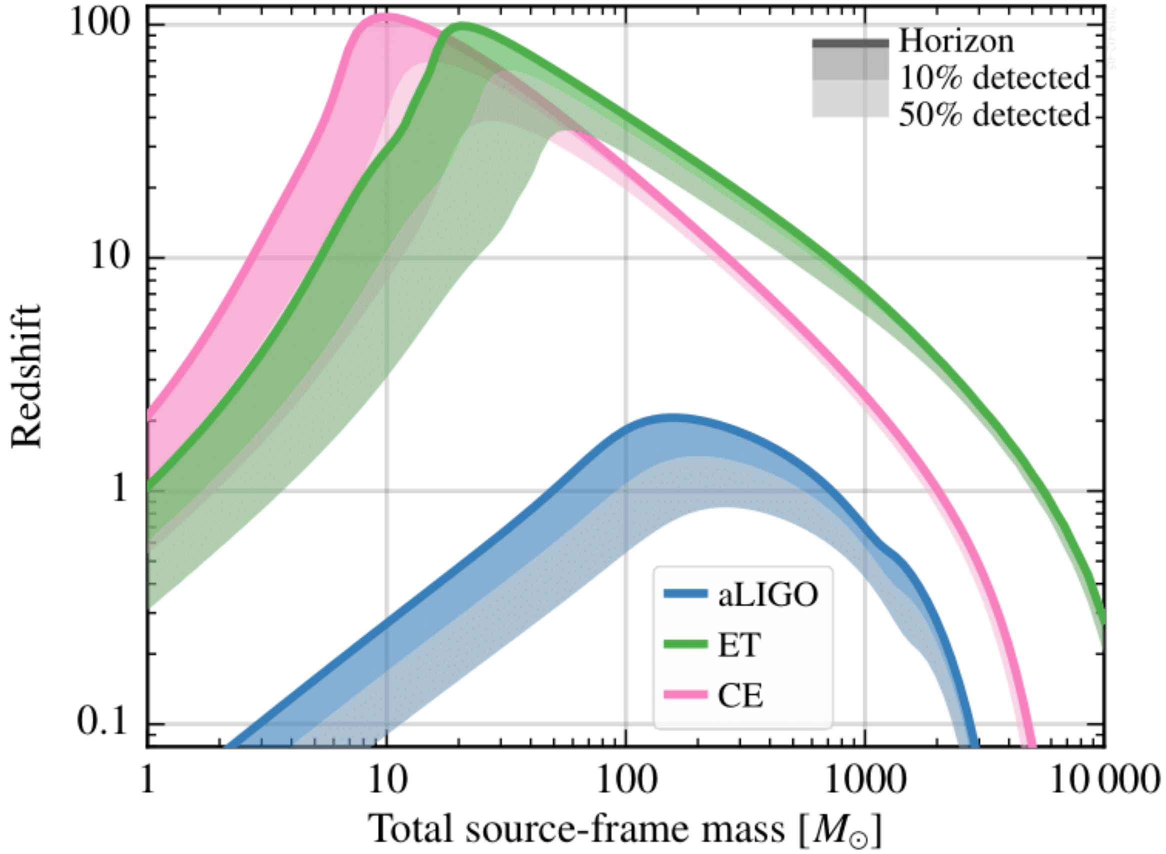
Cosmology with ET



Evans and Hall 2019

Figure in Astro2020 Science White Paper "Cosmology and the Early Universe"

ET will detect:

- NS-BH and BH-BH up to $z \sim 8$
- BNS up to $z \sim 2$ $\mathcal{O}(10^5)$ events/y

Cosmology needs redshift information

Redshift determination from EM counterpart

1) Temporal coincidence with GRB

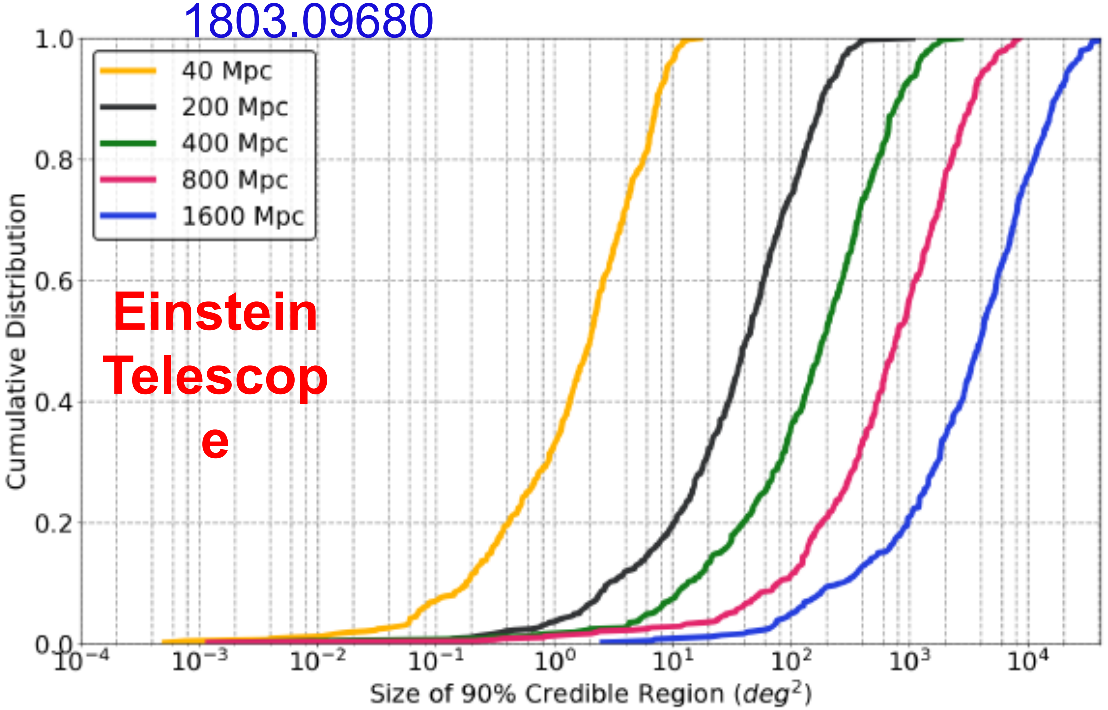
2) For well localized events, follow-up with optical and IR telescopes and identify host galaxy

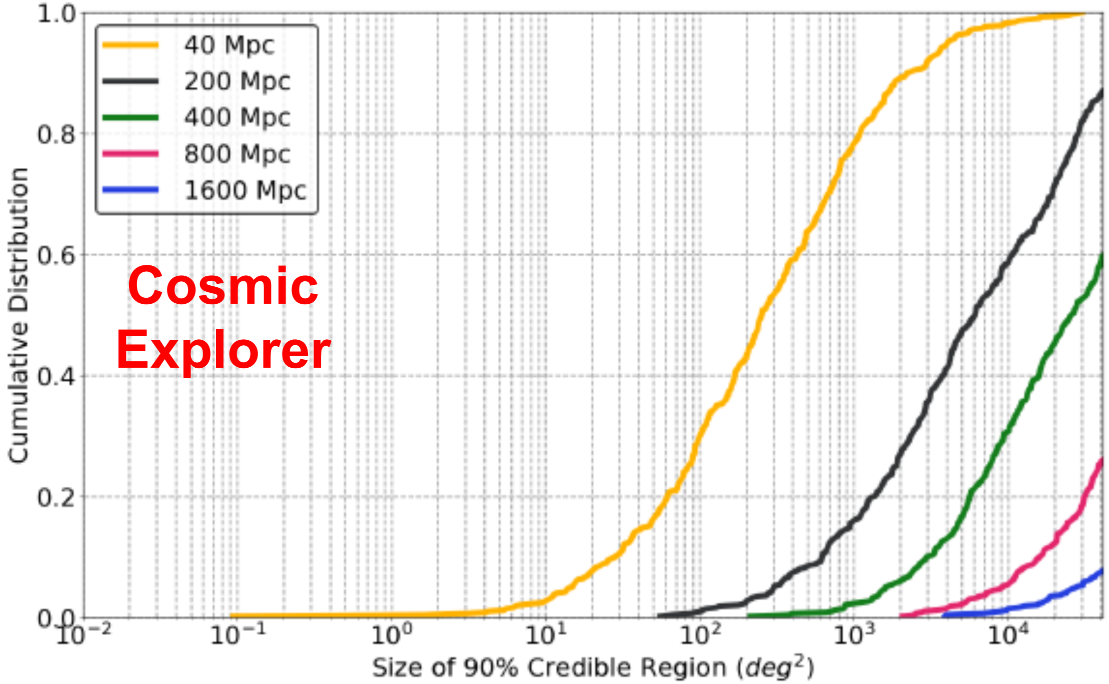
- 3G network, e.g. ET+CE+CE
- Some localization with ET alone using Earth rotation

Localization at single 3G detectors

- For BNS and a low-frequency cut-off of 1Hz, the signal stays 5 days in the detector bandwidth
  - Earth rotation $\Longrightarrow$ 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 to within 2 deg^2
  - For CE only 250 deg^2 at the same distance

Chan, Messenger, Heng and Hendry
1803.09680


Einstein Telescope


Cosmic Explorer

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

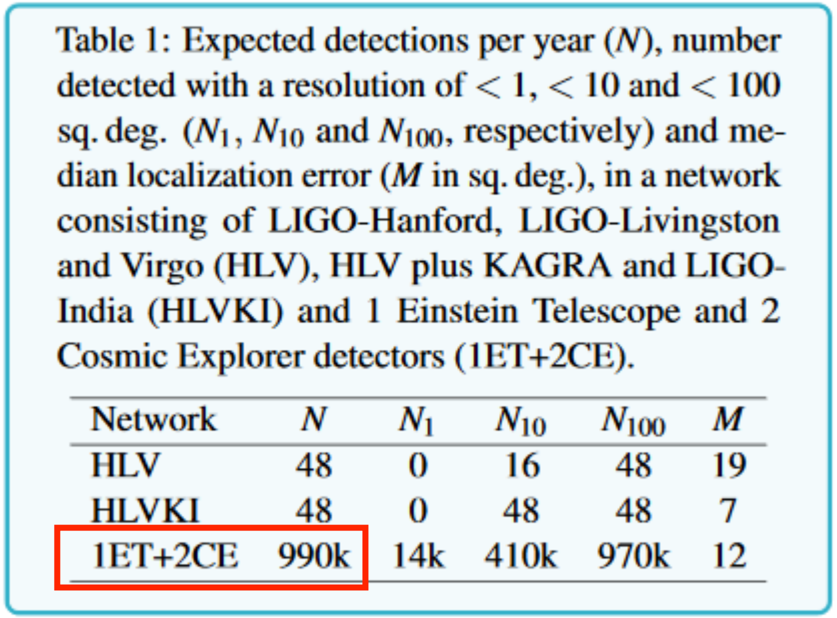


Table 1: Expected detections per year (N), number detected with a resolution of < 1, < 10 and < 100 sq. deg. (N_1, N_{10} and N_{100}, respectively) and median localization error (M in sq. deg.), in a network consisting of LIGO-Hanford, LIGO-Livingston and Virgo (HLV), HLV plus KAGRA and LIGO-India (HLVKI)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

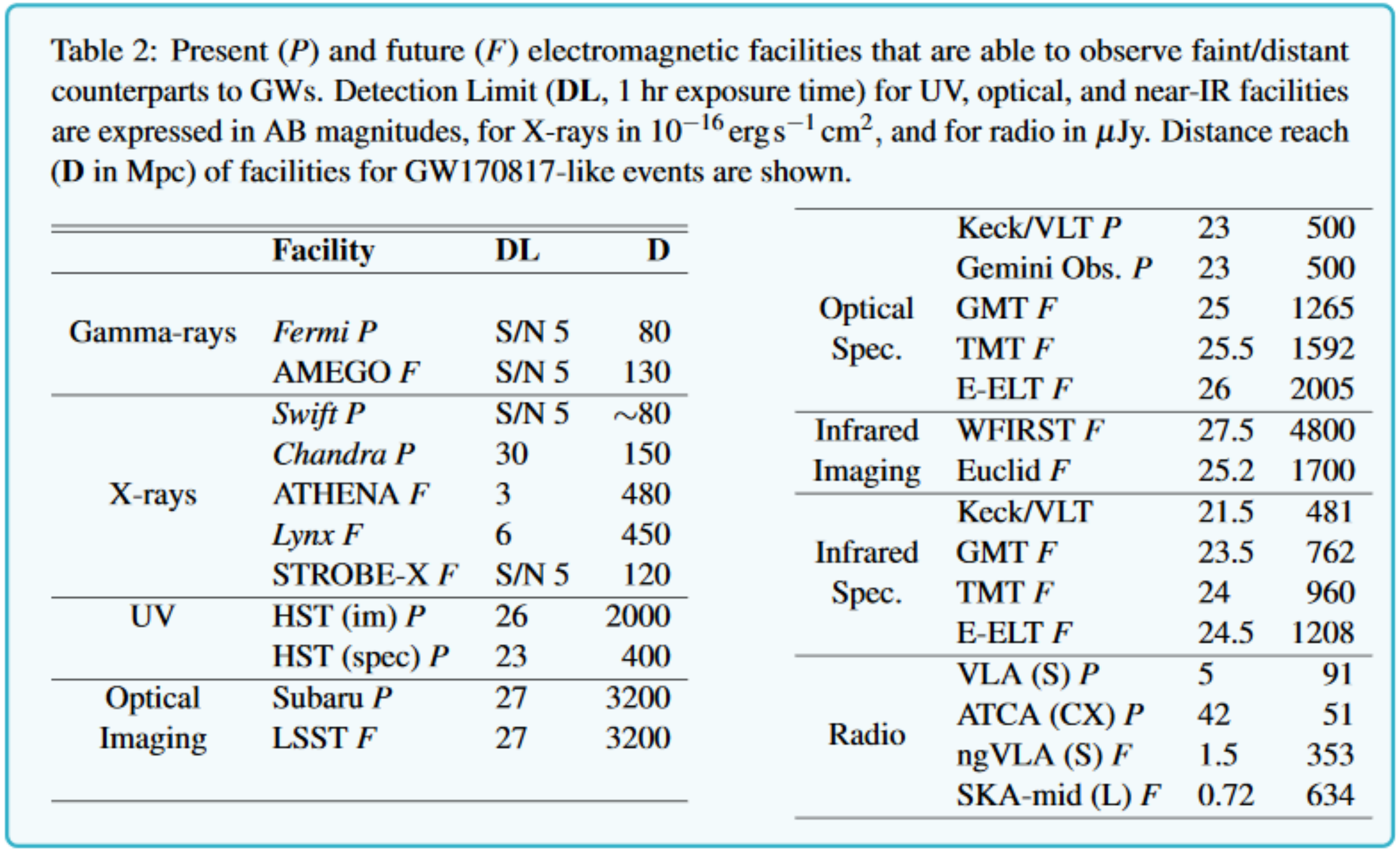


Table 2: Present (P) and future (F) electromagnetic facilities that are able to observe faint/distant counterparts to GWs. Detection Limit (**DL**, 1 hr exposure time) for UV, optical, and near-IR facilities are expressed in AB magnitudes, for X-rays in $10^{-16}\,\mathrm{erg\,s^{-1}\,cm^2}$, and for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

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 $z \sim 0.1 - 0.3$

Large uncertainties in time and costs

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 $z \sim 0.1$

Joint GW/GRB detections at ET/THESEUS

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

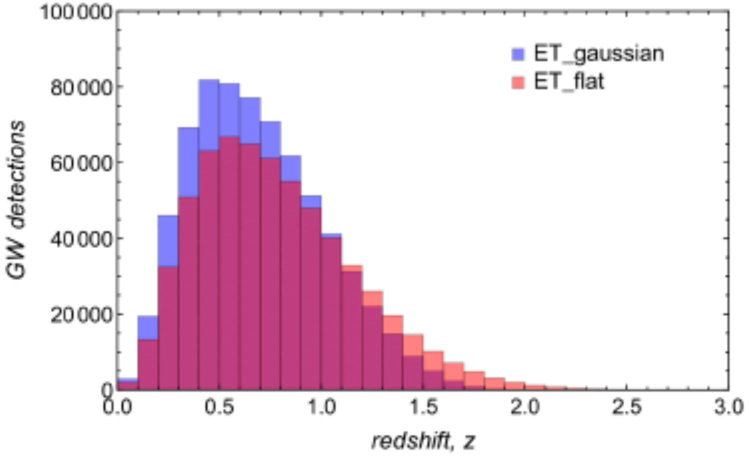
Simulation of a population of BNS based on Regimbau et al. 2015, ApJ 799, 69

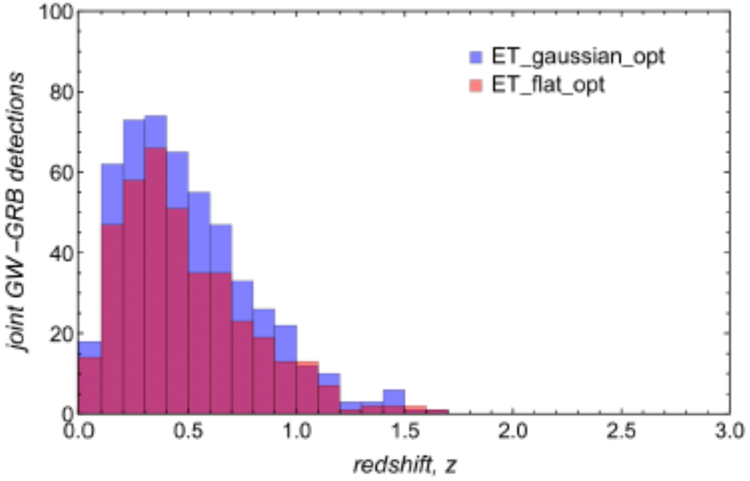
- Evaluation of the coalescence rate using star formation rate and a probability distribution for the delay between formation and coalescence of the binary system (modeled according to Dominik et al. 2012, ApJ 759, 52)
- Exponential probability distribution for the time interval between two successive 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

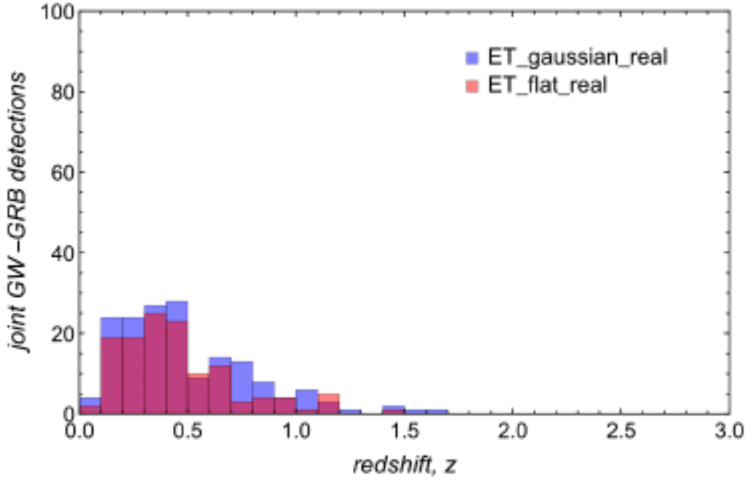
EM counterpart

- 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







CAVEAT:
Estimates here are too optimistic acording to more recent forecasts, see talk by Marica Branchesi

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

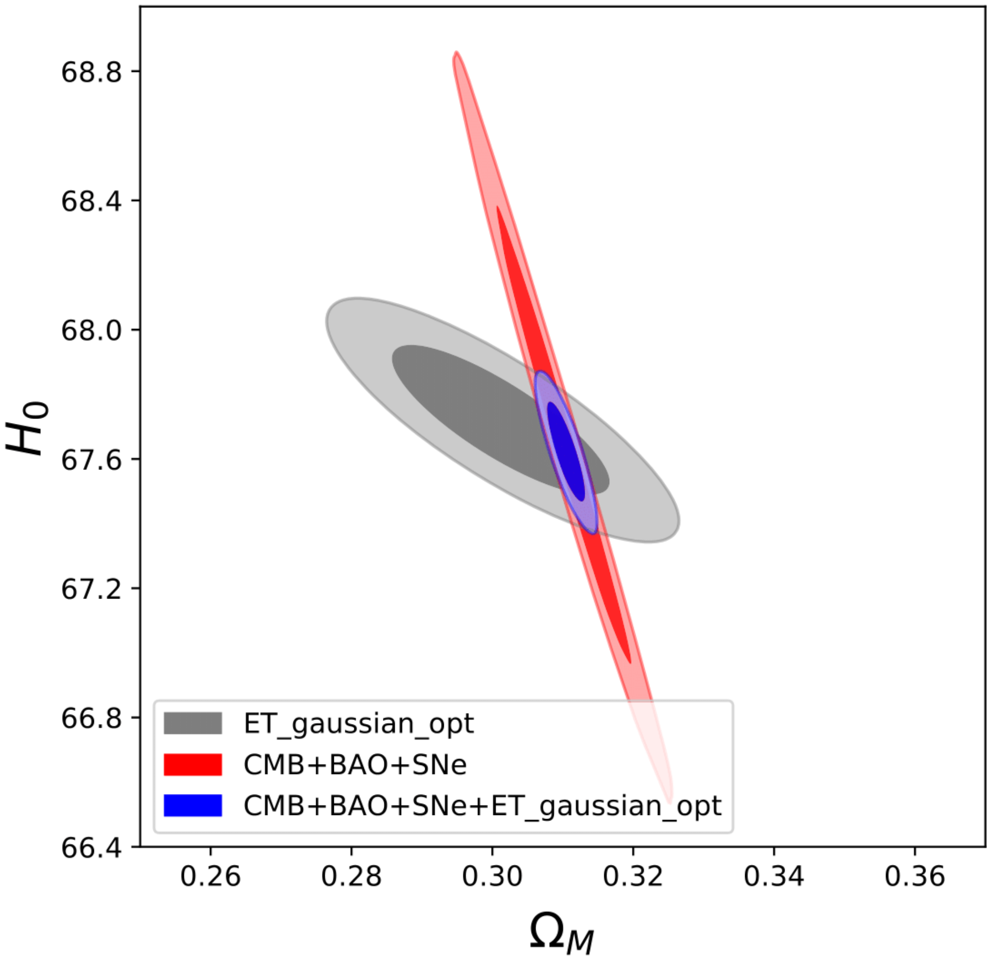
FLAT	GAUSSIAN
6.2×10^5	6.9×10^5

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

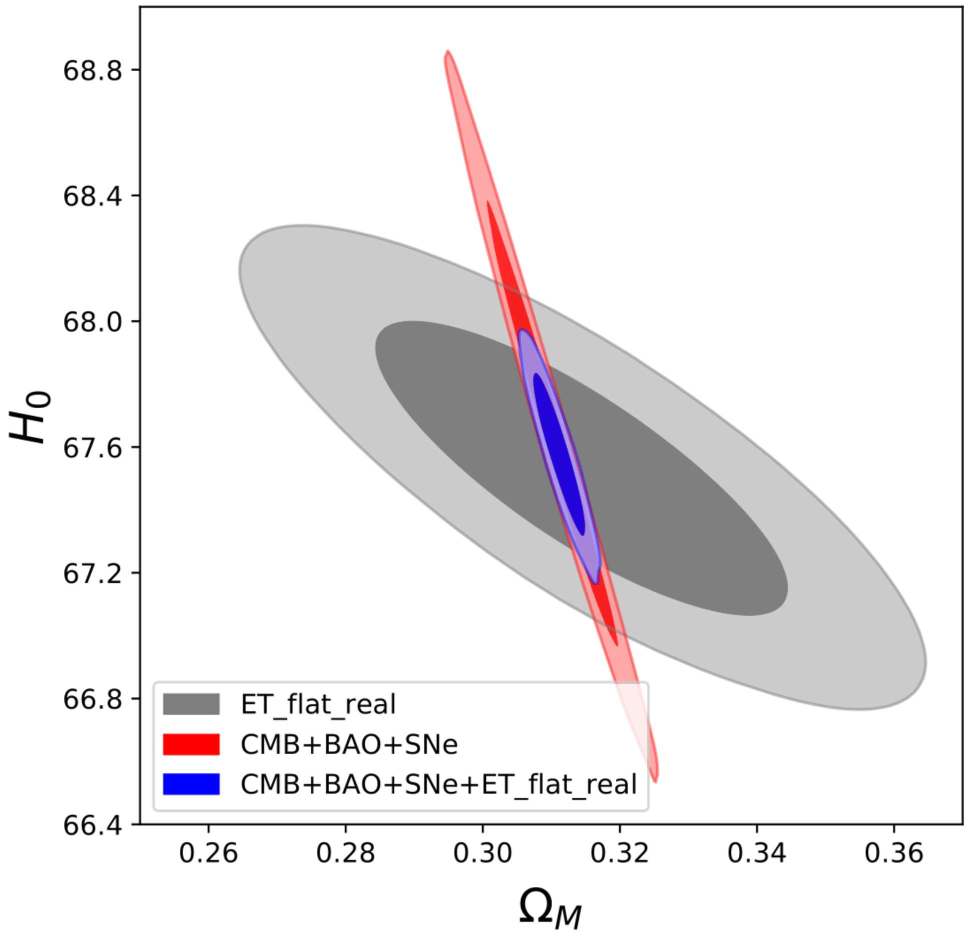
	$\Delta H_0/H_0$	$\Delta\Omega_M/\Omega_M$
ET_gaussian_opt	0.23 %	3.38 %
CMB+BAO+SNe	0.72 %	2.11 %
CMB+BAO+SNe+ET_gaussian_opt	0.15 %	0.57 %

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



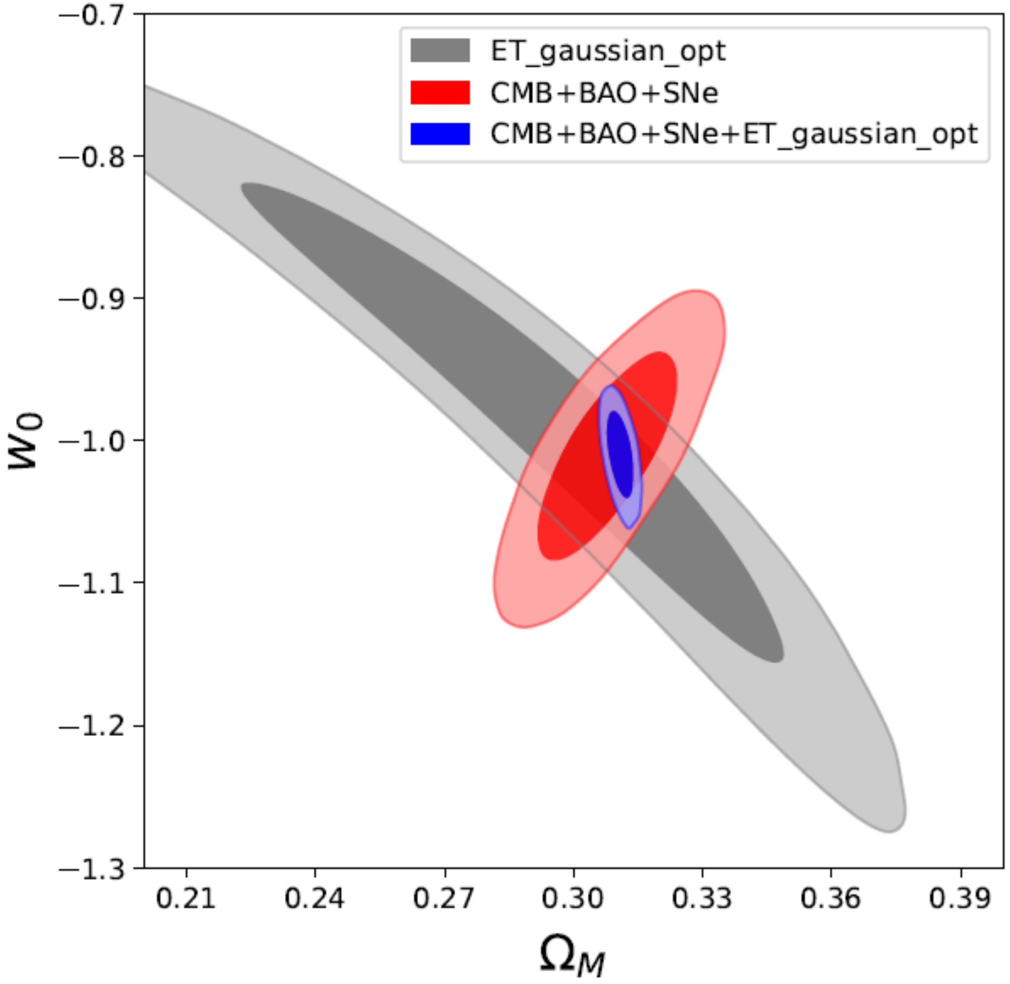
Constraints on ΛCDM parameters

Significant improvements



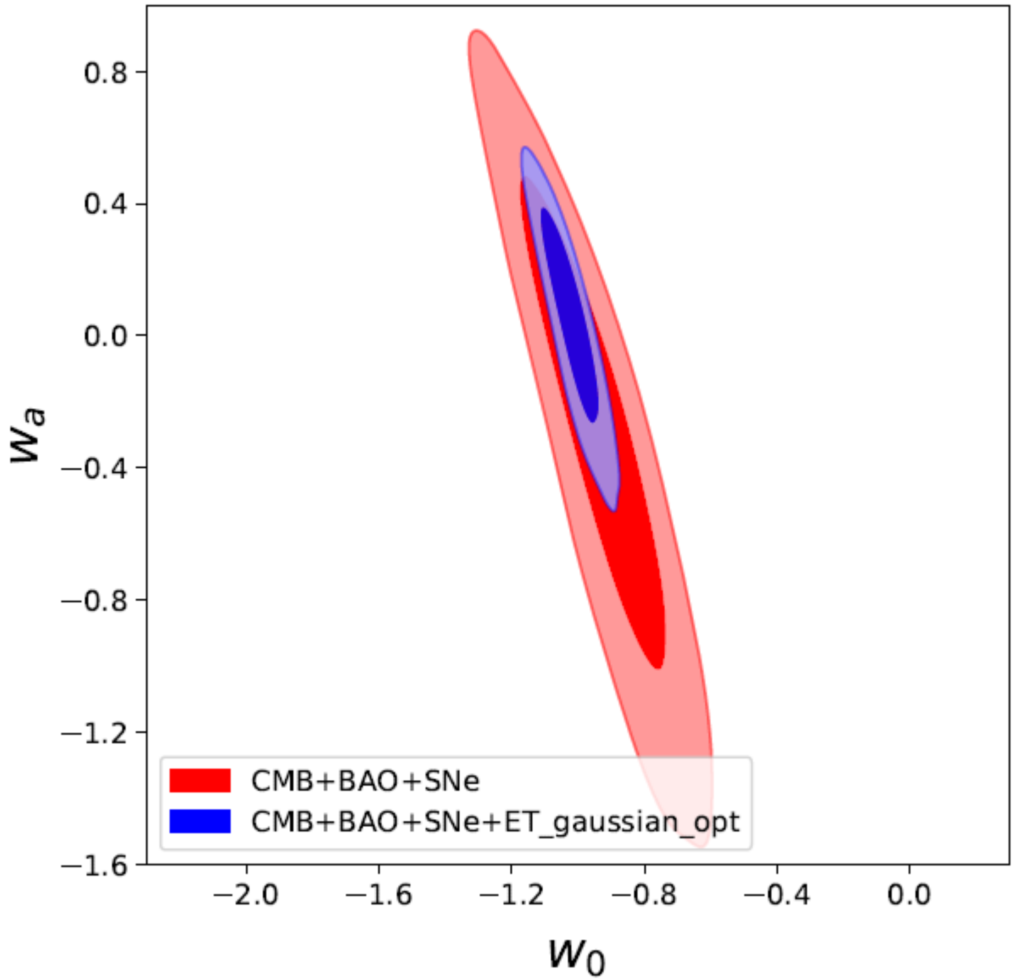
Dark Energy EoS

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

ET+CE+CE/THESEUS

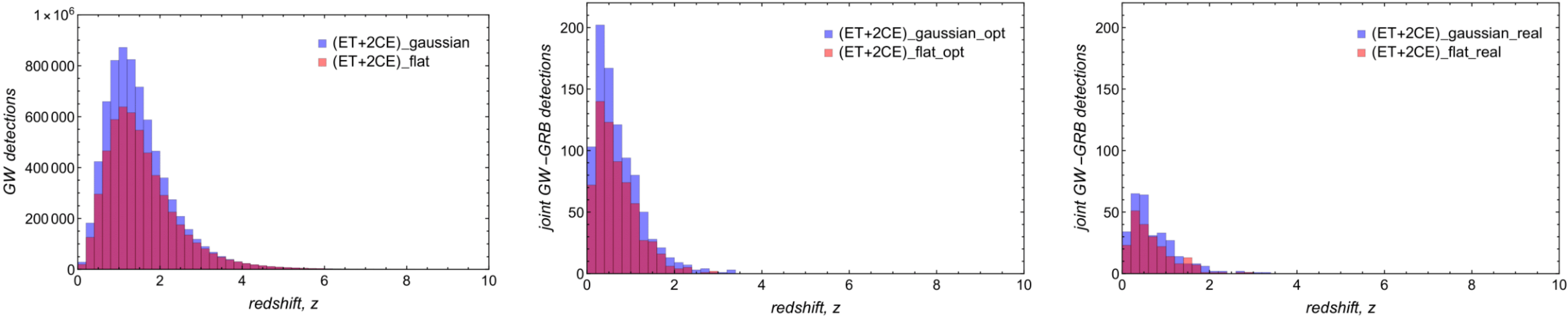
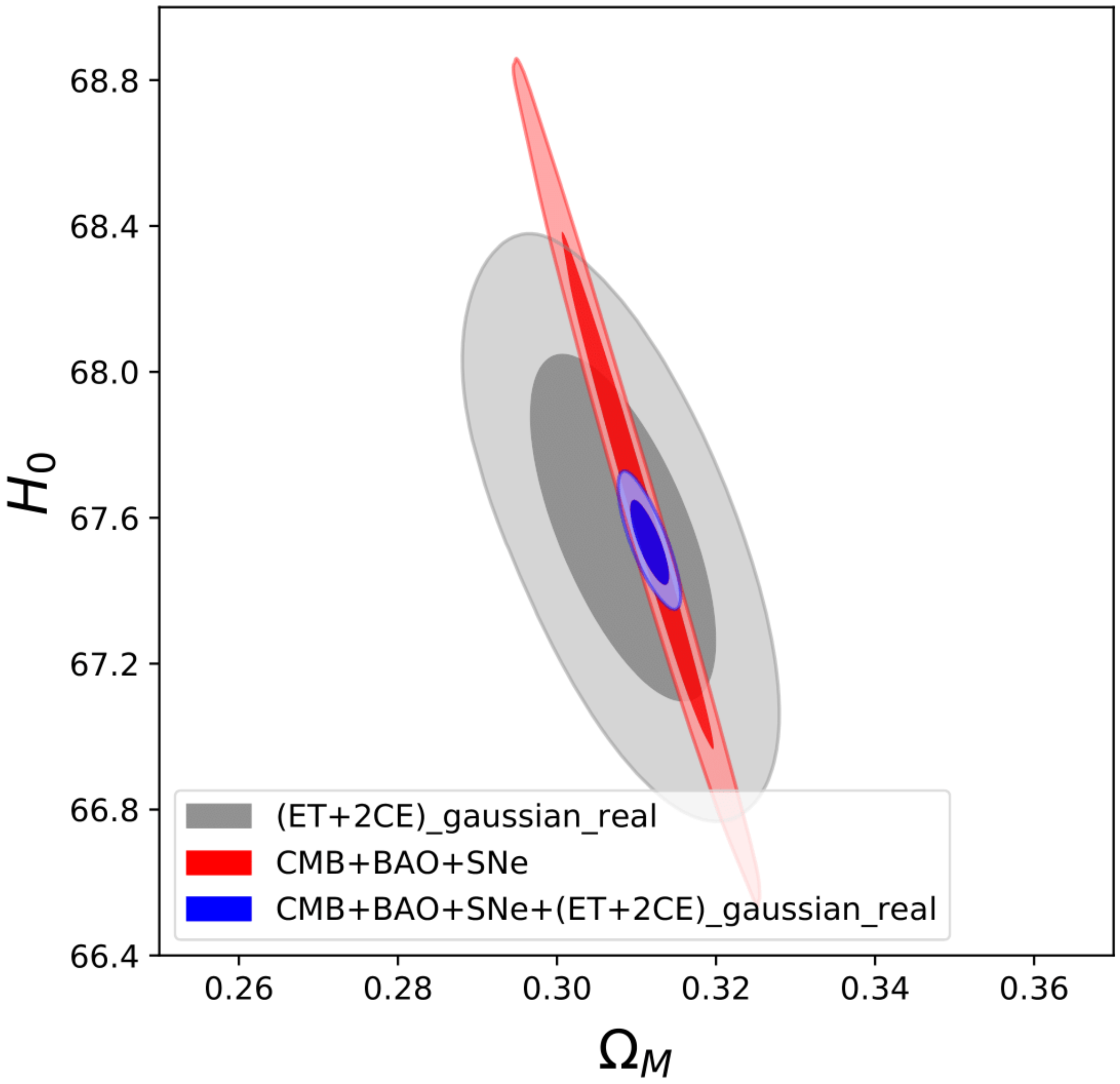


Figure from Belgacem, Dirian, Foffa, Howell, Maggiore, Regimbau 1907.01487

- 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 $z_{\max} \simeq 3.4$



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

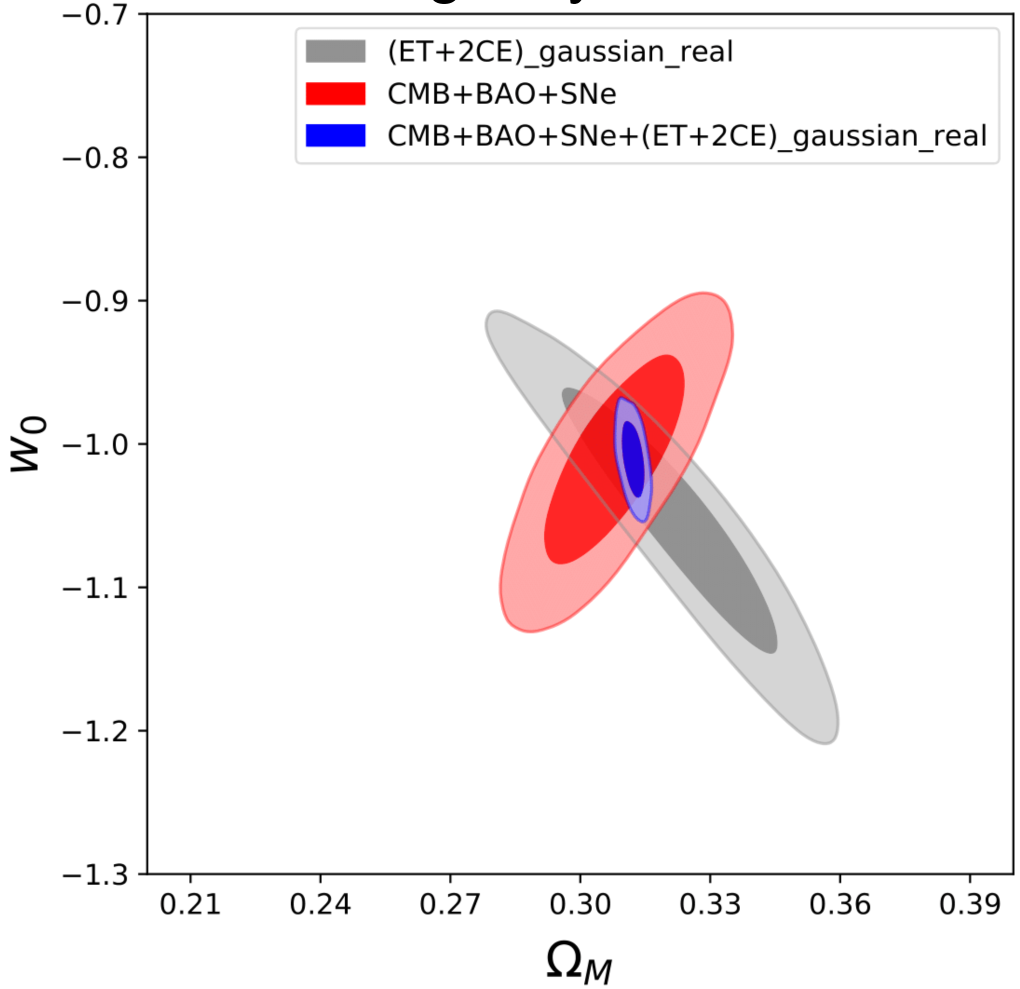
Even considered on their own, GW data at ET+CE+CE will H_0 constrain better than current CMB+BAO+SNe

$\Downarrow$

important role for the Hubble tension

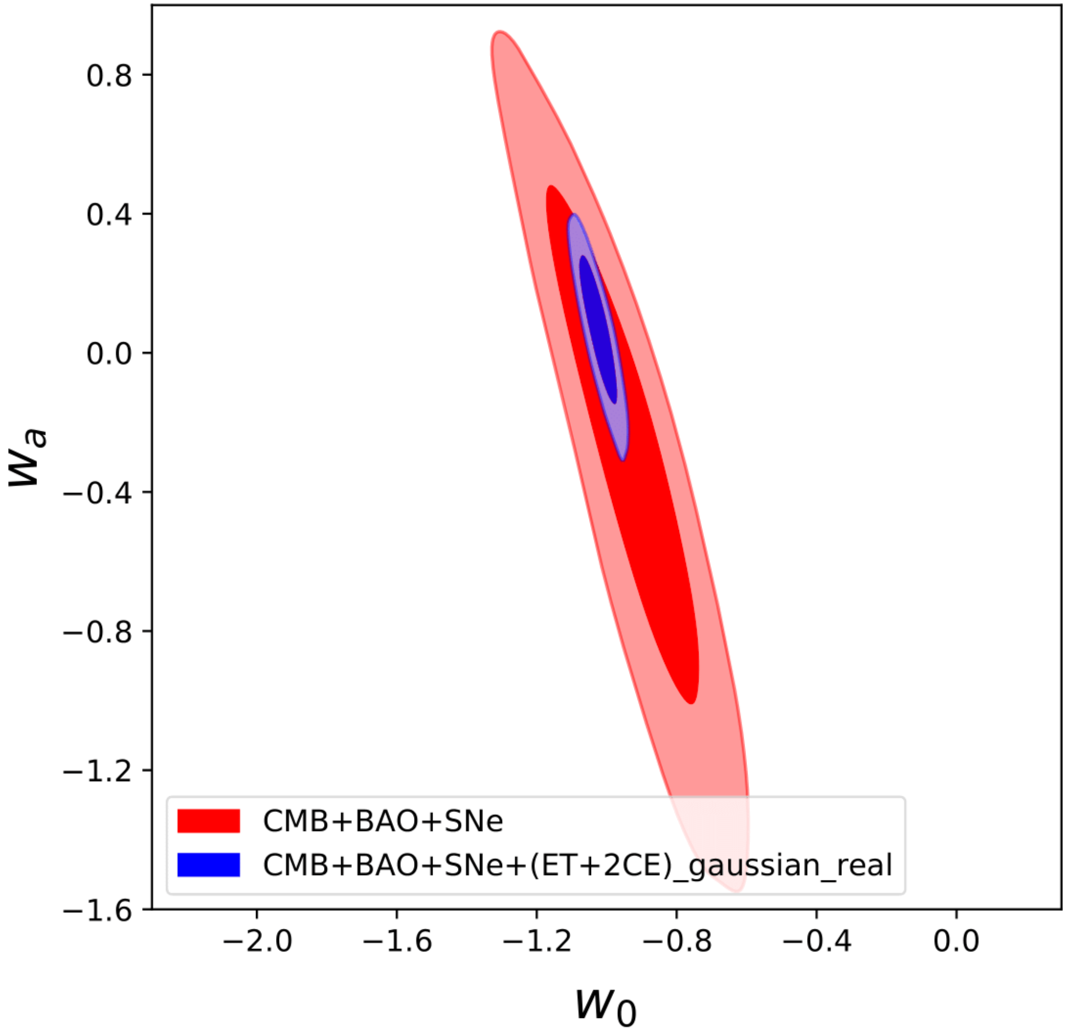
Dark Energy EoS

using only w_0



$w_0$only extra parameter	Δw_0
ET+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

Other cosmological observables testable with ET ?

Yes, in the next slides!

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

- 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), 2019

- 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

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

- 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

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

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

- 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 $\Lambda\mathrm{CDM}$

$\Lambda\mathrm{CDM}$

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

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

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:

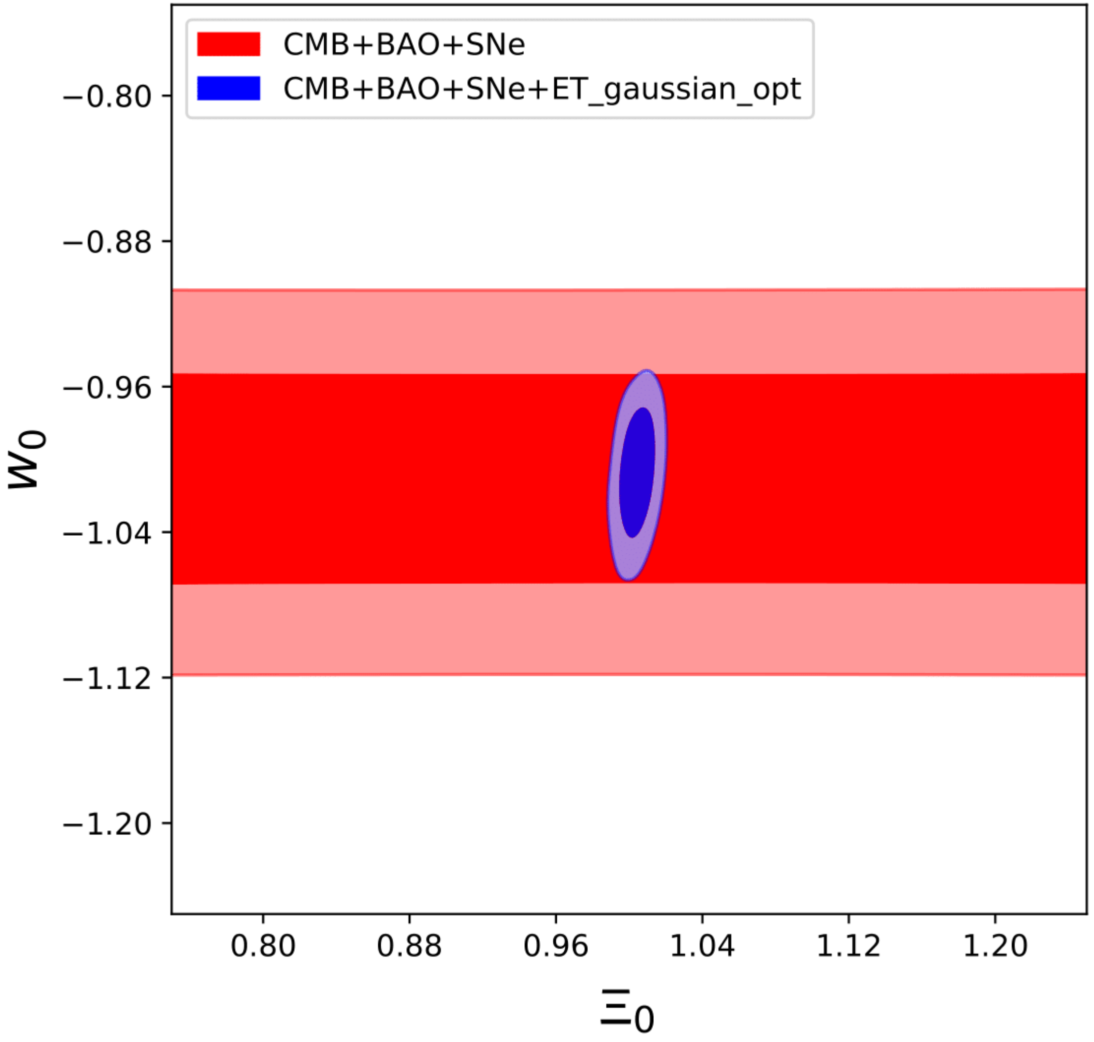
background (w_0, w_a)

scalar perturbations (Σ, μ)

tensor perturbations (Ξ_0, n)

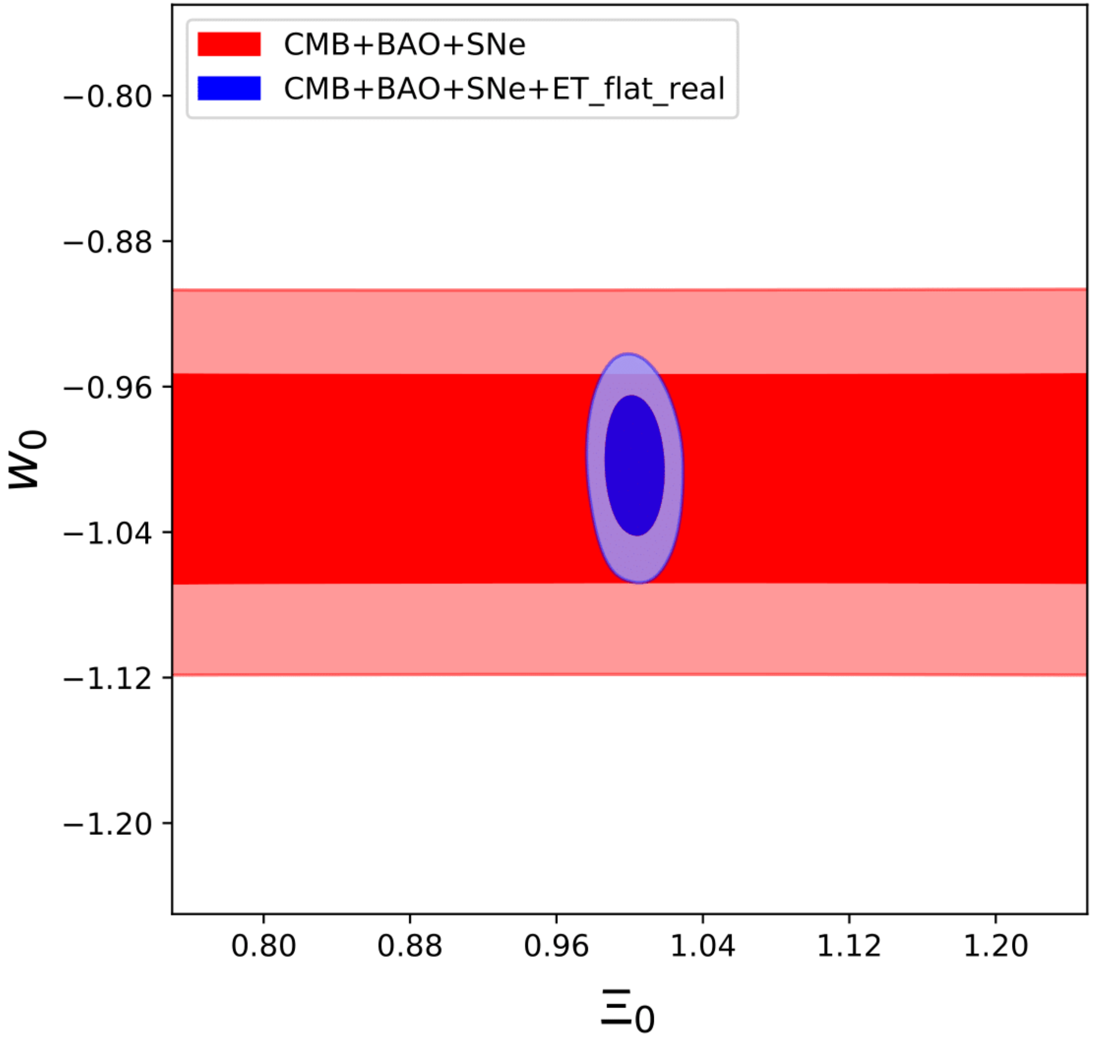
Ξ_0 and w_0 are the most relevant parameters for dark energy studies with standard sirens

Modified GW propagation at ET



CMB+BAO+SNe+ET_gaussian_opt

$\Delta\Xi_0 = 0.007 \qquad \Delta w_0 = 0.024$

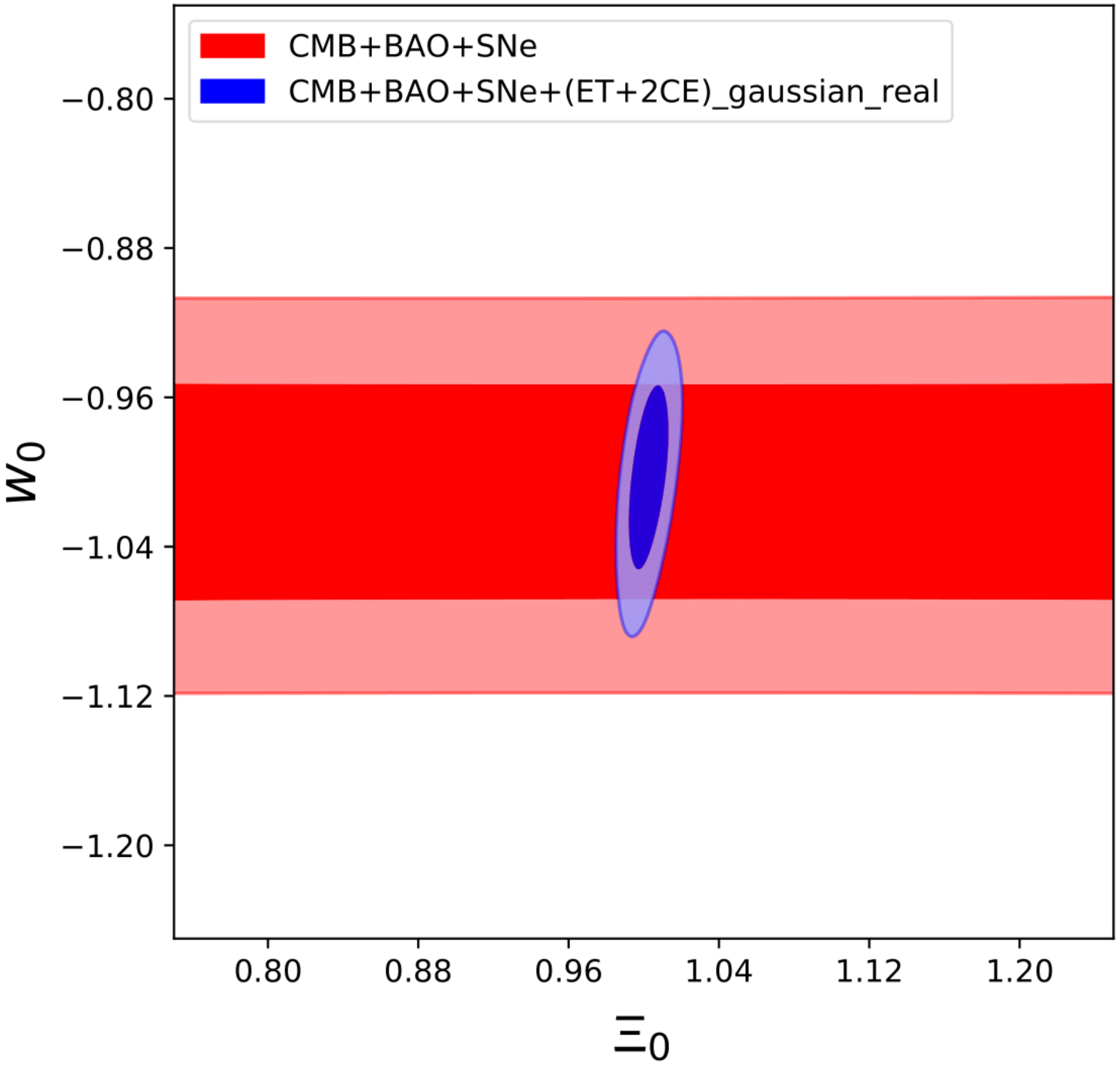


CMB+BAO+SNe+ET_flat_real

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

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

Modified GW propagation at ET+CE+CE



(w_0, Ξ_0) extension	Δw_0	$\Delta \Xi_0$
CMB+BAO+SNe	0.045	----
CMB+BAO+SNe+ET+CE+CE	0.033	0.007

CONCLUSIONS

- **3G detectors can have an important impact on H_0 measurements and DE equation of state**

- **In modified gravity there is a GW luminosity distance**

- **Modified GW propagation is important for DE studies using standard sirens:**

1) It can only be probed by GW observations
2) Ξ_0 can be measured better than w_0
3) It allows to test many modified gravity models

Significant physical observable for 3G detectors