VANDERBILT UNIVERSITY

NANOGrav

CUTTING-EDGE RESULTS FROM PULSAR TIMING

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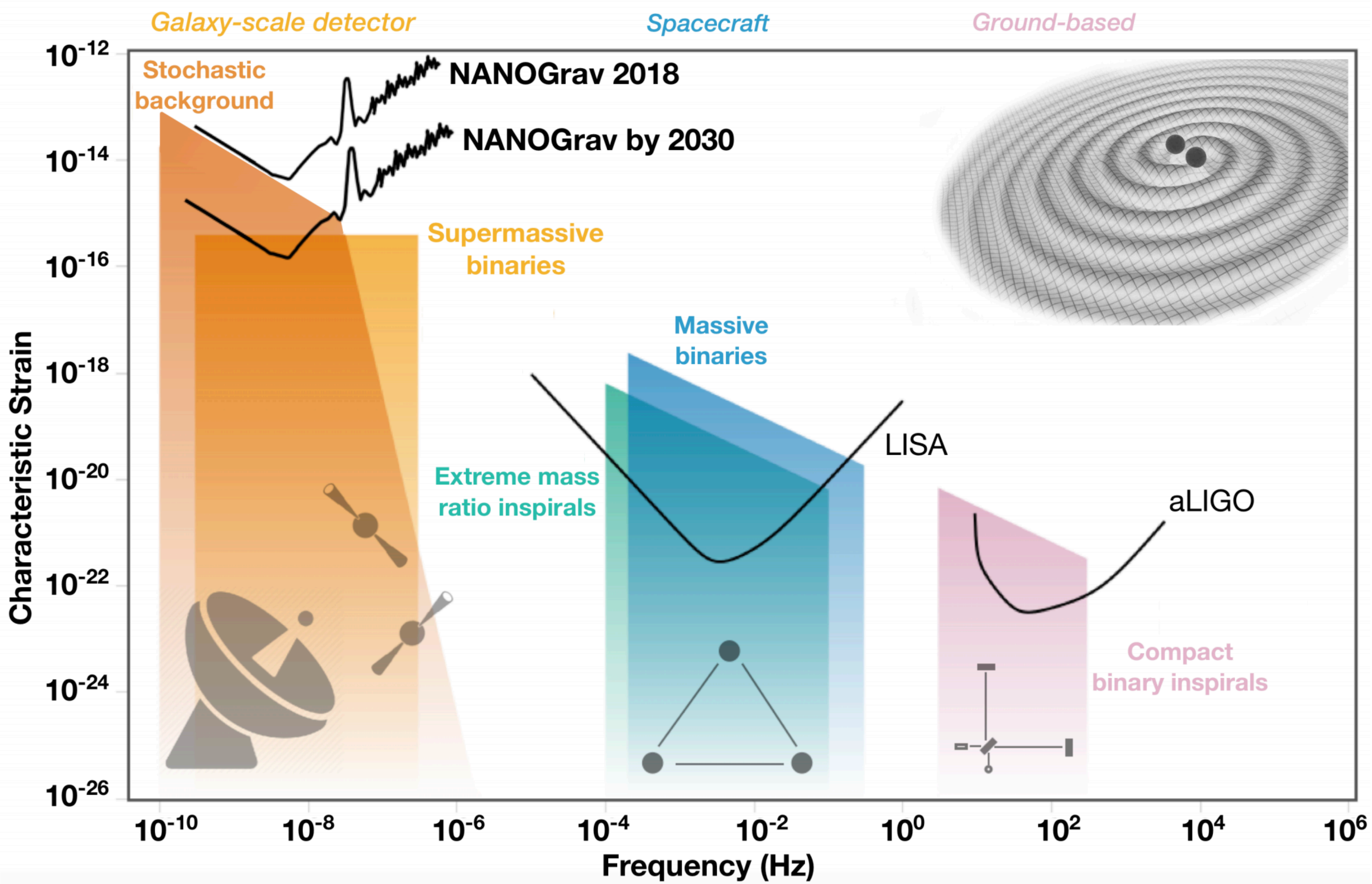
Anomalies 2021, November 10-12 2021

NANOGrav Physics Frontiers Center

The Gravitational Wave Landscape



S. Taylor & C. Mingarelli, adapted from gwplotter.org (Moore, Cole, Berry 2014) and based on a figure in Mingarelli & Mingarelli (2018). Illustration of merging black holes adapted from R. Hurt/Caltech-JPL/EPA

Pulsars

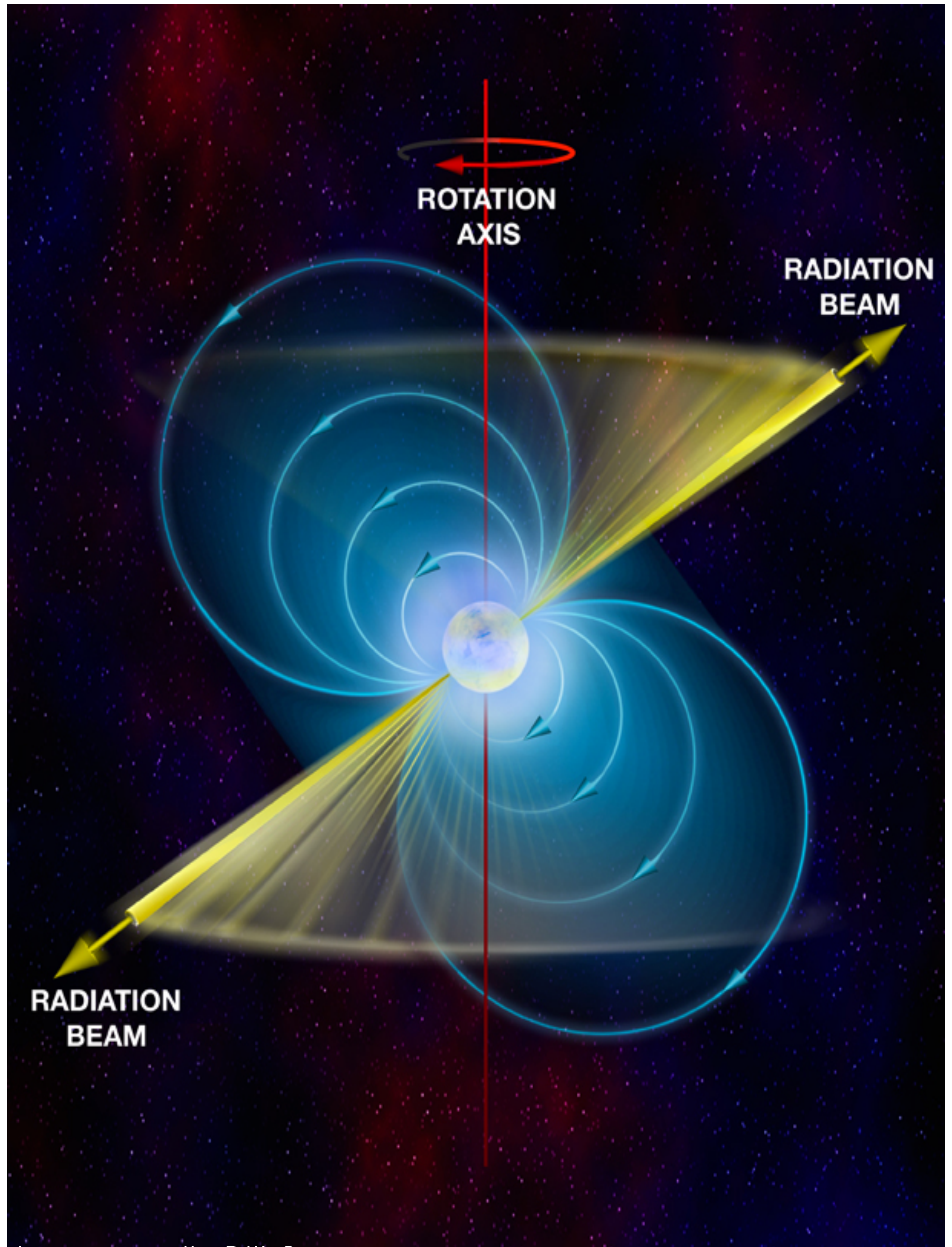
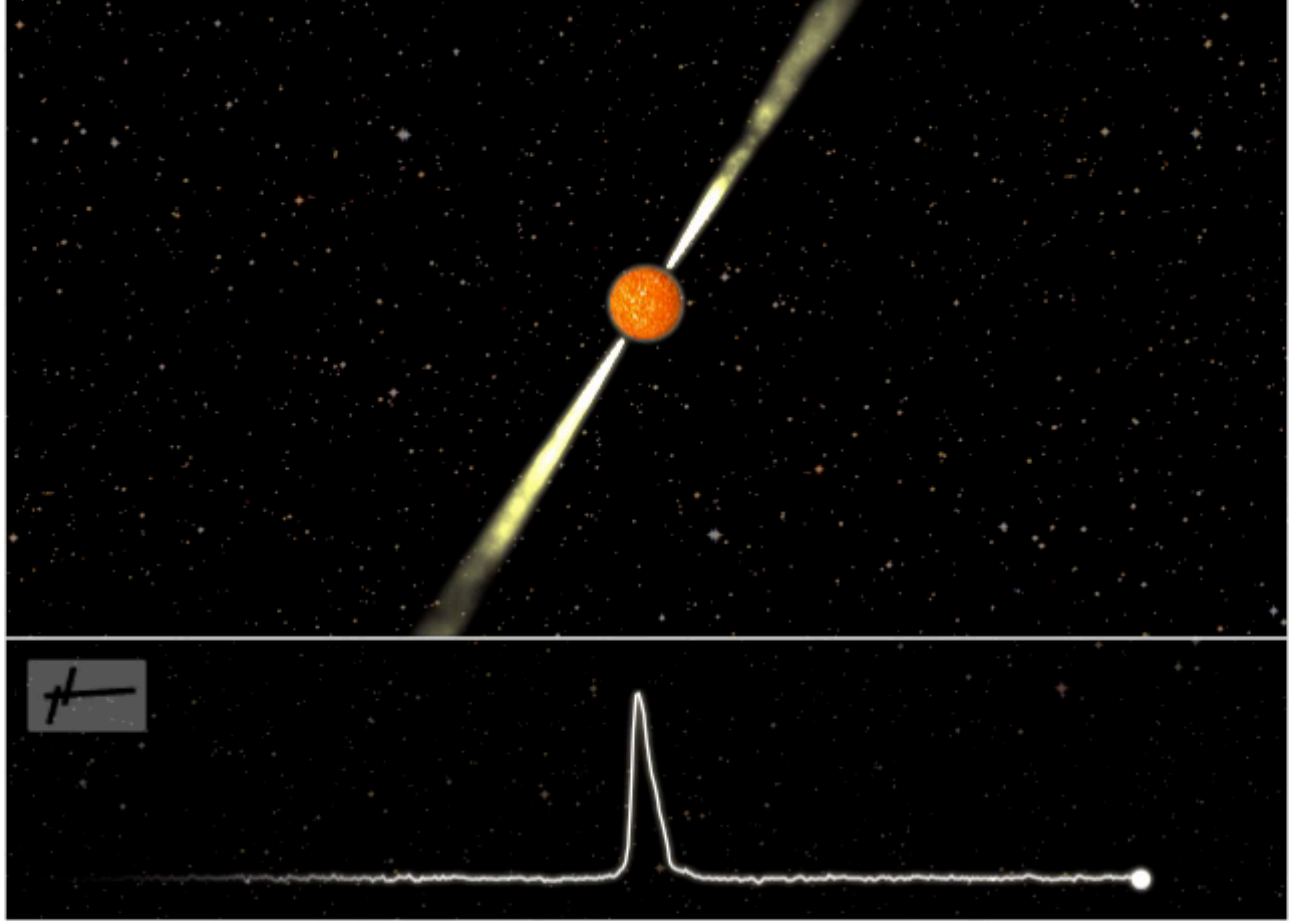
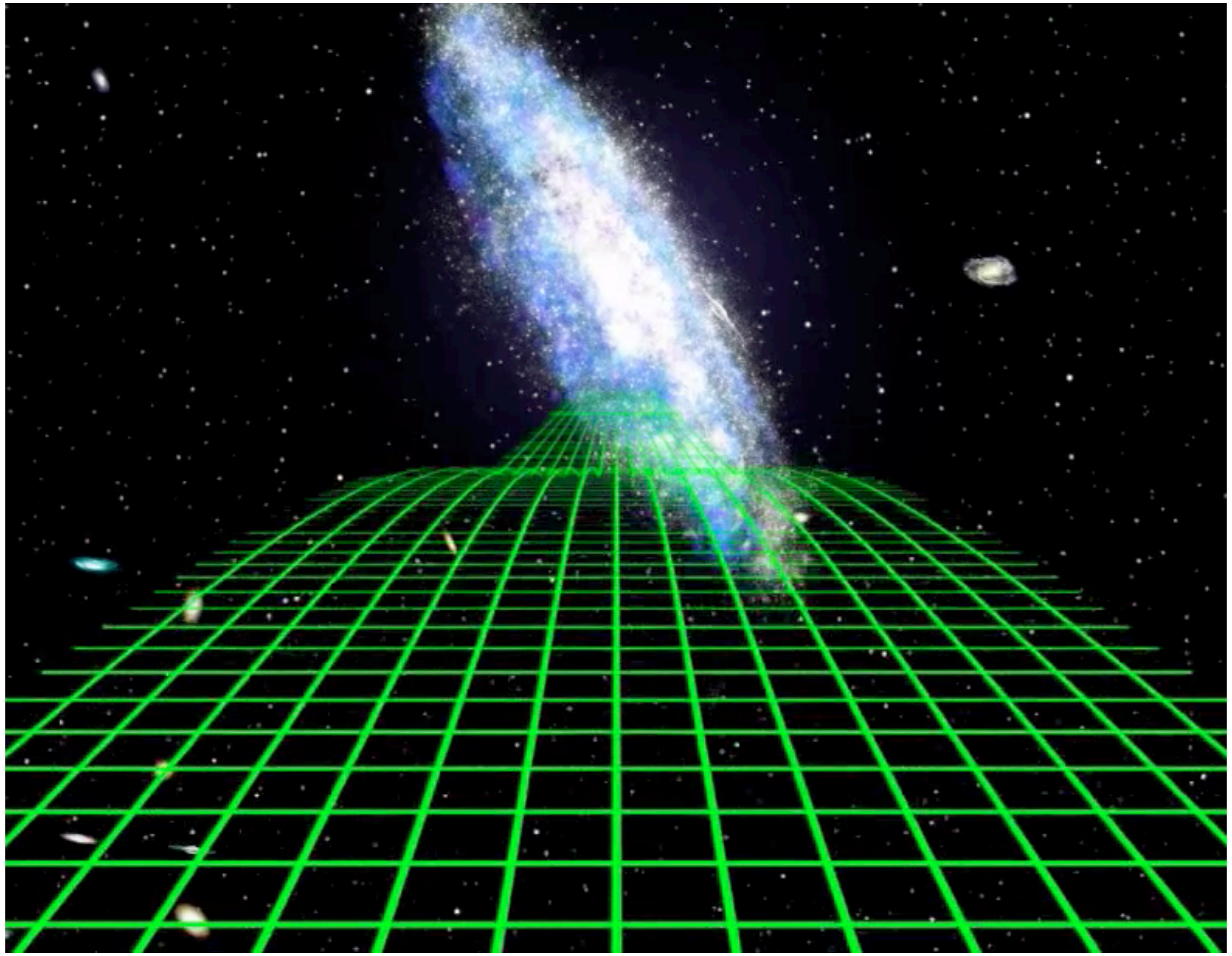


Image credit: Bill Saxton

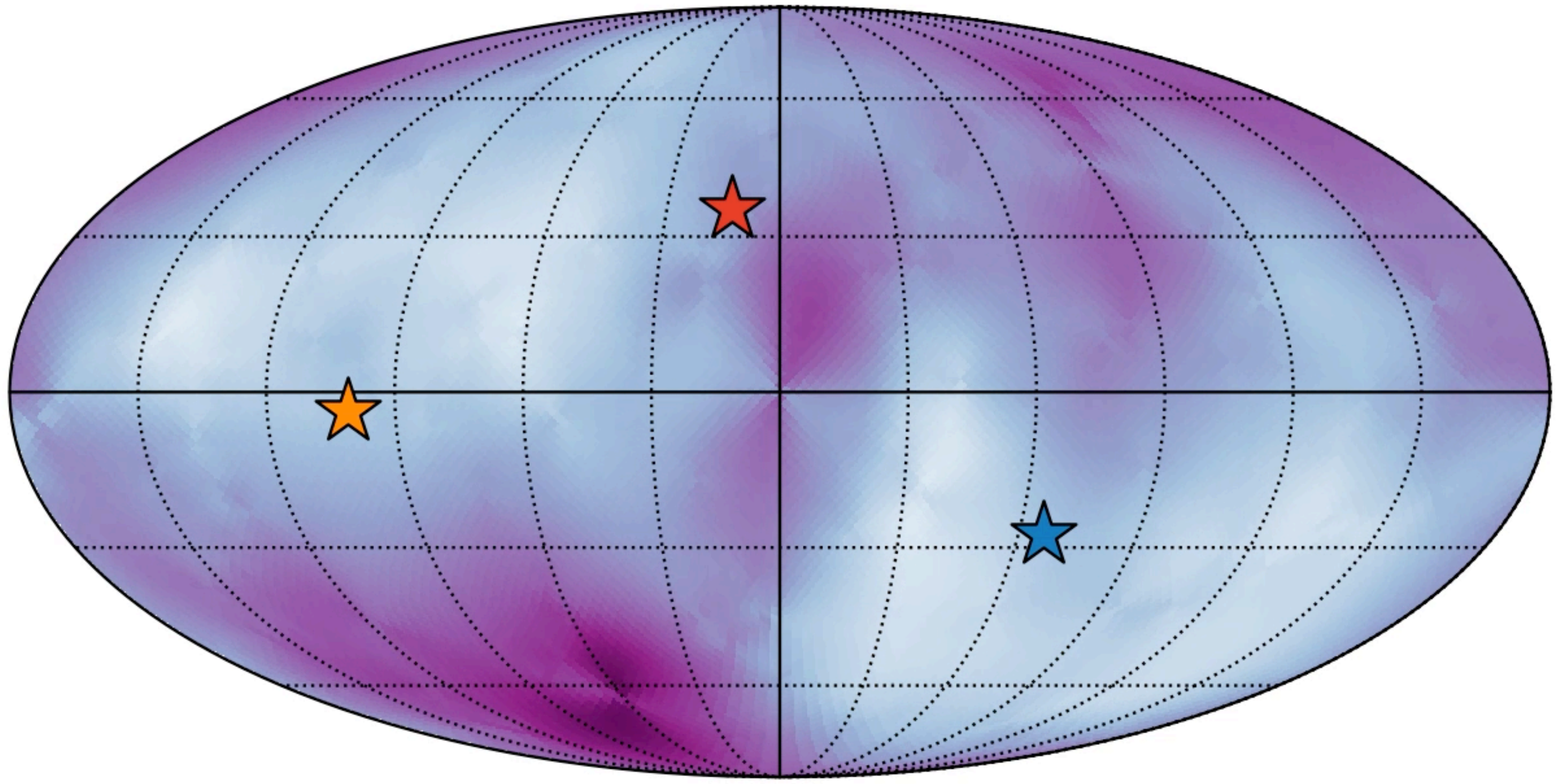

Joeri van Leeuwen

Pulsar Timing Arrays

1 pulsar



an array of pulsars



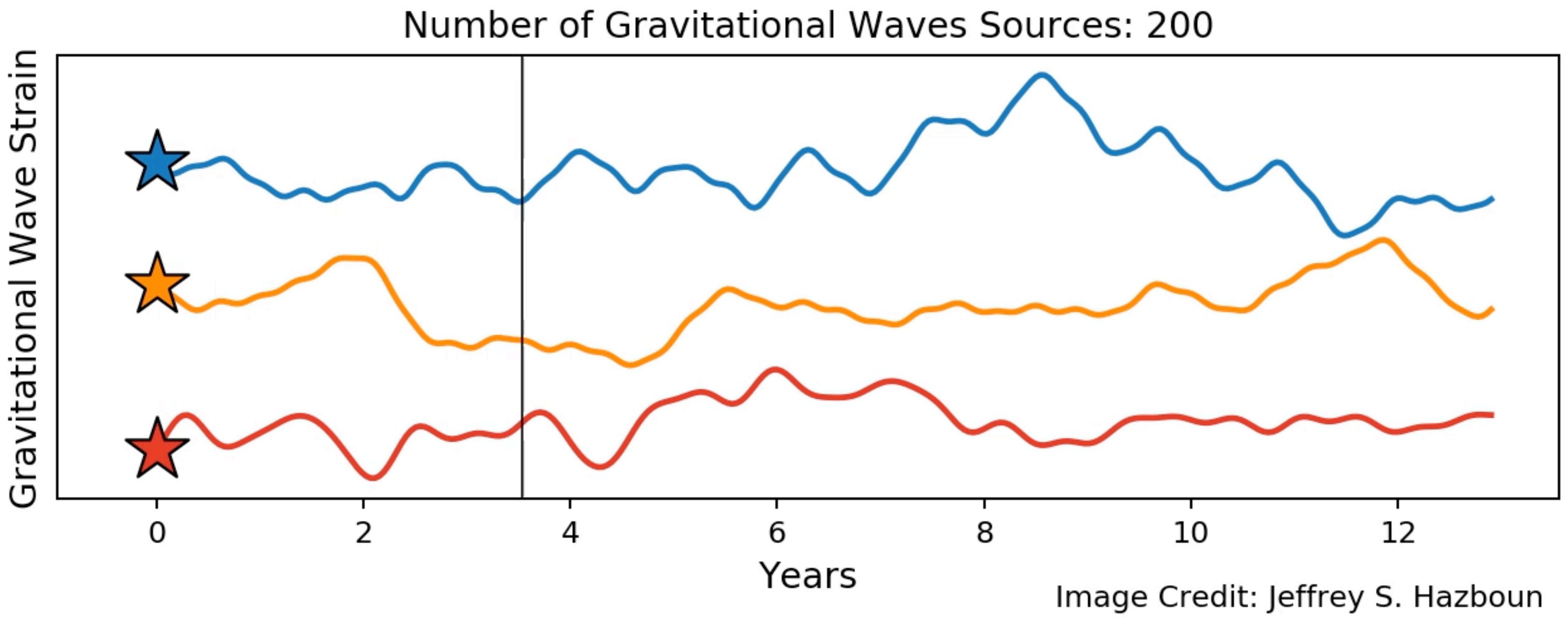
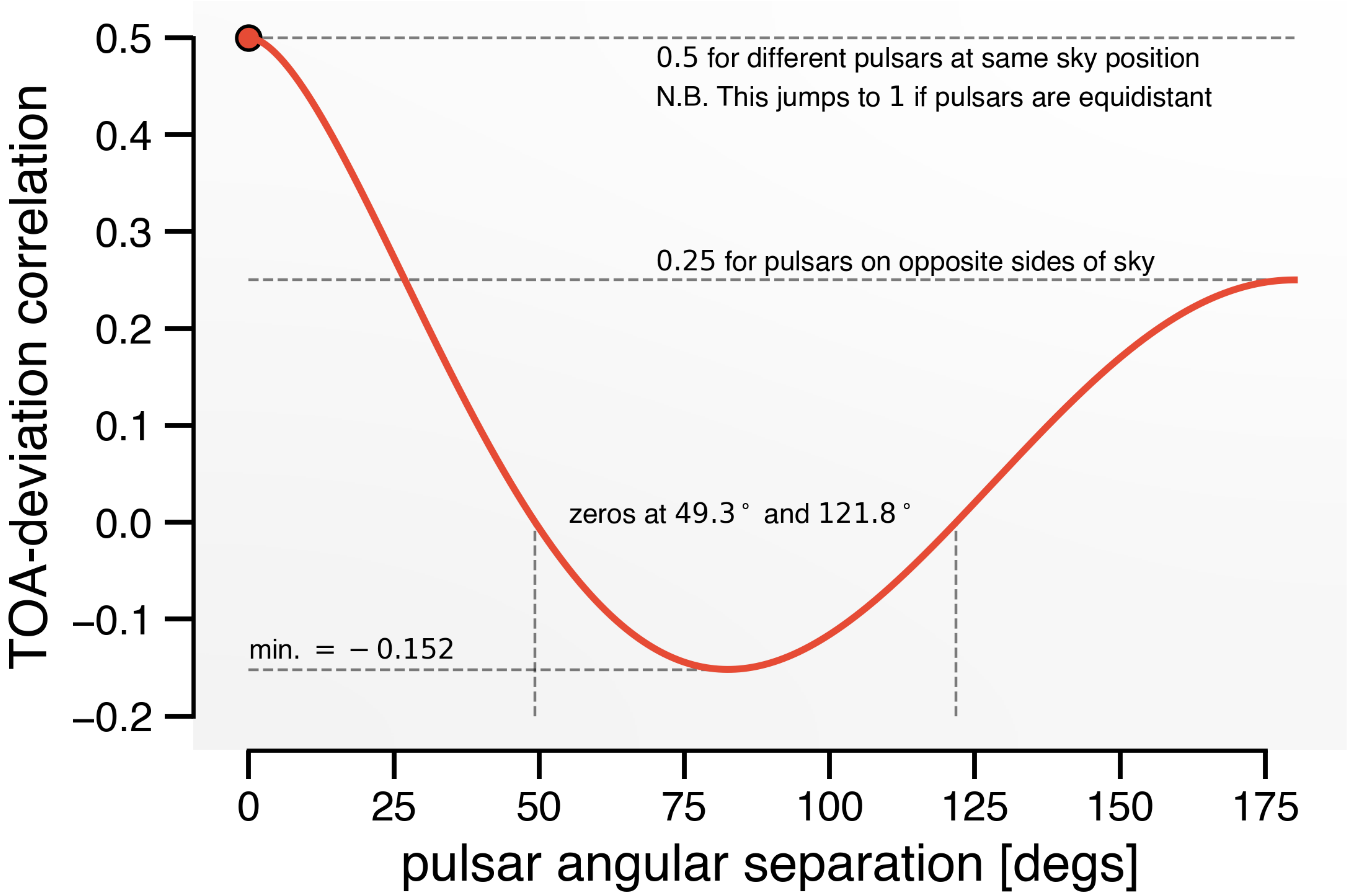


Image Credit: Jeffrey S. Hazboun

Pulsar Timing Arrays



- Detection requires measuring **quadrupolar correlation** signature between pulsars.

"Hellings & Downs curve"

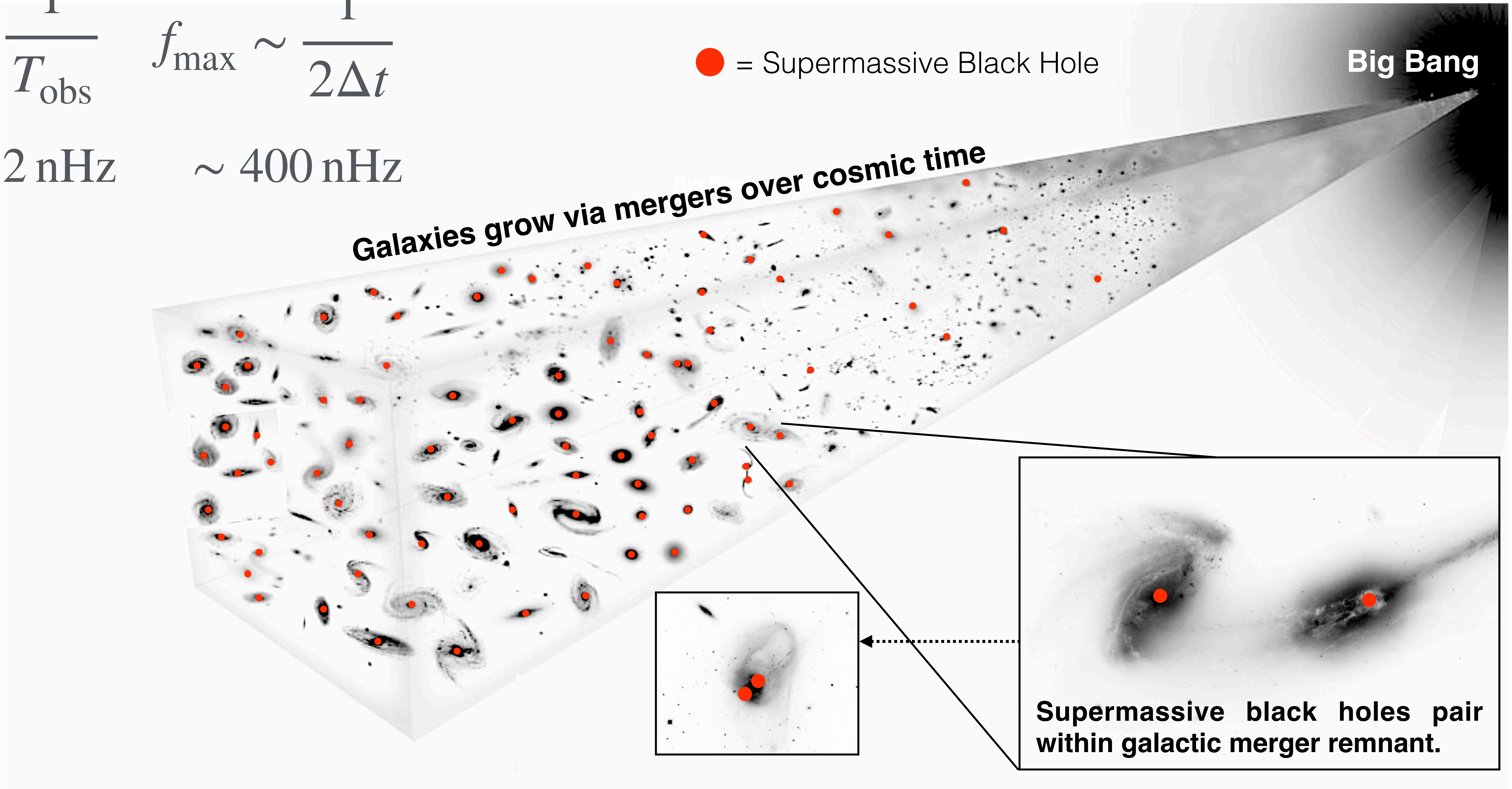
- **Many pulsars** needed.

Credit: NANOGrav Space Public Outreach Team

Supermassive Binary Black Holes

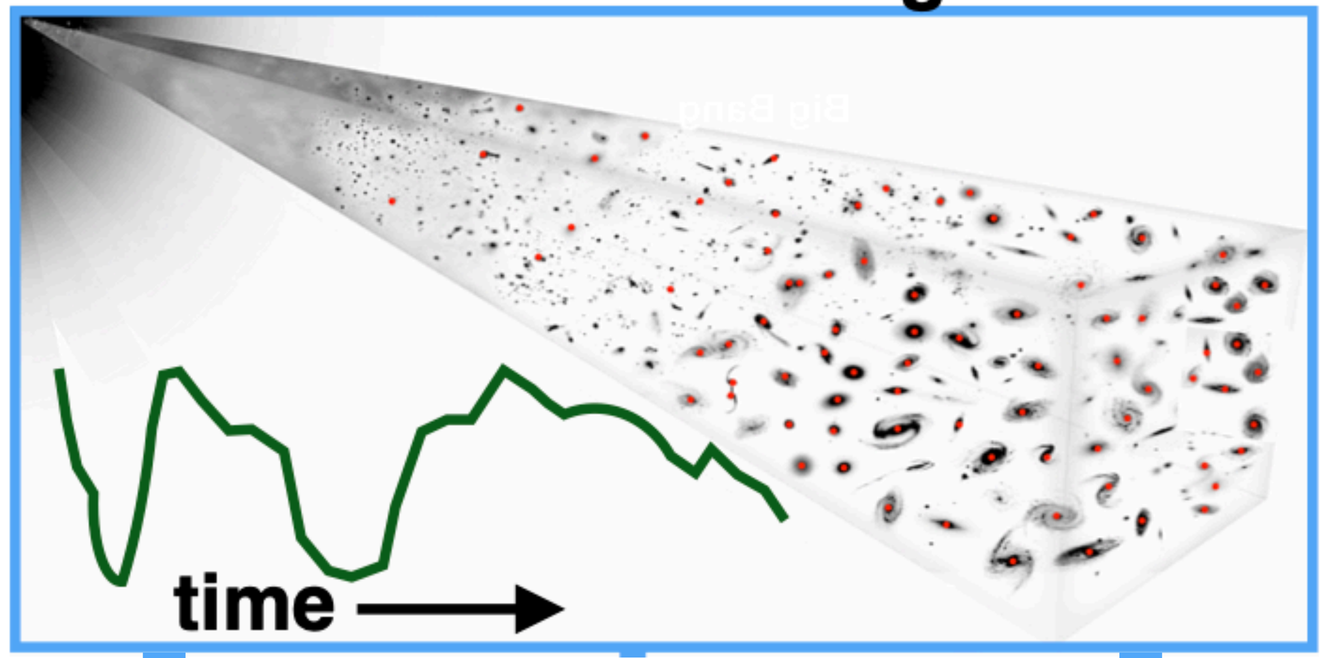
$$f_{\min} = \frac{1}{T_{\text{obs}}} \qquad f_{\max} \sim \frac{1}{2\Delta t}$$

$$\sim 2\,\text{nHz} \qquad \sim 400\,\text{nHz}$$



Detection Timeline

stochastic GW background



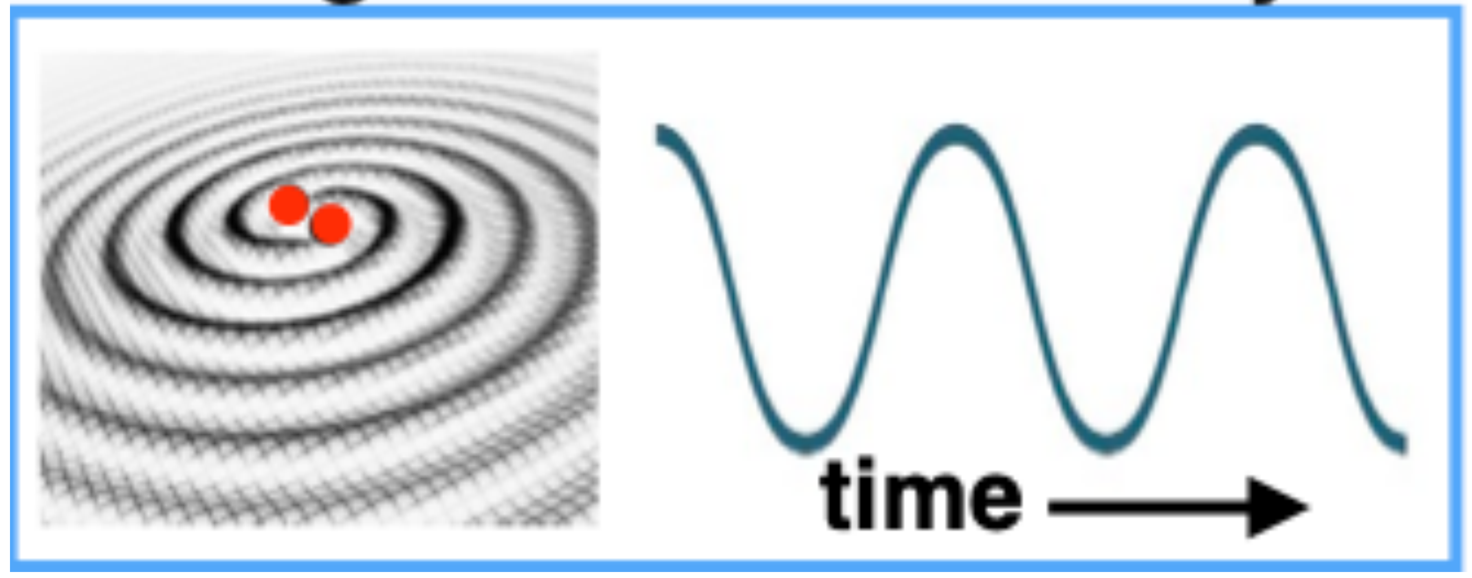
- Rosado+2015
- Mingarelli+2017 [inc. Taylor]
- Kelley+2018 [inc. Taylor]

~2022-2026

~2027-2030

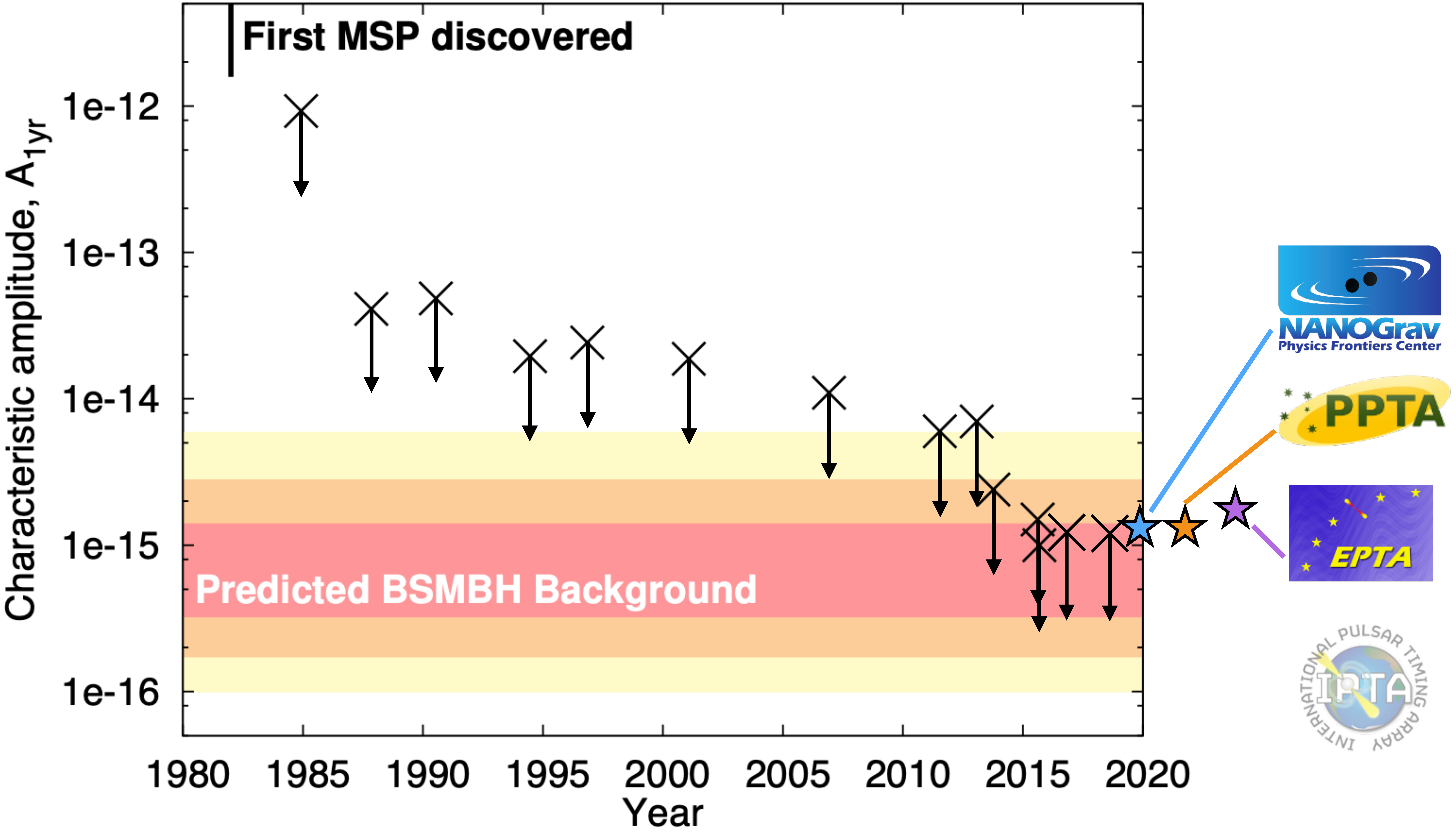
- Siemens+2013
- Rosado+2015
- Taylor+2016
- Kelley+2017 [inc. Taylor]

single resolvable binary



Detection Timeline

Adapted from
Burke-Spolaor et al. (2015)



The NANOGrav 12.5-year Data Set: Search For An Isotropic Stochastic Gravitational-Wave Background

Zaven Arzoumanian,[1] Paul T. Baker,[2] Harsha Blumer,[3,4] Bence Bécsy,[5] Adam Brazier,[6] Paul R. Brook,[3,4] Sarah Burke-Spolaor,[3,4,7] Shami Chatterjee,[6] Siyuan Chen,[8,9,10] James M. Cordes,[6] Neil J. Cornish,[5] Fronefield Crawford,[11] H. Thankful Cromartie,[12] Megan E. DeCesar,[13,14,*] Paul B. Demorest,[15] Timothy Dolch,[16] Justin A. Ellis,[17] Elizabeth C. Ferrara,[18] William Fiore,[3,4] Emmanuel Fonseca,[19] Nathan Garver-Daniels,[3,4] Peter A. Gentile,[3,4] Deborah C. Good,[20] Jeffrey S. Hazboun,[21,*] A. Miguel Holgado,[22] Kristina Islo,[23] Ross J. Jennings,[6] Megan L. Jones,[23] Andrew R. Kaiser,[3,4] David L. Kaplan,[23] Luke Zoltan Kelley,[24] Joey Shapiro Key,[21] Nima Laal,[25] Michael T. Lam,[26,27] T. Joseph W. Lazio,[28] Duncan R. Lorimer,[3,4] Jing Luo,[29] Ryan S. Lynch,[30] Dustin R. Madison,[3,4,*] Maura A. McLaughlin,[3,4] Chiara M. F. Mingarelli,[31,32] Cherry Ng,[33] David J. Nice,[13] Timothy T. Pennucci,[34,35,*] Nihan S. Pol,[3,4] Scott M. Ransom,[34] Paul S. Ray,[36] Brent J. Shapiro-Albert,[3,4] Xavier Siemens,[25,23] Joseph Simon,[28,37] Renée Spiewak,[38] Ingrid H. Stairs,[20] Daniel R. Stinebring,[39] Kevin Stovall,[15] Jerry P. Sun,[25] Joseph K. Swiggum,[13,*] Stephen R. Taylor,[40] Jacob E. Turner,[3,4] Michele Vallisneri,[28] Sarah J. Vigeland,[23] Caitlin A. Witt,[3,4]

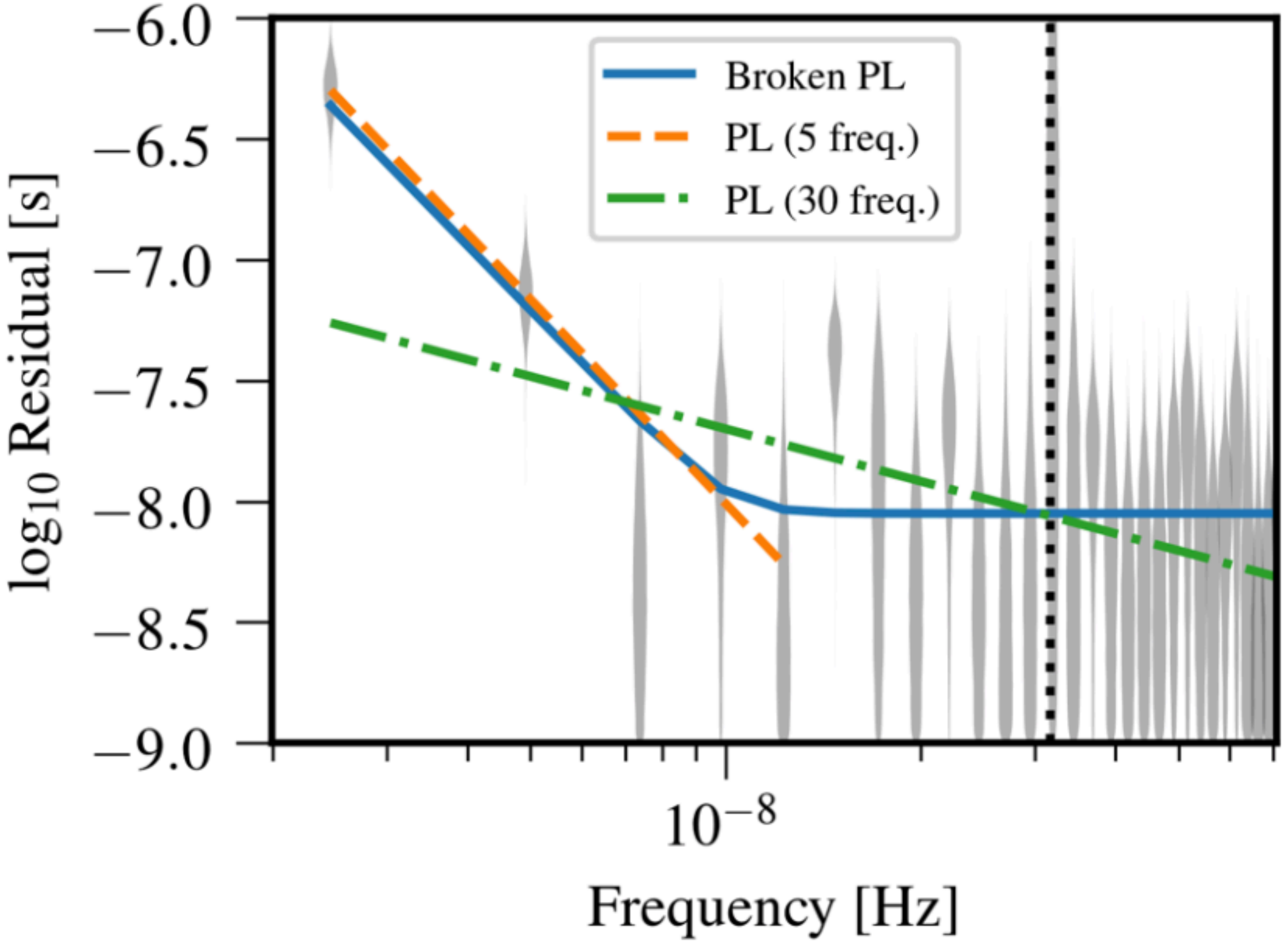
The NANOGrav Collaboration

NANOGrav 12.5yr Dataset Search (arXiv:2009.04496),
The Astrophysical Journal Letters, Volume 905, Number 2 (2020)
corresponding author: Joe Simon (JPL / CU-Boulder)

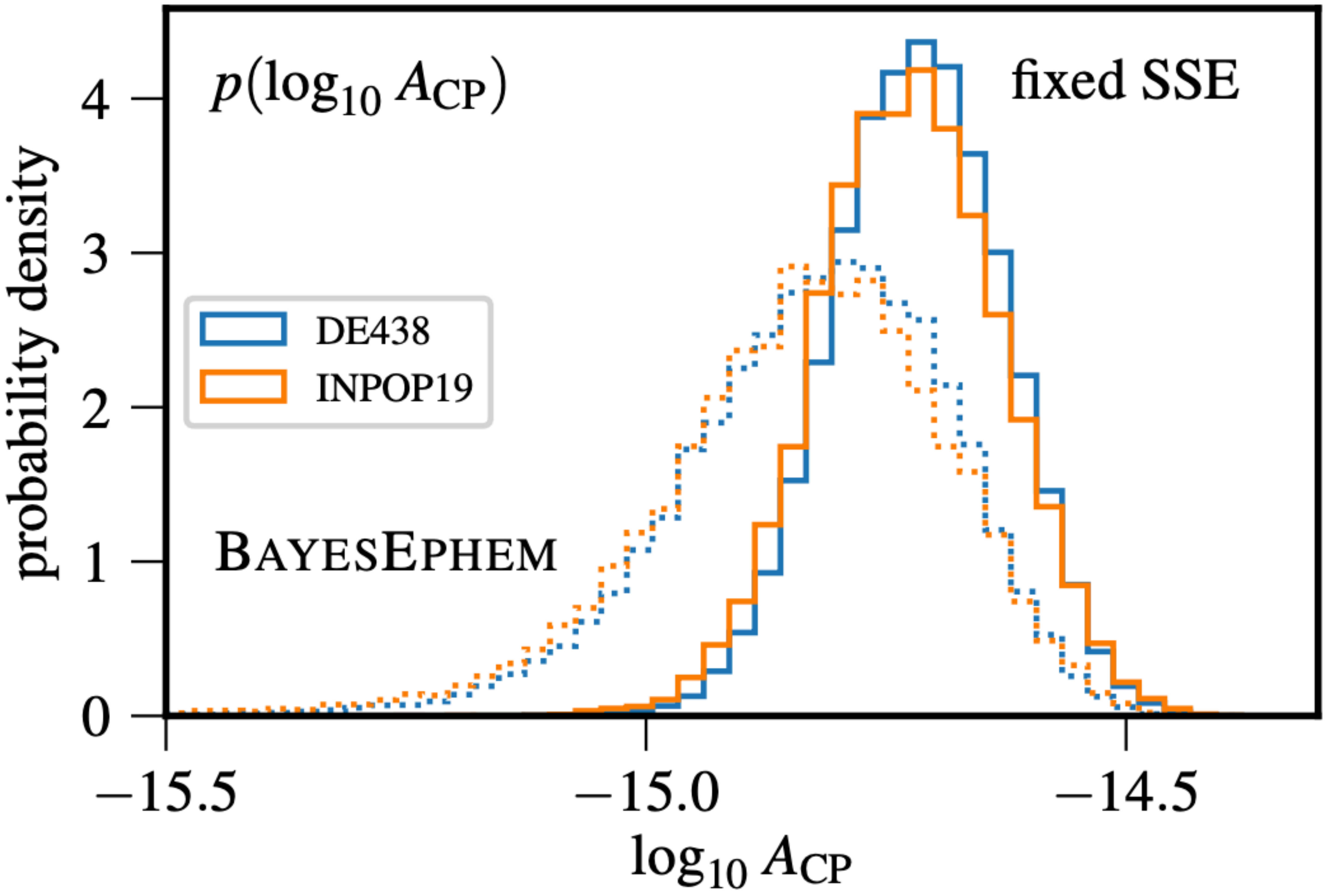
251 citations since Sep 2020

A Common-spectrum Process

NANOGrav 12.5yr Dataset Search (arXiv:2009.04496),
corresponding author: Joe Simon (JPL / CU-Boulder)



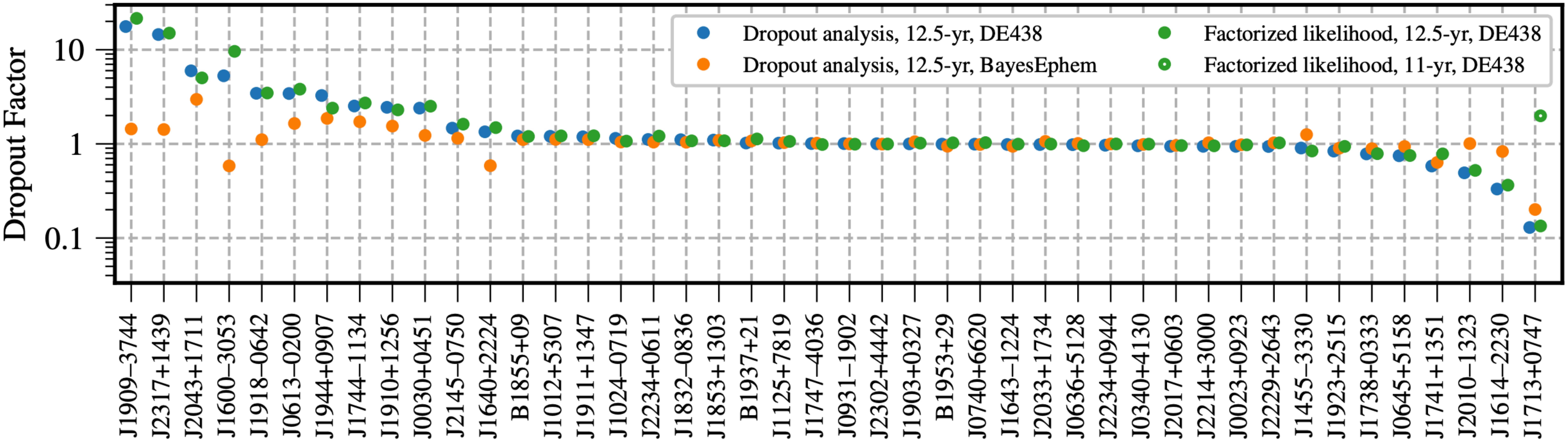
A steep-spectrum process in common across NANOGrav's 45-pulsar array with max-baseline 12.9 years.



Assuming this is a GW background of SMBHB origin *(fixes the spectral shape)*, the median amplitude is $\sim 1.9 \times 10^{-15}$

A Common-spectrum Process

NANOGrav 12.5yr Dataset Search (arXiv:2009.04496), *corresponding author: Joe Simon (JPL / CU-Boulder)*

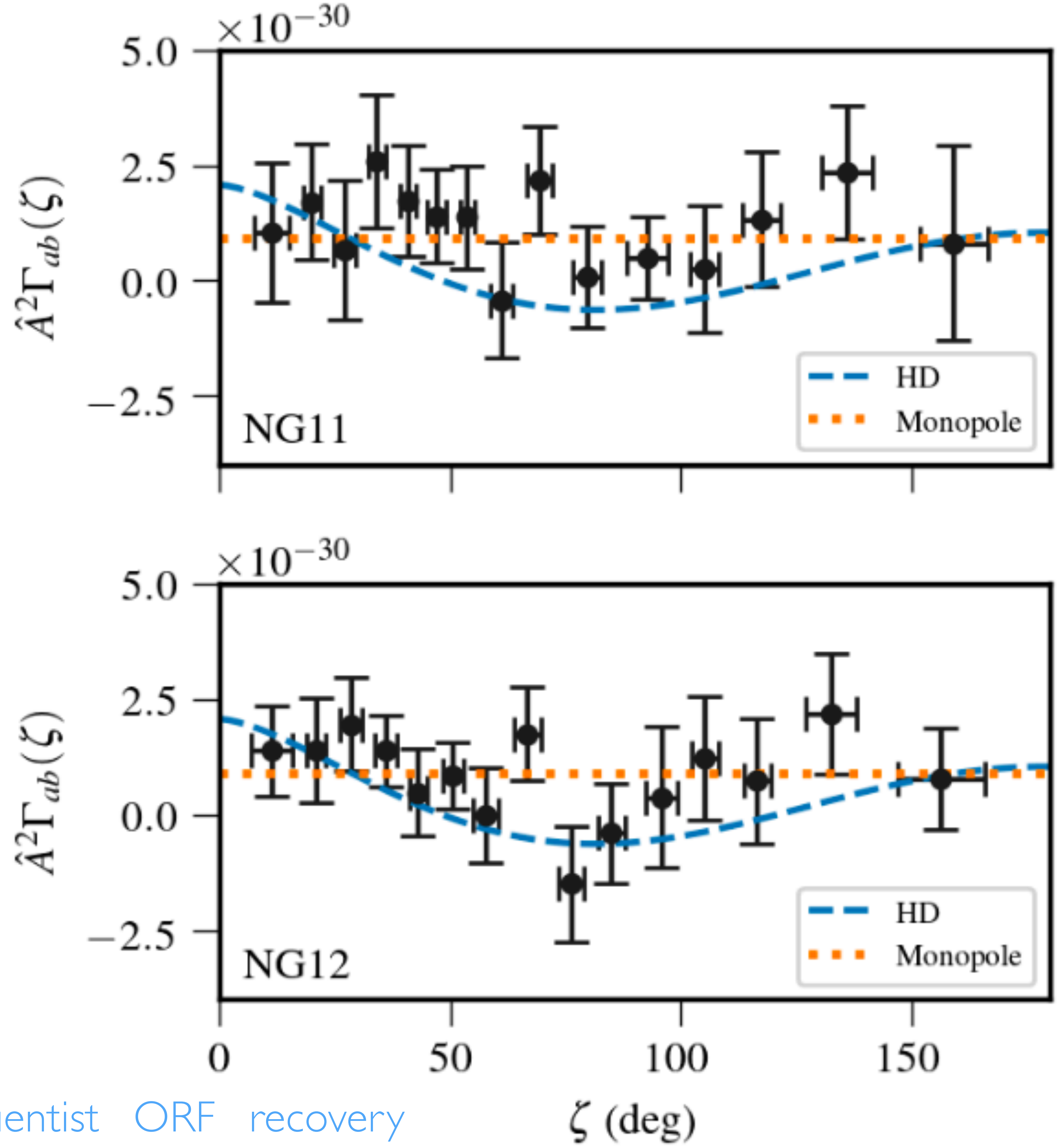


Dropout factor = cross-validation probability

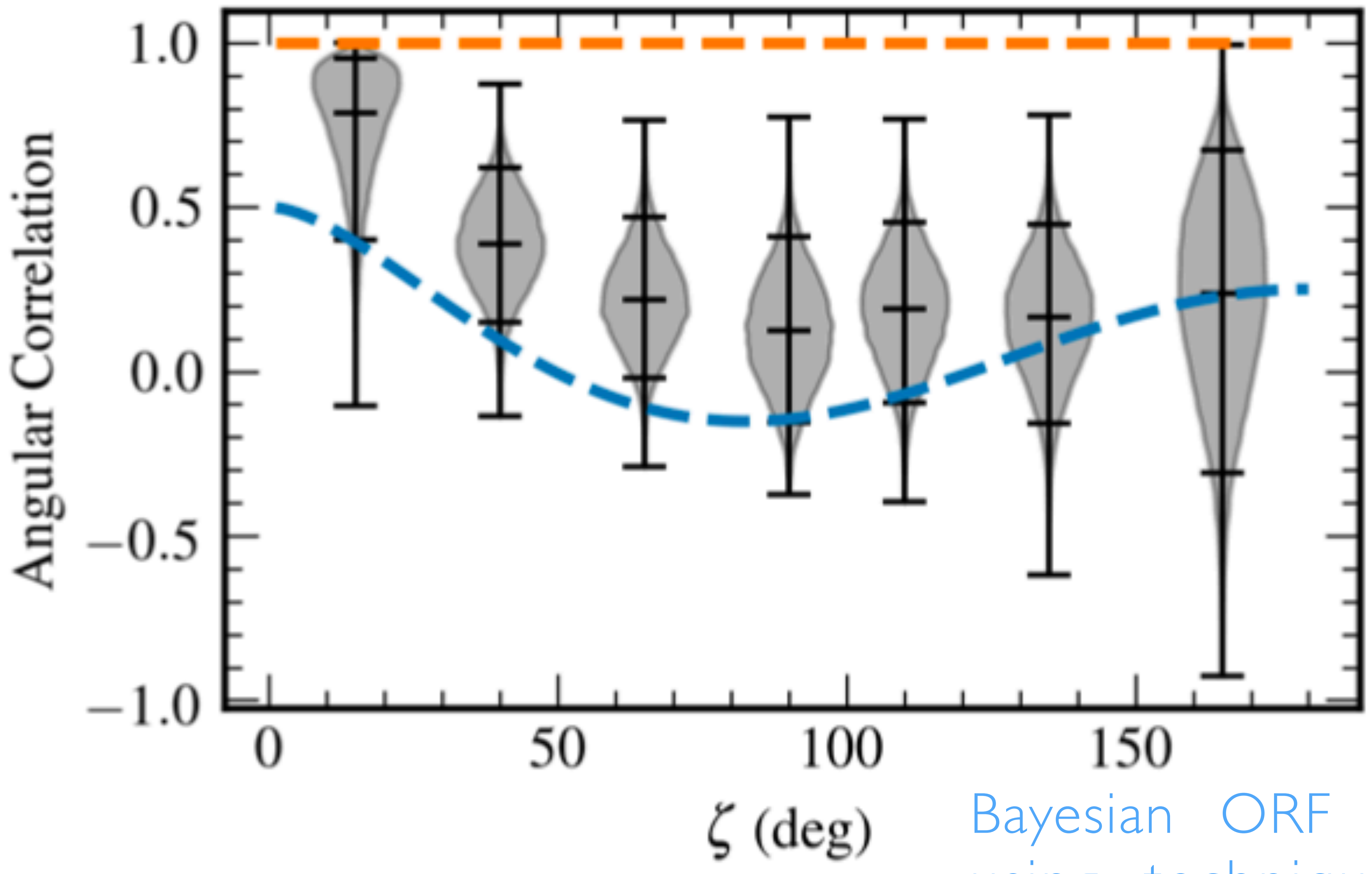
i.e. how much does this pulsar support what is found by all other pulsars?

A Common-spectrum Process

NANOGrav 12.5yr Dataset Search (arXiv:2009.04496), *corresponding author: Joe Simon (JPL / CU-Boulder)*



Frequentist ORF recovery —> Vigeland et al. (2018), Chamberlin et al. (2015), etc.

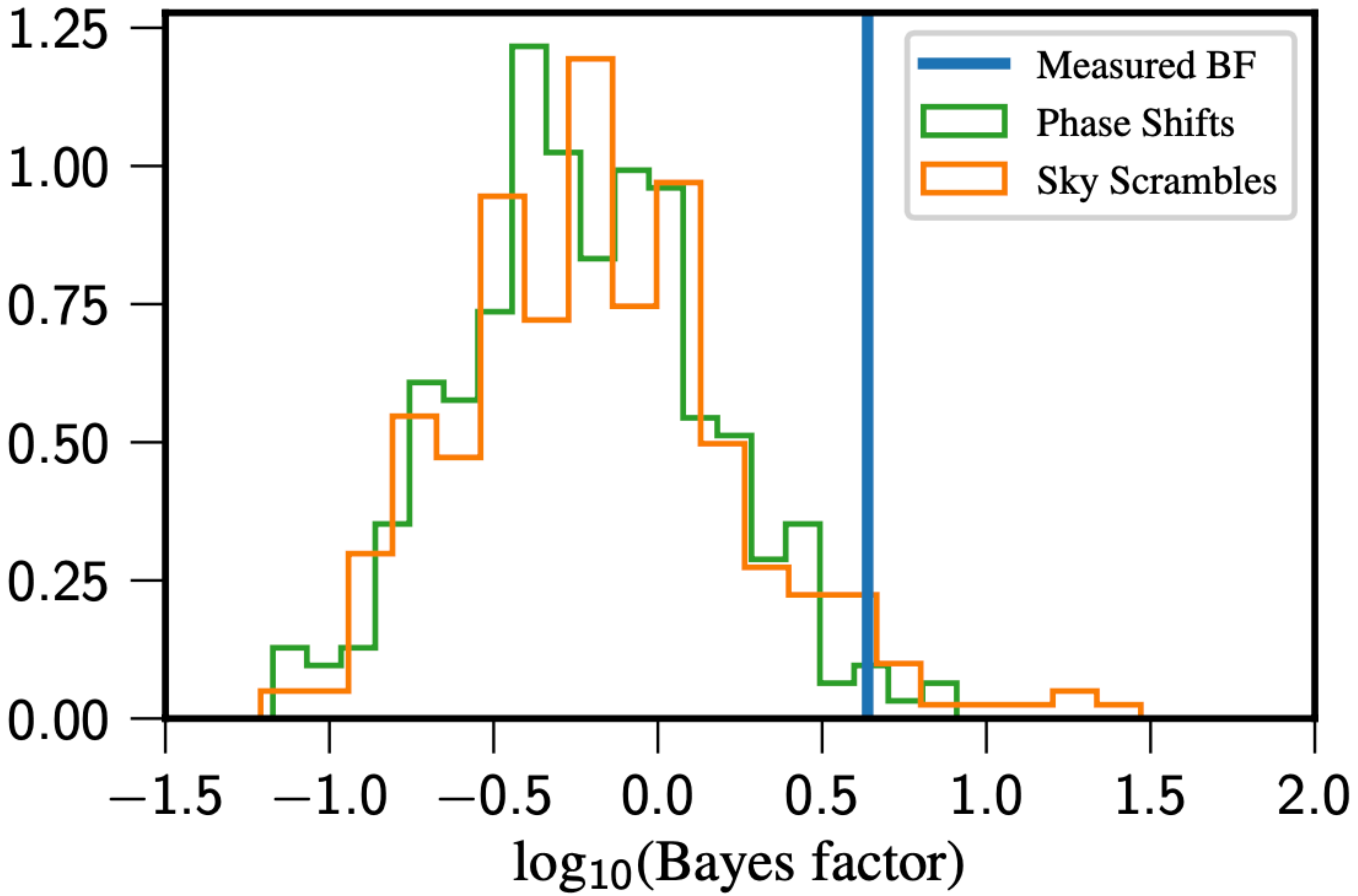


Bayesian ORF recovery using techniques from Taylor, Gair, Lentati (2013)

- Inter-pulsar correlations remain insignificant.
- Odds ratios for Hellings & Downs correlations **~2–4** depending on ephemeris modeling.

A Common-spectrum Process

NANOGrav 12.5yr Dataset Search (arXiv:2009.04496),
corresponding author: Joe Simon (JPL / CU-Boulder)

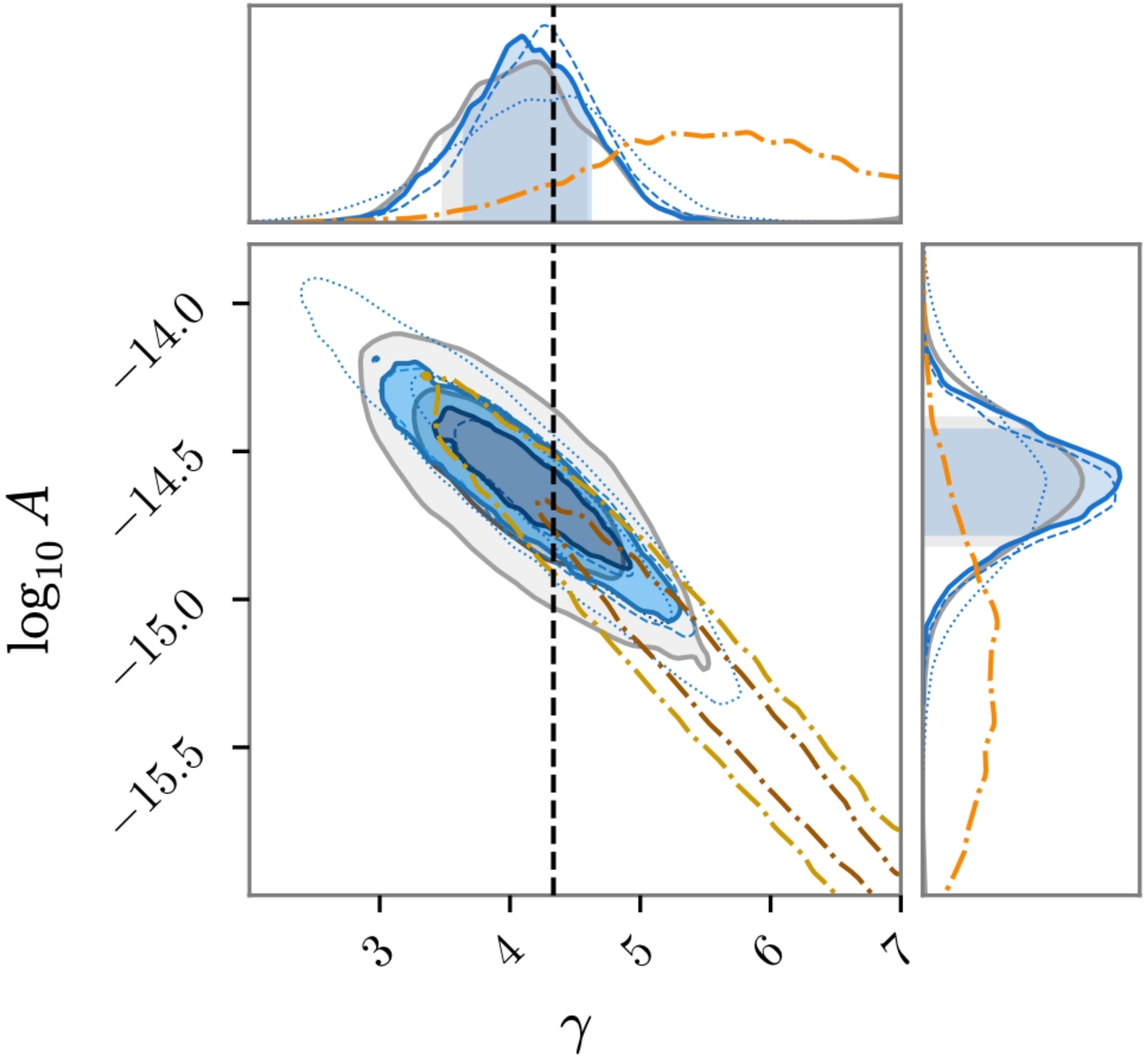


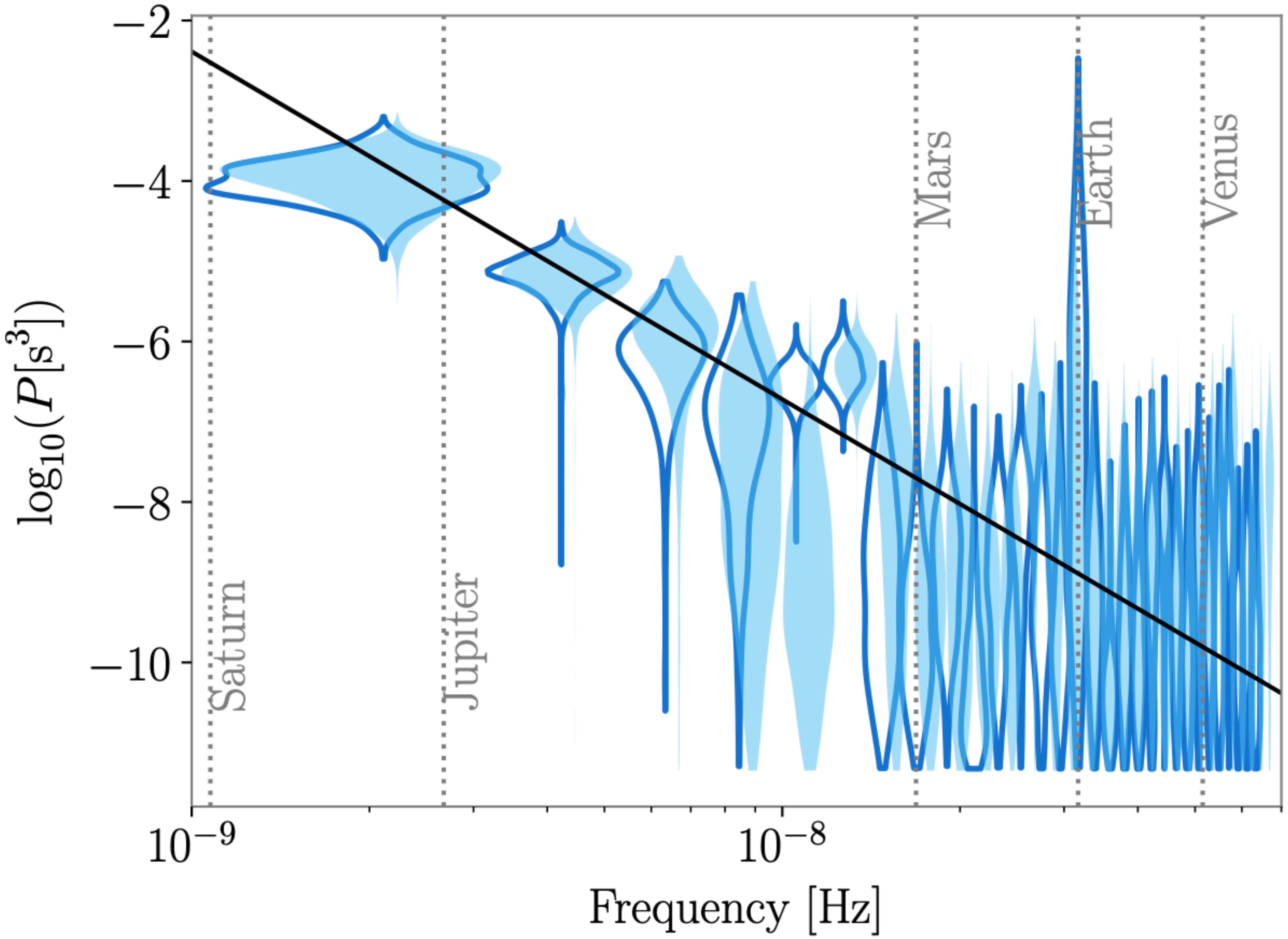
- Assess the significance of spatial correlations by constructing null distribution.
- LIGO-Virgo use time slides…we use **phase shifts (Taylor et al. 2017)** and **sky scrambles (Cornish & Sampson 2016; Taylor et al. 2017).**
- p ~ 5-10%

Independent validation

PPTA Search (arXiv:2107.12112),
corresponding author: Boris Goncharov (Swinburne/GSSI)

Independent **PPTA** analysis shows consistency!

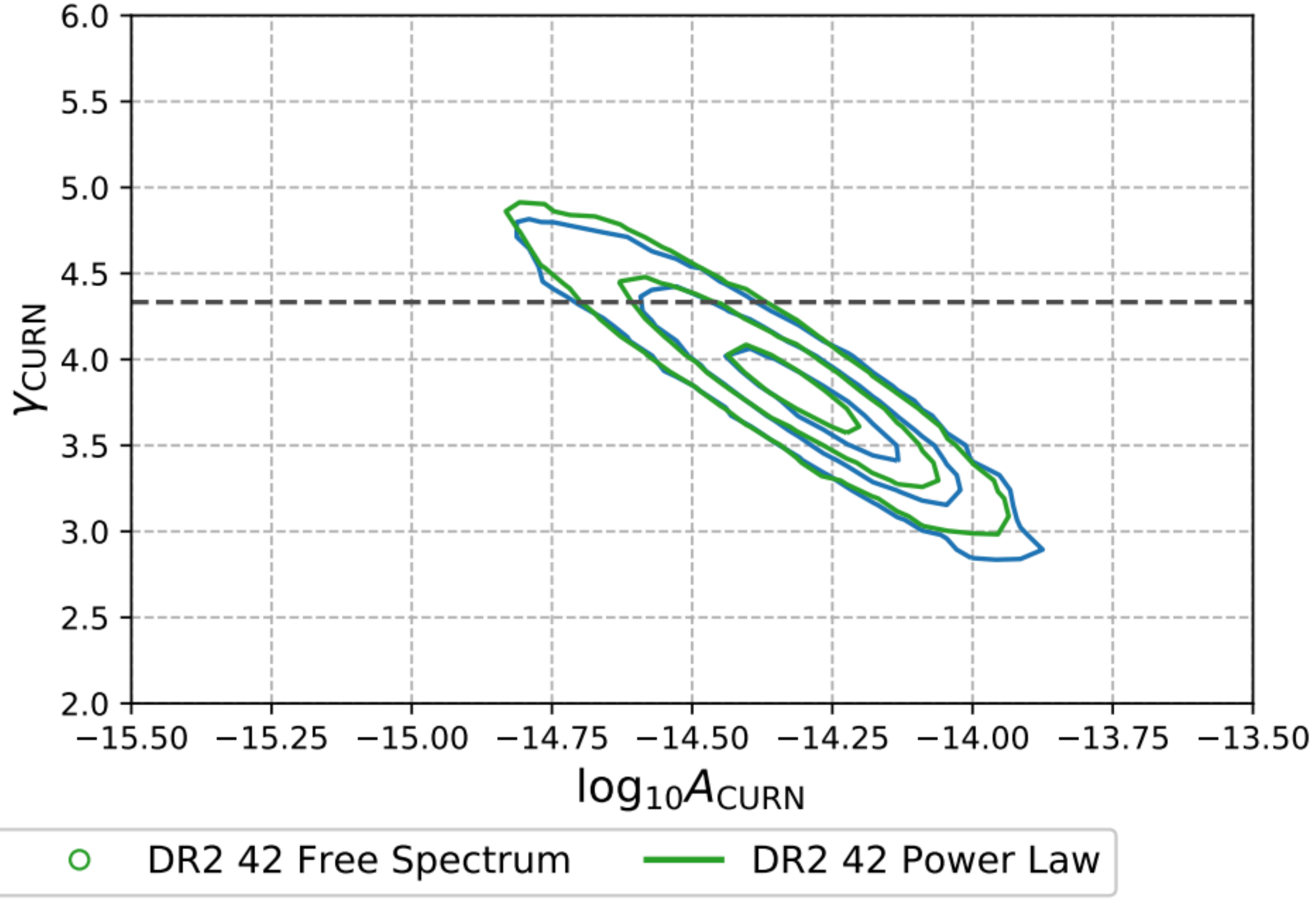


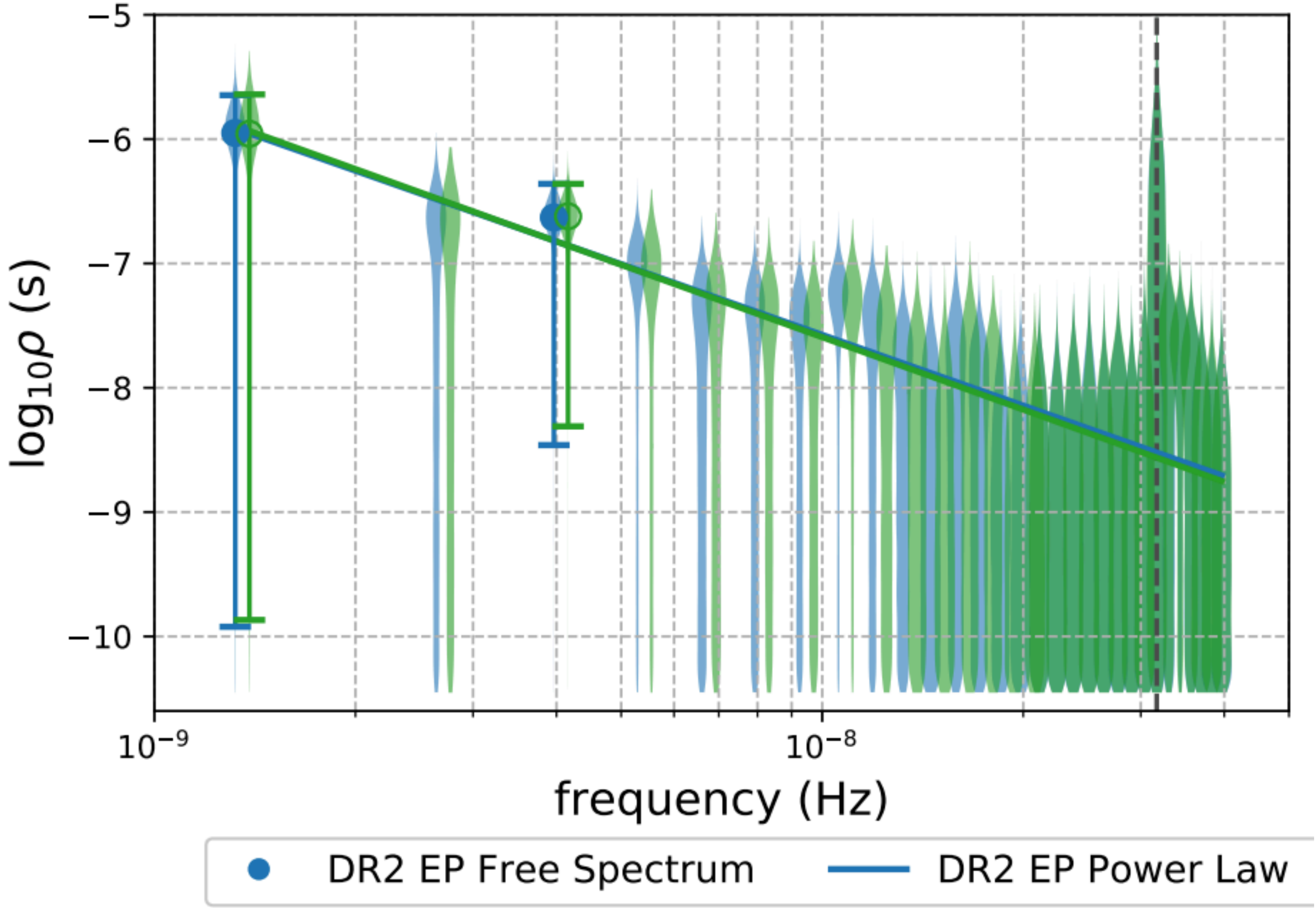


Independent validation

EPTA Search (arXiv:2110.1318),
corresponding author: Siyuan Chen (CNRS)

Independent **EPTA** analysis shows consistency! — ***IPTA** results coming very soon*





The Road To & Beyond Detection

…Or "what to expect when you're expecting to detect a signal".

Dr. Nihan Pol

Simulate up to 20 years of PTA data, forecasting from the 45 pulsars in the NG 12.5yr data

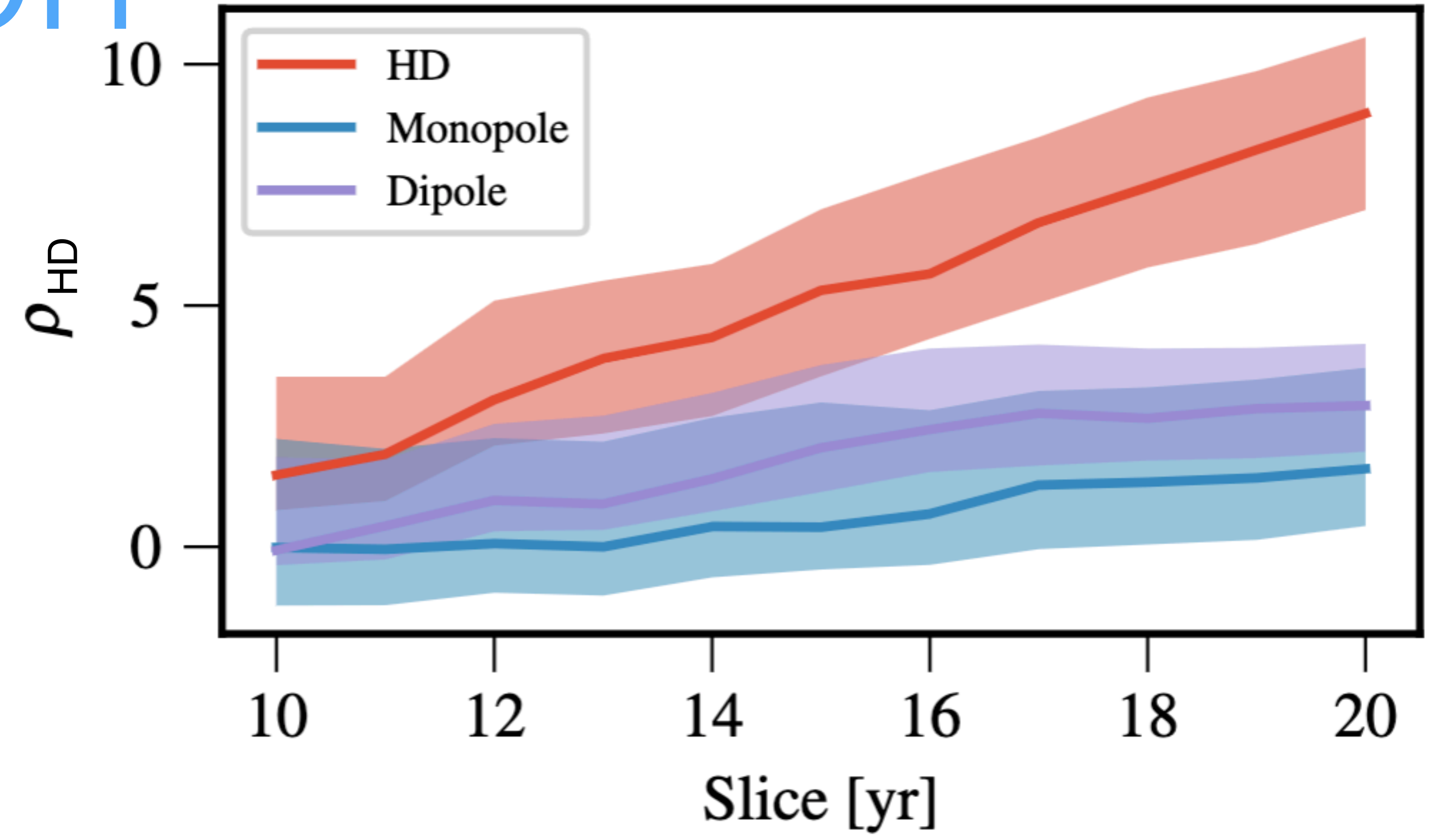
$\hat{\rho}$ = total S/N *(from full log-likelihood ratio)*

$\rho_{\rm HD}$ = cross-correlation S/N

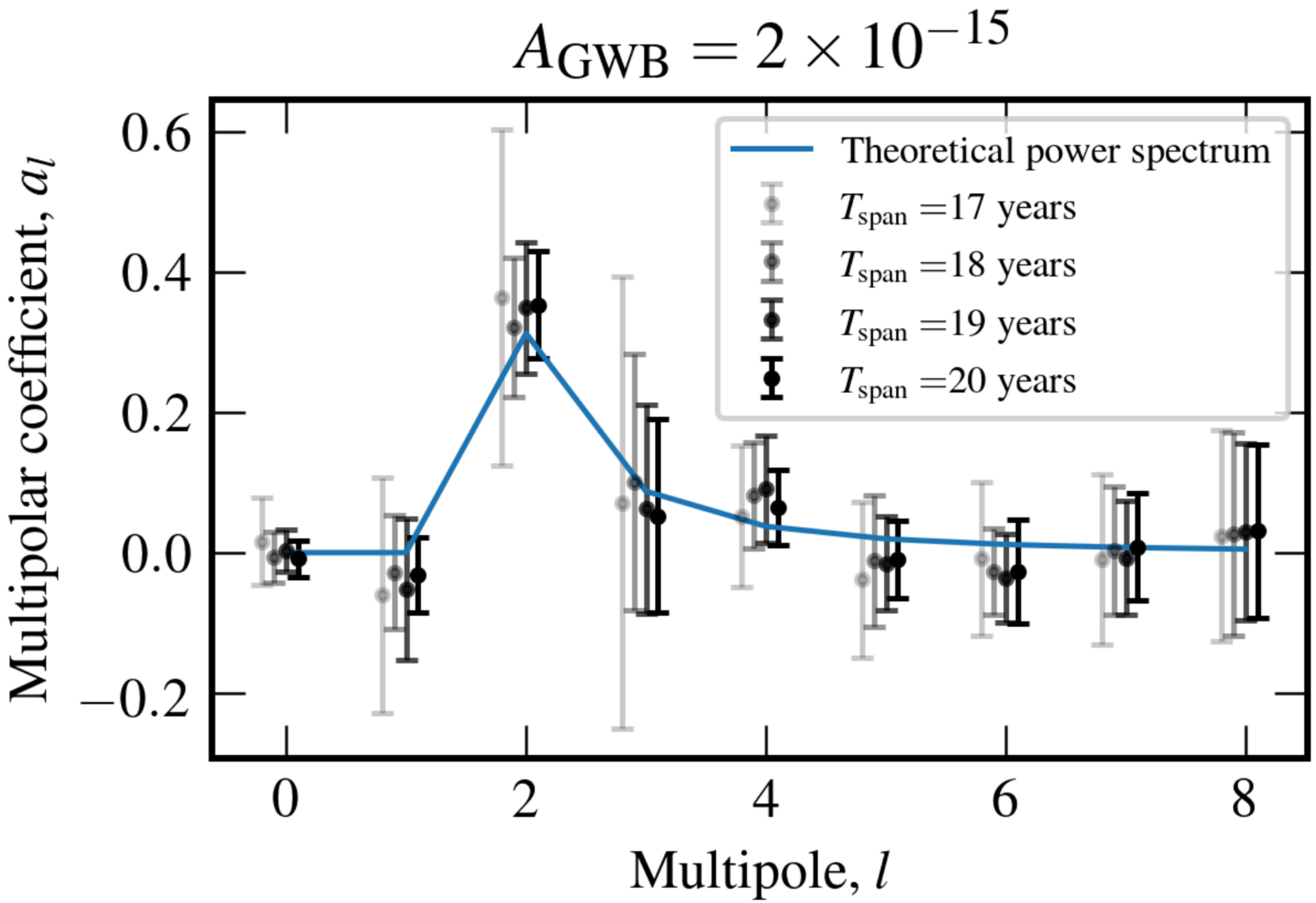
Full team: Nihan Pol, Stephen Taylor, Luke Kelley, Joe Simon, Sarah Vigeland, Siyuan Chen

The Road To & Beyond Detection

…Or "what to expect when you're expecting to detect a signal".



Probe the multipolar structure of the inter-pulsar correlations



$$\Gamma_{ab} = \sum_{l=0}^{\infty} a_l P_l(\cos\theta_{ab})$$

Isotropic GWB:

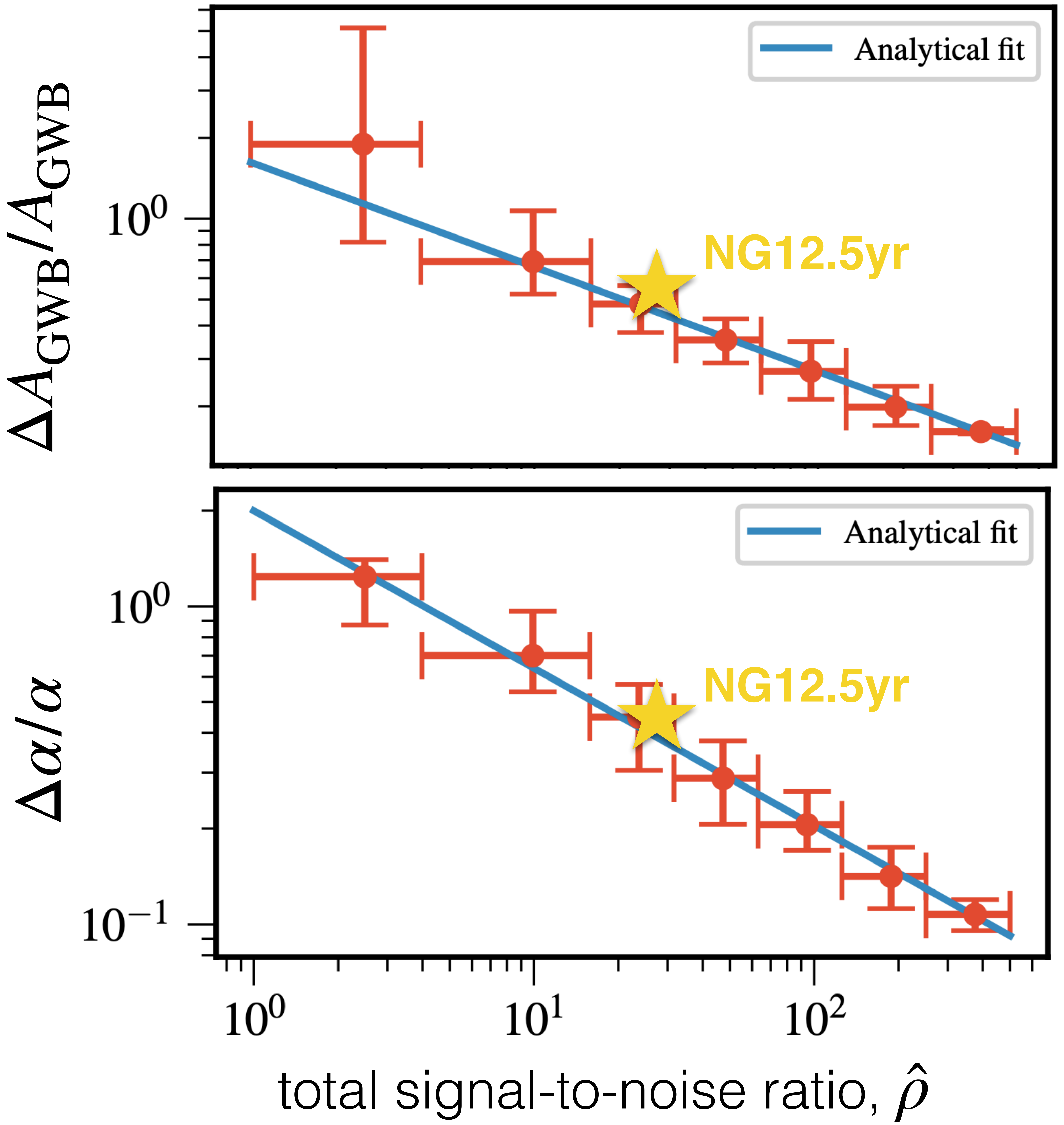
$$\begin{cases} a_l = \frac{3}{4} N_l^2 (2l+1) \\ N_l = \sqrt{\frac{2(l-2)!}{(l+2)!}} \end{cases}$$

Gair, Romano, Taylor, Mingarelli (2014)

The Road To & Beyond Detection

…Or *"what to expect when you're expecting to detect a signal"*.

$$h_c(f) = A_{\mathrm{GWB}} \left(\frac{f}{1\,\mathrm{yr}^{-1}} \right)^{\alpha}$$



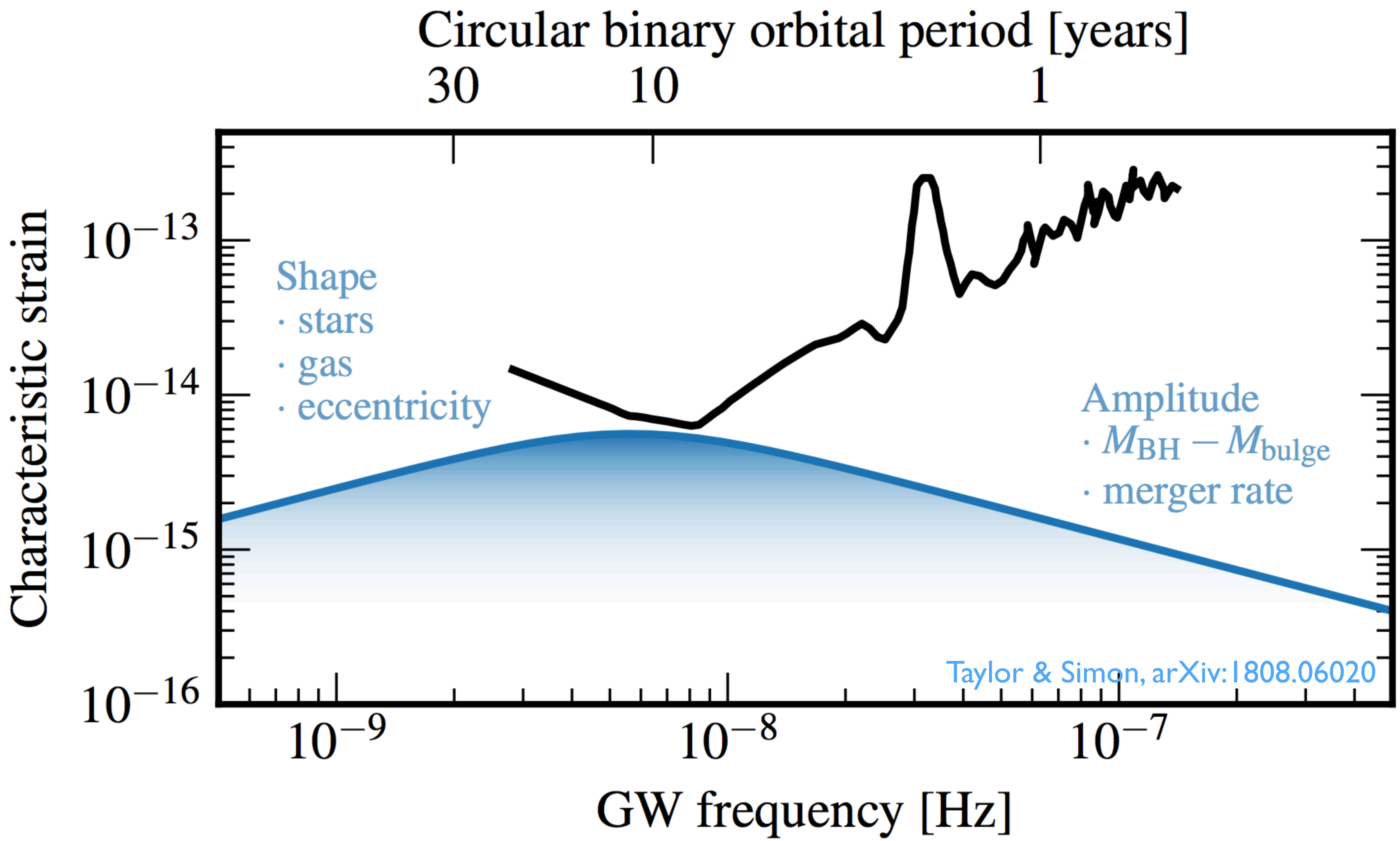
parameter uncertainty scaling laws

$$\Delta A_{\mathrm{GWB}}/A_{\mathrm{GWB}} = 44 \times \left(\frac{\hat{\rho}}{25} \right)^{-2/5} \%$$

$$\Delta\alpha/\alpha = 40 \times \left(\frac{\hat{\rho}}{25} \right)^{-1/2} \%$$

Can relate $\hat{\rho}$ to ρ_{HD} and factors like T, σ_{RMS}, N_{pulsar}, etc.

Stochastic Background Characterization

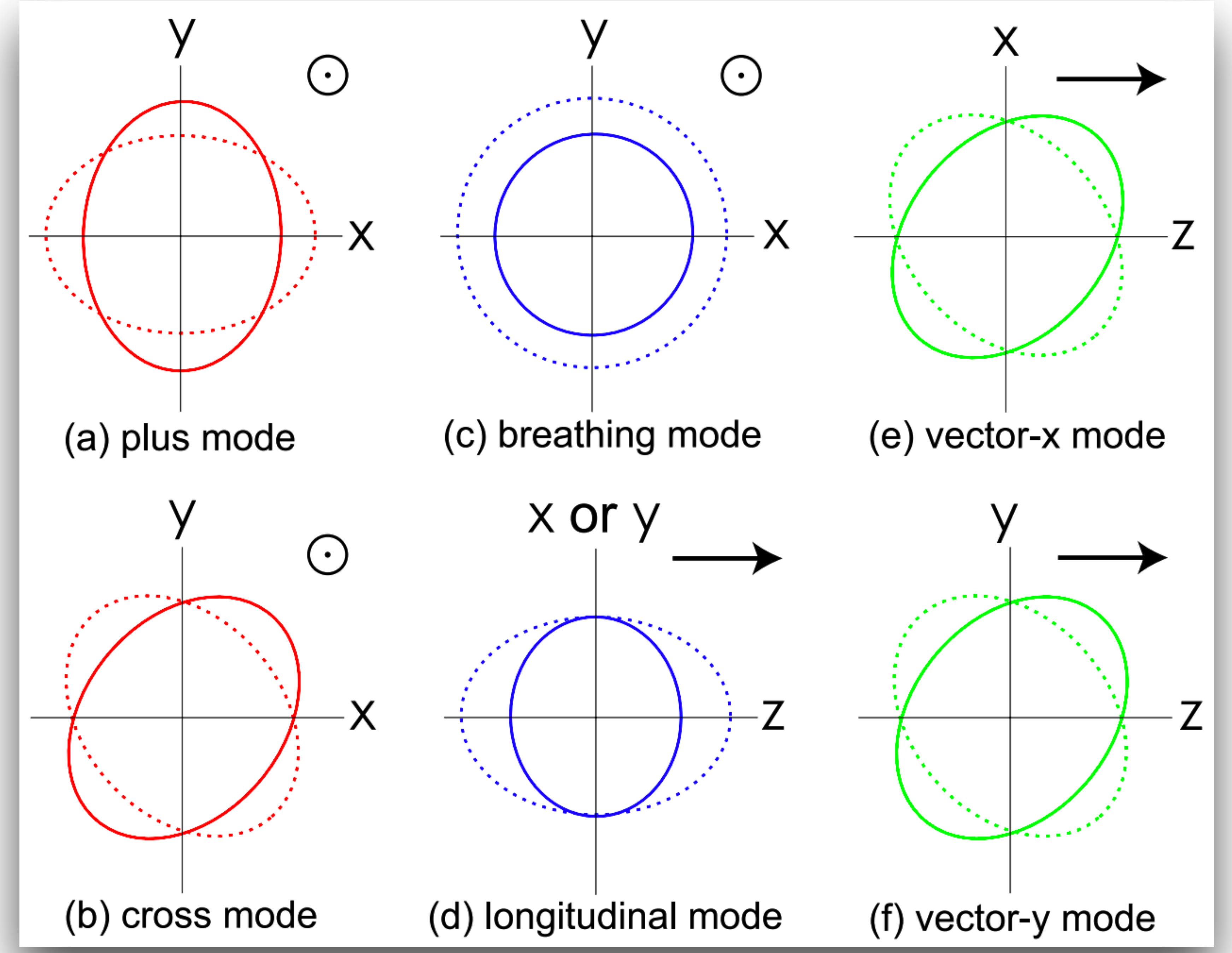


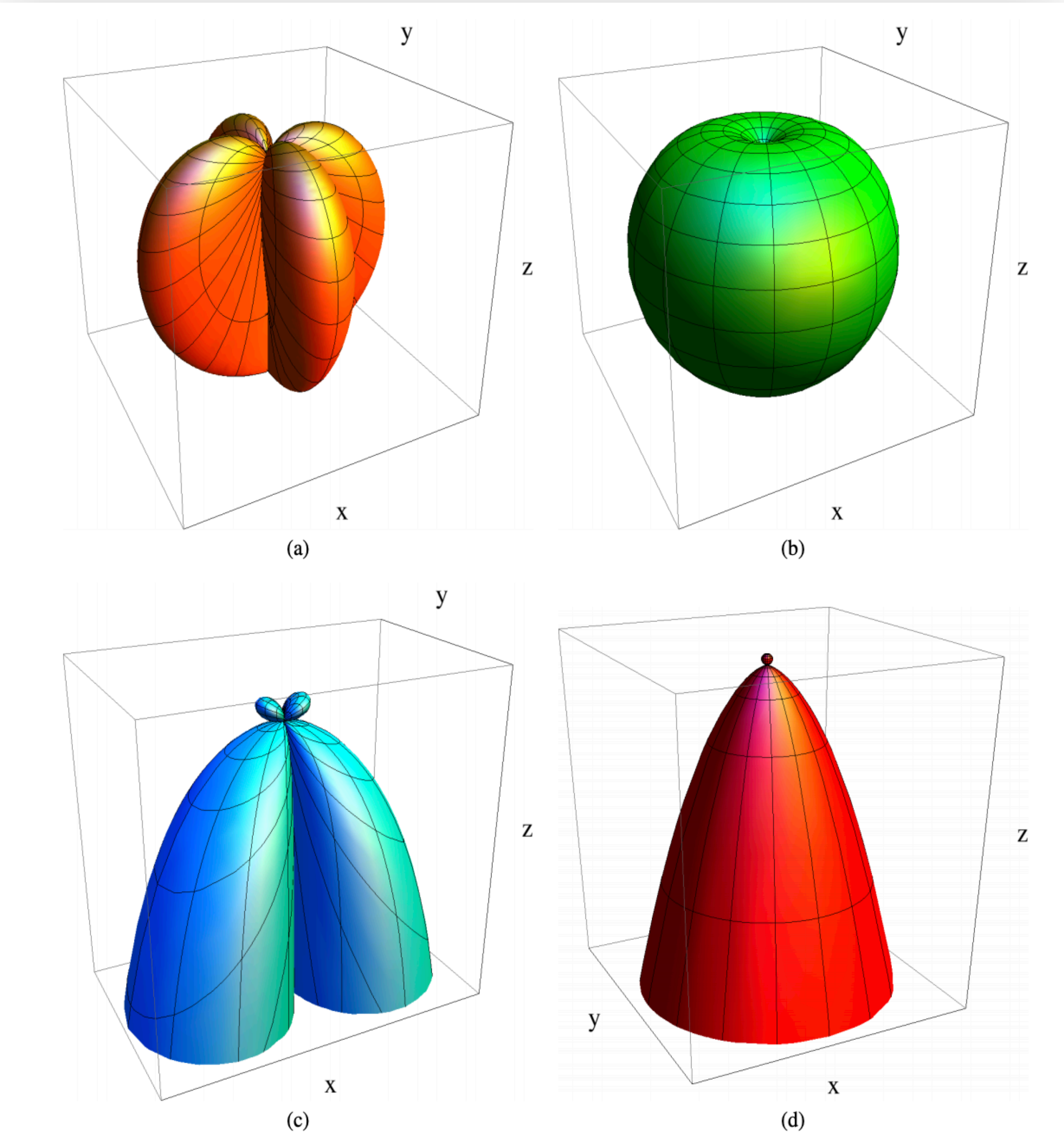
Probe the amplitude for rate factors, and the shape for final-parsec dynamics

e.g. Sampson et al. (2016), Taylor et al. (2017), Chen et al. (2017)

"Astrophysics Milestones For Pulsar Timing Array Gravitational Wave Detection",
Pol, Taylor et al., arXiv:2010.11950

Tests of Gravity





Chamberlin & Siemens (2012)

auto-correlation

$$\Gamma^{\mathrm{TT}}_{aa} \propto \text{constant}$$

$$\Gamma^{\mathrm{SL}}_{aa} \propto fL$$

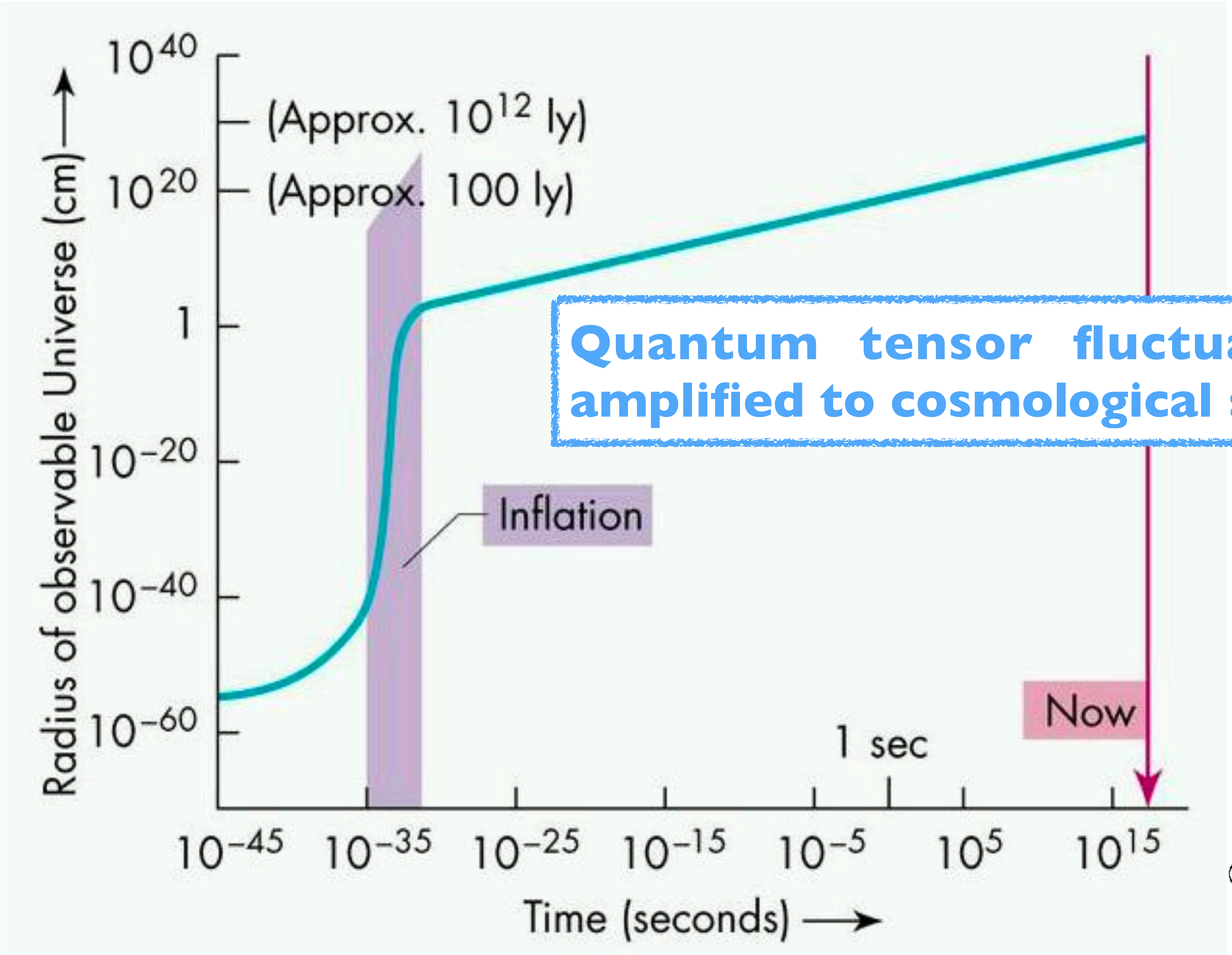
$$\Gamma^{\mathrm{VL}}_{aa} \propto \ln\left(4\pi fL\right)$$

See

- Lee et al. (2008)
- Chamberlin & Siemens (2012)
- Cornish, O'Beirne, Taylor, Yunes (2018), PRL 120, 181101
- Logan, Cornish, Vigeland, Taylor (2019), arXiv:1904.02744

- Generic metric theory of gravity allows **4 more polarization states than GR**'s + and x.
- Includes scalar/vector longitudinal modes that cause very strong autocorrelation signatures in pulsars (with **strong frequency dependence**).

Primordial GWs



Quantum tensor fluctuations amplified to cosmological scales

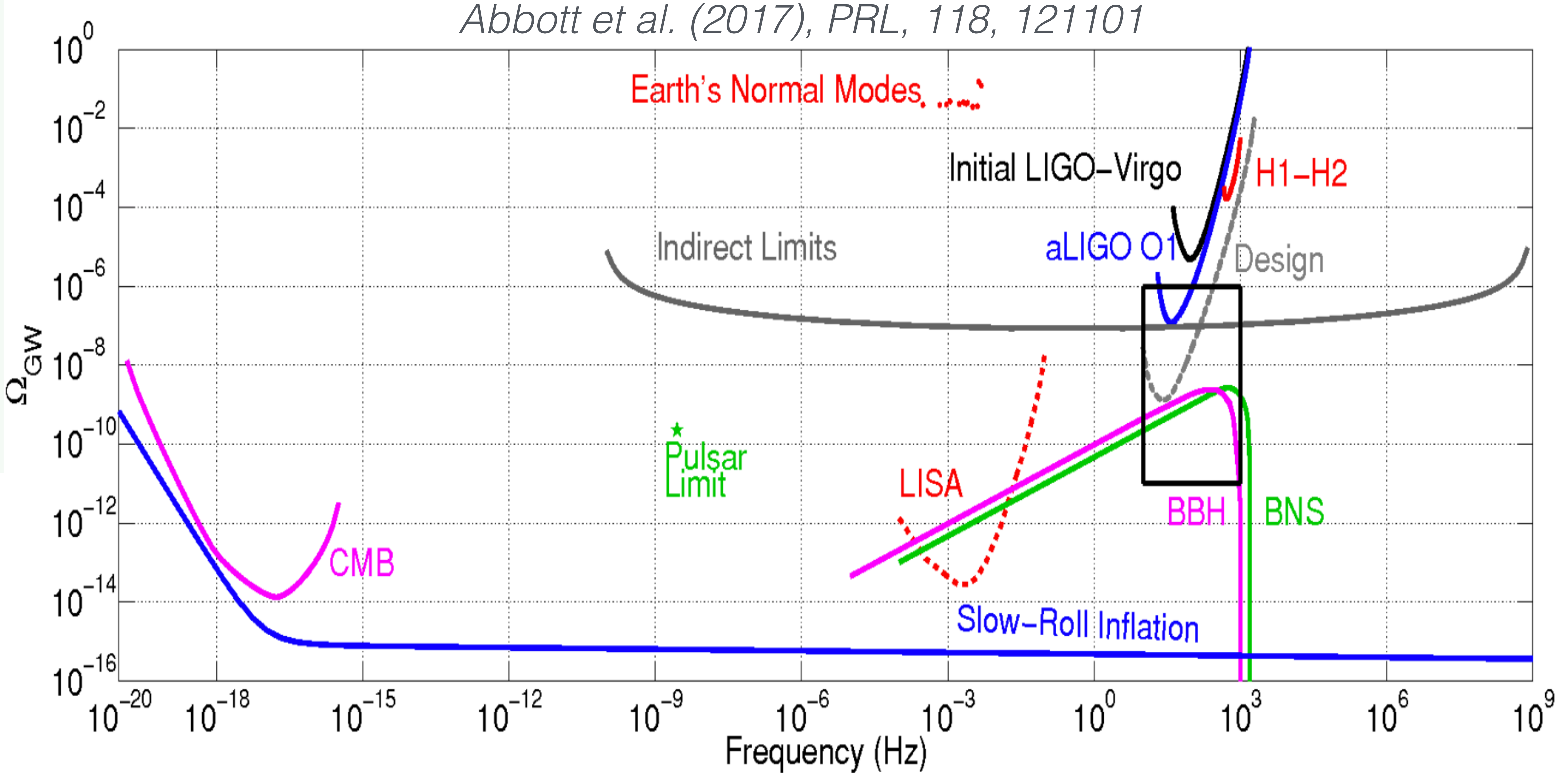
Grishchuk (1976), (1977)
Starobinsky (1980)
Linde (1982)

$$\Omega_{\rm GWB}(f)h^2 = \frac{2\pi^2}{3H_0^2} f^2 h_c^2(f)$$

$$\leq 3.4(1) \times 10^{-10}$$

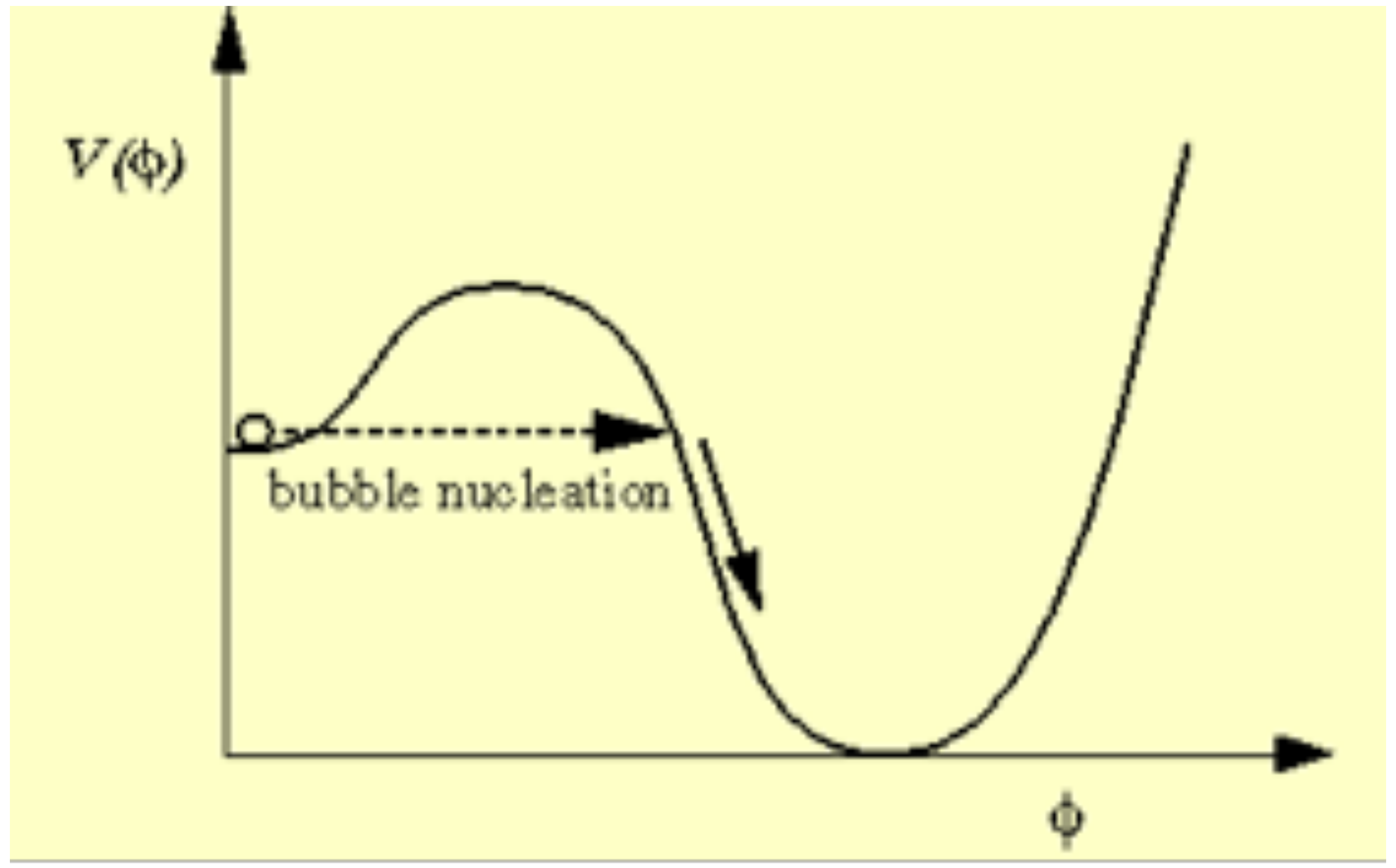
$$@ \quad f = 1/\text{year}$$

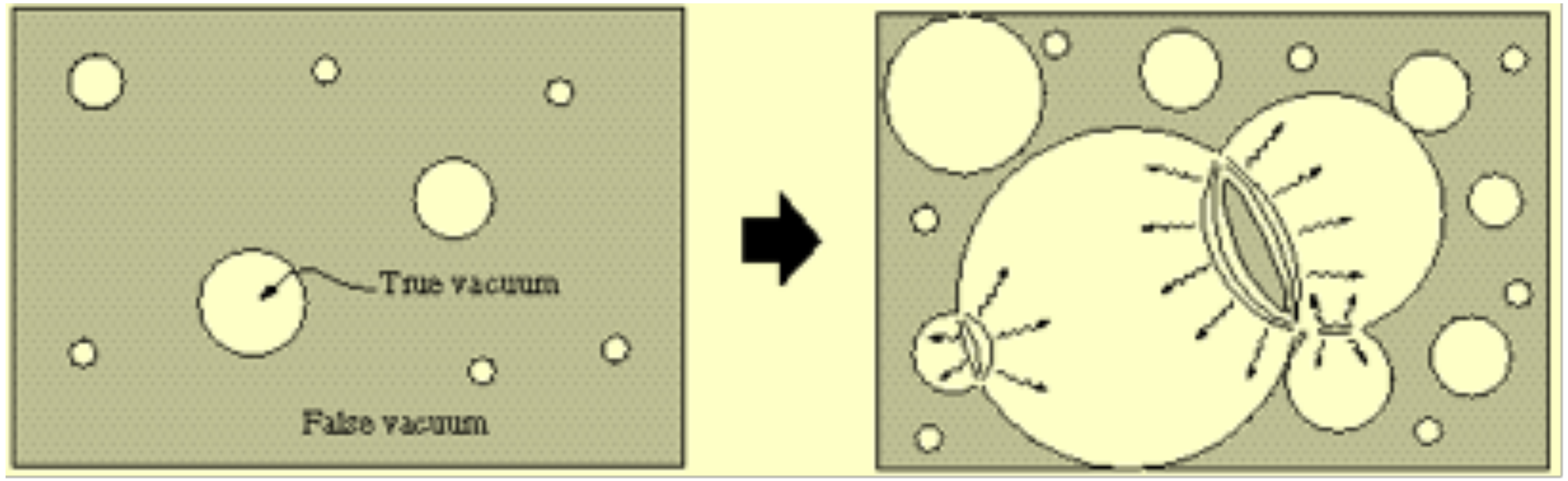
Abbott et al. (2017), PRL, 118, 121101



See Lentati et al. (2015), Shannon et al. (2015), Arzoumanian et al. (2018), Lasky et al. (2016)

Cosmological Phase Transitions



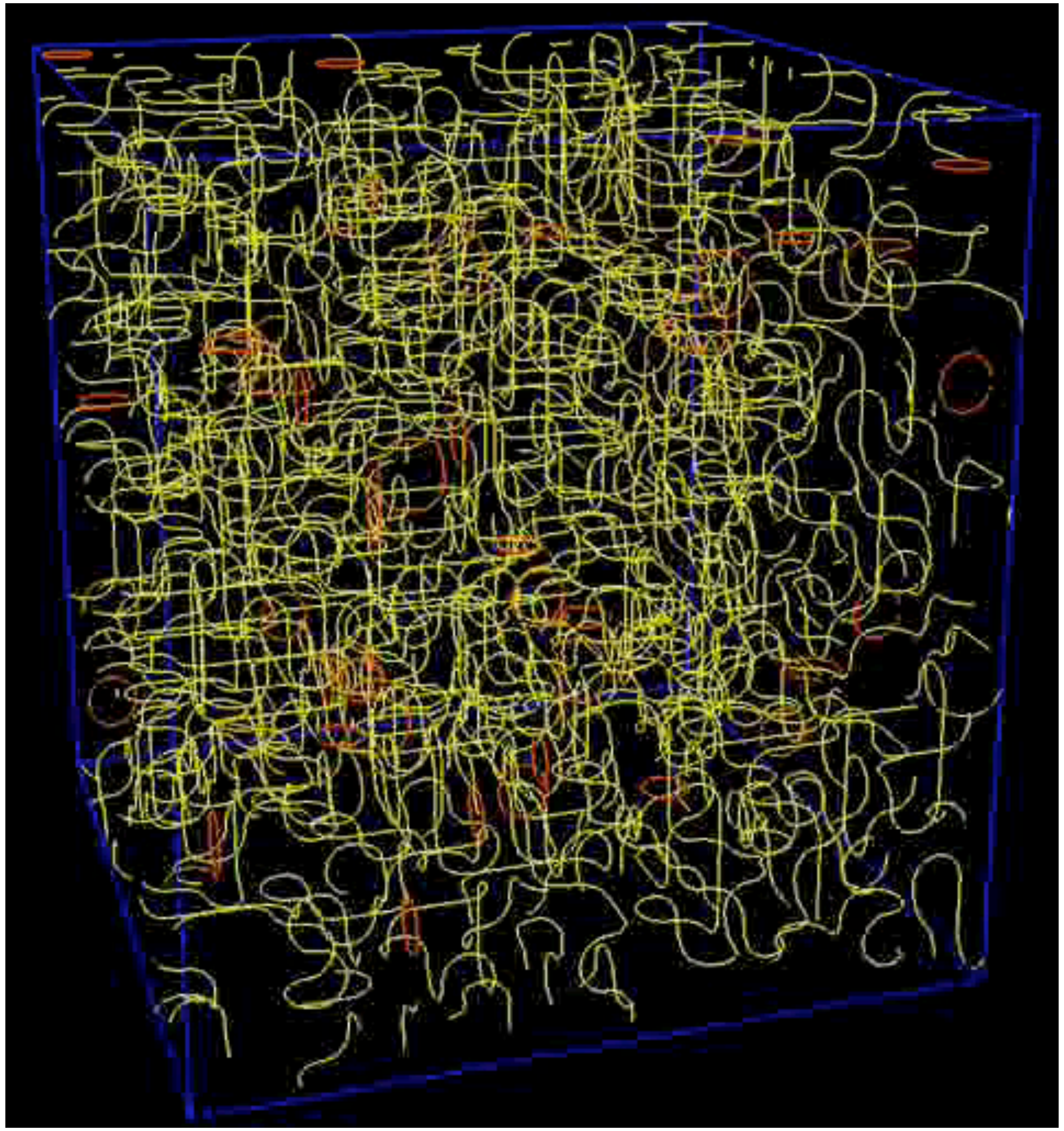


$$f_0^{\rm peak} \simeq 0.113\,{\rm nHz}\left(\frac{f_*^{\rm peak}}{\beta_*}\right)\left(\frac{\beta_*}{H_*}\right)\left(\frac{T_*}{\rm MeV}\right)\left(\frac{g_*}{10}\right)^{1/6}$$

- **NANOGrav** 12.5 Phase Transition Search (*corresponding author:* ***Andrea Mitridate***); arXiv: 2104.13930
  - $T_* \lesssim 10$ Mev, possibly a dark sector transition
  - *In review with PRL.*
- **PPTA** Phase Transition Search (arXiv:2110.03096)
  - PPTA sensitive to $T_* \sim 1 - 100\,{\rm MeV}$
  - *Accepted in PRL.*

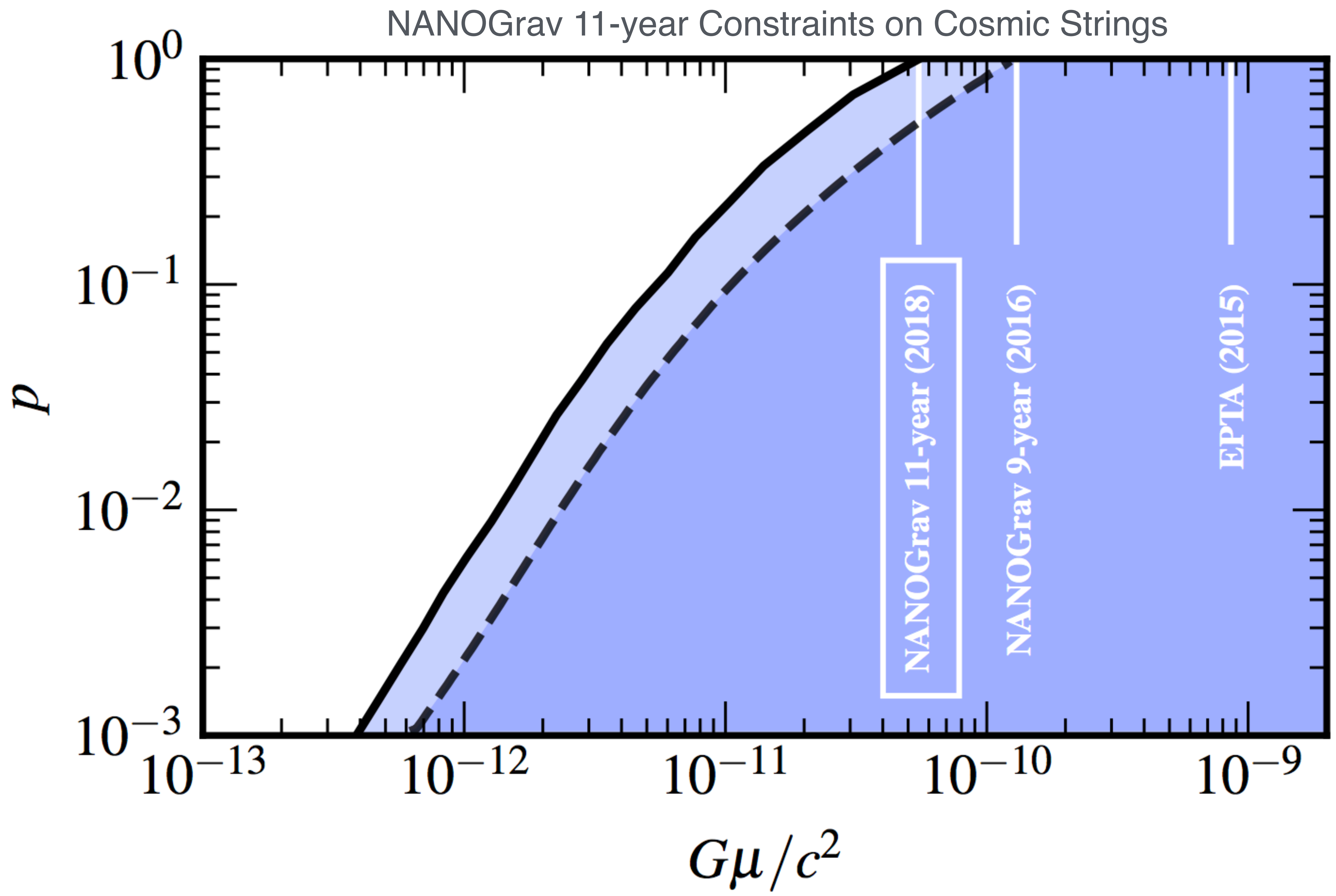
Cosmic Strings

Blanco-Pillado & Olum (2017),
Blanco-Pillado, Olum, Siemens (2018)

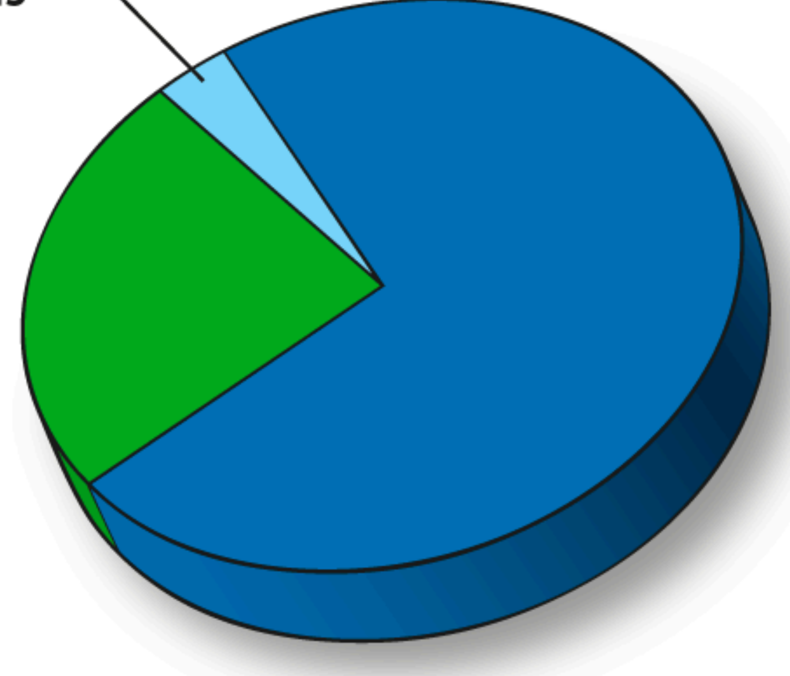


C. Martins & E. P. Shellard

- Topological defects formed during early-Universe phase transition.
- Intersecting strings chop off small loops, which vibrate relativistically, emitting GWs. e.g. Vilenkin (1985)



Dark Matter

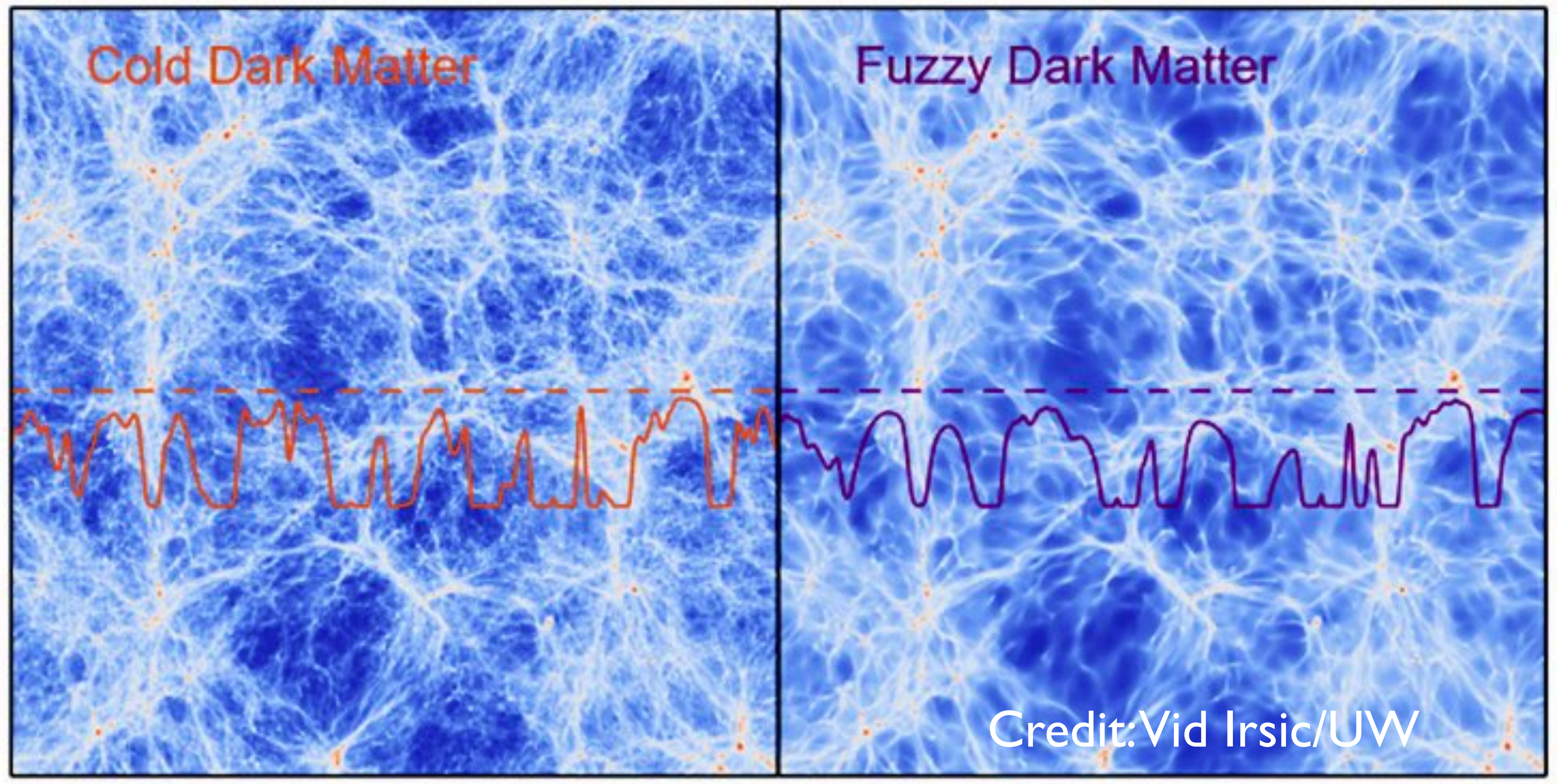


Ultralight scalar-field dark matter (“fuzzy” DM)

Hu et al. (2000), Hui et al. (2010), Porayko et al. (2018)

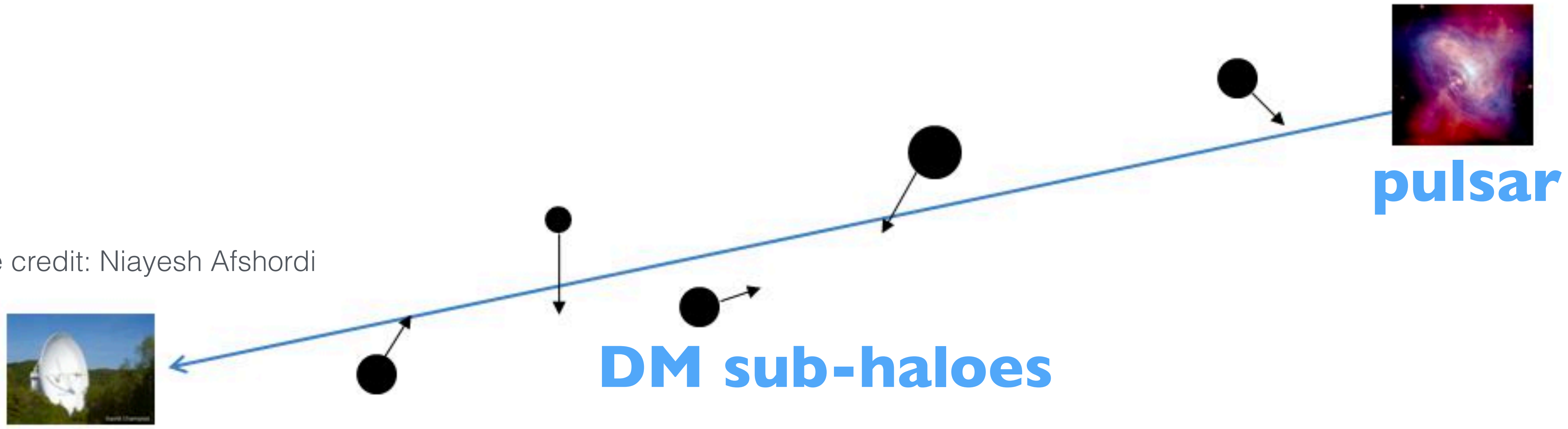
$$\frac{\lambda_{\rm dB}}{2\pi} \approx 60\,{\rm pc}\left(\frac{10^{-22}{\rm eV}}{m}\right)\left(\frac{10^{-3}v}{c}\right)$$

$$f \approx 4.8 \times 10^{-8}\,{\rm Hz}\left(\frac{m}{10^{-22}{\rm eV}}\right)$$



NANOGrav 12.5yr Constraints On Fuzzy Dark Matter *on the way (led by Brendan Drachler, GS at RIT)*

Cold Dark Matter Sub-structure



Siegel et al. (2007), arXiv: astro-ph/0702546
Baghram et al. (2011), arXiv:1101.5487
Lee, Taylor, Trickle, Zurek (2021), arXiv:2104.05717

- Pulses delayed propagating through potential of dark-matter sub-haloes [Integrated Sachs-Wolfe effect]
- Pulses delayed as sub-halo pulls on Earth or pulsar [Doppler effect] (dominant effect)

The Future

- **Pulsar Timing Arrays** will detect nanohertz gravitational waves.
- They are sensitive to the **most massive binary black holes in the Universe**.
- Detection and characterization could be within a few years (expedited by fusing datasets together in the IPTA).
- The road beyond detection will inform **demographics and final-parsec binary dynamical interactions of supermassive binary black holes**.
- *Although expected to be weaker than black-hole signals, cosmological signals may be lurking beneath, e.g., cosmic string network, primordial GW backgrounds, phase transitions.*