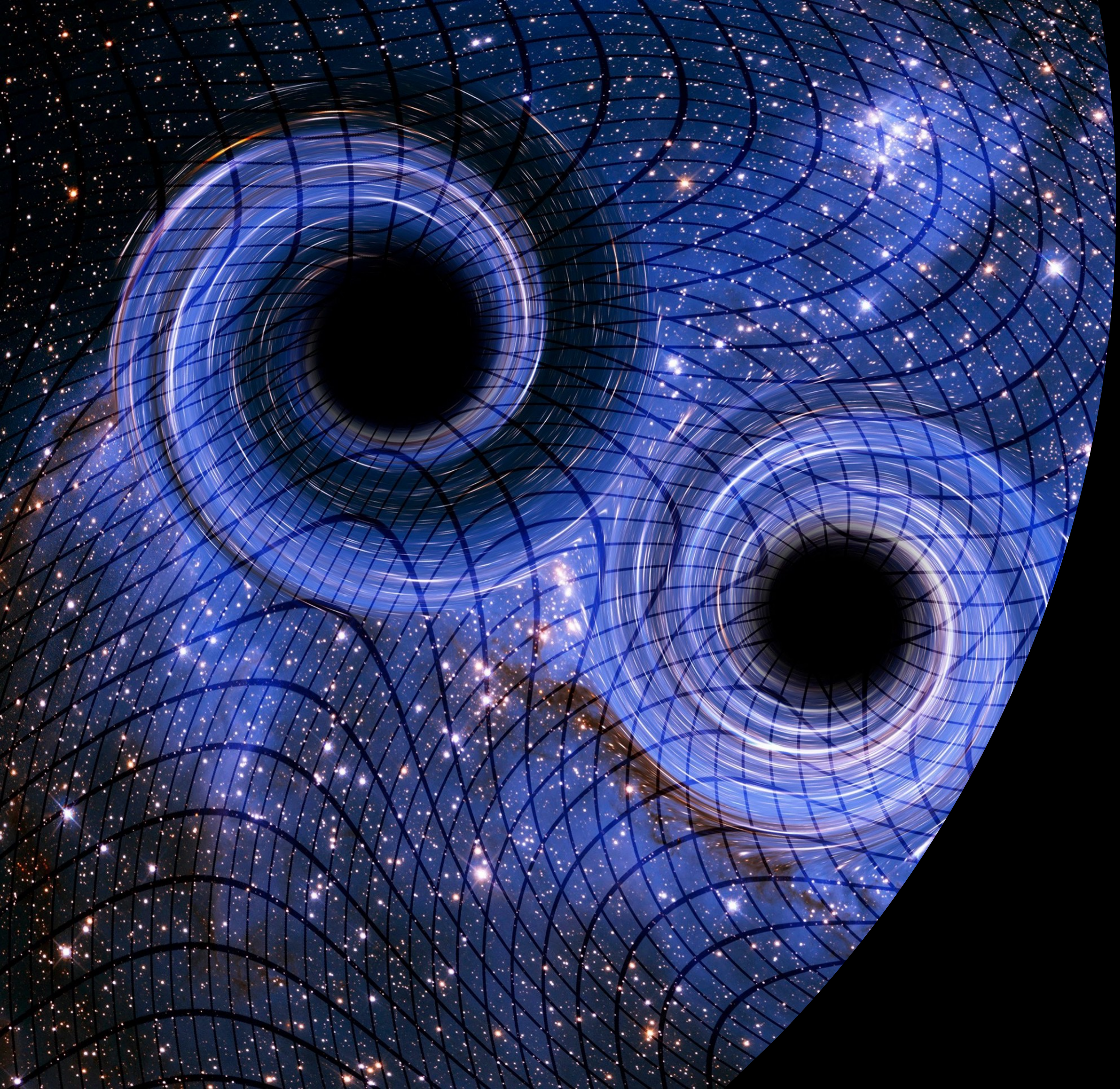

Prospects for testing late-time cosmology with weak lensing of GW and galaxy surveys

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In collaboration with:
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GW luminosity distance in LCDM

- Cosmological distances inferred through measures of fluxes are known as luminosity distances.
- For GW the luminosity distance is directly associated to the dampening of the wave amplitude: $h(t) \propto \frac{1}{d_L^{GW}}$
- When only the background expansion in considered $$\bar{d}_L^{GW}(z) = c(1+z)\int_z^\infty \frac{dz'}{H(z')}$$
- However, as GW propagate in a inhomogeneous Universe the measured d_L picks up corrections and an angular dependence

$$d_L^{GW}(z,\hat{n}) = \bar{d}_L^{GW}(z) + \Delta d_L^{GW}(z,\hat{n})$$

Bertacca et al. (2018) found

$$\frac{\Delta d_L^{GW}}{\bar{d}_L^{GW}} = \underbrace{-\kappa}_{lensing} - \underbrace{(\phi+\psi)}_{V\,dilation} + \underbrace{\frac{1}{\chi}\int_0^\chi d\tilde{\chi}(\phi+\psi)}_{time\,delay} + \underbrace{\frac{1}{\chi\mathcal{H}}\phi}_{SW} + \underbrace{v_\parallel\left(1-\frac{1}{\chi\mathcal{H}}\right)}_{Doppler} - \underbrace{\left(1-\frac{1}{\chi\mathcal{H}}\right)\int_0^\chi d\tilde{\chi}(\phi'+\psi')}_{ISW}$$

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Noise for measurements of the BG expansion

Signal for measurements of the perturbations

Tomographic observables

1st order corrections to D_L

$$\frac{\Delta d_L^{GW}}{\bar{d}_L^{GW}} \sim -\kappa_{gw}$$

Convergence estimator

$$\hat{\kappa}_{gw} \equiv 1 - \frac{d_L^{GW}(z,\hat{n})}{\bar{d}_L^{EM}(z)}$$

Ours observables then become the cross-correlations of density contrast field, galaxies weak lensing and GW weak lensing

$$C_{i,j}^{XY}(\ell) = \int_0^{z_{\max}} \frac{\mathrm{d}z}{\chi^2(z)H(z)} W_X^i(k,z) W_Y^j(k,z) P_{\mathrm{p}}(k)$$

Galaxy-only obsevables

$C_\ell^{\delta\delta}$, $C_\ell^{\kappa_g\kappa_g}$, $C_\ell^{\delta\kappa_g}$

GW observables

$C_\ell^{\kappa_{\mathrm{gw}}\kappa_{\mathrm{gw}}}$, $C_\ell^{\kappa_{\mathrm{gw}}\delta}$, $C_\ell^{\kappa_{\mathrm{gw}}\kappa_g}$

Tomographic observables

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Convergence estimator

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We require bright GW events (broadly defined)

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GW observables

$$C_\ell^{\kappa_{\mathrm{gw}}\kappa_{\mathrm{gw}}},\ C_\ell^{\kappa_{\mathrm{gw}}\delta},\ C_\ell^{\kappa_{\mathrm{gw}}\kappa_g}$$

Effective Field Theory of Modified Gravity

- Unifying language that encompasses several DE models
- Separate background evolution from linear perturbations
- Write an action with all operators giving *at most* second order equations of motion and
- Reflecting the symmetries of the FLRW metric $\longrightarrow$ operators coefficients (EFT functions) are functions of time

We further restrict to Horndeski with $c_T^2 = 1$

With this set-up, to parametrize any model in a general way one only needs to choose

The background expansion history

✓ $w_{\rm DE} = w_0 + w_a(1-a)$

$$\longrightarrow \begin{cases} \rho_{\rm DE} = \rho_{\rm DE}^0 \, a^{-3(1+w_0+w_a)} e^{-3w_a(1-a)} \\ \mathcal{H}^2 = \dfrac{8\pi G}{3}(\rho_m + \rho_\nu + \rho_{DE}) \end{cases}$$

3 EFT functions

$\Omega(a) \longrightarrow$ non-minimal coupling

$\gamma_1(a) \longrightarrow$ kineticity

$\gamma_2(a) \longrightarrow$ braiding

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The non minimal coupling term introduces dissipation, so that the inferred background GW luminosity distance becomes

$$\bar{d}_L^{GW} = \sqrt{1+\Omega(z)}\bar{d}_L^{EM}$$

In Horndeski theories, weak lensing is still the dominant correction to d_L and is not *explicitly* modified

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$$\frac{\Delta d_L^{GW}}{\bar{d}_L^{GW}} = -\kappa + ...$$

The GW convergence estimator then becomes

$$\hat{\kappa}_{GW} \equiv 1 - \frac{d_L^{GW}(z,\hat{n})}{\bar{d}_L^{EM}(z)} = 1 - \sqrt{1+\Omega(z)}(1-\kappa_{GW})$$

$$C_\ell^{X_i Y_j} = \int_0^{z_{\max}} \frac{\mathrm{d}z}{\chi^2(z)H(z)} \boxed{[\Theta_X(z)\Theta_Y(z)]}\, W_{X,i}(k,z) W_{Y,i}(k,z) P_{\mathrm{p}}(k), \quad \Theta_X(z) = \begin{cases} 1, \; X = [\delta, \kappa_g] \\ \sqrt{1+\Omega(z)}, \; X = \kappa_{\mathrm{gw}} \end{cases}$$

To obtain forecasts on cosmological parameters, we performed a Fisher matrix analysis

$$\mathcal{F}_{\alpha\beta} = \sum_{\ell=\ell_{\rm min}}^{\ell_{\rm max}} \frac{2\ell+1}{2} \sum_{i,j,m,n} \sum_{A,B,C,D} \frac{\partial C_{ij}^{AB}(\ell)}{\partial \theta_\alpha} \left[K^{-1}(\ell)\right]_{jm}^{BC} \frac{\partial C_{mn}^{CD}}{\partial \theta_\beta} \left[K^{-1}(\ell)\right]_{ni}^{DA}$$

We used **EFTCAMB** (Hu et al., 2014) for power spectra generation and **CosmicFish** (Raveri et al., 2016) for the Fisher matrix calculation

We considered different observational scenarios, varying:

- The number of measured bright GW sources
- The accuracy on the luminosity distance measurement
- The error on the counterpart redshift – either a spectroscopic or a photometric measurement

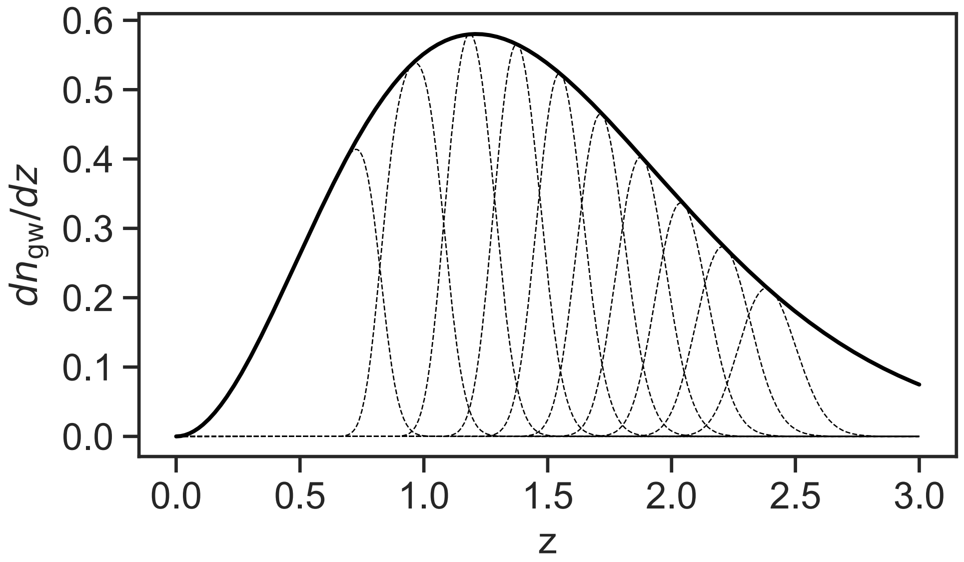

Figure: normalized GW sources distribution

Each time, we varied all parameters! Noise, LCDM parameters and MG parameters

Results - EFT of MG

Model M1: The background is not fixed, with

$$\rho_{\rm DE} = \rho^0_{\rm DE}\, a^{-3(1+w_0+w_a)} e^{-3w_a(1-a)} \quad , \quad \Omega(a) = \Omega_0 \frac{\rho_{DE}}{\rho^0_{DE}} \quad , \quad \gamma_1(a) = 0 \quad , \quad \gamma_2(a) = 0$$

Ω_0 - photometric

$\sigma_{d_L^{\rm gw}}/d_L^{\rm gw}$ \ N_{gw}	$5\cdot10^3$	10^4	$5\cdot10^4$	10^5	$5\cdot10^5$	10^6
0.5%	6.7 %	6.4 %	5.1 %	4.4 %	3 %	2.6 %
1%	6.7 %	6.5 %	5.3 %	4.6 %	3.2 %	2.7 %
5%	7 %	6.9 %	6.6 %	6.4 %	4.8 %	4.1 %
10%	7 %	7 %	6.9 %	6.8 %	6 %	5.4 %

Ω_0 - spectroscopic

$\sigma_{d_L^{\rm gw}}/d_L^{\rm gw}$ \ N_{gw}	$5\cdot10^3$	10^4	$5\cdot10^4$	10^5	$5\cdot10^5$	10^6
0.5%	4.8 %	4.1 %	2.8 %	2.4 %	1.6 %	1.4 %
1%	6 %	5.5 %	3.9 %	3.3 %	2.3 %	1.9 %
5%	7 %	6.9 %	6.6 %	6.2 %	4.8 %	4.1 %
10%	7 %	7 %	6.9 %	6.8 %	6 %	5.4 %

Balaudo et al. (2022) [arXiv:2210.06398]

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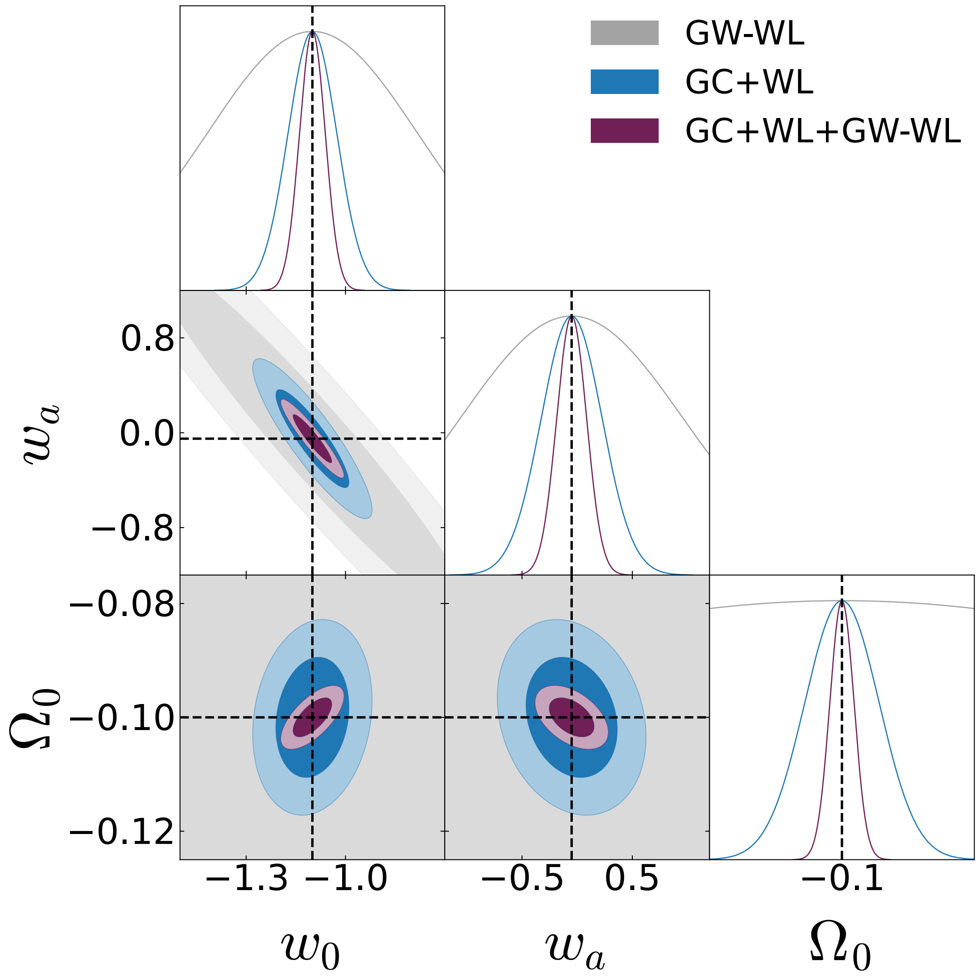
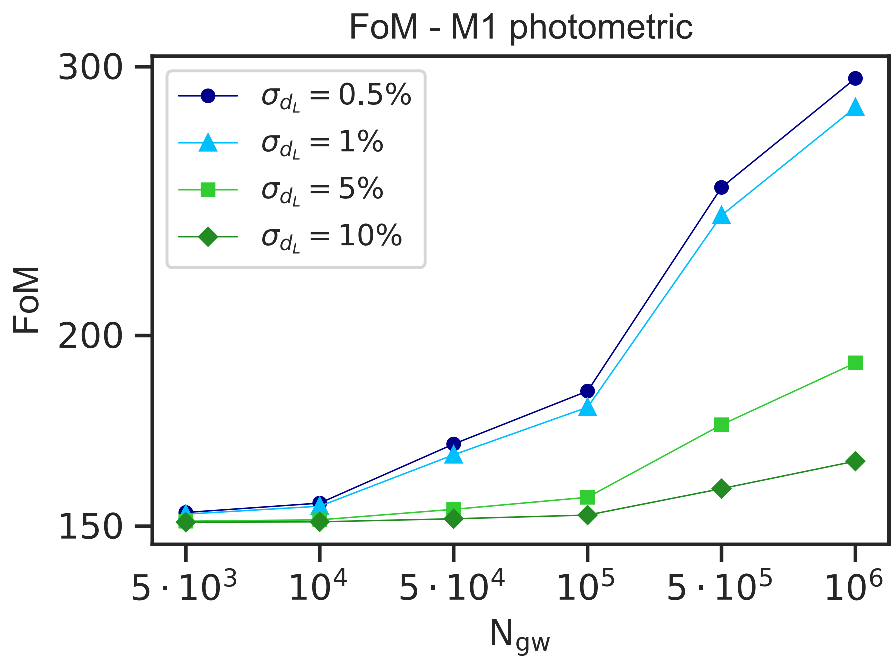


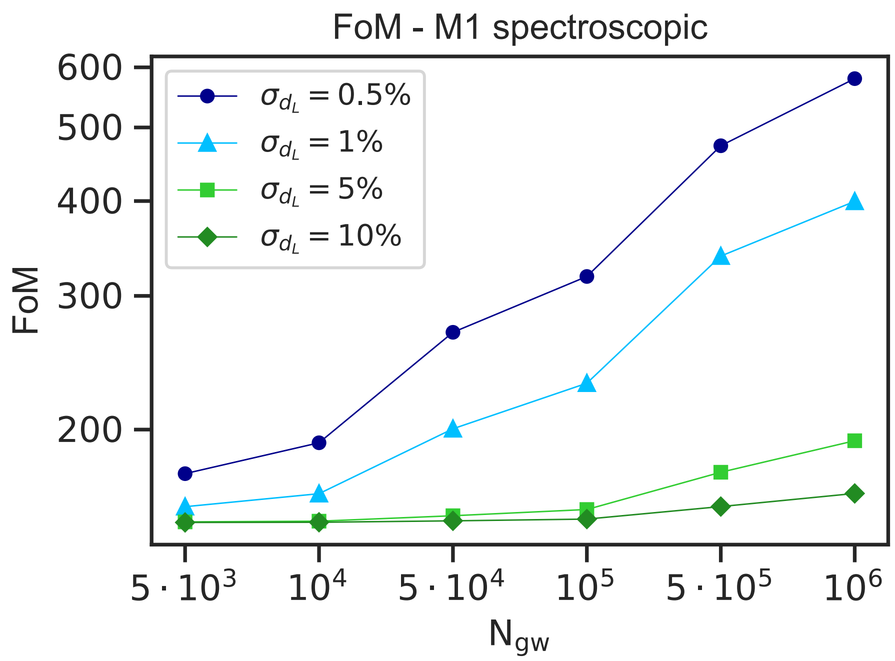
Marginalized forecasts on MG parameters, for a futuristic scenario in which 10^5 sources are detected with a spectroscopic redshift

Results - EFT of MG

We defined a Figure of Merit $\mathrm{FoM} = \det(\mathcal{F}_{\alpha,\beta})^{\frac{1}{2\mathrm{N}}}$ with N = number of free parameters

This FoM is inversely proportional to the N-th root of the 1σ volume in the parameter space





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Conclusions

- Single near future experiments might have too poor source statistics for GW weak lensing to provide crucial information

- We showed however that it is possible to define a convergence estimator containing crucial information over MG parameters

- Weak lensing could become a valuable source for GW experiments in the long run, especially to probe the growth parameters, that cannot be constrained though sirens

- In this optics, the main thing to improve on is the accuracy on luminosity distance and sky-location determination, to facilitate host identification

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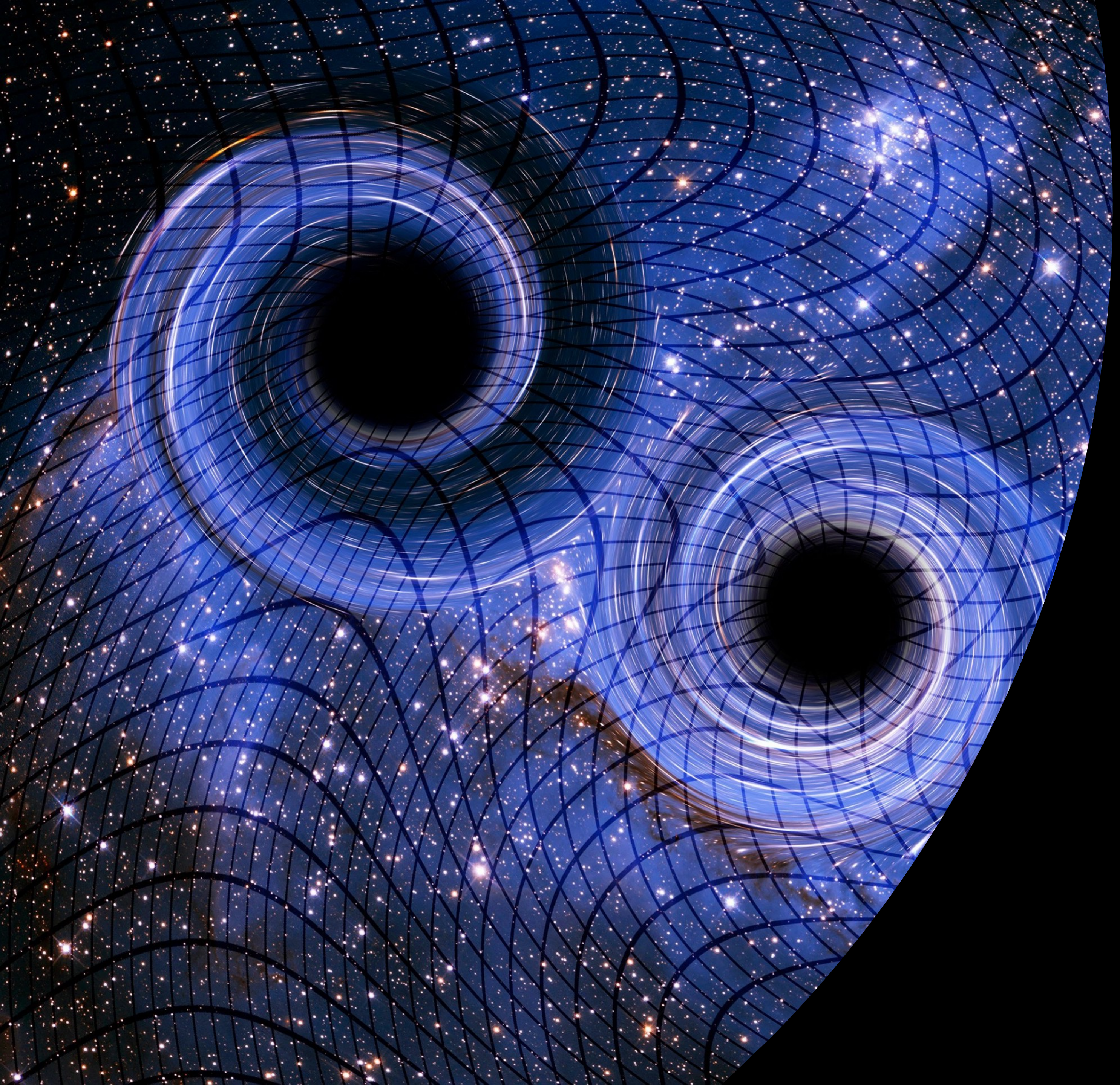
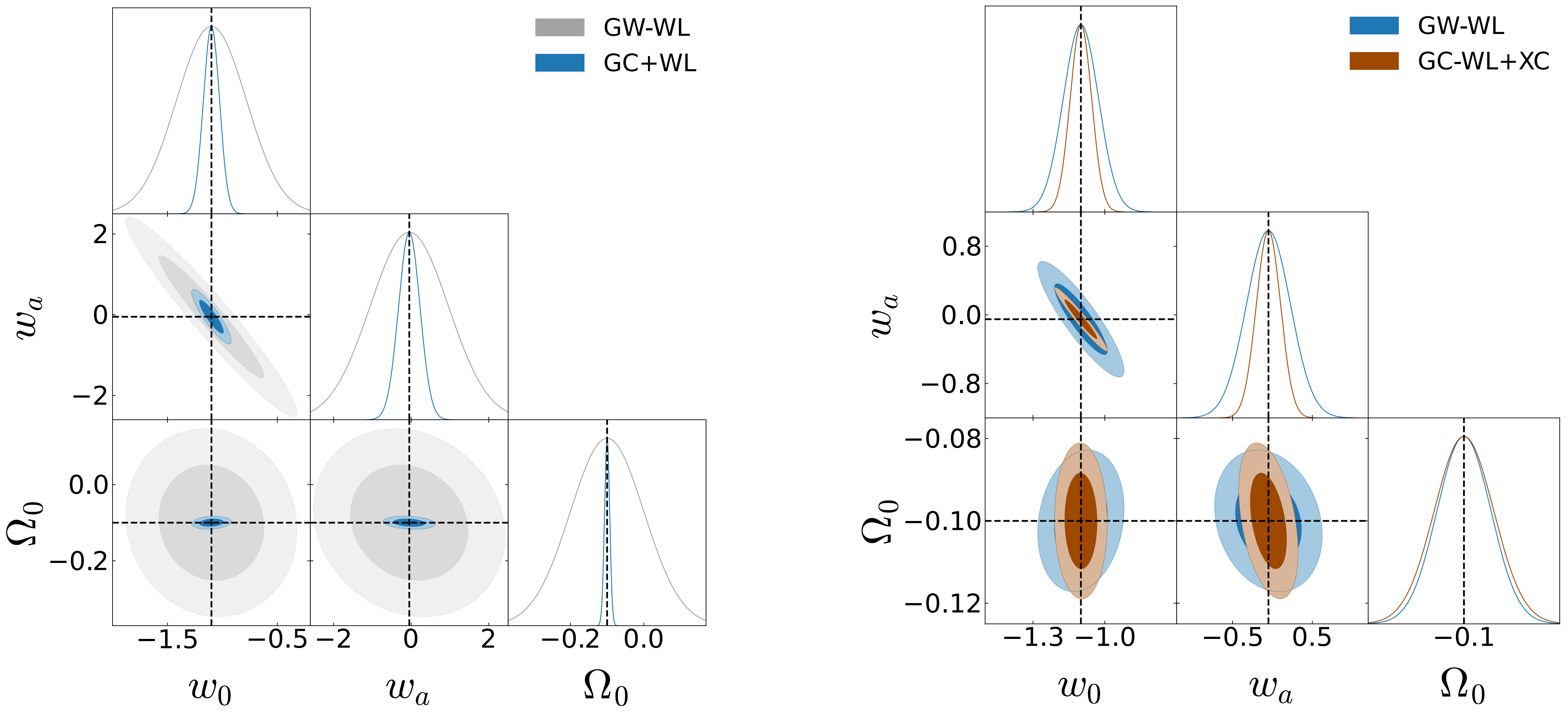
Thank you!

And thanks to Alice Garoffolo, Matteo Martinelli, Suvodip Mukherjee and Alessandra Silvestri




GW-WL
GC+WL
w_a
Ω_0
w_0
w_a
Ω_0
2
0
−2
0.0
−0.2
−1.5
−0.5
−2
0
2
−0.2
0.0
GW-WL
GC-WL+XC
0.8
0.0
−0.8
−0.08
−0.10
−0.12
−1.3
−1.0
−0.5
0.5
−0.1