Pulsar Timing Arrays as Galactic Scale Gravitational Wave Detectors: Systems-level Overview

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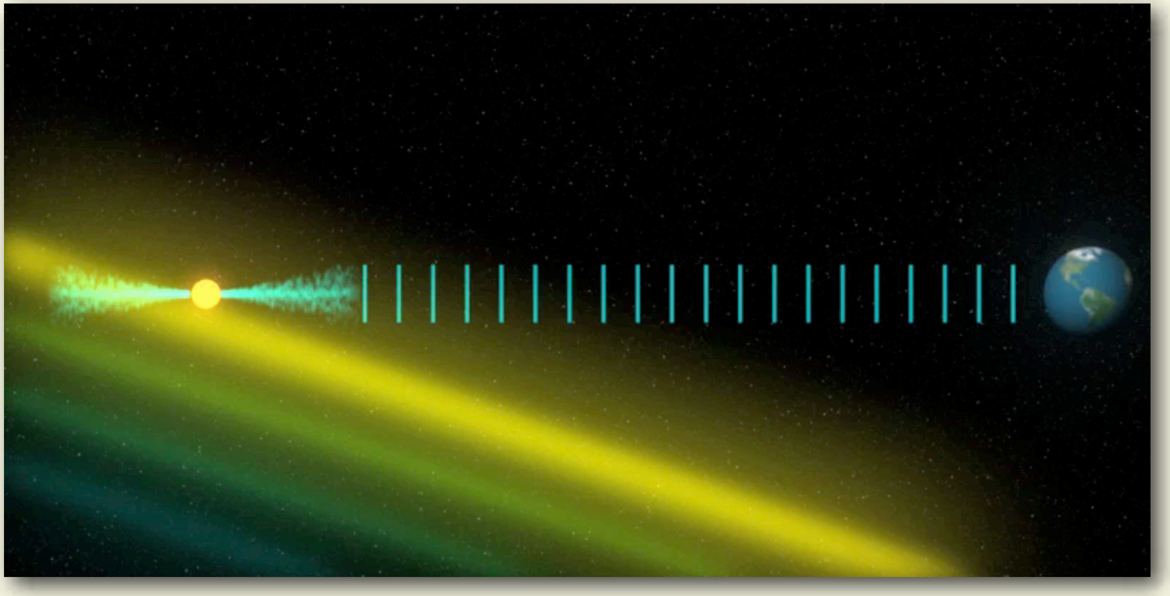
A Galactic Scale Gravitational Wave Detector for nanohertz frequencies

- How PTAs work
- PTA Target Science
- The International PTA Collaboration
- The PTA Observing System

Gravitational waves disturb pulse arrival times

Passing gravitational waves change distance traveled by successive EM pulses



Signal is *irregularity in pulse arrival times*

(Magnitude: $h/\omega_{gw} \sim$ ns)

Measure pulse arrival times and compare against expectation

Gravitational wave disturbance is correlated among pulsars; so, *time an array of pulsars:* The Pulsar Timing Array

Pulsar Timing GW “antennas” operate in the (very!) large antenna limit

- Ground-based detectors
  - Size: $L \sim$ m – km
  - GW wavelength $\lambda = c/f \sim 10^3 - 10^5$ km
  - *Small antenna limit:* $L/\lambda \ll 1$
- Space-based detectors
  - Size $L \sim 3{\cdot}10^6$ km
  - GW wavelength $\lambda \sim 3{\cdot}10^6 - 10^{10}$ km
  - *Small to full-wave antenna:* $L/\lambda \lesssim 1$:
- Pulsar timing
  - Size $L \sim$ kpc ($3 \cdot 10^{16}$ km)
  - Radiation wavelength $c/f \sim$ 5e13 km
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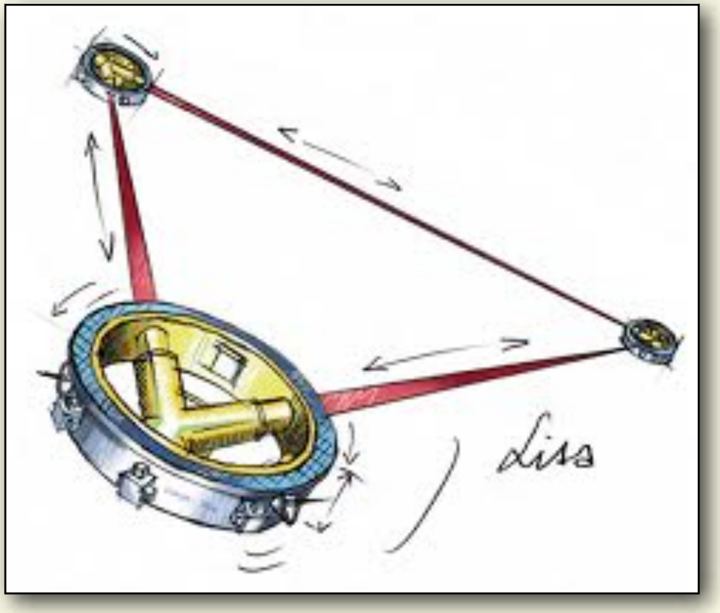

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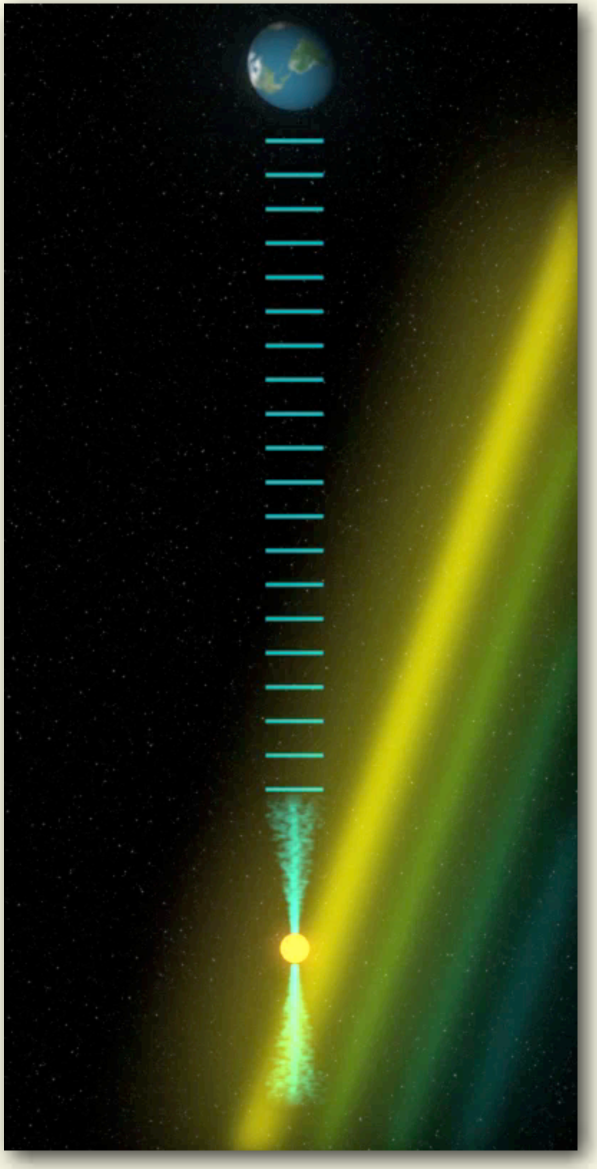

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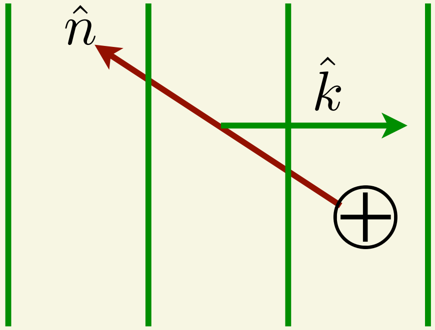
Response



$\hat{k}$	**Grav wave propagation direction**
$\hat{n}$	**Direction toward pulsar**

Pulse arrival time disturbance owing to gravitational waves

$$\begin{aligned}\Delta\tau_{\rm gw} &\sim \int_L^0 n^i n^j h_{ij}(t-l, l\hat{n})dl \\ &\sim \frac{h}{\omega_{\rm gw}}(1-\hat{k}\cdot\hat{n})\left[1-e^{-i\omega_{\rm gw}L(1+\hat{k}\cdot\hat{n})}\right]e^{i\omega_{\rm gw}t}\end{aligned}$$

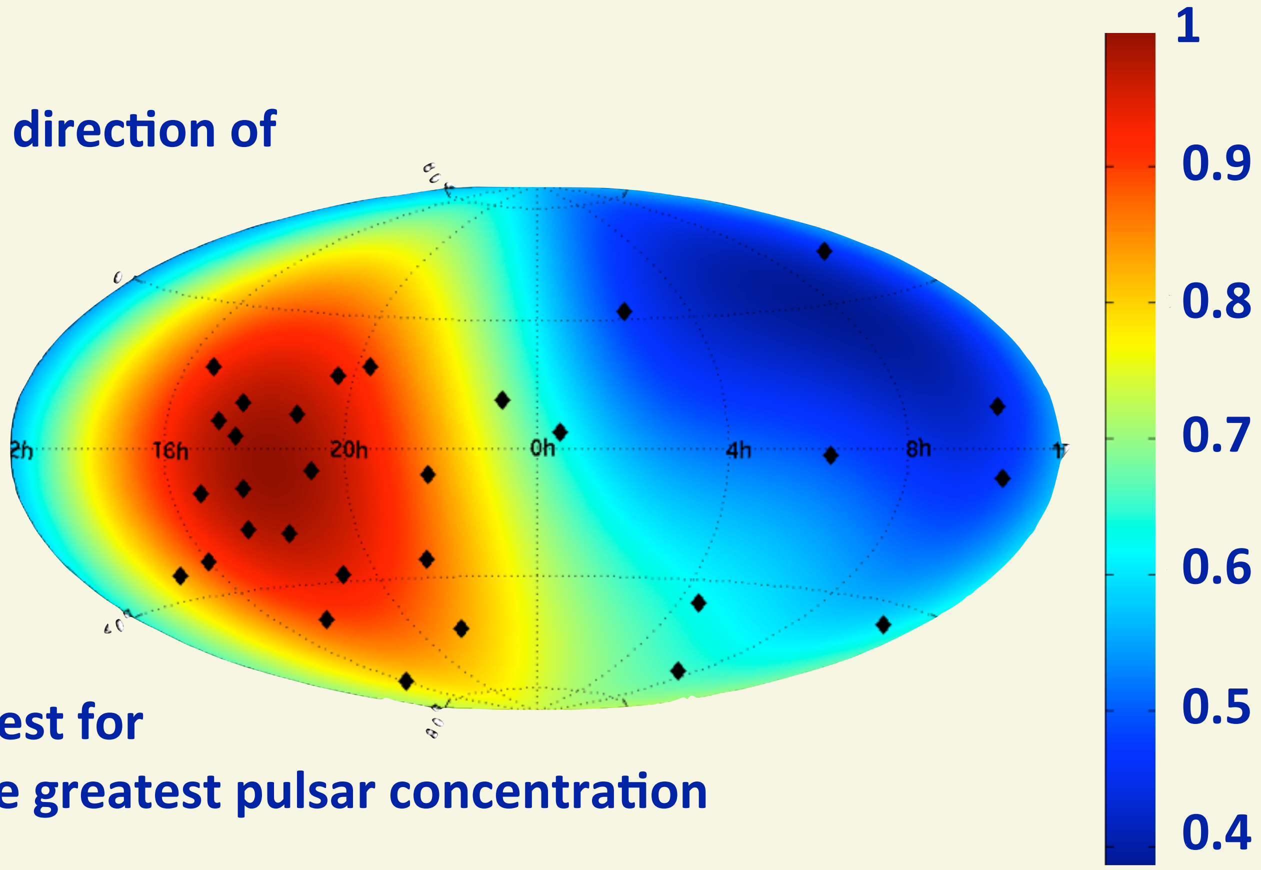
$\frac{h}{\omega_{\rm gw}}$ **Response amplitude**

$(1-\hat{k}\cdot\hat{n})$ **Source location response amplitude envelope**

$\cos\left[\omega_{\rm gw}L(1+\hat{k}\cdot\hat{n})\right]$ **$\omega_{\rm gw}L \sim 3\cdot10^3$: response strongly dependent on wave frequency, source location, & pulsar distance(!)**

Mean-square response for 30 best timing pulsars

Most timers are in direction of galactic center

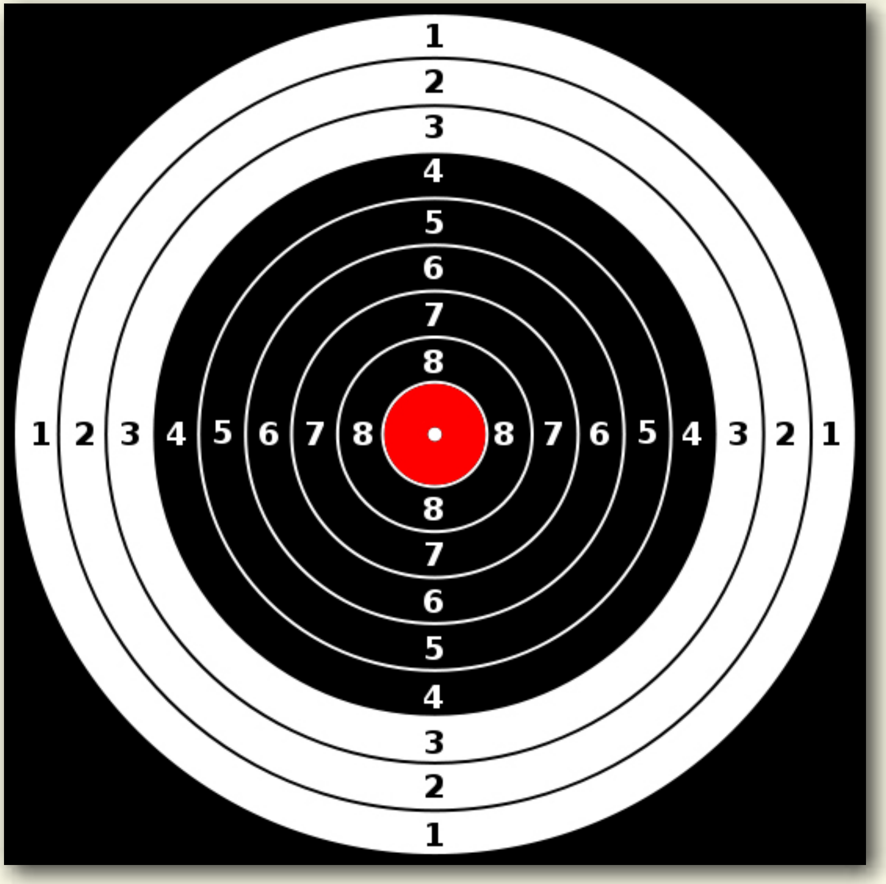


Sensitivity is greatest for sources toward the greatest pulsar concentration

Known pulsars are concentrated in direction of galactic center

Target Science

- Galactic mergers & last parsec problem
- Hierarchical galaxy formation
- Exotic physics (e.g., cosmic strings)



Principal Source in 5-100 nHz Band: Supermassive black hole binary systems

- Not chirping
- Isolated sources
- Confusion limit
- Bursts?

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Supermassive: ~ 10^9 Msol
Distance: 100 Mpc
Period: 1 yr
h ~ 10^{-15} corresponds to few ns timing residual

A sampling of gravitational wave limits from 30 years of millisecond pulsar timing

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Romani RW and Taylor JH. **1983**. An **upper limit on the stochastic background** of ultralow-frequency gravitational waves. ApJ 265:L35–L37.

Stinebring DR, Ryba MF, Taylor JH, and Romani RW. **1990**. **Cosmic gravitational-wave background - Limits** from millisecond pulsar timing. Physical Review Letters 65:285–288.

Lommen AN and Backer DC. **2001**. **Using Pulsars to Detect Massive Black Hole Binaries via Gravitational Radiation: Sagittarius A* and Nearby Galaxies**. ApJ 562:297.

Jenet FA, Lommen AN, Larson SL, and Wen L. **2004**. **Constraining the Properties of Supermassive Black Hole Systems Using Pulsar Timing: Application to 3C 66B**. ApJ 606:799.

Yardley DRB, Hobbs GB, Jenet FA, et al. **2010**. The **sensitivity of the Parkes Pulsar Timing Array to individual sources of gravitational waves**. Monthly Notices of the Royal Astronomical Society 407:669.

van Haasteren R, Levin Y, Janssen GH, et al. **2011**. Placing **limits on the stochastic gravitational-wave background** using European Pulsar Timing Array data. Monthly Notices of the Royal Astronomical Society 414(4):3117–3128.

Demorest PB, Ferdman RD, Gonzalez ME, et al. **2012**. **Limits on the Stochastic Gravitational Wave Background** from the North American Nanohertz Observatory for Gravitational Waves.

The International Pulsar Timing Array Collaboration

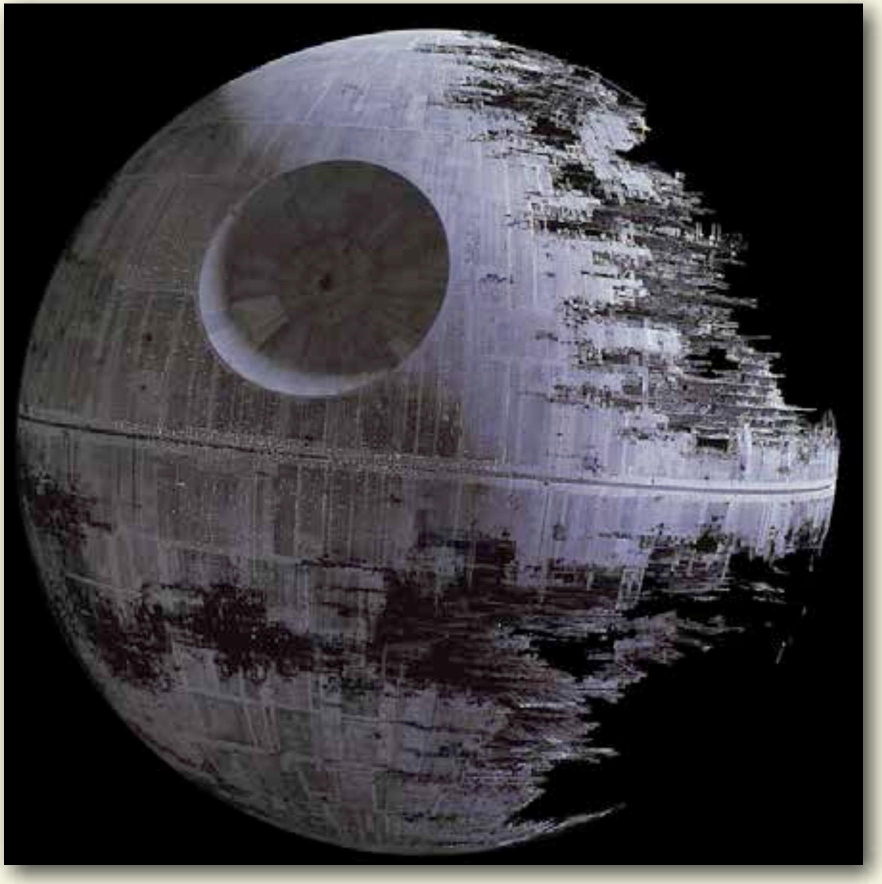
EPTA

NANOGrav

PPTA

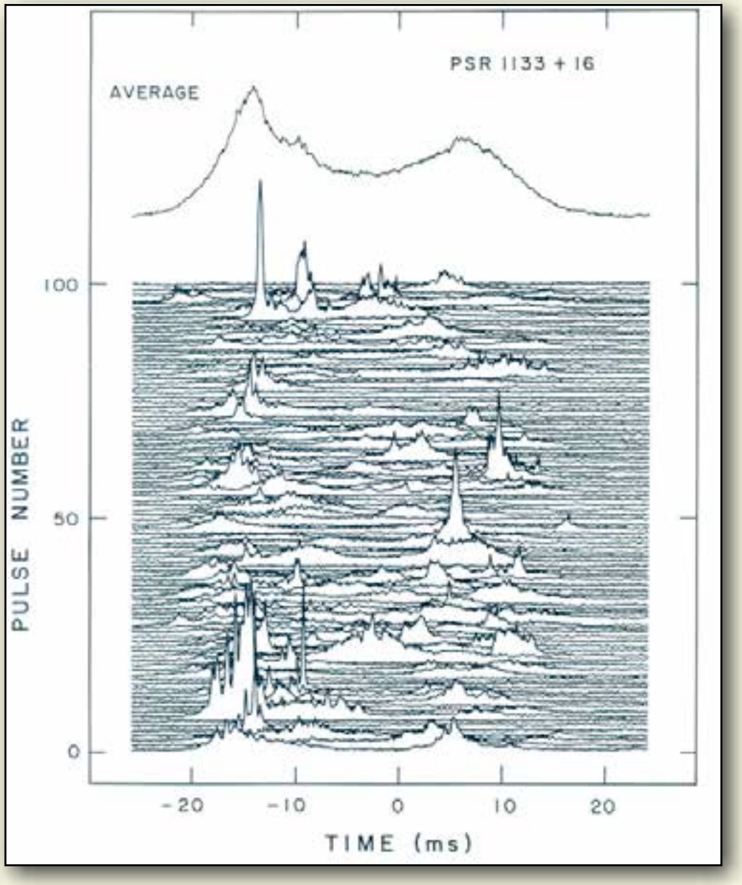
The Pulsar Timing Array Observing System: *Building* a Galactic-Scale Gravitational Wave Observatory

- **Pulsars**
- **Interstellar medium**
- **Radio telescope observatories**
- **Timing model**
- **Time standards & time transfer**

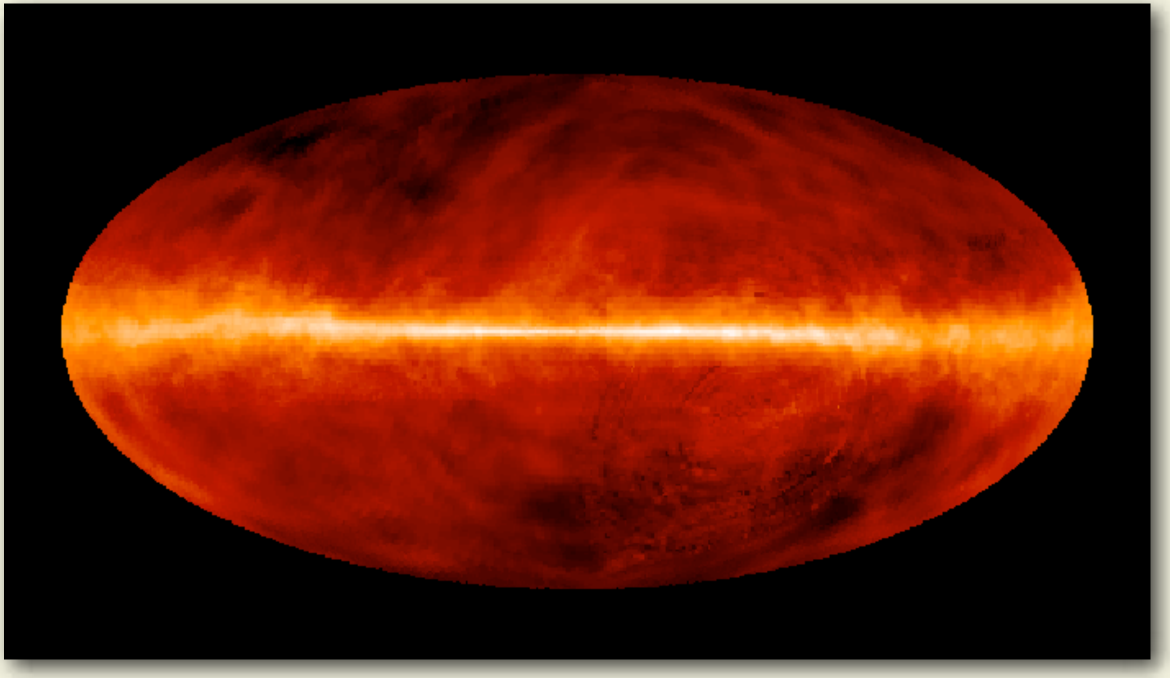


Pulsars

- Pulse jitter
- Spin noise
- Location



Interstellar Medium



- Dispersion
- Refraction
- Scintillation

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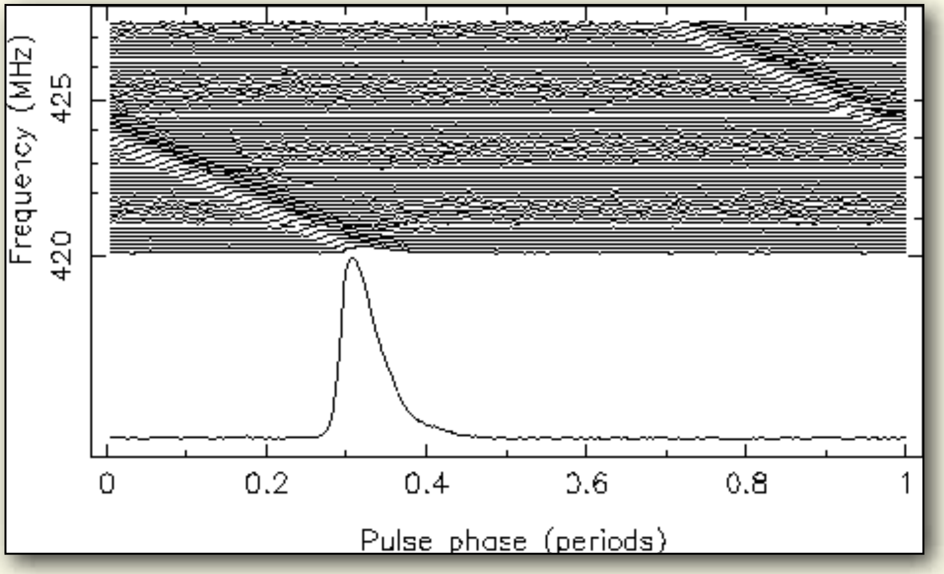

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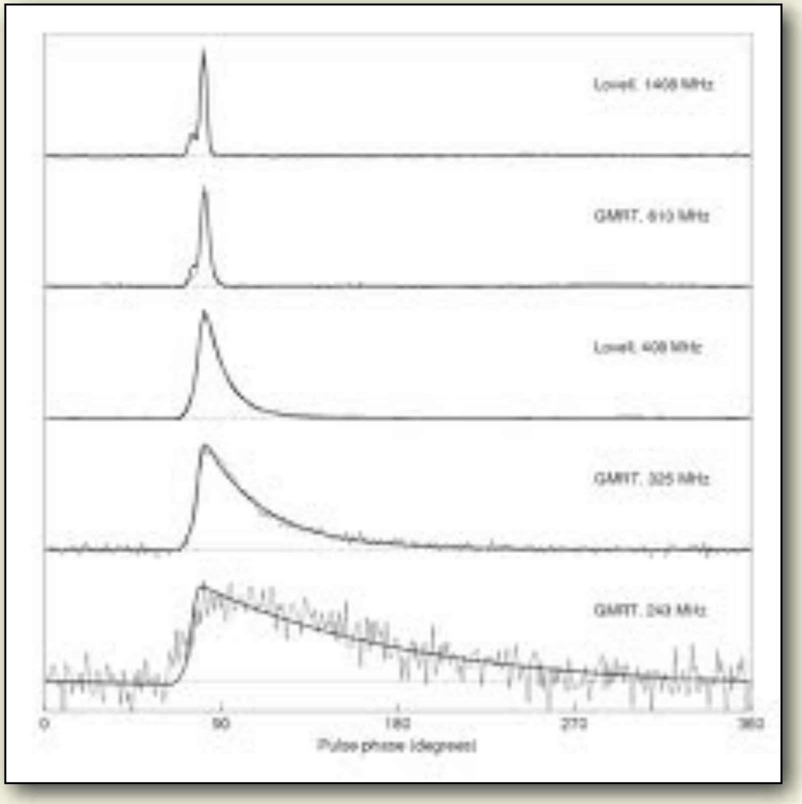

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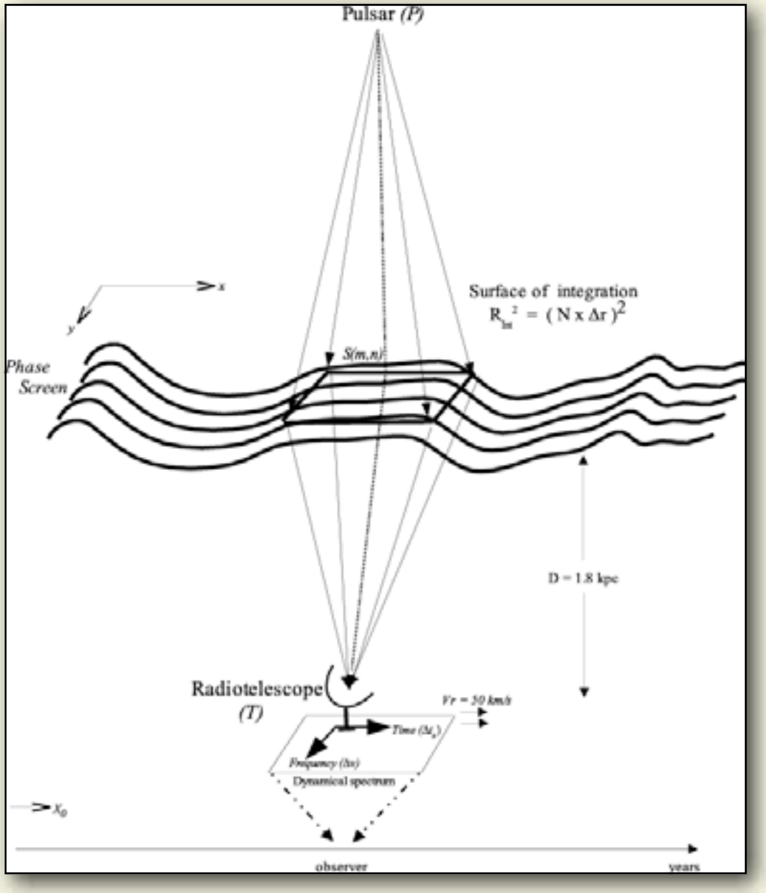

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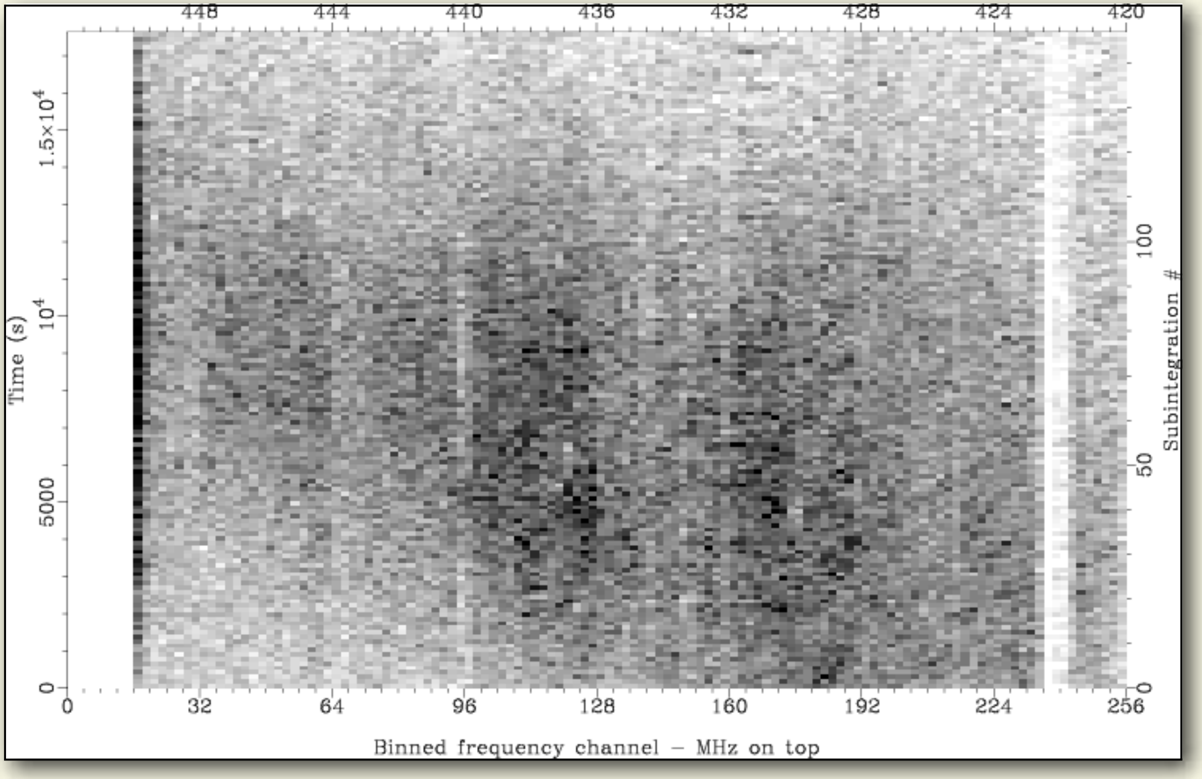
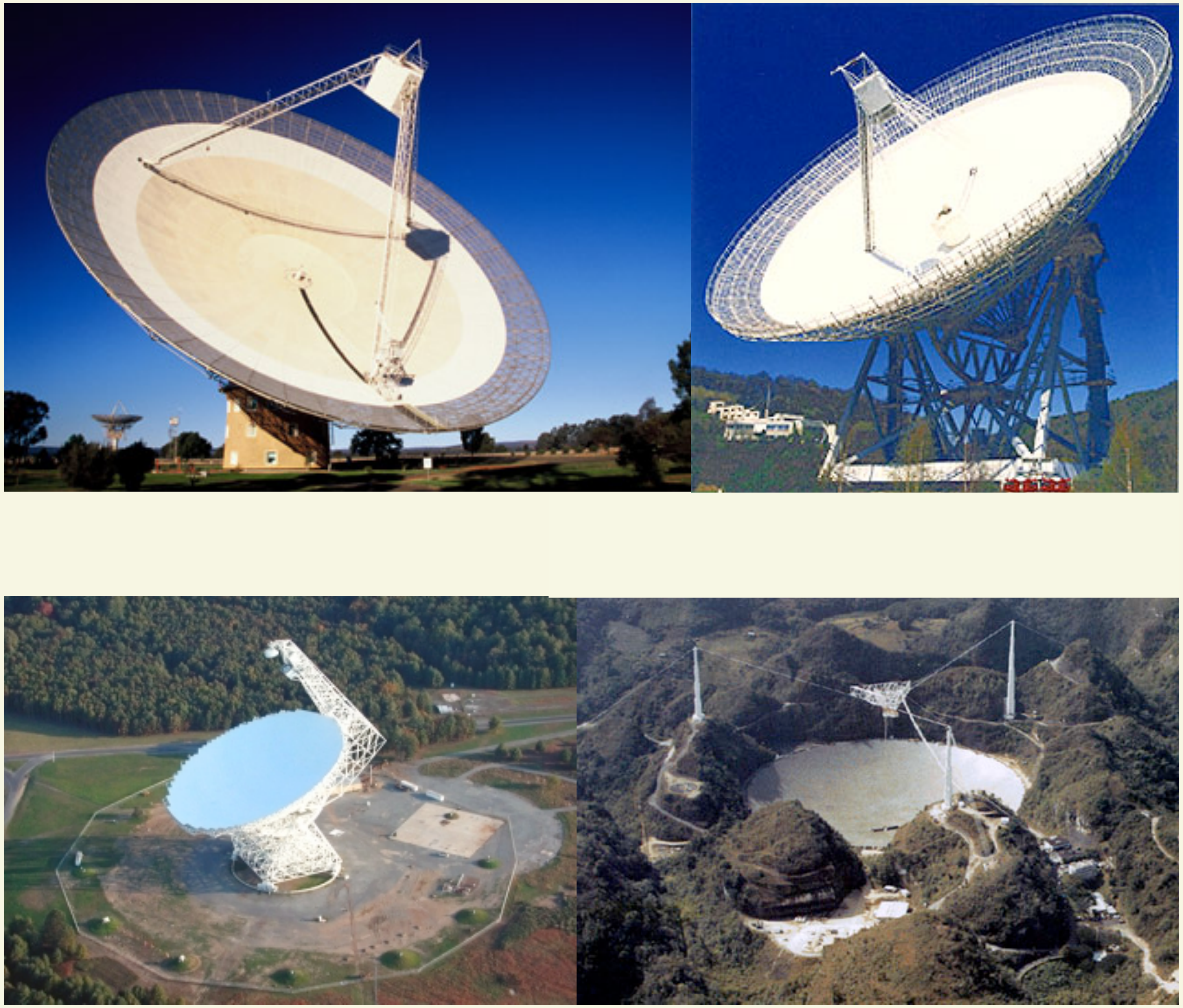


Radio Telescope Observatories

- Antennas
- Receivers and back-ends
- Local time standards
- Location



The Timing Model accounts for (almost) everything that affects pulse arrival times

Gravitational waves manifest themselves as deviations between actual and expected pulse arrival times

Timing model describes expected pulse arrival times

$$t_{\mathrm{a}}^{\mathrm{obs}} = t_{\mathrm{e}}^{\mathrm{psr}} + \Delta_{\mathrm{B}} + \Delta_{\mathrm{IS}} + \Delta_{\odot}$$

"Intrinsic" Pulsar system effects

Pulsar system motion and ISM

Solar system contributions

Timing model must be accurate to ns level over 20+ years!

The Timing Model accounts for (almost) everything that affects pulse arrival times

$$t_{\mathrm{a}}^{\mathrm{obs}} = t_{\mathrm{e}}^{\mathrm{psr}} + \Delta_{\mathrm{B}} + \Delta_{\mathrm{IS}} + \Delta_{\odot}$$

Pulsar spin-down (f, f-dot, f-ddot)

Pulsar motion in binary

- Geometric effects
- Relativistic doppler
- Gravitational redshift
- Shapiro delay

The Timing Model accounts for (almost) everything that affects pulse arrival times

$$t_{\rm a}^{\rm obs} = t_{\rm e}^{\rm psr} + \Delta_{\rm B} + \Delta_{\rm IS} + \Delta_{\odot}$$

Pulsar system proper motion
(Shklovskii effect)

Interstellar dispersion, diffraction,
refraction, scintillation

The Timing Model accounts for (almost) everything that affects pulse arrival times

$$t_{\mathrm{a}}^{\mathrm{obs}} = t_{\mathrm{e}}^{\mathrm{psr}} + \Delta_{\mathrm{B}} + \Delta_{\mathrm{IS}} + \Delta_{\odot}$$

Pulsar location on sky

Roemer delay

Pulsar parallax

Gravitational redshift

Relativistic Doppler

Shapiro delay from Sun, major planets

Atmospheric delays

Solar wind dispersion

Involves solar system ephemeris including:

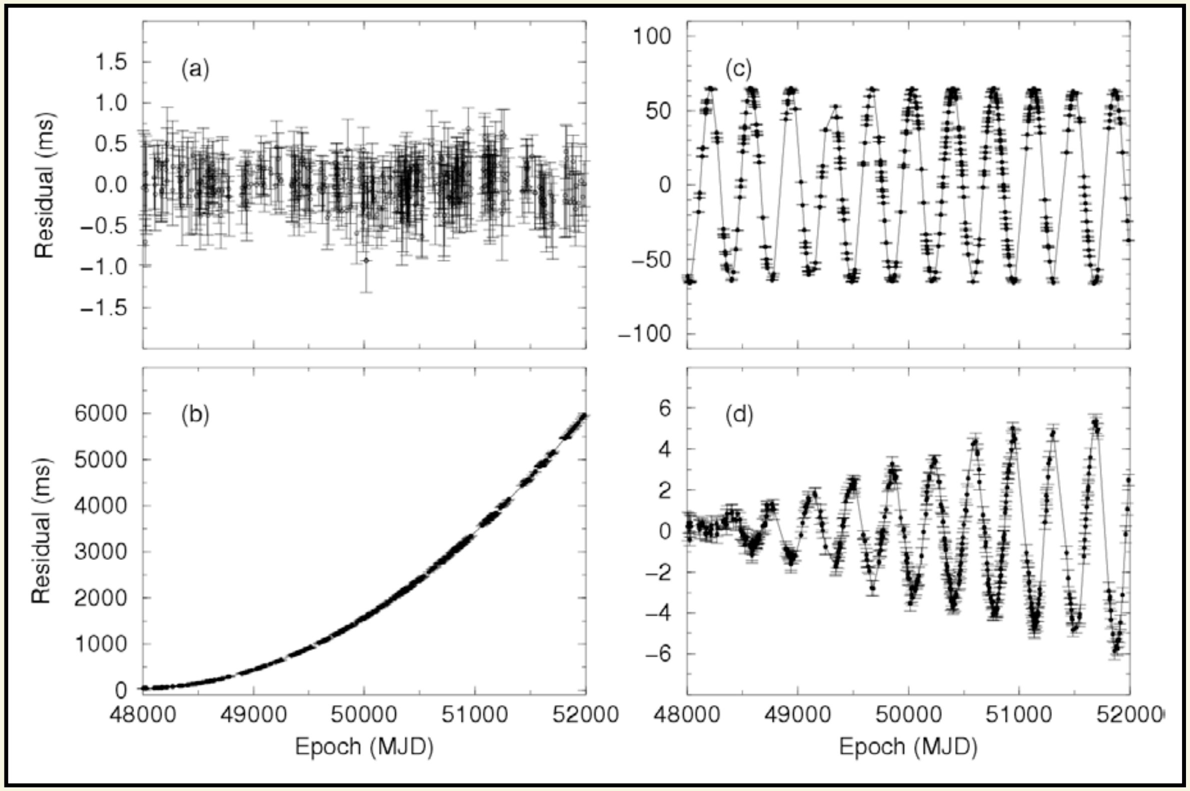
Point interaction of Sun, planets, Moon, major asteroids

Perturbation to Earth, Moon, Mars of 300+ asteroids

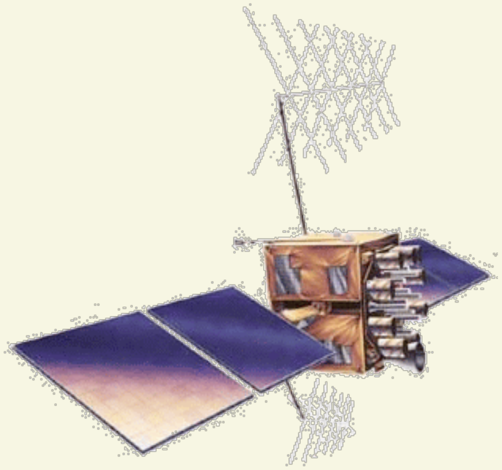
Post-Newtonian corrections

Moon motion due to Earth tides raised by Sun, Moon

Timing model



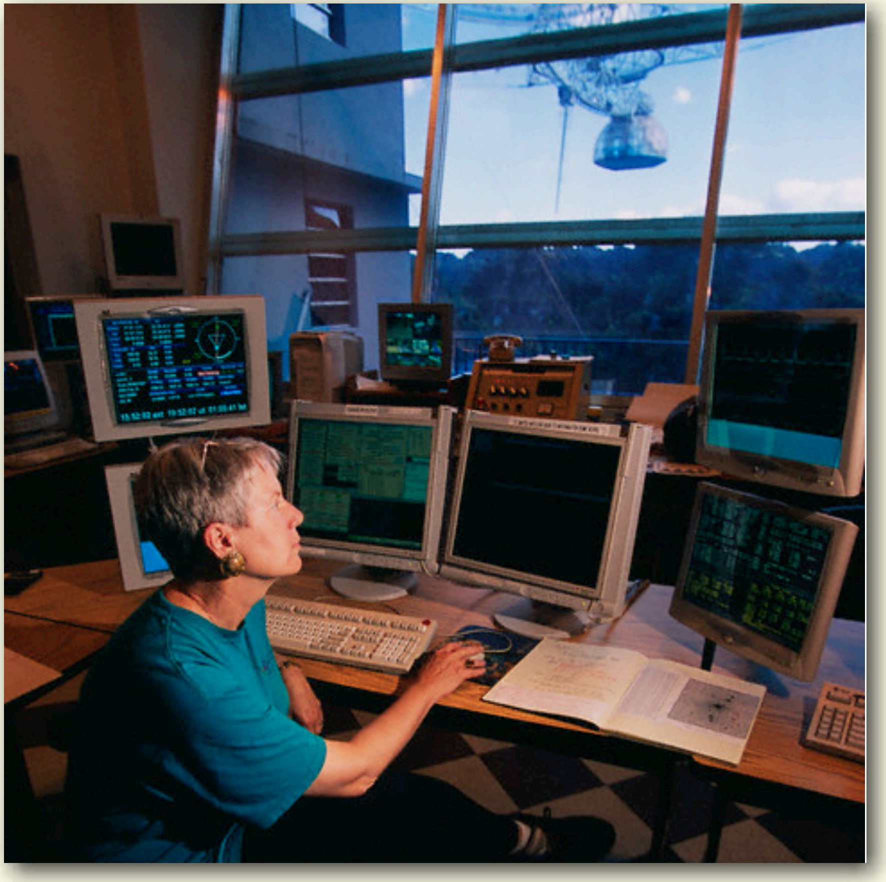
Time standards & time transfer



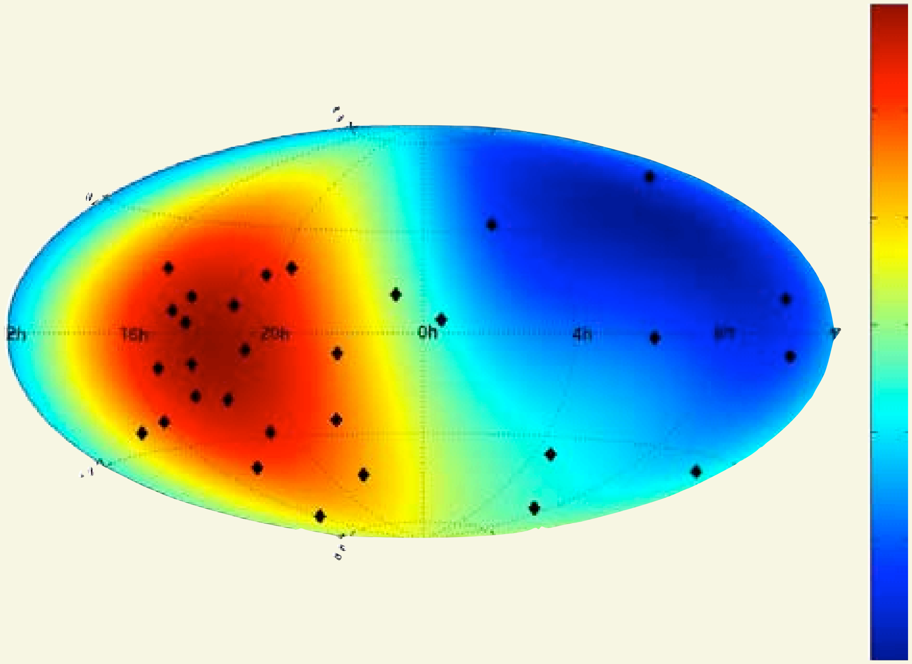
- Time, time transfer errors must be no greater than ~ ns over multi-year timescales
- Observatories host hydrogen maser clocks
  - **Allan dev. ~ $3 \cdot 10^{-15}$ @ 10^3 s; $2 \cdot 10^{-16}$ @ 1 d**
- Observatory clocks synced to GPS
- GPS synced to global time standard TDT and thence to TDB

The Pulsar Timing Array Observing System: *Operating* a Galactic-Scale Gravitational Wave Observatory

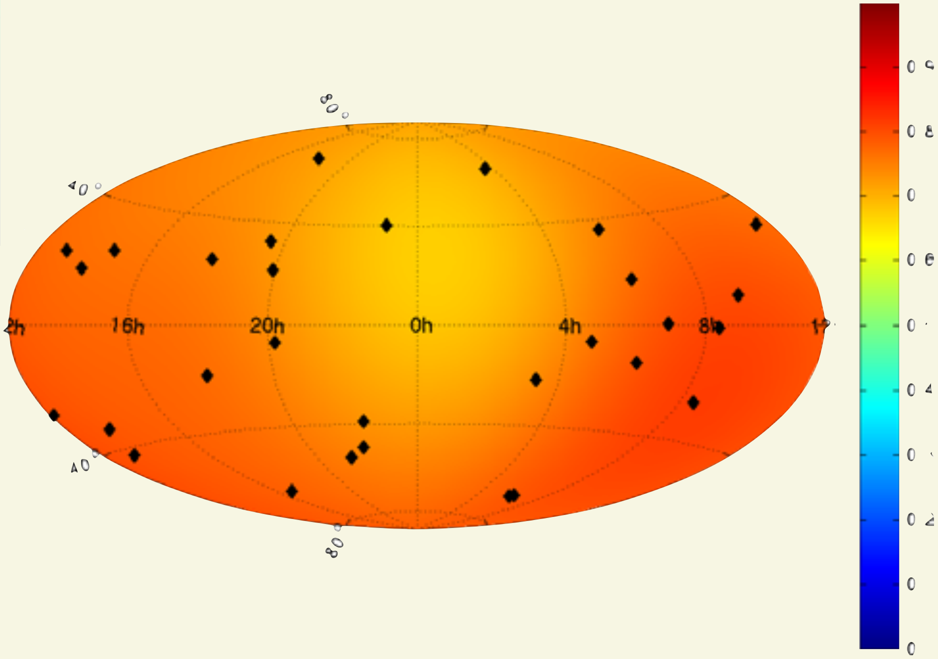
- Goals
  - Earliest discovery? Source localization/characterization? Array performance/flexibility?
- Resources
  - Observing time & telescopes
  - ‘scopes heavily over-subscribed; TAC allocations not fungible
- Choices
  - Choice of timers; integration time per pulsar; timing cadence; survey vs. timing



Choice of timers and timing/survey time allocation



Mean-square sensitivity for 30 IPTA pulsars. Sensitivity is concentrated where pulsars are concentrated



Mean-square sensitivity for 30 identical pulsars distributed randomly across sky. Sensitivity is uniform across sky.

Pulsar Timing Arrays Work!

Principal source: SMBH binaries

Principal science: galactic mergers, last parsec problem, hierarchical galaxy formation

Effort is an international "coop-etition"

Arrays are actively constructed and operated