

Cosmology and Dark Energy
from joint Gravitational Wave-GRB Observations

COSMO 19

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based on *Belgacem, Dirian, Foffa, Howell, Maggiore, Regimbau,*

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GW-GRB: Multi-messenger Astronomy

New observational window for cosmology

- GWs from 11 mergers by O1+O2 LIGO/Virgo
- GWs from 1 inspiralling BNS: GW170817
 - γ -ray burst counterpart: GRB170817A by FERMI and INTEGRAL
 - ▶ $\tilde{h}''_{+,x} + 2\mathcal{H}\tilde{h}'_{+,x} + c_T^2(\eta)k^2\tilde{h}_{+,x} = 0, \implies |c_T(\eta_0) - c|/c \approx 10^{-15}$
 - Dramatic consequences for modified gravity theories

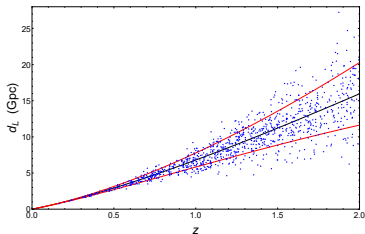
[Creminelli+, Sakstein+, Ezquiaga+, Baker+ (2017)]

- BNS easily used as “standard sirens”

[Schutz (1986)]

- ▶ GW amplitude $\sim d_L^{-1}$
 - ▶ Electromagnetic counterparts give z
- $d_L(z) \Rightarrow$ Hubble diagram for GWs

\implies Cosmological constraints

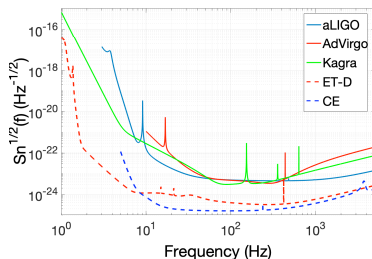


[Belgacem+ (2018)]

Cosmological Constraints from Standard Sirens

Forecast sensitivity of 2G and 3G detectors

- Focus on forecast constraints given GW+GRB coincidences from BNS mergers
- GW events:
 - ▶ 2G: LIGO+aVIRGO+KAGRA+LIGO India (HLVKI)
 - ▶ 3G: Einstein Telescope (ET) and ET+2×Cosmic Explorer (CE)
[ET+2×CE: GWIC 3G baseline configuration]



- Electromagnetic (EM) counterpart
 - ▶ 2G: Fermi-GBM specifications
 - ▶ 3G: THESEUS specifications

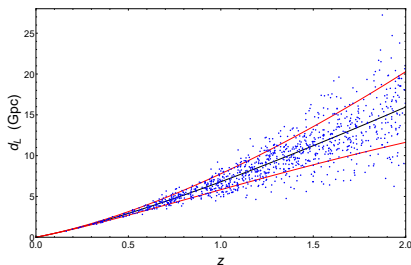
Cosmological Constraints from Standard Sirens

Building up mock catalogues: GW events & EM counterpart

- Redshift drawn from $\rho(z) \sim \text{SFR}$ and formation-merger delay time dist. $P(t_d)$
- $d_L(z)$ drawn from Gaussian dist. with observational error Δd_L :

$$\frac{\Delta d_L(z)}{d_L} \equiv 1/\text{SNR}$$

- ▶ Assume a Λ CDM cosmology best-fitting CMB(P15)+SNIa(JLA)+BAO
- ▶ $\text{SNR} \sim h_{+,x}, F_{+,x}$: sampled from $\hat{\theta}$ through Monte Carlo



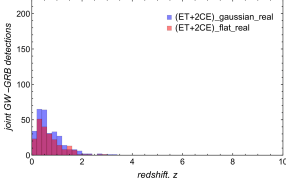
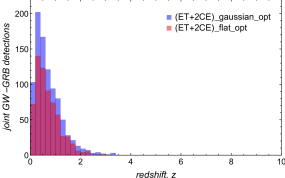
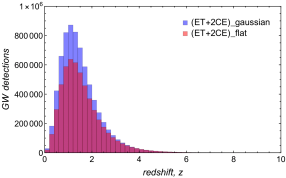
Cosmological Constraints from Standard Sirens

Number of GW and GW+GRB events

- For 10 years, for 2G+Fermi, (ET and ET+CE+CE) + full (1/3) THESEUS

Network	GW events	Joint GW-GRB events
HLVKI	814	15
ET	688,426	511 (169)
ET+CE+CE	7,077,131	907 (299)

- Redshift reach: ET: $z = 2 - 3$, +CE: $z \simeq 9$, +THESEUS: $z \simeq 3.4$

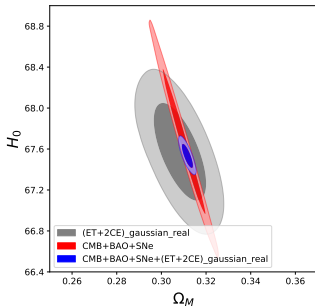


- Number of GW+GRB detections is orders of magnitude smaller than GW detections
 - GRB detector sensitivity is limited to smaller redshifts than GW detector threshold
 - GRB detection number “saturates”: insufficient dedicated GRB/optical/IR telescopes

Cosmological Constraints from Standard Sirens

$H_0 - \Omega_M$ in standard Λ CDM given CMB+SNIa+BAO+GW

	CMB+	(CMB+)+HLVKI	ET+2CE	(CMB+)+ET+2CE
$\Delta H_0/H_0$	0.72%	0.66% (1.09)	0.23% (3.13)	0.11% (6.54)
$\Delta \Omega_M/\Omega_M$	2.11%	1.96% (1.08)	2.09% (1.01)	0.51% (4.14)



→ New (multi-messenger) cosmic complementarity

Cosmological Constraints from Standard Sirens

Dark Energy given 2G

- Modified propagation for GWs: $\tilde{h}''_{+, \times} + 2\mathcal{H}[1 - \delta(\eta)]\tilde{h}'_{+, \times} + k^2\tilde{h}_{+, \times} = 0$

- Modified luminosity distance for standard sirens w.r.t Λ CDM:

$$\tilde{h}_{+, \times} \sim \frac{1}{d_L^{\text{gw}}(z)}, \quad \text{with} \quad d_L^{\text{gw}}(z) = d_L^{\text{em}}(z) \exp\left(-\int_0^z \frac{dz'}{1+z'}\delta(z')\right)$$

- Useful parametrisation: $\frac{d_L^{\text{gw}}(z)}{d_L^{\text{em}}(z)} = \Xi_0 + \frac{1}{(1+z)^n}(1 - \Xi_0)$, where $n \equiv 5/2$

- We use w_0 CDM and $w_0\Xi_0$ CDM parametrisation

HLVKI	CMB+BAO+SNe	combined
Δw_0	0.045	0.035 (1.29)

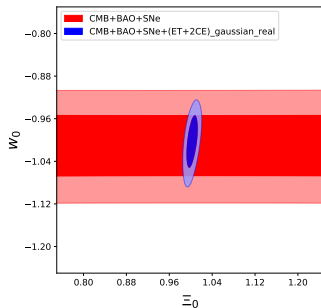
HLVKI	CMB+BAO+SNe	combined
Δw_0	0.045	0.042 (1.07)
$\Delta \Xi_0$	-	0.125

Cosmological Constraints from Standard Sirens

Dark Energy given (ET+2CE)+THESEUS real.

ET+CE+CE	CMB+BAO+SNe	ET+CE+CE	combined
Δw_0	0.045	0.063 (0.71)	0.018 (2.5)

ET+CE+CE	CMB+BAO+SNe	combined
Δw_0	0.045	0.033 (1.36)
$\Delta \Xi_0$	—	0.007



→ Constraints on Ξ_0 are ~ 6 times stronger than on w_0

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- GWs from 1 inspiralling BNS: GW170817

→ γ -ray burst counterpart: GRB170817A by FERMI and INTEGRAL

▶ $\tilde{h}''_A + 2\mathcal{H}\tilde{h}'_A + c_T^2(\eta)k^2\tilde{h}_A = 0, \implies |c_T(\eta_0) - c|/c \approx 10^{-15}$

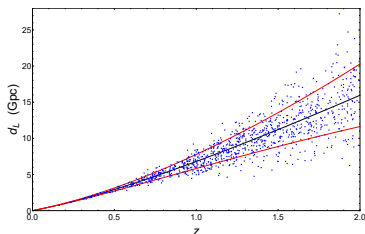
→ Dramatic consequences for modified gravity theories

[Creminelli+, Sakstein+, Ezquiaga+, Baker+ (2017)]

- Restricted PN approximation gives

$$h_+(t) = \frac{(1+\cos^2\iota)}{d_L(z)} (GM_c)^{5/3} [\pi f(t)]^{2/3} \cos\Phi(t)$$

$$h_\times(t) = \frac{4\cos\iota}{d_L(z)} (GM_c)^{5/3} [\pi f(t)]^{2/3} \sin\Phi(t)$$



[Belgacem et al. (2018)]

Cosmological Constraints from Standard Sirens

Building up mock catalogues: GW events

- Sample GW detector-specific parameters $\hat{\theta}$ from Monte Carlo method
 $\Rightarrow h_{+, \times}, F_{+, \times}$

- Redshifts are drawn from:

$$p(z) \equiv \frac{R_z(z)}{\int_0^{10} R_z(\bar{z}) d\bar{z}}, \quad \text{where} \quad R_z(z) = \frac{R_m(z)}{1+z} \frac{dV}{dz}$$

$$\text{with} \quad R_m(z) = \int_{t_{min}}^{t_{max}} R_f[t(z) - t_d] P(t_d) dt_d,$$

R_f : formation rate of massive binaries \sim cosmic SFR (Springel-Hernquist form)

$\rightarrow t_d$ is the NS formation-merging delay time, $P(t_d) \sim t_d^{-1}$, $t_{min} = 20$ Myr

\rightarrow Normalisation chosen so that $R_m(z=0) = 662(\text{flat})/920(\text{gaussian}) \text{ Gpc}^{-3} \text{ yr}^{-1}$

- The Signal-to-Noise Ratio (SNR) is provided by

$$\rho_a^2 = 4 \int_0^{+\infty} \frac{|F_{+,a} h_+ + F_{\times,a} h_{\times}|^2}{S_{n,a}(f)} df,$$

\rightarrow Detection are characterised by $\text{SNR} > 12$

\rightarrow 10 years of running with 80% of duty cycle

Cosmological Constraints from Standard Sirens

Building up mock catalogues: EM counterpart

- EM counterparts:

- ▶ Global detection strategy: obs. flux beyond the detector flux limit
→ Gaussian structured jet profile model of GRB170817A:

$$L(\theta_V) \simeq L_p \exp\left(-\frac{\theta_V^2}{2\theta_c^2}\right)$$

where L_p drawn from $\Phi(L_p)$, broken power law.

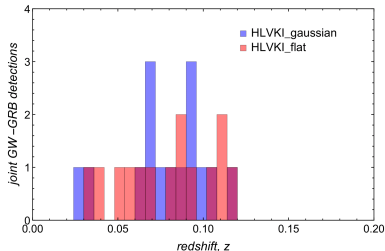
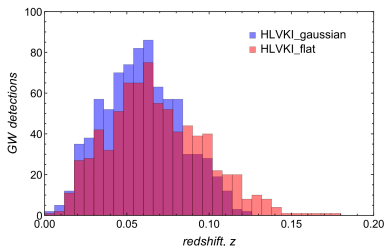
→ The flux is then obtained as: $\mathcal{F}(\theta_V) = L(\theta_V)/(4\pi d_L^2)$

- ▶ 2G: Fermi-GBM $\Rightarrow 1.1 \text{ ph s}^{-1} \text{ cm}^{-2}$ in 50 – 300keV for 0.6 time-av. sky fraction
- ▶ 3G: THESEUS $\Rightarrow 0.2 \text{ ph s}^{-1} \text{ cm}^{-2}$ in 50 – 300keV for 0.5 time-av. sky fraction

Cosmological Constraints from Standard Sirens

Number of GW and GW+GRB events

- 2G: HLVKI+Fermi for 10 years, flat or gaussian BNS mass dist.



Network	GW events		Joint GW-GRB events	
	Flat	Gaussian	Flat	Gaussian
HLVKI	768	814	14	15

- Number of GW+GRB detections is orders of magnitude smaller than GW detections
→ GRB detector sensitivity is limited to smaller redshift than GW detector

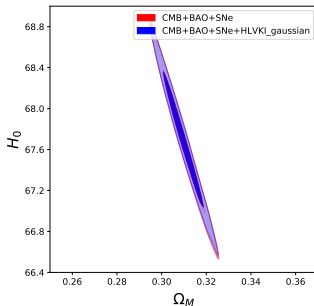
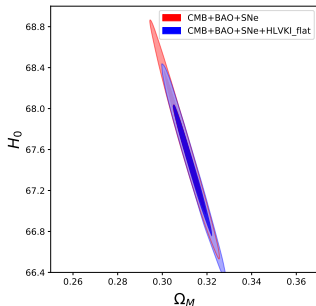
Cosmological Constraints from Standard Sirens

$H_0 - \Omega_M$ in standard Λ CDM given HLVKI

- Hubble diagram for GW constrains H_0 and Ω_M

$$d_L(z) = \frac{1+z}{H_0} \int_0^z \frac{d\bar{z}}{\sqrt{\Omega_M(1+\bar{z})^3 + (1-\Omega_M)}}$$

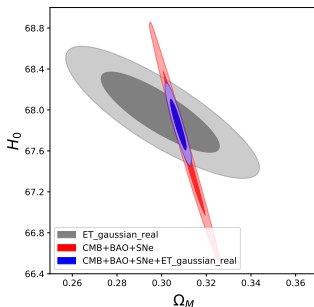
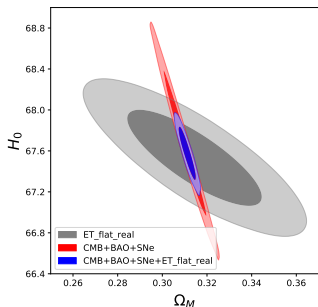
	CMB+BAO+SNe	combined 2G, flat	combined 2G, gaussian
$\Delta H_0/H_0$	0.72%	0.65% (1.11)	0.66% (1.09)
$\Delta \Omega_M/\Omega_M$	2.11%	1.91% (1.10)	1.96% (1.08)



Cosmological Constraints from Standard Sirens

$H_0 - \Omega_M$ in standard Λ CDM given ET+THESEUS realistic

	CMB+ BAO+SNe	ET, flat	ET, gaussian	combined, flat	combined, gaussian
$\Delta H_0/H_0$	0.72%	0.42% (1.71)	0.39% (1.85)	0.26% (2.77)	0.25% (2.88)
$\Delta \Omega_M/\Omega_M$	2.11%	6.17% (0.34)	5.88% (0.36)	0.82% (2.57)	0.82% (2.57)



→ New kind of cosmic complementarity