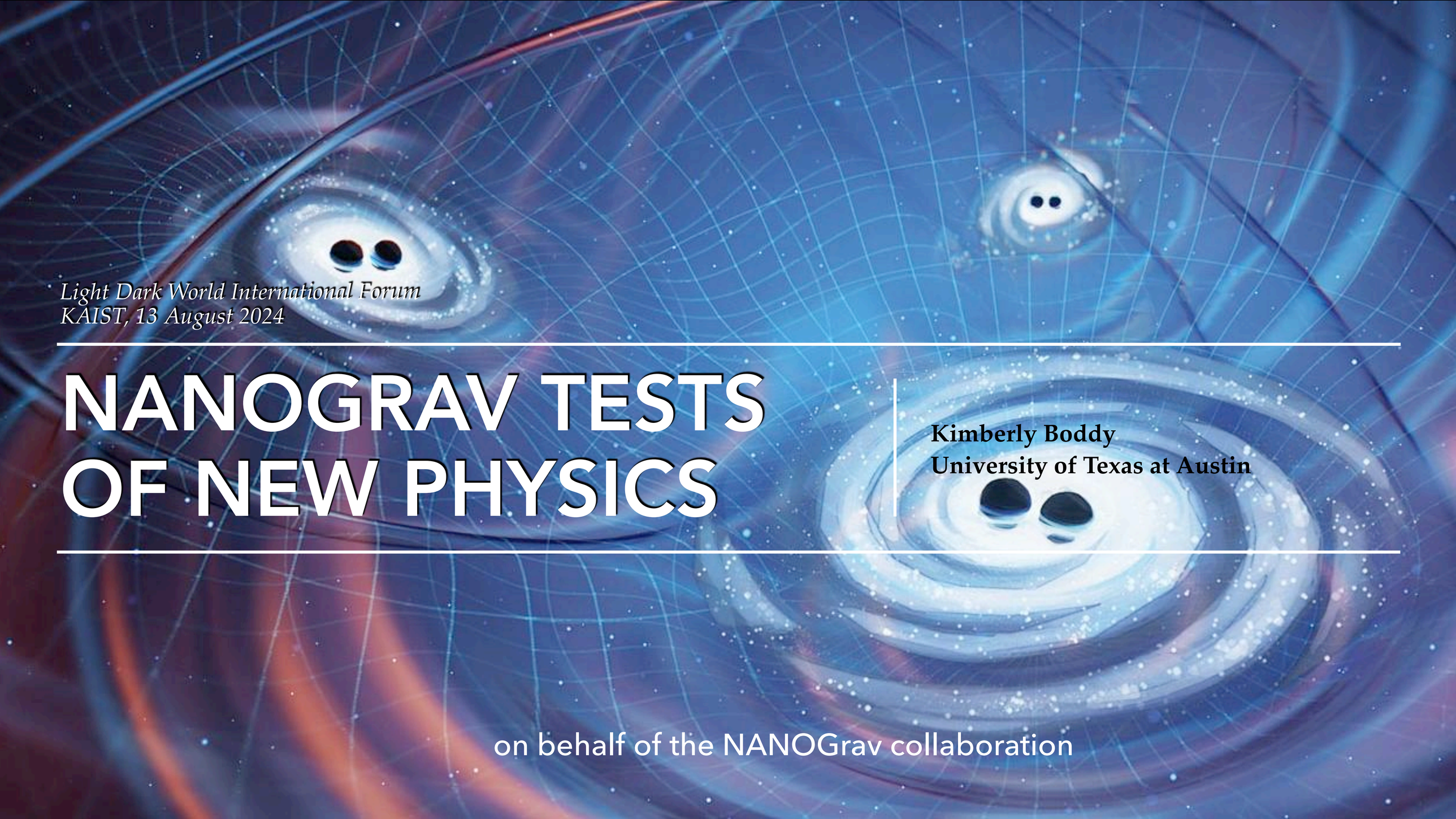


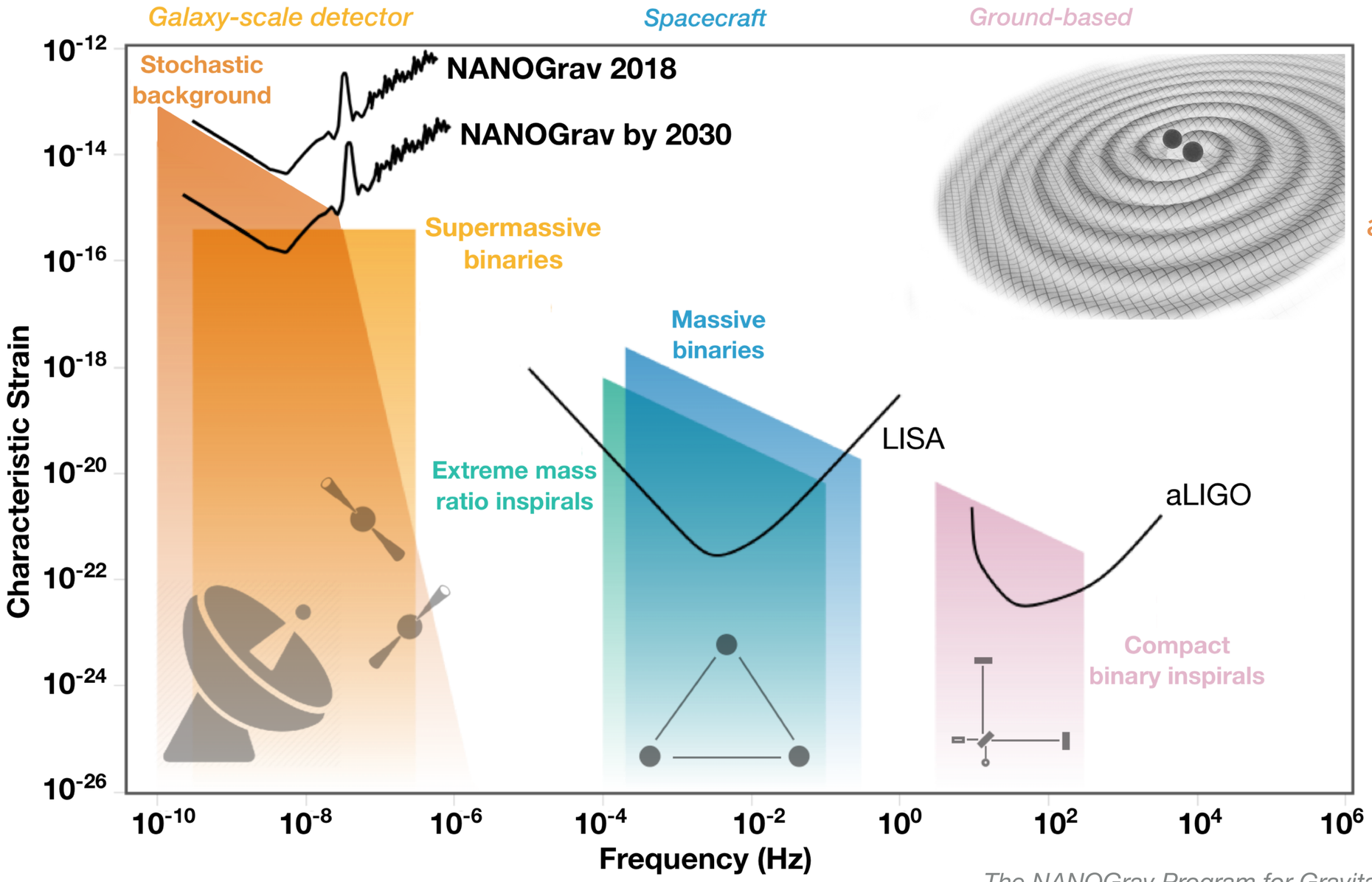
Light Dark World International Forum
KAIST, 13 August 2024

NANOGRAV TESTS OF NEW PHYSICS

Kimberly Boddy
University of Texas at Austin

on behalf of the NANOGrav collaboration

Gravitational Wave Spectrum



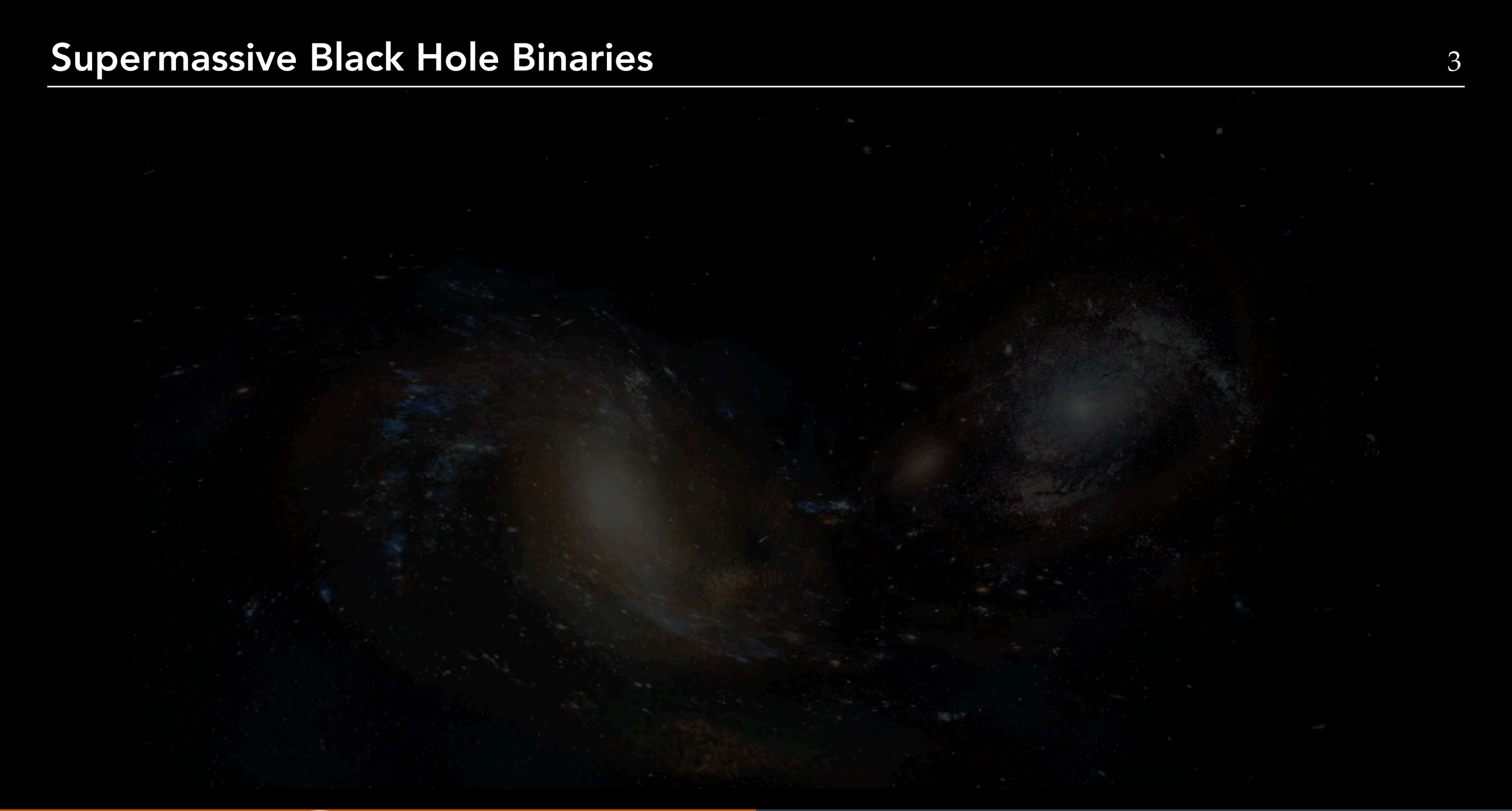
Stochastic background arises from large number of unresolved binary sources

$$h_c = A\left(\frac{f}{f_0}\right)^{\alpha}$$

Benchmark: $\alpha = -2/3$
or $\gamma = 2\alpha - 3 = -13/3$

Astro2020 White Paper (1908.05356)
The NANOGrav Program for Gravitational Waves and Fundamental Physics

Supermassive Black Hole Binaries



Worldwide Pulsar Timing Array (PTA) Experiments

Figure credit: T. Cromartie

Announcement in June 2023

Multiple pulsar timing array experiments reported evidence for background of nHz gravitational waves

NANOGrav
- SGWB search (2306.16213)
- Observation & Timing (2306.16217)
- Detector & Noise (2306.16218)
- New physics (2306.16219)
- SMBHB (2306.16220)
- Anisotropy (2306.16221)
- Continuous waves (2306.16222)
- Pipeline (2306.16223)

EPTA / InPTA
- SGWB search (2306.16214)
- Data & Timing (2306.16224)
- Noise (2306.16225)
- Continuous waves (2306.16226)
- Signal sources (2306.16227)
- ULDM (2306.16228)

PPTA
- SGWB search (2306.16215)
- Noise (2306.16229)
- Data (2306.16230)

CPTA
- SGWB search (2306.16216)

NANOGrav Collaboration

Over 190 members at over 70 partner institutions

NANOGrav
Physics Frontiers Center

Natural Sciences and Engineering Research Council of Canada

Canadian Institute for Advanced Research

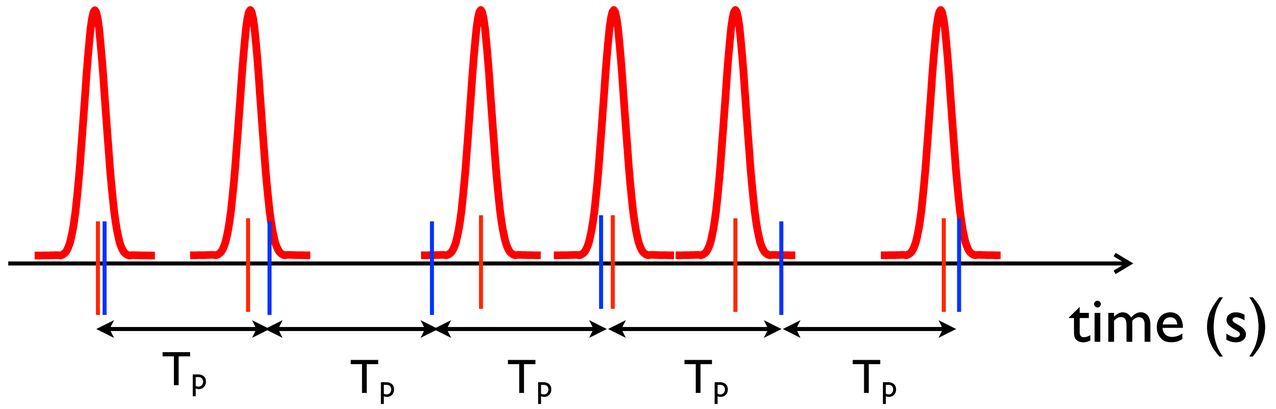
Gordon and Betty Moore Foundation

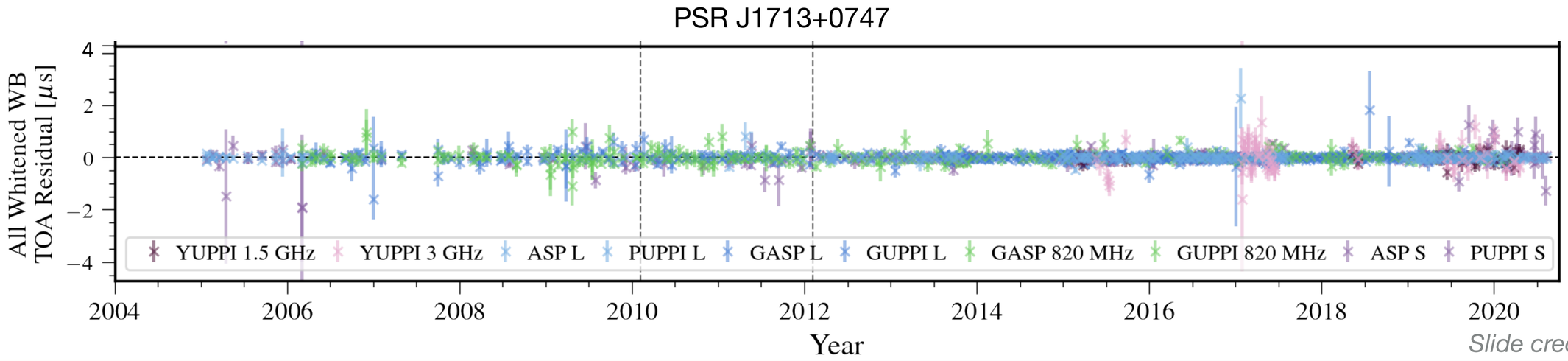
High-Precision Timing of Millisecond Pulsars

Animation by NSF

Pulsar Timing Measurements

timing residual = observed arrival time — predicted arrival time
= unmodeled deterministic processes + noise + GWs





Slide credit: J. Romano

Timing Data Summary: 15-Year Data Set, 68 Pulsars

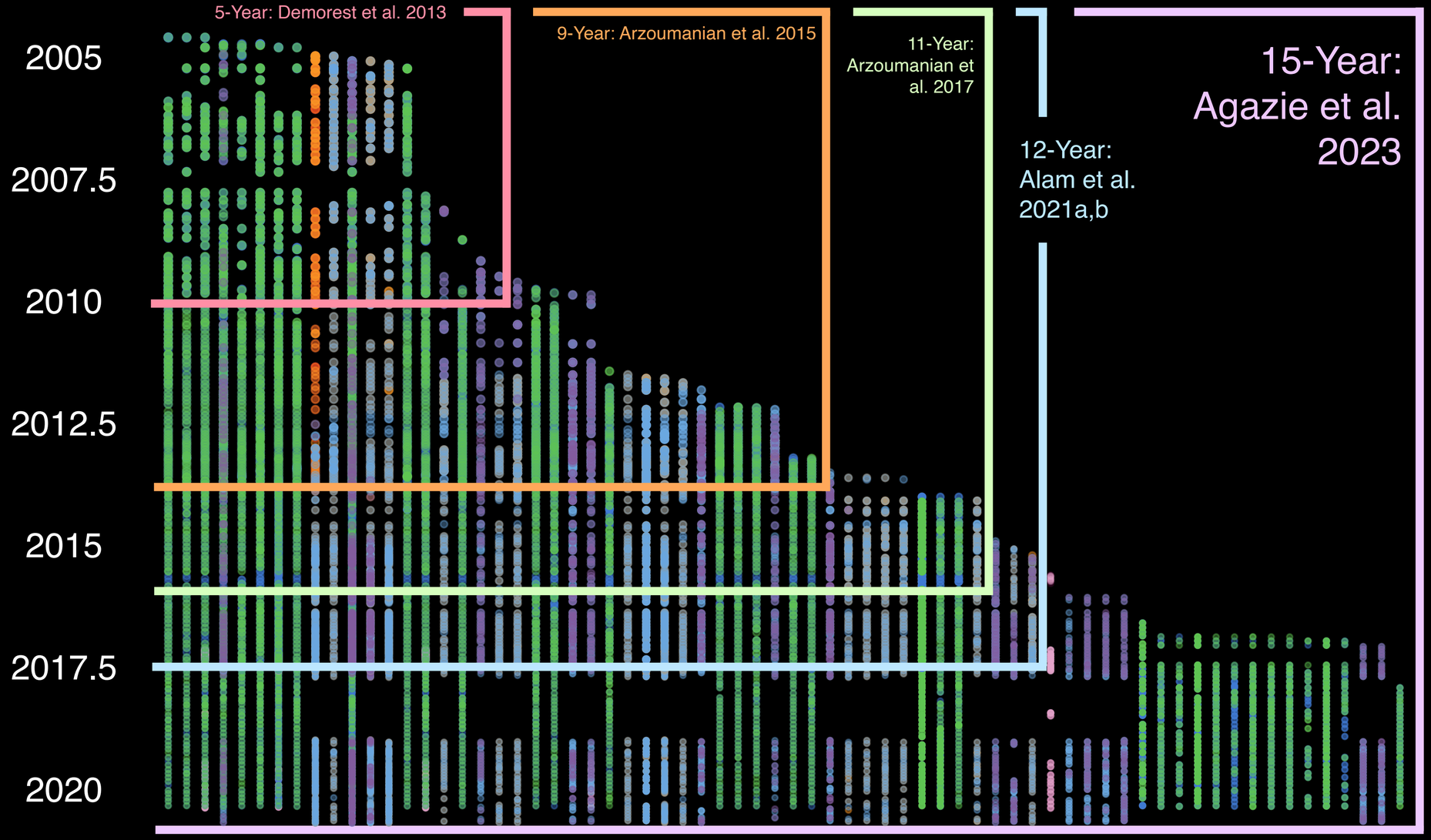
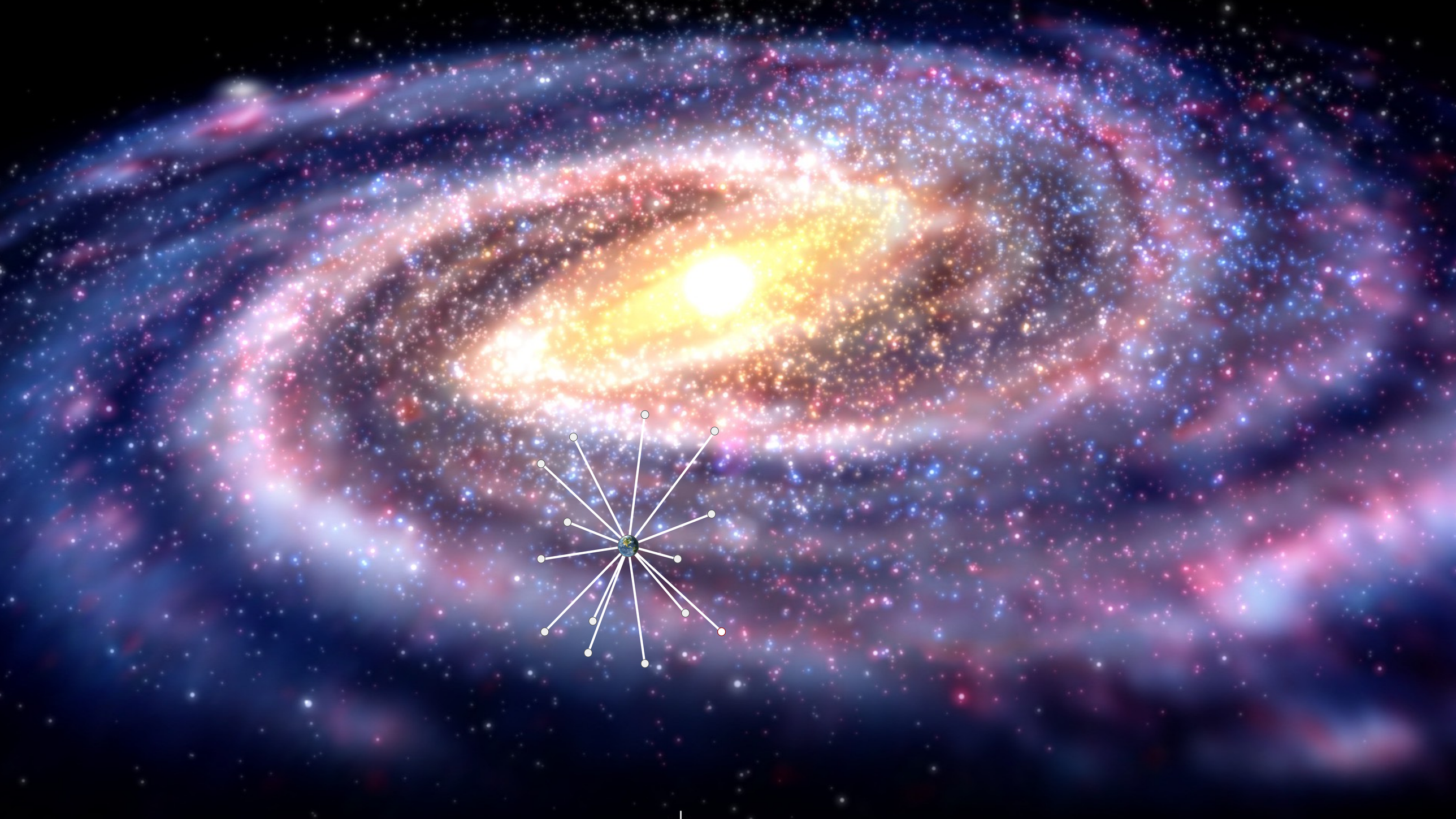


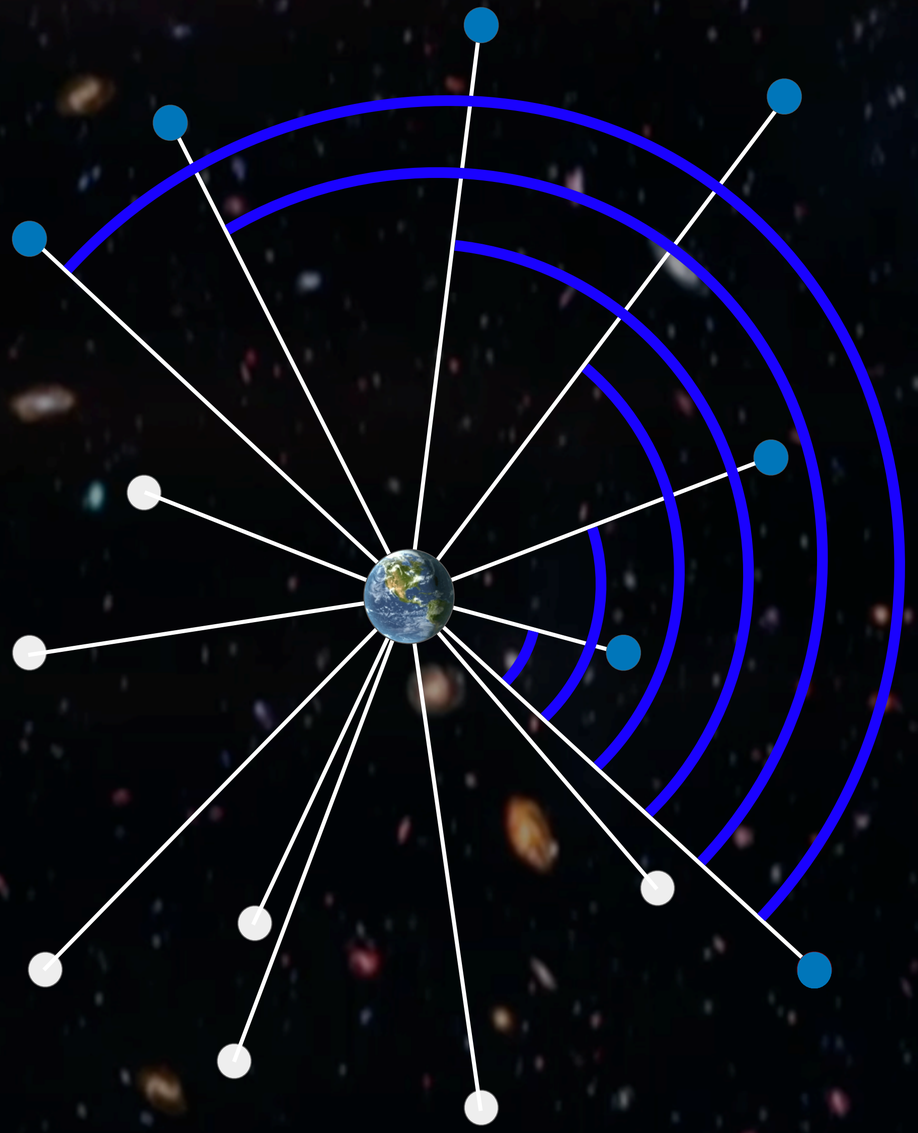
Figure credit: T. Cromartie

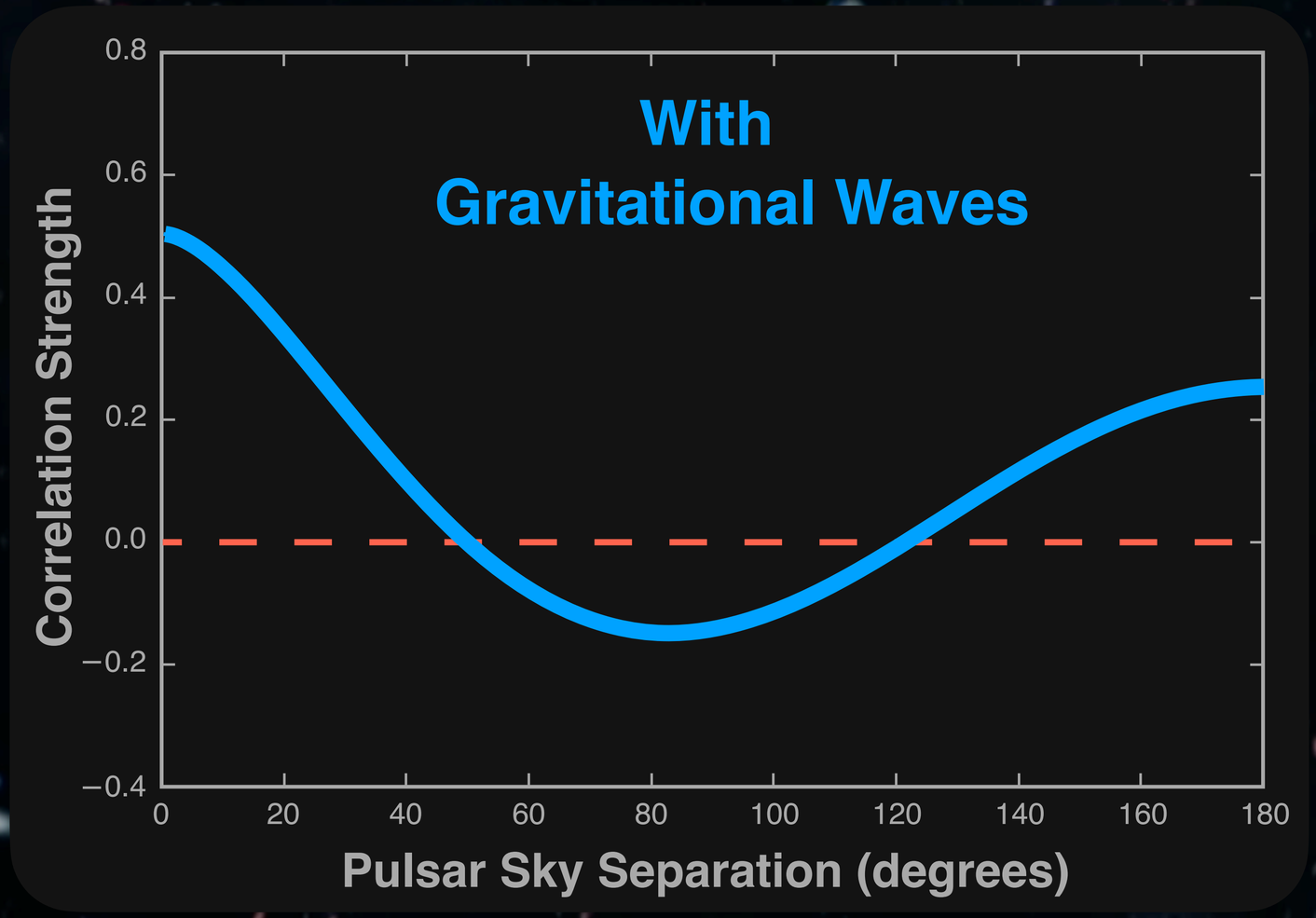
Galaxy-Sized Gravitational Wave Antenna

Image credit: ESA/Gaia/DPAC

Pulsar Timing Array

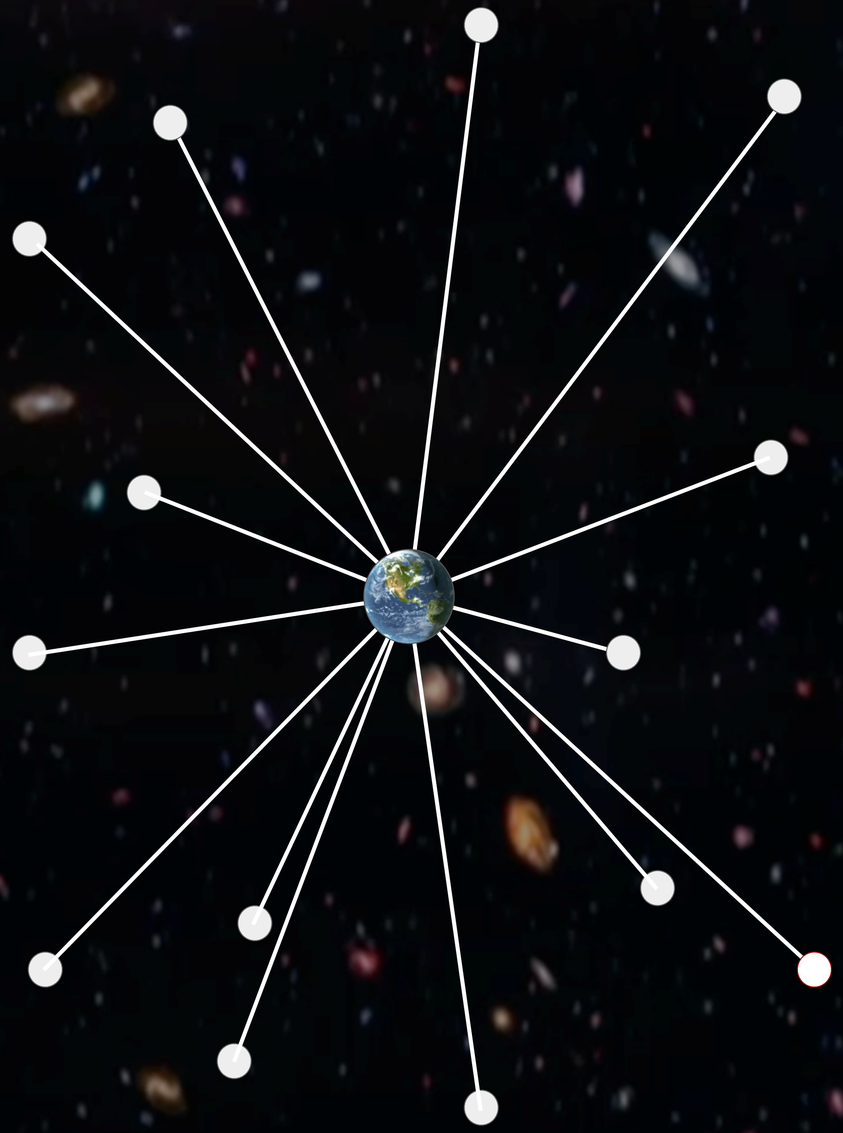


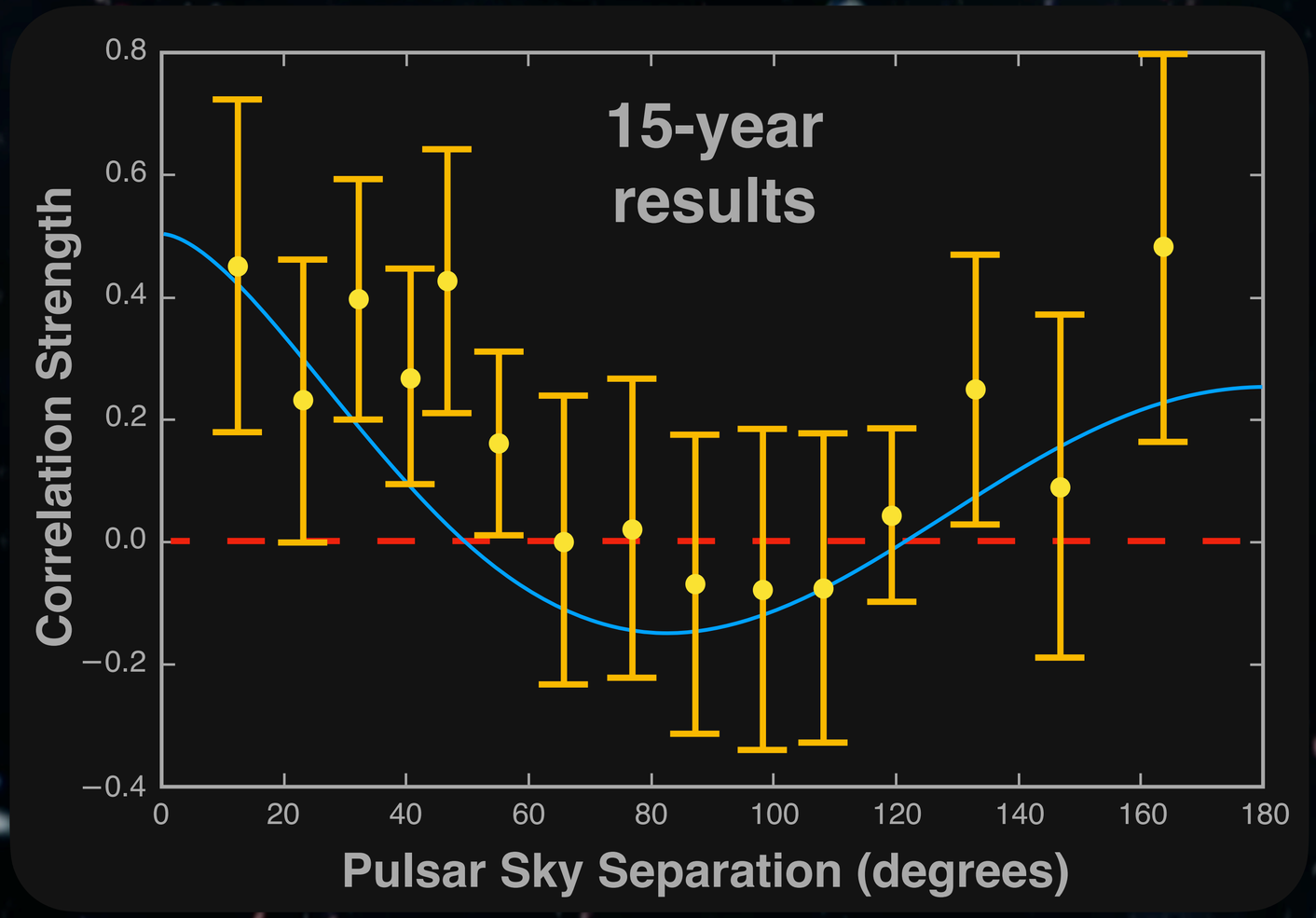




Background by Little Shadow

Animation concept by Olivia Young

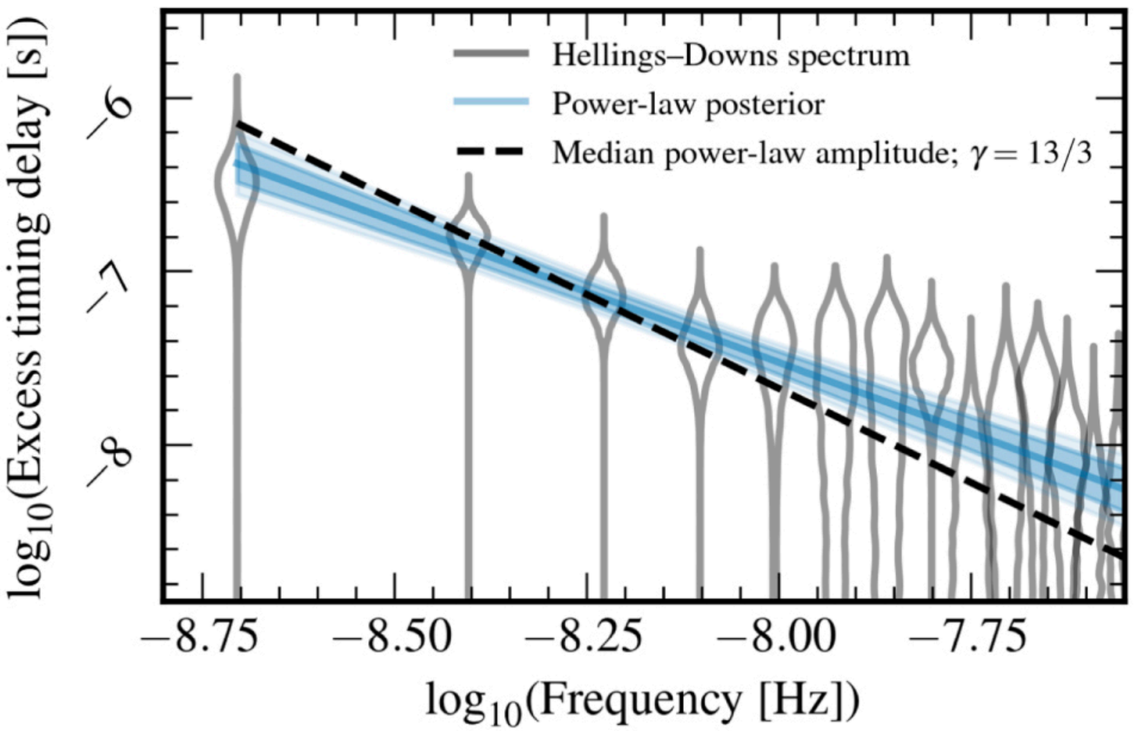


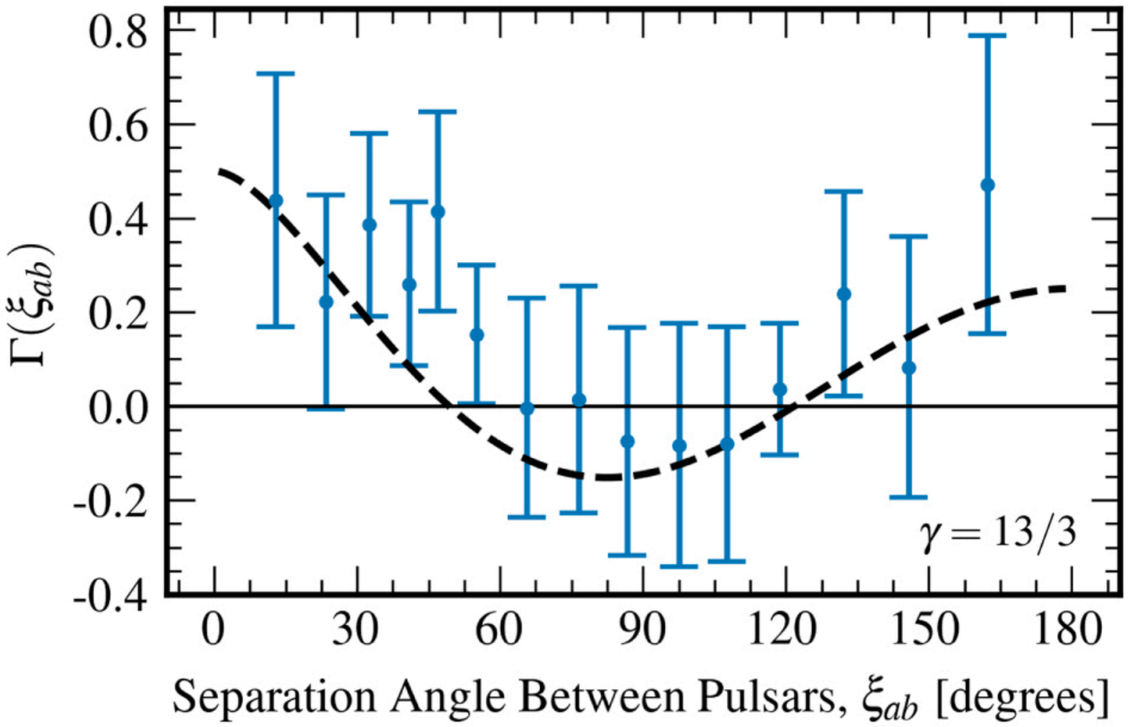


Background by Little Shadow

Animation concept by Olivia Young

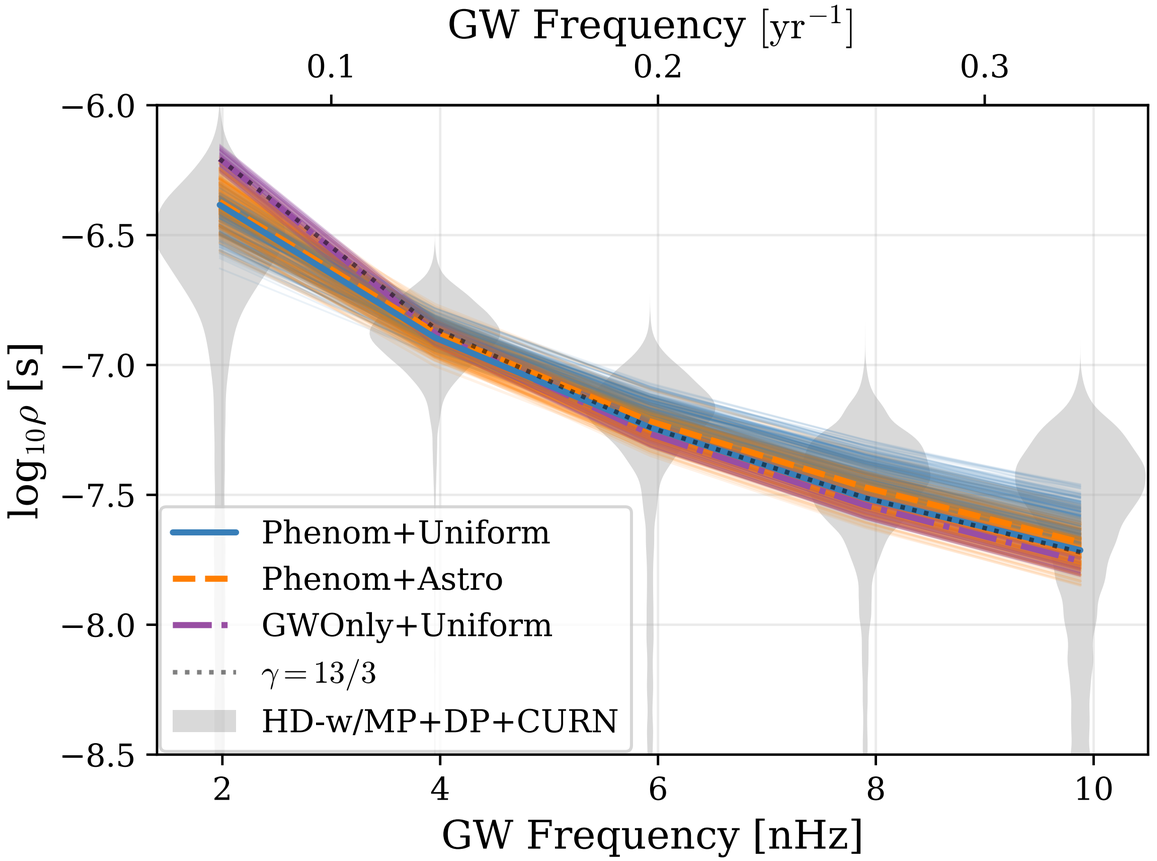
NANOGrav 15-year Results

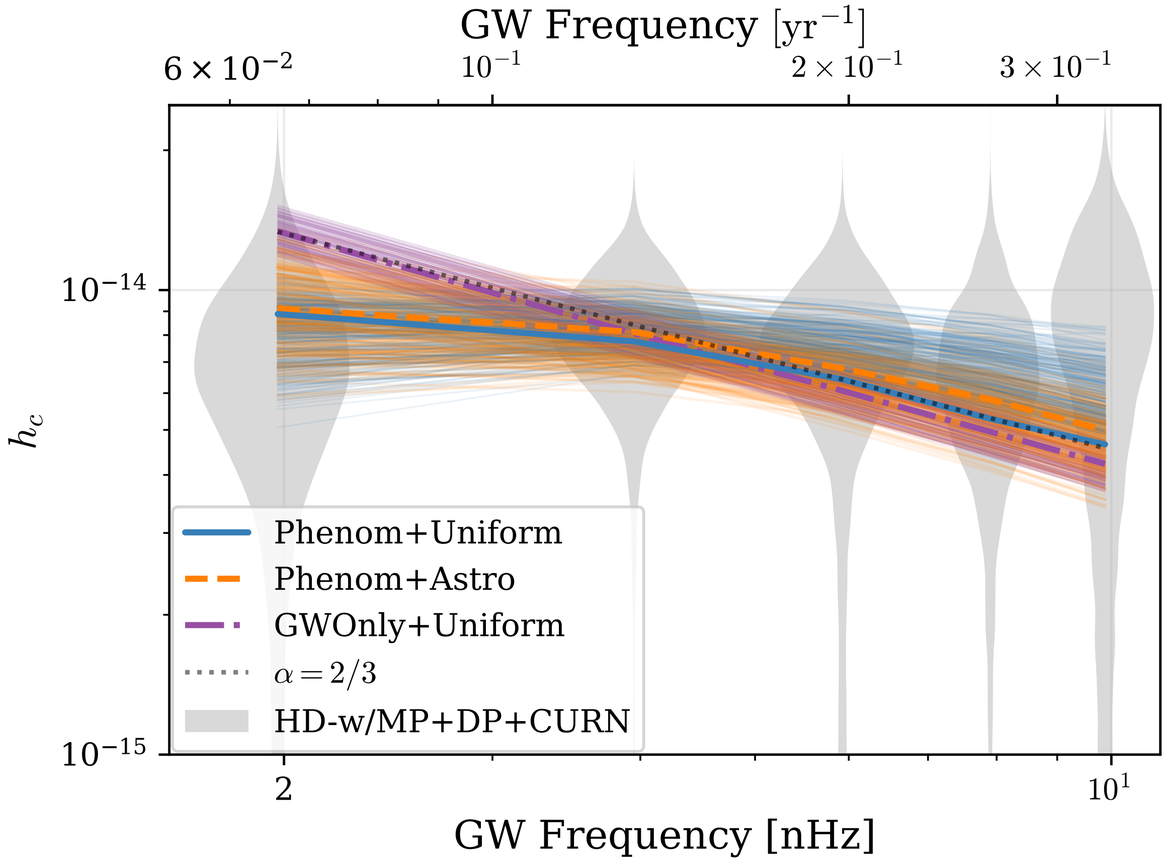




NANOGrav (2306.16213)

Astrophysical Interpretation: Supermassive Black Hole Binaries

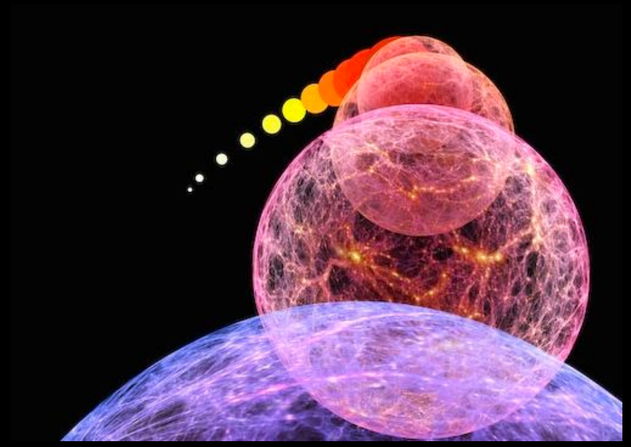




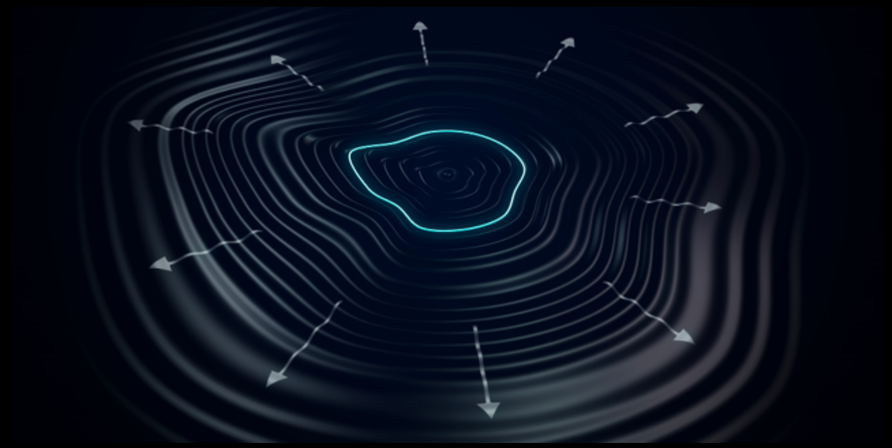
NANOGrav (2306.16220)

Cosmological Interpretation: New Physics Models

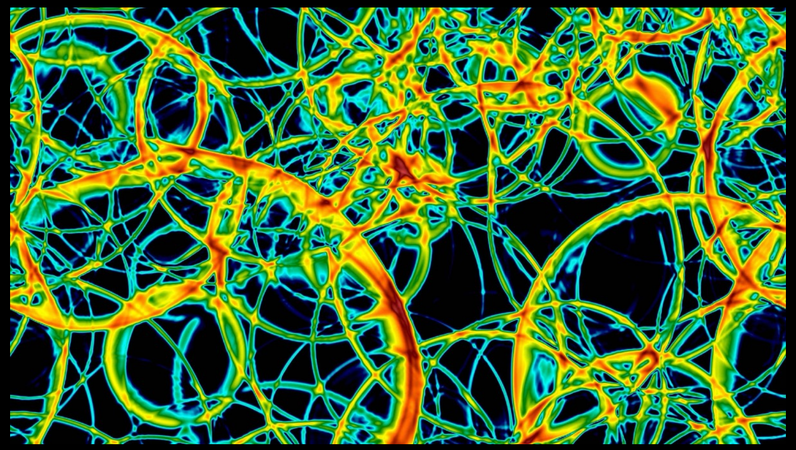
Inflation
- Non-minimal blue-tilted models



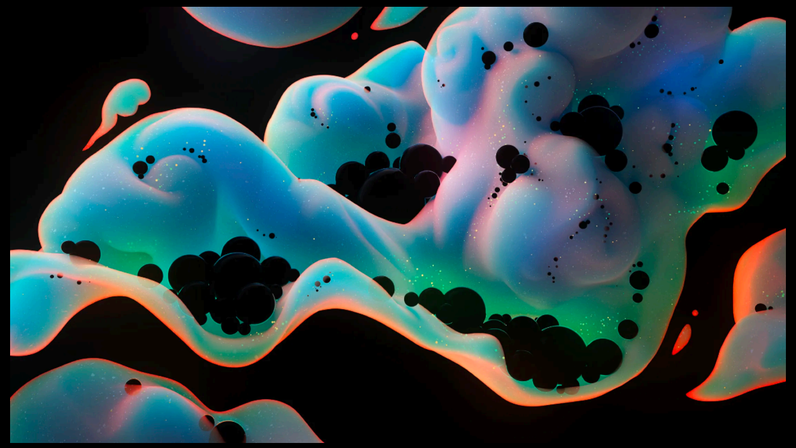
Topological defects
- Cosmic strings, domain walls



Phase transitions
- QCD transition in BSM, dark sector

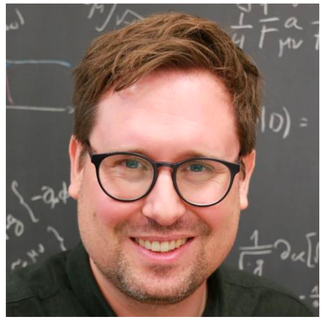


Enhanced scalar perturbations
- Primordial black hole production



NANOGrav New Physics Search

Andrea Mitridate



Kai Schmitz

Jonathan Nay

The NANOGrav 15-year Data Set: Search for Signals from New Physics

Adeela Afzal,[1,2] Gabriella Agazie,[3] Akash Anumarlapudi,[3] Anne M. Archibald,[4] Zaven Arzoumanian,[5] Paul T. Baker,[6] Bence Bécsy,[7] Jose Juan Blanco-Pillado,[8,9,10] Laura Blecha,[11] Kimberly K. Boddy,[12] Adam Brazier,[13,14] Paul R. Brook,[15] Sarah Burke-Spolaor,[16,17] Rand Burnette,[7] Robin Case,[7] Maria Charisi,[18] Shami Chatterjee,[13] Katerina Chatziioannou,[19] Belinda D. Cheeseboro,[16,17] Siyuan Chen,[20] Tyler Cohen,[21] James M. Cordes,[13] Neil J. Cornish,[22] Fronefield Crawford,[23] H. Thankful Cromartie,[13,*] Kathryn Crowter,[24] Curt J. Cutler,[25,19] Megan E. DeCesar,[26] Dallas DeGan,[7] Paul B. Demorest,[27] Heling Deng,[7] Timothy Dolch,[28,29] Brendan Drachler,[30,31] Richard von Eckardstein,[32] Elizabeth C. Ferrara,[33,34,35] William Fiore,[16,17] Emmanuel Fonseca,[16,17] Gabriel E. Freedman,[3] Nate Garver-Daniels,[16,17] Peter A. Gentile,[16,17] Kyle A. Gersbach,[18] Joseph Glaser,[16,17] Deborah C. Good,[36,37] Lydia Guertin,[38] Kayhan Gültekin,[39] Jeffrey S. Hazboun,[7] Sophie Hourihane,[19] Kristina Islo,[3] Ross J. Jennings,[16,17,†] Aaron D. Johnson,[3,19] Megan L. Jones,[3] Andrew R. Kaiser,[16,17] David L. Kaplan,[3] Luke Zoltan Kelley,[40] Matthew Kerr,[41] Joey S. Key,[42] Nima Laal,[7] Michael T. Lam,[30,31] William G. Lamb,[18] T. Joseph W. Lazio,[25] Vincent S. H. Lee,[19] Natalia Lewandowska,[43] Rafael R. Lino dos Santos,[44,32] Tyson B. Littenberg,[45] Tingting Liu,[16,17] Duncan R. Lorimer,[16,17] Jing Luo,[46,‡] Ryan S. Lynch,[47] Chung-Pei Ma,[40,48] Dustin R. Madison,[49] Alexander McEwen,[3] James W. McKee,[50,51] Maura A. McLaughlin,[16,17] Natasha McMann,[18] Bradley W. Meyers,[24,52] Patrick M. Meyers,[19] Chiara M. F. Mingarelli,[37,36,53] Andrea Mitridate,[54] Jonathan Nay,[12] Priyamvada Natarajan,[55,56] Cherry Ng,[57] David J. Nice,[58] Stella Koch Ocker,[13] Ken D. Olum,[59] Timothy T. Pennucci,[60] Benetge B. P. Perera,[61] Polina Petrov,[18] Nihan S. Pol,[18] Henri A. Radovan,[62] Scott M. Ransom,[63] Paul S. Ray,[41] Joseph D. Romano,[64] Shashwat C. Sardesai,[3] Ann Schmiedekamp,[65] Carl Schmiedekamp,[65] Kai Schmitz,[32] Tobias Schröder,[32] Levi Schult,[18] Brent J. Shapiro-Albert,[16,17,66] Xavier Siemens,[7,3] Joseph Simon,[67,§] Magdalena S. Siwek,[68] Ingrid H. Stairs,[24] Daniel R. Stinebring,[69] Kevin Stovall,[27] Peter Stratmann,[32] Jerry P. Sun,[7] Abhimanyu Susobhanan,[3] Joseph K. Swiggum,[58,†] Jacob Taylor,[7] Stephen R. Taylor,[18] Tanner Trickle,[70] Jacob E. Turner,[16,17] Caner Unal,[71,72] Michele Vallisneri,[25,19] Sonali Verma,[73,74] Sarah J. Vigeland,[3] Haley M. Wahl,[16,17] Qiaohong Wang,[18] Caitlin A. Witt,[75,76] David Wright,[77] Olivia Young,[30,31] and Kathryn M. Zurek[78]

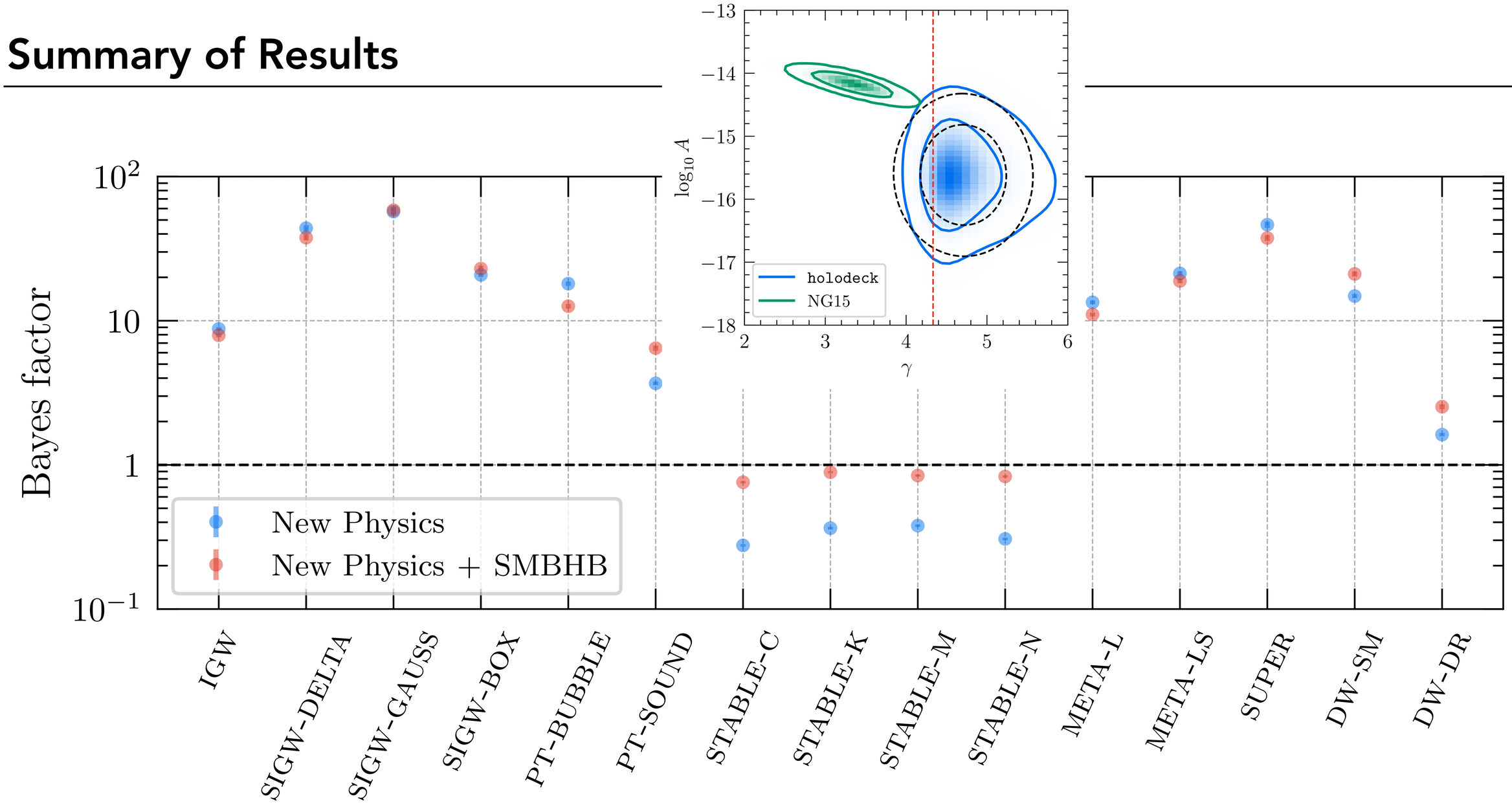
NANOGrav (2306.16219)

New Physics Models: Summary

amplitude
spectral features
both

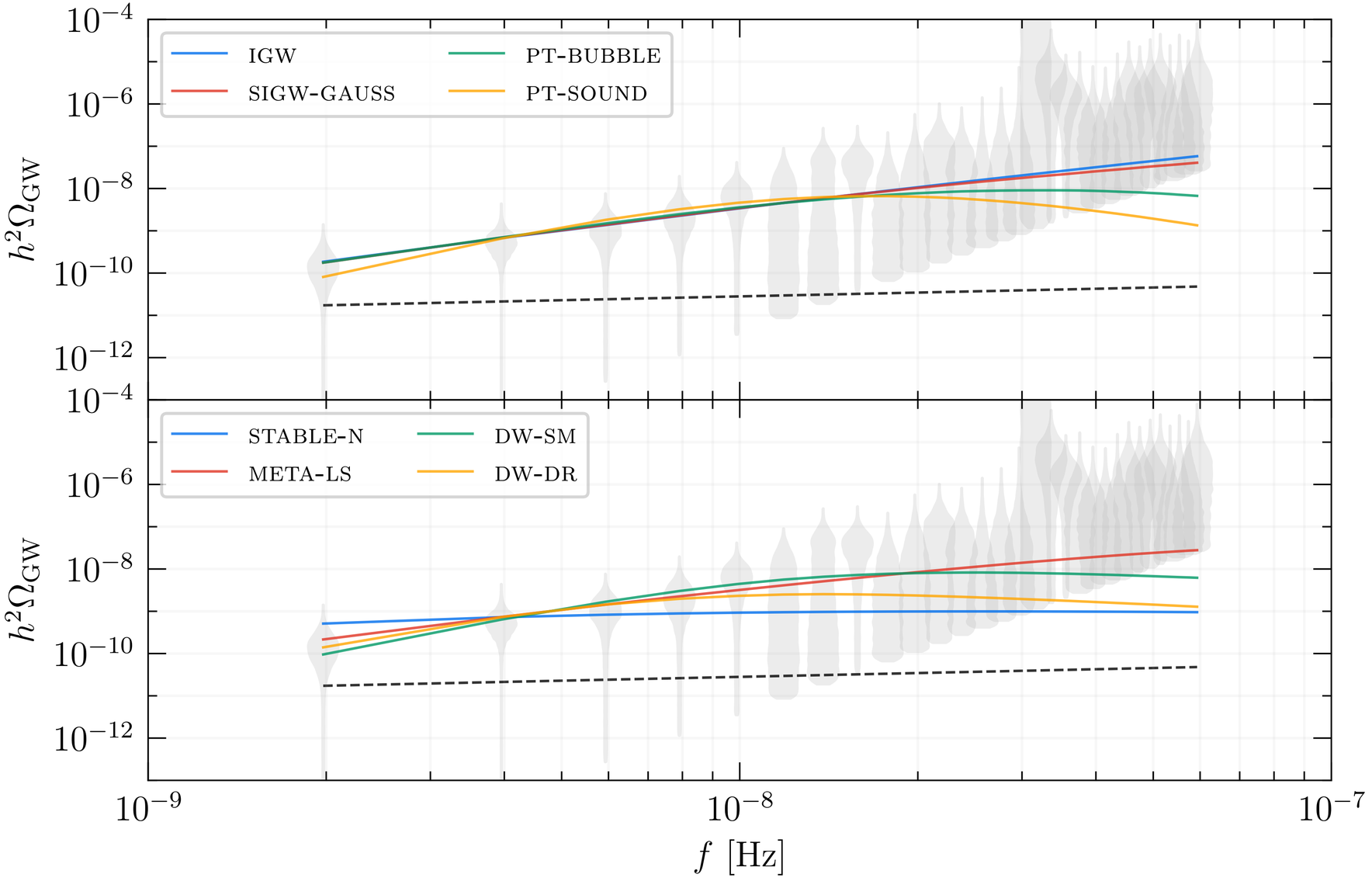
- IGW: Inflationary Gravitational Waves
  tensor-to-scalar ratio, tensor spectral index, reheating temperature
- SIGW: Scalar-Induced Gravitational Waves
  scalar amplitude, frequency shape parameters (delta, gauss, box)
- PT: Phase Transitions (sound-wave analysis & bubble-collisions only)
  transition temperature and strength, bubble separation, low/high-frequency slope, spectral-shape width
- STABLE: Stable Cosmic Strings (cusps, kinks, monochromatic, numerical)
  string tension
- META: Metastable Cosmic Strings (loops only, loops and segments)
  string tension, decay parameter
- SUPER: Cosmic Superstrings
  string tension, intercommutation probability
- DW: Domain Walls
  transition temperature, energy fraction, high-frequency slope, spectral-shape width

Summary of Results



NANOGrav (2306.16219)

Median GWB Frequency Spectra



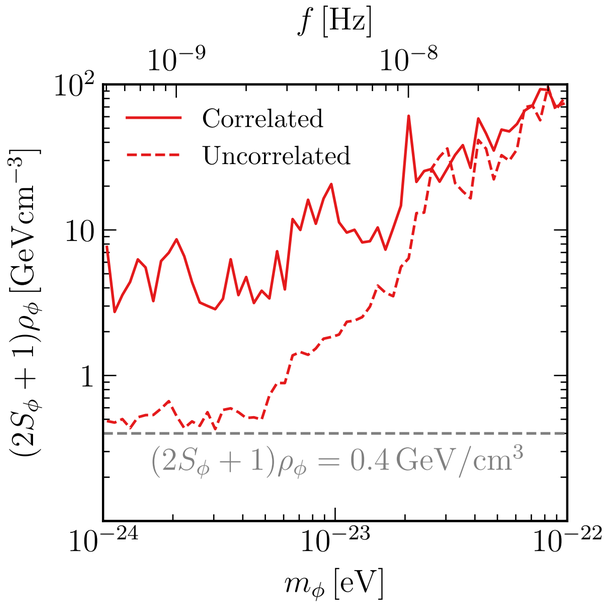
NANOGrav (2306.16219)

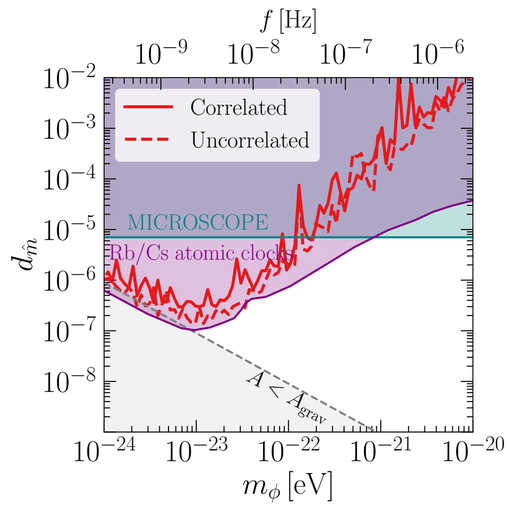
New Physics Models: Deterministic Signatures

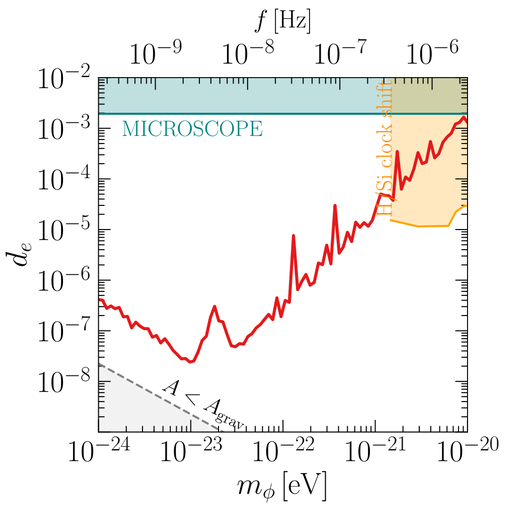
- Ultralight dark matter with gravitational coupling only
  - Substructure exhibits pressure oscillations
- Ultralight dark matter coupled to Standard Model
  - Doppler signal – vector ULDM accelerates pulsar
  - Pulsar spin fluctuations – scalar ULDM causes particle mass fluctuations
  - Reference clock shifts – scalar ULDM alters reference atomic clocks

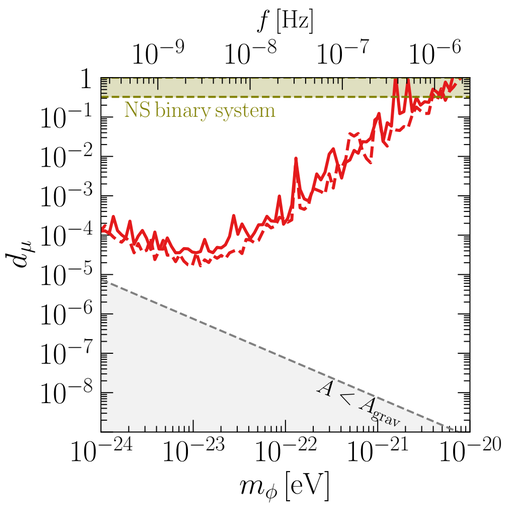
$$\mathscr{L} \supset \frac{\phi}{\Lambda}\left[\frac{d_\gamma}{4e^2}F_{\mu\nu}F^{\mu\nu} + \frac{d_g\beta_3}{2g_3}G^A_{\mu\nu}G_A^{\mu\nu} - \sum_{f=e,\mu} d_f m_f \bar{f}f - \sum_{q=u,d}(d_q + \gamma_q d_g)m_q\bar{q}q\right]$$

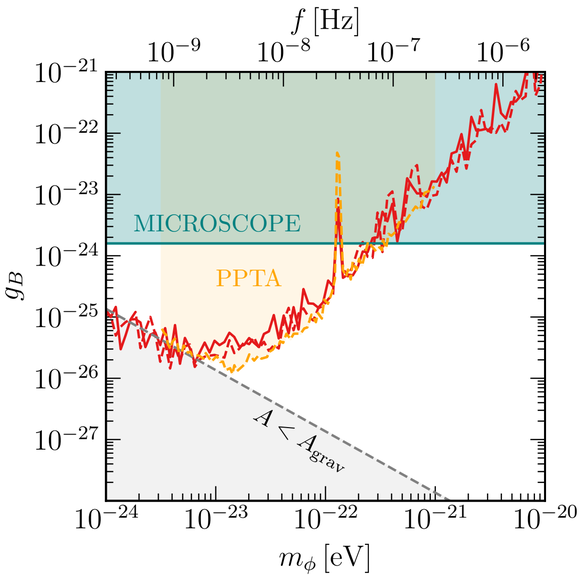
Ultralight Dark Matter Results

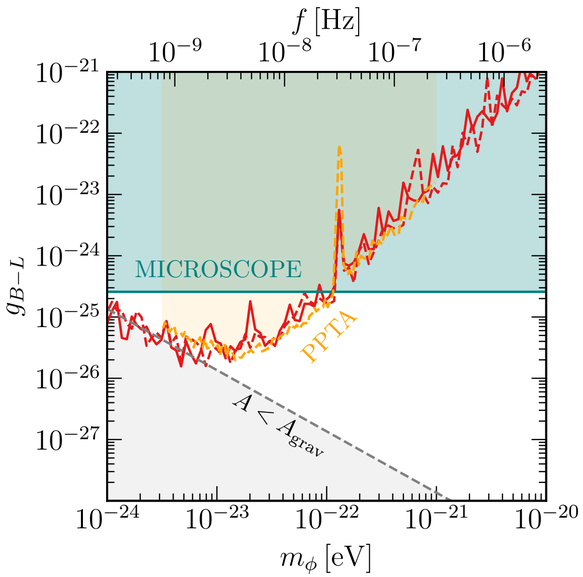


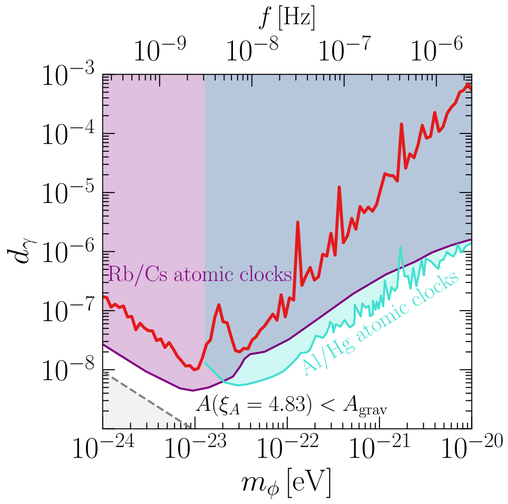


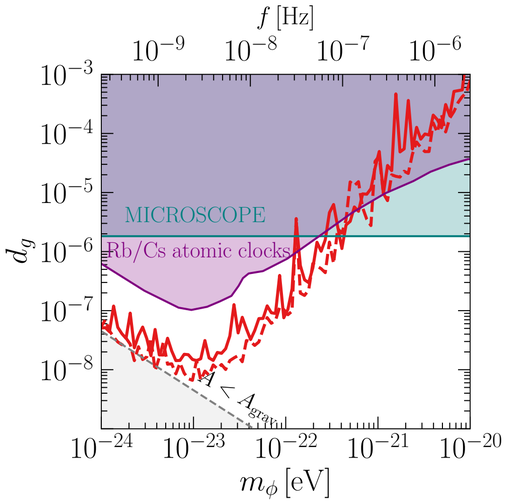








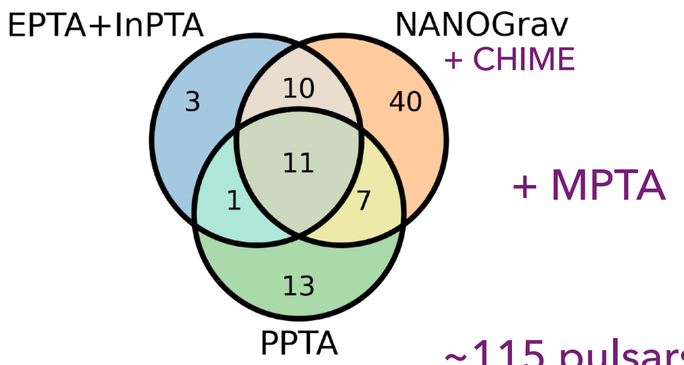




NANOGrav (2306.16219)

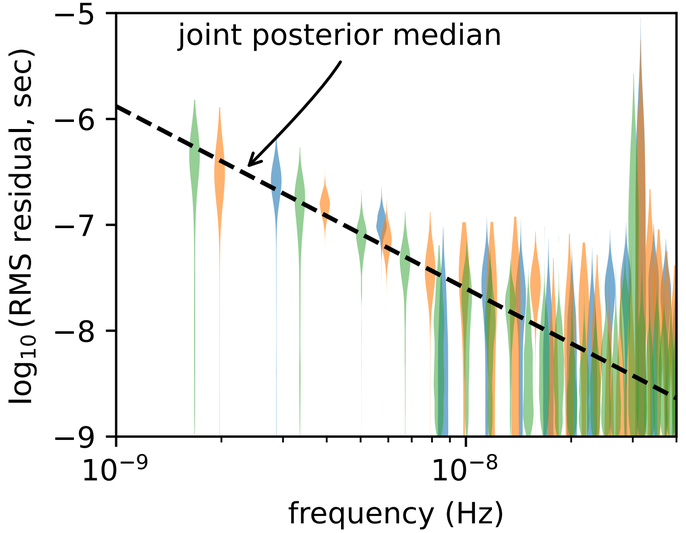
Upcoming Prospects

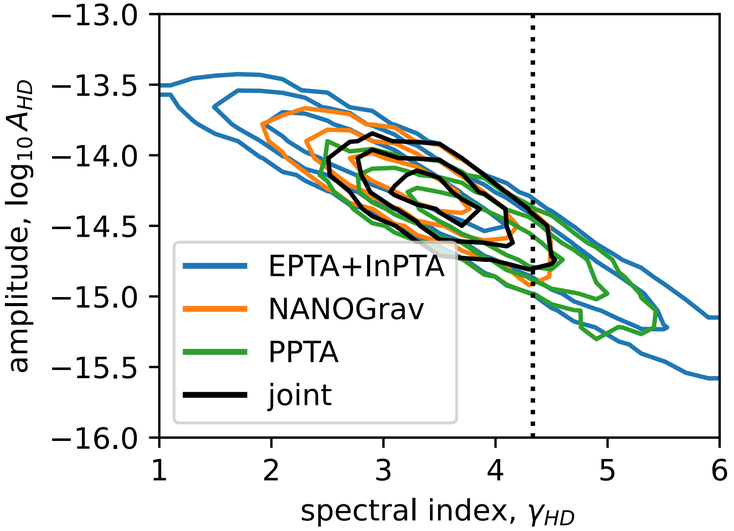
- IPTA is assembling DR3



+ MPTA

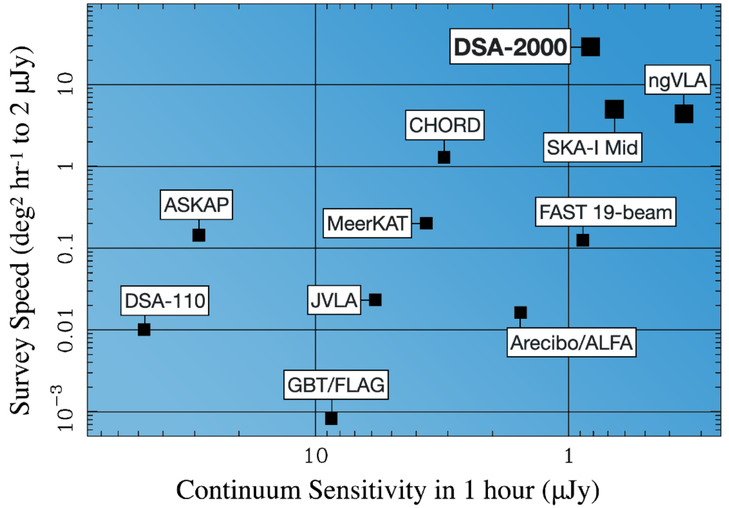
~115 pulsars



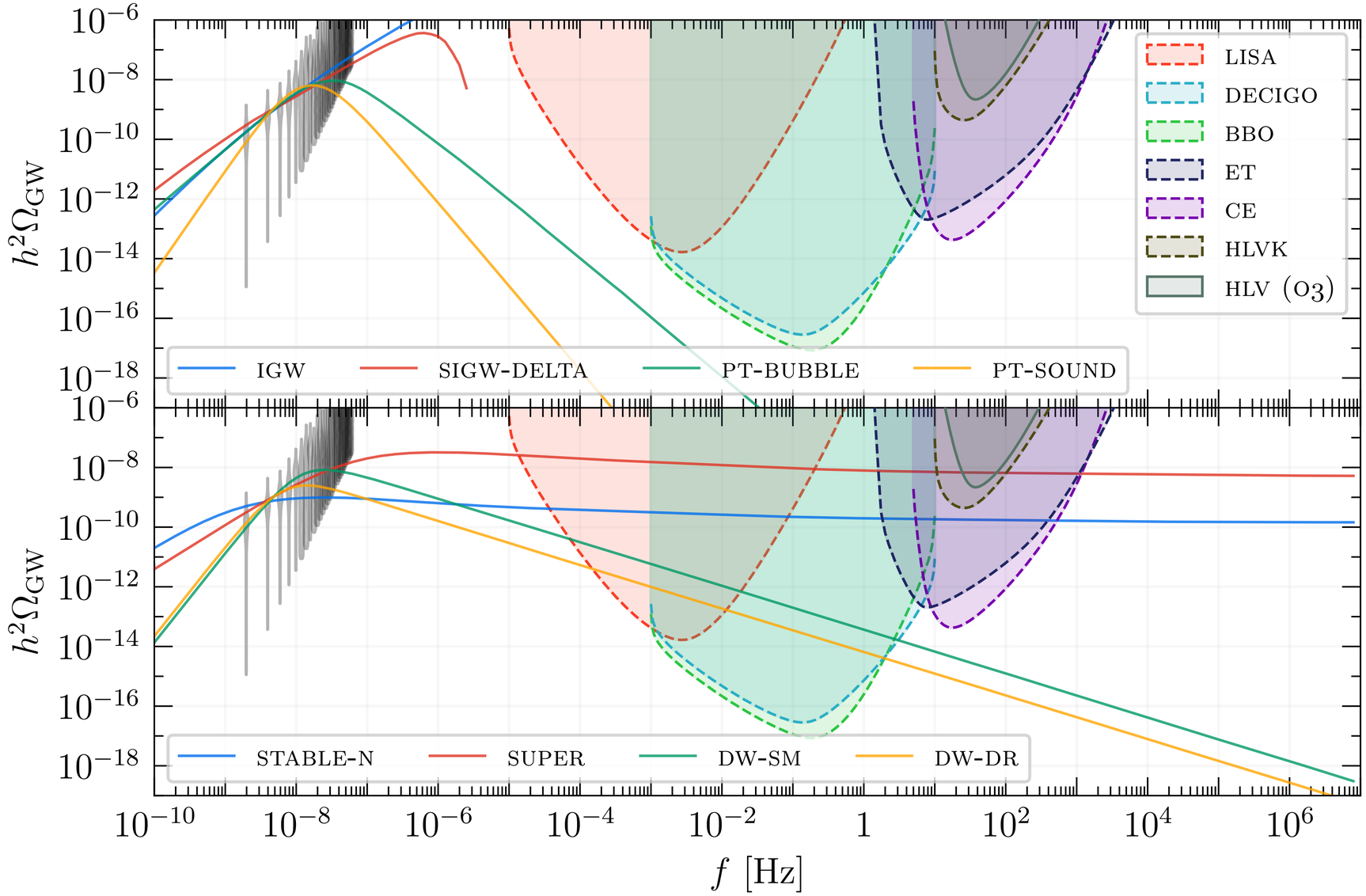


IPTA (2309.00693)

- Future of US pulsar timing: Deep Synoptic Array (DSA-2000) – 25% allocation



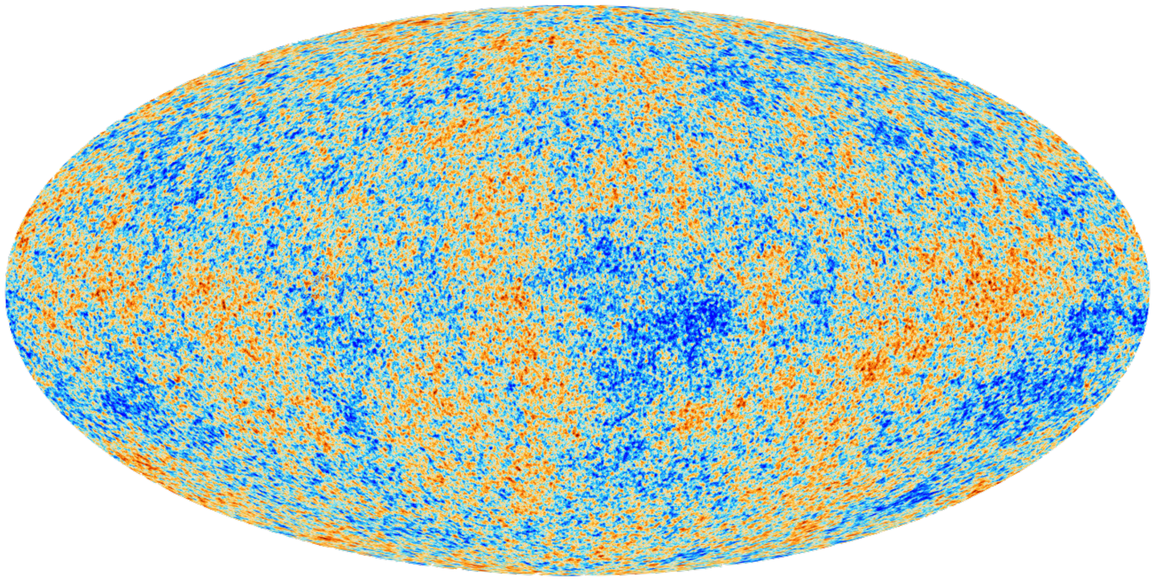
How can we understand sources? Spectral features?



NANOGrav (2306.16219)

How can we understand sources? Anisotropies?

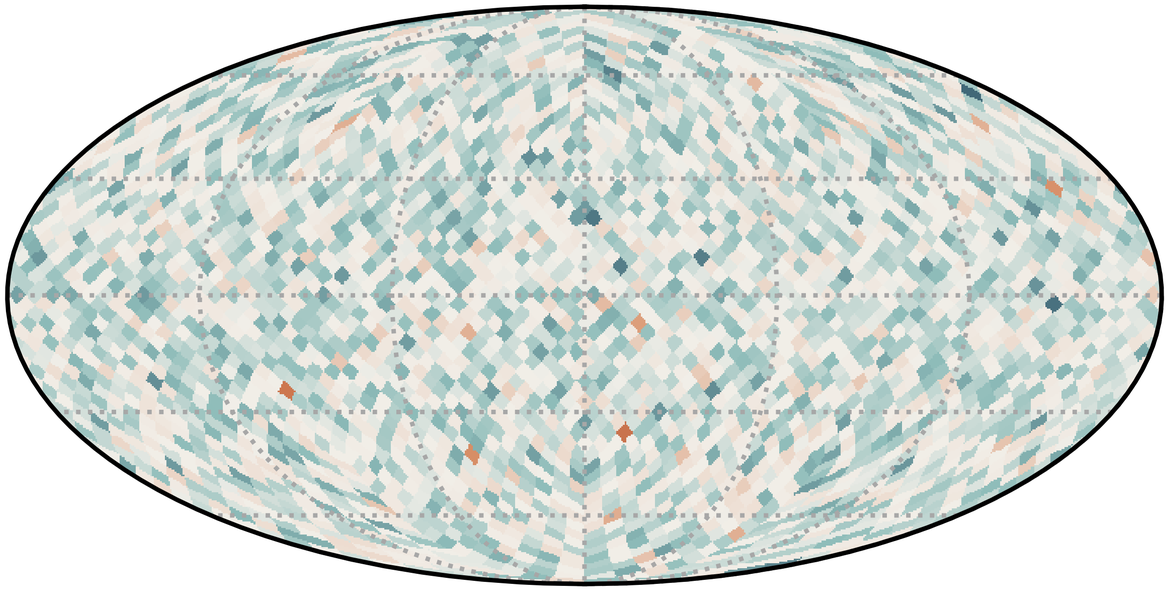
Cosmic Microwave Background



(observed)

ESA and Planck Collaboration

Gravitational Wave Background

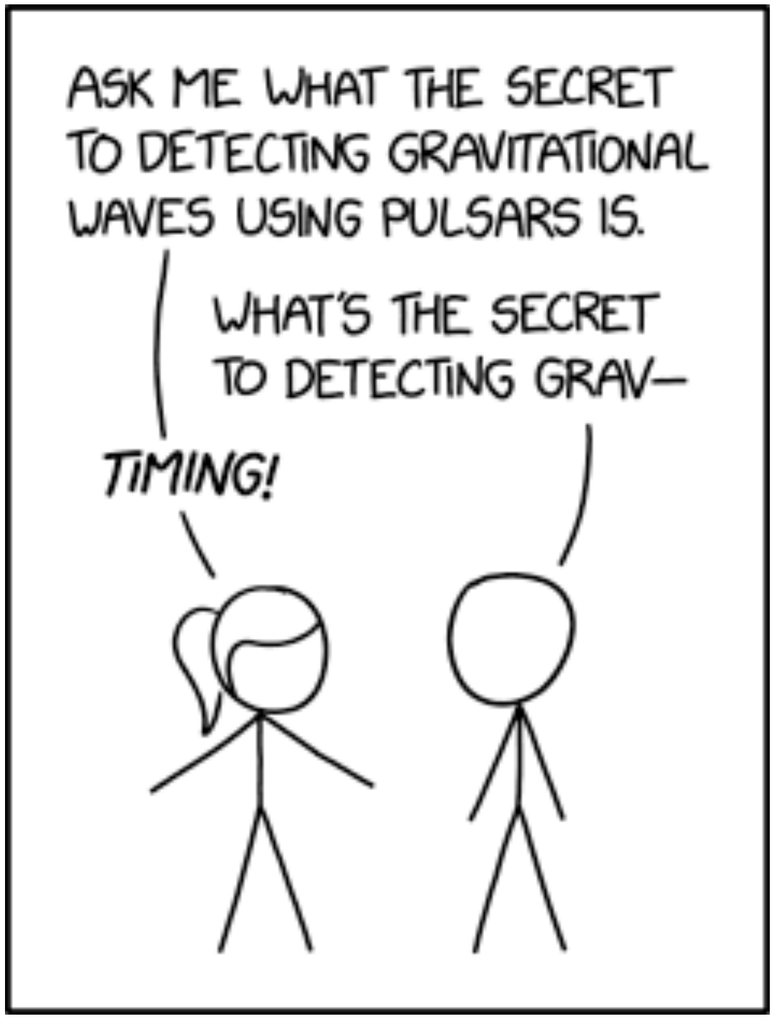


(simulated)

Sato-Polito and Kamionkowski (2305.05690)

Just the beginning!

https://xkcd.com/2358/



The most important attributes of a vector in 3-space are {Location, Location, Location}

We have a new window into astrophysics and early Universe cosmology!

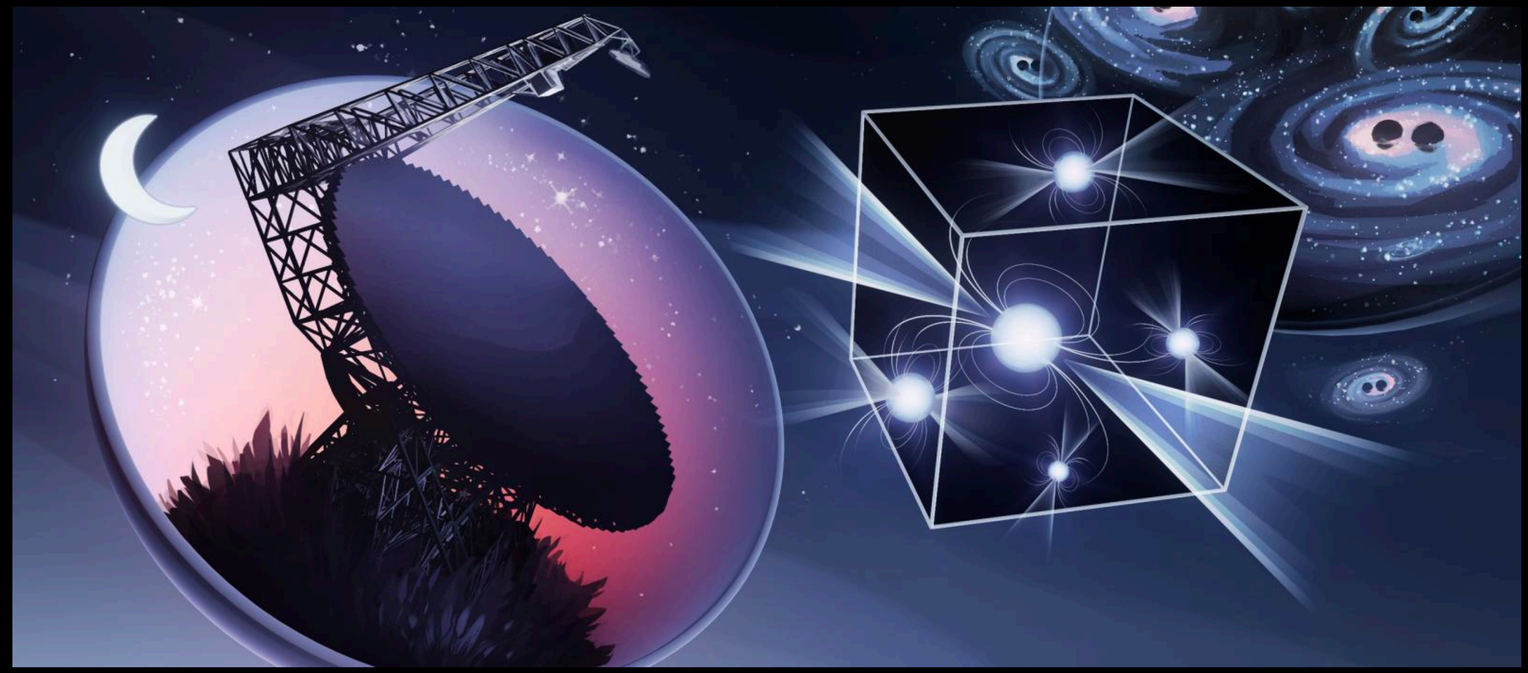
But more work needs to be done to extract possible primordial signals.

"The prospect of determining the properties of these supermassive black hole binaries… is really exciting…

But to me, there is something even more exciting that's on the horizon… and that's to use gravitational waves to probe the birth of the universe."

—Kip Thorne

Thank you to



Natural Sciences and Engineering
Research Council of Canada

Canadian Institute for
Advanced Research

Gordon and Betty Moore Foundation