NANOGrav Physics Frontiers Center

Follow the Monarchs
A Journey to Explore the Cosmos at (Sub)milliarcsecond Scales with the ngVLA

Finding and Resolving Supermassive Black Hole Binaries

T. Joseph W. Lazio

Jet Propulsion Laboratory
California Institute of Technology











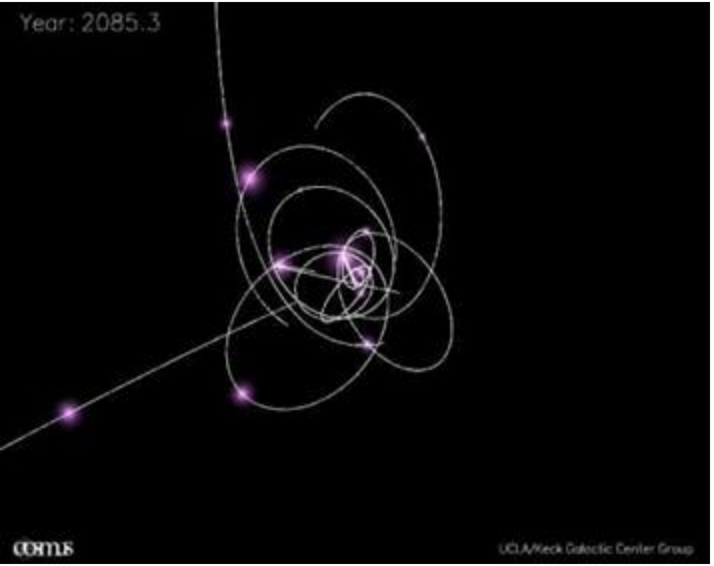


Chiara Mingarelli (Yale)
Sarah Burke-Spolaor (West Virginia Univ.)
Caitlin Witt (Northwestern)
Nikita Agarwal (West Virginia Univ.)
Lankeswar Dey (West Virginia Univ.)
London Willson (Yale)
Bjorn Larson (Yale)
Bence Bécsy (OSU)
Forrest Hutichison (Yale)
Andrew Casey-Clyde (Yale)
Rohan Shivakumar (Yale)

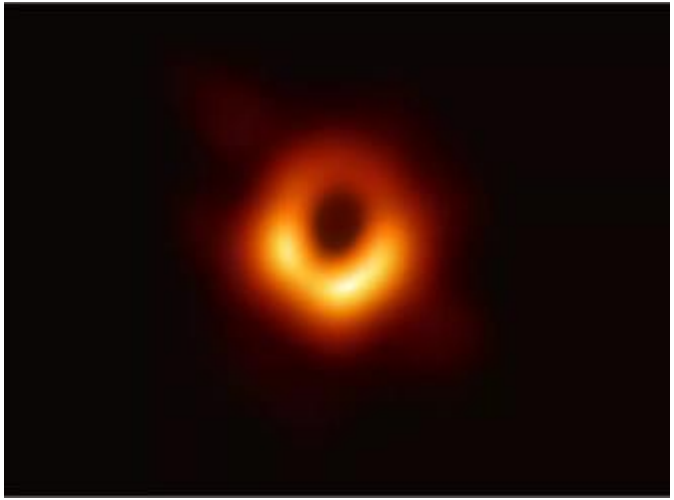



Sonia Hernandez (Blue Origin)
Marin Anderson (Jet Propulsion Laboratory, California Institute of Technology)
Geoffrey Bower (ASIAA)
Eric Burt (Jet Propulsion Laboratory, California Institute of Technology)
Emily Doughty (Continuum Space)
Todd Ely (Jet Propulsion Laboratory, California Institute of Technology)

Galaxies Host Supermassive Black Holes



Sgr A* - Milky Way black hole



Event Horizon Telescope

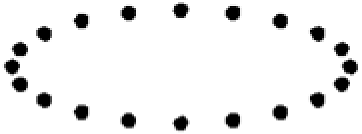
Active Galactic Nuclei

Merging Galaxies and Supermassive Black Holes

Projections that merging supermassive black holes lead to gravitational wave background date at least to Rajagopal & Romani (1995)

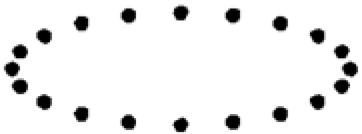
NGC 3521, NGC 4651
(Credit: R. Jay GaBany)

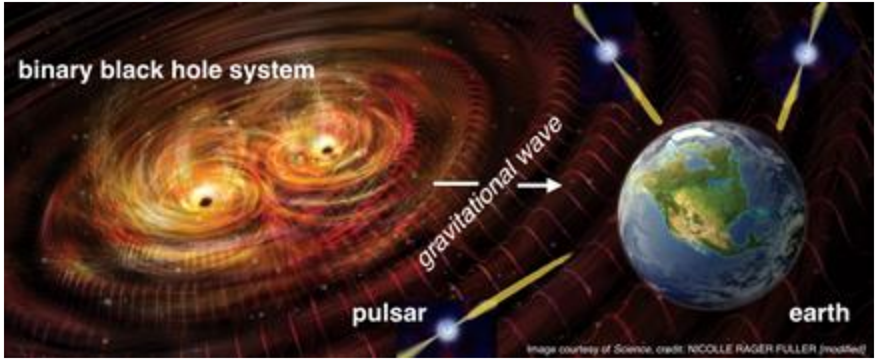
Gravitational Wave Telescope



Gravitational waves perturb spacetime.

Gravitational Wave Telescope

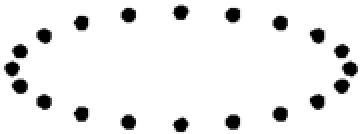


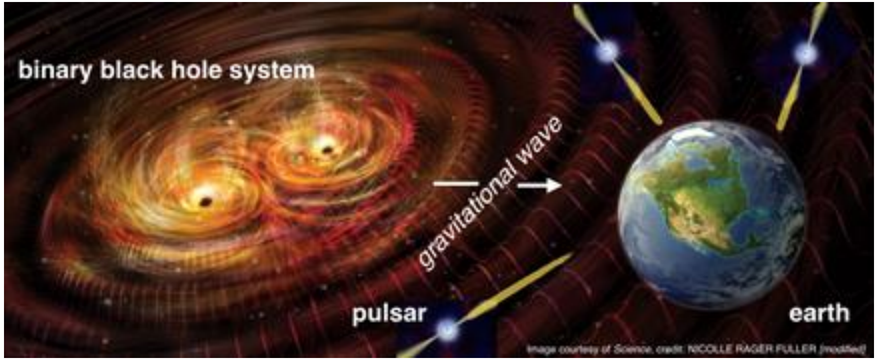


Arrival times of radio pulses crossing perturbed spacetime are advanced or delayed.

Gravitational waves perturb spacetime.

Gravitational Wave Telescope

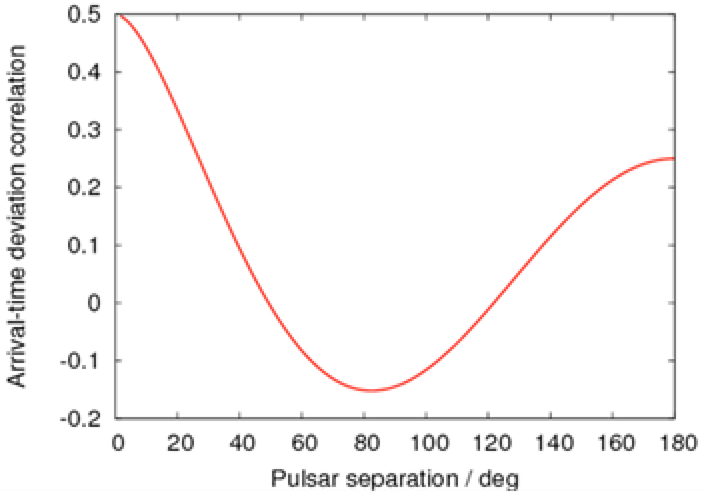




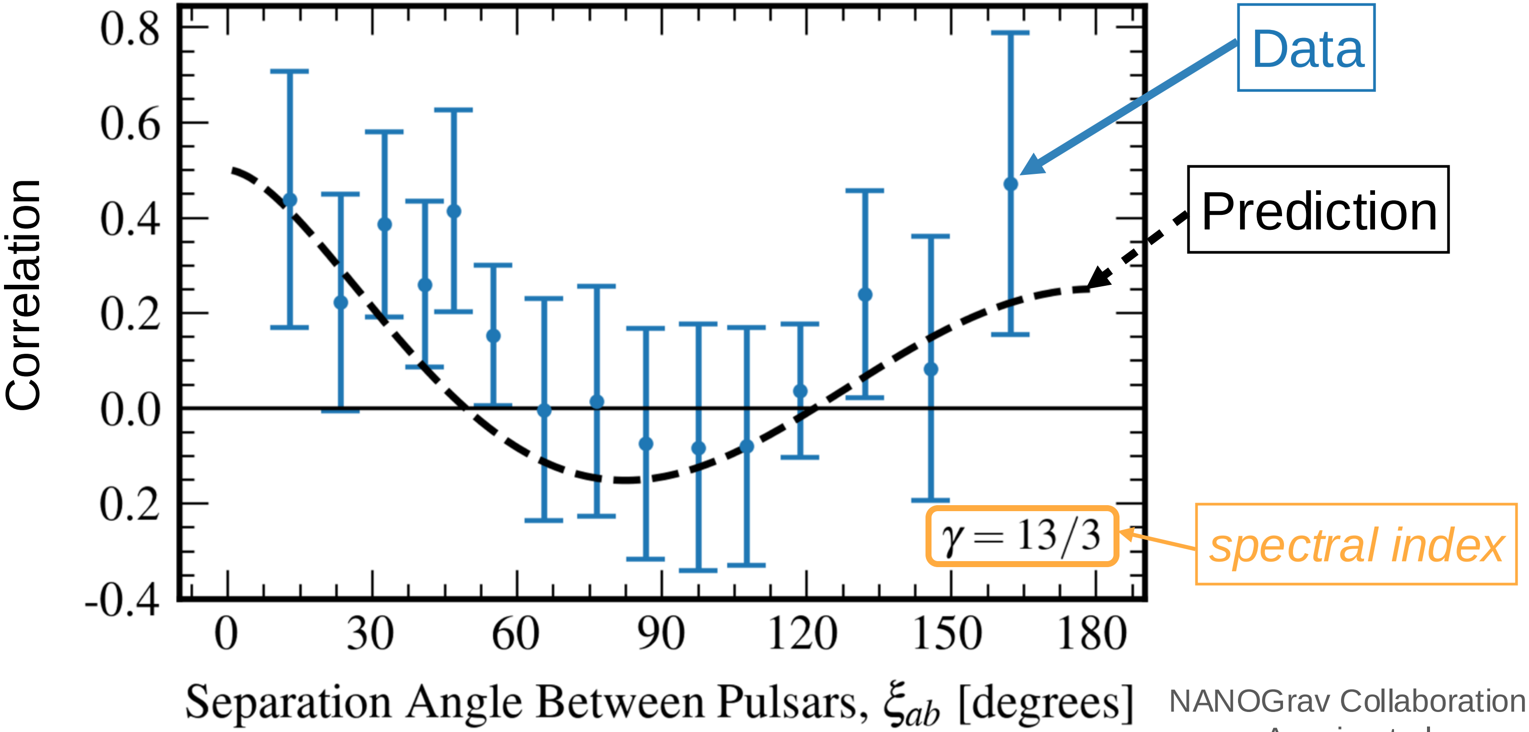
Gravitational waves perturb spacetime.

Arrival times of radio pulses crossing perturbed spacetime are advanced or delayed.

General Relativity predicts spatial correlation of pulse arrival time changes.

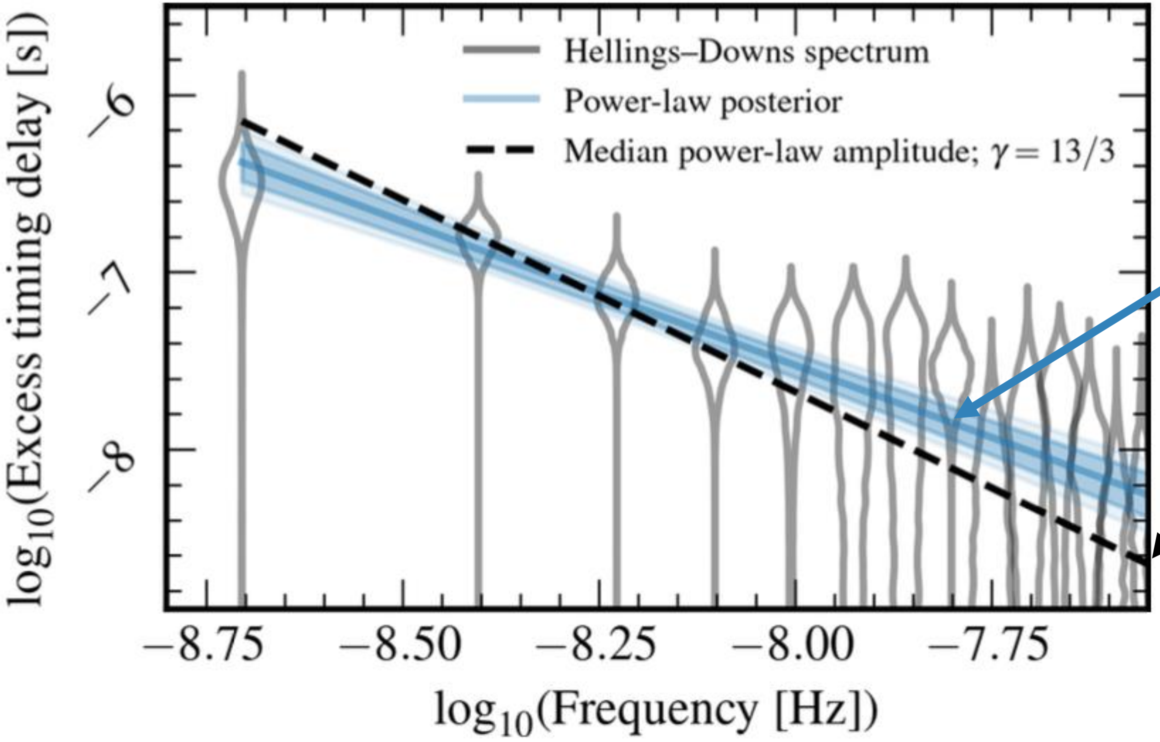


Evidence for Gravitational Wave Background



NANOGrav Collaboration: Agazie et al.

Gravitational Wave Background Spectrum

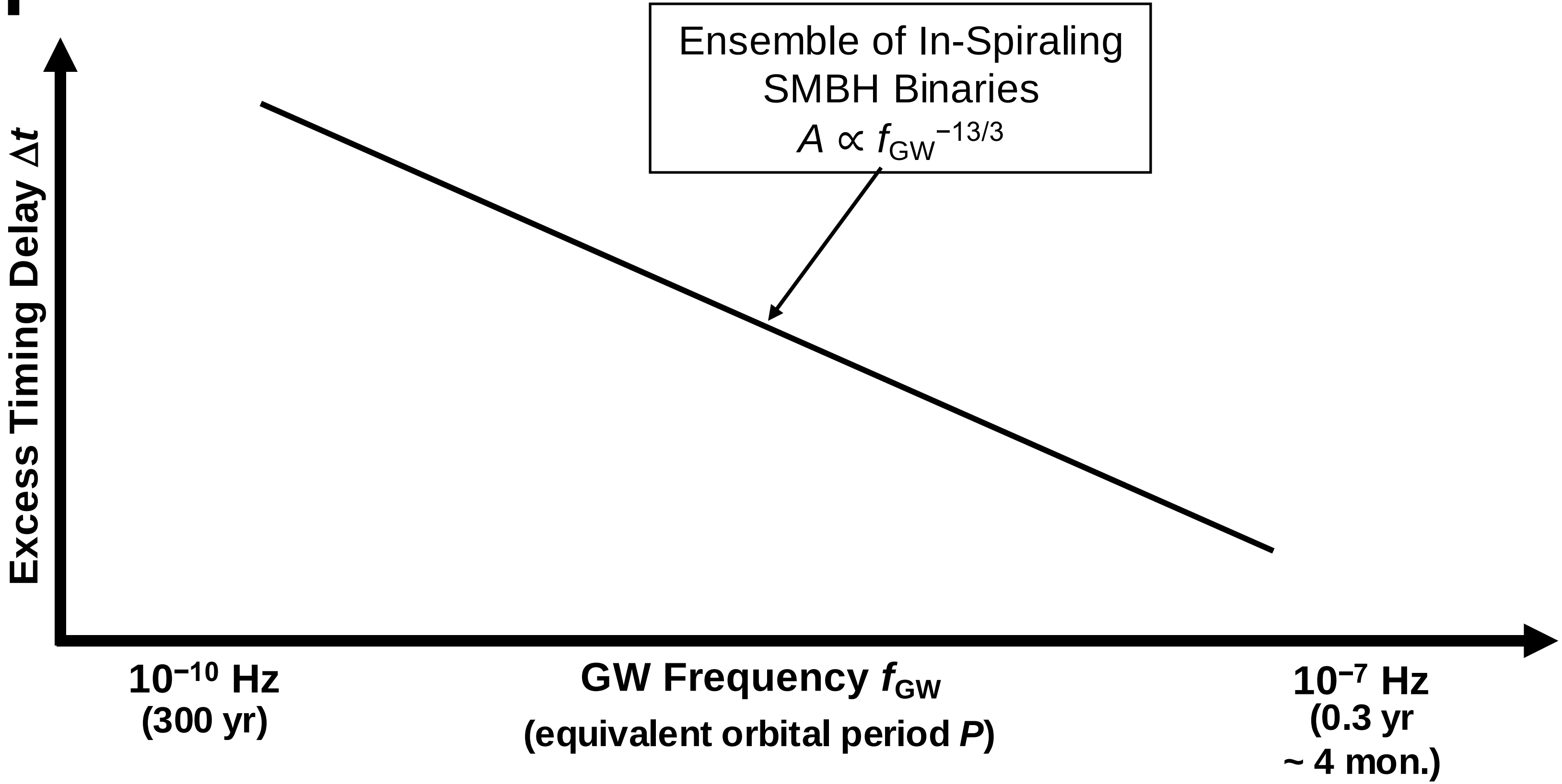


Posterior from Data

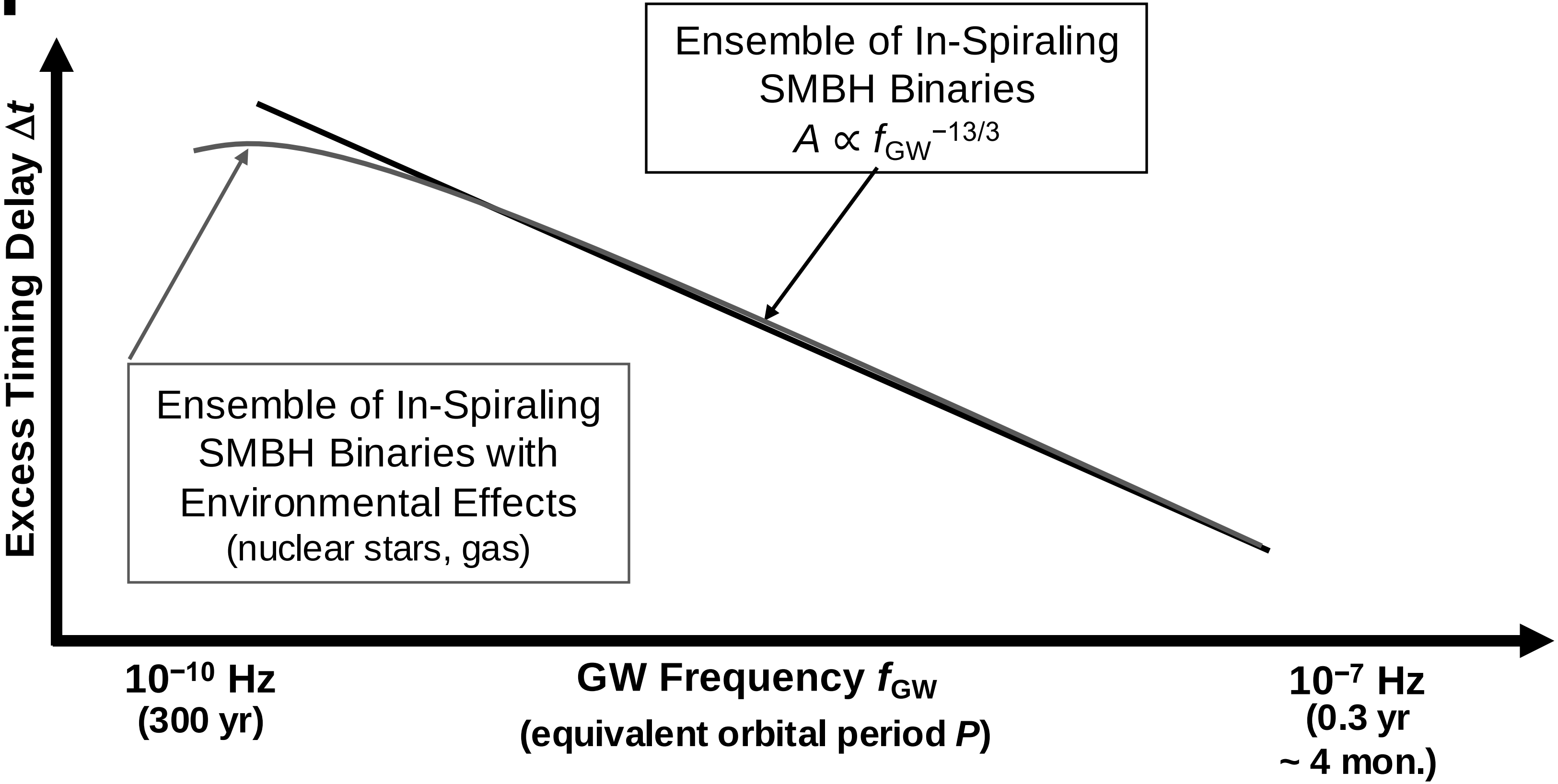
Prediction: In-Spiraling SMBH Binaries
$\gamma = 13/3$

NANOGrav Collaboration: Agazie et al.

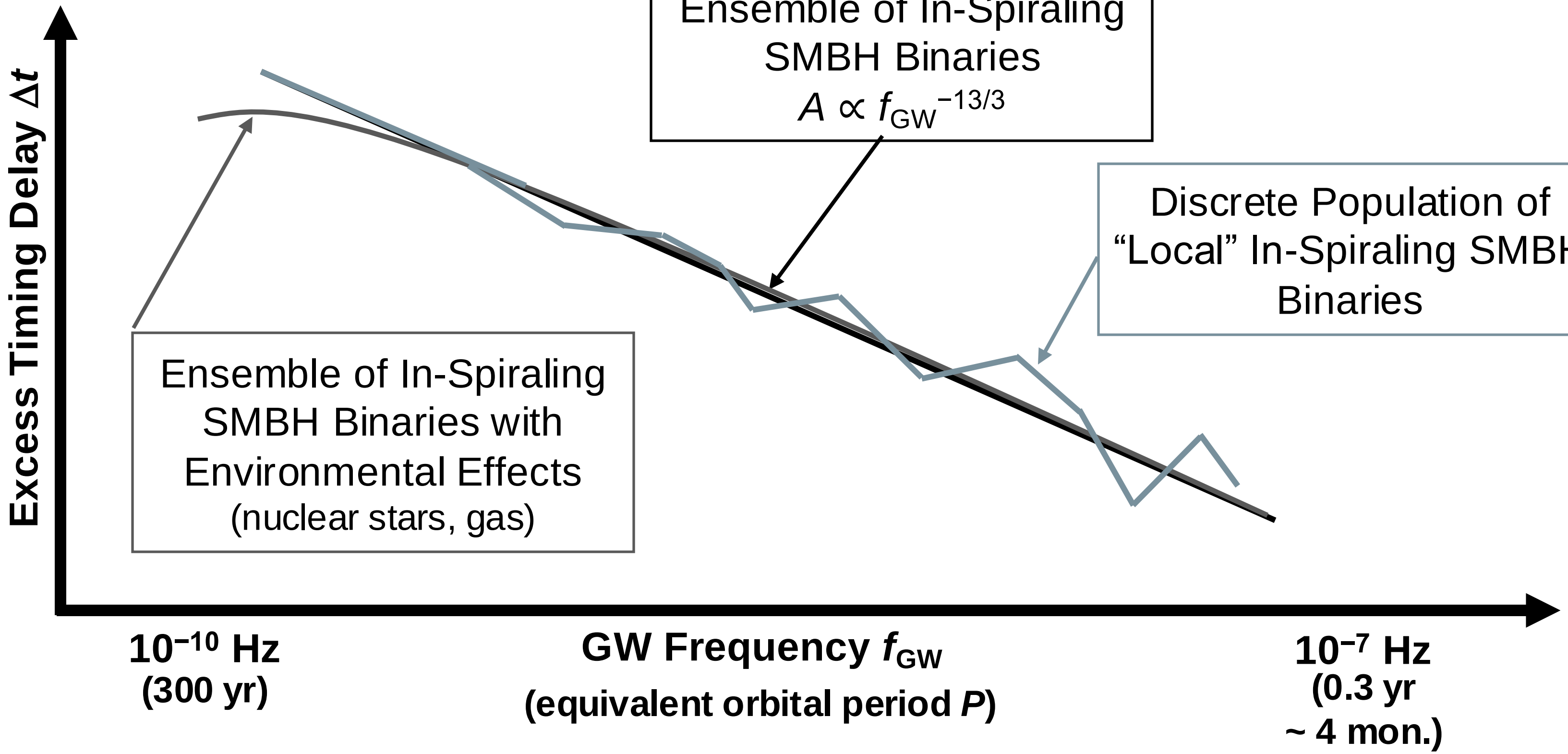
Gravitational Wave Background Spectrum



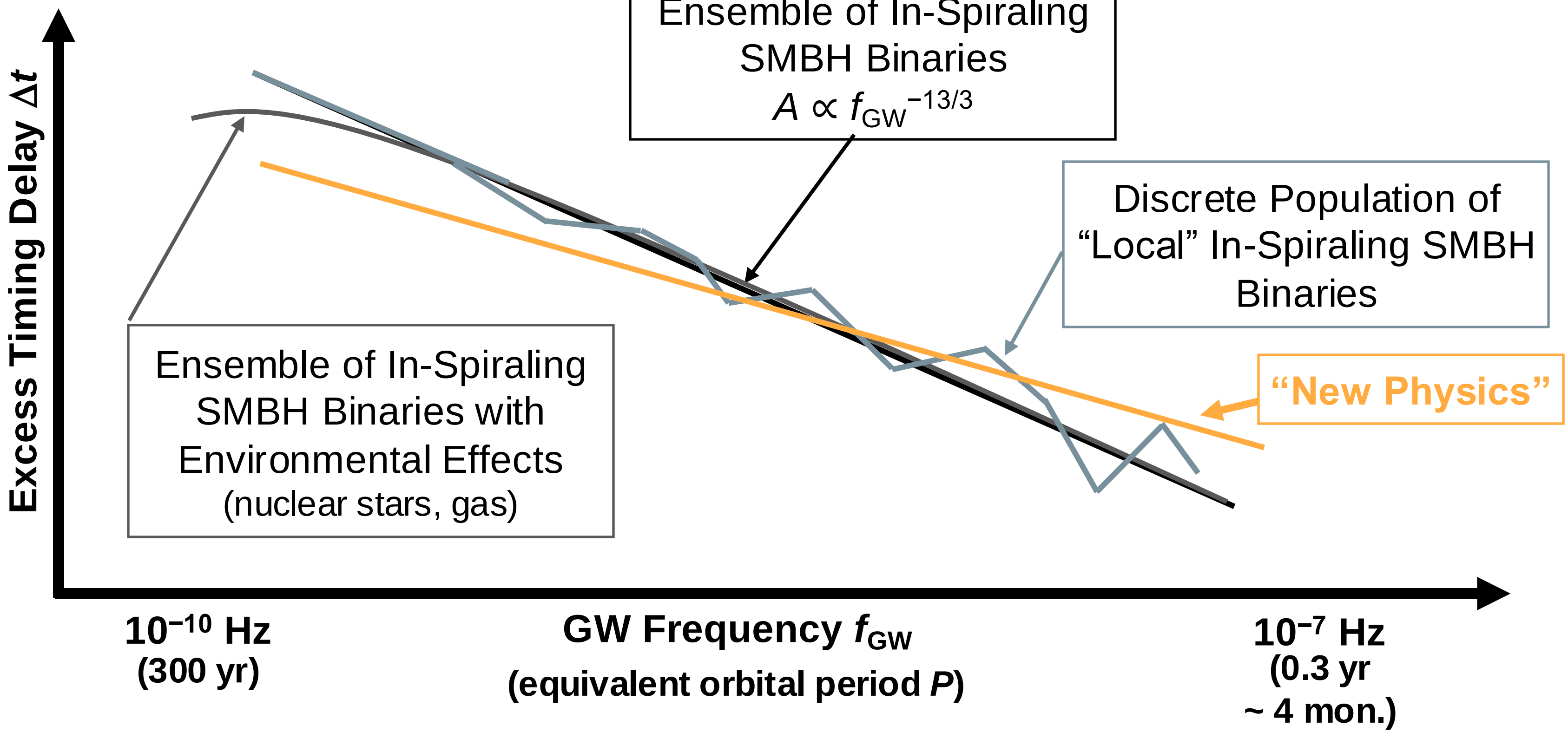
Gravitational Wave Background Spectrum



Gravitational Wave Background Spectrum



Gravitational Wave Background Spectrum



Looking Toward the Future

What produces nanohertz GW stochastic background?

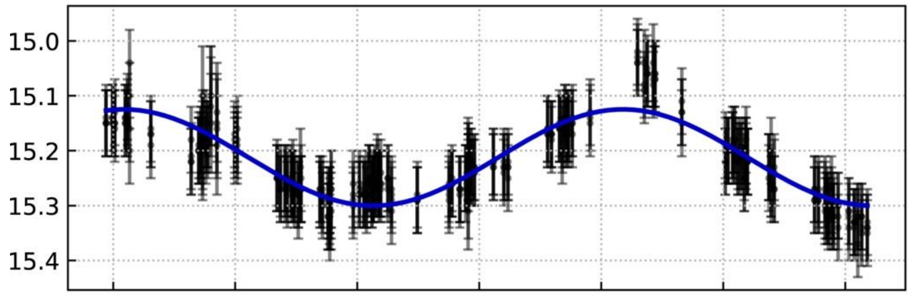
- **In-spiraling SMBH binaries?**

  With environmental effects? Local "granularity"?

- **"New Physics"?**

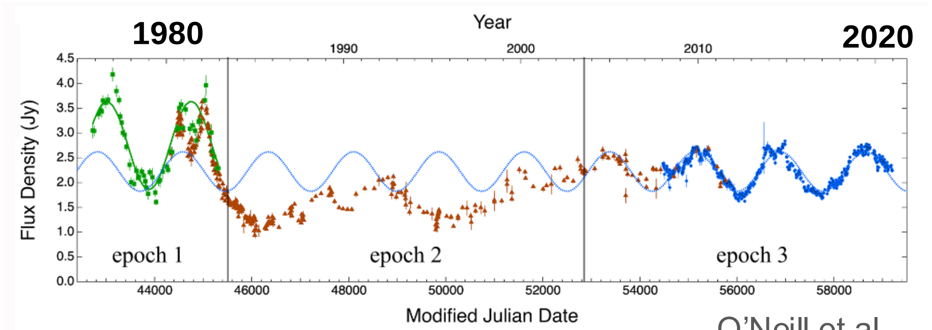
  Physics beyond the Standard Model, effects in early Universe, …

Candidate SMBH Binaries



2005.356 **Epoch** **2013.570**

Xin et al.



O’Neill et al.

Targeted Gravitational Wave Search

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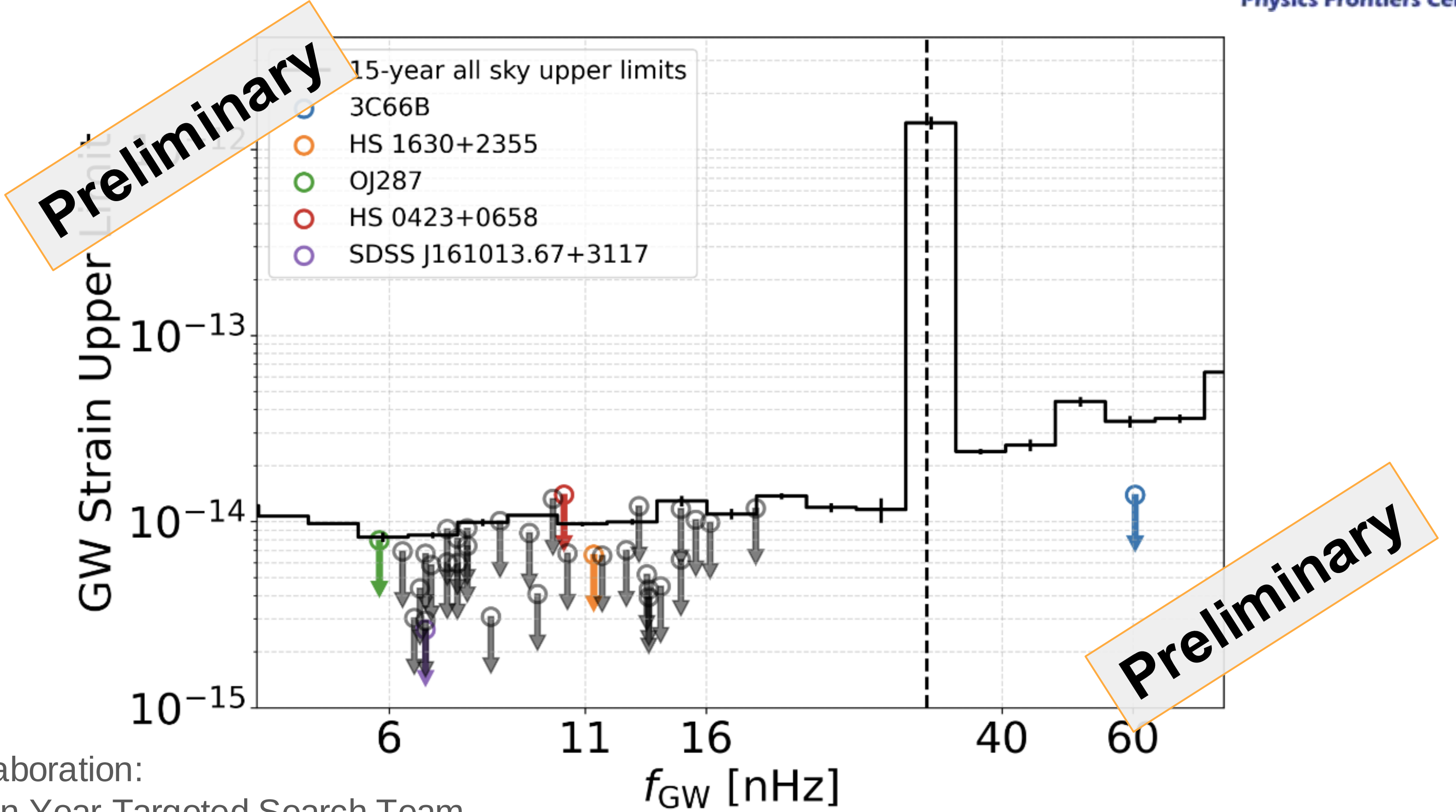
Candidate	$\log_{10}$(Mass) [10^9 $M_\odot$]	Orbital Period (yr)	Redshift	Candidate	$\log_{10}$(Mass) [10^9 $M_\odot$]	Orbital Period (yr)	Redshift
SDSS J092911.35+203708.5	9.92	4.9	1.845	SDSS J160730.33+144904.3	9.82	4.7	1.8
HS 0926+3608	9.95	4.3	2.15	HS 1630+2355	9.86	5.6	0.821
SDSS J114857.33+160023.1	9.9	5.1	1.224	SDSS J164452.71+430752.2	10.15	5.5	1.715
SDSS J131706.19+271416.7	9.92	4.6	2.672	SNU J13120+0641	9.14	4.1	0.242
SDSS J133516.17+183341.4	9.76	4.7	1.192	PKS 2131−021	9.69	2.1	1.285
SDSS J134855.27−032141.4	9.89	3.9	2.099	OJ 287	10.26	10.9	0.306
SDSS J140704.43+273556.6	9.94	4.3	2.222	3C 66B	9.08	~1	0.021

Targeted Gravitational Wave Search



NANOGrav Collaboration:
B. Larson, Fifteen-Year Targeted Search Team

Looking Toward the Future

What produces nanohertz GW stochastic background?

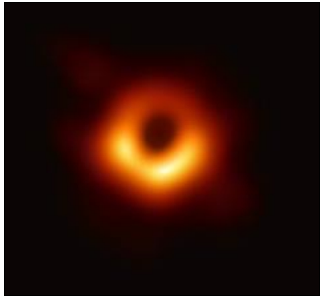
- In-spiraling SMBH binaries?
  - With environmental effects?
  - Local "granularity"?
- "New Physics"?
  - Physics beyond the Standard Model, effects in early Universe, …

Role of the ngVLA

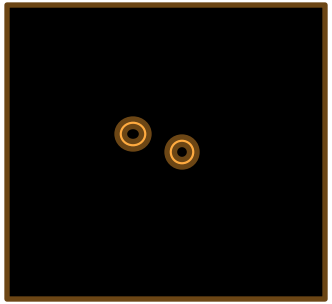
- Conduct precise timing observations of millisecond pulsars
  - Improve estimate of spectral index
- Resolve progenitors of GW-emitting SMBH binaries
- Resolve GW-emitting SMBH binaries!(?)

Angular Resolution!

Is it possible to discriminate between these two possibilities?



?



Credit: EHT Collaboration

Angular Resolution of ngVLA

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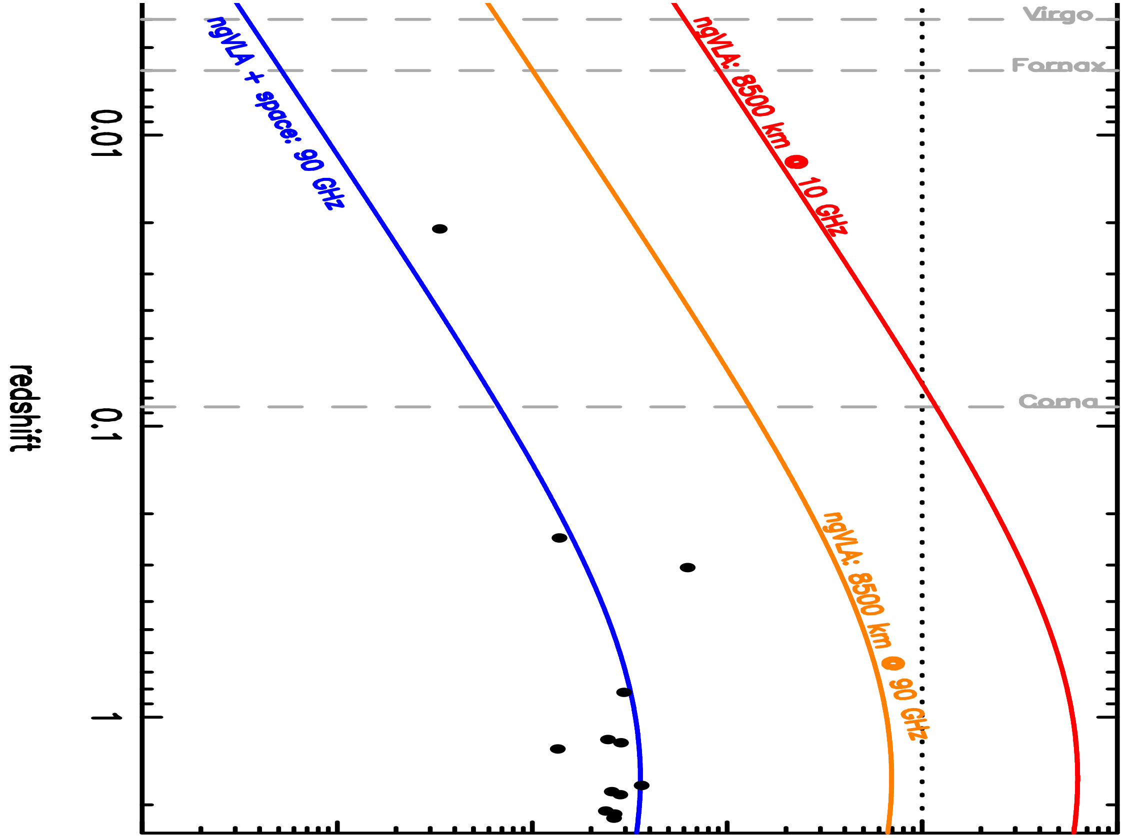


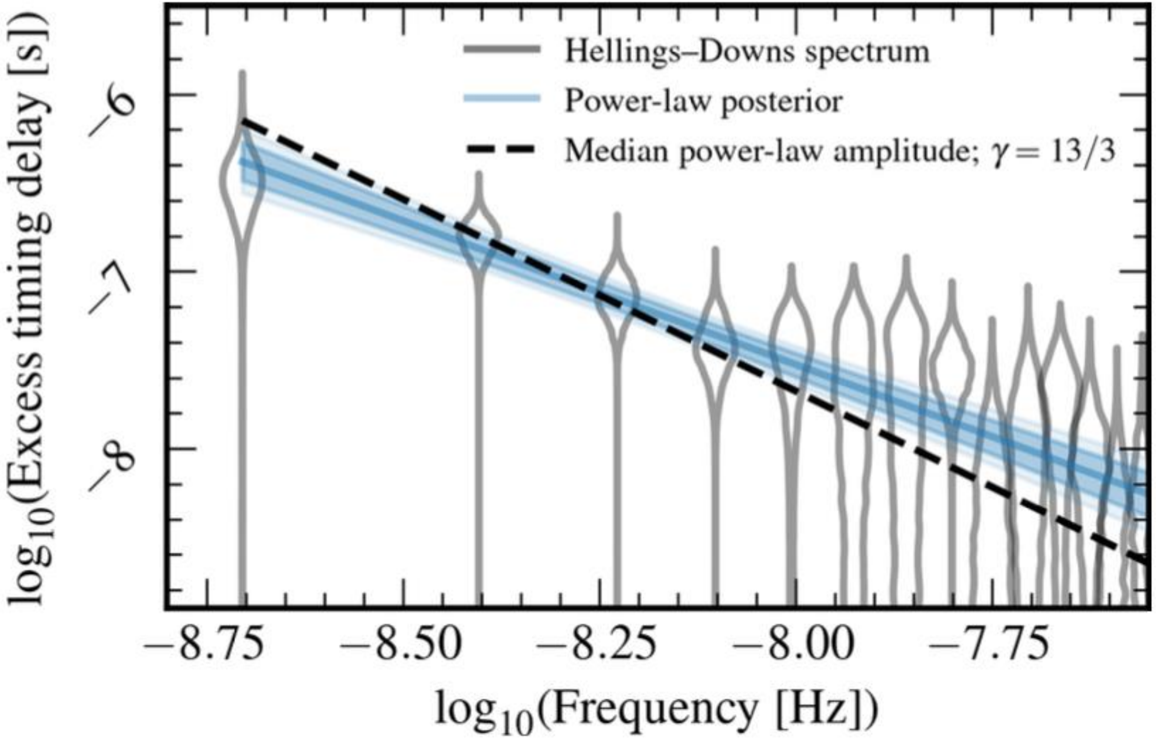
GW emission drives in-spiral

- Candidate SMBH binaries

— Nearby clusters of galaxies (e.g., Wrobel & Lazio)

based on Burke-Spolaor et al.

ngVLA+Space: Illustrative Use Case

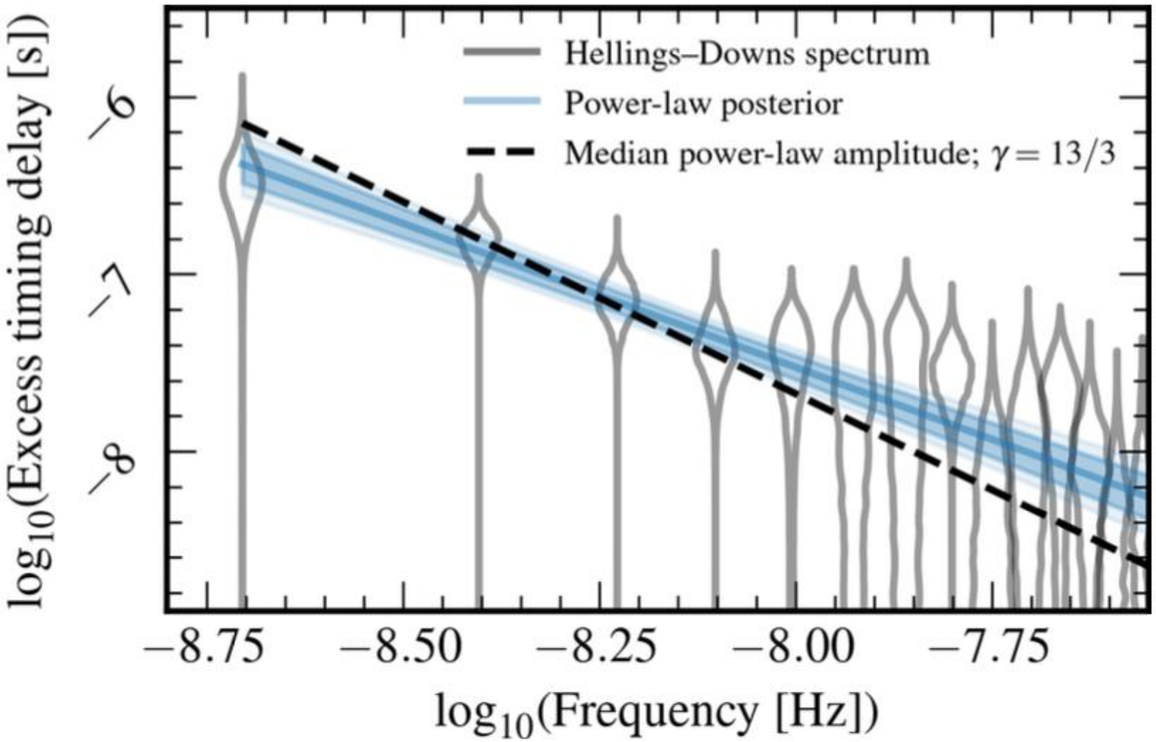


$f_{GW} \approx$ 10 nHz $\approx 10^{-8}$ Hz

About, but slightly higher than most sensitive NANOGrav frequency

NANOGrav Collaboration: Agazie et al.

ngVLA+Space: Illustrative Use Case



$f_{GW} \approx 10$ nHz $\approx 10^{-8}$ Hz

➢ $P \approx 6$ yr

Gravitational wave frequency and orbital period

$f_{GW} = f_{GW\oplus}(1 + z)$

$f_{GW} = 2/P$

NANOGrav Collaboration: Agazie et al.

ngVLA+Space: Illustrative Use Case

Suppose such a GW-emitting system existed, could it be resolved?

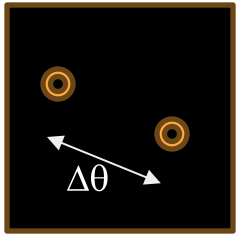
$f_{GW} \approx 10$ nHz $\approx 10^{-8}$ Hz

$P \approx 6$ yr

Semi-major axis $a \sim 3000$ au

Assumed mass $M \sim 5 \times 10^9\ M_\odot$

- Distance $D \sim 100$ Mpc
- Angular separation $\Delta\theta \sim 30\ \mu$as



ngVLA+Space: Illustrative Use Case

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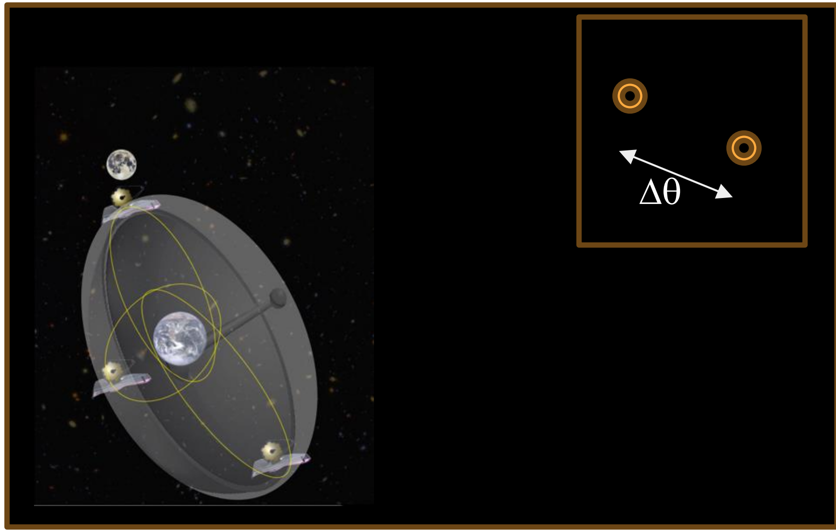

$f_{\mathrm{GW}} \approx$ 10 nHz $\approx 10^{-8}$ Hz

$P \approx$ 6 yr

Semi-major axis a ~ 3000 au

Assumed mass $M \sim 5 \times 10^9\ M_\odot$

Distance D ~ 100 Mpc

- **Angular separation $\Delta\theta$ ~ 30 μas**
- **Angular resolution requirement θ_{beam} = 10 μas**

➢ **Interferometric baseline ~ 70,000 km @ 3 mm (90 GHz)**

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ngVLA Angular Resolution Requirements

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Illustrative Use Case