Panorama of the Universe with multi-messenger observations

Suvodip Mukherjee

PERIMETER INSTITUTE

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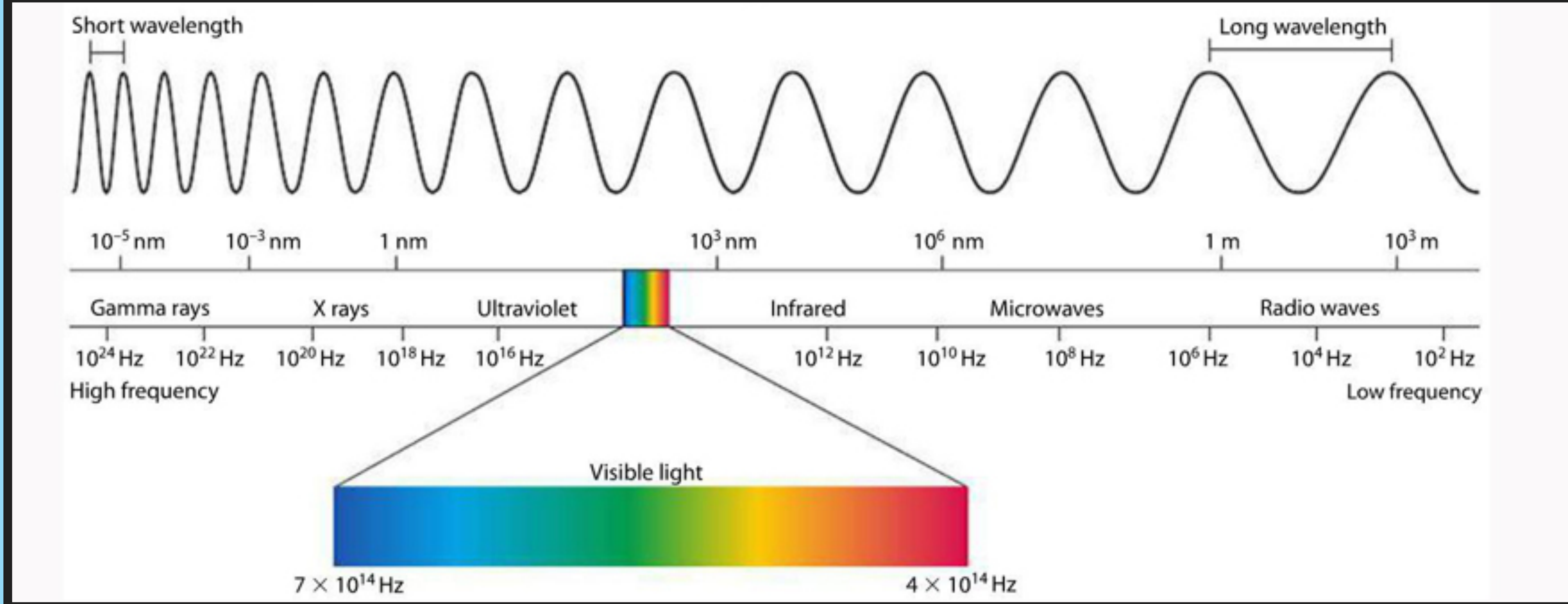
WE EXPLORE THE NATURE BY MULTI-MESSENGER PROBES

WE EXPLORE THE NATURE BY MULTI-MESSENGER PROBES

CAN WE STUDY COSMOLOGY USING MULTI-MESSENGER PROBES

Electromagnetic probes of the Universe



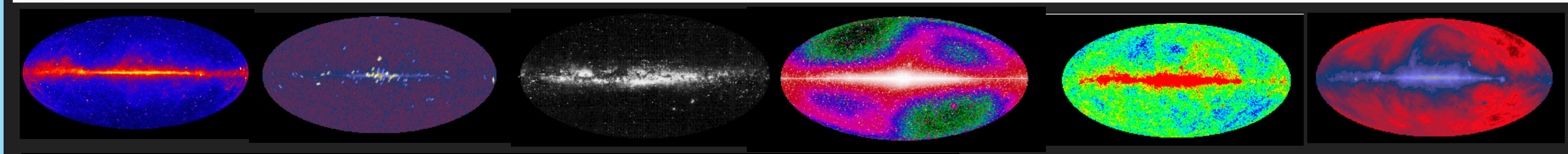
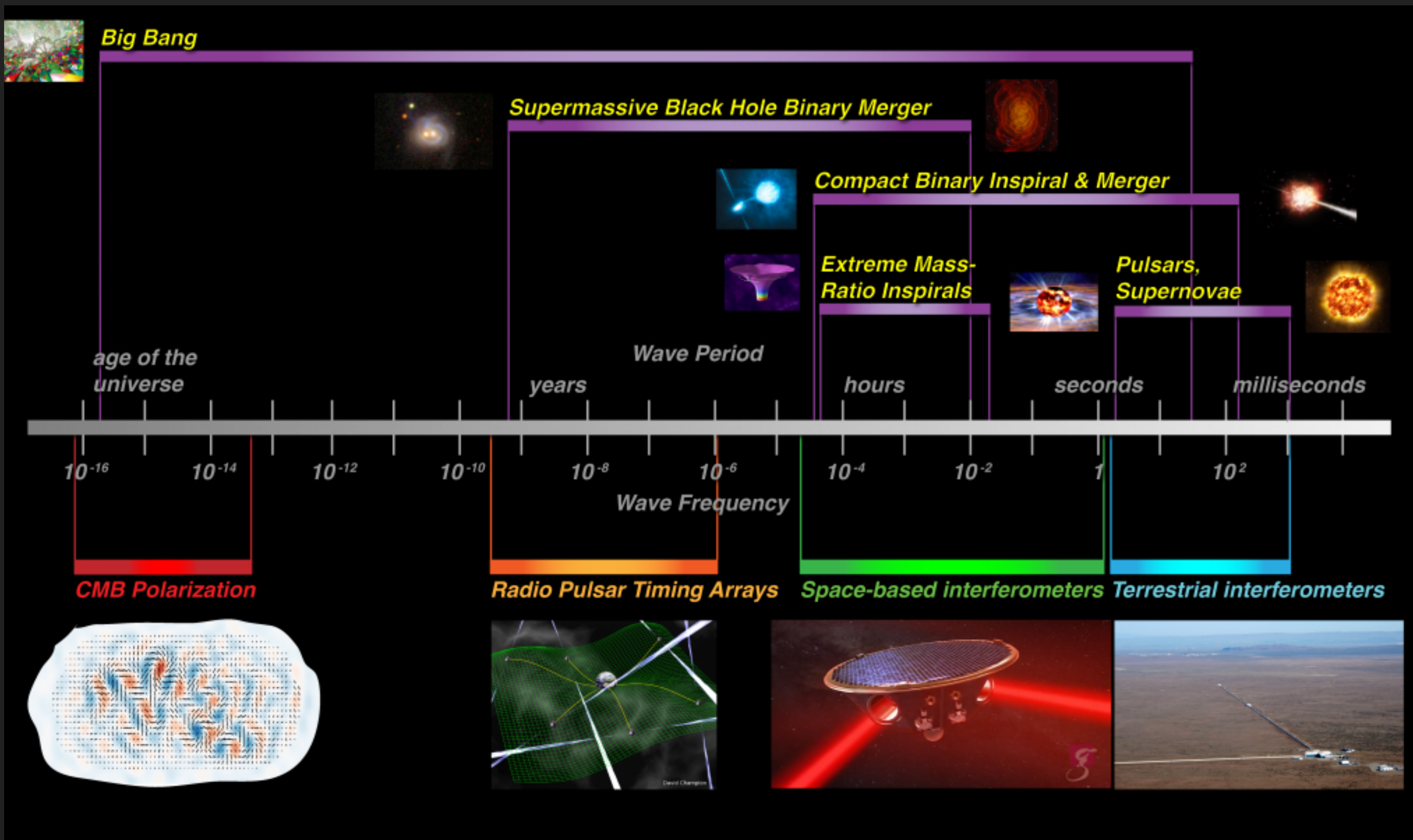


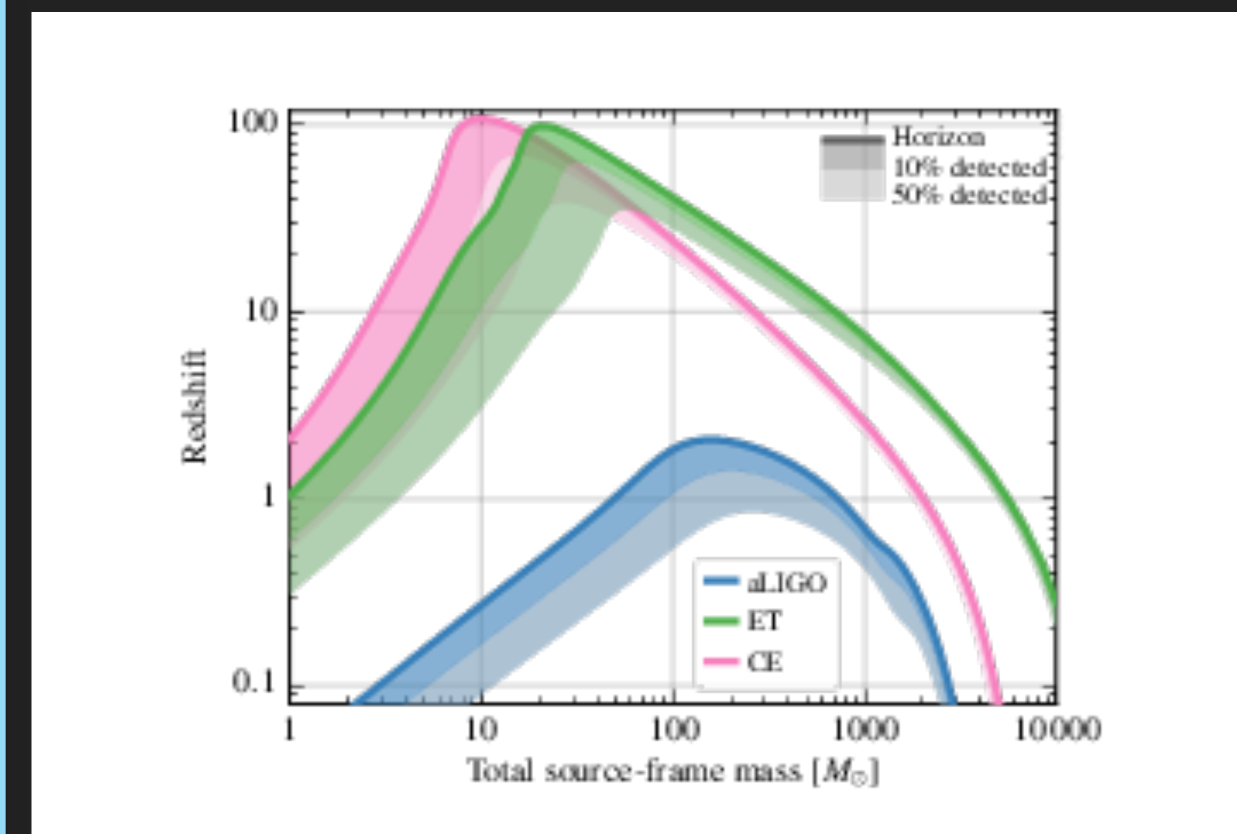
Image credit: https://apod.nasa.gov/htmltest/jbonnell/www/multiw_sky.html

Gravitational wave probes of the Universe

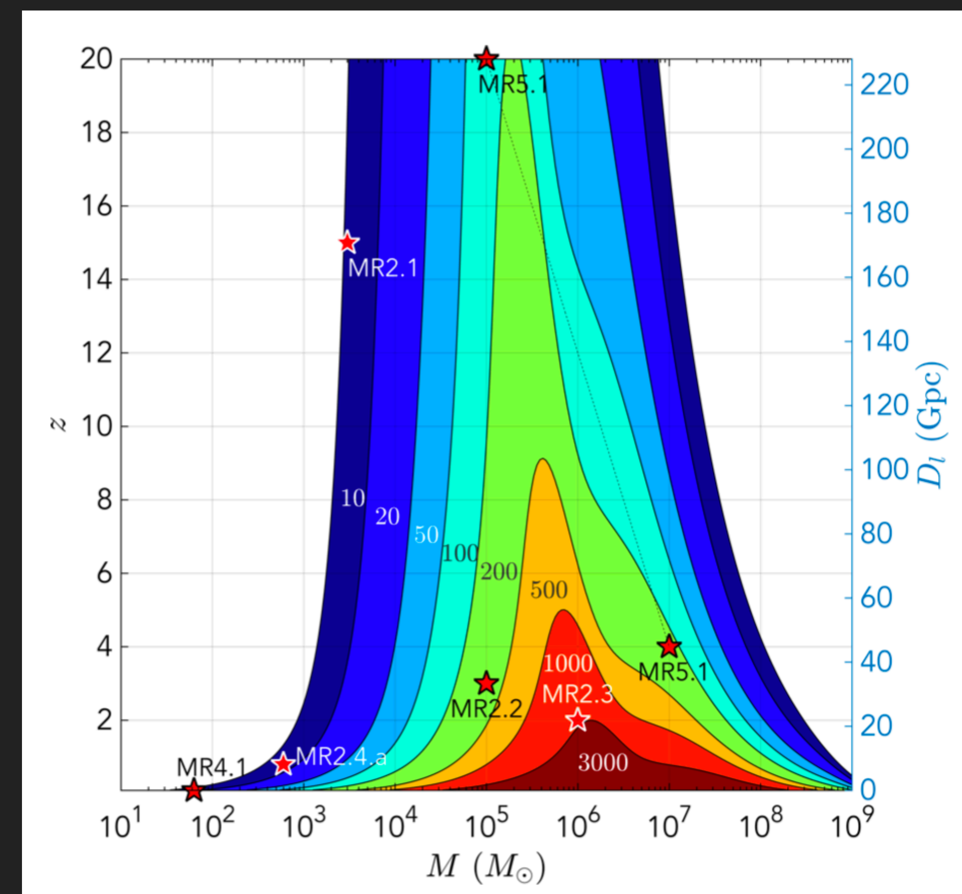


Gravitational wave probes of the Universe

ACCESSIBLE GW MASS AND REDSHIFT RANGES



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



LISA Science book

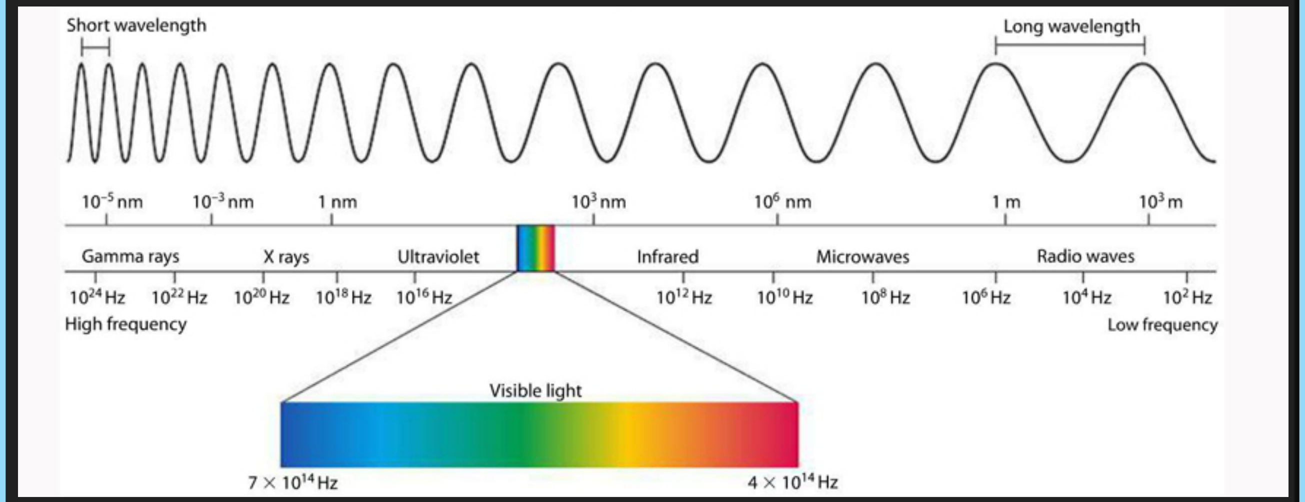
Type of sources: Binary Neutron Stars (BNS), Binary Black holes (BBHs), and Neutron Star-Black holes (NSBHs)

Type of sources: Supermassive Binary Black holes (SMBBHs)

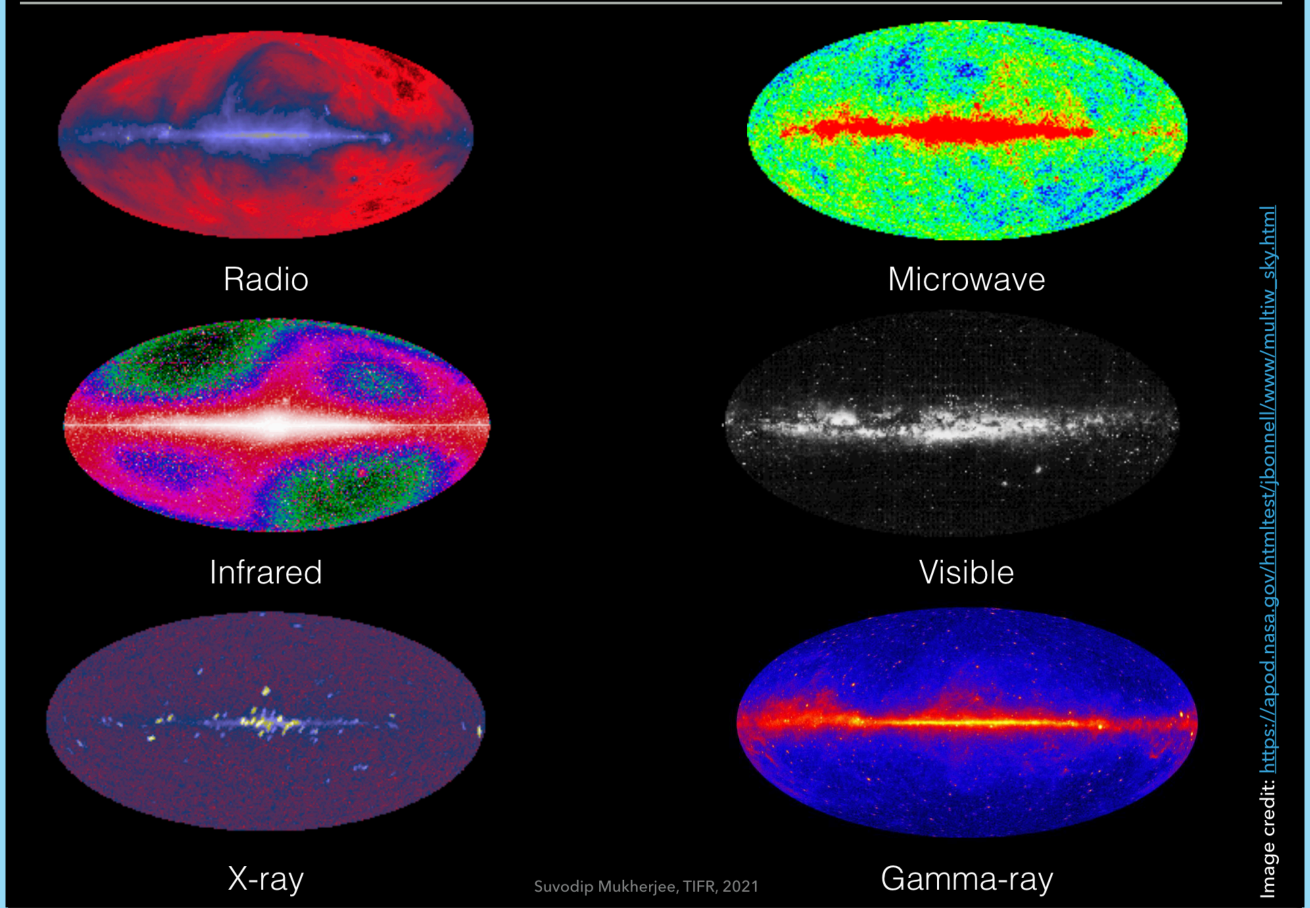
Terrestrial GW detectors

Space-based GW detector

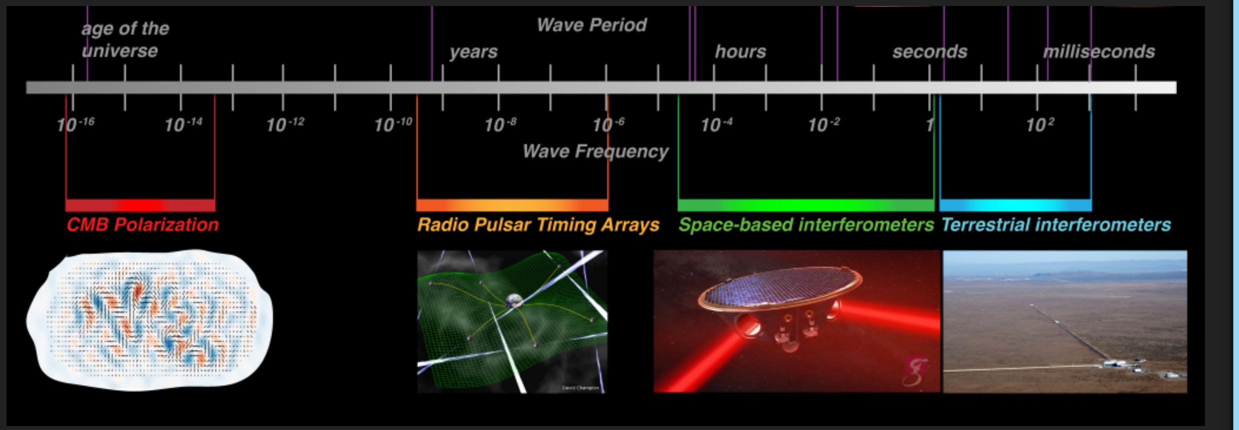
EM Probes of the Universe

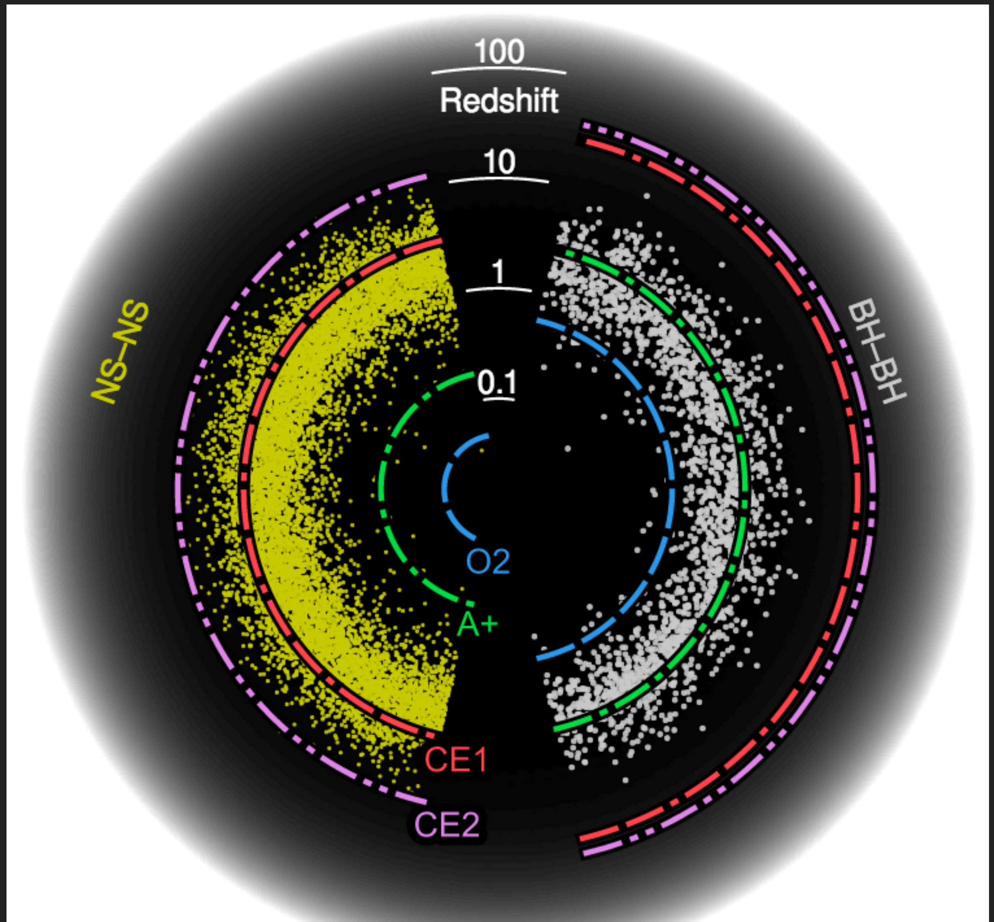


SKY IN DIFFERENT EM FREQUENCY BANDS



GW Probes of the Universe

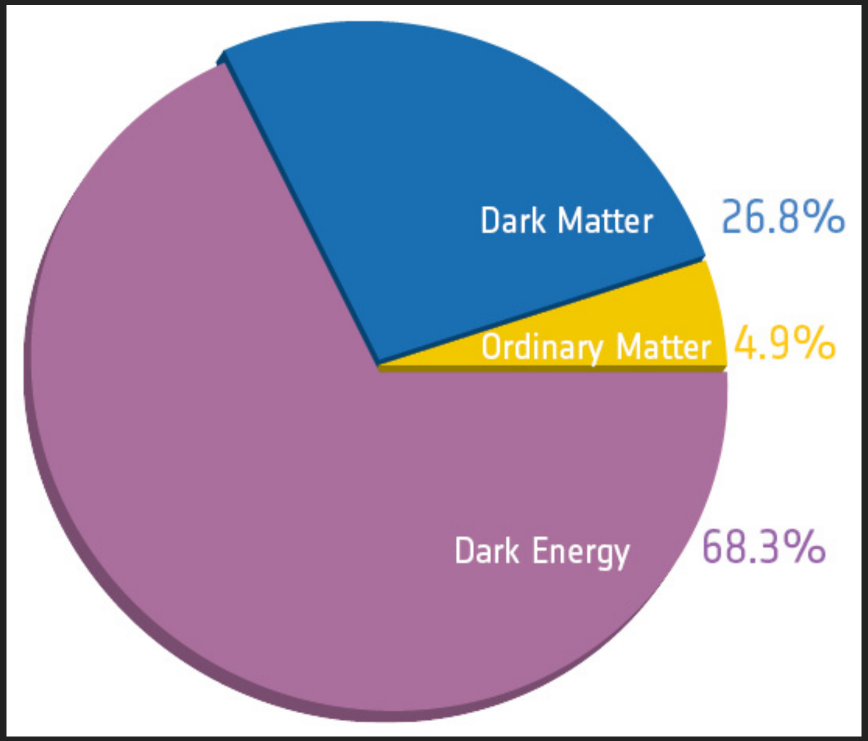




Credit: Reitze et al. (2020)

SALIENT DISCOVERIES ABOUT THE UNIVERSE (UNTIL TODAY)

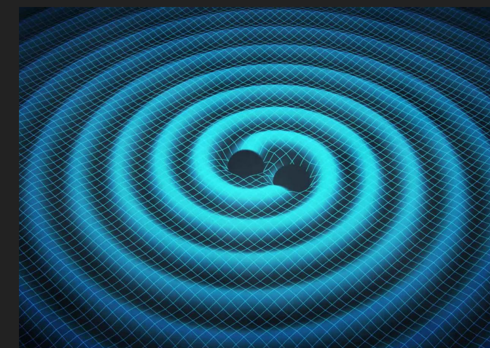
- Universe is expanding and accelerating.
- The visible part of the Universe is only about 5%.
- 27% unknown matter gravitates but does not interact electromagnetically (invisible).
- 68% unknown component of the Universe drives acceleration.

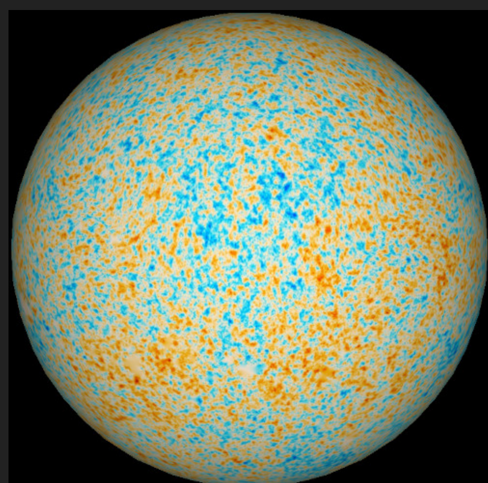


Planck 2015

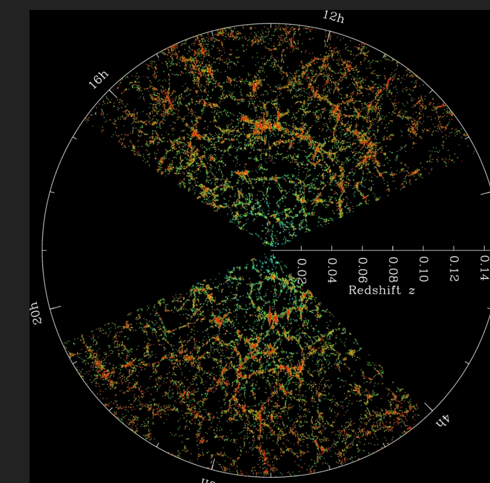
High quality observations has led to an era of precision cosmology which questions our current understanding of fundamental physics

WHAT CAN WE LEARN ABOUT THE COSMOS USING MULTI-MESSENGER OBSERVATIONS





LCDM



- What is the current expansion rate of the Universe ?
- What is cold dark matter (CDM)?
- What is dark energy ? Is it cosmological constant (Lambda)?
- Is General theory of Relativity the correct theory of gravity?

TRANSIENT SOURCES OUT TO HIGH REDSHIFT: HOW CAN WE USE THESE TO STUDY THE PHYSICAL COSMOLOGY

Image credit: ESA

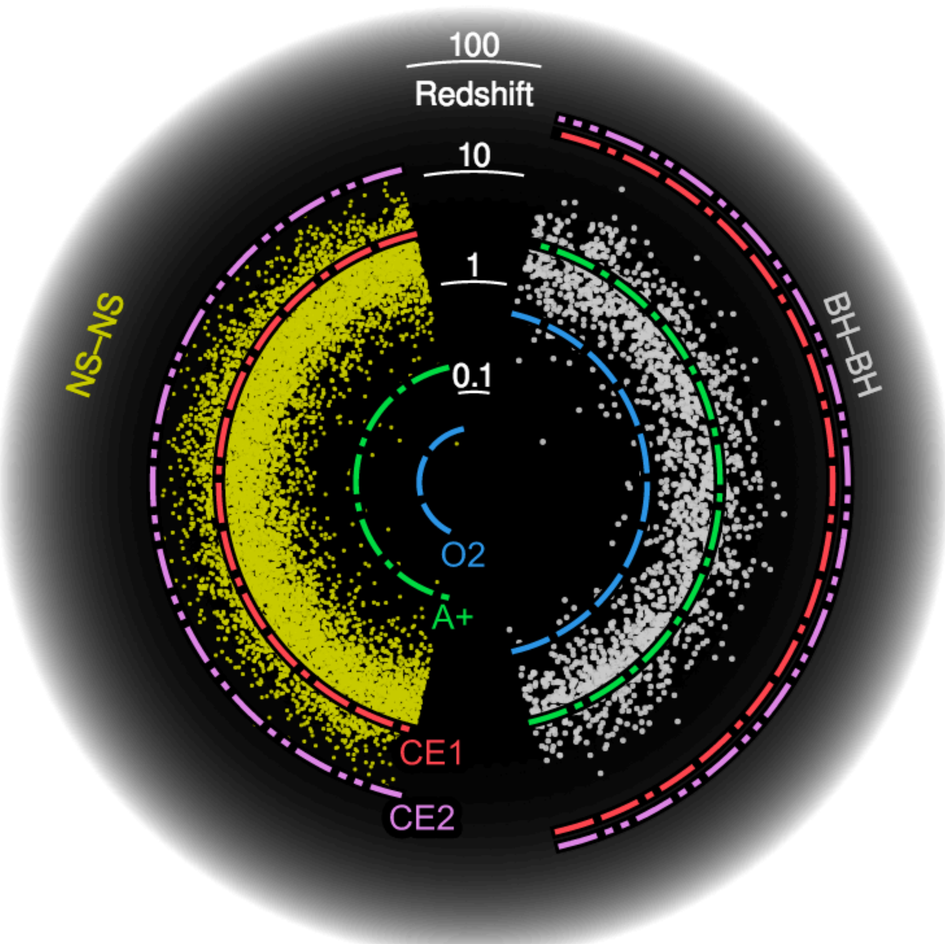
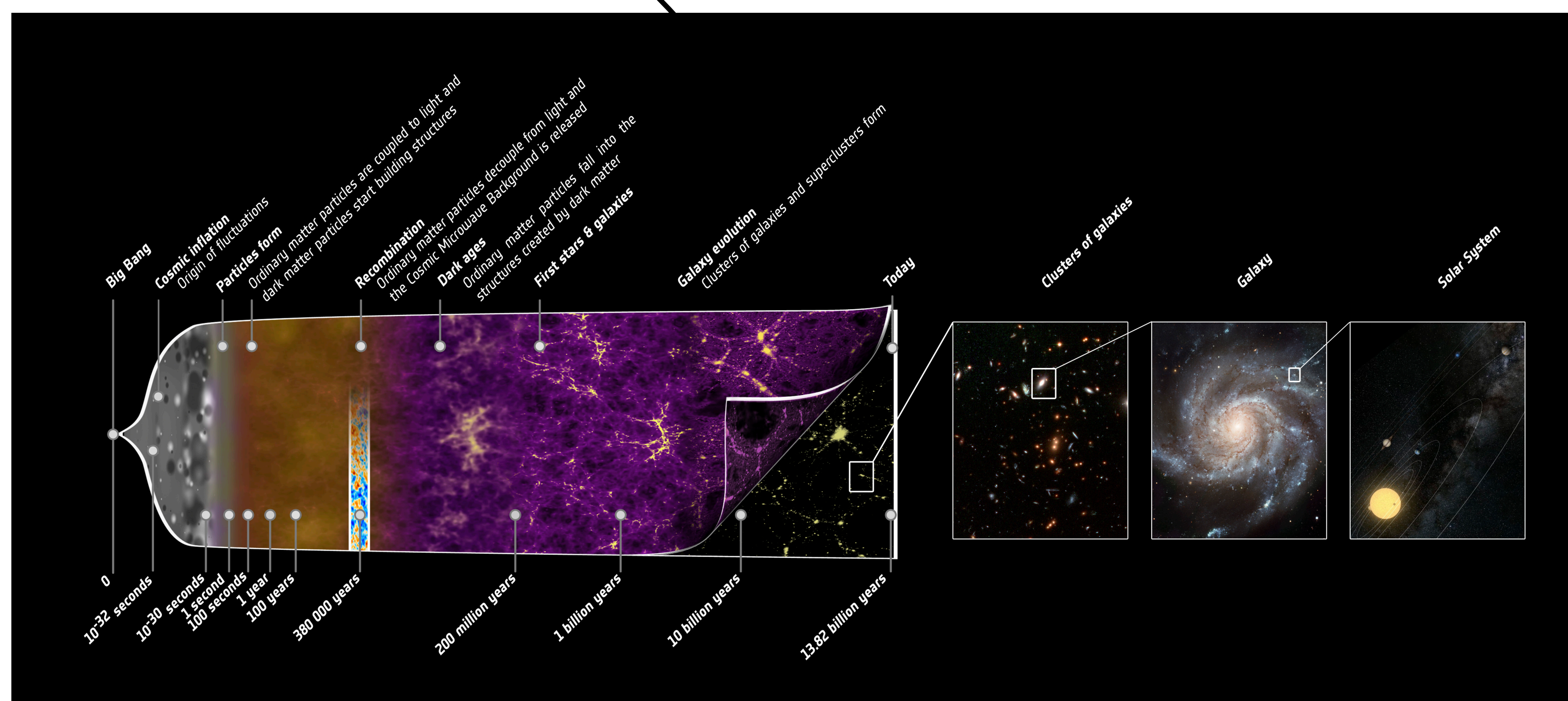


Image credit:
Reitze et al. (2020)



HOW TO UNDERSTAND THE PROPERTIES OF THE TRANSIENT SOURCES KNOWING THE COSMIC HISTORY

MAPPING THE EXPANSION HISTORY OF THE UNIVERSE

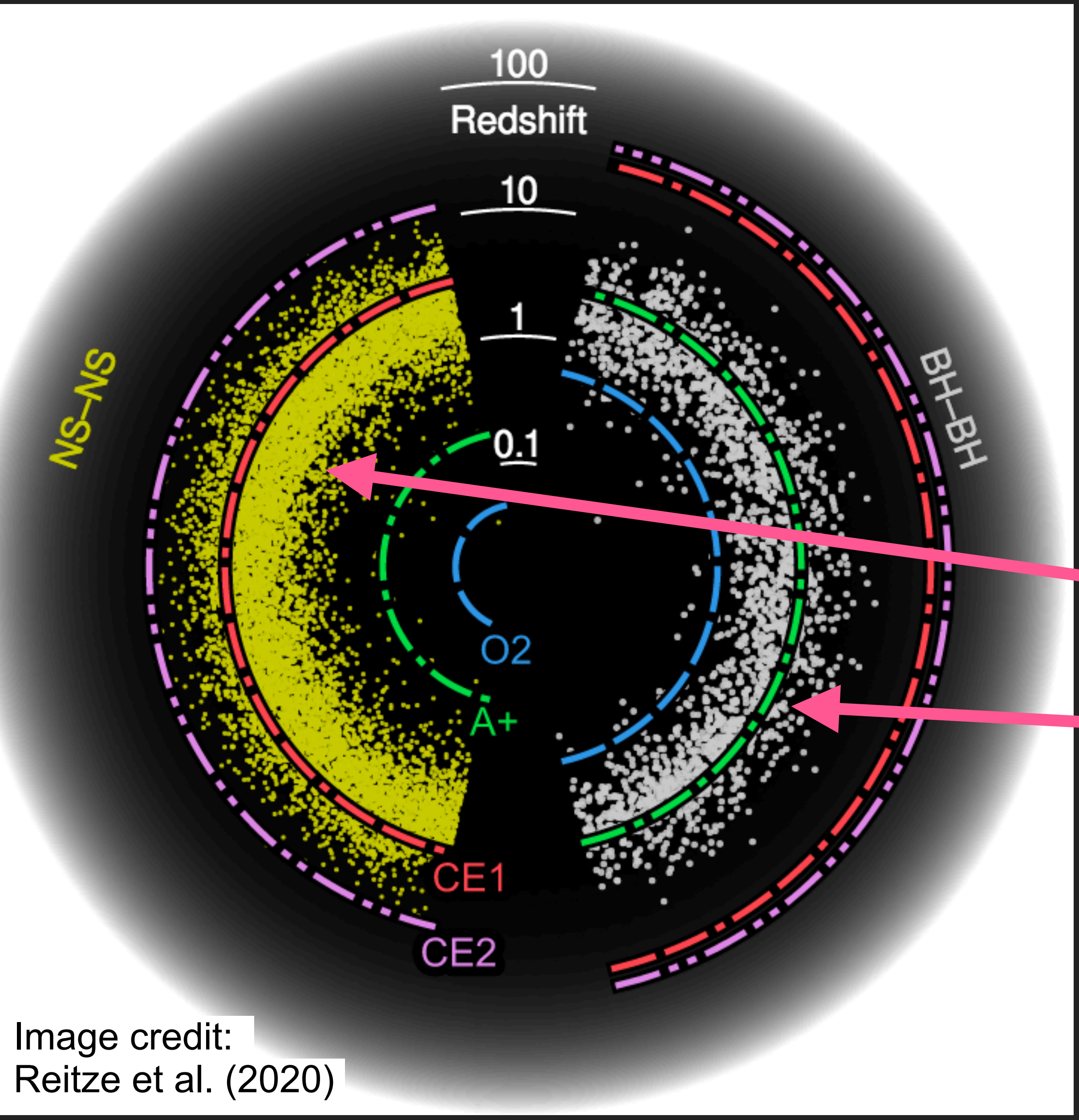
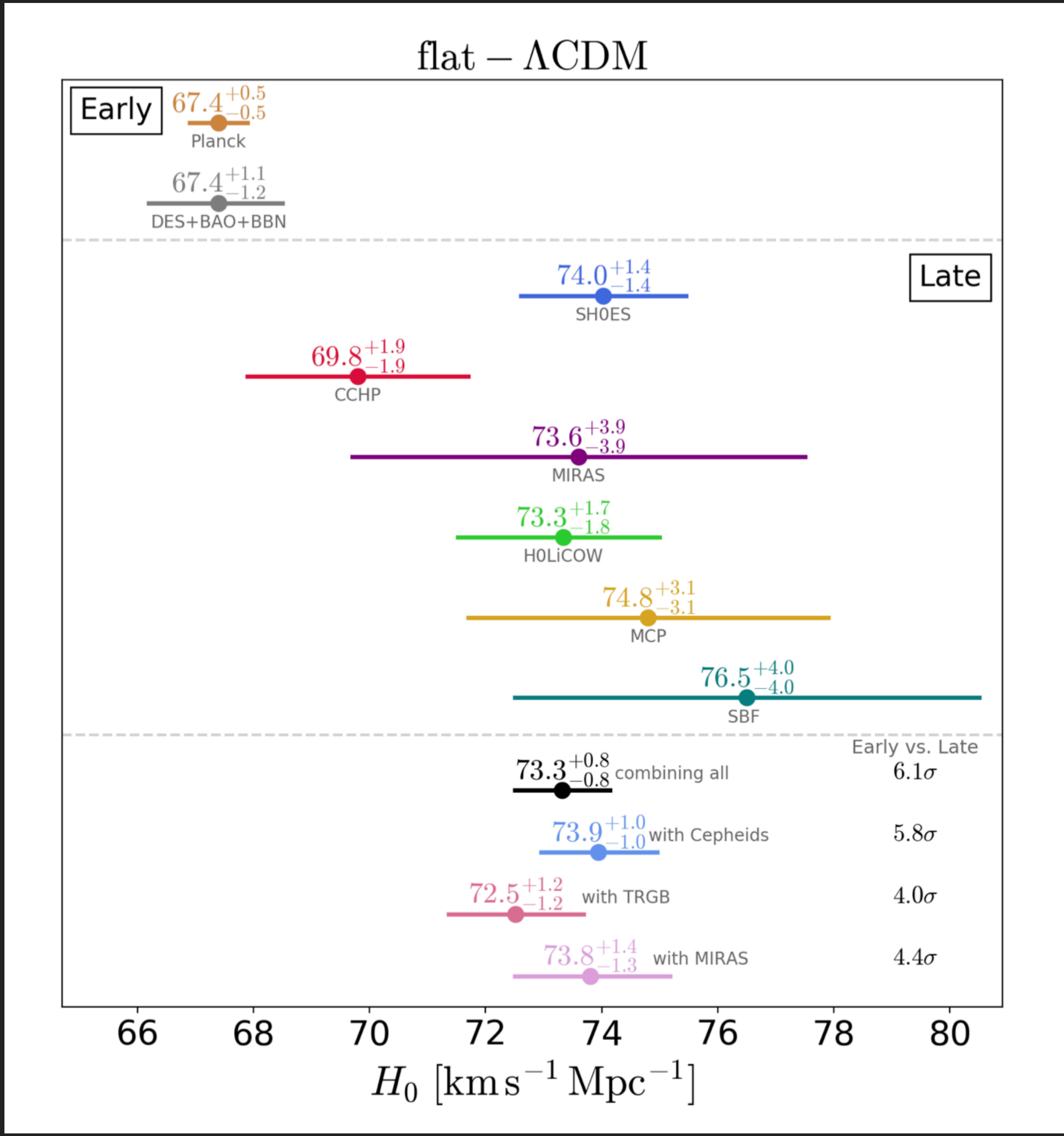


Image credit:
Reitze et al. (2020)

Sources with EM counterpart

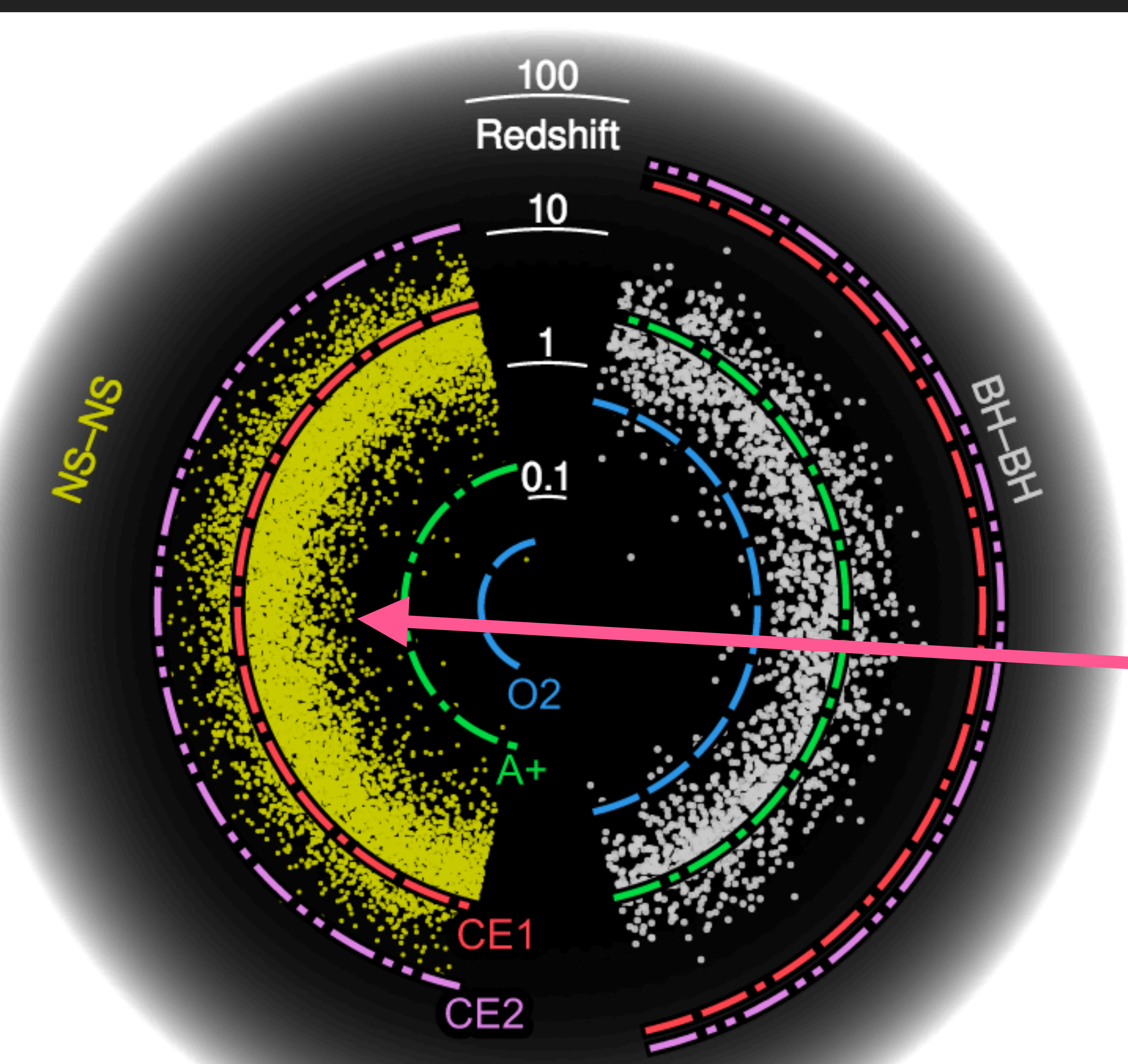
Sources without EM counterpart

EARLY UNIVERSE PROBES DIFFER FROM THE LATE UNIVERSE PROBES



Verde, Treu, Riess (2019)

HUBBLE CONSTANT



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Sources with EM counterpart

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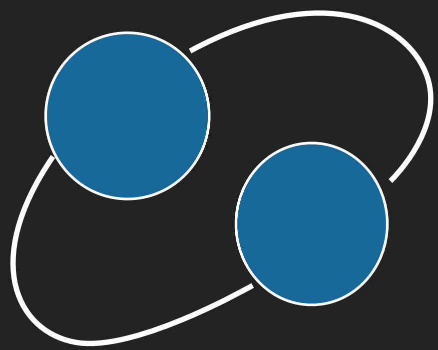
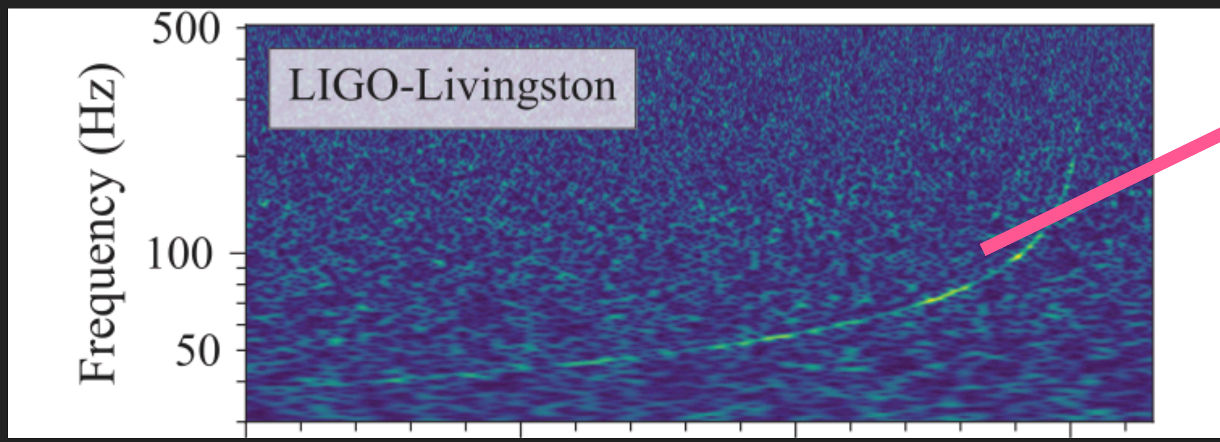


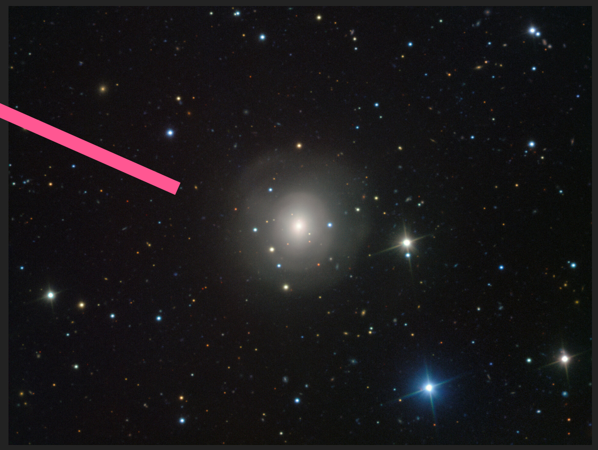
FIRST MEASUREMENT OF HUBBLE CONSTANT FROM BNS

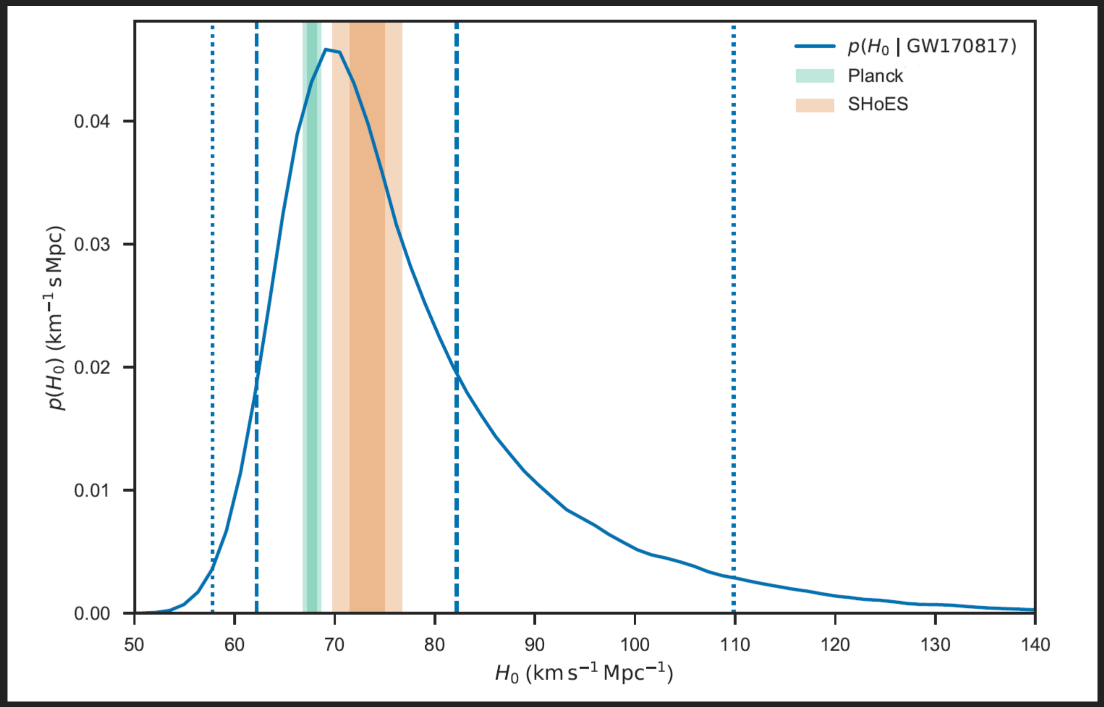
$$H_0 = \frac{cz + v_p}{D_l}$$

Independent measurement of the host of the GW source



LIGO-Virgo Collaboration

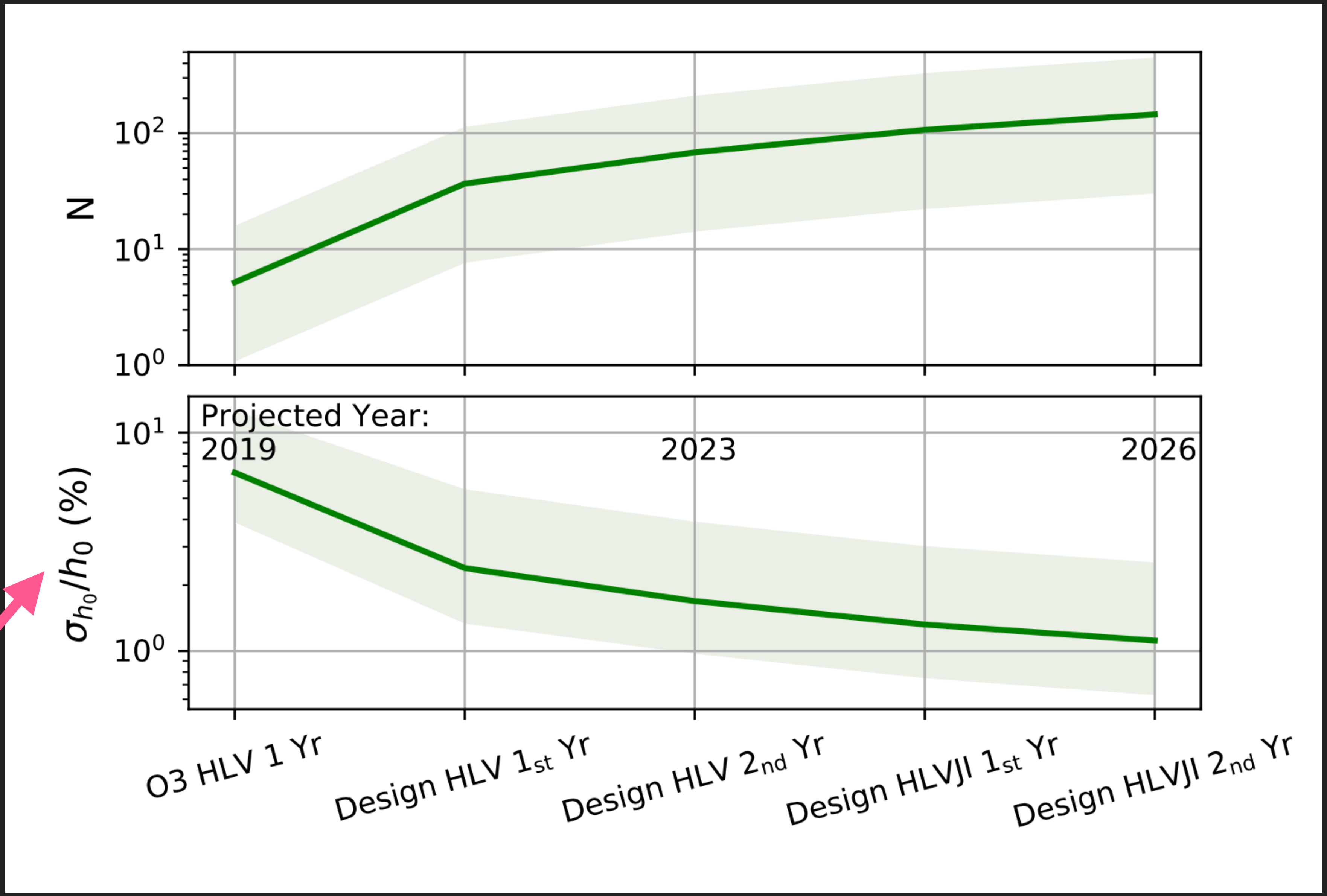




LIGO Virgo Collaboration Nature **551**, 85, 2017

FORECAST: FOR MEASUREMENT OF THE HUBBLE CONSTANT FROM BNS

Forecast from sources with EM counterpart



Chen, Fishbach, Holz (2017)
See also: Feeney et al. (2018)

$$H_0 = 100 h_0 \, \mathrm{km/s/Mpc}$$

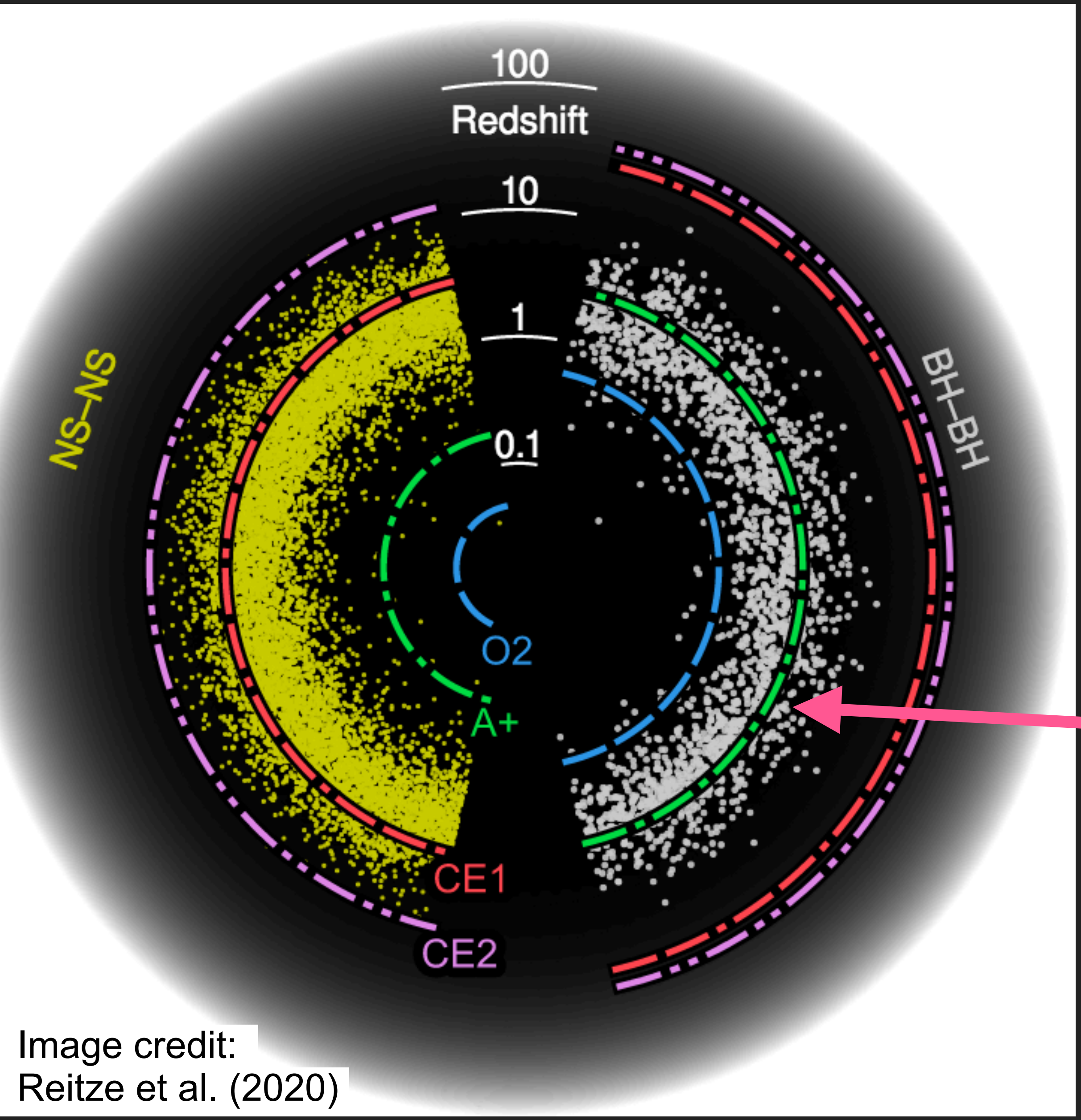


Image credit:
Reitze et al. (2020)

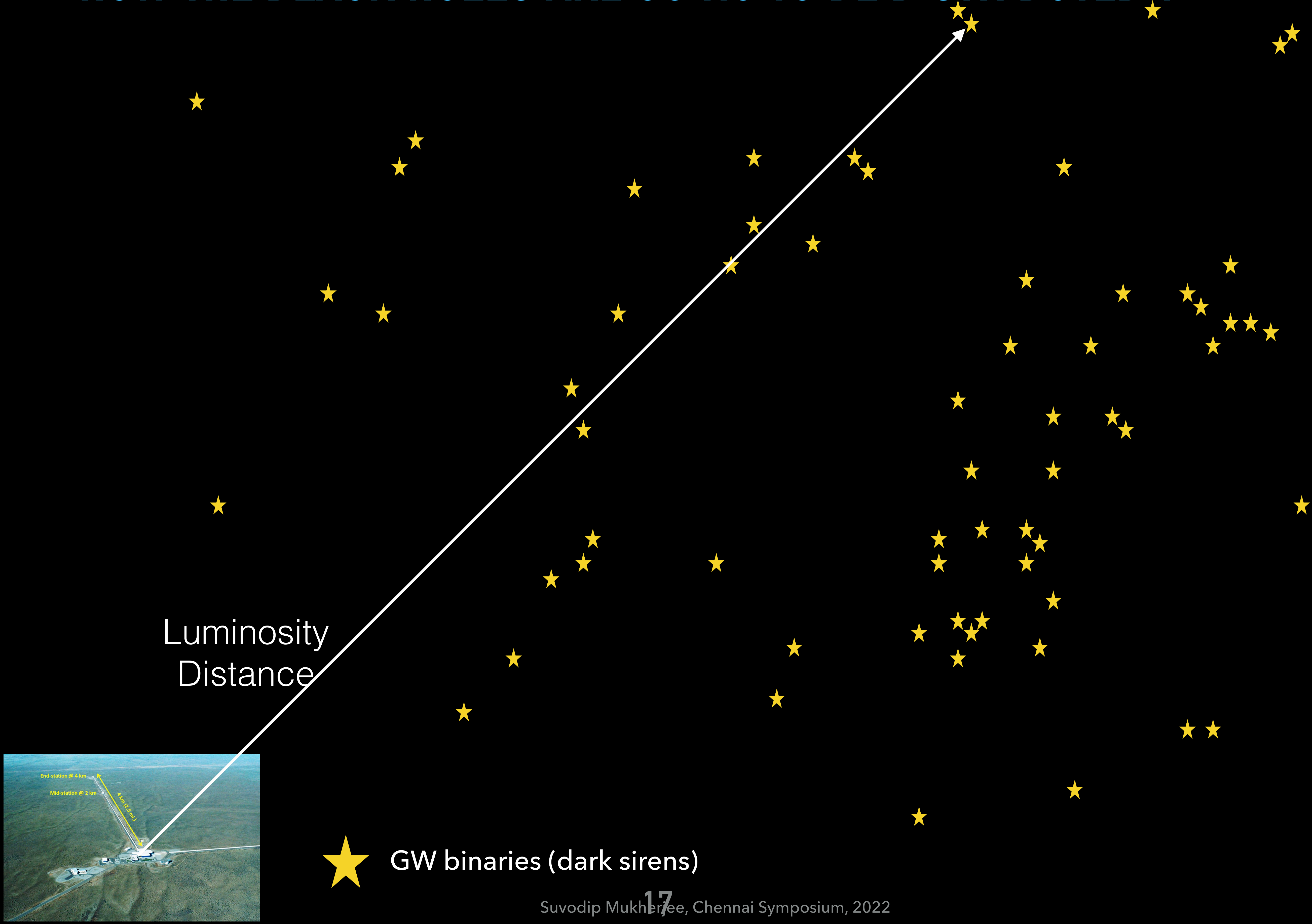
MAPPING THE EXPANSION HISTORY OF THE UNIVERSE

Sources with EM counterpart

Sources without EM counterpart

+ Farther distances
+ More Sources
+ Cosmological parameters beyond H_0

HOW THE BLACK HOLES ARE GOING TO BE DISTRIBUTED ?



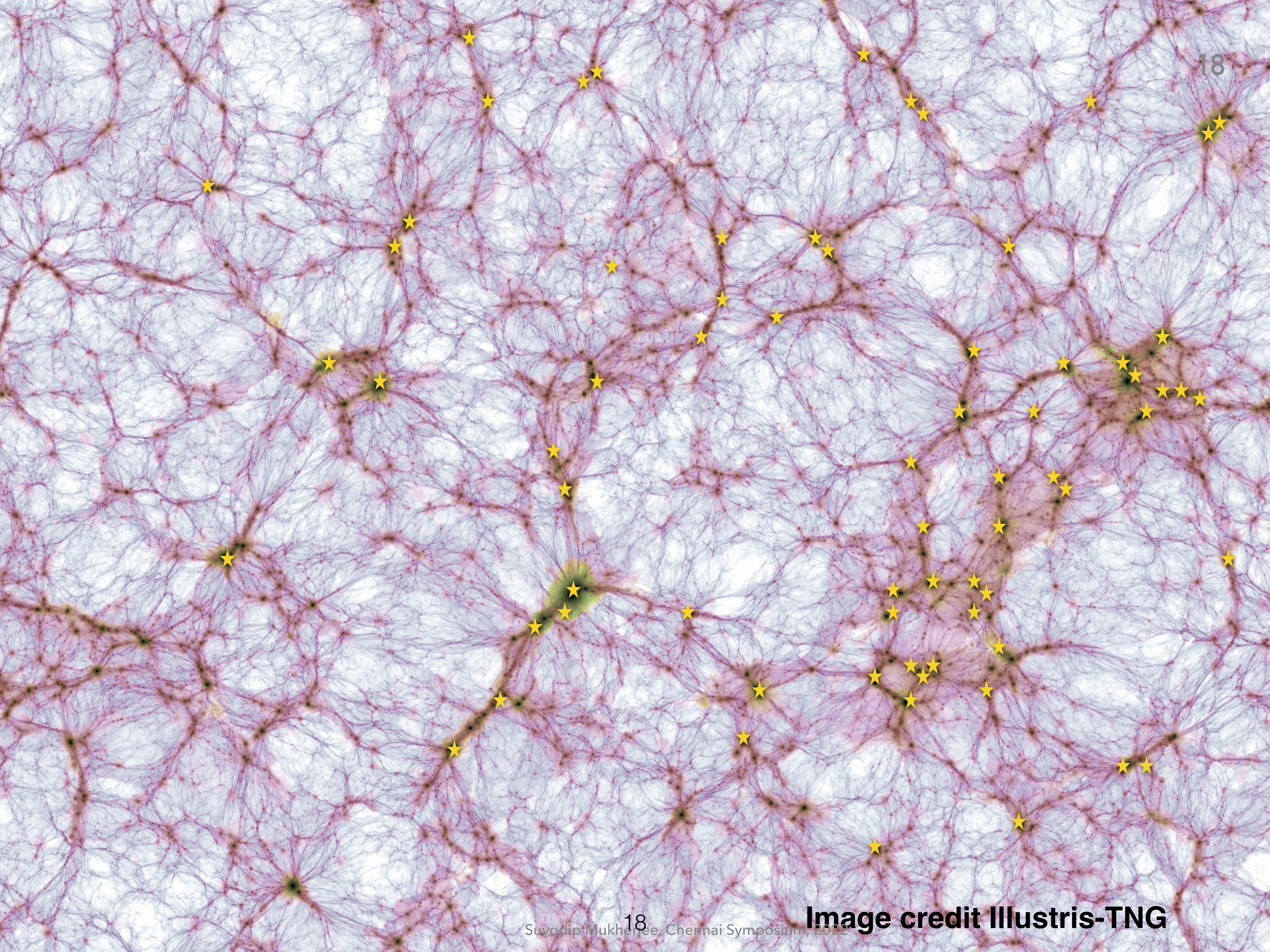


Image credit Illustris-TNG

How GW sources trace the Dark Matter distribution

$$b(z) = b_{GW}(1+z)^{\alpha}$$

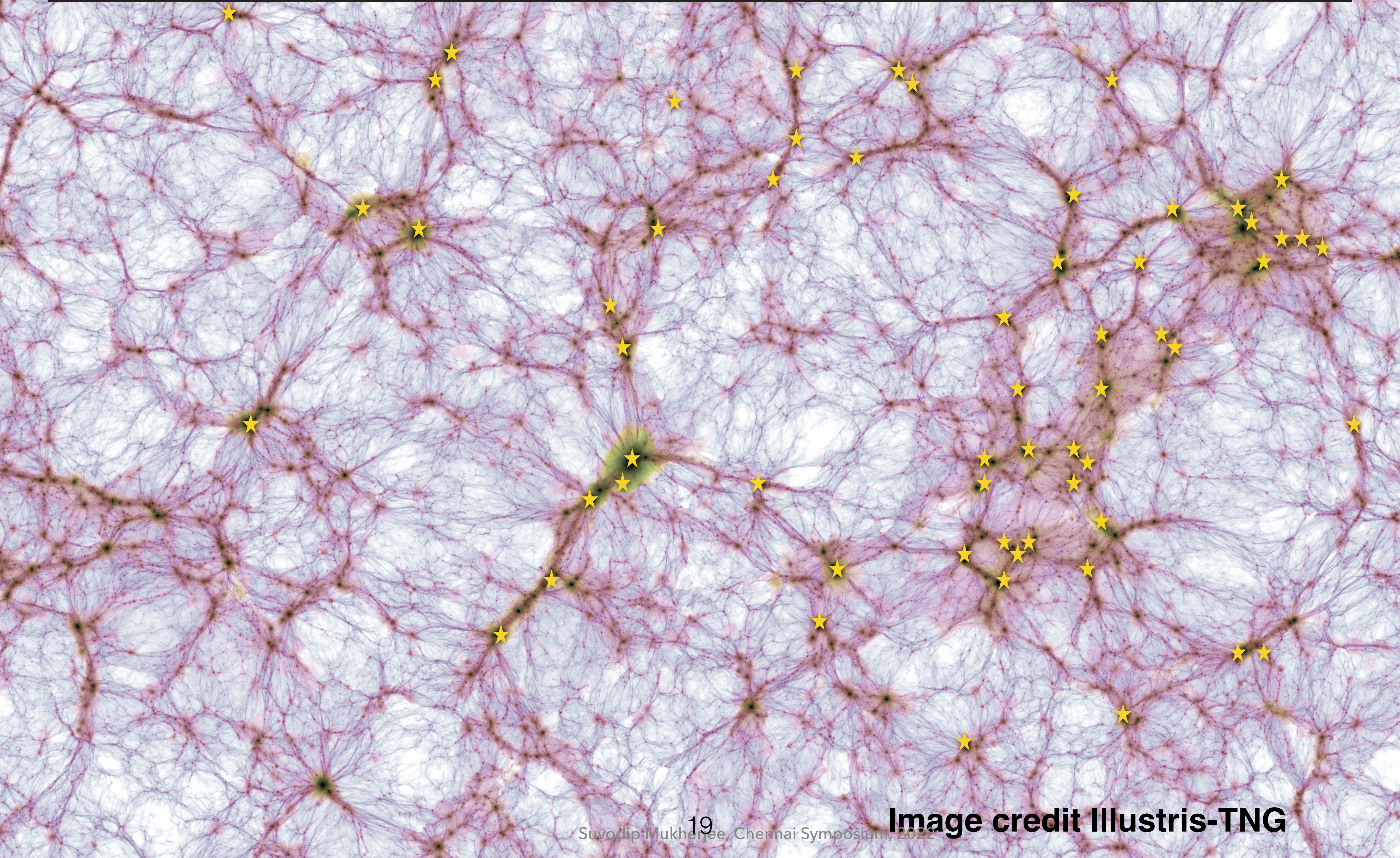
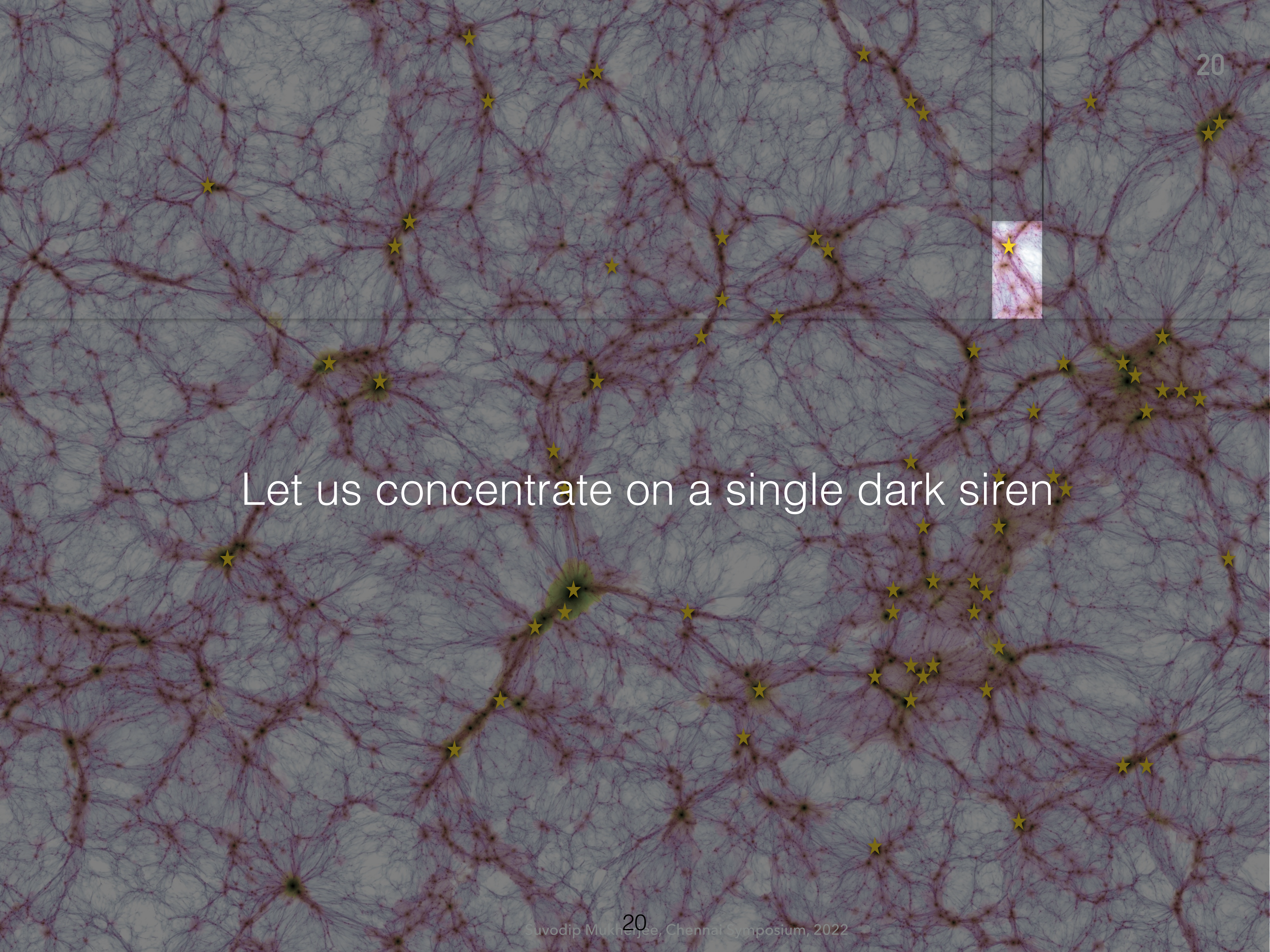


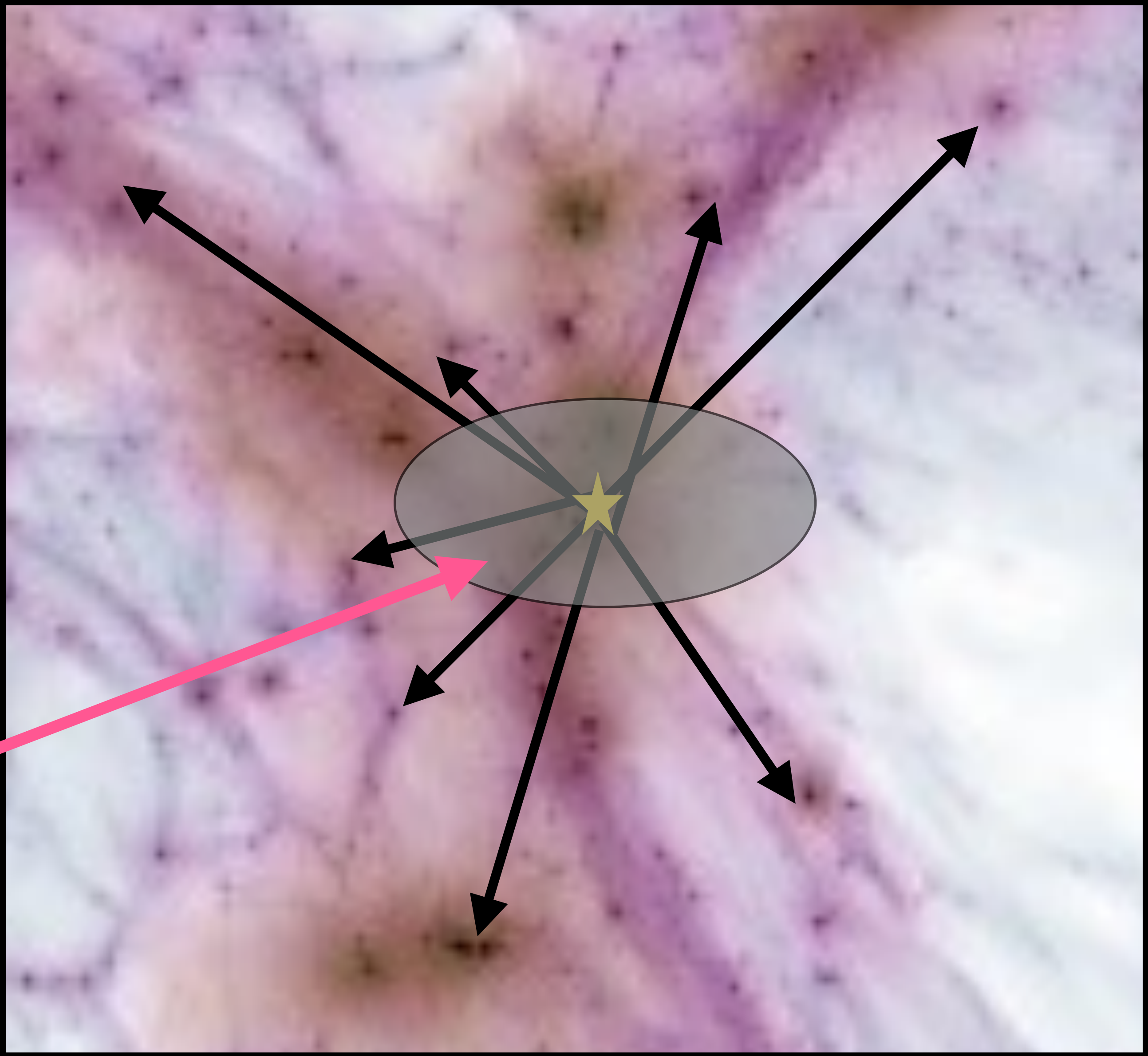
Image credit Illustris-TNG



Let us concentrate on a single dark siren

Spatial clustering with galaxies can be used to measure the redshift of the GW source even in the absence of an EM counterpart

Mukherjee, Wandelt, Silk (MNRAS, 494, 2, 1956, 2020), (1908.08951)
Mukherjee, Wandelt, Nissanke, Silvestri (Phys. Rev. D 103, 043520, 2021) (2007.02943)

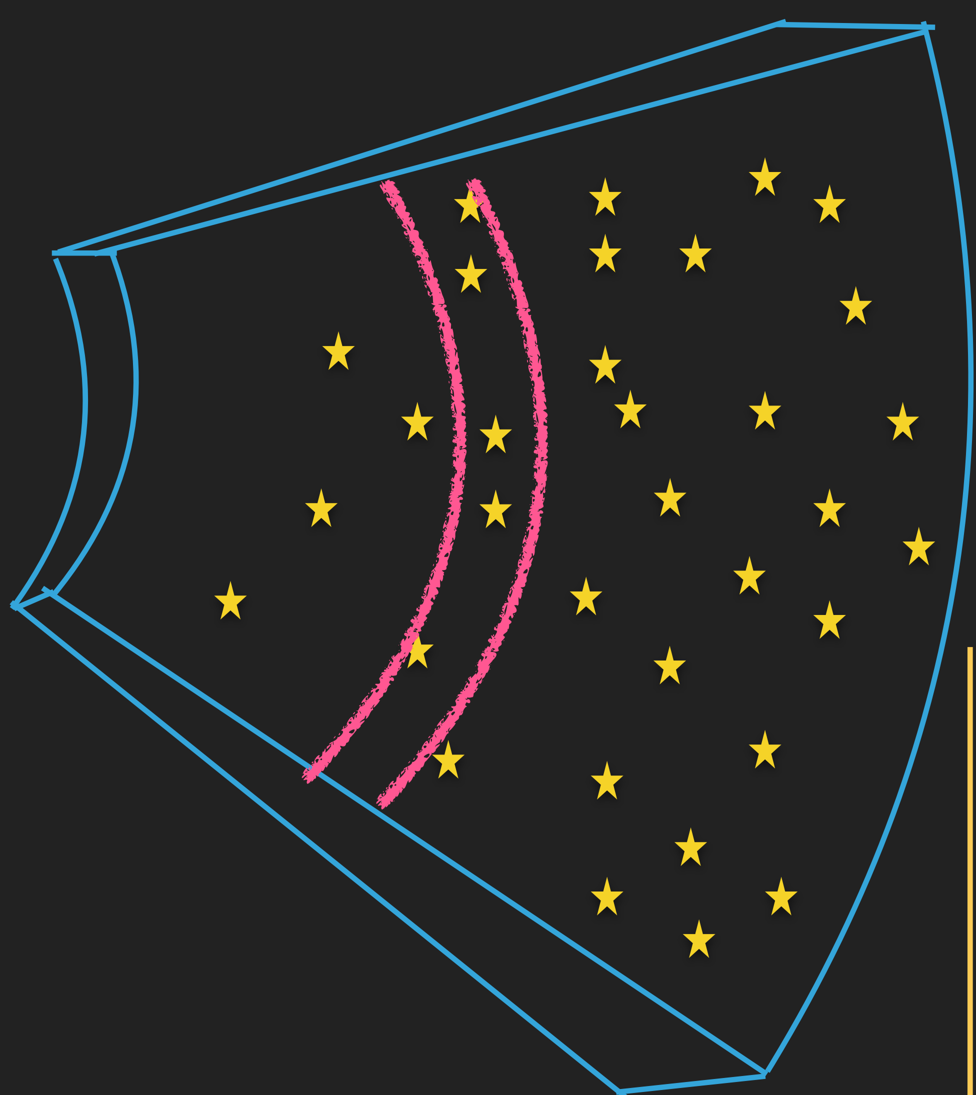


Sky localisation error

CROSS-CORRELATION OF GW SOURCES WITH GALAXIES

Mukherjee, Wandelt, Nissanke, Silvestri (Phys. Rev. D 103, 043520, 2021) (2007.02943)

$$dP = n_{GW} n_g (1 + \xi(r)) dV_{GW} dV_g$$



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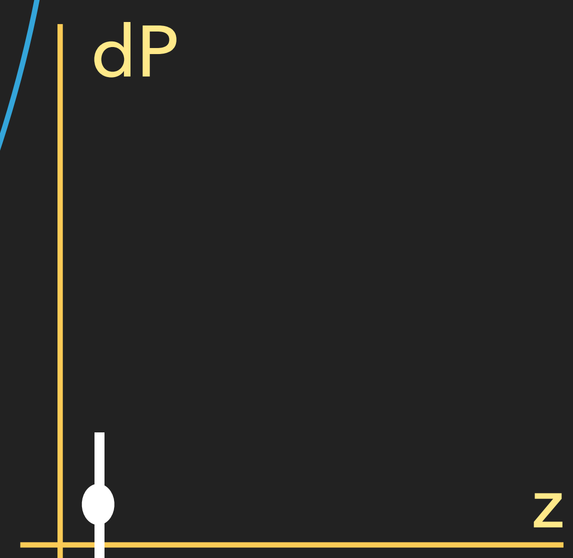

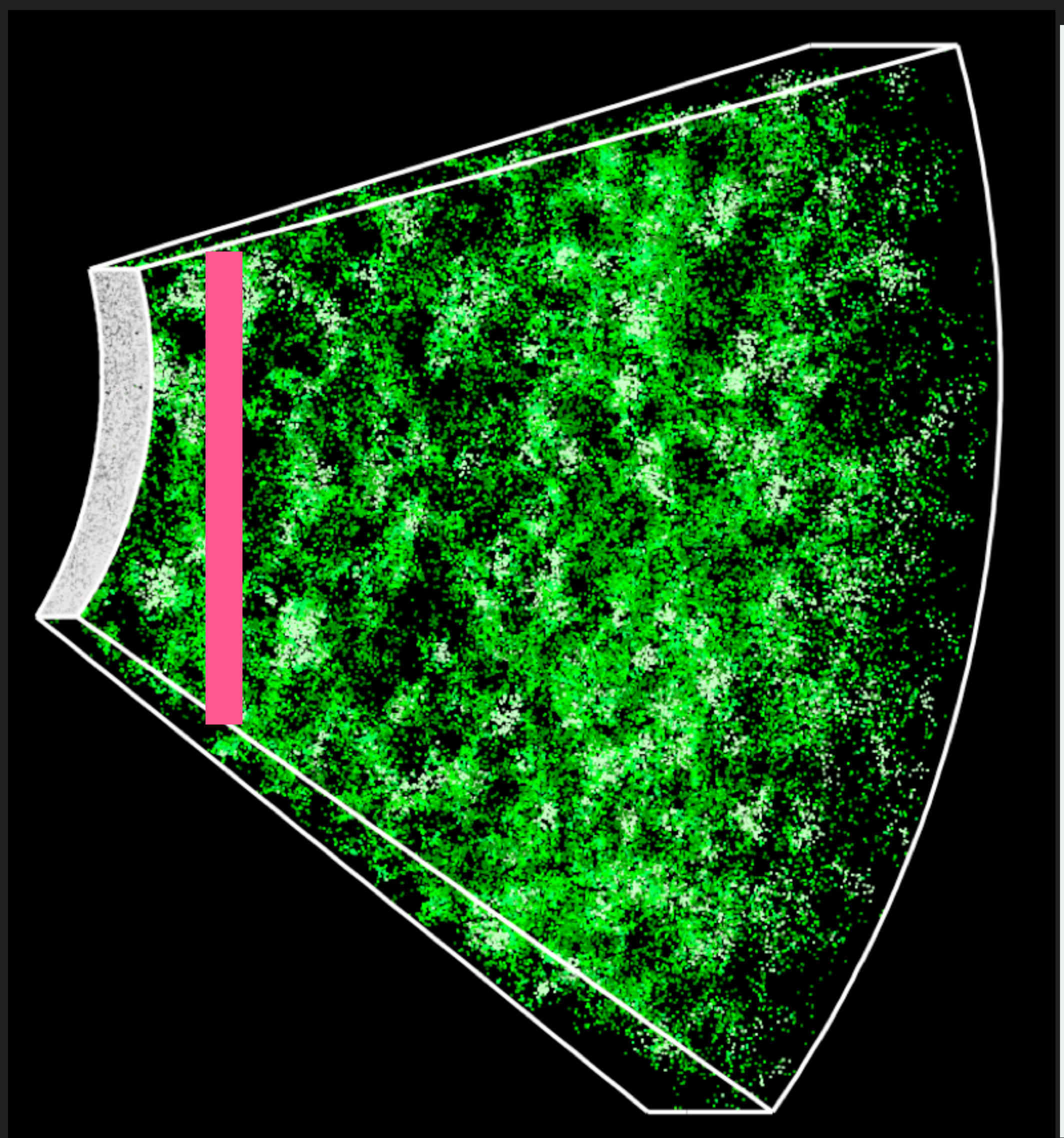

Image credit: Jeremy Tinker and the SDSS-III collaboration

Dark sirens observed in luminosity distance space

Galaxy samples observed in redshift space

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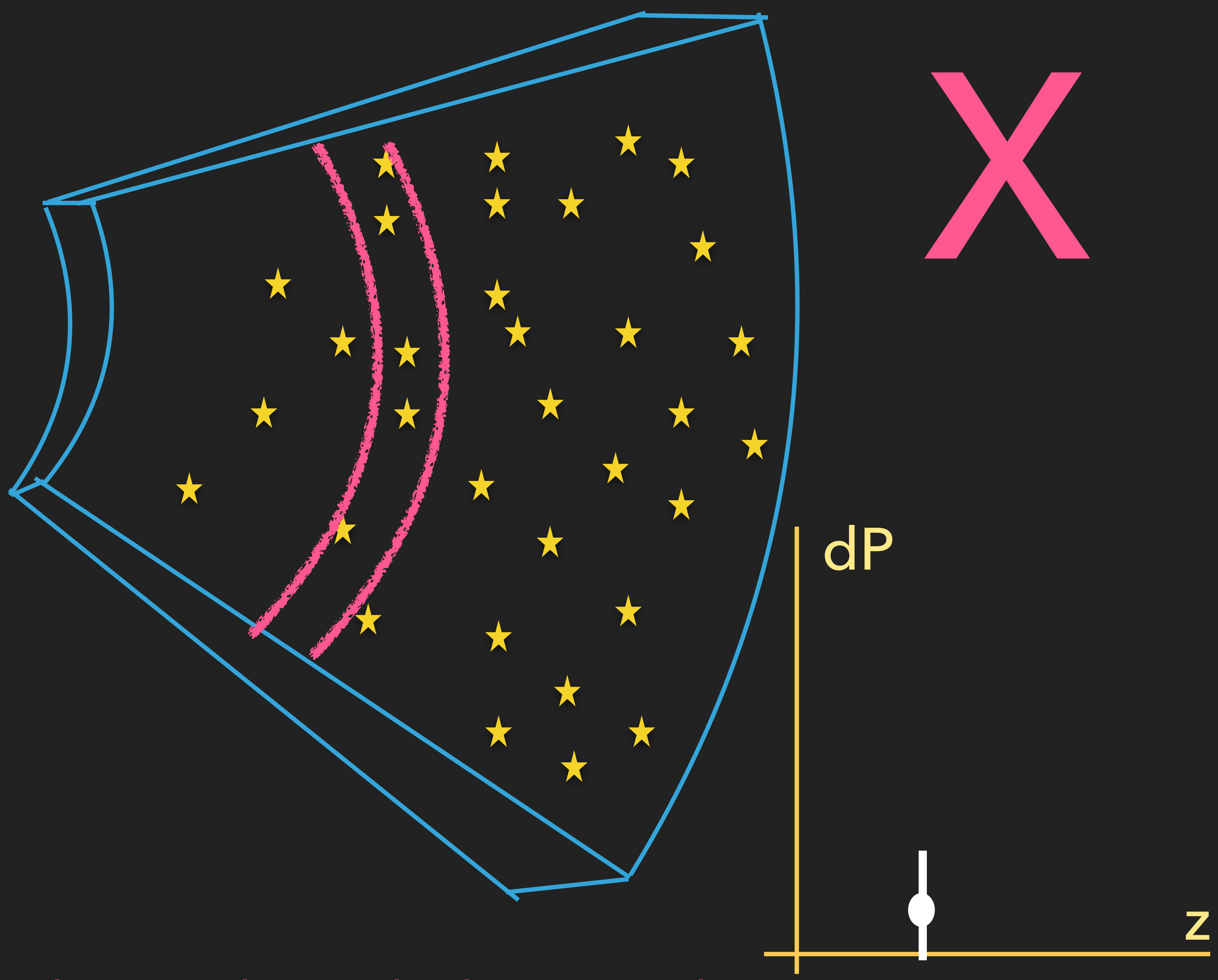

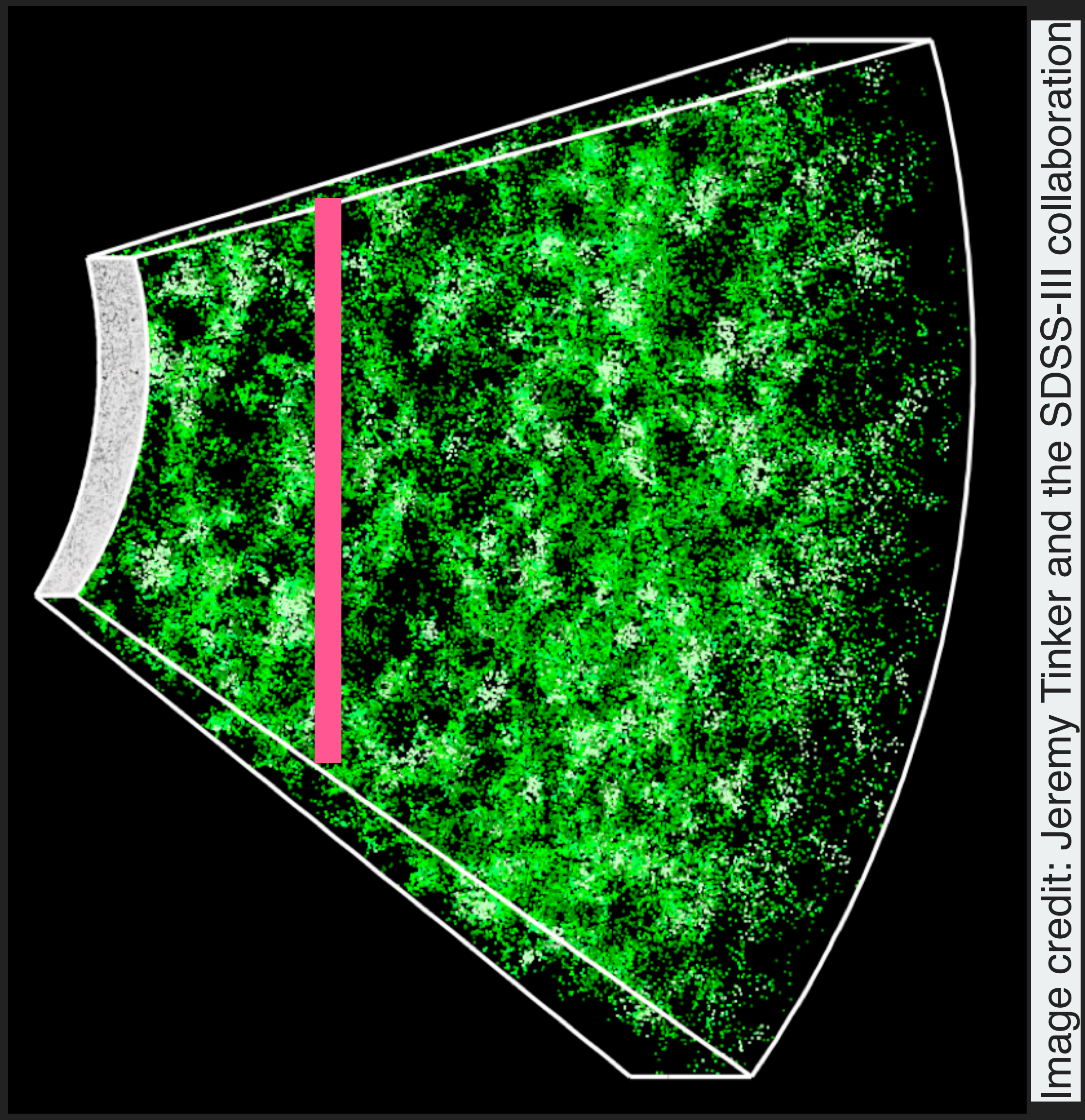

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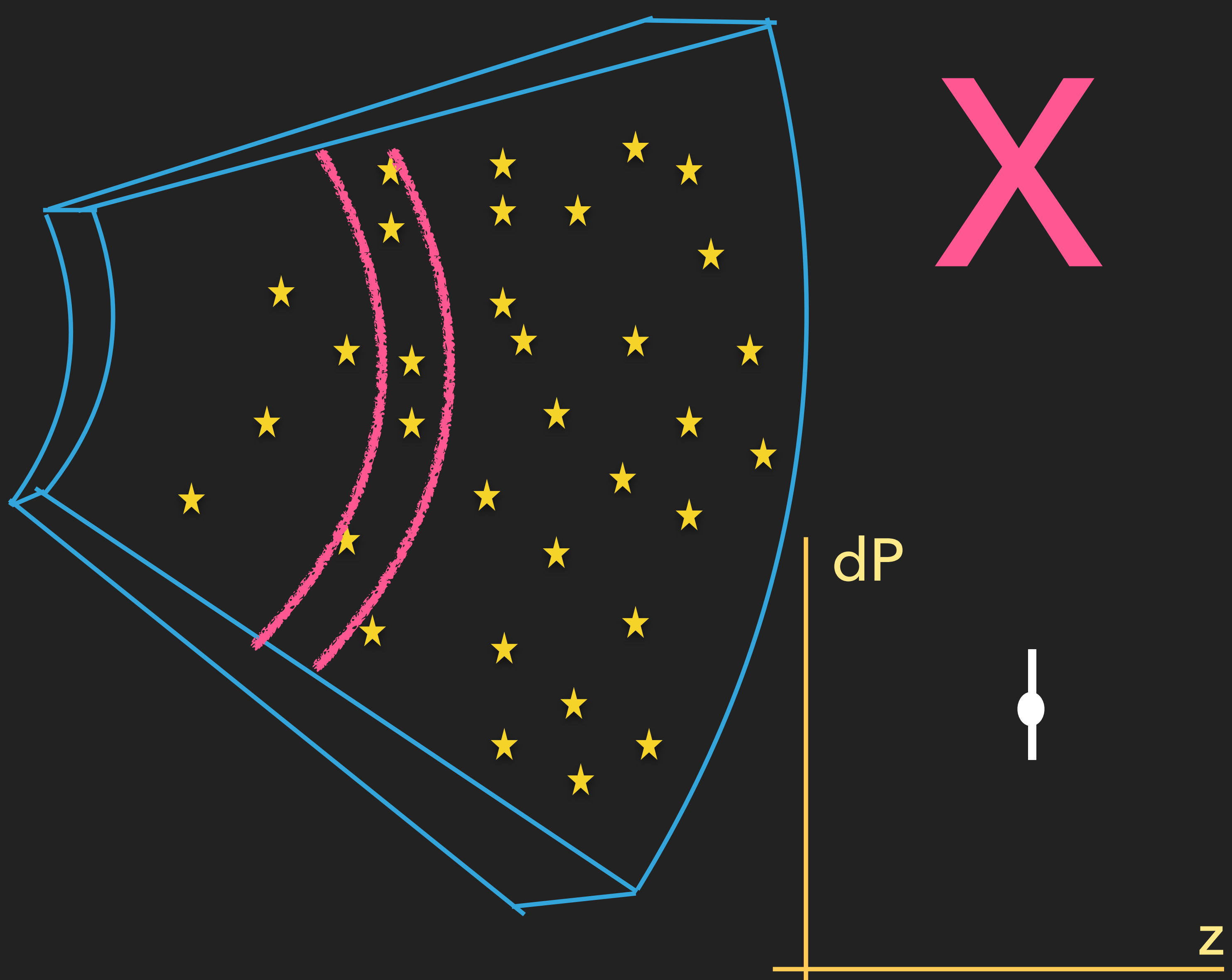

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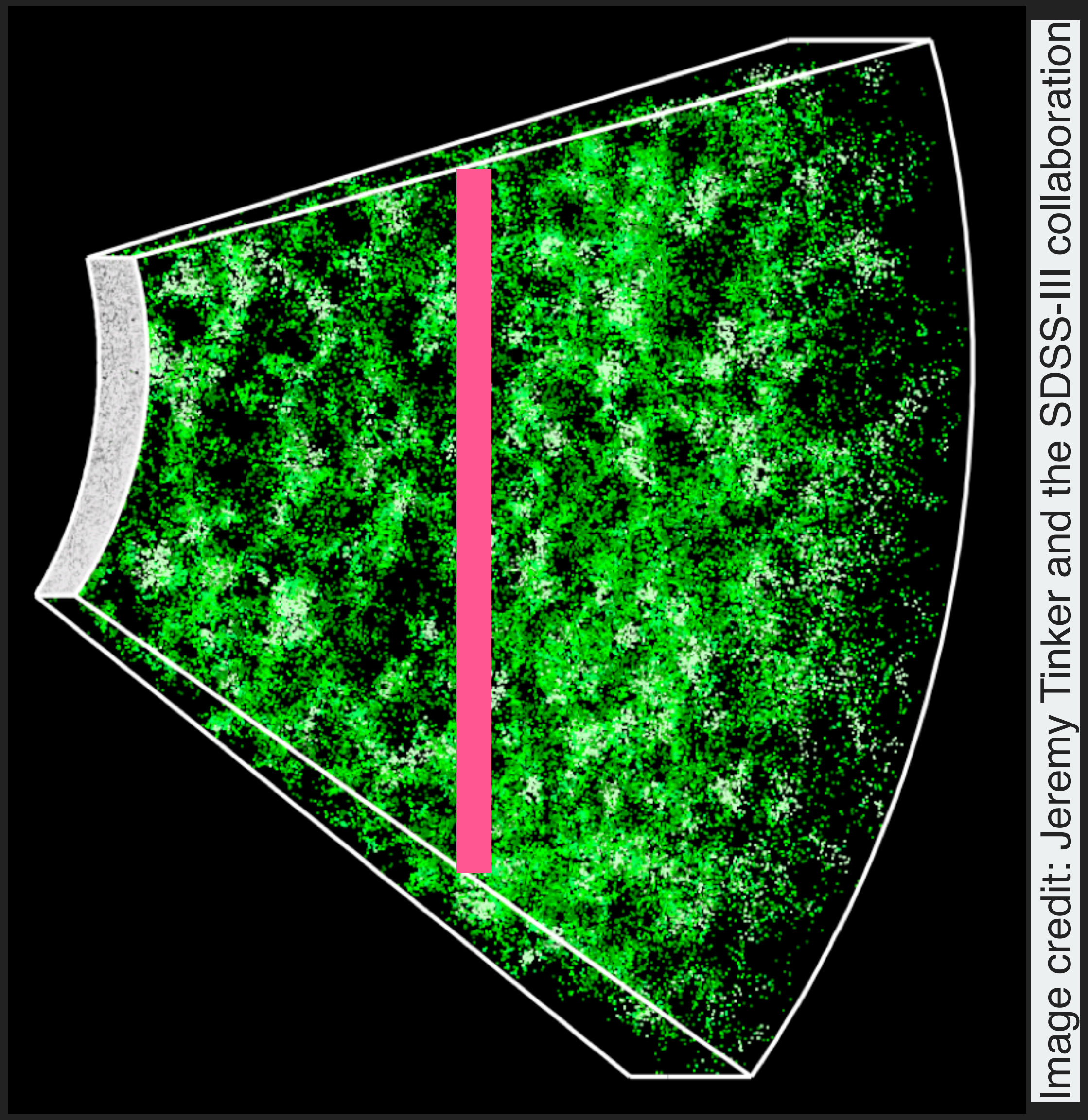

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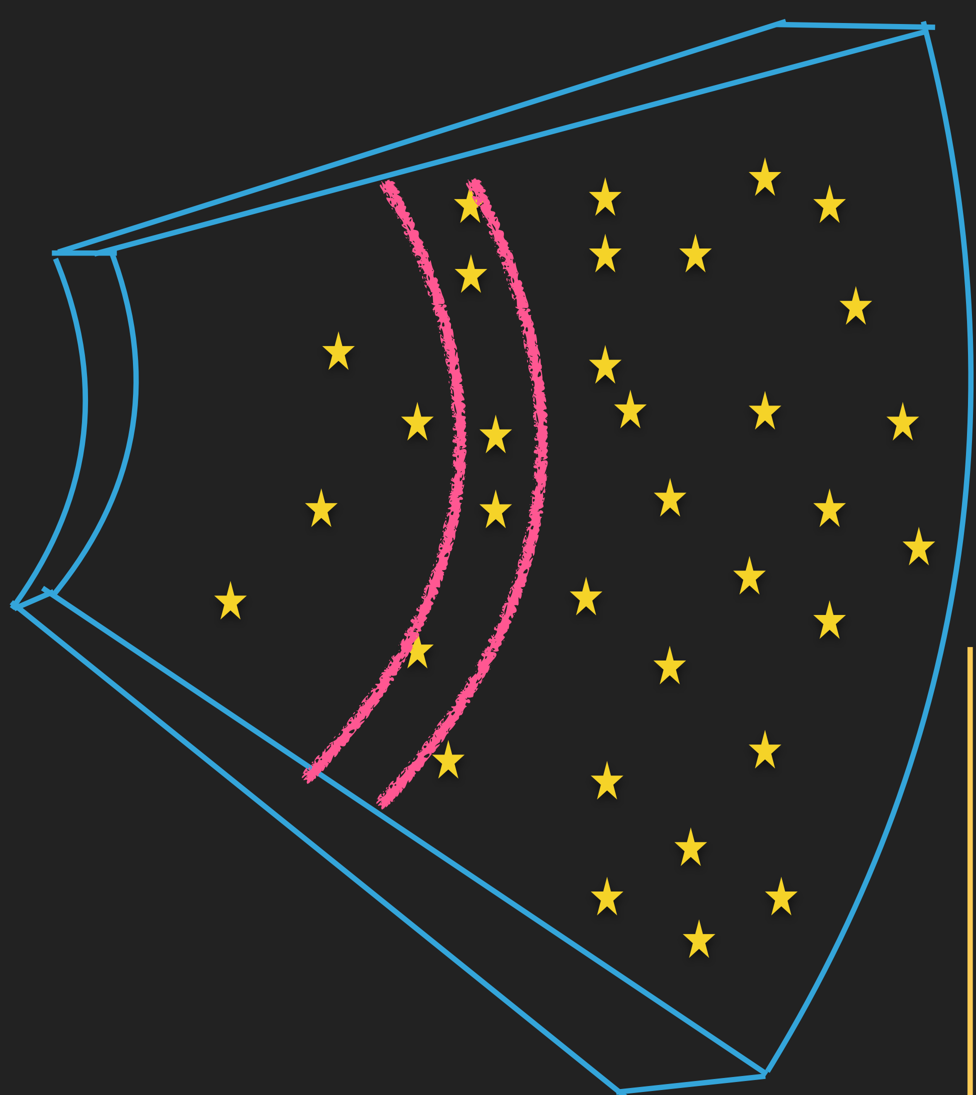

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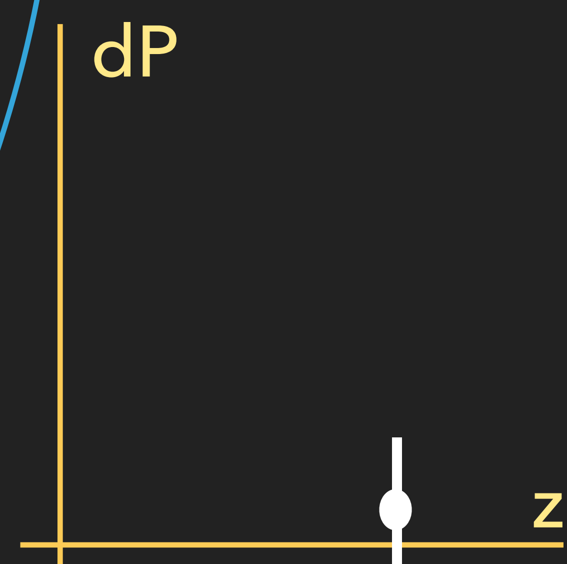

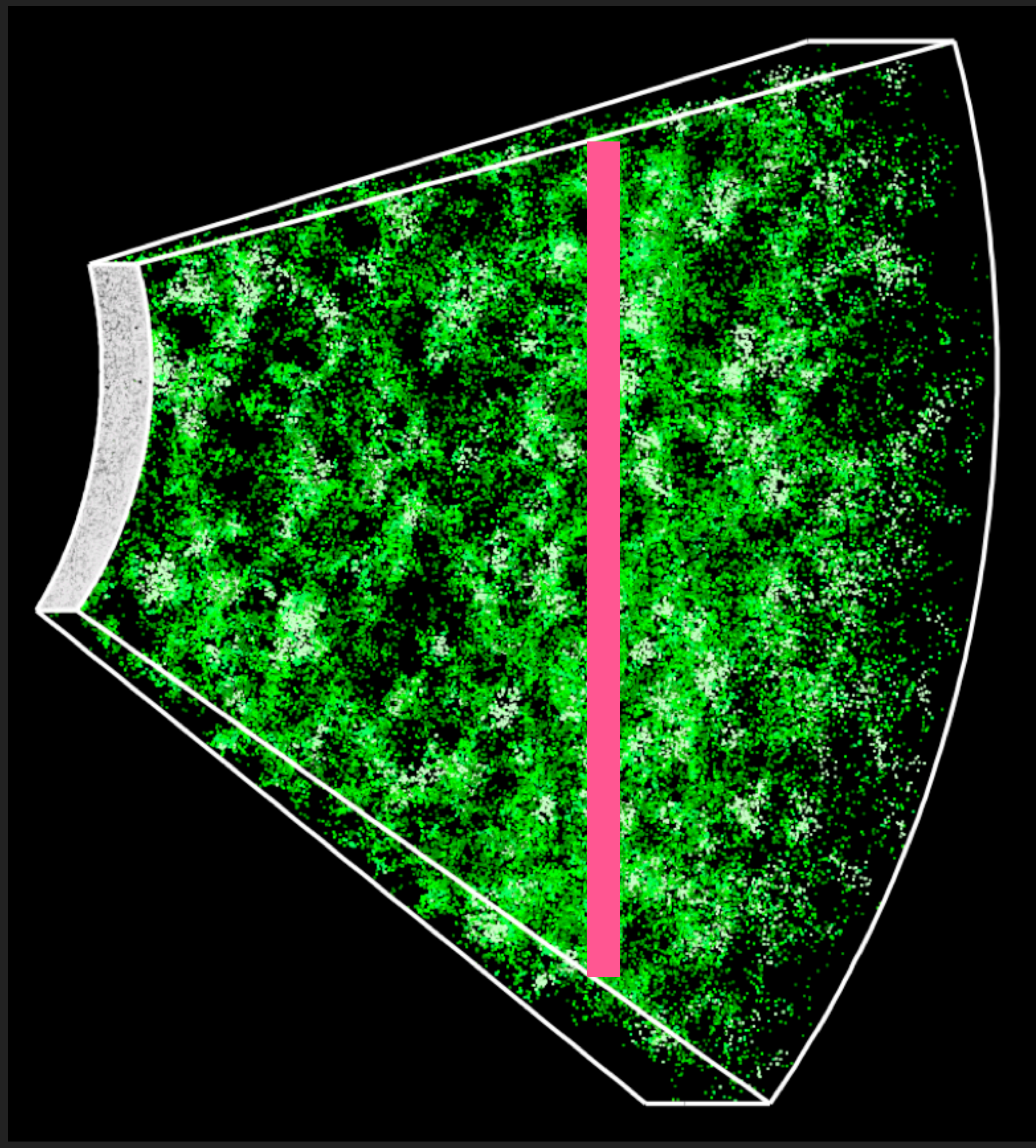

Image credit: Jeremy Tinker and the SDSS-III collaboration

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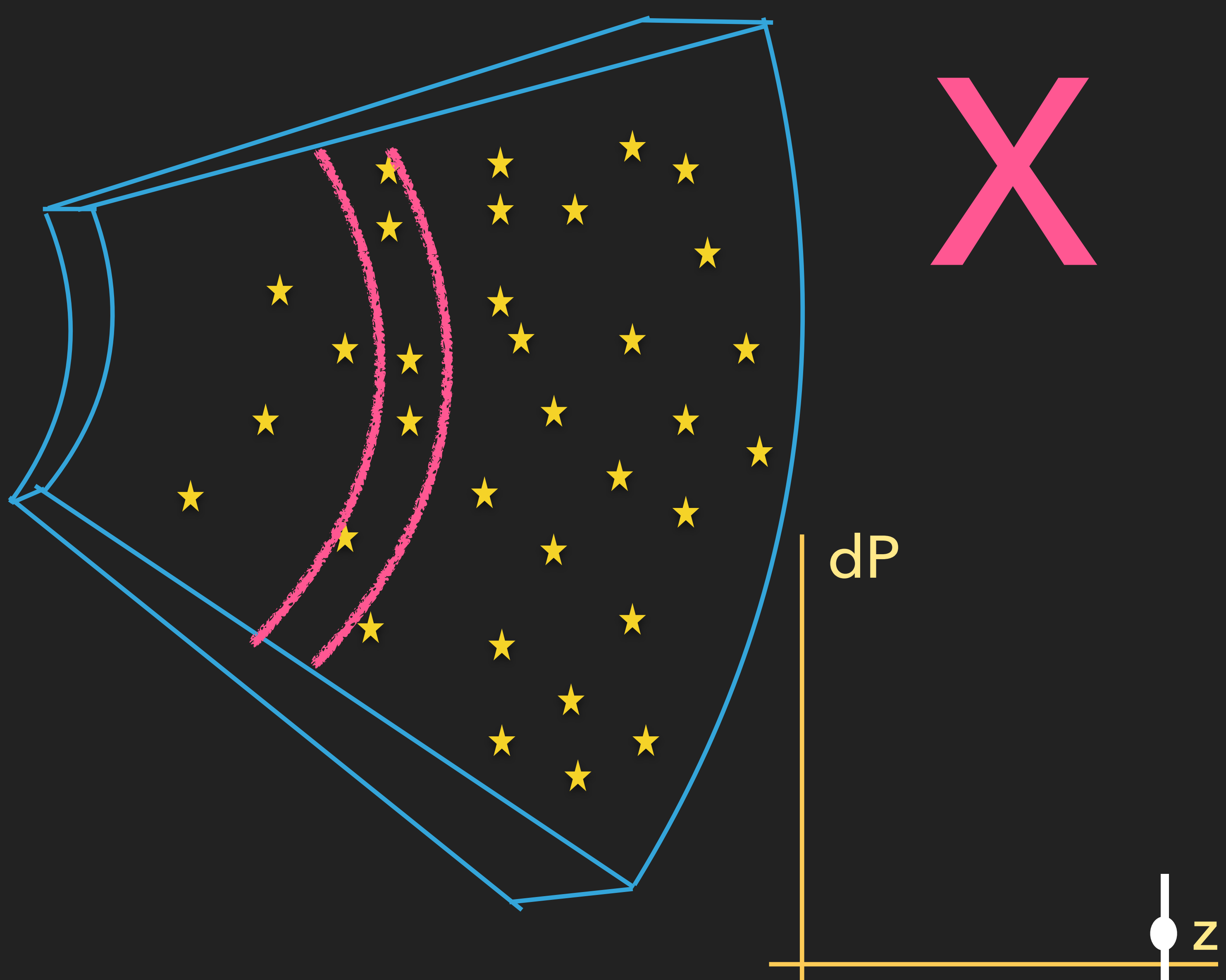

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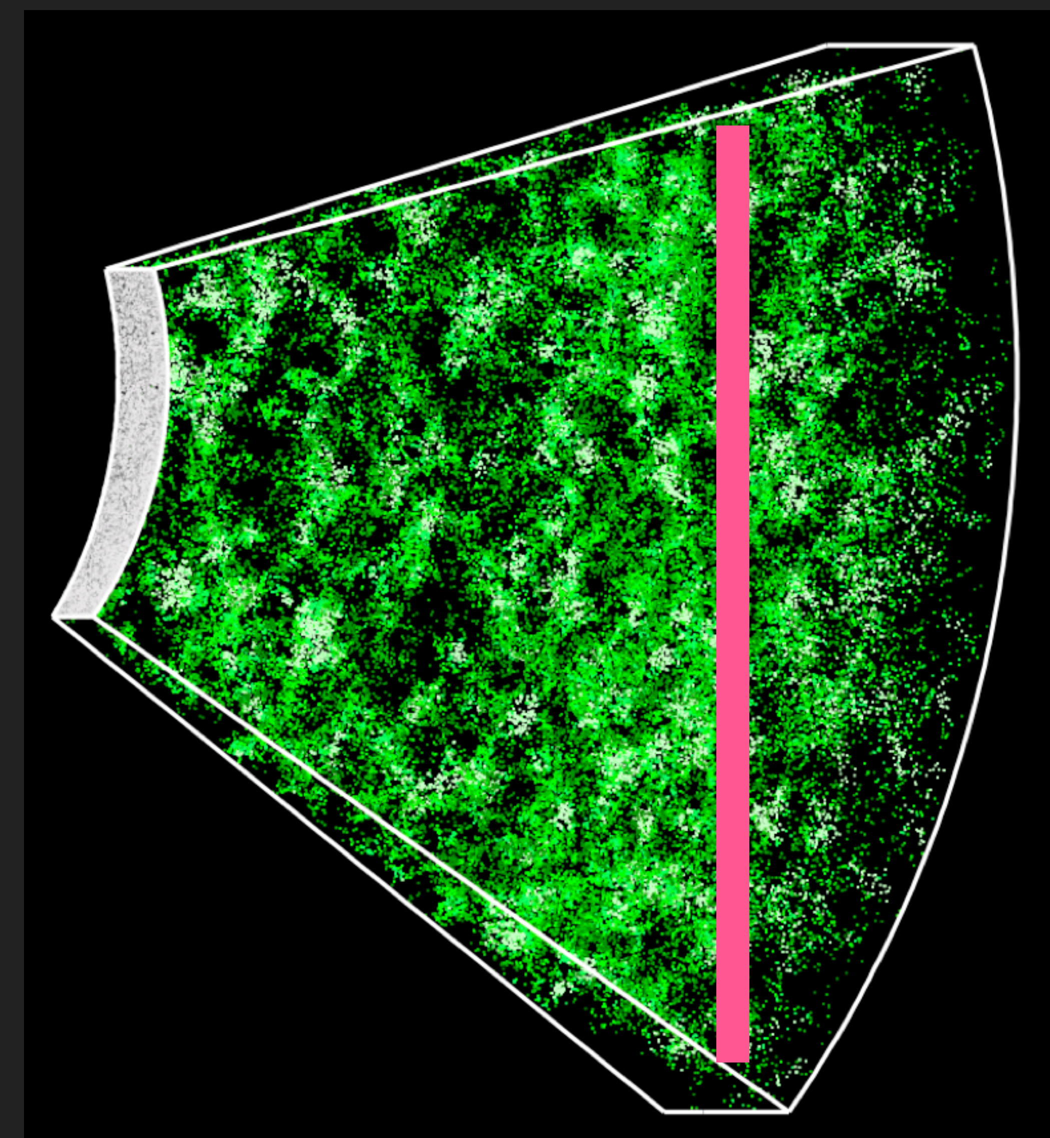

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Galaxy samples observed in redshift space

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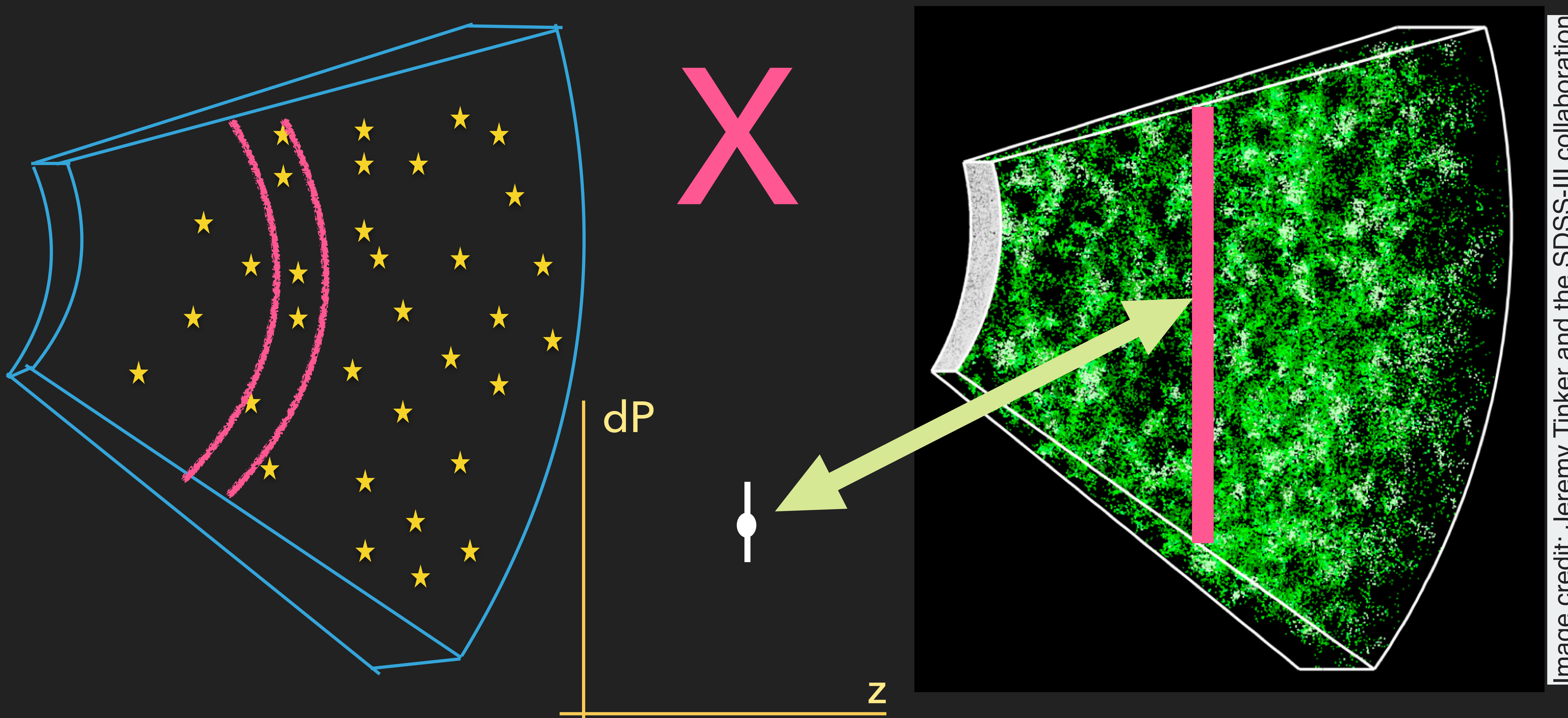
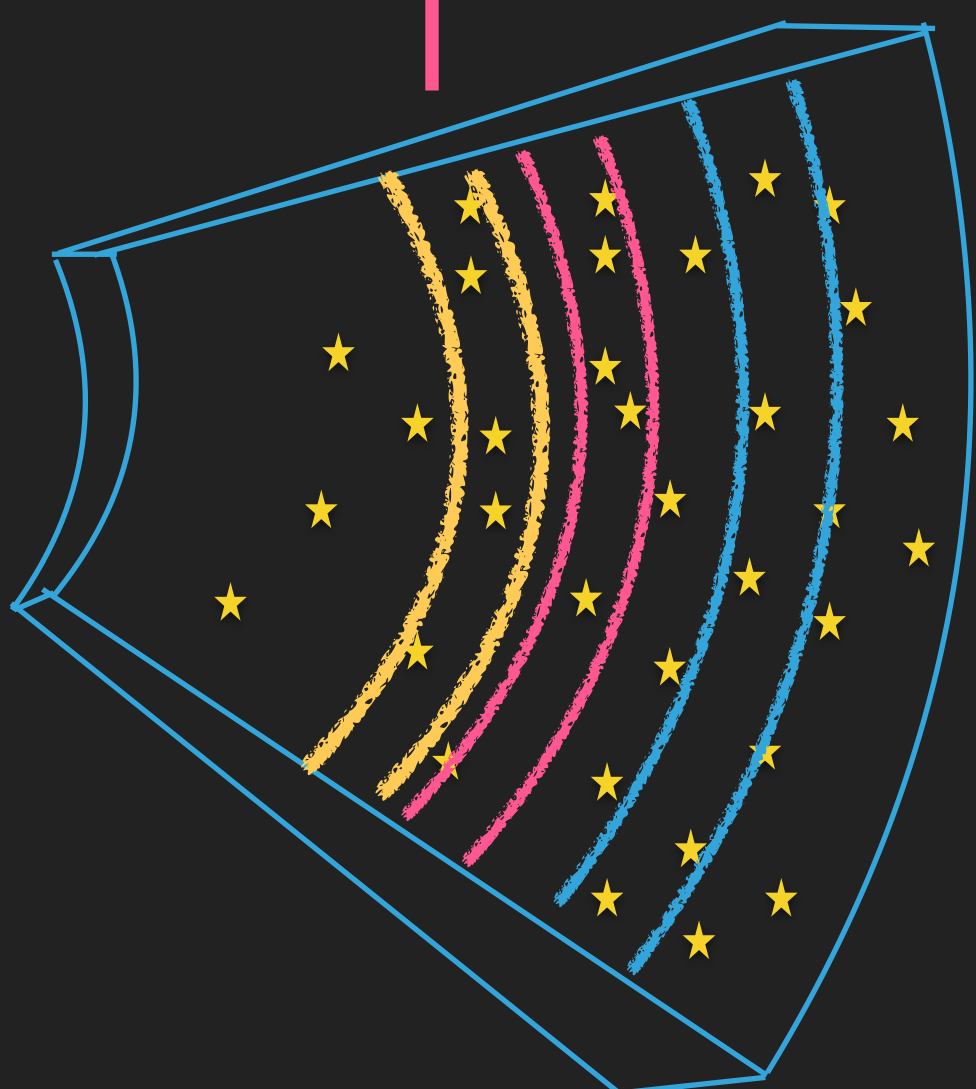


Dark sirens observed in luminosity distance space

Galaxy samples observed in redshift space

EXPANSION HISTORY USING DARK SIRENS THROUGH CROSS-CORRELATION

$$d_l = \frac{c}{H_0}(1+z)\int_0^z \frac{dz'}{\sqrt{\Omega_m(1+z')^3 + \Omega_{DE}(z')}}$$



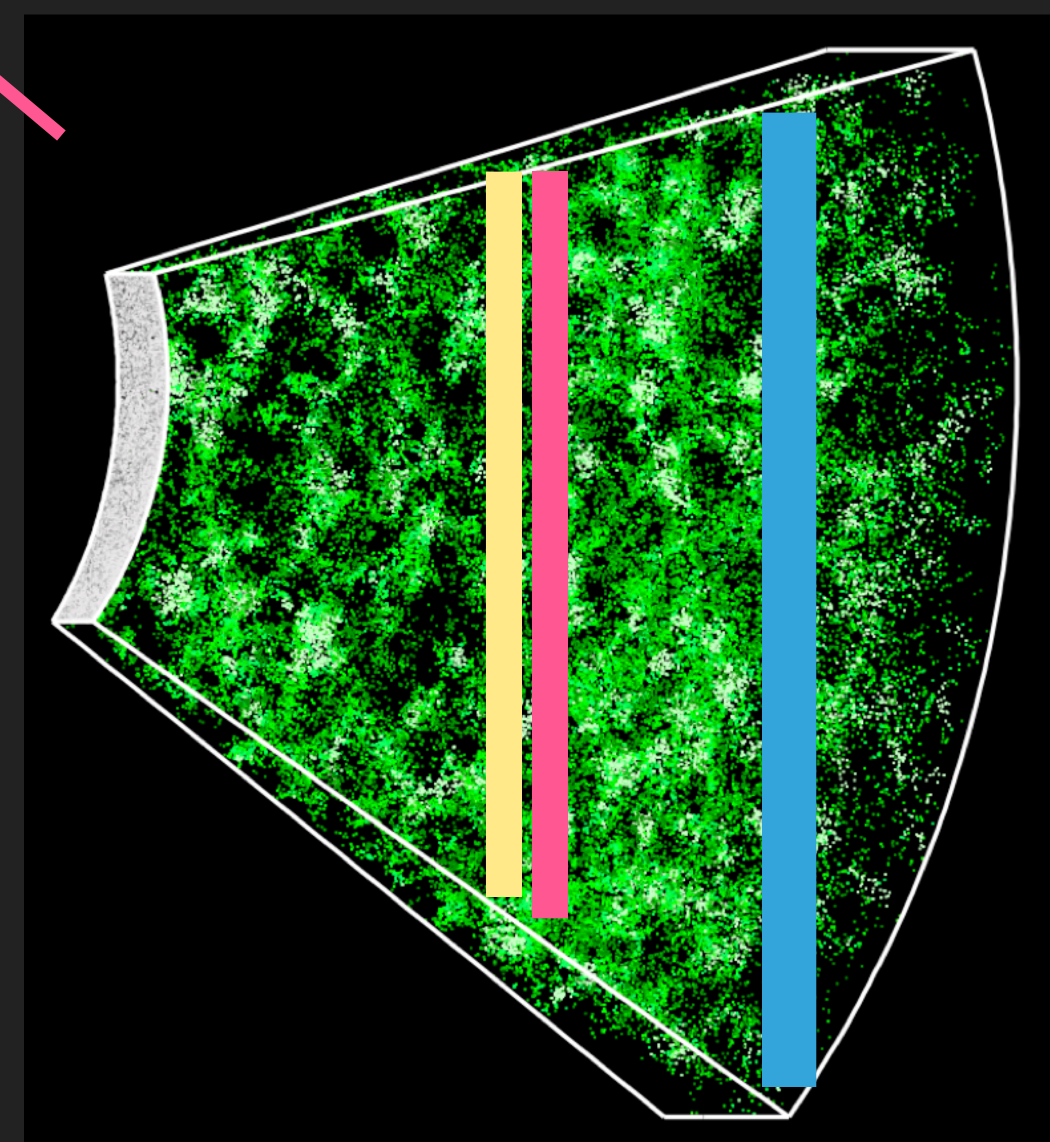


Image credit: Jeremy Tinker and the SDSS-III collaboration

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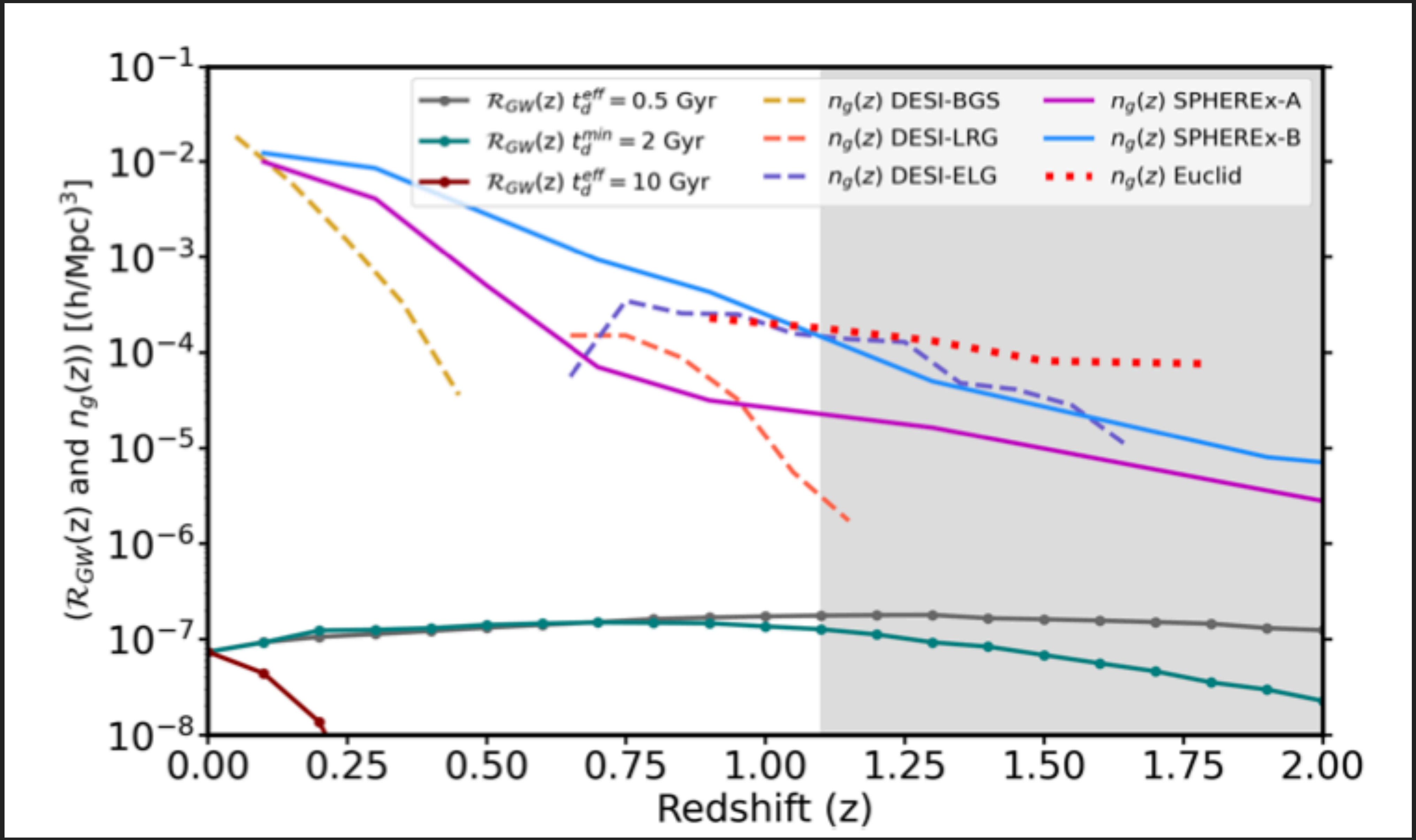
LVK+SPHEREX AND LVK+DESI ARE PROMISING COMBINATIONS



Diaz and Mukherjee (2107.12787)

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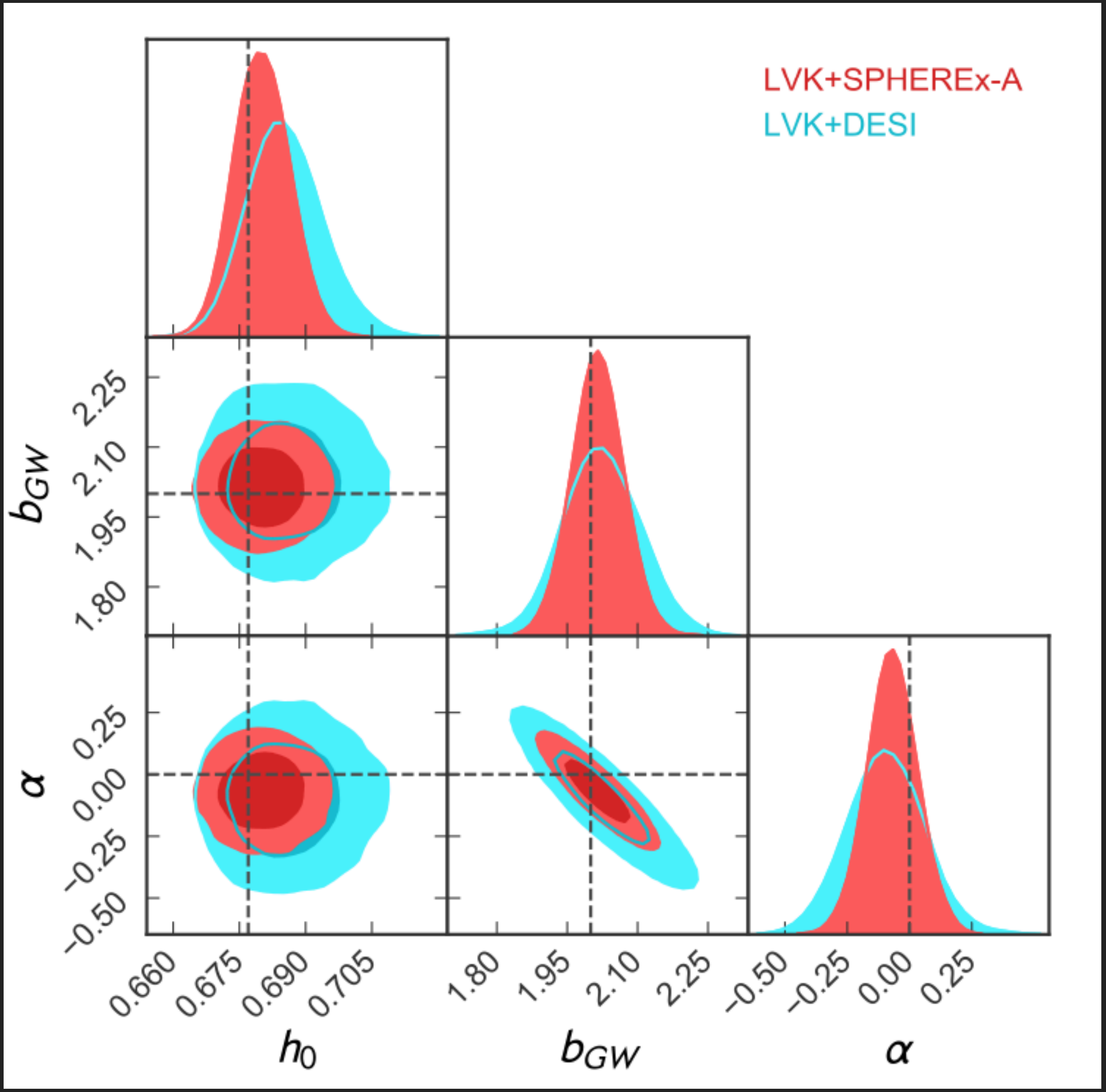
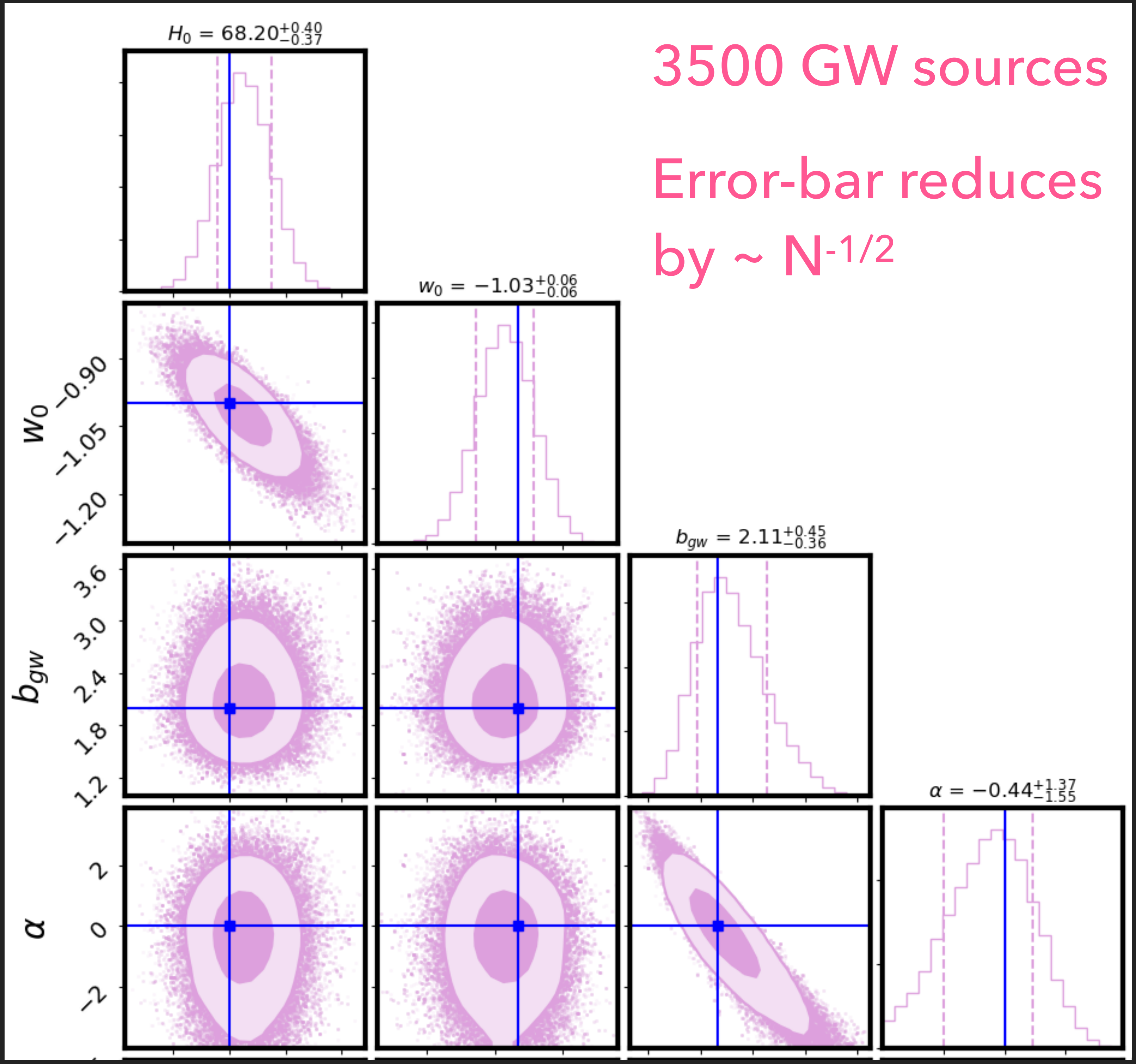


Diaz and Mukherjee (2107.12787)

LVK DETECTOR NETWORK WILL RECONSTRUCT THE DARK ENERGY EQUATION OF STATE USING BINARY BLACK HOLES



$$w(z) = w_0 + w_a\left(\frac{z}{1+z}\right)$$

$$b(z) = b_{GW}(1+z)^{\alpha}$$

Mukherjee, Wandelt, Nissanke, Silvestri (Phys. Rev. D 103, 043520, 2021) (2007.02943)

Mukherjee, Wandelt, Silk (*MNRAS*, 502,1136, 2021, 2012.15316)

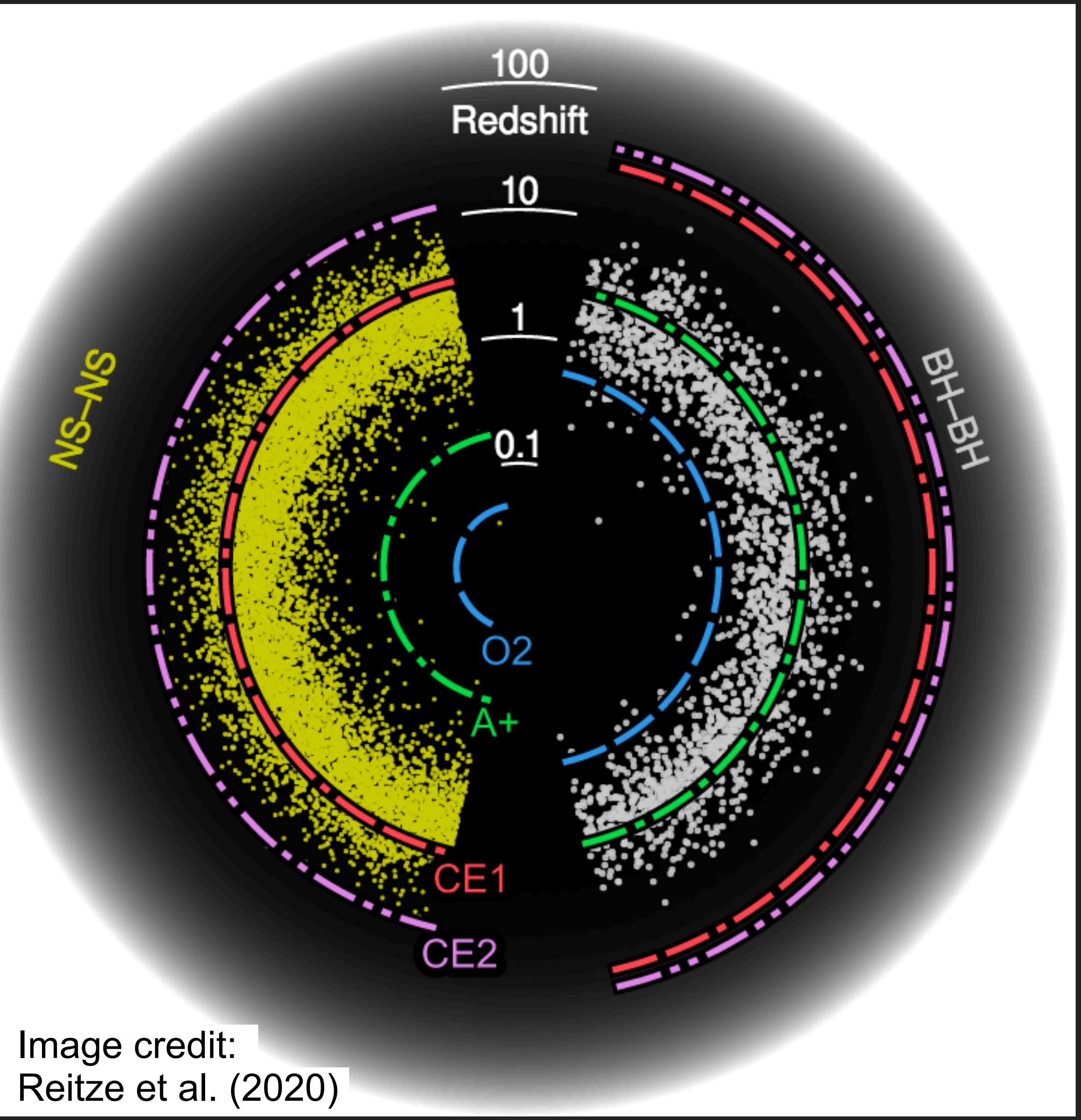
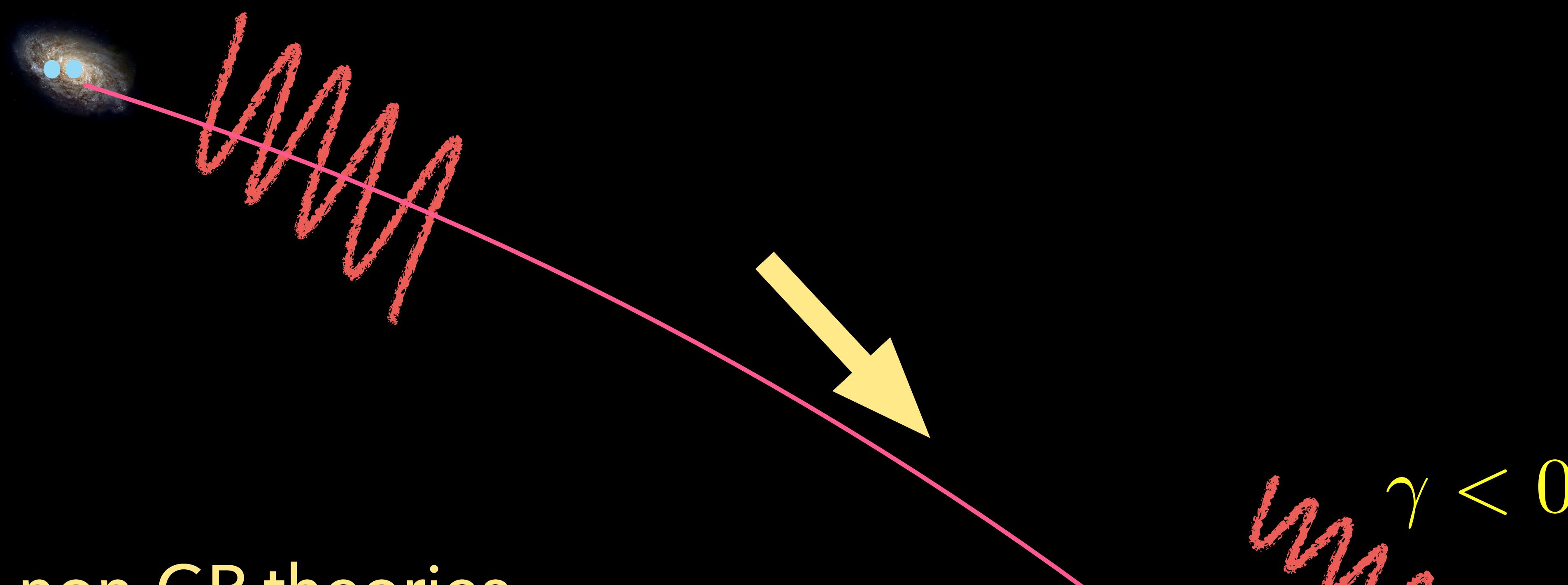
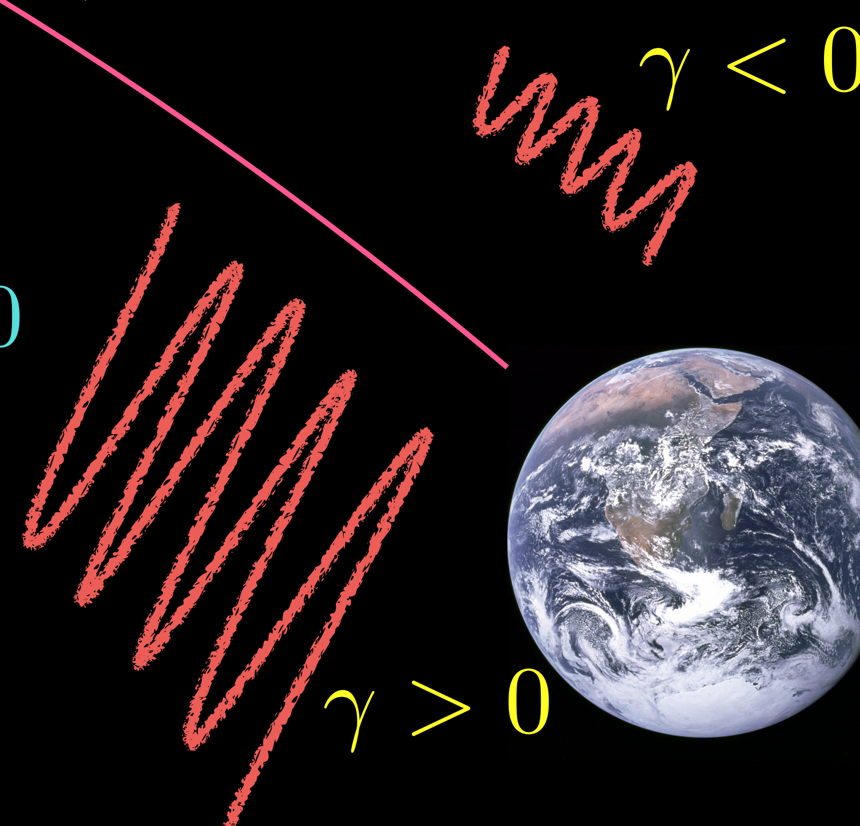


Image credit:
Reitze et al. (2020)

TESTING GENERAL THEORY OF RELATIVITY USING GW PROPAGATION

GW PROPAGATION THROUGH SPACE-TIME IS A PROBE TO TEST GENERAL THEORY OF RELATIVITY





GW propagation in non-GR theories

$$h''_{ij} + 2(1 - \gamma(z))\mathcal{H}h'_{ij} + (c_T^2 k^2 + a^2\mu^2)h_{ij} = 0$$

EM–GW PROBES TO MEASURE THE FRICTIONAL TERM

Unknown

$$d_l^{GW}(z) = \exp\left(- \int dz' \frac{\gamma(z')}{1+z'} \right) d_l^{EM}(z)$$

From GW data

Unknown

For dark sirens: z is unknown

DATA DRIVEN TEST OF GENERAL RELATIVITY BY COMPARING THREE SCALES

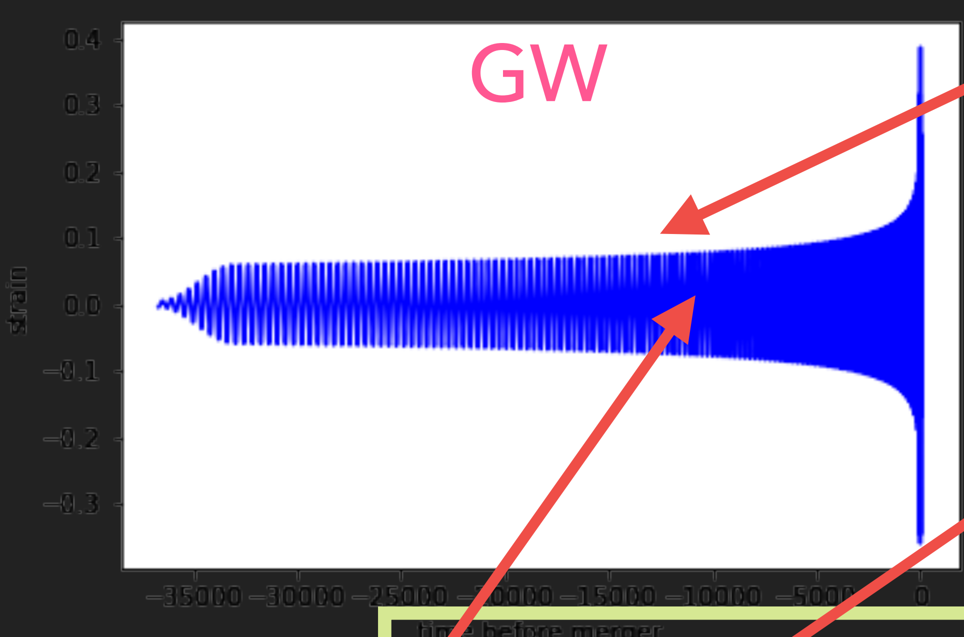
Sound horizon at the drag epoch

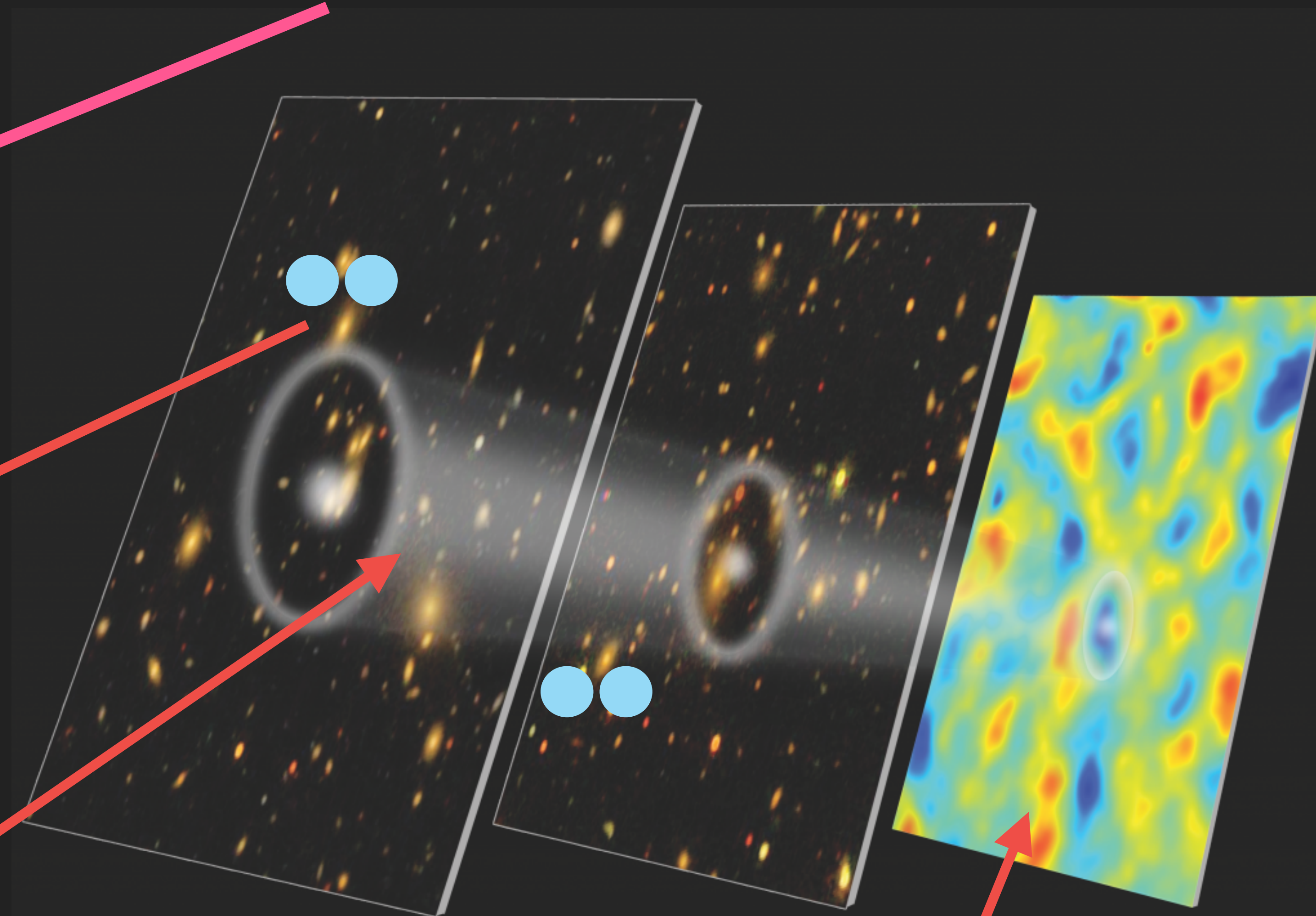
Mukherjee, Wandelt, Silk (*MNRAS*, 502,1136, 2021)

Angular diameter distance

$$\theta_{BAO}(z) = \frac{r_s}{(1+z)d_A(z)}$$

$$d_A(z) = d_l^{EM}(z)/(1+z)^2$$





Galaxy map 3.8 billion years ago

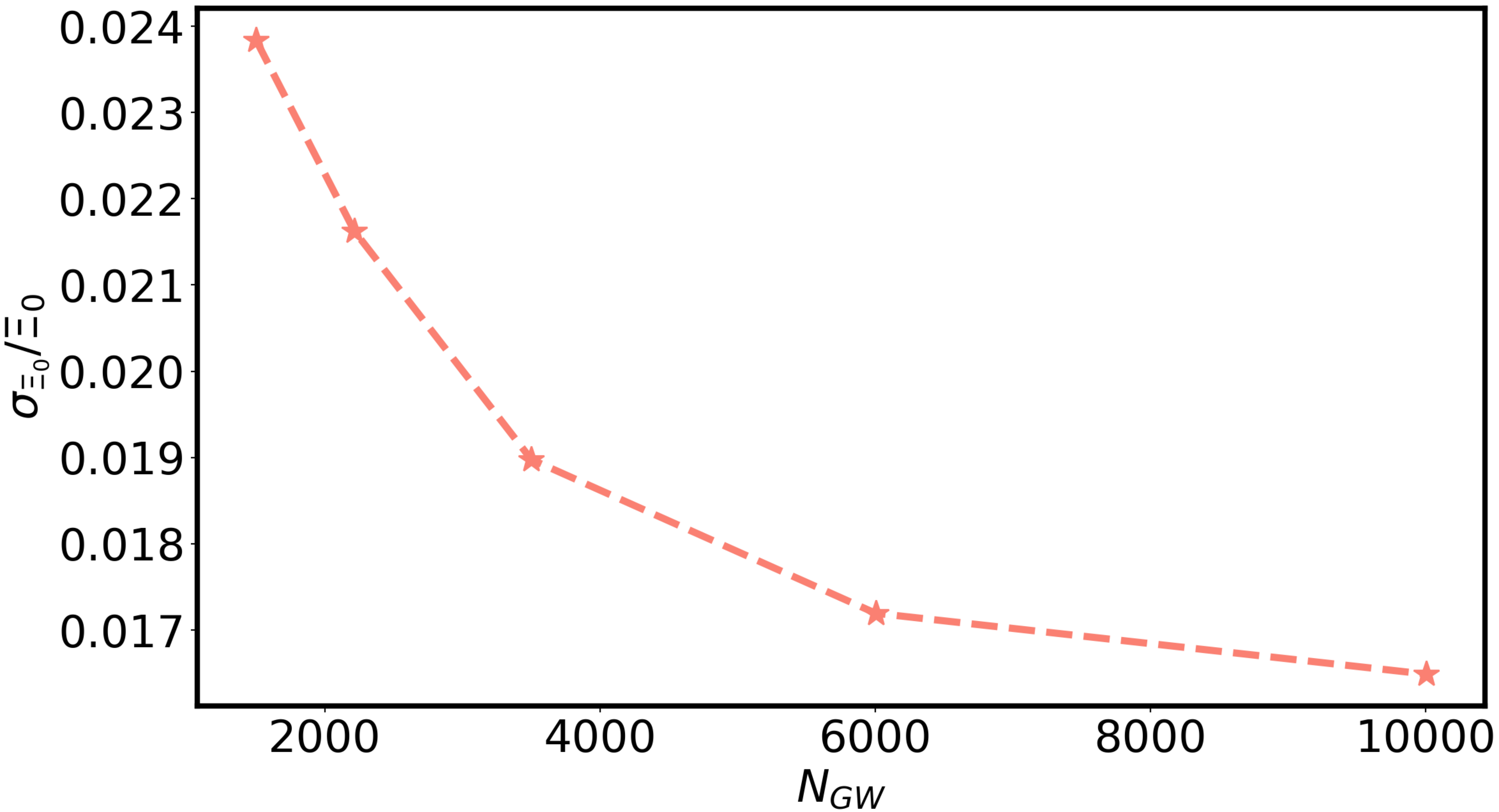
Galaxy map 5.5 billion years ago

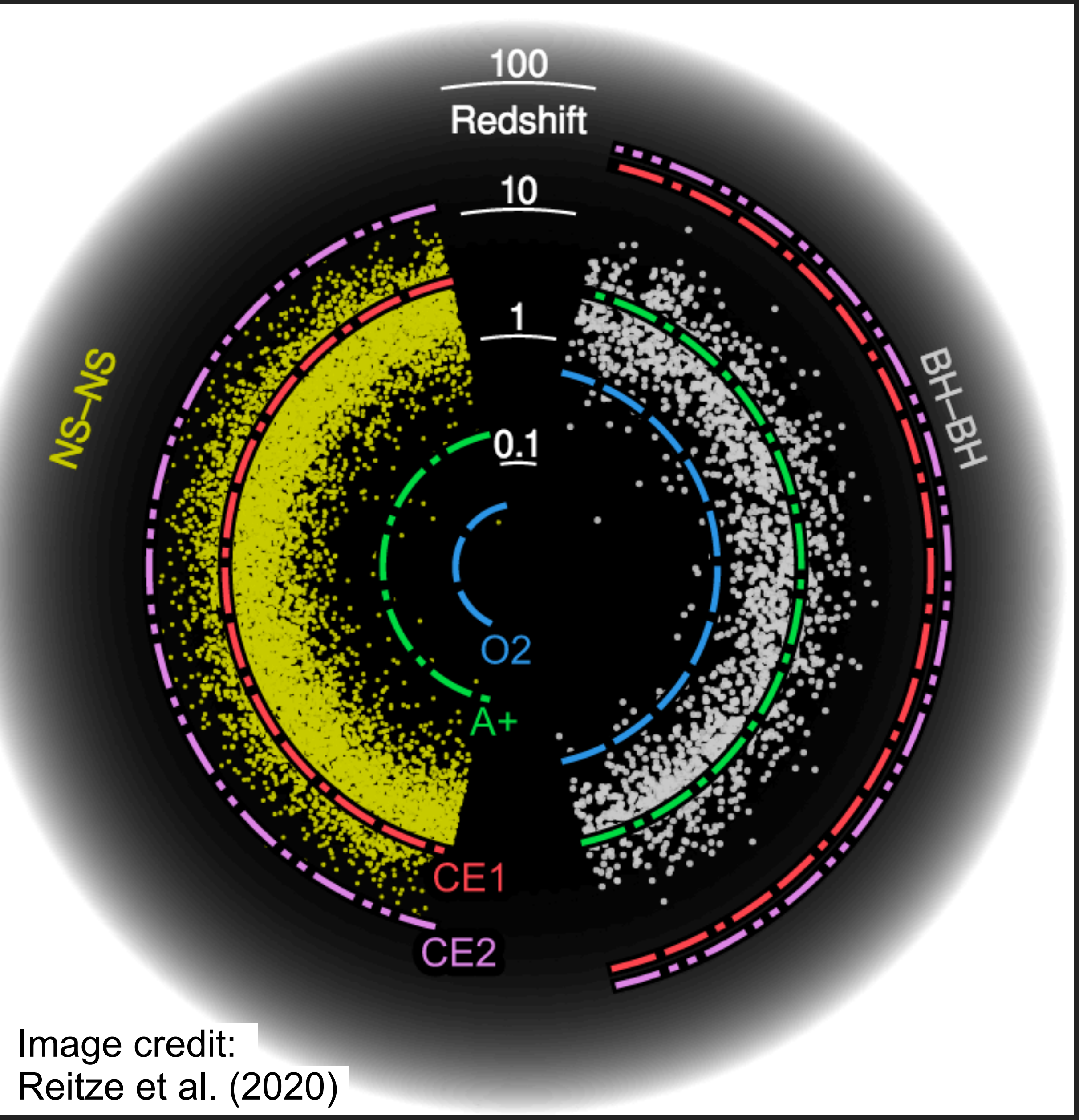
CMB 13.7 billion years ago

$$d_l^{GW}(z)\theta_{BAO}(z) = \left(\Xi_0 + \frac{1-\Xi_0}{(1+z)^n}\right)(1+z)r_s$$

FORECAST TO MEASURE THE FRICTIONAL TERM FROM LVK

Mukherjee, Wandelt, Silk (*MNRAS*, 502,1136, 2021)





MULTI-MESSENGER VIEW ON DARK MATTER

+ Primordial black holes

HOW CAN WE DISTINGUISH BETWEEN ASTROPHYSICAL AND PRIMORDIAL BLACK HOLES ?

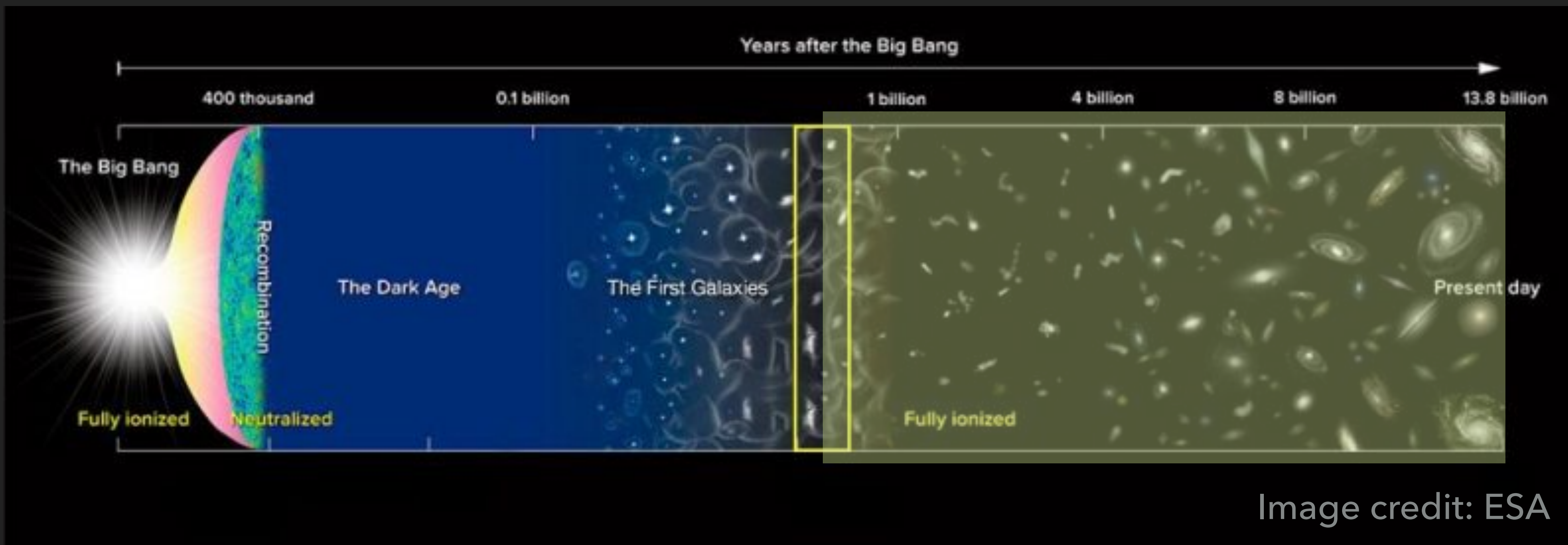
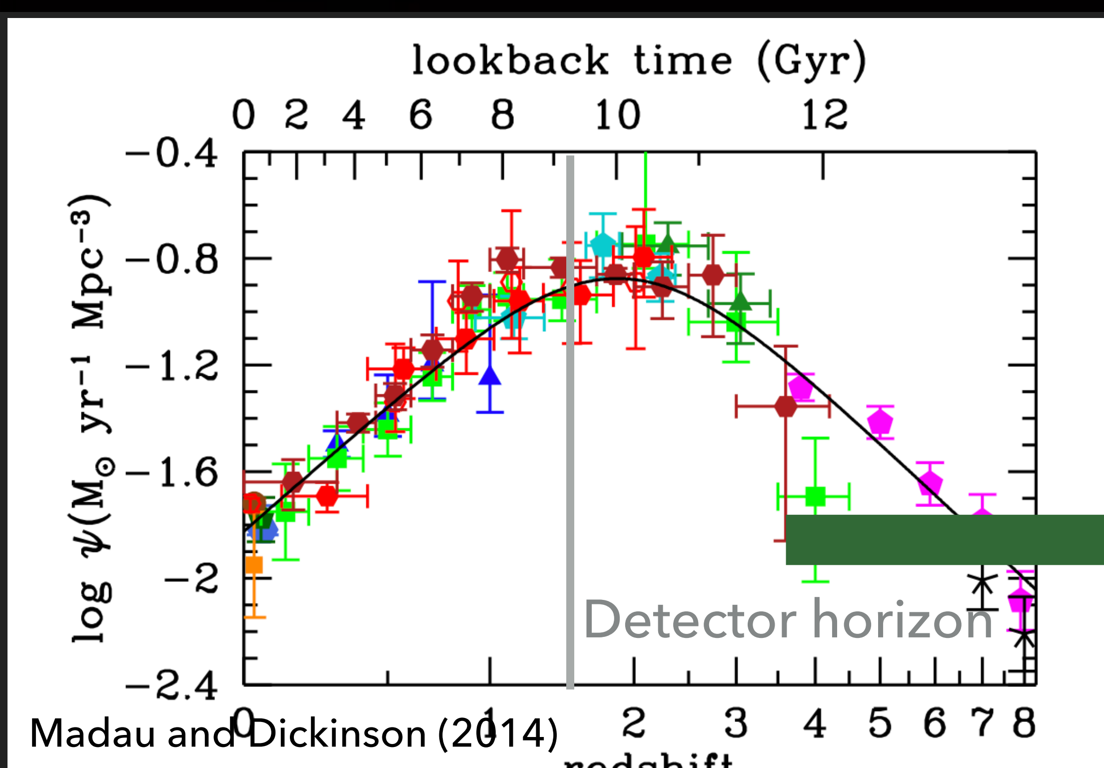
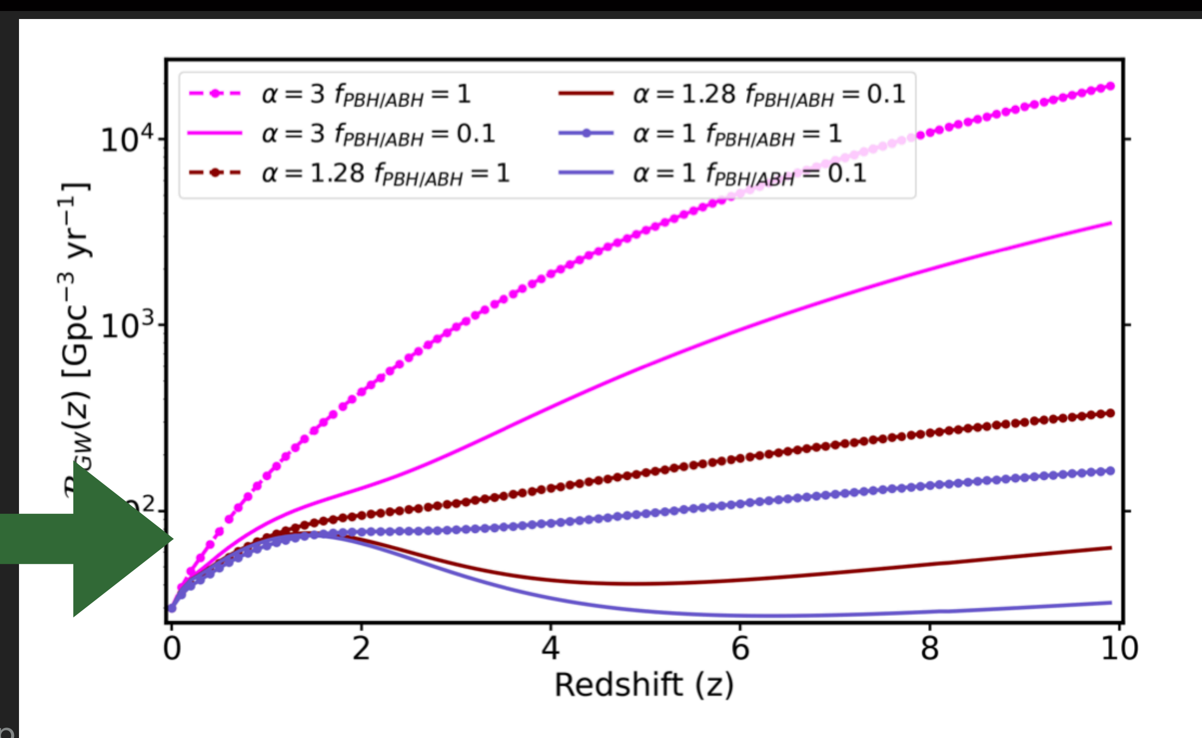


Image credit: ESA

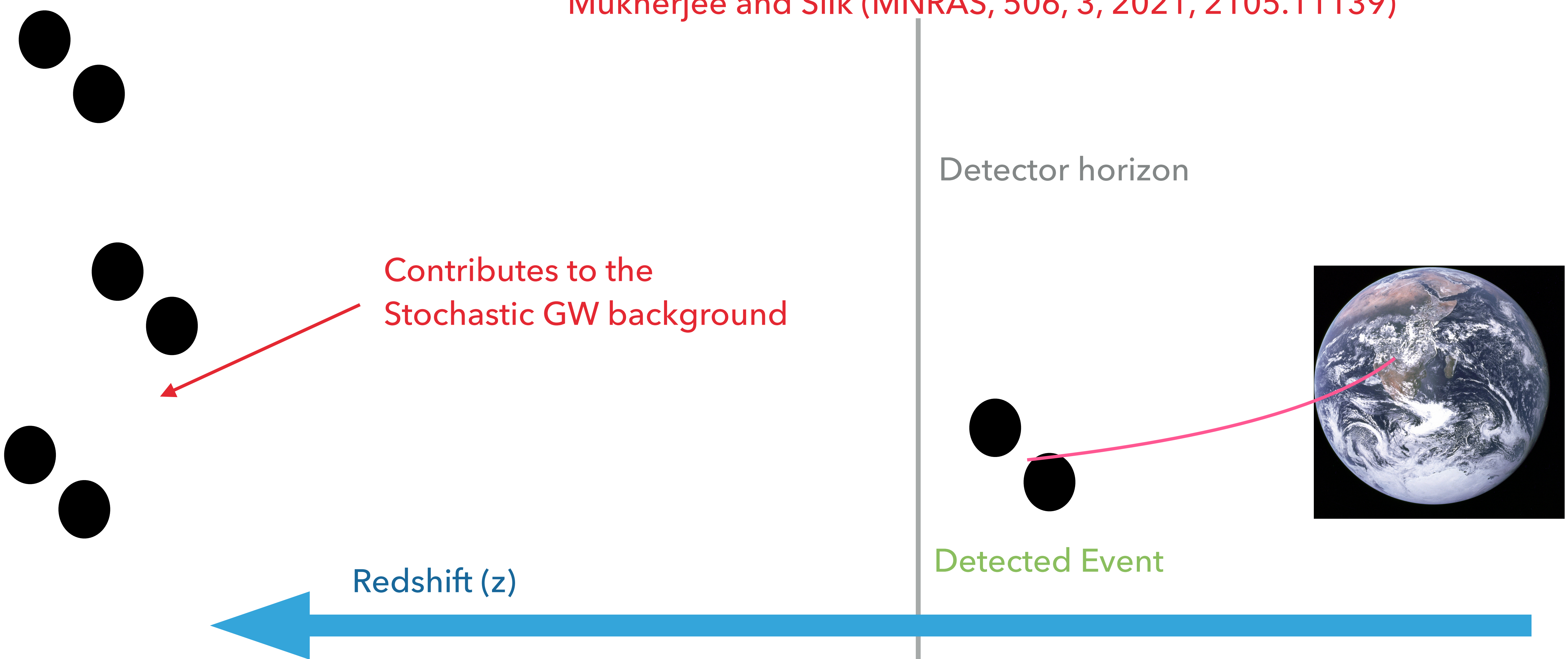


Madau and Dickinson (2014)



LESS OBJECTS COALESCING AT HIGH REDSHIFT LEAD TO WEAK STOCHASTIC BACKGROUND

Mukherjee and Silk (MNRAS, 491, 4, 2020, 1912.0757)
Mukherjee and Silk (MNRAS, 506, 3, 2021, 2105.11139)



Distribution of the astrophysical system's source parameters

Rate of the astrophysical events

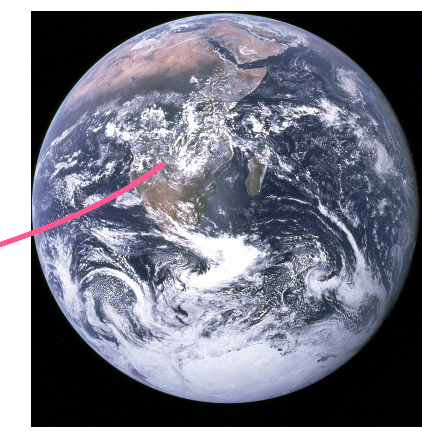
$$\Omega_{GW}(f) = \frac{f}{\rho_c c^2} \int d\theta \, p(\theta) \int_{z_{min}}^{z_{max}} dz \frac{R(z,\theta) dE_{GW}(\theta)/df_r}{(1+z)H(z)}$$

MORE OBJECTS COALESCING AT HIGH REDSHIFT LEAD TO LOUD STOCHASTIC BACKGROUND

Mukherjee and Silk (MNRAS, 491, 4, 2020, 1912.0757)
Mukherjee and Silk (MNRAS, 506, 3, 2021, 2105.11139)

Detector horizon

Contributes to the Stochastic GW background



Detected Event

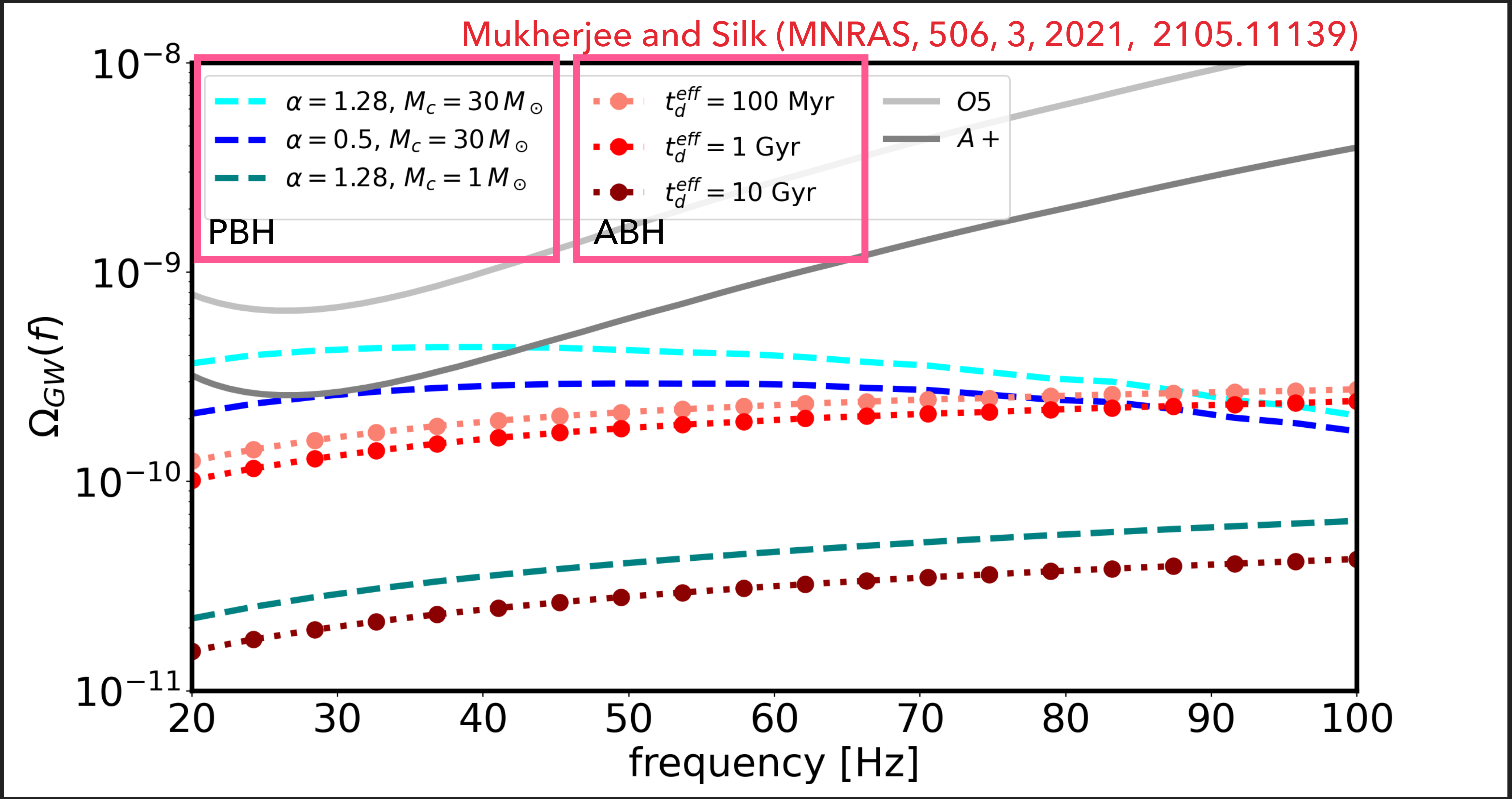
Redshift (z)

Distribution of the astrophysical system's source parameters

Rate of the astrophysical events

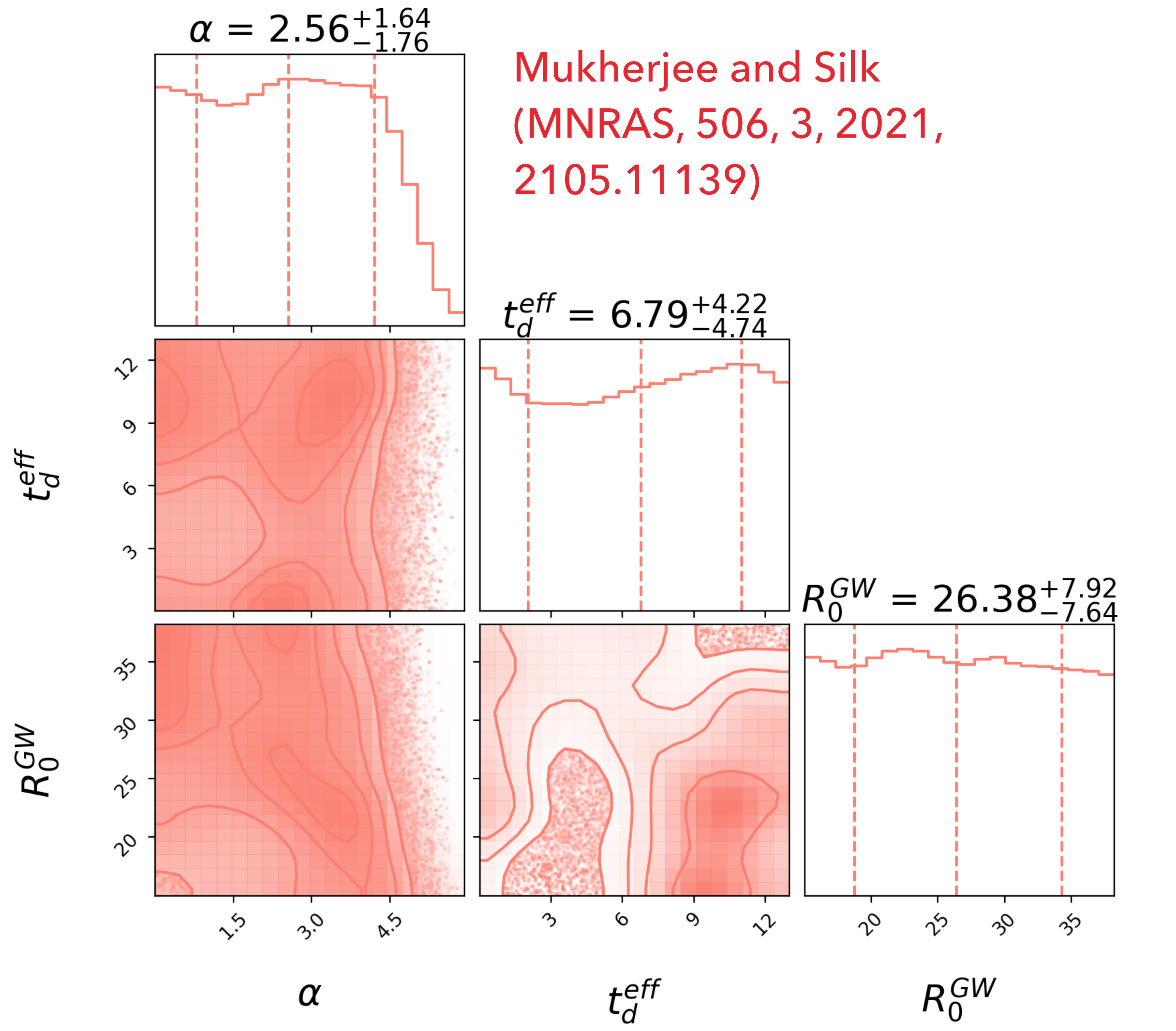
$$\Omega_{GW}(f) = \frac{f}{\rho_c c^2} \int d\theta \, p(\theta) \int_{z_{min}}^{z_{max}} dz \frac{R(z,\theta) dE_{GW}(\theta)/df_r}{(1+z)H(z)}$$

STOCHASTIC GW BACKGROUND FOR DIFFERENT SCENARIOS



BOUND FROM THE O3 DATA OF LIGO-VIRGO

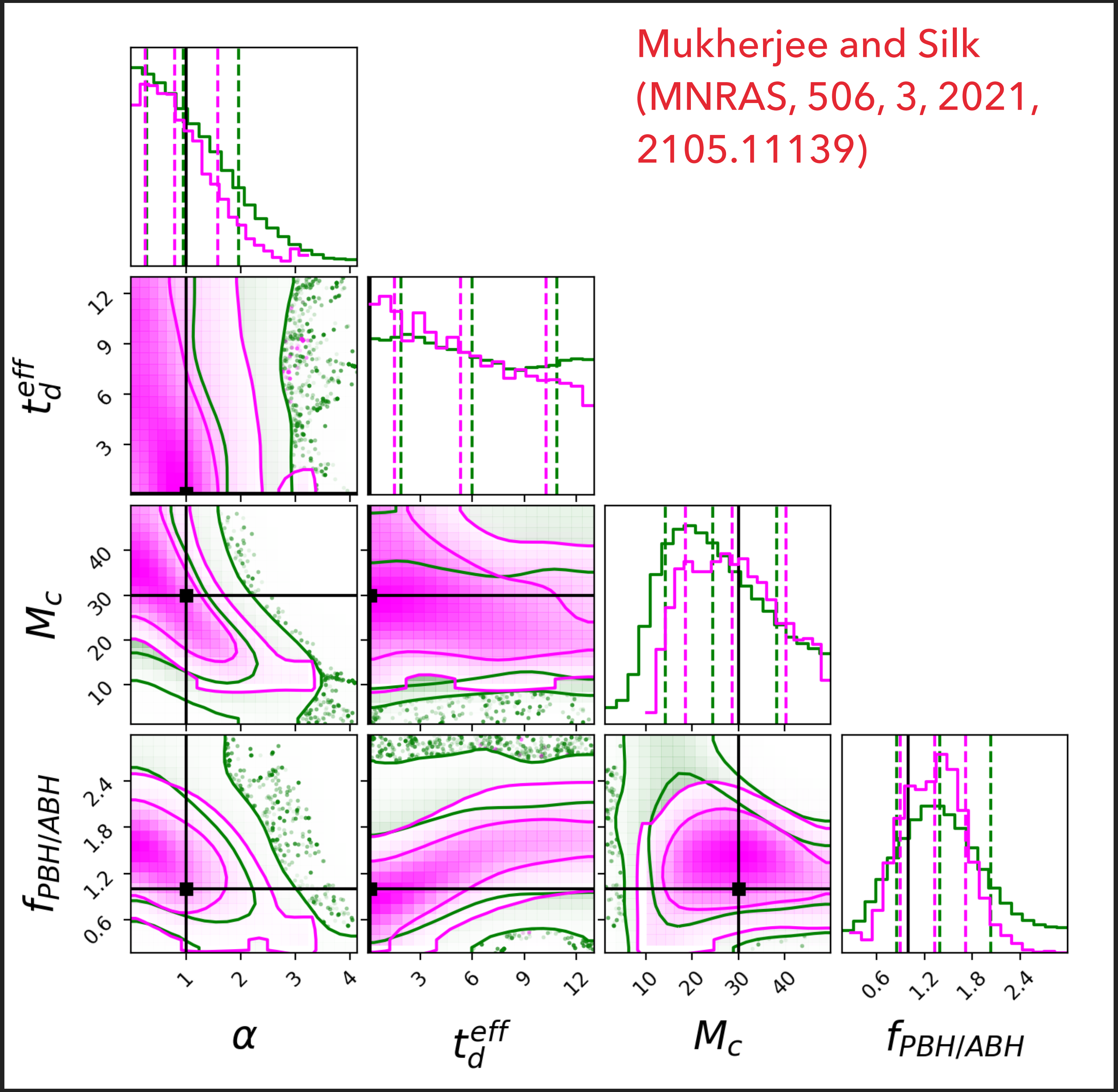
Weak constraints from the current observations.



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

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.



** only a partial list

Multi-messenger Cosmology

A new probe to study the Cosmos

Resolved events

BNS, NS-BH, BBH, SMBH

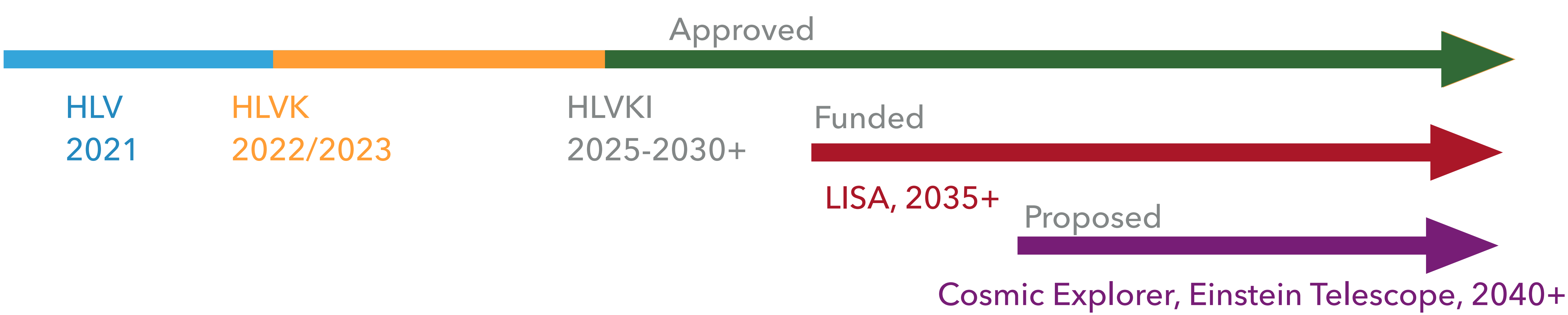
- Hubble constant
- Dark energy EoS
- GW bias parameter
- Testing General Relativity

Unresolved events

Stochastic GW background

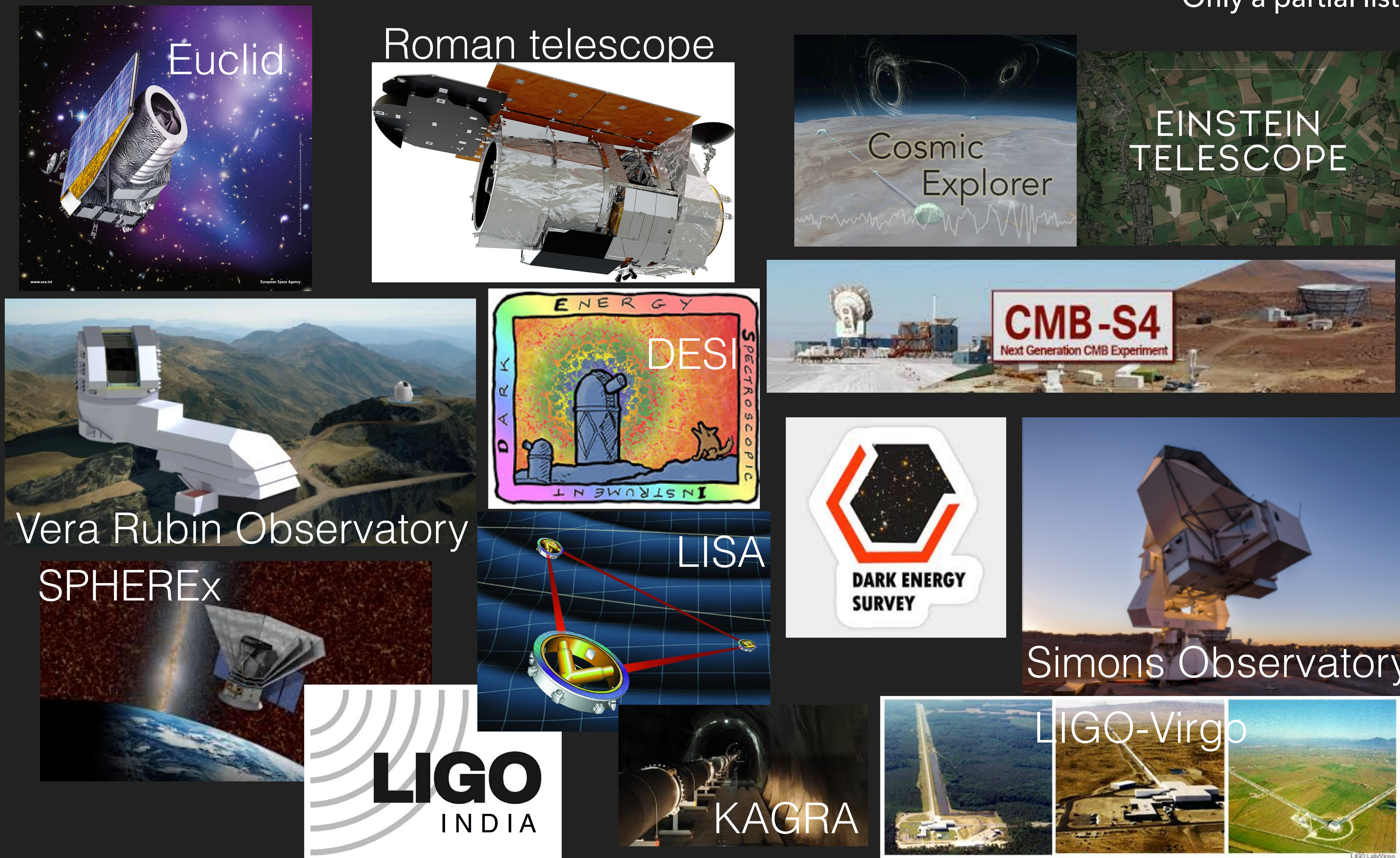
- High redshift merger rate
- Dark Matter

Time-line of the GW observatories

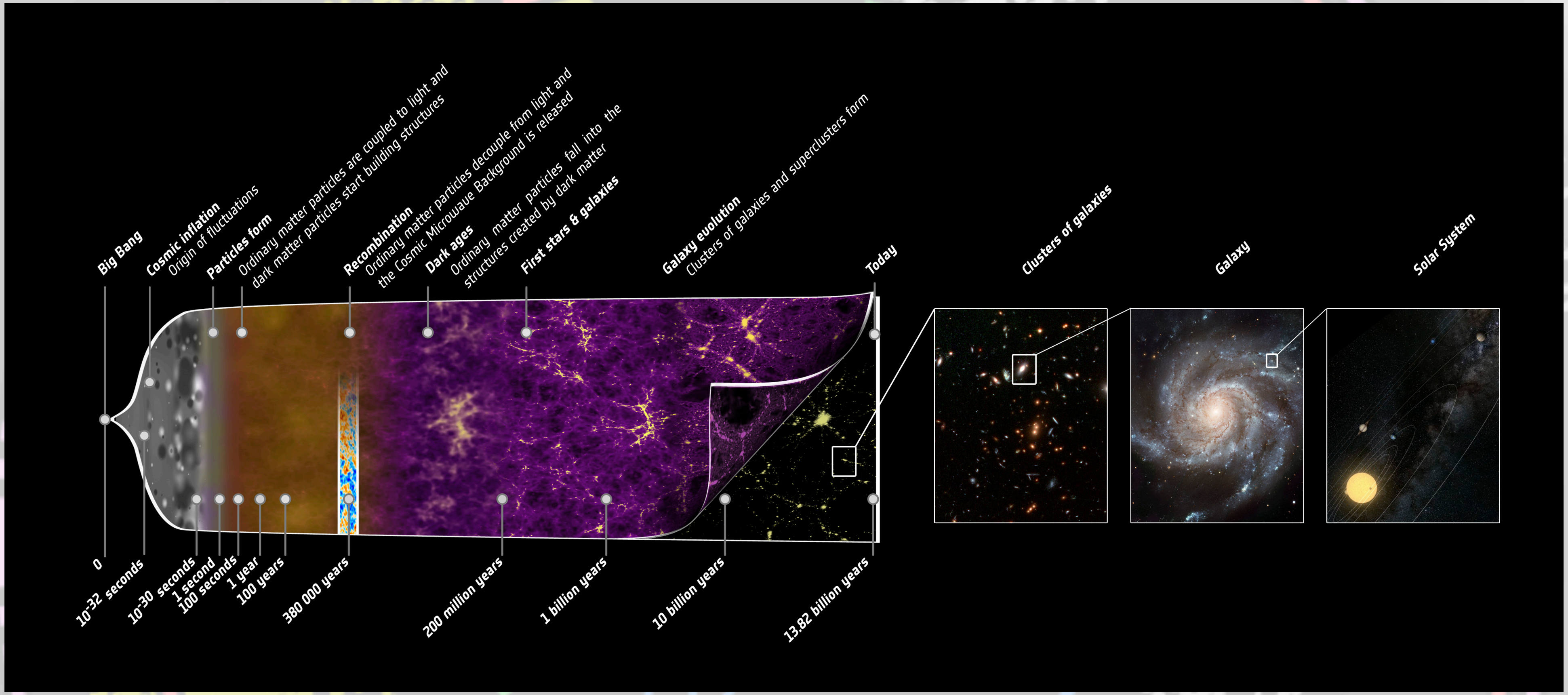


A GOLDEN ERA FOR THE MULTI-MESSENGER COSMOLOGY

**Only a partial list

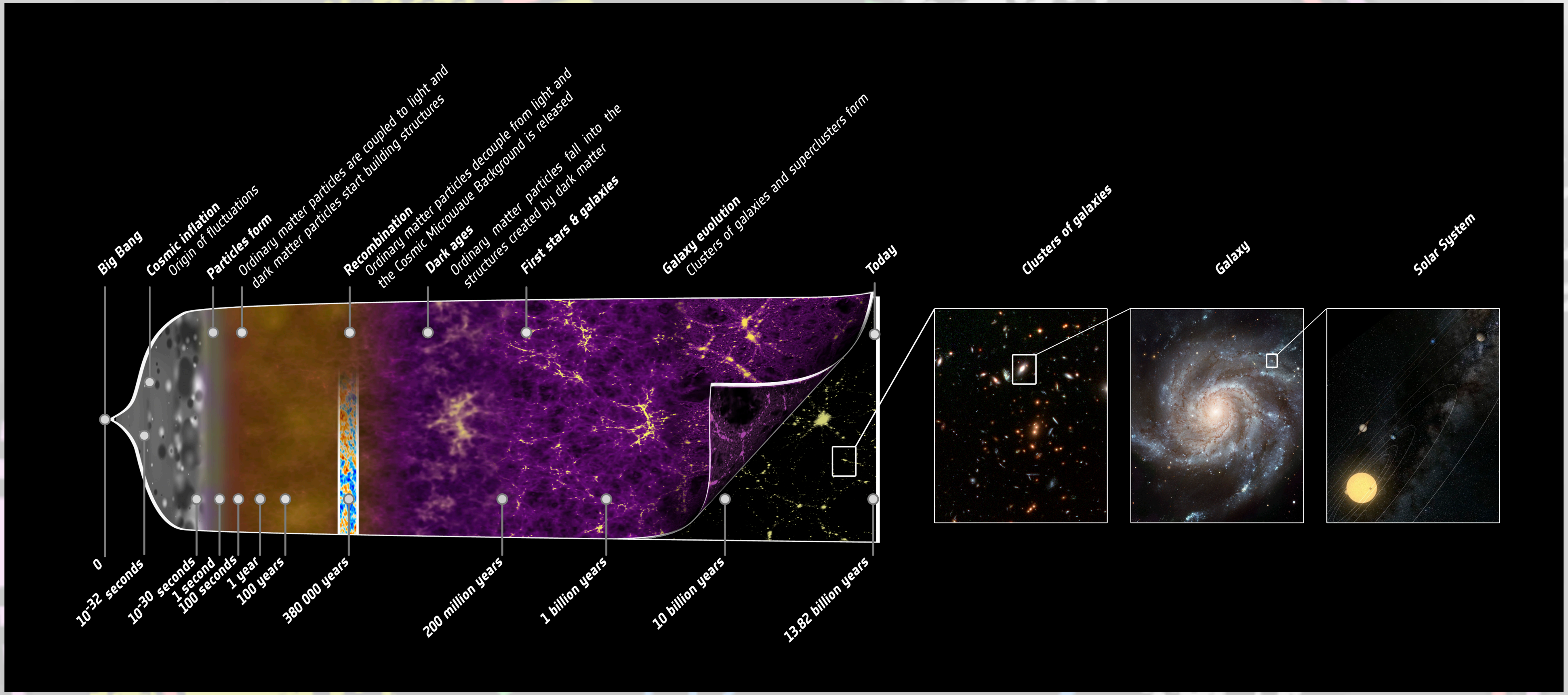


PANORAMA OF UNIVERSE WITH MULTI-MESSENGER OBSERVATIONS WILL SHED LIGHT TO NEW PHYSICS



- GW sources will be able to provide an independent measurement of the expansion history of the Universe.
- GW bias parameter and its redshift evolution can be measured.
- By combining the EM sector with the GW sector, we will make unique test to the theory of gravity at cosmological scales.
- We can distinguish between astrophysical and primordial black holes using the stochastic GW signal.

PANORAMA OF UNIVERSE WITH MULTI-MESSENGER OBSERVATIONS WILL SHED LIGHT TO NEW PHYSICS



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Thank you