Clustering effects on GWs Dark Sirens determination of Ho

Marios Kalomenopoulos – Cosmo from Home – 2022

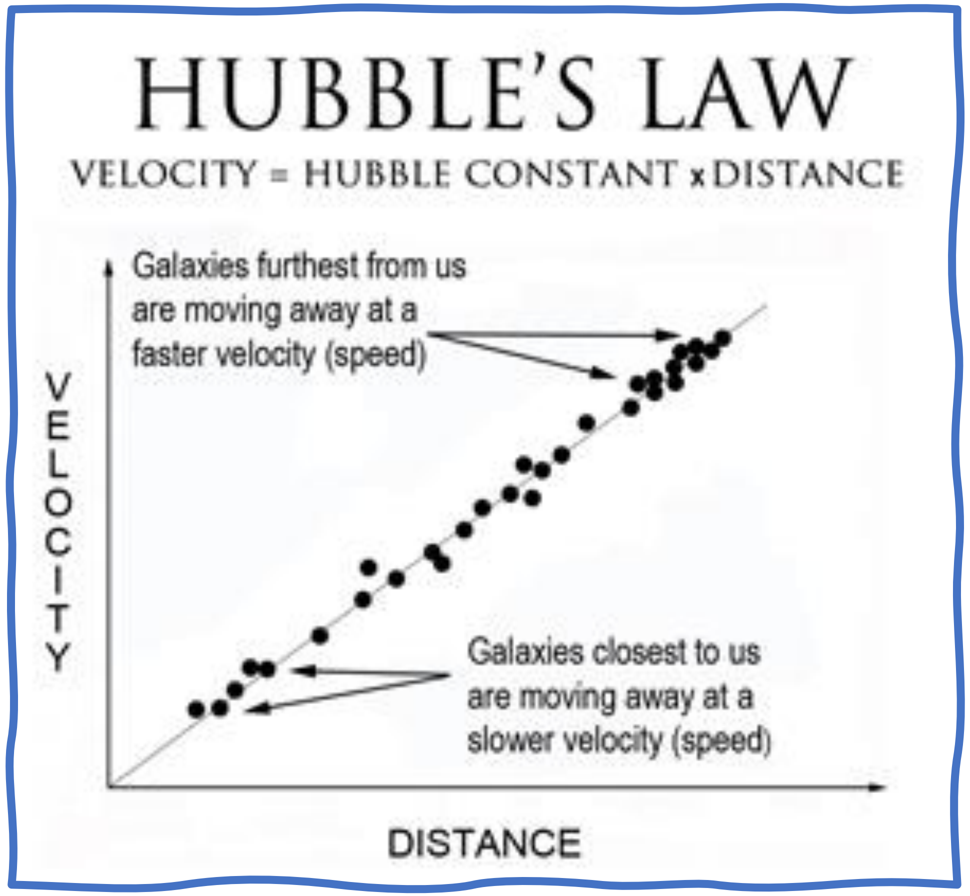
Work with: S. Khochfar, R. McGibbon (University of Edinburgh), R. Barbieri, J. Gair (Max Planck – AEI Potsdam)

The Expanding Universe

The Hubble constant parameterises the expansion of the Universe:

$$V_{total} = H_o \times D + V_{pec}$$

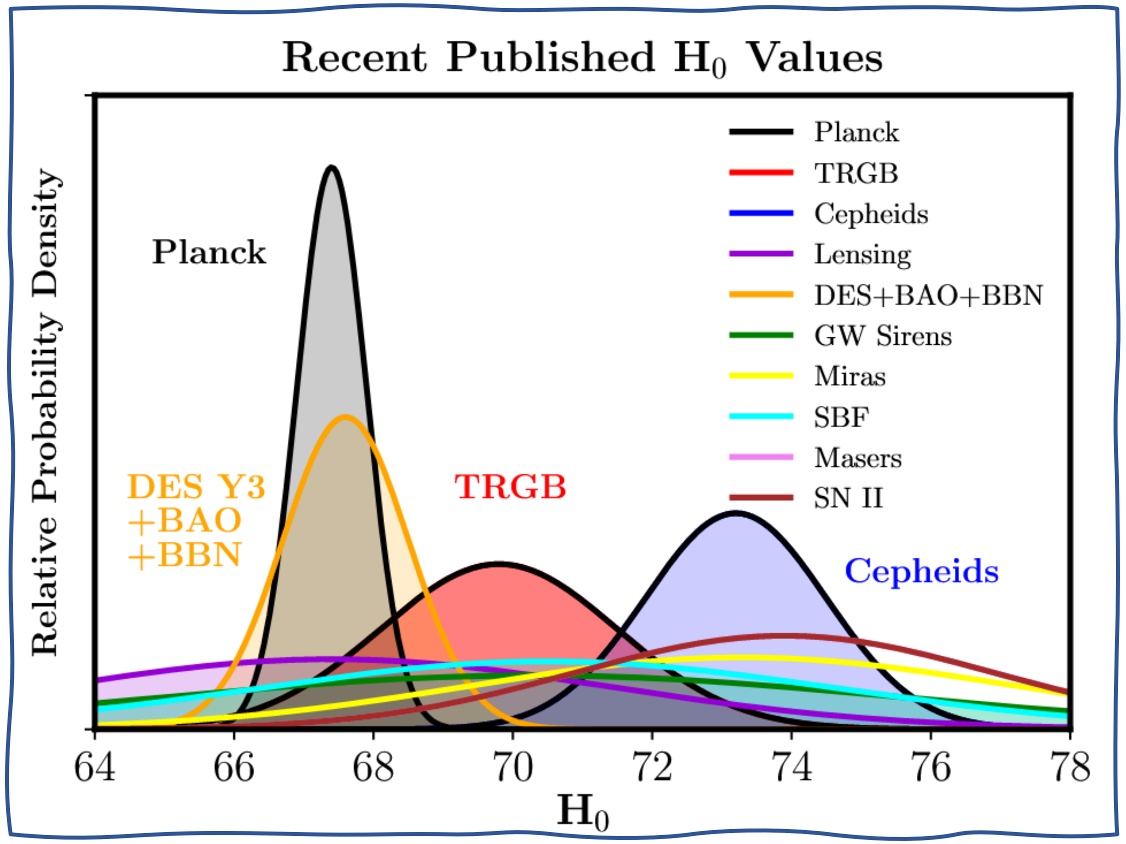
- Most measurements of the Hubble constant (H_0) require a precise determination of the velocity of expansion (through redshift z) and distance to the source (D).



Edwin Hubble 1929

Hubble Trouble?

- There seems to be a discrepancy between different methods of determining H_0: Systematics? Or New physics?

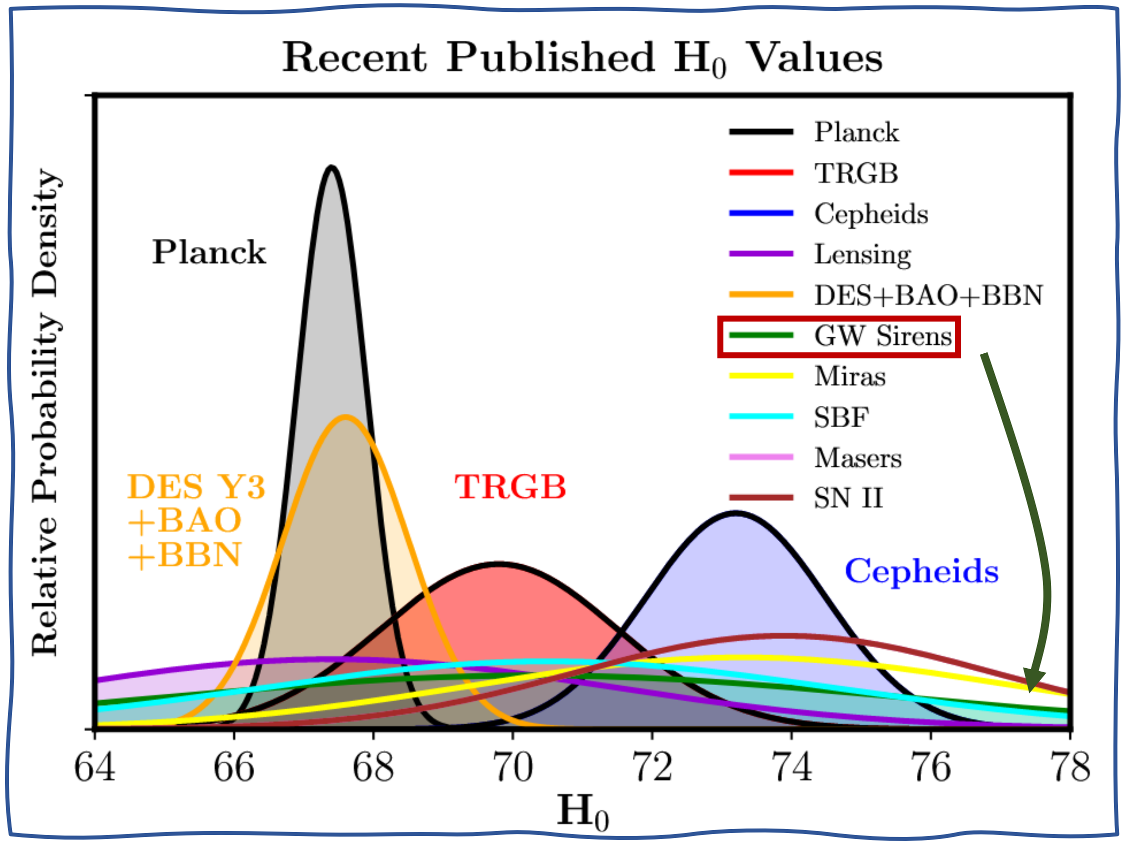


Wendy L. Freedman 2021

Hubble Trouble?

- There seems to be a discrepancy between different methods of determining H_0. Systematics? Or New physics?

- GWs can provide an independent probe to the Hubble constant and help resolve the current tension.



Wendy L. Freedman 2021

GWs and H_0

H_0 from GWs

$$v = H_0 d$$

- **Distance** → from GW signal
- **Velocity** → from redshift

*Based on D. Steer, 2021

Ho from GWs

- **Distance** → from GW signal ✓

- **Redshift**

1) A direct EM counterpart

2) A collection of galaxies in GW localisation volume

3) Knowledge of source-frame mass distribution

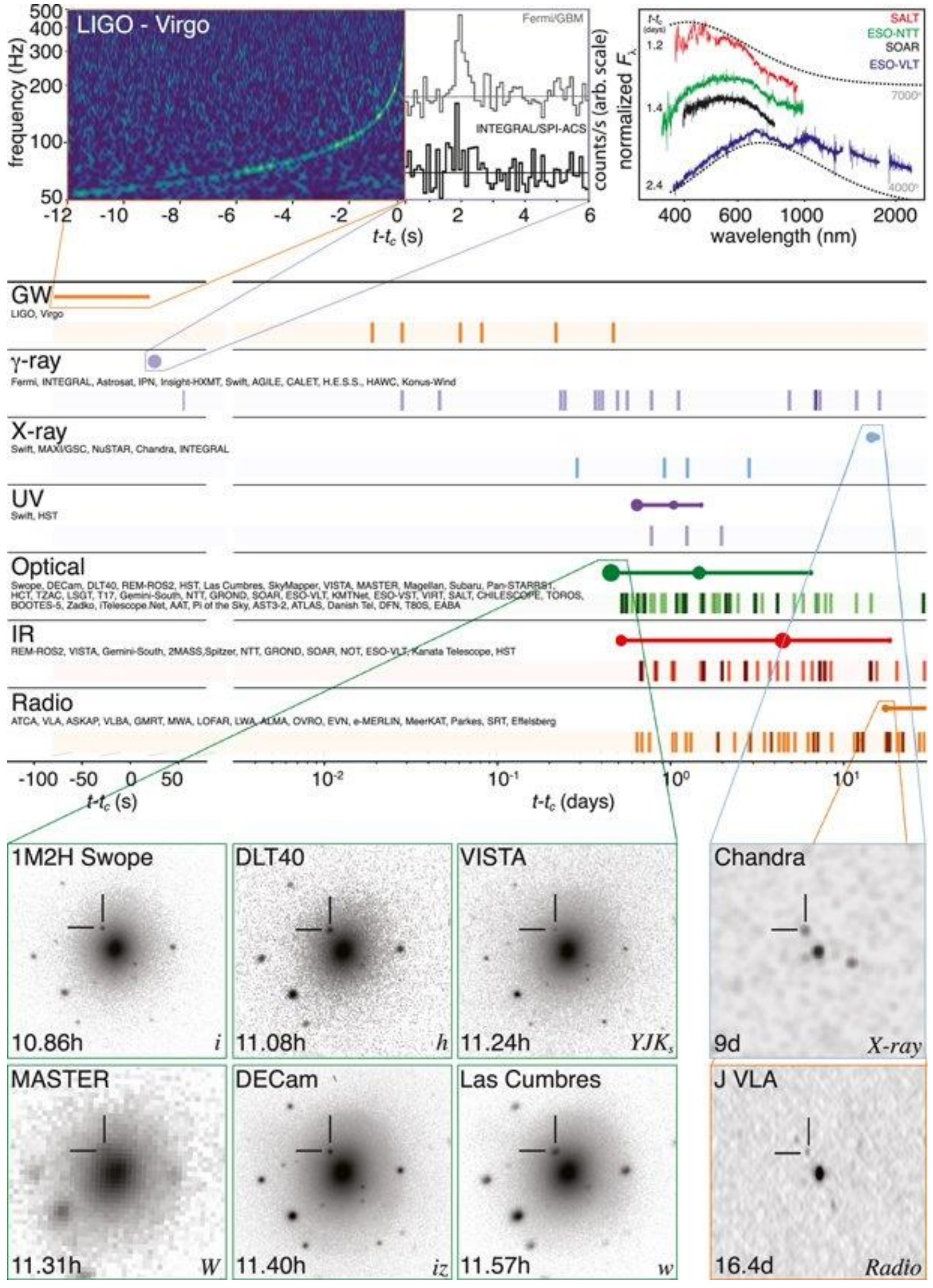
4) For NS: measure of tidal deformability & EoS

1) What is a Standard Siren?

- A GW merger provides a direct absolute measurement of luminosity distance.
- For redshift information, we need an EM counterpart*.
- Direct way to connect luminosity distance with redshift.

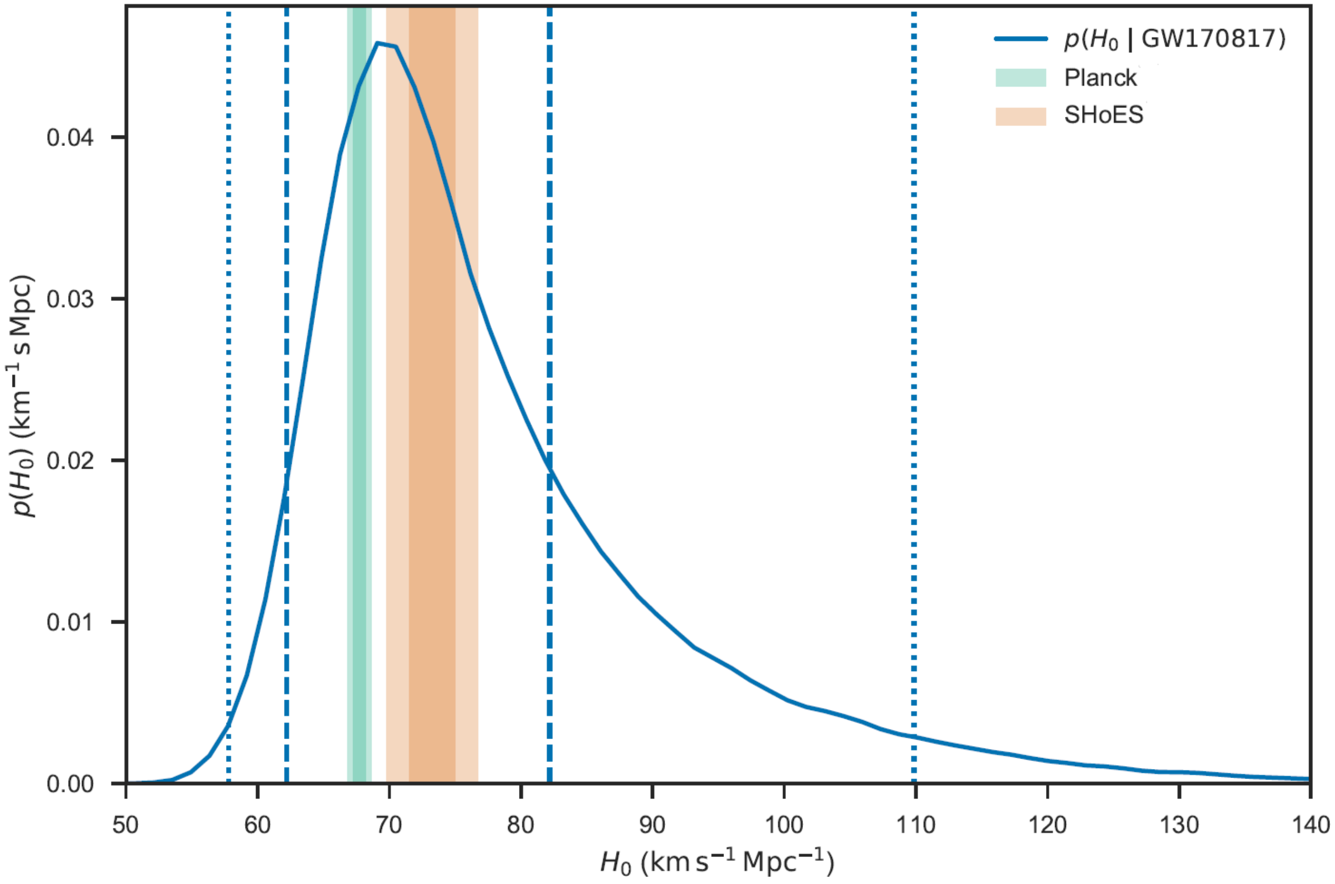
Schutz 1986; Holz & Hughes 2005

*in most cases.

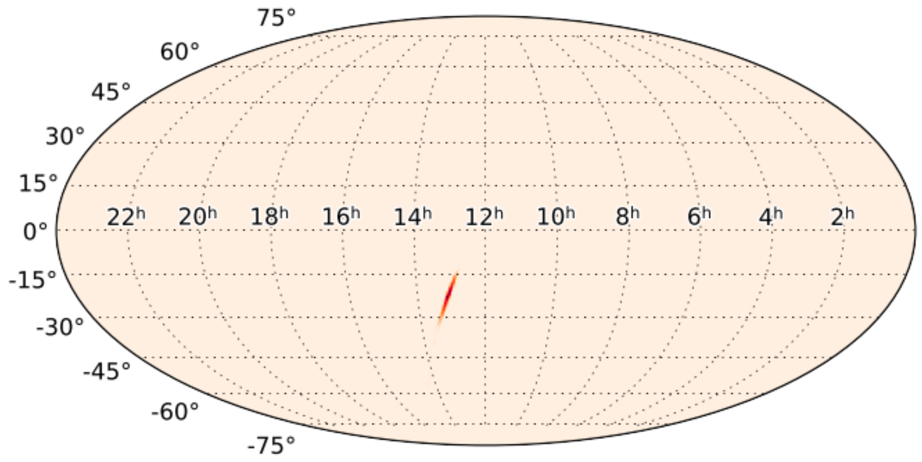


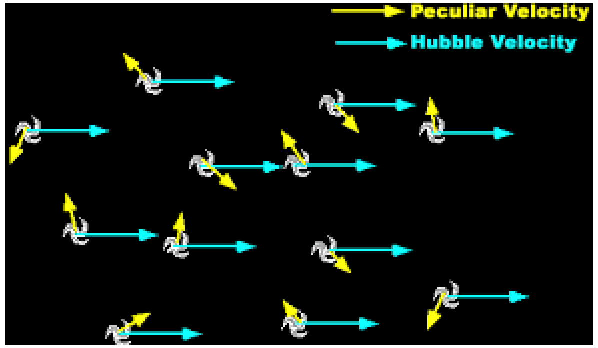
B. P. Abbott et al. 2017a

1) A gravitational-wave standard siren measurement of the Hubble constant



B. P. Abbott et al. 2017b





$$V_{total} = H_0 \times D + V_{pec}$$

Dark Sirens (and the Hubble tension)

2) What is a Dark Siren?

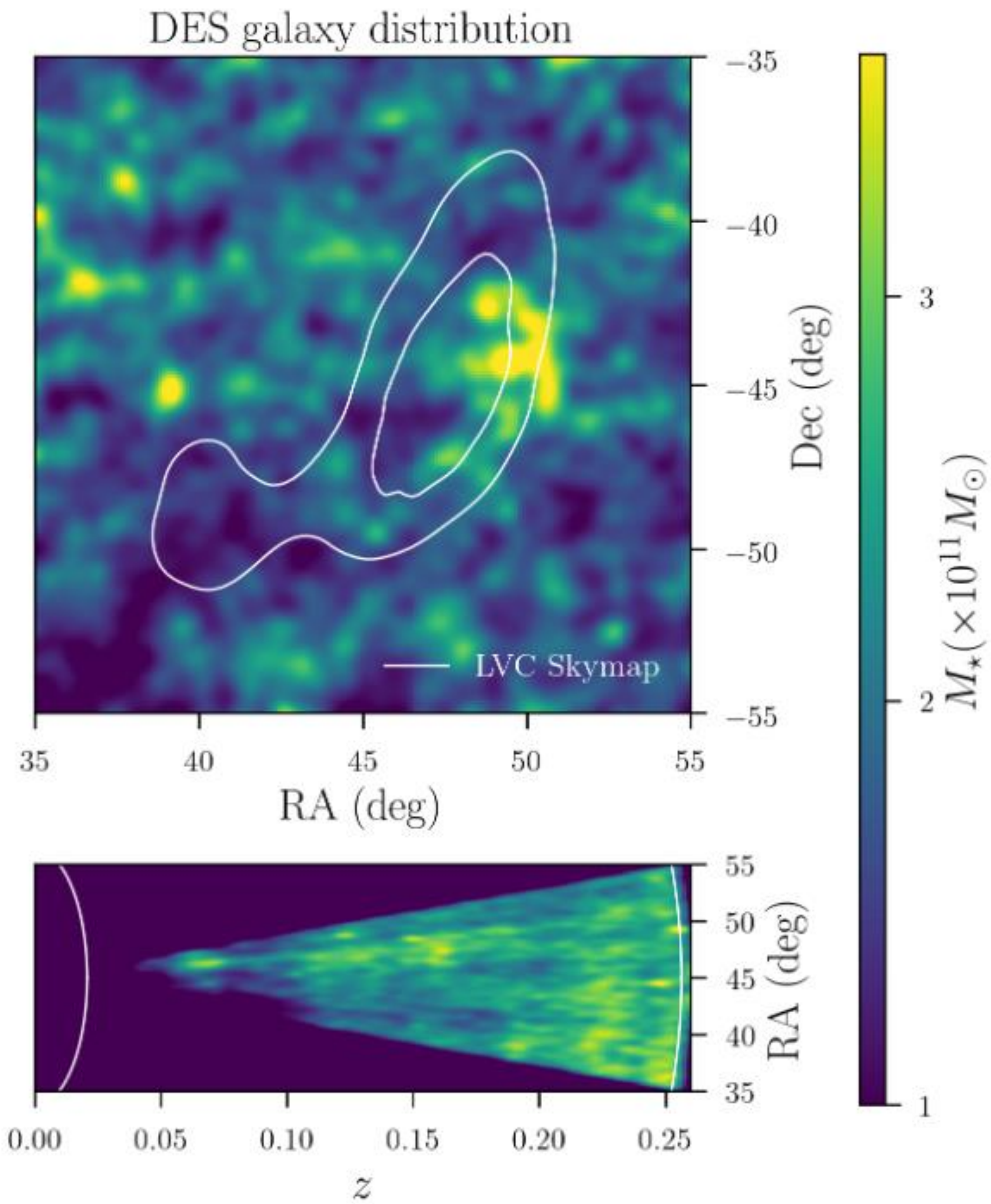
- A GW merger provides a direct absolute measurement of luminosity distance.

- For redshift information, we need an EM counterpart*.

- Direct way to connect luminosity distance with redshift.

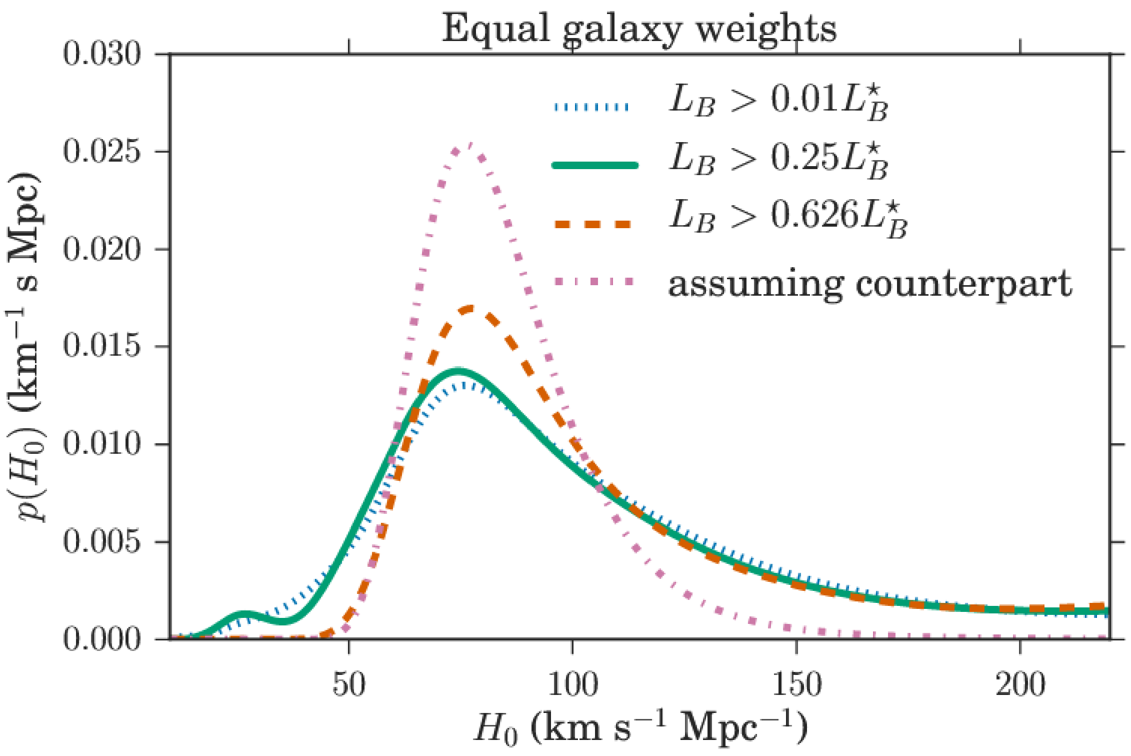
Schutz 1986; Holz & Hughes 2005

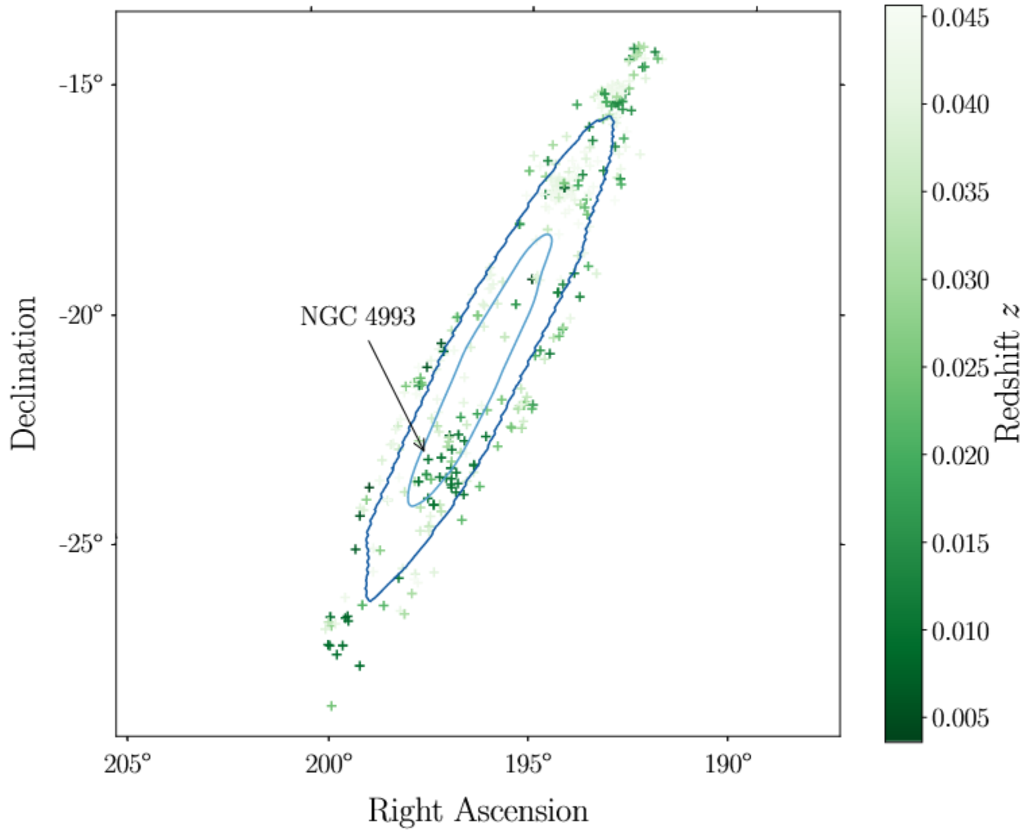
GW170814



M. Soares-Santos et al. 2019

2) A gravitational-wave standard siren measurement of the Hubble constant (without a counterpart)





Fisbach et al. 2019

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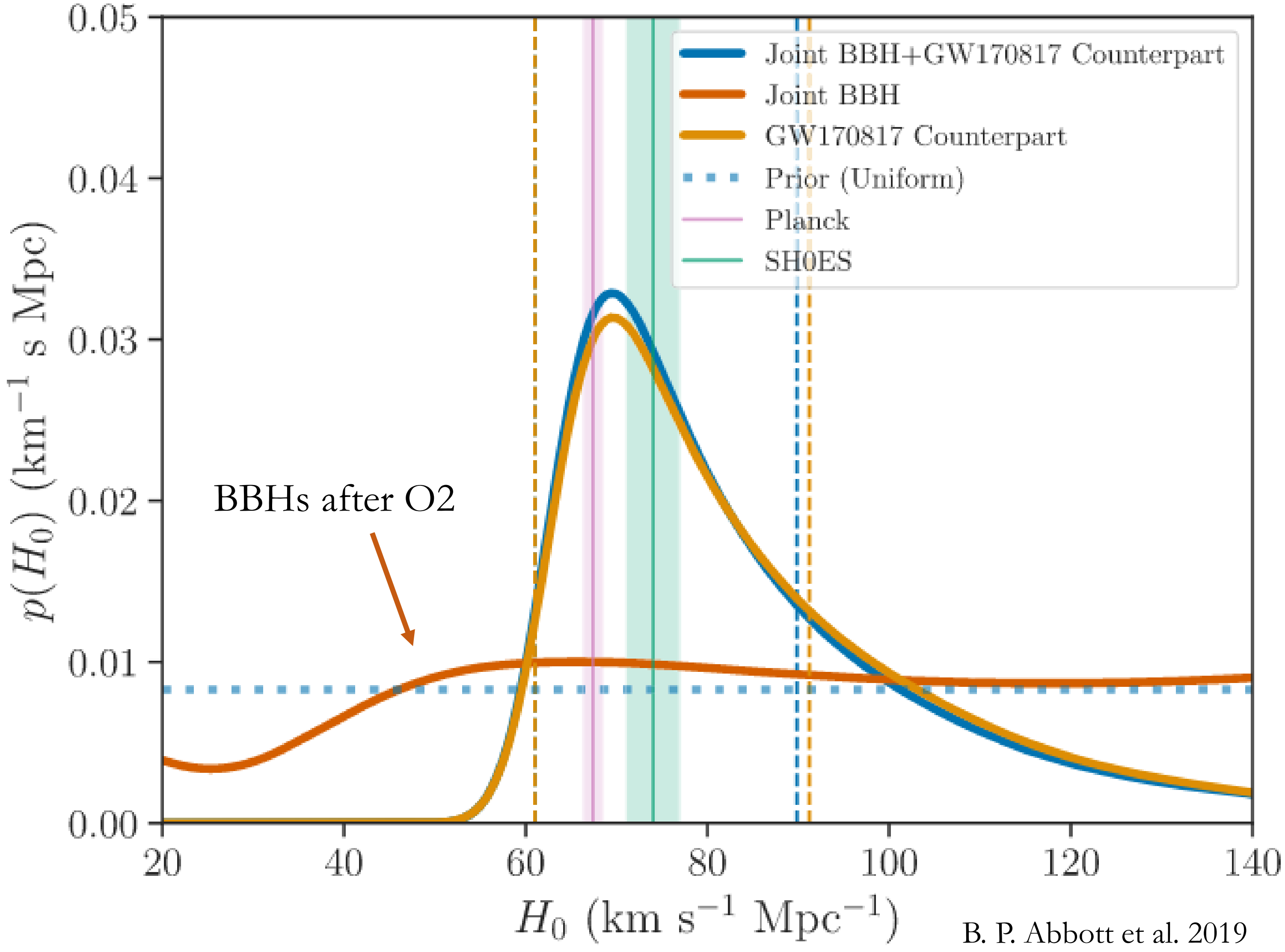


B. P. Abbott et al. 2019

Very active research area:

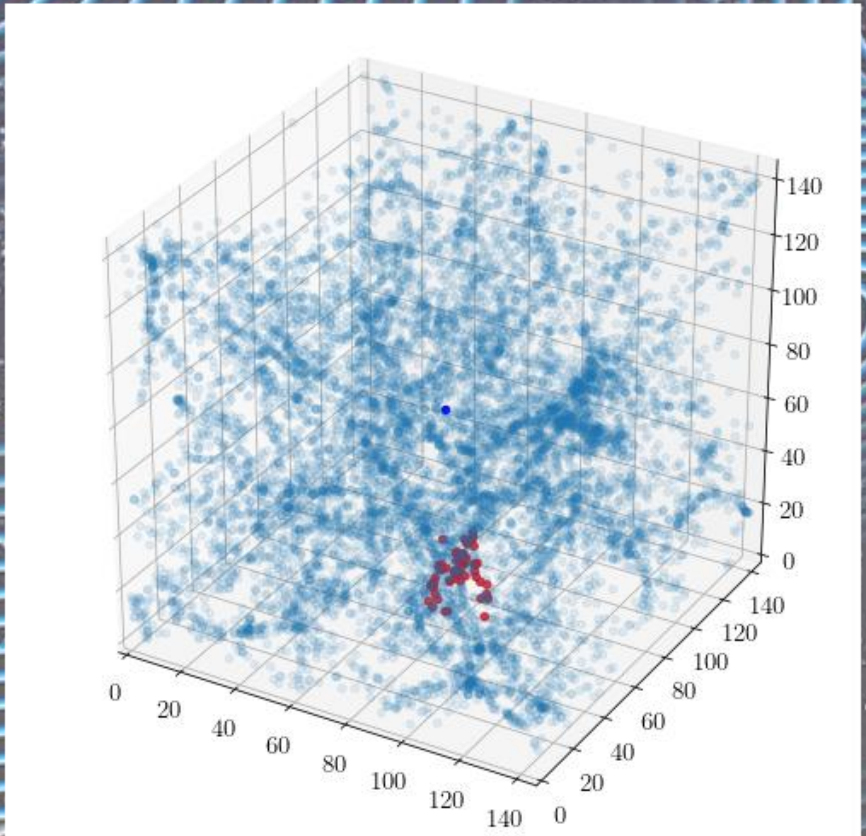
Chen et al. 2017
Nair et al. 2018
Gray et al. 2019
Bera et al. 2020
Palmese et al. 2021
Finke et al. 2021
Muttoni et al. 2021
Chen et al. 2022
…

Dark Sirens in Simulations*

In 5 + 1 steps:

1) We observe a GW, with no counterpart. In the simulations, we model the GW **3D sky region as a cone.**

2) We **find all haloes in the cone** and calculate their distances to the observer. Observer at the centre of the box. Centres of cones at random halo positions in the box.



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Credit: APS/Carin Cain

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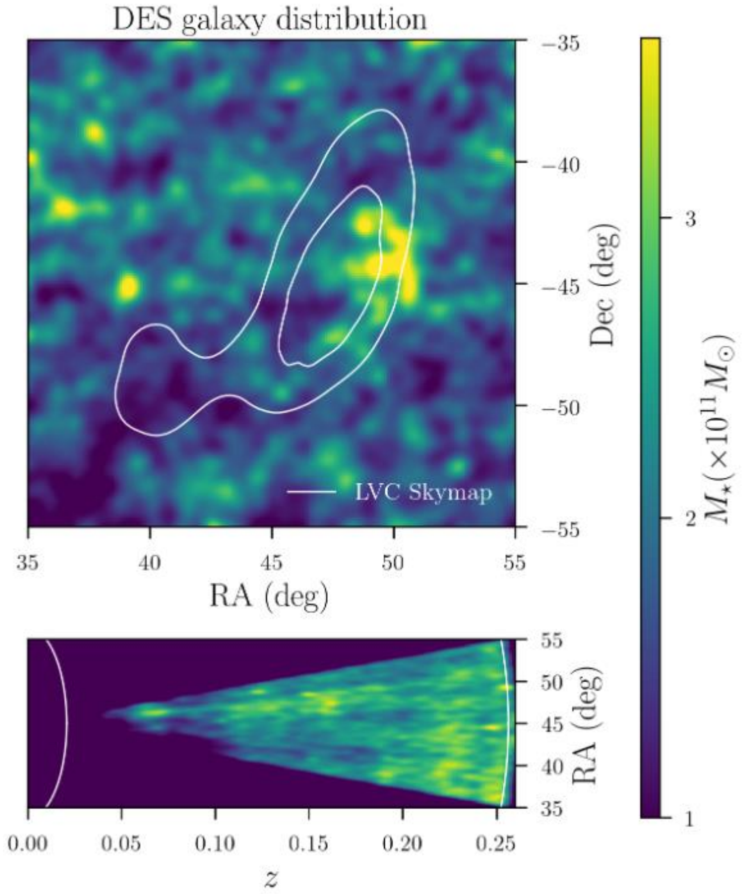
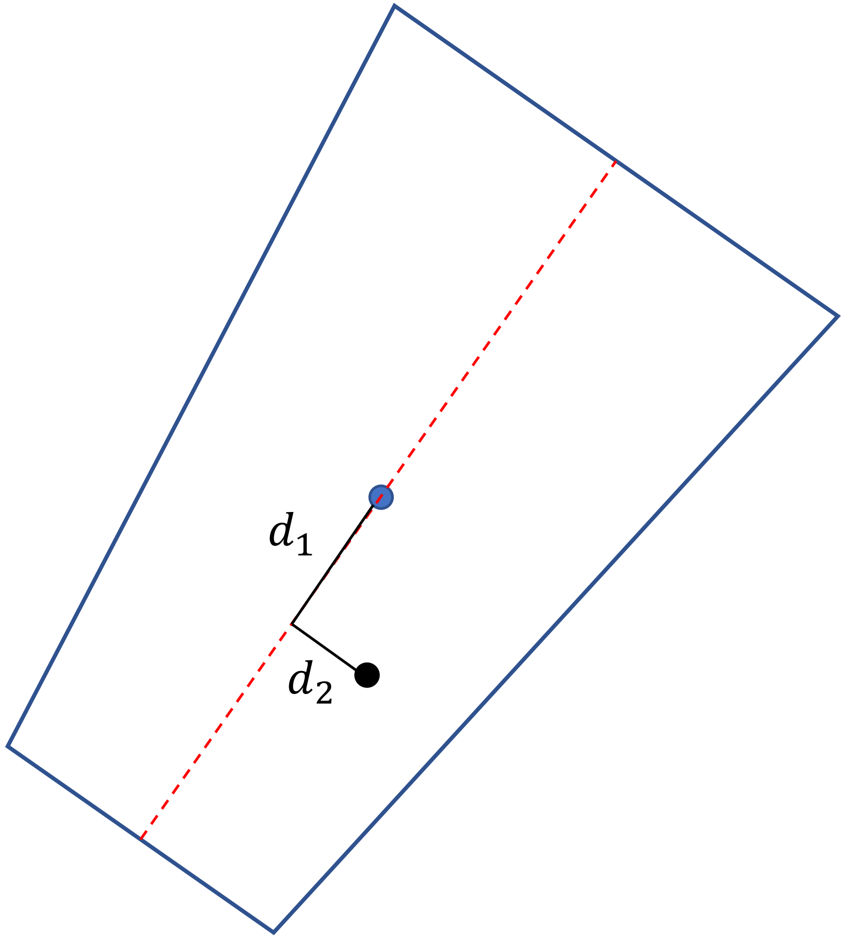
3) To construct the cone we assume 2 main errors, following observations (**LOS distance, sky localisation area**). These also give different weights to the potential sources.



M. Soares-Santos et al. 2019



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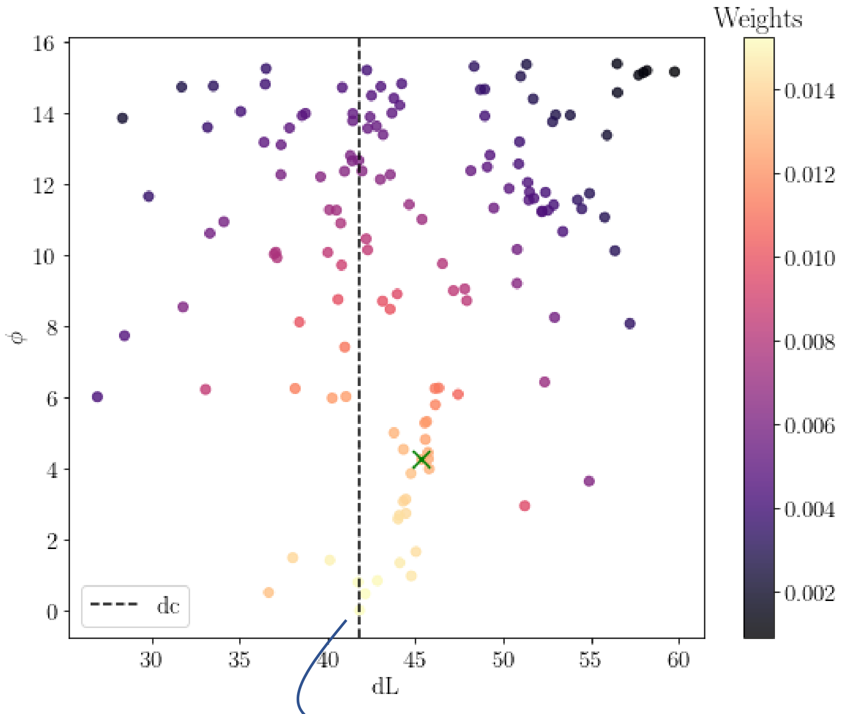
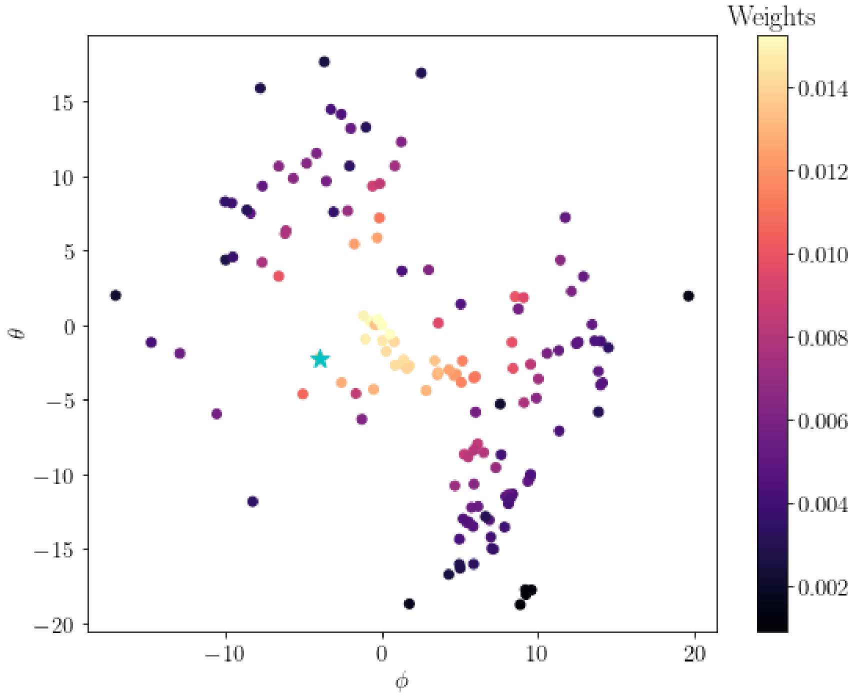
4) **Randomly** choose one distance as the "true" GW distance (**GW source**).



Distance between observer and centre of the cone

2D projected distribution of galaxies in the cone



Weights depend on **angular position, distance from the centre** of the cone & **selection effects** due to the cone geometry (larger at higher distances)

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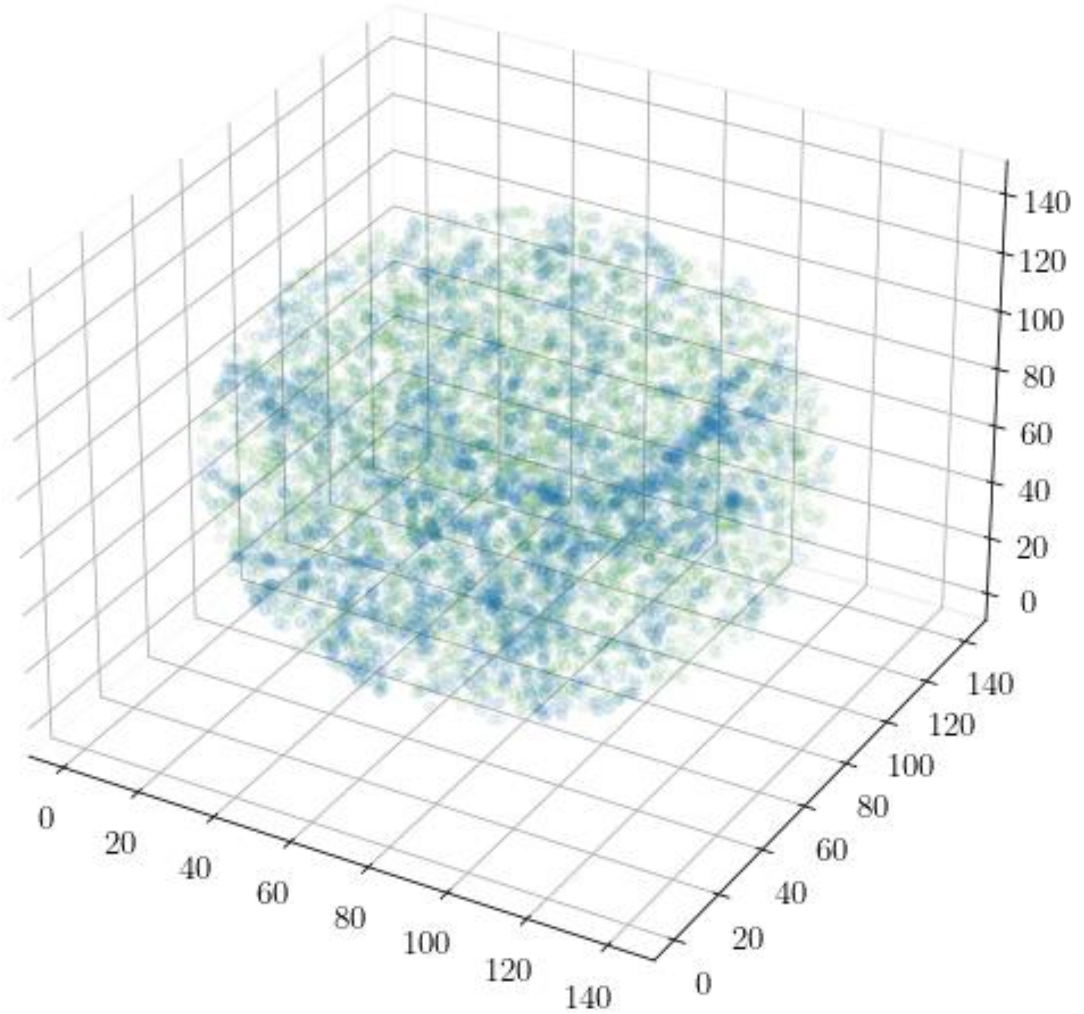
5) Expect, that due to **clustering**, there is higher probability the “true” distance to be shared among many haloes.



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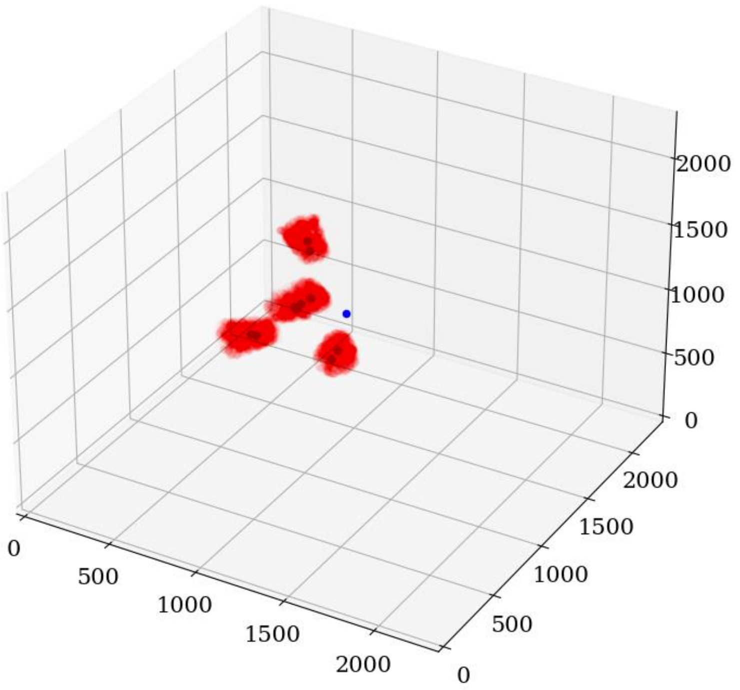
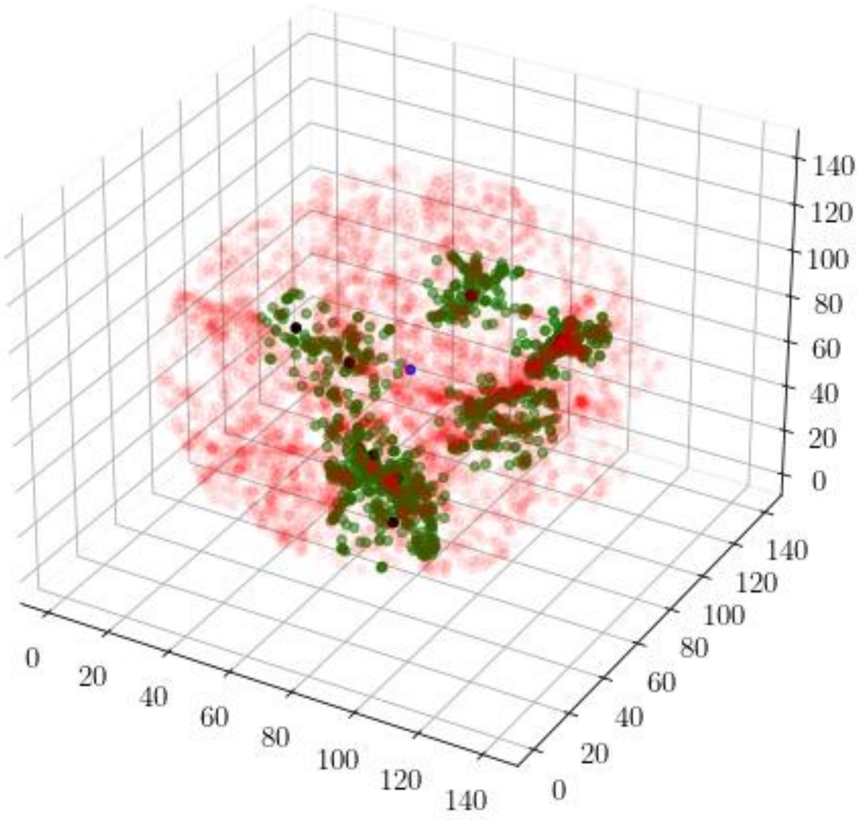
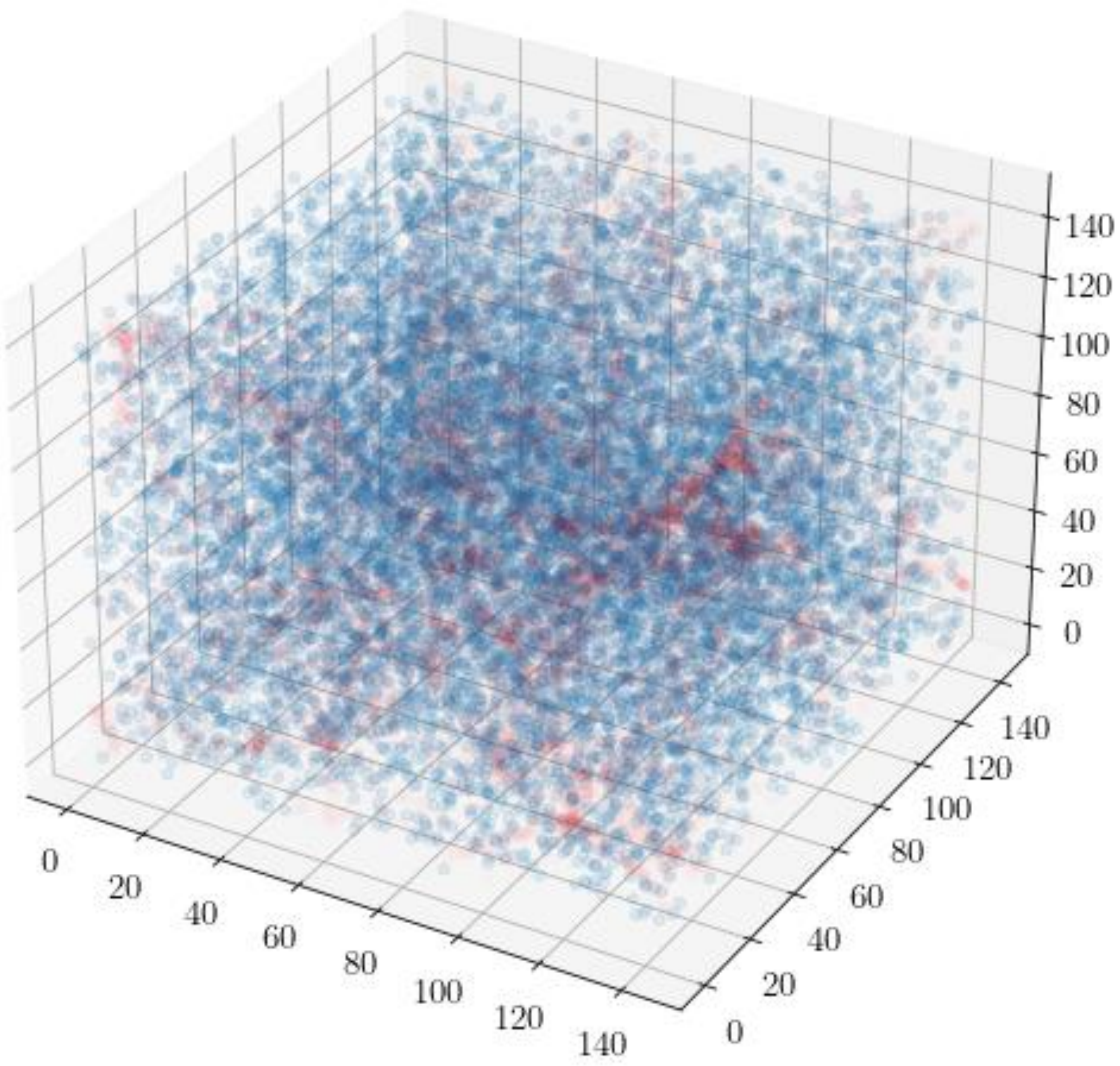
6) **Power of the method lies in the statistics**: Repeat for many cones and "add" together!



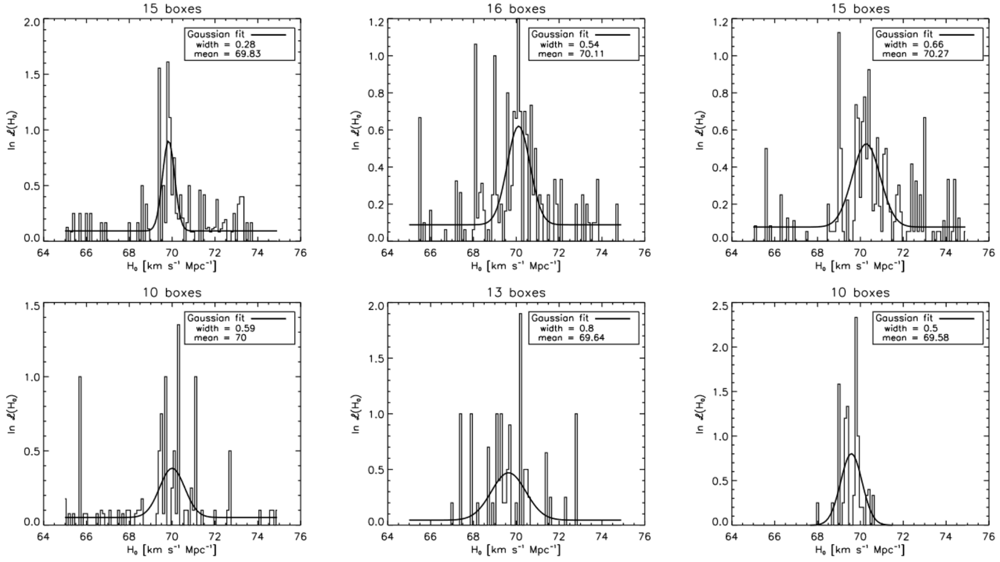


Base model – uniform box

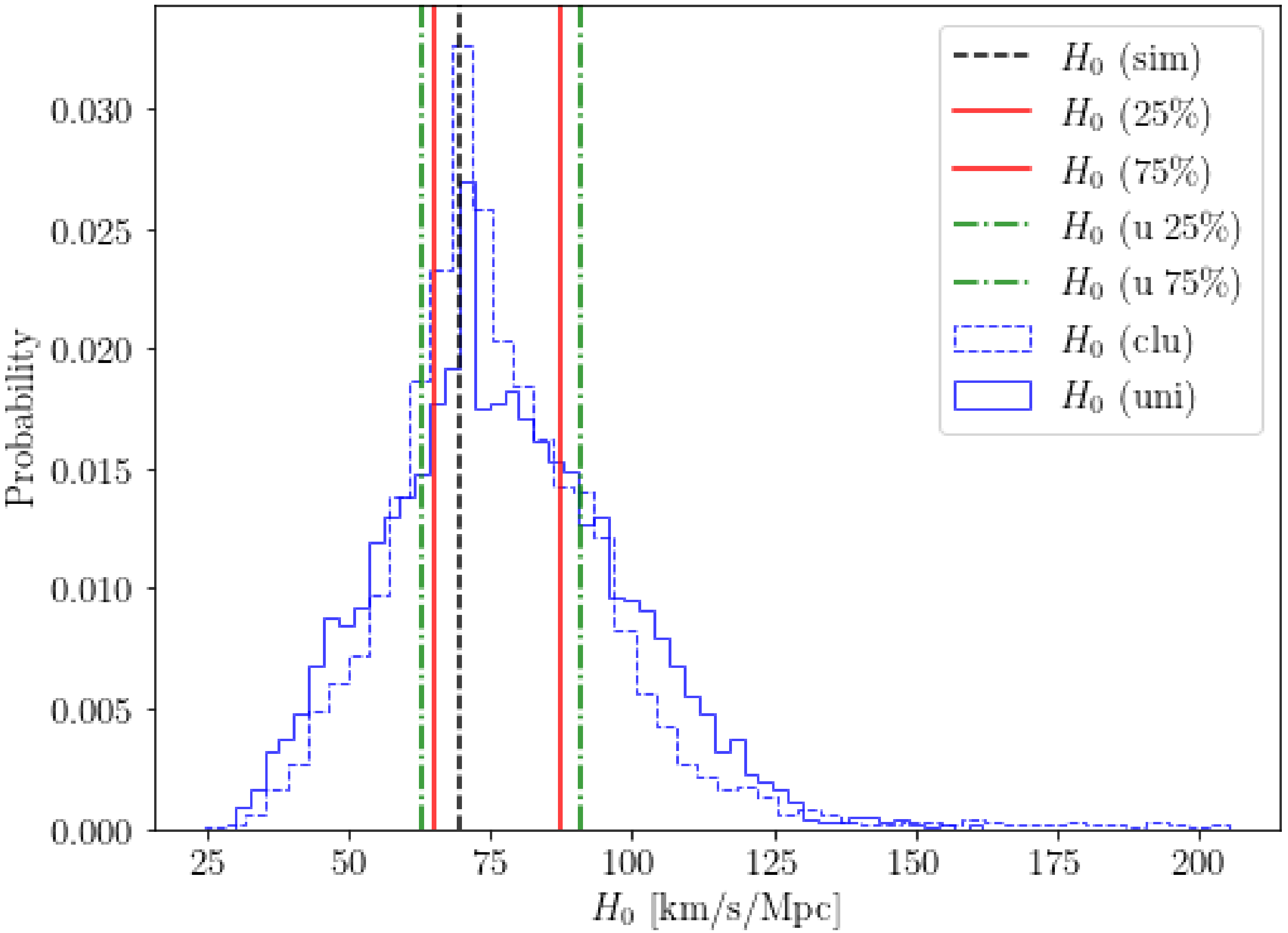


Coordinates **uniform** (blue) and **clustered** (red).

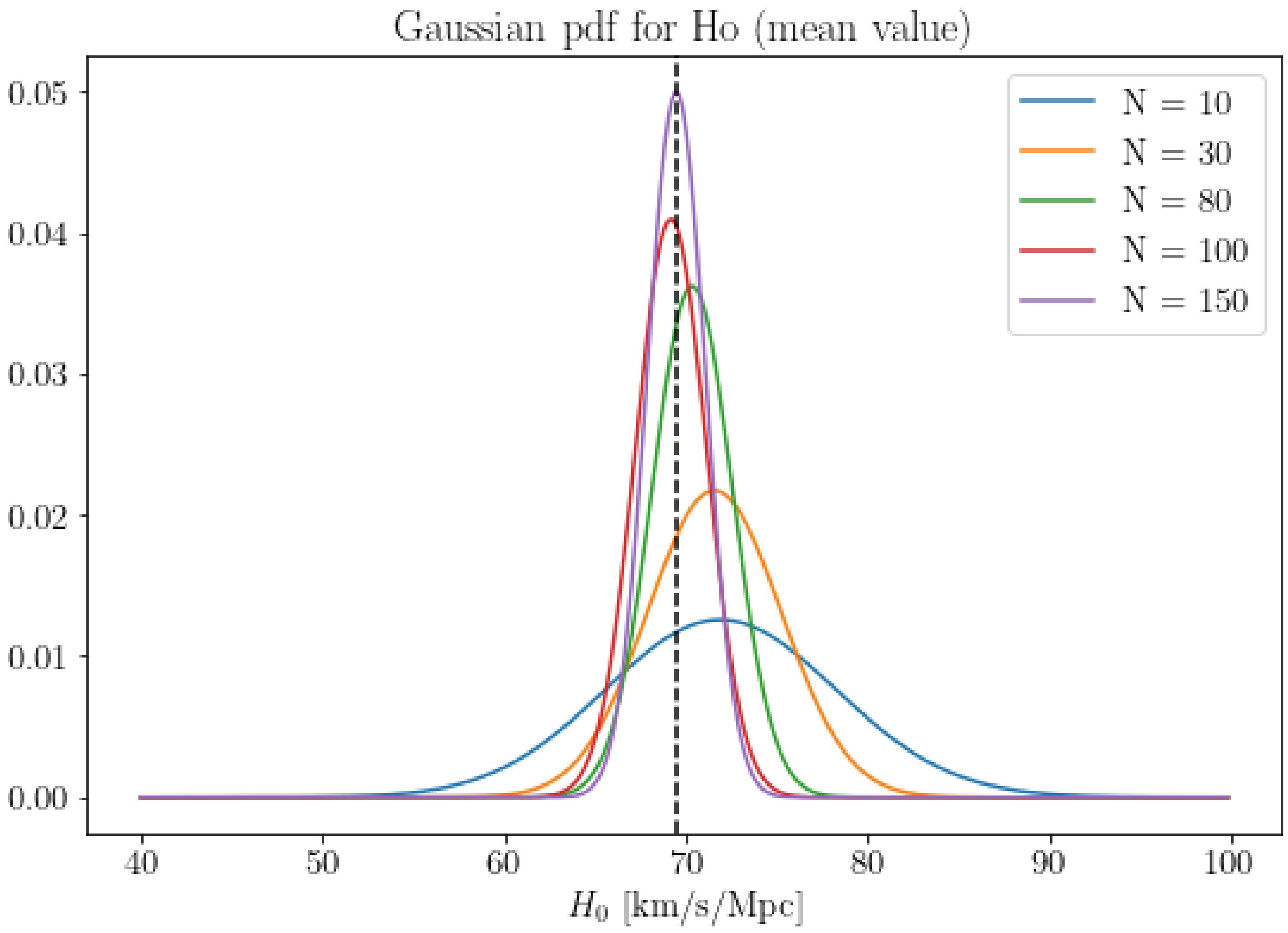
Ho Stacking



MacLeod & Hogan 2008



Dark Sirens in Simulations



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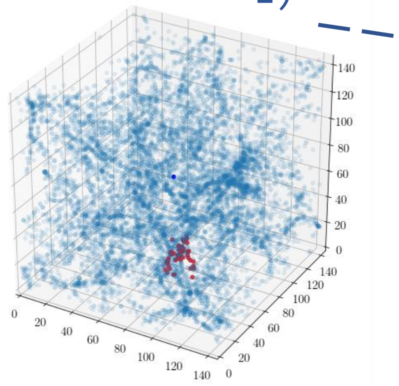
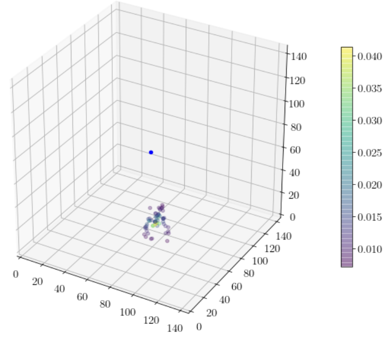
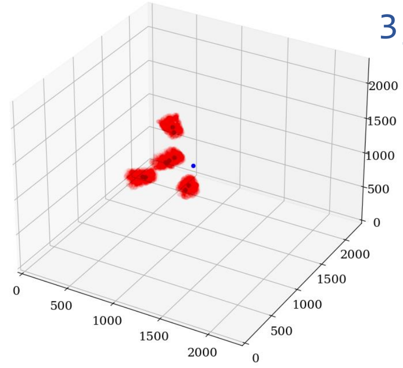
1)



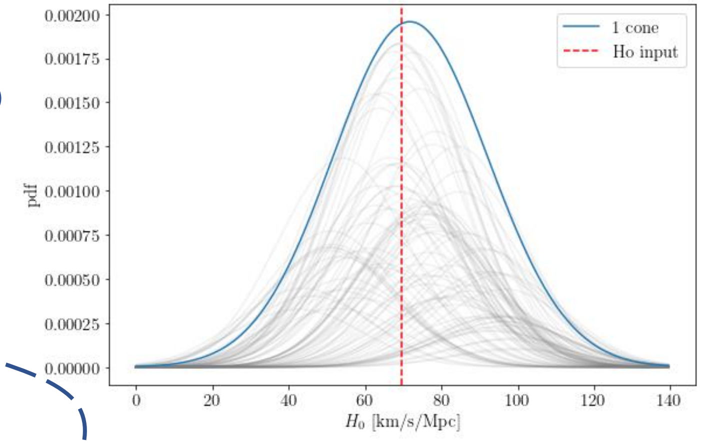
2)



3, 4, 5)

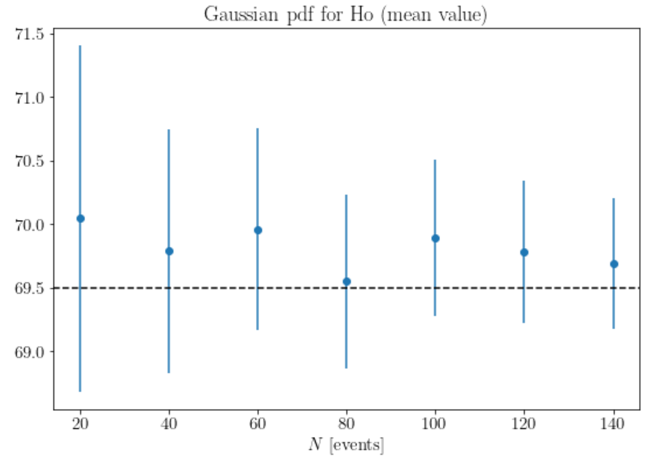


6a)



Results from single observations (grey lines: effects of single galaxies in the region), combine to give a single posterior (blue, solid line)

6b)

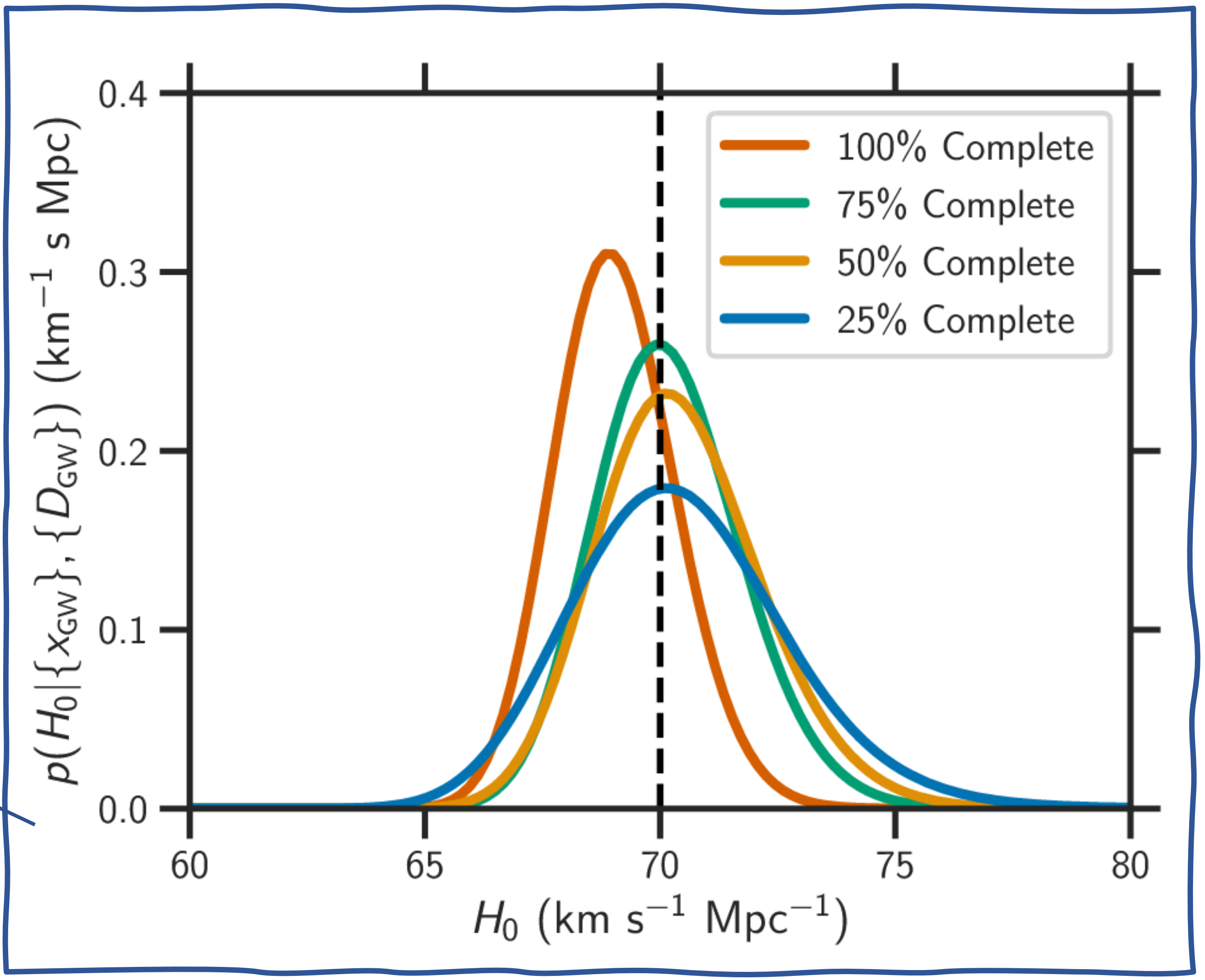


Results converging with number of observations (cones) as $1/\sqrt{N}$

Dark Sirens in Simulations

Completeness Issues:

- Surveys can't resolve all galaxies.
- Cuts based on luminosities.
- "Complete" the catalogues, by randomly putting galaxies in.



Checking completeness, but not from a realistic galaxy configuration.

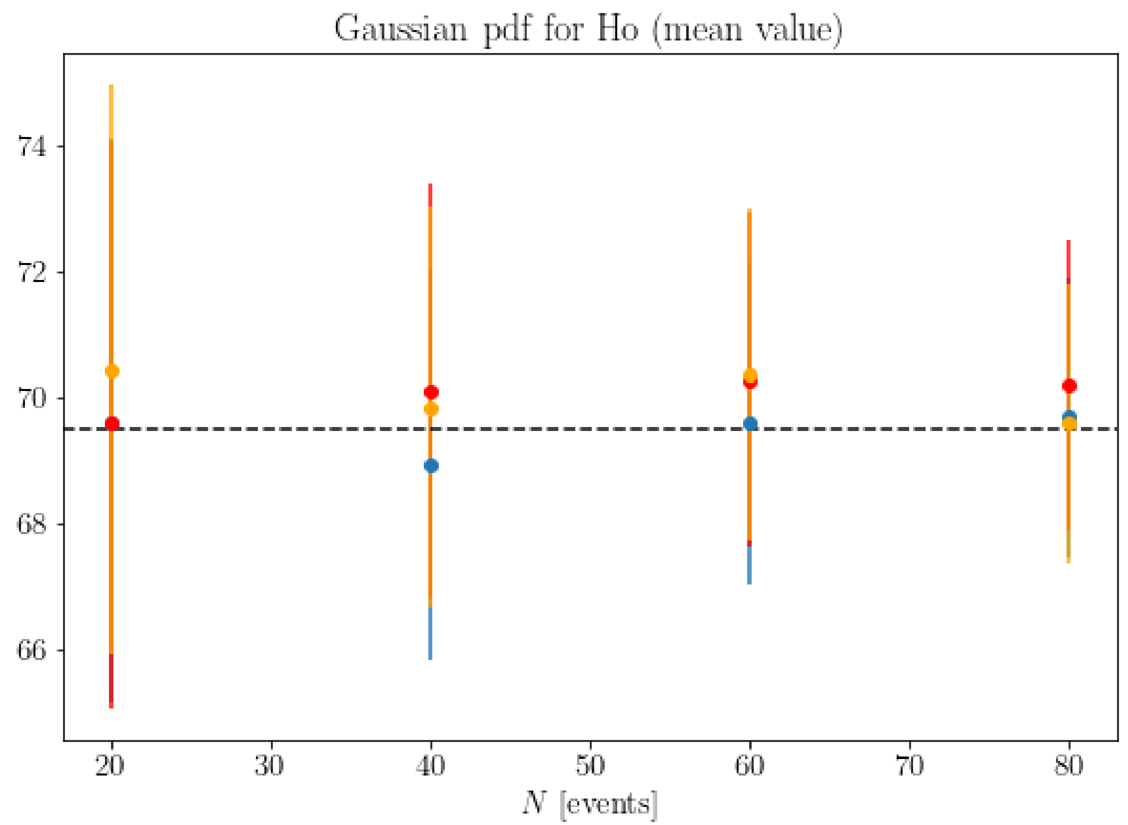
Gray et al. 2020

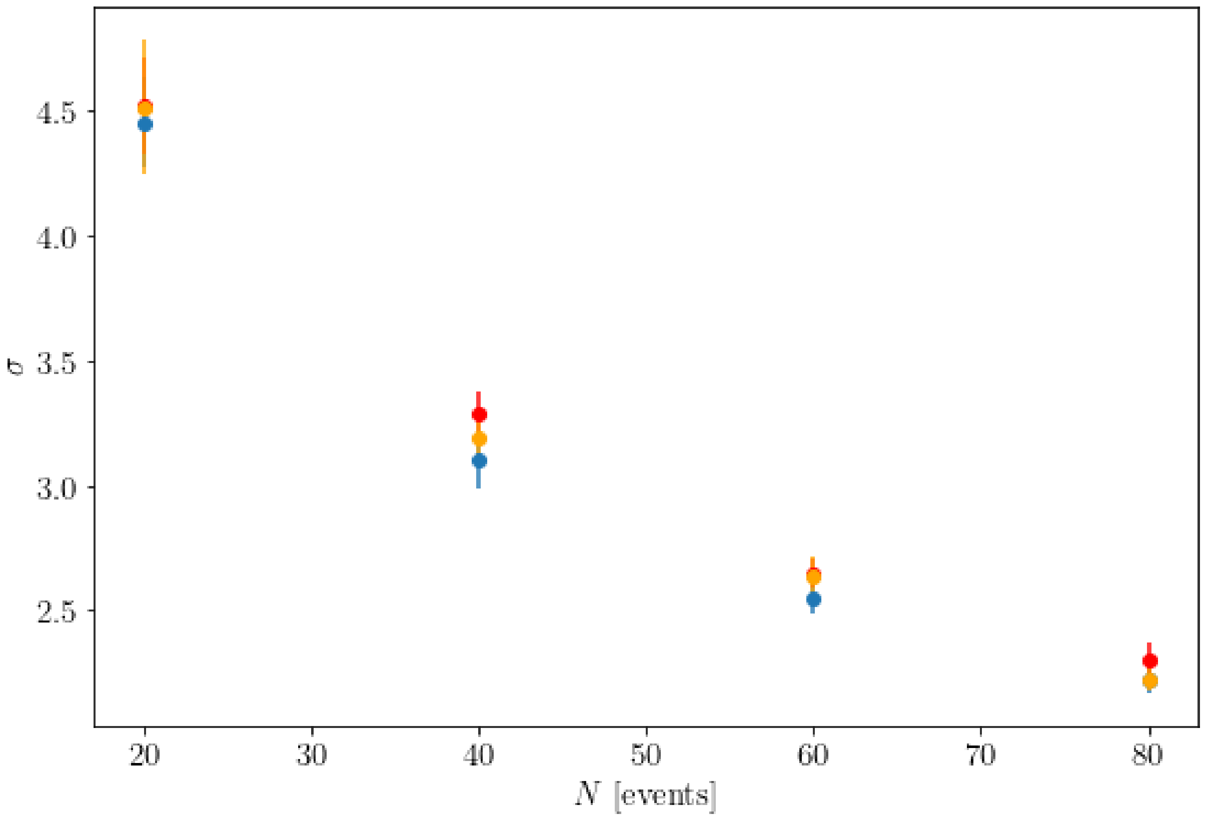
Dark Sirens in Simulations

Completeness Issues: **work in progress**

A more realistic approach, will take into account **clustering**. This increases the possibility of identifying the true host, hence we expect to **improve convergence**.

Uniform
Complete (clustered)
85% (clustered)





Dark Sirens in Simulations (Summary)

*Soon on the ArXiv!

- Dark Sirens can provide a robust method of calculating H_0.

- Clustering reduces scatter in Ho posterior → faster convergence with number of events (about a 2% improvement versus a uniform catalogue).

- Clustering introduces less scattering in incomplete catalogues.

What we want to check next:

- Introduce back galaxies, based on clustering information, rather than randomly (led by R. Barbieri).

Thank you!

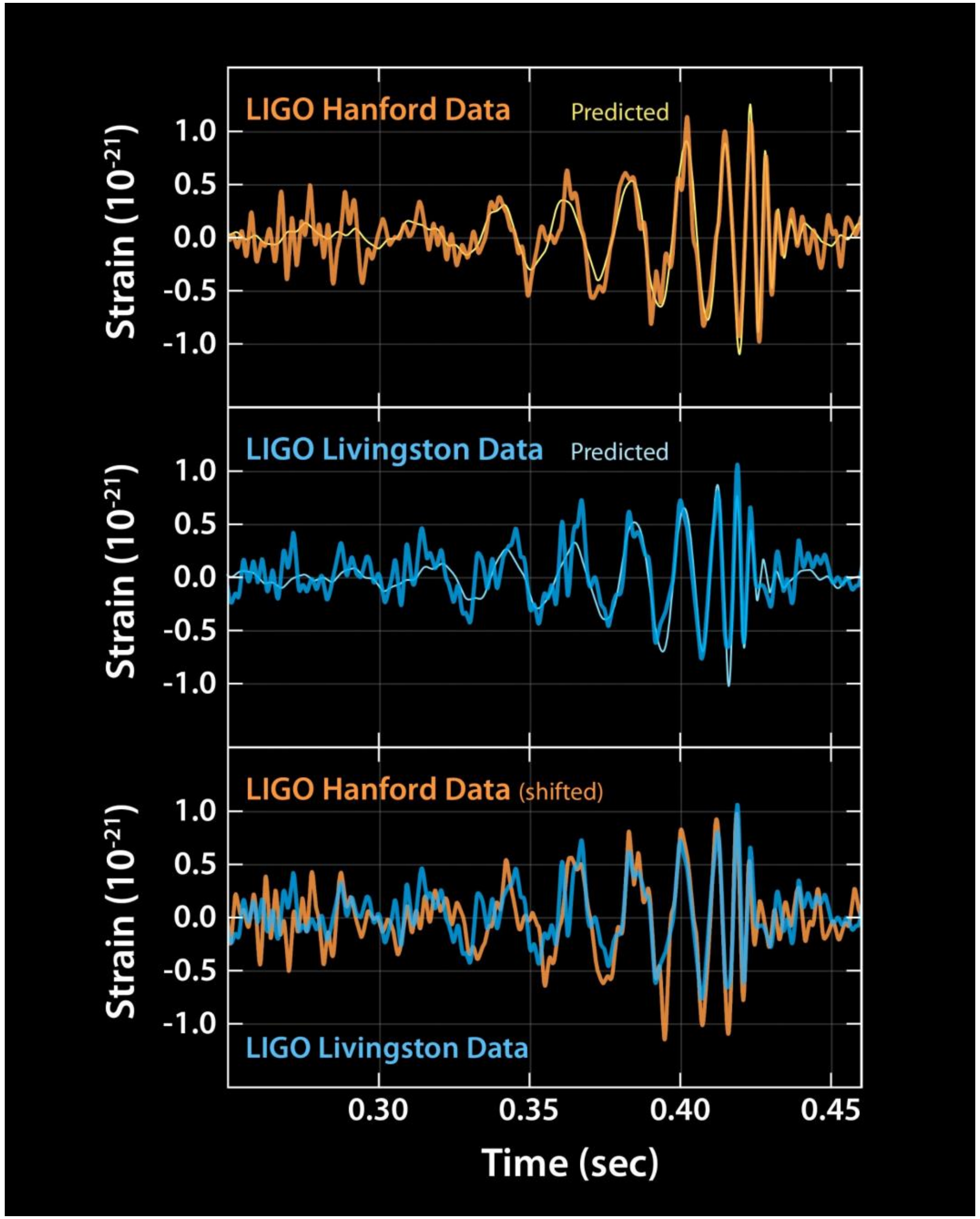
For questions, feel free to contact me at: **mariok@roe.ac.uk**

- Bonus slides below (for extra details)

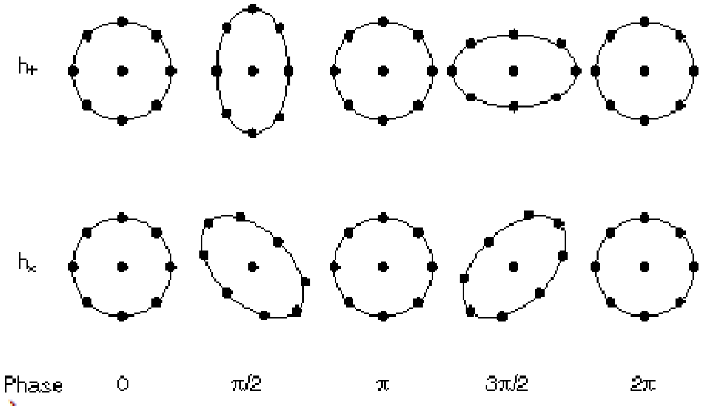
Bonus Slides

Distance from GWs

Start by fitting a template to the observed signal.



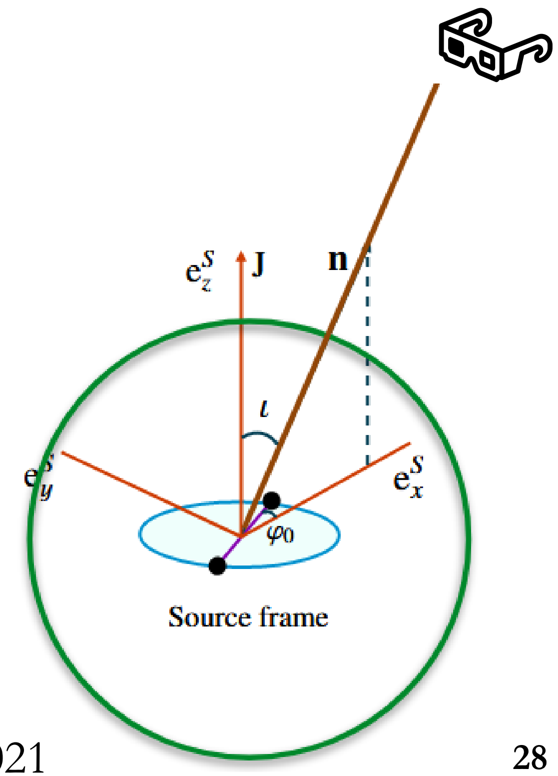
Distance from GWs



$$h_+(t,i) = \frac{4}{d_L(z)} (G\mathcal{M}_z)^{5/3} (\pi f(t^{\rm ret}))^{2/3} \left(\frac{1+\cos^2 i}{2}\right) \cos(2\Phi(t^{\rm ret}))$$

$$h_\times(t,i) = \frac{4}{d_L(z)} (G\mathcal{M}_z)^{5/3} (\pi f(t^{\rm ret}))^{2/3} \cos i \sin(2\Phi(t^{\rm ret}))$$

$$\mathcal{M}_c \equiv (1+z)M_c = (1+z)\mu^{3/5}m^{2/5}$$



*Based on D. Steer, 2021

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If we measure $h_x, h_+, \dot{f}$:

$$\dot{f}_{\rm gw}^{\rm (obs)} = \frac{96}{5} \pi^{8/3} \left(\frac{G\mathcal{M}_c(z)}{c^3}\right)^{5/3} [f_{\rm gw}^{\rm (obs)}]^{11/3}$$

$$h_+ \rightarrow h_c(1+\cos^2 \iota)/2$$

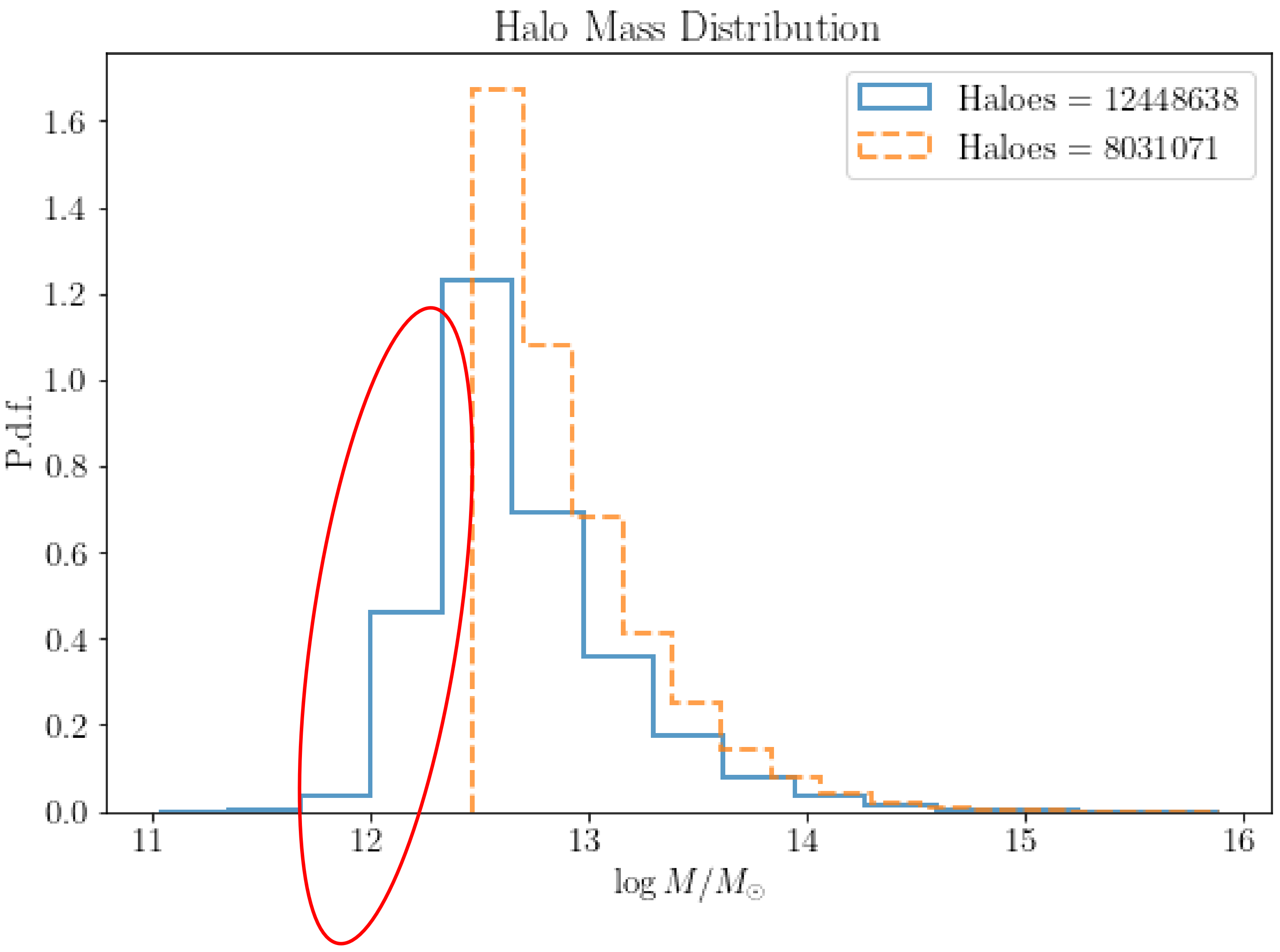
$$h_\times \rightarrow h_c \cos \iota$$

$\cos \iota$

$d_L(z)$

Dark Sirens (Simulation Technicalities)

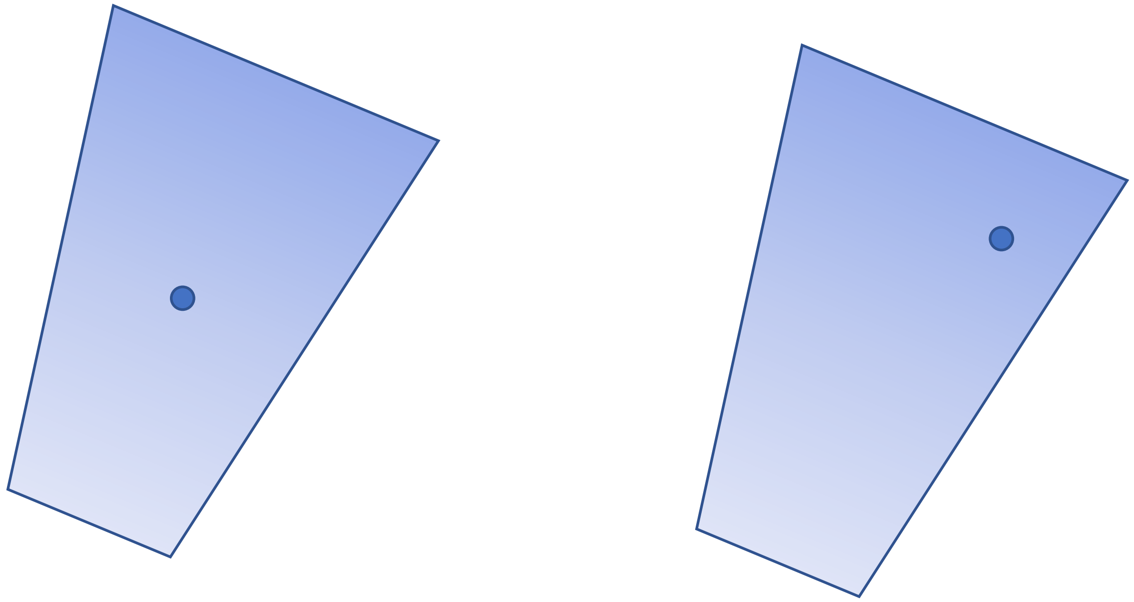
Mass threshold



These low-mass objects correspond to artificial haloes due to resolution limitations. We ignore them in our analysis.

Cone Biases

- **GW source selection**
- Cone centre selection
- Periodic Boundary conditions



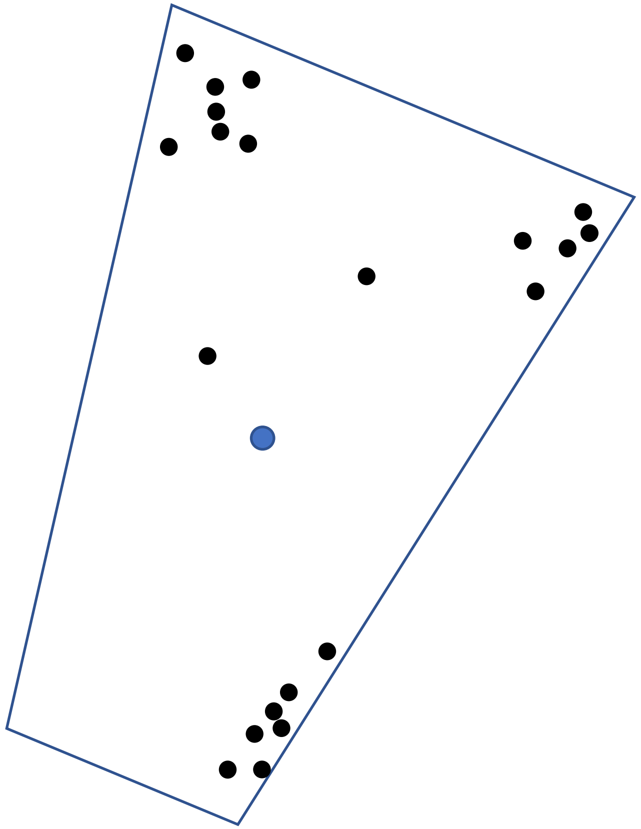
A: Centre

B: Random

Cone Biases

Possible artificial configurations

- GW source selection
- **Cone centre selection**
- Periodic Boundary conditions

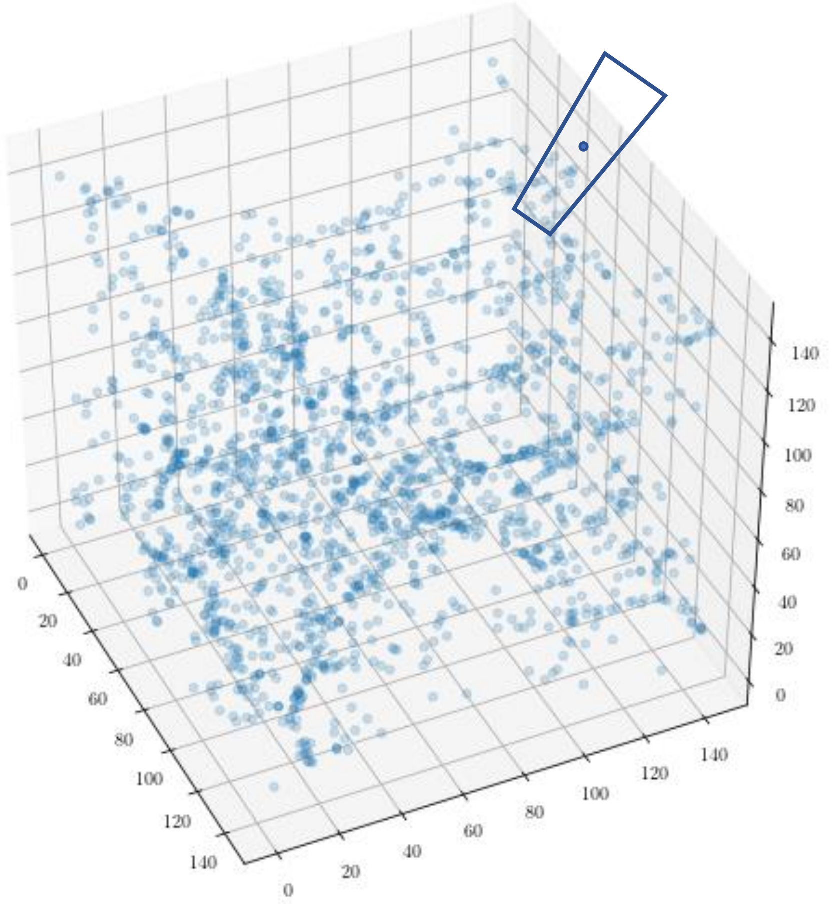


Centre in random coordinates (instead of halo)
– not that important in terms of statistics.

Cone Biases

Missing galaxies (bias towards lower Ho)

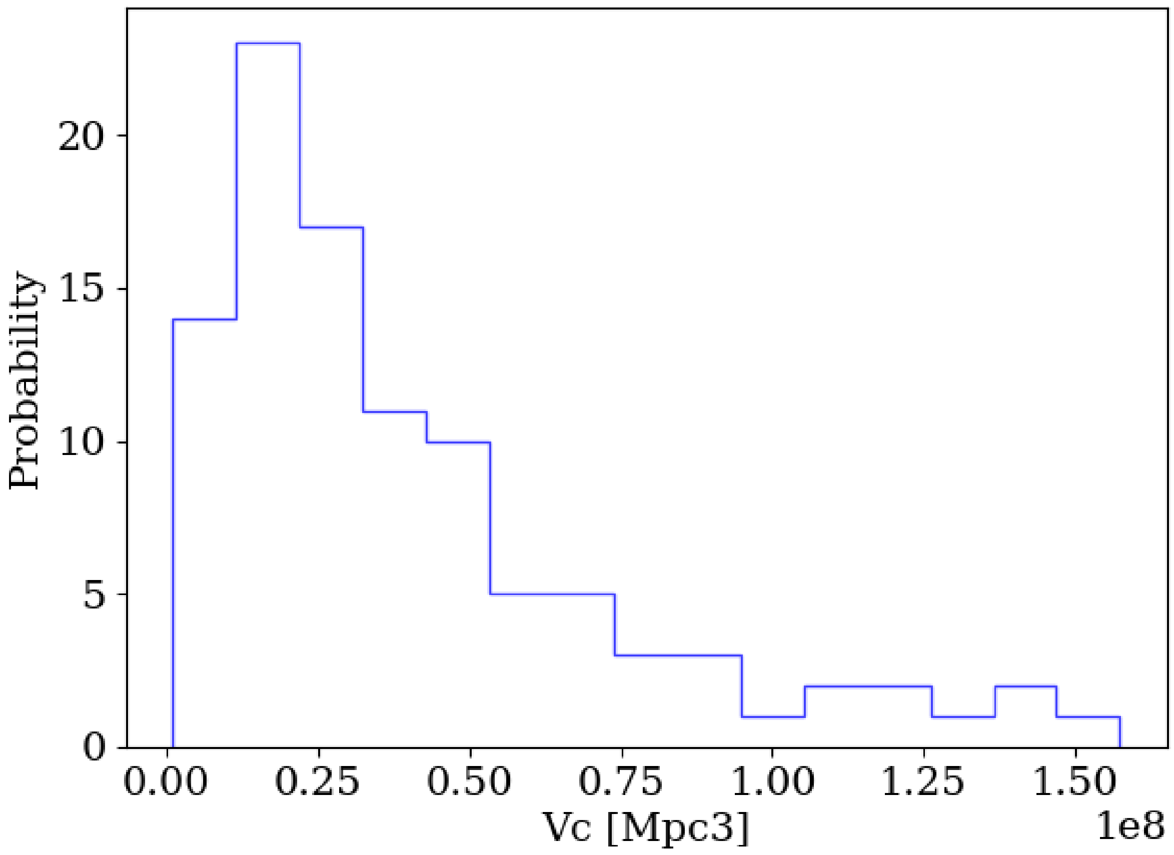
- GW source selection
- Cone centre selection
- **Periodic Boundary conditions**



Cone Biases

- Volume effects

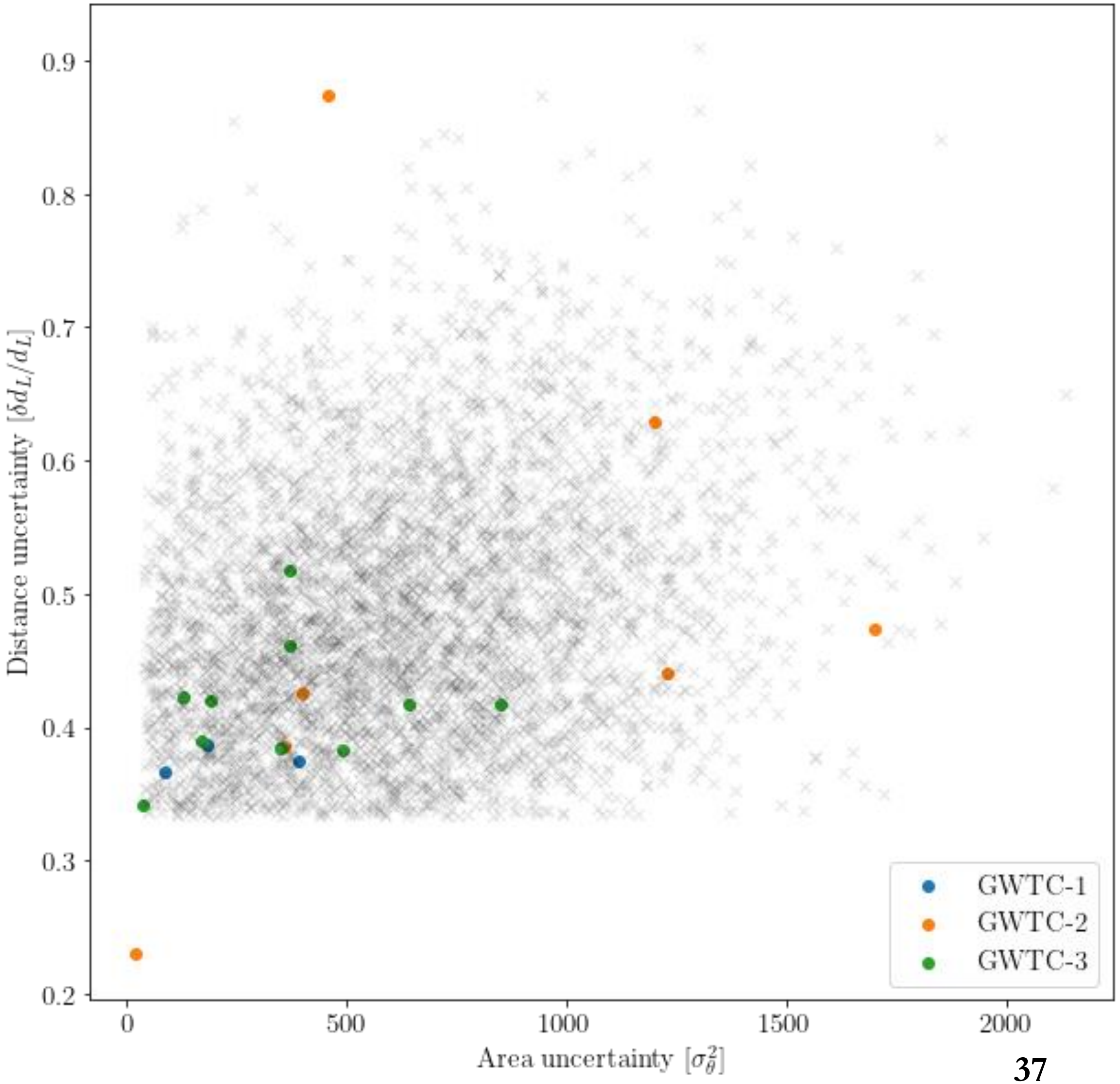
The volumes of our cones, in the fiducial case are consistent with observations, but we have about an order of magnitude fewer haloes inside our cones (than observations).



Dark Sirens (and the Hubble tension)

Error Distribution

When selecting the cone sizes, we draw the distance & sky localisation errors from a distribution that mimics well localised events from the first three observing runs.



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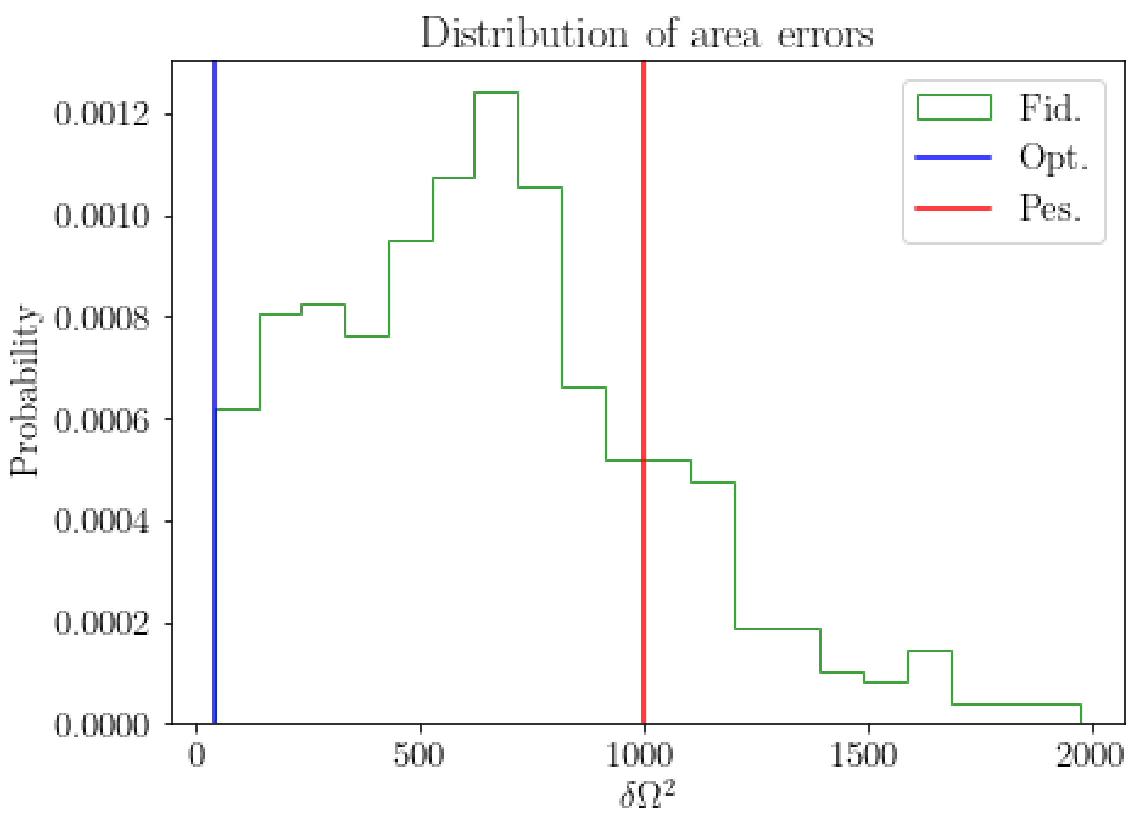
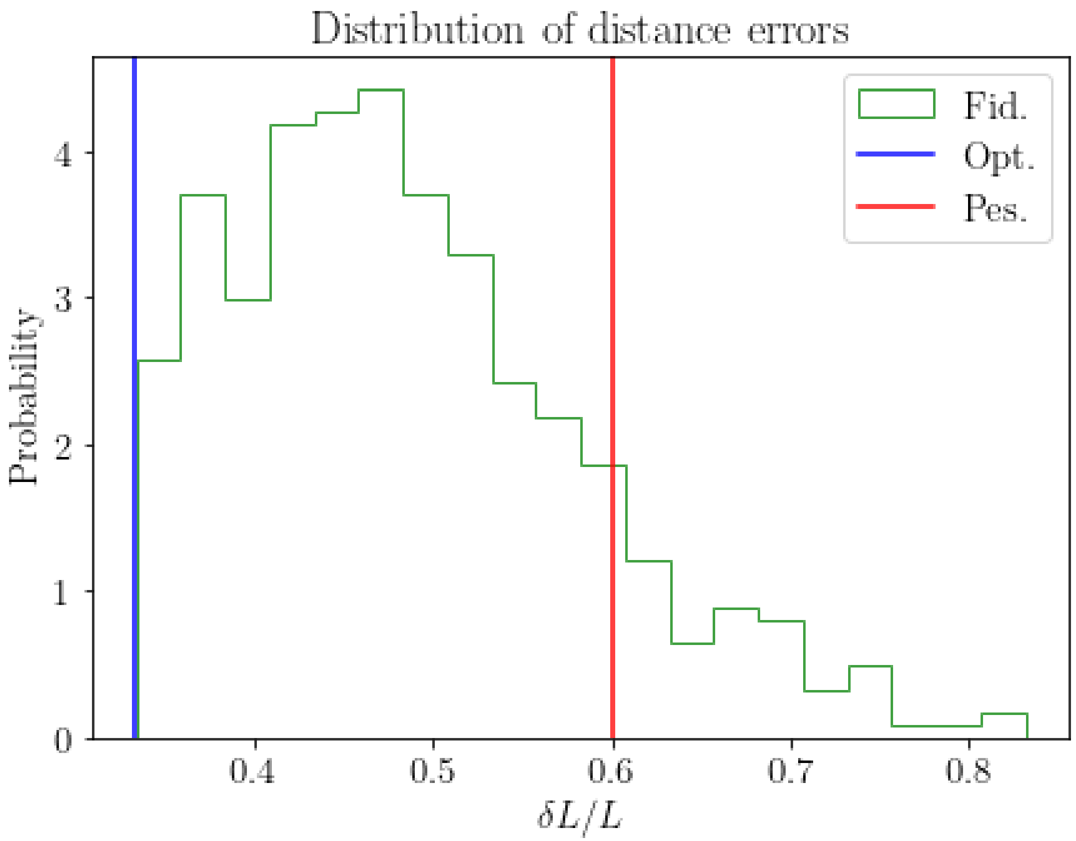


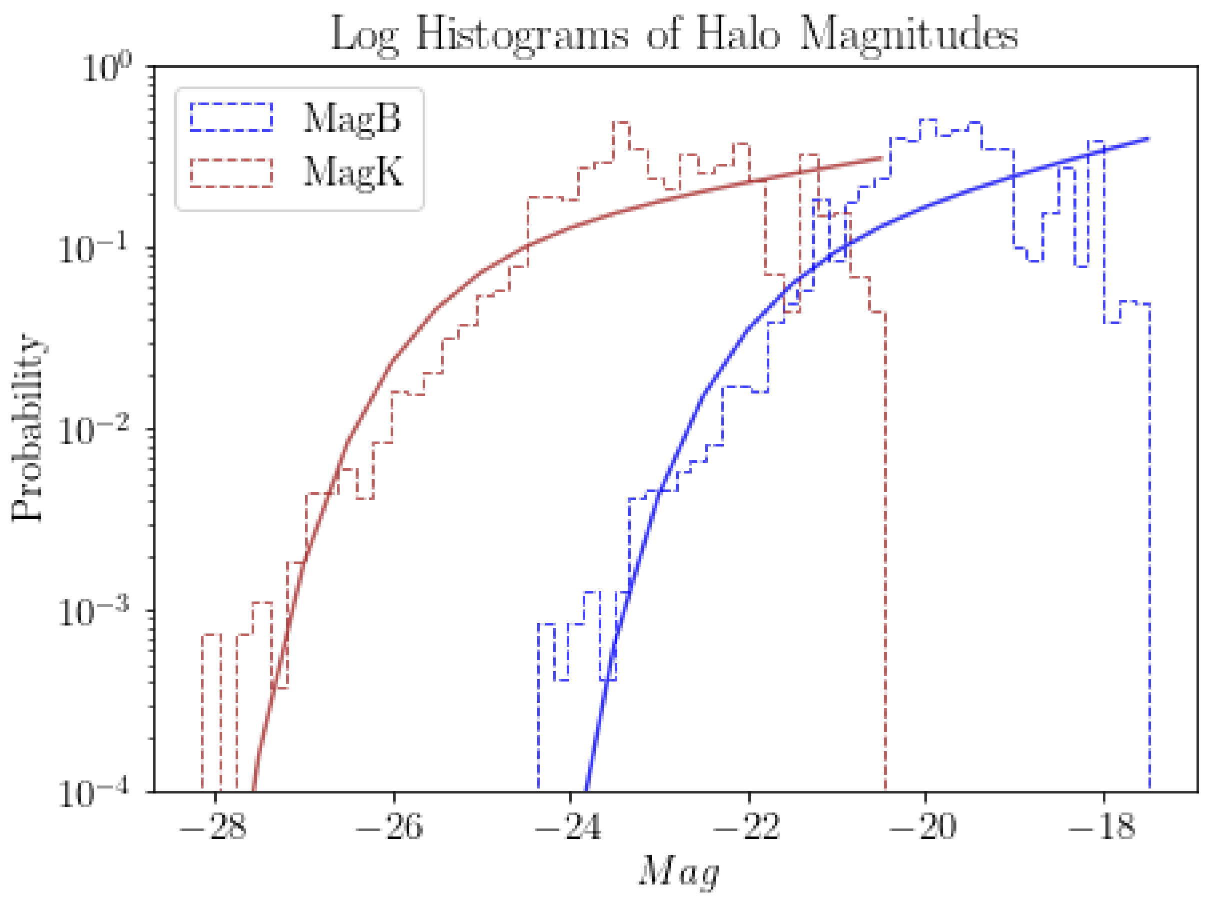


Magnitudes & Masses of the galaxies

We give physical properties to our haloes, by using a ML approach, trained on IllustrisTNG data. The latter provide eight bands: U, B, V, K, g, r, i, z. Magnitudes based on the summed-up luminosities of all the stellar particles of the group.

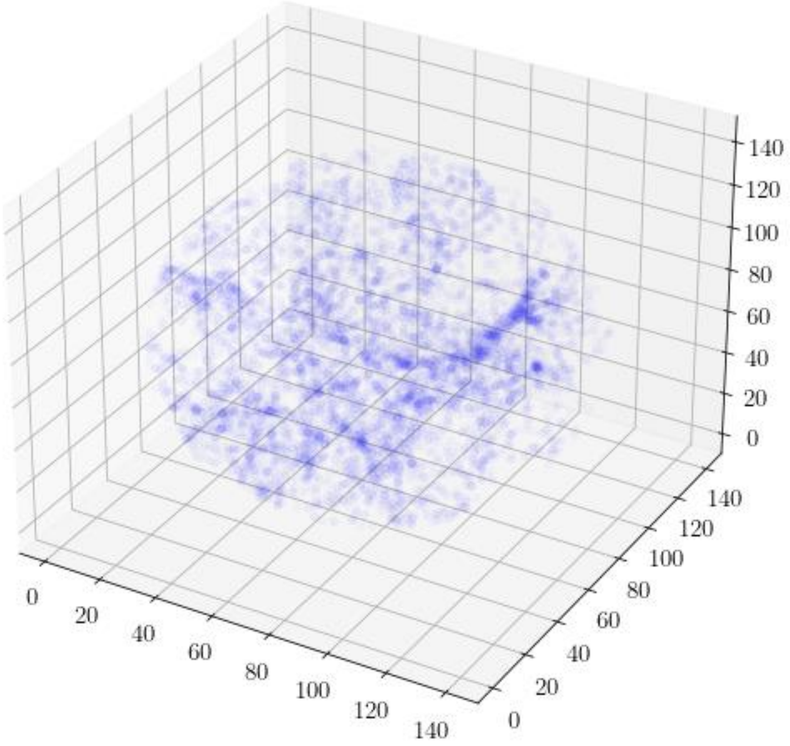
By using *SubhaloSpin*, *SubhaloVmax*, *SubhaloVelDisp*, and *SubhaloMass*, as our probes, we provide B & K magnitudes & SFRs for our DM haloes (see McGibbon & Khochfar 2021 for details). Galaxies masses are calculated using the Stellar-to-Halo mass relation from Girelli et al. 2020).

Right: Sanity check that our ML magnitudes follow a Schechter magnitude function.

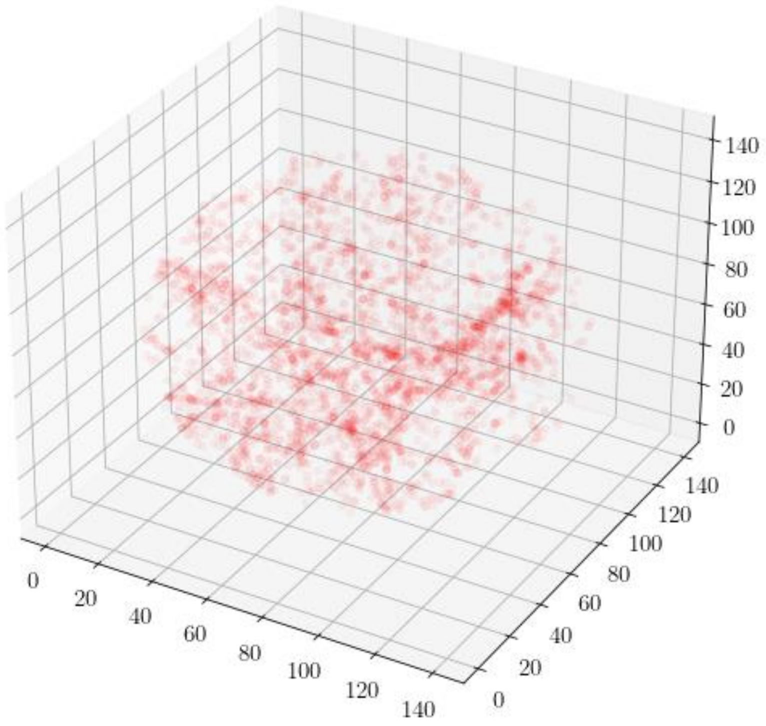


Completeness fractions

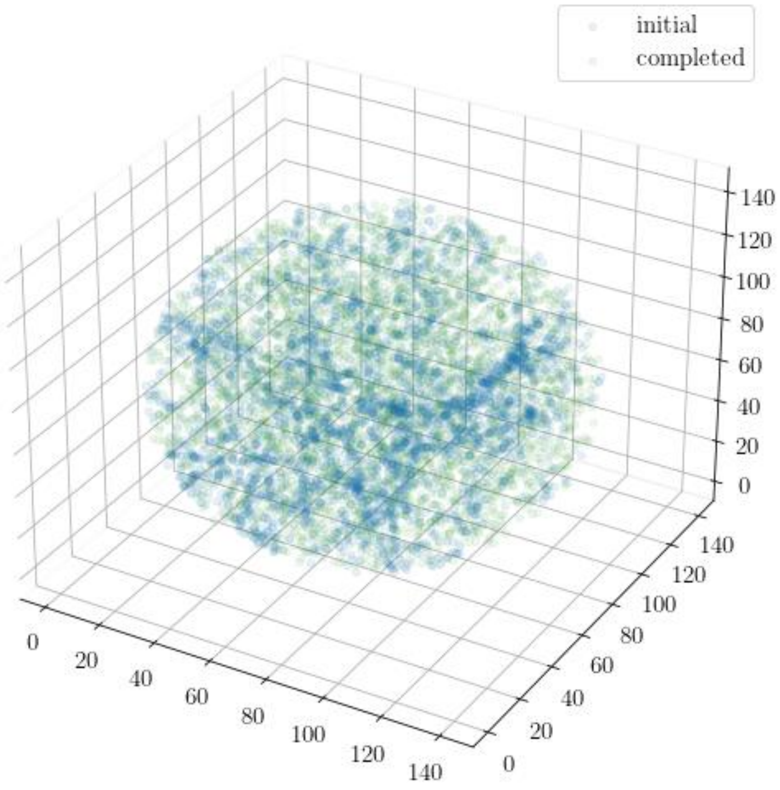
Observational limitations would lead to galaxies missing from the surveys. We need to take these into account when calculating the Ho posterior. We do this by uniformly completing the surveys, before analysing them.



Original Sphere



Sphere after cut



Sphere after completion

Example, where 50% of the galaxies are thrown away, based on a mass threshold.

Completeness fractions

When completing the survey, we make sure that the missing galaxies in each cone follow the global completeness fraction.