What can we learn about *stellar-origin binary black holes* with LISA?

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Cosmology From Home 2022 – Parallel talk

with S. Babak, C. Caprini, D. Figueroa, N. Karnesis, P. Marcoccia, G. Nardini, M. Pieroni, A. Ricciardone, A. Sesana

[arXiv:2207.XXXXX] (background) and [arXiv:2207.YYYYYY] (individual events)

LIGO/Virgo/KAGRA GTWC-3 – Abbot et al. '21a

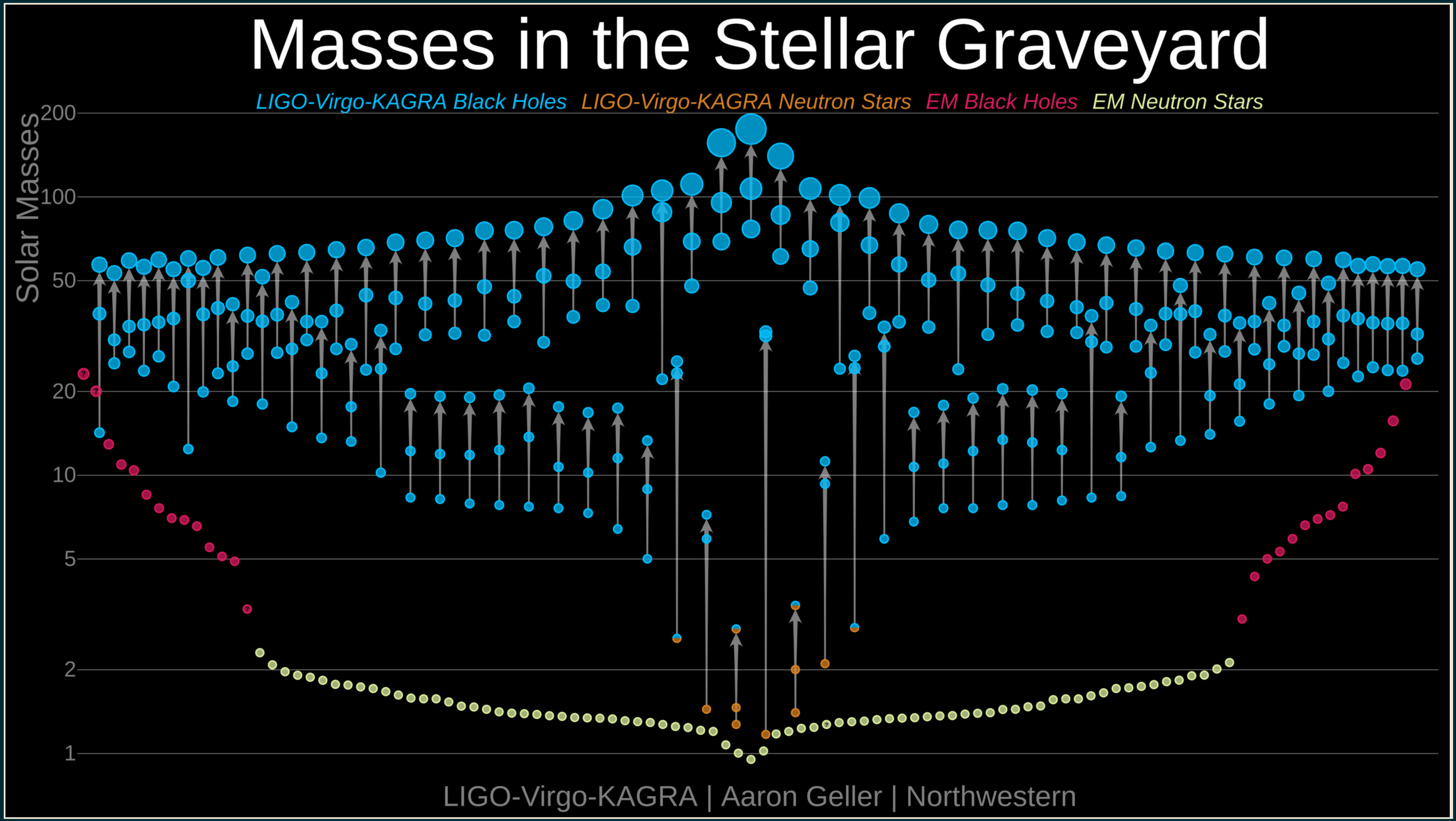
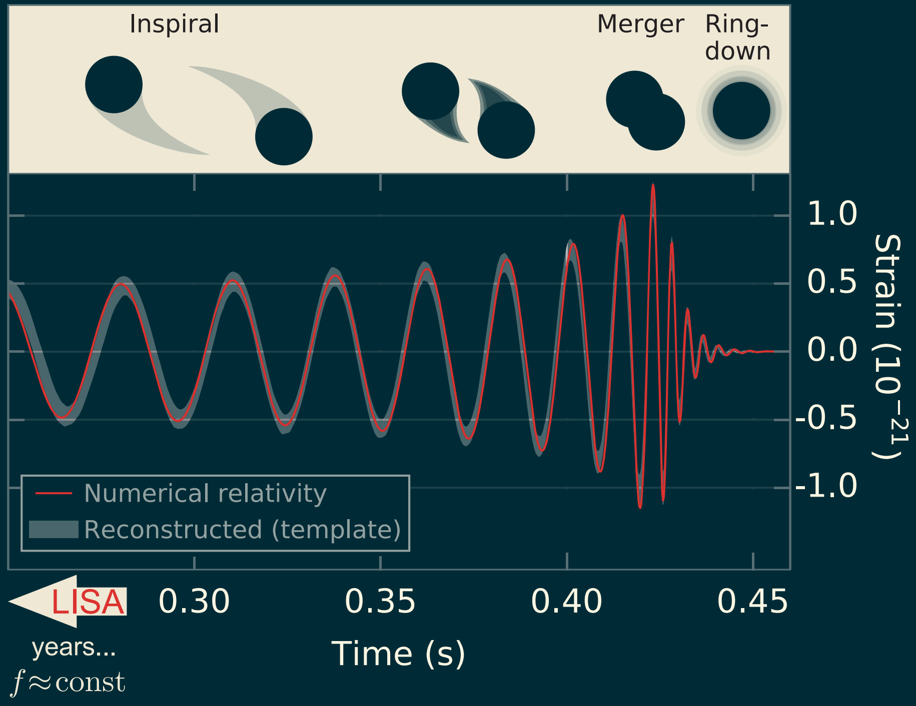
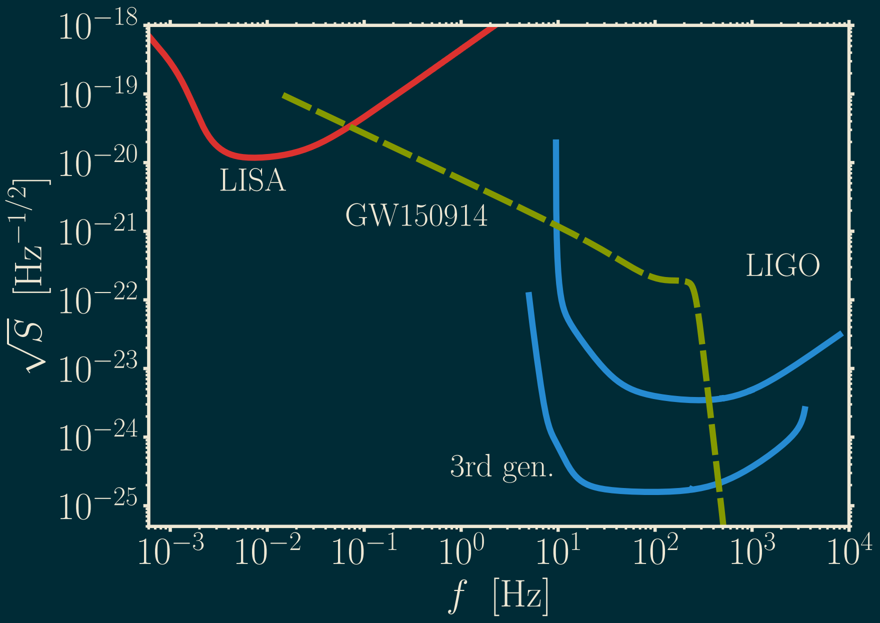


Fig. from LIGO-Virgo / Aaron Geller / Northwestern University

$\sim$ 70 binary black hole merging events with stellar-like mass

Stellar-origin binary black-hole systems (SOBBHs)





Figs. from LV '16 (GW150914 discovery)
and Tso et al. '18 (both modified)

LVK ($f \sim 30 - 7 \cdot 10^3$ Hz) observes **transient merging** signals (last $\sim 0.1s$)

LISA ($f \sim 5 \cdot 10^{-4} - 10^{-2}$ Hz) will detect **continuous inspiraling** signals:

- some **resolved** as **peaks** on the spectrum $(f \sim \mathrm{const})$
- a **confusion noise background** of unresolved events $\left(\Omega_{\mathrm{GW}} h^2 \propto f^{2/3}\right)$

LVK population inference

LVK performs inference on the parameters of individual events, and uses that to place constraints on the parameters of a **population model** that would have produced the observed events (Abbot et al. '21b).

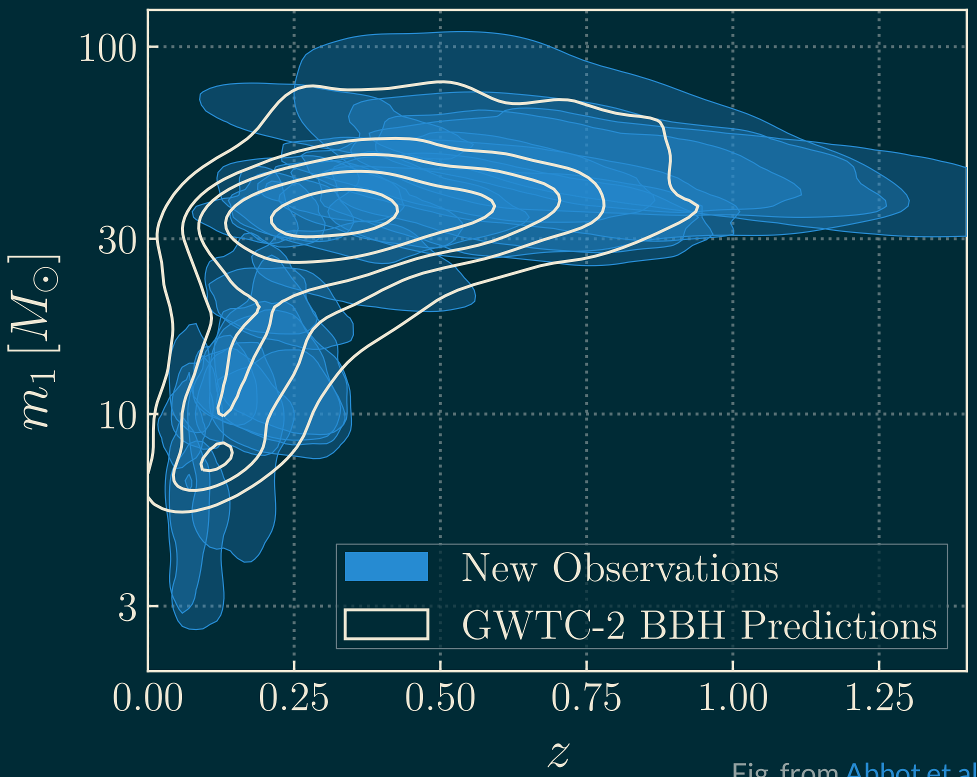


Fig. from Abbot et al. '21b (GWTC-3 pop. inference)

This is hard! Detection & selection effects, high-dim parameter space...

LVK population inference $\Rightarrow$ LISA

Our work: use **LVK**'s population inference to infer, for **LISA**:

- what is the shape and amplitude of the **confusion noise background**?
- how many (and which) **resolved** inspiraling events would be observed?

Outline:

1. A look at the population model

2. Confusion background:

    - Computation for a set of population parameters
    - LVK prediction for the amplitude and its uncertainty
    - LISA precision forecast

3. Resolved inspiraling binaries observed by LISA

Population model – Abbot et al. '18

$$\frac{dN}{d\xi\, dz} = R(z;\theta)\frac{dV_c}{dz}(z)\frac{T_{tot}}{1+z}p(\xi;\theta)$$

$R(z;\theta)$ rate of events per unit time and comov volume

$\frac{dV_c}{dz}(z)$ accounting for physical size of comoving volume

$\frac{T_{tot}}{1+z}$ time during which events are generated

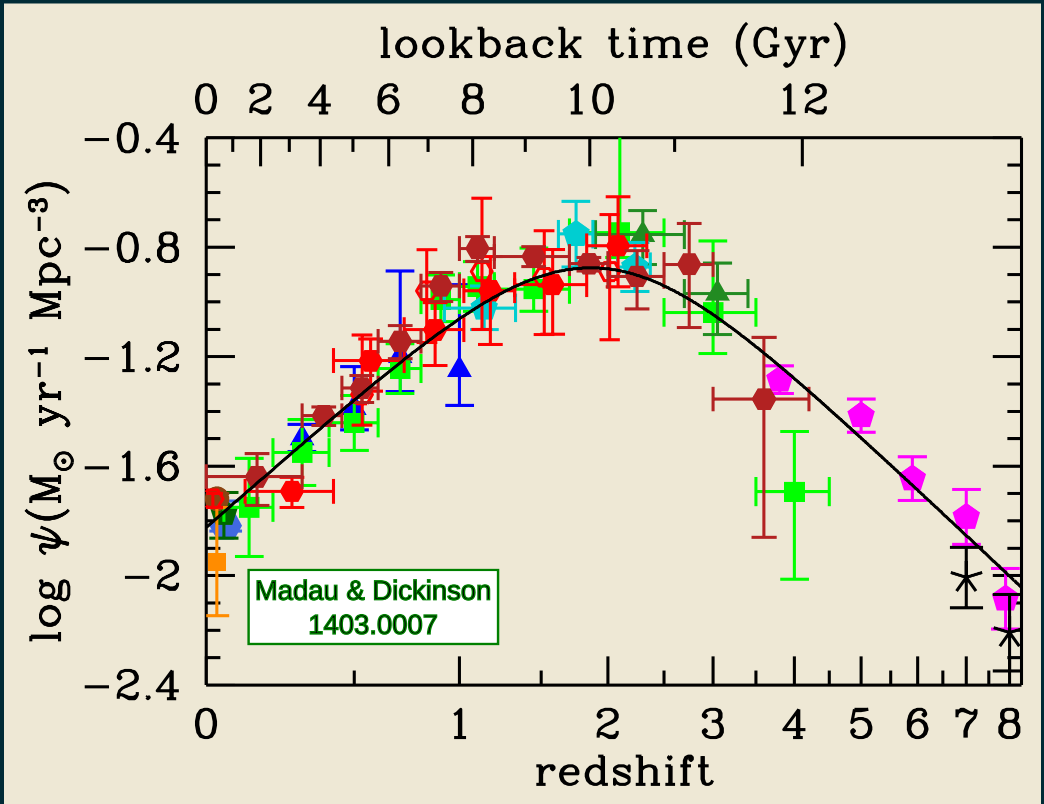
$p(\xi;\theta)$ distribution of masses, spins...

The functional form of $R(z;\theta)$ and $p(\xi;\theta)$ and their *hyperparameters* θ define the **population model**.

Population model – merger rate $R(z)$

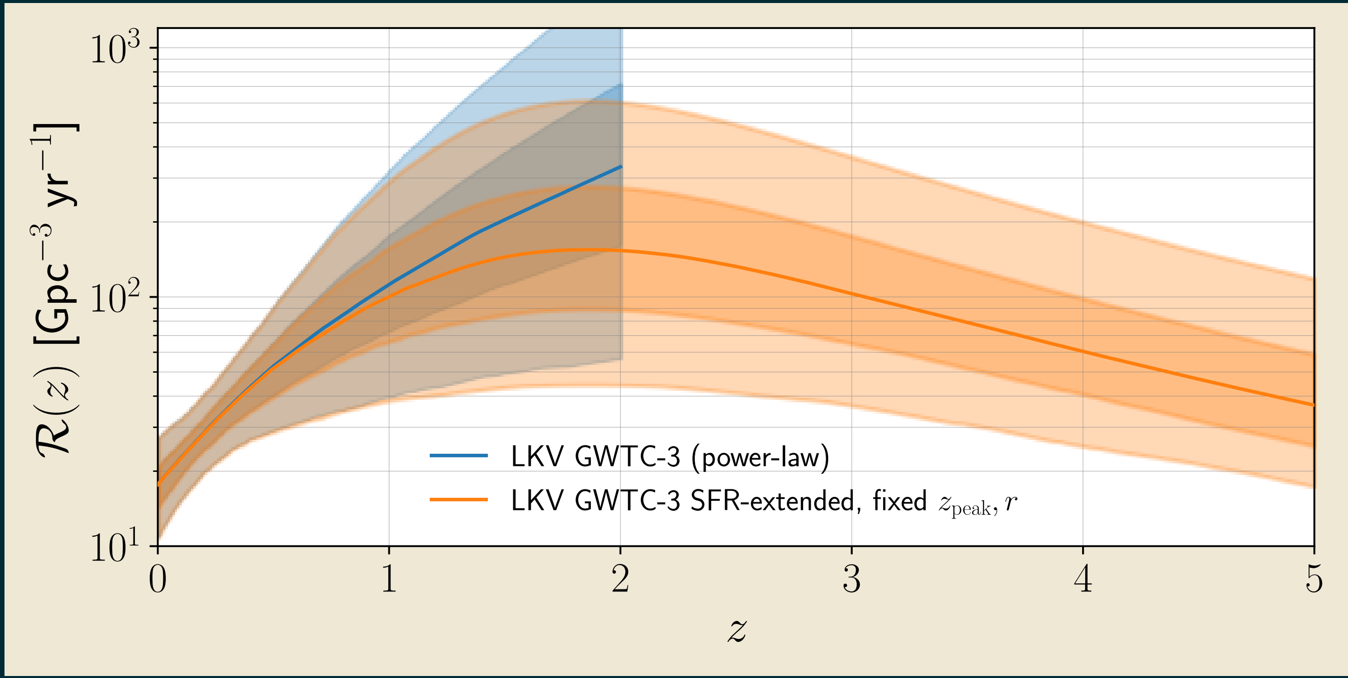
$$R(z; d, r, z_{\rm peak}) = R_0 \frac{(1+z)^d}{1 + \frac{d}{-r}\left(\frac{1+z}{1+z_{\rm peak}}\right)^{d-r}}$$

Assumption: the rate of SOBBH mergers follows the **Star Formation Rate**



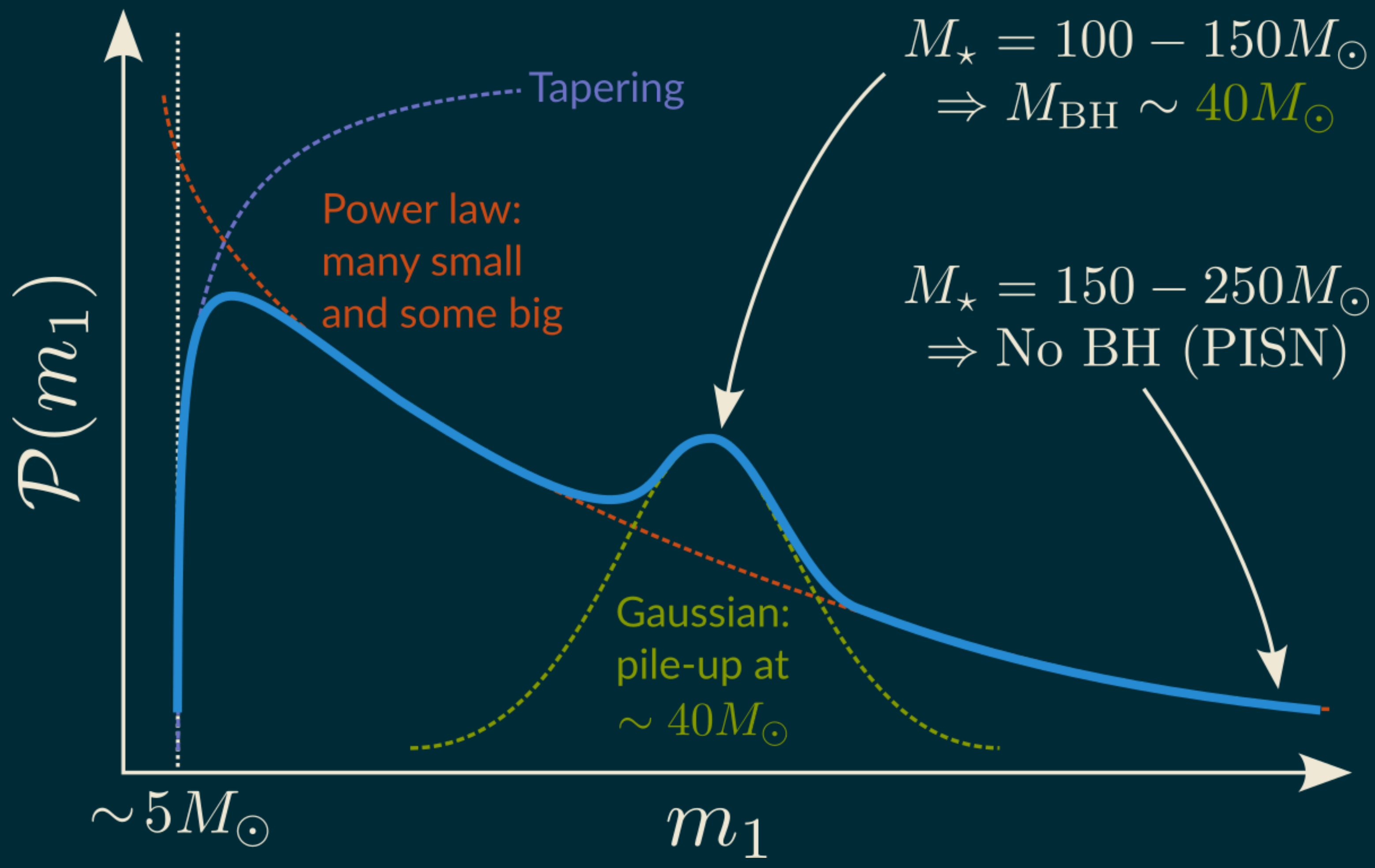
Population model – merger rate $R(z)$ – II

$$R(z; d, r, z_{\rm peak}) = R_0 \frac{(1+z)^d}{1 + \frac{d}{-r}\left(\frac{1+z}{1+z_{\rm peak}}\right)^{d-r}}$$



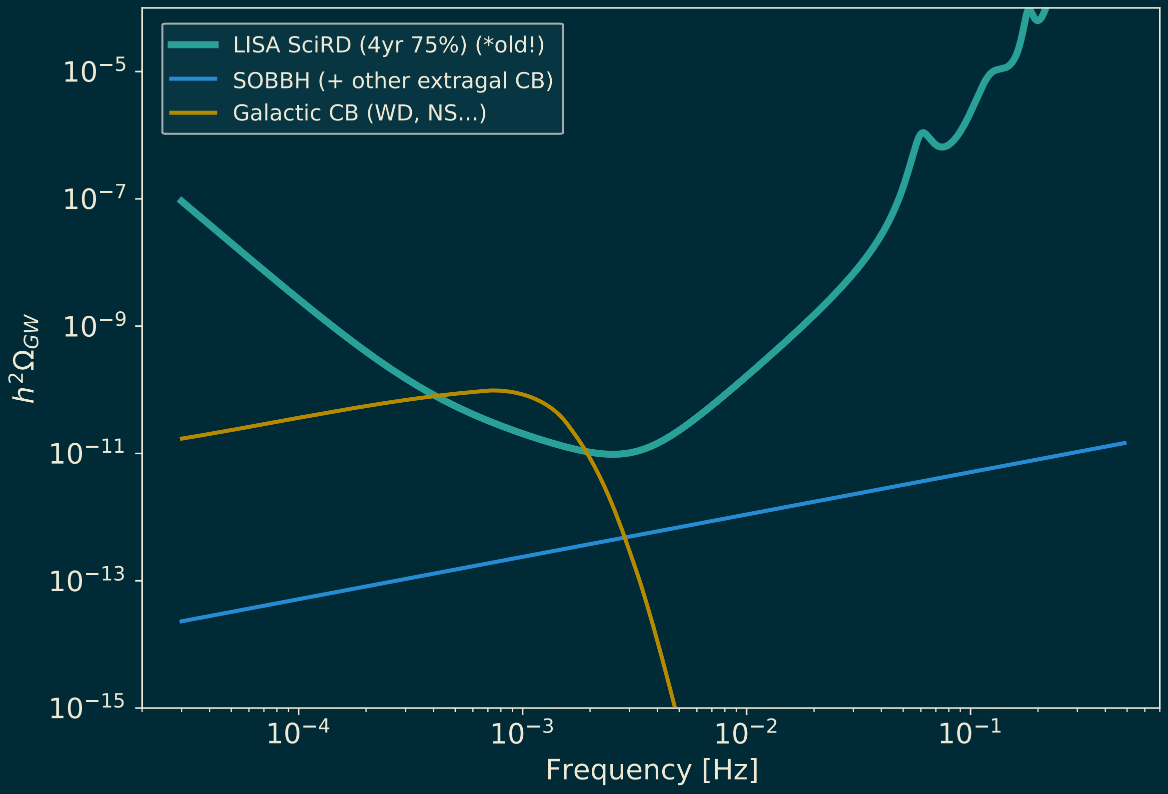
- $z \lesssim 0.5 \Leftarrow$ **individual events**
- $z \lesssim 5 \Leftarrow$ **background of unresolved events**

Mass distributions – *"Power-law + Peak"* – Talbot & Thrane '18



Ratio $q = m_2 / m_1 \Rightarrow$ Power law suppressed

Background of unresolved events



Given a set of population model (hyper)parameters, it can be computed:

- analytically
- from a synthetic population:
    - as a Monte Carlo sum of the analytical formula
    - as a (more or less) full simulation of LISA's pipeline

Background computation I: Analytical

Energy spectrum radiated by a single **inspiraling** binary of *chirp mass* $\mathcal{M}$:

$$\frac{dE_{\rm GW}}{df_r} = \frac{\pi}{3}\frac{1}{G}\frac{(G\mathcal{M})^{5/3}}{\pi^{1/3} f_r^{1/3}}\bigg|_{f_r=f(1+z)} \qquad \mathcal{M} = (m_1+m_2)^{2/5}\left(\frac{m_1 m_2}{m_1+m_2}\right)^{3/5}$$

Integrated over the population (natural units):

$$\Omega_{\rm GW}(f)h^2 = \frac{8\pi}{3}\frac{h^2}{H_0^2}\int_0^\infty dz\,\frac{dn}{dz}\frac{1}{1+z}f_r\frac{dE_{\rm GW}}{df_r}\bigg|_{f_r=f(1+z)}$$

Phinney '01

Using the **population model** for $\mathrm{d}n/\mathrm{d}z$ and simplifying:

$$\Omega_{\rm GW}(f)h^2 = \frac{8\pi^{5/3}}{9}\frac{h^2}{H_0^2}f^{2/3}\int_0^\infty \mathrm{d}\mathcal{M}\,p(\mathcal{M}(m_1,m_2))\mathcal{M}^{5/3}\int_0^\infty \mathrm{d}z\,R(z)\frac{(1+z)^{2/3}}{H(z)}$$

Sesana '16

Power law: $\Omega_{\rm GW}(f)h^2 \propto f^{2/3}$

Population details $\longrightarrow$ Amplitude

Background computation II: Monte Carlo

Integrals over a number density can be approximated by a sum over synthetic populations consistent with it:

$$\int \mathrm{d}x \, \frac{\mathrm{d}N}{\mathrm{d}x} f(x) \approx \sum_{x_i \in \mathrm{pop}} f(x_i)$$

Re-writing the backgroung integral as a sum over a population:

$$\Omega_{\mathrm{GW}}(f) h^2 = \frac{2\pi^{2/3}}{9} \frac{h^2}{H_0^2} \frac{1}{T_{\mathrm{tot}}} \left(\sum_{i \in \mathrm{pop}} \frac{\mathcal{M}_i^{5/3}}{d_{c,i}^2 (1+z_i)^{1/3}} \right) f^{2/3}$$

Q: how much is the **Poisson realisation uncertainty**, i.e. randomness of the population realisation?

WHY? like *Cosmic Variance*, it would need to be added to the likelihood covariance if of the order of forecasted sensitivity.

A: (PRELIMINARY) $\lesssim 0.5\%$ (background is sum over **many** small amplitudes)

Background computation III: Simulation

Q: Is the analytical computation **realistic** enough?

WHY? There may be instrumental effects, and full simulations are expensive!

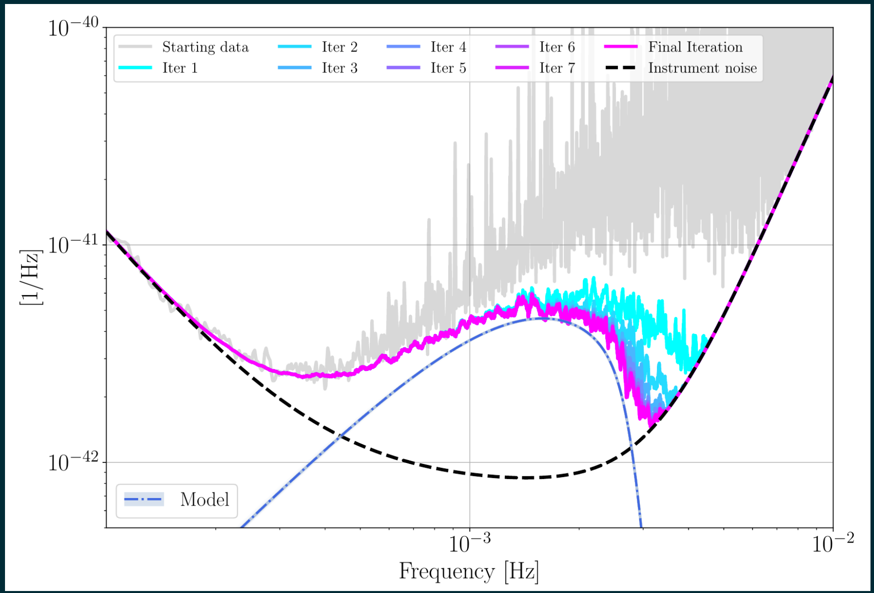
Fast LISA simulation – Karnesis et al. '21

1. Start with a population, assume perfect subtraction of loud events.

2. Compute confusion background smoothing over signal.

3. Subtract events with high SNR wrt this iteration's background.

4. Recompute background, check convergence / go back to 1.



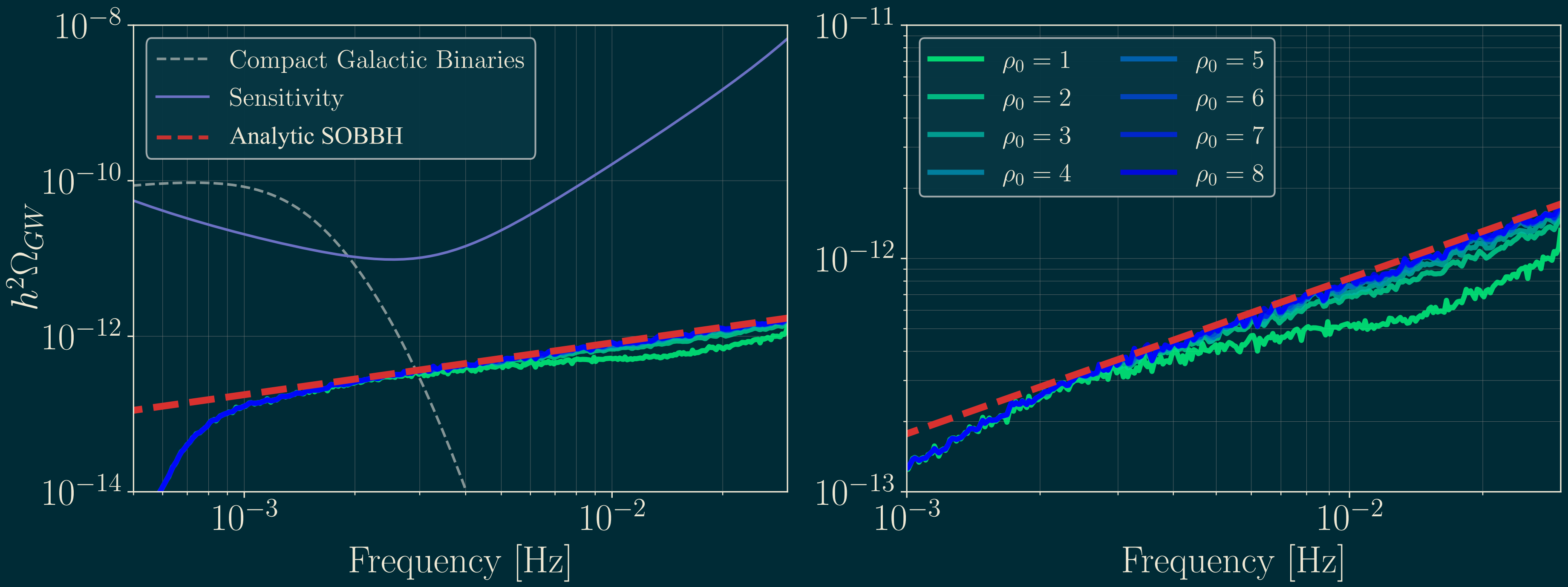
Provides **both** background **and** individual detectable sources (at given SNR)

Background computation IV: Comparison

Q: Is the analytical computation **realistic** enough?

WHY? There may be instrumental effects, and full simulations are expensive!

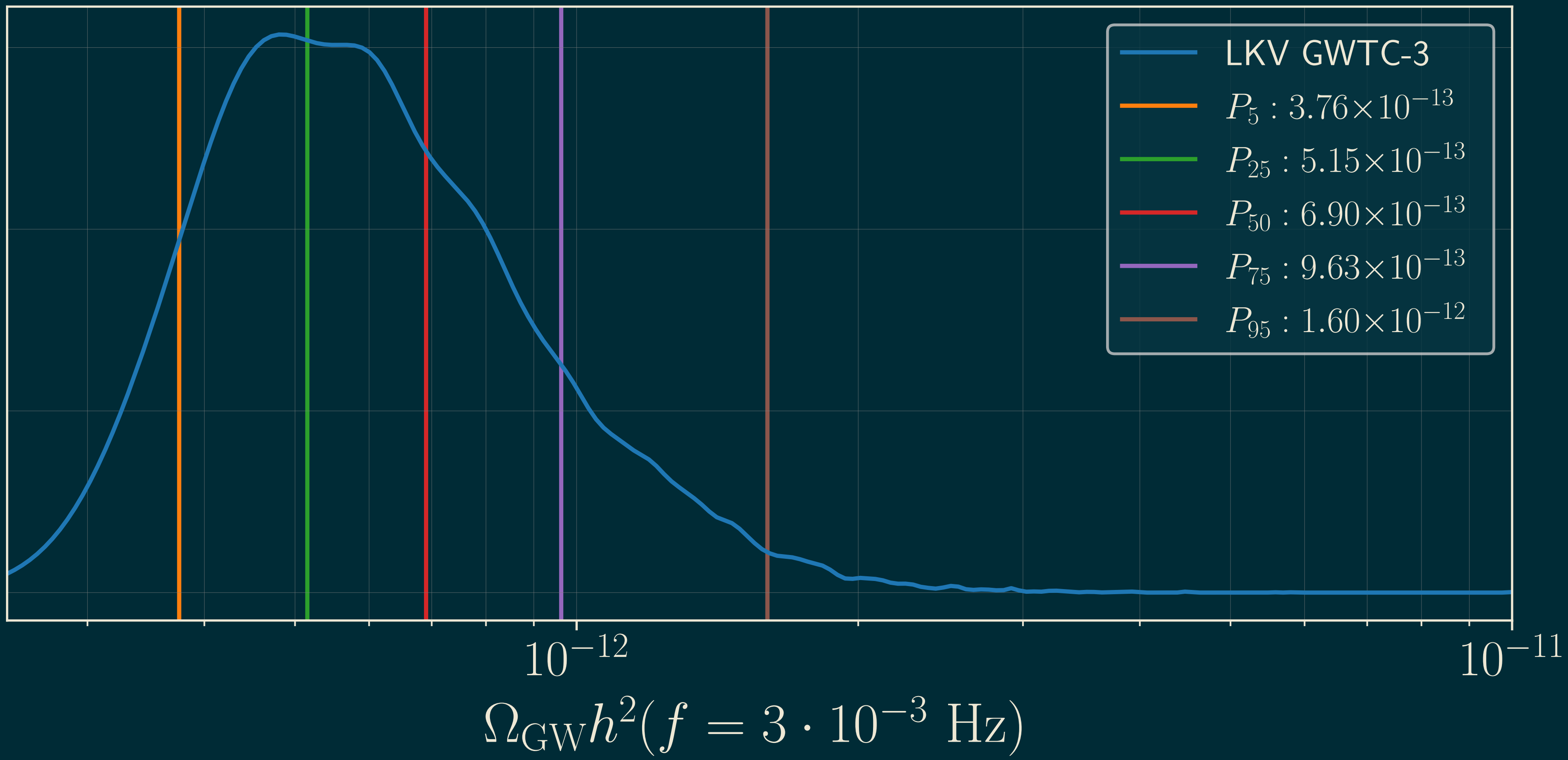
A: Fast simulation *is* realistic (up to non-physical effects, e.g. τ_c cut)



But would take forever! $\sim 500 \cdot 10^6$ events for $z_{\max} = 5$ (above $z_{\max} = 1$)

We can use the simulator to subtract individual events, injecting a full **analytic** background!!!

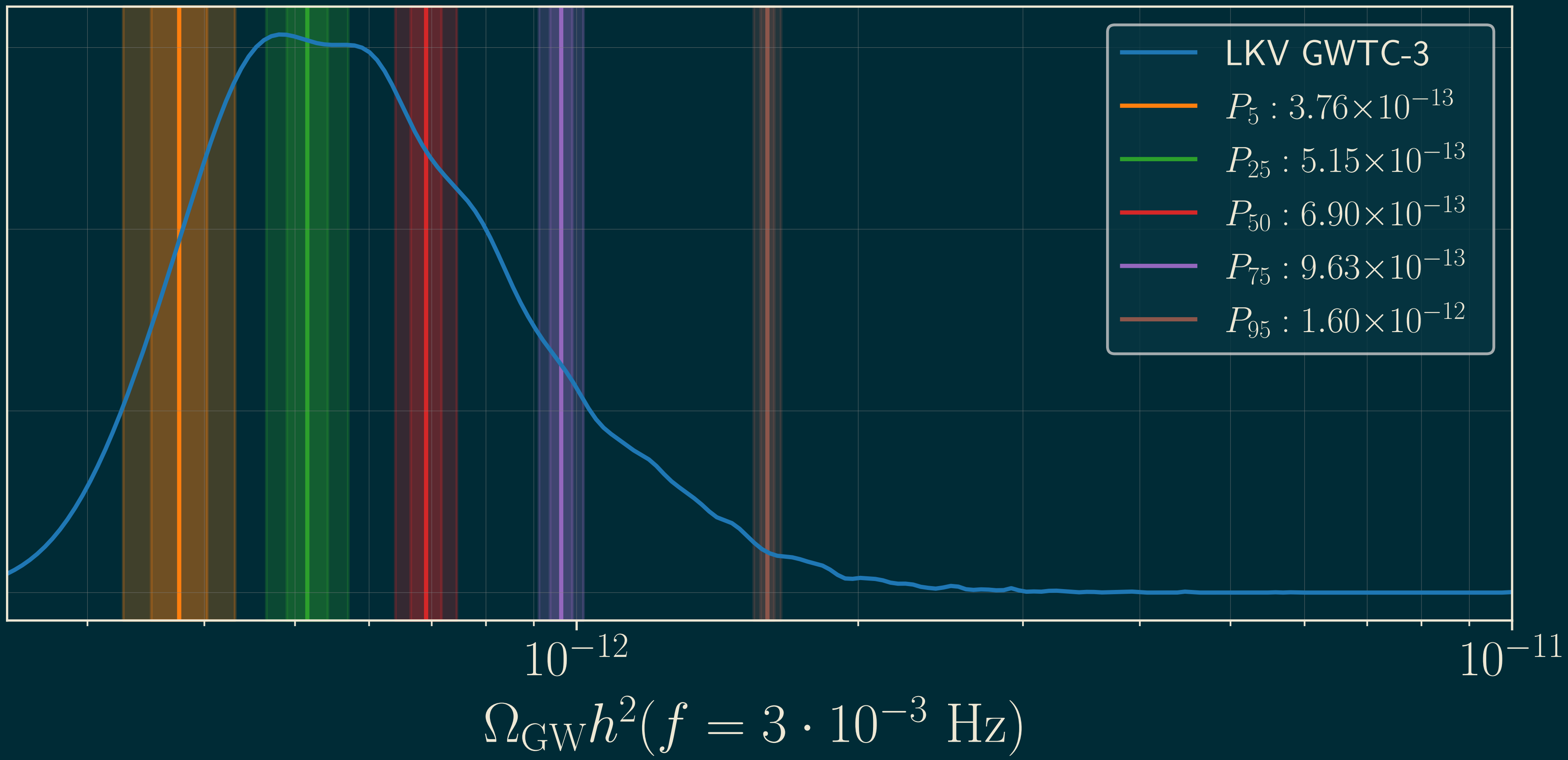
Background prediction from LVK GWTC-3 (approximate)



Density of GWTC-3 posterior samples on the background, analytic computation with high-z $R(z)$ extension (optimistic LVK prediction)

Showing percentiles $5, 25, 50, 75, 95$ (mind log-scaled x axis).

Background prediction from LVK GWTC-3 (approximate)



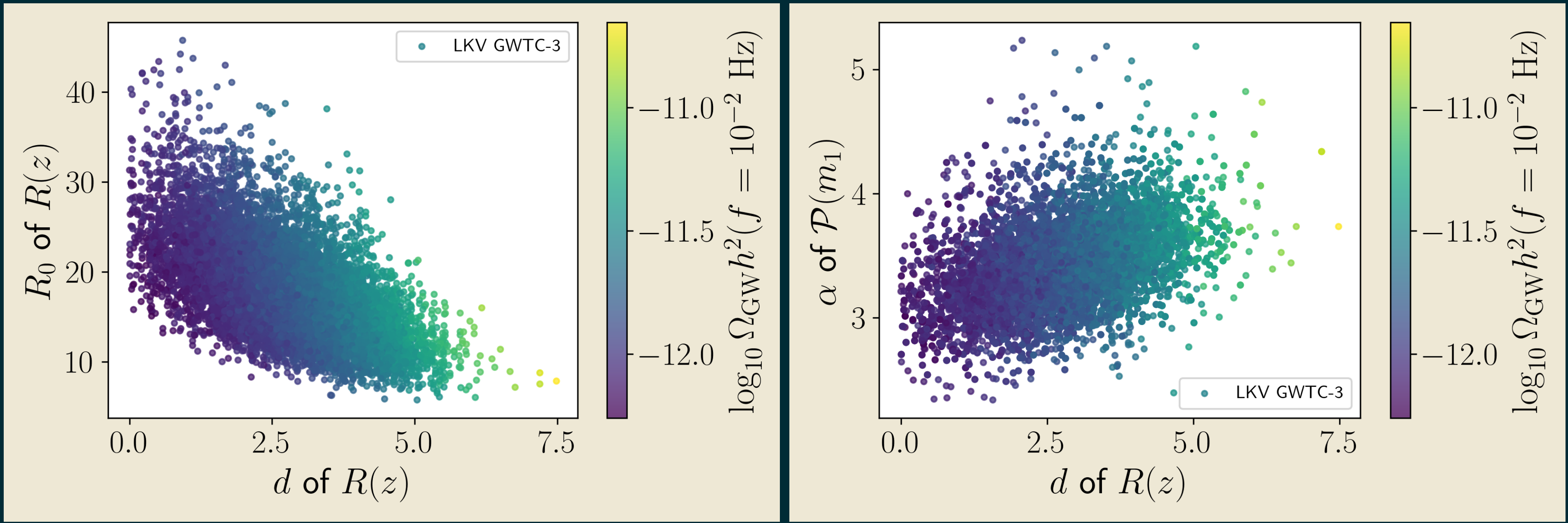
LISA forecast per percentile: $\sim\ \times 20$ precision re **LVK**' SOBBH prediction!

Method: LISA 3-channels, $4\ \rm yr$, marged over tilt + galactic CB ($+10\%\sigma$) + noise. Fisher, cross-checked with full MC.

Population parameter constraints from the background?

Since LISA will measure the background with high precision, can it further constrain population parameters?

Which ones? z-distribution, $\mathcal{M}$-distribution (but not e.g. spins, position)



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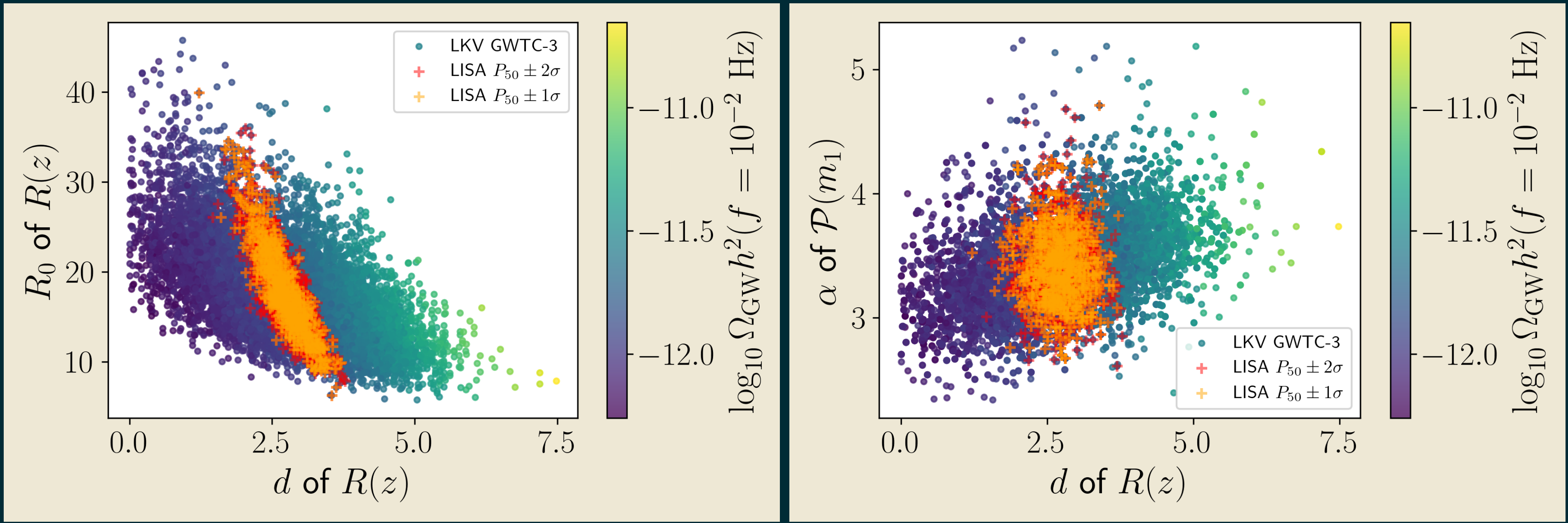


Inject e.g. median, select samples within LISA-forecasted error band, and look at compatible population parameters.

Very preliminary and optimistic (would need harder proper analysis). Not an actual result of ours (yet). Just peeking behind the curtain!

Individual events

We mentioned that the *fast simulator* let us characterise individual events, in particular, get their **SNR** in the presence of realistic instrument + astro noise.

Simulating a full population is very expensive: too many events! ($\sim 500\mathrm{M}$)

Since the analytic computation of the background is realistic, let us:

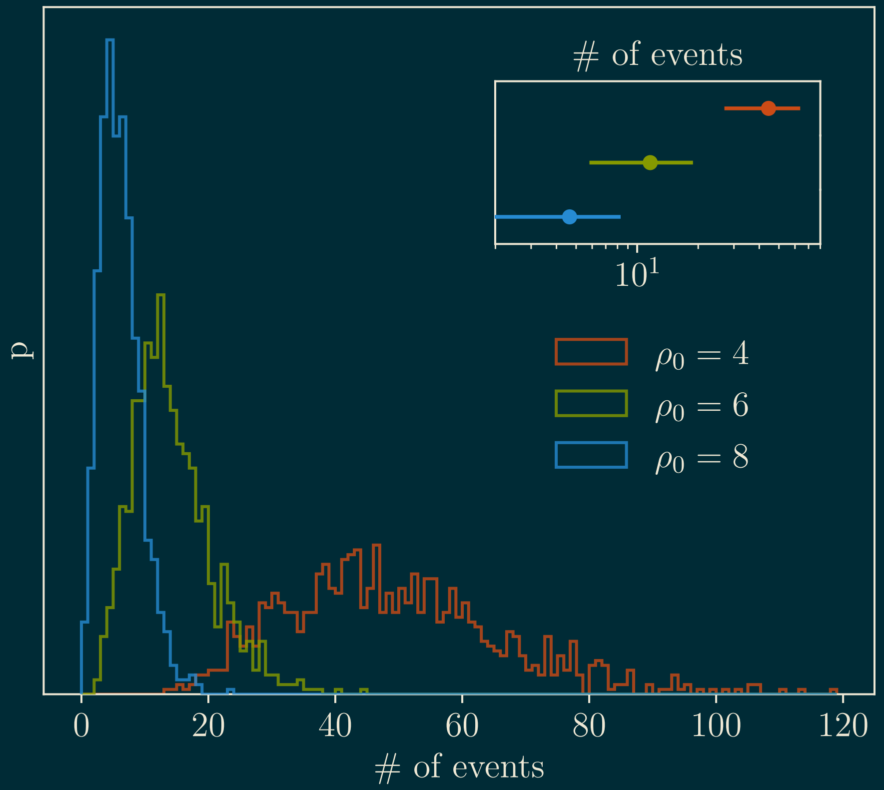
- Inject a background following the analytic computation
- Simulate a reduced number of sources, with **approx SNR** ≥ 2 (e.g.)
- Select sources with **real SNR** higher than some threshold (usually 8).

This allow us to do thousands of simulations in mere hours.

One (or more) such simulations per GWTC-3 posterior sample

$\Rightarrow$ **probability distribution of #sources with** $\mathrm{SNR}_{\mathrm{LISA}} > \rho$**!**

Individual events – II



- Few **detectable** events: $\mathrm{SNR}_{\mathrm{LISA}} > 8$
- Many **archival search** candidates: $\mathrm{SNR}_{\mathrm{LISA}} > 4$ (Ewing, Sachdev et al. '20)
- Potential for (multi-messenger) **forewarning** with intermediate SNR: high $f \longrightarrow$ high $\mathrm{SNR}_{\mathrm{LISA}}$ **AND** high $f \longrightarrow$ faster f evolution $\longrightarrow$ closer to merging $\longrightarrow$ maybe observable by LKV, ET...

Conclusions

- LISA can measure very precisely the SOBBH background predicted by LVK
  $\Rightarrow$ can be accounted-for in parameter-free cosmological SGWB reconstructions
- The combination of individual events from LVK and background from LISA would further constrain the population model (more work needed!)
- LISA will see just a few inspiraling events, but many archival search candidates, maybe some forewarning.
- Future work from our team:
  - add other degenerate sources to formalism: BNSs, NSBHs
  - proper population parameter constraints
  - characterisation of forewarning events

Thanks!

(References in next slide)

References

Abbot et al. '21a: *GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run*, the LIGO Scientific Collaboration, the Virgo Collaboration and the KAGRA Collaboration (arXiv:2111.03606)

Abbot et al. '21b: *The population of merging compact binaries inferred using gravitational waves through GWTC-3*, the LIGO Scientific Collaboration, the Virgo Collaboration and the KAGRA Collaboration (arXiv:2111.03634)

LV '16 (GW150914 discovery): *Observation of Gravitational Waves from a Binary Black Hole Merger*, the LIGO Scientific Collaboration and the Virgo Collaboration, **Phys. Rev. Lett. 116, 061102 (2016)** (arXiv:1602.03837)

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Talbot & Thrane '18: *Measuring the binary black hole mass spectrum with an astrophysically motivated parameterization*, C. Talbot and E. Thrane, **ApJ 856 173 (2018)** (arXiv:1801.02699)

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Ewing, Sachdev et al. '20: *Archival searches for stellar-mass binary black holes in LISA*, B. Ewing, S. Sachdev, S. Borhanian and B.S. Sathyaprakash, **Phys. Rev. D 103, 023025 (2021)** (arXiv:2011.03036)

Some recent related works

Upper Limits on the Isotropic Gravitational-Wave Background from Advanced LIGO's and Advanced Virgo's Third Observing Run, the LIGO Scientific Collaboration, the Virgo Collaboration and the KAGRA Collaboration, **Phys. Rev. D 104, 022004 (2021)** (arXiv:2101.12130)

Impact of LIGO-Virgo binaries on gravitational wave background searches, M. Lewicki and V. Vaskonen (arXiv:2111.05847)

Constraining changes in the merger history of (P)BH binaries with the stochastic gravitational wave background, V. Atal, J.J. Blanco-Pillado, A. Sanglas and N. Triantafyllou (arXiv:2201.12218)