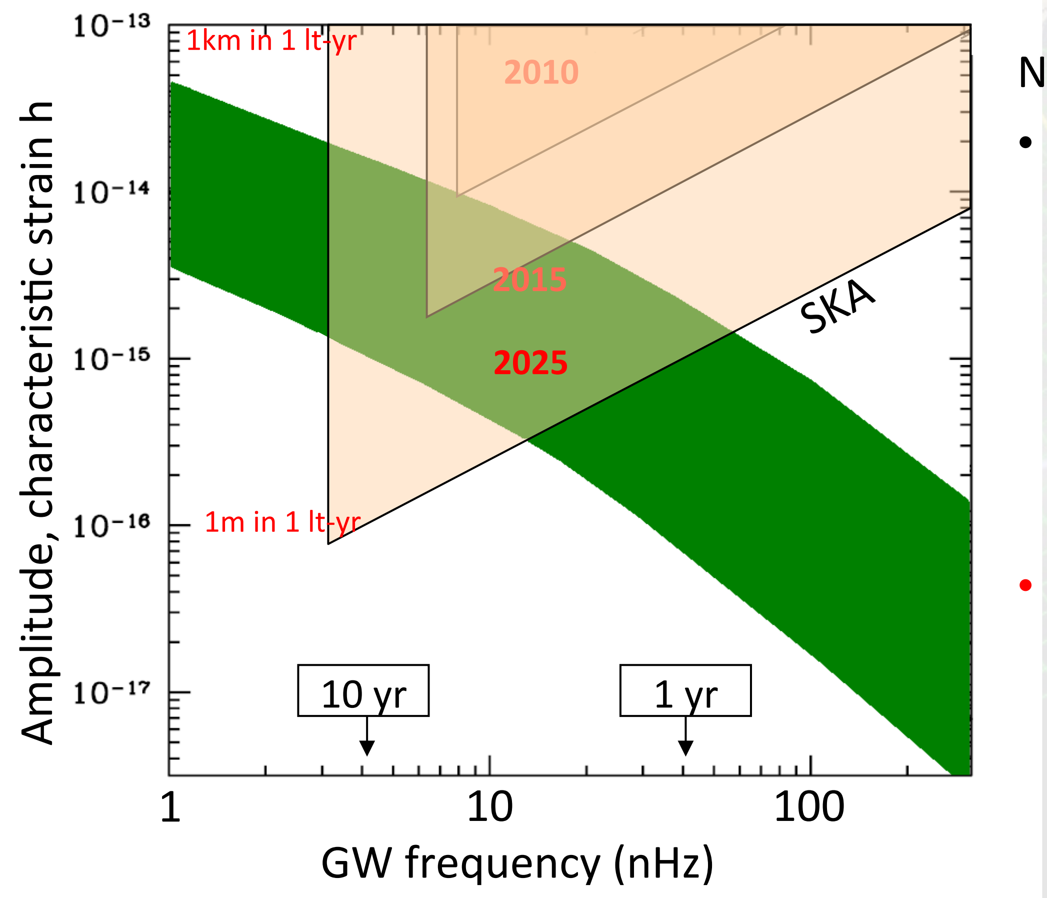

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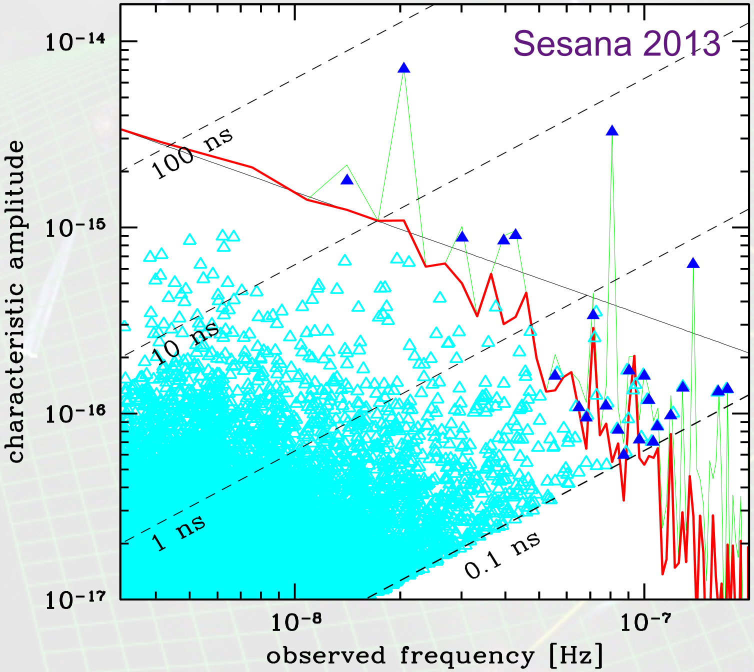
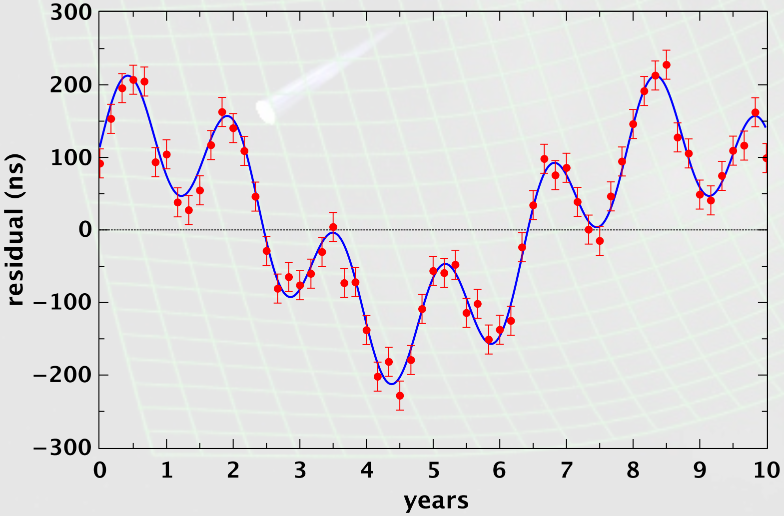
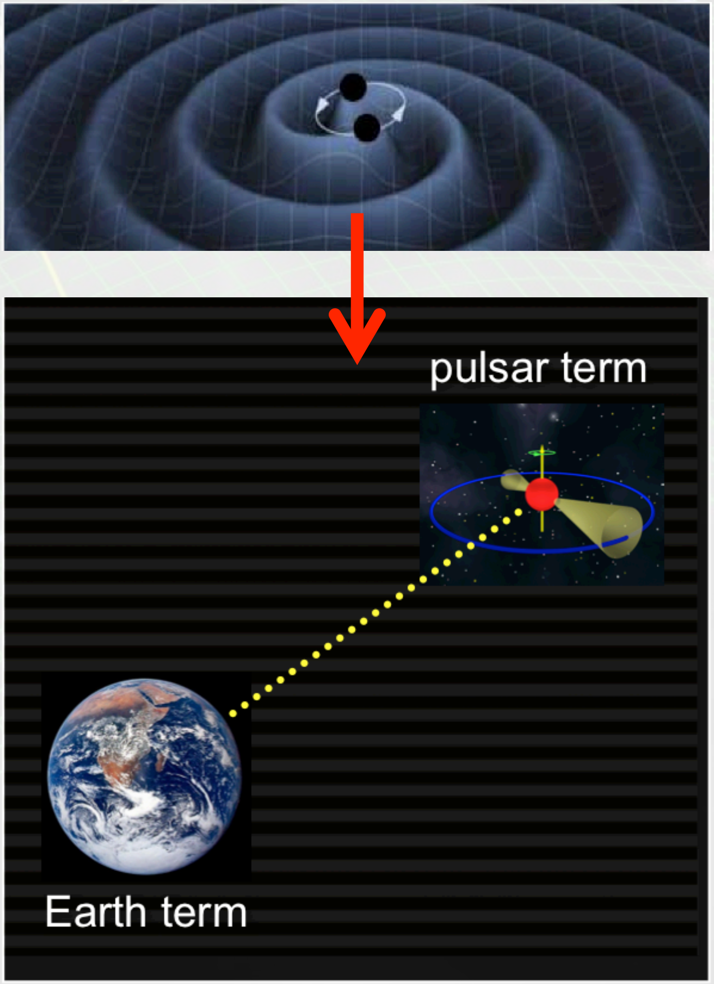
Single GW source in the PTA band





- Single binary SMBH produces periodic signal
- Also dc-term due to memory effect (e.g. van Haasteren & Levin 2010)
- Signal contains information from two distinct epochs



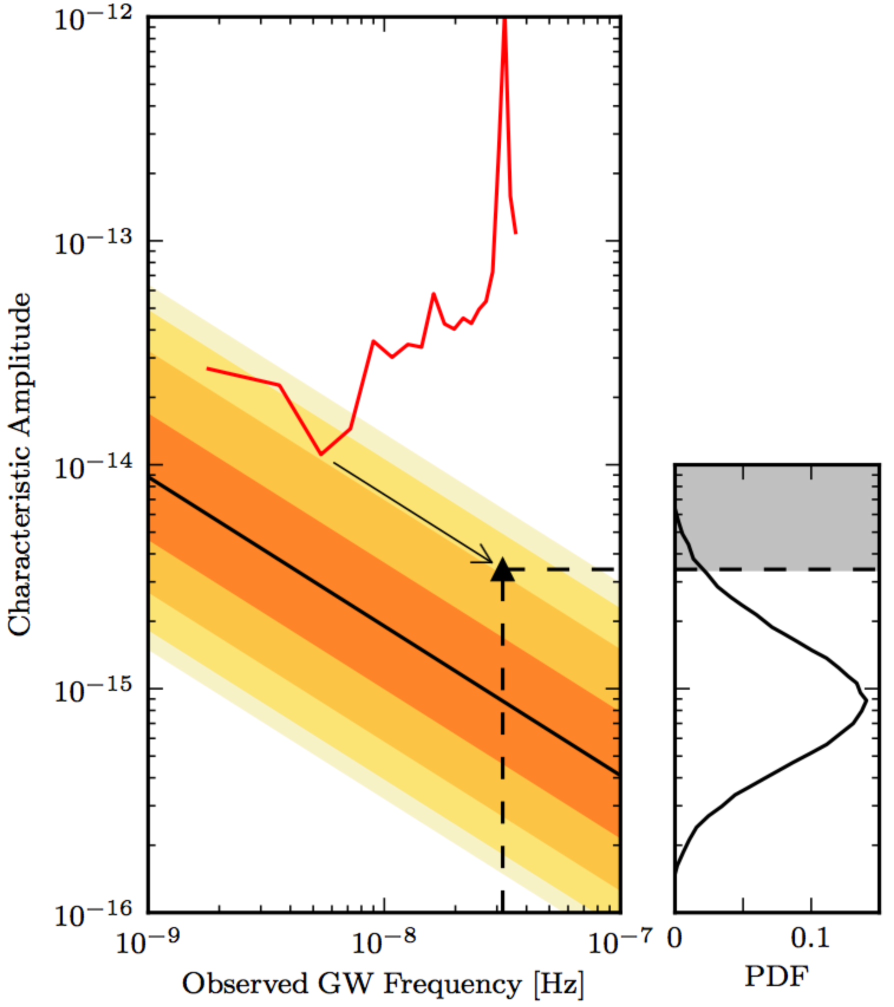
Early GW work with SKA1

- SKA to improve chances of detection
- Improved sensitivity will overcome timing issues
- Census will provide extra pulsars to increase Npsr

- Transition from GW limits to detection

Weak regime: $N_p c A^2 T^{13/3}/\sigma^2$
Intermediate regime: $N_p c^{3/26}(A/\sigma)^{3/13}T^{1/2}$
(Siemens et al. 2013)

- Improvement required for all the above



A Amplitude
N_p # of pulsars
c cadence
σ pulsar RMS
T obs time

Recent EPTA limit curve from Lentati et al. 2015, see also similar curves from PPTA/ NANOGrav (Shannon/Ellis)

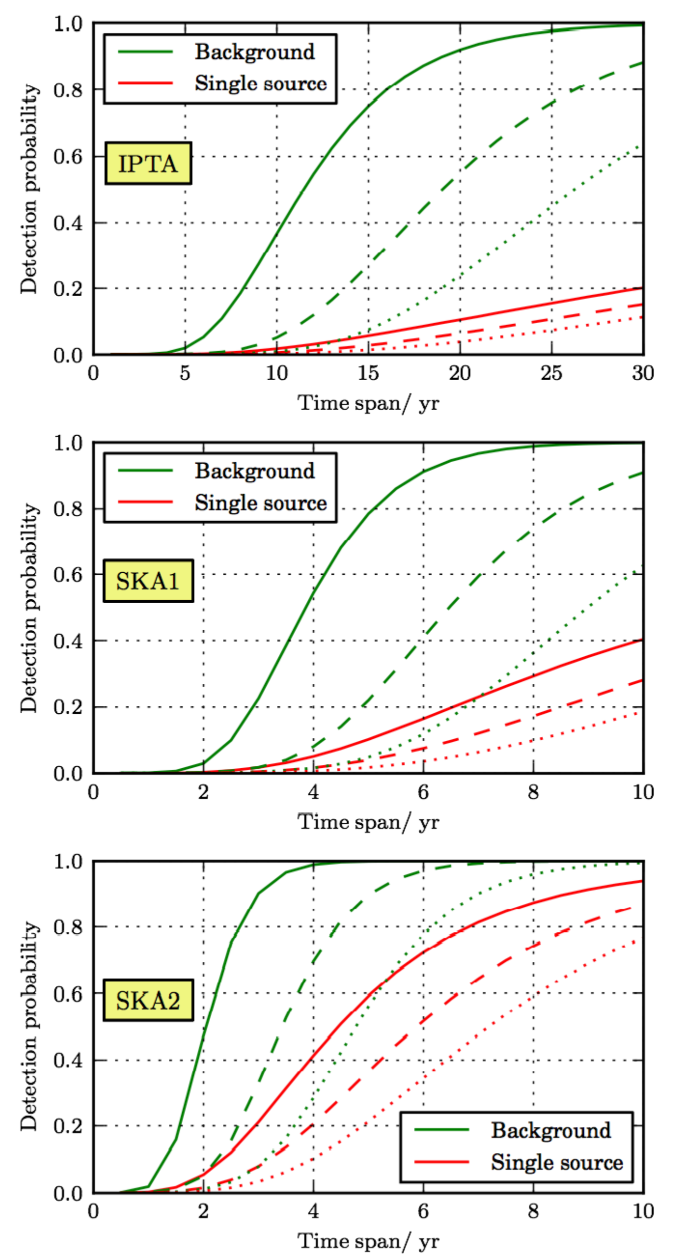
From limit to detection to GW astronomy

IPTA is getting close already!

SKA1 – make/confirm first detection

SKA2 – GW astronomy

A Amplitude
N_p # of pulsars
c cadence
σ pulsar RMS
T obs time



Rosado, Sesana & Gair 2015, MNRAS 451, 2417

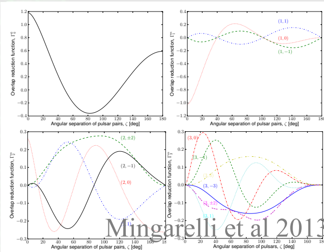
GW astronomy with the SKA

Before and early stages SKA :

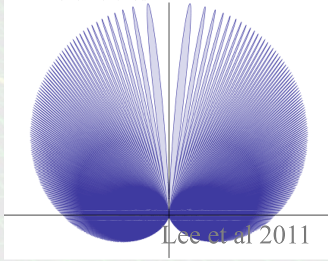
- Confirmation of the signal
- Source identification (characterize spectrum)
- Background characterization (anisotropy search)
- Source localization

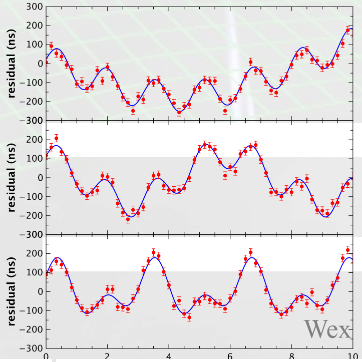
(Full-)SKA science: GW astronomy

- Constrain/study Galaxy evolution
- Characterization of inspiral phase of SMBHBs
- Tests of gravity
  - Polarization properties
  - Mass of graviton



Mingarelli et al 2013


Lee et al 2011



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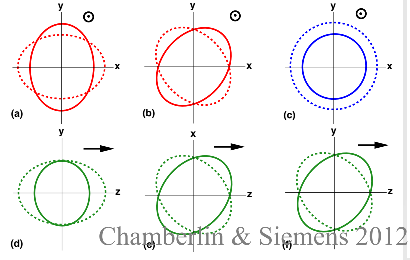
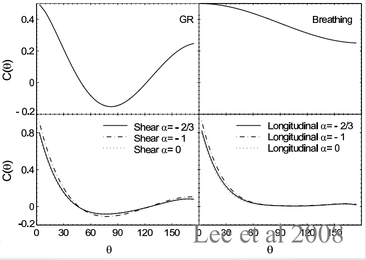
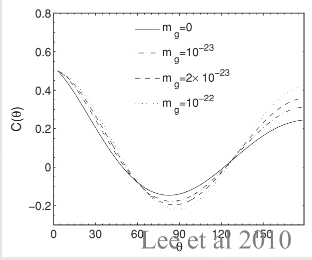


Chamberlin & Siemens 2012



Lee et al 2008



Lee et al 2010

SKA: pulsar timing requirements

- SKA$_1$-Mid: sensitivity/large collecting area is essential
  - High precision timing best done in Bands 2 and 3
  - Lower bands essential for ISM effects; higher bands for Galactic center regions
  - Subarraying for stronger pulsars and flexibility/efficiency

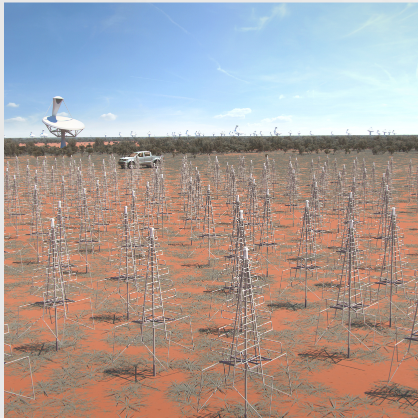
- SKA$_1$-Low: ISM measurements and correction
  - overall observing efficiency can increase
  - steep-spectrum pulsars
  - beamformer for pulsar observations! ECP accepted

- General: regular-cadence observations, multifrequency, long timespan, large number of pulsars, calibration, stable reference clock!
- General: VLBI: independent astrometry, immediate high-precision timing; increased sensitivity for f=1/yr and 1/0.5yr

SKA1-Low and timing

- Advantages:
  - Wider fractional band: stronger ISM constraints
  - Less ISM effects at top of band
  - Potential for high-cadence observations with multiple beams
  - Overall observing efficiency can increase
  - Steep-spectrum pulsars
  - Model pulse-shape variations

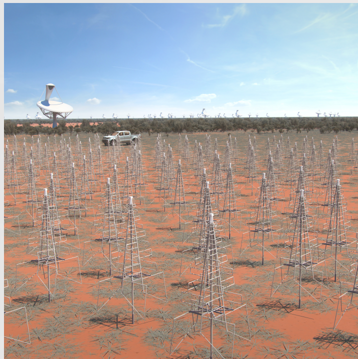
- Potential issues:
  - polarisation calibration
  - Chromatic DMs needs modelling -> correction may require higher frequencies or wider band



Combination of Mid & Low optimal to **time** all the pulsars

Discussion items for the PSWG:

- (Re-)Definition of KSPs
- Resources:
  - What internal resources are required by the KSP group
  - What primary/secondary resources are required from the SKA
  - What resources are required from external organisations
- People and collaborations
  - How do current collaborations flow into “new” SKA KSP groups
- Observing strategies and commensality, noise/cal requirements
  - What are the requirements and possibilities
- Data output/access/publication
  - What are the output products and what policies are required



Conclusions

- Using pulsars, the SKA will probe science from solid states physics to gravitation:

  See SKA Science Book Chapters for a detailed overview of the breadth of science!
- 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
- There will be superb synergies with GAIA, ELTs, LSST, CTA, AdvLIGO, LISA etc.
- We are trying/will try a lot of the techniques: AI, LEAP, FAST, MeerKAT etc.

A combination of SKA1-Mid and SKA1-Low

required to provide the best scientific outcome