observational cosmology with gravitational-wave populations

from current ground-based to future space-based detectors

L2IT, Toulouse

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L2IT toulouse

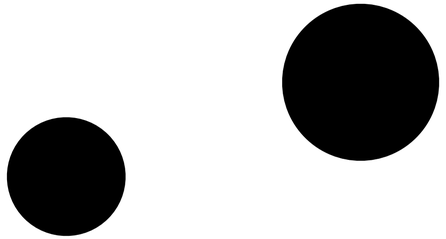
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outline

1. **introduction and methods**
   - a method for the Universe
   - gravitational-wave cosmology
   - hierarchical inference
2. **current ground-based detectors**
   - phenomenological modelling
   - agnostic modelling
   - cosmological inference
   - prospects and problems
3. **future space-based detectors**
   - massive black holes binaries
   - extreme mass-ratio inspirals
4. **discussion and conclusions**



1. introduction and methods

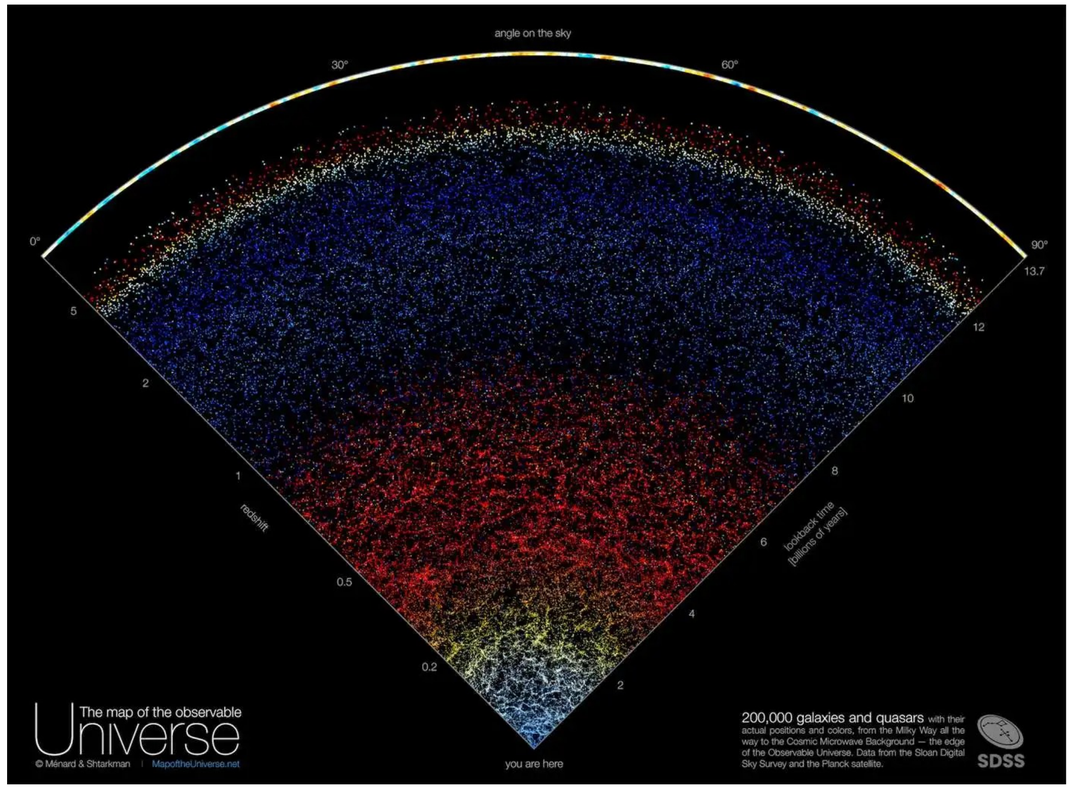
1.1 a model of the Universe



physical cosmology

how to study the Universe?

cosmology is the study of the Universe as a physical system



although a very peculiar one

- it is studied from within
- it contains all other physics and systems by definition

not a fundamental model but an effective description driven by properties at some scales

we need to define what scales are relevant

basic properties

what is its history?

initial dense state

↓

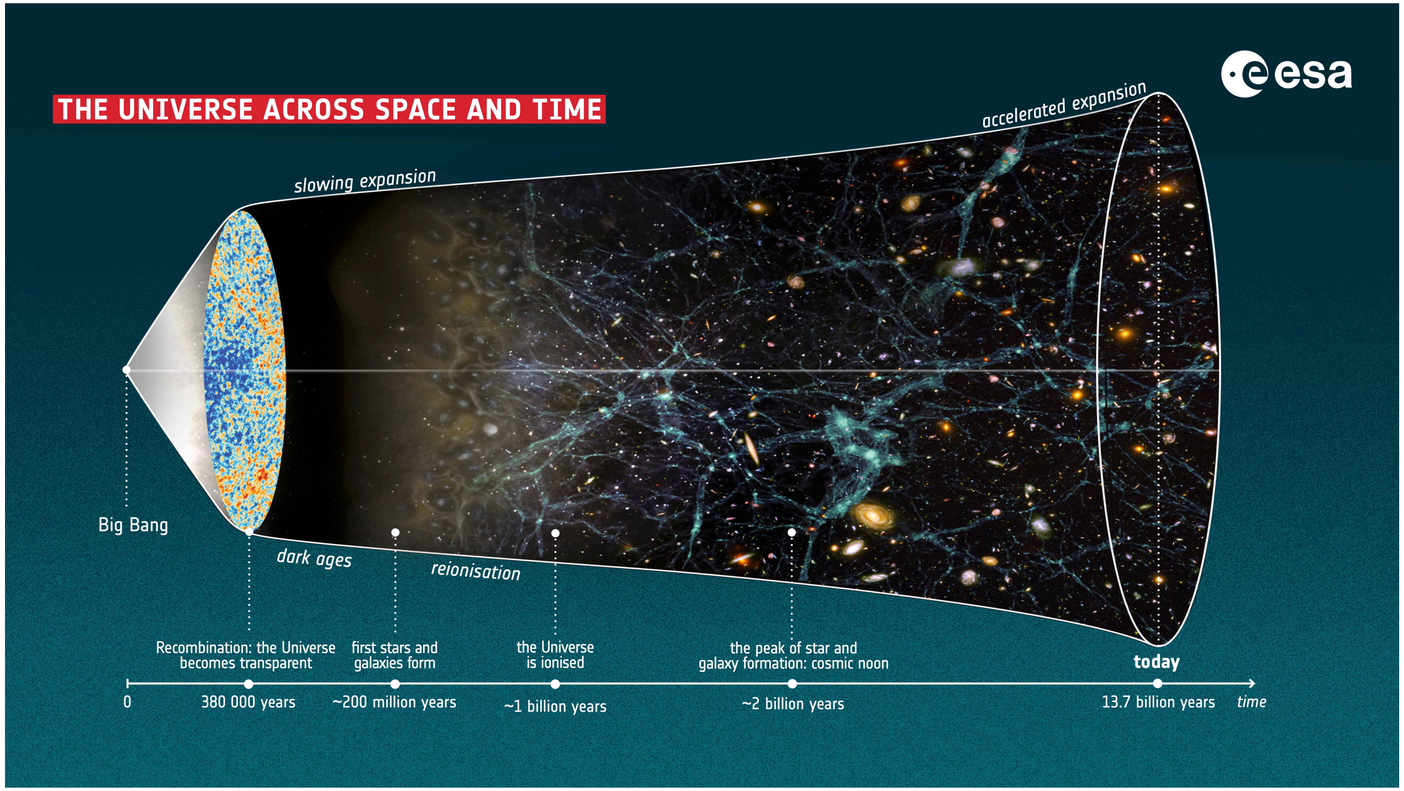
expansion and cooling down

↓

formation of structure

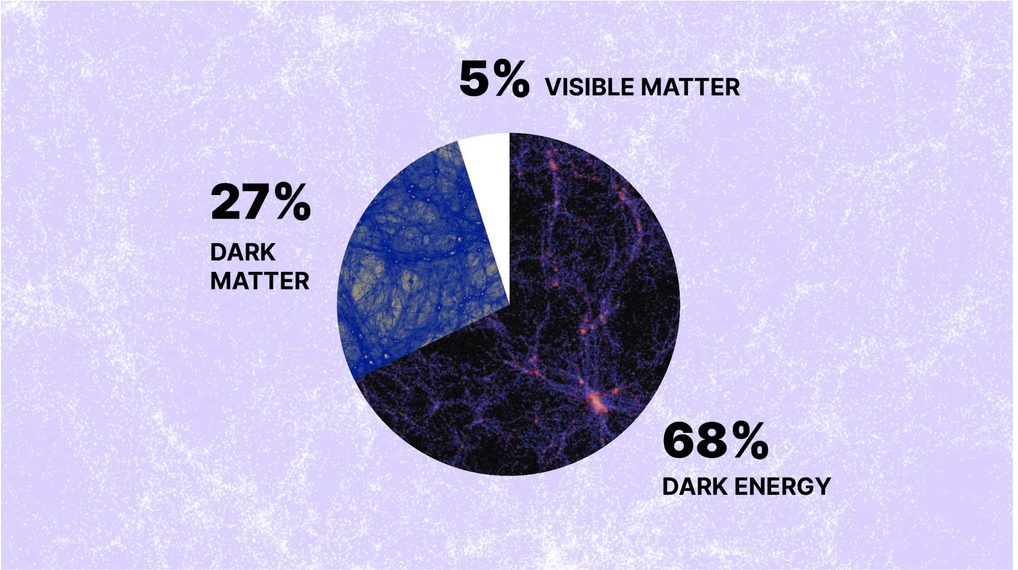
minimal summary of our Universe

- same properties at every location and in any direction
- time evolution with increasing distance between points



statistical framework

how do we know?



a century of experiments and

few observational milestones

- recessional velocity correlates with distance (1929)
- larger velocity dispersions (1933) and galaxy rotational curves (1939)
- light elements from nuclear reactions (1948)
- cosmic microwave background (1965)
- dimmer supernovae at given redshift (1998)

framed into a set of assumptions

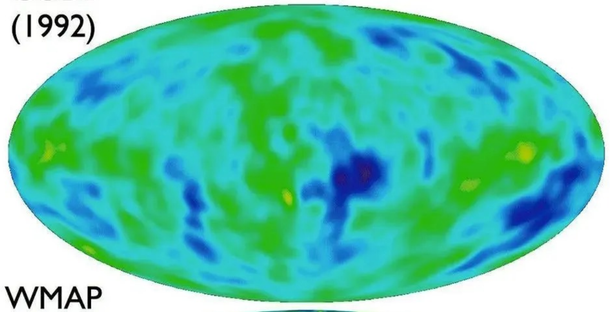
- theory of gravity
- cosmological principle
- big bang
- cosmological origin of large-scale structures
- dark sector
- inflation
- cosmological redshift

→ **ΛCDM model**

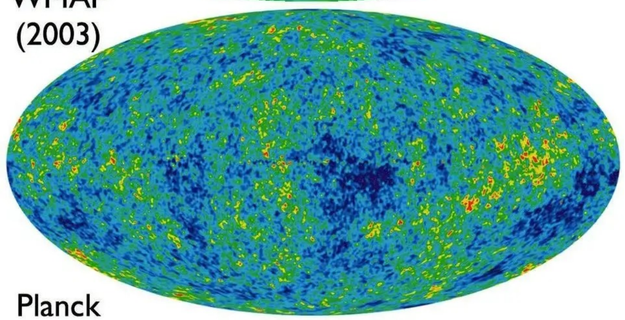
the main probes

cosmic microwave background

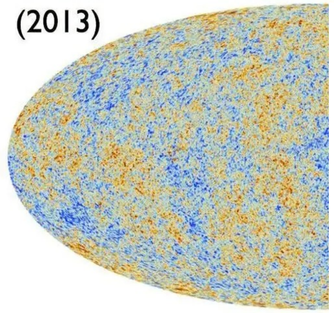
COBE (1992)

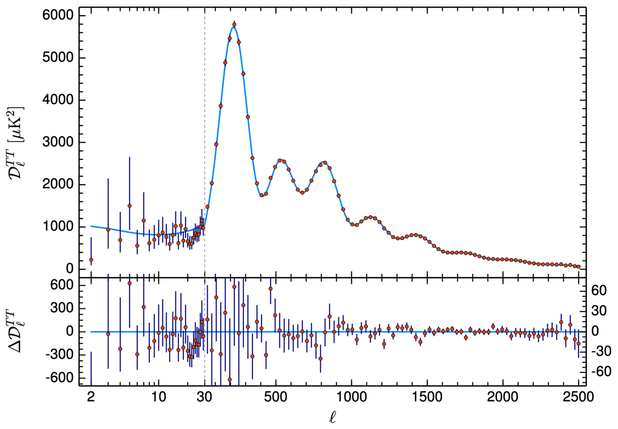


WMAP (2003)

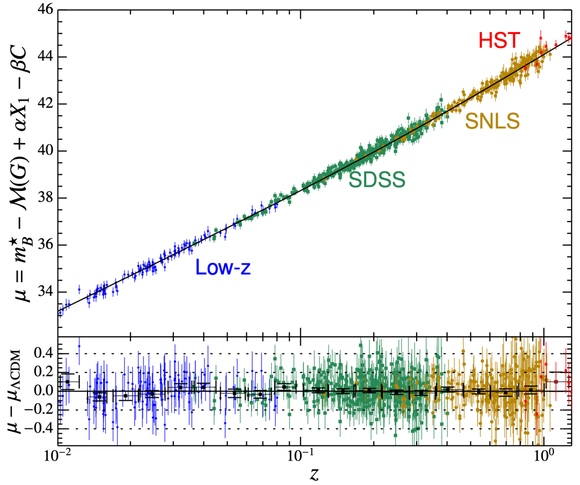


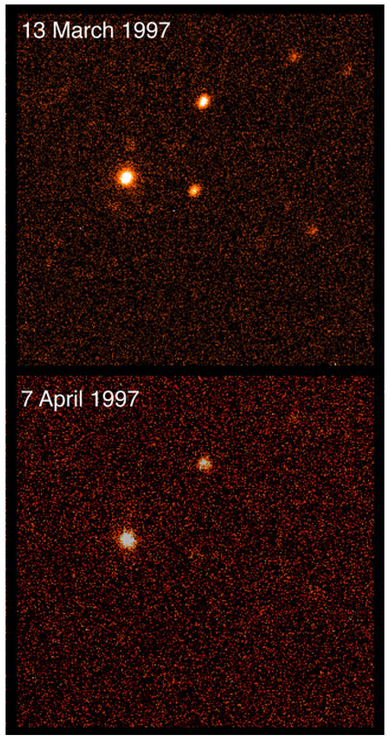
Planck (2013)



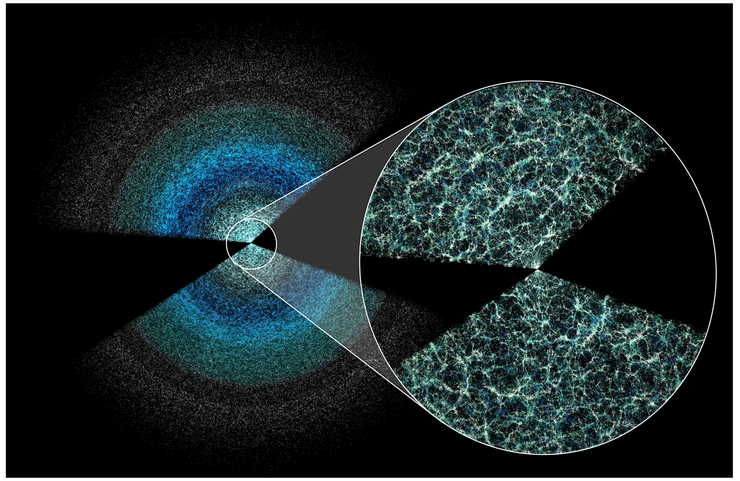


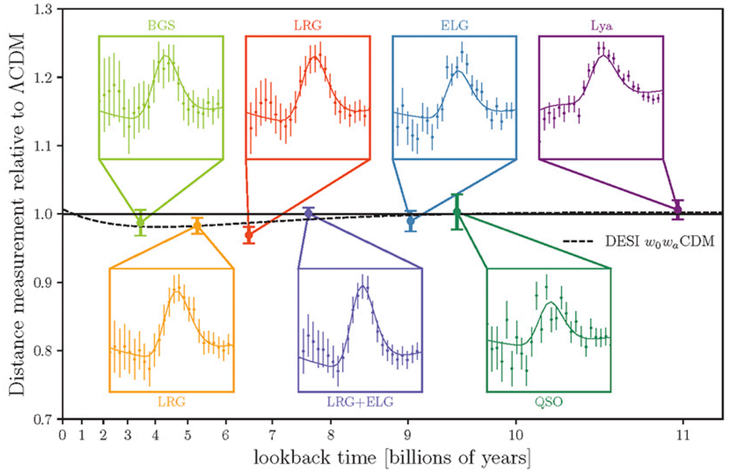
supernova Ia





baryonic acoustic oscillations





and many more...

statistical discrepancies

is this description robust?

however, this concordance model suffers from several observational inconsistencies

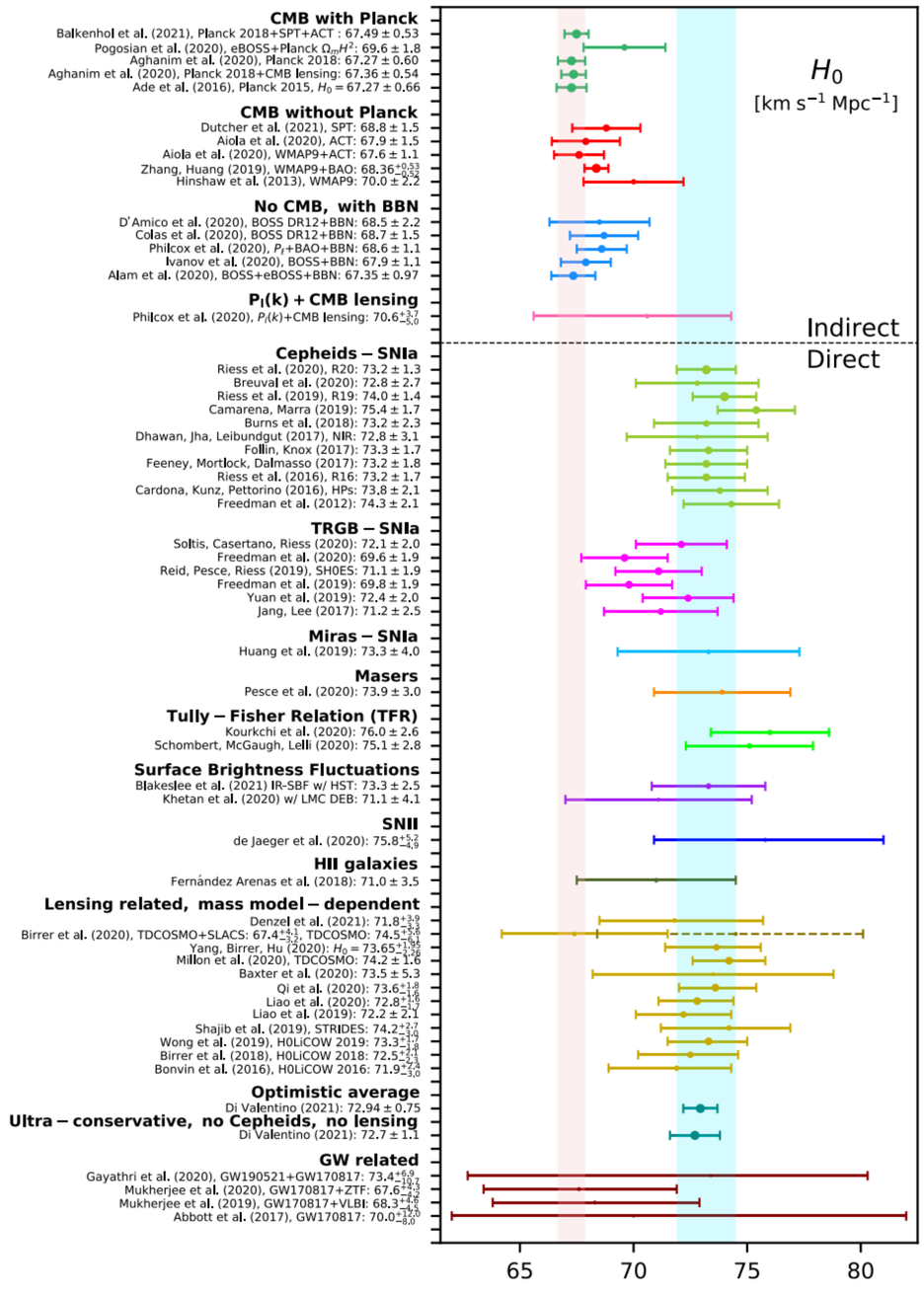
- large structure growth rate
- light elements abundance
- flatness
- dark matter modelling
- others

(either data or theoretical modelling)

possibly the biggest is the difference between the early- and late-Universe measurements of the expansion rate

⟶ the **Hubble tension**

Di Valentino+ (2021) [2103.01183]



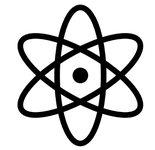
new information

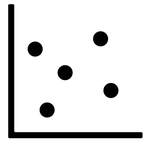
how do we solve these tensions?

cosmology relies on electromagnetic observations

independent observations could provide

- physical processes
- statistical tools
- experiments
- systematics









this does not ensure any knowledge advancement

but worth trying

→ *gravitational waves*

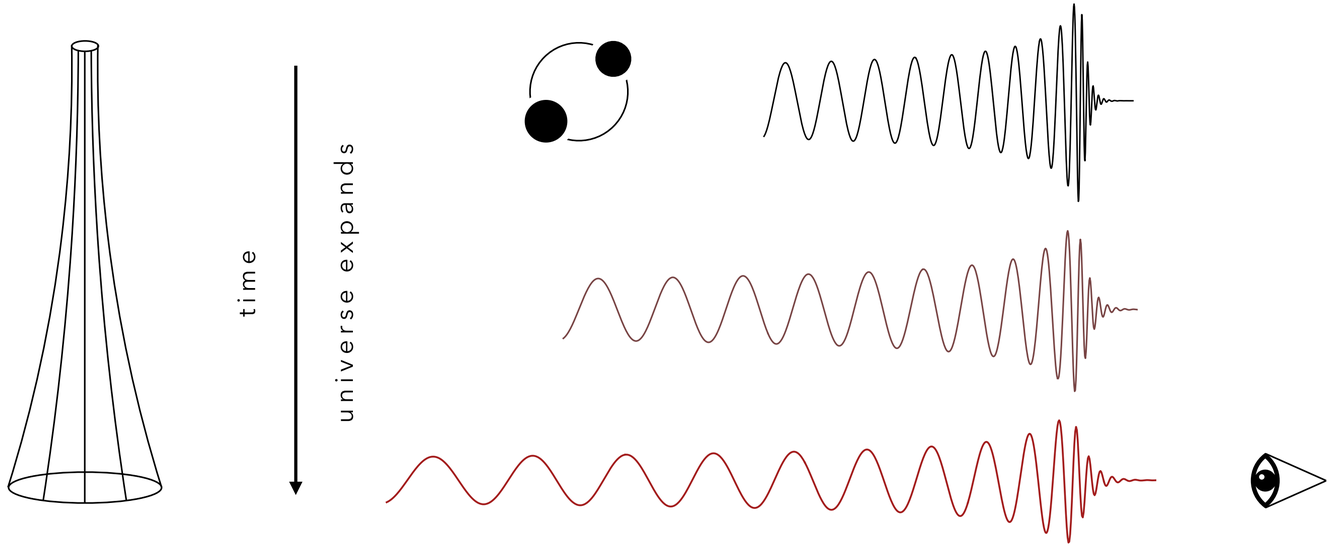
1.2 gravitational-wave cosmology

gravitational waves

gravitational waves are

propagating degrees of freedom

of a dynamical gravitational field



- the system scale and time are those at the observer
- the distance measured is the *luminosity distance*

$$m_o = m_s\,(1+z)$$

we cannot simultaneously measure the scale, the distance and the redshift, which would directly constrain cosmological parameters

$$d_L = \frac{1+z}{H_0}\,f(\Omega_{m,0}, z)$$

luminosity distance-redshift relation

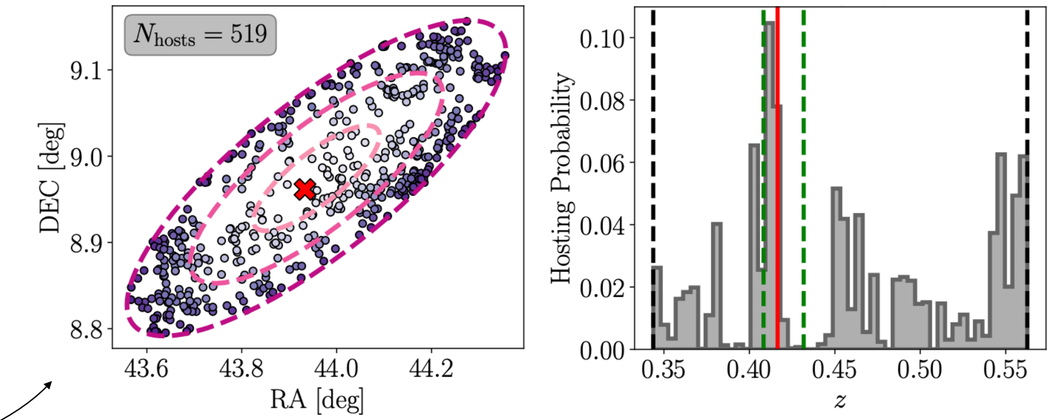
gravitational-wave cosmology

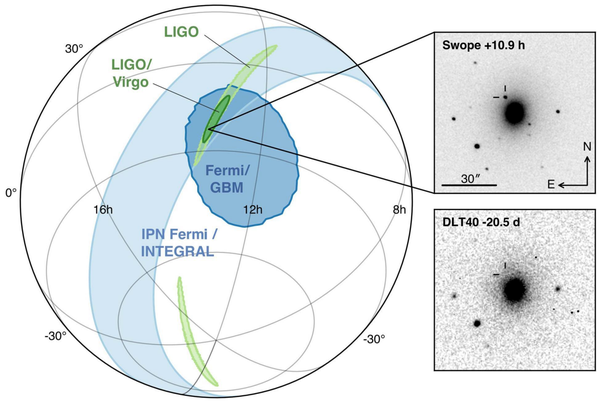
how to get the redshift?

we need to break scale invariance

- couple GW events with EM information
  - **galaxy catalogs**
    - statistical match
    - counterparts (GW170817)
  - others (galaxy clusters, hydrogen intensity maps, cross correlations, ...)
- **gravitational-wave population**
  - features in the distribution (*spectral sirens*)

Muttoni+ (2023) [2303.10693]





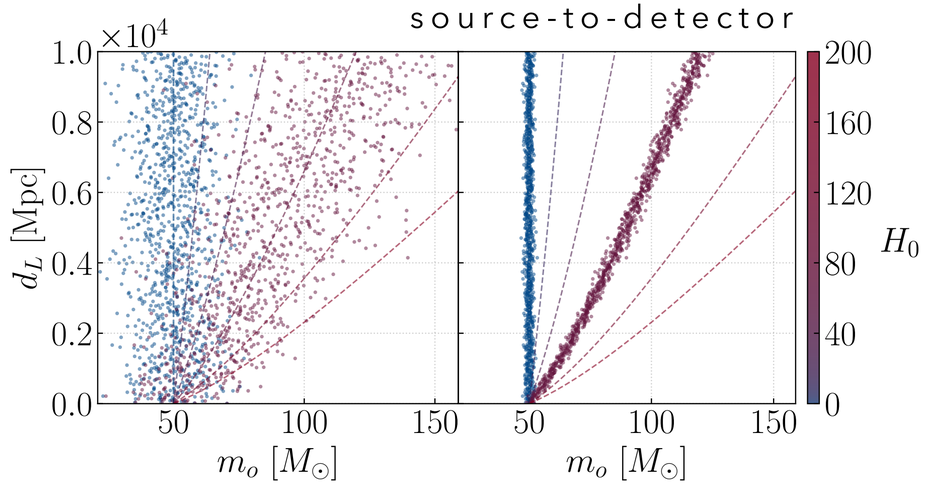
LVK+ (2017) [1710.05833]

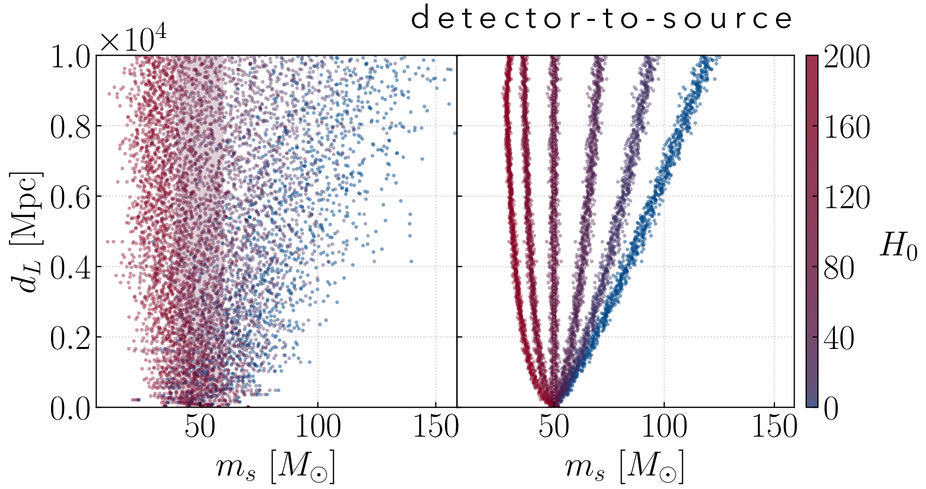
→ *combining multiple events always requires modelling the population!*

this thesis focuses on that

population-based cosmology

how does it work?





we define the conditions to extract redshift information from event combination

- cosmological parameters relate the signal from source to observer
- information on the signal at source breaks the degeneracy and resolves the redshift

if event distribution properties are known, they can be incorporated in the population model to break redshift degeneracy

→ *assumptions on the source population*

properties and motivation

- the only assumption used in the literature is that of a **stationary source distribution**,
  i.e. a population that does not evolve in time
  (source information could exploit other properties)

- without knowledge on the source distribution, population-based cosmology is
  uninformative
  (although cosmology also enters the coming volume if using the rate)

- the basics of this method is also its main limitation: if source assumptions are
  inaccurate, the inference is
  (e.g. intrinsic evolution, see backup slides)

population inference represents the basis of aggregated analyses

- always required when multiple events are combined
- most of the current cosmological information comes from the population

1.3 hierarchical inference

statistical framework

how to combine events?

the analysis is formulated in terms of **Bayesian statistics**

$$p(\,model\,|\,data\,) \longleftrightarrow p(\,data\,|\,model\,)$$

functional form for the BH distribution

GW events to be combined

$$p(\mathbf{\Lambda}|\{\mathbf{d}\}) \propto \mathcal{L}_H(\{\mathbf{d}\}|\mathbf{\Lambda})\, p(\mathbf{\Lambda})$$

posterior — likelihood — prior

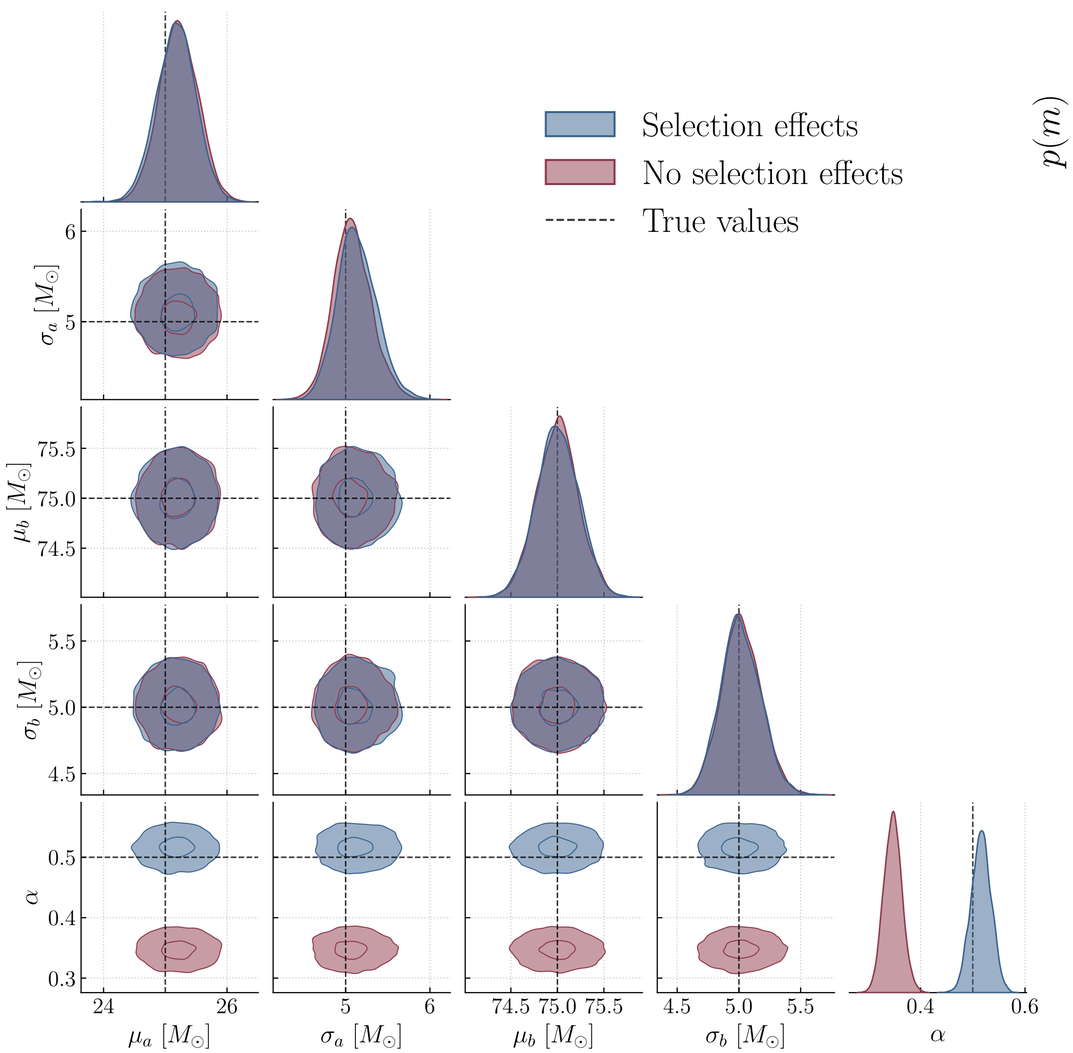
the likelihood represents

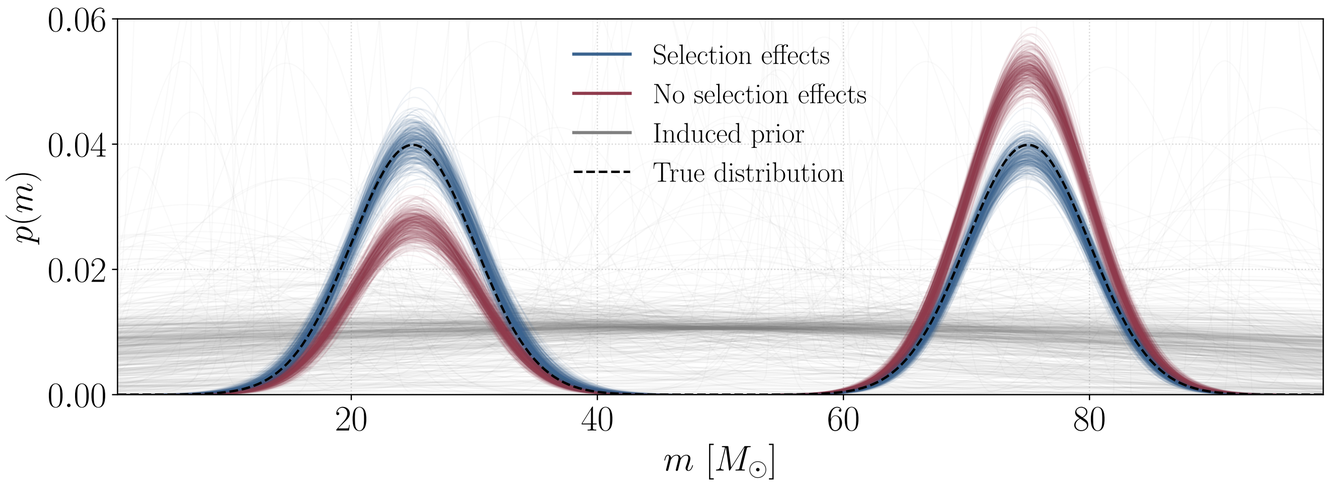
- independent observations
- measurement uncertainties
- selection effects

$$\mathcal{L}_H(\{\mathbf{d}\}|\mathbf{\Lambda}) \propto \prod_i^{\text{events}} \frac{\int \mathrm{d}\theta_i\ \mathcal{L}(\mathrm{d}_i|\theta_i)\ p_{\text{pop}}(\theta_i|\mathbf{\Lambda})}{\int \mathrm{d}\theta\ p_{\text{det}}(\theta)\ p_{\text{pop}}(\theta|\mathbf{\Lambda})}$$

event properties and detection probability are weighted by the population

a simple example





- in reality, we do not have direct access to the underlying distribution
- the distribution outside the detector horizon is not a physical observable, but still enters the analysis through model extrapolation

how to model the population?

phenomenological

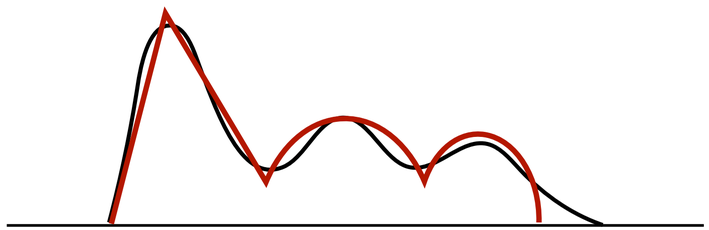
assume a functional form for the distribution

pros

- easy to interpret
- faster astrophysical interpretation

cons

- prone to systematics
- more prior dependent



agnostic

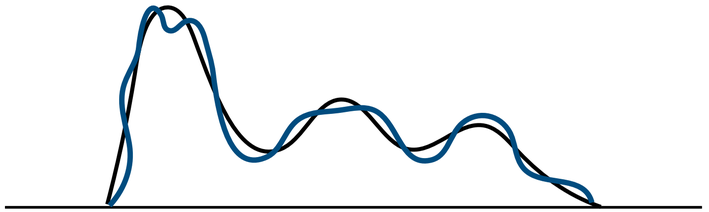
flexible reconstruction from the data

pros

- highly flexible
- less dependent on assumptions

cons

- prone to overfitting
- more difficult to extrapolate



ignoring parameters

in this thesis, we focus on the **mass distribution of black-hole mergers**

- masses are well measured
- mass carries cosmological information

other parameters can affect population or cosmological inference (e.g. spins)

the limits when this assumption is exact,

i.e. when the integral is trivial, are

- the population coincides with the prior
- the posterior coincides with the prior,
  i.e. is uninformative

settings

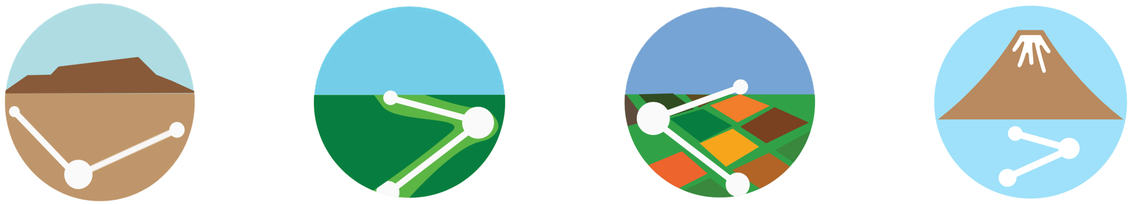
- all analyses use the ICAROGW software
- likelihood via Monte Carlo integration
- likelihood is tapered for numerical stability
- we use a nested sampler (dynesty or nessai)
- use sufficient number of live points (2000)
- sensitivity estimates from LVK

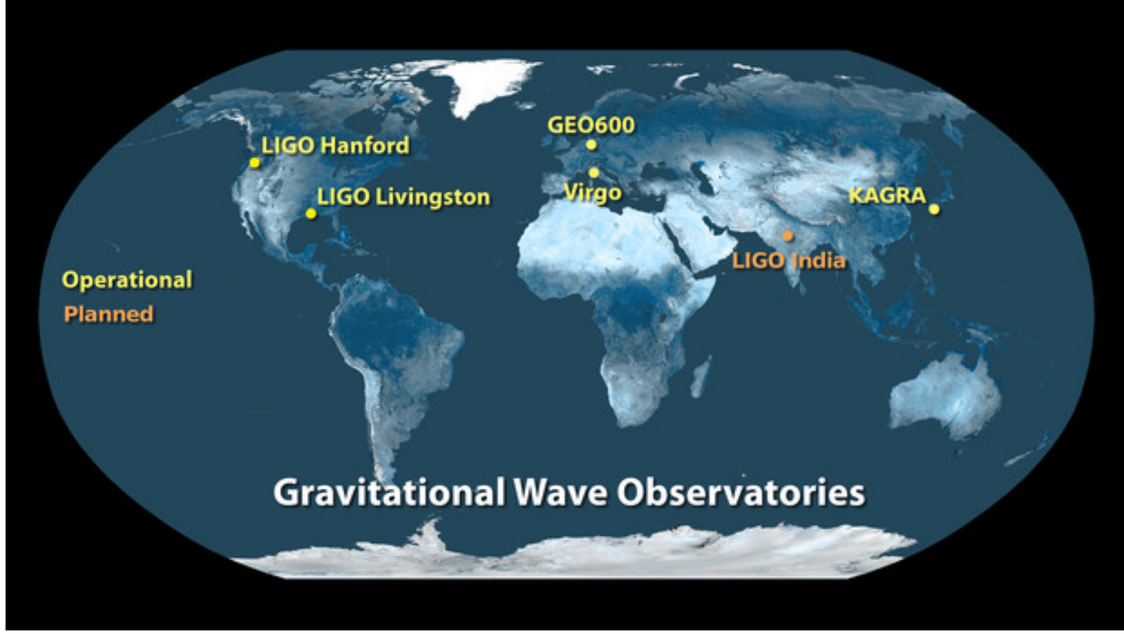
2. current ground-based detectors

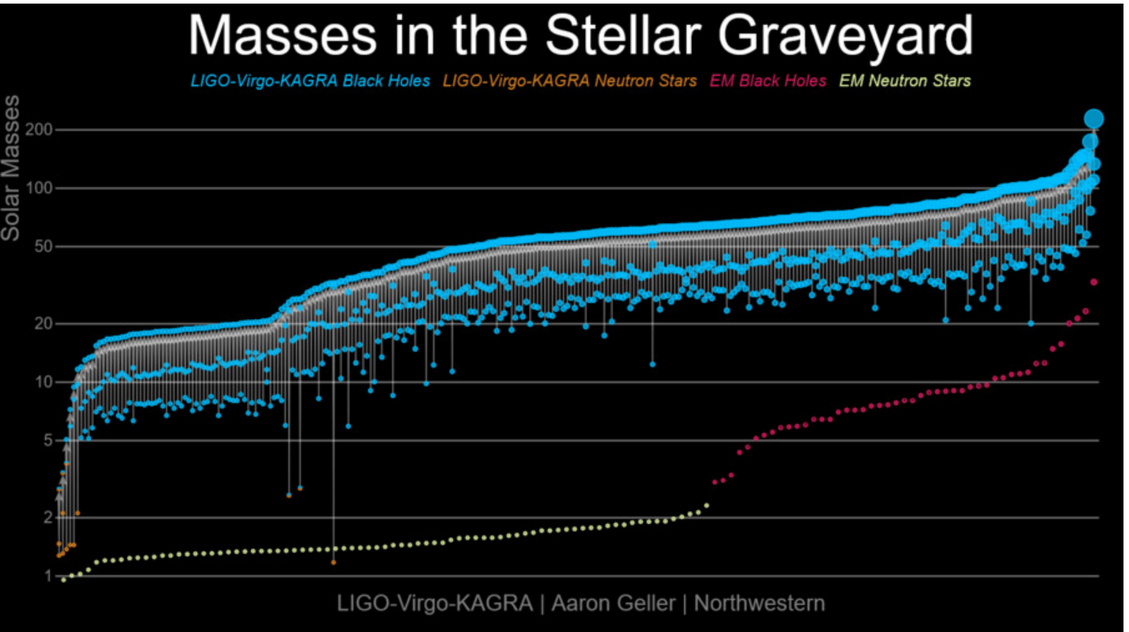
LIGO-Virgo-KAGRA

the current network comprises

four gravitational-wave detectors







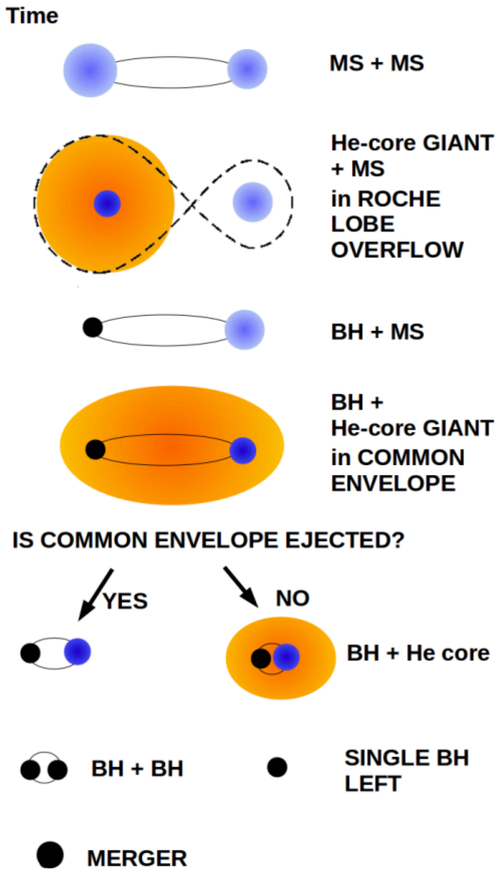
from the first detection in 2015, we have now observed about 390 events, mostly black hole mergers

enabling population analysis

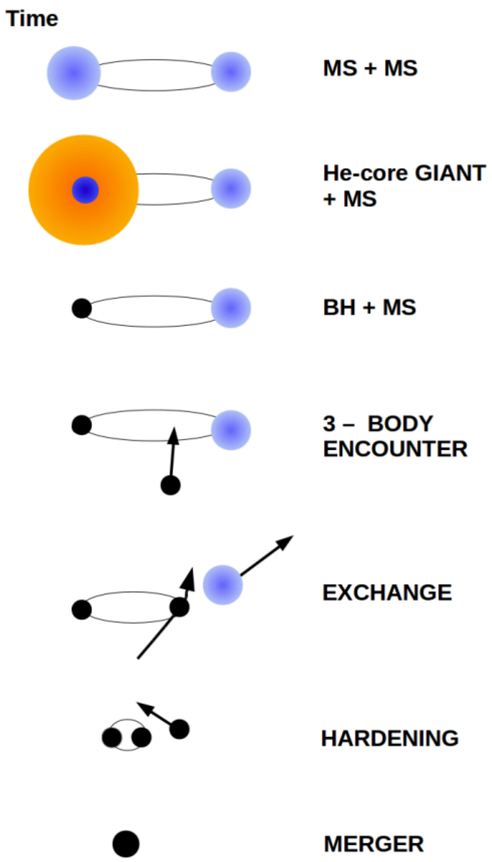
where do they come from?

formation channels

isolated binaries



dynamical

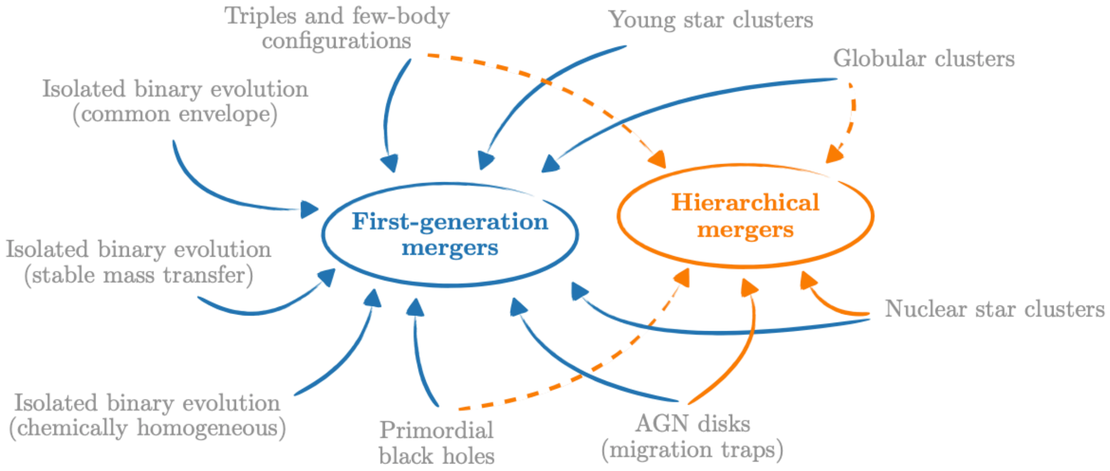


Mapelli+ (2021) [2106.00699]

the population contains information on the underlying astrophysical processes that make up the black hole mergers

- different channels provide specific signatures
- still unable to distinguish them from the data

repeated mergers



Gerosa+ (2021) [2105.03439]

science objectives

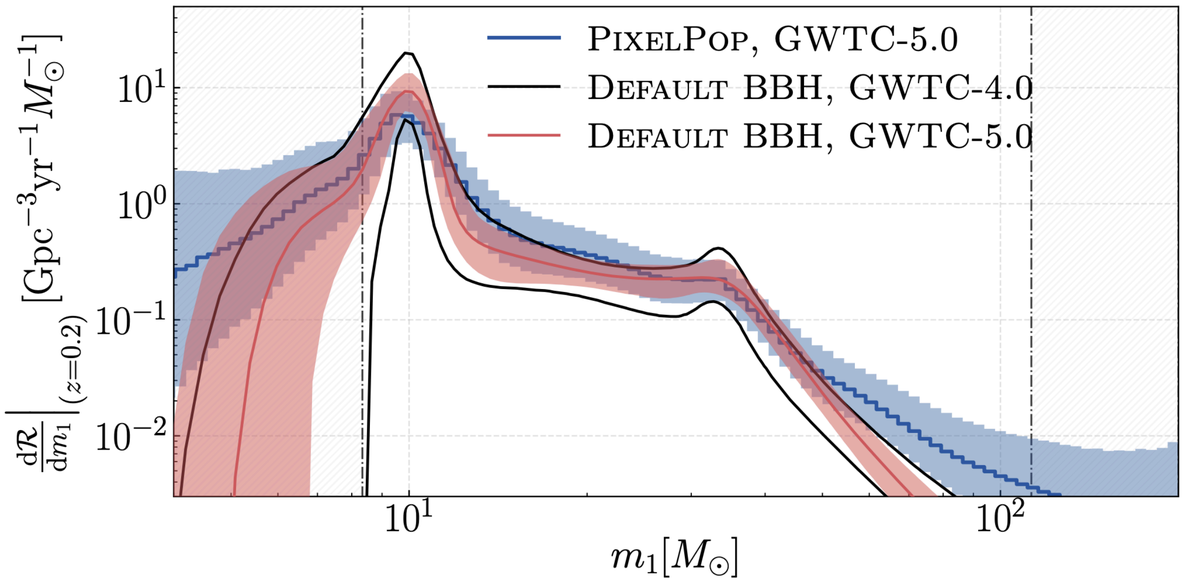
large catalogues enable population analyses

current results?

- learn about astrophysical channels forming black hole mergers
- measure the Universe expansion with gravitational waves

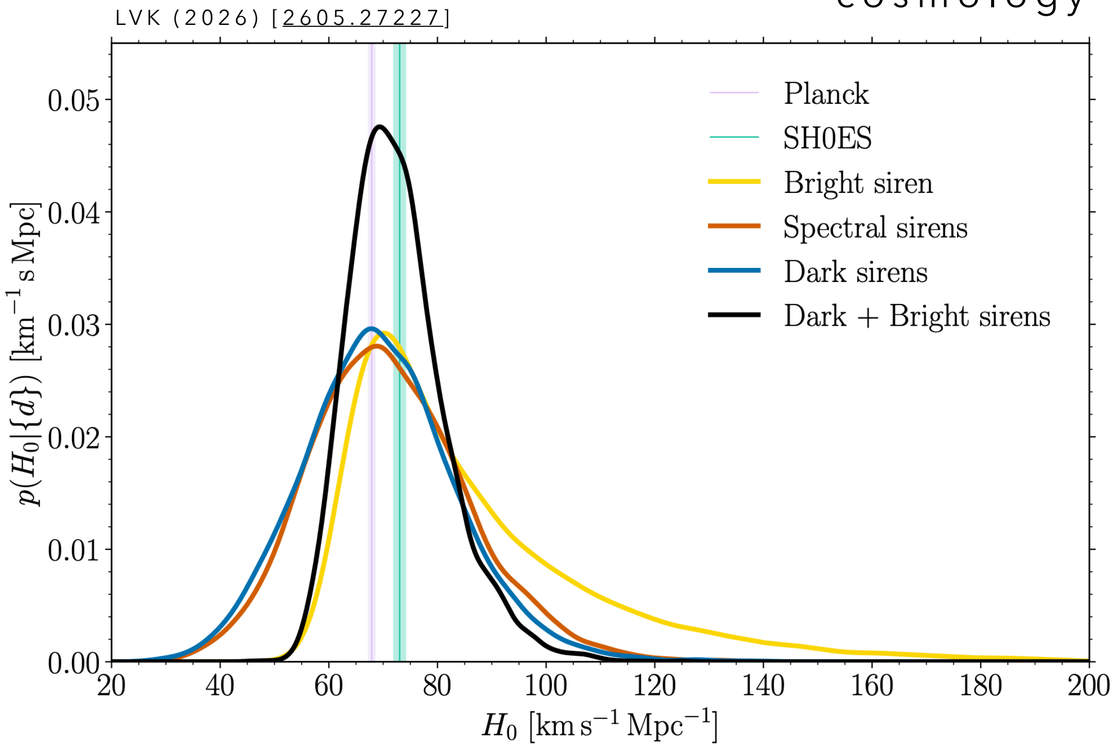
astrophysics

LVK (2026) [2605.27226]



cosmology

LVK (2026) [2605.27227]



open questions

what motivated our work?

on the **population distribution**

- what features in the mass distribution are robust?
- what role modelling assumptions play?

on the **cosmological inference**

- what features drive the cosmological inference?
- how can we mitigate modelling systematics?

...let's get started!

2.2 phenomenological modelling

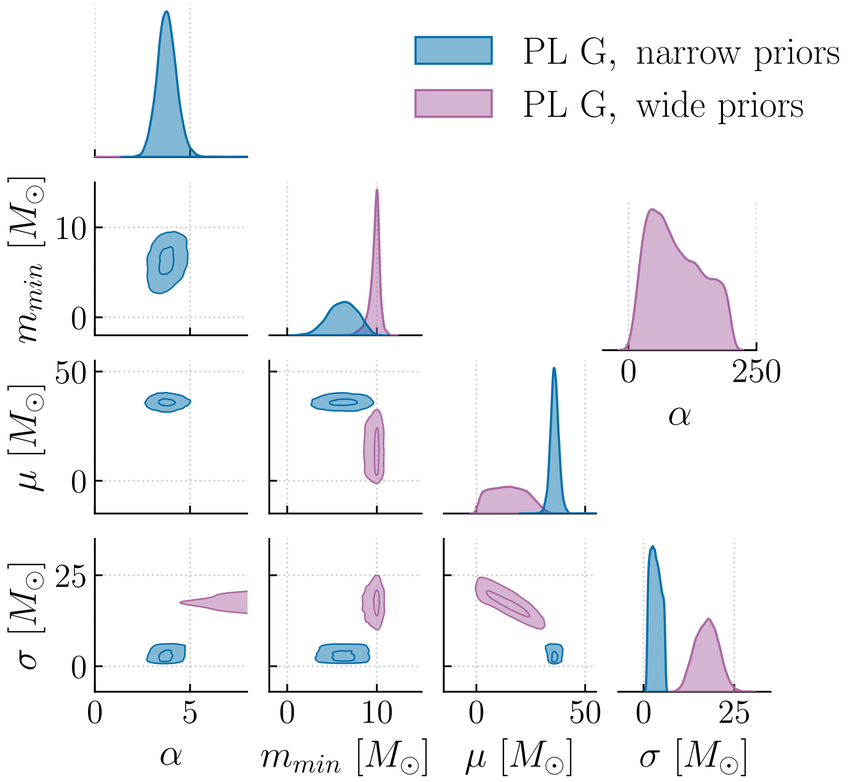
simple parametrisations

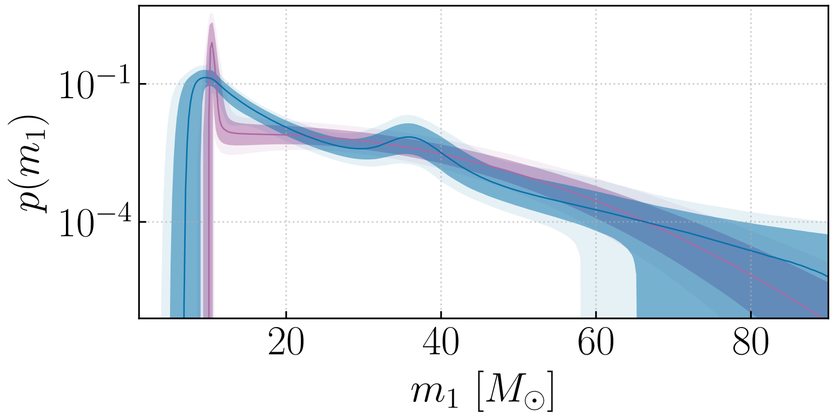
was it enough?

Gennari+ (2025) [2502.20445]

a power-law + gaussian model has widely been used in the literature

- results are unstable against changes in the prior ranges
- a sharper low-mass peak is preferred
- the model cannot capture both the $10M_\odot$ and $35M_\odot$ peaks





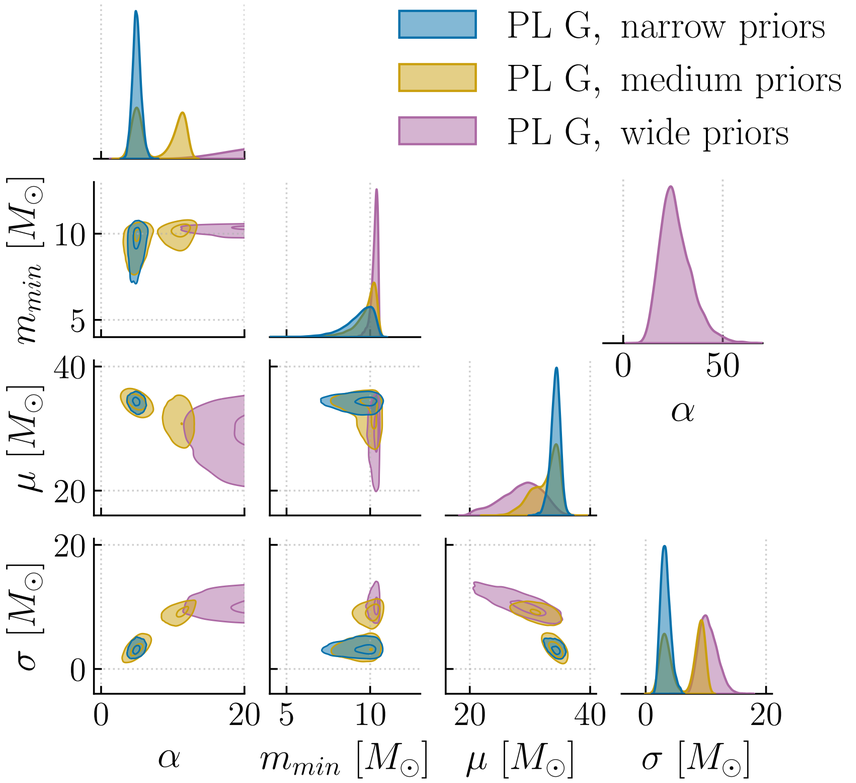
simulated data

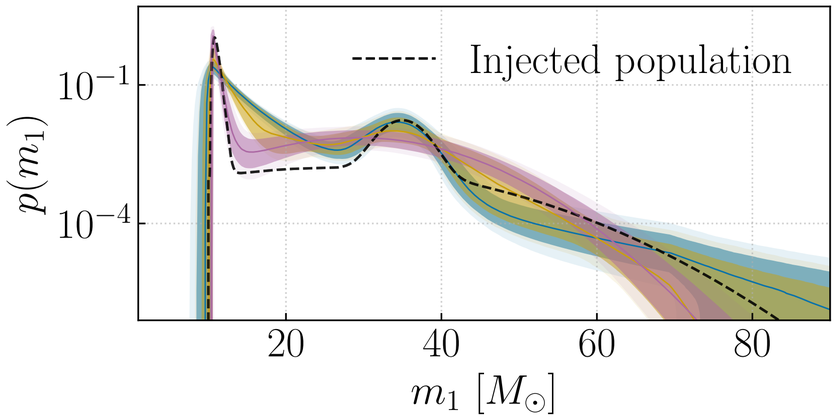
Gennari+ (2025) [2502.20445]

generate events from a model with both features and recover with a simpler one

- bimodal likelihood where the usual reconstruction represents a local minimum
- a sharper low-mass peak is preferred

→ *careful with phenomenological models!*

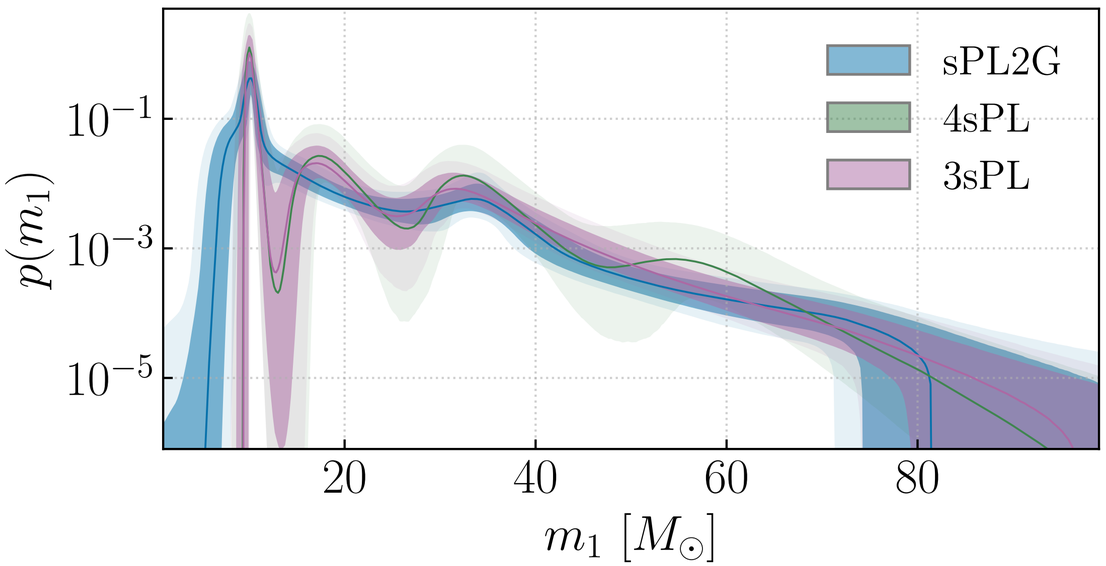




more complex parametrisations

what about adding components?

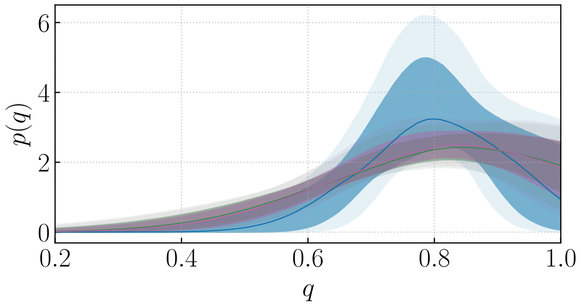
Bertheas, Gennari+ (2026) [2603.06792]

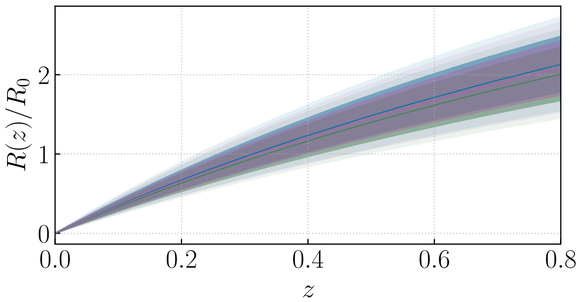


power-law-only models can capture

more structure in the mass distribution

- models with three or four power-laws fit both $10M_\odot$ and $35M_\odot$ features
- more structure at low-mass: peak at $20M_\odot$ preceded by a gap
- fourth overdensity at about $60M_\odot$





how robust there features are?

2.3 agnostic modelling

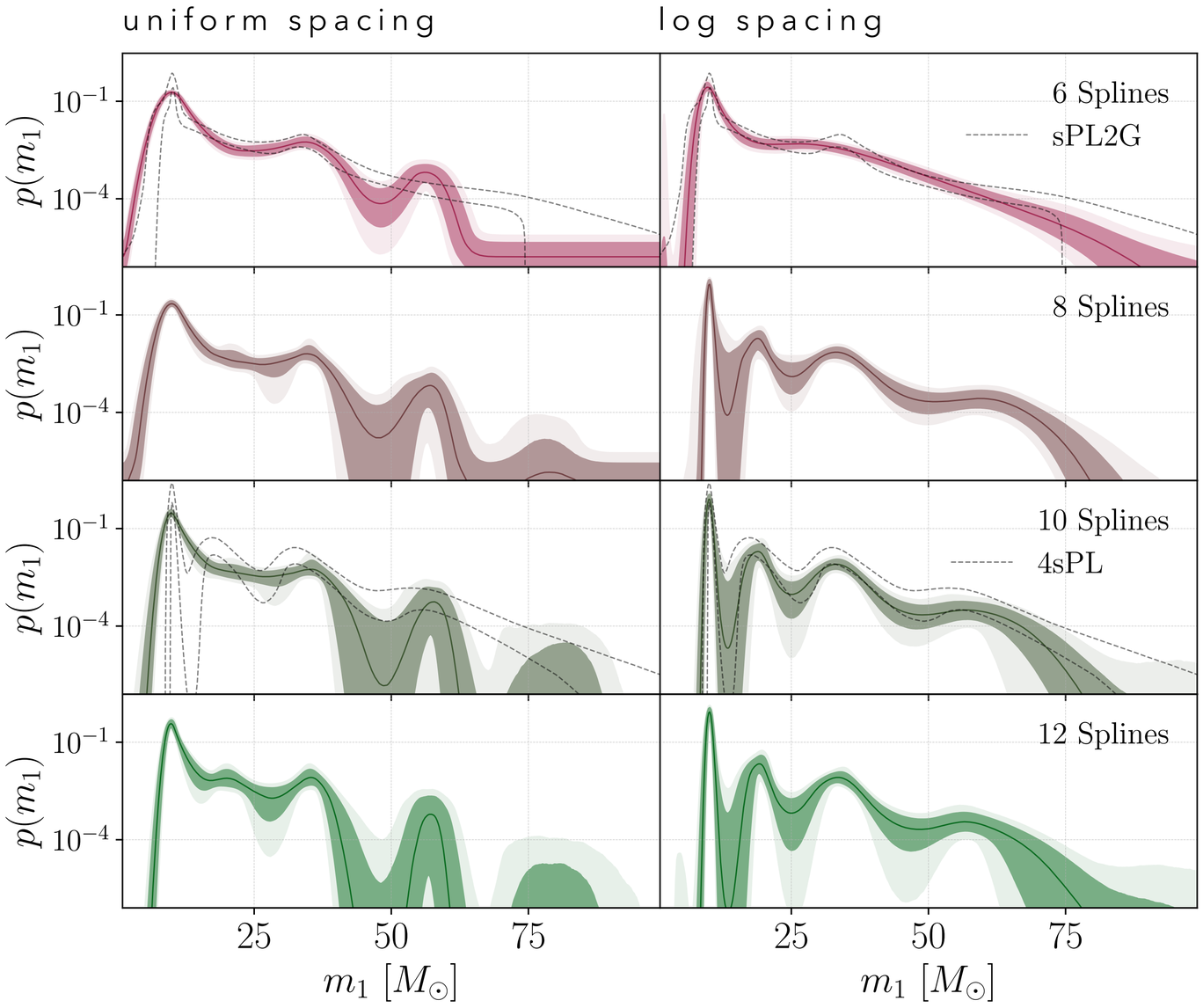
resolution scan of the mass distribution

Gennari+ (2026) [2604.14290]

change the number of spline elements to increase flexibility

- uniform spacing finds **high-mass structure**
- log spacing finds **low-mass structure**

log spacing is favoured by Bayes factors and agrees with phenomenological models

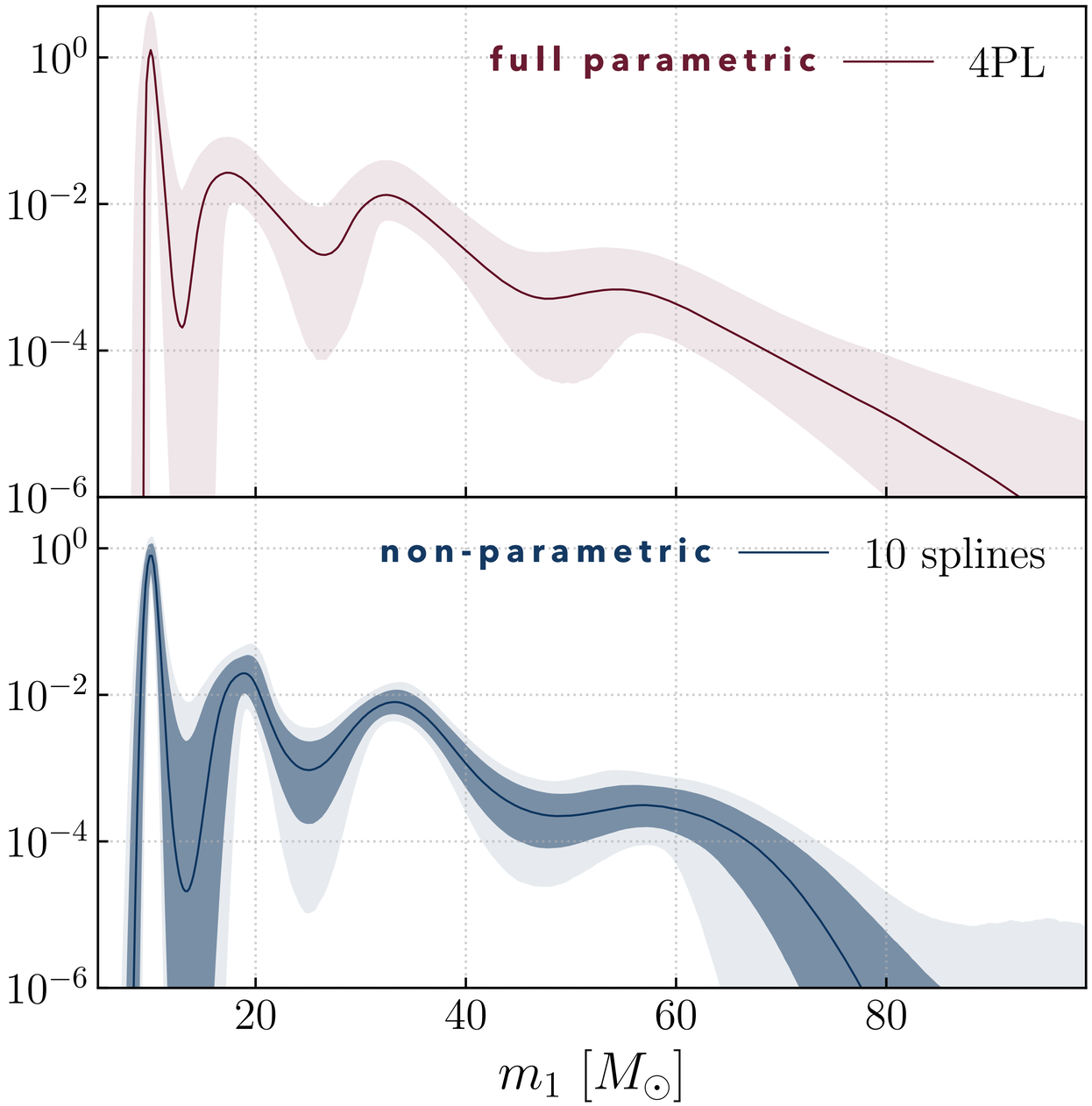


approach comparison

- a four-power-law model is equivalent to ten quadratic splines for the log(PDF)

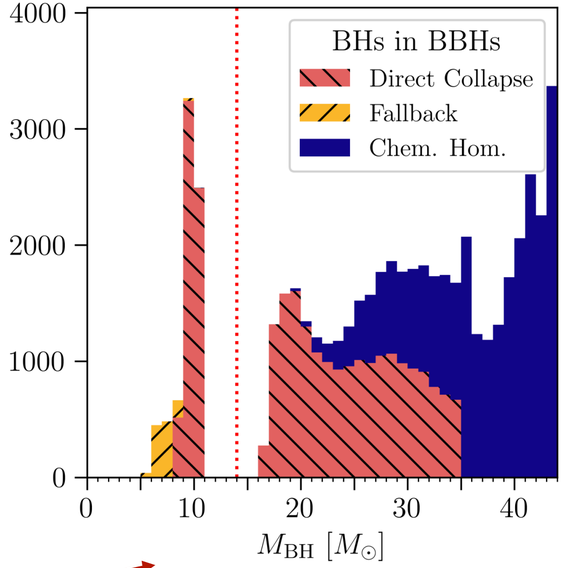
- features closely match
  - sharp $10\,M_\odot$ peak
  - $15\,M_\odot$ under-density
  - $20\,M_\odot$ and $35\,M_\odot$ peaks
  - $\sim 60\,M_\odot$ over-density

what is the physics behind?

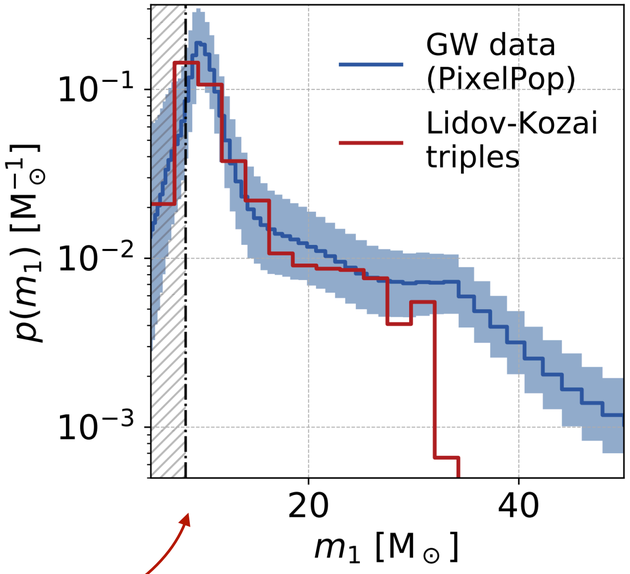


potential explanations

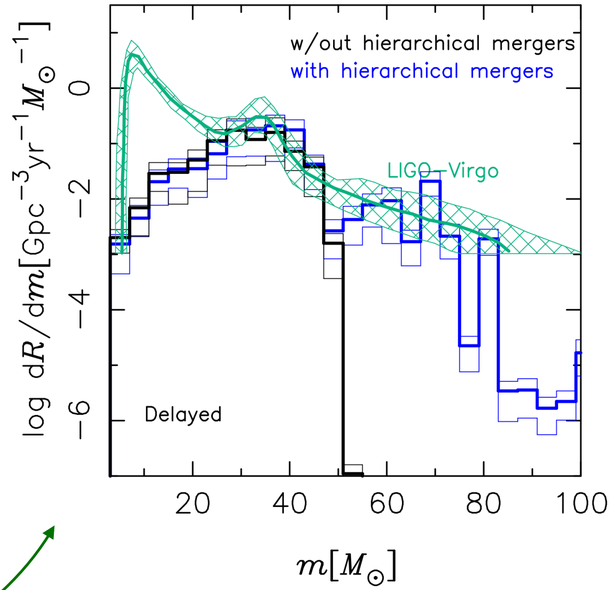
Willcox+ (2025) [2510.07573]

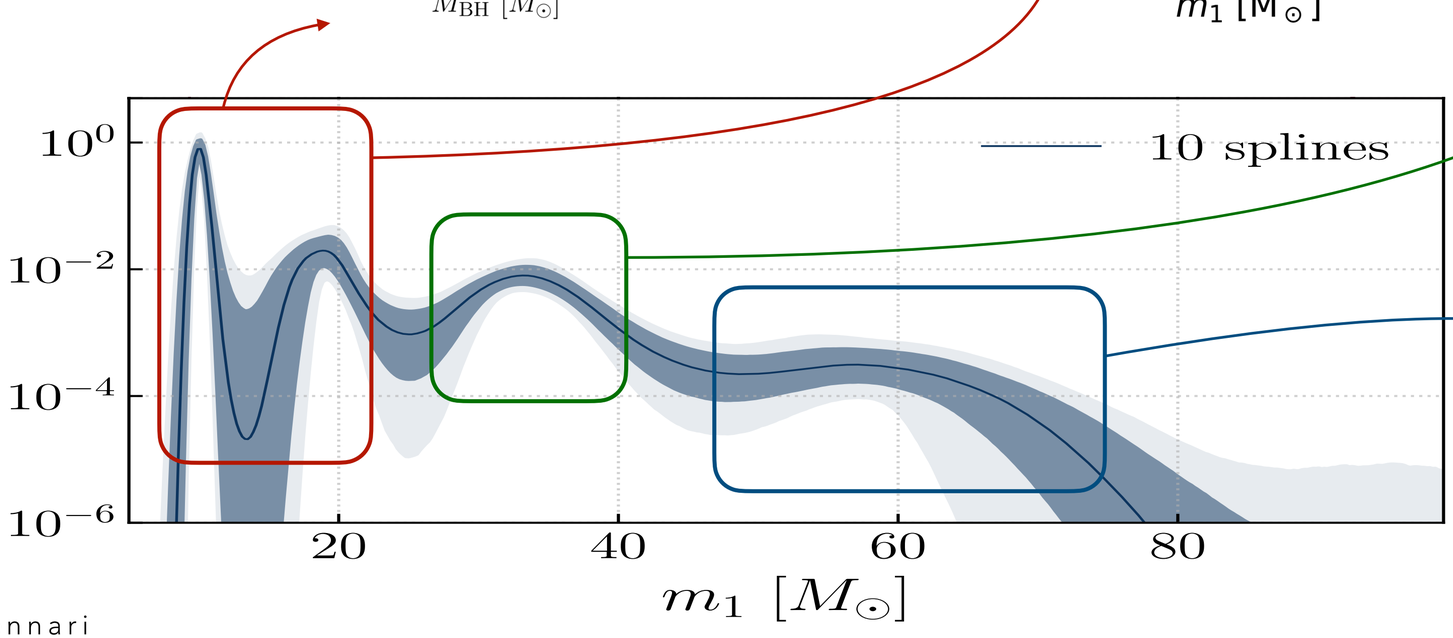


Stegmann+ (2026) [2609.30378]

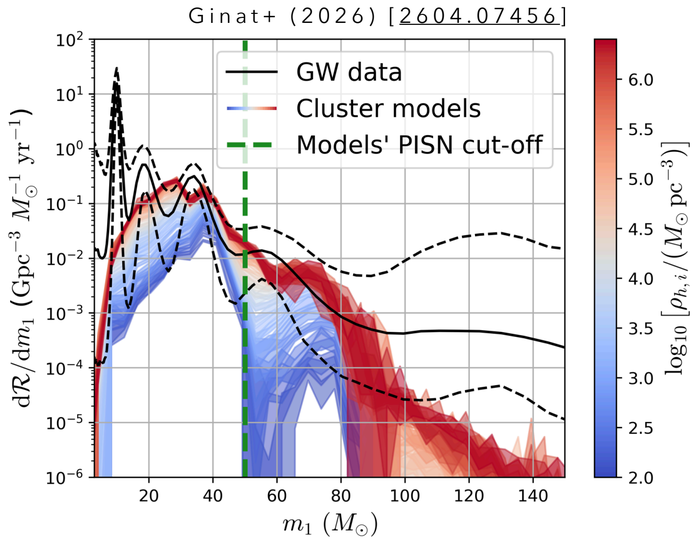


Antonini+ (2022) [2208.01081]





Ginat+ (2026) [2604.07456]



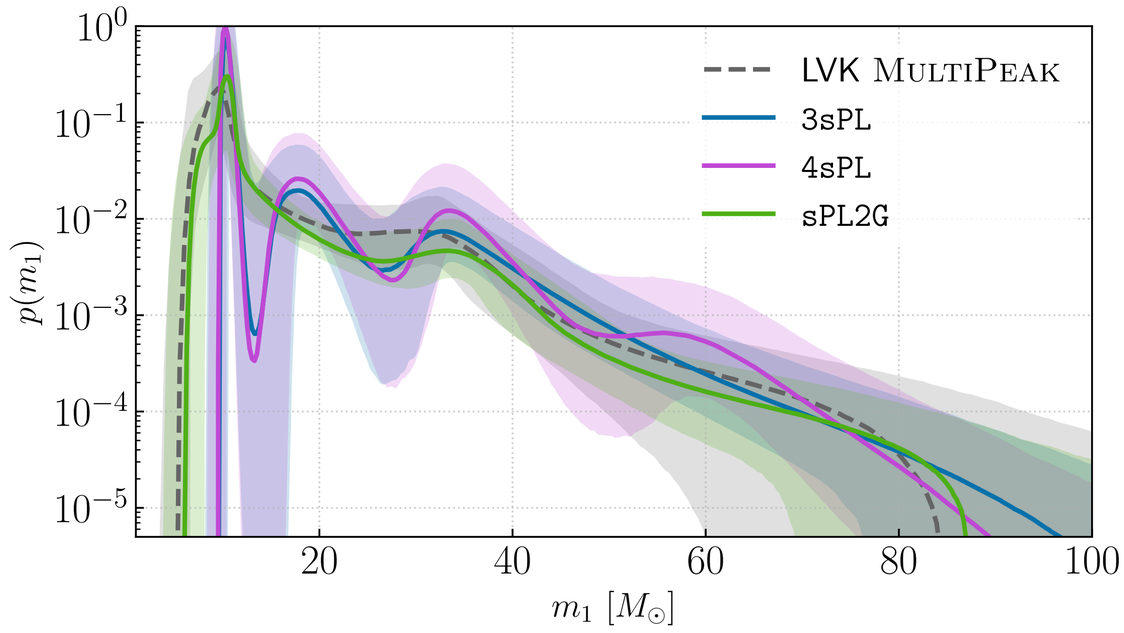
2.4 cosmological inference

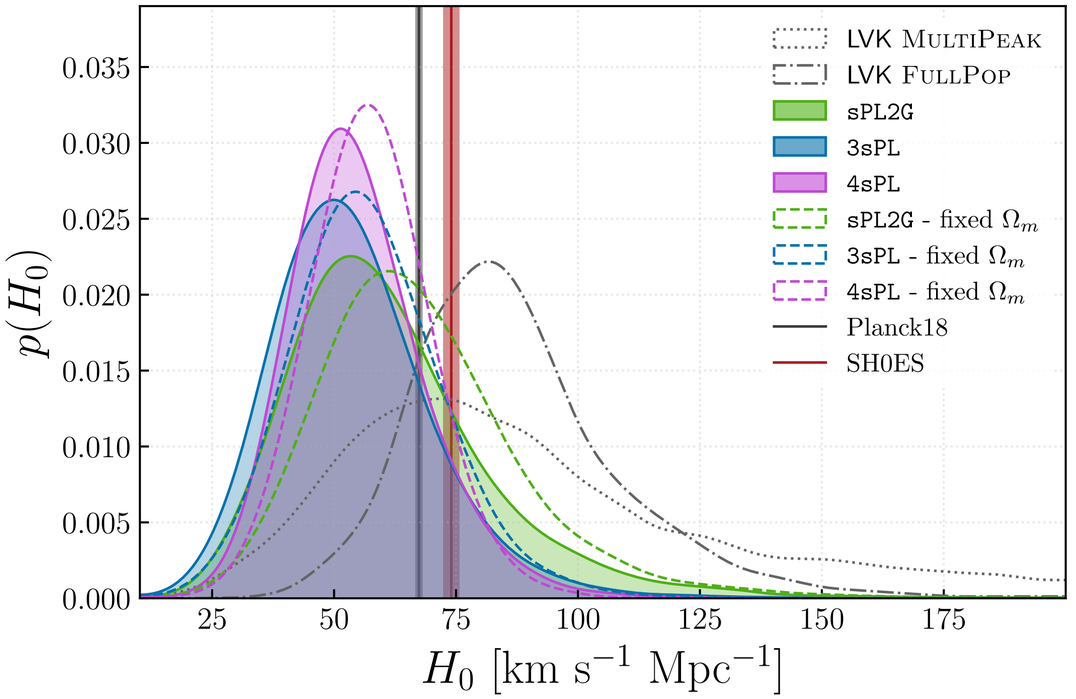
GWTC-4 with power-laws

Bertheas, Gennari+ (2026) [2603.06792]

23 % **precision**!

- improvement compared to LVK analysis
- constraints comparable to BBHs+NSBHs, but only using BBHs



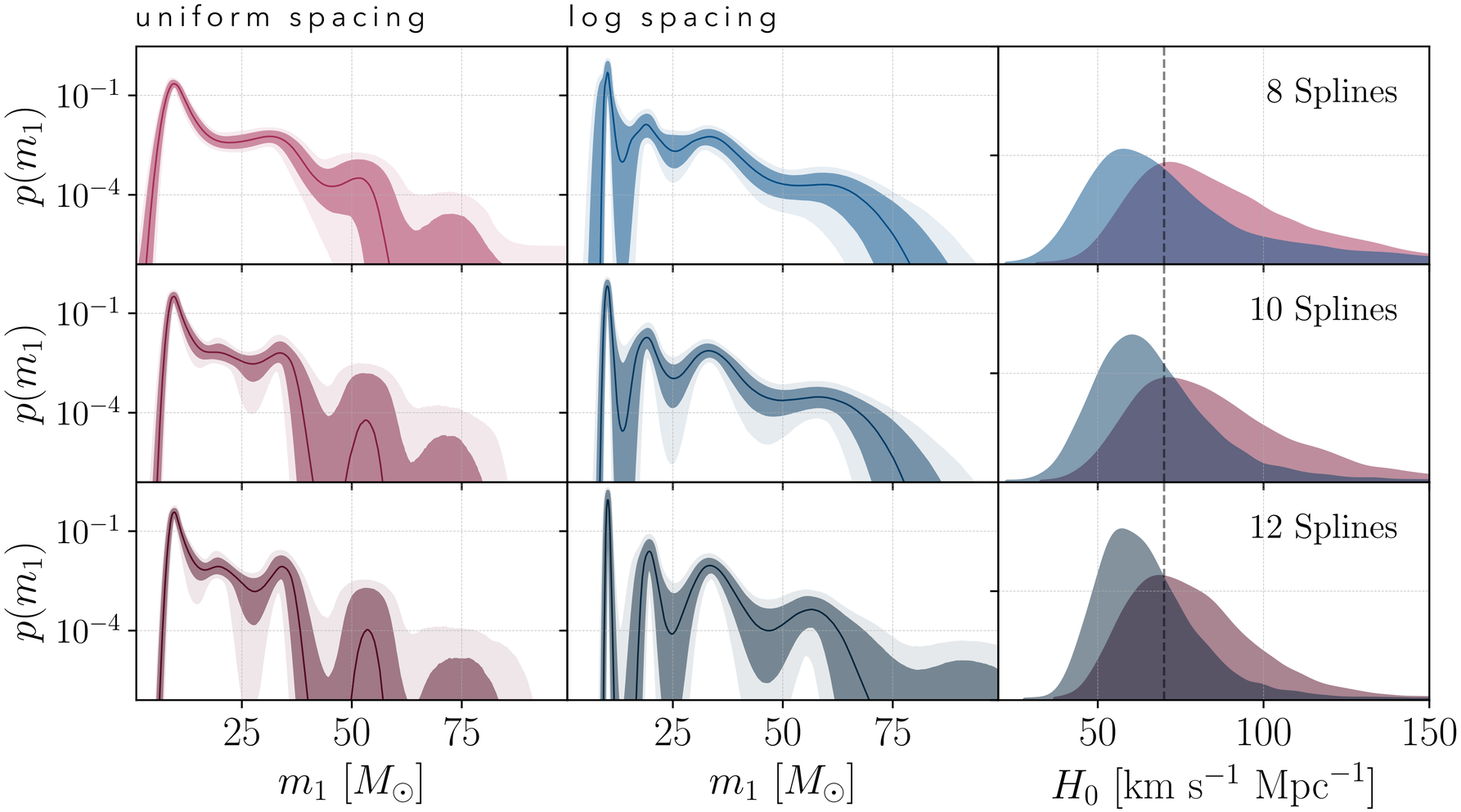


expected by resolving more structure

how much does it depend on the modelling assumptions?

using B-splines

more structure, better constraints



isolating sub-populations

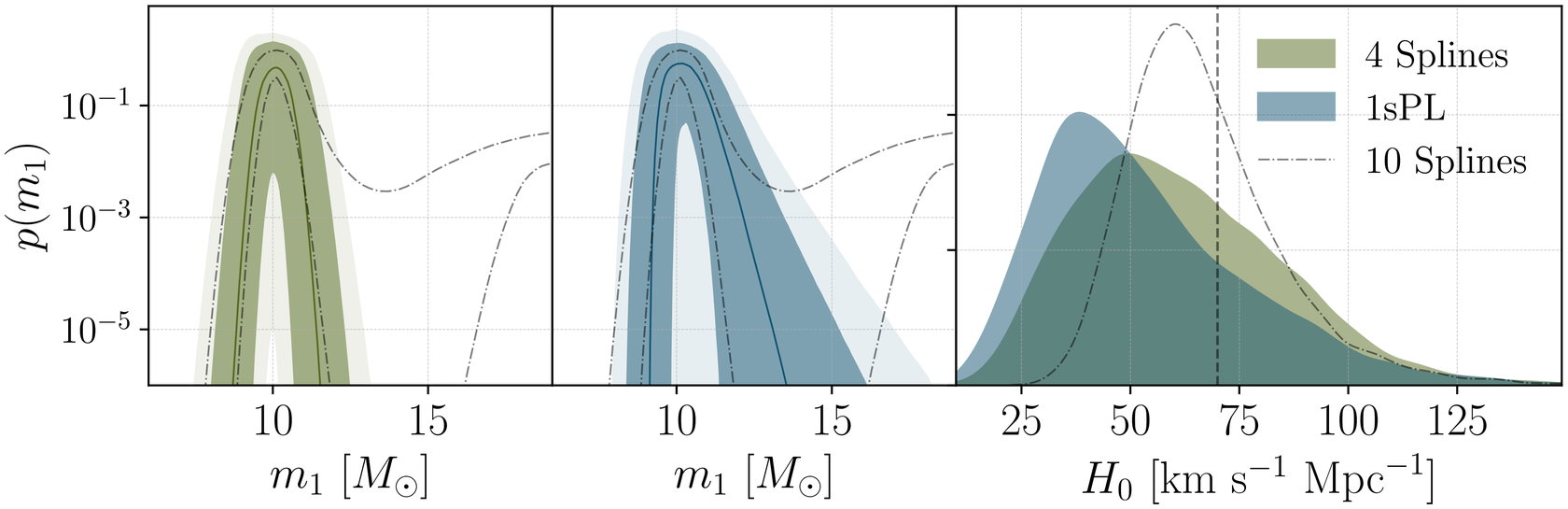
could it work?

Gennari+ (2026) [2604.14290]

manually select

events "belonging"

to the $10M_\odot$ peak



- confirms that most of the cosmological information comes from this feature
- sub-population reconstruction is consistent with the full analysis

it may be a new direction to mitigate systematics

- compactness peaks provide confined populations with shared astrophysics

→ *need to robustly characterise selection effects*

2.5 prospects and problems

O5 forecasts

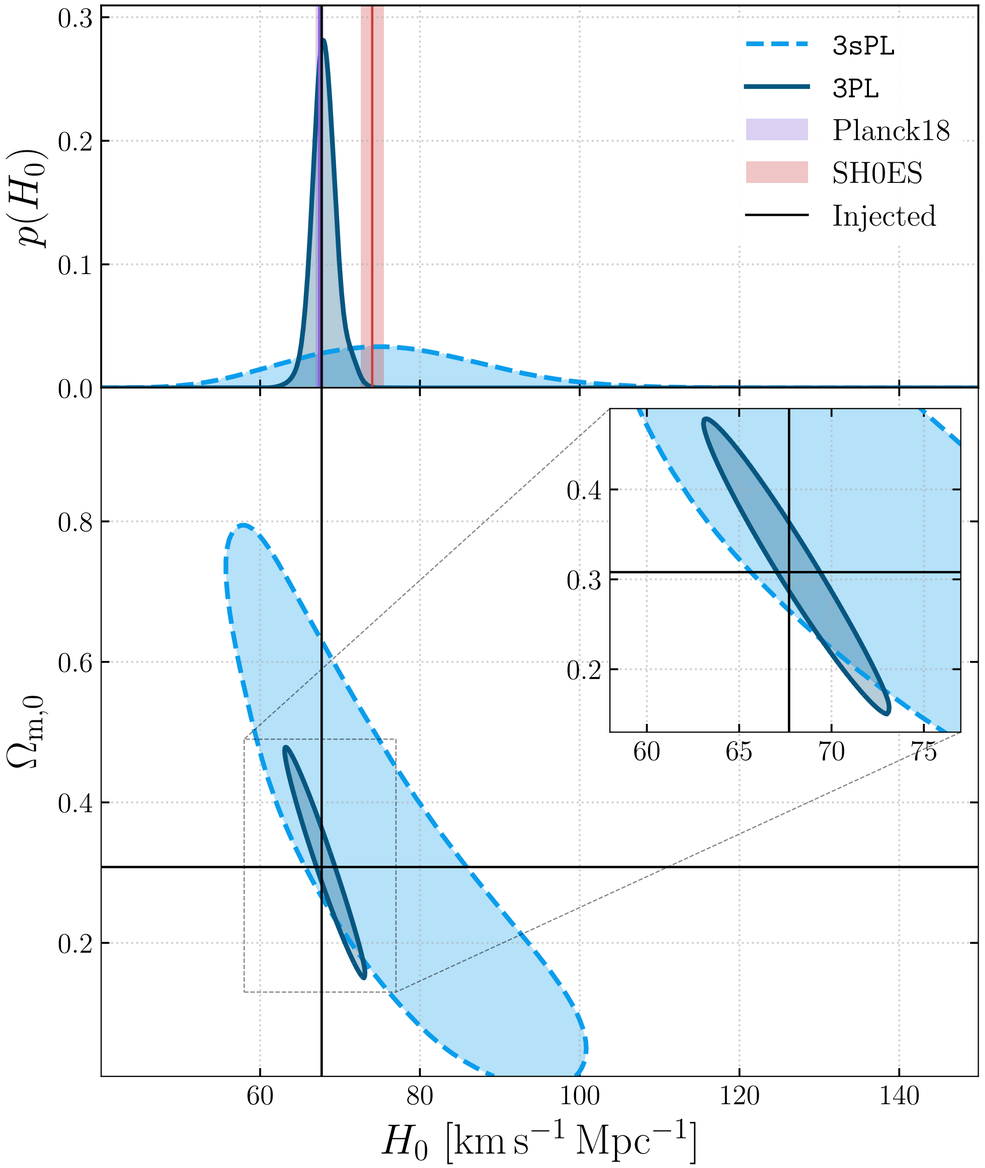
what about the future?

Bertheas, Gennari+ (2025) [2508.19331]

simulated datasets from current data fits of power-law models using 1500 events

- results significantly depend on the underlying population model
- a very sharp $10M_\odot$ peak may deliver $\sim 3\%$ precision and solve the Hubble tension using the population alone

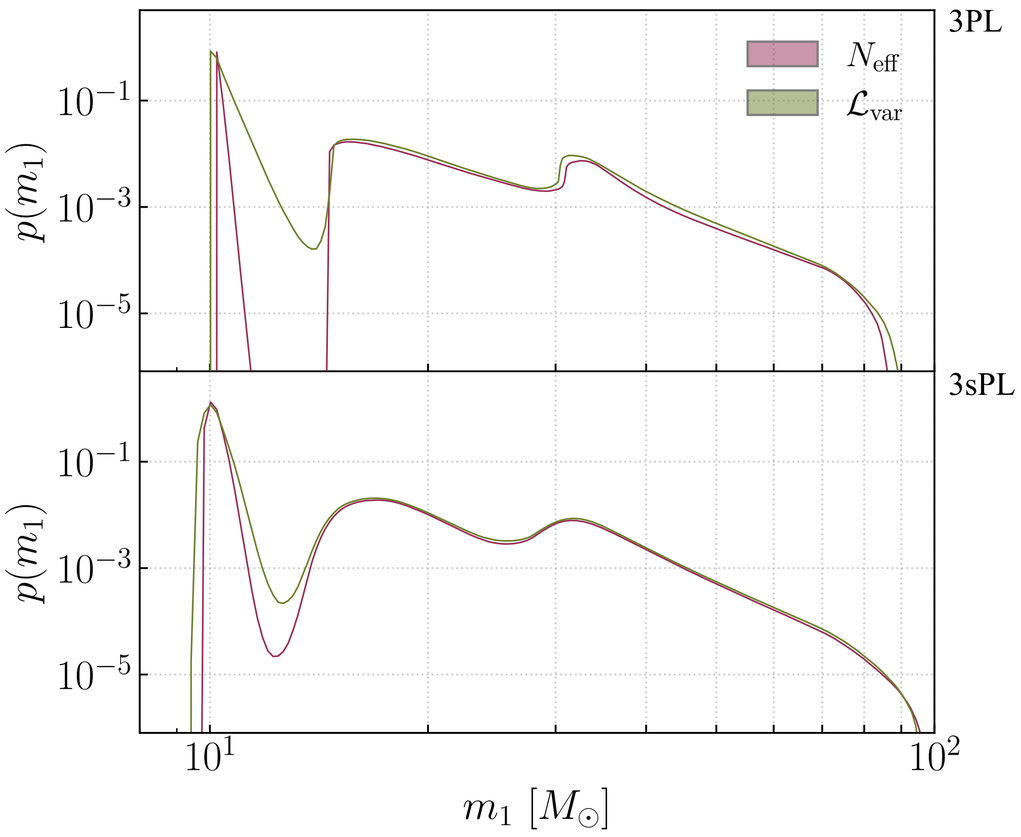
results depend on the population model



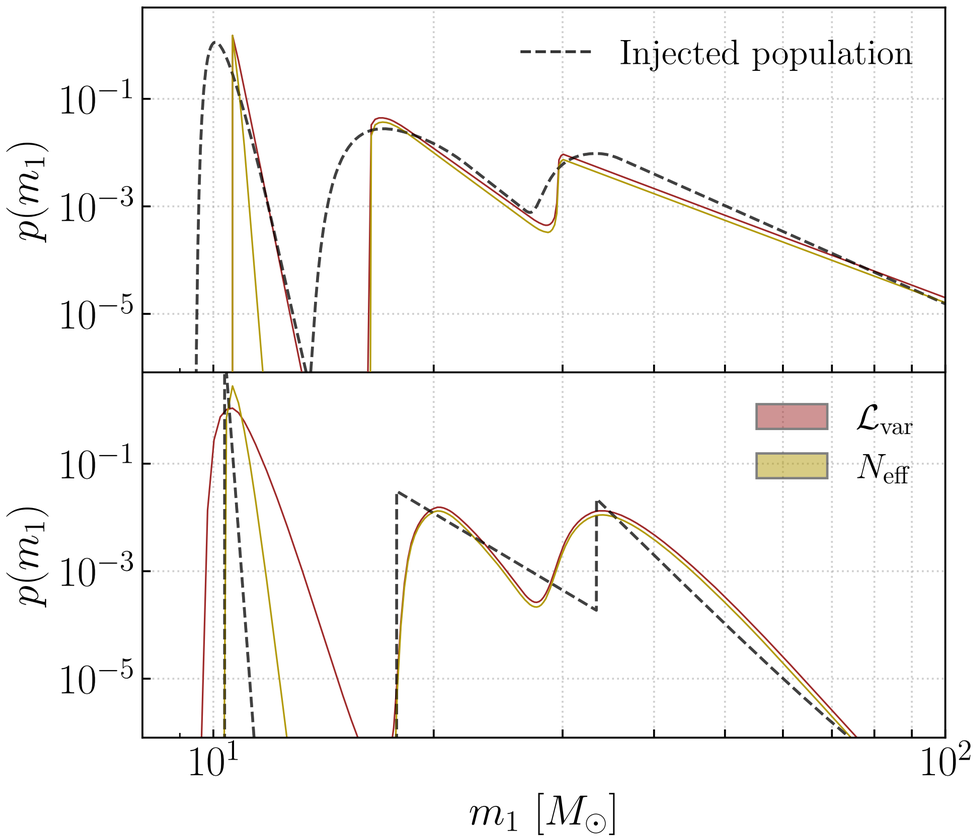
numerical stability

both the numerical stability cut and the smoothing determine the sharpness of the $10 M_\odot$ peak

real data



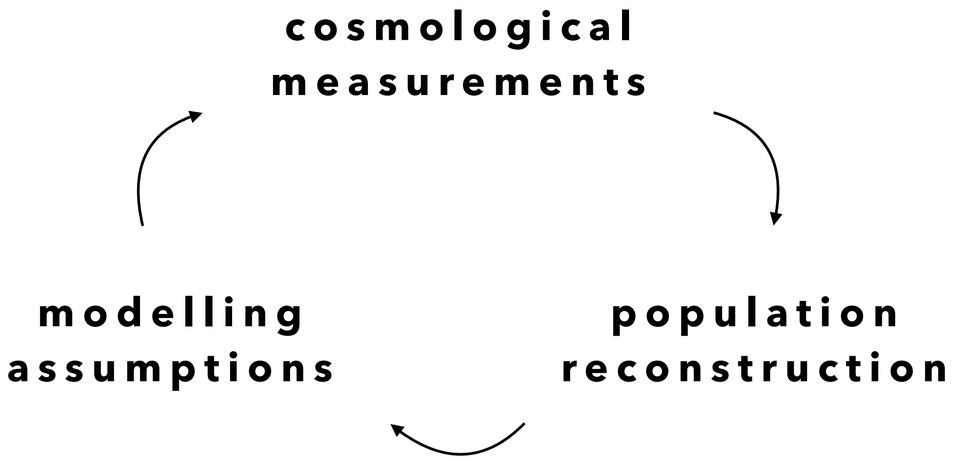
simulation



this affects Bayes factors: high likelihood values in the excised parameter space

current status

is this approach actually reliable?



the main results obtained

- current data support a narrow low-mass population, which may provide accurate cosmological measurements
- the characterisation of this feature is beyond the reach of current sensitivities with current methods

open questions

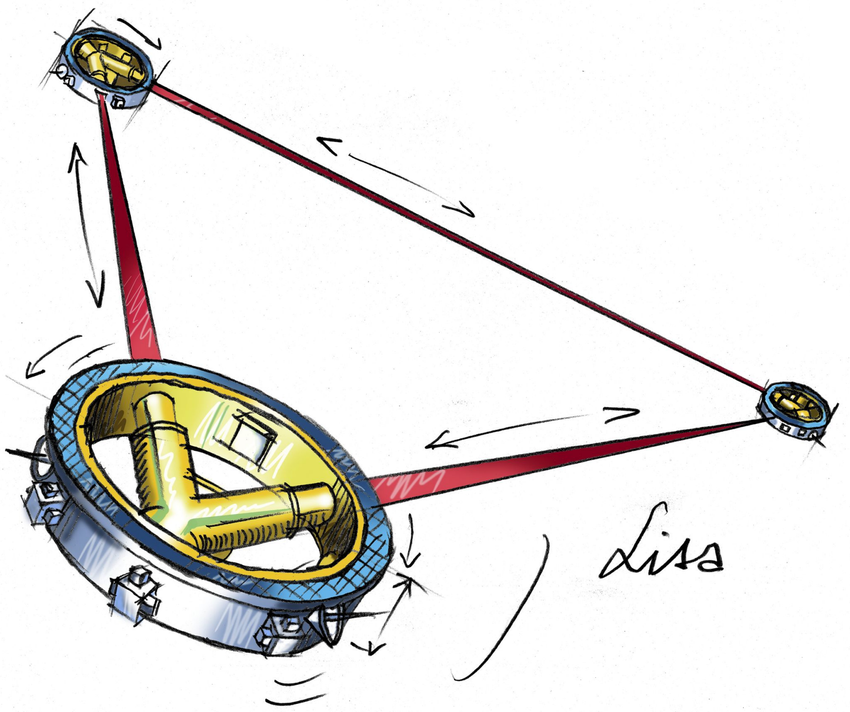
- development of methods to characterise its intrinsic width (e.g. population sampling, entropy bounds)
- isolate subpopulations (statistics and astrophysics)

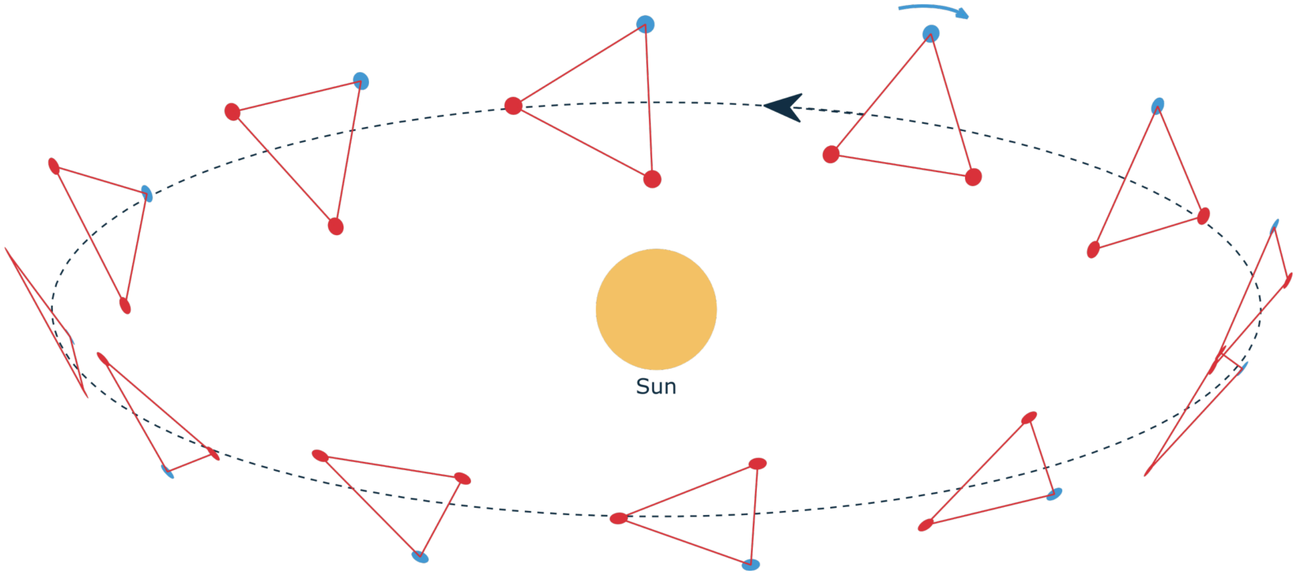
3. future space-based detectors

LISA

space-based detector

planned for 2035



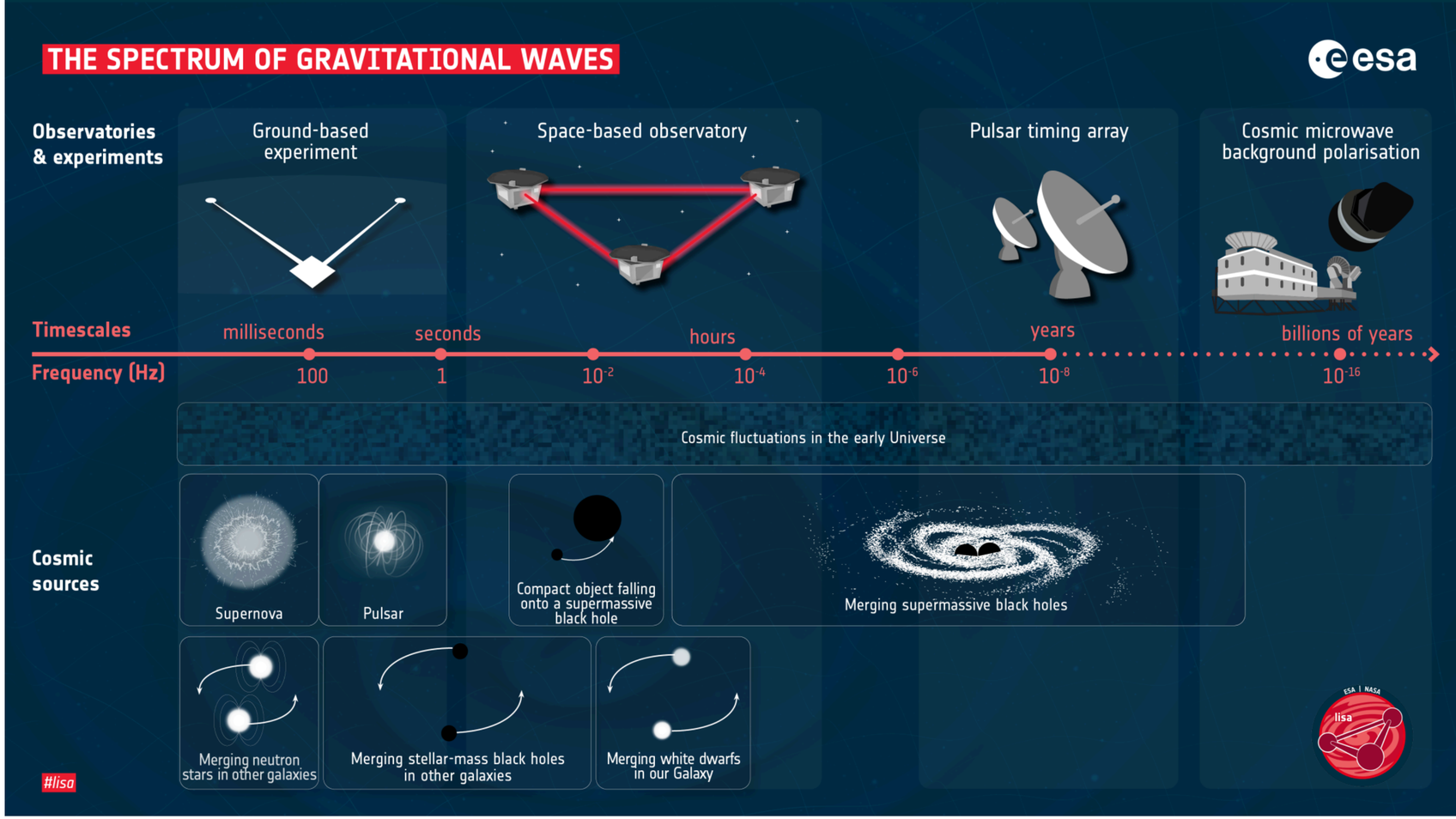


- first gravitational-wave detector in space
- 2.5 millions km arms
- new sources in the millihertz band

what science will we be able to do?

objectives

- probing evolution of massive black holes
- dynamics around massive black holes
- fundamental physics
- binary stars in our galaxy
- probe the expansion of the Universe



Colpi+ (2025) [2402.07571]

what populations will we see?

which features will they have?

will we be able to do cosmology?

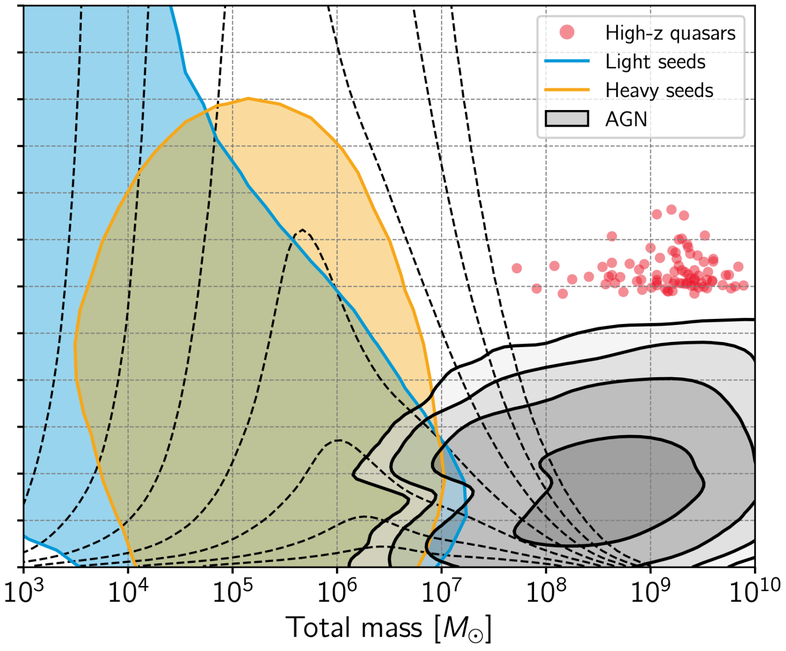
→ need to rely on simulations

massive black hole predictions

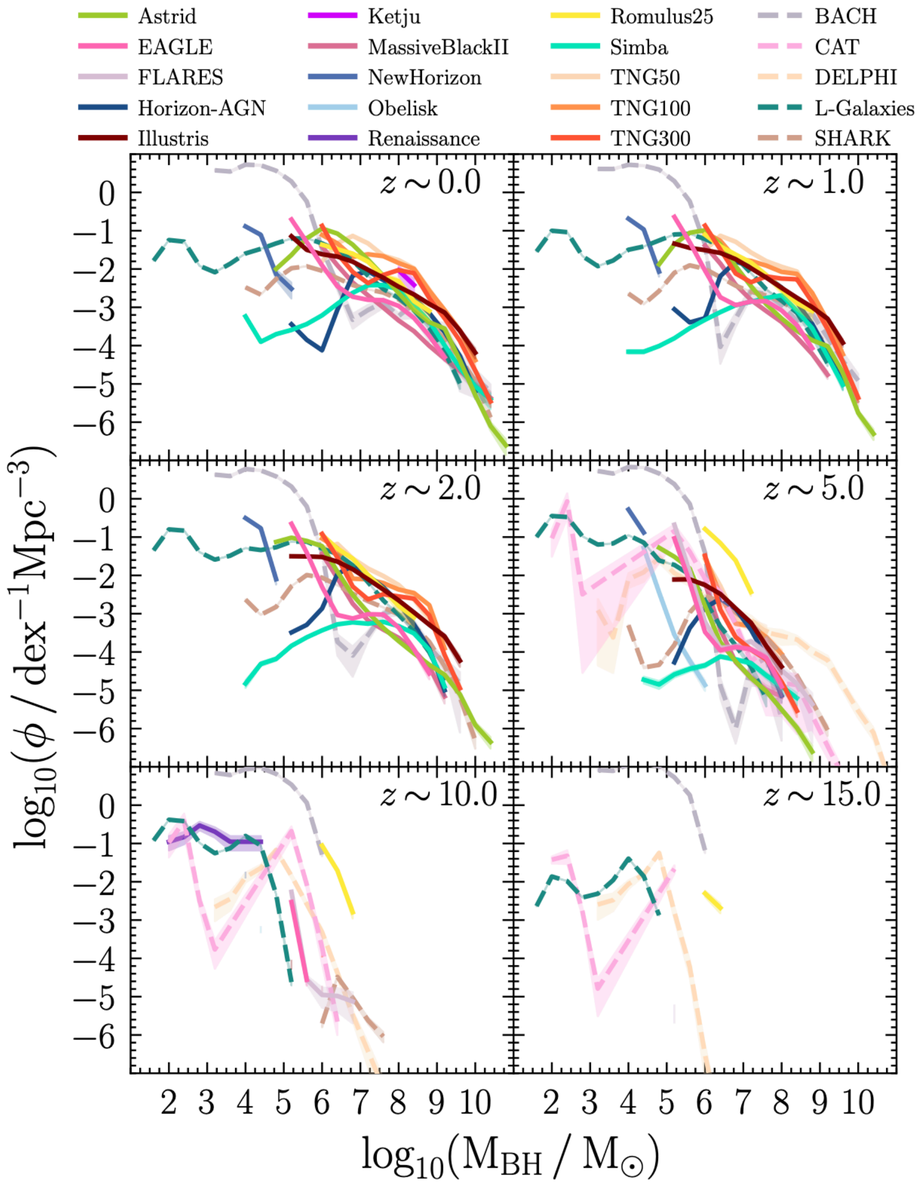
two main ways of creating a future massive black hole

- **heavy seeds** redshifts $10-20$, masses 10^3-10^5
- **light seeds** redshifts $15-30$, masses 10^2-10^3

Colpi+ (2025) [2402.07571]



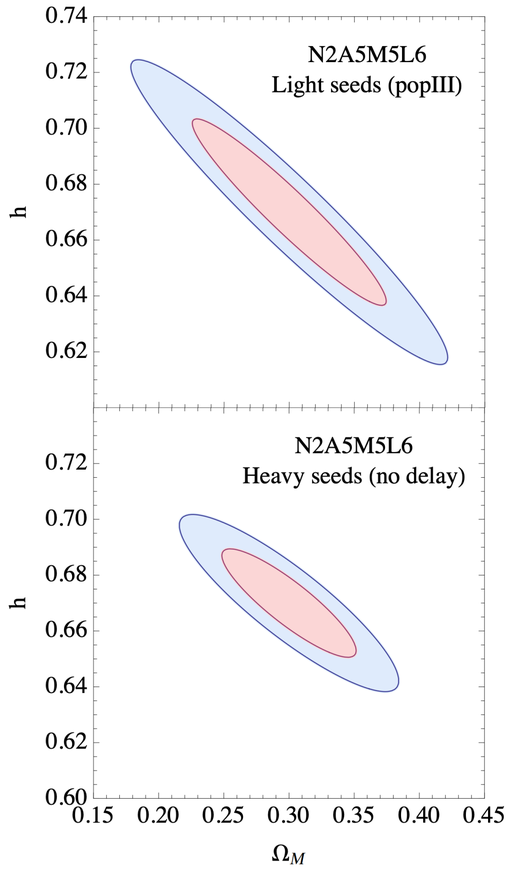
Izquierdo-Villalba+ (2026) [2605.00092]



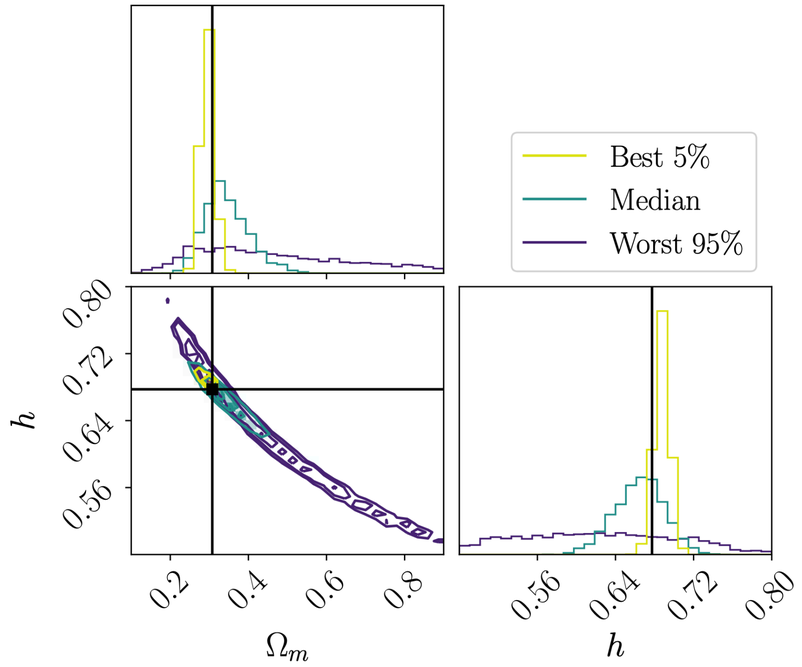
cosmology with MBHs

MBHBs with counterparts

Tamanini+ (2016) [1601.07112]

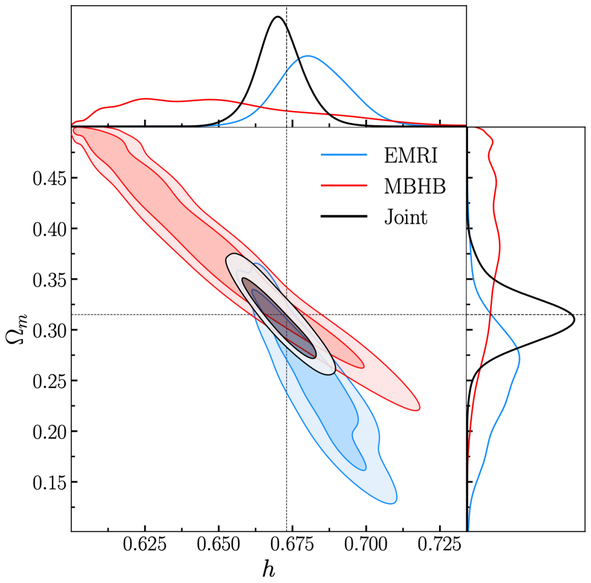


Mangiagli+ (2023) [2312.04632]



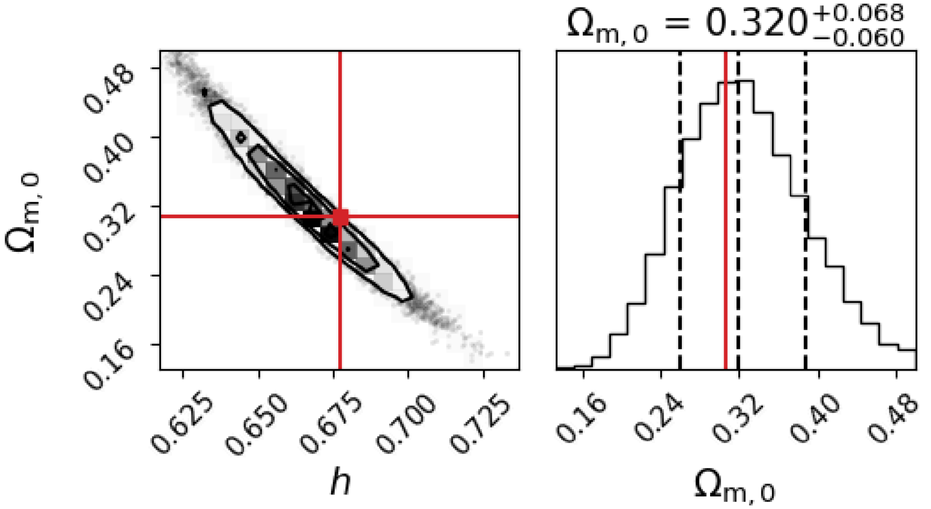
galaxy catalogues

Laghi+ (2026) [2603.23612]



EMRIs

quasi-periodic oscillations



open questions

what motivated our work?

on the **population distribution**

- lack of realistic population inference in the literature
- apply current state-of-the-art methods to LISA sources

on the **cosmological inference**

- no population-based inference in the literature
- implementing the first of this kind

...let's continue!

3.1 massive black hole binaries

Barausse (2012) [1201.5888]

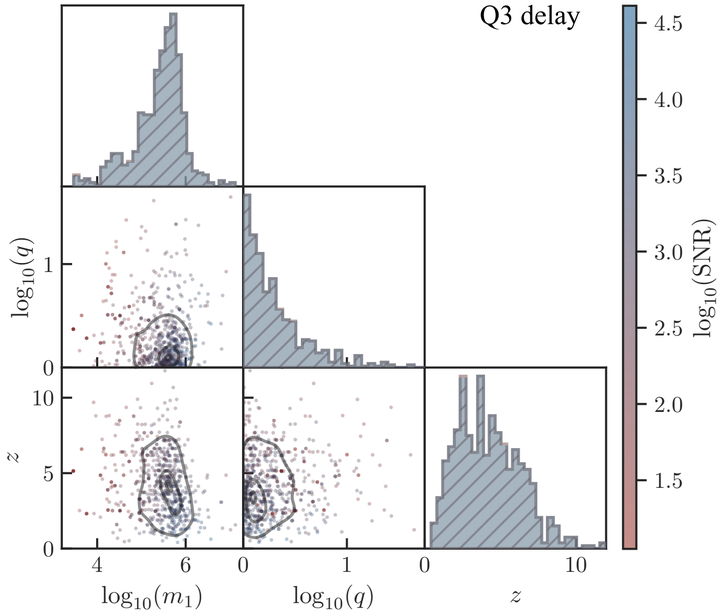
Antonini+ (2015) [1506.02050]

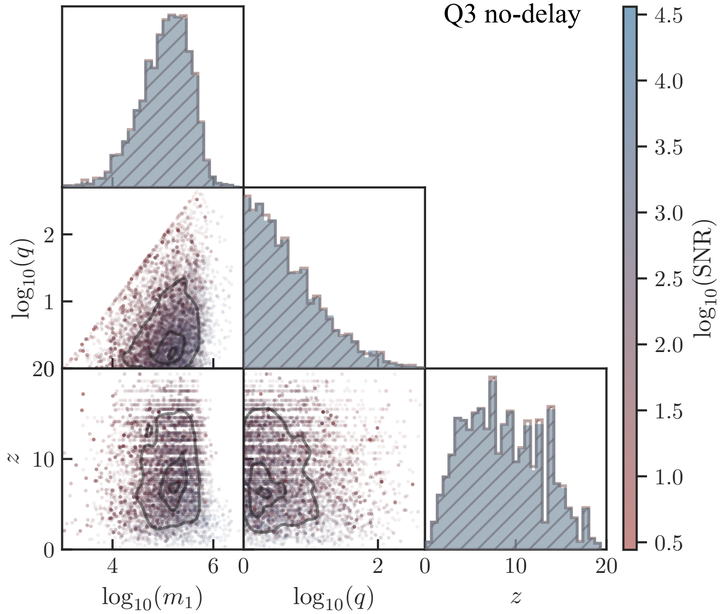
MBHB catalogues

how are they distributed?

we consider two models of heavy-seed populations

- large population uncertainties
- potentially high redshifts





different catalogue size depending on the simulation assumptions

Q3nd

10 yrs ~1200 events

4 yrs ~500 events

Q3d

10 yrs ~70 events

4 yrs ~30 events

being generated semi-analytically, there is no closed-form expression for the population

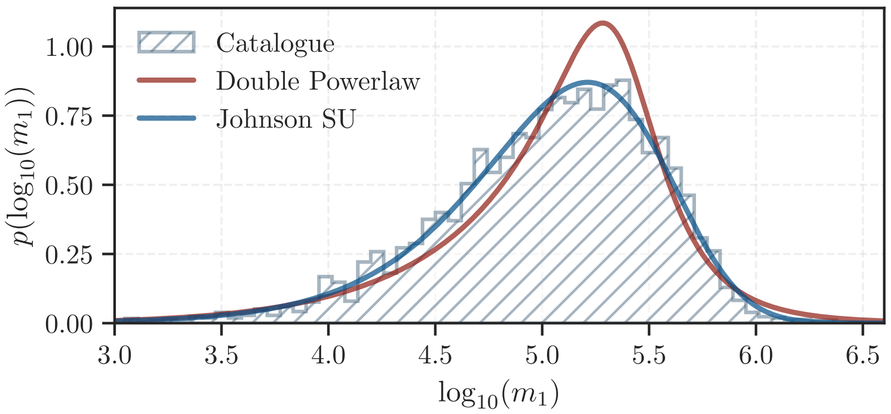
→ *need to find a suitable parametrisation!*

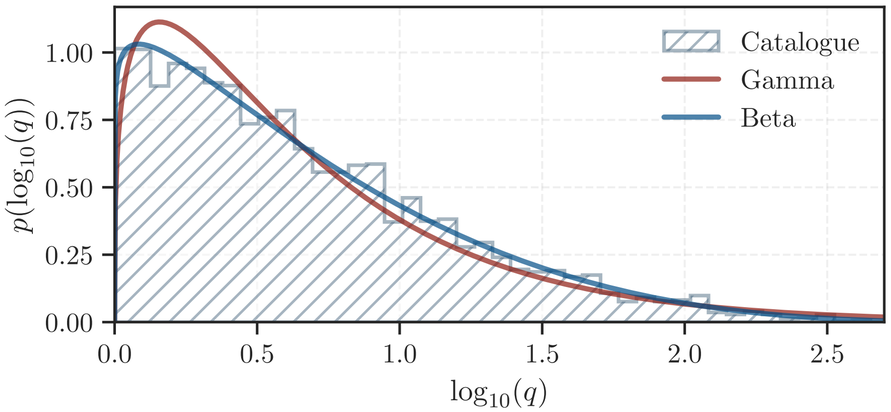
population modelling

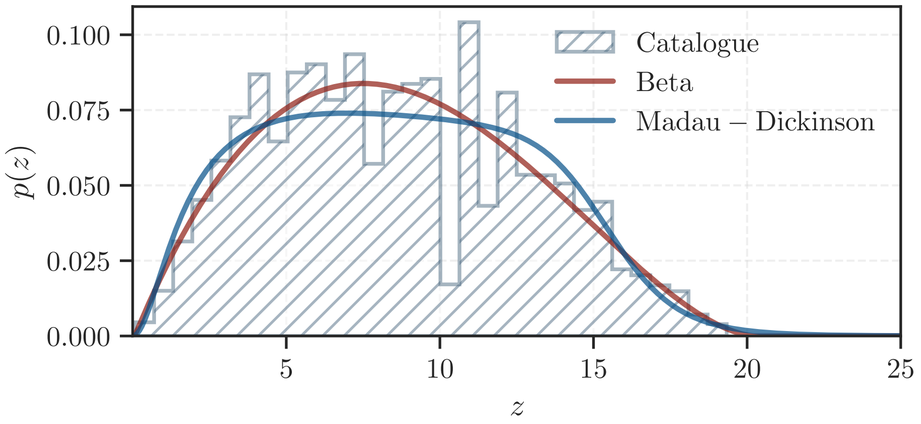
we fit different phenomenological models to the astrophysical data

- choose the model with higher estimated maximum-likelihood
- use both the rate evolution and redshift probability

we use these fits to generate a population that is not affected by systematics *(idealised analysis)*







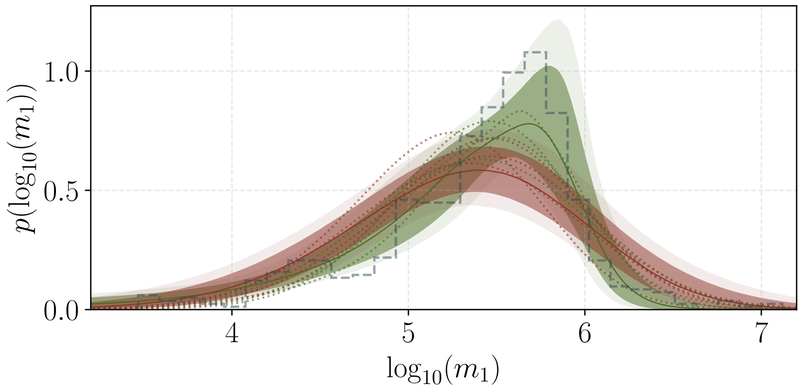
no-delay

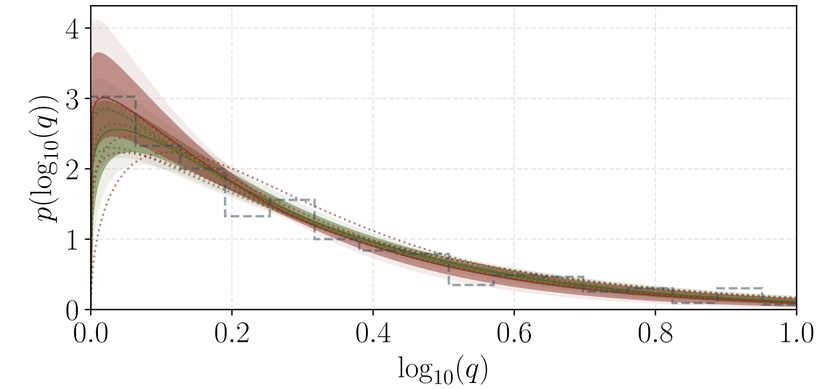
population inference Q3d

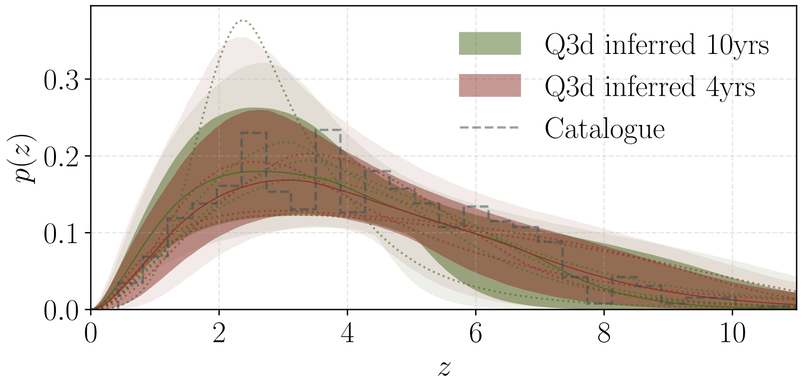
apply hierarchical inference on the datasets

- larger variations on the semi-analytic model
- depend on mission realisation
- consistent results with simulated data

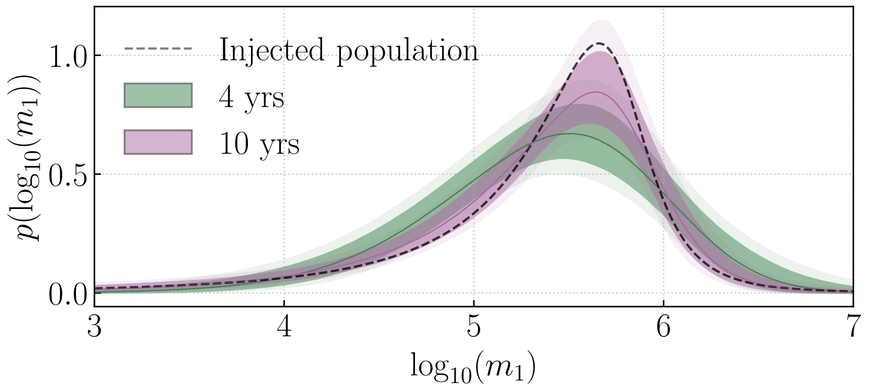
semi-analytic

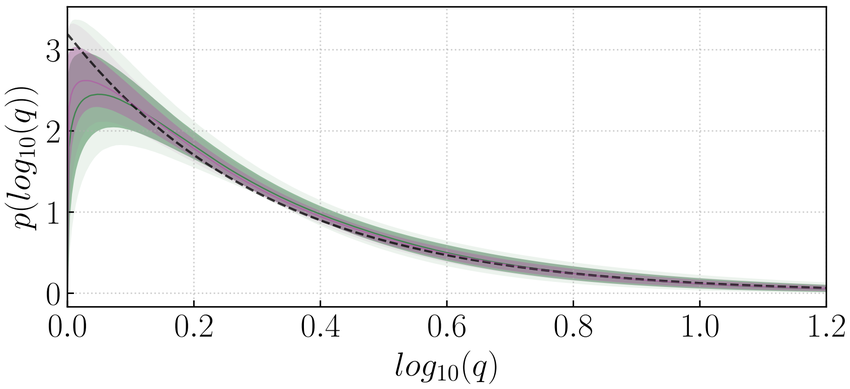


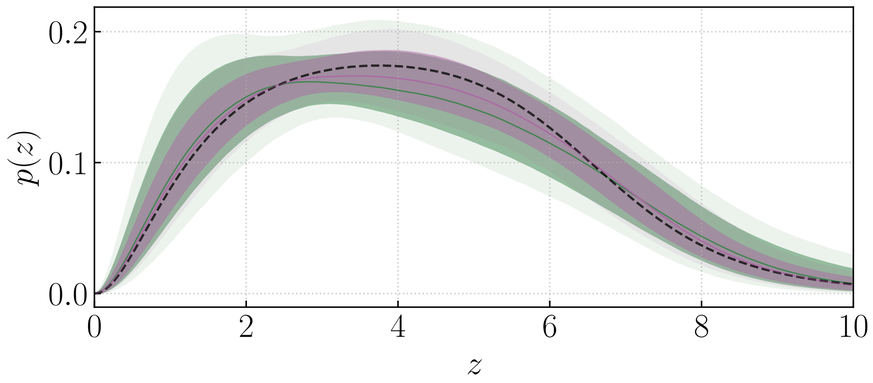




exact population





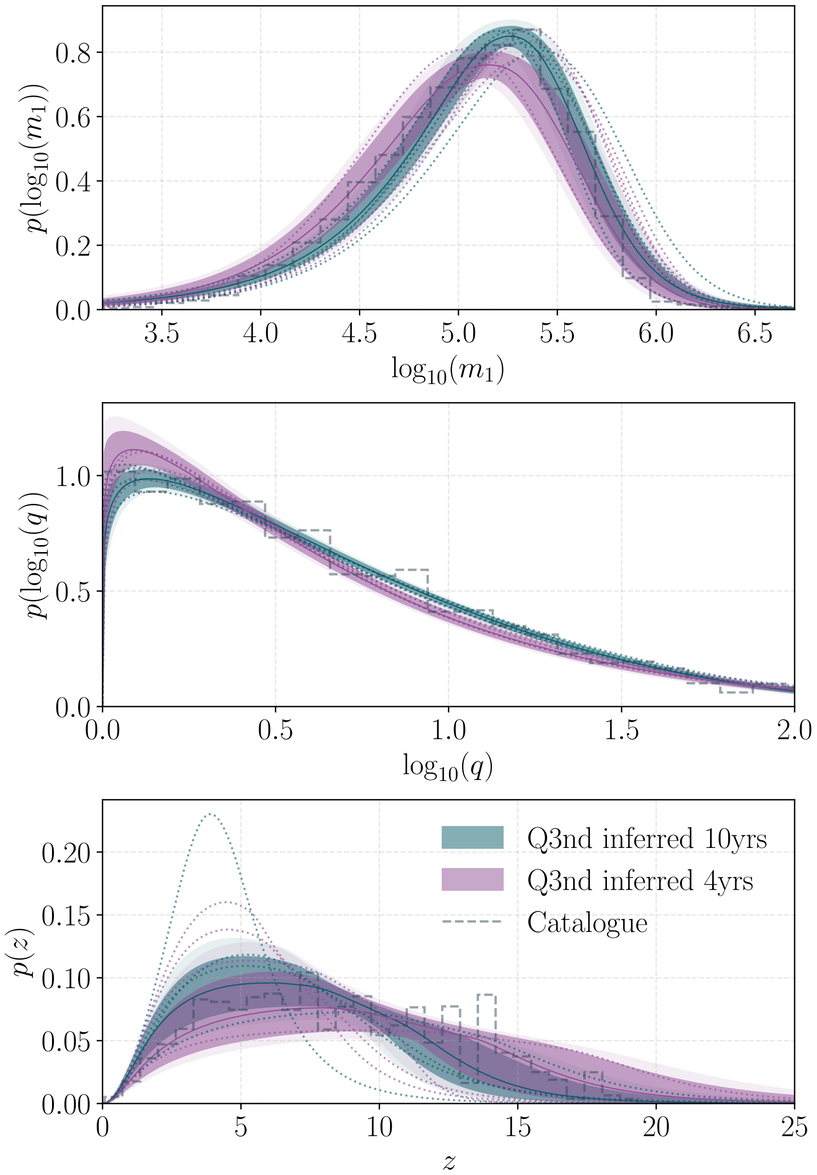


population inference Q3nd

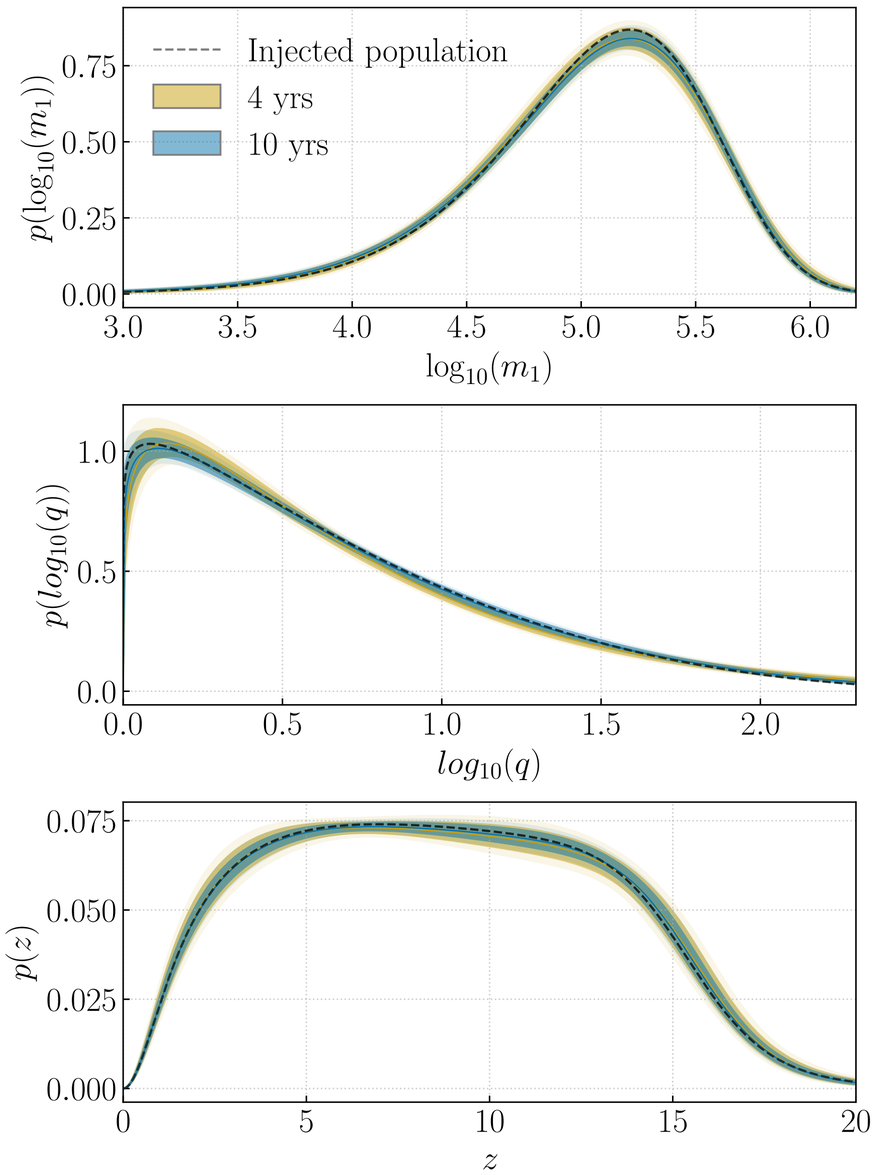
apply hierarchical inference on the datasets

- larger variations on the semi-analytic model
- depend on mission realisation
- consistent results with simulated data

semi-analytic



exact population



cosmological inference

we find in general poor constraints due to the lack of features

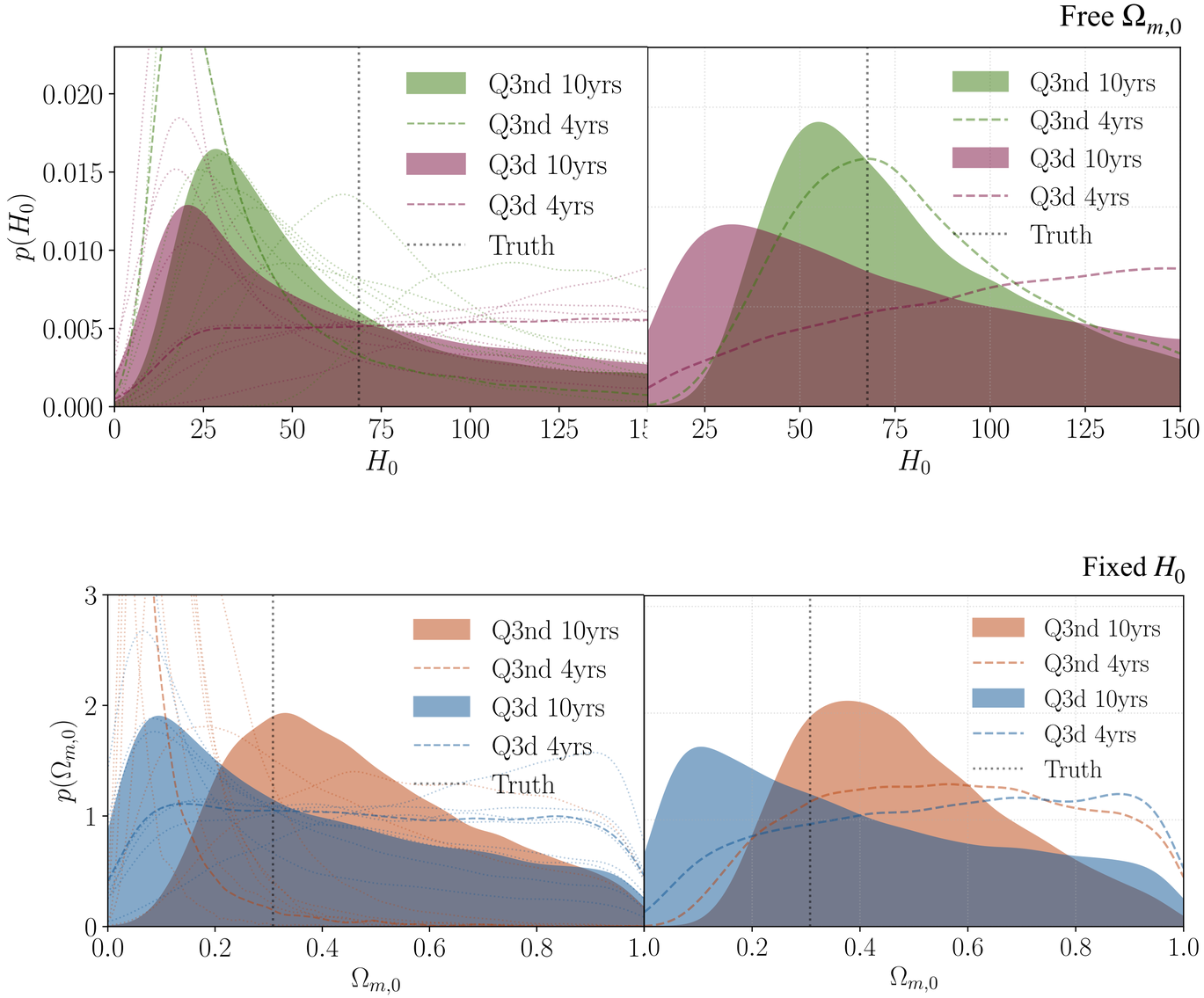
many things may improve it

- richer astrophysics (more features)
- combination with other probes

in the absence of better catalogues *only LISA will tell...*

semi-analytic

exact population



3.2 extreme mass-ratio inspirals

EMRI catalogues

Babak+ (2017) [1703.09722]

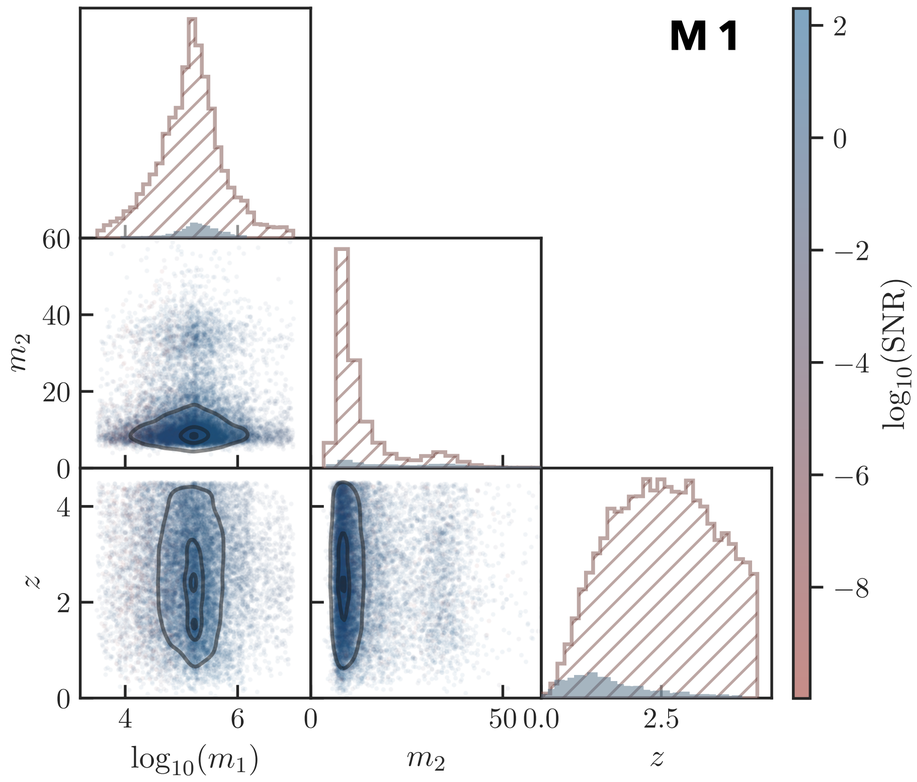
Piarulli+ (in prep.)

EMRI detections are very uncertain,
ranging from zero to thousands events

only one fiducial catalogue for the moment

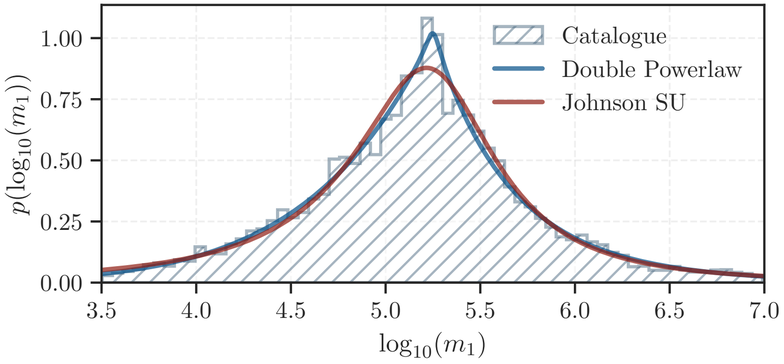
- selection effects are highly relevant
- smaller redshifts than MBHBs
- secondary object may have more structure

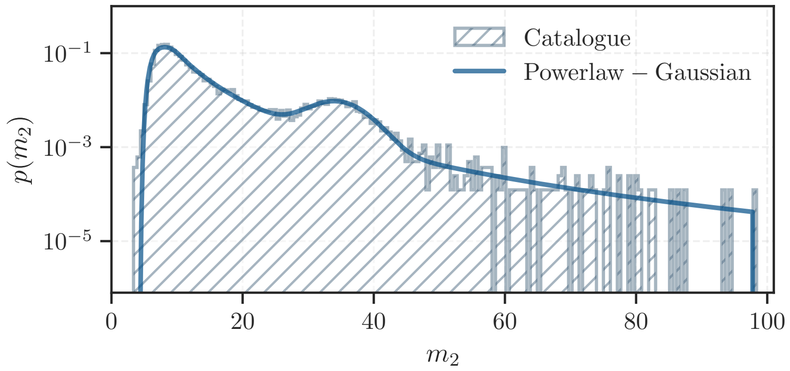
SNR evaluation very expensive, not easy to estimate selection effects

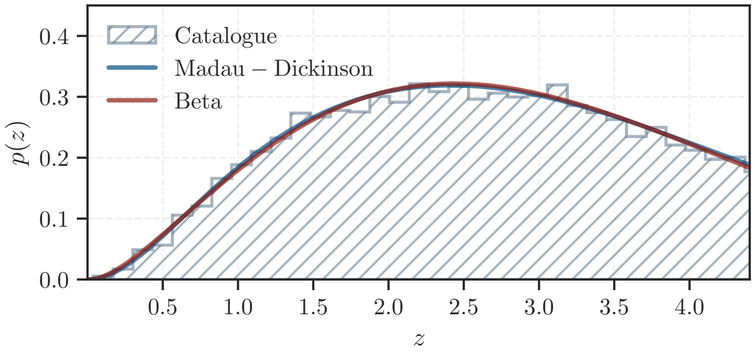


same procedure used for MBHBs:
population fits, hierarchical inference,
population-based cosmology

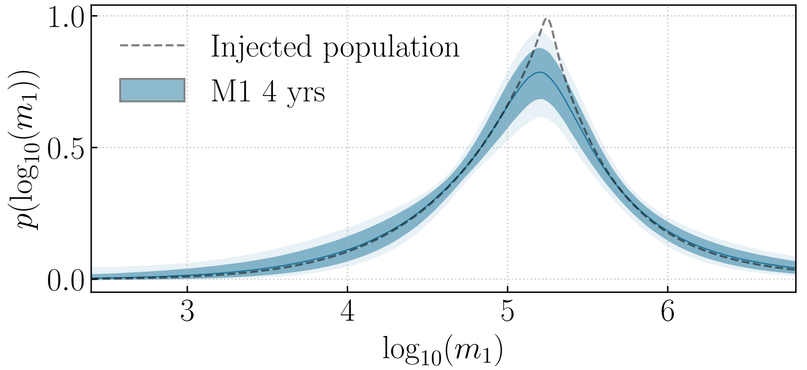
population modelling and inference

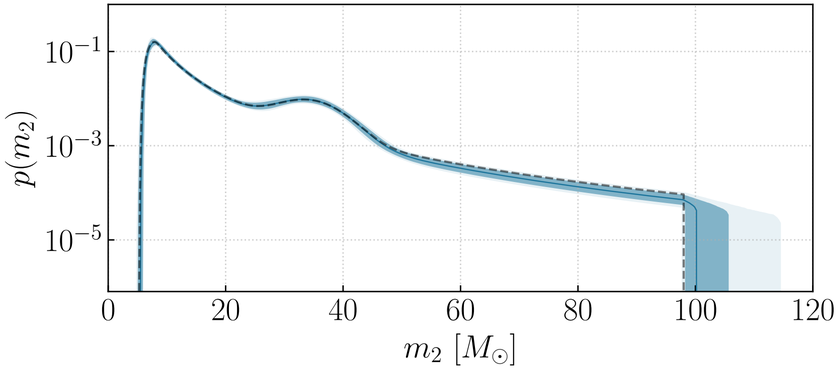


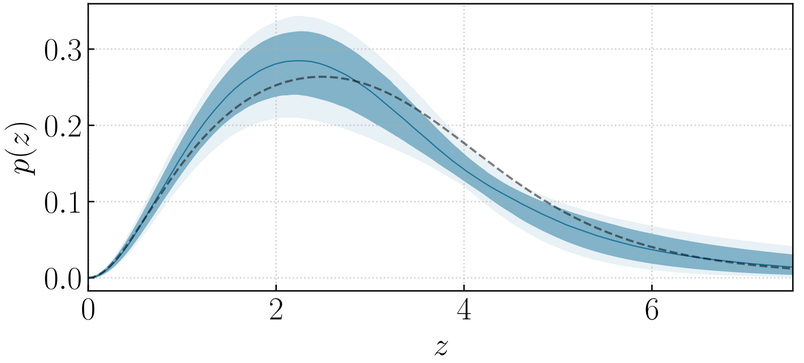




fitting to hierarchical inference







cosmology and source combination

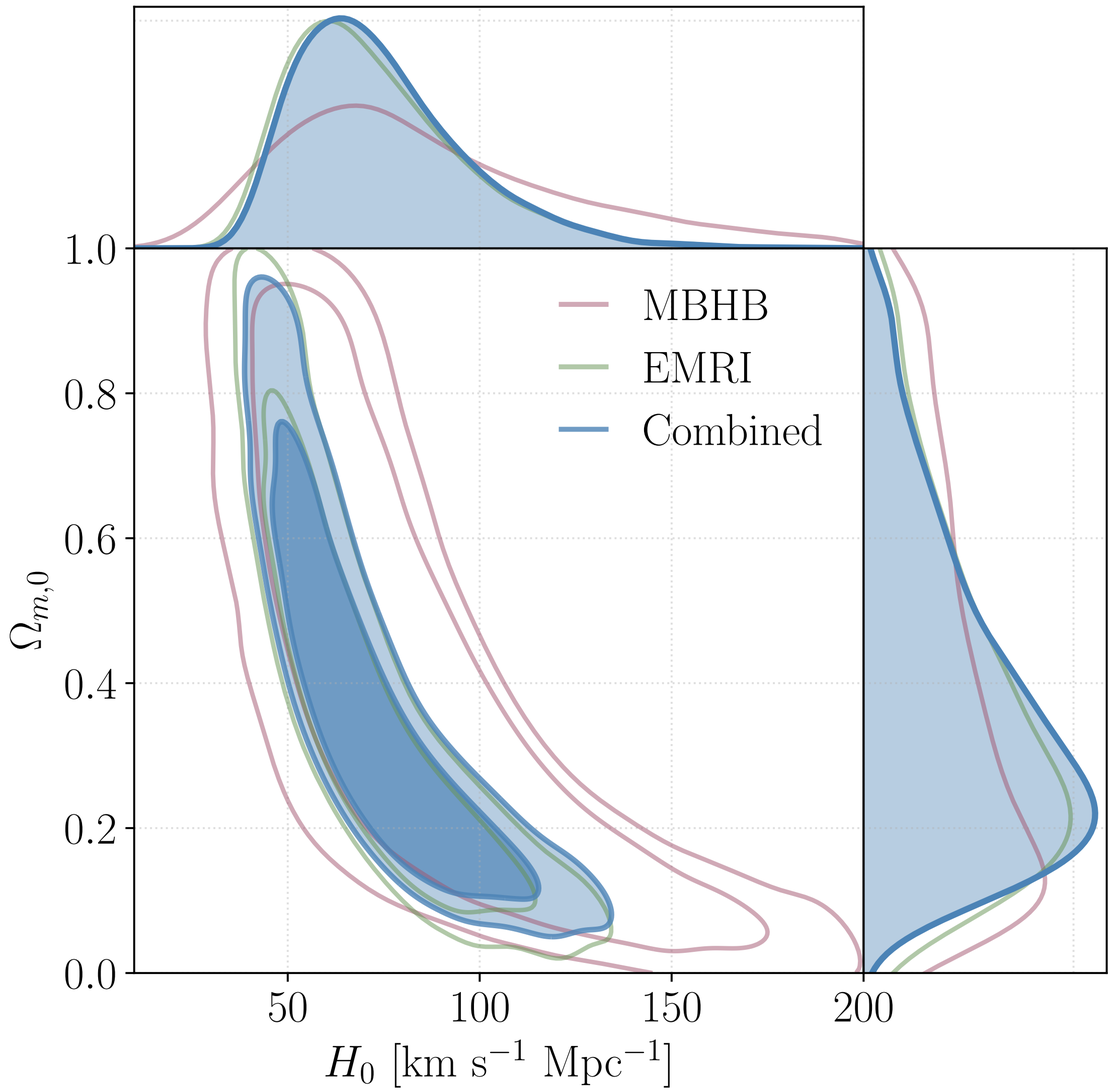
can we improve on cosmological constraints?

improved results compared to MBHBs

but still far from precision cosmology

- unique high-redshift information but insufficient population features
- need more reliable predicted populations but unknown until LISA will fly

cosmology with LISA will likely require combination with EM information



current status

population-based cosmology with LISA?

the main results

- population-based inference with massive black holes does not seem a reliable route due to the scales of the populations
- features in the secondary object of EMRIs may improve constraints

open questions

- need a more accurate predictions of the EMRI secondary object
- combine EM information (e.g. cross-correlations, backgrounds, counterparts)

4. discussion and conclusions

discussion

how to get to precision cosmology with gravitational waves

the main current problems of population-based inference (in my opinion)

- characterise limitations of redshift evolution-cosmology degeneracy
- improved methods to handle numerical stability
- Bayesian subpopulation isolation (events sharing the same formation channel)

probes combination may be particularly effective

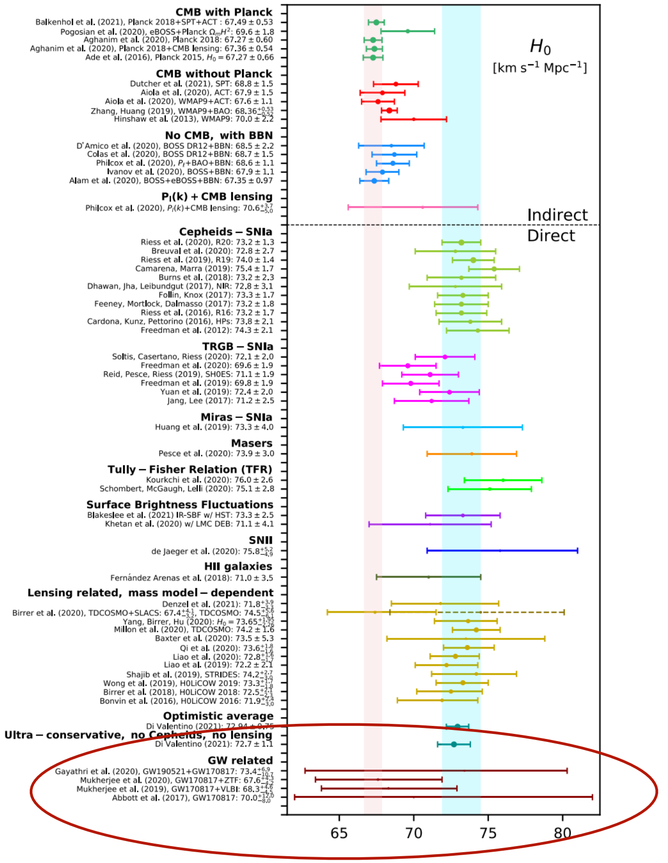
- the $10M$ population with galaxy catalogues (e.g. both cover low redshift, high SNR, good sky localisation: catalogues may be informative)
- for LISA, it seems the best route although need more developments

discussion

however, EM combination need careful treatment

the additional information comes at the cost of

- **importing systematic**
  - can we control EM systematics better than GW?
  - what is the role of GWs if information comes from EM data?
- **combine inconsistent datasets**
  - how to define statistically inconsistent experiments?



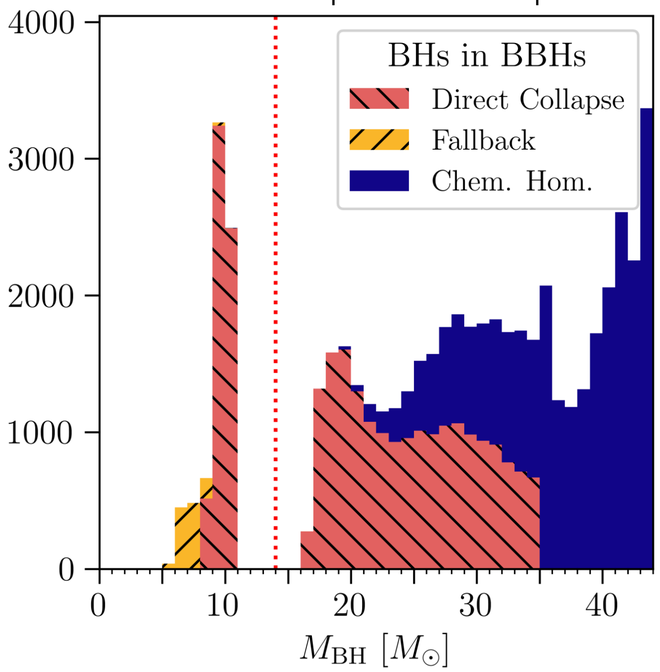
the future of gravitational-wave cosmology is still unclear, but its study has already enabled us to advance our understanding on astrophysics and statistics

thank you for your attention

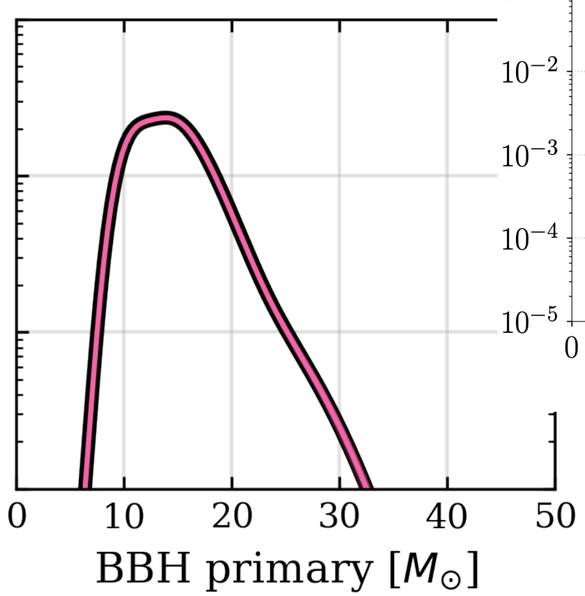
backup slides

population synthesis codes

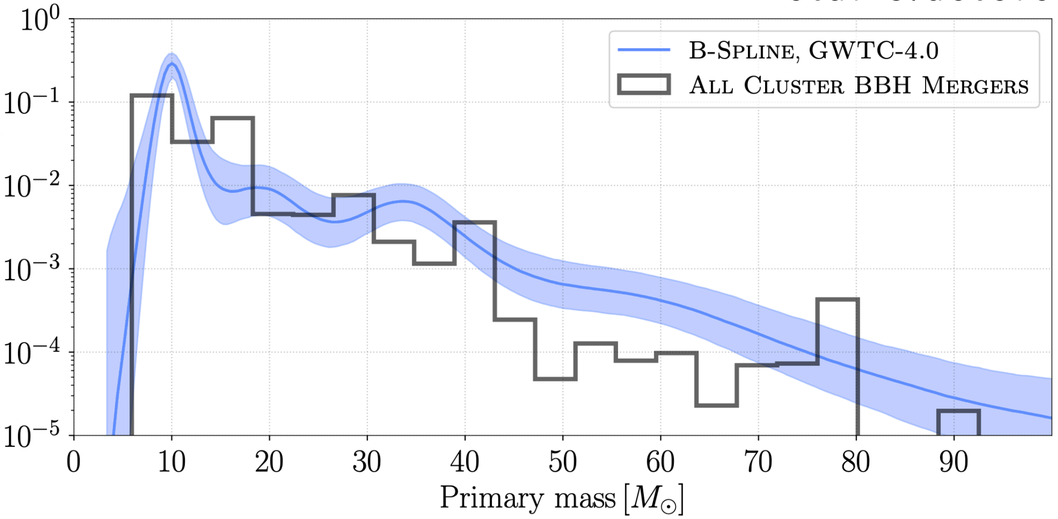
compactness peaks



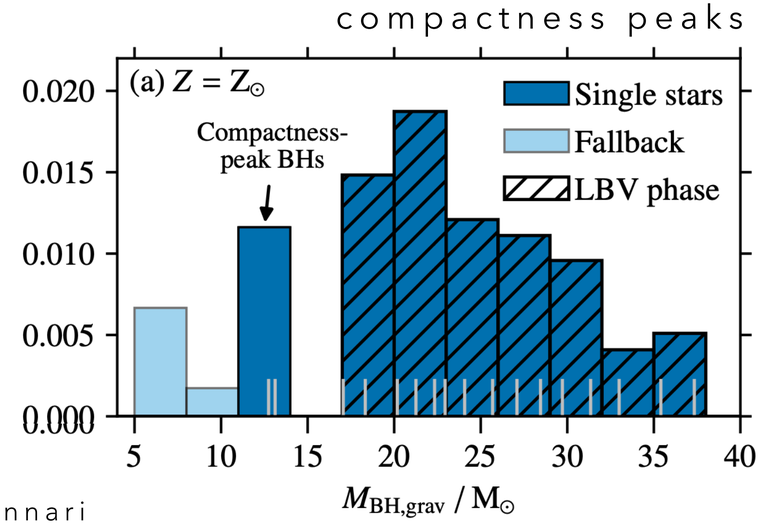
isolated binaries



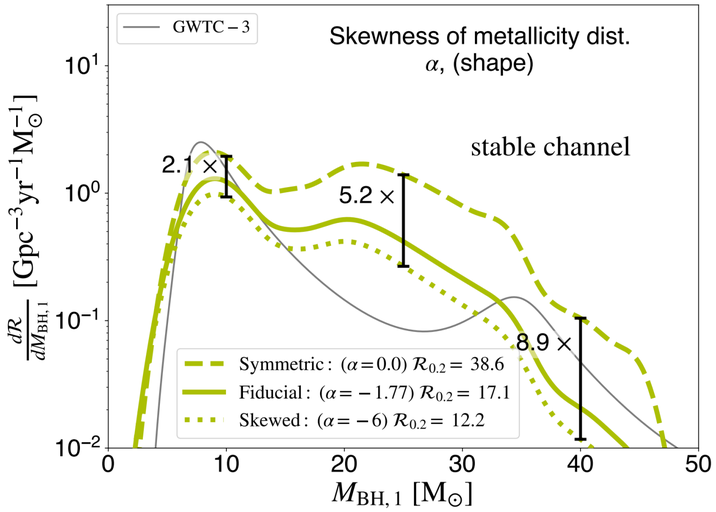
star clusters



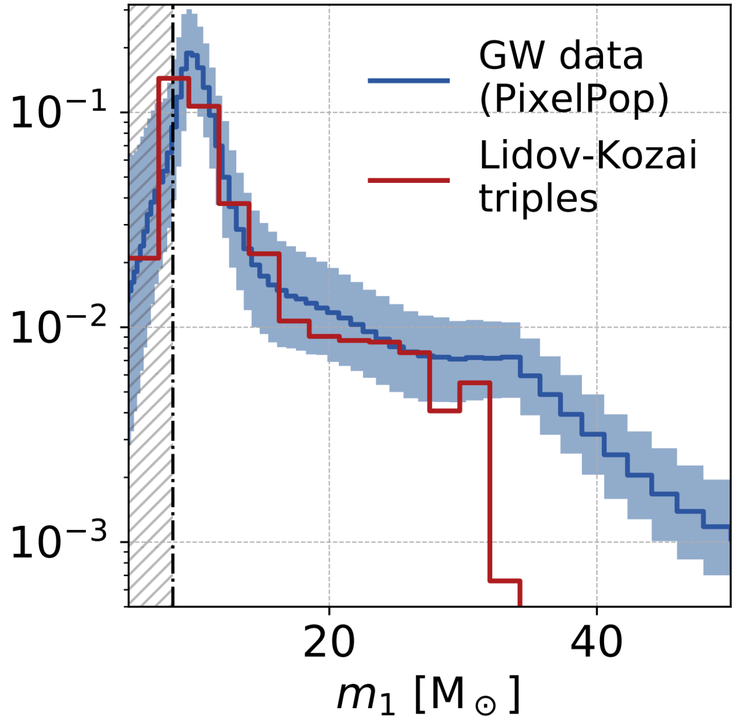
compactness peaks



isolated binaries

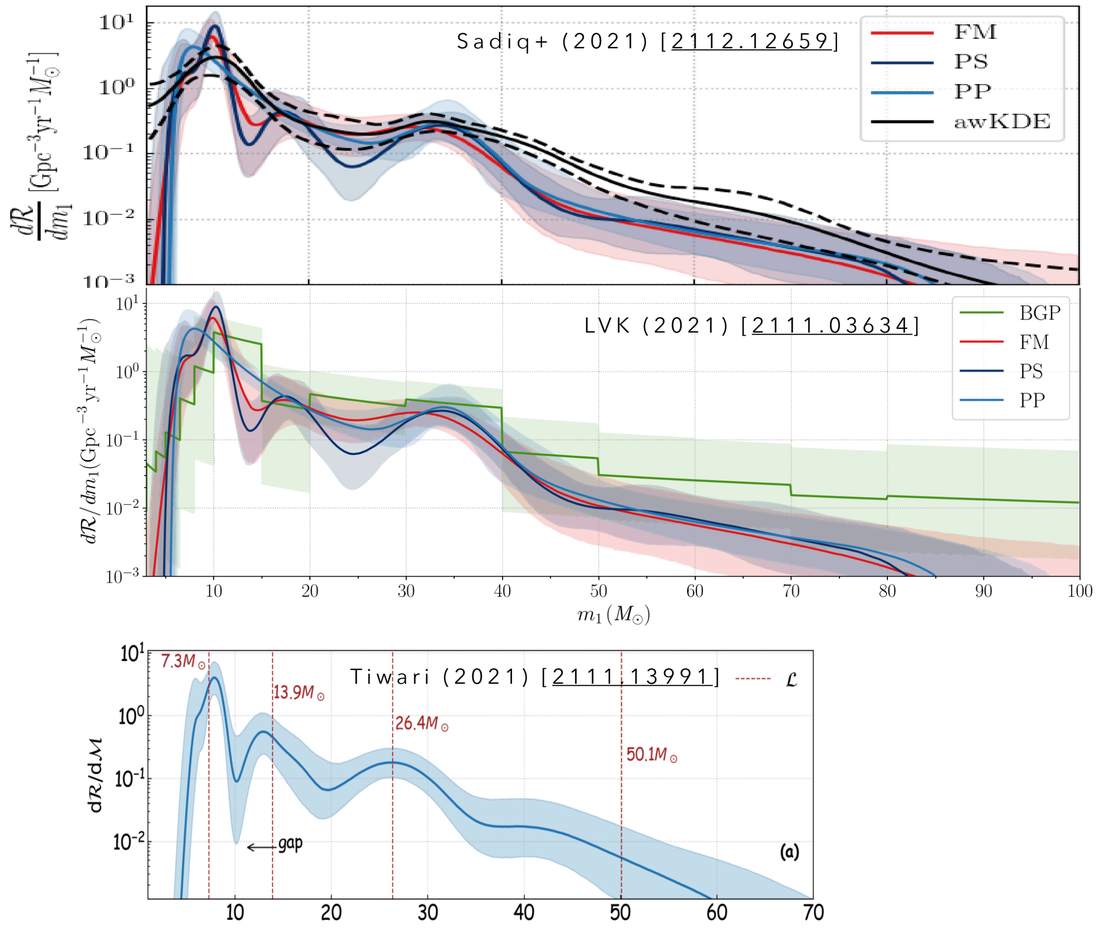


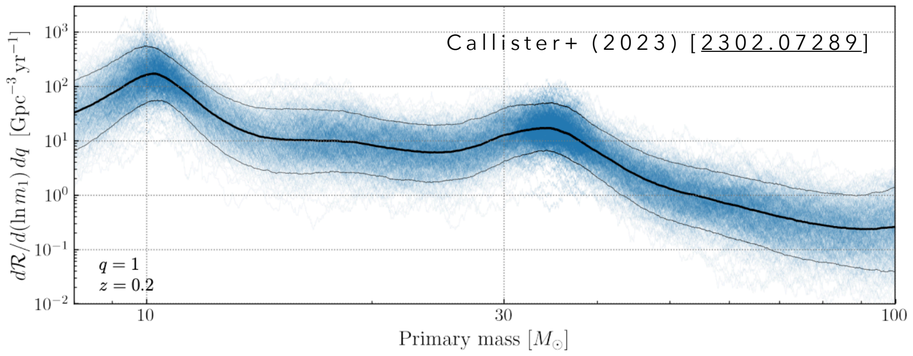
hierarchical triples

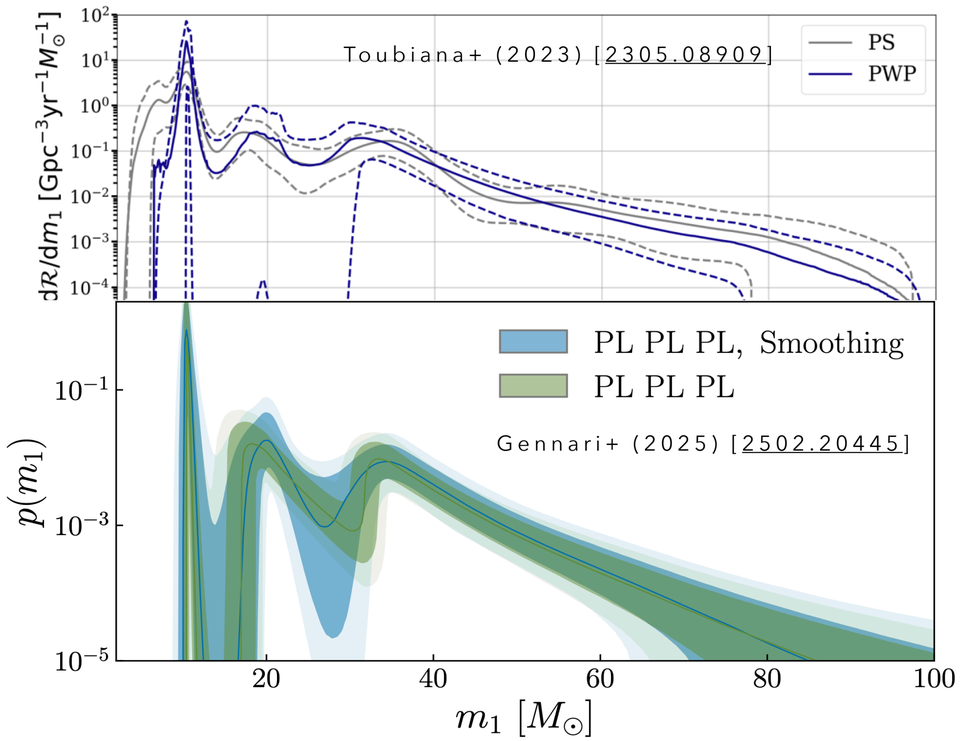


GWTC-3 highlights

how does the mass distribution looks like?



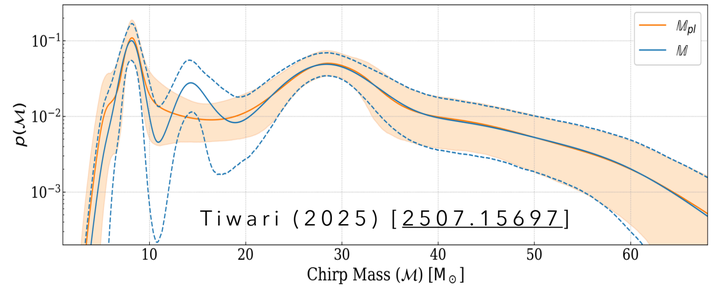


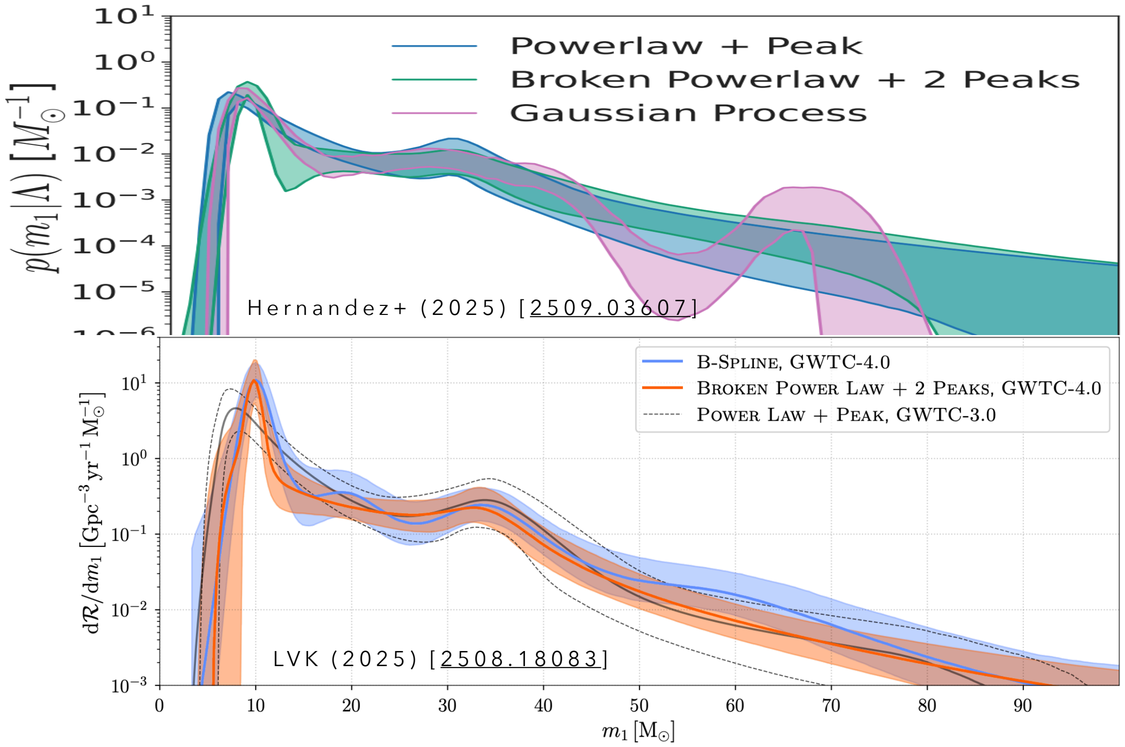


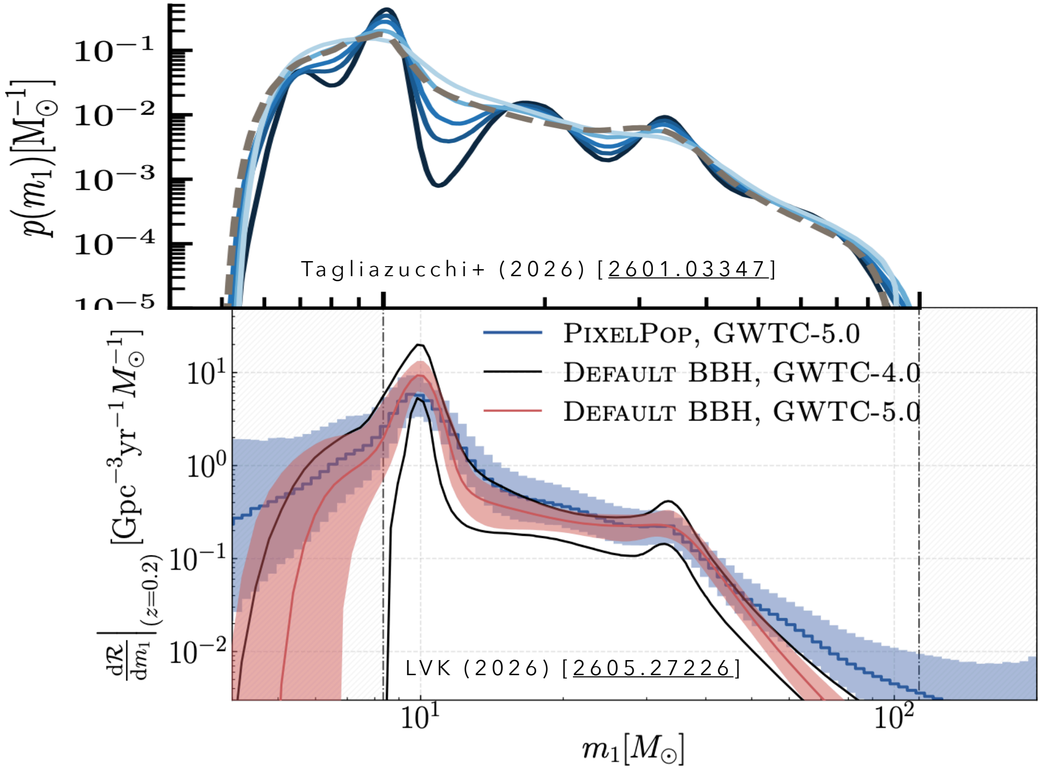
- wide variety for different methods

GWTC-4/5 highlights

what about the latest data?







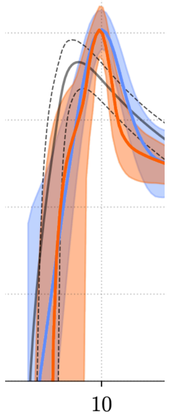
- same features as GWTC-3 overall
- differences between parametric and non-parametric

current structure

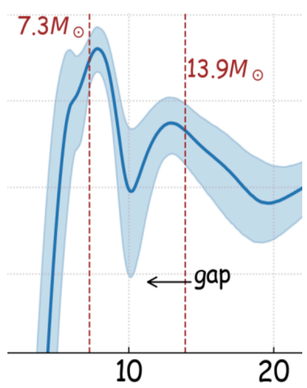
how robust these features are?

- low-mass
  - peak at $10M_\odot$
  - gap at $15M_\odot$?
- med-mass
  - $\sim 35M_\odot$ overdensity
  - another peak at $20M_\odot$?
- high-mass
  - overdensity at $60-70M_\odot$?

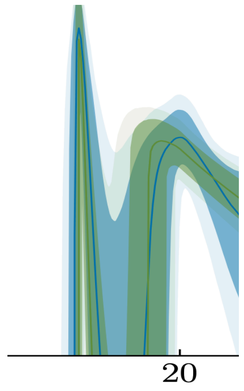
[2508.18083]



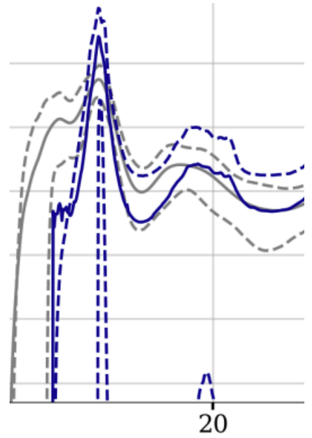
[2111.13991]



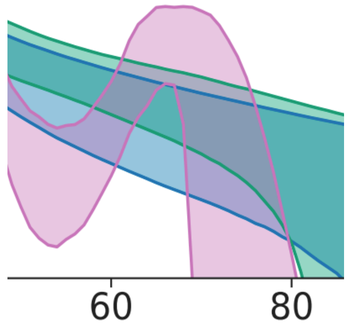
[2502.20445]



[2305.08909]

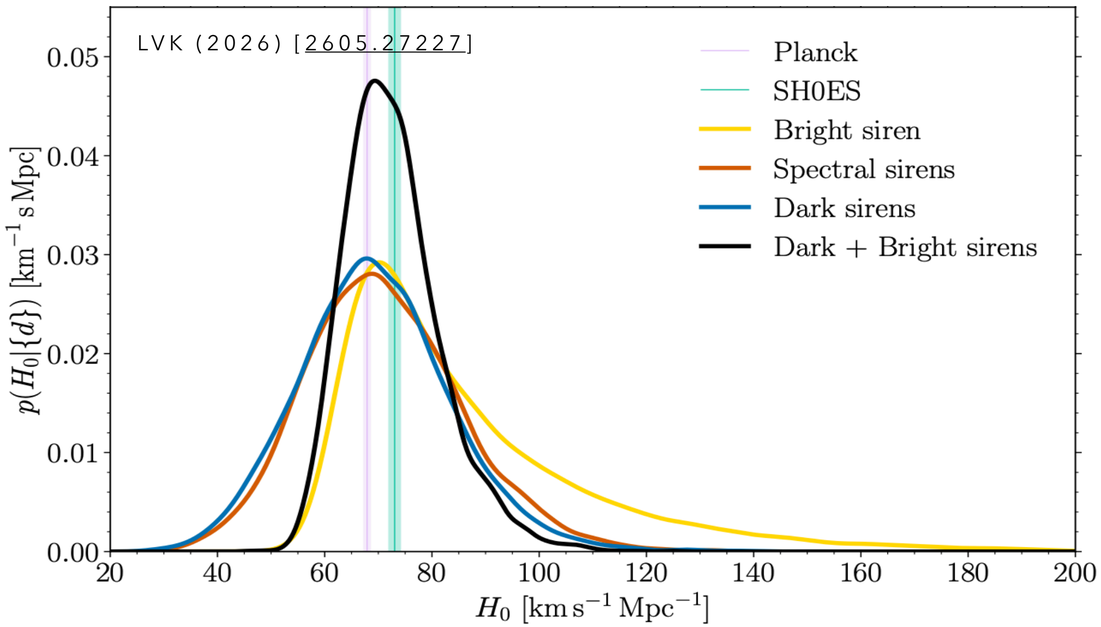


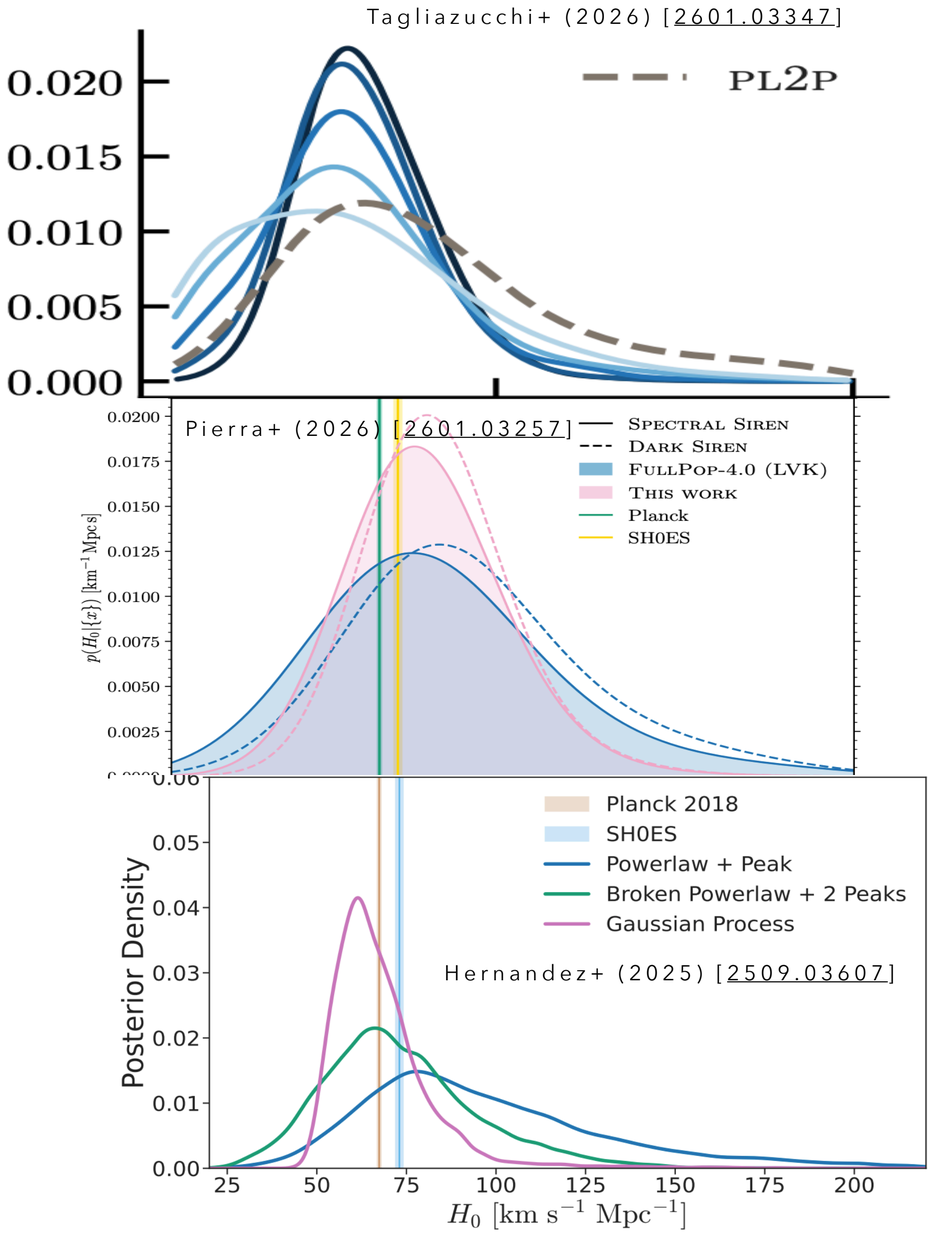
[2509.03607]



- *how sharp the $10M_\odot$ peak is?*
- *do parametric and non-parametric agree?*

GWTC-4/5 highlights





- galaxy catalogs are mostly uninformative
- large differences between different modelling assumptions

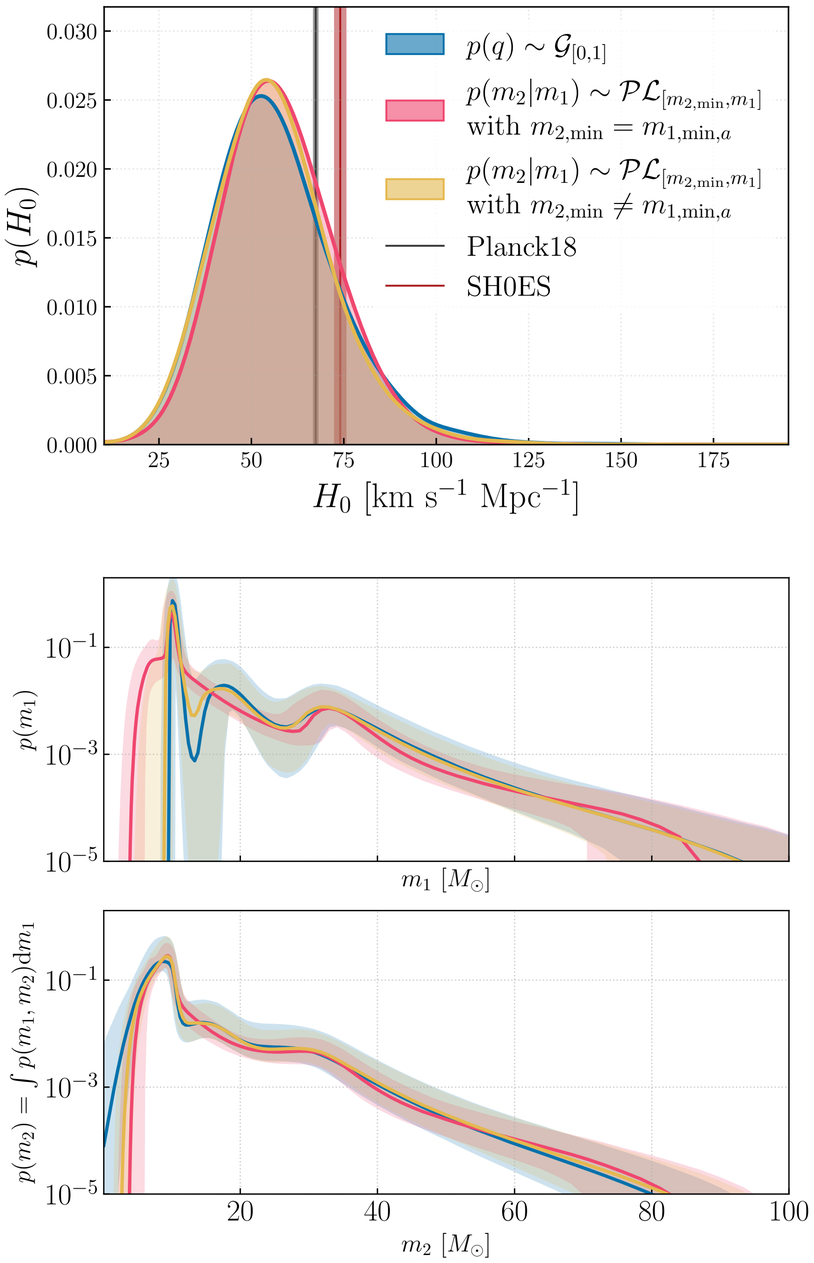
can we do better, and at which cost?

secondary mass

Bertheas, Gennari+ (2026) [2603.06792]

instead of using the mass ratio, we model the secondary mass conditioned on the primary

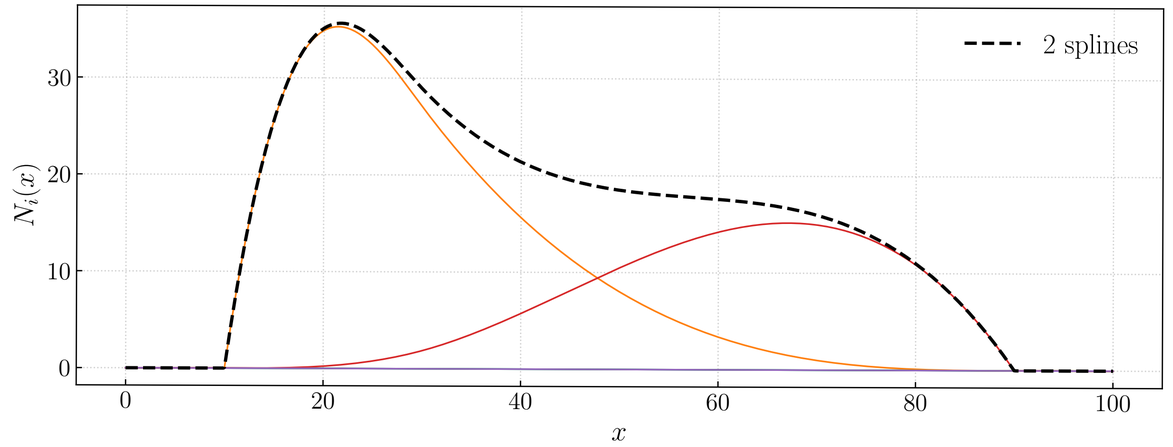
- the secondary-mass parametrisation can change the reconstructed distribution
- the posteriors on the Hubble constant are invariant

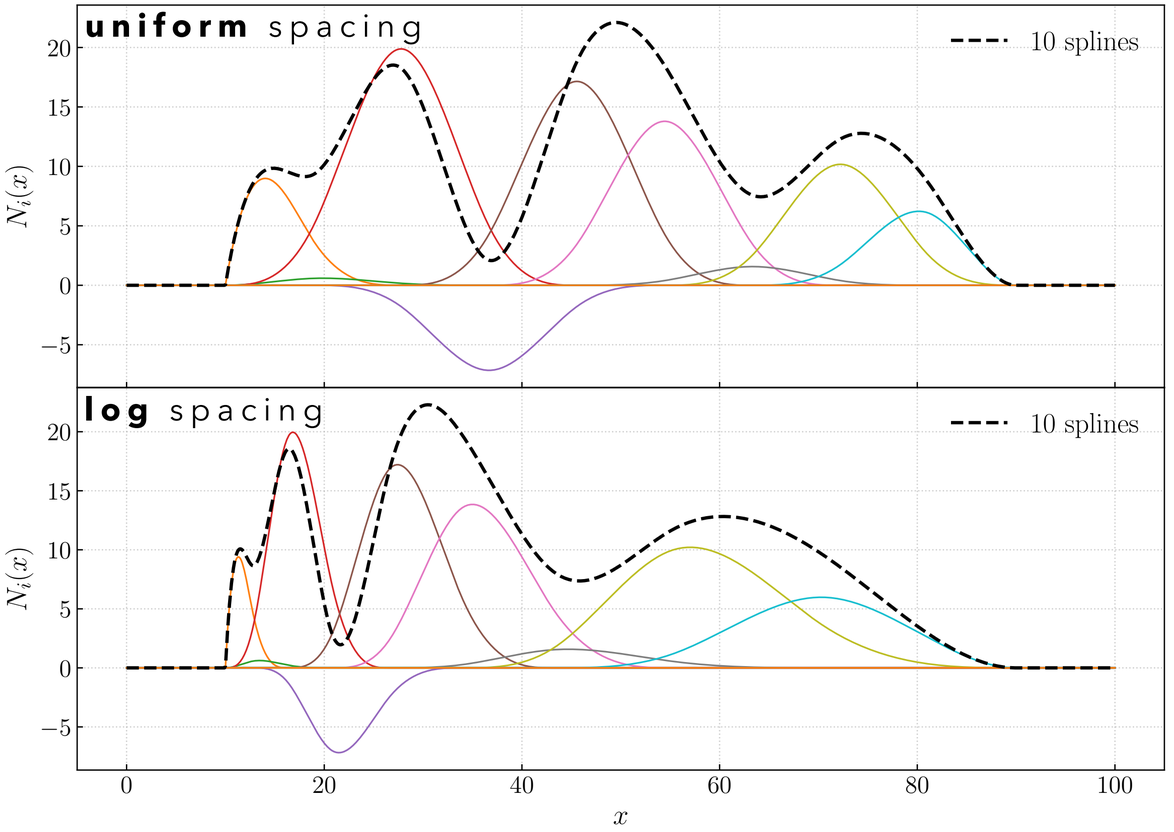


B-splines

how to capture complexity?

- B-splines are build from polynomial bases over knots
- the knot grid is free to vary with the minimum and maximum mass
- varying the number of components allows to model richer structure
- we model the log(PDF) with B-splines

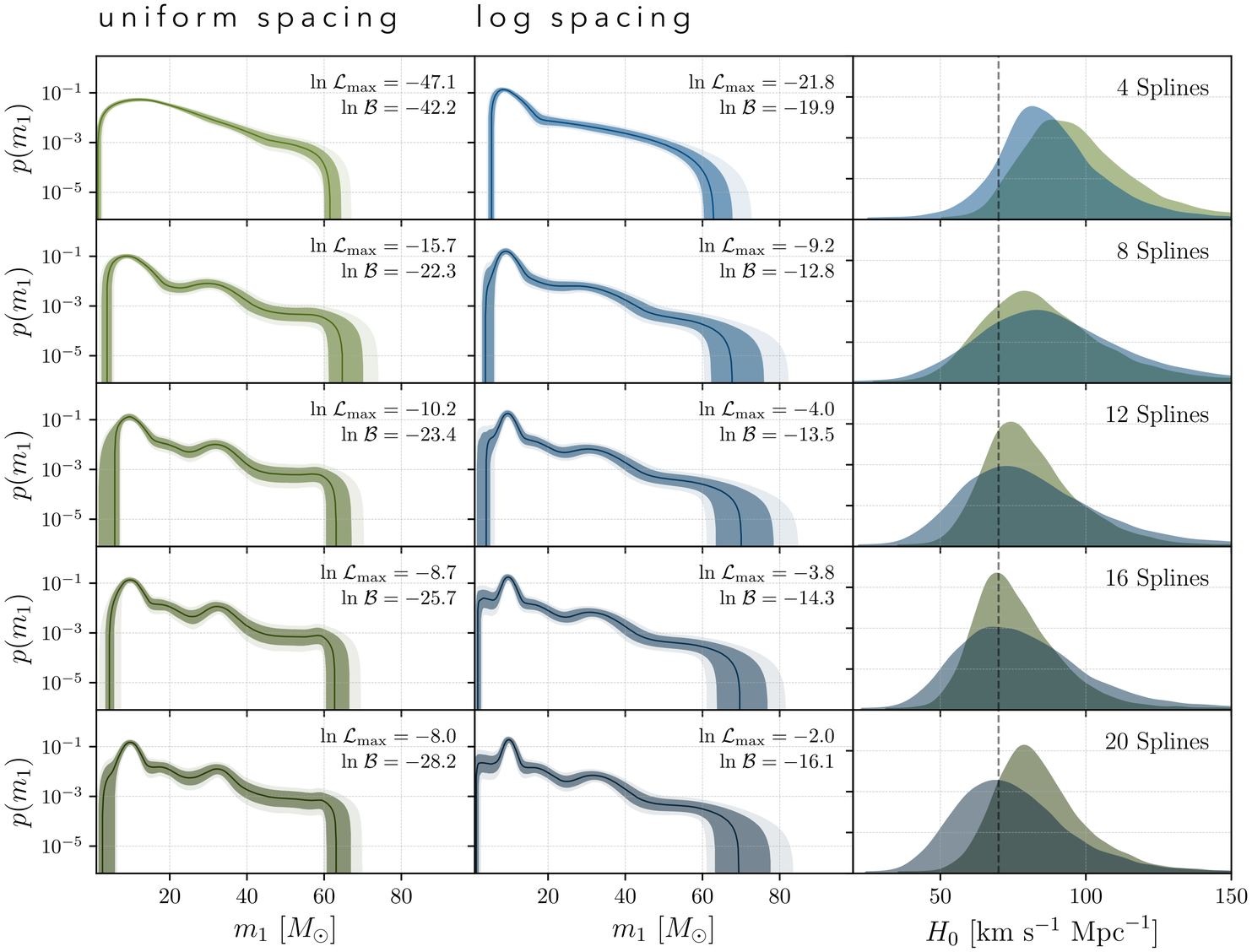




other splines

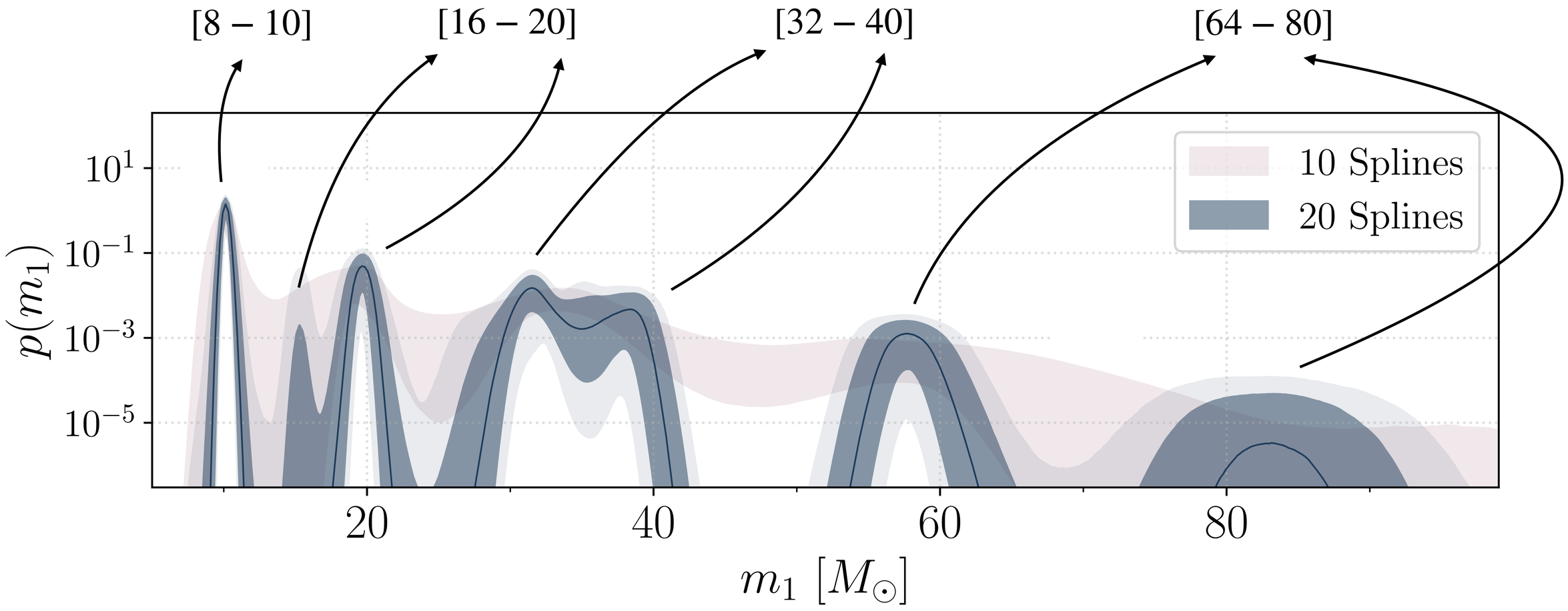
we model the PDF directly with B-splines

- the reconstruction depends on the modelling assumptions
- not able to reproduce sharp features



a possible astrophysical interpretation?

Gennari+ (2026) [2604.14290]



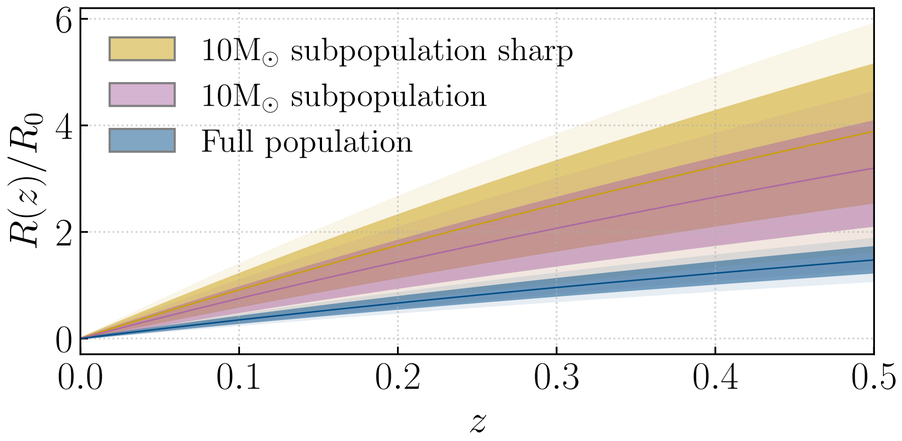
the distribution is likely overfitted, but it may indicate **hierarchical mergers**

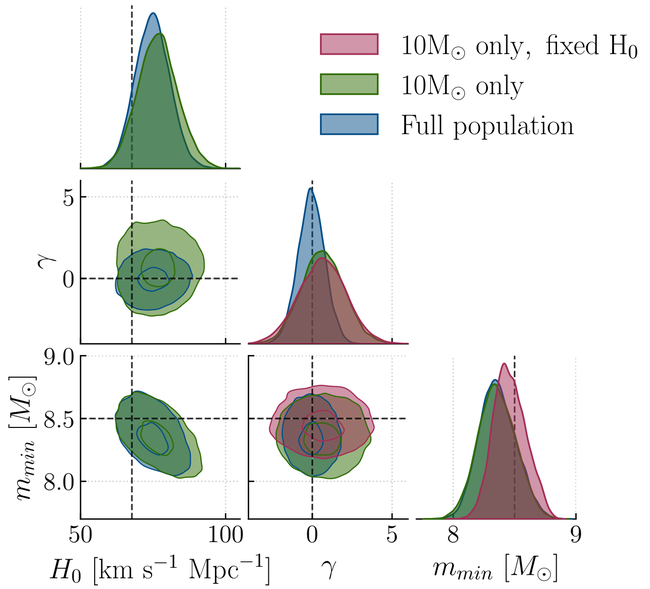
event-rate and validation

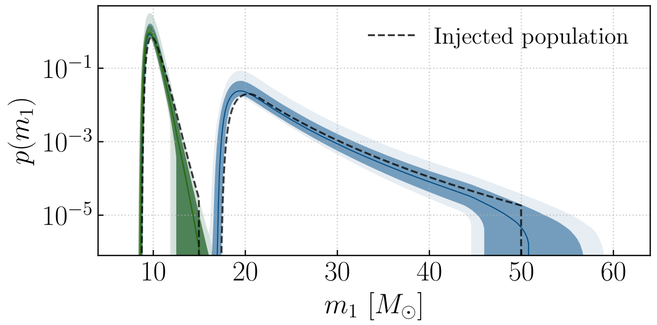
Gennari+ (2026) [2604.14290]

we observe a steeper rate evolution in redshift targeting $10M_\odot$ events only

- supports specific formation channel for this feature
- independently confirmed in [2605.25980] and by ongoing multi-population analyses



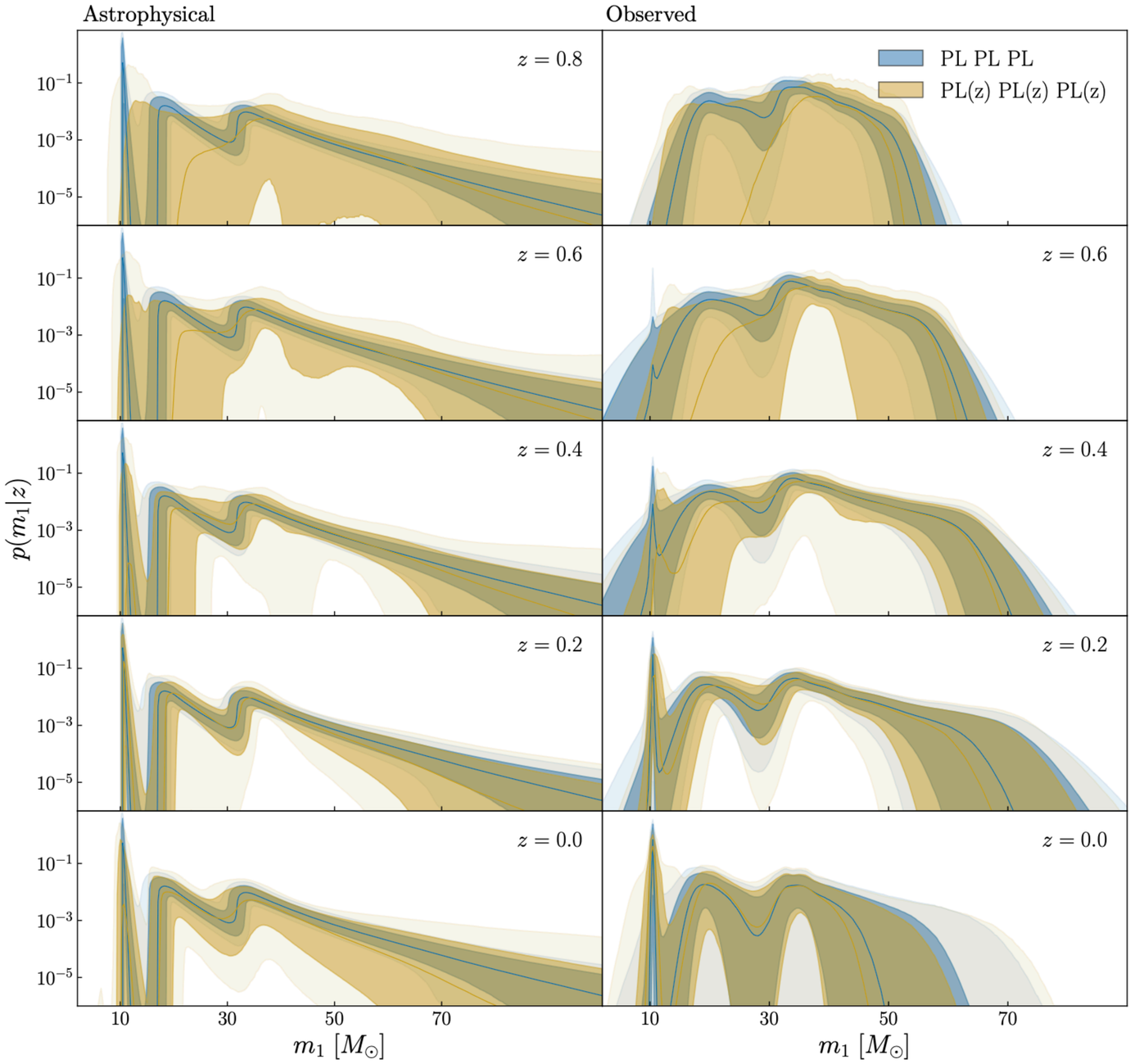




simulation-based validation of the method with separate populations

intrinsic evolution

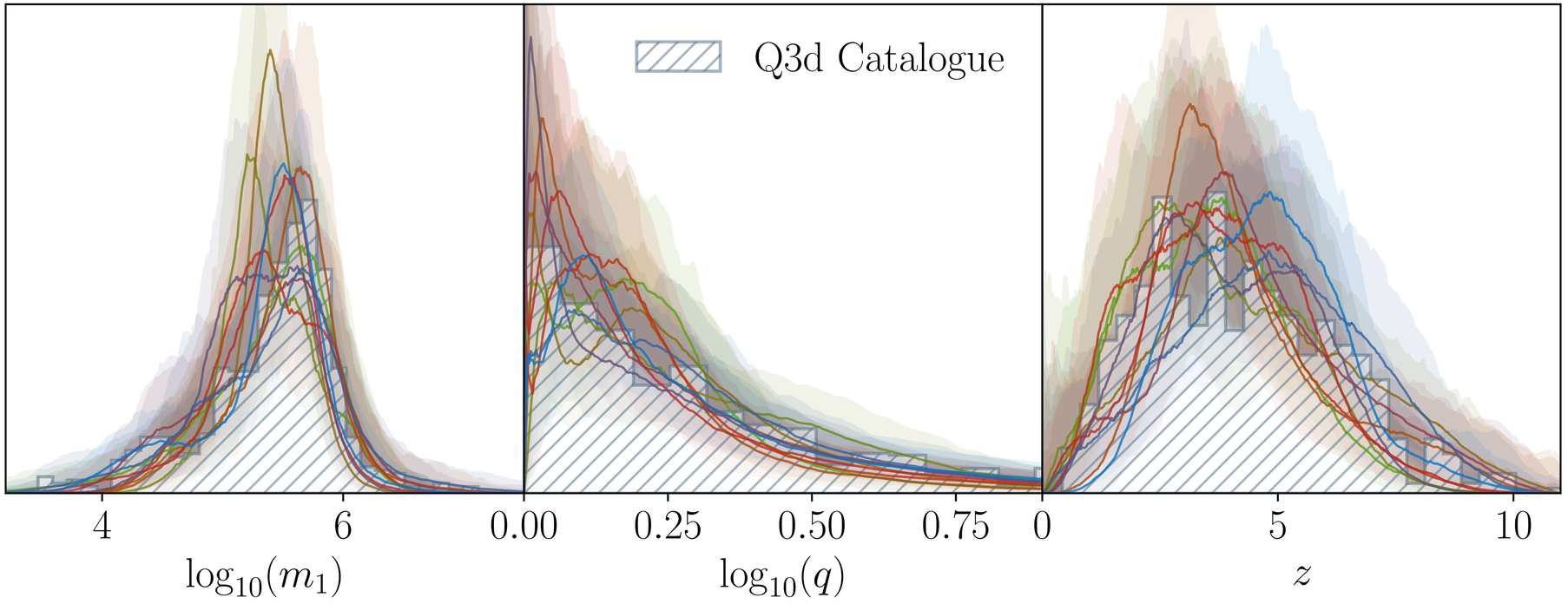
- linear evolution of the features and mixing fractions in redshift
- no evidence for redshift evolution on GWTC-3
- interplay between evolution and selection effects



poisson noise

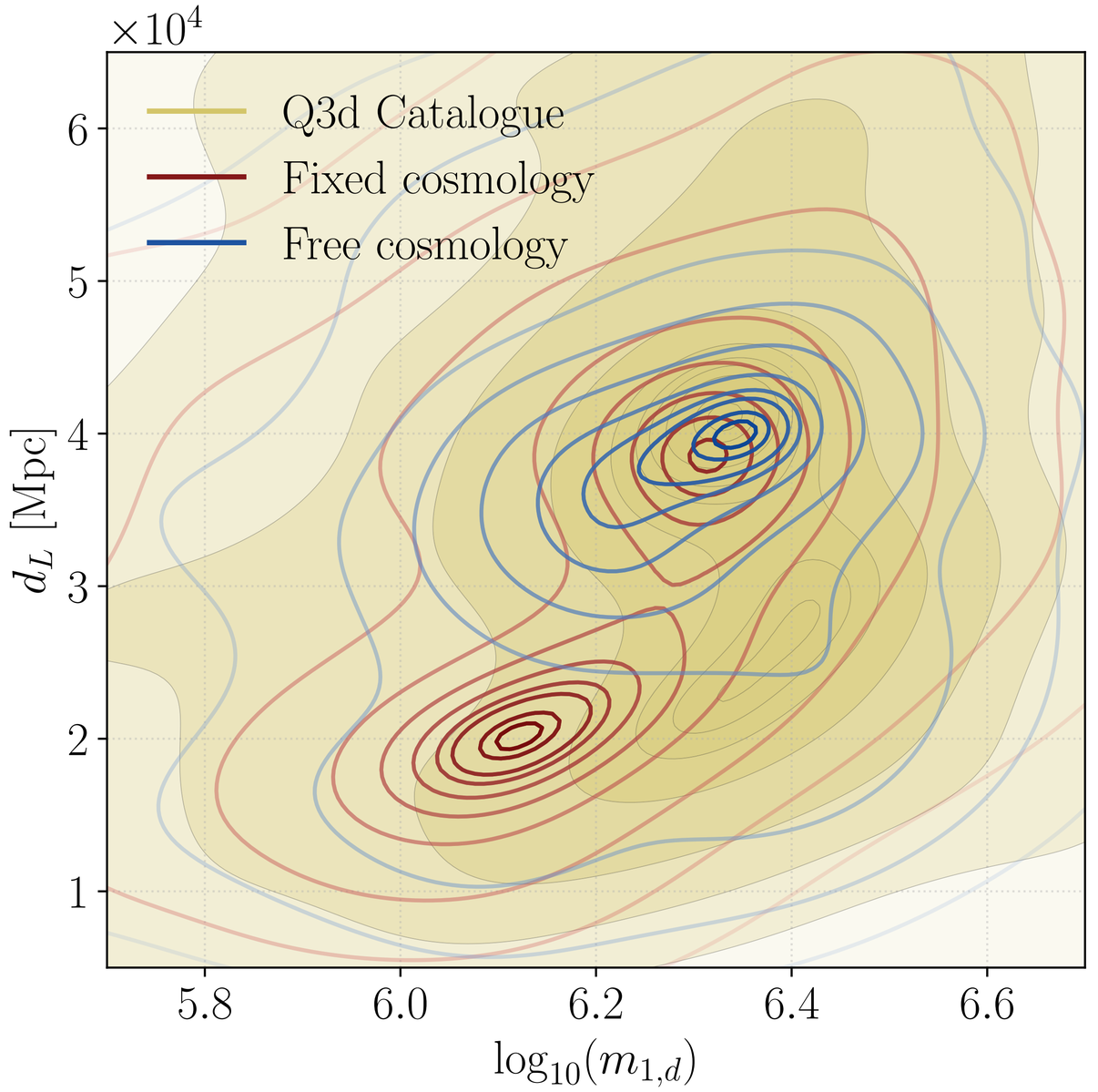
a catalogue with few detected events is strongly affected by Poisson noise

the interaction between the population modelling and specific realisation becomes less clear

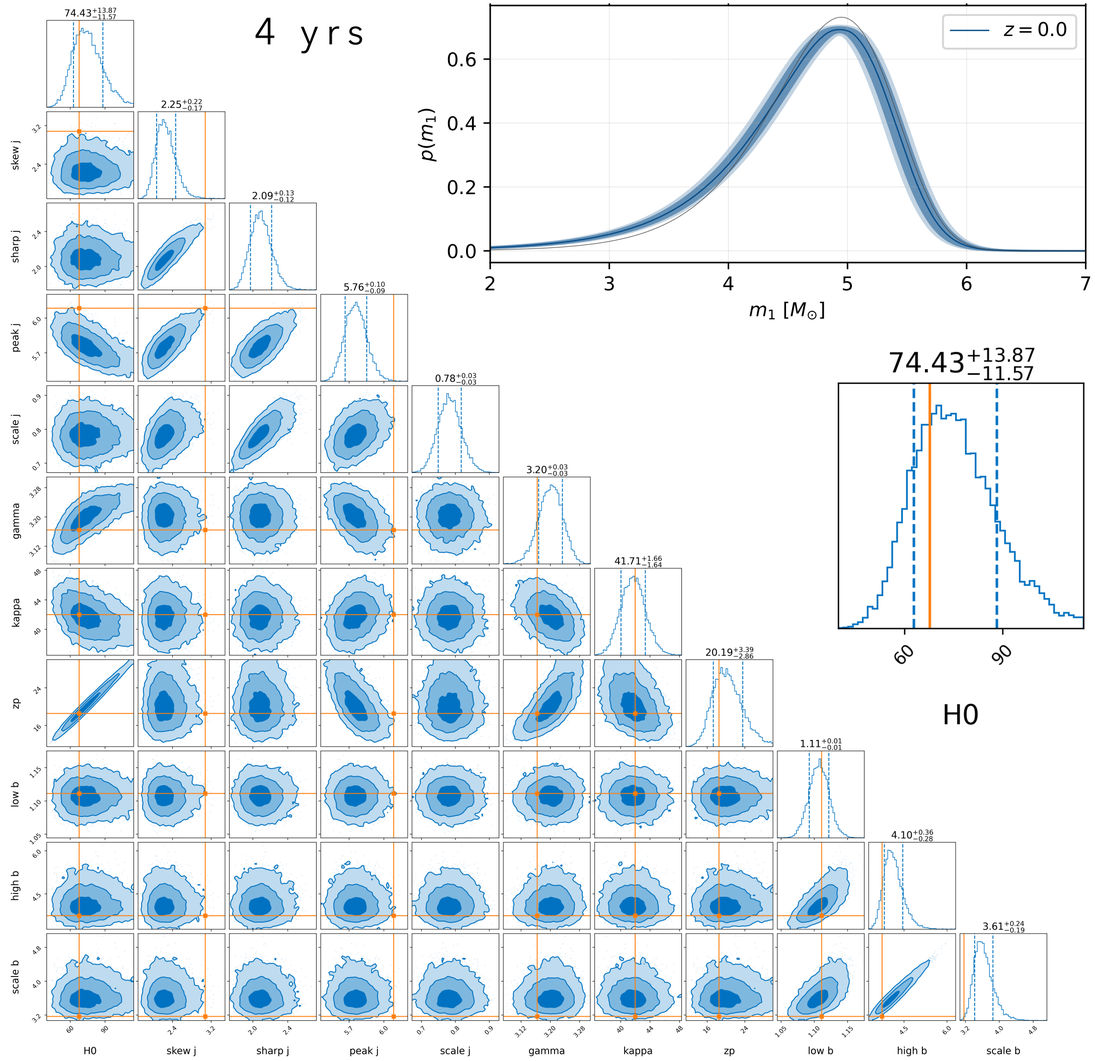


cosmology on semi-analytic catalogues

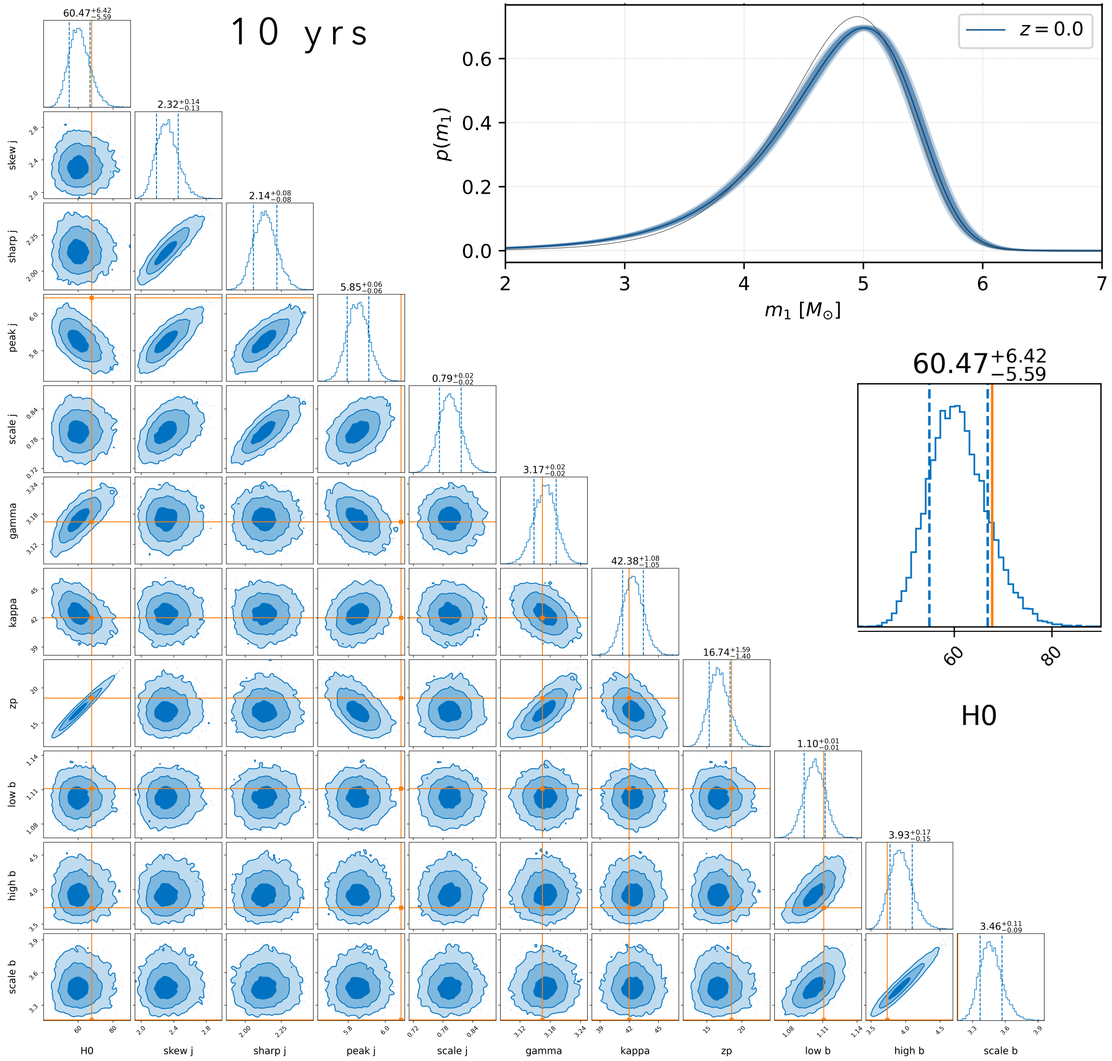
- maximum likelihood value of each run
- source-frame distribution mapped to the observer frame
- the one with free cosmology better fits the data inferring a wrong value of the cosmological parameters
- cosmological parameters are effectively used to improve the fit



HSnod-like catalogues



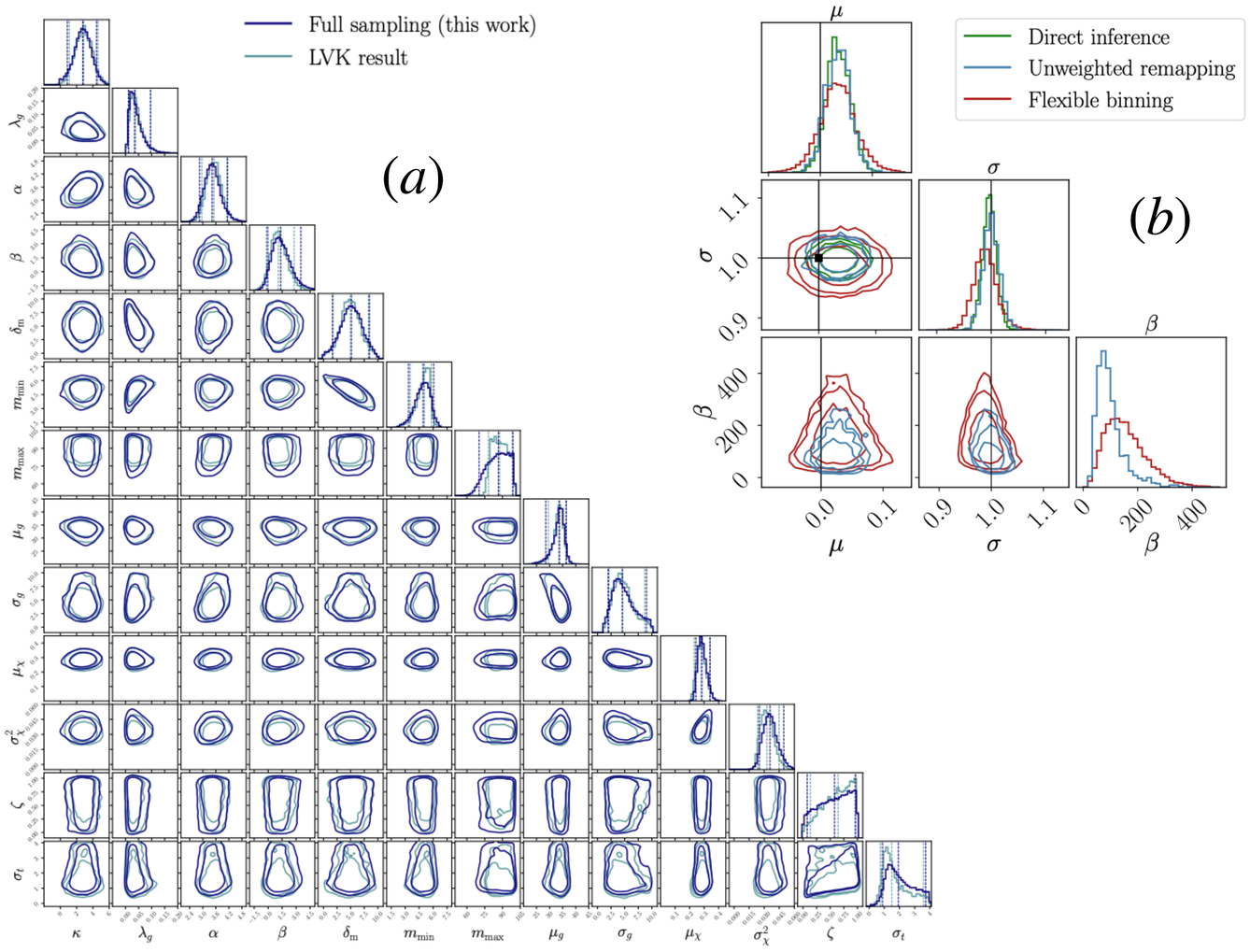
~16000 events



~40000 events

recent developments

Rinaldi+ (2025) [2506.05153]

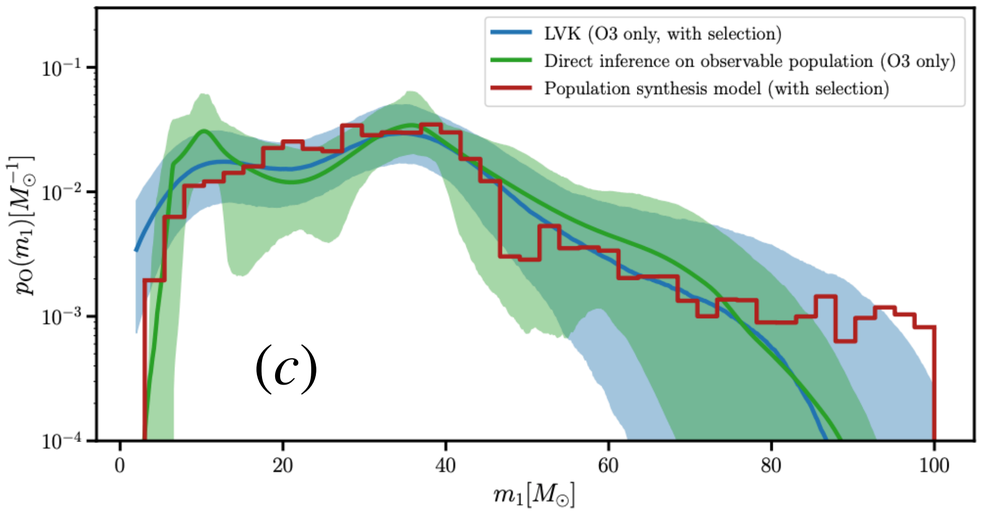


Mancarella+ (2025) [2502.12156]

a lot of effort is dedicated to improving current techniques

- directly sample hierarchical likelihood *(a)*
- non-parametric to parametric mapping *(b)*
- sampling the observed distribution *(c)*

Toubiana+ (2026) [2507.13249]



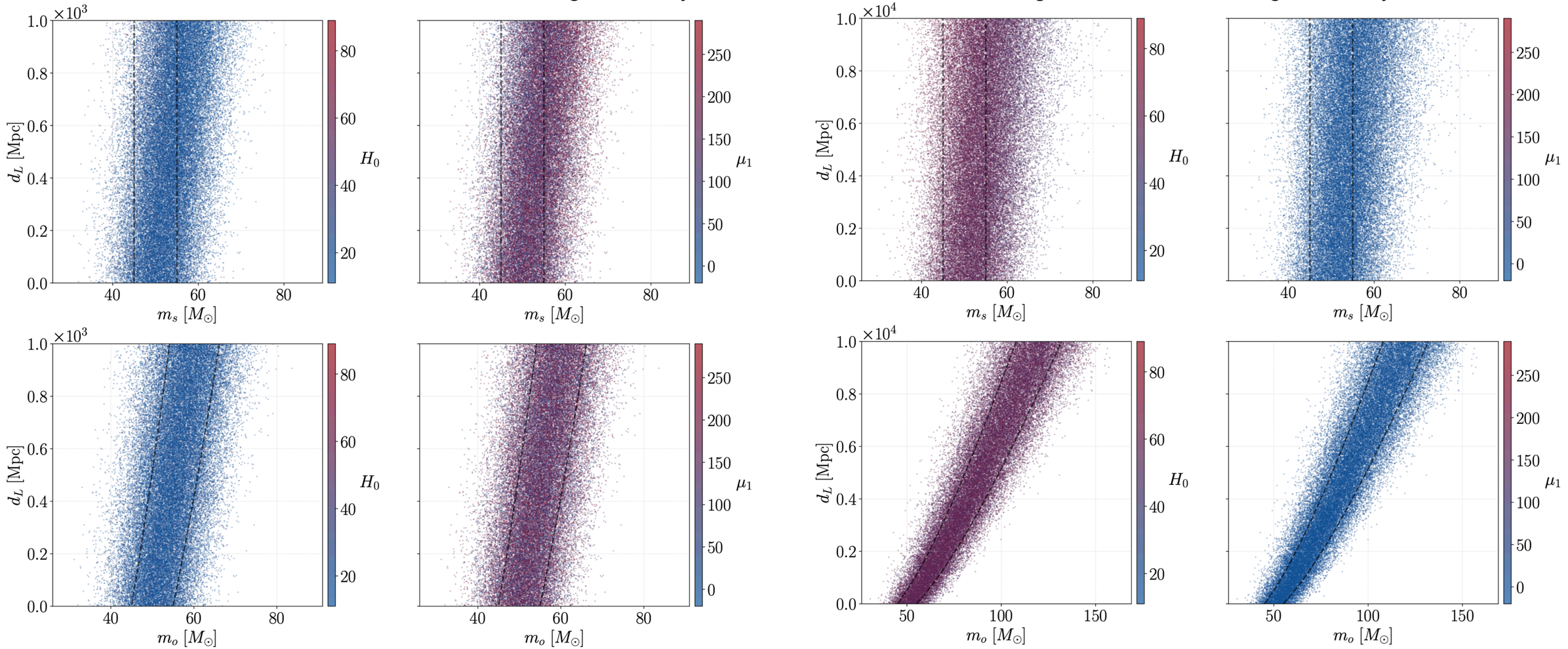
cosmology-evolution degeneracy

cosmology and linear evolution

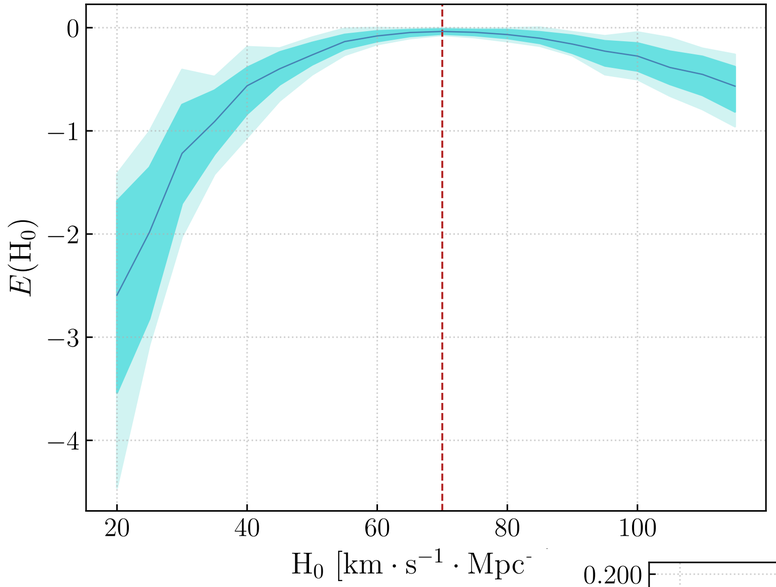
simultaneously inferred

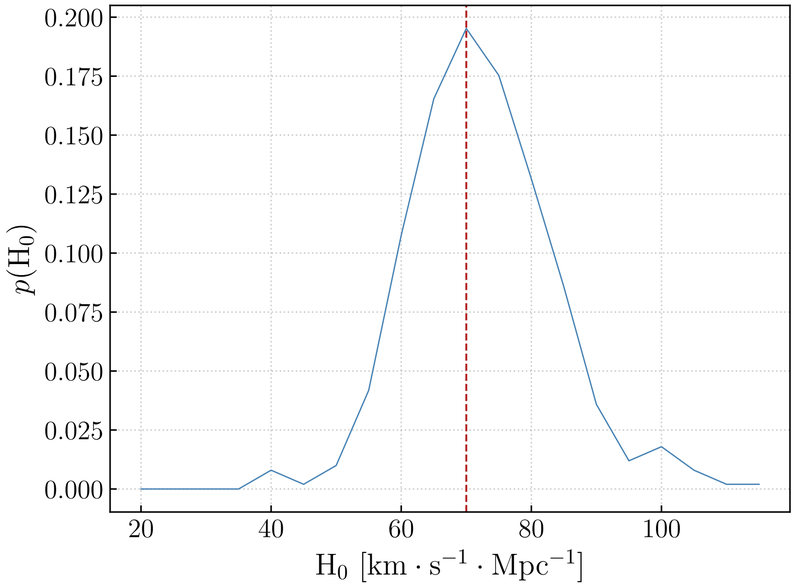
short distances (degeneracy)

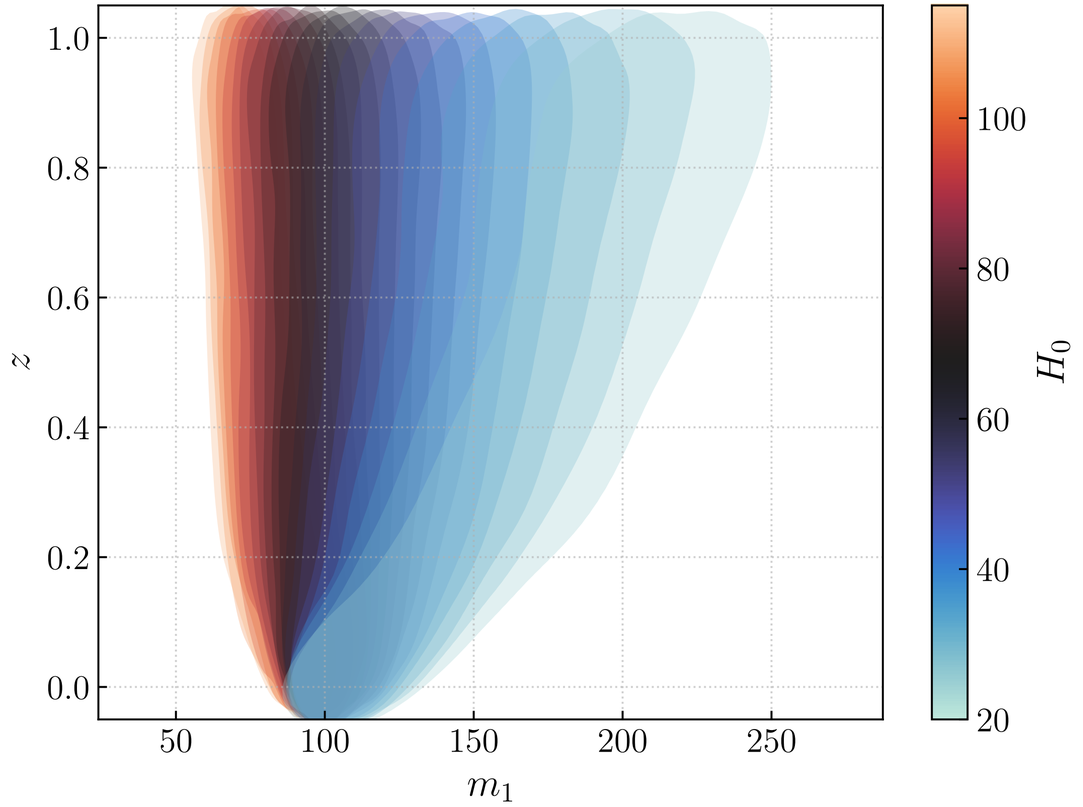
large distances (degeneracy broken)



cosmology from information





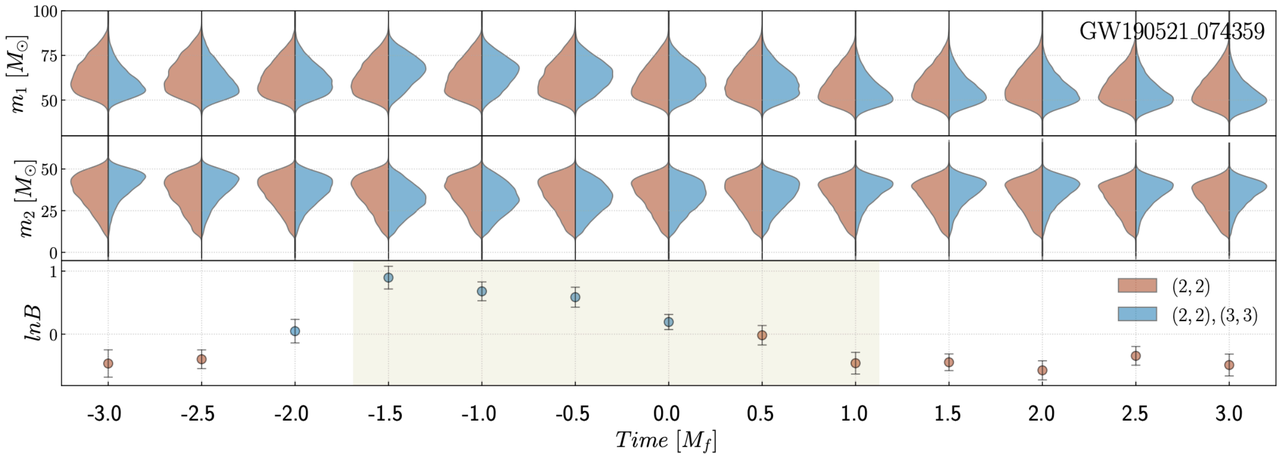


computes the entropy of the data mapped to the source frame for different cosmologies

the true one is that minimising the information

ringdown analyses

several contributions to ringdown data analysis and tests of general relativity



- post-merger model currently used by the LVK in the TGR paper

- contribution to an important review on the status of ringdown

- PWT of the LVK paper on GW250114 TGR

