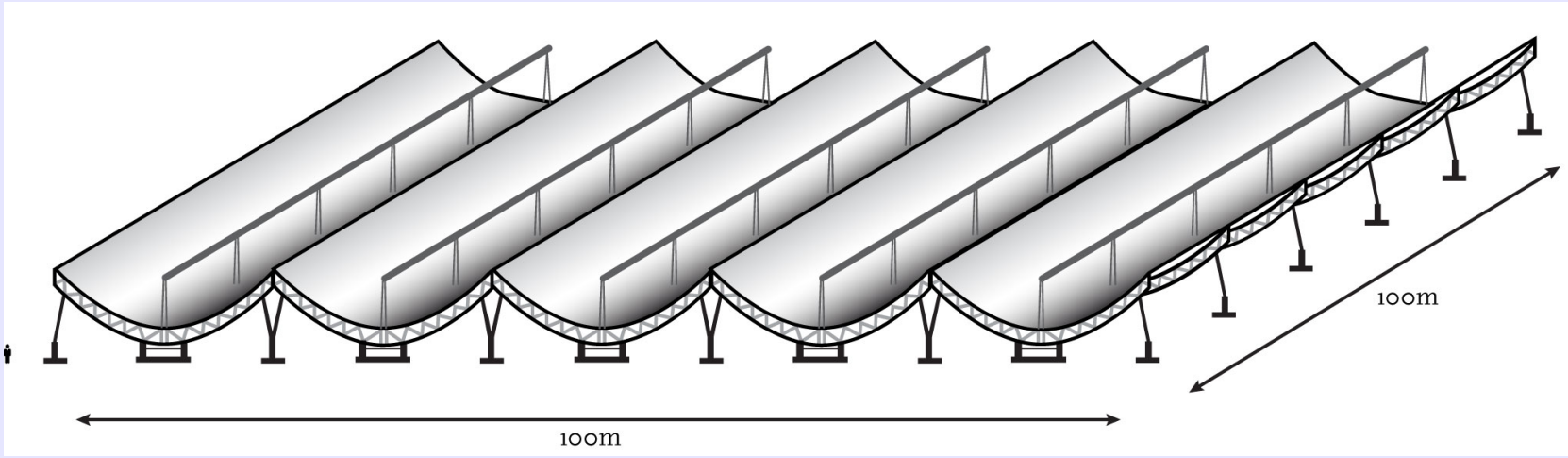
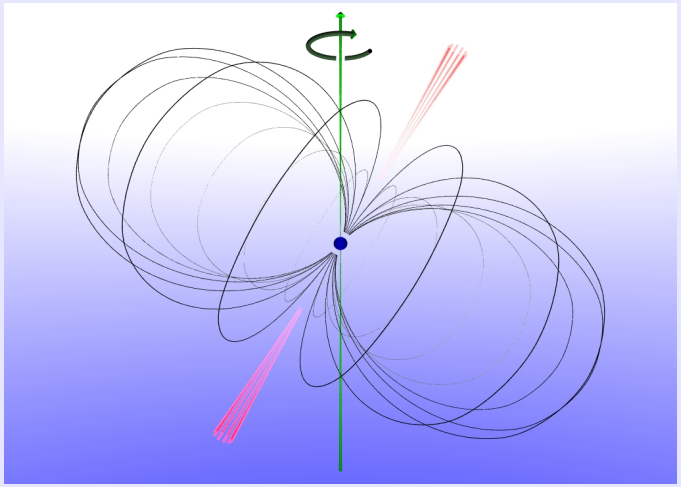
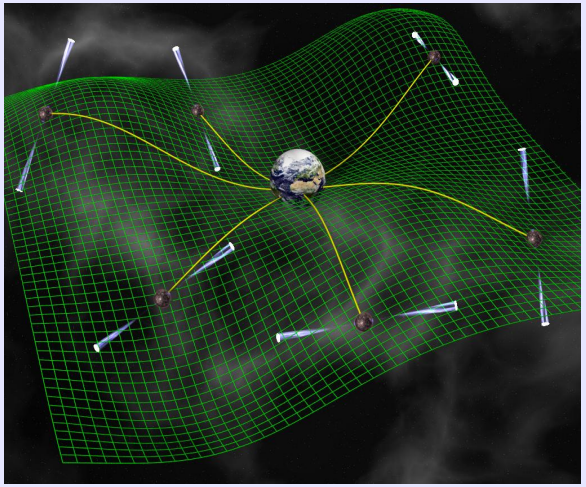
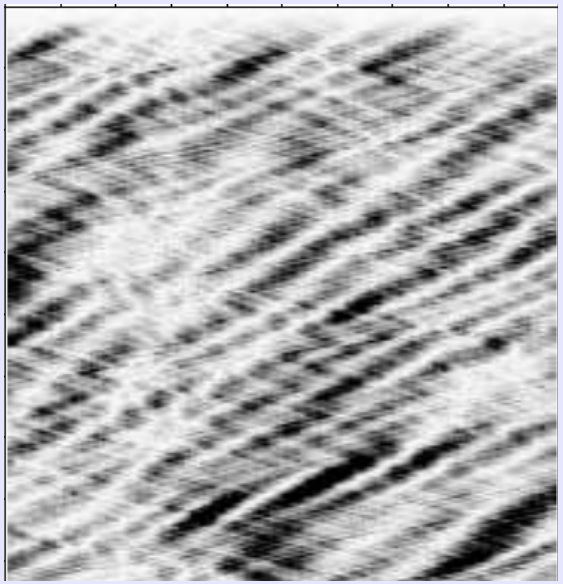
Pulsars and CHIME:
Gravitational Waves, the ISM and More!





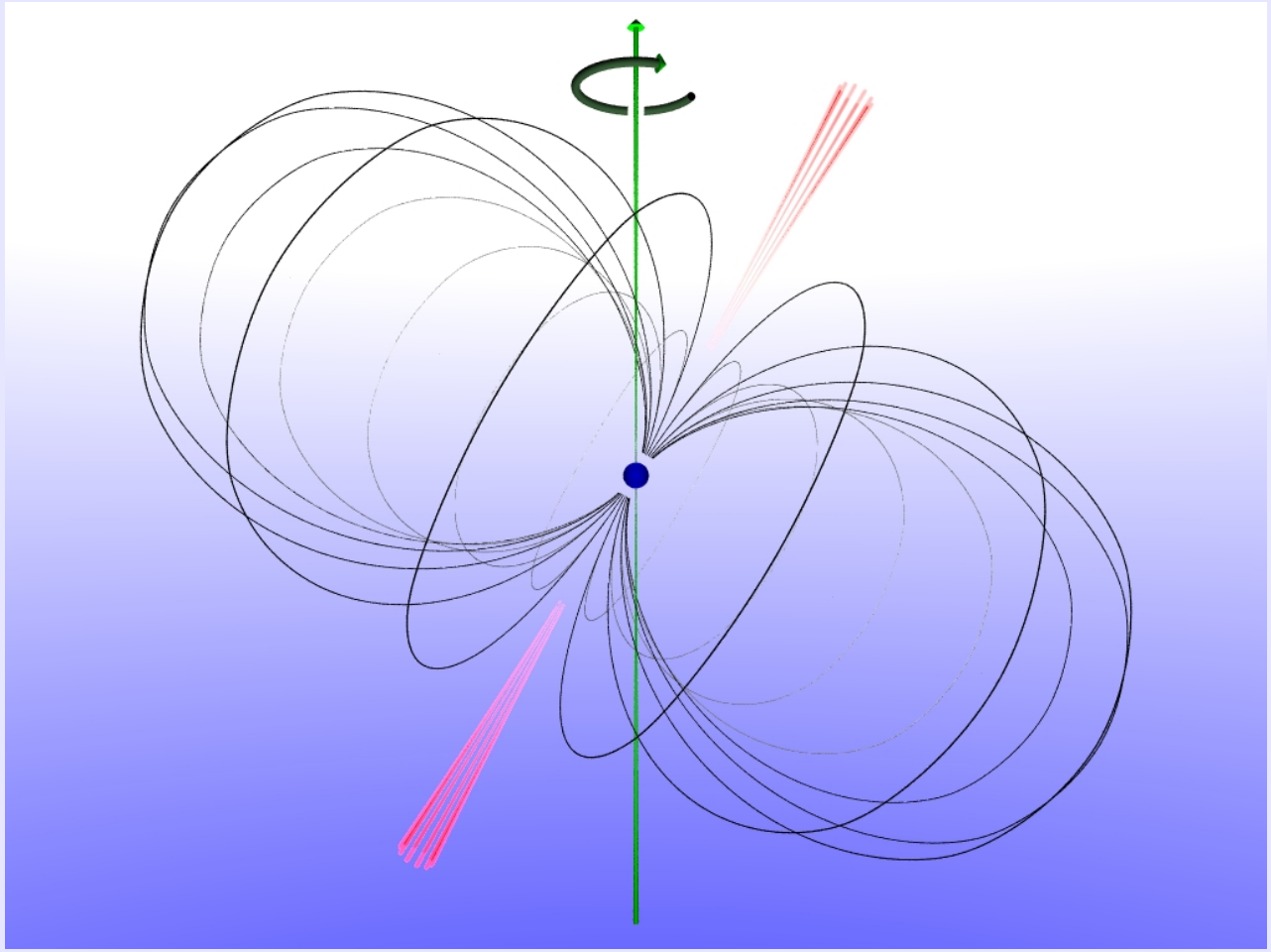




Paul Demorest (NRAO)
for NANOGrav collaboration, CHIME pulsar team
John Galt Symposium, DRAO, Sept 23, 2014

Outline

- Pulsar stuff:
  - Pulsar timing and gravitational wave detection (pulsar timing arrays). NANOGrav project.
  - Pulsars as a probe of the ISM.
    - John Galt connection!
- CHIME as a pulsar telescope:
  - Planned instrumentation
  - Unique capabilities
- “... and more” = CHIME and FRBs

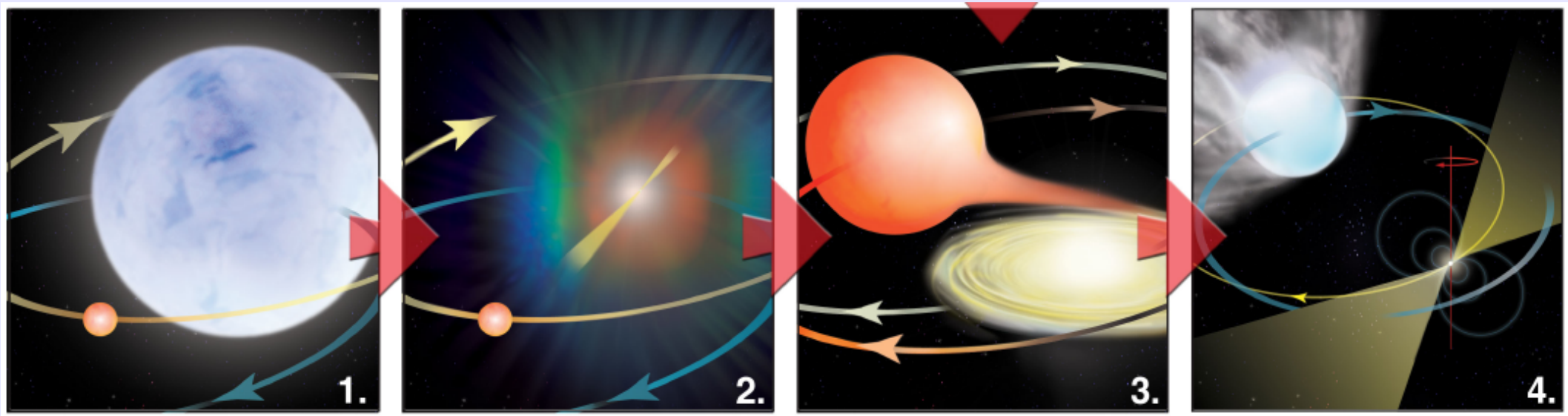


Rotating, magnetized neutron stars

Beamed radio emission is generated by plasma interactions in the star's magnetosphere.

We take advantage of this naturally-occurring pulsed signal source as a unique tool for making precise astrophysical measurements!

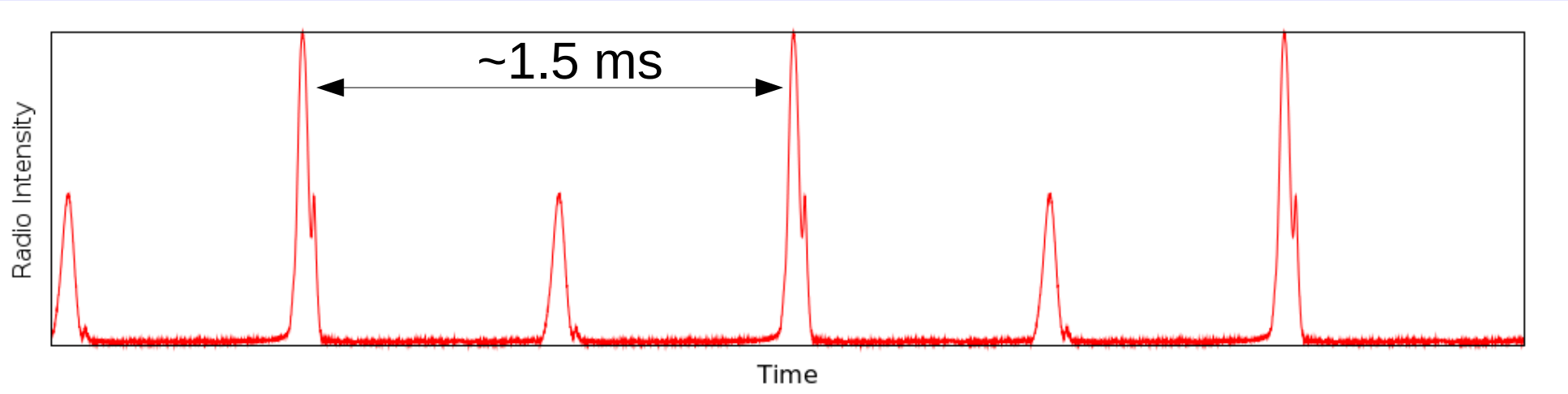
About 10% of known radio pulsars are “recycled” millisecond pulsars (MSPs). These are spun up by accreting matter from a companion star:



(Image: B. Saxton, NRAO)

This produces very “clean” compact binary systems (NS-WD or NS-NS).

By tracking pulse times of arrival over many years, MSPs act as *extremely* precise astronomical clocks:

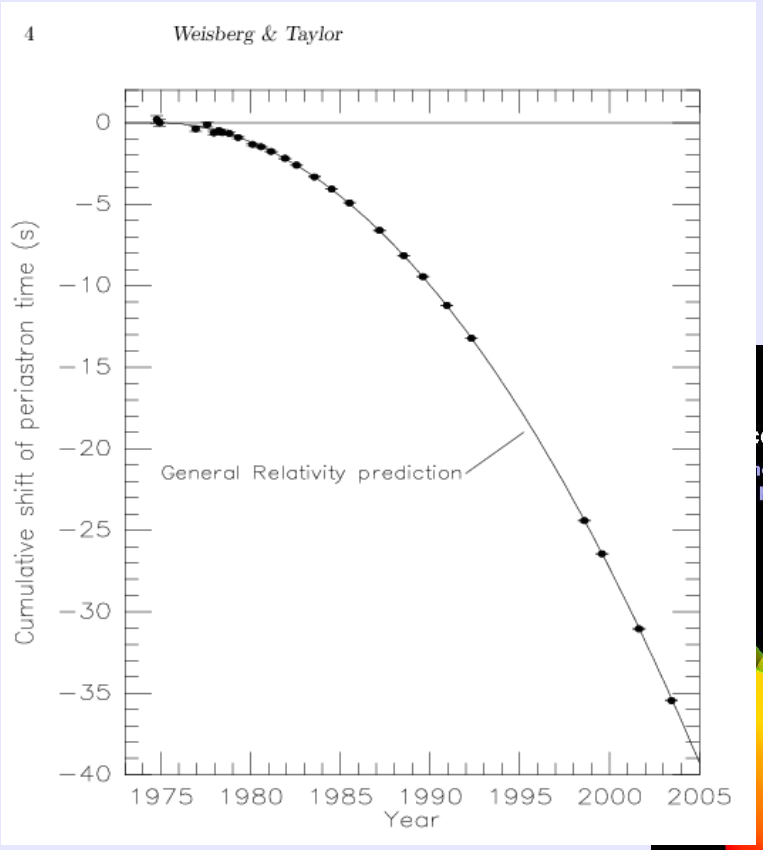


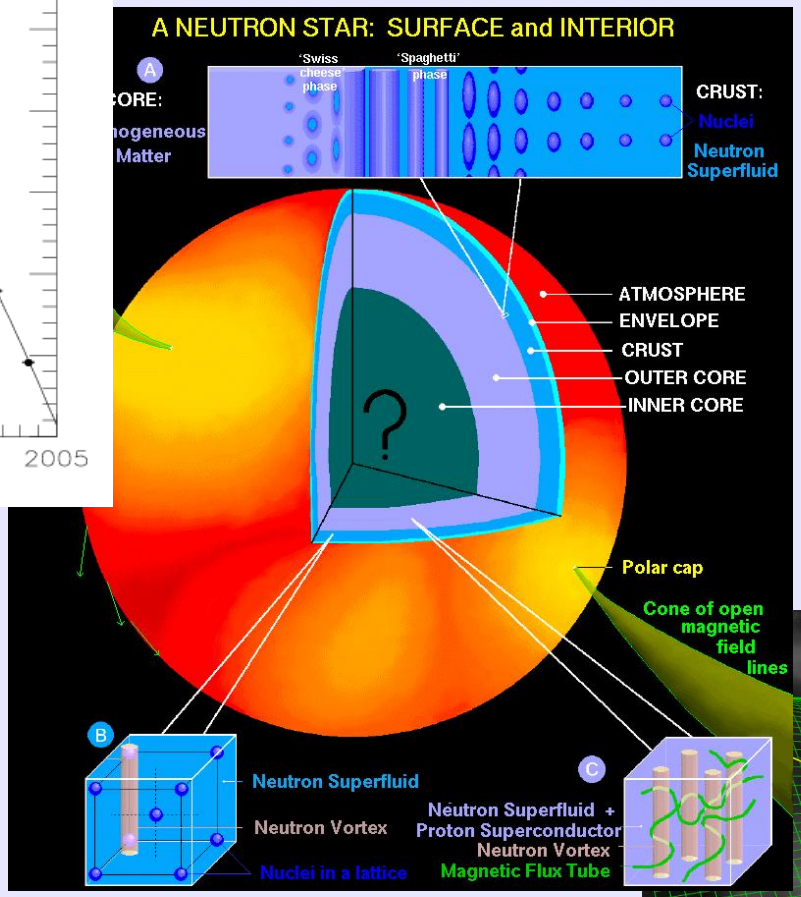
Average spin period of PSR B1937+21 :

P = 1.557806468819794**5** ms
+/- 0.000000000000000**4** ms !

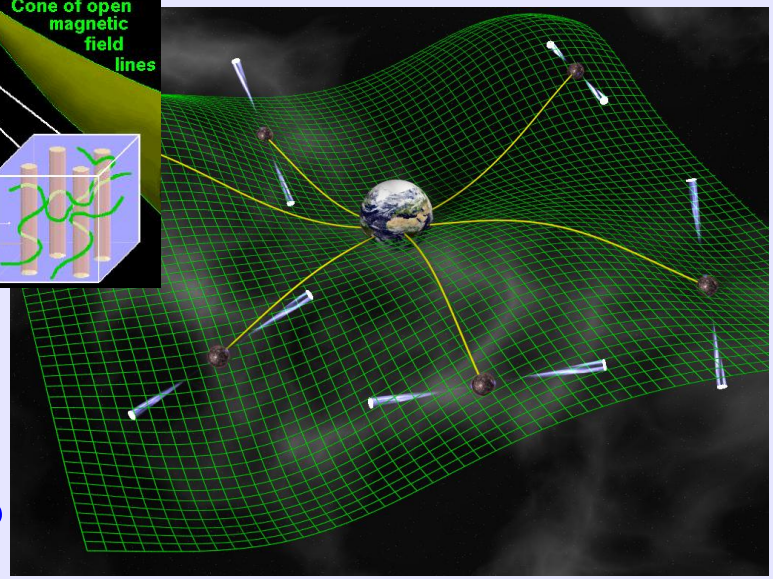
Enables high-precision measurements of orbits and other gravitational effects.

Testing gravity / GR



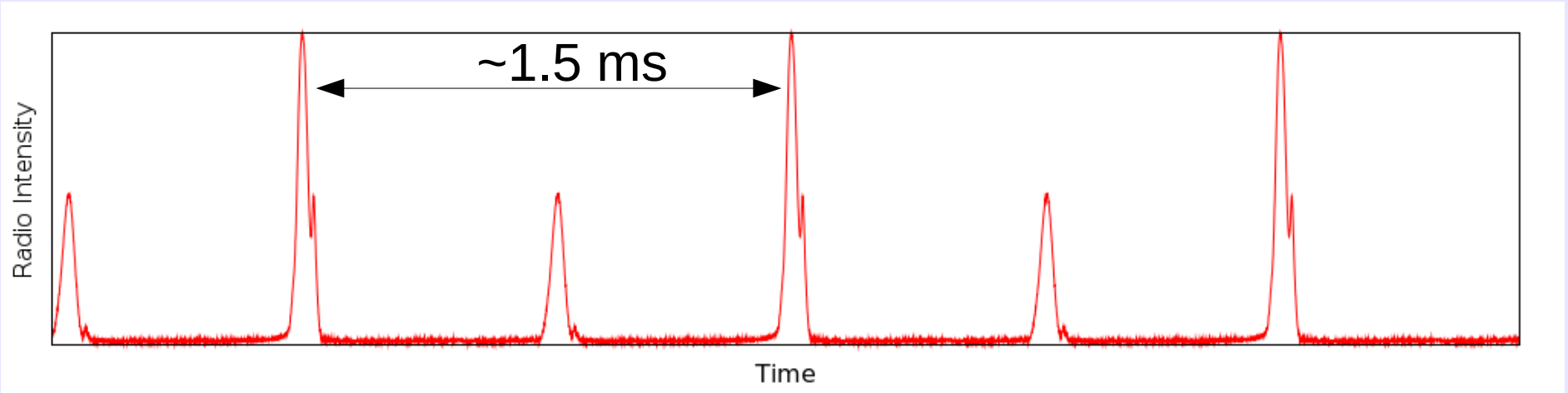


Properties of nuclear matter

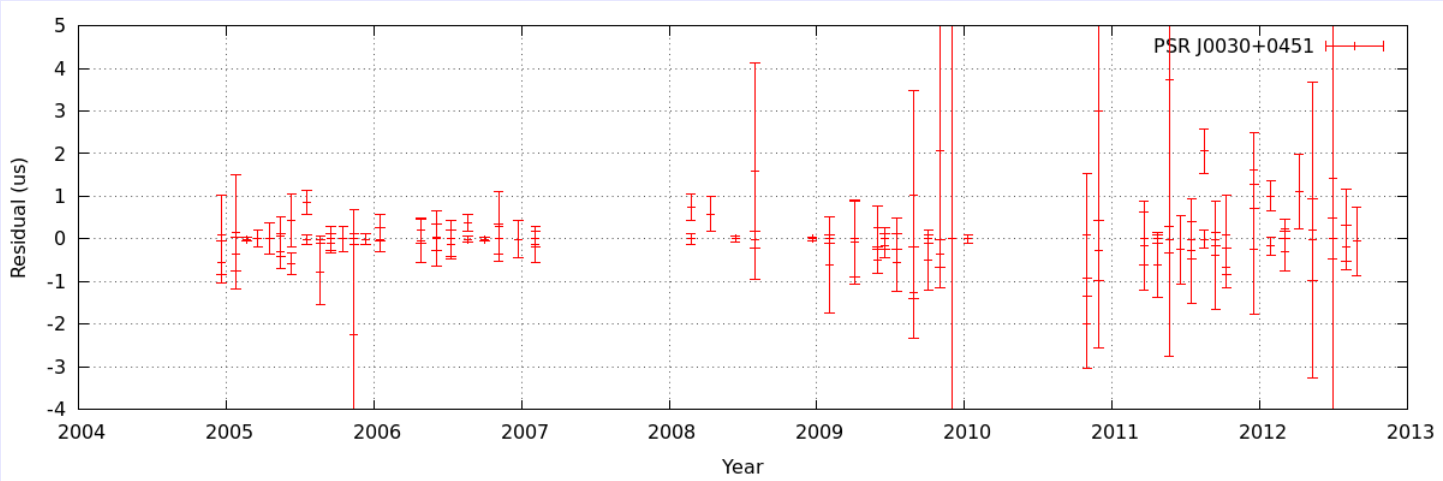


Detecting GW?

Pulsar timing - “phase connected timing model”



Measure pulse times of arrival (TOAs) and track phase of the pulse train over many years, relative to a physical timing model. Effectively we are counting every single rotation of the NS.



Observed minus predicted residuals ~ 10s of ns in best cases!

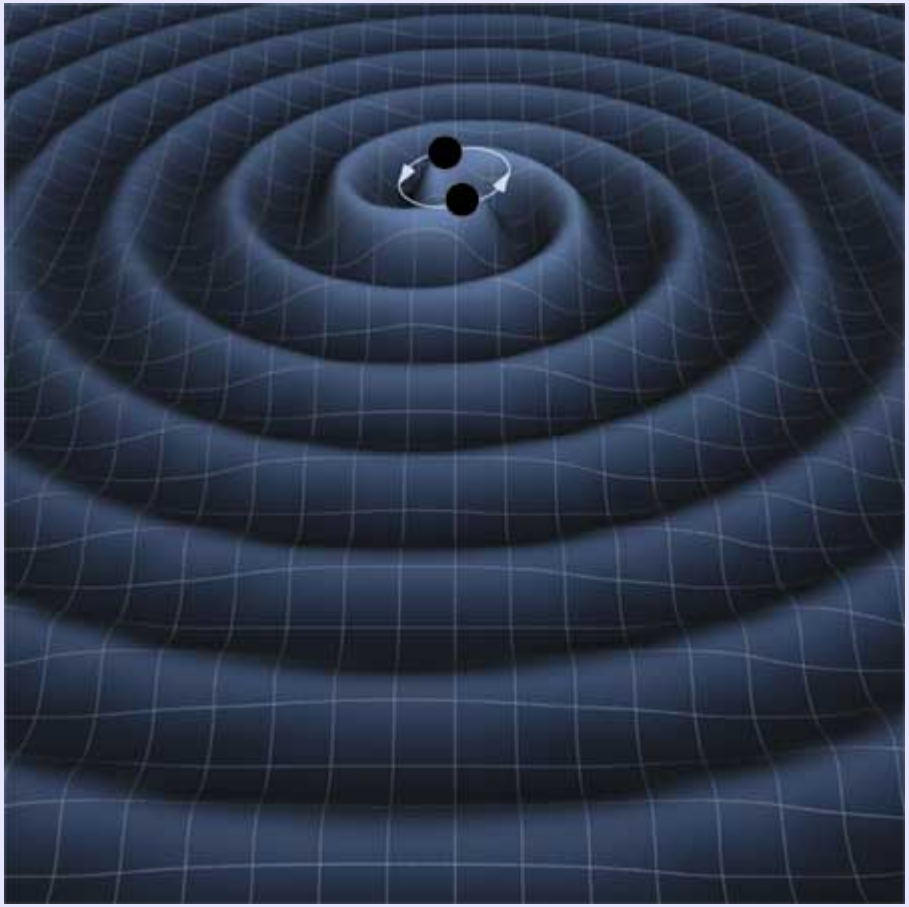
Gravitational waves:

Freely-propagating “space-time ripples” predicted by GR.

Generated by almost any moving mass (binaries, etc).

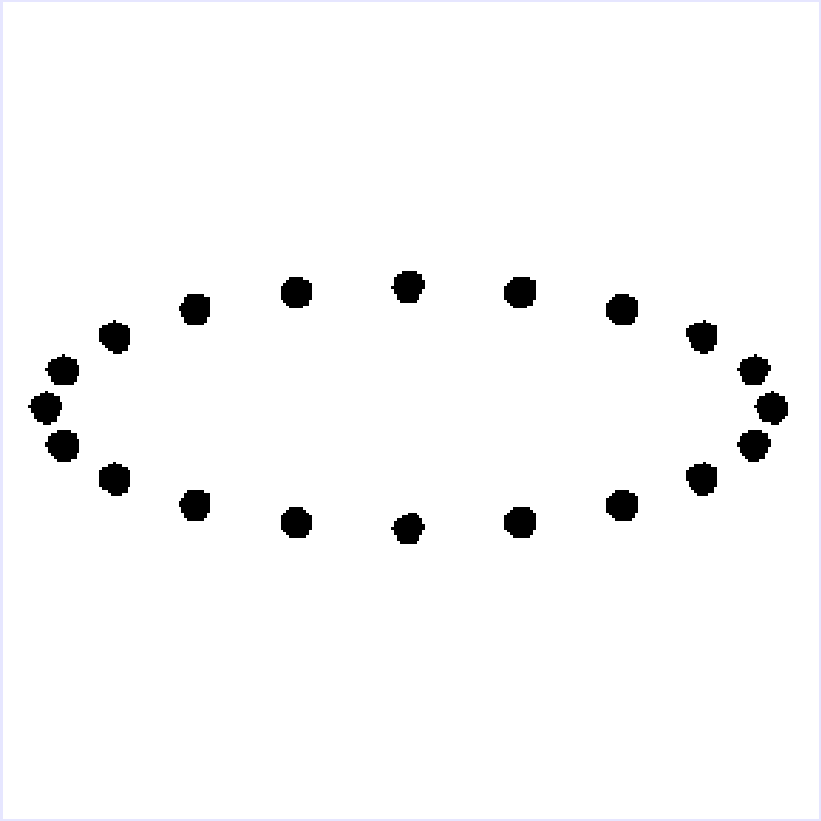
Are *very* weak and not yet directly detected.

Detection will be another confirmation of GR. And will enable gravitational wave astronomy.

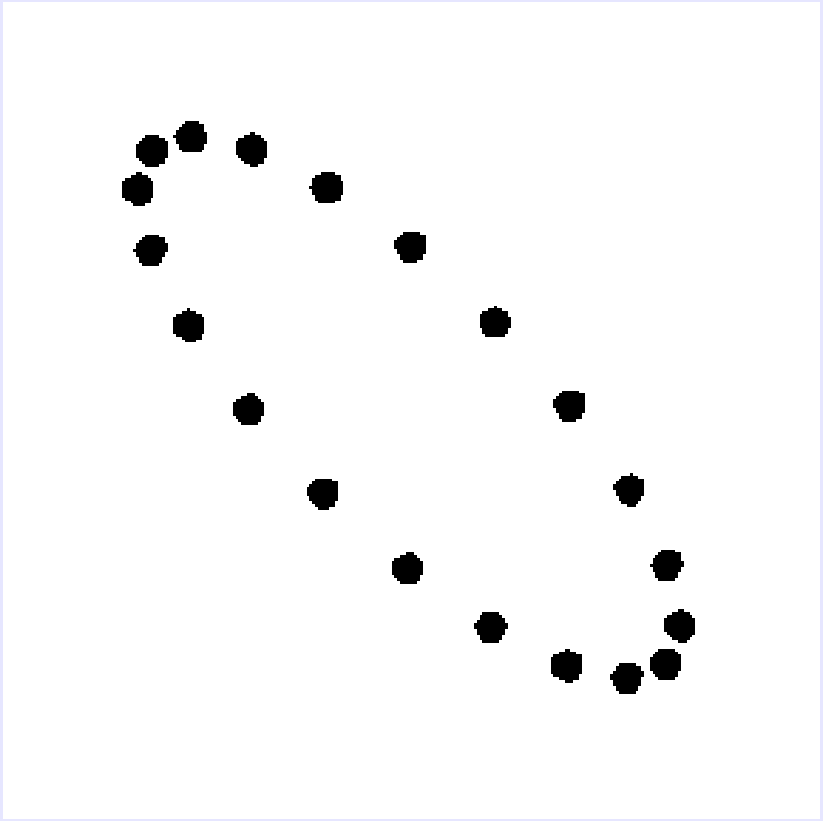


GW are two-polarization, quadrupolar waves:

"Plus" polarization



"Cross" polarization

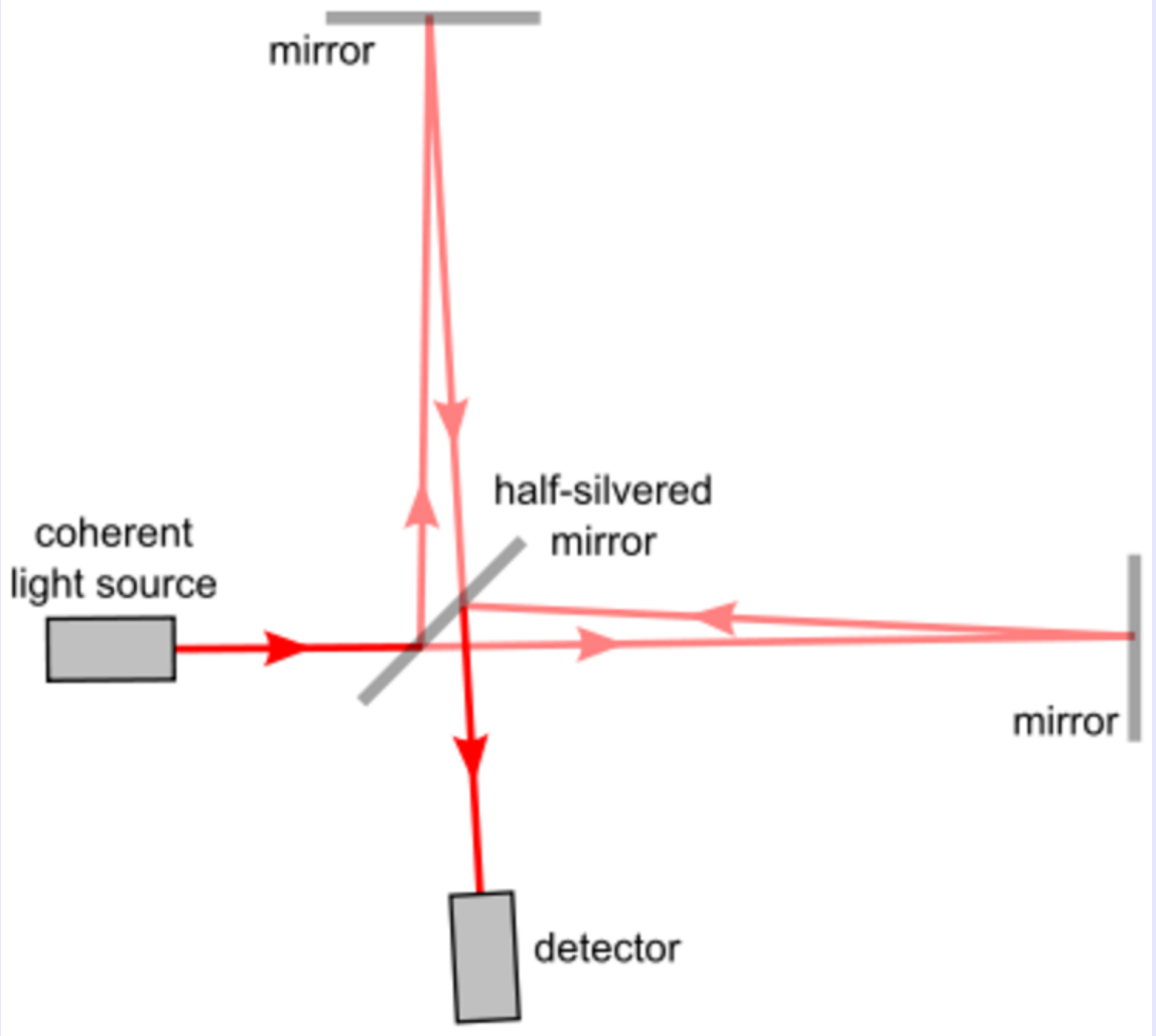


Quantified by dimensionless strain aka metric tensor h_{ij} from GR. Gives fractional change in length: Typical values for astronomical sources 10^{-20} to 10^{-15}!

All modern GW detection experiments use light as a probe of the gravitational field:

For example, a laser interferometer is sensitive to GW-induced path length changes:

GW sensitivity: h ~ dL / L



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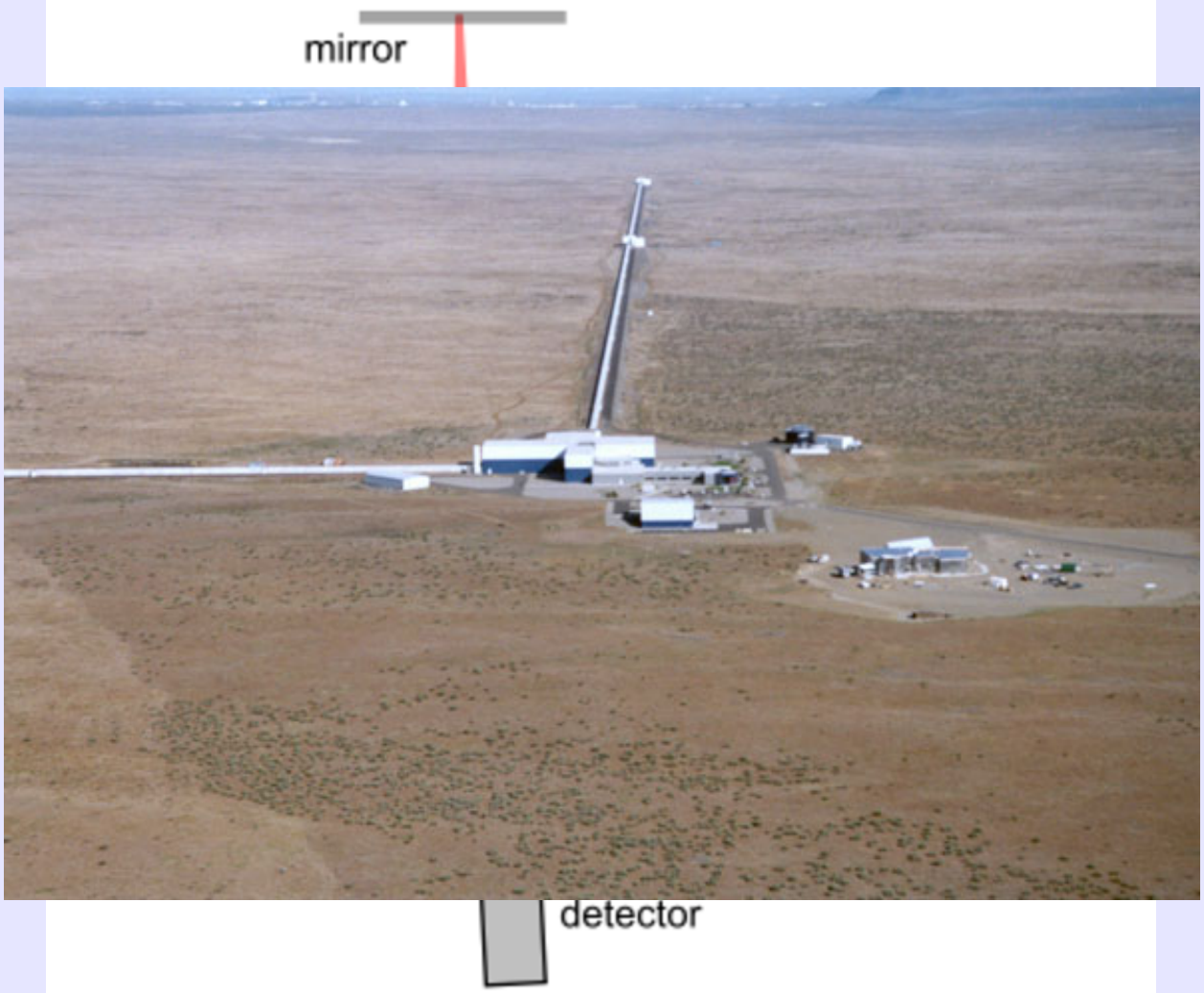
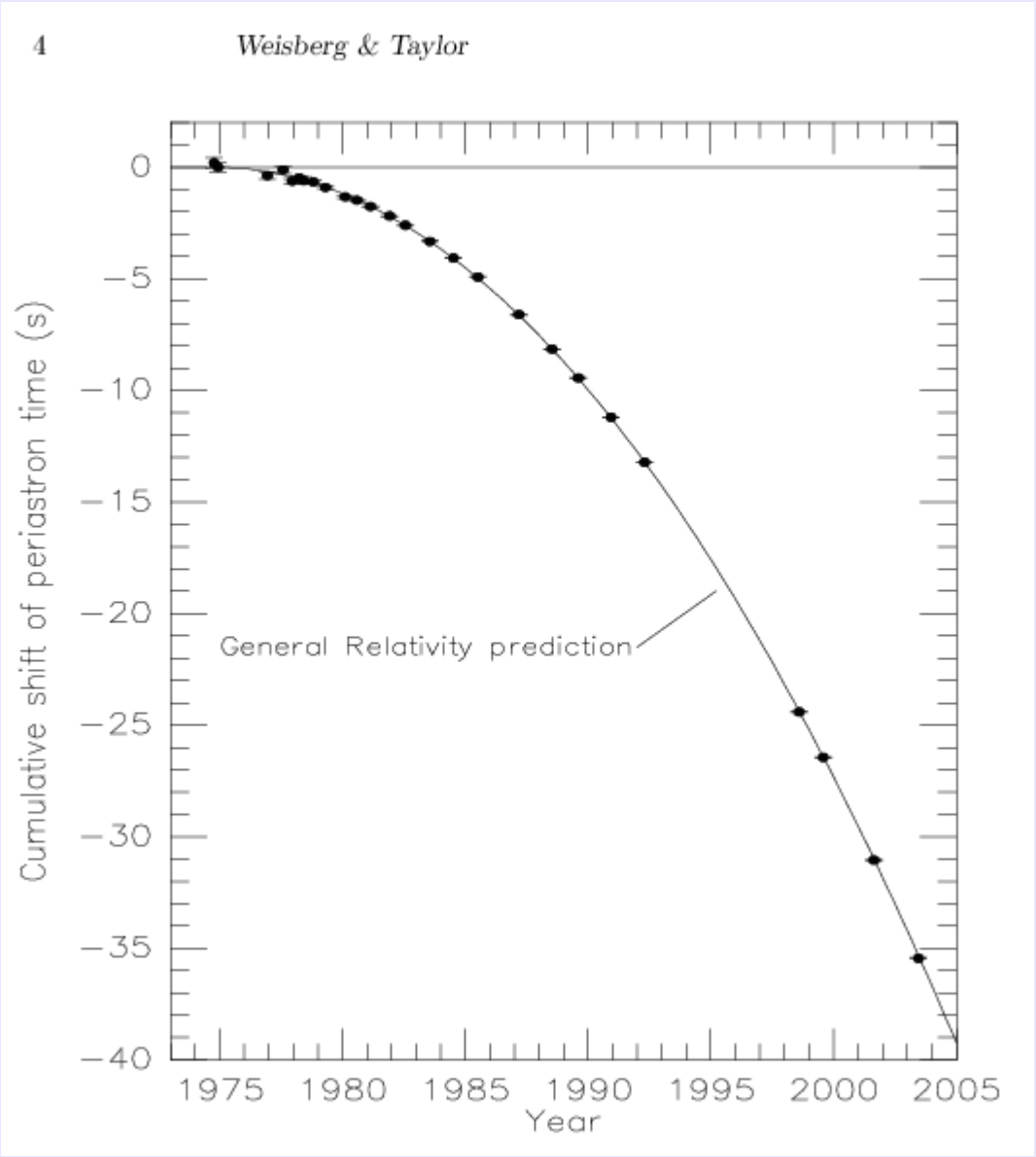


(Photo: LIGO Labs)

But so far ~zero direct GW detections have been made.

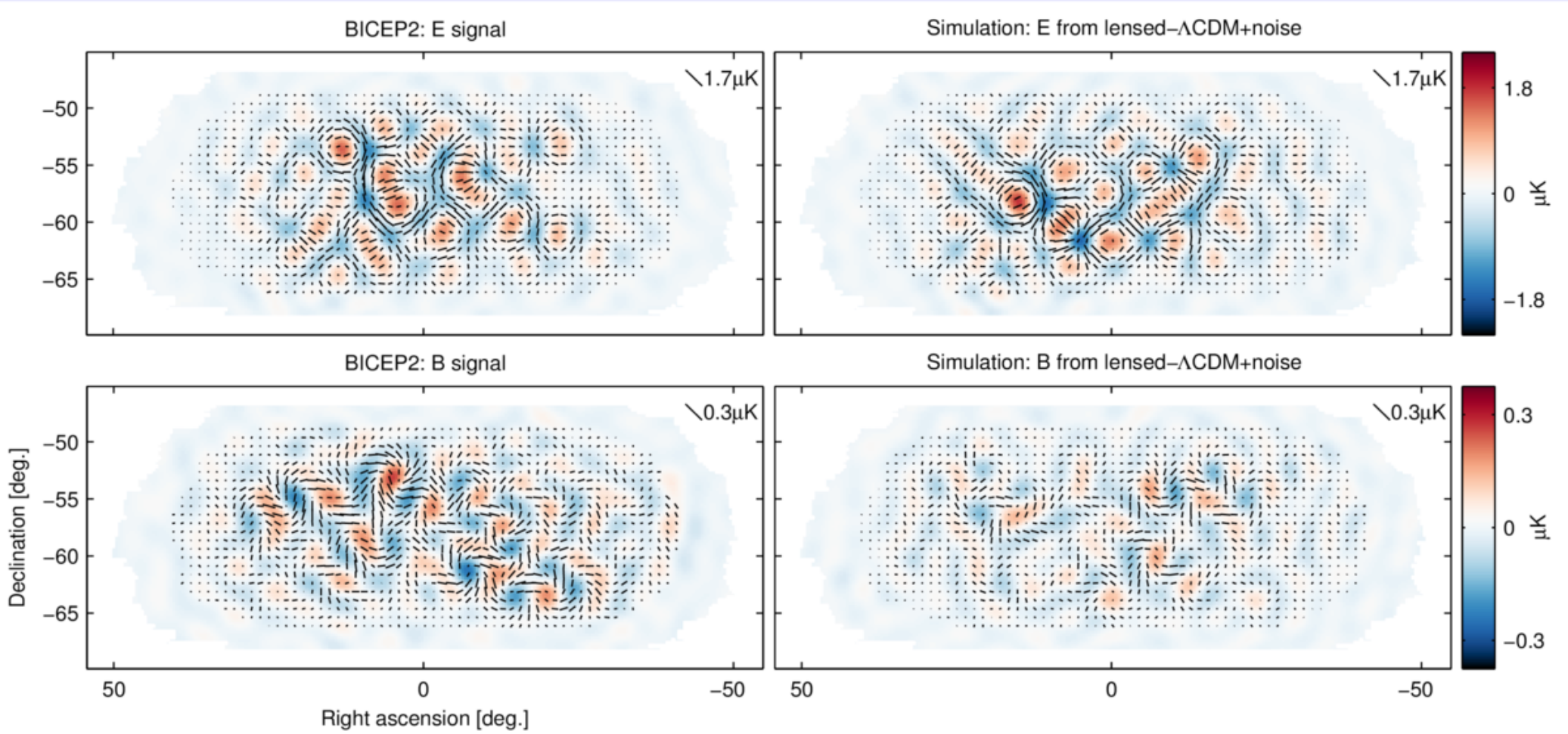


The only (non-controversial) experimental evidence for GW comes from pulsars!

Orbital decay of PSR B1913+16 measured by radio timing *exactly* matches expected energy loss to GW emission.

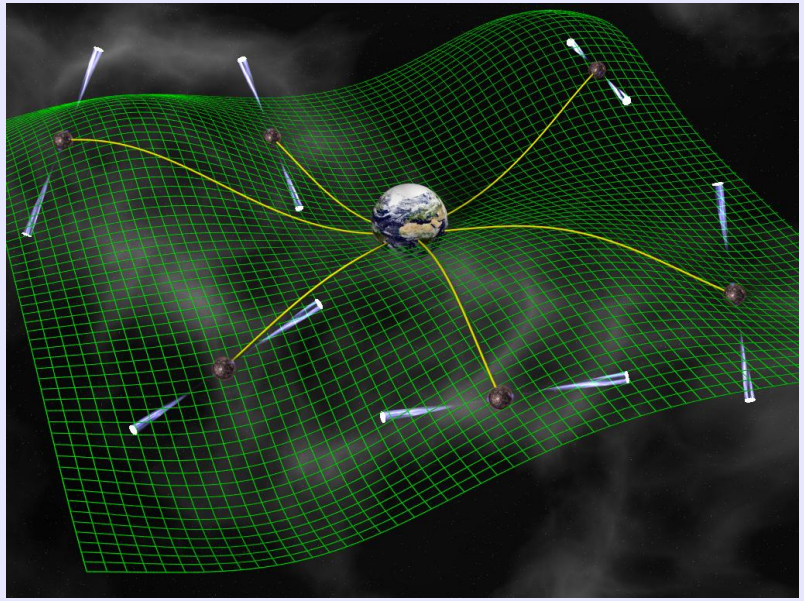
Physics Nobel prize for Hulse & Taylor in 1993.

But so far ~zero direct GW detections have been made.



(BICEP2 team, 2014)

Pulsar Timing Array

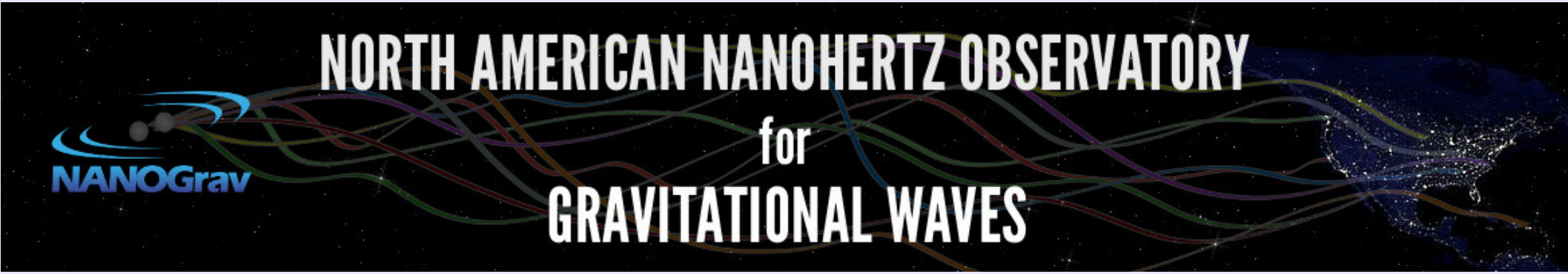


GW distort pulsar → earth light travel time (similar to laser expts.)

h ~ dt / T (rather than dl / L); $h \sim 10^{-15}$ → dt~10s of ns!

Original concept not new (Detweiler 1979, Hellings and Downs 1982, …) but has seen dramatically increased interest in recent years.

What is NANOGrav?

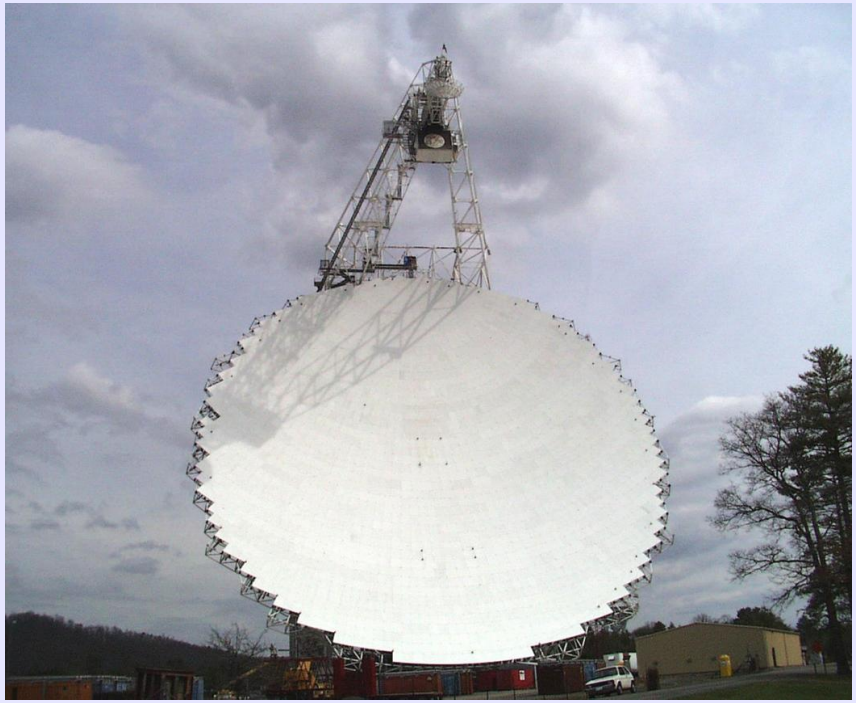


- A pulsar timing array experiment: We aim to use precise timing of radio MSPs as a nHz-frequency GW detector.
- North American: NANOGrav members are mostly US/Canada-based, the main instruments are Arecibo and the Green Bank Telescope.
- We monitor a set of ~40 MSPs monthly with these instruments; project started ~2005.
- Other similar projects around the world (PPTA, EPTA); collaborate via International Pulsar Timing Array (IPTA)

Current NANOGrav Telescopes

Green Bank Telescope (GBT),
West Virginia

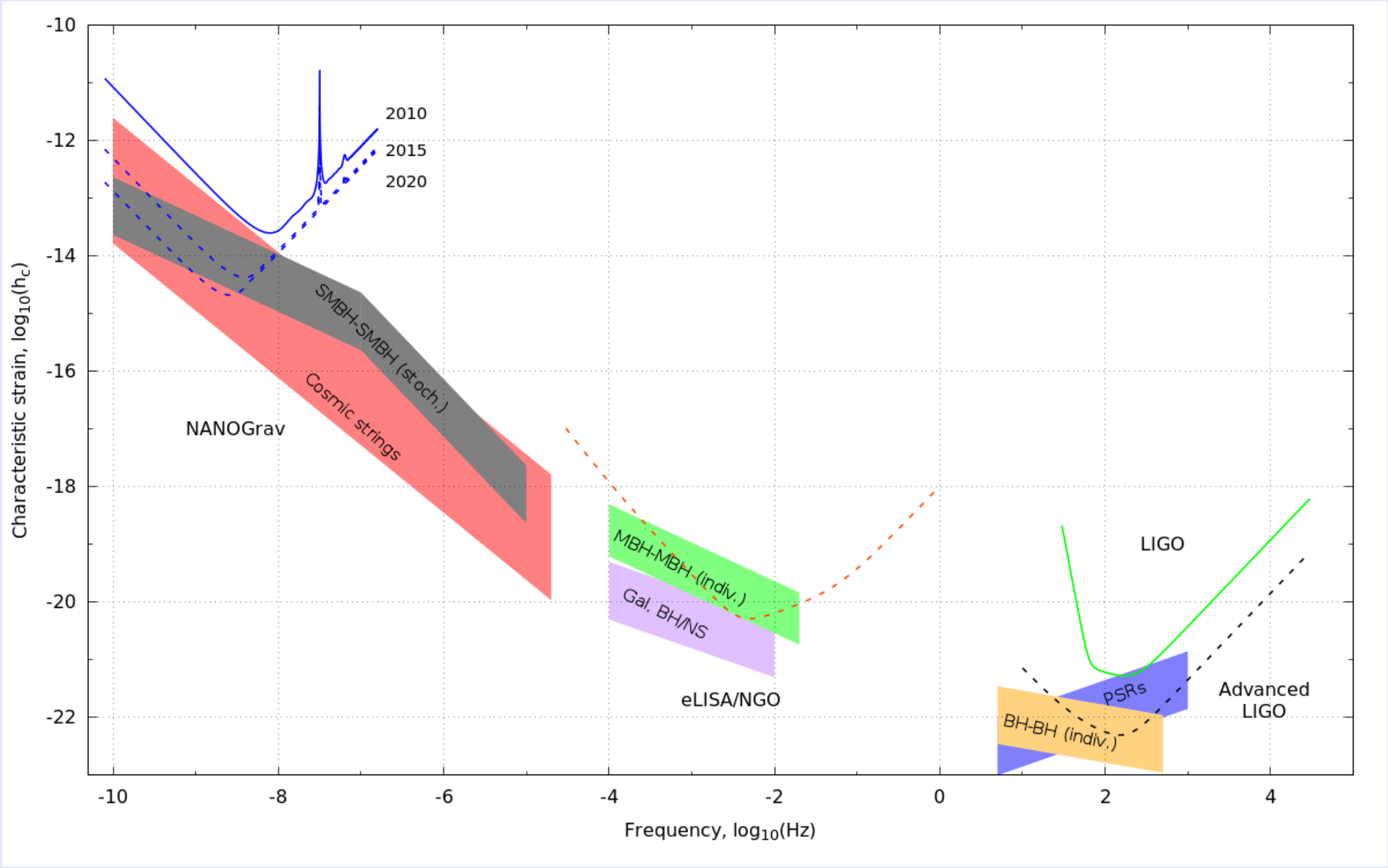
100-m fully steerable dish: dec > -45 degrees; L-band SEFD ~ 10 Jy.



Arecibo Observatory,
Puerto Rico

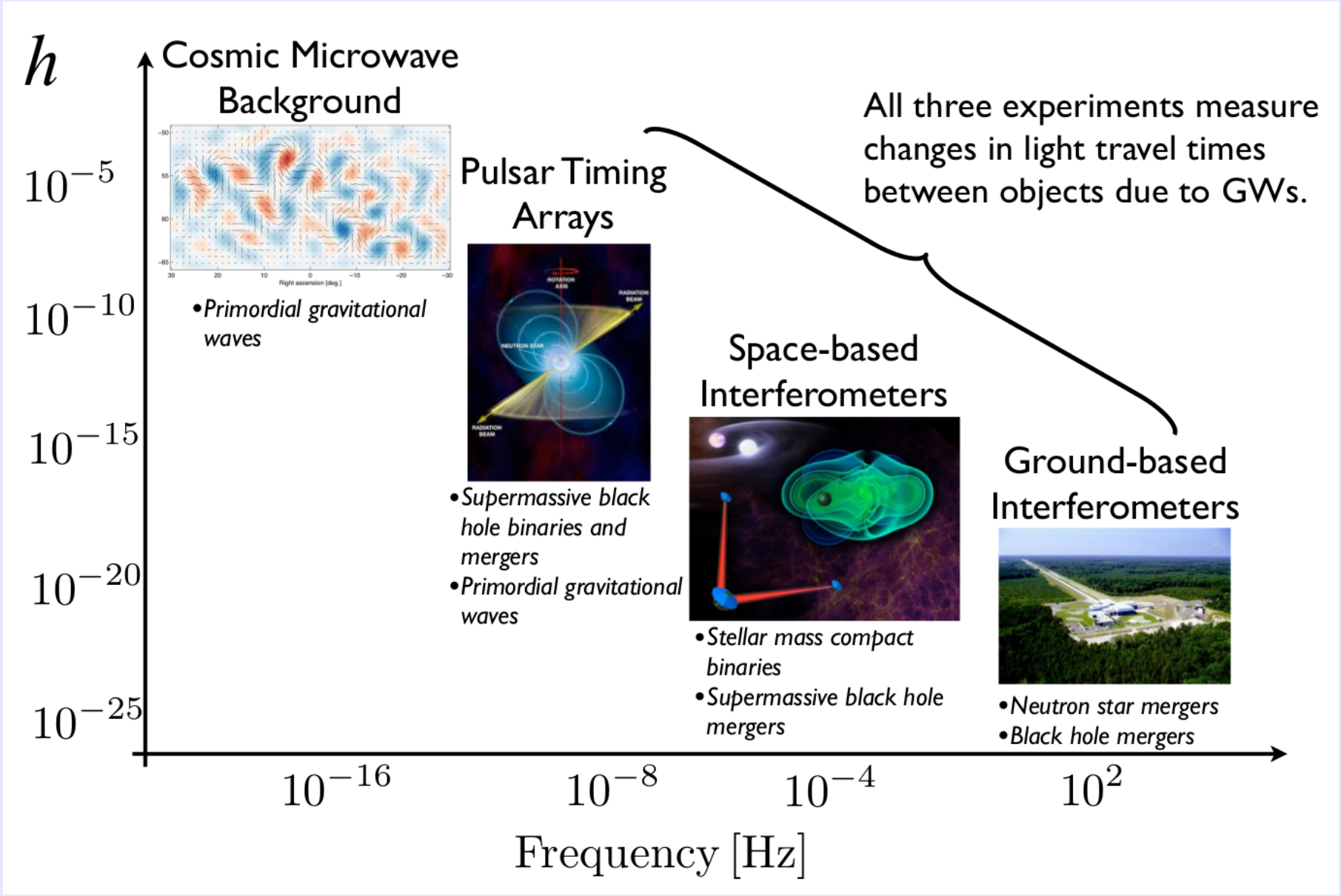
305-m fixed dish: 0 < dec < 30 degrees; L-band SEFD ~ 2 Jy

The gravitational wave spectrum:



PTAs like NANOGrav are complementary to ground- and space-based laser interferometer experiments.

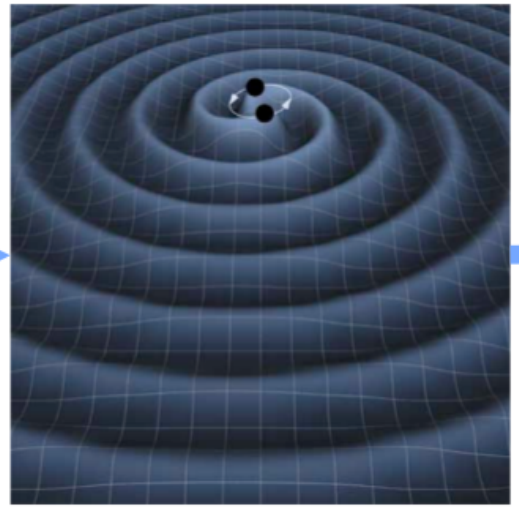
The gravitational wave spectrum:

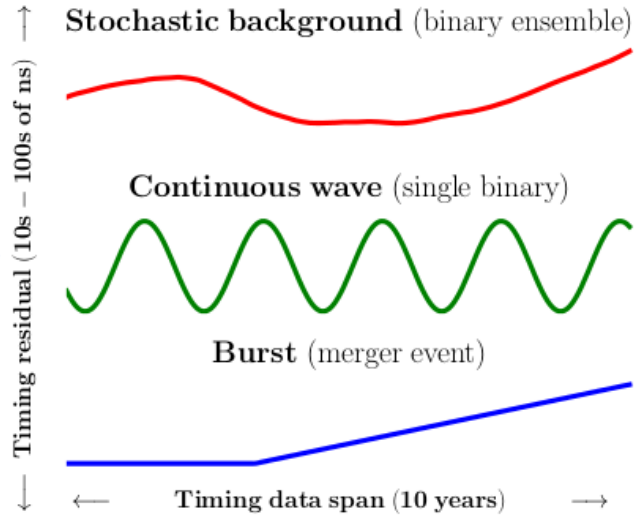


PTAs like NANOGrav are complementary to ground- and space-based laser interferometer experiments.

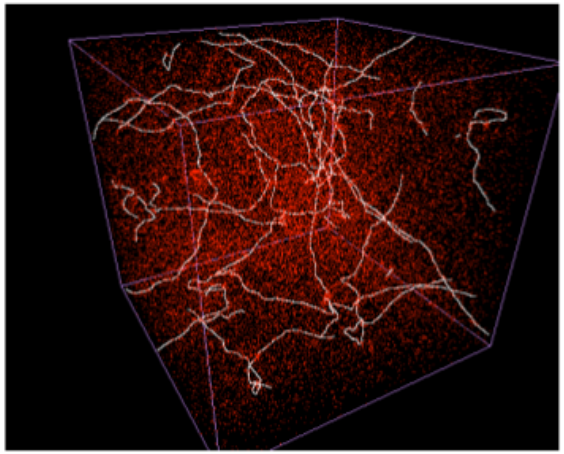
Sources of nHz gravitational waves:

The most promising sources are supermassive binary black holes (SMBBHs):

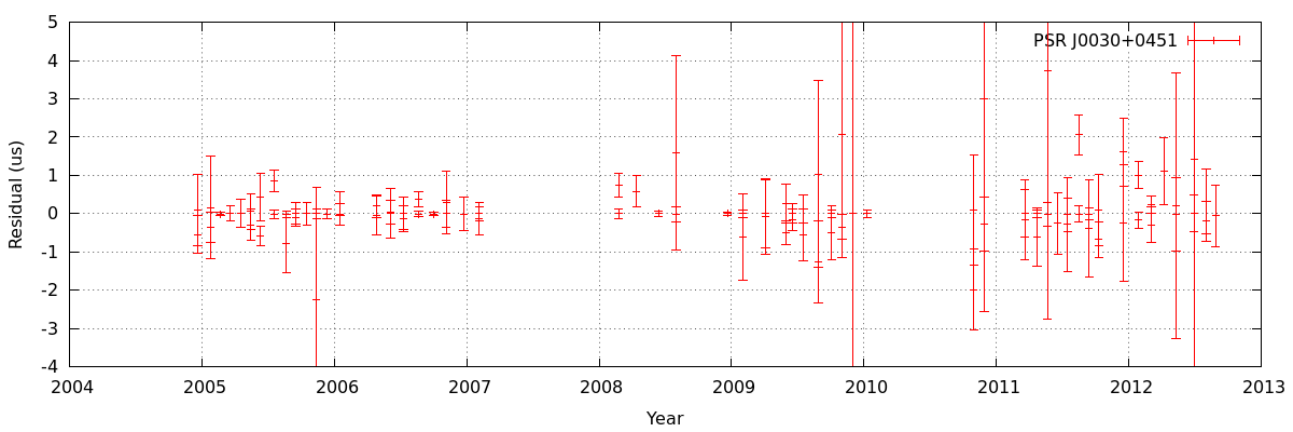




Other sources at nanohertz frequencies include cosmic strings, inflation, and phase transitions in the early universe.

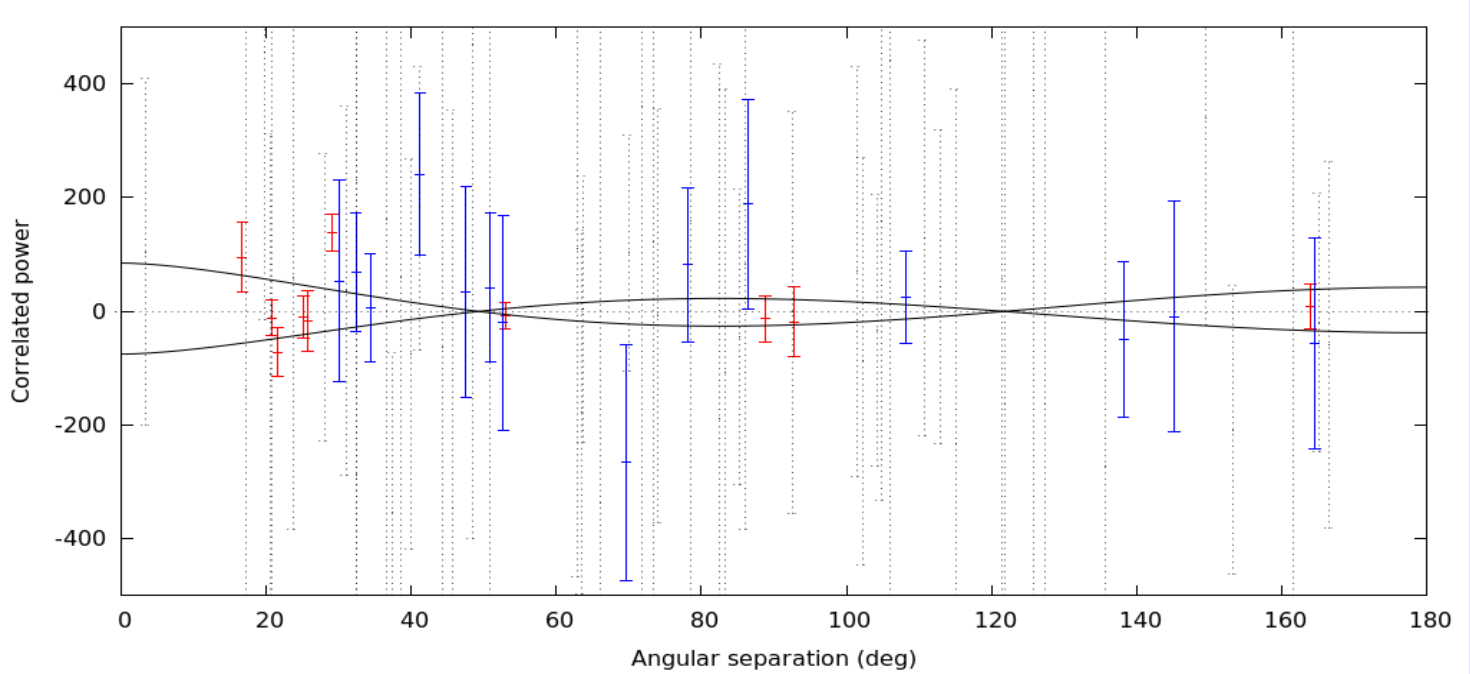


GW detection via pulsar timing



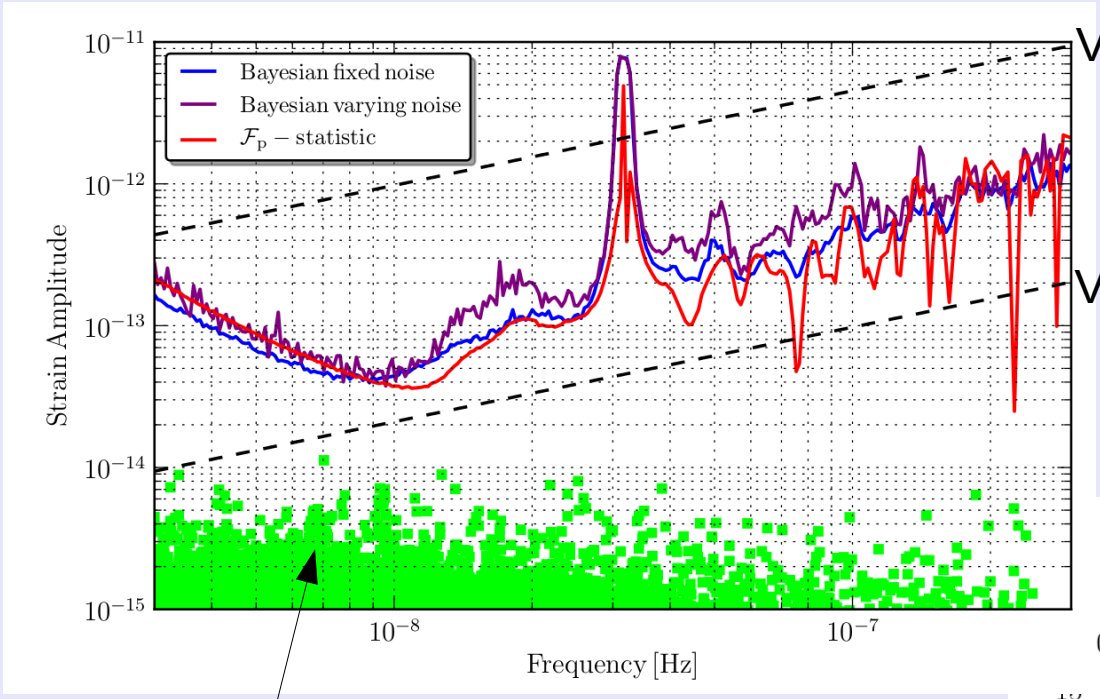
Tiny (sub-us) pulse time-of-arrival fluctuations over many year timescales …

… are correlated between different MSPs in the presence of GW (e.g., Hellings & Downs curve for stochastic GW background).



NANOGrav Five-year GWB analysis (2005–2010) of 17 MSPs put limit at h_c(1 year) < 7 x 10^{-15} level (95%; Demorest et al 2013).

GW signals: Individual MBH binaries

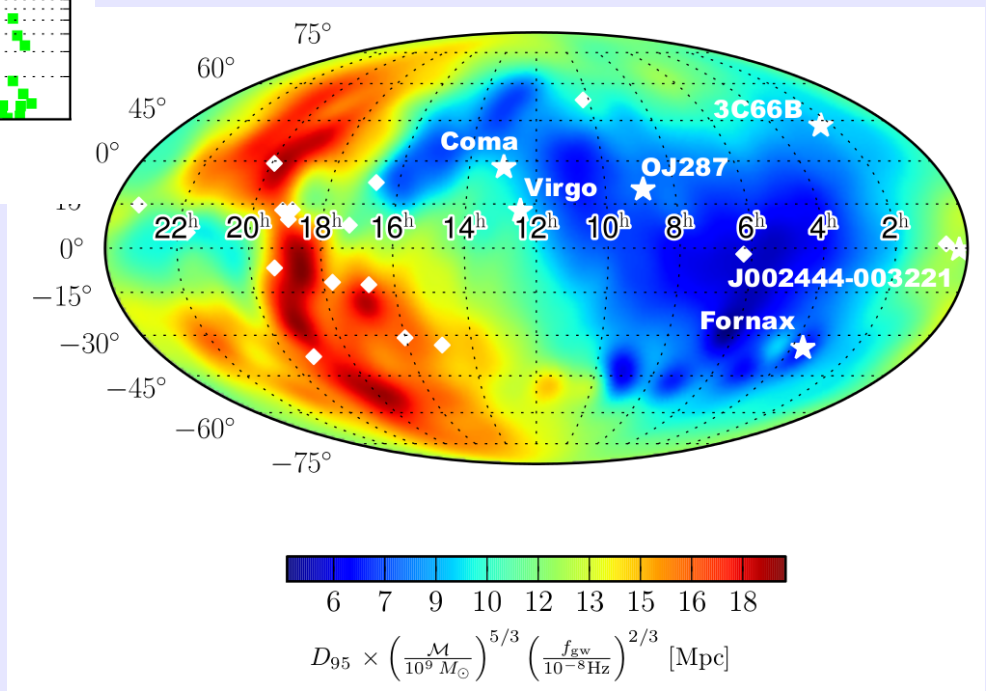


Virgo M~10^{10}

Virgo M~10^{9}

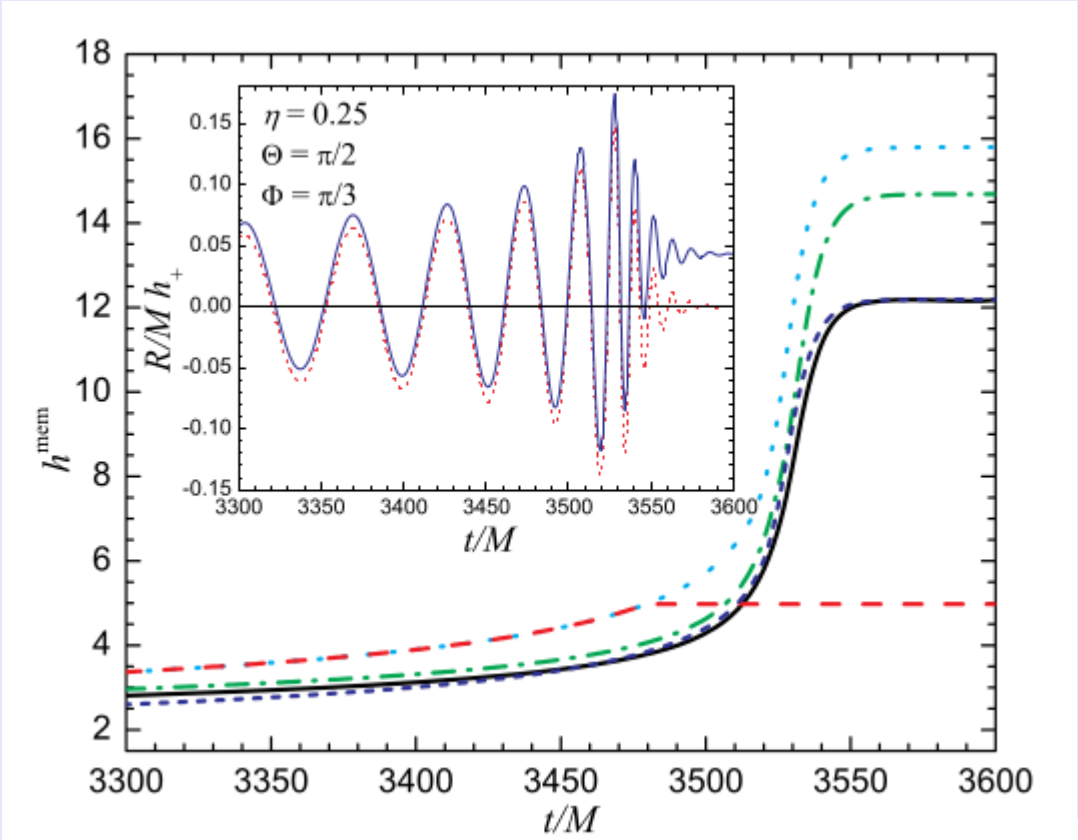
GWB@limit

Five-year CW analysis: arXiv:1404.1267 (Arzoumanian et al 2014; lead J. Ellis).



Results ~3x better (in strain) than previous best limits (PPTA; Yardley et al 2010).

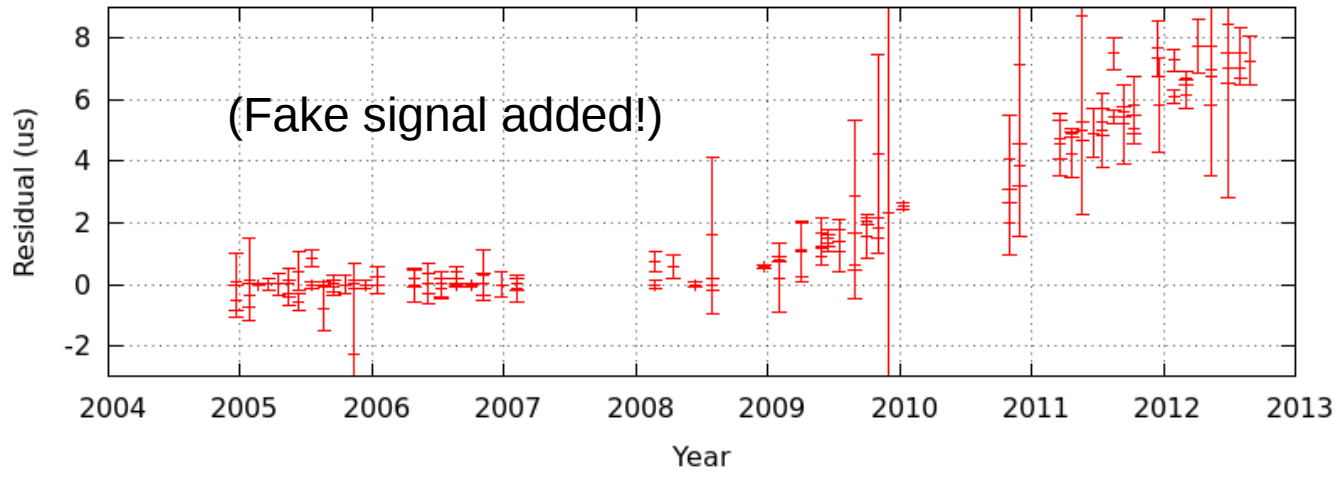
GW signals: Bursts “with memory”



(Favata 2009)

Strain step following merger event.

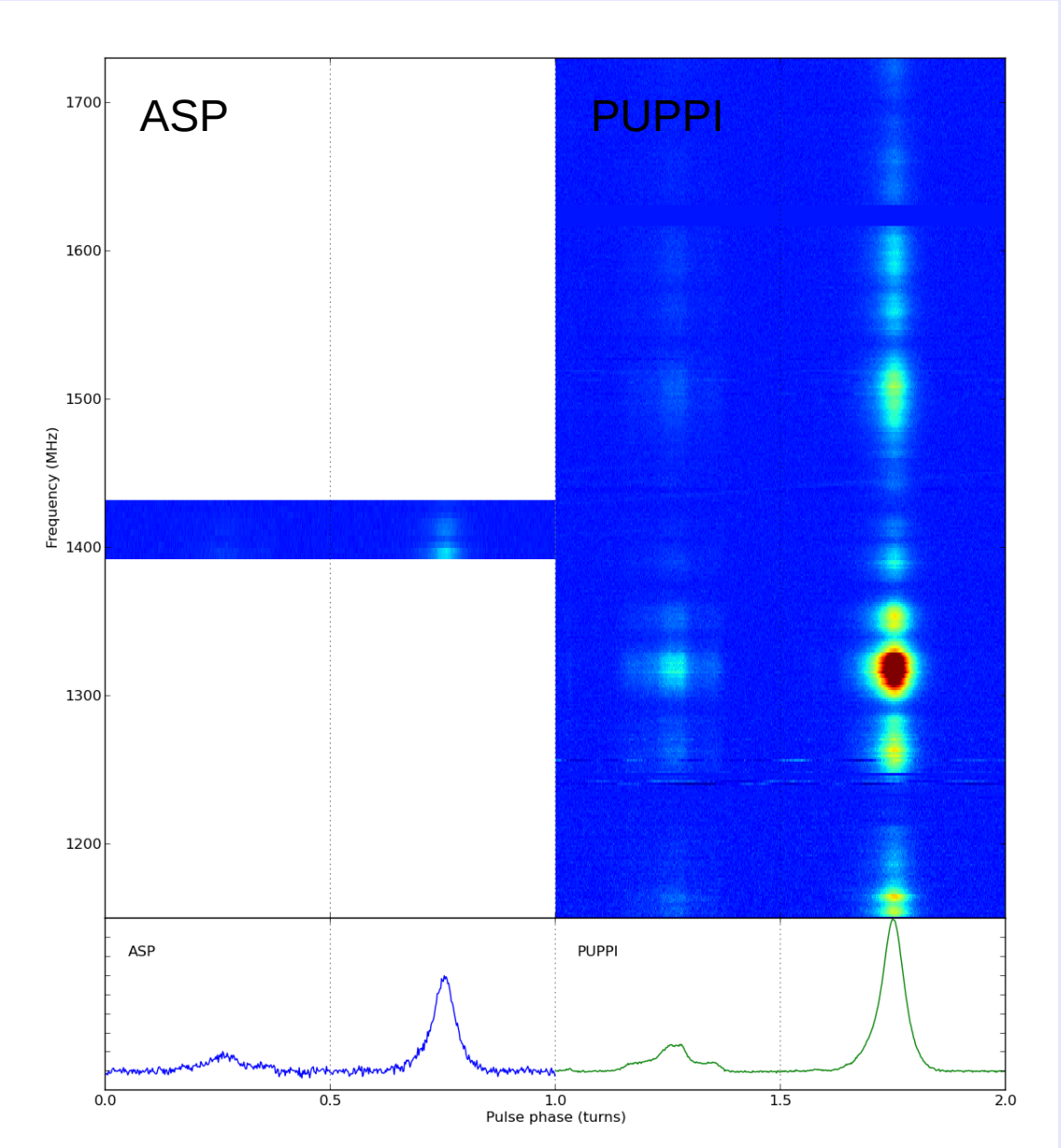
Accumulates vs time in timing, looks like (correlated) “glitch” in pulsars.



Five-year BWM analysis: lead D. Madison, in prep

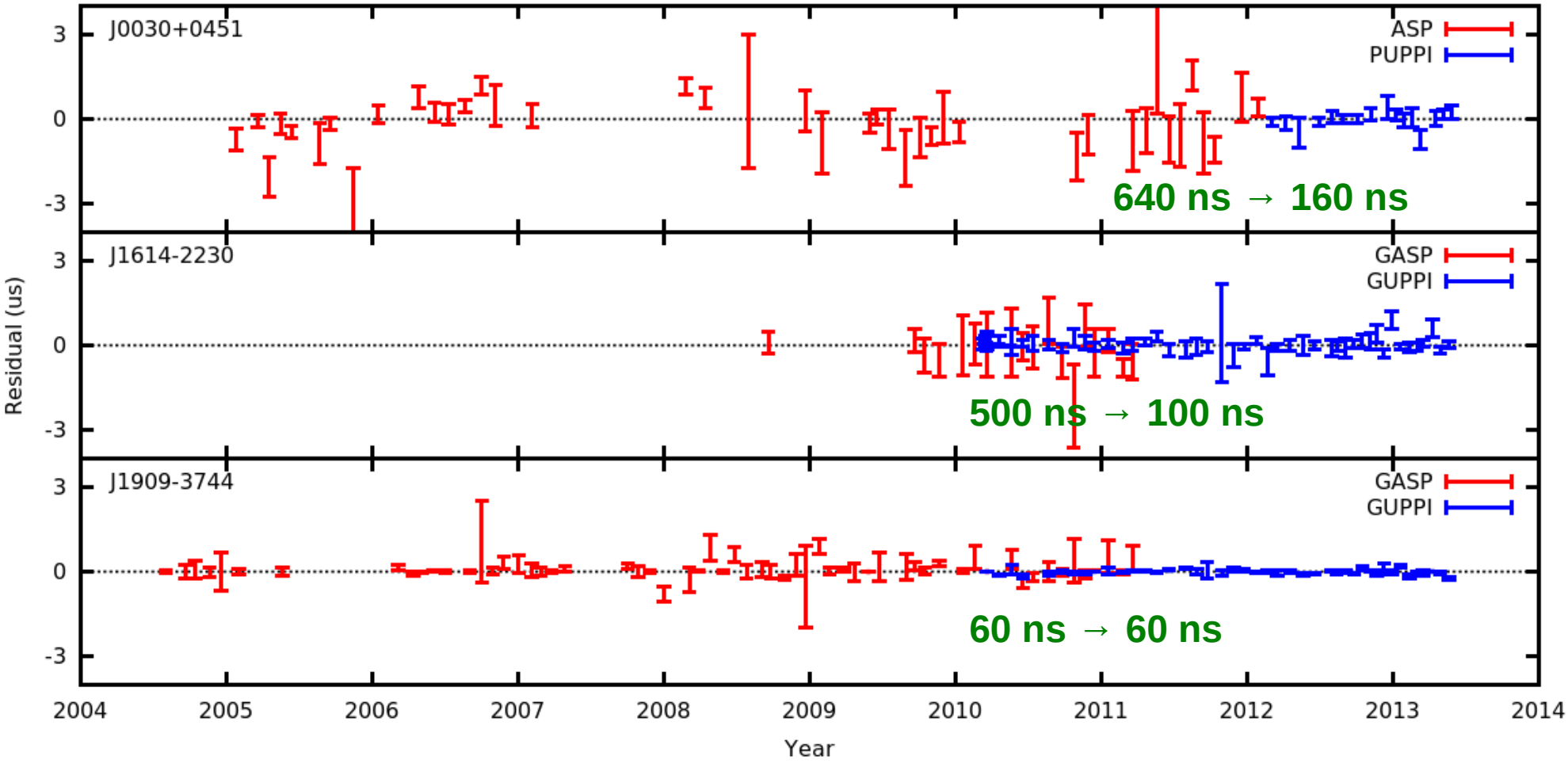
Upcoming nine-year NANOGrav data set

- Longer timespan!
  - ~2005 – 2013
  - GWB signals are “red”
- More pulsars!
  - 17 → 34 (now 42)
  - Driven by Fermi, GBNCC, PALFA, et al PSR surveys.
  - Critical for stochastic GWB detection.
- Better instrumentation!
  - GUPPI/PUPPI give >10x increase in BW.



(Simultaneous Arecibo observation of PSR J2214+3000)

Improvement in timing precision:



Improvement for most PSRs is a factor of ~2—3x in RMS timing residual.

Wider bandwidth also reduces scintillation-induced variation in S/N.

Improvement in timing precision:

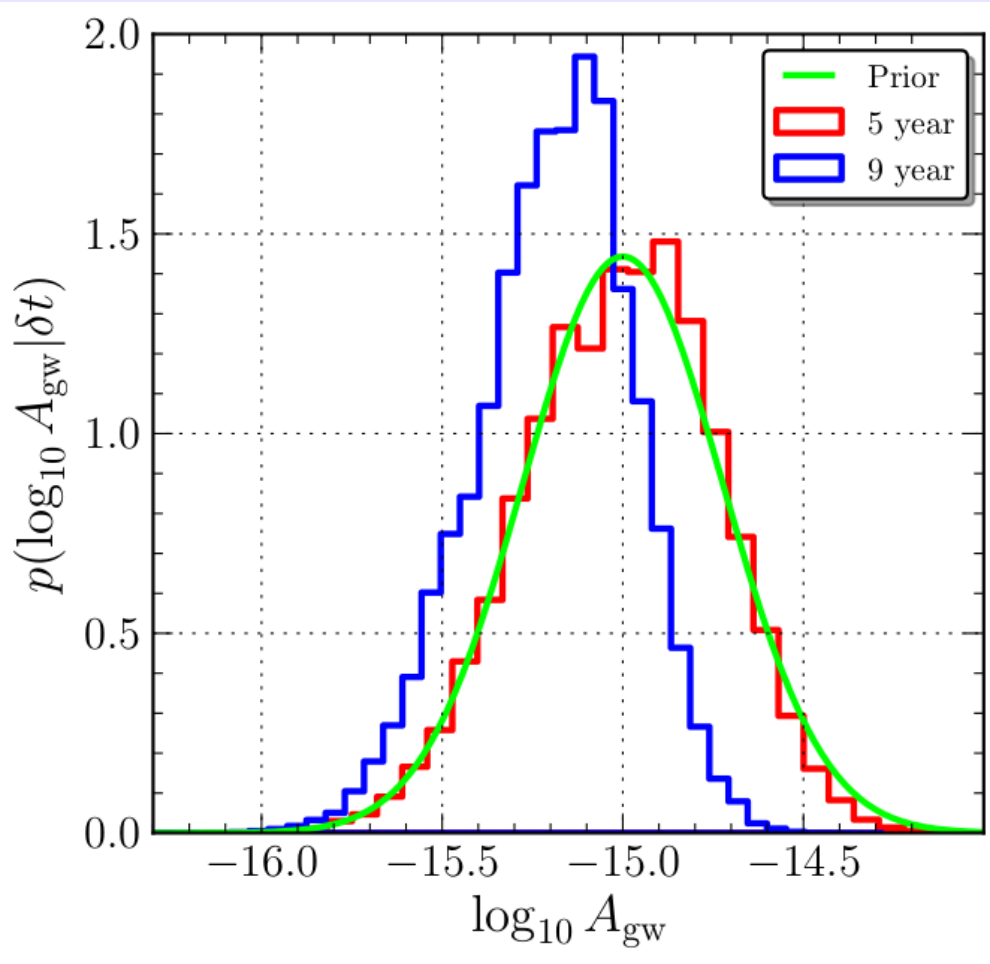
Source	ASP/GASP RMS (μs)	GUPPI/PUPPI RMS (μs)
J1909-3744	0.058	0.060
J1713+0747	0.137	0.071
J2317+1439	-	0.089
J2043+1711	0.709	0.097
J1832-0836	-	0.102
J1614-2230	0.491	0.111
J1600-3053	0.264	0.129
J0645+5158	-	0.147
J0030+0451	0.659	0.166
J2017+0603	0.314	0.183
J1744-1134	0.218	0.190
J0613-0200	0.627	0.196
J1944+0907	0.417	0.219
J1024-0719	1.996	0.242
J0023+0923	0.784	0.244
J2145-0750	0.605	0.274
J1738+0333	1.442	0.340
J2010-1323	1.282	0.346
J0931-1902	-	0.365
B1855+09	0.617	0.383
J1923+2515	0.310	0.389
B1953+29	0.836	0.411
J1012+5307	0.599	0.471
J0340+4130	-	0.507
J1455-3330	3.008	0.550
J1910+1256	0.853	0.712
J1918-0642	0.593	0.832
J1747-4036	-	0.916
J1643-1224	1.688	1.187
J2214+3000	3.340	1.348
J1949+3106	-	2.470

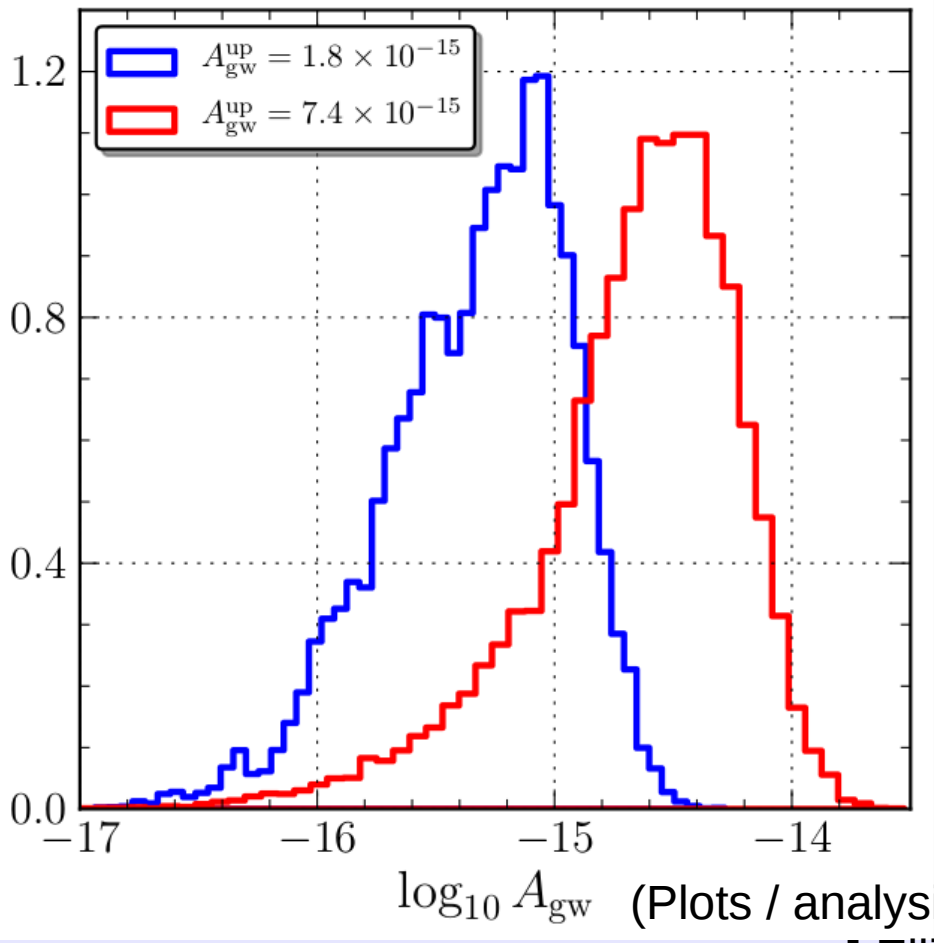
Preliminary weighted RMS residuals for pulsars in the eight-year data release.

8-year dataset has ~12 PSRs under 200 ns RMS, versus ~4 in the five-year analysis.

GUPPI/PUPPI improvement for most PSRs is a factor of ~2—3x in RMS timing residual.

Preliminary GW results: Stochastic background

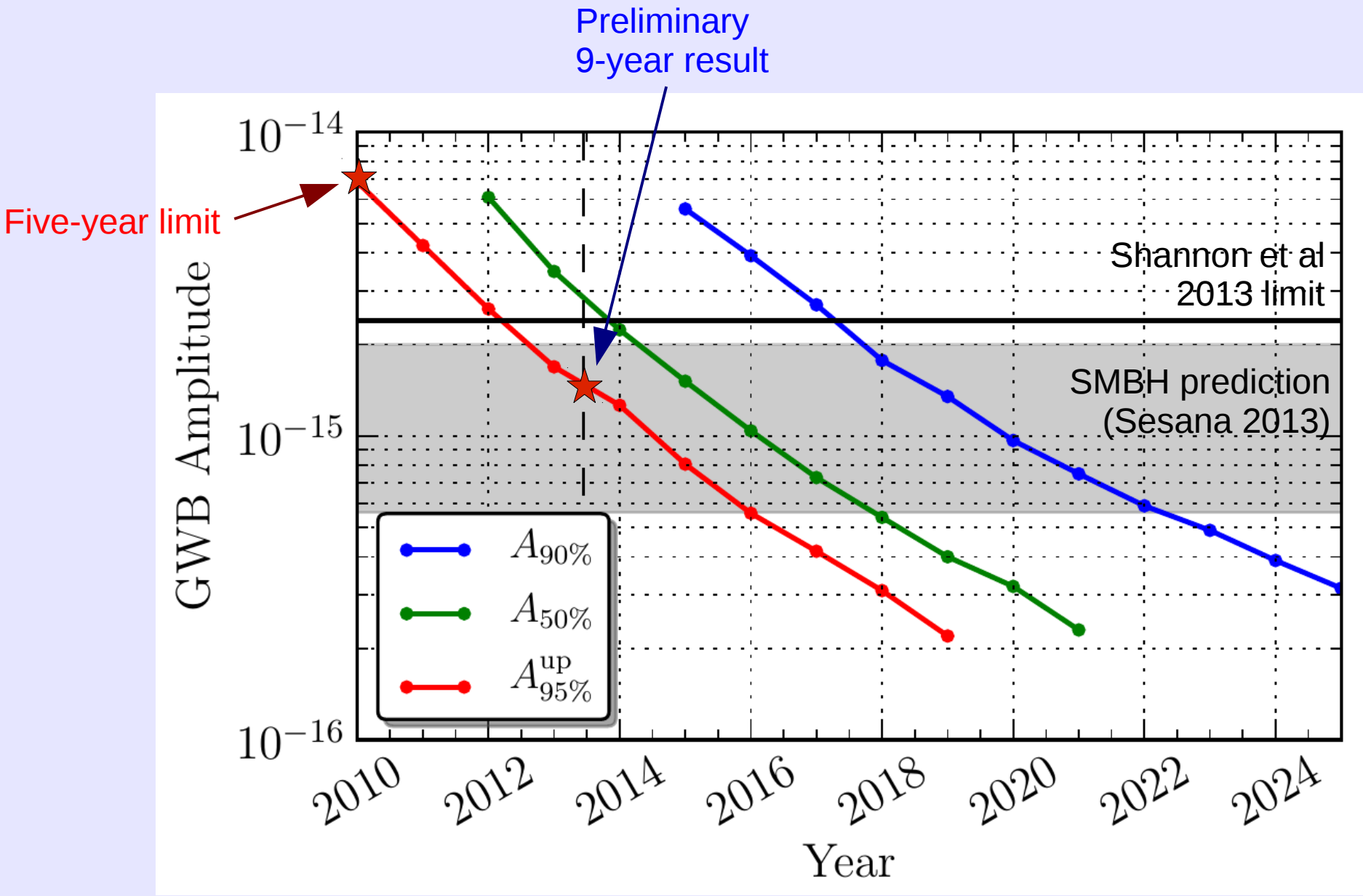




(Plots / analysis: J.Ellis)

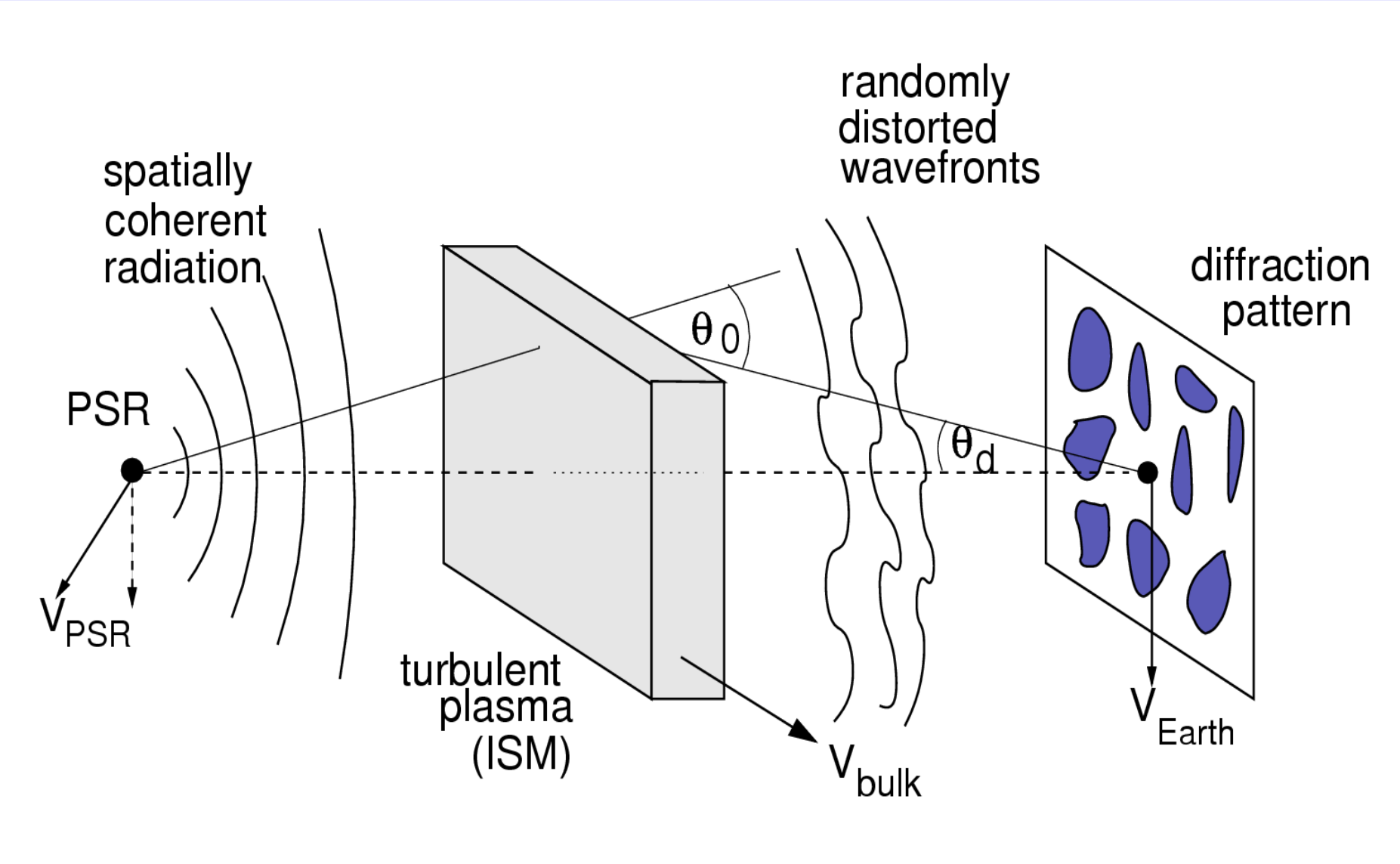
MBH-MBH upper limit h_c ~1.8 x 10^{-15} @ 1 year (“usual units”).

How close is a GW detection?

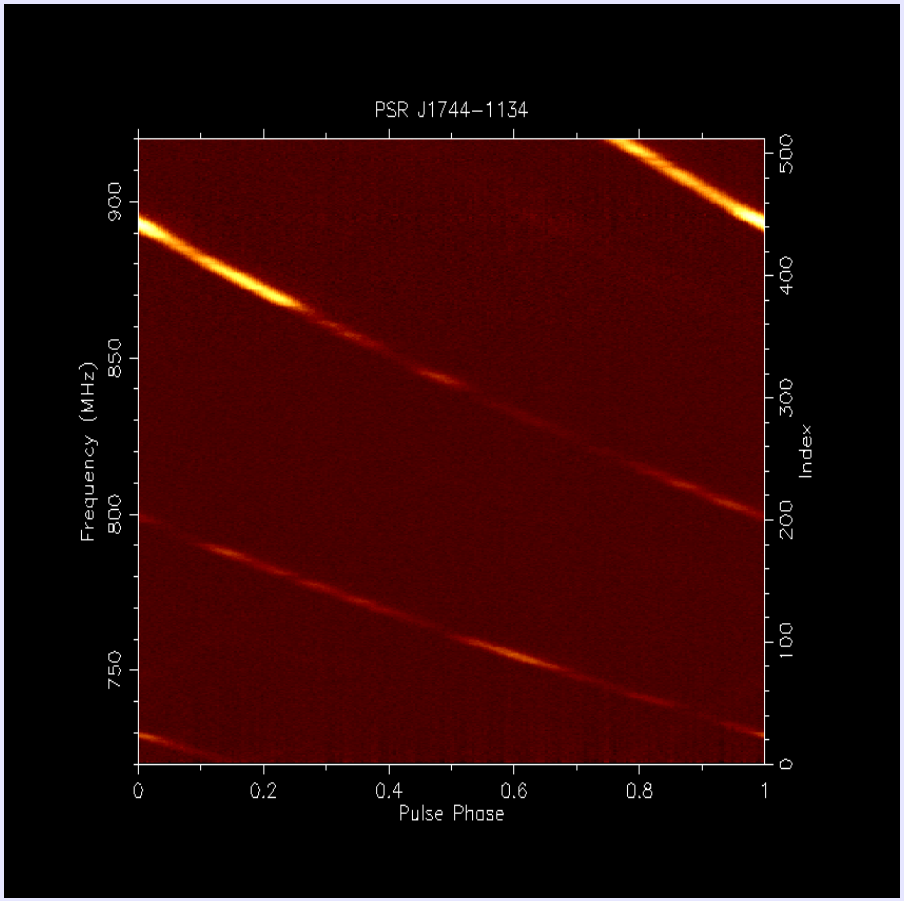


(figure: NANOGrav collaboration; see also Siemens et al 2013)

Pulsars as a probe of the ionized ISM:

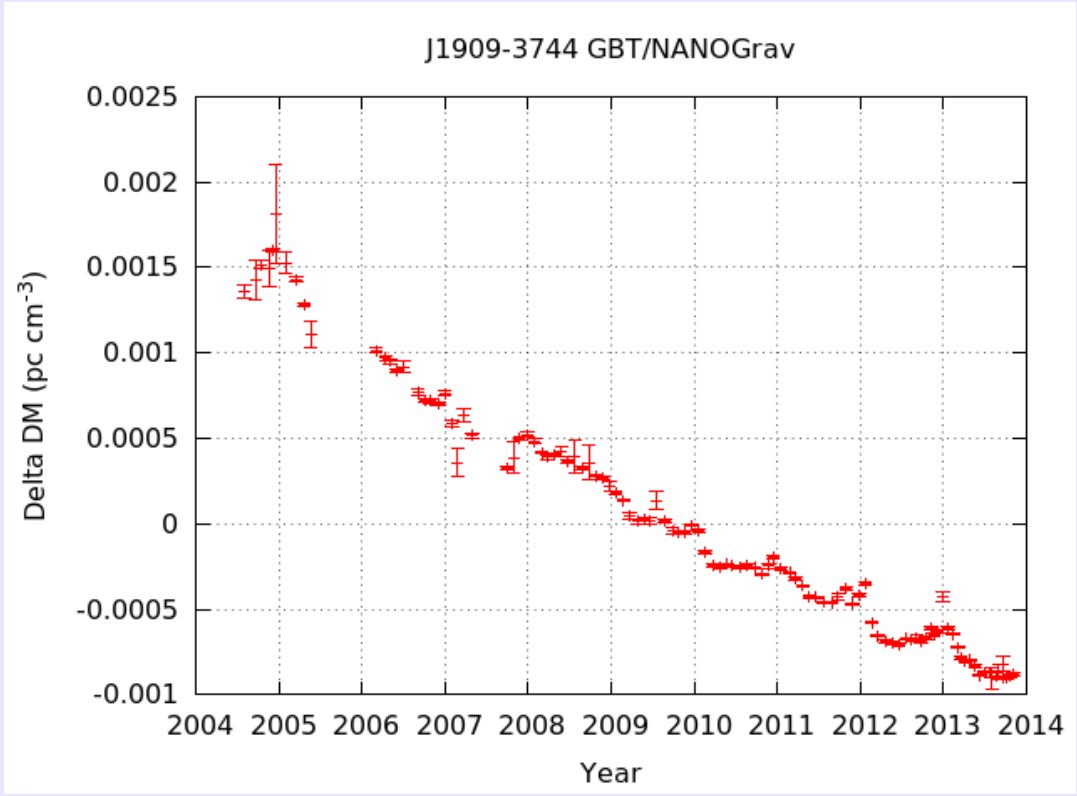


Dispersion measure variation:



Freq-dependent arrival time due to radio wave propagation in ISM. One parameter (DM) == electron column density.

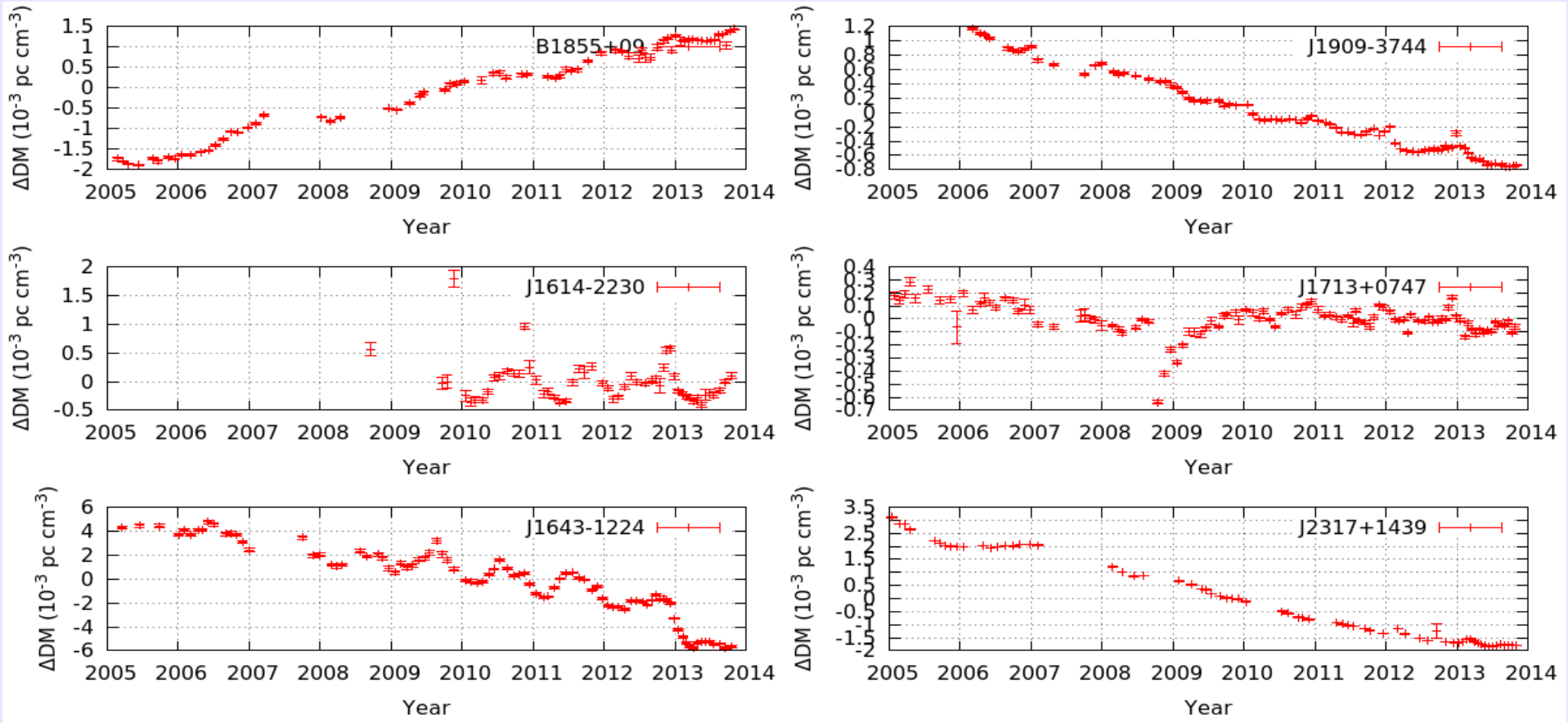
Varies due to pulsar--Earth line-of-sight motion through ISM.



DM(t) is a “foreground” for GW detection:

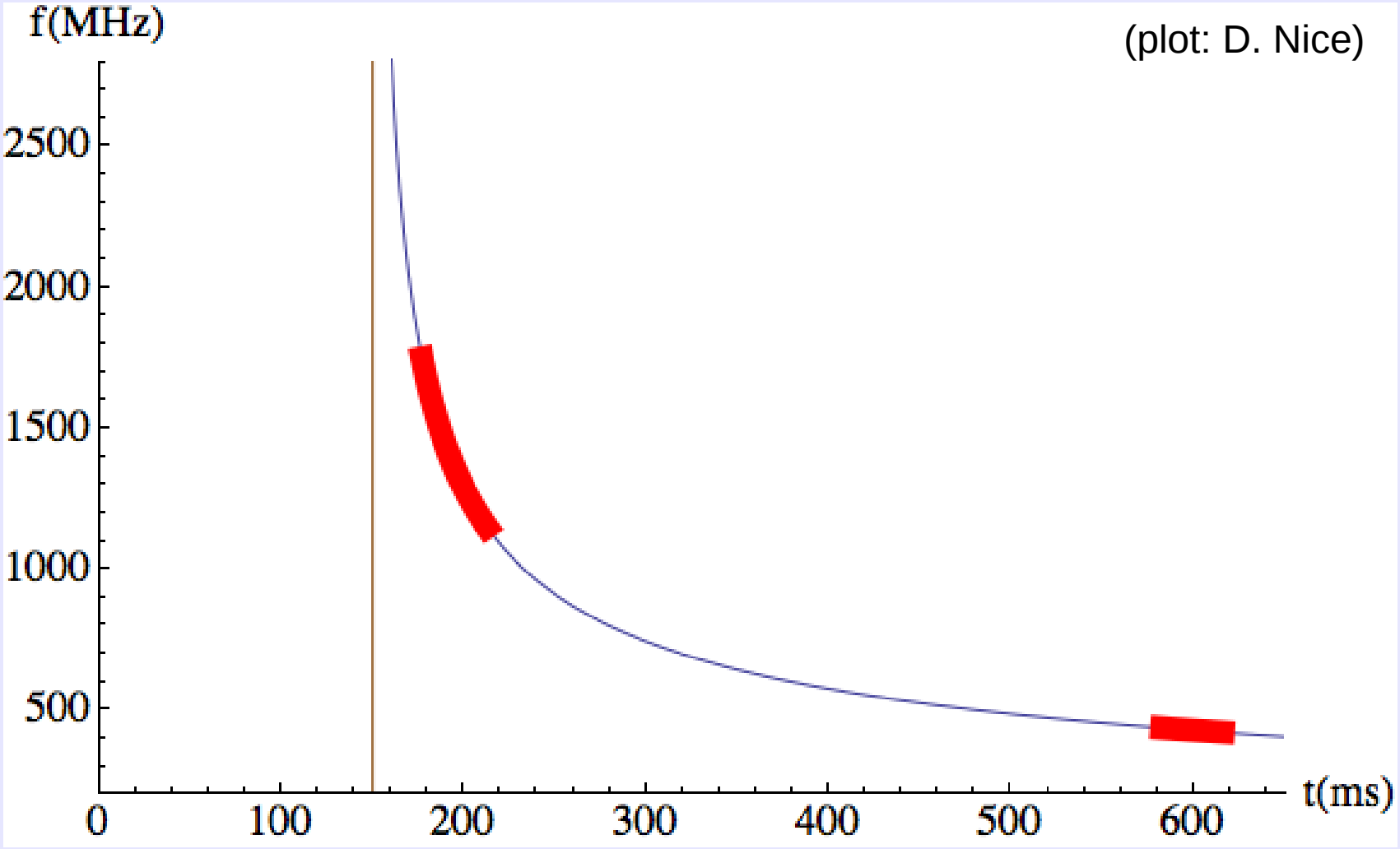
If uncorrected, 10^{-3} pc cm^{-3} → 1 us timing variation

Dispersion measure variation:



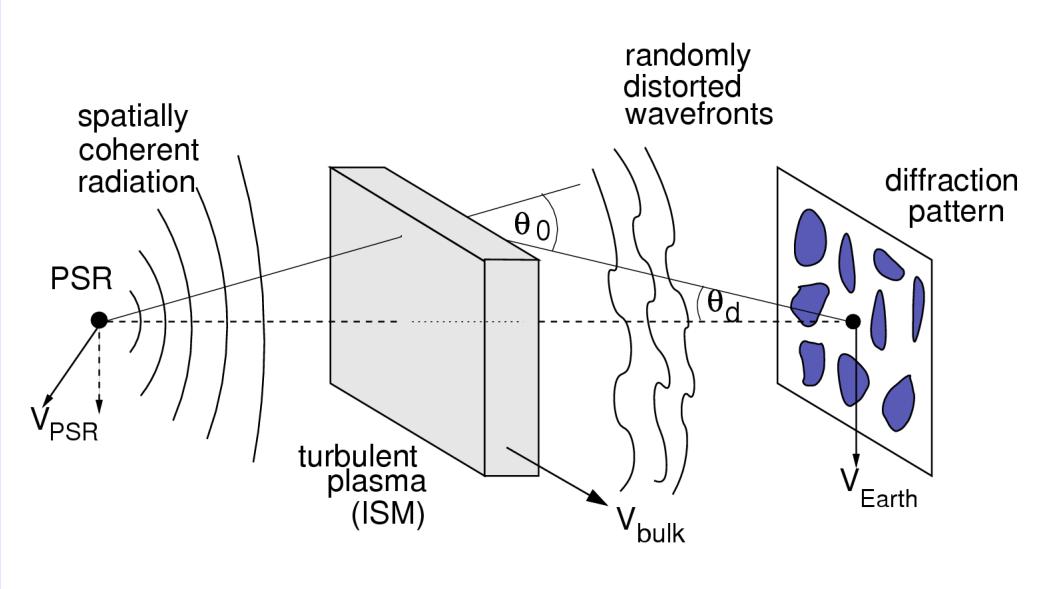
From NANOGrav 9-year data set

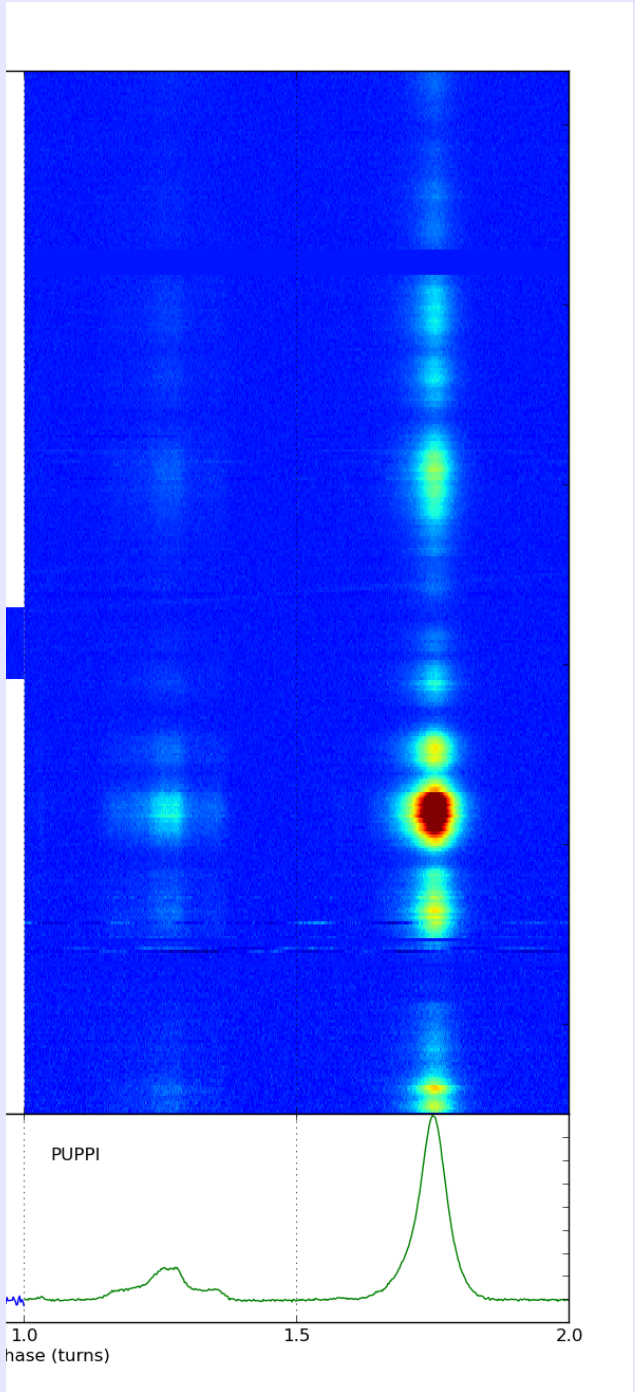
DM improvement with bandwidth:



Wide bandwidth “lever” improves separation of DM from achromatic timing shifts (ie, GW).

Multi-path propagation (aka scattering or scintillation)





Mon. Not. R. astr. Soc. (1972) **158,** 281–290.

THE INTERSTELLAR SCINTILLATION PATTERN OF PSR 0329+54

J. A. Galt and A. G. Lyne

(Received 1972 March 2)

SUMMARY

The pulsar PSR 0329+54 was observed at 4
an entire day at Jodrell Bank and Penticton. The
sufficient to permit detection of motions of the
by irregularities in the interstellar medium. The
that the scintillation pattern is stable. If this i
indicate a decorrelation length of 77 000 km ar
at position angle 295° referred to the local star
is high compared to most motions in the Galax
velocity estimates made on the basis of single
motion can be attributed to either the interst
itself. Although this experiment does not dist
possibilities, it may indicate the existence of hig
by certain theories of pulsar formation.

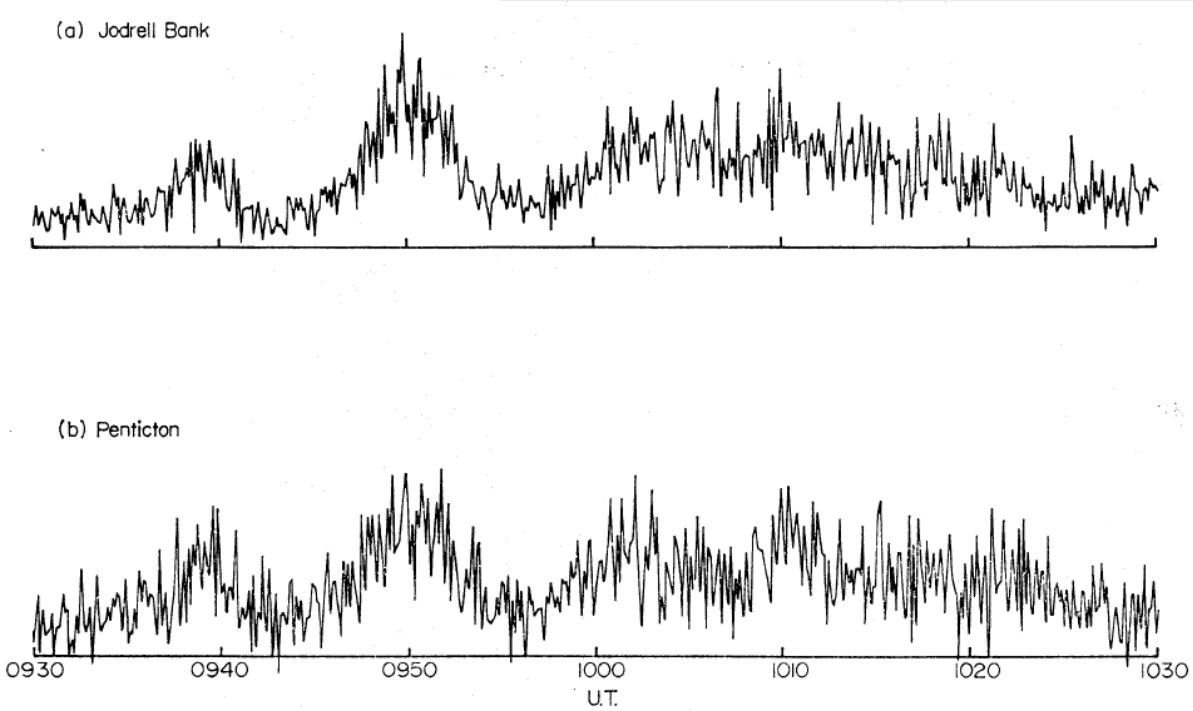


FIG. 2. *The pulsar intensities observed at Jodrell Bank and Penticton over an interval of 1 hr on 1970 October 16. Ten pulses have been added at a time to give this display.*

Dynamic spectra

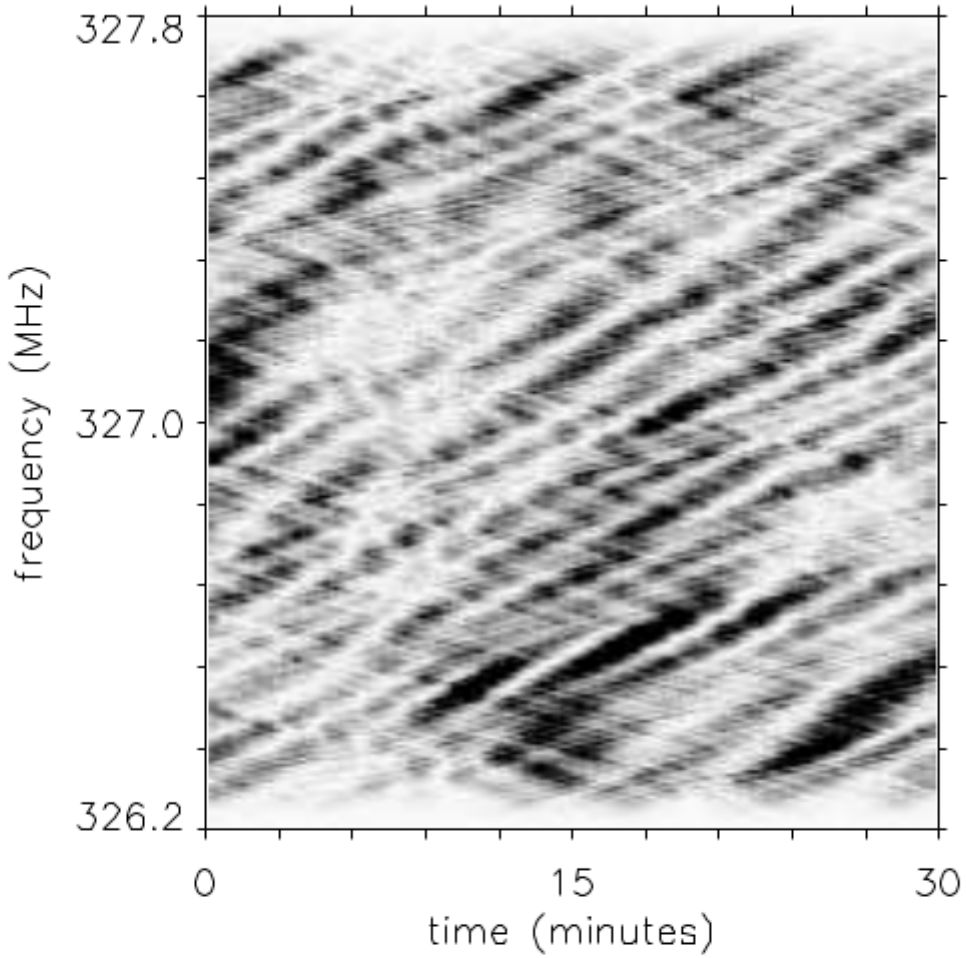
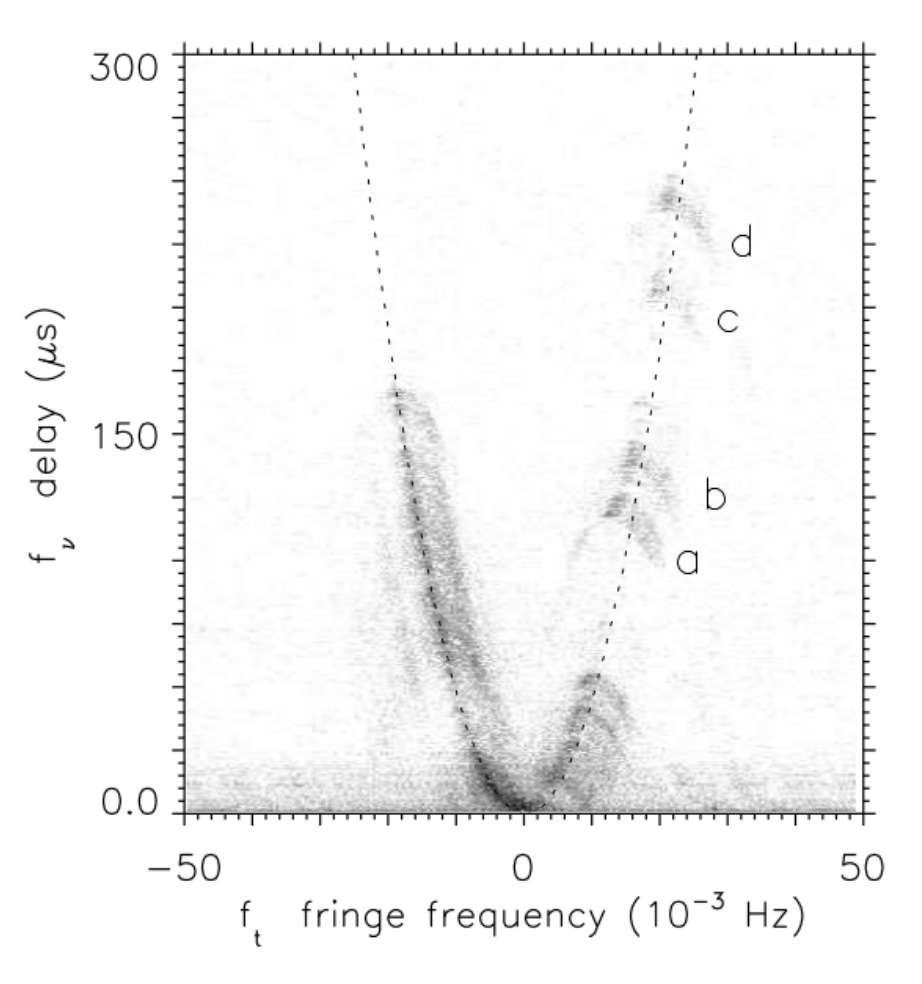


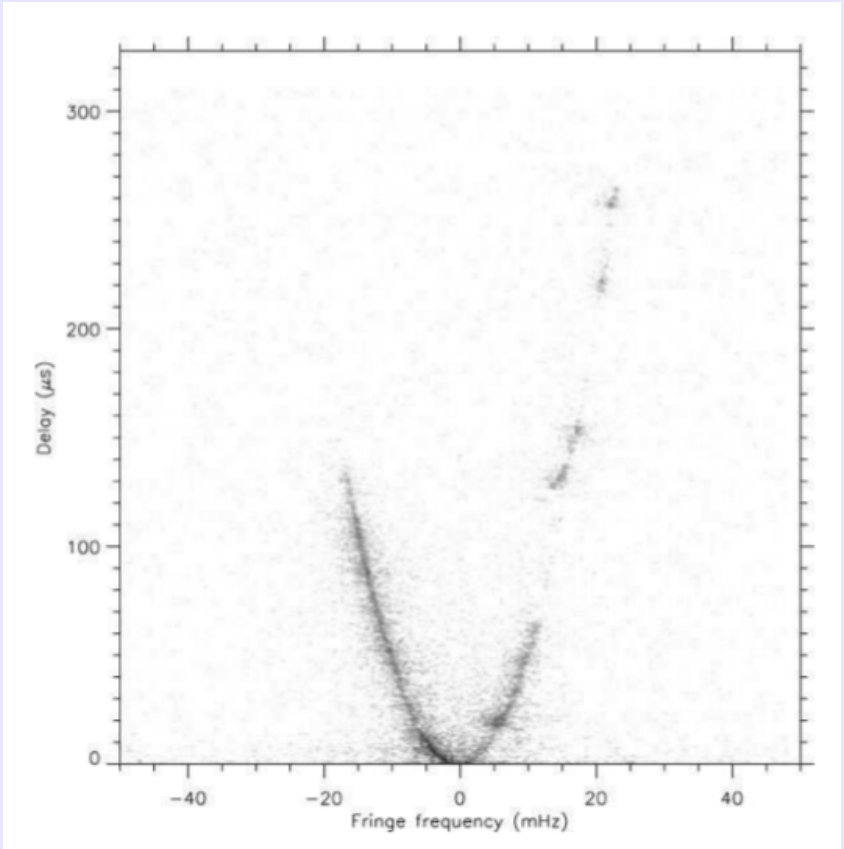
FIG. 1.— The dynamic spectrum of PSR B0834+06 observed on 2003 Dec 31. The flux density as a function of frequency and time is shown using a grayscale that is linear in power, with dark regions indicating high power. The crisscross pattern is due to radio waves reaching the observer from a variety of angles ($\sim$ 10 mas away from the pulsar position), as detailed in the text.

(Hill et al 2004)

“Secondary spectra”



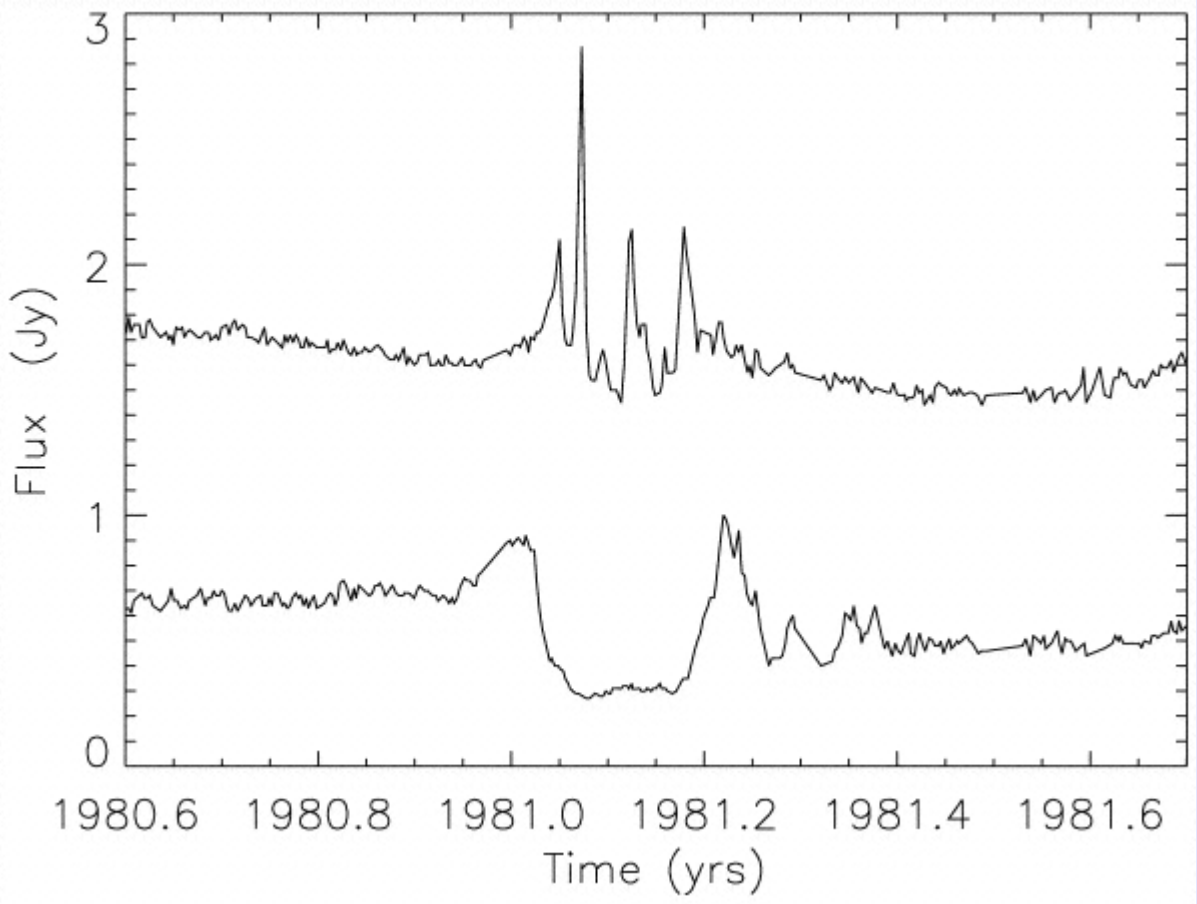
Raw SS (Hill et al 2004)



Deconvolved SS (Walker et al 2008)

Implies “1-D” and/or discrete ~AU-scale structures present in the ISM.

Extreme Scattering Events



(Quasar 0954+658; Fiedler et al 1987)

EXTREME SCATTERING EVENTS AND GALACTIC DARK MATTER

MARK WALKER AND MARK WARDLE
Special Research Centre for Theoretical Astrophysics, School of Physics, University of Sydney, NSW 2006, Australia
Received 1998 February 11; accepted 1998 March 17; published 1998 April 21

ABSTRACT

"Extreme scattering events" (ESEs) are attributed to radio wave refraction by a cloud of free electrons crossing the line of sight. We present a new model in which these electrons form the photoionized "skin" of an underlying cool, self-gravitating cloud in the Galactic halo. In this way, we avoid the severe overpressure problem that afflicts other models. The UV flux in the Galactic halo naturally generates electron densities of the right order. We demonstrate, for the first time, a good reproduction of the prototypical ESE in the quasar 0954+658. The neutral clouds are a few astronomical units in radius and have masses $\lesssim 10^{-3}\ M_{\odot}$. The observed rate of ESEs implies that a large fraction of the mass of the Galaxy is in this form.

Subject headings: Galaxy: halo — ISM: clouds — scattering

Pulsar scintillations from corrugated reconnection sheets in the ISM

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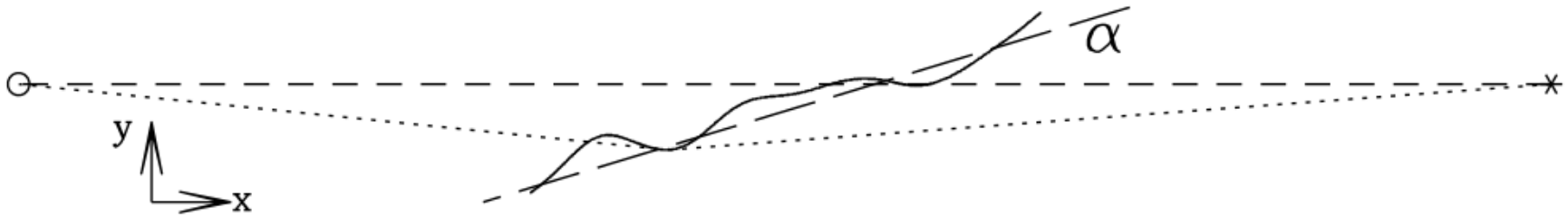
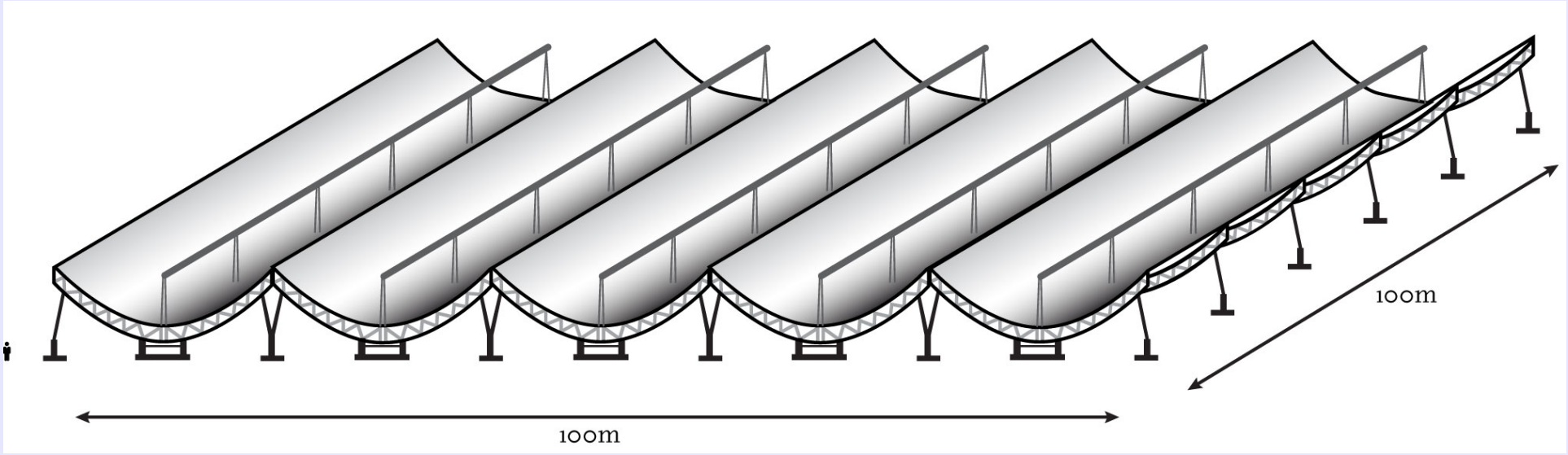
[1] *Canadian Institute for Theoretical Astrophysics, University of Toronto, M5S 3H8 Ontario, Canada*
[2] *Monash University, Australia*



Pulsars and CHIME:

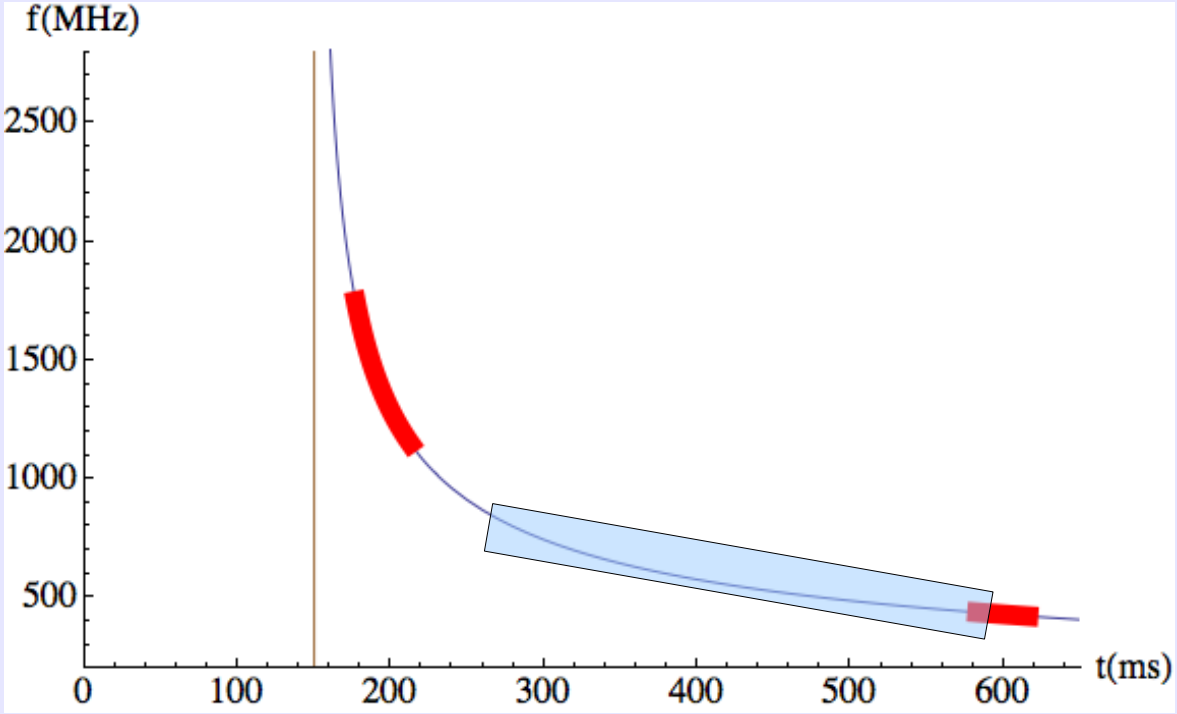


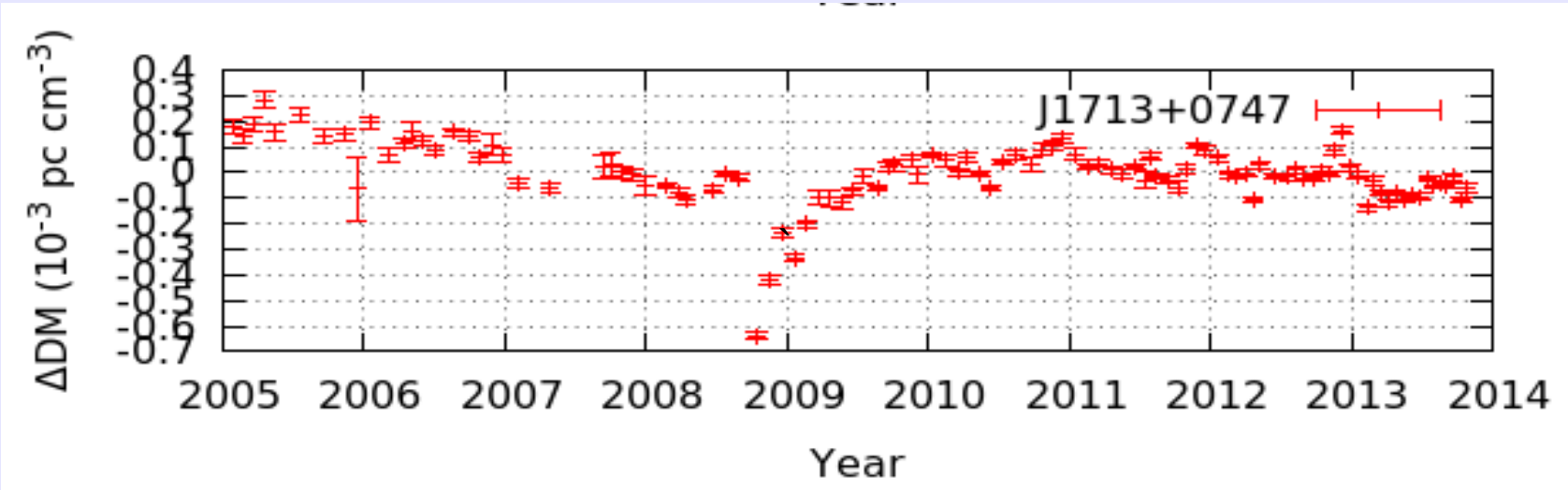
CHIME will see all ~northern pulsars for 5—10 minutes per day with ~GBT sensitivity.

400—800 MHz band is ideal for daily DM tracking! (and other ISM scattering measurements)

If combined with GBT 1—2 GHz data, will result in factor of ~2 improvement in DM-corrected MSP timing for NANOGrav.

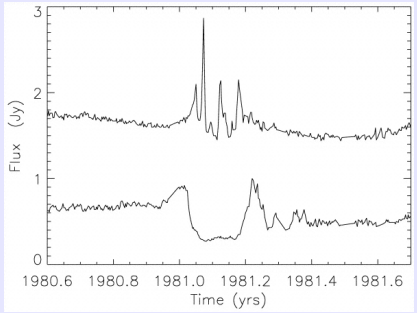
Dispersion Measure monitoring

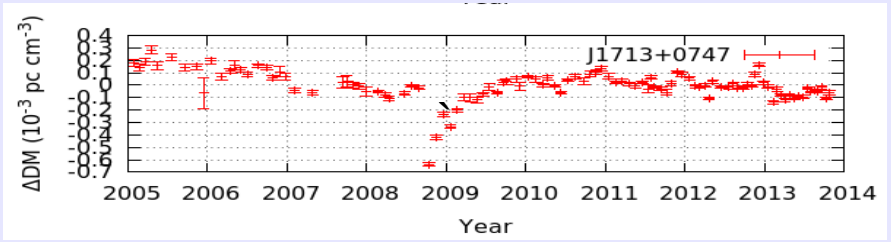




Sky coverage and relevant sources

- CHIME can see any northern hemisphere pulsar for ~5/cos(dec) minutes per day.
  - This means that per timing beam, ~200 pulsars could be monitored every day.
- For comparison:
  - Total number of pulsars at dec>0 ~ 600 (ATNF catalog)
  - Number of MSPs at dec>0 = 83 (Lorimer list)
  - Number of dec>0 MSPs currently observed by NANOGrav = 23
    - Currently ~1 hour per month total per pulsar → on average ~2 min per day!
- Long-term, daily monitoring of this many sources with a high-sensitvity, wide-BW instrument is unprecedented in pulsar astronomy!





Pulsars and CHIME:

GBT's GUPPI system

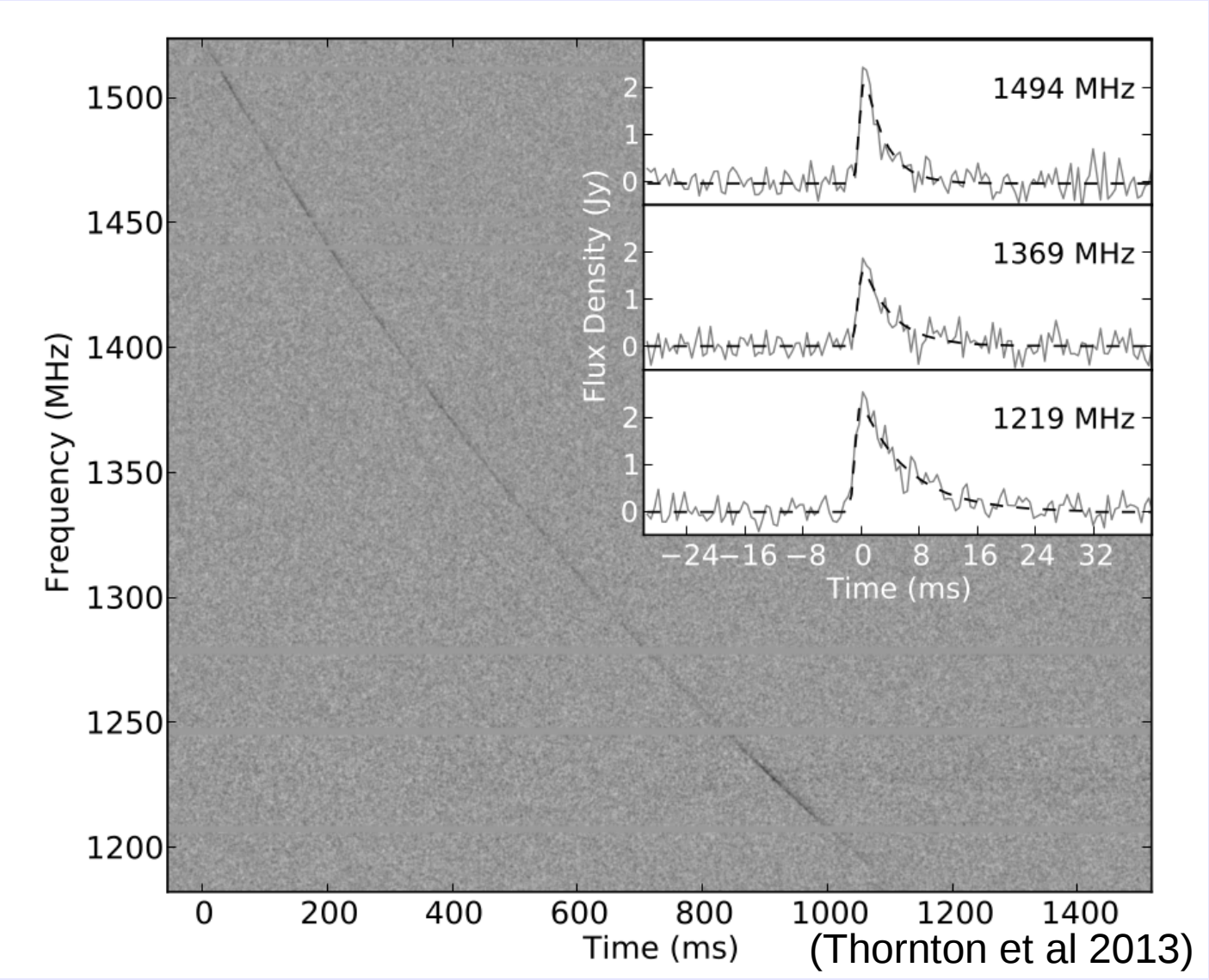
Pulsar backend systems are now mainly “just” software.

Real-time GPU signal processing for coherent dedispersion – typically ~100—200 MHz processed per GPU.

Approved RTI grant to fund cluster to process ~10 CHIME beams simultaneously for timing (Kaspi, Stairs, et al).

Will receive data from CHIME correlator systems, and process using existing pulsar code.

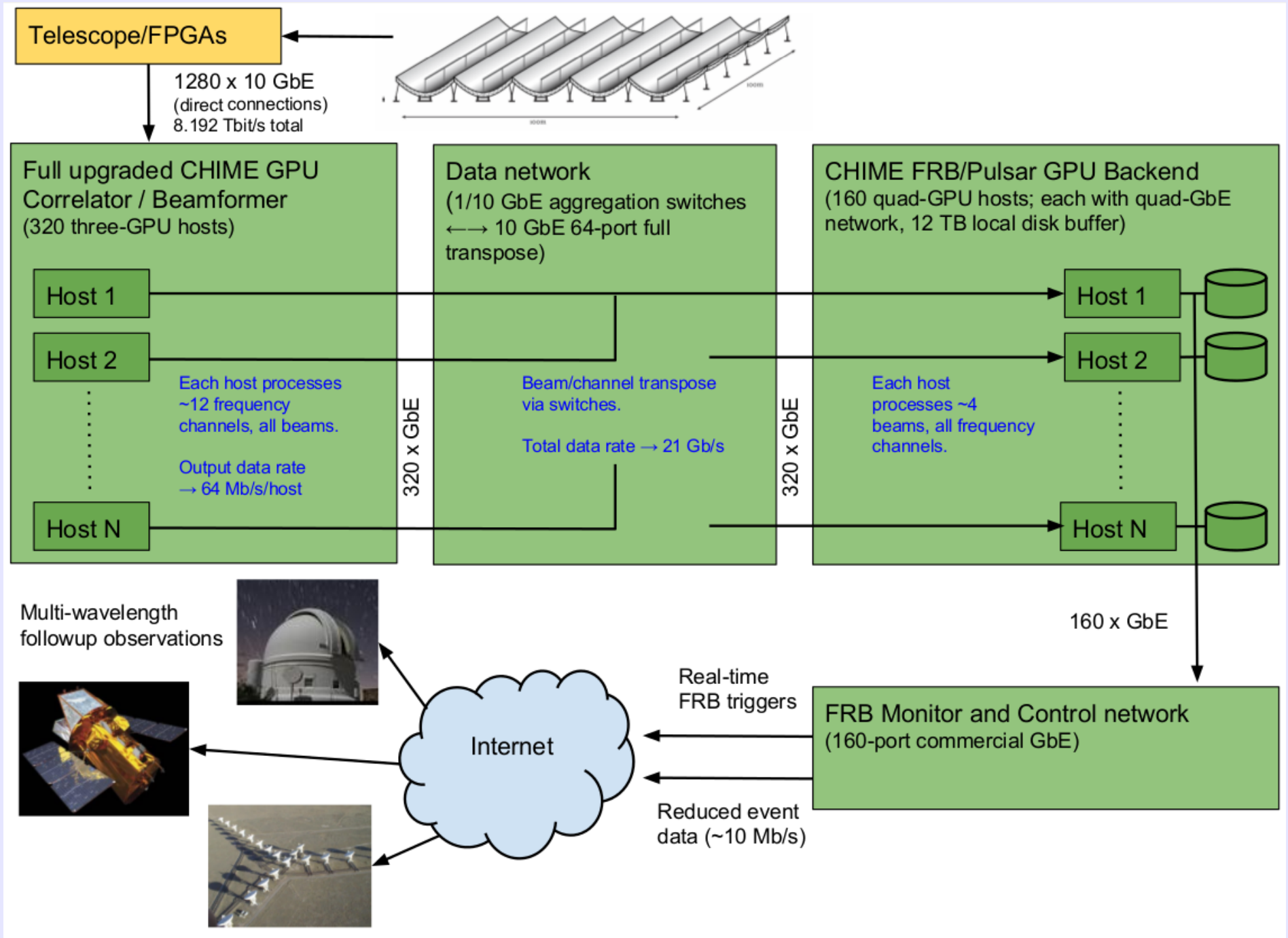
Fast Radio Bursts



(Thornton et al 2013)

To date, ~10 events detected. With appropriate instrumentation, CHIME could detect ~30—1000 per day due to its large FOV!

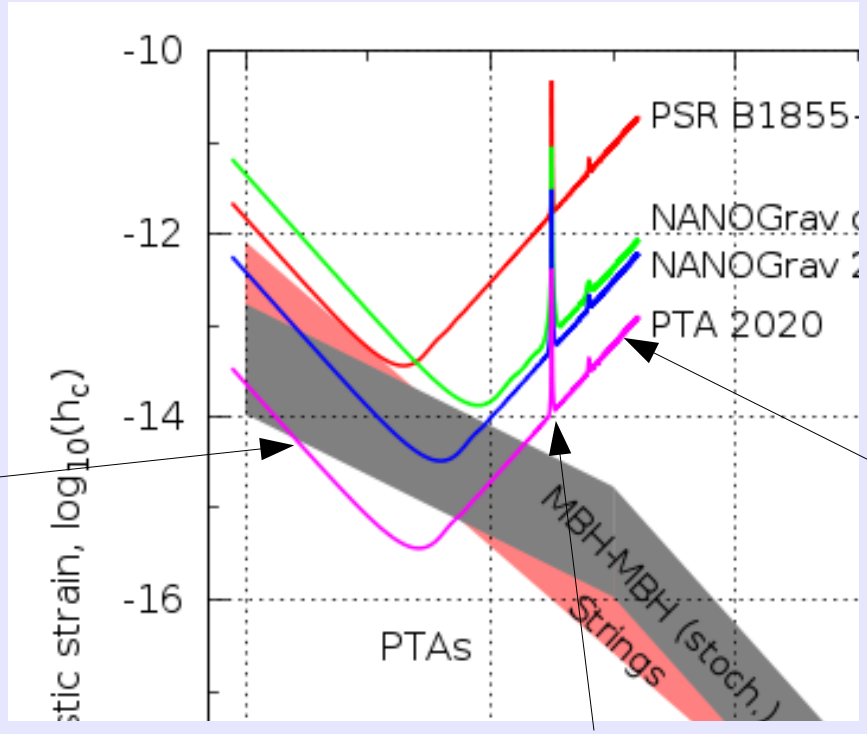
FRBs and CHIME



Summary

- NANOGrav project aims to detect GW via MSP timing.
  - CHIME will help via improved measurement of DM(t)!
  - See www.nanograv.org for more info.
- Pulsars provide a unique probe of the ionized ISM.
  - CHIME will provide sensitive, high-cadence, wide-BW observations of hundreds of sources.
  - Discover and characterize “rare” events (ESEs, etc).
- FRBs are an intriguing astrophysical mystery.
  - CHIME will increase # of detected FRBs by many orders of magnitude!

GW sensitivity: Effect of timing model



Fit for P, spindown

Fit for position, parallax

“ $dt = \int h\, ds$ “

Fitting timing model (pulsar astrometry, orbit, spindown, etc) affects sensitivity to similar-looking GW signals.

Methods for dealing with this refined over past several years (e.g., Demorest+ 2007, 2013, van Haasteren+ 2009, 2011, 2013, Ellis+ 2013, ….)
Bayesian/MCMC approach currently preferred by NANOGrav.