The First Evidence for Nanohertz-Frequency Gravitational Waves

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Chair — NANOGrav Collaboration

NANOGrav Physics Frontiers Center

NSF

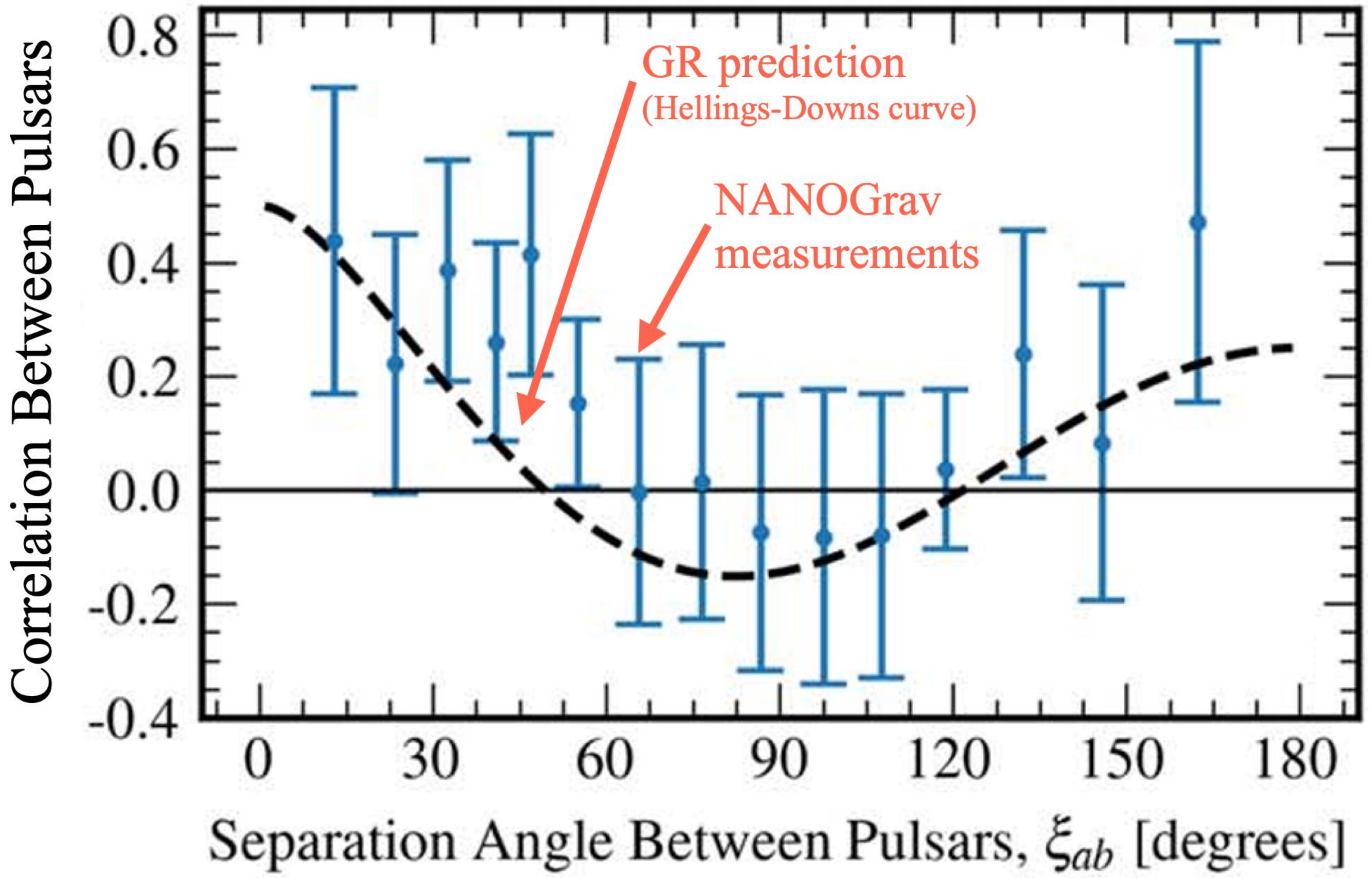
INTERNATIONAL PULSAR TIMING ARRAY IPTA

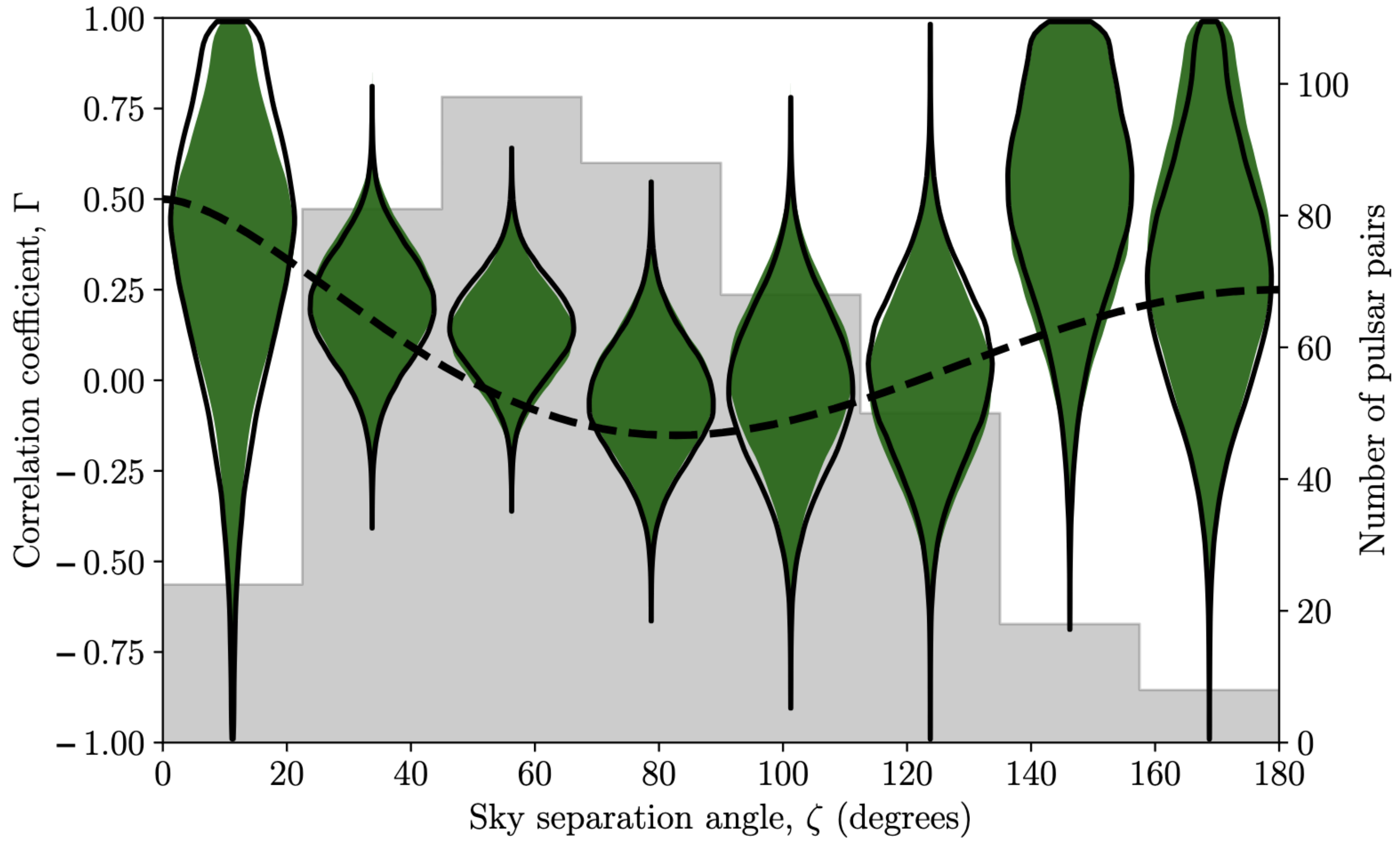
Illustration: Olena Shmahalo

Evidence for a Gravitational Wave Background

UTC 00:00, June 29 2023

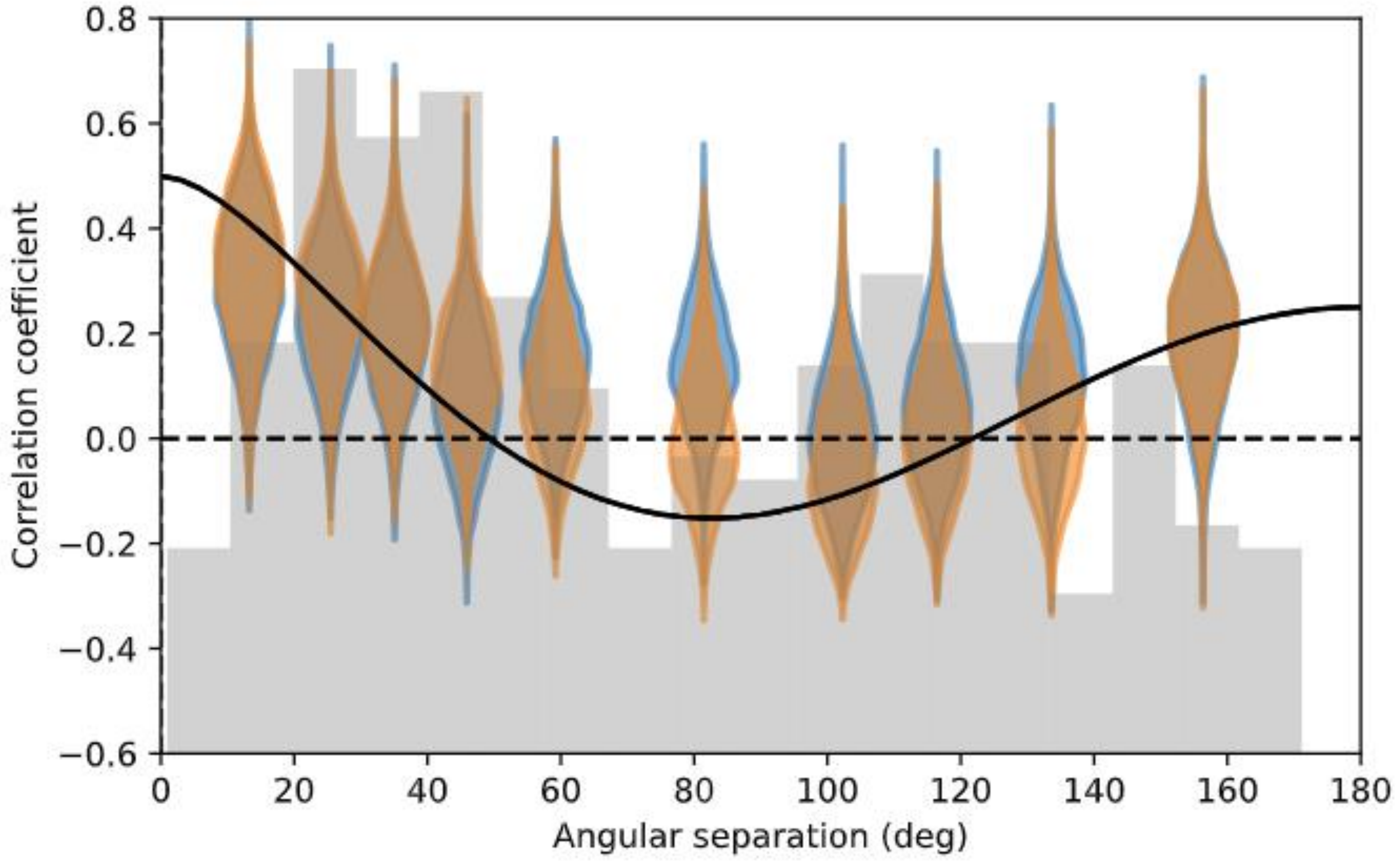
NANOGrav

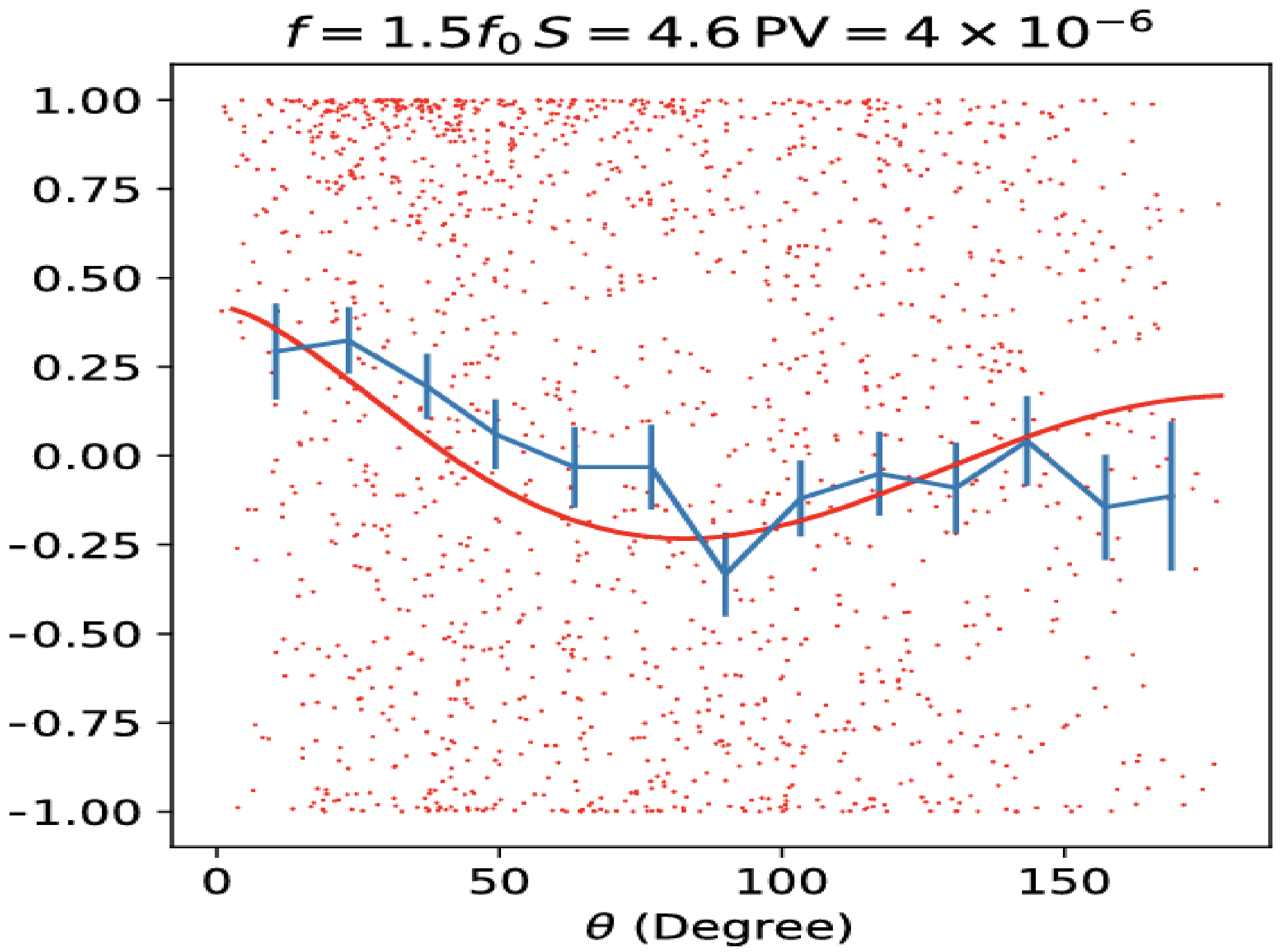




PPTA

EPTA





CPTA

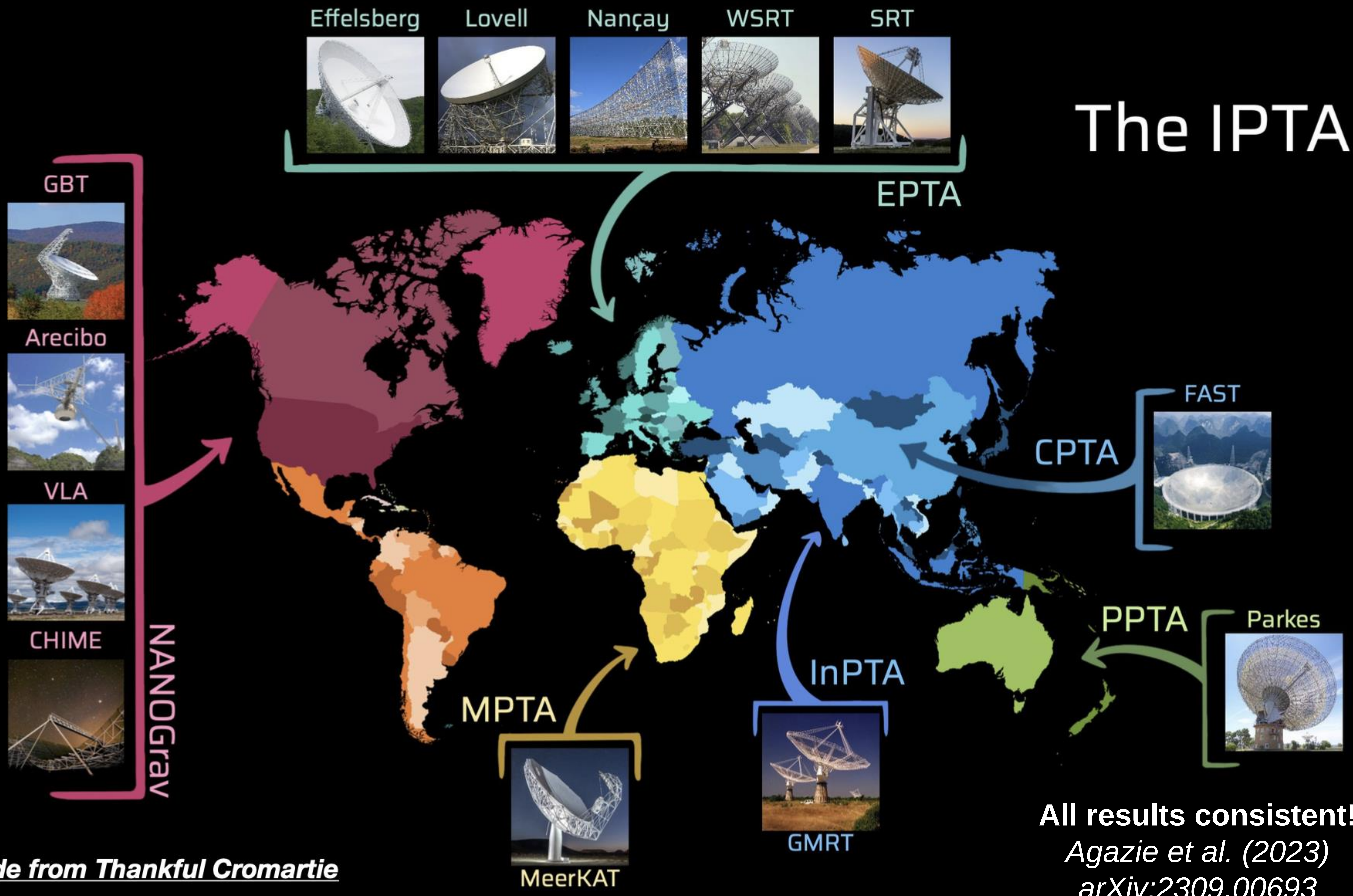
Evidence for a Gravitational Wave Background

NANOGrav GWB paper		https://arxiv.org/abs/2306.16213
EPTA GWB paper	S. Chen (Fri 10:00, Hall 10)	https://arxiv.org/abs/2306.16214
PPTA GWB paper		https://arxiv.org/abs/2306.16215
CPTA GWB paper	K. Lee (in ~30 mins)	https://arxiv.org/abs/2306.16216
NANOGrav data paper		https://arxiv.org/abs/2306.16217
NANOGrav noise model paper		https://arxiv.org/abs/2306.16218
NANOGrav "new physics" paper		https://arxiv.org/abs/2306.16219
NANOGrav SMBH binary paper		https://arxiv.org/abs/2306.16220
NANOGrav anisotropy paper		https://arxiv.org/abs/2306.16221
NANOGrav continuous GW paper		https://arxiv.org/abs/2306.16222
NANOGrav code review paper		https://arxiv.org/abs/2306.16223
EPTA data paper		https://arxiv.org/abs/2306.16224
EPTA noise model paper		https://arxiv.org/abs/2306.16225
EPTA continuous GW paper		https://arxiv.org/abs/2306.16226
EPTA implications paper		https://arxiv.org/abs/2306.16227
EPTA ultralight dark matter paper		https://arxiv.org/abs/2306.16228
PPTA noise model paper		https://arxiv.org/abs/2306.16229
PPTA data paper		https://arxiv.org/abs/2306.16230

+ CPTA

18 papers on arXiv on UTC 00:00, June 29, 2023!

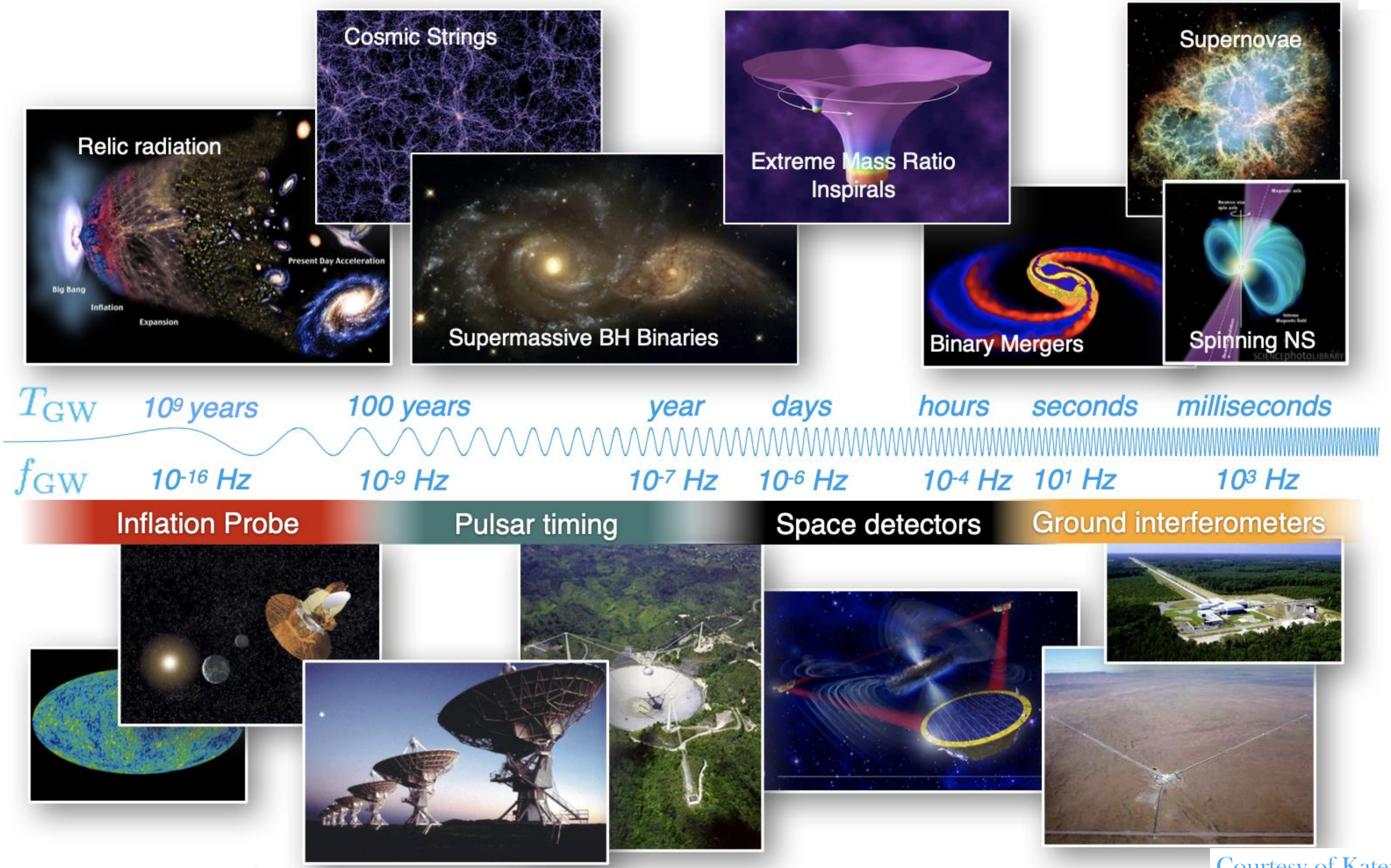
The IPTA



All results consistent!
Agazie et al. (2023)
arXiv:2309.00693

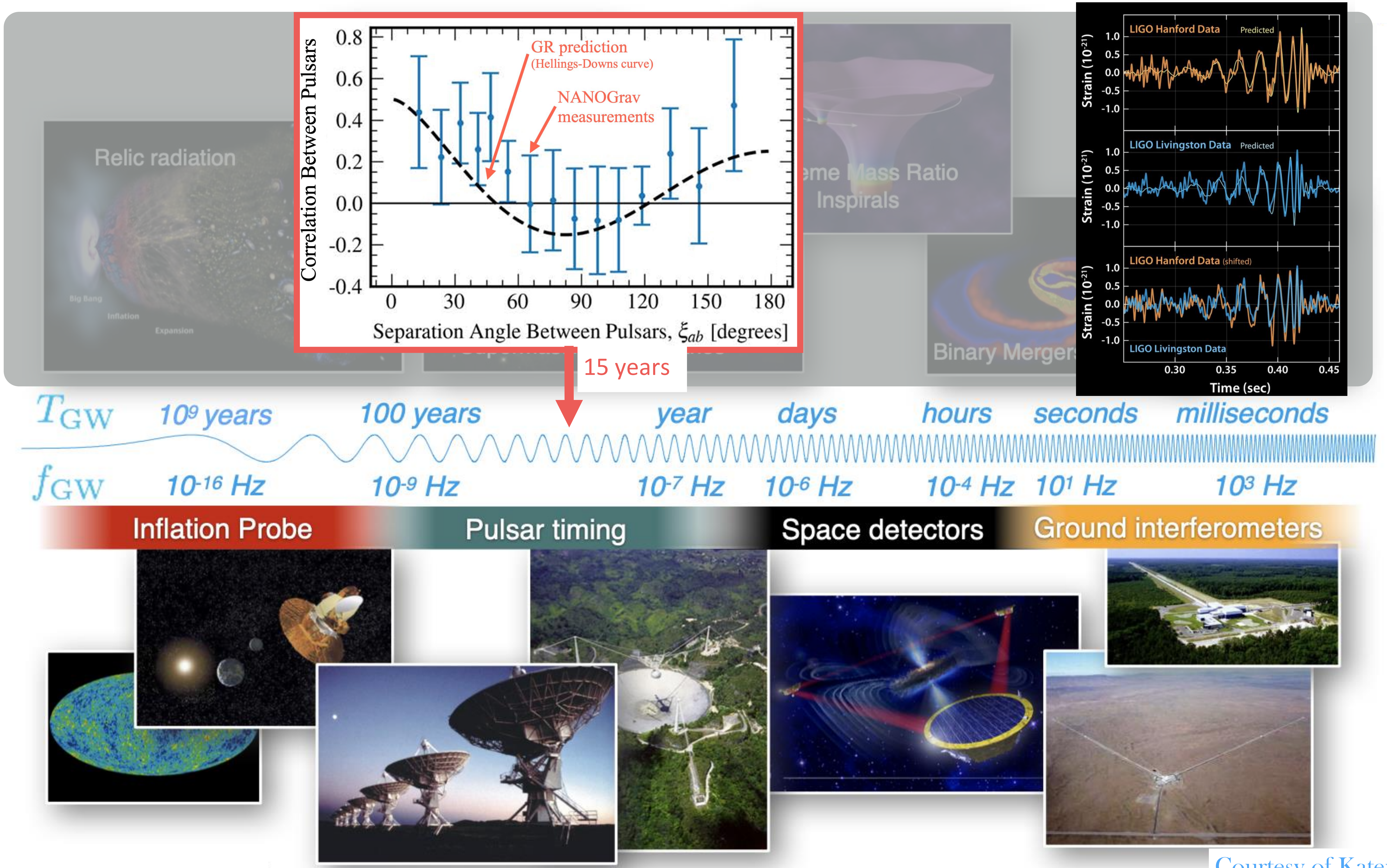
Slide from Thankful Cromartie

The Gravitational Wave Landscape



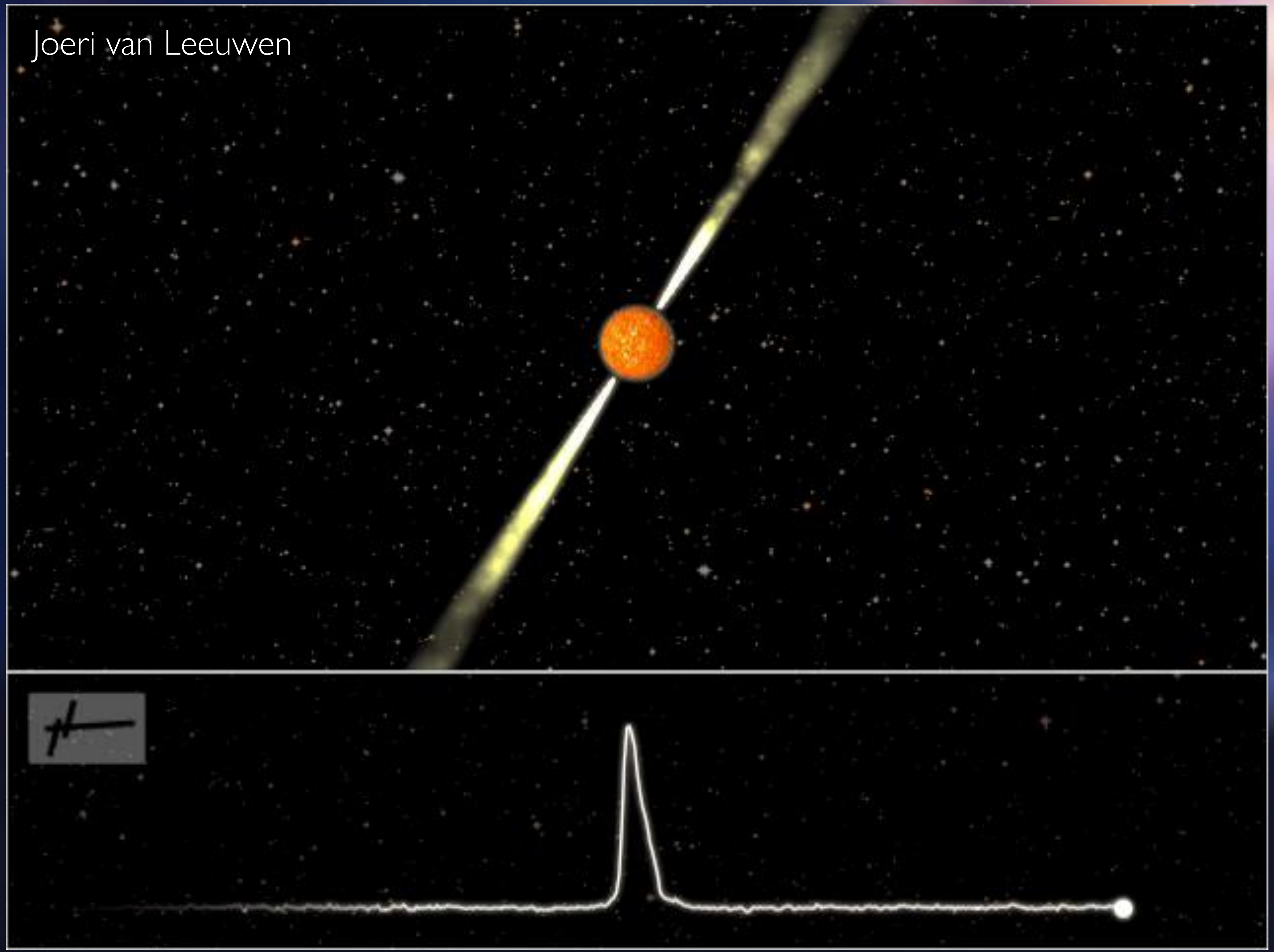
Courtesy of Katerina Chatziioannou

The Gravitational Wave Landscape

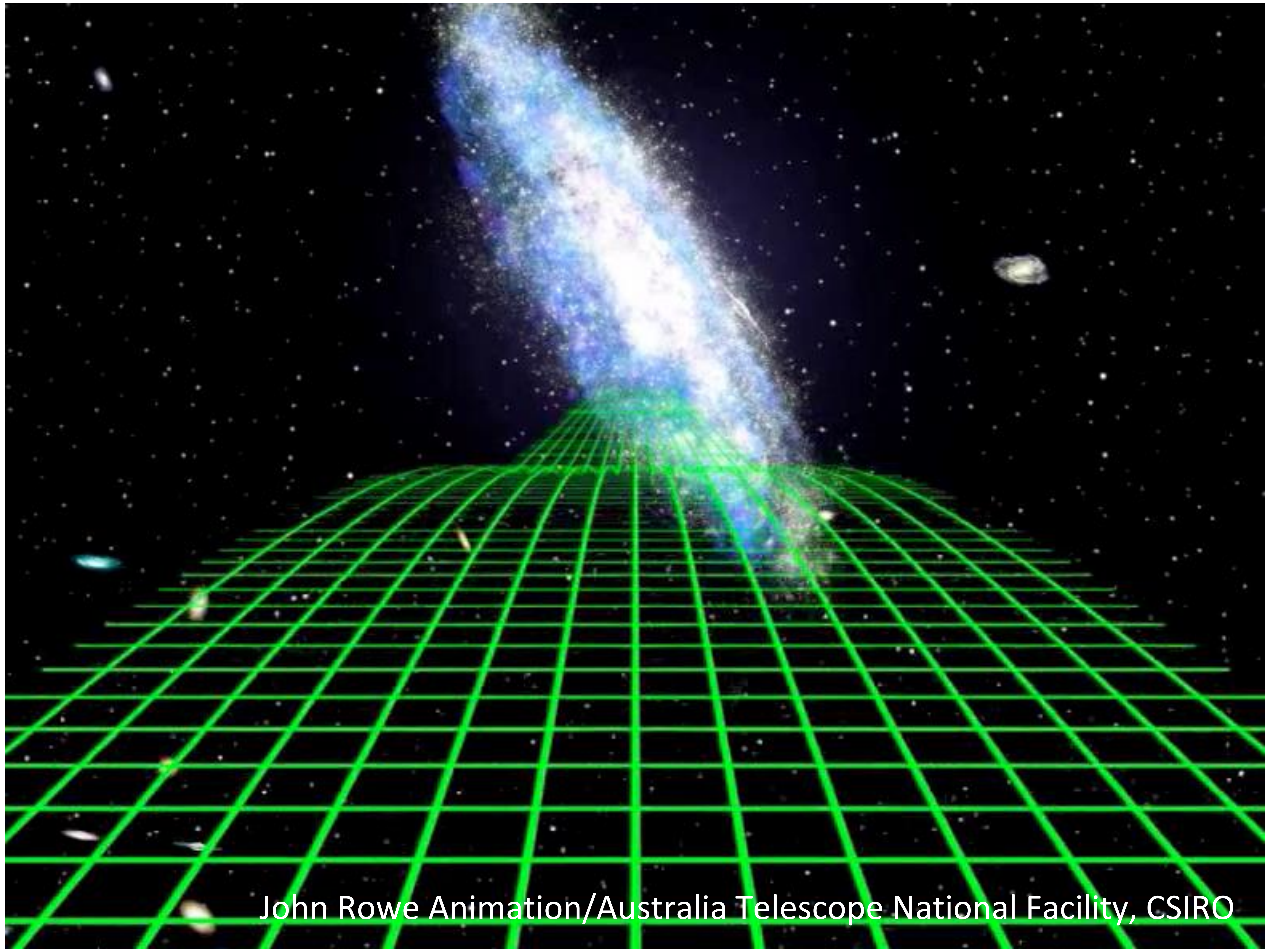


Courtesy of Katerina Chatziioannou

Pulsars As Cosmic Clocks



Pulsar Timing Response to GWs



$$z(t,\hat{\Omega}) = \frac{1}{2}\frac{\hat{p}^a\hat{p}^b}{1+\hat{\Omega}\cdot\hat{p}}\Delta h_{ab}(t,\hat{\Omega})$$

$$\Delta h_{ab}(t,\hat{\Omega}) \equiv h_{ab}(t_e,\hat{\Omega}) - h_{ab}(t_p,\hat{\Omega})$$

$$t_p = t_e - L(1+\hat{\Omega}\cdot\hat{p})/c$$

$$\delta t \sim \frac{h}{2\pi f}$$

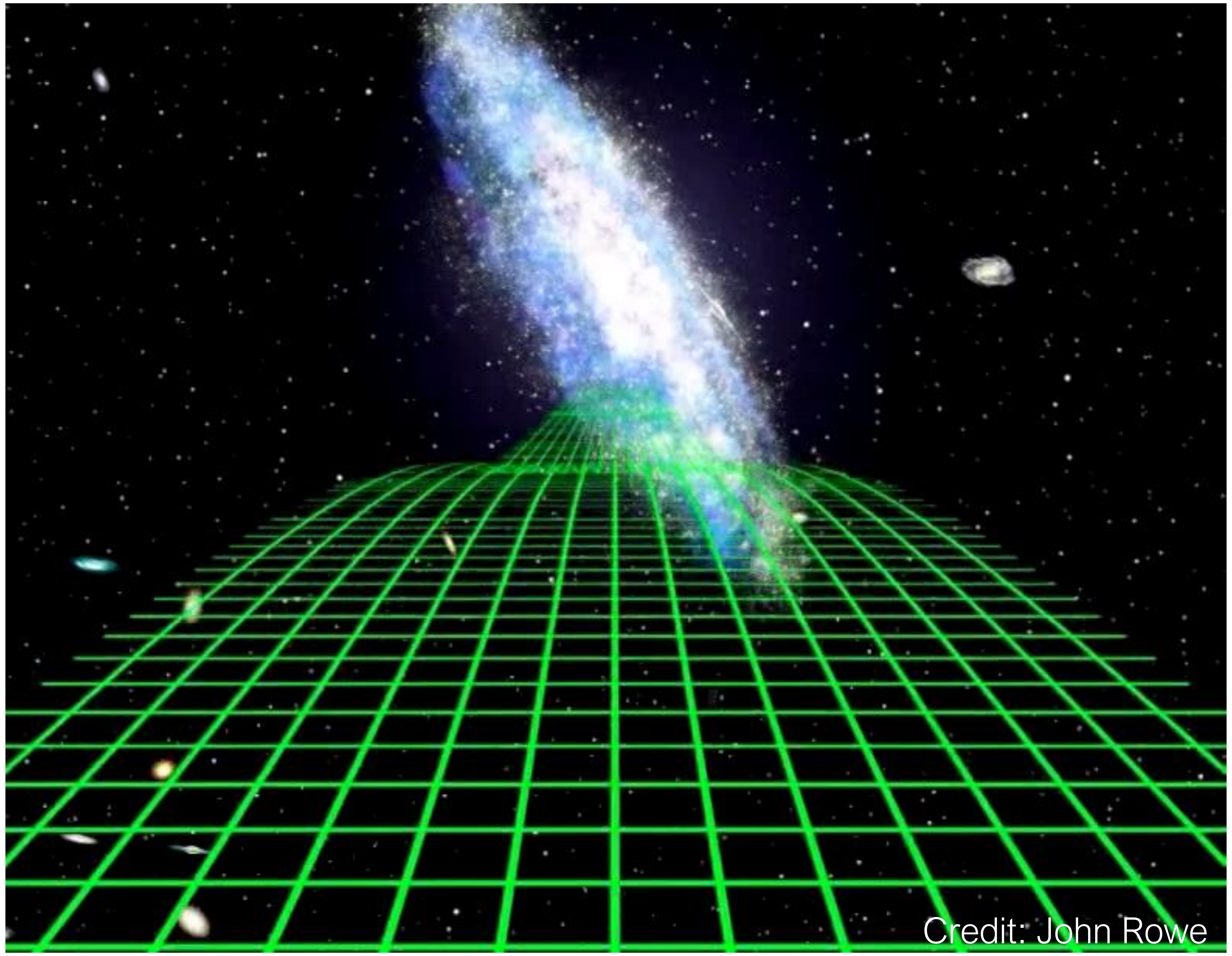
$$h = 10^{-15}$$

$$f = 10^{-9}\mathrm{Hz}$$

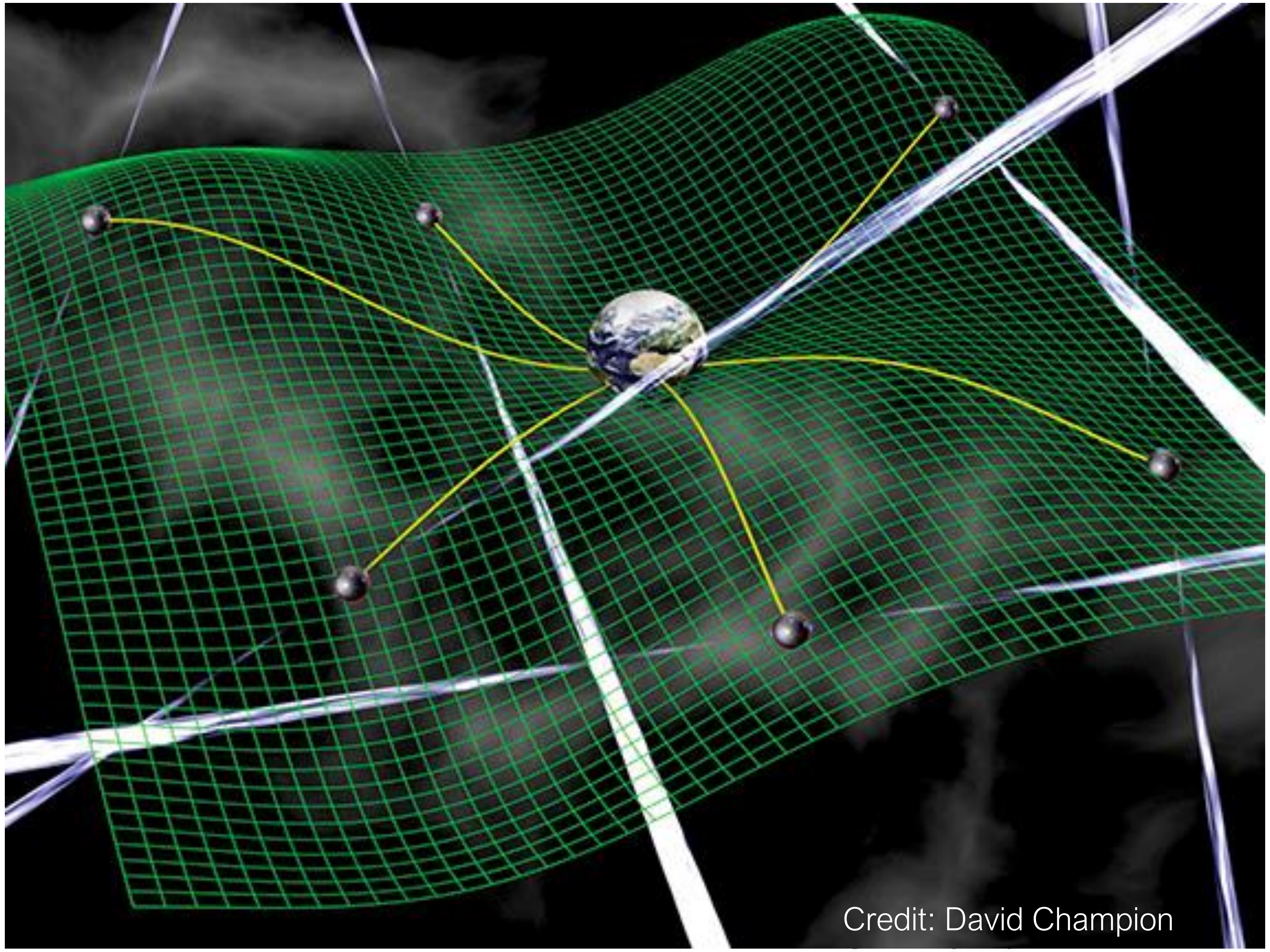
$$\delta t \sim 100\mathrm{ns}$$

Pulsar Timing Arrays as GW Detectors

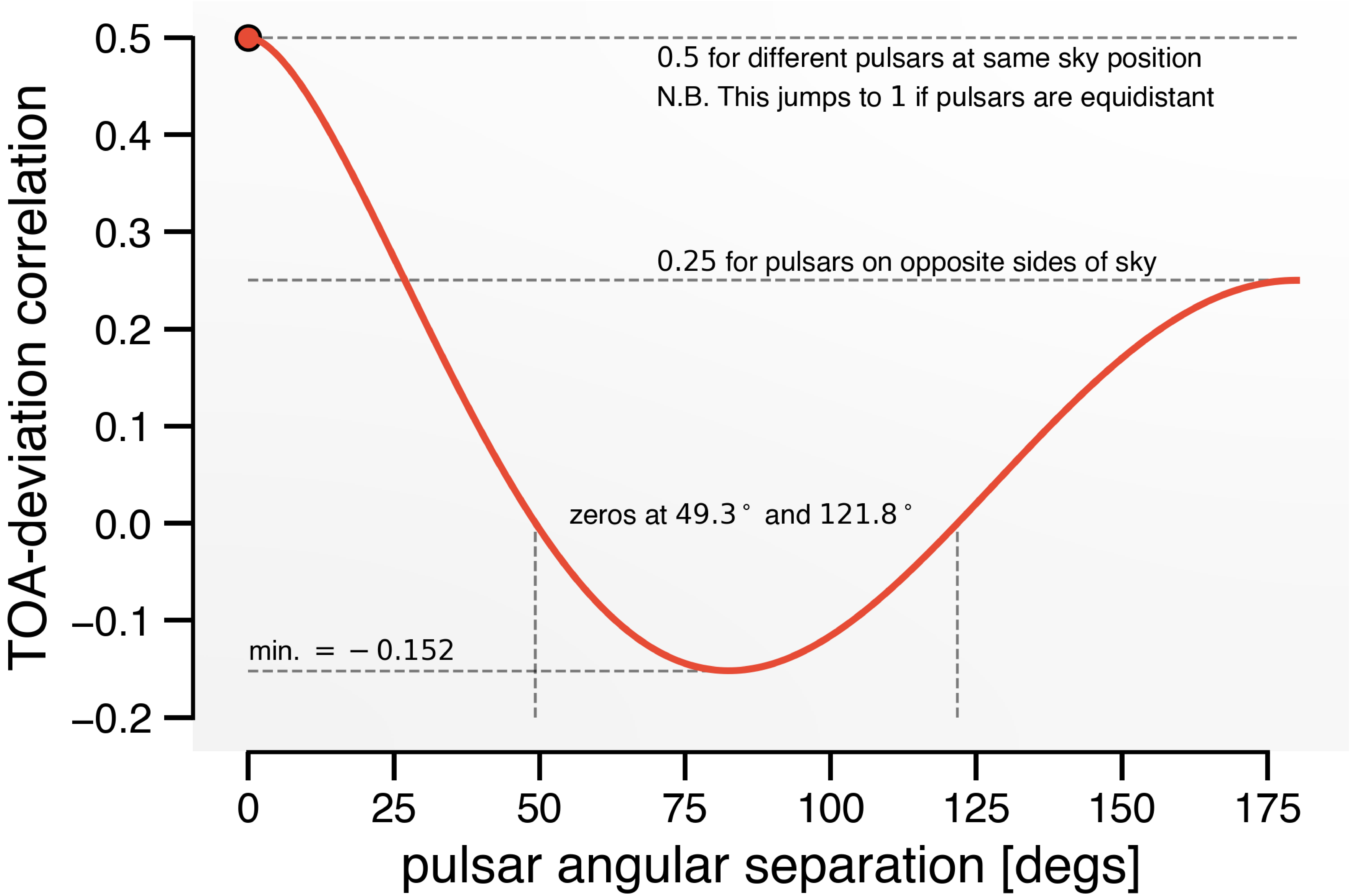
1 pulsar



an array of pulsars



40 years of the *Hellings & Downs Curve*



Hellings & Downs (1983)

Many pulsars needed for successful strategy (Siemens et al. 2013)

Other spatially correlated processes may include:

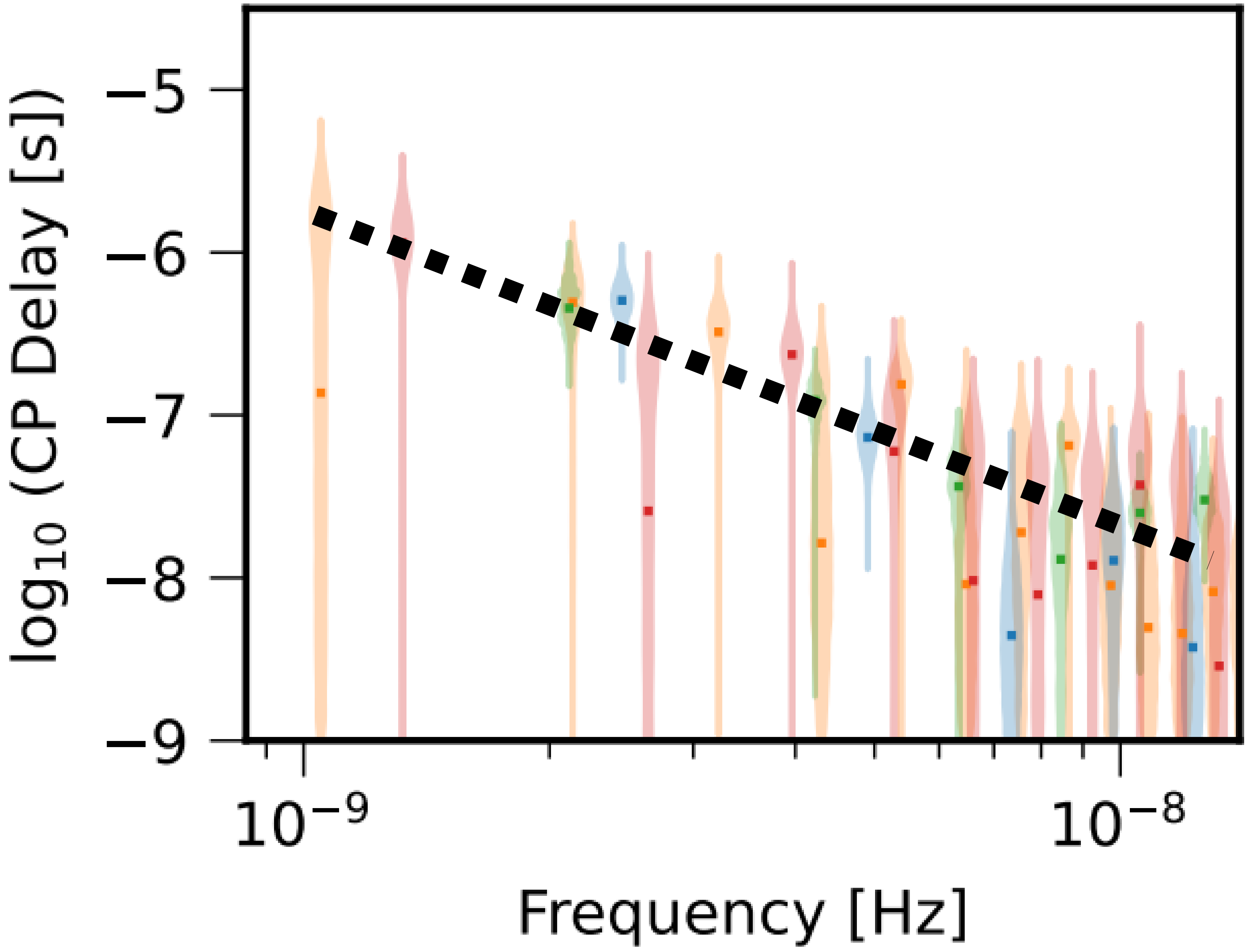
- Global time-standard drifts (*monopole*)
- Solar-system ephemeris errors (*dipole*)

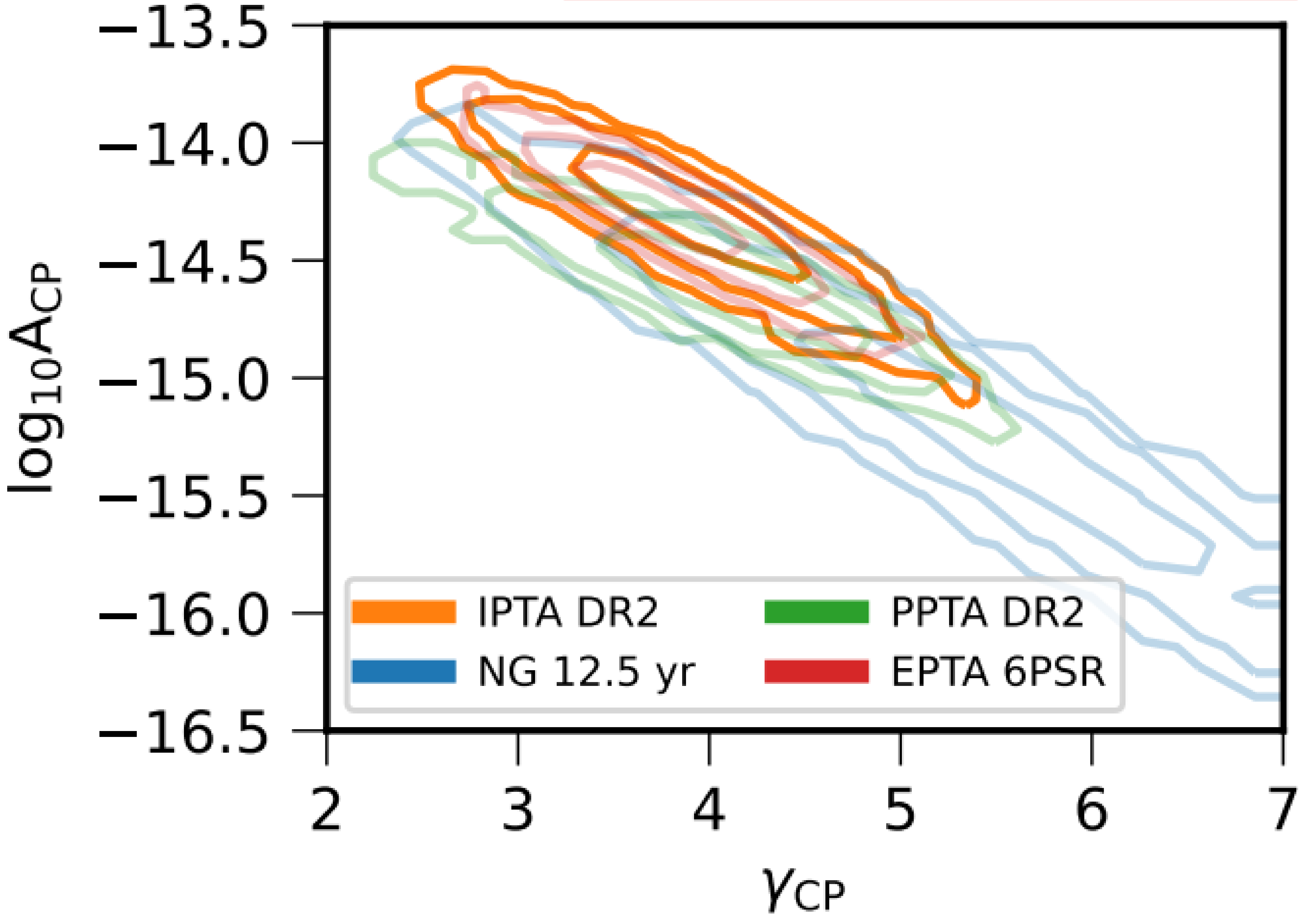
Credits: E.C. Ferrara / NANOGrav

First signs in 2020 — a common-spectrum process

IPTA DR2 Search
(MNRAS 2022, arXiv:2201.03980),
Corresponding author: Siyuan Chen (CNRS/KIAA Peking)

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

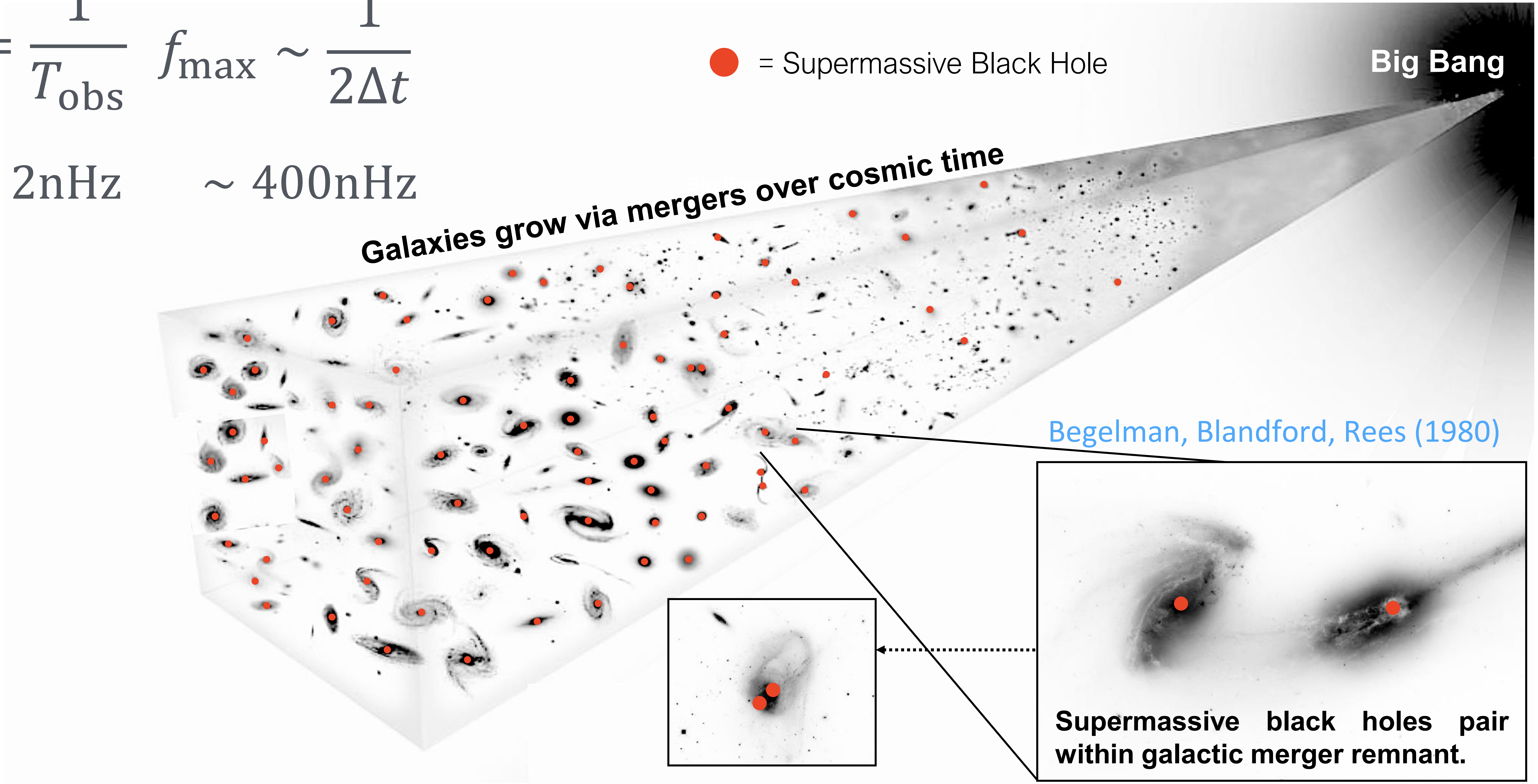




Supermassive Binary Black Holes

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

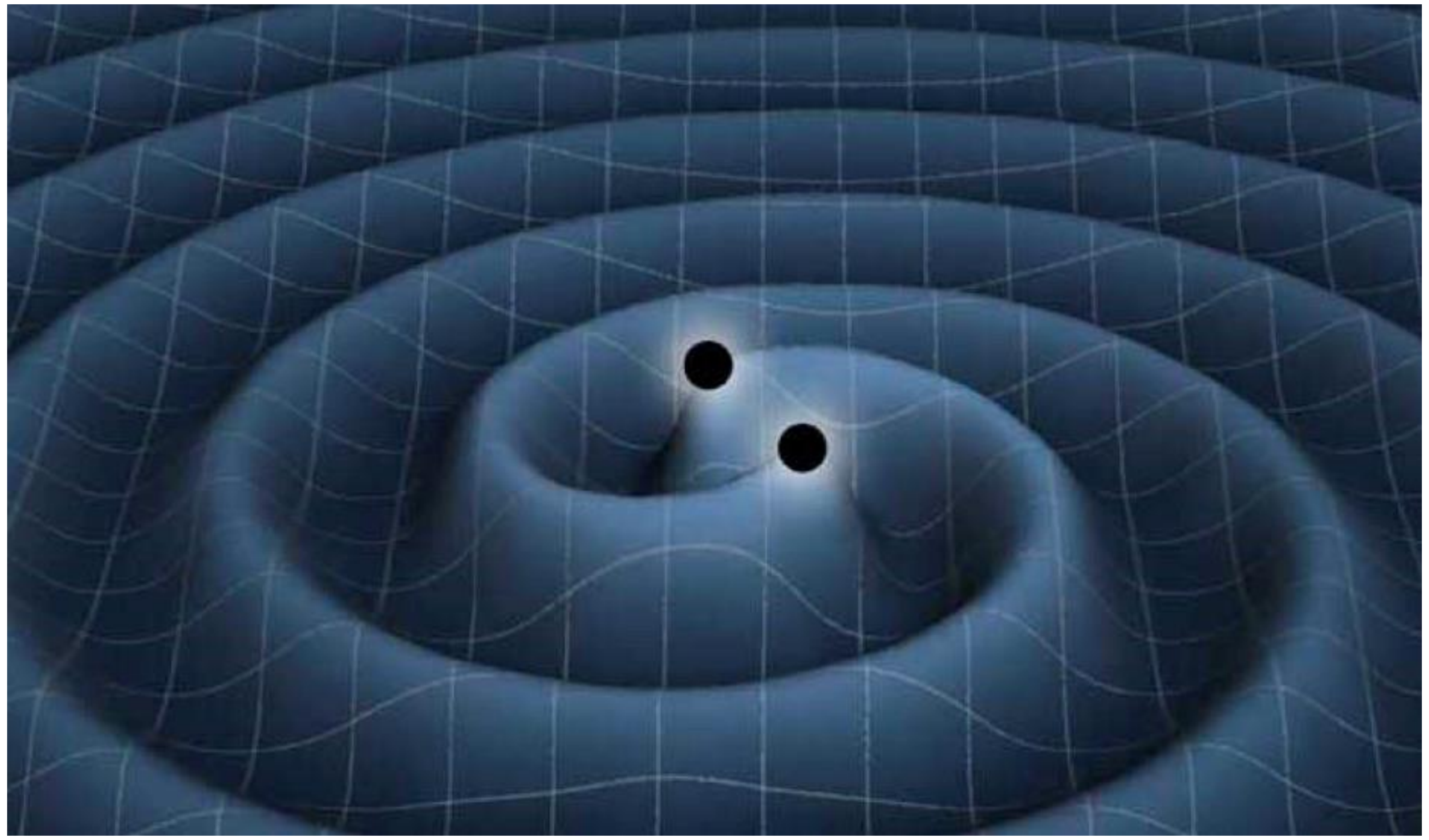
$$\sim 2\text{nHz} \qquad \sim 400\text{nHz}$$



Supermassive Binary Black Holes

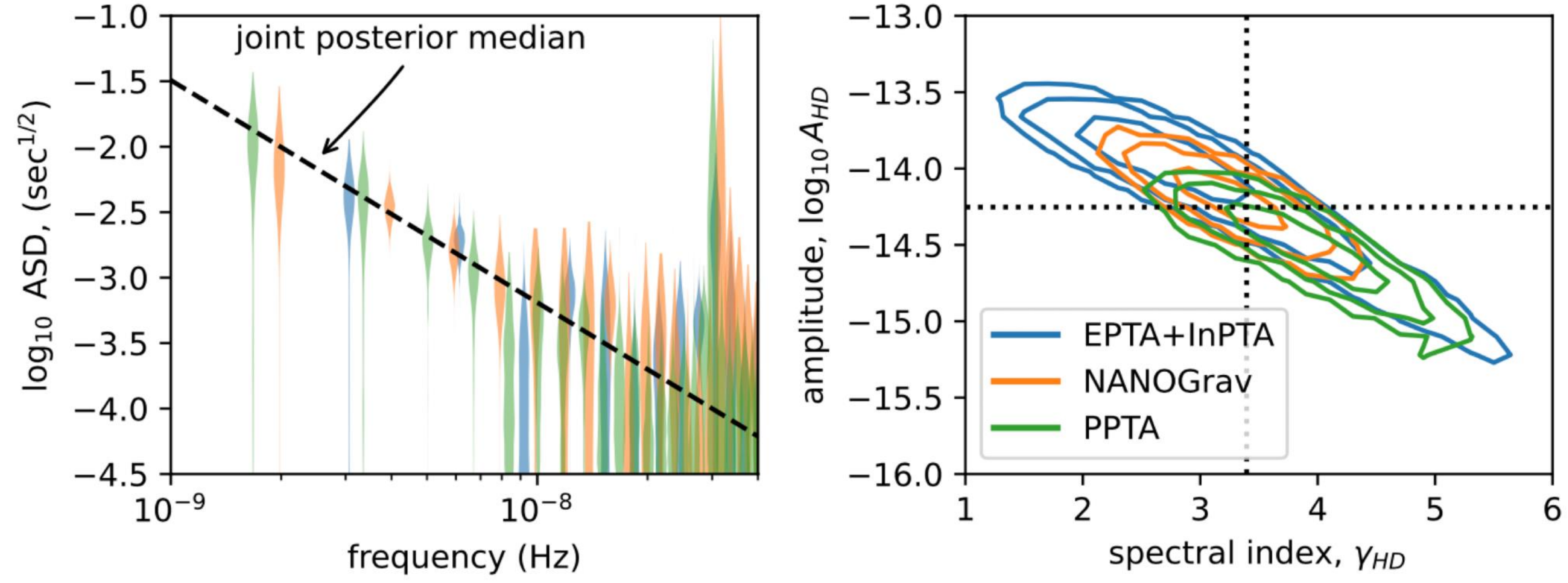
Phinney (2001)

$$h_c(f) \propto f^{-2/3}$$



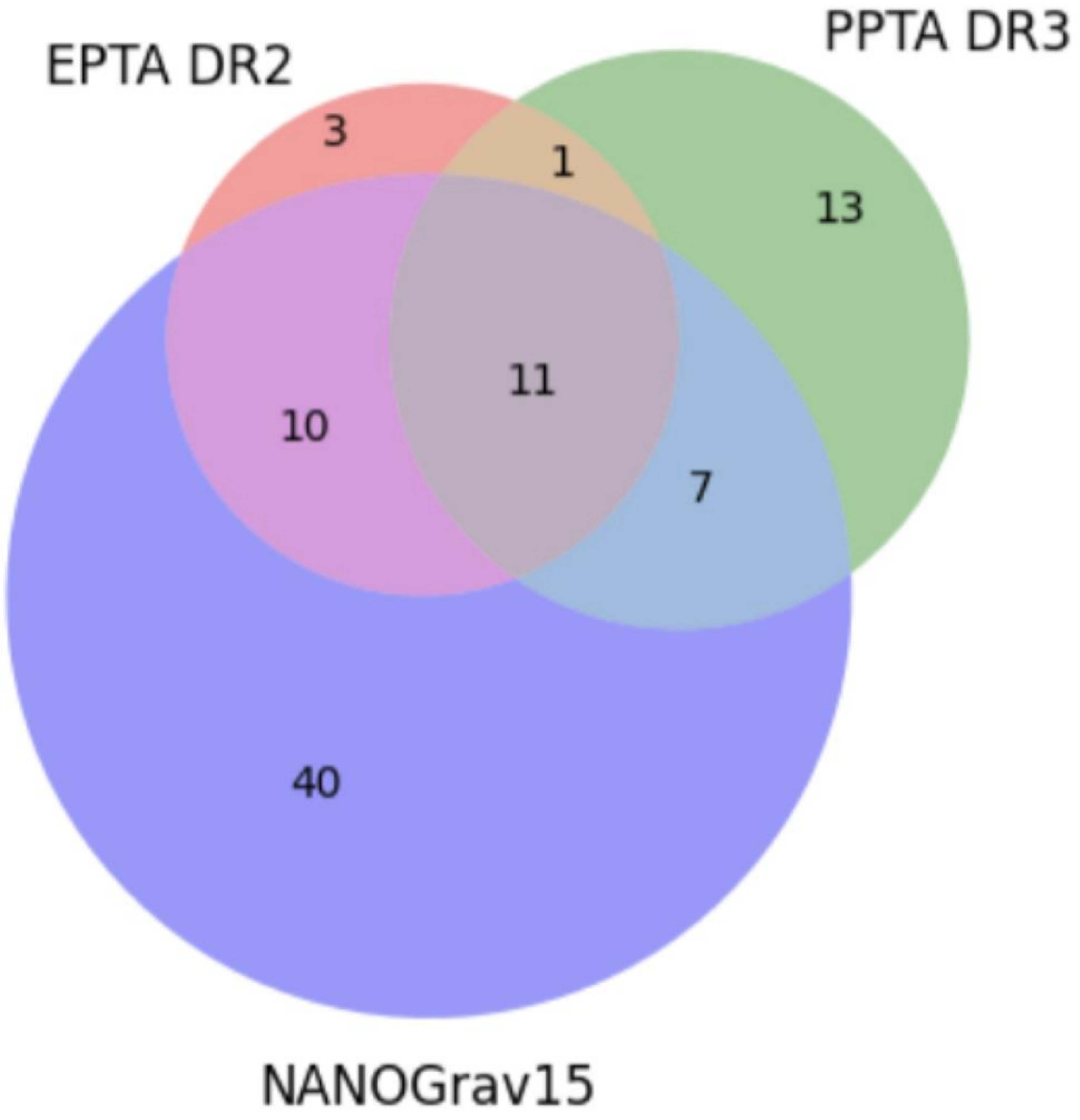
$$S_{\delta t}(f) \propto \frac{h_c^2}{12\pi^2 f^3} \propto f^{-13/3}$$

Characterizing The Spectrum



All results spectrally consistent!

Agazie et al. (2023)
[corresponding author: Paul Baker],
2309.00693

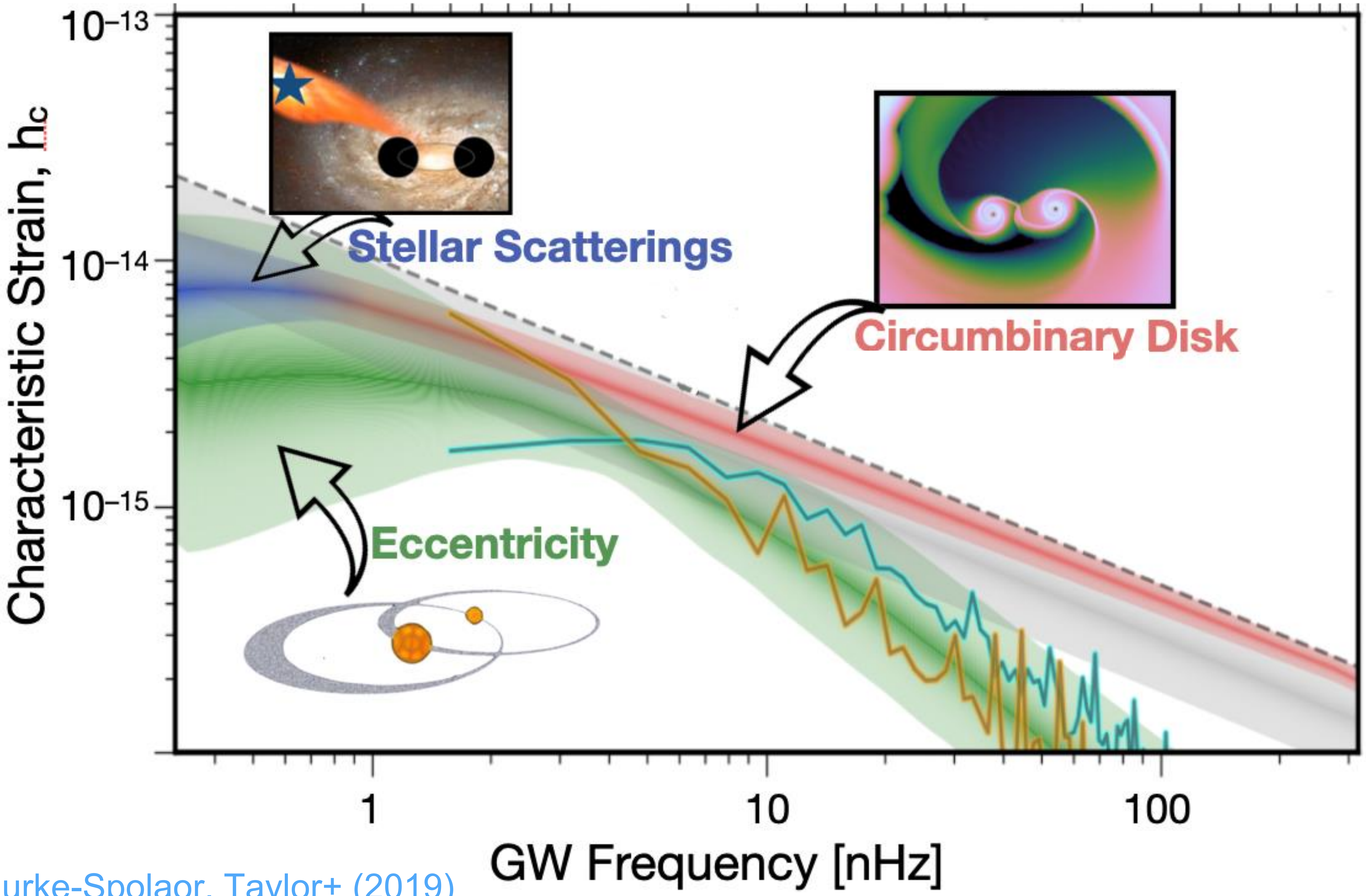


Credit: Paul Ray

With spectral characterization, your mileage may vary! Sensitive to noise models, though detection statistics appear robust.

GWB detection significance
3-4 sigma for NANOGrav,
~3-sigma for EPTA+InPTA
~2 sigma for PPTA.
CPTA reports 4.6 sigma significance.

Astrophysical Interpretation



Burke-Spolaor, Taylor+ (2019)

Amplitude = rate factors

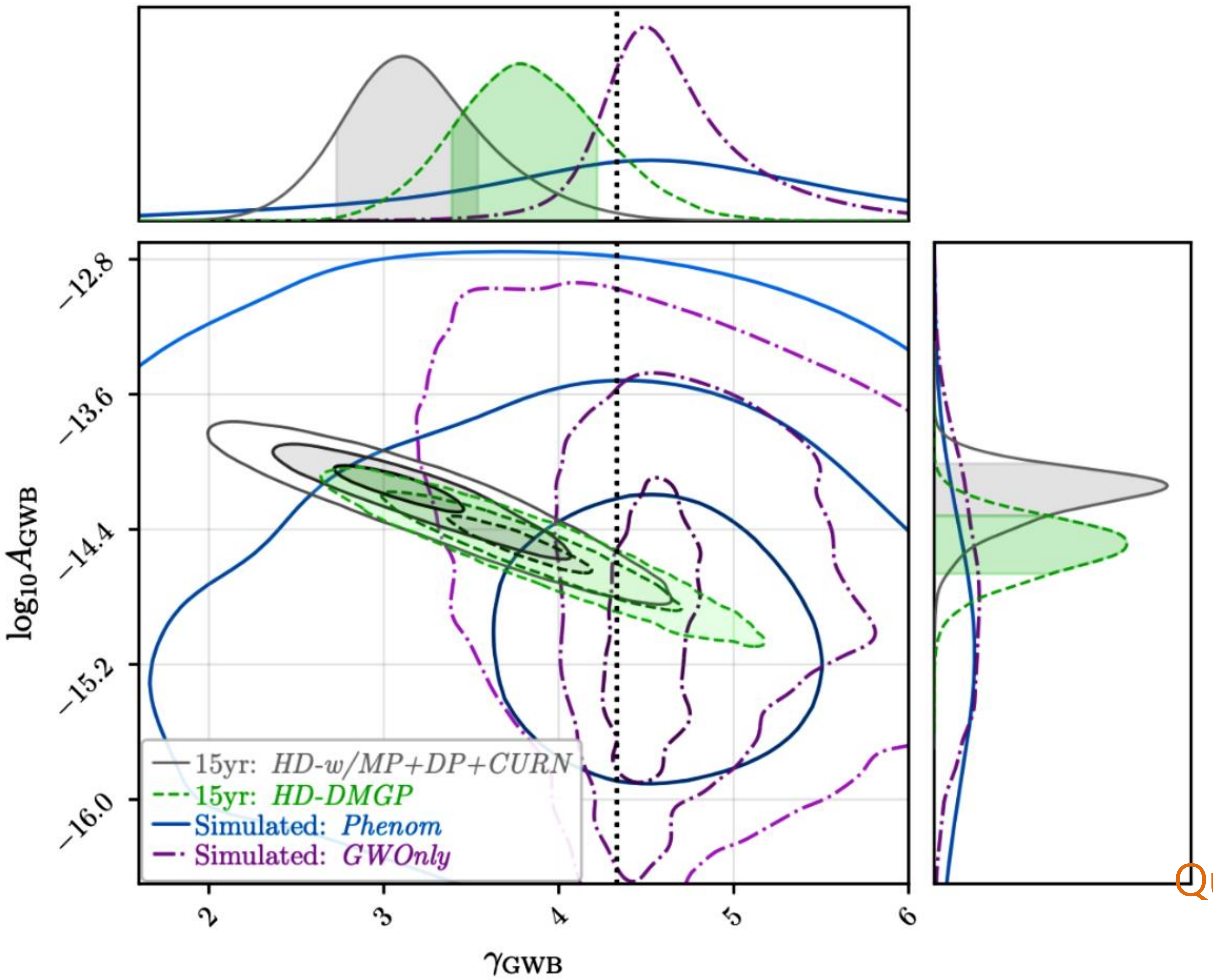
Shape = final-parsec dynamics

Spectral characterization methods:

- **Flexible turnover model:** e.g., Sampson et al. (2016),
- **SAM-fitting prescriptions:** e.g., Chen et al. (2017)
- **Population emulator:** e.g., Taylor et al. (2017)

Astrophysical Interpretation

github.com/nanograv/holodeck



NG: 2306.16220

- A population of *Supermassive Black-hole Binaries* **can** explain the signal.
- NANOGrav signal prefers higher SMBHB masses (through $M_{\mathrm{BH}} - M_{\mathrm{bulge}}$ normalization), with "short" binary lifetimes ($\lesssim$ few Gyr).
- Even GW-only evolution produces large deviations from expected power-law shape (Poisson variance).

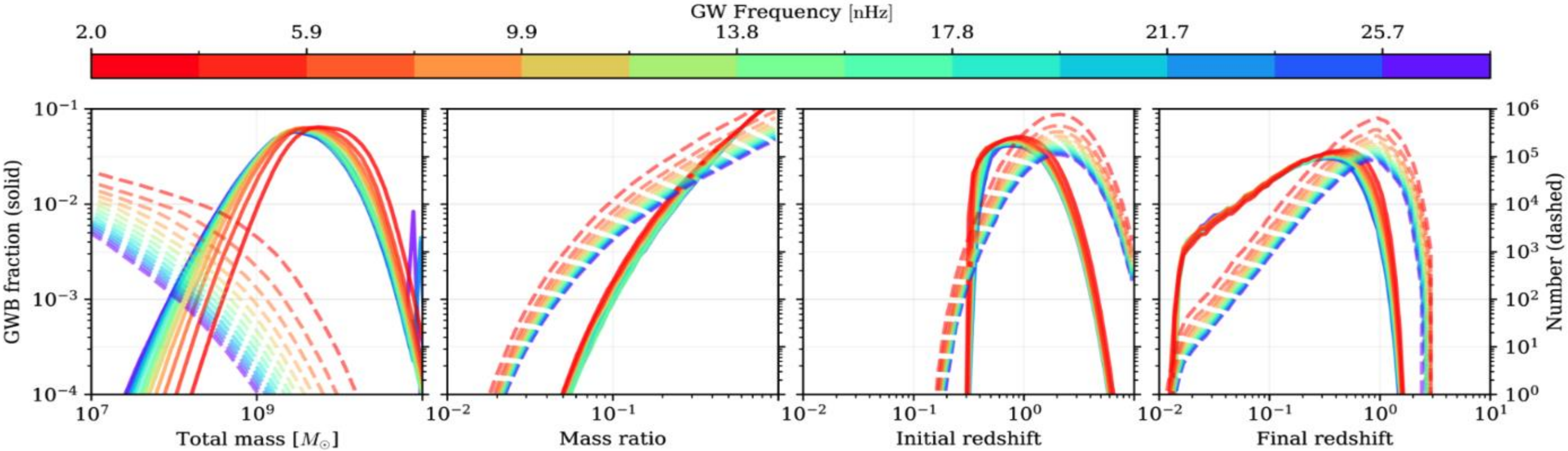
Qualitatively similar results found by EPTA+InPTA 2306.16227

Astrophysical Interpretation

NG: 2306.16220

Dashed lines are emitting binaries in underlying population

Solid lines are emitting binaries dominating GWB contribution

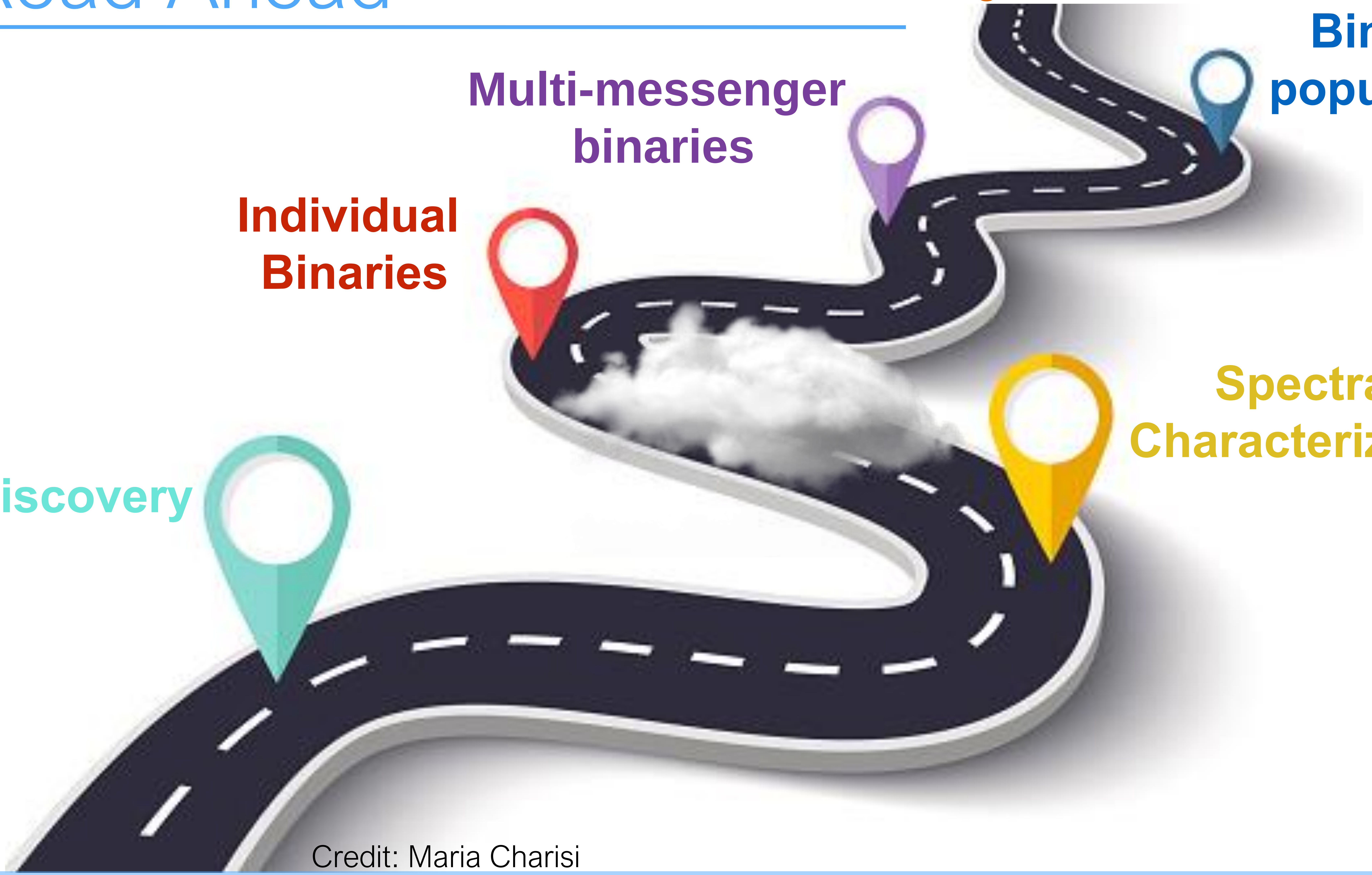


The GWB is produced by a small (and biased) sub-sample of a broader binary population.

$$M_{\rm tot} \sim 10^9 - 10^{9.5} M_\odot, q \sim 1, z \lesssim 1$$

$\sim 10^{-7} Mpc^{-3} dex^{-1}$ for $M = 10^9 M_\odot$ at $z = 0.25$

The Road Ahead



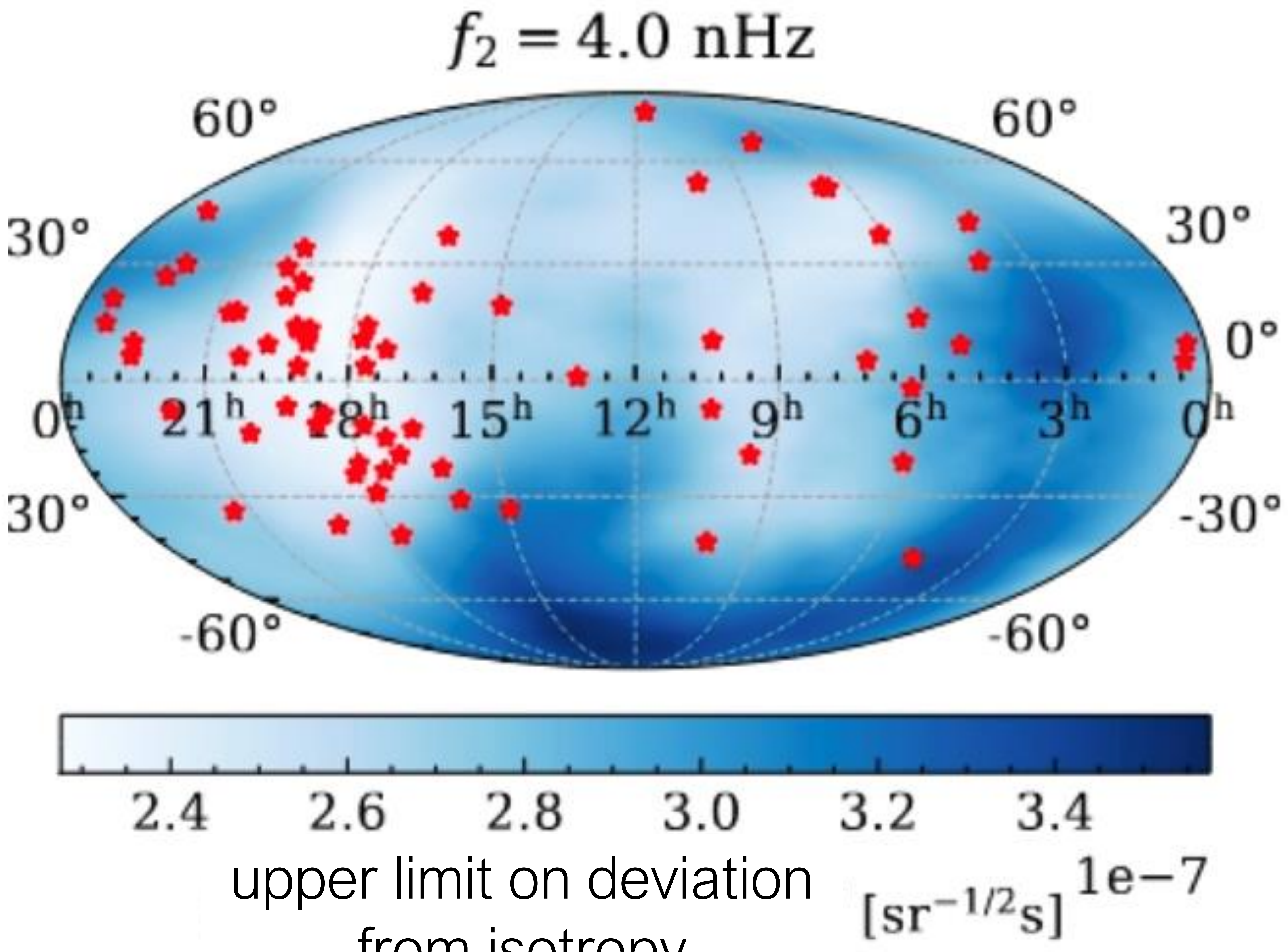
Credit: Maria Charisi

Mapping The GW Nanohertz Background

arXiv:2306.16221

- No evidence of anisotropy.
  (Not yet sensitive enough)
- Upper limits lowest near pulsars (red stars).

- Anisotropy from binary population may be detectable in ~5 years
  (Pol, Taylor, Romano 2022)
- *Expected anisotropy increases with frequency, and* **could help validate SMBHBs over cosmological signals***.* (*Gardiner+2023, 2309.07227)*

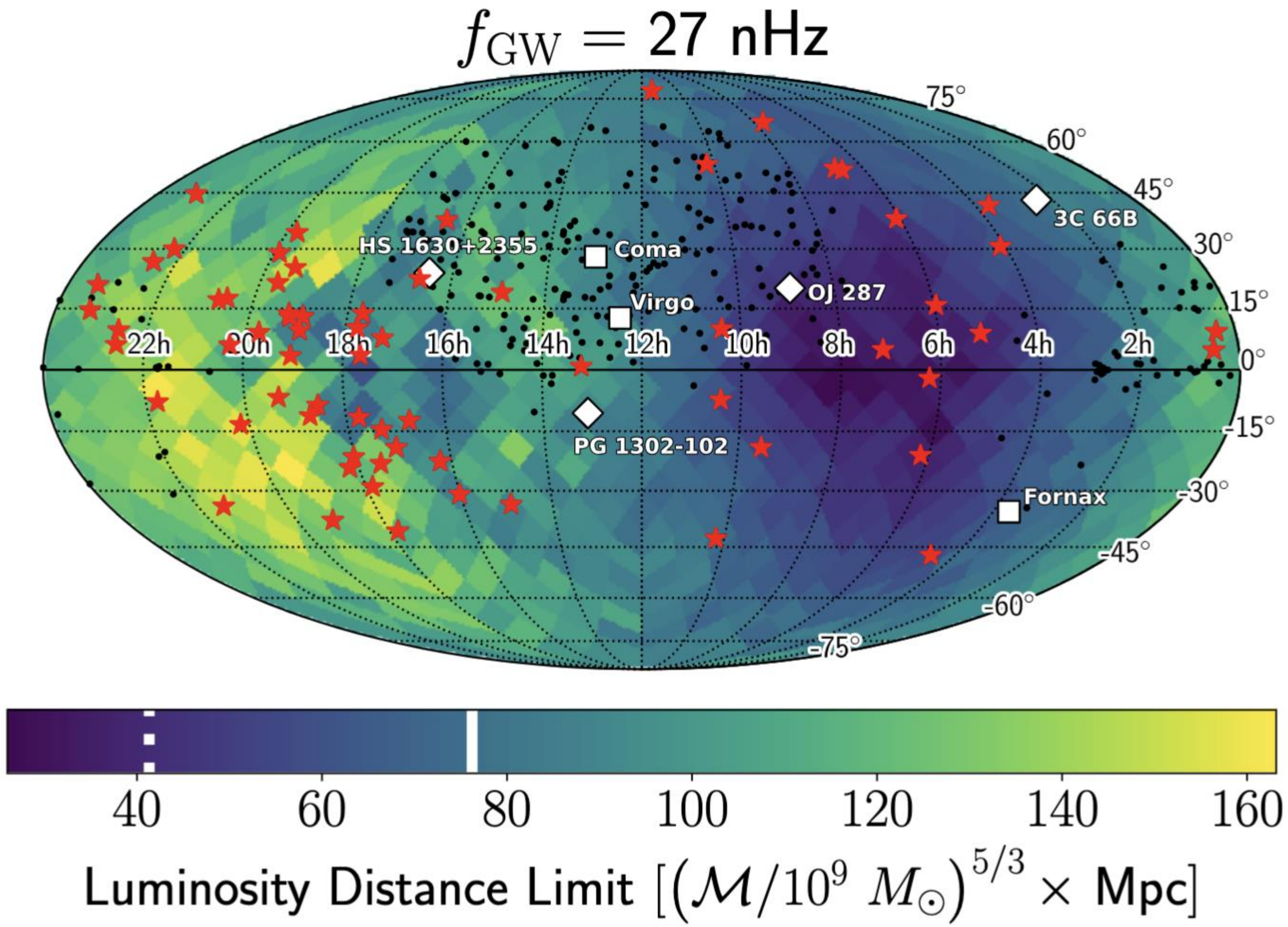


upper limit on deviation from isotropy

Resolving Individual Binary Signals

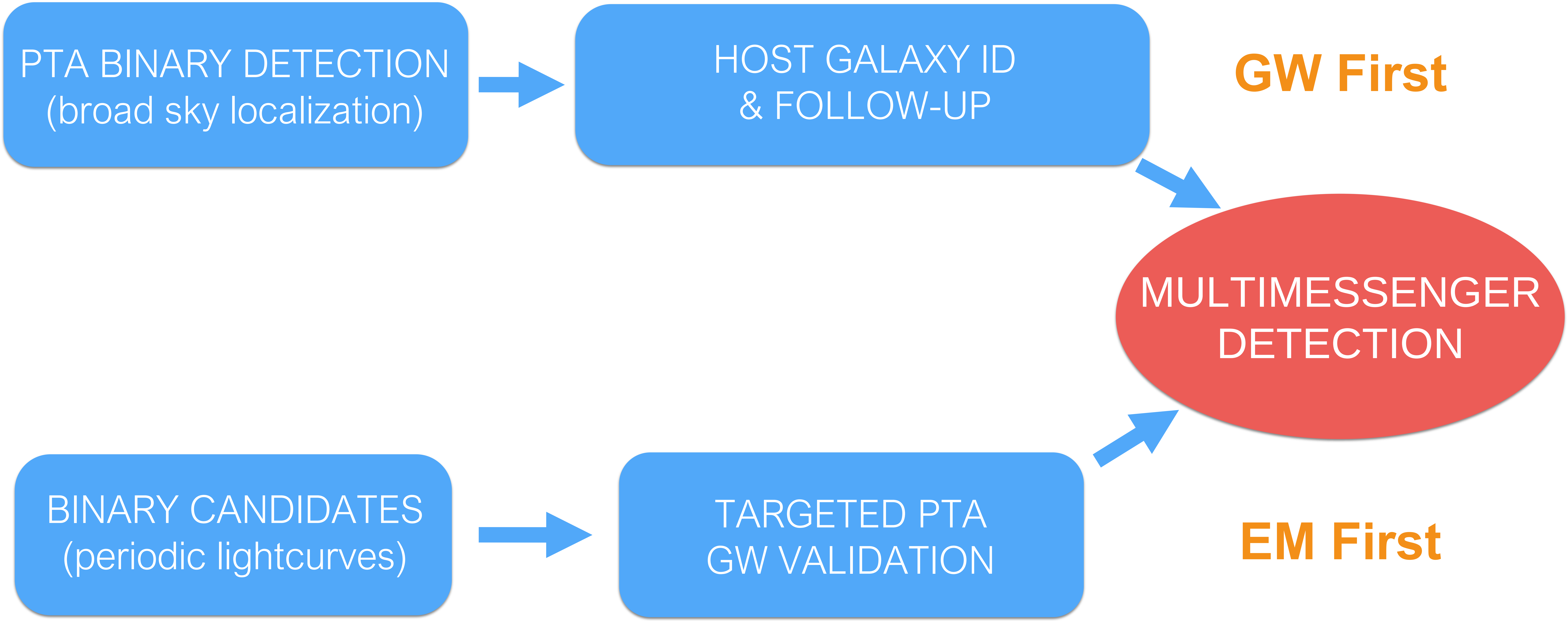
EPTA+InPTA: 2306.16

NG: 2306.16222 *No evidence for single sources yet (as expected).*



- Red stars = pulsars
- White squares = galaxy clusters
- White diamonds = prominent candidate binaries,
  e.g., 3C66B targeted by NANOGrav in 2005.07123 and 2309.17438.
- Black points = periodic quasar lightcurve candidates.

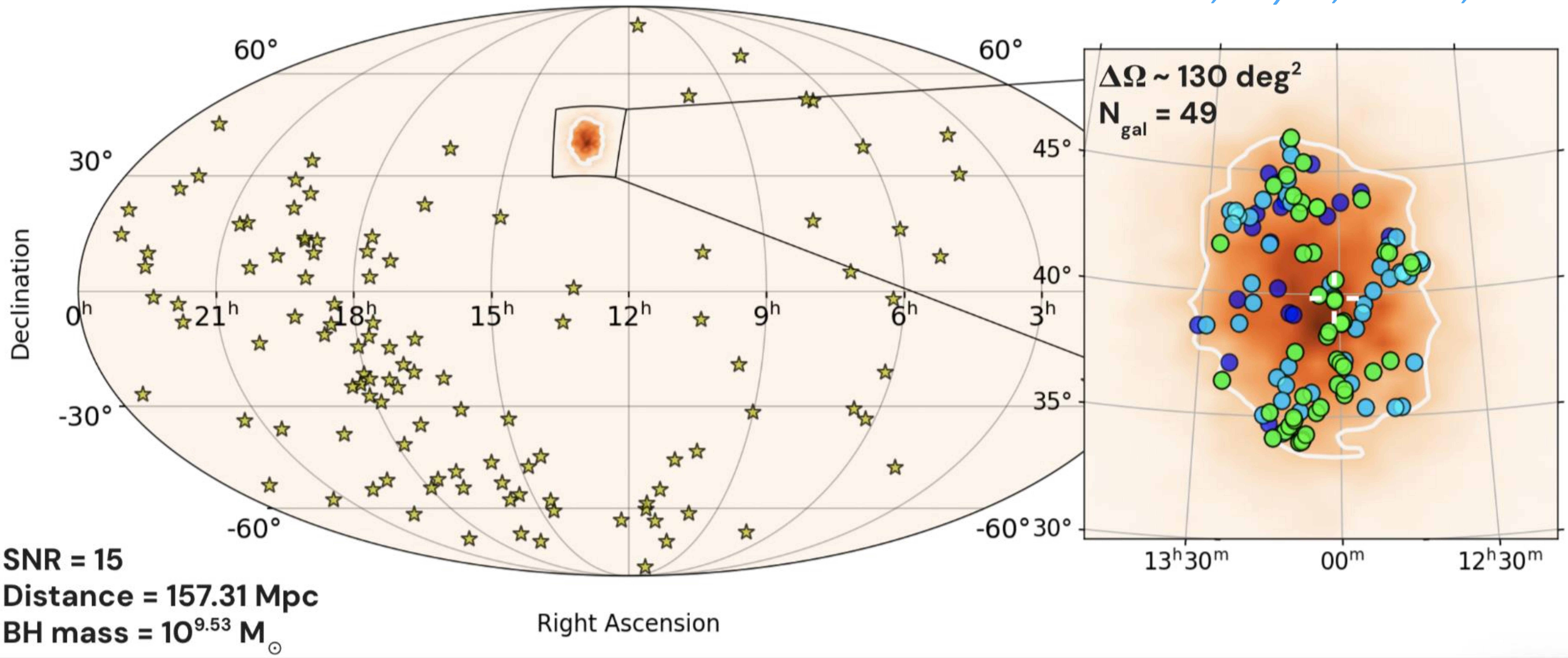
Multimessenger PTA Detection



Localizing the host galaxy

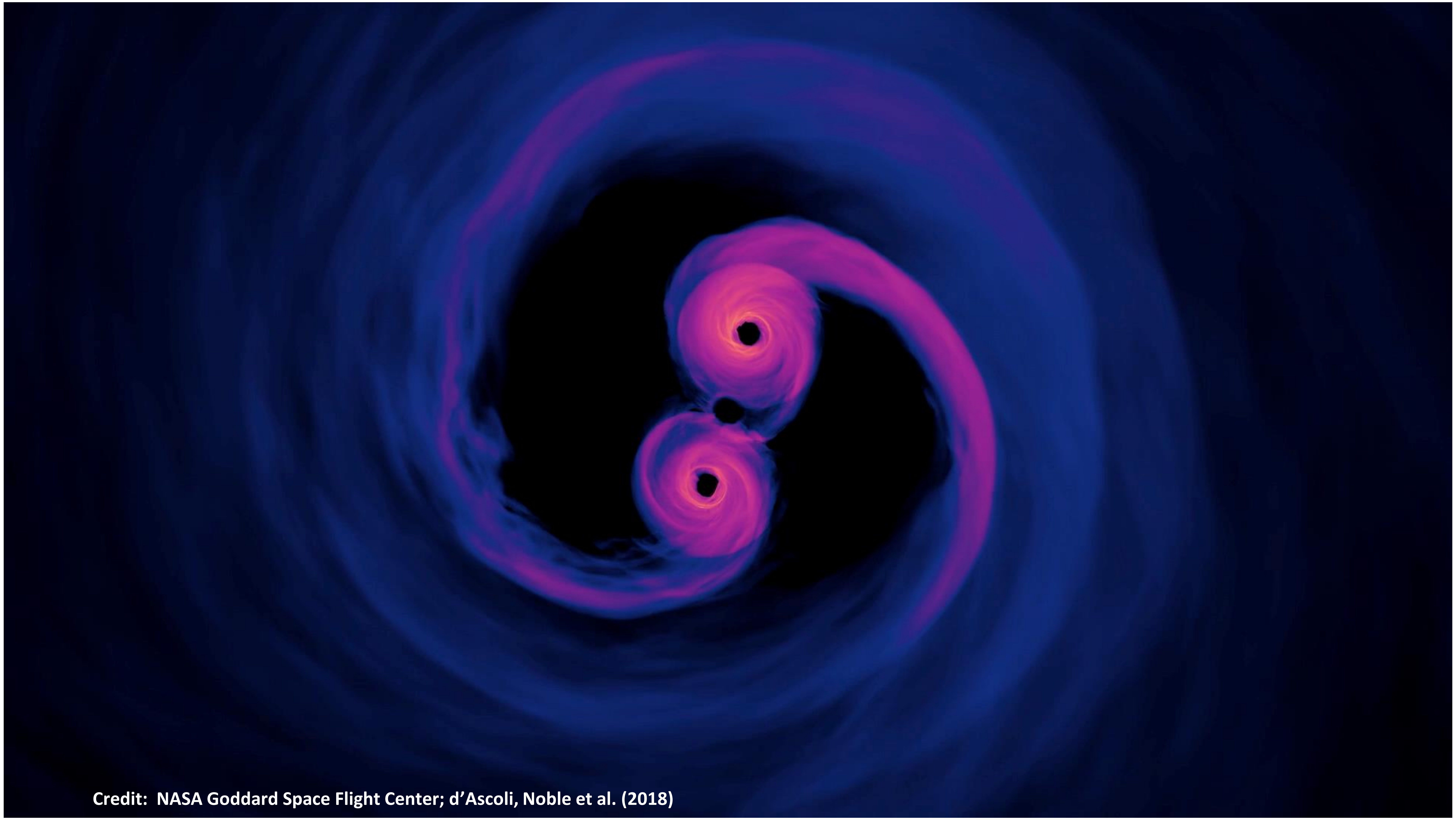
GW First

***Petrov**, Taylor, Charisi, Ma*



SNR = 15
Distance = 157.31 Mpc
BH mass = $10^{9.53}$ $M_\odot$

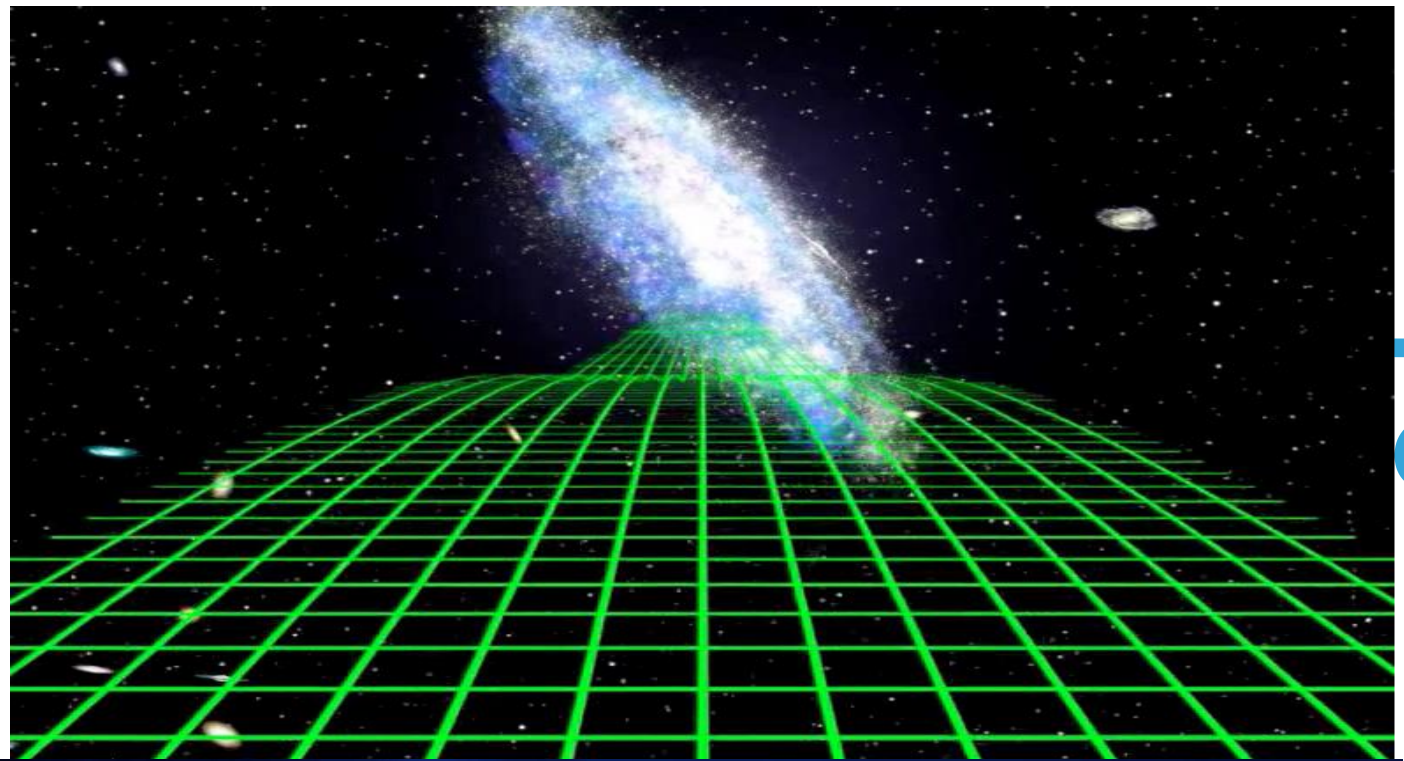
The Next Ten Years — EM counterparts



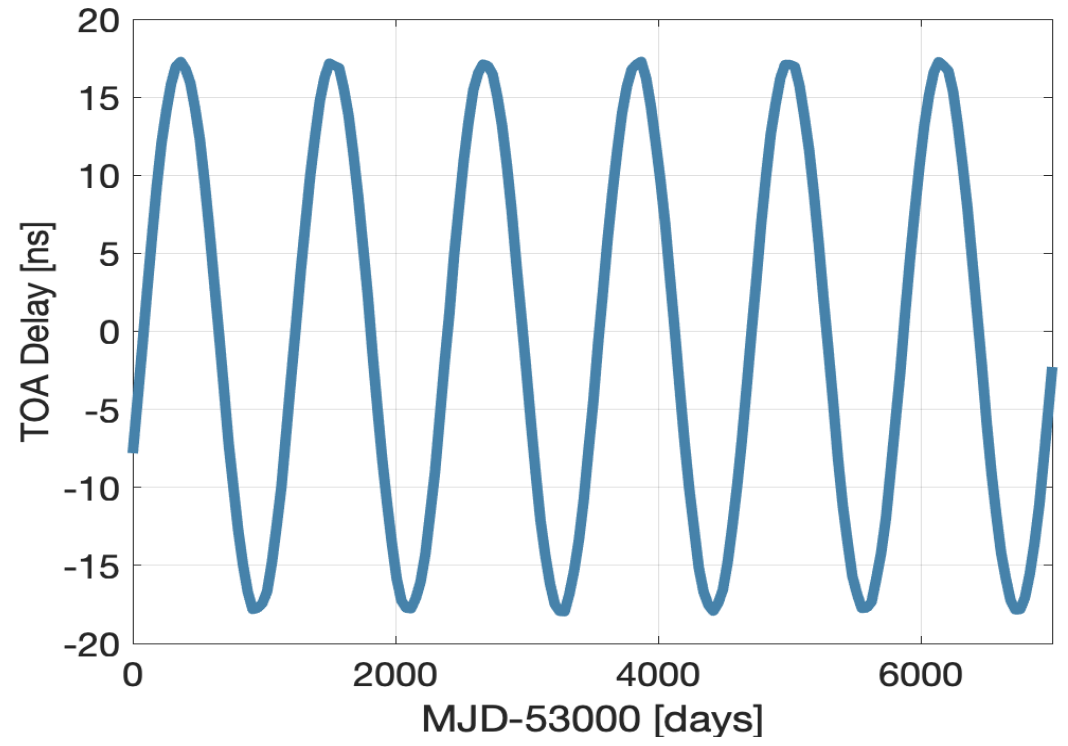
Multimessenger PTA Detection

Related:
Z. Haiman, Thur 14:00, Hall 10
Y. Shen, Fri 10:50, Hall 10

- *GW emission* + *EM Doppler-boosting* map the binary orbital dynamics in different ways.



GW



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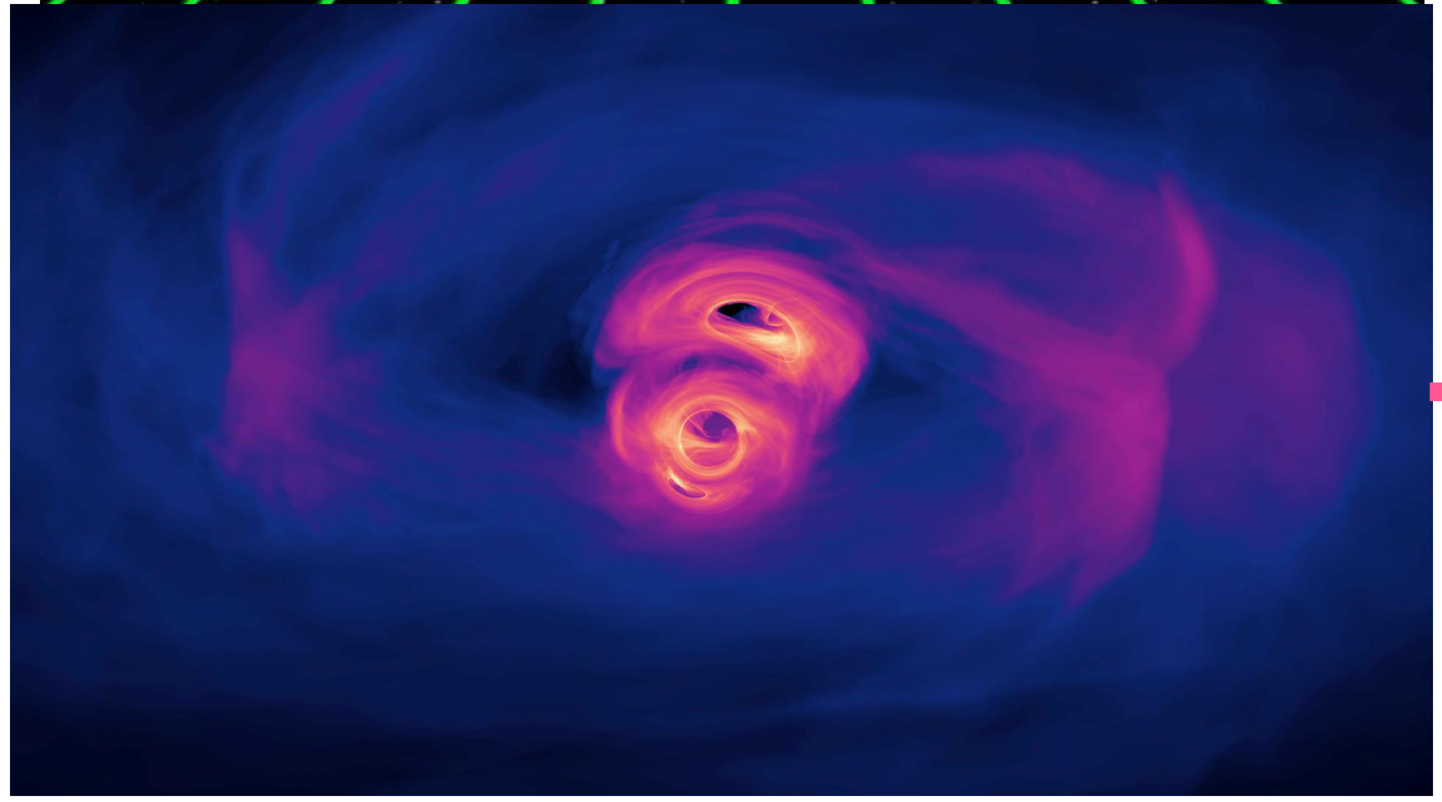
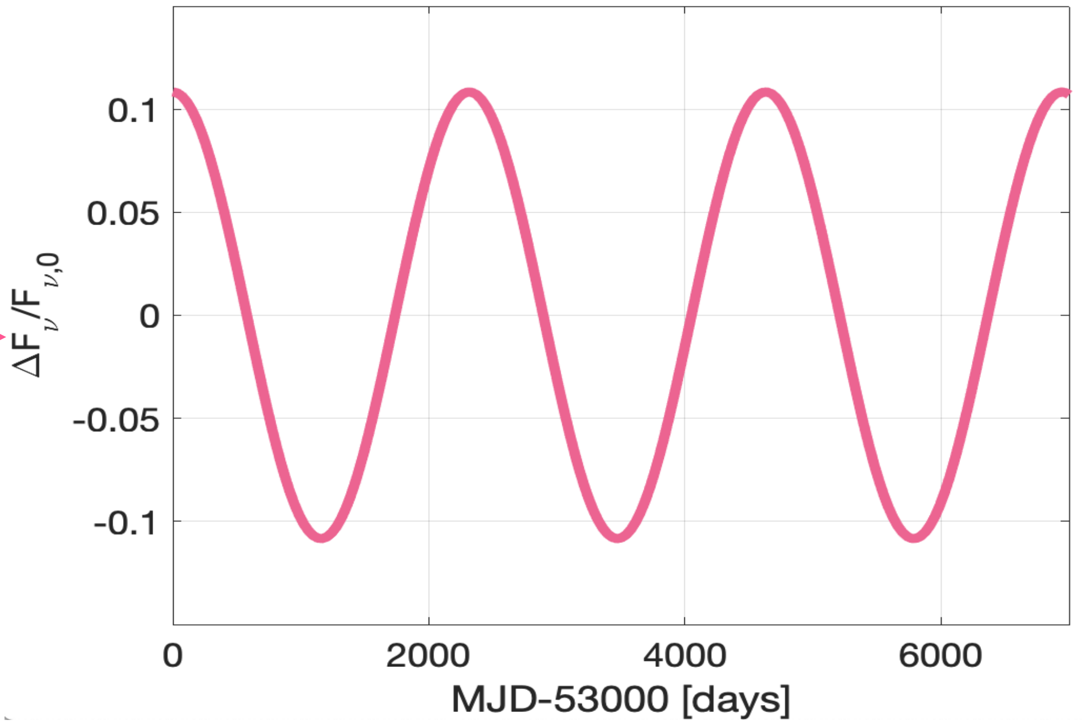
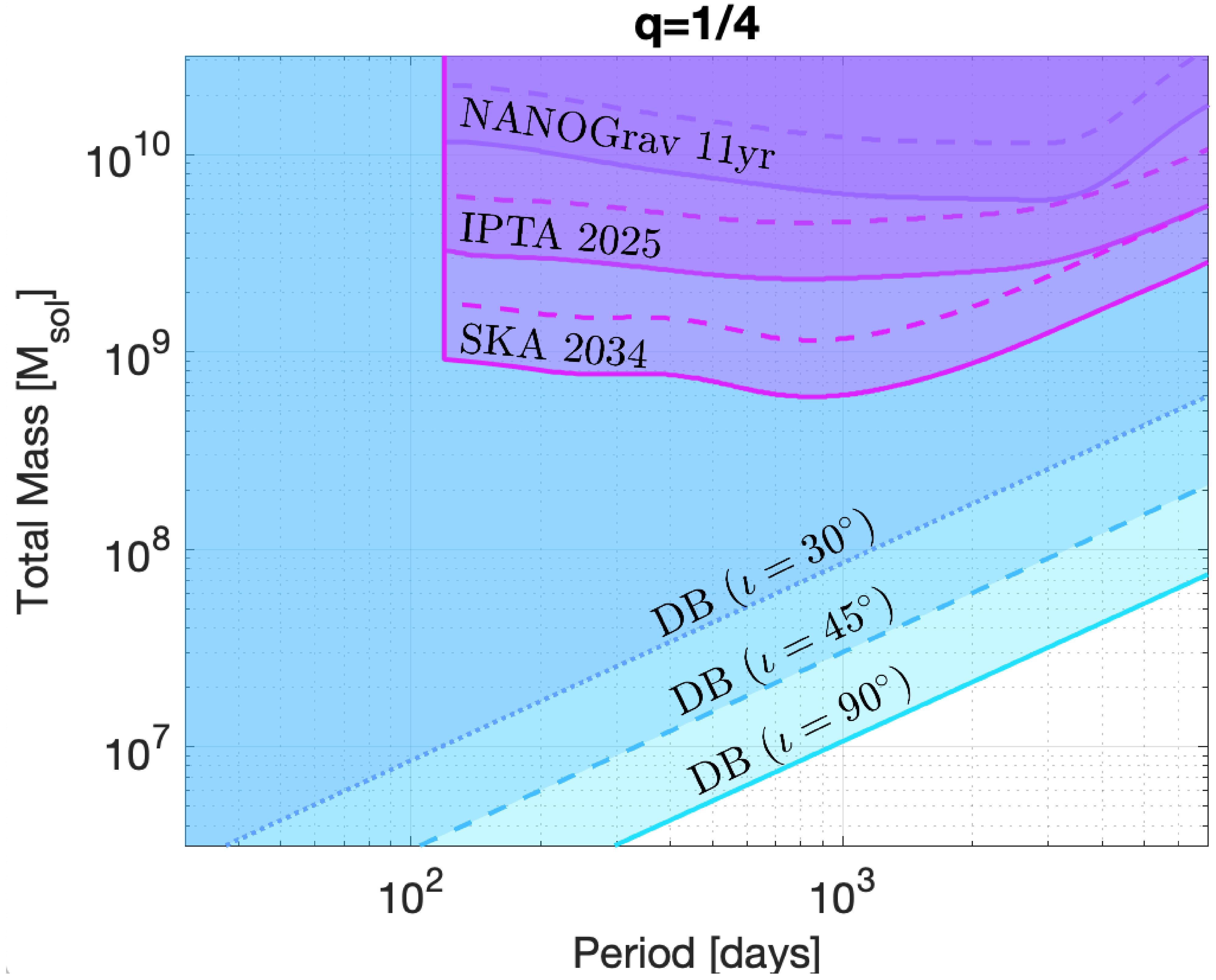


EM



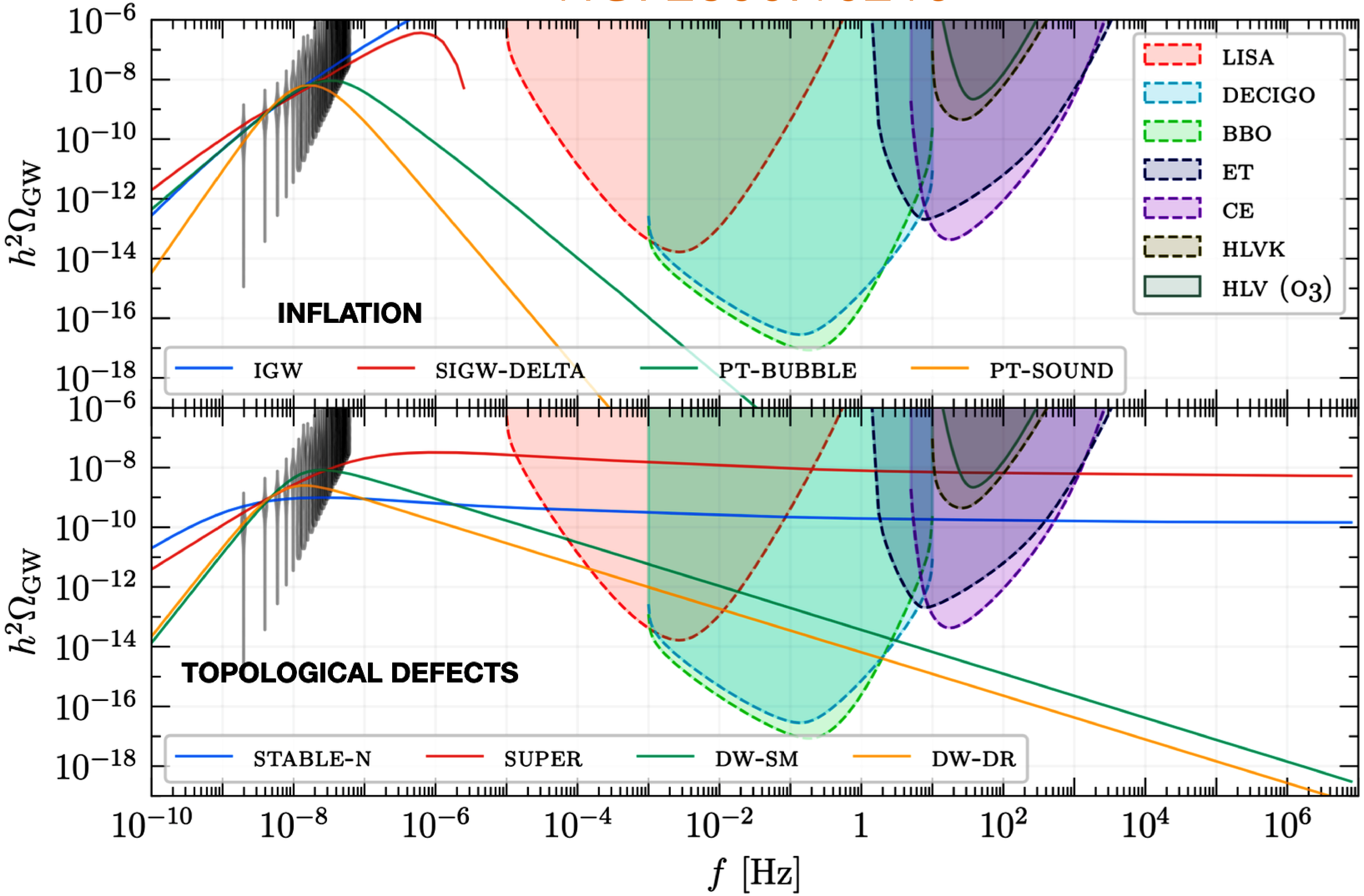
EM First



Charisi, Taylor, Runnoe, Bogdanovic, Trump (2022)
Charisi, Taylor, Witt, Runnoe (2023)

Cosmological Interpretation

NG: 2306.16219



Inflation, scalar-induced GWs, first-order phase transitions, cosmic strings, domain walls.

No evidence of new physics.

But can't be ruled out either *(except for stable field-theory strings)*.

Superstrings more consistent.

No evidence of ultralight dark matter.

But constraints outperform torsion balance and atomic clock tests.

Open questions in PTA science

- What's the origin of the signal?
- How much information can we get from the spectrum?
- When will background studies be limited by cosmic variance?

GW Background — population studies

- When will individual binary gravitational-wave signals be found?
- What will the emergence of an individual signal look like?
- How will information from galaxy catalogs and periodic-lightcurve quasars be combined into a multi-messenger picture of binary--disk dynamics?

Single GW Events — dynamics and MMA

- What probes of fundamental physics and cosmology can pulsar-timing arrays uniquely tackle?

New Physics and Beyond GR

IPTA Data Release 3 =
EPTA + InPTA + NG (+CHIME) + MPTA + PPTA

~115 pulsars!

Data Combination Hack Week happening right now in Bonn!