ModIC 2024 - Model-Independent Cosmology with gravitational waves, large-scale structures, and high-energy surveys

Dark Sirens Cosmology with neutral hydrogen intensity mapping

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in collaboration with

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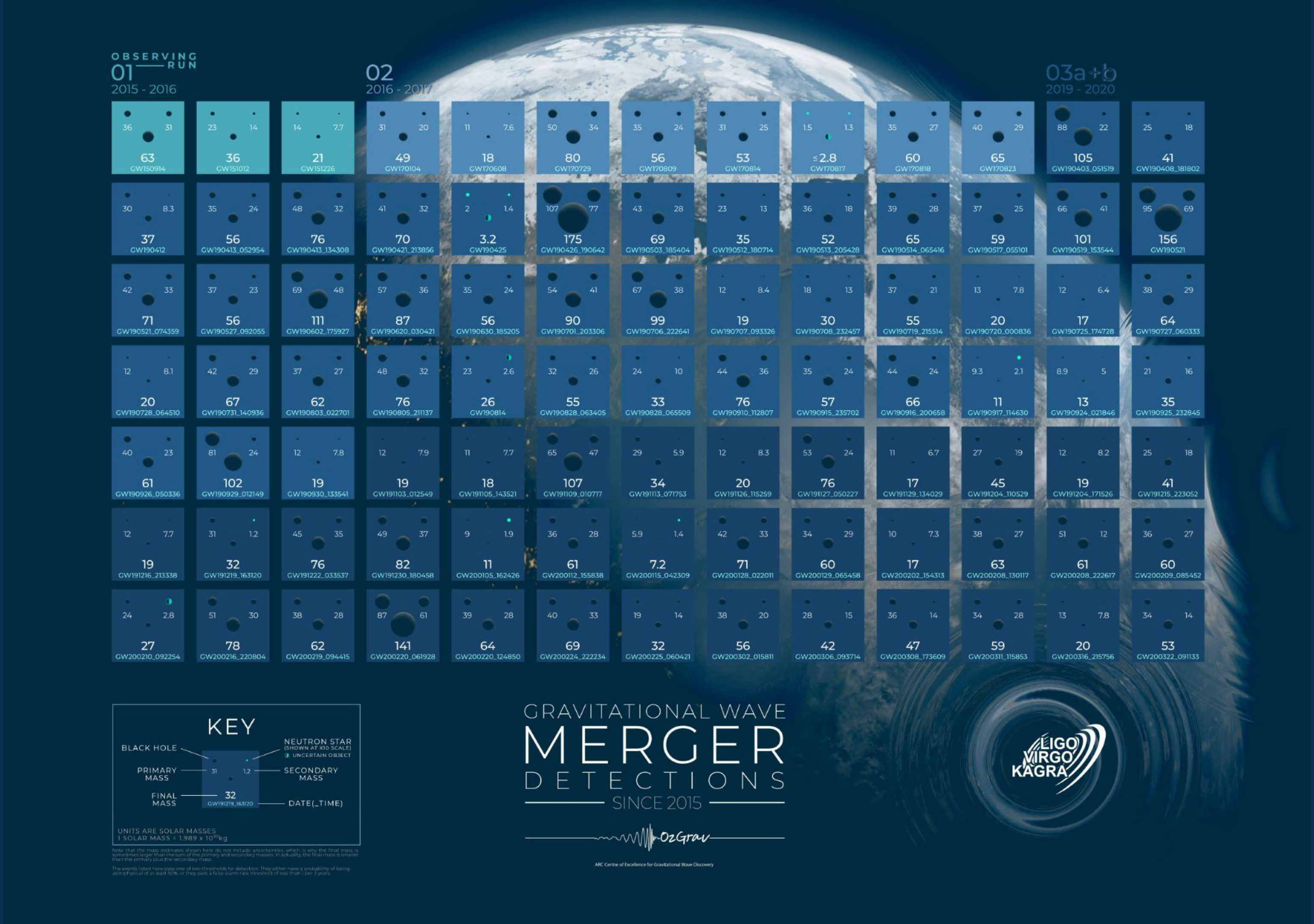
GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

A brief summary

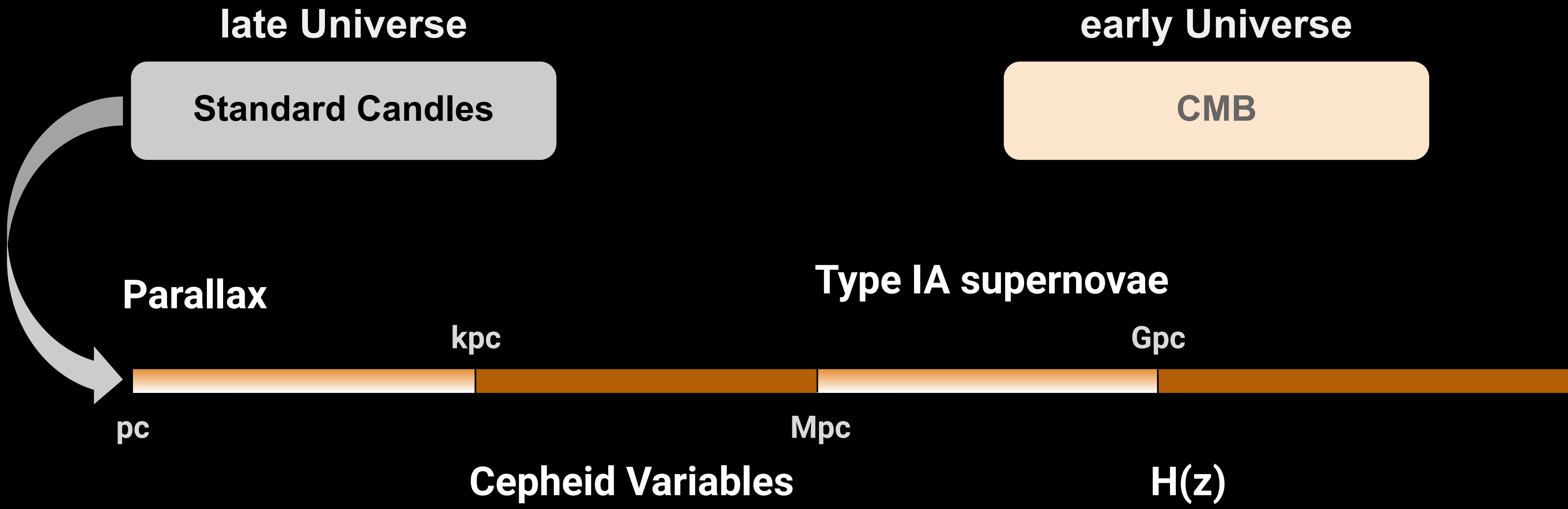

OBSERVING RUN
01
2015 - 2016
02
2016 - 2017
O3a+b
2019 - 2020
36 31 63 GW150914
23 14 36 GW151012
14 7.7 21 GW151226
31 20 49 GW170104
11 7.6 18 GW170608
50 34 80 GW170729
35 24 56 GW170809
31 25 53 GW170814
1.5 1.3 ≤2.8 GW170817
35 27 60 GW170818
40 29 65 GW170823
88 22 105 GW190403_051519
25 18 41 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
BLACK HOLE
NEUTRON STAR (SHOWN AT X10 SCALE)
UNCERTAIN OBJECT
PRIMARY MASS
SECONDARY MASS
FINAL MASS
DATE(_TIME)
31 1.2 32 GW191219_163120
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

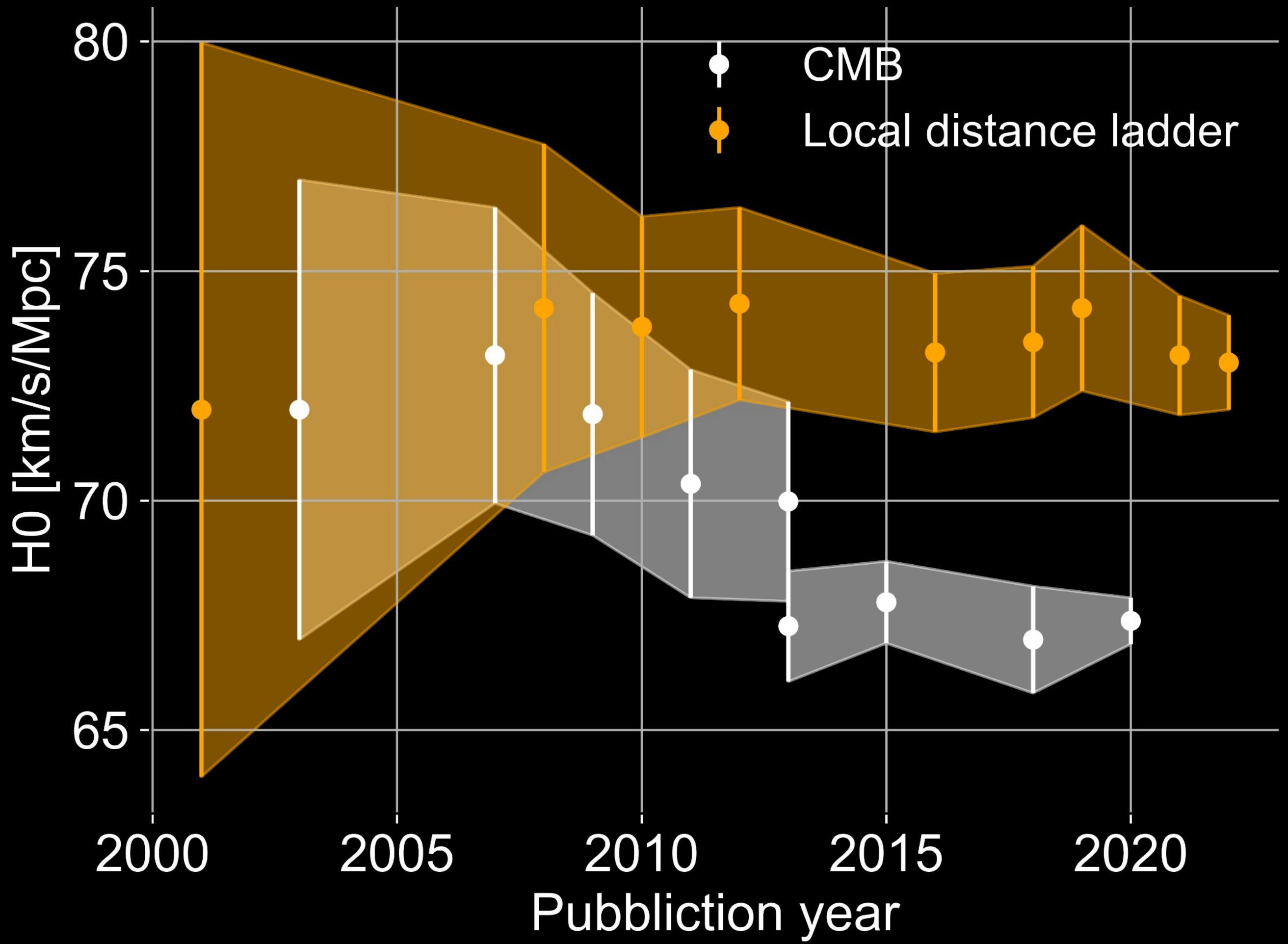
Measuring the expansion: a **distance-redshift relation**

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

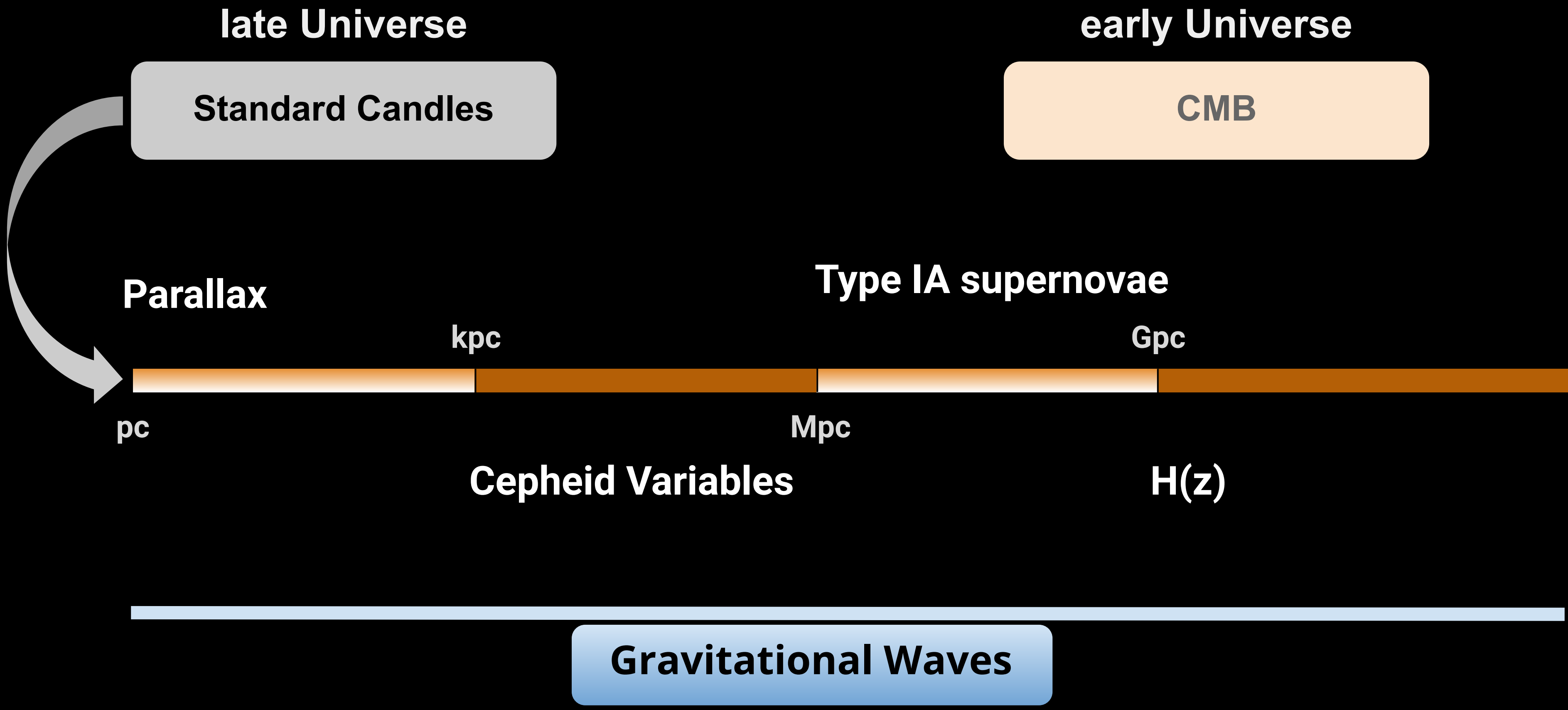
$$H(z) = H_0\sqrt{\Omega_{\mathrm{m}}(1+z)^3 + \Omega_\Lambda + \Omega_{\mathrm{r}}(1+z)^4 + \Omega_{\mathrm{k}}(1+z)^2}$$

- Ω_{m}: **dark matter**
- Ω_Λ: **dark energy**
- Ω_{r}: **radiation**
- Ω_{k}: **curvature**


late Universe
early Universe
Standard Candles
CMB
Parallax
Type IA supernovae
kpc
Gpc
pc
Mpc
Cepheid Variables
H(z)



[Data from review paper: ArXiv:2105208]


late Universe
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Cepheid Variables
H(z)
Gravitational Waves

Standard sirens

- Gravitational waves are self-calibrated distance indicators: **cosmic rulers**

$$h_+ \propto \frac{c}{d_\mathrm{L}} \left(\frac{G\mathcal{M}_z}{c^3} \right)^{5/6} \frac{1}{f^{7/6}} \left(\frac{1 + \cos^2 \iota}{2} \right) e^{i\Psi_+}$$

$$h_\times \propto \frac{c}{d_\mathrm{L}} \left(\frac{G\mathcal{M}_z}{c^3} \right)^{5/6} \frac{1}{f^{7/6}} \cos \iota e^{i\Psi_\times}$$

- **No direct redshift measurement** from the gravitational signal

Standard sirens

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- ➔ Methods based on complementary observations:
  - ◆ Direct EM counterpart with GW170817 (**bright sirens**)
  - ◆ Statistical association with galaxy catalogs (**dark sirens**)
  - ◆ Cross-correlations with LSS tracers (**hydrogen**)

- ➔ Methods based on astrophysical models:
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- ➔ Methods based on astrophysical models:
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What we would like to do

Multi-tracing approach

Resolved GW events from stellar-mass BBHs

Next-generation GW observatories: ET (+ CE)

+

Intensity mapping of 21cm line from neutral hydrogen

Future large scale structure surveys as SKAO

→

Cross - correlating different tracers of the underlying dark matter distribution

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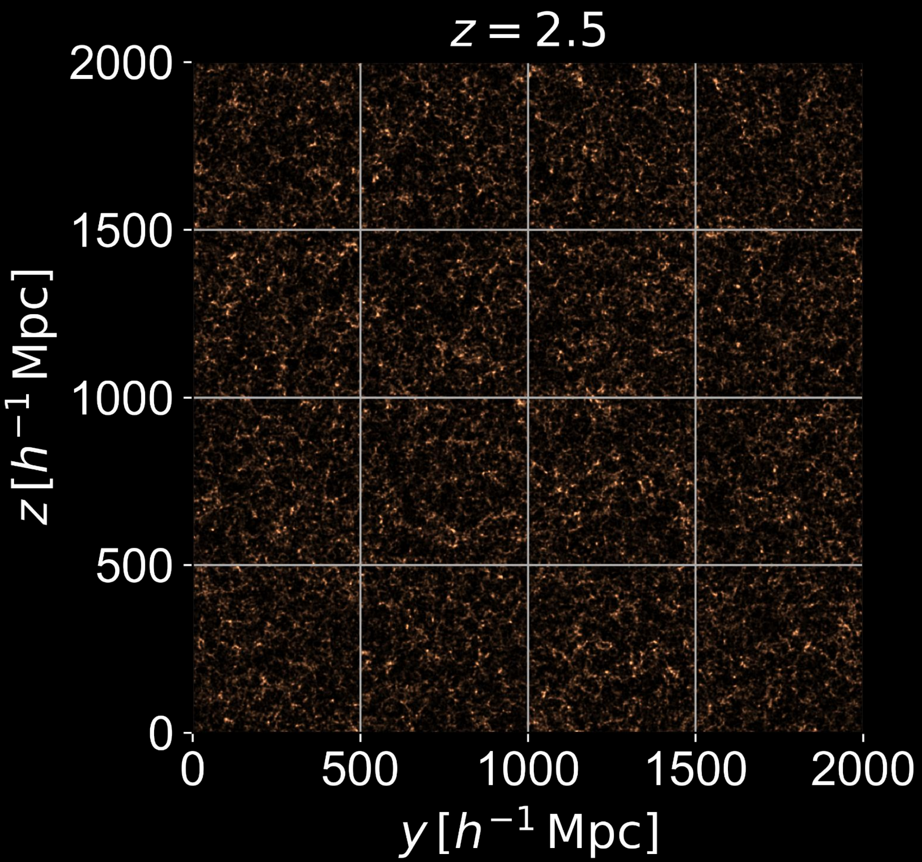
Cross - correlating different tracers of the underlying dark matter distribution

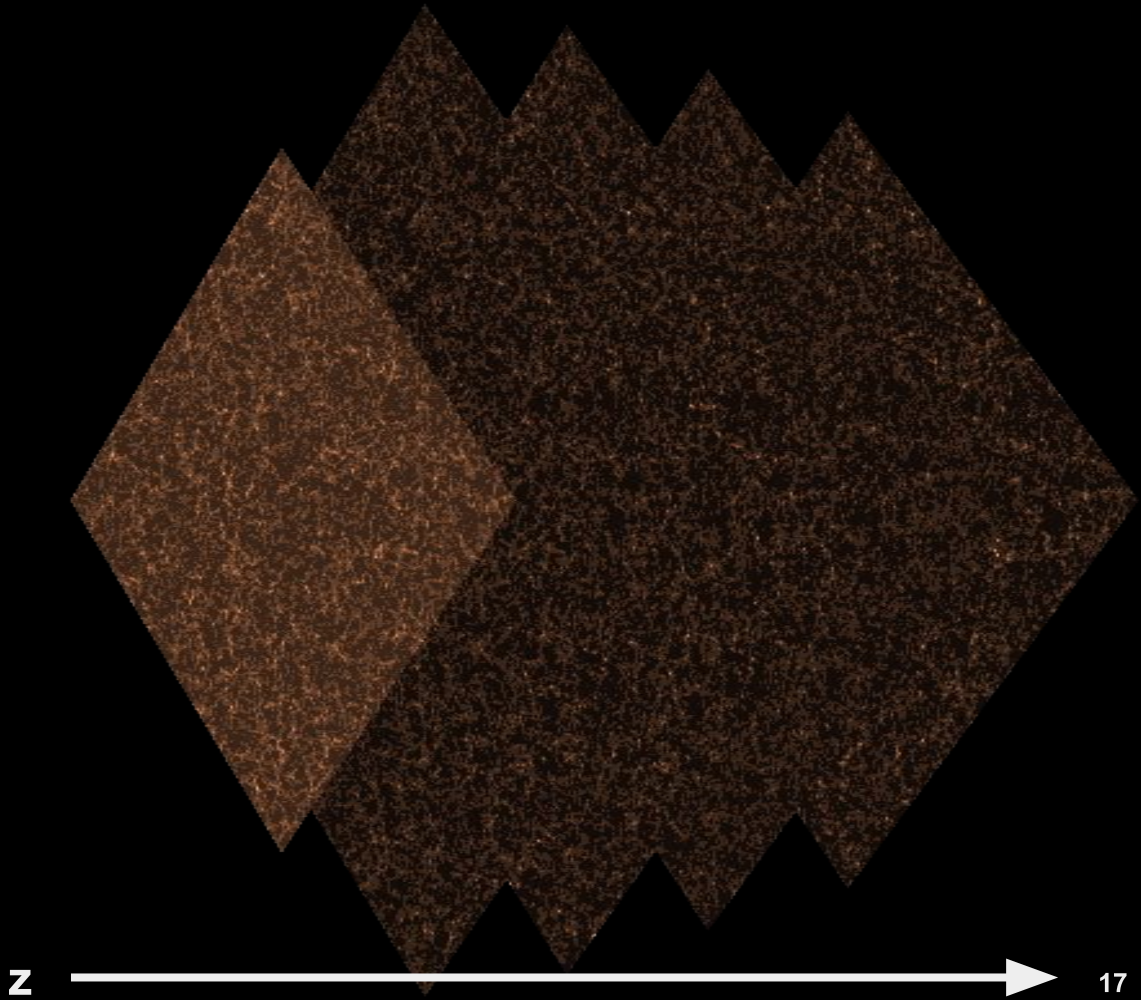
Hi-Fi mocks [GitHub]

- Neutral hydrogen overdensity maps (21cm line)
- Tested against IllustrisTNG
- Precision at $5h^{-1}$Mpc



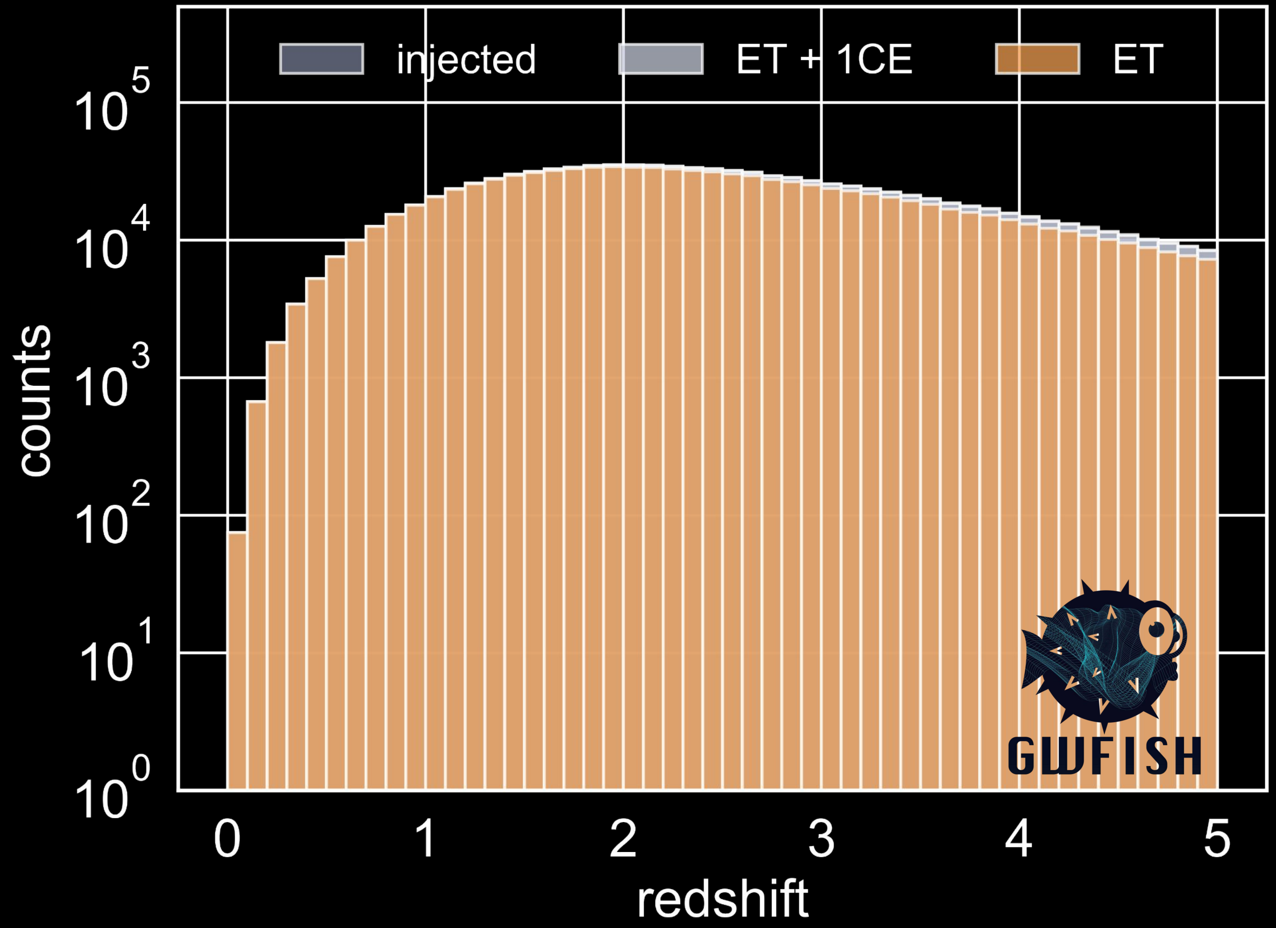
[Obuljen+ 2022]

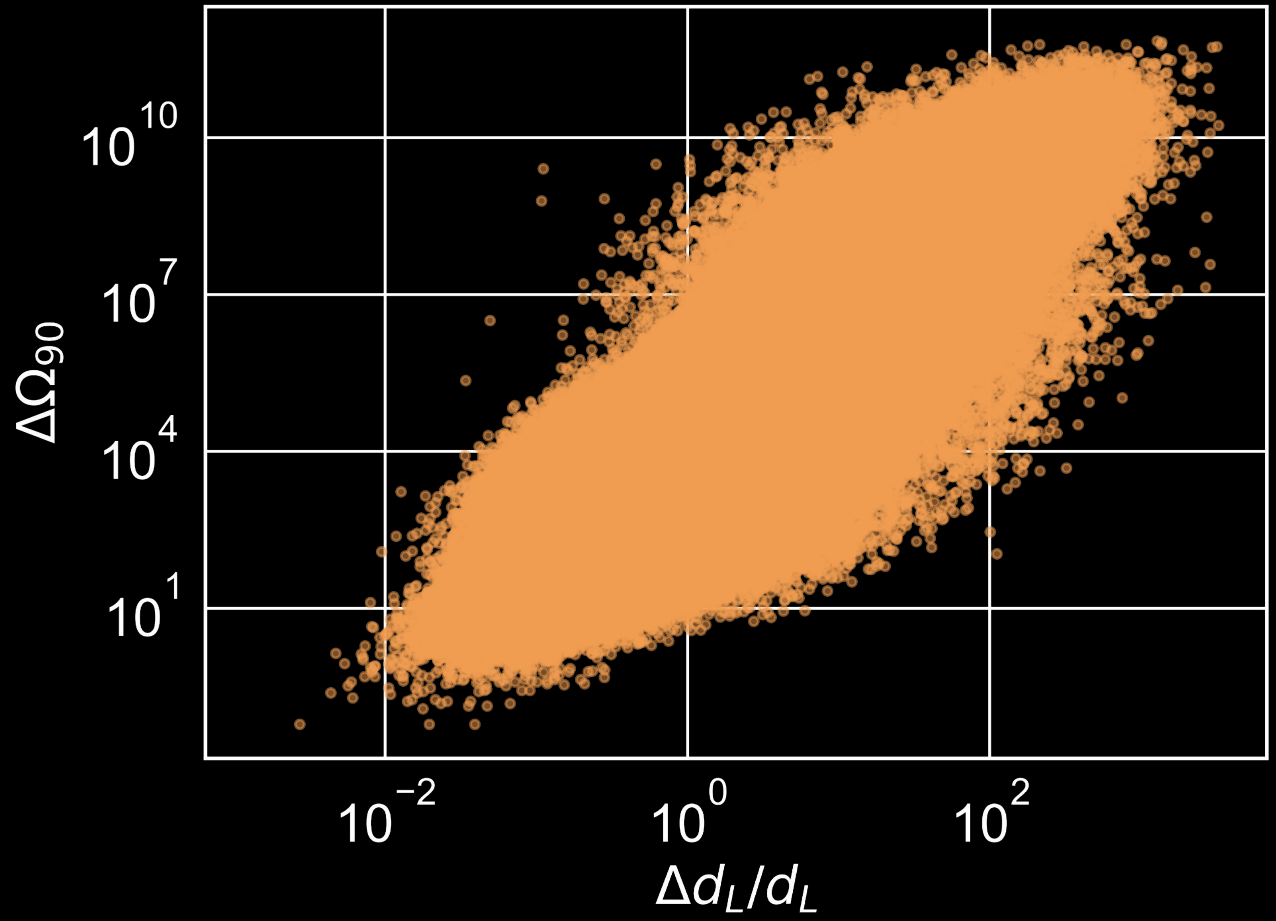
Reconstructing the HI light cone



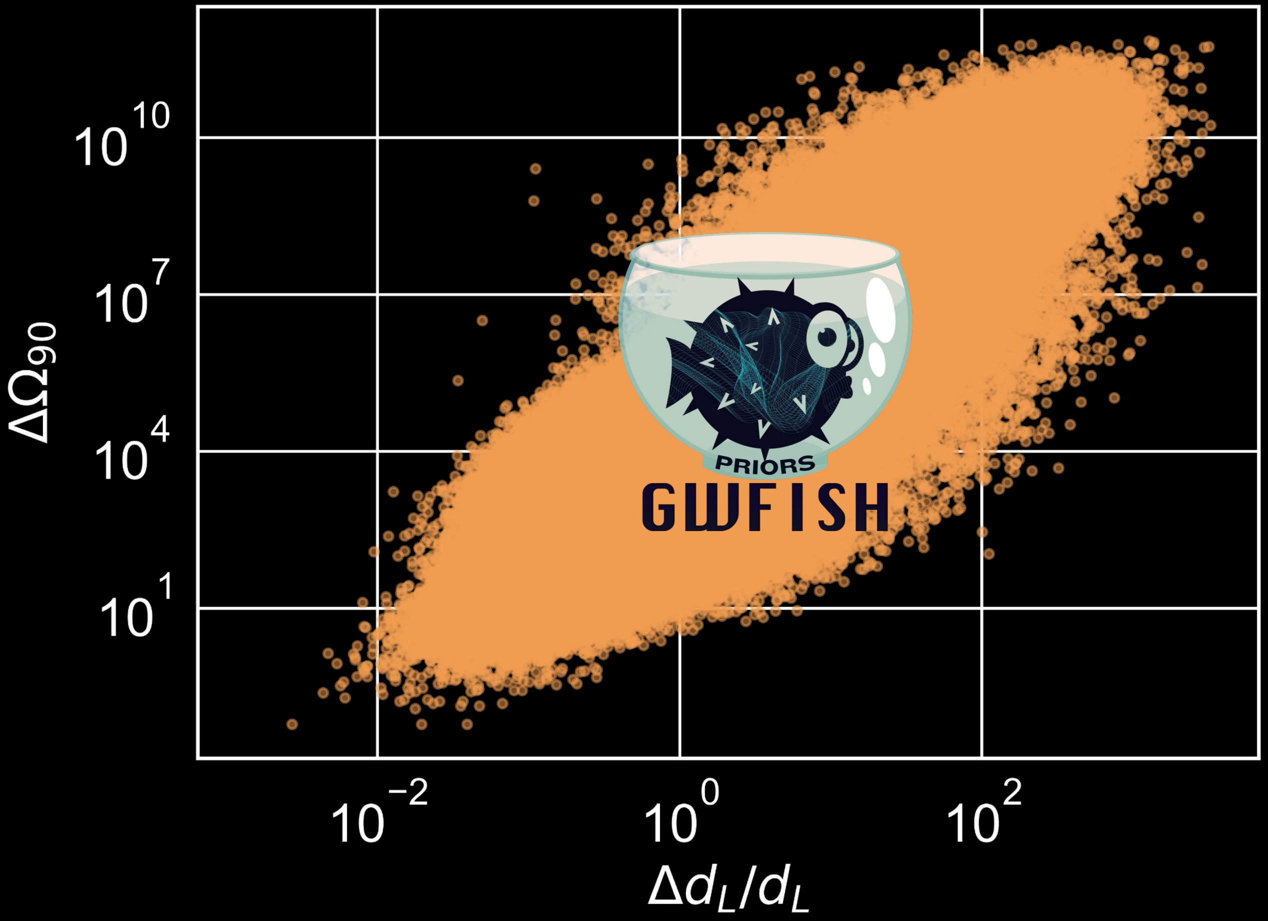
Gravitational data

- ➔ **BBH population** [Mapelli's group]:
  - ◆ **10 years** of forecast for XG generation (~1e6 events)
  - ◆ Fiducial population model


injected
ET + 1CE
ET
10^5
10^4
10^3
10^2
10^1
10^0
counts
0
1
2
3
4
5
redshift
GWFISH



10^{10}
10^{7}
10^{4}
10^{1}
$\Delta\Omega_{90}$
10^{-2}
10^{0}
10^{2}
$\Delta d_L/d_L$

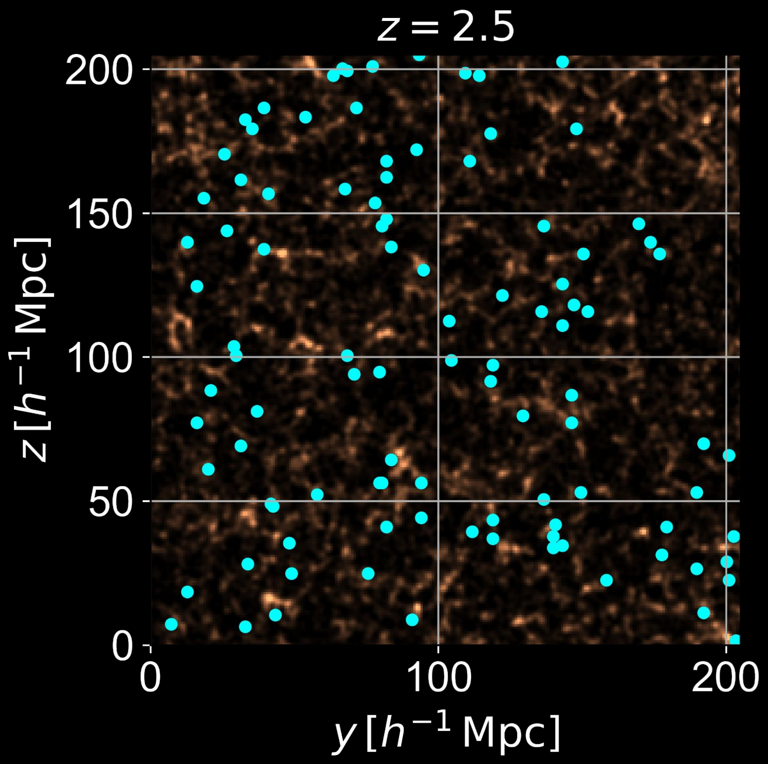


10^{10}
10^{7}
10^{4}
10^{1}
$\Delta\Omega_{90}$
PRIORS
GWFISH
10^{-2}
10^{0}
10^{2}
$\Delta d_L/d_L$

How should we distribute BBH events:

- ➔ Isotropically?
- ➔ **Following the HI field?**
- ➔ …

Distributing BBHs following HI field



- ➔ Extract redshift information from HI maps
- ➔ Extract distance information from BBHs
- ➔ Inference on H(z)

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Hierarchical Bayesian inference (?)

Hierarchical Bayesian Inference

2-level inference:
single events level
+ population level

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

posterior on hyperparameters

Likelihood of the sample of observed GW events

prior on hyperparameters

$$p(H_0|\{\vec{x}_i\}) \propto \mathcal{L}(\{\vec{x}_i\}|H_0)\boxed{\pi(H_0)}$$

$$H_0 \longrightarrow H(z)$$

$$\mathcal{L}(\{\vec{x}_i\}|\vec{\lambda}) = \frac{e^{-N_{\rm exp}(\vec{\lambda})}\left(N_{\rm exp}(\vec{\lambda})\right)^{N_{\rm obs}}}{N_{\rm obs}!} \prod_i^{N_{\rm obs}} \frac{\int d\vec{\theta}\, \mathcal{L}_{\rm GW}(\vec{x}_i|\vec{\theta})\, p_{\rm CBC}(z)}{\int d\vec{\theta}\, p_{\rm det}(\theta)\, p_{\rm CBC}(z)}$$

Poisson statistics

the events are independent!

Likelihood of single GW event

probability of detection

redshift probability

selection effects

[Mandel et al. 2019, Gair et al. 2023]

- **Selection effects**:
  - Hi-Fi mocks does not simulate the whole sky for HI field
  - GWs (BBHs) are all-sky
  - Probability of detection based on SNR
- GW likelihood:
  - Full posterior on distance
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Other effects?

Let’s discuss!