PULSAR TIMING ARRAYS: III
Cutting-edge Results

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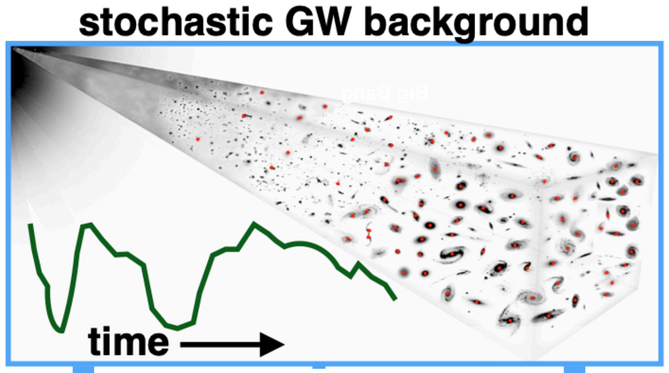
NBIA Summer School On GW Astrophysics, August 2-6 2021

Detection Timeline

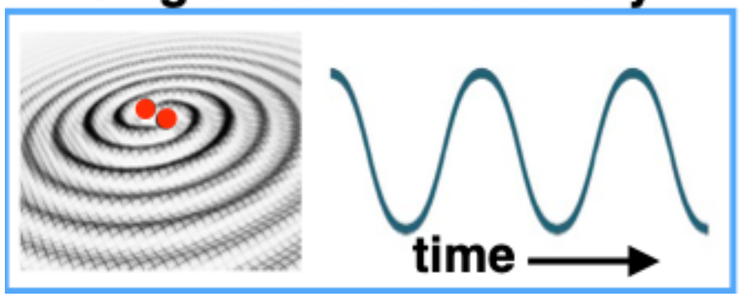


~2022-2026

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

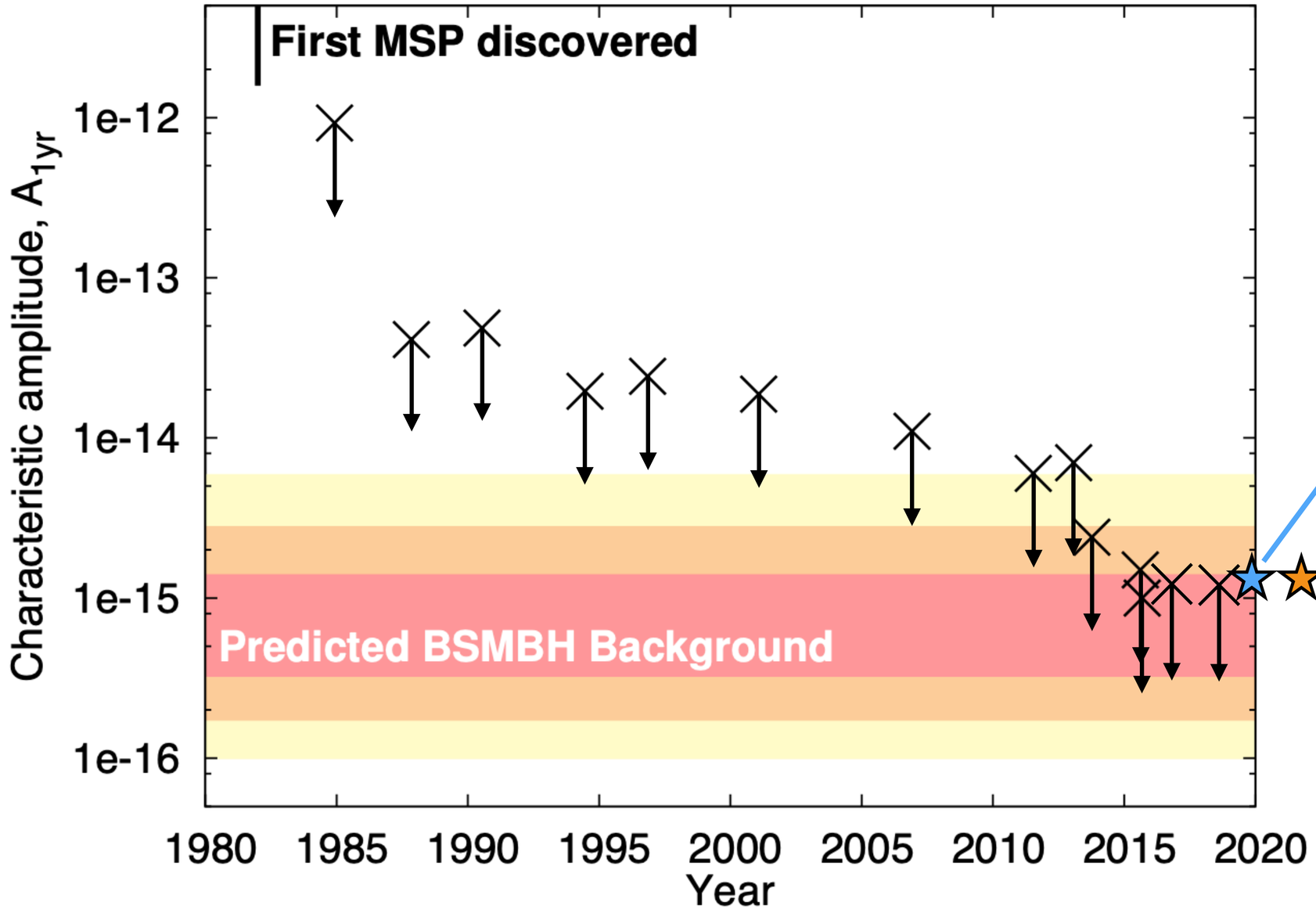
~2027-2030

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



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

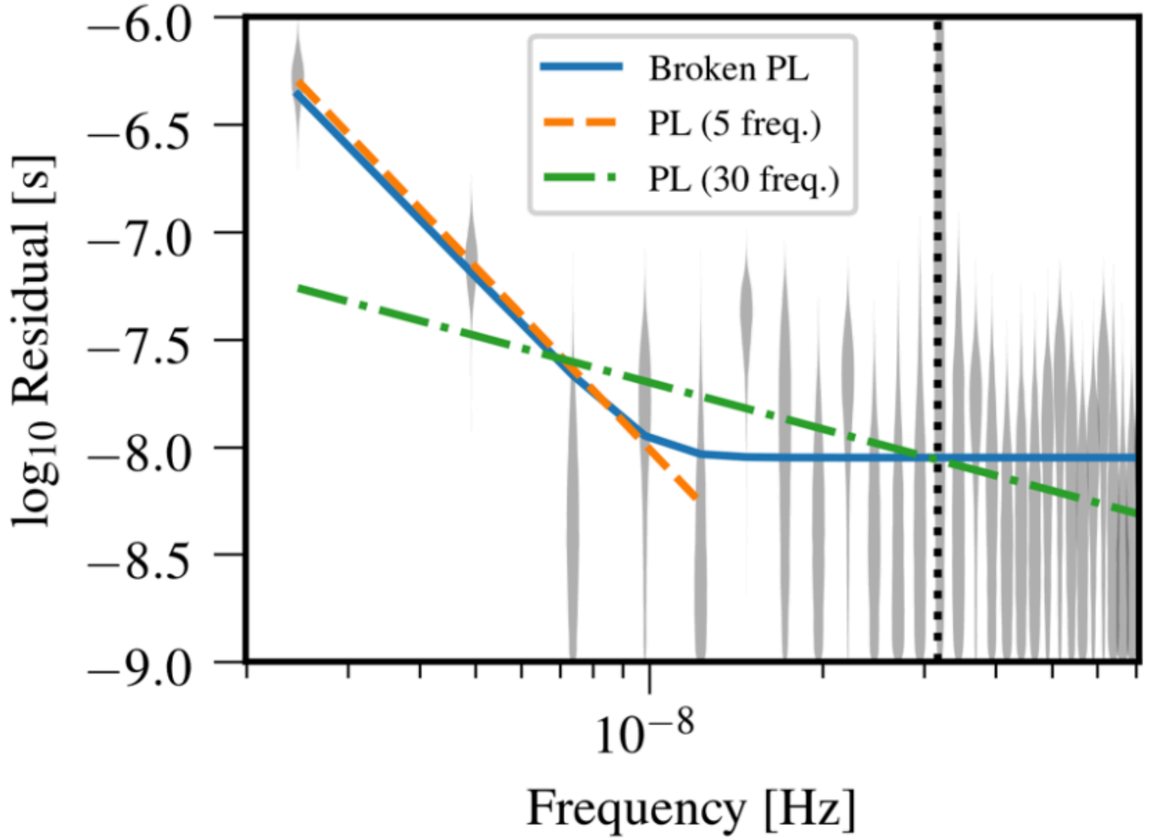
NANOGrav 12.5yr Dataset Search (arXiv:2009.04496),
The Astrophysical Journal Letters, Volume 905, Number 2 (2020)

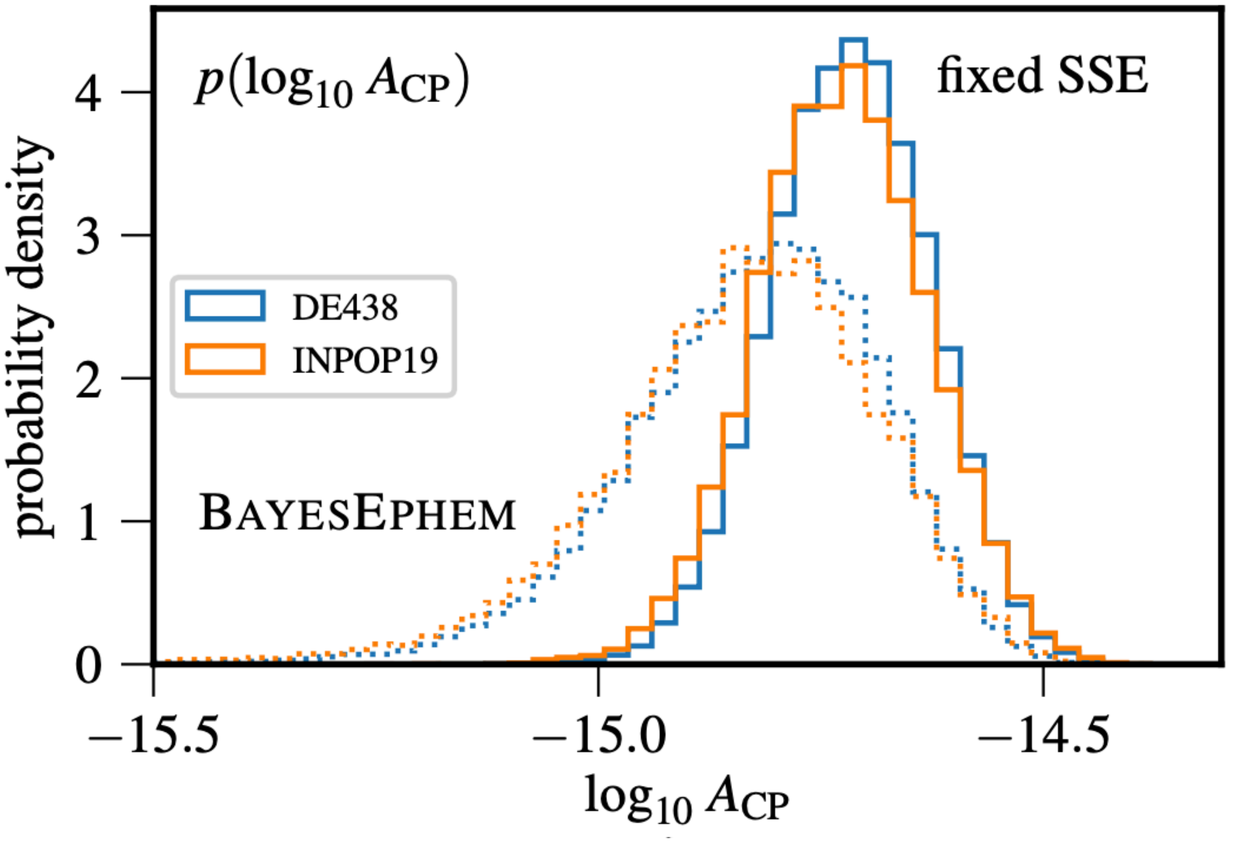
corresponding author: Joe Simon (JPL / CU-Boulder)

181 citations since Sep 2020

A Common-spectrum Process

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



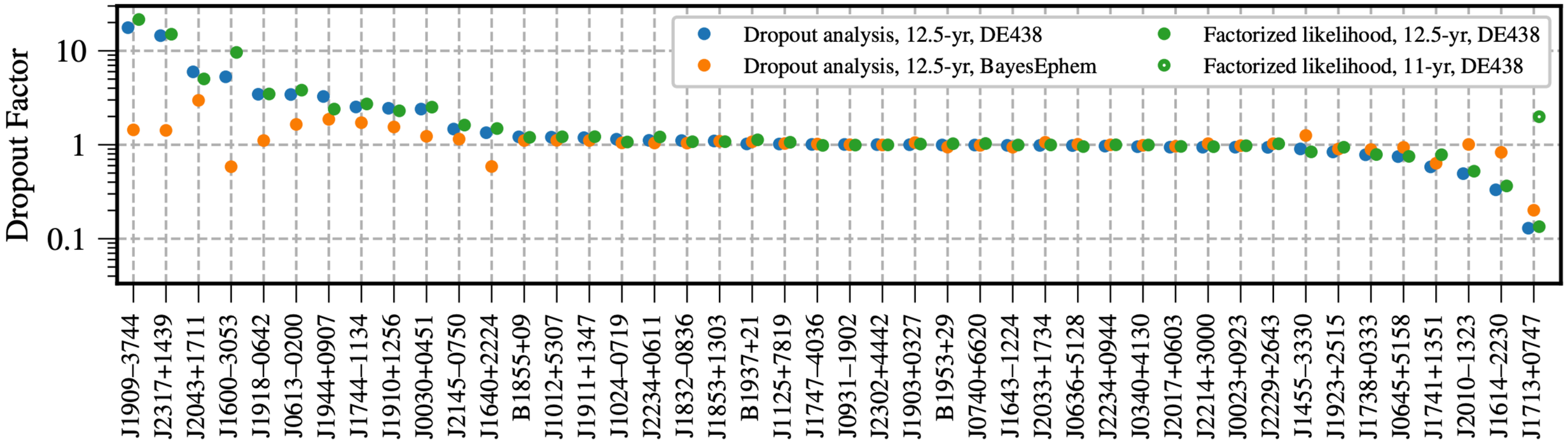


A steep-spectrum process in common across NANOGrav's 45-pulsar array with max-baseline 12.9 years.

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

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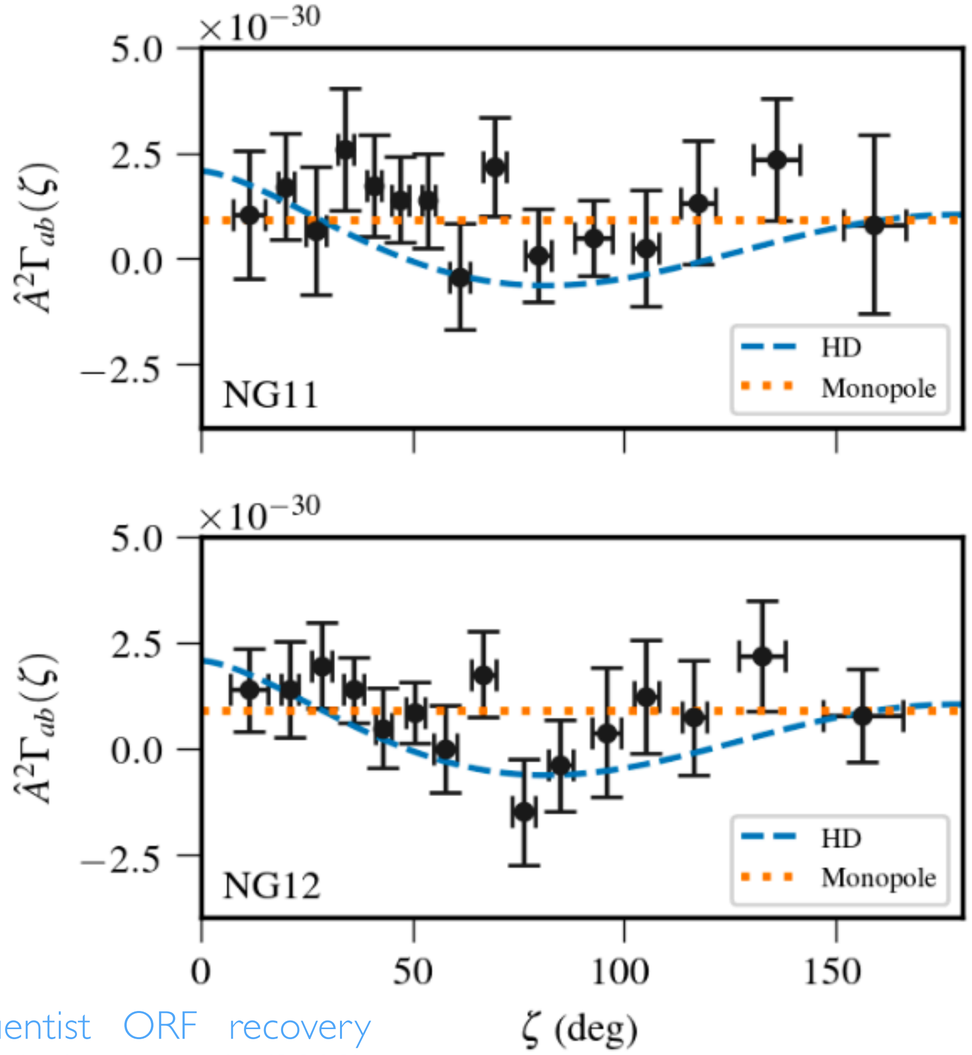
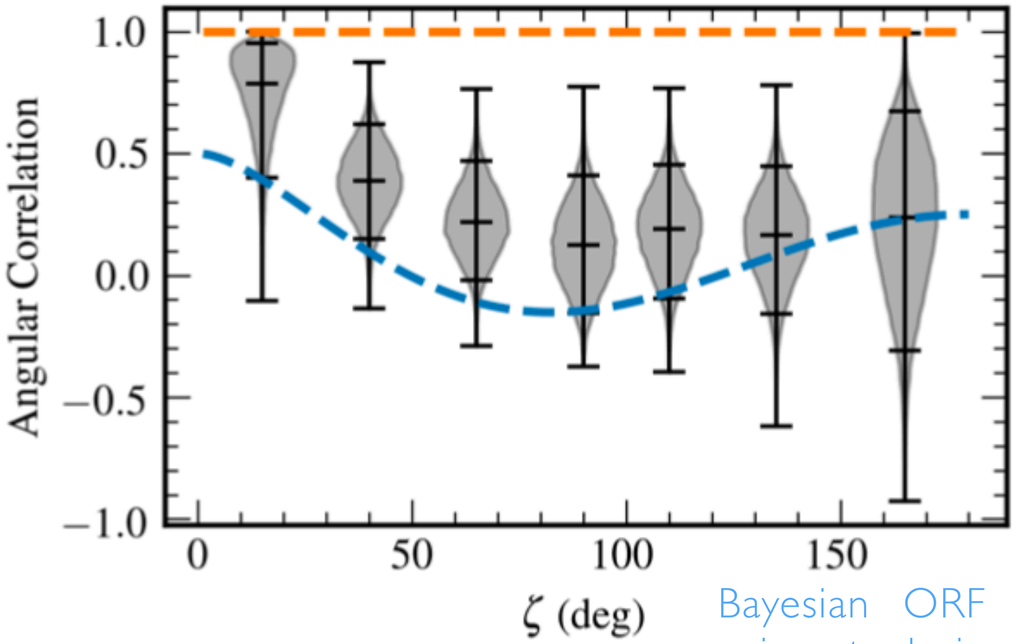


Frequentist ORF recovery —> Vigeland et al. (2018), Chamberlin et al. (2015), etc.

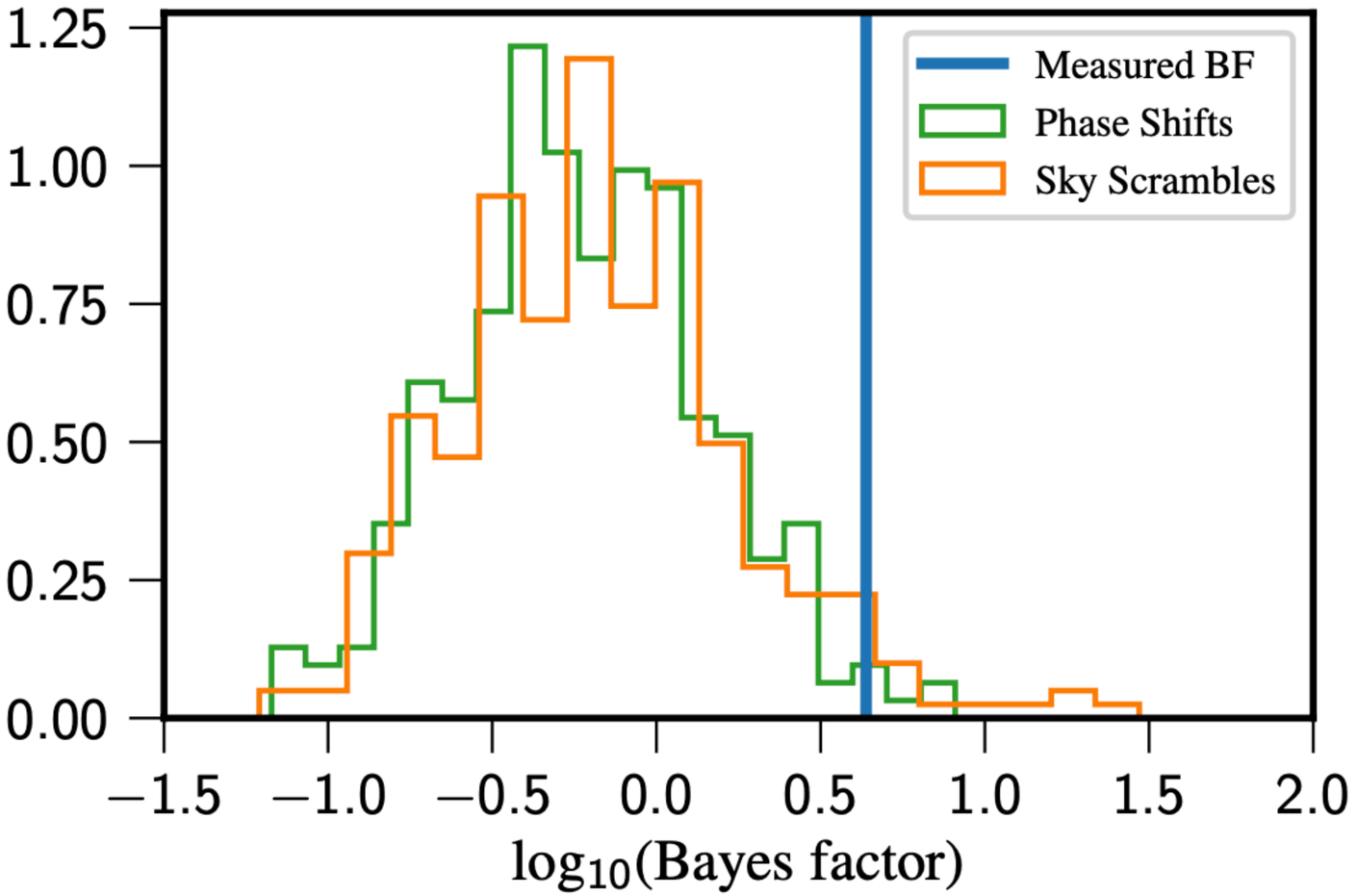


Bayesian ORF recovery using techniques from **Taylor, Gair, Lentati (2013)**

- 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)

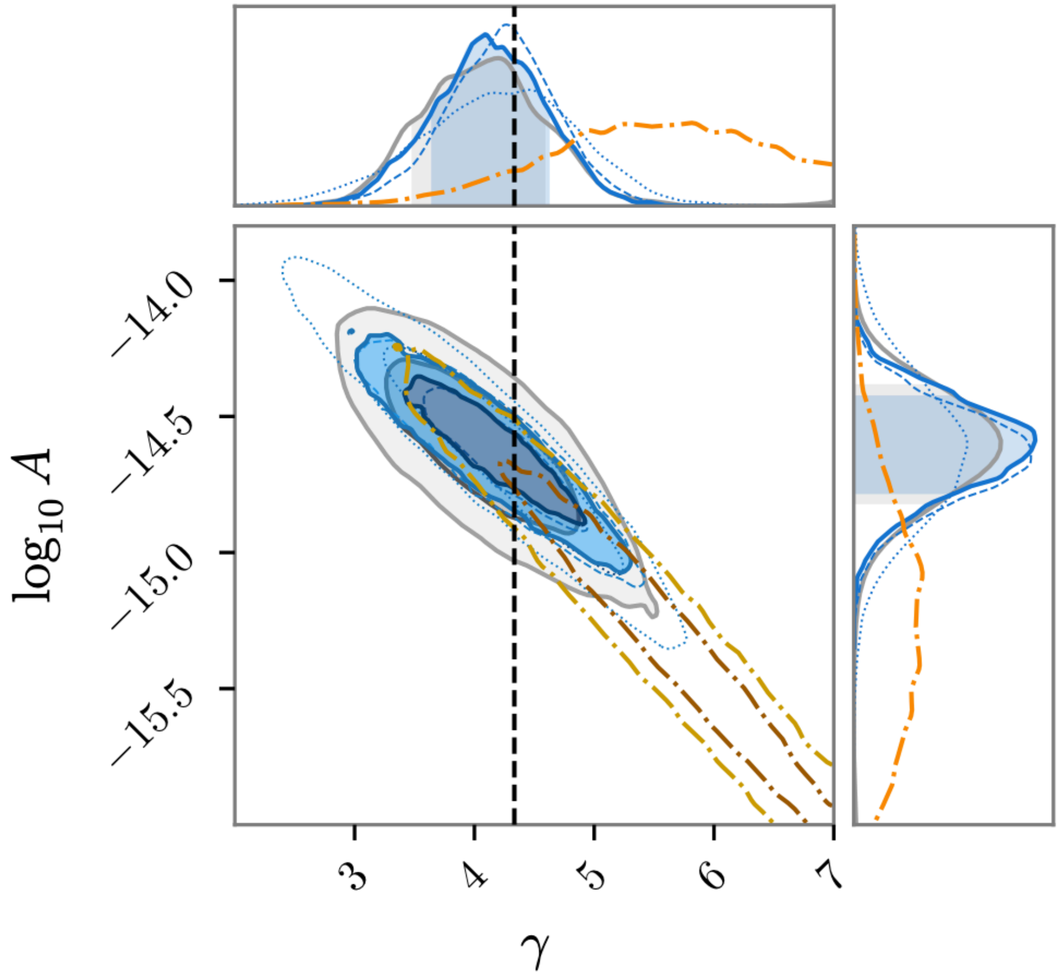


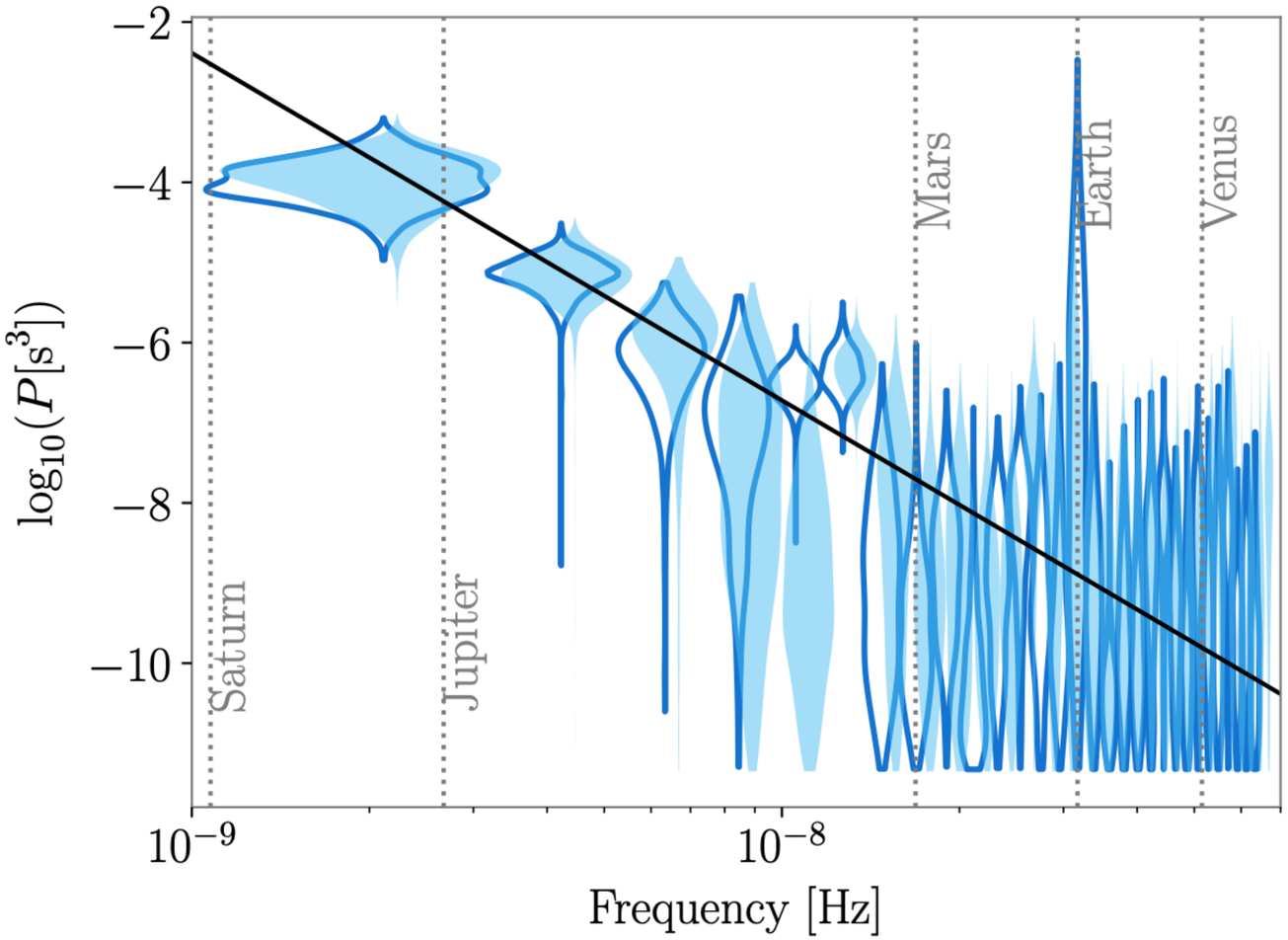
- Assess the significance of spatial correlations by constructing null distribution.
- LIGO-Virgo use time slides…we use **phase shifts (Taylor et al. 2017)** and **sky scrambles (Cornish & Sampson 2016; Taylor et al. 2017).**
- p ~ 5-10%

Independent validation

PPTA Search (arXiv:2009.04496),
corresponding author: Boris Goncharov (Swinburne/GSSI)

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





IPTA Data Release 2

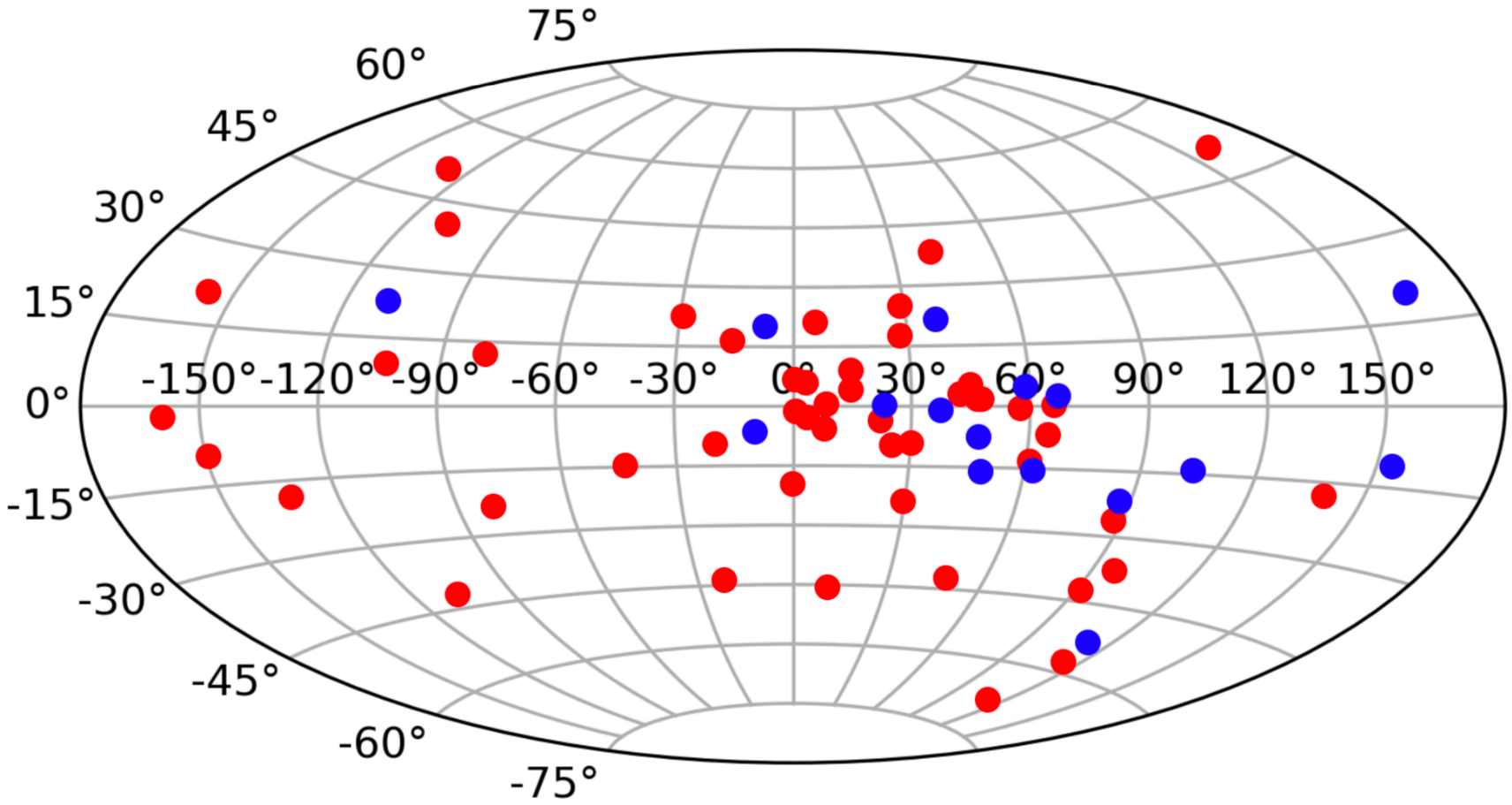
Perera et al. (2019), MNRAS, Volume 490, Issue 4, p.4666-4687

- **EPTA DR1** – 1996-2015 (Desvignes+ 2016)
- **NANOGrav 9-yr DR** – 2004-2013 (Arzoumanian+ 2015)
- legacy data for 3 PSRs (Zhu+ 2015, Kaspi+ 1994)
- **PPTA DR1** – 2005-2011 (Manchester+ 2013)
- newer data (Reardon+ 2016, Shannon+ 2015)
- legacy data (Verbiest+ 2008, 2009)

65 unique MSPs, some with $T_{\rm obs} > 20$ yr

Slide credit: Paul Baker

IPTA Data Release 2



- **Results coming very soon!**
- Things look very consistent with regional PTA analyses.
- Corresponding author: ***Siyuan Chen***

(in DR1) (new to DR2: 16)

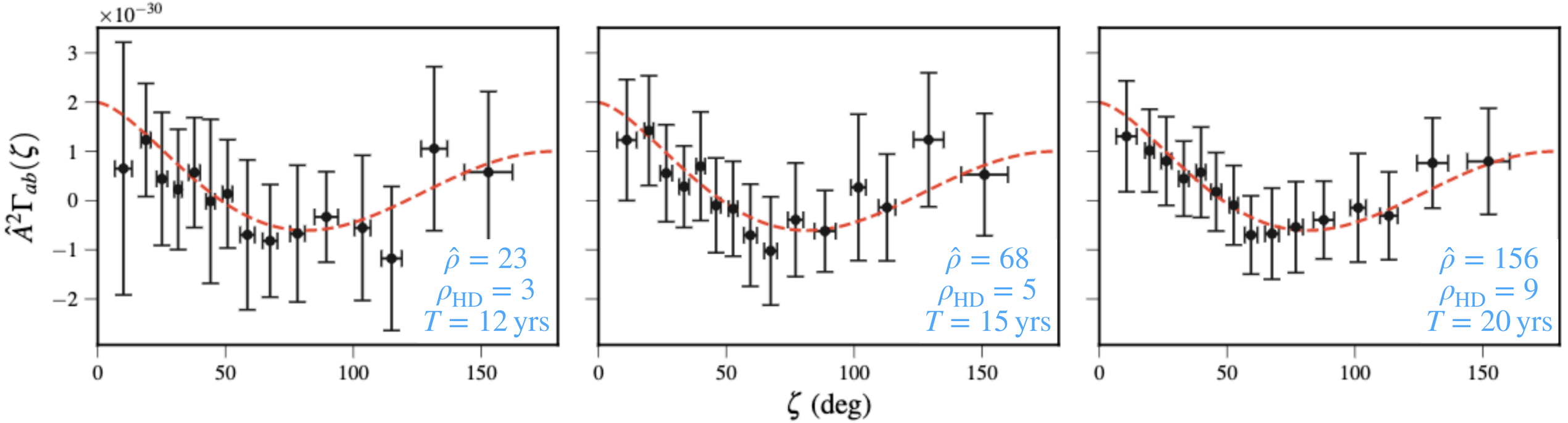
Slide credit: Paul Baker

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

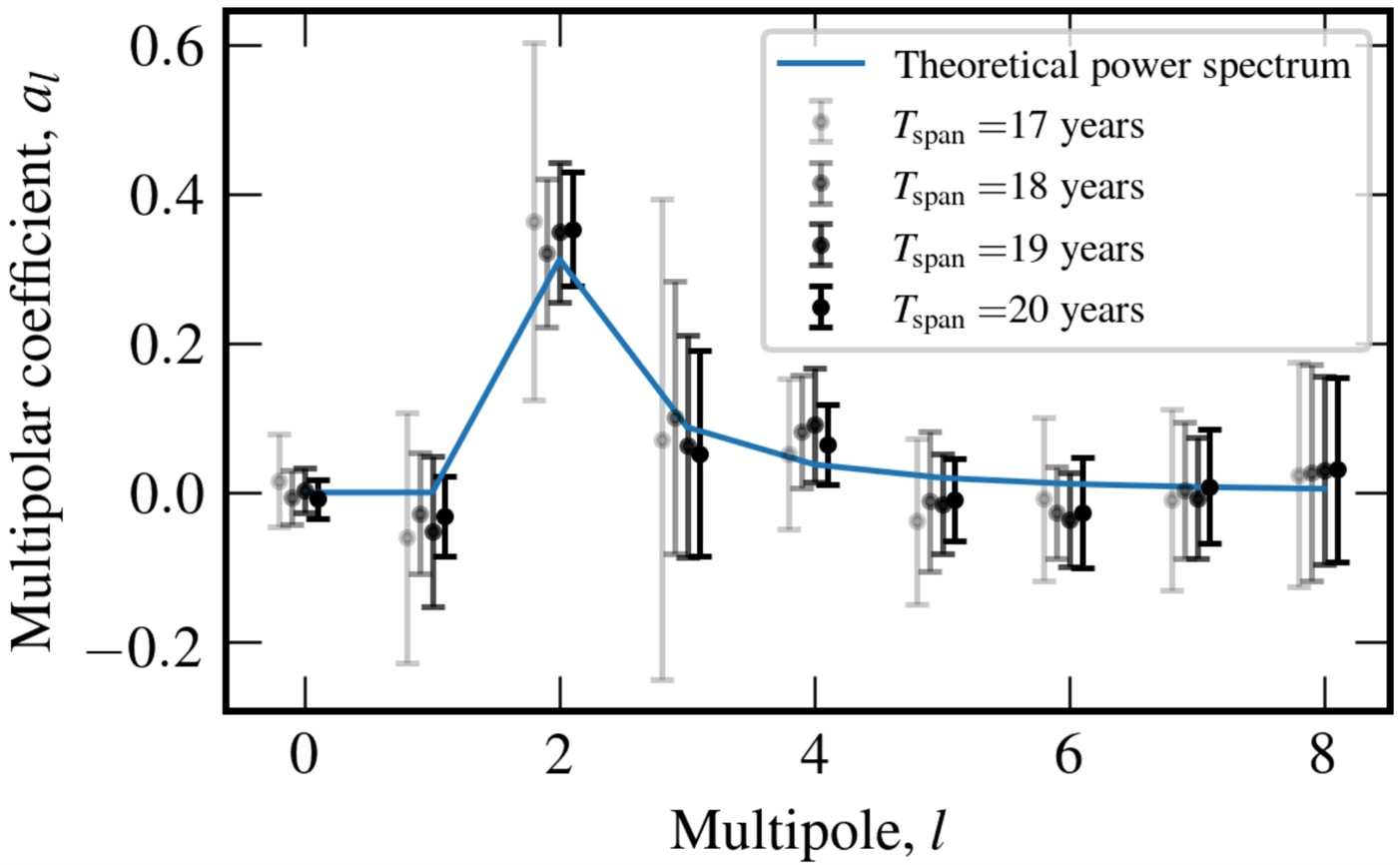
Full team: Nihan Pol, Stephen Taylor, Luke Kelley, Joe Simon, Sarah Vigeland, Siyuan Chen

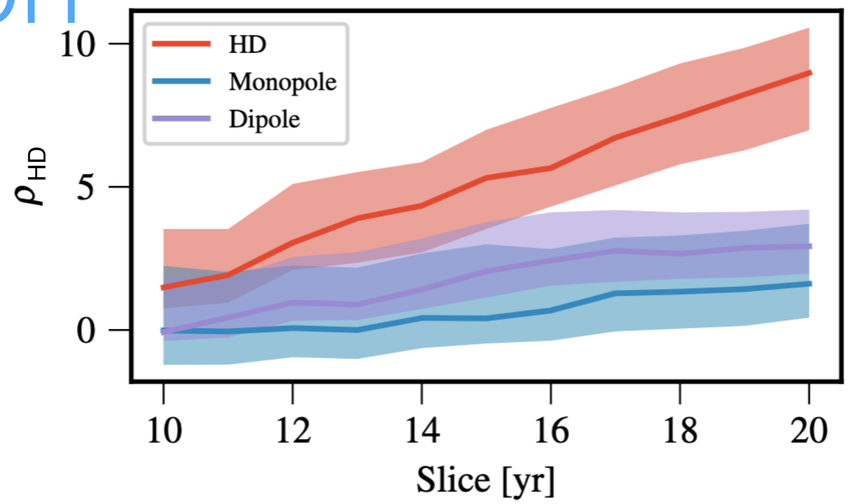
The Road To & Beyond Detection

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

Probe the multipolar structure of the inter-pulsar correlations

$$A_{\rm GWB} = 2 \times 10^{-15}$$





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

Isotropic GWB:

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

Gair, Romano, Taylor, Mingarelli (2014)

The Road To & Beyond Detection

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

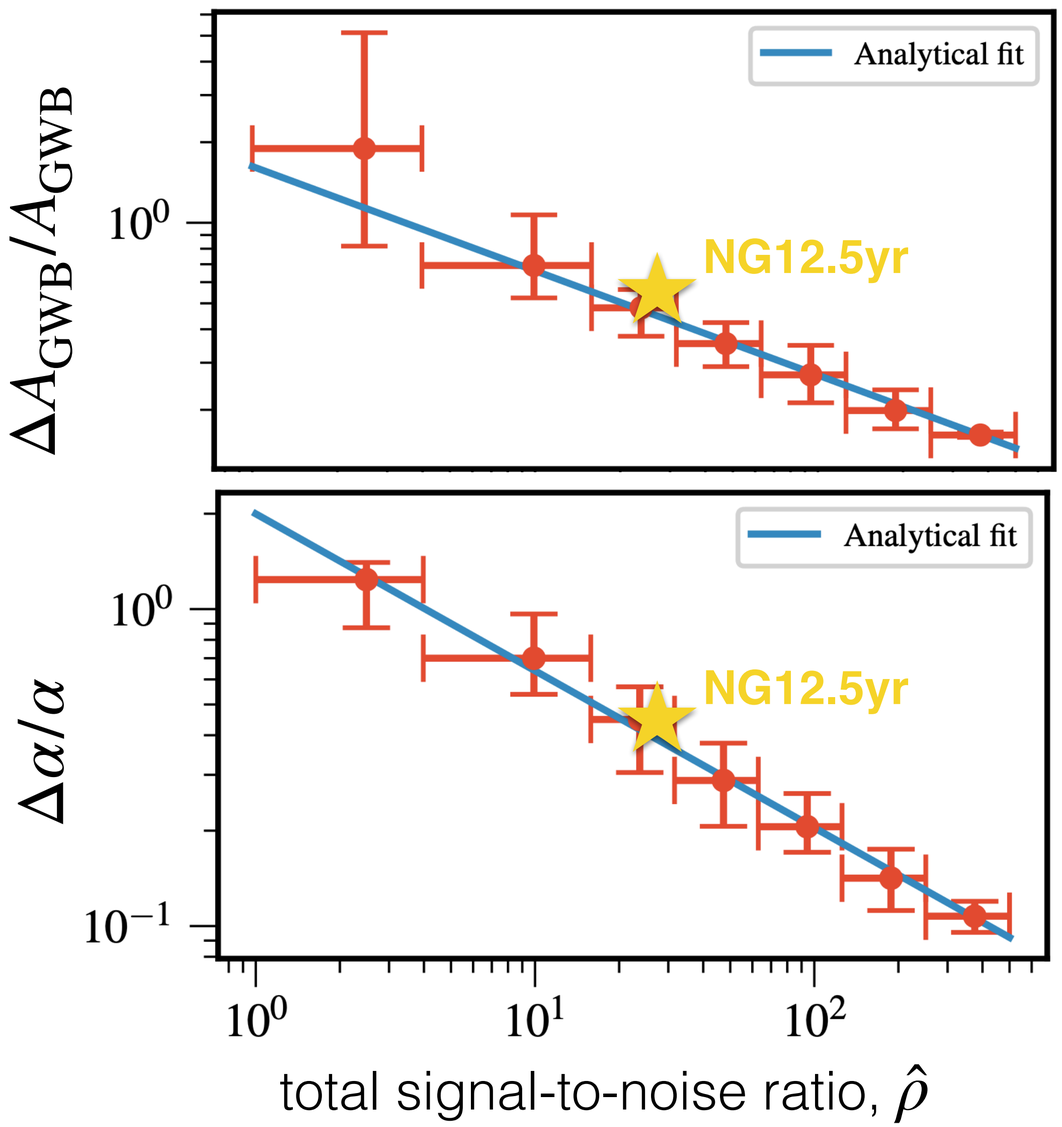
$$h_c(f) = A_{\rm GWB}\left(\frac{f}{1\,{\rm yr}^{-1}}\right)^{\alpha}$$

parameter uncertainty scaling laws

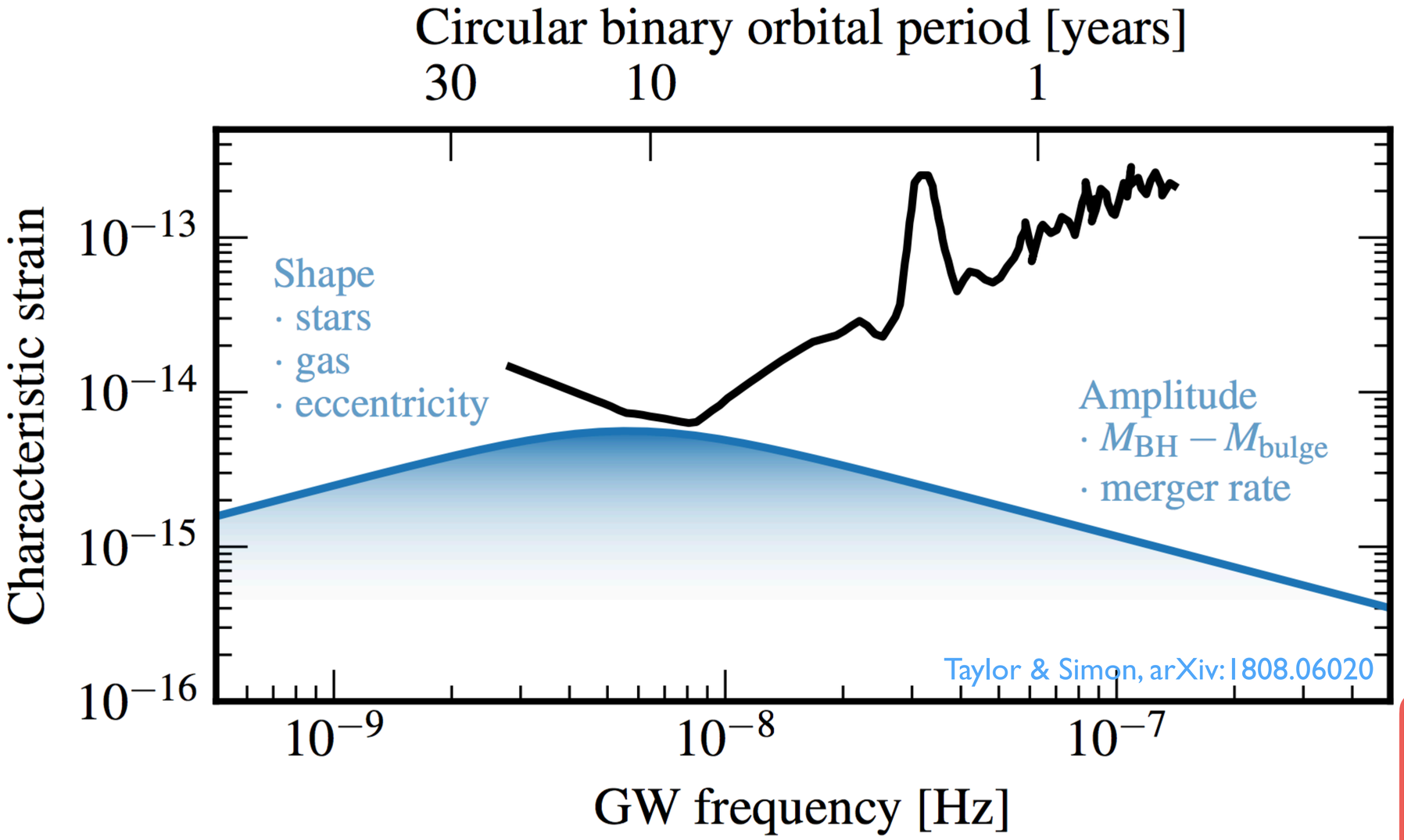
$$\Delta A_{\rm GWB}/A_{\rm GWB} = 44 \times \left(\frac{\hat{\rho}}{25}\right)^{-2/5} \%$$

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

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



Stochastic Background Characterization

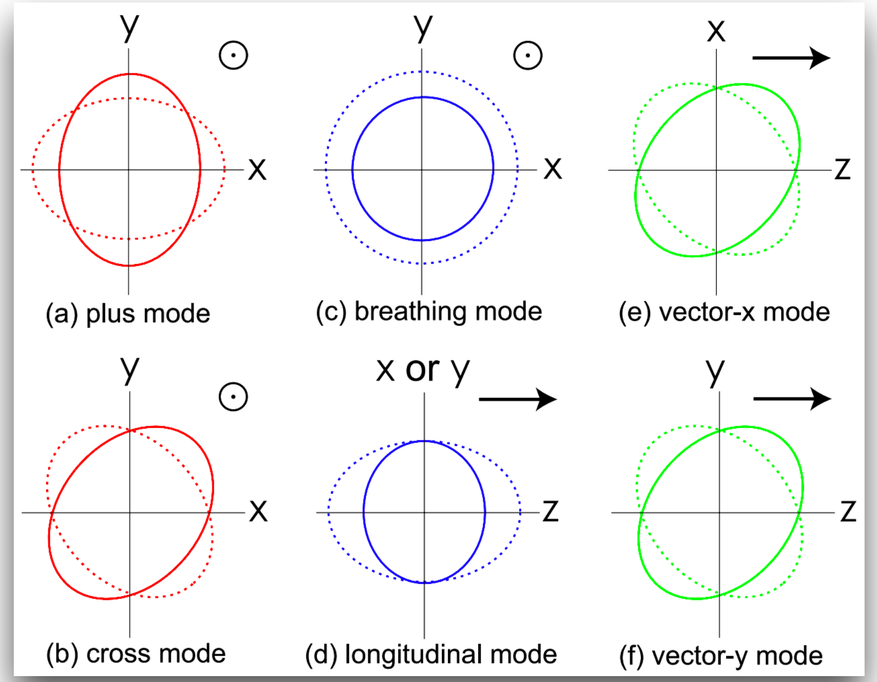


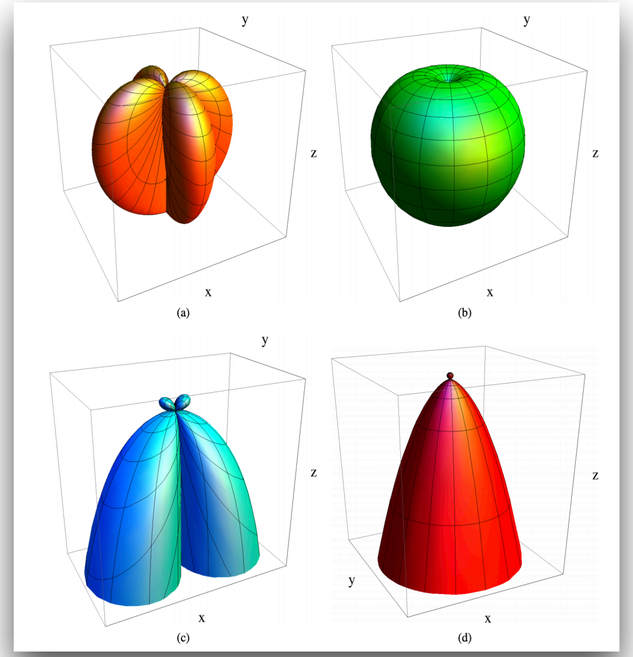
Probe the amplitude for rate factors, and the shape for final-parsec dynamics

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

$$\Gamma_{aa}^{\mathrm{TT}} \propto \text{constant}$$

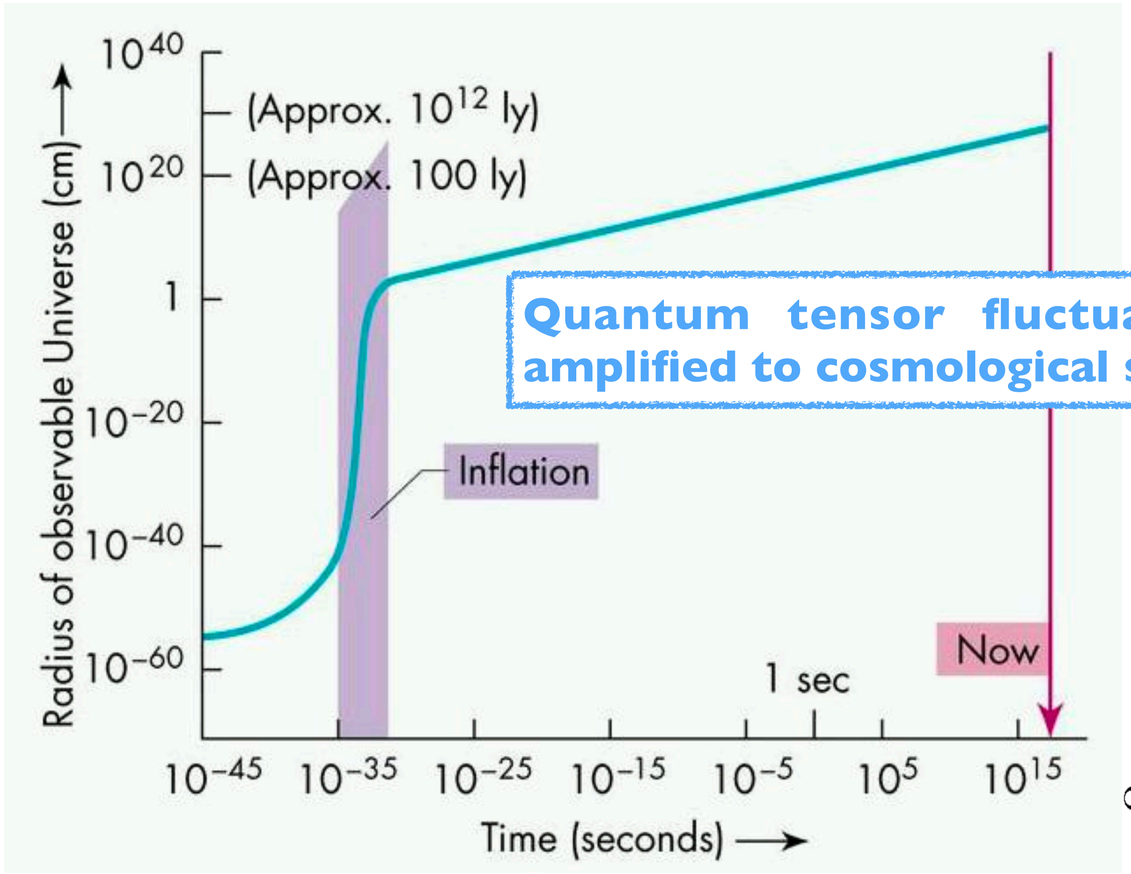
$$\Gamma_{aa}^{\mathrm{SL}} \propto fL$$

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

- Generic metric theory of gravity admits 4 more polarization states than GR's + and x.
- These include scalar and vector longitudinal modes that induce very strong autocorrelation signatures in pulsars.

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

Primordial GWs



Quantum tensor fluctuations amplified to cosmological scales

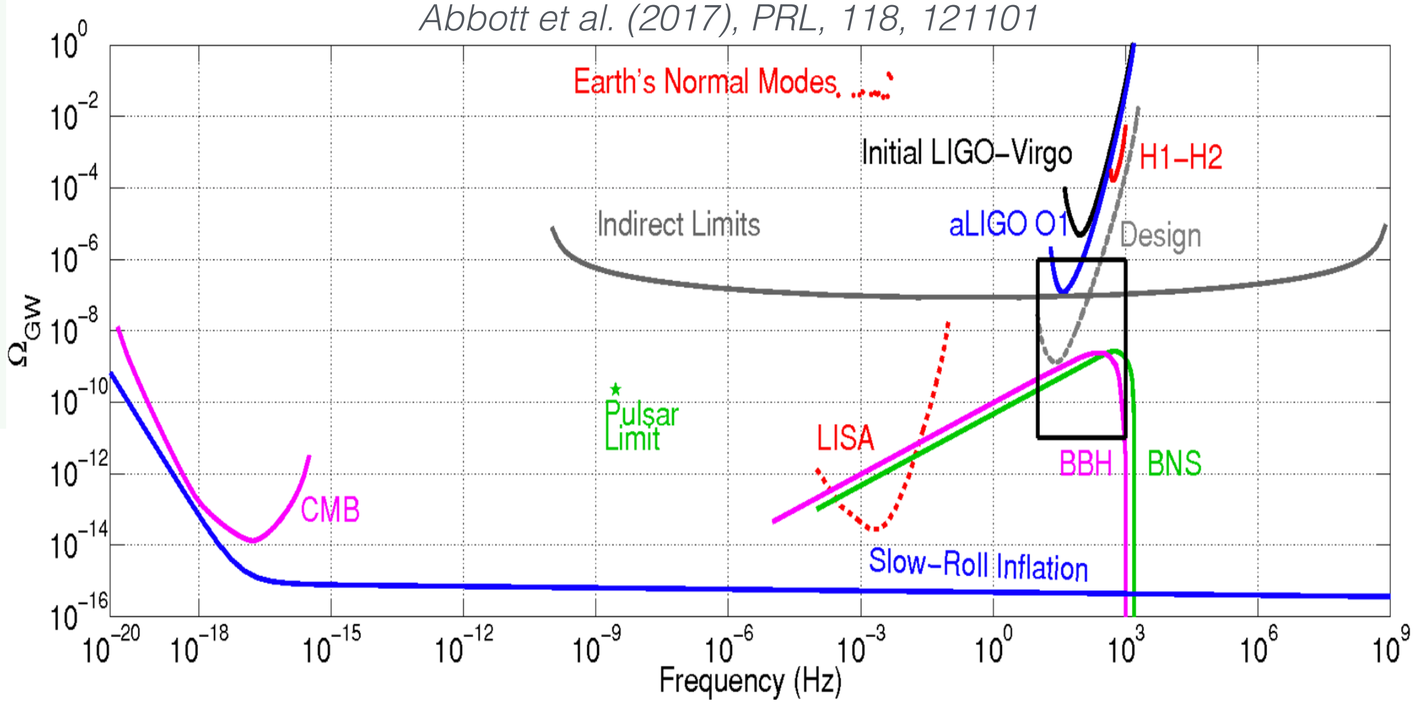
Grishchuk (1976), (1977)
Starobinsky (1980)
Linde (1982)

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

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

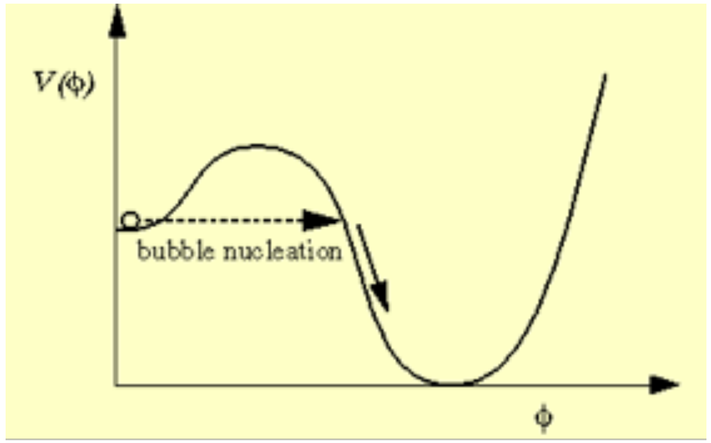
$$@ \ f = 1/\text{year}$$

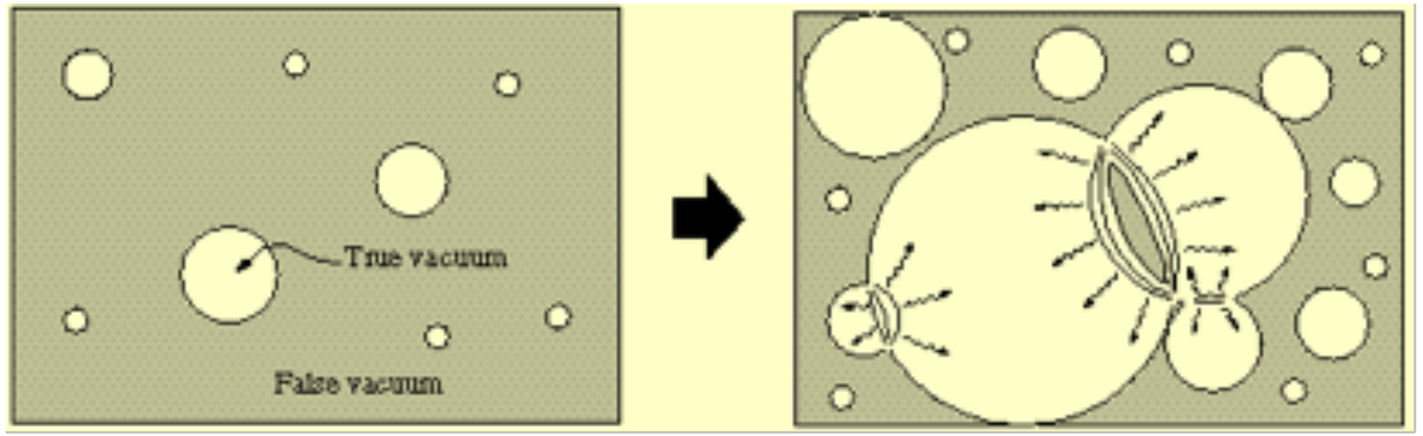
Abbott et al. (2017), PRL, 118, 121101

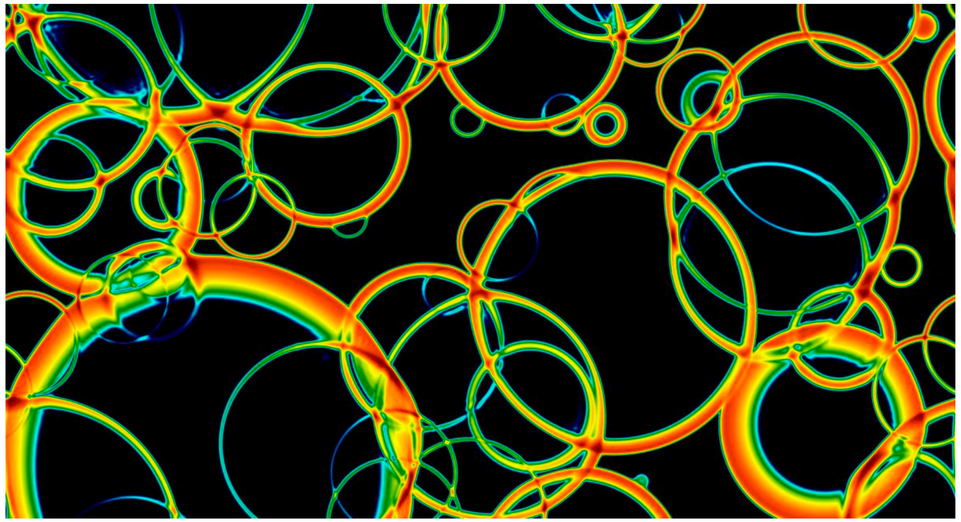


See Lentati et al. (2015), Shannon et al. (2015), Arzoumanian et al. (2018), Lasky et al. (2016)

Cosmological Phase Transitions



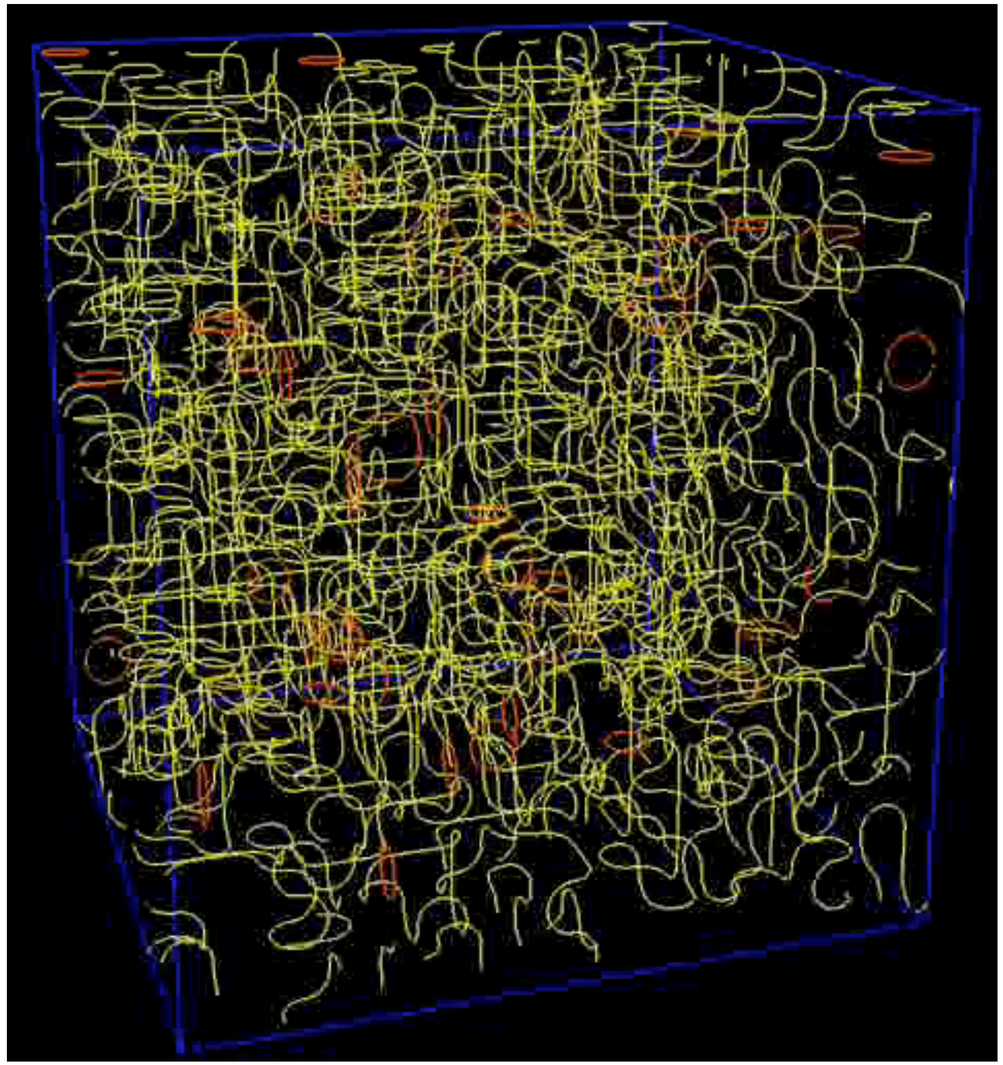




- **NANOGrav** 12.5 Phase Transition Search (corresponding author: ***Andrea Mitridate***); arXiv: 2104.13930
  - $T_* \lesssim 10$ Mev, possibly a dark sector transition
  - Submitted to PRL
- **PPTA** Phase Transition Search
  - Submitted

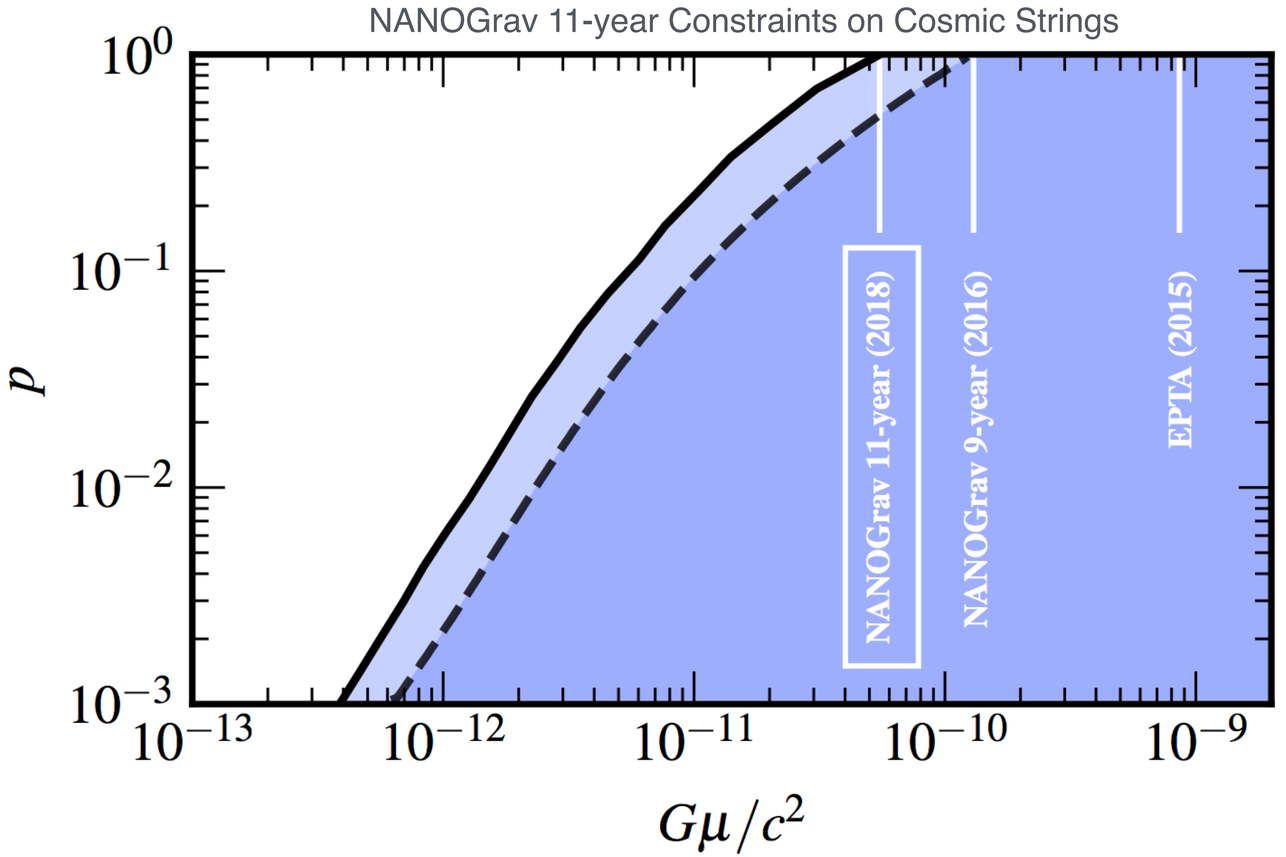
Cosmic Strings

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

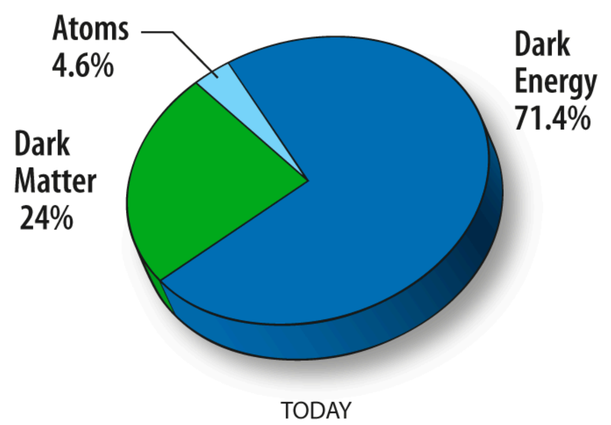


C. Martins & E. P. Shellard

- 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

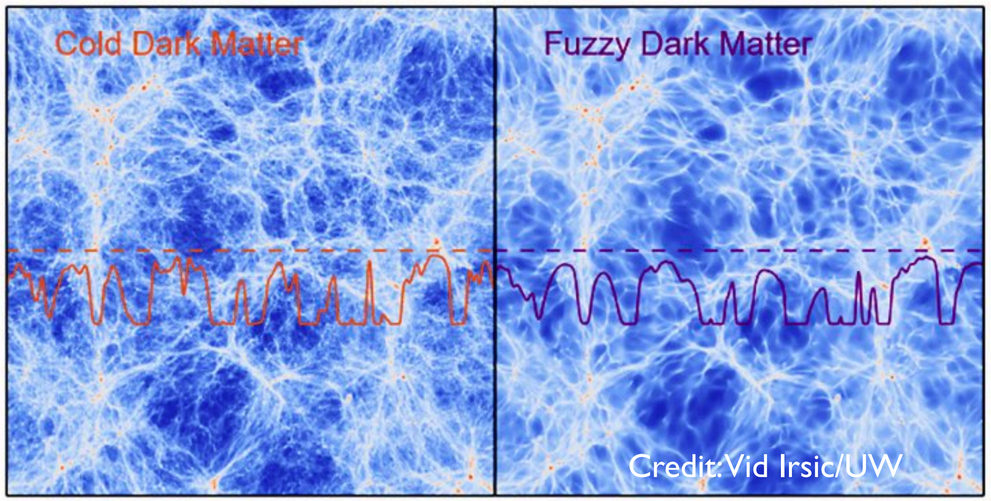


Ultralight scalar-field dark matter ("fuzzy" DM)

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

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

$$f \approx 4.8\times10^{-8}\,{\rm Hz}\left(\frac{m}{10^{-22}{\rm eV}}\right)$$



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

Cold Dark Matter Sub-structure

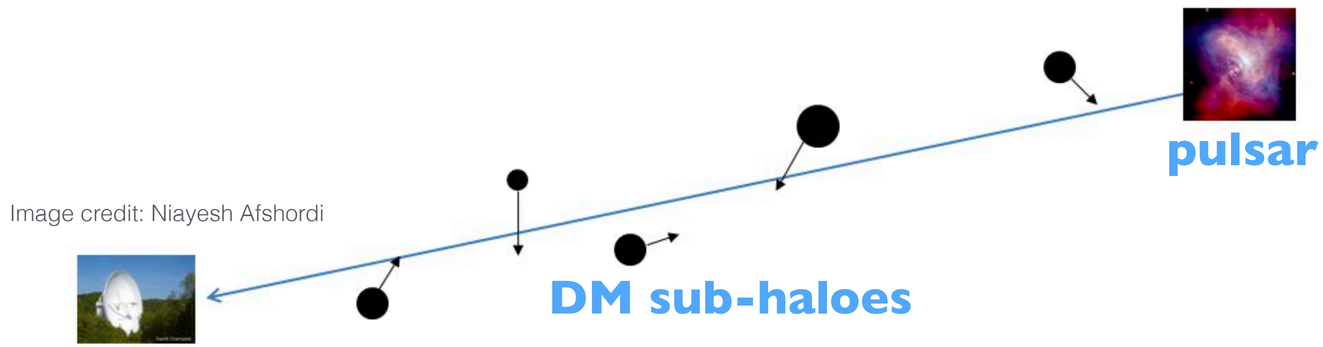


Image credit: Niayesh Afshordi

Siegel et al. (2007), arXiv: astro-ph/0702546
Baghram et al. (2011), arXiv:1101.5487

- 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.
- If recent results hint at a GWB, then **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.
- PTAs may detect **multi-messenger supermassive binary black holes**.
- PTAs can also access primordial GW backgrounds and early-Universe cosmology.