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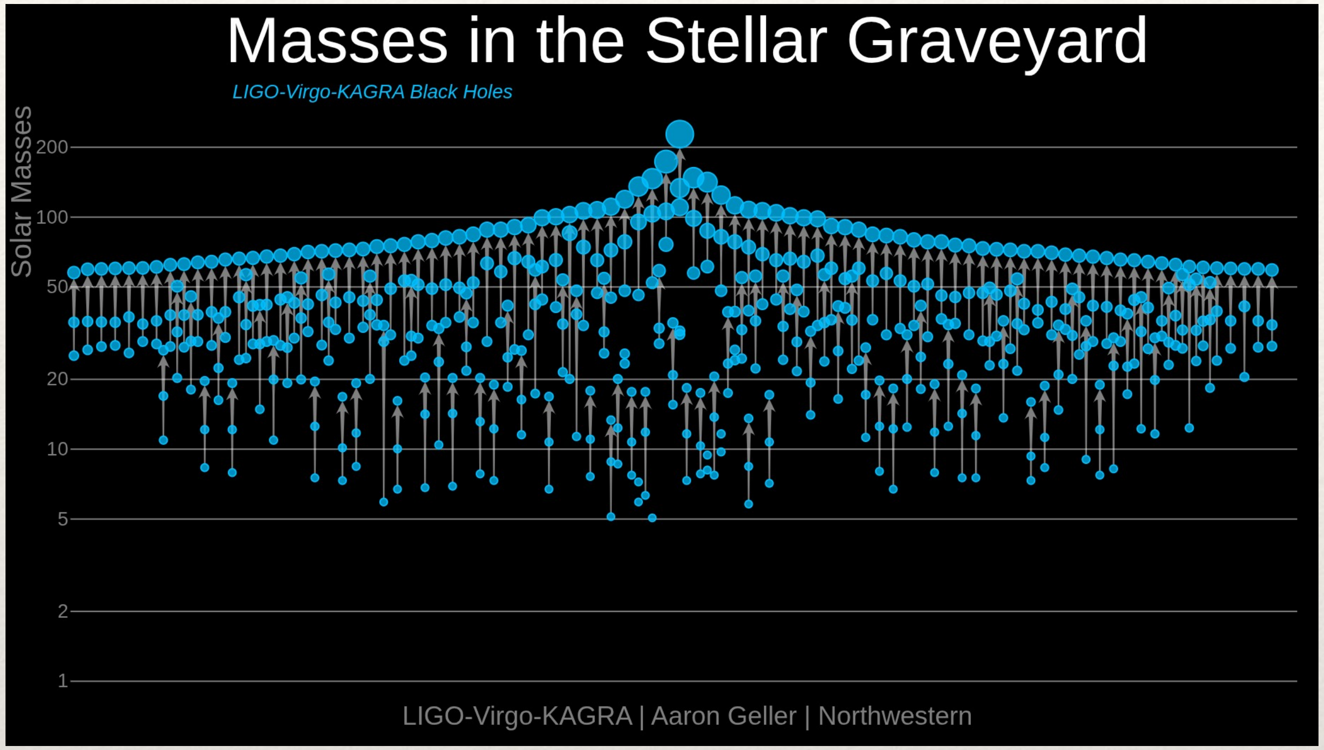
Where did heavy binaries go? Gravitational-wave populations using Delaunay triangulation with optimized complexity

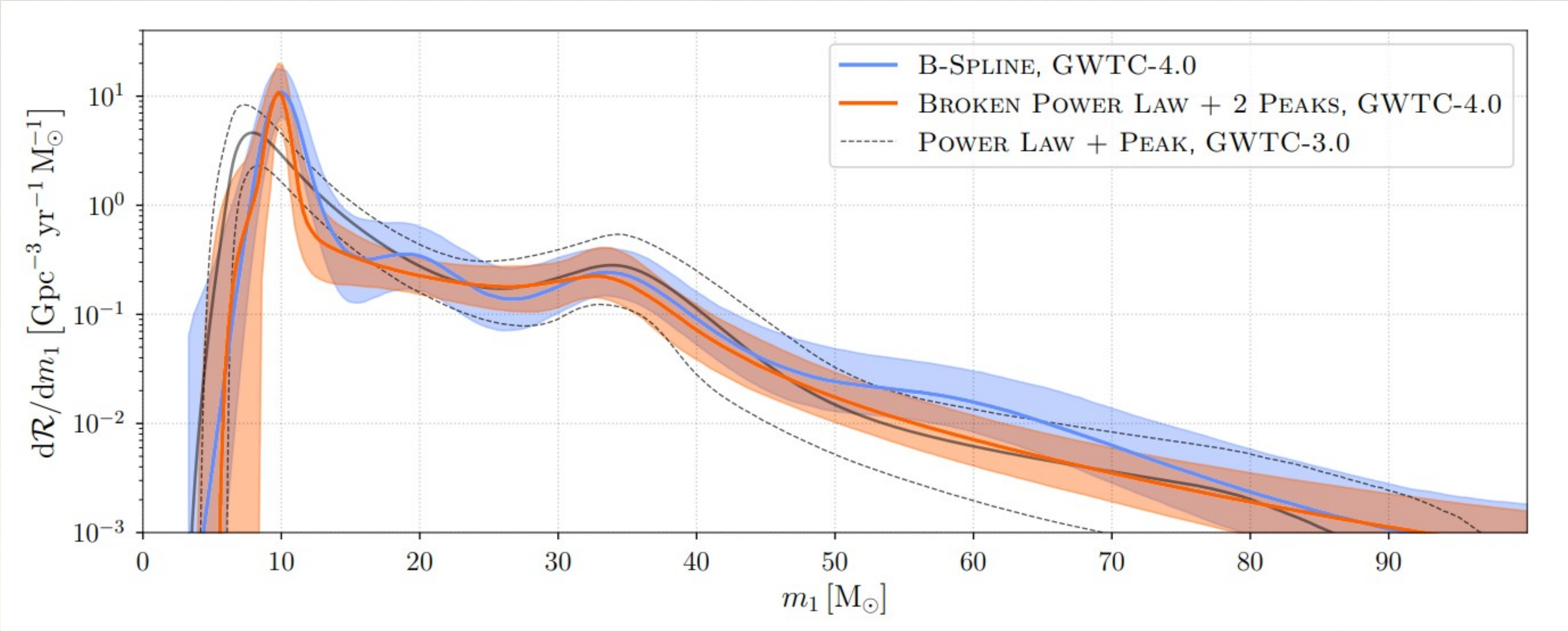
Tenorio, Toubiana, Bruel, Gerosa, Gair

arXiv:2509.19466

Population analysis



$$p_{\rm astro}(m_1, m_2, \chi_1, \chi_2, z|\Lambda)$$



Credits: LVK 2025

Correlations at the population level

- Parameters $(m_1,\ m_2,\ \chi_1,\ \chi_2,\ z)$ often treated as independent, but…

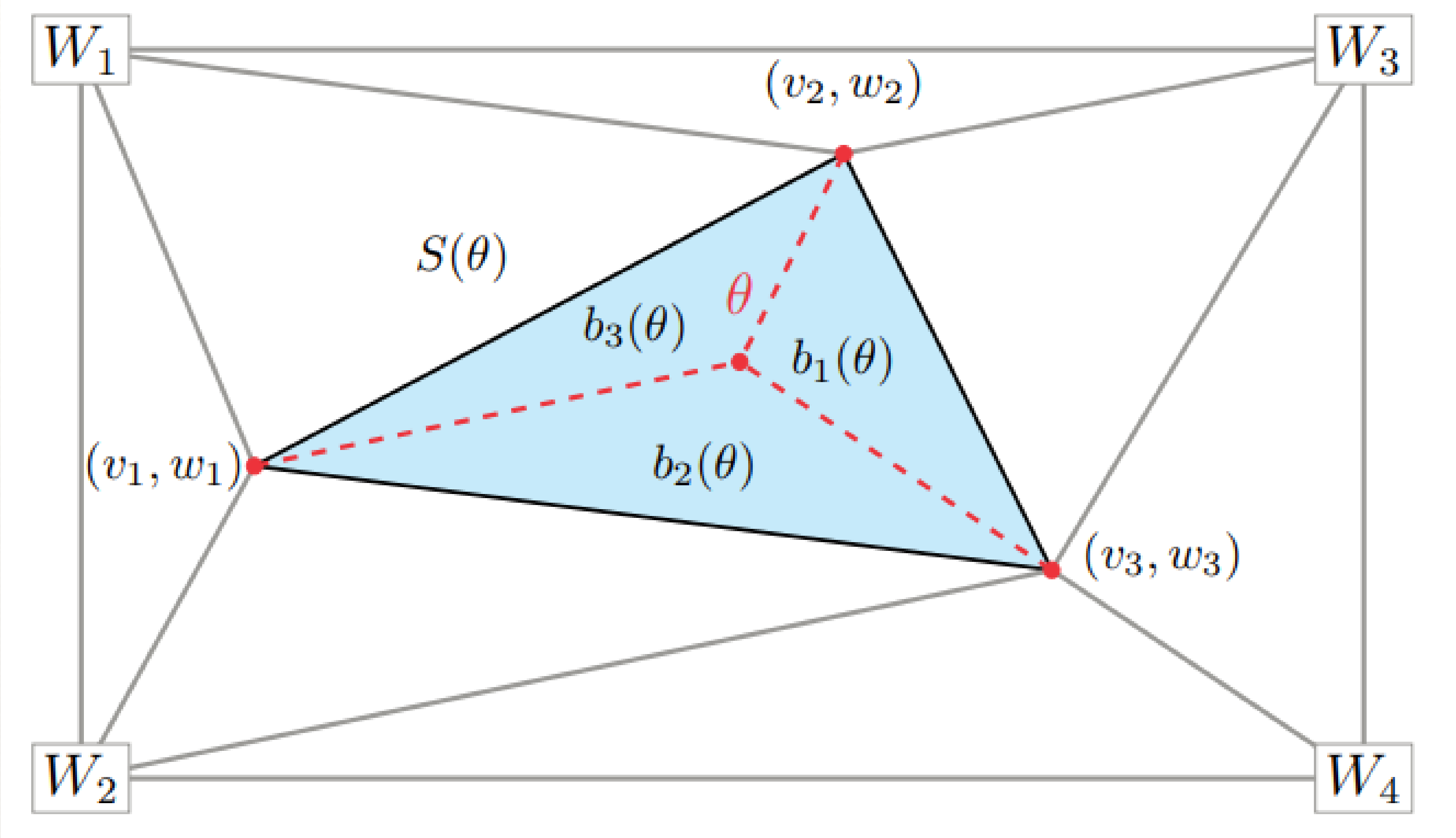
- Correlations are expected from the astrophysical point of view:
  - mass and spins (2nd generation merger should have larger, likely misaligned, spins)
  - mass/spin and redshift (metallicity, contribution of different channels)

$$\vdots$$

- Simple analytic functions not suited to capture complex multi-dimensional features

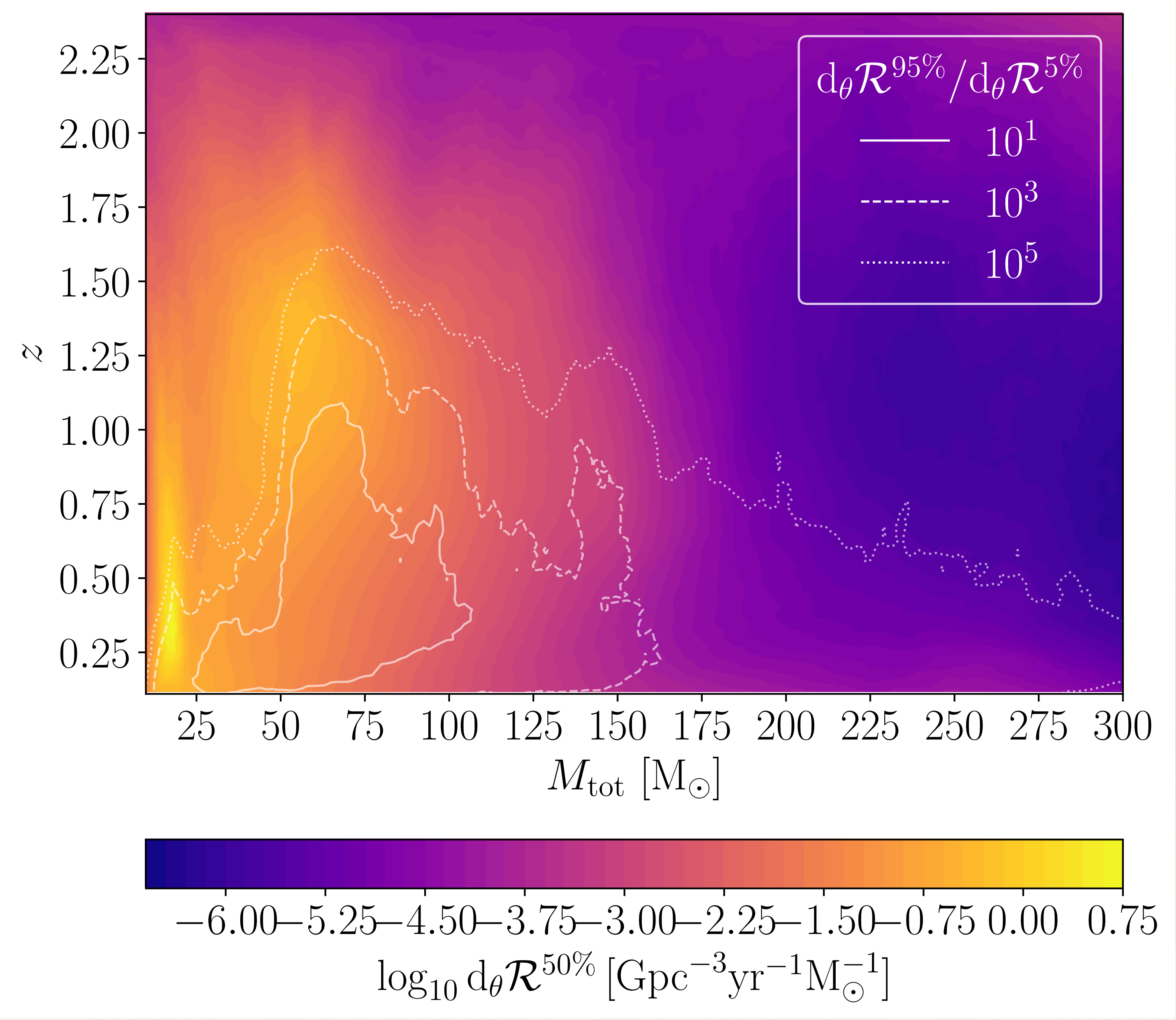
- Toubiana, Katz, Gair MNRAS 2023: linear interpolation with flexible number of knots in 1D
  In 2D, no natural interpolation scheme

Delaunay triangulation



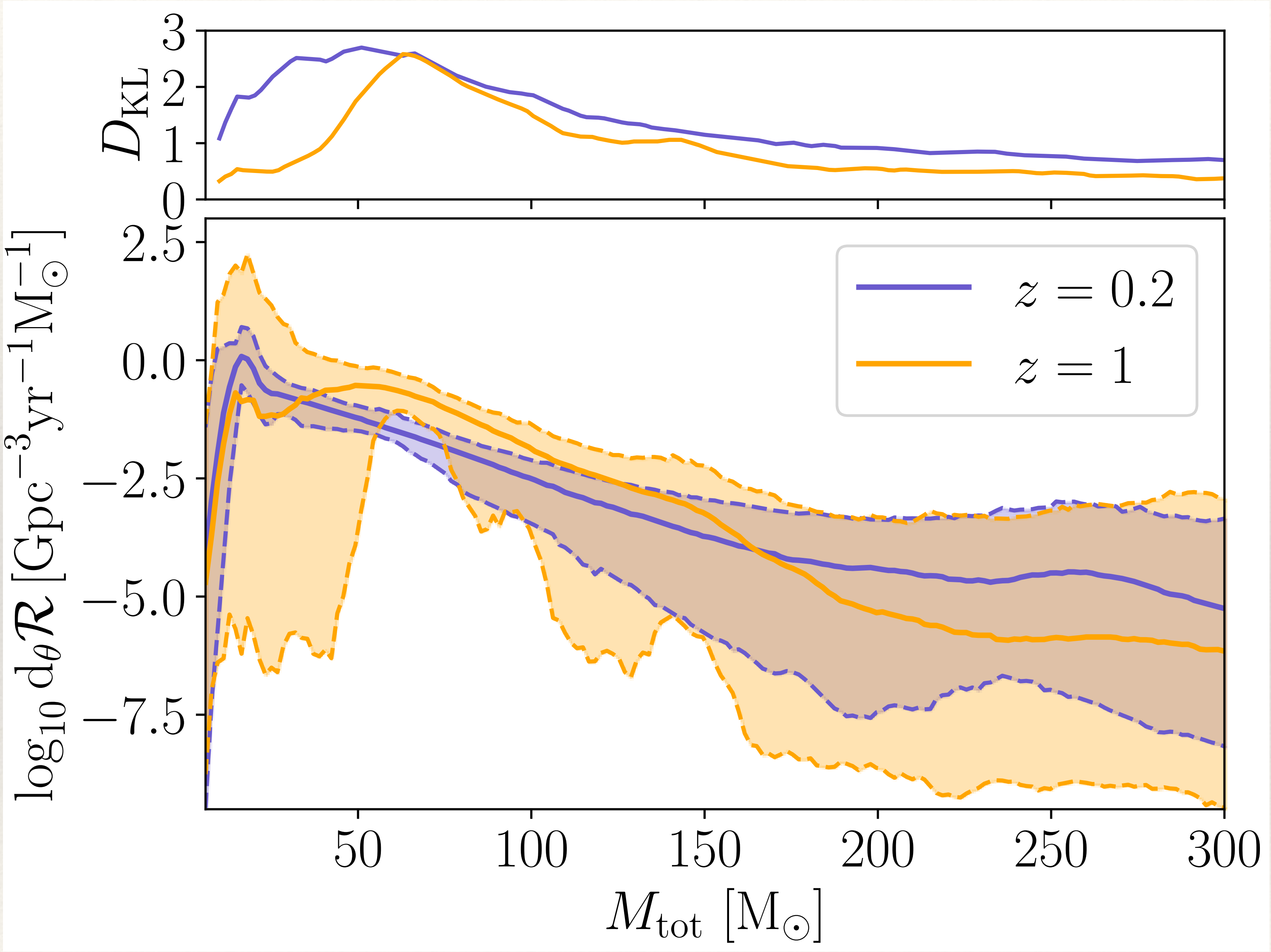
- "Optimal" triangulation of a convex surface
- Our implementation:
  - Position of the corners is fixed
  - Number and position of central vertices + rate at all vertices are free (use reversible-jump MCMC)
  - Linearly interpolate log rate

Results on GWTC-4



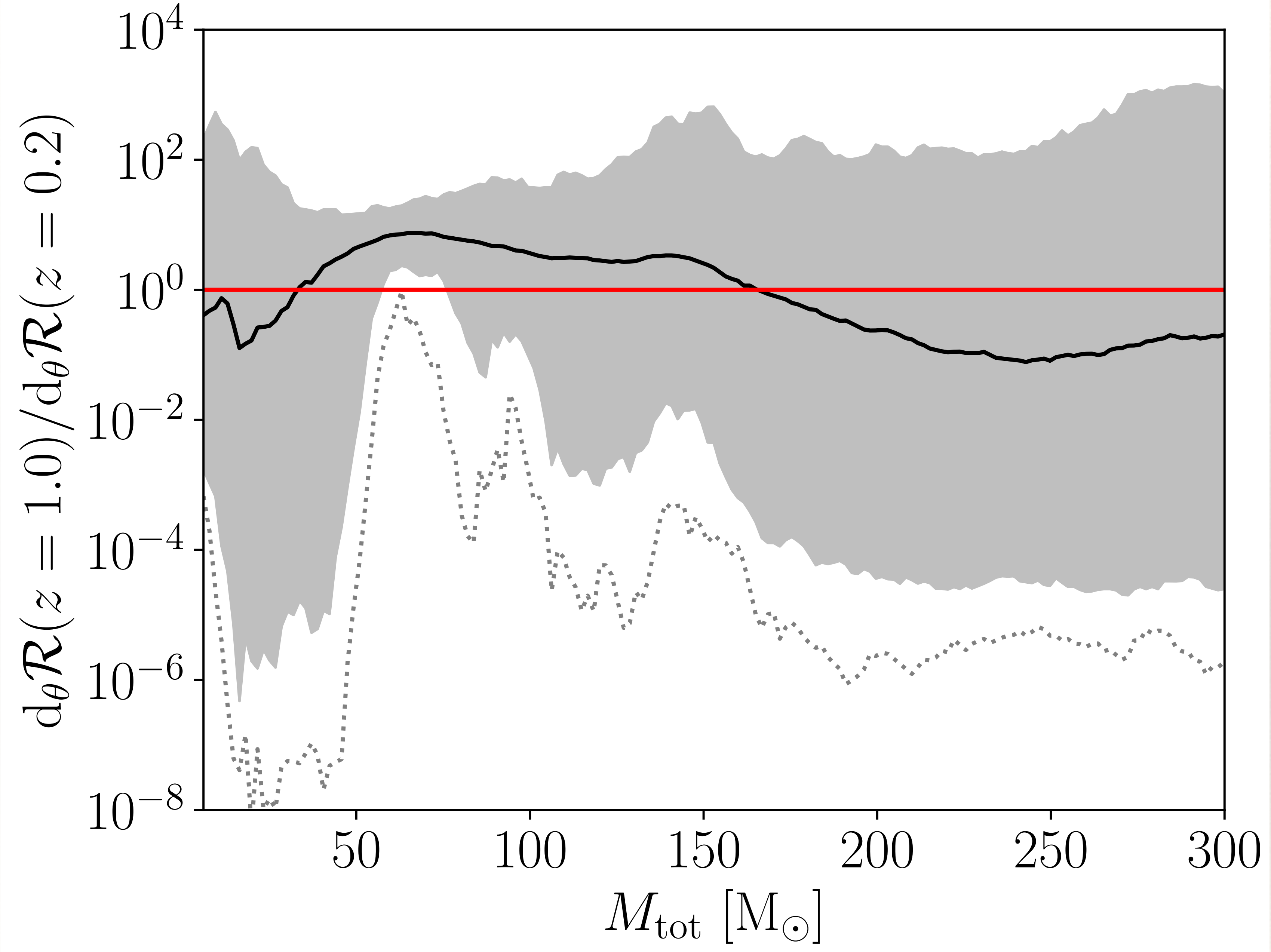
Suggests existence of two sub-populations

Results on GWTC-4



No evidence for a peak at low redshift, seems to appear for $z \gtrsim 0.7$

Results on GWTC-4



98.5% confidence that the rate evolves with redshift, but compatible with mass-independent evolution

Astrophysical interpretation

- Several scenarios could explain the disappearance of the peak:
  - Peak from pulsational pair-instability, disappears as metallicity increases due to lighter stars
  - Peak comes from single stars formed in low-metallicity environments that paired later
  - Peak comes from contribution of binaries formed dynamically
- Process that generates the peak likely has short time-delays (if power-law, index ≤ -1)

Higher dimensional correlations will allow to disentangle (mass ratio, spins, eccentricity)

Conclusions

- Flexible methods are needed to uncover the properties of the population of compact objects
  Delaunay triangulation with reversible-jump MCMC: optimal complexity 2D interpolation

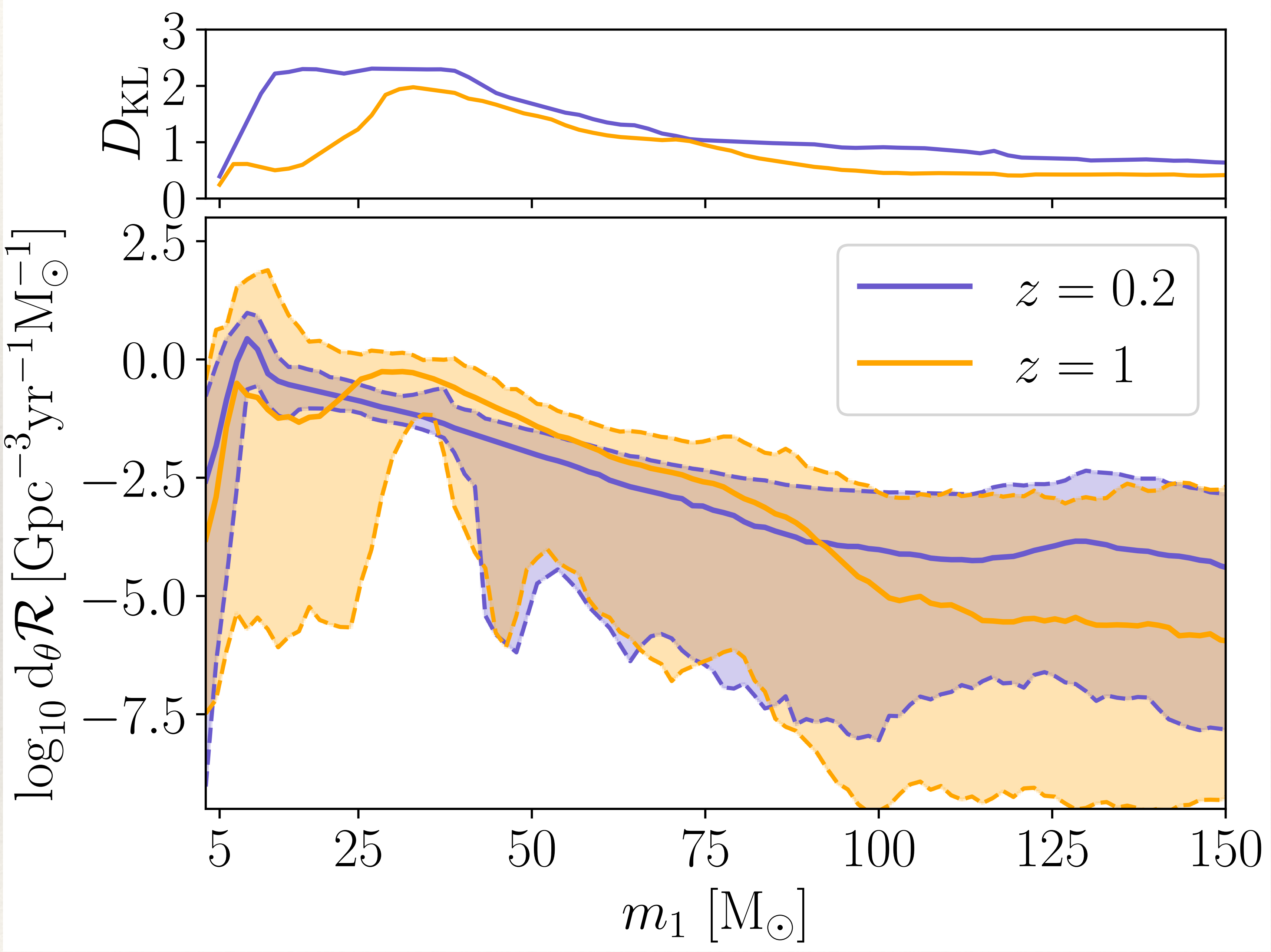
- First hint of an evolution of the mass spectrum with redshift
  Analysis on GWTC-4 cannot establish statistically the evolution of the mass spectrum, but suggests that the peak disappears at low redshift

- New perspective on formation scenarios of binary black holes
  Constraint on contribution from multiple channels/time delays

- Next: investigate 3D/4D correlations

Thank you for your attention!

Results on GWTC-4



Spin-mass ratio

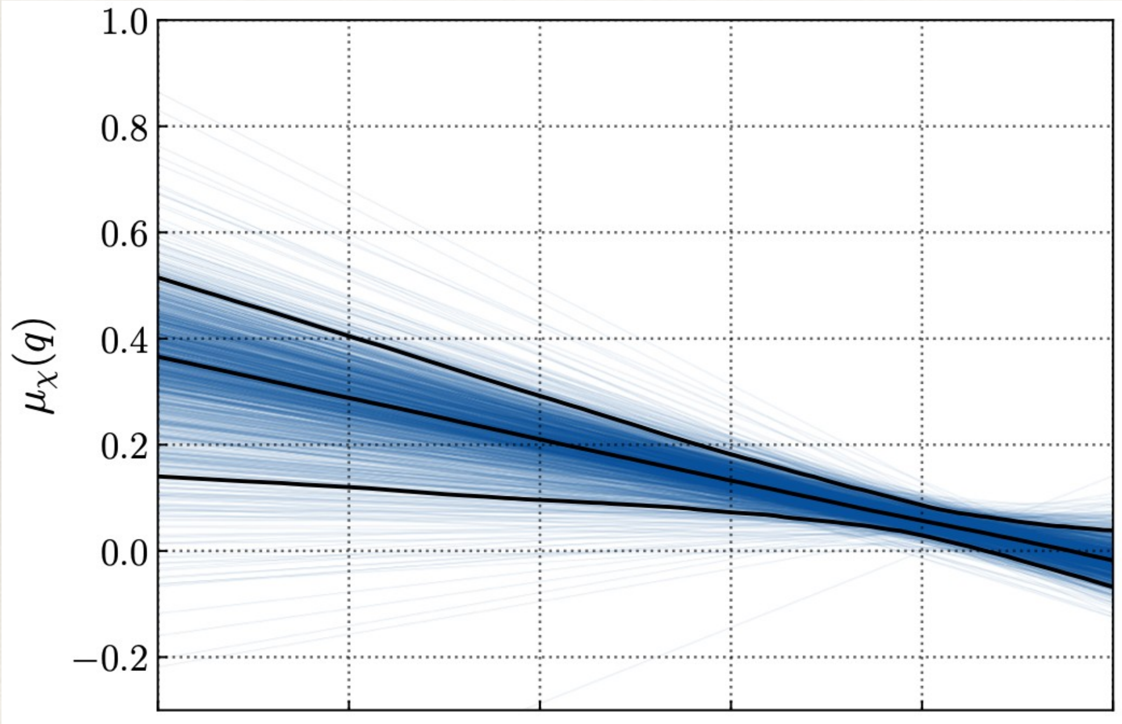
$$\chi_{eff} = \frac{m_1 \vec{\chi}_1.\vec{L} + m_2 \vec{\chi}_2.\vec{L}}{m_1 + m_2}$$

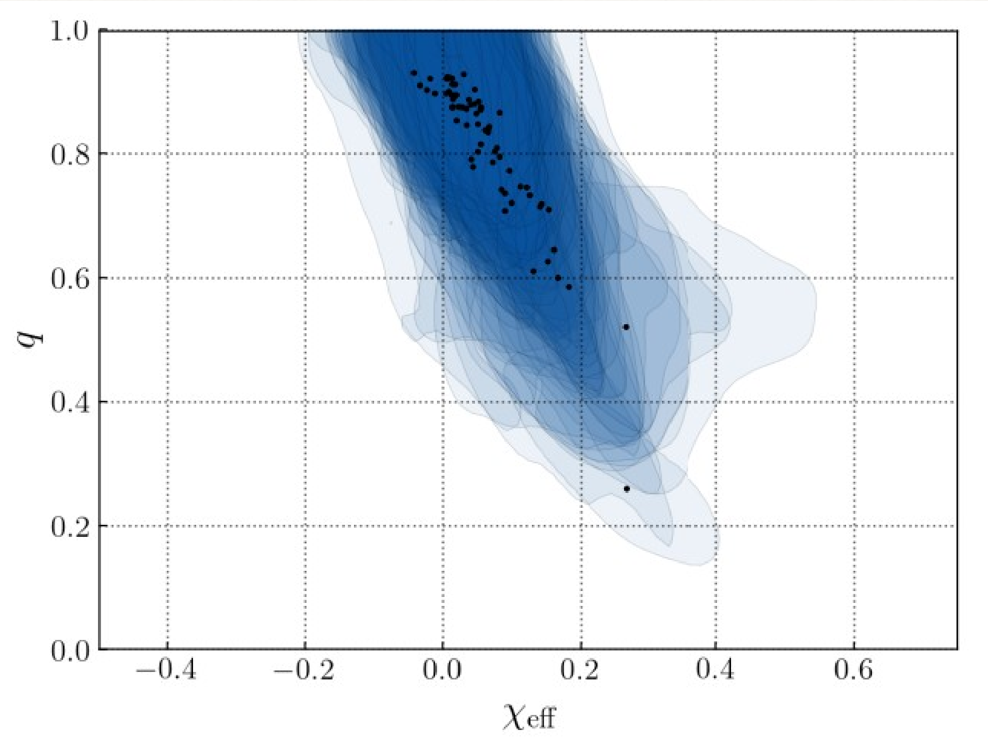
$$q = \frac{m_2}{m_1} \leq 1$$

$$p(\chi_{\rm eff}|q) \propto \exp\left[-\frac{(\chi_{\rm eff} - \mu(q))}{2\sigma(q)^2}\right]$$

$$\mu(q) = \mu_0 + \alpha(q-1)$$

$$\log_{10}\sigma(q) = \log_{10}(\sigma_0) + \beta(q-1)$$





LIGO/Virgo/KAGRA PRX 2023

- Possible explanation:
  - binaries formed in AGN (N[th] generation + 1G black hole)
  - stable mass transfer in isolated binaries