Cosmology with gravitational waves

Enis Belgacem
Université de Genève

RICAP-24

September 25th 2024

SELECTED TOPICS

1. Standard sirens

- Bright sirens
- Dark sirens

2. Detection of cosmological stochastic backgrounds

- Impact of the astrophysical background

STANDARD SIRENS: self-calibrated distance rulers

GWs from binaries give a direct measurement of the luminosity distance

Schutz 1986

If redshift information is also known then we can infer cosmological parameters

Low-redshift events mainly constrain H_0

$$d_L(z) \simeq \frac{c}{H_0} z$$

Important for Hubble tension: global VS local measurements of the Hubble constant

- PLANCK 2018: H_0 =67.4 ± 0.5 km/s/Mpc Planck 2018 [1807.06209]
- SH0ES: H_0 =73.04 ± 1.04 km/s/Mpc Riess et al. [2112.04510]

5σ tension !

Spatially flat ΛCDM: $d_L(z) \simeq \frac{c}{H_0}(1+z)\int_0^z \frac{dz'}{\sqrt{\Omega_M(1+z')^3+1-\Omega_M}}$

(Radiation contribution is negligible)

Extension to other cosmological parameters: DE EoS and modified gravity (more on this later)

How to get redshift?

BRIGHT SIRENS
have EM counterpart:
identify redshift of the host galaxy

DARK SIRENS
do not have EM counterpart, then statistical methods can be used

GALAXY CATALOG method:
cross-correlate GW sky localization volume with galaxy catalogs

SPECTRAL SIRENS:
assume a model on the population statistics of source-frame parameters (masses, spin, merger rate). Since the observed quantities are «redshifted»
e.g. $m_{1,2} \rightarrow (1+z)m_{1,2}$
then we get information on redshift

Only one bright siren so far at LIGO-Virgo: joint GW/GRB detection GW170817/GRB 170817 A $z \simeq 0.01$

$$H_0 = 70^{+12}_{-8} \text{ km s}^{-1}\text{Mpc}^{-1}$$ Abbott et al., Nature 551, 85 (2017)

Prospects on H_0 from future LVK runs, from BNS and NS-BH with detected EM counterpart

2% in 5 yr, 1% in 10 yr — Chen et al. (2018)

2% by 2030 — Feeney et al. (2019, 2021)

But low constraining power on other cosmological parameters $\Omega_M, w_0, \ldots$

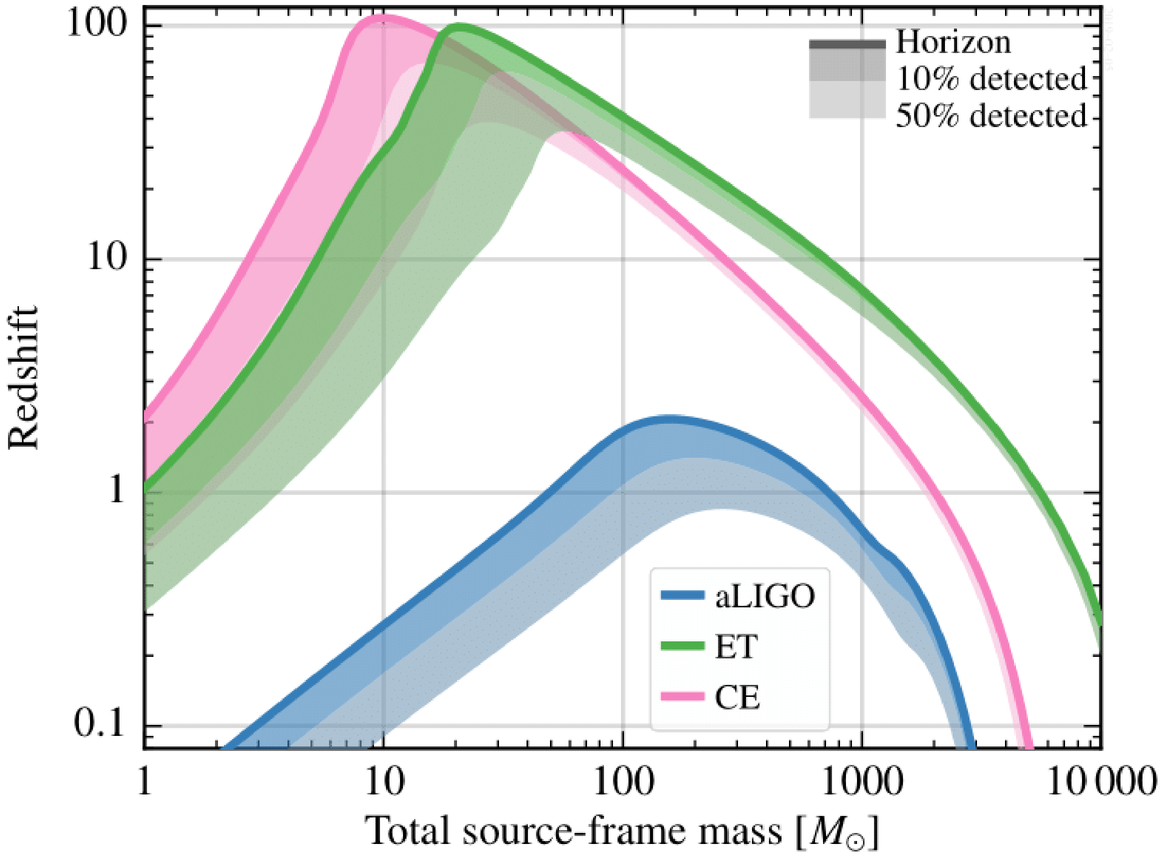
Using the galaxy catalog method with 47 sources from GWTC-3

$$H_0 = 68^{+8}_{-6} \text{ km s}^{-1}\text{Mpc}^{-1}$$ Abbott et al. (LVK) [2111.03604]

Small improvement, but possibility to use many more events compared to bright sirens

Things will change with 3G detectors in the 2030s:
Einstein Telescope (ET) and Cosmic Explorer (CE)

Evans and Hall 2019



Similar to more updated works:
Branchesi et al. 2023 [2303.15923]
Evans et al. 2021 [2109.09882]

ET alone will detect:

Science Case for the Einstein Telescope, Maggiore et al. (2020)

- BBH out to $z \sim 20$
- BNS up to $z \sim 2 - 3$

Bright sirens method (BNS) requires redshift determination from EM counterpart

1) Temporal coincidence with sGRB, then find redshift from X-ray afterglow

2) For well localized events, follow-up (optical and IR telescopes) and identify host galaxy

- 3G network, e.g. ET+CE+CE
- Some localization with ET alone using Earth rotation

Number of sources detected by ET in 1 yr (for various SNR thresholds)

BBH

Configuration	SNR ≥ 8	SNR ≥ 12	SNR ≥ 50	SNR ≥ 100	SNR ≥ 200
Δ-10km-HFLF-Cryo	103 528	87 568	13 674	2298	282
Δ-15km-HFLF-Cryo	111 231	101 308	26 092	5730	759
2L-15km-45°-HFLF-Cryo	107 661	97 205	23 491	4933	644
2L-20km-45°-HFLF-Cryo	110 698	103 773	34 009	8828	1267
2L-15km-0°-HFLF-Cryo	104 935	94 015	24 088	5143	642
2L-20km-0°-HFLF-Cryo	106 417	98 274	32 915	8551	1246
Δ-10km-HF	87 125	65 092	5595	773	98
Δ-15km-HF	102 149	85 698	13 697	2360	292
2L-15km-45°-HF	97 881	81 210	12 089	1987	248
2L-20km-45°-HF	105 032	93 050	20 551	4144	515
2L-15km-0°-HF	89 707	73 696	10 688	1732	201
2L-20km-0°-HF	104 558	92 308	21 970	4540	569
Δ-10km-HFLF-Cryo+CE-40km	115 179	110 118	44 676	12 590	1805
2L-15km-45°-HFLF-Cryo+CE-40km	116 328	112 661	50 947	15 545	2355
2L-15km-0°-HFLF-Cryo+CE-40km	114 816	110 265	49 034	14 820	2243
Δ-10km-HFLF-Cryo+2CE	117 045	113 910	52 092	16 109	2505
2L-15km-45°-HFLF-Cryo+2CE	117 436	115 166	57 678	19 028	3126
2L-15km-0°-HFLF-Cryo+2CE	116 639	113 597	55 218	17 849	2917
LVKI-O5	8603	2861	47	4	2

BNS

Configuration	SNR ≥ 8	SNR ≥ 12	SNR ≥ 50	SNR ≥ 100	SNR ≥ 150
Δ-10km-HFLF-Cryo	107 902	36 985	458	57	19
Δ-15km-HFLF-Cryo	213 583	89 910	1206	159	38
2L-15km-45°-HFLF-Cryo	190 528	77 458	1052	134	33
2L-20km-45°-HFLF-Cryo	275 595	129 821	2018	243	64
2L-15km-0°-HFLF-Cryo	192 030	78 675	1040	136	33
2L-20km-0°-HFLF-Cryo	274 395	132 486	2048	250	65
Δ-10km-HF	44 713	13 410	166	18	9
Δ-15km-HF	116 349	41 181	516	55	17
2L-15km-45°-HF	101 550	34 956	447	52	15
2L-20km-45°-HF	176 396	70 441	961	115	32
2L-15km-0°-HF	103 539	35 817	443	57	17
2L-20km-0°-HF	184 799	74 805	989	124	37
Δ-10km-HFLF-Cryo+CE-40km	348 434	177 925	2836	312	87
2L-15km-45°-HFLF-Cryo+CE-40km	392 680	212 260	3677	418	116
2L-15km-0°-HFLF-Cryo+CE-40km	402 234	220 023	3770	414	119
Δ-10km-HFLF-Cryo+2CE	406 630	220 725	3961	436	120
2L-15km-45°-HFLF-Cryo+2CE	442 526	252 136	4900	559	152
2L-15km-0°-HFLF-Cryo+2CE	448 798	258 615	4974	531	162
LVKI-O5	250	71	3	0	0

Branchesi et al. 2023 [2303.15923]

Localization with a single 3G detector

- For BNS and a low-frequency cut-off of 1Hz, the signal stays 5 days in the detector bandwidth
- In the meantime the Earth rotates and induces a time dependence in the antenna pattern function
- The time-dependent response helps localizing the source even with a single detector!

The success of the method depends on the sensitivity at low frequencies (works for ET, but not for CE)

- In this way ET can localize 50% of BNS at 40 Mpc within 2 deg^2
- CE only reaches 250 deg^2 for the same fraction at the same distance

Chan, Messenger, Heng and Hendry 1803.09680

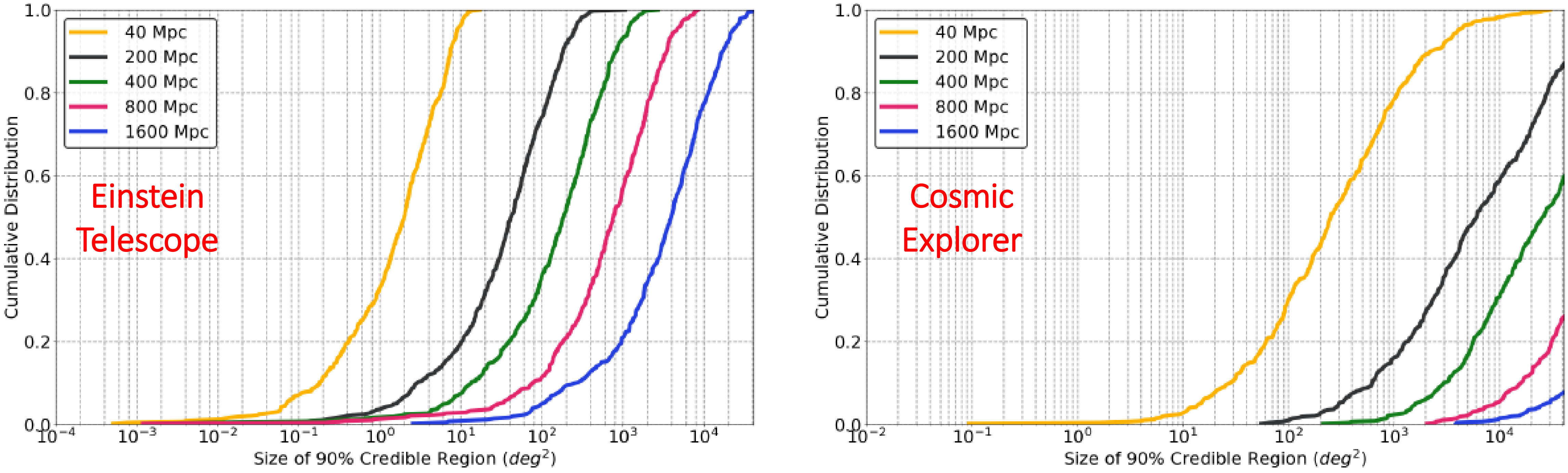


Table from Astro2020 Science White Paper
“Multimessenger Universe with GWs from binaries”

Follow-up for well localized sources, e.g.

WFIRST, up to $z \simeq 0.76$

Subaru and LSST, up to $z \simeq 0.55$

other telescopes, up to $z \sim 0.1-0.3$

Table 2: Present (*P*) and future (*F*) electromagnetic facilities that are able to observe faint/distant counterparts to GWs. Detection Limit (**DL**, 1 hr exposure time) for UV, optical, and near-IR facilities are expressed in AB magnitudes, for X-rays in $10^{-16}\,\mathrm{erg\,s^{-1}\,cm^{2}}$, and for radio in μJy. Distance reach (D in Mpc) of facilities for GW170817-like events are shown.

	Facility	**DL**	**D**
Gamma-rays	*Fermi P*	S/N 5	80
	AMEGO *F*	S/N 5	130
X-rays	*Swift P*	S/N 5	~80
	Chandra P	30	150
	ATHENA *F*	3	480
	Lynx F	6	450
	STROBE-X *F*	S/N 5	120
UV	HST (im) *P*	26	2000
	HST (spec) *P*	23	400
Optical Imaging	Subaru *P*	27	3200
	LSST *F*	27	3200
Optical Spec.	Keck/VLT *P*	23	500
	Gemini Obs. *P*	23	500
	GMT *F*	25	1265
	TMT *F*	25.5	1592
	E-ELT *F*	26	2005
Infrared Imaging	WFIRST *F*	27.5	4800
	Euclid *F*	25.2	1700
Infrared Spec.	Keck/VLT	21.5	481
	GMT *F*	23.5	762
	TMT *F*	24	960
	E-ELT *F*	24.5	1208
Radio	VLA (S) *P*	5	91
	ATCA (CX) *P*	42	51
	ngVLA (S) *F*	1.5	353
	SKA-mid (L) *F*	0.72	634

But there are large uncertainties in costs and dedicated time

For LSST a realistic estimate is 1% of time for GW follow up

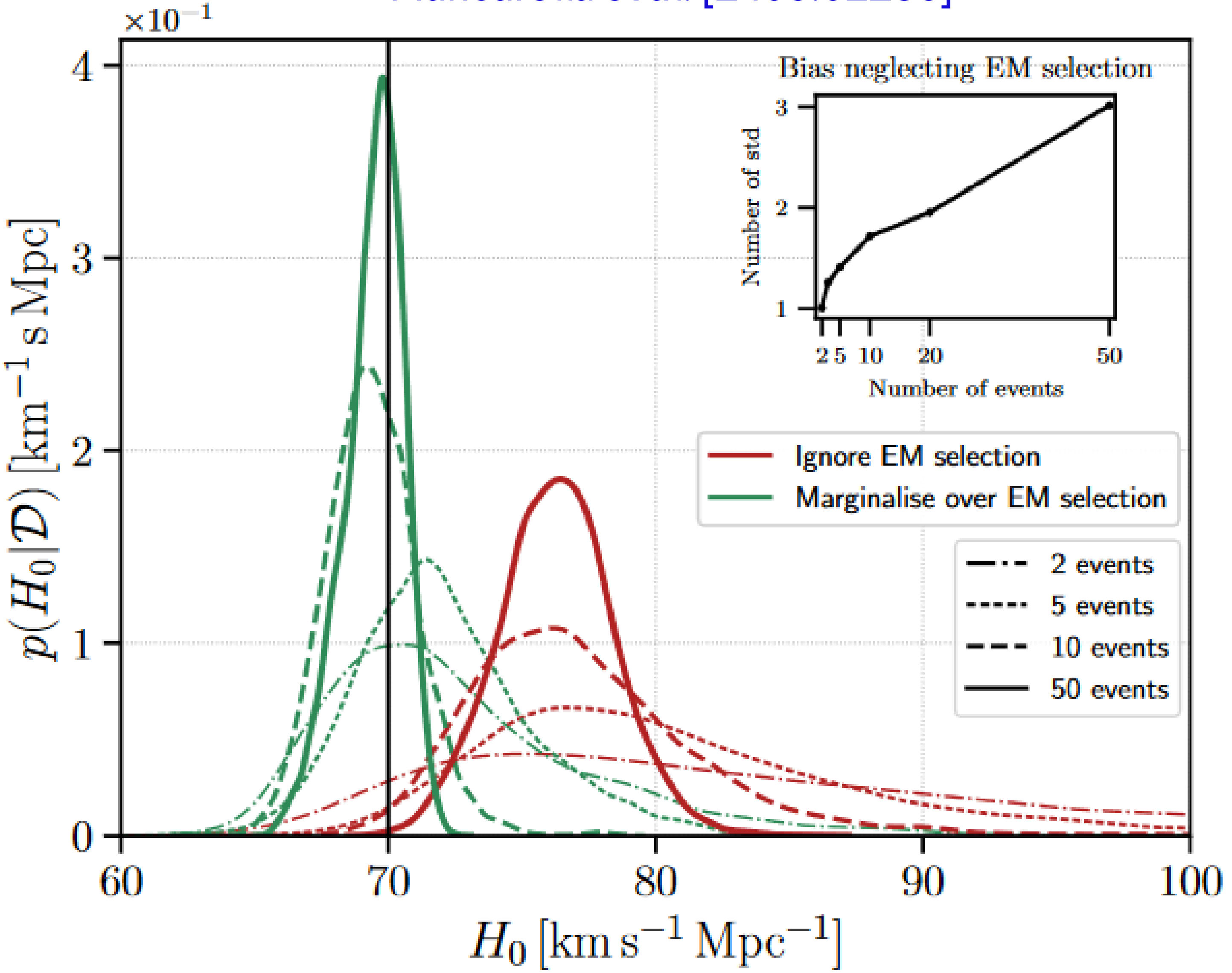
$\mathcal{O}(10)$ counterparts per year at $z \sim 0.5$

$\mathcal{O}(100)$ counterparts per year at $z \sim 0.1$

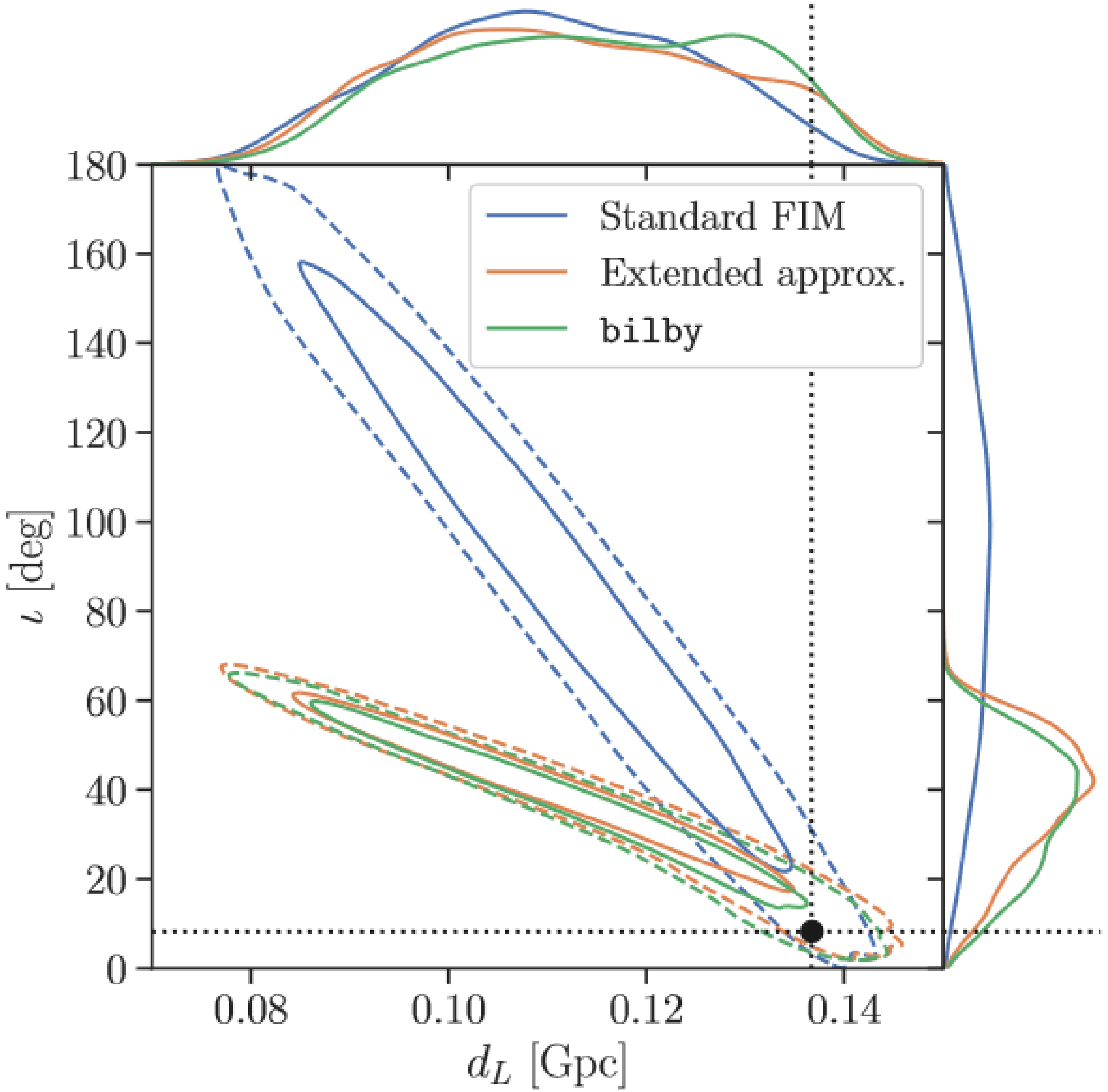
EM selection effects and $d_L - \iota$ degeneracy for bright sirens

- Short GRBs can only be detected for small inclination angles ι
- But inclination angle and luminosity distance are correlated in the GW signal, in particular for small ι
  - This leads to a bias on the Hubble constant prediction, if the EM selection effects are not included in the calculation of the posterior
- Limited knowledge on GRB production mechanism makes it very difficult to just impose a reliable prior on ι

Mancarella et al. [2405.02286]



- Full Bayesian parameter estimations are computationally expensive
- But the Fisher Information Matrix approximation fails at small inclination angles
- Adopt an hybrid approach: exact on d_L, ι , but Fisher on the other parameters
- The reconstructed distance is pushed to smaller values wrt the true one (black dot), this is the origin of the bias in H_0

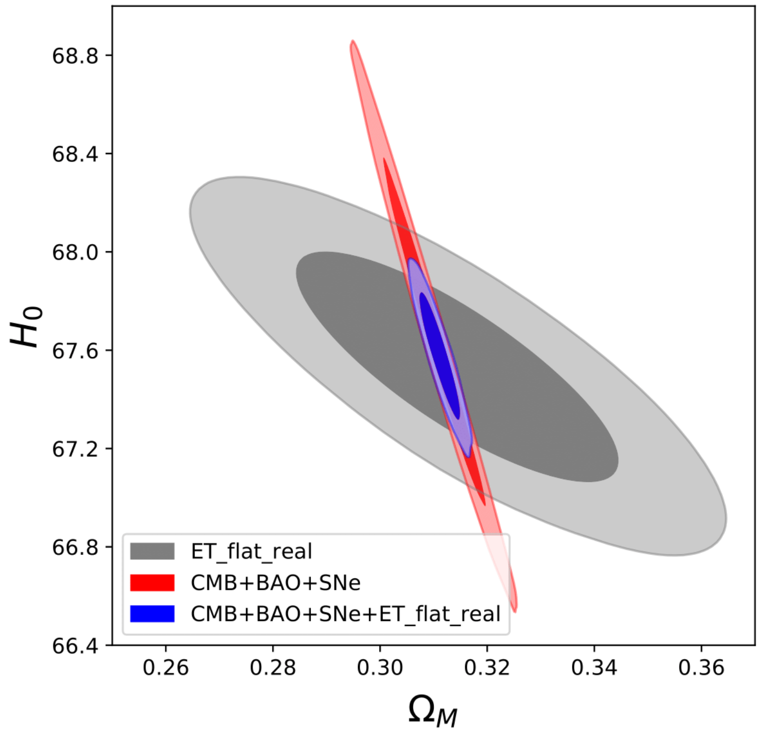


Mancarella et al. [2405.02286]

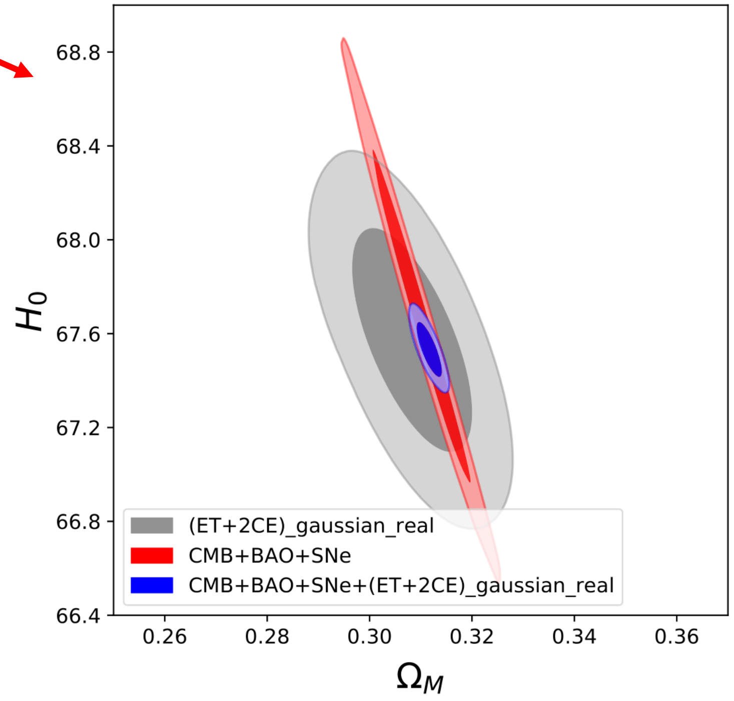
Prospects on cosmological parameters with bright sirens at 3G detectors

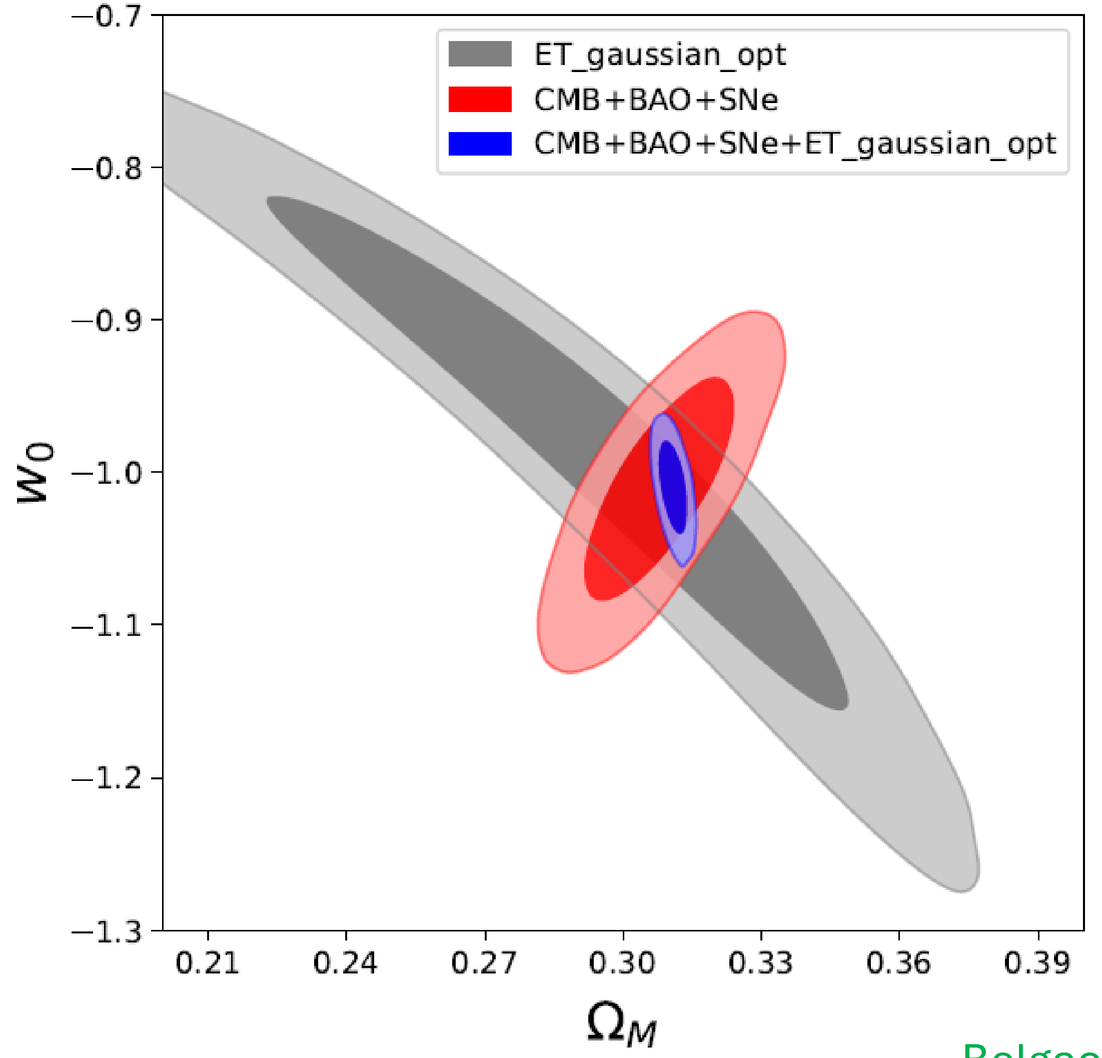
Sub-percent precision on H_0 in a few years of multimessenger observations: $\mathcal{O}(100)$ events

Cai and Yang (2016), Zhao and Wen (2017), Belgacem et al.(2019), Califano et al. (2022), Alfradique et al. (2022)



Joint GW/GRB detections at ET/THESEUS give significant improvements wrt current cosmological data

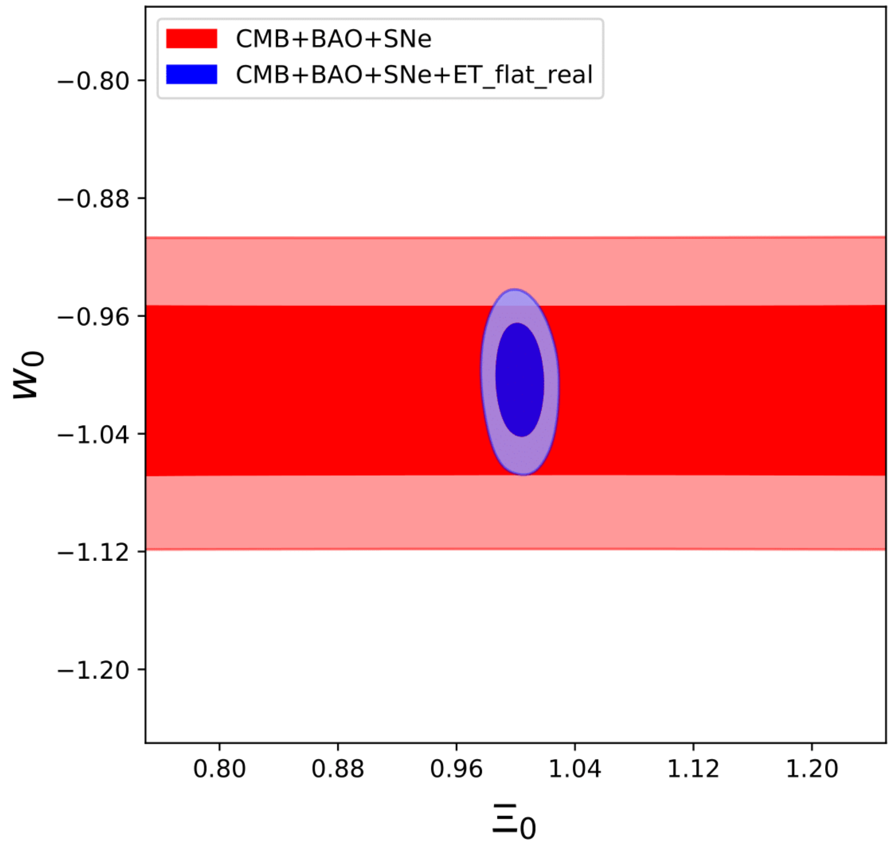




Belgacem et al. (2019)

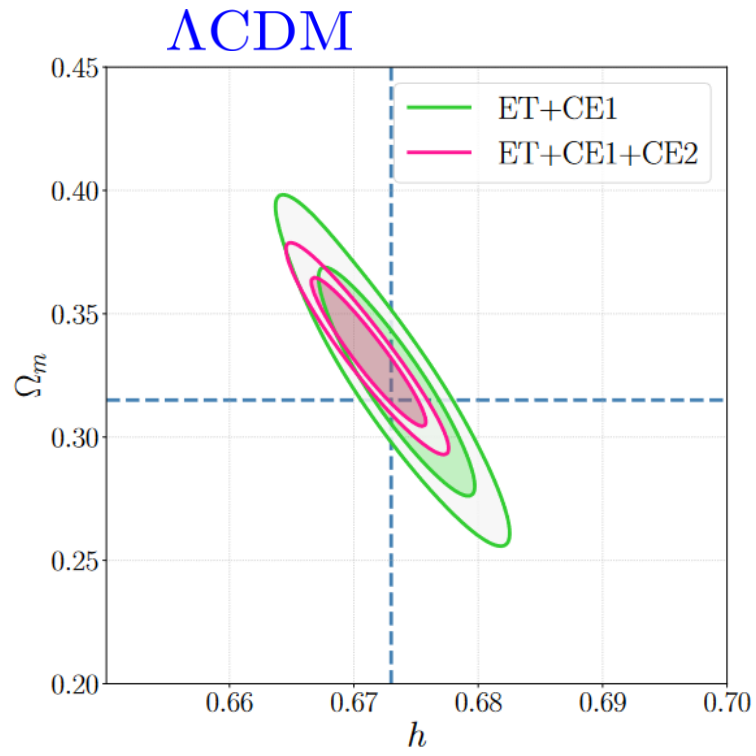
Belgacem, Dirian, Foffa, Maggiore
PRD 2018, 1805.08731

$$\frac{d_L^{gw}(z)}{d_L^{em}(z)} = \Xi_0 + \frac{1-\Xi_0}{(1+z)^n}$$



$$\Delta\Xi_0 = 0.011 \qquad \Delta w_0 = 0.026$$

DARK SIRENS AT 3G DETECTORS



Muttoni et al. [2303.10693]

- 200 (ET+CE1) or 300 (ET+CE1+CE2) loud BBH events (SNR>300) assuming a complete galaxy catalog up to z=1

- Percent measurement of H_0 with 10'000 BBH events at ET or CE, using the expected distribution of the coalescence redshift

Leandro et al. [2109.07537]

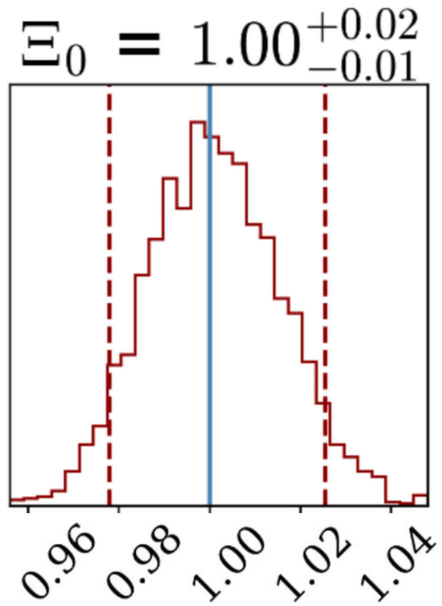
DE and MG

- 5% measurement of w_0 with 10'000 BNS events at CE (1 yr), assuming BNS rate follows star formation rate

Ye, Fishbach [2103.14038]

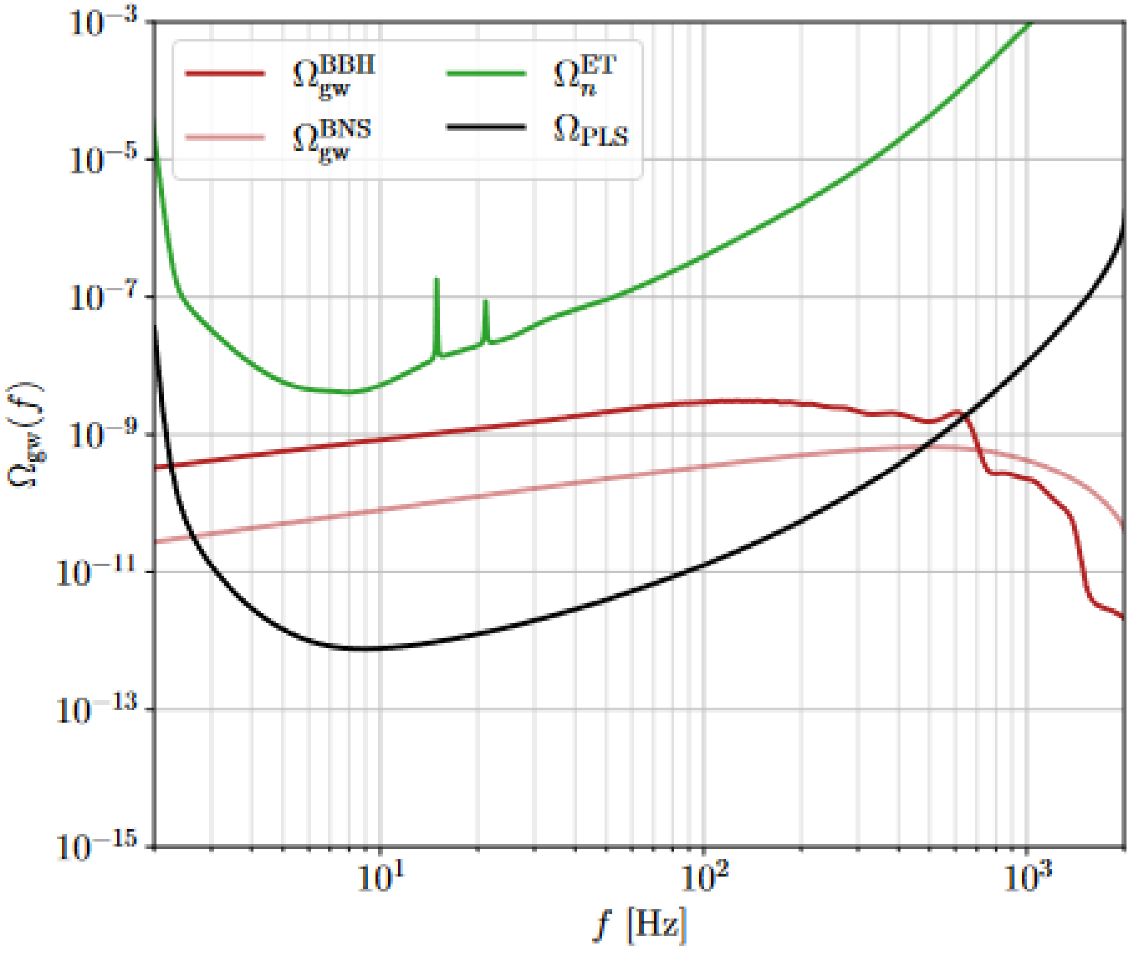
- Percent measurement of Ξ_0 with 4600 well-localized BNS at ET

Iacovelli et al. [2203.09237]



DETECTION OF COSMOLOGICAL STOCHASTIC BACKGROUNDS IN THE PRESENCE OF ASTROPHYSICAL BACKGROUNDS

Belgacem, Iacovelli, Maggiore, Mancarella, Muttoni, *Confusion noise from astrophysical backgrounds at third-generation gravitational-wave detector networks*, in preparation

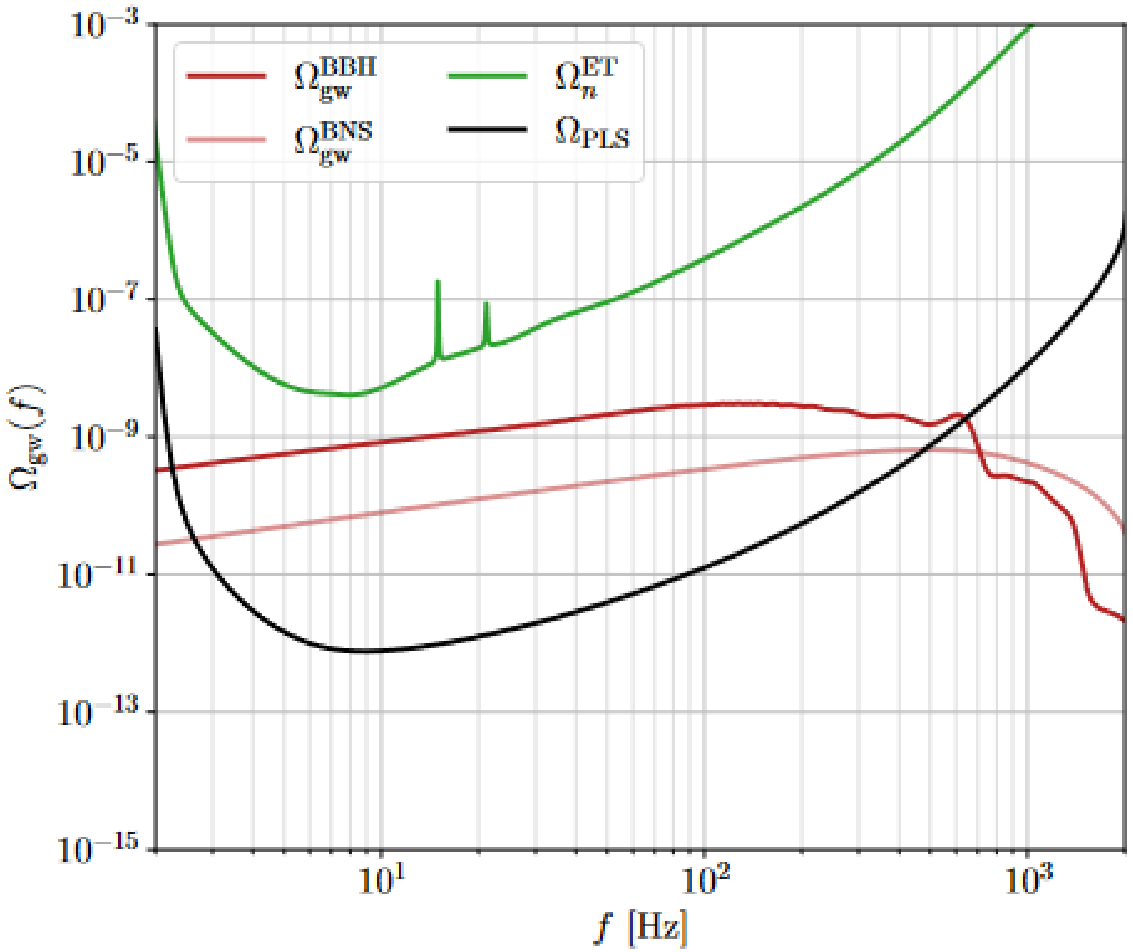


Comparison between the energy density $\Omega_{gw}(f)$ produced by BBHs and BNSs, the equivalent energy density $\Omega_n^{ET}(f)$ of the noise of a single ET detector, and the PLS curve obtained correlating for 1 yr the three ET detectors in the triangle configuration (colors as in legend).

$$\Omega_{gw}^{astro}(f) = \frac{4\pi^2}{3H_0^2}\frac{f^3}{T}\sum_{i=1}^{N_{ev}}\left[|\tilde{h}_{+,i}(f)|^2 + |\tilde{h}_{\times,i}(f)|^2\right]$$

- Astrophysical energy density **even before subtraction** is well below the equivalent noise one

- Noise correlations due to the astrophysical background are small compared to the instrumental noise already in a detector



Comparison between the energy density $\Omega_{gw}(f)$ produced by BBHs and BNSs, the equivalent energy density $\Omega_n^{ET}(f)$ of the noise of a single ET detector, and the PLS curve obtained correlating for 1 yr the three ET detectors in the triangle configuration (colors as in legend).

- PLS curve built from cross-correlations between detectors by choosing the filter that maximizes the SNR of the cosmological background
- This plot does **not** mean that a cosmological background has to overcome the astrophysical energy densities to be detectable, just like in the absence of astrophysical events we do not need the cosmological background to be above the equivalent noise energy density!

The proper way to go:

- Total output of a detector is $\tilde{\sigma}_a(f) = \tilde{n}_a(f) + \tilde{h}_a^{\rm conf}(f) + h_a^{\rm cosmo}(f)$
- The astrophysical background is an addition source noise

$$\tilde{h}_a^{\rm conf}(f) = \sum_{i=1}^{N_{\rm ev}} \left[\tilde{h}_{a,i}^{\rm true}(f) - \tilde{h}_{a,i}^{\rm obs}(f)\theta(\mathrm{SNR}_i^{\rm obs} - \mathrm{SNR_{th}})\right]$$

$$\tilde{n}_a^{\rm eff}(f) \equiv \tilde{n}_a(f) + \tilde{h}_a^{\rm conf}(f)$$

- The effective noise exhibits correlations between different detectors $\langle \tilde{n}_a^*(f)\tilde{n}(f)_b\rangle_n = \delta(f-f')\frac{1}{2}\mathcal{N}_{ab}(f)$

- The PLS curve that takes into account the astrophysical confusion noise will be very close to the old one.

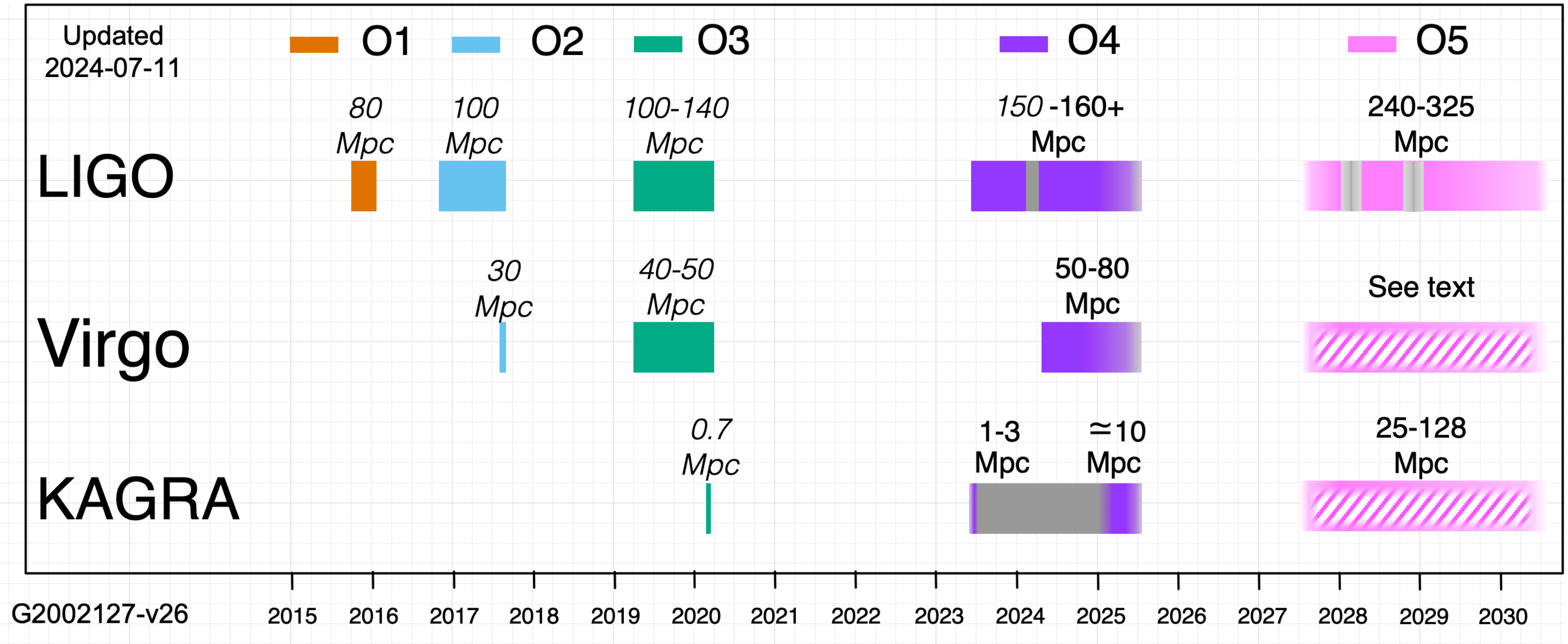
- **But** we also need to be sure that the signal from the cosmological background overcomes the «signal» actually due to noise correlations. This gives a notion of **extended PLS** curves

$$S = \frac{T}{2}\int_{-\infty}^{+\infty} df\, \left[\mathcal{N}_{12}(f) + \mathcal{H}_{12}(f)\right]\tilde{Q}(f) \qquad S_{\mathcal{N}} = \frac{T}{2}\int_{-\infty}^{+\infty} df\, \mathcal{N}_{12}(f)\,\tilde{Q}(f) \qquad S_{\mathcal{H}} = \frac{T}{2}\int_{-\infty}^{+\infty} df\, \mathcal{H}_{12}(f)\,\tilde{Q}(f)$$

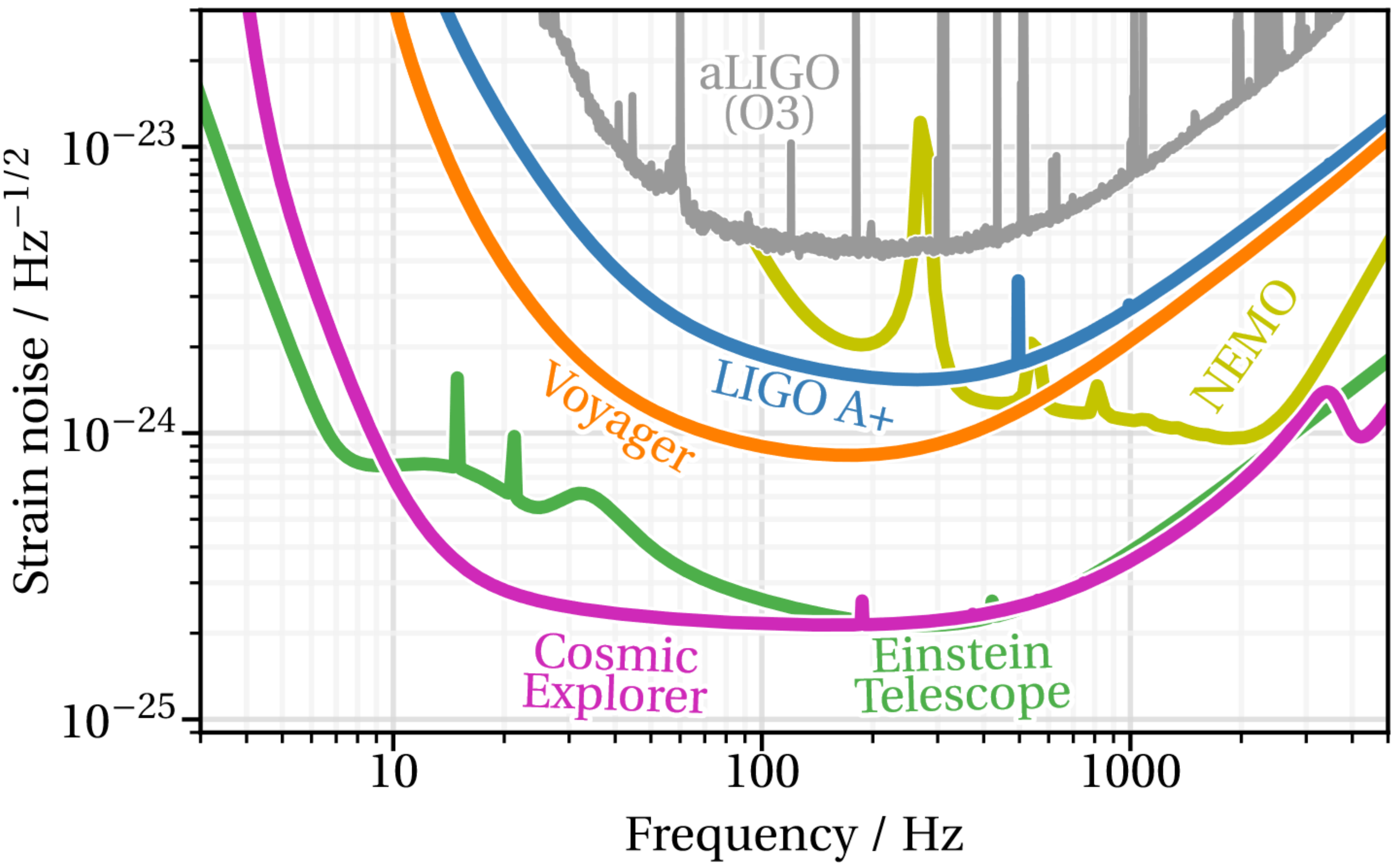
General derivation of optimal filter with Gaussian correlated noise studied in

E. Belgacem, *Matched filtering and the search for stochastic gravitational-wave backgrounds in the presence of noise correlations between detectors*, in preparation

BACKUP SLIDES



Updated
2024-07-11
O1
O2
O3
O4
O5
LIGO
80 Mpc
100 Mpc
100-140 Mpc
150 -160+ Mpc
240-325 Mpc
Virgo
30 Mpc
40-50 Mpc
50-80 Mpc
See text
KAGRA
0.7 Mpc
1-3 Mpc
≃10 Mpc
25-128 Mpc
G2002127-v26
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030



aLIGO (O3)
LIGO A+
Voyager
NEMO
Cosmic Explorer
Einstein Telescope
10^{-23}
10^{-24}
10^{-25}
10
100
1000
Strain noise / $Hz^{-1/2}$
Frequency / Hz

HUBBLE TENSION

Discrepancy between H_0 measurements from cosmological probes at early times and values deduced from distance measurements at local scales (**more than 4σ** in ΛCDM)

Global measurements: CMB anisotropies (*Planck*), baryon acoustic oscillations (BAO), cosmic chronometers (up to $z \sim 2$)

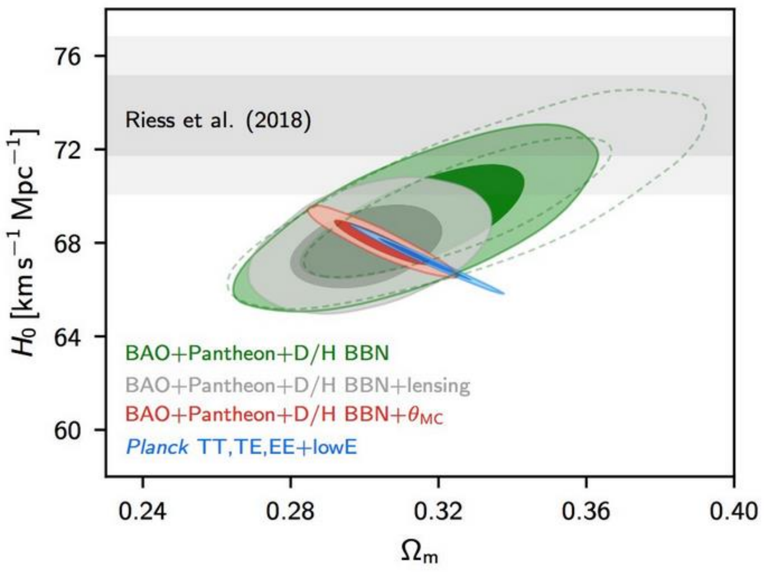
Local measurements:

SNIa luminosity distance —calibration→ Cepheids (SH0ES); tip of the red giant branch (TRGB)

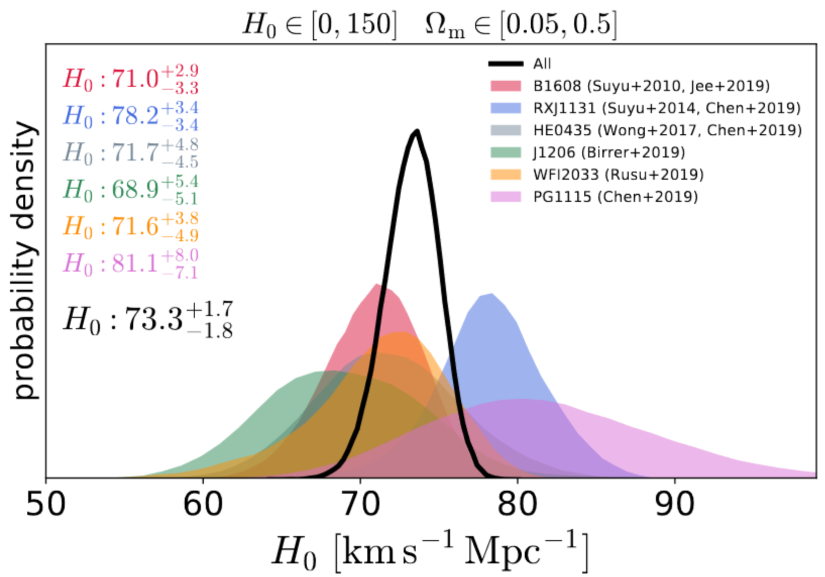
Time delays of multiple images of strongly lensed quasars (H0LiCOW)

Other distance indicators (e.g. Mira variables, surface brightness fluctuations)

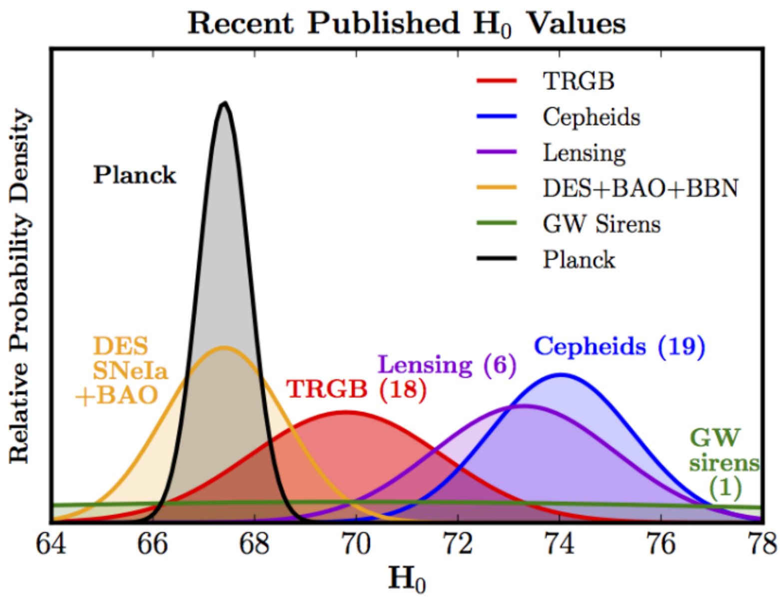
- PLANCK 2018: H_0 =67.4 ± 0.5 km/s/Mpc   Planck 2018 [arXiv: 1807.06209]
- SH0ES: H_0 =73.04 ± 1.04 km/s/Mpc   Riess et al. (2022)
- H0LiCOW: H_0 =73.3 ± 1.8 km/s/Mpc   Wong et al [arXiv: 1907.04869]
- TRGB: H_0 =69.6 ± 0.8 (stat) ± 1.7 (sys) km/s/Mpc   Freedman et al [arXiv: 2002.01550 , 2106.15656]



SH0ES



H0LiCOW



SEVERAL PROBES

Table 1: Expected detections per year (N), number detected with a resolution of < 1, < 10 and < 100 sq. deg. (N_1, N_{10} and N_{100}, respectively) and median localization error (M in sq. deg.), in a network consisting of LIGO-Hanford, LIGO-Livingston and Virgo (HLV), HLV plus KAGRA and LIGO-India (HLVKI) and 1 Einstein Telescope and 2 Cosmic Explorer detectors (1ET+2CE).

Network	N	N_1	N_{10}	N_{100}	M
HLV	48	0	16	48	19
HLVKI	48	0	48	48	7
1ET+2CE	990k	14k	410k	970k	12

Joint GW/GRB detections at ET/THESEUS

EB, Dirian, Foffa, Howell, Maggiore, Regimbau,
JCAP 1908 (2019) 015

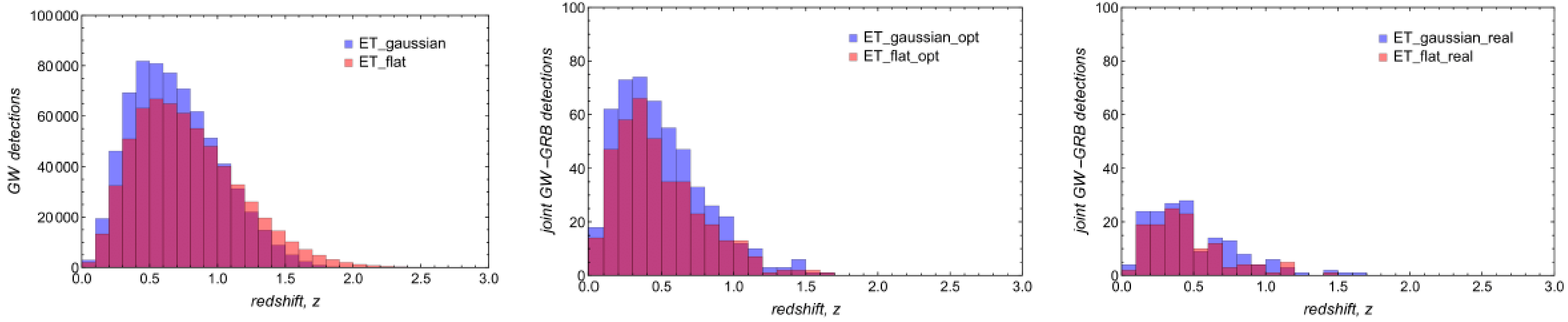
Simulation of a population of BNS based on Regimbau et al. 2015, ApJ 799, 69

- Evaluation of the coalescence rate using star formation rate and a probability distribution for the delay between formation and coalescence of the binary system (modeled according to Dominik et al. 2012, ApJ 759, 52)
- Exponential probability distribution for the time interval between two successive events (i.e. assume coalescence in the observer frame is a Poisson process)
- 2 possibilities for the neutron stars mass distribution are considered: flat or gaussian
- Compute the SNR for each event to assess its GW detectability

EM counterpart

- Redshift is determined from temporal coincidence with GRB, assumed to be detected by the proposed THESEUS mission Amati et al., Adv. Space Res. 62 (2018) 191-244, 1710.04638
- Only the events with a peak flux of GRB emission above the THESEUS flux limit are kept in the final catalog
- We consider 2 different possibilities for the THESEUS FoV: 6 sr (optimistic) and 2 sr (more realistic)

EB, Dirian, Foffa, Howell, Maggiore, Regimbau, JCAP 1908 (2019) 015



Total number of events at ET with SNR>12
(10 years of data and 80% duty cycle)

FLAT	GAUSSIAN
6.2×10^5	6.9×10^5

CAVEAT:
Some estimates below are too optimistic acording to more recent forecasts

Number of events at ET with EM counterpart at THESEUS
(10 years of data and 80% duty cycle for ET)

FLAT OPT	GAUSSIAN OPT	FLAT REAL	GAUSSIAN REAL
389	511	128	169

ET+CE+CE/THESEUS

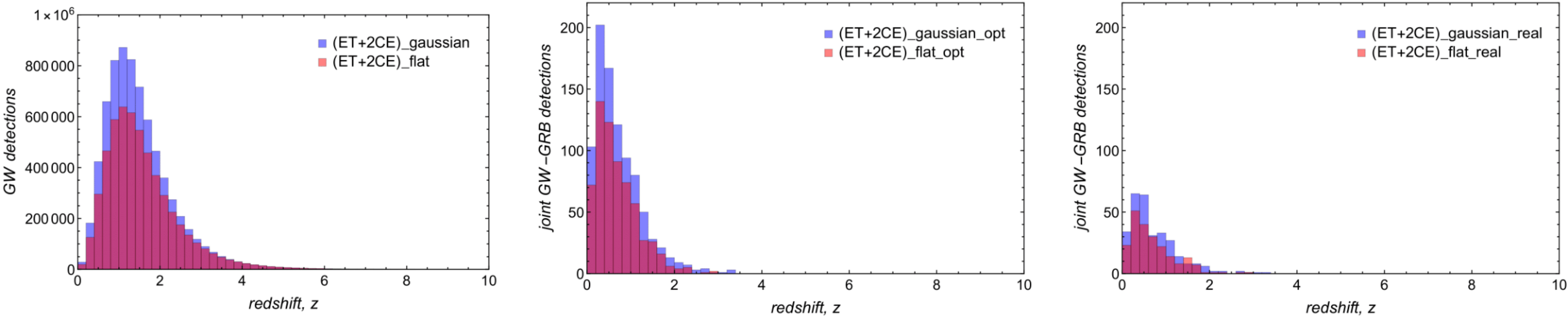


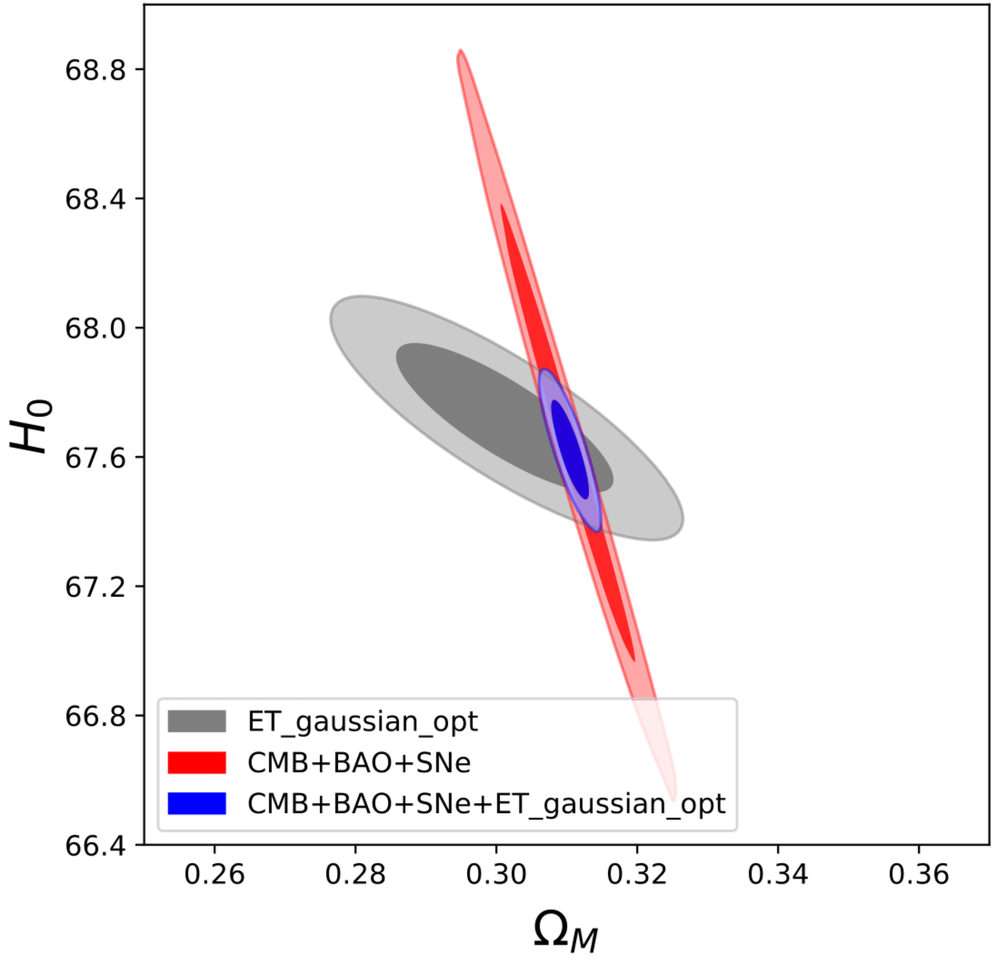
Figure from Belgacem, Dirian, Foffa, Howell, Maggiore, Regimbau 1907.01487

- 10 yrs of events, 80% duty cycle for each GW detector

	GW events	Joint GW-GRB events
ET+CE+CE 10 years	7 millions $z_{\max} \simeq 9.6$	optimistic 900, more realistic 300 $z_{\max} \simeq 3.4$

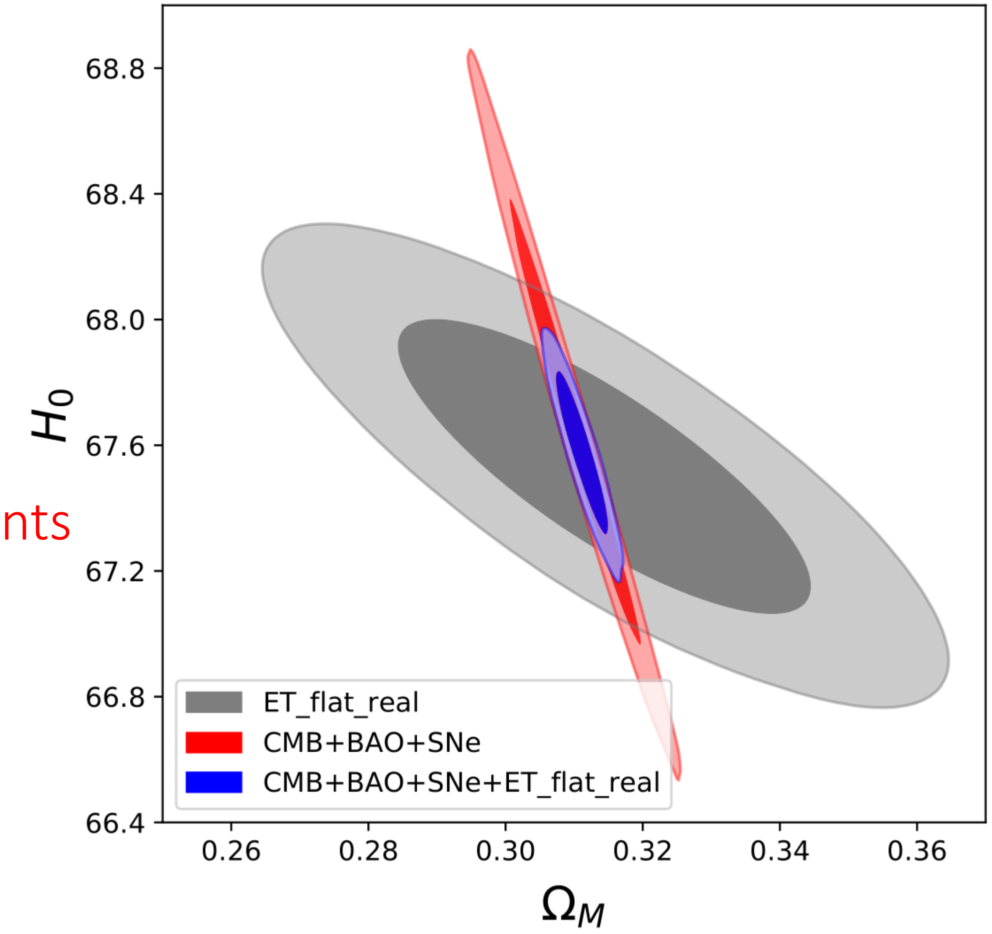
	$\Delta H_0/H_0$	$\Delta\Omega_M/\Omega_M$
ET_gaussian_opt	0.23 %	3.38 %
CMB+BAO+SNe	0.72 %	2.11 %
CMB+BAO+SNe+ET_gaussian_opt	0.15 %	0.57 %

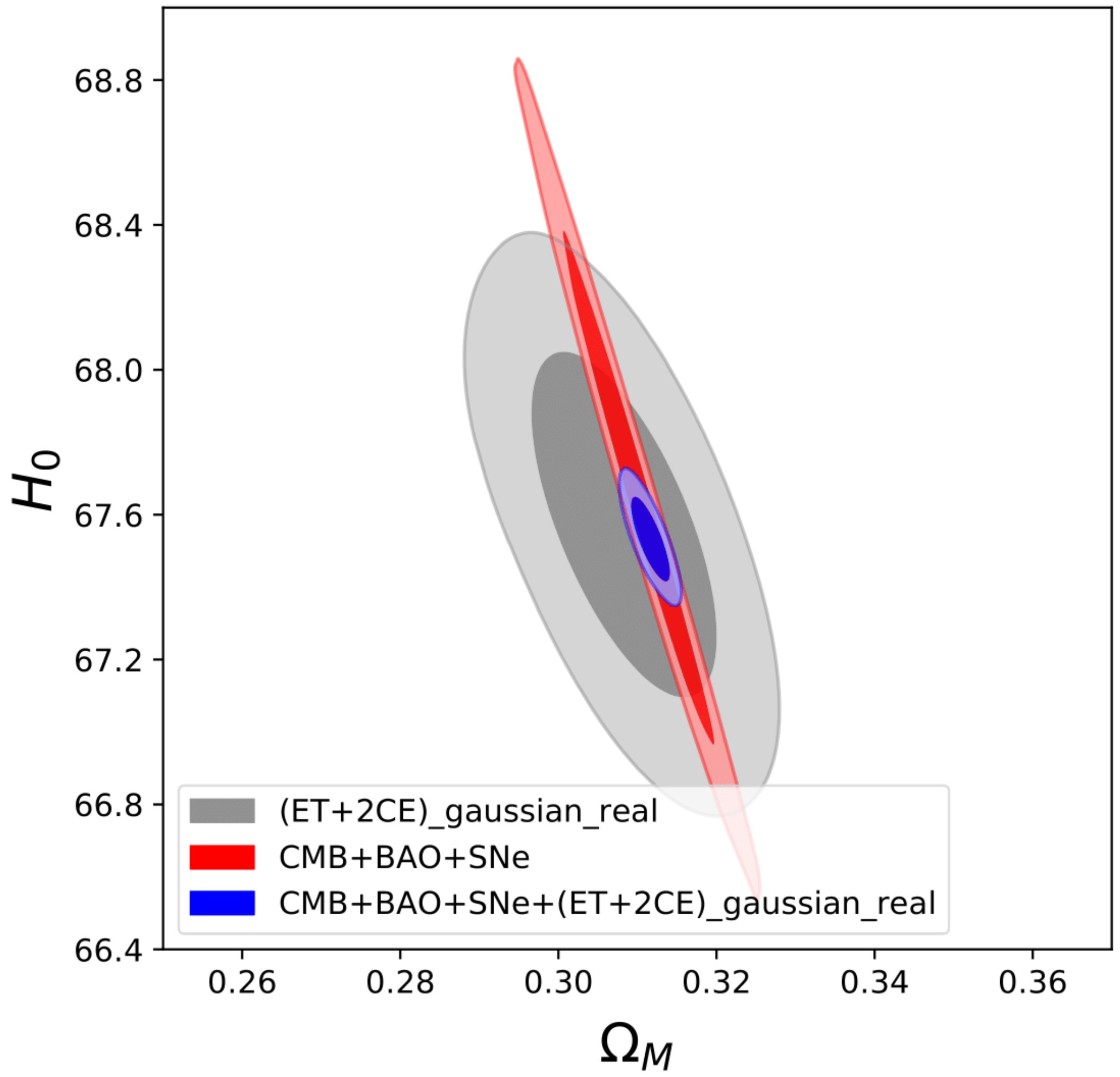
	$\Delta H_0/H_0$	$\Delta\Omega_M/\Omega_M$
ET_flat_real	0.42 %	6.17 %
CMB+BAO+SNe	0.72 %	2.11 %
CMB+BAO+SNe+ET_flat_real	0.26 %	0.82 %



Constraints on ΛCDM parameters

Significant improvements





ΛCDM	$\Delta H_0/H_0$	$\Delta\Omega_M/\Omega_M$
ET+CE+CE	0.23 %	2.09 %
CMB+BAO+SNe	0.72 %	2.11 %
CMB+BAO+SNe+ET+CE+CE	0.11 %	0.52 %

Significant improvements wrt current cosmological data

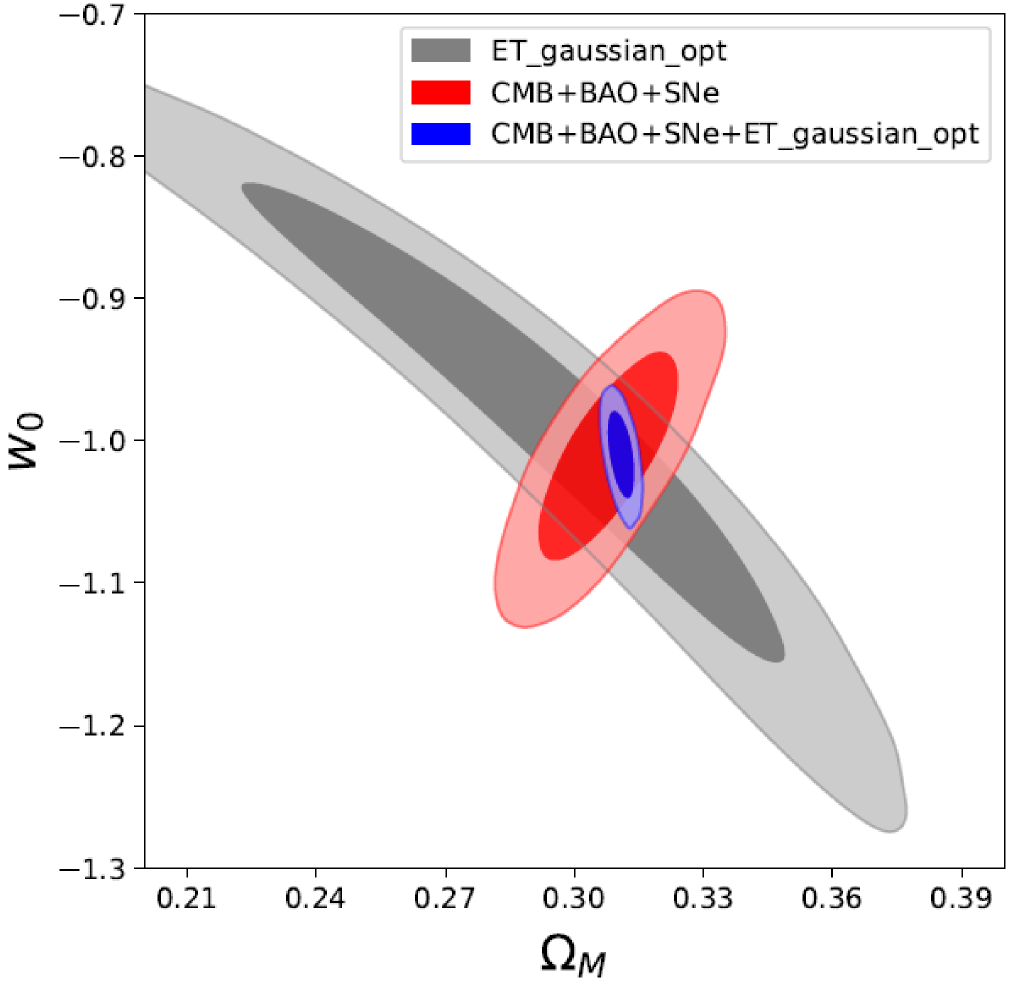
Even considered on their own, GW data at ET+CE+CE will constrain H_0 better than current CMB+BAO+SNe

$\Downarrow$

important role for the Hubble tension

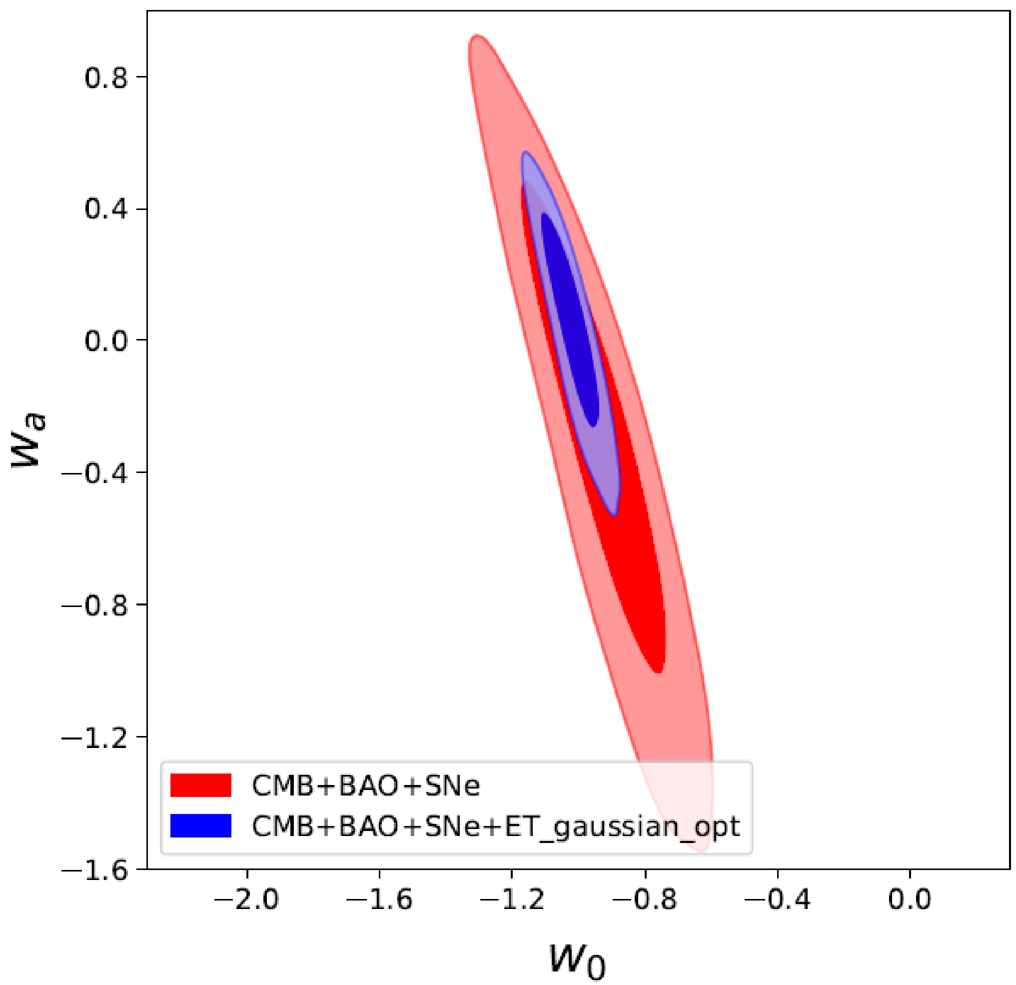
Dark Energy EoS

using only w_0



w_0 only extra parameter	Δw_0
ET	0.116
CMB+BAO+SNe	0.045
CMB+BAO+SNe+ET	0.021

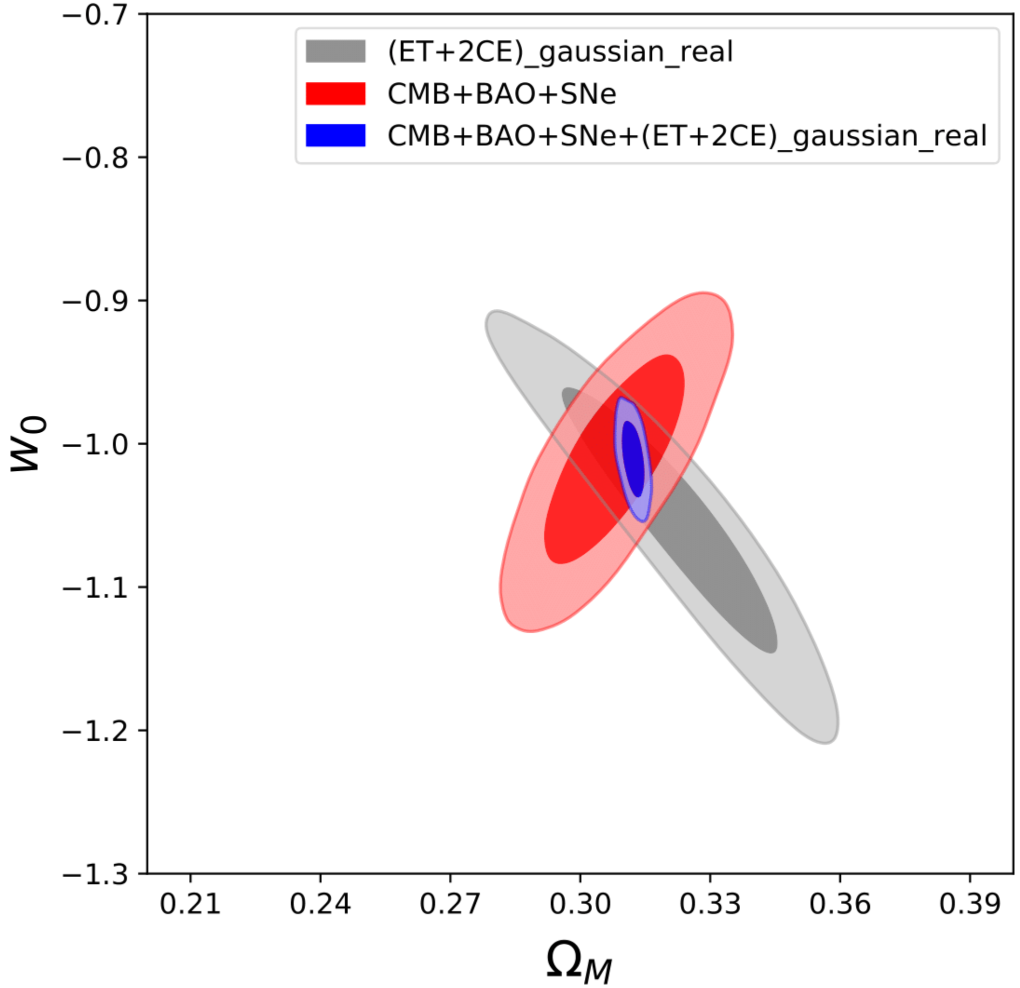
(w_0, w_a) parametrization



(w_0, w_a) extension	Δw_0	Δw_a
CMB+BAO+SNe	0.140	0.483
CMB+BAO+SNe+ET	0.058	0.224

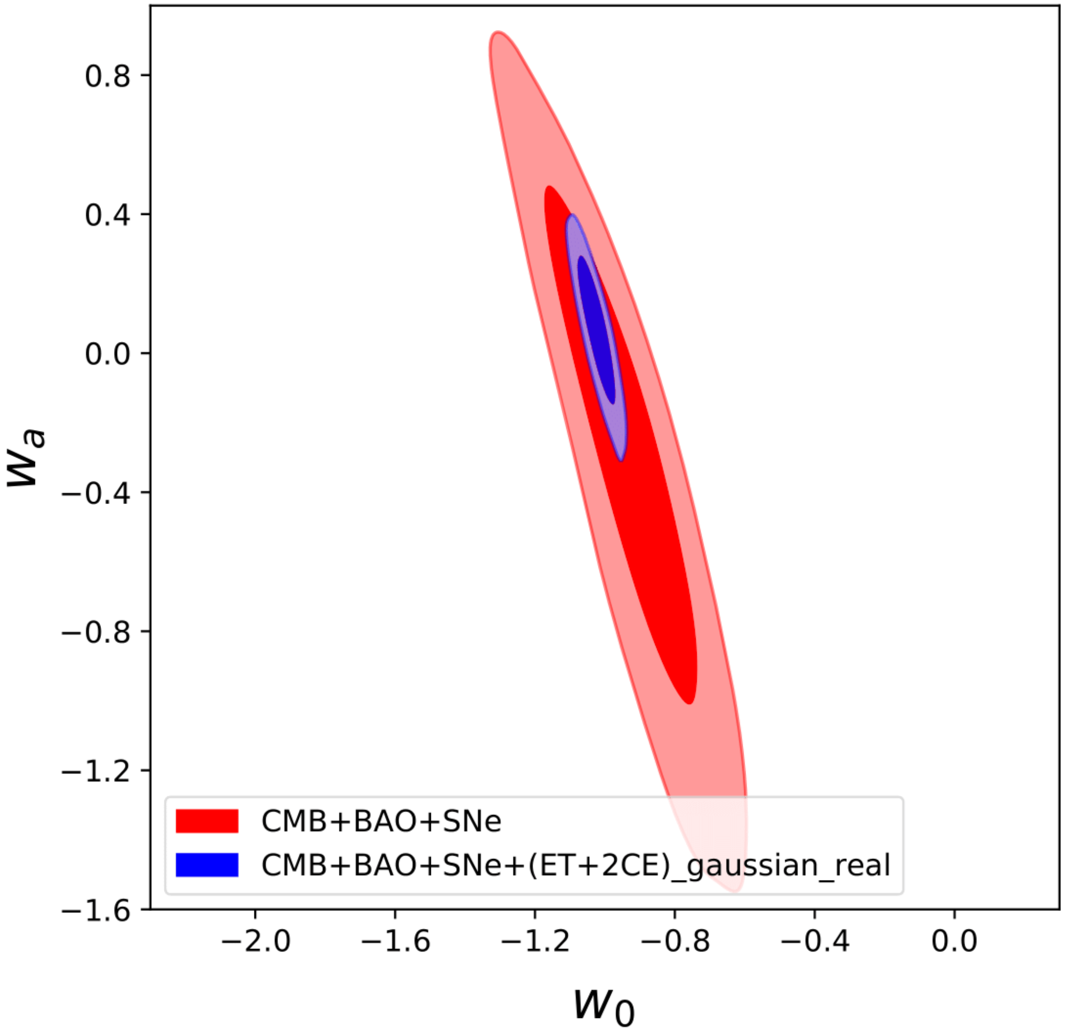
Dark Energy EoS

using only w_0



w_0 only extra parameter	Δw_0
ET+CE+CE	0.063
CMB+BAO+SNe	0.045
CMB+BAO+SNe+ET+CE+CE	0.018

(w_0, w_a) parametrization



(w_0, w_a) extension	Δw_0	Δw_a
CMB+BAO+SNe	0.140	0.483
CMB+BAO+SNe+ET+CE+CE	0.037	0.145

Standard sirens can be used to probe gravity on cosmological scales and to test modified gravity cosmology against ΛCDM

ΛCDM

There is only one notion of luminosity distance, valid for both standard candles and standard sirens

$$d_L(z) = \frac{1+z}{H_0}\int_0^z \frac{dz'}{\sqrt{\Omega_M(1+z')^3+\Omega_\Lambda}}$$

Modified gravity cosmology

There are 2 effects:

1) The EM luminosity distance is different because of the different values of cosmological parameters and a non-trivial DE EoS

$$d_L^{em}(z) = \frac{1+z}{H_0}\int_0^z \frac{dz'}{\sqrt{\Omega_M(1+z')^3+\rho_{DE}(z')/\rho_0}}$$

2) On top of that, modified GW propagation must be taken into account

$$d_L^{gw}(z) = \exp\left[-\int_0^z \frac{dz'}{1+z'}\delta(z')\right] d_L^{em}(z)$$

GW propagation

Let us first recall how it works in GR

- Tensor perturbations around FRW background, with Fourier modes $h_A(\eta, \mathbf{k})$

Free propagation: $h''_A + 2\mathcal{H}h'_A + k^2 h_A = 0$ $\qquad \mathcal{H} \equiv \frac{a'(\eta)}{a(\eta)}$

- Write $h_A(\eta, \mathbf{k}) = \frac{\chi_A(\eta, \mathbf{k})}{a(\eta)}$ to obtain $\chi''_A + \left(k^2 - \frac{a''}{a}\right)\chi_A = 0$

- For modes inside the horizon, it gives a wave equation for $\chi_A(\eta, \mathbf{k})$

$$\chi''_A + k^2 \chi_A = 0$$

- speed of GWs = speed of light $\quad c_{gw} = c$

GW propagation in modified gravity

- Tensor perturbations around FRW background, with Fourier modes $h_A(\eta, \mathbf{k})$

$$h''_A + 2\mathcal{H}\left[1 - \delta(\eta)\right] h'_A + k^2 h_A = 0$$

EB, Dirian, Foffa, Maggiore
PRD 2018, 1712.08108
PRD 2018, 1805.08731

- It is a very general feature of modified gravity models, e.g.

  - Scalar-tensor theories: Horndeski (f(R), galileons, Brans-Dicke), DHOST
  - Nonlocal gravity
  - Higher dimensions: DGP
  - Bigravity

Deffayet and Menou 2007
Saltas et al. 2014,
Lombriser and Taylor 2016,
Nishizawa 2017,
EB, Dirian, Foffa, Maggiore 2017, 2018
EB et al. (LISA Cosmology WG),

- Write $h_A(\eta, \mathbf{k}) = \frac{\chi_A(\eta,\mathbf{k})}{\tilde{a}(\eta)}$ where $\frac{\tilde{a}'(\eta)}{\tilde{a}(\eta)} = \mathcal{H}\left[1 - \delta(\eta)\right]$

and obtain $\chi_A'' + \left(k^2 - \frac{\tilde{a}''}{\tilde{a}}\right)\chi_A = 0$

- For modes inside the horizon, it gives a wave equation for $\chi_A(\eta, \mathbf{k})$

$$\chi_A'' + k^2\chi_A = 0$$

- No modification in the $k^2\chi_A$ term to comply with constraints on speed of GWs

GW170817/GRB 170817A $|c_{gw} - c|/c < \mathcal{O}(10^{-15})$ LIGO and Virgo collaborations, ApJ 848, L13 (2017)

Standard sirens (coalescing binaries)

GR ⟵ $\chi_A'' + k^2 \chi_A = 0$ ⟶ Modified gravity

GR

$$h_A(\eta, \mathbf{k}) = \frac{\chi_A(\eta,\mathbf{k})}{a(\eta)}$$

- Amplitude decreases as the inverse of the (EM) luminosity distance

$$h_A(\eta, \mathbf{k}) \propto \frac{1}{d_L(z)}$$

- Direct measurement of the (EM) luminosity distance

Modified gravity

$$h_A(\eta, \mathbf{k}) = \frac{\chi_A(\eta,\mathbf{k})}{\tilde{a}(\eta)}$$

$$\delta(\eta) \neq 0 \quad \longrightarrow \quad \tilde{a}(\eta) \neq a(\eta)$$

- Amplitude decreases as the inverse of a **new GW luminosity distance different from the EM one**

$$h_A(\eta, \mathbf{k}) \propto \frac{1}{d_L^{gw}(z)}$$

$$d_L^{gw}(z) = \frac{a(z)}{\tilde{a}(z)} d_L^{em}(z) = \exp\left[-\int_0^z \frac{dz'}{1+z'}\delta(z')\right] d_L^{em}(z)$$

- Direct measurement of the GW luminosity distance

Standard sirens can be used to probe gravity on cosmological scales and to test modified gravity cosmology against ΛCDM

ΛCDM

There is only one notion of luminosity distance, valid for both standard candles and standard sirens

$$d_L(z) = \frac{1+z}{H_0}\int_0^z \frac{dz'}{\sqrt{\Omega_M(1+z')^3+\Omega_\Lambda}}$$

Modified gravity cosmology

There are 2 effects:

1) The EM luminosity distance is different because of the different values of cosmological parameters and a non-trivial DE EoS

$$d_L^{em}(z) = \frac{1+z}{H_0}\int_0^z \frac{dz'}{\sqrt{\Omega_M(1+z')^3+\rho_{DE}(z')/\rho_0}}$$

2) On top of that, modified GW propagation must be taken into account

$$d_L^{gw}(z) = \exp\left[-\int_0^z \frac{dz'}{1+z'}\delta(z')\right] d_L^{em}(z)$$

A parametrization for modified GW propagation

$$\frac{d_L^{gw}(z)}{d_L^{em}(z)} = \Xi_0 + \frac{1-\Xi_0}{(1+z)^n}$$

EB, Dirian, Foffa, Maggiore
PRD 2018, 1805.08731

It fits a large class of modified gravity models

EB et al. (LISA Cosmology WG), 2019

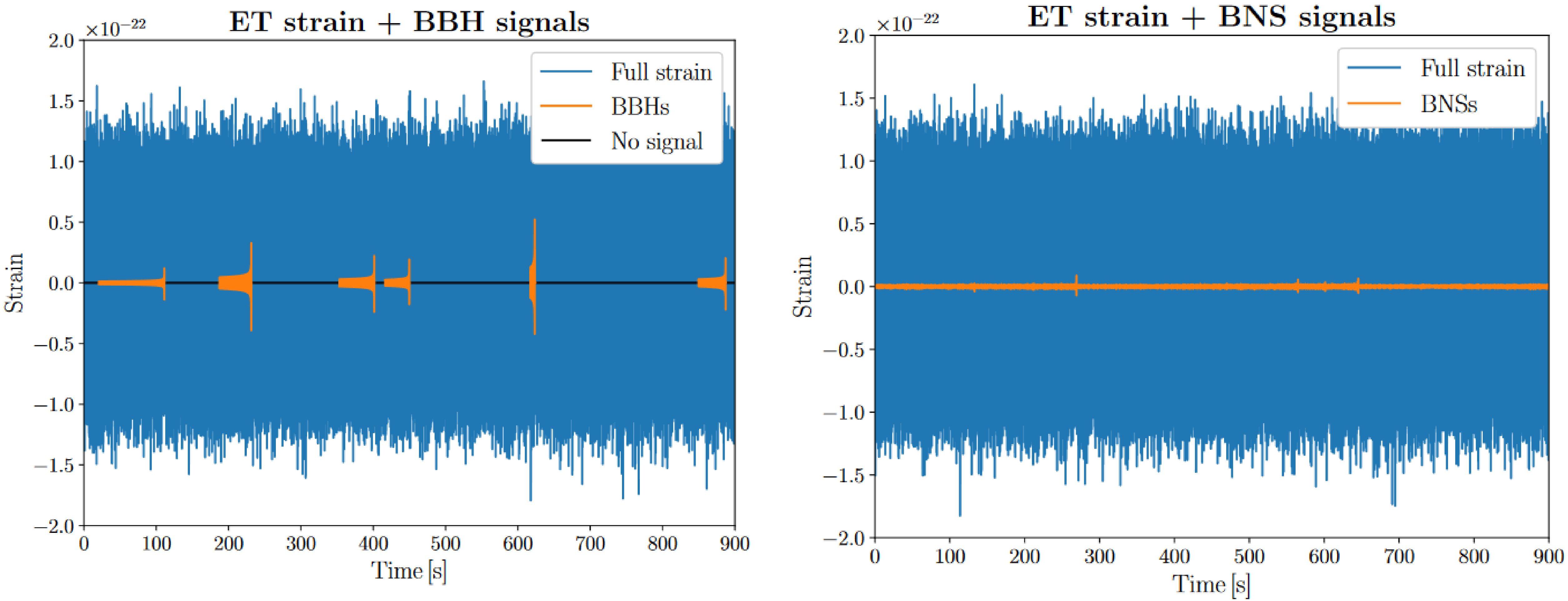
Resulting DE sector parametrization:

background (w_0, w_a)

scalar perturbations (Σ, μ)

tensor perturbations (Ξ_0, n)

Ξ_0 and w_0 are the most relevant parameters for dark energy studies with standard sirens



Representative simulated time-domain strain for 15 min of data-taking at one ET interferometer. We add mock BBH and BNS signals to the upper and lower panel, respectively, both obtained from the populations adopted in Sect. VI. To simulate the time-domain signals we employ the `IMRPhenomTHM` and `IMRPhenomT` approximants [84] for BBHs and BNSs, respectively. In the upper panel we highlight in black the data segments where no signal is present.