Gravitational Wave Cosmology

Suvodip Mukherjee

Tata Institute of Fundamental Research

Understanding Cosmological Observations

August 3rd, 2023

Image Credit: LIGO/T. Pyle

OUR UNDERSTANDING ABOUT THE COSMOS…… SO FAR

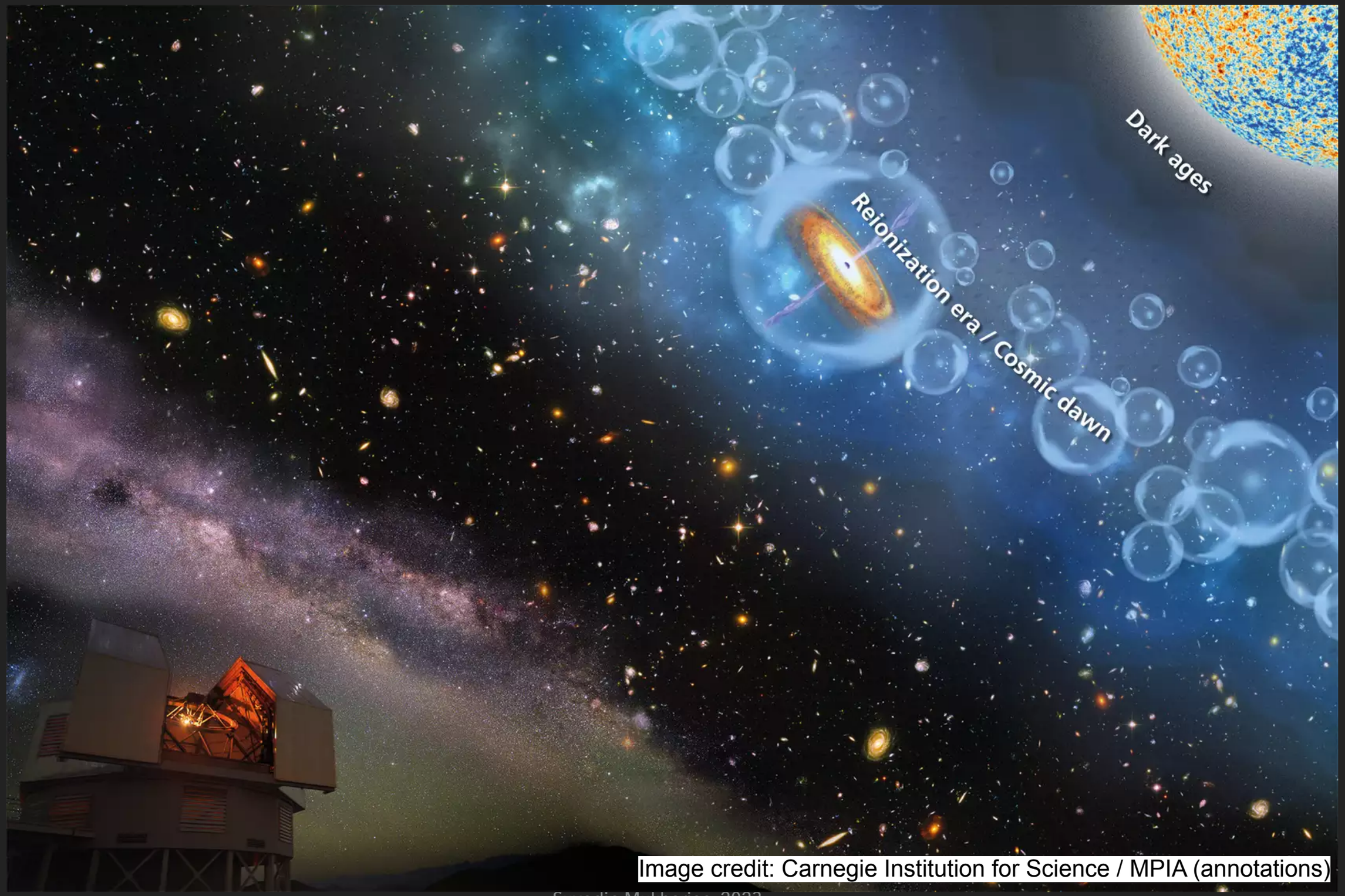


Image credit: Carnegie Institution for Science / MPIA (annotations)

PROBING THE COSMIC HISTORY USING STELLAR GRAVEYARDS

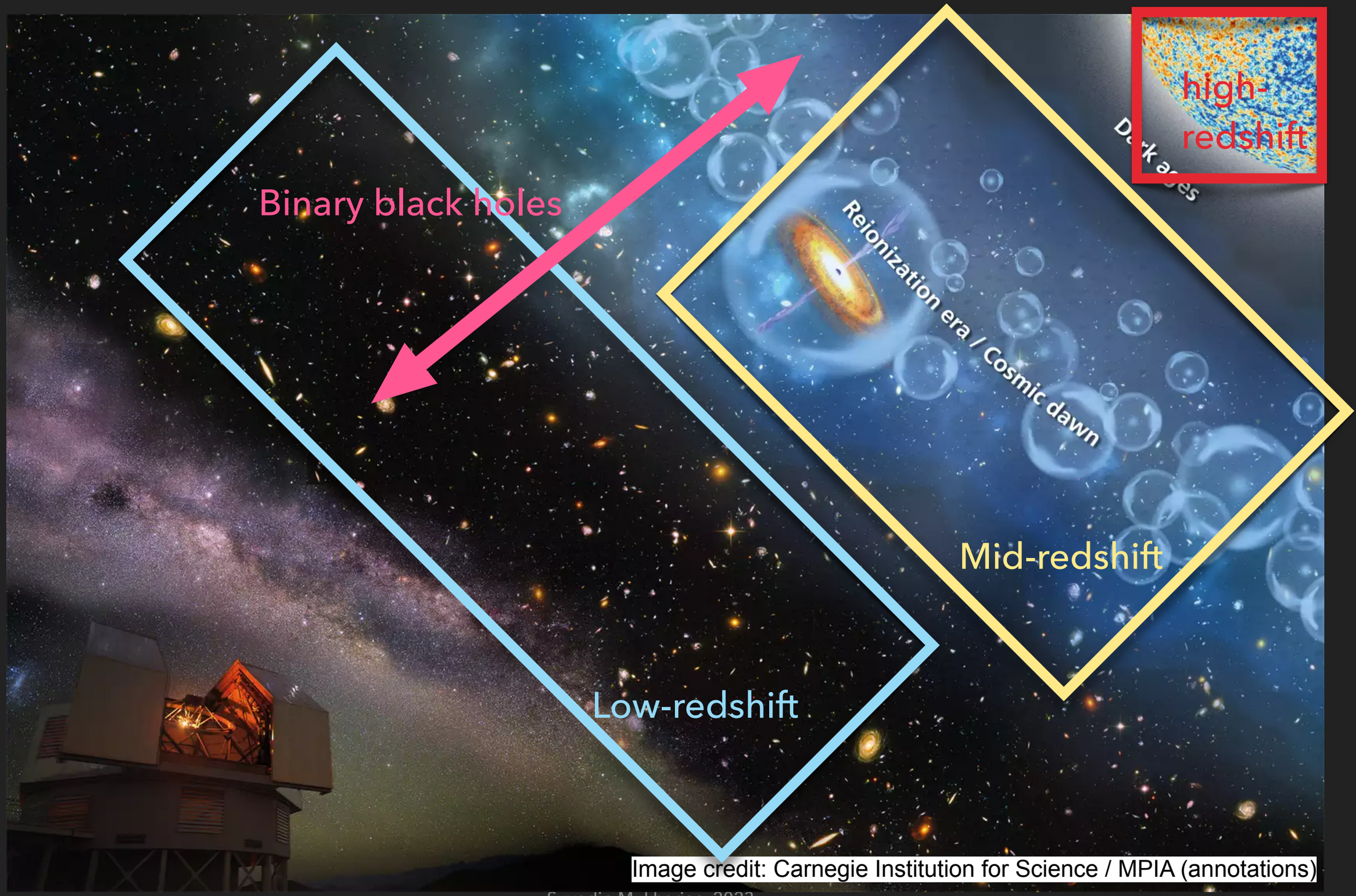
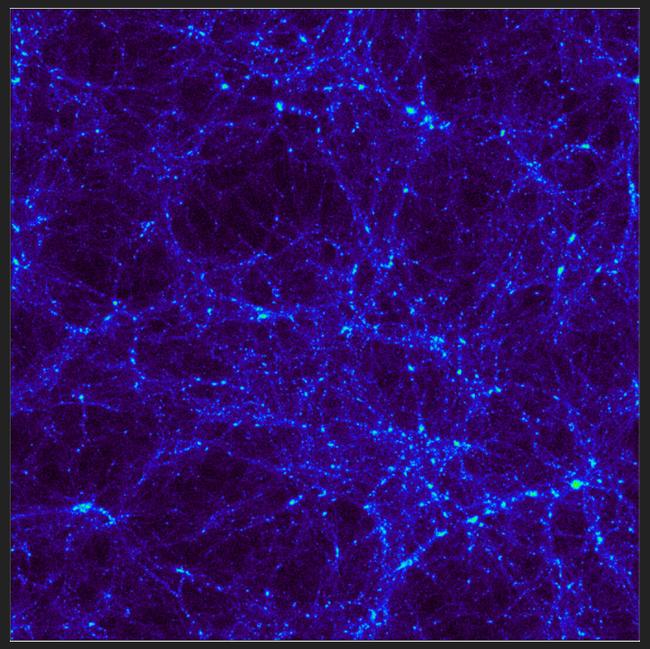


Image credit: Carnegie Institution for Science / MPIA (annotations)

ROADMAP TO UNDERSTAND COSMOLOGY USING GW SOURCES



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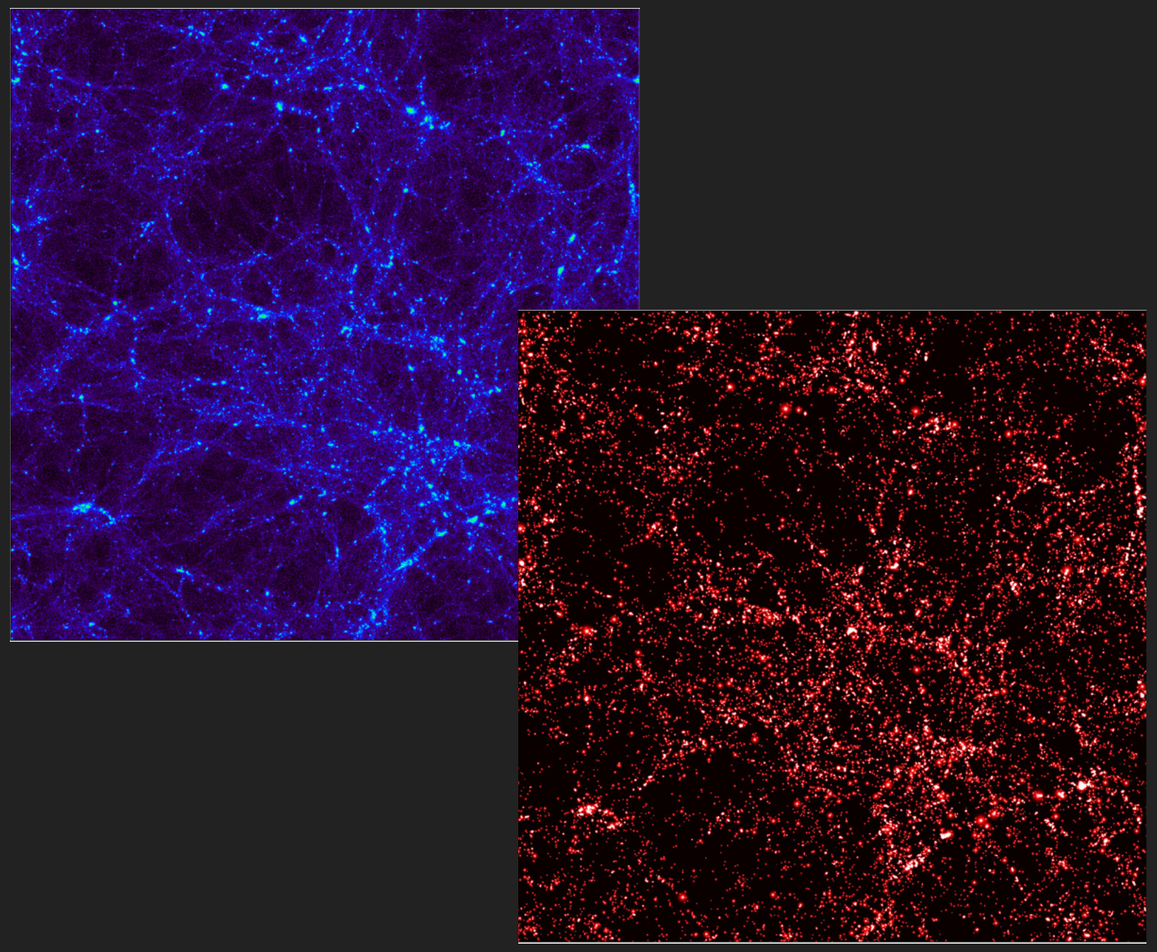

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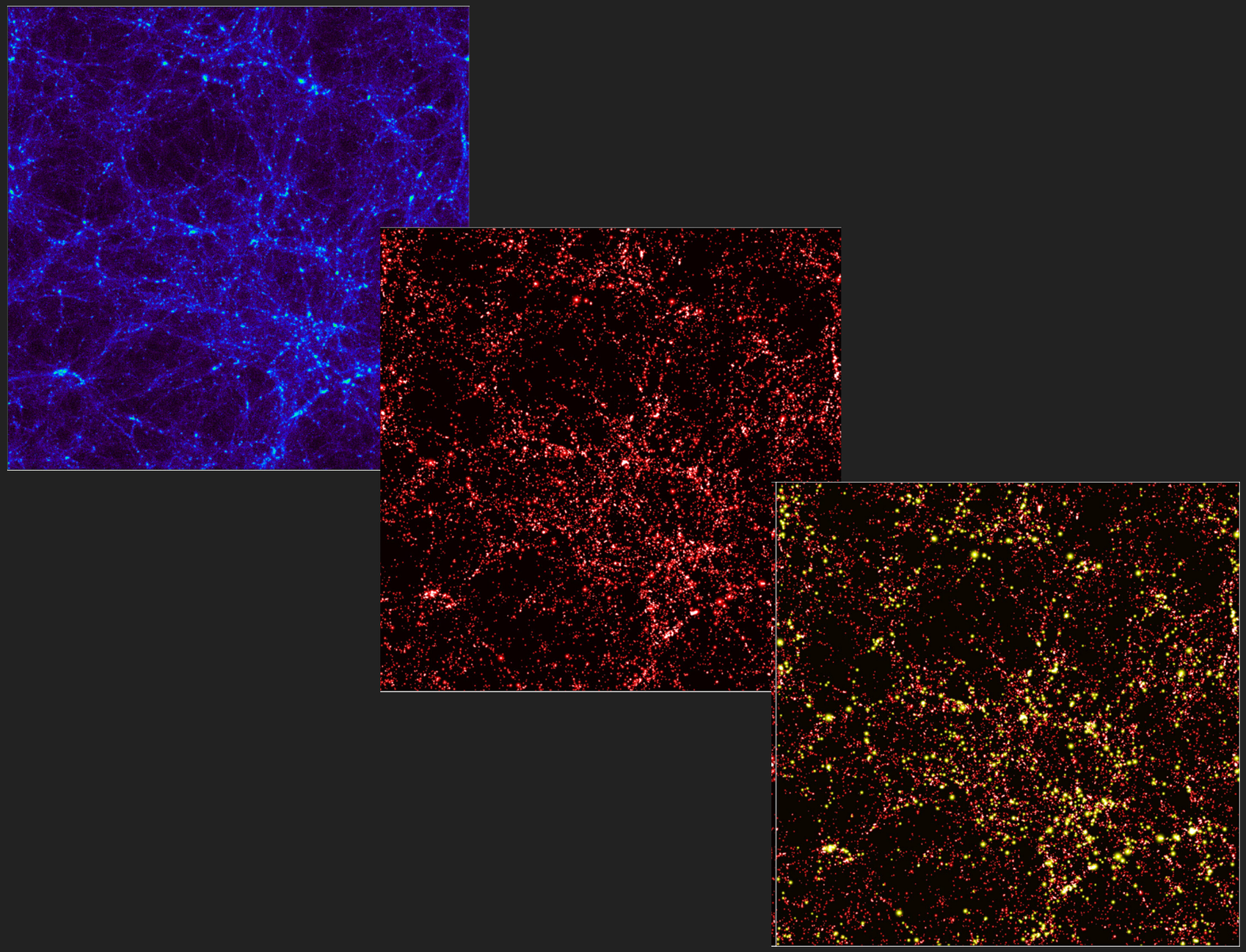

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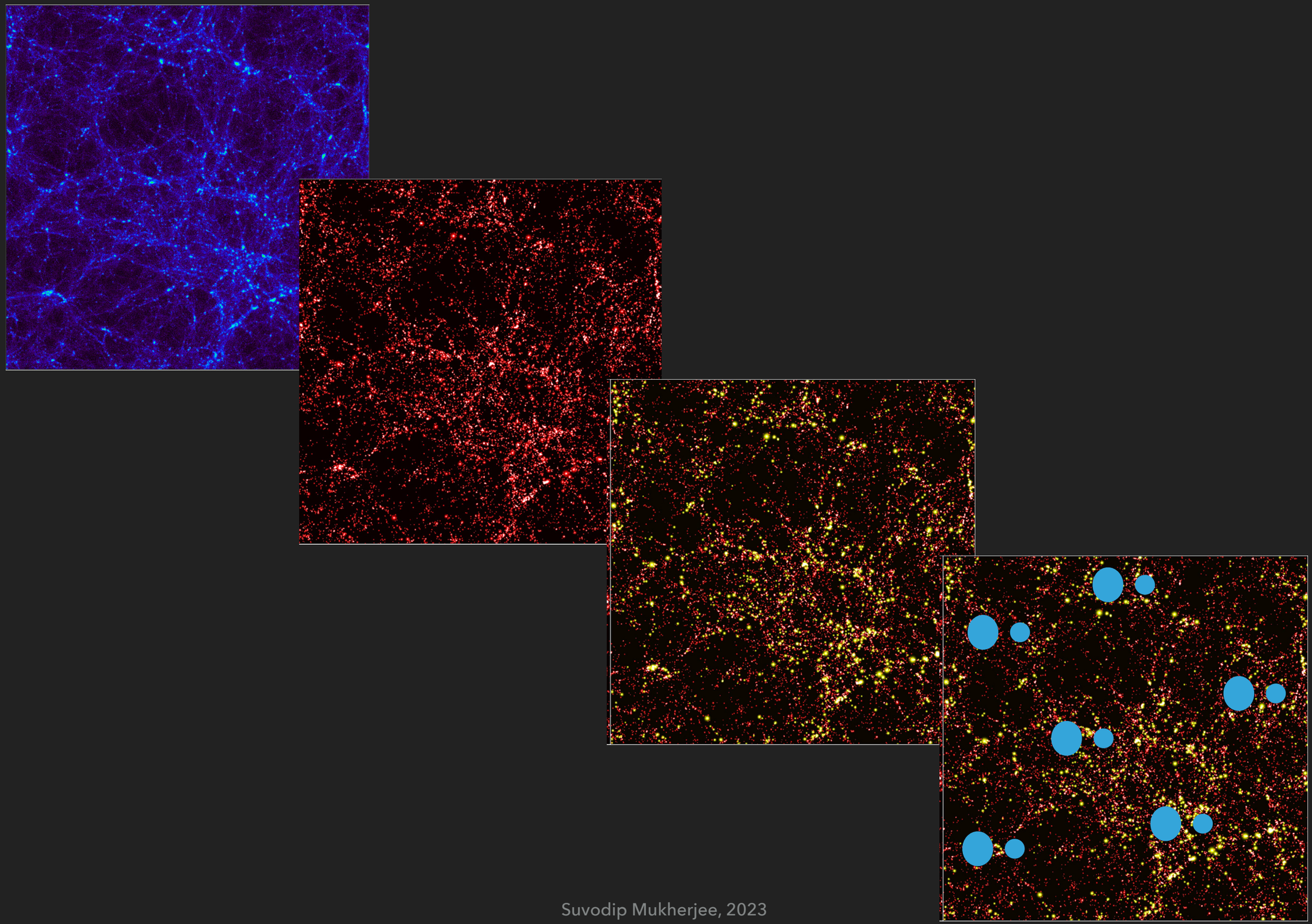

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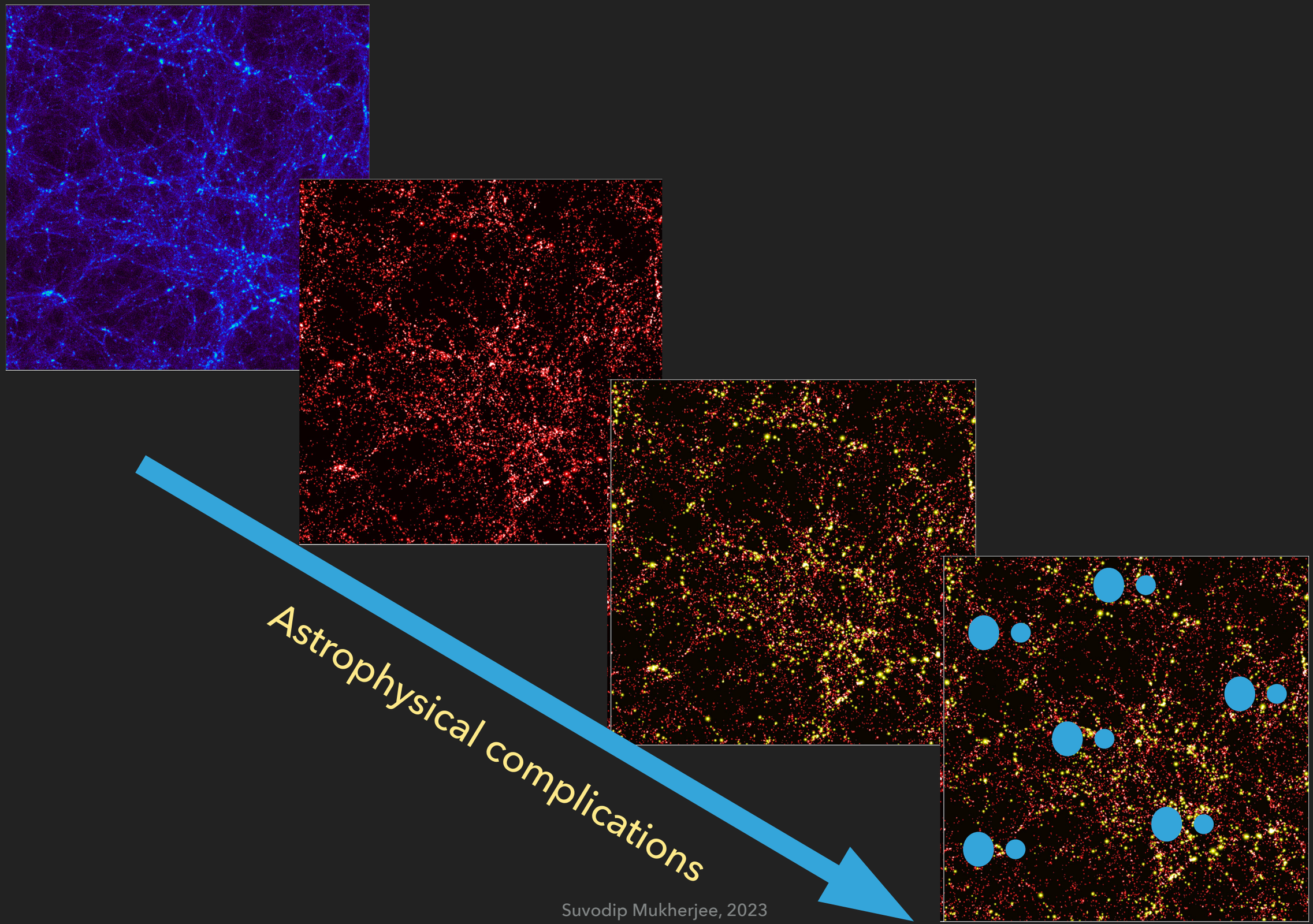

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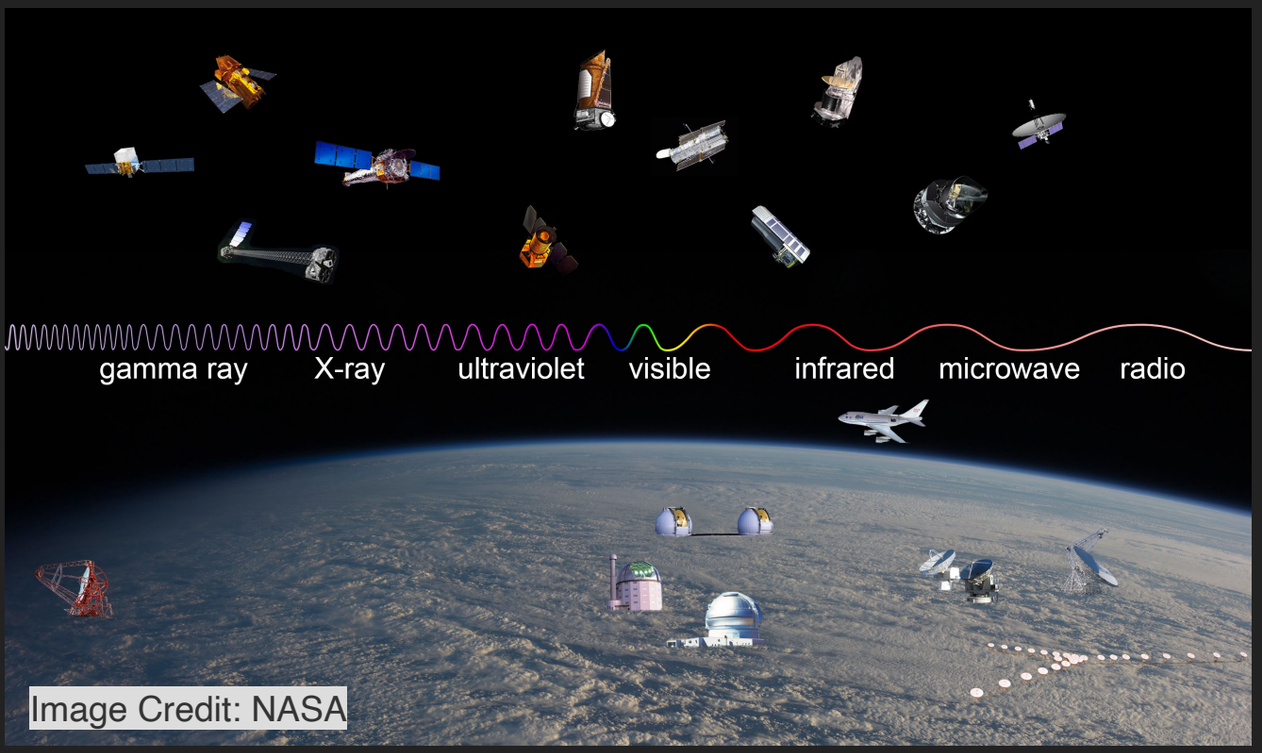
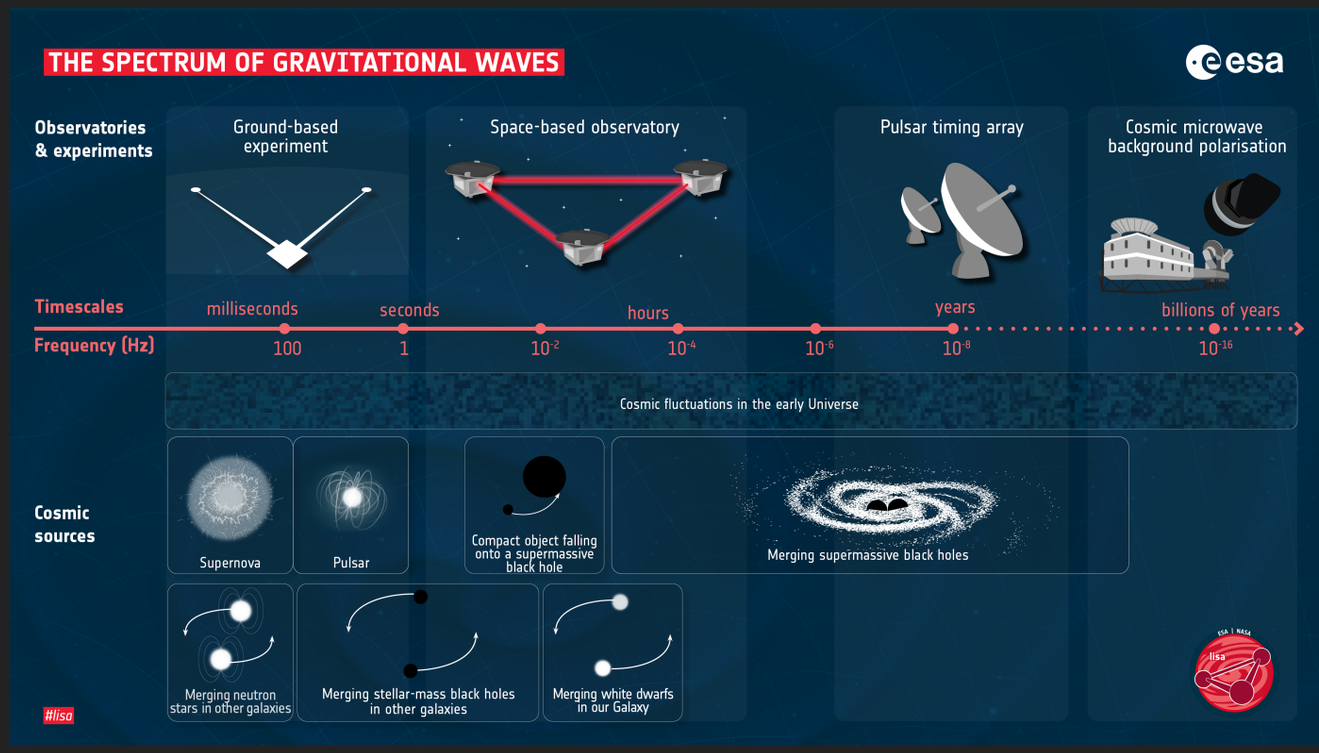
Multi-Messenger Cosmology and Astrophysics



Electromagnetic waves



Gravitational waves

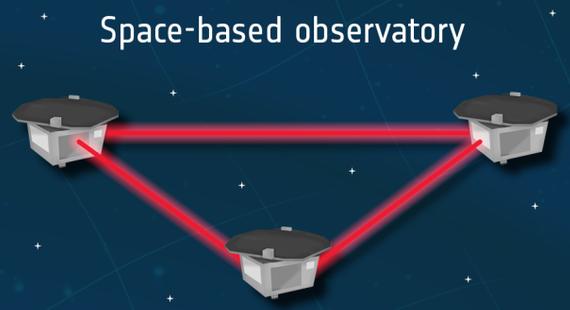
THE SPECTRUM OF GRAVITATIONAL WAVES

esa

Observatories & experiments

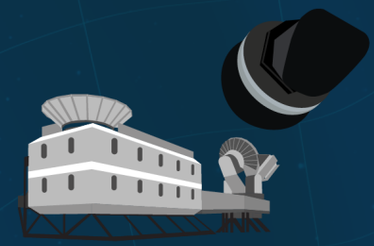
Ground-based experiment

Space-based observatory



Pulsar timing array

Cosmic microwave background polarisation



Timescales

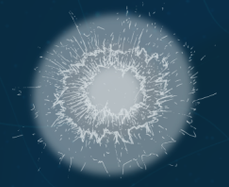
milliseconds — seconds — hours — years — billions of years

Frequency (Hz)

10^{2} — 100 — 1 — 10^{-2} — 10^{-4} — 10^{-6} — 10^{-8} — 10^{-16}

Cosmic fluctuations in the early Universe

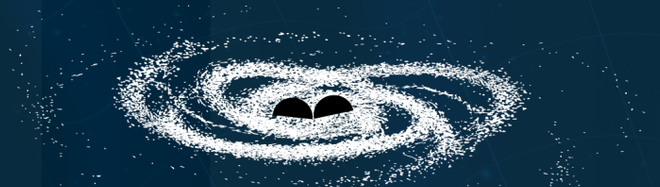
Cosmic sources



Supernova

Pulsar

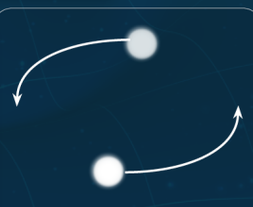
Compact object falling onto a supermassive black hole



Merging supermassive black holes

Merging neutron stars in other galaxies

Merging stellar-mass black holes in other galaxies



Merging white dwarfs in our Galaxy

#lisa

LIGO–India Scientific Collaboration

LIGO VIRGO KAGRA

LISA CONSORTIUM

INTERNATIONAL PULSAR TIMING ARRAY
IPTA

PARQUE ASTRONÓMICO ATACAMA, CHILE | ELEVATION 5640m | 22° 59' 47" S | 67° 47' W | www.simonsobservatory.org
SIMONS OBSERVATORY

CMB-S4
Next Generation CMB Experiment

Suvodip Mukherjee, 2023

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esa

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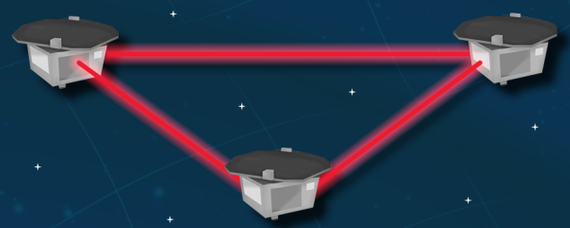

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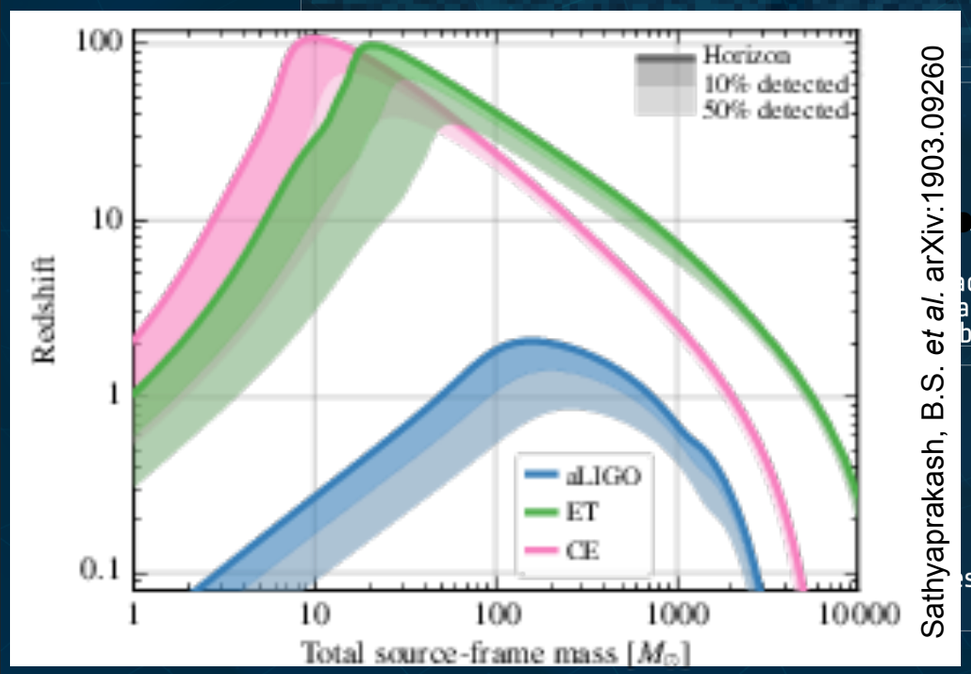


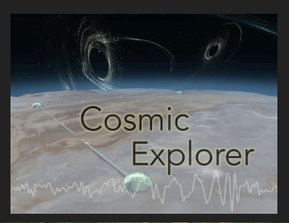
Sathyaprakash, B.S. *et al.* arXiv:1903.09260

Cosmic fluctuations in the early Universe

…act object falling …a supermassive …black hole

Merging supermassive black holes

Merging white dwarfs in our Galaxy



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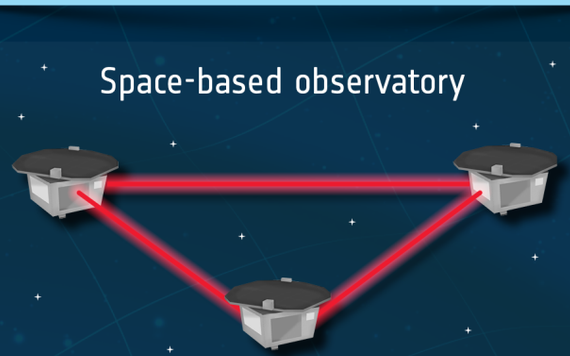

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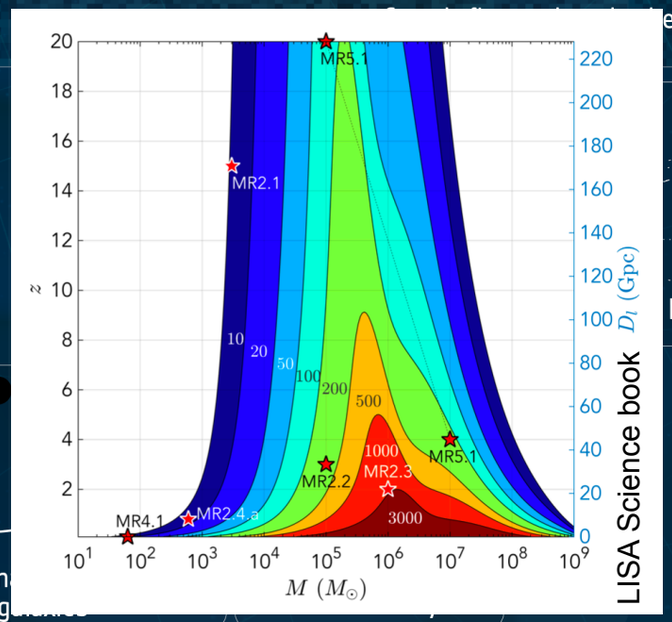

LISA Science book

e early Universe

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Merging supermassive black holes

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Merging stellar-m… in other g…

#lisa

Cosmic Explorer

LISC
LIGO–India Scientific Collaboration

LIGO VIRGO KAGRA

LISA CONSORTIUM

EINSTEIN TELESCOPE

INTERNATIONAL PULSAR TIMING ARRAY
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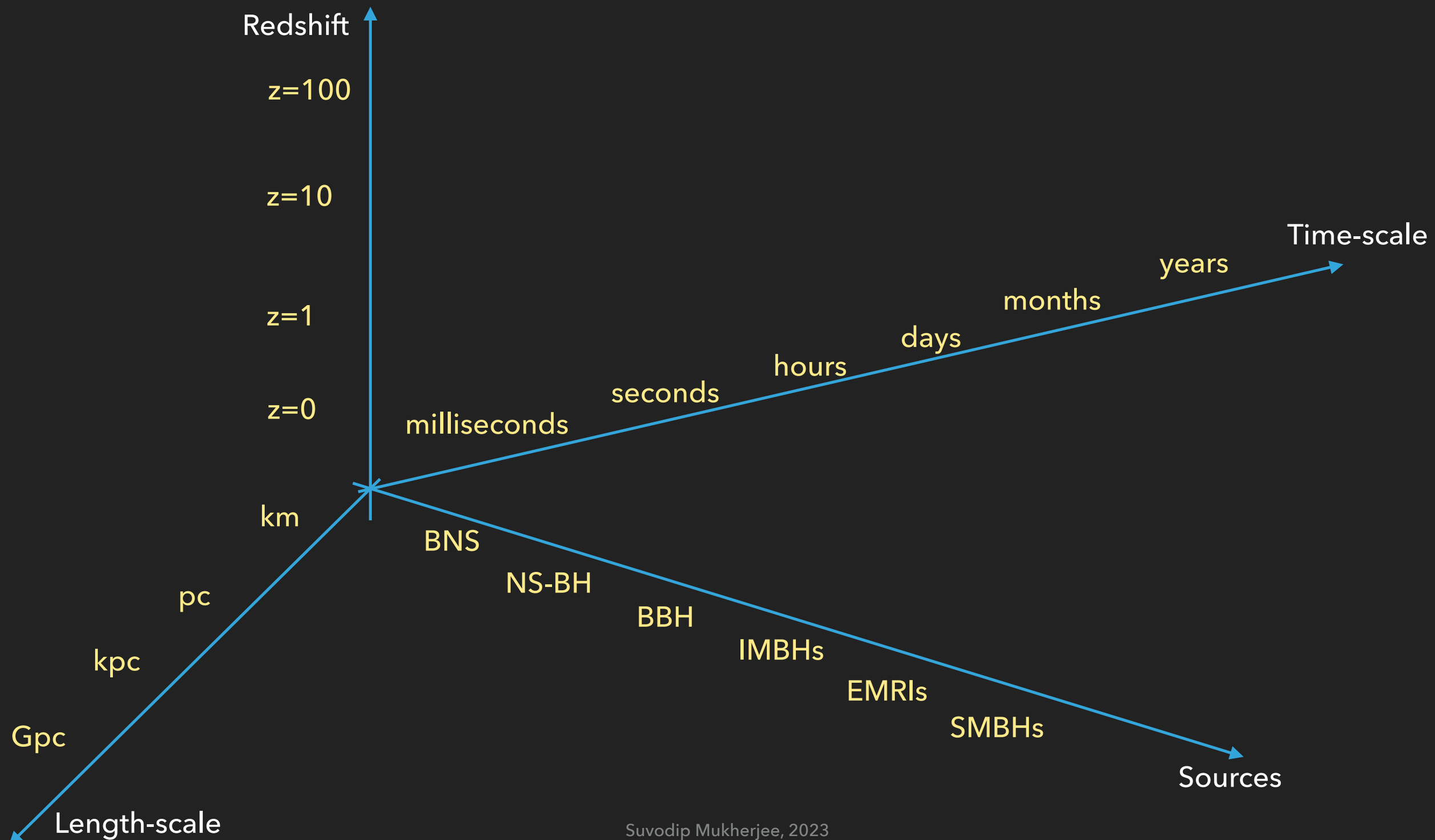
CMB-S4
Next Generation CMB Experiment

Suvodip Mukherjee, 2023

LENGTH-REDSHIFT-SOURCE-TIMESCALE

NUMEROUS 'STANDARD' TIME-VARIABLE HIGH REDSHIFT PROBE TO THE UNIVERSE PROBING 'MULTIPLE' LENGTH SCALES



LEARNING PHYSICS ACROSS COSMIC HISTORY AND LENGTH SCALES

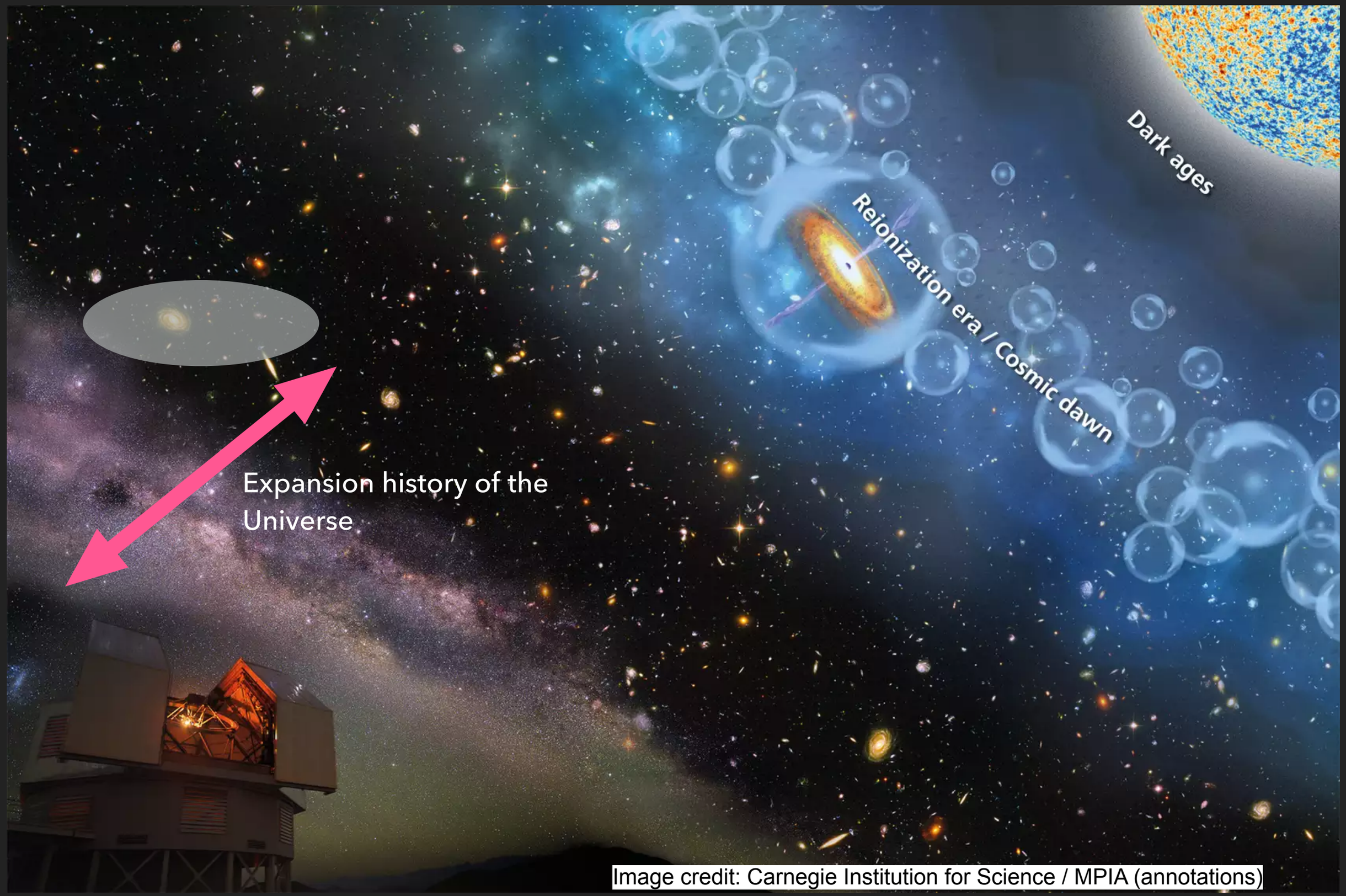


Image credit: Carnegie Institution for Science / MPIA (annotations)

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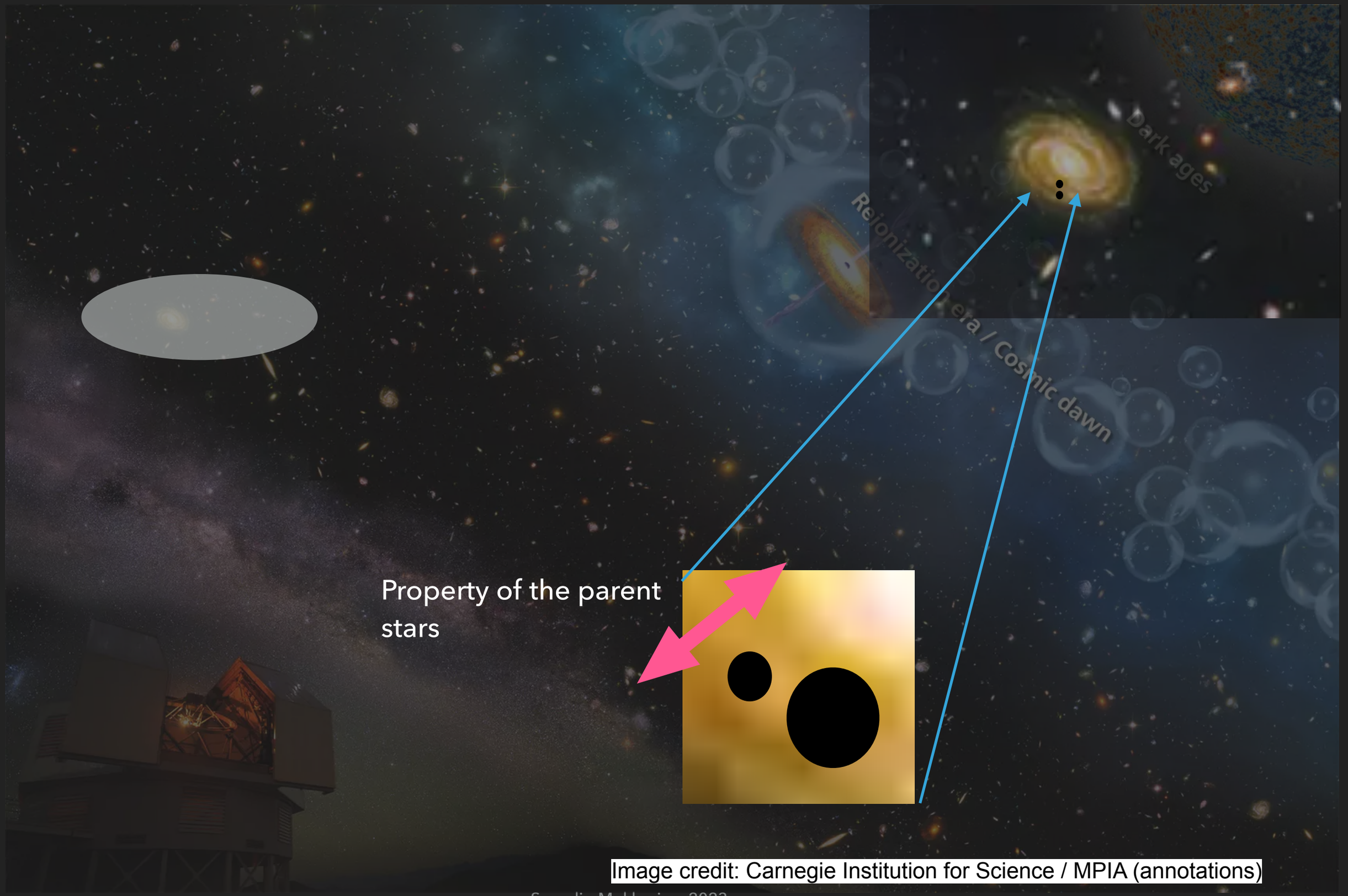

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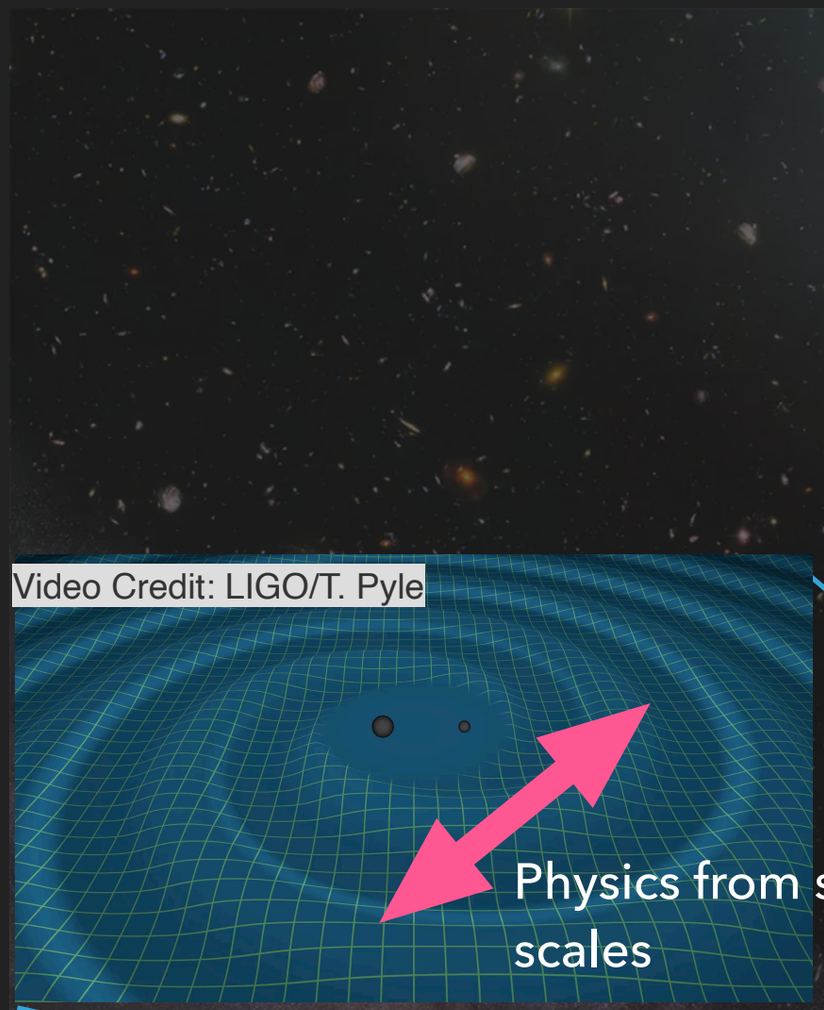


Image credit: Carnegie Institution for Science / MPIA (annotations)

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

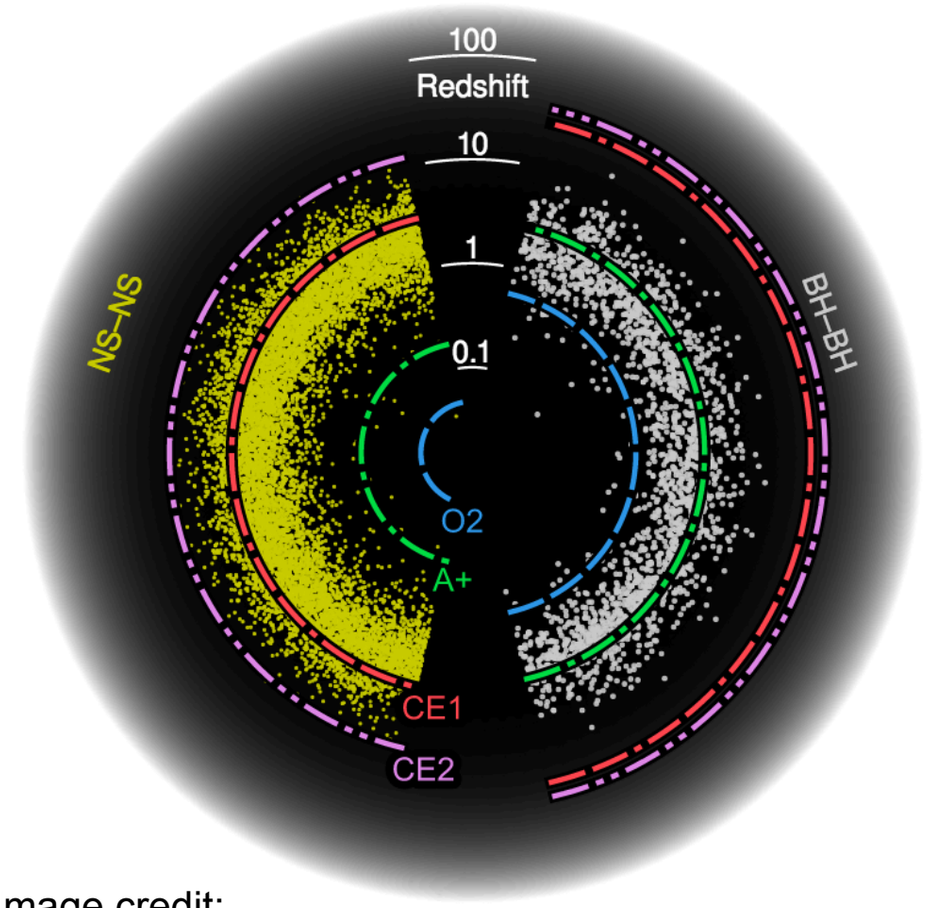


Image credit:
Reitze et al. (2020)

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

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

WHY IS THIS AN EXCITING TIME FOR MULTI MESSENGER SCIENCE?

Experiments

- Ground-based GW detectors
- Space-based GW detectors
- Pulsar Timing Arrays
- Electromagnetic observations

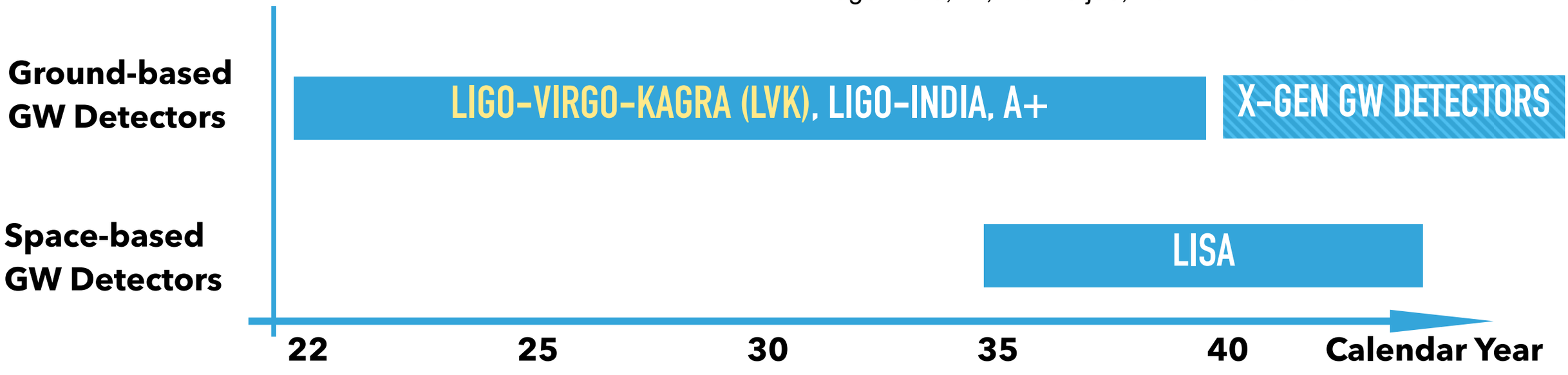
Science investigations

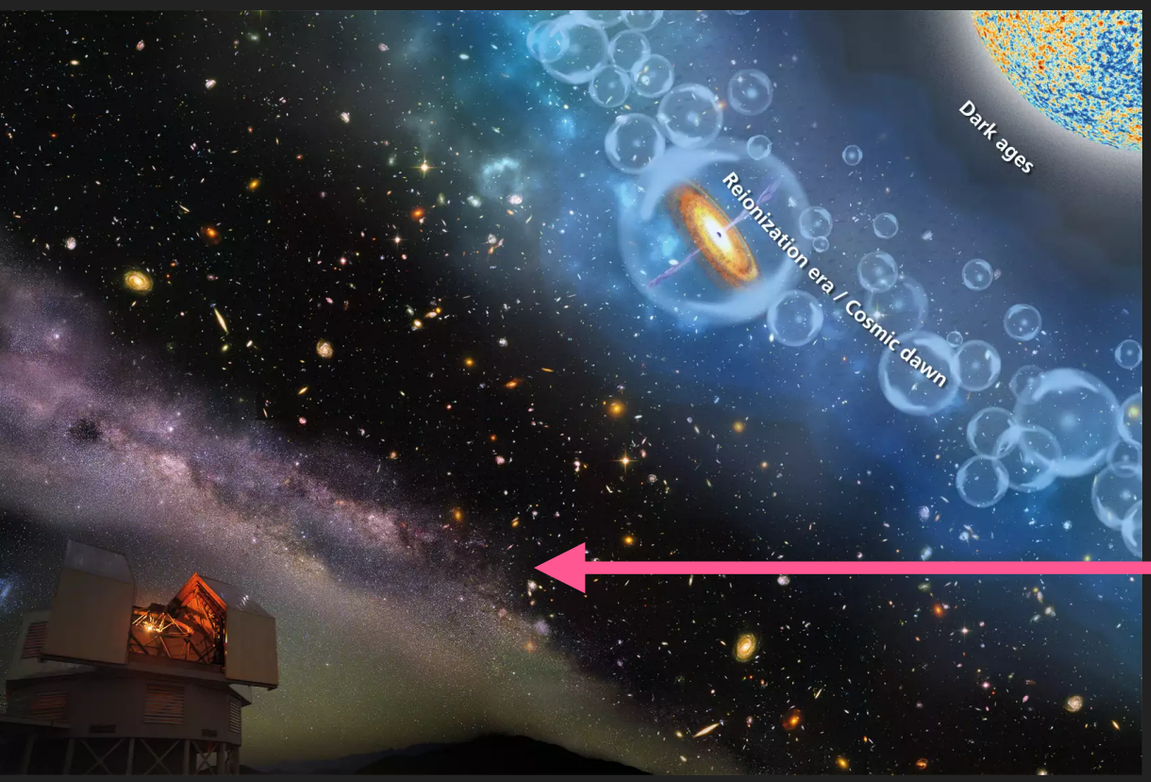
- Tests of strong gravity
- Tests of black hole spacetimes and dynamics
- Cosmological gravitational waves
- Gravitational signatures of dark matter
- Multimessenger cosmology

Fundamental physics

- Spacetime singularities, phase transitions
- QFT in curved spacetime, information paradox
- BSM physics, modified gravity
- Astroparticle physics

Image: Berti,…., Mukherjee,…arXiv:2203.06240





MAPPING THE EXPANSION HISTORY OF THE UNIVERSE

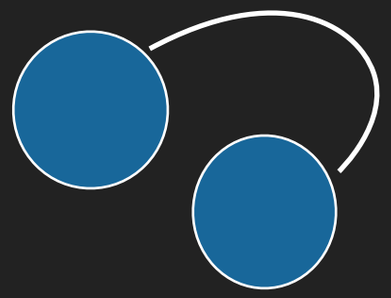
Sources with EM counterpart

Sources without EM counterpart

+ Farther distances

+ More Sources

+ Cosmological parameters beyond H_0

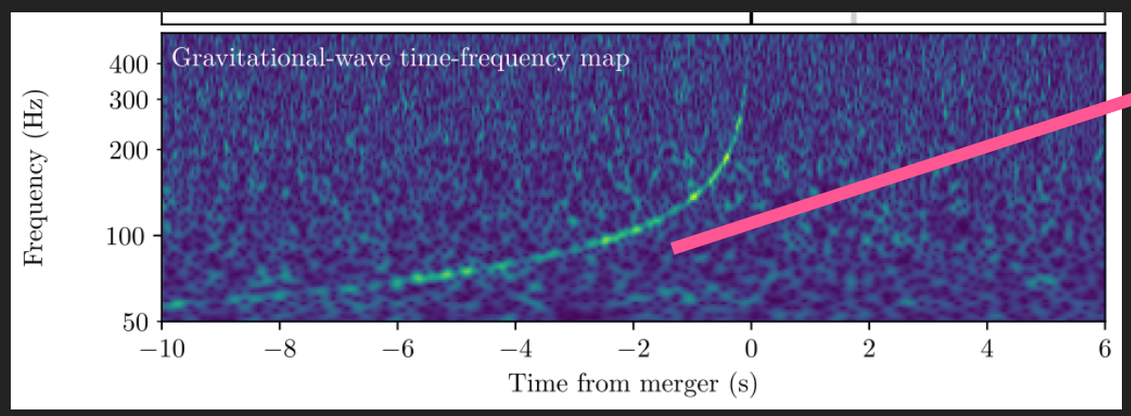


GW IS A PROBE TO MEASURE THE HUBBLE CONSTANT

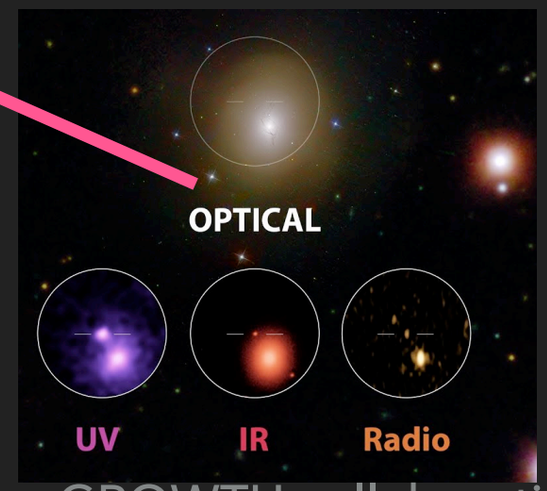
$$H_0 = \frac{cz + v_p}{D_l}$$

Schutz 1986

Independent measurement of the host of the GW source



LIGO-Virgo Collaboration



GROWTH collaboration

Inclination angle uncertainties affect luminosity distance estimation.

Two major sources of astrophysical uncertainties

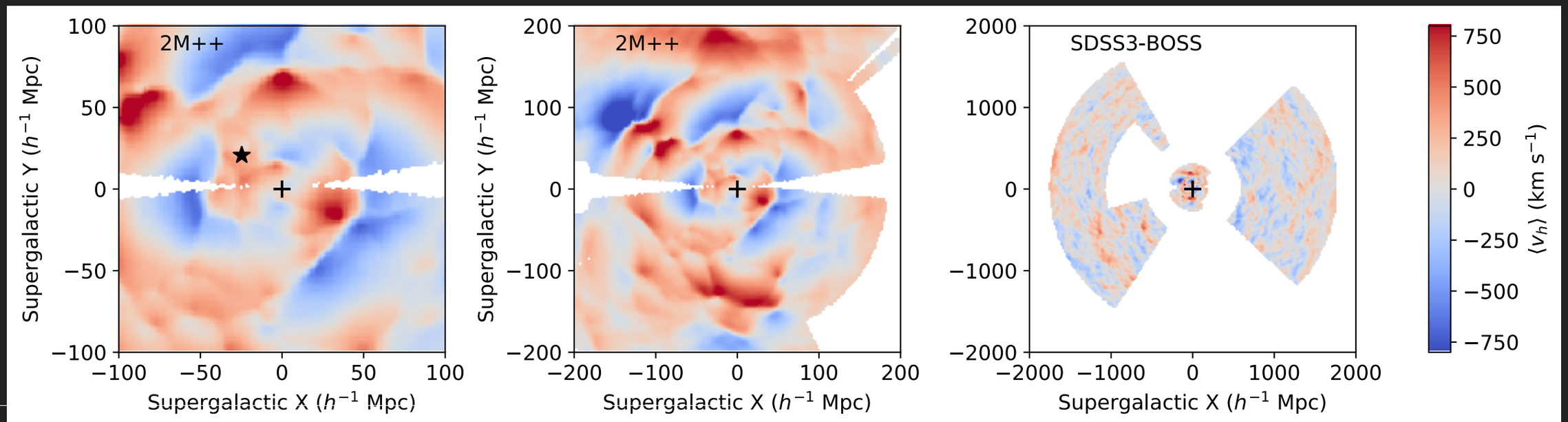
Peculiar velocity uncertainties affect redshift estimation.

PAVES: PECULIAR VELOCITY ESTIMATES FOR SIRENS

BORG:

Bayesian Origin Reconstruction from Galaxies

(Jasche & Wandelt 2013a;
Jasche et al. 2015;
Lavaux & Jasche 2016



Mukherjee, Lavaux, Bouchet et al. (arXiv:1909.08627)

Reconstructing the velocity field from large scale observations.

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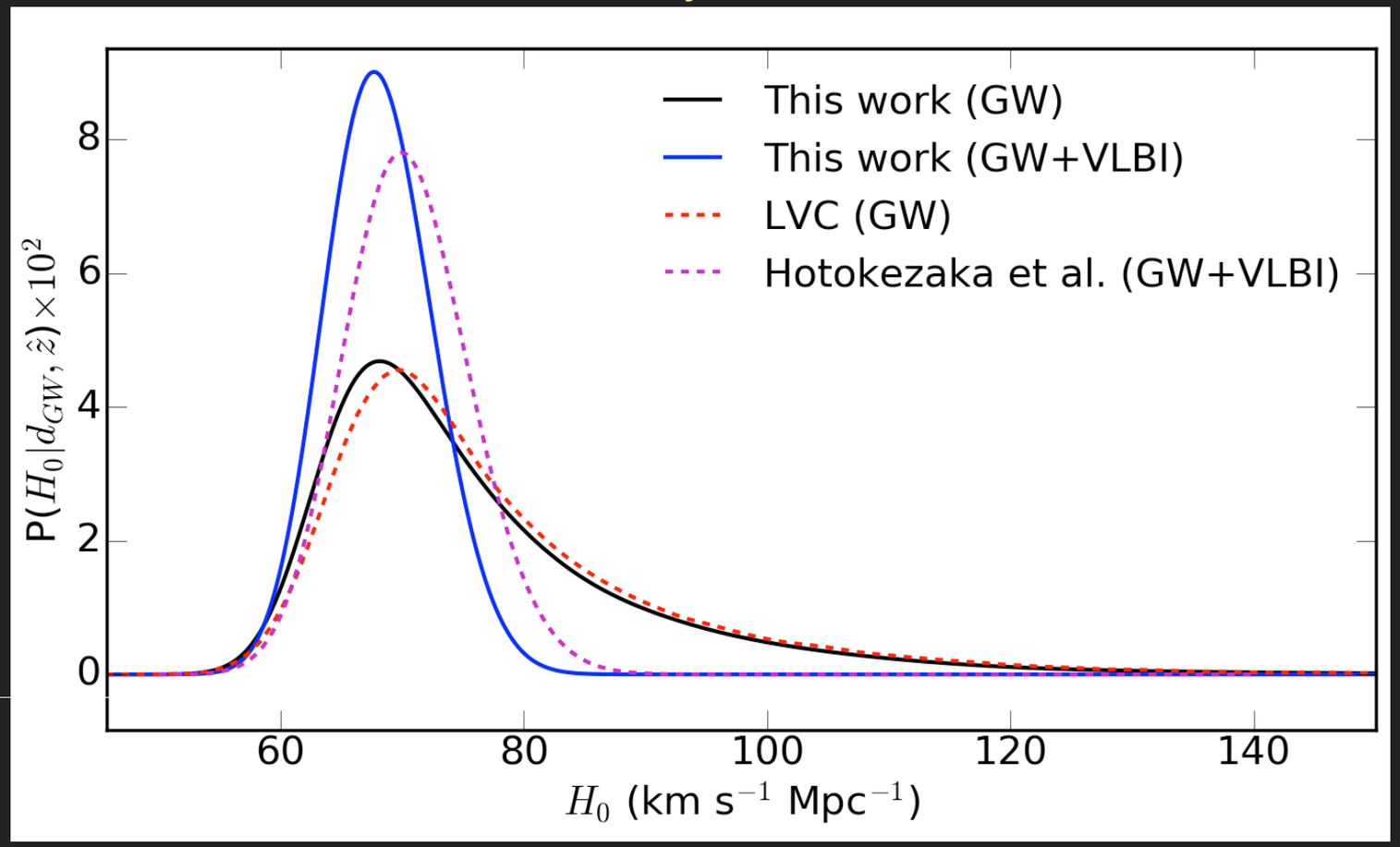
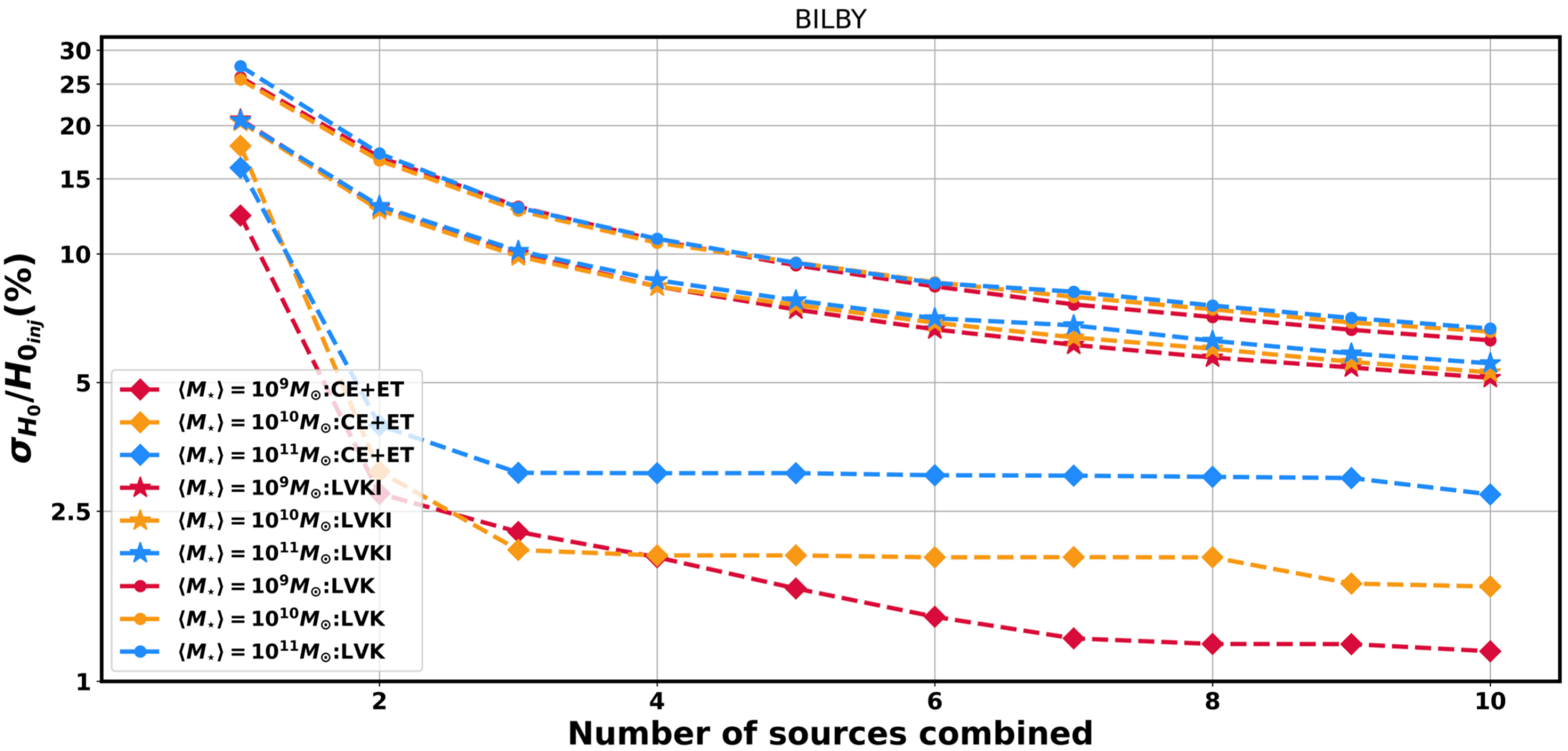


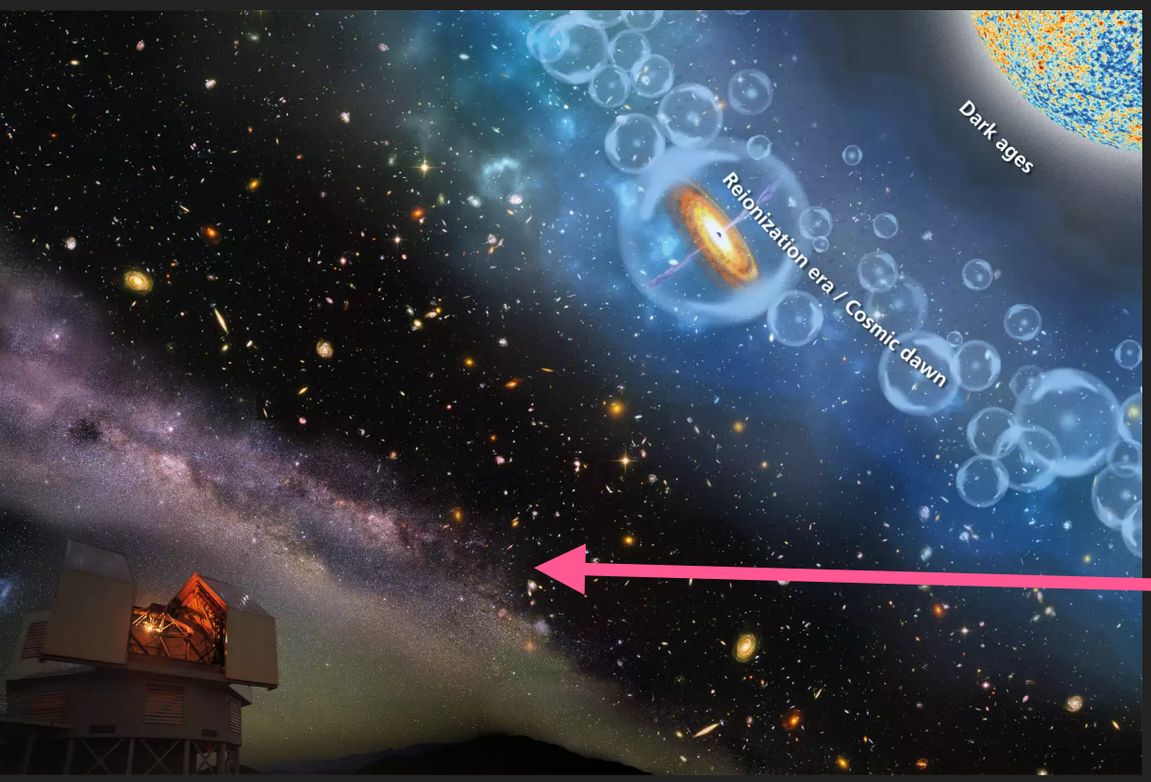
Impacts both mean value and the error-bar of the Hubble constant

FORECAST: UNCERTAINTY ON THE HUBBLE CONSTANT FROM BNS

Forecast from sources with EM counterpart



Nimonkar and Mukherjee (2023)



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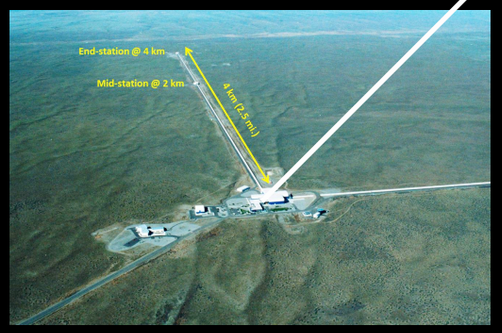
HOW THE BLACK HOLES ARE GOING TO BE DISTRIBUTED ?

Luminosity Distance



GW binaries (dark sirens)

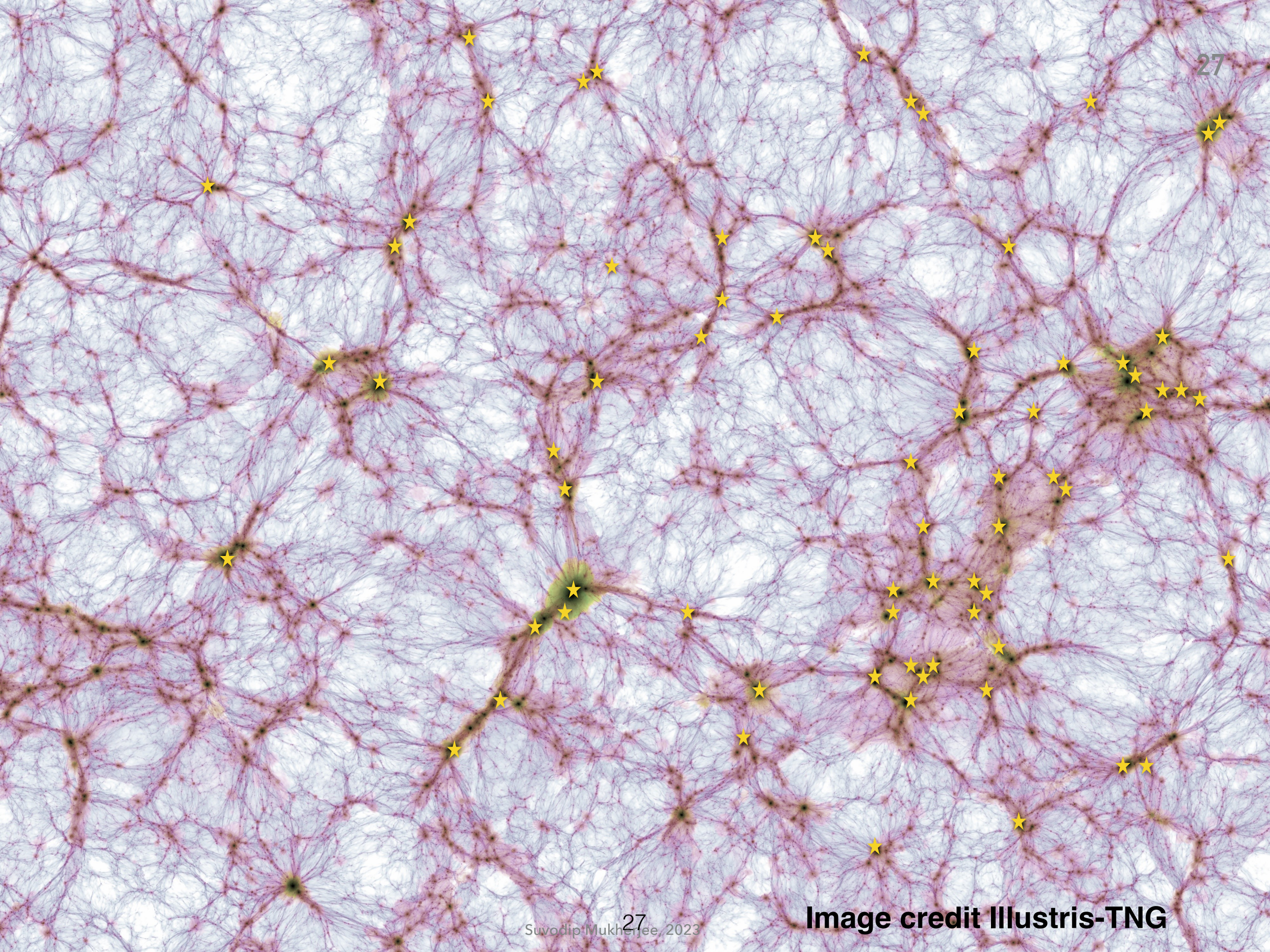
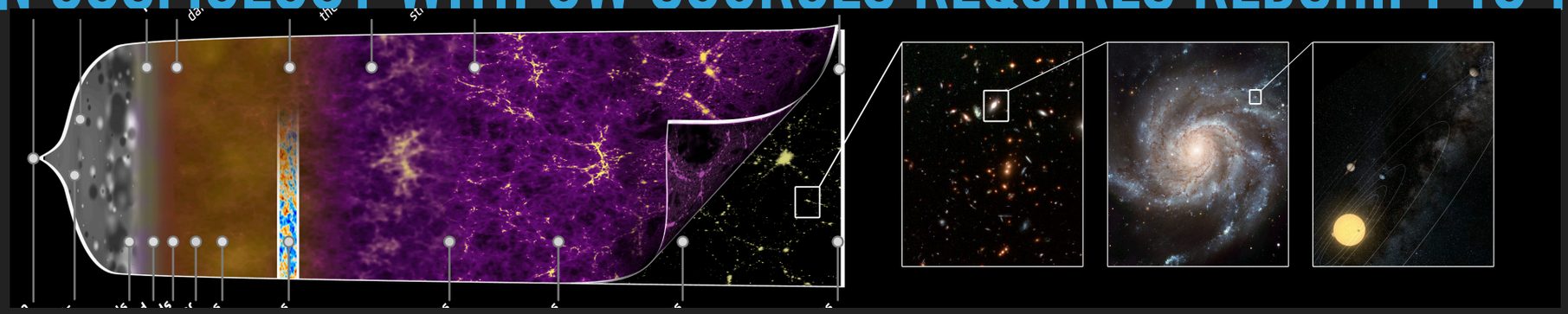
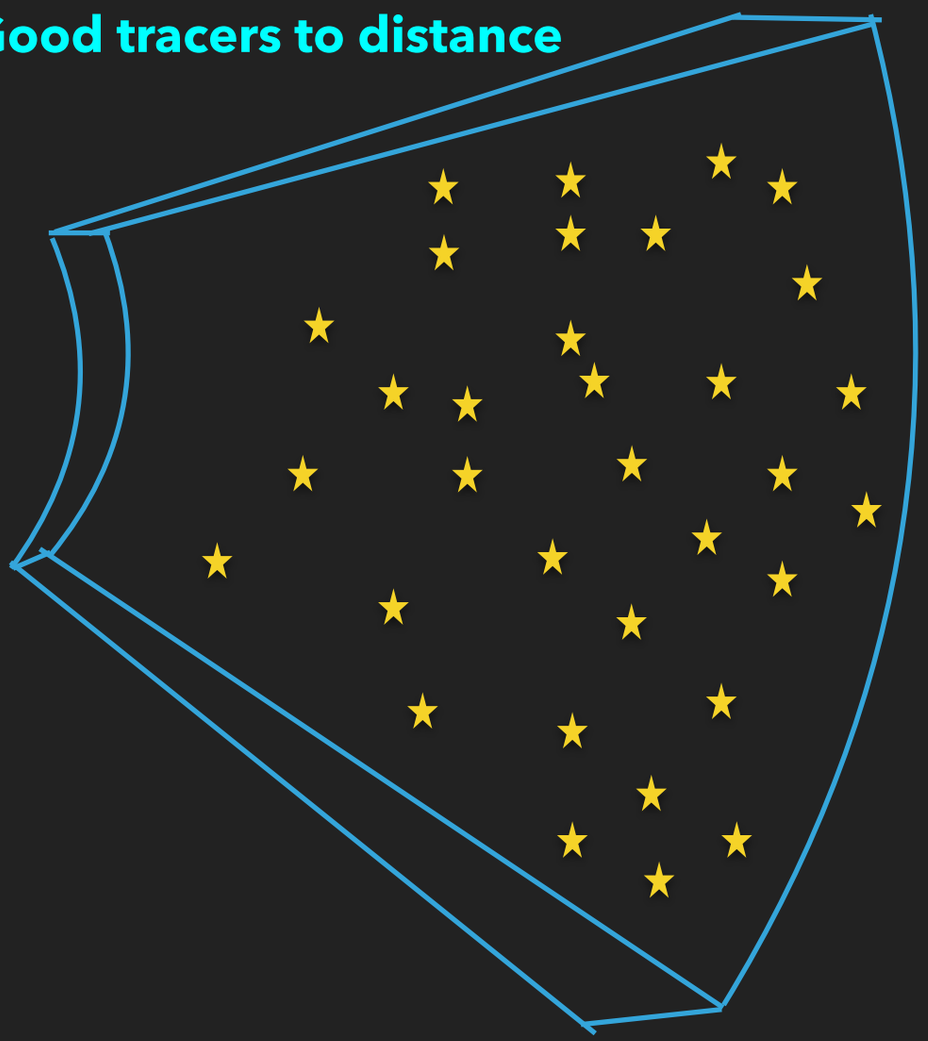


Image credit Illustris-TNG

PRECISION COSMOLOGY WITH GW SOURCES REQUIRES REDSHIFT TO THE SOURCE



Good tracers to distance



How to connect these two sides

Good tracers to redshift

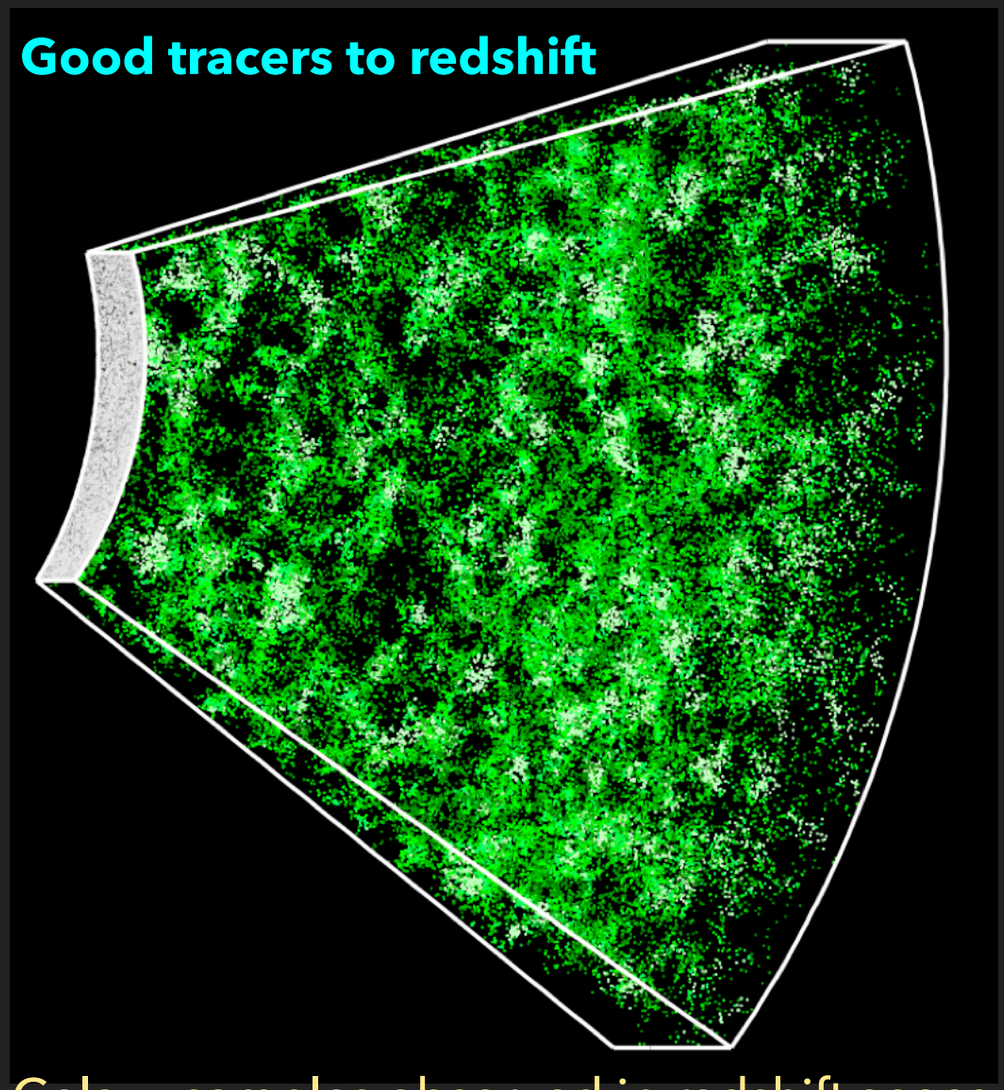


Image credit: Jeremy Tinker and the SDSS-III collaboration

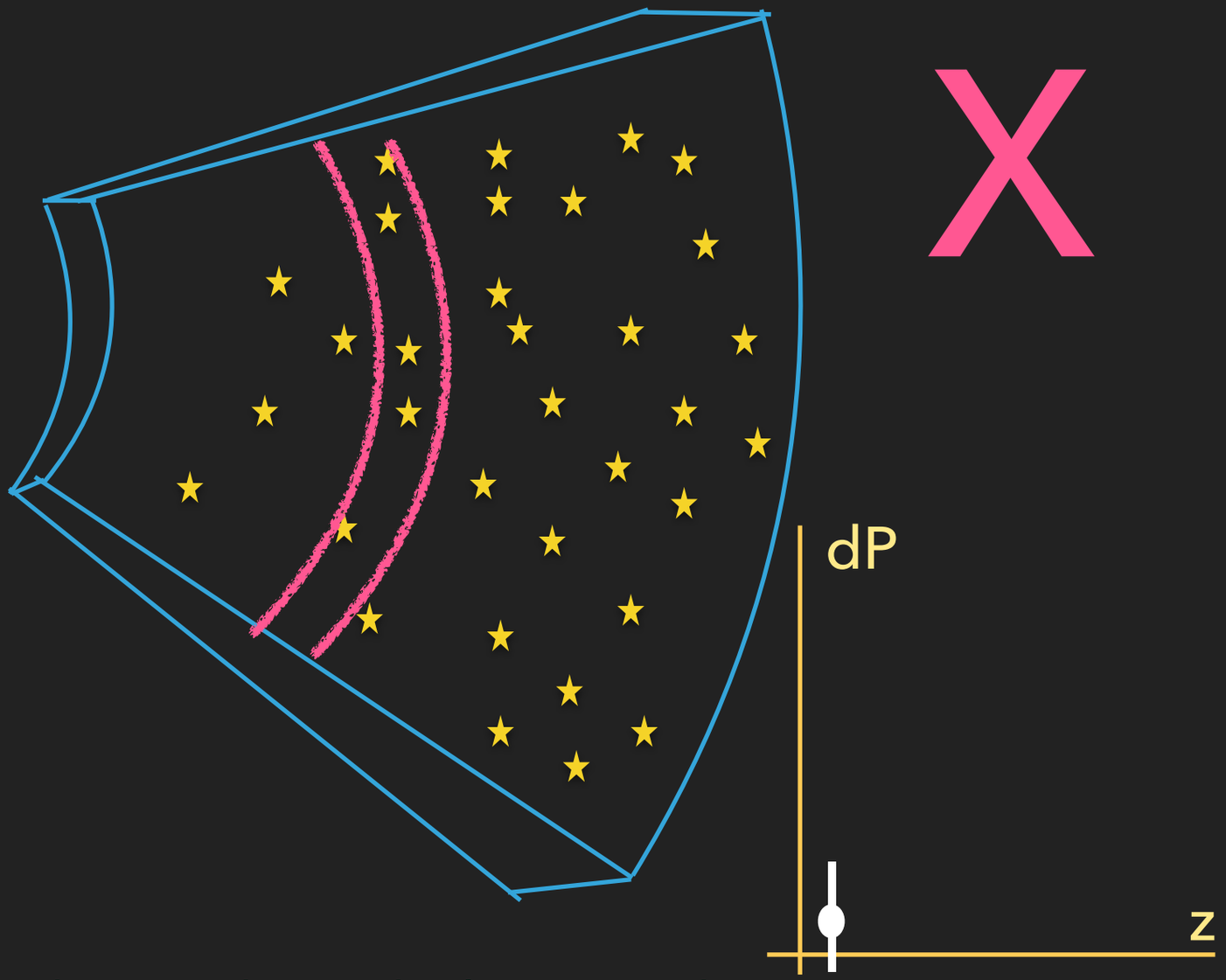
Dark sirens observed in luminosity distance space

Galaxy samples observed in redshift space

Mukherjee, Wandelt (2018), Mukherjee, Wandelt, Silk (2019), Mukherjee et al. (2020)

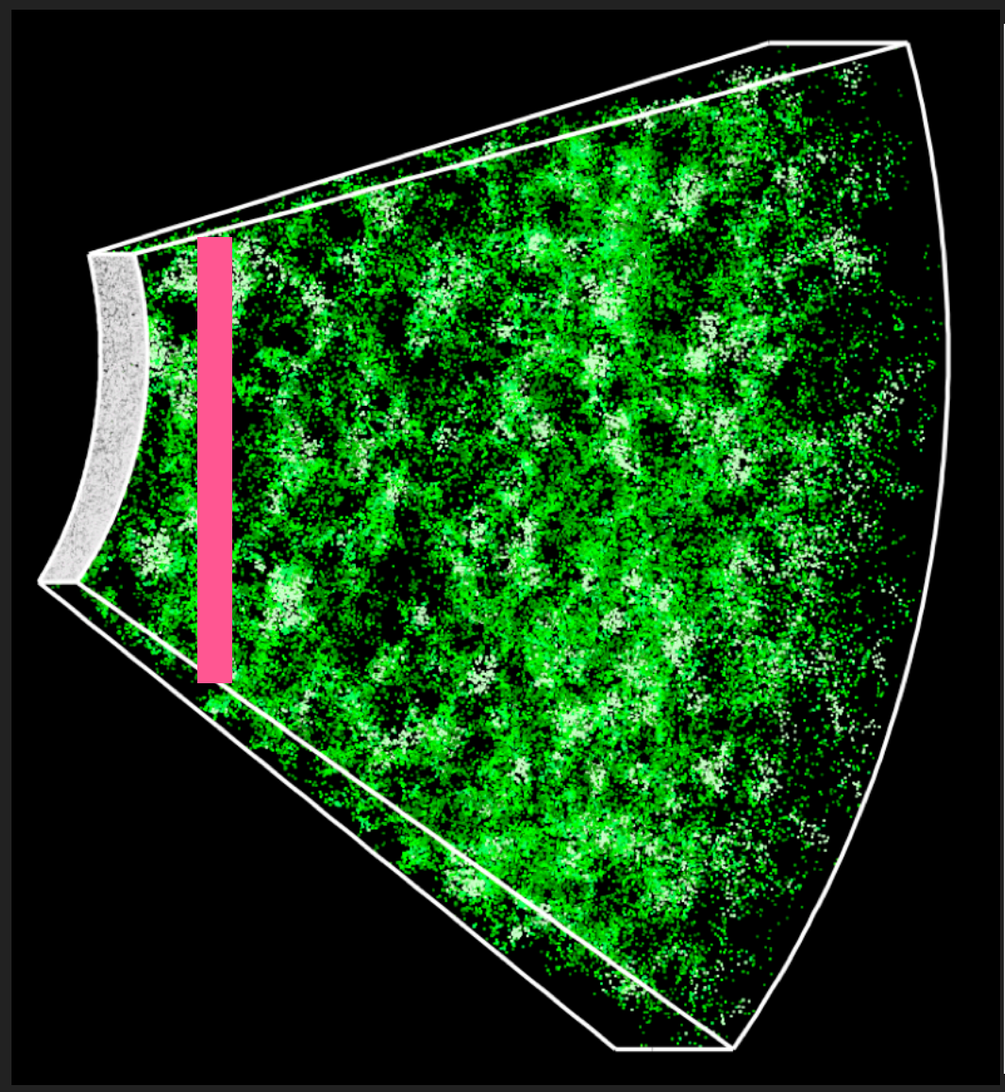
CROSS-CORRELATION OF GW SOURCES WITH GALAXIES

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



Dark sirens observed in luminosity distance space

X



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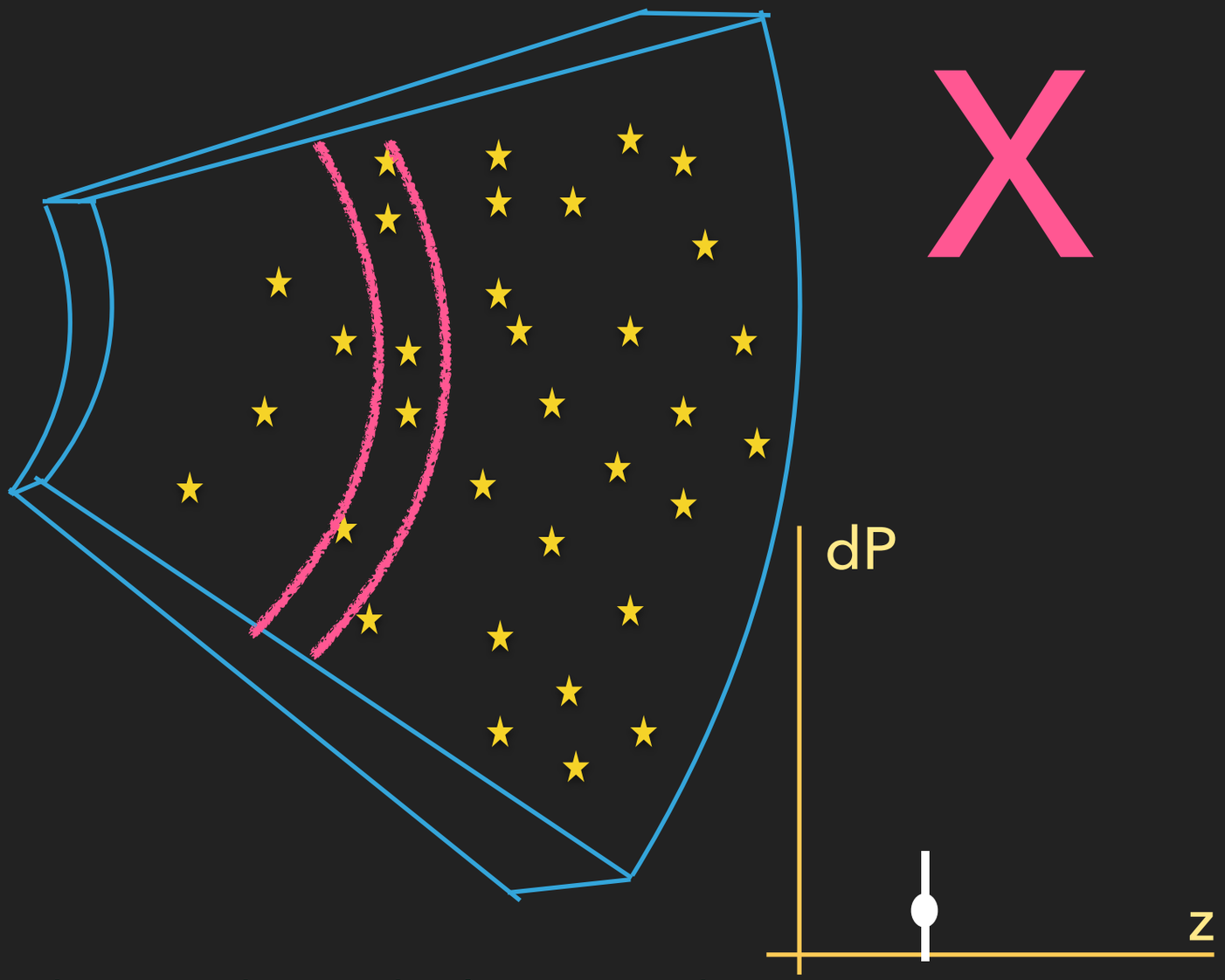

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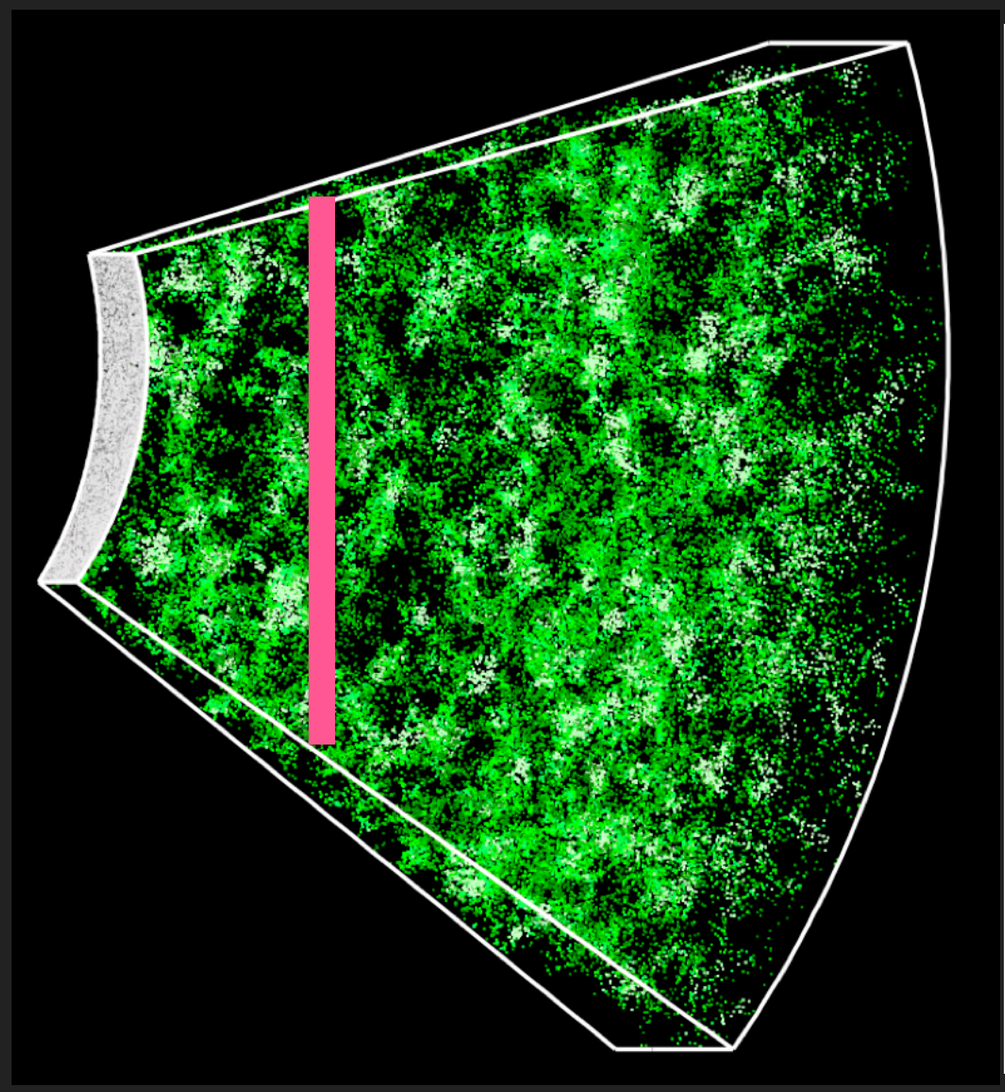

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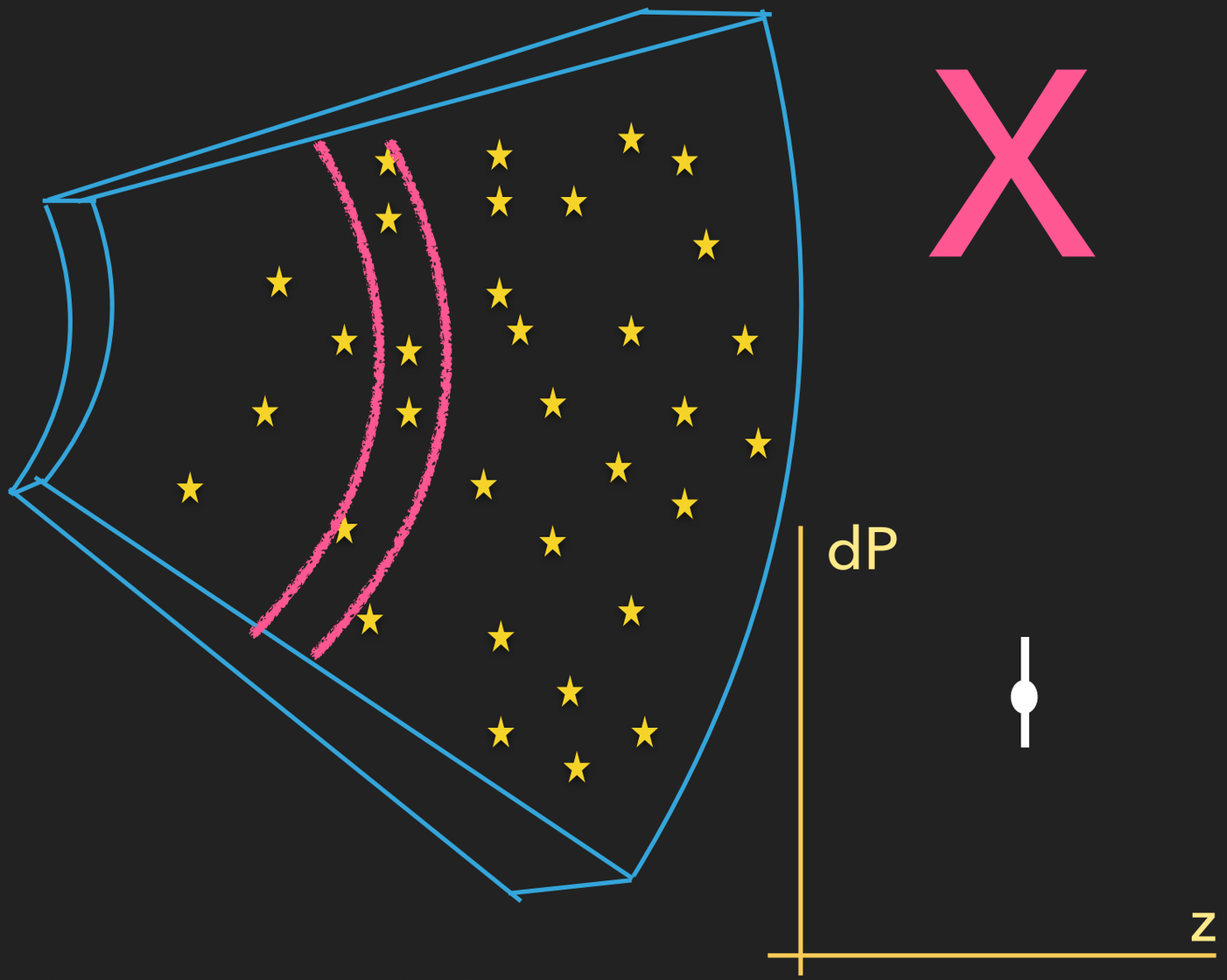

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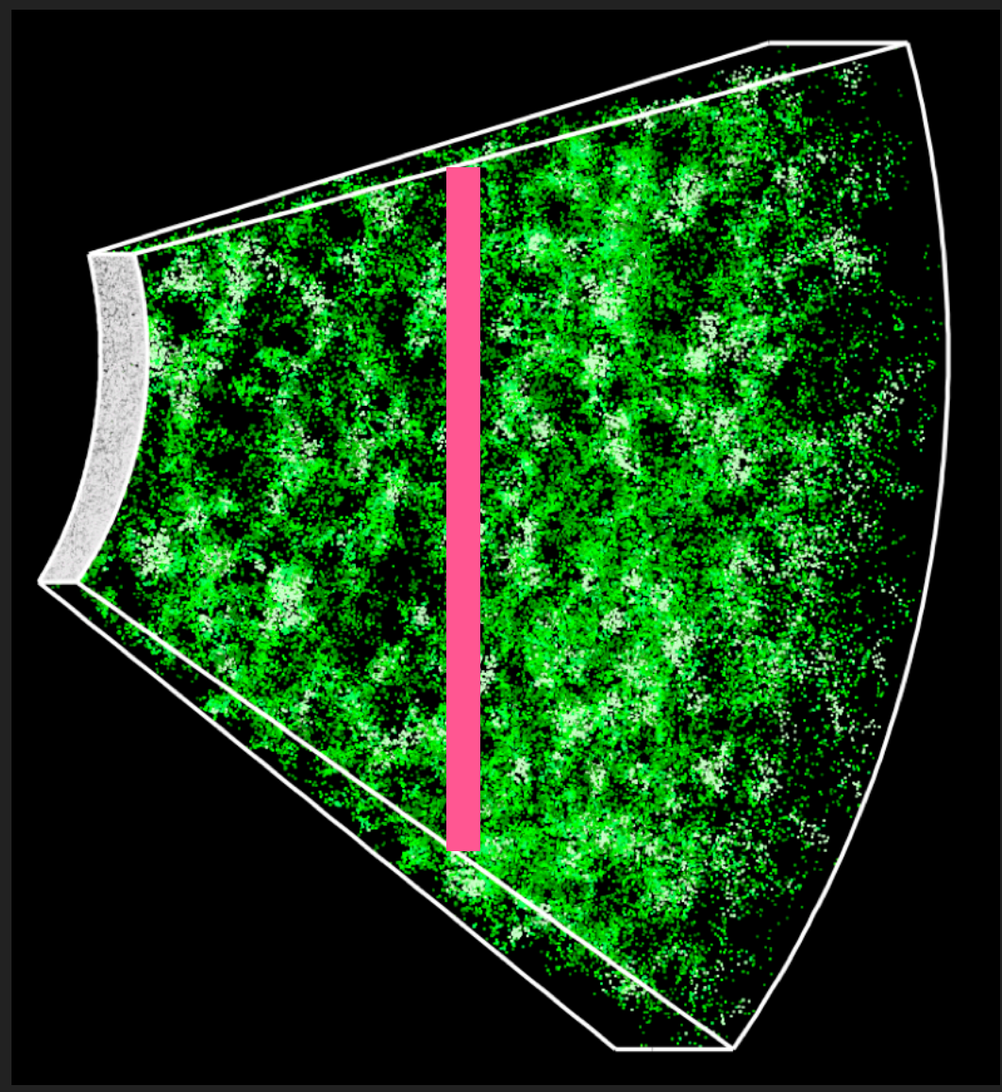

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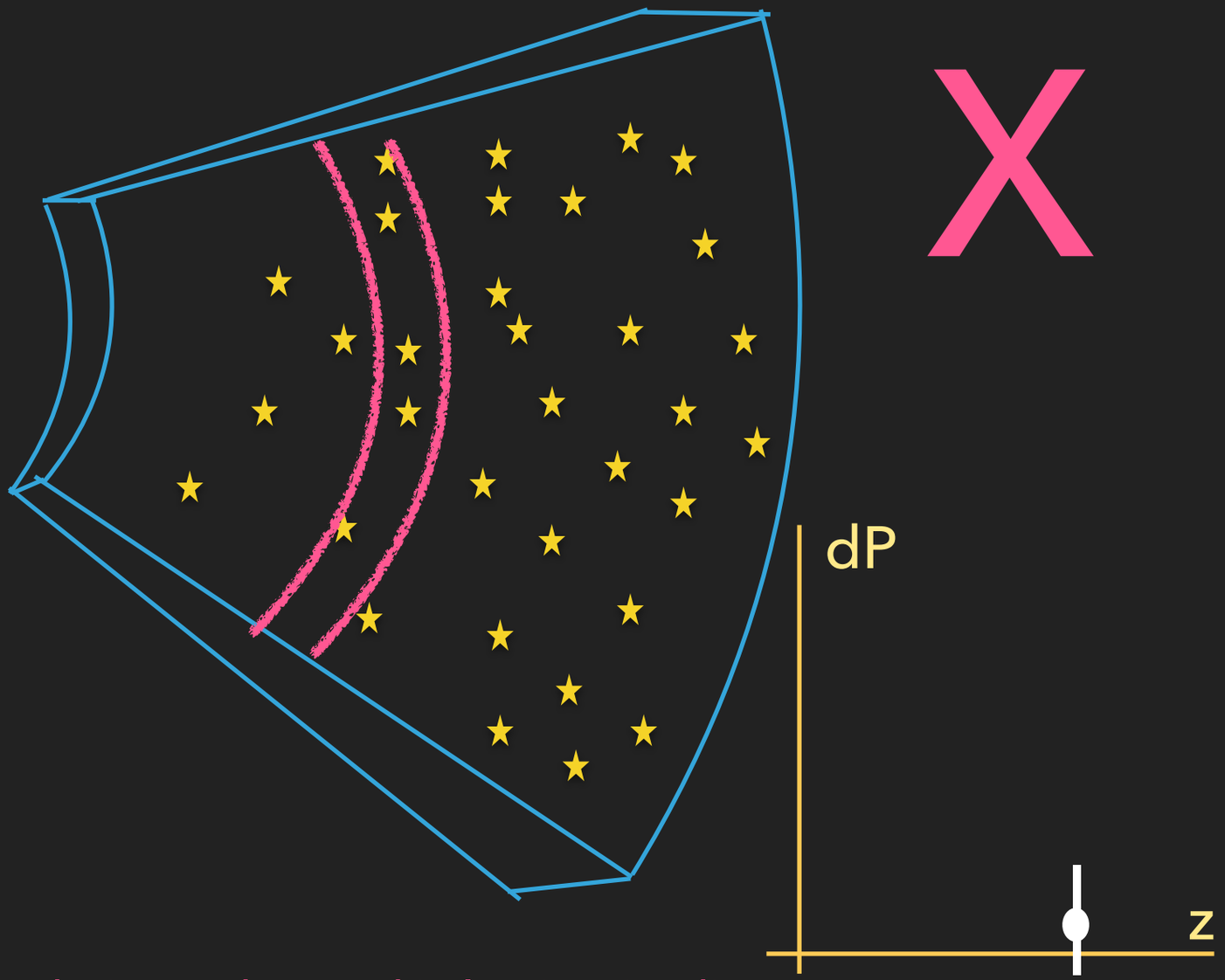
$$dP = n_{GW} n_g (1 + \xi(r)) dV_{GW} dV_g$$



Dark sirens observed in luminosity distance space

X

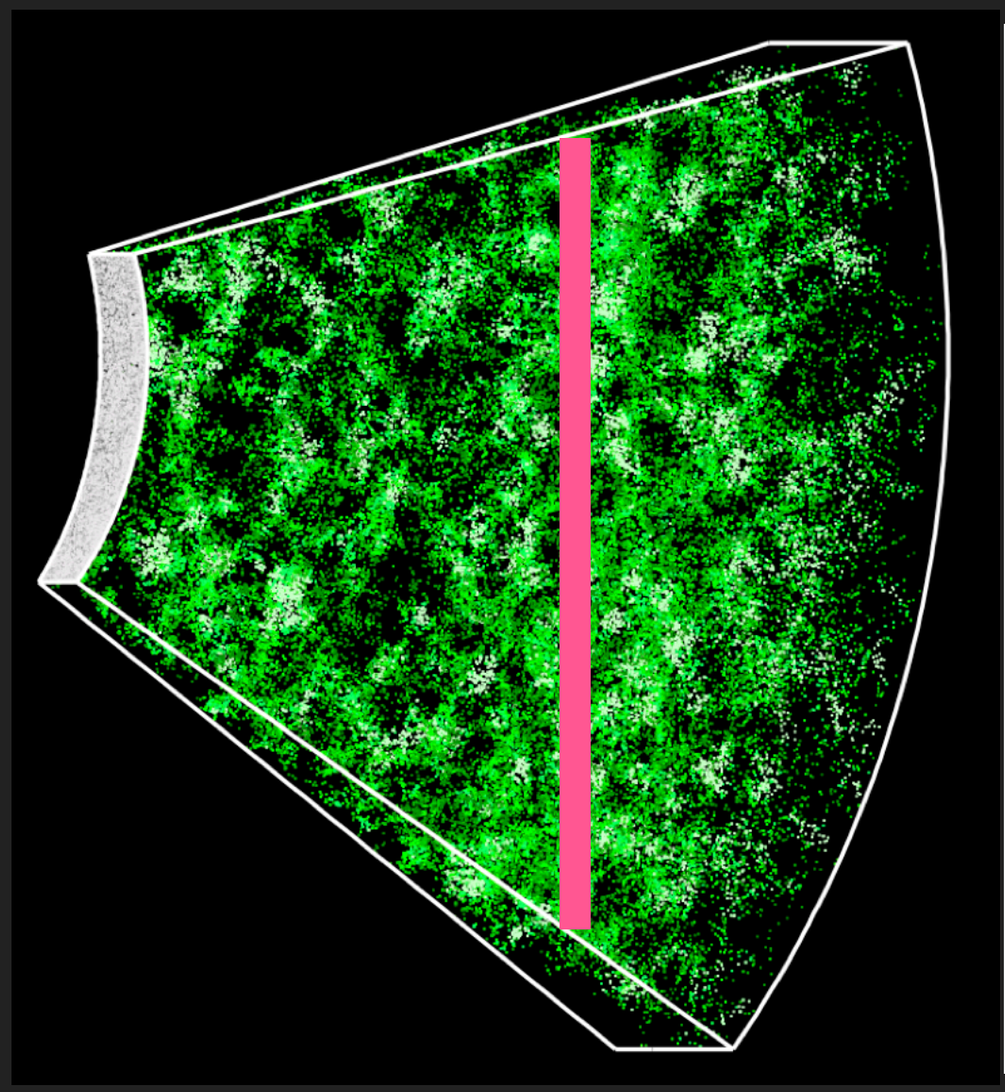
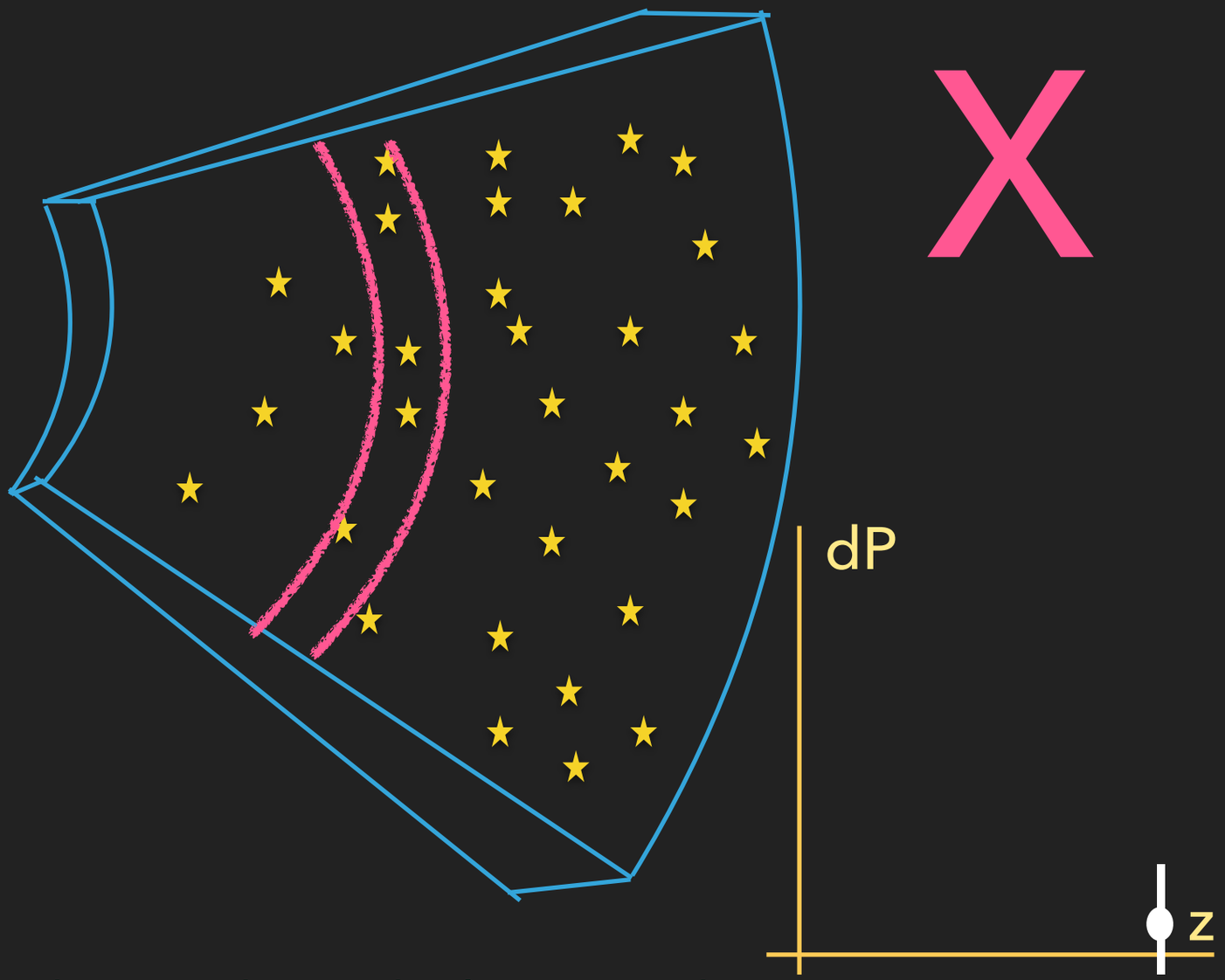


Image credit: Jeremy Tinker and the SDSS-III collaboration

Galaxy samples observed in redshift space

CROSS-CORRELATION OF GW SOURCES WITH GALAXIES

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



Dark sirens observed in luminosity distance space

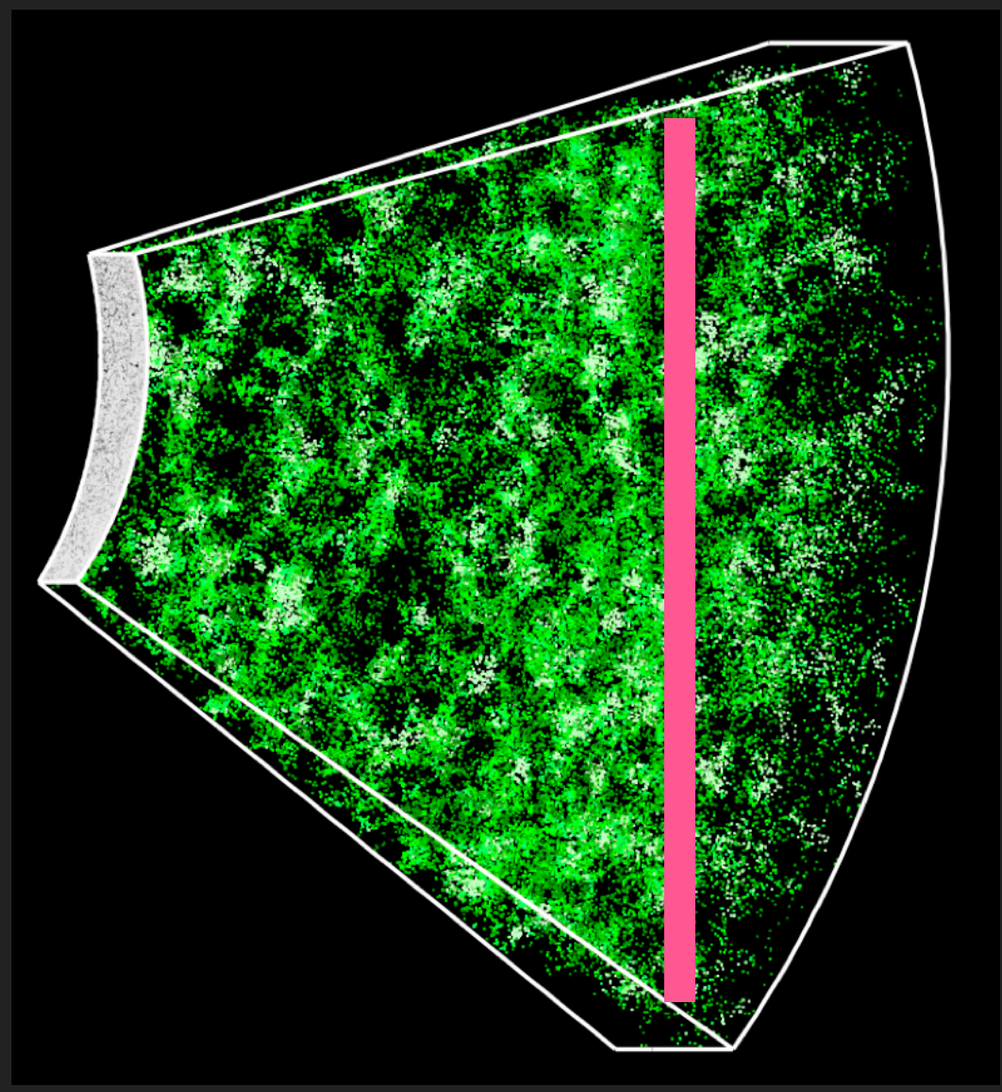


Image credit: Jeremy Tinker and the SDSS-III collaboration

Galaxy samples observed in redshift space

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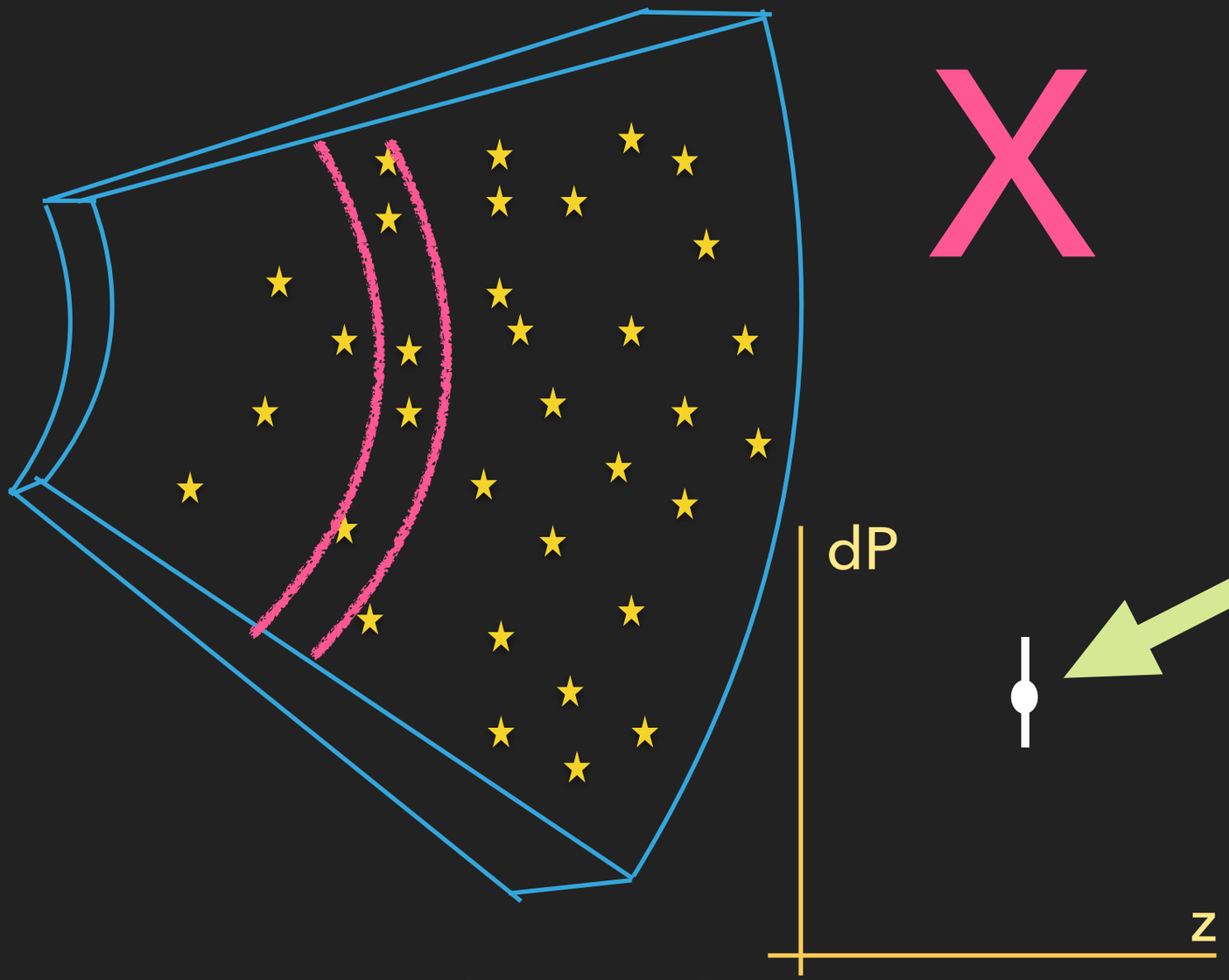


Dark sirens observed in luminosity distance space

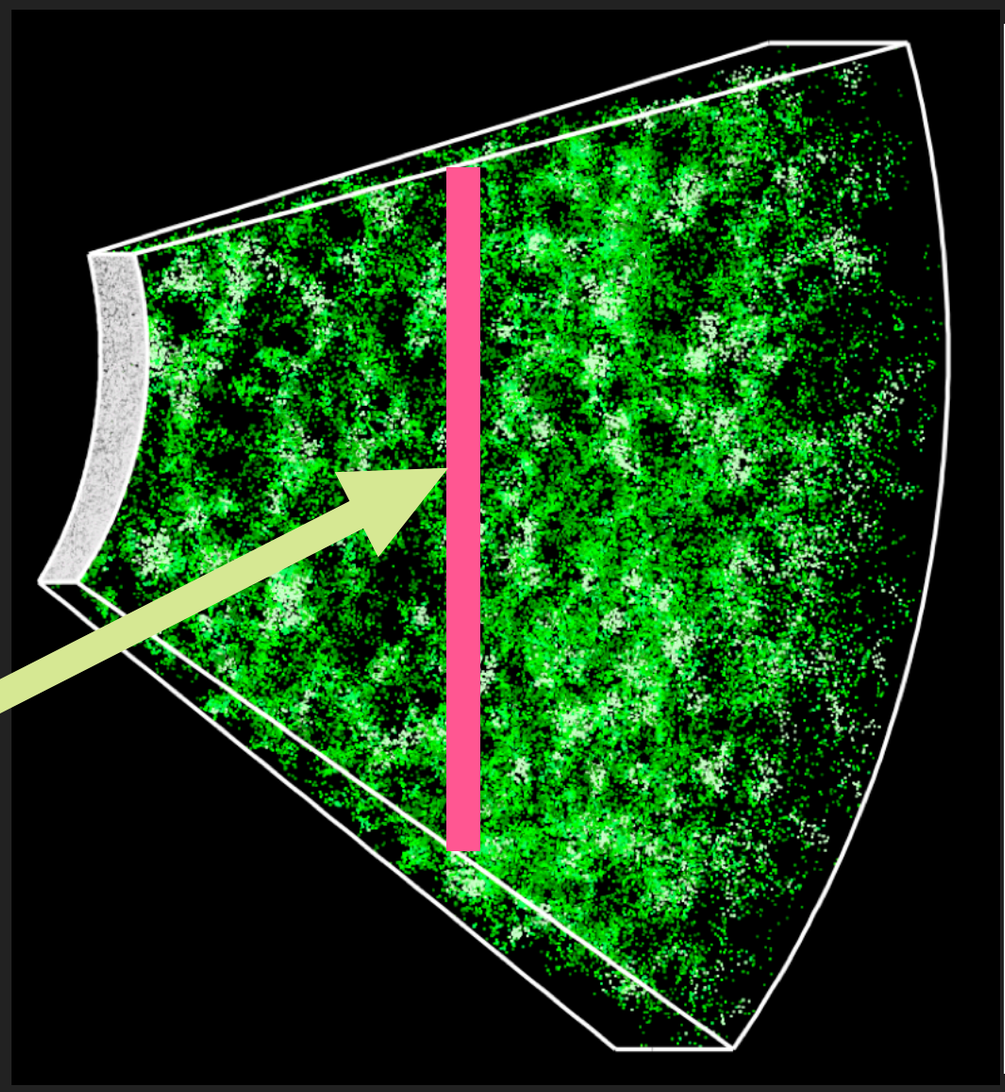
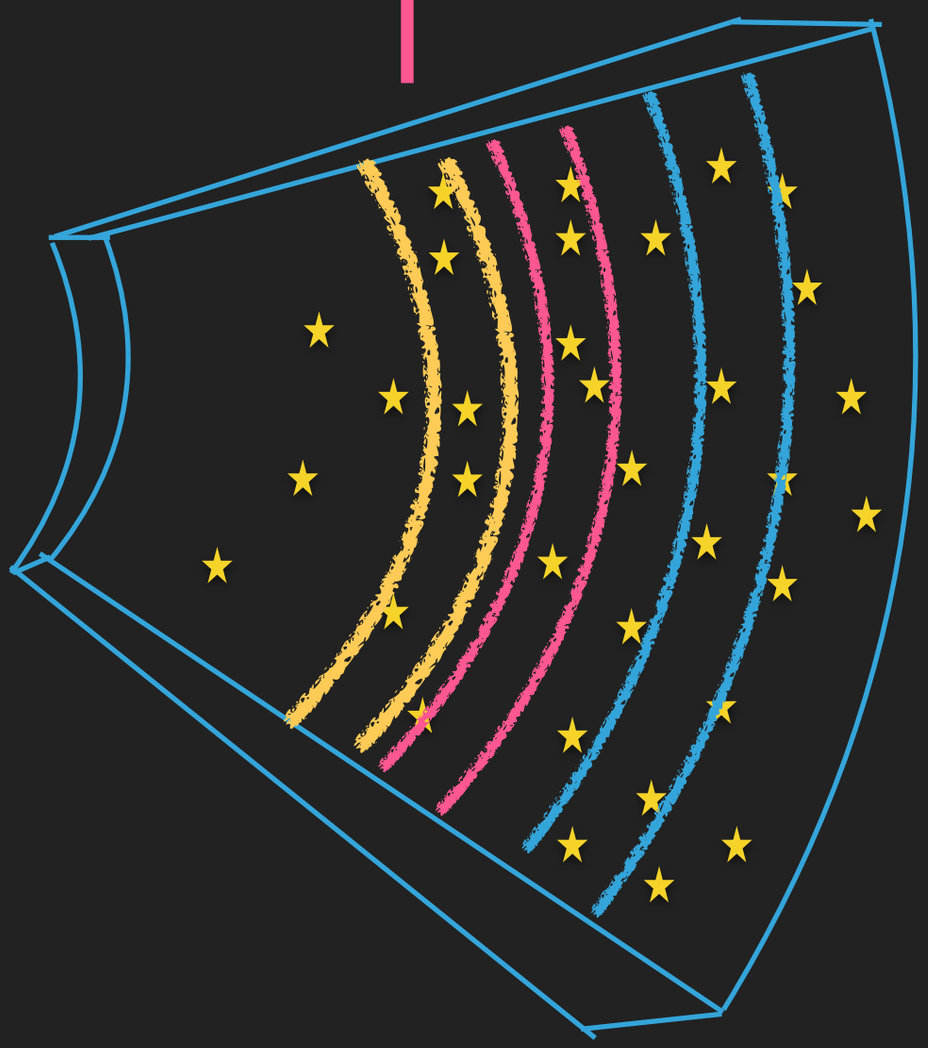


Image credit: Jeremy Tinker and the SDSS-III collaboration

Galaxy samples observed in redshift space

EXPANSION HISTORY USING DARK SIRENS THROUGH CROSS-CORRELATION

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



Dark sirens observed in luminosity distance space

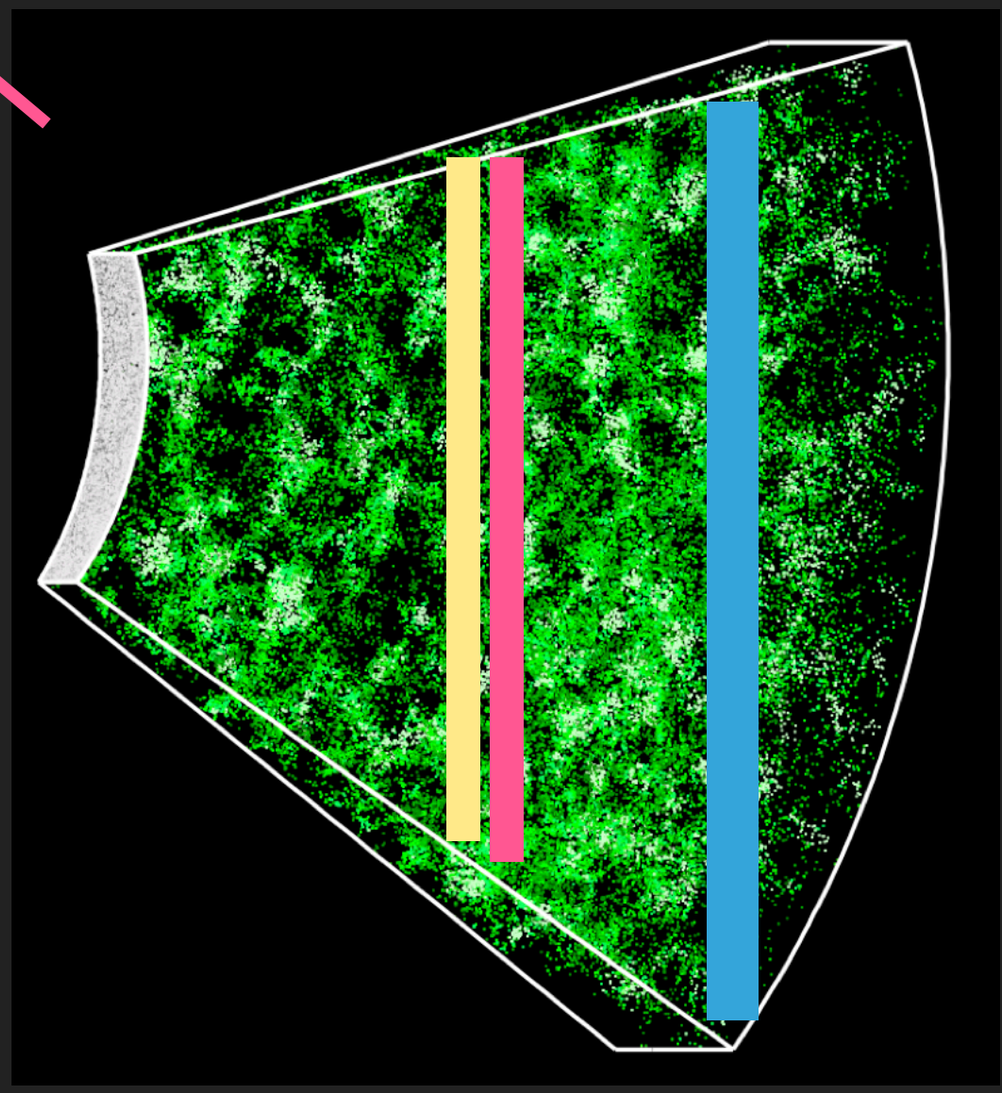
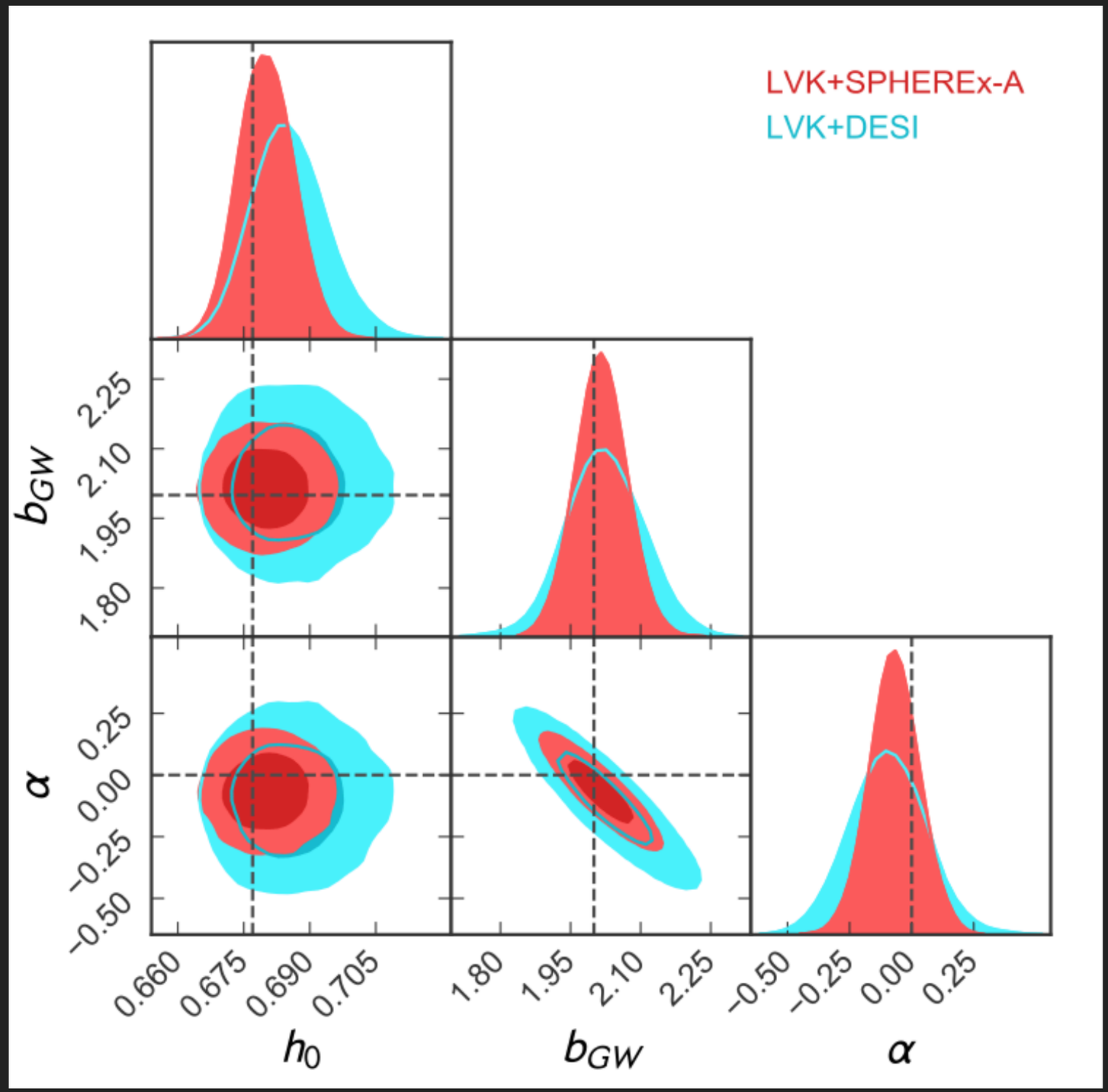


Image credit: Jeremy Tinker and the SDSS-III collaboration

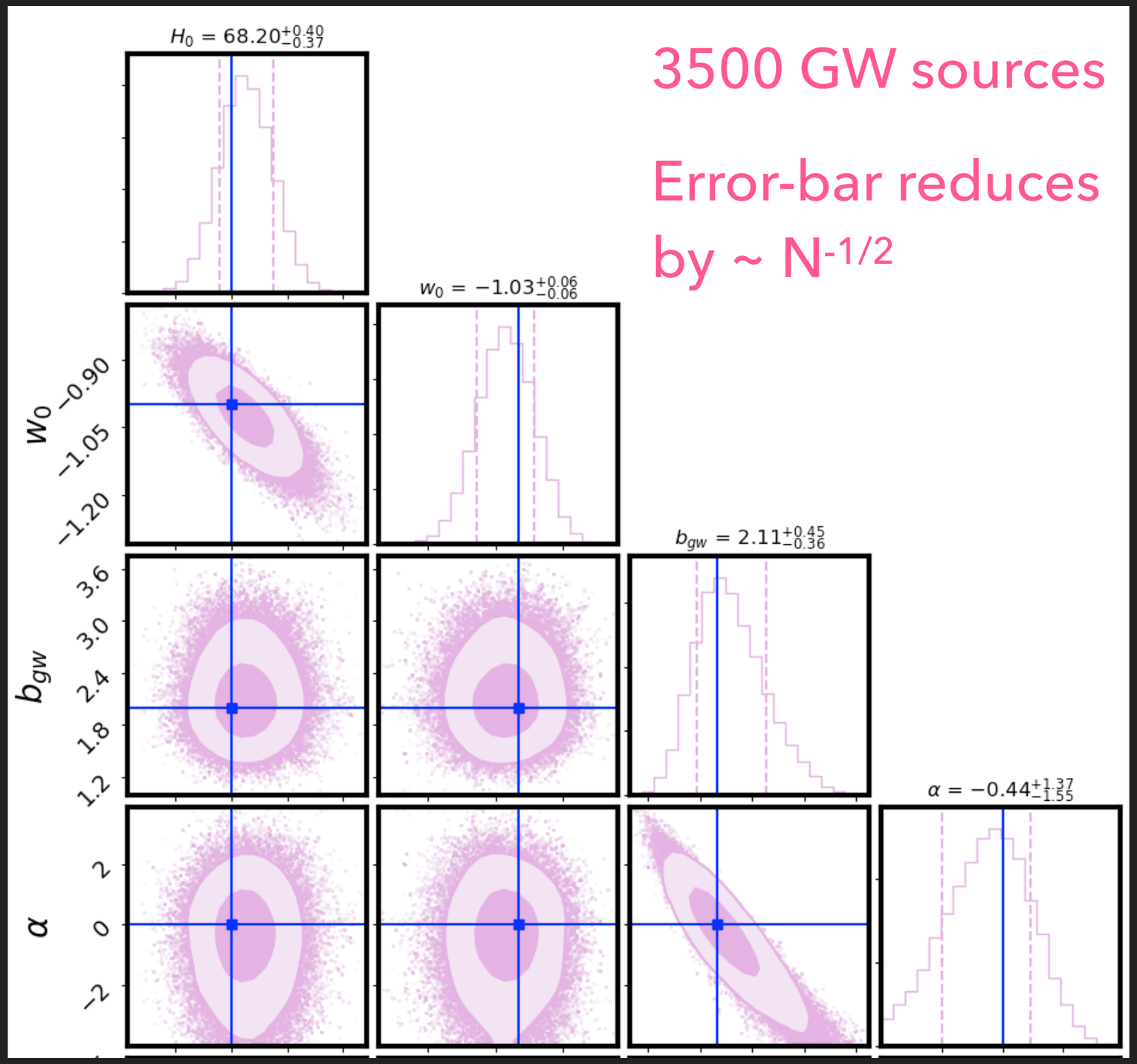
Galaxy samples observed in redshift space

LVK+SPHEREX AND LVK+DESI AFTER 5 YEARS OF OBSERVATION TIME



Diaz and Mukherjee (2022)

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



3500 GW sources

Error-bar reduces by ~ $N^{-1/2}$

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

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

Mukherjee, Wandelt, Silk (*2020*)

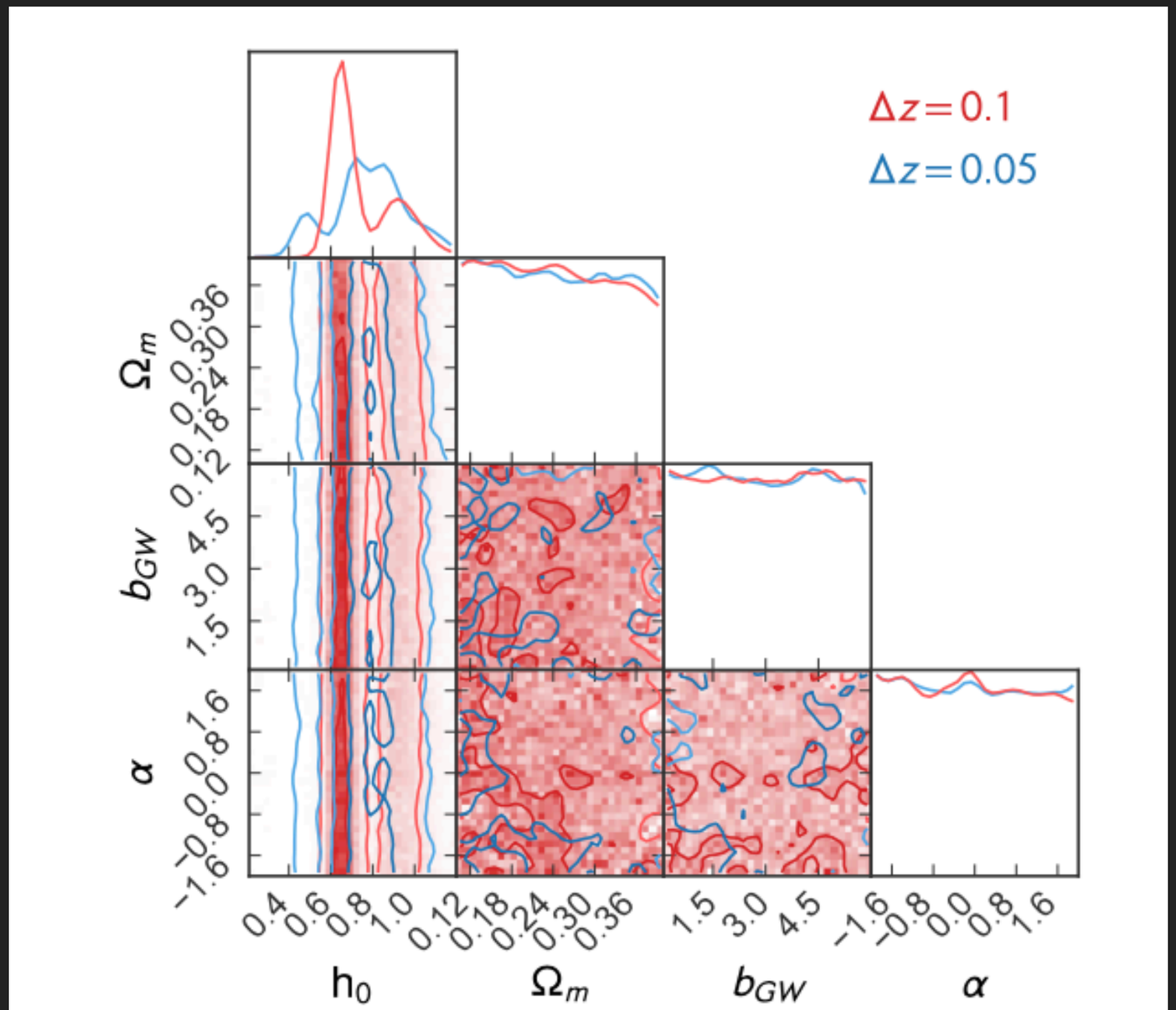
APPLICATION OF CROSS-CORRELATION TECHNIQUE ON GWTC-3

.....only a proof of principle

CONSTRAINTS ON THE COSMIC EXPANSION HISTORY FROM DARK SIRENS

Mukherjee, Krolewski, Wandelt, Silk (2022)

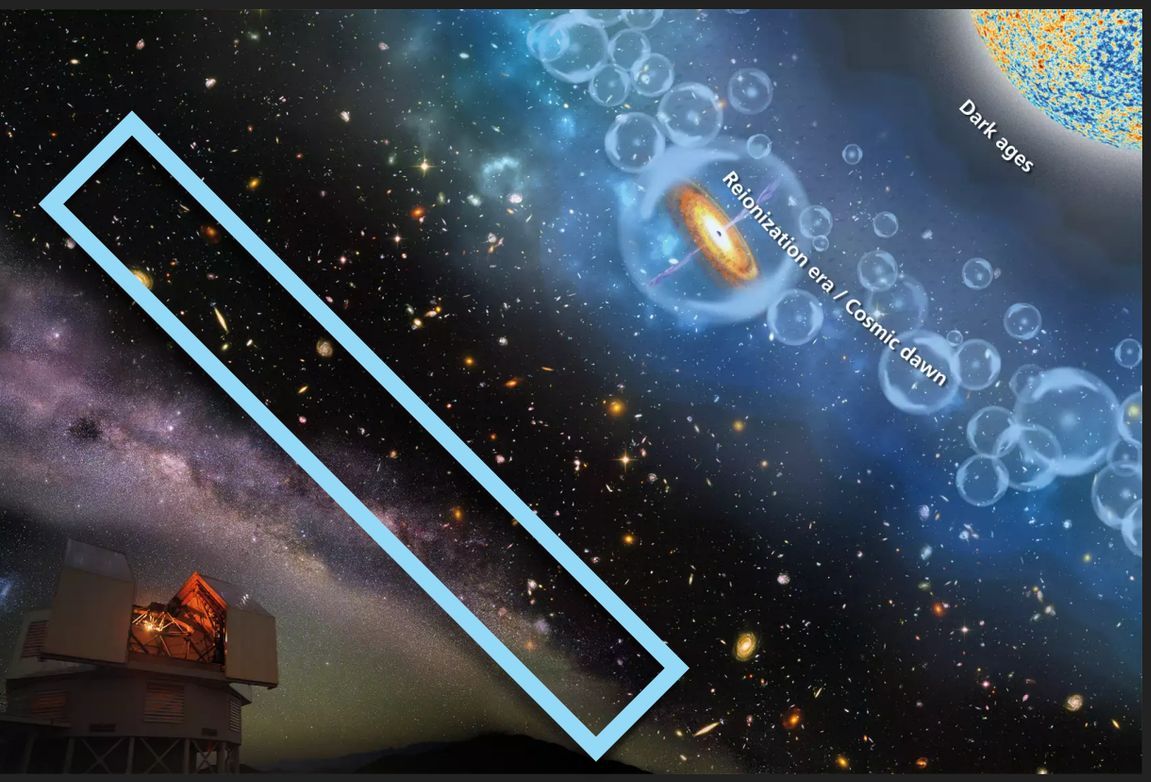
A VERY weak measurement



Suvodip Mukherjee, 2023

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

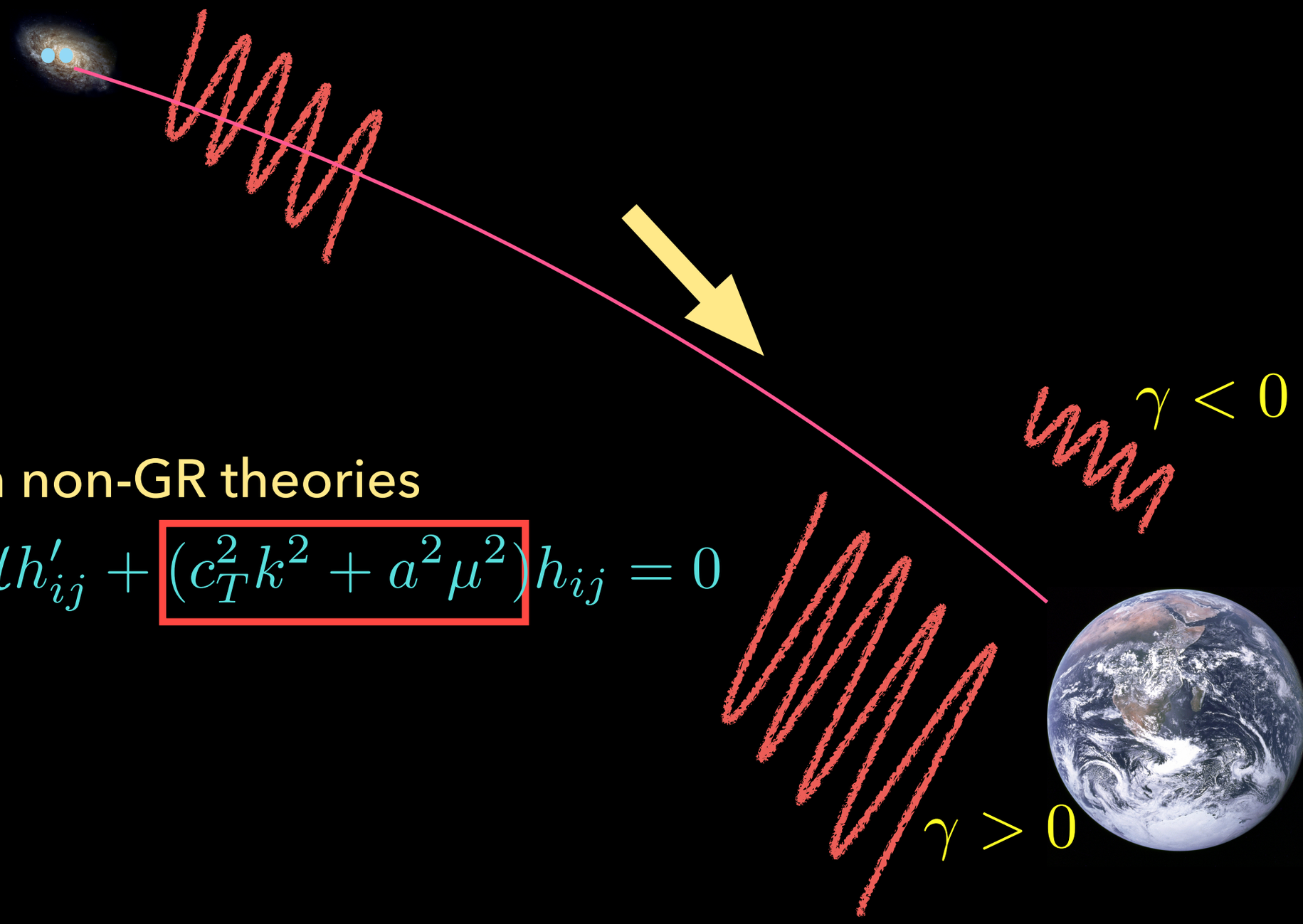
GW bias parameter



TESTING ALTERNATIVE THEORIES OF GRAVITY

Using GW propagation

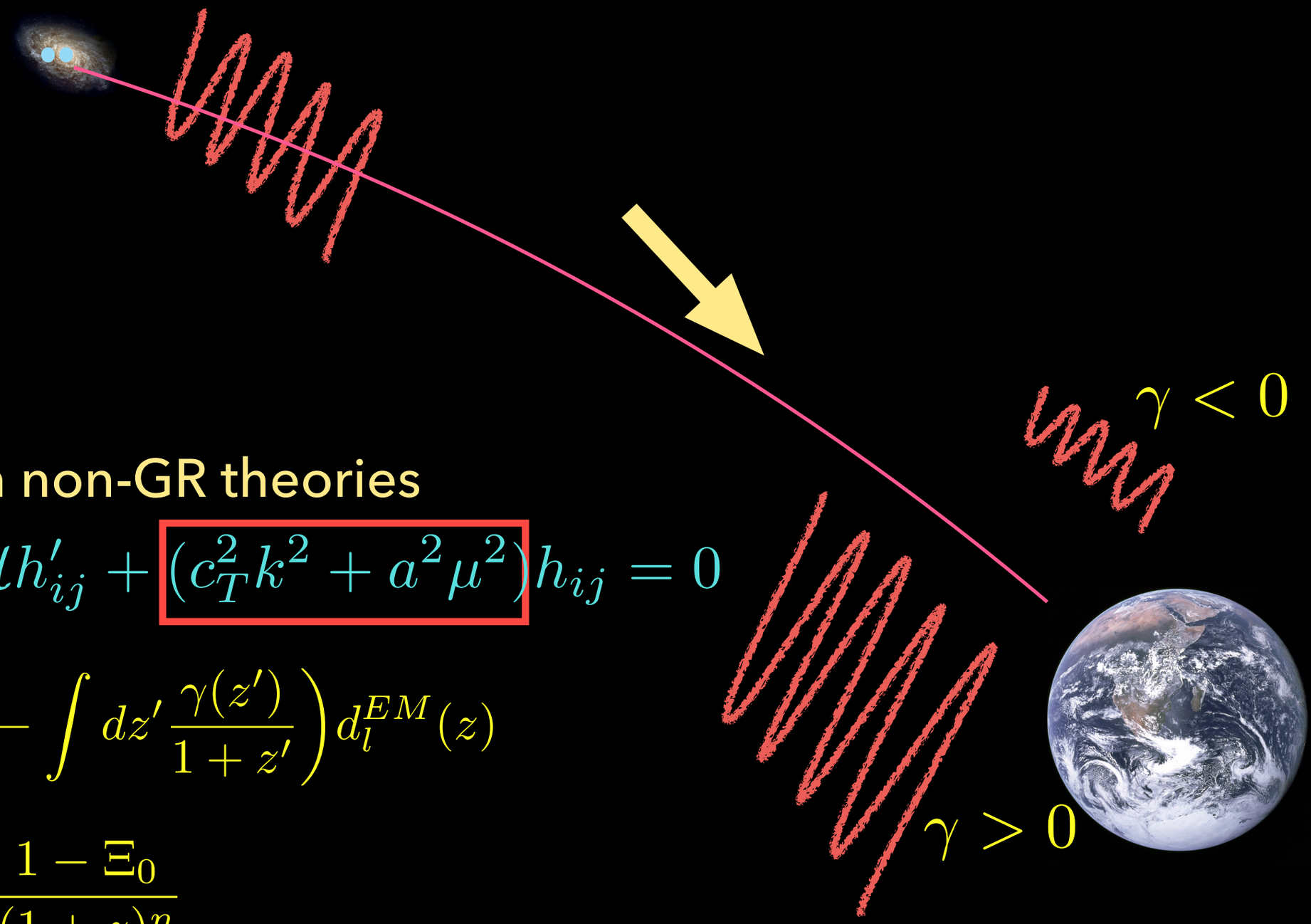
GW PROPAGATION THROUGH SPACE-TIME IS A PROBE OF THE ALTERNATIVE THEORIES OF GRAVITY



GW propagation in non-GR theories

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

GW PROPAGATION THROUGH SPACE-TIME IS A PROBE OF THE ALTERNATIVE THEORIES OF GRAVITY



GW propagation in non-GR theories

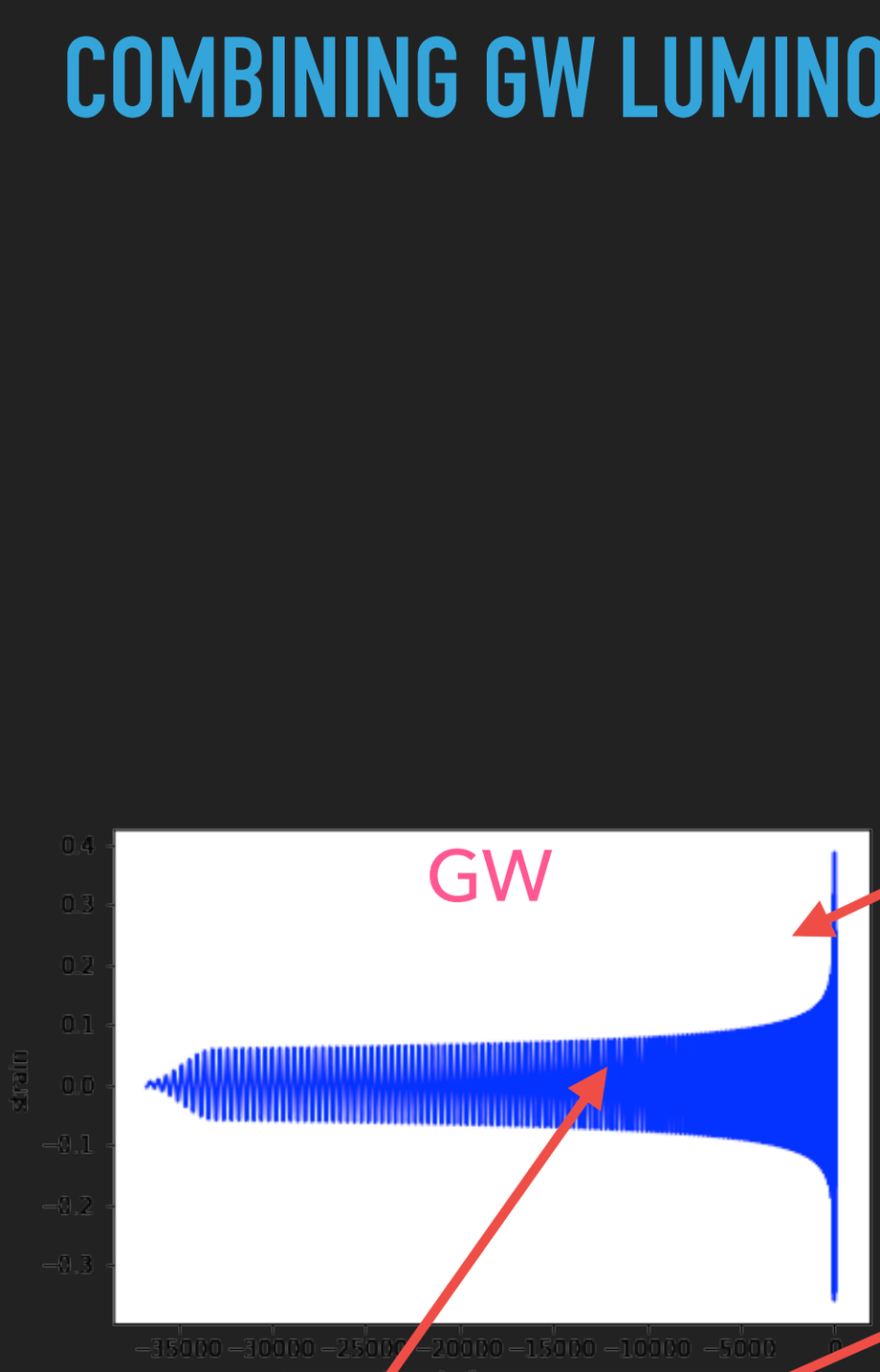
$$h''_{ij} + 2(1 - \gamma(z))\mathcal{H}h'_{ij} + (c_T^2 k^2 + a^2\mu^2)h_{ij} = 0$$

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

$$\frac{d_l^{GW}(z)}{d_l^{EM}(z)} = \Xi_0 + \frac{1-\Xi_0}{(1+z)^n}$$

COMBINING GW LUMINOSITY DISTANCE, BAO, AND SOUND HORIZON

Mukherjee, Wandelt, Silk (2021)



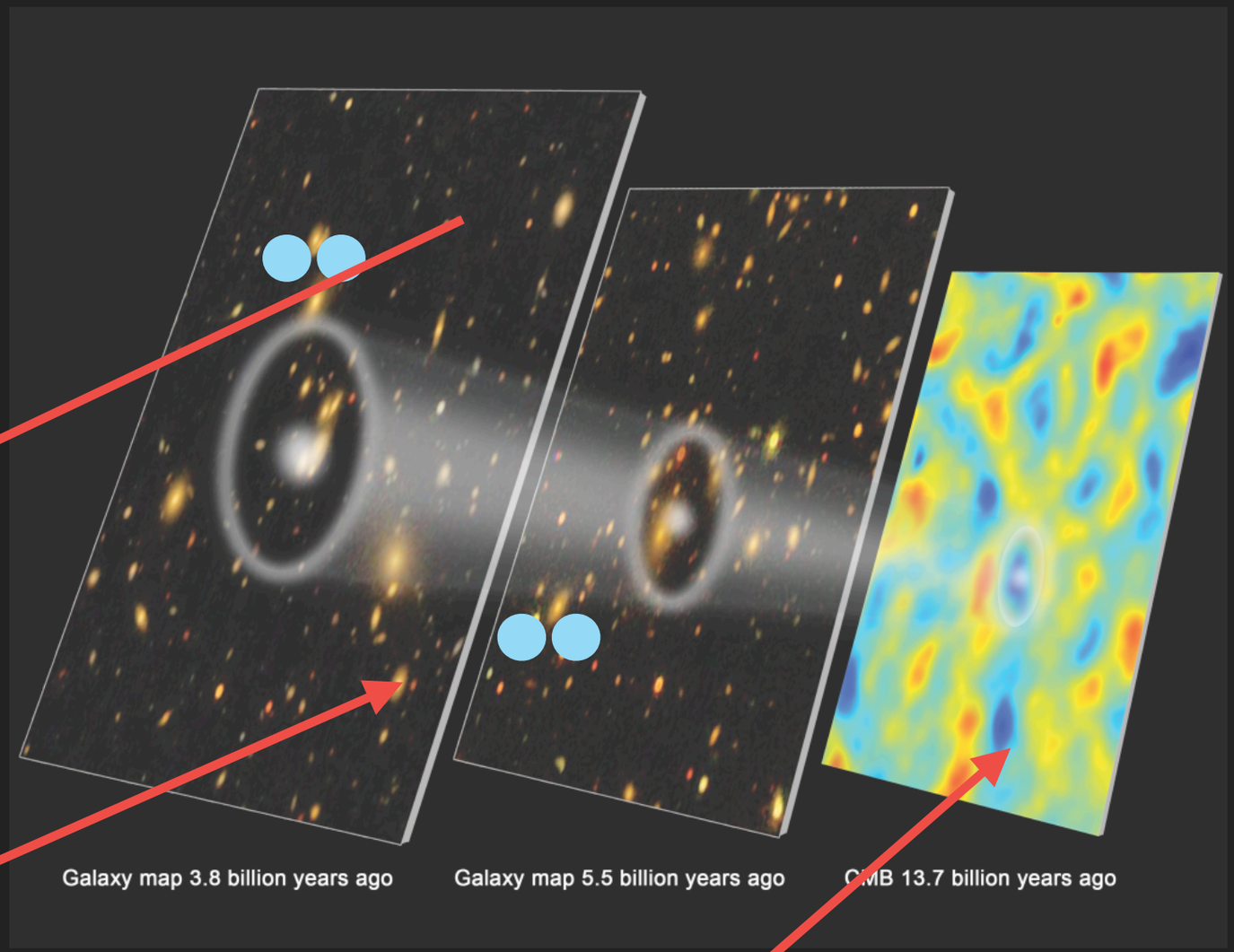
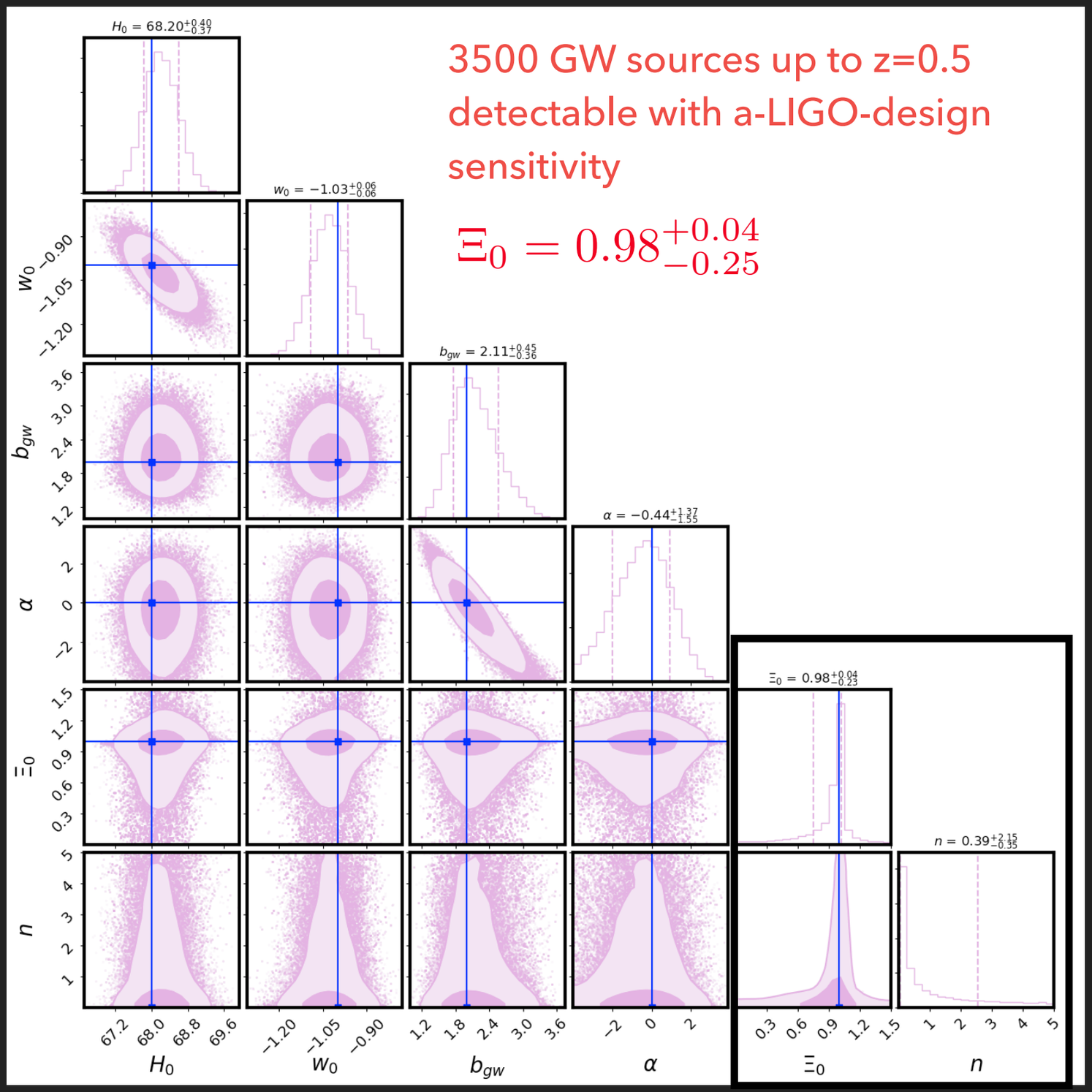


Image credit: ESA

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

FORECAST TO MEASURE THE FRICTIONAL TERM



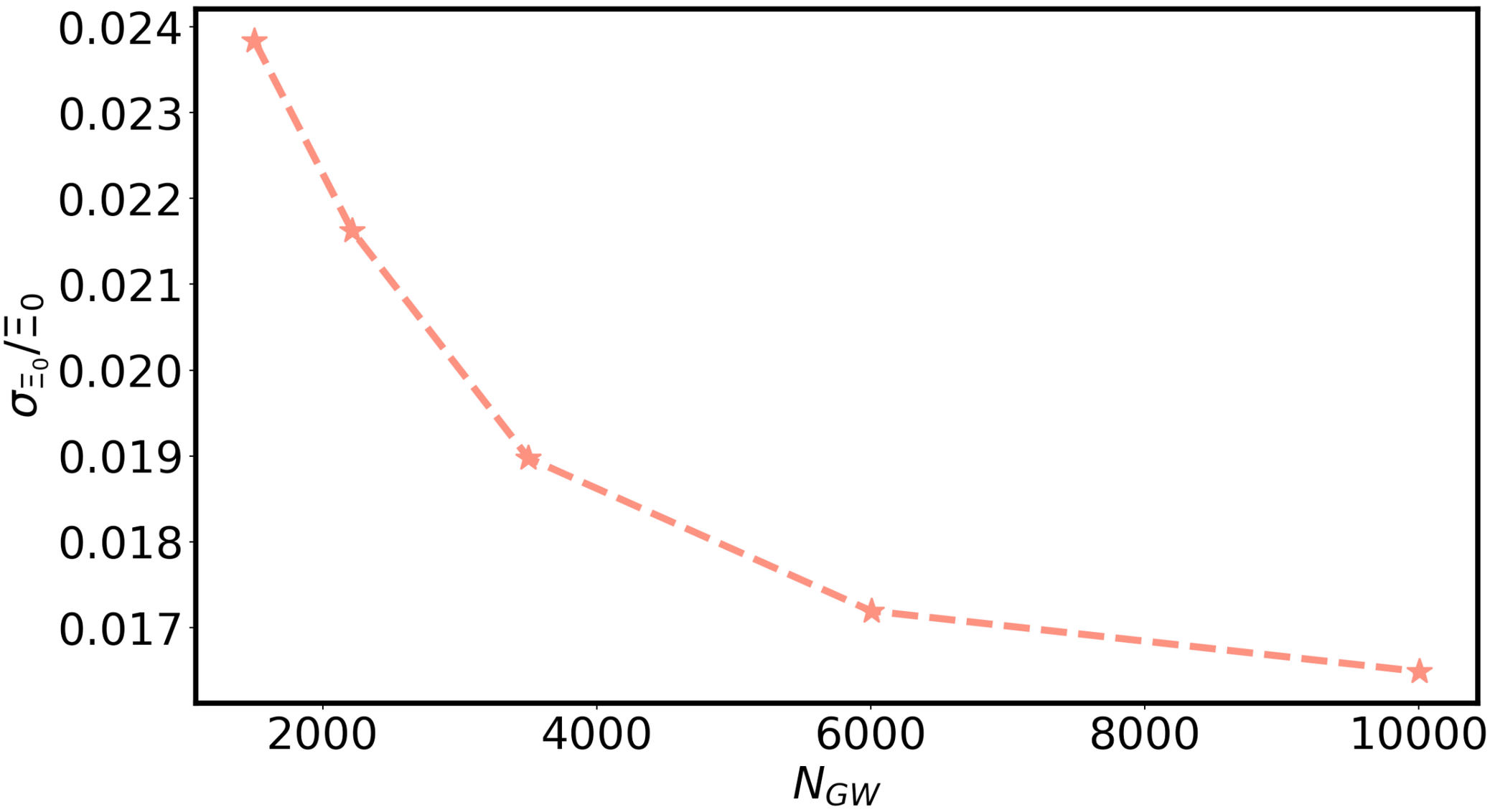
3500 GW sources up to z=0.5 detectable with a-LIGO-design sensitivity

$$\Xi_0 = 0.98^{+0.04}_{-0.25}$$

Mukherjee, Wandelt, Silk (2021)

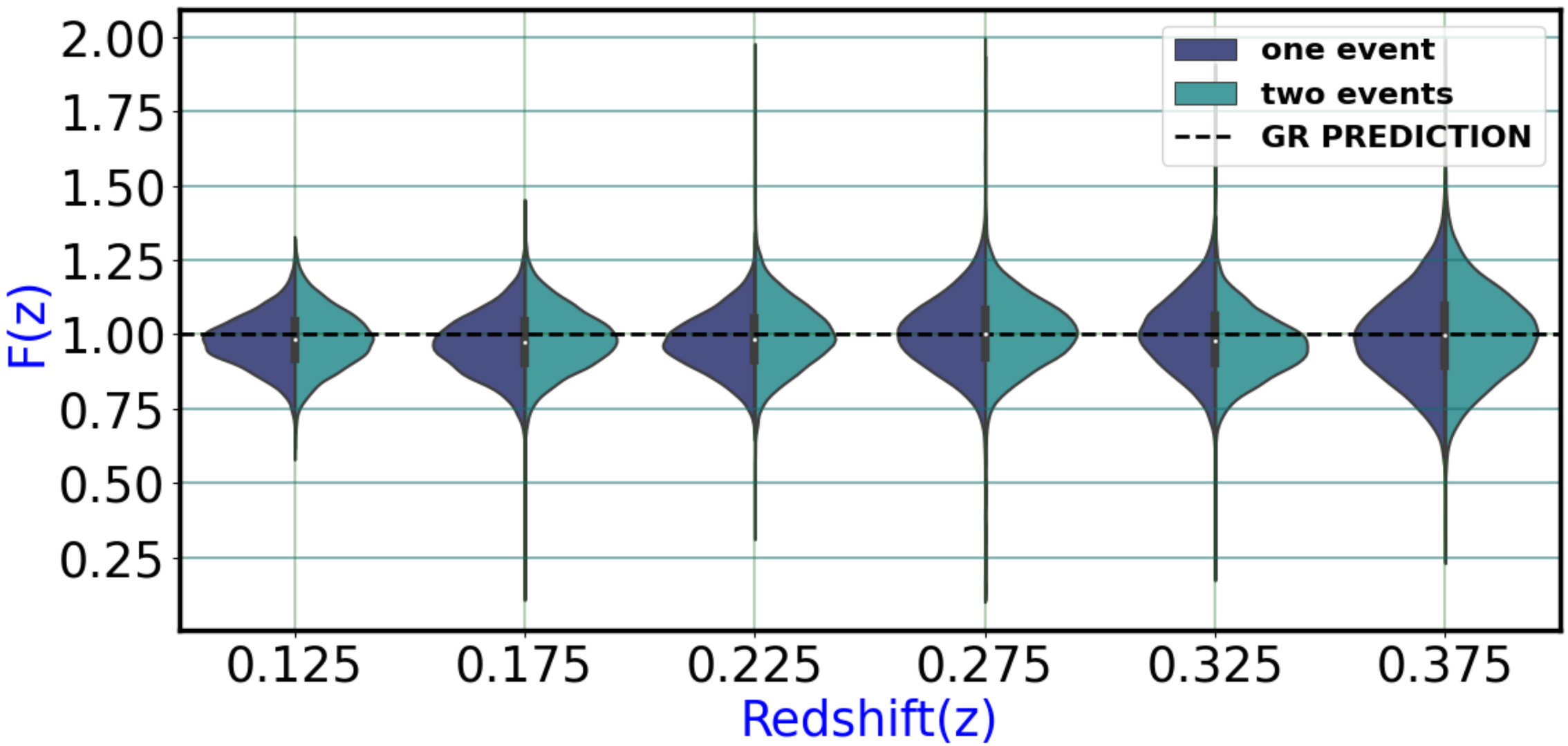
FORECAST TO MEASURE THE FRICTIONAL TERM FROM BBH

Mukherjee, Wandelt, Silk (2021)



FORECAST TO MEASURE THE FRICTIONAL TERM FROM NSBH

Afroz and Mukherjee (in preparation)



MULTI-MESSENGER VIEW ON BLACK HOLE POPULATION(S)

+ Events

+ Backgrounds

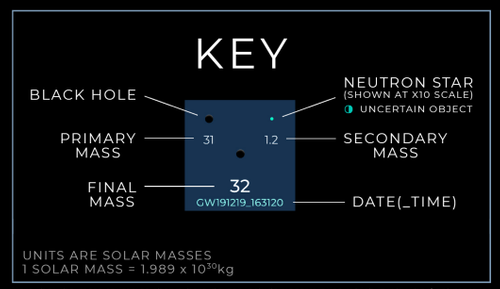
OBSERVING RUN 01
2015 - 2016

02
2016 - 2017

03a+b
2019 - 2020

36 31 63 GW150914	23 14 36 GW151012	14 7.7 21 GW151226	31 20 49 GW170104	11 7.6 18 GW170608	50 34 80 GW170729	35 24 56 GW170809	31 25 53 GW170814	1.5 1.3 ≤2.8 GW170817	35 27 60 GW170818	40 29 65 GW170823	88 22 105 GW190403_051519	25 18 41 GW190408_181802
30 8.3 37 GW190412	35 24 56 GW190413_052954	48 32 76 GW190413_134308	41 32 70 GW190421_213856	2 1.4 3.2 GW190425	107 77 175 GW190426_190642	43 28 69 GW190503_185404	23 13 35 GW190512_180714	36 18 52 GW190513_205428	39 28 65 GW190514_065416	37 25 59 GW190517_055101	66 41 101 GW190519_153544	95 69 156 GW190521
42 33 71 GW190521_074359	37 23 56 GW190527_092055	69 48 111 GW190602_175927	57 36 87 GW190620_030421	35 24 56 GW190630_185205	54 41 90 GW190701_203306	67 38 99 GW190706_222641	12 8.4 19 GW190707_093326	18 13 30 GW190708_232457	37 21 55 GW190719_215514	13 7.8 20 GW190720_000836	12 6.4 17 GW190725_174728	38 29 64 GW190727_060333
12 8.1 20 GW190728_064510	42 29 67 GW190731_140936	37 27 62 GW190803_022701	48 32 76 GW190805_211137	23 2.6 26 GW190814	32 26 55 GW190828_063405	24 10 33 GW190828_065509	44 36 76 GW190910_112807	35 24 57 GW190915_235702	44 24 66 GW190916_200658	9.3 2.1 11 GW190917_114630	8.9 5 13 GW190924_021846	21 16 35 GW190925_232845
40 23 61 GW190926_050336	81 24 102 GW190929_012149	12 7.8 19 GW190930_133541	12 7.9 19 GW191103_012549	11 7.7 18 GW191105_143521	65 47 107 GW191109_010717	29 5.9 34 GW191113_071753	12 8.3 20 GW191126_115259	53 24 76 GW191127_050227	11 6.7 17 GW191129_134029	27 19 45 GW191204_110529	12 8.2 19 GW191204_171526	25 18 41 GW191215_223052
12 7.7 19 GW191216_213338	31 1.2 32 GW191219_163120	45 35 76 GW191222_033537	49 37 82 GW191230_180458	9 1.9 11 GW200105_162426	36 28 61 GW200112_155838	5.9 1.4 7.2 GW200115_042309	42 33 71 GW200128_022011	34 29 60 GW200129_065458	10 7.3 17 GW200202_154313	38 27 63 GW200208_130117	51 12 61 GW200208_222617	36 27 60 GW200209_085452
24 2.8 27 GW200210_092254	51 30 78 GW200216_220804	38 28 62 GW200219_094415	87 61 141 GW200220_061928	39 28 64 GW200220_124850	40 33 69 GW200224_222234	19 14 32 GW200225_060421	38 20 56 GW200302_015811	28 15 42 GW200306_093714	36 14 47 GW200308_173609	34 28 59 GW200311_115853	13 7.8 20 GW200316_215756	34 14 53 GW200322_091133

KEY



UNITS ARE SOLAR MASSES
1 SOLAR MASS = 1.989 x 10^{30}kg

Note that the mass estimates shown here do not include uncertainties, which is why the final mass is sometimes larger than the sum of the primary and secondary masses. In actuality, the final mass is smaller than the primary plus the secondary mass.

The events listed here pass one of two thresholds for detection. They either have a probability of being astrophysical of at least 50%, or they pass a false alarm rate threshold of less than 1 per 3 years.

GRAVITATIONAL WAVE
MERGER
DETECTIONS
SINCE 2015

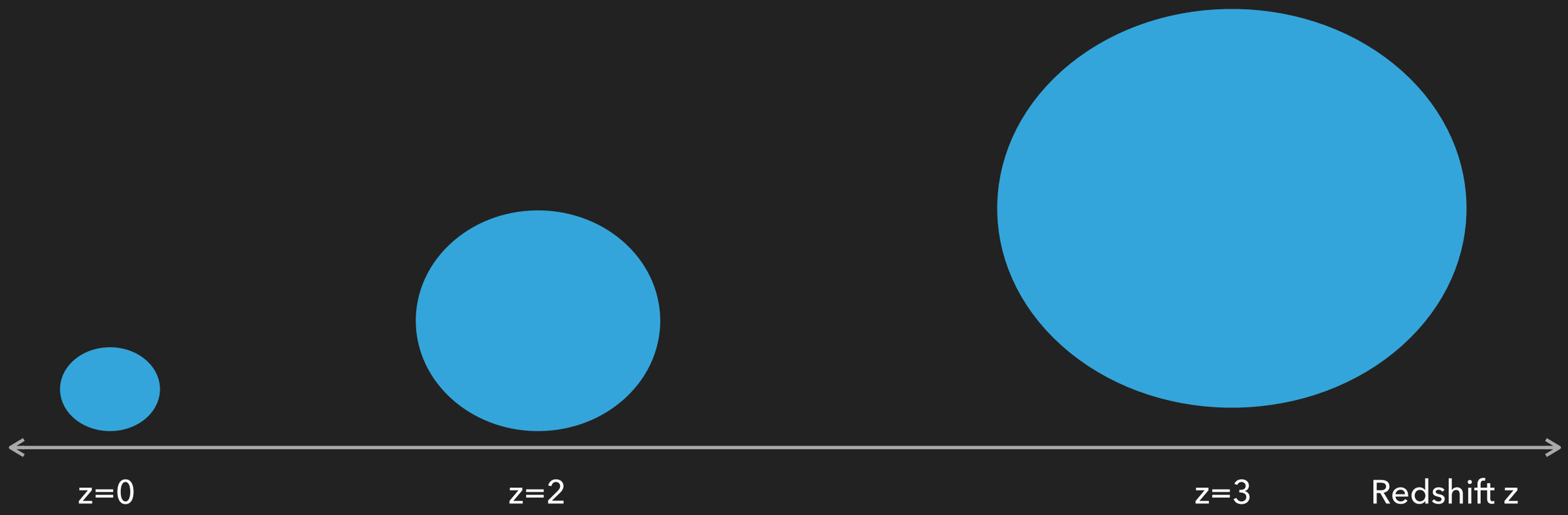
OzGrav
ARC Centre of Excellence for Gravitational Wave Discovery

LIGO VIRGO KAGRA

WHAT CHARACTERISES THE BLACK HOLE POPULATION (SO FAR)

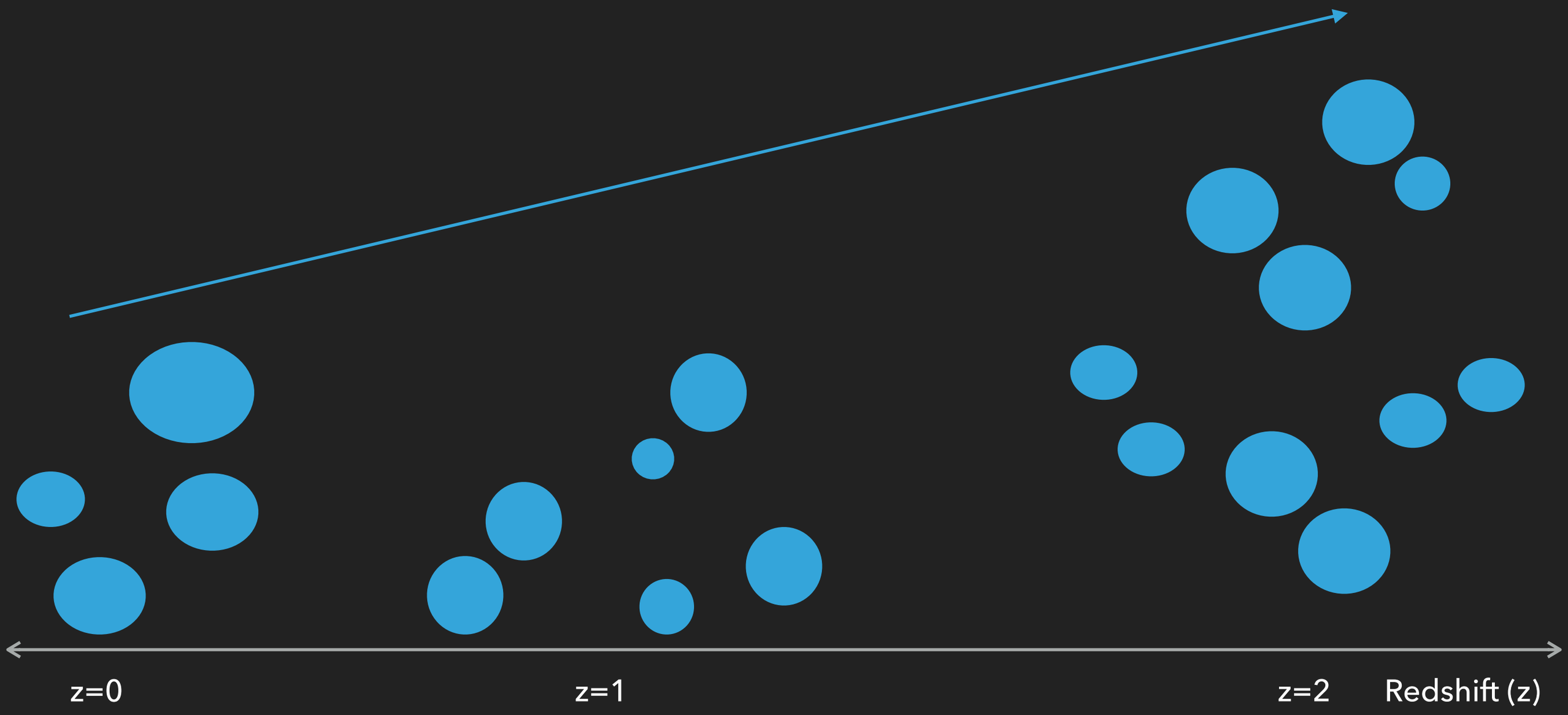
- We observe ‘redshifted masses’

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



WHAT CHARACTERISES THE BLACK HOLE POPULATION (SO FAR)

- Merger rate of compact objects



BINARY BLACK HOLES: TRACER TO THE LAST FEW BILLION YEARS OF THE UNIVERSE

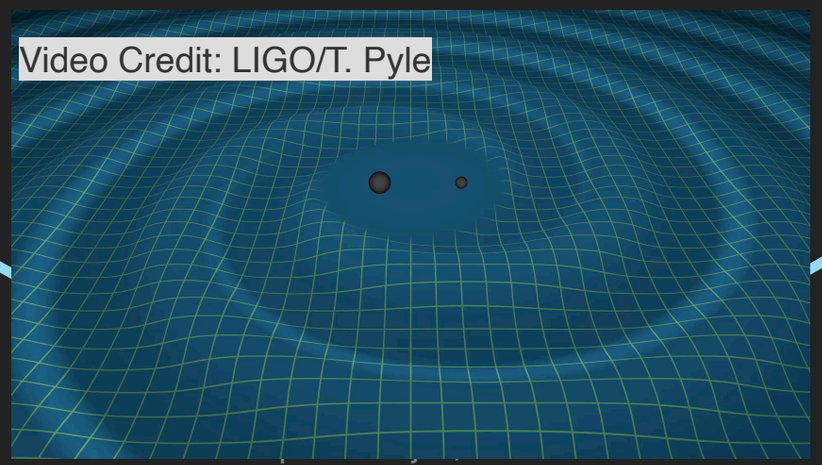
Property of the galaxies

Star formation rate

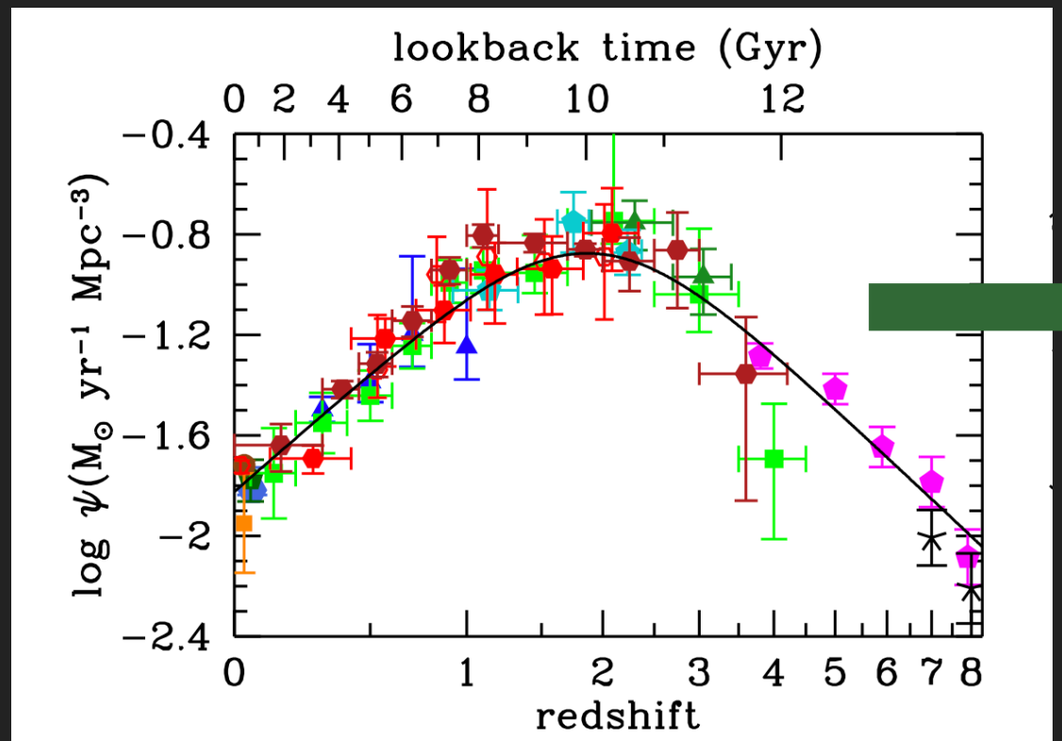
Stellar Metallicity

Stellar mass

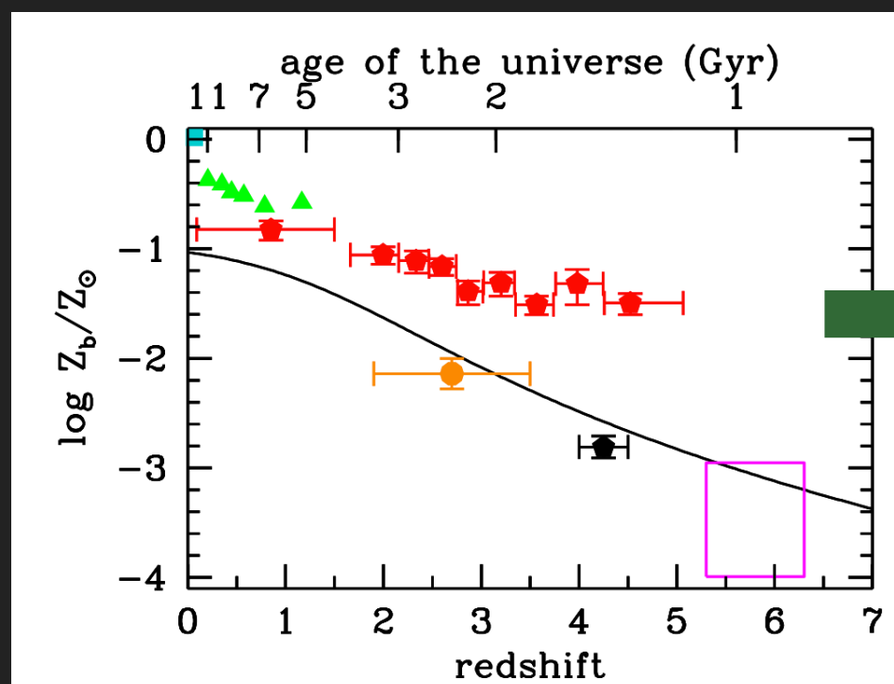
Binary Black hole formation channels

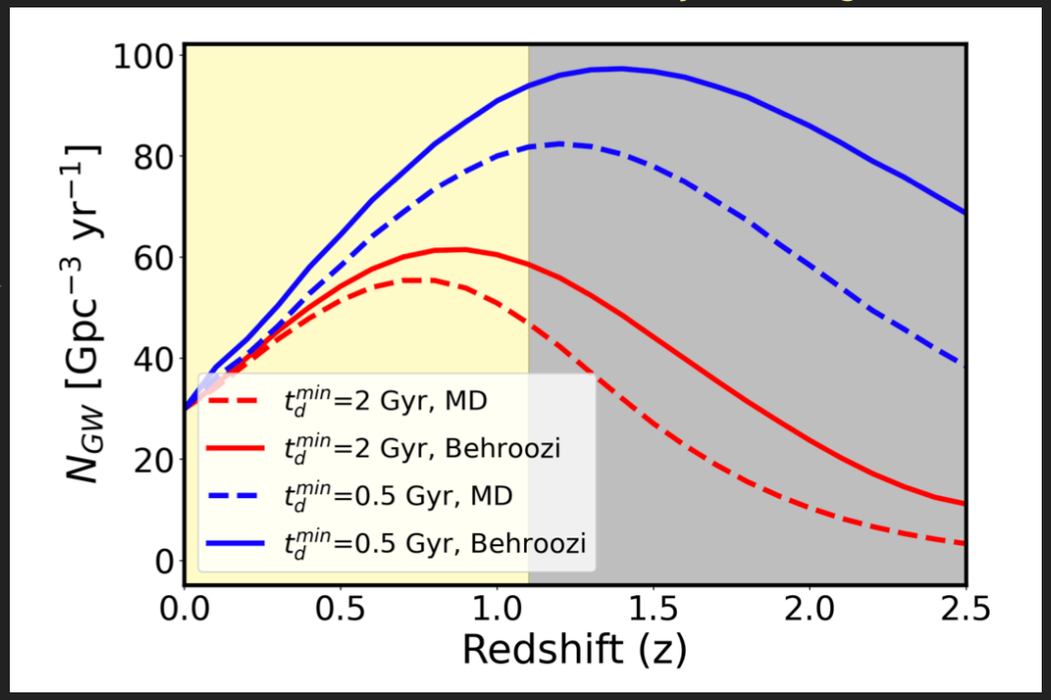


BINARY BLACK HOLE MERGER RATE INTERPLAY WITH SFR AND METALLICITY

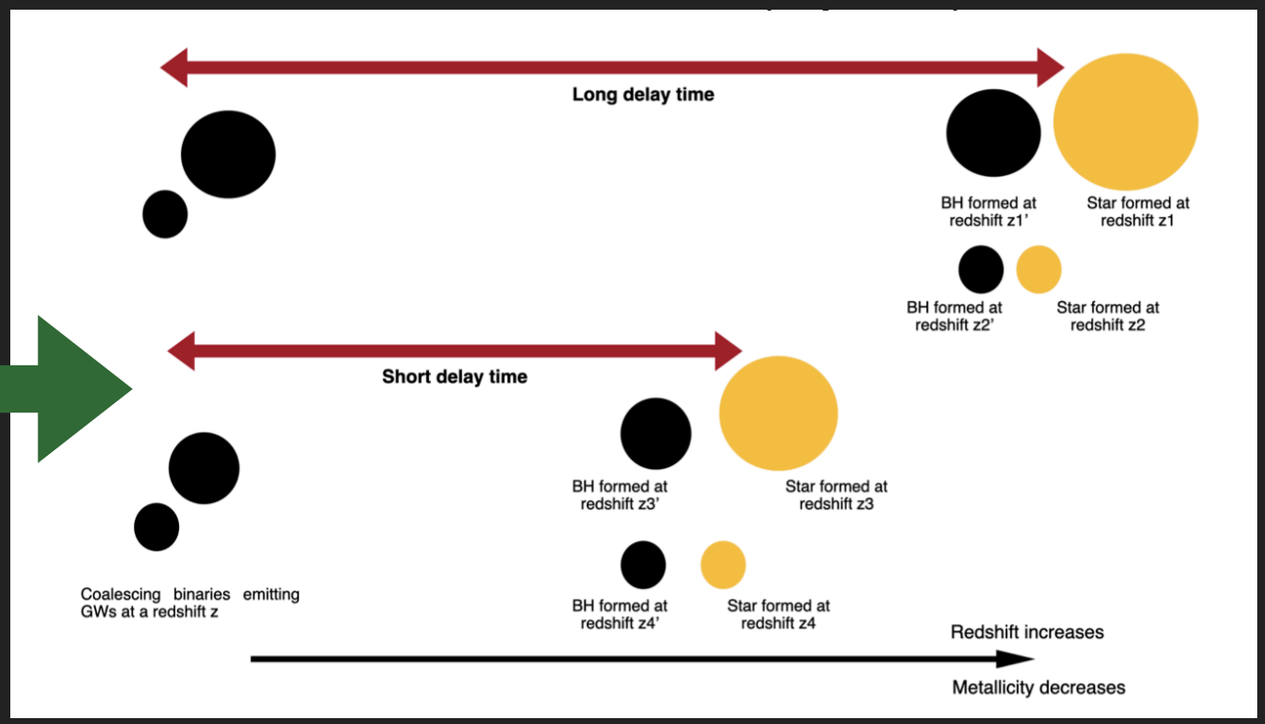


Madau & Dickinson (2014)





Mukherjee & Dizgah (2022)



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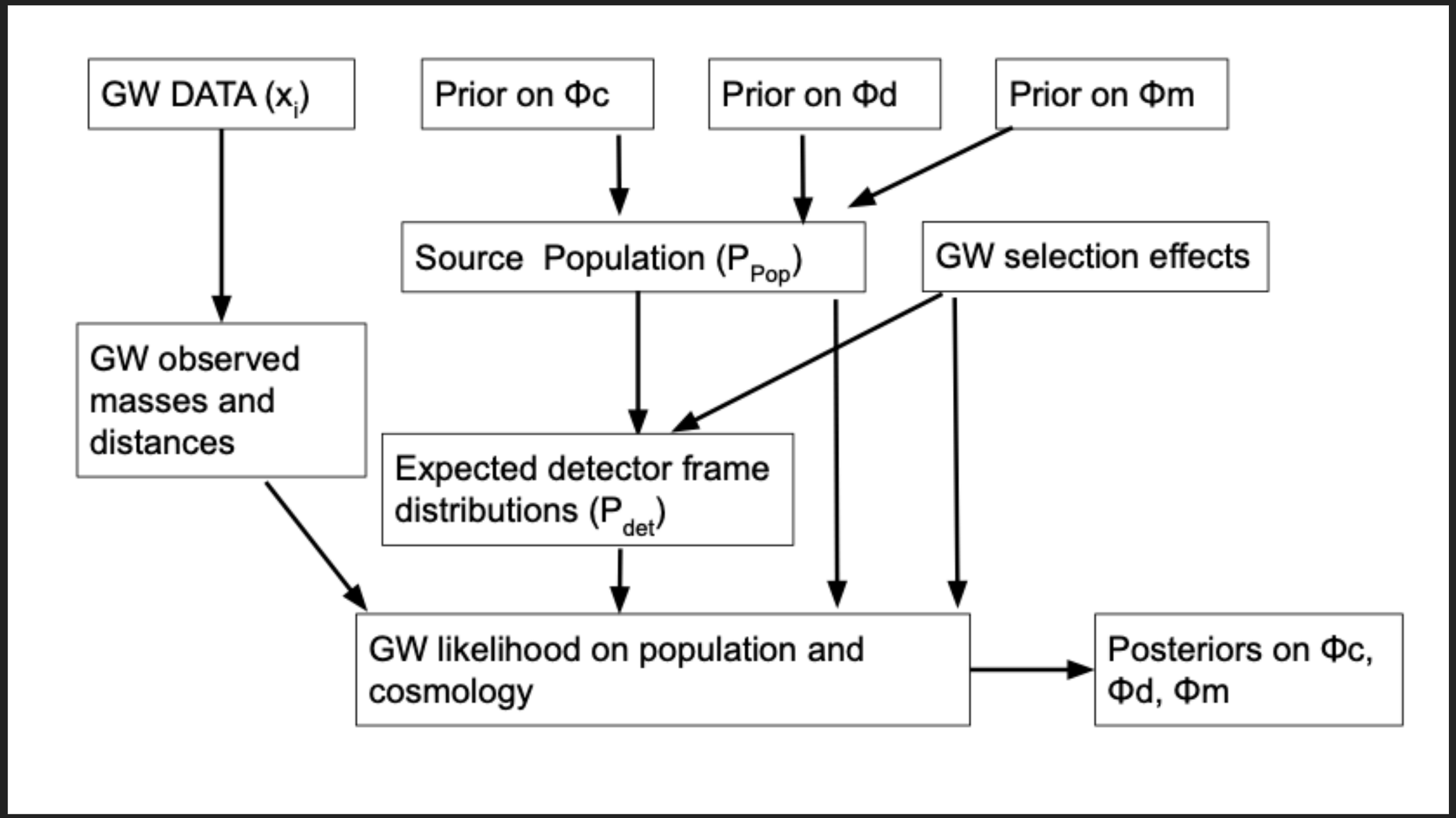
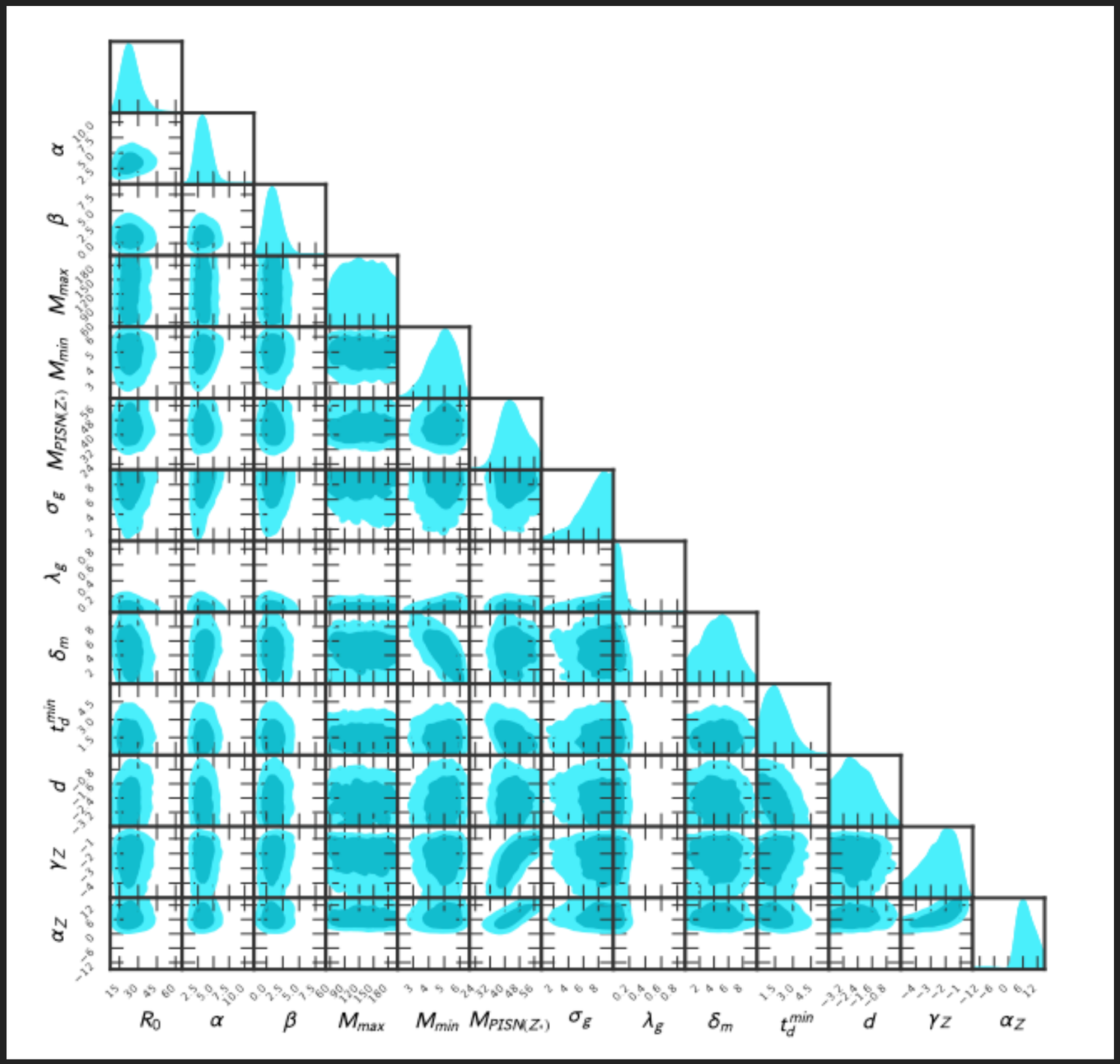
Mukherjee (2022)

FLOWCHART OF THE CODE

Karathanasis, Mukherjee, Mastrogiovanni (2023)



ESTIMATION OF BLACK HOLE POPULATION USING A PHYSICS DRIVEN MODEL

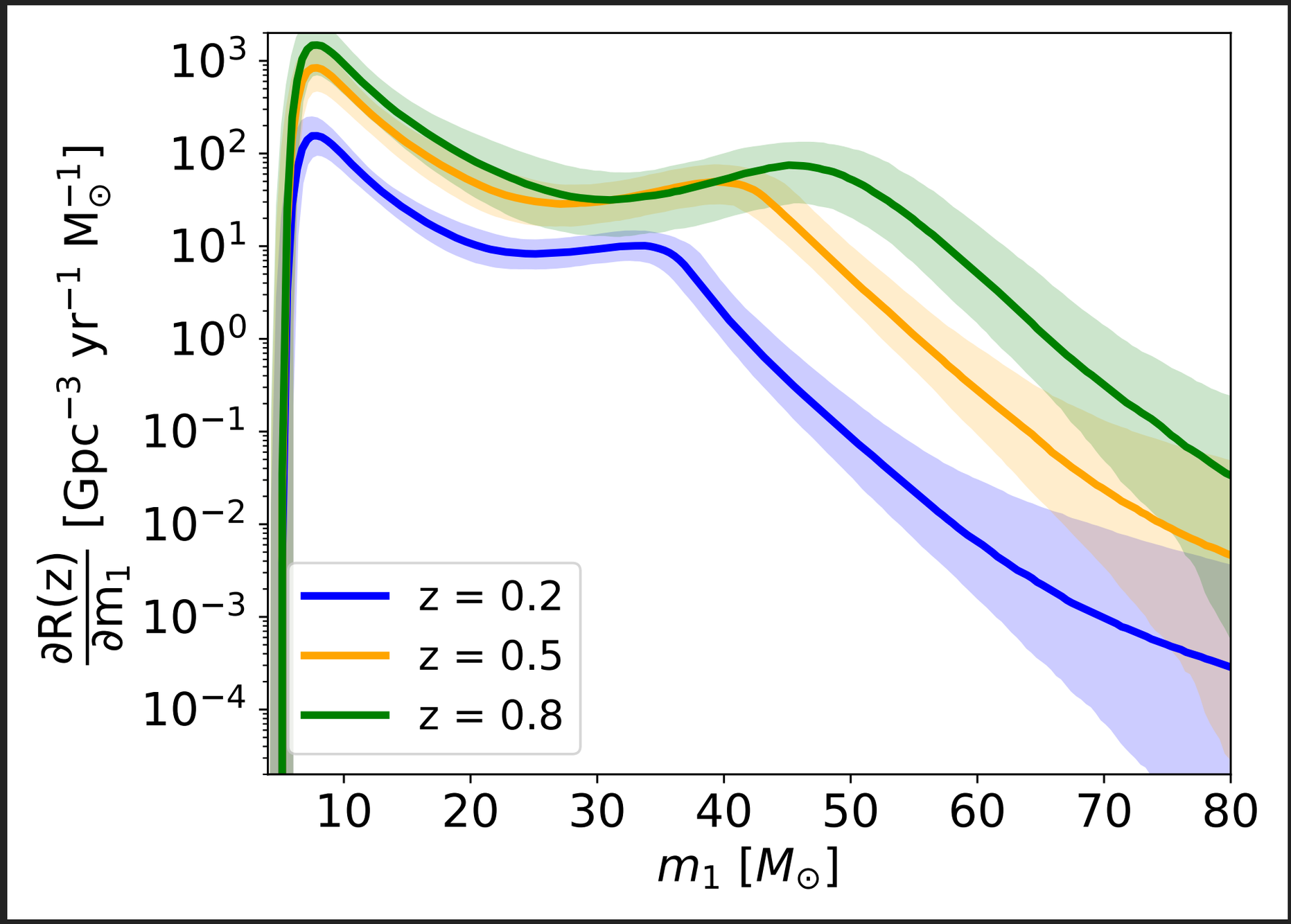


Karathanasis, Mukherjee, Mastrogiovanni (2023)

Suvodip Mukherjee, 2023

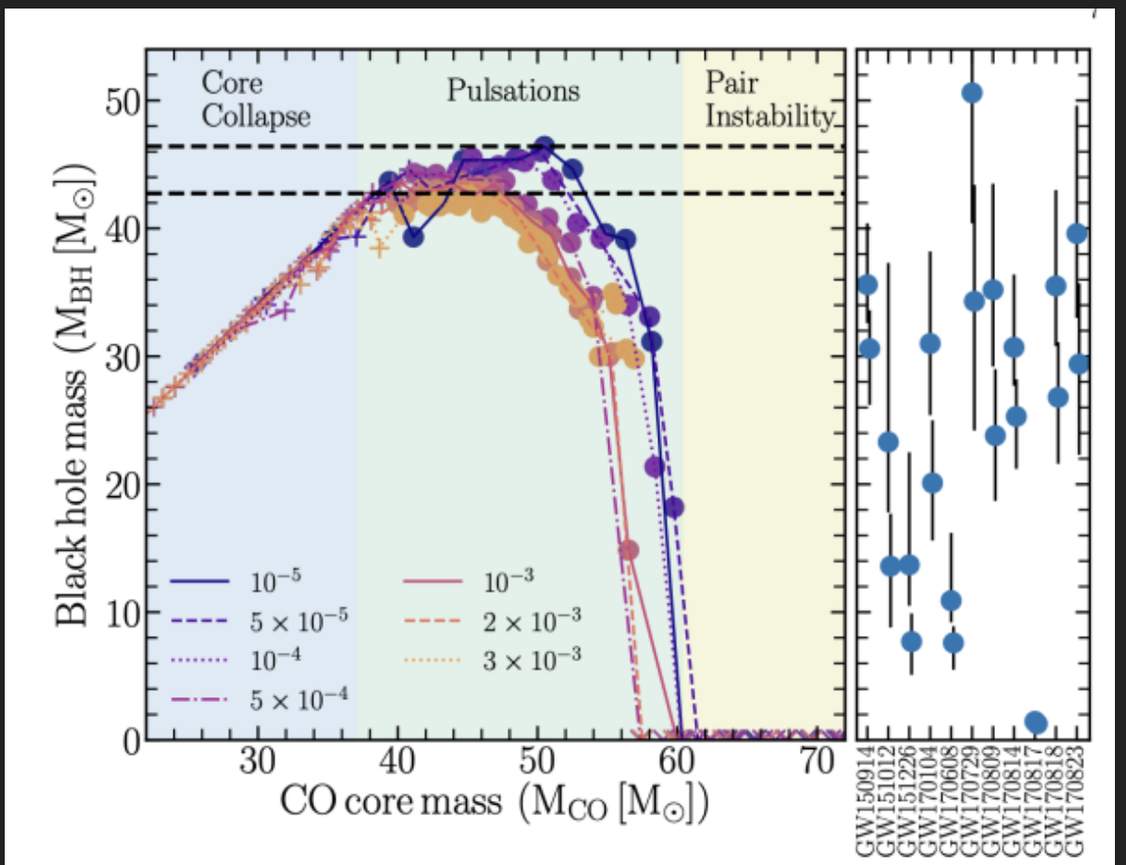
ESTIMATION OF REDSHIFT DEPENDENT MERGER RATE OF BBHS

Karathanasis, Mukherjee, Mastrogiovanni (2023)

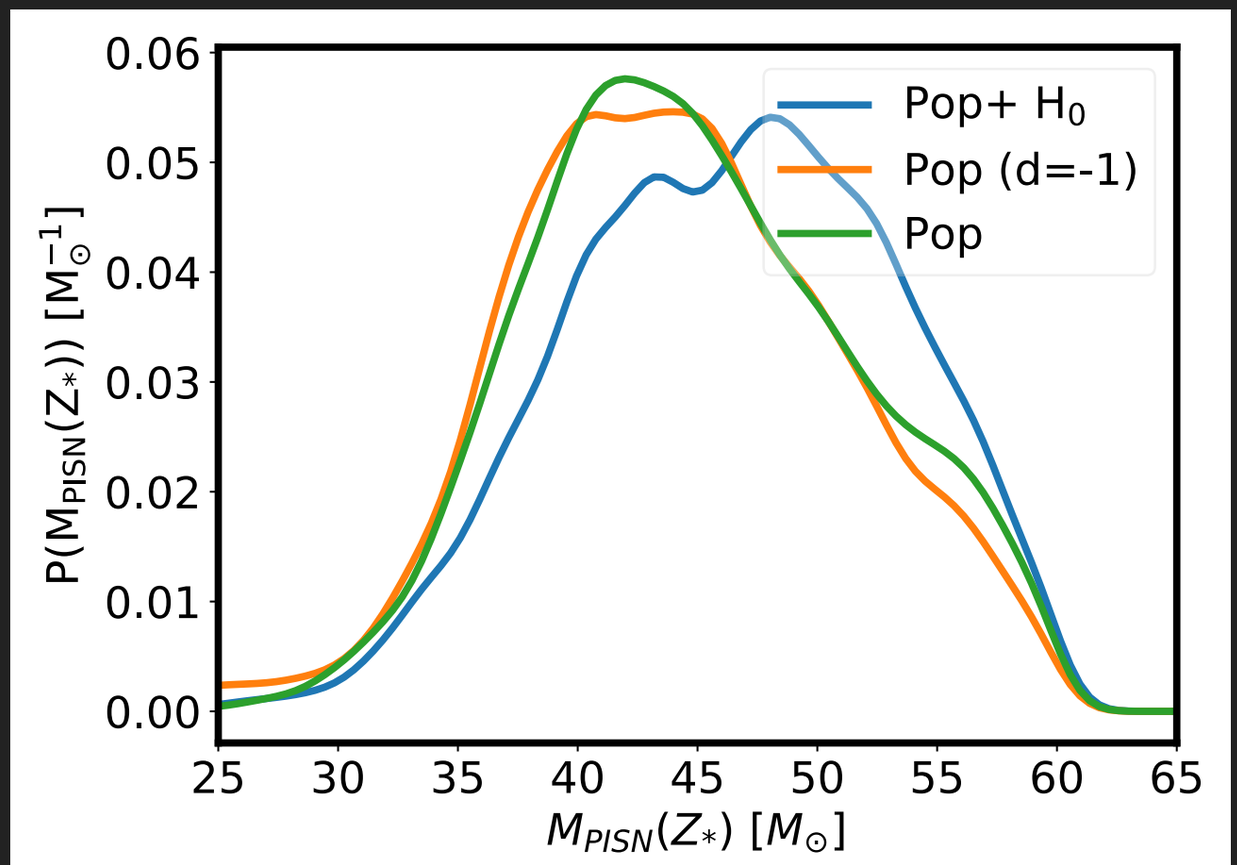


ESTIMATION OF PISN MASS SCALE

Farmer et al (2020)



Karathanasis, Mukherjee, Mastrogiovanni (2023)



GW ASTROCHEMISTRY CONNECTION

EMISSION LINES: A TRACER TO STELLAR METALLCITY

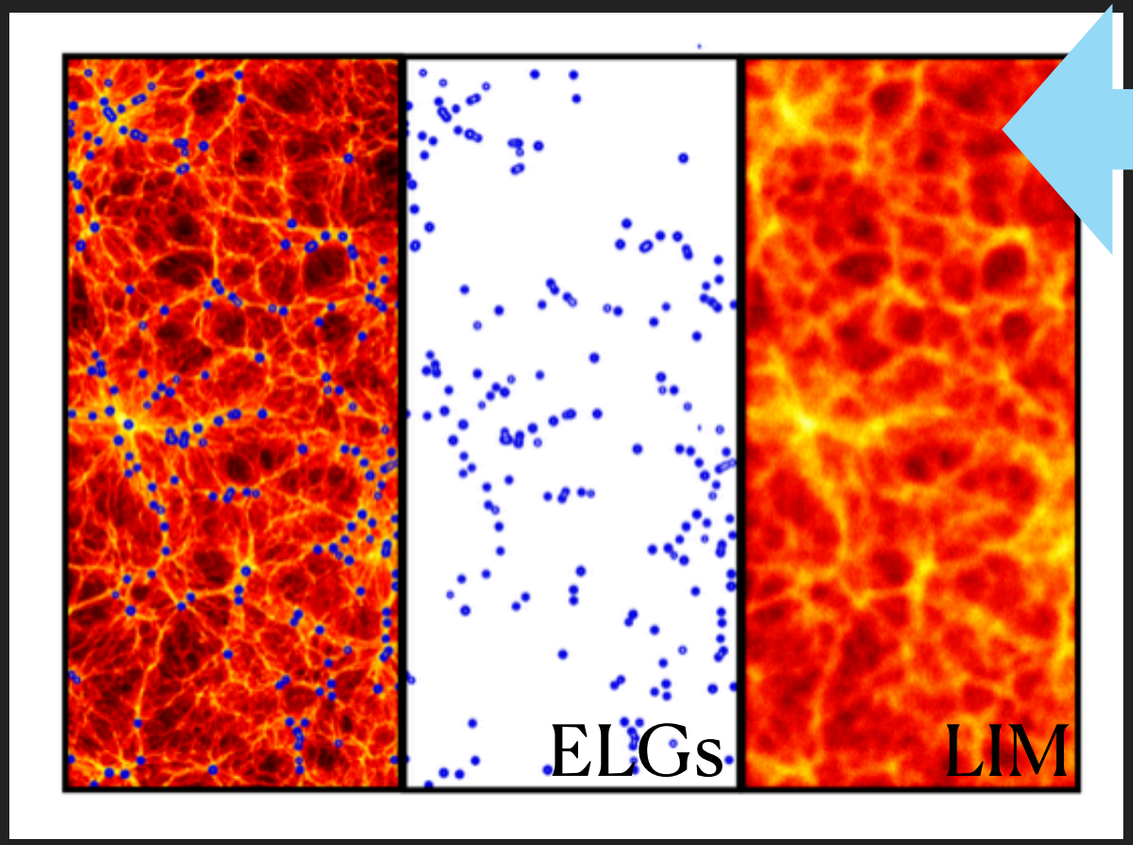
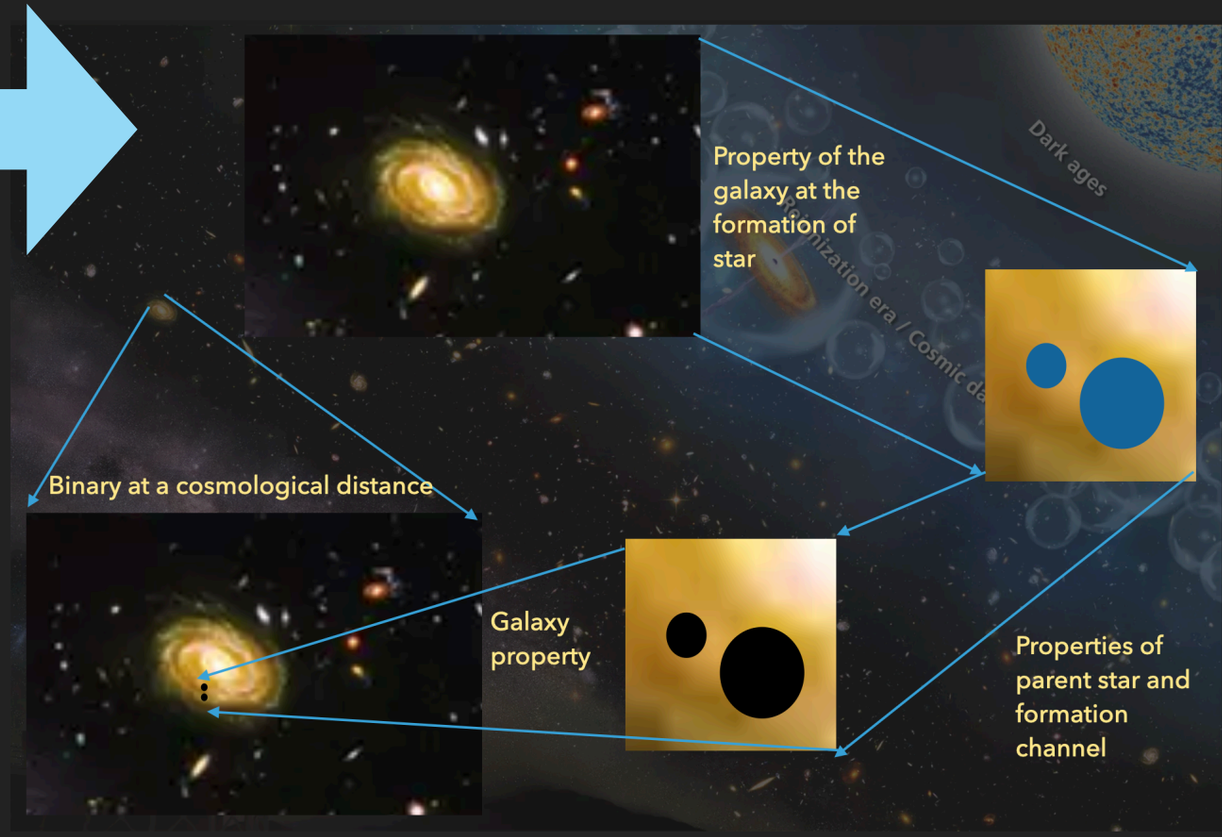


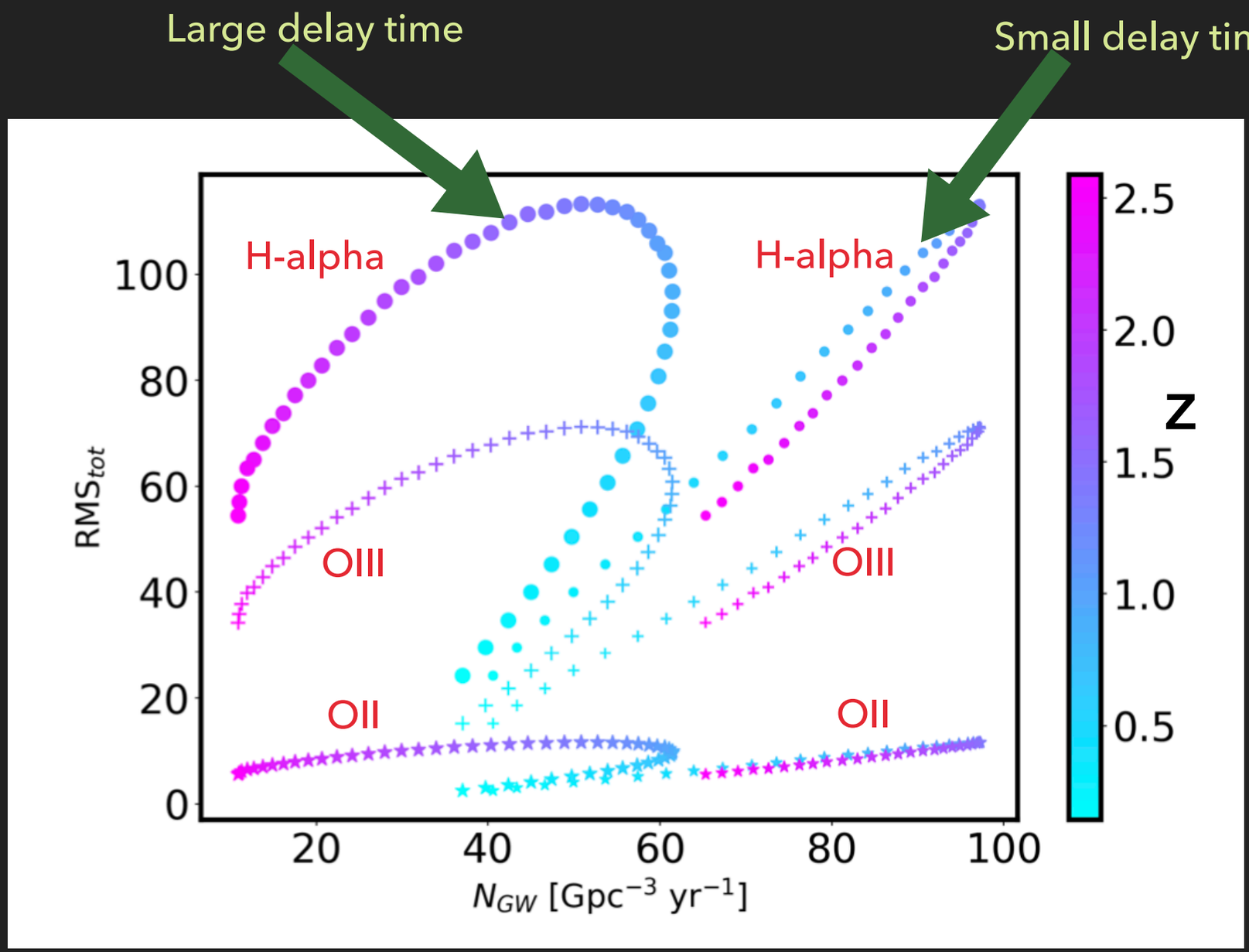
Image courtesy: Phil Korngut



SYNERGY BETWEEN GW AND INTENSITY MAPPING/EMISSION LINE GALAXIES

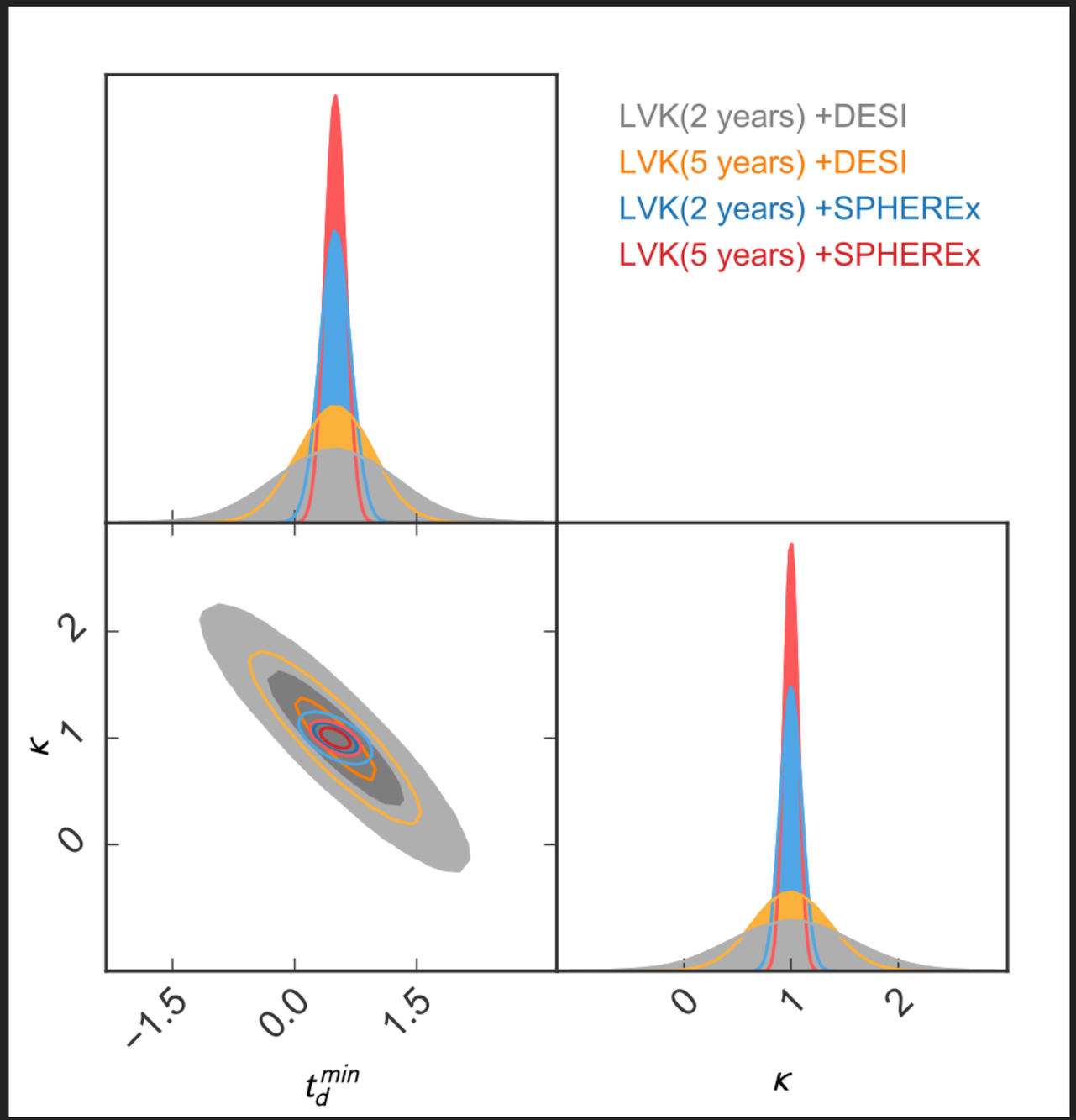
INEVITABLE CORRELATION BETWEEN EMISSION LINE GALAXIES OR LINE INTENSITY MAPPING WITH GW MERGER RATE

Mukherjee & Dizgah APJL (2022)



MEASURABILITY FROM LVK-SPHEREX AND LVK-DESI

Mukherjee & Dizgah APJL (2022)

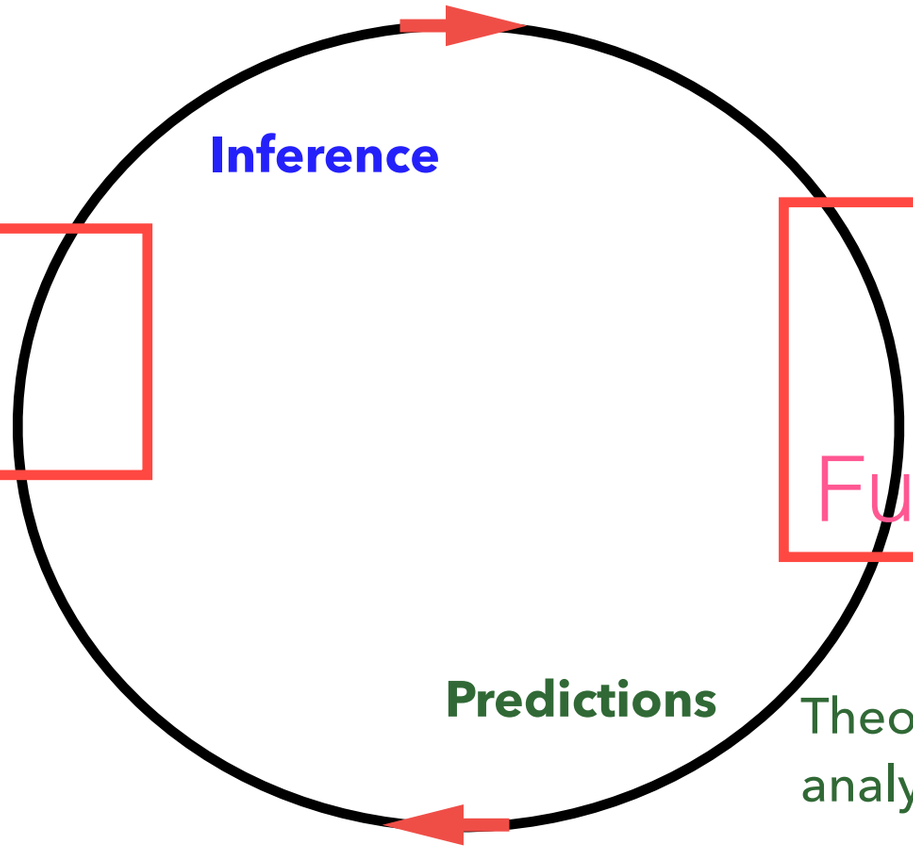


Suvodip Mukherjee, 2023

Data Driven Exploration using Gravitational Waves

Data analysis robust
statistical frameworks

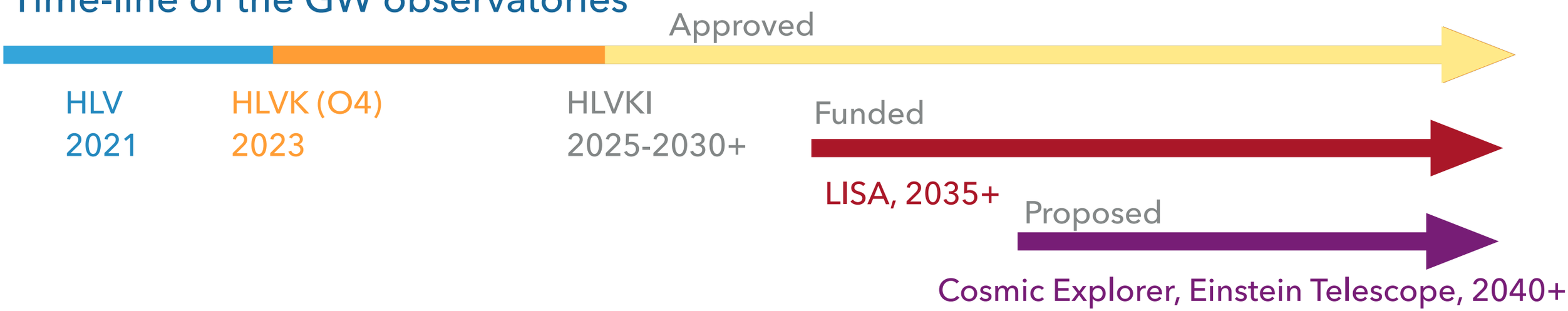
Multi-band
observations



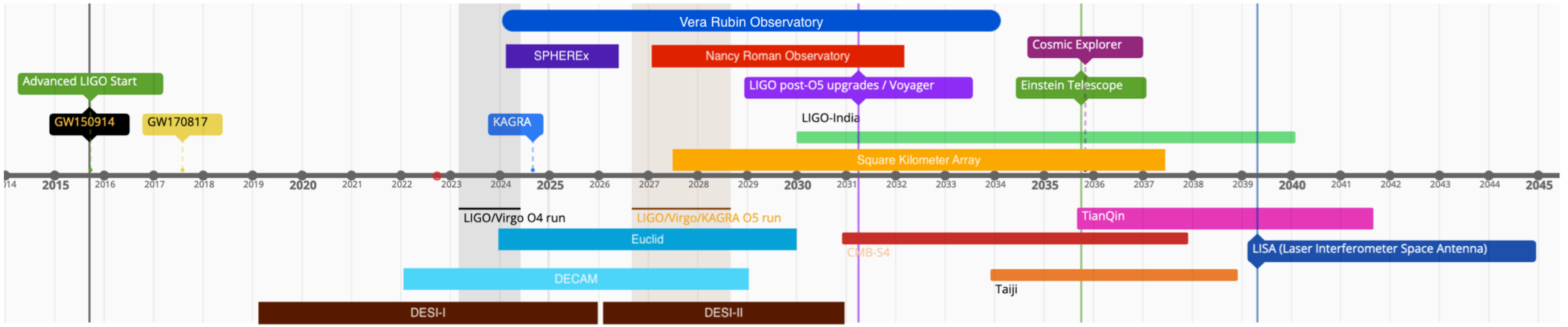
Astrophysics/
Cosmology/
Fundamental Physics

Theoretical modelling using
analytical/numerical techniques

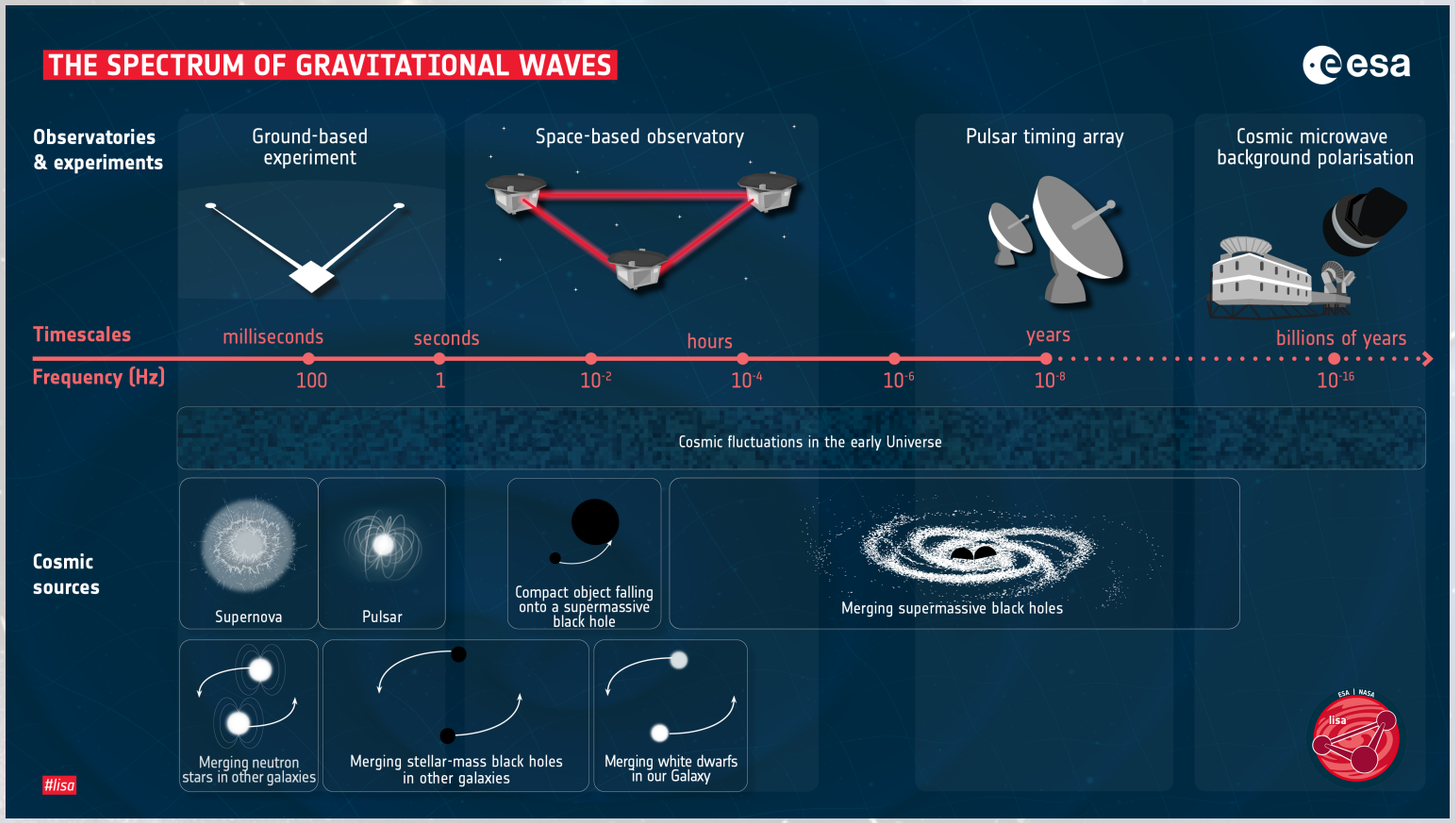
Time-line of the GW observatories



SYNERGY BETWEEN GW AND EM PROBES



DATA DRIVEN GW COSMOLOGY: A NEW FRONTIER



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- Mapping the expansion history using GWs can shed light on cosmic tension and beyond.
- GWTC-3 hints towards a redshift evolving mass distribution of Binary Black Holes.
- Synergy between ELGS and LIM with the GW observation can tell us about the delay time distribution and its dependence on the chemical composition of the Universe.

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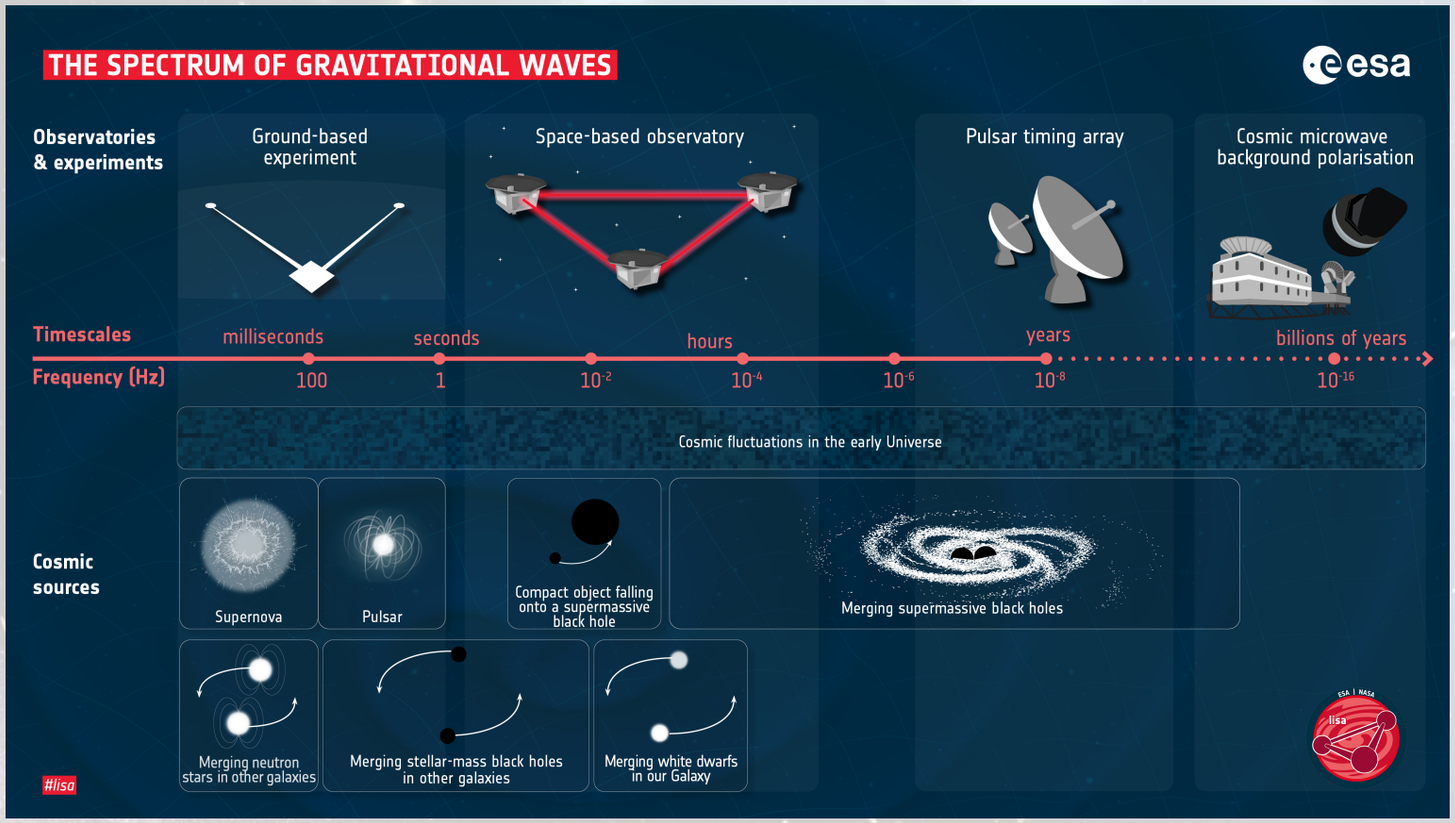

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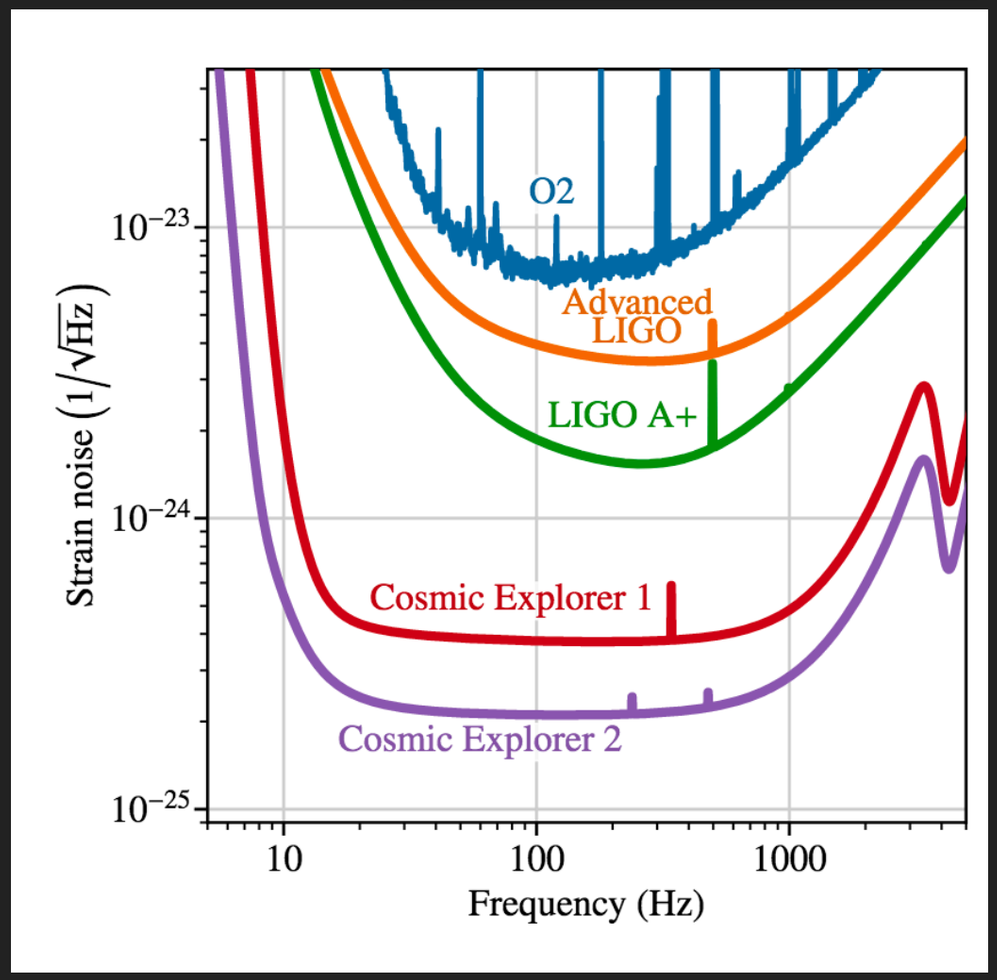
Thank you

EXTRA SLIDES

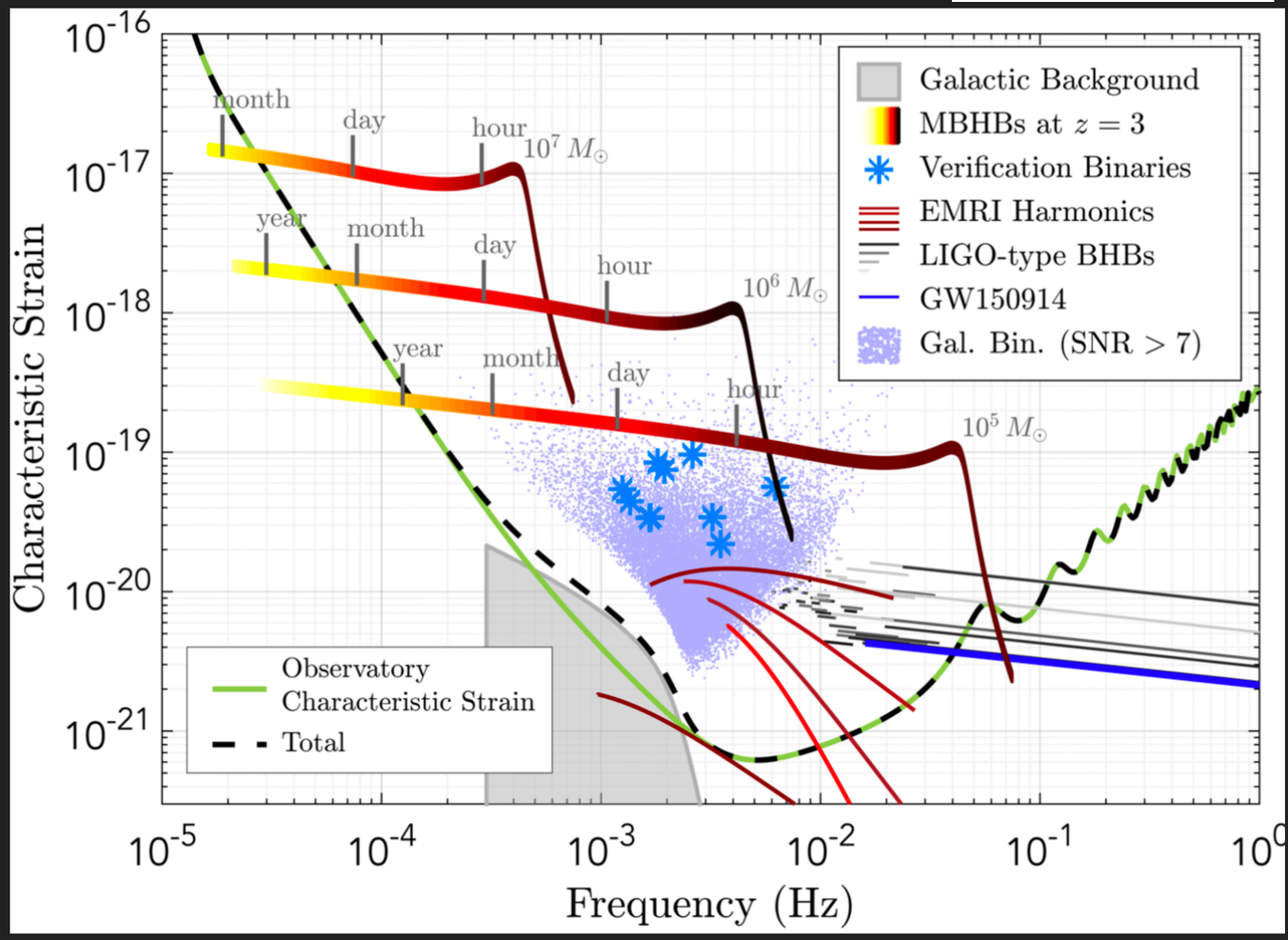
ONGOING/UPCOMING GW DETECTORS

Reitze et al. (2020) 1903.04615



Terrestrial GW detectors

LISA Science book



Space-based GW detector