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ICHEP 2022

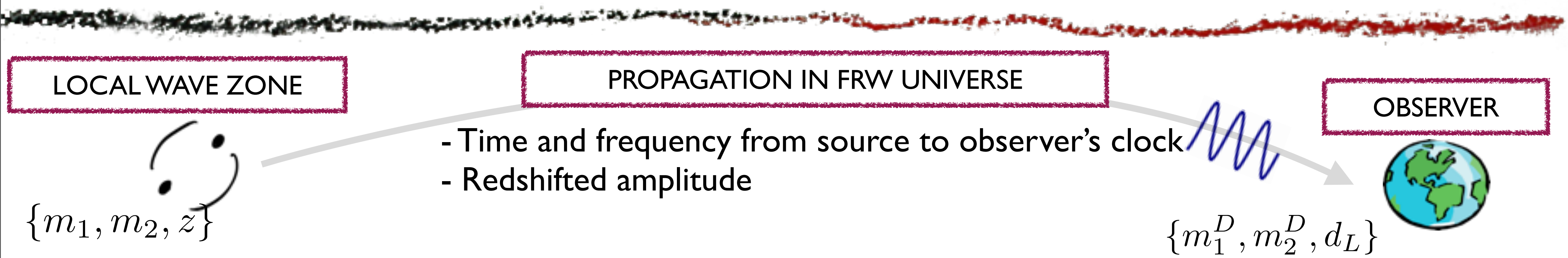
Gravitational-wave cosmology with dark sirens: state of the art and perspectives for 3G detectors

Michele Mancarella

Université de Genève & Gravitational Wave Science Center

Michele.Mancarella@unige.ch

COSMOLOGY WITH GWs



- DIRECT DISTANCE MEASUREMENT 😎 **"standard siren".** Modified beyond LCDM.

$$d_L^{\mathrm{GW}}(z) = \left[(1+z)\int_0^z \frac{\mathrm{d}z'}{H(z'; H_0, \Omega_{\mathrm{m}}, w_0, ...)}\right] \times \left[\Xi_0 + \frac{1-\Xi_0}{(1+z)^n}\right]$$

ELECTROMAGNETIC LUMINOSITY DISTANCE: MEASURE EXPANSION HISTORY

MODIFIED GW PROPAGATION: TEST GRAVITY

- DIRECT PROBE OF TENSOR PERTURBATIONS 😎

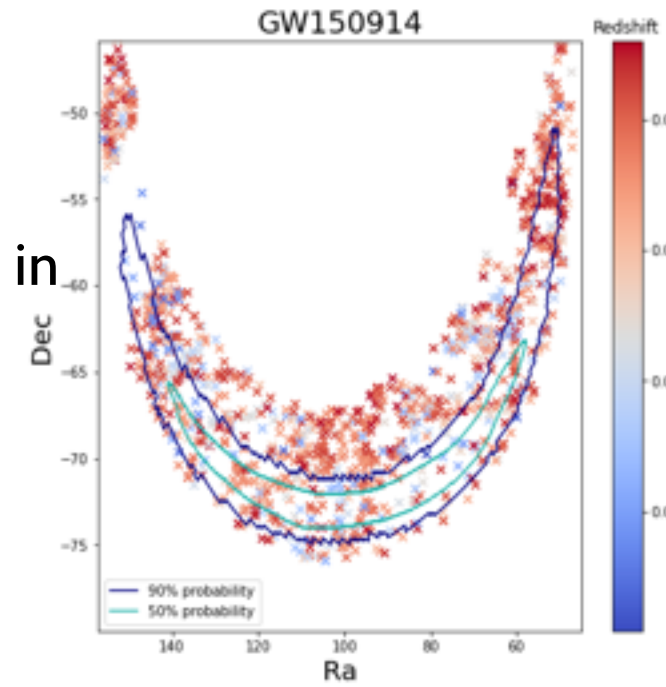
$$h''_A + [2 + \alpha_M(\eta)]\mathcal{H}h'_A + c^2k^2h_A = 0$$

- **NO REDSHIFT MEASUREMENT** 😩 Redshift reabsorbed in redefinition of the mass ("detector-frame" mass)

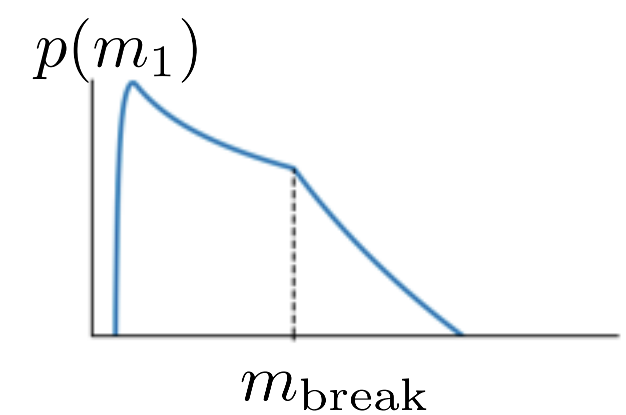
- COUNTERPARTS CAN BE CHALLENGING:
  - Expected for small fraction of sources (BNS); only 1.5/90 so far
  - More difficult to detect at high redshift, needed to test gravity (e.g. GW170817 dos not constrain Ξ_0).
  - Depend on EM experiments. GW170817 not likely to repeat soon. Other methods with GWs alone?

COSMOLOGY WITH DARK SIRENS

- "Population priors" add statistical information on the redshift. Methods applied to GWTC-3:
  - Statistically associate a host from a **galaxy catalog** using galaxies in the GW localization region *Schutz 1986*
    - GW side: good localization needed
    - Catalog incompleteness is the main limiting factor



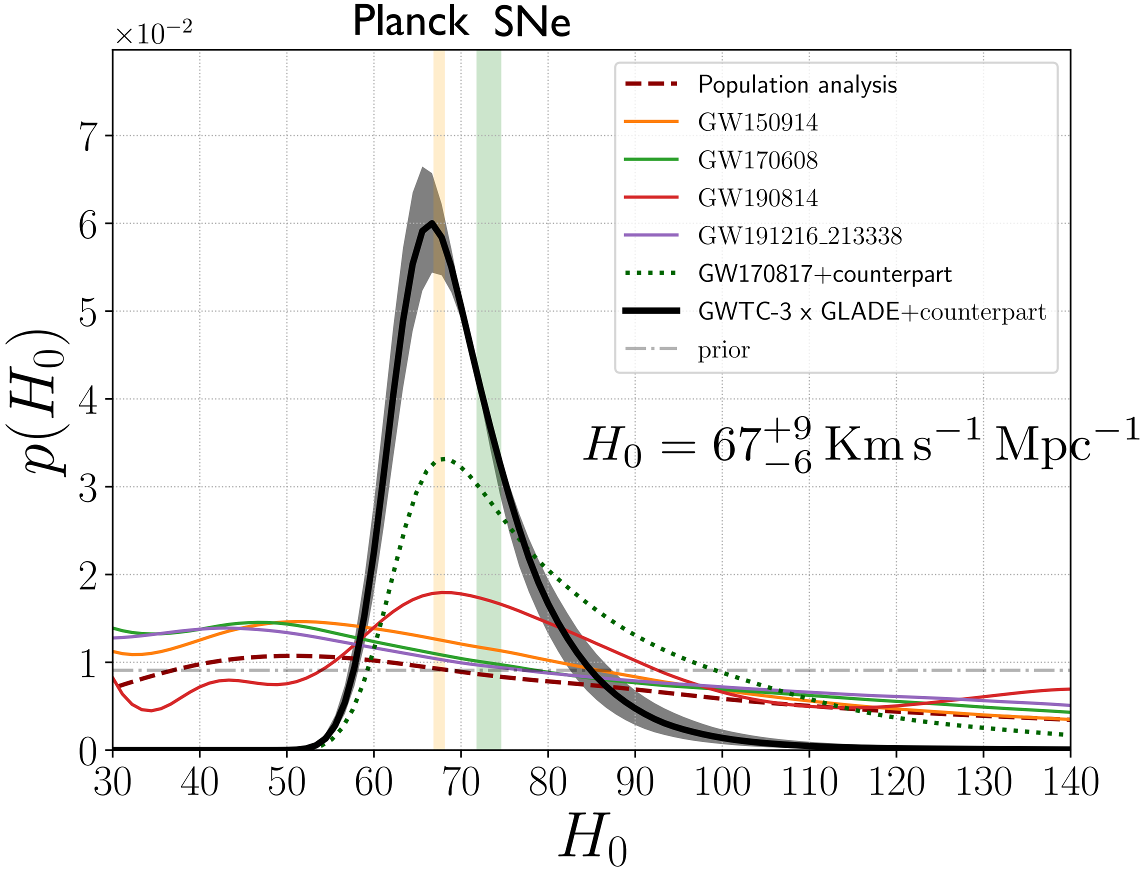
  - Features in the BBH **mass distribution** break mass-redshift degeneracy $m_i^D = m_i \times (1+z)$ *Farr, Fishbach, Ye, Holz 1908.09084*
    - PISN process imprints mass scale
    - Effect of Ξ_0 cumulates with redshift - changes shape of reconstructed merger rate evolution



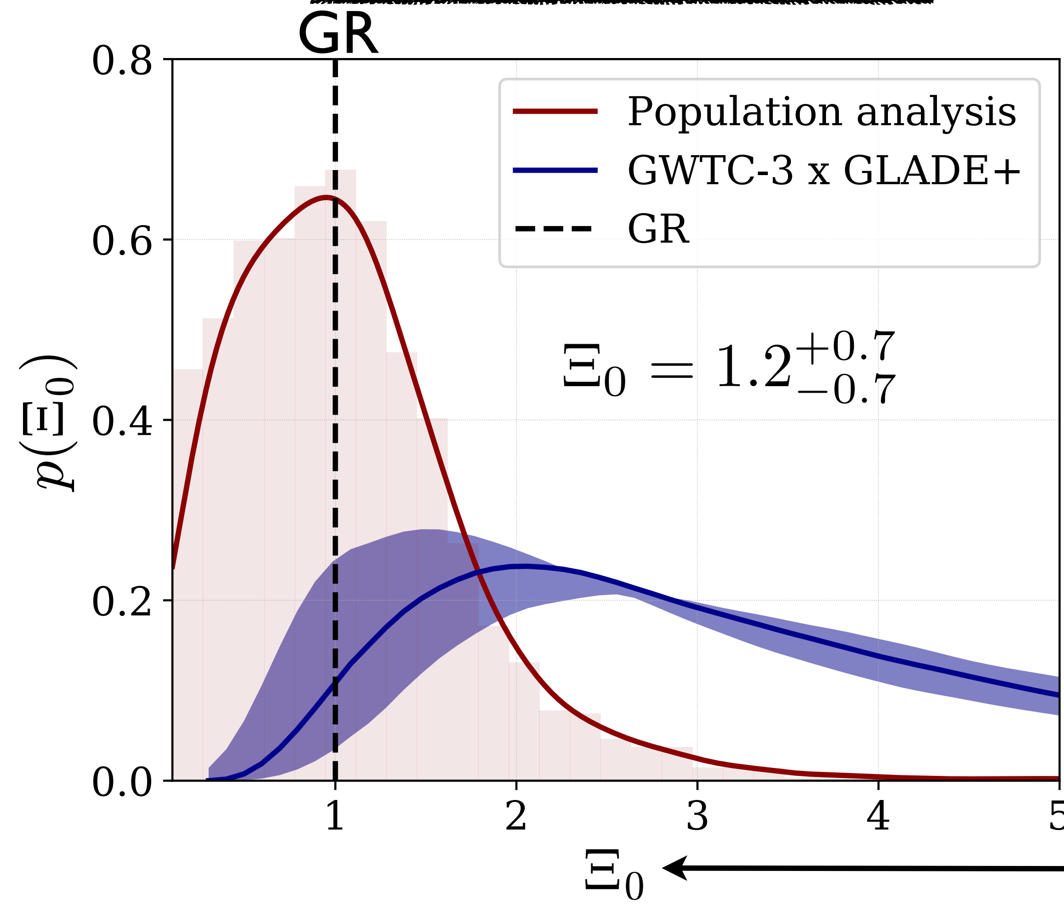
  - \+ many other methods proposed for 2-3G detectors
- Require to model population and cosmology together (**selection bias**)
- 2 independent pipelines: **https://github.com/CosmoStatGW/** *with Finke, Iacovelli @ University of Geneva*

COSMOLOGY WITH GWTC3: SUMMARY

H_0 fixing Ξ_0=1 (GR)



Ξ_0 fixing H_0 to Planck



- i) GWTC3 + BBH mass distribution

  PRD 105 (2022) 6 + code MGCosmoPop

  see also icarogw, Mastrogiovanni et al 2021; Leyde et al 2202.00025 , LVK 2111.03604

  - Joint cosmo+population inference. Mass scale around 35-40 solar masses detected and marginalized
  - Best bound on Ξ_0

- ii) GWTC3 + galaxy catalog

  JCAP 08 (2021) 026 + code DarkSirensStat
  Proceedings Moriond 2022, 2203.09238

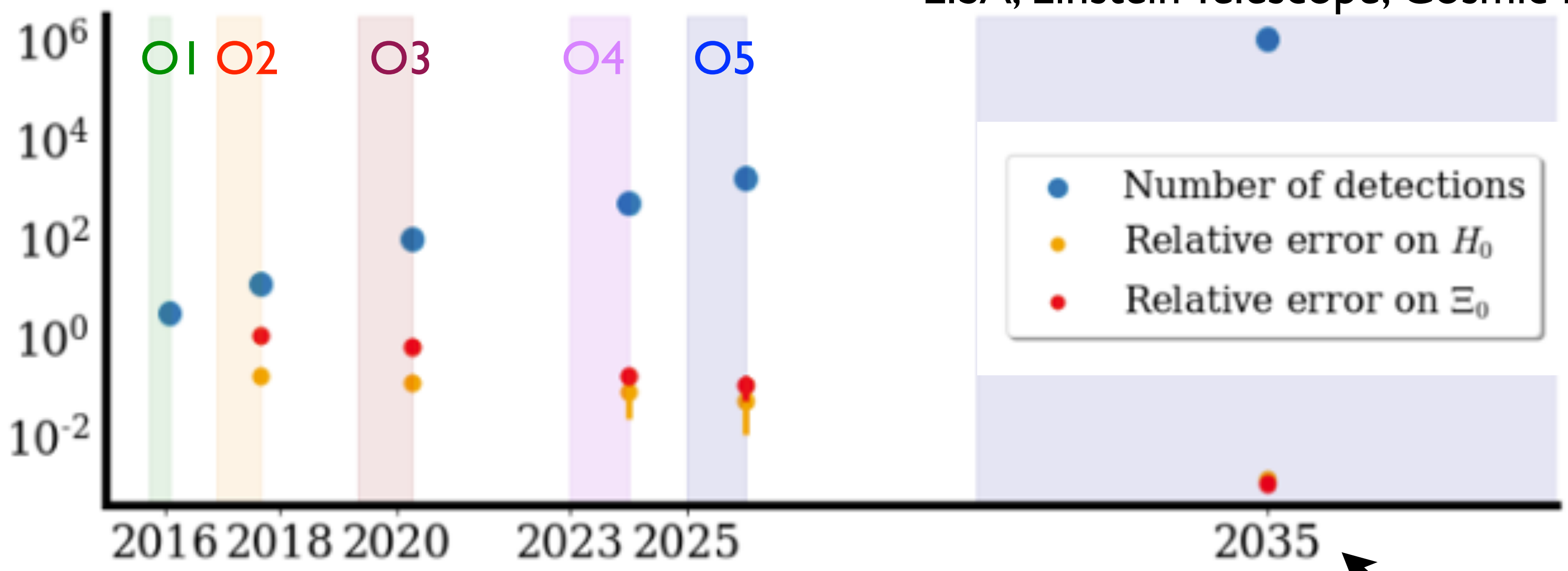
  see also gwcosmo Gray et al 2019-2022

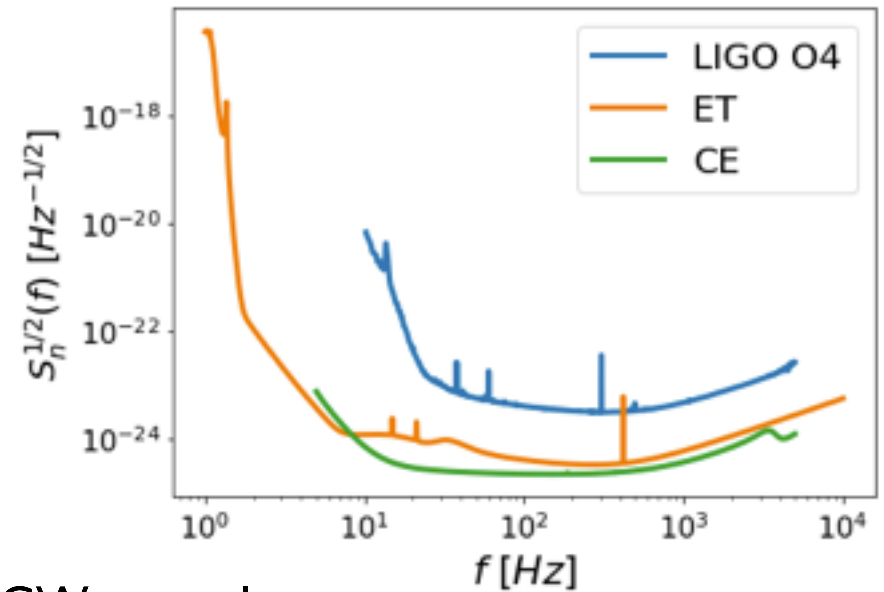
  - Corrected for incompleteness of the galaxy catalog
  - Selection effects: select GW events in complete regions
  - Population fixed at best fit from step i), systematic uncertainty in grey

PERSPECTIVES

LIGO-Virgo-Kagra

LISA, Einstein Telescope, Cosmic Explorer





Proof-of-principle level.
Astrophysical systematic uncertainty<statistical uncertainty

Astrophysical systematic uncertainty~statistical uncertainty

Precision GW cosmology.

- Next generation: high precision measurements for a large number of sources (not the case for 2G).
- Scalable, fast and reliable forecast tools needed NOW for the science cases

gwbench - Borhanian 2020
gwfish - Harms + 2022
gwfast - Iacovelli + 2022

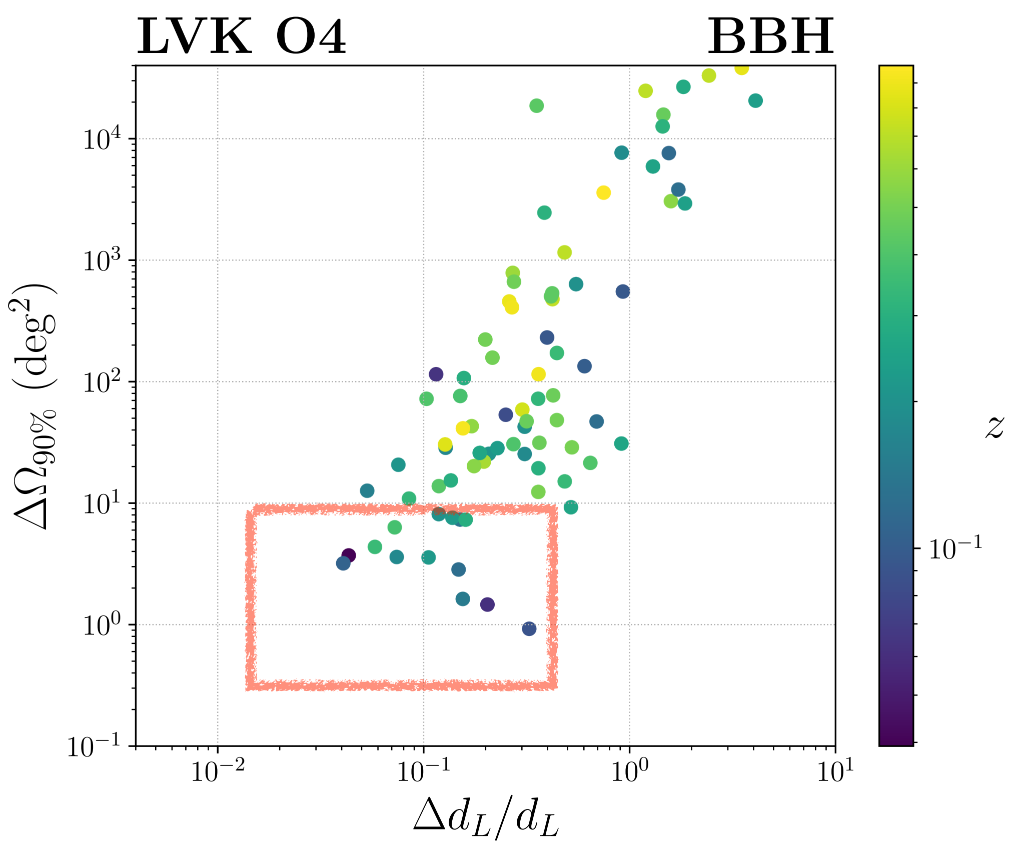
- **GWFAST**: a Fisher forecast code for 3G detectors **https://github.com/CosmoStatGW/gwfast**
  - Fast, scalable, parallelizable - automatic differentiation in jax
  - Vectorized LAL waveforms in python
  - Includes rotation of the Earth

on the arXiv today !

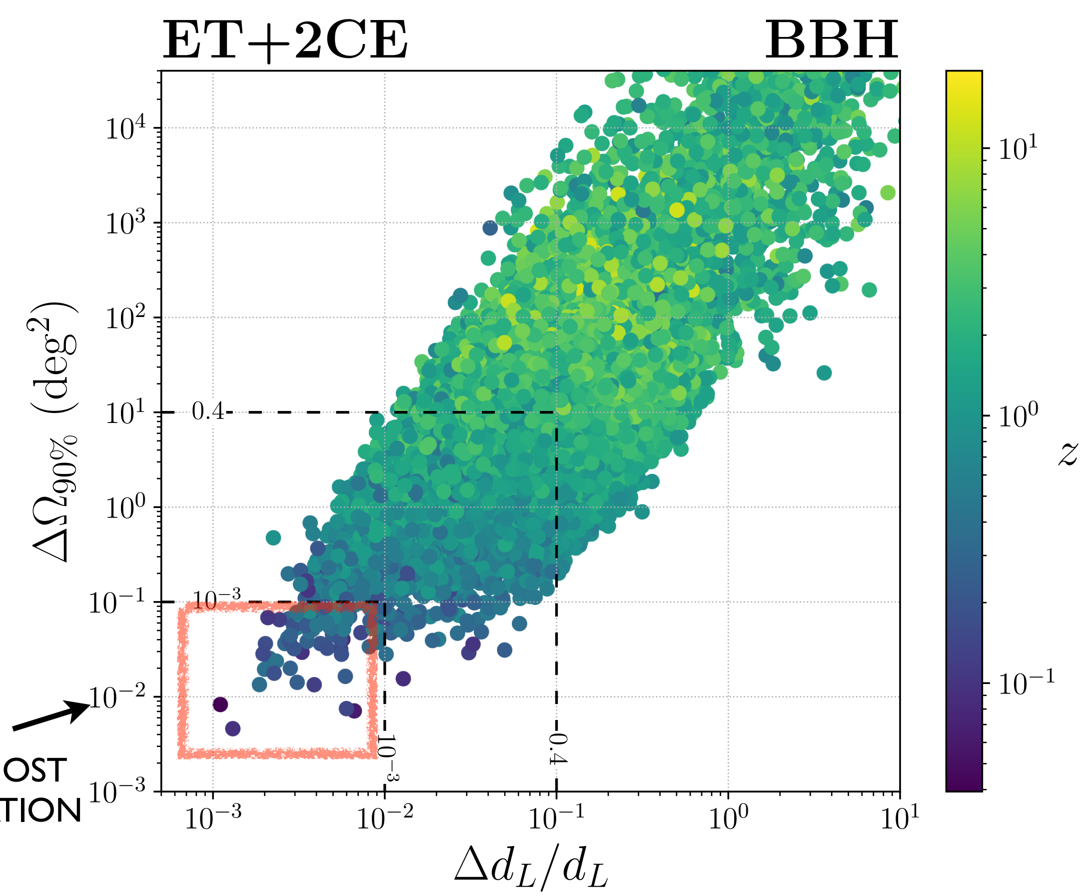
with Iacovelli, Foffa, Maggiore

LOCALIZATION AT 2G AND 3G FORECASTED WITH GWFAST

- **BBHs**: up to O(10^5)/year



on the arXiv today !
Iacovelli, Mancarella, Foffa, Maggiore

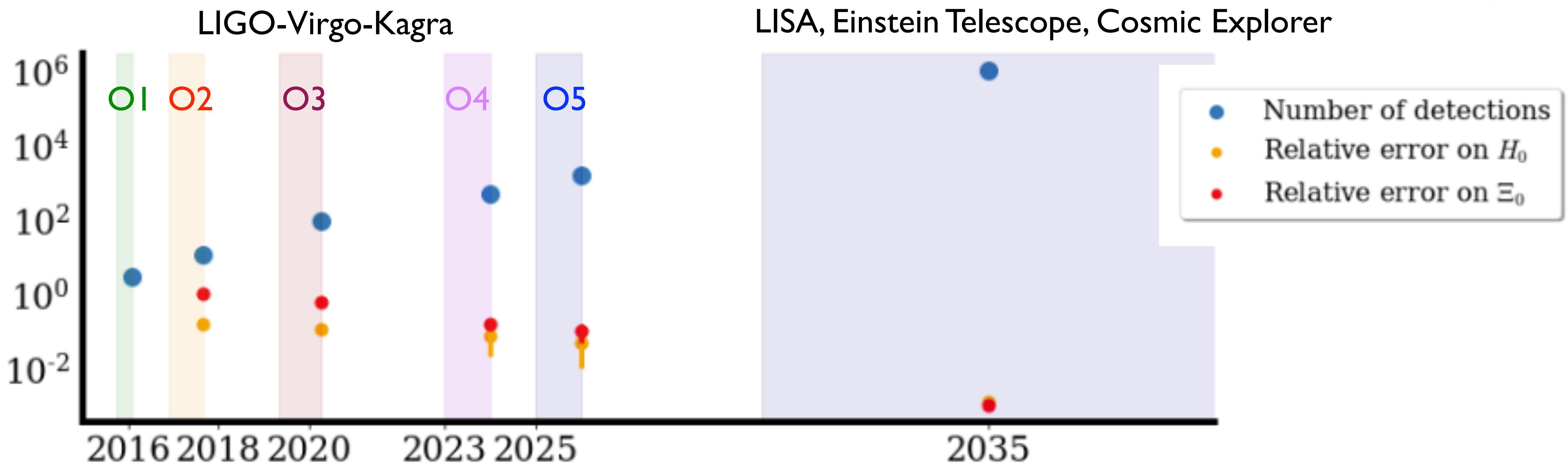


ALLOW UNIQUE HOST GALAXY LOCALIZATION

- **BNS**: O(10^5-10^6)/year. Can stay in the detection band for long time - rotation of the Earth improves localization

BNS					
Network	Detected	Analysed	SNR $\geq$ 30	$\Delta d_L/d_L \leq 10\%$	$\Delta\Omega_{90\%} \leq 100\,\mathrm{deg}^2$
LVK–O4	4	3	0	1	1
ET	9577	7532	770	9	29
ET+2CE	40107	35029	5289	1678	27704

CONCLUSIONS



- 2018-2021. First applications of statistical methods to modified GW propagation (+Hubble). No deviations from GR (but nothing conclusive). Independent codes.
- 2018-2021. Challenges: interplay with astrophysics, computational cost. Turn systematics into statistical uncertainty.
- Next generation: Different sources available with large rates. Precision GW cosmology. Need adequate statistical analysis tools (accurate, scalable, fast), both for forecasts and analysis
- GWs=unique distance tracers. New cornerstone of precision cosmology.

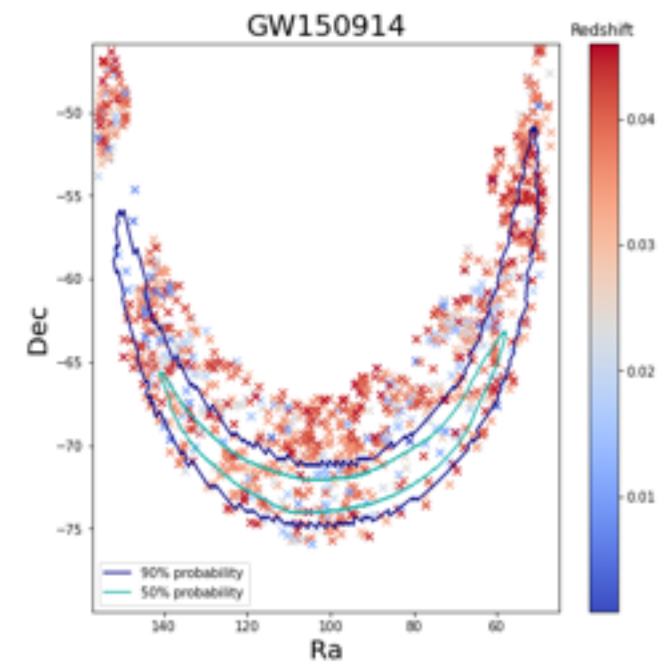
https://github.com/CosmoStatGW/

SUPPLEMENTARY SLIDES

INFORMATION FROM A GALAXY CATALOG

- Statistically associate potential host to all galaxies in the localization region

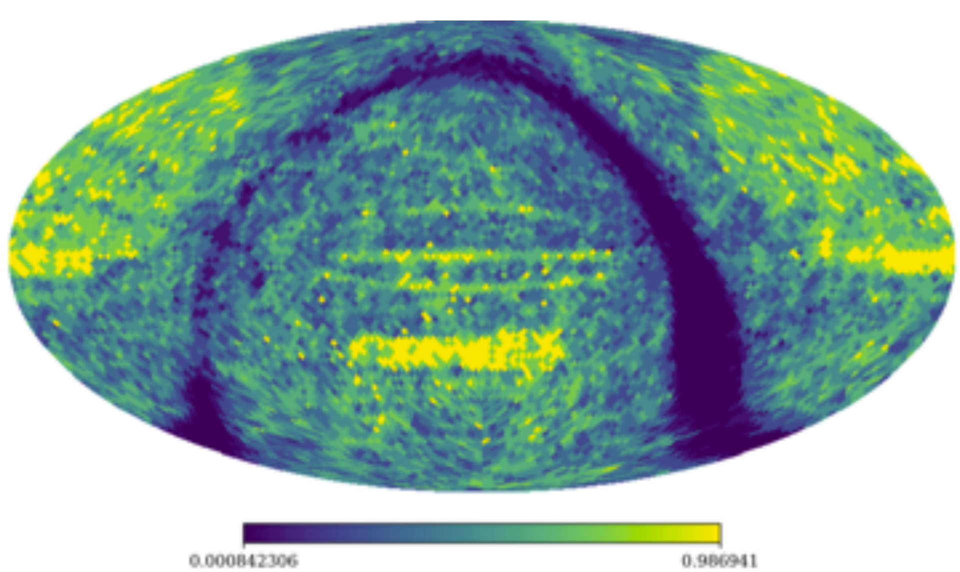
Schutz 1986

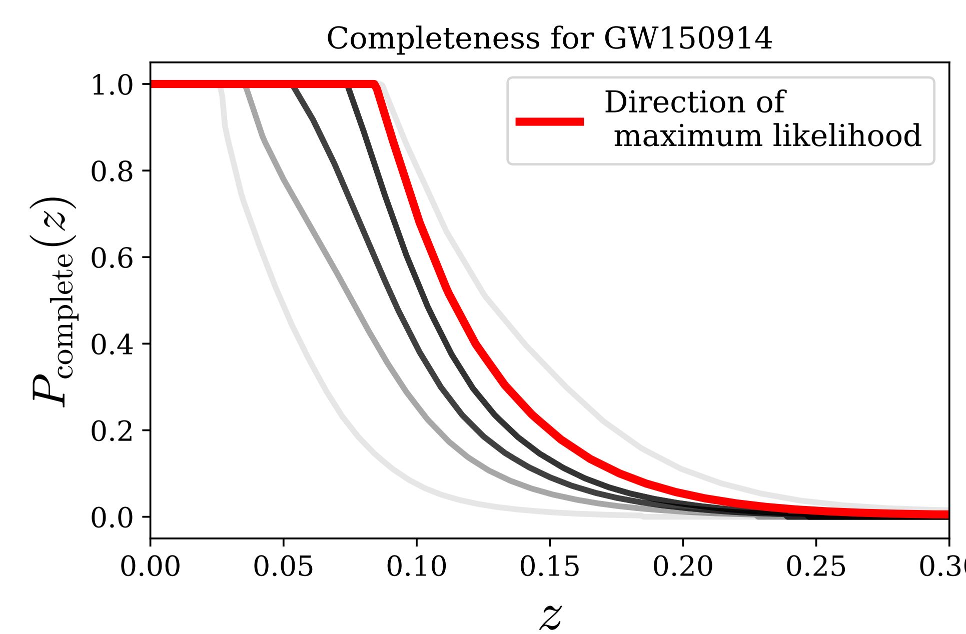


- GW side: good localization needed
- Catalog **incompleteness** is the main limiting factor
- Knowledge of **astrophysics** - BBH population used in evaluating selection effects
- GW+galaxy catalog code including modified GW propagation: **https://github.com/CosmoStatGW/DarkSirensStat**
  - Completeness: include angular dependence
  - Selection effects: include possibility of selecting GW events in complete regions

Finke, Foffa, Iacovelli, Maggiore, MM 2101.12660

see also gwcosmo Gray et al 2019-2022





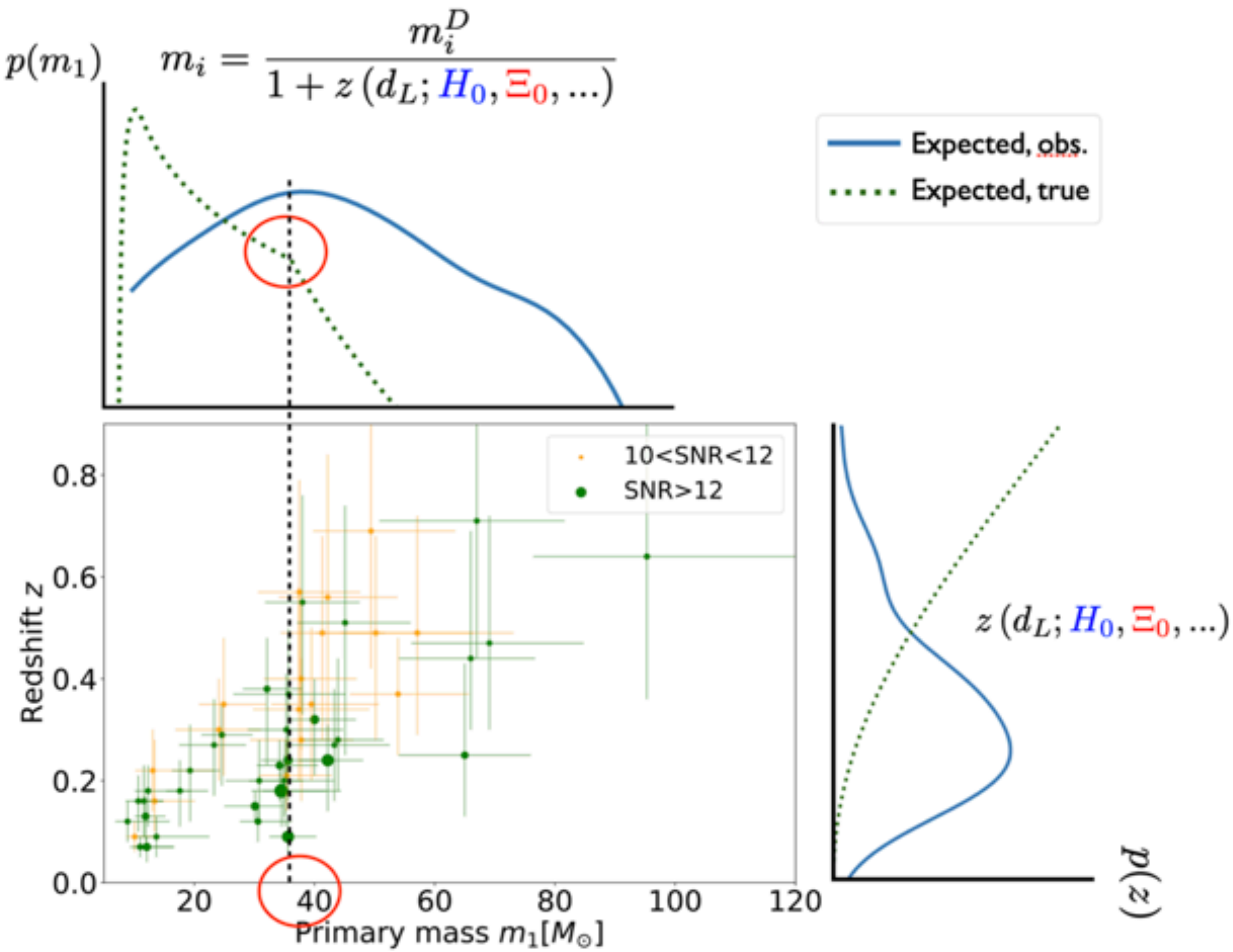
INFORMATION FROM BBH MASS DISTRIBUTION

- Use information on the **source frame mass:** features in the mass distribution

$$m_i^D = m_i \times (1+z)$$

$$d_L^{\rm GW}(z; H_0, \Xi_0, \ldots)$$

Farr, Fishbach, Ye, Holz 1908.09084



- Pair Instability SuperNova (PISN) process imprints a mass scale
- Joint population and cosmological inference
- Effect of Ξ_0 cumulates with redshift - changes shape of reconstructed merger rate evolution/shifts mass scale differently
- Hierarchical bayesian inference code including modified GW propagation:

https://github.com/CosmoStatGW/MGCosmoPop

PRD 105 (2022) 6 with *Genoud-Prachex, Maggiore*

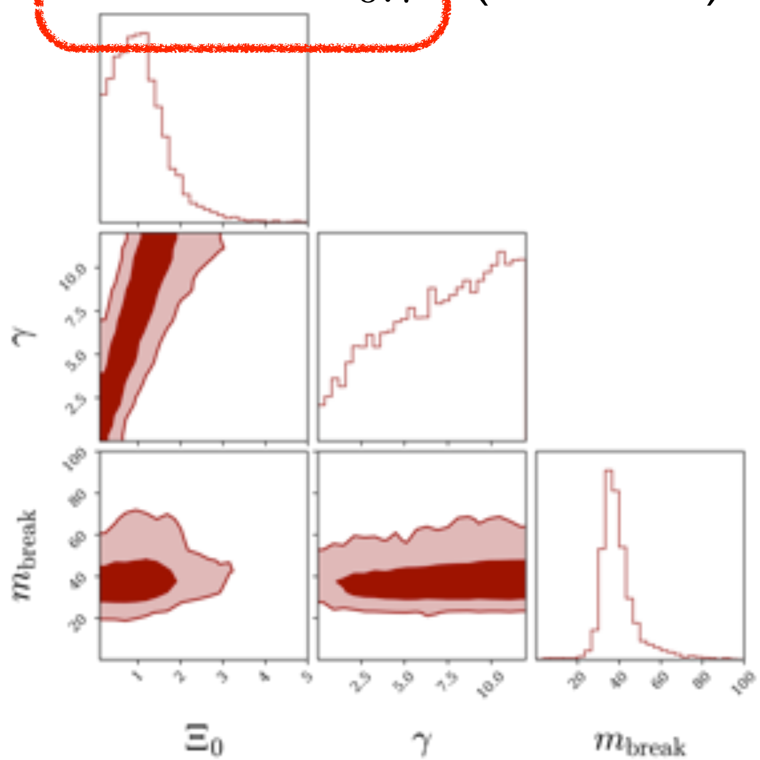
see also icarogw, Mastrogiovanni et al 2021

COSMOLOGY WITH GWTC3 (I)

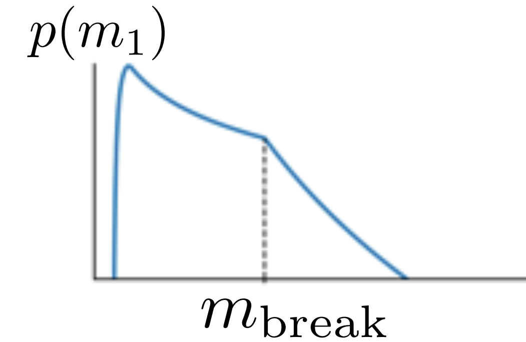
PRD 105 (2022) 6 with *Genoud-Prachex, Maggiore + code MGCosmoPop*

- Always 2 separate cases: (i) Ξ_0 fixing H_0 , (ii) H_0 fixing $\Xi_0 = 1$ (GR)
- Step 1: GWs + population model

$\Xi_0 = 1.2^{+0.7}_{-0.7}$ (=1 in GR)

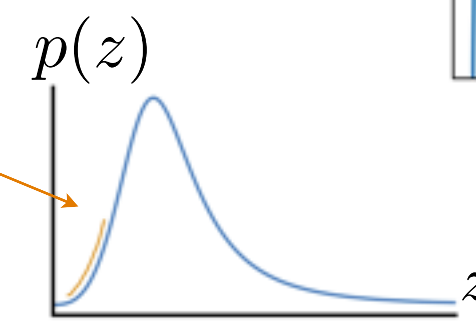


- "Broken power law" mass distribution



- Madau-Dickinson rate

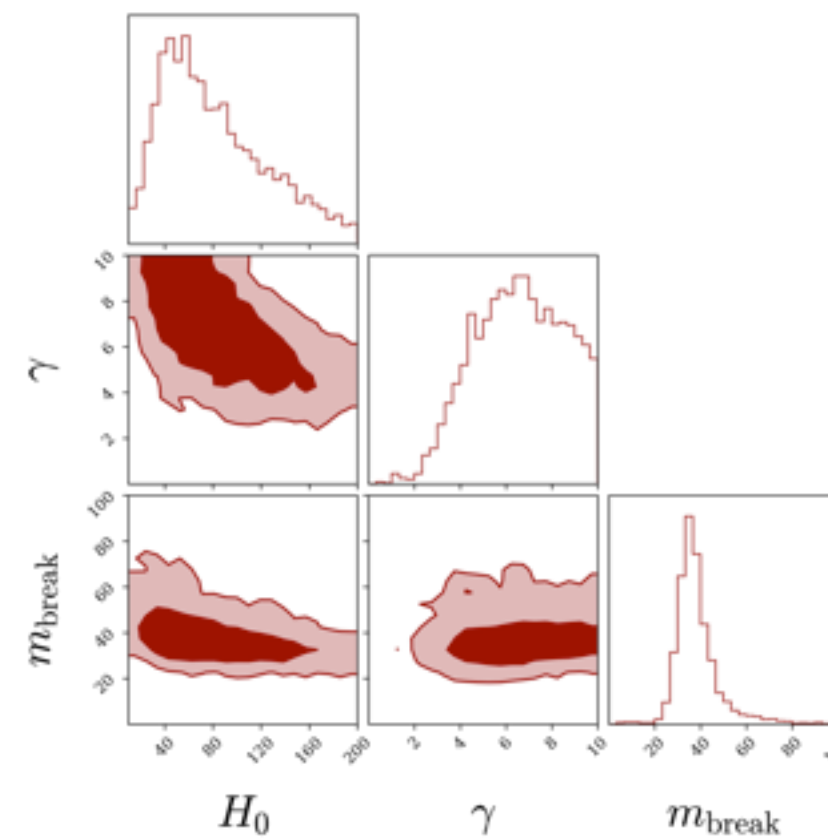
$$R(z) \propto (1+z)^{\gamma}$$



- 35 events with SNR>12 (robust to inclusion/ exclusion of GW190521)
- Constraint driven by mass scale
- Large effect on reconstruction of merger rate

see also Leyde et al 2202.00025 , LVK 2111.03604

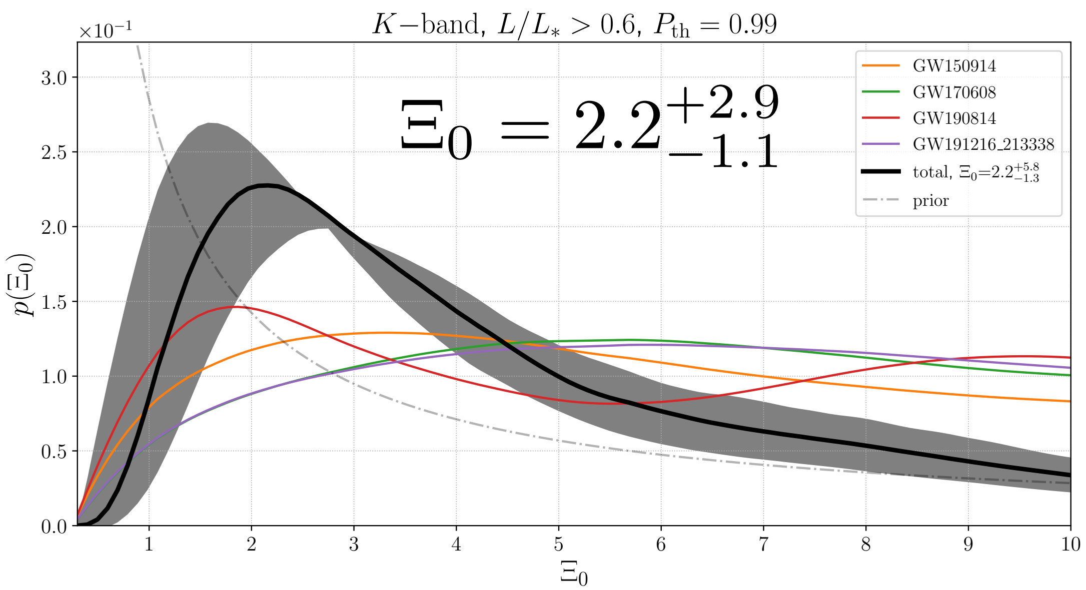
$$H_0 = 50^{+53}_{-26}\,{\rm km\,s^{-1}\,Mpc^{-1}}$$

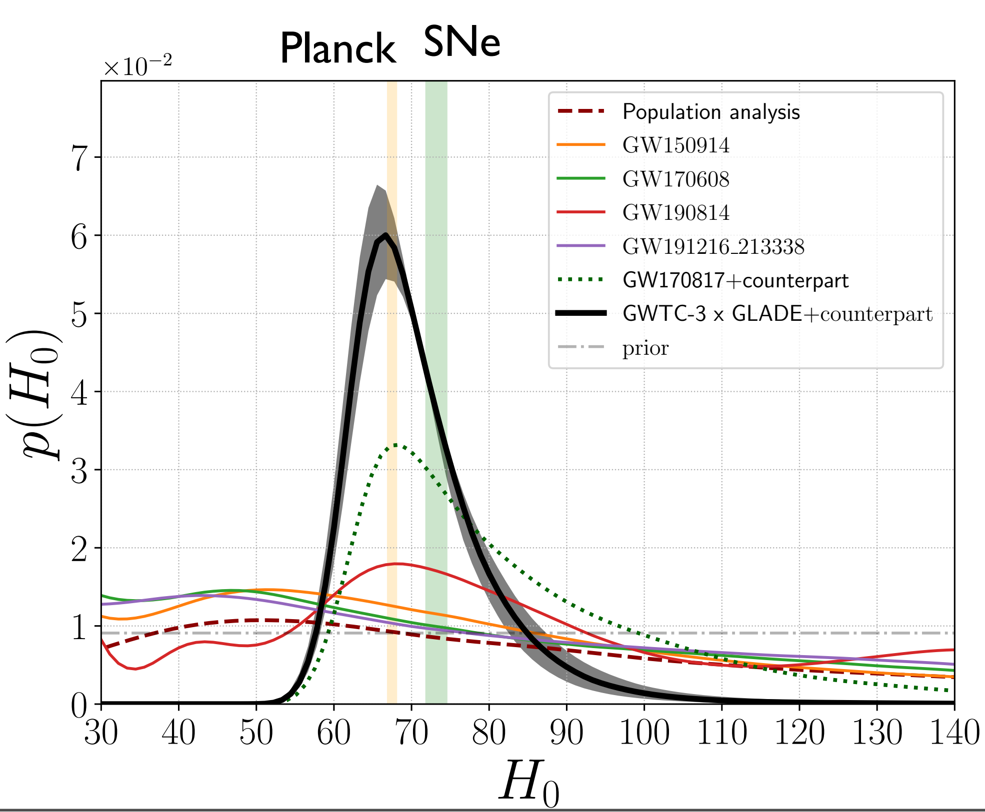


COSMOLOGY WITH GWTC3 (II)

JCAP 08 (2021) 026 with Finke, Foffa, Iacovelli, Maggiore+ code DarkSirensStat
Proceedings of Moriond 2022, 2203.09238

- Always 2 separate cases: (i) Ξ_0 fixing H_0, (ii) H_0 fixing $\Xi_0 = 1$ (GR)
- Step 2: GWs + galaxy catalog





- GLADE+ catalog, K-band luminosity weights, only events with position at 100% completeness
- Only one parameter free, otherwise too computationally expensive
- Selection effects: use population model as determined by step 1, <u>uncertainty treated as systematic</u> (gray band)
- Counterpart dominates constraint on H_0, useless for Ξ_0 (too low redshift)

(ask me later for an interesting story about a second candidate counterpart and modified GW propagation...)

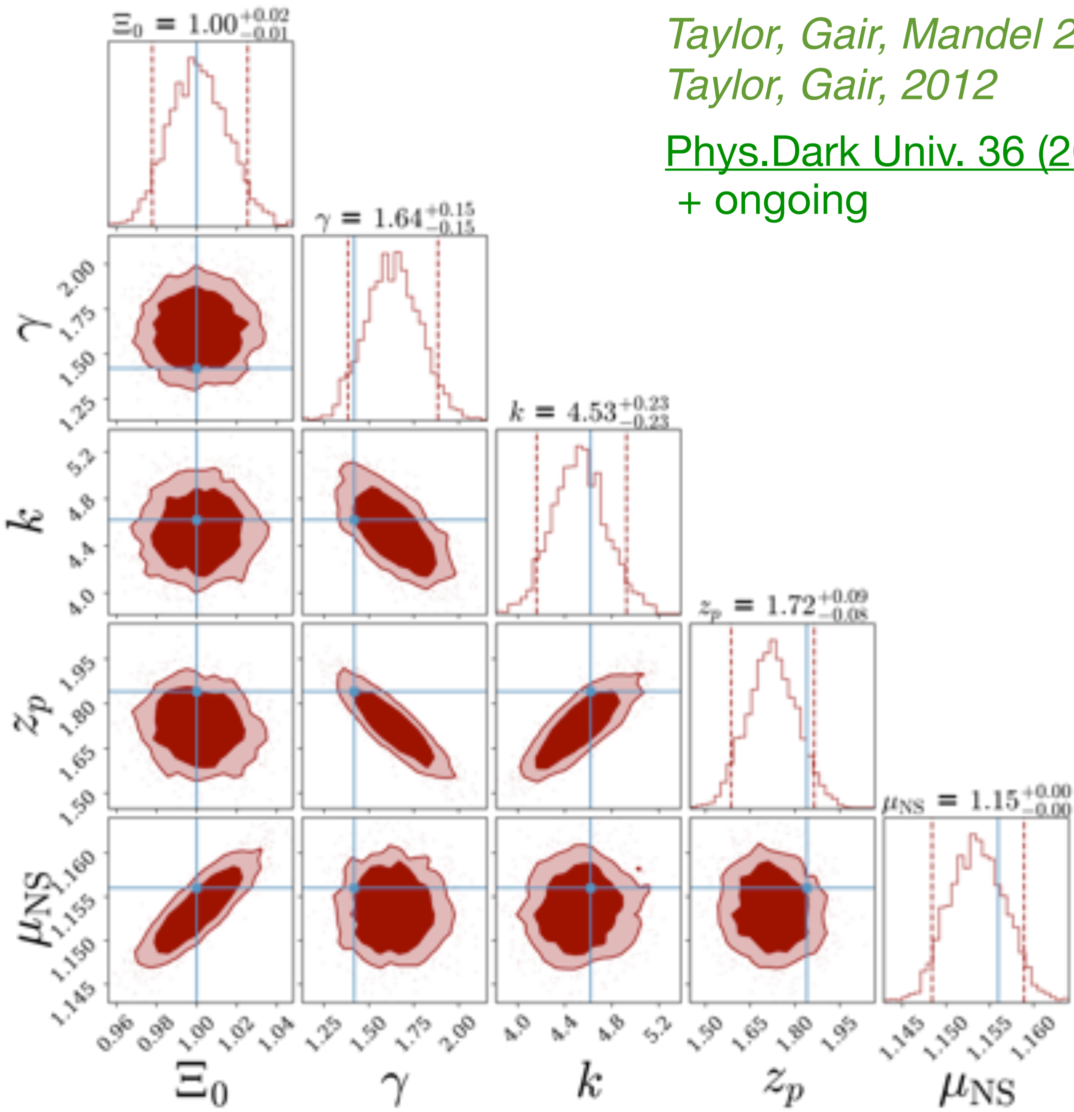
$$H_0 = 67^{+9}_{-6}\,\mathrm{Km\,s^{-1}\,Mpc^{-1}}$$

see also LVK 2111.03604

COSMOLOGY WITH THE BNS MASS FUNCTION

Taylor, Gair, Mandel 2011
Taylor, Gair, 2012

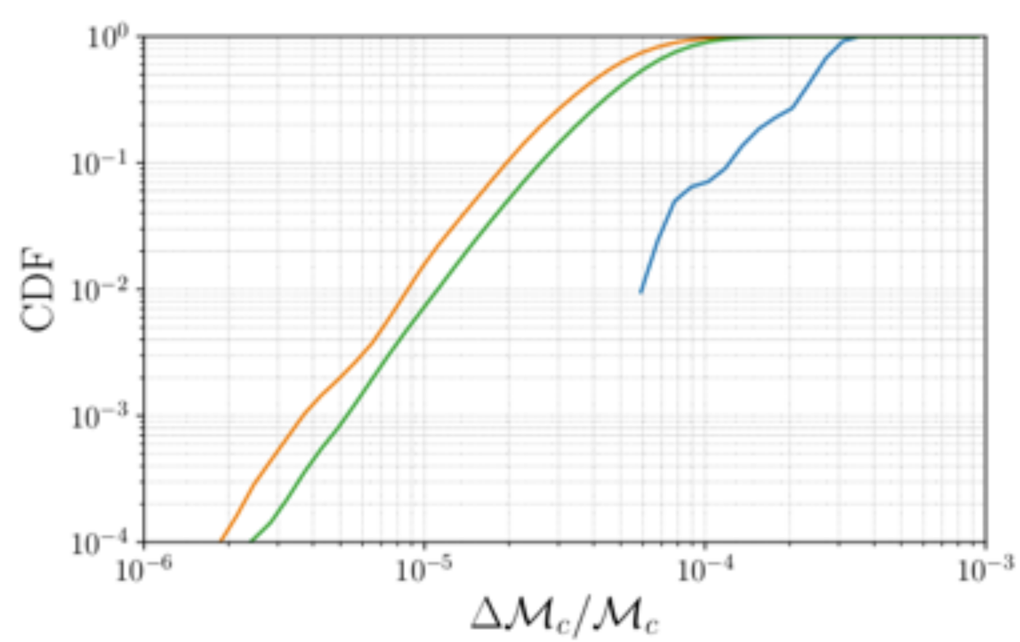
Phys.Dark Univ. 36 (2022) 100994/proceedings of Moriond 2022 with Finke, Foffa, Iacovelli, Maggiore
+ ongoing

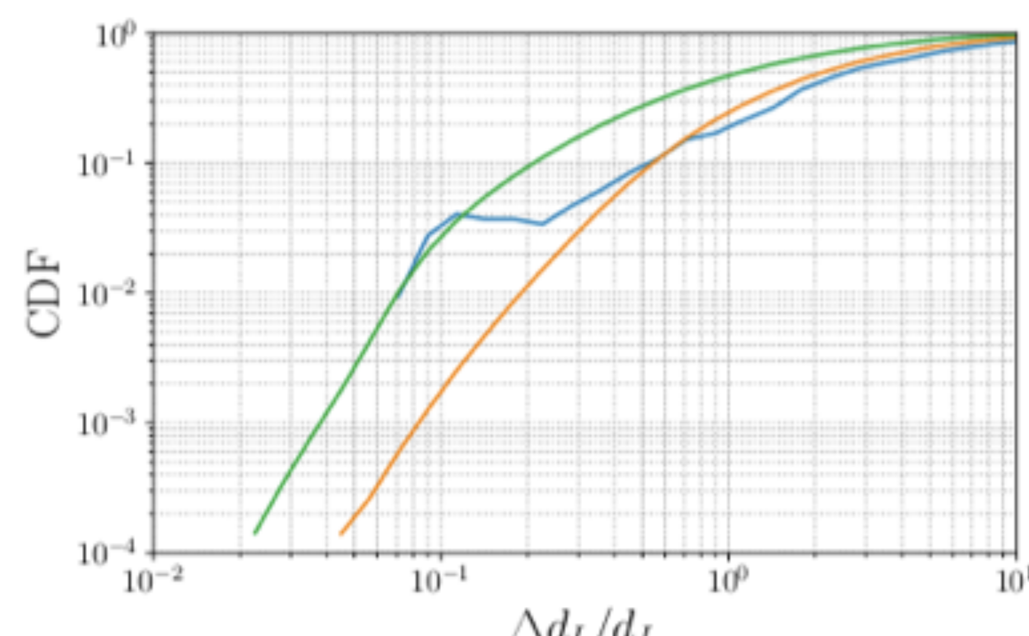


- NS mass function is narrow and (hopefully) less subject to evolution wrt BBH mass distribution.
- ET will detect many with small error on the mass

$$m_i^D = m_i \times (1+z)$$

$$d_L^{GW}(z; H_0, \Xi_0, ...)$$





OTHER METHODS

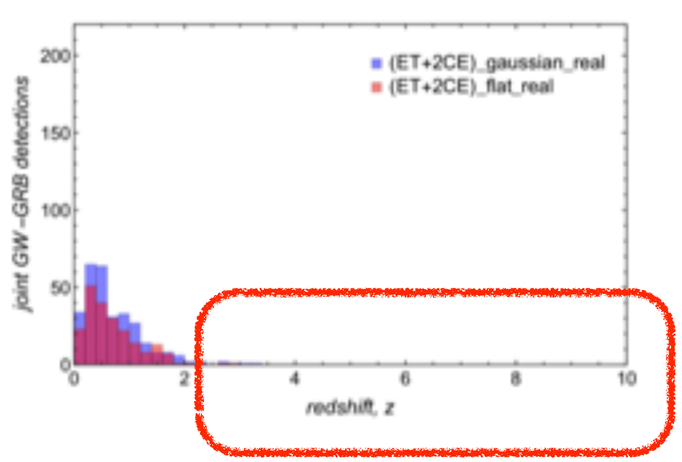
- Many other methods proposed
  - Tidal effects in NS — *Messenger, Read 2011*
  - Clustering information — *Mukherjee et al, 2019, (applied in Mukherjee et al, 2022)*
  - Spin-induced precession in NS-BH — *Vitale & Chen 2018*
  - Rate evolution — *Fishbach et al, 2021*
  - Strong lensing — *Hannuksela et al. 2019; Finke, Foffa, Iacovelli,Maggiore, MM 2021*
  - BNS mass distribution — *Taylor, Gair, Mandel 2011; Finke, Foffa, Iacovelli,Maggiore, MM 2021*
  - Fraction of AGN flares — *Palmese et al 2021*

- Combination of techniques? E.g. use full mass spectrum (BNS+BBH) — *Ezquiaga & Holz 2022*

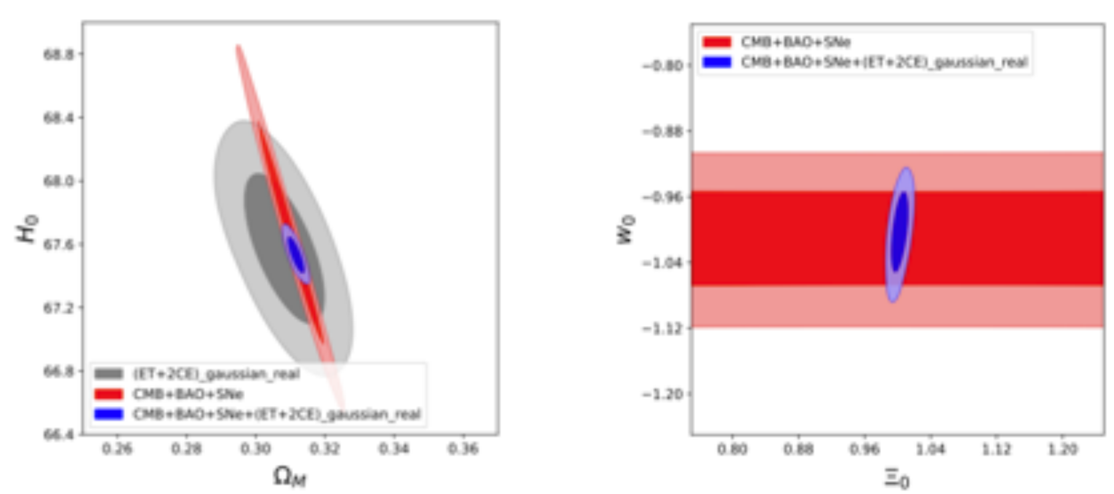
- Don't forget counterparts. BUT: difficult to forecast detection rates; depend crucially on status of EM experiments. More challenging for testing gravity. Detection rates of dark sirens so high that they could be as significant as bright sirens.

Belgacem et al 1907.01487 (BNSs + GRBs)

O(100)/yr IF Theseus is operational ?



Still -% constraints

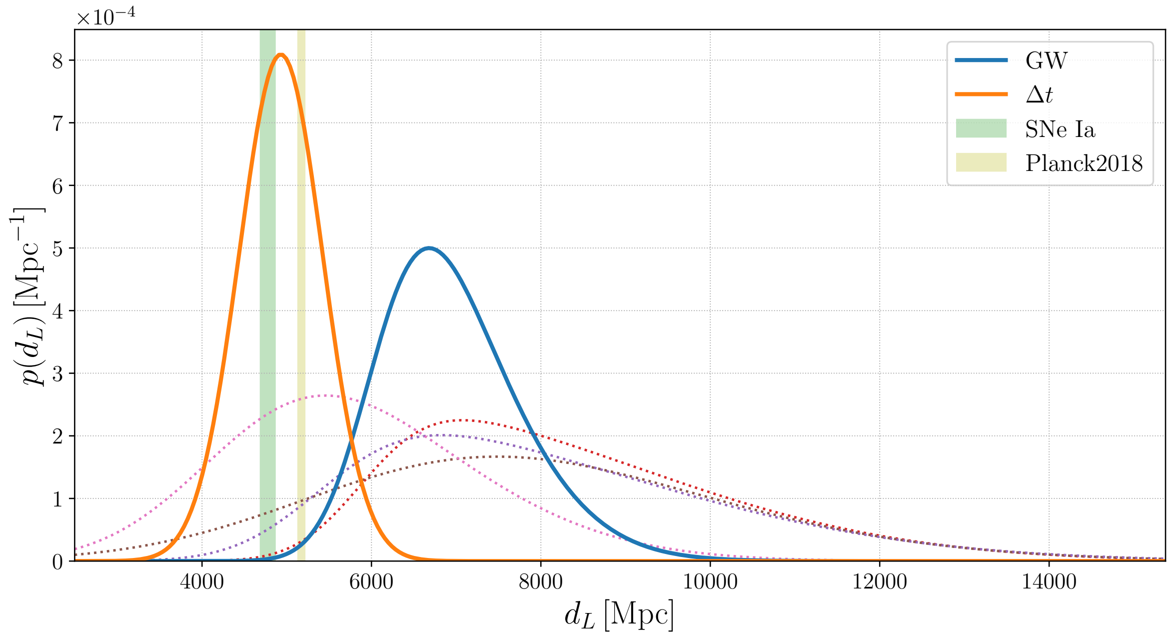


see Ronchini + 2204.01746 for extensive updated study

STRONGLY LENSED EVENTS: STANDARD SIRENS WITHOUT COUNTERPARTS

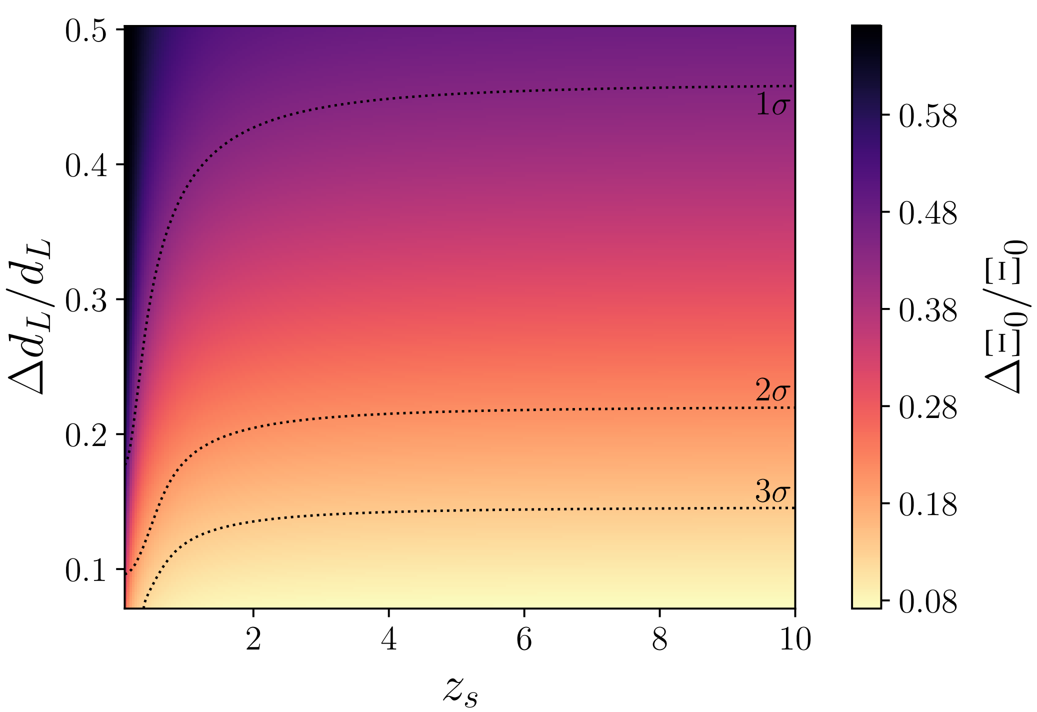
PRD 104 (2021) 8, 084057 with Finke, Foffa, Iacovelli, Maggiore

- Quadruply lensed GW events allow reconstruction of source-lens system   Hannuksela et at 2004.13811

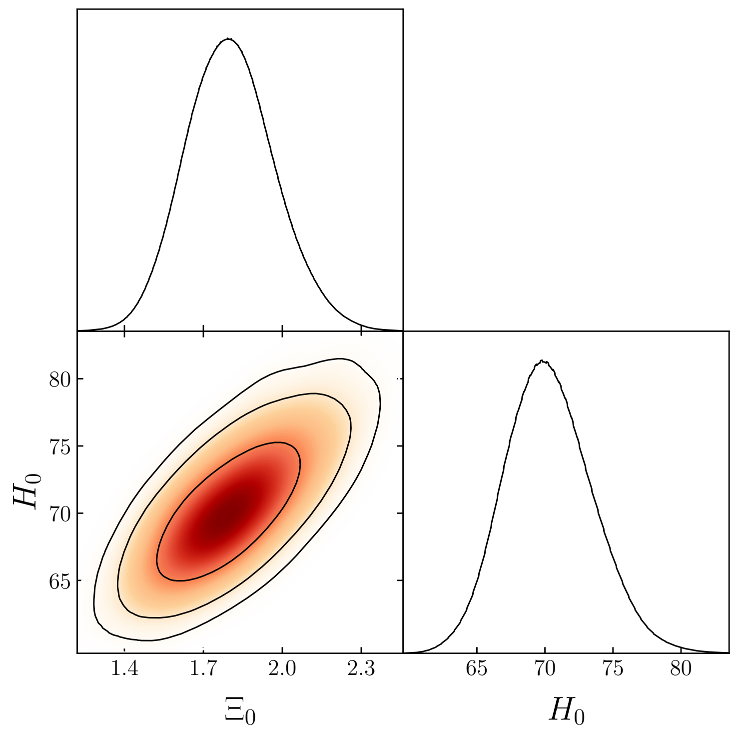


- Can localize GW source to a few galaxies with EM follow-up...
- ..but this is also a standard siren giving 1+4 distance estimates at the same time:
  - time delays give EM luminosity distance
  - GW images give GW luminosity distance

Can test GR (with only one good event !)...



... without external prior on H_0



SELECTION BIAS - AN ILLUSTRATION

$$p(\Lambda|\mathcal{D}_{GW}) \propto \pi(\Lambda) N_{det}(\Lambda)^{N_{obs}} e^{-N_{det}(\Lambda)} \prod_{i=1}^{N_{obs}} \frac{\int d\theta_i \mathcal{L}(\mathcal{D}_{GW}|\theta_i) p_{pop}(\theta|\Lambda)}{\beta(\Lambda)}$$

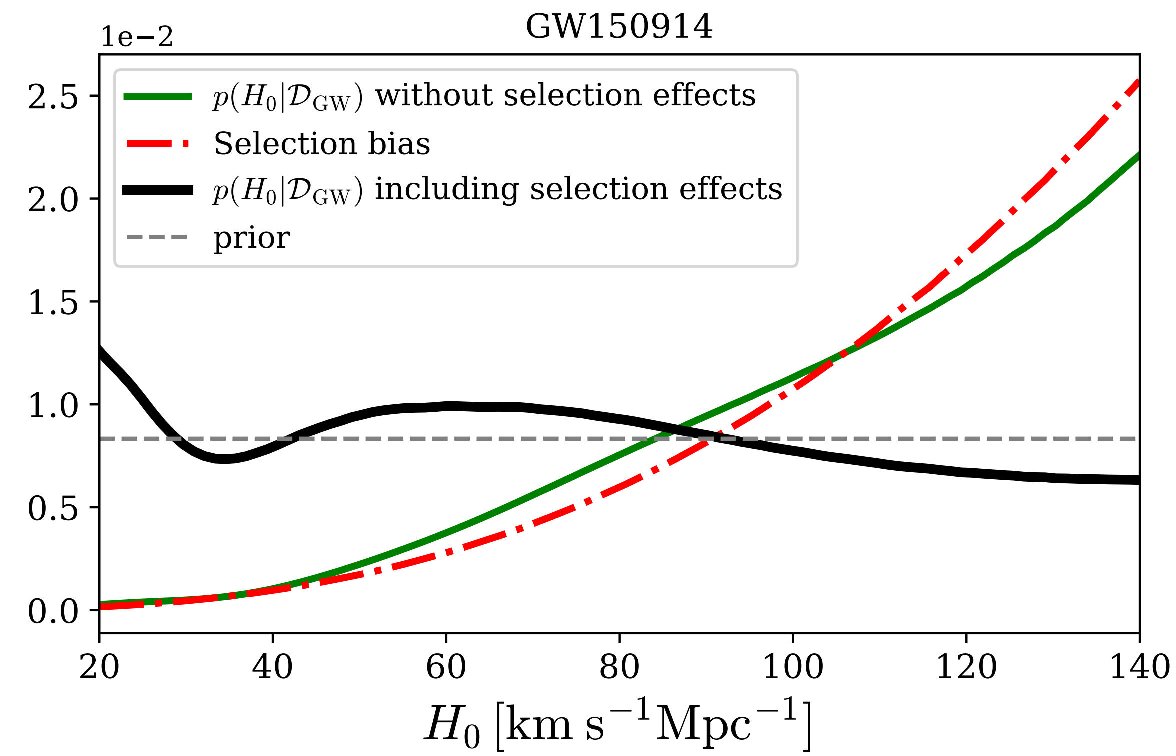
- Physical meaning: $\beta(\Lambda)$ = fraction of expected events detected at given Λ

Mandel, Farr, Gair '19

$d_L \sim \frac{z}{H_0}$

for event @ true redshift z, increasing H_0 moves it *closer* to us, making it easier to observe !

Detecting higher correlation at high H_0 is just a consequence of selection bias: nearby events are easier to observe
Biased result if this is not accounted for.

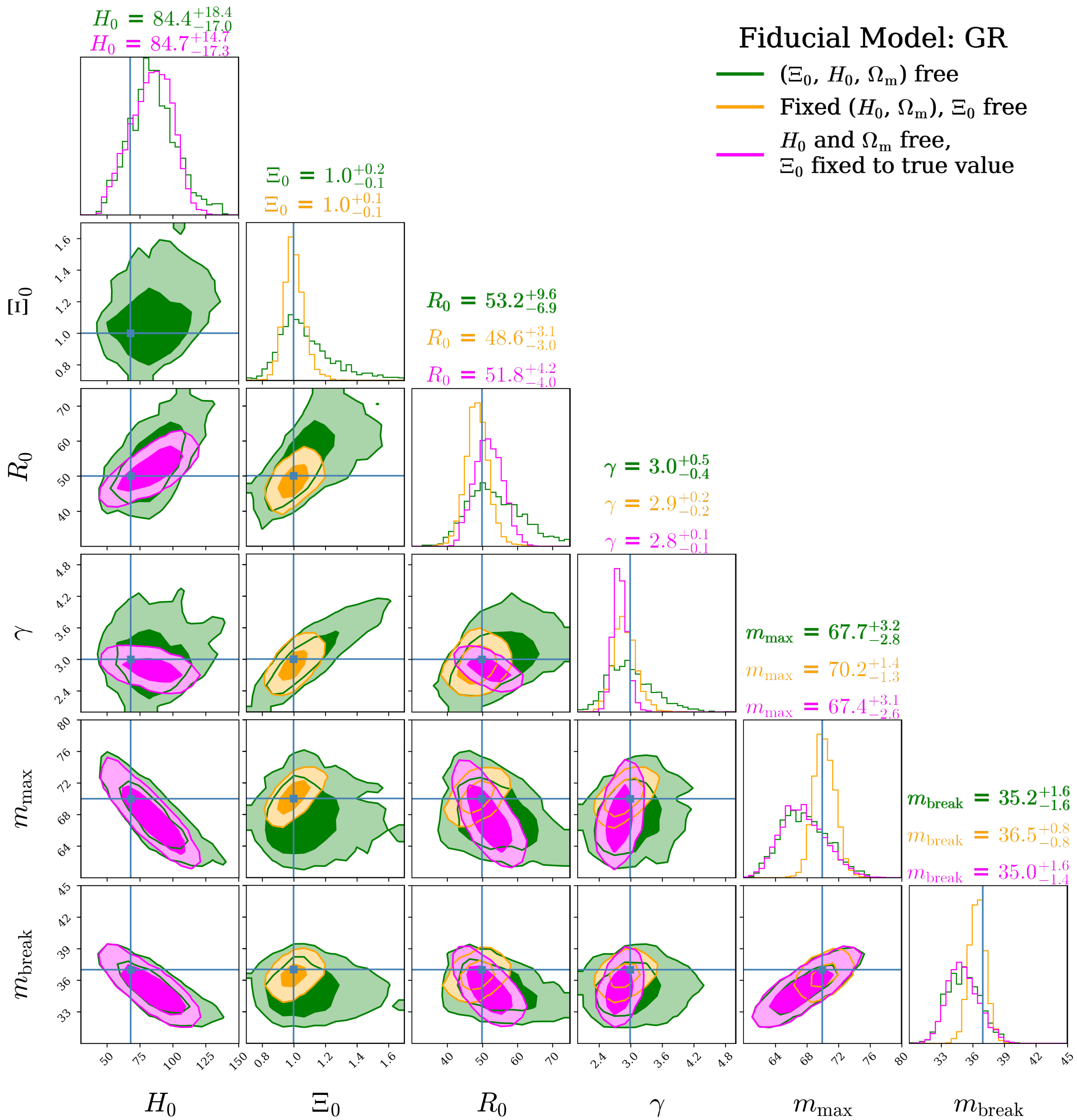


- Evaluation:
  - generate mock events from *reference population* (*source* mass+redshift distribution)
  - check how many events are detected by the experiment (SNR>8)
  - compute fraction of detected events

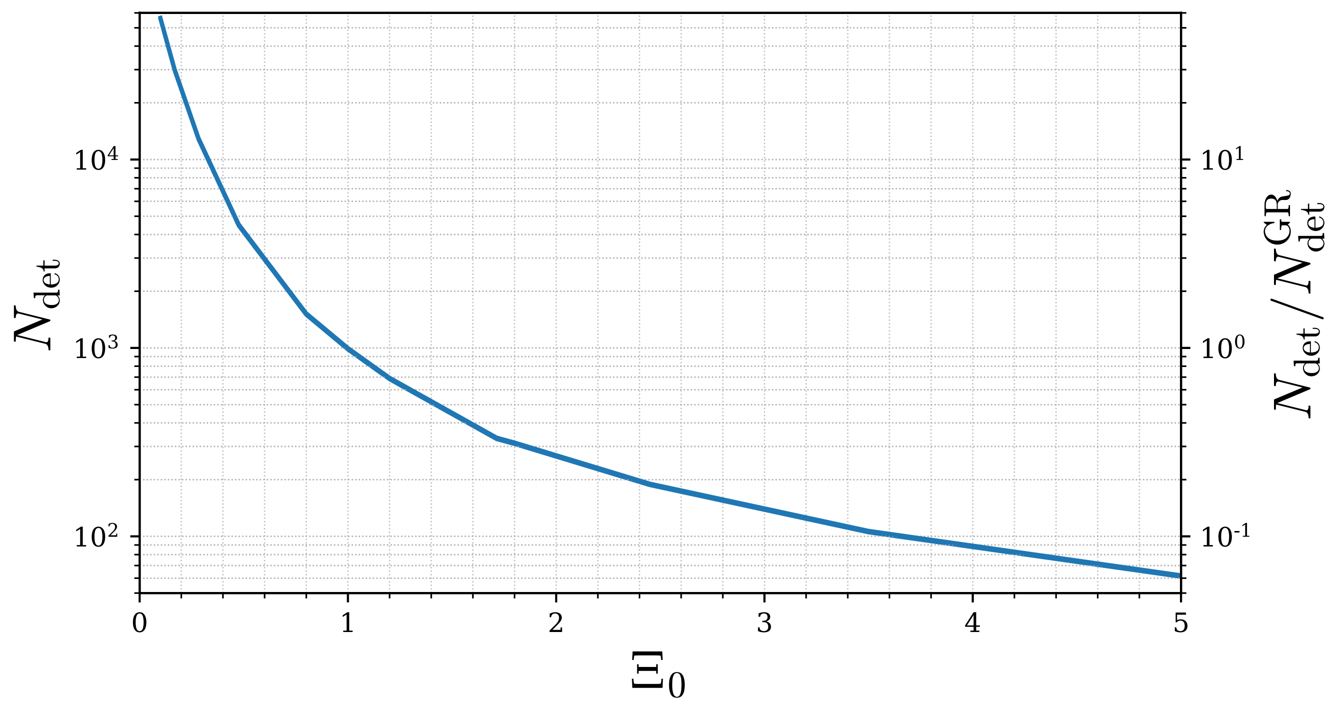
- Need to know population or infer it simultaneously

FORECASTS FOR O5

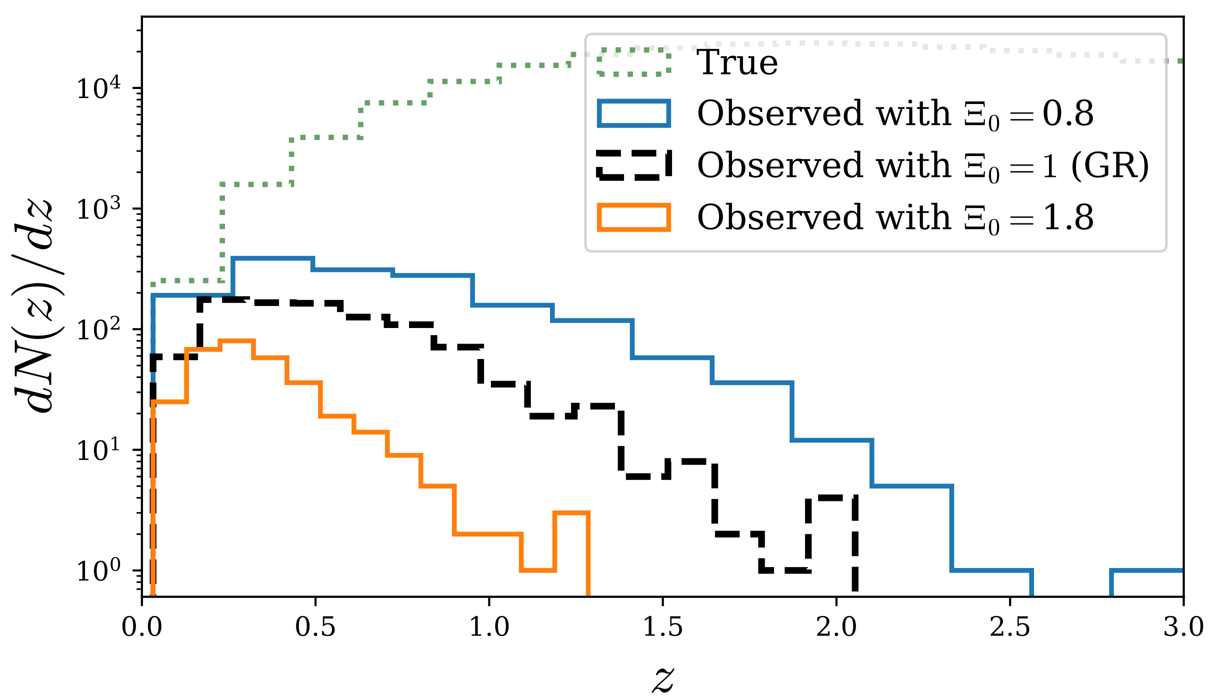
PRD 105 (2022) 6 with *Genoud-Prachex, Maggiore*



DETECTION RATES



PRD 105 (2022) 6 with *Genoud-Prachex, Maggiore*

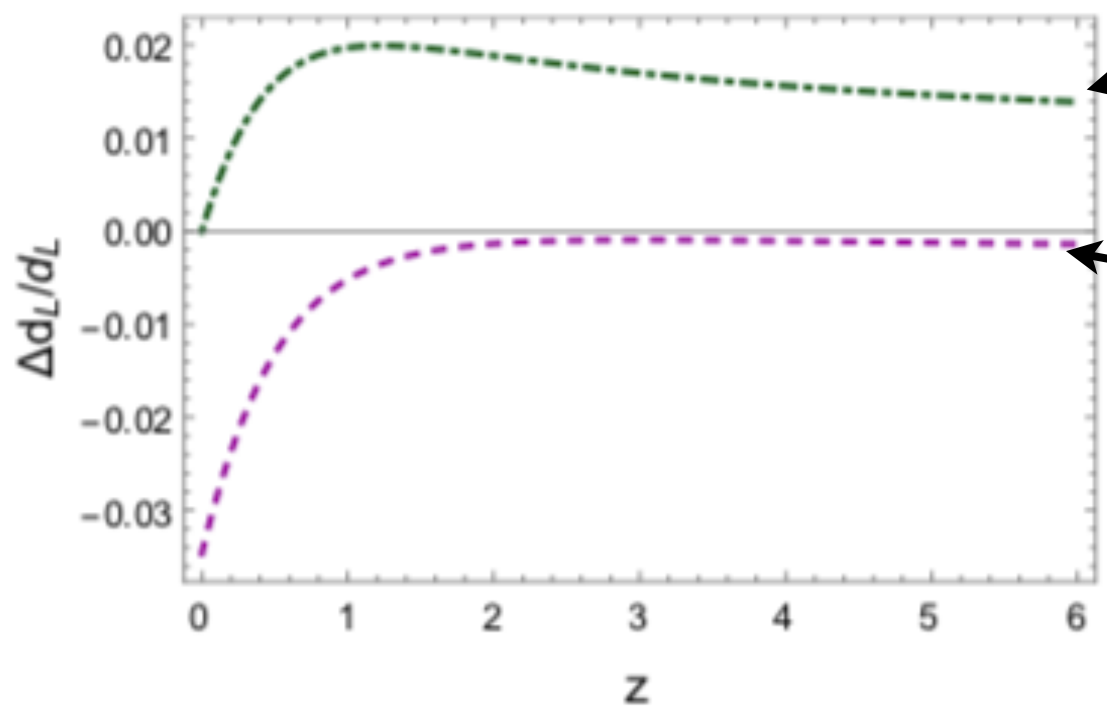


w_0 vs Ξ_0

$$d_L^{\rm gw}(z) = \left[\Xi_0 + \frac{1-\Xi_0}{(1+z)^n}\right] \times \frac{c}{H_0}(1+z)\int_0^z \frac{dz'}{\sqrt{\Omega_{\rm M}(1+z')^3 + \rho_{\rm DE}(z')/\rho_0}}$$

- CMB, BAO are distance scales. When changing w_0 , the other parameters change so to keep those fixed. This fixes EM luminosity distance.
- GW luminosity distance is additionally changed by Ξ_0. This becomes the dominant term

Belgacem, Dirian, Foffa, Maggiore 1805.08731



fixing the other parameters to same value

w_0 = -1.1

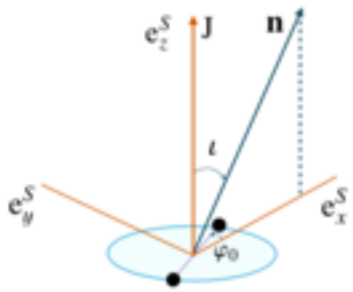
re-fitting w. MCMC on CMB+BAO+SNe

$$\left(\frac{\Delta d_L}{d_L}\right)^{\rm GW} \simeq (\Xi_0 - 1) - \left(\frac{\Delta d_L}{d_L}\right)^{\rm em}$$

COSMOLOGY WITH GWs: MODIFIED GW PROPAGATION

PROPAGATION IN FRW UNIVERSE

LOCAL WAVE ZONE



OBSERVER

GR

$$h''_A + 2\mathcal{H}h'_A + c^2k^2h_A = 0$$

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

$$\chi''_A + (k^2 - a''/a)\chi_A = 0$$

SUB-HORIZON

$$h_A = \frac{\chi_A}{a} \propto 1/d_L$$

plane wave
+ redshifted amplitude

Modified Gravity

$$h''_A + [2 + \alpha_M(\eta)]\mathcal{H}h'_A + c^2k^2h_A = 0$$

Horndeski/DHOST
Higher dim
Non-local
Bigravity
.....

$$\chi_A(\eta,\vec{k}) = a_{GW}(\eta)\, h_A(\eta,\vec{k})$$

$$a'_{GW}/a_{GW} = \mathcal{H}\,[1 + \alpha_M(\eta)/2]$$

GWs FEEL "EFFECTIVE SCALE FACTOR"

$$h_A = \frac{\chi_A}{a_{GW}} \propto 1/d_L^{\rm GW}$$

Amendola, Sawicki, Kunz, Saltas 1712.08623
Belgacem, Dirian, Foffa, Maggiore 1712.08108
Lagos, Fishbach, Landry, Holz 1901.03321

Baker et al 2203.00566 for frequency-dependent extension

GRAVITATIONAL-WAVE LUMINOSITY DISTANCE

$$d_L^{\rm GW}(z) = d_L^{\rm em}(z)\exp\left\{\frac{1}{2}\int_0^z \frac{dz'}{1+z'}\,\alpha_M(z')\right\}$$

THIS IS MEASURED FROM GWs !

COSMOLOGY WITH GWs: (Ξ_0, n) PARAMETRIZATION

- General strategy to constrain the dark sector: parametrize deviations from GR

BASE PARAMETERS		$(H_0, \Omega_M, ...)$	CMB+BAO+SNe
BACKGROUND	Weird pressure	(w_0, w_a)	CMB+BAO+SNe
SCALAR	▷ Effective Newton`s constant	$G_{\rm eff}(t,k)$	LSS
	▷ Effective anisotropic stress	$\eta(t,k)$	WL
TENSOR	**Modified GW propagation**	(Ξ_0, n)	GWs

$$h_A'' + [2 + \alpha_M(\eta)]\mathcal{H} h_A' + c^2 k^2 h_A = 0$$

$$h_A \propto \frac{1}{d_L^{\rm GW}}$$

$$d_L^{\rm GW}(z) = d_L^{\rm em}(z) \exp\left\{\frac{1}{2}\int_0^z \frac{dz'}{1+z'}\,\alpha_M(z')\right\}$$

Belgacem, Dirian, Foffa, Maggiore 1712.08108
Belgacem et al. (LISA cosmoWG), 1906.01593

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

GW-analog of (w_0, w_a)

Dominant effect, measured much better than (w_0, w_a)