Testing gravity on cosmological scales with gravitational waves

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What will I talk about?

Gravitational waves (GWs)

- Tiny wave-like distortions in the space-time ($\sim 10^{-22}$) caused by extreme events

Image: NASA

What will I talk about?

Gravitational waves (GWs) → feel → the cosmological model

- Tiny wave-like distortions in the space-time ($\sim 10^{-22}$) caused by extreme events

- ΛCDM → H_0
- Its extensions like from Modified Gravity

Image: NASA

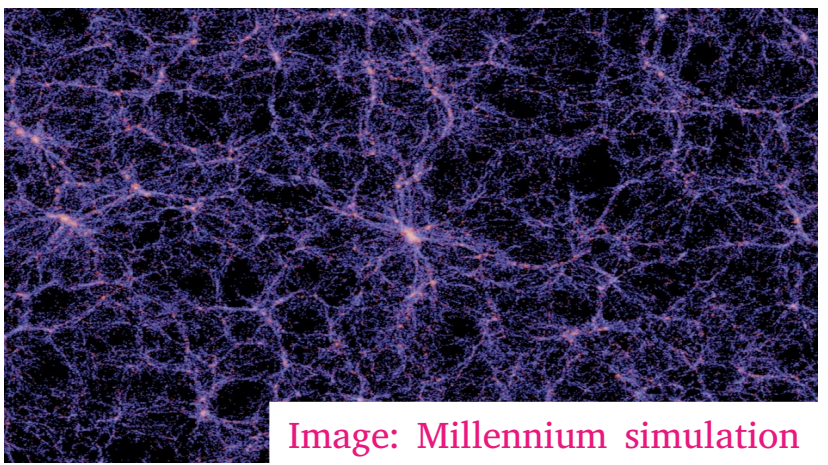

Image: Millennium simulation

Some methods for GW cosmology

- Bright standard sirens → GW + electromagnetic counterparts
  - Time delay → $c_{\rm gw} = 1$
  - Distance-redshift relation → $h \sim 1/D_{\rm gw}$ "GW distance"

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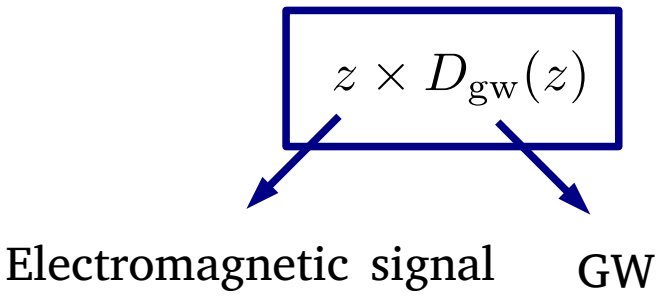
  - Cross-correlating with galaxy catalogs
- Stochastic GW Background

Other methods: strongly lensed GWs, reconstruction of velocity field ...

GW distance-redshift relation in modified gravity



- The Einstein Telescope might see hundreds of bright sirens

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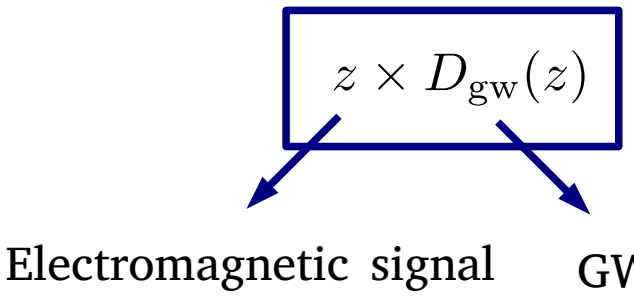


- The Einstein Telescope might see hundreds of bright sirens

- A time-dependent effective Planck mass changes the GW distance

$$M_*^2 \propto \frac{1}{G_{\rm eff}}$$

$$D_{\rm gw}(z) = D_L(z)\sqrt{\frac{M_*^2(0)}{M_*^2(z)}}$$

Amendola et al. (2018)

This signature also appears in the SGWB

Lobato, **Matos**, Calvão, Waga (2022)

Gravitational slip

- The GW speed and the Planck mass running split the two gravitational potentials

$$\Phi \neq \Psi$$

→ Like an anisotropic stress

- Gravitational slip → equals unity in GR (late times)

$$\eta := \frac{\Phi}{\Psi}$$

→ observable from large-scale structure (LSS)

- The combination of GW data with slip measurements can constrain modified gravity

Saltas et al. (2014)

Matos, Bellini, Calvão, Kunz (2023)

Matos, Calvão, Waga (2021)

Bright sirens forecasts with the Einstein Telescope

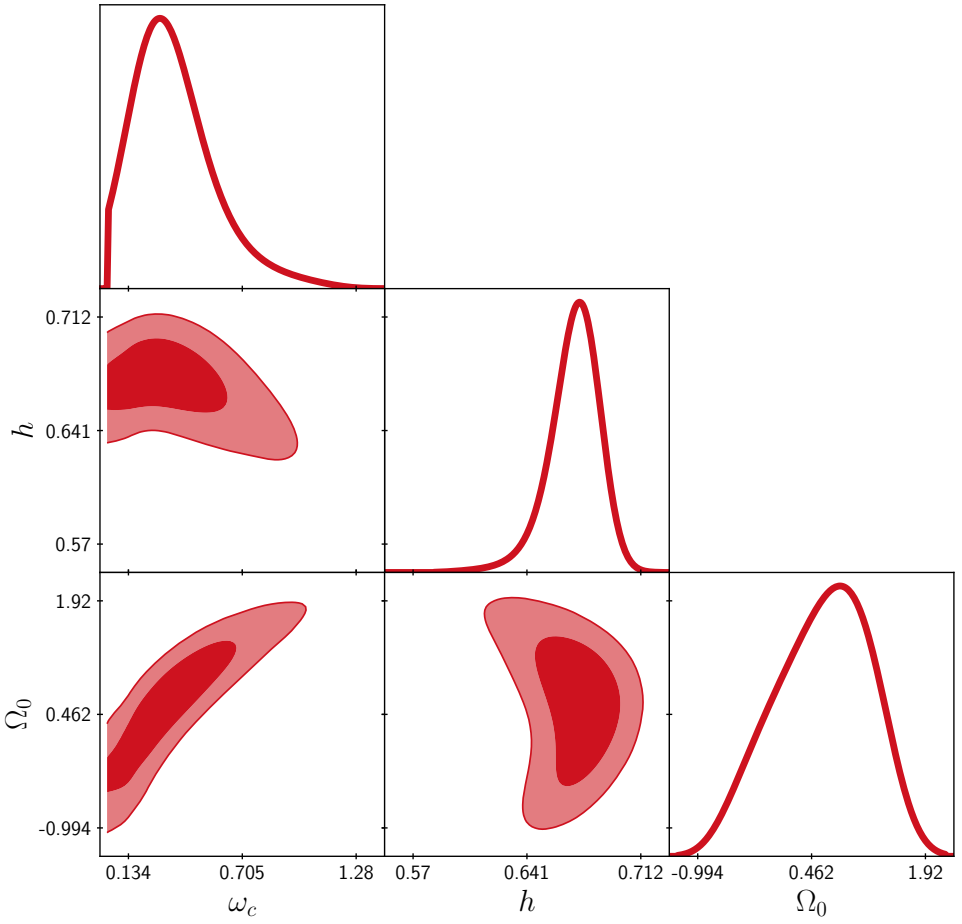
1000 standard sirens

- ΛCDM → $\frac{\Delta H_0}{H_0} \sim 1\%$
- for any viable f(R), above a certain z

$$\frac{D_{\rm gw}}{D_L} \sim 1 + \frac{f_{R0}}{2} \quad \text{in the best scenario} \rightarrow \boxed{|f_{R0}| \lesssim 10^{-2}}$$

- Large degeneracies between the cosmological parameters and the modified gravity ingredient M_*^2

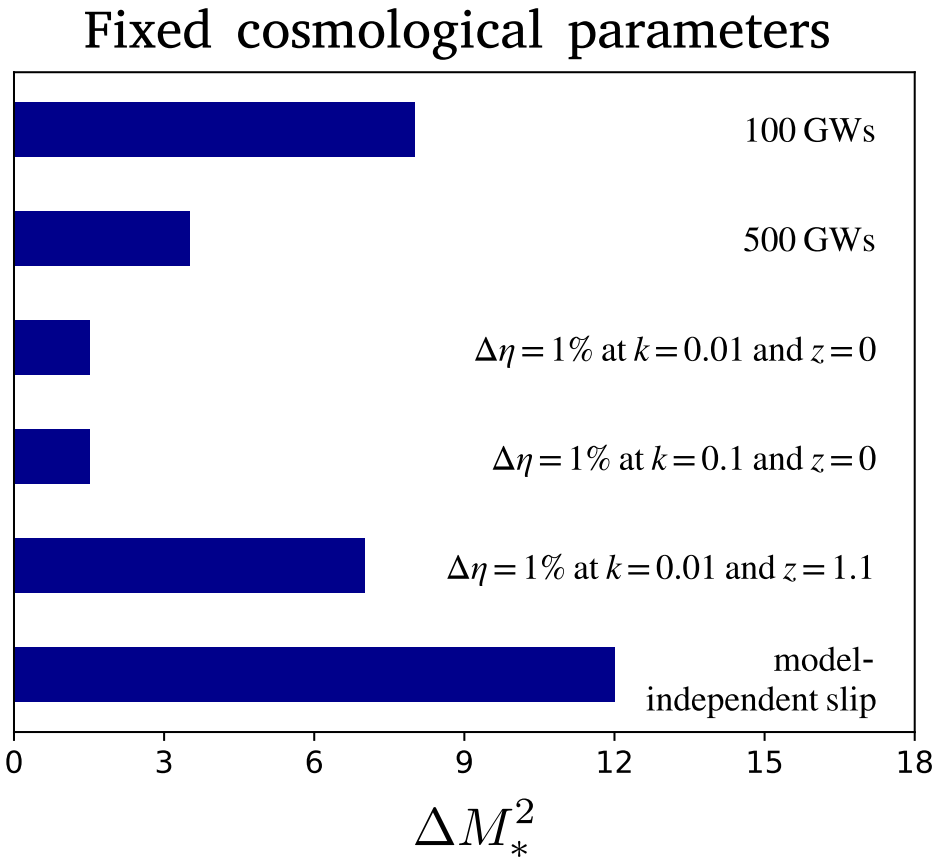
Matos, Bellini, Calvão, Kunz (2023)



Matos, Bellini, Calvão, Kunz (2023)

Slip vs GWs

Slip and GW distance have similar constraining power



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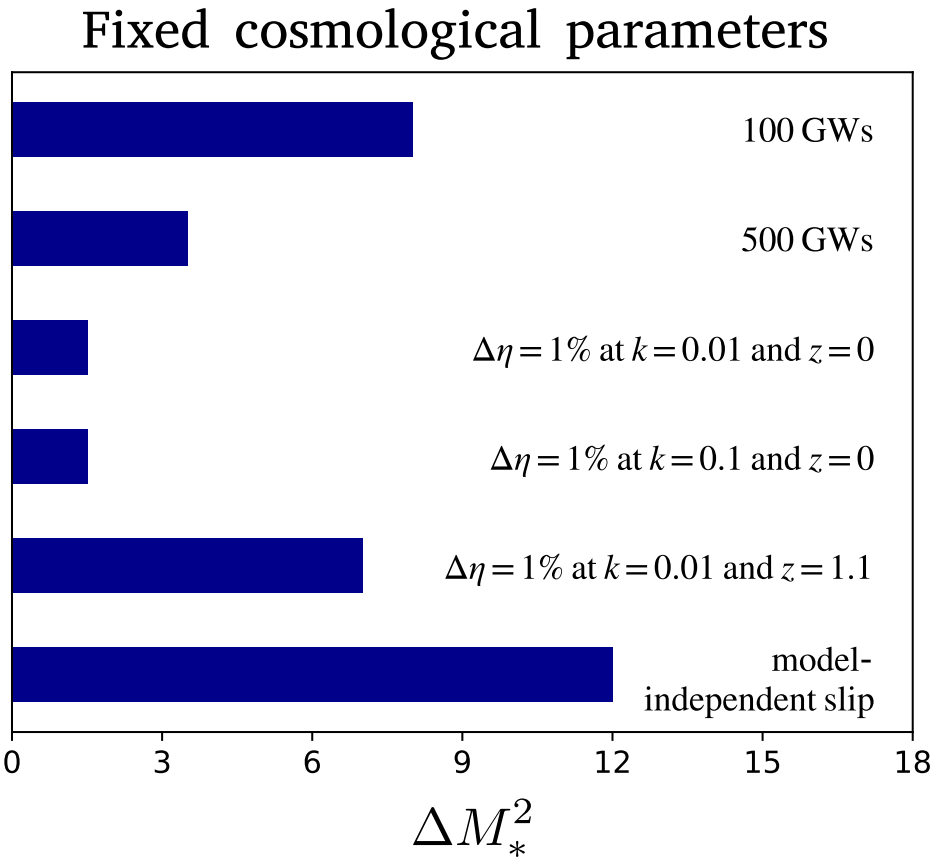
LSS Euclid-like surveys will give more precise measurements than standard sirens but more model-dependent



Take home message

GWs provide various independent tests of the ΛCDM model and its extensions

→ Advantage of the test for modified gravity: they are sensitive to a single extra function $M_*^2(z)$

→ Distance-redshift relation: degeneracies between the cosmological and modified gravity parameters

→ The combination of GWs with other probes is crucial

Perspectives

- Break degeneracies combining SNe and bright sirens

Model-independent test $D_L \times D_{\rm gw}$

In prep., with Quartin, Amendola & Kunz

Perspectives

- Break degeneracies combining SNe and bright sirens

Model-independent test $D_L \times D_{\rm gw}$

In prep., with Quartin, Amendola & Kunz

- Dark sirens + galaxy catalogs

with R. Sturani

$\rho(H_0|\{D_{\rm gw}\},\{z\})$ Joint probability of GW data and redshifts of galaxies

What if the catalog is incomplete?

Thank you!