Learning the High Redshift Universe using nano-hertz and hecto-hertz GW Background

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Tata Institute of Fundamental Research

HEARING BEYOND THE STANDARD MODEL WITH COSMIC SOURCES OF GRAVITATIONAL WAVES

ICTS-TIFR,
January 7th, 2025

Image Credit: LIGO

PROBING THE COSMIC HISTORY

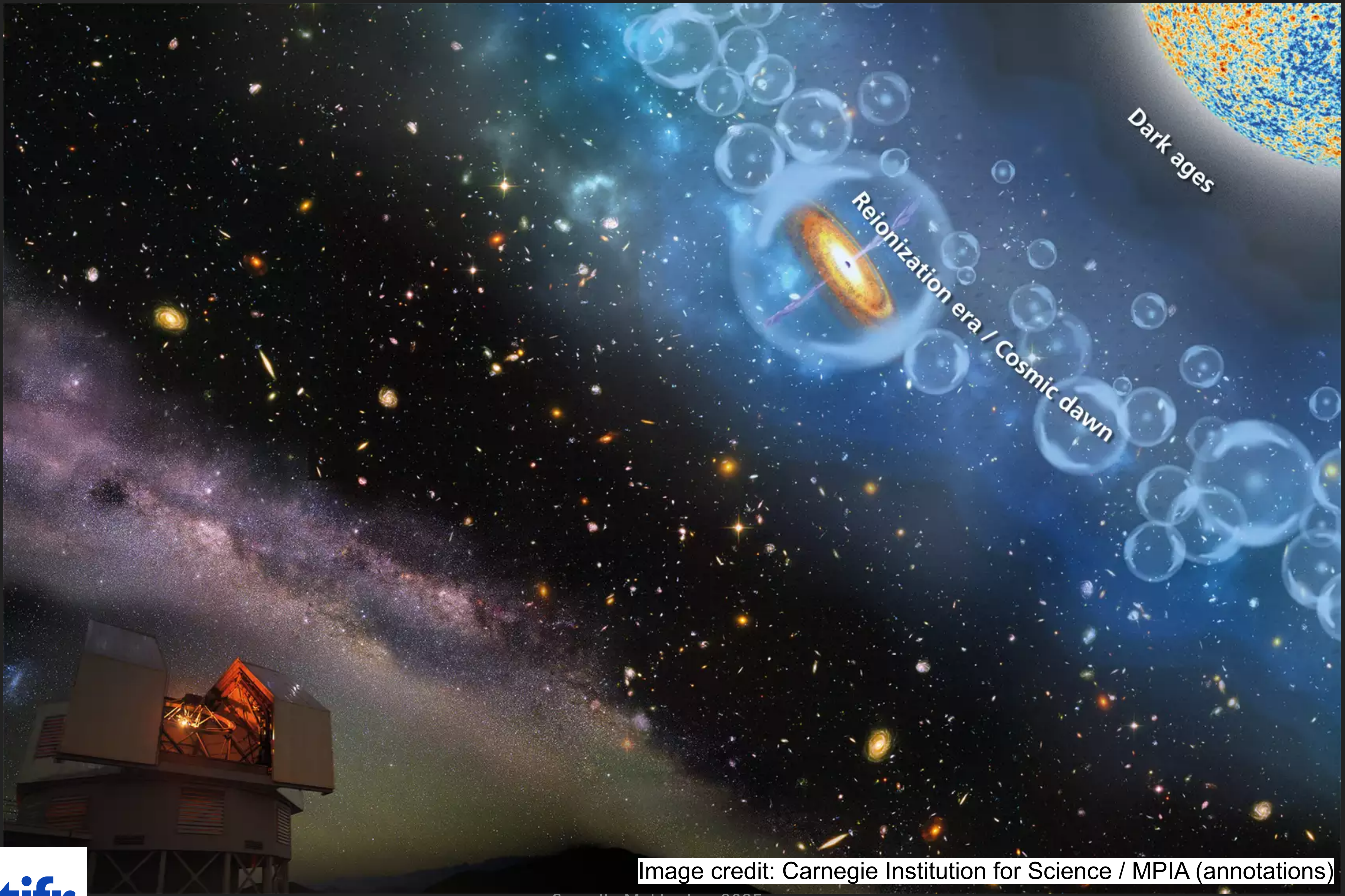


Image credit: Carnegie Institution for Science / MPIA (annotations)

PROBING THE COSMIC HISTORY

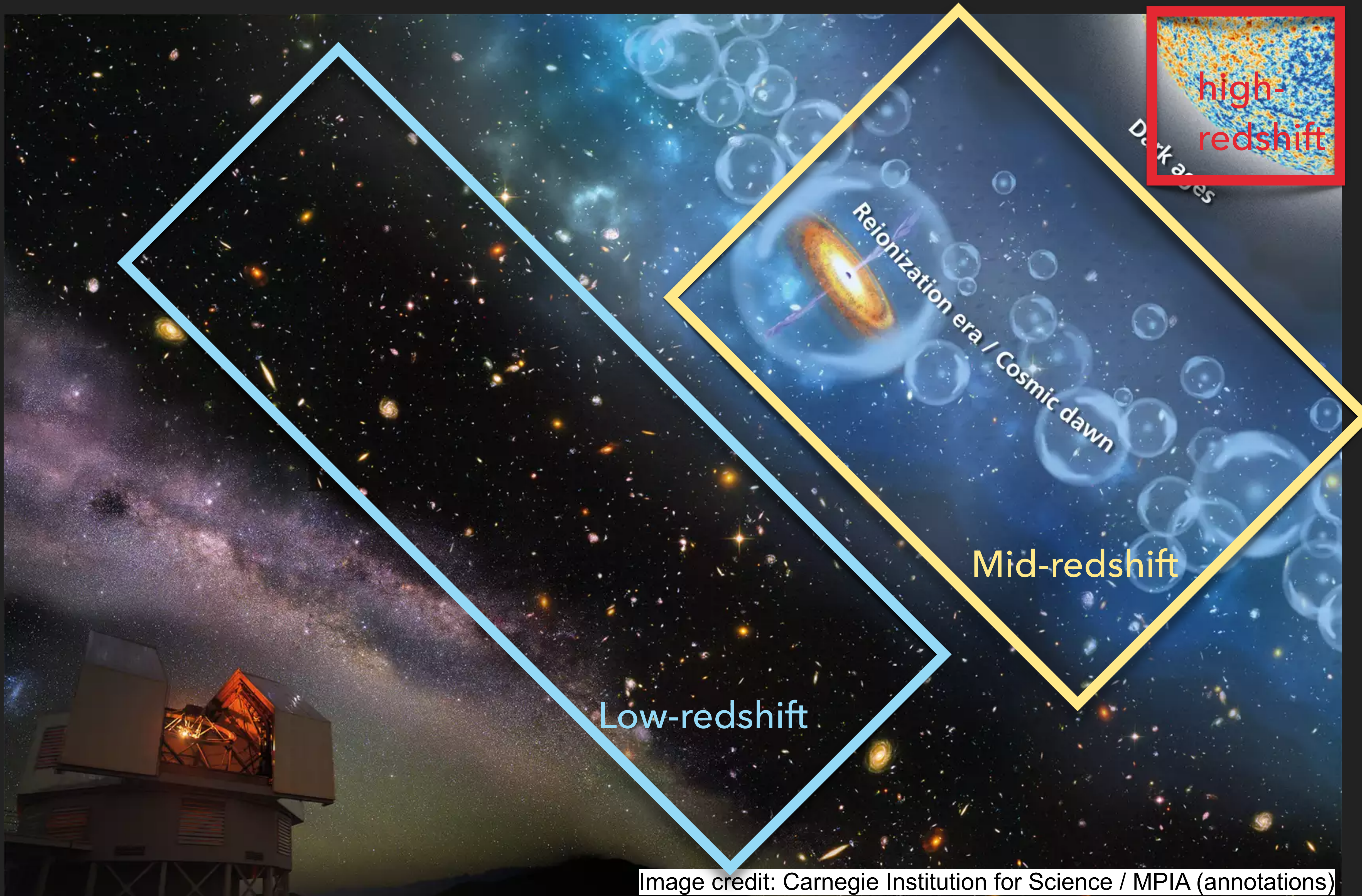
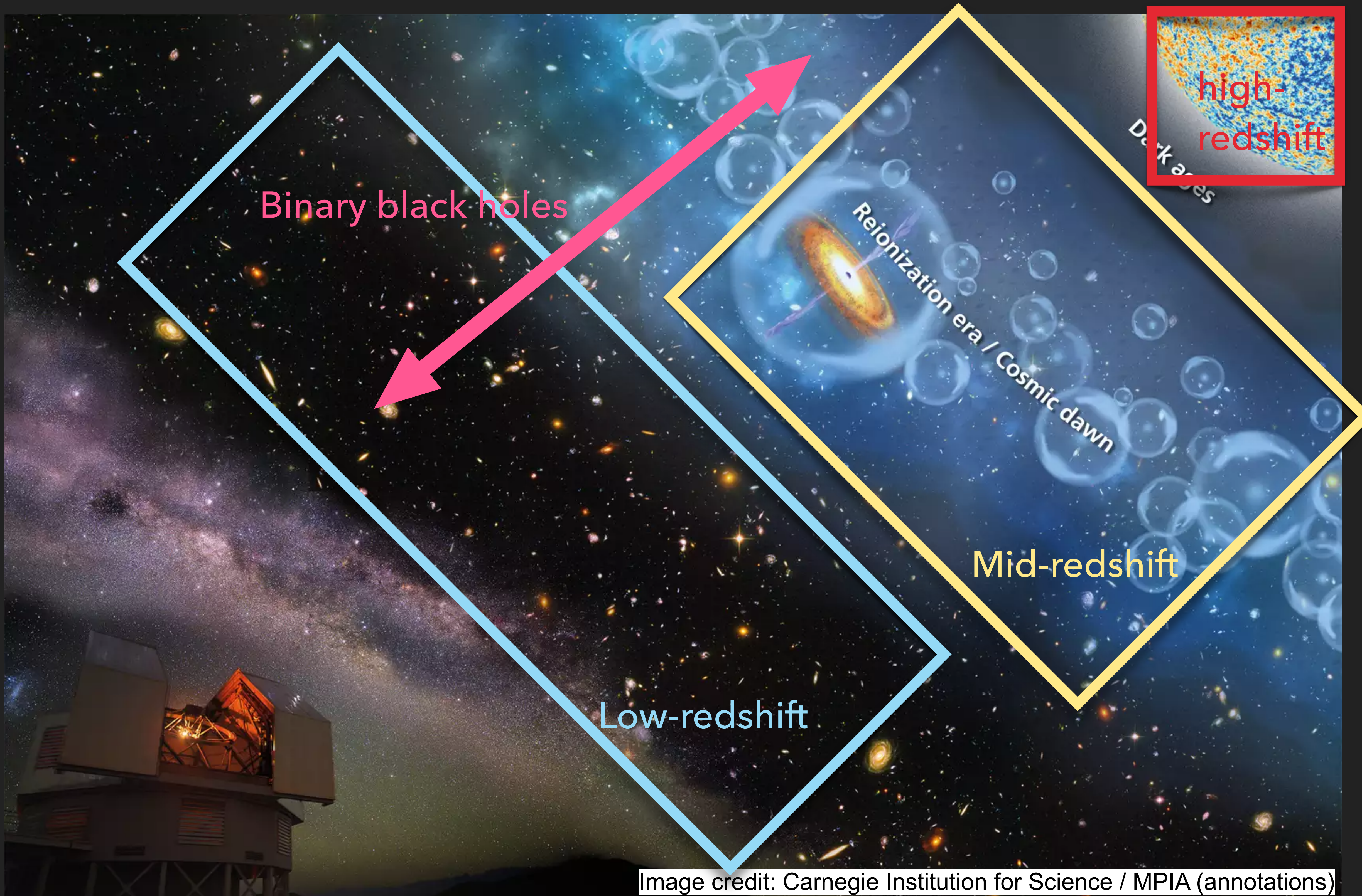
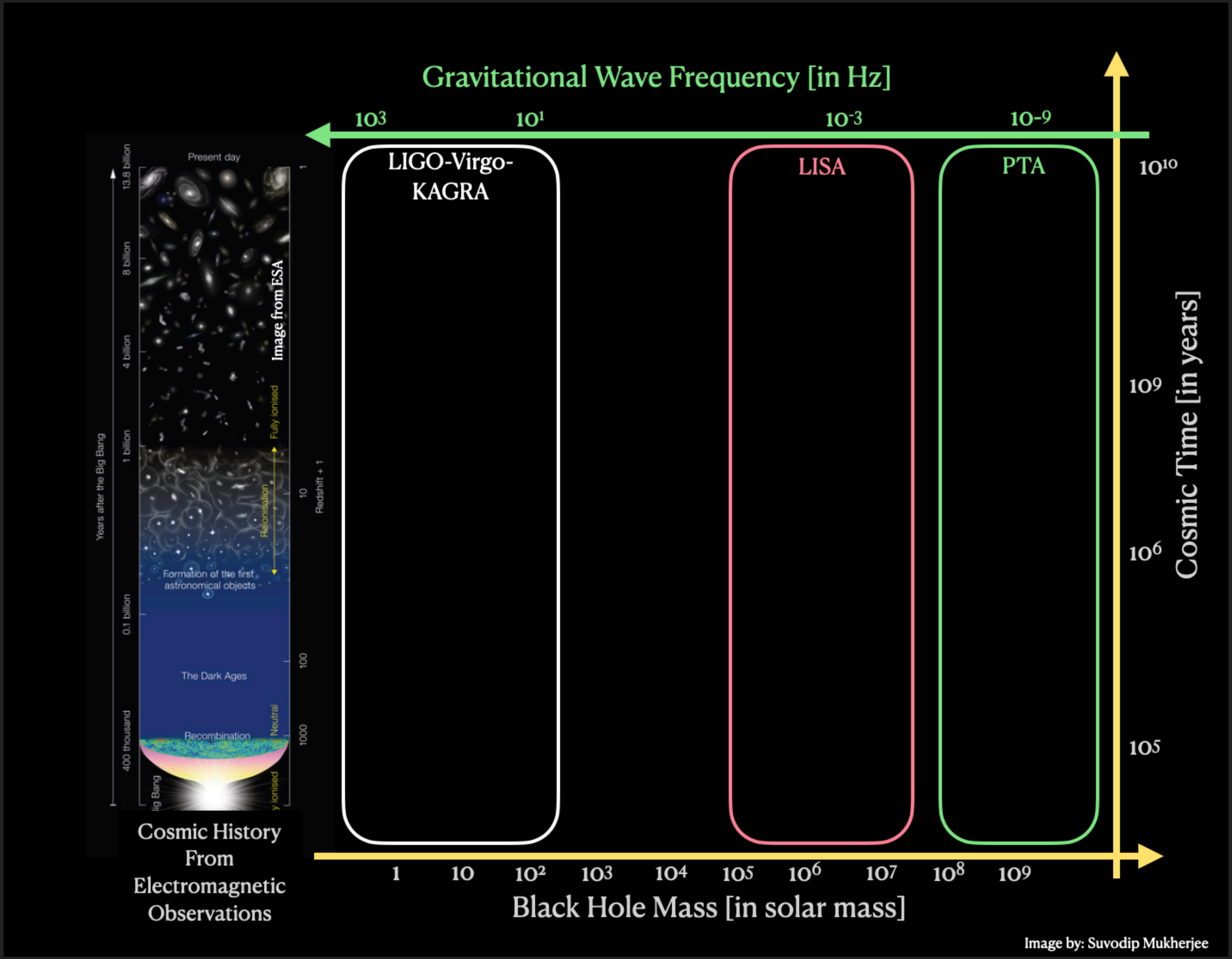


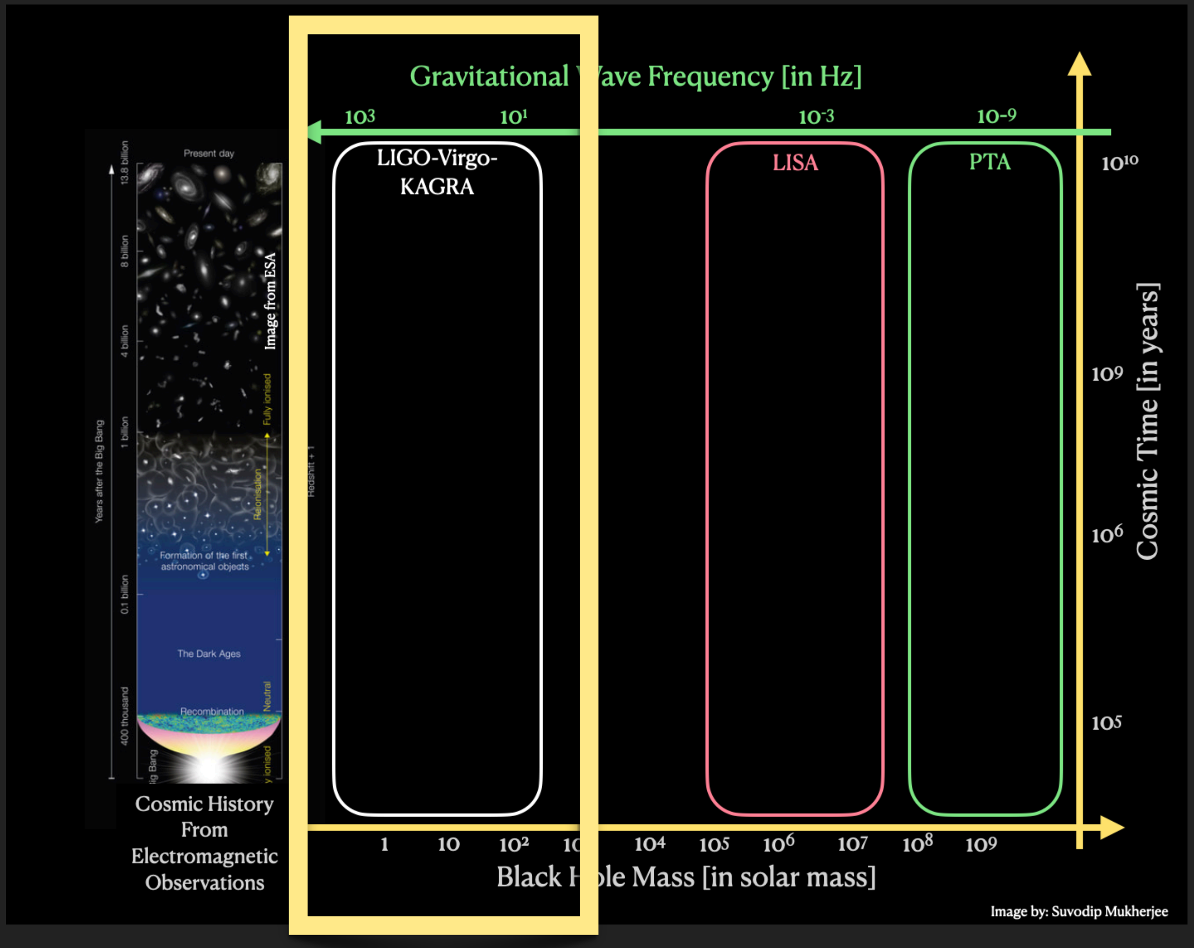
Image credit: Carnegie Institution for Science / MPIA (annotations)

PROBING THE COSMIC HISTORY USING STELLAR GRAVEYARDS



PROBING THE COSMIC HISTORY USING STELLAR GRAVEYARDS FROM HECTO-HERTZ TO NANO-HERTZ

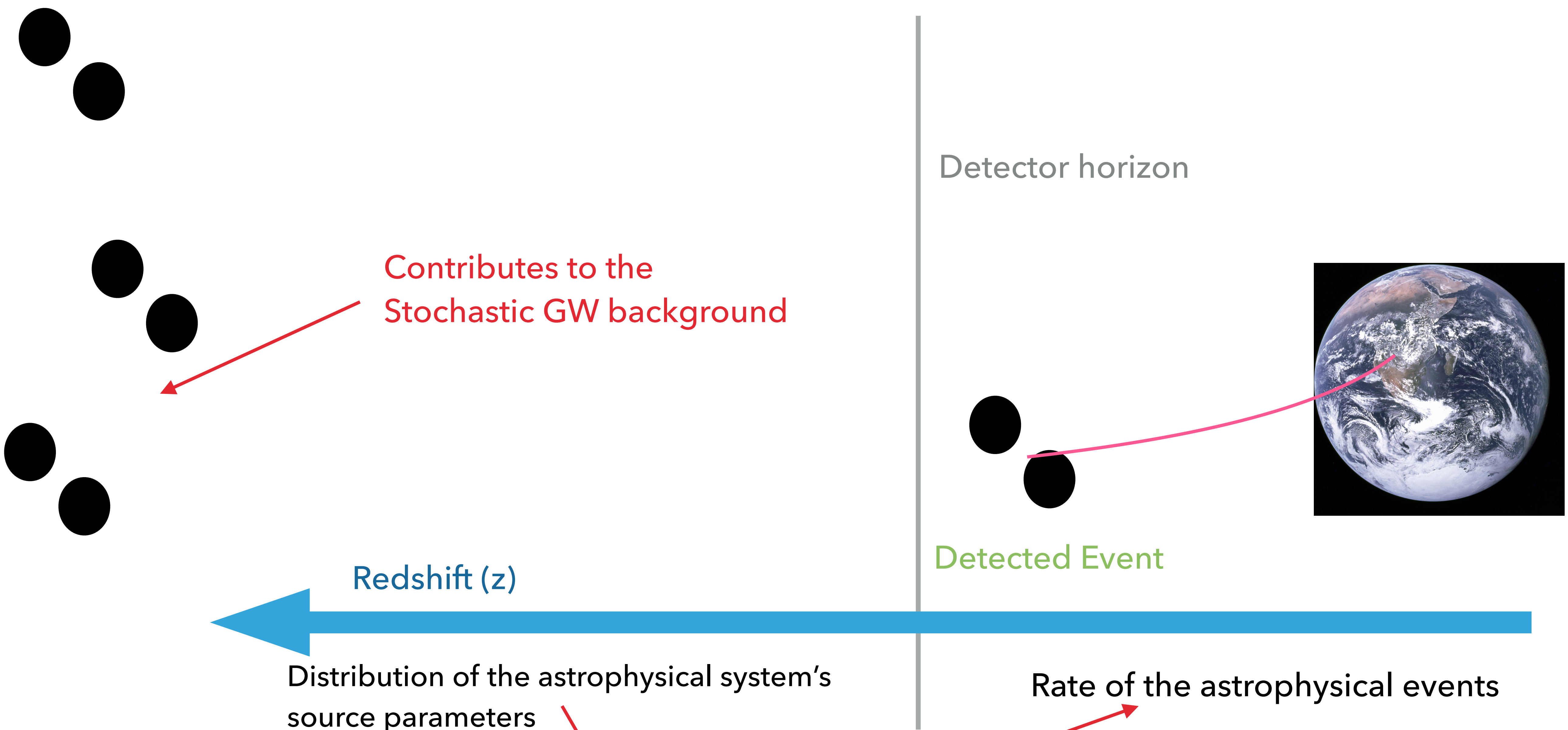




WHERE AND HOW THE BLACK HOLE FORM?

- Events (Low redshift)
- Backgrounds (High redshift)

LESS OBJECTS COALESCING AT HIGH REDSHIFT LEAD TO WEAK STOCHASTIC BACKGROUND

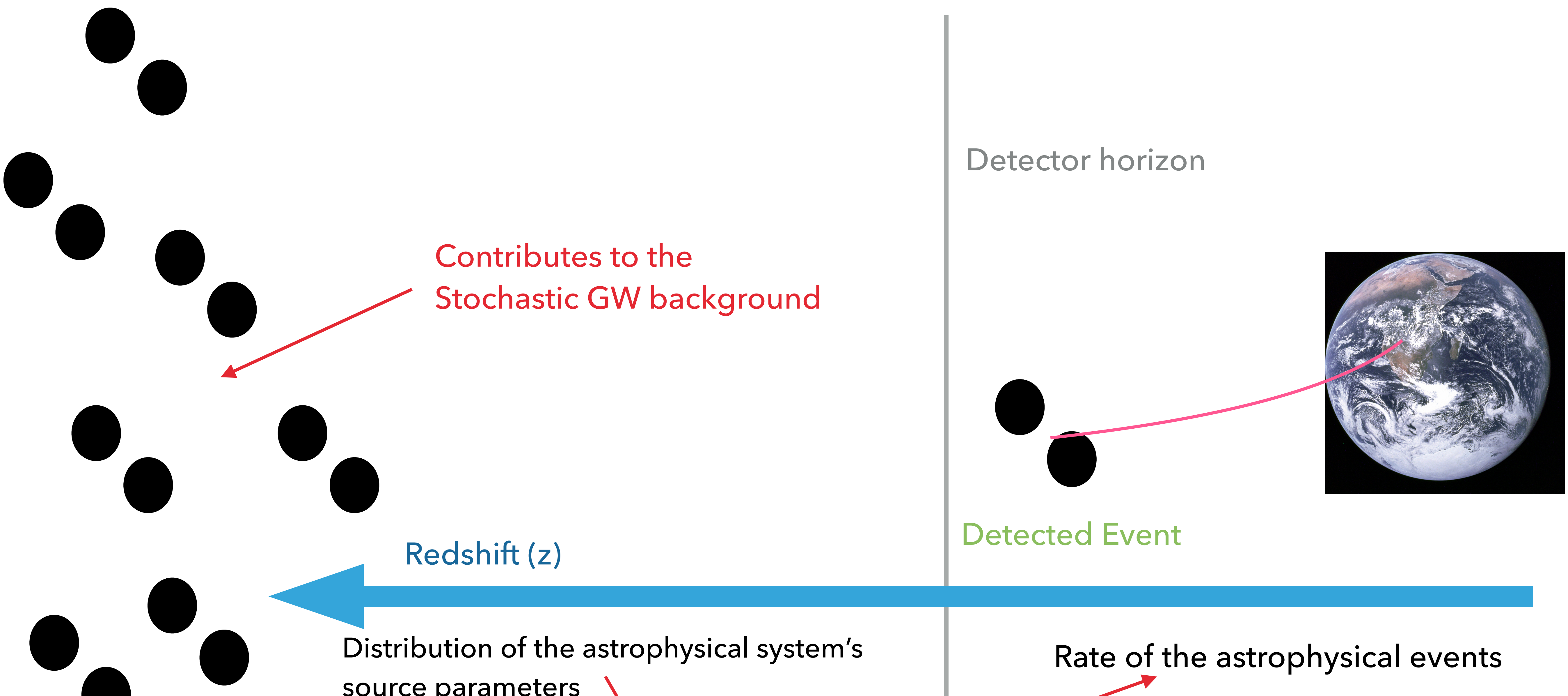


Distribution of the astrophysical system's source parameters

Rate of the astrophysical events

$$\Omega_{GW}(f) = \frac{f}{\rho_c c^2} \int d\theta \, p(\theta) \int_{z_{min}}^{z_{max}} dz \frac{R(z,\theta) dE_{GW}(\theta)/df_r}{(1+z)H(z)}$$

MORE OBJECTS COALESCING AT HIGH REDSHIFT LEAD TO LOUD STOCHASTIC BACKGROUND



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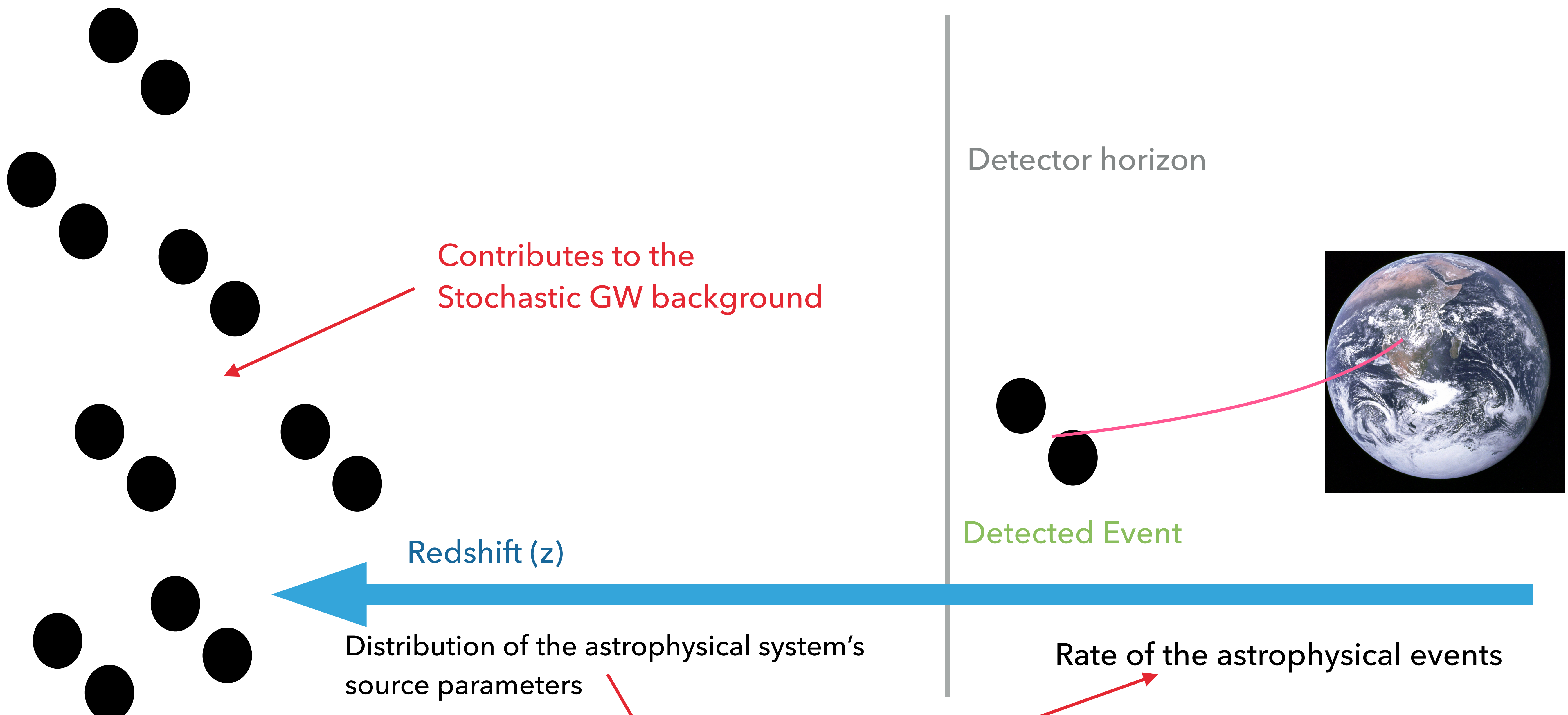
tifr

MORE OBJECTS COALESCING AT HIGH REDSHIFT LEAD TO LOUD STOCHASTIC BACKGROUND

HOW CAN WE INFER THE SOURCES AT HIGH REDSHIFT FROM BACKGROUND?



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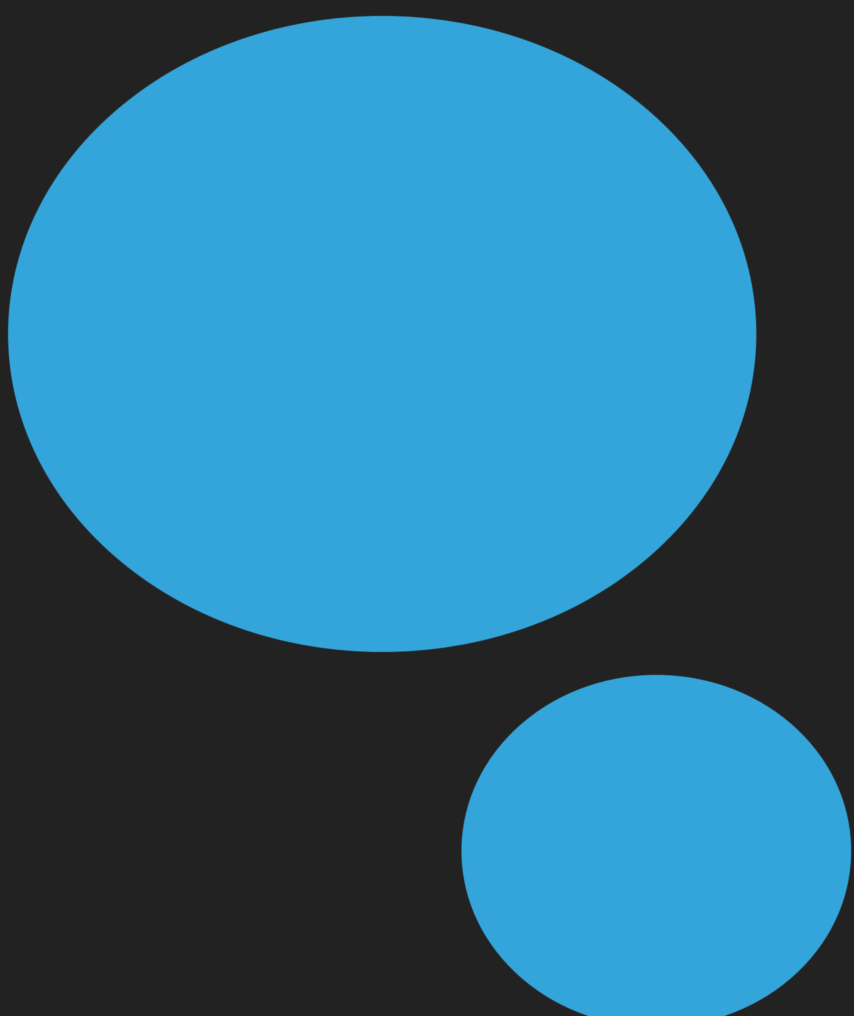
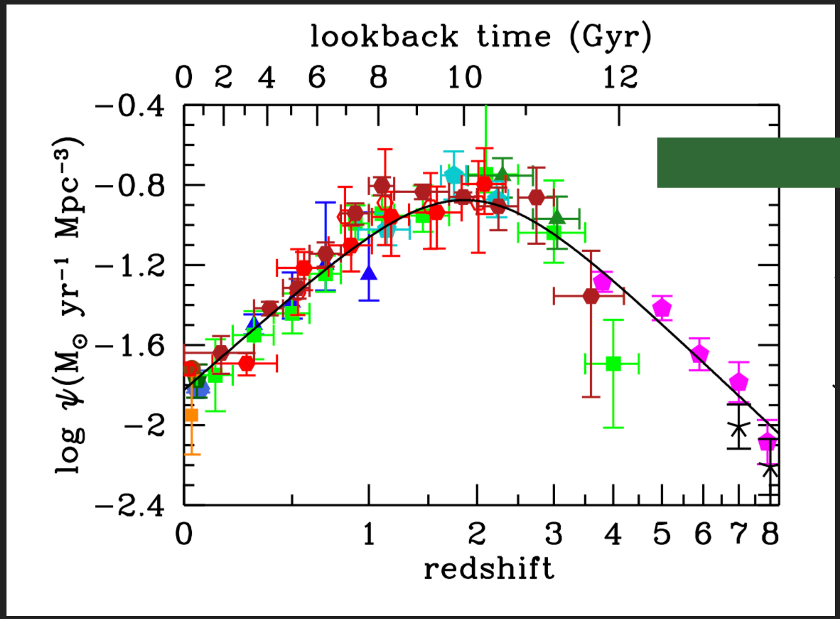
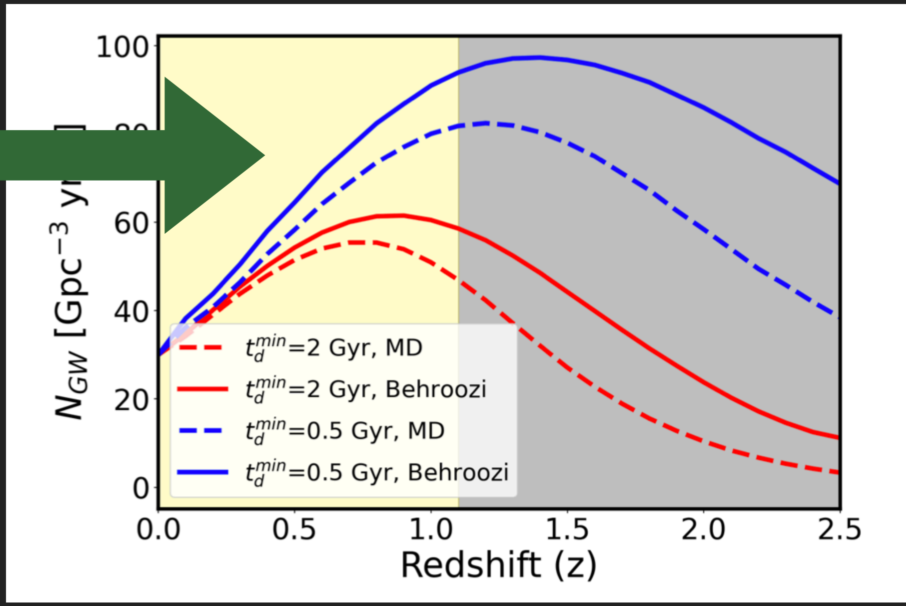
MASS-REDSHIFT PLANE TO DISTINGUISH

ASTROPHYSICAL BLACK HOLE OR PRIMORDIAL BLACK HOLE?



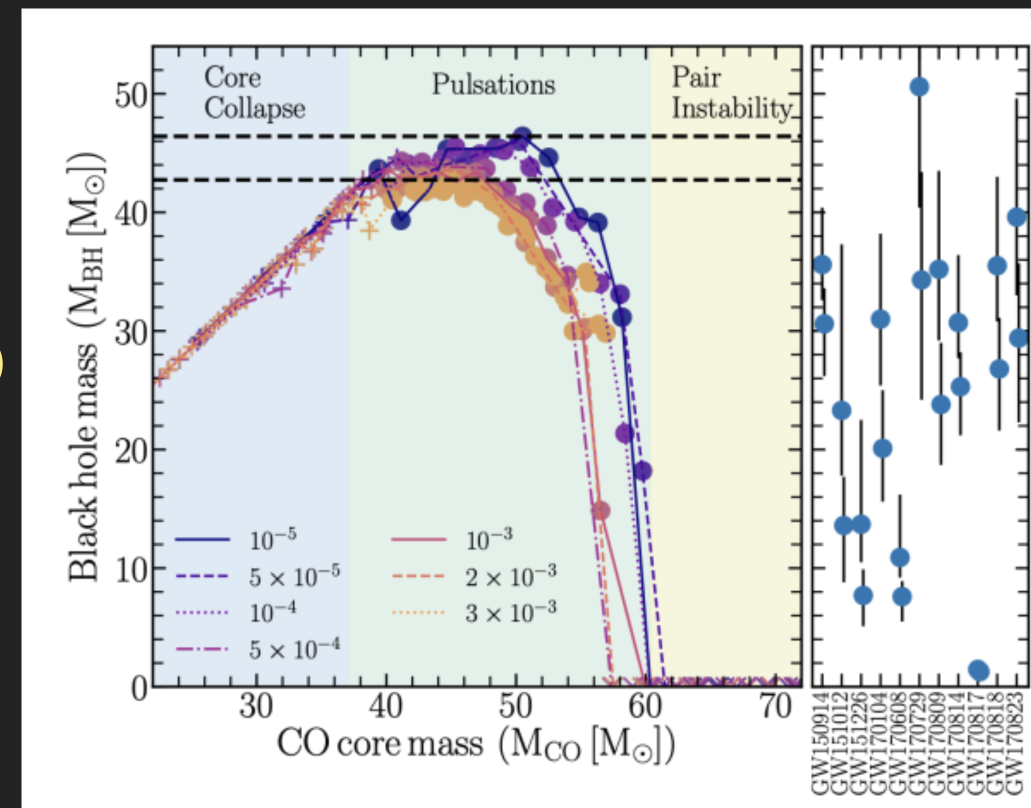
ASTROPHYSICAL BLACK HOLES: WILL TRACE STAR FORMATION RATE

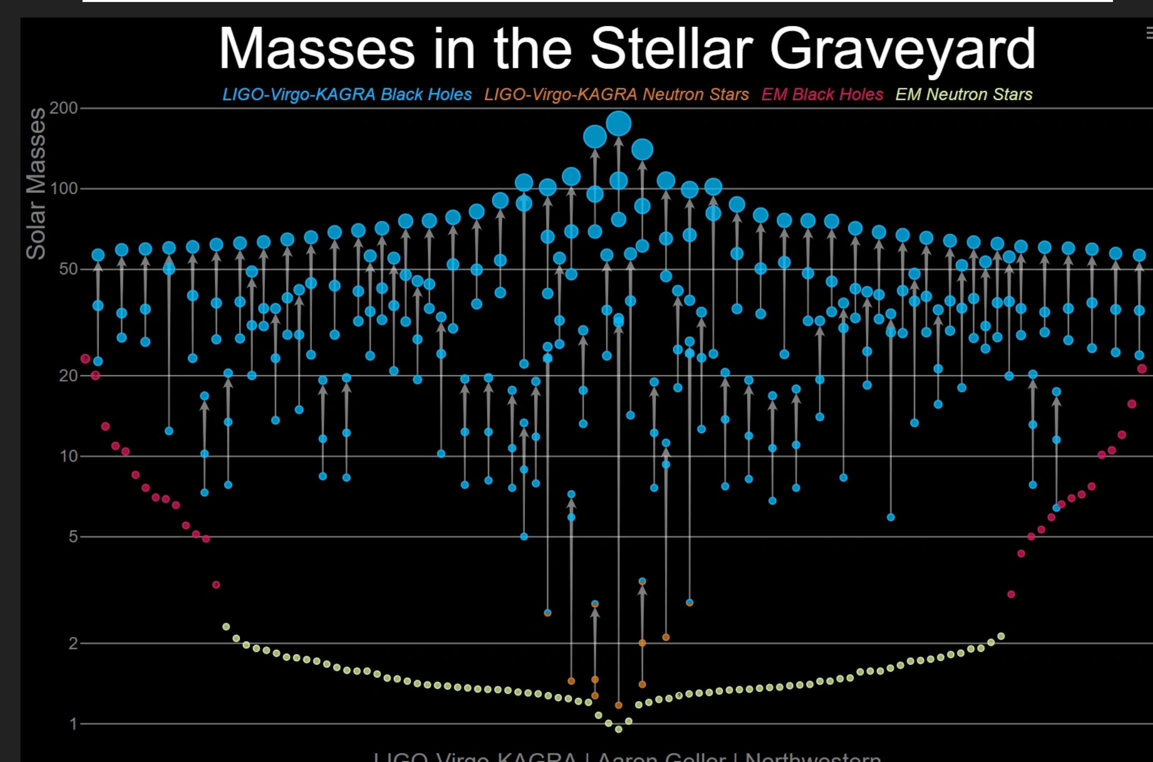




ASTROPHYSICAL BLACK HOLES: MASS DISTRIBUTION WILL HAVE GAPS

Farmer et al (2020)

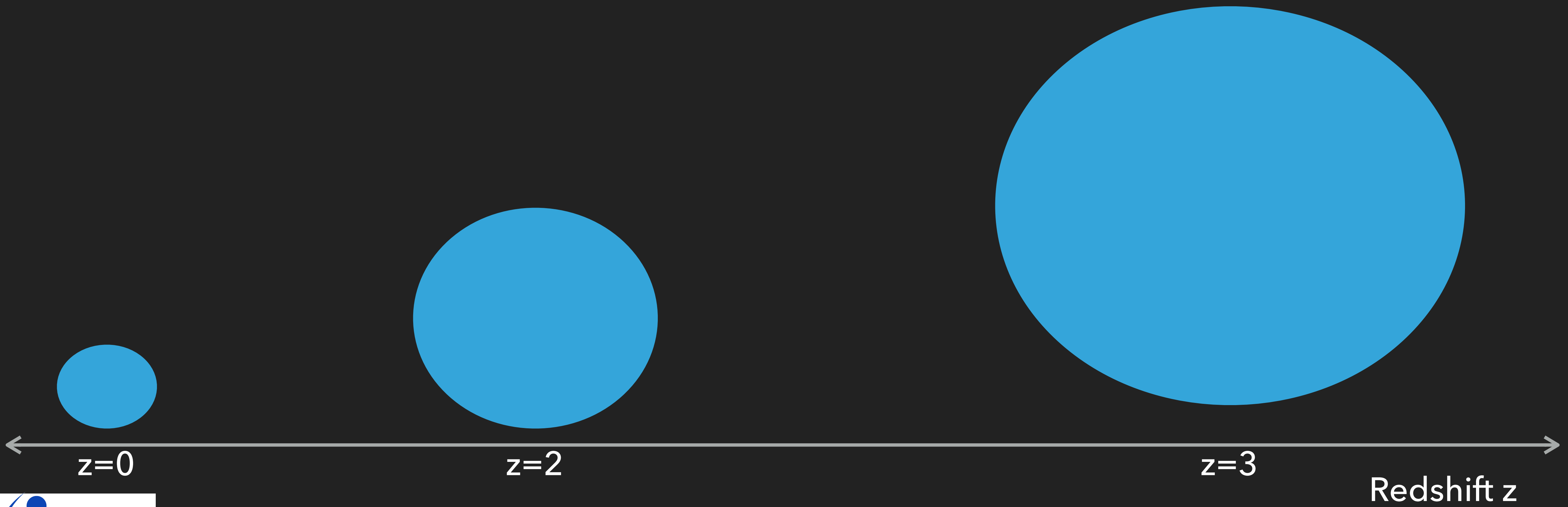




WHAT CHARACTERISES THE BLACK HOLE POPULATION (SO FAR)

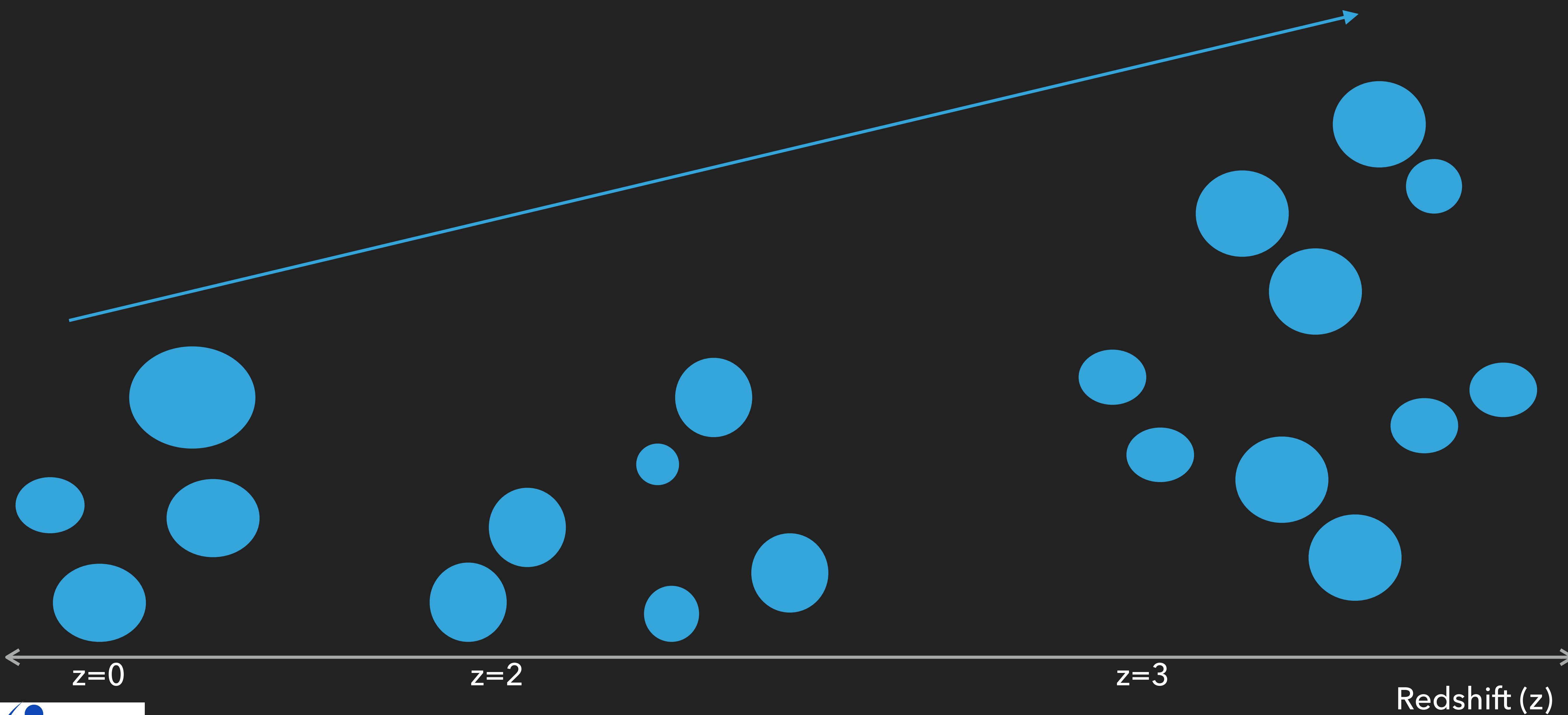
- We observe ‘redshifted masses’

$$M_z = (1+z)M_{true}$$

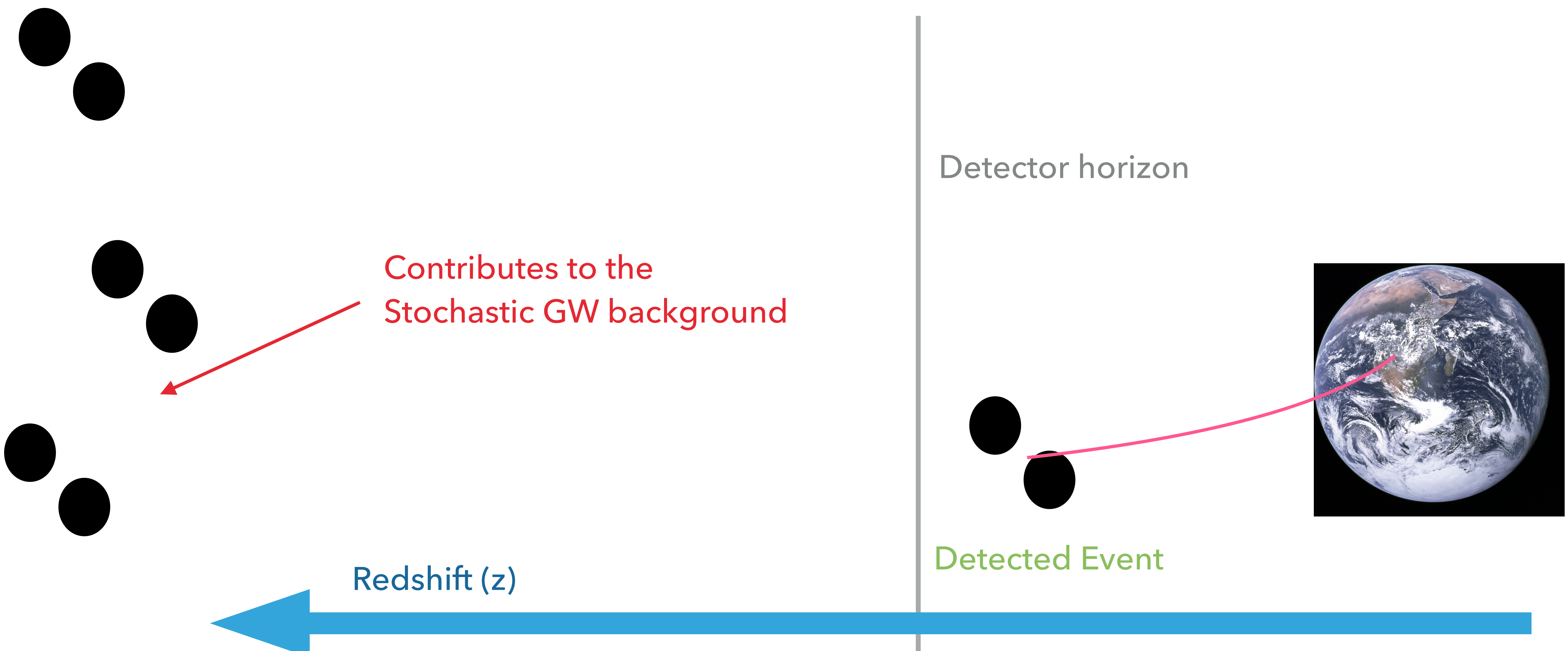


WHAT CHARACTERISES THE BLACK HOLE POPULATION (SO FAR)

- Merger rate of compact objects



LESS OBJECTS COALESCING AT HIGH REDSHIFT LEAD TO WEAK STOCHASTIC BACKGROUND



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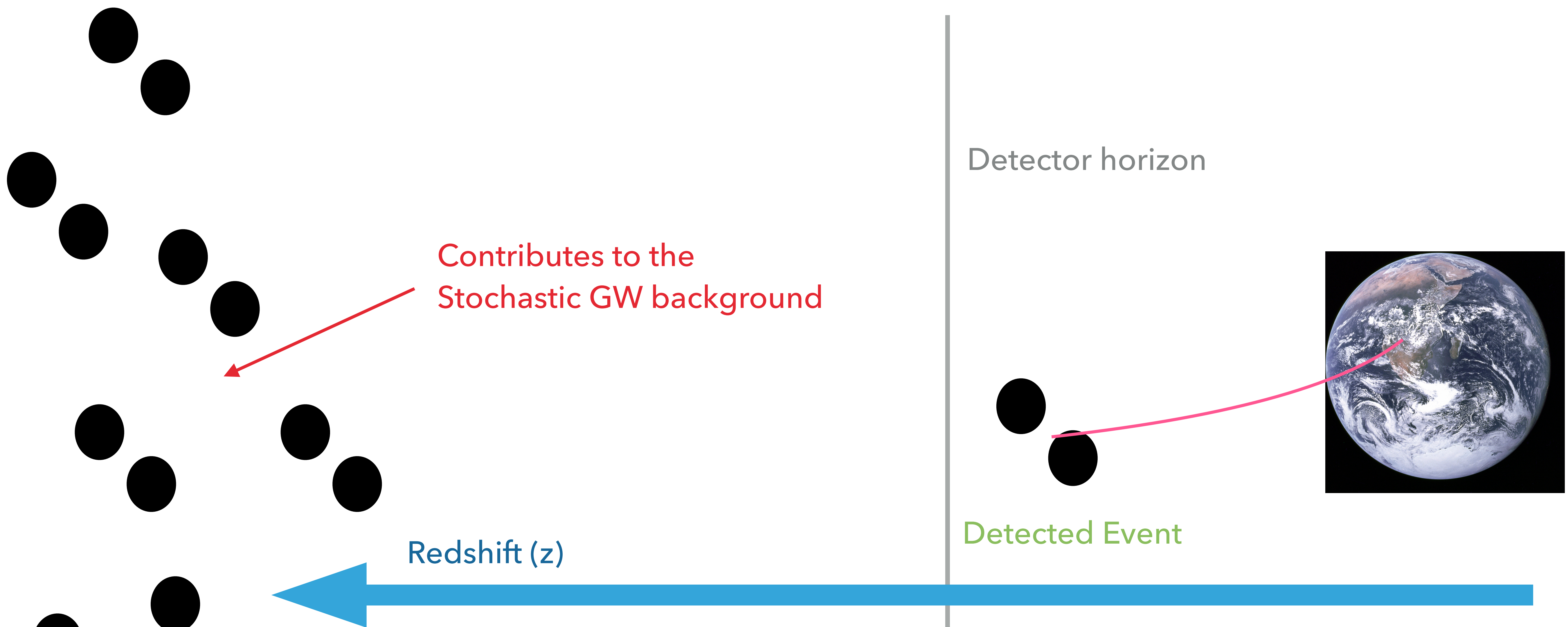
MORE OBJECTS COALESCING AT HIGH REDSHIFT LEAD TO LOUD STOCHASTIC BACKGROUND



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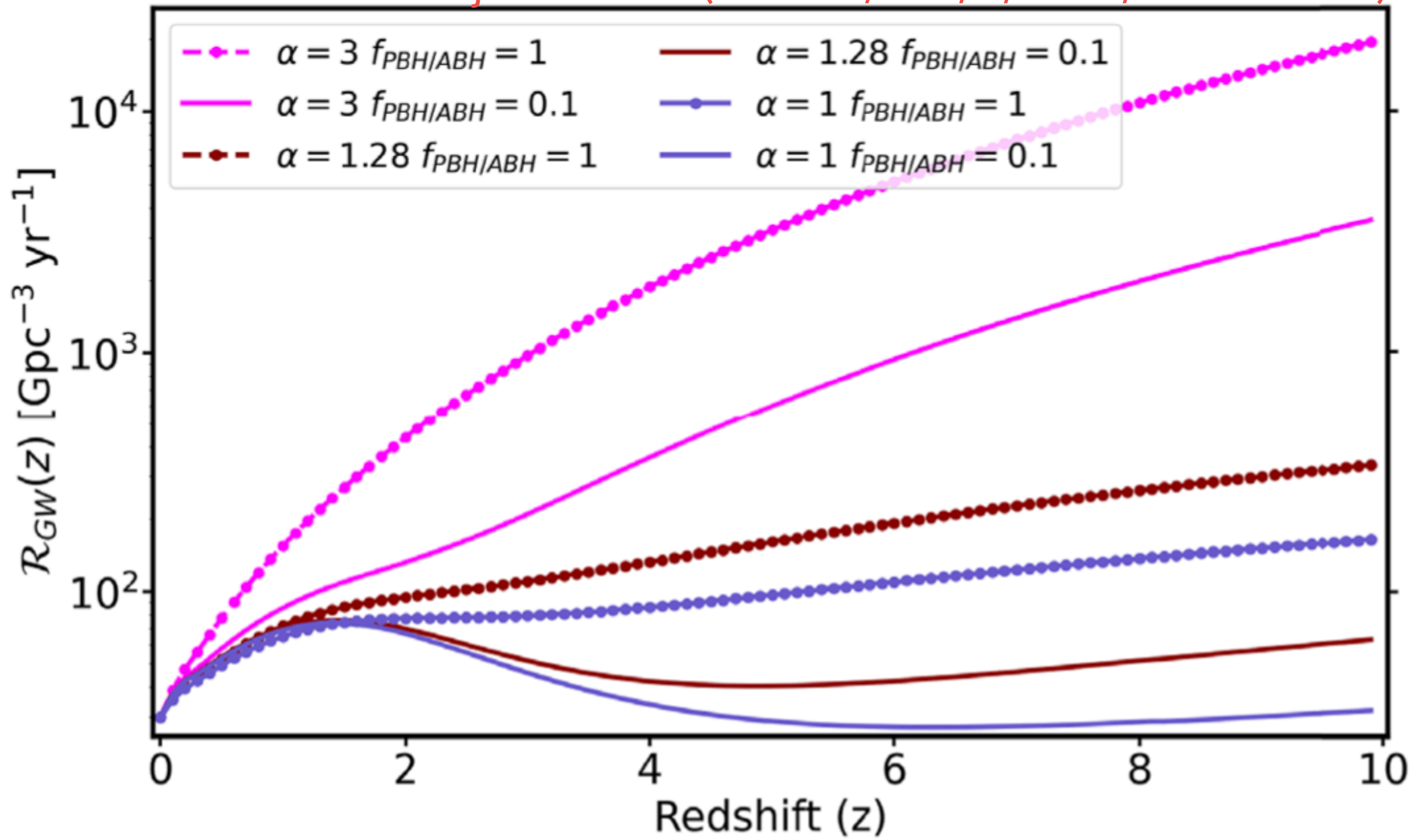
MERGER RATE

Mukherjee and Silk (MNRAS, 506, 3, 2021, 2105.11139)



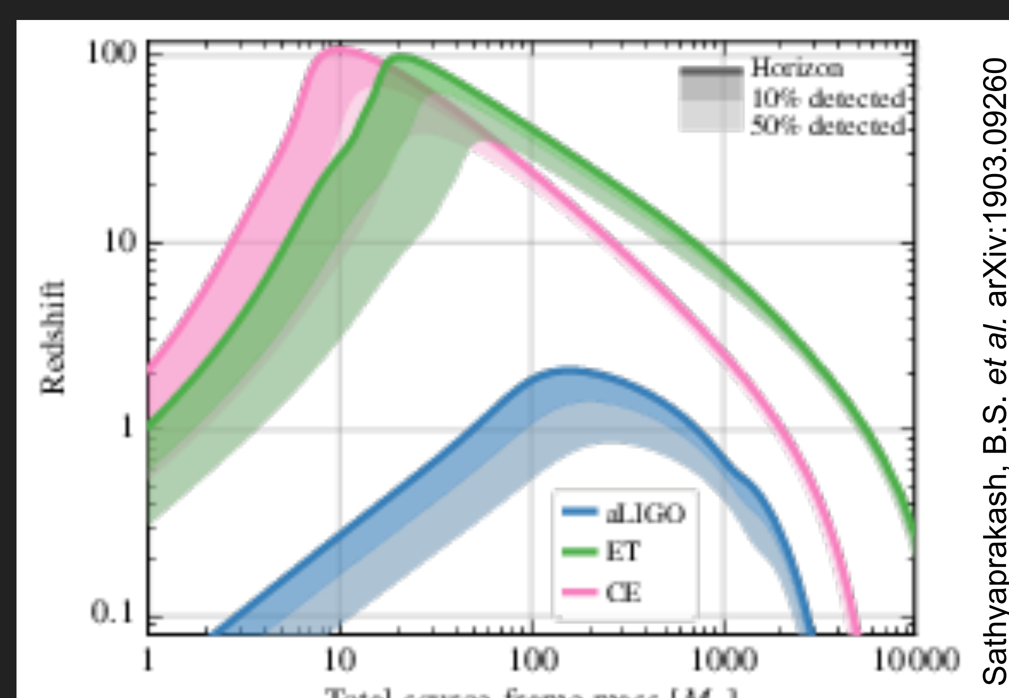
Redshift evolution of the merger rate is more reliable than the amplitude of the merger rate.

MASS-REDSHIFT RANGE WHERE BLACK HOLES CAN BE DISTINGUISHED

	Mass < 1 msun	Mmin<Mass < MPISN	Mass >MPISN
Redshift > 2	Yes	Not sure	Yes
Redshift < 2	Yes	Not sure	Not sure

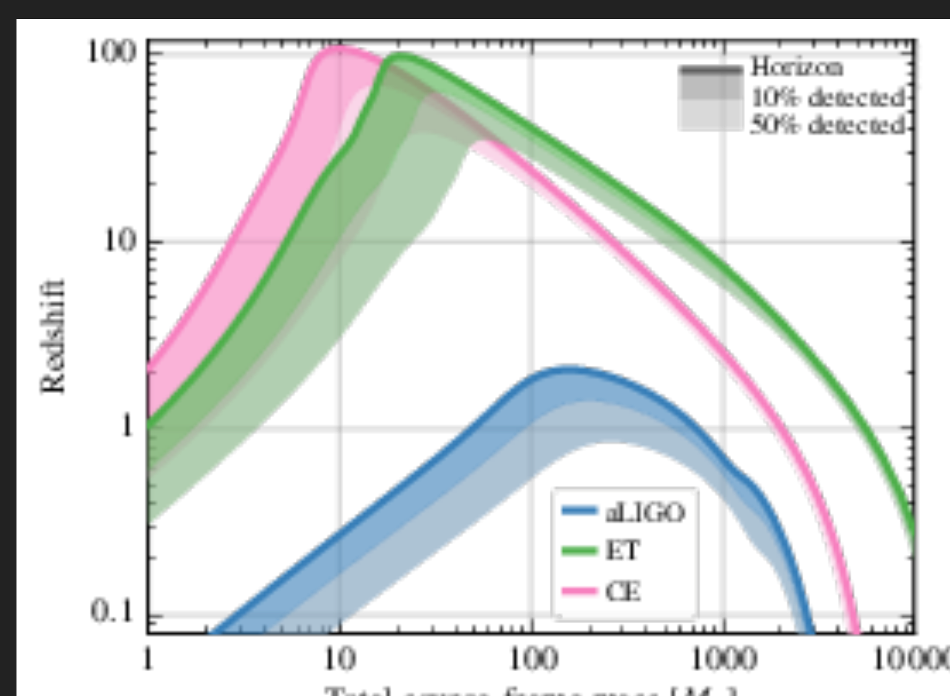
MASS-REDSHIFT RANGE WHERE BLACK HOLES CAN BE DISTINGUISHED

	Mass < 1 msun	Mmin<Mass < MPISN	Mass >MPISN
Redshift > 2	Yes	Not sure	Yes
Redshift < 2	Yes	Not sure	Not sure



STOCHASTIC GW BACKGROUND CAN PROVIDE SMOKING GUN SIGNATURE FOR PBHS

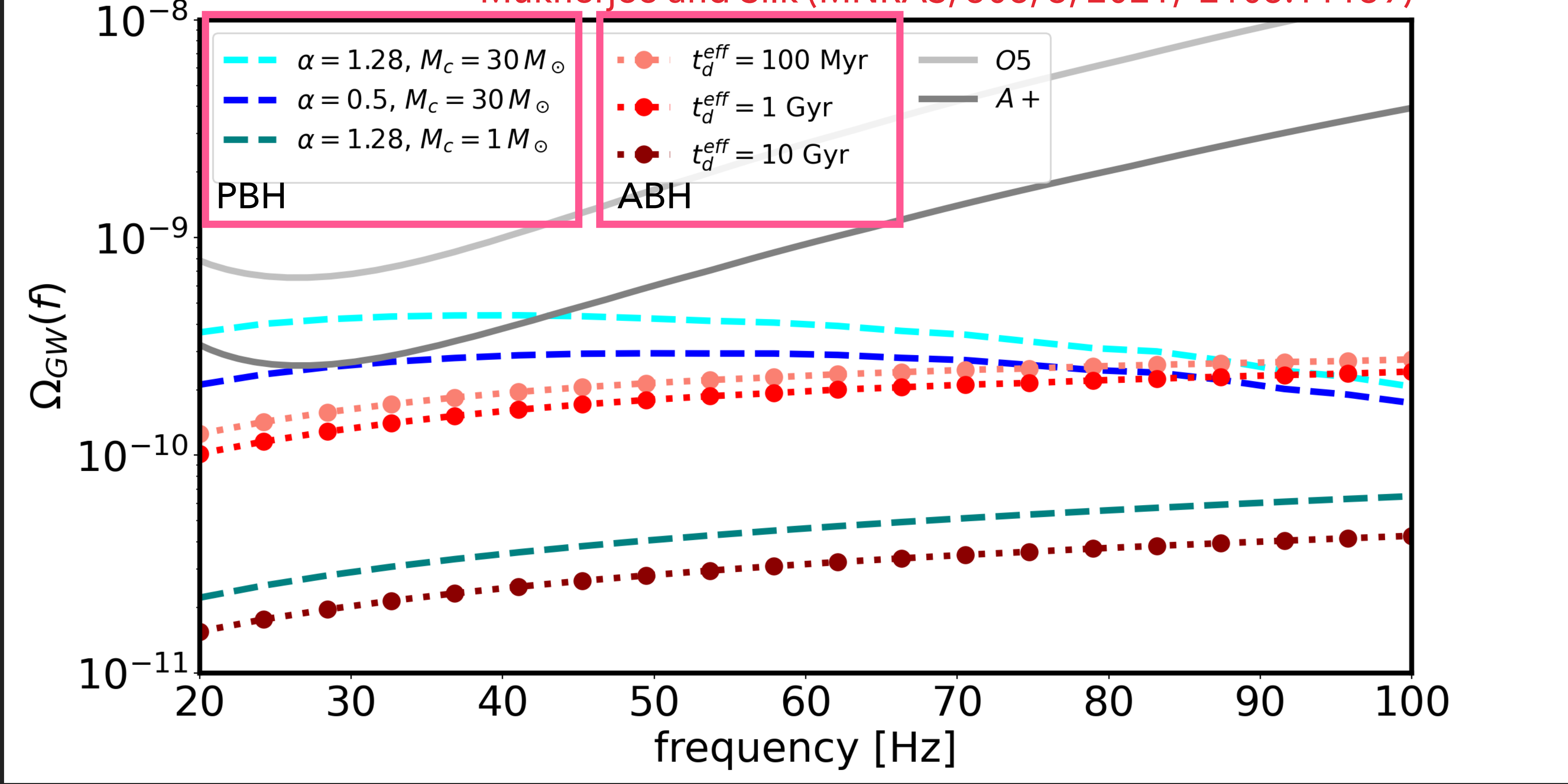
	Mass < 1 msun	Mmin<Mass < MPISN	Mass >MPISN
Redshift > 2	SGWB	Not sure	SGWB
Redshift < 2	Yes	Not sure	Not sure



Sathyaprakash, B.S. *et al.* arXiv:1903.09260

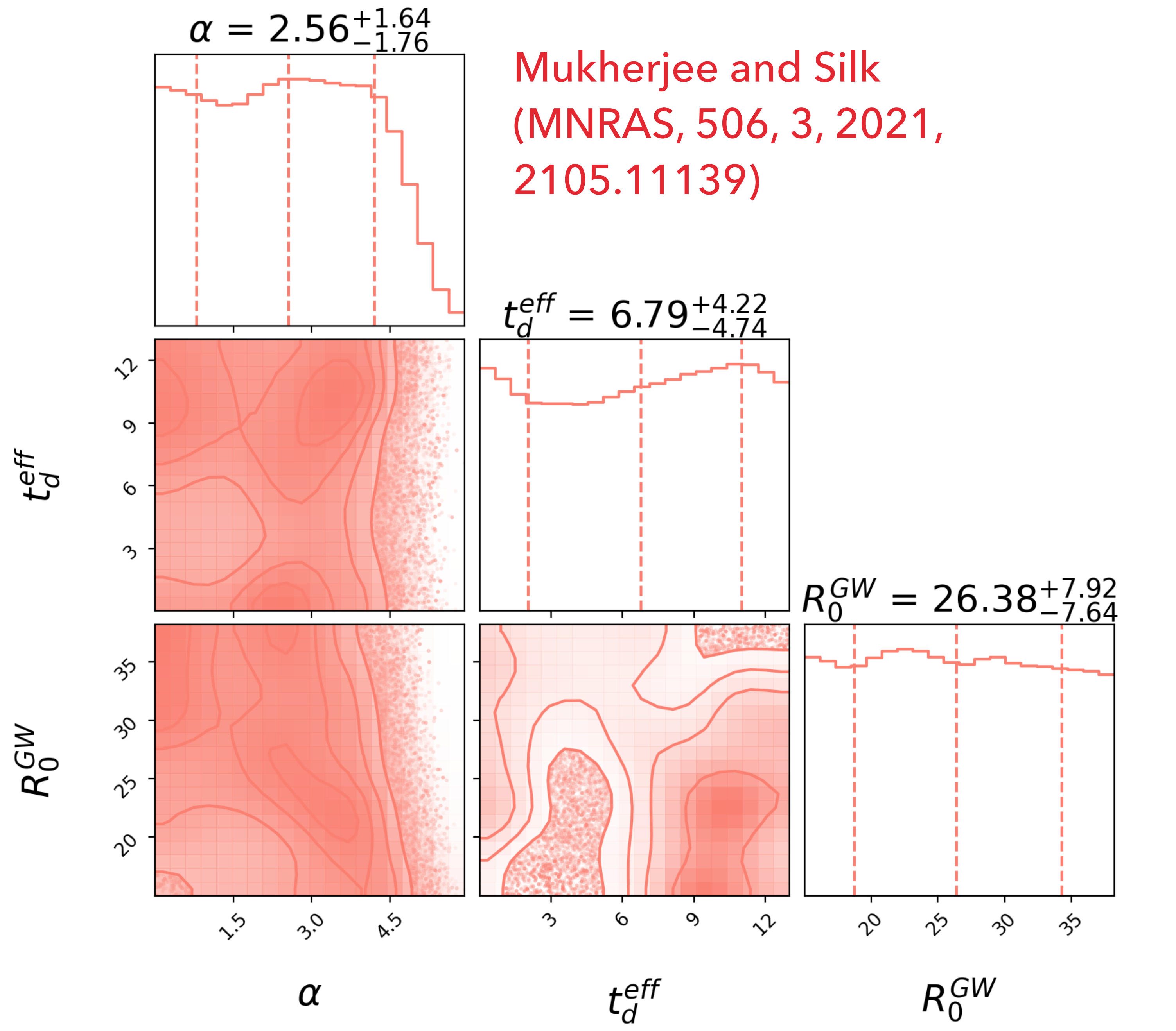
STOCHASTIC GW BACKGROUND FOR DIFFERENT SCENARIOS

Mukherjee and Silk (MNRAS, 506, 3, 2021, 2105.11139)



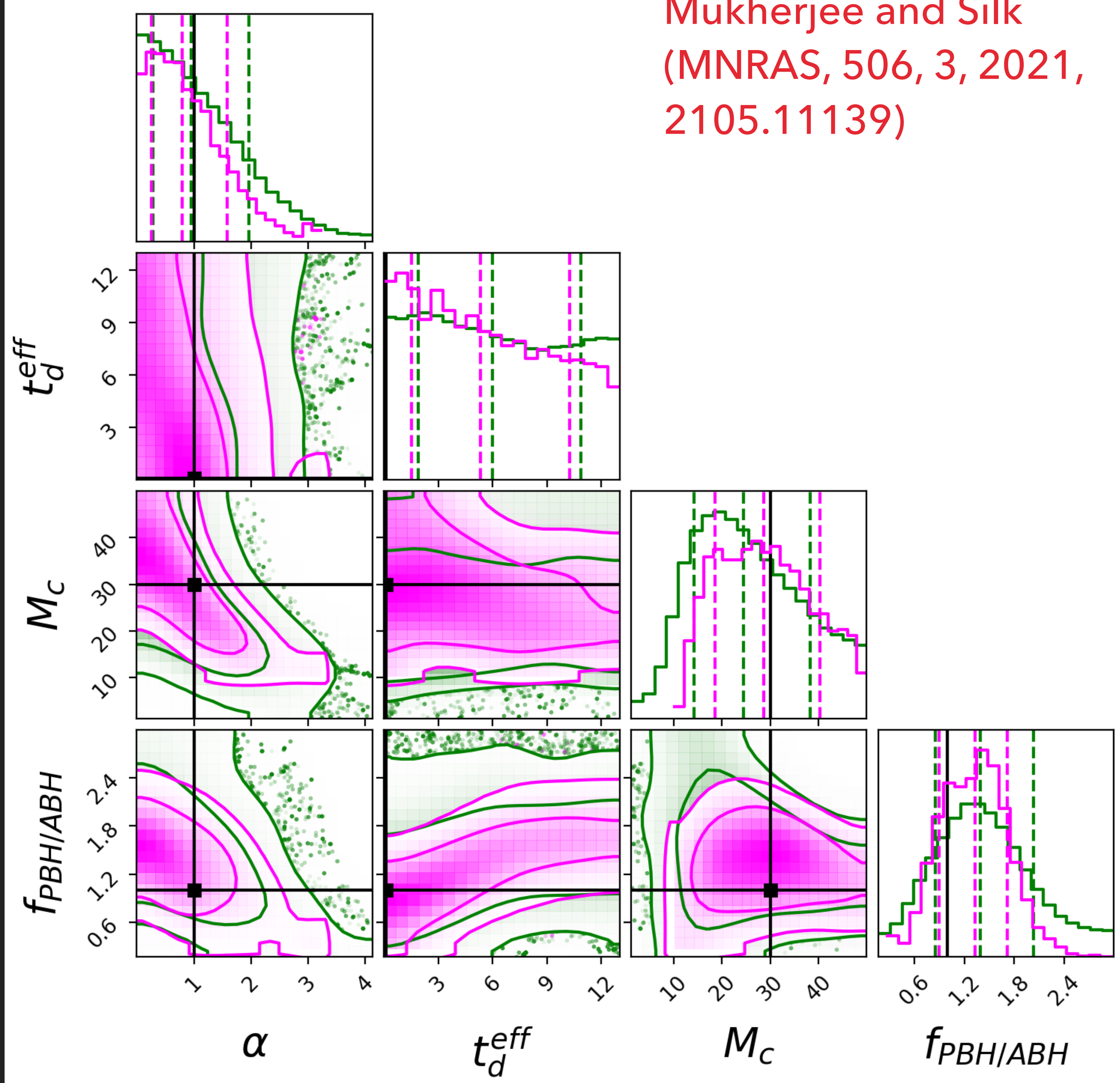
BOUND FROM THE O3 DATA OF LIGO-VIRGO

Weak constraints from the current observations.



FORECAST FOR O5 AND A+ SENSITIVITY TO DISTINGUISH ABHS AND PBHS

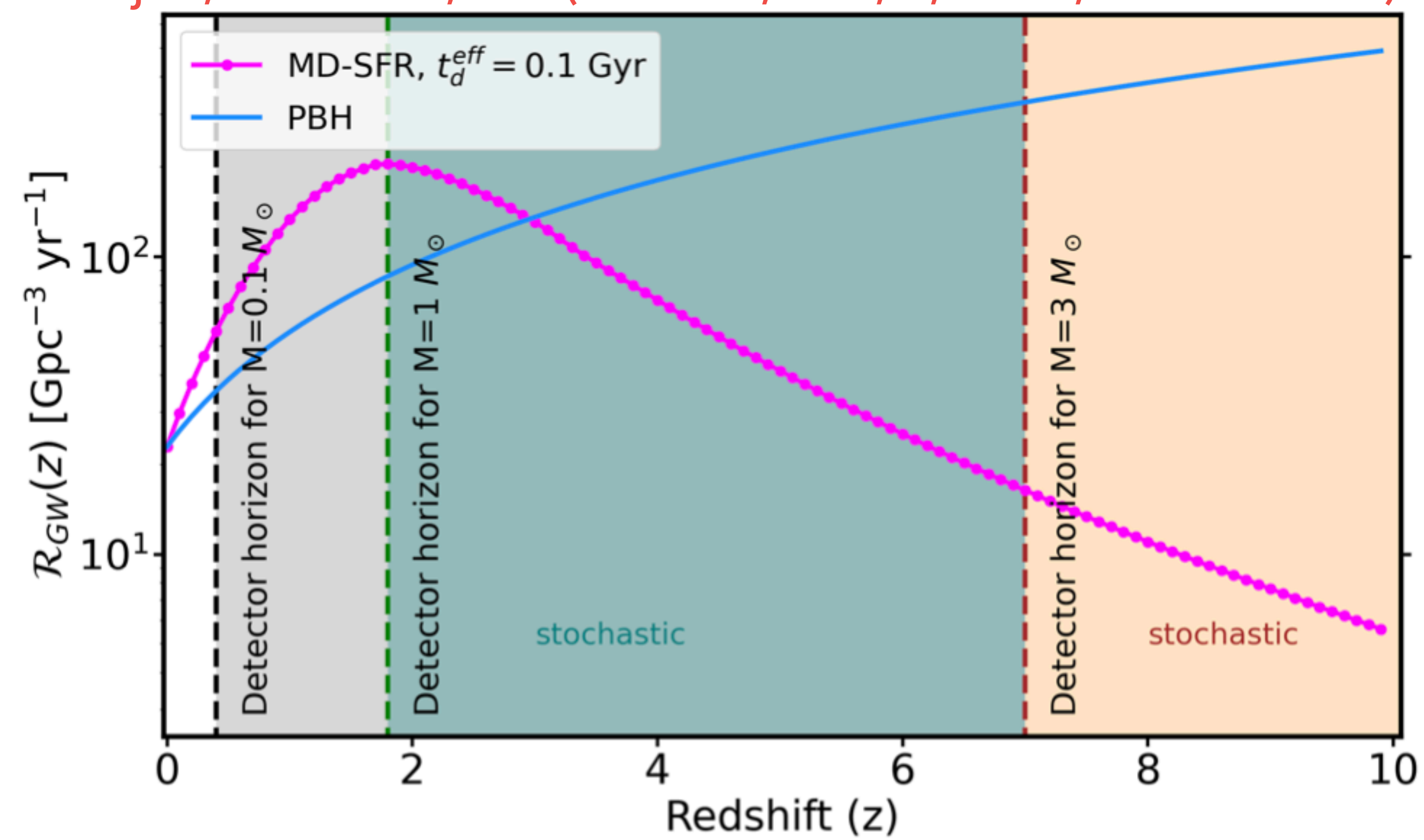
Take home message: We can distinguish between the population of ABHs and PBHs using the stochastic GW background.



Mukherjee and Silk (MNRAS, 506, 3, 2021, 2105.11139)

MERGER RATE

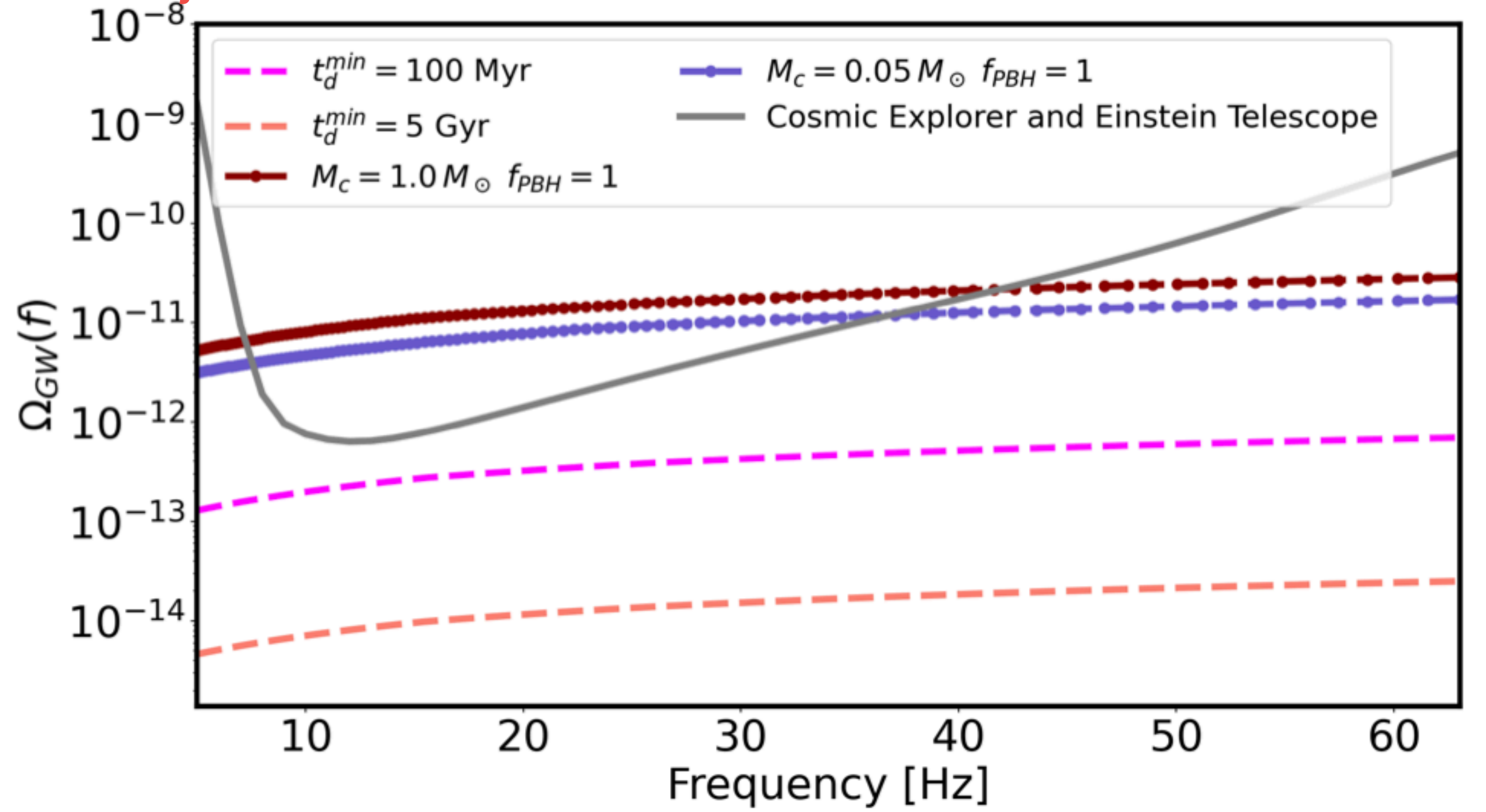
Mukherjee, Meinema, Silk (MNRAS, 510, 4, 2022, 2107.02181)



Redshift evolution of the merger rate is more reliable than the amplitude of the merger rate.

STOCHASTIC GW BACKGROUND FOR DIFFERENT SCENARIOS

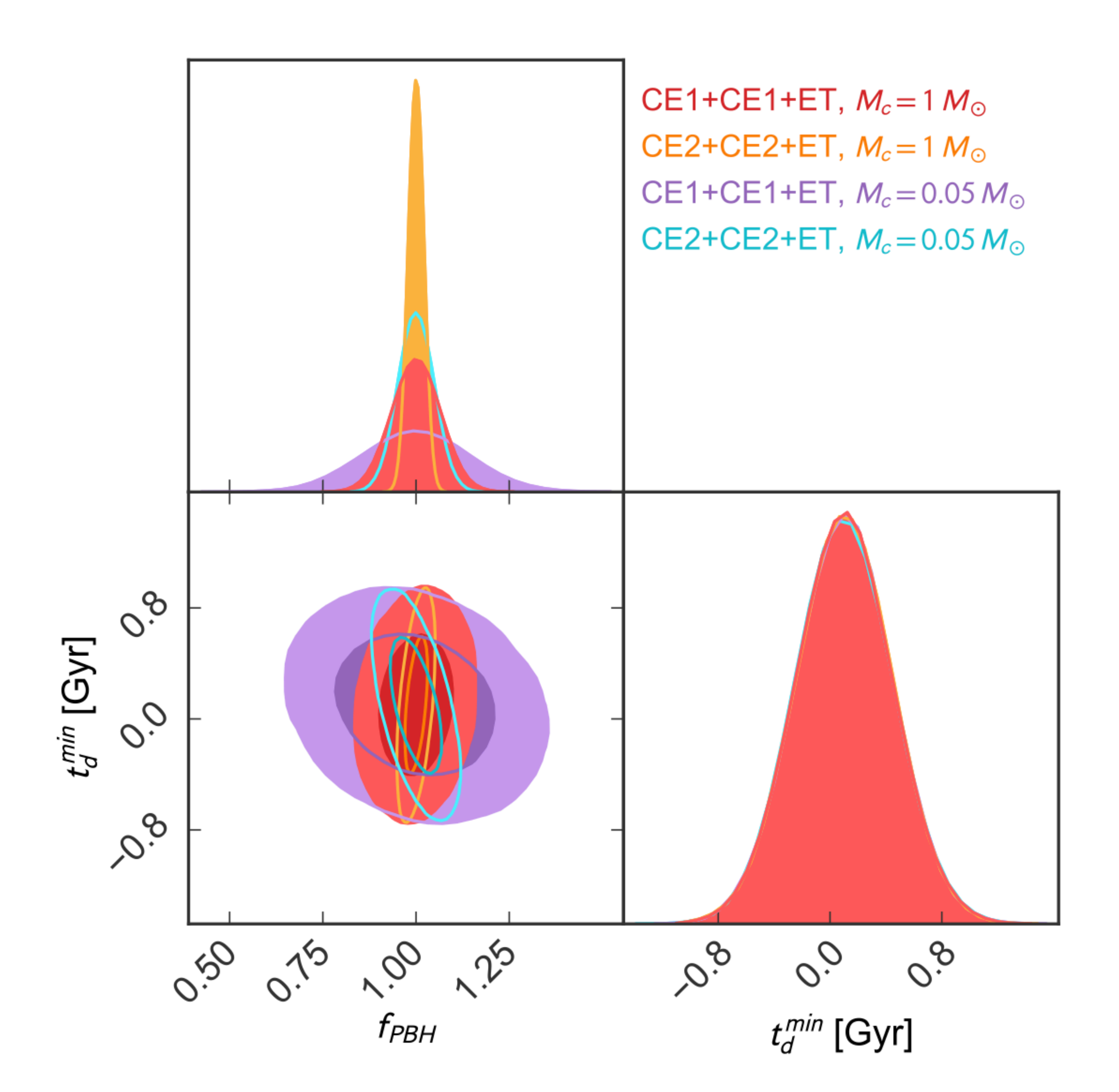
Mukherjee, Meinema, Silk (MNRAS, 510, 4, 2022, 2107.02181)



FORECAST FOR CE AND ET SENSITIVITY TO DISTINGUISH ABHS AND PBHS

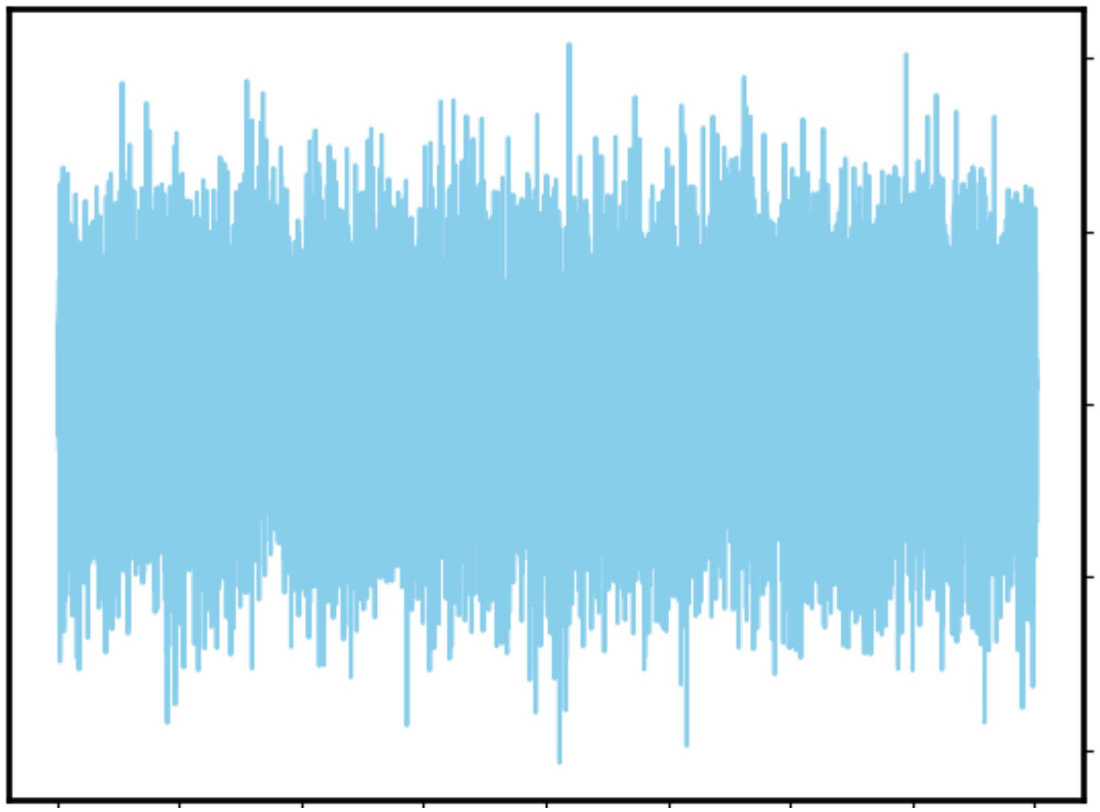
Take home message: We can distinguish between the population of ABHs and PBHs at the lower mass end.

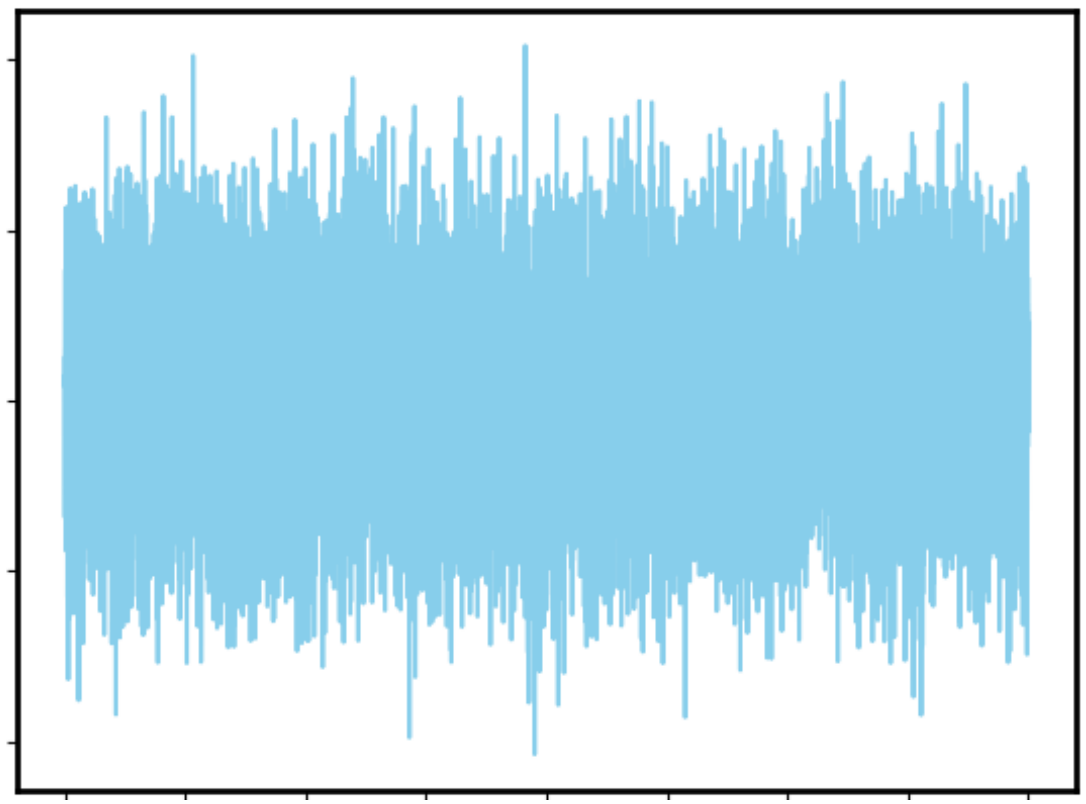
Mukherjee, Meinema, Silk (MNRAS, 510, 4, 2022, 2107.02181)



IS POWER SPECTRUM THE SUFFICIENT STATISTICS?

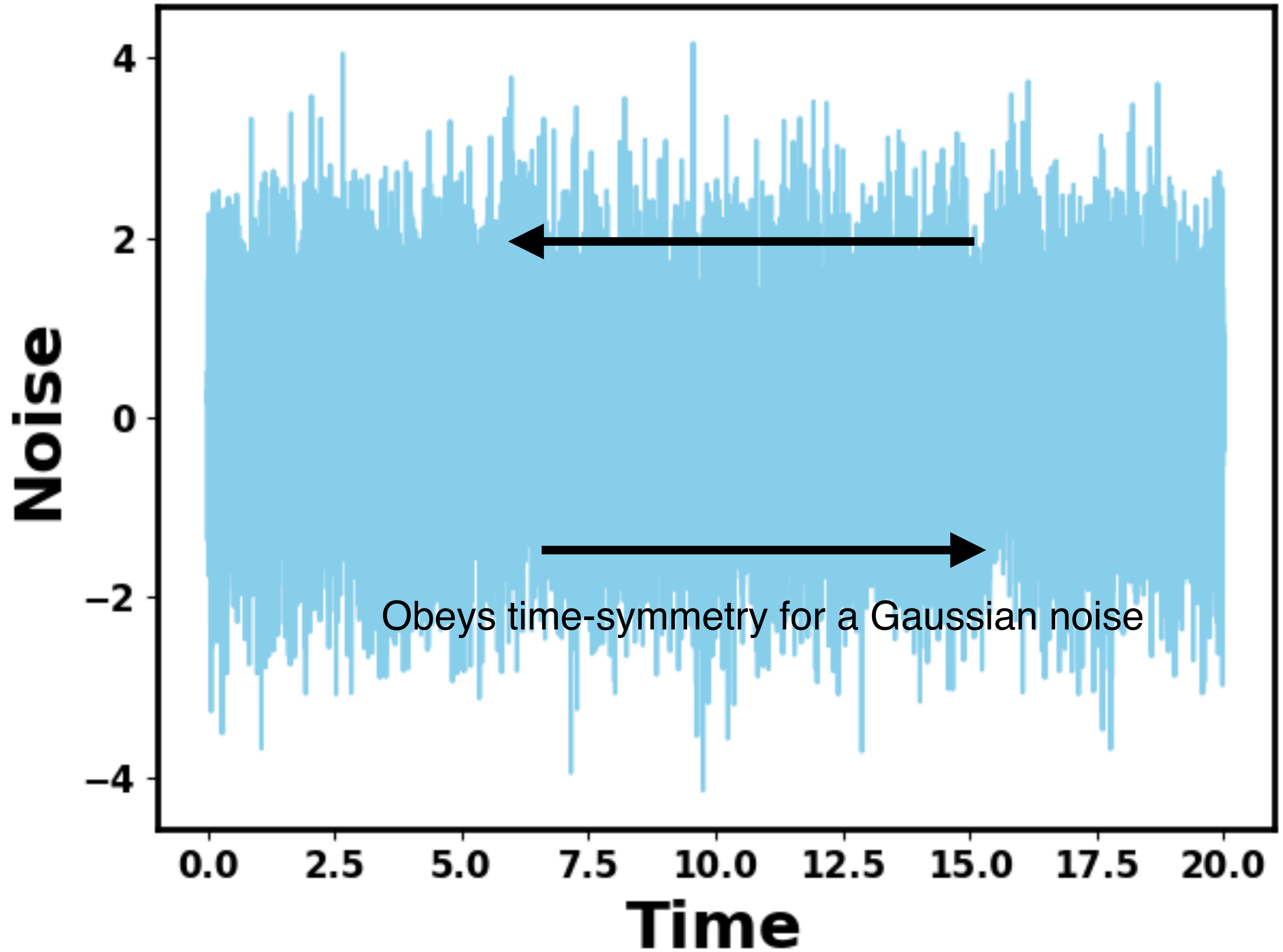
IS SGWB SIGNAL TIME-REVERSAL?





IS SGWB SIGNAL TIME-REVERSAL?

Sah and Mukherjee (2023)



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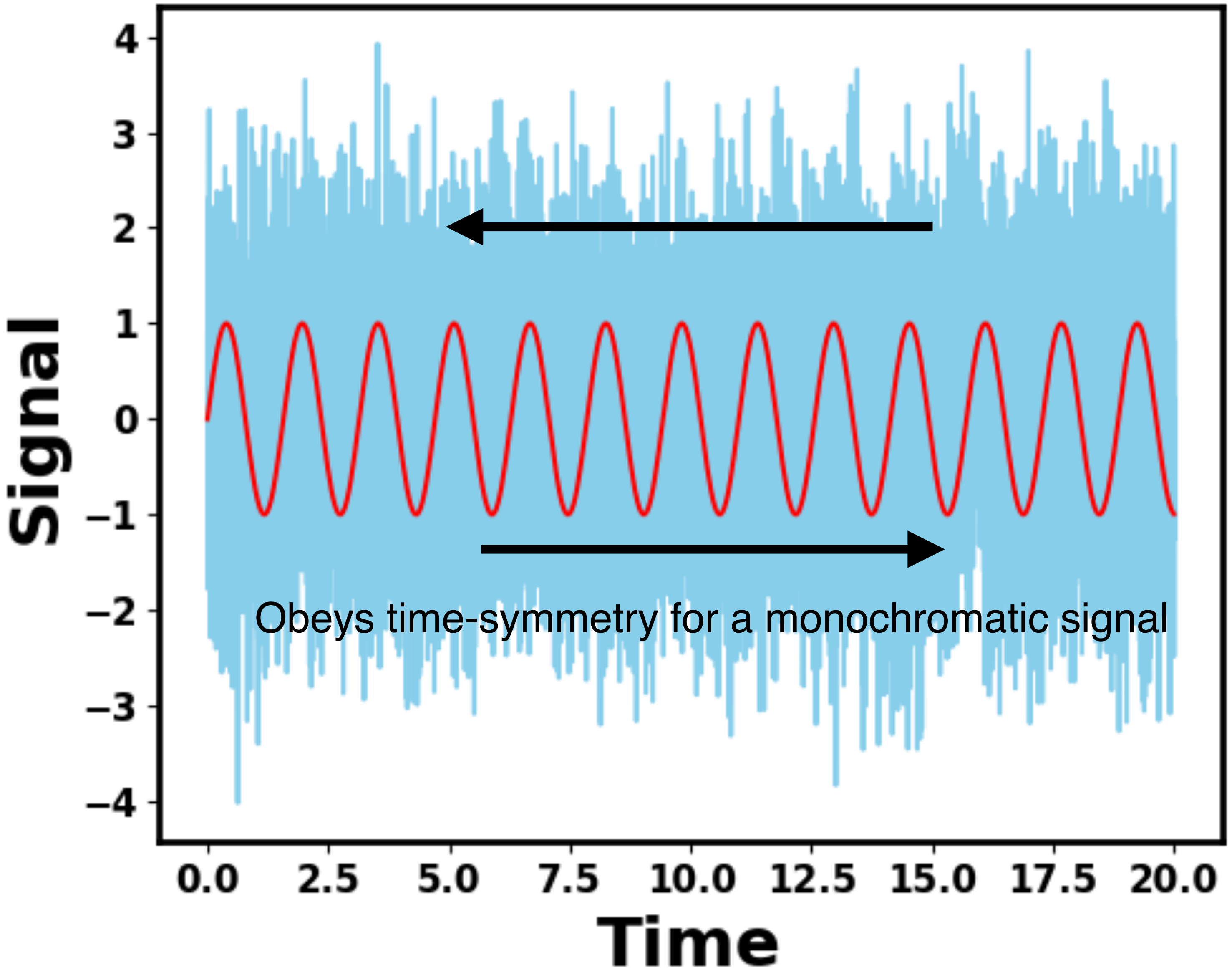
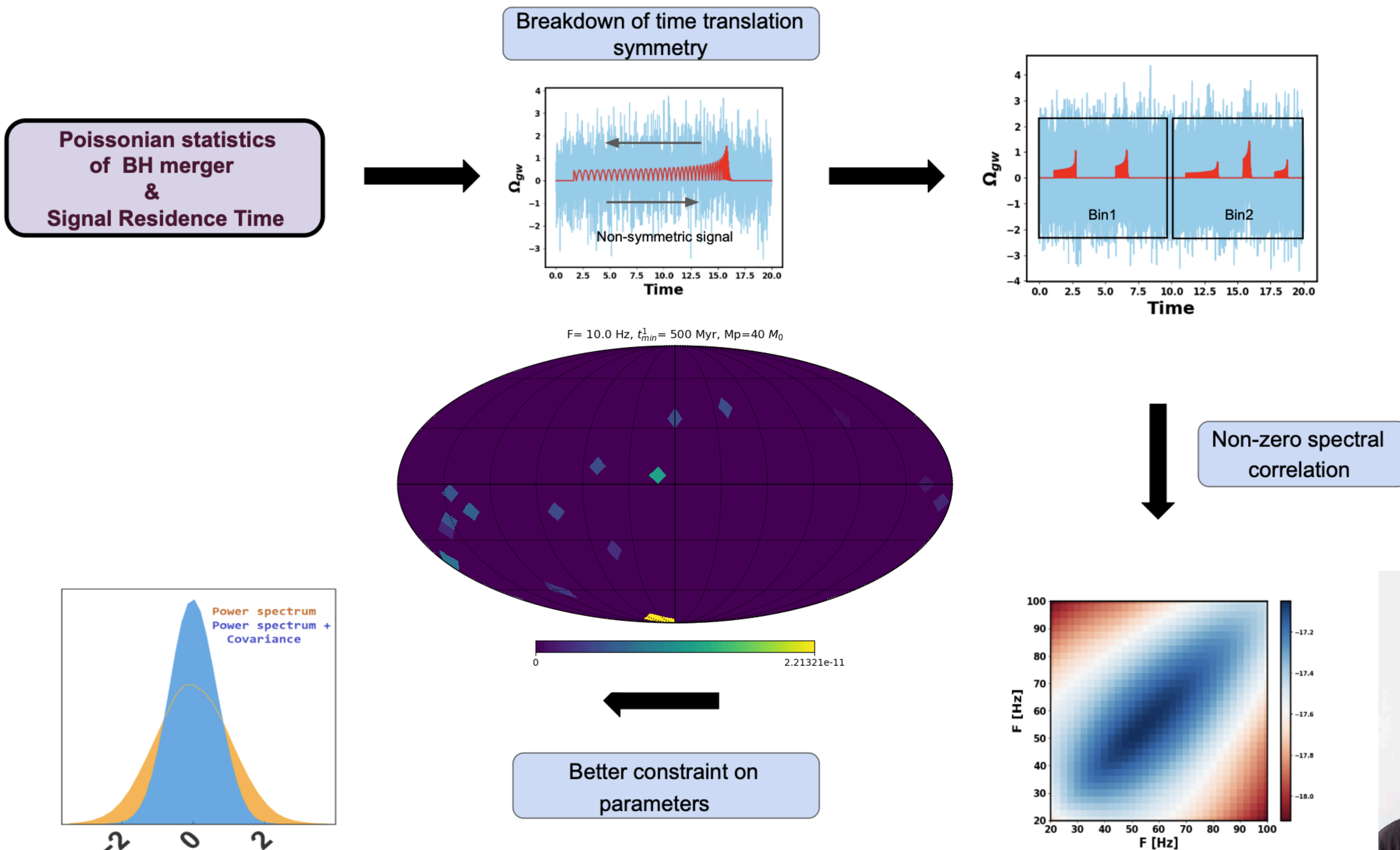


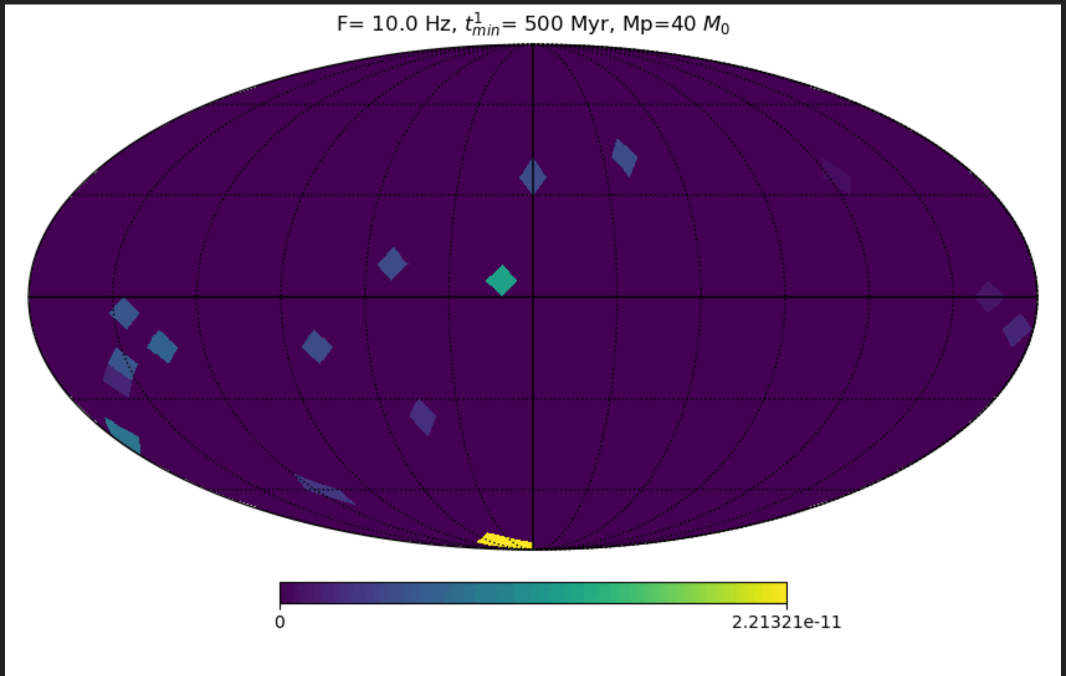
BREAK DOWN OF TIME-TRANSLATION SYMMETRY LEADS TO CORRELATION IN THE SIGNAL COVARIANCE MATRIX

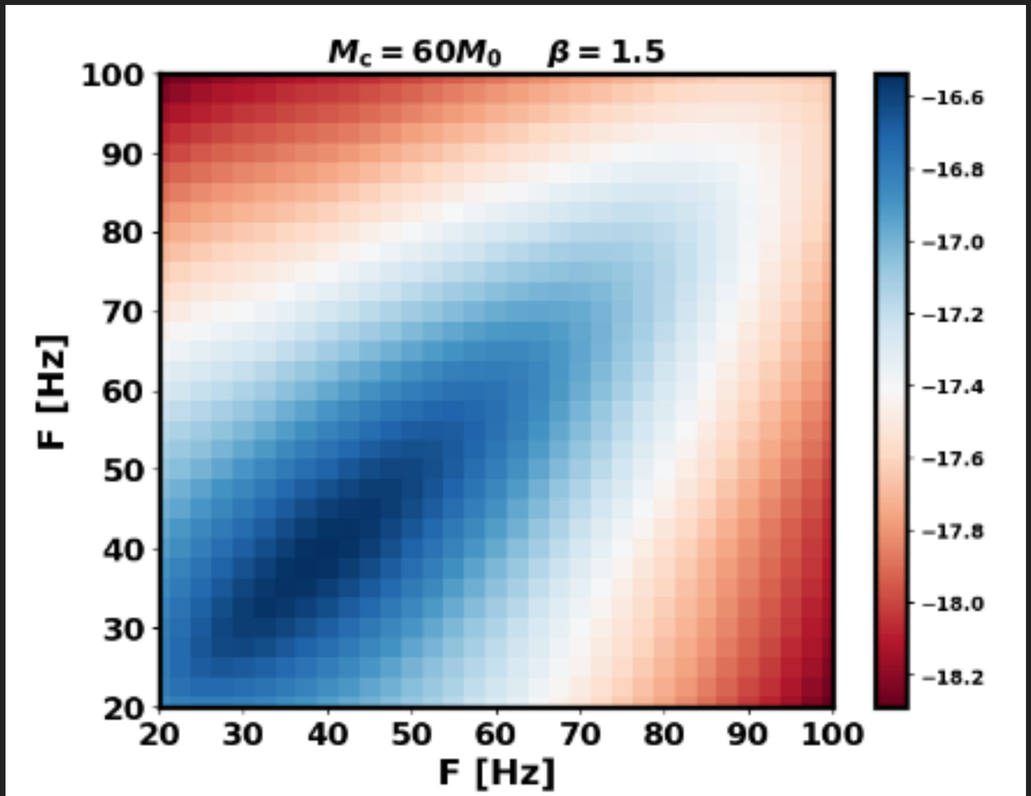
Sah and Mukherjee (2023)

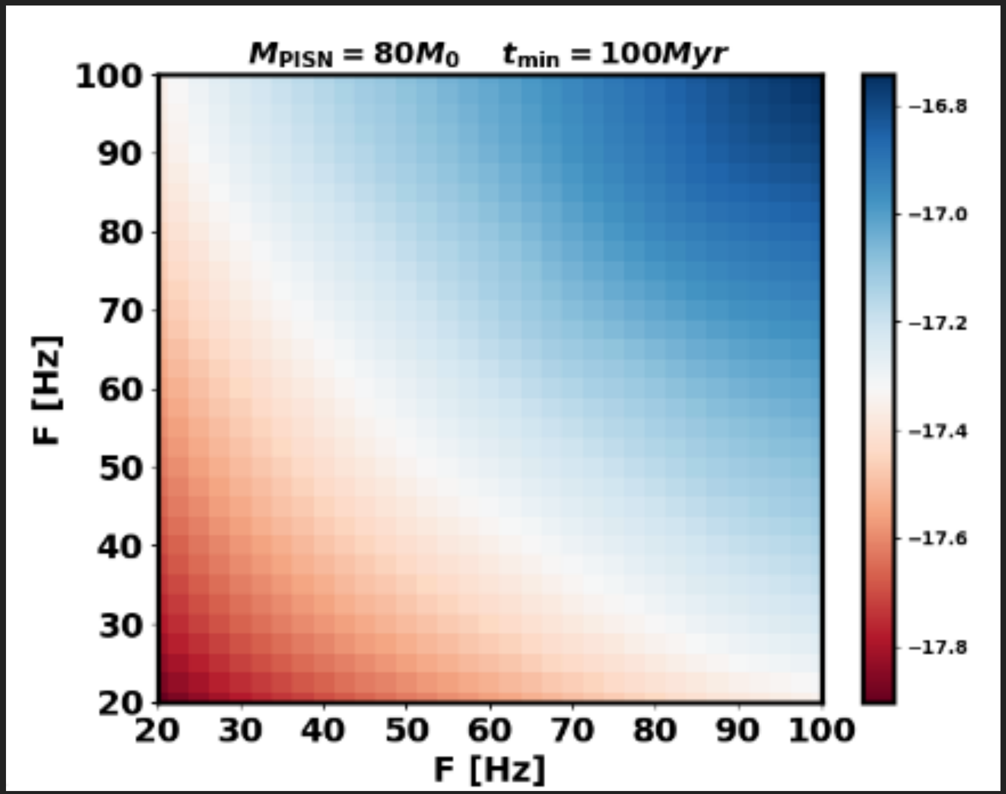


BLACK HOLE PROPERTIES AT HIGH REDSHIFT CAN BE PROBED USING BREAKDOWN OF TIME-SYMMETRY

Sah and Mukherjee (2023)







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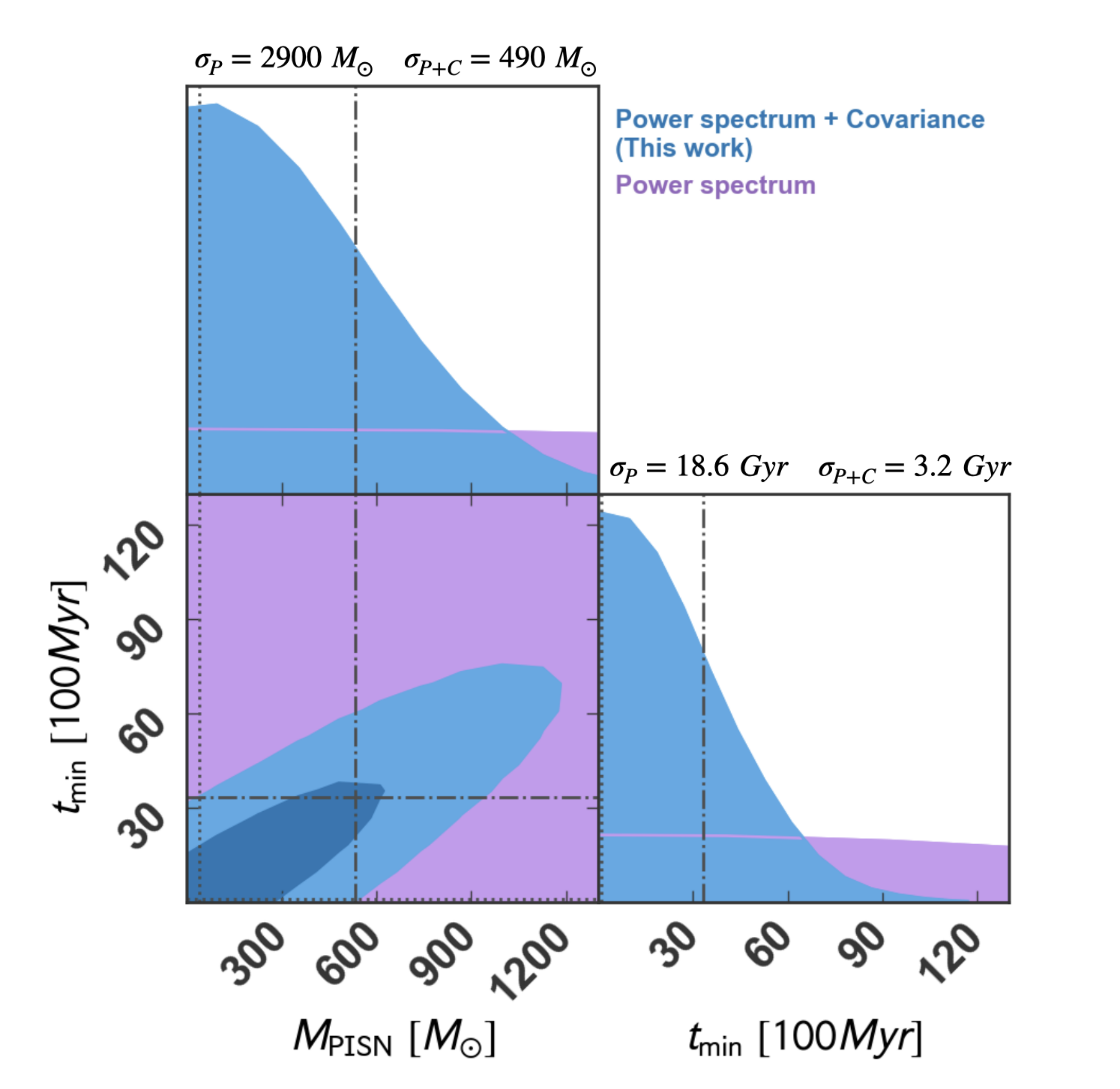
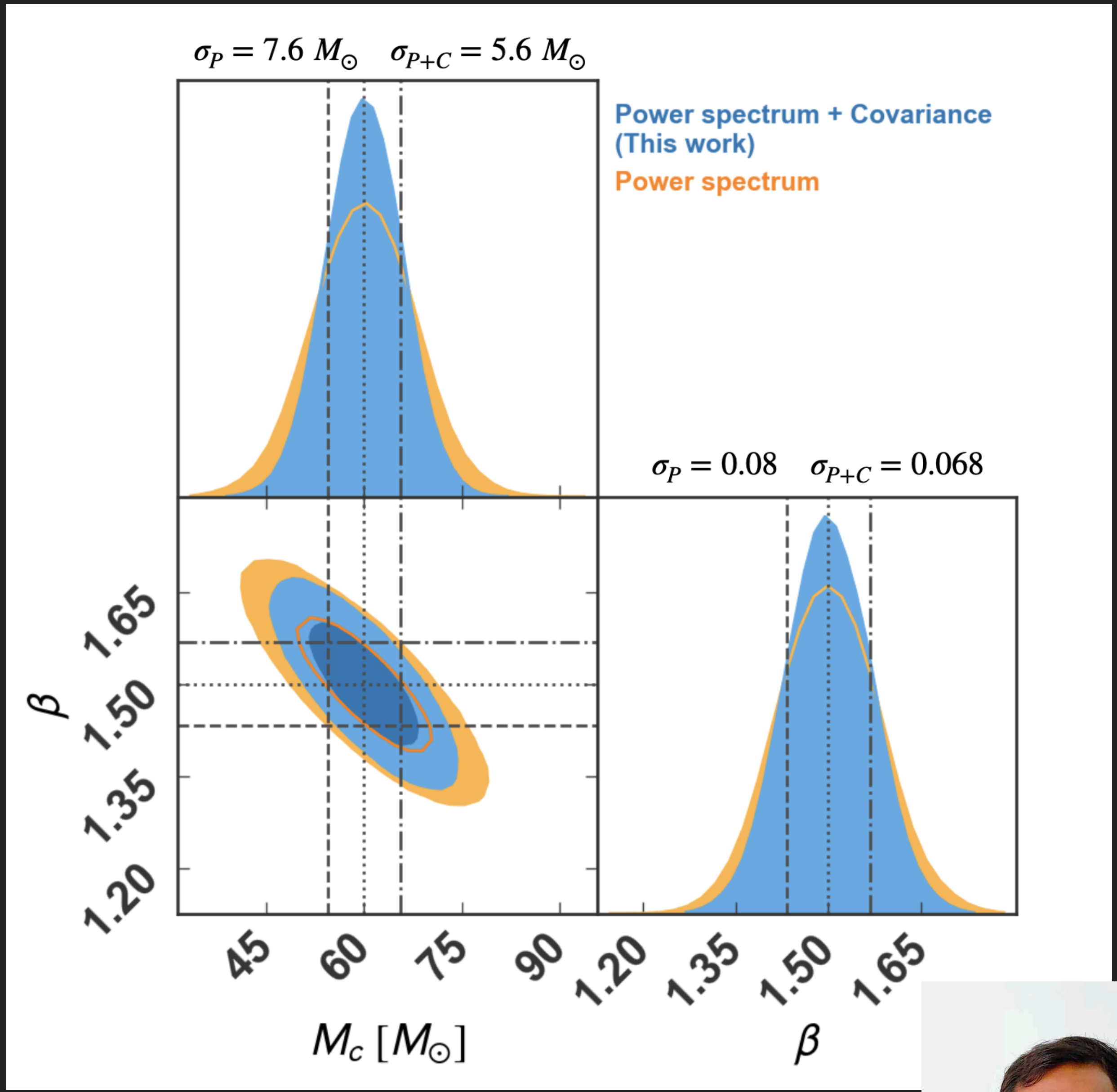
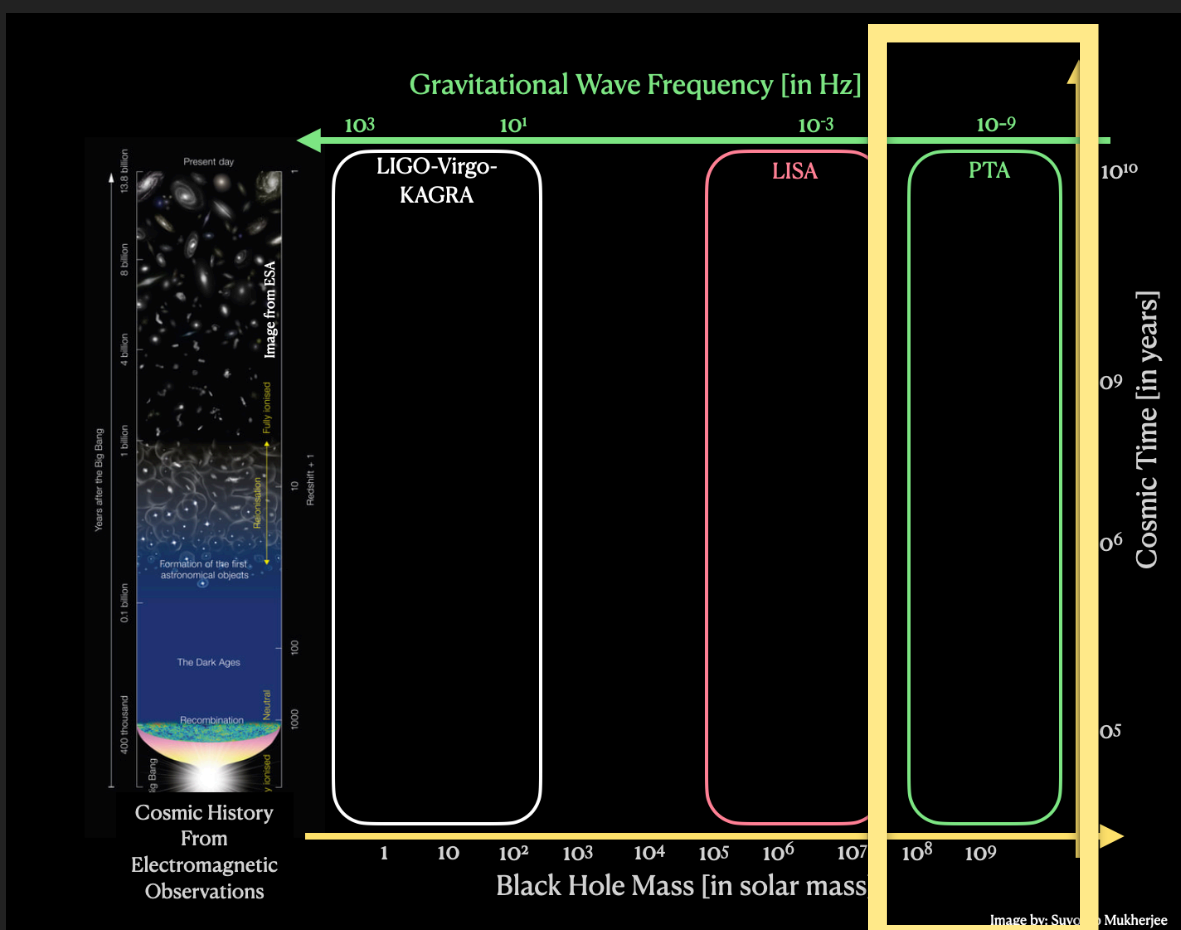


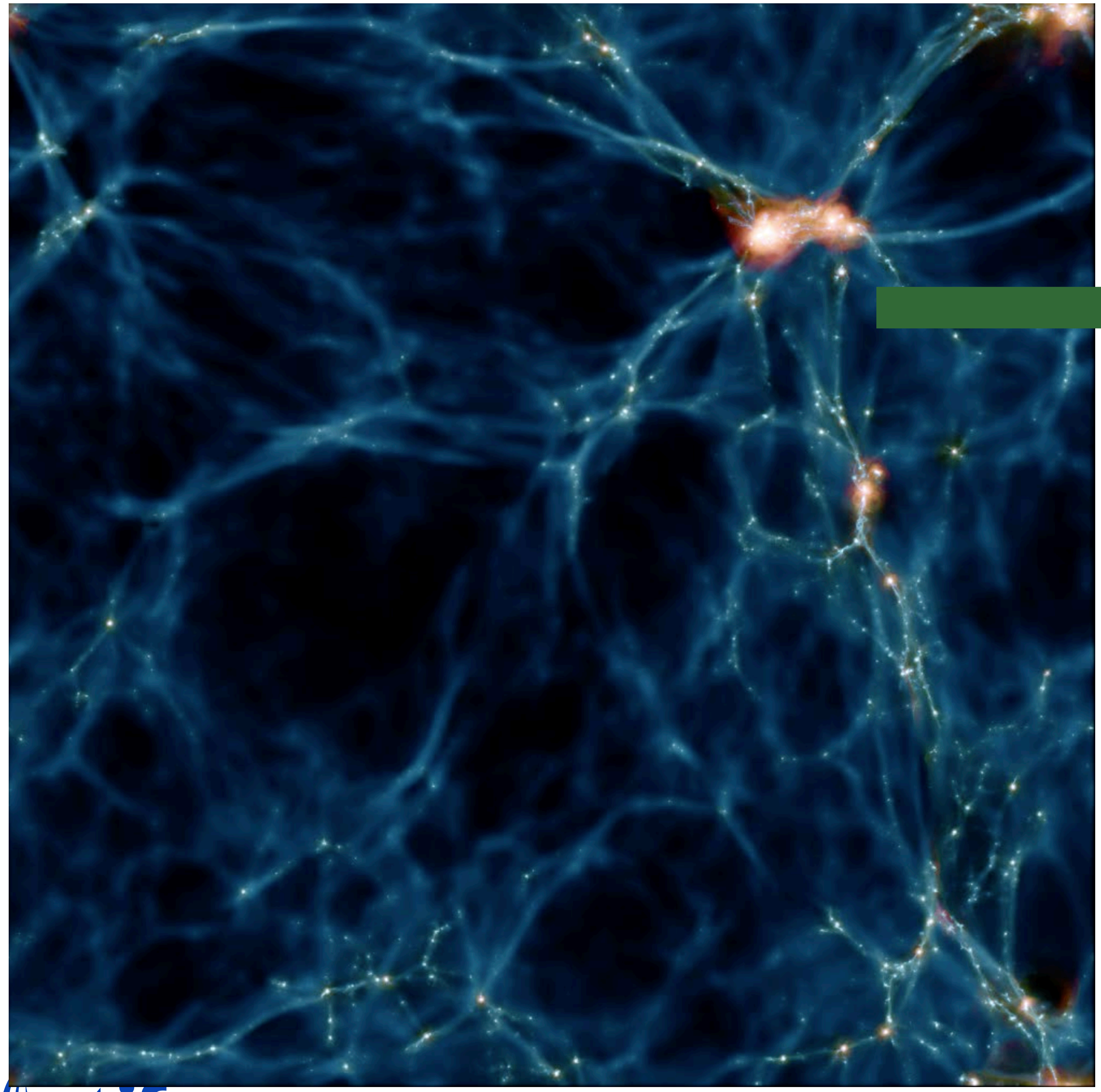




HIGH REDSHIFT UNIVERSE @NANO-HERTZ

Using PTA GW sources

WHERE ARE THE BIG BLACK HOLES FORMING?

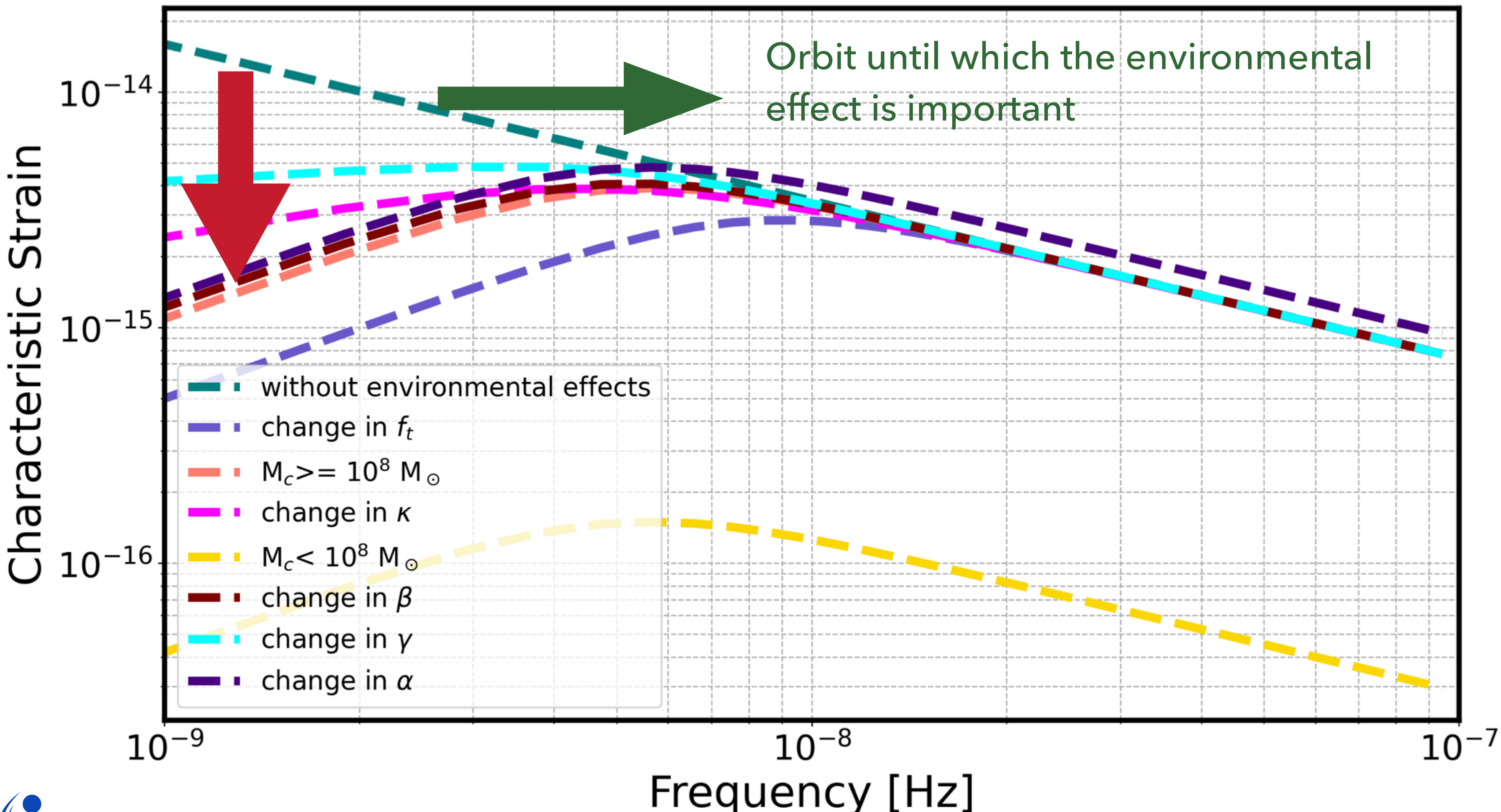


Gravitational Waves from VERY Big Black Holes

ASTROPHYSICAL SGWB SIGNAL IN THE NANO-HZ RANGE FROM SMBBHS

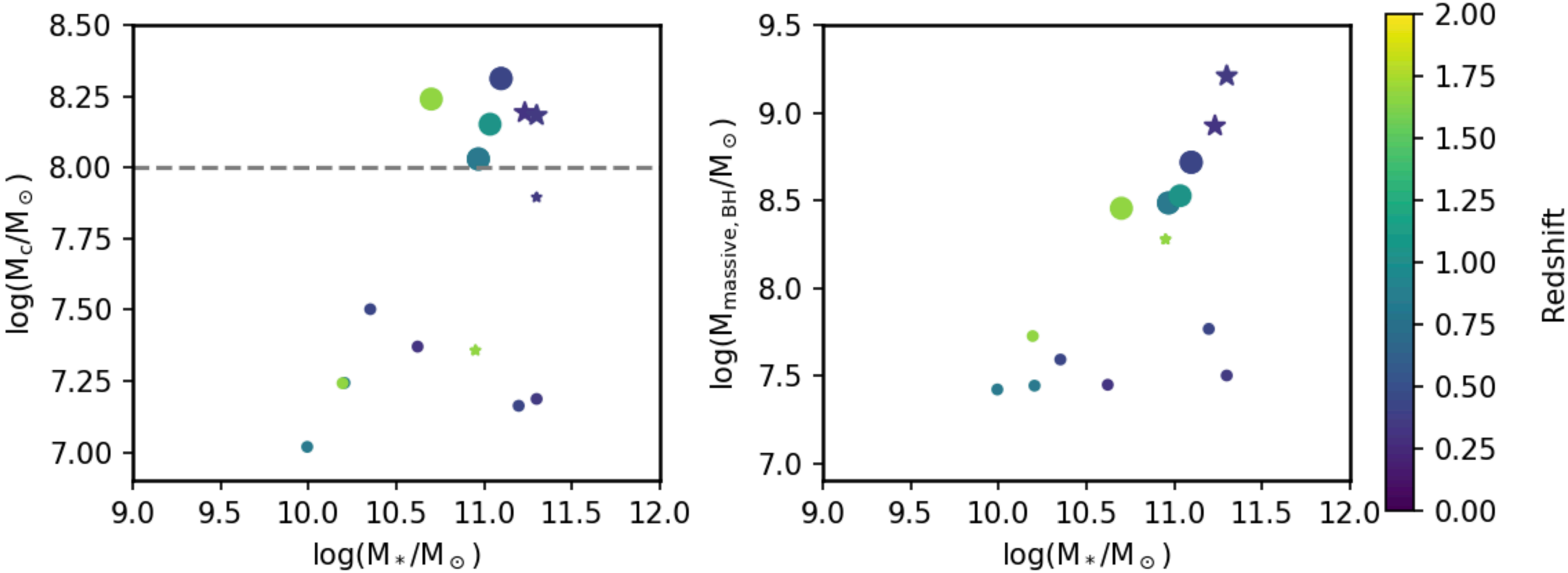
How much energy is lost in the interaction with the environment

Saeedzadeh , Mukherjee, Babul, Tremmel, Quinn (2024)



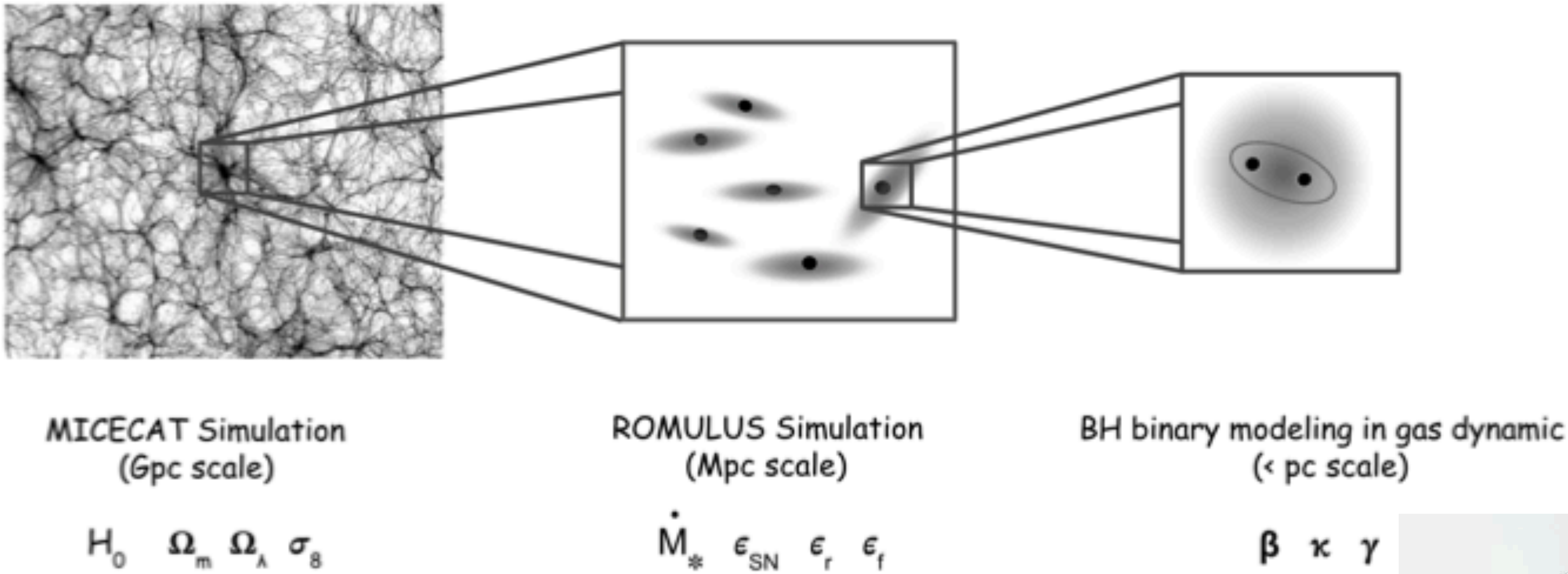
PROPERTIES OF THE SOURCES OF THE HOST OF THE BLACK HOLES

Saeedzadeh , Mukherjee, Babul, Tremmel, Quinn (2024)



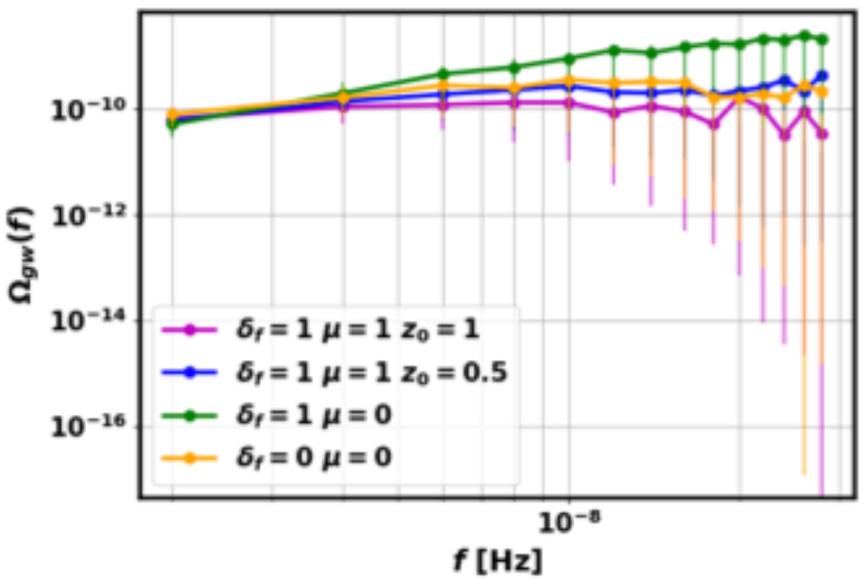
BRIDGING THE SCALES: ADAPTIVE TECHNIQUE

Sah, Mukherjee, Saeedzadeh, Babul, Tremmel, Quinn (2024)

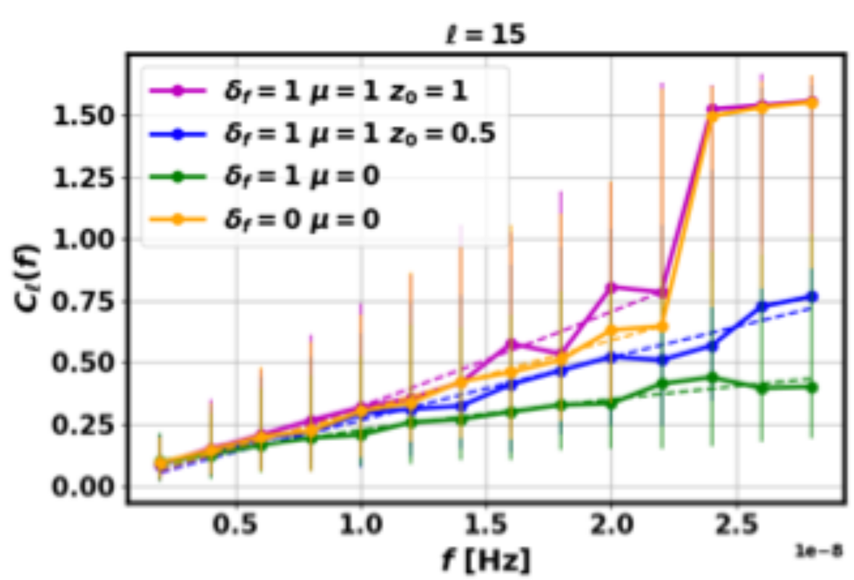


SPECTRAL AND SPATIAL ANISOTROPY IN NANO-HERTZ GW

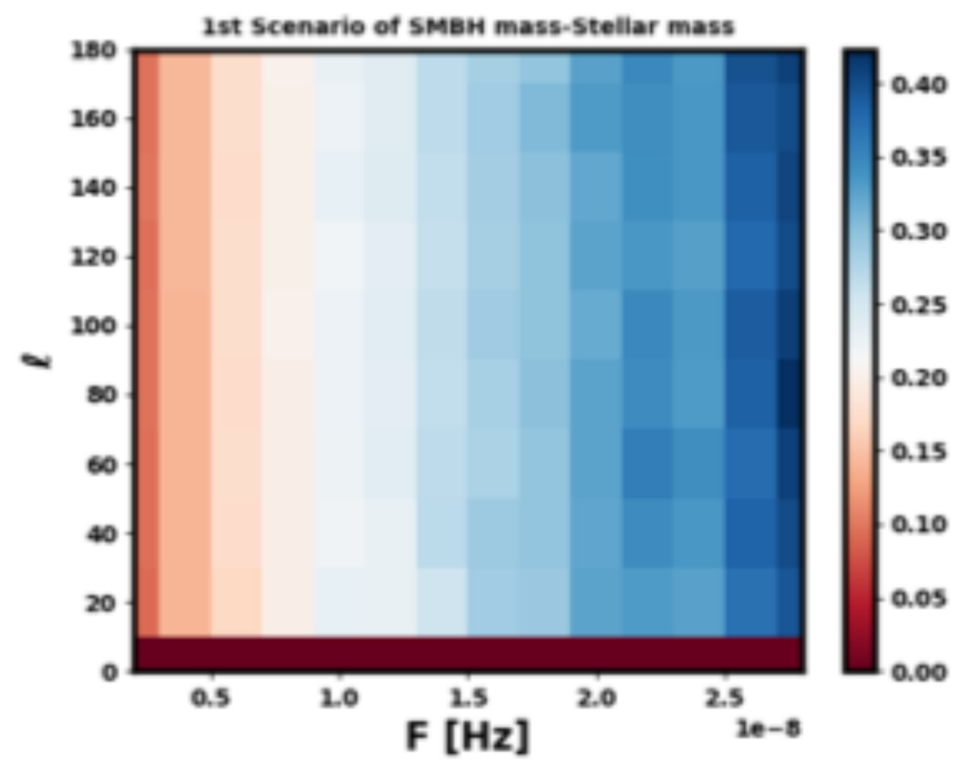
Sah, Mukherjee, Saeedzadeh, Babul, Tremmel, Quinn (2024)



(a)



(b)

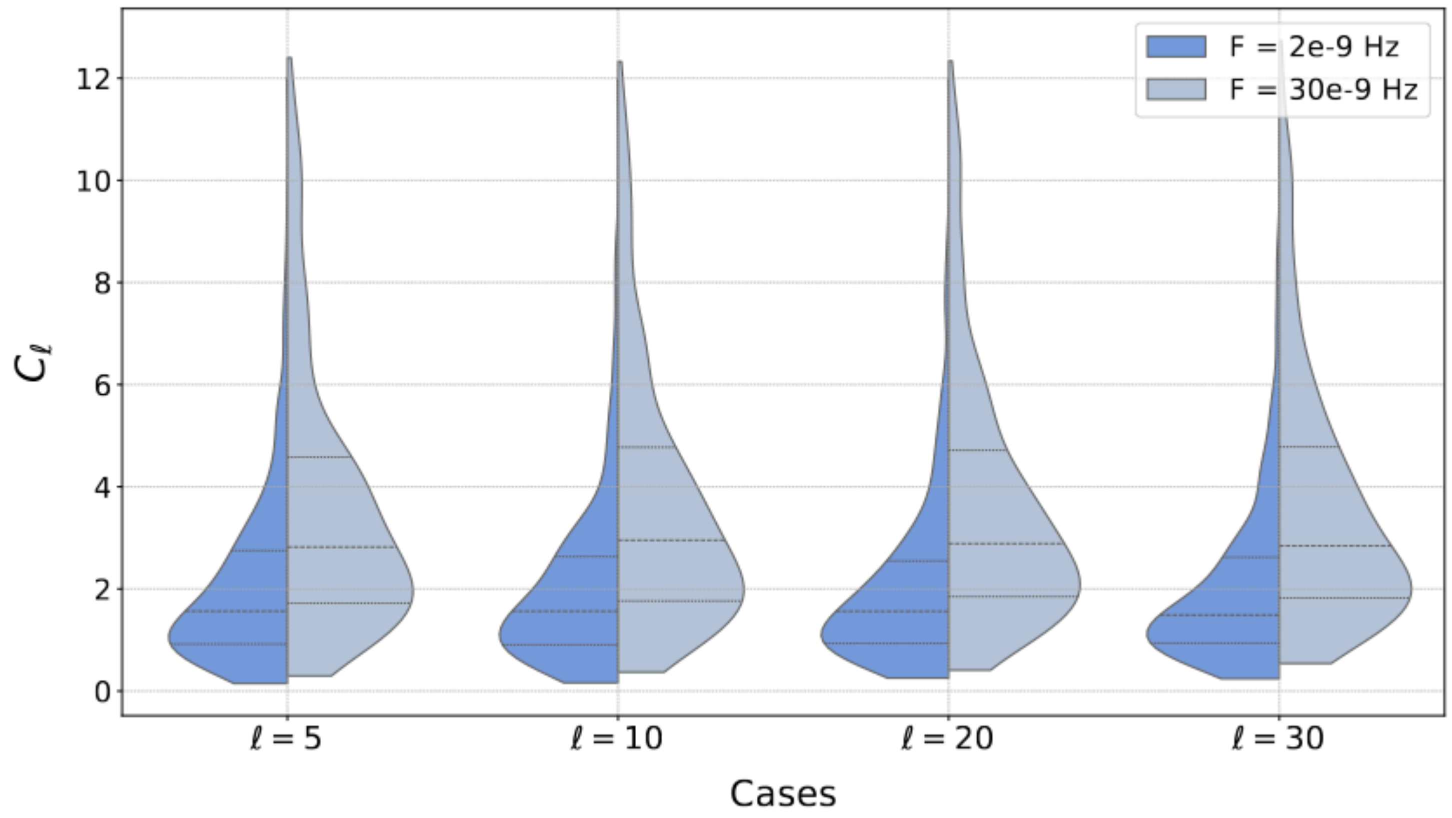


(a)

SPECTRAL AND SPATIAL ANISOTROPY IN NANO-HERTZ GW: HOW TO FIND THEM?

Sah and Mukherjee (2025)

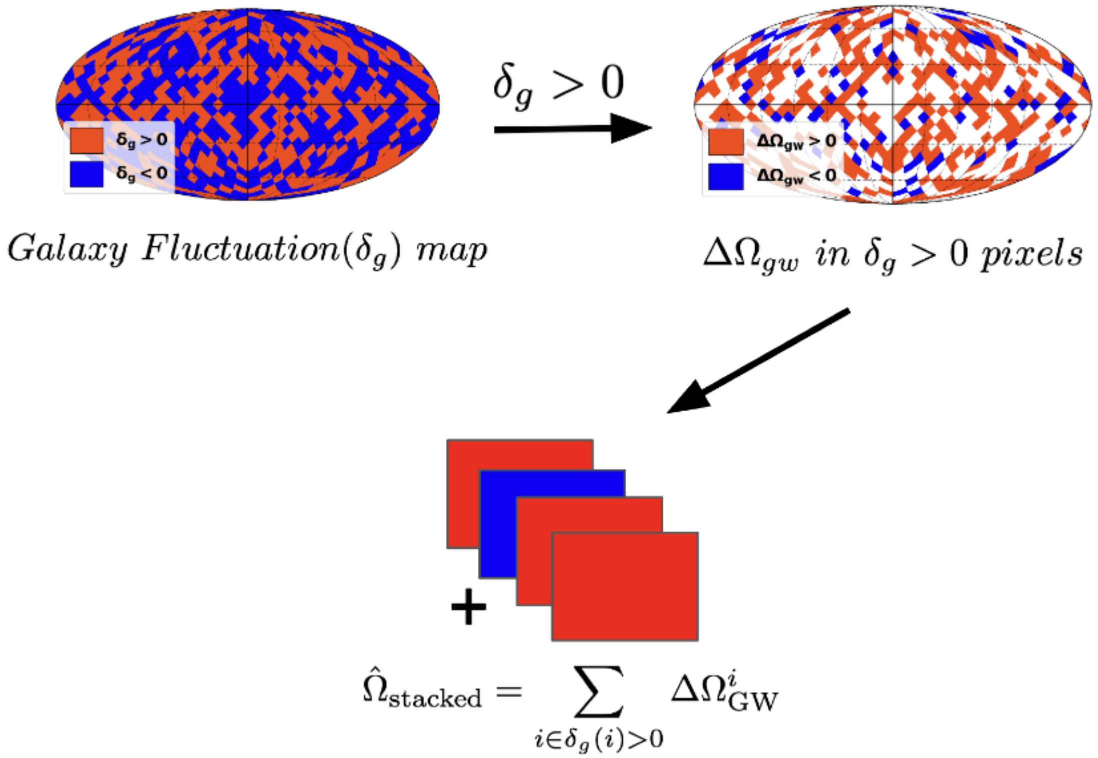
Can we use the angular power spectra?



MULTI-TRACER CORRELATED STACKING: A NEW TECHNIQUE

Sah and Mukherjee (2025)

Can discover anisotropy in nano-hertz GW



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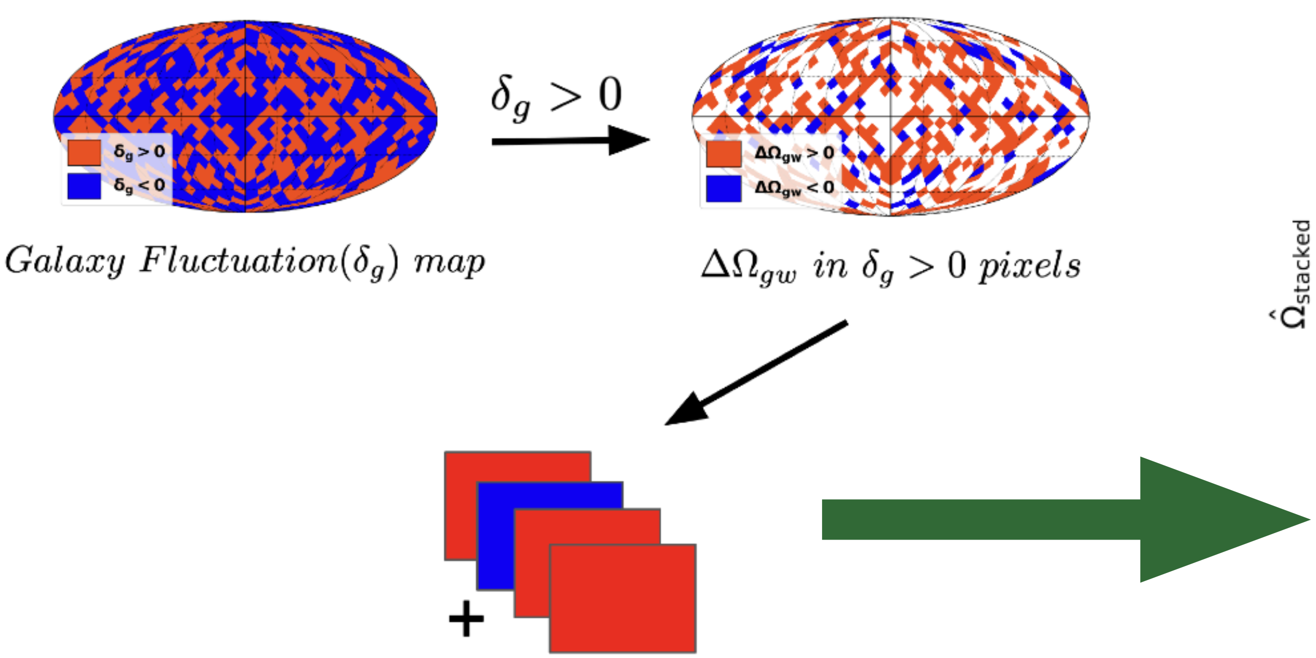
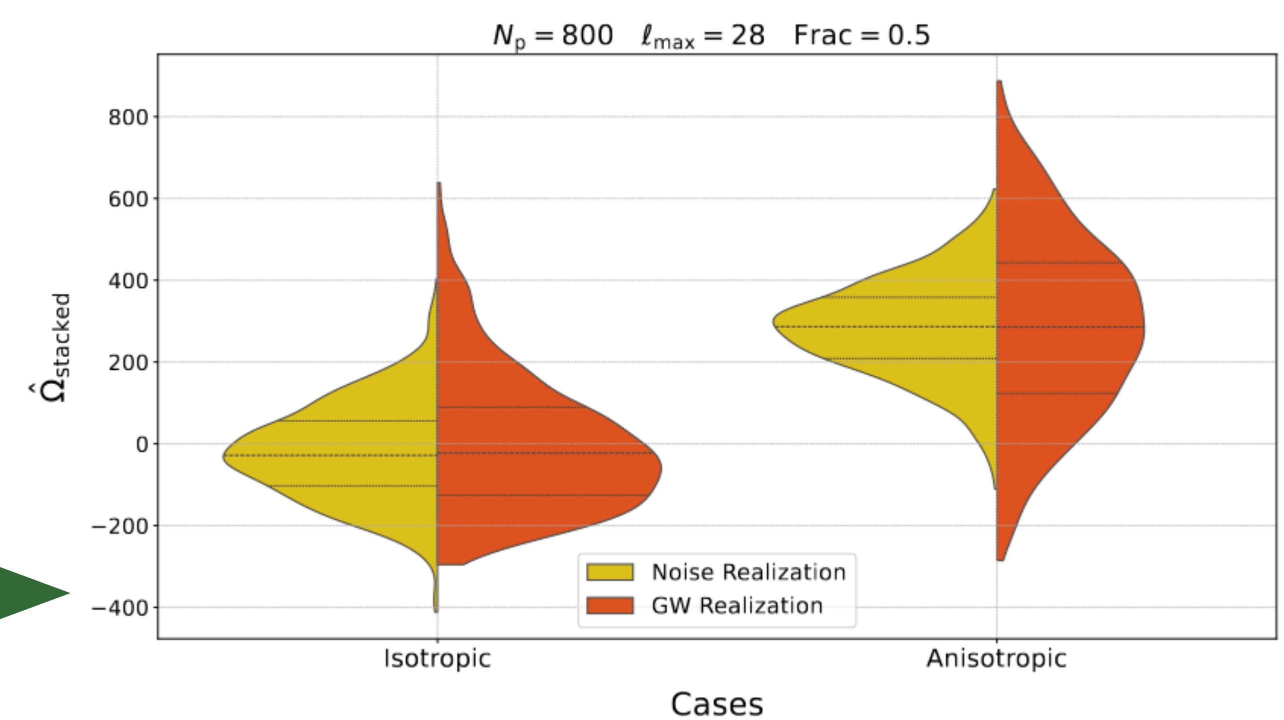


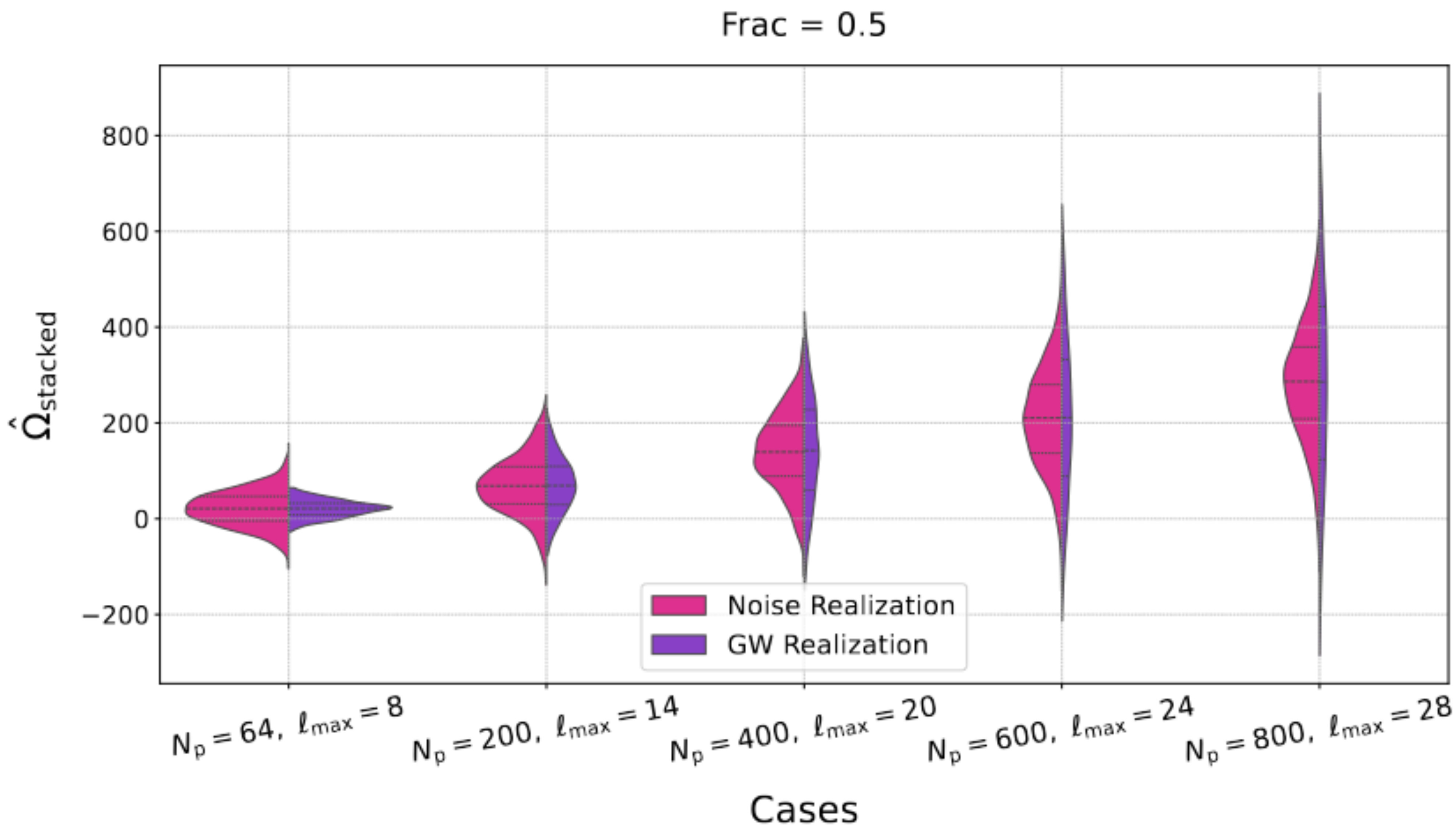
$$\hat{\Omega}_{\rm stacked} = \sum_{i \in \delta_g(i) > 0} \Delta\Omega^i_{\rm GW}$$



MULTI-TRACER CORRELATED STACKING: VARIATION WITH NUMBER OF PULSARS

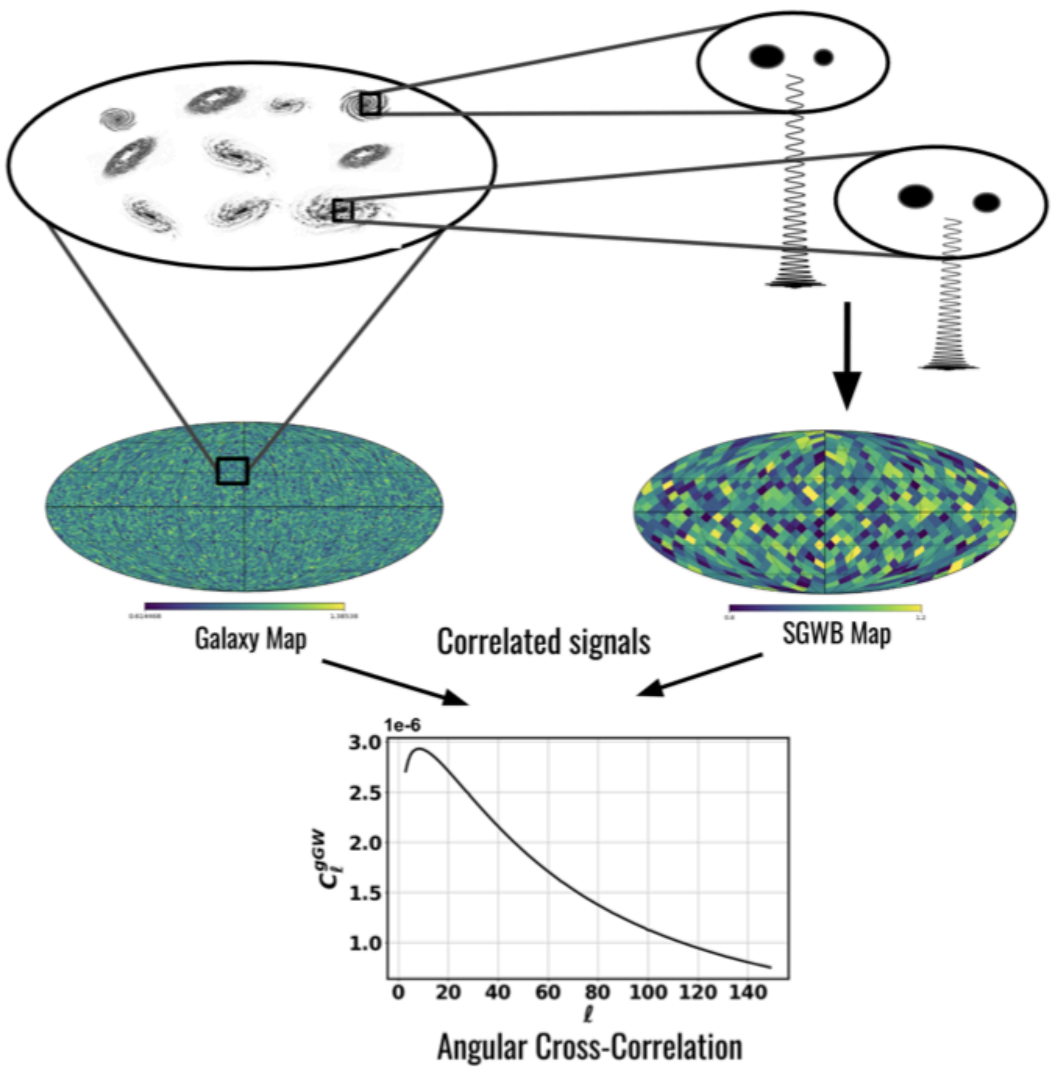
Sah and Mukherjee (2025)

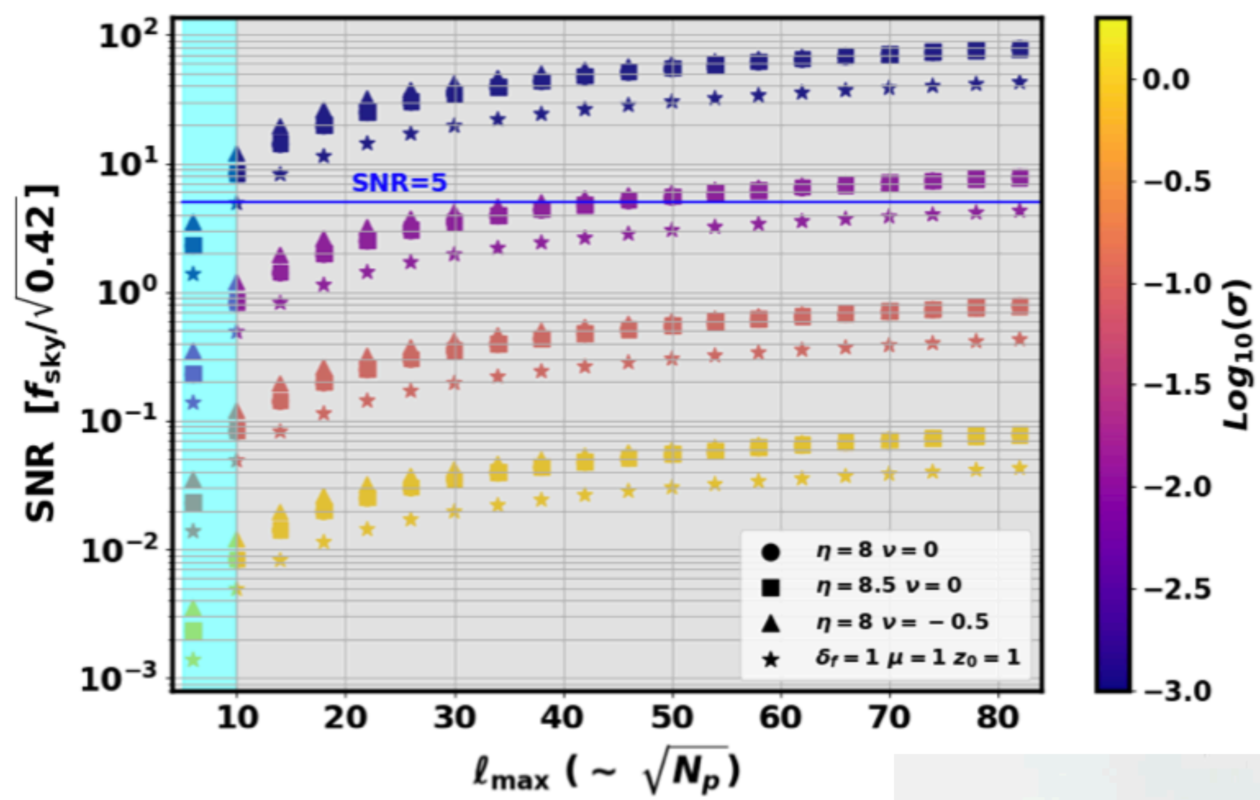
Can discover anisotropy in nano-hertz GW



COSMIC EVOLUTION OF SUPERMASSIVE BLACK HOLES

Sah and Mukherjee (2024)





PROBING THE COSMOS USING STELLAR GRAVEYARDS

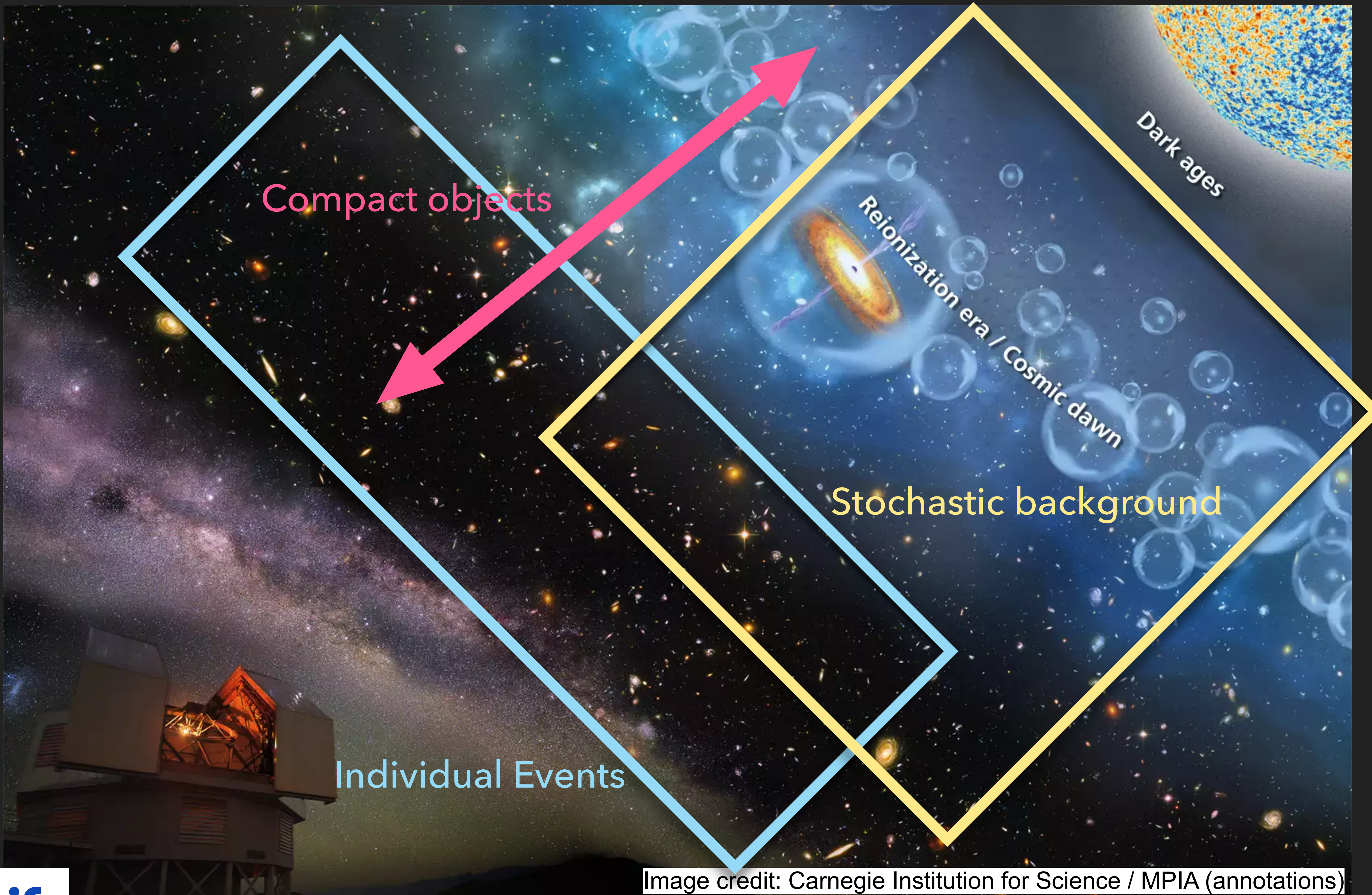
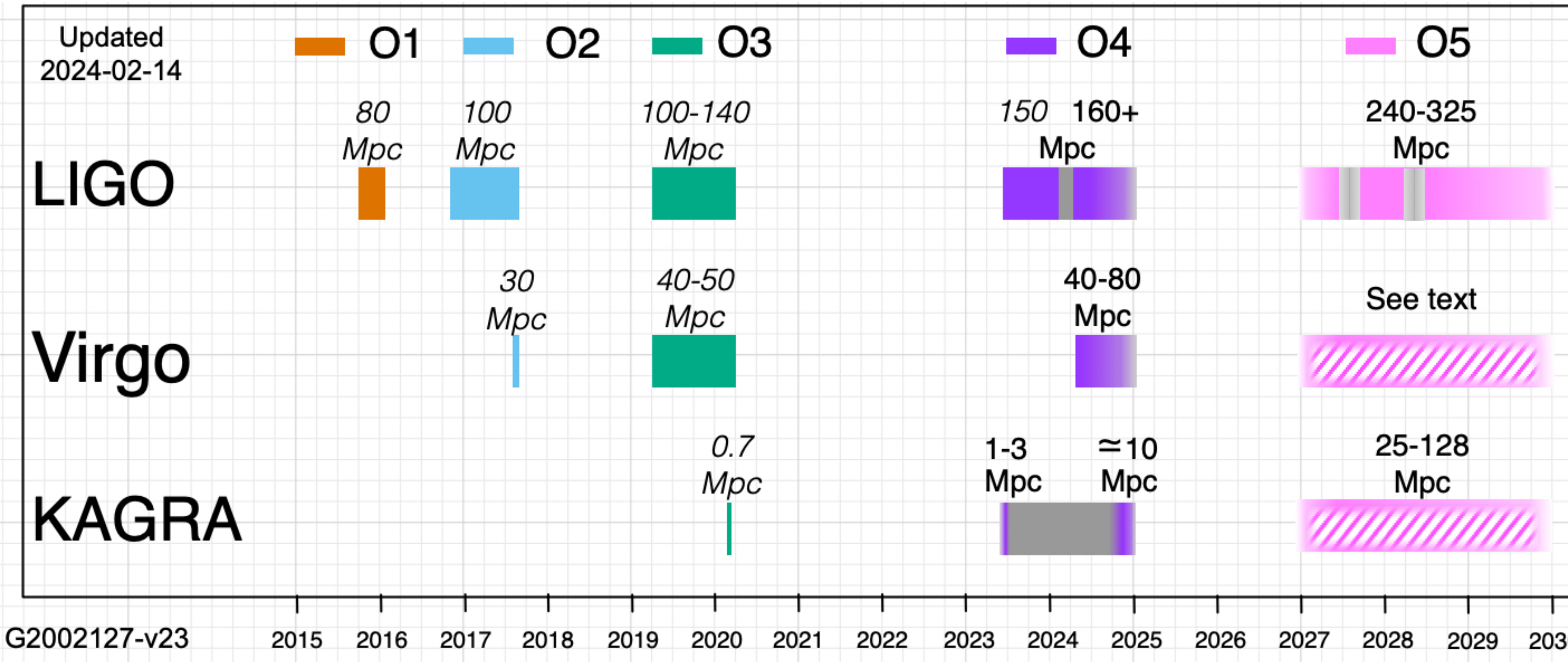


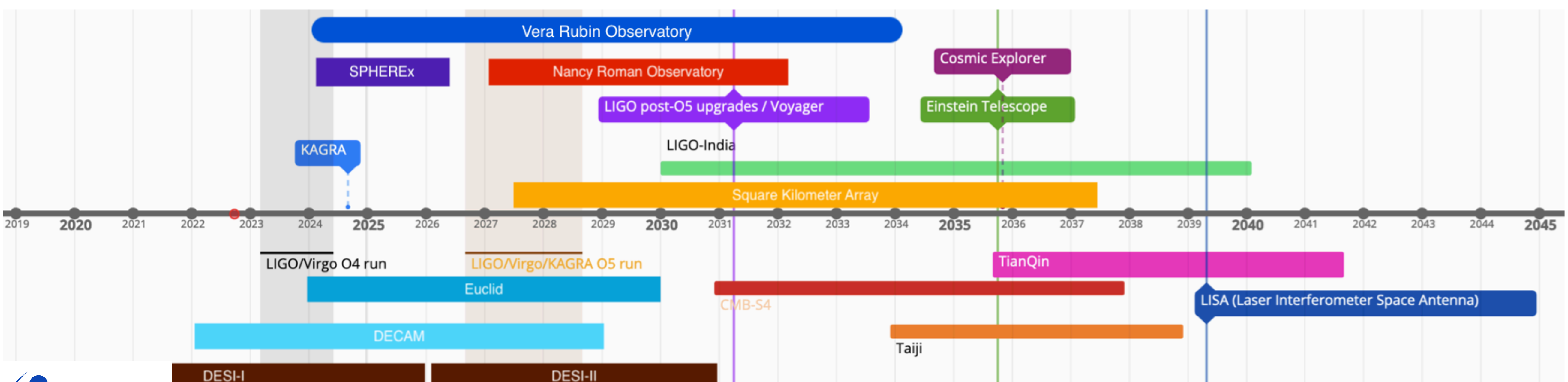
Image credit: Carnegie Institution for Science / MPIA (annotations)

NEW SCIENCE FRONTIERS WITH NEW OBSERVATIONAL PROBES



Marking National Technology Day 2023, the Prime Minister launched several scientific projects.

By 2030, the LIGO facility is expected to be operational in Aundha in the Hingoli district of Maharashtra, located approximately 450 km to the east of Mumbai.



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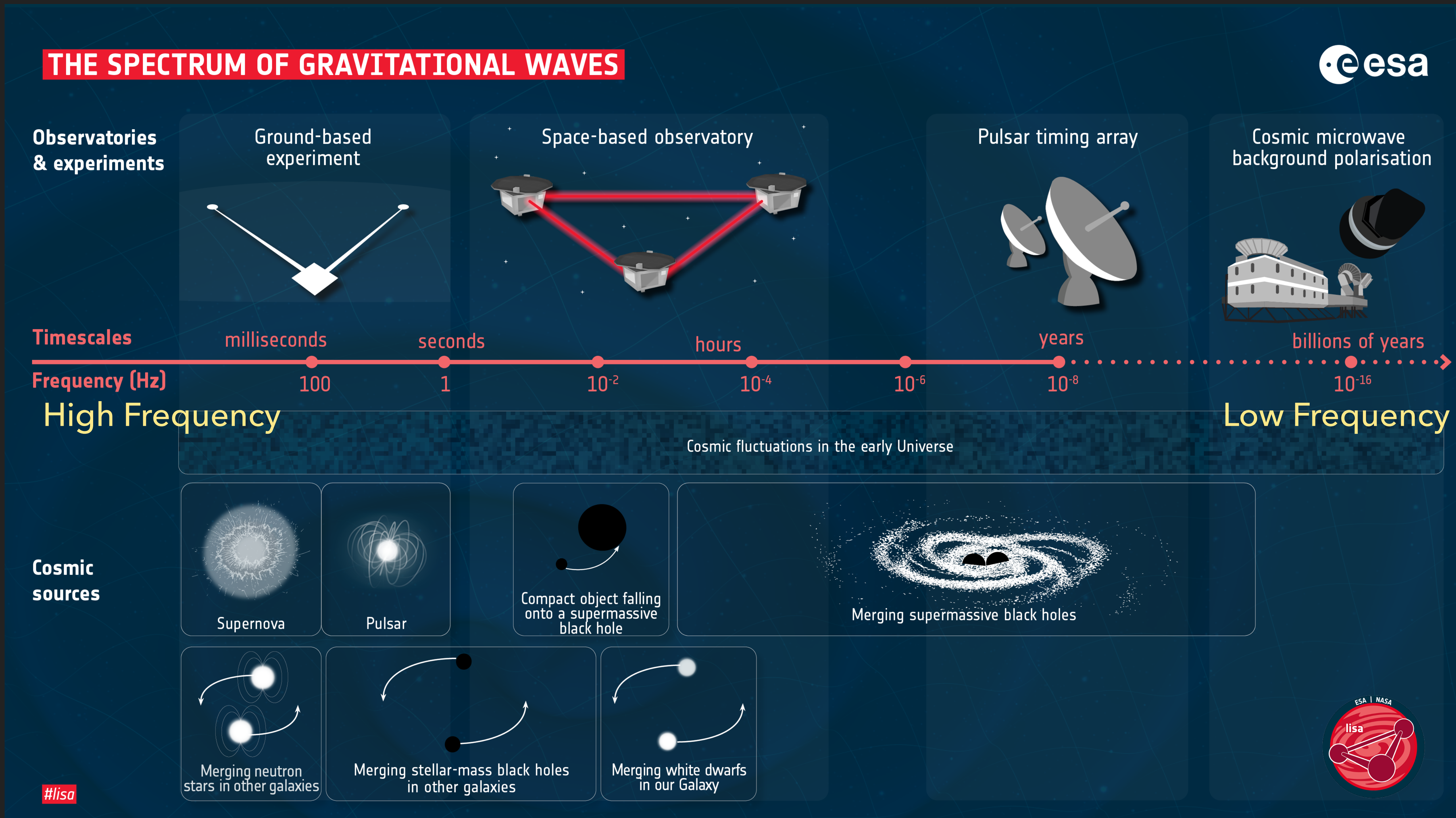
<Data | Theory> Universe Lab@TIFR

WE EXPLORE THE UNIVERSE USING ALL BANDS OF GRAVITATIONAL WAVES



LIGO VIRGO KAGRA

LISC LIGO–India Scientific Collaboration

LISA CONSORTIUM

INTERNATIONAL PULSAR TIMING ARRAY IPTA

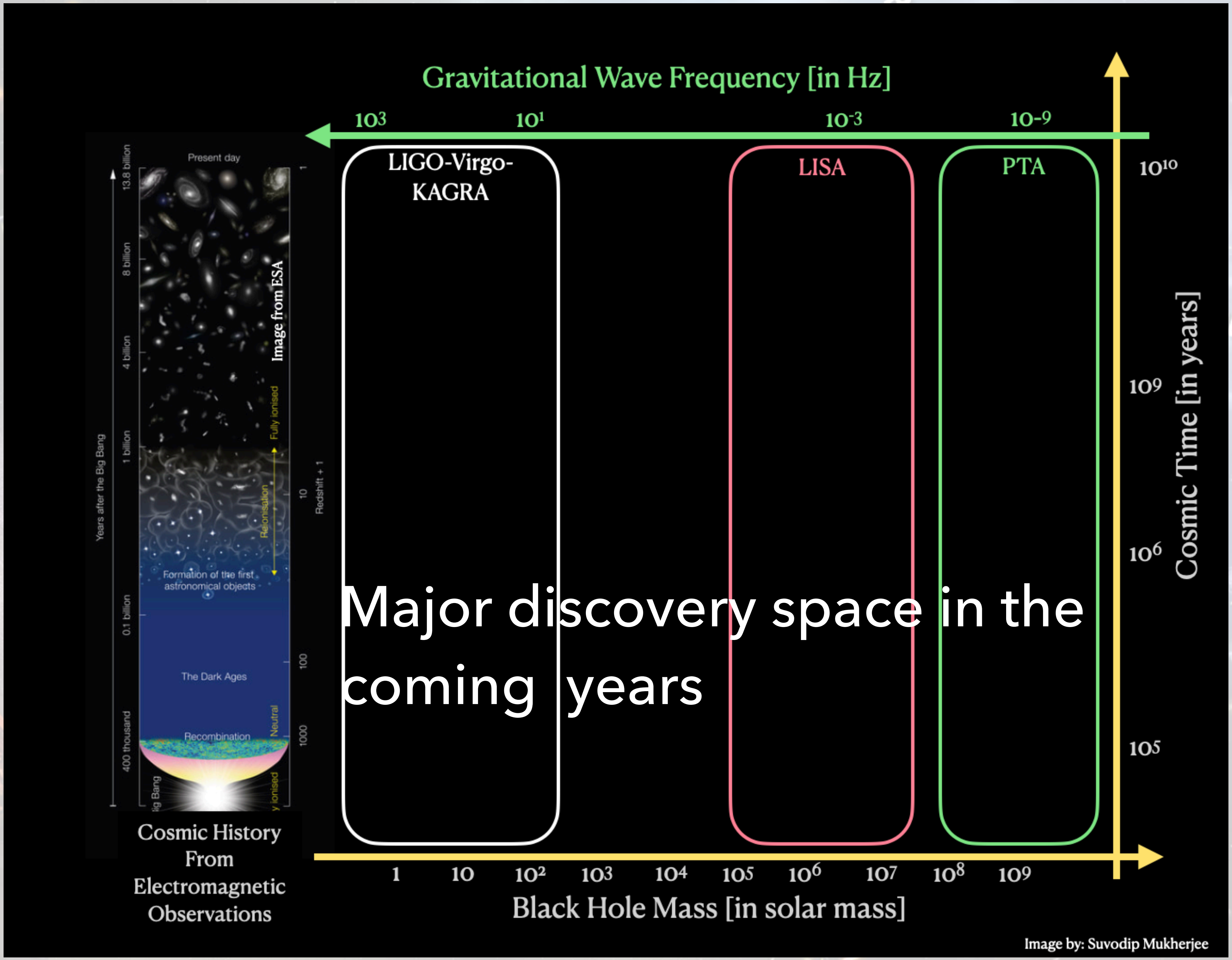
CMB-S4 Next Generation CMB Experiment

tifr

Cosmic Explorer

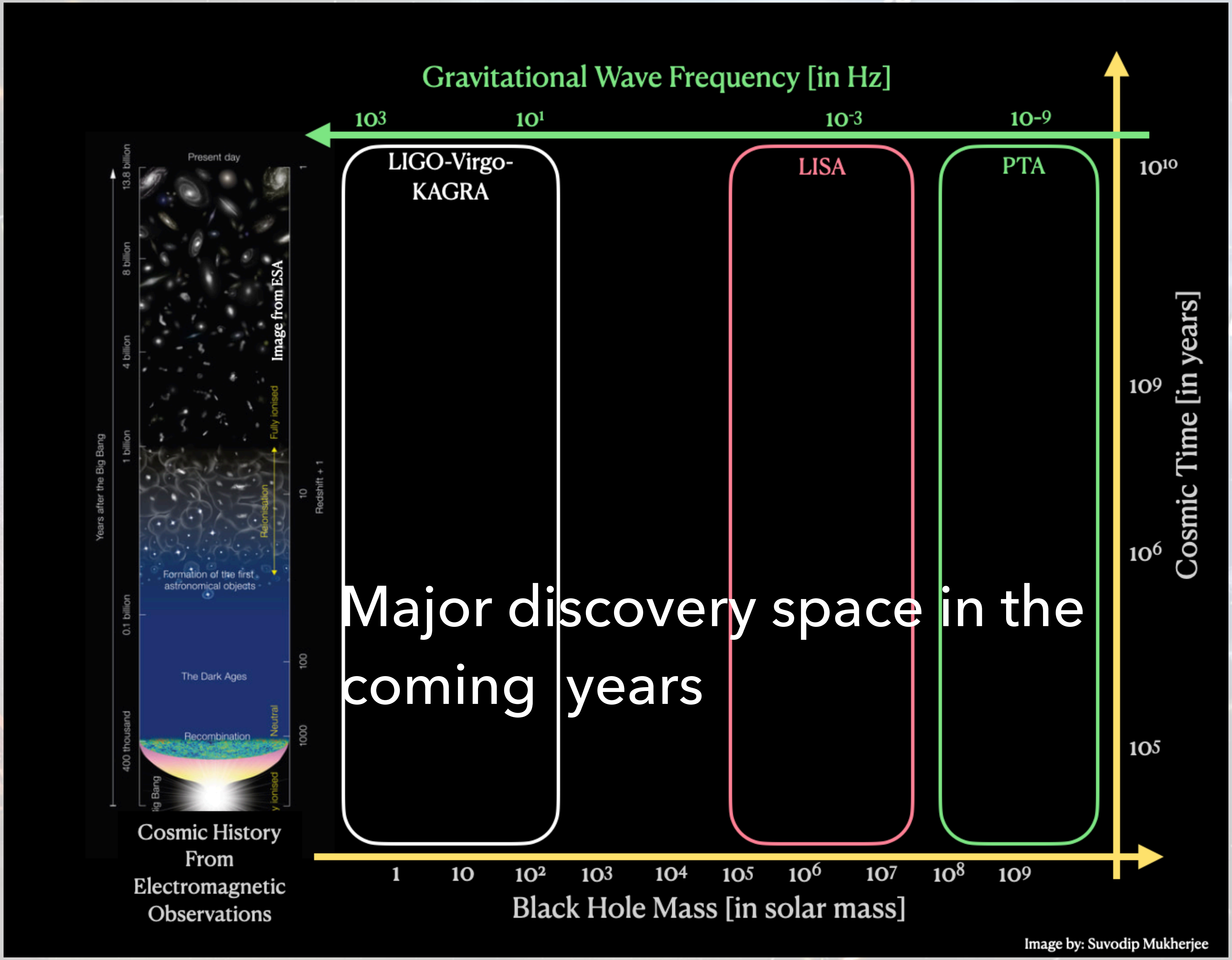
LGWA

DATA DRIVEN INFERENCE OF THE HIGH REDSHIFT UNIVERSE



Major discovery space in the coming years

DATA DRIVEN INFERENCE OF THE HIGH REDSHIFT UNIVERSE

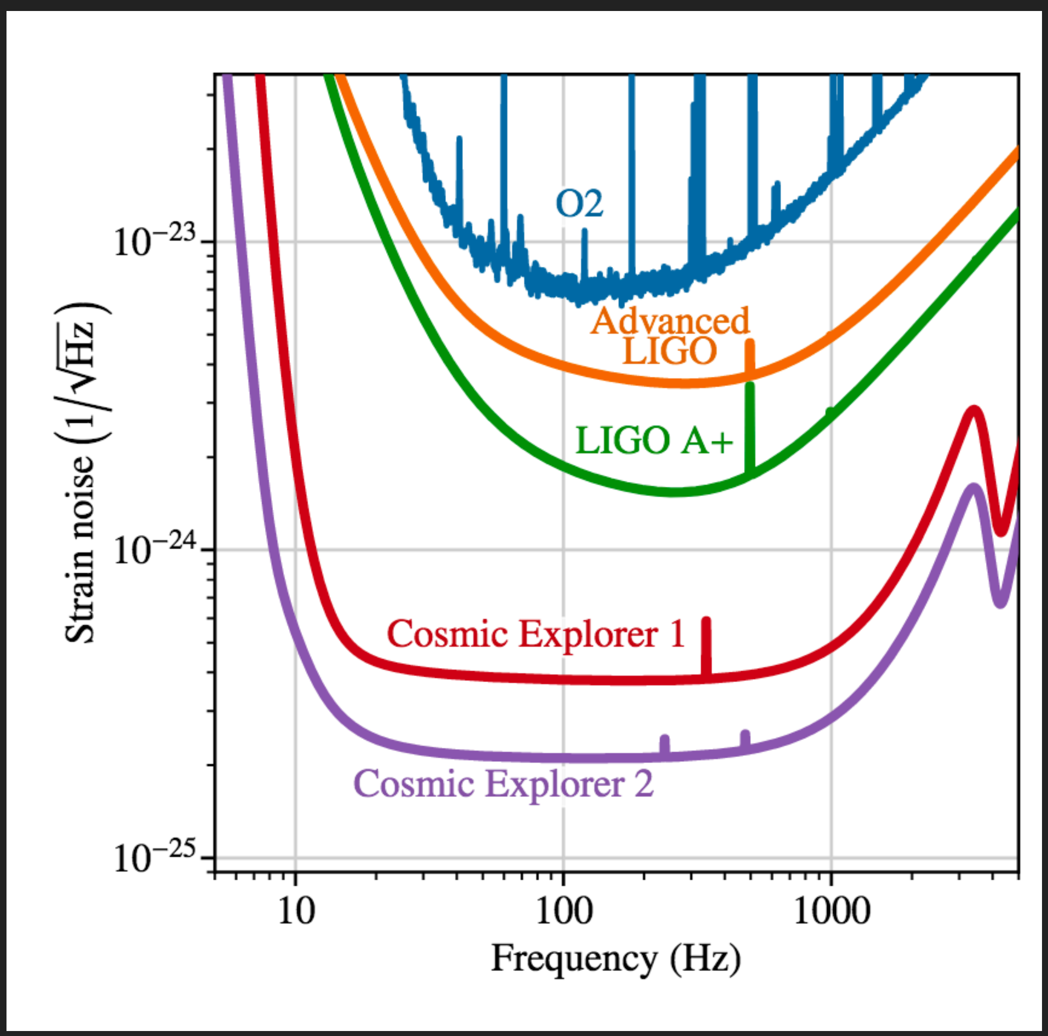


Major discovery space in the coming years

EXTRA SLIDES

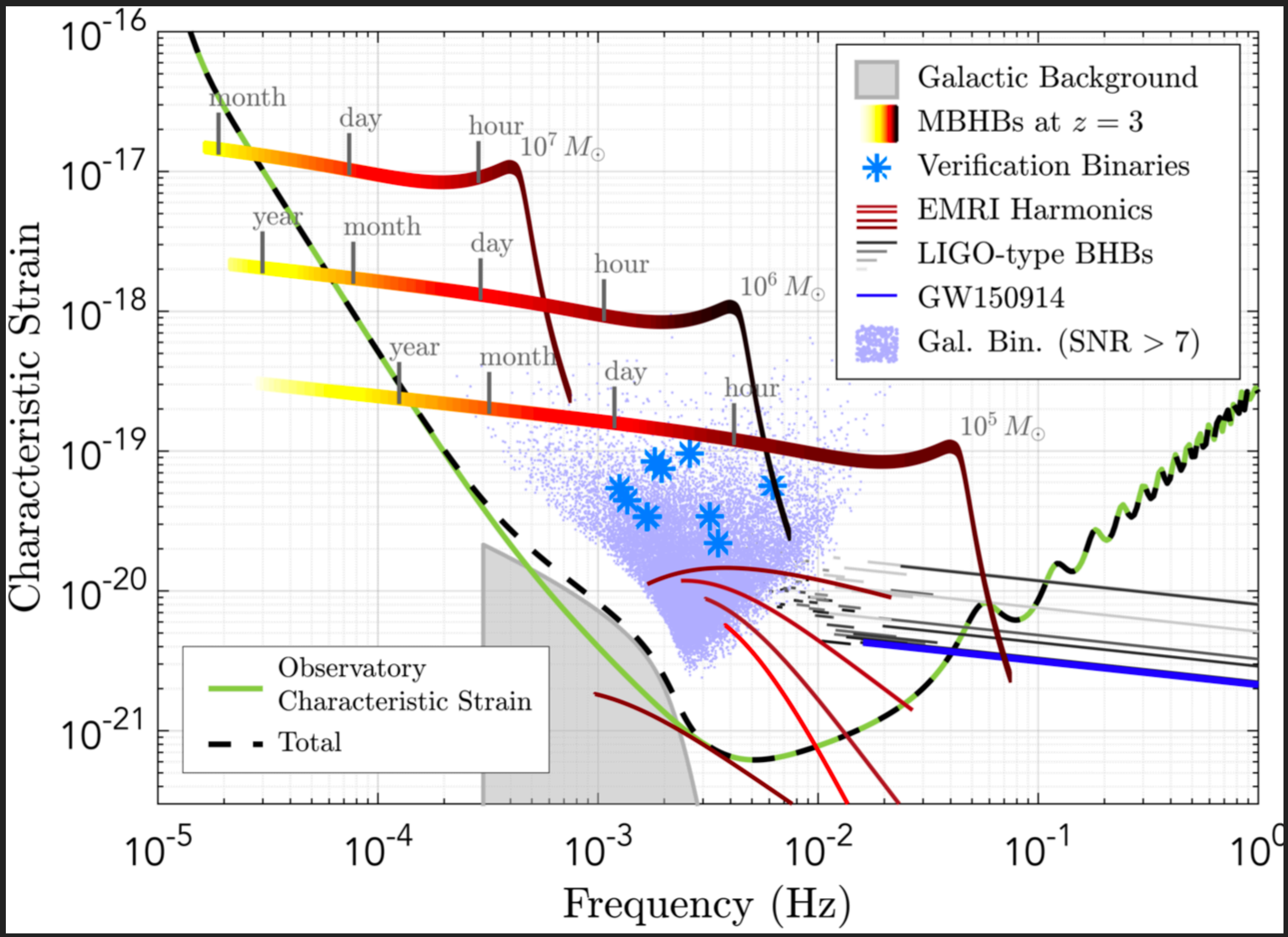
ONGOING/UPCOMING GW DETECTORS

Reitze et al. (2020) 1903.04615



Terrestrial GW detectors

LISA Science book



Space-based GW detector