Precsion Pulsar Timing and the Interstellar Medium

Paul Demorest, NRAO Charlottesville

April 30, 2009

Outline

Pulsar Timing and Gravitational Waves

Systematic Timing Effects / ISM

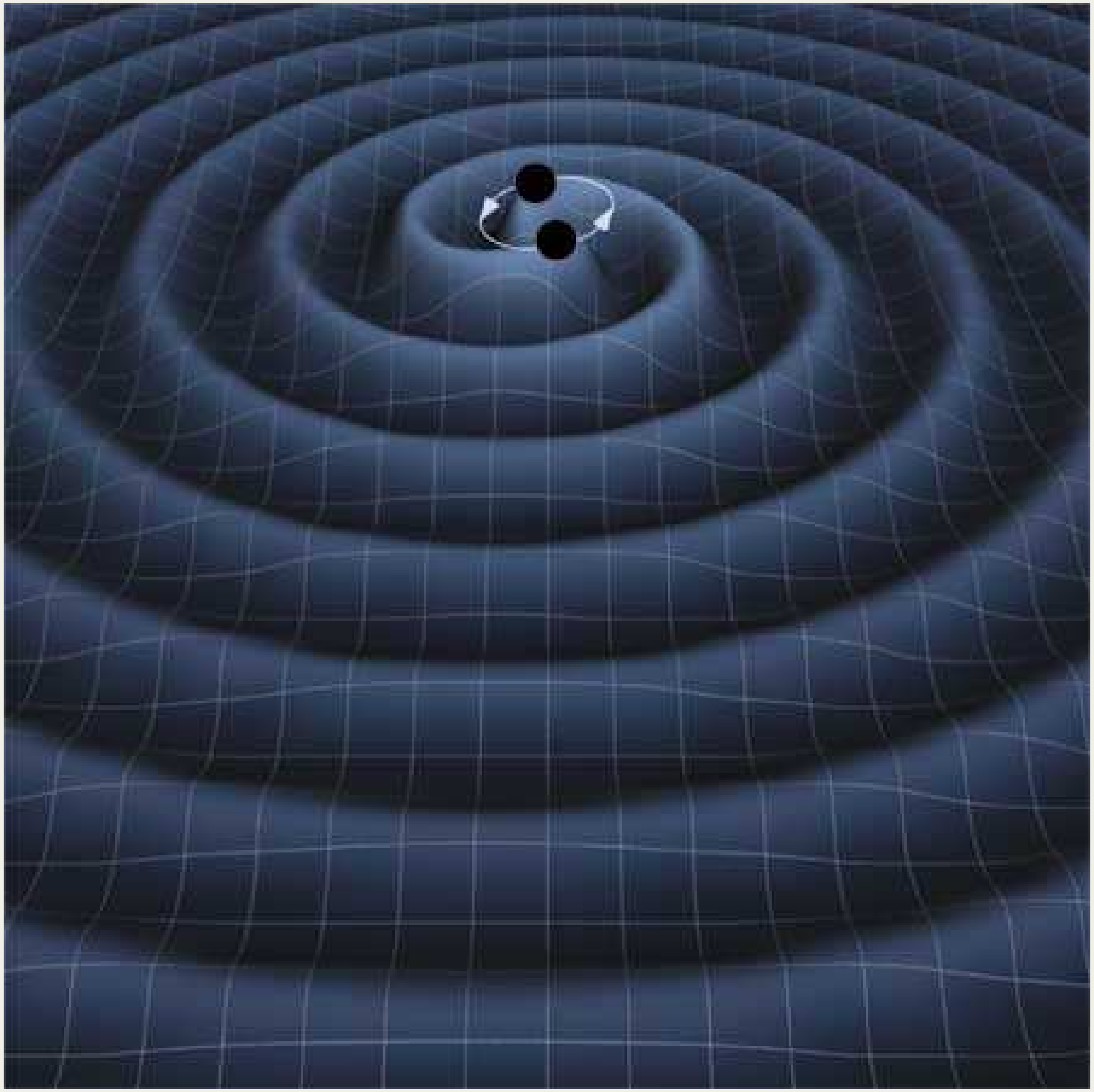
Advances in Pulsar Spectroscopy

Recent Observational Results

Collaborators:

- GW: NANOGrav collaboration (`http://www.nanograv.org`)
- ISM: Mark Walker, Willem van Straten

Gravitational Waves

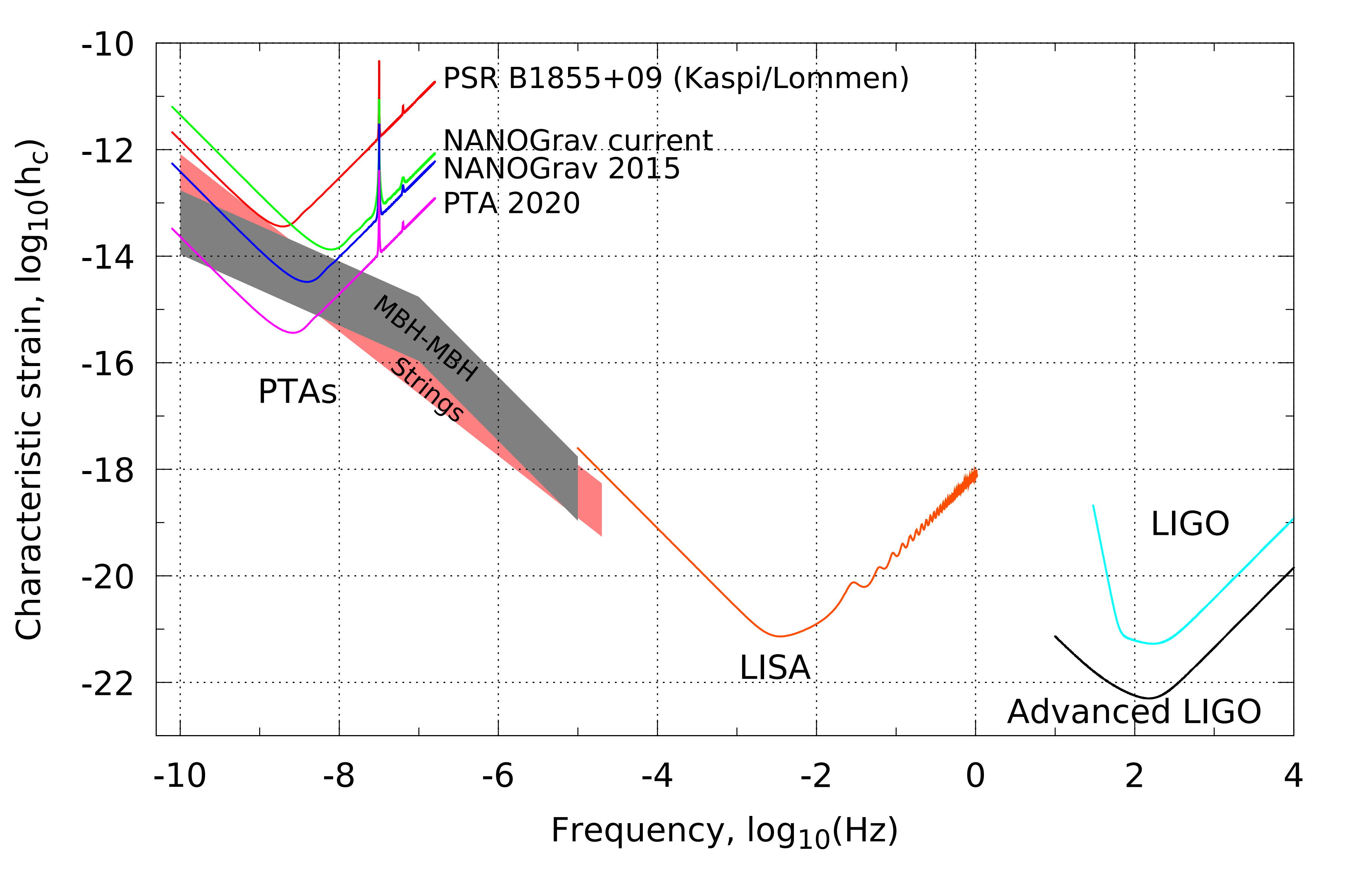


GW Detectors

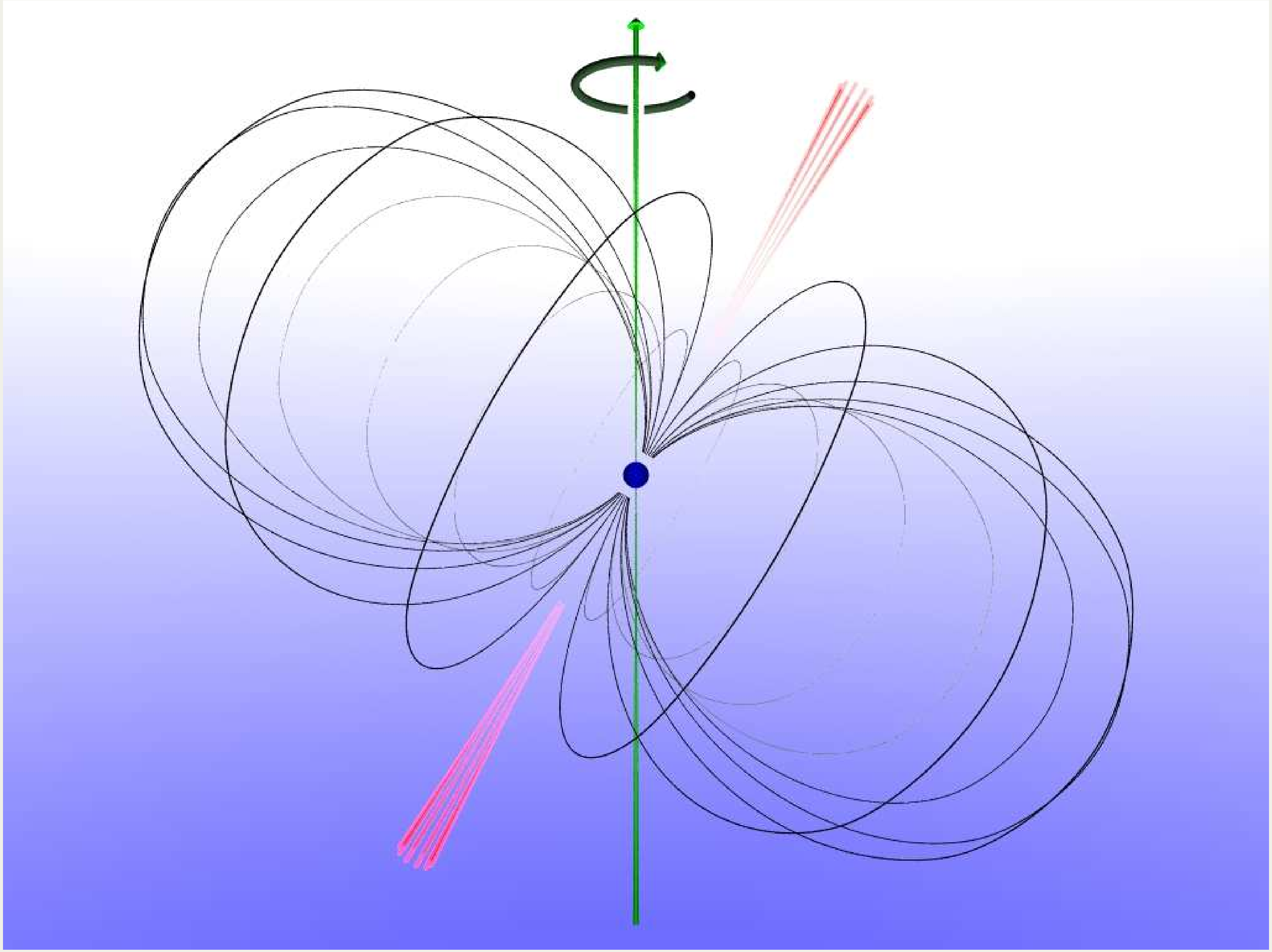
- LIGO = Laser Interferometer Gravitational Wave Observatory
  - $\nu_{GW} \sim$ kHz
  - Main targets are galactic sources (WD, NS, BH binaries)
  - Currently operating, major upgrade planned.
- LISA = Laser Interferometer Space Antenna
  - $\nu_{GW} \sim$ mHz
  - Both galactic and extragalactic (MBH) sources.
  - Still in planning stages.
- PTA = Pulsar Timing Array(s)
  - $\nu_{GW} \sim$ nHz
  - Extragalactic/cosmological sources (MBH, cosmic strings)
  - Several ongoing international efforts: NANOGrav (N. America), PPTA (Parkes), EPTA (Europe).

GW Spectrum

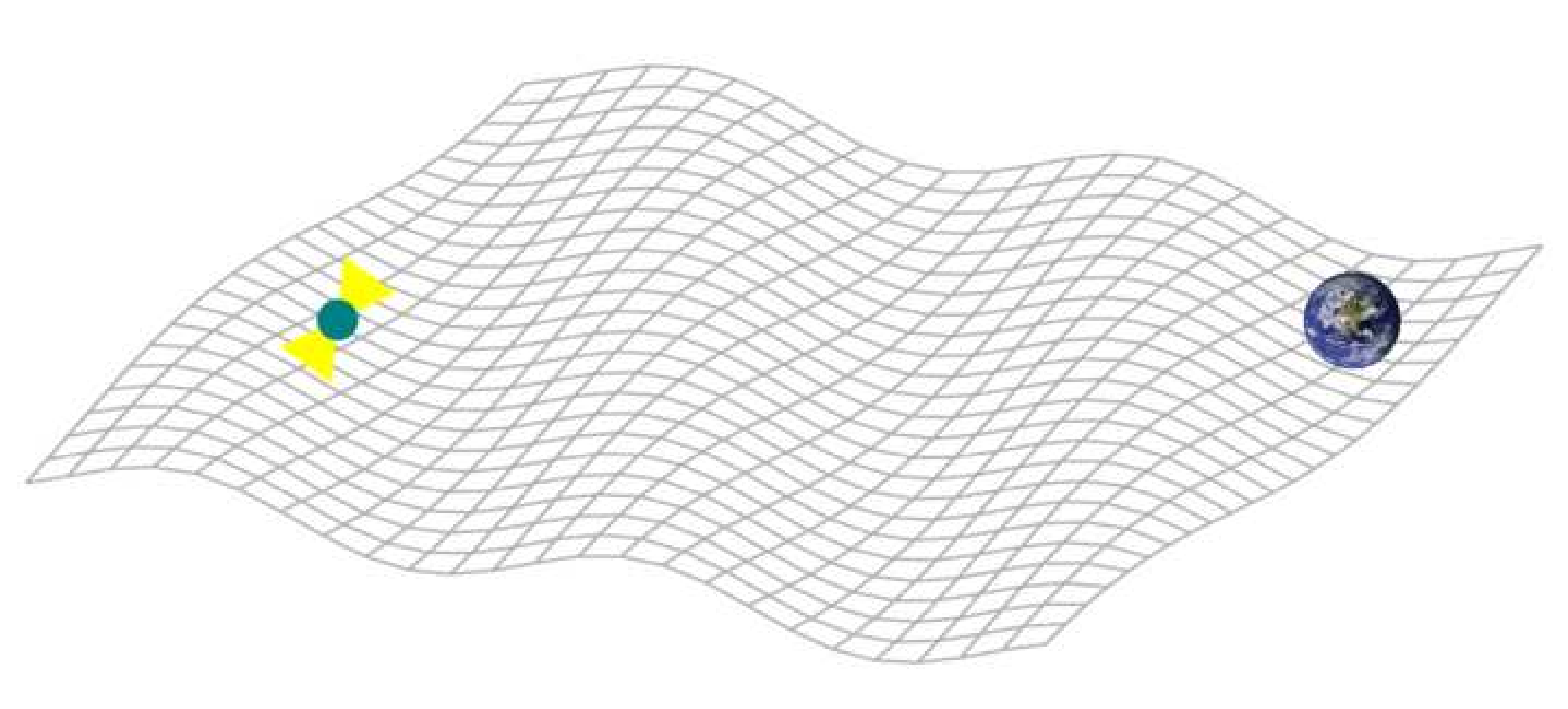
Detector complementarity:



Pulsars as GW detectors

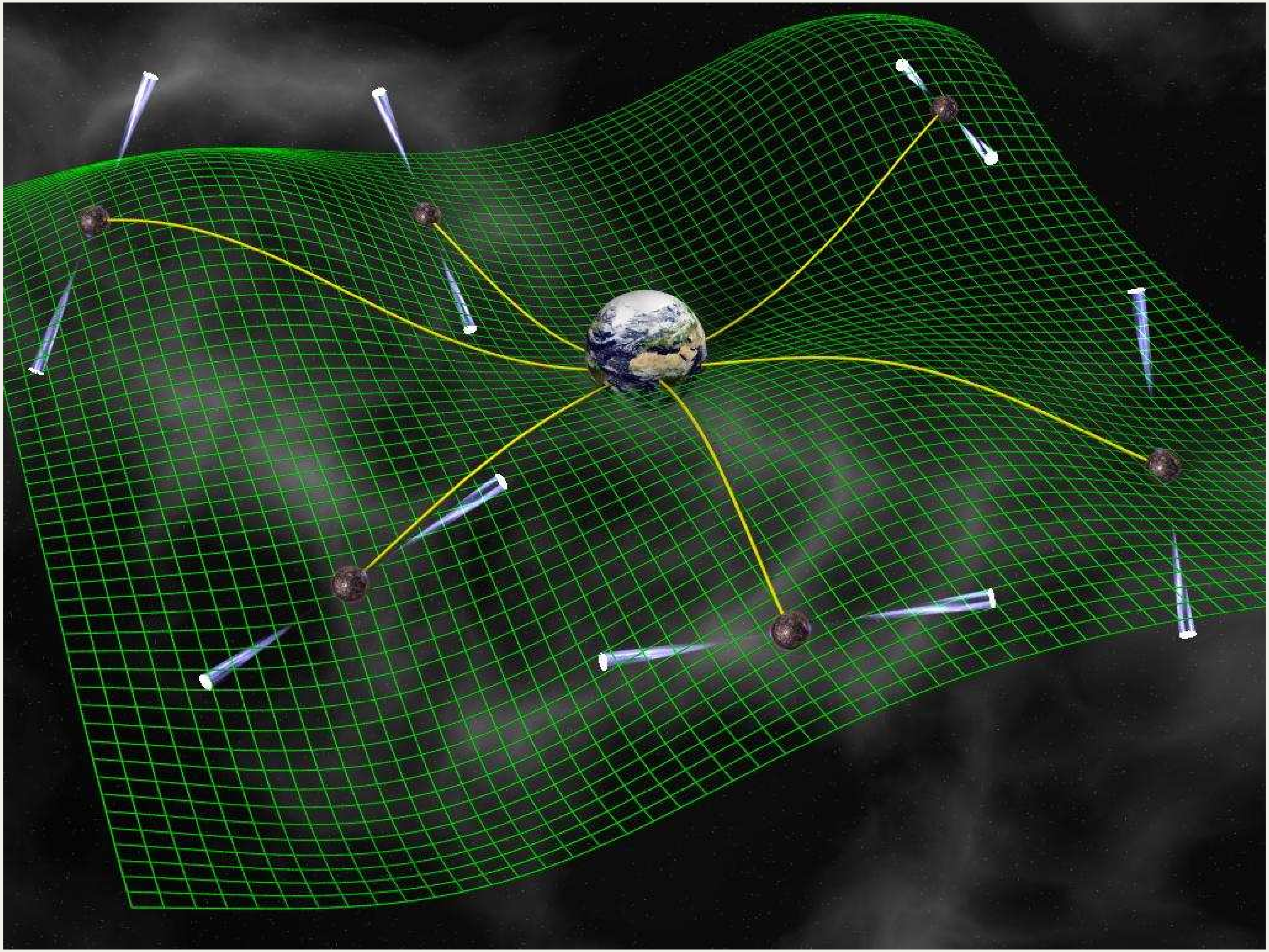


Pulsars as GW detectors



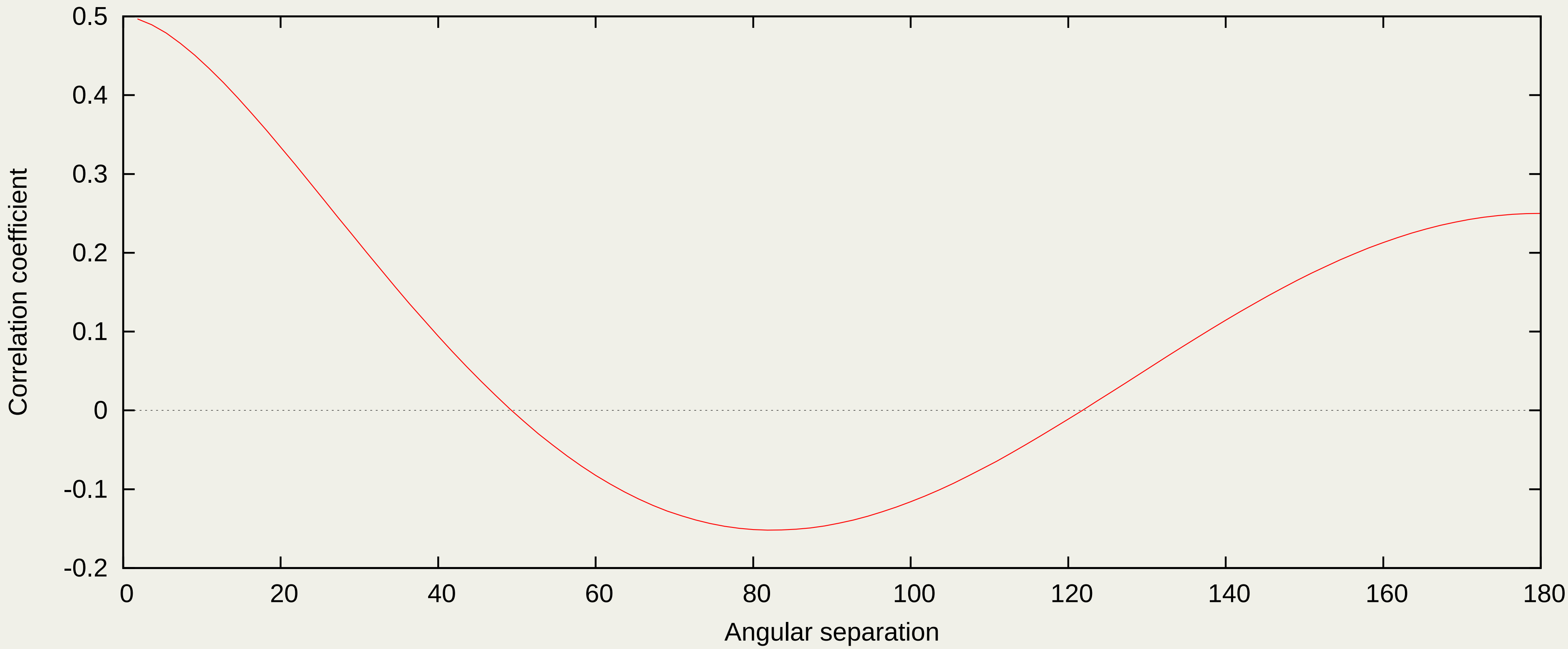
Radio pulses travelling through GW to Earth acquire additional delays.

Pulsar Timing Array



Pulsar Timing Array

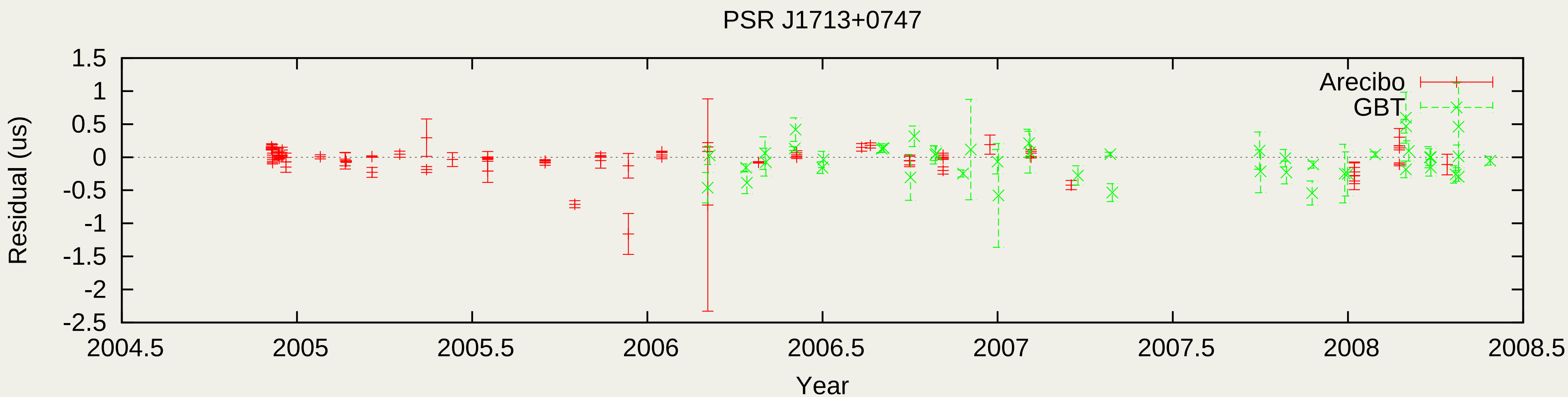
GW-induced timing fluctuations will be correlated between different pulsars (Hellings & Downs, 1982):

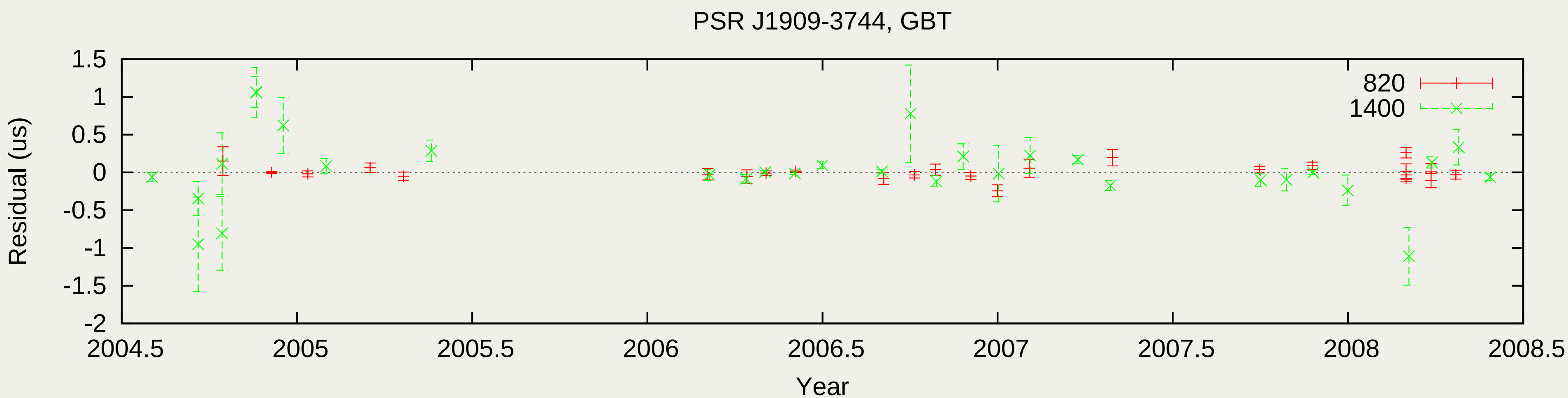


This method makes GW *detection* possible!

Timing Results

Best NANOGrav MSP timing results have RMS ~ 100 ns:



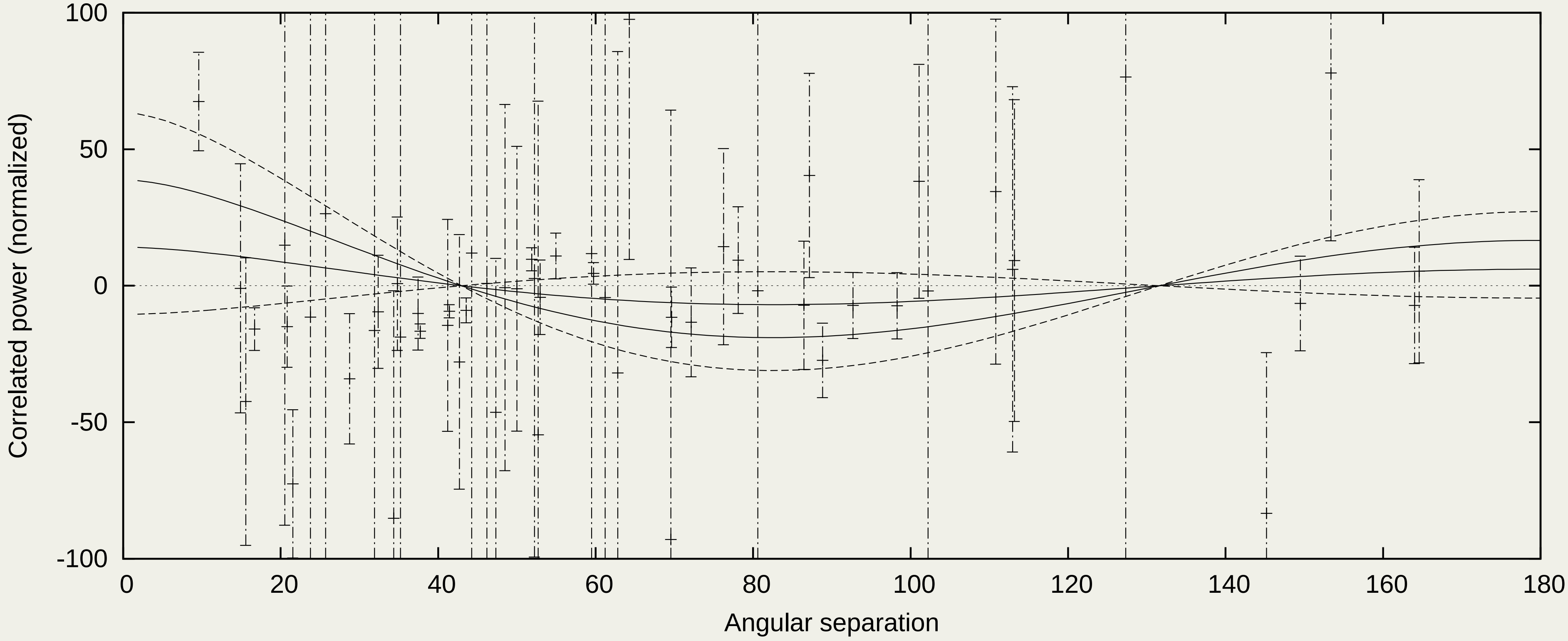


Order-of-magnitude GW sensitivity is $\sim \delta t/T$.

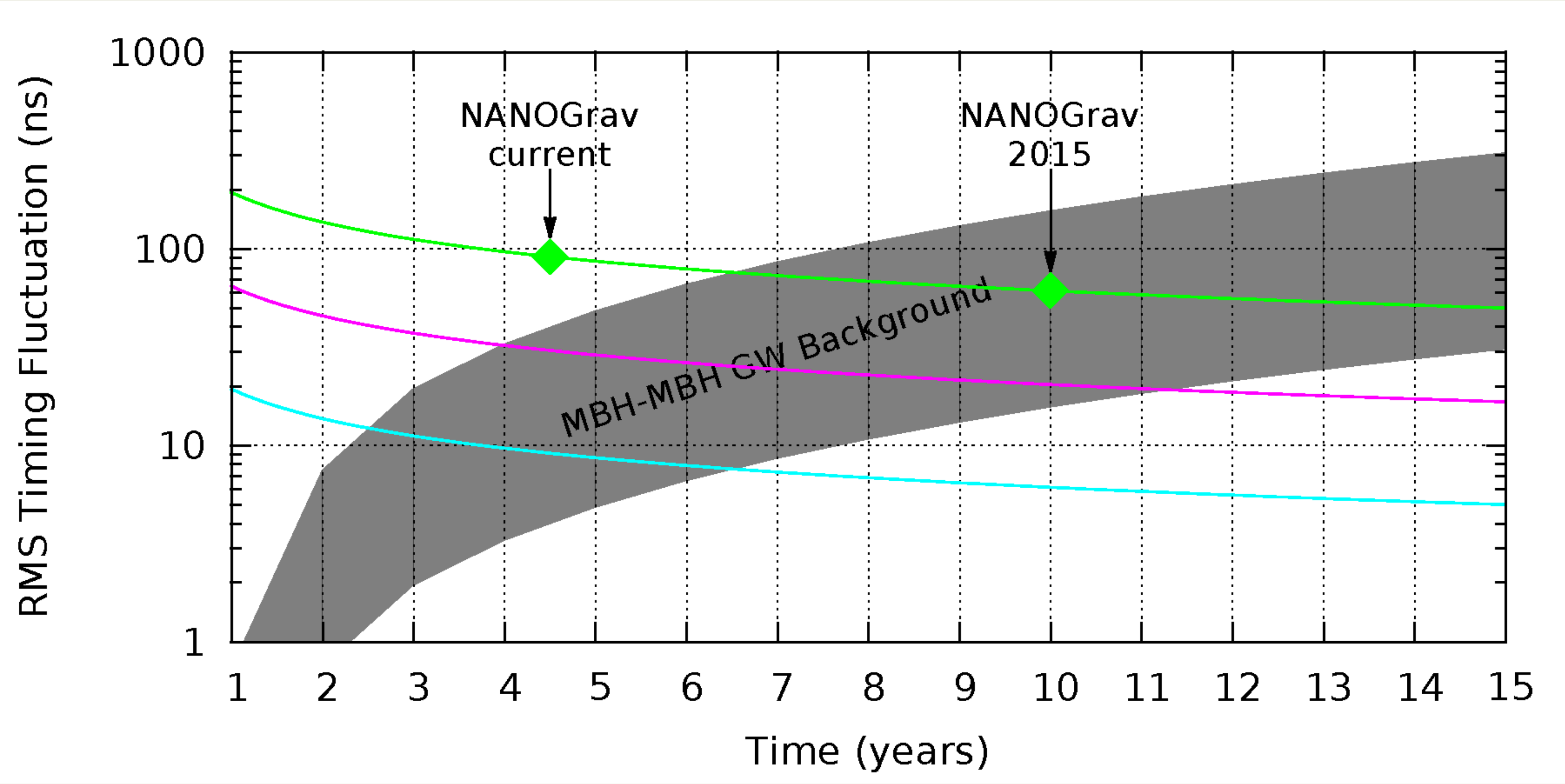
Timing Array Limits

Correlation analysis of first ∼4 years of NANOGrav data:

$h_c(1\ \mathrm{y}^{-1}) < 7 \times 10^{-15}$

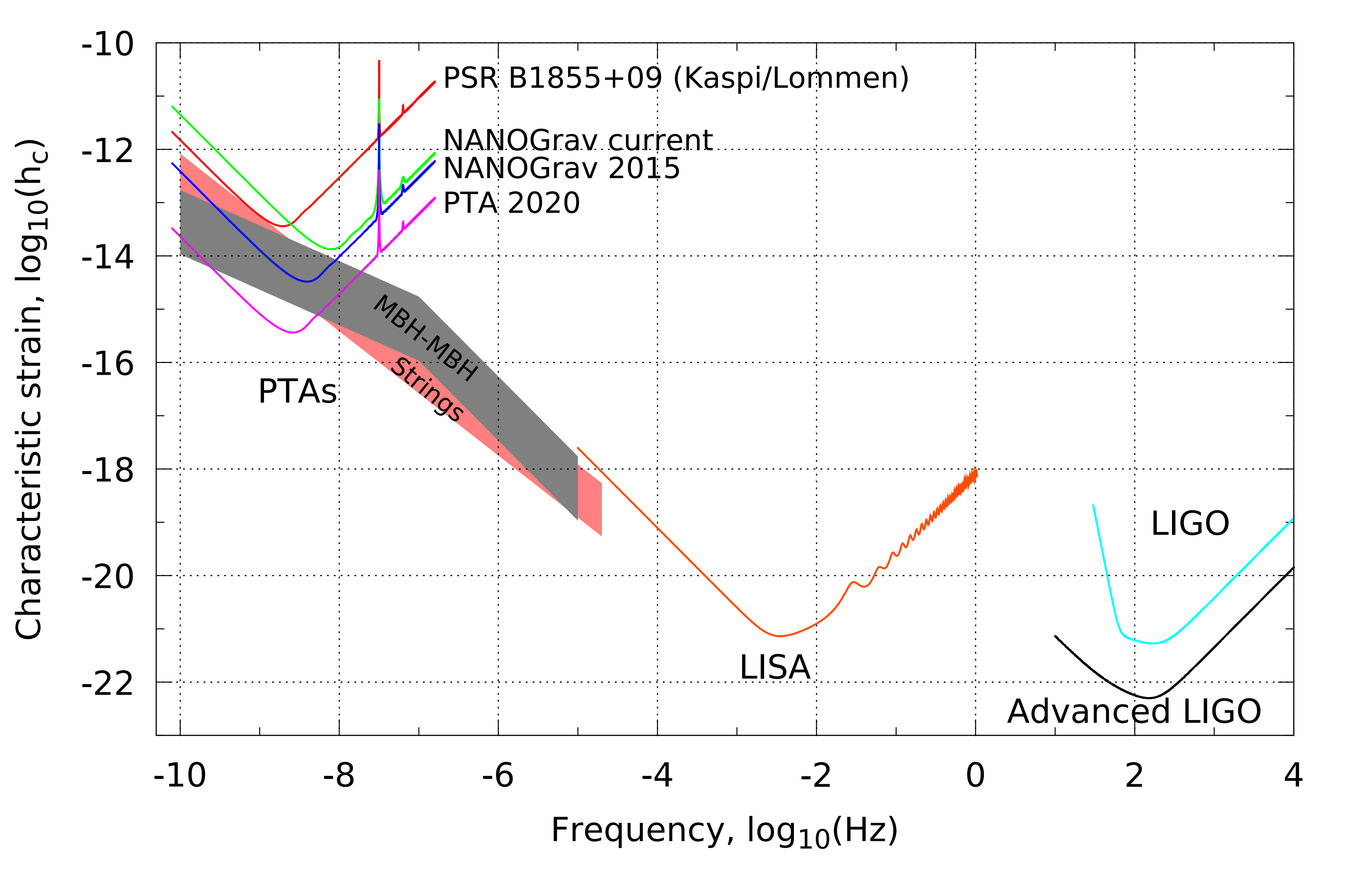


Improvement with time



GW Spectrum

Improvement with time:



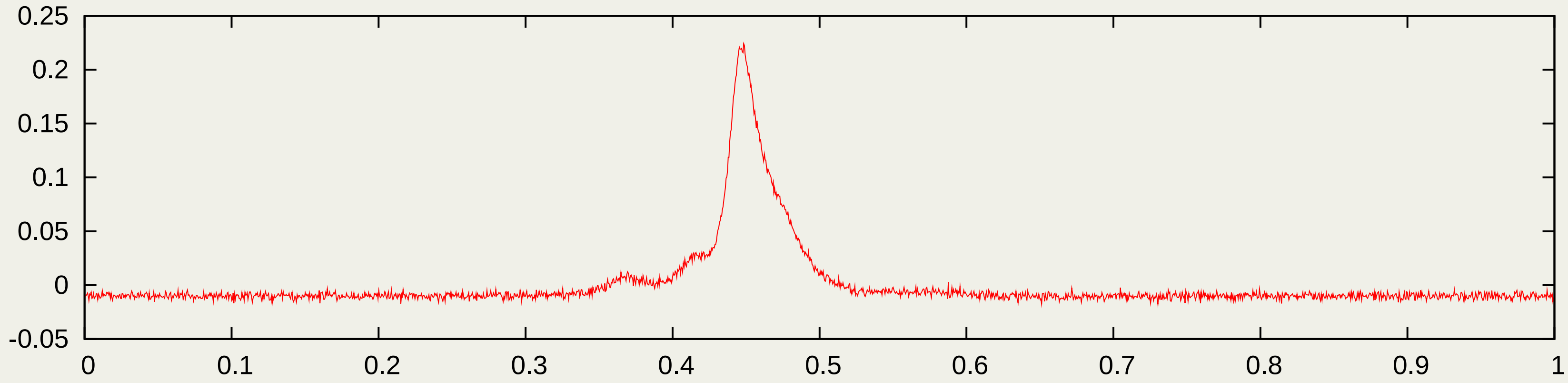
Timing Array Summary

- Current NANOGrav PTA limits are comparable to the 20-year single pulsar limit.
- Another $\sim$3–5 years reaches into plausible detection territory.
- Jenet et al. (2005) estimate that we need 20–40 pulsars at 100 ns for 5 years for a “guaranteed” robust ($> 4\sigma$) detection.
- More good-timing pulsars are needed.
  - Searching for new pulsars.
  - Increasing BW, G/T to improve currently known pulsars.
  - *Reduce systematic effects*, improve analysis algorithms.

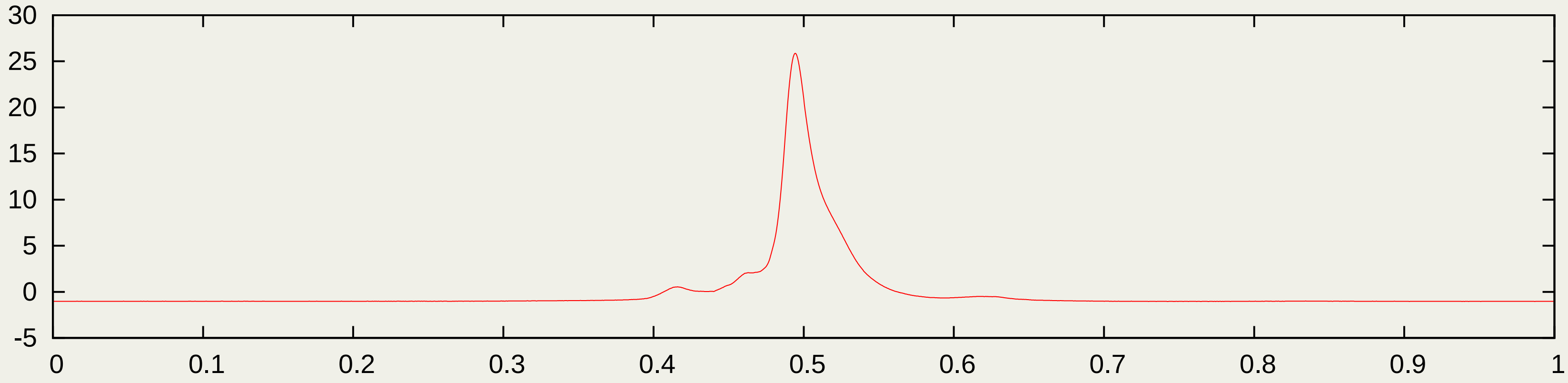
(See also Demorest et al. (2009) Astro2010 WP)

Systematic Timing Effects

We compute arrival times (TOAs) by matching data:



to a scaled, shifted “template”:

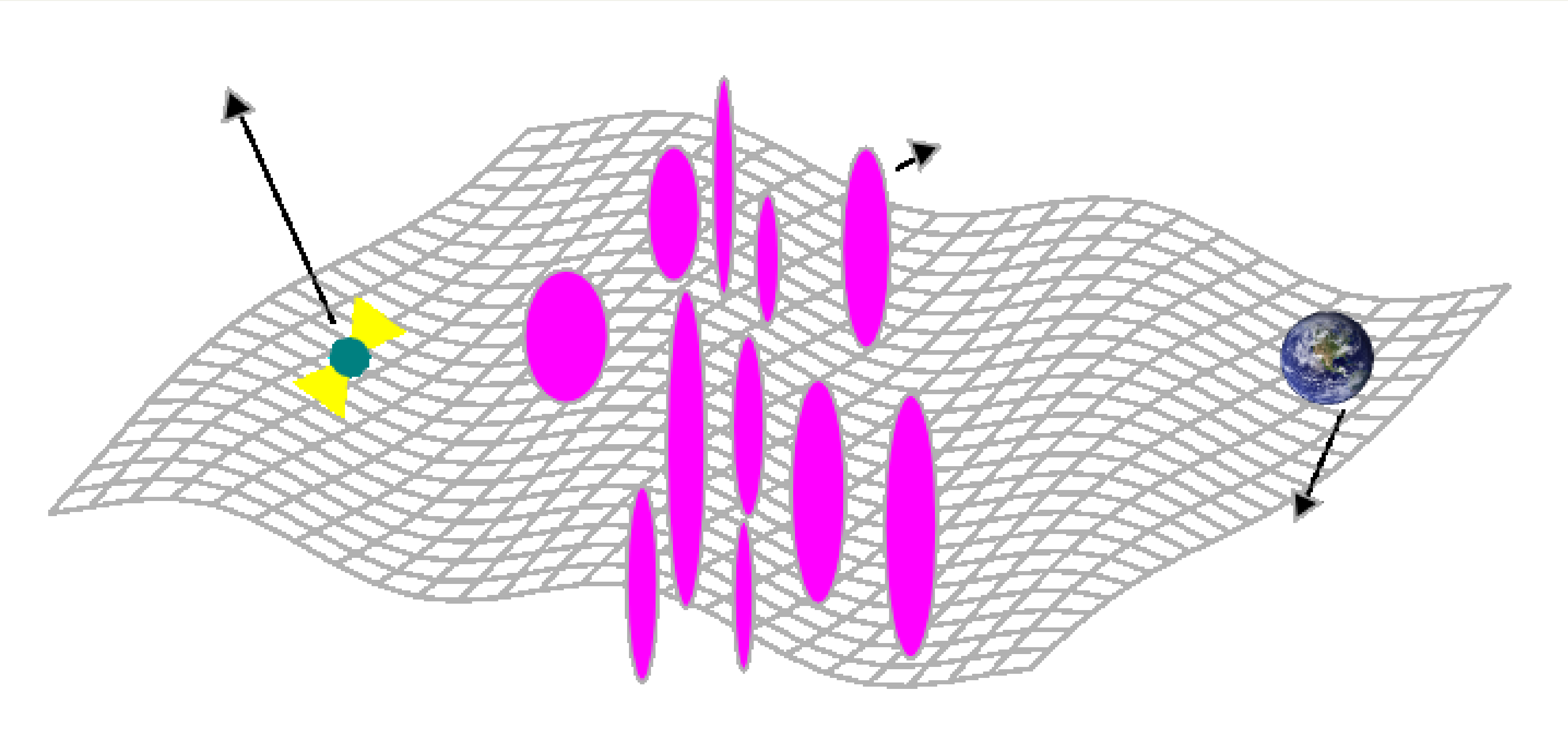


Any corruption in the measured profile shape can affect timing.
$100\ \mathrm{ns} \sim 10^{-5}$ turns.

Systematic timing effects

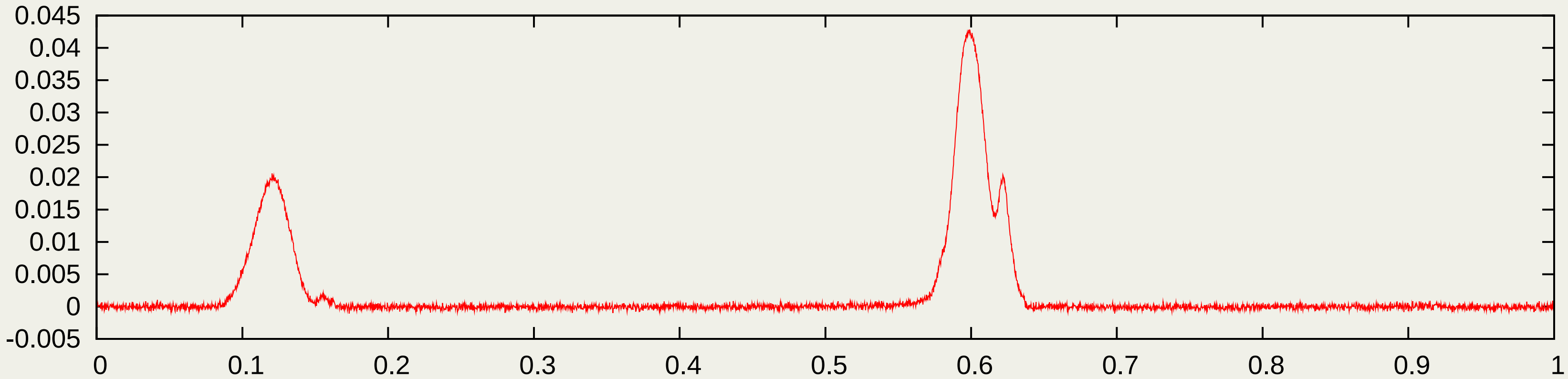
- Local:
  - Polarimetry / calibration procedures
  - Radio-frequency interference
  - Instrumental effects
- ISM:
  - DM variation with time (and maybe frequency)
  - Scattering/scintillation
  - Refraction
- Intrinsic:
  - Pulse-to-pulse “jitter”
  - “Timing noise”

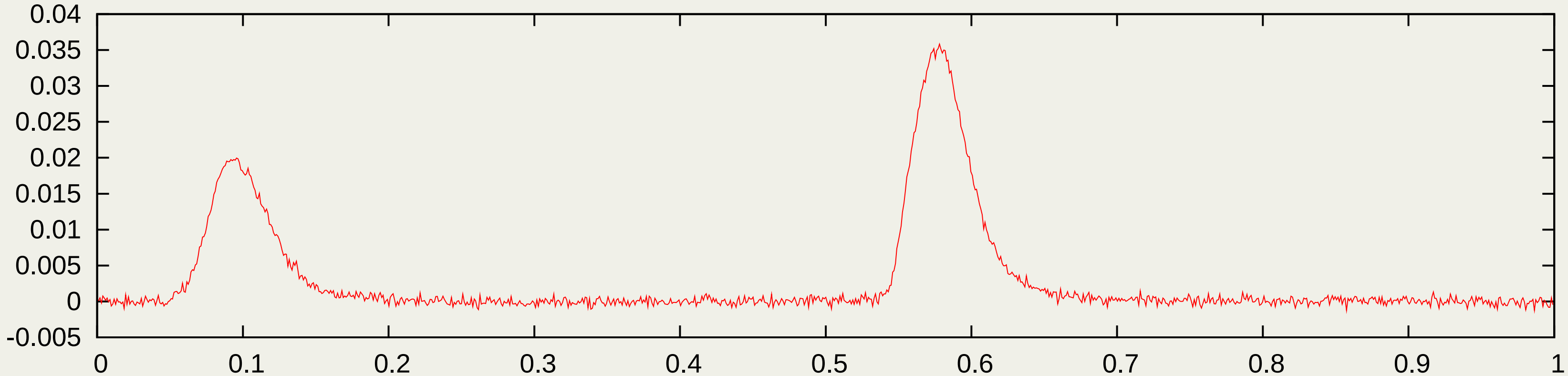
ISM



ISM effects

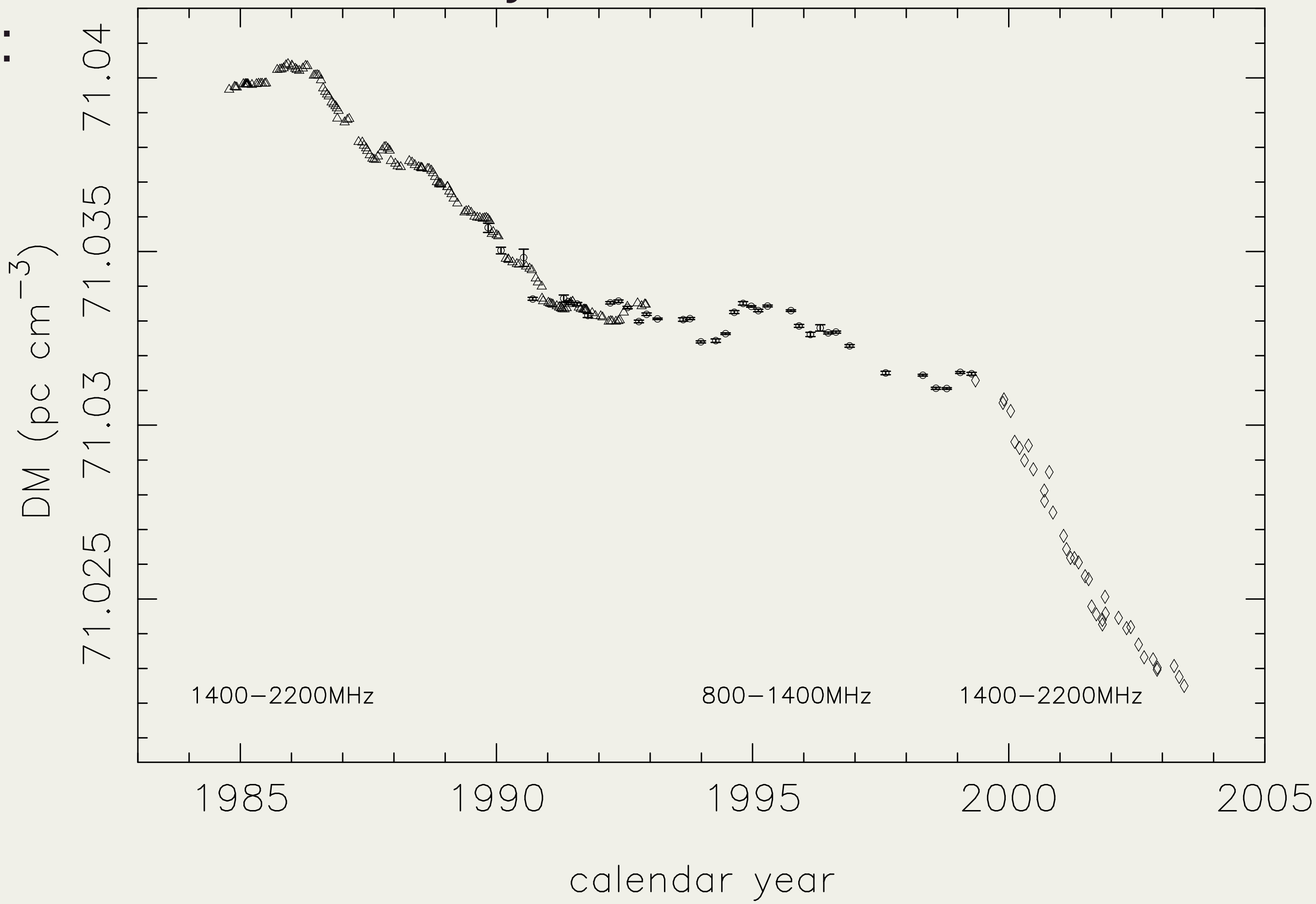
- Come from radio wave propagation through interstellar e^- plasma; strongly λ-dependent, based on plasma dispersion relation.
- Effects include $\mathrm{DM}(t)$, scattering/scintillation.
- One solution: Observe at higher RF, but psrs get weaker.





DM Variation

Total electron column density varies due to motions of Earth, PSR, and ISM:

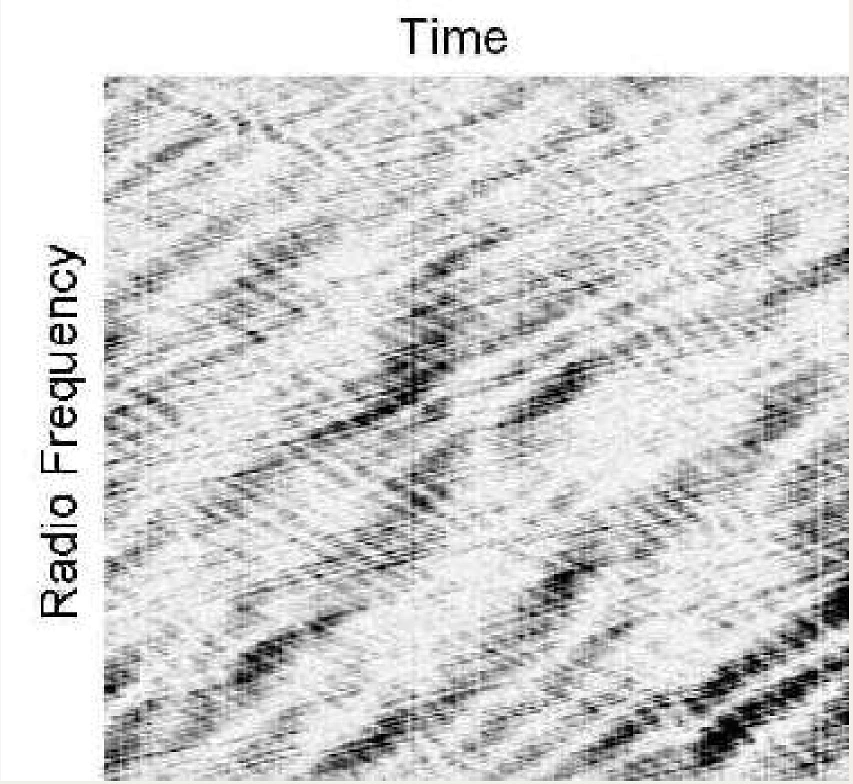


(PSR B1937+21; Ramachandran et al. 2006)

Can be measured/removed with multi-frequency timing measurements.

Scattering/Scintillation

Electron density variation transverse to the line-of-sight causes constructive/destructive interference:



(Walker et al. 2008)

Typical scales $\nu \sim$ kHz–MHz, $T \sim$ sec–hours. Determined by LOS/ISM velocity and ISM length scales.

Can be thought of as a (time-varying) "filter" with transfer function $H(\nu)$ or impulse response $h(t)$. This affects profile shapes!

Pulsar Spectroscopy

How to compute spectra from measured pulsar voltage signal $x(t)$:

Standard pulsar spectroscopy:

- Signal is divided into many radio frequency channels.
- In each channel, on-pulse and off-pulse flux are detected, integrated for some time and subtracted (“gating”).
- Results in dynamic spectrum $S(t,\nu)$.

Limitations of this approach:

- Gate width and frequency resolution are coupled (via usual uncertainty principle).
- Discards all pulse shape information.
- Can only directly determine $|H(\nu)|^2$.

Pulsar Spectroscopy

In *cyclic spectroscopy*, we compute correlations as a function of pulse phase:

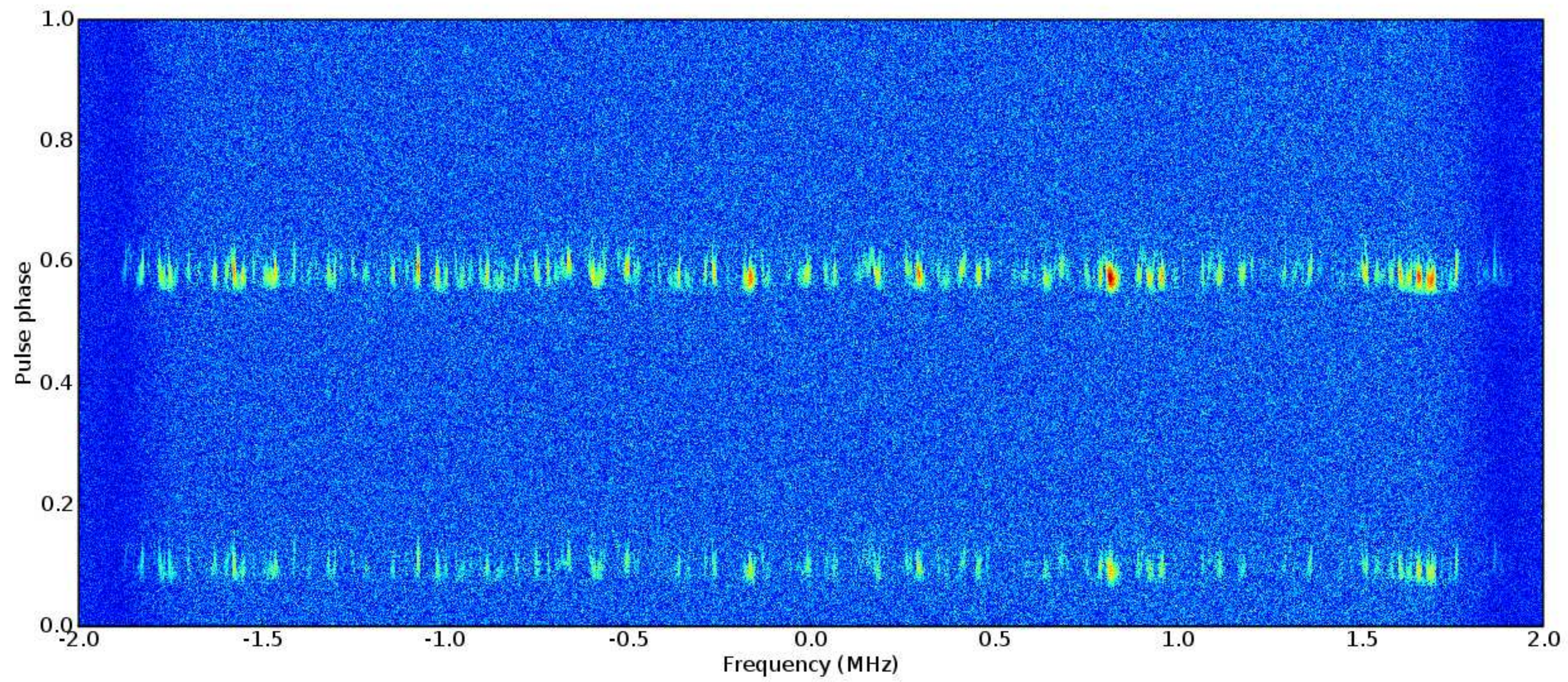
- Signal is delayed by many different lags τ.
- Each is cross-multiplied with original signal and averaged modulo the pulse period for some integration time ("folding").
- Results in periodic correlation $C(t, \tau, \phi) \rightarrow S(t, \nu, \phi)$.

Advantages of this approach:

- Number of lags (hence freq resolution) not constrained by pulse width or period.
- Makes full use of pulse shape information.
- Directly recovers $H(\nu)$ with phase!
- see reviews by Gardner (1991, 1992), Antoni (2007)

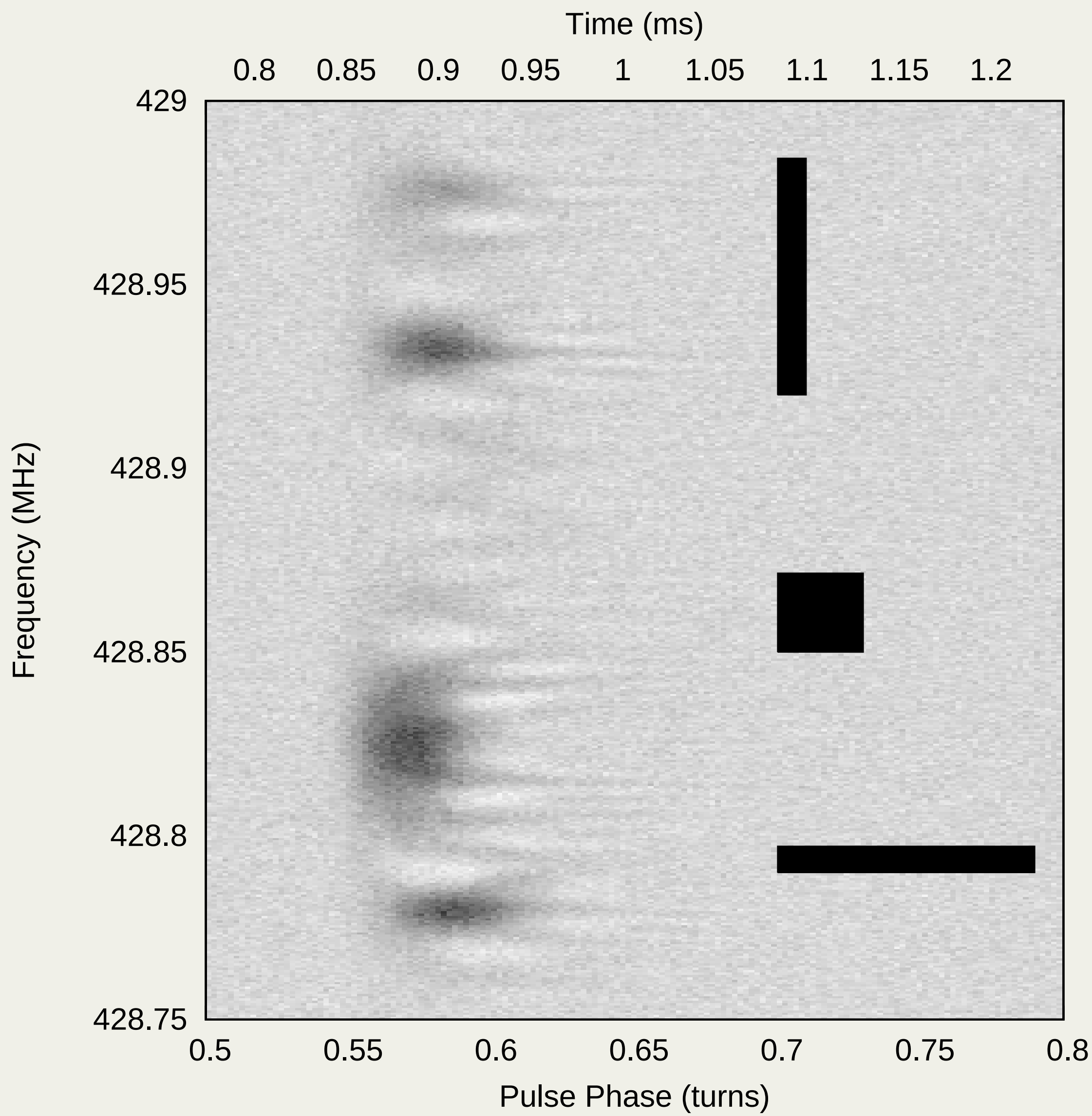
Cyclic Spectra

PSR B1937+21 at 430 MHz, Arecibo/ASP:



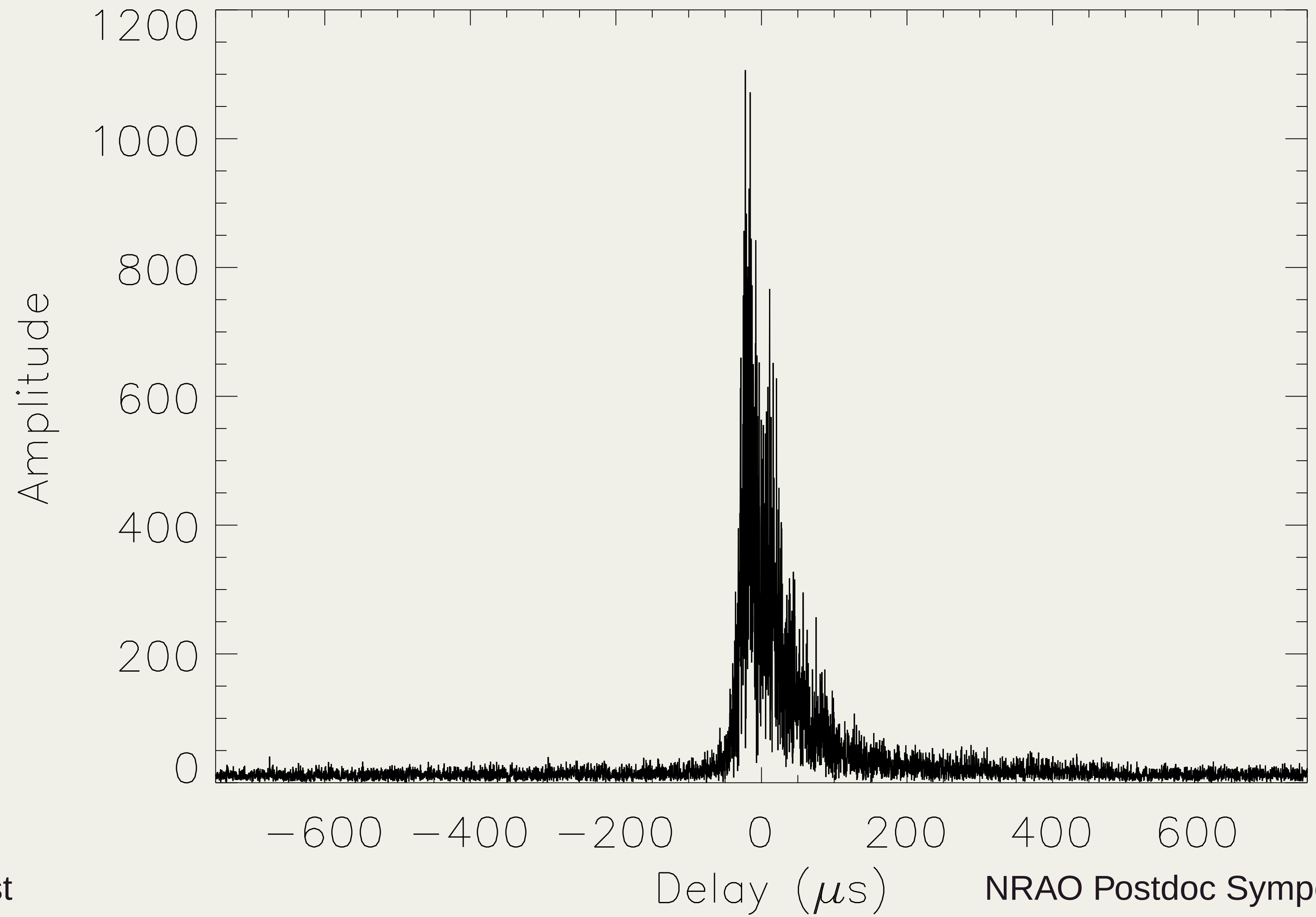
Cyclic Spectra

Same thing, zoomed in:



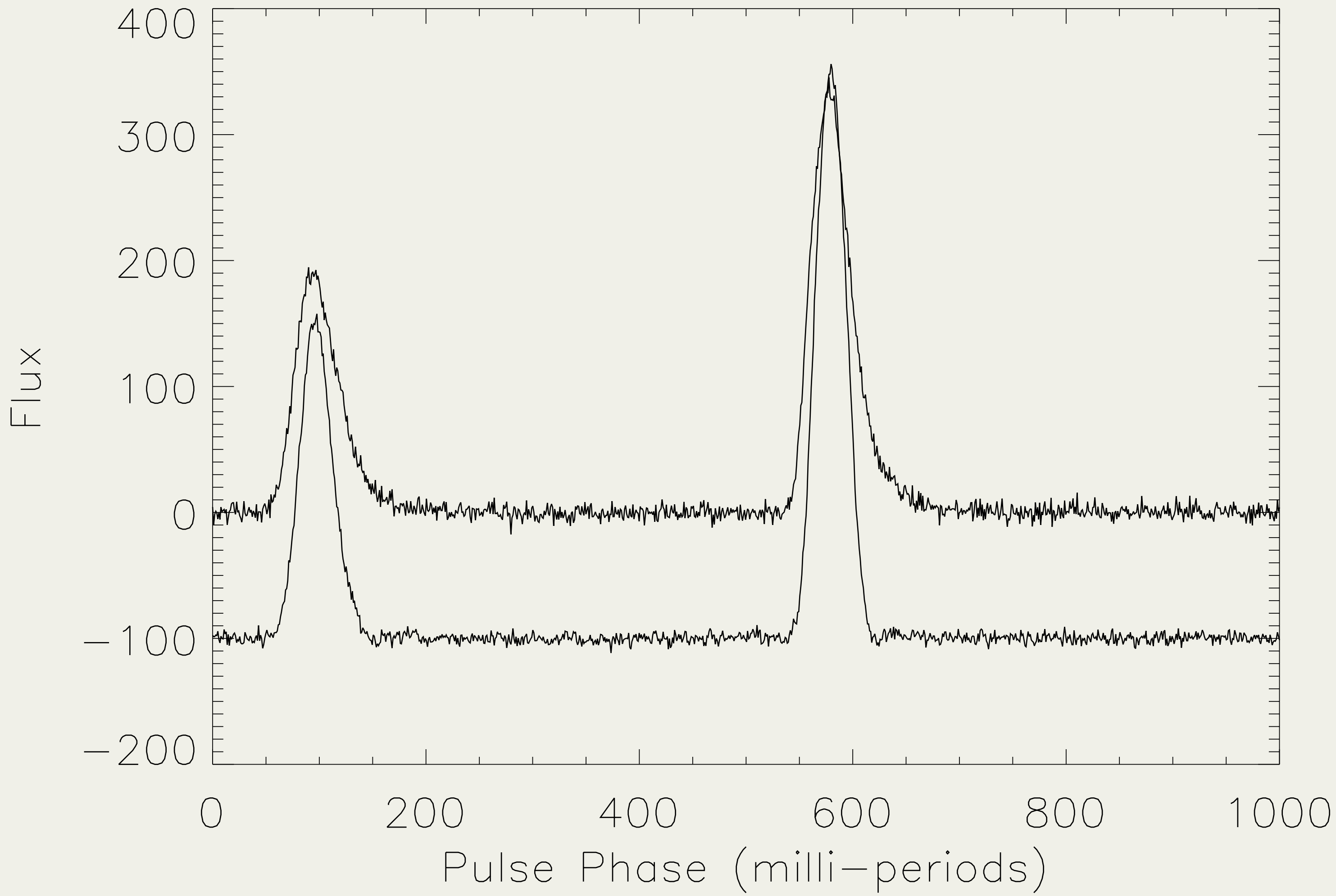
ISM De-scattering

“Snapshot” ISM impulse response $h(t)$ determined from data:



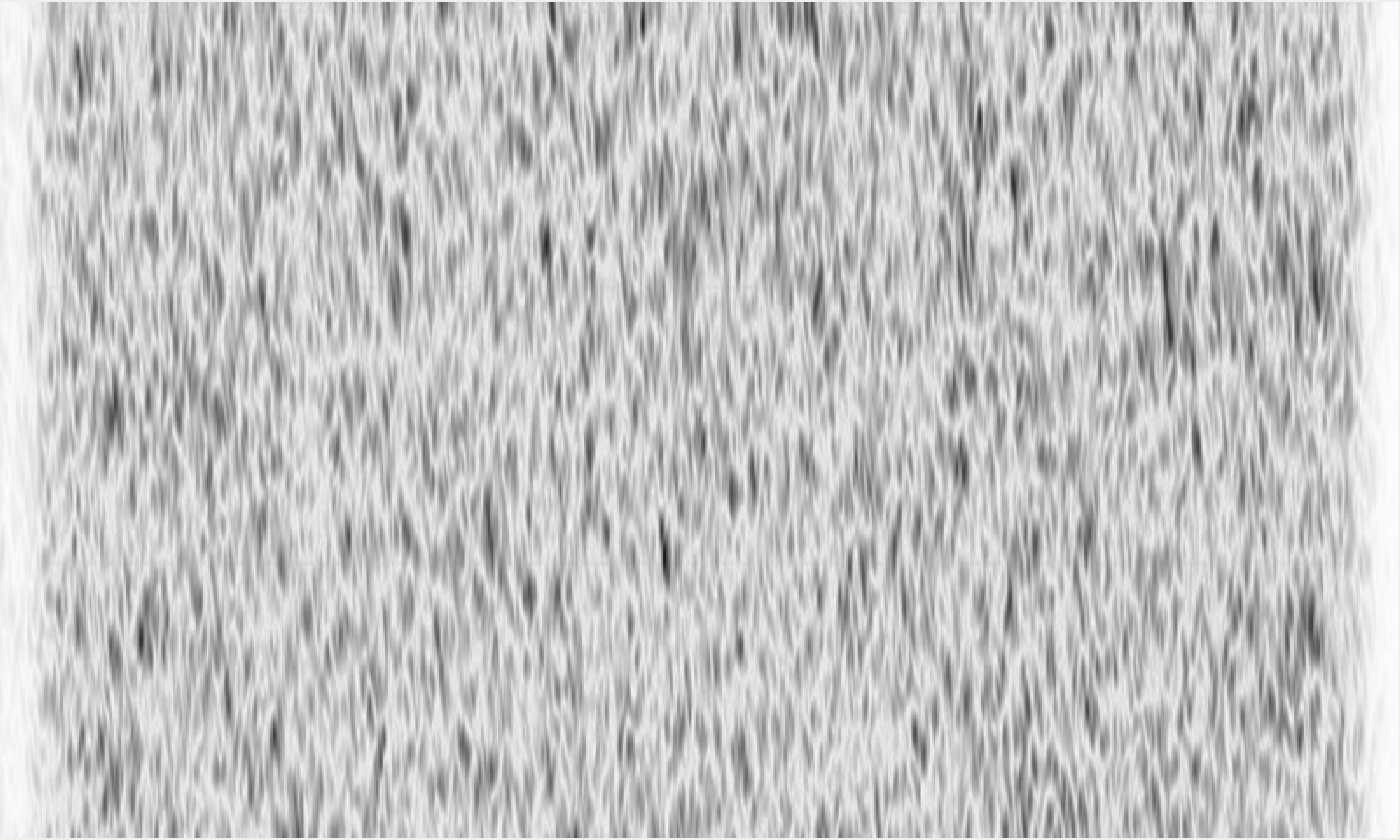
ISM De-scattering

Comparison of uncorrected and intrinsic pulse profiles:



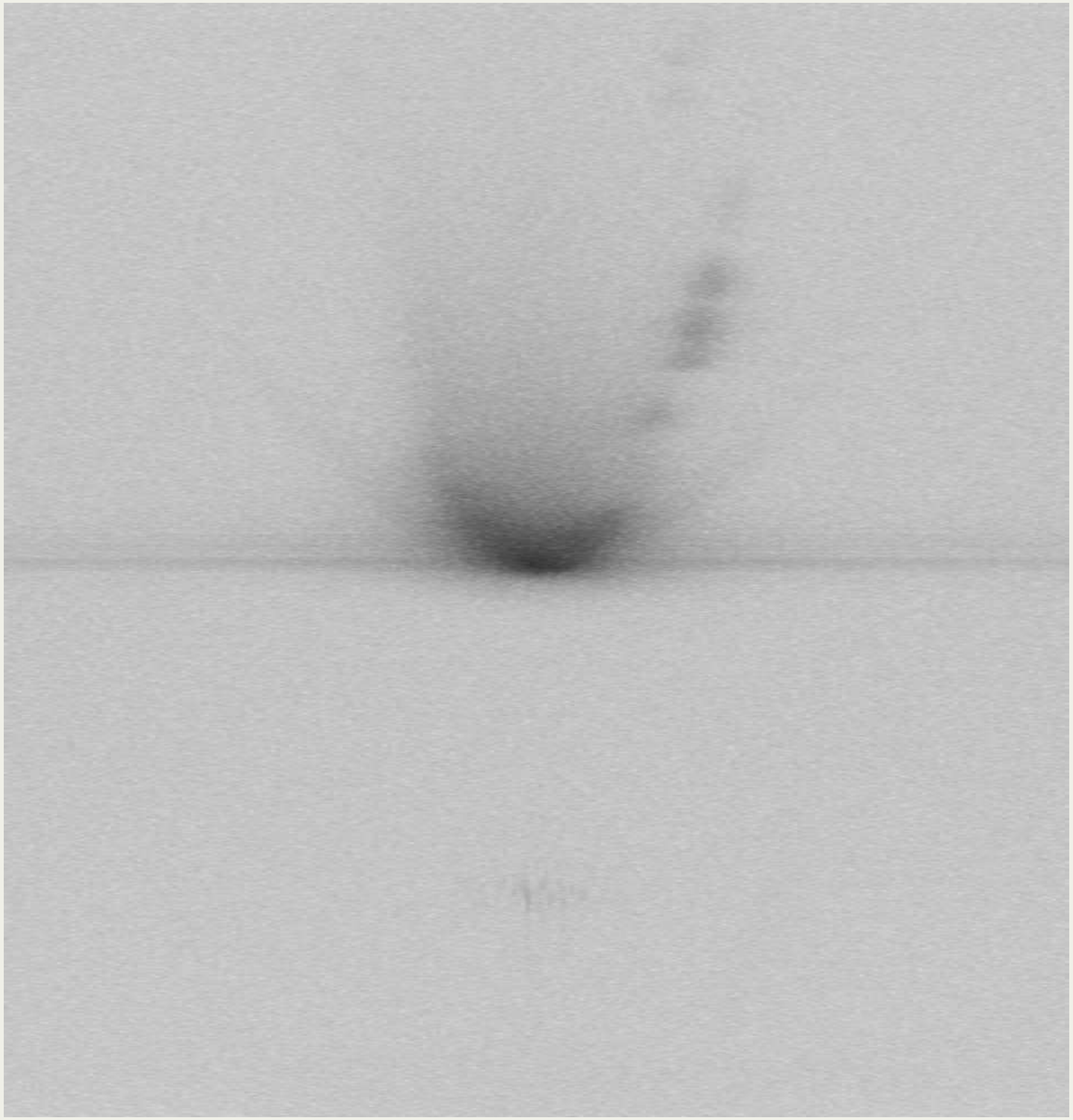
Dynamic Spectra

B1937+21, ν=430MHz, BW=4 MHz, $\Delta\nu$=0.64 kHz, T$\sim$1 hour



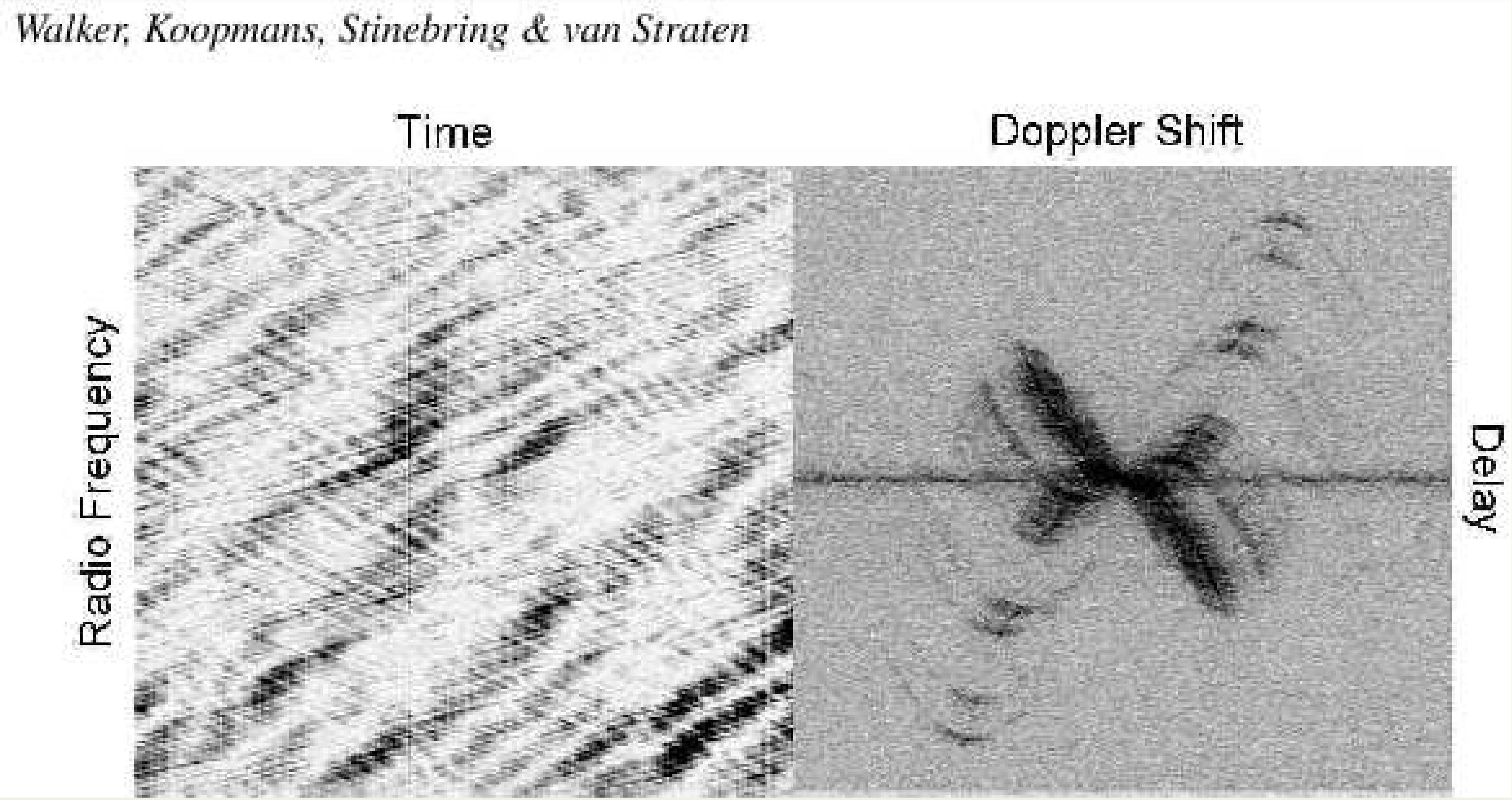
Secondary Spectra

2-D FT of dynamic spectrum, shows clear “arc” structure.



Secondary Spectra

Contrast with methods based on traditional dynamic spectra:



Future Directions

- Get scattering-corrected TOAs, improve timing
- Investigate polarimetry aspects
- Explore more strongly scattered sources
- Work towards physical ISM images
- . . .