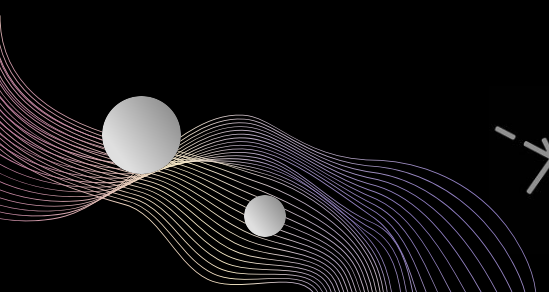
Korea–Italy Workshop on Multi-Messenger Astrophysics and Cosmology

L'Aquila, 27 October 2026

Radio sirens: inferring the Hubble constant with binary black holes and neutral hydrogen in the Einstein Telescope – SKA Observatory era

Ulyana Dupletsa











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Radio sirens: inferring the Hubble constant with binary black holes and neutral hydrogen in the Einstein Telescope – SKA Observatory era

In collaboration with Simone Mastrogiovanni, Marta Spinelli, Tommaso Ronconi, Matteo Schulz, Riccardo Murgia, Jan Harms, Tessa Baker, Matteo Calabrese, Carmelita Carbone, Steven Cunnington, Ian Harrison, Konstantin Leyde, Dounia Nanadoumgar-Lacroze

arXiv: 2605.12606

$$d_{\rm L} = c(1+z)\int_0^z \frac{dz'}{H(z')}$$

Two independent measurements are required:

$$d_{\mathrm{L}} = c(1+z)\int_0^z \frac{dz'}{H(z')}$$

Two independent measurements are required:
distance and **redshift**

GWs

$$d_{\mathrm{L}} = c(1+z)\int_0^z \frac{dz'}{H(z')}$$

Gravitational waves are ***standard sirens***

GWs

$$d_{\mathrm{L}} = c(1+z)\int_0^z \frac{dz'}{H(z')}$$

- No external redshift source: modelling of feature in the mass spectrum (***spectral sirens***)

GWs

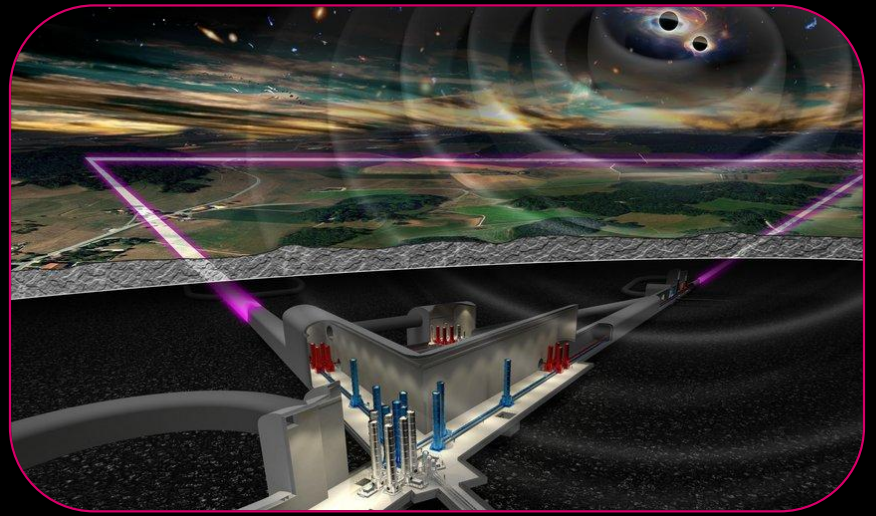
$$d_{\mathrm{L}} = c(1+z)\int_0^z \frac{dz'}{H(z')}$$

- External electromagnetic redshift source:
  - Identification of host galaxy: unique host (***bright sirens***), statistical association in localization volume (***dark sirens***)
  - Intensity mapping of large scale structure tracer through neutral hydrogen (***radio sirens***) to model the line of sight redshift prior

SKA Observatory

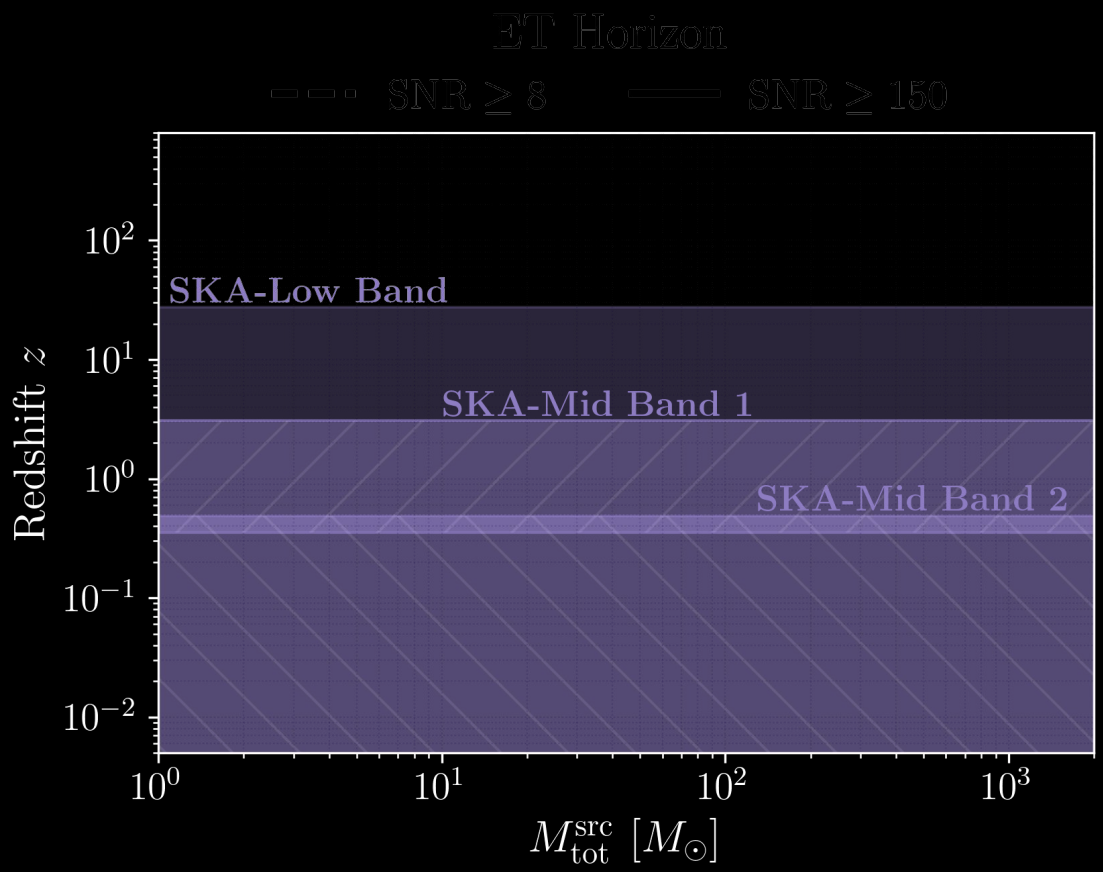


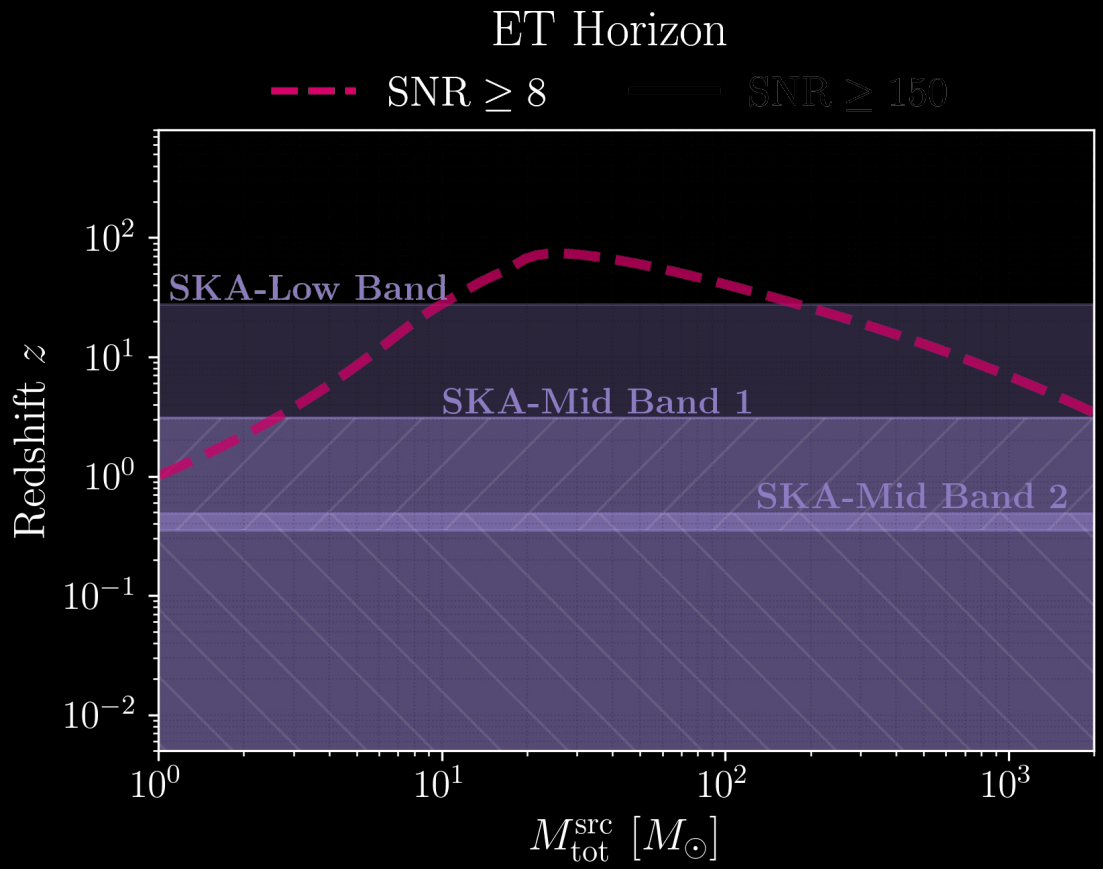
Einstein Telescope

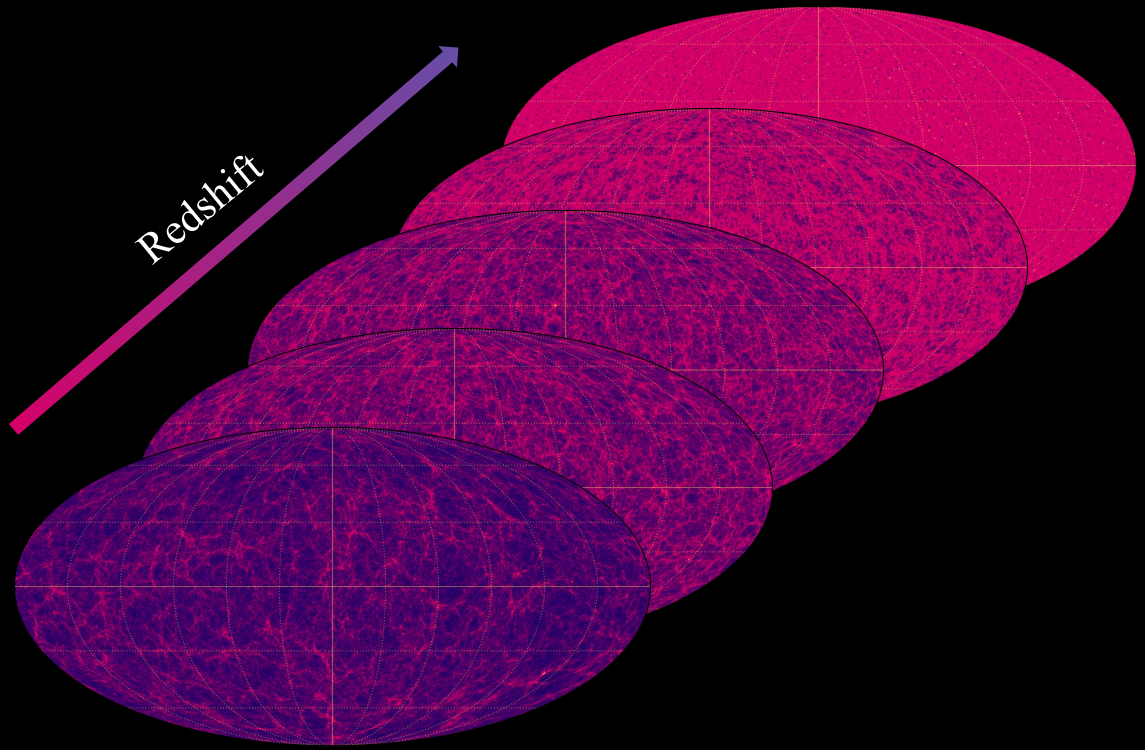


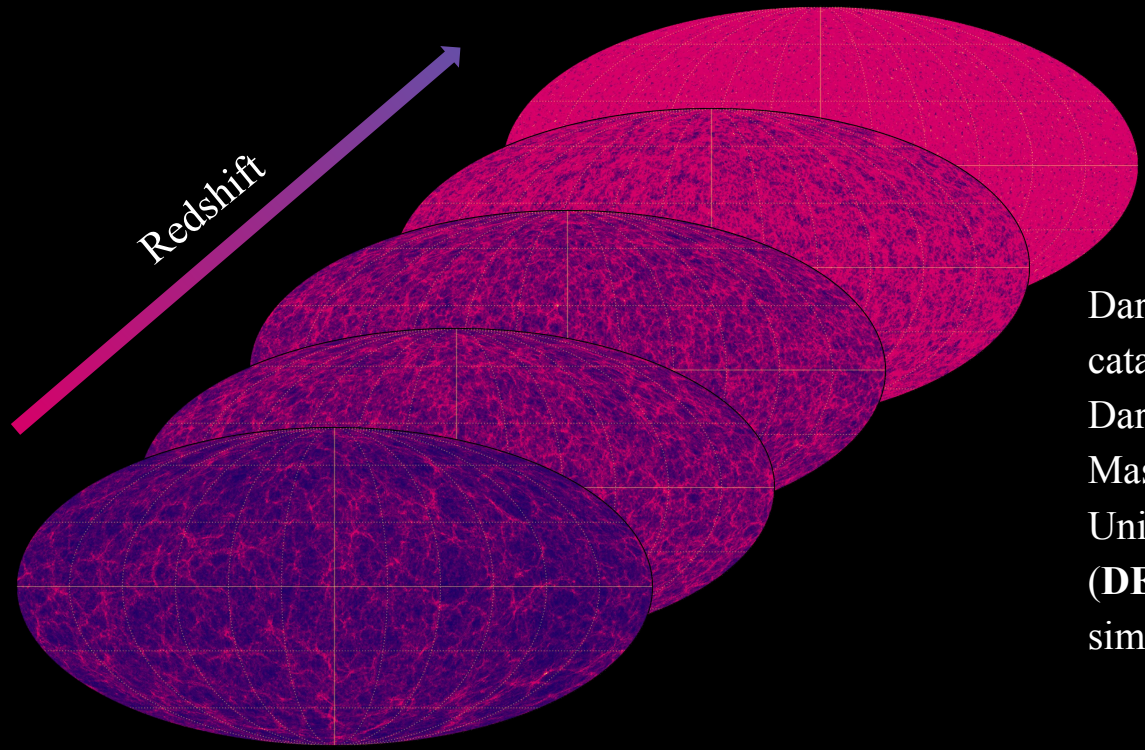
~2030

~2040


ET Horizon
SNR ≥ 8
SNR ≥ 150
SKA-Low Band
SKA-Mid Band 1
SKA-Mid Band 2
Redshift z
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{0}
10^{1}
10^{2}
10^{3}
$M_{\rm tot}^{\rm src}$ $[M_\odot]$


ET Horizon
SNR ≥ 8
SNR ≥ 150
SKA-Low Band
SKA-Mid Band 1
SKA-Mid Band 2
Redshift z
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{0}
10^{1}
10^{2}
10^{3}
$M_{\rm tot}^{\rm src}$ $[M_\odot]$

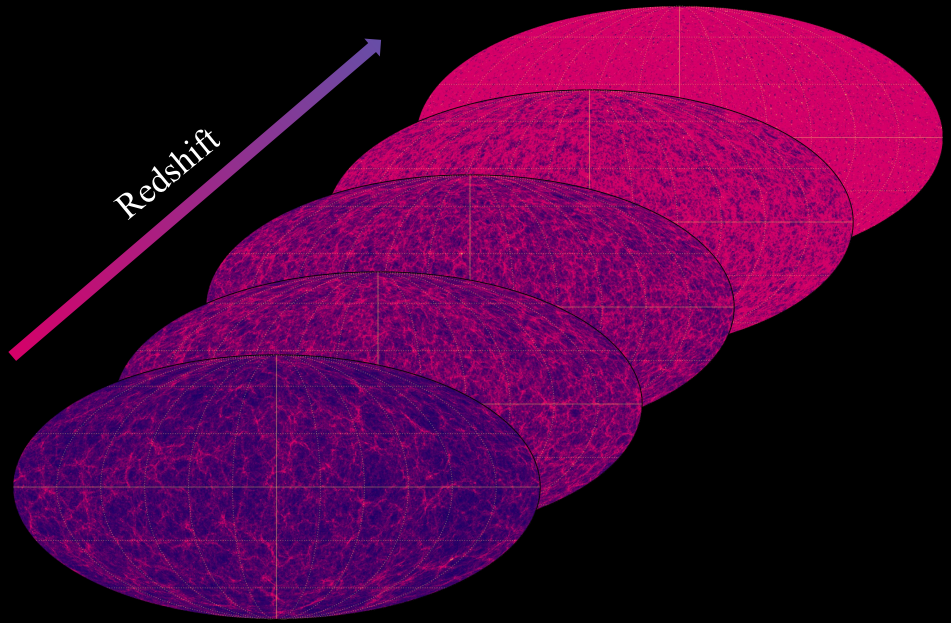

Redshift



Dark matter halo catalogs from the Dark Energy and Massive Neutrino Universe (**DEMNUni**) N-body simulations

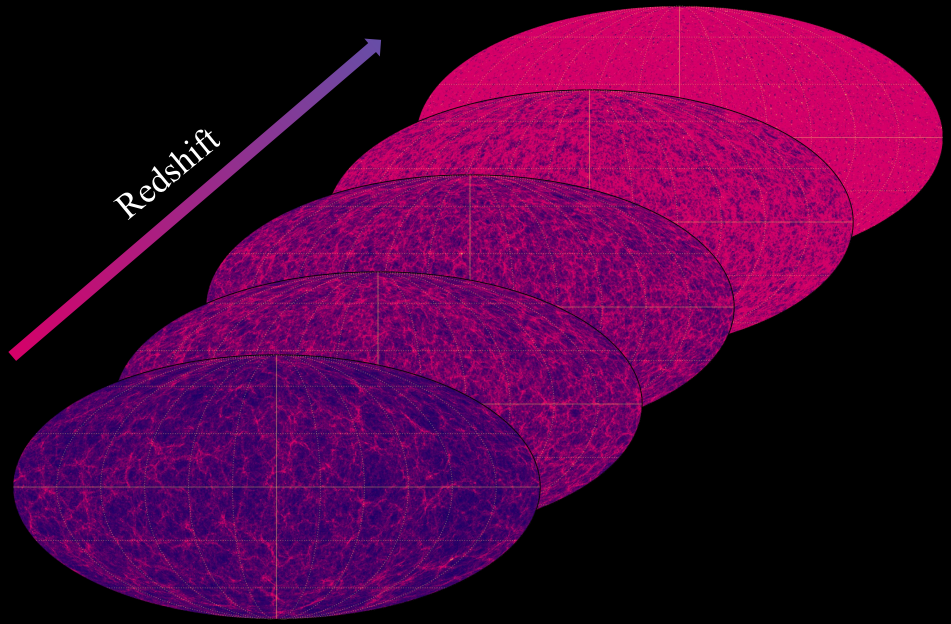
[Castorina et al. 2015, Carbone et al. 2016, Parimbelli et al. 2021]

HI

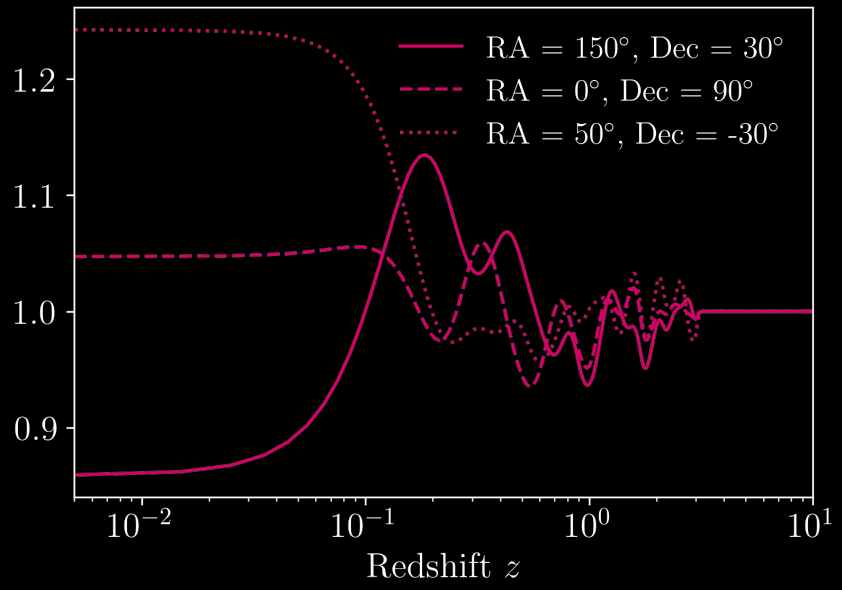


Neutral hydrogen follows the dark matter maps and supplies the line of sight redshift prior

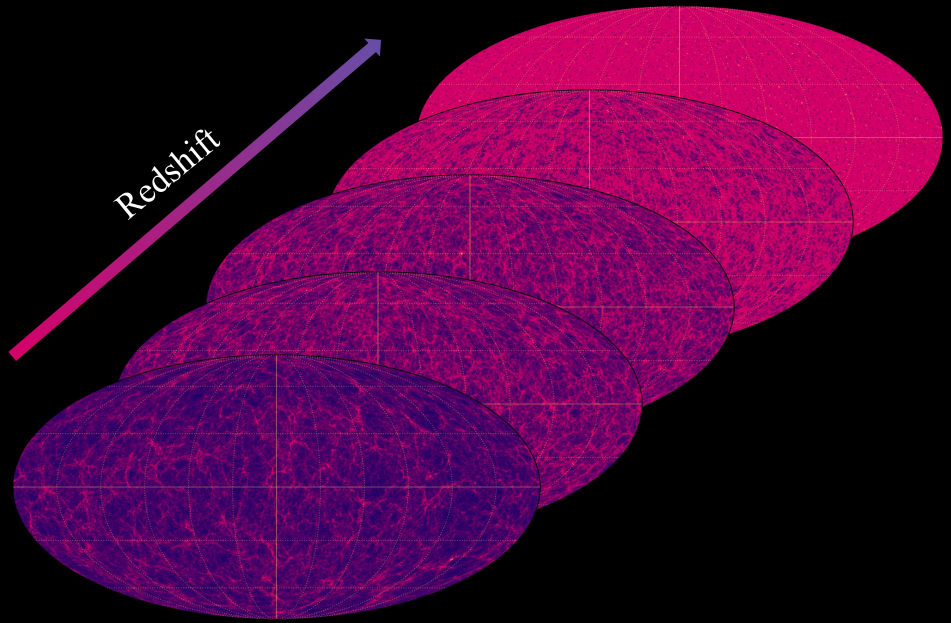
HI



Neutral hydrogen follows the dark matter maps and supplies the line of sight redshift prior

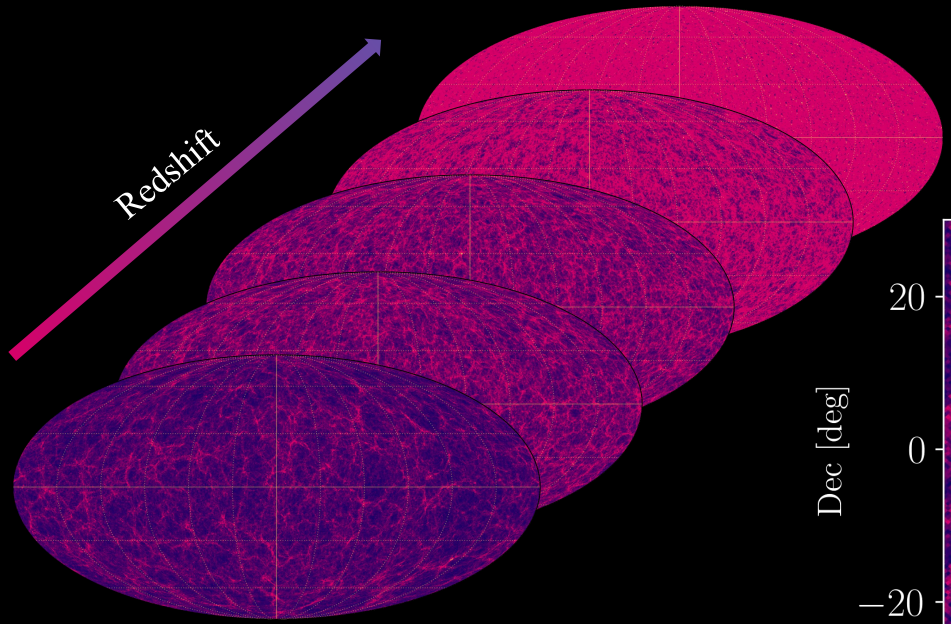


BBHs

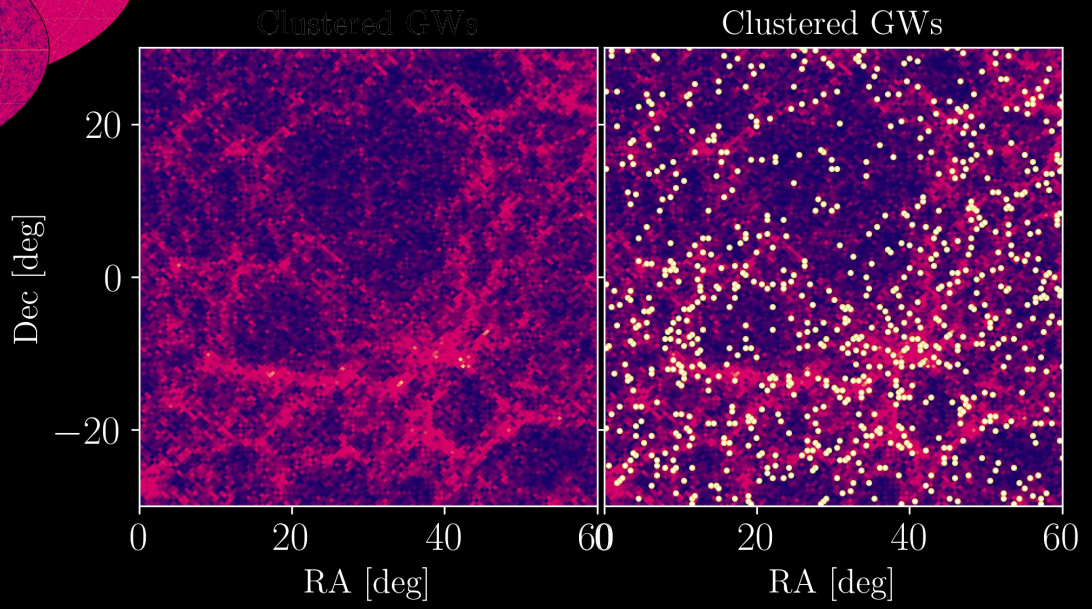


Mock binary black holes are distributed according the same dark matter maps

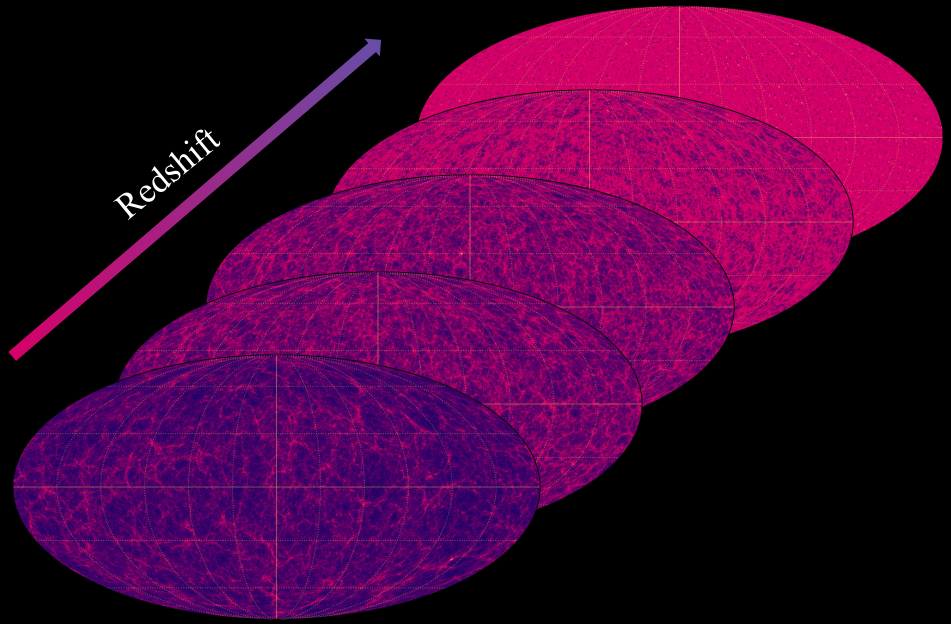
BBHs



Mock binary black holes are distributed according the same dark matter maps

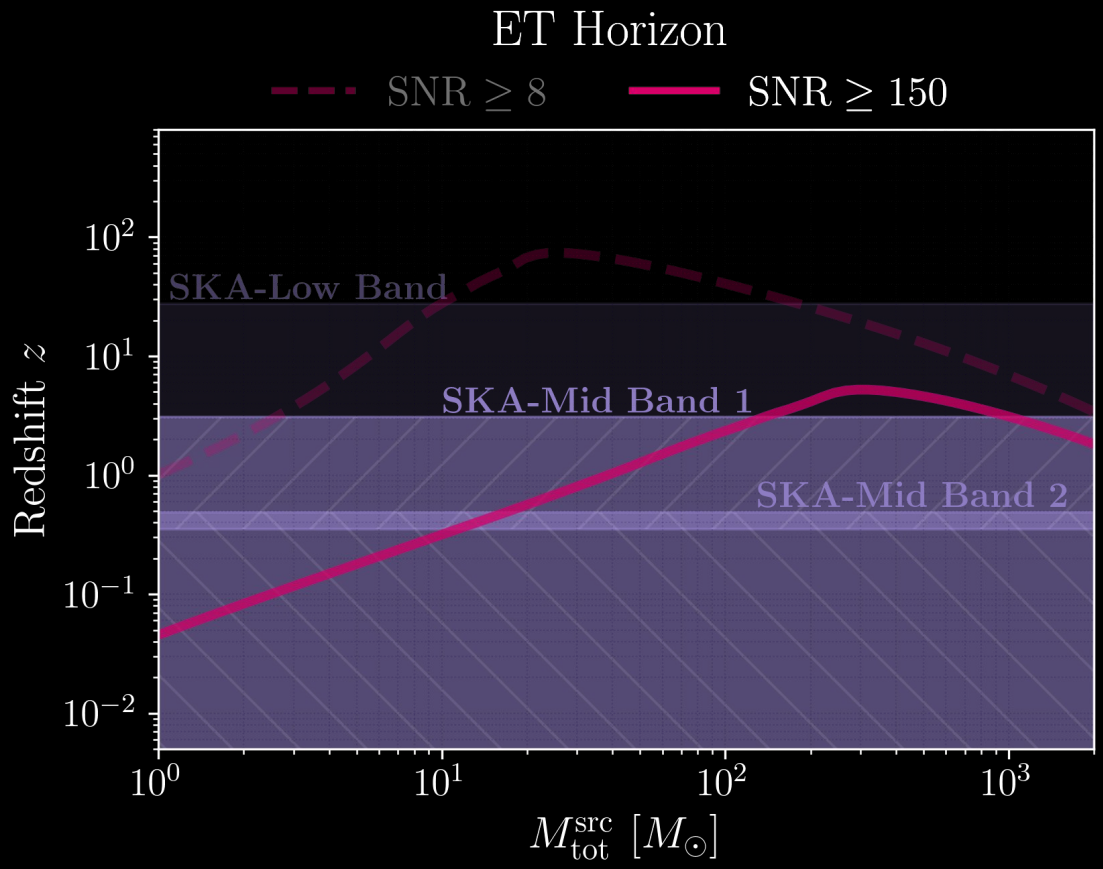


BBHs



Mock binary black holes are distributed according the same dark matter maps

~ **3100** detected events with a signal to noise ratio of at least **150** with Fisher matrix based posteriors


ET Horizon
SNR ≥ 8
SNR ≥ 150
SKA-Low Band
SKA-Mid Band 1
SKA-Mid Band 2
Redshift z
10^2
10^1
10^0
10^{-1}
10^{-2}
10^0
10^1
10^2
10^3
$M_{\rm tot}^{\rm src}$ $[M_\odot]$



How constraining is the information encoded in the HI-supplied **line-of-sight redshift priors**?

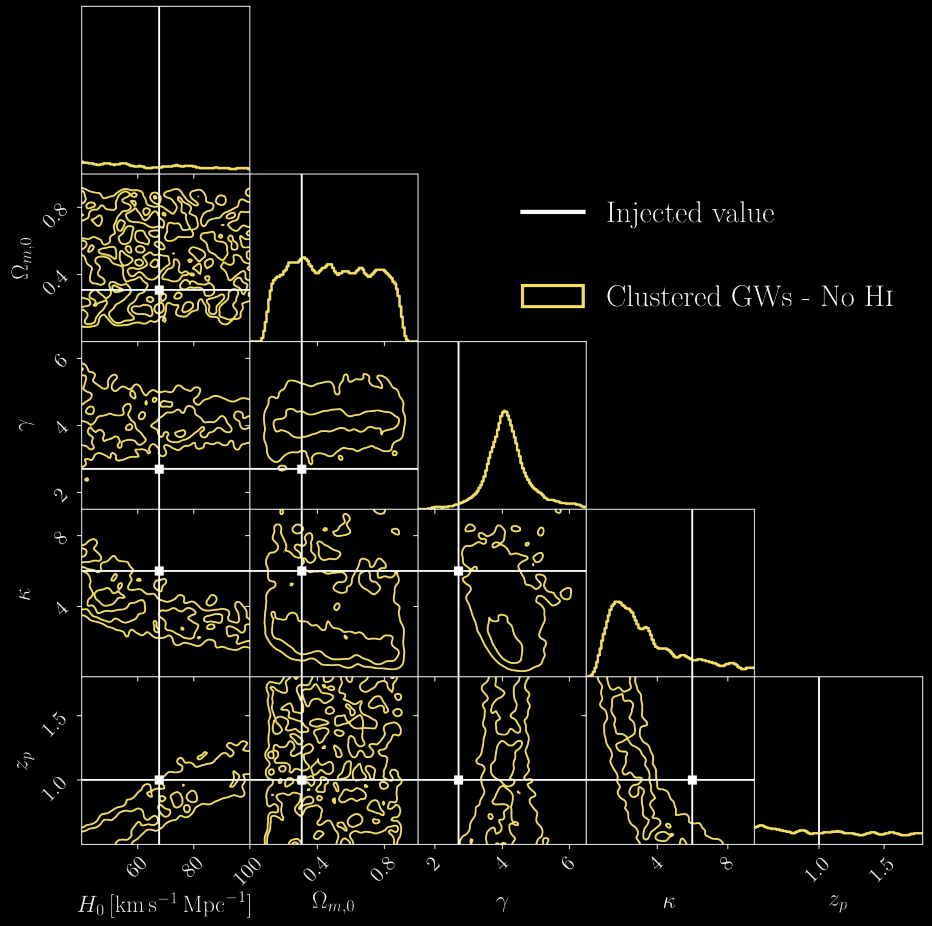


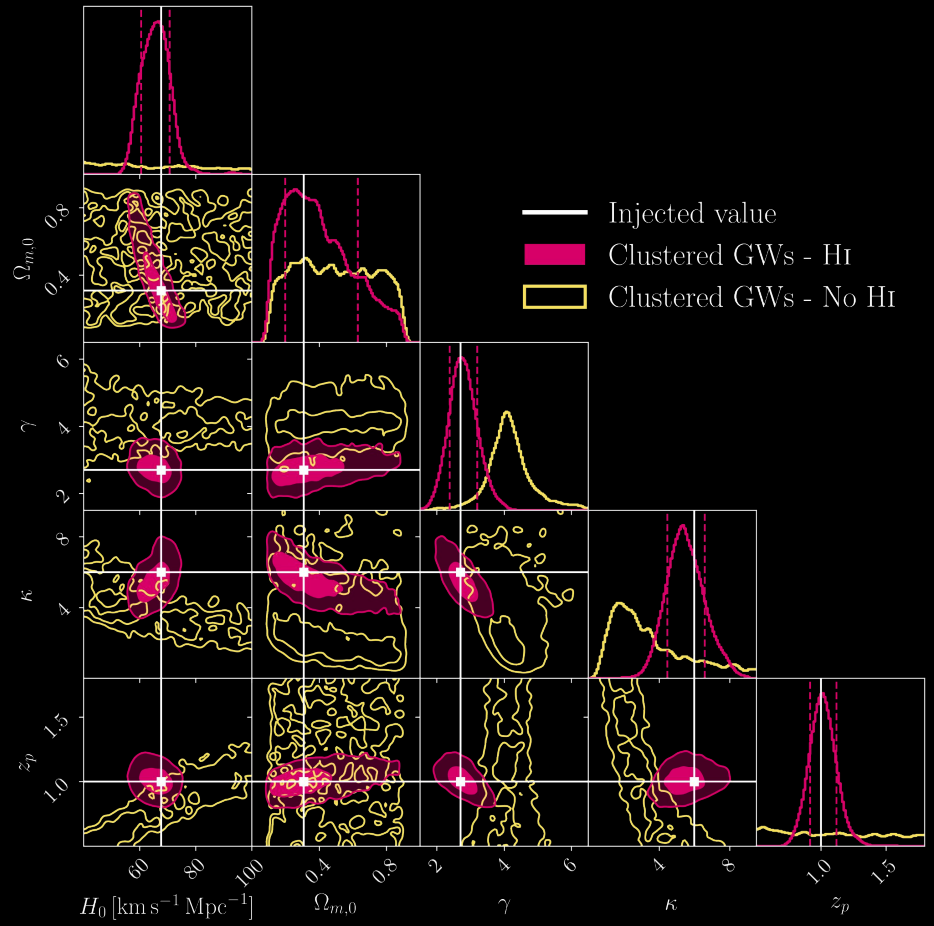
For forecasts on the **cross-correlation** constraining power see **Matteo's talk**!

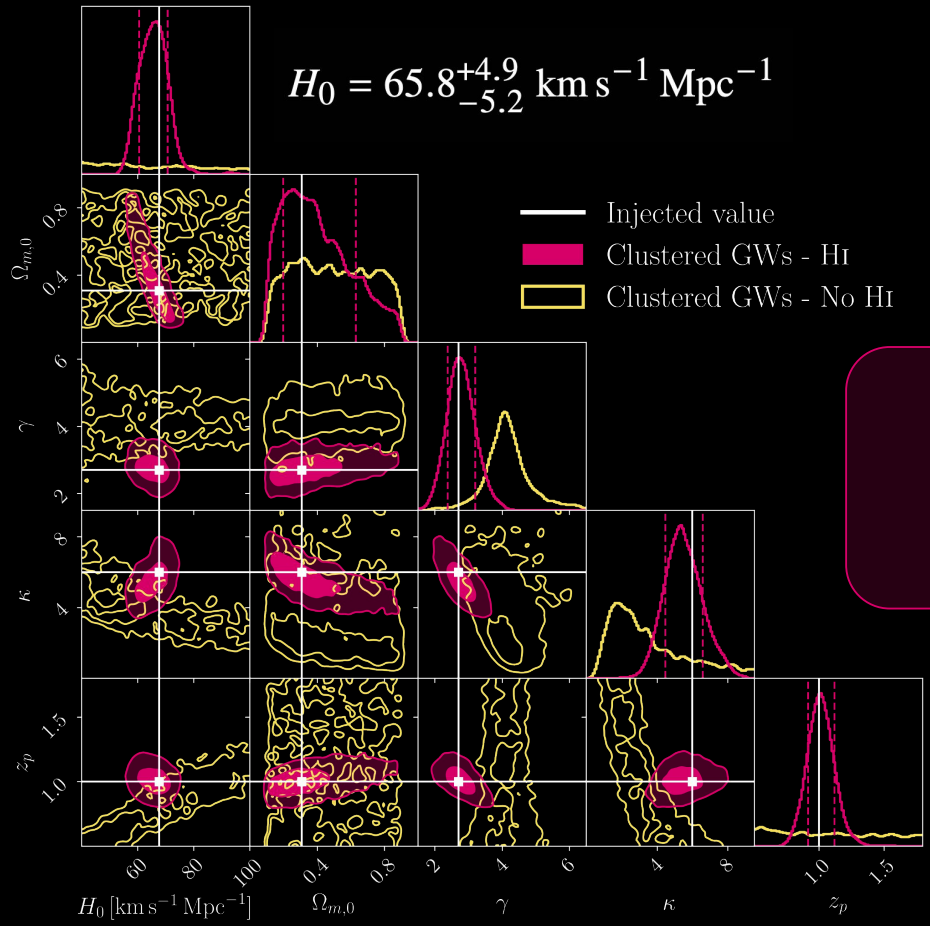


We only supply the HI information (+ a Madau-Dickinson rate model)

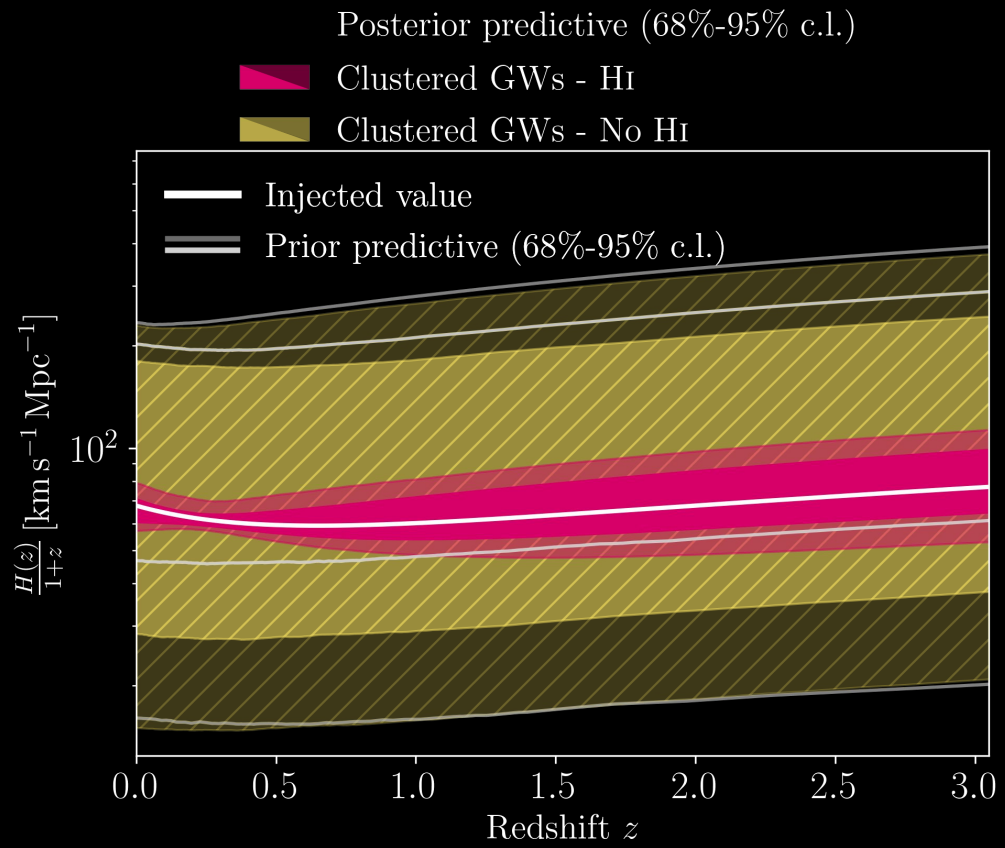
We do NOT use spectral sirens!

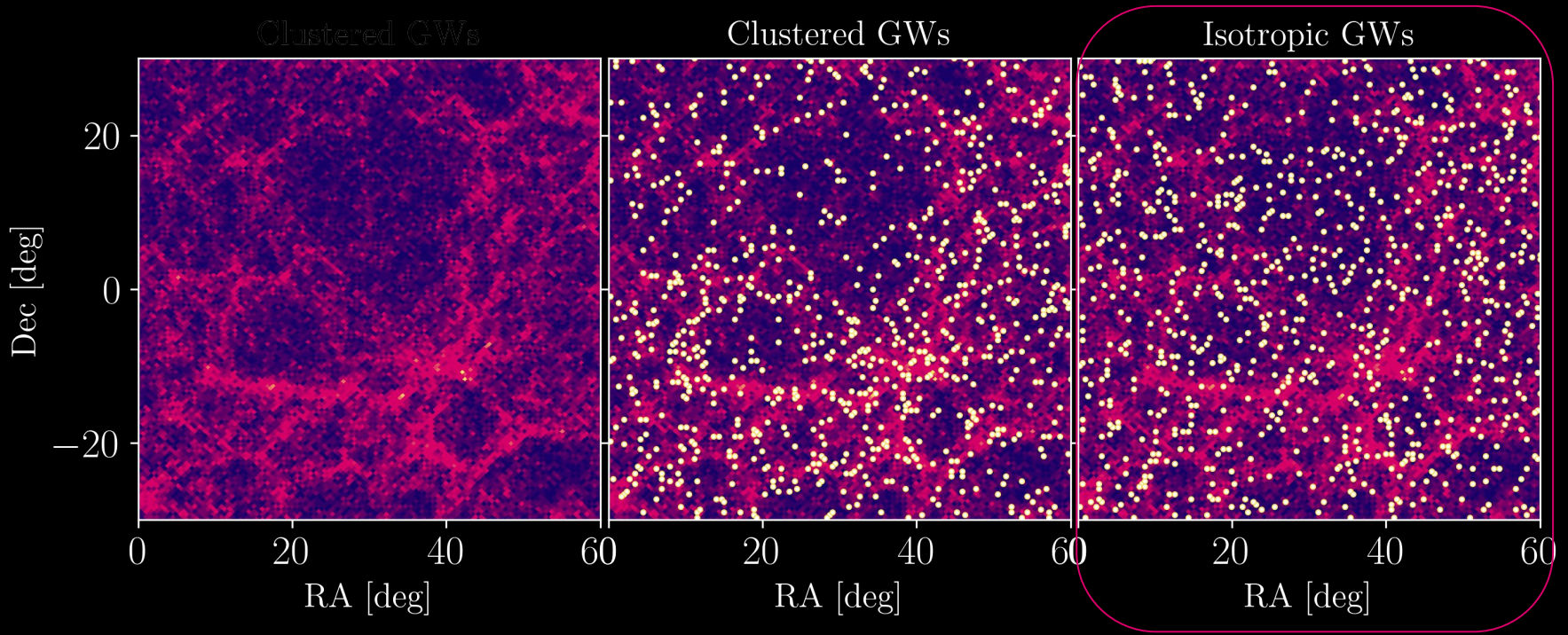

Injected value
Clustered GWs - No HI
H_0 [km s^{-1} Mpc^{-1}]
$\Omega_{m,0}$
γ
κ
z_p

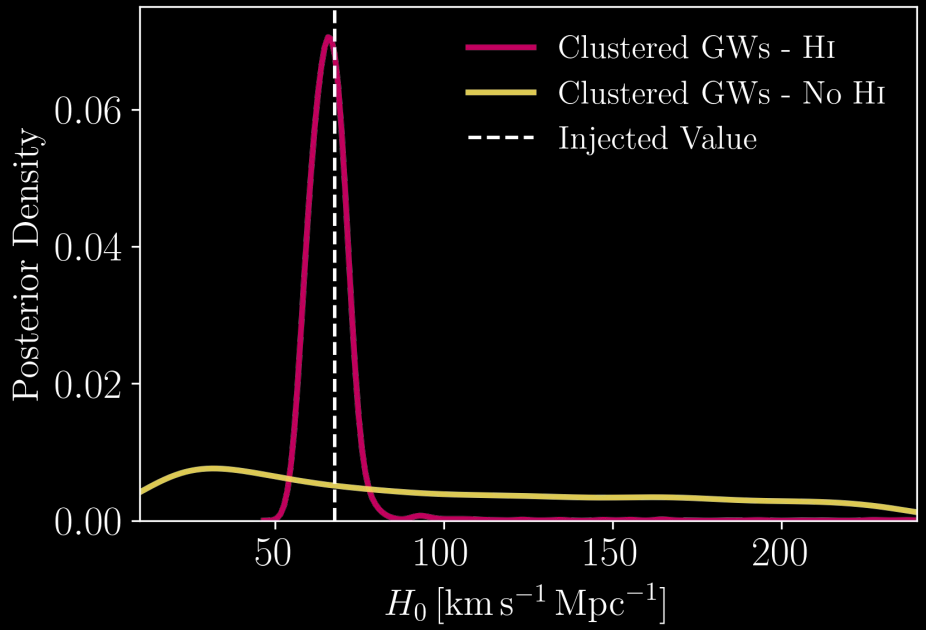

Injected value
Clustered GWs - HI
Clustered GWs - No HI
H_0 [km s^{-1} Mpc^{-1}]
$\Omega_{m,0}$
γ
κ
z_p

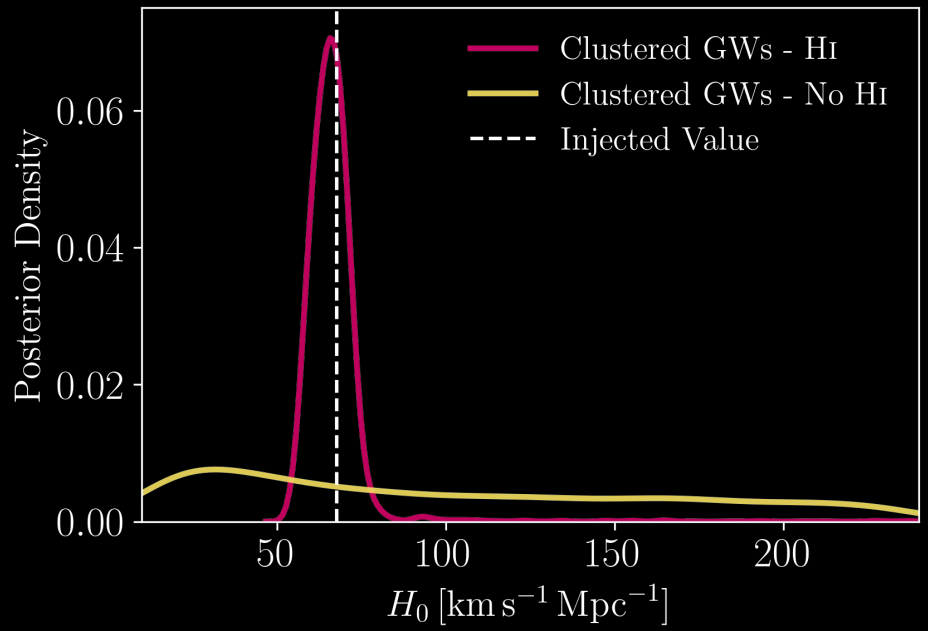


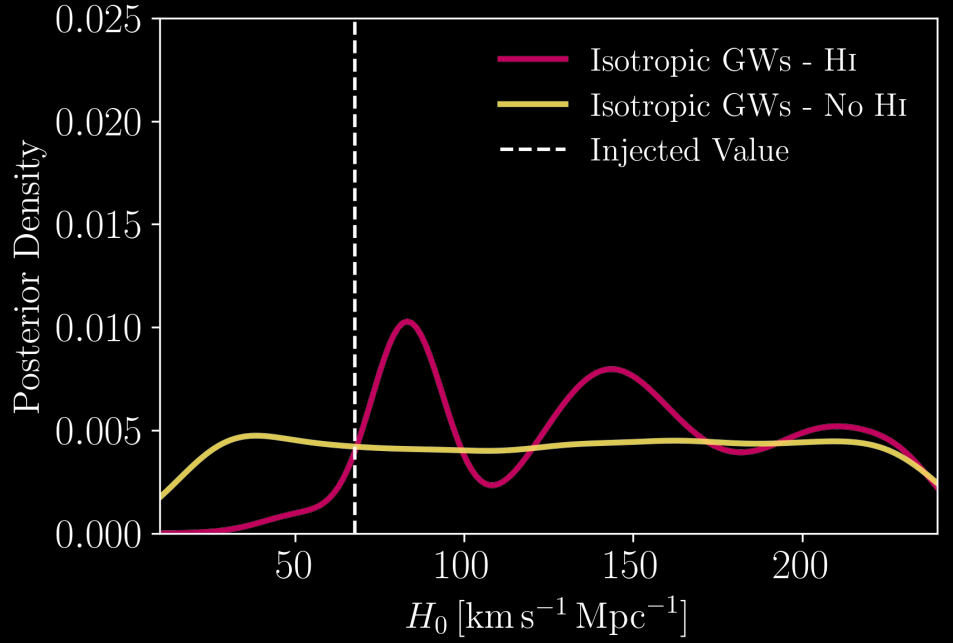
8% precision!
90% better than not considering HI information

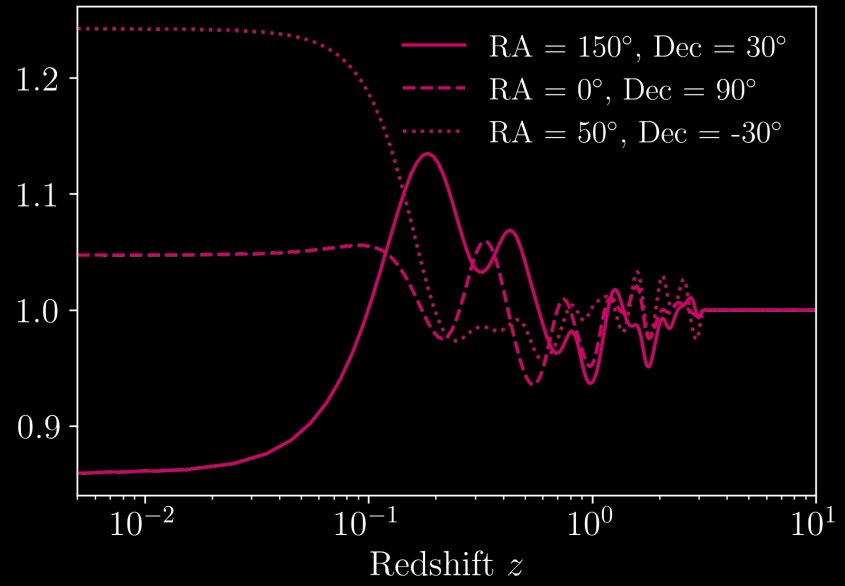

Posterior predictive (68%-95% c.l.)
Clustered GWs - HI
Clustered GWs - No HI
Injected value
Prior predictive (68%-95% c.l.)
$\frac{H(z)}{1+z}$ [km s^{-1} Mpc^{-1}]
10^2
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Redshift z


Clustered GWs
Clustered GWs
Isotropic GWs
Dec [deg]
20
0
−20
0
20
40
60
RA [deg]
RA [deg]
RA [deg]

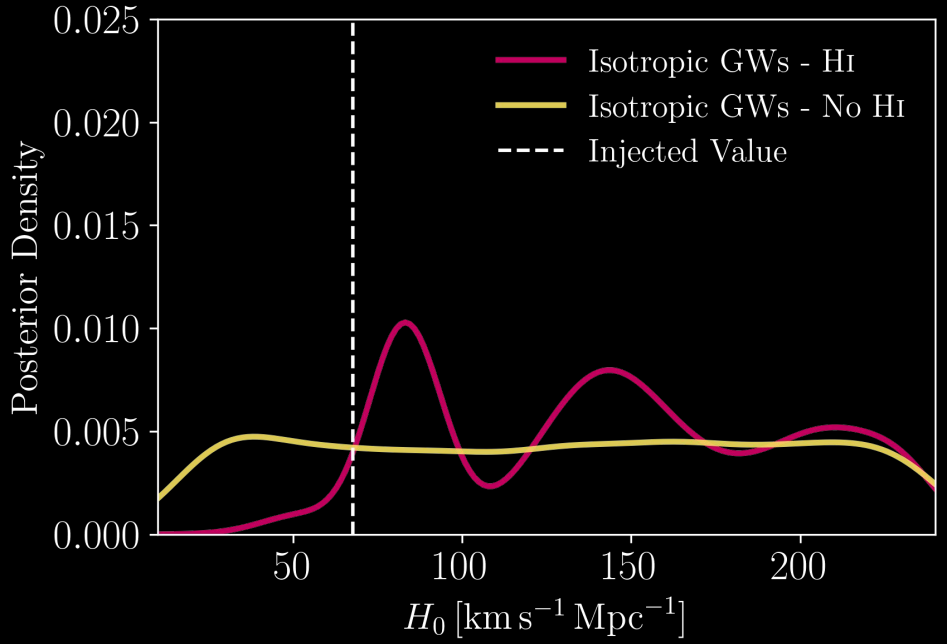

Clustered GWs - HI
Clustered GWs - No HI
Injected Value
Posterior Density
0.00
0.02
0.04
0.06
50
100
150
200
H_0 [km s^{-1} Mpc^{-1}]

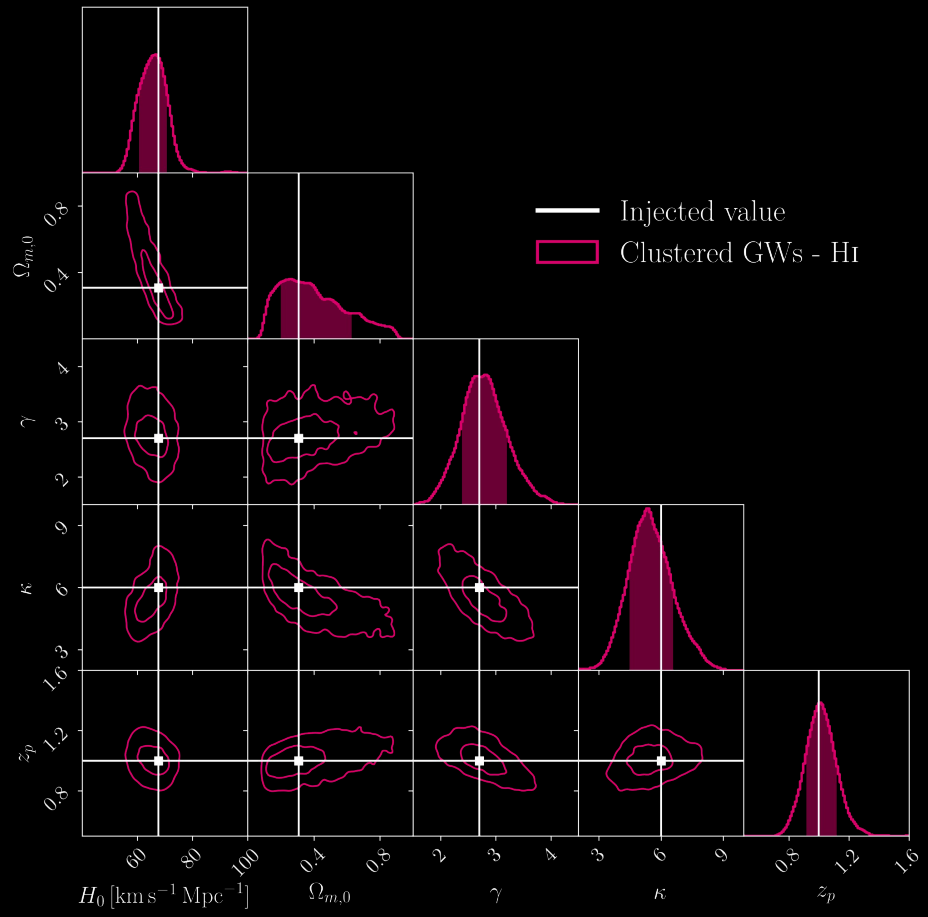

Clustered GWs - HI
Clustered GWs - No HI
Injected Value
Posterior Density
0.00
0.02
0.04
0.06
50
100
150
200
H_0 [km s^{-1} Mpc^{-1}]


Isotropic GWs - HI
Isotropic GWs - No HI
Injected Value
Posterior Density
0.000
0.005
0.010
0.015
0.020
0.025
50
100
150
200
H_0 [km s^{-1} Mpc^{-1}]



$$d_L \sim \frac{cz}{H_0}$$




Injected value
Clustered GWs - HI
H_0 [km s^{-1} Mpc^{-1}]
$\Omega_{m,0}$
γ
κ
z_p

HI → HI*

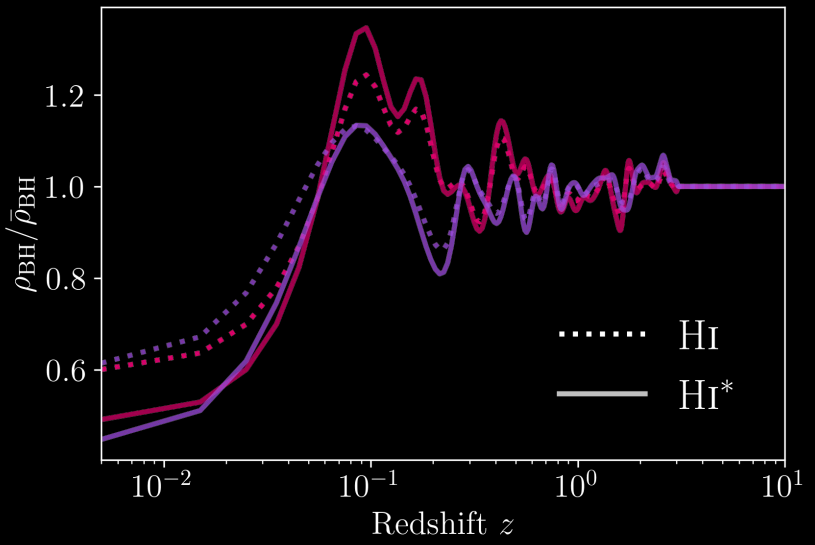
We model the HI mass as a function of the dark matter halo mass; the HI mass distribution provides the line of sight redshift prior

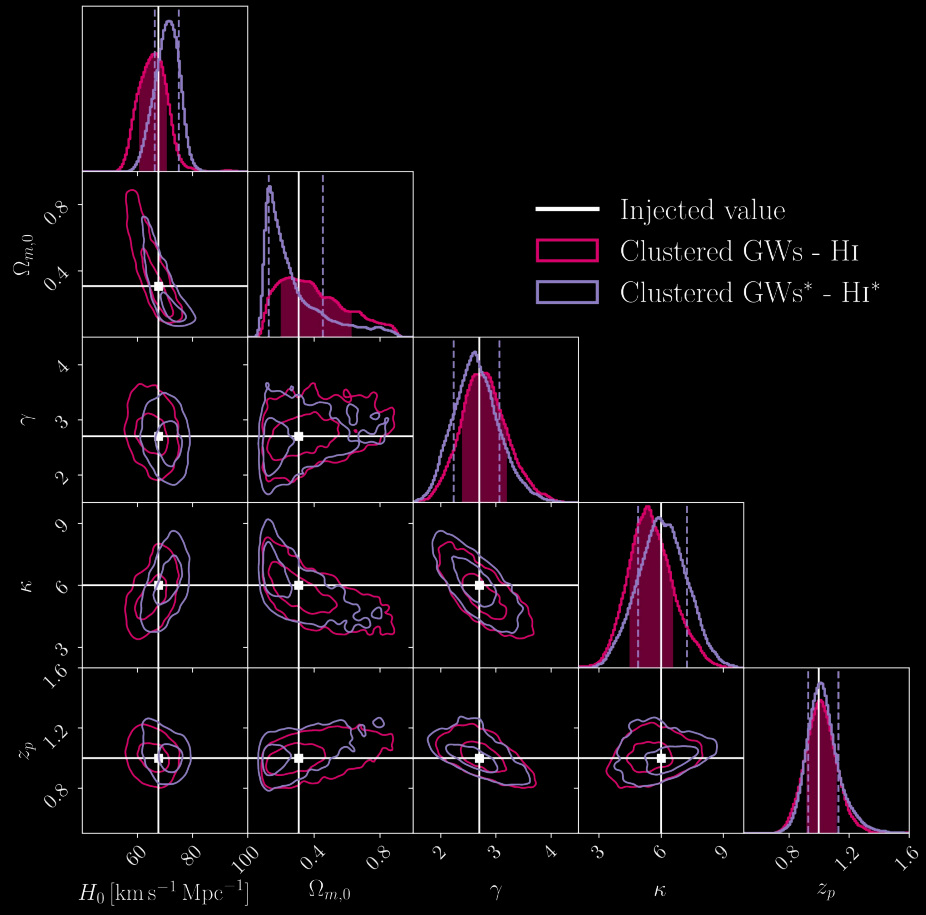
[Kamran et al. 2026]

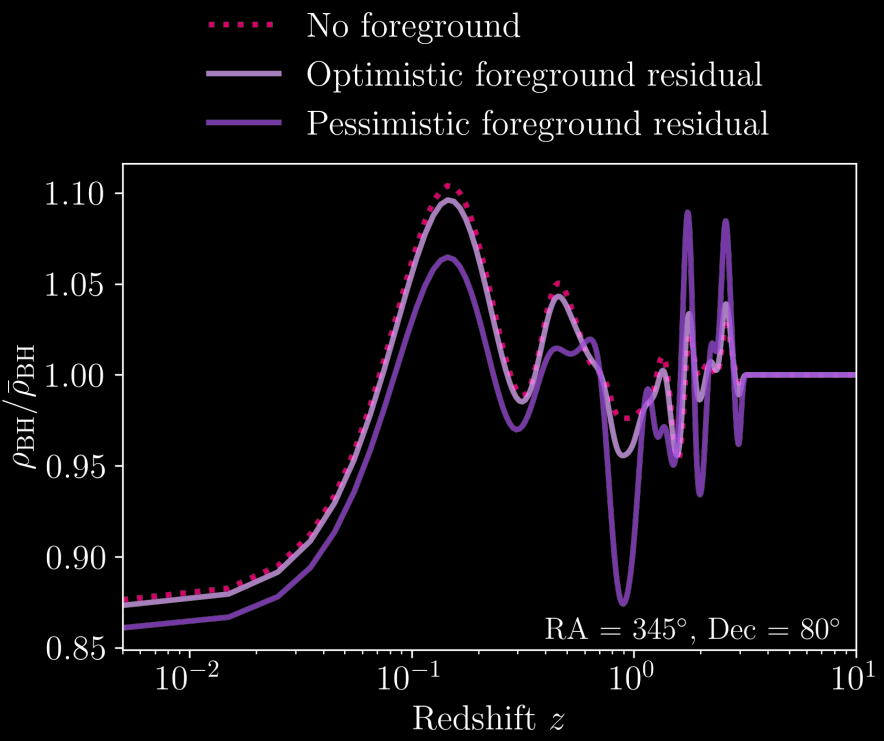
GWs → GWs*

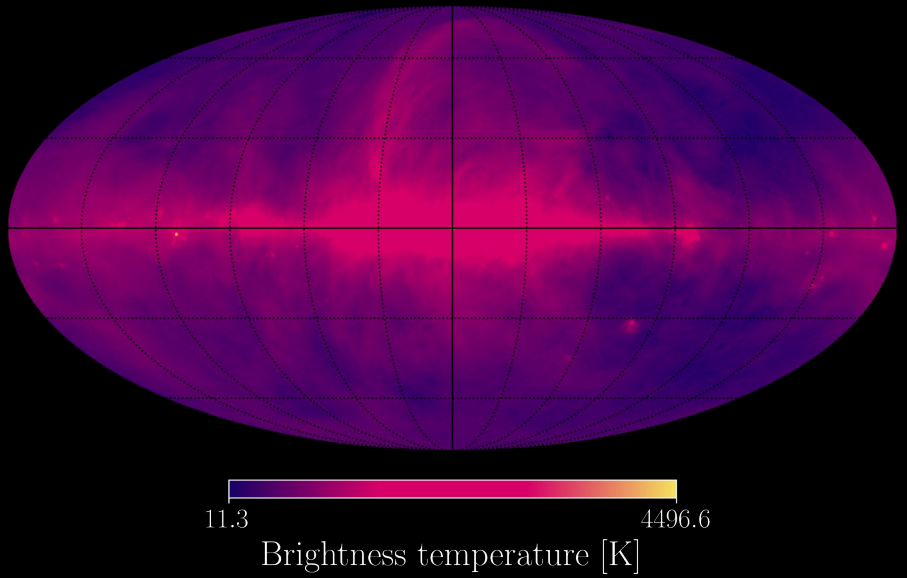
We model the stellar mass as a function of the dark matter halo mass; BBHs are distributed according to the stellar mass distribution

[Shuntov et al. 2022]

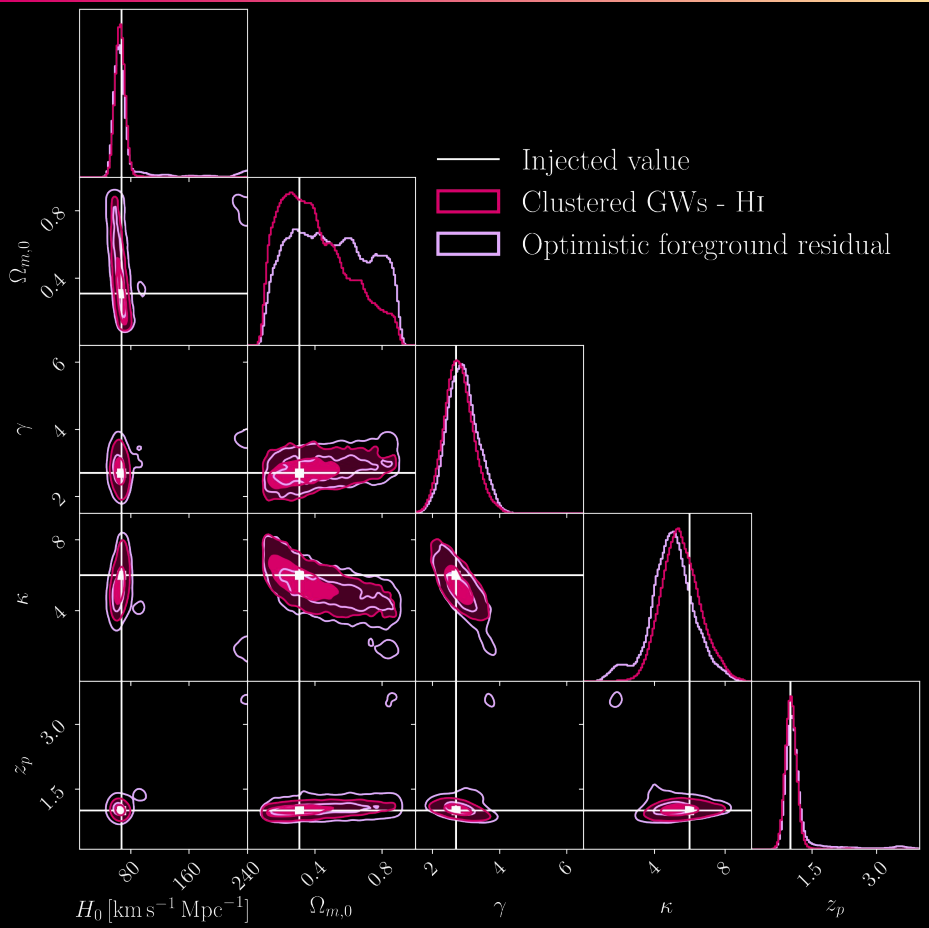



Injected value
Clustered GWs - HI
Clustered GWs* - HI*
H_0 [km s^{-1} Mpc^{-1}]
$\Omega_{m,0}$
γ
κ
z_p

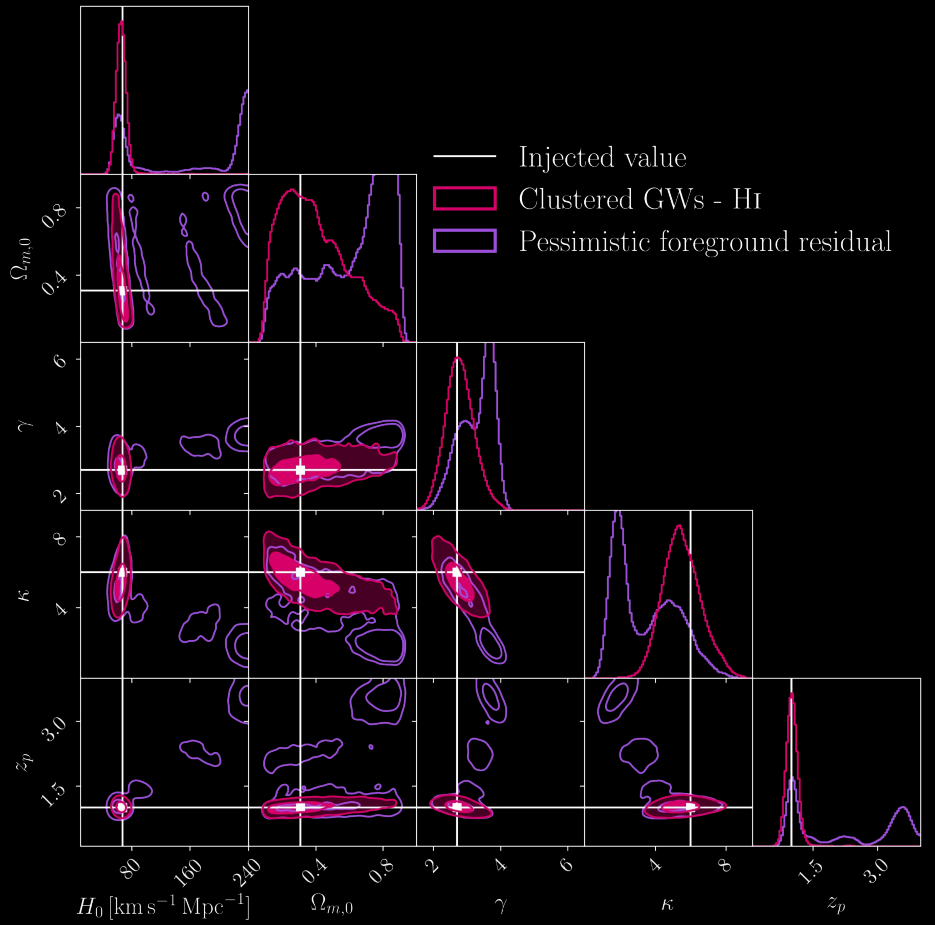




[Remazeilles et al. 2015]


Injected value
Clustered GWs - HI
Optimistic foreground residual
$H_0\,[\mathrm{km\,s^{-1}\,Mpc^{-1}}]$
$\Omega_{m,0}$
γ
κ
z_p

Strong residuals affect both cosmological and rate parameters



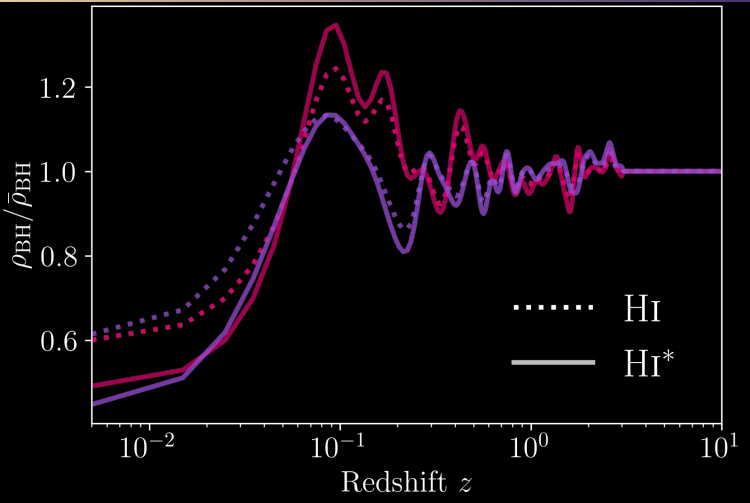
HI

HI directly traces the DM halo distribution (*HI*)

HI mass distribution is modelled based on HI-halo mass relation (*HI)**

Simulated dark matter halos (DEMNUni)
BBHs and HI are tracers of the DM field

BBHs



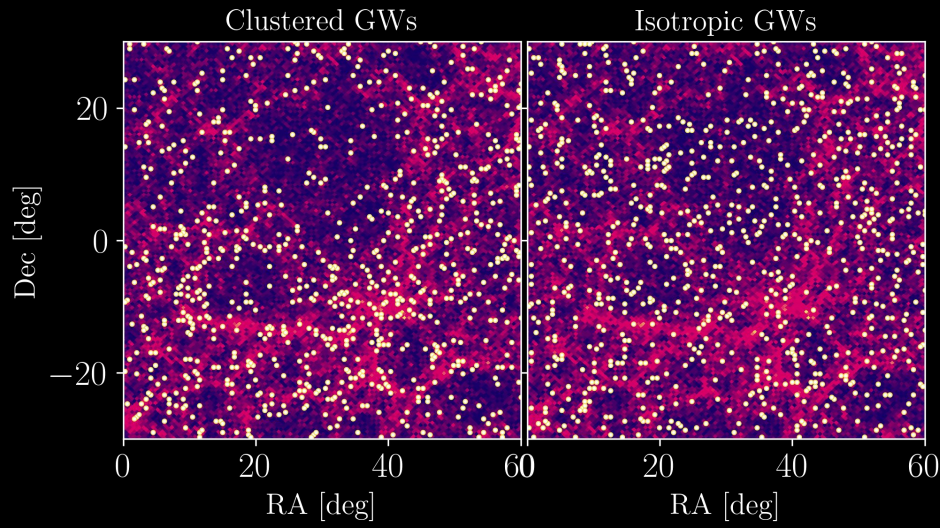
Simulated dark matter halos (DEMNUni)
BBHs and HI are tracers of the DM field

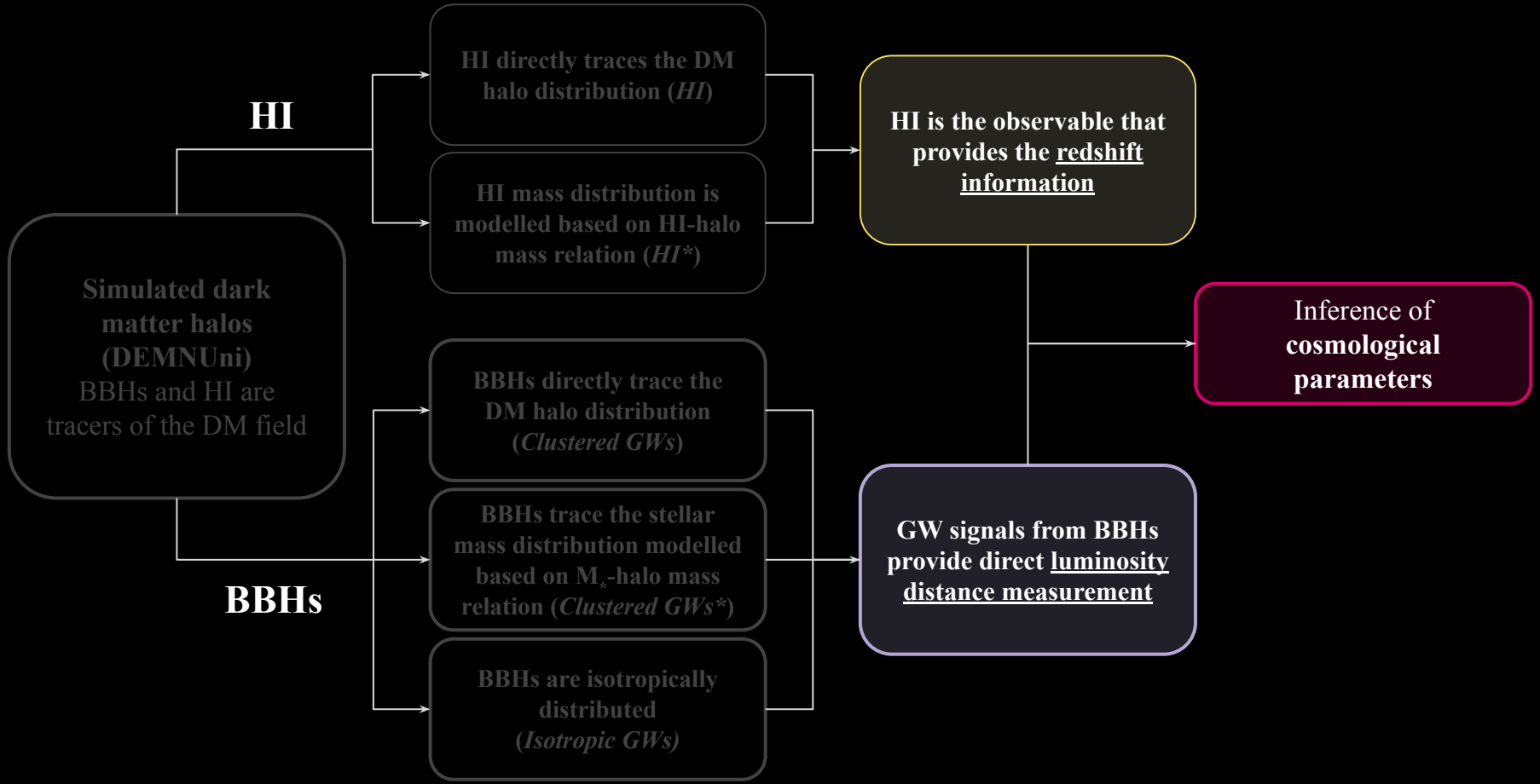
HI

- HI directly traces the DM halo distribution (*HI*)
- HI mass distribution is modelled based on HI-halo mass relation (*HI**)

BBHs

- BBHs directly trace the DM halo distribution (*Clustered GWs*)
- BBHs trace the stellar mass distribution modelled based on M_*-halo mass relation (*Clustered GWs**)
- BBHs are isotropically distributed (*Isotropic GWs*)



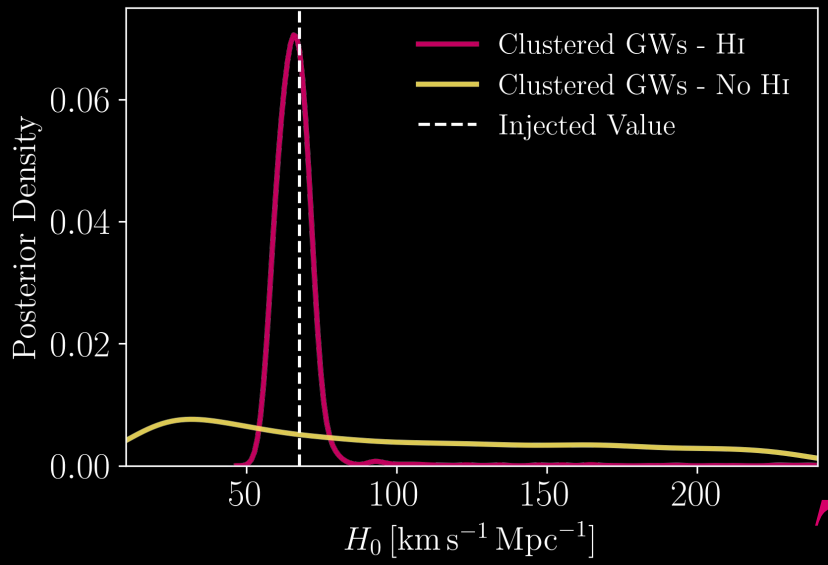

HI
BBHs
Simulated dark matter halos (DEMNUni)
BBHs and HI are tracers of the DM field
HI directly traces the DM halo distribution (HI)
HI mass distribution is modelled based on HI-halo mass relation (HI*)
BBHs directly trace the DM halo distribution (Clustered GWs)
BBHs trace the stellar mass distribution modelled based on M*-halo mass relation (Clustered GWs*)
BBHs are isotropically distributed (Isotropic GWs)
HI is the observable that provides the redshift information
GW signals from BBHs provide direct luminosity distance measurement
Inference of cosmological parameters

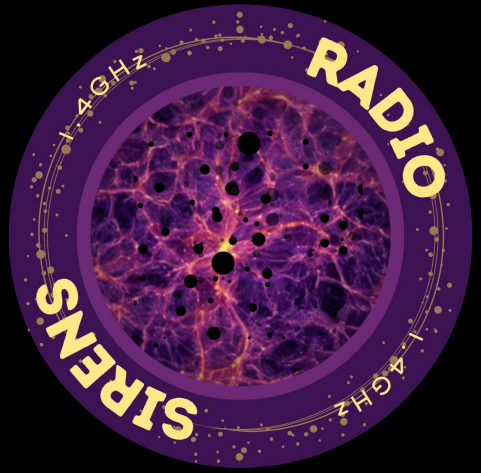
Proof-of-concept study of the ***radio sirens*** framework

HI provides constraints on H_0 at **8% precision** in our headline result

Bias in the H_0 inference when the clustering information is not correctly accounted for

Several **simplifying assumptions** on HI need to be relaxed in future work: sky coverage, instrumental noise, foreground removal [see Nanadoumgar-Lacroze et al. 2026]





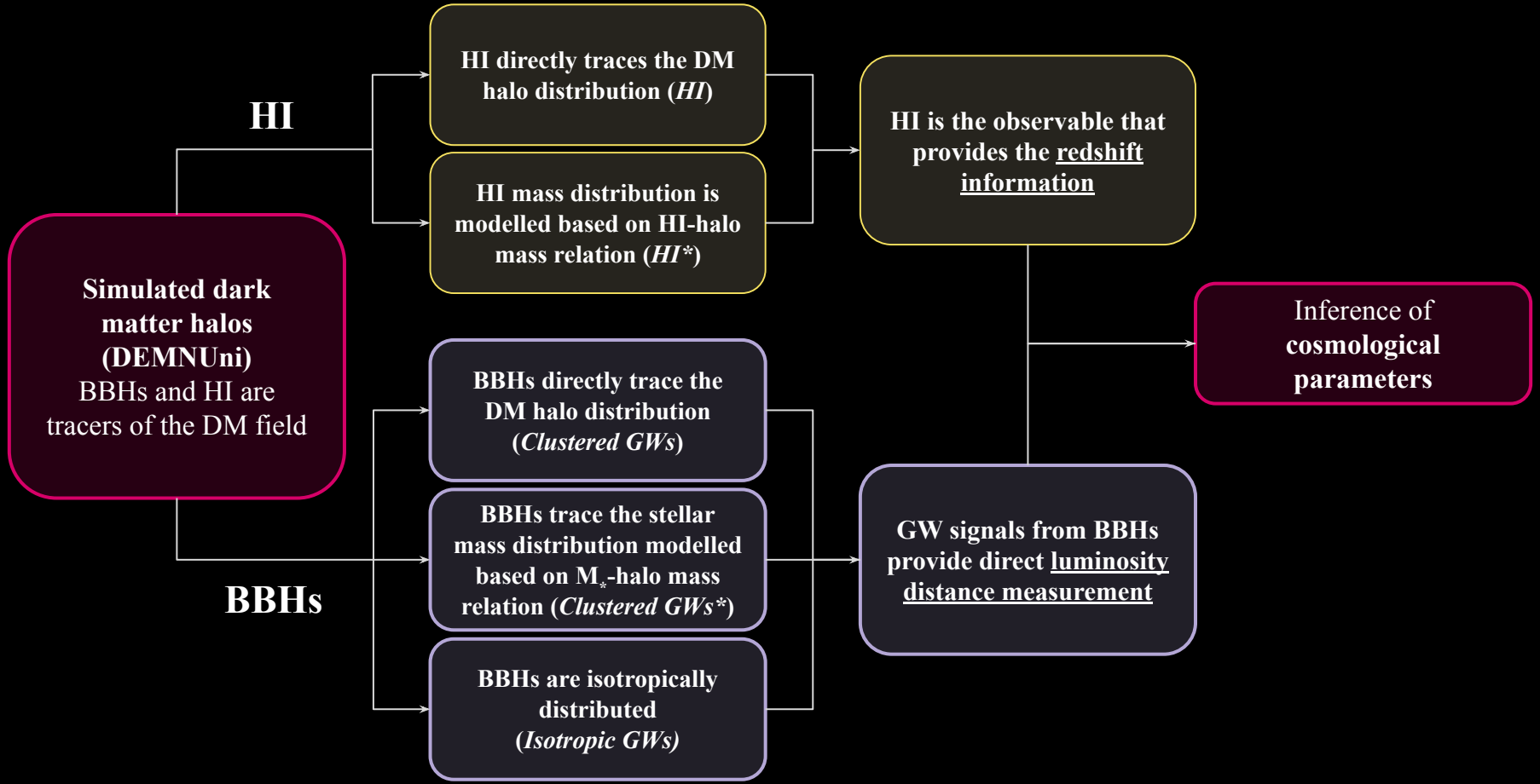
zenodo

Link

GitHub

arXiv: 2605.12606

Thank you!


HI
BBHs
Simulated dark matter halos (DEMNUni)
BBHs and HI are tracers of the DM field
HI directly traces the DM halo distribution (HI)
HI mass distribution is modelled based on HI-halo mass relation (HI*)
BBHs directly trace the DM halo distribution (Clustered GWs)
BBHs trace the stellar mass distribution modelled based on M*-halo mass relation (Clustered GWs*)
BBHs are isotropically distributed (Isotropic GWs)
HI is the observable that provides the redshift information
GW signals from BBHs provide direct luminosity distance measurement
Inference of cosmological parameters

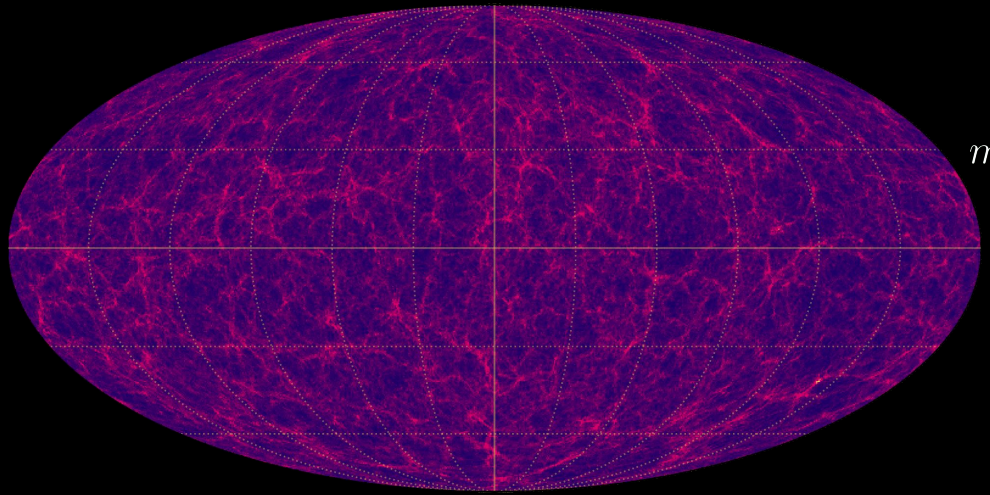
$$\nu_{\rm obs} = \nu_{21}/(1+z)$$

$$\nu_{21} = 1420 \text{ MHz}$$

SKA-MID: z ~ 0 - 3
band 2 (950–1760 MHz)
band 1 (350–1050 MHz)



SKA-Low: z ~ 3 - 20
(50 – 350MHz)



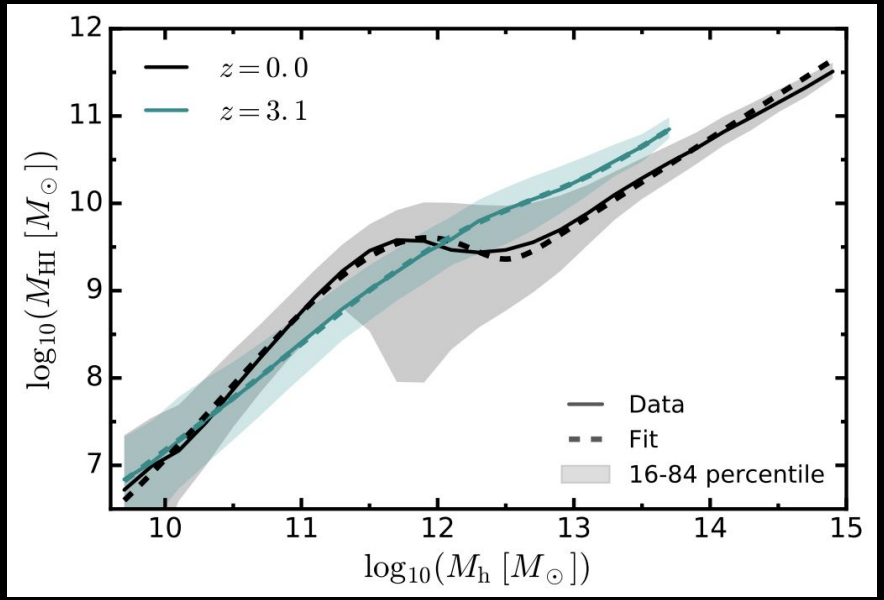
$$map(z, pix_i) = \frac{N(z, pix_i) - \bar{N}_{pix}(z)}{\bar{N}_{pix}(z)}$$

$$\bar{N}_{pix}(z) = \frac{1}{n_{pix}} \sum_i N(z, pix_i)$$

Dark Energy and Massive Neutrino Universe (**DEMNUni**) N-body simulations

[Castorina et al. 2015, Carbone et al. 2016, Parimbelli et al. 2021]

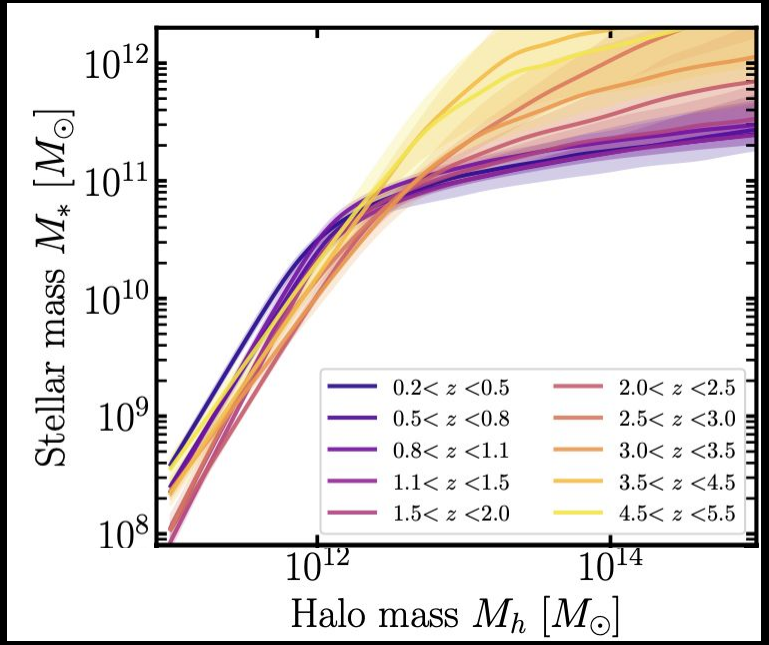
$$M_{\rm HI}(M_{\rm h}) = M_{\rm h}\left[a_1\left(\frac{M_{\rm h}}{10^{10}\,h^{-1}M_\odot}\right)^{\beta} e^{-(M_{\rm h}/M_{\rm break})^{\alpha}} + a_2\right] e^{-(M_{\rm min}/M_{\rm h})^{\gamma}}$$



[Kamran et al. 2026]

$$\log\left(f^{-1}_{\rm SHMR}(M_*)\right) = \log(M_h)$$

$$= \log(M_1) + \beta \log\left(\frac{M_*}{M_{*,0}}\right) + \frac{\left(\frac{M_*}{M_{*,0}}\right)^{\delta}}{1+\left(\frac{M_*}{M_{*,0}}\right)^{-\gamma}} - \frac{1}{2}$$



[Shuntov et al. 2026]

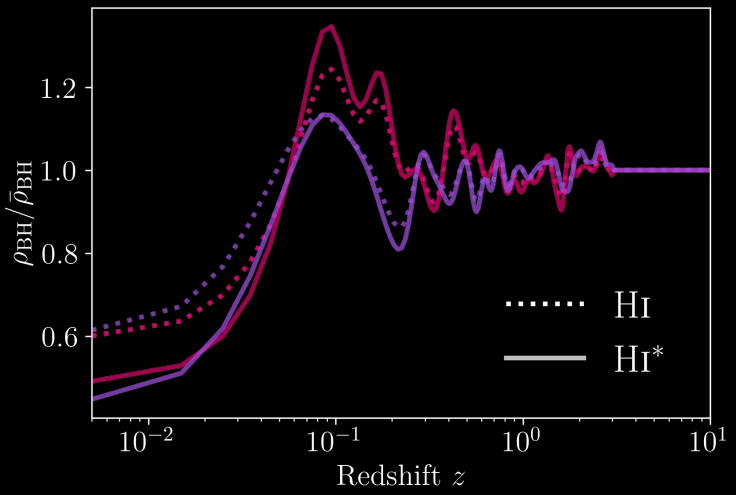
$$\frac{\mathrm{d}N_{\mathrm{CBC}}}{\mathrm{d}z\,\mathrm{d}t\mathrm{d}\Omega} = \frac{\mathrm{d}N_{\mathrm{CBC}}}{\mathrm{d}M_{\mathrm{BH}}\,\mathrm{d}t_{\mathrm{src}}} \frac{1}{1+z} \frac{\mathrm{d}M_{\mathrm{BH}}}{\mathrm{d}z\,\mathrm{d}\Omega}$$

$$\frac{\mathrm{d}M_{\mathrm{BH}}}{\mathrm{d}z\,\mathrm{d}\Omega} = \frac{\mathrm{d}M_{\mathrm{BH}}}{\mathrm{d}V_c} \frac{\mathrm{d}V_c}{\mathrm{d}z\,\mathrm{d}\Omega} = \rho_{\mathrm{BH}}(z,\Omega) \frac{\mathrm{d}V_c}{\mathrm{d}z\,\mathrm{d}\Omega}$$

$$\rho_{\mathrm{BH}}(z,\Omega) \approx \bar{\rho}_{\mathrm{BH}}[1 + b_{\mathrm{GW}}(1+z)^{\alpha_{\mathrm{GW}}}\delta_{\mathrm{DM}}(z,\Omega)]$$

$$\begin{aligned}\frac{\mathrm{d}N_{\mathrm{CBC}}}{\mathrm{d}M_{\mathrm{BH}}\,\mathrm{d}t_{\mathrm{src}}} &= R_{\mathrm{BH}}\,\psi(z \mid \gamma, \kappa, z_p) \\ &= R_{\mathrm{BH}}\ \left[1 + (1+z_p)^{-\gamma-\kappa}\right] \frac{(1+z)^{\gamma}}{1 + \left[\frac{1+z}{1+z_p}\right]^{\gamma+\kappa}}\end{aligned}$$

[Madau-Dickinson 2014]



Hierarchical Bayesian Analysis



[Mastrogiovanni et al. 2023]

$$p(\vec{\lambda}|\{\vec{x}_i\}) \propto \mathcal{L}(\{\vec{x}_i\}|\vec{\lambda})\pi(\vec{\lambda})$$

posterior on hyperparameters

likelihood

prior on hyperparameters

Poisson statistics

independent events

single event likelihood

$$\mathcal{L}(\{x\}|\Lambda) \propto \exp\left[-N_{\rm exp}(\Lambda)\right] \prod_{i=1}^{N_{\rm obs}} T_{\rm obs} \int \mathcal{L}_{\rm GW}\left(x_i|\theta,\Lambda\right) \frac{{\rm d}N_{\rm CBC}}{{\rm d}t{\rm d}\theta}(\Lambda){\rm d}\theta$$

hyperparameters (population level)

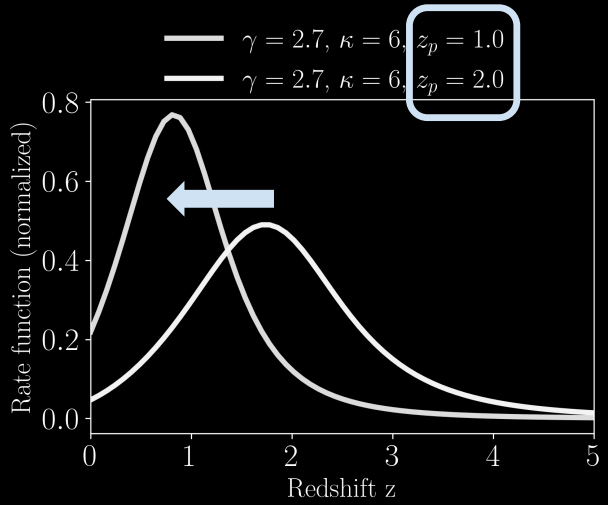
selection effects

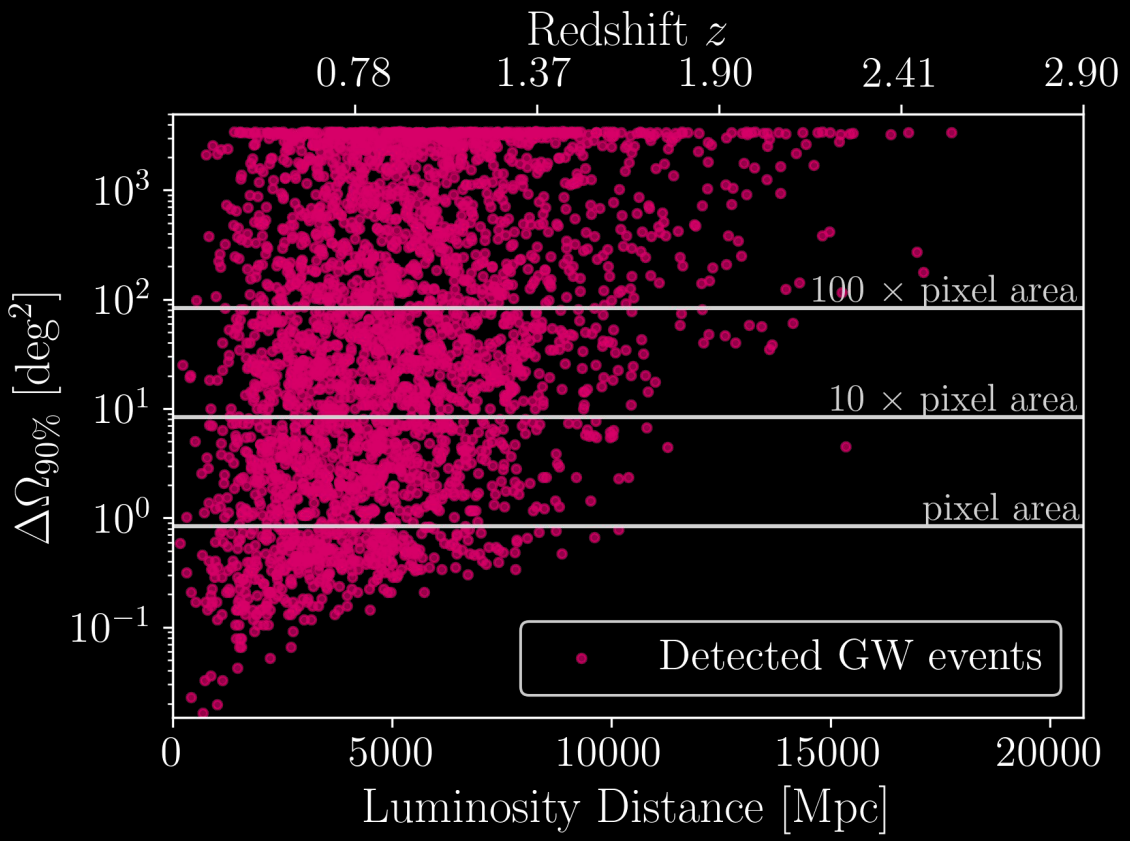
$$N_{\rm exp}(\Lambda) = T_{\rm obs} \int p_{\rm det}(\theta) \frac{{\rm d}N_{\rm CBC}}{{\rm d}t{\rm d}\theta}(\Lambda){\rm d}\theta$$

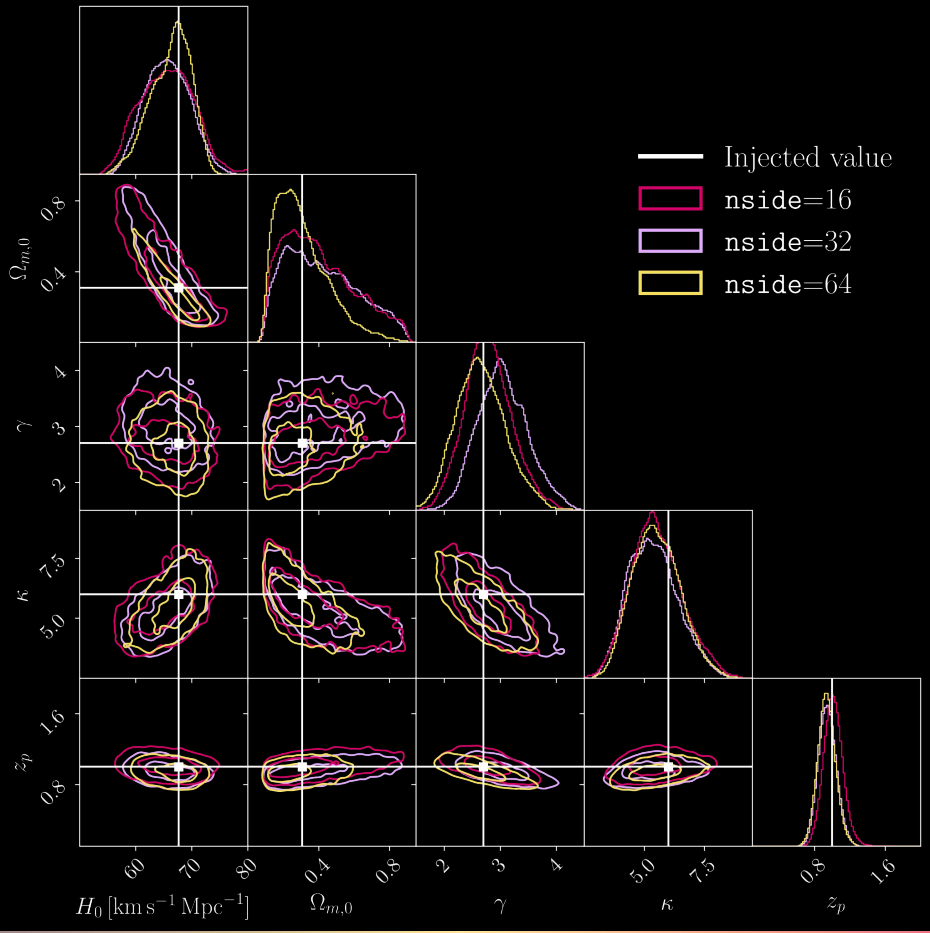
Parameter	Prior range	Injected value
H_0 [km s^{-1} Mpc^{-1}]	$\mathcal{U}[10, 240]$	67.7
$\Omega_{m,0}$	$\mathcal{U}[0.1, 0.9]$	0.308
γ	$\mathcal{U}[0, 12]$	2.7
κ	$\mathcal{U}[0, 12]$	6
z_p	$\mathcal{U}[0, 4]$	1

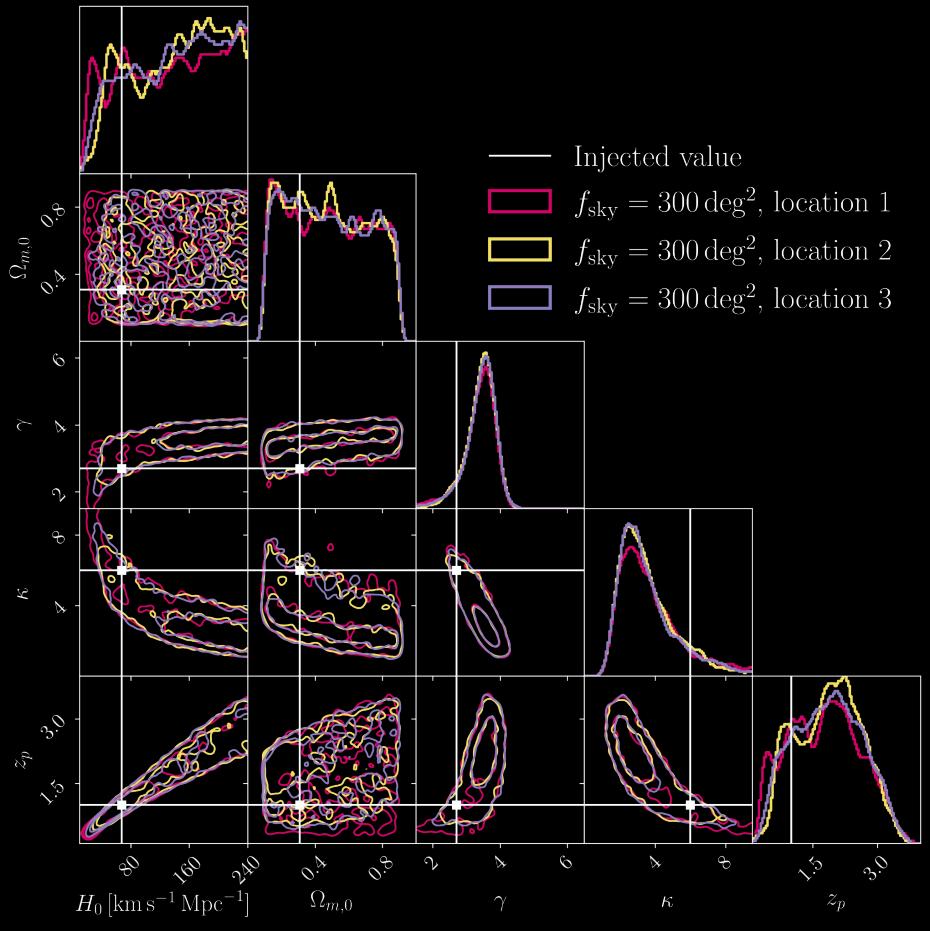
Simulating observations of GWs and HI maps

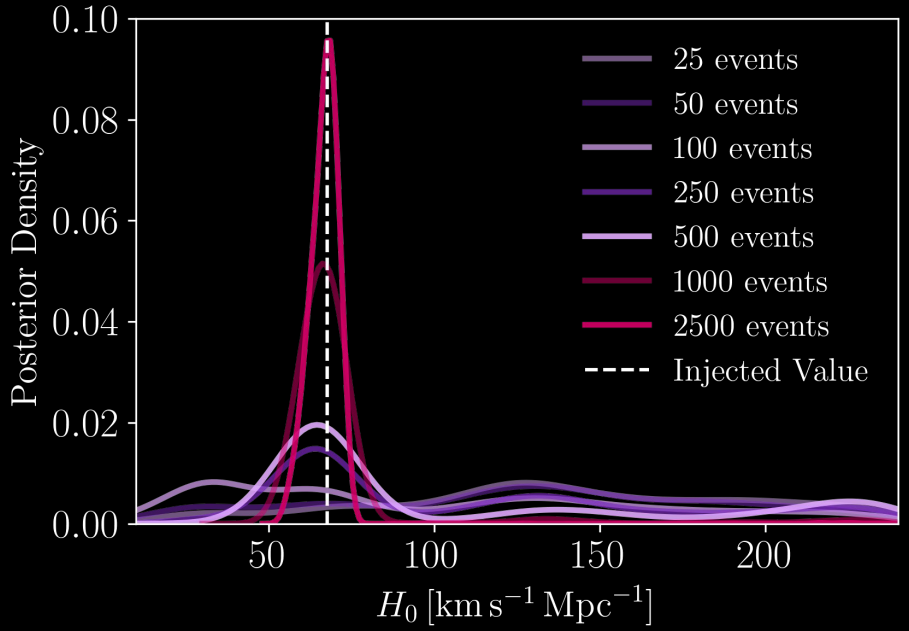
- 1e4 BBH events (one year of observations with a modified Madau-Dickinson rate) in the redshift range covered by HI maps, $z \in [0, \sim 3]$
- Uniform distribution of masses in detector frame in the range $[5M_\odot, 300M_\odot]$
- Uniform and uniform on the sky distribution for all the other GW parameters
- Parameter estimation with **GWFish** and post-processing with priors sampling from truncated multivariate Gaussian [Dupletsa et al. 2023, 2025]

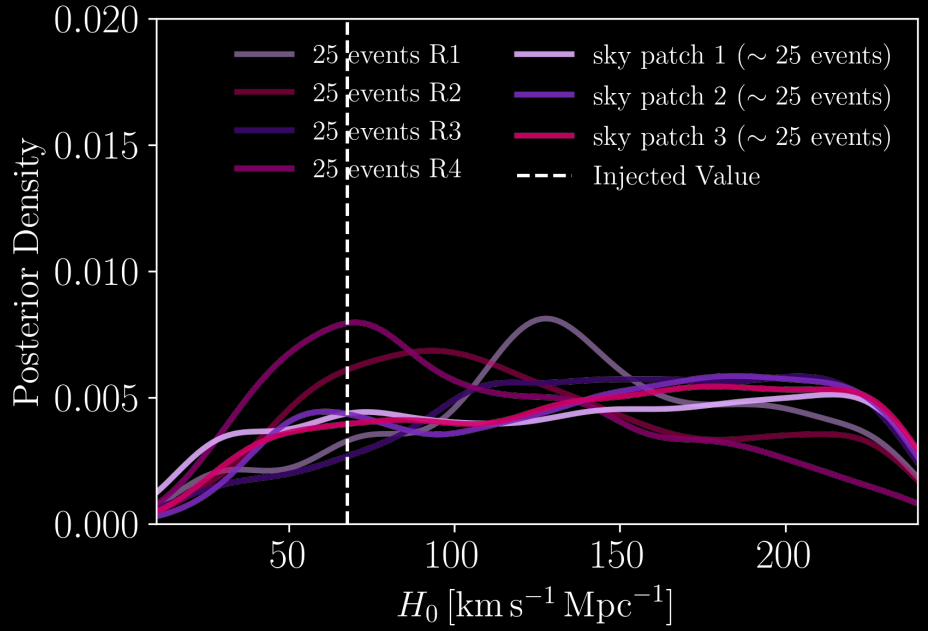


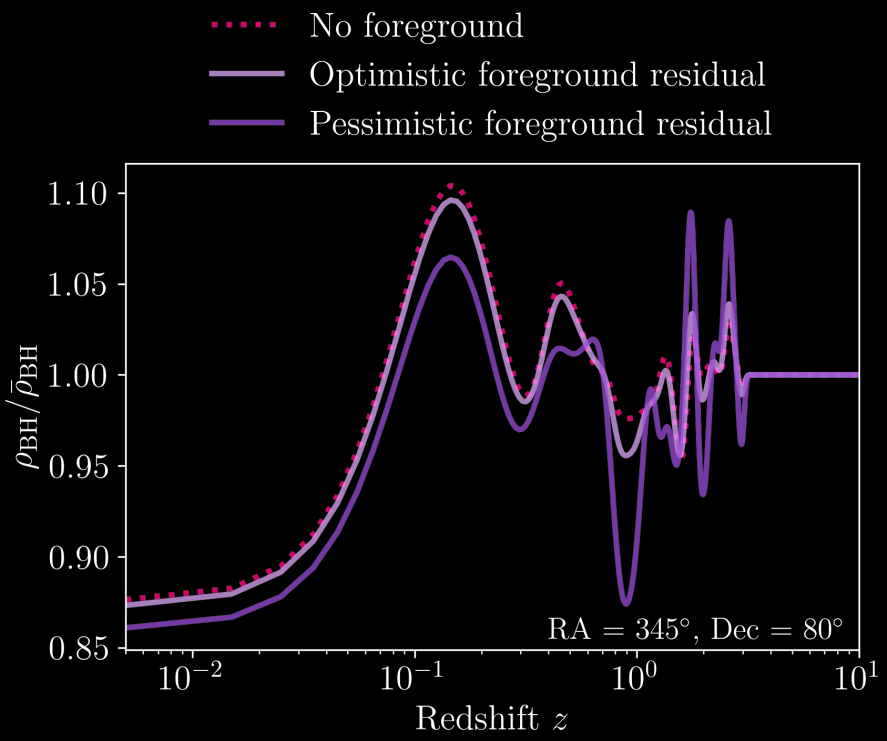

Redshift z
0.78
1.37
1.90
2.41
2.90
10^3
10^2
10^1
10^0
10^{-1}
$\Delta\Omega_{90\%}$ [deg^2]
100 × pixel area
10 × pixel area
pixel area
Detected GW events
0
5000
10000
15000
20000
Luminosity Distance [Mpc]

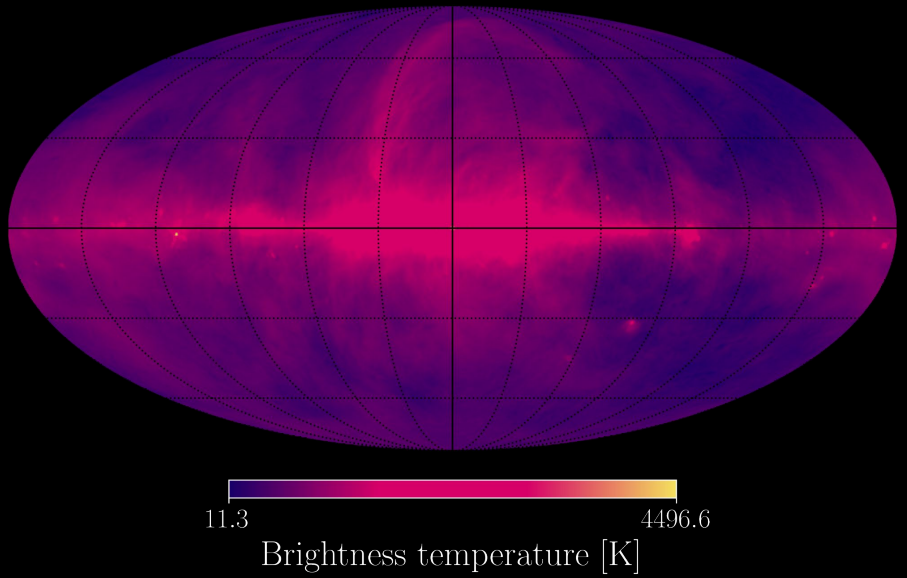

Injected value
nside=16
nside=32
nside=64
H_0 [km s^{-1} Mpc^{-1}]
$\Omega_{m,0}$
γ
κ
z_p

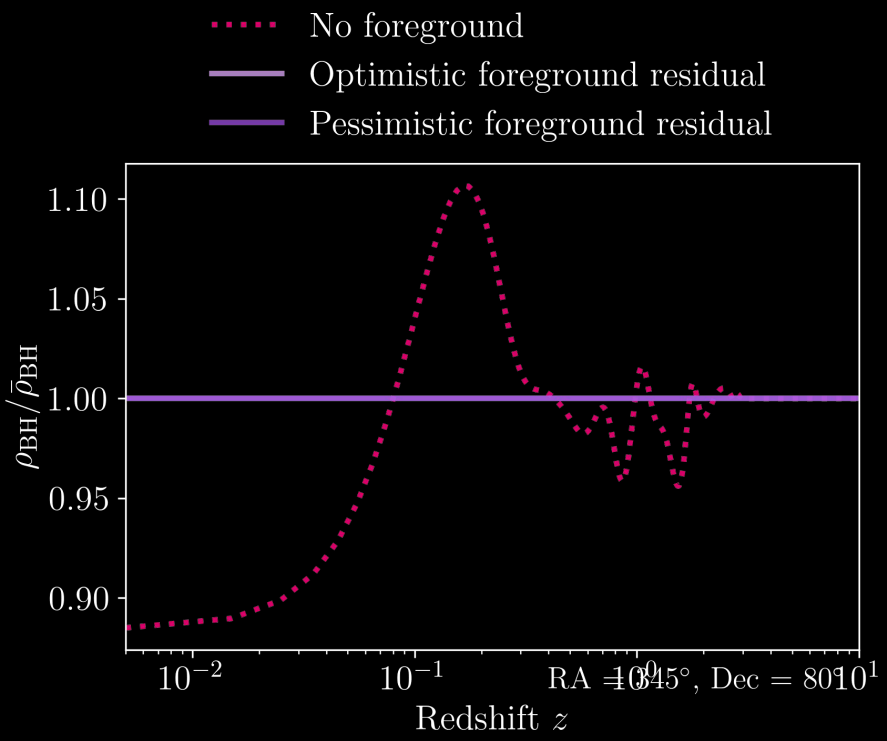

Injected value
$f_{\rm sky} = 300\,{\rm deg}^2$, location 1
$f_{\rm sky} = 300\,{\rm deg}^2$, location 2
$f_{\rm sky} = 300\,{\rm deg}^2$, location 3
$H_0\,[{\rm km\,s^{-1}\,Mpc^{-1}}]$
$\Omega_{m,0}$
γ
κ
z_p

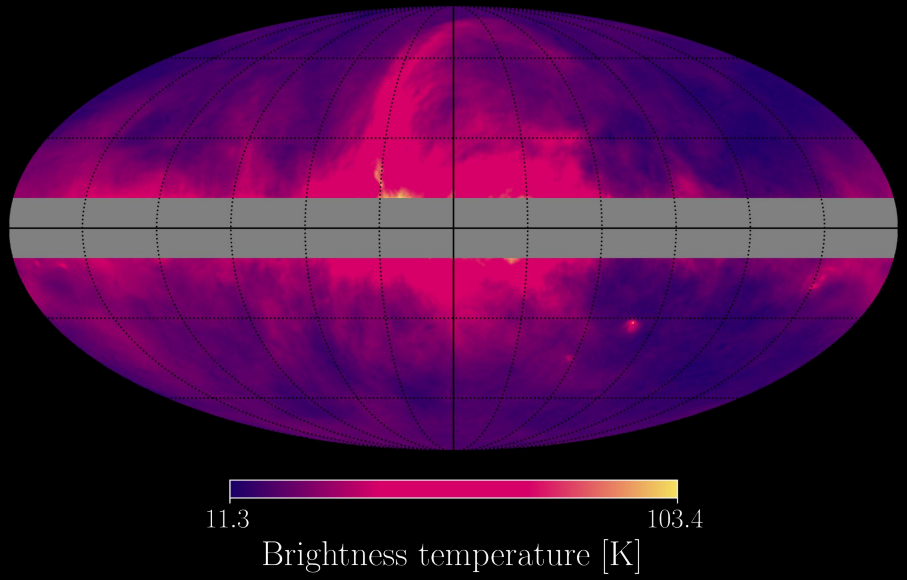

0.10
0.08
0.06
0.04
0.02
0.00
Posterior Density
50
100
150
200
H_0 [km s^{-1} Mpc^{-1}]
25 events
50 events
100 events
250 events
500 events
1000 events
2500 events
Injected Value


0.020
0.015
0.010
0.005
0.000
Posterior Density
50
100
150
200
H_0 [km s^{-1} Mpc^{-1}]
25 events R1
25 events R2
25 events R3
25 events R4
sky patch 1 (∼ 25 events)
sky patch 2 (∼ 25 events)
sky patch 3 (∼ 25 events)
Injected Value

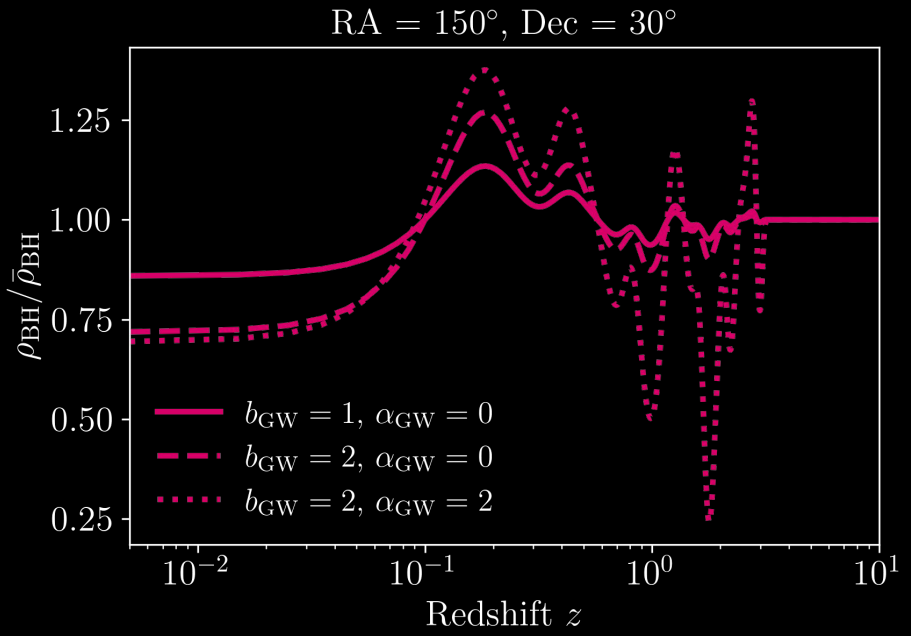

No foreground
Optimistic foreground residual
Pessimistic foreground residual
1.10
1.05
1.00
0.95
0.90
0.85
$\rho_{\rm BH}/\bar{\rho}_{\rm BH}$
RA = 345°, Dec = 80°
10^{-2}
10^{-1}
10^{0}
10^{1}
Redshift z


11.3
4496.6
Brightness temperature [K]


No foreground
Optimistic foreground residual
Pessimistic foreground residual
1.10
1.05
1.00
0.95
0.90
$\rho_{\rm BH}/\bar{\rho}_{\rm BH}$
10^{-2}
10^{-1}
10^{0}
10^{1}
RA = 345°, Dec = 80°
Redshift z


11.3
103.4
Brightness temperature [K]

- **b_GW** controls the amplitude fluctuations enhancing the contrast between underdense and overdense regions
- **a_GW** controls the redshift dependence: the modulation is stronger at higher z where the matter field is otherwise more homogeneous



$$\rho_{\rm BH}(z,\Omega) \approx \bar{\rho}_{\rm BH}[1 + b_{\rm GW}(1+z)^{\alpha_{\rm GW}}\delta_{\rm DM}(z,\Omega)].$$

