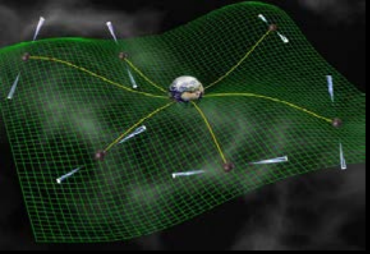
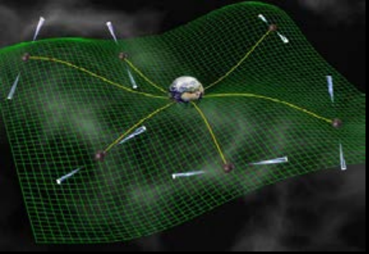


Pulsar Timing Arrays
Current and Future Instrumentation

Joseph Lazio

Jet Propulsion Laboratory,
California Institute of Technology



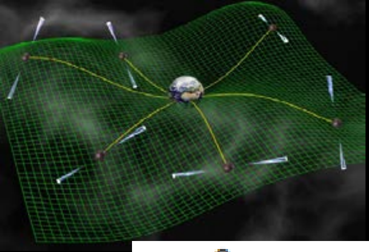
Pulsar Timing Arrays
Current and Future Instrumentation

- What are the requirements?
  - Timing precision and instrumental performance
- What exists?
  - Telescopes
  - Feeds, receivers, and backends
  - IT infrastructure
- What is on the horizon?

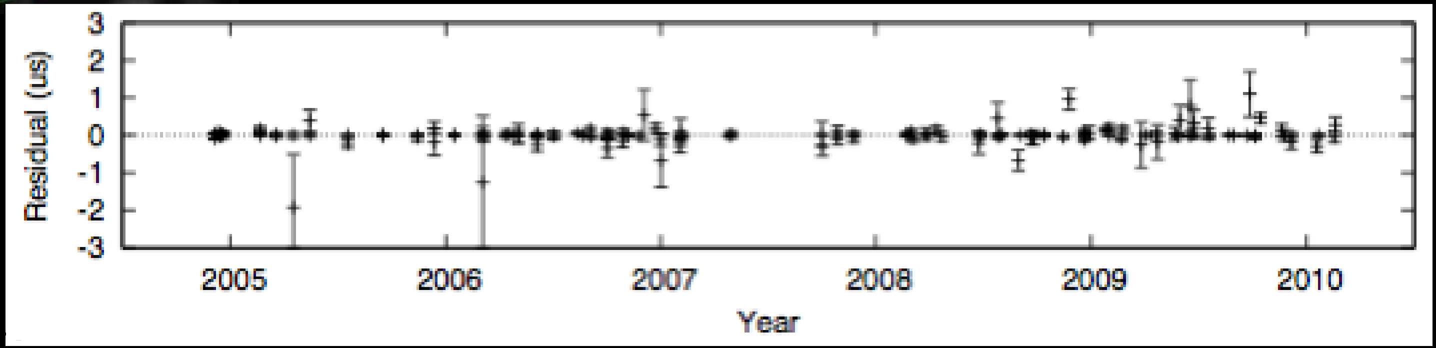
PPTA

EPTA

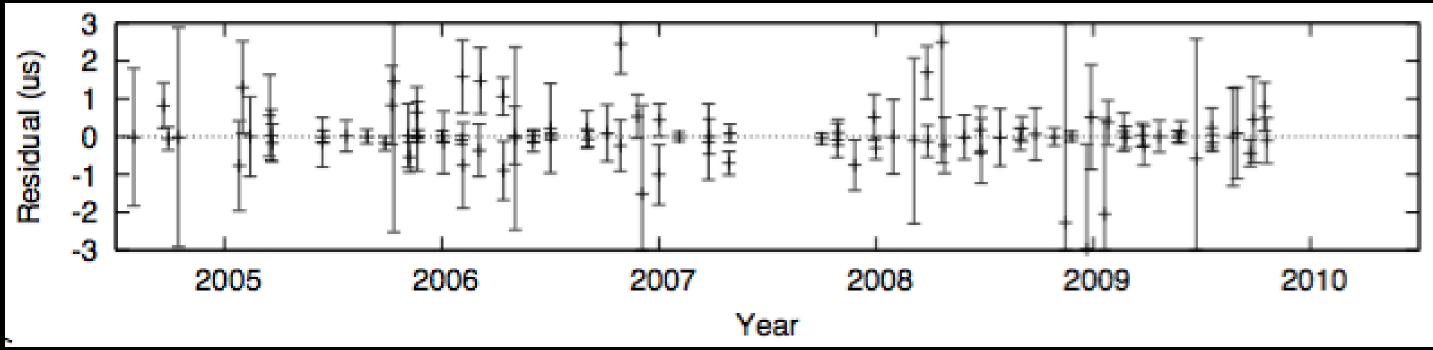
NANOGrav



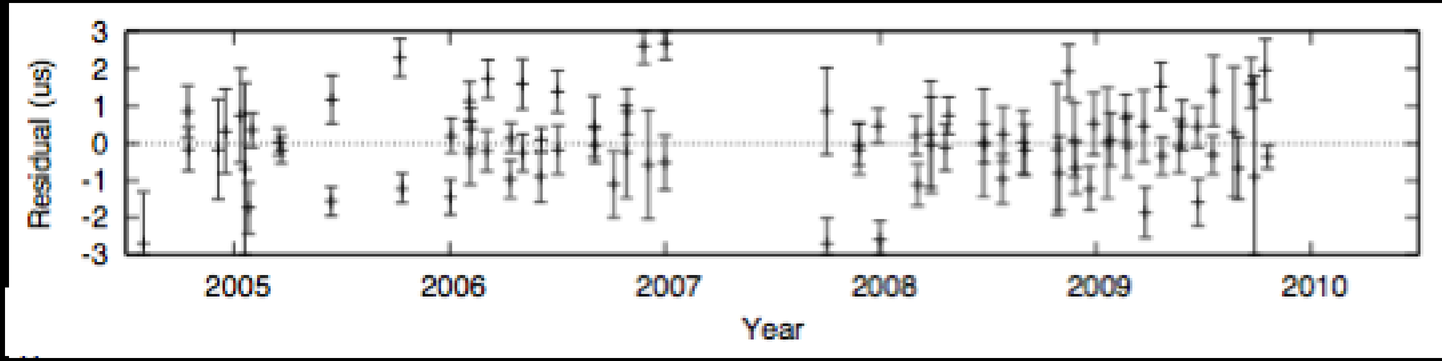
Pulsar Timing Arrays
Current Results



J1713+0747
30 ns RMS

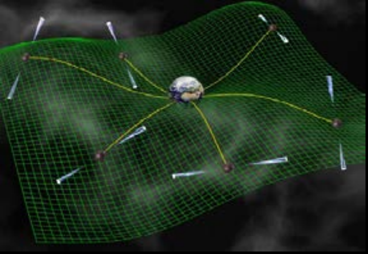


J1012+5307
280 ns RMS



J1643-1224
1500 ns RMS

Demorest et al. 2012, submitted

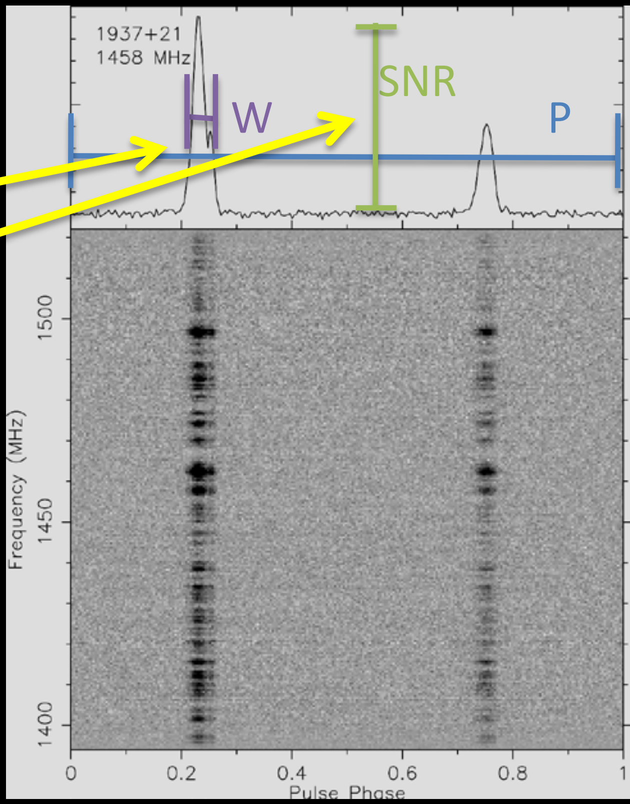


Timing Precision

- Assume $\sigma_{TOA} \leq 100$ ns

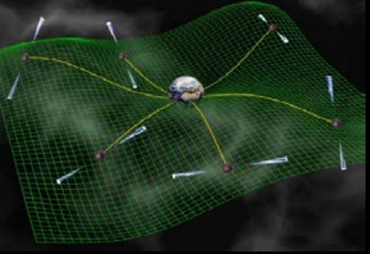
  May be necessary, but not sufficient condition

$$\sigma_{\mathrm{TOA,\,n}} = \frac{W}{\mathrm{SNR}}$$

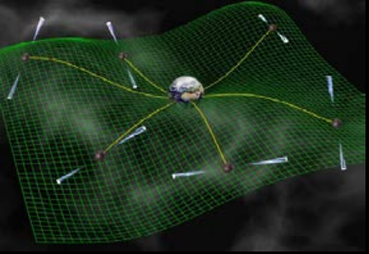


- *W* ➔ pulse width
- SNR ➔ signal-to-noise ratio
- Assumes sufficient calibration of telescope system

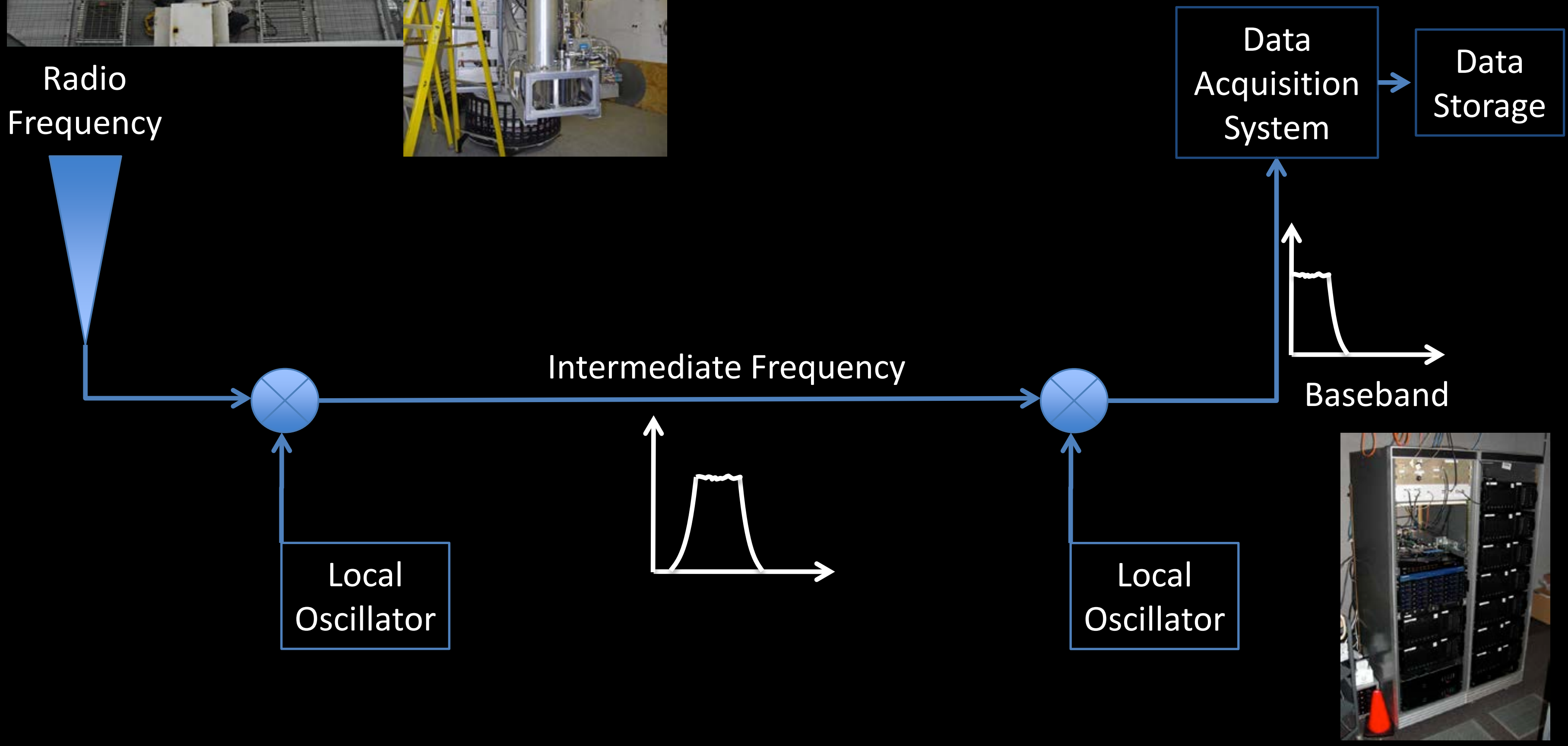
  Other contributions can include pulse-phase jitter, uncorrected propagation effects

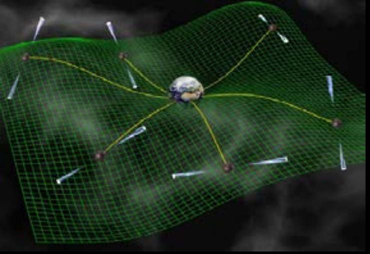


Radio Telescope

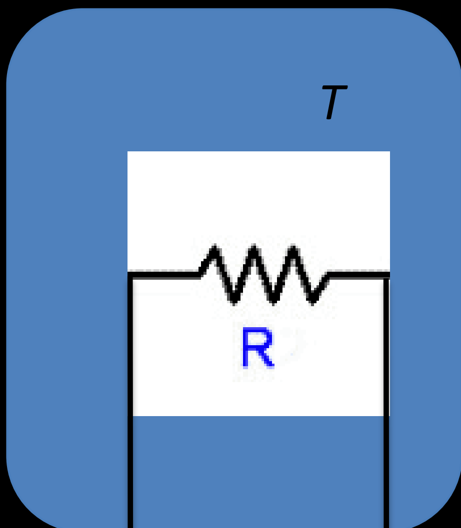


Radio Telescope



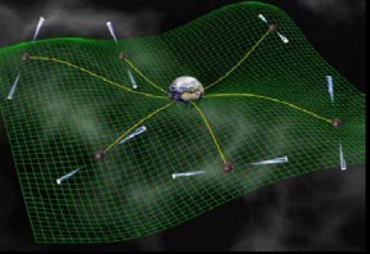


Radio Telescope



Noise Temperature

- Replace entire telescope system by resistor in a heat bath
- Output voltage equivalent
- Not necessarily physical temperature
- $T_{sys} = T_{sky} + T_{spill} + T_{Rx} + \ldots$
- $P = k_B T \Delta \nu$



Radiometer Equation

For $T_{PSR} << T_{sys}$

$$\Delta T = \frac{T_{sys}}{\sqrt{2\Delta\nu\Delta t}}$$

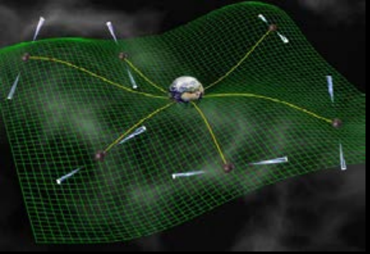
$$\Delta S = \frac{2k_B T_{sys}}{A_{eff}\sqrt{2\Delta\nu\Delta t}}$$

Where can improvements be made?

- T_{sys} portion determined by telescope
  $T_{sys} = T_{sky} + T_{spill} + T_{Rx} + \ldots$
- $\Delta\nu$ – processed bandwidth
- A_{eff} – effective area of telescope
- Δt – observation time
  within limits imposed by pulsar or ISM

➢ Improvements benefit both timing *and* survey programs

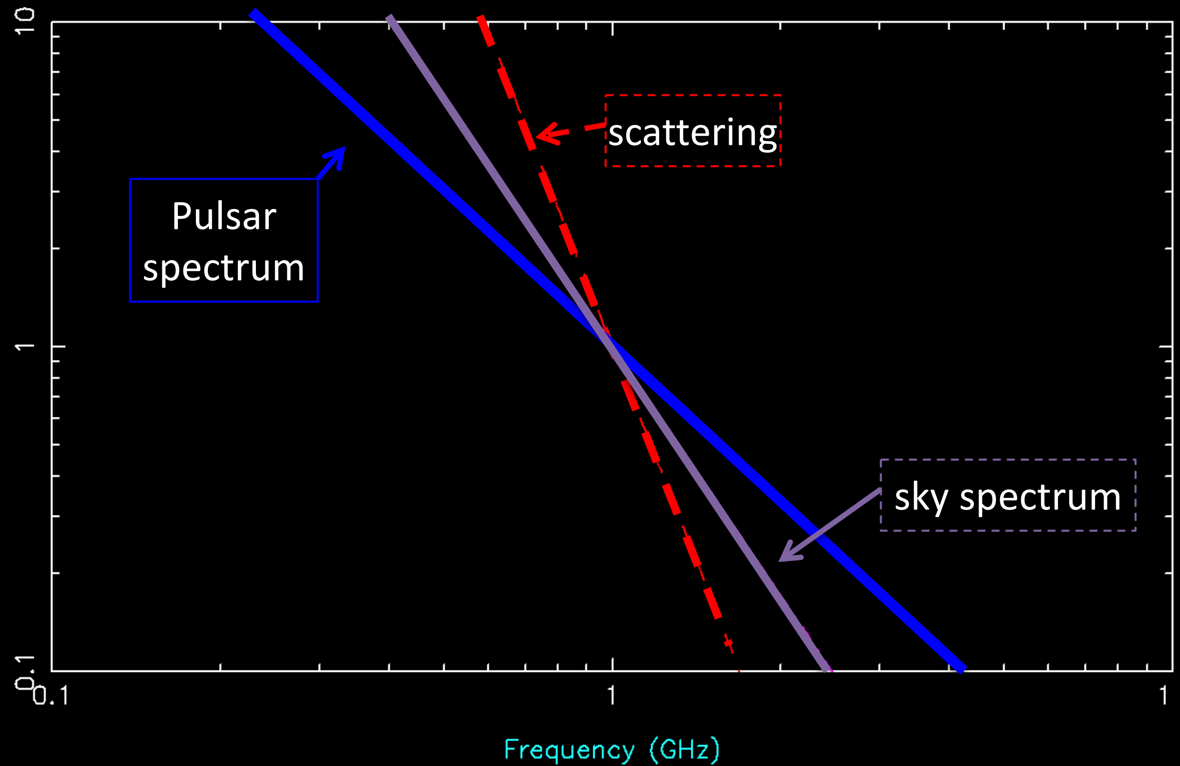
S ➔ spectral flux density [$W/m^2/Hz$]
1 Jy = 10^{-26} $W/m^2/Hz$



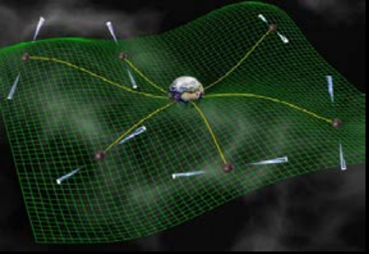
Pulsar Observations

Observational frequency determined by balancing
- pulsar spectrum vs.
- sky spectrum vs.
- scattering

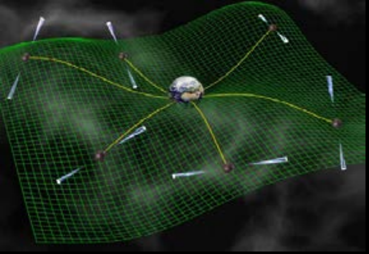
Typically about 1 GHz

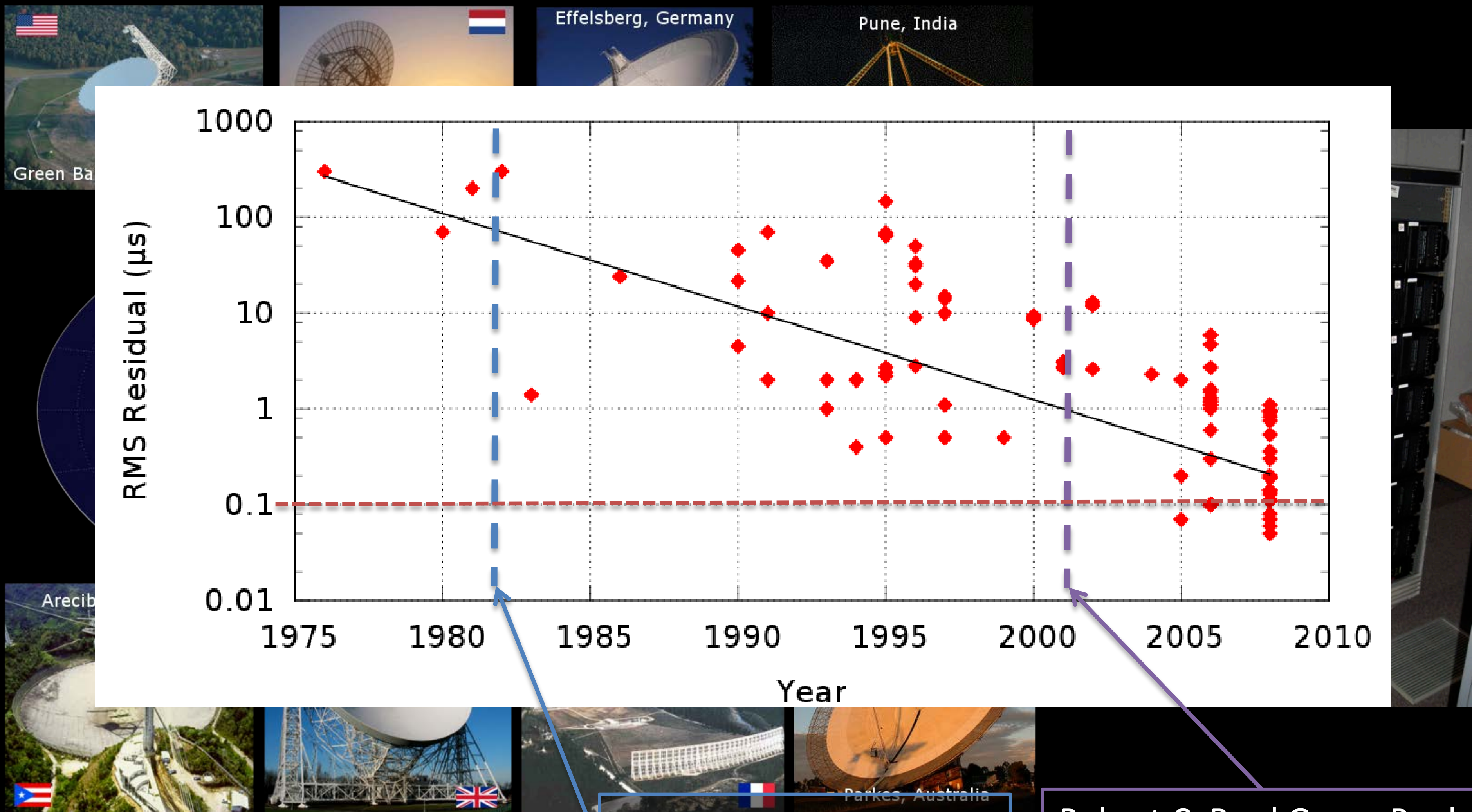


Pulsar Timing Arrays
Current Instrumentation



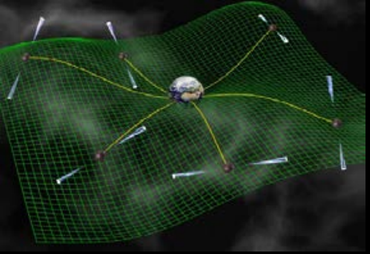
Pulsar Timing Arrays
Current Instrumentation





Discovery of millisecond pulsars (MSPs)

Robert C. Byrd Green Bank Telescope (GBT) dedicated

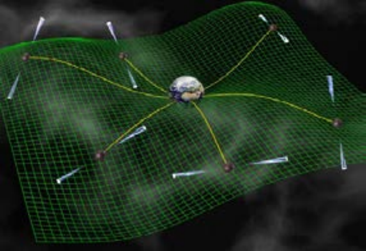


Pulsar Timing
Historical Context

- 1974: Hulse-Taylor binary pulsar
  - Arecibo telescope @ 430 MHz
  - ≤ 8 MHz bandwidth
  - 175 K system temperature

    T_{sky} = 25 K @ 430 MHz
- 1982: first millisecond pulsar (B1937+21)
  - Arecibo telescope @ 1400 MHz
  - 16 MHz bandwidth
  - 40 K system temperature

    T_{sky} ~ 7 K @ 1400 MHz



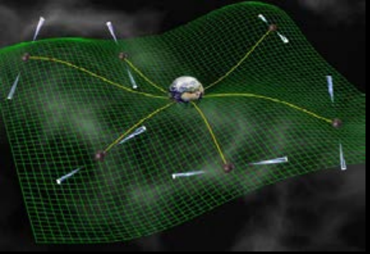
Pulsar Timing Arrays
Current Instrumentation

Typical Parameters

- A_{eff} ~ 100 m
- $\Delta\nu$ ~ 100 MHz
- T_{sys} ~ 30 K
- Δt ~ 15 min.

Current Publications

- Yardley et al. 2011, "On detection of the stochastic gravitational-wave background using the Parkes pulsar timing array," *Mon. Not. R. Astron. Soc.*, **414**, 1777
- van Haasteren et al. 2011, "Placing limits on the stochastic gravitational-wave background using European Pulsar Timing Array data," *Mon. Not. R. Astron. Soc.*, 414, 3117
- Demorest et al. 2012, "Limits on the Stochastic Gravitational Wave Background from the North American Nanohertz Observatory for Gravitational Waves," ApJ, in press
- Hobbs et al. 2010, "The International Pulsar Timing Array project: using pulsars as a gravitational wave detector," *Class. Quant. Grav.*, **27**, 084013



Pulsar Timing Arrays
Near Future

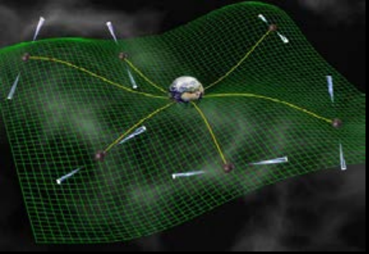
Instrumentation

Receiver performance reaching fundamental limits, e.g.,

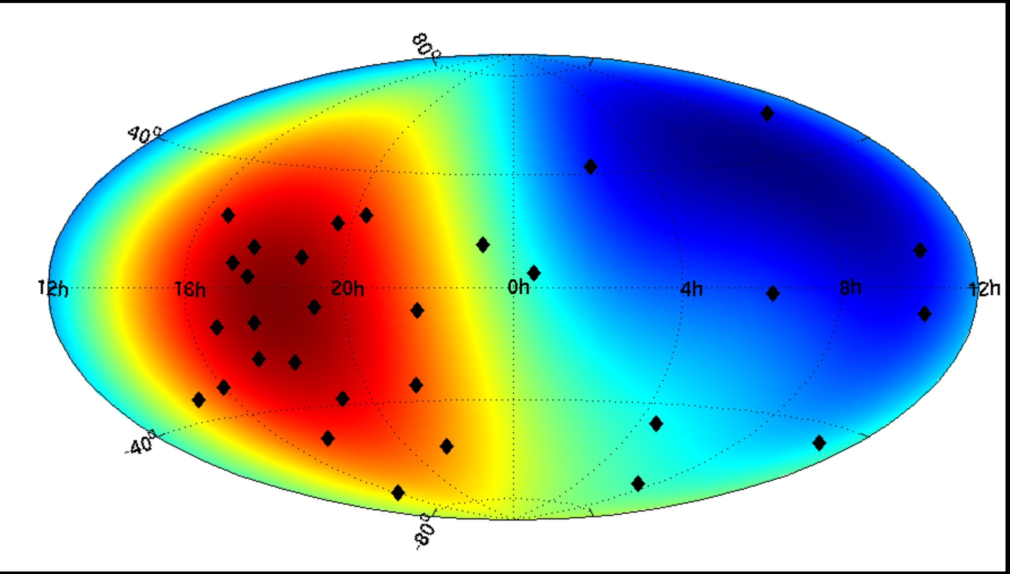
- $T_{sys} \approx 20$ K
- $\Delta\nu$ ~ 1 GHz for observations near 1 GHz

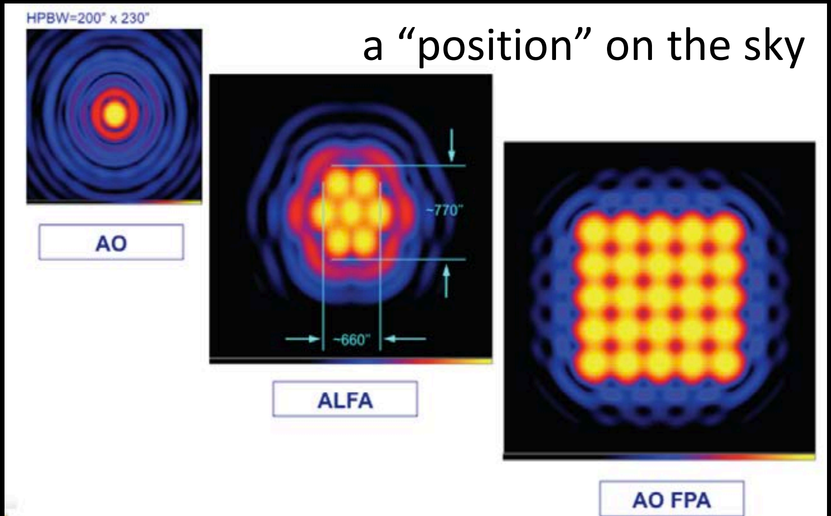
New Pulsars

- Major radio pulsar surveys worldwide
  - HTRU (Parkes)
  - GBNCC (GBT)
  - GBT drift scan (GBT)
  - P-ALFA (Arecibo)
- Multi-wavelength MSPs
  a.k.a. *Fermi*

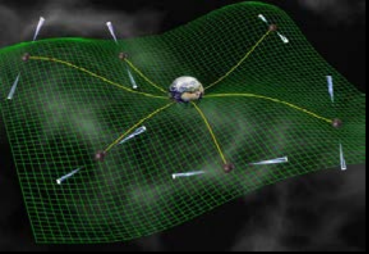


Pulsar Surveys



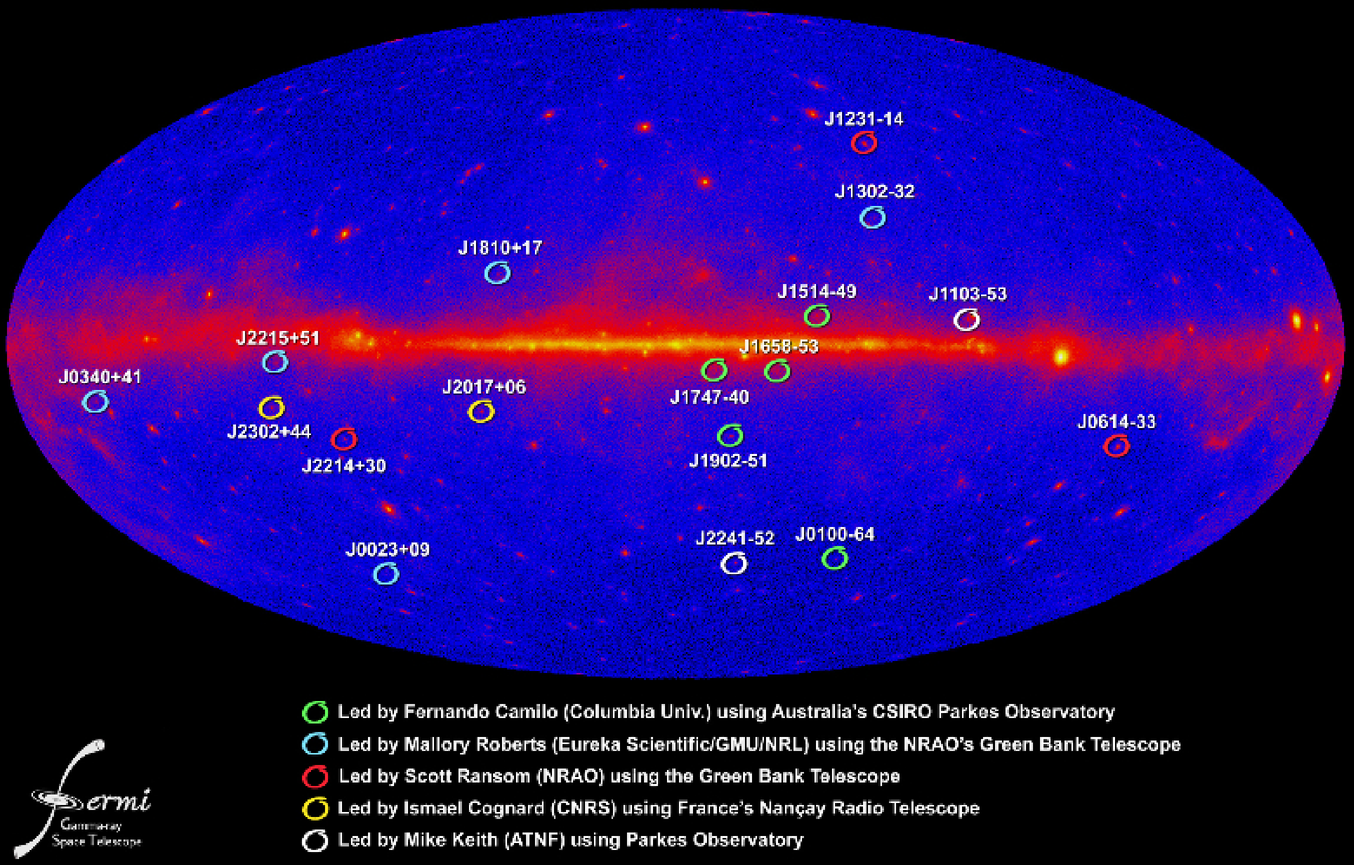


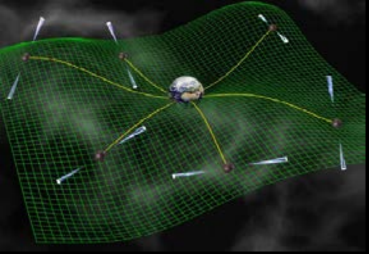
- New pulsars
  - Add more arms to PTA, increase sensitivity; **or**
  - For fixed amount of observing time, improve quality of PTA
- Survey algorithm
  1. Observe position on sky
  2. Search resulting time series for periodic signal at period P with dispersion DM, with orbital parameters
  - Loop



Pulsar Timing Arrays
Near Future

New Millisecond Radio Pulsars Found in Fermi LAT Unidentified Sources

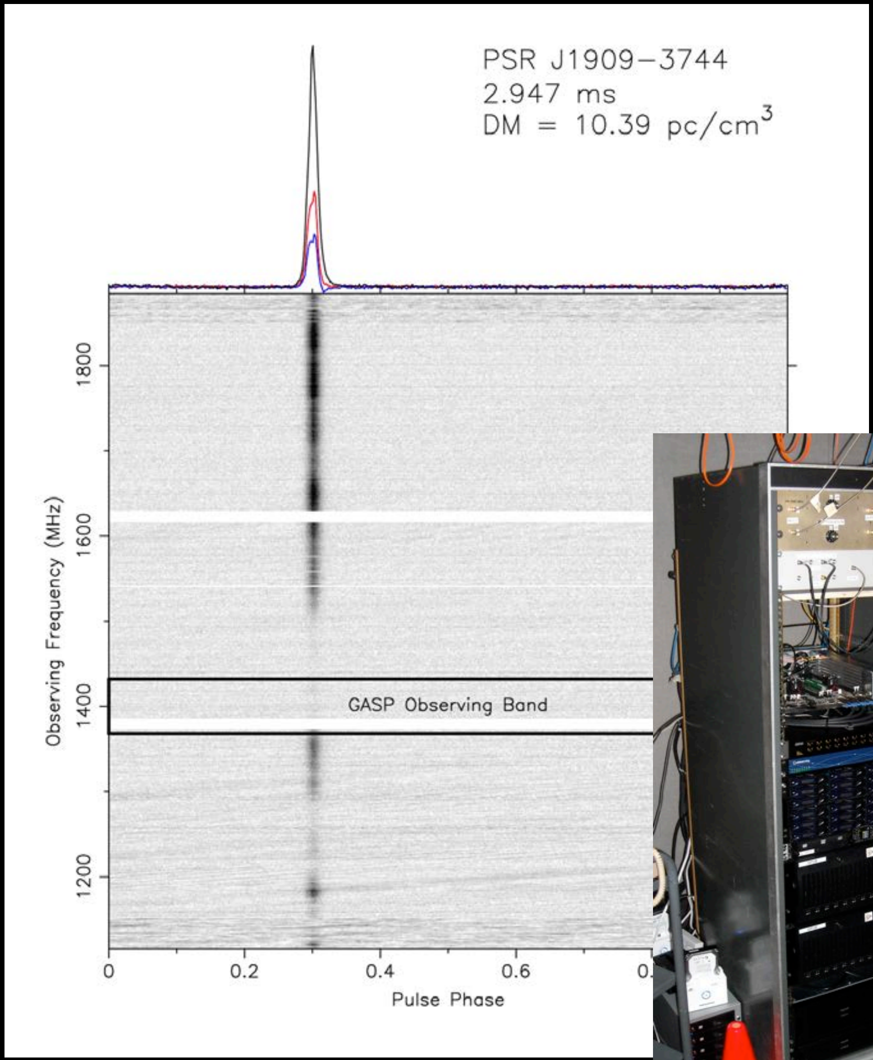


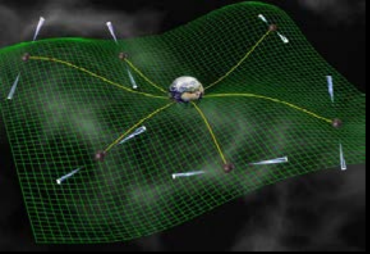


Pulsar Timing Arrays Digital Backends

Green Bank Ultimate Pulsar Processing Instrument (GUPPI)

- BEE2 feeds 8 gaming systems w/NVIDIA GPUs
- 100, 200, or 800 MHz bandwidth
- Large improvement in timing precision
- ~1 TFLOP in real time
- operational



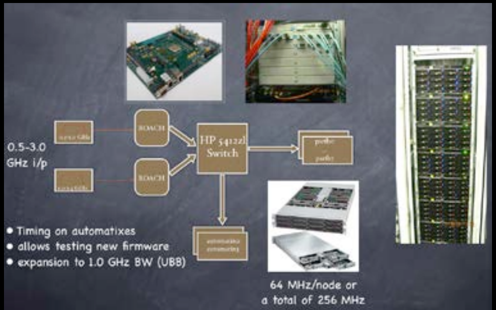


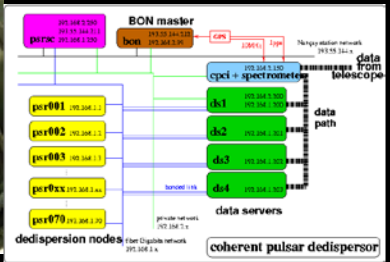
Pulsar Timing Arrays
Digital Backends

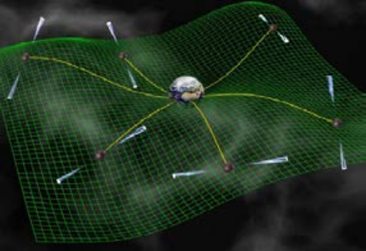
Wide-bandwidth (1+ GHz), real-time systems implementing RFI mitigation and folding
(in construction)

- Parkes HIPSR
- Effelsberg ASTERIX and follow-on
- Arecibo PUPPI
  Clone of GBT GUPPI

FPGA-based Reconfigurable Open Architecture Computing Hardware (ROACH), developed by Center for Astronomical Signal Processing and Electronics Research (CASPER, at UC Berkeley)



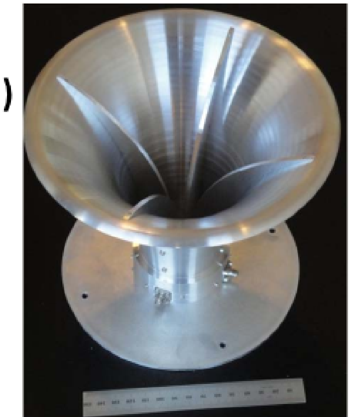


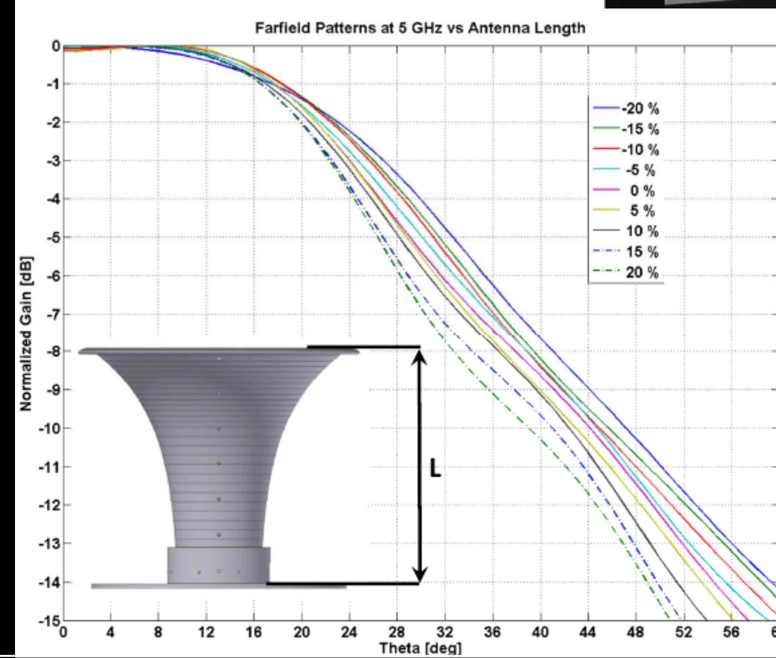


Pulsar Timing Arrays
New Feed & Rx Systems

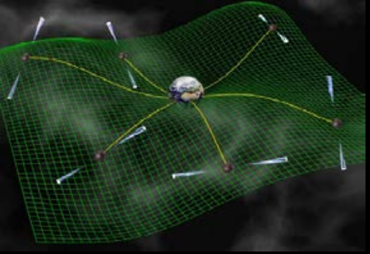
- GBT Wide-Band Pulsar System
- Arecibo Wide-Band System
- Effelsberg Ultra-broad Band
- Arecibo AO40
- *Five-hundred metre Aperture Spherical Telescope (FAST)* multi-feed system
  - 19 or 100 feed horns

CIT Quad-ridge Flared Horn (QRFH)
Frequency Range: 2 – 12 GHz
Dimensions: 20 x 20 x 20 cm
(slightly bigger than 3164-05)
Mass: < 1 lbs
(less than 3164-05)





T_{sys} ~ 29K (5K sky + 9K spill + 4K coax jct + 7K dewar jct + 3K LNA)



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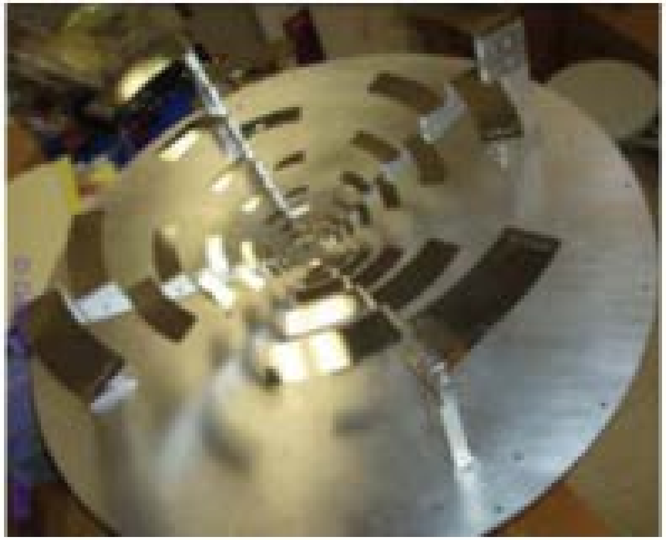
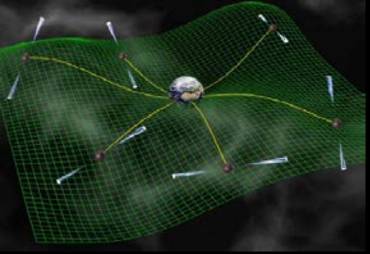
QSC Feed (Cornell)



Quasi Self-Complementary Feed
(developed under U.S. SKA auspices)



Pulsar Timing Arrays
New Feed & Rx Systems

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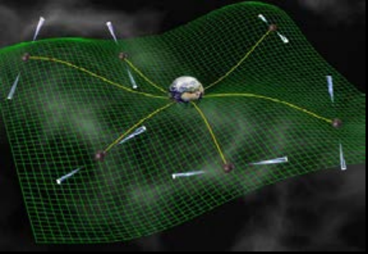
- *Five-hundred metre Aperture Spherical Telescope (FAST)* multi-feed system

  19 or 100 feed horns

continuous coverage from 600-3000 MHz

cryogenically cooled receiver

design by Weinreb (JPL/TDP) + MPIfR



Pulsar Timing Arrays
New Feed & Rx Systems

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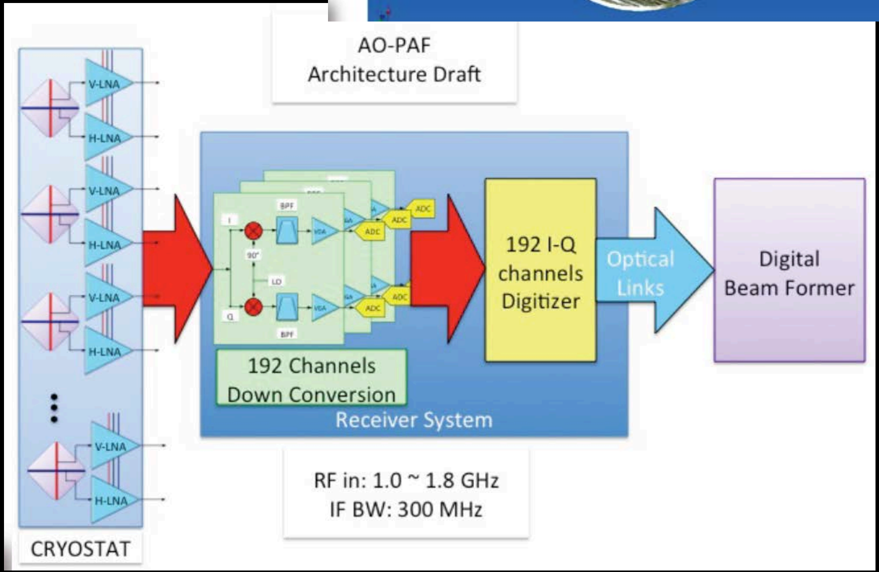
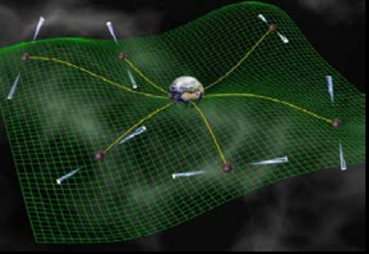
  ? 19 or 100 feed horns

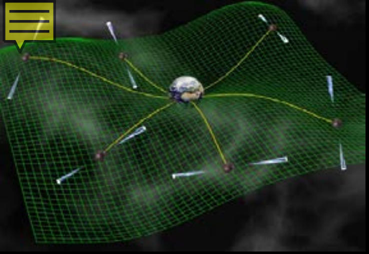




Pulsar Timing Arrays
New Approaches

The European Pulsar Timing Array (EPTA): 100-m class telescopes

Ultimately forming the Large European Array for Pulsars (LEAP)

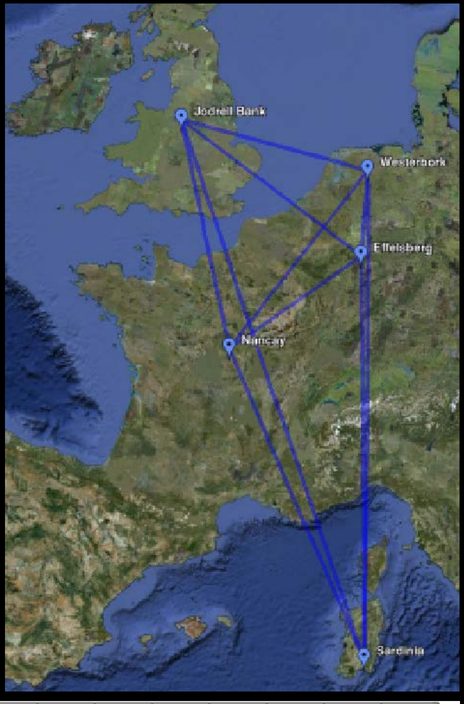


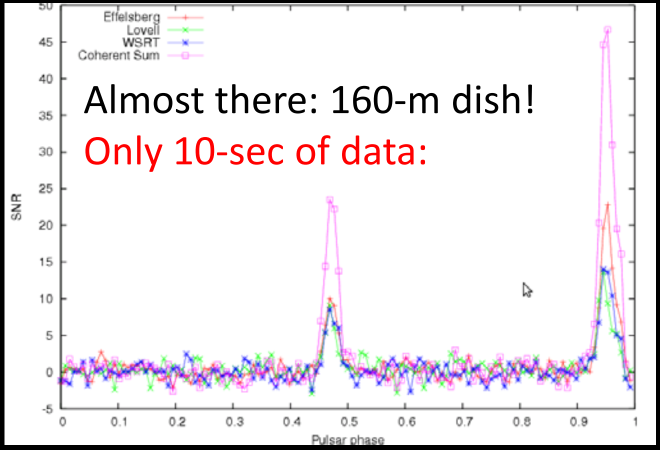
Pulsar Timing Arrays
New Approaches

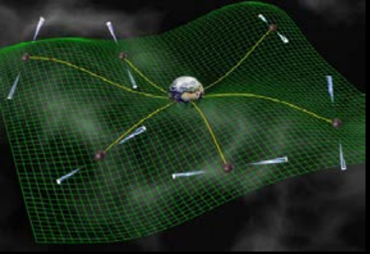
Large European Array for Pulsars = LEAP!

Current status:

- Hardware to record >128 MHz BW, 8 bits, baseband data in place at all telescopes:
  - ASTERIX-like systems at Effelsberg and Jodrell Bank
  - PUMA-II at Westerbork
  - BON at Nançay
  - DFB (in APSR-mode, to be tested) at Sardinia
- 24 hr observations at L-band, once per month *(in addition to regular EPTA observations – 30 TB/site/session)*
- Data currently shipped by disk, internet tested
- Successful addition of EFF-JB-WSRT, Nançay added within days/week, SRT in Q4/2012





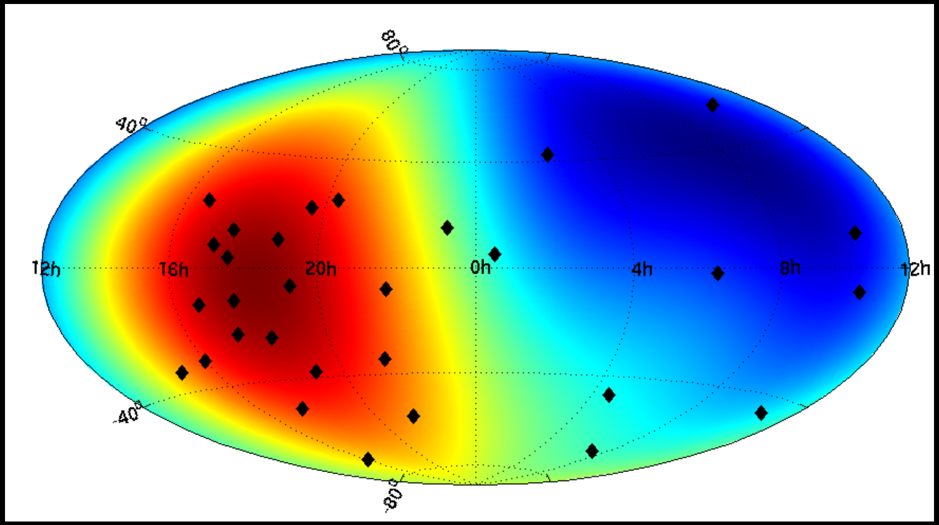


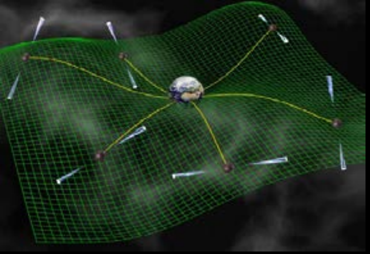
Pulsar Timing Arrays
New Approaches

For a set of N telescopes and M pulsars, what is the optimal scheduling that maximizes the probability of detecting gravitational waves?

Telescope Infrastructure

Pulsar Sample





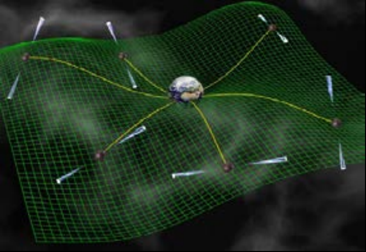
Pulsar Timing Arrays
Future Telescopes

Karl G. Jansky Very Large Array

- A_{eff} ~ 130 m
- YUPPI backend
  Clone of GUPPI, implemented in existing correlator
- Primarily a timing instrument

Five-hundred metre Aperture Spherical Telescope (FAST)

- D_{eff} ~ 300 m
- 19 or 100-beam system
- ~ 500 new MSPs discovered (projected)



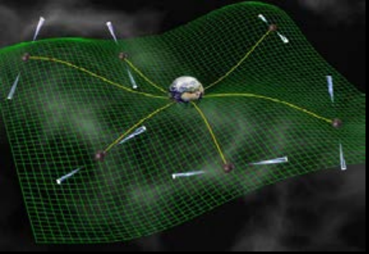
Pulsar Timing Arrays
Future Telescopes

Australian Square Kilometre Array Pathfinder (ASKAP)

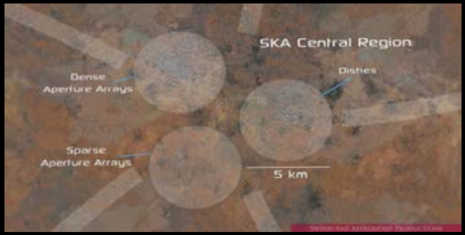
- A_{eff} ~ 60 m
- Phased array feed ~ 30 deg^2 field of view
- Primarily a search instrument

Karoo Array Telescope (MeerKAT)

- A_{eff} ~ 100 m
- Primarily a timing instrument



Square Kilometre Array

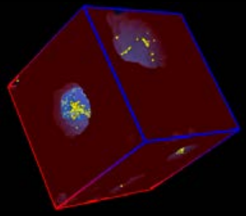


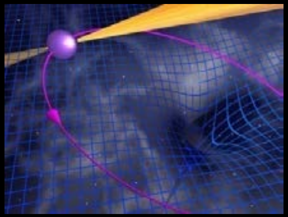
The Global Radio Wavelength Observatory

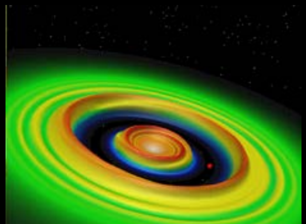
- Originally: “Hydrogen telescope”
  - Detect H I 21-cm emission from Milky Way-like galaxy at $z \sim 1$

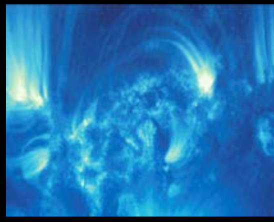
- SKA science much broader
  - $\Rightarrow$ Multi-wavelength, multi-messenger

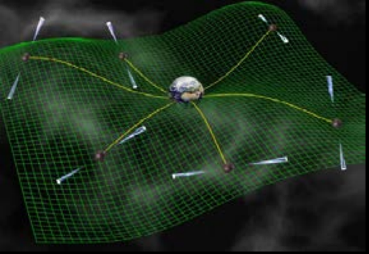
- On-going technical development
- International involvement



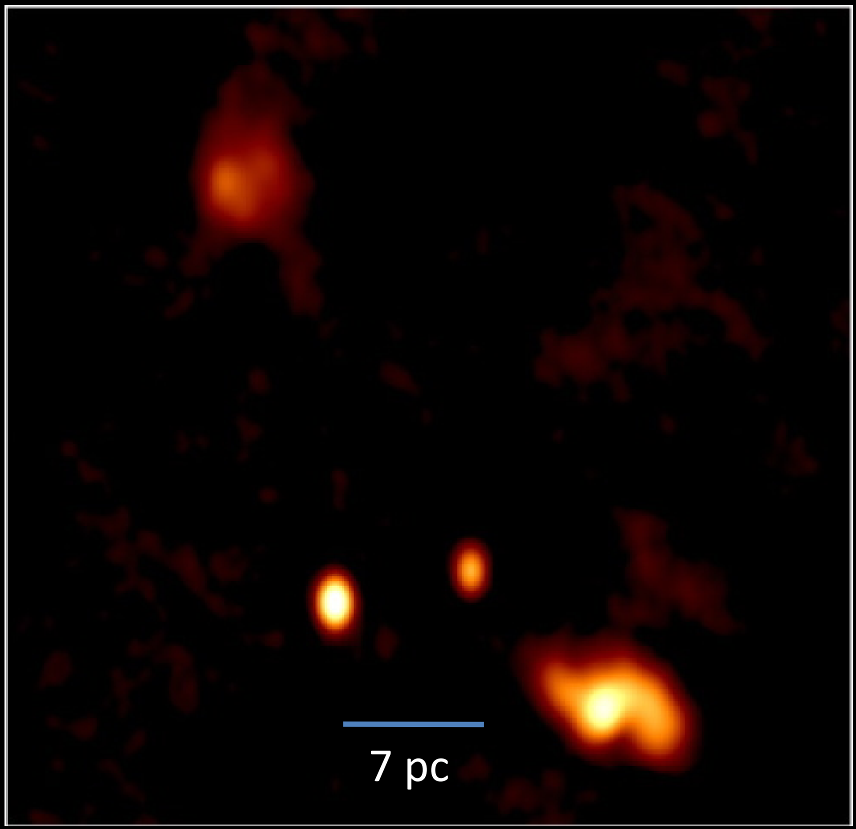








Radio Telescopes and Astrophysical Sources



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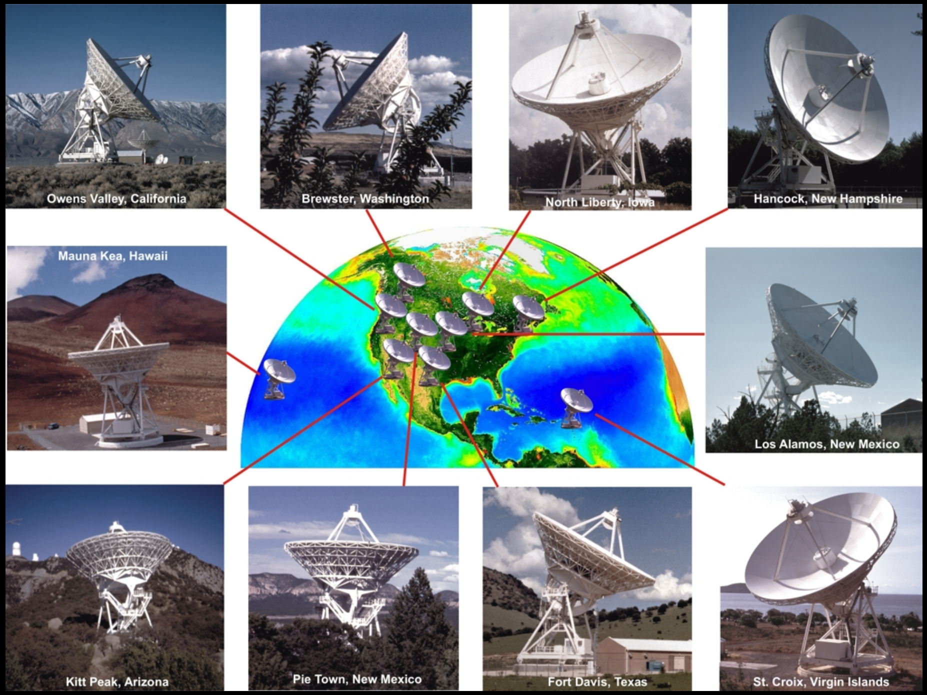
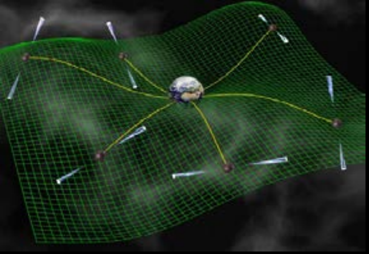
Search for additional dual SMBHs, progenitors of GW-emitting binary SMBHs

- With VLBA now, SKA in the future
- Relevant for future space-based GW mission



Very Long Baseline Array (VLBA)



Pulsar Timing Arrays
Current and Future Instrumentation

- What are the requirements?
    - Instrumental performance improving steadily
- What exists?
    - Powerful set of telescopes
- What is on the horizon?
    - Increasing capability with new telescopes

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