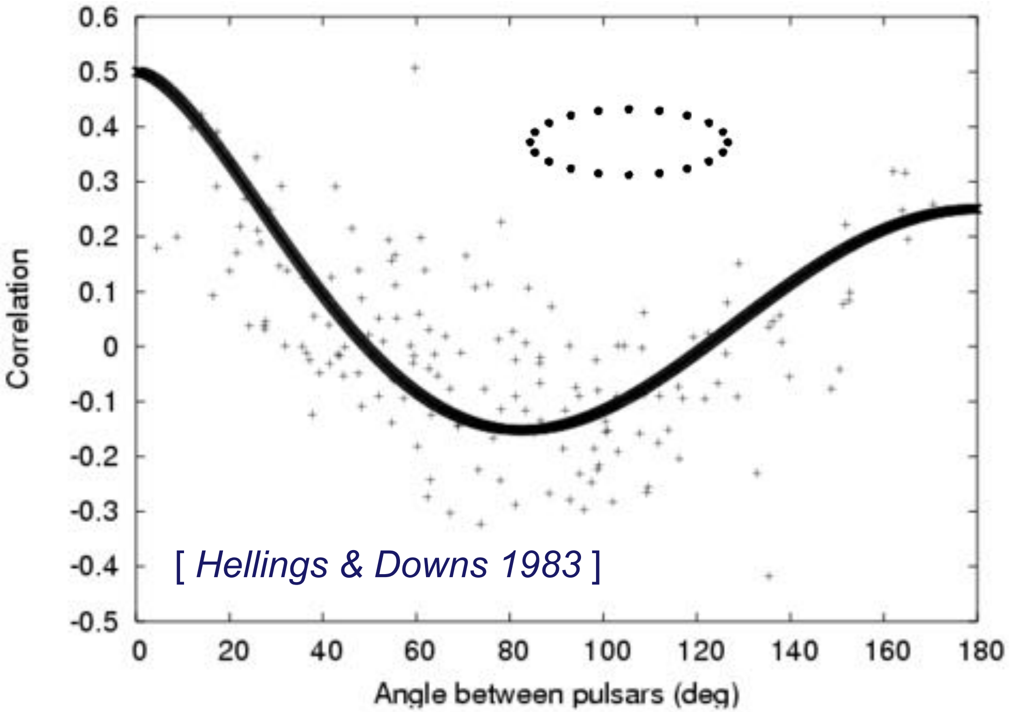
Outline

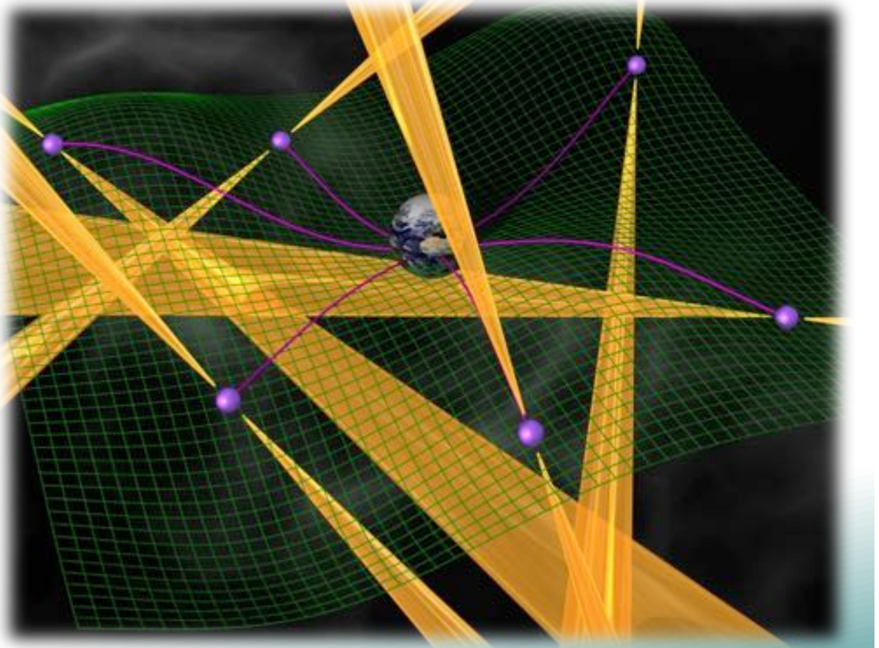
- Introduction
- Pulsars & binaries: testing GR and its alternatives
- Pulsar Timing Arrays (PTAs): detecting GWs
- The (far & near) future: SKA + EHT/BHC
- Conclusions

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





Detecting low-frequency GWs

- 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 detectable soon.

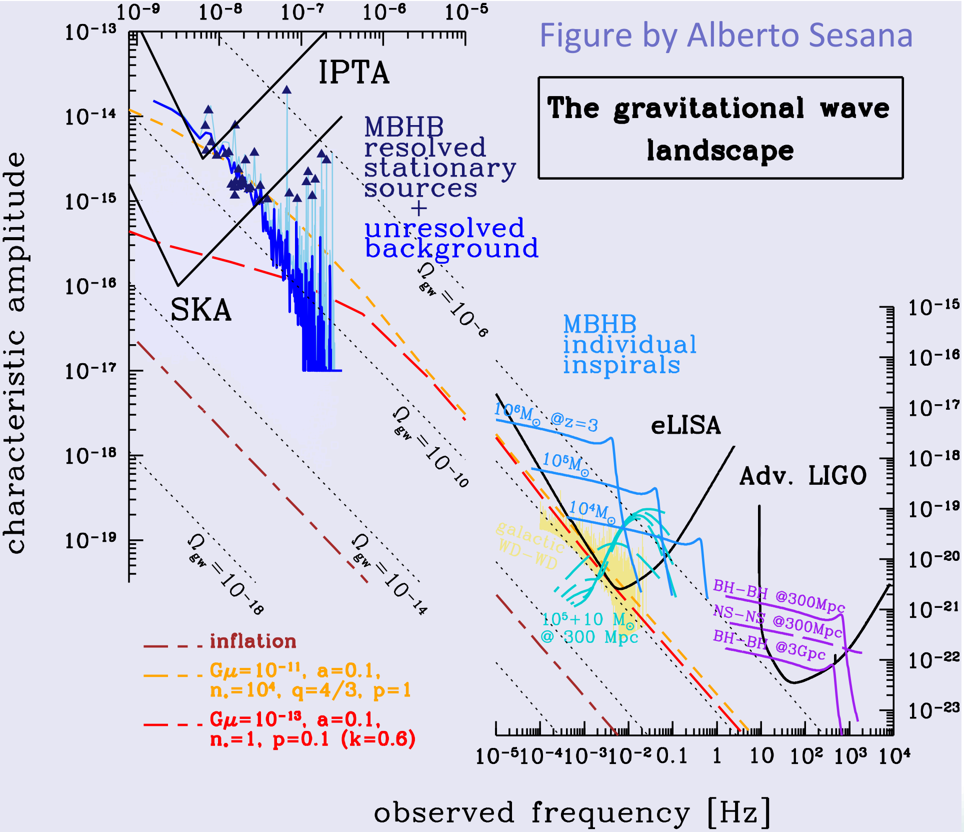


Figure by Alberto Sesana

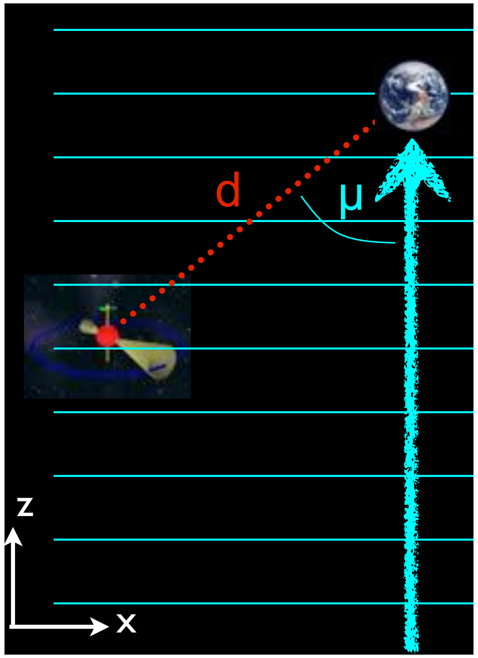
The gravitational wave landscape

We expect single sources and also a stochastic background

Detecting gravitational waves

- Sazhin (1978) and Detweiler (1979) first showed that a GW signal causes a fluctuation in the observed pulse frequency δν/ν
- The timing residual is the integral over these variation over the duration of the timing experiment:

$$R(t) = -\int_0^t \frac{\delta\nu(t)}{\nu} dt$$



With Doppler shift given by

$$\frac{\delta\nu}{\nu} = H^{ij}(h^e_{ij} - h^p_{ij})$$

geometry Earth pulsar

$c T_{\mathrm{obs}} \sim \lambda \ll d$ -> short wavelength approximation

Detecting gravitational waves

- Sazhin (1978) and Detweiler (1979) first showed that a GW signal causes a fluctuation in the observed pulse frequency δν/ν
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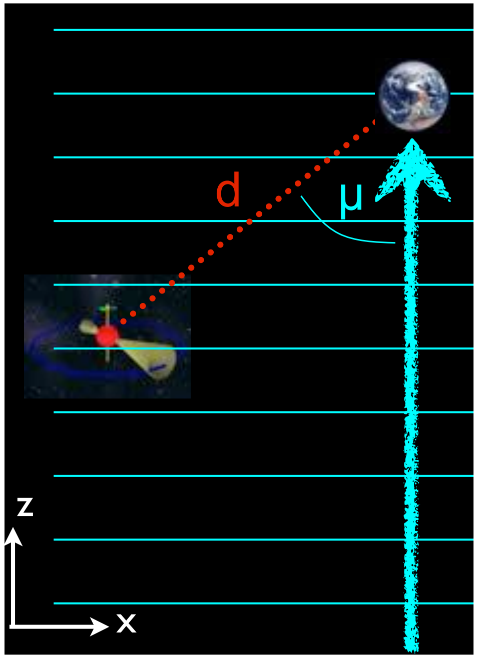


$$R(t) = \frac{1}{2}(1 + \cos\mu)[r_{+}(t)\cos(2\psi) + r_{\times}(t)\sin(2\psi)],$$

$$r_{+,\times}(t) = r^{e}_{+,\times}(t) - r^{p}_{+,\times}(t),$$

$$r^{e}_{+,\times}(t) = \int_0^t h^{e}_{+,\times}(\tau)\, d\tau, \qquad \text{"Earth term"}$$

$$r^{p}_{+,\times}(t) = \int_0^t \overset{\text{Retardation}}{\boxed{h^{p}_{+,\times}\left[\tau - \frac{d}{c}(1 - \cos\mu)\right]}} d\tau, \qquad \text{"pulsar term"}$$

[Detweiler 1979, Jenet et al. 2004]

Expected amplitudes & sources

- Highest frequency is given by cadence: ~1 per month => ~400 nHz
- Lowest frequency is given by observing length: ~10 years => ~3 nHz
- Timing residuals for a monochromatic GW (i.e. $h = h_0 \cos(2\pi ft)$)

$$r(t) = \int_0^t h(\tau)\, d\tau = \frac{h_0}{2\pi f} \sin(2\pi f t)$$

- In order to get residuals of 100 ns, on needs:

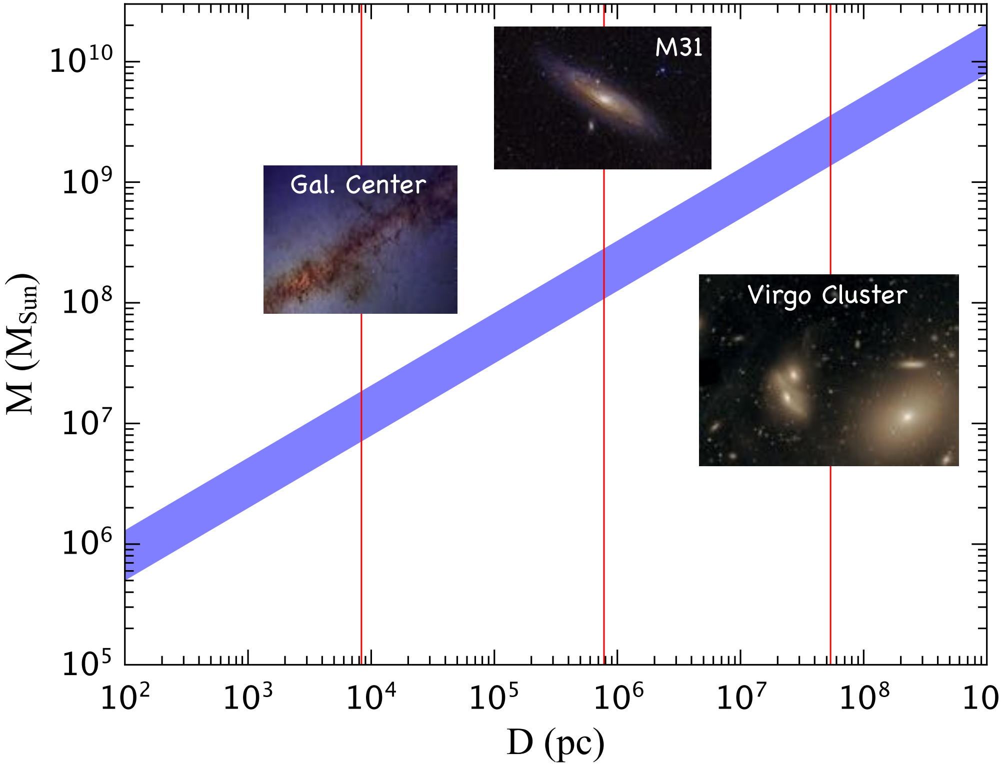
  $h_0 = 1.9 \times 10^{-15}$ at 3 nHz
  $h_0 = 2.5 \times 10^{-15}$ at 400 nHz

What sources can produce those?

Binary system (m_1=m_2):

$$h_0 = \frac{c}{D} \left(\frac{GM}{c^3} \right)^{5/3} (\pi f)^{2/3}$$

$$r_0 = \frac{c}{2D} \left(\frac{GM}{c^3} \right)^{5/3} (\pi f)^{-1},$$



Slide courtesy N. Wex

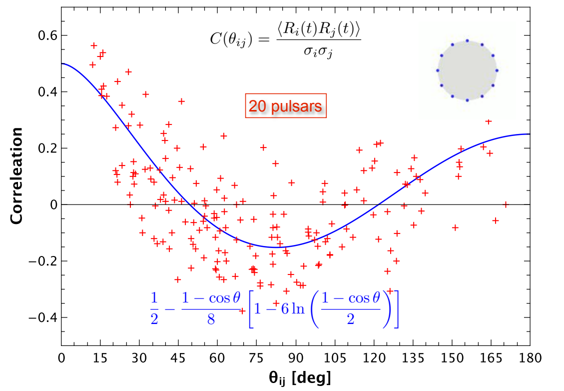
Searching for a stochastic GWB

- We are looking for a "red noise" signal with a period comparable to the length of the data set, using frequentist and Bayesian methods
- Competing noise sources:
  - pulsar deterministic "noise" (orbital motion, spin-down etc.)
  - pulsar intrinsic white noise + instrumental (thermal) white noise
  - pulsar intrinsic red noise (pulse jitter, timing irregularities)
  - variation in the interstellar medium ("Weather", DM variation, scattering)
  - "common noise": planetary ephemeris errors, clock errors
  - stochastic noise due to GWB

- In order to extract GWB signal, a number of pulsars need to be observed
- Note that adding more pulsars should improve signals (α N) but can also add additional noise:

  fewer good pulsars may be better than many less good ones

  but: perhaps only way to find common noise



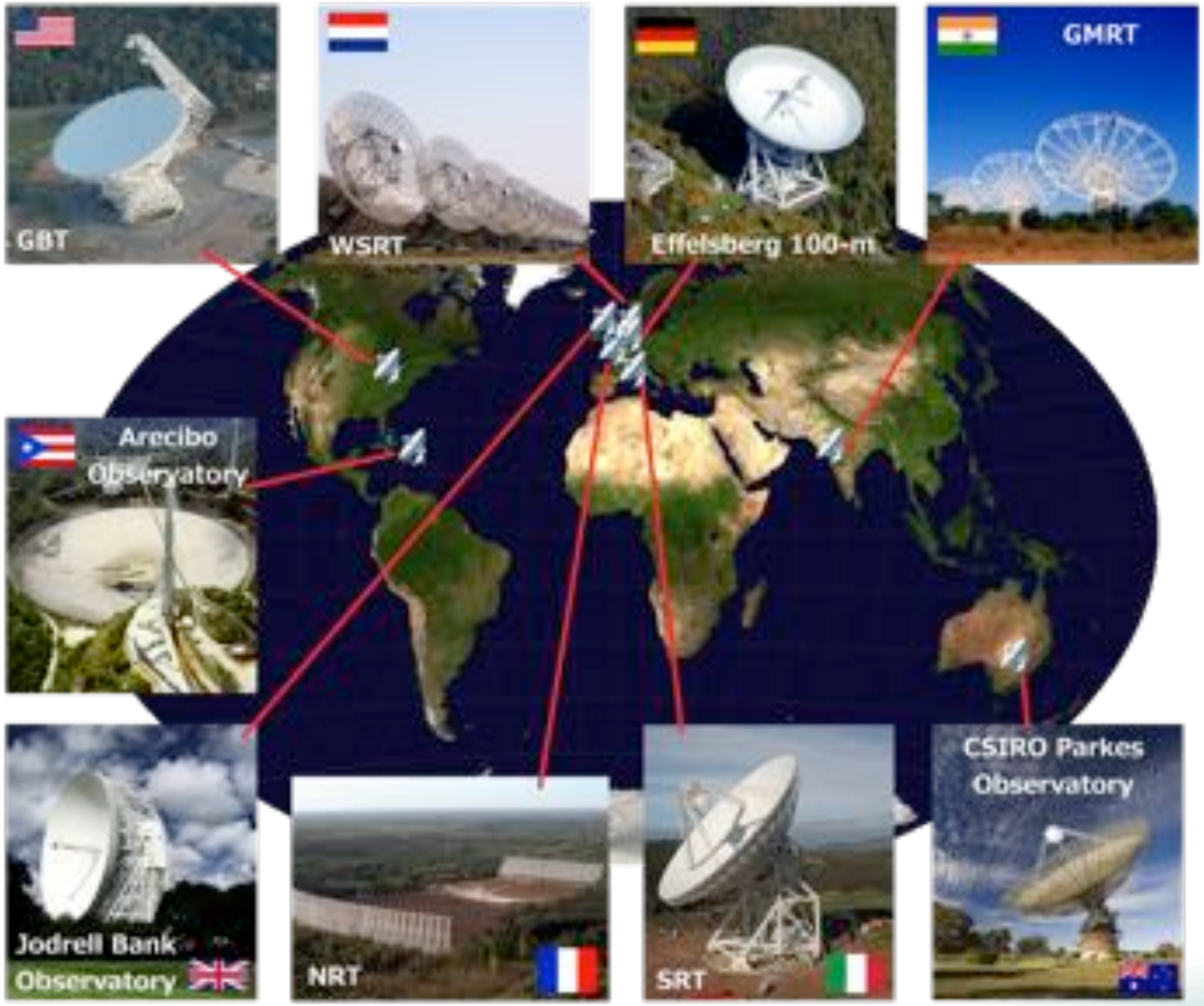
The International Pulsar Timing Array (IPTA)

INTERNATIONAL PULSAR TIMING ARRAY
IPTA

EPTA

NANOGrav

PPTA



•Brian Burt

Currently timing 50 MSPs at six radio frequencies with seven (soon nine) telescopes. There are roughly 50,000 TOAs spanning 10 years in the current IPTA data release.

The European Pulsar Timing Array (EPTA)

An array of 100-m class telescopes to form a pulsar timing array


SRT, Sardinia, Italy

INAF – Osservatorio Astronomico di Cag


Effelsberg 100-m, Germany


Lovell, Jodrell Bank, UK


NRT, Nancay, France


WSRT, Westerbork, NL

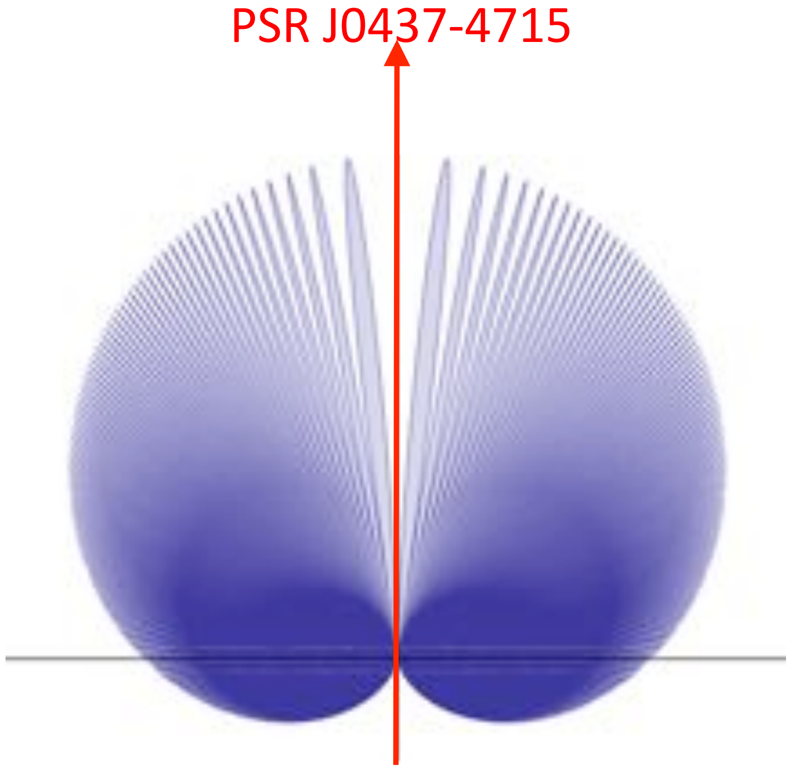
Plus theory:

and ultimately forming the Large European Array for Pulsars (LEAP)

Locating a (non-evolving) single source with the SKA-PTA

Response pattern for PSR J0437-4715

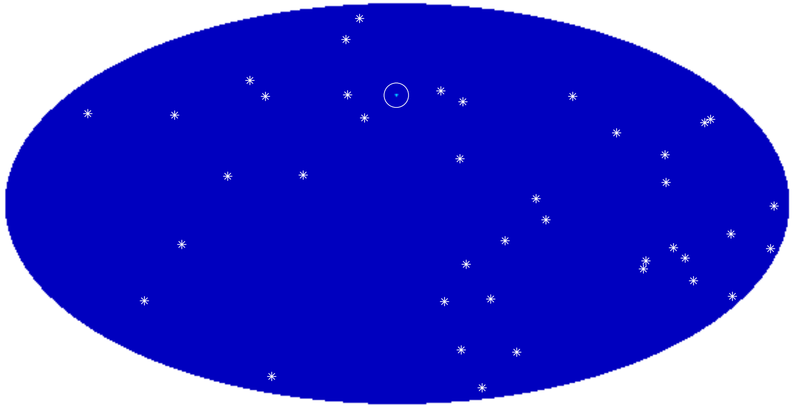
for a 6.3 nHz gravitational wave

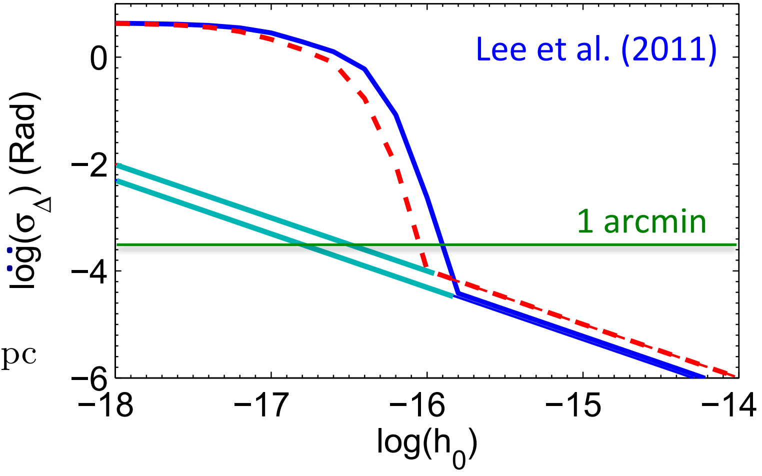


With a SKA-PTA, we can locate the binary SMBH in the sky:

40 millisecond pulsars at ~2 kpc distance

One 15 ns TOA every two weeks for 5 years





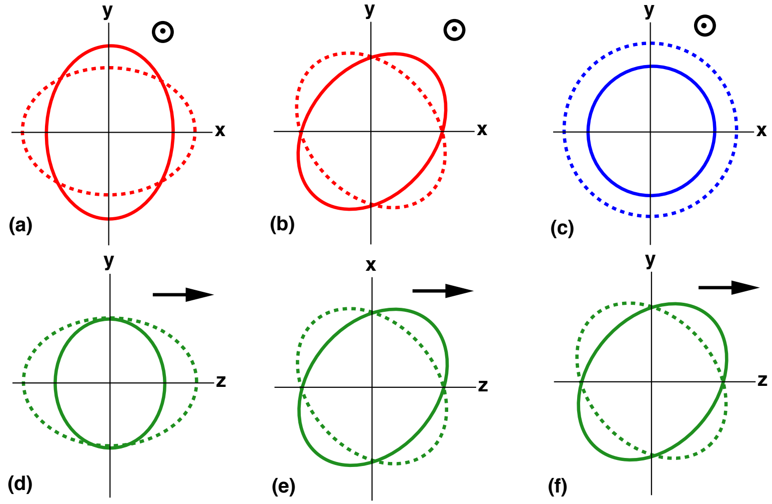
Enabling by spectacular SKA distance measurements:

$$\sigma_{D_{\rm psr}} = \frac{4\sqrt{2}\,\sigma_{\rm n} D_{\rm psr}^2}{\sqrt{N_{\rm obs}}\, r_\oplus^2 \cos^2\beta_{\rm psr}} \simeq \frac{2.34}{\cos^2\beta_{\rm psr}} \left(\frac{N_{\rm obs}}{100}\right)^{-\frac{1}{2}} \left(\frac{D_{\rm psr}}{1\,{\rm kpc}}\right)^2 \left(\frac{\sigma_{\rm n}}{10\,{\rm ns}}\right)\ {\rm pc}$$

Allowing EM follow-up of GW sources!

Testing the properties of gravitons with the SKA-PTA

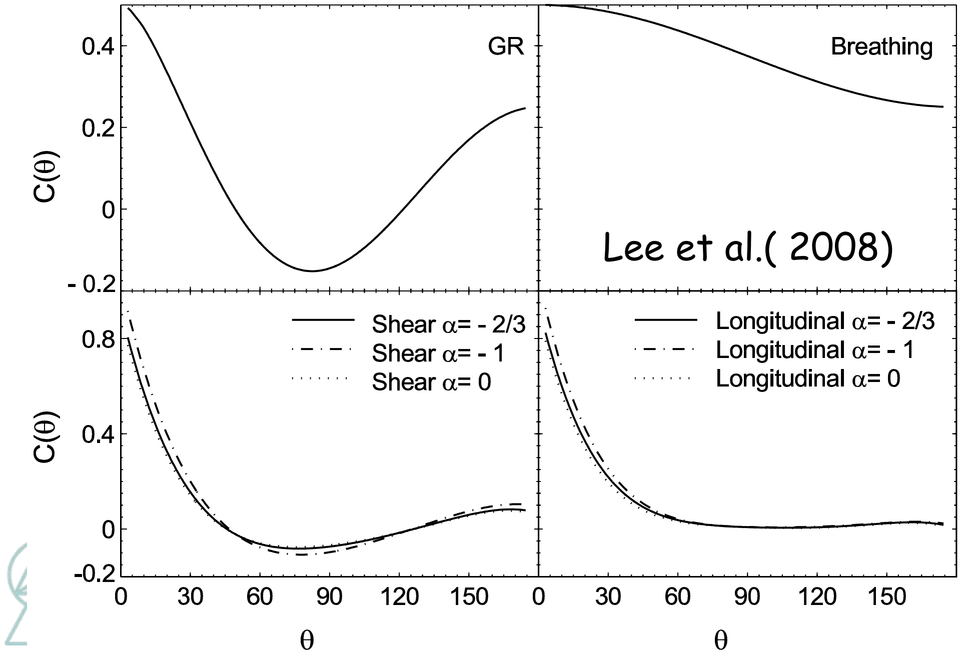
Polarization modes – Spin 2?



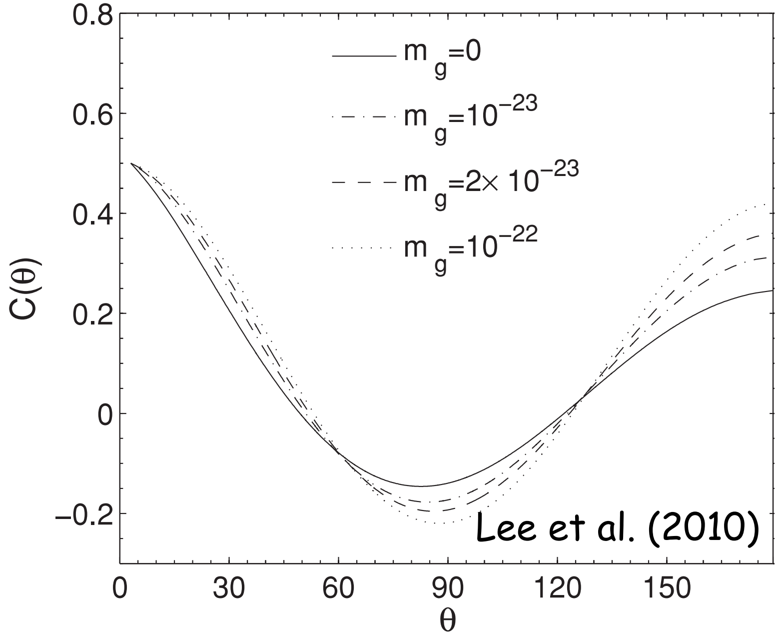
Dispersion relation: massive graviton?

$$\boxed{\mathbf{k}_{\mathrm{g}}(\omega_{\mathrm{g}}) = \frac{\left(\omega_{\mathrm{g}}^2 - \omega_{\mathrm{cut}}^2\right)^{\frac{1}{2}}}{c}\,\hat{\mathbf{e}}_z}$$

$$\boxed{\omega_{\mathrm{cut}} \equiv m_{\mathrm{g}} c^2/\hbar}$$



Lee et al.(2008)



Lee et al. (2010)

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Radio Astronomy Sensitivity

Sensitivity:

$$S_{\min} = \frac{2kT_{sys}}{A_{eff}\sqrt{\tau.\Delta\nu}} = \frac{T_{sys}}{G}\frac{1}{\sqrt{\tau.\Delta\nu}}$$

Gain:

$$G = \frac{A_{eff}}{2k}$$

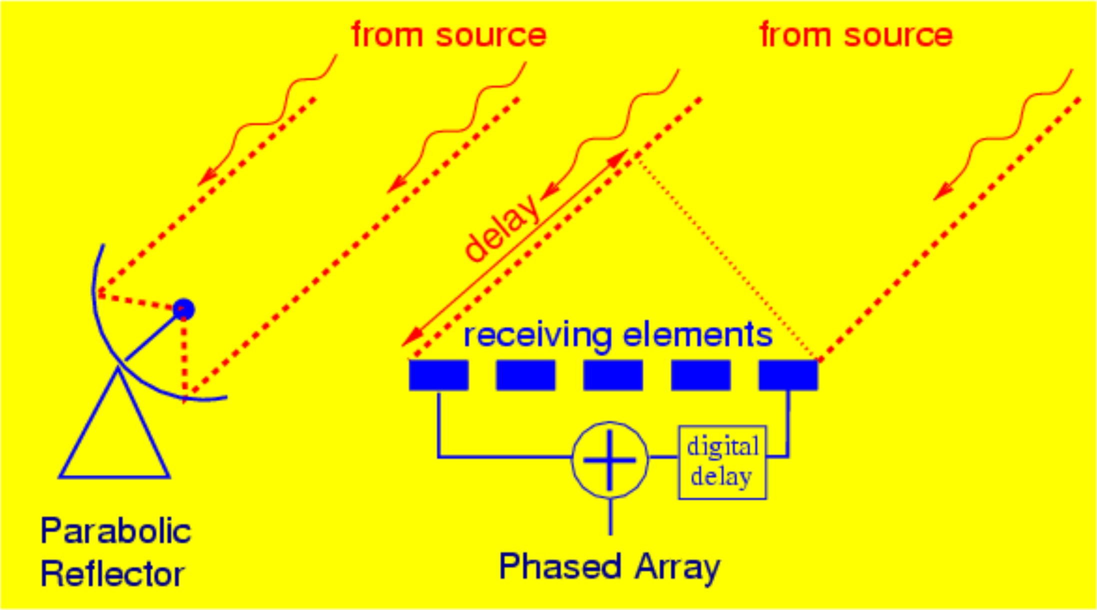
Most Receivers are already at the quantum limit = T_{sys} already minimal

Need to find other ways to improve sensitivity:

- Increase gain = collecting area = bigger telescopes!
- Increase bandwidth (despite increasing man-made RFI!)
- Enable longer integration time = cover more sky per minute!

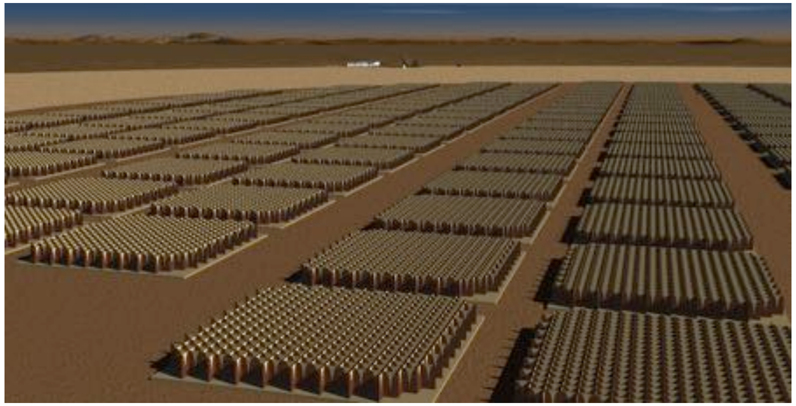
A Revolution in Radio Astronomy

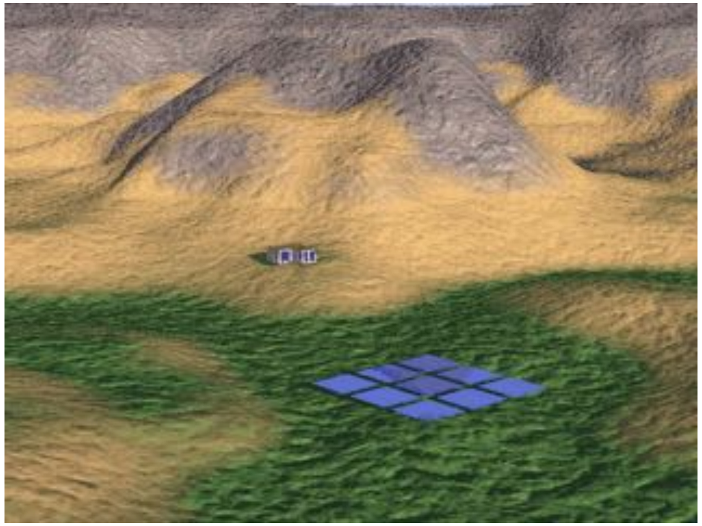
- *Go digital!* Ability to sample, digitze & process wide bandwidths
- Use of commodity computing power (incl. GPUs) and FPGAs
- Ways of obtaining "cheap" collecting area
- Replacing hardware (i.e. metal) with electronic and software
- Build "radio cameras" to increase "field-of-view" on sky and even
- allow to look in (sometimes) vastly different directions:



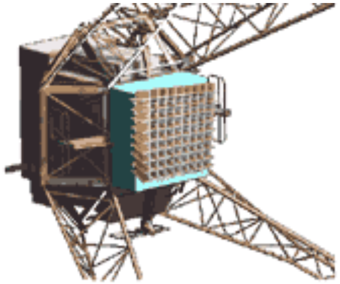
Aperture Arrays & Focal Plane Arrays

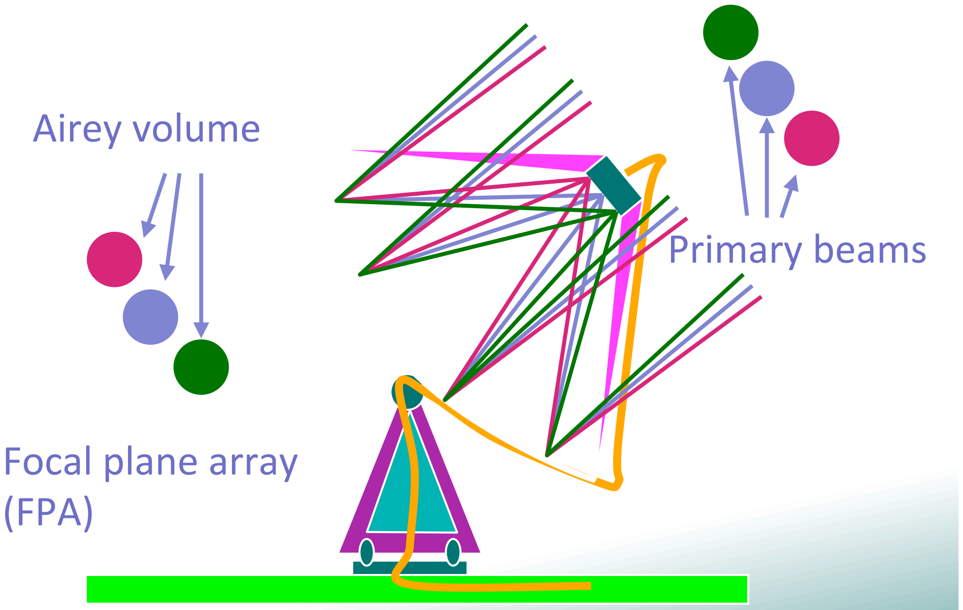
= phased array on ground





= phased array in focus of dish





Field-of-View

Airey volume

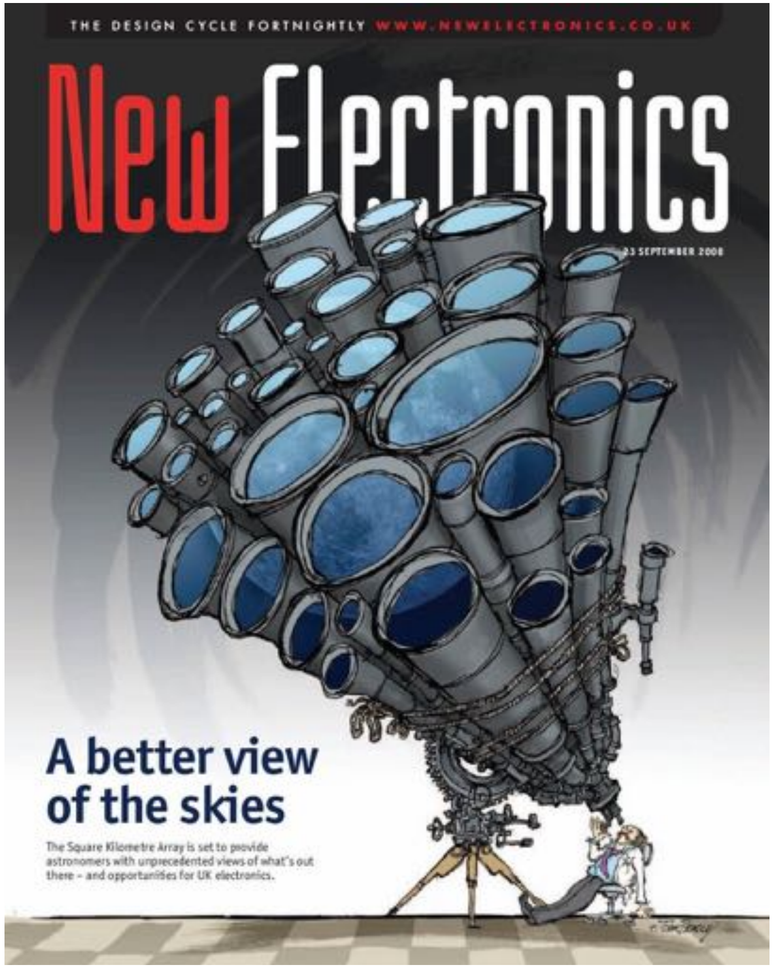
Primary beams

Focal plane array (FPA)

NEW: HUGE Field-of-View and multiple beams within FoV!

Aperture Arrays & Focal Plane Arrays

= phased array on ground



THE DESIGN CYCLE FORTNIGHTLY WWW.NEWELECTRONICS.CO.UK

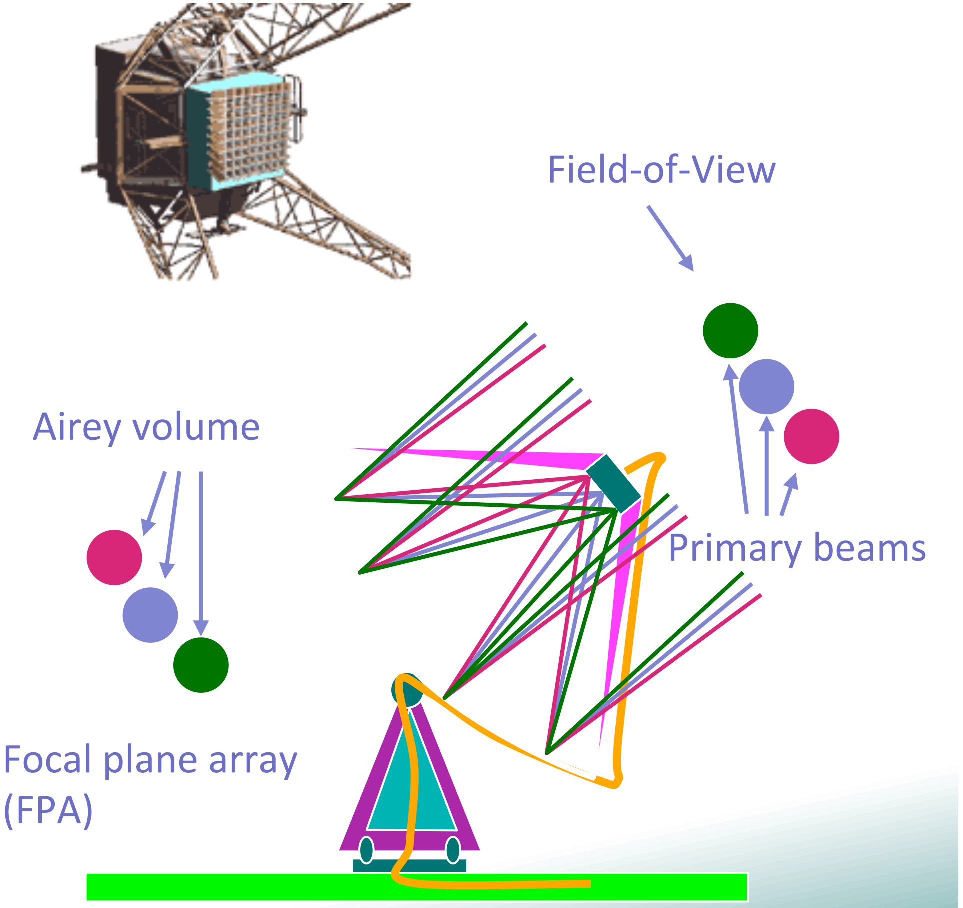
New Electronics

23 SEPTEMBER 2008

A better view of the skies

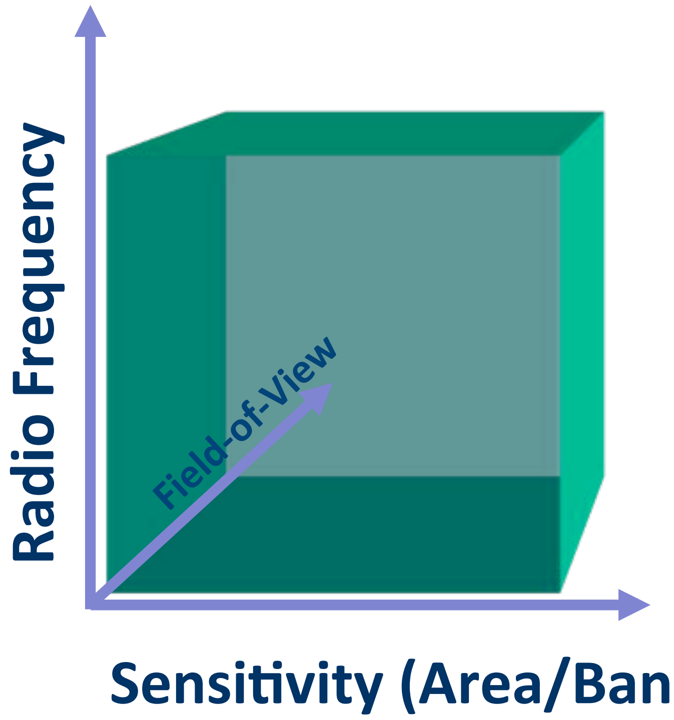
The Square Kilometre Array is set to provide astronomers with unprecedented views of what's out there – and opportunities for UK electronics.

= phased array in focus of dish



NEW: HUGE Field-of-View and multiple beams within FoV!

New technology: Huge increase in phase space



- Sampling large bandwidths (20-50%)
- Providing huge FoVs (>30 sq-deg)

  hence huge survey speed
- Large frequency range, e.g. opening
- low-frequency sky
- Brute-force increases in

  collecting area
- Digital signal processing
- Huge computing power…

➔ New science and new discoveries!

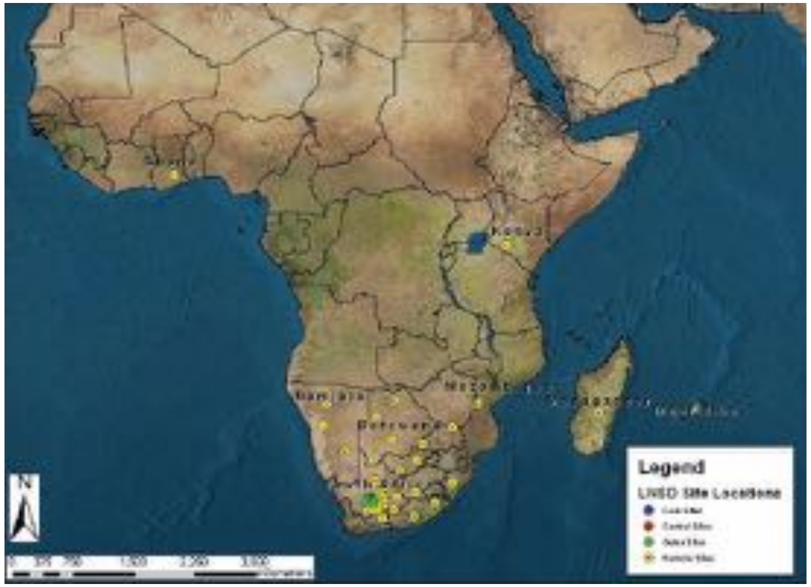
HPC as integral part of telescope – and beyond

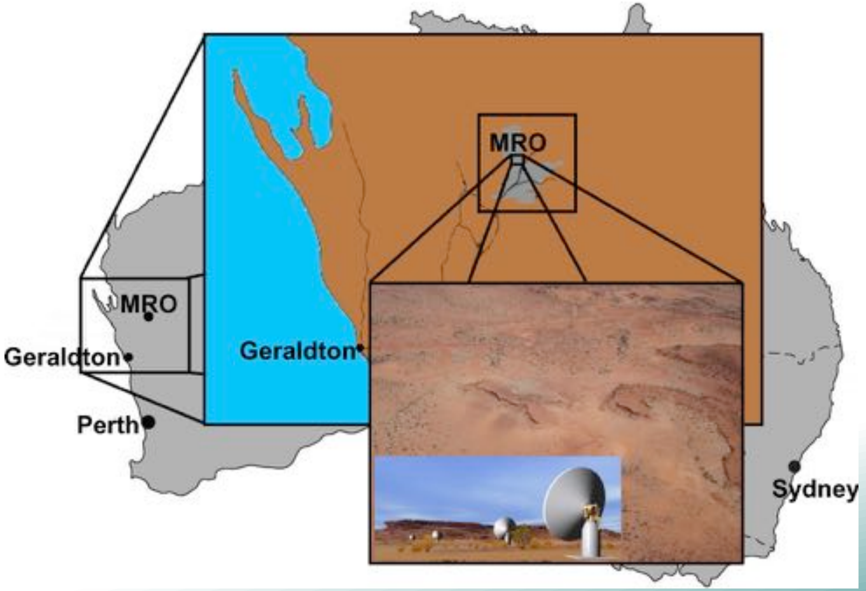
- Severe requirements for operation and long-term storage:
  - Raw data rate ~1 PB/s – many times the global internet traffic today!
  - After on-line processing, still need to archive about 3 EB/year
- SKA as a „leading edge“ HPC application
  - 200 Pflops (2019)
  - ca. 2.5 Eflops (2024)
- Central Signal Processing (CSP) and Science Data Processing (SDP)

# 2013 estimate by SKA South Africa	MeerKAT Pre-Cursor 2014-15	SKA Phase 1 2017-19	SKA Phase 2 Est. 2020-24
Data into CSP	2 Tbps	50 Tbps	up to 5 Pbps
Data into SDP	0.4 Tbps	20 Tbps	up to 500 Tbps
Into Storage	35 Gbps	300+ Gbps	up to 2 Tbps
Computing load	200 TFlops	30+ PFlops	3+ EFlops

Siting

- Southern hemisphere (for astronomical reasons)
- Far away from population centres and harmful radio interference
- Rigorous site decision process over many years – decided in April 2012
- Southern Africa and Western Australia

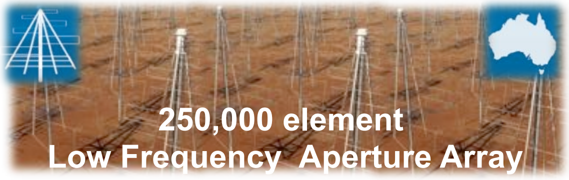




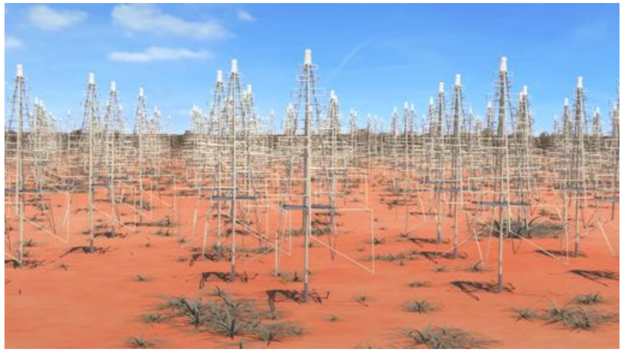
The SKA: Two sites, one telescope

Phase I = 10% SKA

Phase I : 2023



€650M capital cost (capped) + 10-12% operation costs

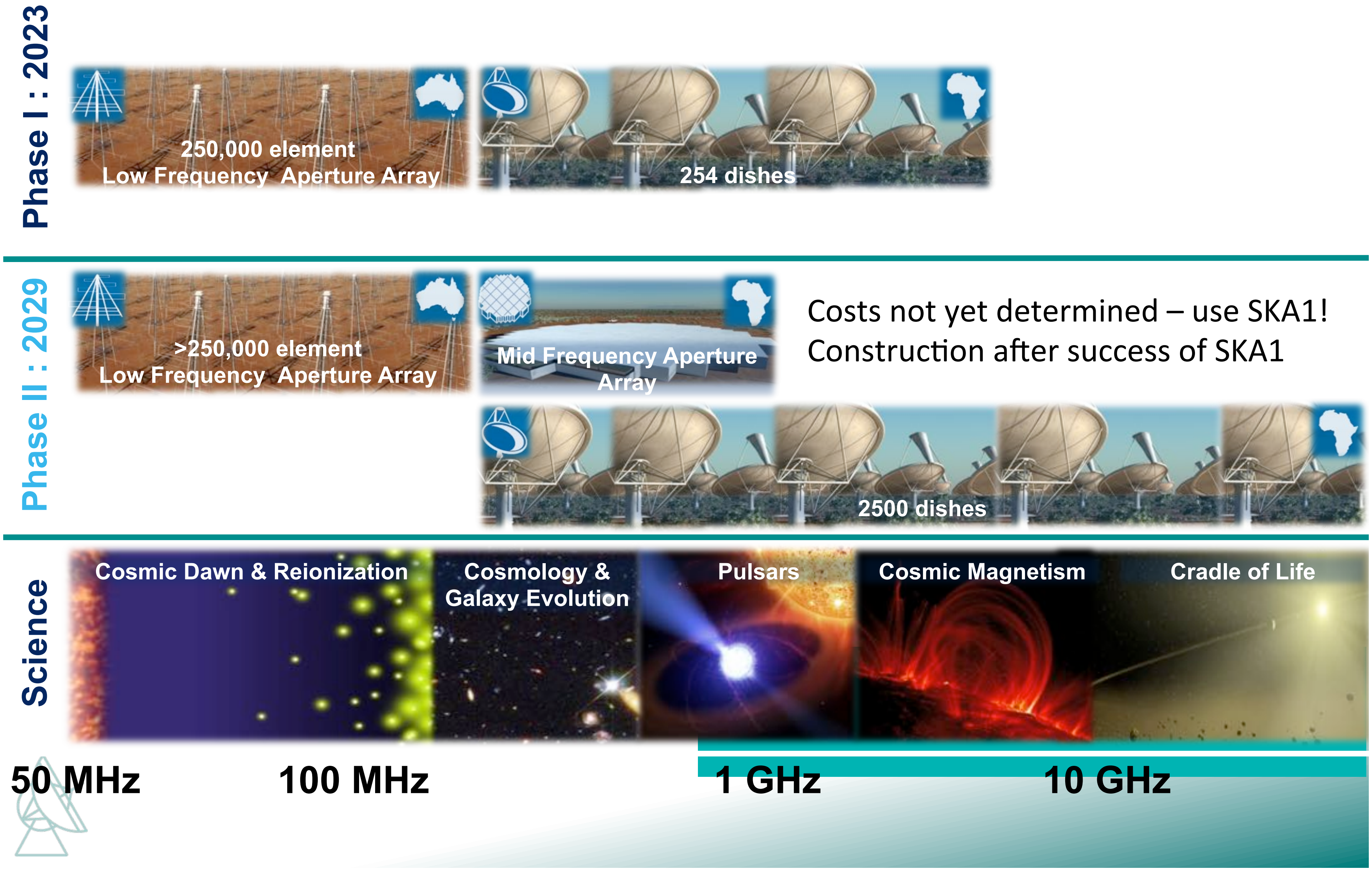


Two sites: SA+AUS
Two antennae types
Freq. 50 MHz – 3 GHz
Construction: 2013-2023
Early science: 2020

•Scienc

•50 MHz 100 MHz 1 GHz 10 GHz

Phased construction



Phase I : 2023

250,000 element
Low Frequency Aperture Array

254 dishes

Phase II : 2029

>250,000 element
Low Frequency Aperture Array

Mid Frequency Aperture Array

Costs not yet determined – use SKA1!
Construction after success of SKA1

2500 dishes

Science

Cosmic Dawn & Reionization

Cosmology & Galaxy Evolution

Pulsars

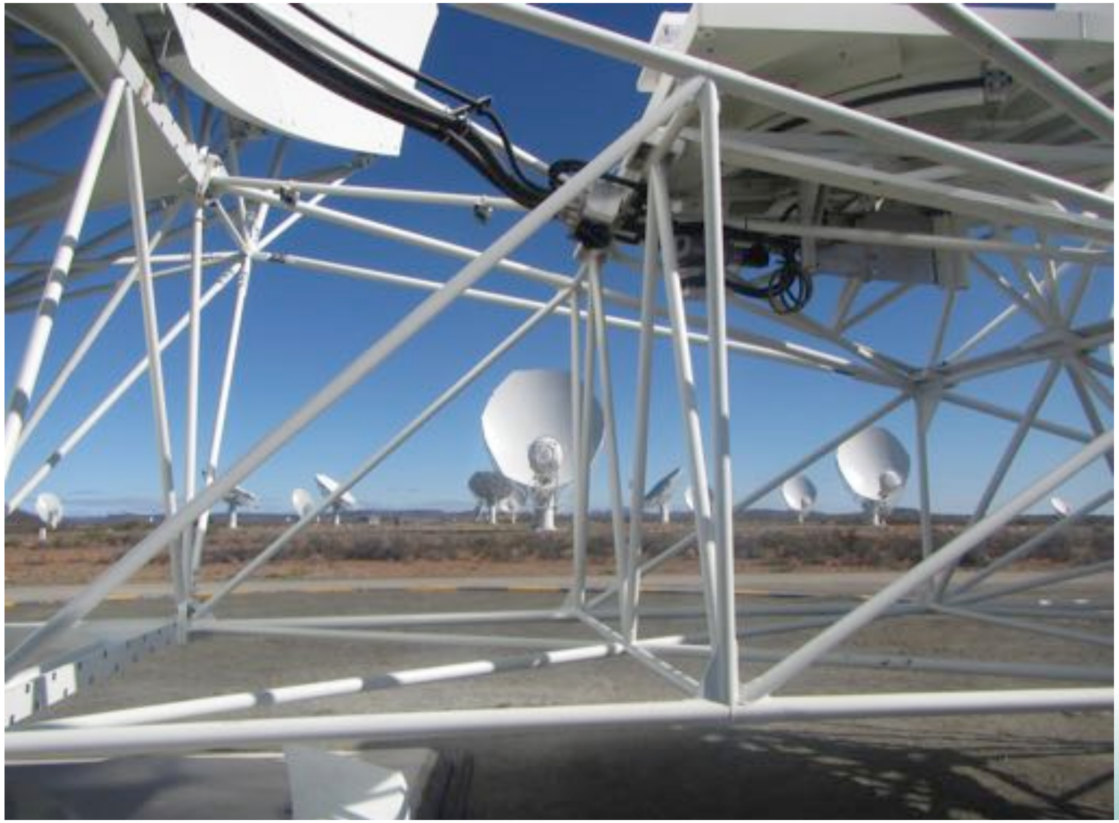
Cosmic Magnetism

Cradle of Life

MeerKAT – first step towards SKA

It will find pulsars – and will time all Southern ones with unprecedented sensitivity

- MeerKAT – first light based on 16 dishes – completed in 2017
  - Increases sensitivity in Southern hemisphere by factor ~5
  - More sensitive than Effelsberg or GBT and similar to VLA
  - MeerTime (PI Bailes, TRAPUM (PIs Stappers/Kramer)



First light of initial 16-telescope array:

Astronomy

South African super-telescope reveals distant galaxies and black holes

At only a quarter of its eventual capacity, the MeerKat radio telescope captures 1,300 galaxies in tiny corner of universe where only 70 were known before

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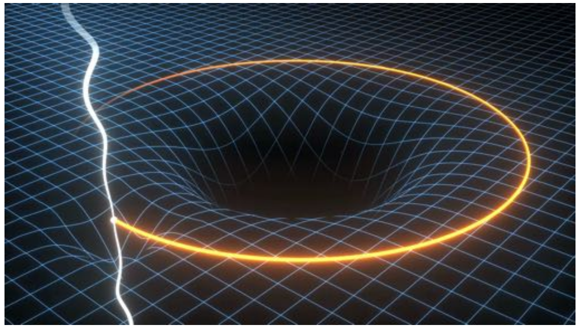
The ultimate system: PSR-BH

- We'd like 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!



- BH properties from 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, we practically need the SKA:

BH mass with precision < 0.1%

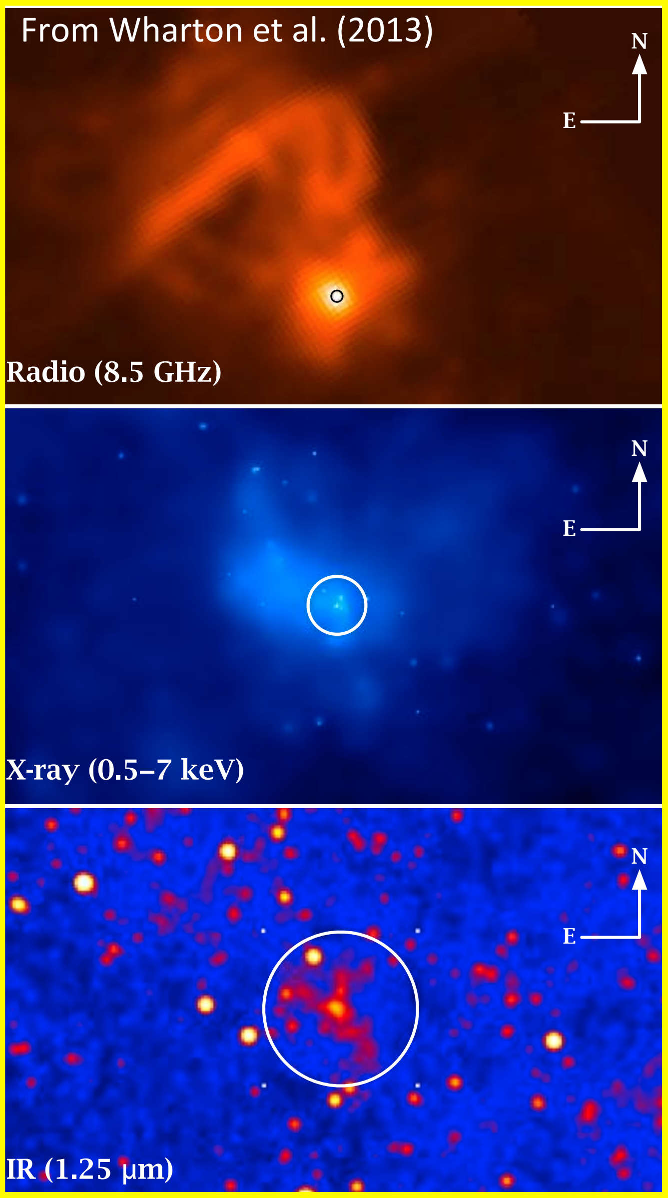
BH spin with precision < 1%

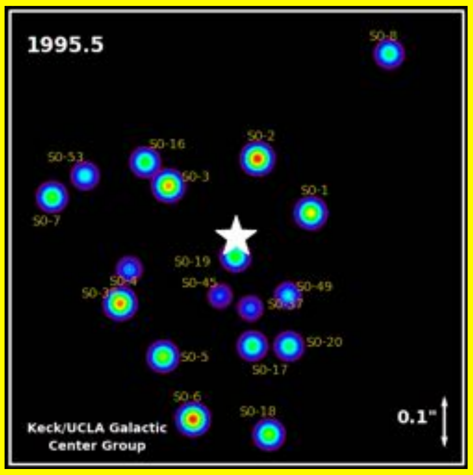
Cosmic Censorship: $S < GM^2/c$

Where or how do we find one?

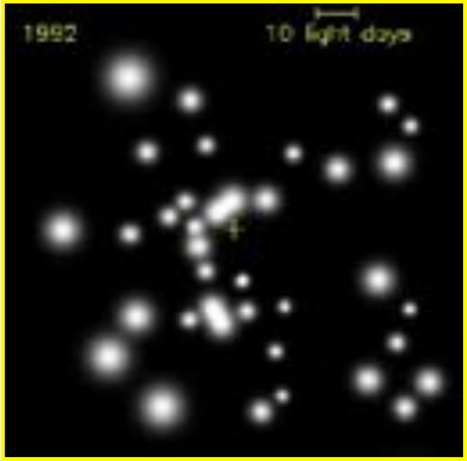
- Find "all" pulsars with the SKA
- or look where you know a black hole to be...

A well-known super-massive Black Hole


From Wharton et al. (2013)



UCLA



MPE/Cologne

From astrometry of orbiting stars::

[Gillesen et al. 2008]

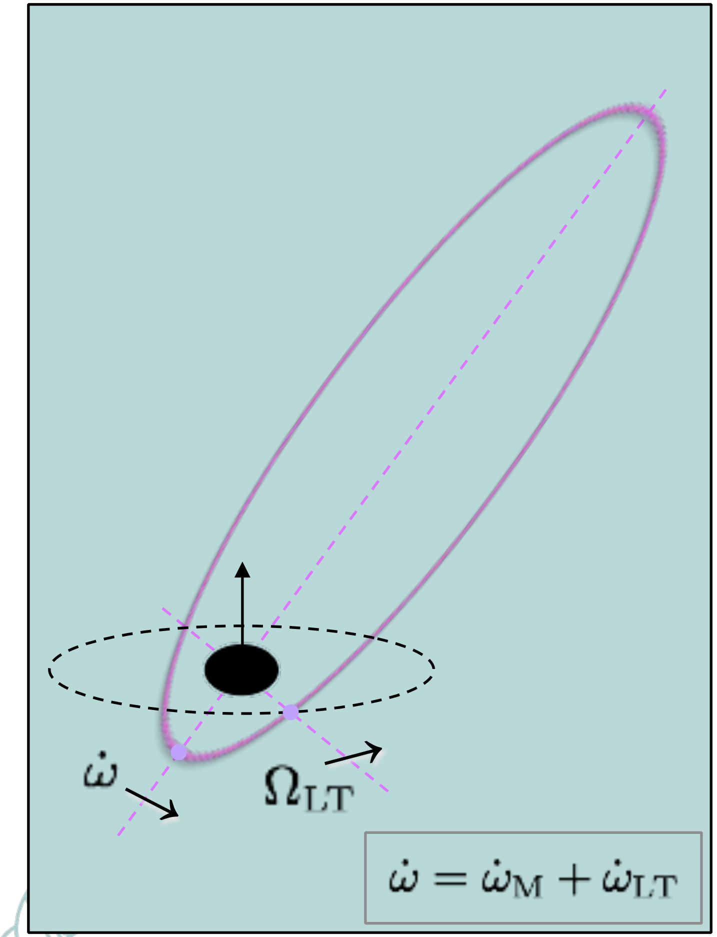
Mass: $\boxed{(4.3 \pm 0.2_{(\mathrm{stat})} \pm 0.3_{(\mathrm{sys})}) \times 10^6\, M_\odot}$

Spin: $\chi = 0.2 \ldots 0.99$

[Genzel et al. 2003, 2008;
Aschenbach et al. 2004;
Belanger et al. 2006;
Aschenbach 2010]

Relativistic effects for a pulsar orbit around Sgr A*

Pulsar in a 0.3 yr eccentric (e=0.5) orbit around Sgr A*



Semi-major axis:	72 AU = 860 R_S
Pericenter distance:	36 AU = 430 R_S
Pericenter velocity:	0.042 c (~ 20 × Double Pulsar)

Pericenter advance:

1pN:	2.8 deg/yr,	ΔL ~ 1.8 AU/yr
2pN:	0.014 deg/yr,	ΔL ~ 1,400,000 km/yr

Einstein delay:

1pN:	15 min
2pN:	1.6 s

Propagation delay (i = 0° / i = 80°):

Shapiro 1pN:	46.4 s /	246.9 s
Shapiro 2pN:	0.2 s /	8.0 s
Frame dragging:	0.1 s /	6.5 s
Bending delay (P = 1s):	0.2 ms /	4.2 ms

Lense-Thirring precession:

Orbital plane Ω_{LT} : 0.052 deg/yr, ΔL ~ 10^7 km/yr

Similar contribution to $\dot{\omega}$

Geod. precession 1.4 deg/yr

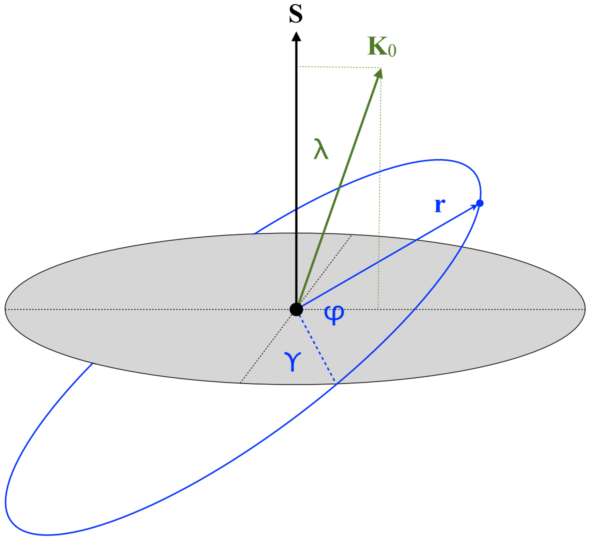
Full 3D-direction of BH spin from pulsar orbit

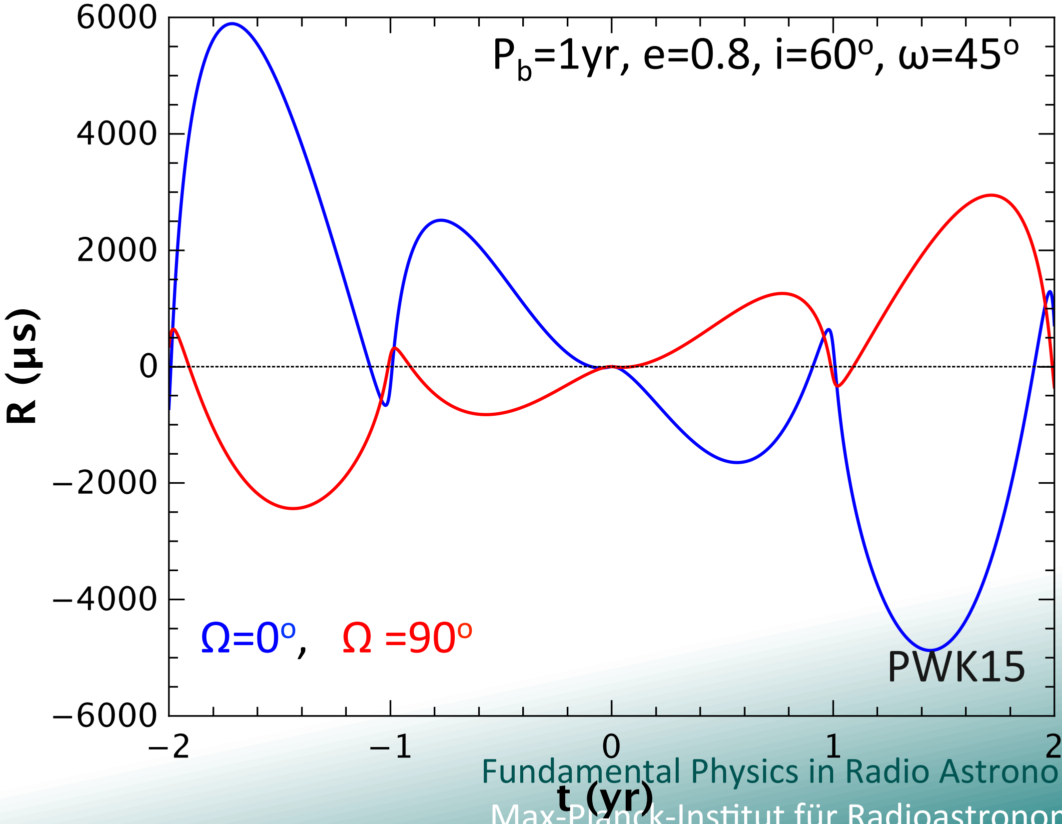
- We can measure the mass of Sgr A* to precision of ~ $1M_\odot$

- Orbital variation of pulsar orbit due to Lense-Thirring gives 2-D projection (Liu et al. 2012)

- Relative motion of pulsar orbit/SGR A* to SSB gives 3rd direction (Psaltis, Wex & MK '15)

➔ Full 3-D orientation plus magnitude to about ~0.1%.





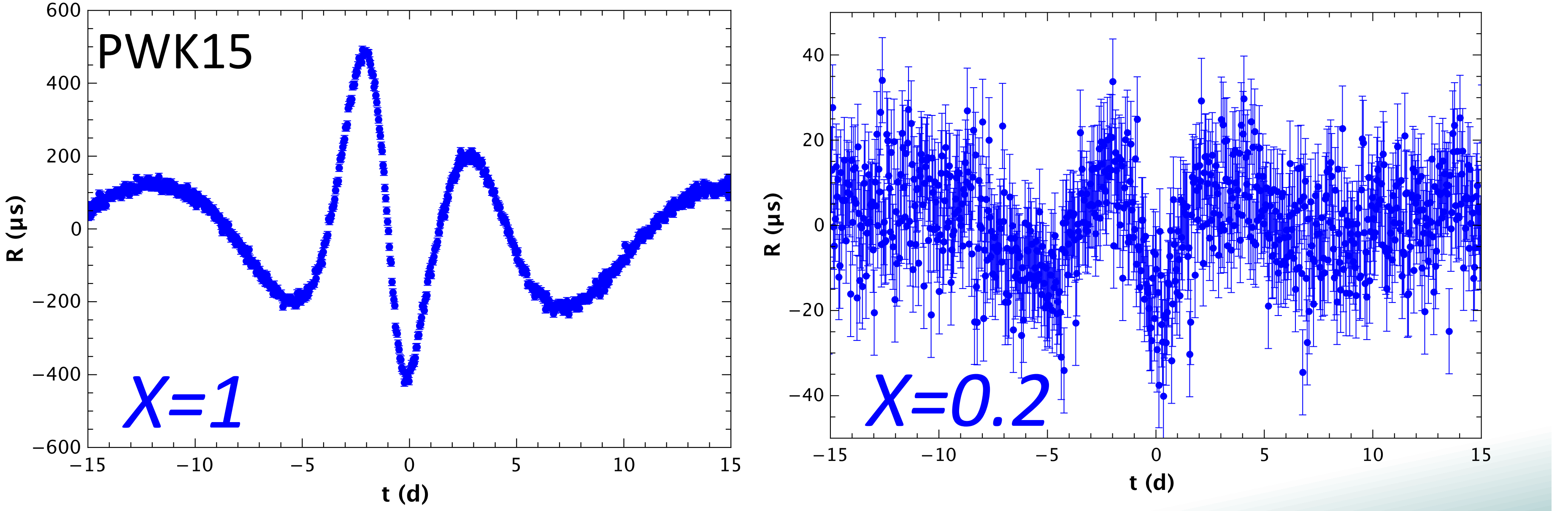
Testing the no-hair theorem

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, but it is not separable from frame-dragging

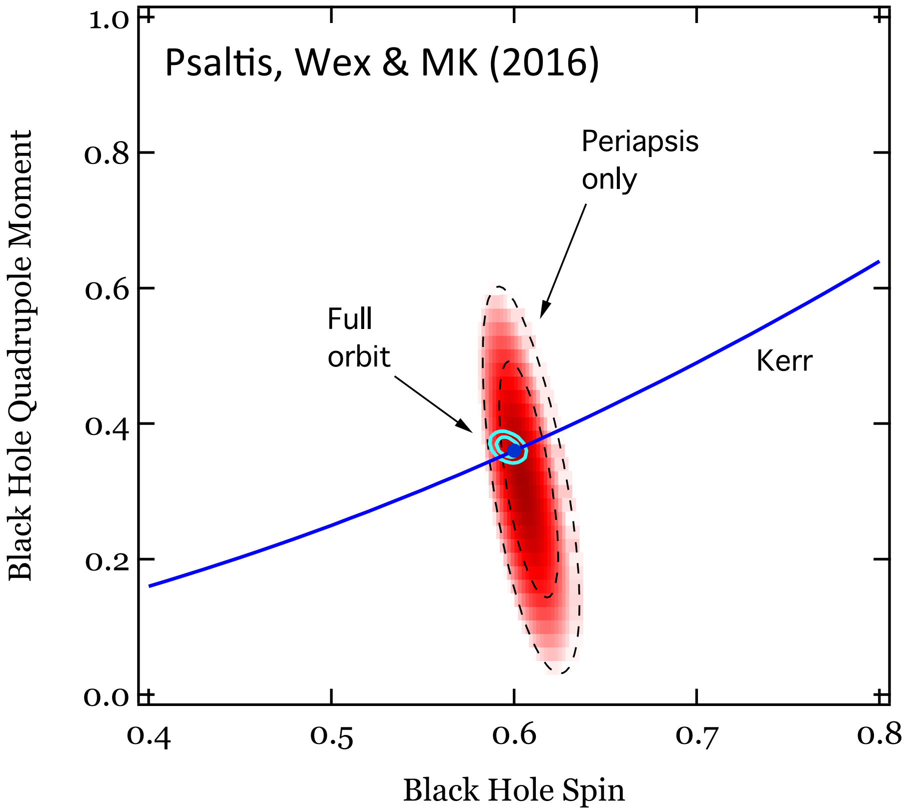
- Fortunately, quadrupole leads to *characteristic periodic residuals* ➔ Q to about 1%



A single (even normal) pulsar is sufficient!

Partial visibility & External perturbations

- Even in case of stellar perturbations – which will act away from periapsis – we can use partial orbit observations!



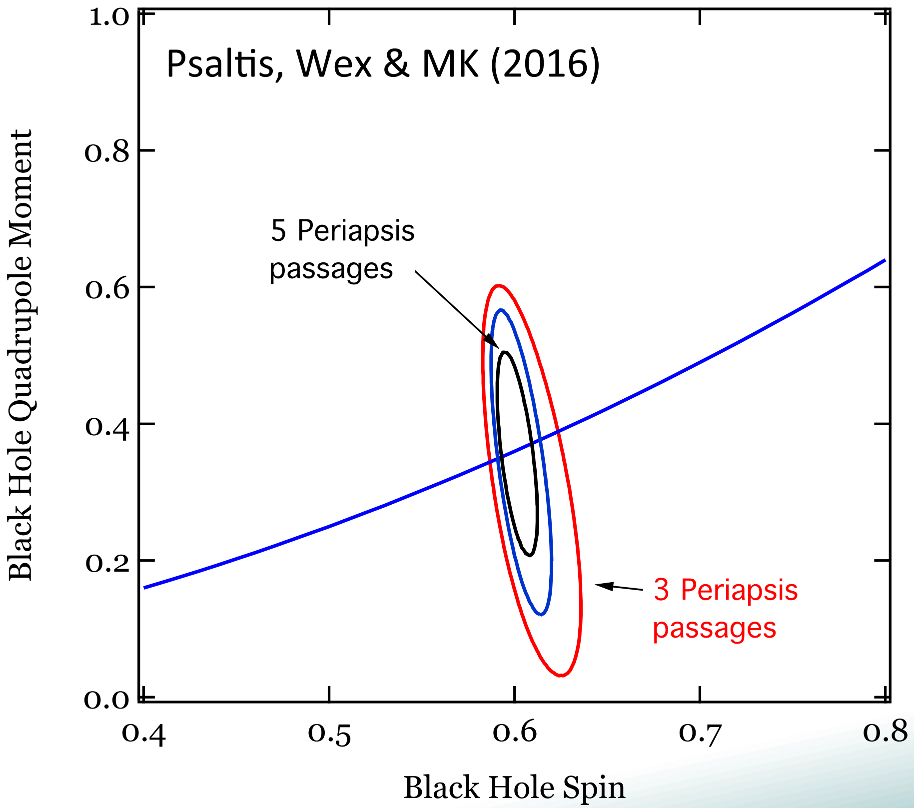
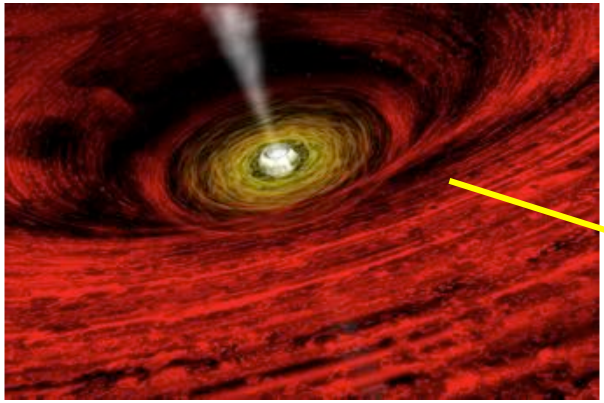


Image of the shadow of the event horizon



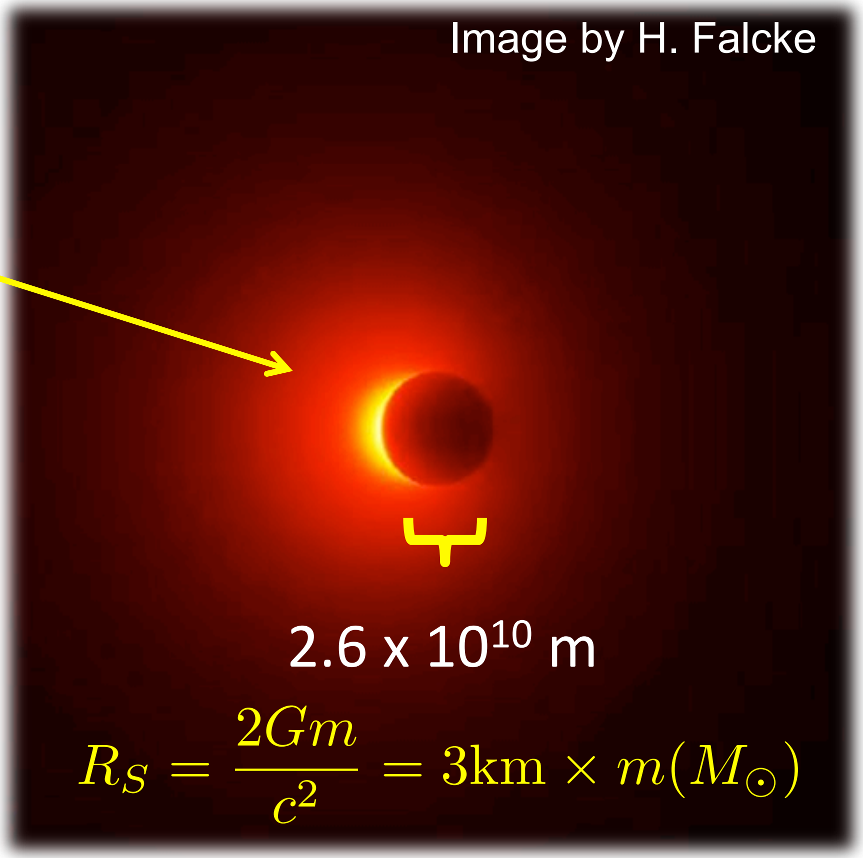


Image by H. Falcke

$$\underbrace{\hphantom{xx}}$$

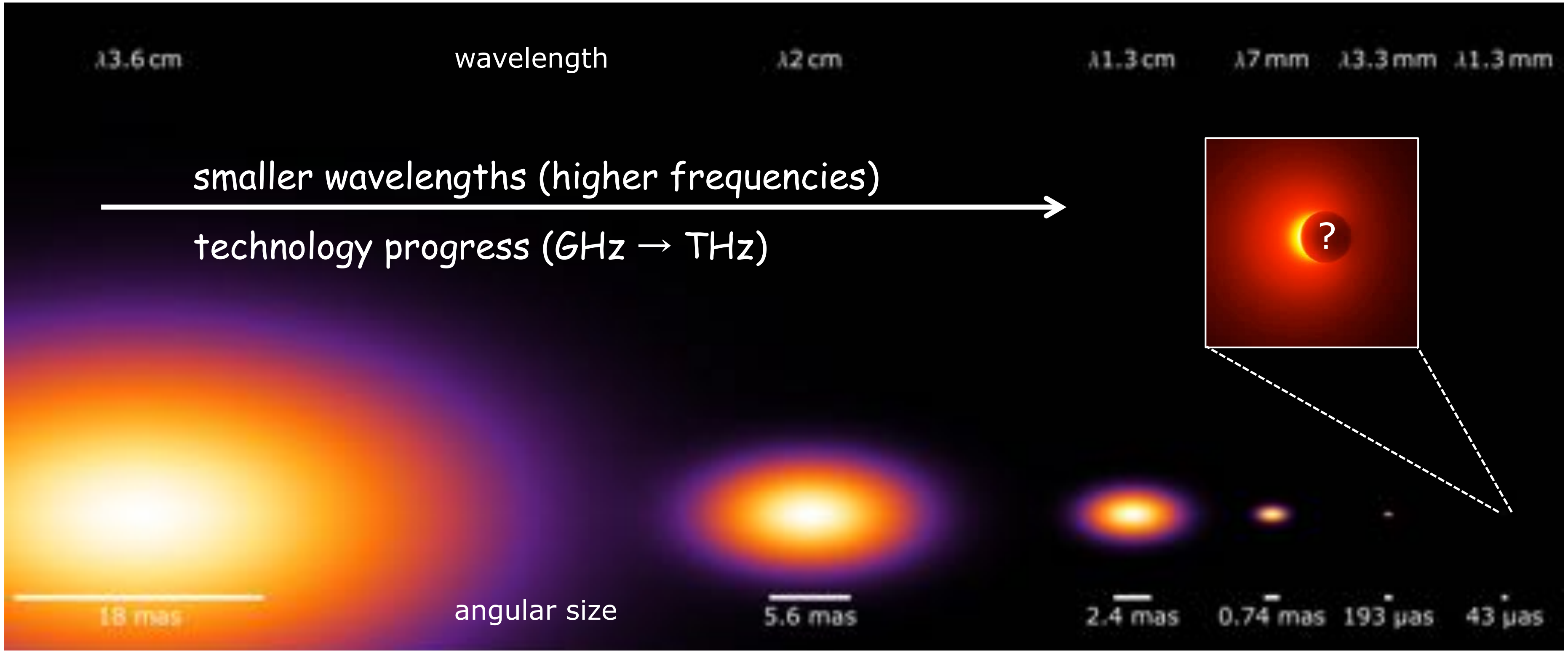
2.6×10^{10} m

$$R_S = \frac{2Gm}{c^2} = 3\mathrm{km} \times m(M_\odot)$$

Blocked in the optical – but visible at radio frequencies!

See Falcke et al. (2000) for the initial idea how,we could see the „shadow“

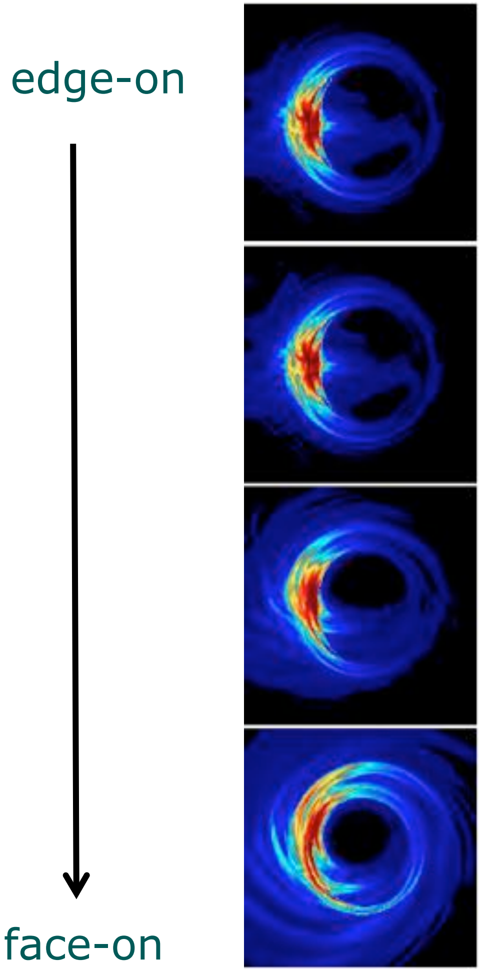
Image of the shadow of the event horizon



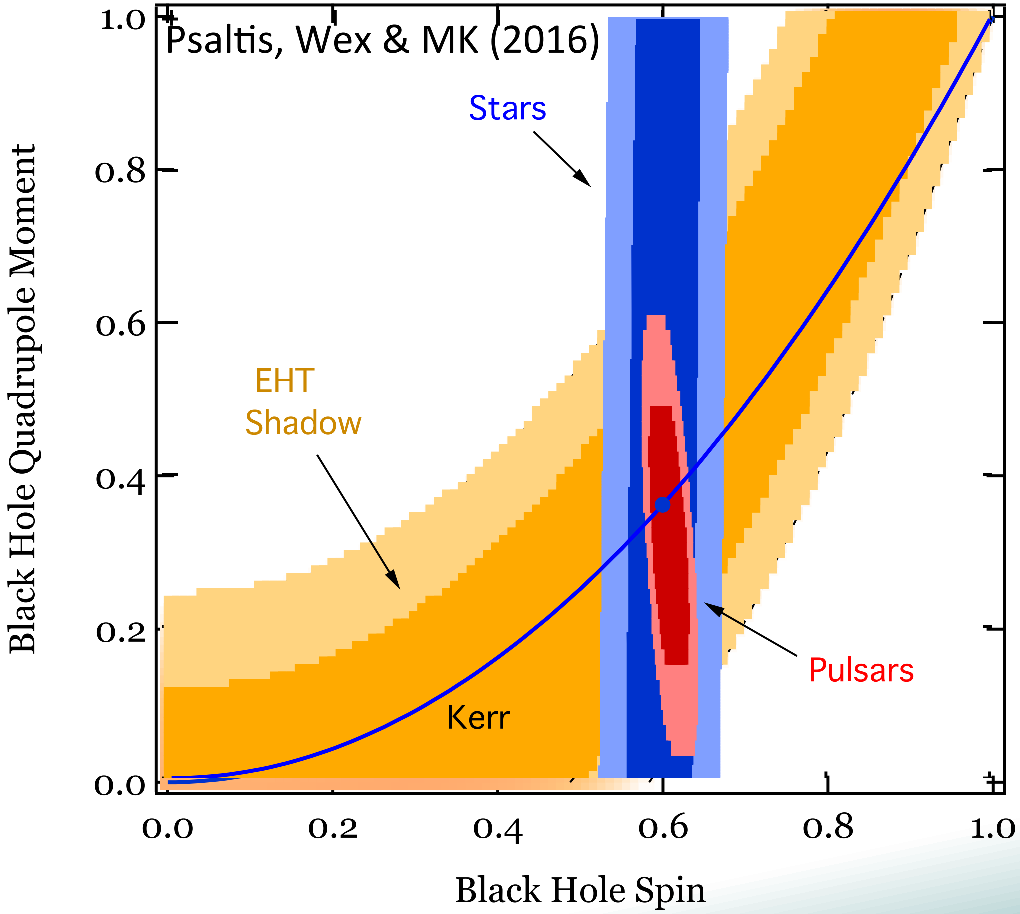
- the shorter the wavelength, the smaller the radio source (scattering!)
- at λ=1.3 mm the radio source becomes the size of the event horizon:
- the event horizon shadow should be 50 µas in diameter
- global mm-wave VLBI (EHT) with ALMA has the resolution to study it
- see Dimitiris talk!

Combining pulsars with other methods

From Event Horizon Telescope/BlackHoleCam imaging observations:

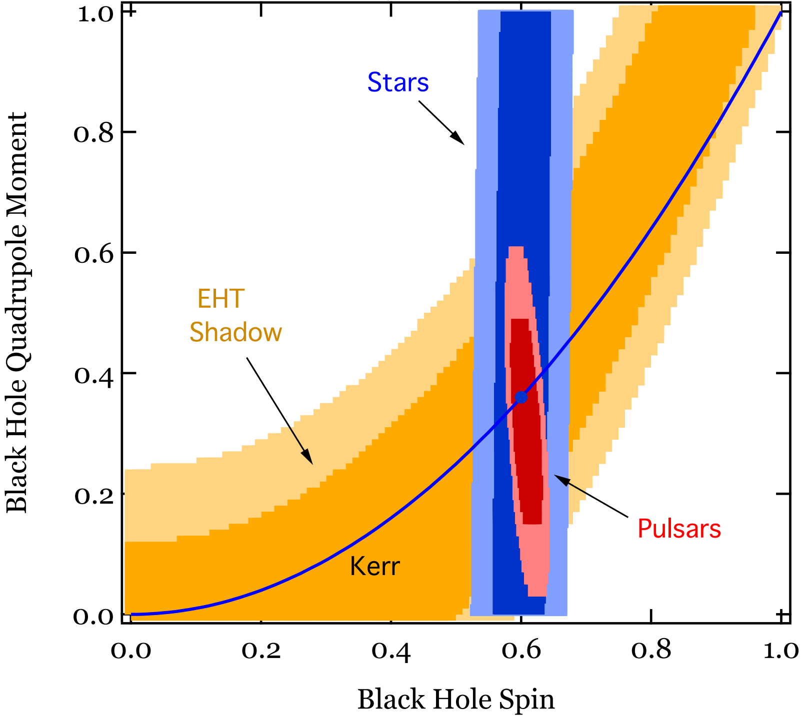


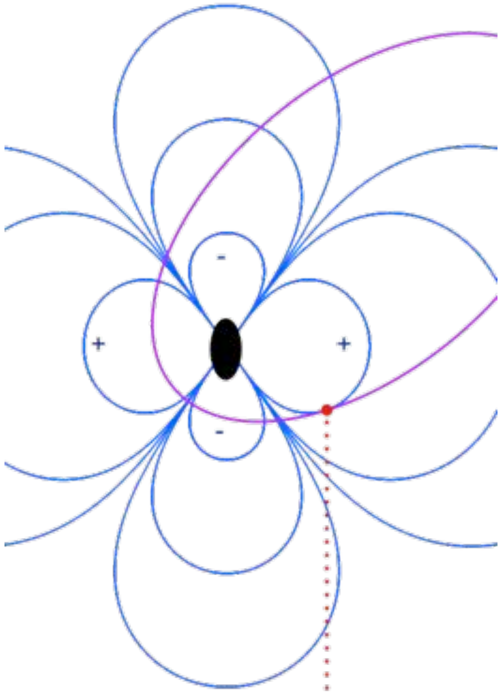
Moscibrodzka et al. (2014)



BHC funded by ERC Synergy Grant:
PIs Falcke, Kramer, Rezzolla

Combining image and pulsars


Psaltis, Wex & MK (2016)



- Space time is probed at different distances (far-field & near-field)
- Impact of possible dark matter near BH will be seen.
- Different systematic uncertainties (and degeneracies):
  - Stars + pulsar orbit precession give spin
  - Pulsar timing gives quadrupole moment
  - EHT shadow may reveal deviation from Kerr value

Combination will lead to uncorrelated measurement of spin and quadrupole moment

Summary

- Unfortunately, Einstein did not live to see discovery of pulsars – and their usage
- Pulsars probe gravity for strongly self-gravitating bodies providing unique tests
- Measurements are usually clean and precise – confirming GR so far
- Tight constraints on alternative theories which need to pass binary pulsar tests
- We have seen new never-seen-before relativistic effects in the Double Pulsar
- New "most-relativistic" binary pulsar discovered – stay tuned
- Beautiful new results for relativistic spin-precession – stay tuned
- Direct detection of gravitational waves maybe soon – also using pulsars
- Ultimately, we will probe BH properties (plus image!) for extreme tests of GR
- Future telescopes - especially the MeerKAT & SKA - will allow so much more!