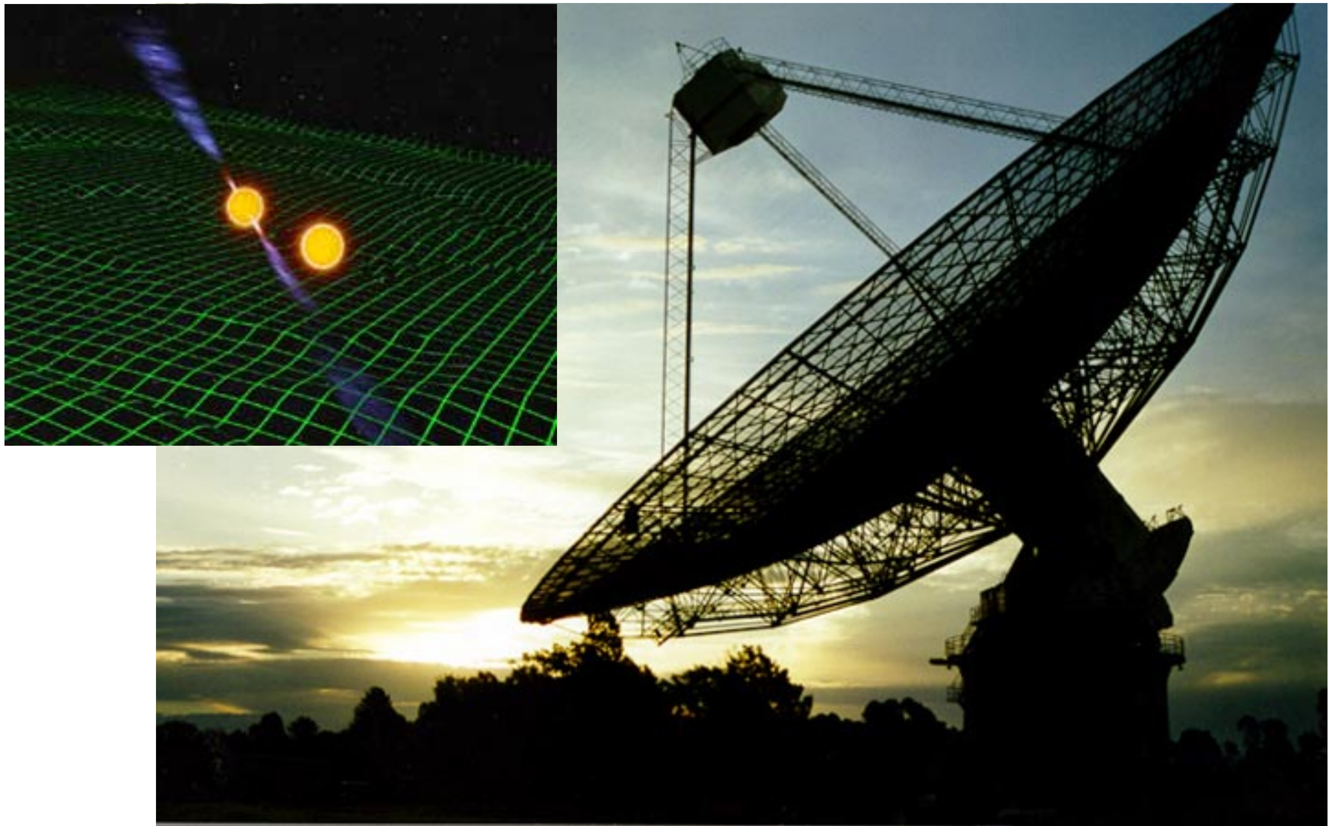

Pulsars and gravitational waves: 3
Existing data sets and sources of GWs

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CSIRO Australia Telescope National Facility
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CSIRO

Purpose of this lecture series

- Provide an overview of pulsars
- Provide an overview of gravitational waves
- Show how, in theory, pulsar observations can be used to detect gravitational waves
- Describe issues with the current data sets
- Describe unsolved problems
- Provide enough information that you can process pulsar observations and develop tools to search for gravitational waves

Review so far

- The pulses from a pulsar can be used like the tick of a clock
- Different phenomena cause variations in the measured pulse arrival times. The different phenomena can be distinguished by searching for correlations between different pulsars.
- The pulsar timing technique makes has been implemented as a software package.
- The tempo2 package can be used to simulate the induced residuals caused by gravitational waves

Purpose of lecture 3

- Describe the expected sources of gravitational waves
- Describe current data sets
- Explain where the data came from
- Show the timing residuals
- Discuss many of the issues necessary for dealing with the data sets.

Part 1

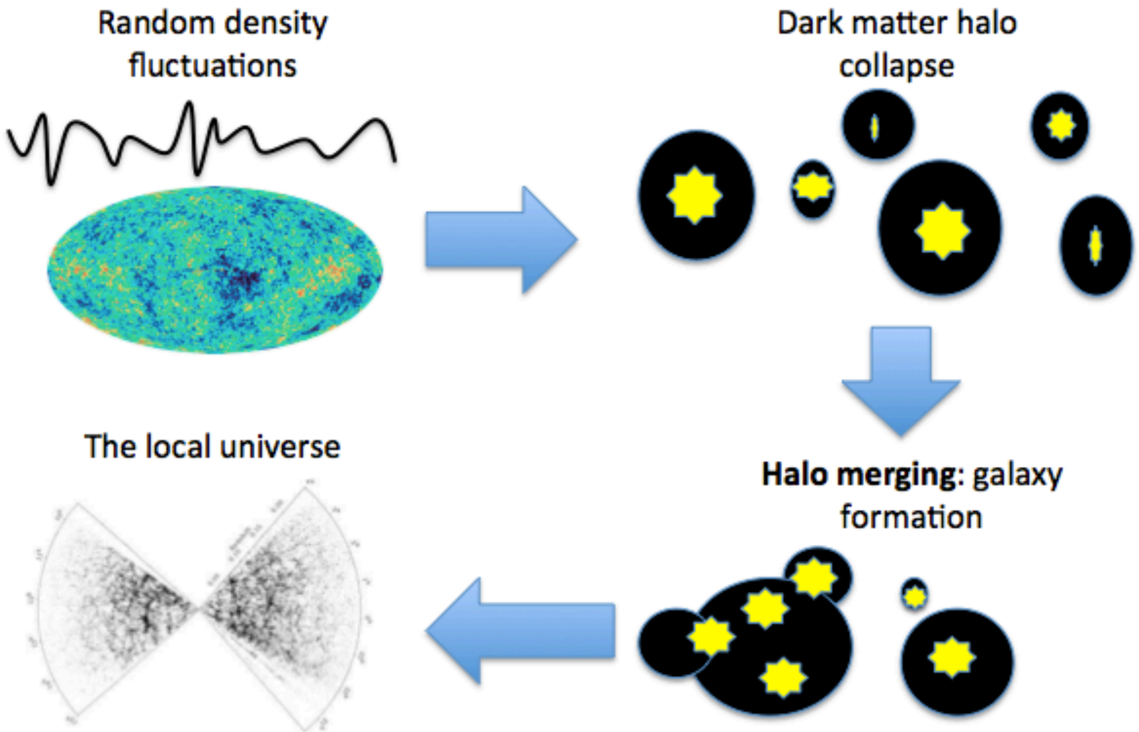
- Part 1: Sources of gravitational waves

Gravitational waves will be produced by coalescing supermassive binary black holes?

Do they exist?

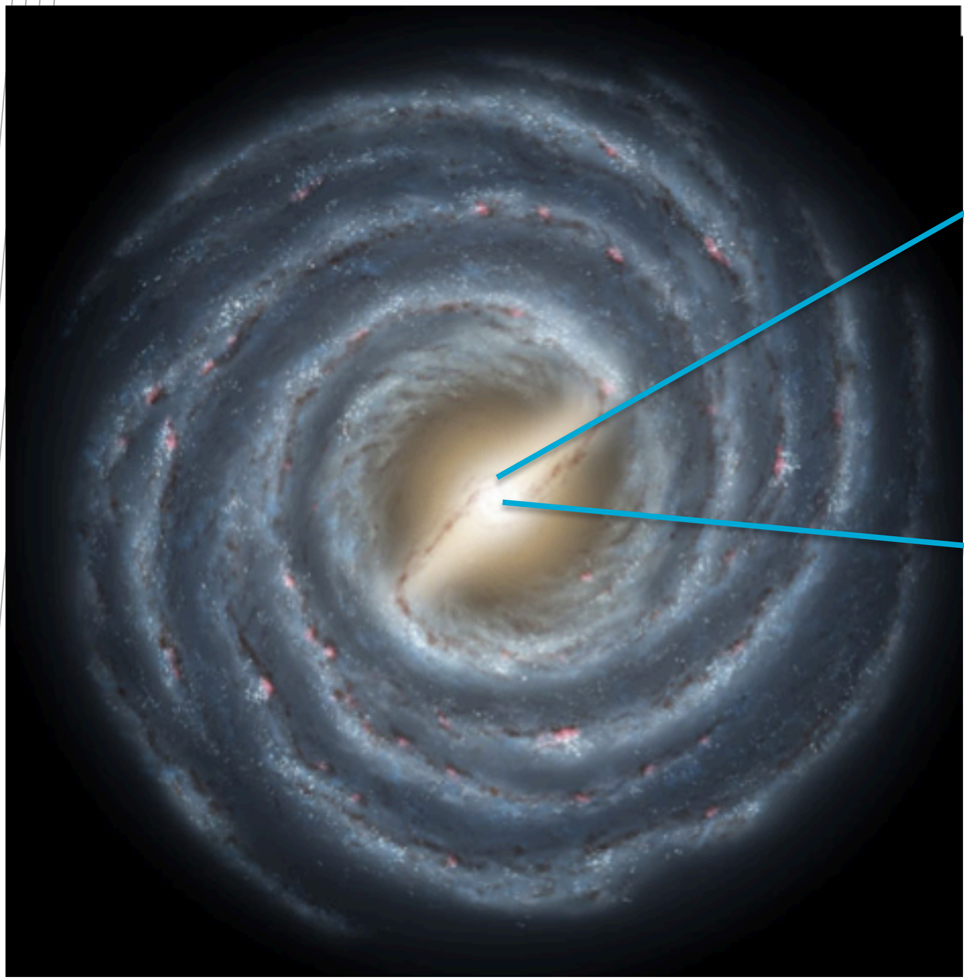
Galaxy formation

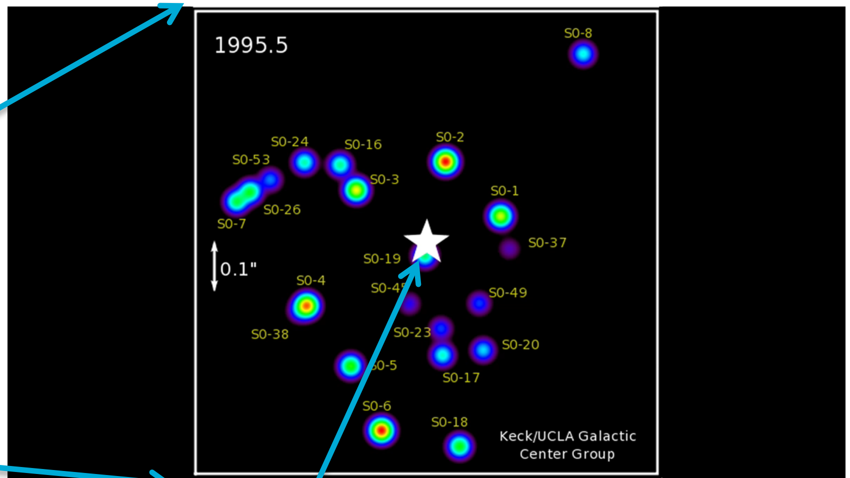
- Dark matter density fluctuations evolve into collapsed halos
- Baryonic gas cools and fragments in the halo potentials
- Black holes – what we see! – initially grow through accretion onto seed holes, and through coalescence.



The Milky Way Galaxy

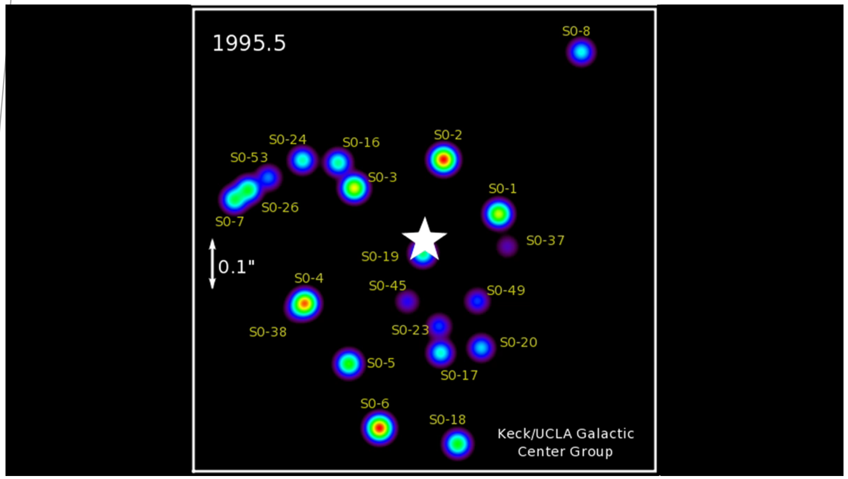
http://www.youtube.com/watch?v=sm-ucbDVyRU

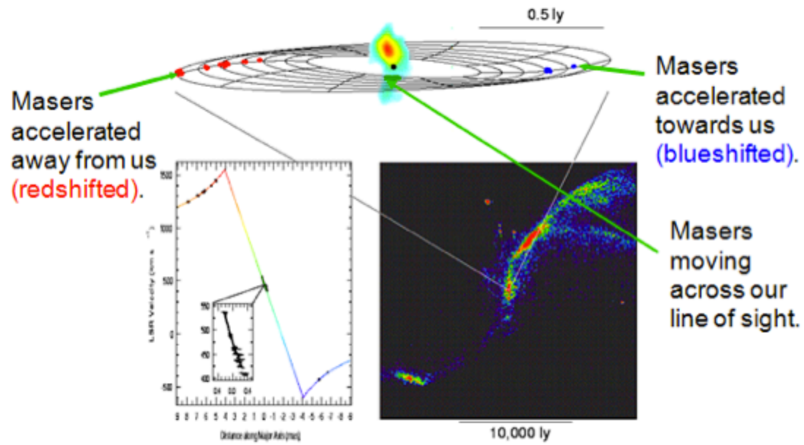




A supermassive black hole at the centre of our galaxy!

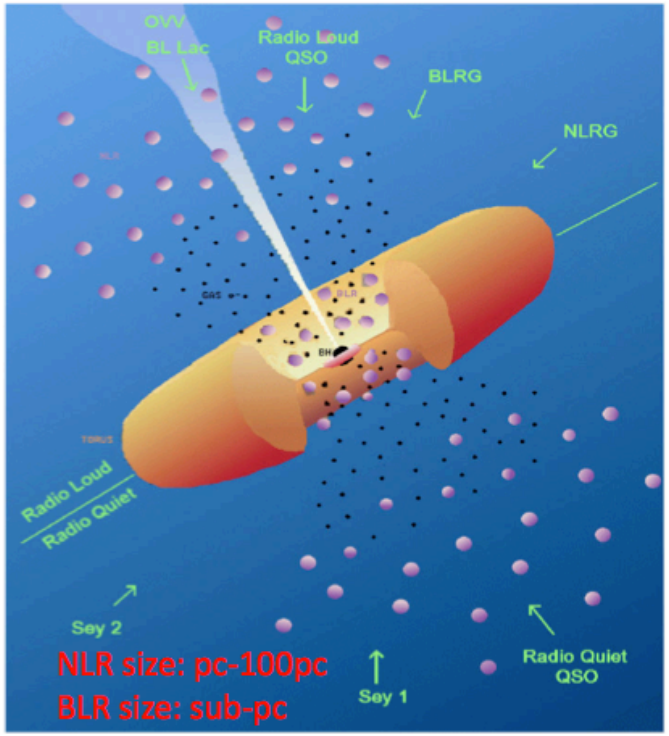
Evidence for supermassive black holes





The **VLBI** discovery of a **Keplerian** disk surrounding the **supermassive black hole** in **NGC** 4258.

http://astronomy.swin.edu.au/cosmos/V/VLBI



AGN unification model

Black holes exists

- Observational evidence exists for supermassive black holes
- Do we ever see binary black hole systems?

The Antennae Galaxies

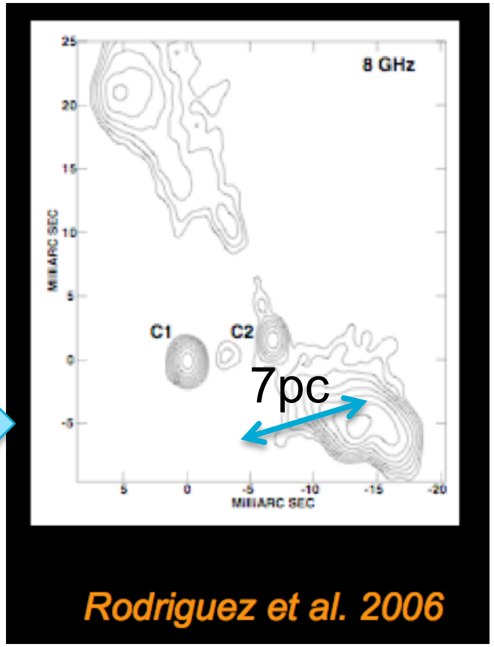
Two supermassive black holes. In the future they will interact with each other!

Black hole mergers

- Supermassive black holes grow through accretion and merging
- NO current observational evidence for a supermassive black hole merging system

http://www.mindruin.com/galaxy-mergers-please-use-turn-signal/

Evidence for “close” black hole systems



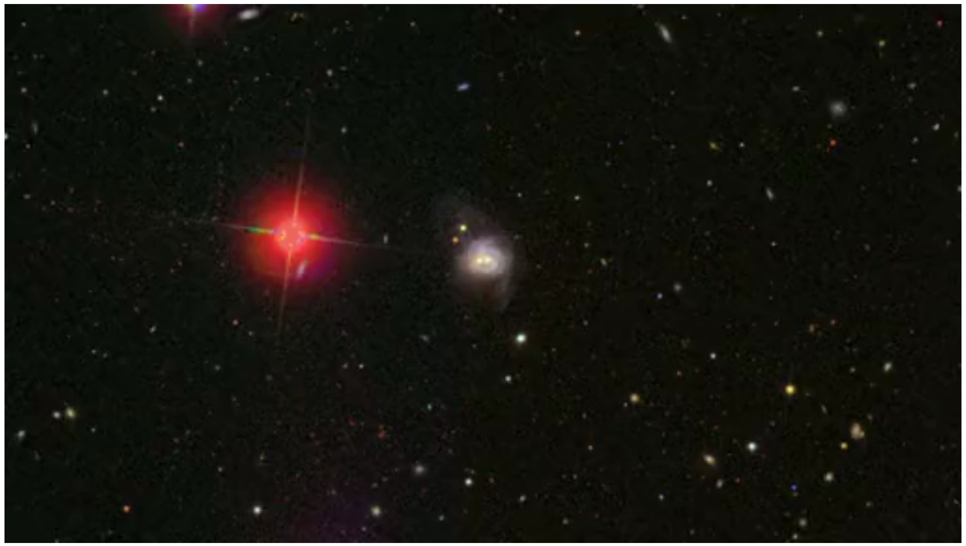
Rodriguez et al. 2006

Figure from Merritt 2008
Source: 0402+379

Burke-Spolaor (2011) used VLBI data for 3114 active galaxies. Only one double system found!

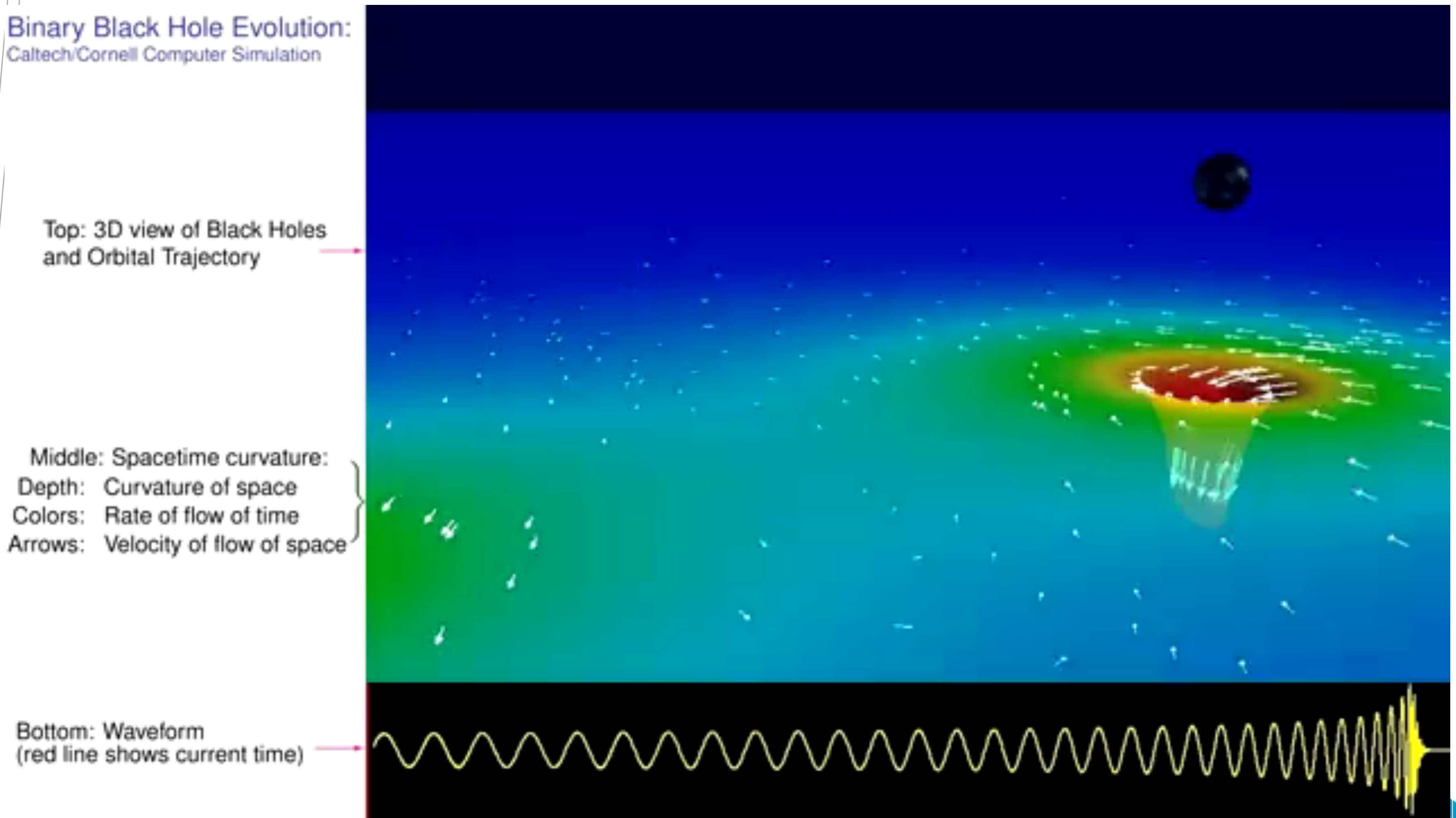
Markarian 739:
http://www.nasa.gov/mission_pages/swift/bursts/monster-black-holes.html


SDSS



The coalescence of the black holes

- http://www.black-holes.org/explore2.html



Gravitational waves from inspiralling binary black holes

Chirp mass: $M_C = (M_1 M_2)^{3/5}(M_1 + M_2)^{1/5}$

Orientation and polarisation averaged strain:

$$h \propto \frac{M_C^{5/3} f^{2/3}}{D(1+z)^{1/3}}$$

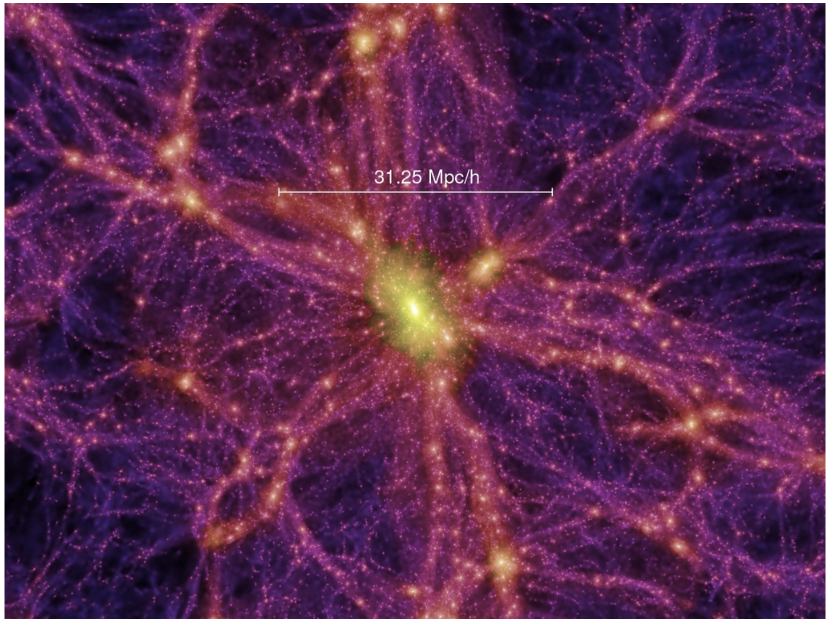
See e.g., Thorne (1987)

Gravitational wave frequency is twice the orbital frequency.

Only sensitive to GWs with periods greater than typical sampling of data (a few weeks) and less than data span (~20 years) => sensitive to waves with ~10^{-9}-10^{-8} Hz

Sources of GWs: simulating the entire Universe (Ravi et al., in preparation)

- Use the Millennium simulation: http://www.mpa-garching.mpg.de/galform/virgo/millennium/
- The *Millennium Run* used more than 10 billion particles to trace the evolution of the matter distribution in a cubic region of the Universe over 2 billion light-years on a side.



Simulating the Universe

- Extract merging systems per comoving volume, per chirp mass, per redshift
- Randomise over the position in the simulation volume
- Generate distributions of all observable sources
- Make list of merger events and determine the properties of the gravitational wave emission
- Use tempo2 to simulate the induced timing residuals caused by those sources

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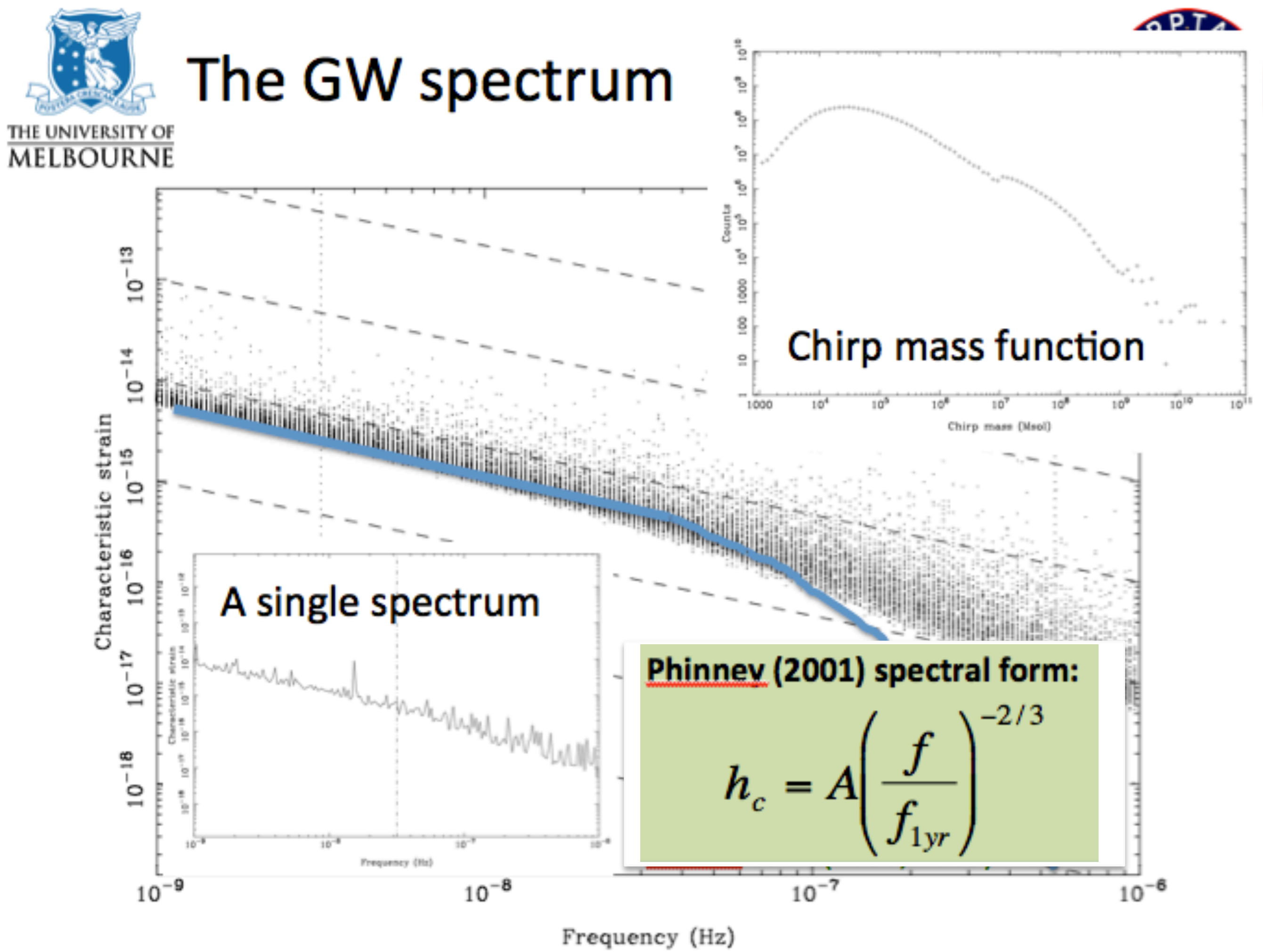
The expected gravitational wave signal

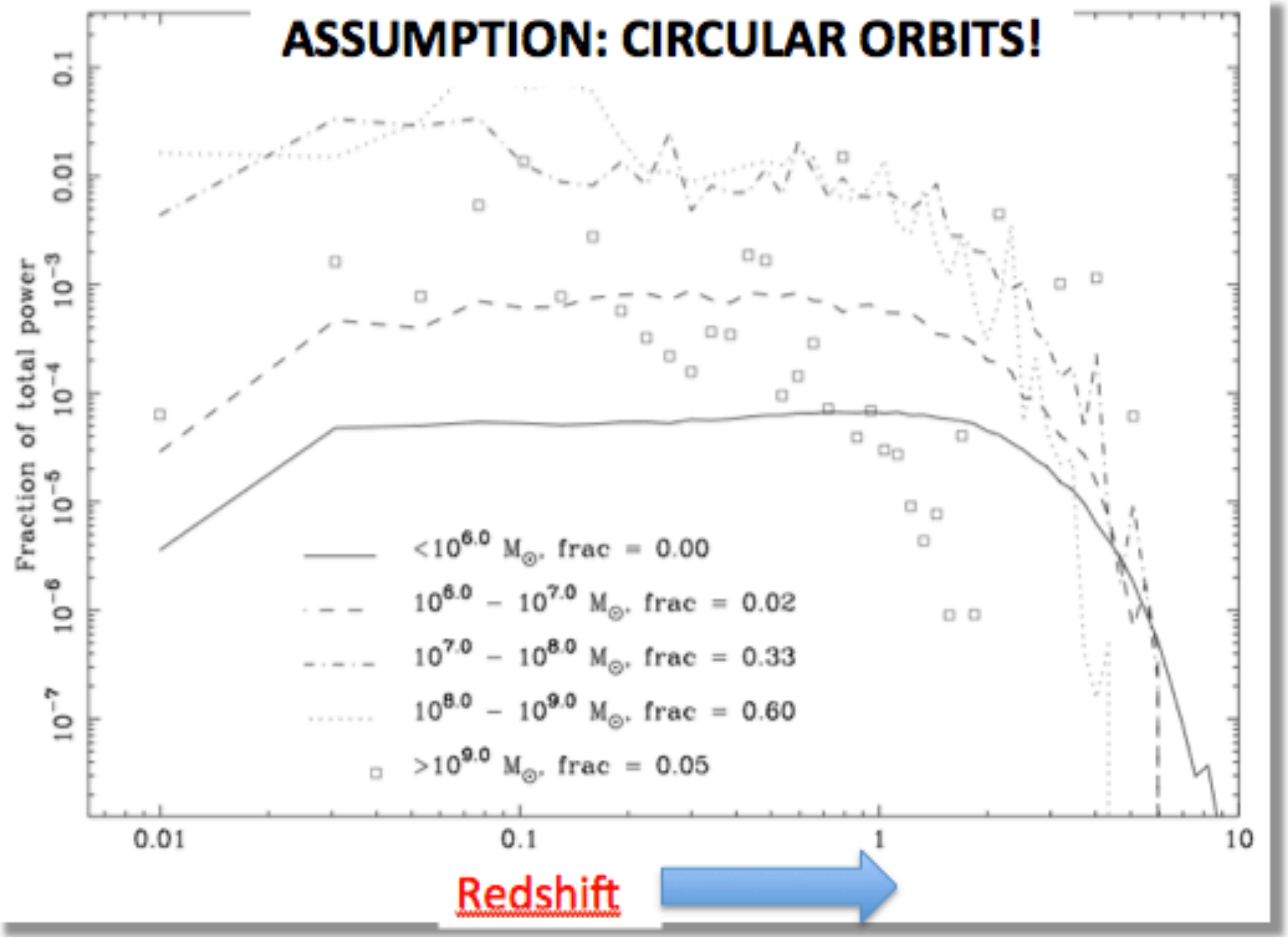
- Ravi et al. (in preparation)

- => will see a background of gravitational waves from supermassive binary black holes



Sources in the background

Contribution to the z=0 energy density in GWs by binary BHs with different **CHIRP MASSES**

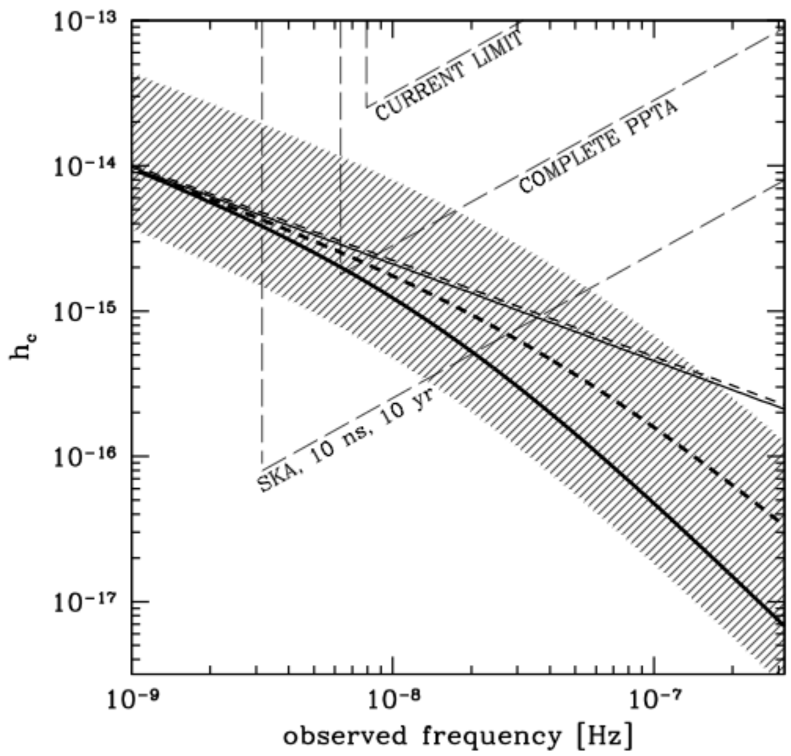


The Sesana et al. papers

- Sesana, Vecchio, Colacino, 2008, “The stochastic gravitational-wave background from massive black hole binary systems: implications for observations with Pulsar Timing Arrays”
- Sesana, Vecchio, Volonteri, 2009, “Gravitational waves from resolvable massive black hole binary systems and observations with Pulsar Timing Arrays”
- Sesana, Vecchio, 2010, “Gravitational waves and pulsar timing: stochastic background, individual sources and parameter estimation”
- Sesana, Vecchio, 2010, “Measuring the parameters of massive black hole binary systems with Pulsar Timing Array observations of gravitational waves”
- Sesana, Roedig, Reynolds, Dotti, 2011, “Multimessenger astronomy with pulsar timing and X-ray observations of massive black hole binaries”

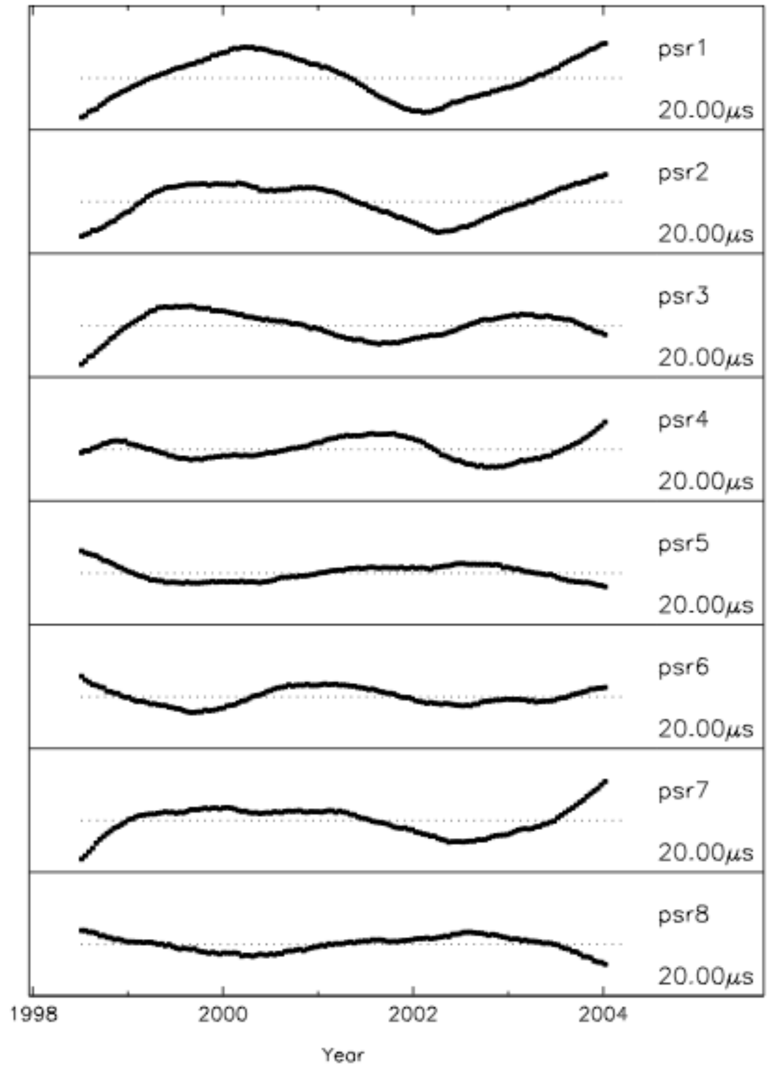
Sesana, Vecchio, Colacino (2008)

- Used Millennium simulation
- Predict:
  - gravitational wave background
  - amplitude ($f=10^{-8}$ Hz) ~ 5×10^{-16} – 8×10^{-15}
  - $h \sim f^{-2/3}$ for low frequencies (steeper for higher frequencies)
  - have about ~10^2 – 10^6 sources contributing to the signal for each frequency channel
  - for higher frequencies have only ~1 source per frequency channel
  - major contribution from massive ($M > 10^8 M_o$) and nearby ($z < 2$) binary systms



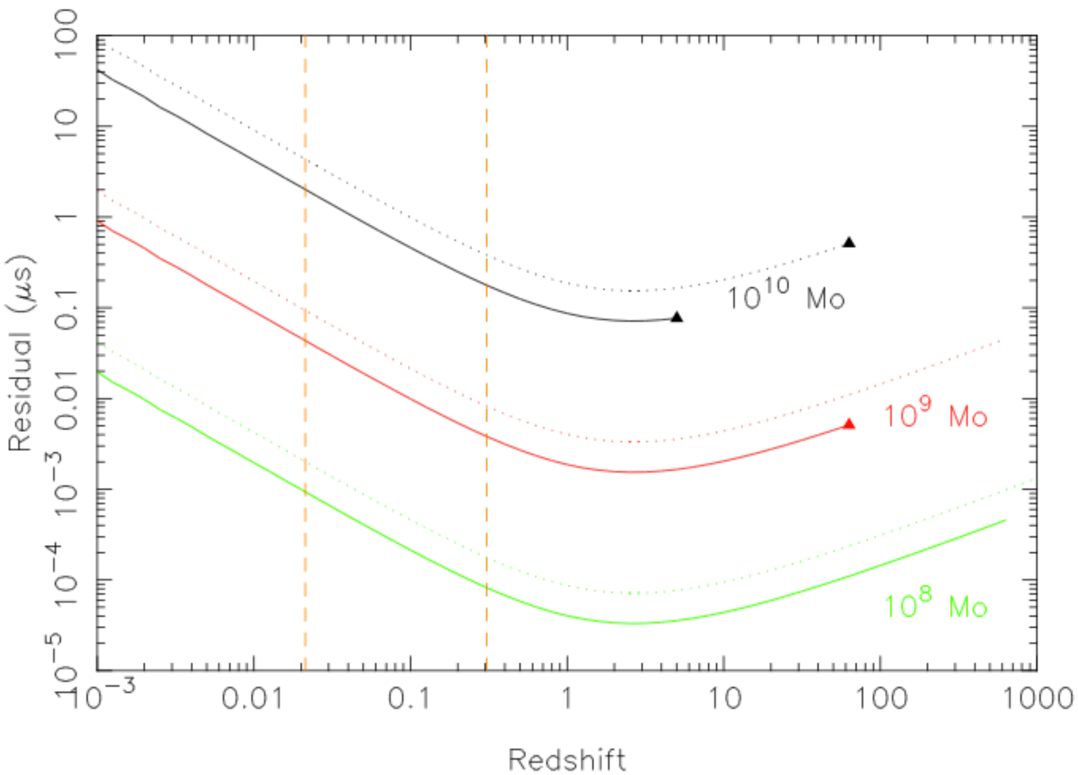
Expected gravitational wave signal from a background

- Expect induced residuals from gravitational waves at the <100ns level



The individual sources

$$t \sim 10\text{ns} \left(\frac{1\text{Gpc}}{d}\right) \left(\frac{M}{10^9 \text{M}_\odot}\right)^{5/3} \left(\frac{10^{-7}\text{Hz}}{f}\right)^{1/3}$$

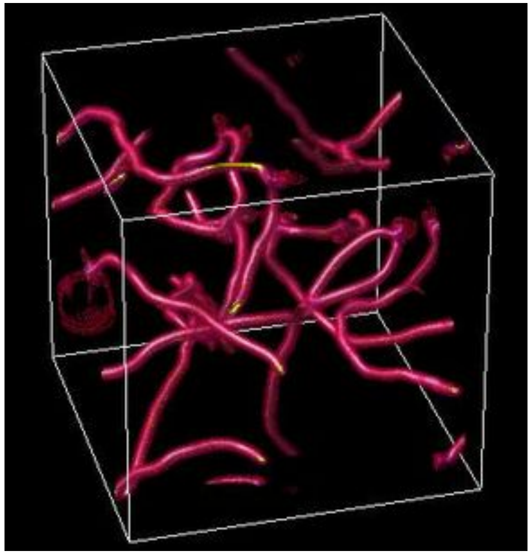


Other gravitational wave sources

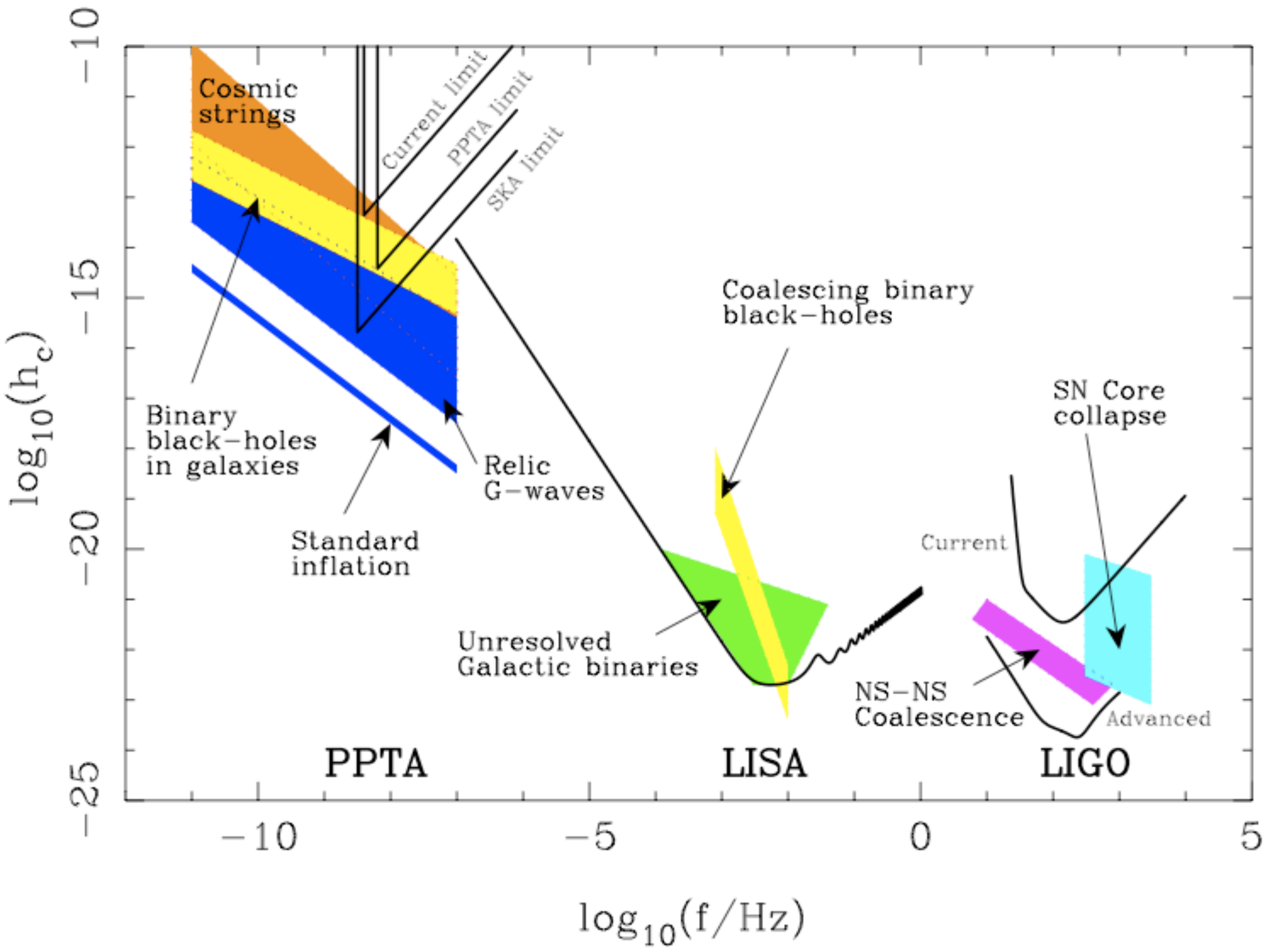
- Cosmic strings
- The inflationary era
- Burst events from eccentric supermassive black hole binaries
- The "gravitational wave memory" effect

Cosmic strings are hypothetical 1-dimensional (spatially) topological defects which may have formed during a symmetry breaking phase transition in the early universe when the topology of the vacuum manifold associated to this symmetry breaking is not simply connected.

-wikipedia!



The spectrum of expected sources



Part 2

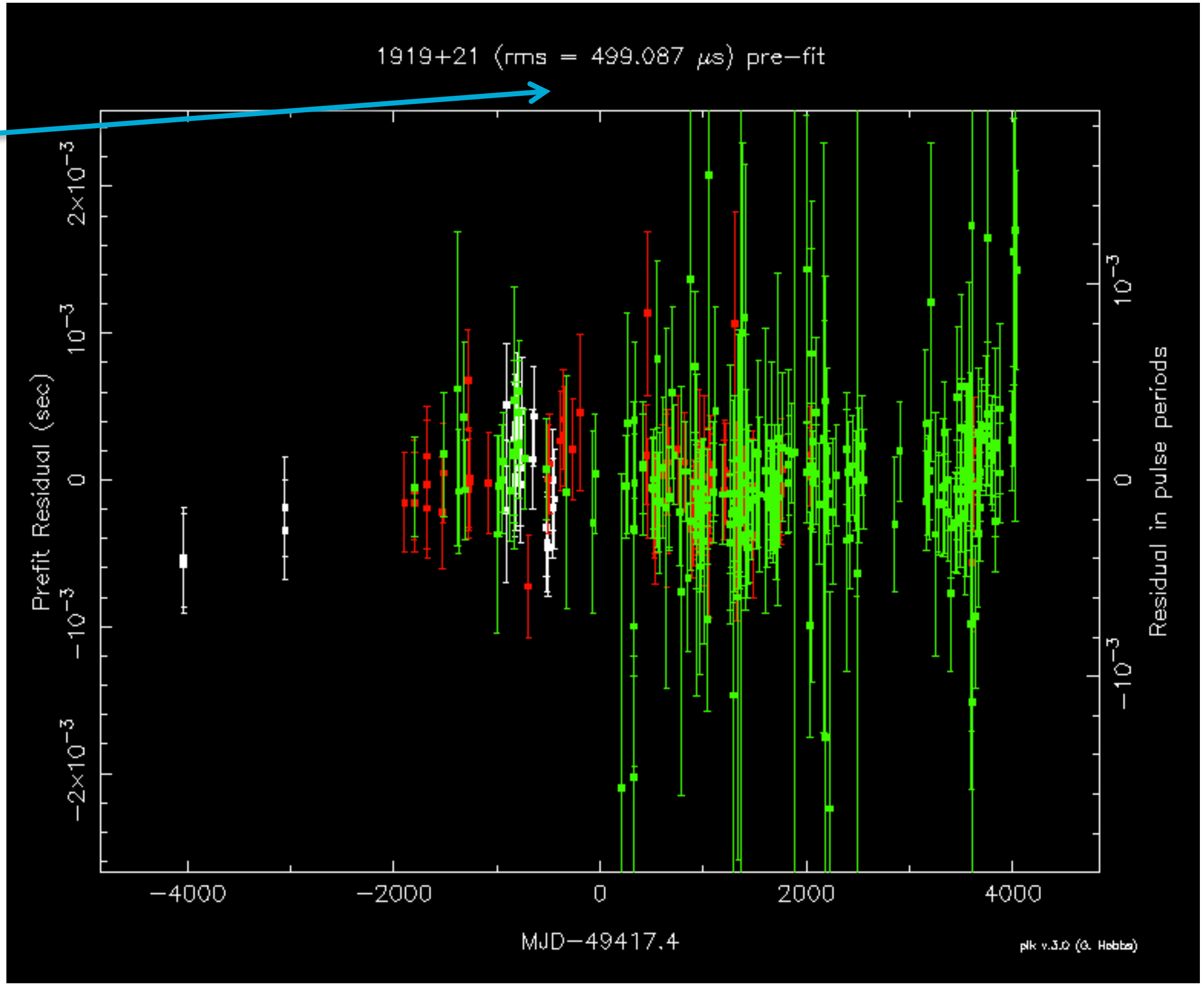
• Part 2: A history of pulsar timing

Finally, we can talk about real data sets!!

A history of pulsar timing: the discovery of B1919+21

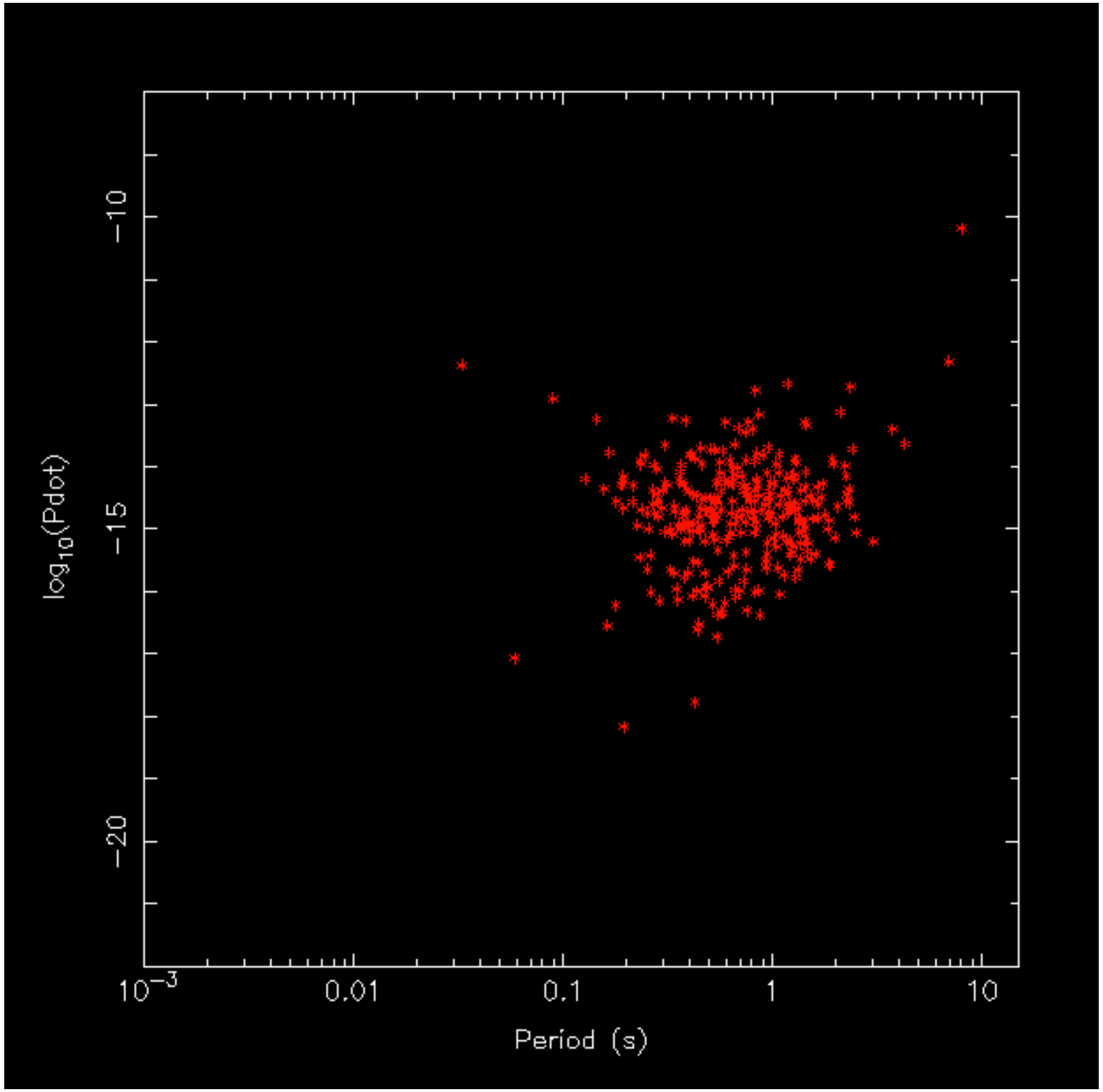
Rms timing residual = 500us

1ms

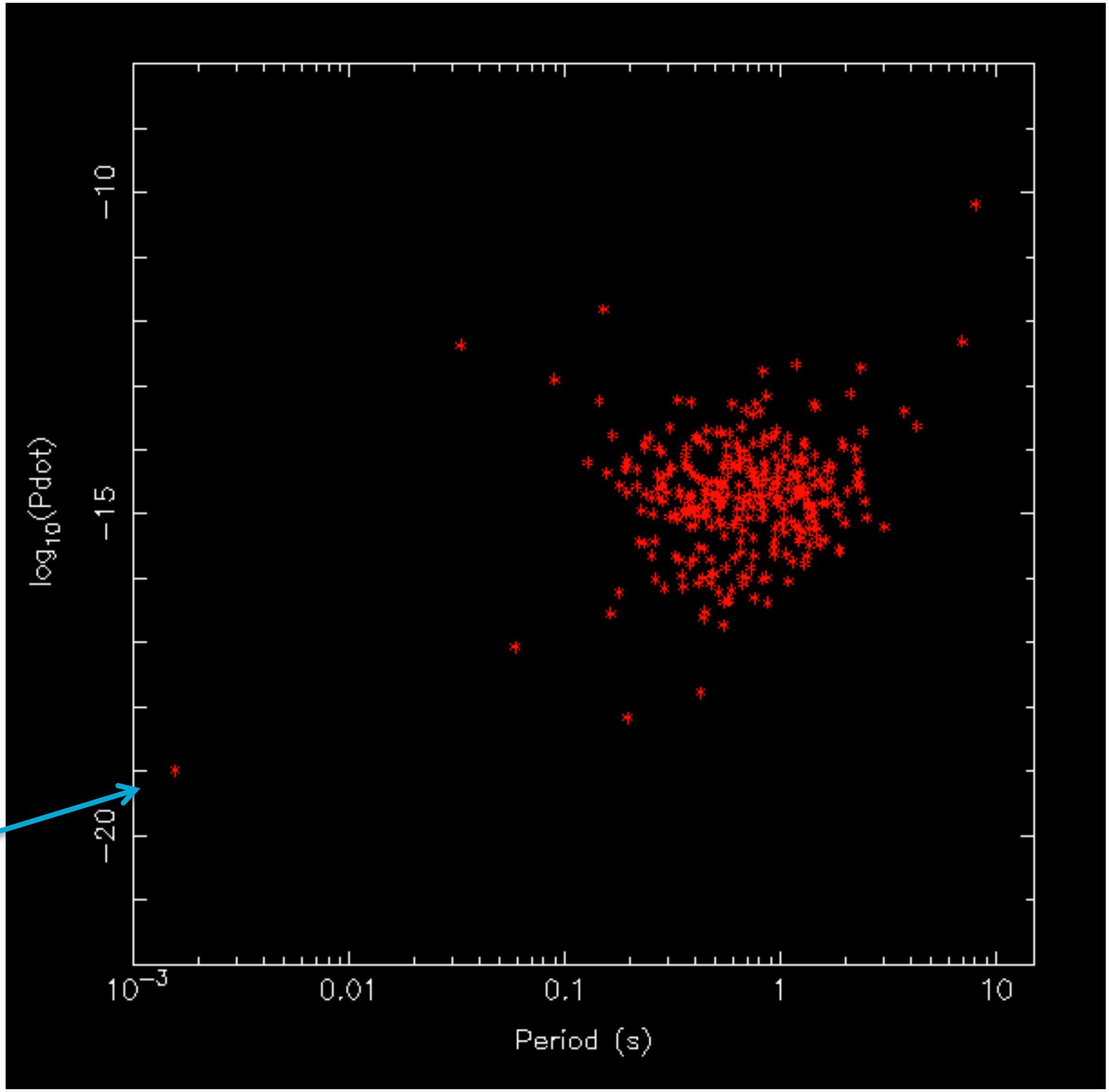


Jodrell Bank data

The pulsar population before 1982



The pulsar population before 1983

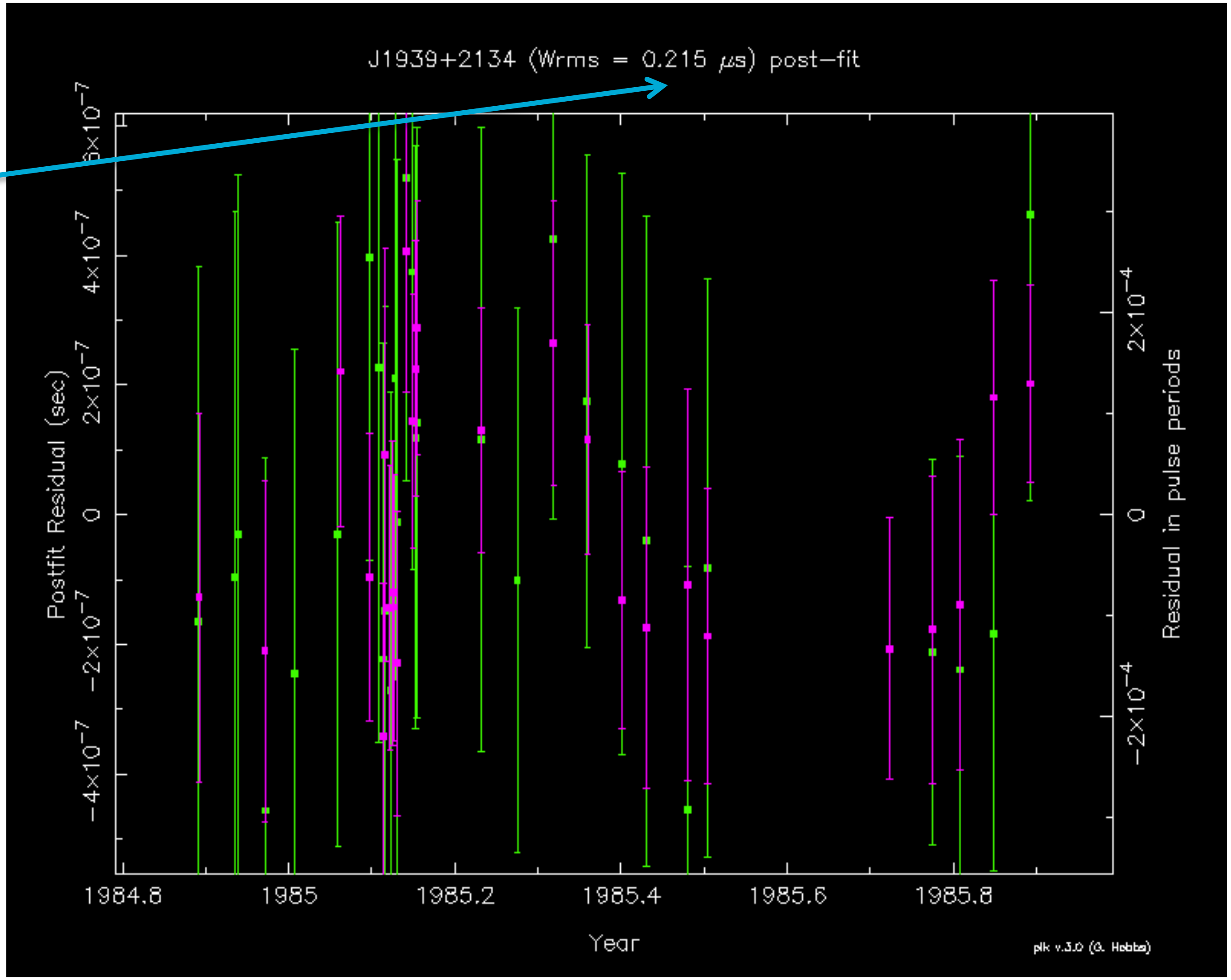


PSR B1937+21 discovered in 1982

PSR B1937+21

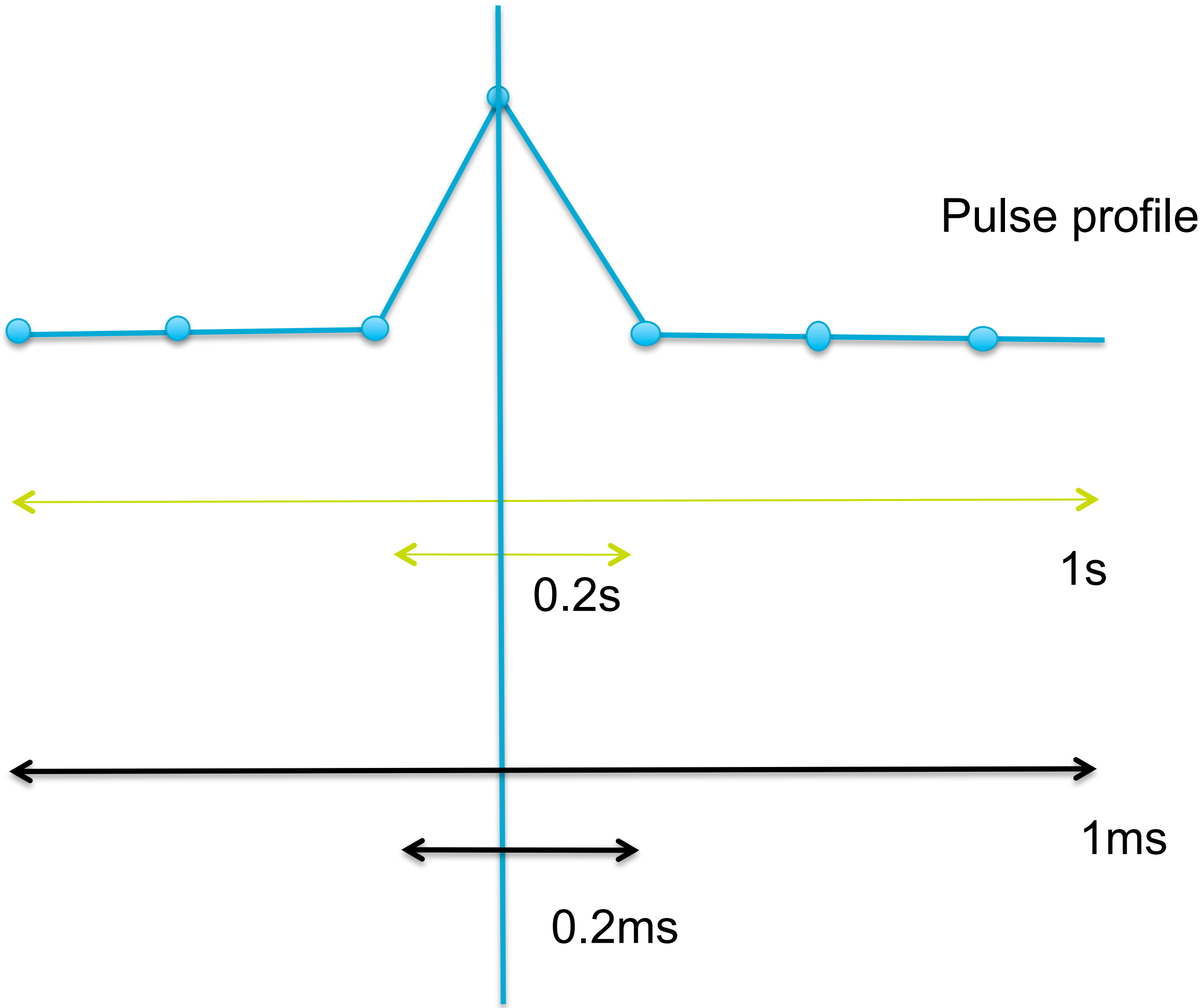
Rms timing residual = 200ns

400ns

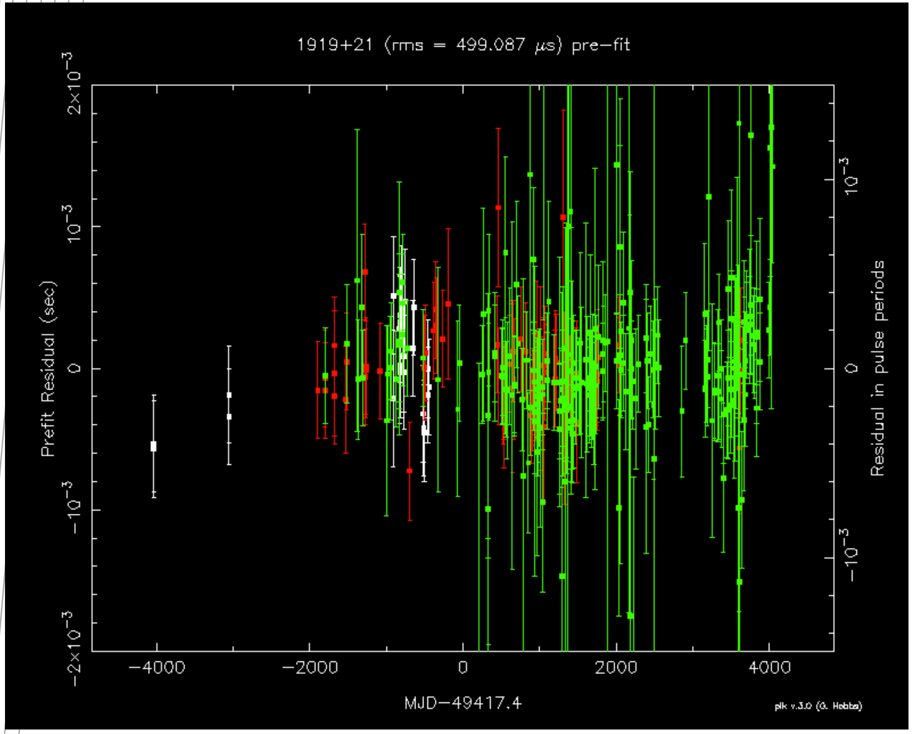


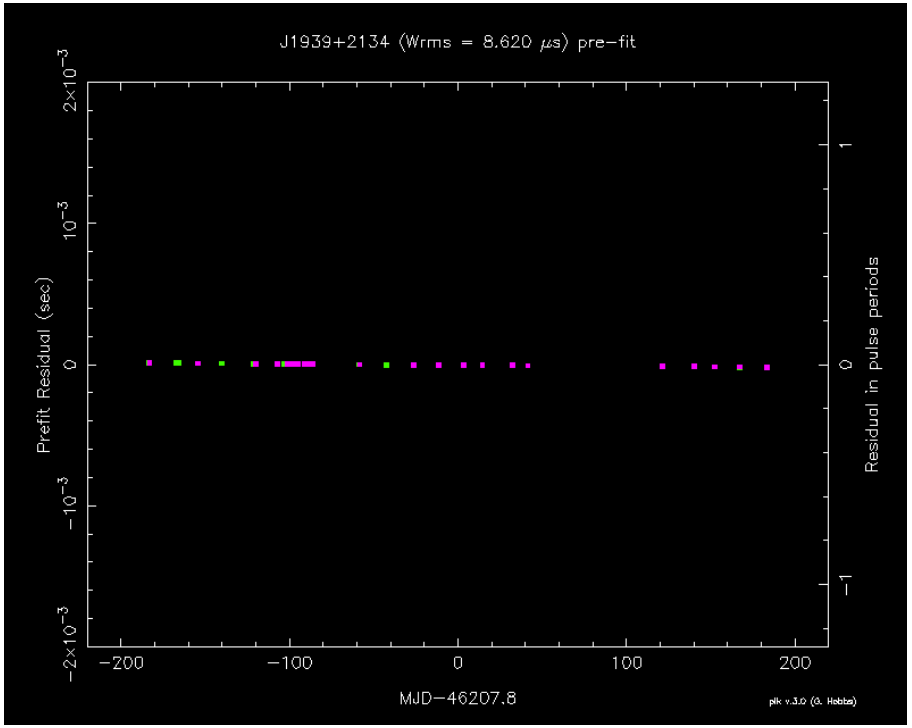
Arecibo data

Why can we determine arrival times with greater precision and accuracy?

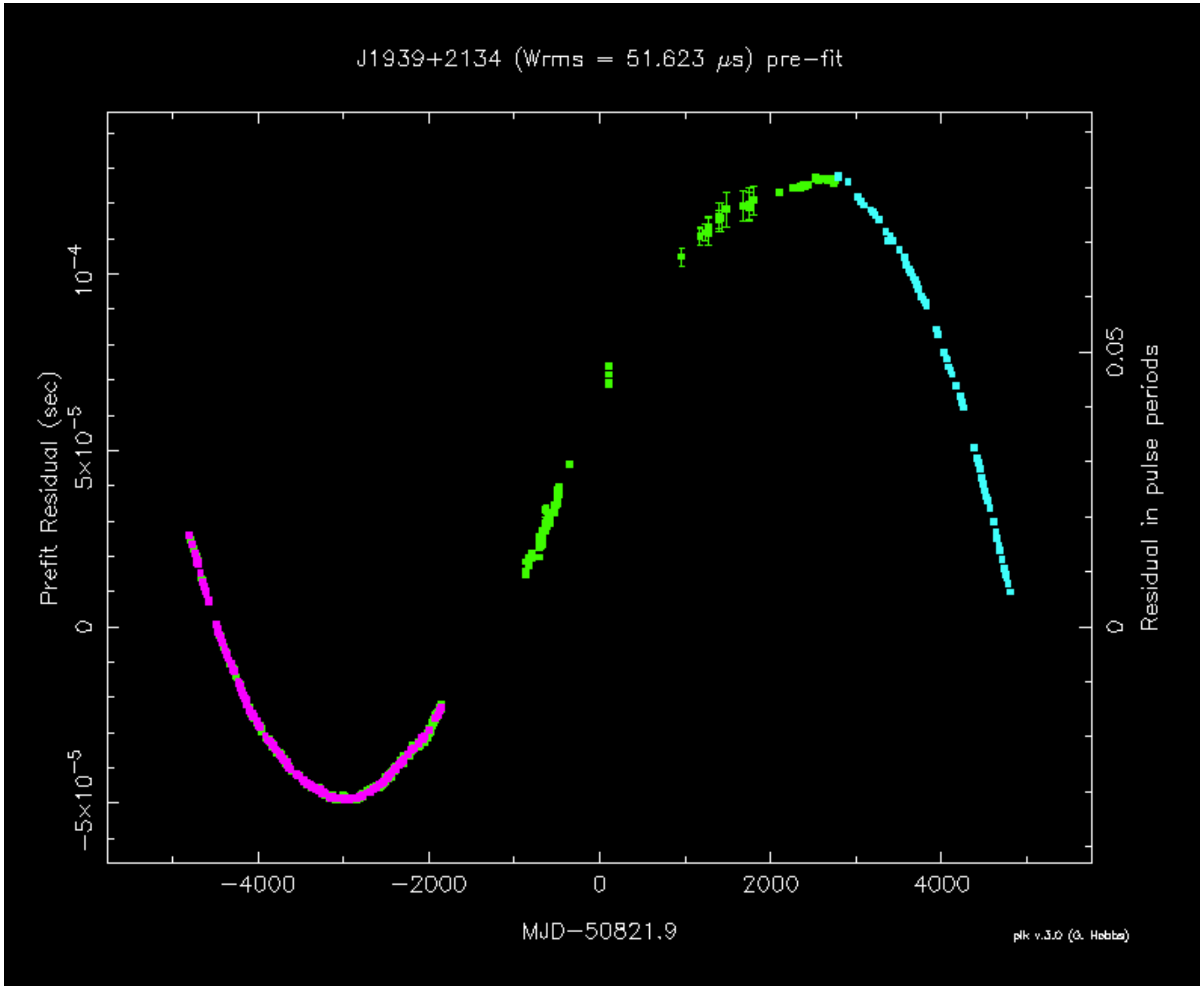


B1937 compared with B1919+21





Problem with B1937+21

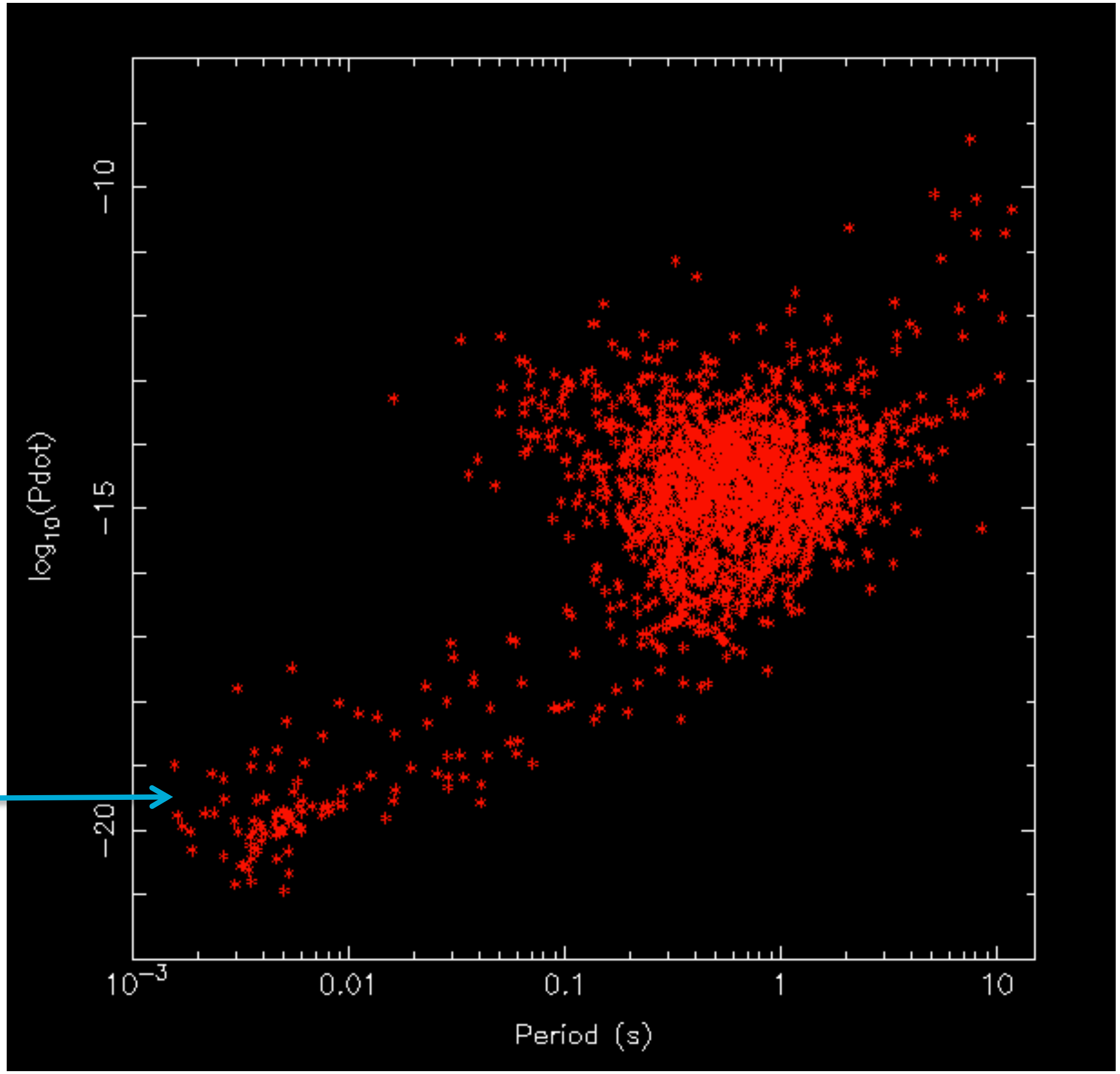


Where is this signal coming from?

It's too large to be a gravitational wave

Arecibo + Parkes data

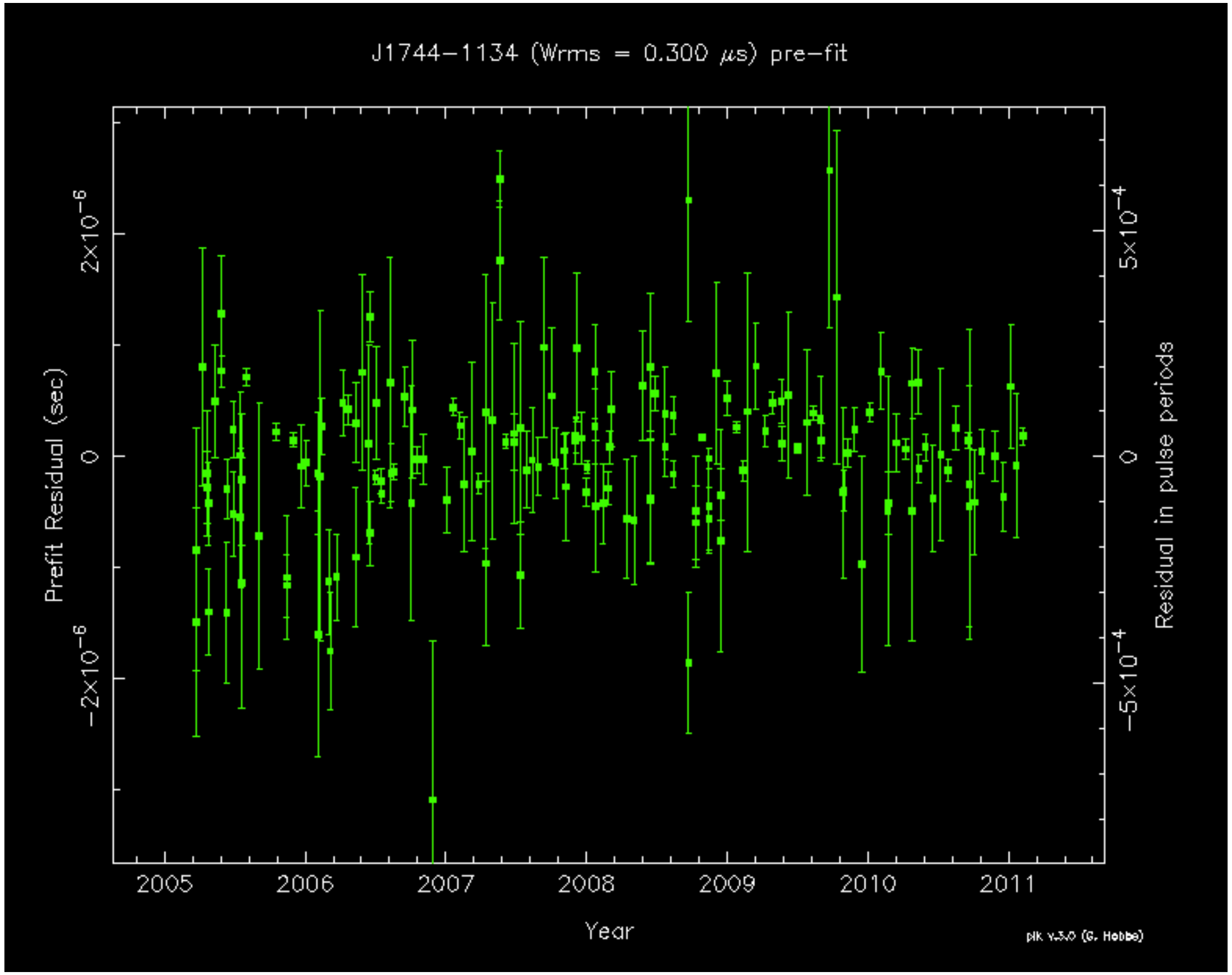
The pulsar population now
(ATNF pulsar catalogue)



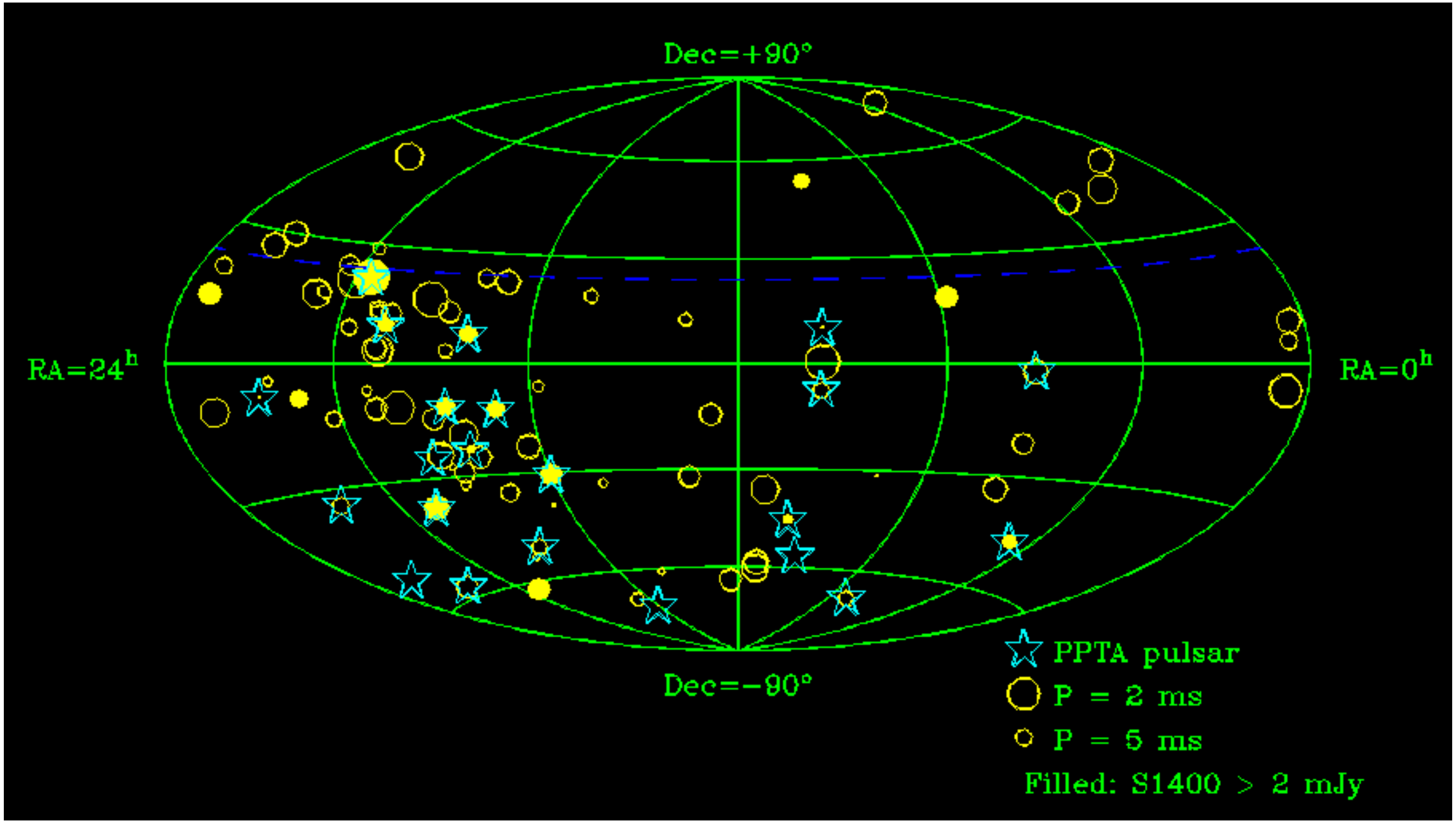
Lots of millisecond pulsars

PSR J1744-1134

- Recent Parkes data



Choosing suitable millisecond pulsars



All (published) MSPs not in globular clusters

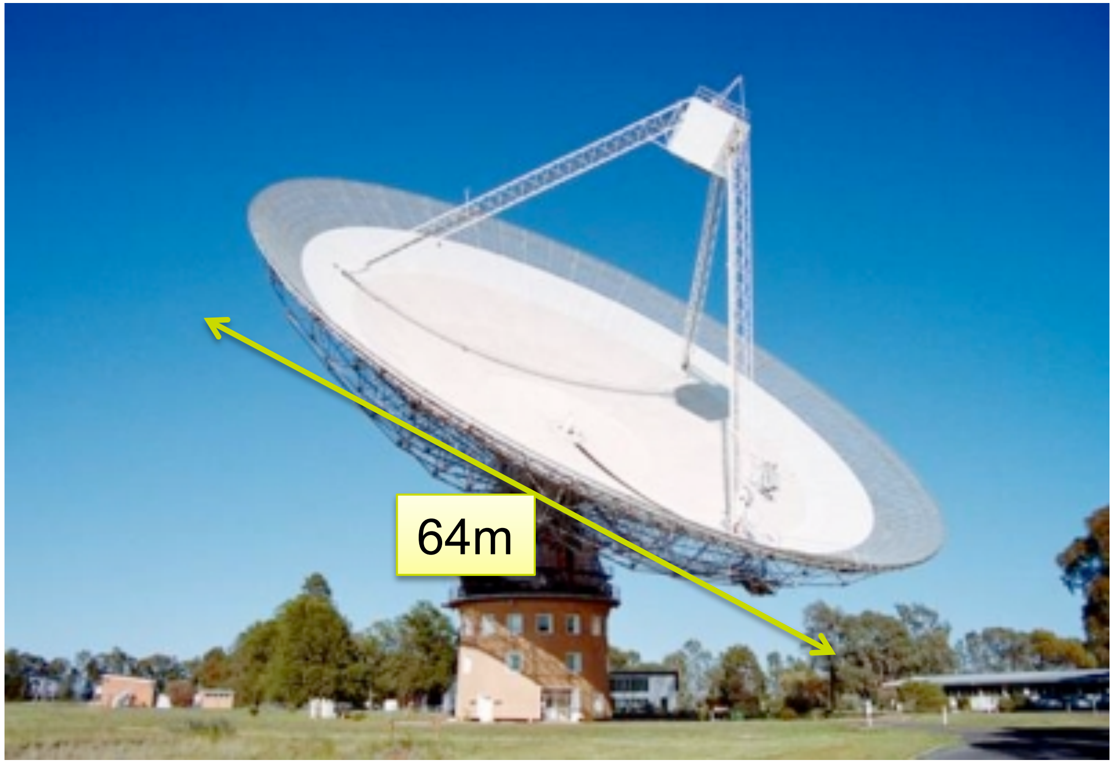
Figure: R. Manchester

High precision pulsar timing experiments: The Parkes Pulsar Timing Array project

Come to Australia

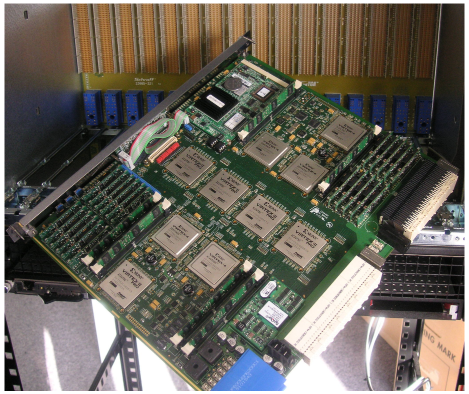
We have a conference near here in 2012

The dish



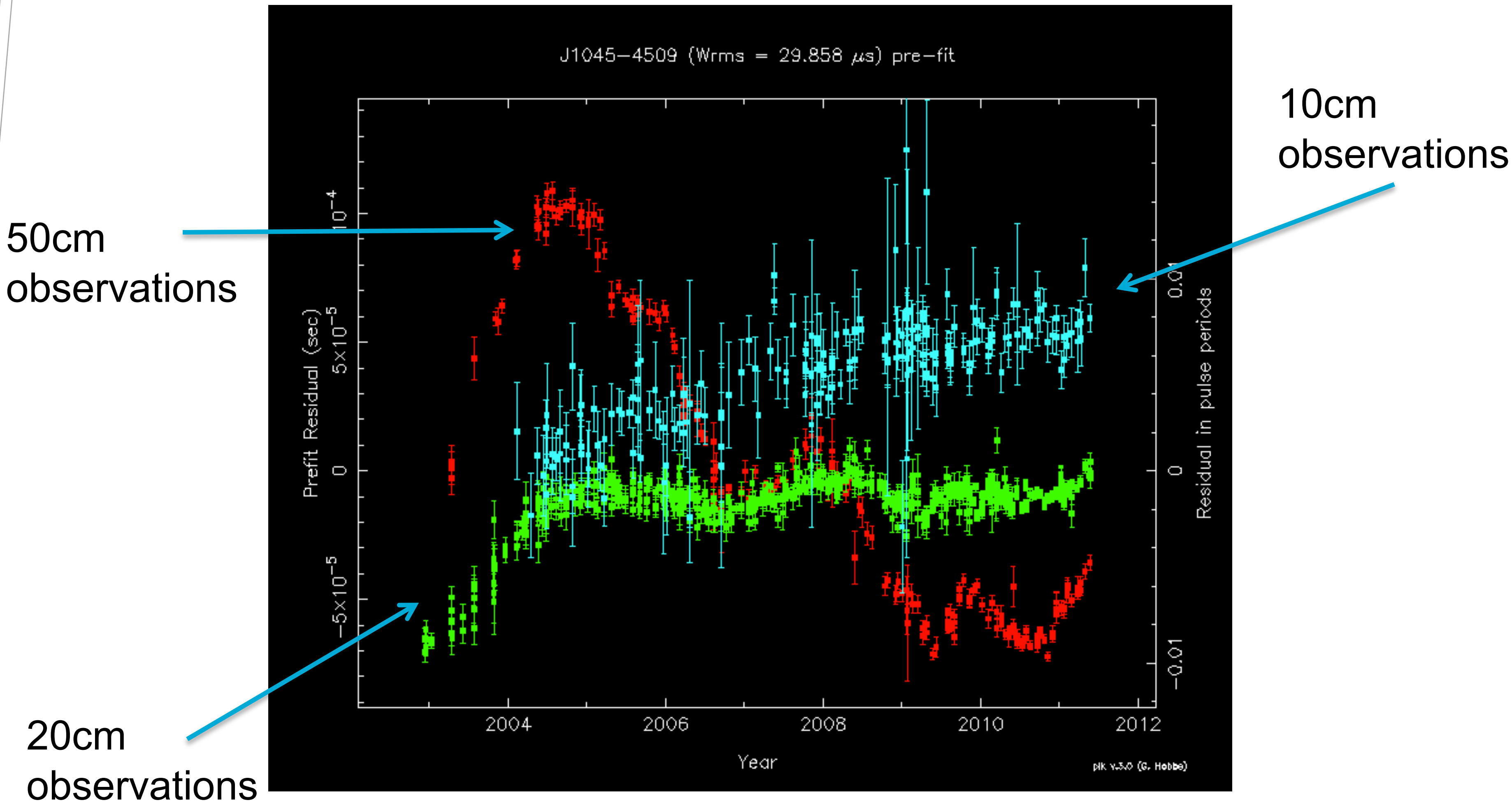
Use 20cm receiver and a 10/50cm dual-band receiver

Online monitor:
http://pulseatparkes.atnf.csiro.au/dev/



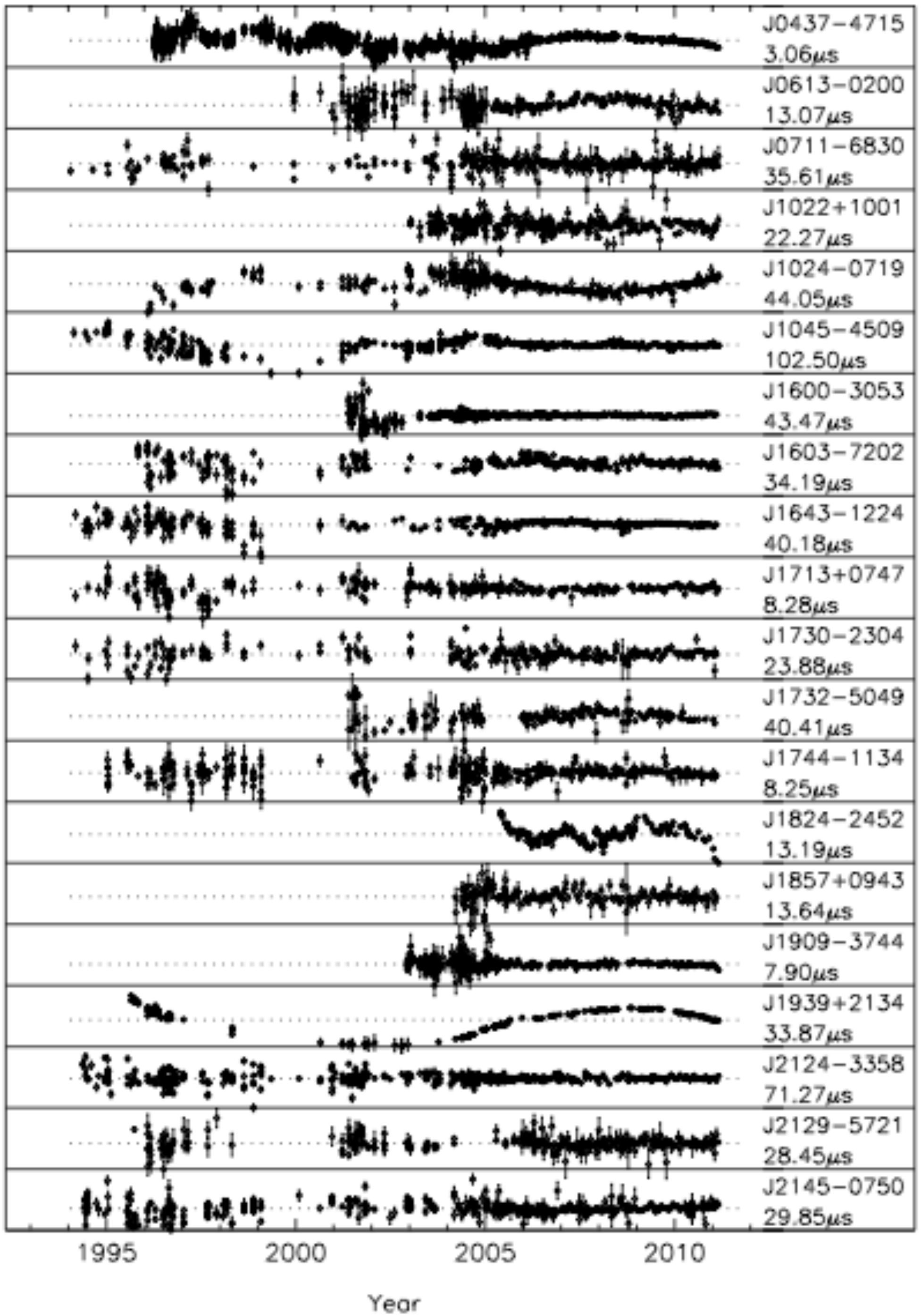
Parkes Pulsar Timing Array data sets:

- PSR J1045-4509



Parkes data

20 pulsars observed



Current IPTA: North America

GreenBank

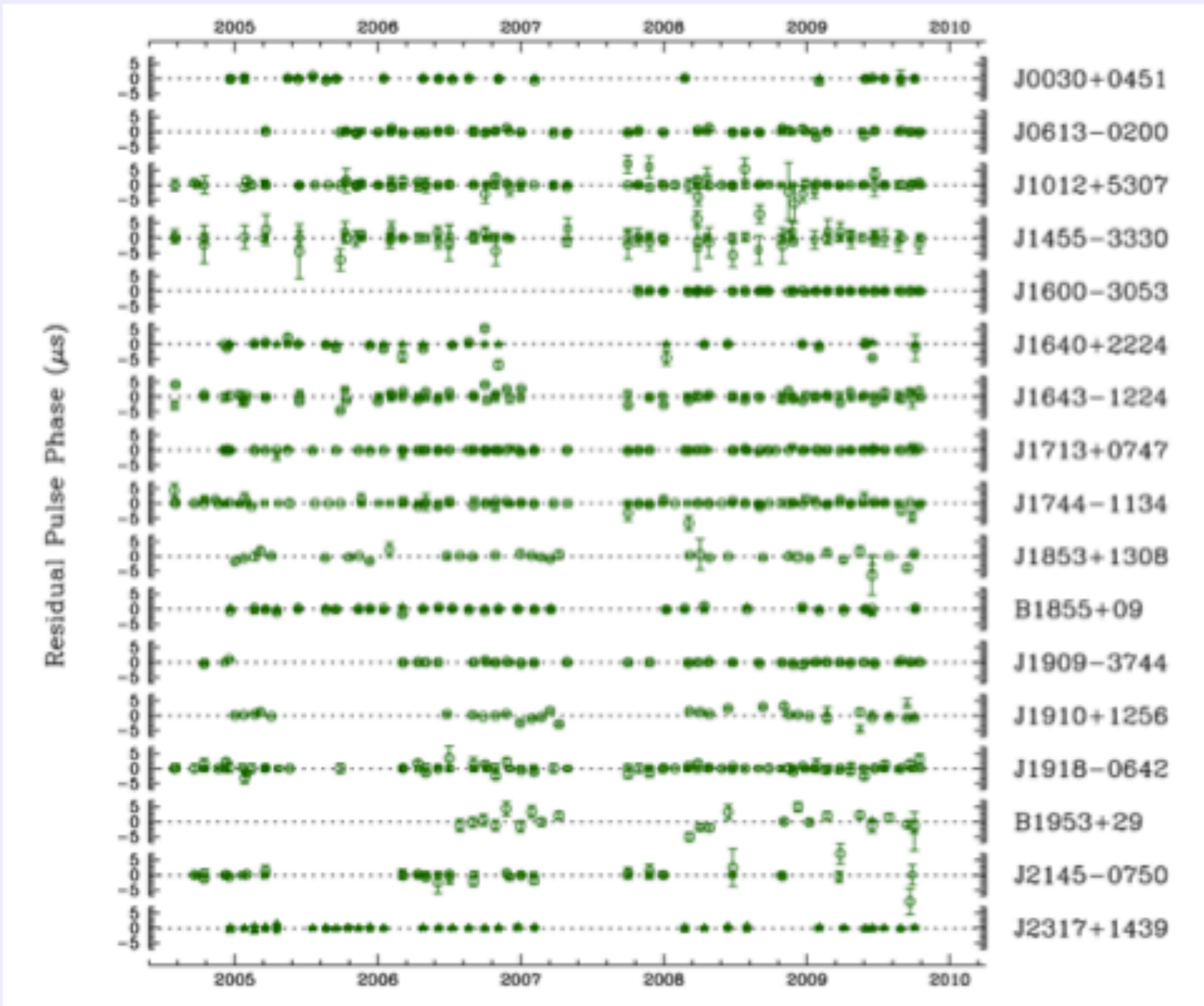
Arecibo

CSIRO

Nanograv

- Slide from P. Demorest
- 2 pulsars have an rms timing residual ~40ns

17 pulsars. 8 in common with the PPTA



(plot: D. Nice)

Current IPTA: Europe

Jodrell Bank Observatory

Effelsberg

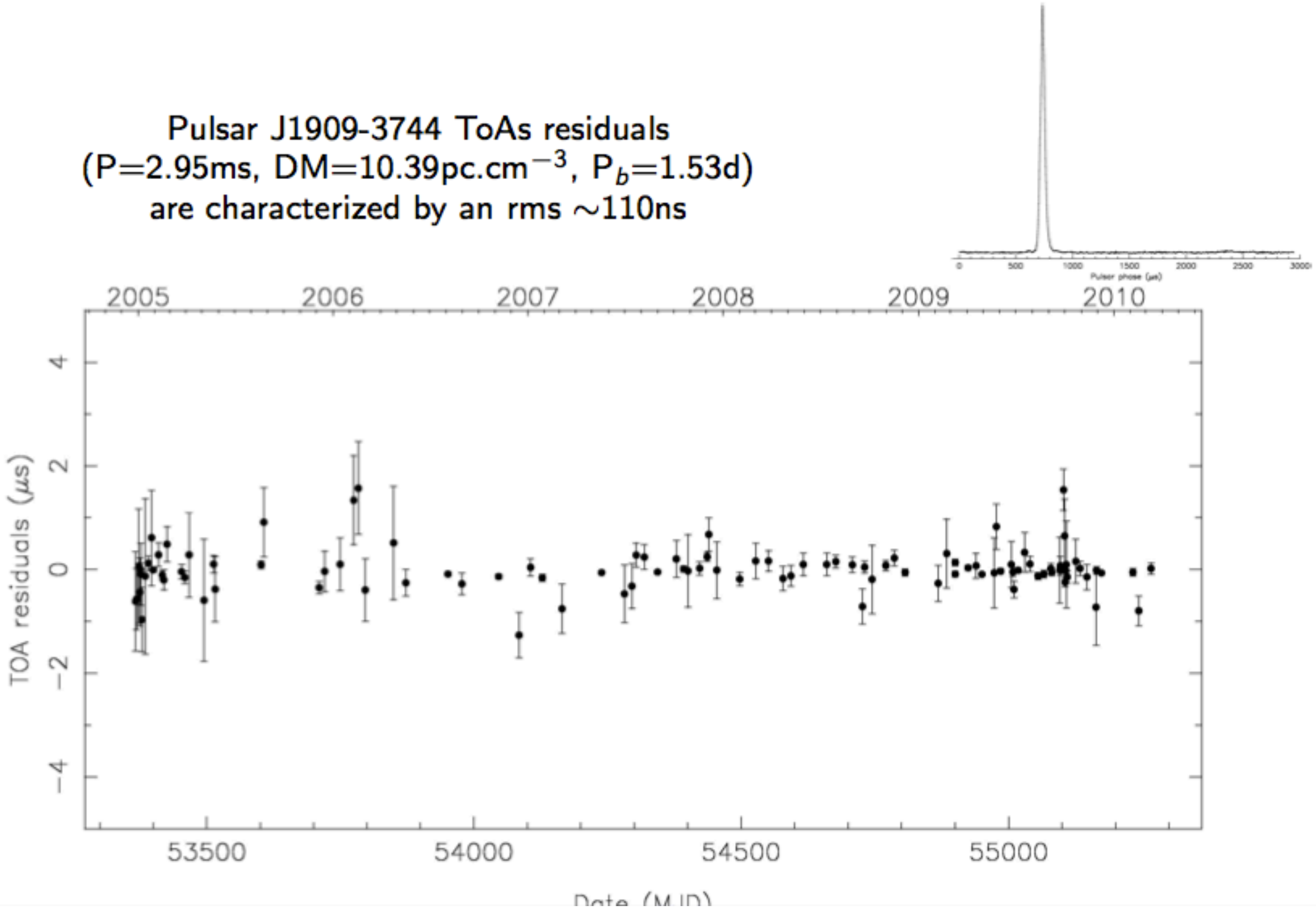
Westerbork

Nancay

Sardinia

Europe

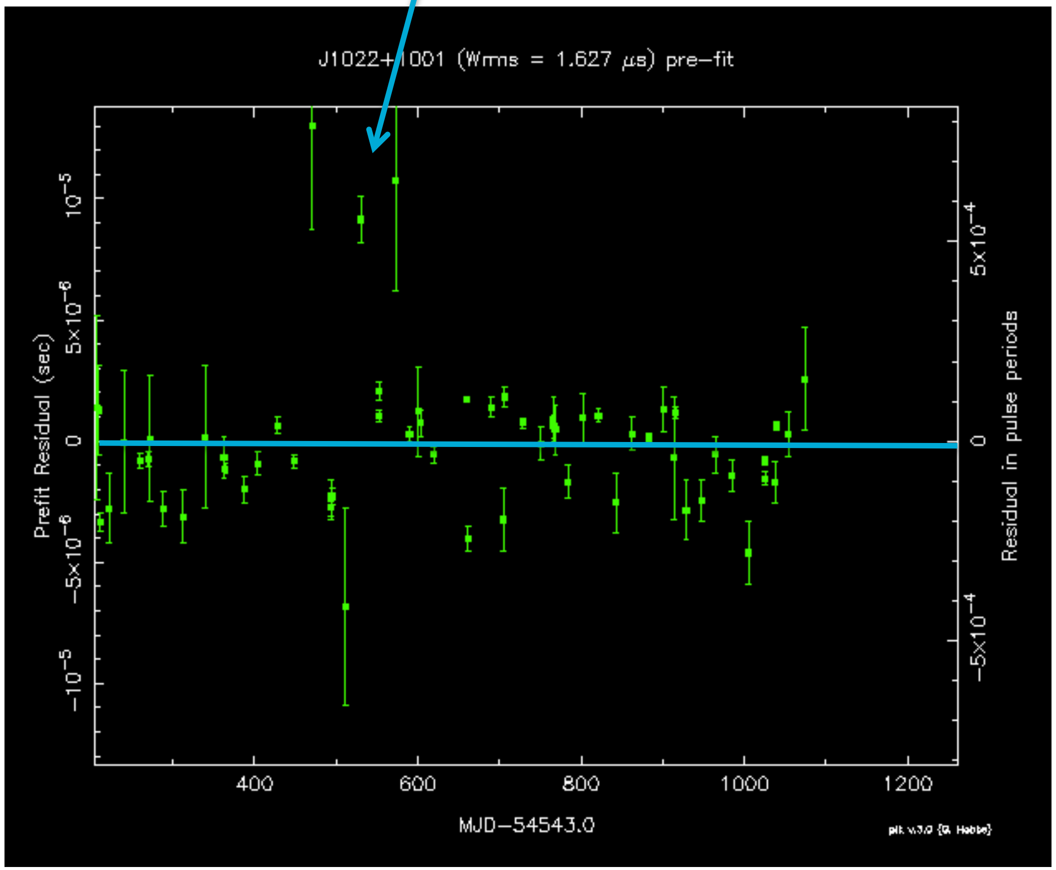
- Slide from Cognard



PSR J1022+1001: why so awful on short timescales?

- Is the pulse shape constant?
- Does our clock suddenly go wrong?
- Does the interstellar medium suddenly change?
- Are the error bars calculated correctly?
- Radio-frequency Interference
- Poor calibration?
- …
- (See Oslowski et al. 2011; Cordes & Shannon 2010 …)

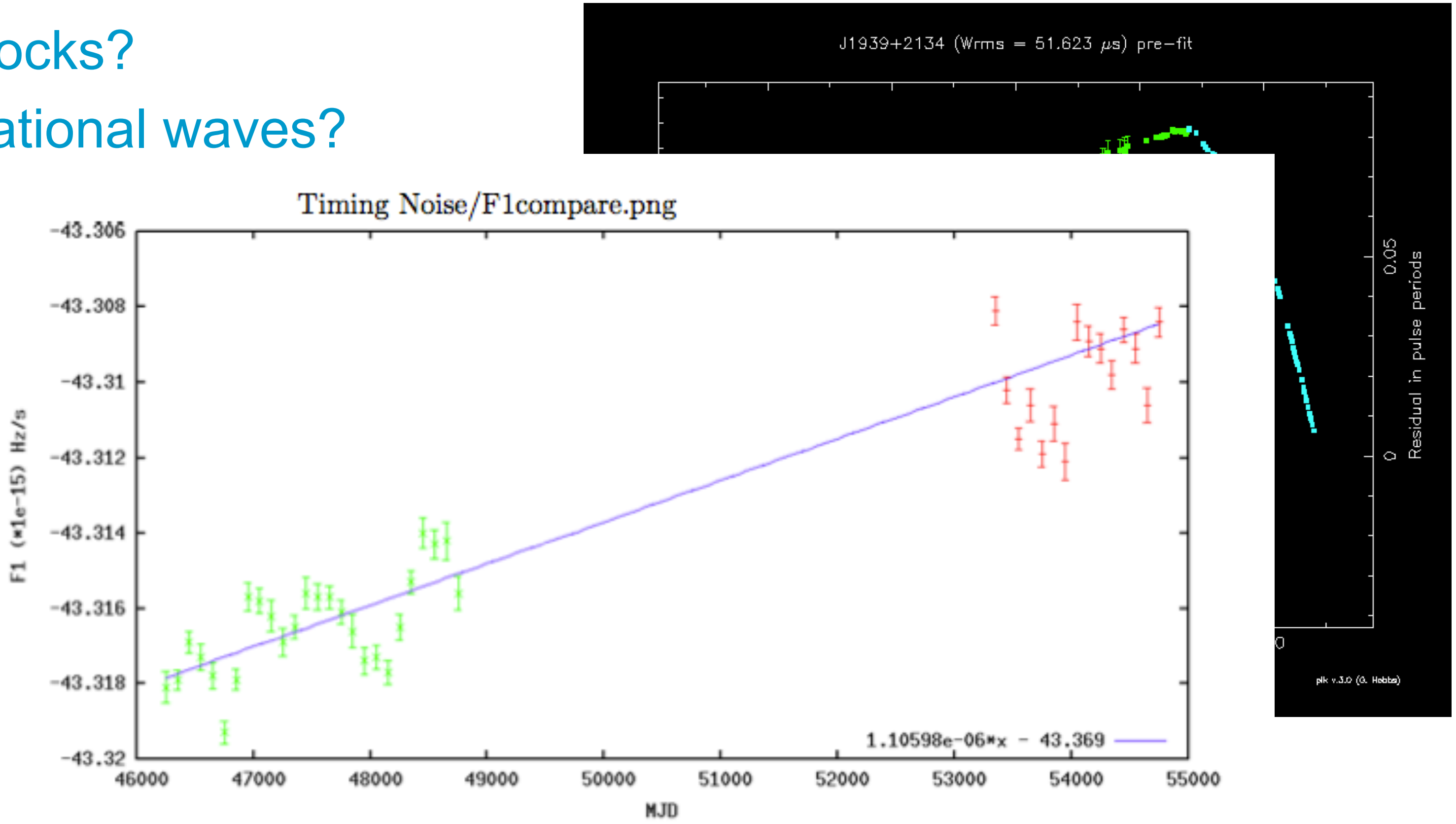
What caused this residual?



Parkes data

PSR B1937+21: Why so awful on long time scales?

- Bad clocks?
- Gravitational waves?
- Irregu
  pulsa
- Unmo
  comp
- Aster
- 2 spir



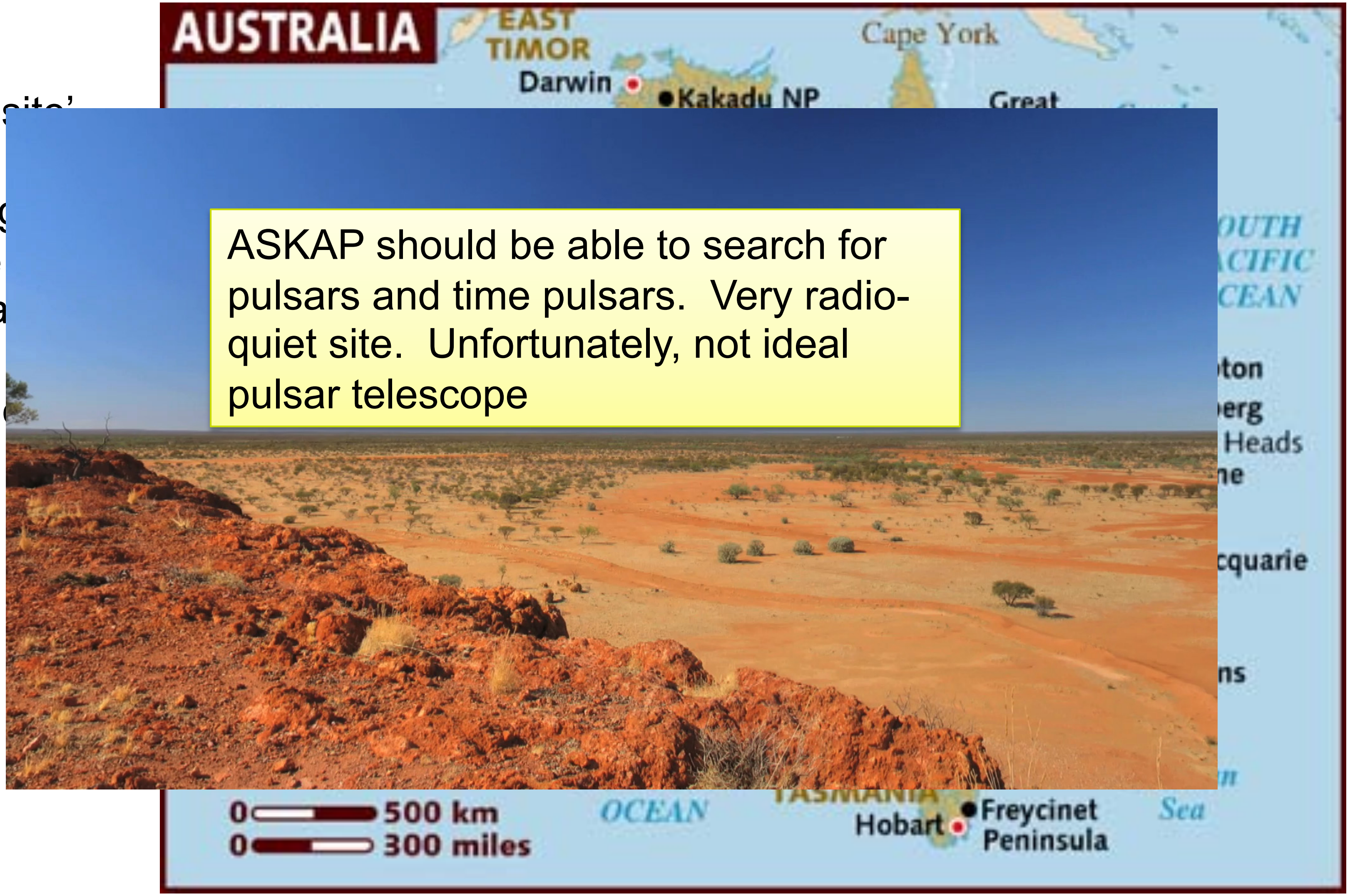
Petroff, unpublished

Future data sets: ASKAP

ASKAP site’

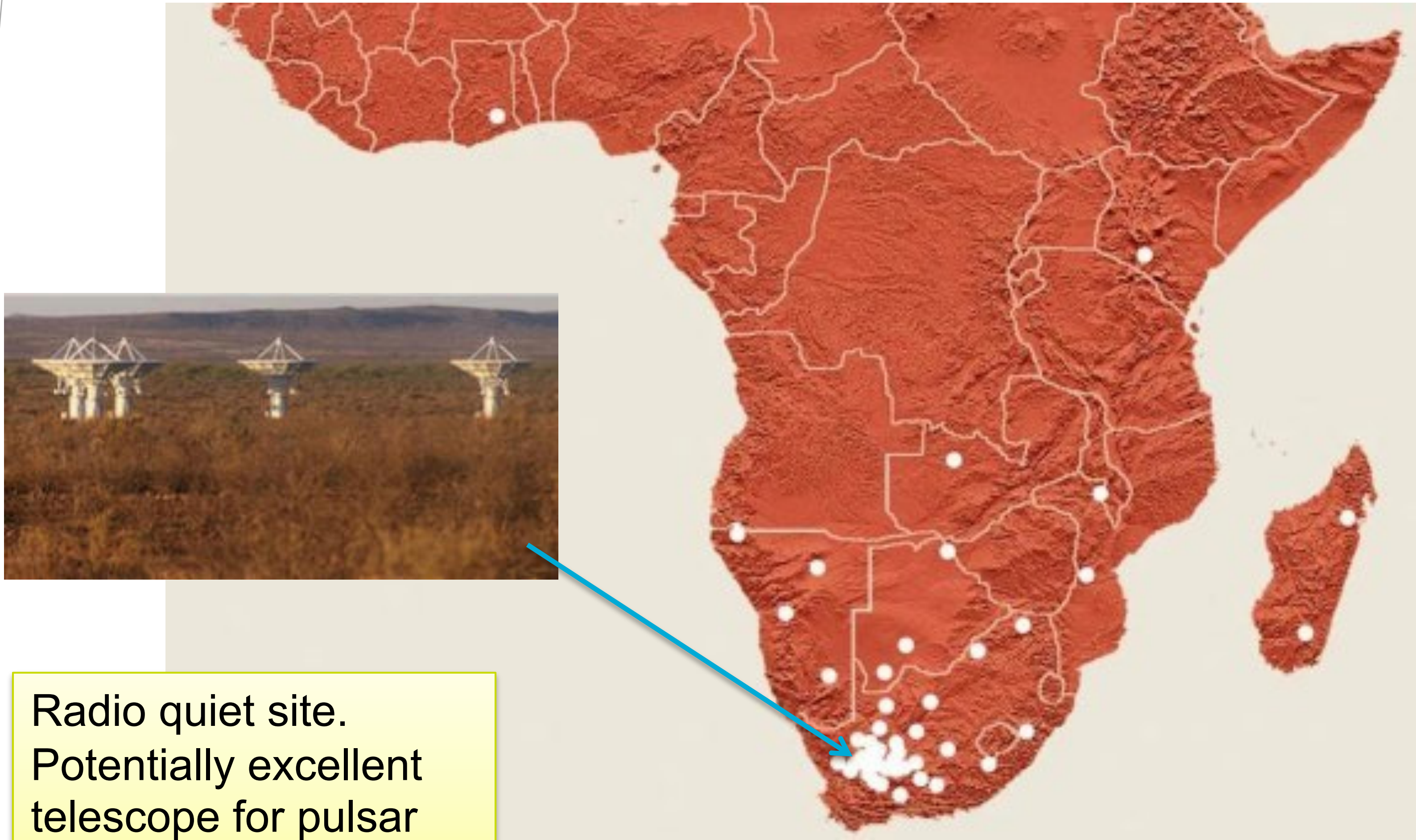
Area larg
than the
Netherla

Populati
~100



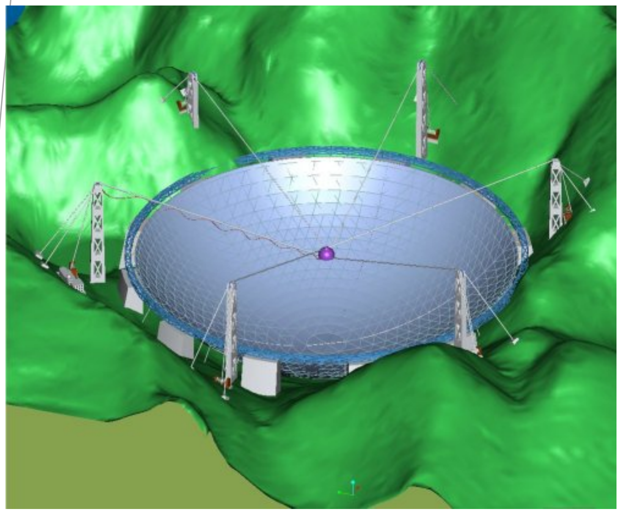
ASKAP should be able to search for pulsars and time pulsars. Very radio-quiet site. Unfortunately, not ideal pulsar telescope

Future data sets: Meerkat



Radio quiet site.
Potentially excellent telescope for pulsar observations

Future data sets: FAST



500m

Will be the largest single dish telescope!
A perfect pulsar telescope?

The telescope that we really want

- Wait for talks on Friday!!

Conclusions

- Expected gravitational wave signal from supermassive binary black holes. So many => a background of gravitational waves
- Size of background gives typical residuals < 100ns
- Lots of existing data sets (recall http://datanet.csiro.au)
- Need to observe millisecond pulsars
- Have unexplained phenomena affecting the residuals
- New telescopes being built that will produce even more data!

Next lecture:
- How do we use our existing data sets to search for gravitational wave signals?