Title: Moving Closer to a Detection of nHz-frequency Gravitational Waves with NANOGrav

Speakers: Scott Ransom

Series: Strong Gravity

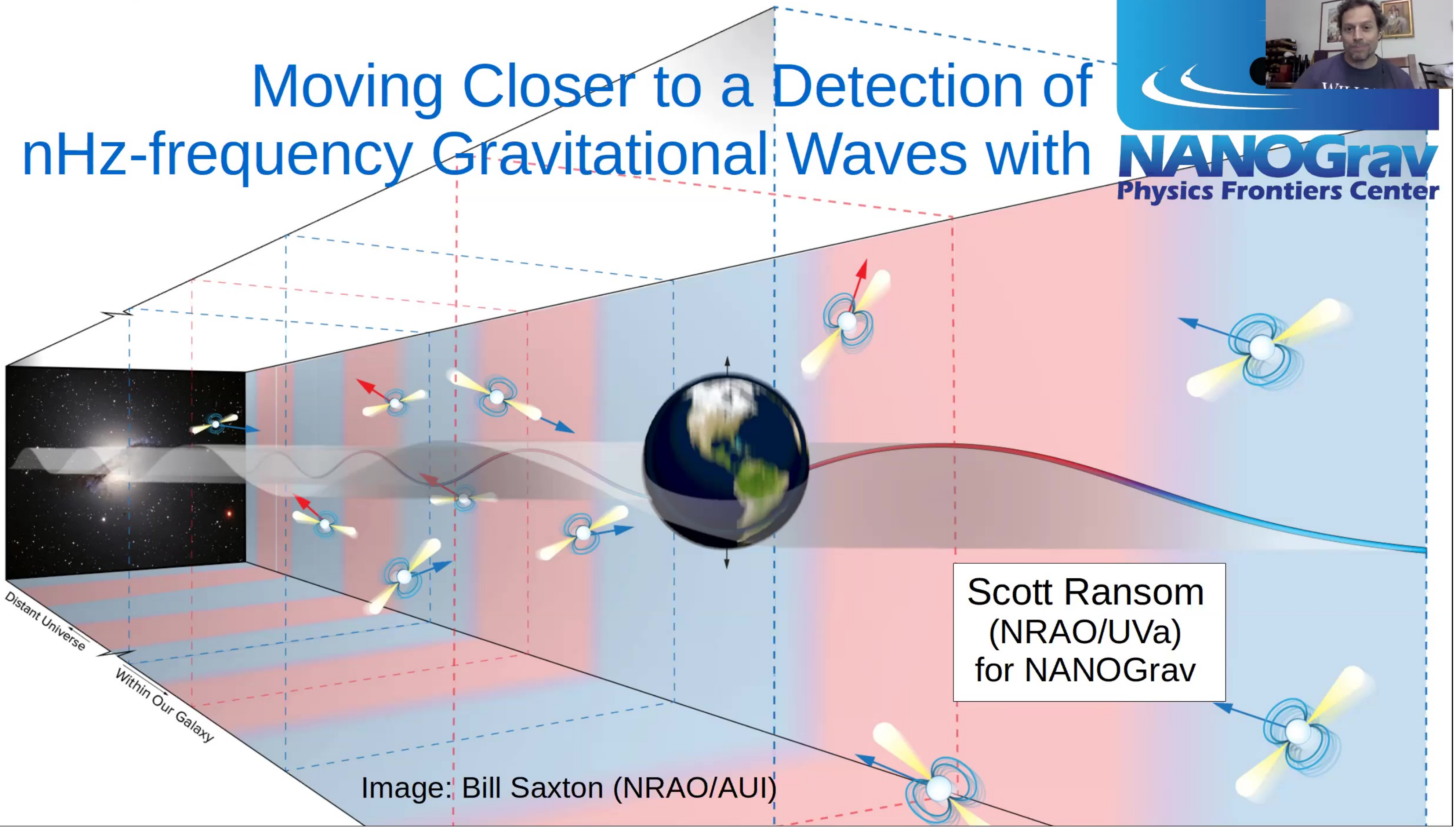
Date: October 29, 2020 - 1:00 PM

URL: http://pirsa.org/20100068

Abstract: Millisecond Pulsars (MSPs) have become reliable and extremely stable workhorses of modern astronomy and physics. The North American Nanohertz Observatory for Gravitational Waves, or NANOGrav, has been observing growing numbers of these systems for over 15 years, and the data look great. High precision timing of almost 80 MSPs has provided unprecedented sensitivity to the gravitational wave Universe at nHz-frequencies, where our upper limits are already constraining the population of super-massive black hole binaries. But our sensitivity is increasing each year as we continue to add MSPs to our timing array and develop new techniques to remove systematics due to the interstellar medium and the uncertain solar system ephemerides. Meanwhile, though, our observations provide a wide variety of astrophysics, such as new neutron star mass measurements and constraints of the dense matter equation of state.

Moving Closer to a Detection of nHz-frequency Gravitational Waves with NANOGrav

Physics Frontiers Center



Scott Ransom
(NRAO/UVa)
for NANOGrav

Image: Bill Saxton (NRAO/AUI)

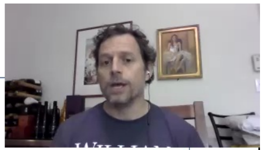
North American Nanohertz Observatory for GWs

http://nanograv.org/

Our mission is to detect nHz frequency gravitational waves from super-massive black hole binaries.

We are over 100 students and scientists and welcome new collaborators and members.

California Institute of Technology
Cornell University
F&M
Lafayette College
Vanderbilt University
Montana State University
NRAO
McGill
UAH The University of Alabama in Huntsville
Penn State
University of Washington Bothell
University of Virginia
UBC
Hillsdale College
The University of California Berkeley
Oberlin College
USRA
The University of Texas Rio Grande Valley
University of Wisconsin Milwaukee
Notre Dame of Maryland University
Harvard-Smithsonian Center for Astrophysics
Illinois University of Illinois at Urbana-Champaign
Fisk University 1866
Columbia University
NCSA
Swarthmore
Max-Planck-Institut für Radioastronomie
Rochester Institute of Technology
National Time Service Center Chinese Academy of Sciences
University of East Anglia
Manchester 1824 The University of Manchester
Flatiron Institute
NASA
U.S. Naval Research Laboratory
Harvard
University of Maryland
Eötvös Loránd University Budapest
spherical cow group



Astro2020 Project White Paper

The NANOGrav Program for Gravitational Waves and Fundamental Physics

NANOGrav
Physics Frontiers Center

The North American Nanohertz Observatory for Gravitational Waves

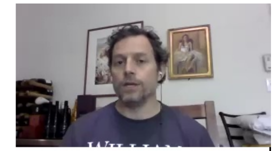
July 10, 2019

Thematic areas: Multi-messenger astronomy and astrophysics; Cosmology and fundamental physics; Formation and evolution of compact objects.

Contact author: Scott Ransom (NANOGrav Chair), NRAO, scott.ransom@nanograv.org

Authors: A. Brazier (Cornell), S. Chatterjee (Cornell), T. Cohen (NMT), J. M. Cordes (Cornell), M. E. DeCesar (Lafayette), P. B. Demorest (NRAO), J. S. Hazboun (UW Bothell), M. T. Lam (WVU, RIT), R. S. Lynch (GBO), M. A. McLaughlin (WVU), S. M. Ransom (NRAO), X. Siemens (OSU, UWM), S. R. Taylor (Caltech/JPL, Vanderbilt), and S. J. Vigeland (UWM) for the NANOGrav Collaboration ($\sim$ 50 institutions, 100+ individuals)

Ransom et al. 2019, Astro2020 Whitepaper



But not just NANOGrav...

NANOGrav

PPTA

Parkes Pulsar
Timing Array

EPTA

European Pulsar
Timing Array

But not just NANOGrav...

NANOGrav

PPTA

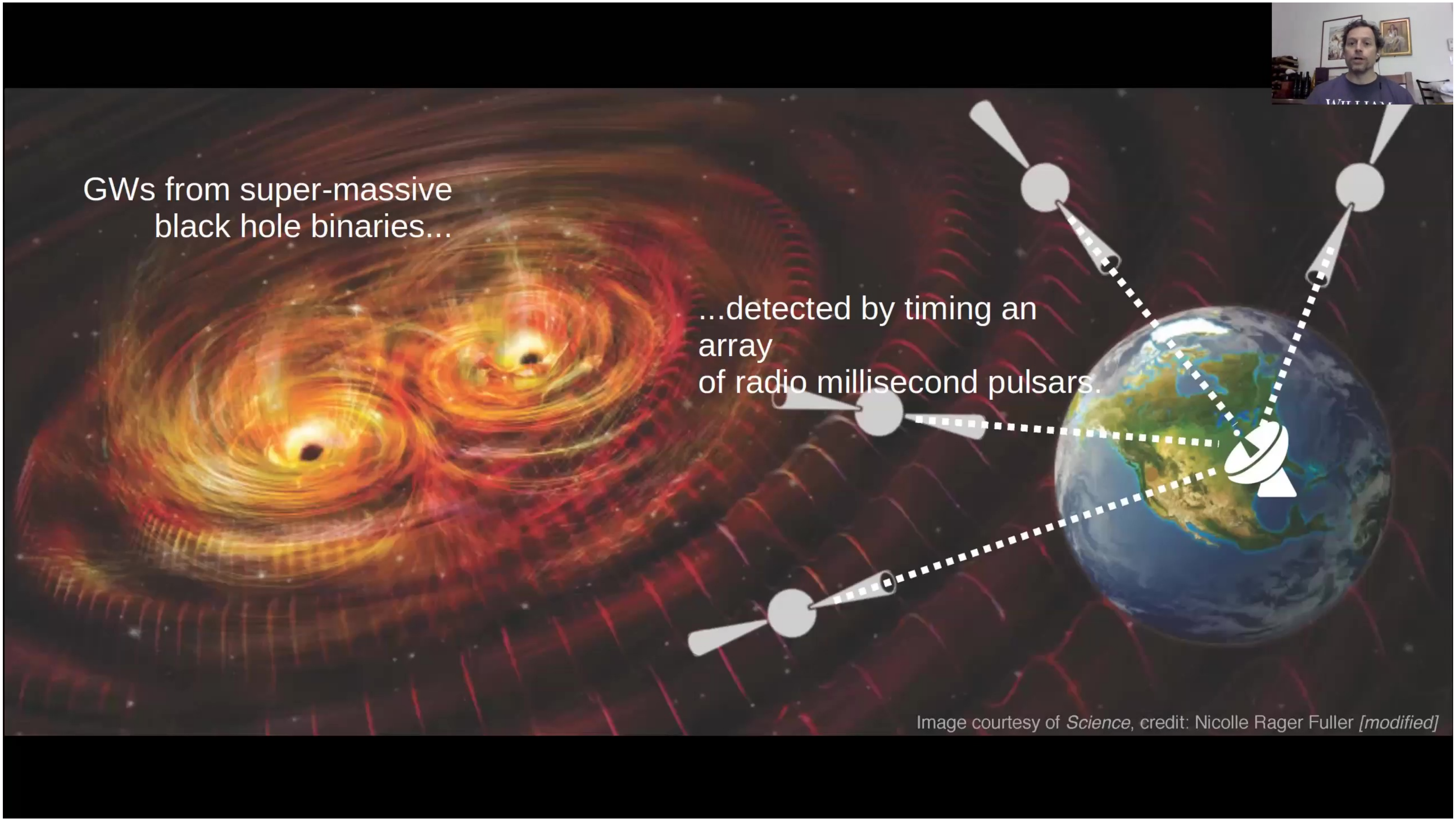
Parkes Pulsar
Timing Array

INTERNATIONAL PULSAR TIMING ARRAY

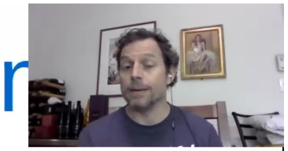
IPTA

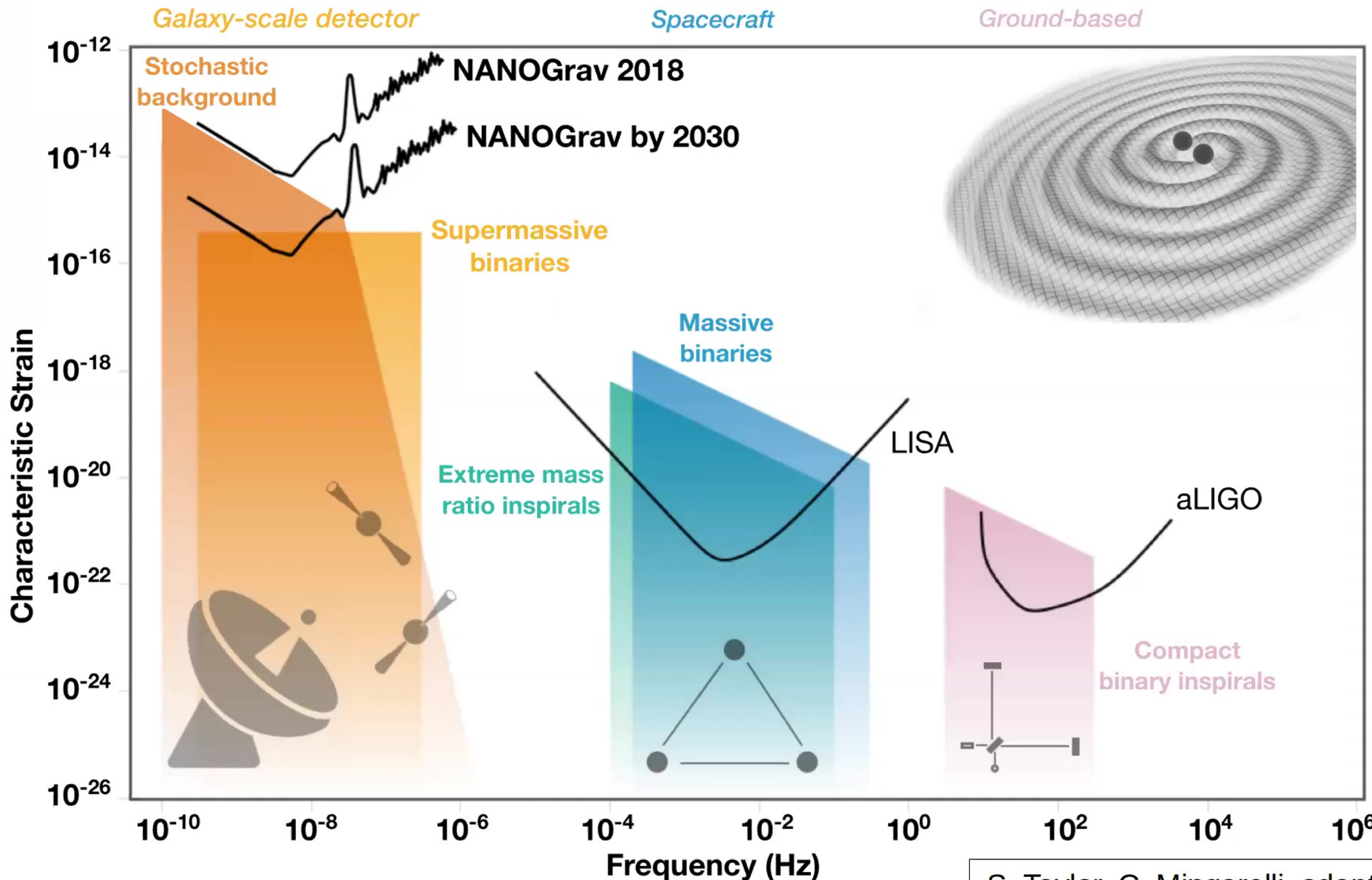
EPTA

European Pulsar
Timing Array

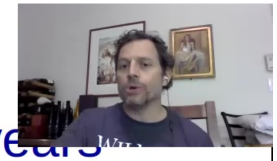

GWs from super-massive
black hole binaries...
...detected by timing an
array
of radio millisecond pulsars.
Image courtesy of *Science*, credit: Nicolle Rager Fuller *[modified]*

The Gravitational Wave Spectrum





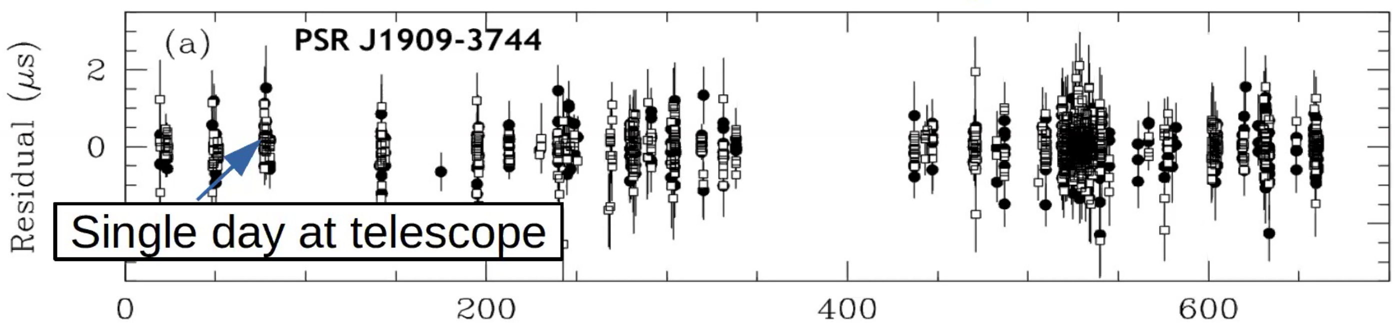
S. Taylor, C. Mingarelli, adapted from gwplotter.org (Moore, Cole, Berry 2014)



Pulsar Timing:

Unambiguously account for every rotation of a pulsar over years

Measurement - Model = Timing Residuals

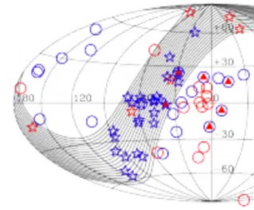


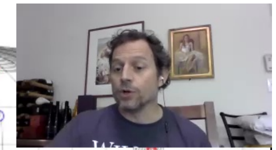
(From Jacoby et al. 2005, ApJL, 629, 113)

Time in days

Predict each pulse to ~200 ns over 2 yrs!

NANOGrav Observing Program





Arecibo Observatory

- Main program: 39 pulsars / dual receiver / every three weeks (began 2004)
- High cadence program: 5 pulsars / dual receiver / every week (began 2015)

Green Bank Telescope

- Main program: 39 pulsars / dual receiver / every month (began 2004)
- High cadence program: 2 pulsars / single receiver /every week (began 2014)

Very Large Array

- Experimental program: 7 pulsars / single or dual receiver
- Sensitive 2-4 GHz system expands frequency coverage
- Can see slightly further south than GBT (1 pulsar)

CHIME **(with CHIME/Pulsar collaboration)**

- 400 to 800 MHz
- All NANOGrav pulsars at $\delta \gtrsim -20^\circ$ observed daily (!)
- Dwell time ~5 min/cos(δ) (began late 2018)
- Still in engineering phase; challenging to calibrate

Slide by David Nice

NANOGrav Physics Frontiers Center

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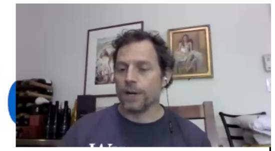
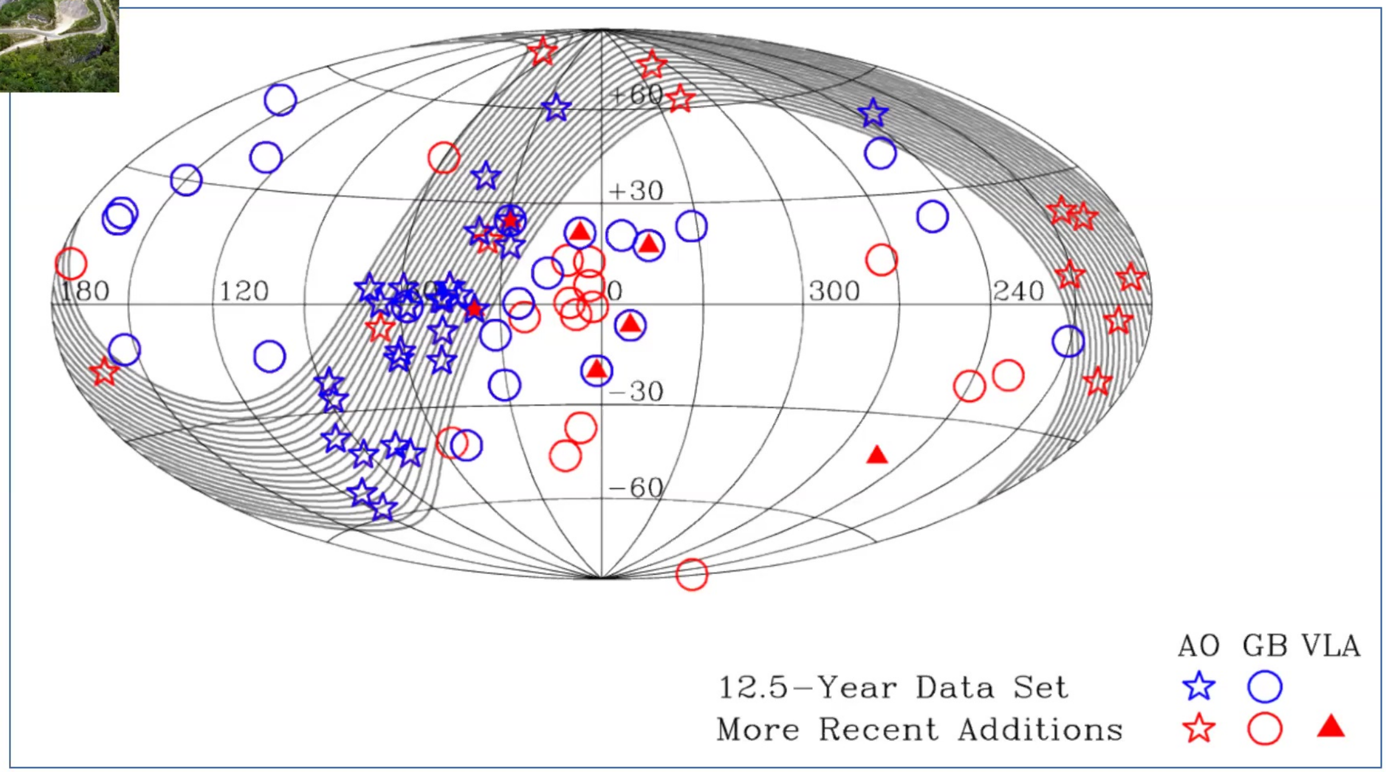
Both Arecibo and the GBT are Cru



Each telescope provides ~50% of our GW sensitivity

- **Arecibo** has 4-5x sensitivity
- **GBT** has 3x sky coverage



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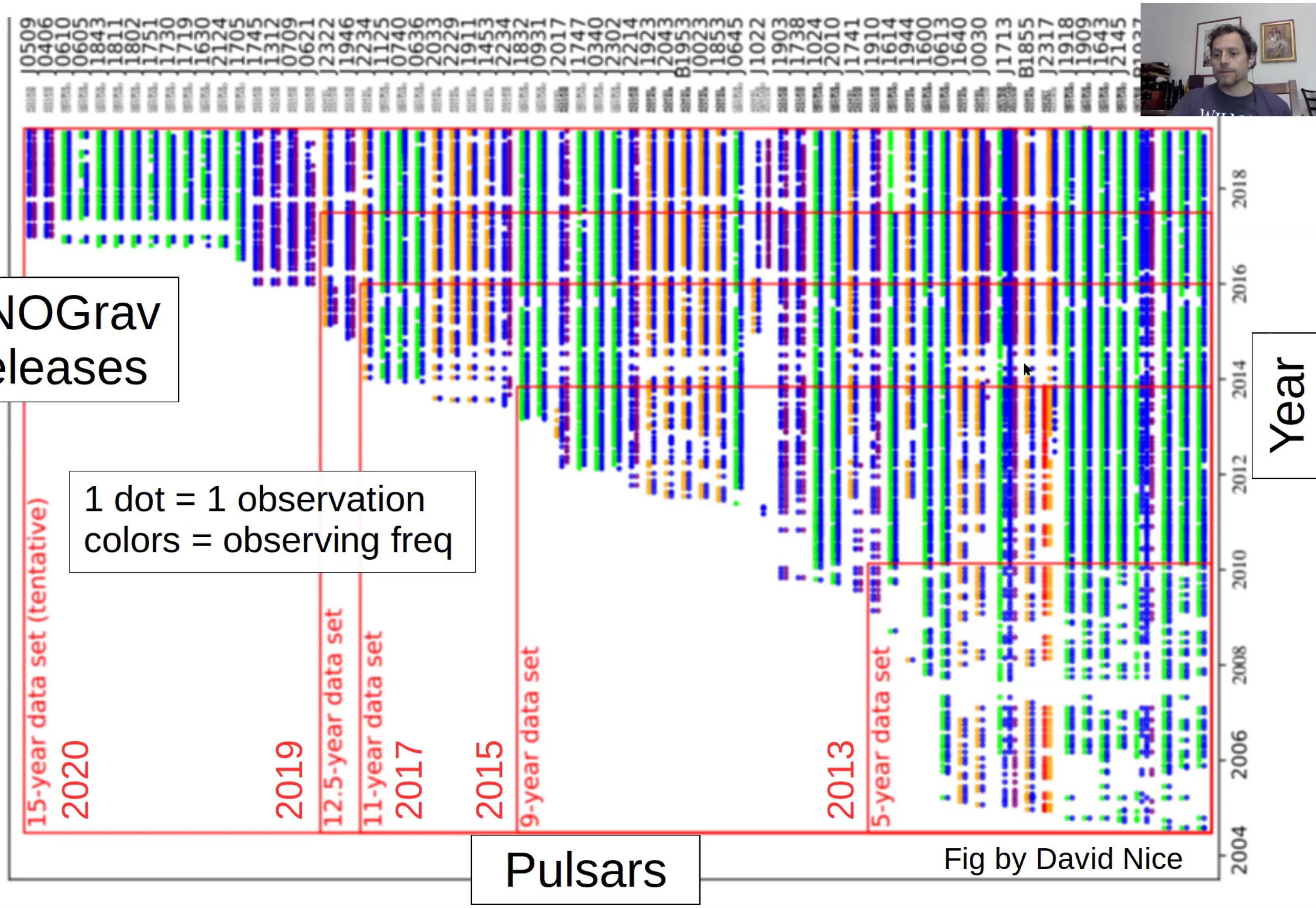
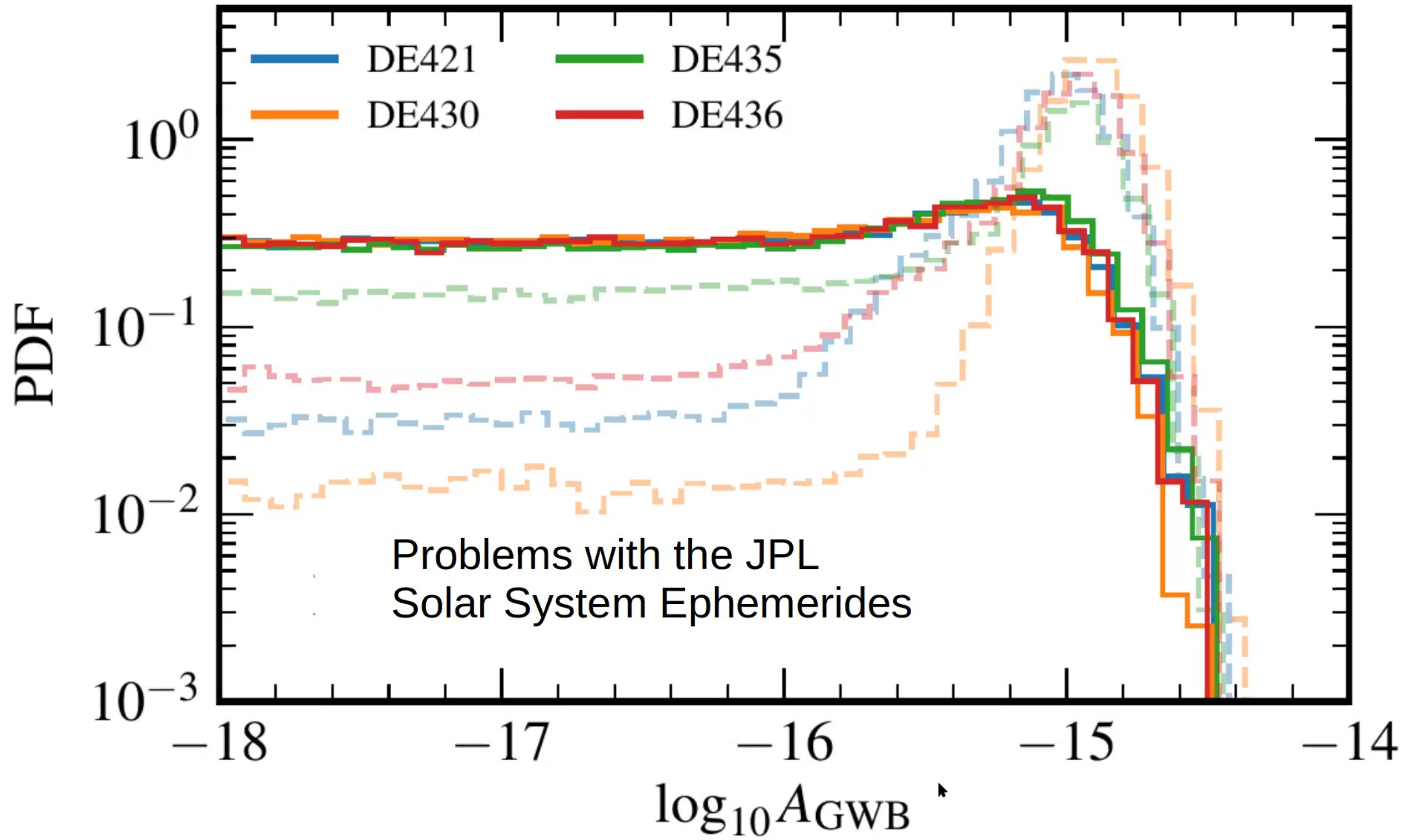
The NANOGrav Data Releases



NANOGrav 11 Year GW Bkgd Resu

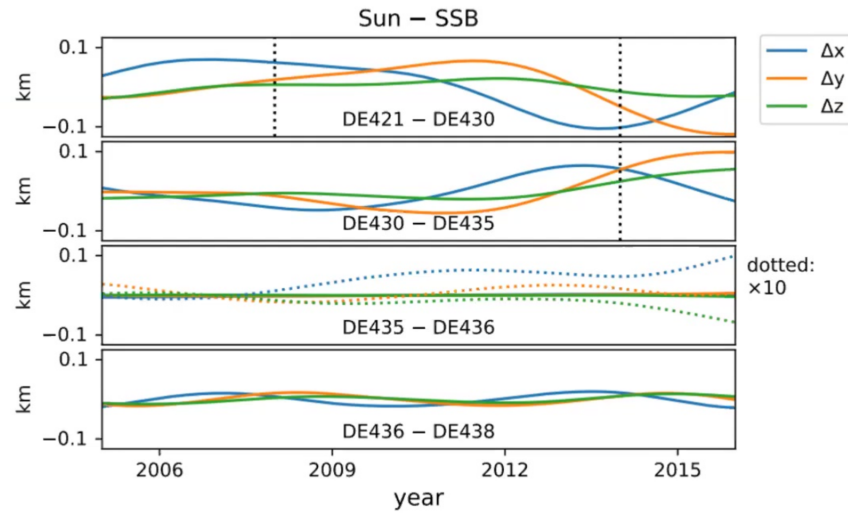


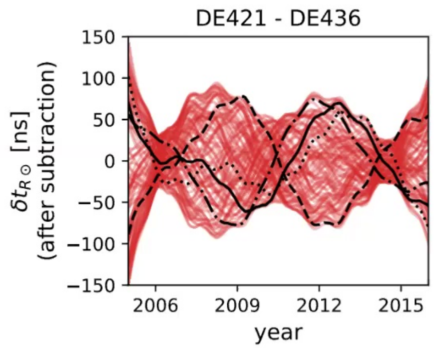
Arzoumanian et al., 2018, ApJ, 859, 47

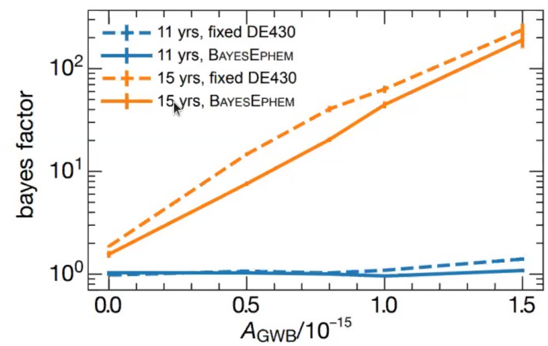
BayesEphem

(aka Modeling the Solar Solar System Ephemeris Uncertainties)

- Solar System ephemerides are uncertain mostly due to orbits of outer planets (esp Jupiter, pre Juno mission)
- Causes ~100m errors in position of Solar System Barycenter
- Can marginalize over this in Bayesian way
- Will become less important with time (we better measure orbits)

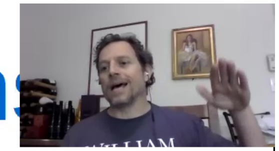


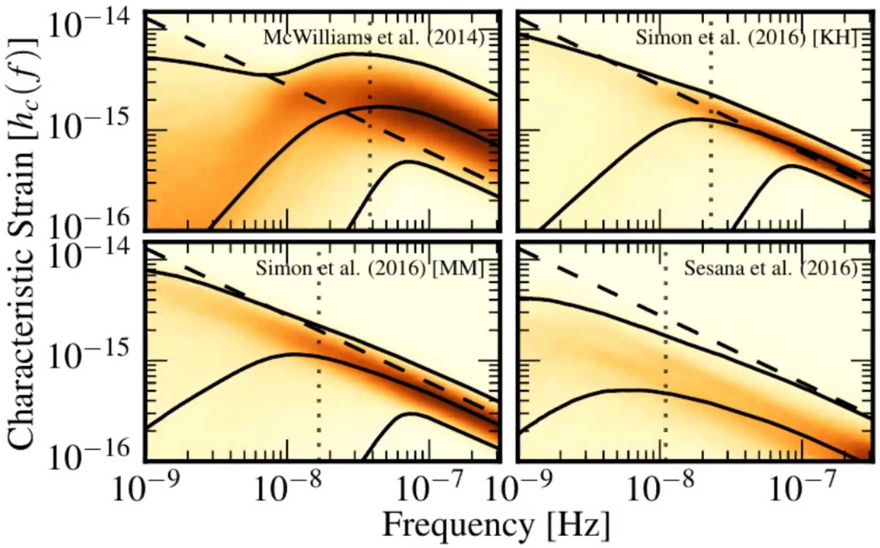




Vallisneri et al. 2020, ApJ, 893, 112

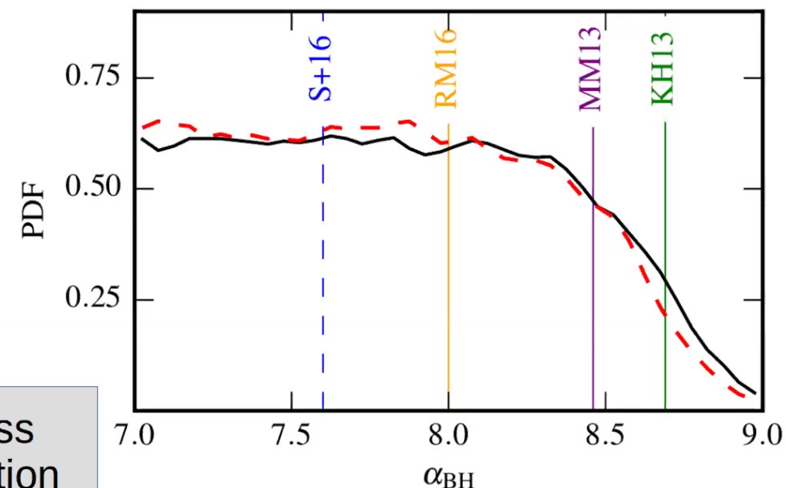
11 Year Astrophysics Implications





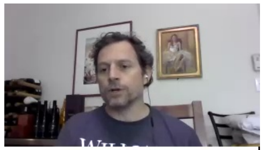
SMBH merger models, plus central stellar density, eccentricity, gas content...

Plus some of best limits on cosmic string tension



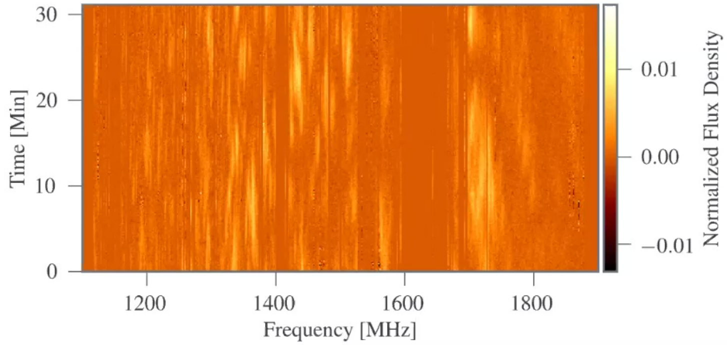
Intercept of the SMBH mass vs Galaxy Bulge mass relation

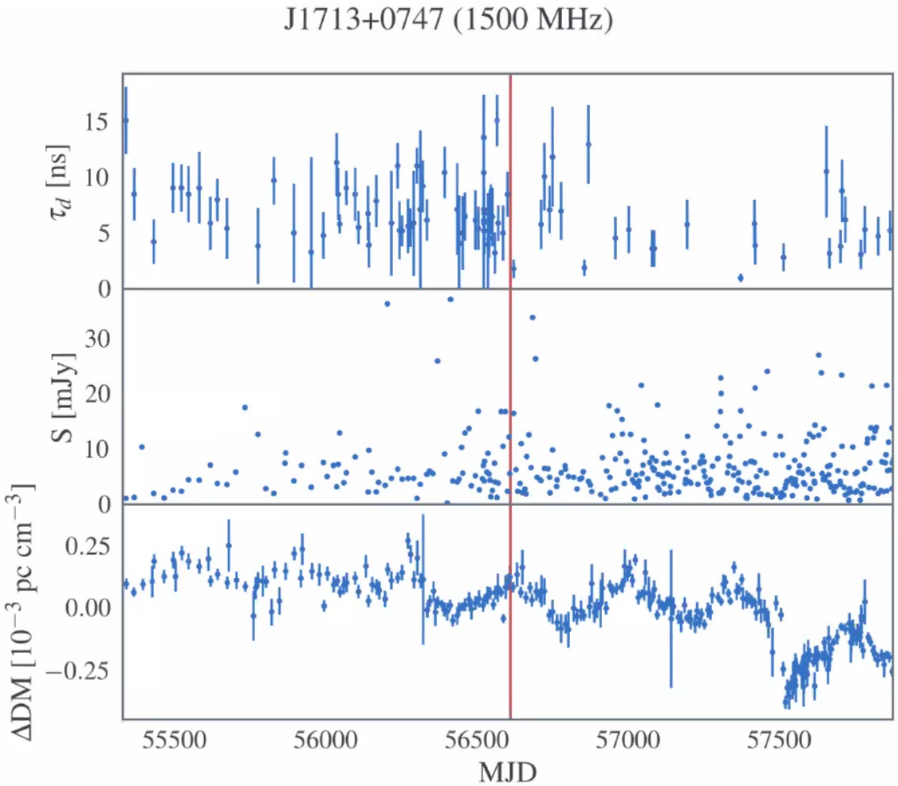
Arzoumanian et al., 2018, ApJ, 859, 47

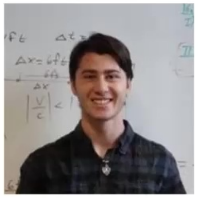


Detailed Studies of ISM

Dispersion and scattering (i.e. pulse broadening are easily measured)





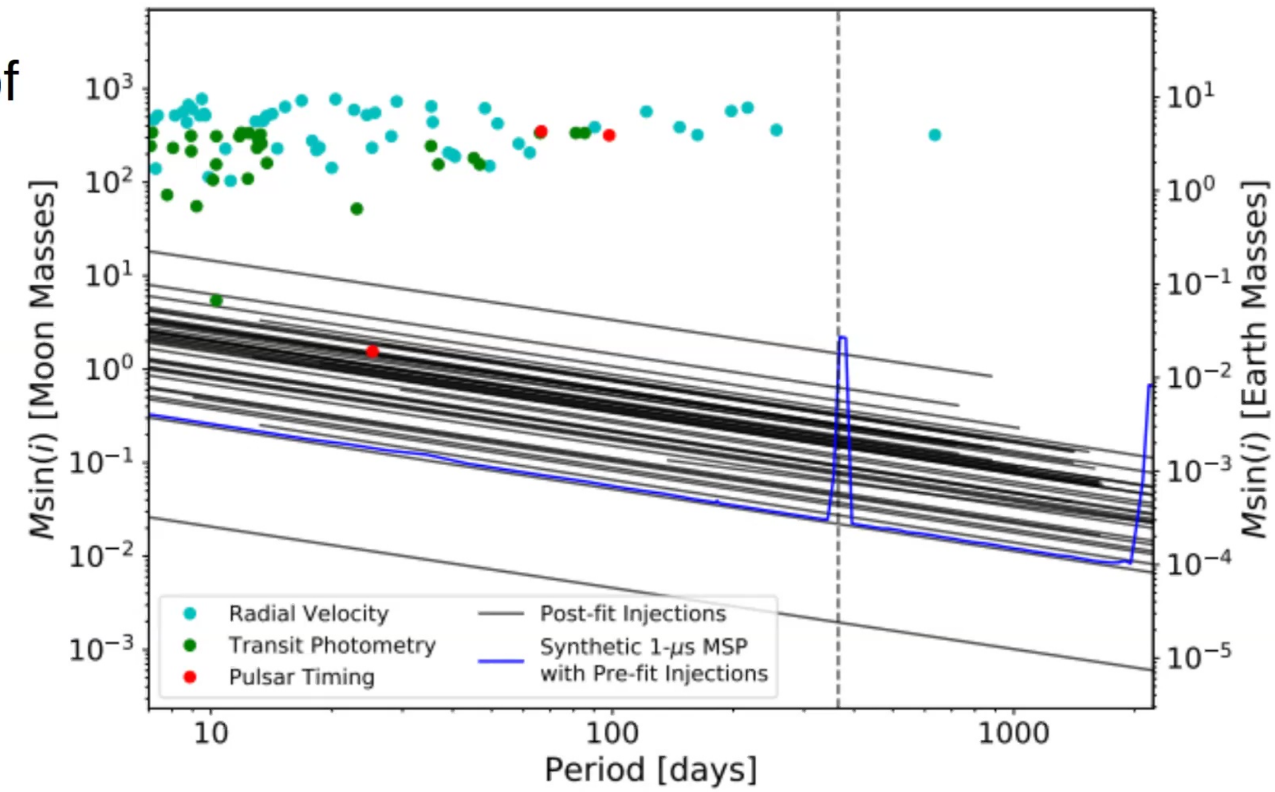


Turner et al. 2020, in prep

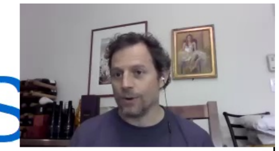
No Planets around NANOGrav MS

Limits on planets down to fraction of Moon mass!

Where are they?



Behrens et al. 2020, ApJ, 893L



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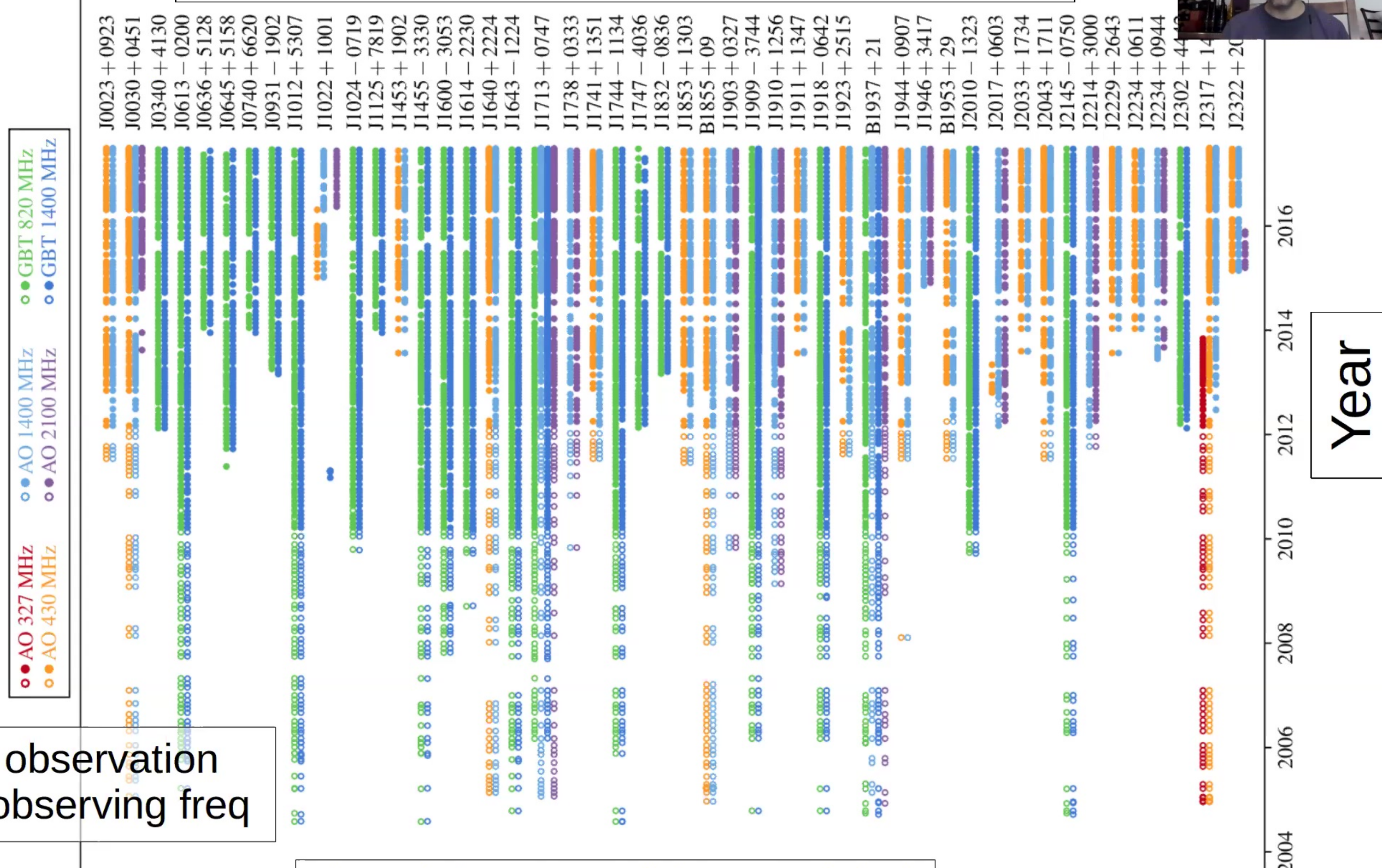
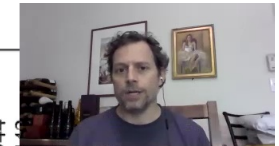
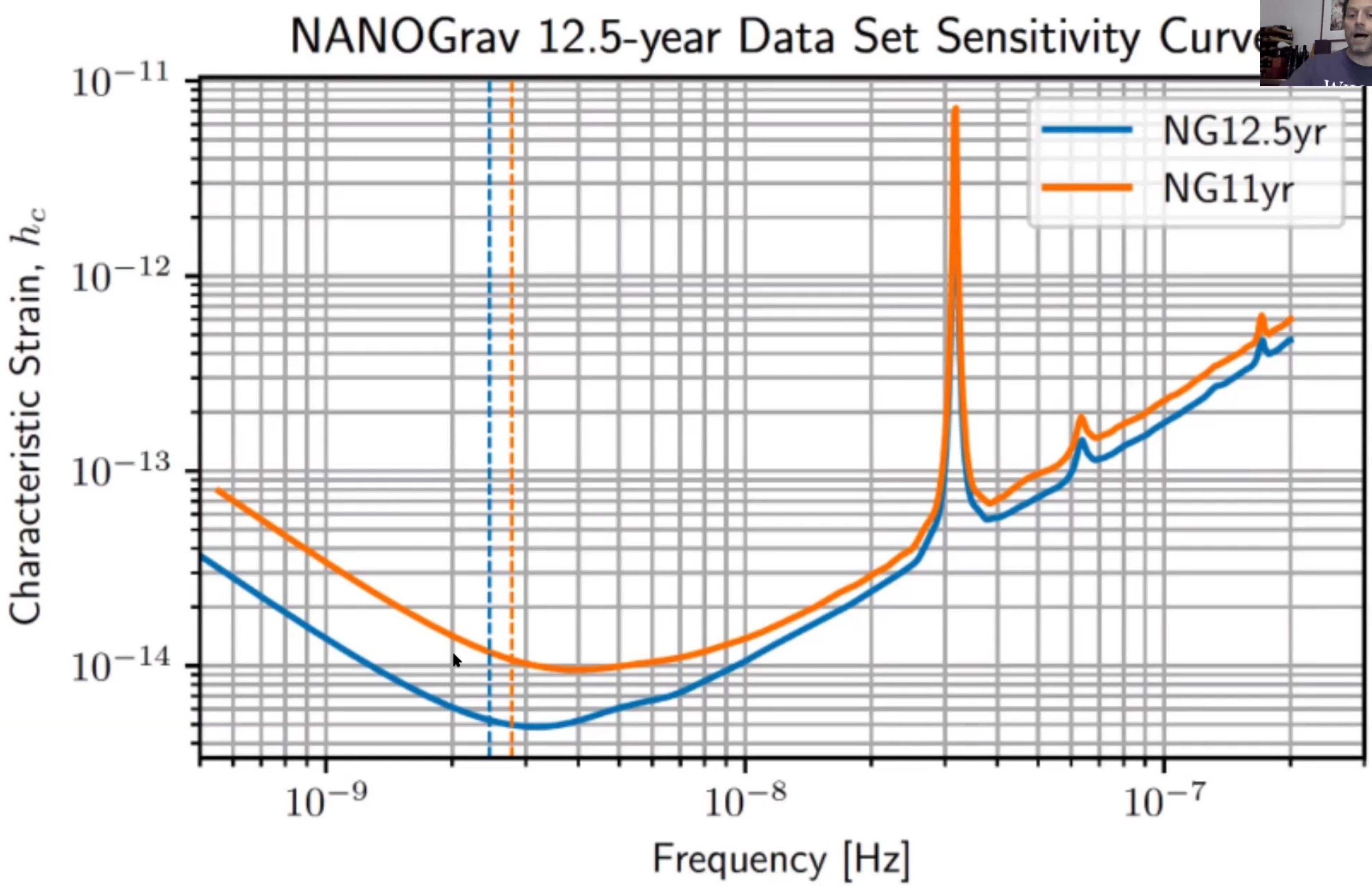
12.5 Year Data Release Pulsars





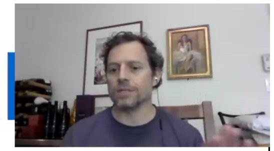
1 dot = 1 observation
colors = observing freq

Alam et al. (NANOGrav Collab), 2020, submitted

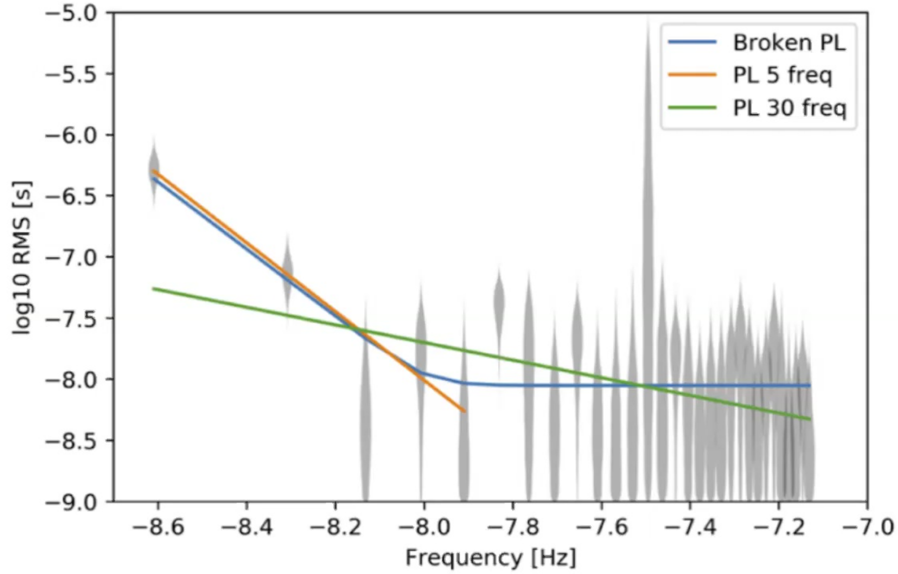


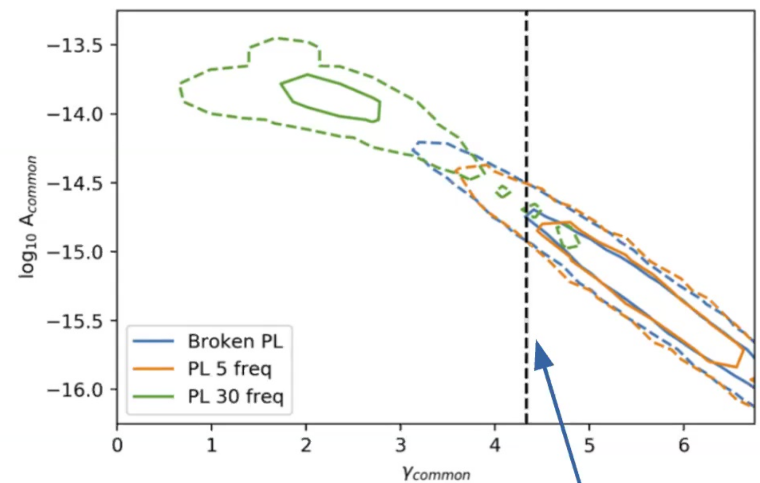
Hazboun, Romano, & Smith, 2019, PhRvD

Preliminary 12.5 Year Bkgd Resul



Seeing significant low-freq noise in the data….

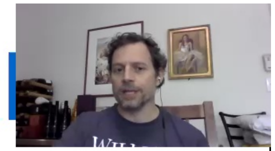




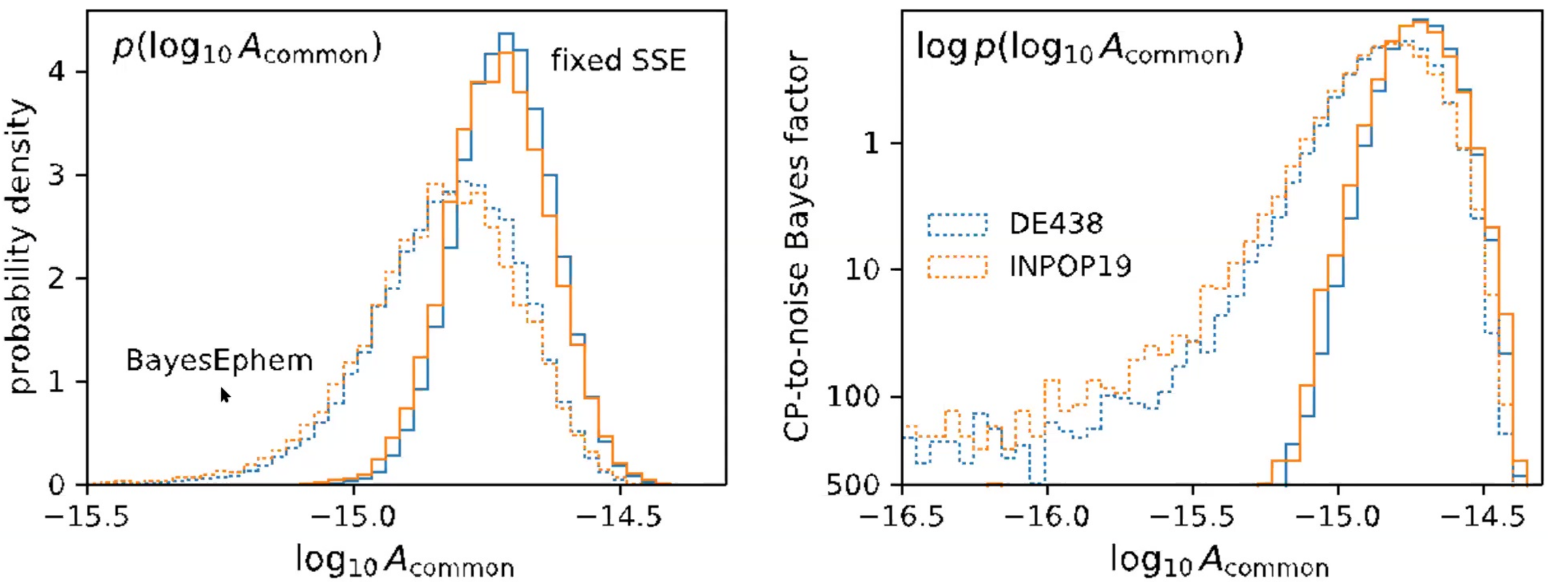
Figures courtesy Joe Simon
(from NANOGrav 12.5yr GW Bkgd submitted)

Expected spectral index for a GWB from in-spiraling SMBHBs (**γ**=13/3)

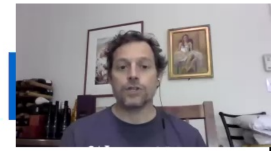
Preliminary 12.5 Year Bkgd Resul



Strong evidence for ***uncorrelated*** **common red noise process**…
(Bayes factors of ~30,000:1 in favor for fixed SS Ephem)



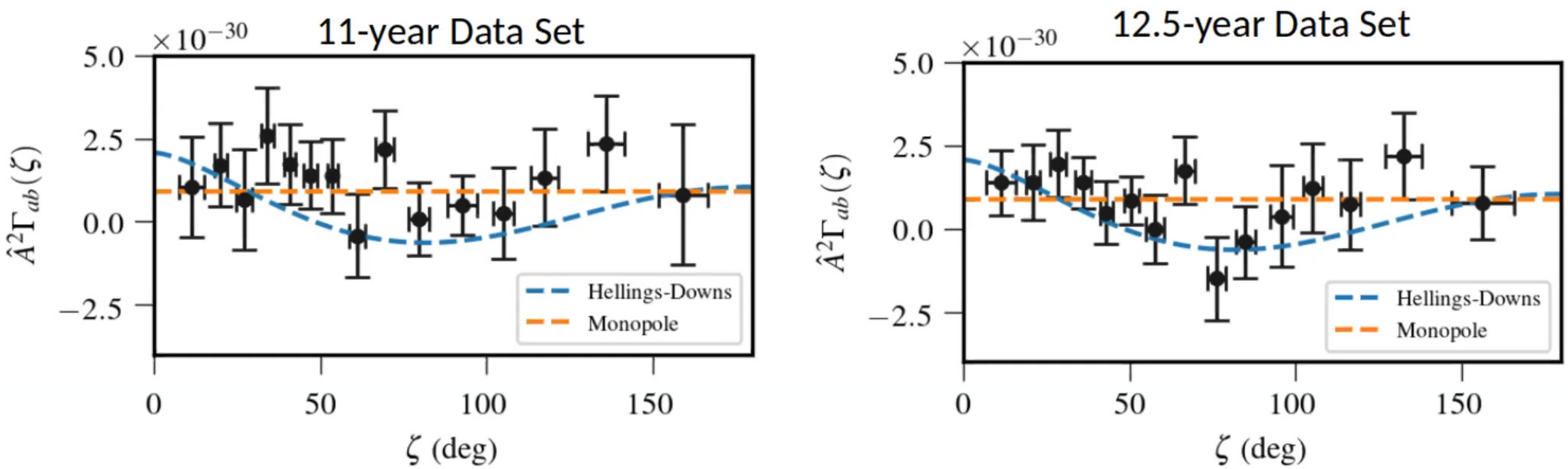
Figures courtesy Joe Simon
(from NANOGrav 12.5yr GW Bkgd submitted)



Preliminary 12.5 Year Bkgd Resul

No good evidence of the required *spatial correlations* yet…

But the data are improving rapidly,
and there are ~2+ more years of data in the bank!



Figures courtesy Joe Simon
(from NANOGrav 12.5yr GW Bkgd submitted)

NANOGrav
Physics Frontiers Center

1. arXiv:2010.04018 [pdf, other] astro-ph.GA
A direct constraint on the Galactic acceleration and the Oort limit from pulsar timing
Authors: Sukanya Chakrabarti, Philip Chang, Michael T. Lam, Sarah J. Vigeland, Alice C. Quillen
Submitted 8 October, 2020; **originally announced** October 2020.
Comments: submitted to ApJ Letters

2. arXiv:2010.03976 [pdf, other] astro-ph.CO gr-qc hep-th
NANOGrav Hints on Planet-Mass Primordial Black Holes
Authors: Guillem Domènech, Shi Pi
Submitted 8 October, 2020; **originally announced** October 2020.
Comments: 7 pages, 3 figures
Report number: IPMU20-0106

3. arXiv:2010.02189 [pdf, other] astro-ph.CO astro-ph.GA hep-ph
Testing Stochastic Gravitational Wave Signals from Primordial Black Holes with Optical Telescopes
Authors: Sunao Sugiyama, Volodymyr Takhistov, Edoardo Vitagliano, Alexander Kusenko, Misao Sasaki, Masahiro Takada
Submitted 5 October, 2020; **originally announced** October 2020.
Comments: 5 pages, 1 figure
Report number: IPMU20-0105

4. arXiv:2009.14663 [pdf, other] astro-ph.CO gr-qc hep-th
Is the NANOGrav signal a hint of dS decay during inflation?
Authors: Hao-Hao Li, Gen Ye, Yun-Song Piao
Submitted 30 September, 2020; **originally announced** September 2020.
Comments: 9 pages,2 figures

5. arXiv:2009.14174 [pdf, other] astro-ph.CO astro-ph.HE
NANOGrav signal from MHD turbulence at QCD phase transition in the early universe
Authors: A. Neronov, A. Roper Pol, C. Caprini, D. Semikoz
Submitted 29 September, 2020; **originally announced** September 2020.
Comments: 5 pages, 2 figures

6. arXiv:2009.13909 [pdf, other] astro-ph.CO gr-qc hep-ph hep-th
Implications of Gravitational-wave Production from Dark Photon Resonance to Pulsar-timing Observations and Effective Number of Relativistic Species
Authors: Ryo Namba, Motoo Suzuki
Submitted 5 October, 2020; **v1** submitted 29 September, 2020; **originally announced** September 2020.
Comments: 13 pages, 2 figures. Minor changes, citation additions

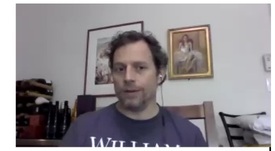
7. arXiv:2009.13893 [pdf, other] astro-ph.CO hep-ph
NanoGrav 12.5-yr data and different stochastic Gravitational wave background sources
Authors: Ligong Bian, Jing Liu, Ruiyu Zhou
Submitted 29 September, 2020; **originally announced** September 2020.
Comments: 18 pages, 5 figures, 1 table; comments welcome

8. arXiv:2009.13452 [pdf, other] hep-ph astro-ph.CO astro-ph.GA gr-qc
Gravitational wave complementarity and impact of NANOGrav data on gravitational leptogenesis: cosmic strings
Authors: Rome Samanta, Satyabrata Datta
Submitted 30 September, 2020; **v1** submitted 28 September, 2020; **originally announced** September 2020.
Comments: 16 pages, 4 figures, typo corrected, refs. updated

9. arXiv:2009.13432 [pdf, other] astro-ph.CO gr-qc hep-ph hep-th
Implications of the NANOGrav pulsar timing results for inflation
Authors: Sunny Vagnozzi
Submitted 28 September, 2020; **originally announced** September 2020.
Comments: 7 pages, 2 figures. Short spoiler: no, **NANOGrav** is very unlikely to be due to inflation. Comments are welcome

10. arXiv:2009.11875 [pdf, other] astro-ph.CO hep-ph
Whispers from the dark side: Confronting light new physics with NANOGrav data
Authors: Wolfram Ratzinger, Pedro Schwaller
Submitted 24 September, 2020; **originally announced** September 2020.
Comments: 10 pages, 5 figures
Report number: MITP/20-056

11. arXiv:2009.11865 [pdf, other] astro-ph.GA gr-qc
Multimessenger pulsar timing array constraints on supermassive black hole binaries traced by periodic light curves
Authors: Chengcheng Xin, Chiara M. F. Mingarelli, Jeffrey S. Hazboun
Submitted 24 September, 2020; **originally announced** September 2020.
Comments: 11 pages, 4 figures, submitted to ApJ



12. arXiv:2009.11853 [pdf, other] astro-ph.CO gr-qc hep-ph hep-th
Solar-Mass Primordial Black Holes Explain NANOGrav Hint of Gravitational Waves
Authors: Kazunori Kohri, Takahiro Terada
Submitted 2 October, 2020; **v1** submitted 24 September, 2020; **originally announced** September 2020.
Comments: 24 pages, 5 figures; minor changes (including the title change)
Report number: KEK-TH-2260, KEK-Cosmo-0263, CTPU-PTC-20-22

13. arXiv:2009.10649 [pdf, other] astro-ph.CO hep-ph
From NANOGrav to LIGO with metastable cosmic strings
Authors: Wilfried Buchmuller, Valerie Domcke, Kai Schmitz
Submitted 22 September, 2020; **originally announced** September 2020.
Comments: 5 pages, 2 figures
Report number: CERN-TH-2020-157, DESY 20-154

14. arXiv:2009.10327 [pdf, other] hep-ph gr-qc
NANOGrav results and Dark First Order Phase Transitions
Authors: Andrea Addazi, Yi-Fu Cai, Qingyu Gan, Antonino Marciano, Kaiqiang Zeng
Submitted 23 September, 2020; **v1** submitted 22 September, 2020; **originally announced** September 2020.
Comments: More details and results on possible WDM-inspired GW spectra added, including more recent numerical tools in the subject. New references added. The main conclusions are substantially unchanged

15. arXiv:2009.09754 [pdf, other] astro-ph.CO gr-qc hep-ph
Gravitational Waves and Dark Radiation from Dark Phase Transition: Connecting NANOGrav Pulsar Timing Data and Hubble Tension
Authors: Yuichiro Nakai, Motoo Suzuki, Fuminobu Takahashi, Masaki Yamada
Submitted 27 September, 2020; **v1** submitted 21 September, 2020; **originally announced** September 2020.
Comments: 9 pages, 4 figures; v2: suppression factor for the sound-wave period included, figures updated, conclusions unchanged
Report number: TU-1109; IPMU20-0100

16. arXiv:2009.08409 [pdf, other] astro-ph.HE
Evaluating Low-Frequency Pulsar Observations to Monitor Dispersion with the Giant Metrewave Radio Telescope
Authors: Megan L. Jones, Maura A. McLaughlin, Jayanta Roy, Michael T. Lam, James M. Cordes, David L. Kaplan, Bhaswati Bhattacharyya, Lina Levin
Submitted 17 September, 2020; **originally announced** September 2020.
Comments: 10 pages, 6 figures. Submitted to The Astrophysical Journal

17. arXiv:2009.08268 [pdf, other] astro-ph.CO gr-qc hep-ph
NANOGrav Hints to Primordial Black Holes as Dark Matter
Authors: V. De Luca, G. Franciolini, A. Riotto
Submitted 17 September, 2020; **originally announced** September 2020.
Comments: 5 pages, 1 figure

18. arXiv:2009.07832 [pdf, other] astro-ph.CO
Did NANOGrav see a signal from primordial black hole formation?
Authors: Ville Vaskonen, Hardi Veermäe
Submitted 30 September, 2020; **v1** submitted 16 September, 2020; **originally announced** September 2020.
Comments: 7 pages, 4 figures

19. arXiv:2009.06607 [pdf, other] astro-ph.CO gr-qc hep-ph hep-th
Has NANOGrav found first evidence for cosmic strings?
Authors: Simone Blasi, Vedran Brdar, Kai Schmitz
Submitted 17 September, 2020; **v1** submitted 14 September, 2020; **originally announced** September 2020.
Comments: 6 pages, 3 figures. v2: revised treatment of the higher cosmic-string modes [see Eq. (6)], resulting in a few numerical but no qualitative changes
Report number: CERN-TH-2020-151

20. arXiv:2009.06555 [pdf, other] astro-ph.CO astro-ph.HE gr-qc hep-ph hep-th
Cosmic String Interpretation of NANOGrav Pulsar Timing Data
Authors: John Ellis, Marek Lewicki
Submitted 16 September, 2020; **v1** submitted 14 September, 2020; **originally announced** September 2020.
Comments: 10 pages, 4 figures. Corrected typos and improved accuracy of the calculation leading to a minor modification of the results
Report number: KCL-PH-TH/2020-53, CERN-TH-2020-150

21. arXiv:2009.04496 [pdf, other] astro-ph.HE astro-ph.GA gr-qc
The NANOGrav 12.5-year Data Set: Search For An Isotropic Stochastic Gravitational-Wave Background
Authors: Zaven Arzoumanian, Paul T. Baker, Harsha Blumer, Bence Becsy, Adam Brazier, Paul R. Brook, Sarah Burke-Spolaor, Shami Chatterjee, Siyuan Chen, James M. Cordes, Neil J. Cornish, Fronefield Crawford, H. Thankful Cromartie, Megan E. DeCesar, Paul B. Demorest, Timothy Dolch, Justin A. Ellis, Elizabeth C. Ferrara, William Fiore, Emmanuel Fonseca, Nathan Garver-Daniels, Peter A. Gentile, Deborah C. Good, Jeffrey S. Hazboun, A. Miguel Holgado , et al. (36 additional authors not shown)
Submitted 9 September, 2020; **originally announced** September 2020.
Comments: 24 pages, 13 figures, 5 tables, 3 appendices. Submitted to The Astrophysical Journal Letters

22. arXiv:2005.13549 [pdf, other] hep-ph astro-ph.CO hep-th
Gravitational waves and proton decay: complementary windows into GUTs
Authors: Stephen F. King, Silvia Pascoli, Jessica Turner, Ye-Ling Zhou

NSF

GREEN BANK OBSERVATORY

NSERC CRSNG

Predictions for Future

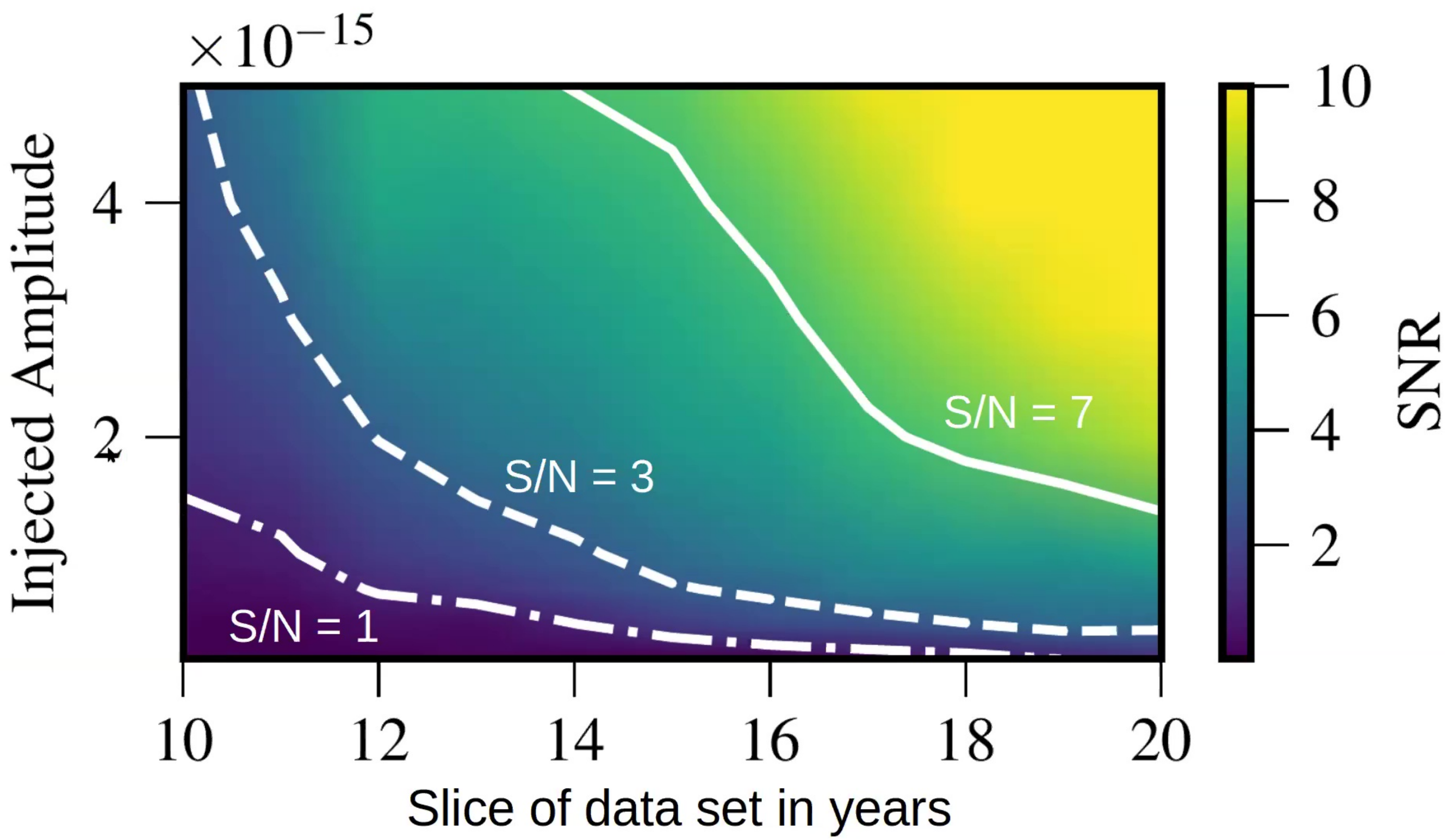


Fig courtesy of Nihan Pol

NANOGrav Physics Frontiers Center

1. arXiv:2010.04018 [pdf, other] astro-ph.GA
A direct constraint on the Galactic acceleration and the Oort limit from pulsar timing
Authors: Sukanya Chakrabarti, Philip Chang, Michael T. Lam, Sarah J. Vigeland, Alice C. Quillen
Submitted 8 October, 2020; originally announced October 2020.
Comments: submitted to ApJ Letters

2. arXiv:2010.03976 [pdf, other] astro-ph.CO gr-qc hep-th
NANOGrav Hints on Planet-Mass Primordial Black Hol
Authors: Guillem Domènech, Shi Pi
Submitted 8 October, 2020; originally announced October 2020.
Comments: 7 pages, 3 figures
Report number: IPMU20-0106

3. arXiv:2010.02189 [pdf, other] astro-ph.CO astro-ph.GA hep-ph
Testing Stochastic Gravitational Wave Signals from Pri
Authors: Sunao Sugiyama, Volodymyr Takhistov, Edoardo Vitagliano,
Submitted 5 October, 2020; originally announced October 2020.
Comments: 5 pages, 1 figure
Report number: IPMU20-0105

4. arXiv:2009.14663 [pdf, other] astro-ph.CO gr-qc hep-th
Is the NANOGrav signal a hint of dS decay during infla
Authors: Hao-Hao Li, Gen Ye, Yun-Song Piao
Submitted 30 September, 2020; originally announced September 2020.
Comments: 9 pages,2 figures

5. arXiv:2009.14174 [pdf, other] astro-ph.CO astro-ph.HE
NANOGrav signal from MHD turbulence at QCD phase
Authors: A. Neronov, A. Roper Pol, C. Caprini, D. Semikoz
Submitted 29 September, 2020; originally announced September 2020.
Comments: 5 pages, 2 figures

6. arXiv:2009.13909 [pdf, other] astro-ph.CO gr-qc hep-ph
Implications of Gravitational-wave Production from D
Number of Relativistic Species
Authors: Ryo Namba, Motoo Suzuki
Submitted 5 October, 2020; v1 submitted 29 September, 2020; originally announ
Comments: 13 pages, 2 figures. Minor changes, citation additions

7. arXiv:2009.13893 [pdf, other] astro-ph.CO hep-ph
NanoGrav 12.5-yr data and different stochastic Gravit
Authors: Ligong Bian, Jing Liu, Ruiyu Zhou
Submitted 29 September, 2020; originally announced September 2020.
Comments: 18 pages, 5 figures, 1 table; comments welcome

8. arXiv:2009.13452 [pdf, other] hep-ph astro-ph.CO astro-ph.GA
Gravitational wave complementarity and impact of NA
Authors: Rome Samanta, Satyabrata Datta
Submitted 30 September, 2020; v1 submitted 28 September, 2020; originally ann
Comments: 16 pages, 4 figures, typo corrected, refs. updated

9. arXiv:2009.13432 [pdf, other] astro-ph.CO gr-qc hep-ph
Implications of the NANOGrav pulsar timing results fo
Authors: Sunny Vagnozzi
Submitted 28 September, 2020; originally announced September 2020.
Comments: 7 pages, 2 figures. Short spoiler: no, NANOGrav is very unlikely to be

10. arXiv:2009.11875 [pdf, other] astro-ph.CO hep-ph
Whispers from the dark side: Confronting light new ph
Authors: Wolfram Ratzinger, Pedro Schwaller
Submitted 24 September, 2020; originally announced September 2020.
Comments: 10 pages, 5 figures
Report number: MITP/20-056

11. arXiv:2009.11865 [pdf, other] astro-ph.GA gr-qc
Multimessenger pulsar timing array constraints on supermassive black hole binaries traced by periodic light curves
Authors: Chengcheng Xin, Chiara M. F. Mingarelli, Jeffrey S. Hazboun
Submitted 24 September, 2020; originally announced September 2020.
Comments: 11 pages, 4 figures, submitted to ApJ

12. arXiv:2009.11853 [pdf, other] astro-ph.CO gr-qc hep-ph hep-th
Solar-Mass Primordial Black Holes Explain NANOGrav Hint of Gravitational Waves
Authors: Kazunori Kohri, Takahiro Terada

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ion from Dark Phase Transition: Connecting NANOGrav Pulsar Timing Data and

servations to Monitor Dispersion with the Giant Metrewave Radio Telescope

Holes as Dark Matter

nordial black hole formation?

for cosmic strings?

OGrav Pulsar Timing Data

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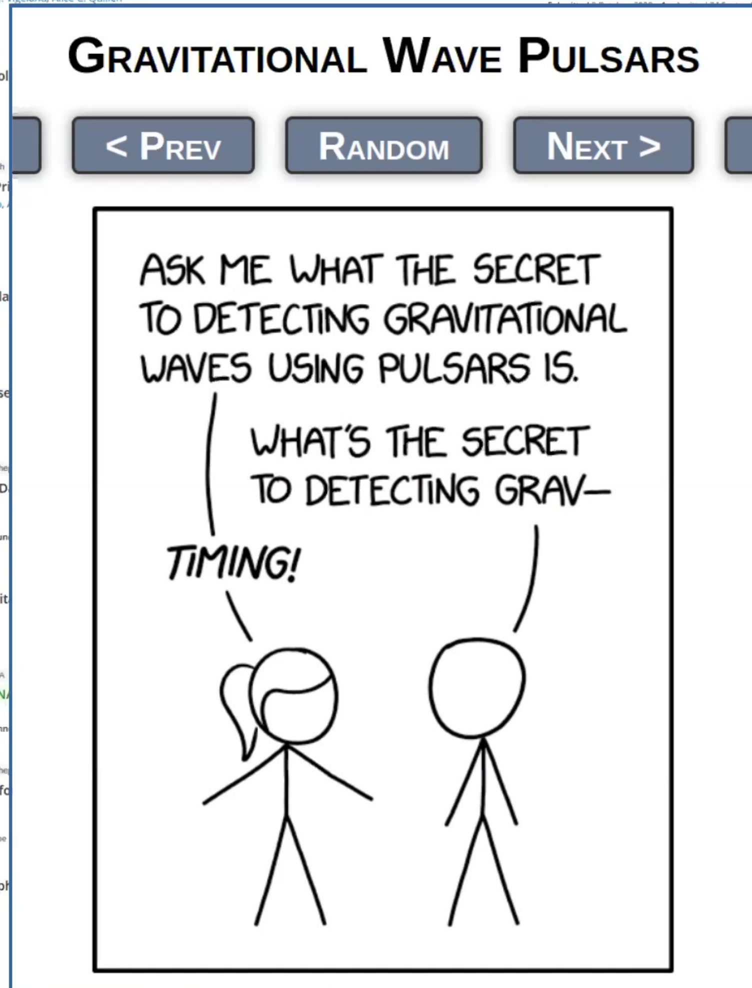
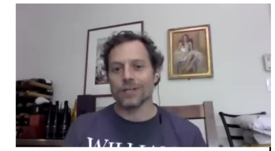
22. arXiv:2005.13549 [pdf, other] hep-ph astro-ph.CO hep-th
Gravitational waves and proton decay: complementary windows into GUTs
Authors: Stephen F. King, Silvia Pascoli, Jessica Turner, Ye-Ling Zhou





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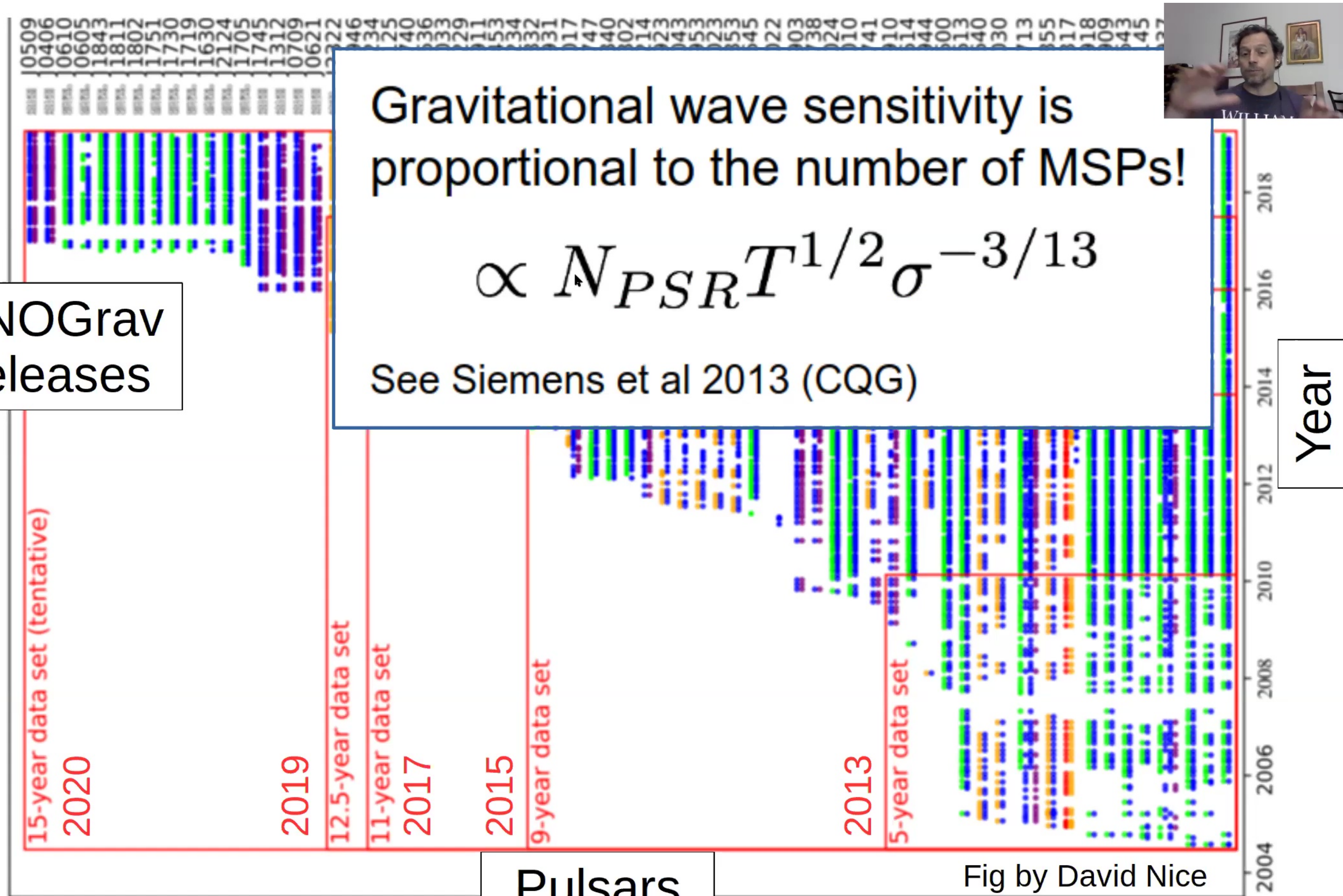
The NANOGrav Data Releases

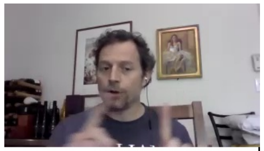


Gravitational wave sensitivity is proportional to the number of MSPs!

$$\propto N_{PSR} T^{1/2} \sigma^{-3/13}$$

See Siemens et al 2013 (CQG)

Predictions for Future



Predictions for future MSPs, using AO, GBT, and DSA2000 telescopes

~200 MSPs timeable at ~1μs

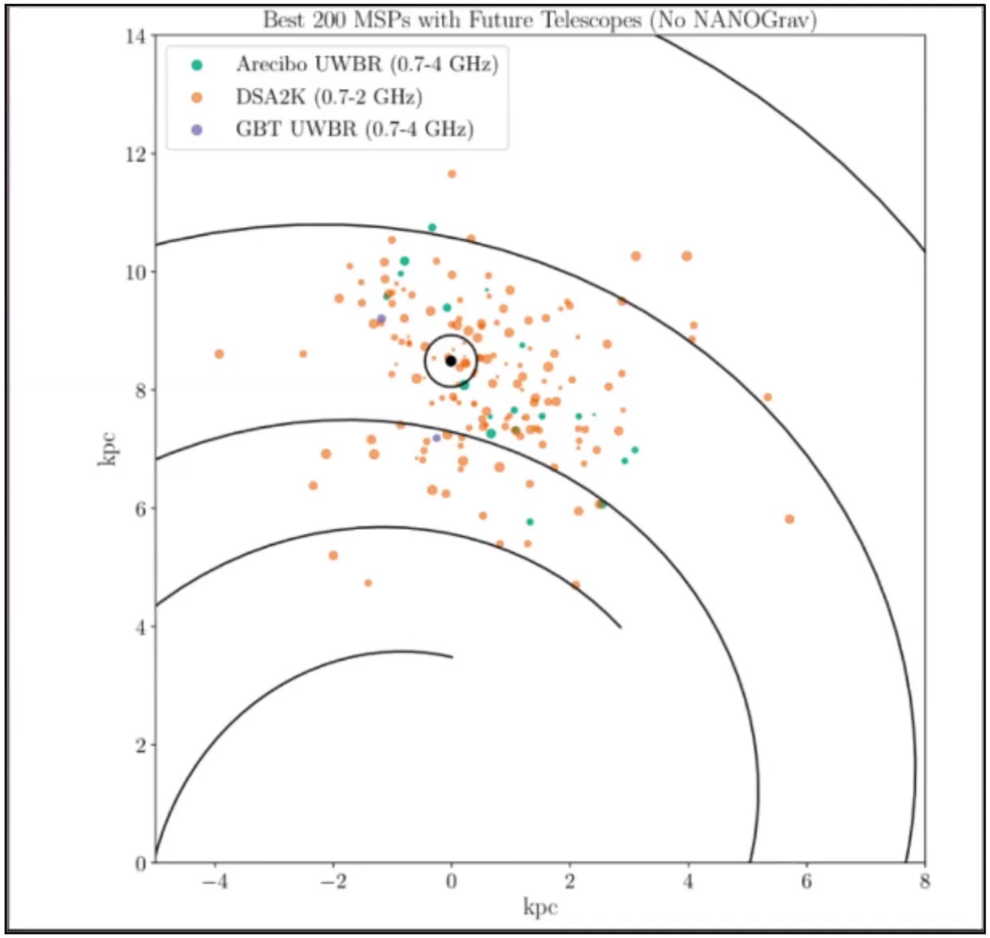
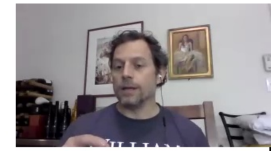


Fig courtesy of Tyler Coher and Paul Demorest

Predictions for Future



Individual SMBHB Sources

Should detect one or more individual SMBHBs by the end of the decade

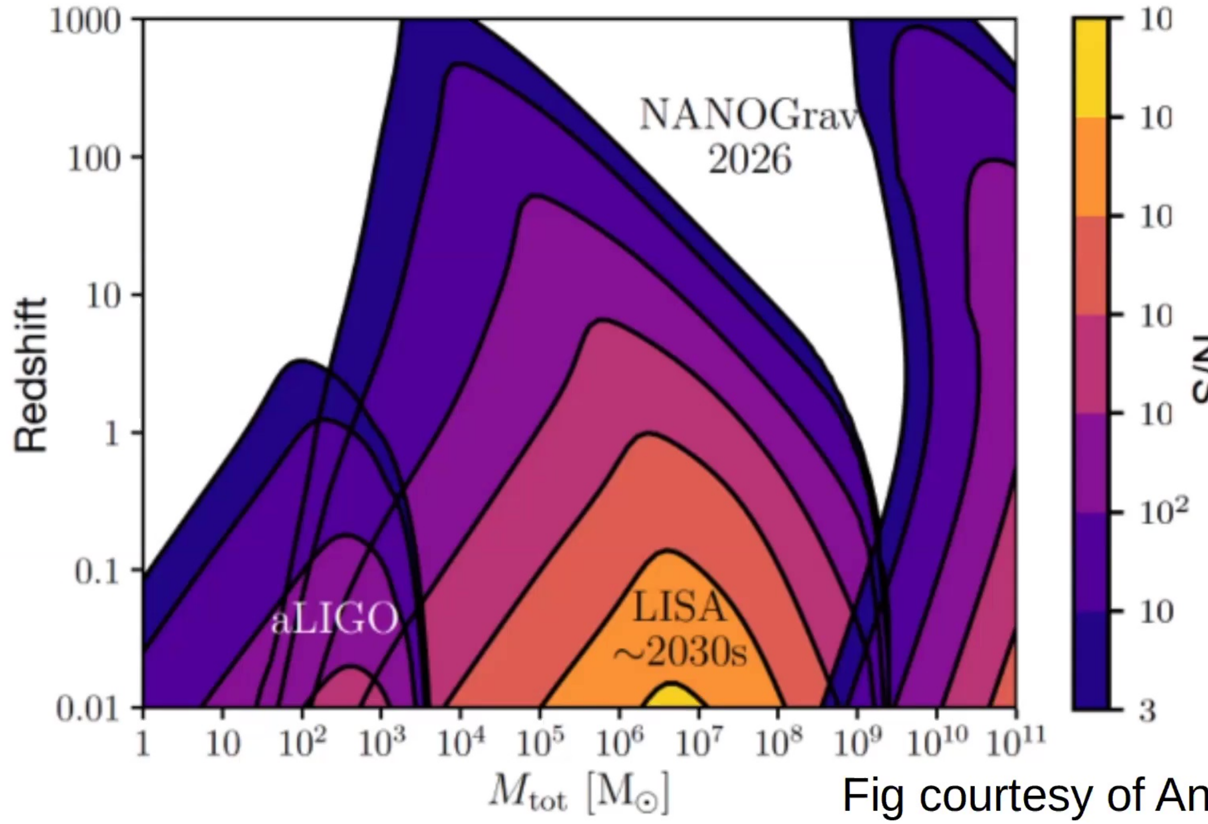
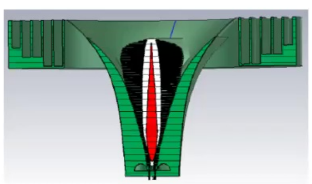


Fig courtesy of Andrew Kaiser

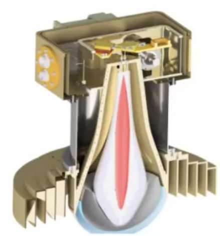
Wideband Receivers for GBT and

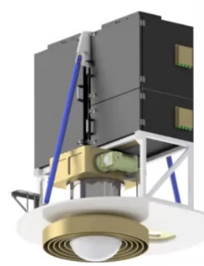
- **Need multi-frequencies for ISM removal**
  - Current systems have <800 MHz BW
  - **Ultra-wideband system** would give 2x better timing, fewer systematics, and more protection from scintillation
- Building a 0.7-4 GHz receiver for GBT, and purchasing one from CSIRO for Arecibo, funded by Moore Foundation

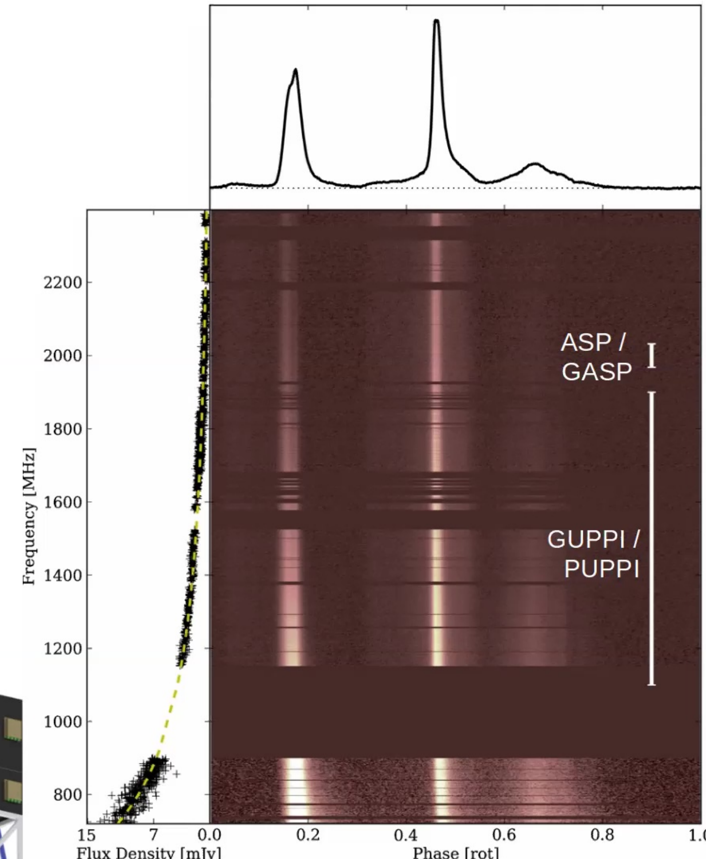


GORDON AND BETTY MOORE FOUNDATION

Hobbs et al. 2019, PASA, in press





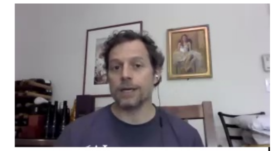


Pennucci et al. 2014, ApJ, 790, 93

Arecibo Damage

- Support cable failure damaged dish.
- Seems to be design flaw, which will require other cables to be braced and then repaired.
- Unknown timescale for repairs: Could be months to year+
- UCF and NSF seems committed to repairs, though

Photo credit: Phil Perillat, Arecibo Obs



Summary

- NANOGrav is doing great – thanks to Arecibo and the GBO
- Our work with IPTA will make things even better
- Data are intriguing and we expect a detection within the next couple years
- In the meantime, tons of other science (e,g,. Cromartie et al. 2019 massive NS)