Title: Astrophysical populations and waveform modelling challenges to study cosmology

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Collection: Gravitational Waves Beyond the Boxes II

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Challenges and opportunities for cosmology with gravitational waves

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Gravitational Waves Beyond the Boxes II @ Perimeter Institute

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NHFP
NASA Hubble Fellowship Program

Background cosmology is common to all events: Cosmological parameters are population-level parameters

Analyzing a single event

Posterior

Likelihood

Prior

$$p(\theta_i \mid \text{data}_i) = \frac{p(\text{data}_i \mid \theta_i) p_0(\theta_i \mid \mathscr{H})}{p(\text{data}_i \mid \mathscr{H})}$$

θ_i: event i's parameters, like masses, spins

Evidence

Parameter estimation assumes a default prior.
Population inference finds the "best" prior, common to all systems

From single events to a population

Find the "best" prior to use for individual events

$$p_{\rm pop}(\theta \mid \lambda, \mathscr{H})$$

Parameter estimation likelihood for event *i*

$$p(\text{data} \mid \lambda, \mathscr{H}) = \prod_i \frac{\int p(\text{data}_i \mid \theta_i) p_{\rm pop}(\theta_i \mid \lambda, \mathscr{H}) \mathrm{d}\theta}{\beta(\lambda, \mathscr{H})}$$

Likelihood given population model and hyperparameters

Selection effects: fraction of detectable systems in the population

See, e.g., Gair+ 2019, Thrane & Talbot 2019, Vitale+ 2020

Cosmology as population inference

Cosmology is correlated with mass and distance distribution in the population model

$$p(\text{data} \mid \lambda, \mathscr{H}) = \prod_i \frac{\int p(\text{data}_i \mid \theta_i) p_{\text{pop}}(\theta_i \mid \lambda, \mathscr{H}) \mathrm{d}\theta}{\beta(\lambda, \mathscr{H})}$$

Cosmology is correlated with mass and distance distribution in the selection effects

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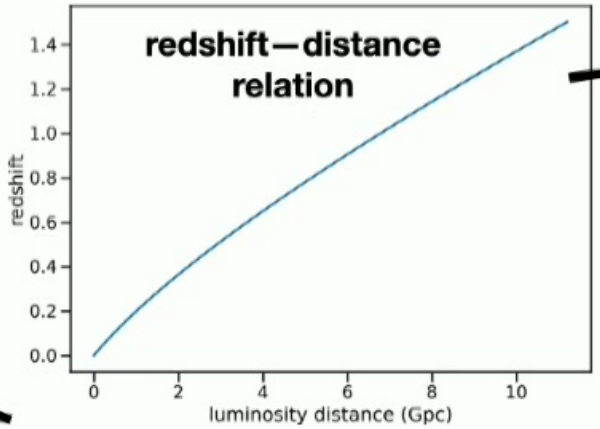
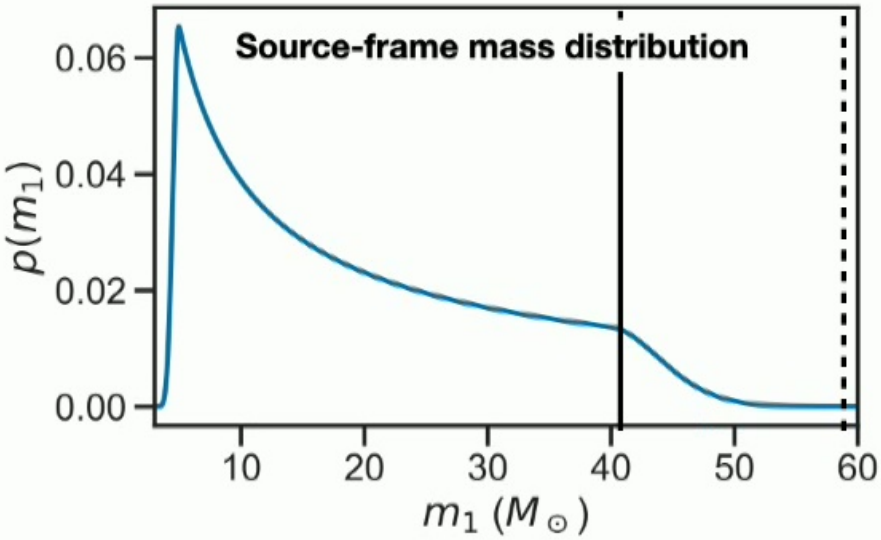
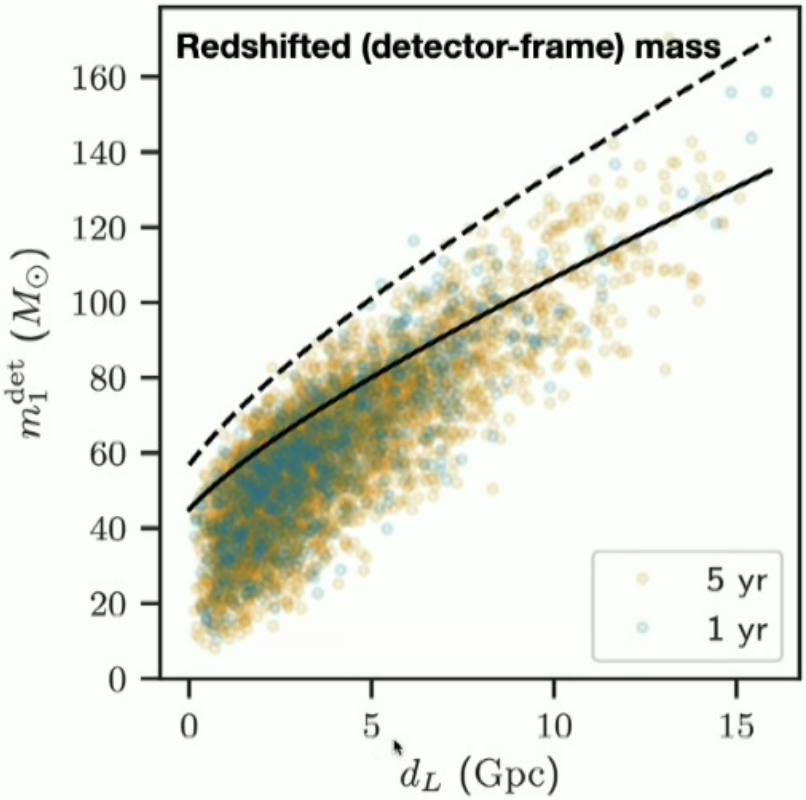
Sometimes we use these correlations explicitly to measure cosmology with the source-frame mass distribution (or the redshift distribution)

Simultaneously infer source population and redshift—distance relation







Farr, MF, Ye & Holz ApJL 883 L42 (2019)

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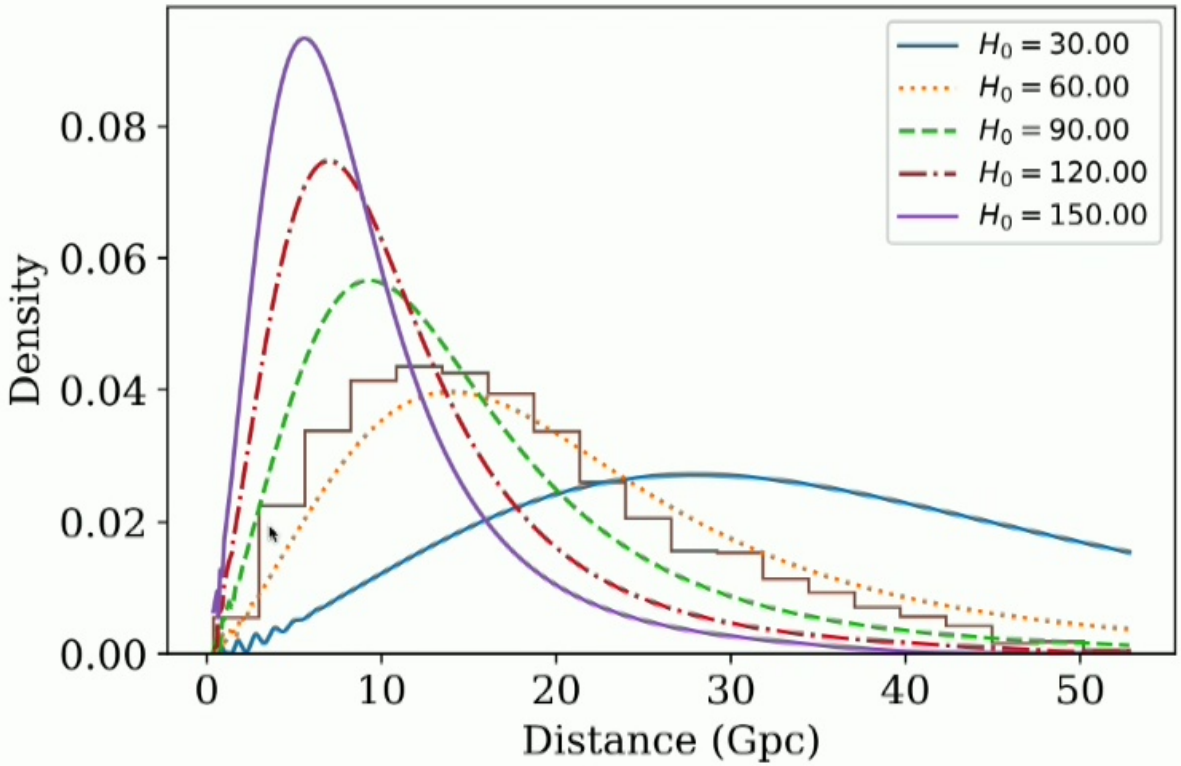
Cosmology with the redshift peak of the merger rate, measured by next-generation detectors

Standard Sirens at Cosmic Noon: Leverage external knowledge of the merger rate as a function of *redshift* to derive cosmological information from the peak in the gravitational-wave *distance* distribution



Ye & MF 2021, PRD 104, 043507

Ignoring the information coming from the population distribution (or any other prior/ modeling choices of the parameters we are marginalizing over) leads to "systematics"/ "bias"

Methods for Standard Siren Cosmography

Assigning redshifts to gravitational-wave distances

- **Counterparts**: identify unique host galaxy
- **Galaxy catalog** as redshift prior, assuming gravitational-wave sources come from galaxies ("statistical" method)
- Other redshift prior with features (e.g. merger rate follows star-formation rate)
- **Cross-correlation** with galaxies, assuming both trace large-scale structure
- Source-frame **mass distribution** (neutron star mass gap and pair-instability mass gap) [to some extent we cannot ignore this source of information in any method]
- Tides in binary neutron star waveforms

Systematics!

- **Counterparts**: possible false association (e.g. GW190521 and AGN flare; see Palmese et al. 2021 arXiv:2103.16069), redshift uncertainty (peculiar velocity, lensing), EM selection effects, population assumptions to some extent
- **Galaxy catalog**: catalog incompleteness, redshift uncertainties (esp photometric redshifts), assigning galaxy host probabilities, population assumptions
- **Source-frame mass distribution**: calibrating redshift evolution in the source-frame distribution, need to use astrophysical theory/ observations (e.g. metallicity-dependence of pair-instability feature)
- For all: calibration, waveform uncertainties, GW selection effects, any approximations in likelihood evaluation (e.g. Monte Carlo integrals)