Inferring astrophysics and cosmology with individual compact binary coalescences and their gravitational-wave stochastic background

Sarah Ferraiuolo, GdR Ondes Gravitationnelles, 16/10/2024

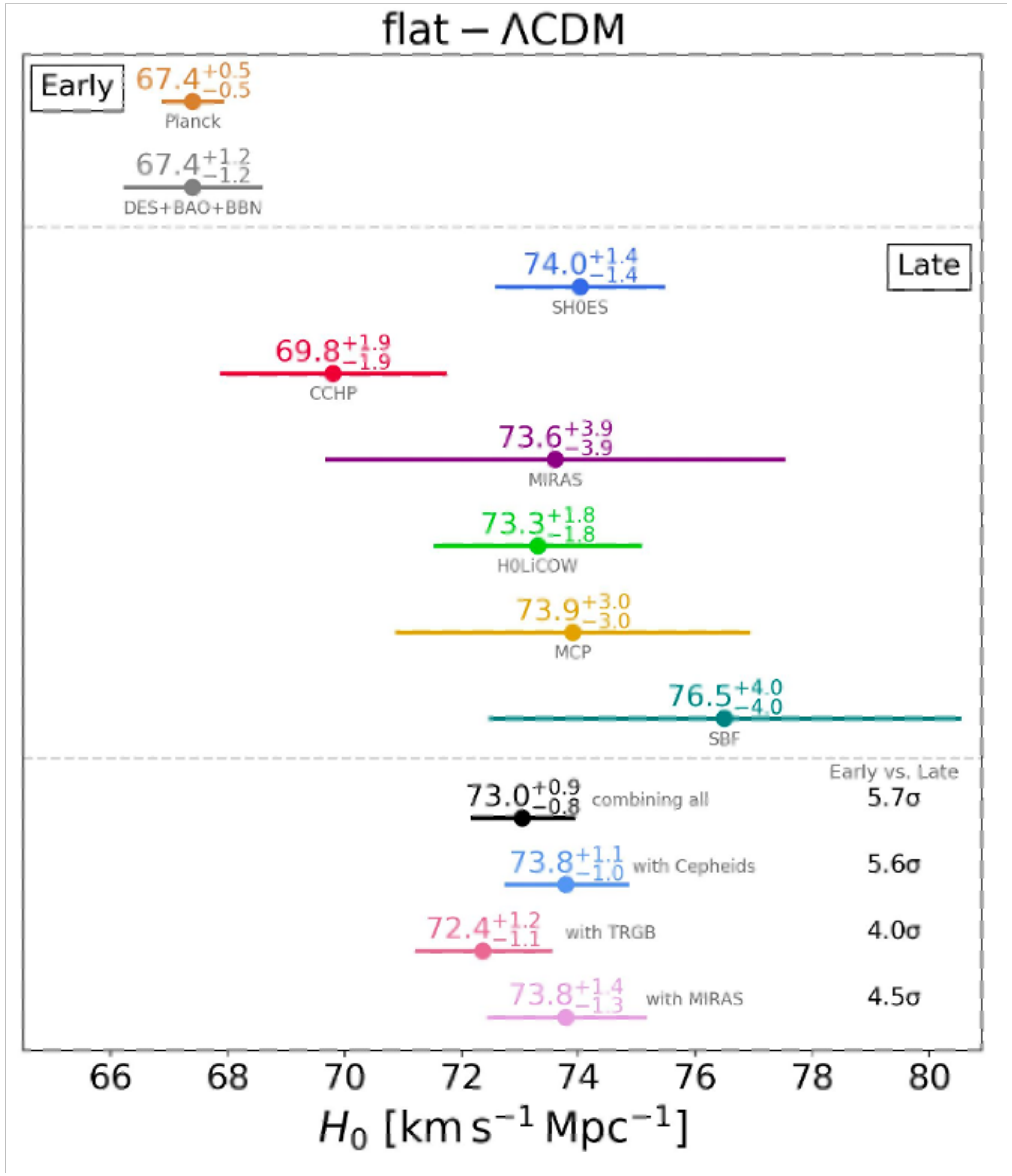
CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE CPPM
amidex Aix Marseille Université
FRANCE 2030
SAPIENZA UNIVERSITÀ DI ROMA
INFN Istituto Nazionale di Fisica Nucleare

Outline

- Introduction: gravitational waves as standard sirens and stochastic gravitational wave background
- Analysis method
- LVK at A+ design sensitivity simulated data
- Preliminary Results

The Hubble tension

- There is a tension between direct and indirect measurements of the Hubble constant
- Although in-depth studies for hidden systematics the tension has not been yet alleviated
- We are required to directly measure the Universe expansion in all the observable Universe

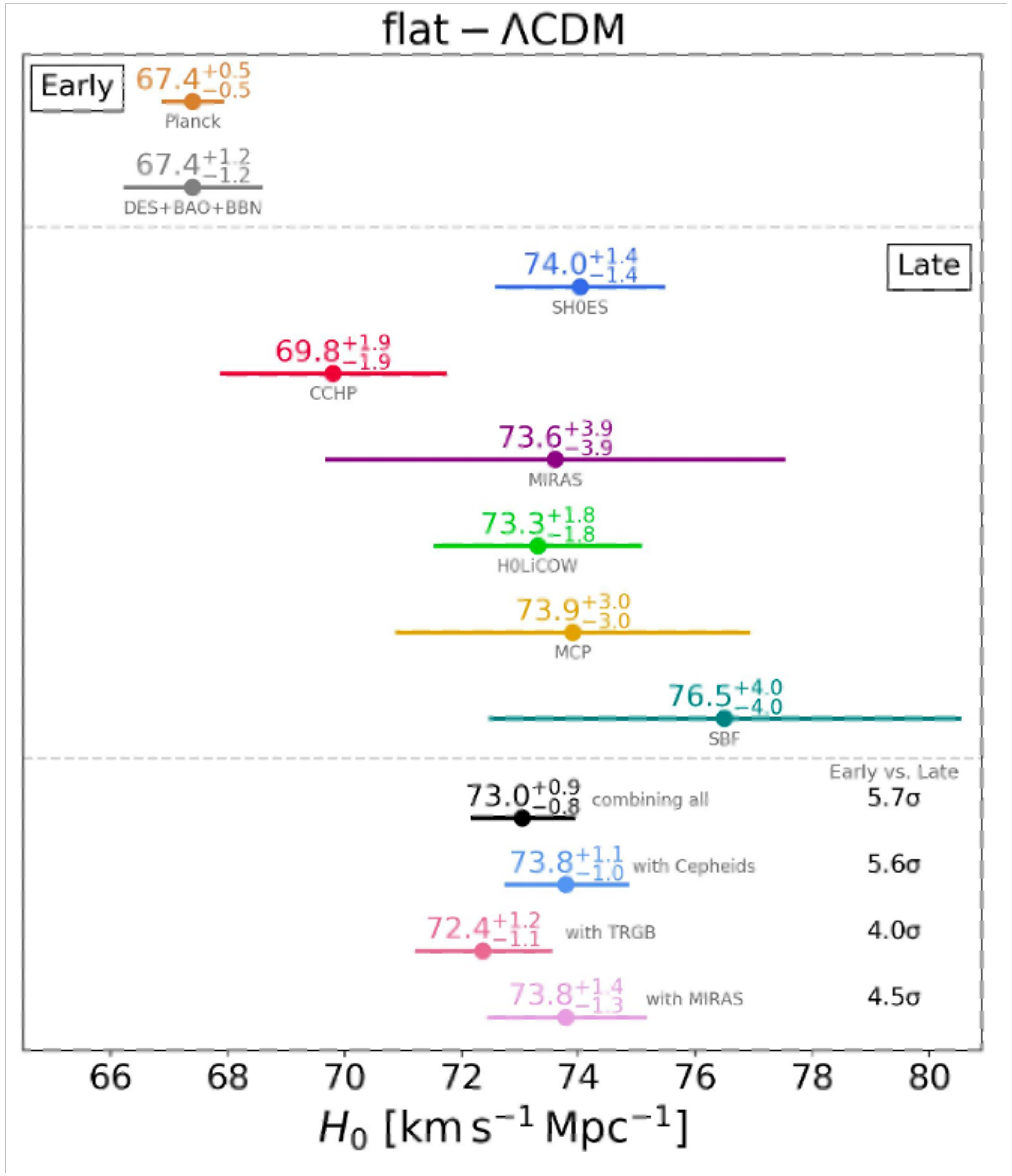


Verde, L., Treu, T. & Riess, A.G. Tensions between the early and late Universe. *Nat Astron* **3,** 891–895 (2019).

The Hubble tension

- There is a tension between direct and indirect measurements of the Hubble constant
- Although in-depth studies for hidden systematics the tension has not been yet alleviated
- We are required to directly measure the Universe expansion in all the observable Universe

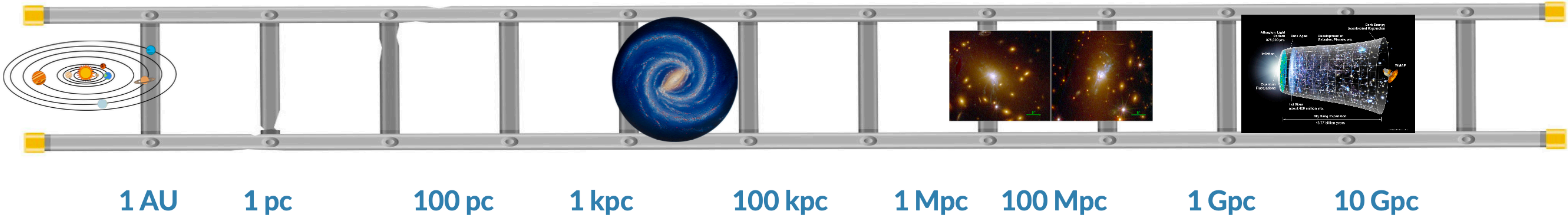
Gravitational Waves!



Verde, L., Treu, T. & Riess, A.G. Tensions between the early and late Universe. *Nat Astron* **3,** 891–895 (2019).

The Hubble tension

Why use gravitational waves for cosmology



Distances with Electromagnetic observations

Radar

Cepheids

Parallax

Type Ia Supernovae

Distances with GW observations

Compact binary coalescenses

Gravitational Waves

They exist in multiple forms:

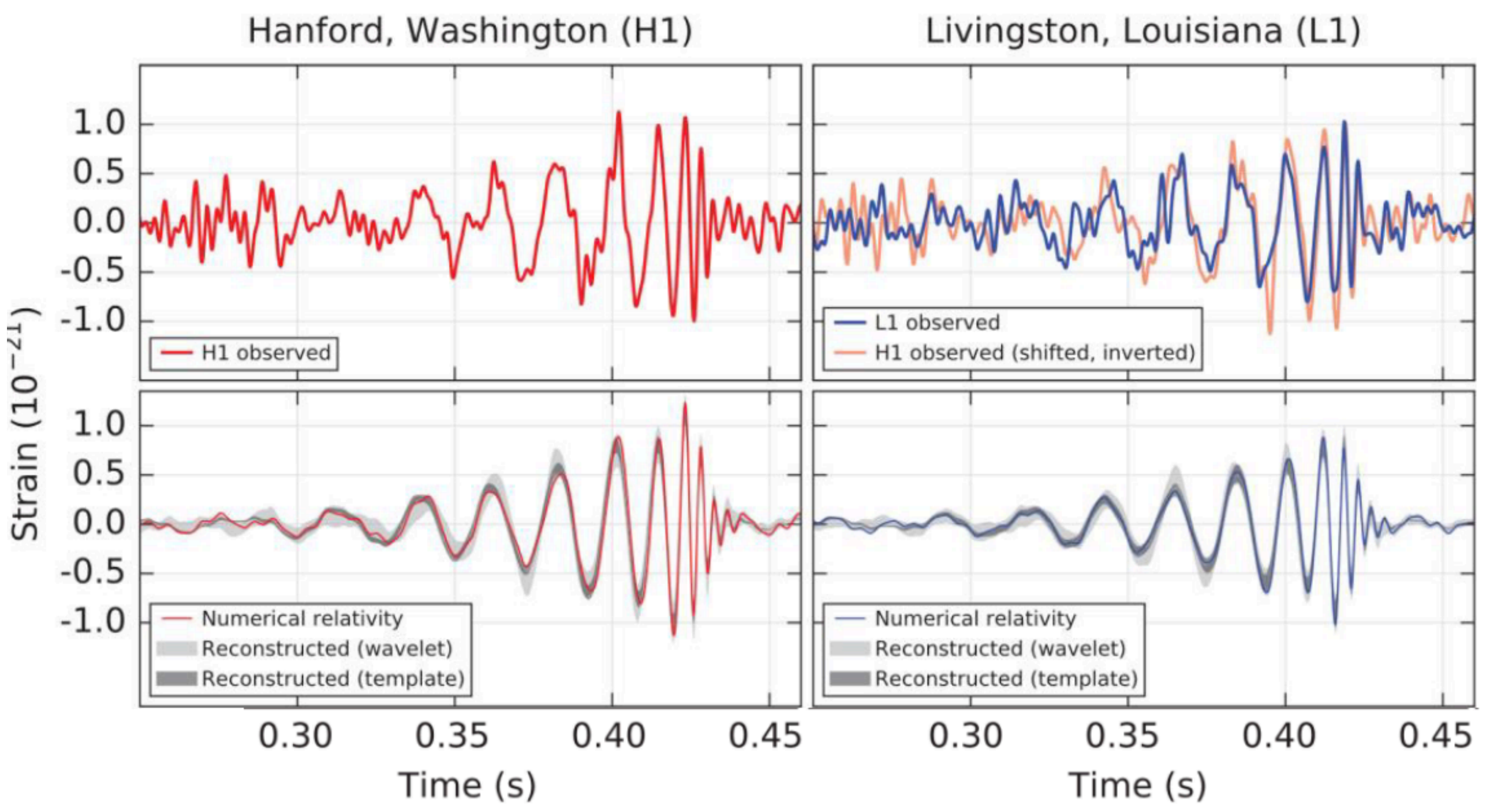
- Transients from compact binary mergers (CBCs)
- Bursts
- Continuous waves
- Stochastic gravitational-wave background (SGWB)

Gravitational Waves

They exist in multiple forms:

- **Transients from compact binary mergers (CBCs)**
- Bursts
- Continuous waves
- Stochastic gravitational-wave background (SGWB)

Phys. Rev. Lett. 116, 061102

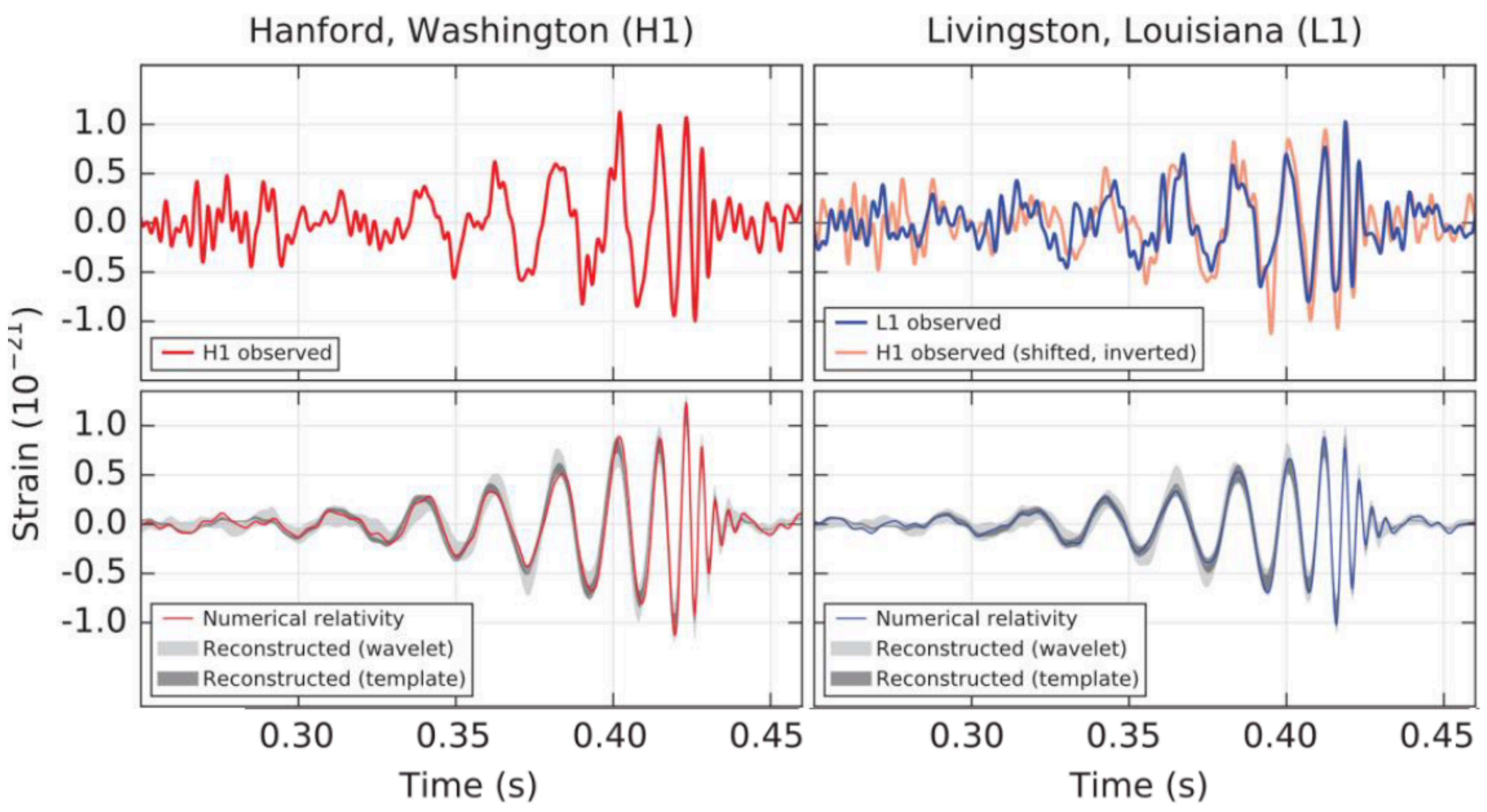


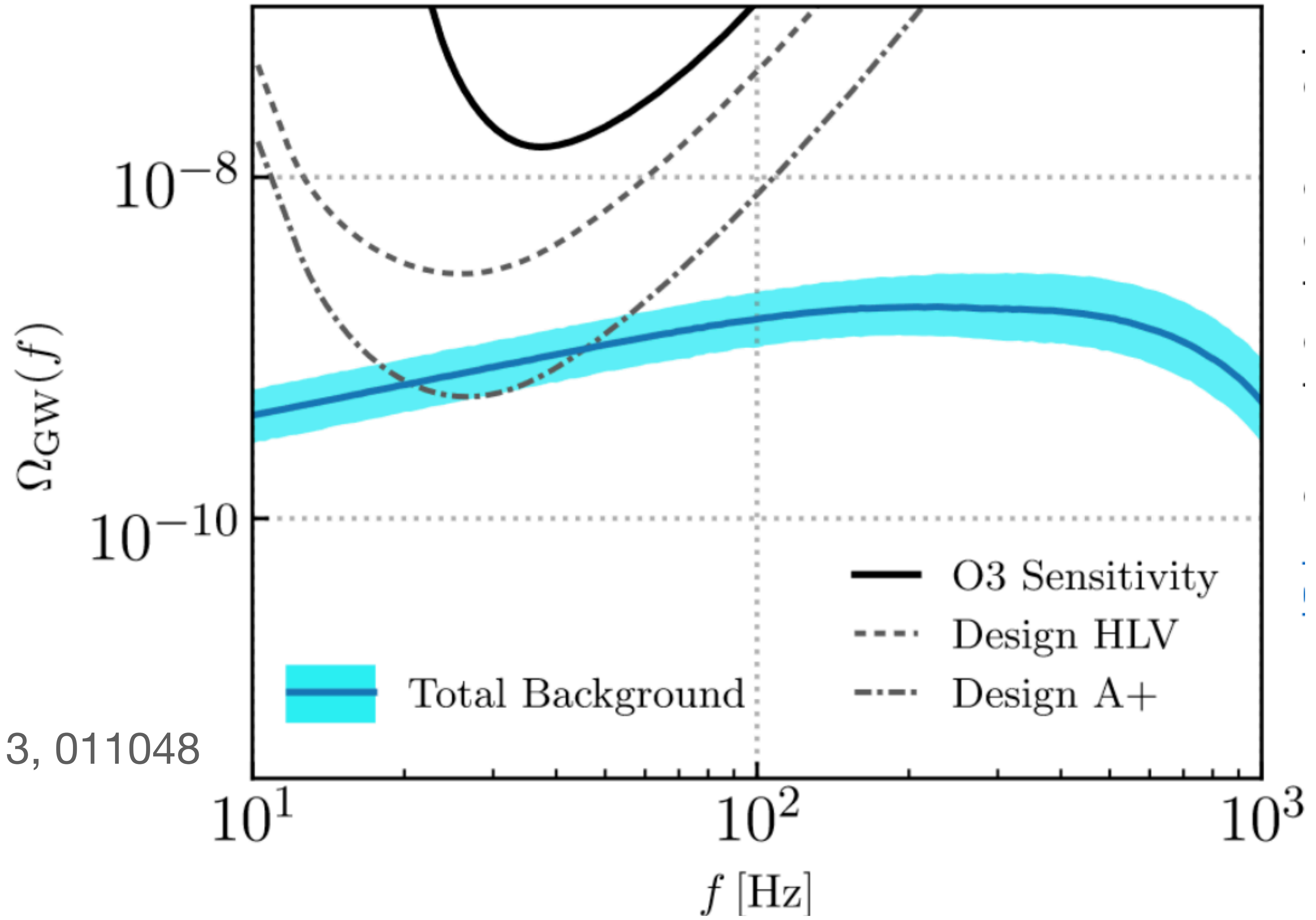
Gravitational Waves

They exist in multiple forms:

- **Transients from compact binary mergers (CBC)**
- Bursts
- Continuous waves
- **Stochastic gravitational-wave background (SGWB)**

Phys. Rev. Lett. 116, 061102

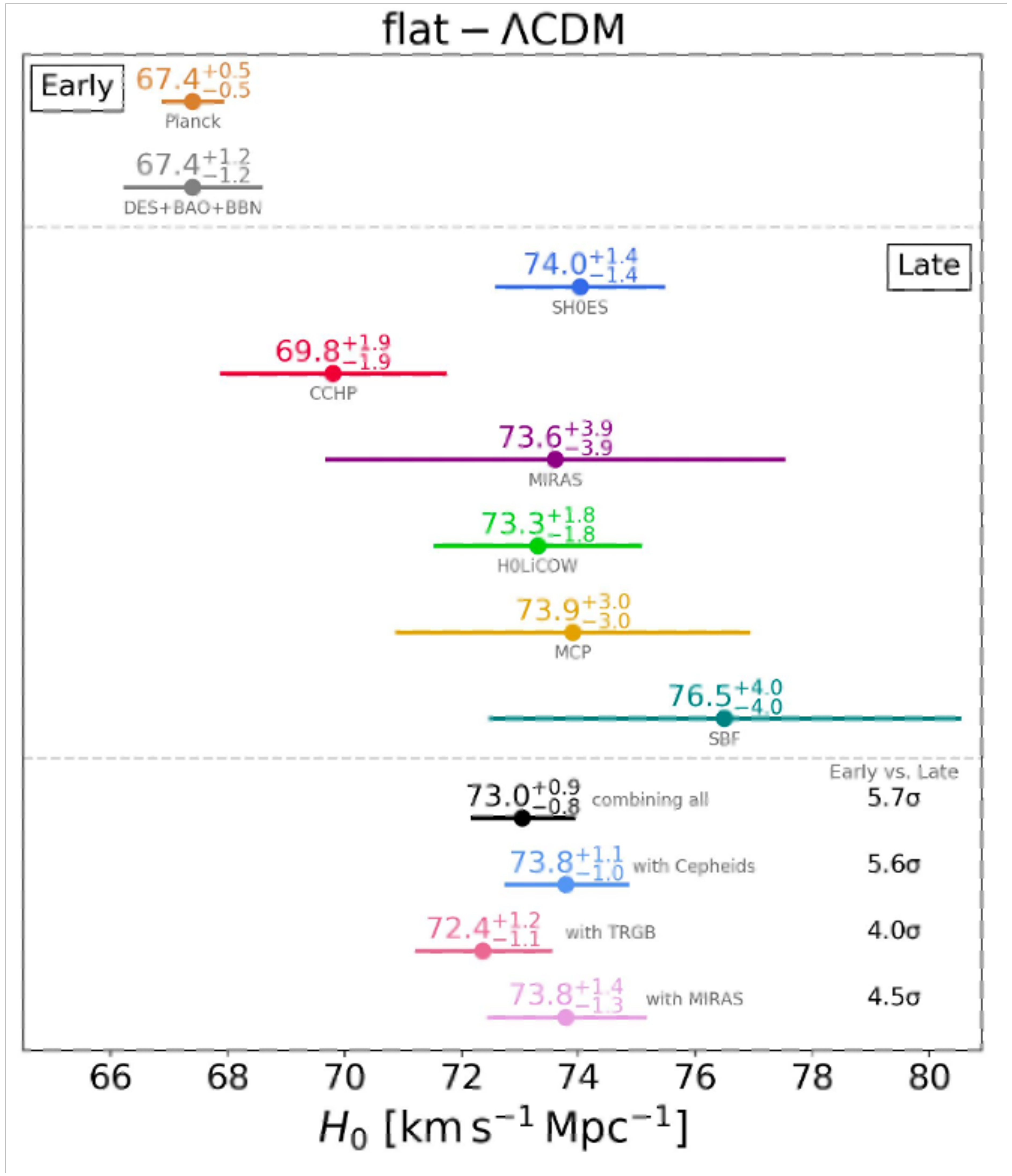




Phys. Rev. X 13, 011048

Standard Sirens with CBCs

- $cz \approx H_0 d_L$



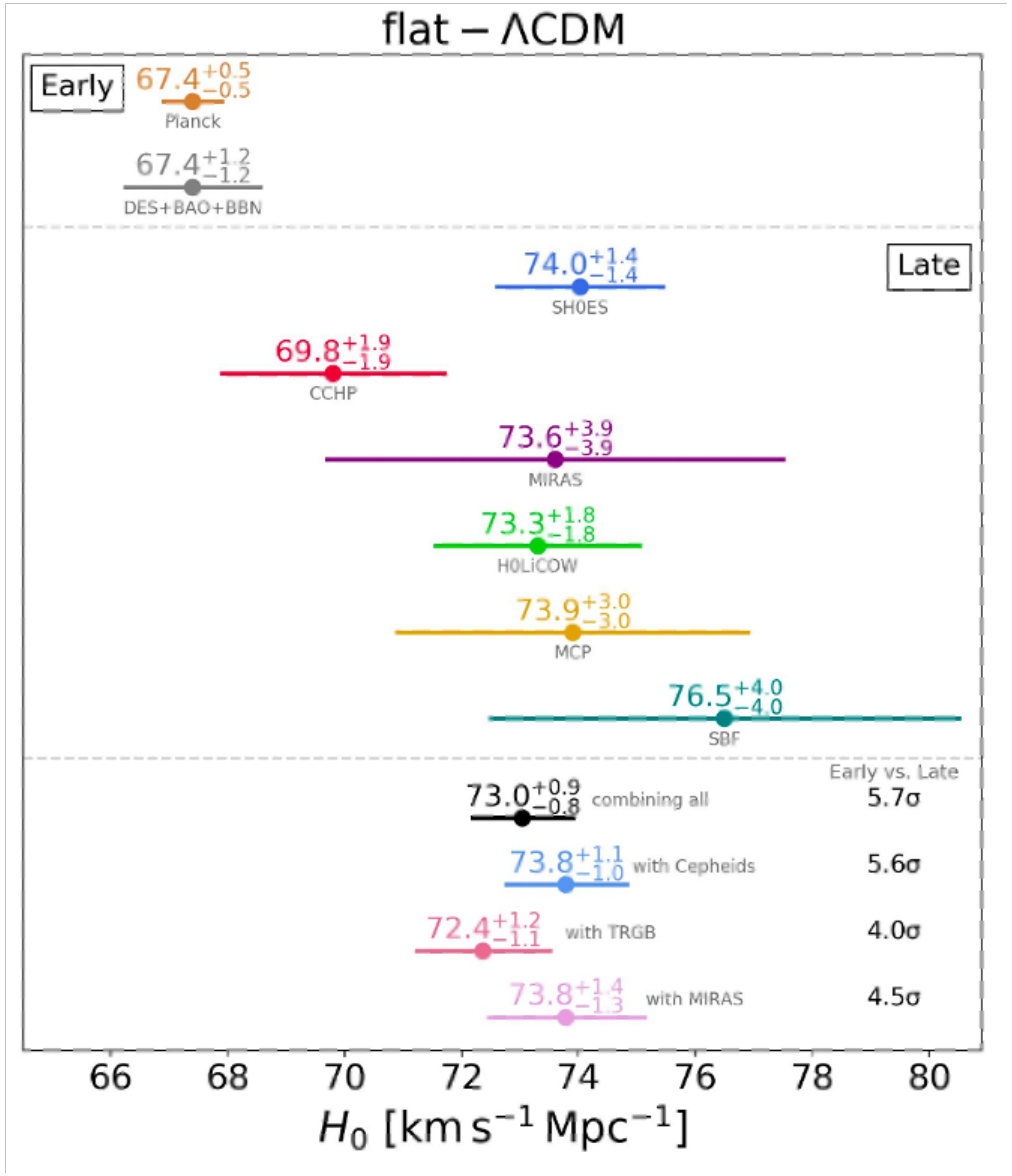
Verde, L., Treu, T. & Riess, A.G. Tensions between the early and late Universe. *Nat Astron* **3,** 891–895 (2019).

Standard Sirens with CBCs

- $cz \approx H_0 d_L$

Luminosity distance: directly measurable from the amplitude of the gravitational wave signal

- $h(t) = A(M_z, d_L, t)e^{i\Phi(M_z, t)}$



Verde, L., Treu, T. & Riess, A.G. Tensions between the early and late Universe. *Nat Astron* **3,** 891–895 (2019).

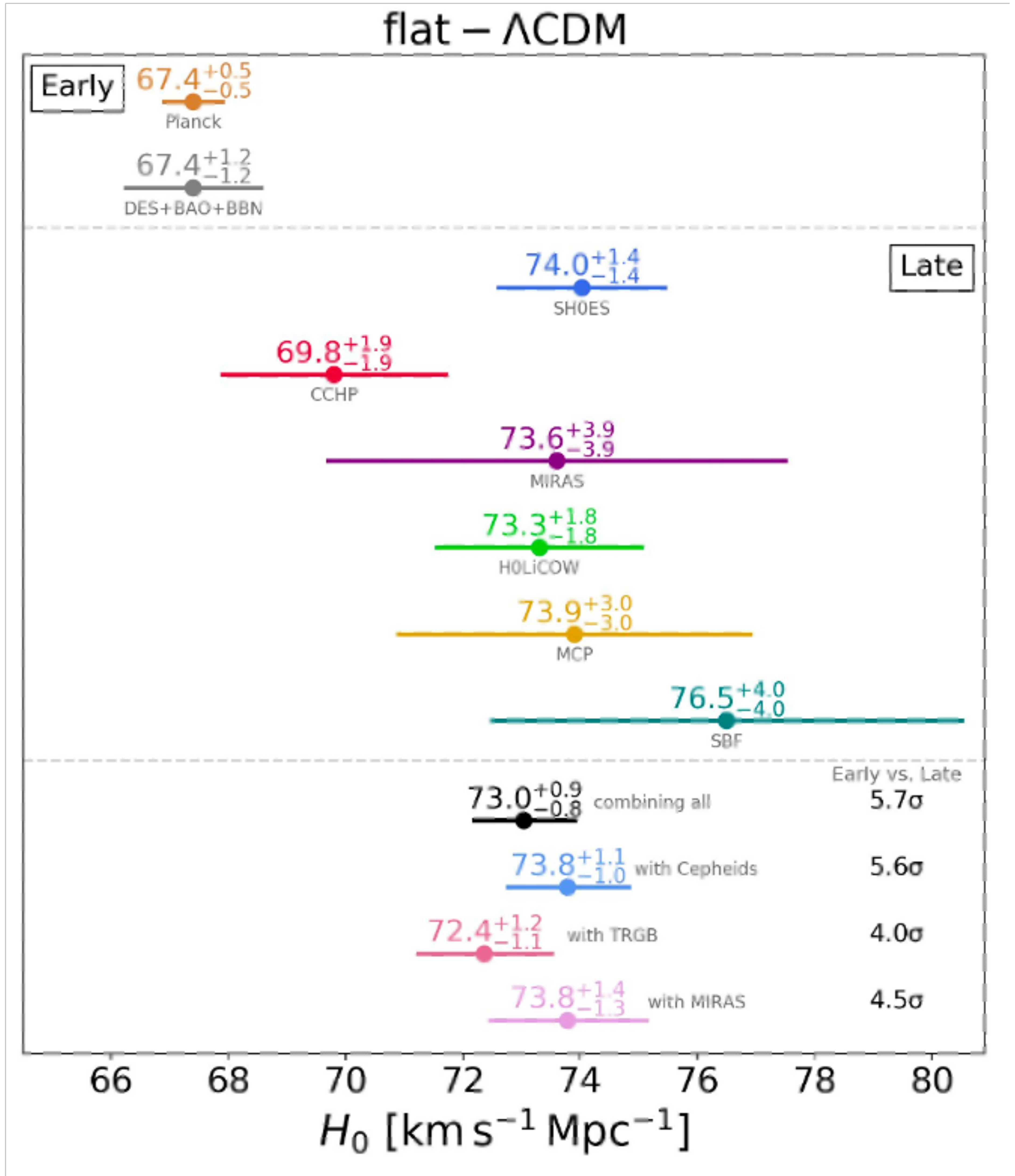
Standard Sirens with CBCs

Redshift: degenerate with mass in the GW signal. Must be found through other methods

- $cz \approx H_0 d_L$

Luminosity distance: directly measurable from the amplitude of the gravitational wave signal

- $h(t) = A(M_z, d_L, t)e^{i\Phi(M_z,t)}$



Verde, L., Treu, T. & Riess, A.G. Tensions between the early and late Universe. *Nat Astron* **3,** 891–895 (2019).

Standard Sirens with CBCs

Detect GW from CBC → Detect EM counterpart?

Standard Sirens with CBCs

Detect GW from CBC → Detect EM counterpart?

Yes ↙

Bright Sirens

- An EM counterpart is observed and used to obtain the host galaxy's redshift
- E.g. GW170817 and NGC4993

Standard Sirens with CBCs

Detect GW from CBC → Detect EM counterpart?

Yes ↙ No ↘

Bright Sirens

- An EM counterpart is observed and used to obtain the host galaxy's redshift
- E.g. GW170817 and NGC4993

Spectral Sirens

- Features in the mass distribution of the GW population break the mass-redshift degeneracy →

$$m_{det} = m_{source}(1 + z)$$

Dark Sirens

- Galaxy surveys are used to provide redshift estimates for potential host galaxies → **the galaxy catalog method**

Standard Sirens with CBCs

Detect GW from CBC → Detect EM counterpart?

Yes → **Bright Sirens**

- An EM counterpart is observed and used to obtain the host galaxy's redshift
- E.g. GW170817 and NGC4993

No → **Spectral Sirens**

- Features in the mass distribution of the GW population break the mass-redshift degeneracy →

$$m_{det} = m_{source}(1 + z)$$

Dark Sirens

- Galaxy surveys are used to provide redshift estimates for potential host galaxies → **the galaxy catalog method**

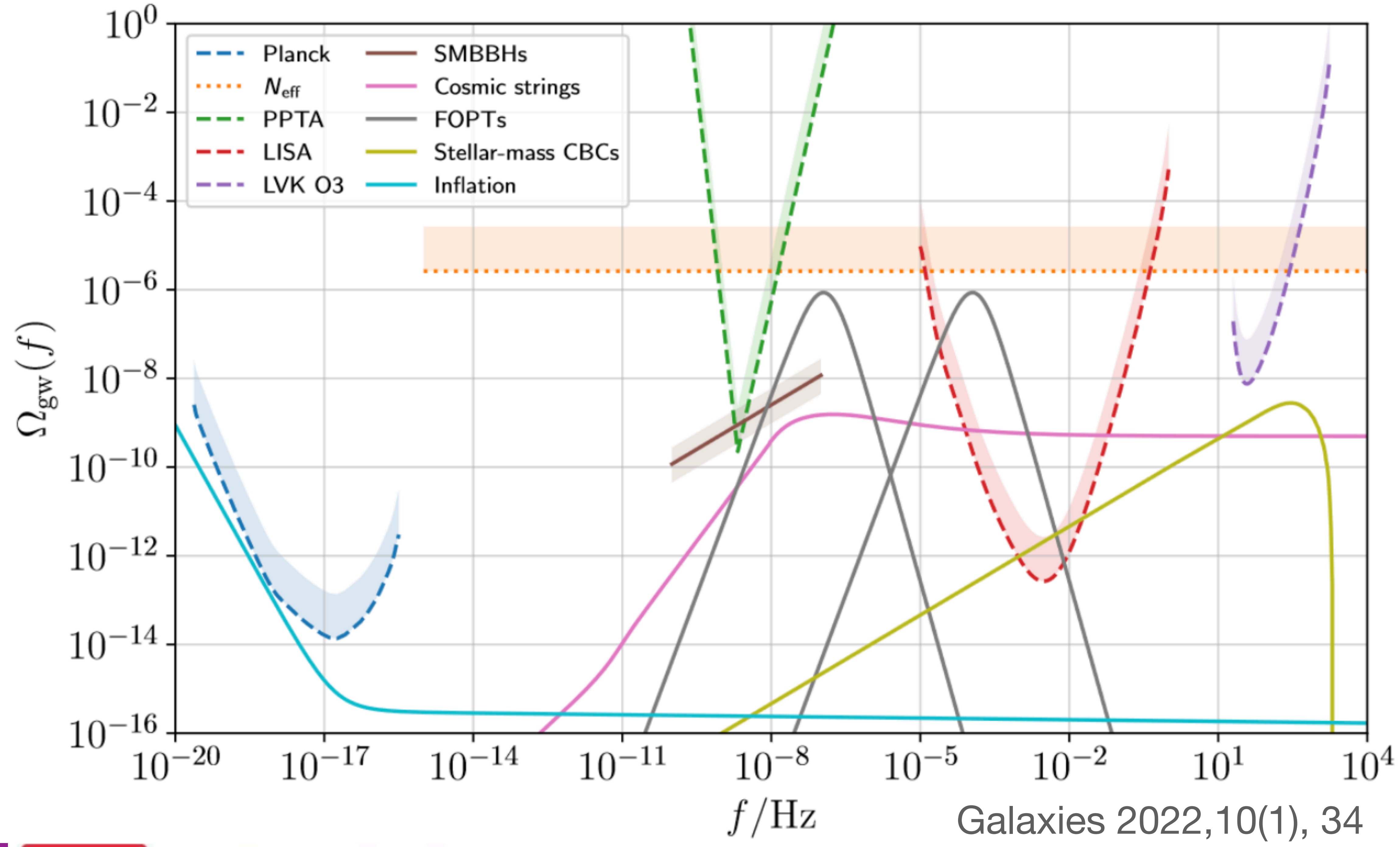
Measure H_0

Stochastic Gravitational Wave Background

The SGWB is a superposition of weak GW sources.

It can exist in many forms from two categories:

- Astrophysical background
- Cosmological background



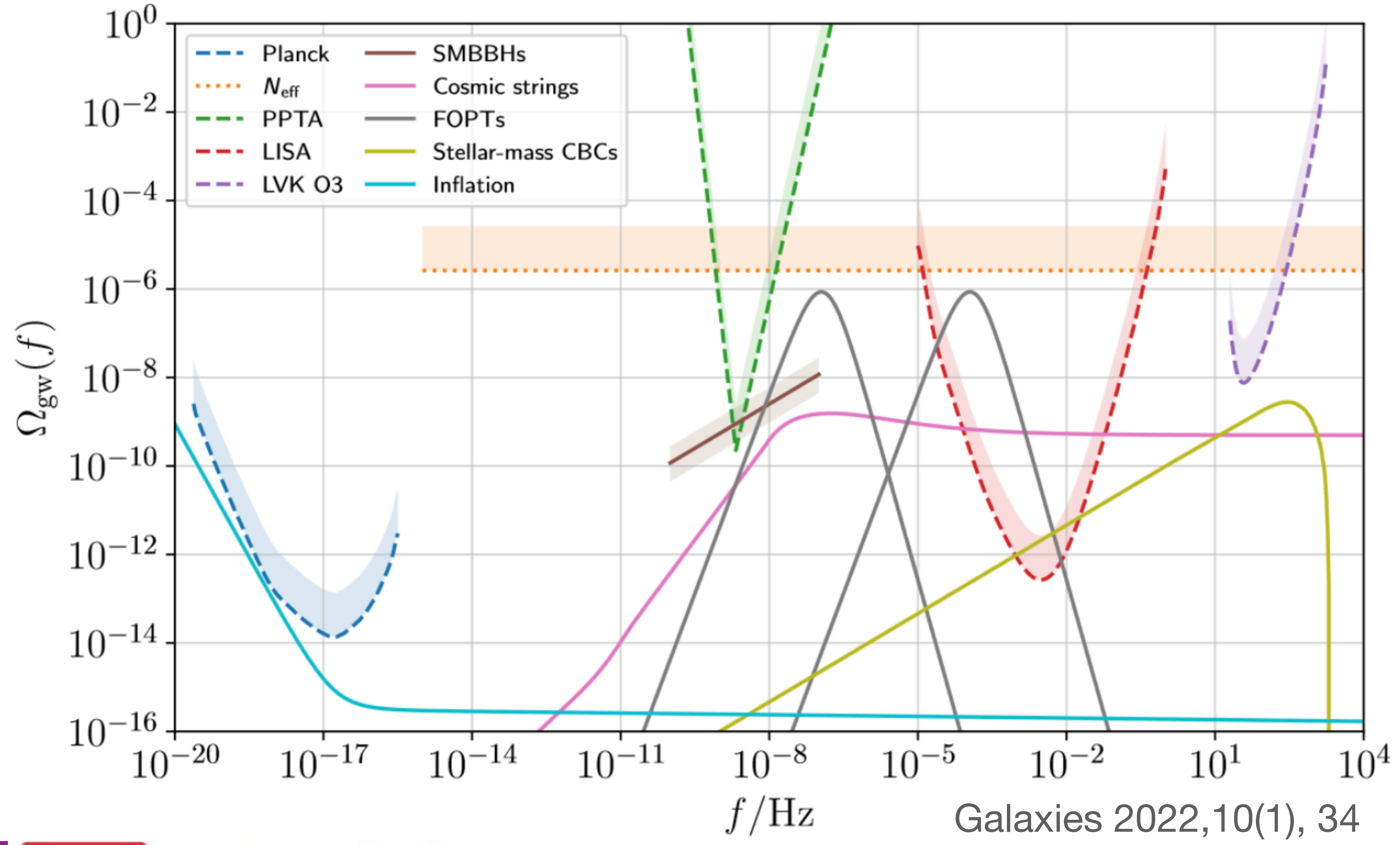
Galaxies 2022,10(1), 34

Stochastic Gravitational Wave Background

The SGWB is a superposition of weak GW sources.

It can exist in many forms from two categories:

- **Astrophysical background**
- Cosmological background



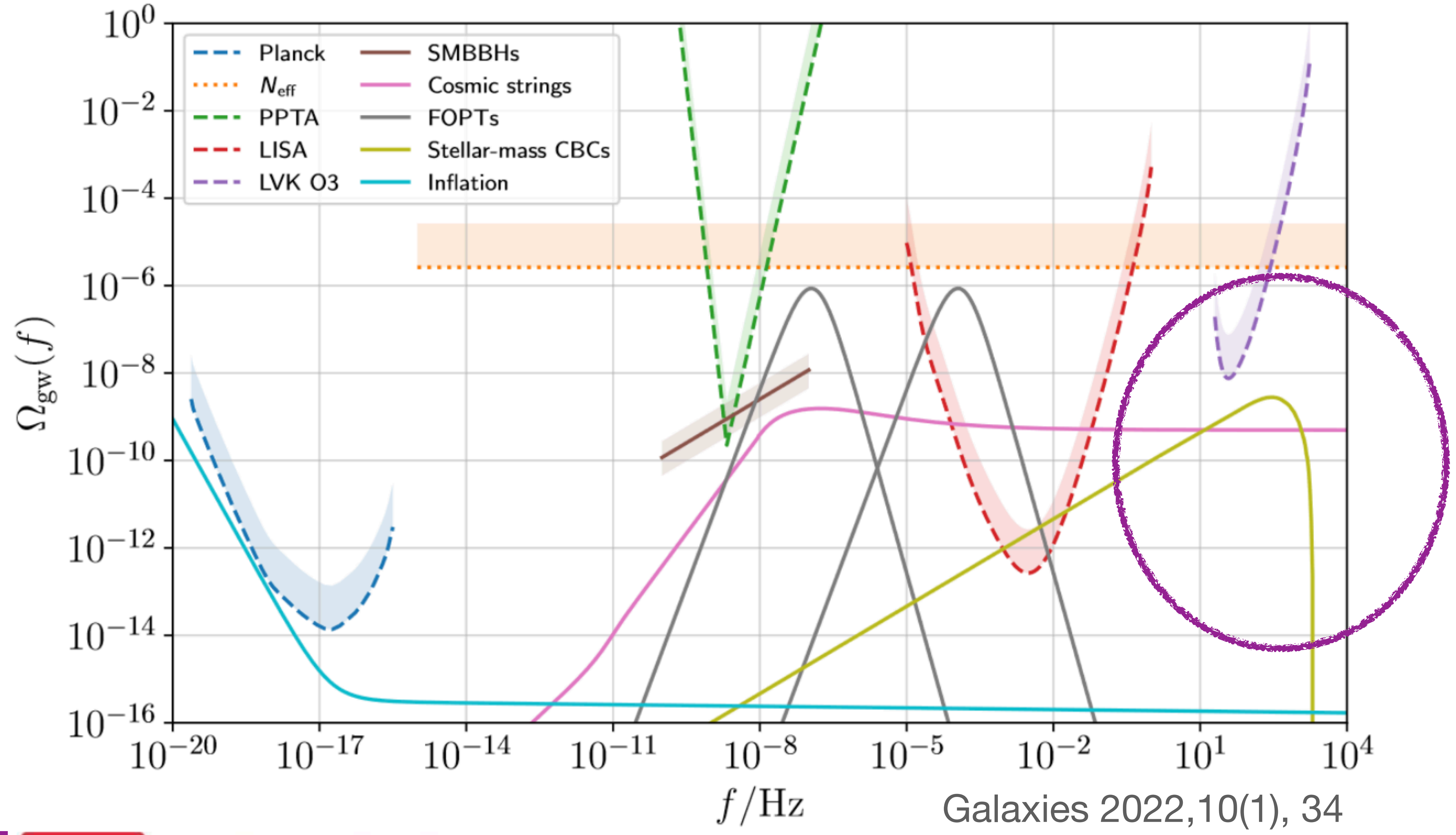
Galaxies 2022,10(1), 34

Stochastic Gravitational Wave Background

The SGWB is a superposition of weak GW sources.

It can exist in many forms from two categories:

- **Astrophysical background**
- Cosmological background



Galaxies 2022,10(1), 34

The SGWB is characterized by dimensionless energy density

$$\Omega_{\rm GW}(f) = \frac{1}{\rho_c}\frac{\mathrm{d}\rho_{\rm GW}(f)}{\mathrm{d}\ln f}$$

Since we are only interested in BBH events, we only look at the astrophysical background from BBHs.

Stochastic Gravitational Wave Background

For a BBH population

$$\Omega_{\rm GW} = \frac{f}{\rho_c} \int_0^{z_{max}} \mathrm{d}z \frac{R(z)}{(1+z)H(z)} \left\langle \frac{\mathrm{d}E_s}{\mathrm{d}f_s} \bigg|_{f(1+z)} \right\rangle$$

Stochastic Gravitational Wave Background

For a BBH population

Merger rate

$$\Omega_{\mathrm{GW}} = \frac{f}{\rho_c} \int_0^{z_{max}} \mathrm{d}z \frac{R(z)}{(1+z)H(z)} \left\langle \frac{\mathrm{d}E_s}{\mathrm{d}f_s} \bigg|_{f(1+z)} \right\rangle$$

Stochastic Gravitational Wave Background

For a BBH population

Merger rate — Source properties

$$\Omega_{\rm GW} = \frac{f}{\rho_c}\int_0^{z_{max}} \mathrm{d}z \frac{R(z)}{(1+z)H(z)} \left\langle \frac{\mathrm{d}E_s}{\mathrm{d}f_s}\Bigg|_{f(1+z)} \right\rangle$$

Stochastic Gravitational Wave Background

For a BBH population

Merger rate

Source properties

$$\Omega_{\mathrm{GW}} = \frac{f}{\rho_c} \int_0^{z_{max}} \mathrm{d}z \frac{R(z)}{(1+z)H(z)} \left\langle \frac{\mathrm{d}E_s}{\mathrm{d}f_s}\bigg|_{f(1+z)} \right\rangle$$

Cosmology

Analysis Method

Turbang et al. 2020, Callister et al. 2023

Individual BBH detections

BBH events

↓

Likelihood on BBH and cosmology parameters (e.g., masses and H_0)

Stochastic Backgrounds

GW data from multiple detectors

↓

Optimal estimator for $\hat{C}$ GWB spectrum $\Omega_{\rm GW}(f)$

$$\mathscr{L}(d_i, \hat{C} \,|\, \Lambda) = \mathscr{L}_{\rm BBH}(d_i \,|\, \Lambda)\mathscr{L}_{\rm GWB}(\hat{C} \,|\, \Lambda)$$

We want to infer hyperparameters Λ consistent with the individual BBH events and the measurements on the GWB

Analysis Method

Likelihood

- Hierarchical Likelihood for a GW dataset x

$$\mathscr{L}_{BBH}(\{x\} \mid \Lambda) \propto e^{-N_{exp}(\Lambda)} \sum_i \int d\theta dz \mathscr{L}_{BBH}(x_i \mid \theta, z, \Lambda) \frac{1}{(1+z)} \frac{N_{CBC}}{(d\theta dz dt_s)}$$

- Gaussian Likelihood

$$\mathscr{L}_{GWB}(\hat{C} \mid \Lambda) \propto exp\left[-\frac{1}{2}\sum_k \left(\frac{\hat{C}(f_k) - \Omega(f_k, \Lambda)}{\sigma(f_k)}\right)^2\right]$$

LVK at A+ design sensitivity simulated data

SGWB Simulation

- We simulated $\hat{C}$ and σ based on O5 sensitivity

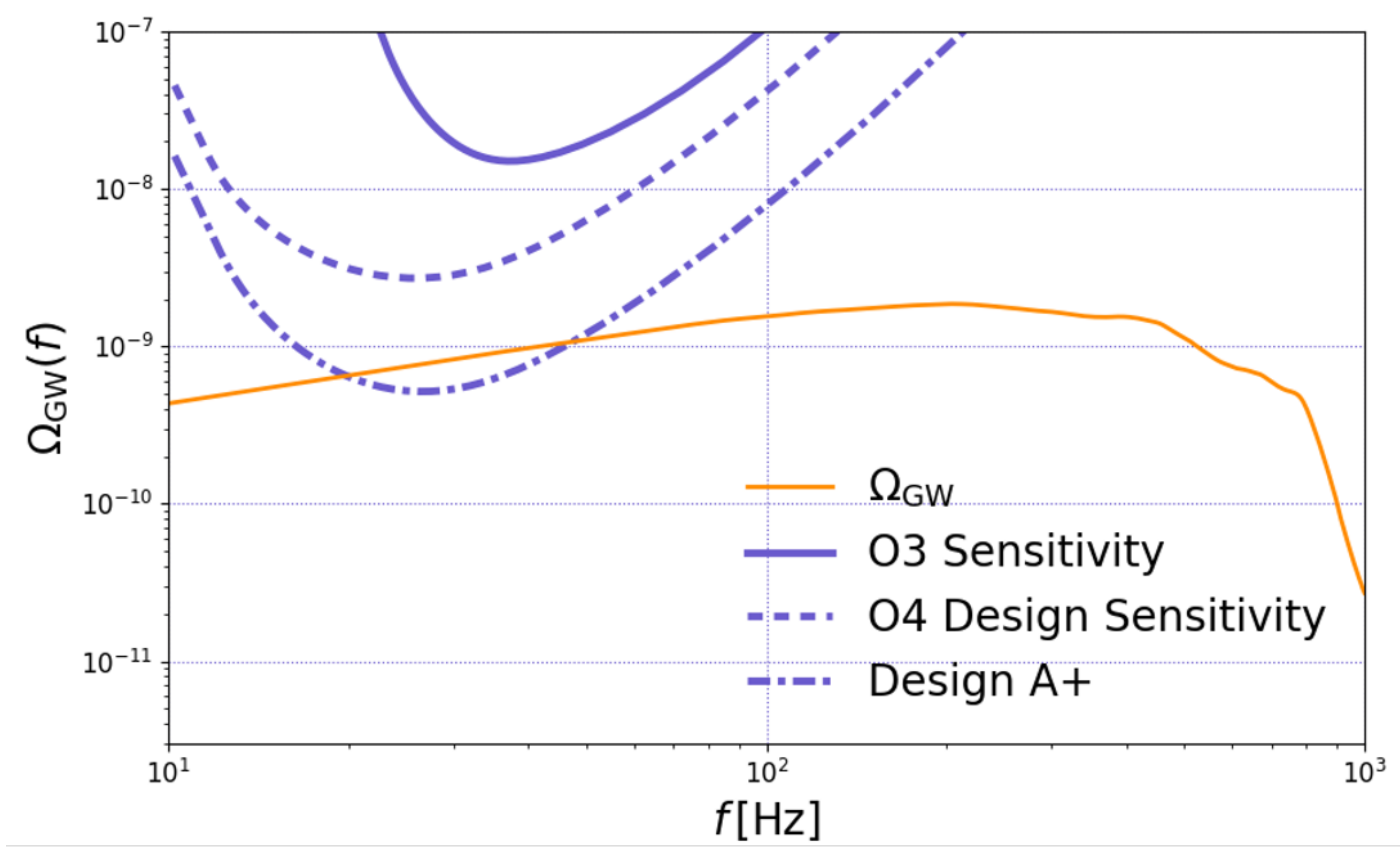
- The simulations rely on a population model of gravitational wave event rates and masses

$$p(m_1 \,|\, m_{min}, m_{max}, \alpha) = (1 - \lambda) \times$$

$$\times P(m_1 \,|\, m_{min}, m_{max}, -\alpha) + \lambda G(m_1 \,|\, \mu_g, \sigma)$$

$$p(m_2 \,|\, m_{min}, m_1, \beta) = P(m_2 \,|\, m_{min}, m_1, \beta)$$

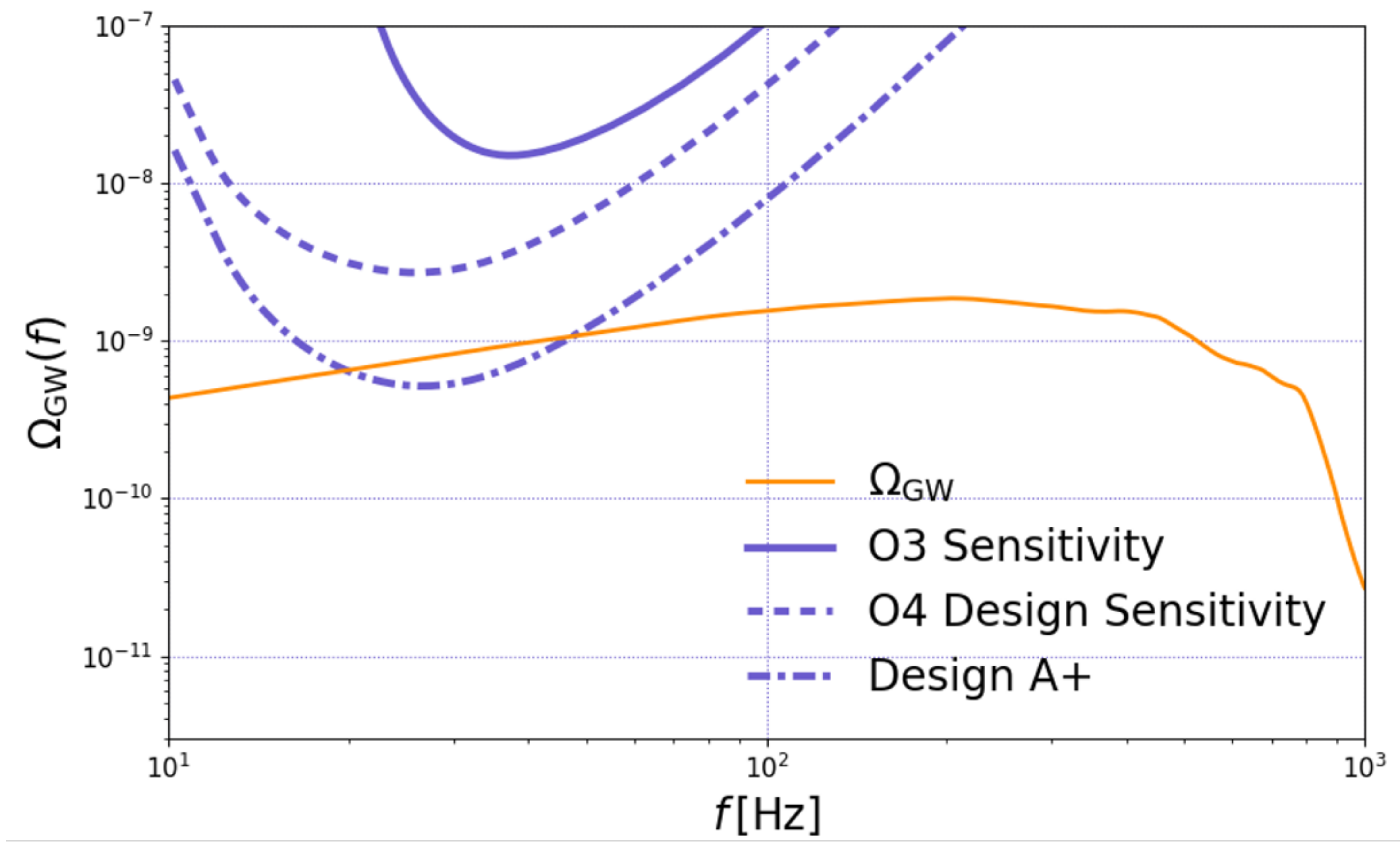
$$\psi(z; \Lambda_p) = \psi_{MD}(z; \gamma, k, z_p)$$



LVK at A+ design sensitivity simulated data

SGWB Simulation

- We simulated $\hat{C}$ and σ based on O5 sensitivity
- The simulations rely on a population model of gravitational wave event rates and masses



$$p(m_1 | m_{min}, m_{max}, \alpha) = (1 - \lambda) \times$$

$$\times P(m_1 | m_{min}, m_{max}, -\alpha) + \lambda G(m_1 | \mu_g, \sigma)$$

$$p(m_2 | m_{min}, m_1, \beta) = P(m_2 | m_{min}, m_1, \beta)$$

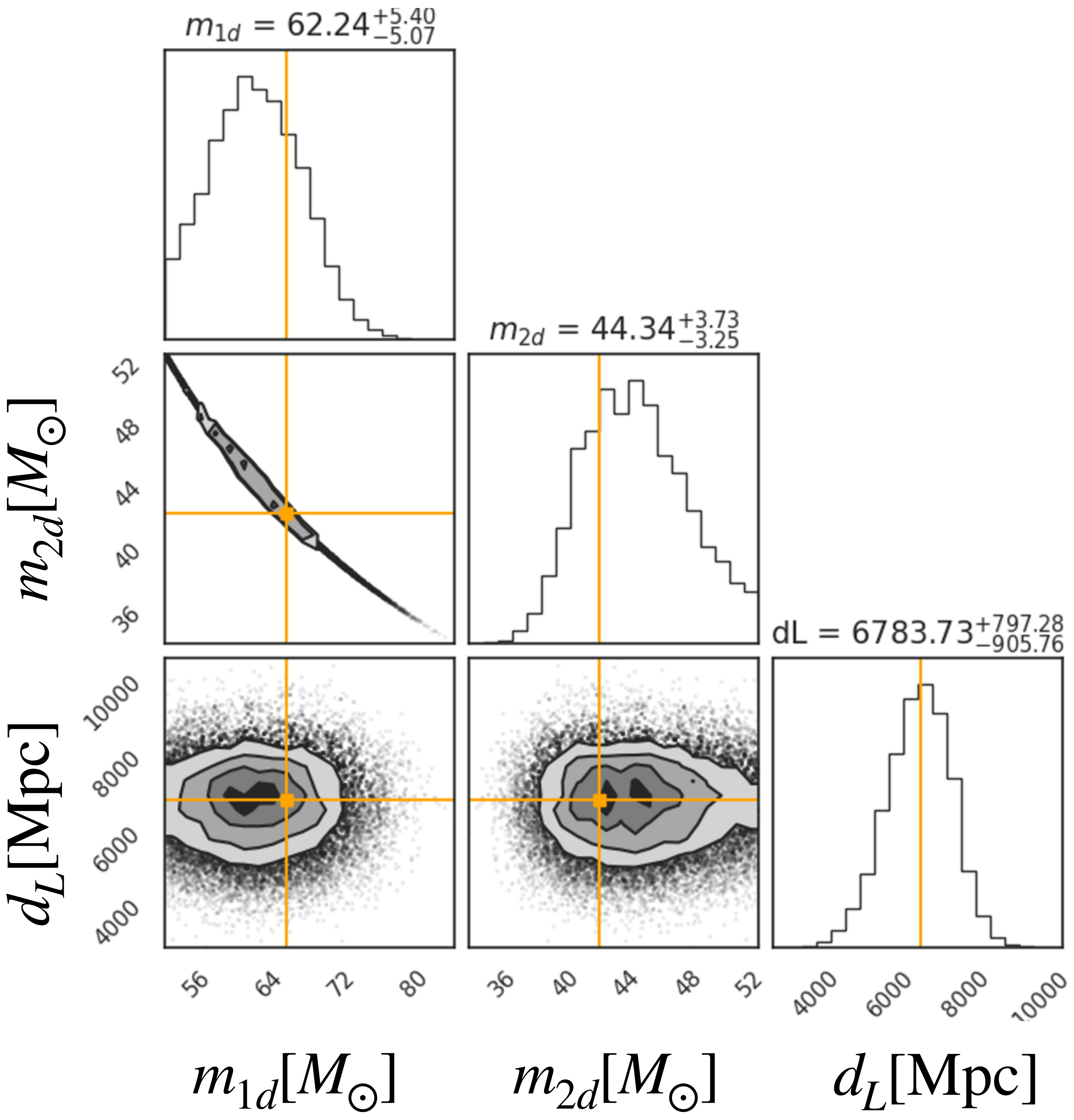
Power Law+Peak model

$$\psi(z; \Lambda_p) = \psi_{MD}(z; \gamma, k, z_p)$$ → Madau Rate model

LVK at design sensitivity simulated data

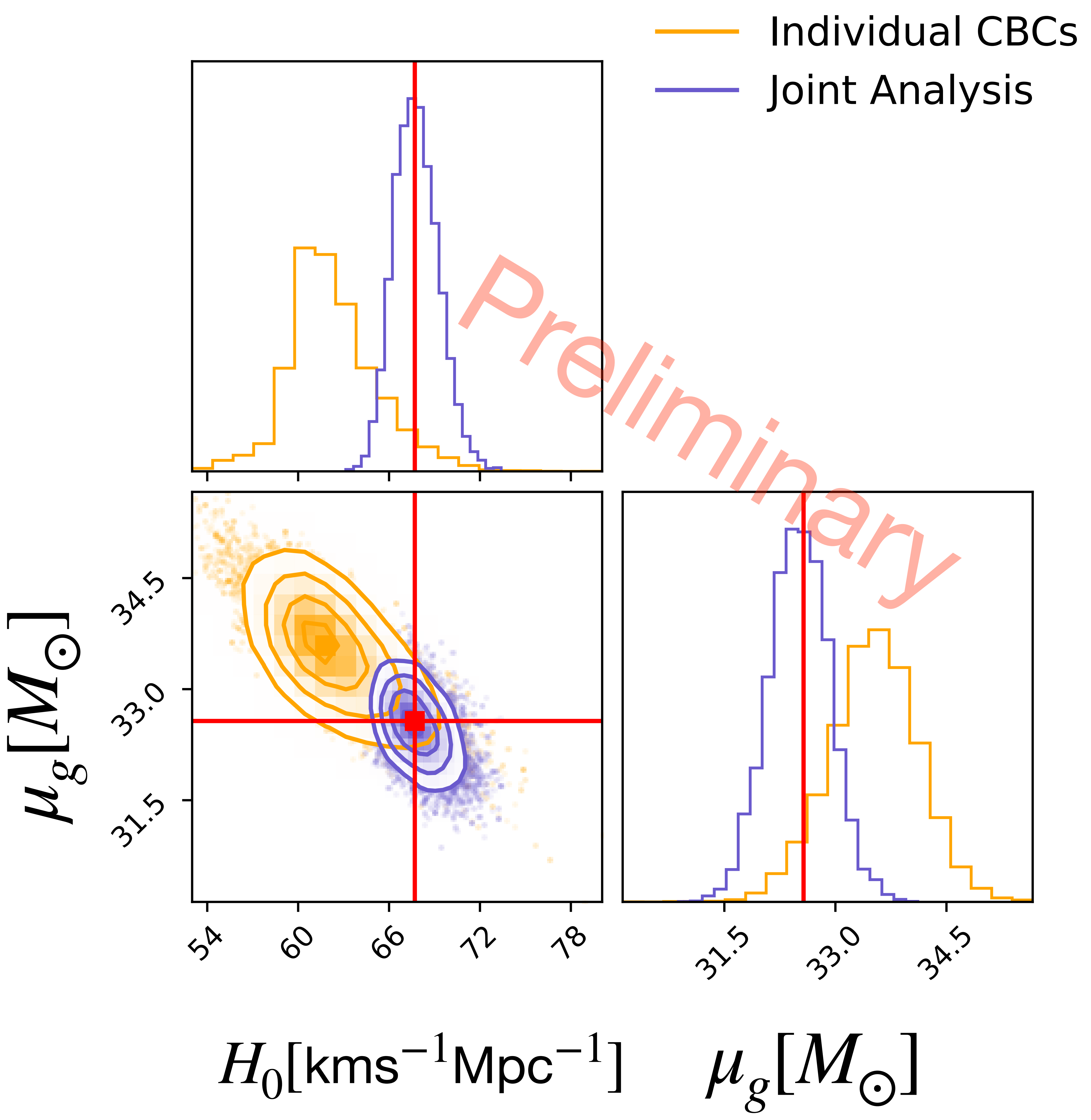
GW Simulation

- We assumed the same population model and merger rate
- A toy model simulates parameter estimation posteriors for 500 detected BBH
- The corner plot show posterior distributions for detector-frame masses and luminosity distance



Preliminary Results

- The prior range for the Hubble constant is set to $H_0[\text{kms}^{-1}\text{Mpc}^{-1}] \in [10,200]$ and for the mean $\mu_g[M_\odot] \in [20,50]$
- The values for H_0 and μ_g are better constrained using the joint analysis
- It assumes the mass spectrum is perfectly known



Conclusions and future steps

- Gravitational Wave sources are rapidly becoming important cosmic tracers
- Adding SGWB data can improve knowledge of H_0 and of the population parameters
- Joint inference can extend to other populations and key cosmological parameters (e.g., Ω_m)
- This approach applies to the Einstein Telescope (ET) for further analysis

Thank you for your attention!