GRAPPA

GRavitation AstroParticle Physics Amsterdam

UNIVERSITY OF AMSTERDAM

SUVODIP MUKHERJEE

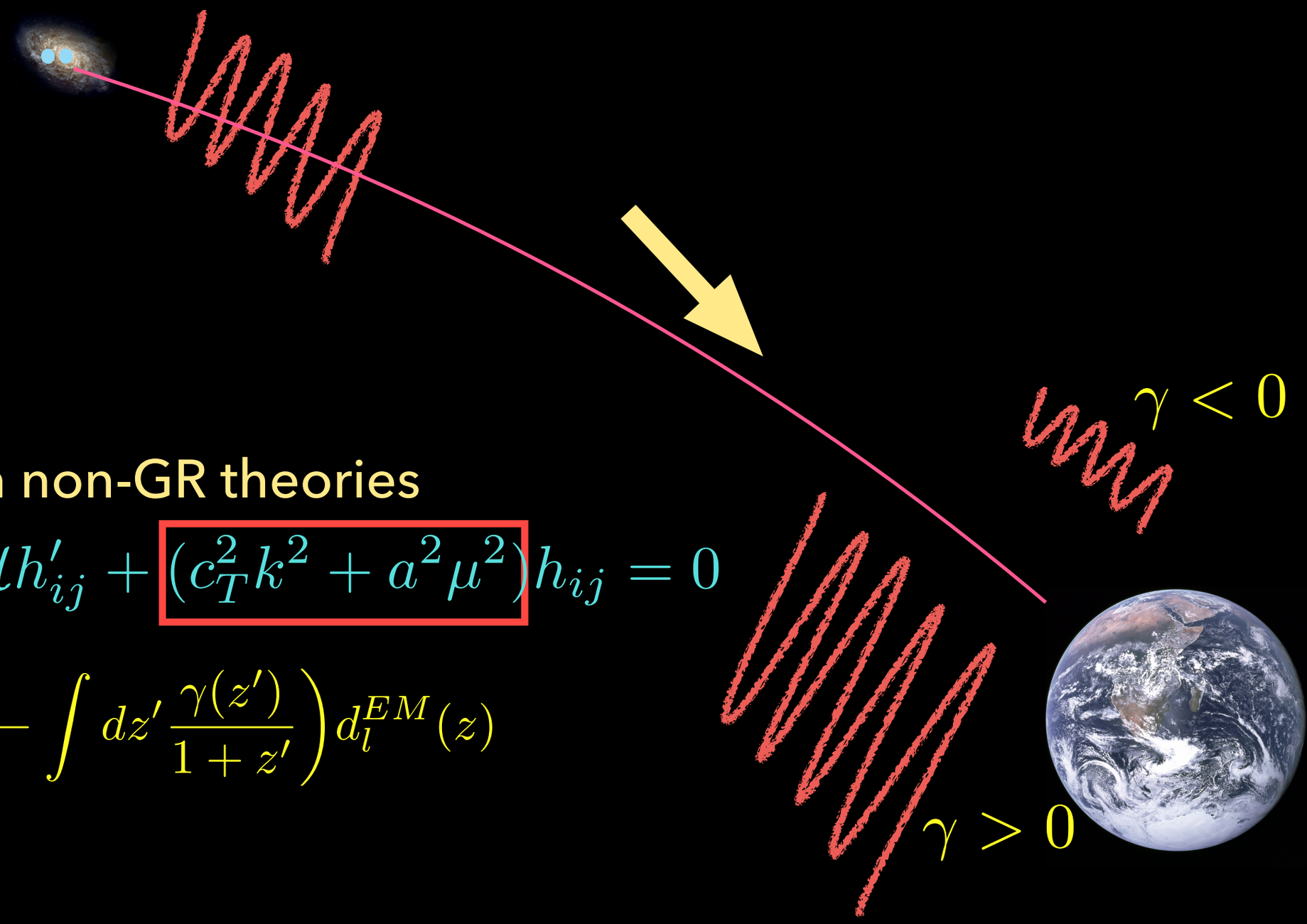
COSMOLOGY WITH DARK GRAVITATIONAL WAVE SOURCES

Image Credit: LIGO/ T, Pyle

Gravitational waves: a new messenger to explore the Universe, IHP, Paris

March 31st, 2021

GW PROPAGATION THROUGH SPACE-TIME IS A PROBE TO COSMIC EXPANSION HISTORY AND FUNDAMENTAL PHYSICS



GW propagation in non-GR theories

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

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

EM-GW PROBES TO MEASURE THE PROPAGATION OF GW

COSMOLOGY DEPENDENT

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

From GW data

Unknown

Unknown

For dark sirens: z is unknown

From sources with EM counterparts: we can only probe **low** redshift with LVK detector network

From sources without EM counterparts: we can probe **high** redshift with LVK detector network

GETTING AN INDEPENDENT MEASURE OF THE EM LUMINOSITY DISTANCE

Sound horizon at the drag epoch

Angular diameter distance

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

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

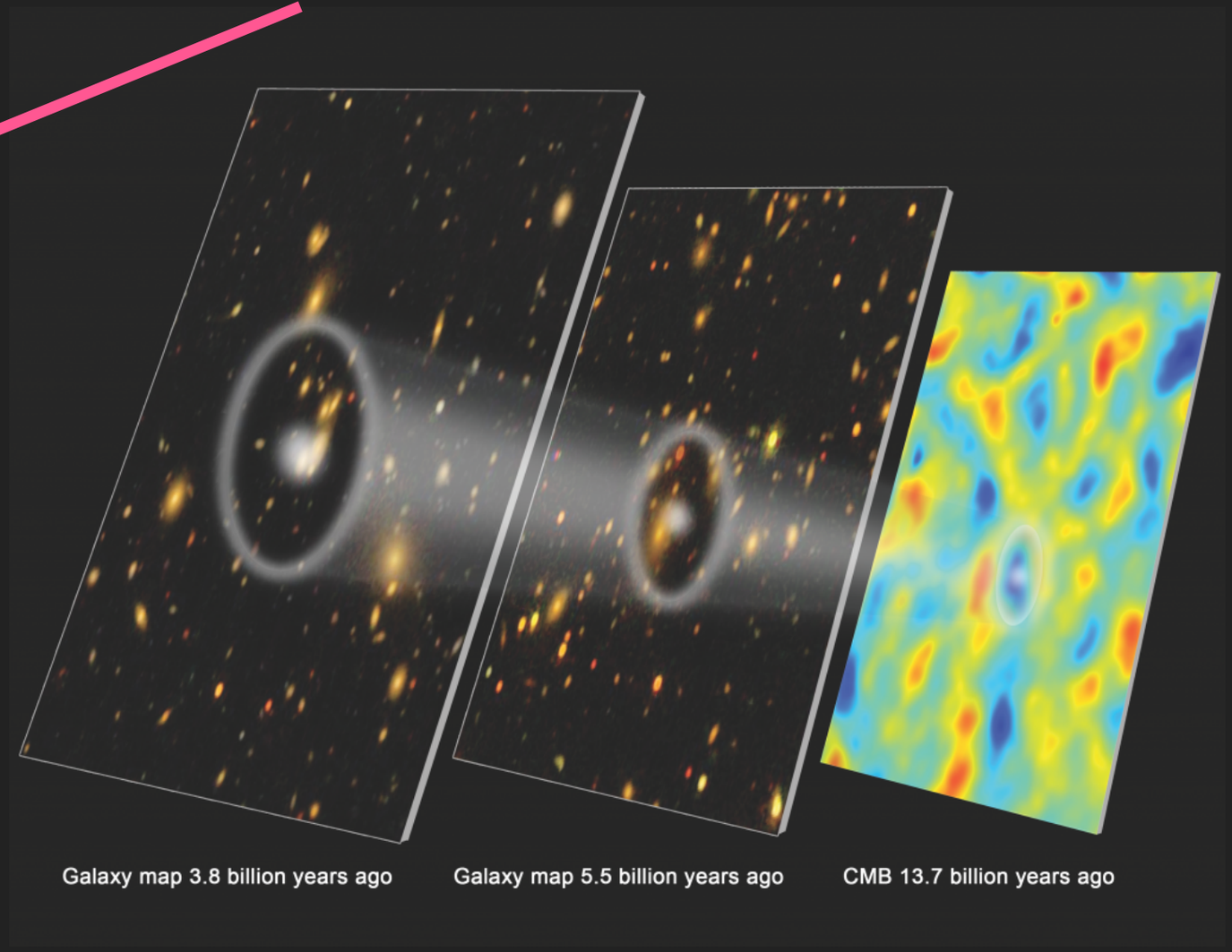


Image credit: ESA

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

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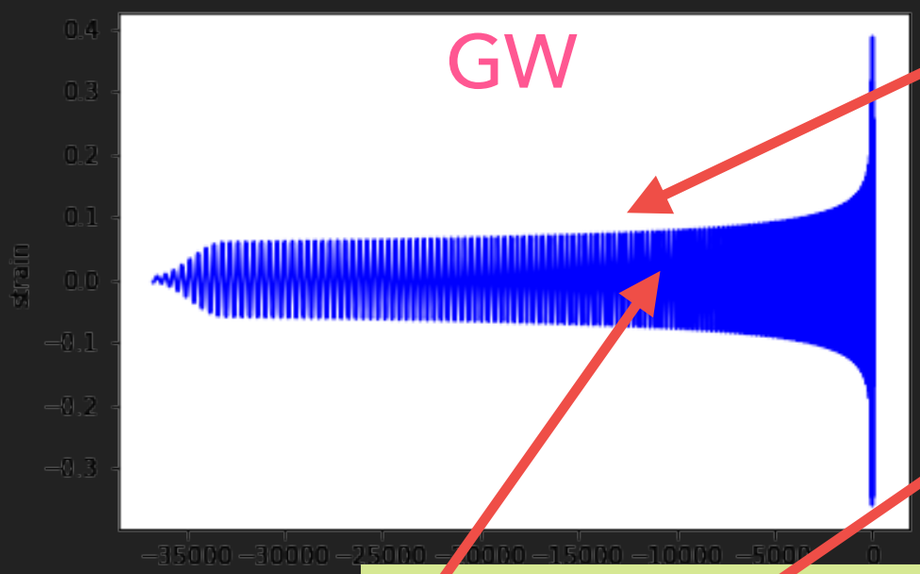
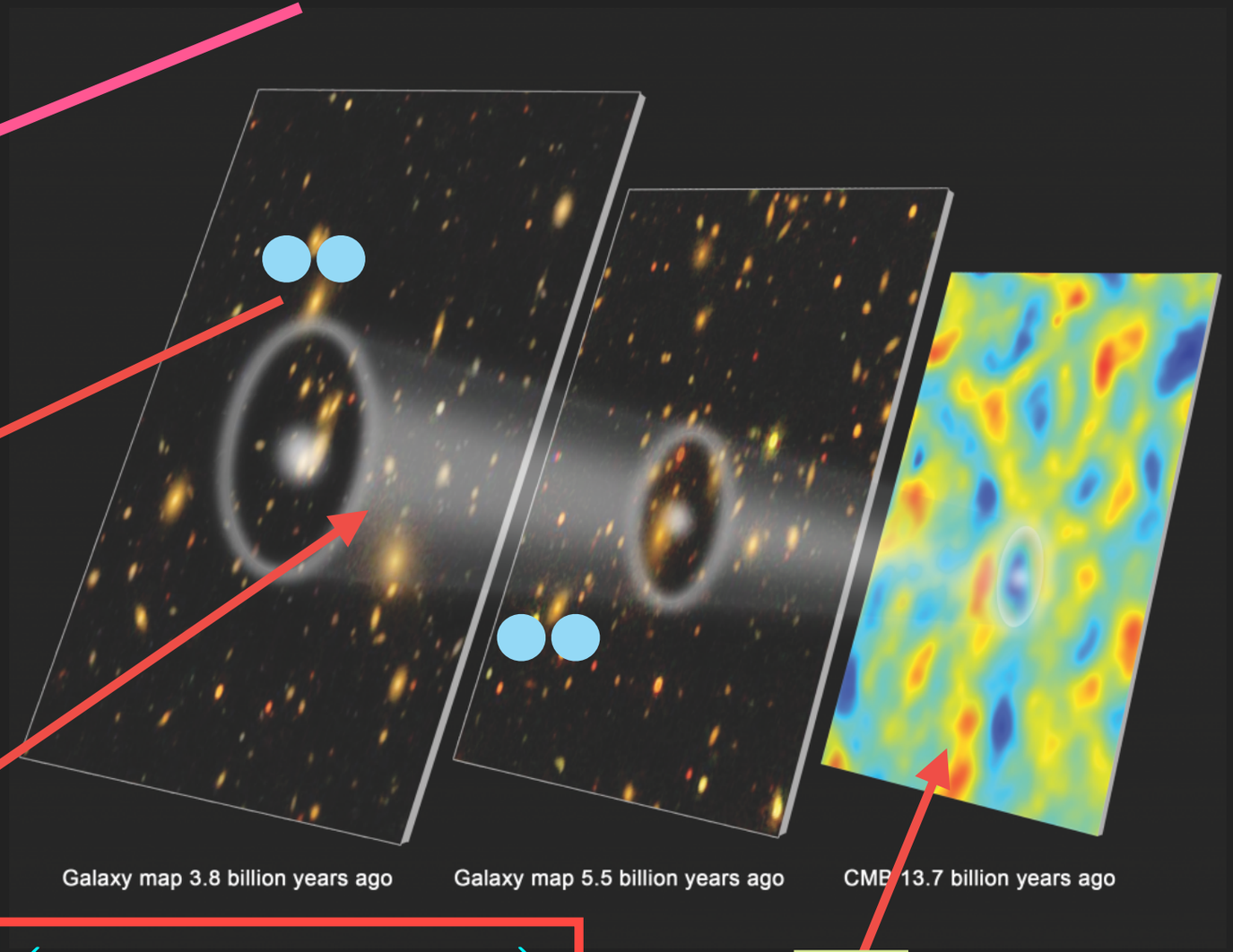




$$d_l^{GW}(z)\theta_{BAO}(z) = \left(\Xi_0 + \frac{1-\Xi_0}{(1+z)^n}\right)(1+z)r_s$$

HOW TO MEASURE THE REDSHIFT OF GW SOURCES

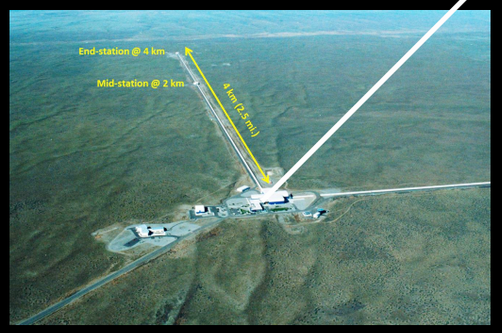
- *Only* GW signal cannot provide the redshift to the source in the absence of a known mass scale.
- Every GW sources will not have electromagnetic counterpart. So, redshift cannot be estimated independently.

48	Binary Black holes (< 1000 Msun)	Unlikely*
?	Black hole- Neutron stars	Likely
1	Binary Neutron stars	Likely
	Super Massive Binary Black holes	Likely

* Unless there are presence of baryons in the BBH surroundings

HOW BLACK HOLES ARE GOING TO BE DISTRIBUTED ?

Luminosity Distance



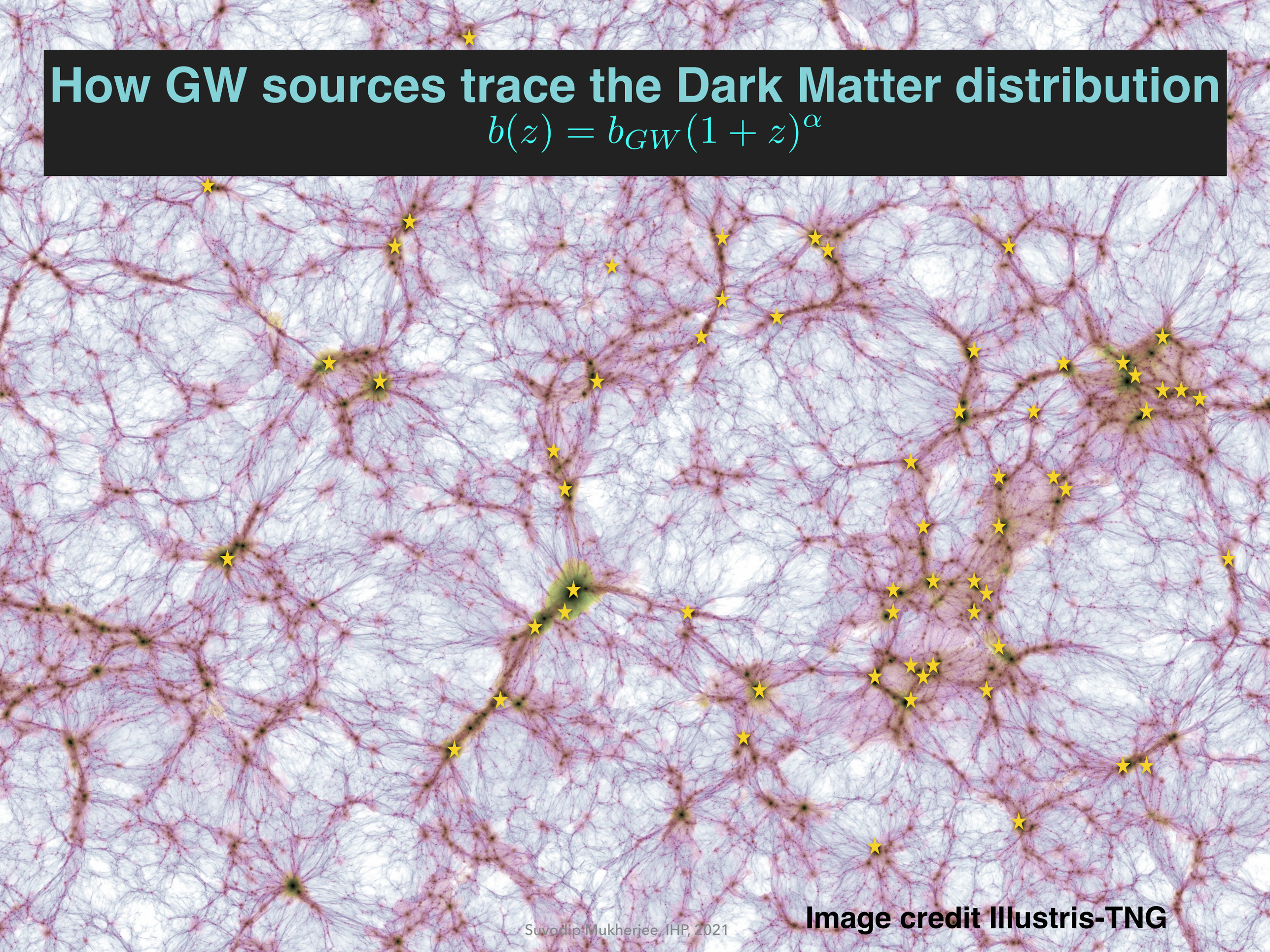
GW binaries (dark sirens)

Suvodip Mukherjee, IHP, 2021

Image credit Illustris-TNG

How GW sources trace the Dark Matter distribution

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



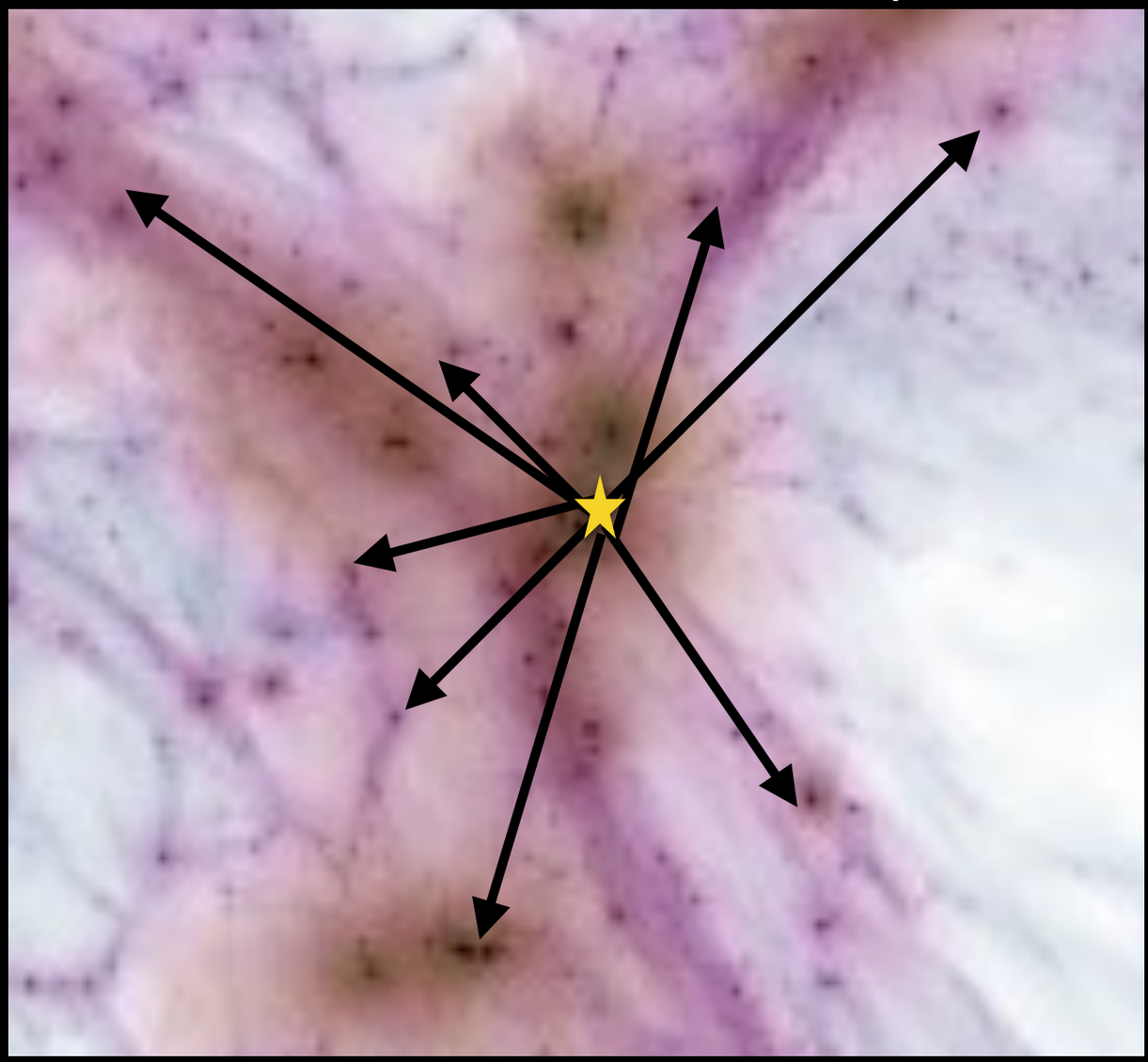
Suvodip Mukherjee, IHP, 2021

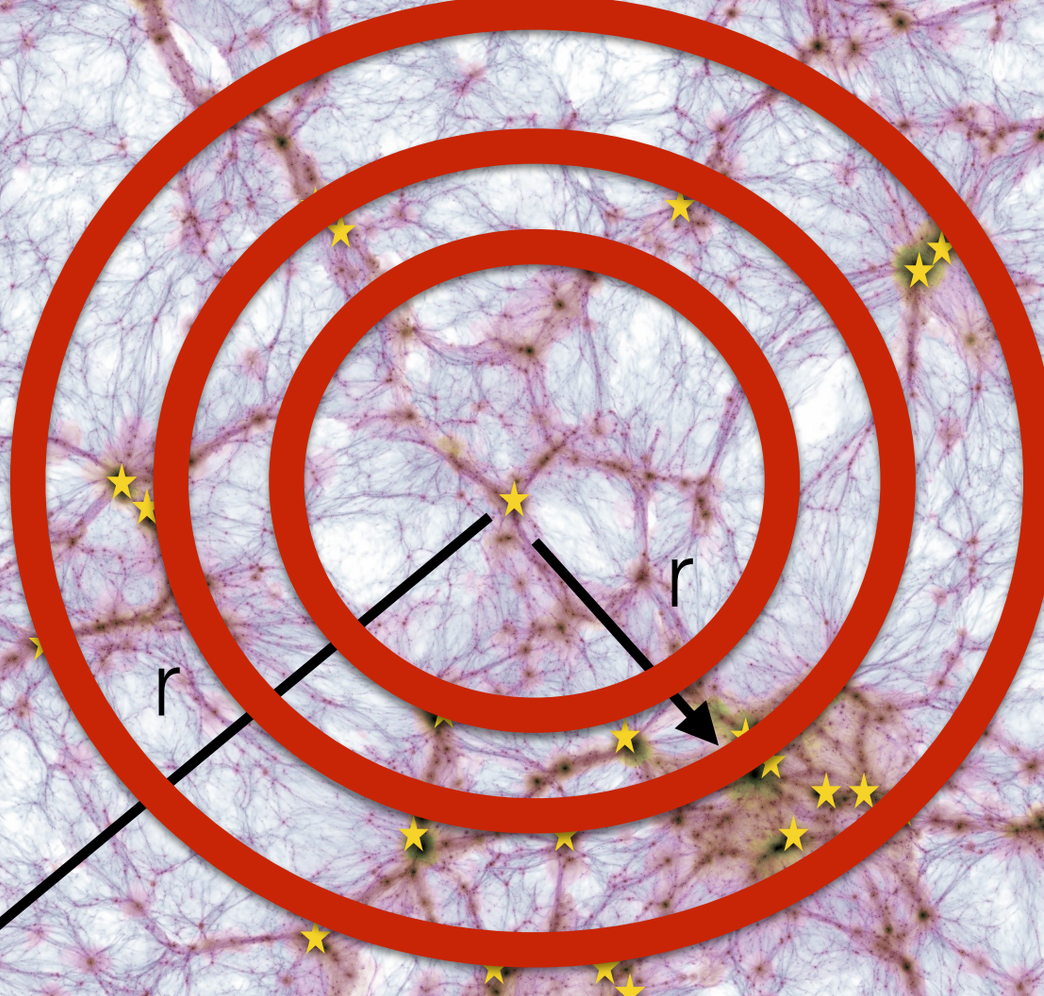
Image credit Illustris-TNG

Let us concentrate on a single dark siren

Three-dimensional spatial clustering with galaxies can be used to measure the redshift of the GW source

Mukherjee, Wandelt (2018)
Mukherjee, Wandelt, Silk (2020)
Mukherjee, Wandelt, Nissanke, Silvestri (2021)





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

CROSS-CORRELATION OF GW SOURCES WITH GALAXIES

Mukherjee et al. (2007.02943)

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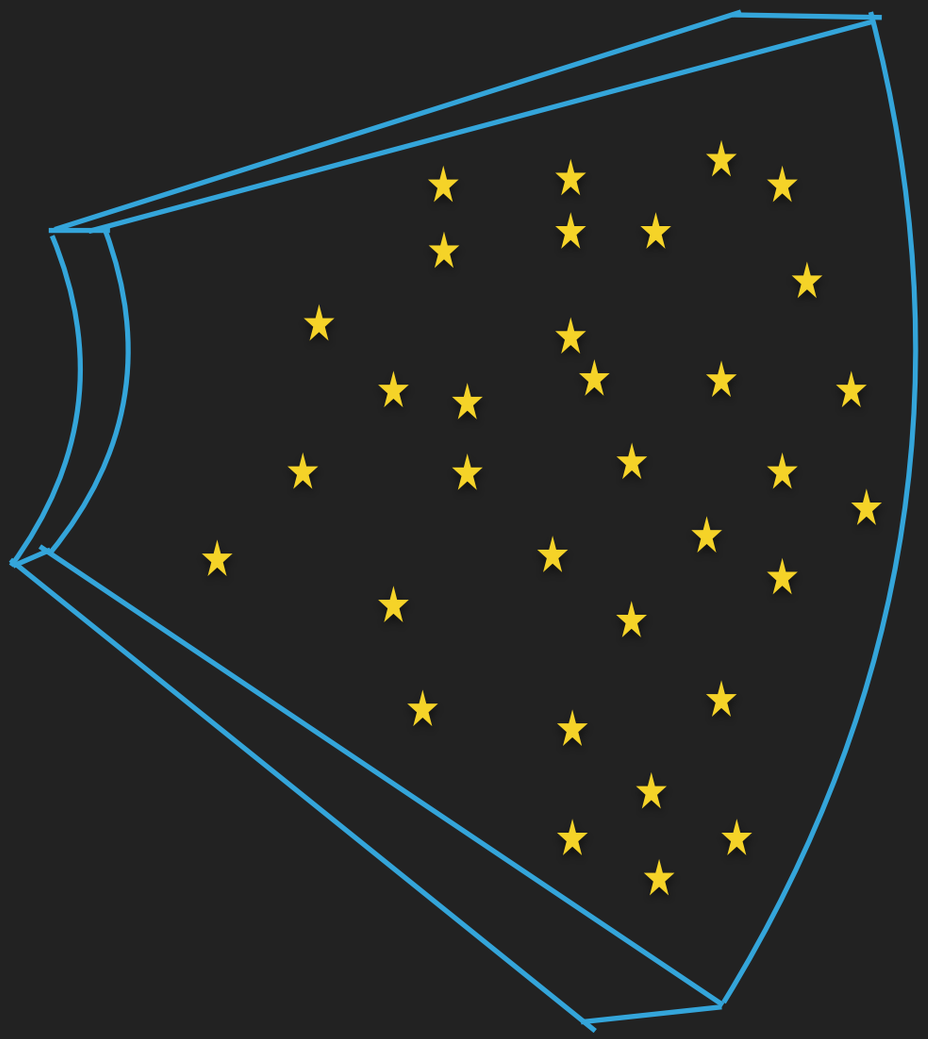

Dark sirens observed in luminosity distance space

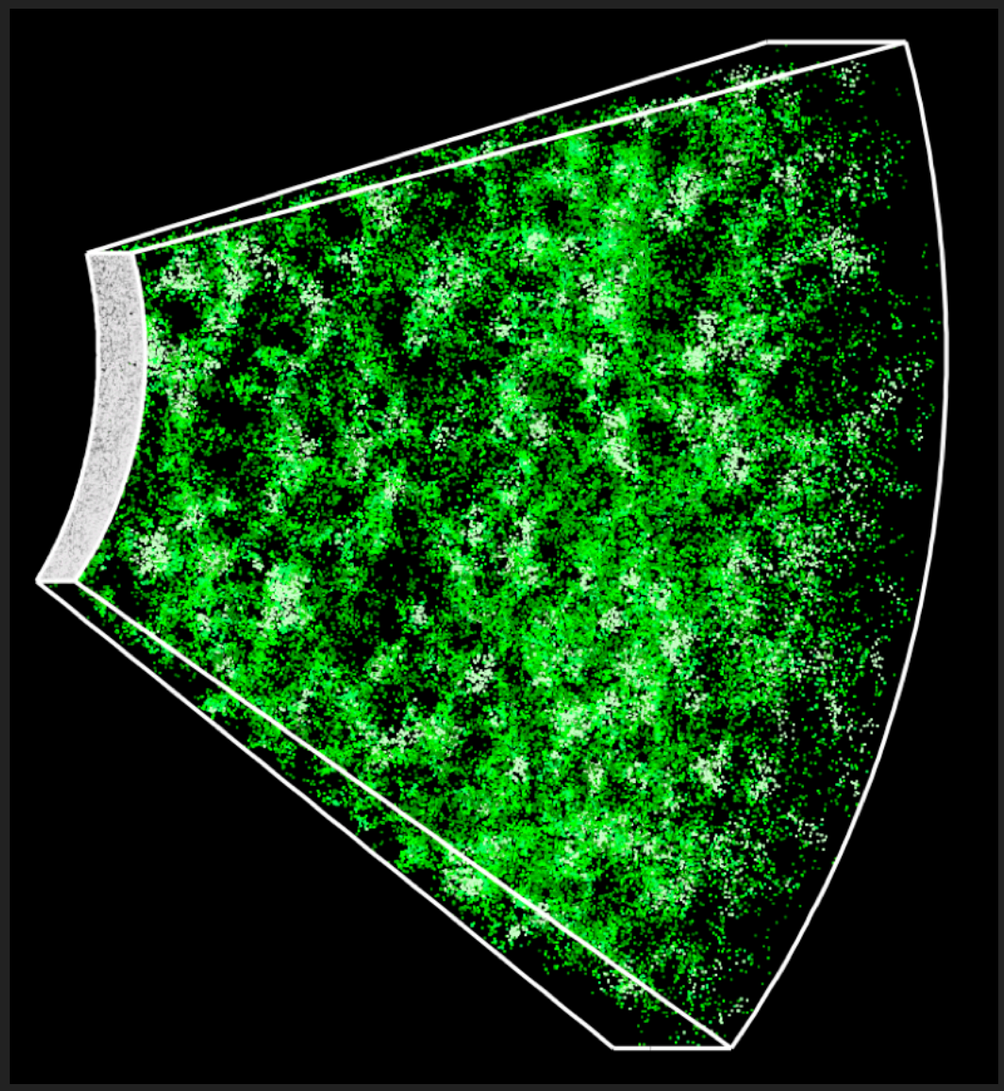

Image credit: Jeremy Tinker and the SDSS-III collaboration

Galaxy samples observed in redshift space

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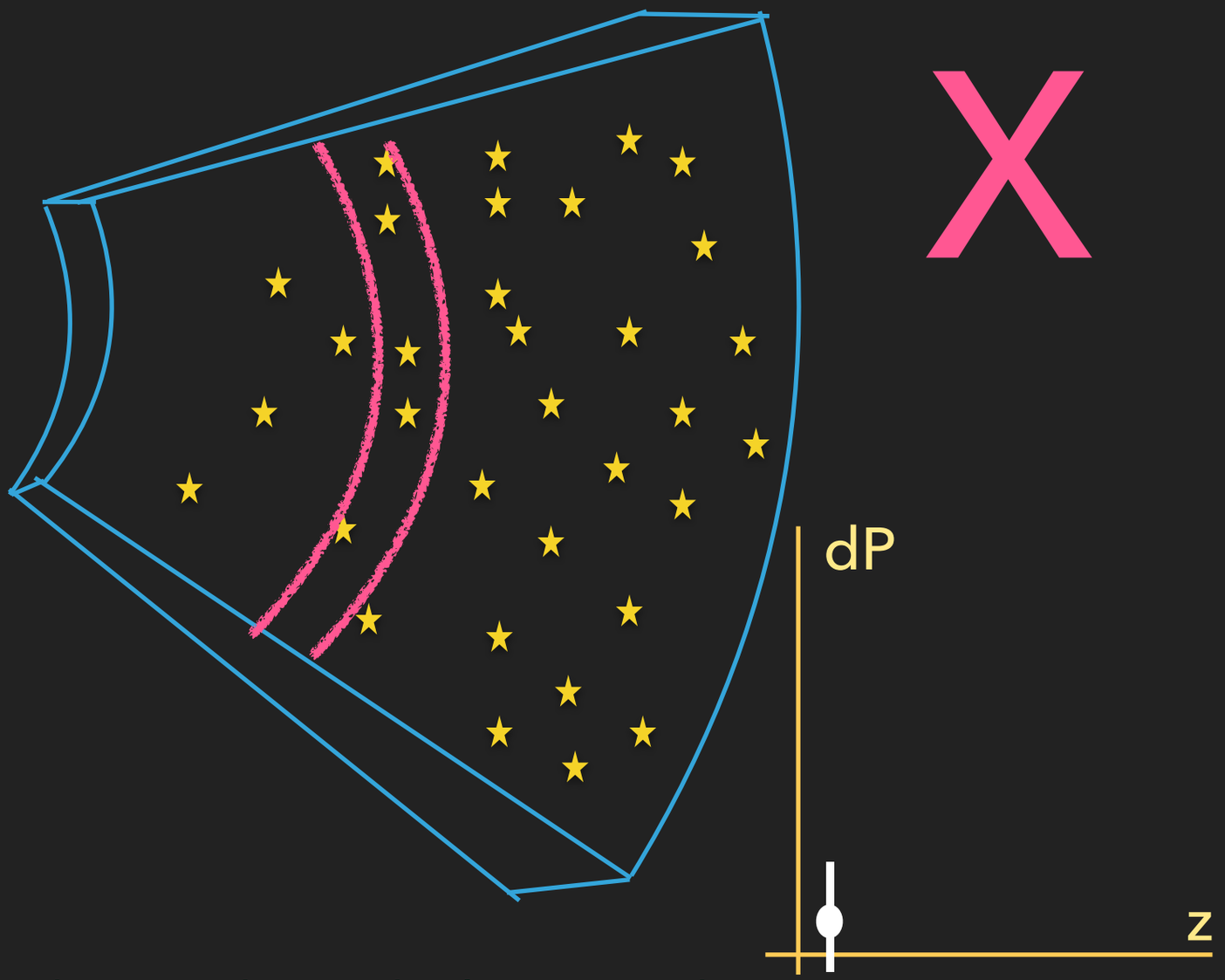

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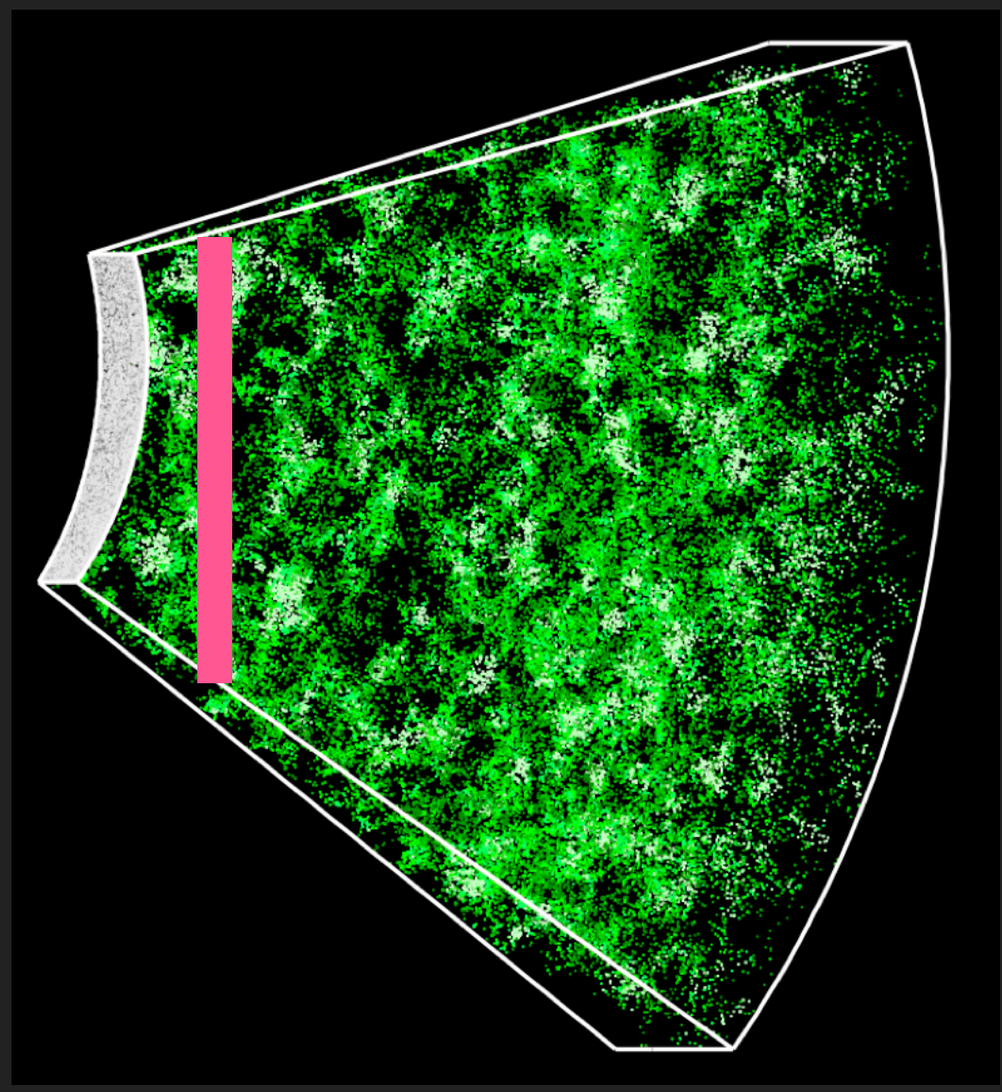

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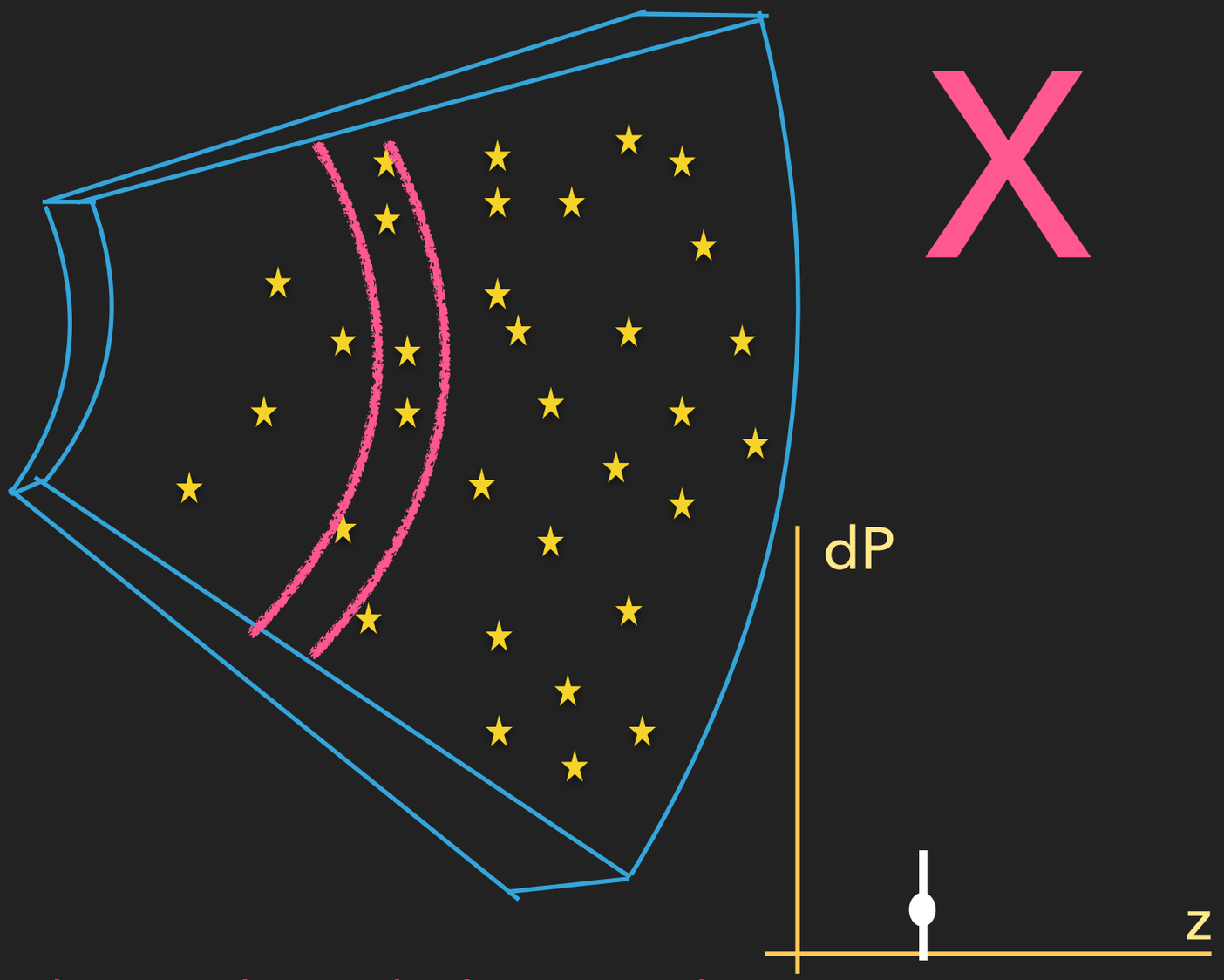

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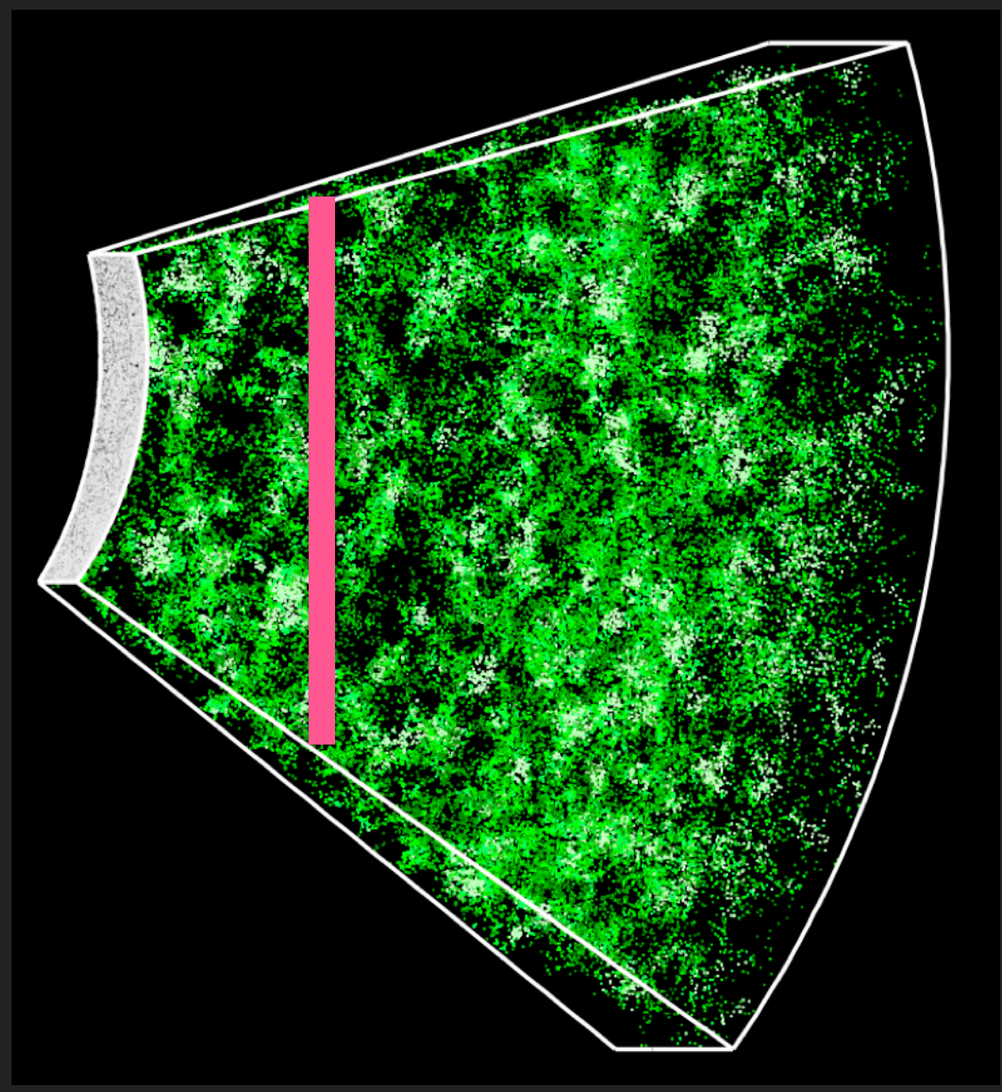

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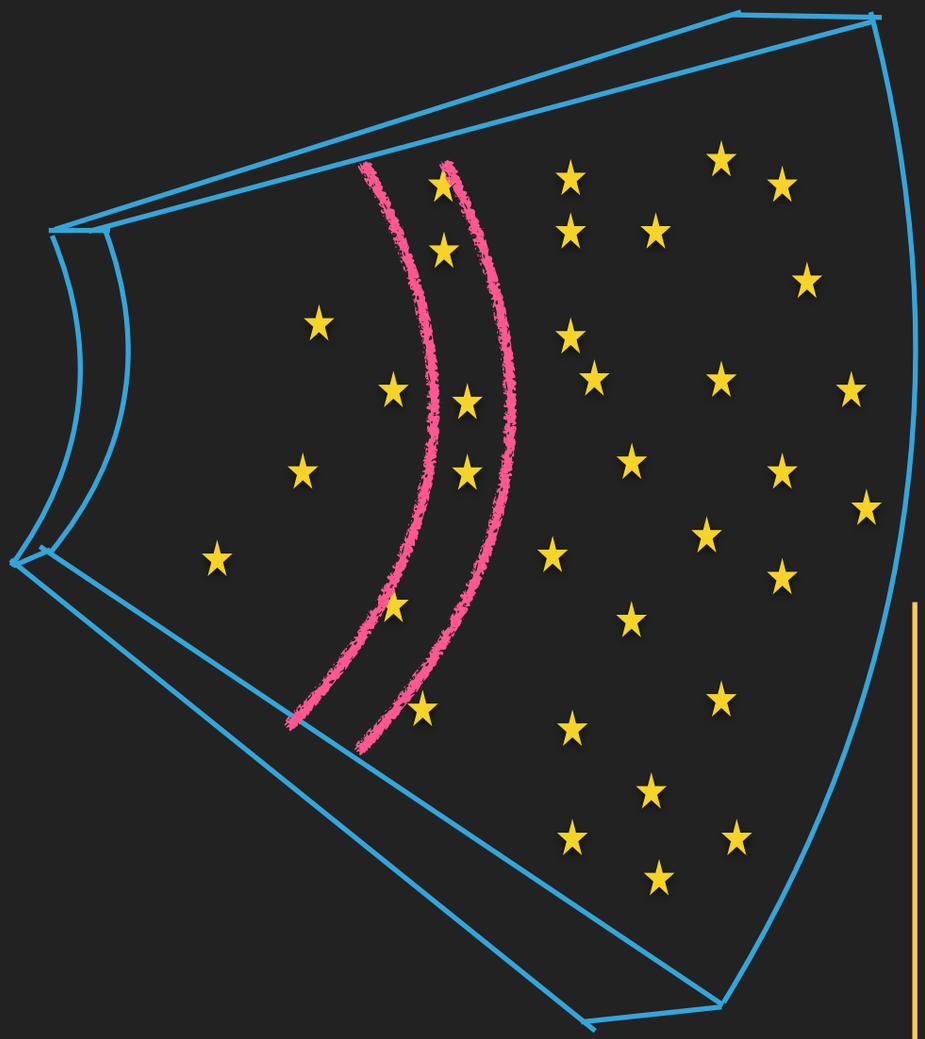
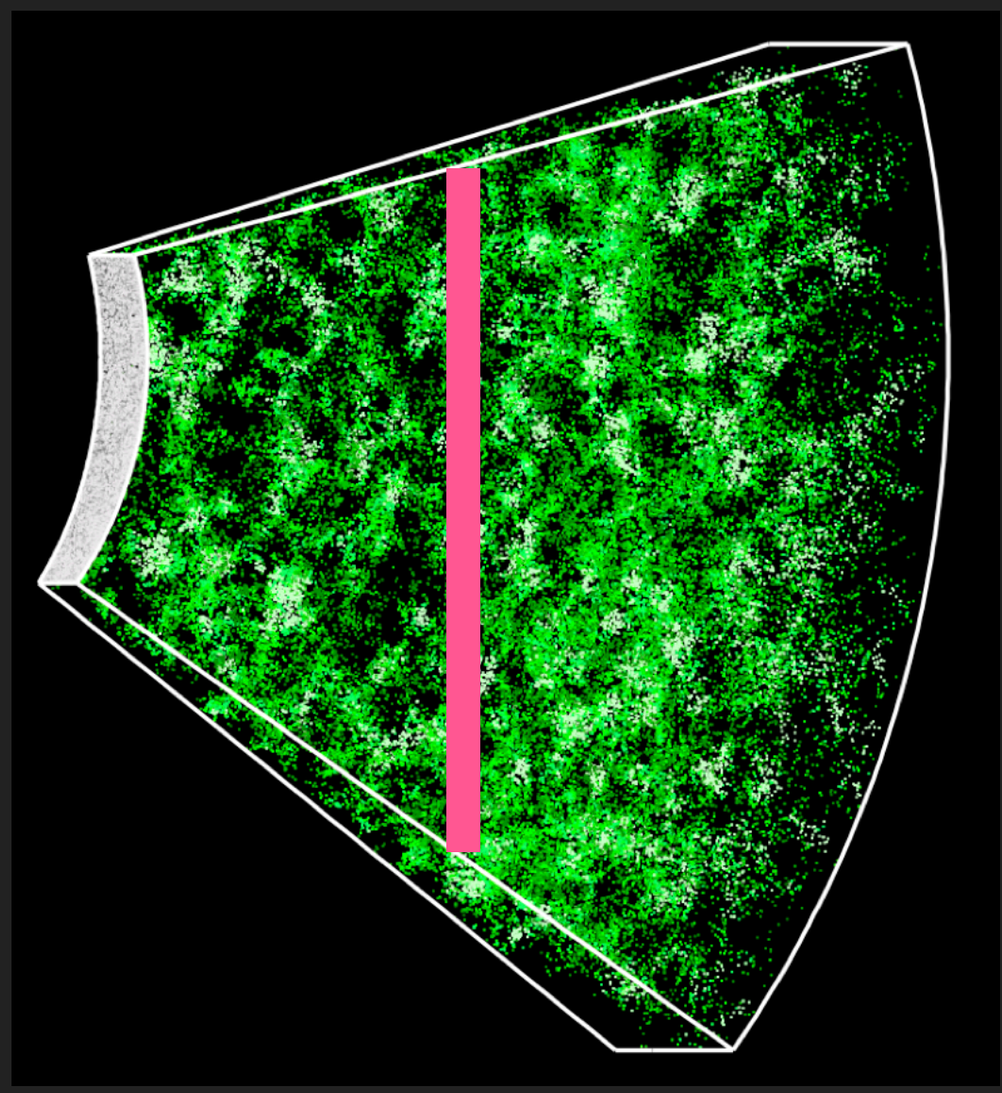


X

Dark sirens observed in luminosity distance space



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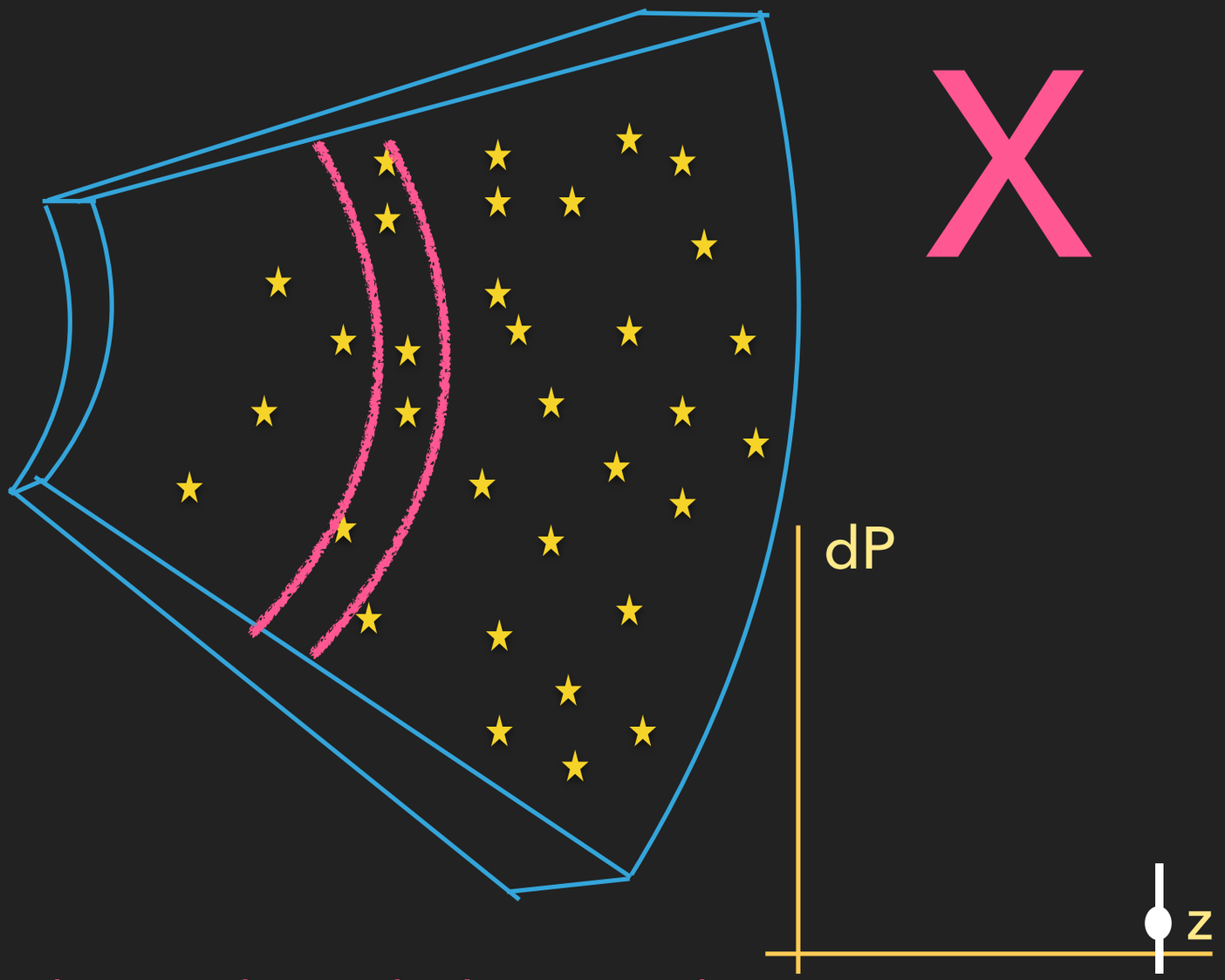

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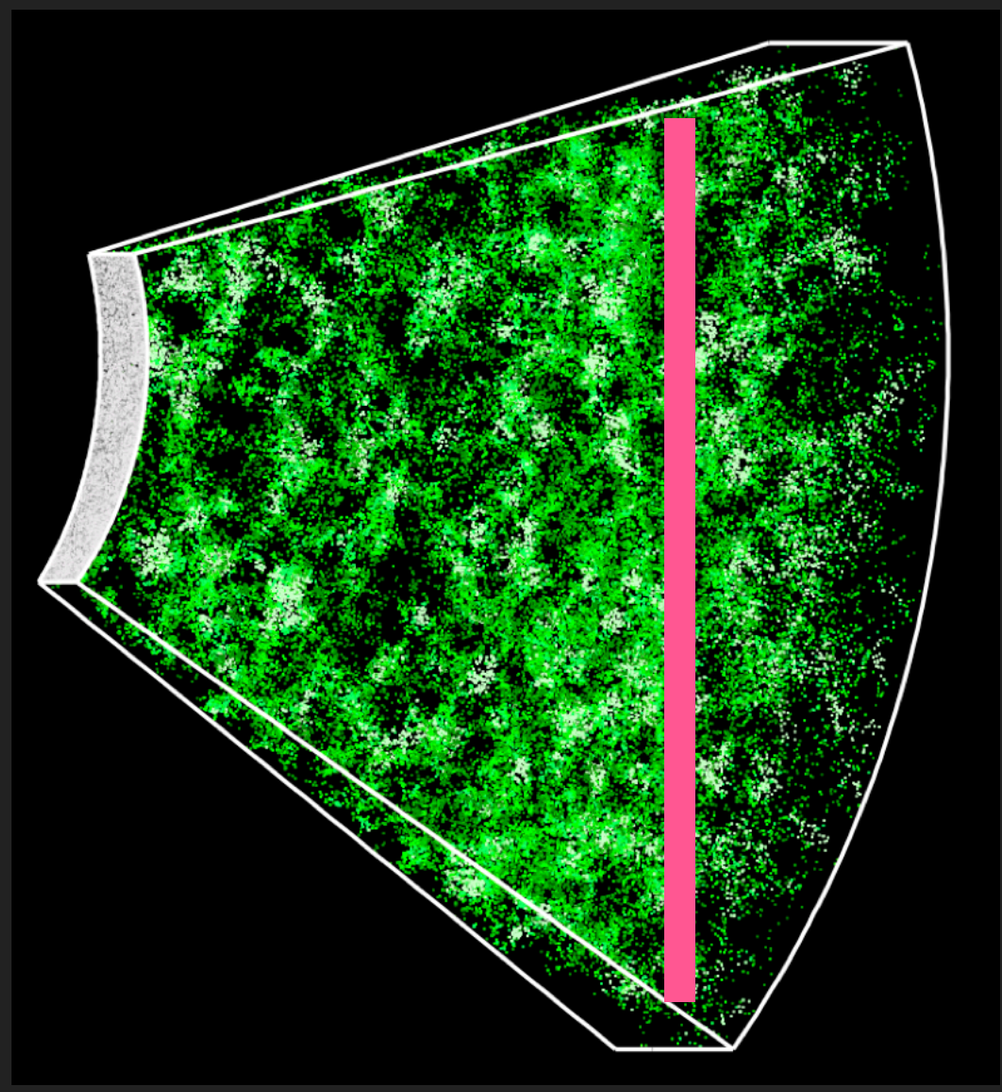

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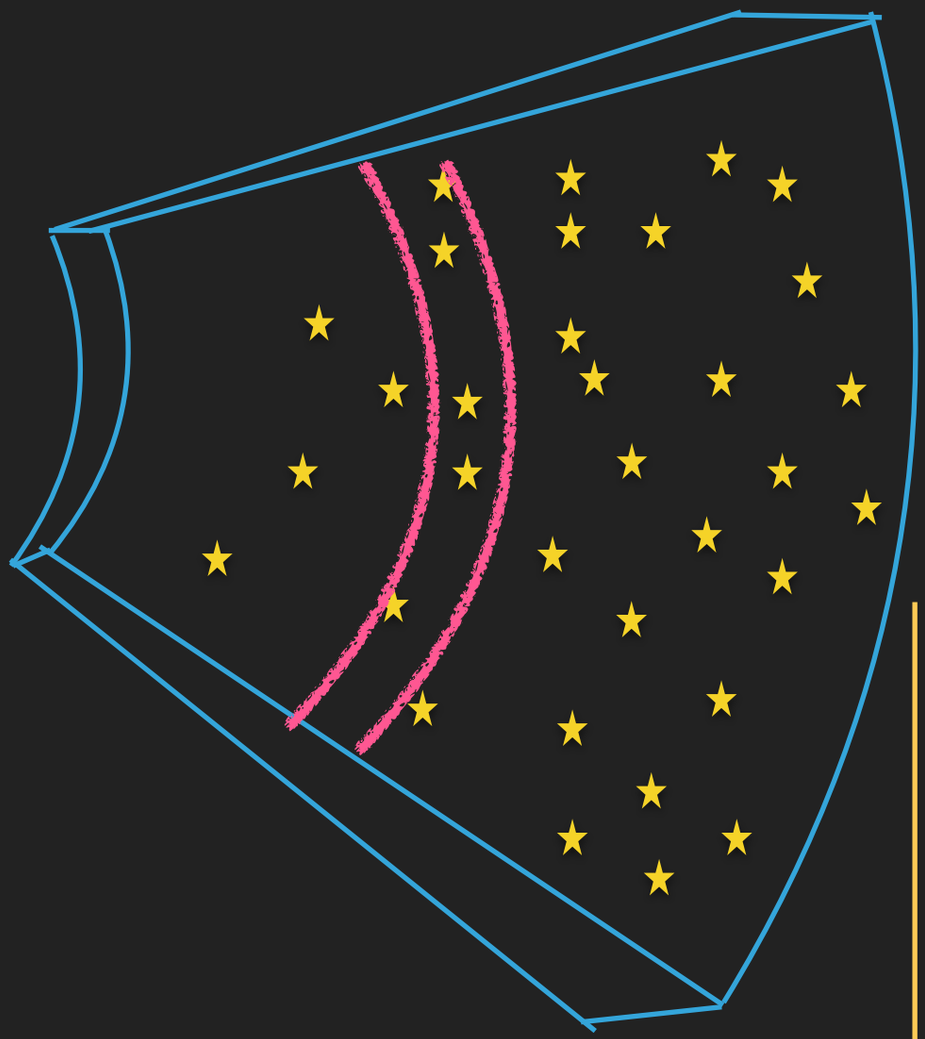

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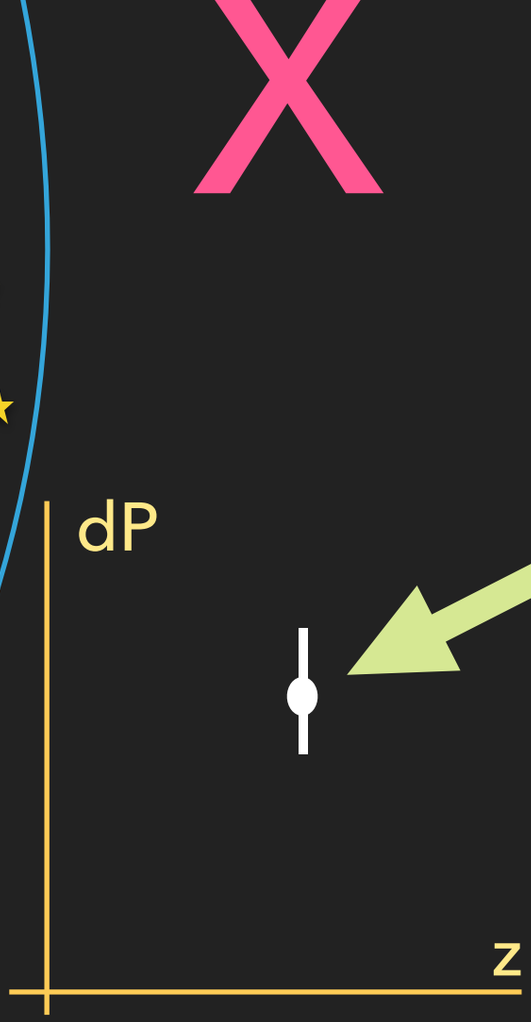
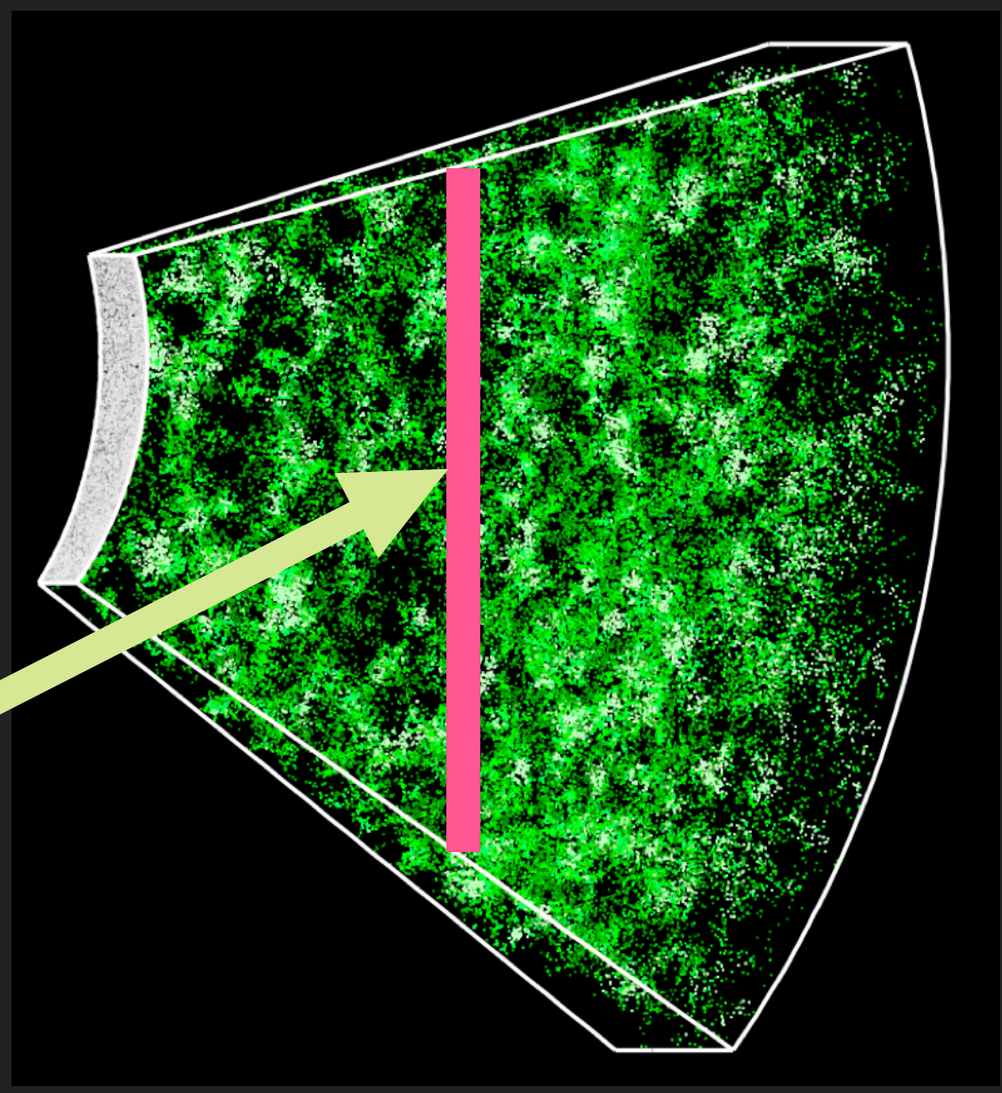
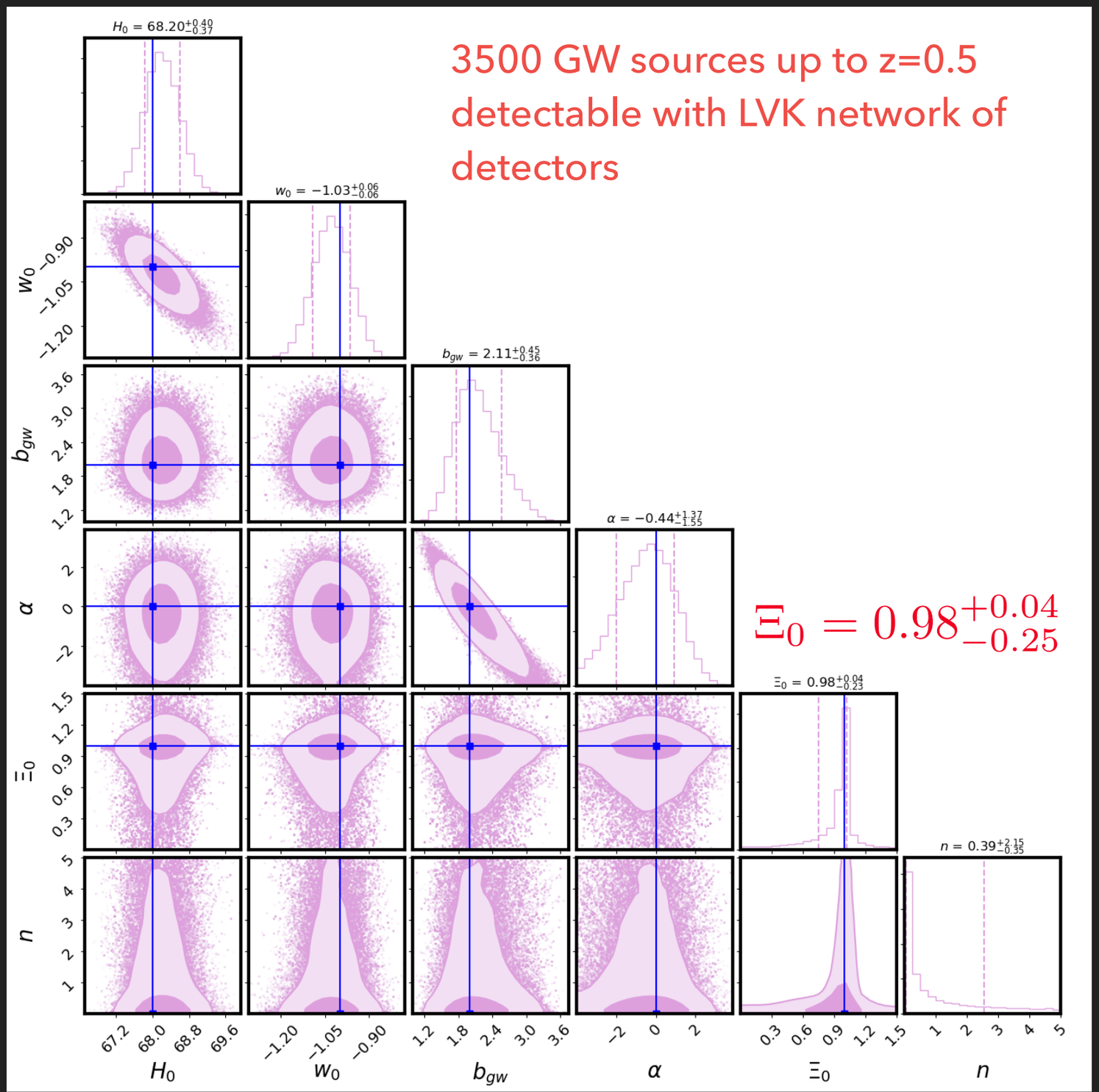




Dark sirens observed in luminosity distance space

Galaxy samples observed in redshift space

FORECAST TO MEASURE THE COSMOLOGICAL PARAMETERS FROM DARK SIRENS



3500 GW sources up to z=0.5 detectable with LVK network of detectors

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

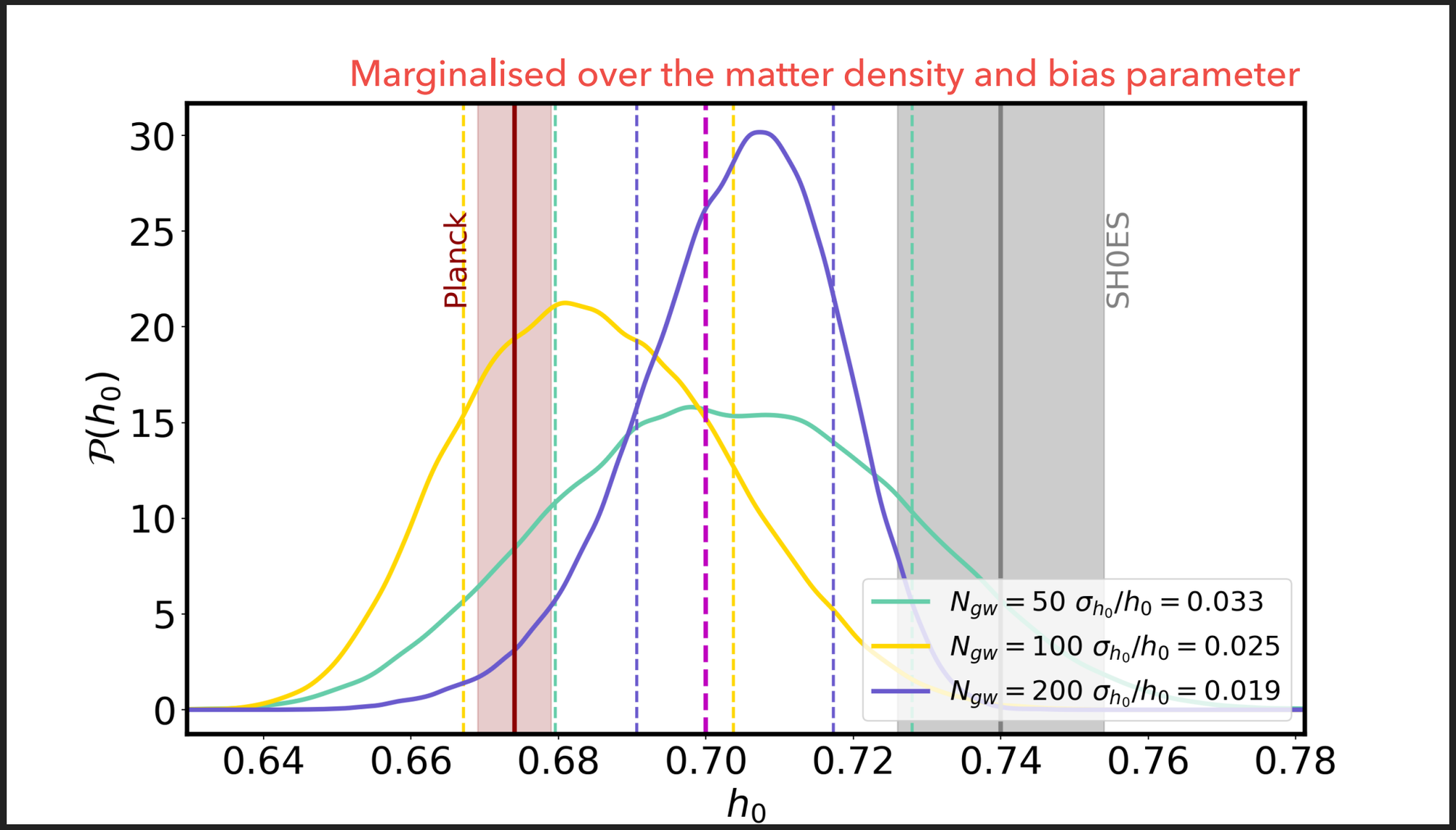
Mukherjee, Wandelt, Silk (*MNRAS*, 502,1136, 2021)

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

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

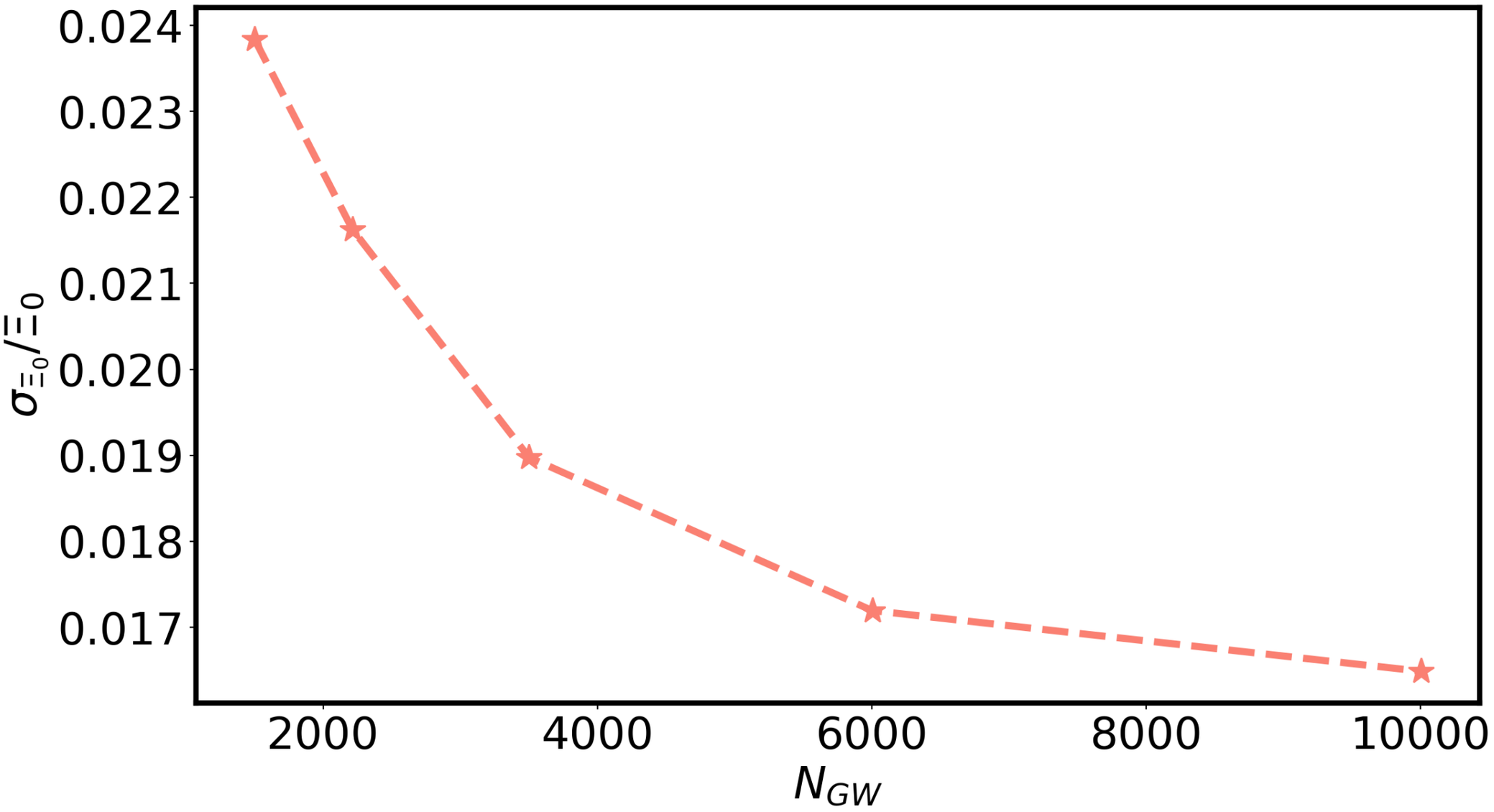
FORECAST: HUBBLE CONSTANT FROM DARK SIRENS USING CROSS-CORRELATION WITH GALAXIES

Mukherjee, Wandelt, Nissanke, Silvestri (2021)



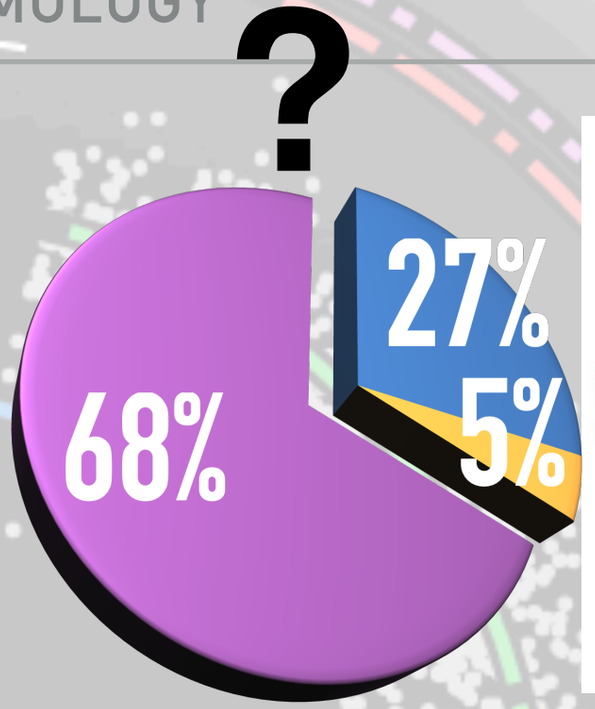
FORECAST: FRICTIONAL TERM FROM DARK SIRENS USING CROSS-CORRELATION WITH GALAXIES

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

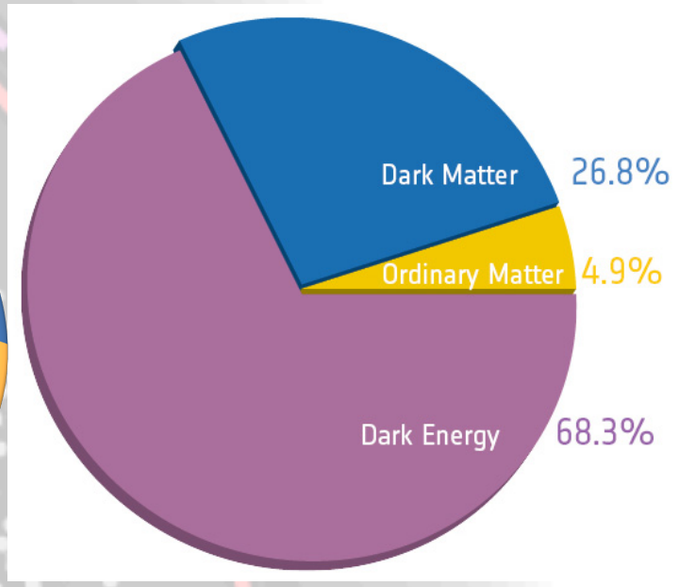


TAKE HOME MESSAGES

- Dark sirens will be able to provide an independent measurement of the cosmic pie chart.
- By combining the EM sector with the GW sector, we will test the theory of gravity at the cosmological scales.
- We will measure the GW bias and its redshift dependence.

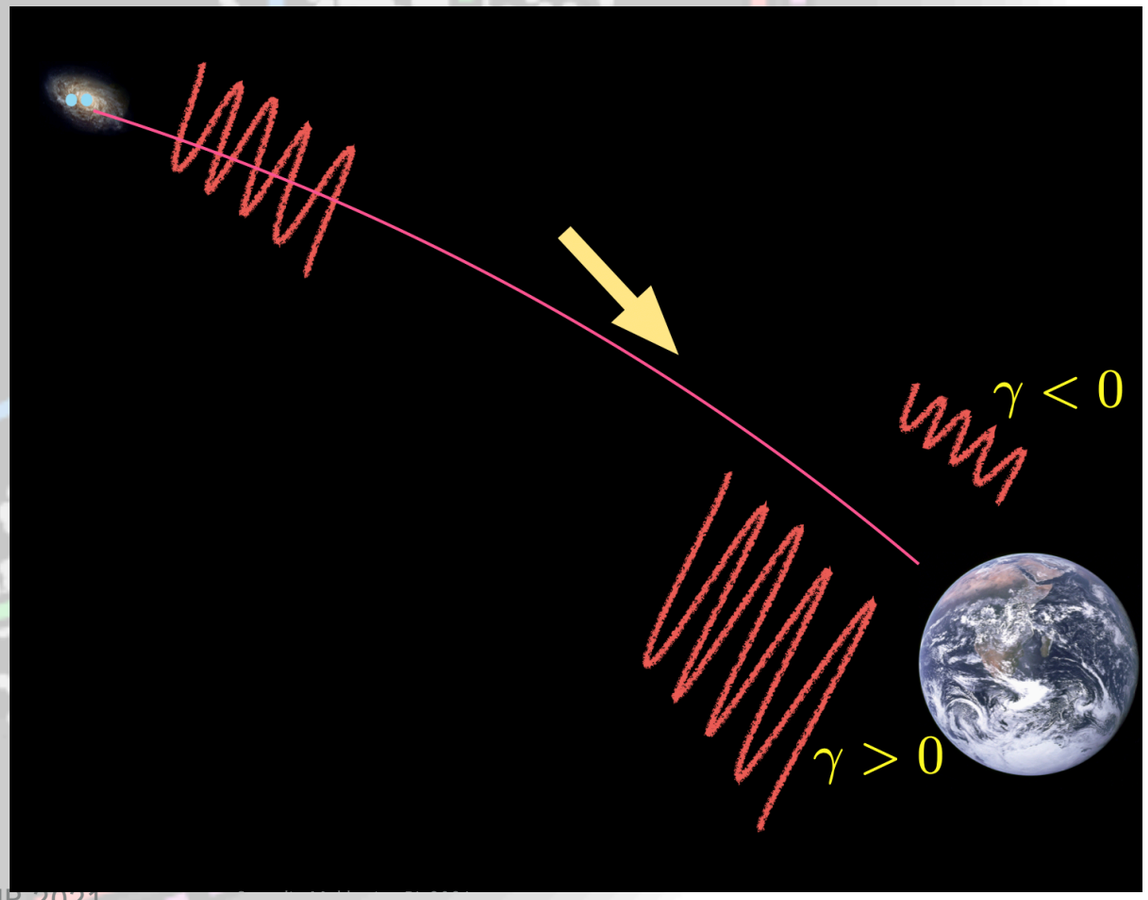


From the GW sector



From the EM sector

(In future)



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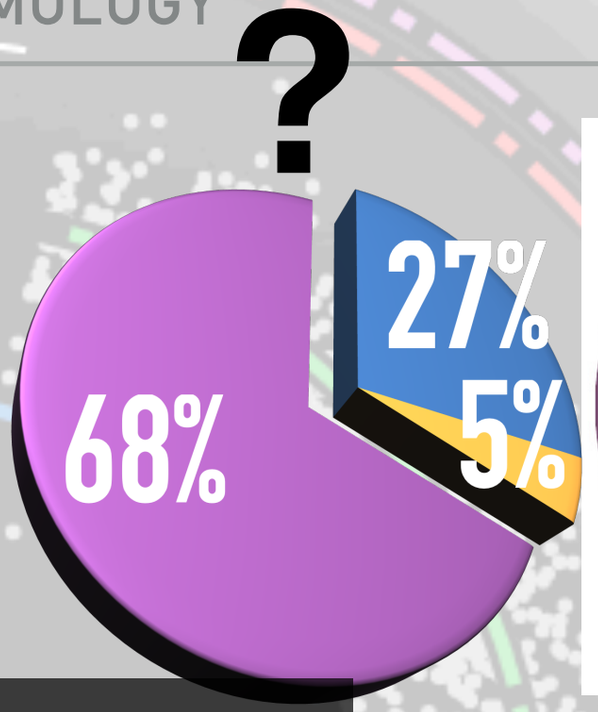
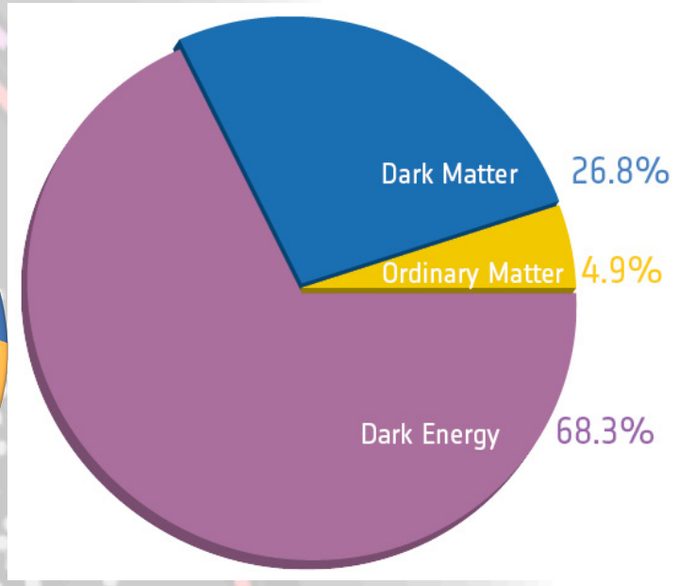


From the GW sector (In future)



From the EM sector

Thank you