Noise Budget and Interstellar Medium Mitigation in the NANOGrav Pulsar Timing Array

Timothy Dolch[2], S. Chatterjee[1], J. M. Cordes[1], J. A. Ellis[3], M. T. Lam[1], NANOGrav Collaboration + Noise Budget Group + Interstellar Medium Mitigation Group

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[3]California Institute of Technology

7/14/17

Amaldi Meeting,

Pasadena, CA

NANOGrav = North American Nanohertz Observatory for Gravitational Waves

The Green Bank Telescope and the Arecibo Observatory

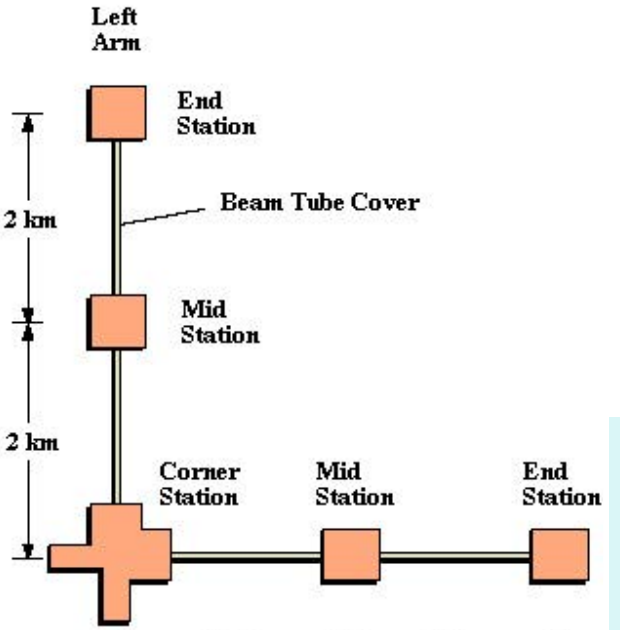
Our measurements are made every 3 weeks (with 5 best pulsars observed weekly), ~30min/pulsar on 49 millisecond pulsars, with the two most sensitive radio telescopes in the world:

Arecibo Observatory (AO), PR
World's largest
single-dish radio
telescope

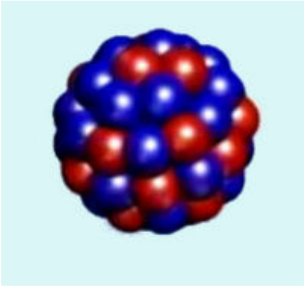
Green Bank Telescope (GBT), WV
World's largest steerable
single-dish radio
telescope

The Very Large Array is also contributing to our data sets, as will the Canadian CHIME telescope at low frequencies

Both LIGO and PTAs probe a ΔL on the scale of their respective "nuclei"

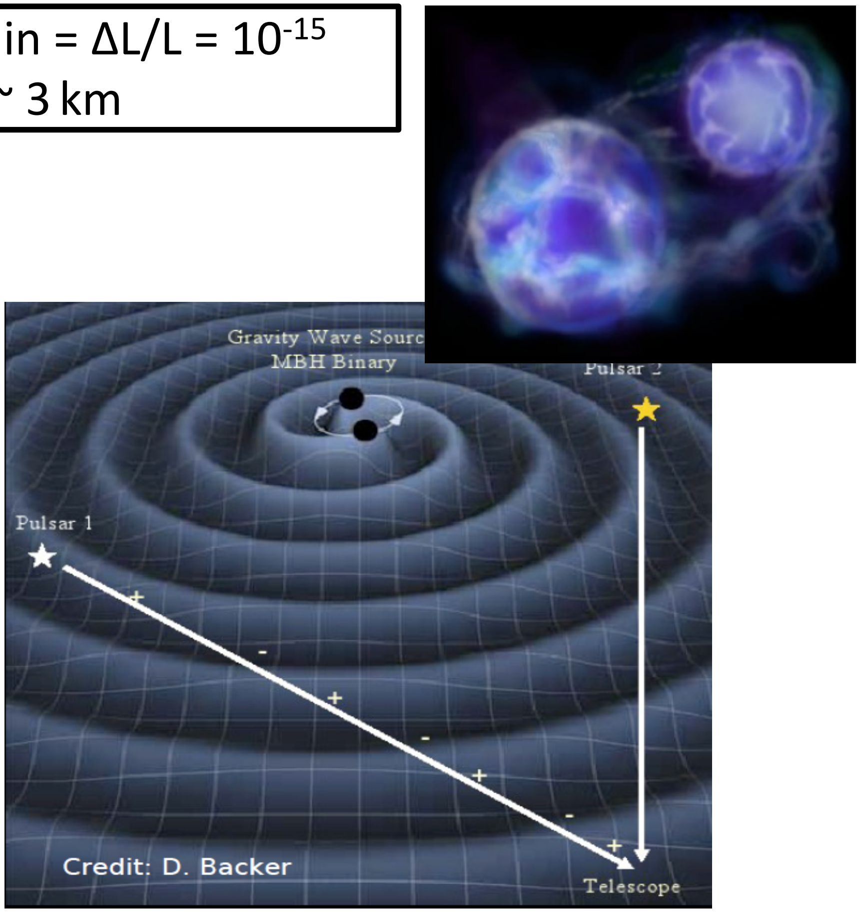


Schematic layout of LIGO Site at Hanford, WA
(Installation at Livingston, LA has no mid-stations)



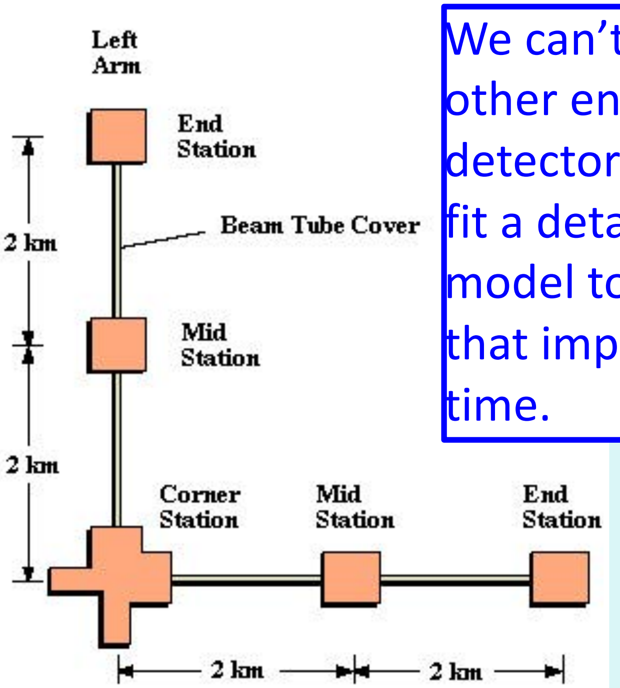
h = strain = $\Delta L/L = 10^{-21}$
LIGO $\Delta L \sim 10^{-19}$ m

h = strain = $\Delta L/L = 10^{-15}$
PTA $\Delta L \sim 3$ km



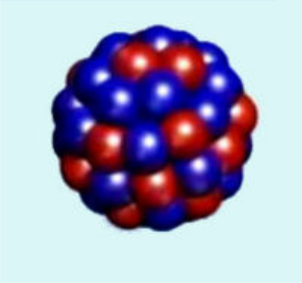
Credit: D. Backer

Both LIGO and PTAs probe a ΔL on the scale of their respective “nuclei”



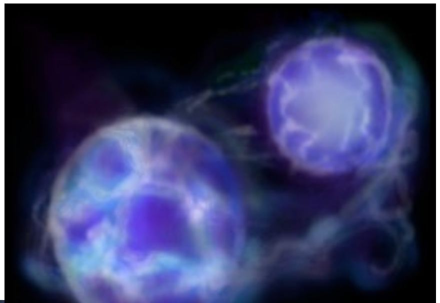
Schematic layout of LIGO Site at Hanford, WA
(Installation at Livingston, LA has no mid-stations)

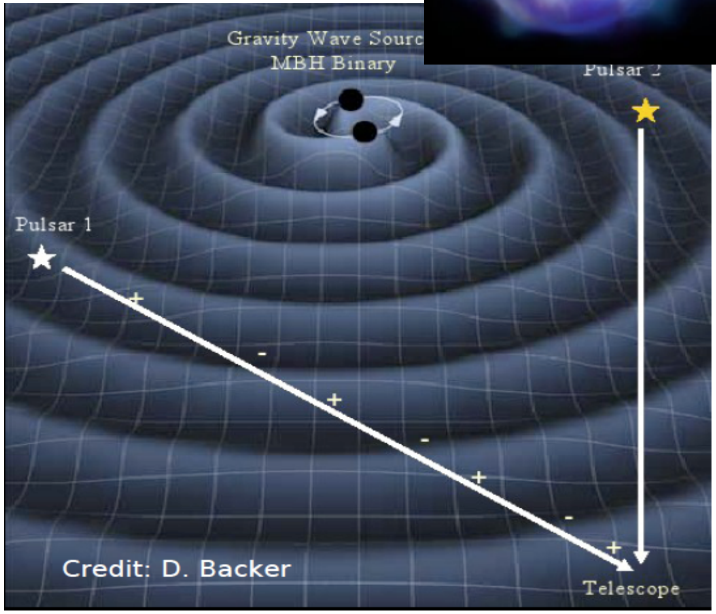
We can’t walk to the other end of our detector arm! So we fit a detailed noise model to the data that improves with time.



h = strain = ΔL/L = 10^{-21}
LIGO ΔL ~ 10^{-19} m

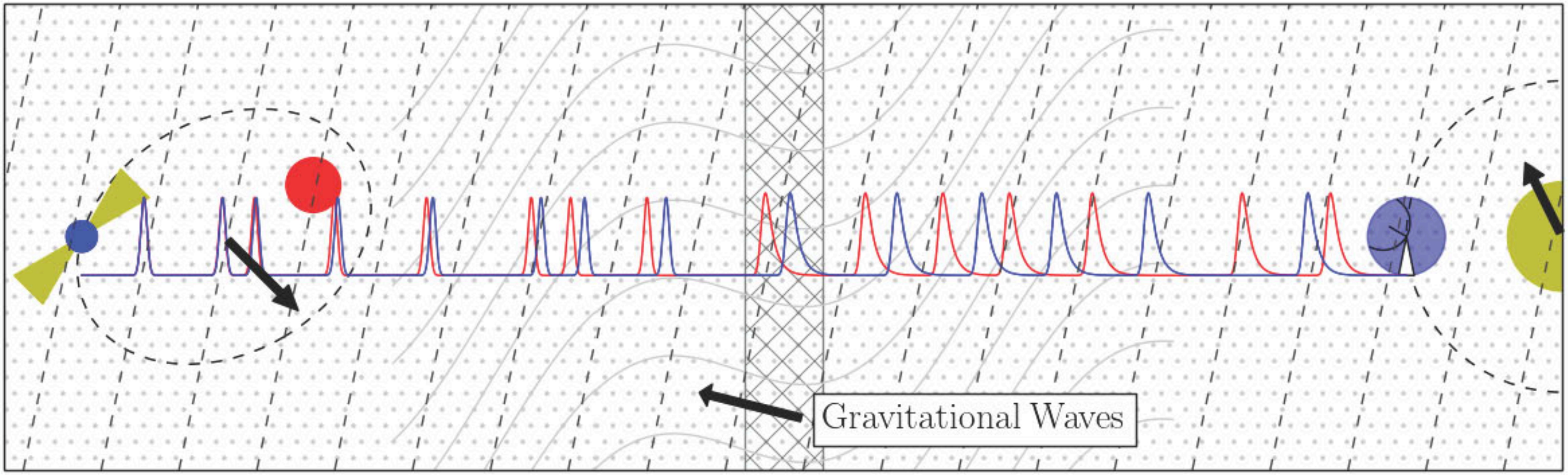
h = strain = ΔL/L = 10^{-15}
PTA ΔL ~ 3 km





Credit: D. Backer

Pulsar Timing Model

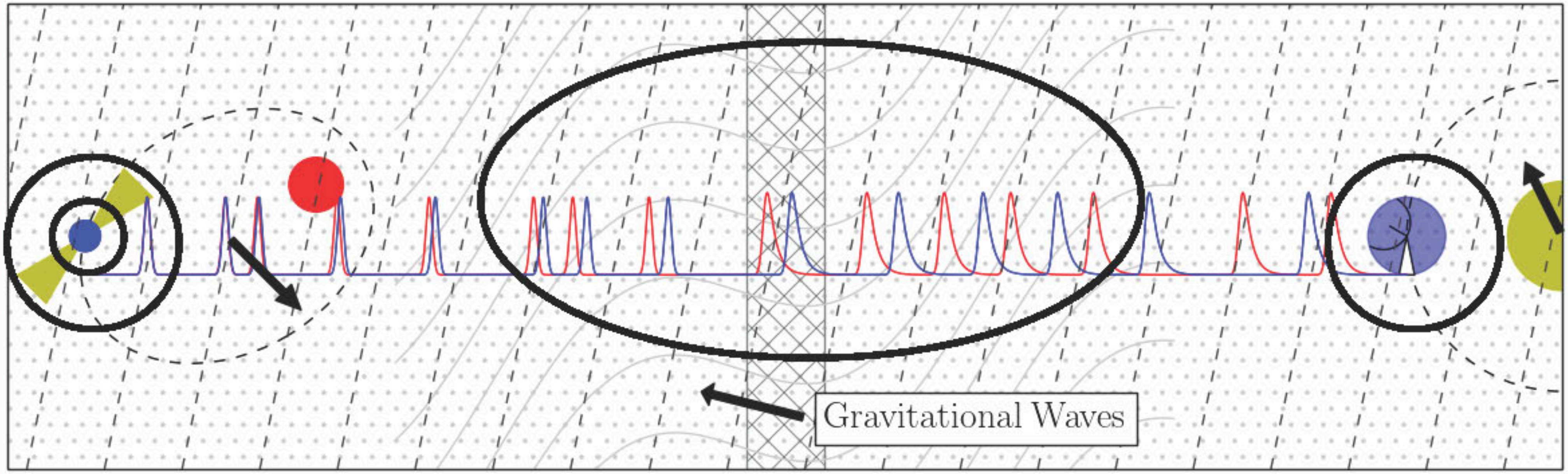


courtesy Michael Lam

Timing Model ↔ Noise Model

Clock mechanism:
Differential rotation
Crust quakes (glitches)
Magnetosphere torques (spin noise)

ISM:
Dispersive delays
Refraction, diffraction, scattering
Magnetic fields (Faraday rotation)



Clock ticks:
Variation of emission altitude with frequency (profile evolution)
Temporal variations (jitter)

Local effects:
TOA correction to SSB (planetary ephemerides, GPS time transfer)
IPM, ionosphere
Instrumental polarization
Radiometer noise

courtesy Michael Lam

- Red noise maximum-likelihood measurements from NANOGrav 11-year dataset (Arzoumanian et al. 2017, in prep)

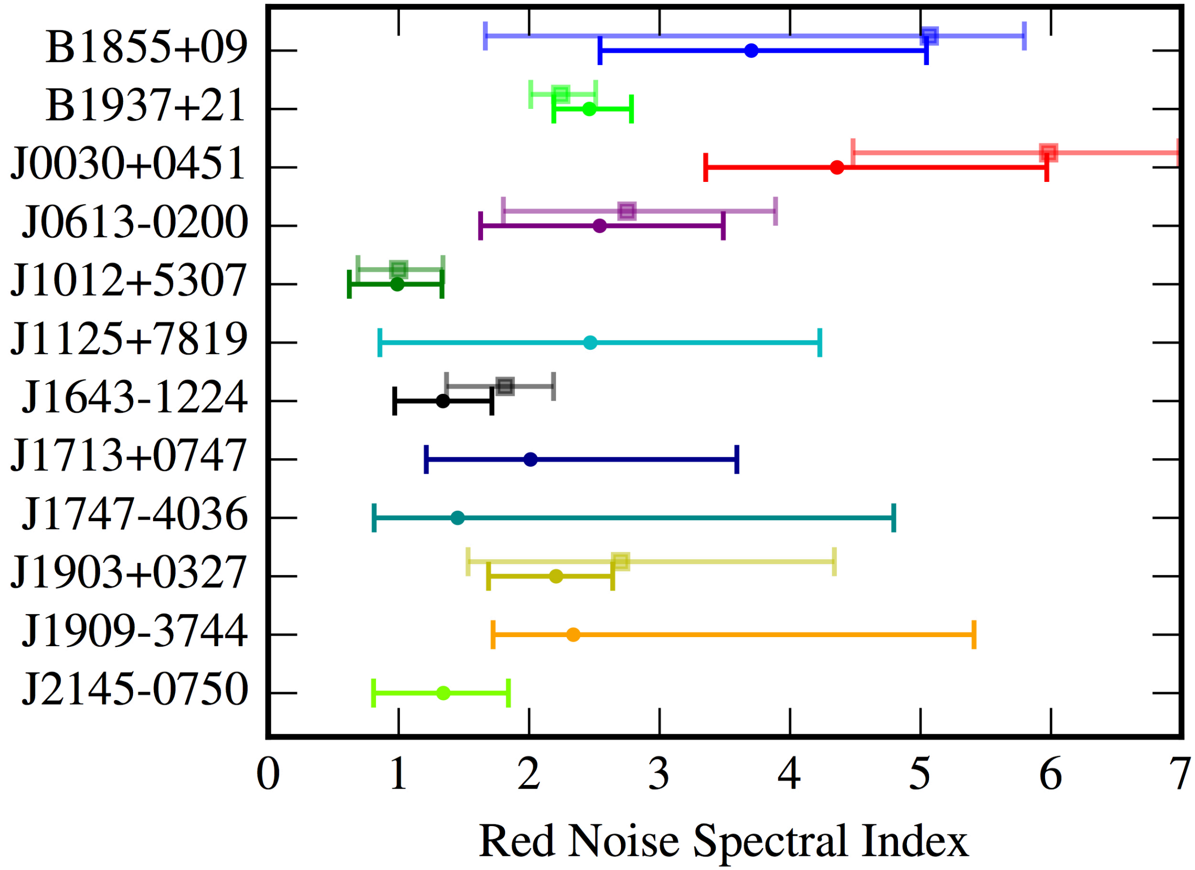
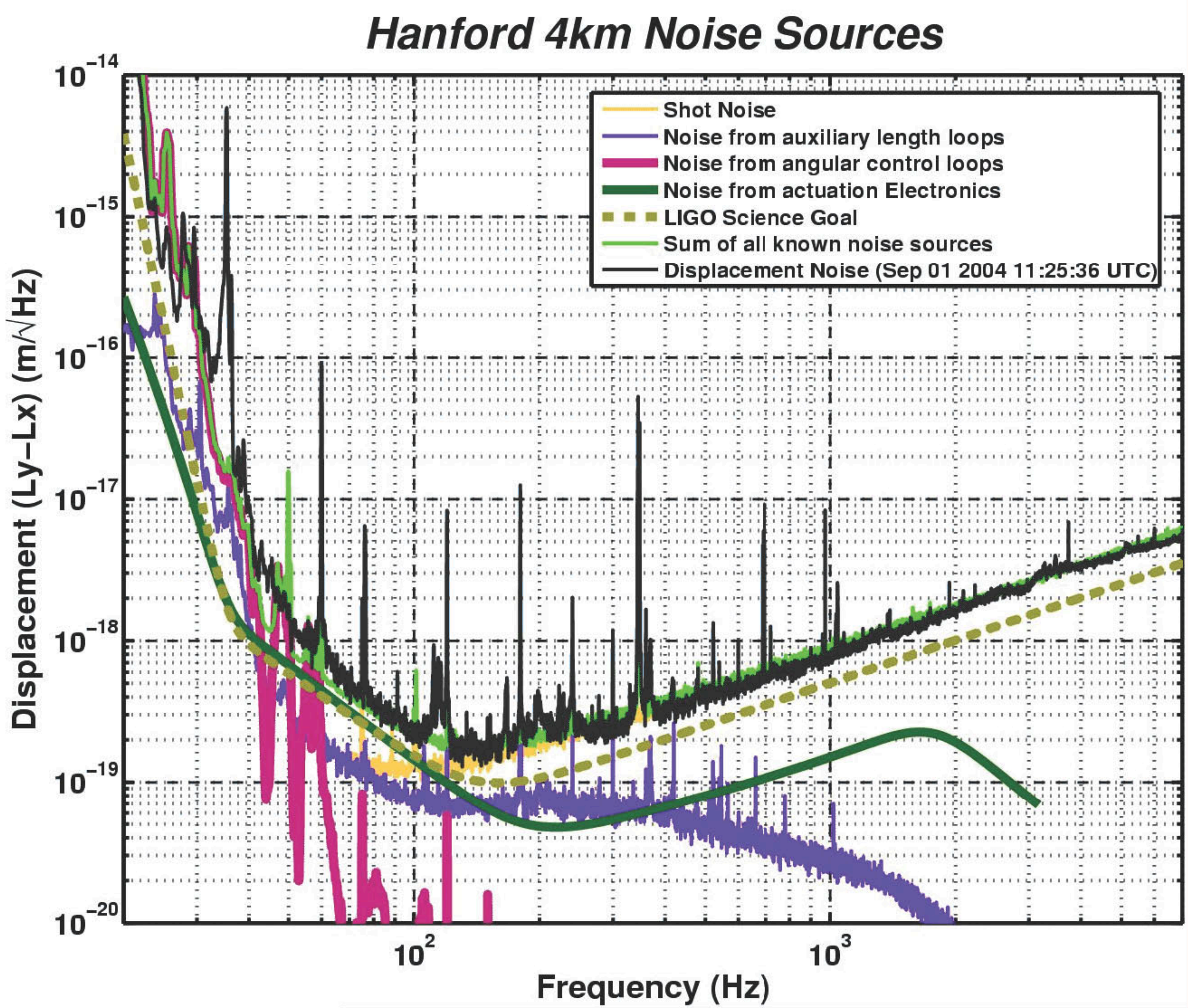
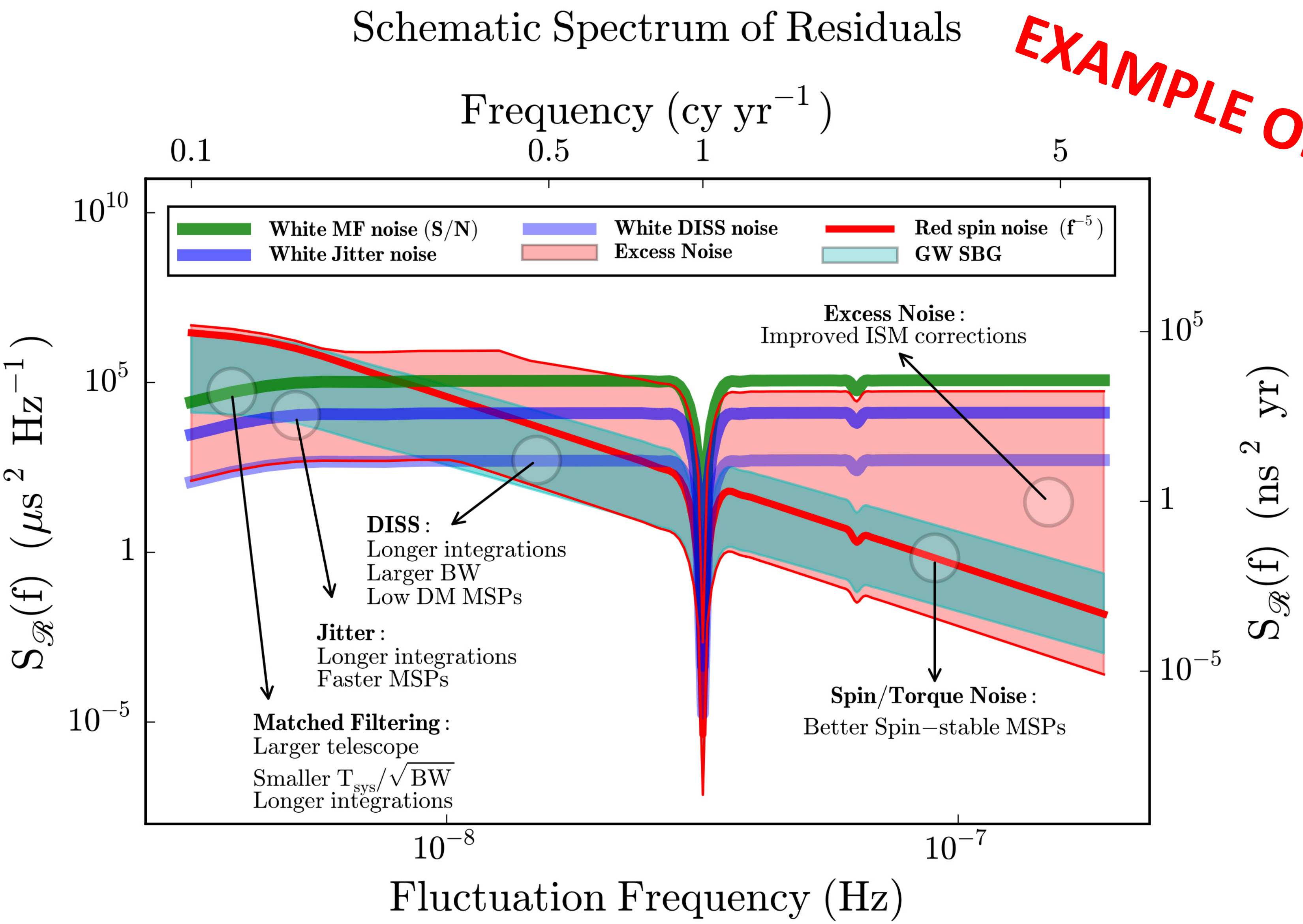


Figure 3. The ML estimates of the spectral index parameters (circles), with 1-sigma uncertainties (bars). Where applicable we have plotted the corresponding credible intervals for the 9-year data release with square markers and 1 sigma-uncertainties.



http://labcit.ligo.caltech.edu/LIGO_web/0409news/H1noise_budget_0904_big.gif

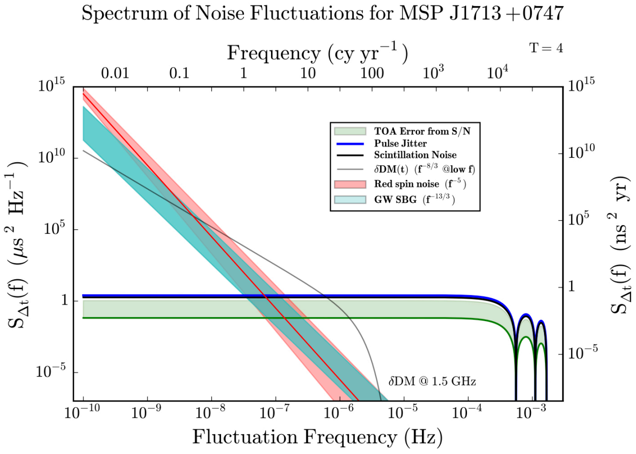
EXAMPLE ONLY



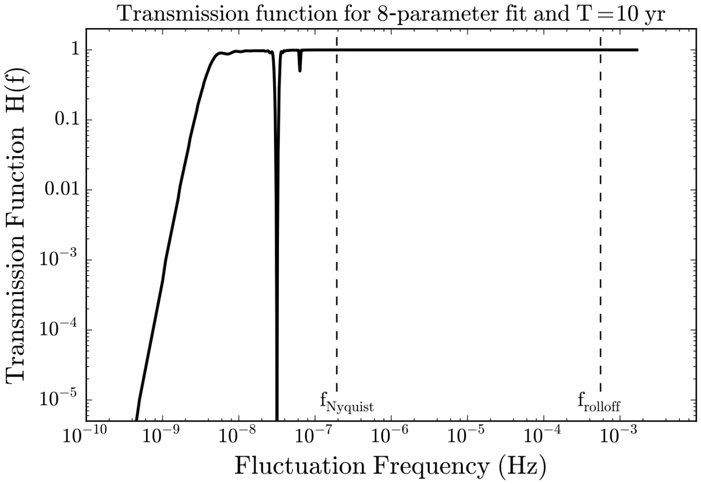
*Schematic spectrum showing noise contributions as labeled in the legend. The **GW contribution** (cyan) is from the 'pulsar' portion of the timing perturbation that is uncorrelated between pulsars. Annotations designate mitigation methods for the different contributions. See the caption of Figure 2 for further explanation.*

courtesy J.M. Cordes

Perturbation Spectrum x Transmission Function = Residuals' Spectrum

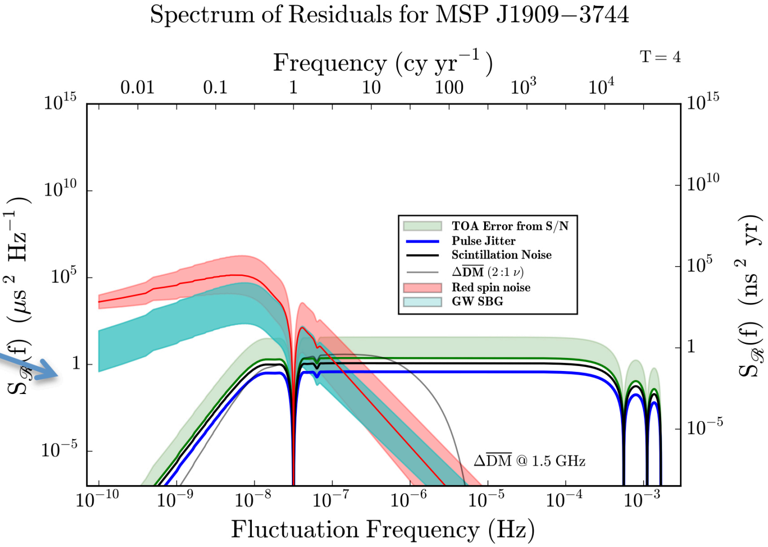

Spectrum of Noise Fluctuations for MSP J1713+0747

x


Transmission function for 8-parameter fit and T = 10 yr

=

Aliasing not yet included

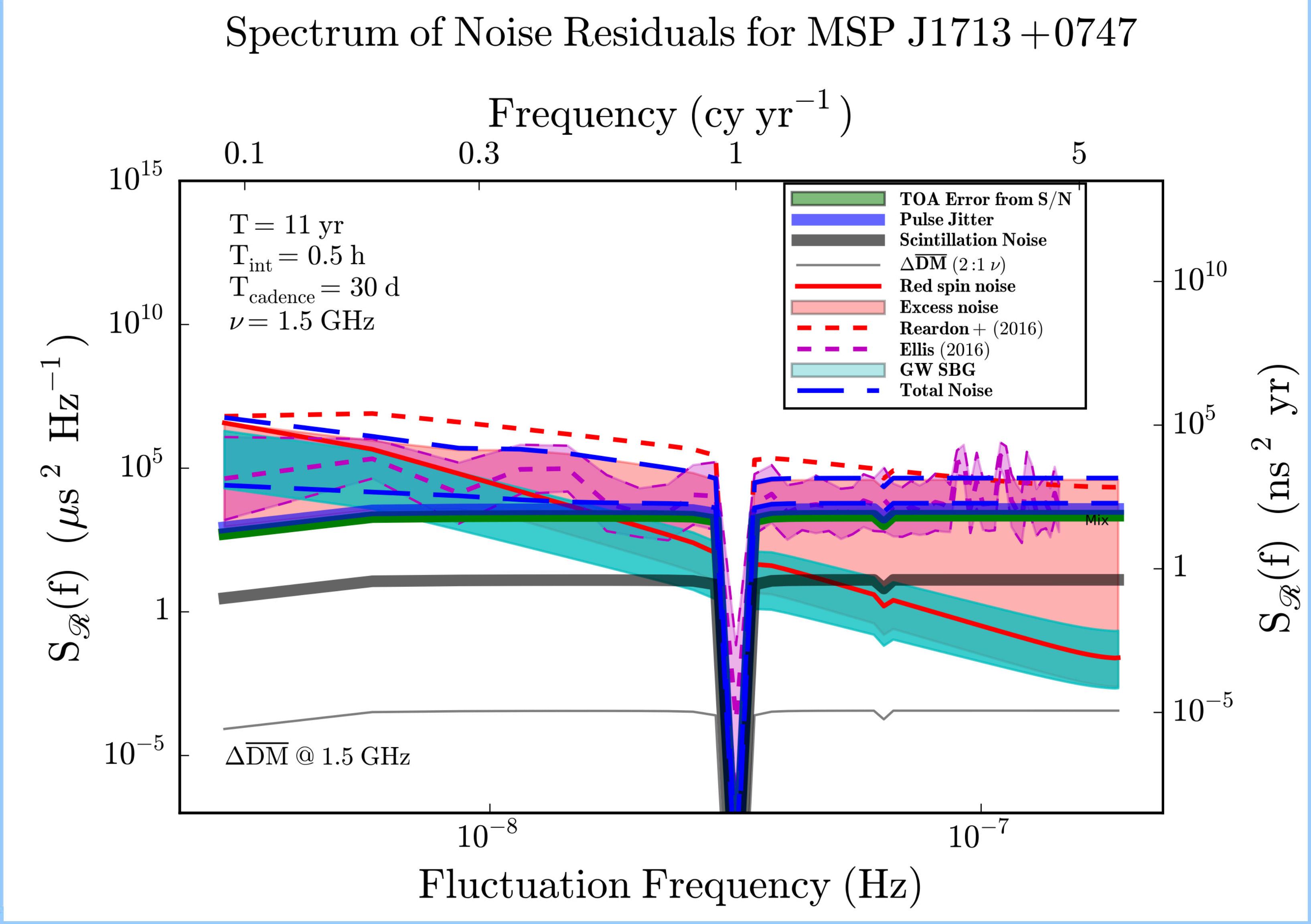

Spectrum of Residuals for MSP J1909−3744

The 8-parameter fit for the transmission function H(f) includes a quadratic polynomial (3) and astrometric terms (5). For small f, the transmission function scales as f^6.

* DM variations are assumed to be removed through two-frequency fitting at each epoch, leaving residuals from the frequency-dependent DM effect

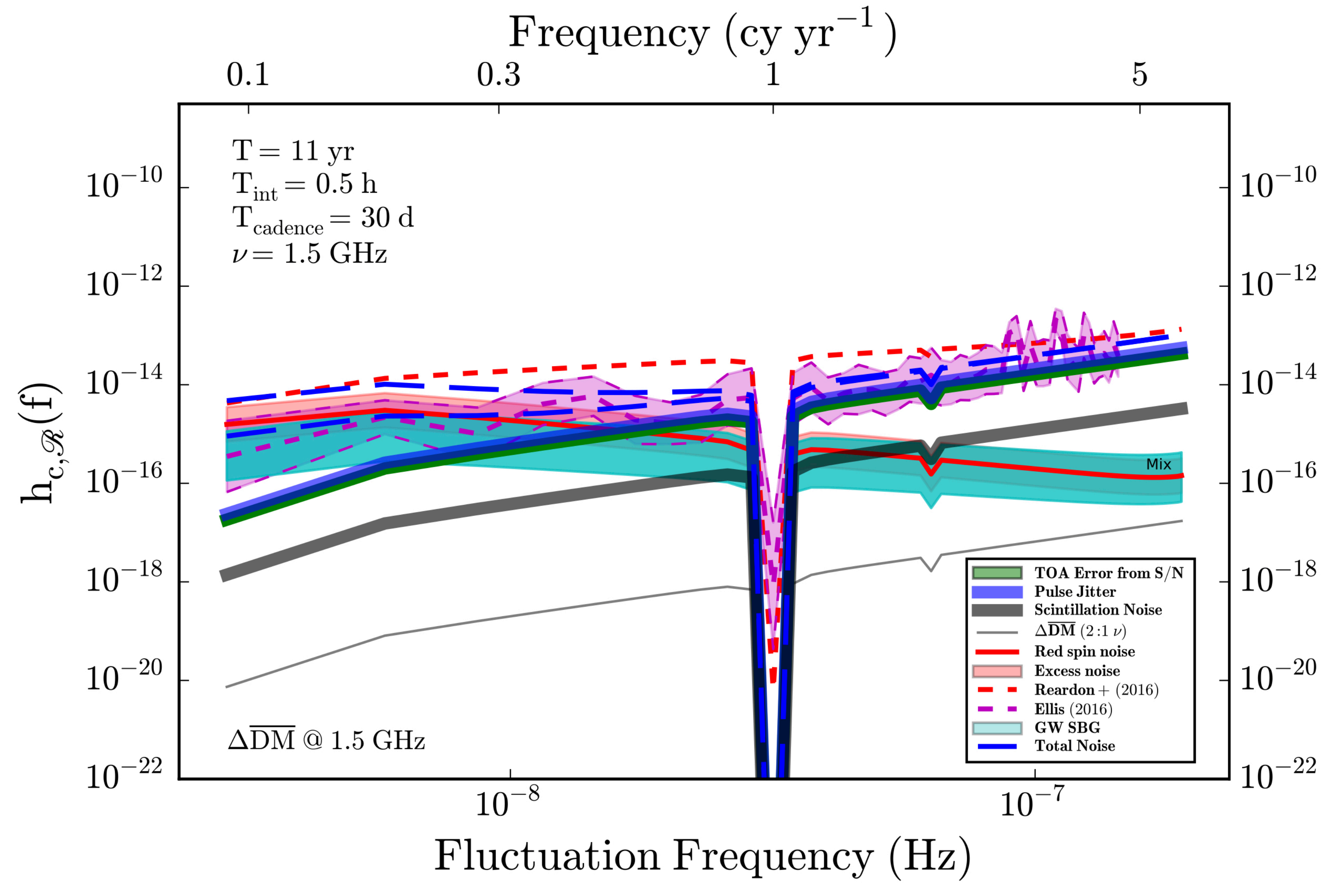
courtesy J.M. Cordes

- **Noise Spectrum of Pulsar J1713+0747**
- **While a single pulsar, it nonetheless dominates NANOGrav sensitivity to GWs**



Courtesy J. Cordes

- **Strain Sensitivity of Pulsar J1713+0747**
- **Note this is a single pulsar – GW signal will emerge through time-of-arrival correlations between different pulsars, reducing noise**

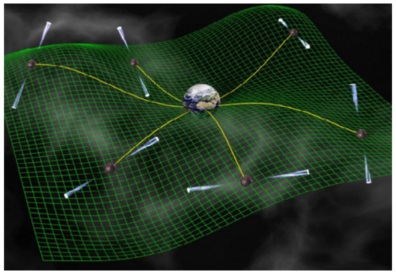


Courtesy J. Cordes

Advances in Noise Descriptions

Components	Method(s)	Example work(s)
Jitter	Frequentist	Craft 1970,Liu+2011,2012, Shannon+Cordes 2012, Shannon+2014,Lam+2016
Glitches, random walk	Frequentist	Cordes 1980,Cordes+Helfand 1980
Variance reduction	Spectral	Blandford, Narayan, Romani 1984
Template fitting	Frequentist	Taylor 1992
DM variations	Frequentist	Demorest+2013
	Spectral	You+2007,Keith+2013
	Bayesian	Lentati+2013
Red (power-law spin) noise	Post-fit Maximum Likelihood	Shannon+Cordes 2010
Red+white noise	Spectral Pre-whitening	Coles+2011
Chromatic: DM(t),DM(ν),Scattering		Lam+2015,Cordes+2016,Palliyaguru +2015,Levin+2015

courtesy Michael Lam



Timing Models, Noise, and Signals in Pulsar Times-of-Arrival

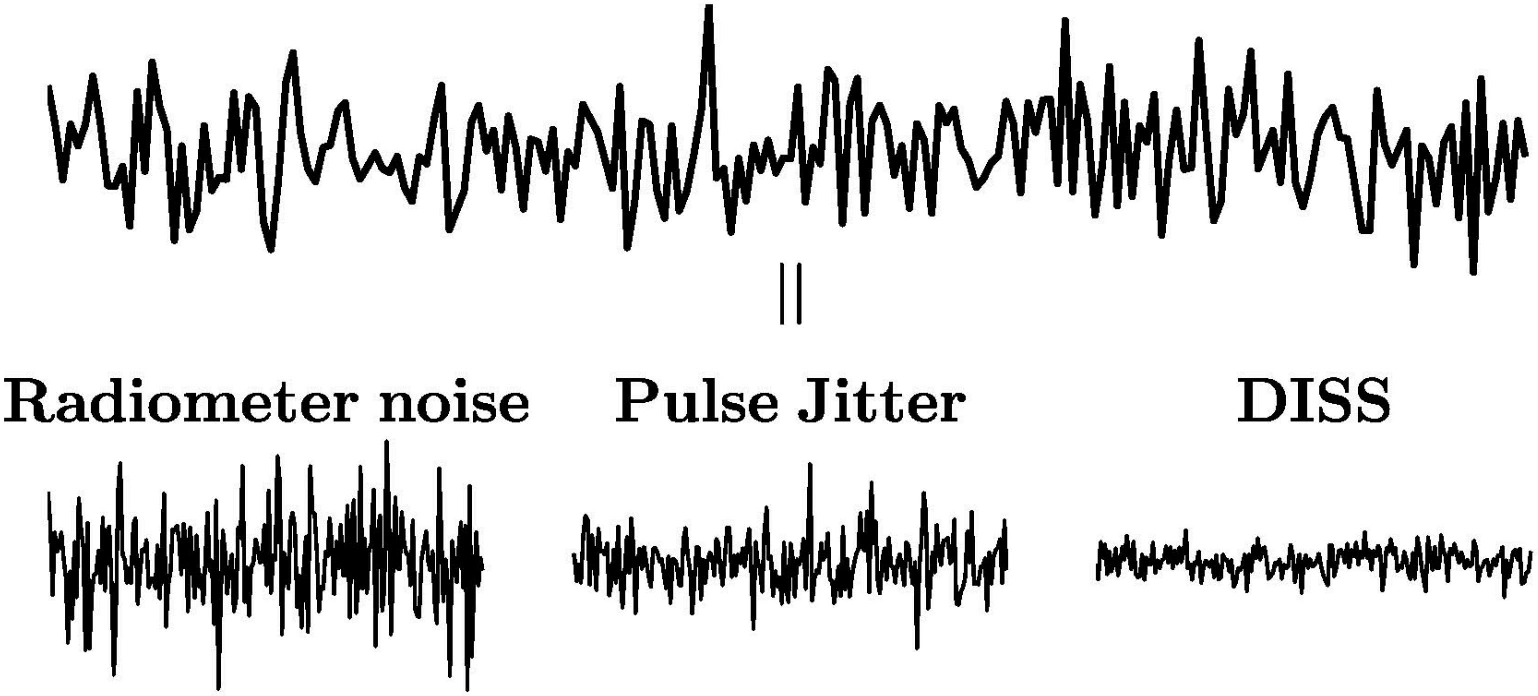
$$t_{\mathrm{SSBC}} = \boxed{\begin{array}{c}\textbf{Deterministic Terms}\\ \text{spindown polynomial}\\ \text{astrometric terms}\\ \text{pulsar orbit}\\ \text{pulse shape vs. } \nu\end{array}} + \boxed{\begin{array}{c}\textbf{Stochastic Terms}\\ \text{white noise}\\ \text{(receiver, jitter \& ISM)}\\ \text{red noise}\\ \text{(spin, ISM)}\end{array}} + \boxed{\begin{array}{c}\textbf{Systematic Errors}\\ \text{planetary ephemeris}\\ \text{time transfer (GPS)}\\ \text{observatory clocks}\\ \text{polarization calibration}\end{array}}$$

$$+ \boxed{\begin{array}{c}\textbf{Gravitational Wave Perturbations}\\ \text{Earth term - Pulsar term}\end{array}} \tag{1}$$

- **The timing noise budget includes:**
  - **spin/torque noise from the neutron star and its magnetosphere;**
  - **pulse-phase jitter from emission regions in the magnetosphere;**
  - **Effects from the interstellar medium (ISM) with strong radio frequency dependences:**
    - **dispersive arrival times (ν^{-2}), diffractive scattering (ν^{-4}), and refractive delays (ν^{-2});**
  - **radiometer causes a TOA error that depends on the signal-to-noise ratio of measured pulses and is the only contribution that depends on telescope size and the system temperature; RFI (radio frequency interference) can also also look like variable white noise**
  - **systematic errors arise from imperfect knowledge of the Earth's location relative to the solar system barycenter and from time transfer of terrestrial time standards using GPS.**

courtesy J.M. Cordes

Short Timescale Model: Precision



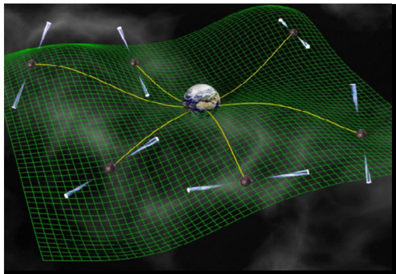
White noise residuals

||

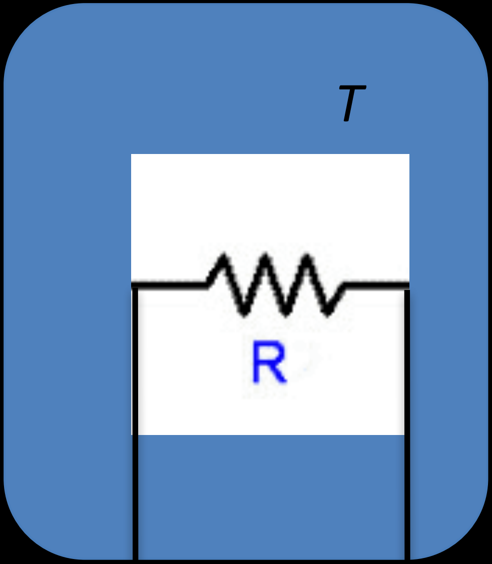
Radiometer noise **Pulse Jitter** **DISS**

$$\sigma_{\mathcal{R}}^2 = \sigma_{\mathrm{S/N}}^2 + \sigma_{\mathrm{J}}^2 + \sigma_{\mathrm{DISS}}^2$$

Courtesy J. Cordes



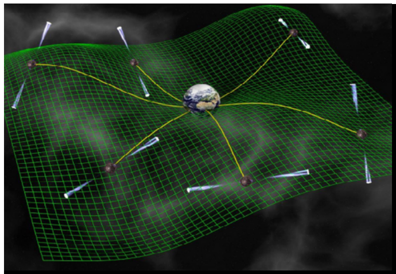
Radio Telescope



Noise Temperature

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

courtesy T. J. W. Lazio



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?

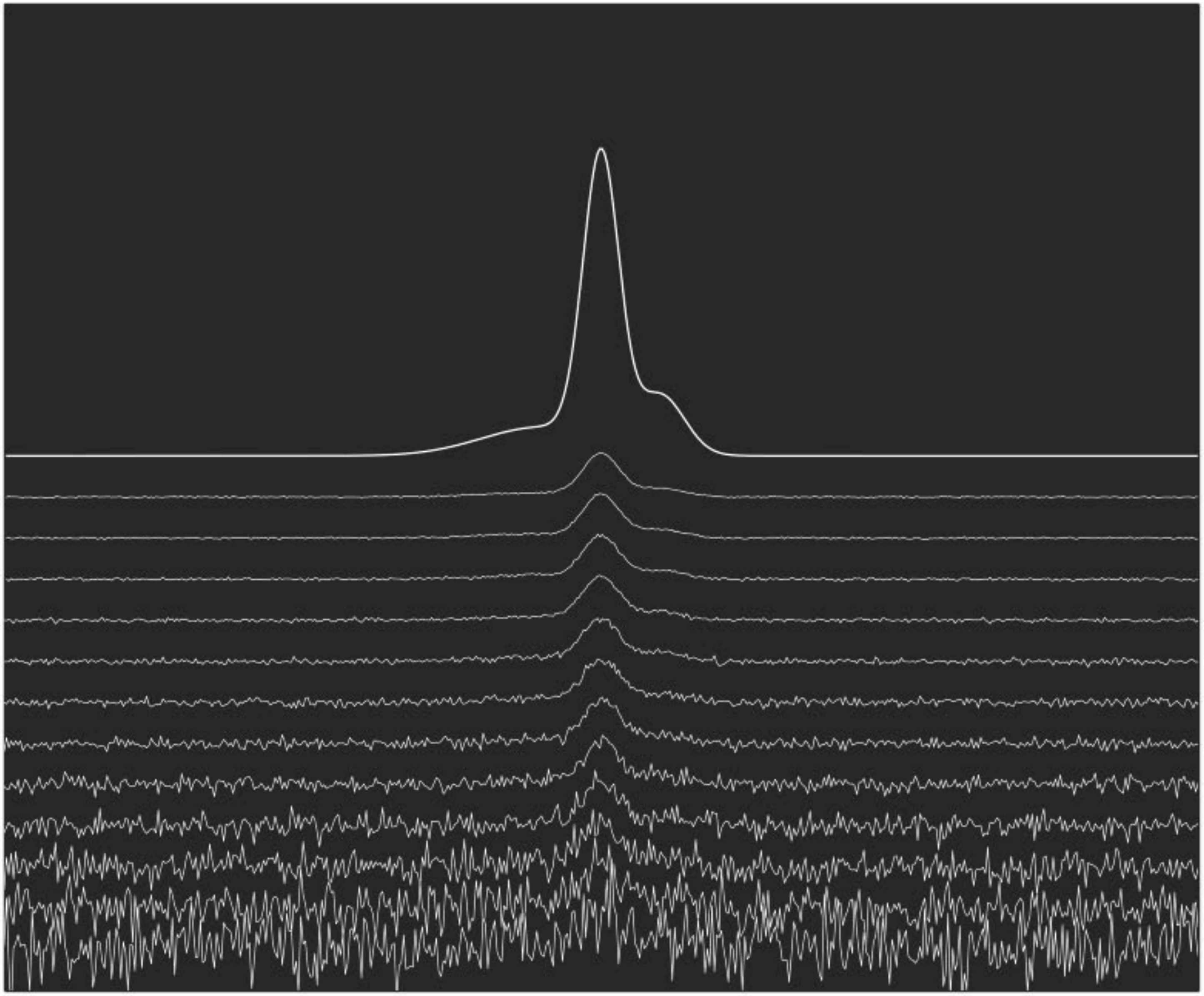
- T_{sys} portion determined by telescope
  $T_{sys} = T_{sky} + T_{spill} + T_{Rx} + \ldots$
- $\Delta\nu$ – processed bandwidth
- A_{eff} – effective area of telescope
- Δt – observation time
  within limits imposed by pulsar or ISM

➢ Improvements benefit both timing *and* survey programs

S ➔ spectral flux density [W/m²/Hz]
1 Jy = 10^{-26} W/m²/Hz

courtesy T. J. W. Lazio

Radiometer Noise

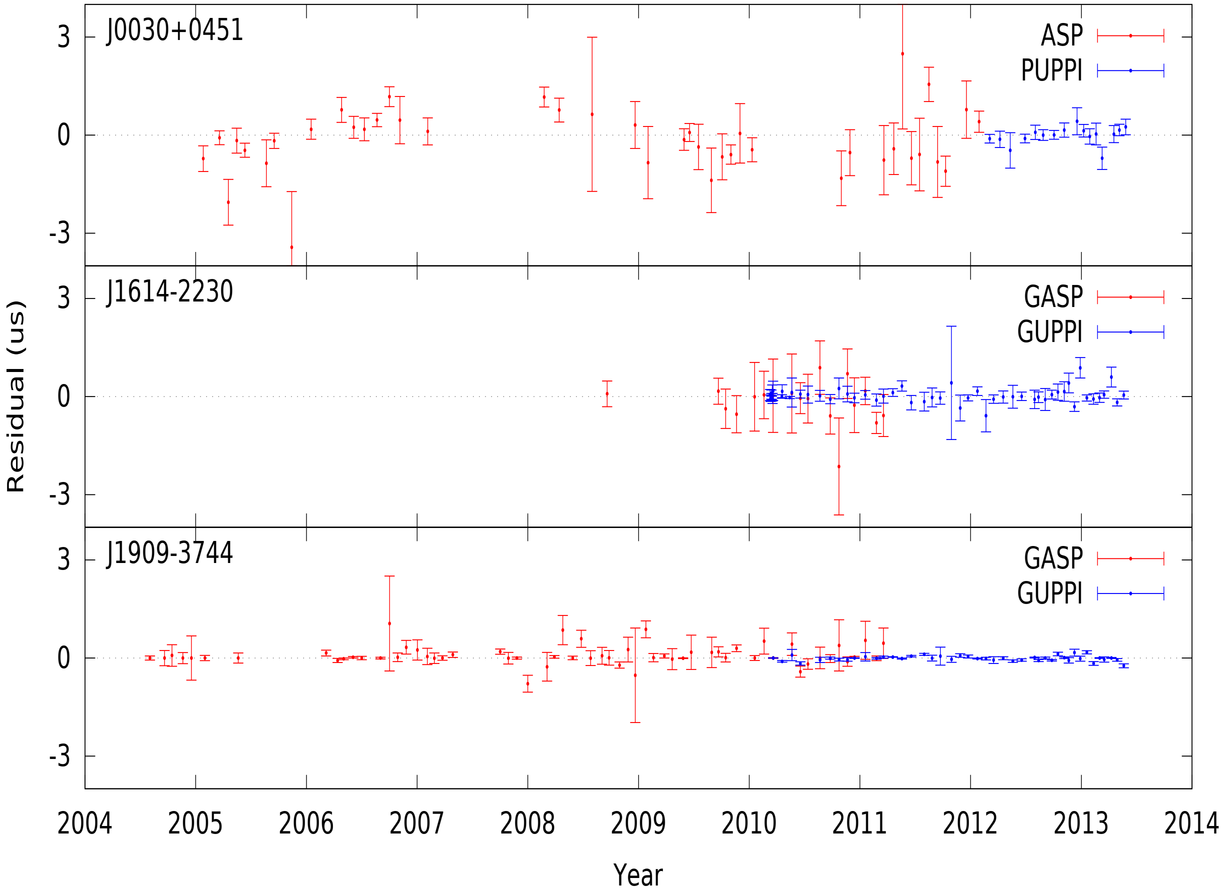


courtesy Michael Lam

$$\sigma_{\mathrm{S/N}} \propto (TB)^{-1/2}$$

Pulsar Timing Arrays: Upgrading the Backend Systems

- Improved receiver systems increased bandwidths from 64 MHz to 800 MHz at Green Bank [2010] and Arecibo [2012]
- Allows for both improvement in the white radiometer noise and better mitigation of the interstellar medium effects



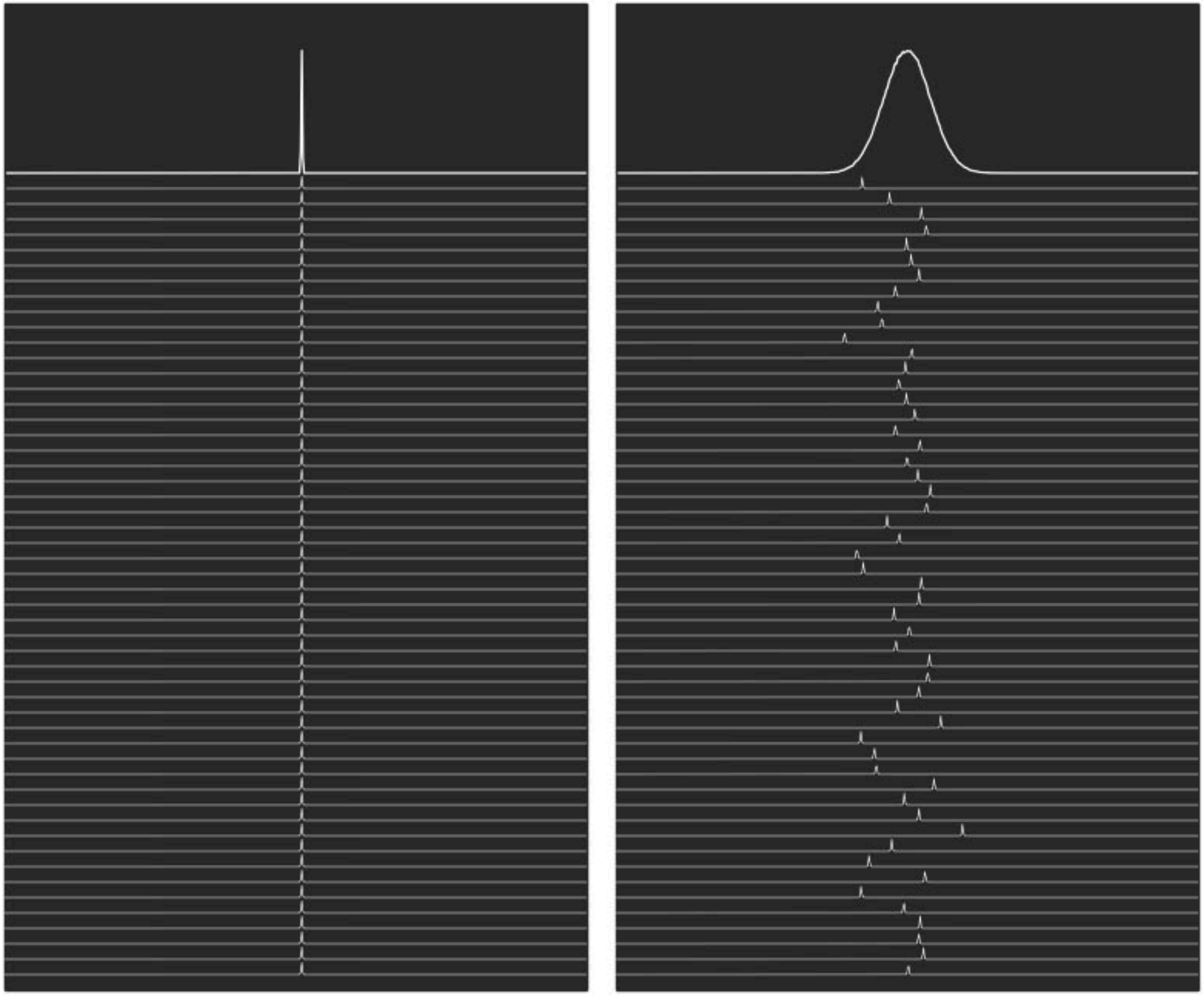
Pulsar J0030+0451: 640 ns -> 163 ns

Pulsar J1614-2230: 500 ns -> 100 ns

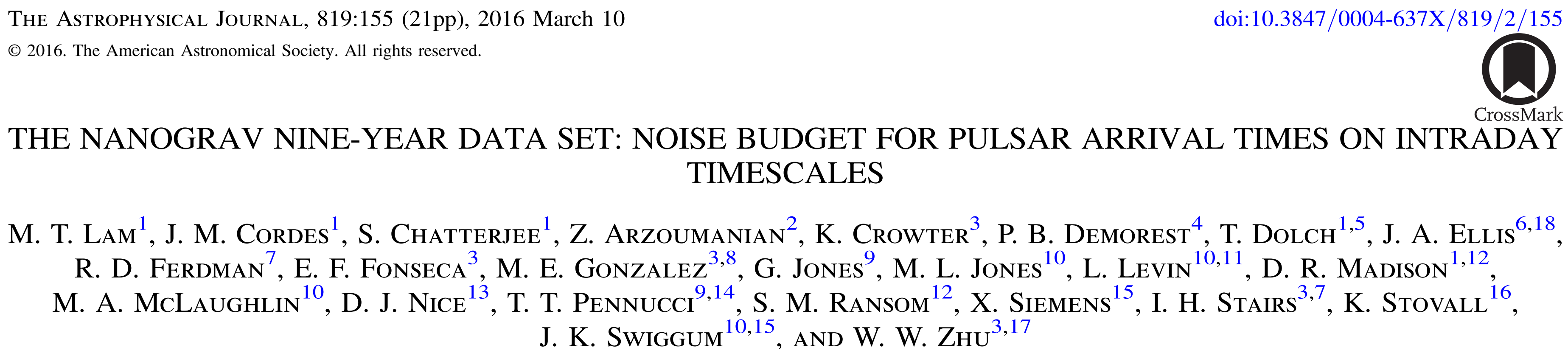
Pulsar J1909-3744: 54 ns -> 36 ns

Courtesy P. Demorest

Jitter Noise



courtesy Michael Lam



The Astrophysical Journal, 819:155 (21pp), 2016 March 10 doi:10.3847/0004-637X/819/2/155

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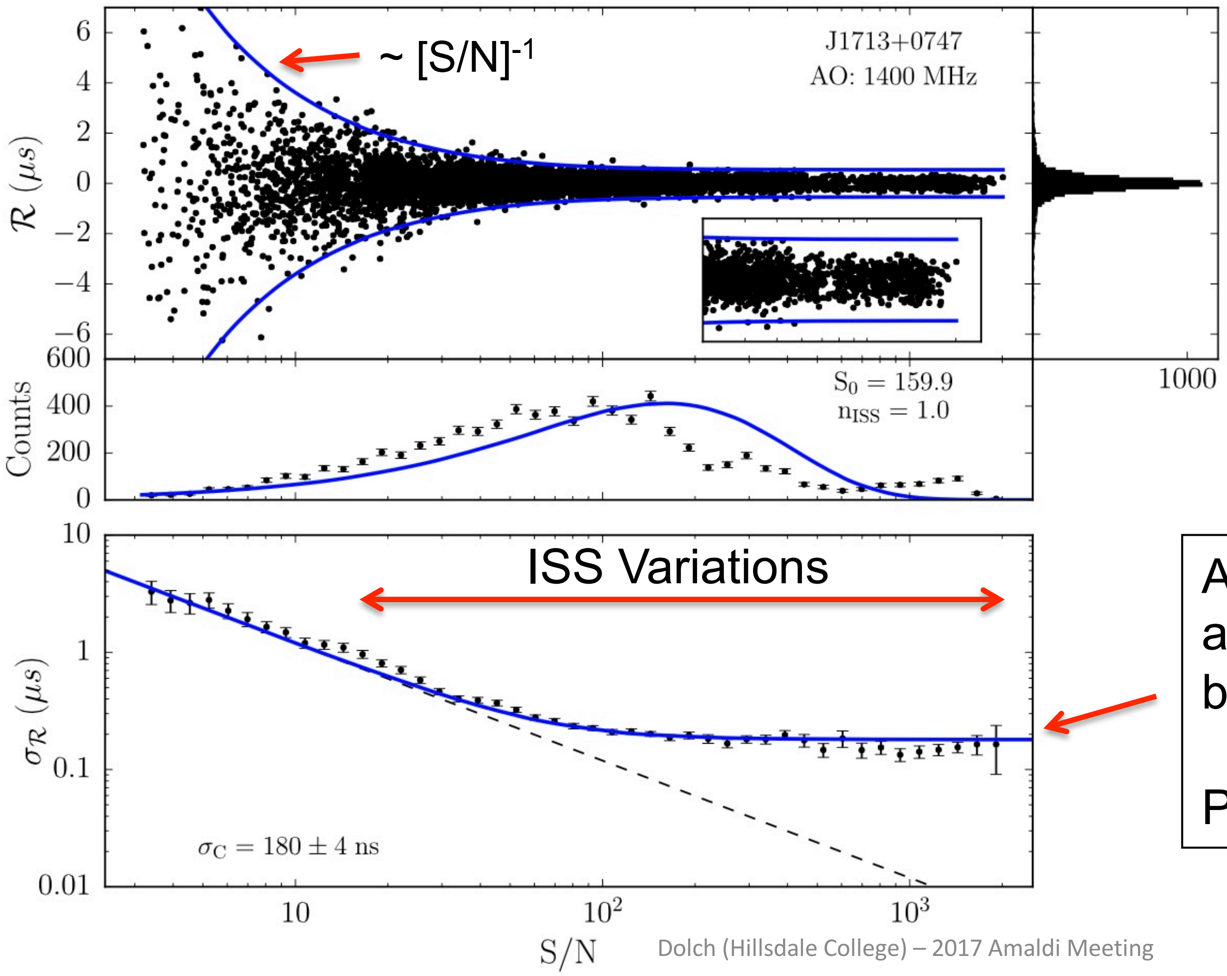
THE NANOGRAV NINE-YEAR DATA SET: NOISE BUDGET FOR PULSAR ARRIVAL TIMES ON INTRADAY TIMESCALES

M. T. Lam[1], J. M. Cordes[1], S. Chatterjee[1], Z. Arzoumanian[2], K. Crowter[3], P. B. Demorest[4], T. Dolch[1,5], J. A. Ellis[6,18], R. D. Ferdman[7], E. F. Fonseca[3], M. E. Gonzalez[3,8], G. Jones[9], M. L. Jones[10], L. Levin[10,11], D. R. Madison[1,12], M. A. McLaughlin[10], D. J. Nice[13], T. T. Pennucci[9,14], S. M. Ransom[12], X. Siemens[15], I. H. Stairs[3,7], K. Stovall[16], J. K. Swiggum[10,15], and W. W. Zhu[3,17]



See also Caballero et al. 2016

Above S/N > 100 for 2 min averages, RMS residual becomes independent of S/N

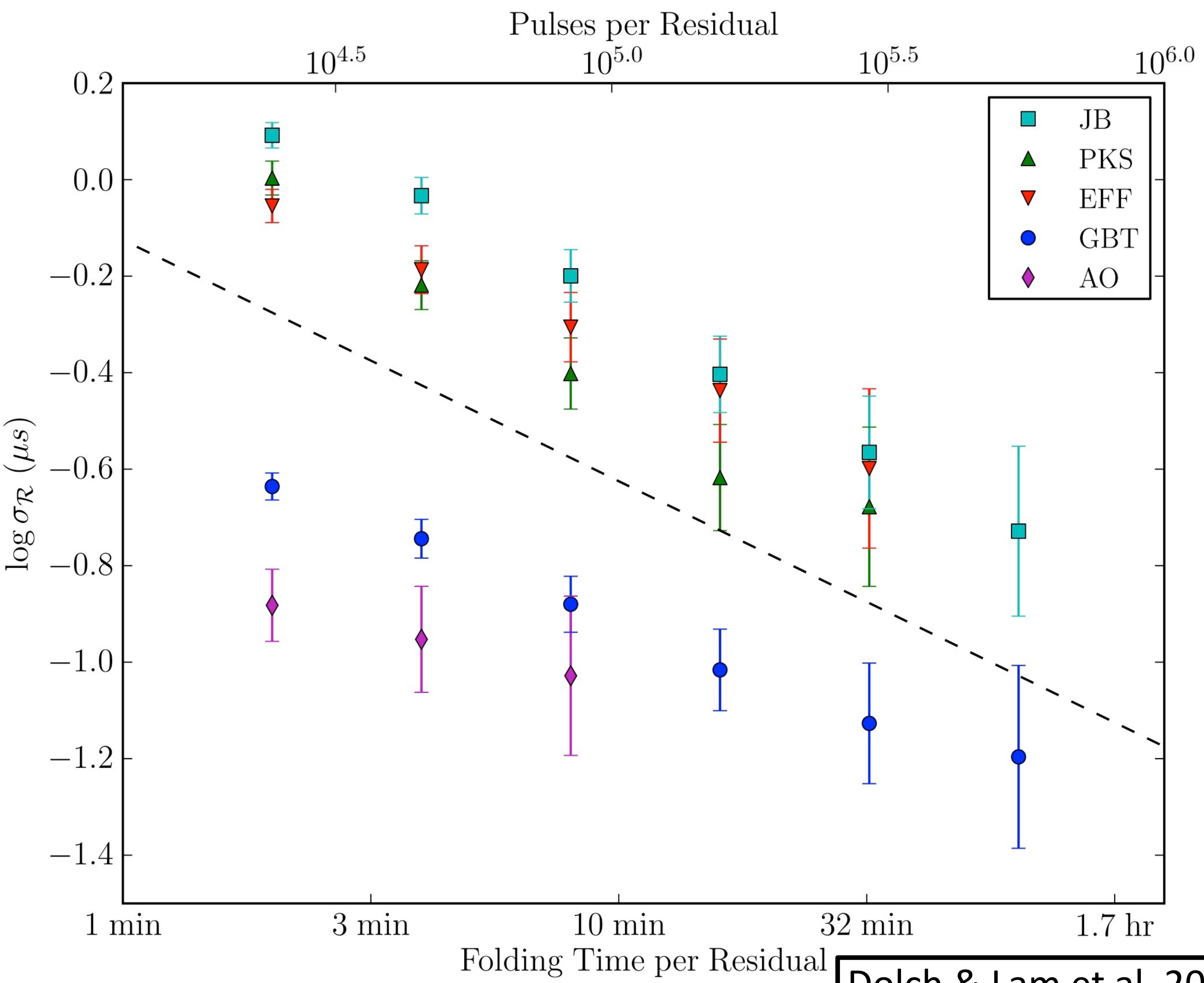
Pulse jitter

The J1713+0747 24hr Global Campaign

The J1713+0747 24hr Global Campaign

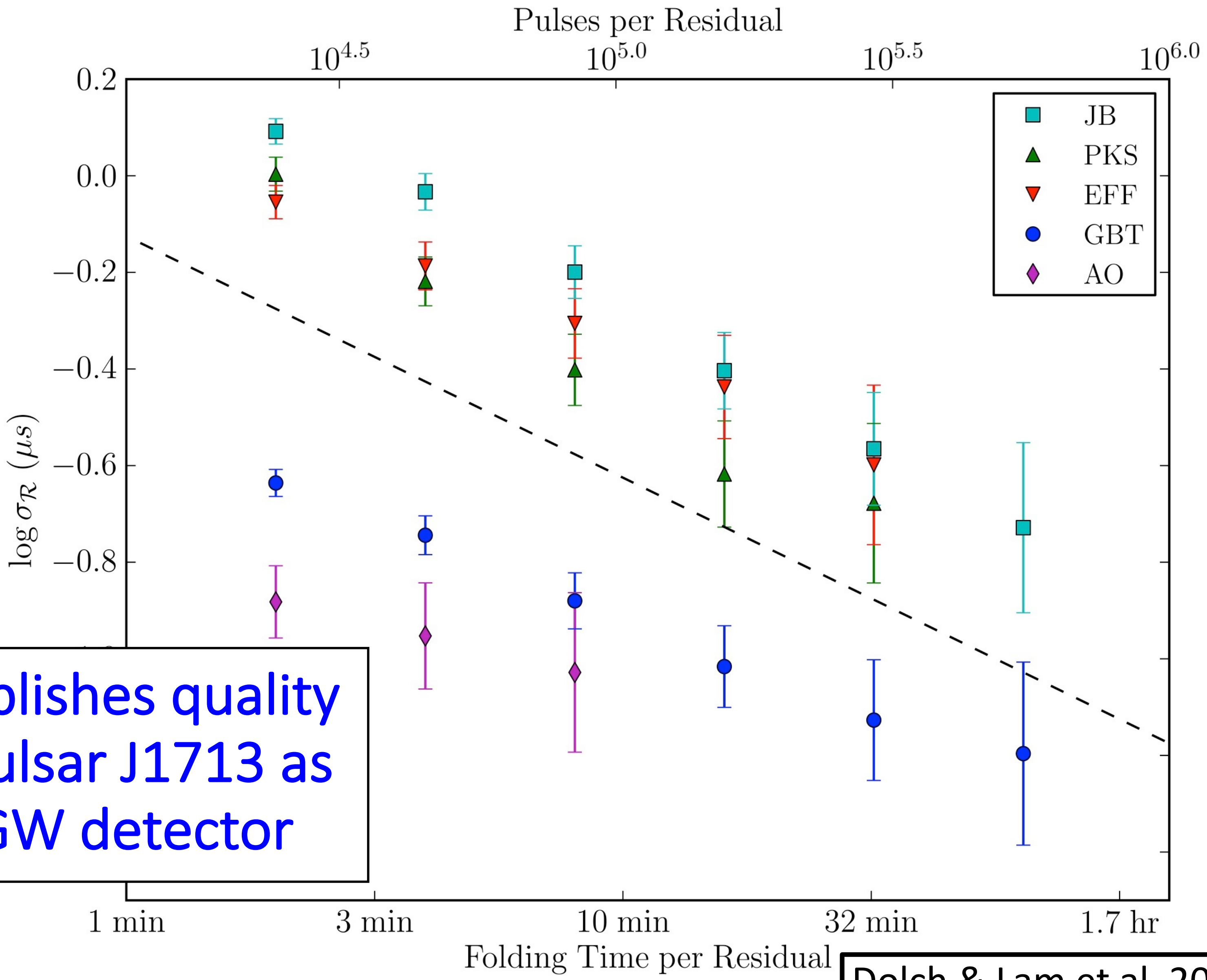
PSR J1713+0747’s times-of-arrival are amongst the highest precision for GW detection

How Timing Accuracy Improves with # of Pulses



Dolch & Lam et al. 2014 ApJ 794, 21

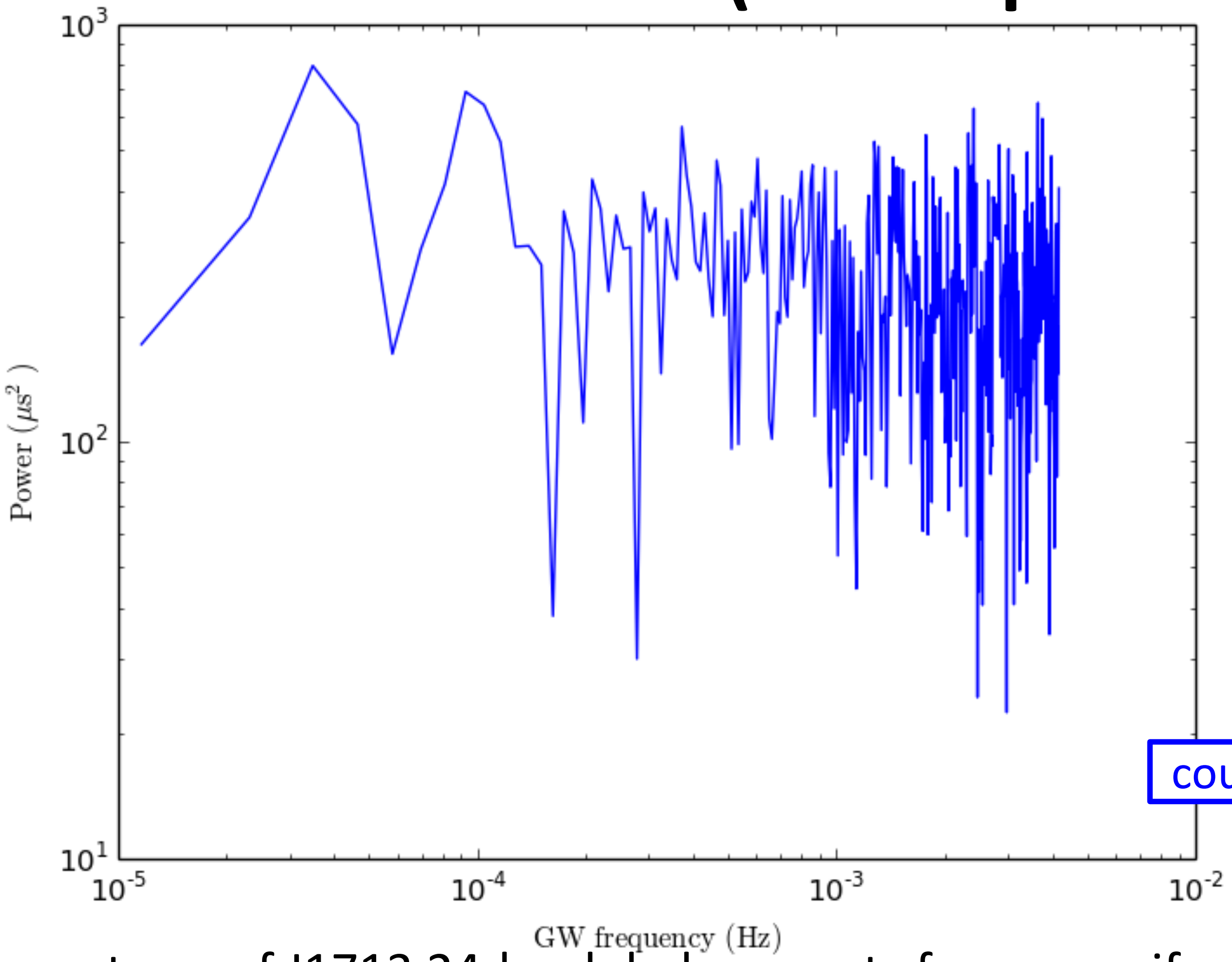
How Timing Accuracy Improves with # of Pulses



establishes quality of pulsar J1713 as a GW detector

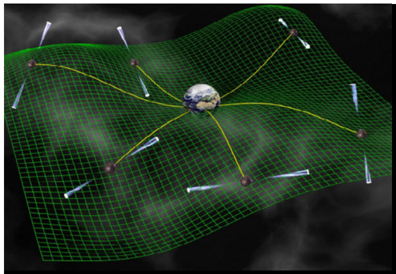
Dolch & Lam et al. 2014 ApJ 794, 21

J1713 24-Hr Global: power spectrum of the broadband residuals (noise spectrum)



courtesy Michael Lam

- power spectrum of J1713 24-hr global accounts for non-uniform sampling and non-uniform weighting of timing residual RMS values (uses CLEAN algorithm)
- no evidence of any significant deviations from white noise

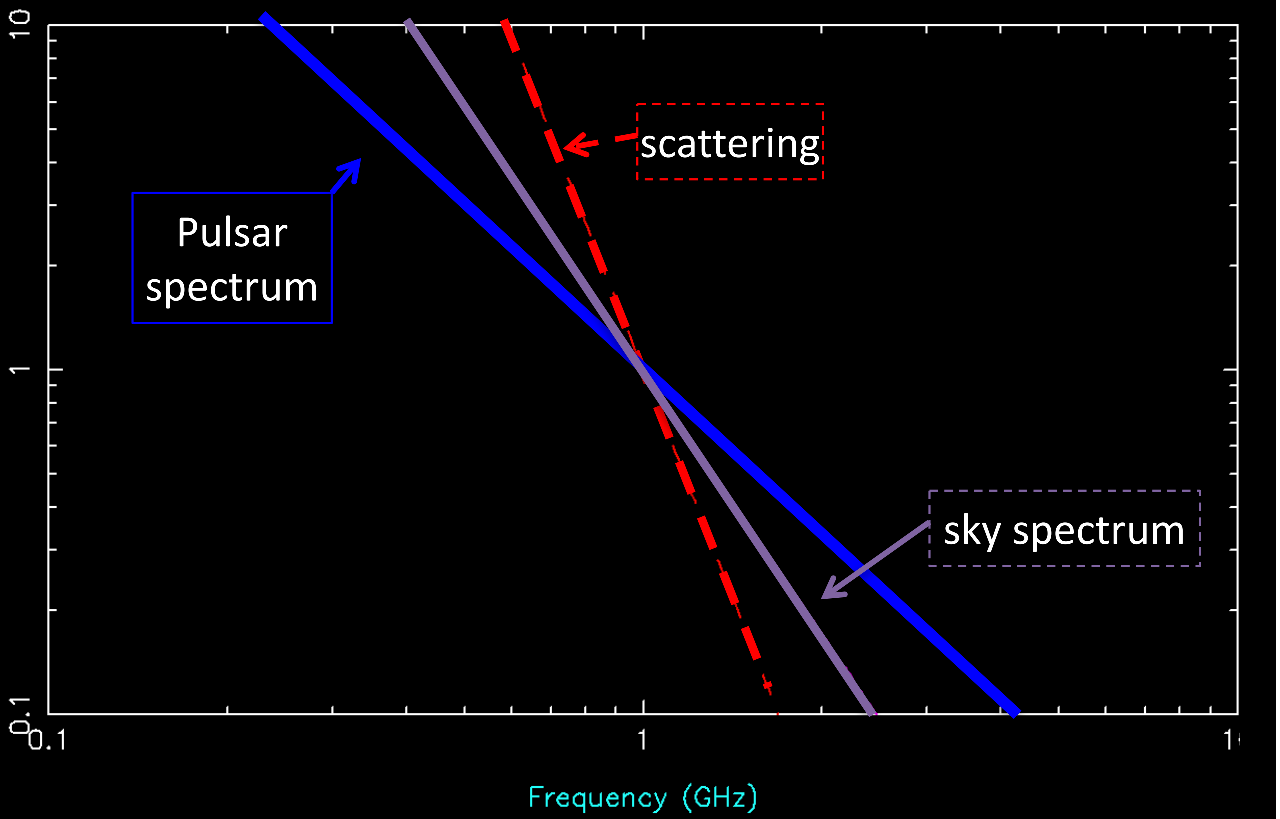


Pulsar Observations

Observational frequency determined by balancing

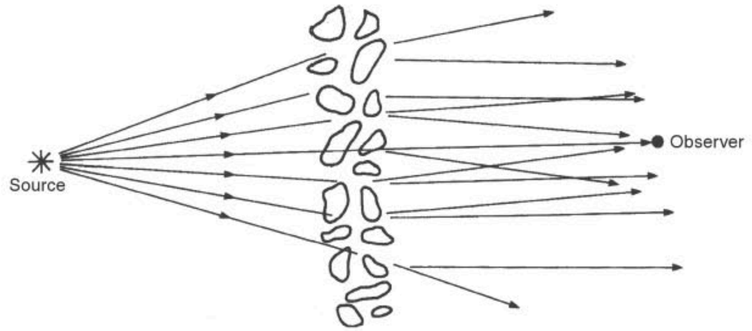
- pulsar spectrum vs.
- sky spectrum vs.
- scattering

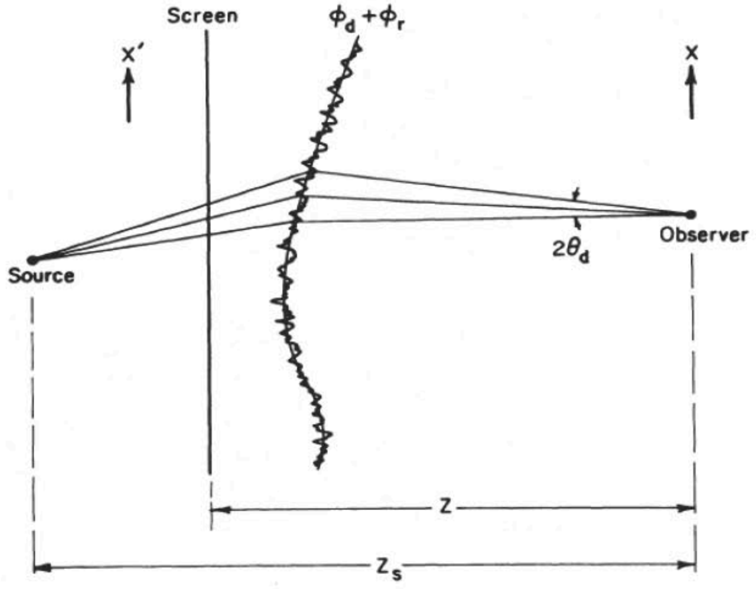
Typically about 1 GHz

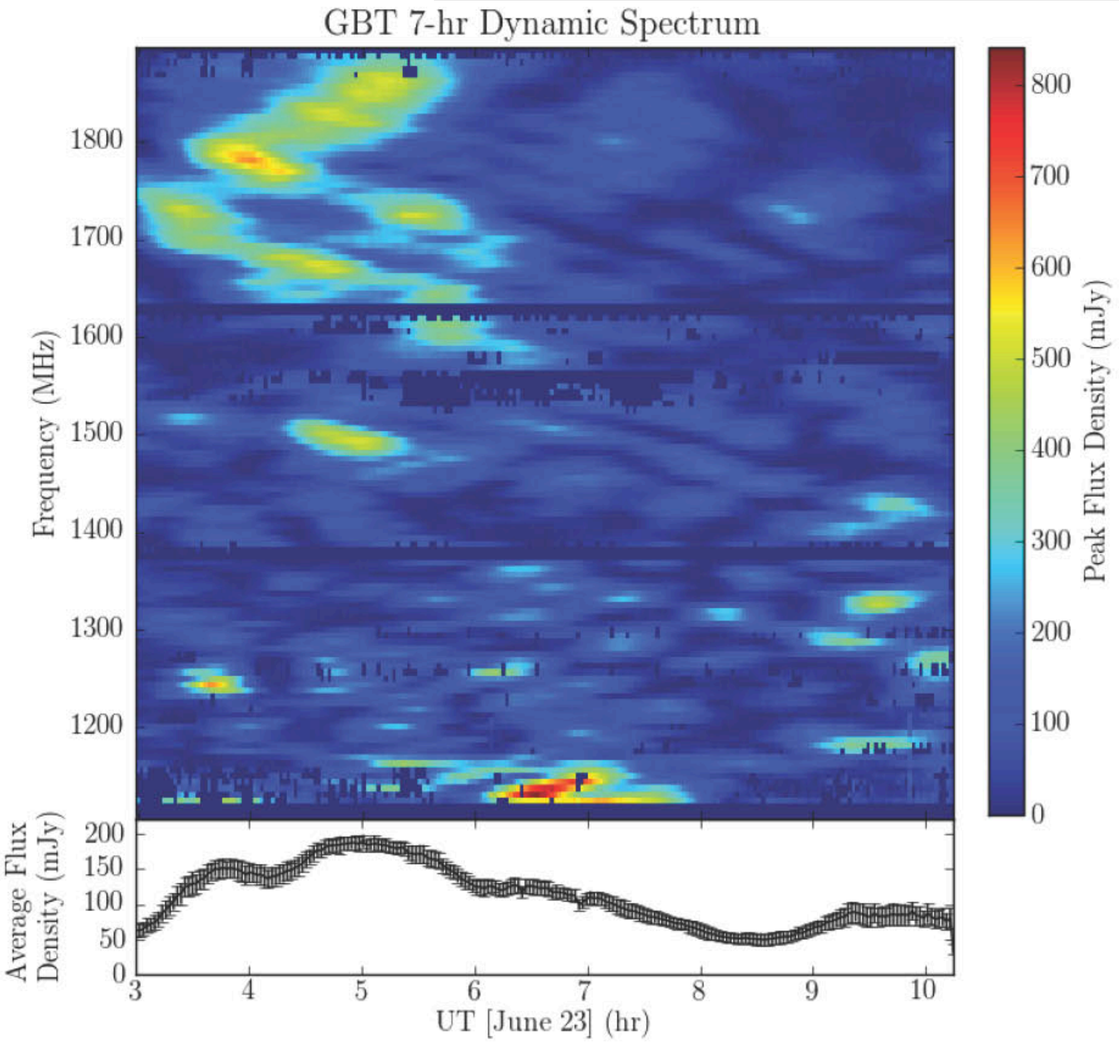


Finite Scintle Effect/Scintillation Noise

Dolch & Lam et al. 2014 ApJ 794, 21







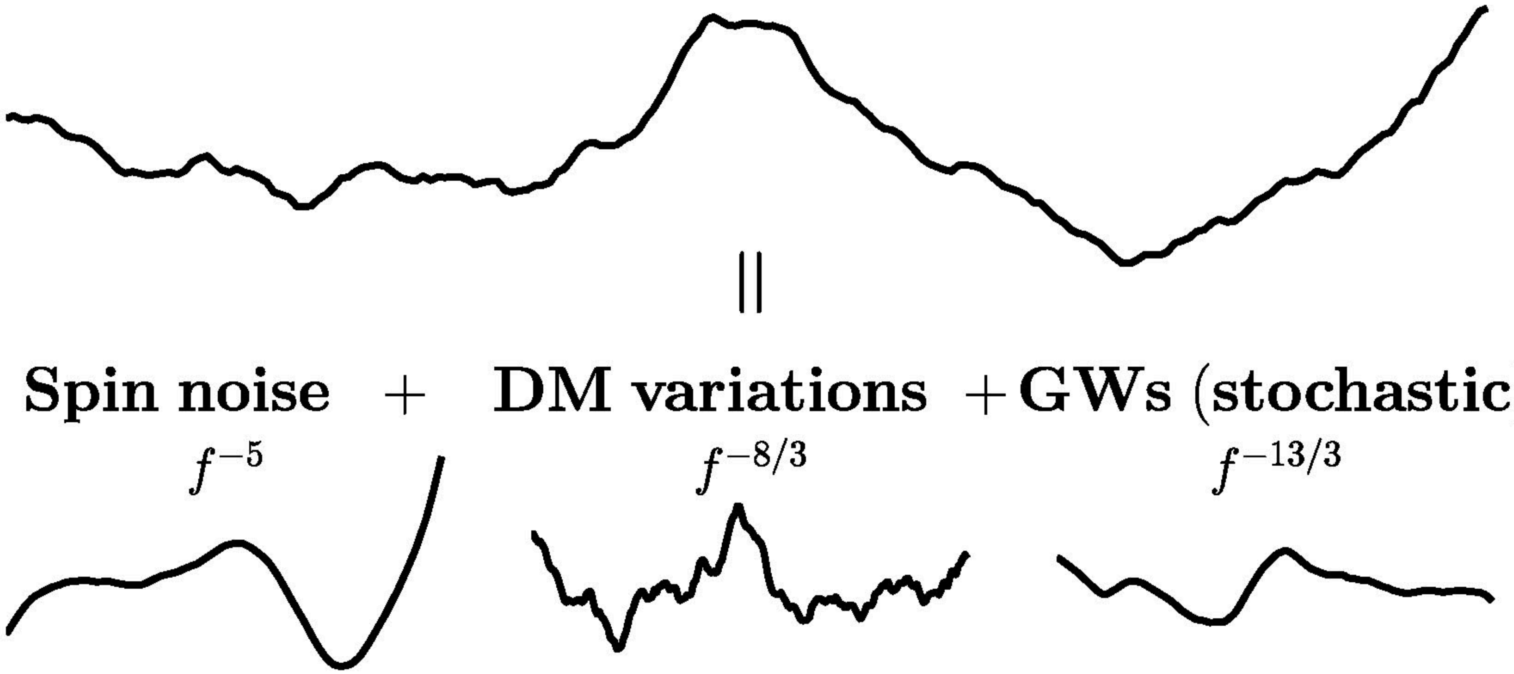
$$\sigma_{\rm DISS} \propto N_{\rm DISS}^{-1/2} \sim (TB)^{-1/2}$$

TL: Lorimer & Kramer 2005
BL: Cordes et al 1986
R Data: NANOGrav/IPTA

courtesy Michael Lam

Long Timescale Model: Accuracy

Red noise residuals



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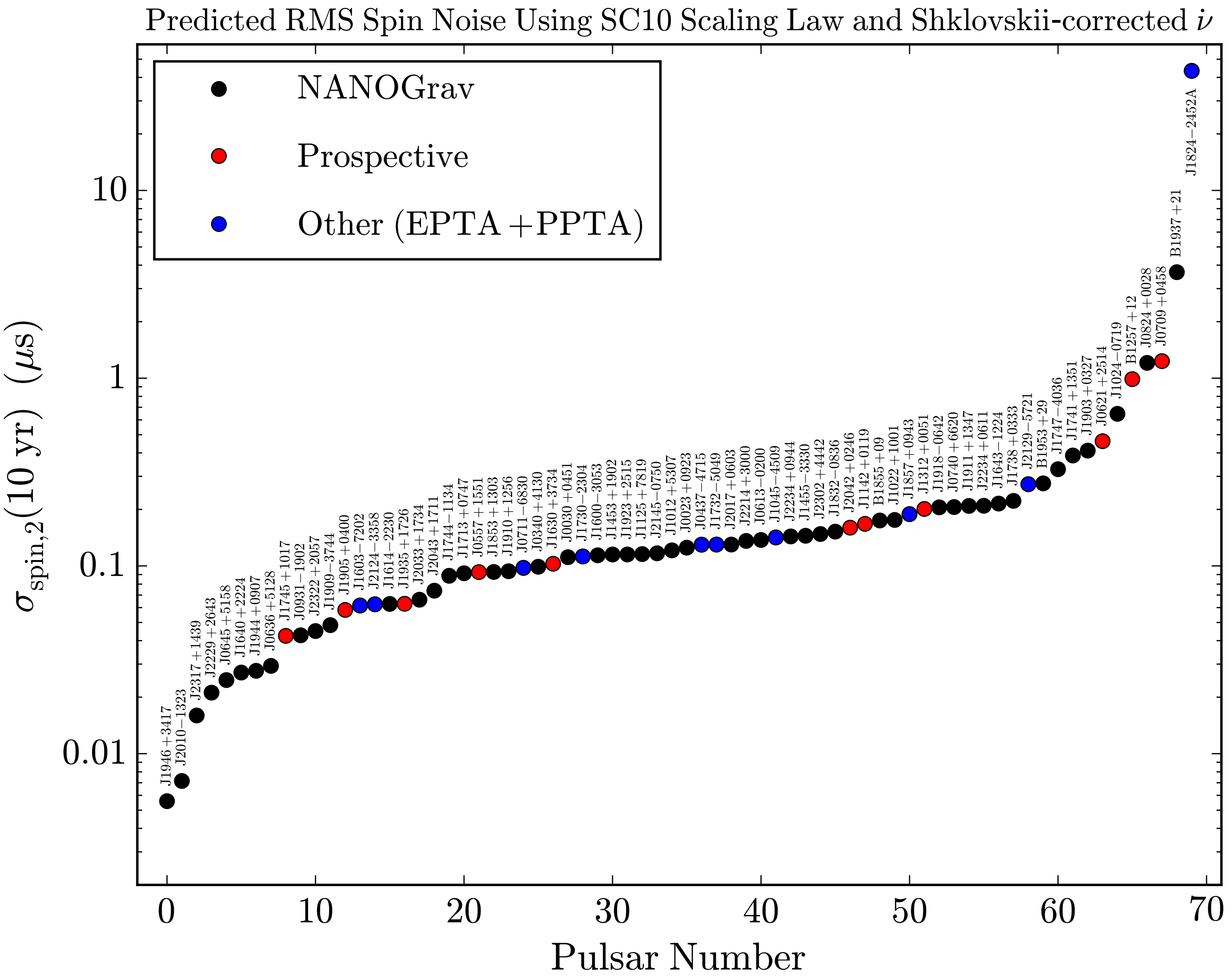
Spin noise + **DM variations** + **GWs (stochastic)**

f^{-5} $f^{-8/3}$ $f^{-13/3}$

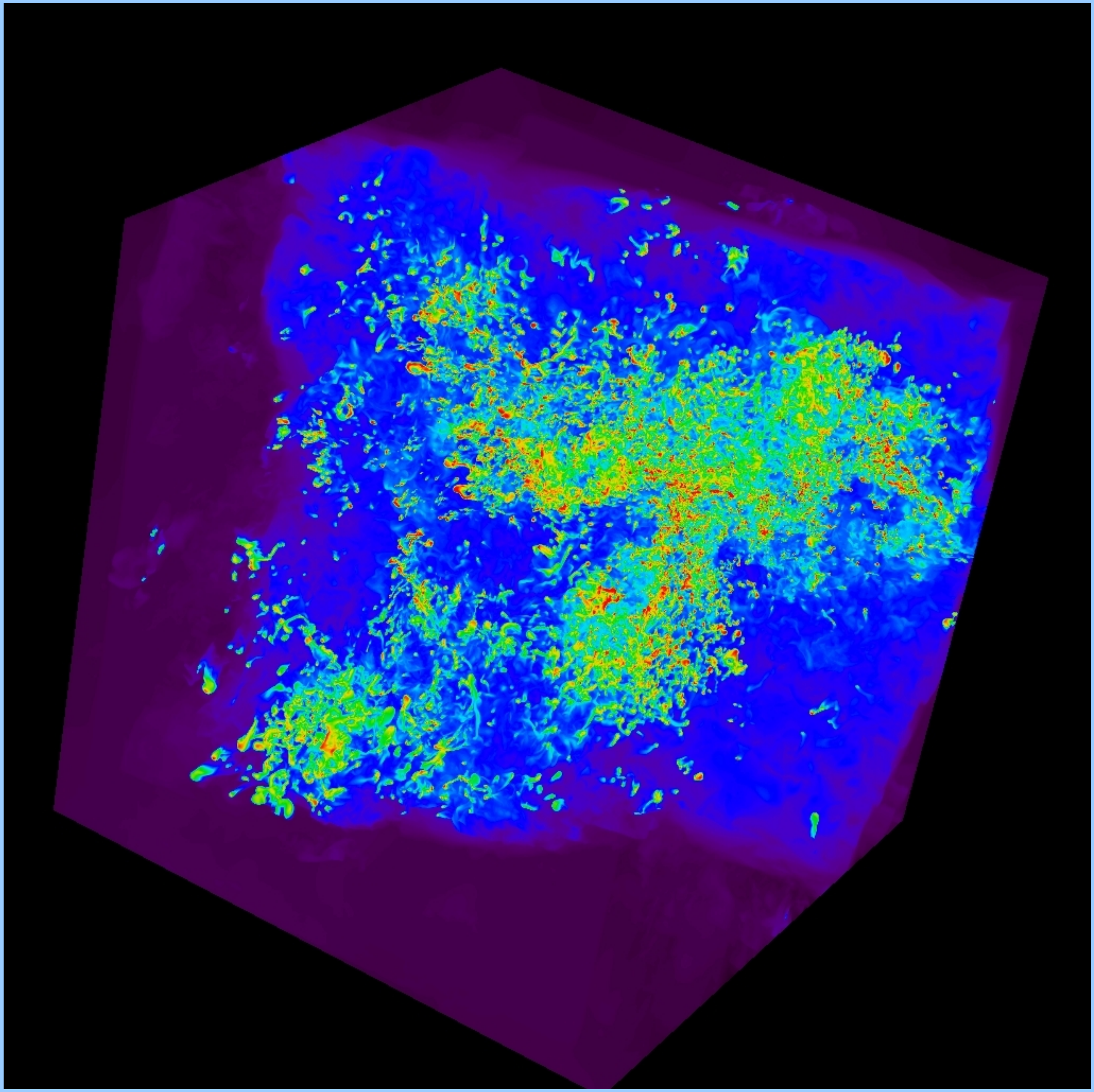
$$\sigma^2_{\mathcal{R}} = \sigma^2_{\rm spin} + \sigma^2_{\delta\rm DM} + \sigma^2_{\rm GW}$$

Courtesy J. Cordes



- Predicted RMS spin noise from the Shannon & Cordes (2010) scaling law after a second-order fit to time series of length T = 10 yr. The points are for the nominal parameter values in Eq. 7. These estimates and the ranking of pulsars are highly provisional and will be superseded by ongoing analyses.

courtesy J.M. Cordes



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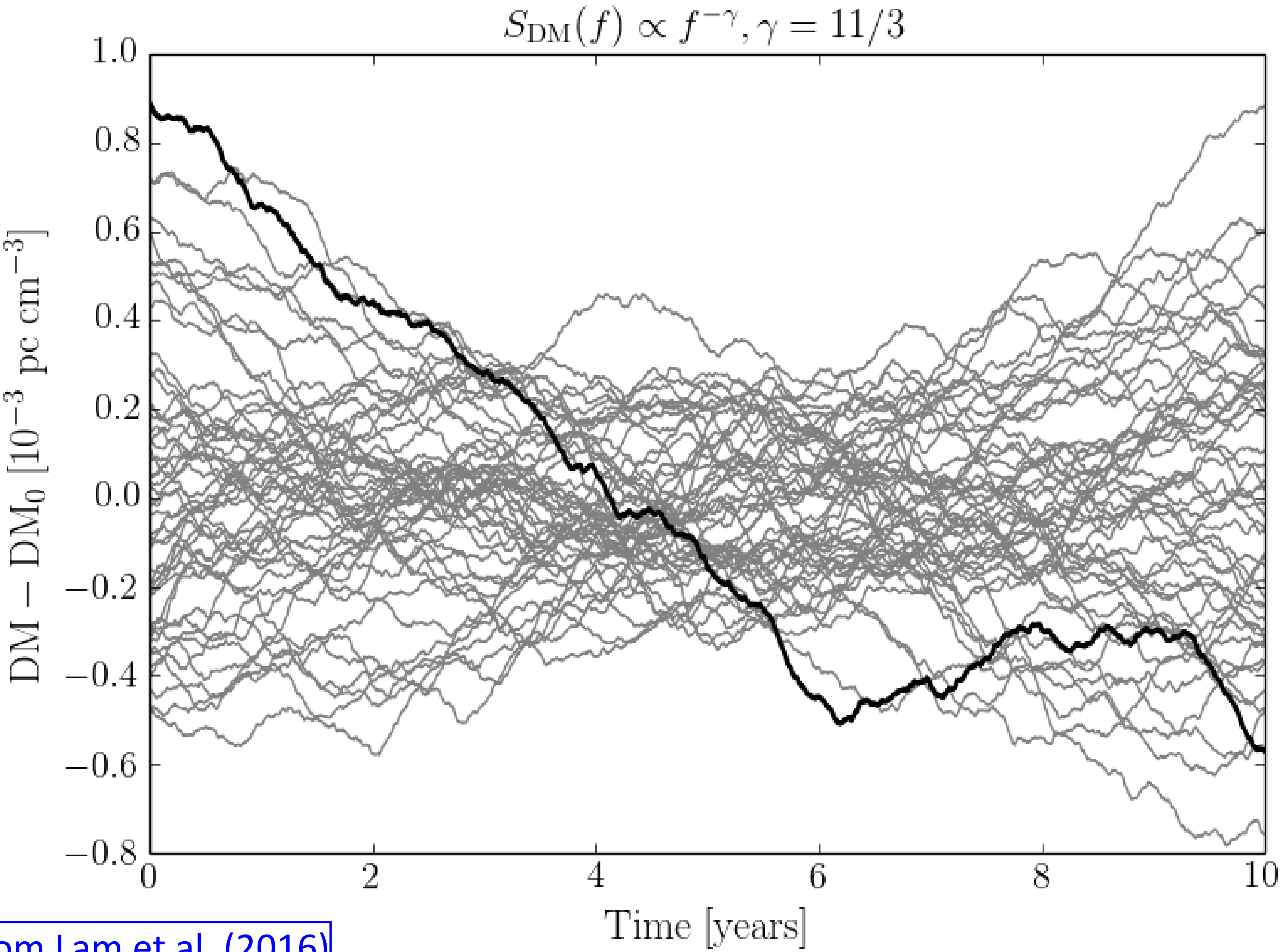
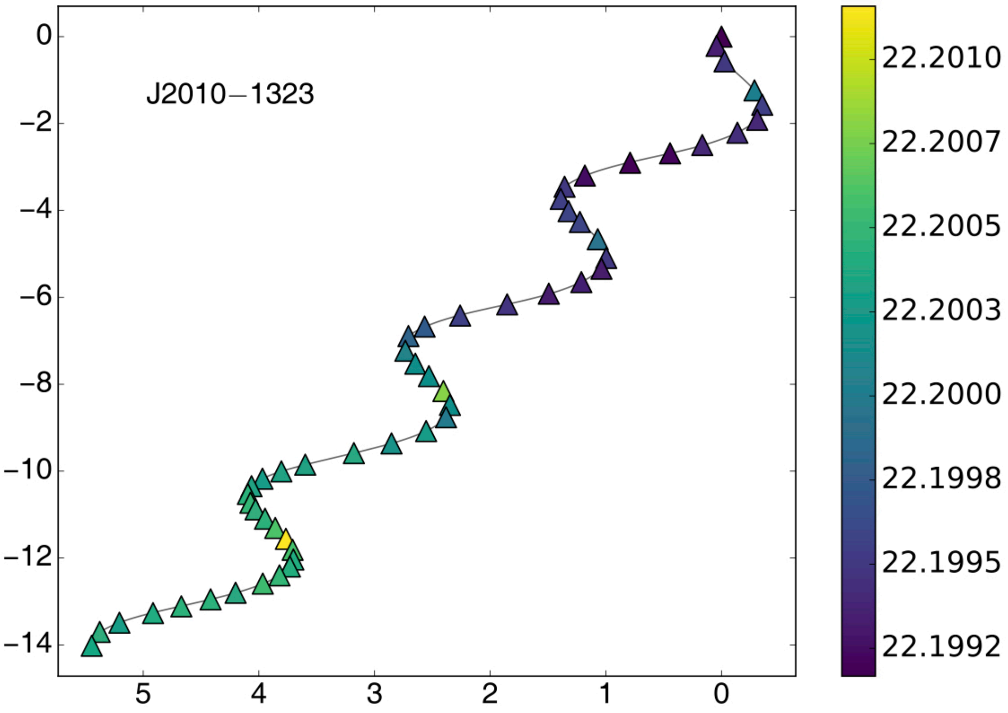
DM(t) Simulations

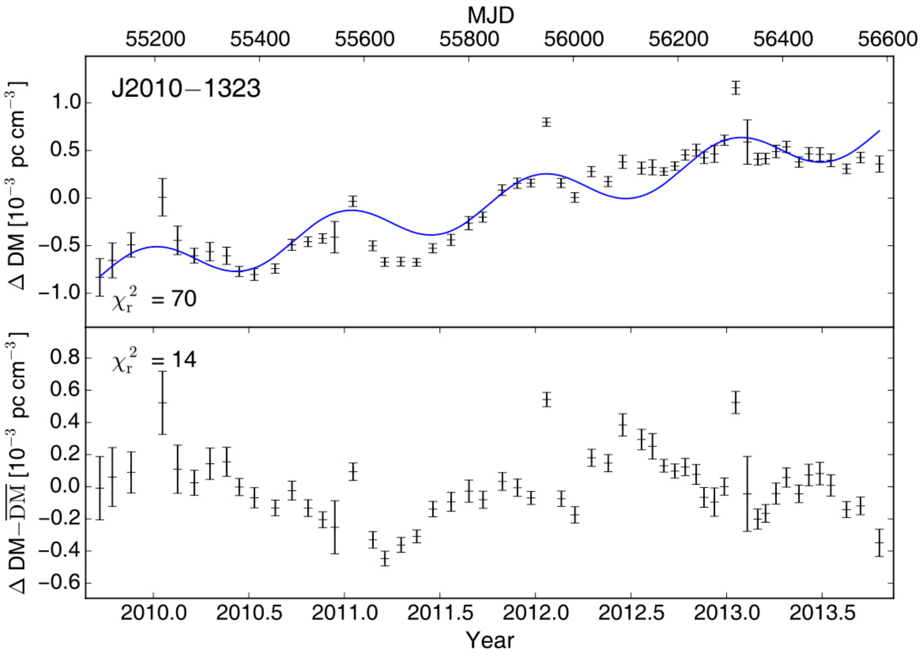


from Lam et al. (2016)

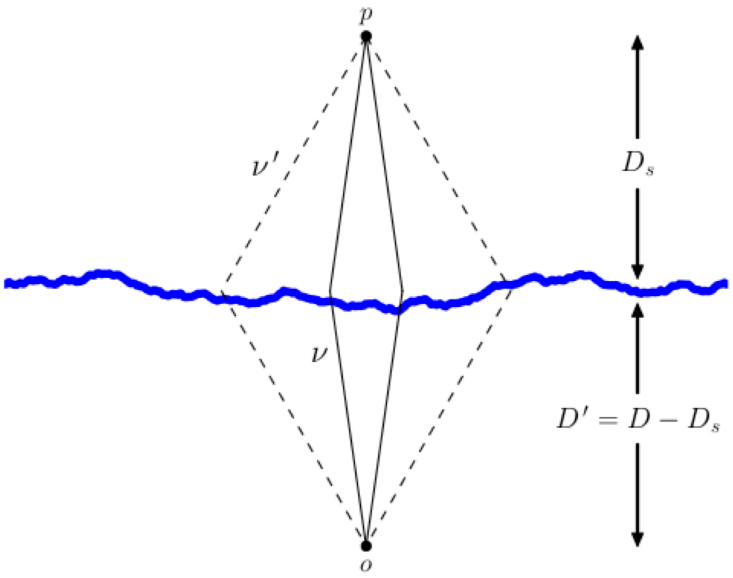
DM Variations have both Deterministic and Stochastic terms

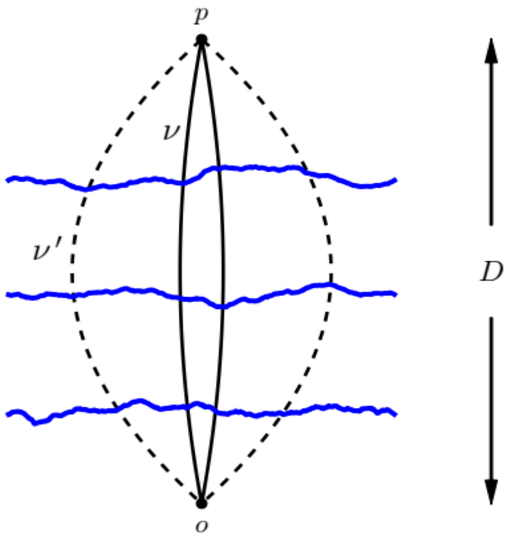
from Jones et al. (2017)





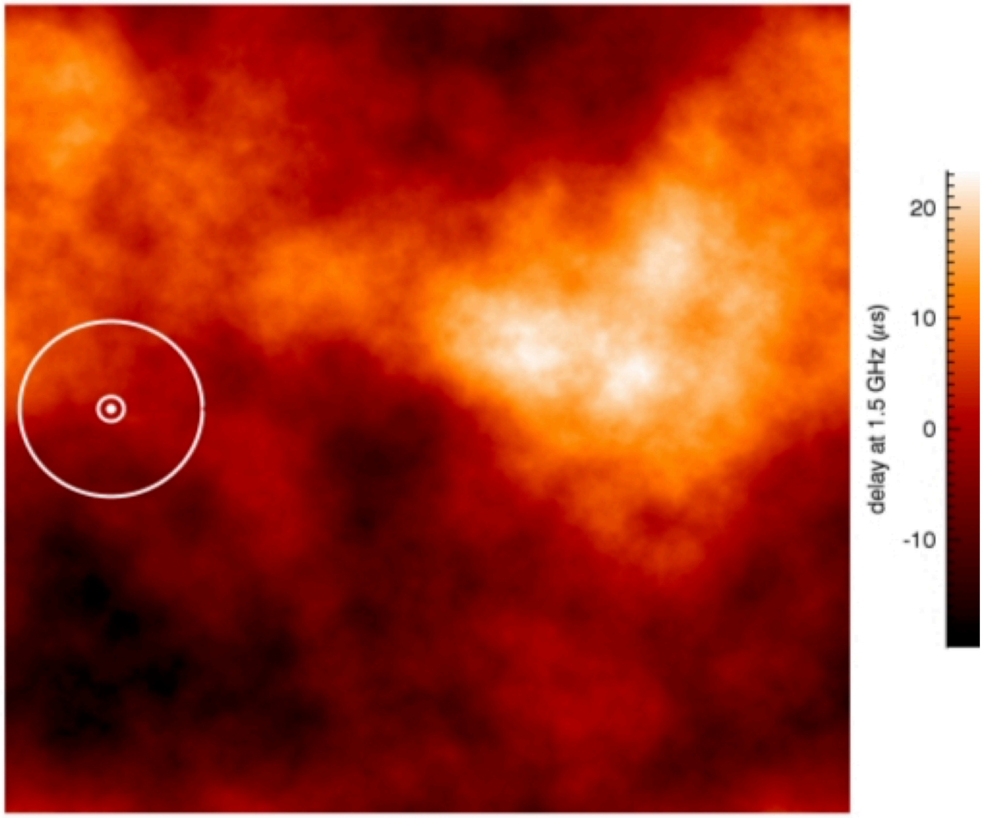
…these can be modeled and measured, so that IISM effects can be mitigated from our data (which is the reason we observe pulsars at high and low radio frequencies



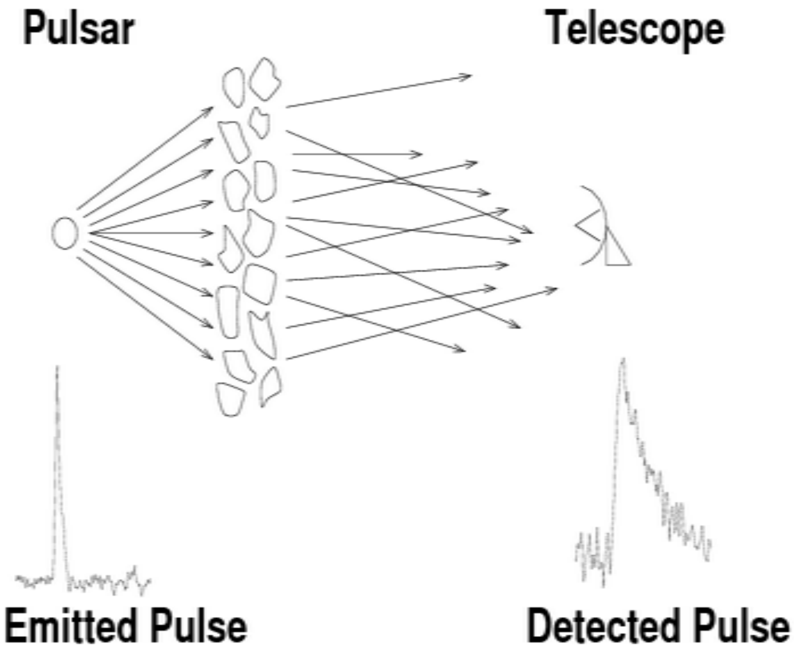


Courtesy J. M. Cordes,
Dan Stinebring

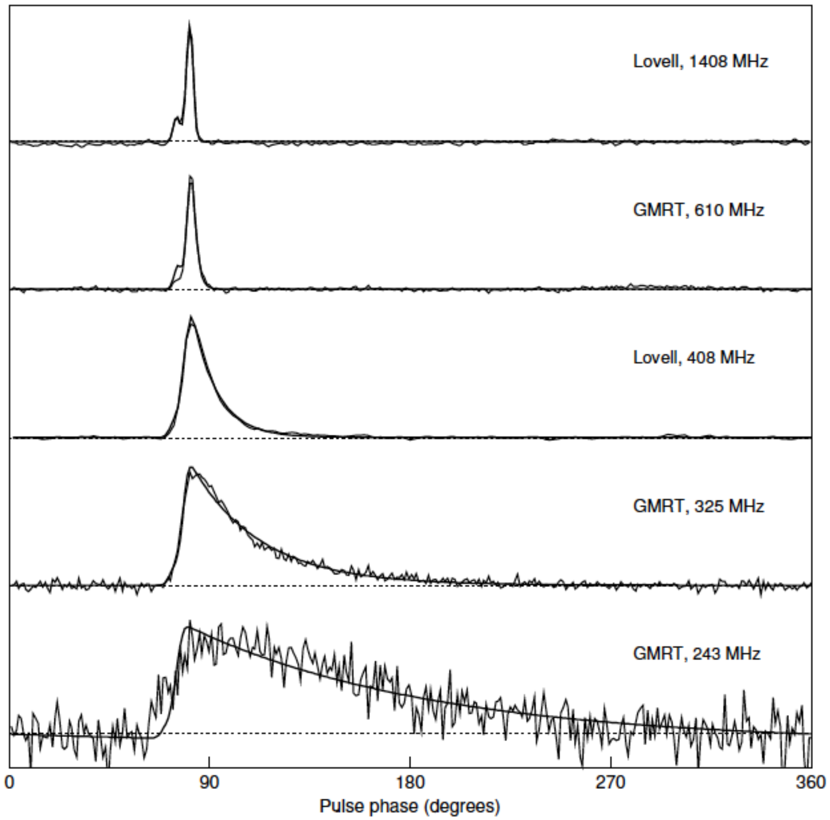
Kolmogorov phase screen. m_B^2 =850. frequencies: 150. to 1500.seed 15



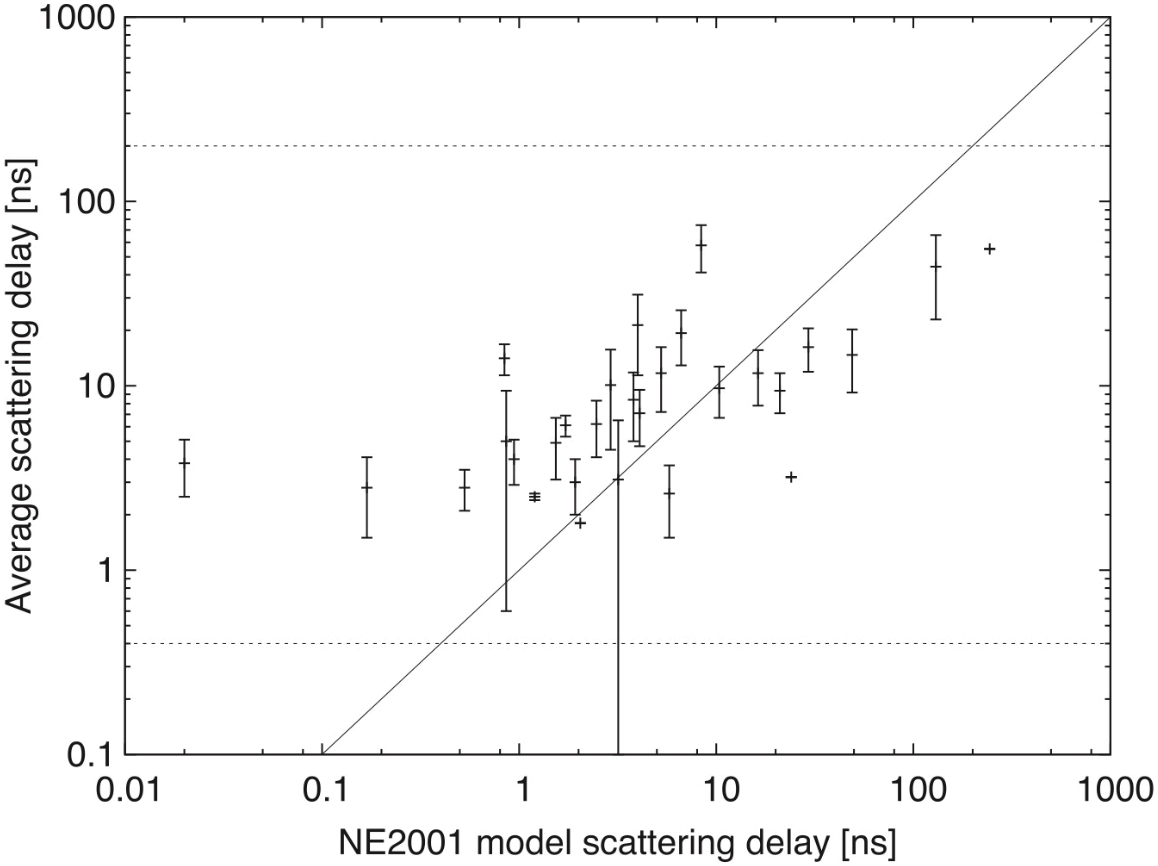
- In future, wide-bandwidth receivers, we may need to account for frequency-dependent dispersion measures
- This effect modeled in Cordes, Shannon, and Stinebring (2016), and can be mitigated



Lorimer, Living Reviews in Relativity



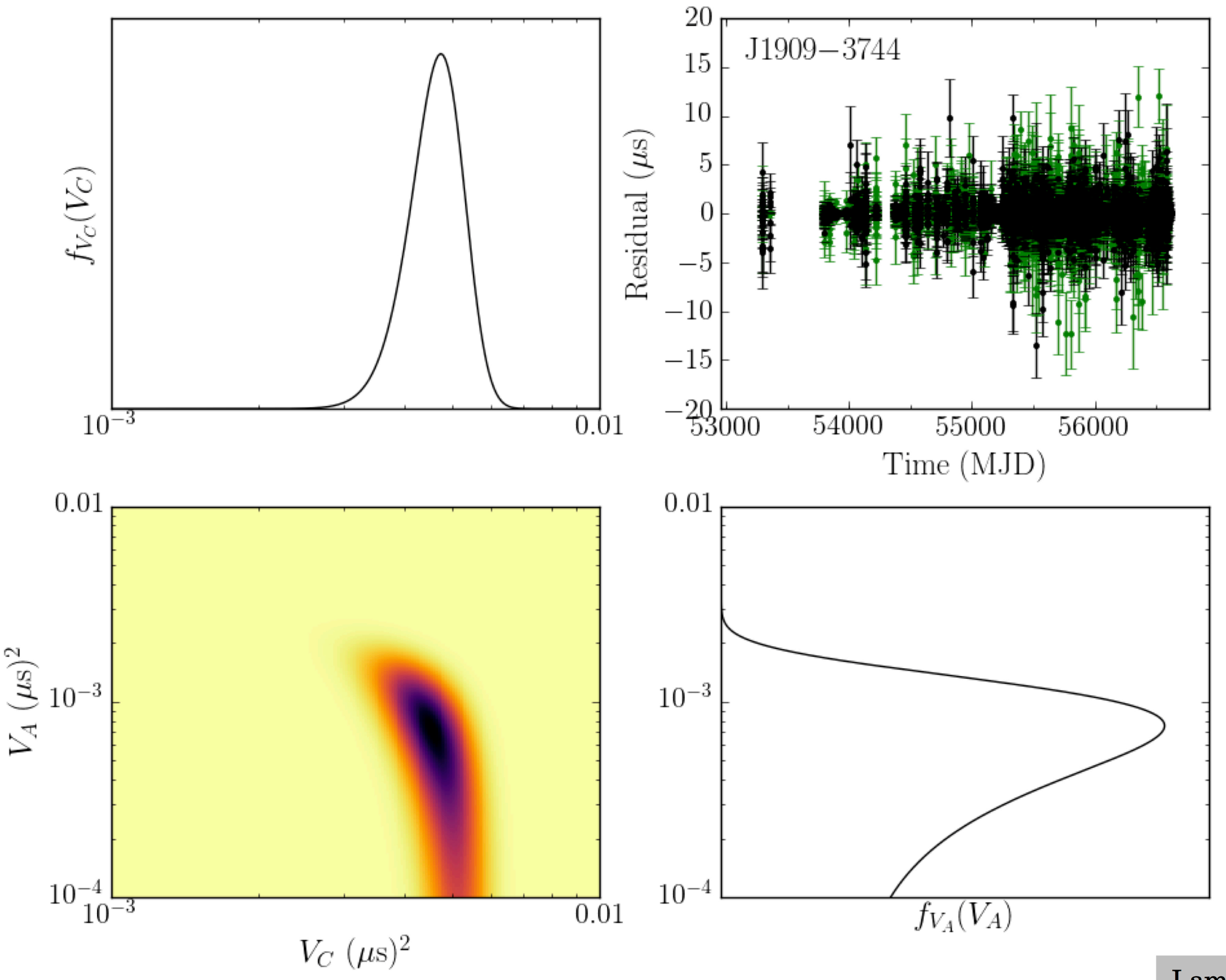
From Lorimer & Kramer, 2005, “Handbook of Pulsar Astronomy”



Scattering delays in NANOGrav 9-year Dataset (Levin et al. 2016)

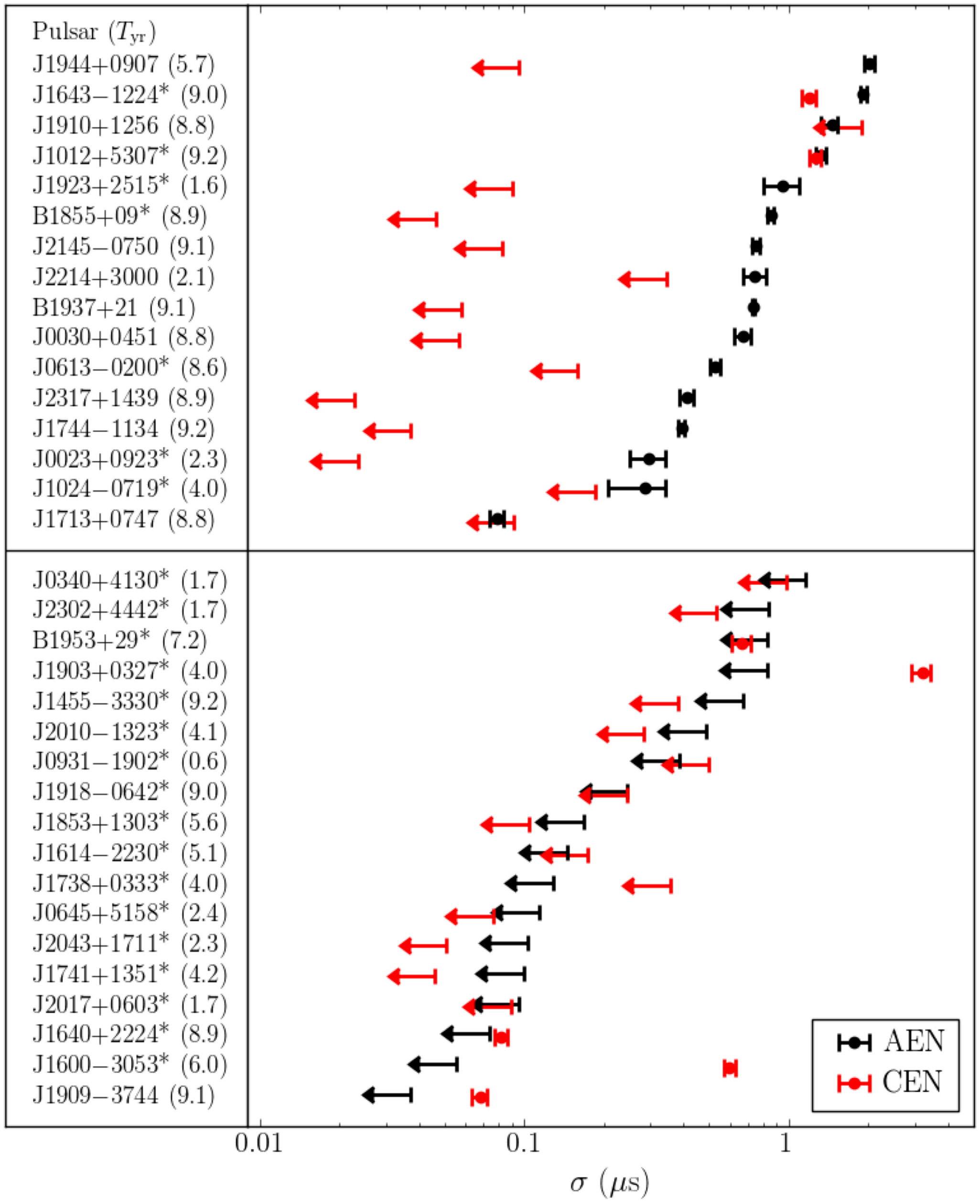
While important to continuously monitor, currently scattering delays are on the order 10s of ns, less of an issue than ephemeris uncertainties

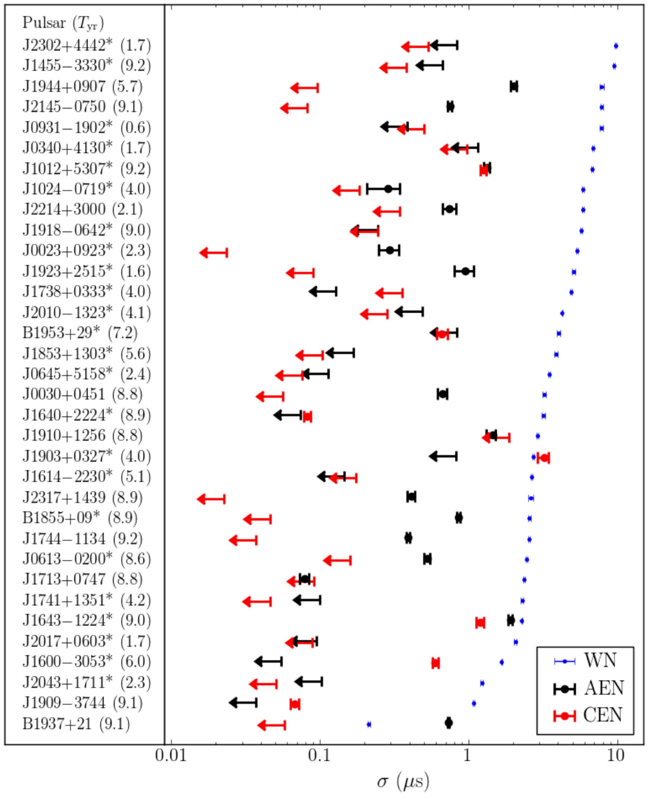
Achromatic/Chromatic Noise



Lam et al. 2017

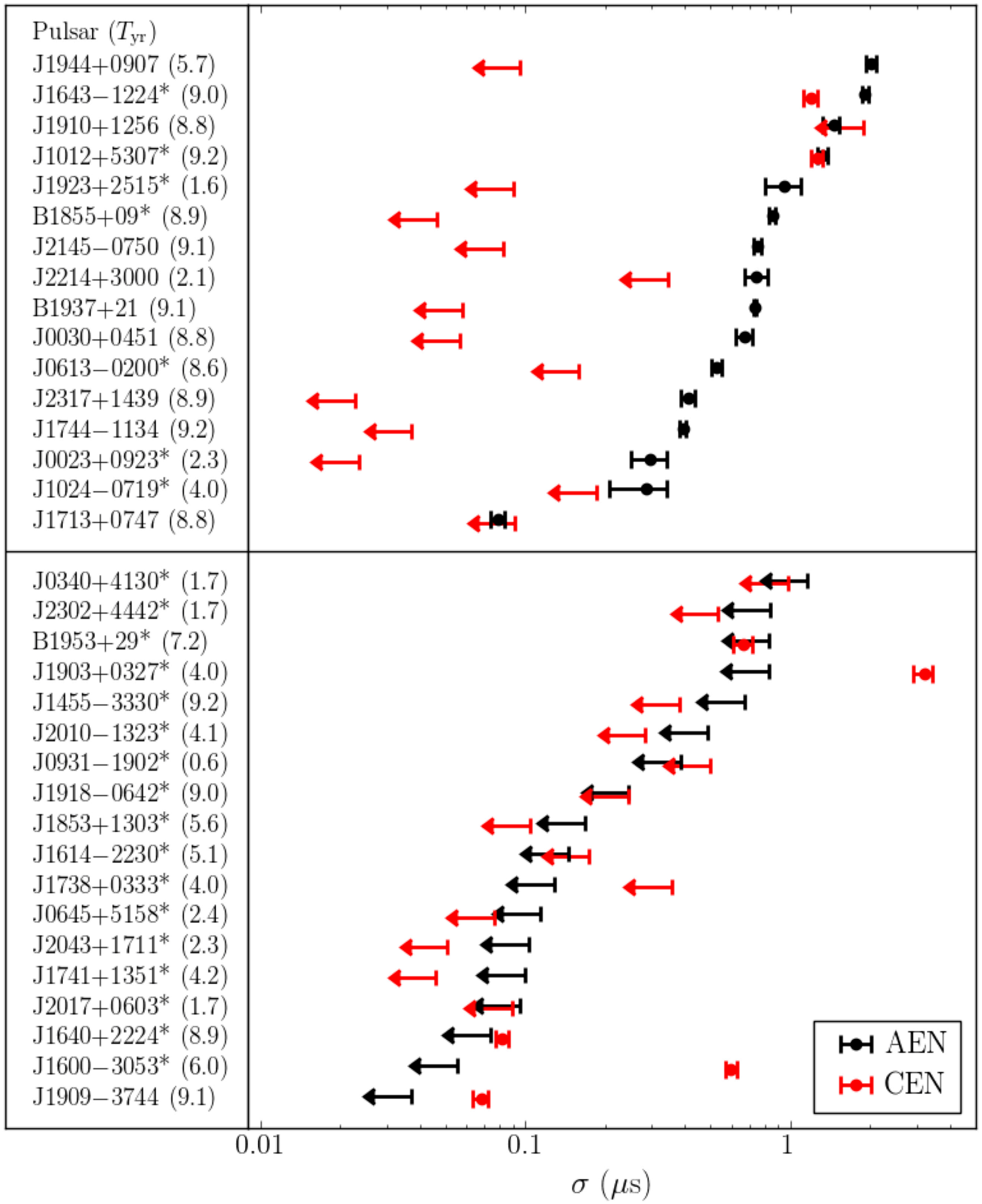
Measuring Chromatic Excess Noise (CEN) vs. Achromatic Excess Noise (AEN) (in 9-year NANOGrav dataset)

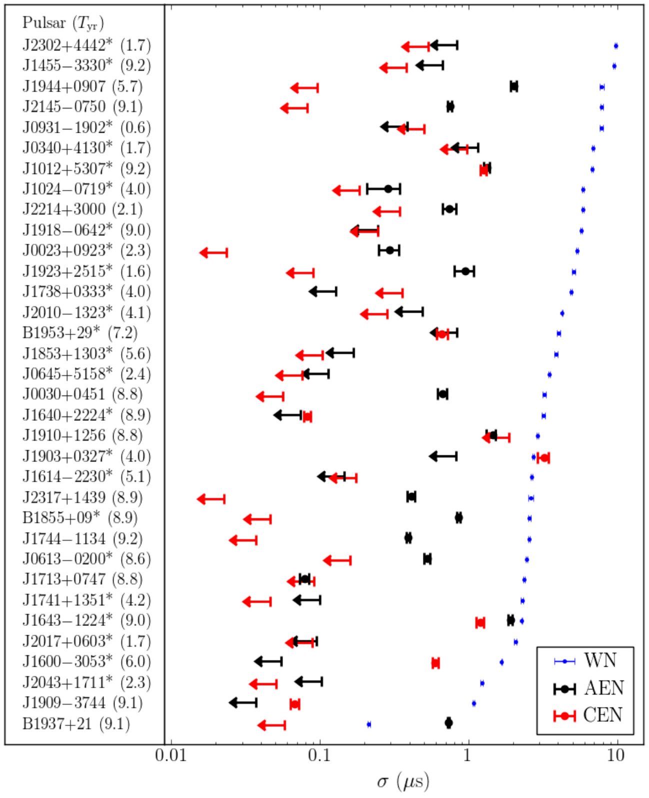




Lam et al. 2017

Measuring Chromatic Excess Noise (CEN) vs. Achromatic Excess Noise (AEN) (in 9-year NANOGrav dataset)

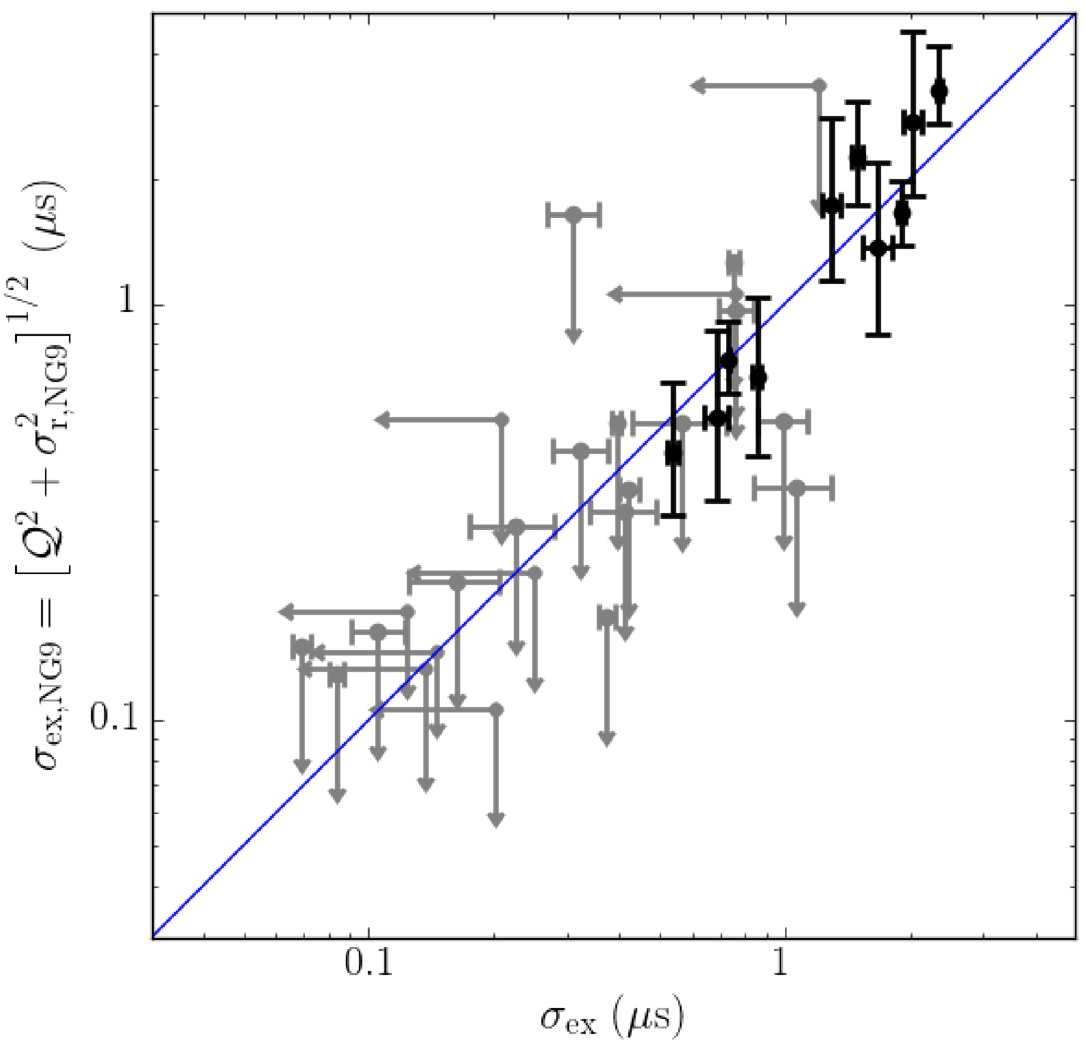




The achromatic excess noise is most likely spin noise (aka timing noise) in individual pulsars.

Lam et al. 2017

Maximum Likelihood Analysis of NANOGrav 9-year Dataset vs. Measrued Excess Noise in Lam et al. (2017). In future data releases (12.5yr +), the measured excess noise values will be used as priors.



Lam et al. 2017

Conclusions

- In NANOGrav 9-year data release and beyond, including forthcoming 11-year data release (Arzoumanian et al. 2017, in prep), noise in timing residuals is modeled
- Timing-residual noise can be characterized as white, red, chromatic, and achromatic, and can be measured and mitigated.
- The chromatic noise component is due to the variations in the IISM
- NANOGrav pulsars' noise power spectrum over potential GW frequencies is characterized and de-composable into known statistical processes
- With each successive data release, noise is better-characterized… long-term, continuous observations (e.g. **DO NOT CLOSE THE ARECIBO OBSERVATORY AND THE GREEN BANK TELESCOPE**) are critical for red noise characterization as well as signal detection!