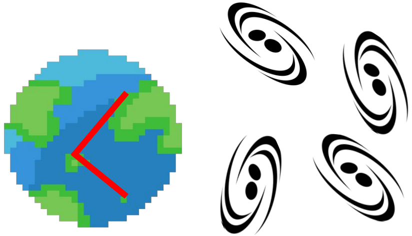
Timing the cosmic expansion with populations of gravitational waves dark sirens

“What can go wrong?”

S. Mastrogiovanni

Gravitational Waves from cosmic distances

Source frame

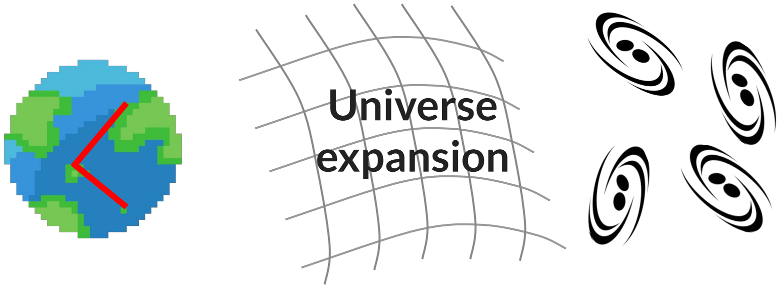


Chirp mass — Source time

$$h(t) \propto \frac{\mathcal{M}^{5/4}(t_c - t)^{-1/4}}{d} e^{\phi(t)}$$

Physical distance

Detector frame



Redshifted chirp mass — Detector time

$$h(t^{\rm det}) \propto \frac{[\mathcal{M}(1+z)]^{5/4}(t_c^{\rm det} - t^{\rm det})^{-1/4}}{d_{\rm L}} e^{\phi(t)}$$

Luminosity distance

Gravitational Waves from cosmic distances

1. Gravitational Waves **directly** provide the luminosity distance of the source.

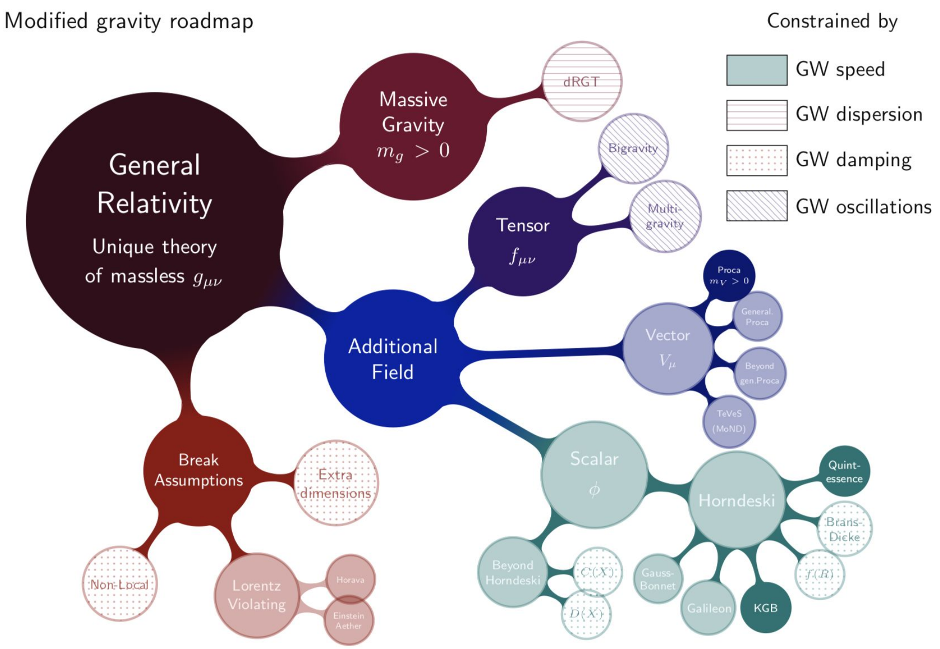
2. Even if we do not observe electromagnetic counterparts, we can invoke **dark sirens** methods (see overview talk) to do cosmolography.

3. With Einstein Telescope and Cosmic Explorer we will have millions of detections, statistics is on our side.

"What can go wrong?"

What can go wrong? General Relativity

- Alternative GR theories are possible solutions to open issues in Standard cosmological model, e.g. dark energy, Hubble constant tension.
- We want to understand how Standard Cosmology parameters mix to GR deviation parameters.



J. M. Ezquiaga+, Front. Astron. Space Sci. 5:44 (2018)

What can go wrong? General Relativity

M. Lagos, Phys. Rev. D 99, 083504 (2019)

$$h'' + 2[1+\alpha_M(\eta)]\frac{a'}{a}h' - c_T\nabla^2 h = 0$$

GW friction

Dispersion relation

Dispersion relation:

- GWs group velocity depends on the frequency.
- GWs modes arrive off-phased at the detector.
- GWs modes show a time delay w.r.t EM counterparts.

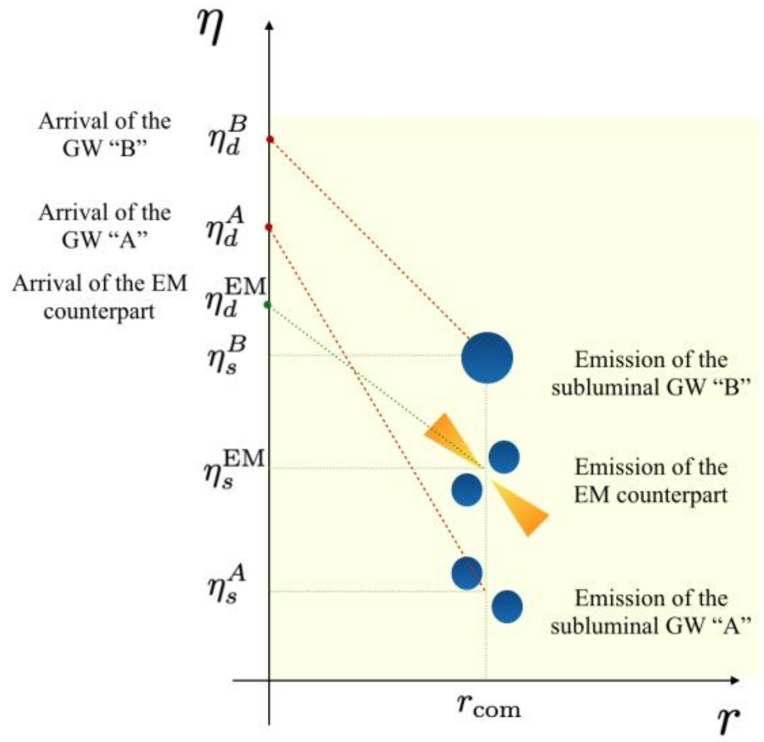
Horava gravity, massive gravity, scalar tensor theories with field derivative couplings

GW friction:

- GWs show an additional energy leakage as they travel.

extra energy dissipation terms, e.g. a running Planck mass, 4+n dimensional gravity, scalar-tensor theories

What can go wrong? General Relativity



***SM+**, Phys. Rev. D 102, 044009 (2020)*

Comoving distance

Dispersion relation:

- GWs group velocity depend on their frequency.
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GW friction:

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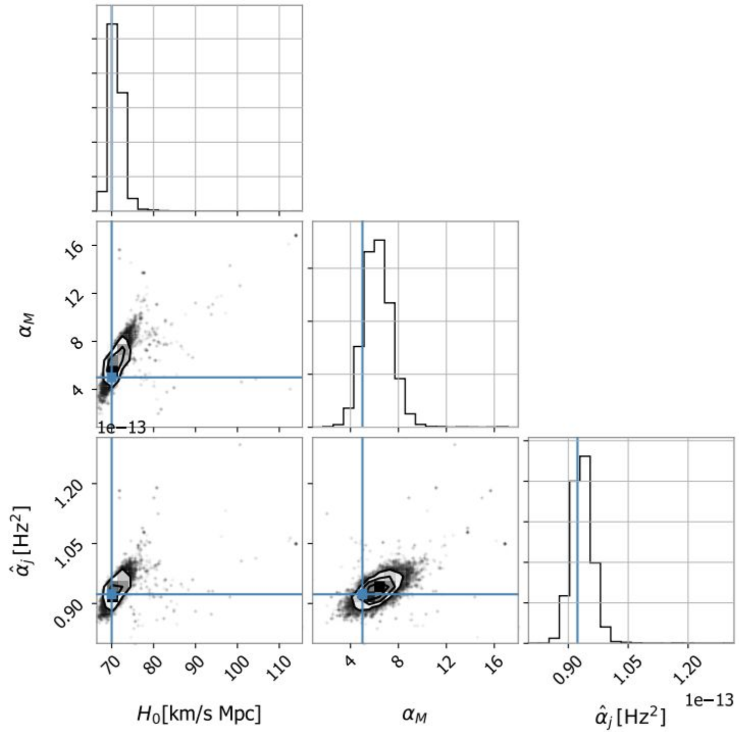
What can go wrong? General Relativity



SM+, *Phys. Rev. D 102, 044009 (2020)*

- To understand the interplay between cosmology (H0), GW friction and GW speed, we simulate the observation of 100 BNS mergers with observed EM counterparts.
- From the GW luminosity distance, galaxy redshift and GW-GRB time delay it is possible to measure H0, GW friction and speed of gravity.
- Correlations among H0 and modified gravity appears at the percent-level precision.

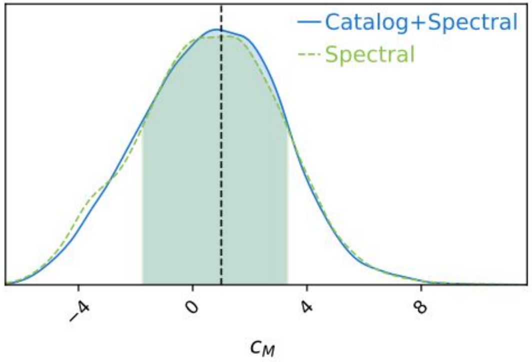
We need to model Modified Gravity to measure H0 at a sub-percent precision.

What can go wrong? General Relativity

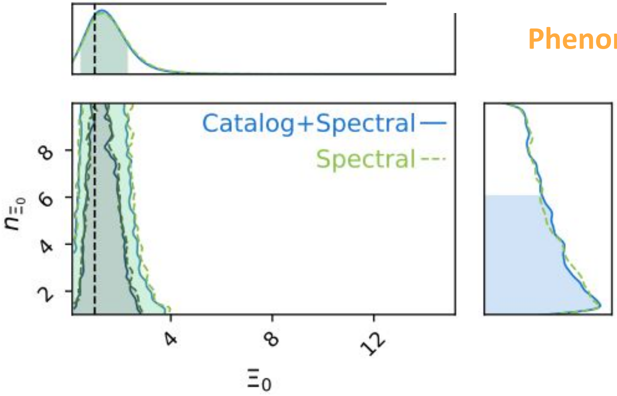
- We looked to GW friction using BBHs from GWTC-3 using the spectral sirens and galaxy catalog method.
- By marginalizing over H0, it is possible to obtain interesting constraints on the GW friction.
- With current GW events, other population-level parameters does not strongly correlate with the determination of Modified Gravity.
- Bayes factors strongly (factor of 10) prefer classical GR, too many degrees of freedom.

Running Planck mass

$$d_L^{GW} = d_L^{EM} \exp\left[\frac{c_M}{2}\int_0^z \frac{1}{(1+z')E^2(z')}dz'\right]$$



Phenom. Parametrization



$$d_L^{GW} = d_L^{EM}\left(\Xi_0 + \frac{1-\Xi_0}{(1+z)^n}\right)$$

SM *et al Phys. Rev. D 102, 044009 (2020), Leyde et al* ***SM*** *JCAP 09012 L (2022), Mancarella M. et al Phys. Rev. D 105, 064030 (2022).*

What can go wrong? Astrophysics

The likelihood for an inhomogeneous Poisson process in presence of selection biases, for a **constant rate in detector time**, is (see Mandel+ 2018 MNRAS, Vitale+ 2020)

Link to icarogw function

ICAROGW

Logo possible thanks to: LIGO-Virgo-KAGRA / Aaron Geller / Northwestern

Rate

$$\mathcal{L}(x|\Lambda) \propto e^{-N_{\rm exp}} \prod_{i=1}^{N_{\rm obs}} T_{\rm obs} \int \mathcal{L}_n(x|\theta,\Lambda) \frac{dN}{dtd\theta} d\theta$$

Noise process

Expected number of detections

$$N_{\rm exp} = T_{\rm obs} \int p_{\rm det}(\theta,\Lambda) \frac{dN}{dtd\theta} d\theta.$$

What can go wrong? Astrophysics

To write down the hierarchical likelihood it is crucial to answer the question:

What is the probability of observing a CBC at a given redshift and in a given sky position?

What can go wrong? Astrophysics

The CBC likelihood is often parametrized in terms of redshift and **source-frame time**

$$\frac{dN_{\rm CBC}(\Lambda)}{d\vec{m}d\vec{\chi}d\Omega dz dt_s} = R_0$$

Rate of CBC [#mergers Gpc^-3 yr^-1]

$$\psi(z;\Lambda)$$

Rate evolution function, e.g. (1+z)^gamma. Two models available

$$p_{\rm pop}(\vec{m},\vec{\chi}|\Lambda)$$

Probabilities for source-frame masses and spins, 8 models for masses, 2 for spins

$$\frac{dV_c}{dz d\Omega}$$

Comoving volume (depends on cosmology)

What can go wrong? Astrophysics

The CBC likelihood is often parametrized in terms of redshift and **source-frame time**

CBC per galaxy per year

Term similar to the vanilla rate

$$\frac{dN_{\rm CBC}(\Lambda)}{dz d\vec{m} d\vec{\chi} d\Omega dt_s} = R^*_{\rm gal,0}\psi(z;\Lambda)p_{\rm pop}(\vec{m},\vec{\chi}|\Lambda)\times$$

$$\left[\frac{dV_c}{dzd\Omega}\phi_*(H_0)\Gamma_{\rm inc}(\alpha+\epsilon+1, x_{\rm max}(M_{\rm thr}), x_{\rm min})+\right.$$

Integral of Schecter function

Number density of galaxies per steradian (completeness correction)

$$\left.\frac{1}{\Delta\Omega}\sum_{j=1}^{N_{\rm gal}(\Omega)} f_L(M(m_j,z);\Lambda)p(z|z^j_{\rm obs},\sigma^j_{\rm z,obs})\right]$$

Number density of galaxies per steradian (catalog)

Luminosity weight

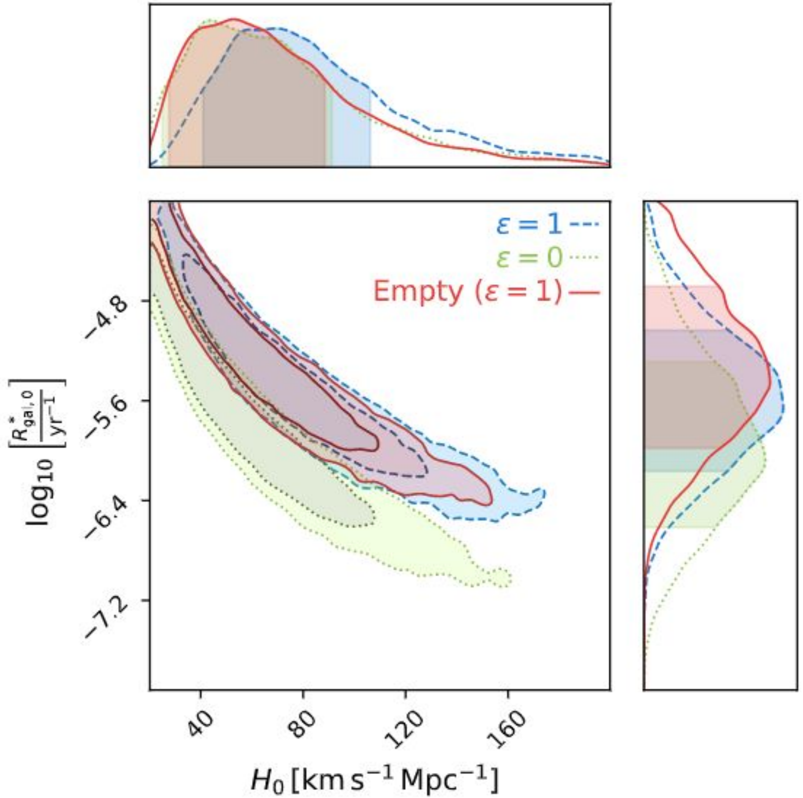
Galaxy localization in redshift

Sky pixel area

What can go wrong? Astrophysics

- With luminosity weights it is easier to exclude low H0 values (galaxy catalog complete).
- With no luminosity weights, the galaxy catalog is too incomplete.
- If brighter galaxies are more likely to emit GWs, the rate of CBC mergers per galaxies should be higher (very few luminous galaxies).
- Determination of CBC rate per galaxy degenerate with Hubble constant: Playing with the Hubble constant changes the galaxy number density in a fixed comoving volume.

***SM+**, Phys. Rev. D 102, 044009 (2020)*

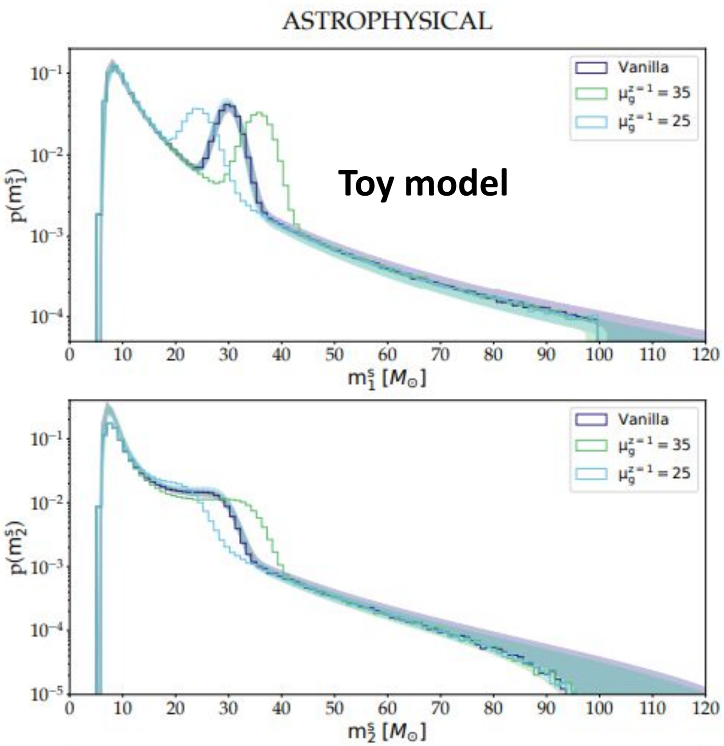


What can go wrong? Astrophysics: BBH mass spectrum

- Current models for BBH mass spectrum does not evolve with redshift

- Astrophysical simulations indicate that the BBH mass spectrum *could* evolve in redshift
  [M. Mapelli *Handbook of GW astronomy* (2021), R. Srinivasan et al **SM** MNRAS 524 (2023)]

- Can an evolving BBH mass spectrum translate to a biased estimation of H0 with spectral sirens?

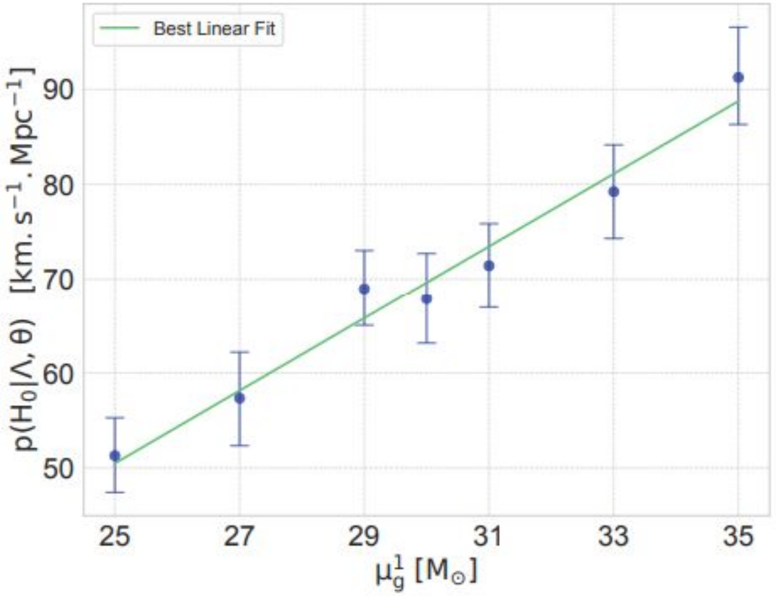


*G. Pierra, **SM+**, S. Perries, M. Mapelli, arXiv 2312.11627*

What can go wrong? Astrophysics: BBH mass spectrum

- An evolution of the mass spectrum can result in a biased on the estimation of the Hubble constant.
- If the peak features evolves the bias could be significant.
- The reconstructed mass distribution are strongly degenerate.

Simulation with 2000 GW detections



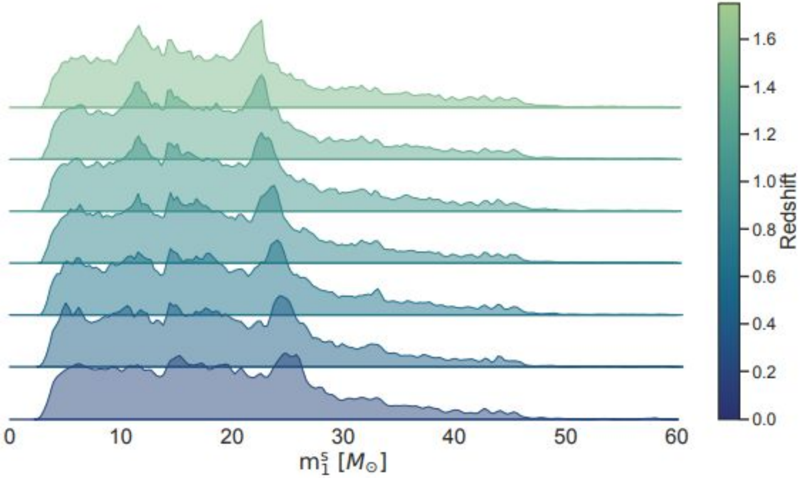
*G. Pierra, **SM+**, S. Perries, M. Mapelli, arXiv 2312.11627*

What can go wrong? Astrophysics: BBH mass spectrum

- We use a synthetic BBH catalog containing 4 different formation channels: isolated binaries and hierarchical mergers in young, globular and nuclear star clusters.
  [M. Mapelli et al MNRAS 511 (2022)]

- The BBH mass spectrum shows a mild evolution in redshift, in particular in the 10-30 solar mass region.

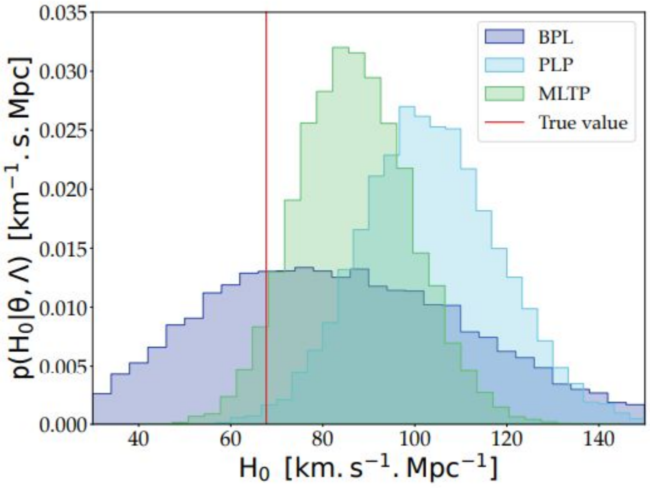
- We simulated 2000 GW detections from the BBH catalog and using simple redshift-independent mass models we inferred the value of H0.



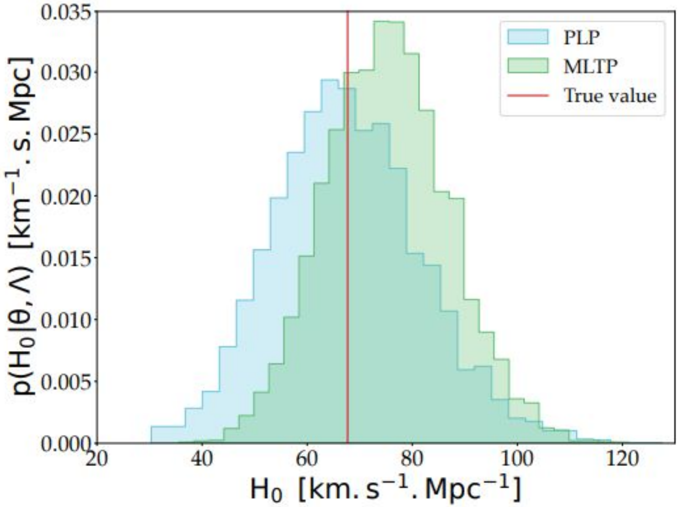
*G. Pierra, **SM+**, S. Perries, M. Mapelli, arXiv 2312.11627*

What can go wrong? Astrophysics: BBH mass spectrum

- Redshift-independent mass models with mass features are more prone to systematics when inferring H0



- The bias is removed when removing the mild redshift dependence from the mass spectrum



*G. Pierra, **SM+**, S. Perries, M. Mapelli, arXiv 2312.11627*

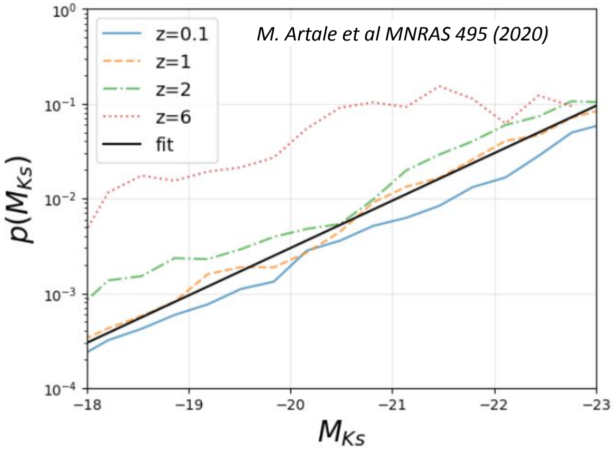
What can go wrong? Astrophysics: Galaxy relations

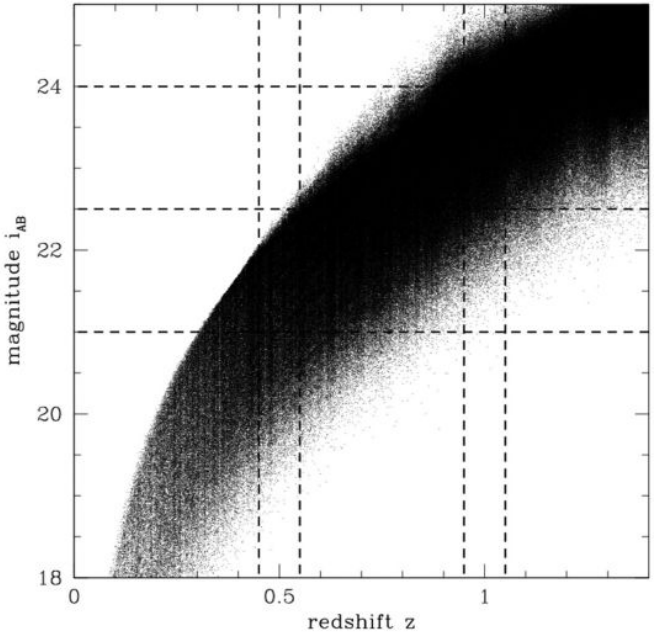
- The MICE Grand Challenge lightcone is a N-body cosmological simulation of 70 billion dark matter particles in which galaxies are formed.

- The MICE galaxies mimic all the properties of our Universe, e.g. clustering length, observational properties etc.

- We simulate GW detections from MICE assuming a relation between GW hosting probability and galaxies' luminosity.

- We use different detection horizons.

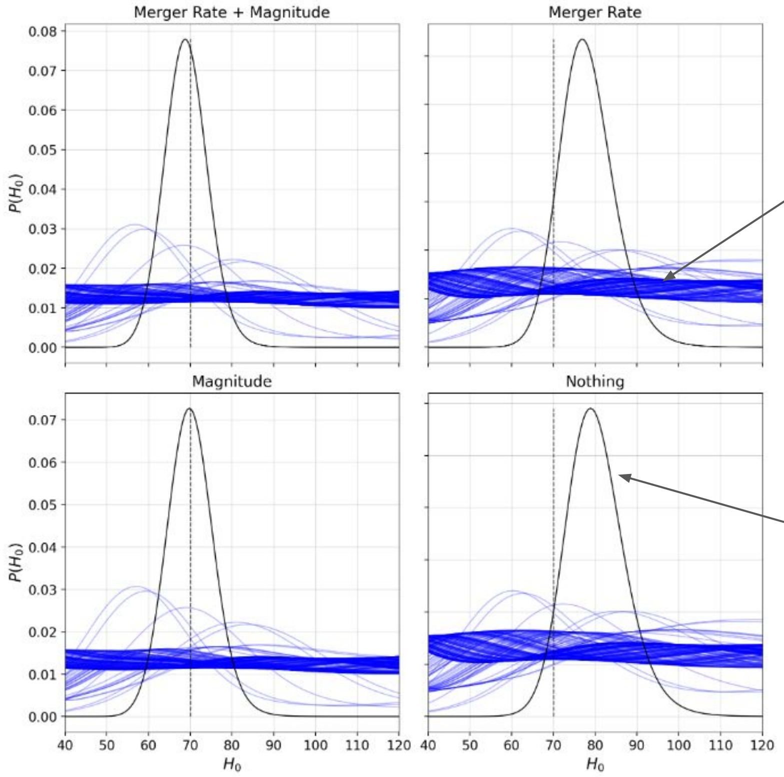




M. Crocce et al MNRAS 453 (2015)

What can go wrong? Astrophysics: Galaxy relations

500 GW events, horizon = 1550 Mpc

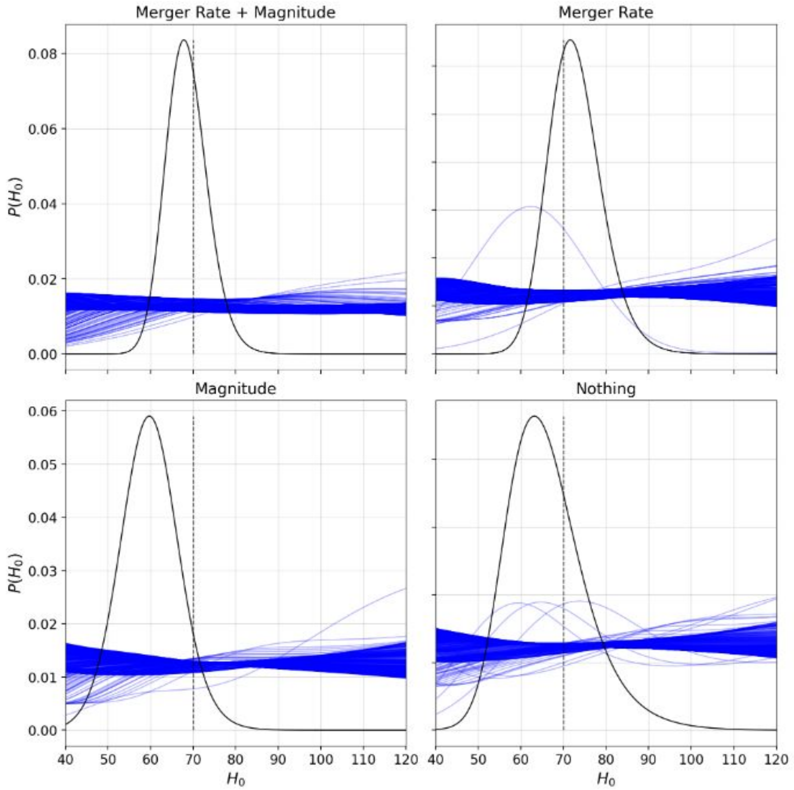


Single events

Combined

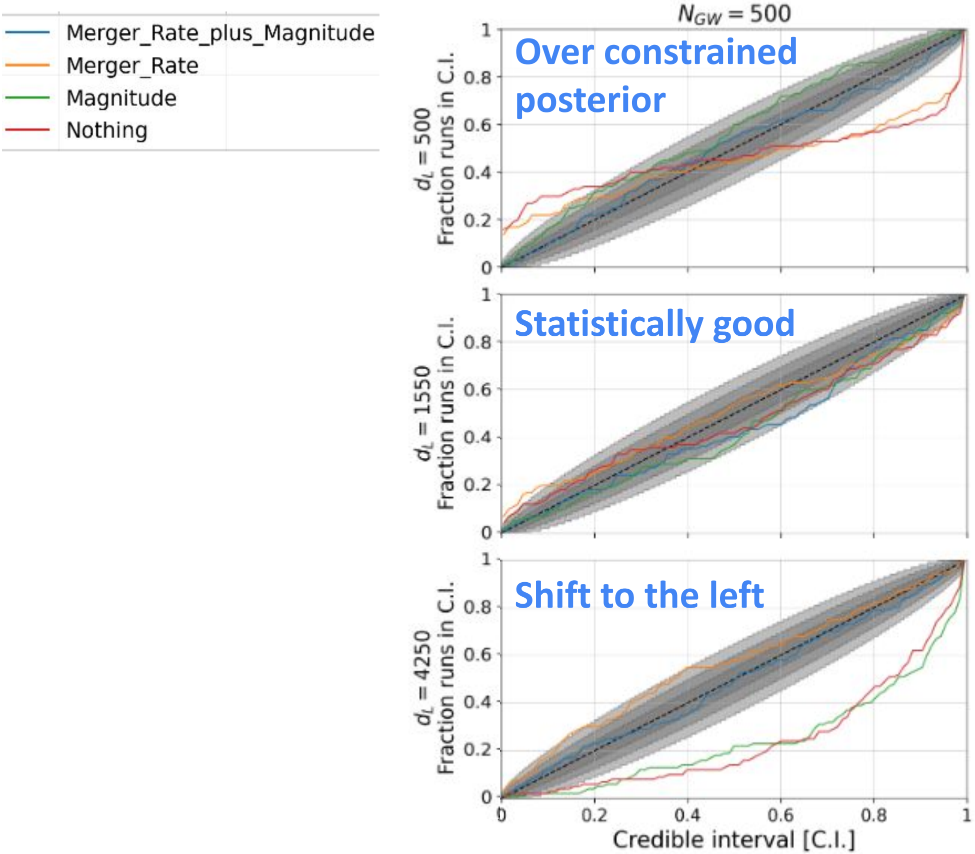
*G. Perna, **SM**, A. Ricciardone in prep.*

500 GW events, horizon = 4250 Mpc



*G. Perna, **SM**, A. Ricciardone in prep.*

What can go wrong? Astrophysics: BBH mass spectrum



- Parameter - Parameter (PP) plots are the definitive tool to check for presence of systematics bias in the inference (even with high statistical errors).
- If the detection horizon is low (or high SNR cut), mismatching the galaxy/GW relation will result in a bias for H0.
- If the detection horizon is high (or low SNR cut), it is important to model accurately the CBC merger rate as function of redshift.

Conclusions

- Gravitational Wave Cosmology is entering in its systematics era
- Modifications to General Relativity on cosmological scales (GW friction and speed), could introduce a systematic in the estimation of H0 at the percent-level precision.
- Mismodeling of the BBH mass spectrum is very likely to introduce a bias in the estimation of H0 even with current BBH detections.
- Well-localized and close dark sirens can inherit a bias on H0 due to the unknown galaxy/GW relation.

Don't Panic

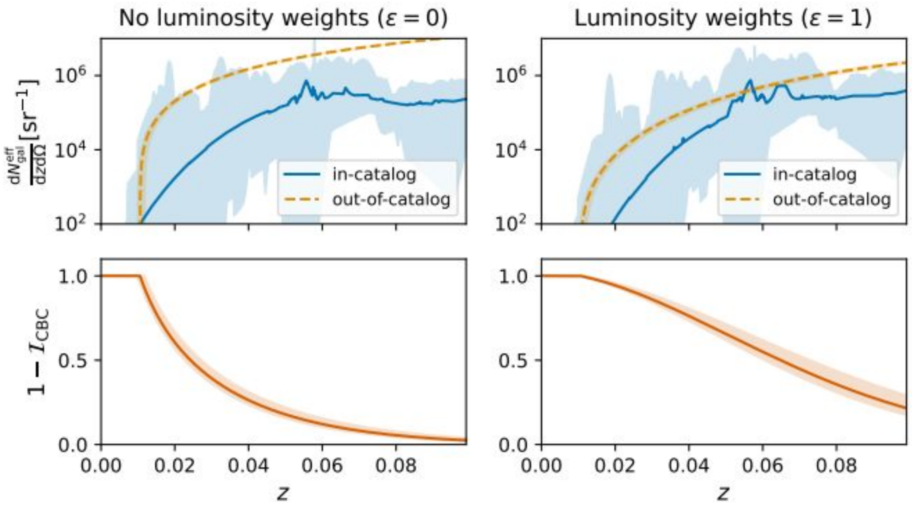
Use Statistics

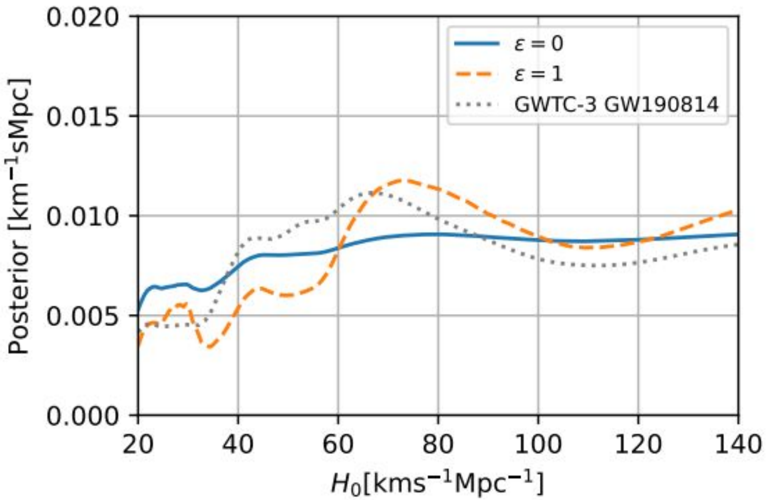
Know your biases

Backup slides

Dark sirens: Cosmology aided by galaxy surveys

Equal host probability | **Red-luminous galaxies preferred hosts**





[Mastrogiovanni+, PRD 2023]

GW hosting models will have an important impact for cosmology

Observables for GR modifications

The GW luminosity distance

EM distance — GW friction

$$d^{\rm GW}(z) = d_{\rm EM}(z)\exp\left[\int_0^z \frac{\alpha_M(z)}{1+z}dz\right]$$

GW-GRB time delay

GW-GRB Prompt delay — GW Peak frequency

$$\Delta t_d^{\rm GW-EM} = (1+z_s)\Delta t_s^{\rm GW-EM} + \frac{f^j_{R,d}}{2}\mathcal{T}_j$$

Mode-delay

$$\mathcal{T}_j = \int_0^{z_s} dz'\hat{\alpha}_j(z)\frac{(1+z')^j}{H_0E(z')}$$

GW Phase modes

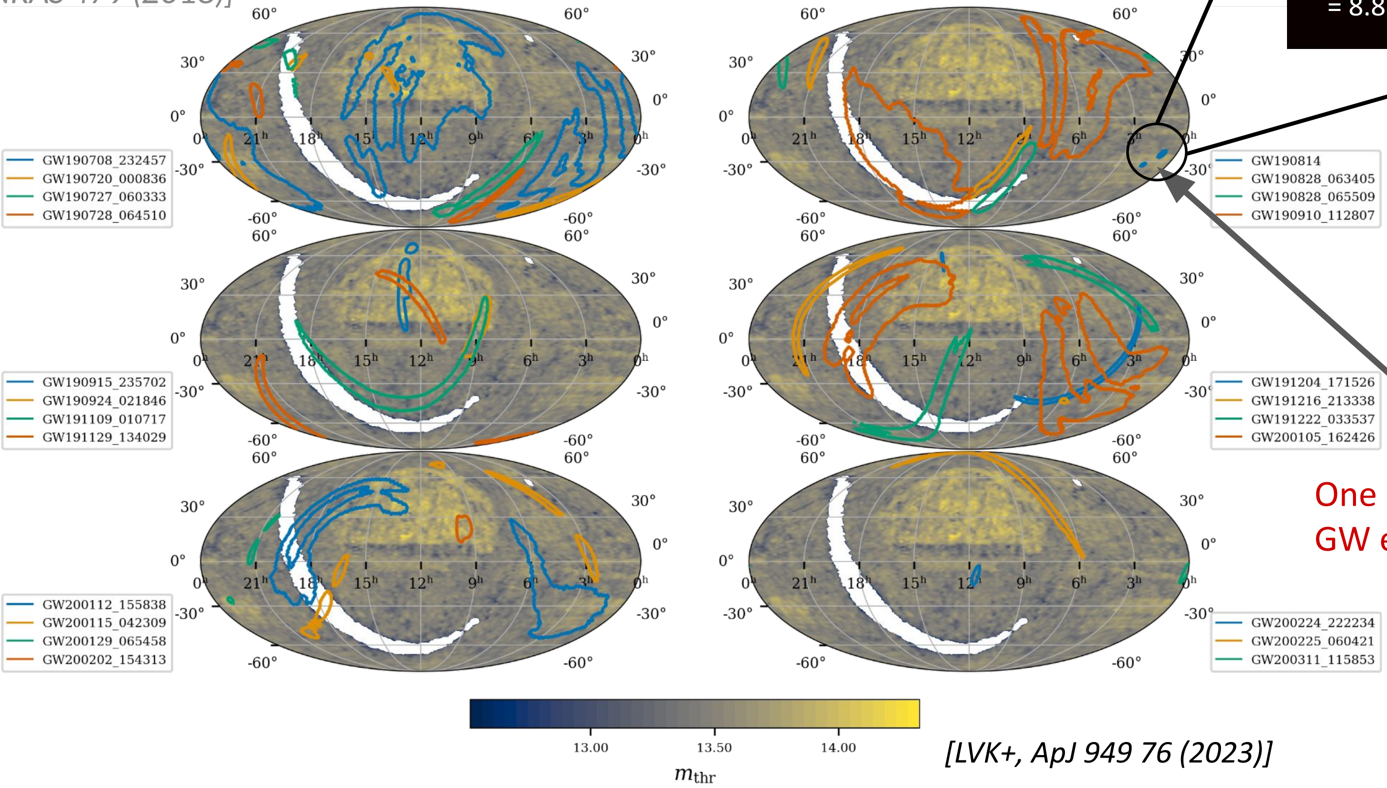
Measured PN coefficient — GR PN coefficient

$$\frac{\psi_{3j+8}(f_d) - \psi_{3j+8,\rm GR}(f_d)}{\psi_{3j+8,\rm GR}(f_d)} = \pi\frac{\mathcal{T}_j}{\beta^{\rm PN}_{3j+8}(j+1)},$$

SM+, *Phys. Rev. D 102, 044009 (2020)*

GW cosmology after GWTC-3: Dark sirens

[Dalya+, MNRAS 479 (2018)]



[LVK+, ApJ 949 76 (2023)]

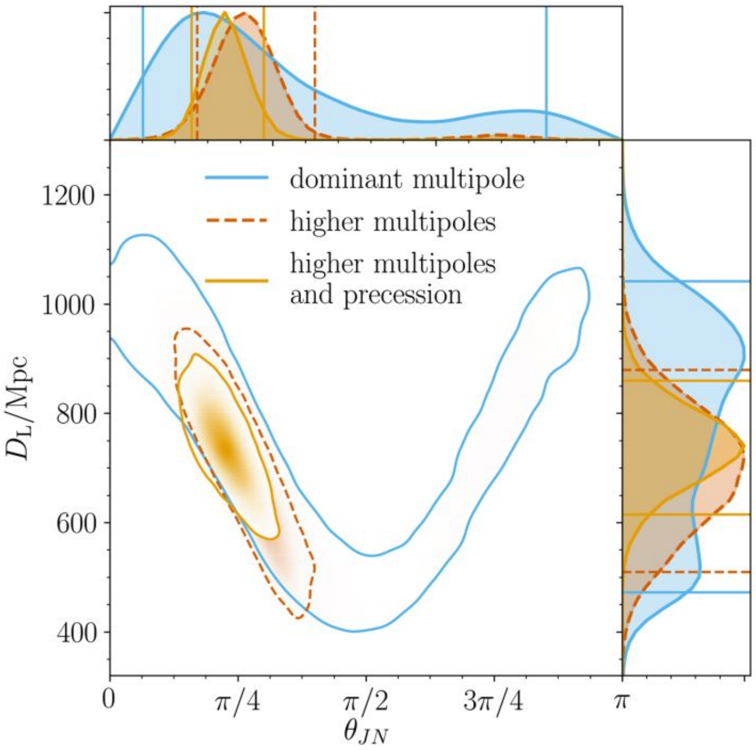
GW190814

Sky area ~ 20 sq. deg.

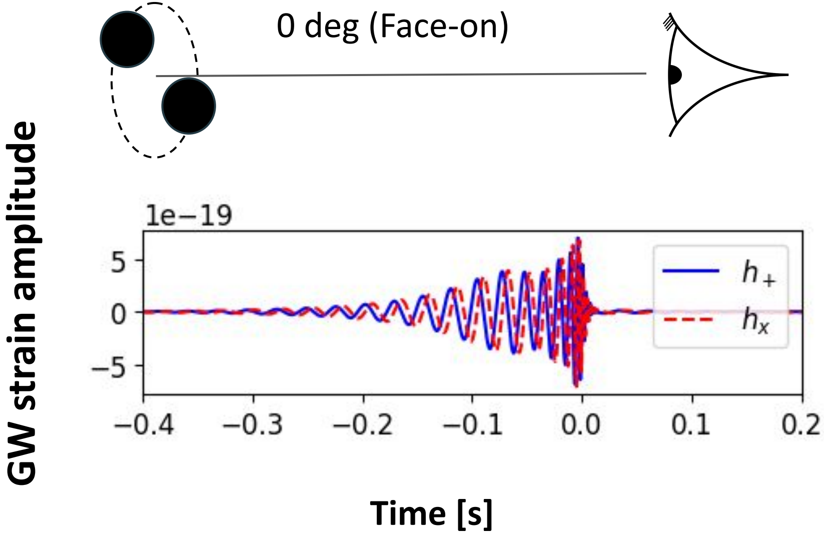
Localisation volume = 8.8 x 10^{-7} Gpc^3

One of the highly localised GW events

Gravitational Wave sources at cosmological scales



[B. P. Abbott, PRD 102, 043015]



There are large uncertainties on the GW estimation of the luminosity distance. The precision can be improved with (i) extra EM information (ii) precession or higher order modes.