Model-independent cosmology with Bright Sirens

1st TEONGRAV workshop - September 17- Rome

Andrea Cozzumbo

Riccardo Murgia Gor Oganesyan Marica Branchesi

INFN LNGS

GSSI

Andrea Cozzumbo

in collaboration with

Ulyana Dupletsa Rodrigo Calderón Riccardo Murgia

Biswajit Banerjee Gor Oganesyan Marica Branchesi

Warm up

$$H(z) = H_0\sqrt{\Omega_{m,0}(1+z)^3 + \Omega_{r,0}(1+z)^4 + \Omega_{k,0}(1+z)^2 + \Omega_{\mathrm{DE},0}\exp\left[3\int_0^z \frac{1+w_{\mathrm{DE}}(z')}{1+z'}dz'\right]}$$

$$w_{\mathrm{DE}}(z) = \frac{P_{\mathrm{DE}}(z)}{\rho_{\mathrm{DE}}(z)}$$

Warm up

$$H(z) = H_0\sqrt{\Omega_{m,0}(1+z)^3 + \Omega_{r,0}(1+z)^4 + \Omega_{k,0}(1+z)^2 + \Omega_{\mathrm{DE},0}\, f_{\mathrm{DE}}(z)}$$

$$w_{\mathrm{DE}}(z) = \frac{P_{\mathrm{DE}}(z)}{\rho_{\mathrm{DE}}(z)}$$

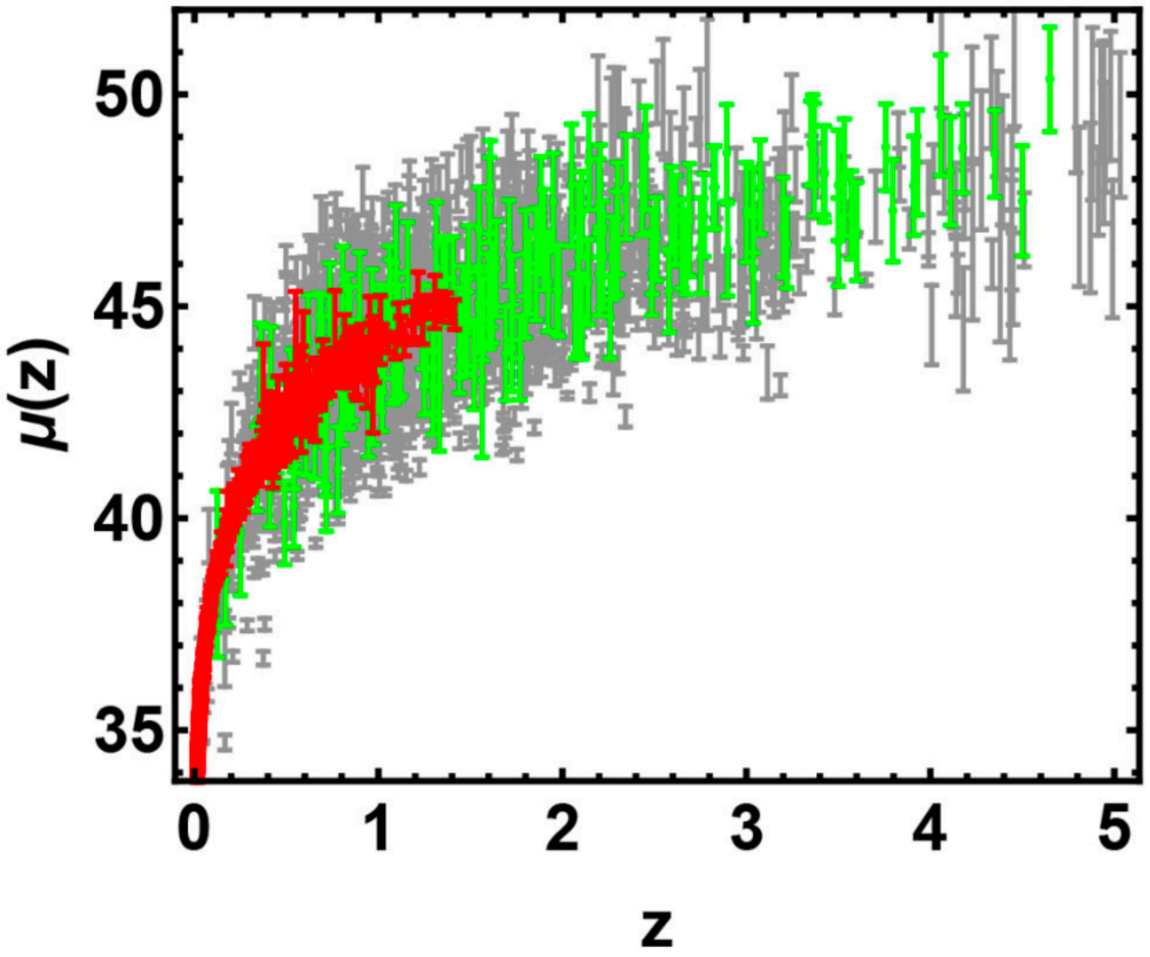
$$f_{\mathrm{DE}}(z) = \frac{\Omega_{\mathrm{DE}}(z)}{\Omega_{\mathrm{DE},0}}$$

$$d_L(z) = c\,(1+z)\int_0^z \frac{dz'}{H(z')}$$

We want to trace the Hubble parameter $H(z)$

Standard candles

Demianski+ 2020



SNIa (Cepheids)

GRBs (SNIa)

QSOs (F_X - F_{UV})

Why GWs

$$\tilde{h}_+(f) \propto \frac{\mathscr{M}^{5/6}}{2\,d_L} f^{-7/6}\, e^{i\phi(\mathscr{M},f)} \left(1+\cos^2(\iota)\right)$$

$$\tilde{h}_\times(f) \propto \frac{\mathscr{M}^{5/6}}{d_L} f^{-7/6}\, e^{i\phi(\mathscr{M},f)+i\,\pi/2} \cos(\iota)$$

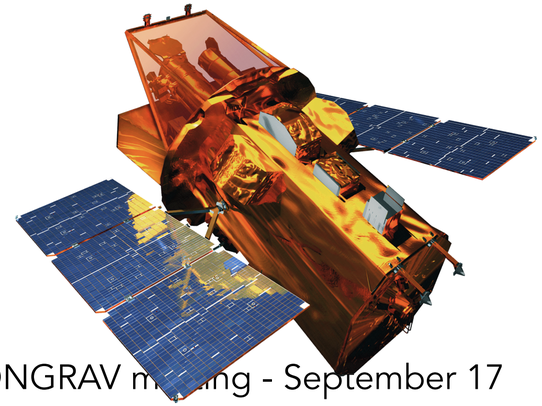
self-calibrated measure of distance

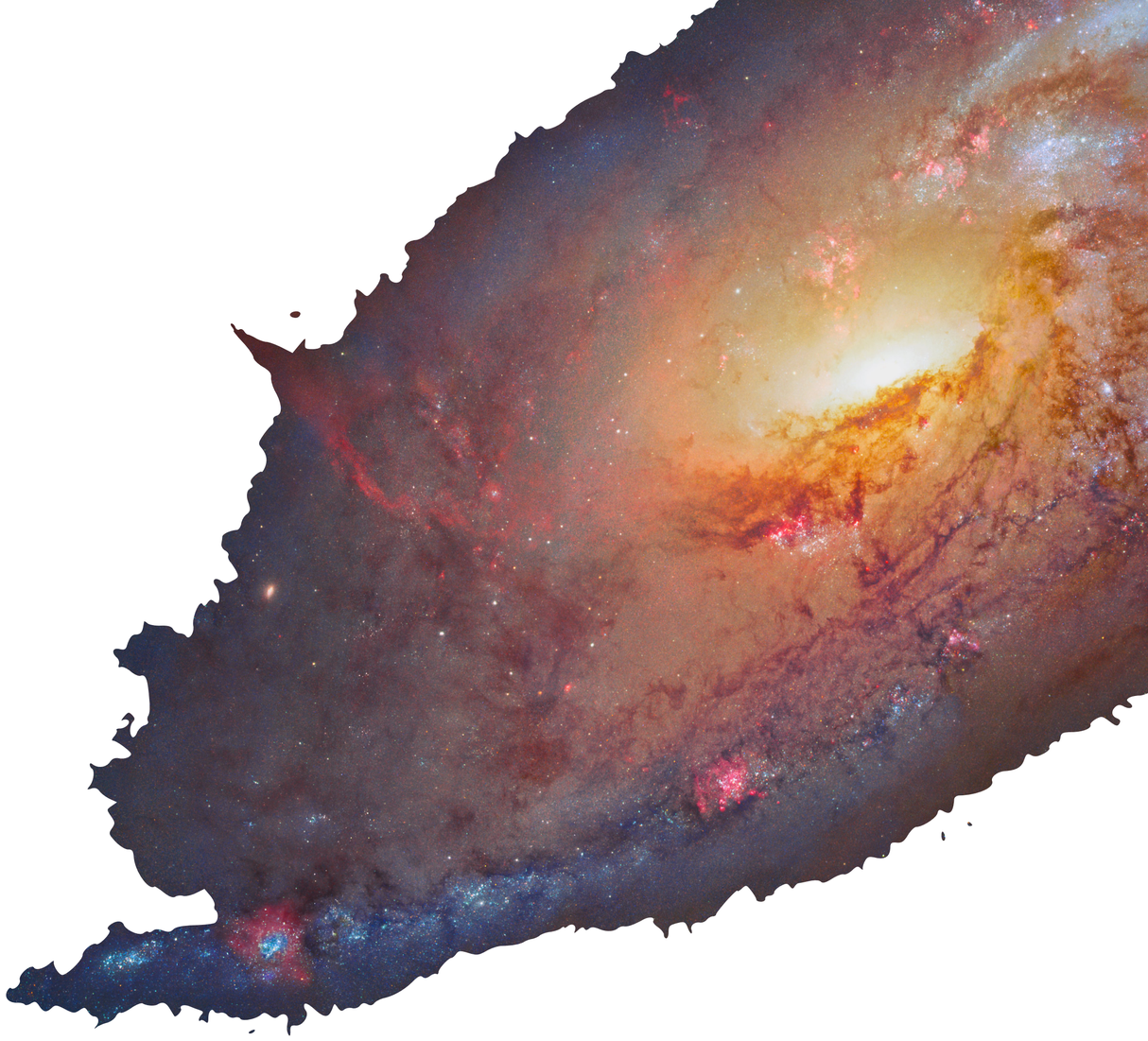
$$d_L(z) = c\,(1+\overset{?}{z}) \int_0^z \frac{dz'}{H(z')}$$

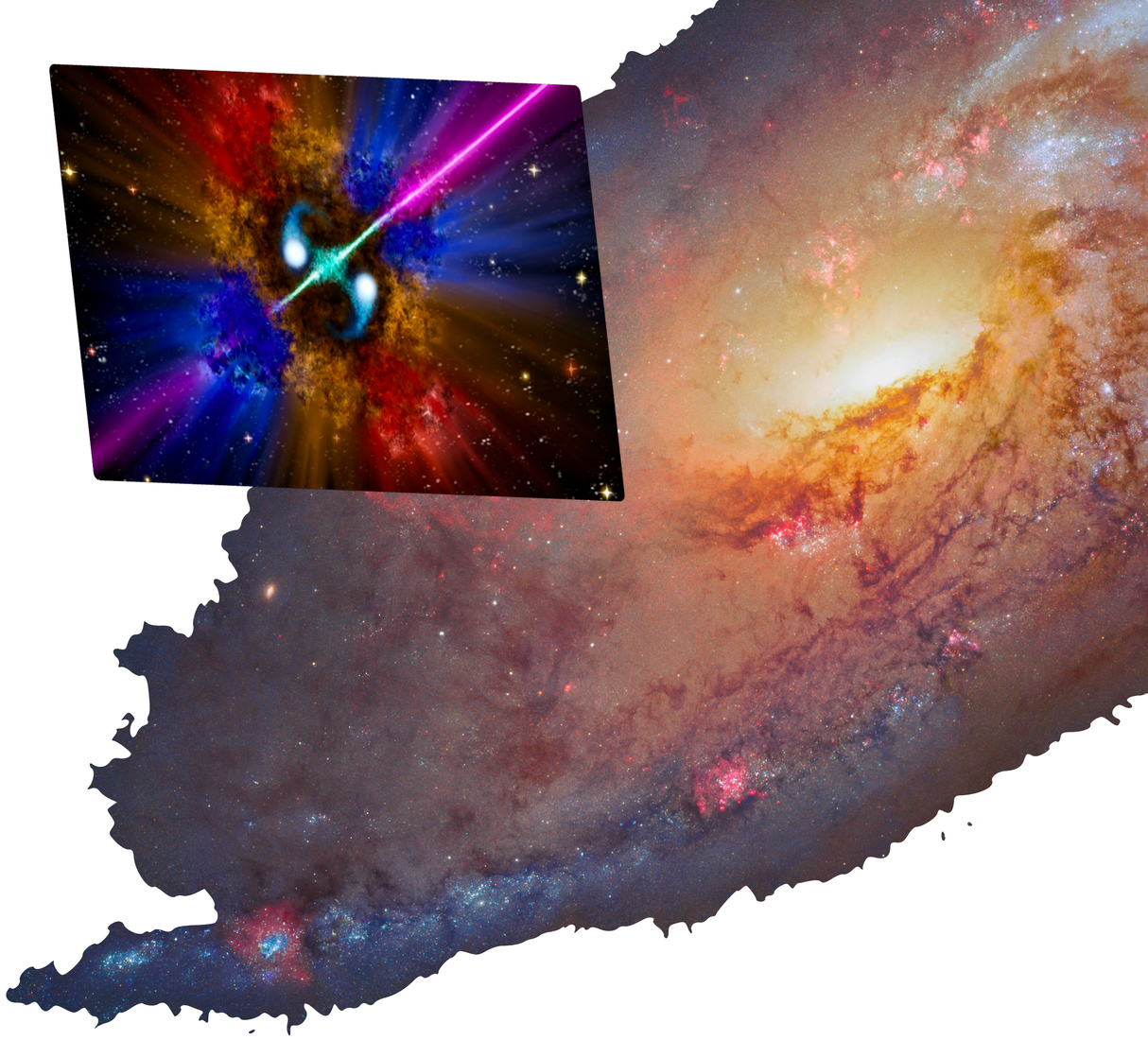
Why GRBs

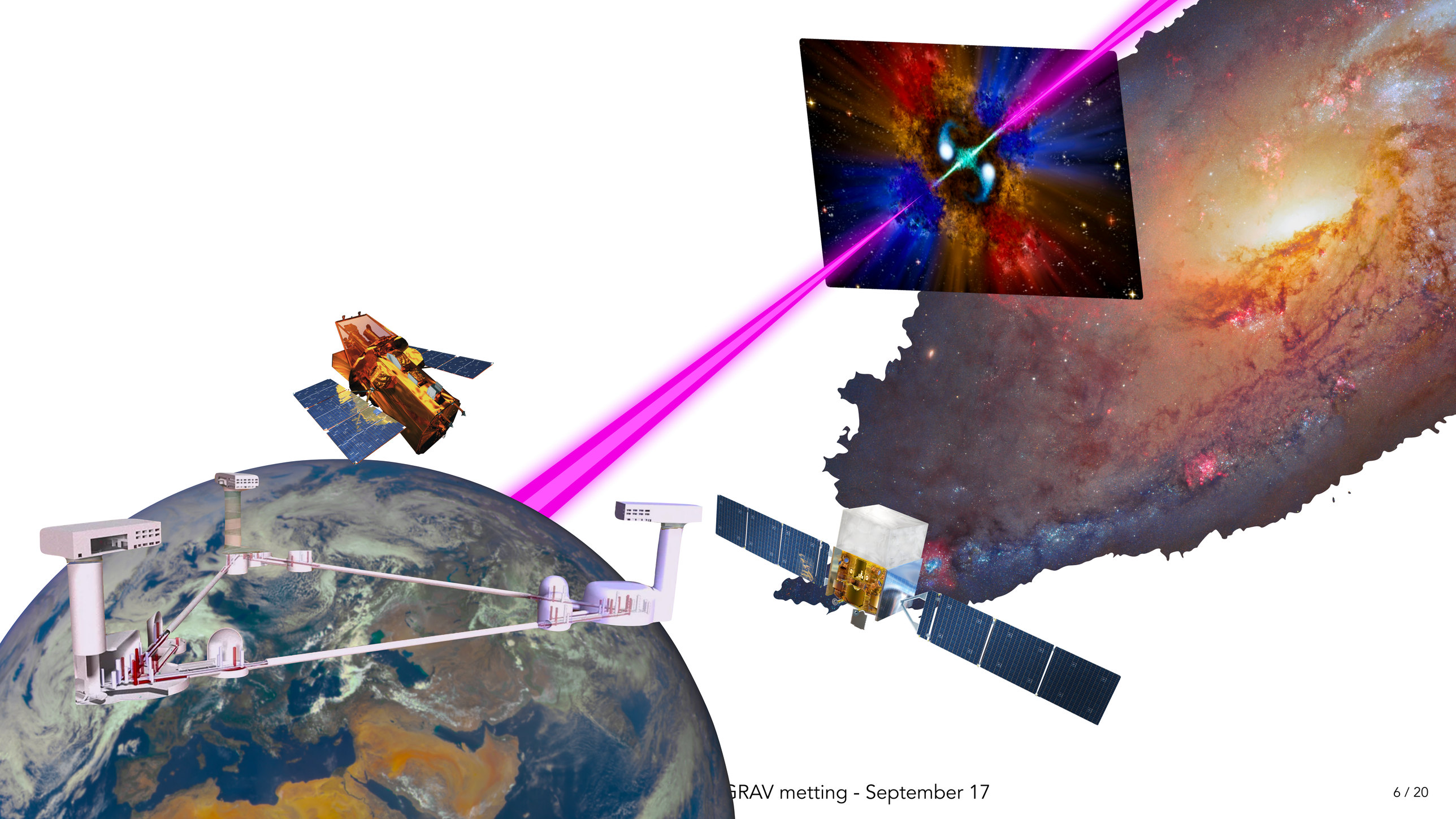
BNS are associated to GW and to the burst of γ-rays → **Multi-messenger astrophysics**

This give us a $\Delta z \sim 0$

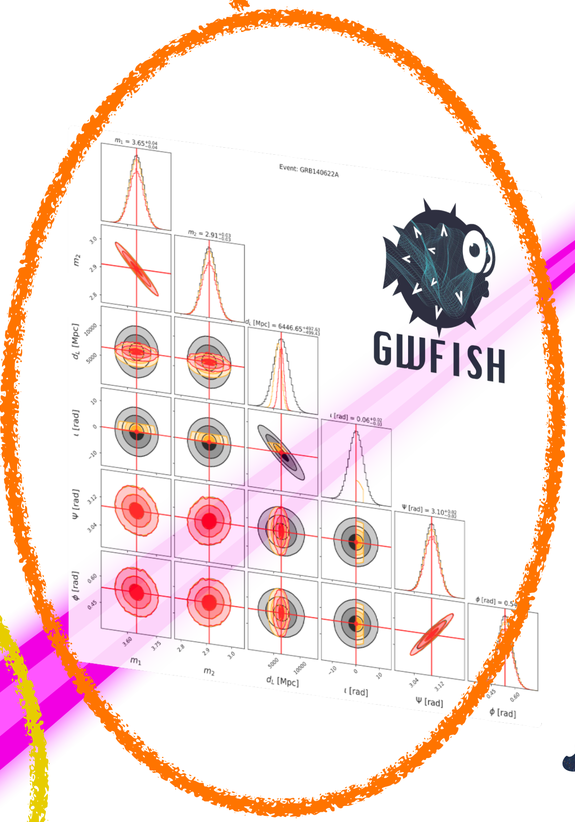


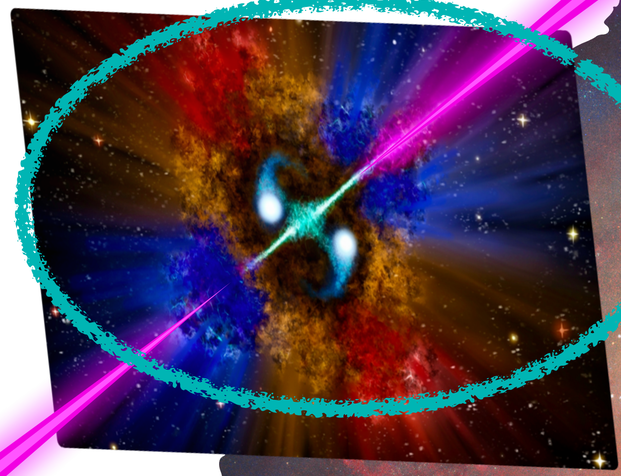


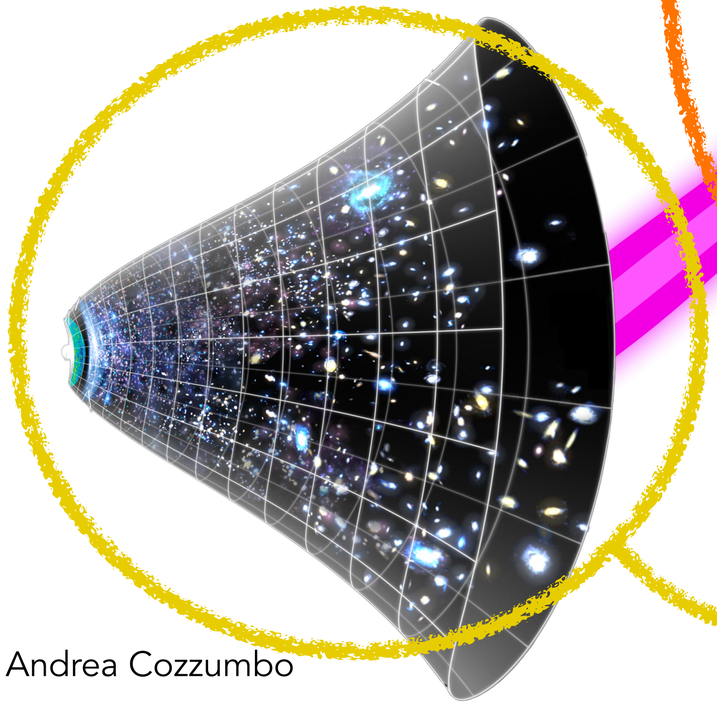




$d_L(z)$







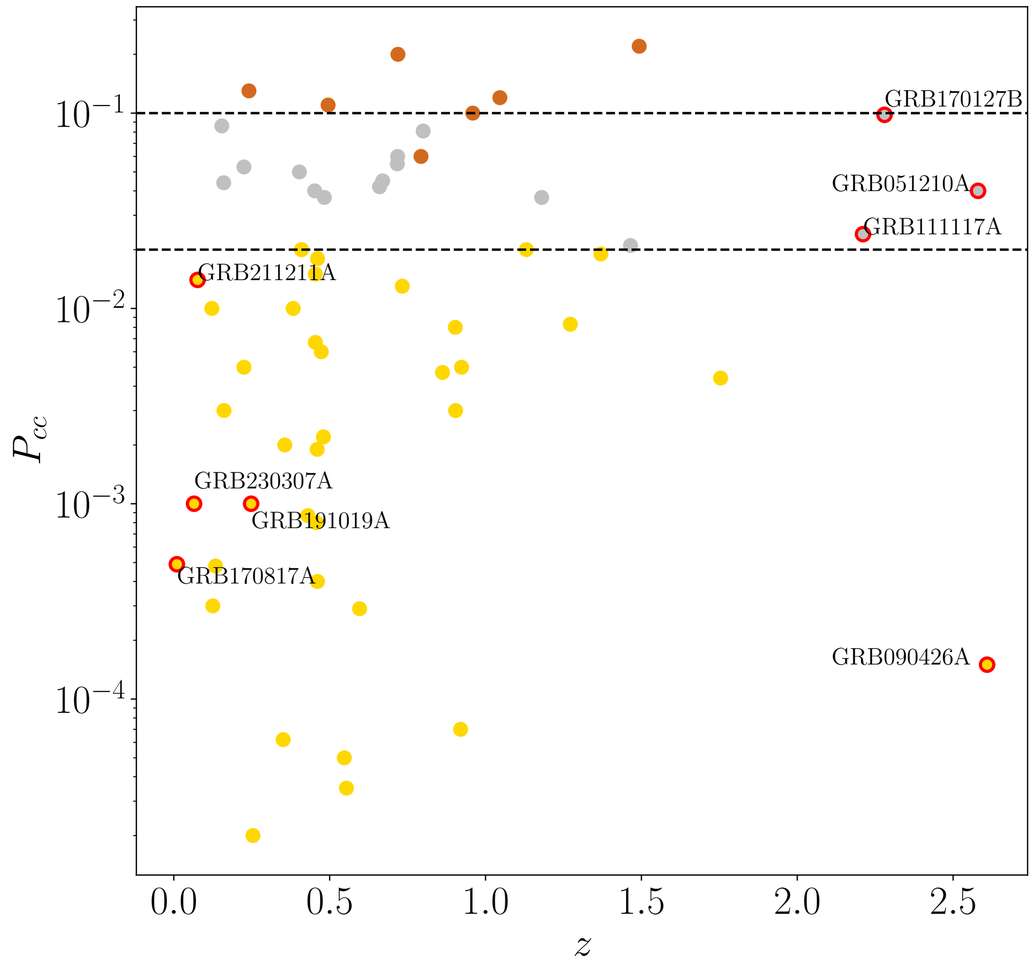
$GP \sim \mathcal{N}(\mu, k)$

$H(z)$

z

GRB data set

Cozzumbo+, **in prep.**



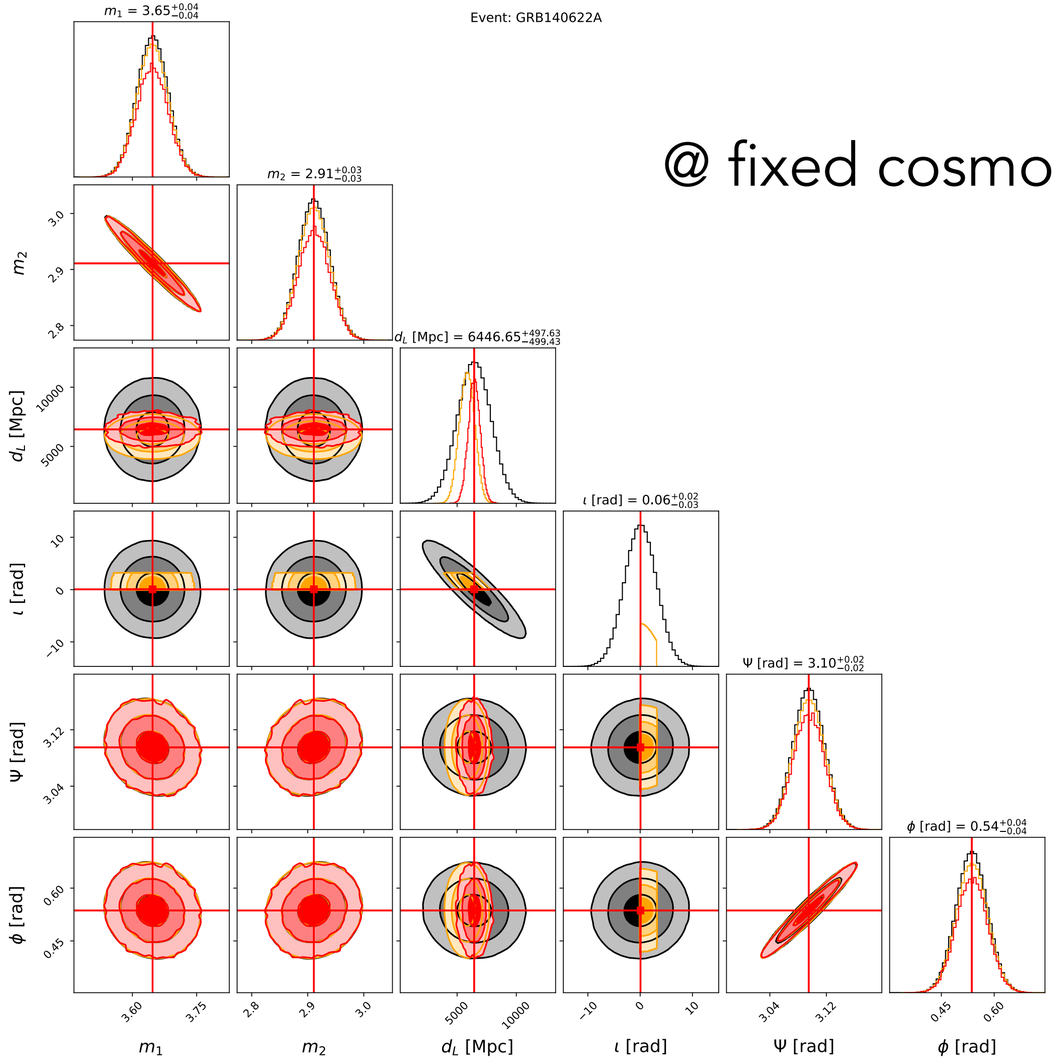
- Fermi-GBM & Swift-BAT/UVOT/XRT
- Merger-driven GRB events
- $\Delta z \leq 7\,\%$

If **Einstein Telescope** existed during the ***Swift*** and ***Fermi*** era, what new insights into cosmology would we have today?

GW posteriors

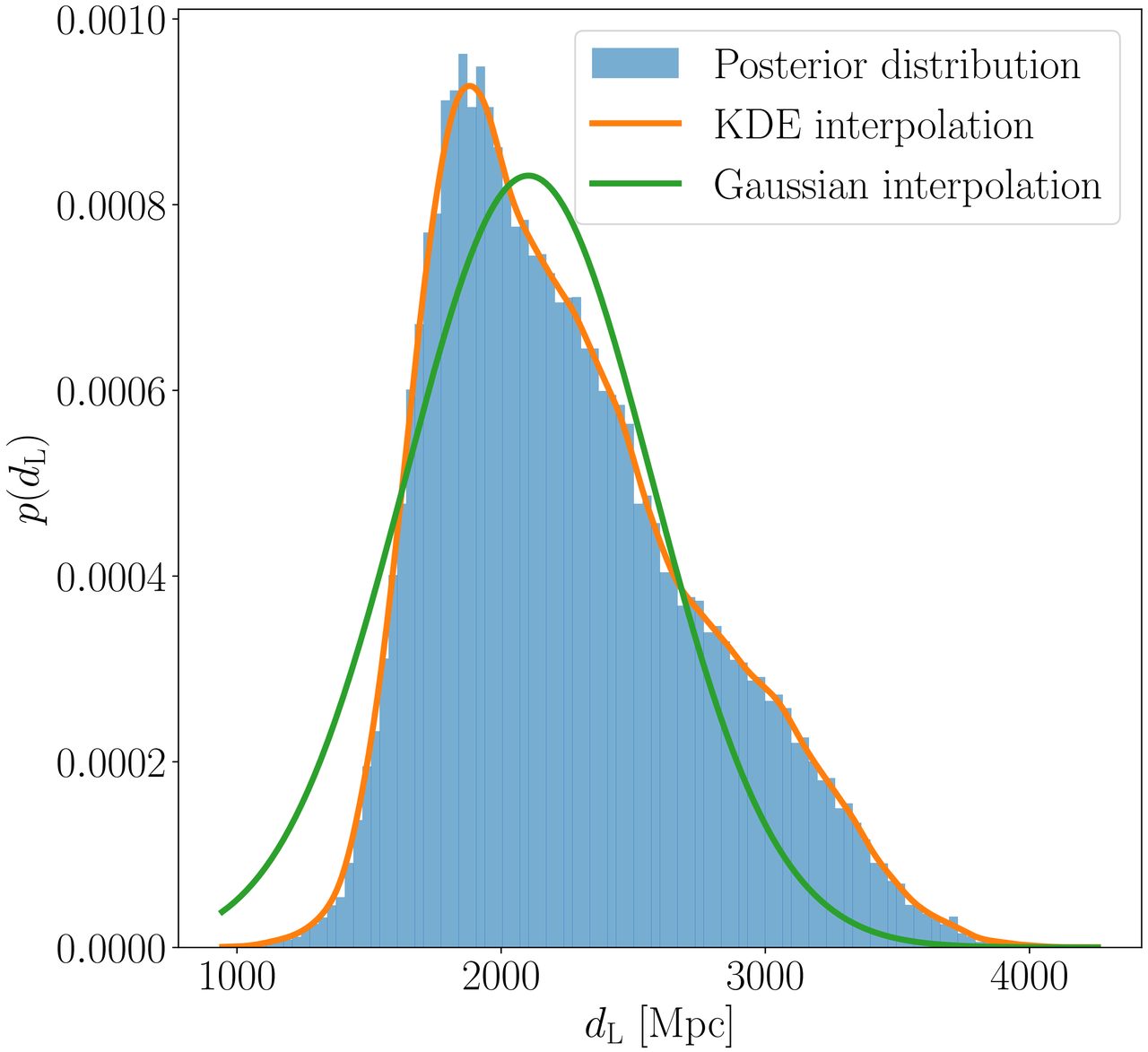
Dupletsa+, 2024

GWFISH



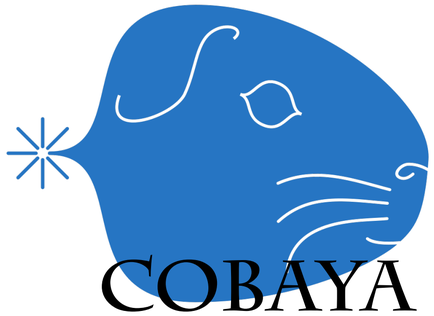
@ fixed cosmology

GW posteriors



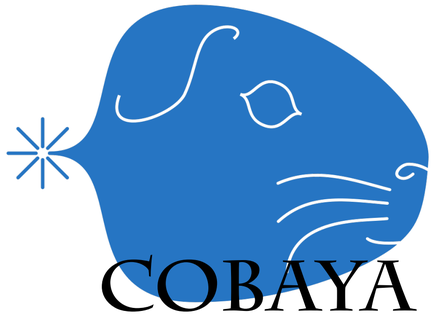
Cosmological MCMC

$$\log \mathscr{L}(\theta) \propto \sum_{i}^{\mathrm{N_{events}}} - \frac{(d_L^{\mathrm{th}}(\theta) - d_L^{\mathrm{obs},i})^2}{2\sigma^2_{d_L,i}}$$



Cosmological MCMC

$$\log \mathscr{L}(\theta) \propto \sum_{i}^{\mathrm{N_{events}}} \mathscr{K}^{i}\left(d_{L}^{\mathrm{th}}\right)$$



Our strategy

- We generate mock joint GW-GRB data assuming 2 different cosmologies

ΛCDM *Planck18*

PEDE *Planck18, eBOSS, Pantheon+*

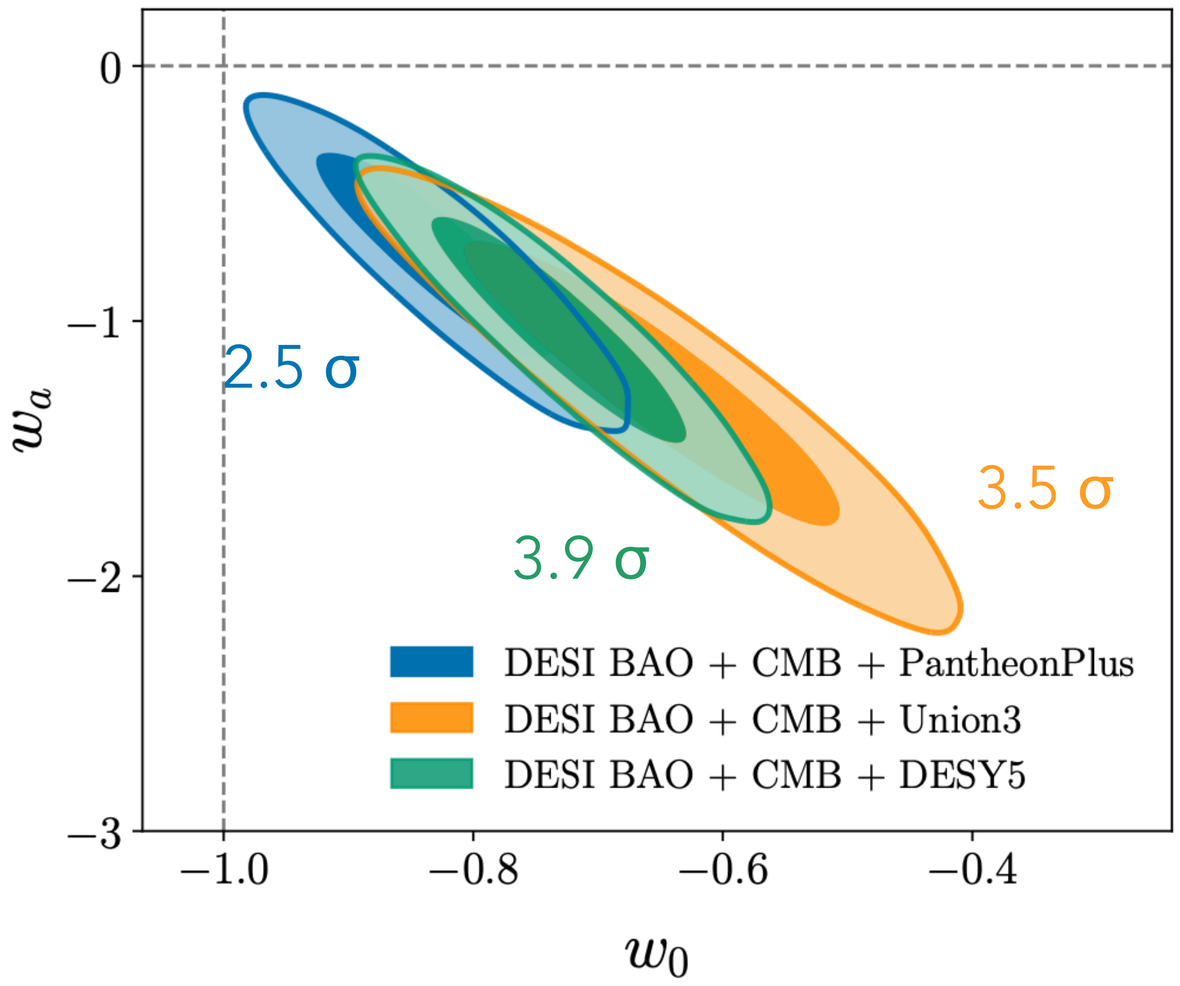
Li and Shafieloo, 2019

- We fit them with a parametric and a non-parametric approach with various observational configurations

- We compare the performances

“Tantalizing suggestion” of dynamical DE

DESI collaboration, Adame+, 2024



Non-parametric approach

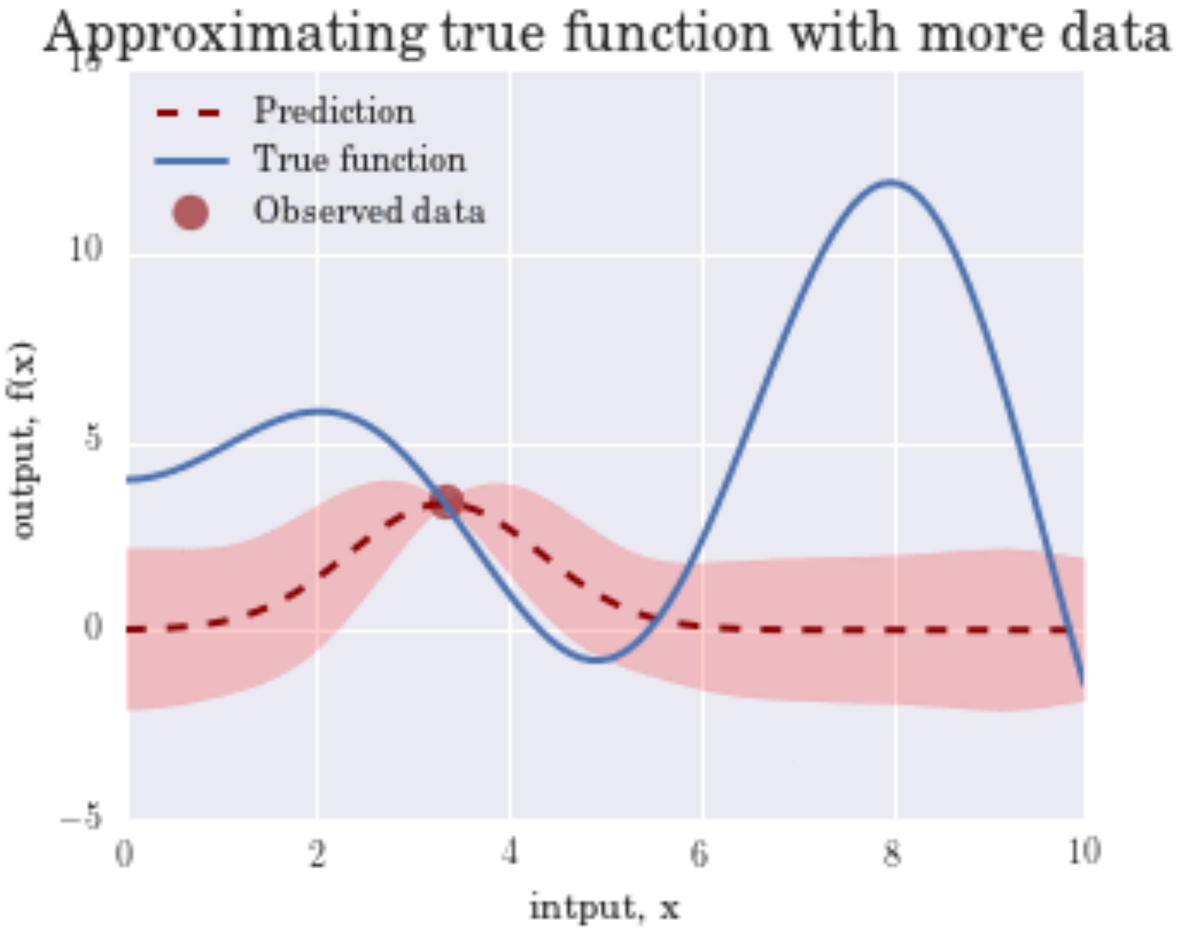
GP → Gaussian Process

$$GP \sim \mathcal{N}(\mu, k)$$

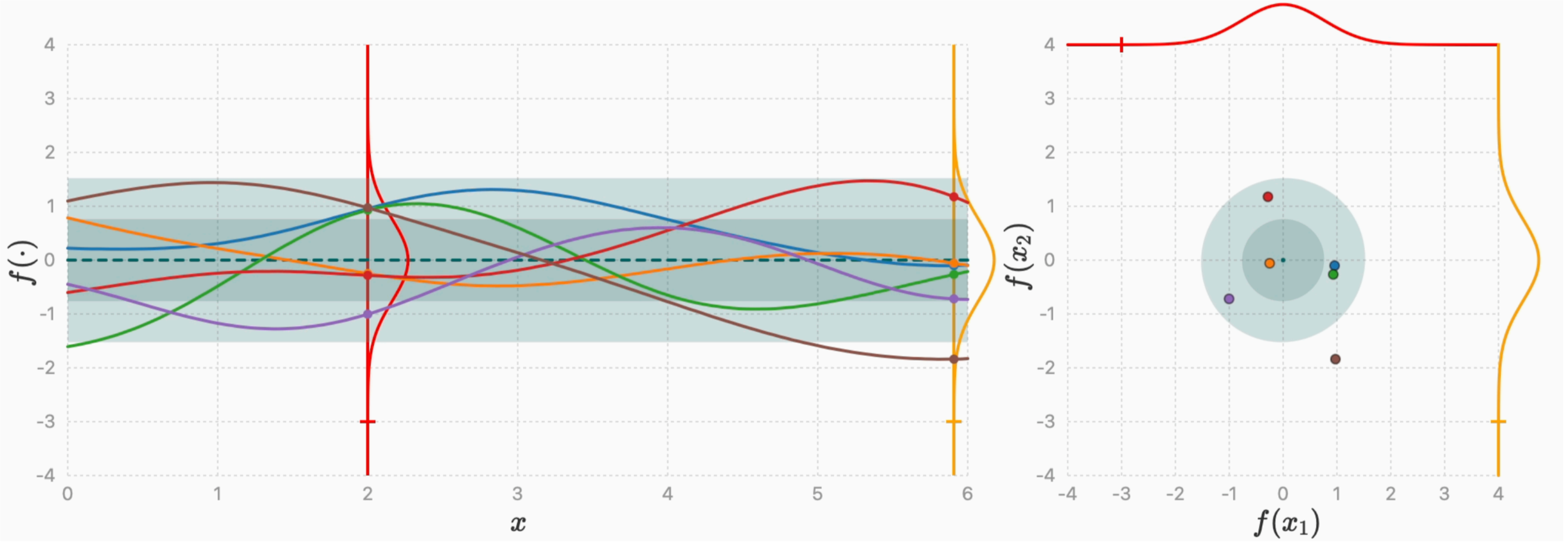
$$h^2(z) = \frac{H^2(z)}{H_0^2} = \Omega_{m,0}(1+z)^3 + (1-\Omega_{m,0}) f_{\rm DE}(z)$$

$$f_{\rm DE}(z) \sim GP(\bar{f}_{\rm DE} = 1, k(\sigma_f, l_f))$$

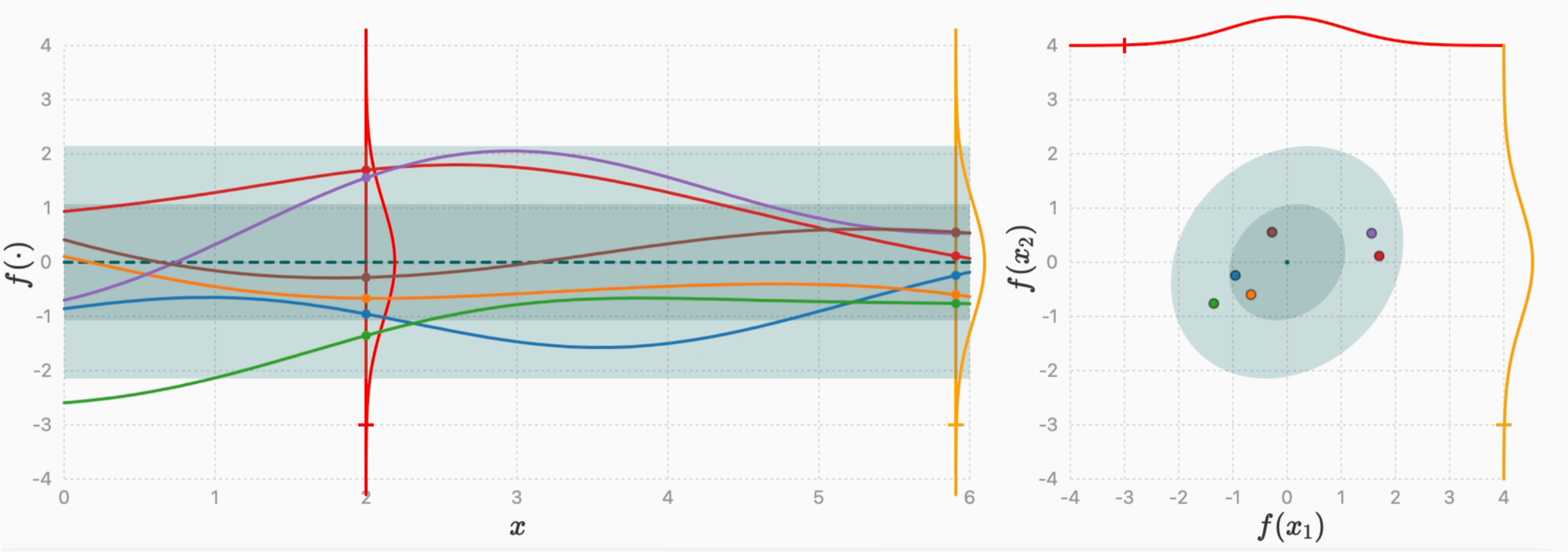
$$k(\sigma_f, l_f) = \sigma_f^2 \, e^{-\frac{(x-x')^2}{2 l_f^2}}$$



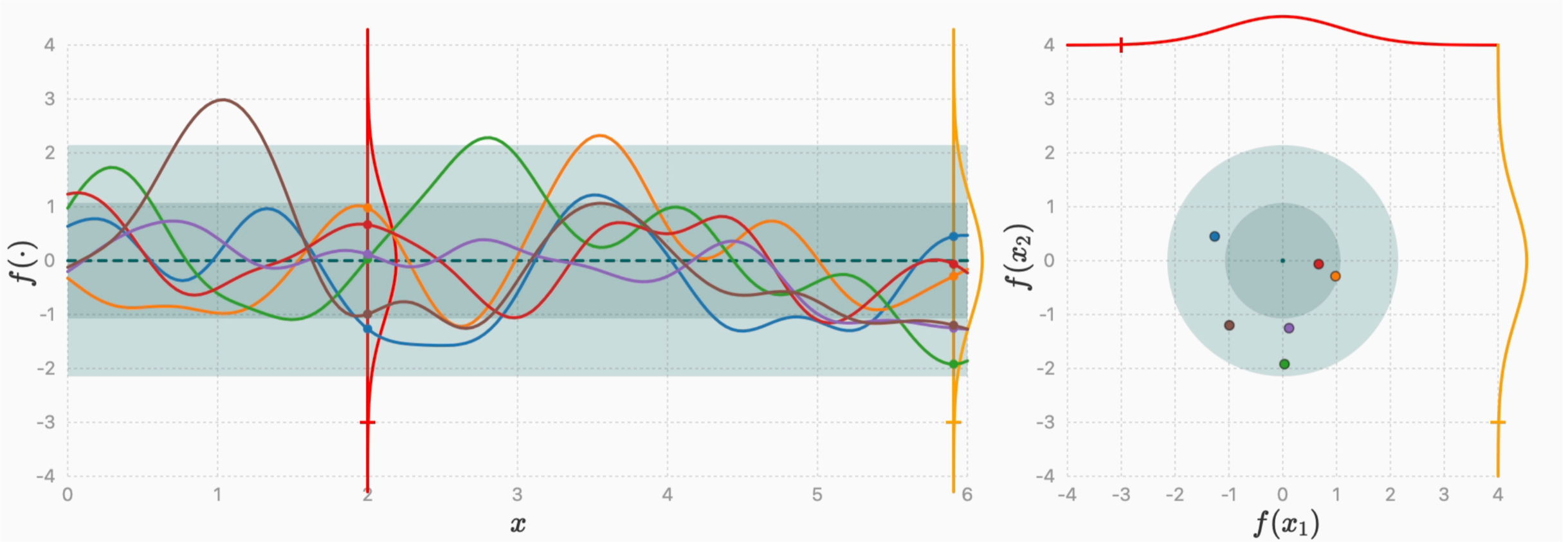
Non-parametric approach



Non-parametric approach



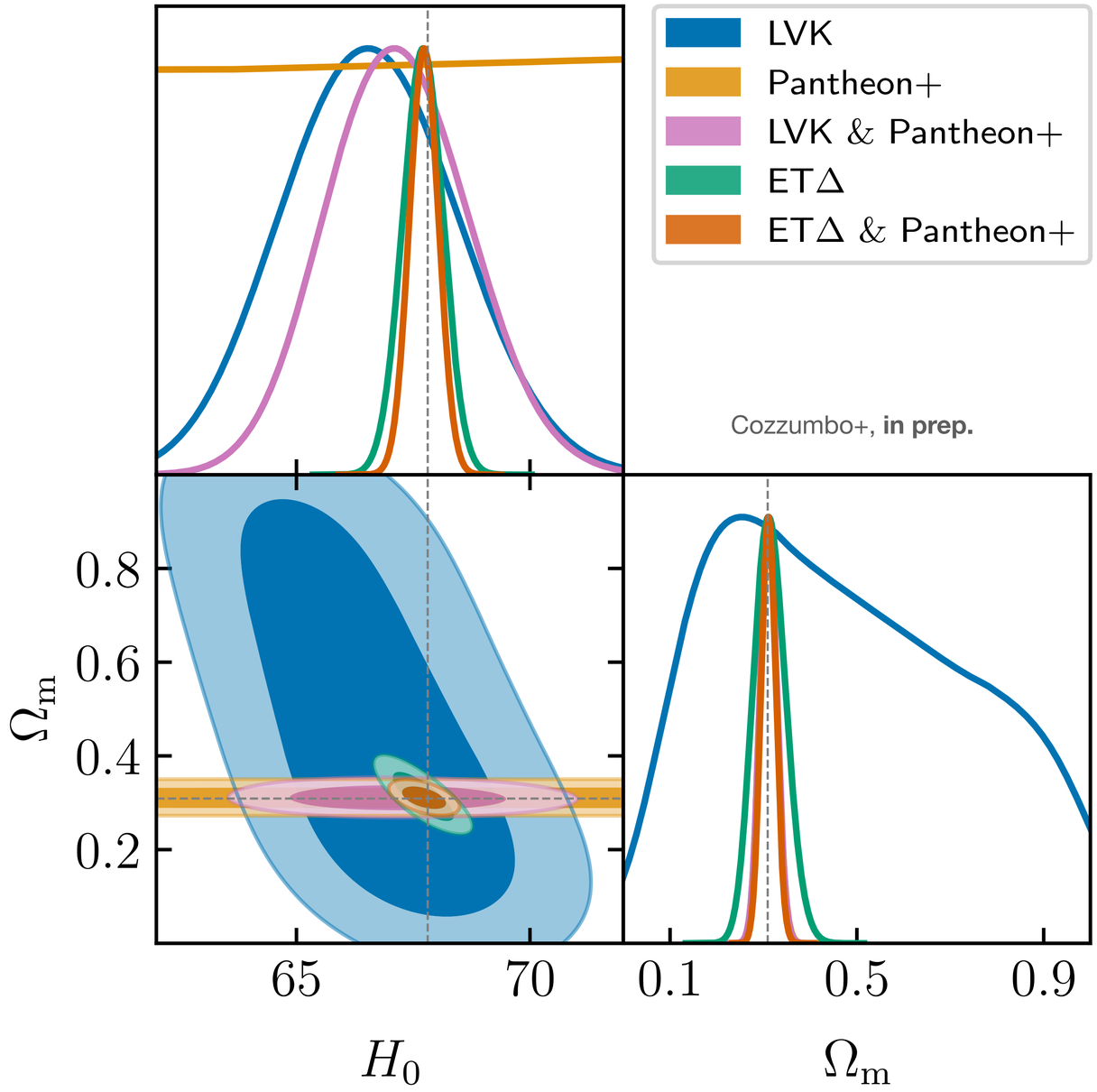
Non-parametric approach



Parametric approach

Injected

ΛCDM *Planck18*



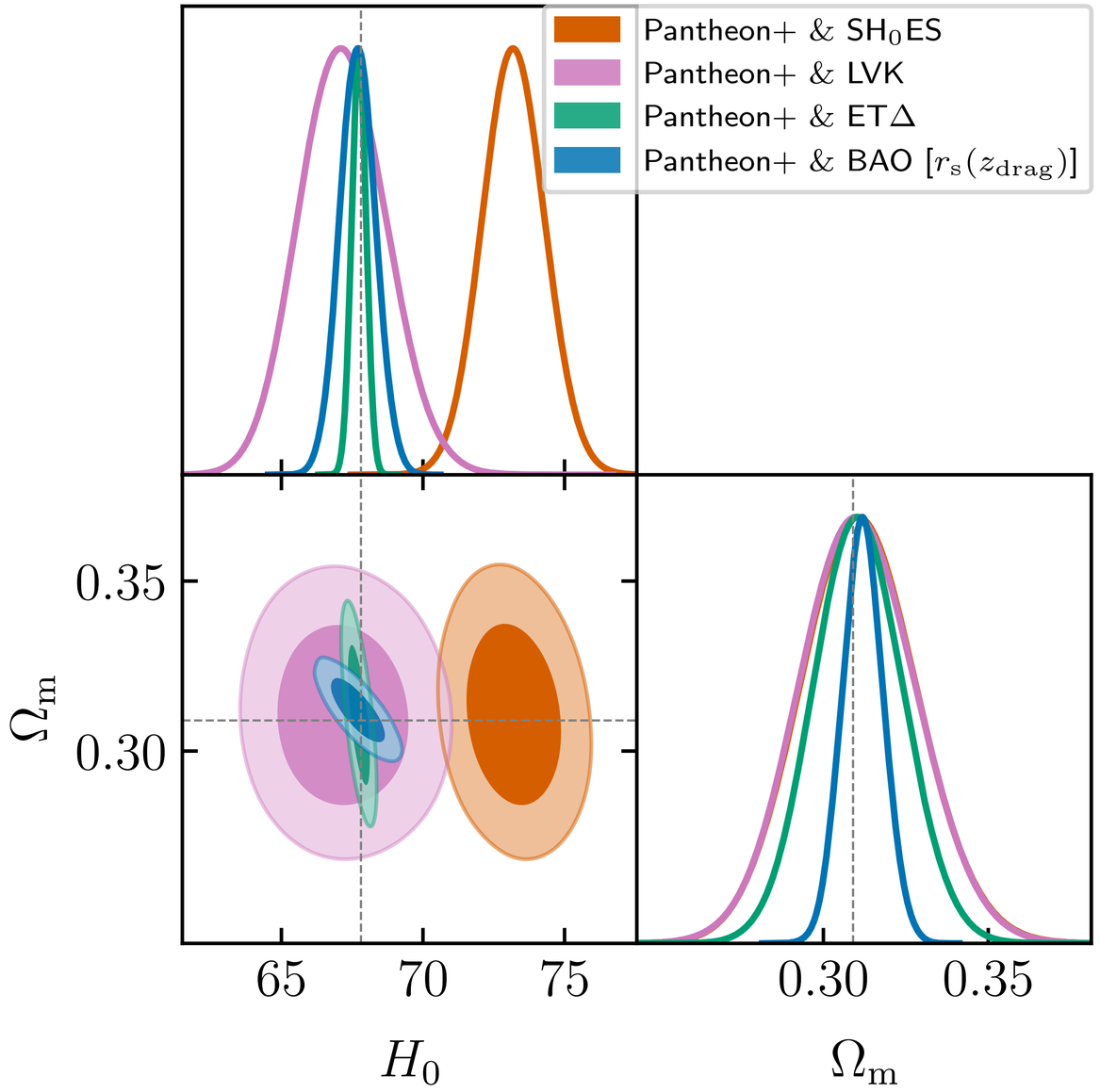
Fit

ΛCDM

Parametric approach

Injected

ΛCDM *Planck18*



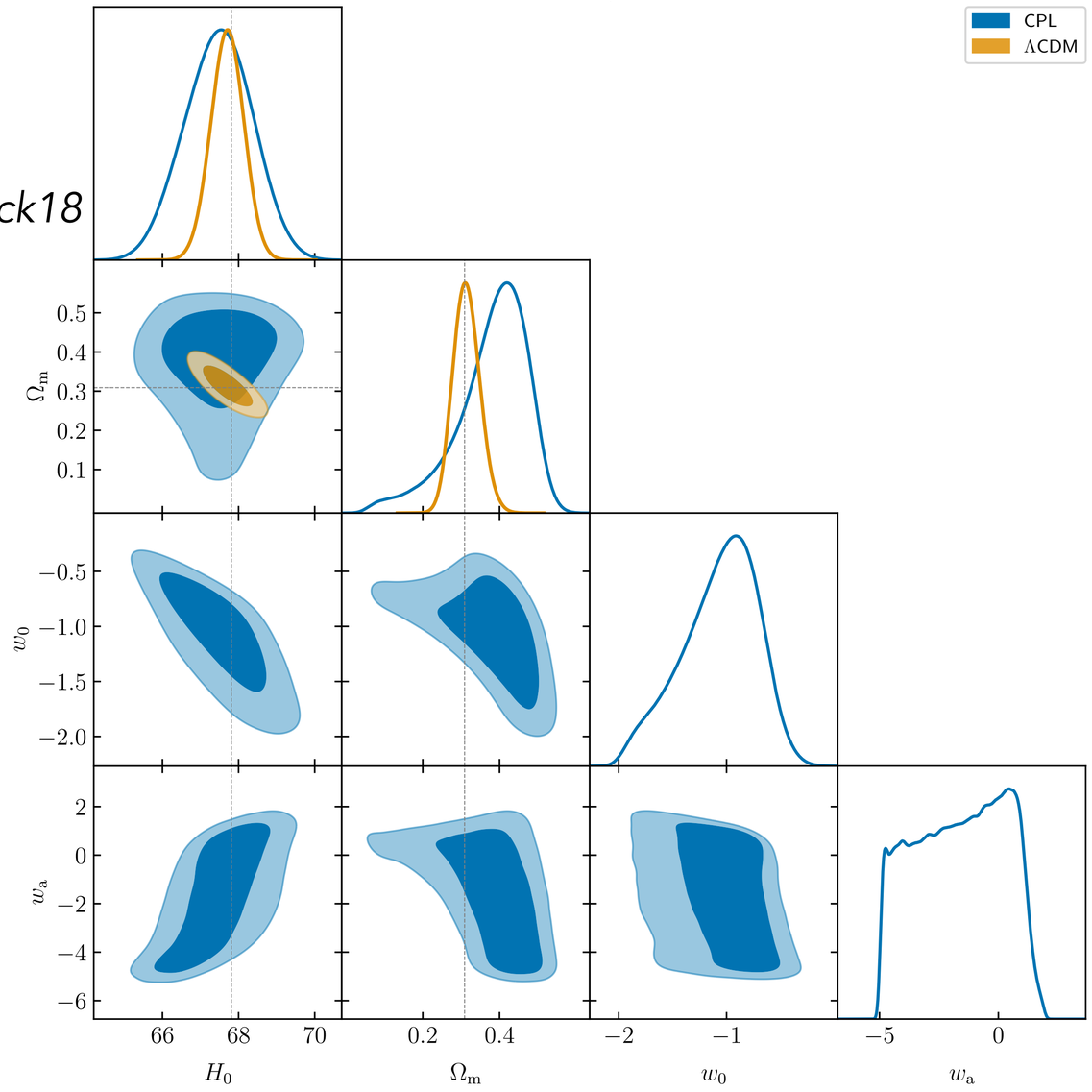
Fit

ΛCDM

Parametric approach

Injected

ΛCDM *Planck18*



Fit

CPL

$$h^2(z) = \frac{H^2(z)}{H_0^2} = \Omega_{m,0}(1+z)^3 + (1-\Omega_{m,0}) f_{\rm DE}(z)$$

$$w(z)^{\rm CPL} = w_0 + w_a \frac{z}{1+z}$$

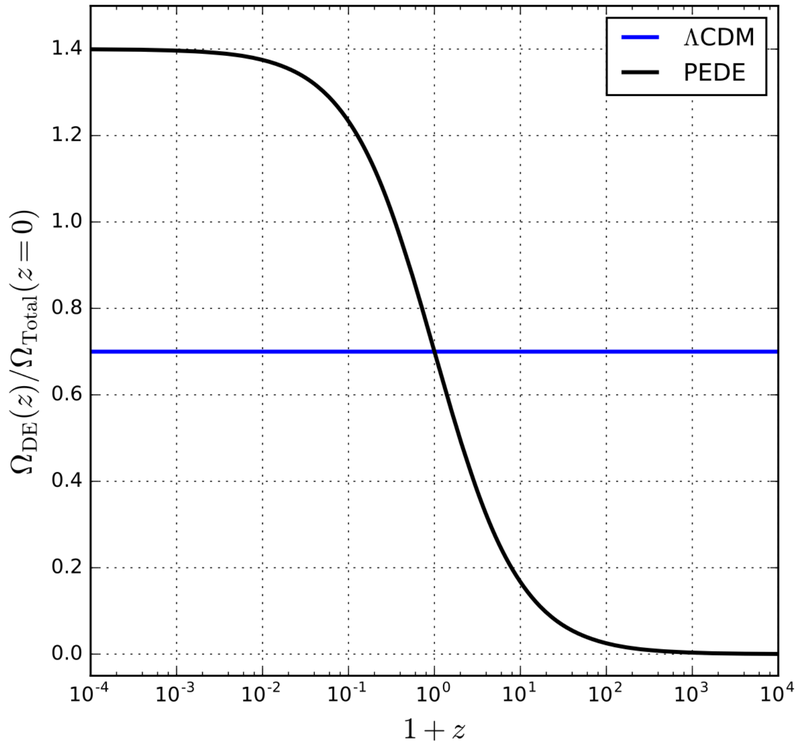
$$f_{\rm DE}(z) = (1+z)^{3(1+w_0+w_a)} \exp\left[\frac{-3w_a z}{1+z}\right]$$

ıbo+, **in prep.**

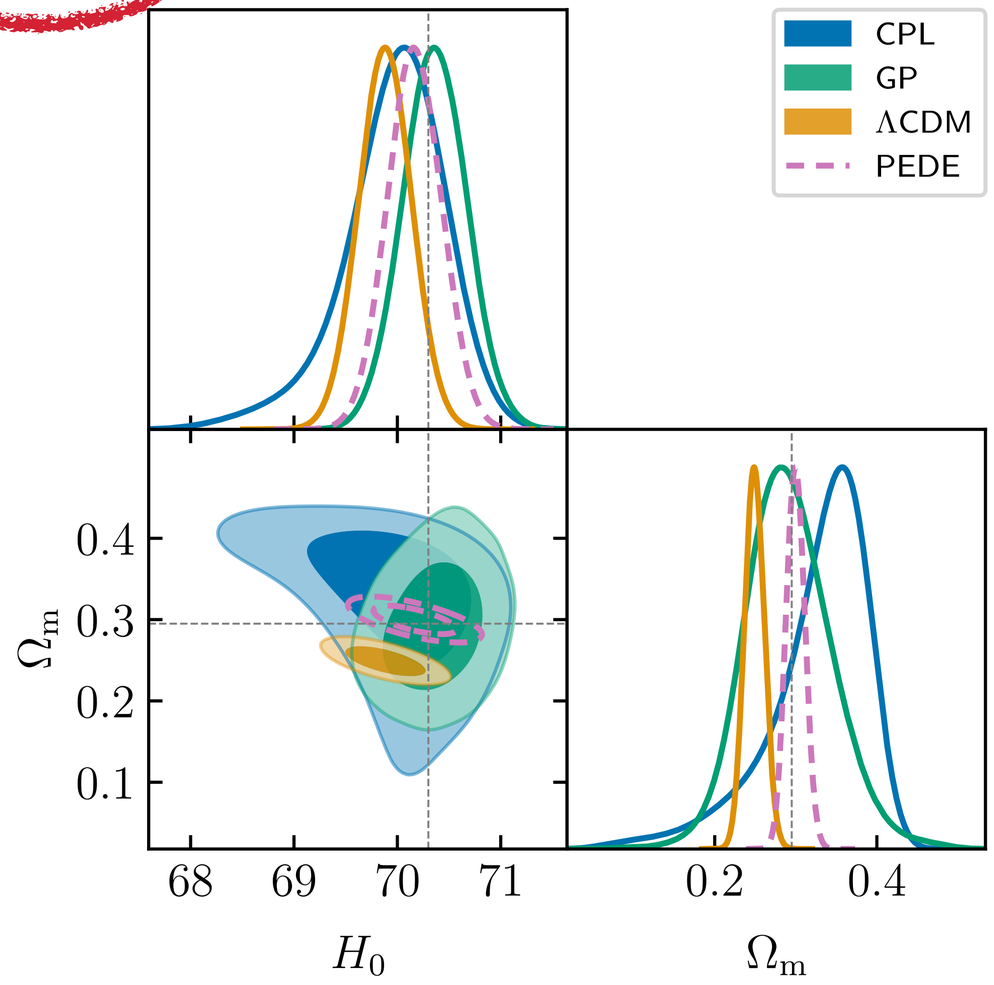
Non-parametric approach

PEDE Universe | Pantheon+ & ET Δ + CE

Phenomenologically Emergent Dark Energy

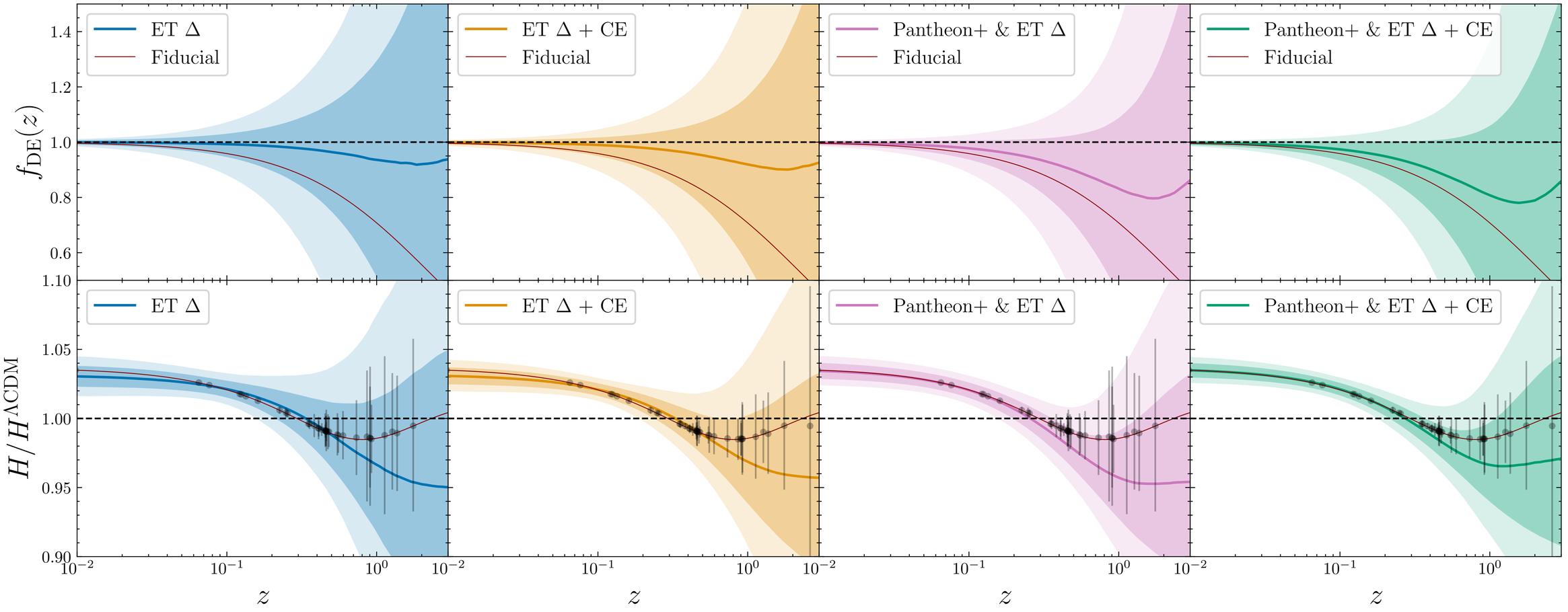


Li and Shafieloo, 2019



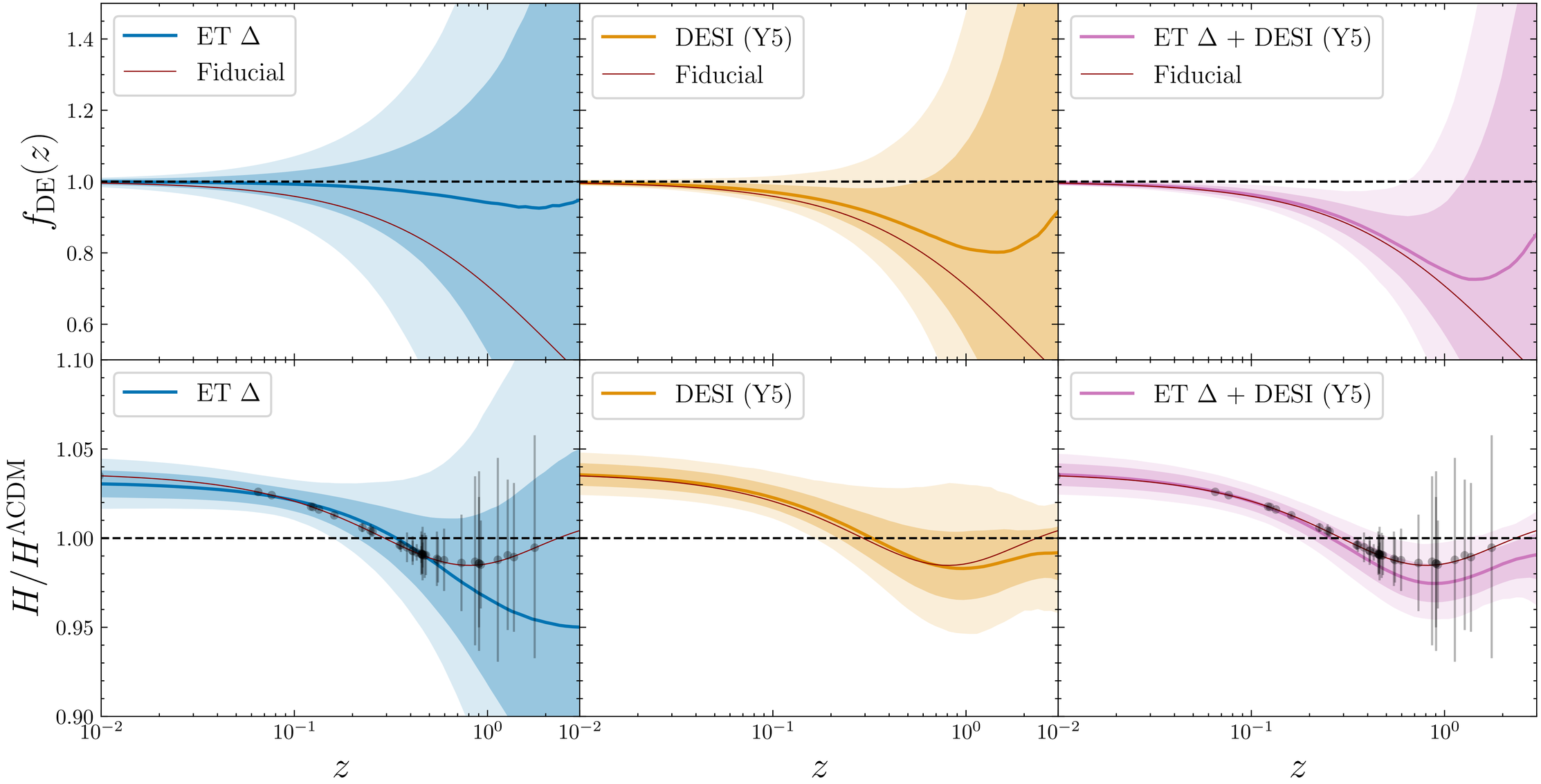
Cozzumbo+, **in prep.**

Non-parametric approach



Cozzumbo+, **in prep.**

Non-parametric approach



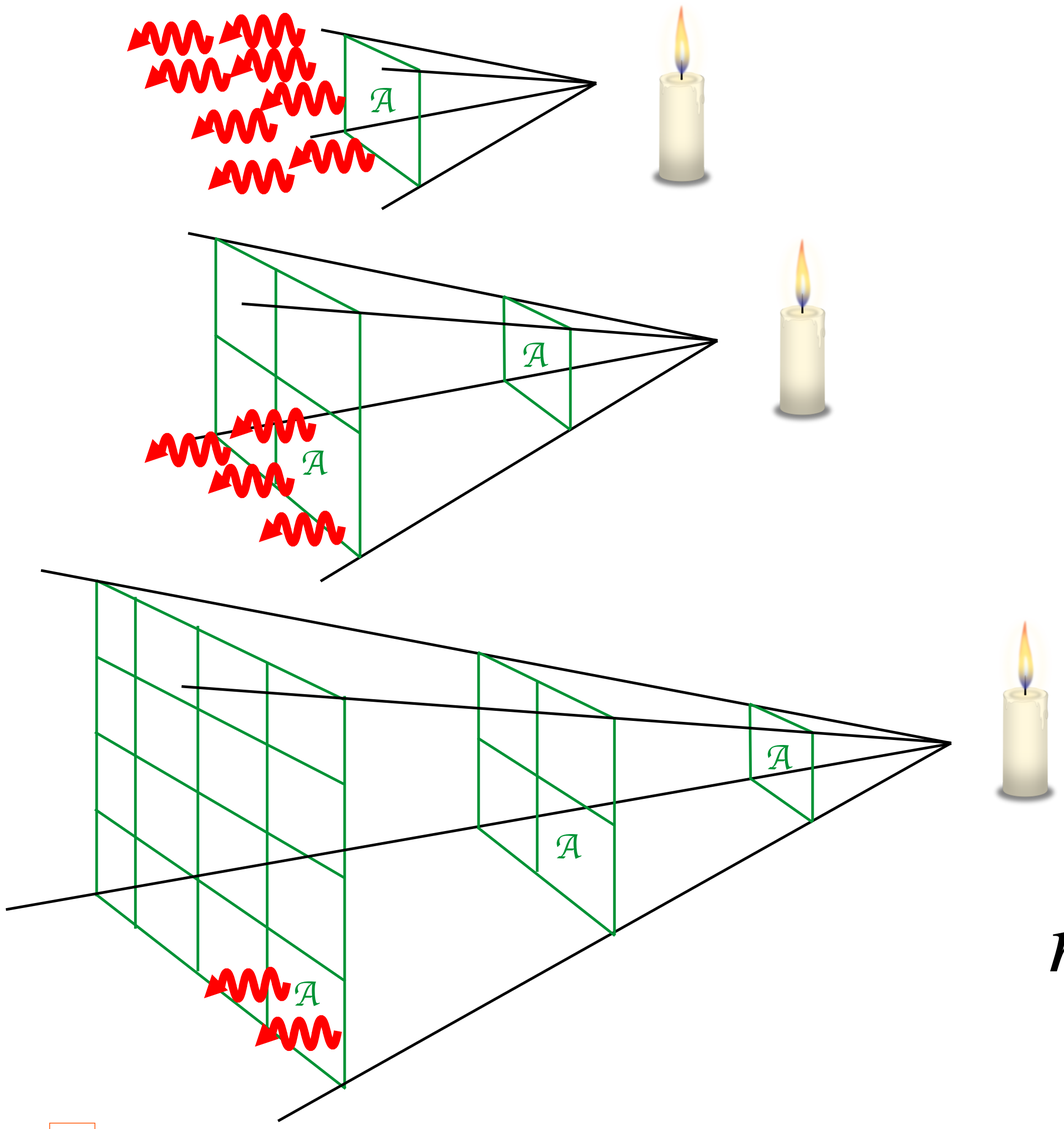
Conclusions

- We compare different catalogs of GRBs and configuration of 3G GW detectors to understand the **future prospects of cosmological constraints with Bright Sirens**

- We compare parametric and non-parametric approaches, underlining the **biases incurring when choosing the wrong fitting model**.
The non-parametric reconstruction is a factor **~1.5 better** than the parametric one.

- We show the potential of a model-independent reconstruction for **Einstein Telescope and next generation cosmological probes**.
With less than **40 GRBs** we will be able to achieve unprecendent precision on H_0 and $\Omega_{\rm m}$ and accurately reconstruct the DE density evolution.

Standard candles



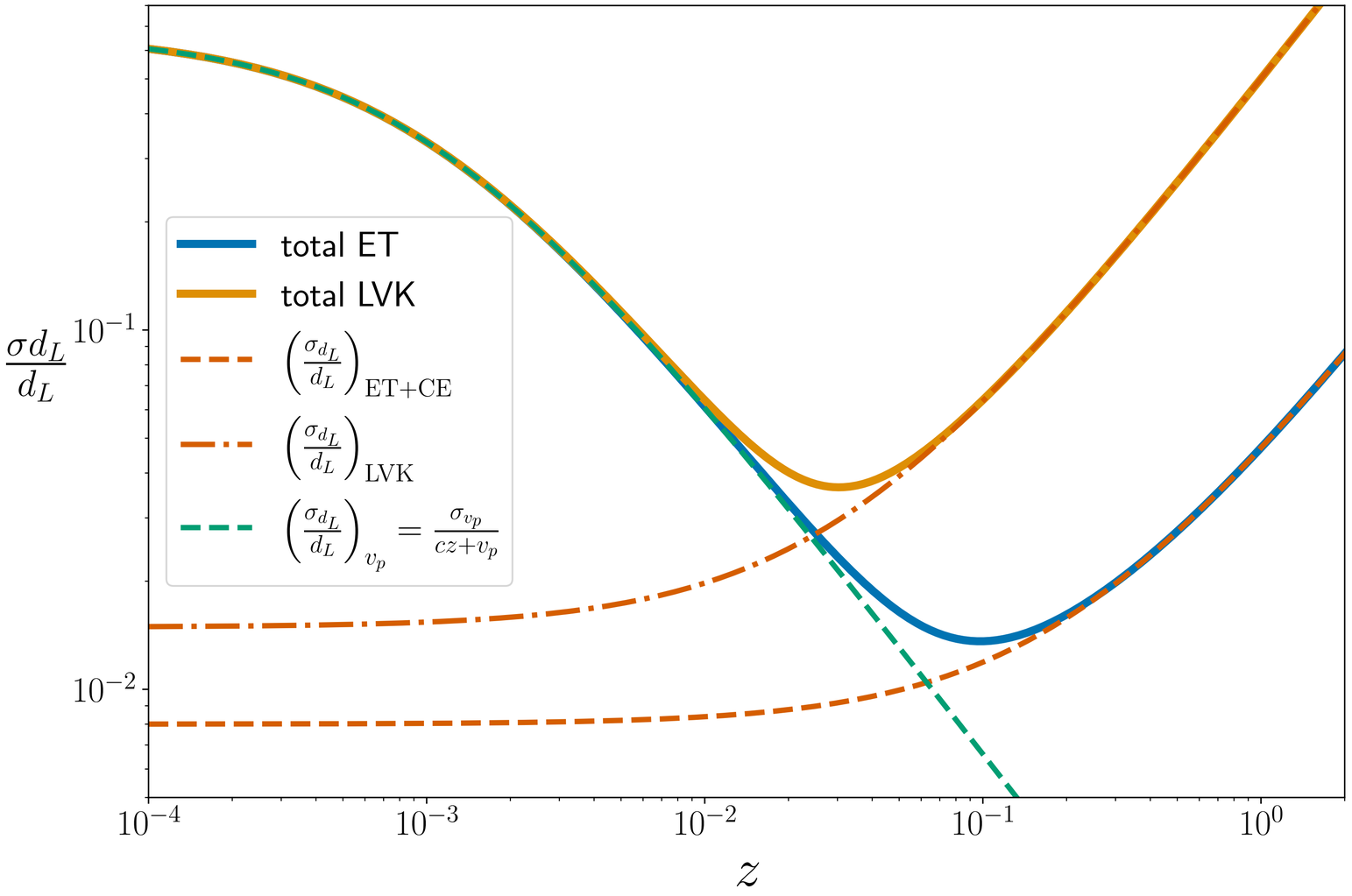
$$d_L^2 = \frac{L}{4\pi F}$$

Related to absolute magnitude (M)

Measured

$$m - M = \mu = 5\log_{10}\left(\frac{d_L}{1\text{Mpc}}\right) + 25$$

Systematics



Systematics