Pulsar Timing Arrays

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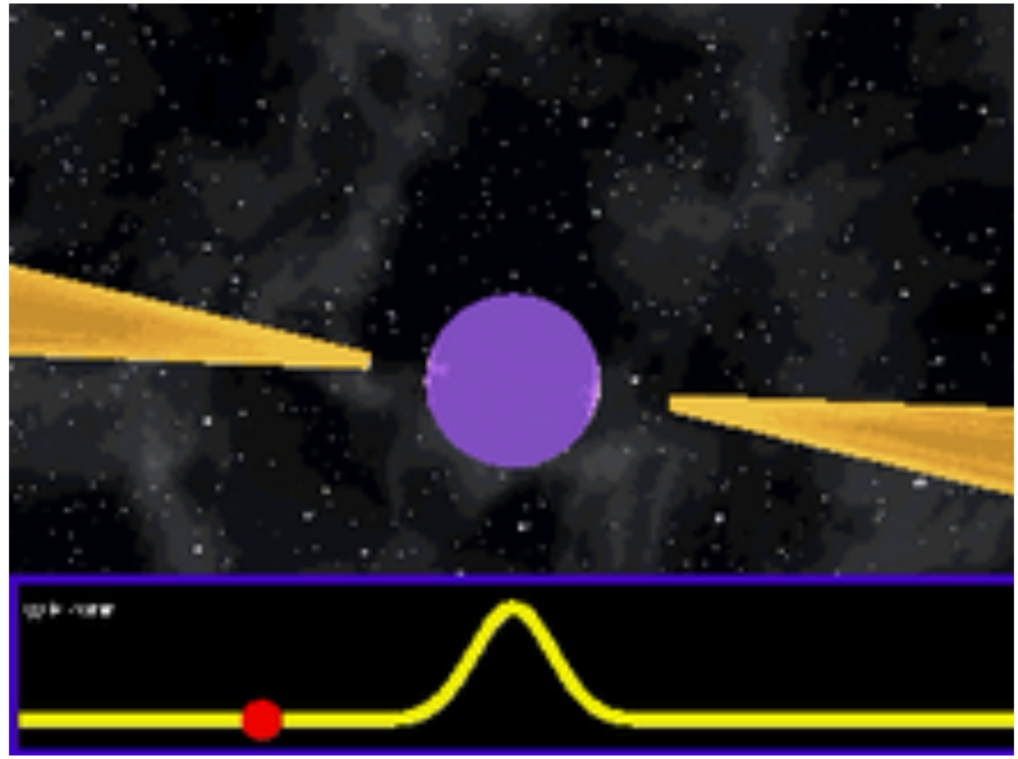
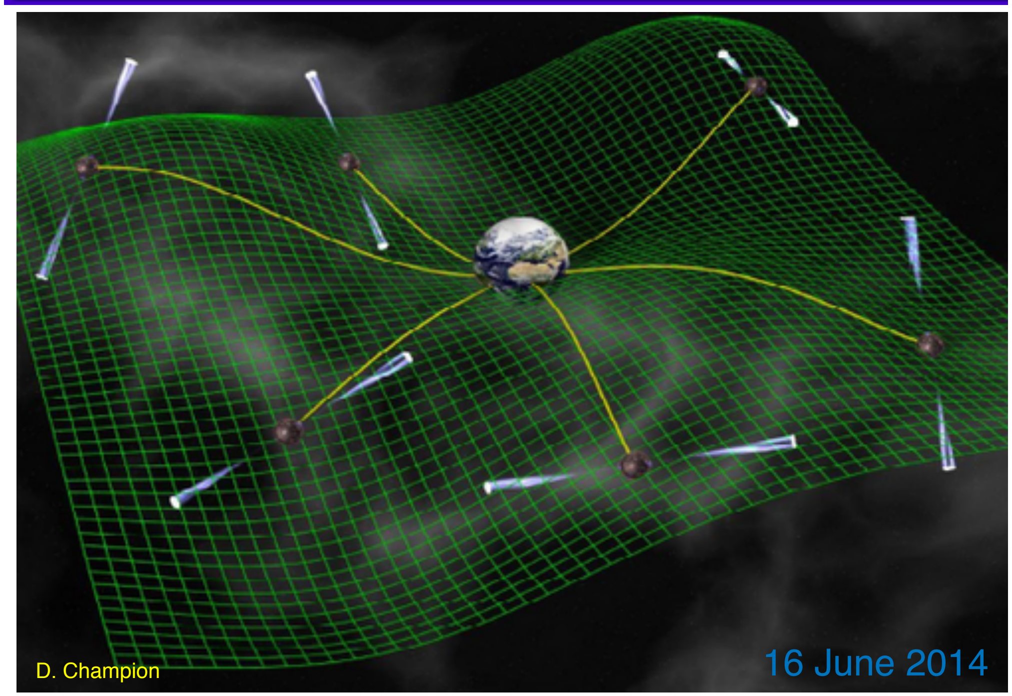




animation: Michael Kramer

Ierapetra, Crete

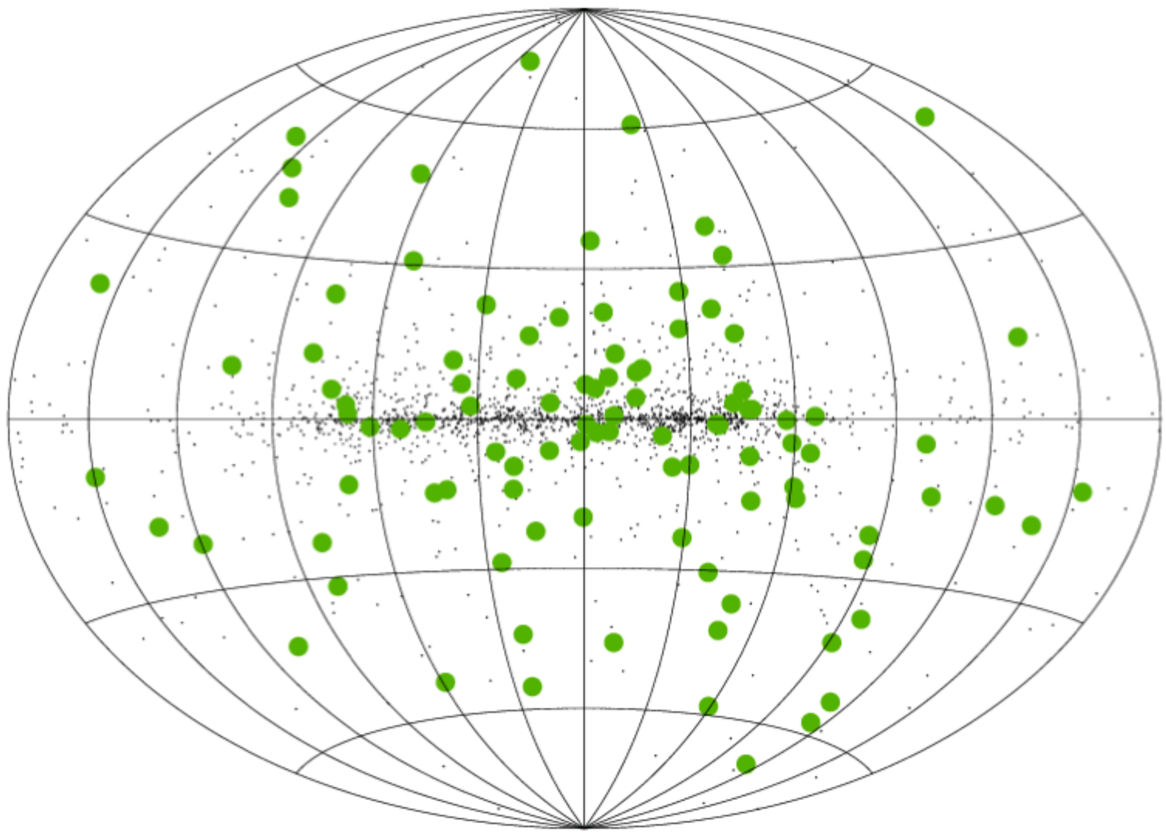
16 June 2014

Pulsar Timing Arrays

- Introduction to pulsar timing arrays
- The major worldwide pulsar timing array efforts
- Pulsar timing array projects
- Using pulsar timing arrays to detect gravitational waves
- Current status and future prospects
- What will the field look like in 5, 10, 20 years?

Pulsar Timing Array

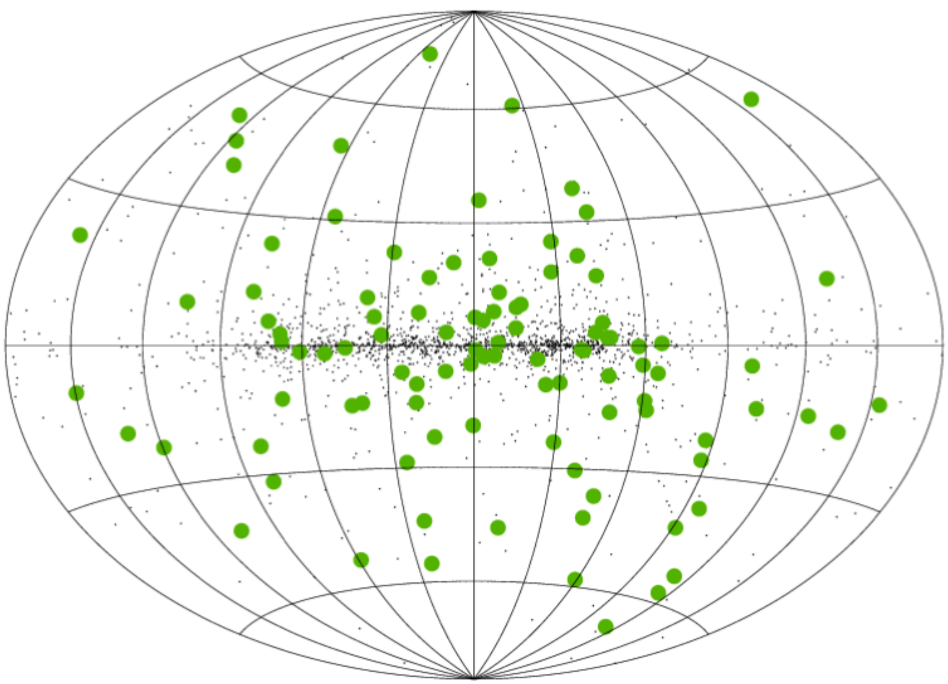
A network of pulsars that can be used to measure various effects that produce correlations in the arrival times of pulses from the members of the array.

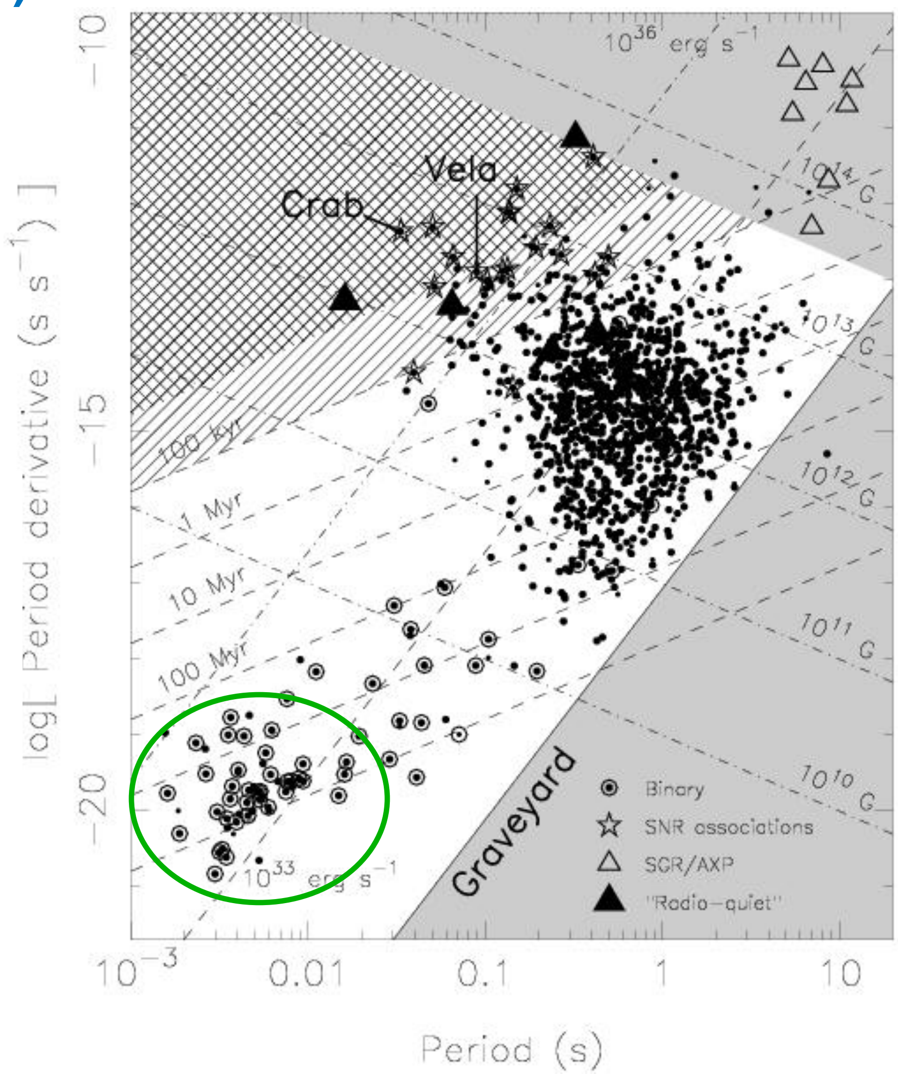


First proposed by Foster and Backer (1990).

Millisecond Pulsars (MSPs)

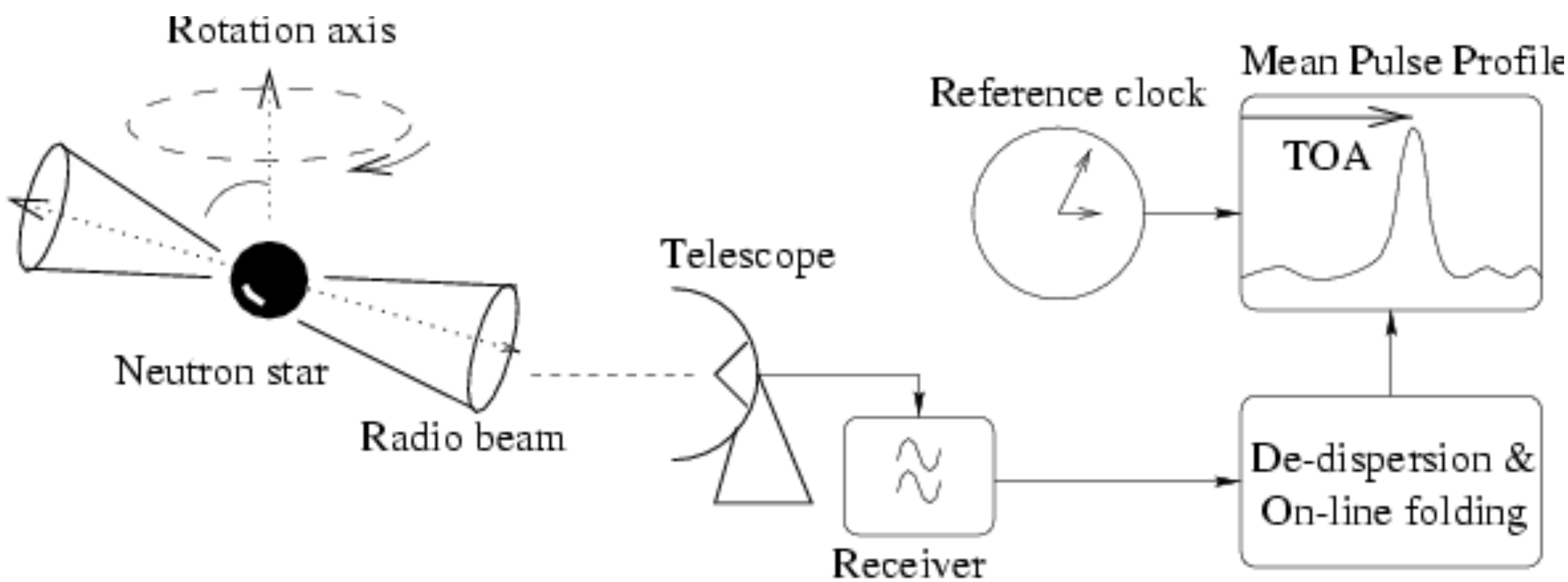
Out of over 2300 known pulsars, there are now over 217 MSPs (P < 20 ms) in our Galaxy, out of roughly 30,000 detectable. Galactic MSPs are local (d ~ 1 kly) and roughly isotropically distributed.





They are incredibly stable rotators, making them excellent fundamental physics laboratories.

What data does a PTA produce? Times-of-arrival!



Lorimer & Kramer, 2005, “Handbook of Pulsar Astronomy”

On-line folding: adding many pulses together to get stable mean pulse profile

De-dispersion: correcting for frequency-dependent interstellar delays

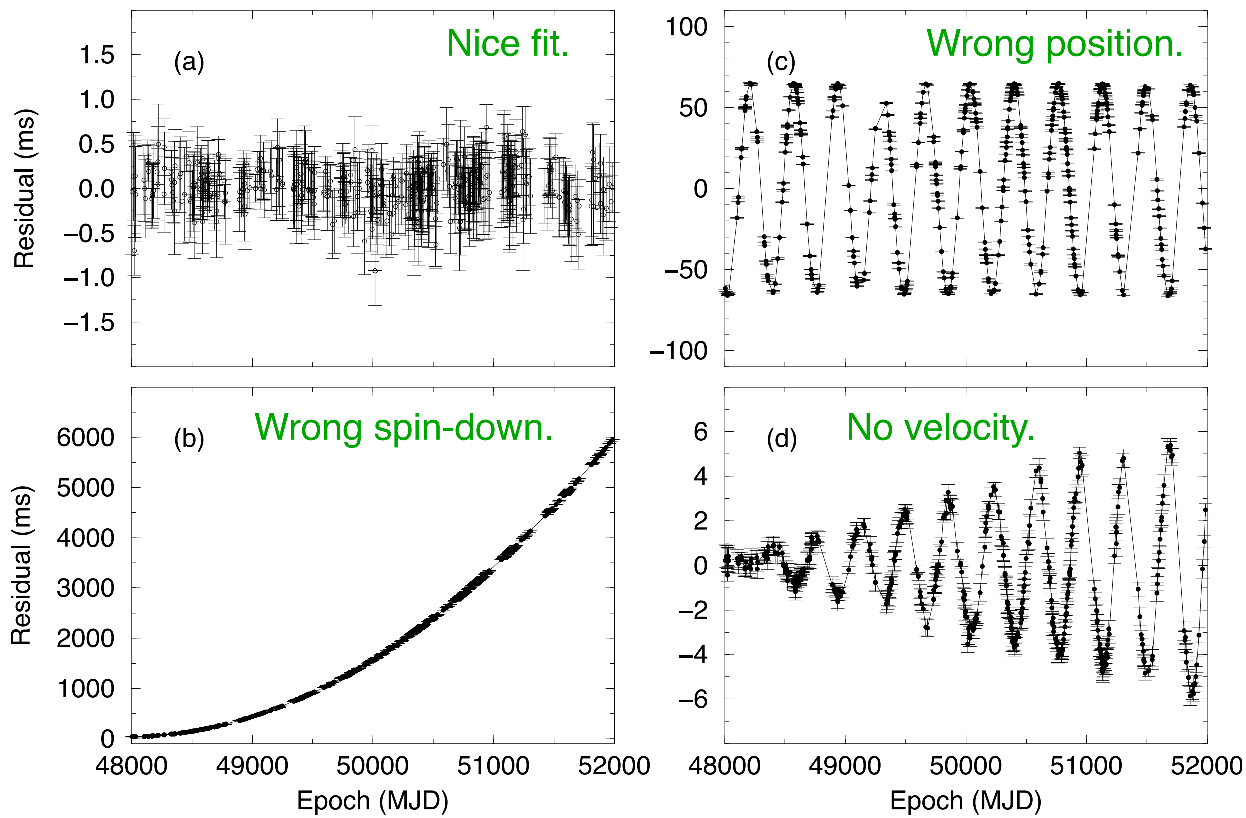
Obtaining a Timing Model and Residuals

$$\mathrm{TOA}_{\mathrm{SSB}} = \mathrm{TOA}_{\mathrm{topo}} + t_{\mathrm{corr}} - \Delta D/f^2 + \Delta_{\mathrm{R}\odot} + \Delta_{\mathrm{S}\odot} + \Delta_{\mathrm{E}\odot}$$

Timing Residuals = Model – Measured TOAs

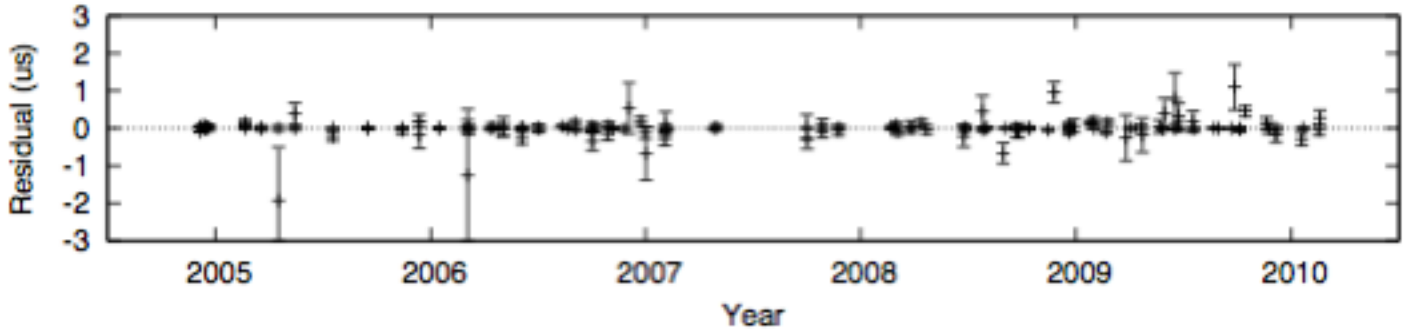
We fit for:

- period
- period derivative
- position
- dispersion measure
- *variations in DM*
- *proper motion*
- *parallax*
- *binary parameters*
- *relativistic binary parameters*



Typical Residuals for a Millisecond Pulsar

J1713+0747 P = 4.57 ms



Demorest et al. 2013, ApJ, 762, 94

σ_{RMS} = weighted root-mean-square residual = 70 ns (6 x 10^{-6} P)

after fitting for spin, astrometric, Keplerian, and post-Keplerian parameters and time-variable dispersion measure changes.

Arrival times measured to tens of nanoseconds and periods to 1 part in 10^{15}.

Today at 9:10 am, the spin period of this pulsar is

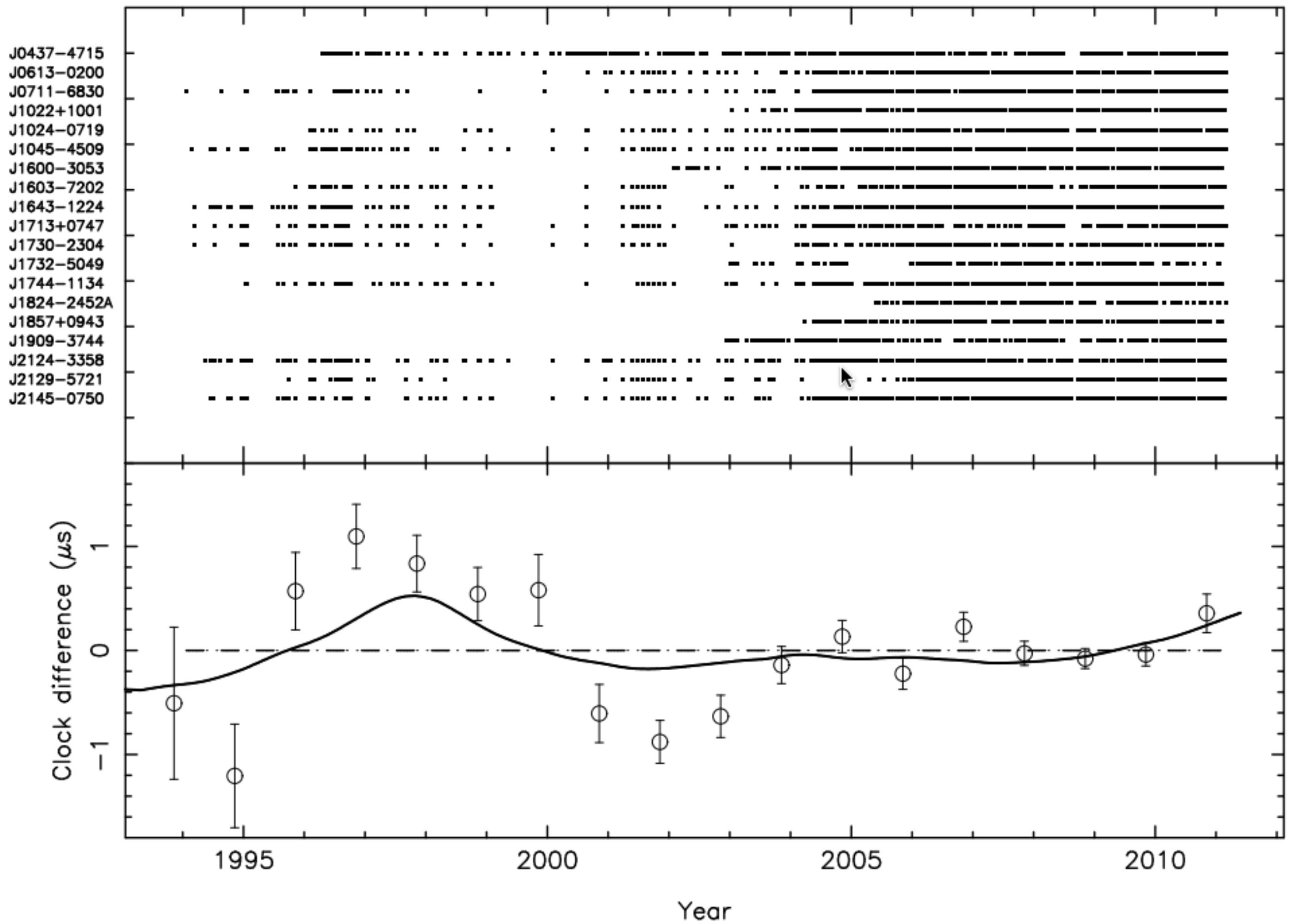
4.5701365286377(3) milliseconds.

Pulsar Timing Array projects

- a pulsar-based timescale -> monopole effect

PTA-based timescales now have precision comparable to commonly-used international timescales.

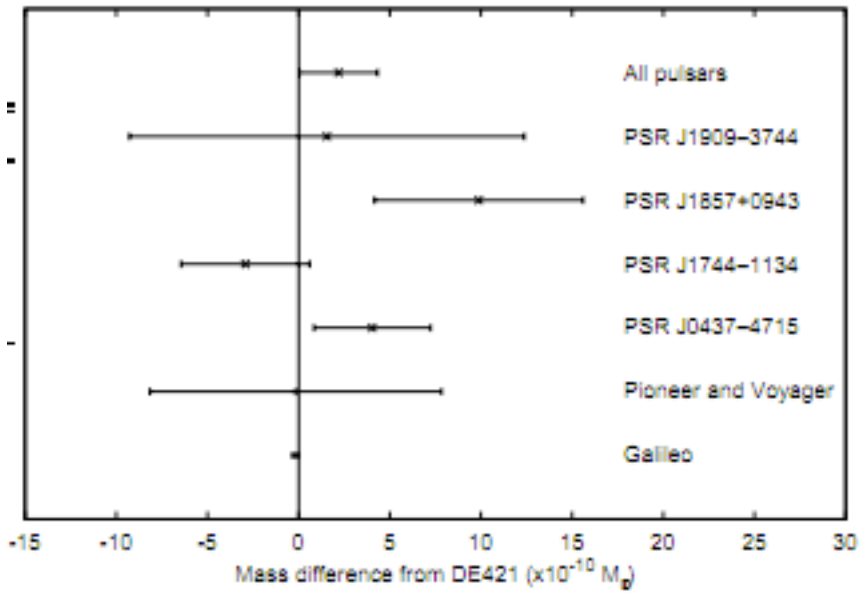
Marginal evidence for differences between pulsar and BIPM time.

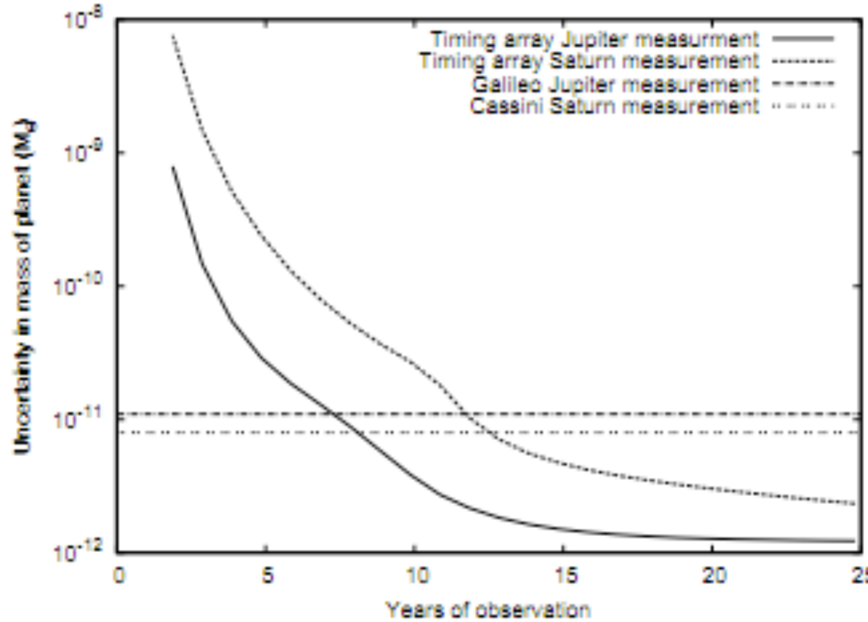


Hobbs et al. 2012, MNRAS, 427, 2780

Pulsar Timing Array projects

- measurement of solar system masses -> dipole effect



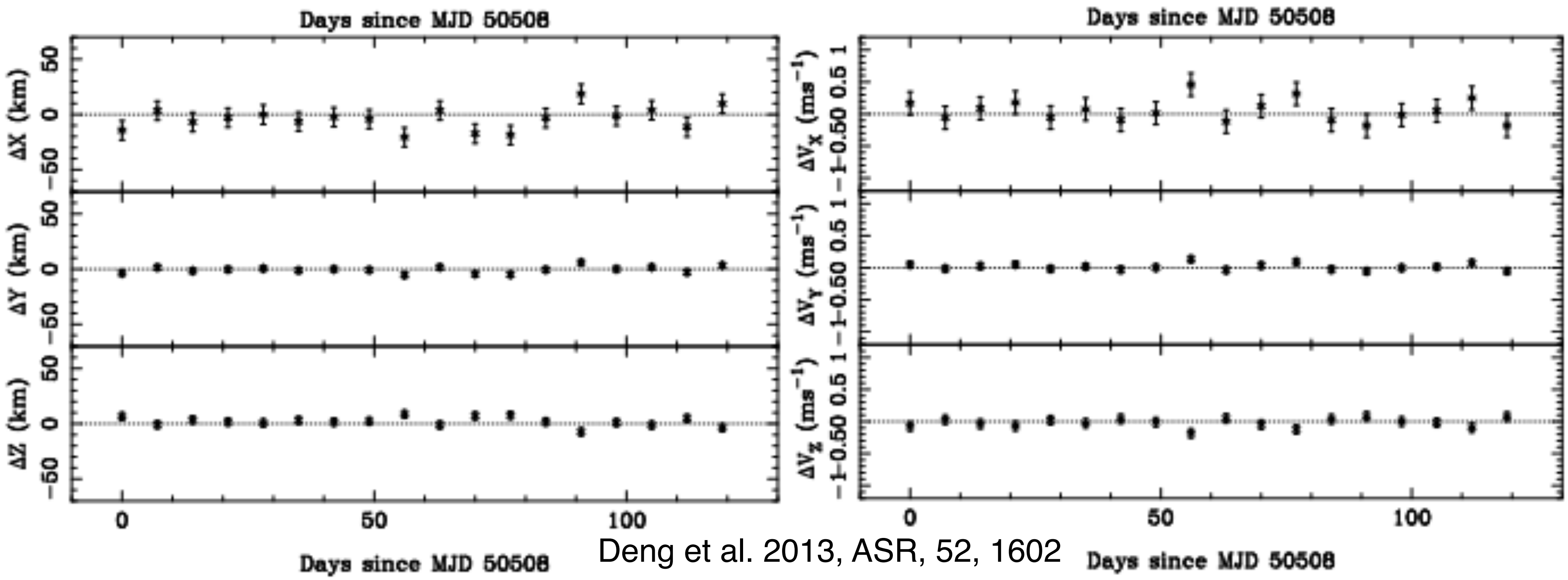


Champion et al. 2010, ApJ, 720, L201

Pulsar timing could provide the most accurate mass measurements for some planets!

Pulsar Timing Array projects

- interplanetary space navigation -> dipole effect



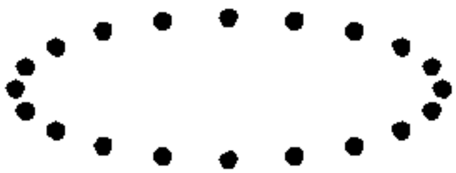
Deng et al. 2013, ASR, 52, 1602

Through X-ray timing measurements of four MSPs observed from an Earth-Mars spacecraft, can determine positions to 20 km and velocities to 0.1 ms.

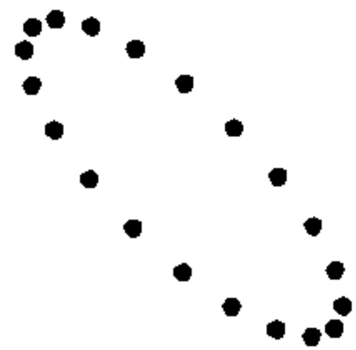
Pulsar Timing Array projects

- gravitational wave detection -> quadrupolar effect

h_+



h_x

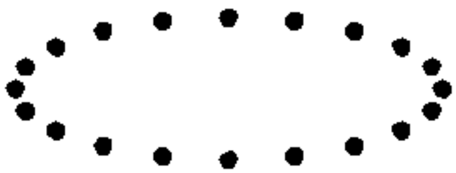


h = strain = $\Delta L/L$ = 0.5
frequency = 1/(2 seconds) = 0.5 Hz
speed = c
wavelength = 6 x 10^8 m

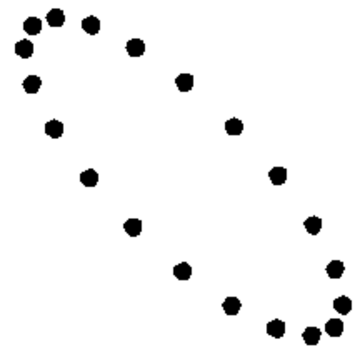
Gravitational Waves

- systems with varying quadrupolar moments will emit GWs

h_+



h_x



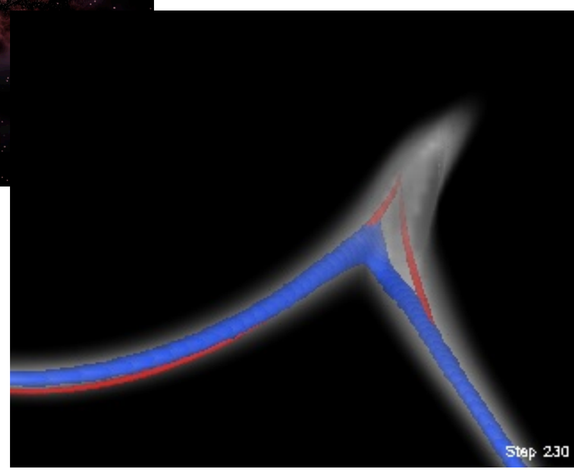
h = strain = ΔL/L = 0.5
frequency = 1/(2 seconds) = 0.5 Hz
speed = c
wavelength = 6×10^8 m

Why study them?

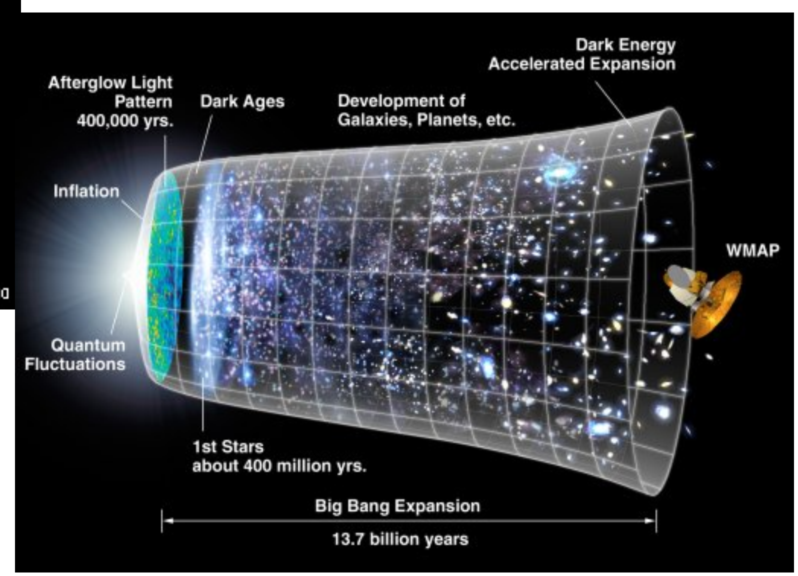
Continuous

Test GR and study things not able to be studied electromagnetically!

Burst



Stochastic

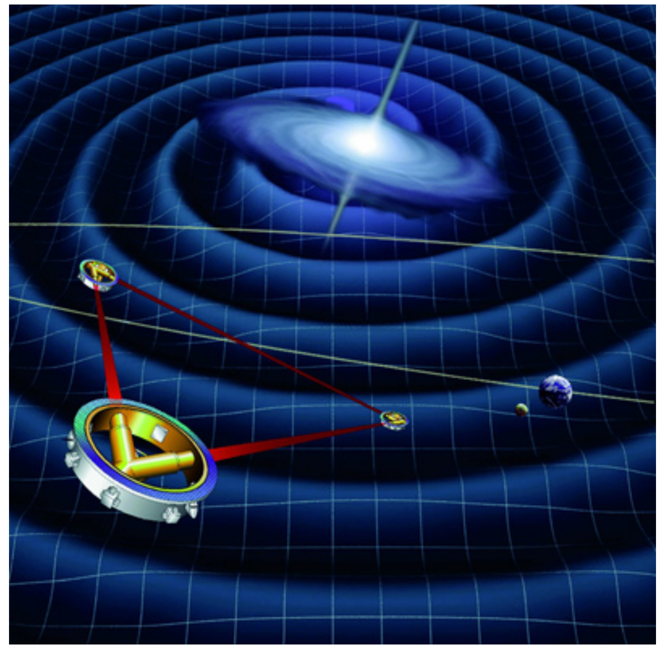


Worldwide direct detection efforts

LIGO

f ~ 1/ms (100 – 1000 Hz)

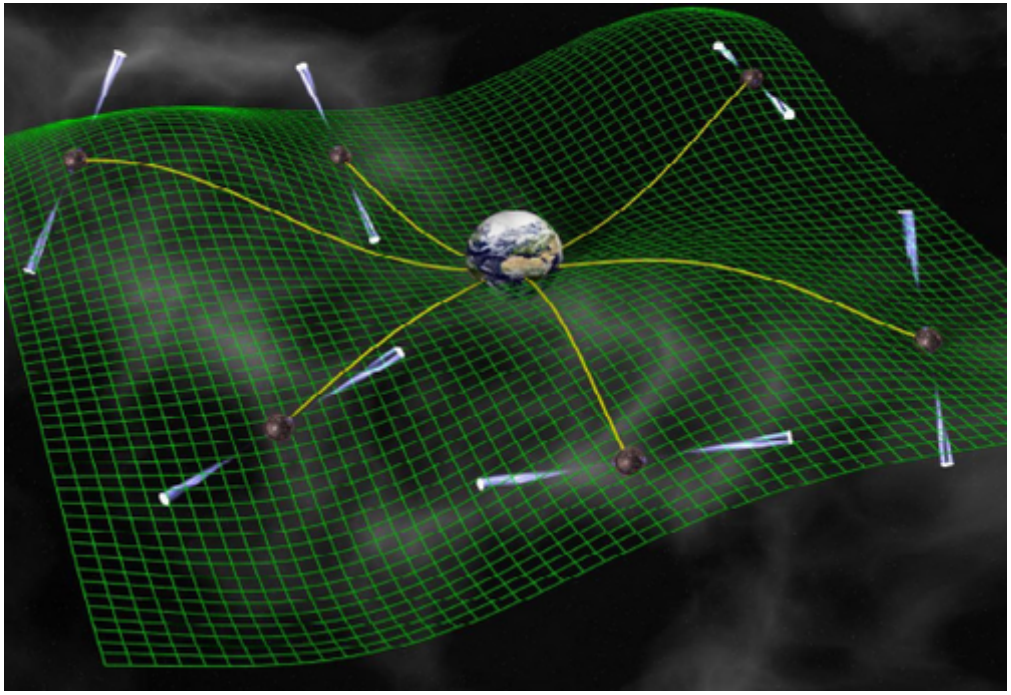
eLISA



f ~ 1/(mins-hrs) (10^{-2} – 10^{-3} Hz)

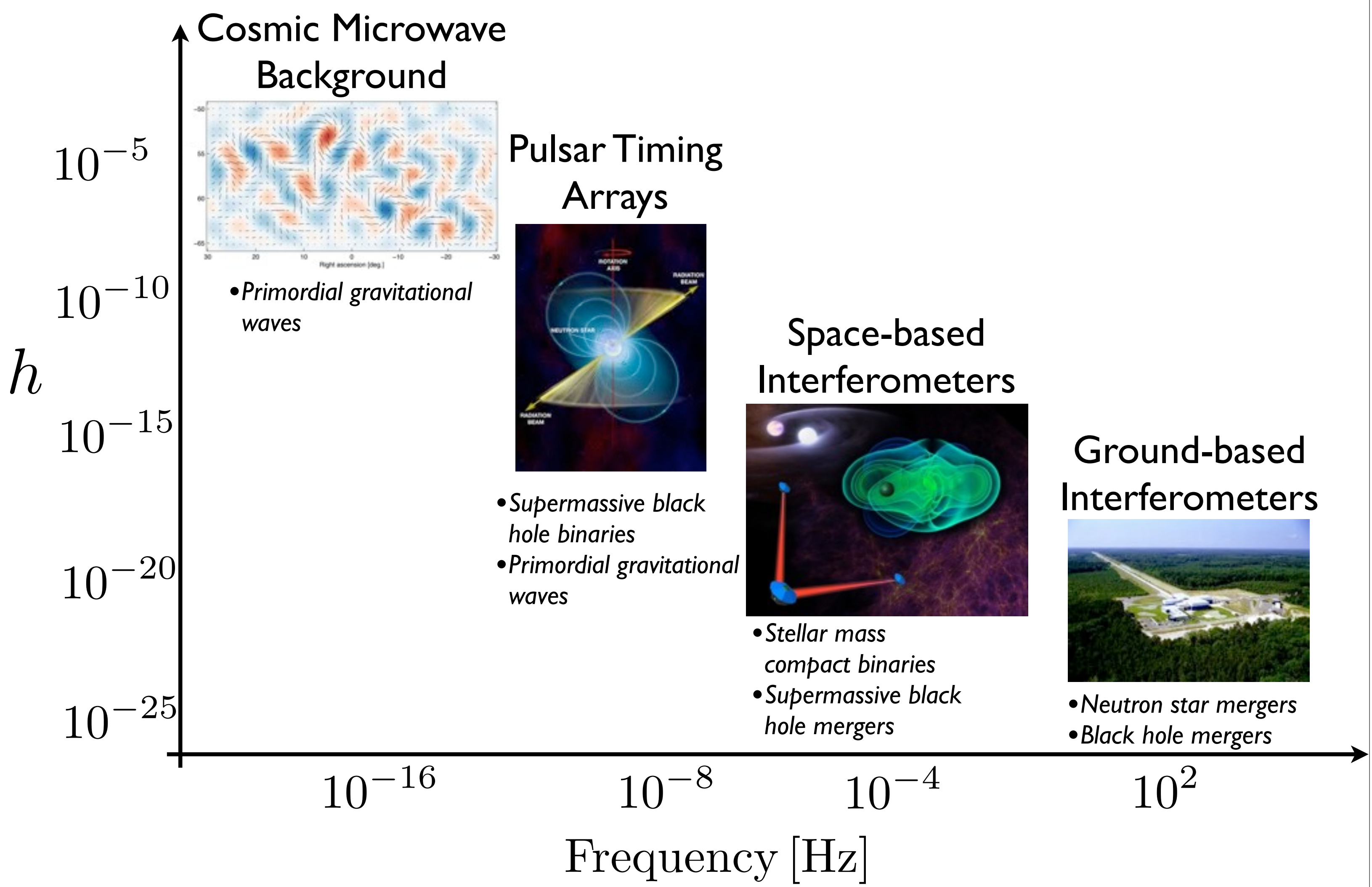
Worldwide direct detection efforts

Pulsar Timing Array



f ~ 1/(weeks-years) ($10^{-6} - 10^{-9}$ Hz)

The big picture of gravitational-wave astronomy



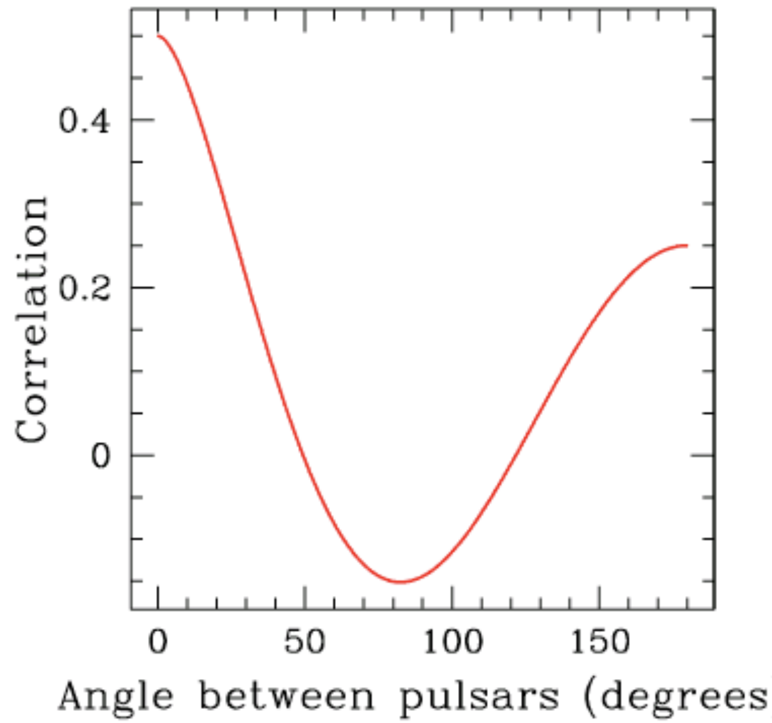
Detecting a stochastic background with a PTA

Expected correlation of residuals for pairs of pulsars versus angular separation on sky. Pulsar terms uncorrelated. Earth terms correlated.

$$C_{y,ij}^{(ab)} = E\left\{y_a(t_i)y_b(t_j)\right\}$$

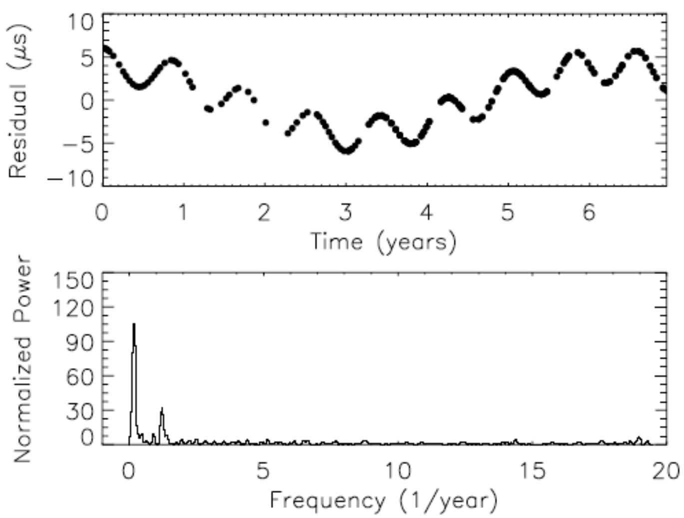
$$= C_y(t_i - t_j)\zeta(\theta_{ab})$$

Clock errors monopole.
Ephemeris errors dipole.
GWs quadrupole.



Hellings & Downs, 1983, ApJ, 265, L39

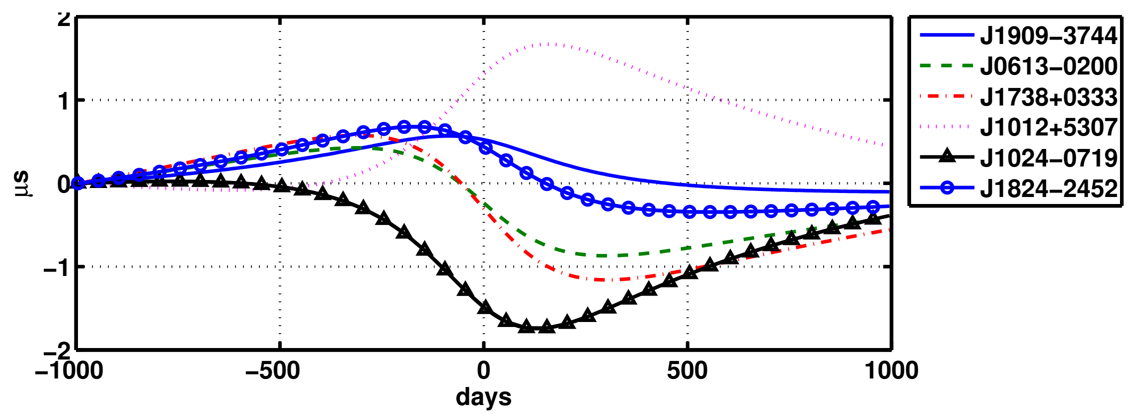
Also continuous wave and burst source detection



Also bursts with memory from SMBH mergers

Jenet et al. 2004, ApJ, 606, 799

50 billion solar mass binary with period of one year at 100 Mpc.



Finn & Lommen, ApJ, 2000, 718 1400

Parabolic encounter of two billion solar mass black holes at 20 Mpc.

Supermassive Binary Black Holes

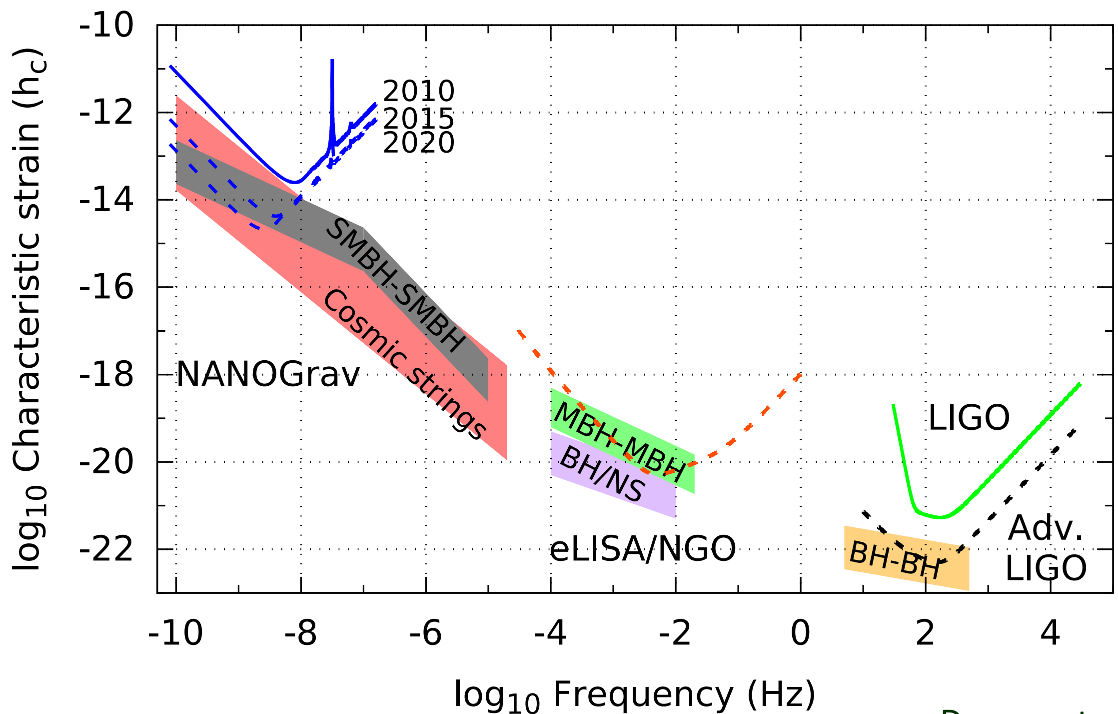
$$h_c(f) = A \left(\frac{f}{\mathrm{yr}^{-1}} \right)^{\alpha}$$

For SMBH binaries, h ~ $f^{2/3}$ and lifetimes τ ~ $f^{-8/3}$. Sum over many systems results in α = -2/3. Amplitudes depend strongly on SMBH masses and galaxy merger rate as a function of redshift, with A α $N^{1/2}$M (Sesana et al. 2008, Sesana 2012).

Other possible sources:

cosmic strings
α = -7/6
(Damour & Vilenkin 2005; Seimens 2007)

early universe inflation
α = -0.1
(Grishchuk 2005)



Demorest

Pulsar Timing Array Efforts

This project involves regular, high-precision observations of as many MSPs as possible at a frequent cadence and at multiple observing frequencies, accompanied by ample development work to correct TOAs for subtle propagation and intrinsic effects and to detect weak signals in noisy data and interpret those in astrophysical contexts.

This is a LOT of work….and requires international collaboration!

The International Pulsar Timing Array

Formed in 2008 and now has roughly 100 members from 30 institutions in 8 countries.

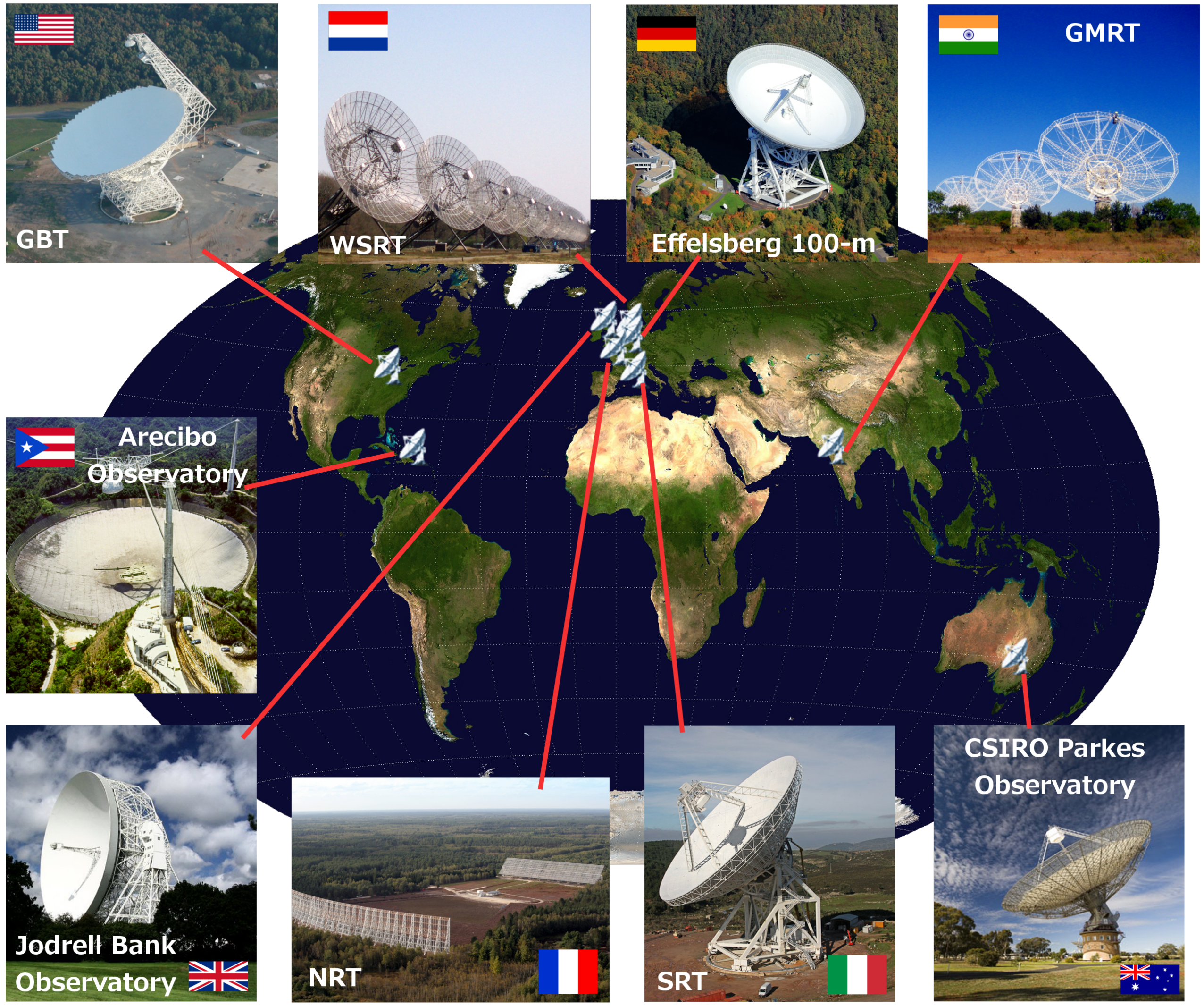
ipta4gw.org

A consortium of consortia

EPTA

NANOGrav

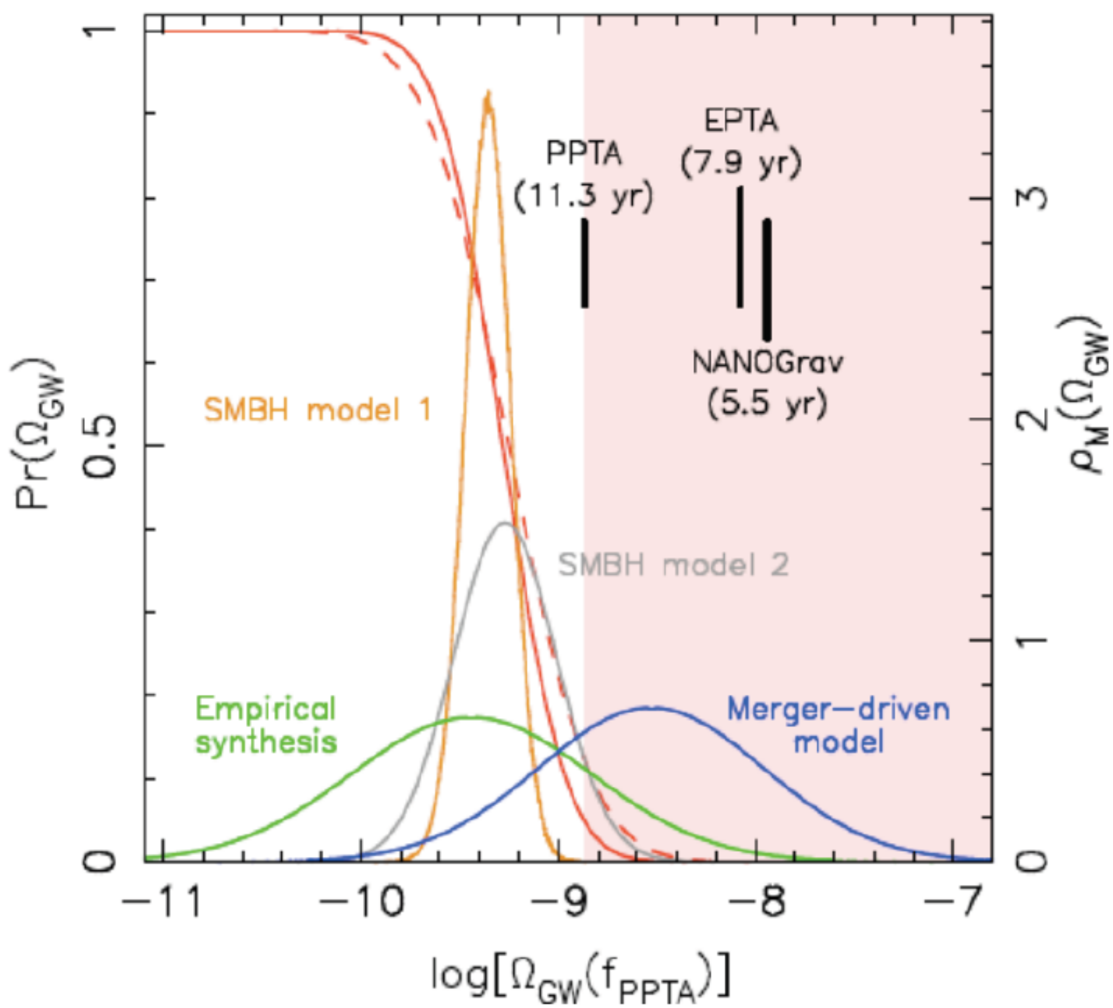
PPTA



Brian Burt

Currently timing 106 MSPs (70 independent MSPs) at six radio frequencies at nine telescopes. There are roughly 50,000 TOAs spanning 10 years in the current release.

Most recent limits are beginning to rule out SMBH formation and evolution models



Shannon et al. 2013 Science, 342, 334

When we will make a detection and how can we get there faster?

$$SNR \propto N_{psr} \left(\frac{\sqrt{c}}{\sigma_{rms}} \right)^{3/13} T^{1/2}$$

N_{psr} = number of pulsars in the array

c = observation cadence

σ_{rms} = average residual RMS

T = total time span of data

See Siemens et al. arXiv:1305.3196.

Improvement 1: Time

Improvement 2: Cadence

TOA TOA TOA

TOA

TOA

TOA

TOA

TOA

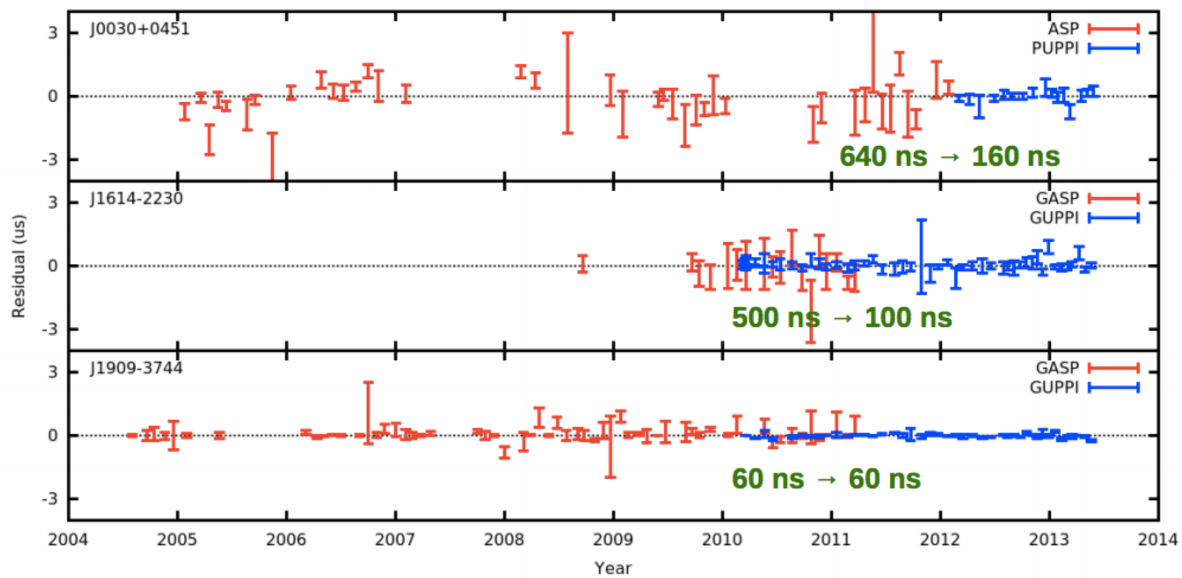
TOA

Improvement 3: More precise TOA measurements

$$\sigma_{\rm RMS} \sim \ \sigma_{\rm TOA} \sim \frac{w}{SNR} \propto \frac{w}{S_{\rm PSR}} \frac{T_{sys}}{A} \frac{1}{\sqrt{BT}}$$

We want *bright pulsars* with *narrow pulses* observed with *sensitive receivers* with *large telescopes* over *large bandwidths* and with *long integration times*.

New instrumentation at all telescopes is dramatically increasing our available bandwidth.

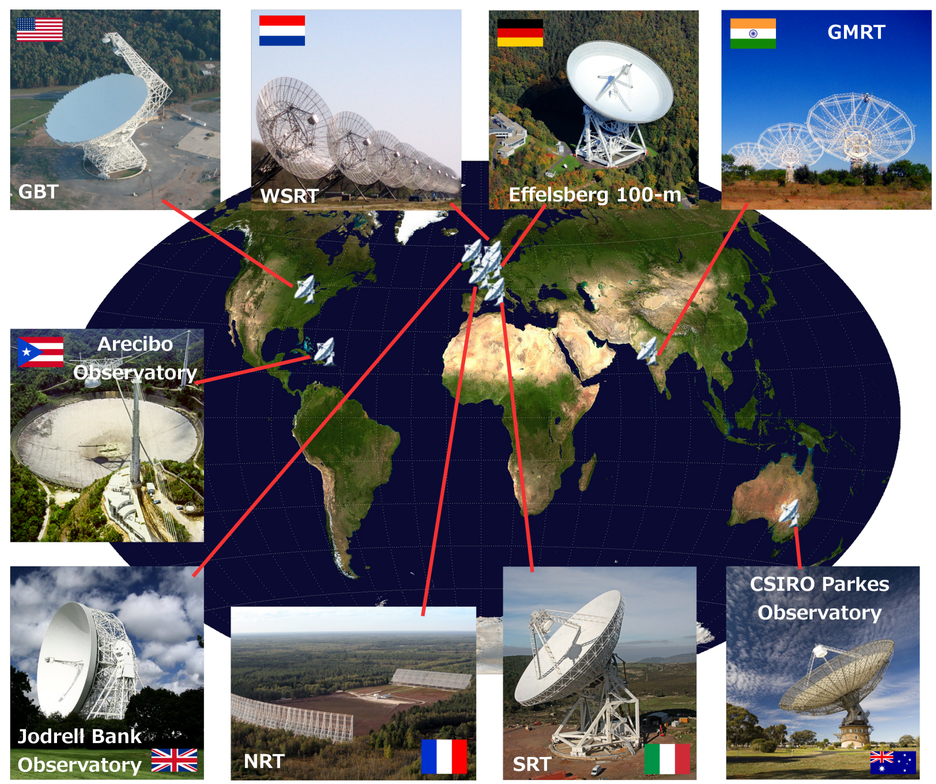


Improvement 3: More precise TOA measurements

$$\sigma_{\mathrm{RMS}} \sim \sigma_{\mathrm{TOA}} \sim \frac{w}{SNR} \propto \frac{w}{S_{\mathrm{PSR}}} \frac{T_{sys}}{A} \frac{1}{\sqrt{BT}}$$

We want *bright pulsars* with *narrow pulses* observed with *sensitive receivers* with *large telescopes* over *large bandwidths* and with *long integration times*.

We are using the most sensitive radio telescopes in the world and are steadily increasing our time on them. ***(We must retain access to these telescopes!!)***

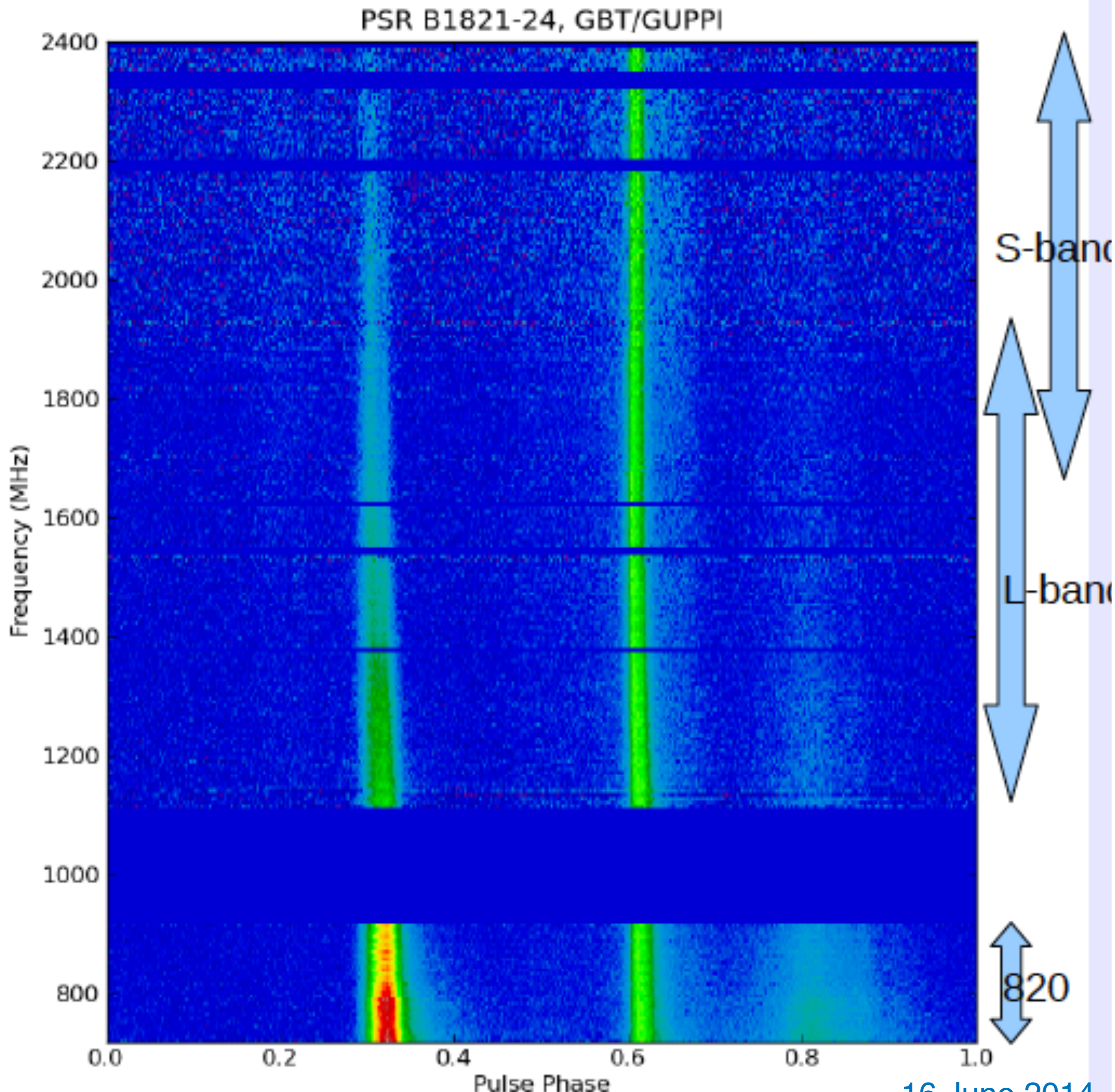


Brian Burt

Improvement 3: More precise TOA measurements

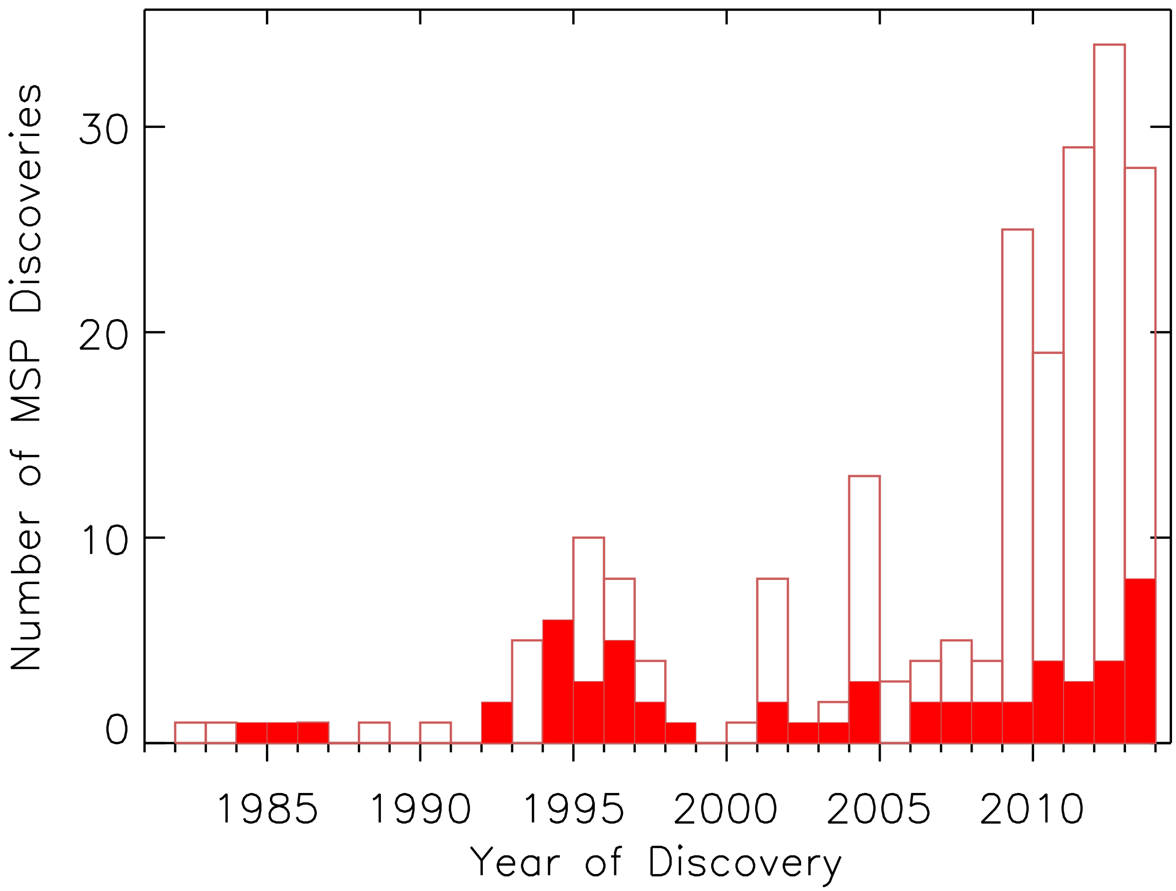
Super-wideband receivers would be optimal for dispersion correction.

Challenge is getting low system temperature and accounting for pulse profile evolution.



Improvement 4: More MSPs

See http://astro.phys.wvu.edu/GalacticMSPs

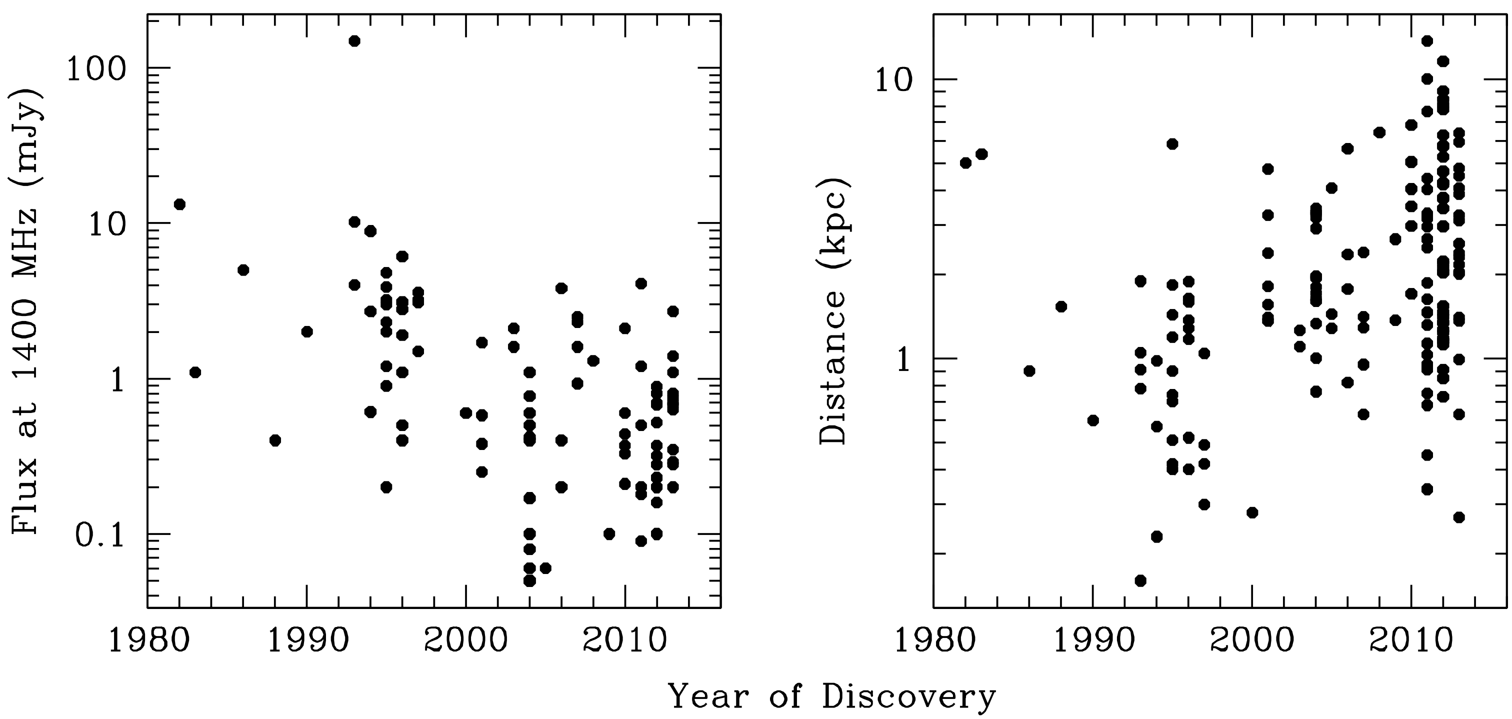


Radio searches (aided by *Fermi* gamma-ray identifications) have ***more than doubled*** the Galactic MSP population since 2010. Ongoing searches with the world's largest telescopes should reveal an additional 100 over the next several years.

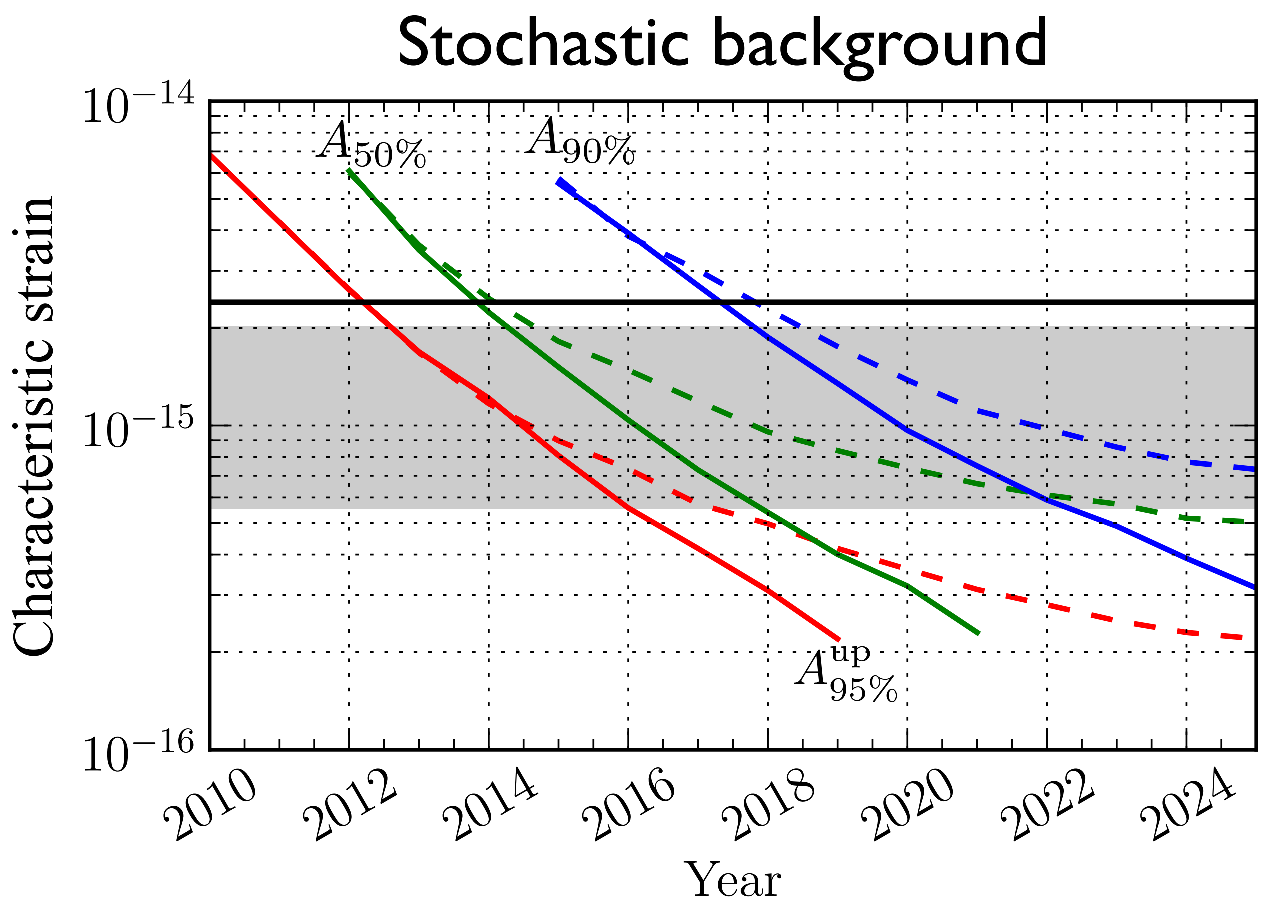
Improvement 4: More MSPs

Many bright and nearby MSPs remain to be found, meaning dramatic increases in our sensitivity are possible.

See http://astro.phys.wvu.edu/GalacticMSPs



When will we detect GWs?



Very likely to make a detection in the next 10 years and possibly in the next 4 years!

It is also possible that a continuous wave source will be the first detection, especially if a follow-up to an electromagnetically identified candidate!

The Future

(i.e. bold and off-the-cuff but not completely unfounded predictions)

- Present – 2015: Building our Observatory

    20 MSPs @ < 200 ns, 5 @ < 50 ns

    - Intensive pulsar searching, investigations of timing noise, and development of timing and detection algorithms.

- 2015 – 2025: The Era of Detection with FAST and SKA Pathfinders

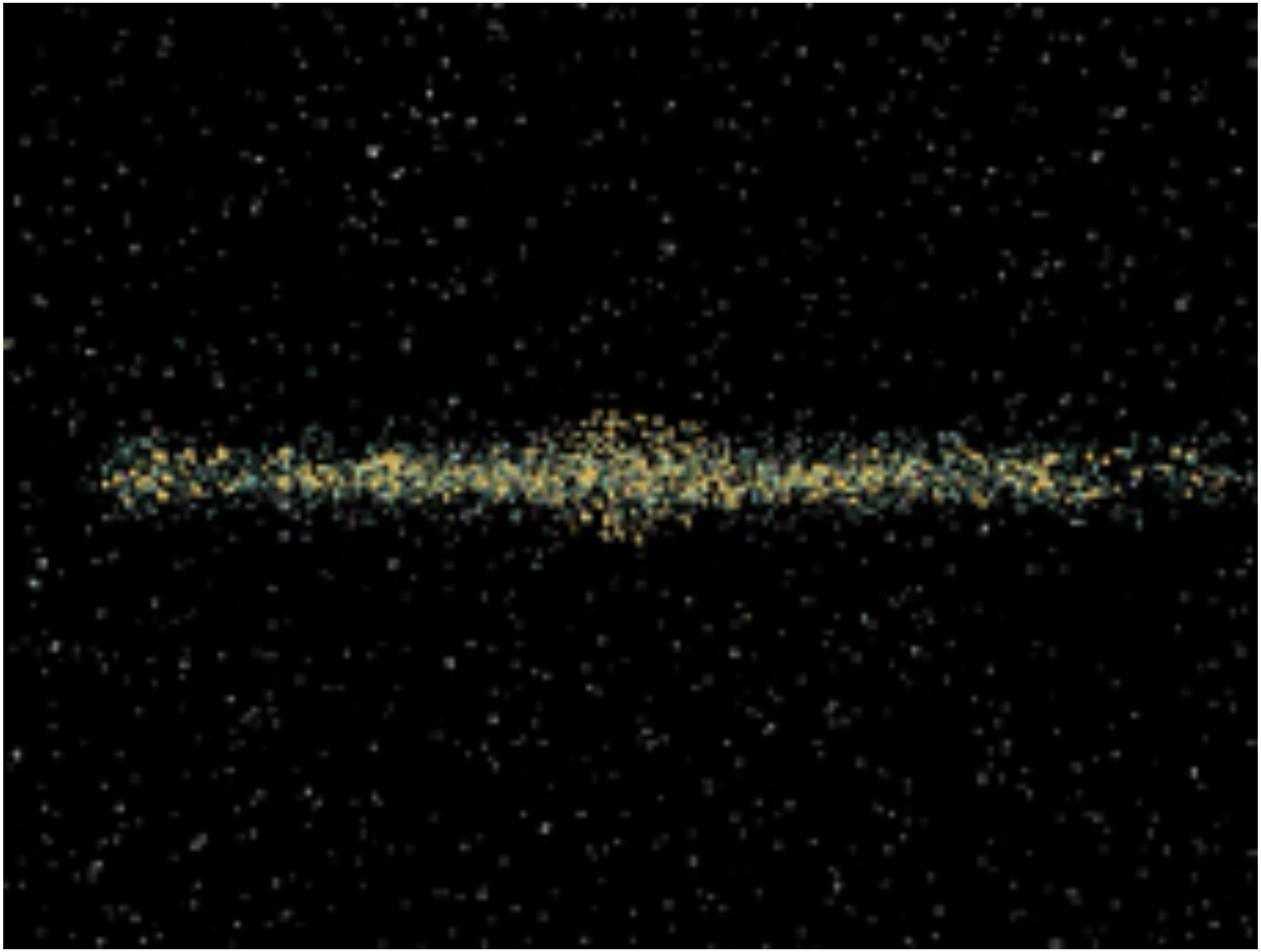
    100 MSPs @ < 200 ns, 10 @ < 50 ns, 2 @ < 10 ns

    - Stochastic background and several single sources detected. Amplitude of GWB measured, with some implications for SMBH binary population. Orbital parameters and burst amplitudes for individual sources estimated.

- 2025 – 2035: The Era of GW Astrophysics with the SKA

    200 MSPs @ < 100 ns, 50 @ < 50 ns, 10 @ < 10 ns

    - Spectral slope of stochastic background determined, allowing multiple contributions to be distinguished, and hundreds of single continuous and burst sources identified, with localization allowing electromagnetic follow-ups.



credit: Michael Kramer

Kramer