

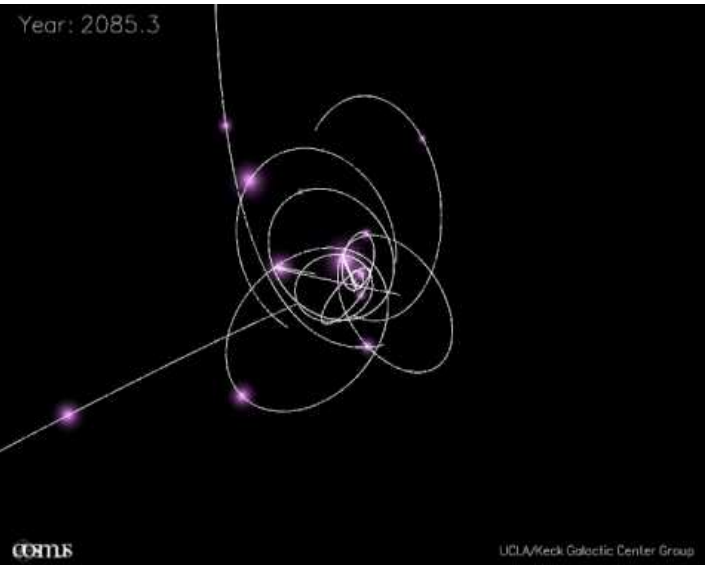
**On the Imaging
of
Supermassive
Black Hole
Binaries**

Ad ASTRA Community
Workshop

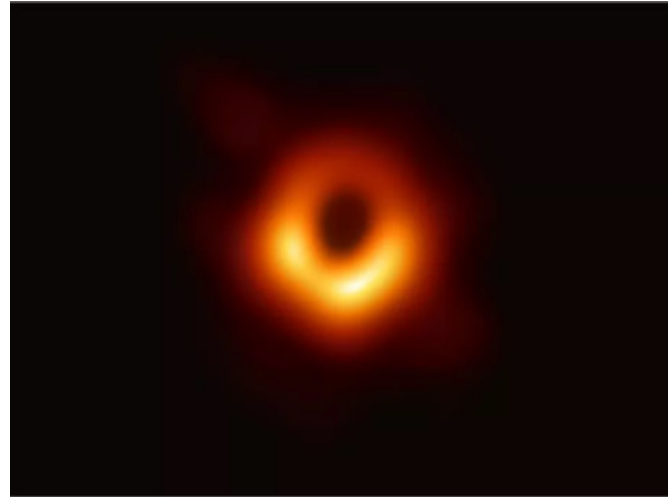
T. Joseph W. Lazio
Cayenne Matt
on behalf of
NANOGrav Astrophysics Working
Group

Galaxies Host Supermassive Black Holes

Background/Motivation and Science Investigation



Sgr A* - Milky Way black hole



Event Horizon Telescope

Active Galactic Nuclei



Galaxies Merge

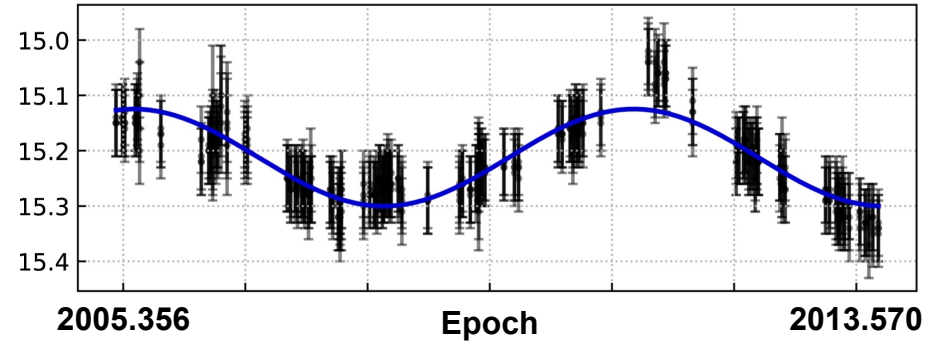
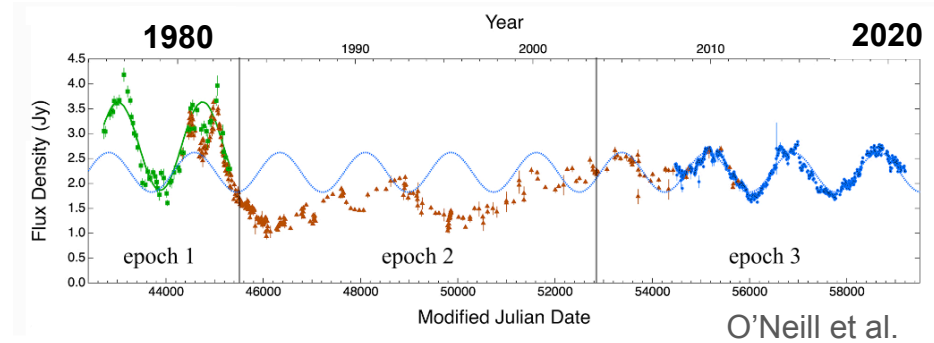
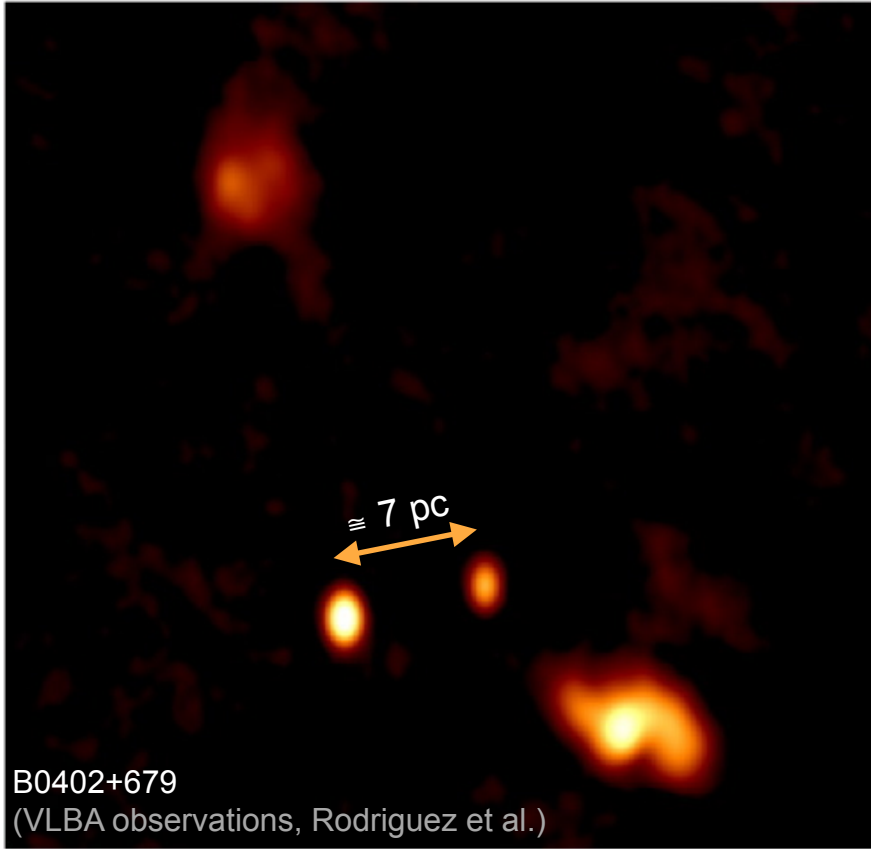
Background/Motivation and Science Investigation



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

Candidate SMBH Binaries

Background/Motivation and Science Investigation



Merging Galaxies and Supermassive Black Holes

Background/Motivation and Science Investigation



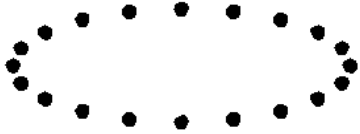
Projections that merging supermassive black holes lead to gravitational wave background date at least to Rajagopal & Romani (1995)



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

Gravitational Wave Telescope

Background/Motivation and Science Investigation



Gravitational waves
perturb spacetime.

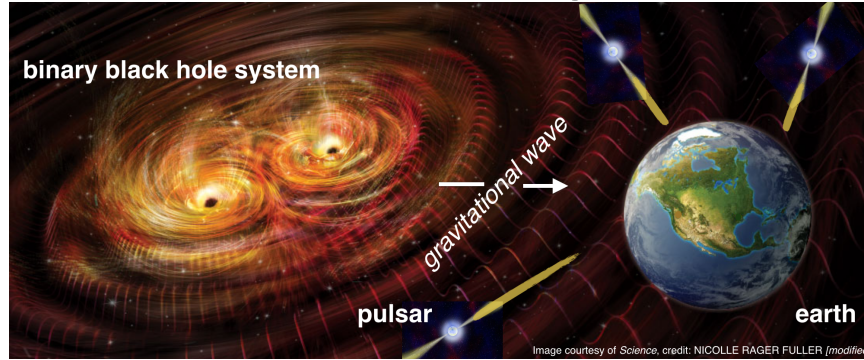
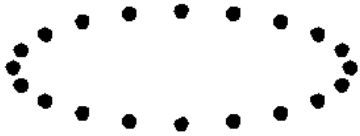
Sidebar/Reminder



Gravitational Wave Telescope

Sidebar/Reminder

Background/Motivation and Science Investigation



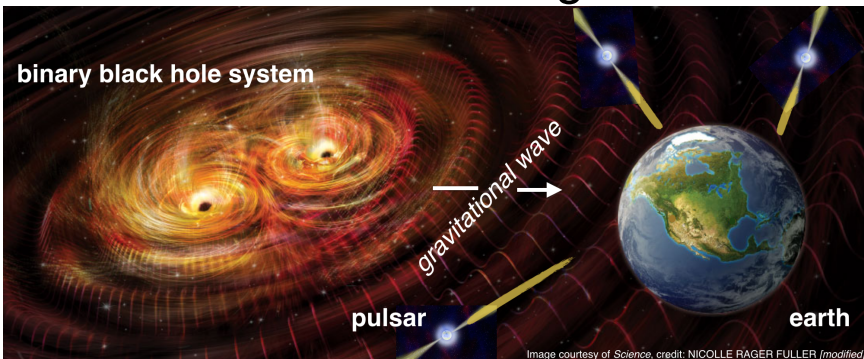
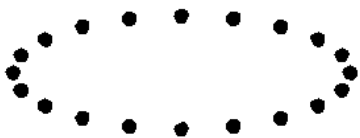
Arrival times of radio pulses
crossing perturbed spacetime
are advanced or delayed.

Gravitational waves
perturb spacetime.

Gravitational Wave Telescope

Sidebar/Reminder

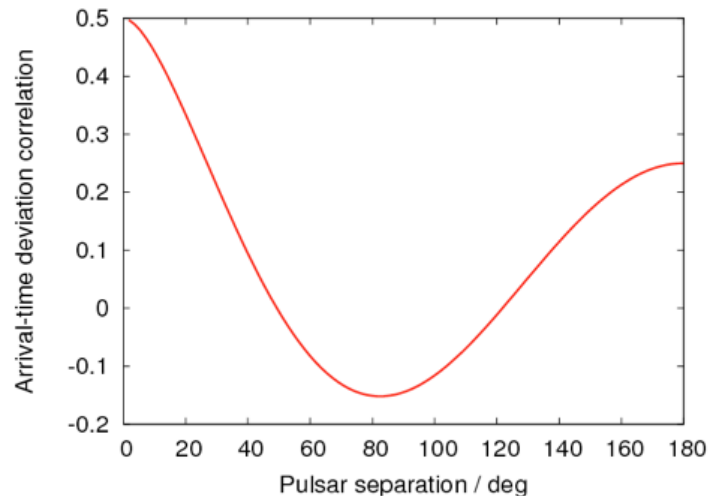
Background/Motivation and Science Investigation



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

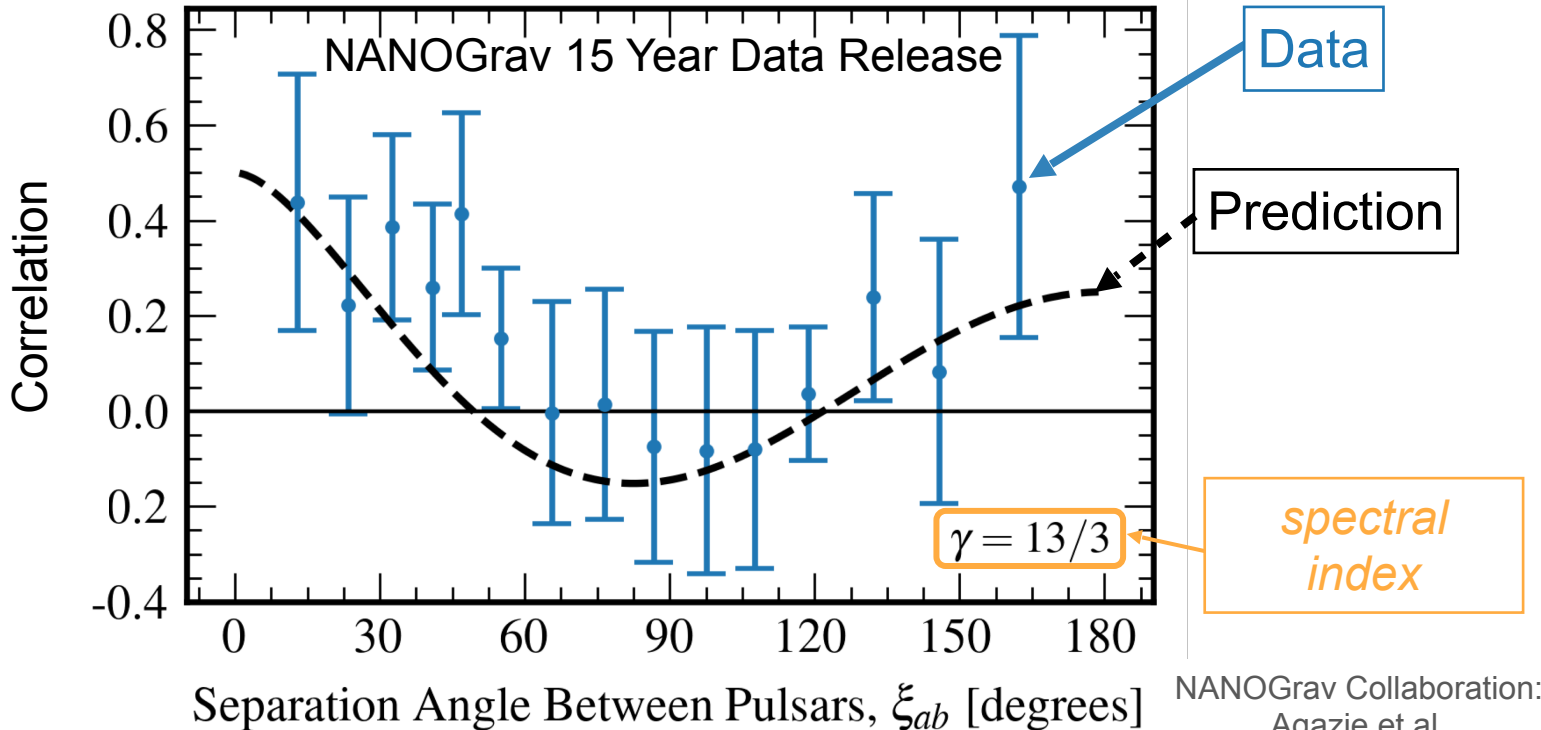
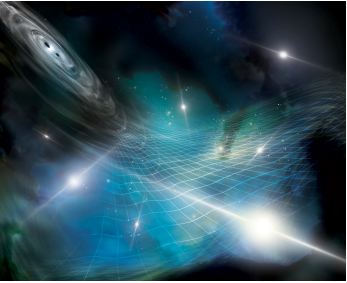
Gravitational waves
perturb spacetime.

General Relativity predicts
spatial correlation of pulse
arrival time changes as
function of angle between
pulsar lines of sight



Evidence for Gravitational Wave Background

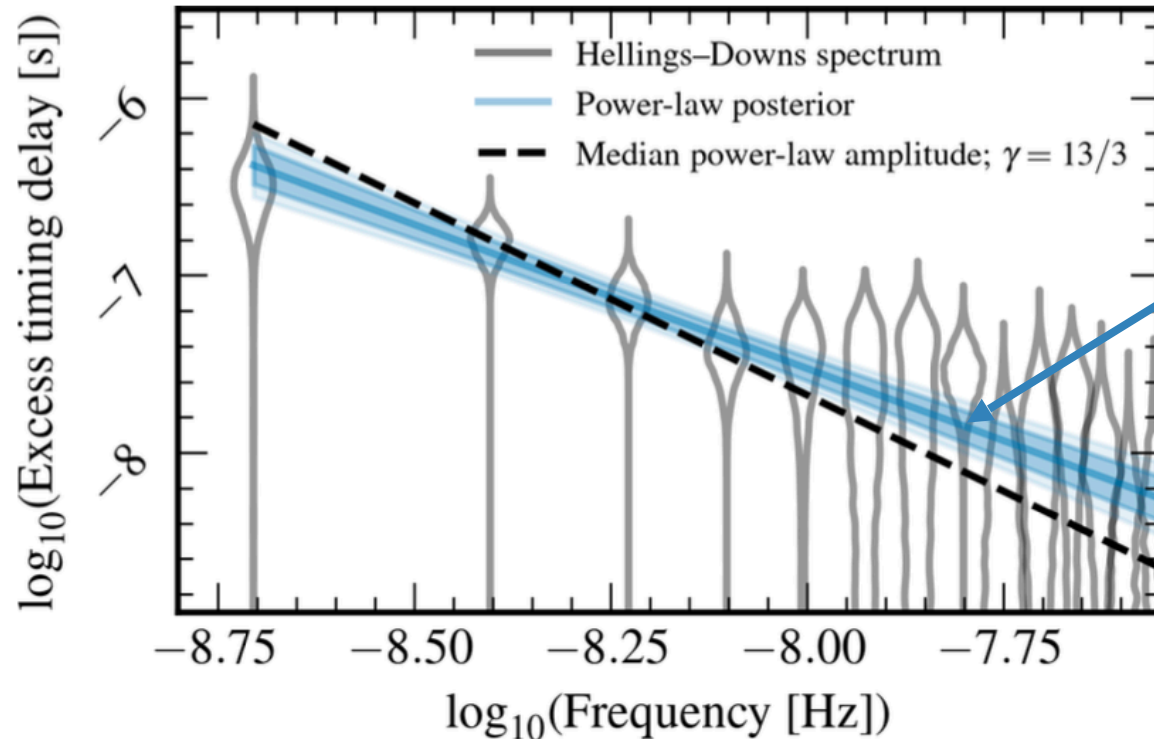
Background/Motivation and Science Investigation



NANOGrav Collaboration:
Agazie et al.

Gravitational Wave Background Spectrum

Background/Motivation and Science Investigation

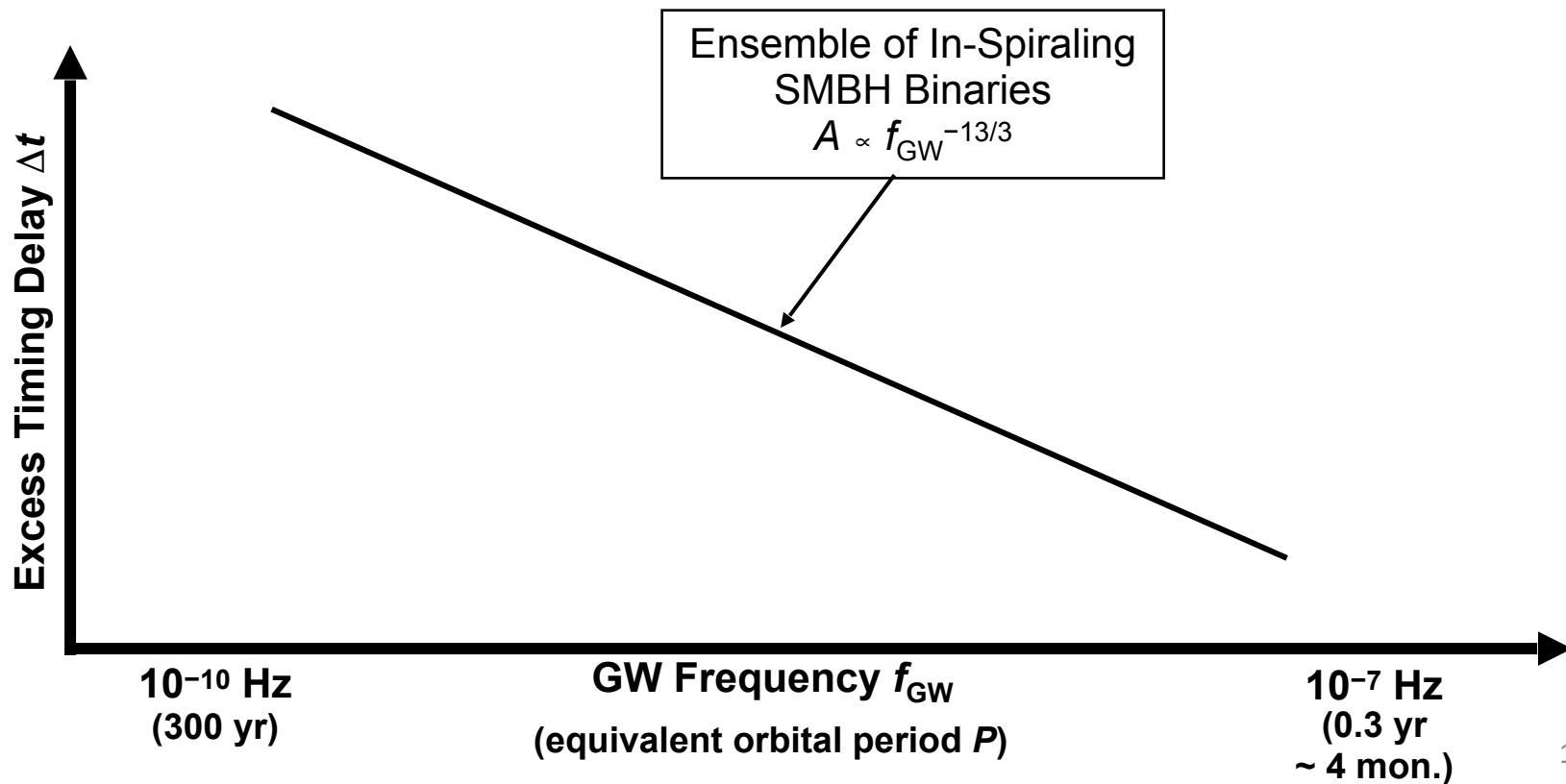


Posterior from Data

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

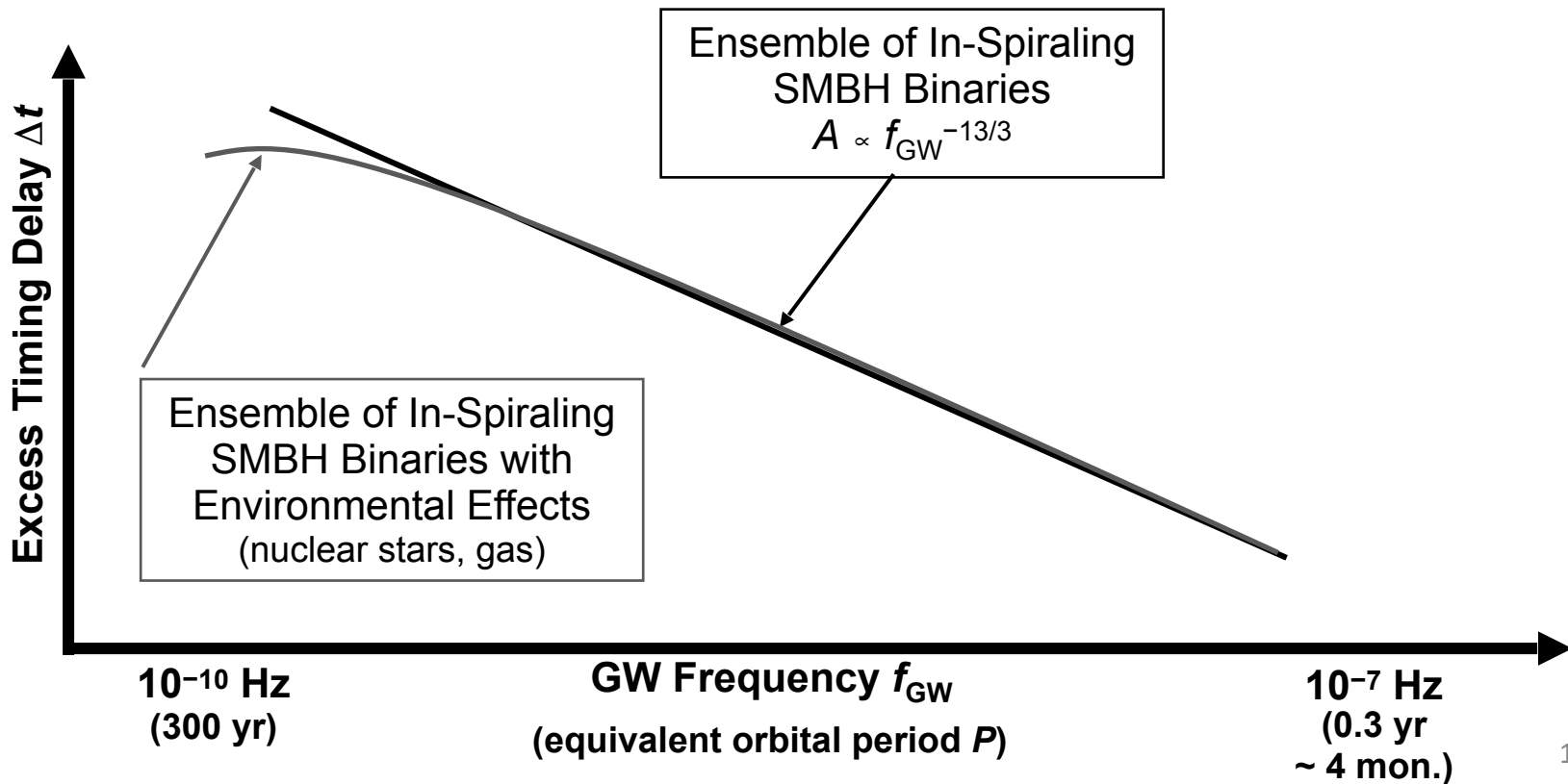
Gravitational Wave Background Spectrum

Background/Motivation and Science Investigation



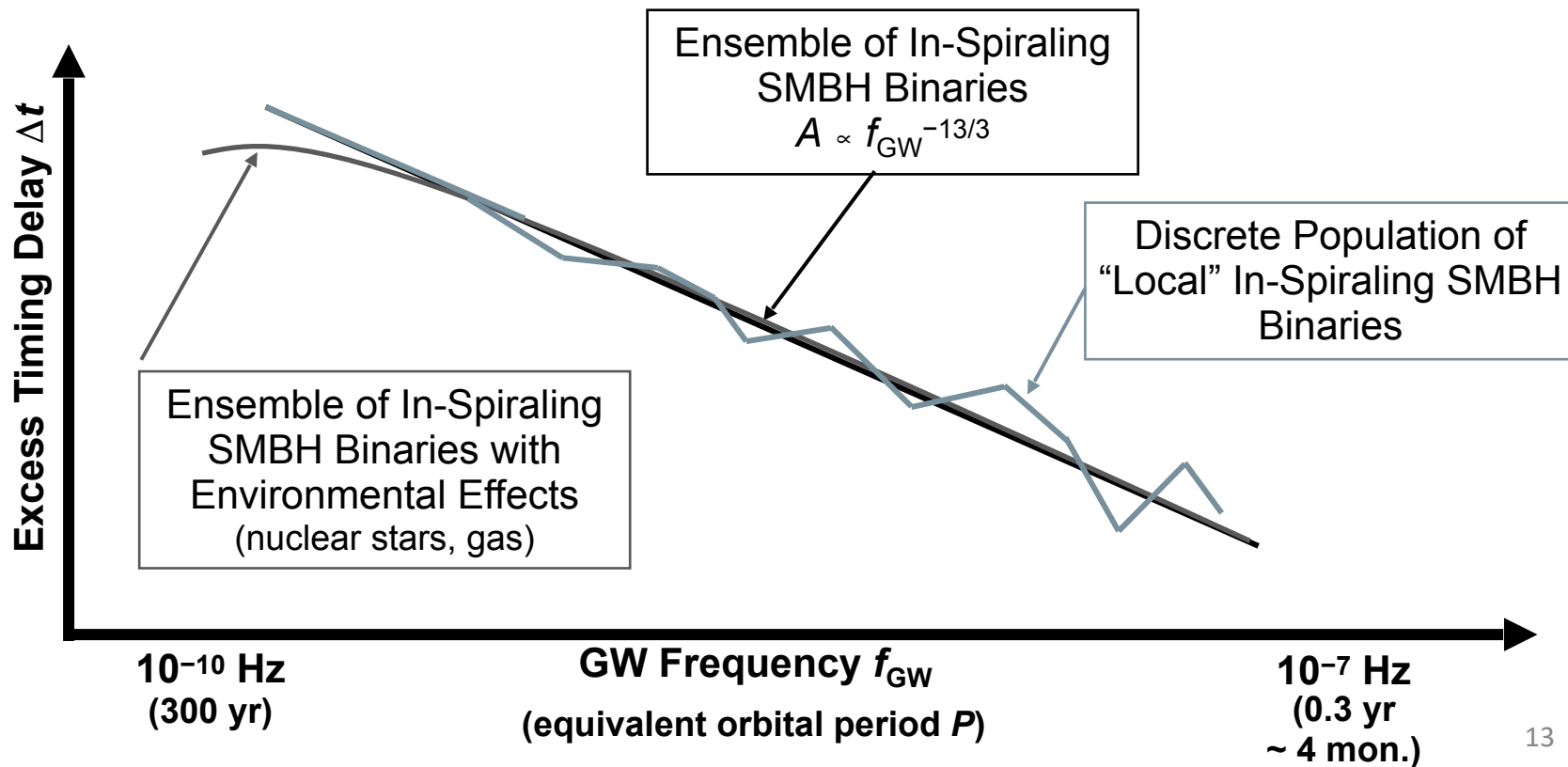
Gravitational Wave Background Spectrum

Background/Motivation and Science Investigation



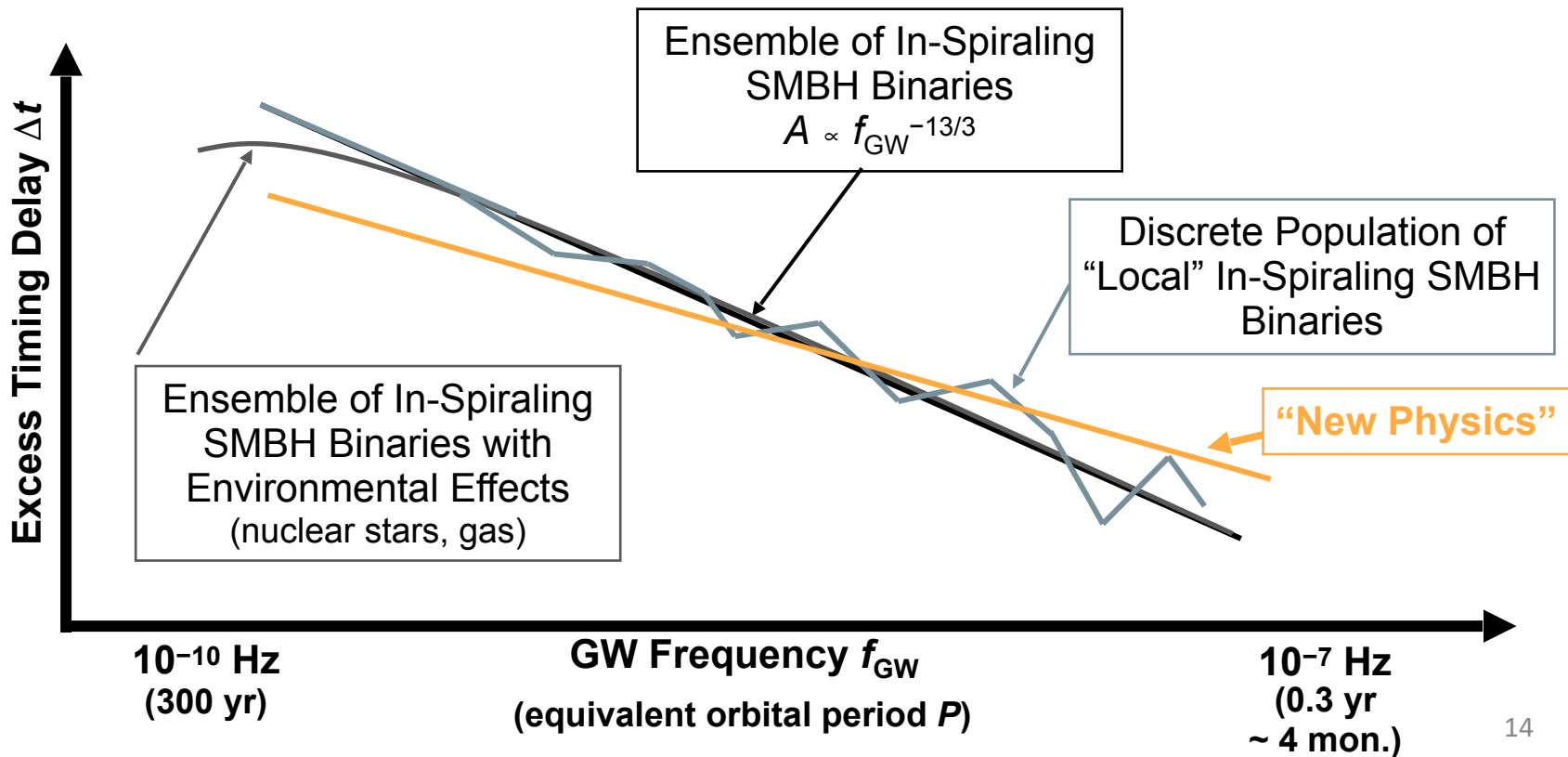
Gravitational Wave Background Spectrum

Background/Motivation and Science Investigation



Gravitational Wave Background Spectrum

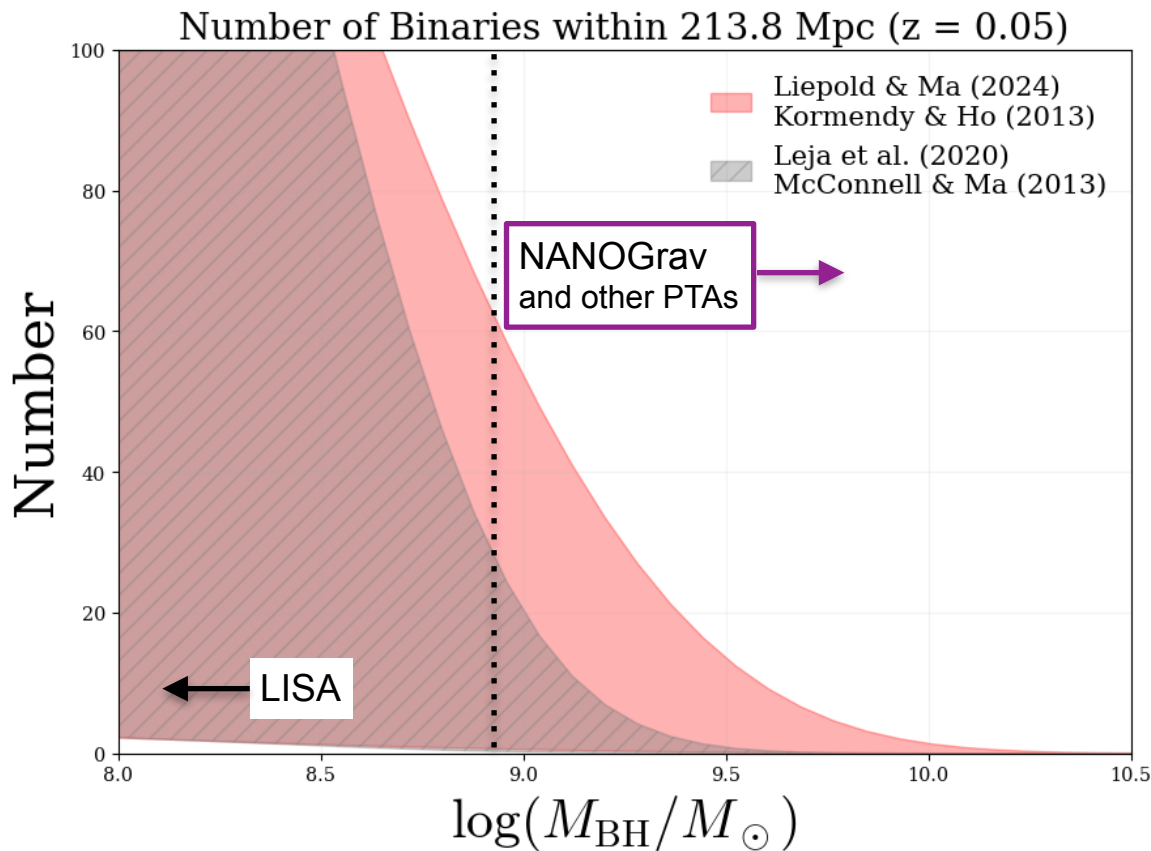
Background/Motivation and Science Investigation



SMBH Binary Population Projections

Background/Motivation and Science Investigation

- **SMBH binaries with $M \gtrsim 10^9 M_\odot$**
- **$D \lesssim 200$ Mpc**
- **Projected number $N \sim 15\text{--}40$**
 - $N \sim 100$ (optimistic)
 - $N \sim 1$ (pessimistic)
- **Highly model-dependent, *and* assumes SMBH binaries are sole contributor to stochastic GW background**



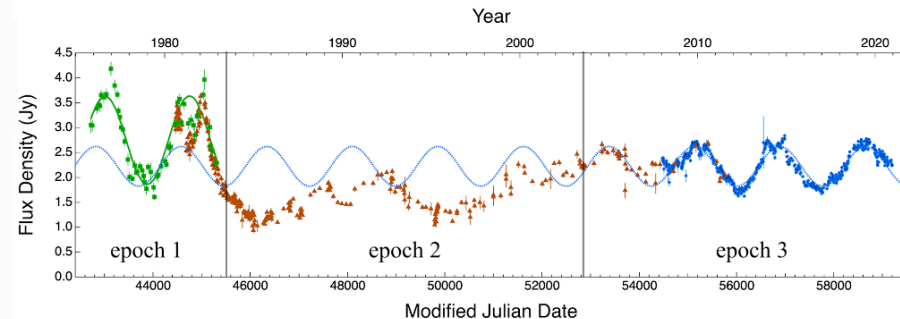
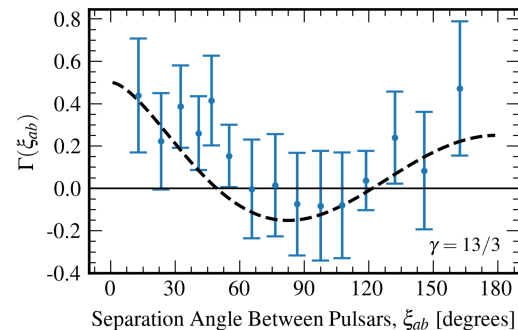
Science Traceability

Scientific Objectives

To determine if number density of SMBH binaries is consistent between/across EM and nanohertz GW datasets

To determine the validity of EM-identified SMBH binary candidates

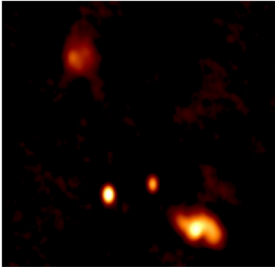
To determine the validity of GW-identified SMBH binary candidates



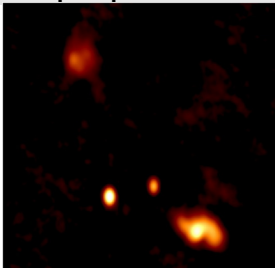
Science Traceability

Scientific Objectives	Physical Parameters
To determine if number density of SMBH binaries is consistent between/across EM and nanohertz GW datasets	masses and mass ratio $M_1, M_2, q = M_2/M_1$ total mass = $M_1 + M_2$ chirp mass = $[M_1^{(3/5)} M_2^{(3/5)} / (M_1 + M_2)^{(1/5)}]$
	semi-major axis a
To determine the validity of EM-identified SMBH binary candidates	eccentricity e
	inclination i
To determine the validity of GW-identified SMBH binary candidates	longitude of the ascending node Ω
	argument of periapsis ω
	orbital period P

Science Traceability

Scientific Objectives	Physical Parameters	Electromagnetic Observables
To determine if number density of SMBH binaries is consistent between/ across EM and nanohertz GW datasets	masses and mass ratio $M_1, M_2, q = M_2/M_1$ total mass = $M_1 + M_2$ chirp mass = $[M_1^{(3/5)} M_2^{(3/5)} / (M_1 + M_2)^{(1/5)}]$ semi-major axis a	angular positions/ separation spectra
To determine the validity of EM-identified SMBH binary candidates	eccentricity e inclination i	orbital proper motion
To determine the validity of GW-identified SMBH binary candidates	longitude of the ascending node Ω argument of periapsis ω orbital period P	

Science Traceability

Scientific Objectives	Physical Parameters	Electromagnetic Observables	Instrumental/Telescope Requirements
To determine if number density of SMBH binaries is consistent between/across EM and nanohertz GW datasets	masses and mass ratio M_1, M_2, q total mass chirp mass	angular positions/ separation	angular resolution
	semi-major axis a	spectra	frequency range
To determine the validity of EM-identified SMBH binary candidates	eccentricity e	orbital proper motion	sensitivity
	inclination i		<i>spectral resolution</i>
To determine the validity of GW-identified SMBH binary candidates	longitude of the ascending node Ω		<i>temporal resolution</i>
	argument of periapsis ω orbital period P		

Instrumental Requirements

Space VLBI Mission Design

Suppose GW-emitting system existed [nearby], could it be resolved?

$$\theta = \frac{\lambda}{D}$$

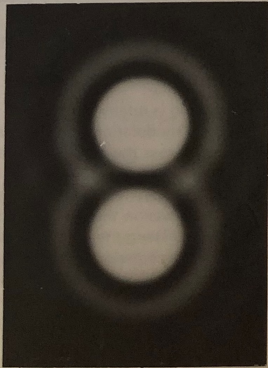


Fig. 10.32 Overlapping images.

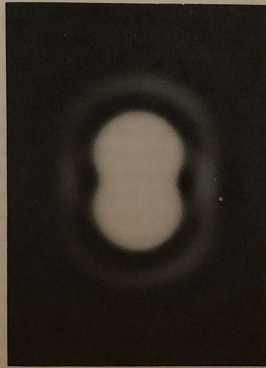
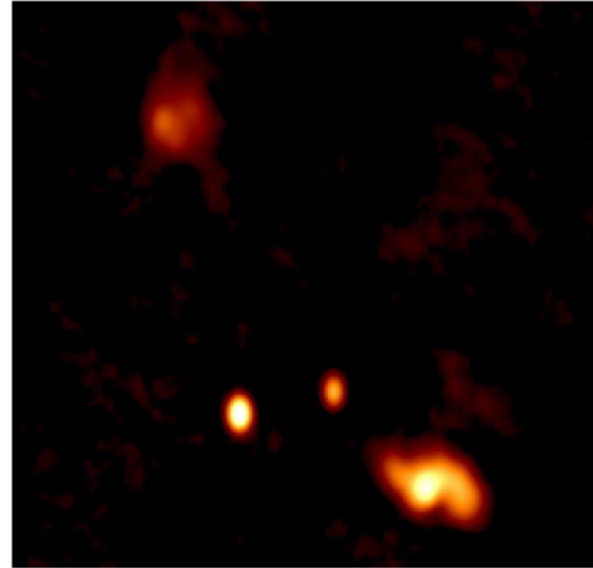


Fig. 10.33 Overlapping images.



Hecht & Zajac *Optics*;
Rodriguez et al.

Angular Resolution

Space VLBI Mission Design

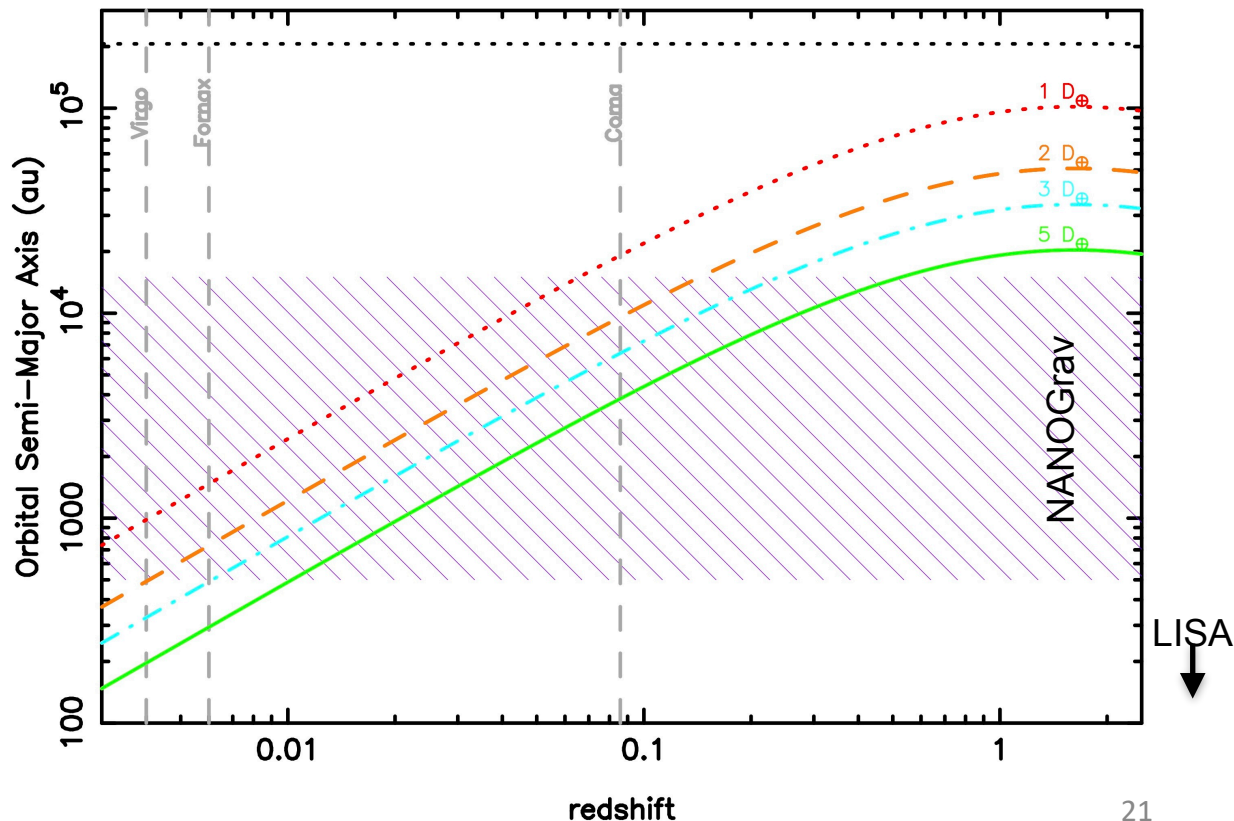
$$\theta = \frac{\lambda}{b} = \frac{c}{\nu b}$$

Assume $\lambda = 3 \text{ mm}$

($\nu = 90 \text{ GHz}$)

Optimum between
feasibility of
implementation and
angular resolution(?)

→ Then $b > 1D_{\oplus}$



Illustrative Use Case

Space VLBI Mission Design

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

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

$$P \approx 6 \text{ yr}$$

$$\text{Semi-major axis } a \sim 3000 \text{ au}$$

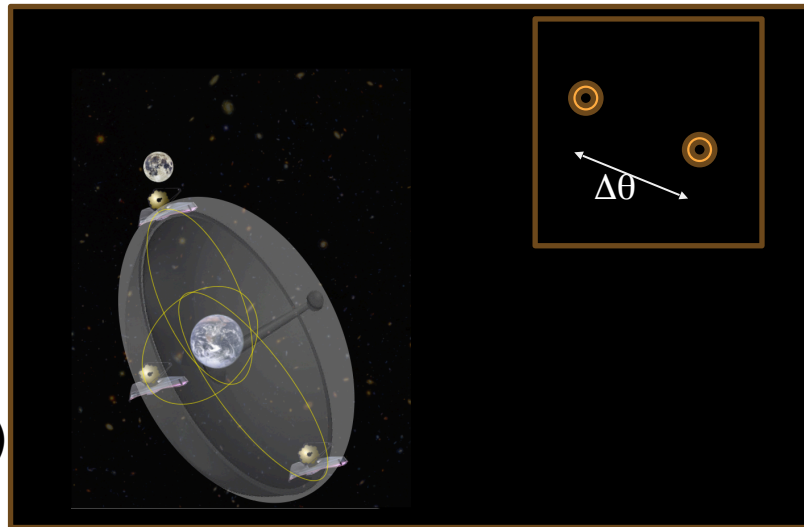
$$\text{Assumed mass } M \sim 5 \times 10^9 M_{\odot}$$

$$\text{Distance [angular] } D \sim 100 \text{ Mpc } (z \sim 0.024)$$

- Angular separation $\Delta\theta \sim 30 \mu\text{as}$

- Angular resolution requirement $\theta_{\text{beam}} = 10 \mu\text{as}$

- Interferometric baseline $\sim 70,000 \text{ km @ } 3 \text{ mm } (90 \text{ GHz})$



Summary

What produces nanohertz GW stochastic background?

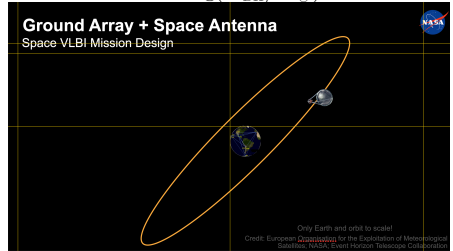
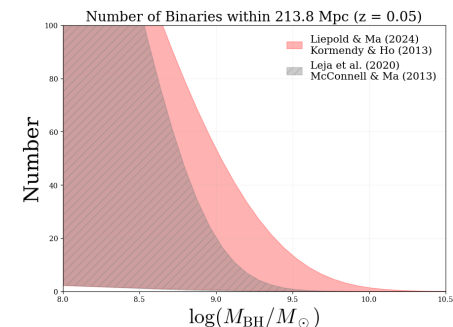
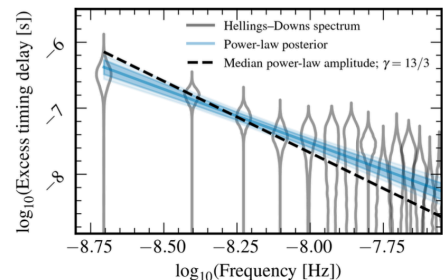
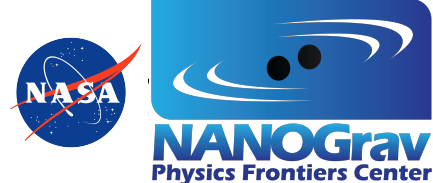
- In-spiraling SMBH binaries?
With environmental effects? Local “granularity”?
- “New Physics”?
Physics beyond the Standard Model, effects in early Universe, ...

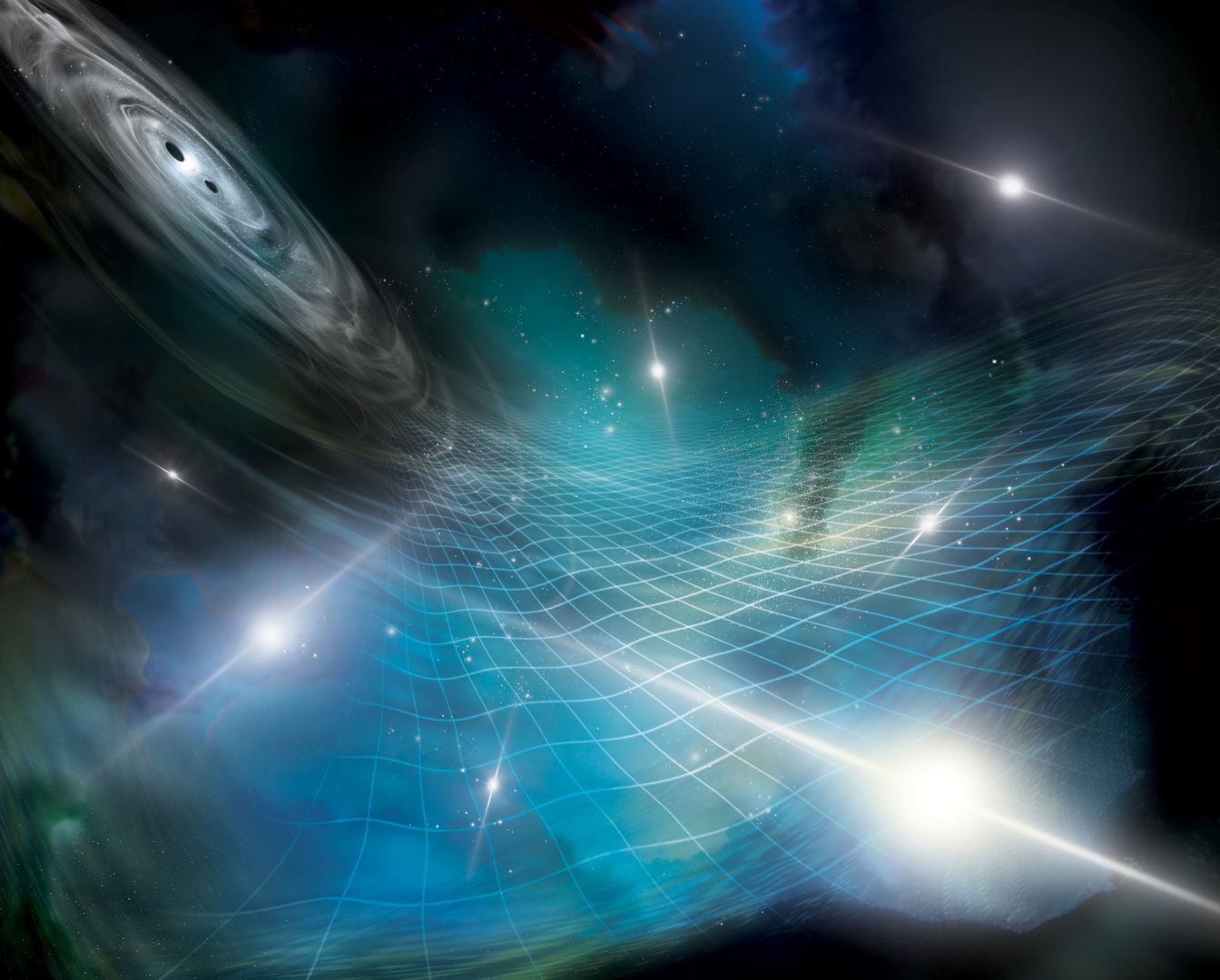
Testable Proposition: Should be SMBH binaries in nearby Universe

Angular Resolution requirement: at least one space-based antenna

Notional requirement: $b = 5 D_{\oplus}$ for $\lambda = 3$ mm

On-going APRA study for verifying angular resolution requirement for future Space VLBI mission





On the Imaging of Supermassive Black Hole Binaries

Lifecycle of Supermassive Black Hole Binaries

Background/Motivation and Science Investigation

Galaxy Merger

SMBHs sink to center via dynamical friction

Stellar Core Merger

Dynamical friction less efficient as SMBHs form binary

Binary Formation

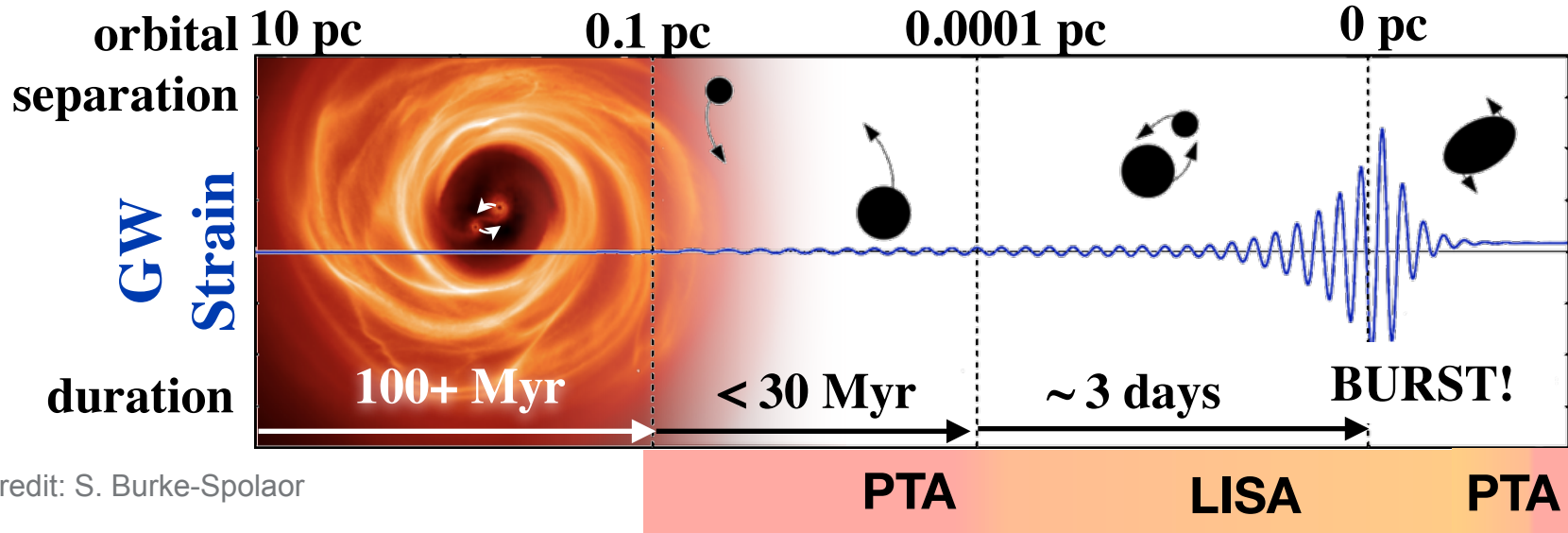
Stellar and gas interactions dominate binary inspiral?

Continuous GWs

Gravitational radiation drives efficient inspiral. Circumbinary disk tracks shrinking orbit?

Coalescence, Memory, Recoil

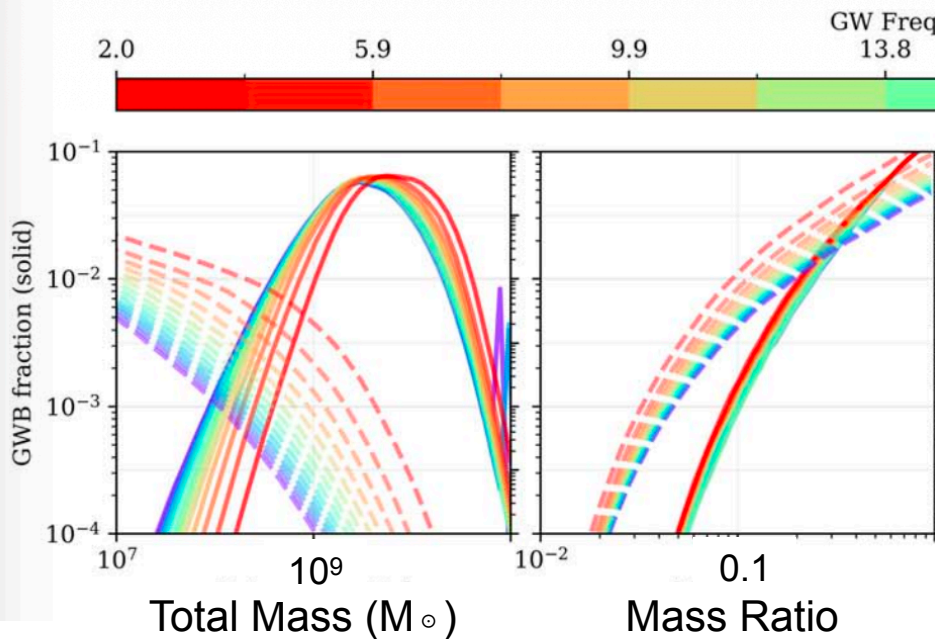
Post-coalescence SMBH may gravitationally recoil.



(Credit: S. Burke-Spolaor)

Gravitational Wave Background and Supermassive Black Hole Binaries

Background/Motivation and Science Investigation



If SMBH produce GW Background, then using models for galaxy stellar mass function, pair fraction, hardening time, find that

- **SMBH binaries with masses $M > 10^9 M_{\odot}$**
- **Nearly equal-mass components or mass ratio $q \sim 1$**

Space VLBI Simulation Process

Space VLBI Mission Design

Step 1: Optimization

- Develop “cost function” that favors large axial ratios ($\theta_y/\theta_x \sim 1$).
- Adopt ground array (EHT 2017 + 3 ngVLA stations).
- Use genetic algorithm to optimize orbit (assuming fixed semi-major axis) for target SMBH binaries at different locations on the sky (α, δ).
 - Assumed only circular orbits ($e = 0$), right ascension of the ascending node (RAAN) = 0°
 - Python Parallel Global Multiobjective Optimizer (PyGMO)

Angular Resolutions/Axial Ratio

Space VLBI Simulations

$$\theta_x = \lambda/b_x$$

$$\theta_y = \lambda/b_y$$

$$\text{Axial Ratio} = \theta_y/\theta_x$$

Axial Ratio ~ 0.9
(Probably good!)



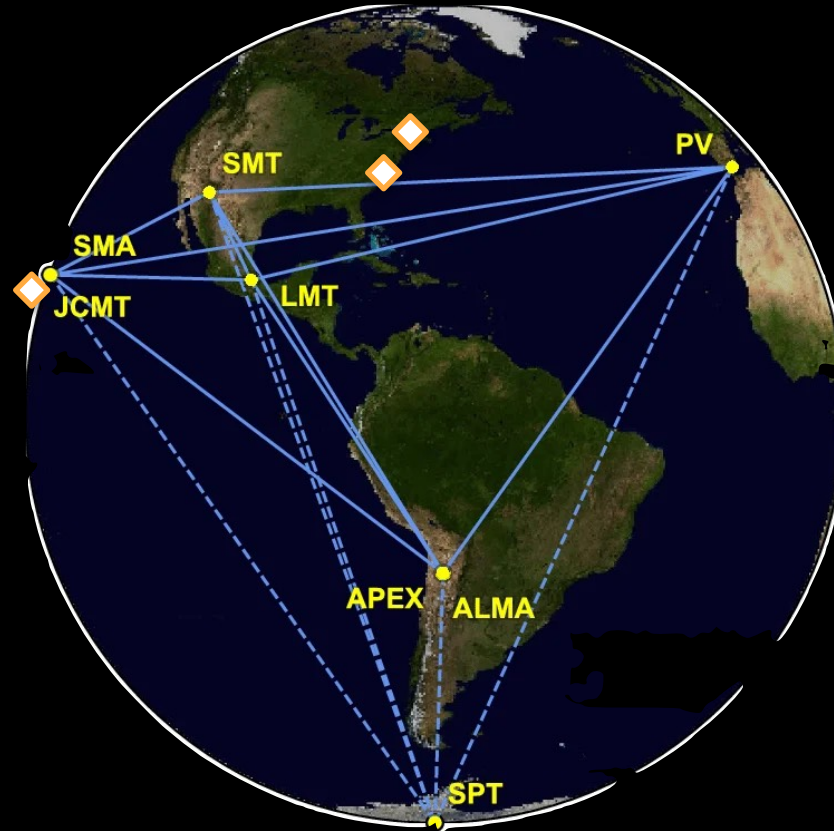
beam
(a.k.a. PSF)

Axial Ratio ~ 0.5
(Probably bad!)



Ground Array

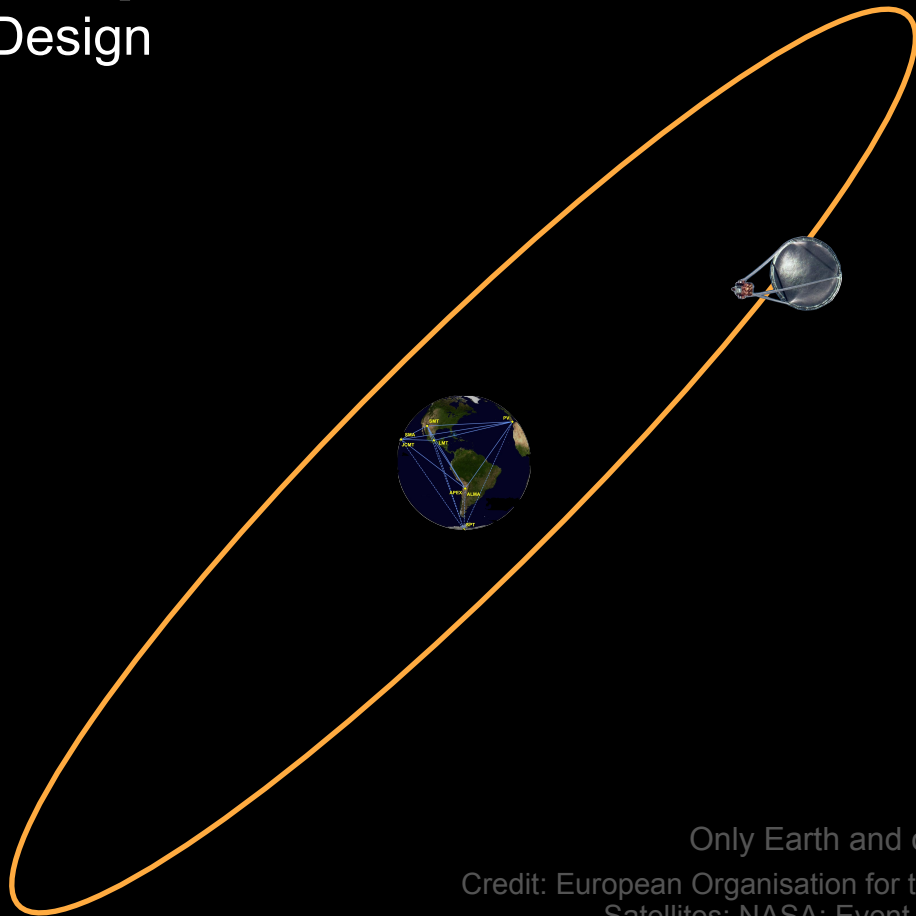
Space VLBI Mission Design



EHT 2017
+
3 ngVLA antennas

Ground Array + Space Antenna

Space VLBI Mission Design



Only Earth and orbit to scale!

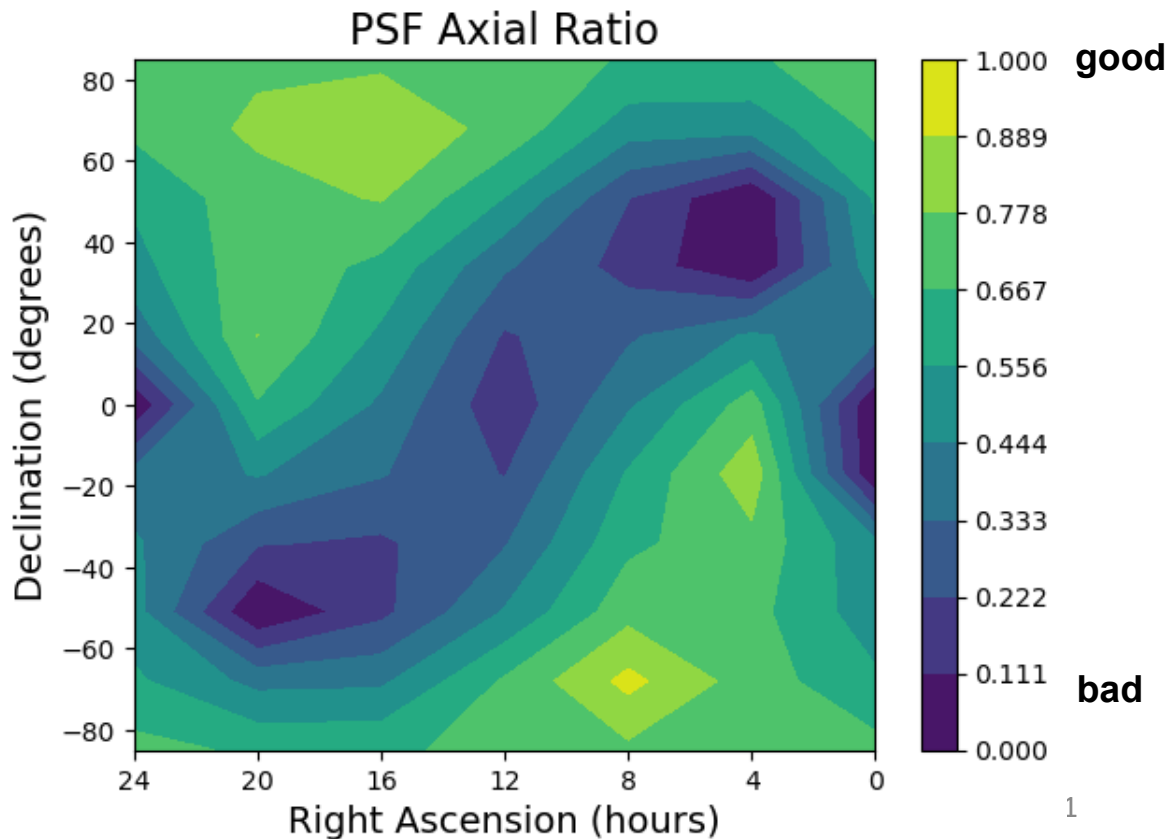
Credit: European Organisation for the Exploitation of Meteorological Satellites; NASA; Event Horizon Telescope Collaboration

Space VLBI Simulation Process

Space VLBI Mission Design

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Space VLBI Simulation Process

Space VLBI Mission Design

Step 2: Injection and Recovery

- **Simulate SMBH binary, with specific parameters, at specific location on sky**

SMBH Binary Parameters: Secondary/Primary flux density ratio, angular separation, orientation

Sky Location: right ascension, declination

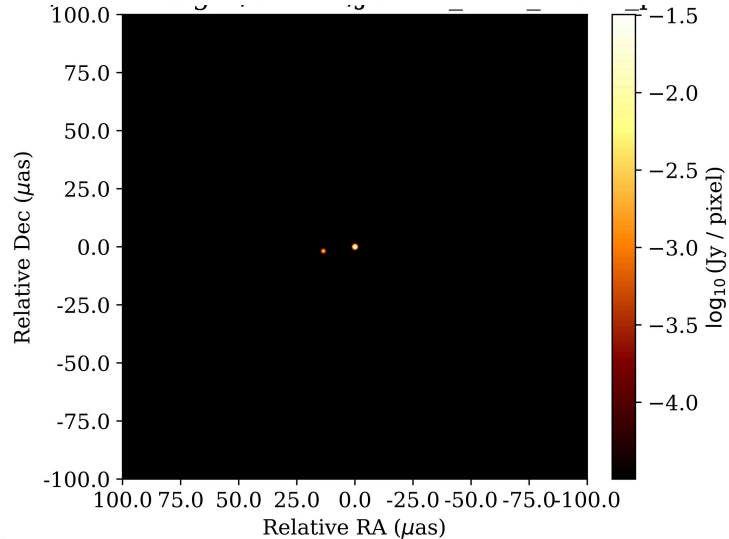
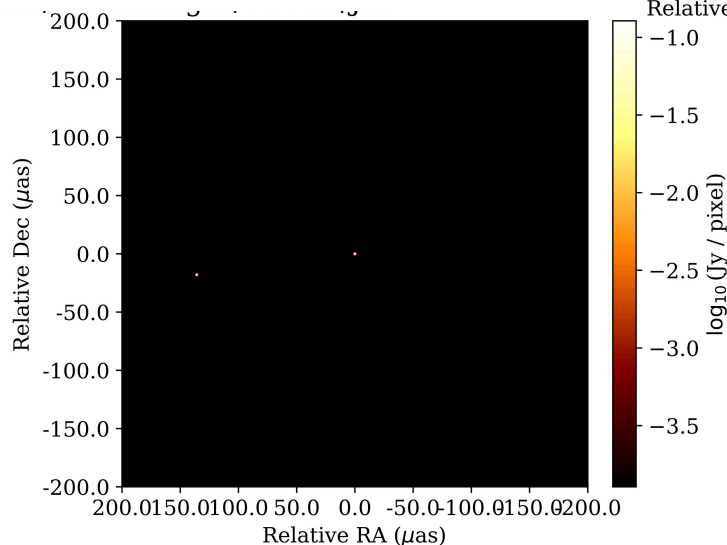
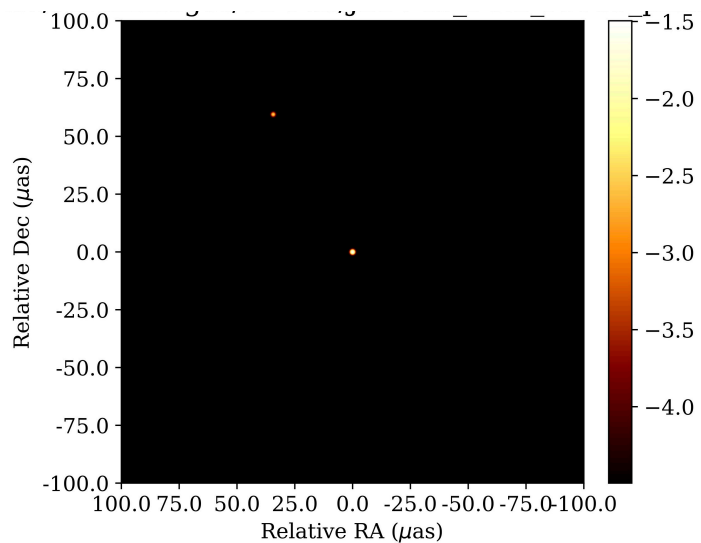
- **Observe with notional array (EHT 2017 + 3 ngVLA stations + Space Antenna) to produce mock visibility data.**
- **Fit mock visibility data for two sources.**
- **Compare recovered SMBH binary parameters within injected SMBH binary parameters.**

Injection and Recovery

Space VLBI Mission Design

Step 2: Injection and Recovery

- Secondary/Primary flux density ratio
- Angular Separation
- Orientation





Space VLBI Performance

Space VLBI Mission Design

Step 2: Injection and Recovery

Assess performance using three metrics

- 1. Is Primary Component at center of image? **
- 2. Recovered vs. injected Secondary/Primary flux density ratio?**
- 3. Recovered vs. injected Angular Separation and Orientation?**

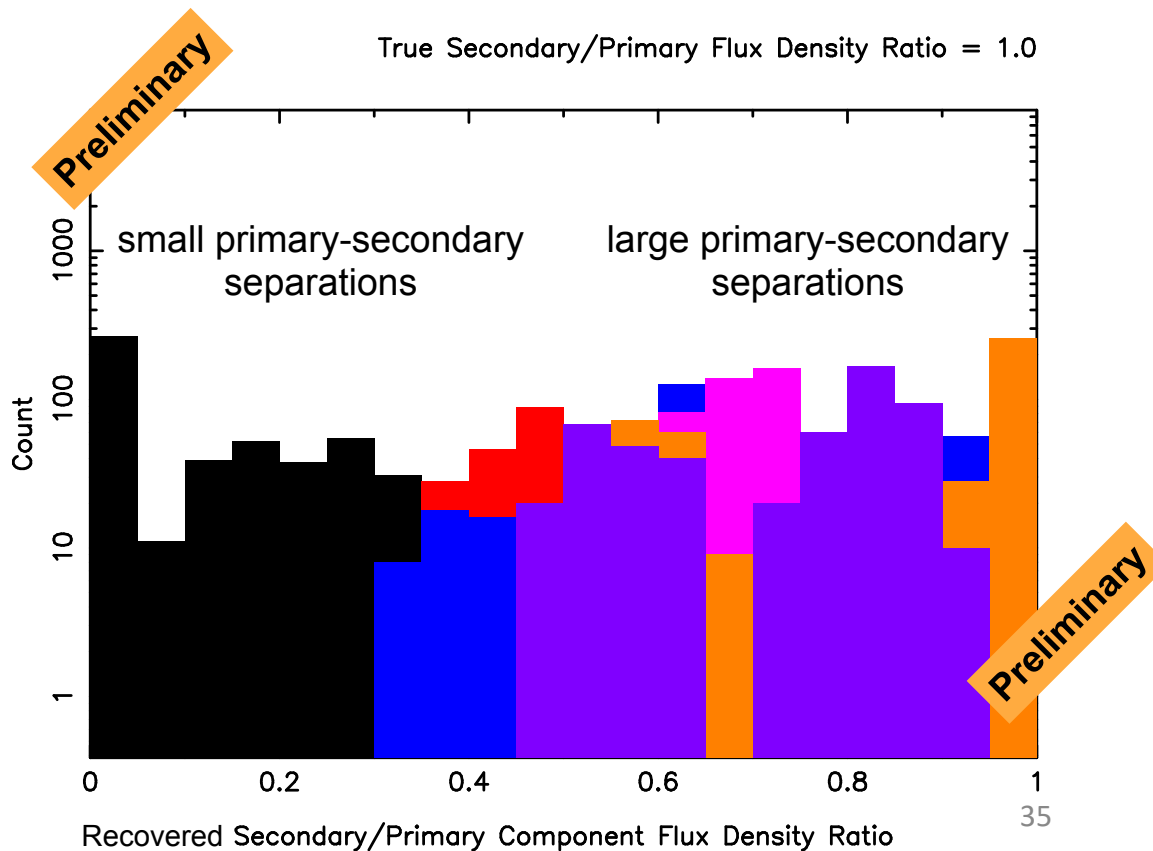
Space VLBI Array Performance

Space VLBI Mission Design

Step 2: Injection and Recovery

Assess performance using three metrics

1. Is Primary Component at center of image?
2. Recovered vs. injected Secondary/Primary flux density ratio?
3. Recovered vs. injected Angular Separation and Orientation?



Angular Resolution

Space VLBI Simulations

$$\theta = \frac{\lambda}{b} = \frac{c}{\nu b}$$

$b \lesssim D_{\oplus} \sim 12,000 \text{ km}$
(Earth's diameter)

λ constrained by
atmospheric
transmission

→ For accessible
wavelengths, on Earth-
diameter baselines,
only small fraction of
multi-messenger
phase space available

