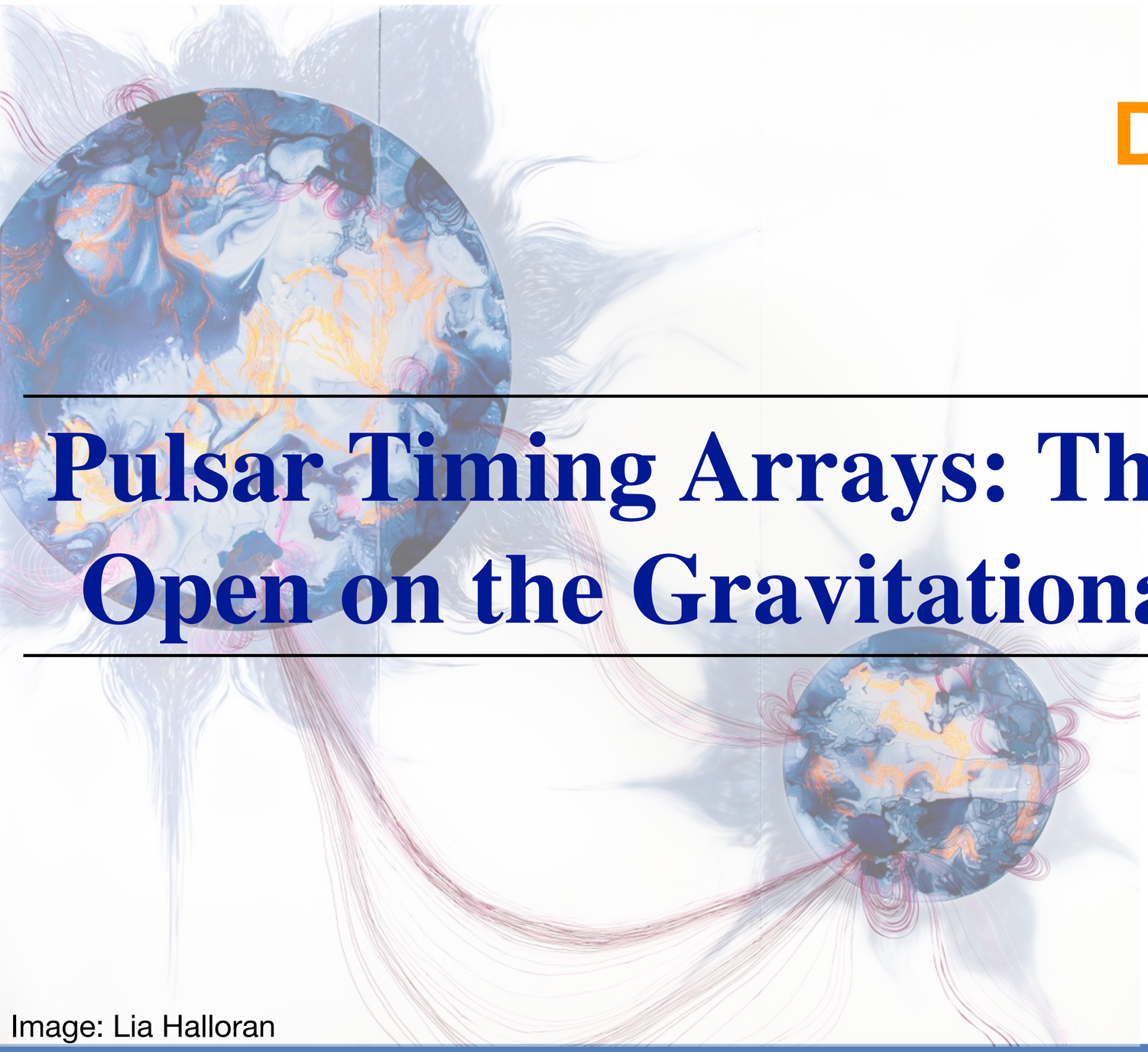

Dark Interactions

November 16th 2022

Pulsar Timing Arrays: The Next Window to Open on the Gravitational-Wave Universe

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Image: Lia Halloran

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Outline

- The gravitational-wave spectrum
- **Pulsar Timing Arrays:** how they work
- Understanding new results from **NANOGrav** 12.5-yr data
- The future! Please send me your thoughts!

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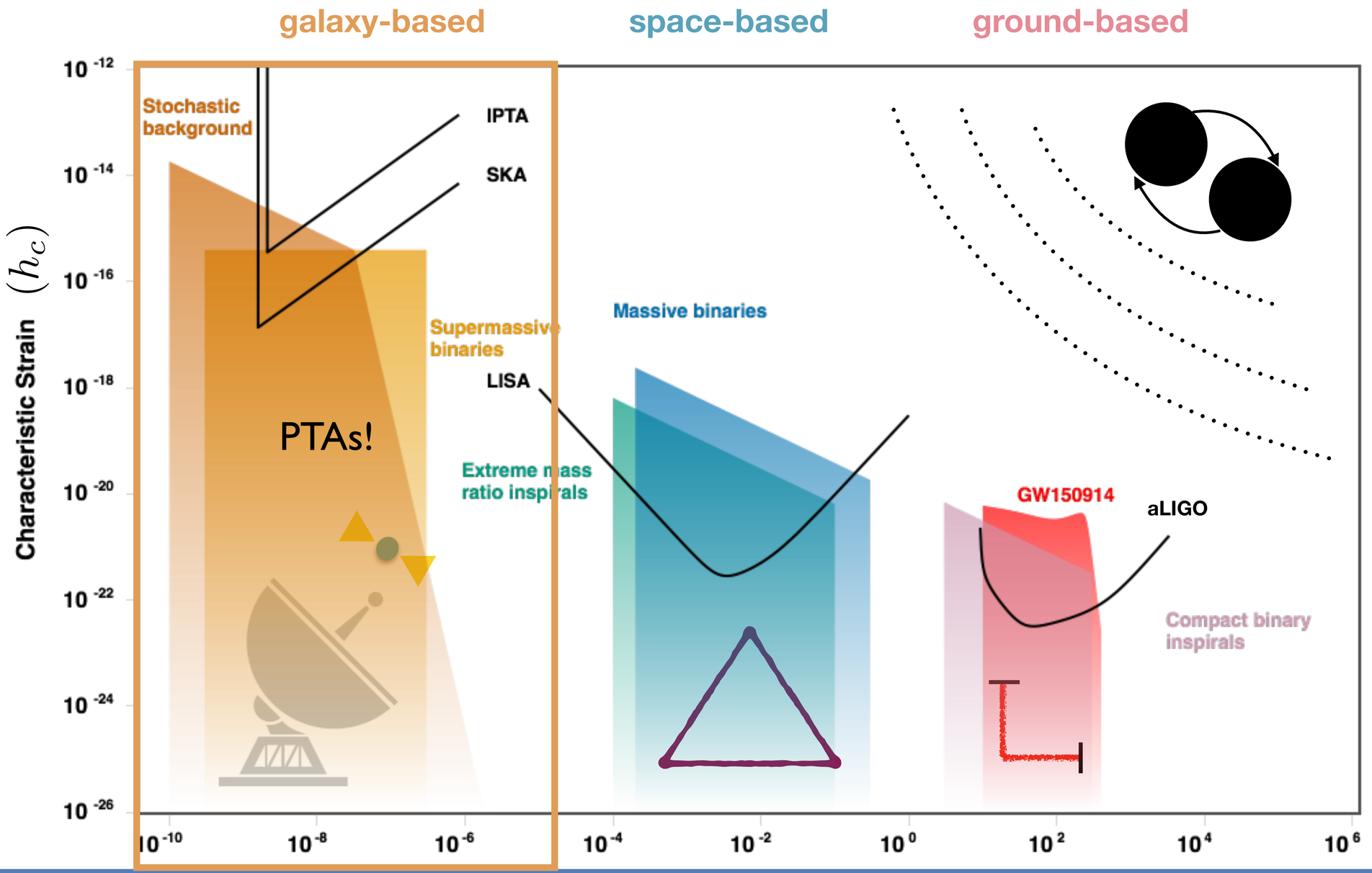
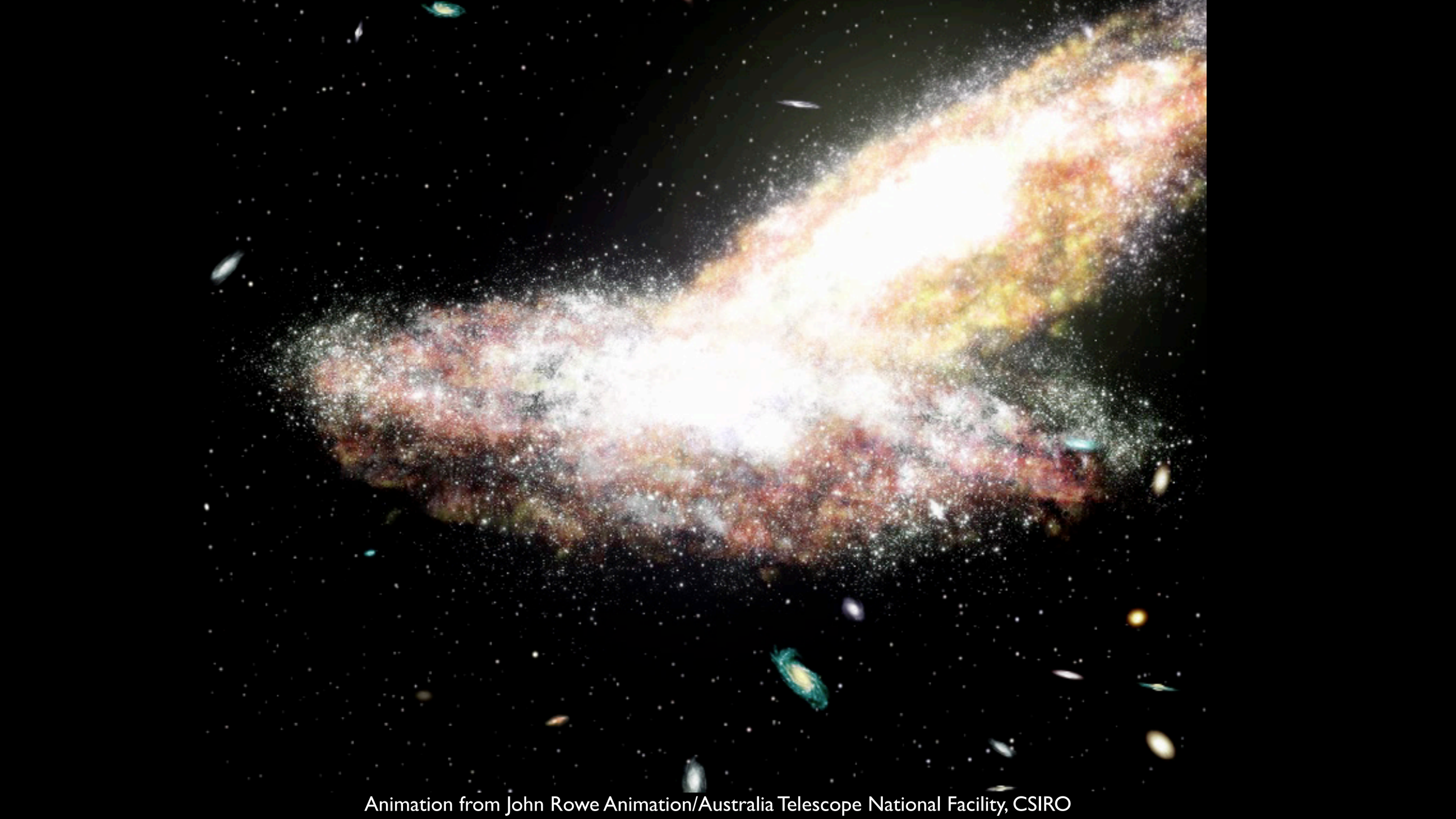
The Gravitational-Wave Spectrum

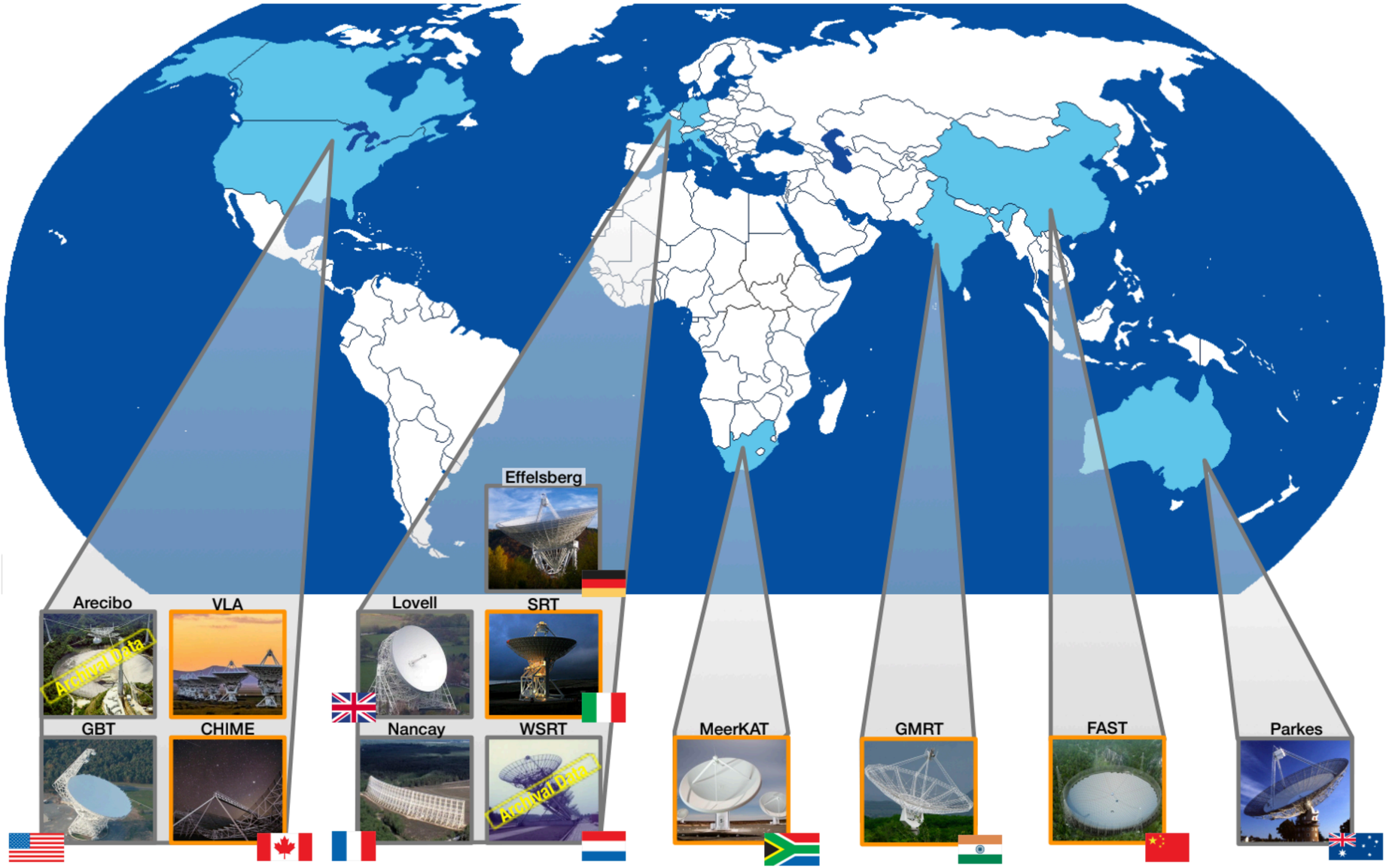


- Complementary GW detectors
- LIGO can't see PTA!
- Strain $h=\Delta t / T$
- 25 Myrs in band



Animation from John Rowe Animation/Australia Telescope National Facility, CSIRO

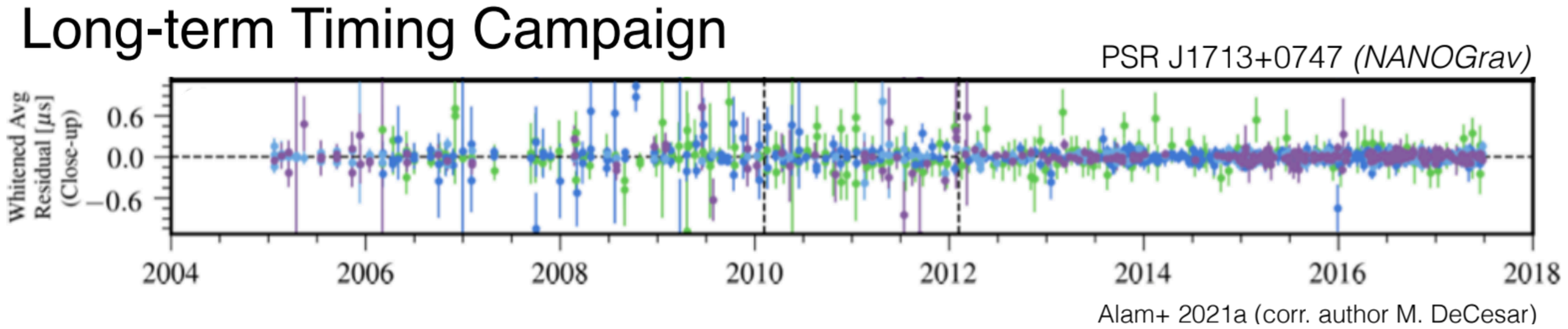
IPTA: Key Project in Radio Astronomy

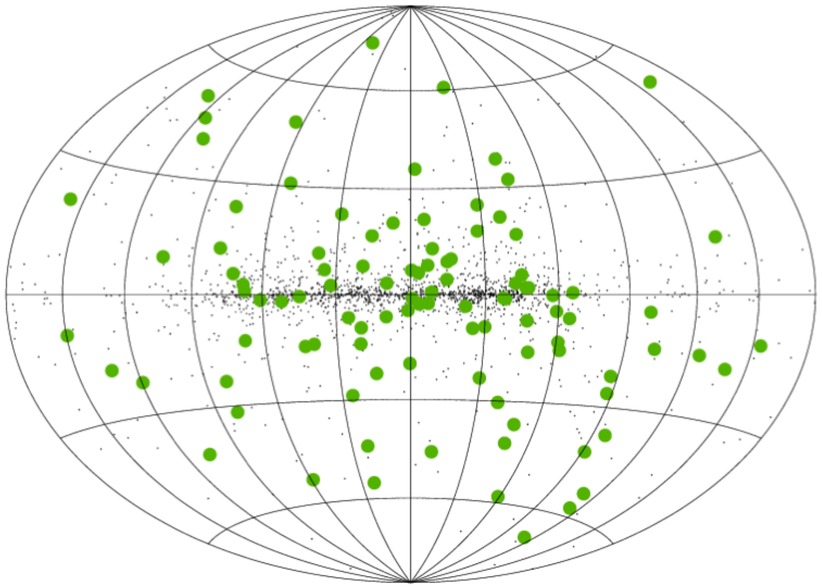


NANOGrav Physics Frontiers Center

INTERNATIONAL PULSAR TIMING ARRAY
IPTA

Millisecond Pulsars





2300 known pulsars, 230 MSPs
Maybe 30,000 detectable!

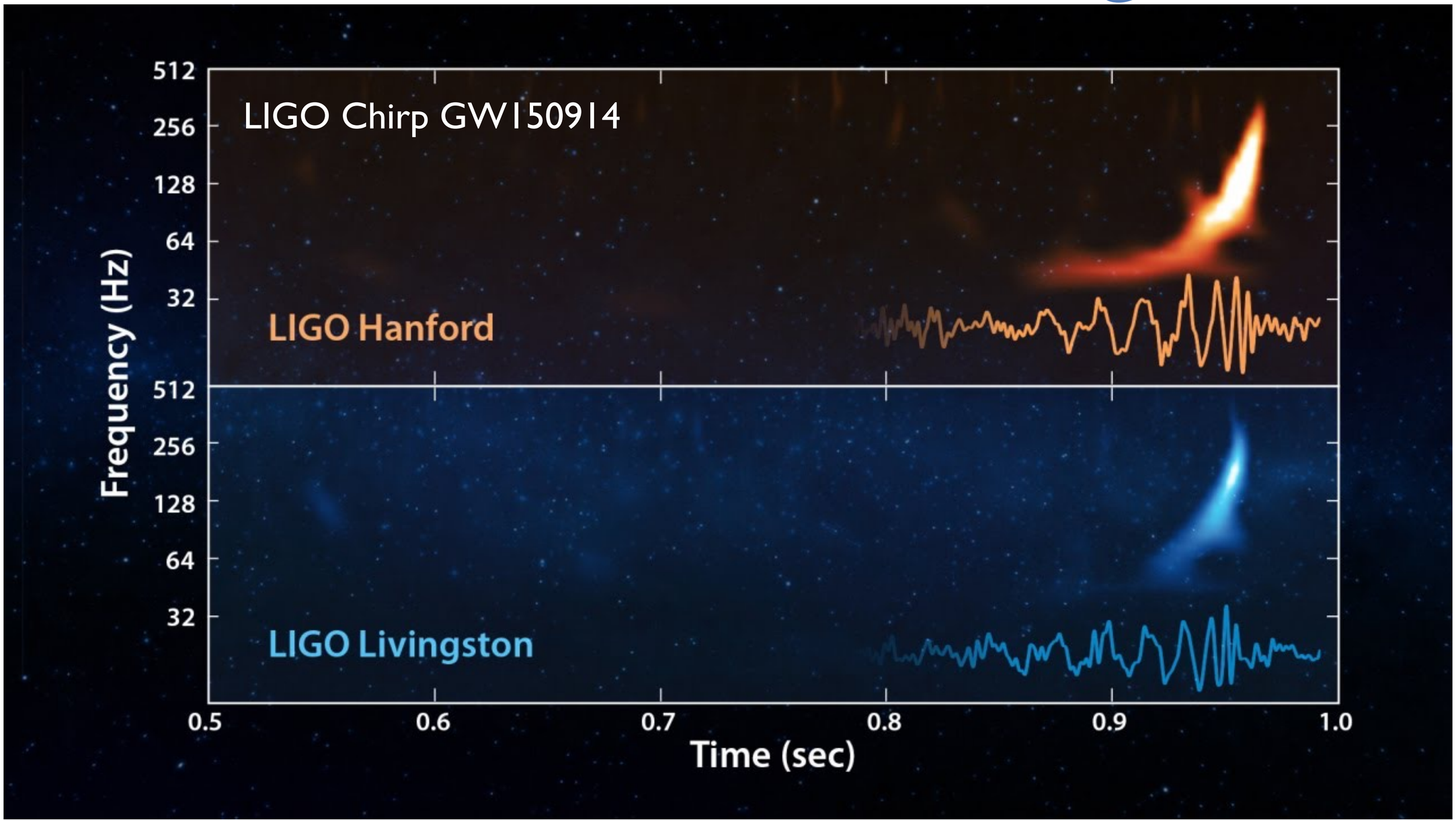
Cross-power spectral density between pulsar a and b

$$S_{ab}(f) = \Gamma_{ab}(f)\,\frac{h_c^{\,2}(f)}{12\pi^2 f^3}$$

Angular correlation function

Sum of the strain emitted by SMBHBs over their cosmic merger history (Phinney 2001)

Gravitational-Wave Backgrounds



The Gravitational-Wave Background

$$h_c^2 \sim f^{-4/3} \int\int dz d\mathcal{M} \frac{d^2n}{dz d\mathcal{M}} \frac{1}{(1+z)^{1/3}} \mathcal{M}^{5/3}$$

Galaxy-galaxy merger rates

chirp mass

$$h_c = A \left(\frac{f}{\mathrm{yr}^{-1}} \right)^{-2/3}$$

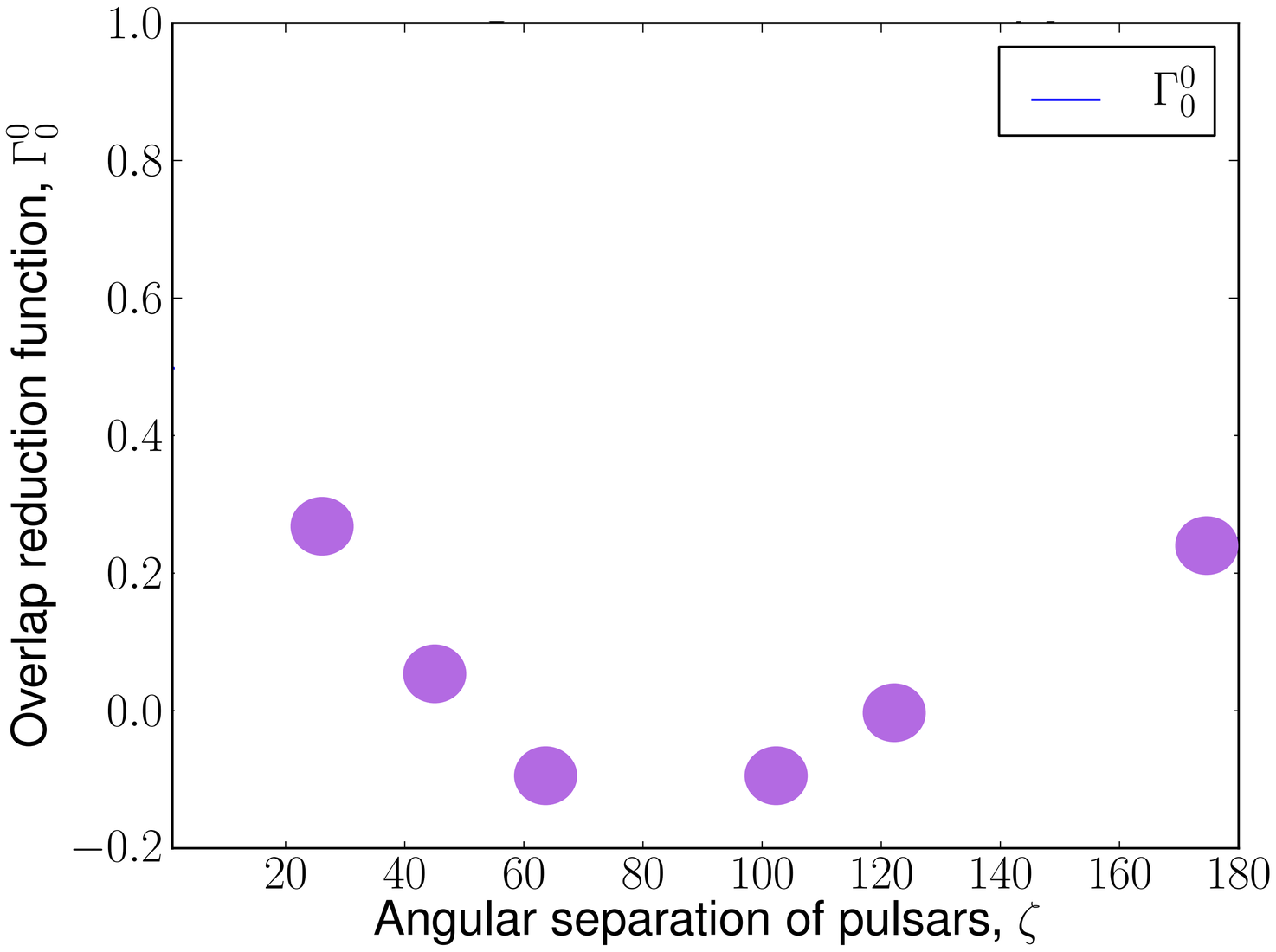
$$\Omega_{\mathrm{gw}}(f) = \frac{2\pi^2}{3H_0^2} f^2 h_c^2$$

$$S_{ab}(f) = \Gamma_{ab}(f) \frac{{h_c}^2(f)}{12\pi^2 f^3}$$

The characteristic strain depends on the astrophysics of SMBH mergers

Phinney (2001); Jaffe & Backer (2003); Sesana (2013); CMFM et al. (2019)

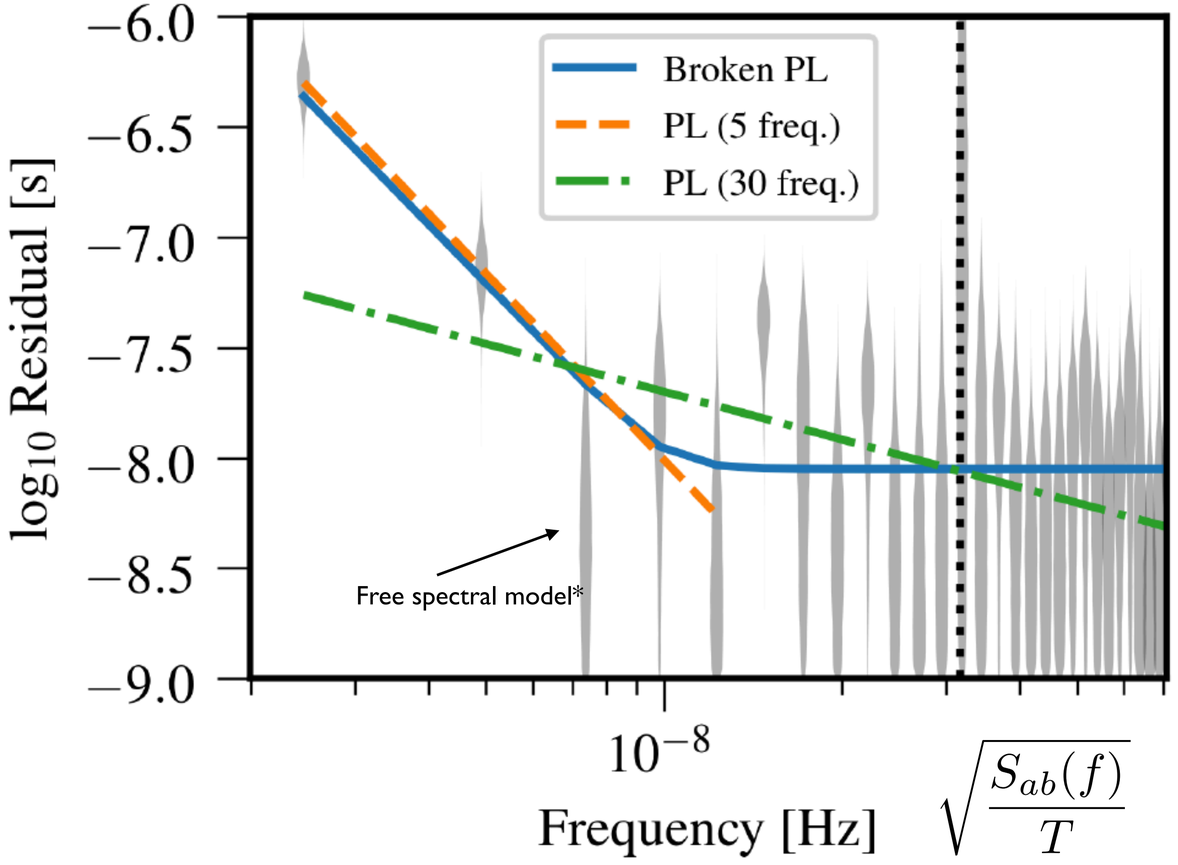
Gravitational-Wave Backgrounds



- SMBHBs, cosmic strings?
- Hellings and Downs curve
- Assumes background is isotropic (is it?)
- Pulsar correlations create “curve”
- Changes for alternative theories of gravity and anisotropic GWBs

$$S_{ab}(f) = \Gamma_{ab}(f)\,\frac{{h_c}^2(f)}{12\pi^2 f^3}$$

What do the NG12.5-yr data show?



This is one ASD that 45 pulsars share in the Bayesian model

There is *something* manifesting at low frequencies in the NG 12.5yr data. What is it?

Common amplitude and power-law behavior in all 45 pulsars

ML power-laws; spatially uncorrelated common spectrum

*Violin plots: marginalized posteriors of the equivalent amplitude of the sine-cosine Fourier pair at the frequencies on the horizontal axis;

$$S_{ab}(f) = \Gamma_{ab}(f)\,\frac{{h_c}^2(f)}{12\pi^2 f^3}$$

CP = common process

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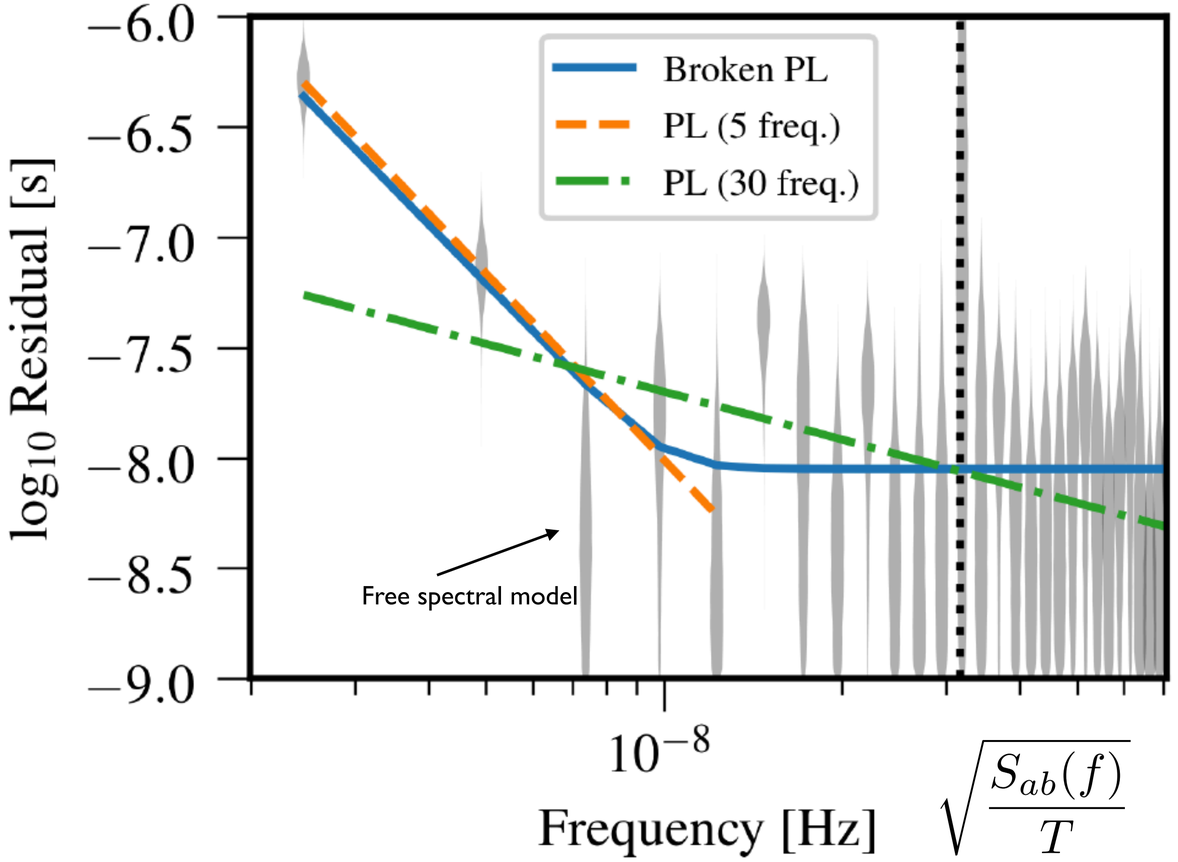
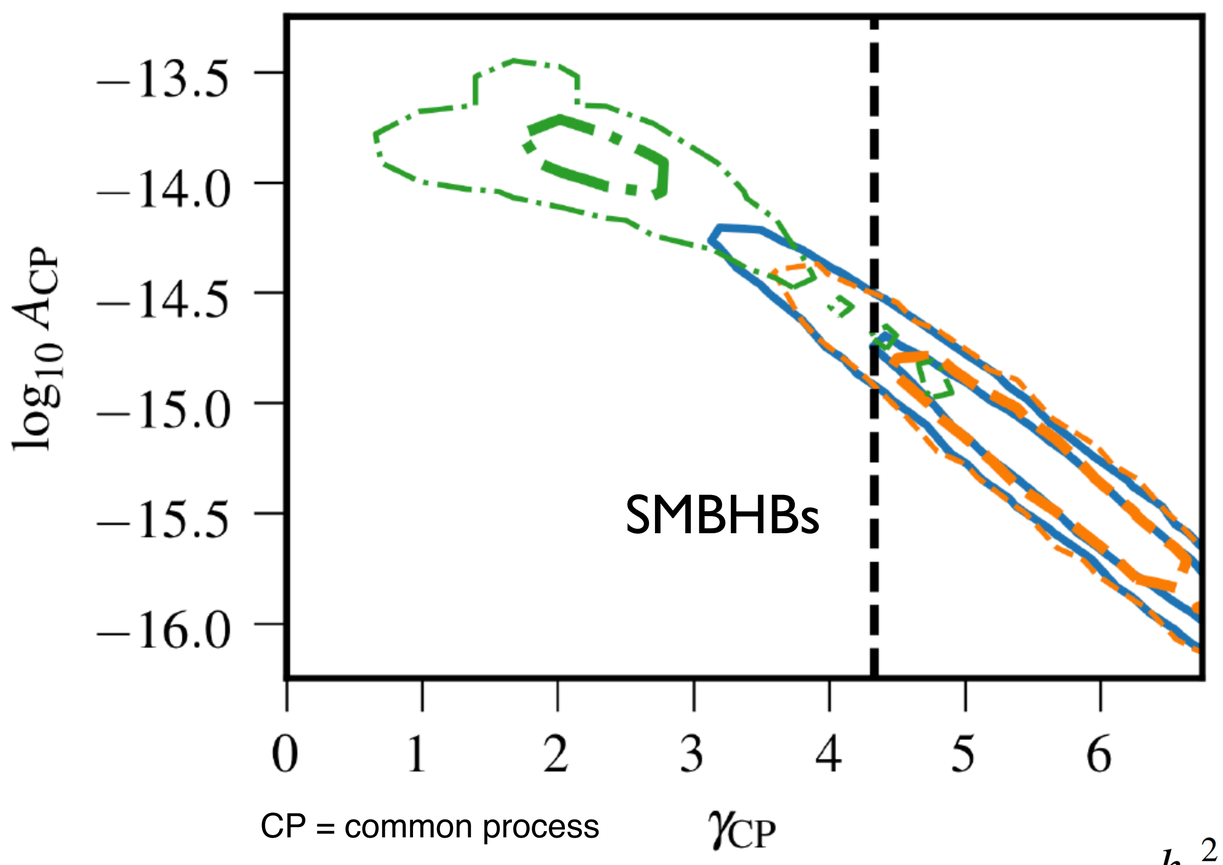
What do the data show?

(No cross-correlations)



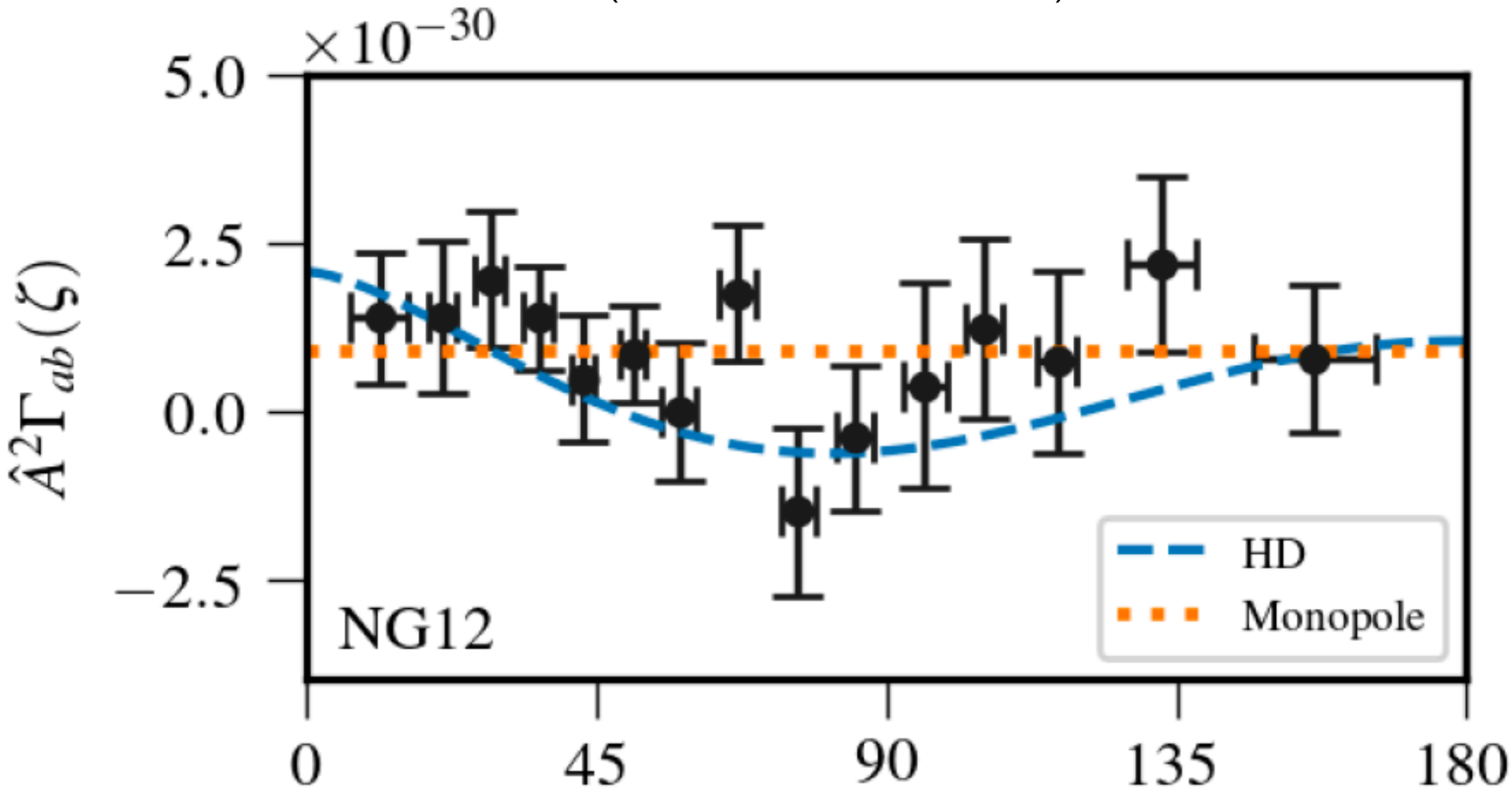


$$S_{ab}(f) = \Gamma_{ab}(f)\,\frac{h_c^2(f)}{12\pi^2 f^3}$$

NG12.5yr isotropic GWB, Arzoumanian et al., ApJL (2020; corr. author J. Simon)

Do we see a HD curve?

(With cross-correlations)



NG12.5yr isotropic GWB, Arzoumanian et al., ApJL (2020; corr. author J. Simon)

What is the evidence for the HD curve?

Is there evidence for a common-amplitude $\gamma = 13/3$ process?

Yes, strong evidence.

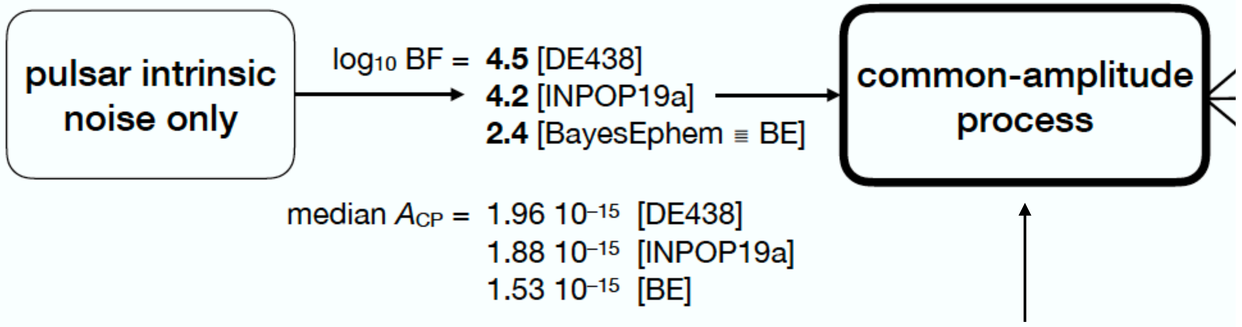
Is there evidence for a spatially correlated $\gamma = 13/3$ process?

No strong evidence for HD correlations, moderate evidence against monopole and dipole.

Is there evidence for a second $\gamma = 13/3$ process on top of HD?

Little evidence either way.

Monopole = clock error
Dipole = ephemeris error



So far we know there is a common-amplitude process

NG12.5yr isotropic GWB, Arzoumanian et al., ApJL (2020; corr. author J. Simon)

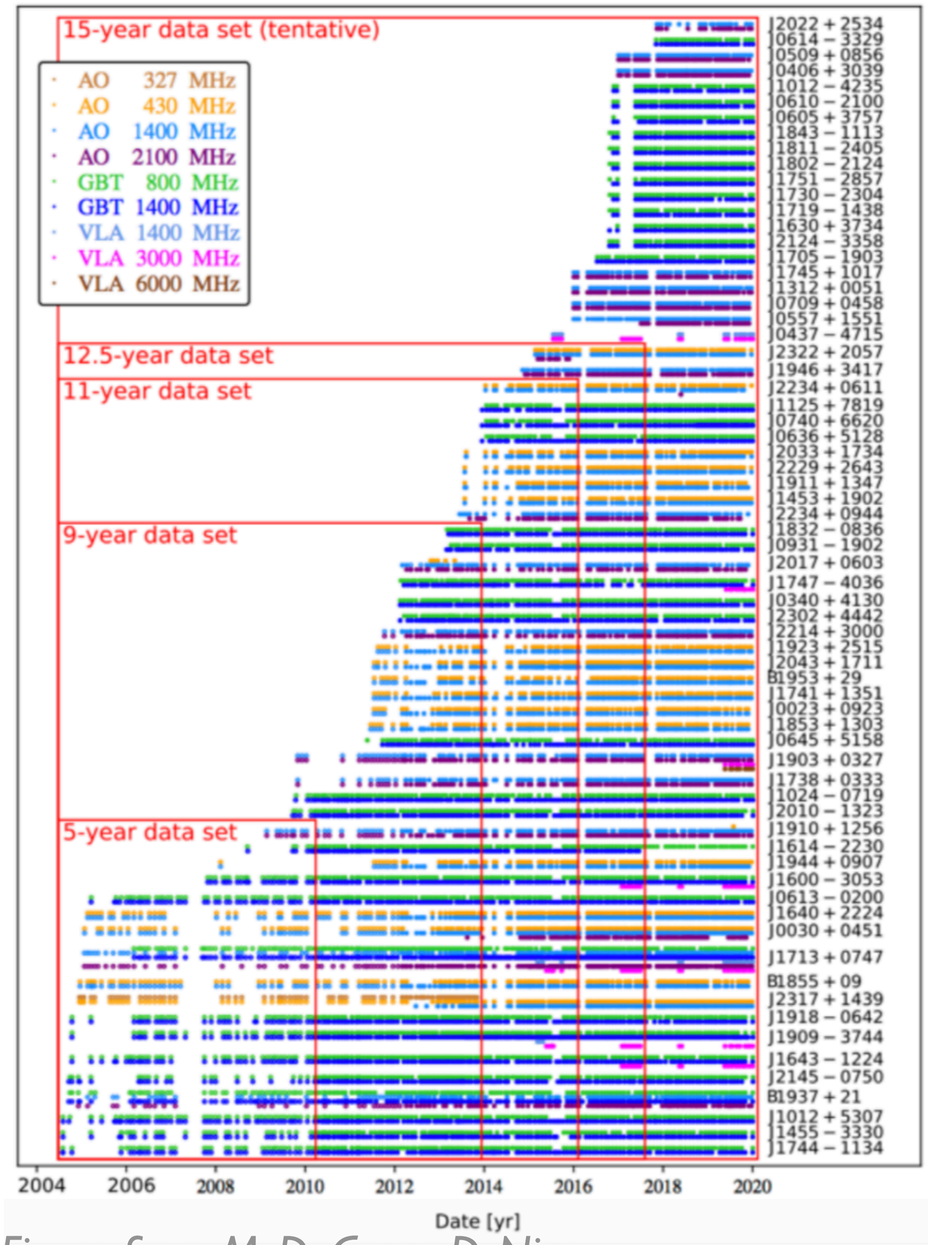


Figure from M. DeCesar, D. Nice

What is next?

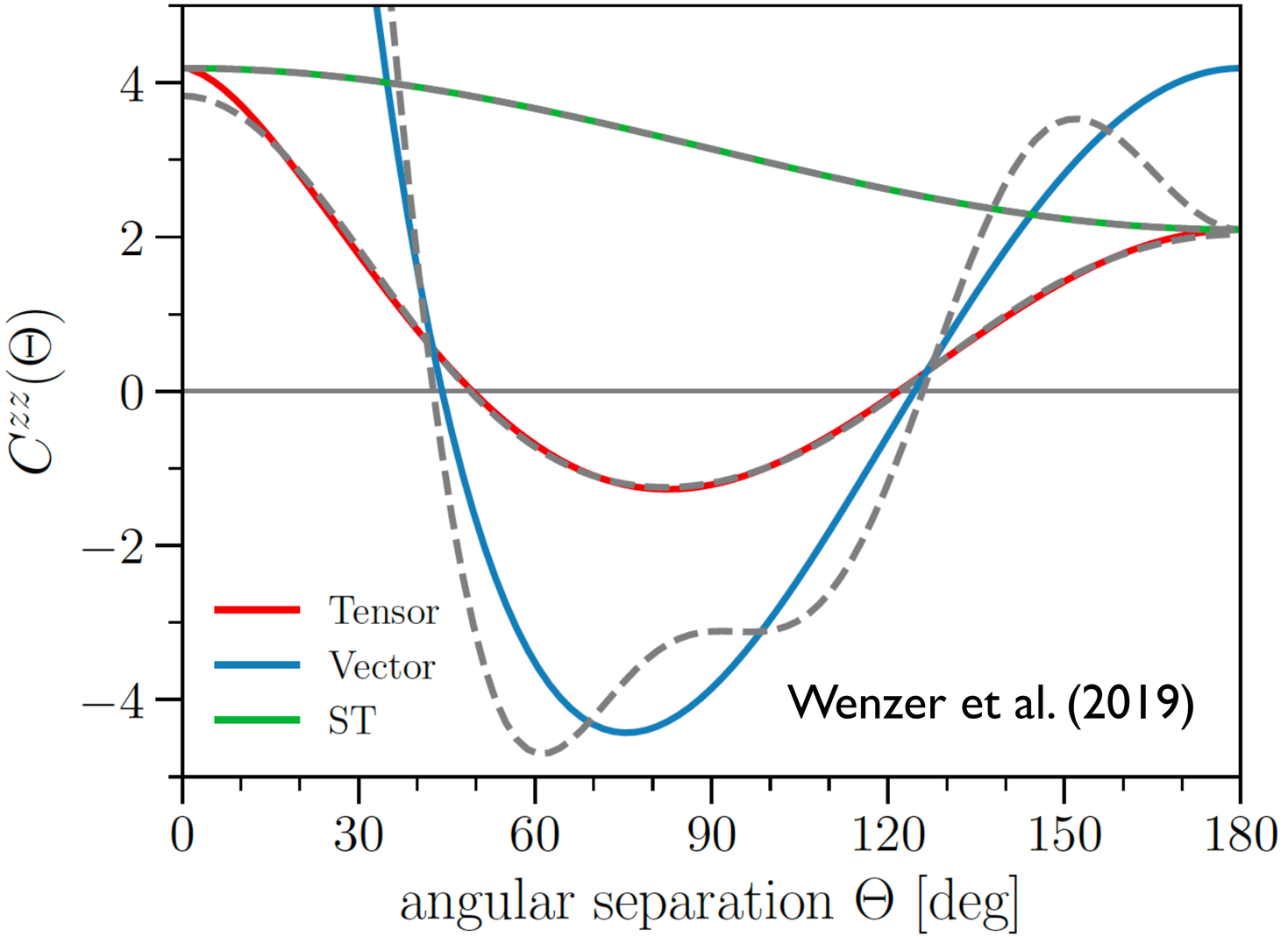
1. NANOGrav 15-yr Data Set

- 68 MSPs
- Timing baselines 3-15 yrs
- If SNR of common process increasing?
- HD significance increasing?
- Timing analysis in progress! Significant effort to automate timing pipeline with PINT (Luo+2021) for reproducibility .

15-yr data lead: Joe Swiggum

What is next?

2. Modify the correlations functions: beyond Hellings and Downs



Γ_2^{-2}

Γ_2^{-1}

Γ_2^{0}

Γ_2^{1}

Γ_2^{2}

on a basis of spherical

ew correlation

he sky is full of

laïmoud et al. (2020;

GR: Lee et al. (2010);

Siemens (2012),

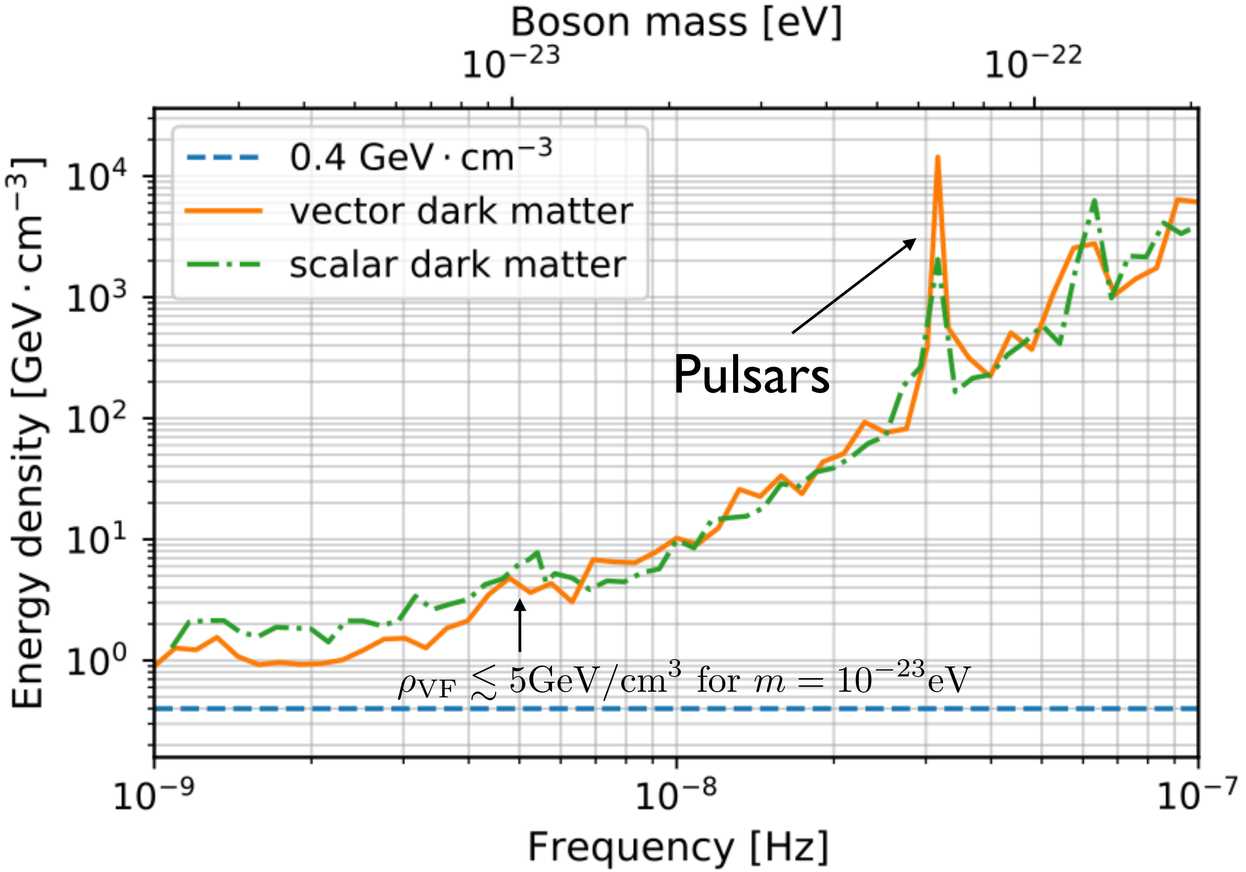
l. (2019)

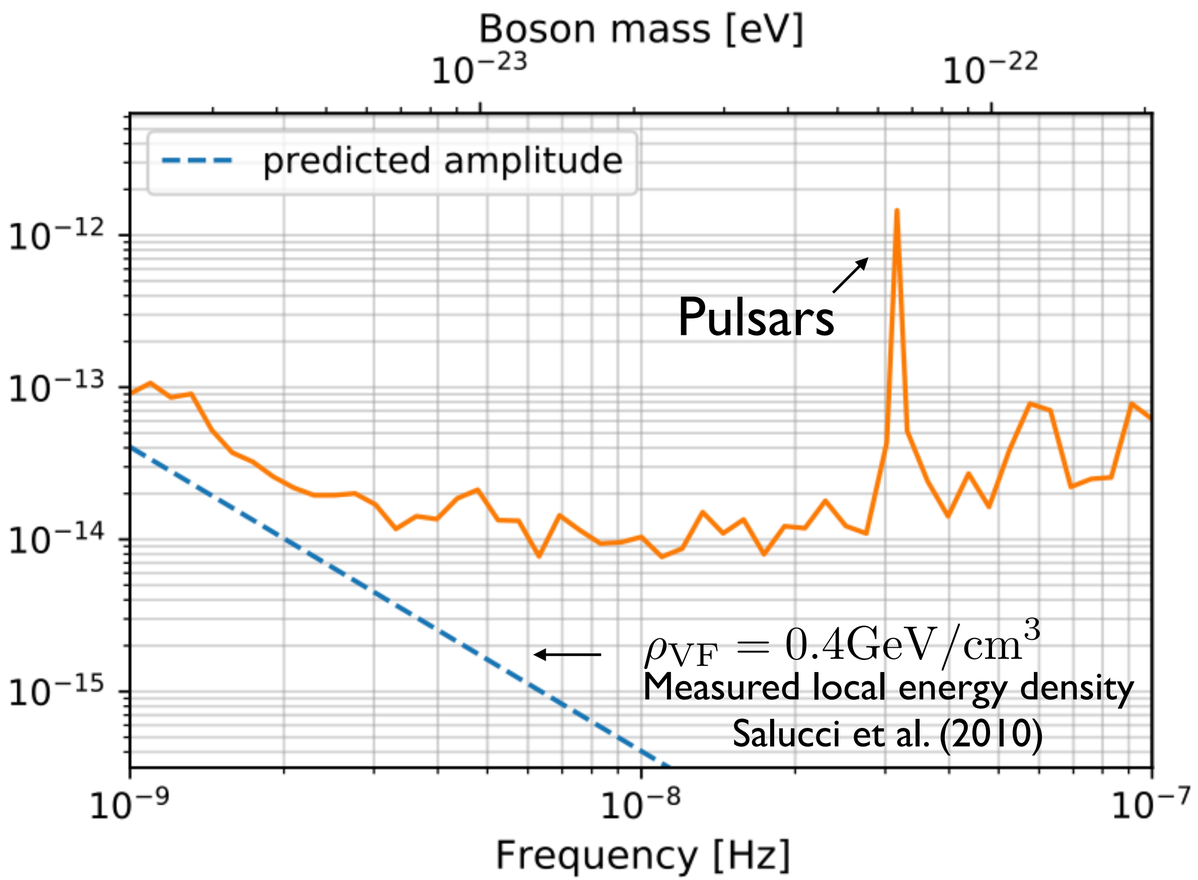
LIGO-band anisotropy, see Thrane et al. (2009);

$$S_{ab}(f) = \Gamma_{ab}(f)\,\frac{h_c^{\,2}(f)}{12\pi^2 f^3}$$

3. Fuzzy Dark Matter?

- Cause oscillations in the galactic potential
- The pulsar pulses are advanced or delayed
- Limits the mass of fuzzy DM





285 papers on ADS with "dark matter pulsar timing"

Graham et al. (2016); Cordes & Chatterjee (2019); Schutz and Liu (2019); Sommer-Larsen, Götz, Portinai (2003); Saito and Yokoyama (2009); Schwaller (2015); Weltman et al. (2020); Dubovsky, Tinyakov, Tkachev (2005); Dror et al. (2019); Mayer-Hasselwander et al. (1998) and hundreds more.

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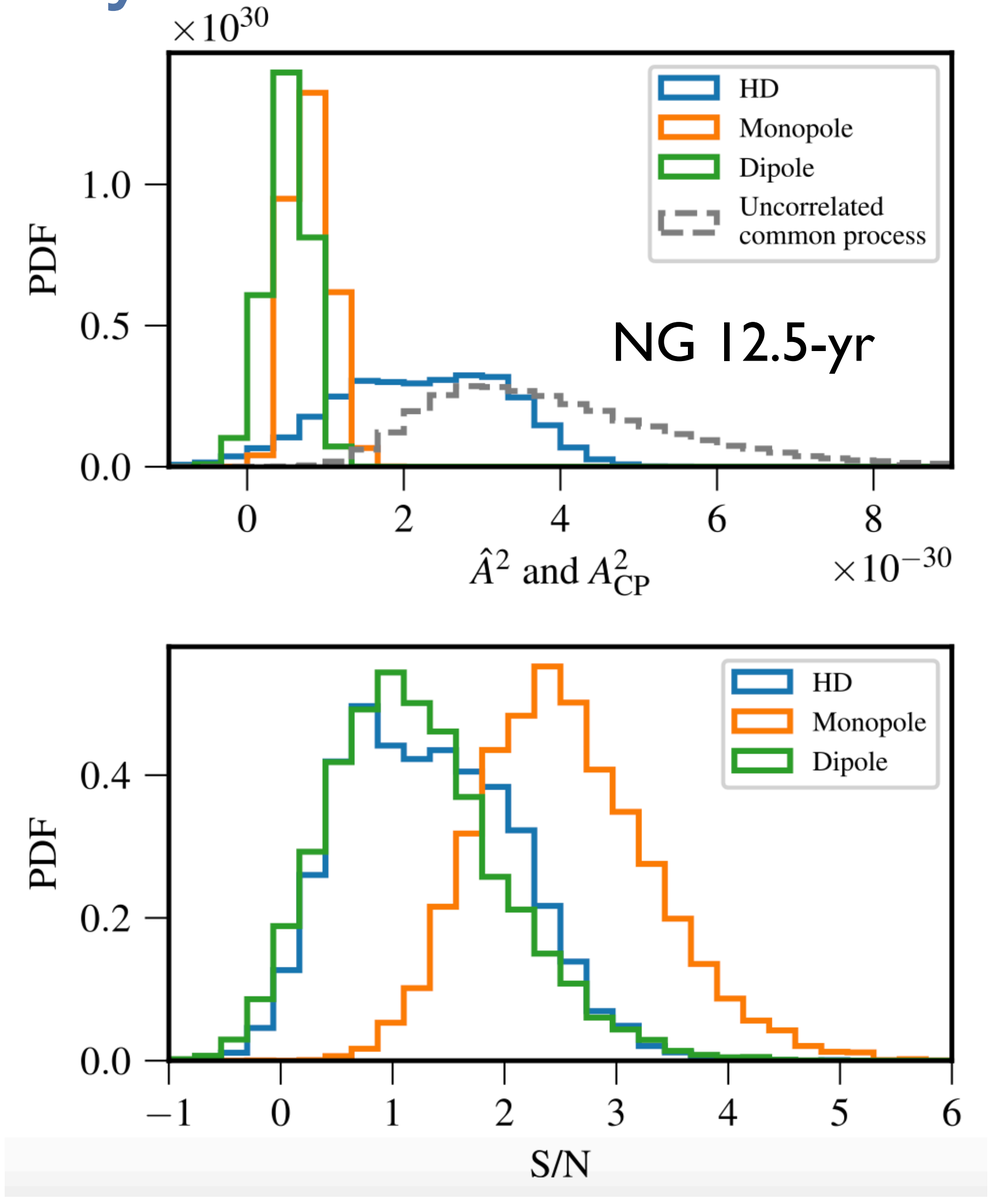
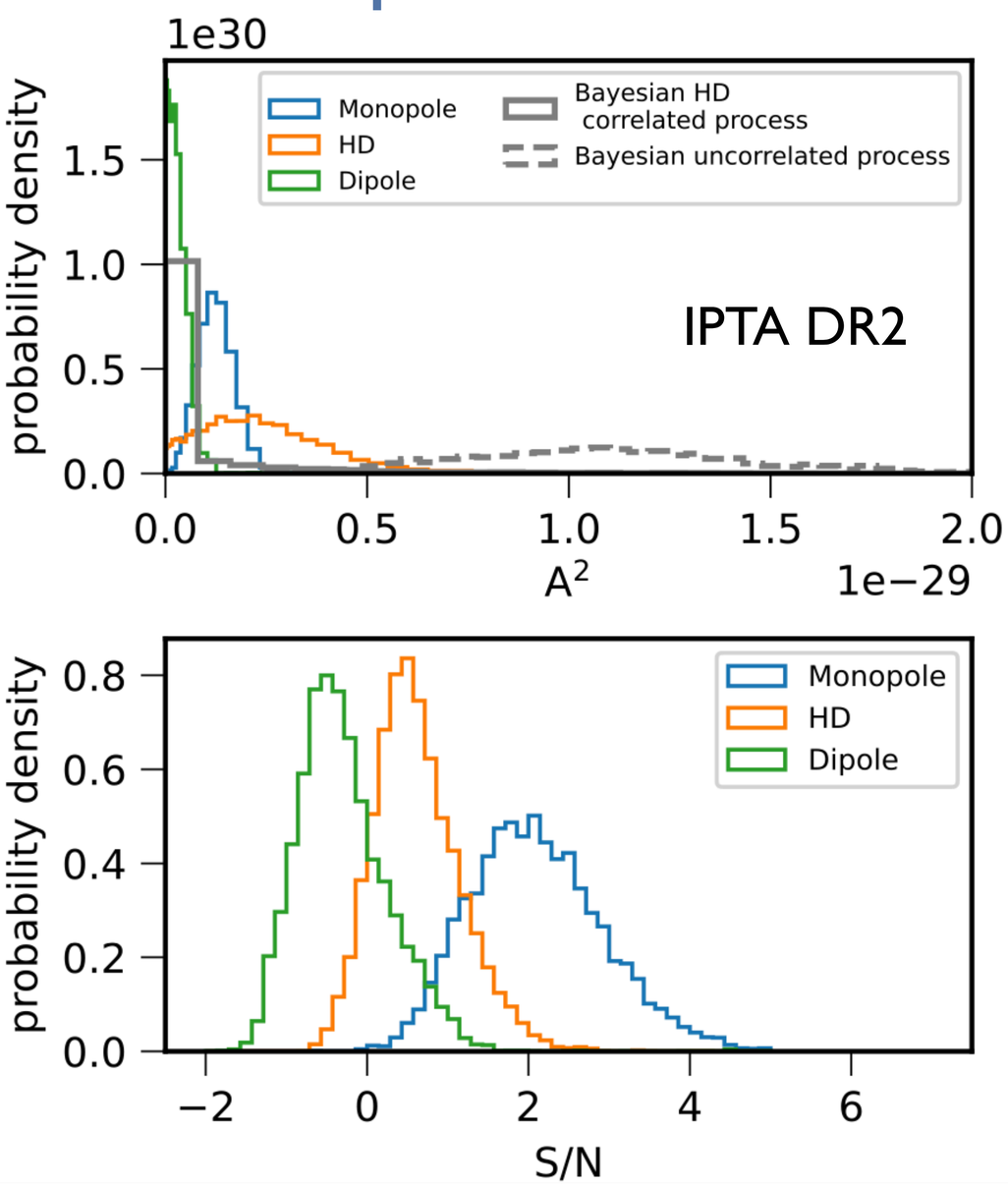
3. Fuzzy Dark Matter? It would be a monopole…

What is next?





NG 12.5-yr, Arzoumanian et al. (2020)

IPTA DR2, Antoniadis et al. (2022)

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4. Telescopes ++

- The Arecibo 305-m telescope tragically collapsed on Dec 1, 2020
- Restructured observing program: GBT (primarily 1.5 GHz), CHIME (400-800 MHz), VLA (1-4 GHz)
- GBT ultra-wideband receiver (0.7-4.2 GHz) is planned to come online in early 2022
- Future facilities
  - Next-Generation Very Large Array
  - 2000-antenna Deep Synoptic Array (DSA-2000)
  - Possible future Arecibo facility

What is next?

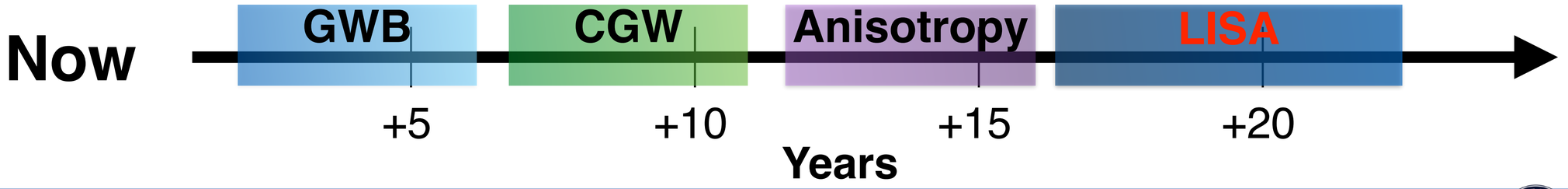
Figure: NRAO/NRCC

Figure courtesy G. Hallinan

Summary

- PTA interdisciplinary and multimessenger science experiment: global radio campaigns, fundamental physics, astrophysics, **dark matter**, and more
- **There is something in the 12.5-year data:** common amplitude and spectral index in all 45 pulsars!
- We already have the 15-yr dataset, analyzing it now!
- Evidence for GWB? If so, **detection in 2-3 more years of data,** local nHz sources ~ **10 years, anisotropy to follow, and LISA!**
- **The Universe Awaits!**

What is next? Everything.



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