The SKA and Pulsar Timing Arrays

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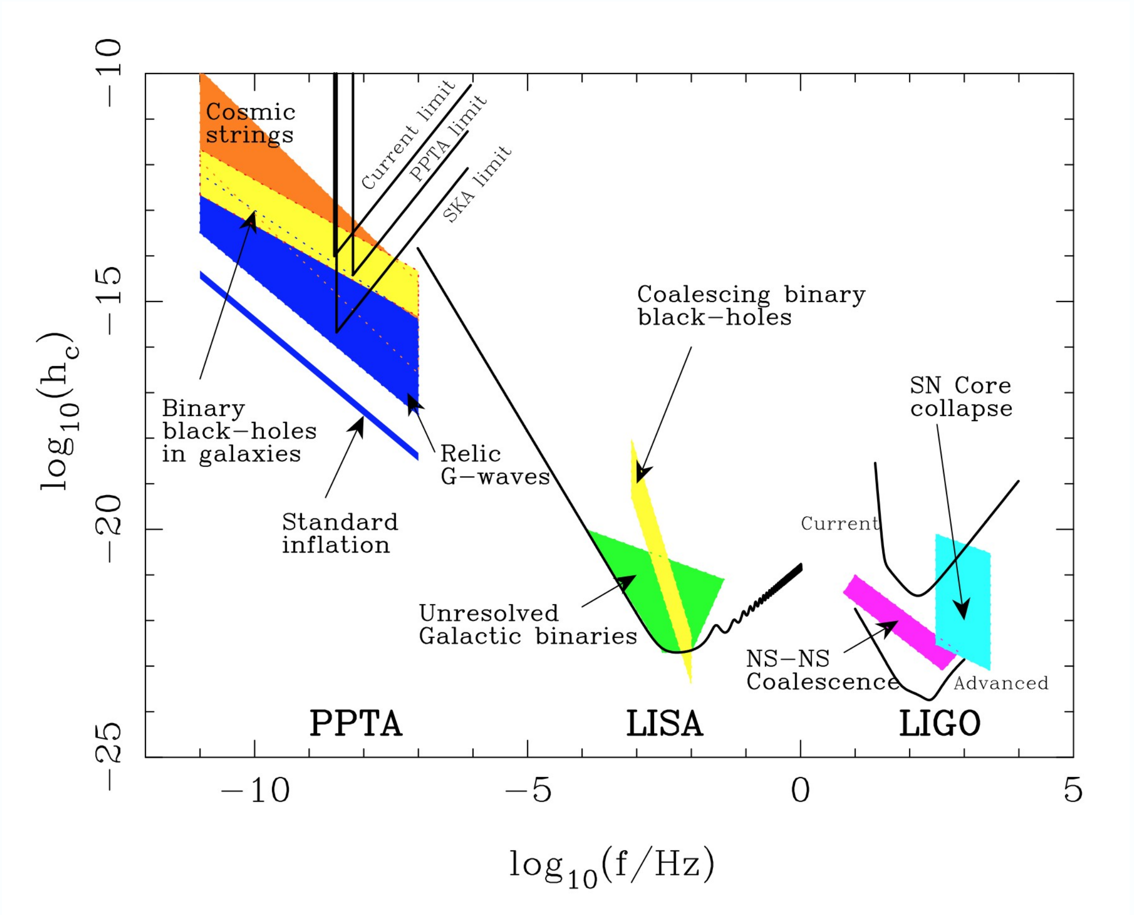
ASTRONOMY AND SPACE SCIENCE
www.csiro.au

Main goal of the pulsar timing arrays

1. To detect gravitational waves
2. Status so far: none detected



Let's go back to 2007: conference on pulsars and the SKA

o Session I - 4 April 2007

10:00 - 10:30: The SKA project - Overview

Michael Kramer: Key Science/Work since Sydney/Report von the SWG (20)

Open Discussion (10)

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o Session II - 4 April 2007

11:00 - 12:00: Future telescopes and SKA pathfinders - I.

Joeri van Leeuwen: ATA (20)
Scott Ransom: EVLA (20)
Nina Wang: FAST and Miyun (20)

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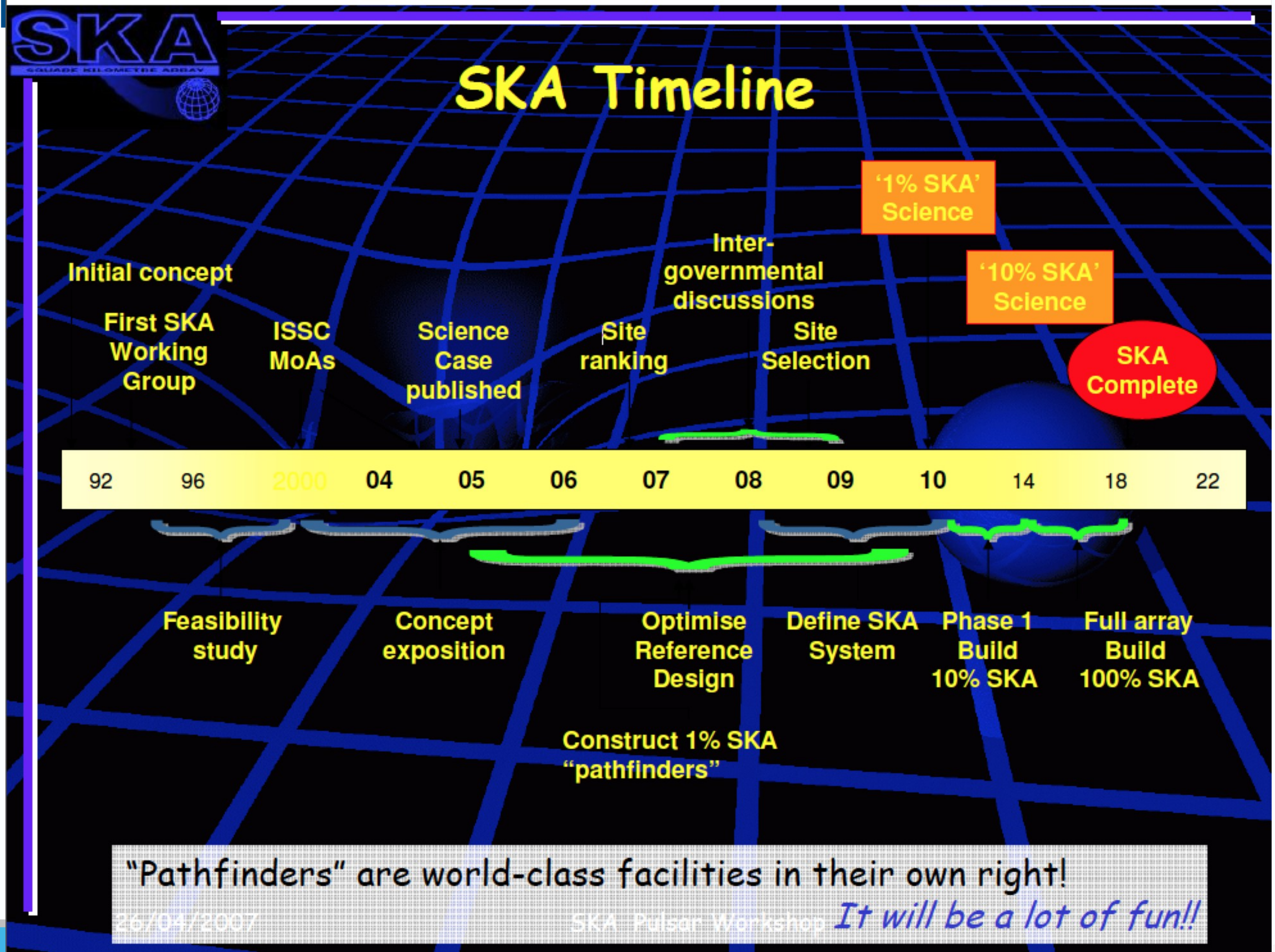
o Session III - 4 April 2007

13:30 - 15:10: Future telescopes and SKA pathfinders - II.

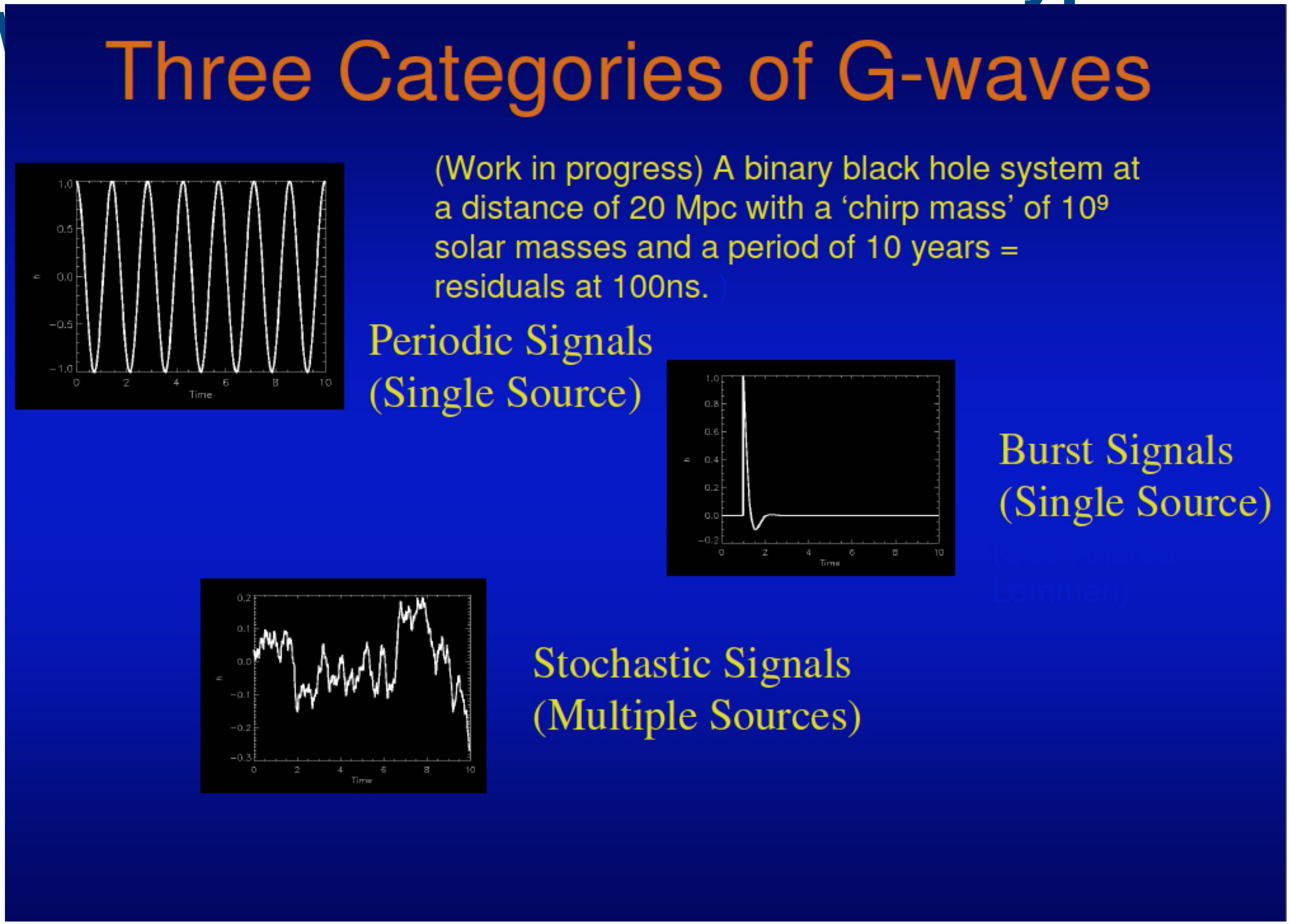
Ben Stappers: LOFAR (20)
Adrian Tiplady: KAT and MeerKat (20)
Andy Faulkner: SKADS & Embrace (20)
Simon Johnston: MIRA and (20)
ATNF pathfinder workshop (10)

Open Discussion (10)

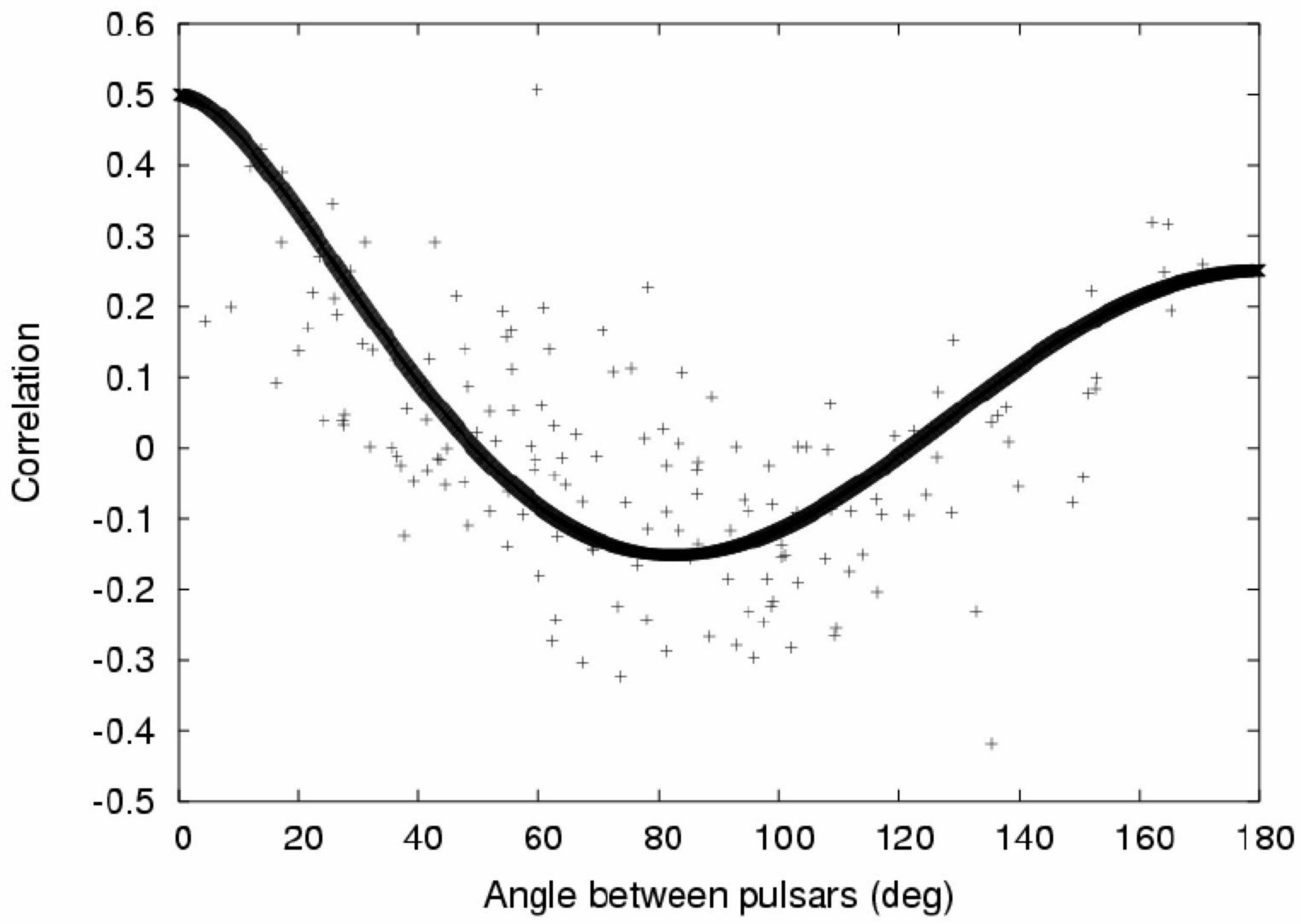
What we knew then: the full SKA would be built by 2018



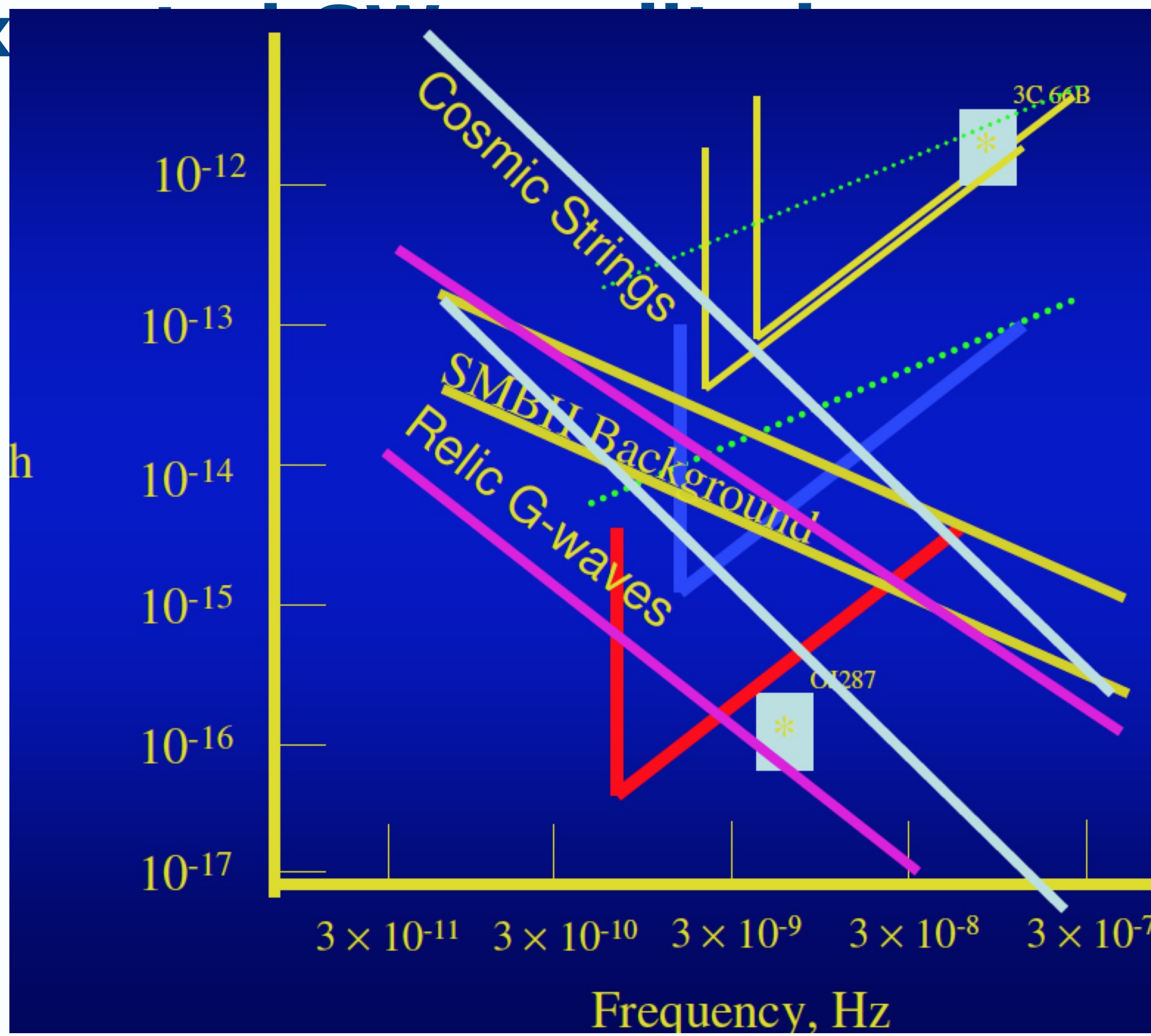
What we knew then: the three types of GW



What we knew then: how to detect GWs



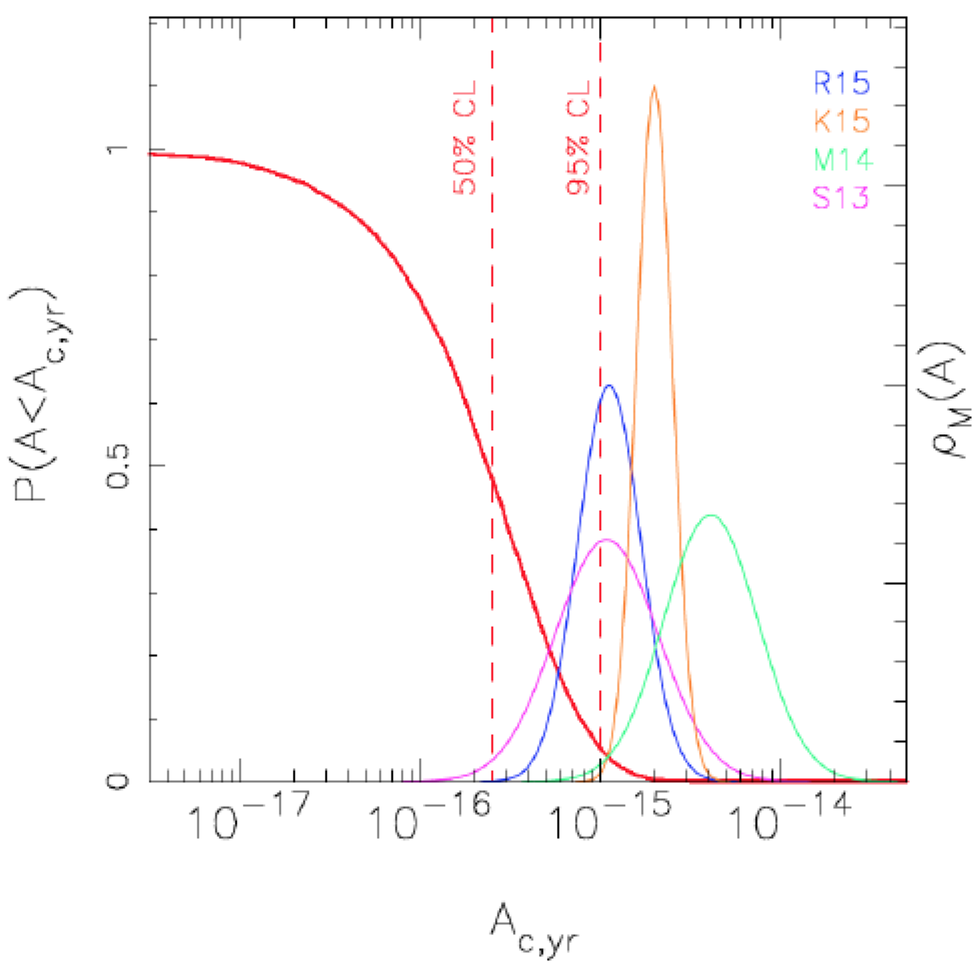
What we knew then: how not to make figures + ex



- A~10^{-15} -> 10^{-14}
- For A~10^{-15} need to time ~20 pulsars over 5 years with 100ns timing precision to get ~3 sigma detection
- Predict SKA will detect GWs or limit A < 6×10^{-17}

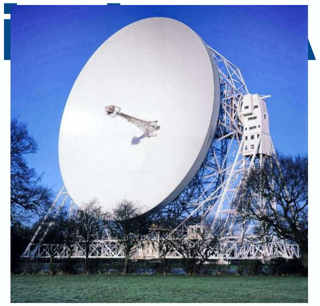
What has happened since? – GW background models converged around A ~ 10^{-15}

1. Quote from Dr(!) Vikram Ravi a year o so ago *"I'd be really surprised if the GW background amplitude was < ~2 x 10^{-15}"*.

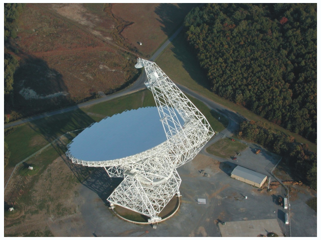


What has happened since? Formed the International Pulsar Timing Array

1. Parkes Pulsar Timing Array observes ~20 pulsars every 2-3 weeks
2. Parkes is relatively small (64m)
3. Join with NANOGrav (Arecibo, GreenBank) and EPTA (Jodrell, Westerbork, Effelsberg, Nancay, Sardinia) to form International Pulsar Timing Array (IPTA)
4. Now have long data sets on 50 pulsars



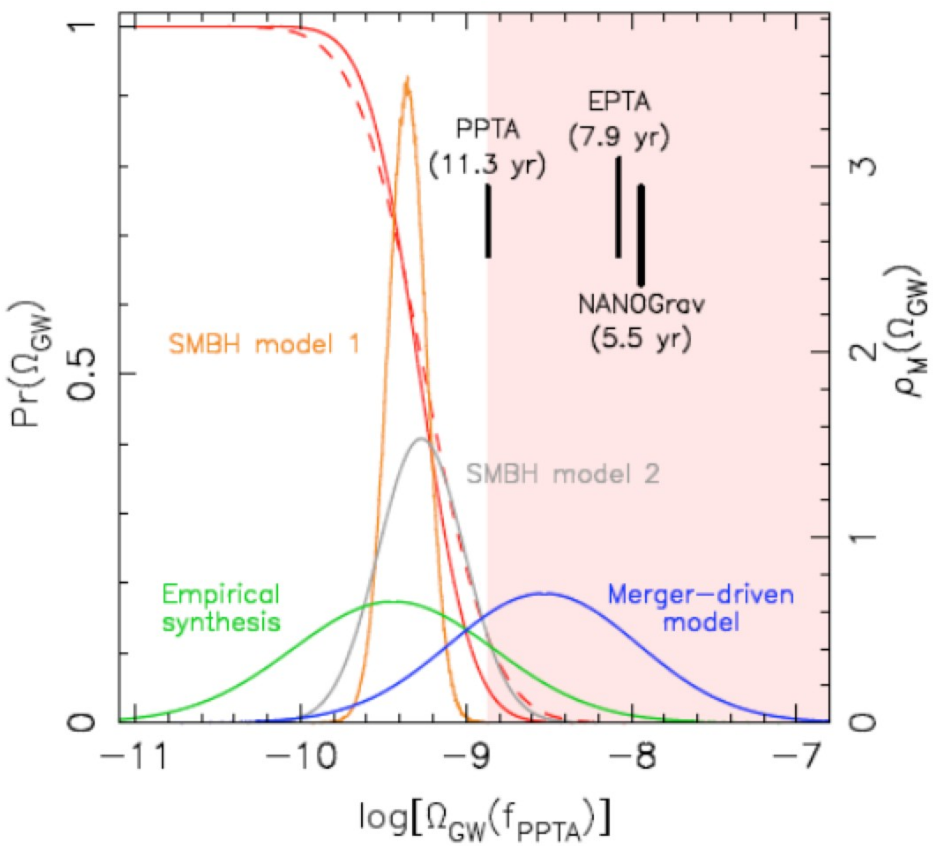






What has happened since? Improved our limits on the GW background

1. Shannon et al. (2013, Science)
2. A(95%) < 2.4×10^{-15}
3. (cf. original predictions of $10^{-15} < A < 10^{-14}$ … we could have already detected GWs)
4. Starting to rule out some models of GW backgrounds
5. Looking very promising for the IPTA and SKA



Expected time-scale (that we thought in 2013) …

1. Individual PTA (e.g., Parkes) makes a low sigma GW background detection (e.g., 2-3 sigma)
2. International Pulsar Timing Array makes a higher significance detection (i.e., around 5 sigma)
3. MeerKAT + early FAST + International timing array improves on the significance
4. SKA + FAST studies the background in detail and finds individual supermassive black holes, tests theories of gravity, ….

(basic idea: Parkes can time around 20 pulsars with timing precisions around 100ns->1us. SKA is much more sensitive => SKA can time around 100 pulsars with sub 100-ns precision)

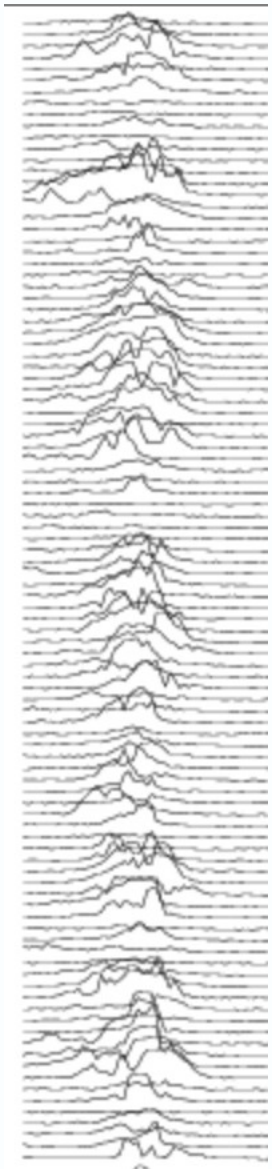
What should I do?

1. Be enthusiastic and optimistic? Say that the huge SKA collecting area will allow us to do amazing things. Time 100s of pulsars with 10ns precision. Detect backgrounds, single sources and bursts (as well as cosmic strings etc.) – see SKA chapter for such text!
2. State our current problems and issues

If 1) not be completely honest

If 2) may give the impression that we have serious problems (when we may not)!

The problem of having a great postdoc … Ryan Shannon’s paper 1: jitter



1. Pulse profiles are not stable => jitter
2. Jitter => cannot achieve ToA precision expected from the telescope sensitivity => SKA not as good as we thought it would be
3. Expected that we’d only need to observe for a few minutes with SKA to get sub-100ns timing precision => can observe a large number of pulsars
4. For a jitter dominated pulsar. Time to achieve 100ns ToA with Parkes ~1 hour

2014MNRAS.443.1463S 1.000 09/2014 A E F X R C U

Shannon, R. M.; Osłowski, S.; Dai, S.; Bailes, M.; Hobbs, G.; Manchester, R. N.; van Straten, W.; Raithel, C. A.; Ravi, V.; Toomey, L.; and 10 coauthors

Limitations in timing precision due to single-pulse shape variability in millisecond pulsars

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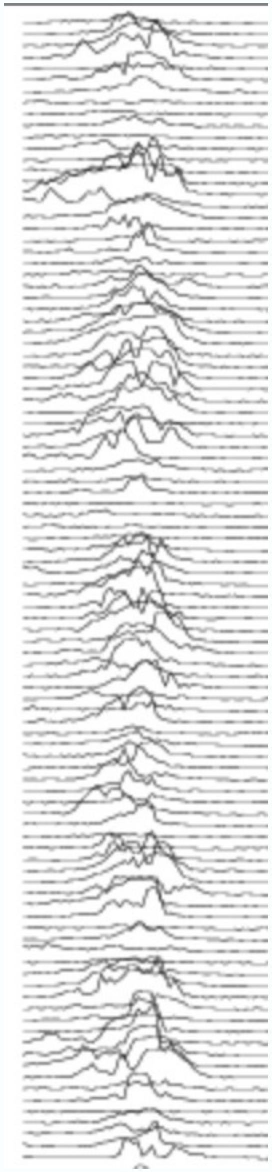
4. For a jitter dominated pulsar time for 100ns ToA with Parkes ~1 hour
5. Same pulsar with GBT ~1 hour
6. Same pulsar with SKA



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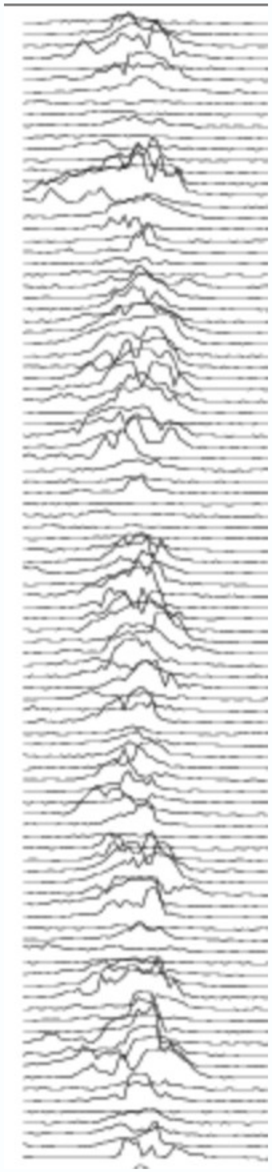

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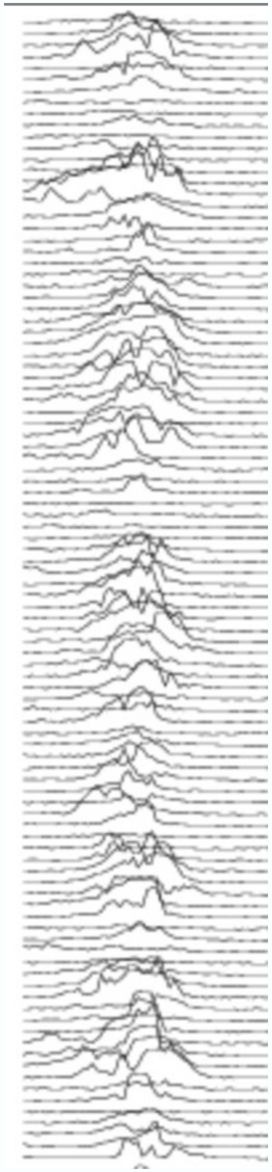
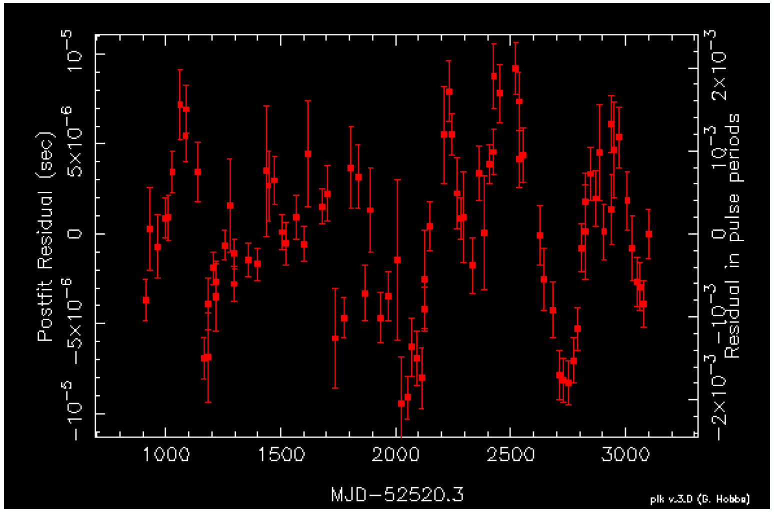
4. For a jitter dominated pulsar time for 100ns ToA with Parkes ~1 hour
5. Same pulsar with GBT ~1 hour
6. Same pulsar with SKA ~1 hour
7. For a jitter dominated pulsar, having a big telescope doesn’t help



The problem of having a great postdoc … Ryan's paper 2: DM correction



1. The dominant noise process in PTA data sets is usually caused by the ISM
2. Must use multi-frequency data to remove this noise before we can search for GWs.
3. PPTA uses dual-band 10/50cm receiver
4. Bill Coles "We can't even get adequate DM corrections for our best sources with the PPTA." -> building ultra-wide-band receivers.
5. Proposal for SKA is to use SKA-mid for timing and SKA-low for DM correction

The problem of having a great postdoc …
Ryan’s paper 2: DM correction

1. Proposal for SKA is to use SKA-mid for timing and SKA-low for DM correction
2. Recent paper (Cordes, Shannon, Stinebring) predicts that it will be challenging to make this work for most pulsars
3. Caused by the DM being slightly different along different propagation paths (spread of paths varies greatly with frequency)
4. Can lead to uncorrectable residuals of microseconds (much larger than the expected GWs)

FREQUENCY-DEPENDENT DISPERSION MEASURES AND IMPLICATIONS FOR PULSAR TIMING

J. M. CORDES[1], R. M. SHANNON[2], D. R. STINEBRING[3]

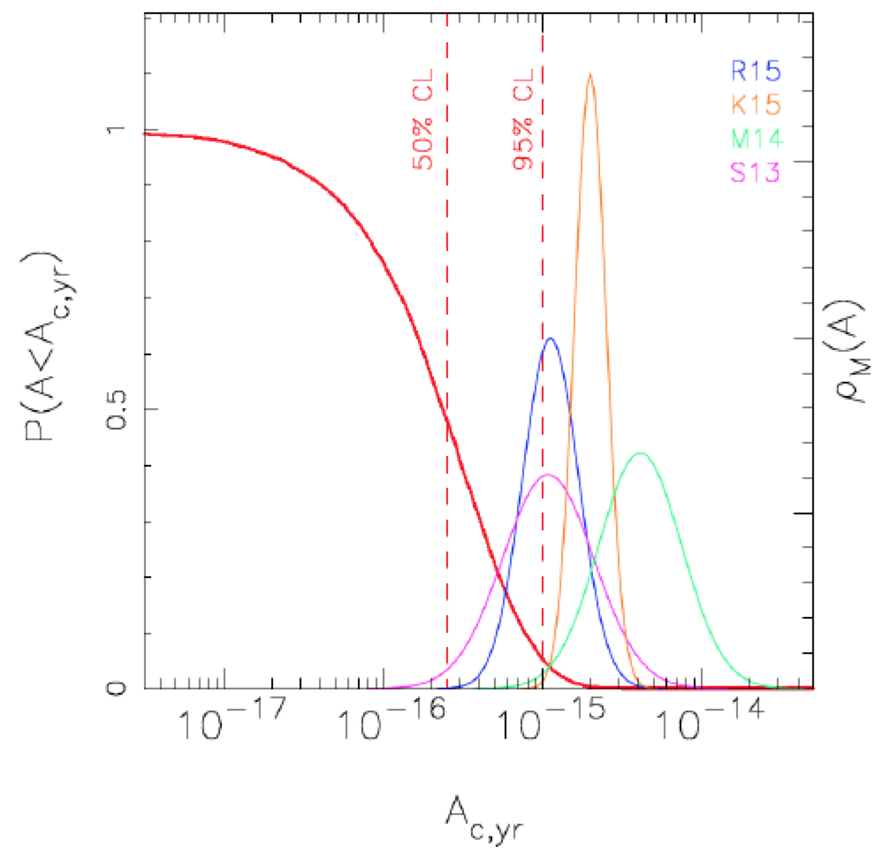
Draft version March 31, 2015

ABSTRACT

We analyze the frequency dependence of the dispersion measure (DM), the column density of free electrons to a pulsar, caused by multipath scattering from small scale electron-density fluctuations. The DM is slightly different along each propagation path and the transverse spread of paths varies greatly with frequency, yielding arrival time perturbations that scale differently than the inverse square of the frequency, the expected dependence for a cold, unmagnetized plasma. We quantify DM and pulse-arrival-time perturbations analytically for thin phase screens and extended media and verify the results with simulations of thin screens. The rms difference between DMs across an octave band near 1.5 GHz $\sim 4\times10^{-5}$ pc cm^{-3} for pulsars at $\sim$ 1 kpc distance. Time-of-arrival errors resulting from chromatic DMs are of order a few to hundreds of nanoseconds for pulsars with DM $\lesssim$ 30 pc cm^{-3} observed across an octave band but increase rapidly to microseconds or larger for larger DMs and wider frequency ranges. Frequency-dependent DMs introduce correlated noise into timing residuals whose power spectrum is ‘low pass’ in form. The correlation time is of order the geometric mean of the refraction times for the highest and lowest radio frequencies used and thus ranges from days to years depending on the pulsar. We discuss the implications for methodologies that use large frequency separations o

The problem of having a great postdoc … Ryan’s paper 3: where are the GWs?

1. Shannon et al., submitted to Science (2015)
2. New PPTA limit: A(95%) < 8 x 10^{-16}
3. (cf. predicted amplitude of 10^{-15} < A < 10^{-14})
4. *“This excludes the expected range”* … oh dear!
5. Now can do amazing tests of cosmology, black hole coalescence, … but cannot predict “when the PPTA (or SKA)



Ryan’s “solutions”

1. Jitter issue “need sub-arrays (or 100 metre telescopes) to time best pulsars”
2. SKA is not going to be made of 100-m telescopes so:
   a) need sub-arrays
   b) need to find “special” pulsars that are not jitter dominated
   c) need to find an observing band in which pulsars are not jitter dominated
   d) need to accept that pulsars will be jitter dominated => “long” observation times per pulsar.
   e) develop algorithms to “mitigate” the effects of jitter
3. Research required (but probably solvable somehow)!

Ryan's "solutions"

1. ISM correction issue "ISM sucks: go to higher frequency (need 3 GHz system)"
2. SKA-phase 1 doesn't have a 3GHz system! What are we going to do:
   a) show that we can use low frequency observations for DM correction (and that the model in the recent paper is incorrect)
   b) go to the 4GHz+ band, but even with SKA-1 collecting area the pulsars will be "weak"
   c) accept excess noise in the data through imperfectly corrected DM variations
3. Research required (but probably solvable somehow)!

Ryan’s “solutions”

1. GW limit rules out existing models: “We should build SKA-survey instead and go find SMBH binaries that way. ” ᄊ
2. Hmmm … that’s not going to go down well!
3. We need more research into new GW predictions. Should we be targetting single sources? Where is the GW background?
4. Research required!

Some good news

1. If Parkes alone can rule out current models for GW backgrounds – image what the SKA is going to do!
2. Now we know the SKA-1 rebaselined system we need to develop methods to deal with ISM correction, etc.
3. The GW background *will* exist at some level that is probably detectable by the SKA. The SKA should also detect individual SMBH sources. We need to work with the cosmology/black-hole/galaxy communities to understand how to improve GW background predictions
4. The SKA *will* revolutionise pulsar astronomy, but perhaps not in the way we expect.

Expected time-scale (previous) …

1. Individual PTA (e.g., Parkes) makes a low sigma GW background detection (e.g., 2-3 sigma)
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Expected time-scale (my current, but changeable, view) …

1. Individual PTA (e.g., Parkes) continues to place more and more stringent constraints on black hole coalescence models until noise is seen in the timing residuals
2. International Pulsar Timing Array confirms that the noise is “GW”-like and shows that the data for the best pulsars are correlated as expected. Have a estimation of GW amplitude.
3. MeerKAT +early FAST + International timing array improves on the significance
4. SKA + FAST actually makes the first direct detection of ultra-low-frequency GWs.

5. NOTE: current efforts need to feed into design of "PTA experiment" on SKA (so need to have as much flexibility as possible in design)

Getting involved 1

1. New 3-year postdoc being advertised very soon at CSIRO to work with the pulsar group and with ASKAP

Getting involved 2

1. Organising 1-day meeting on “Supermassive black holes and their environments: growth and evolution” in Leura, Blue Mountains on 27th July 2015
2. ***Limits from pulsar timing in tension with current models for how SMBH grow and evolve.***

Some questions we will investigate:

3. How were the first SMBHs formed? How many of them were there?
4. How do galaxies and supermassive black holes merge?
5. What do the centres of galaxies look like and how do they affect binary evolution?
6. What is the predicted signal for the cosmological population of SMBH binaries
7. How can we incorporate GW limits into models of Galaxy-SMBH coevolution?
8. *We hope to see you there!*
9. *ipta.phys.wvu.edu*
10. *Contact PPTA team for for information*

Thank you

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