Cosmology with Dark-Sirens : Hubble constant and black-hole population

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With the LIGO-Virgo-Kagra collaboration

Current work

Working in the cosmology group of the collaboration :

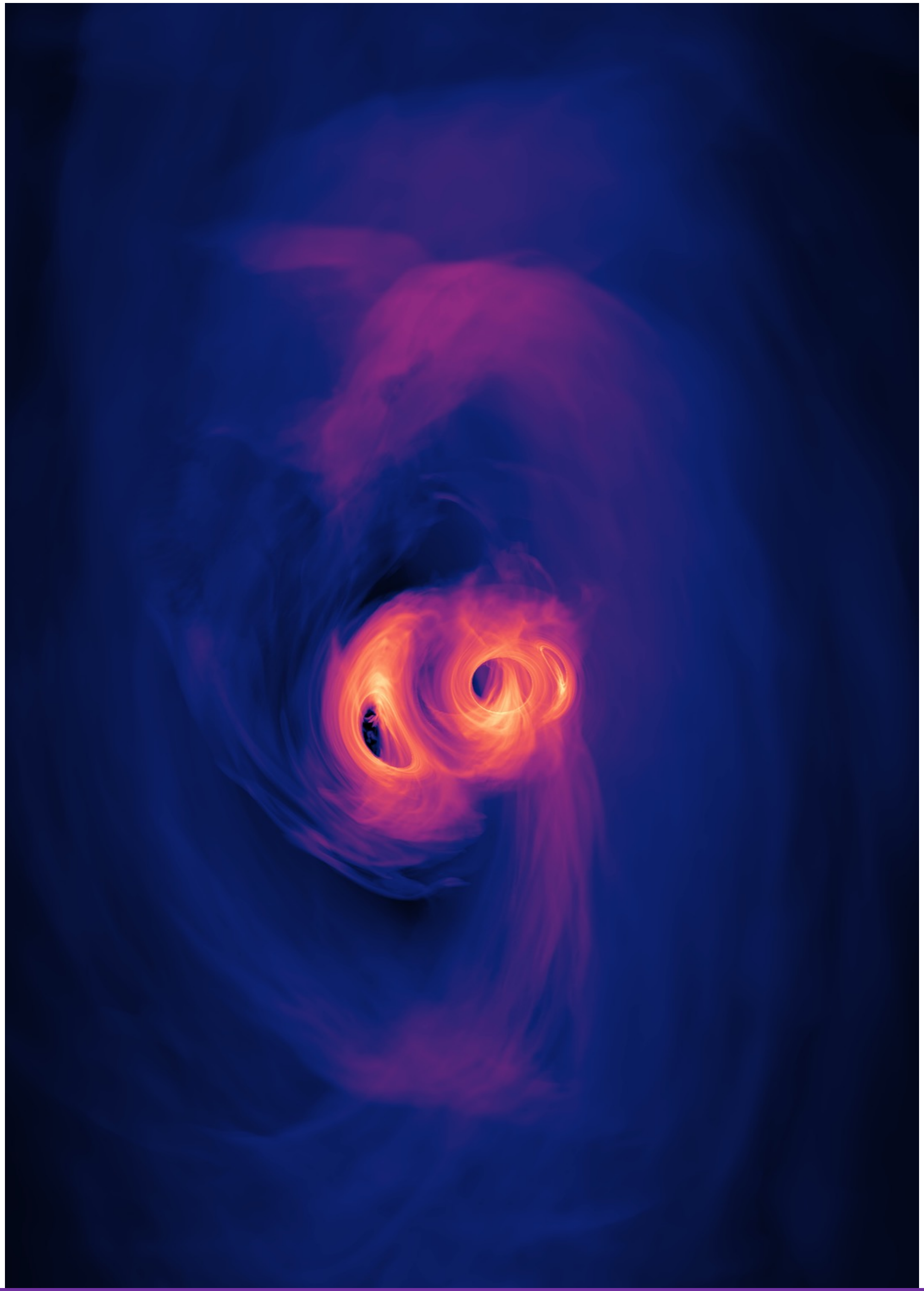
- Actual project : Understanding the bias on the Hubble constant measurement using gravitational-waves
  - How robust are the methods ?
  - What are the sources of bias ?

  - Short author list paper under preparation

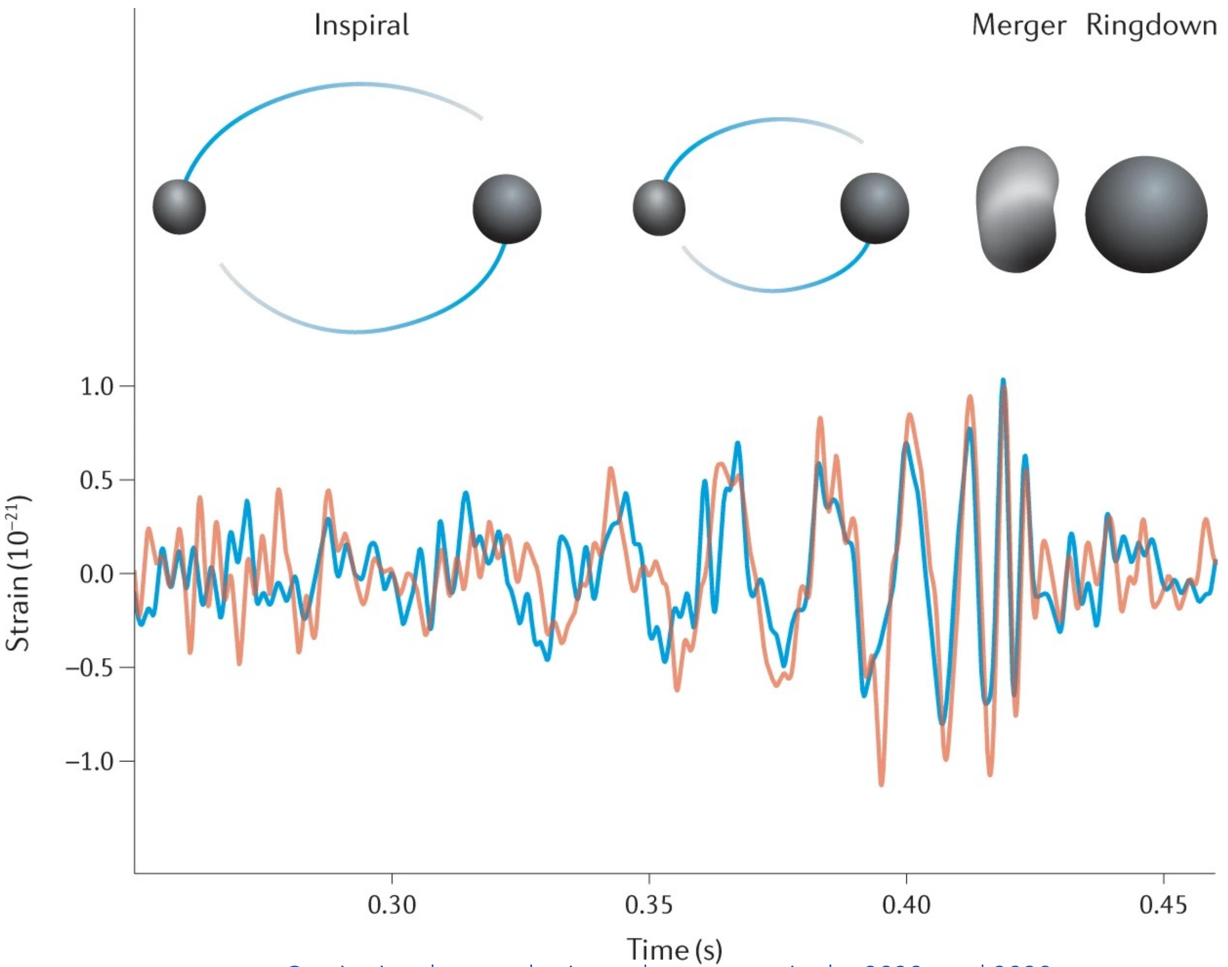
Today’s talk will present binary black hole spins results

Outline

- **Introduction**
  - Gravitational wave
  - Cosmology
- **Dark sirens**
  - Cosmology with GWs
  - IcaroGW
- **Results**
  - Black hole spins



Gravitational merger



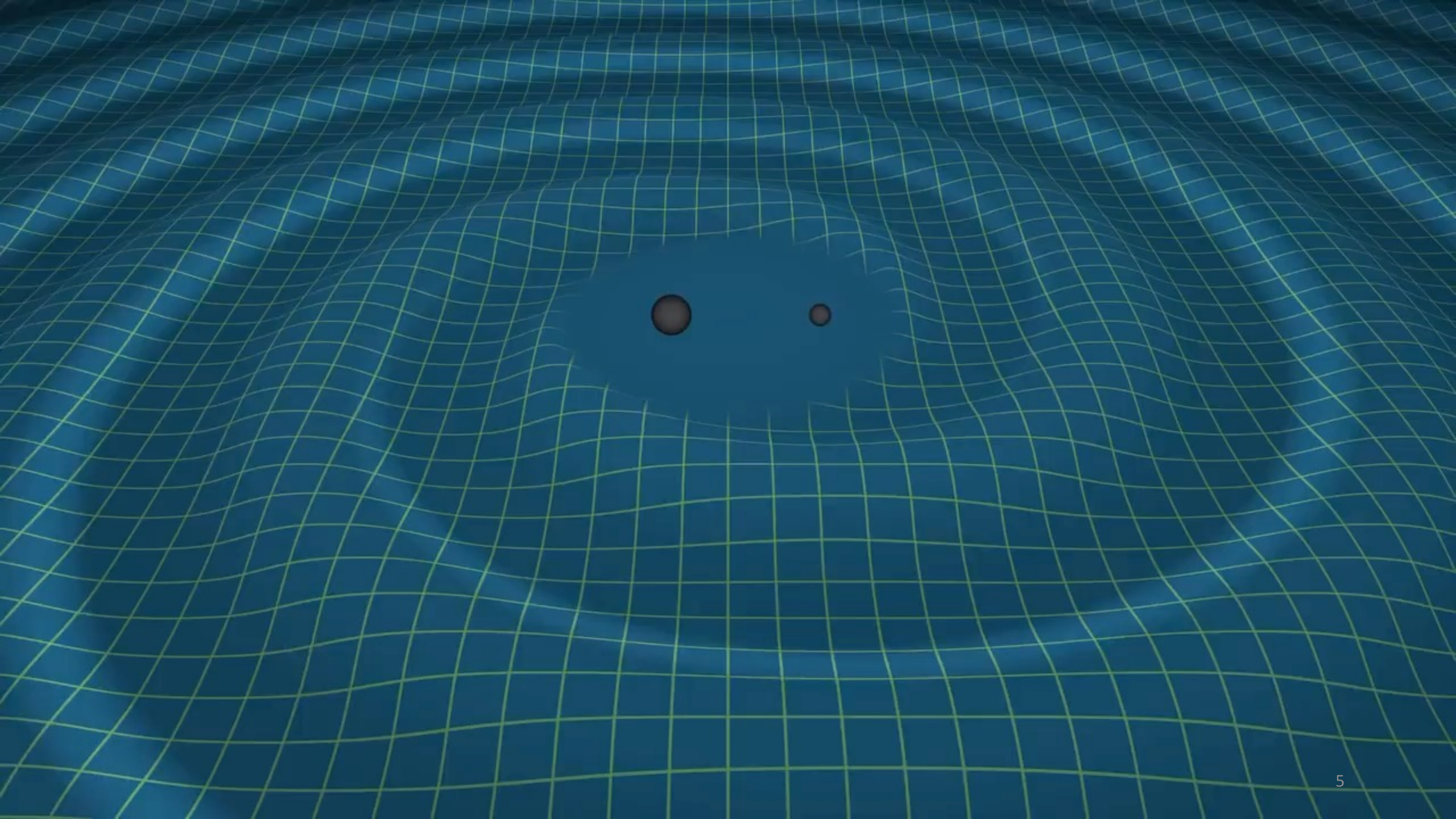
Gravitational-wave physics and astronomy in the 2020s and 2030s

- Main source of GWs are compact binary mergers
- Merger has 3 phases
- Several properties about the source can be deduced directly from the GW signal :

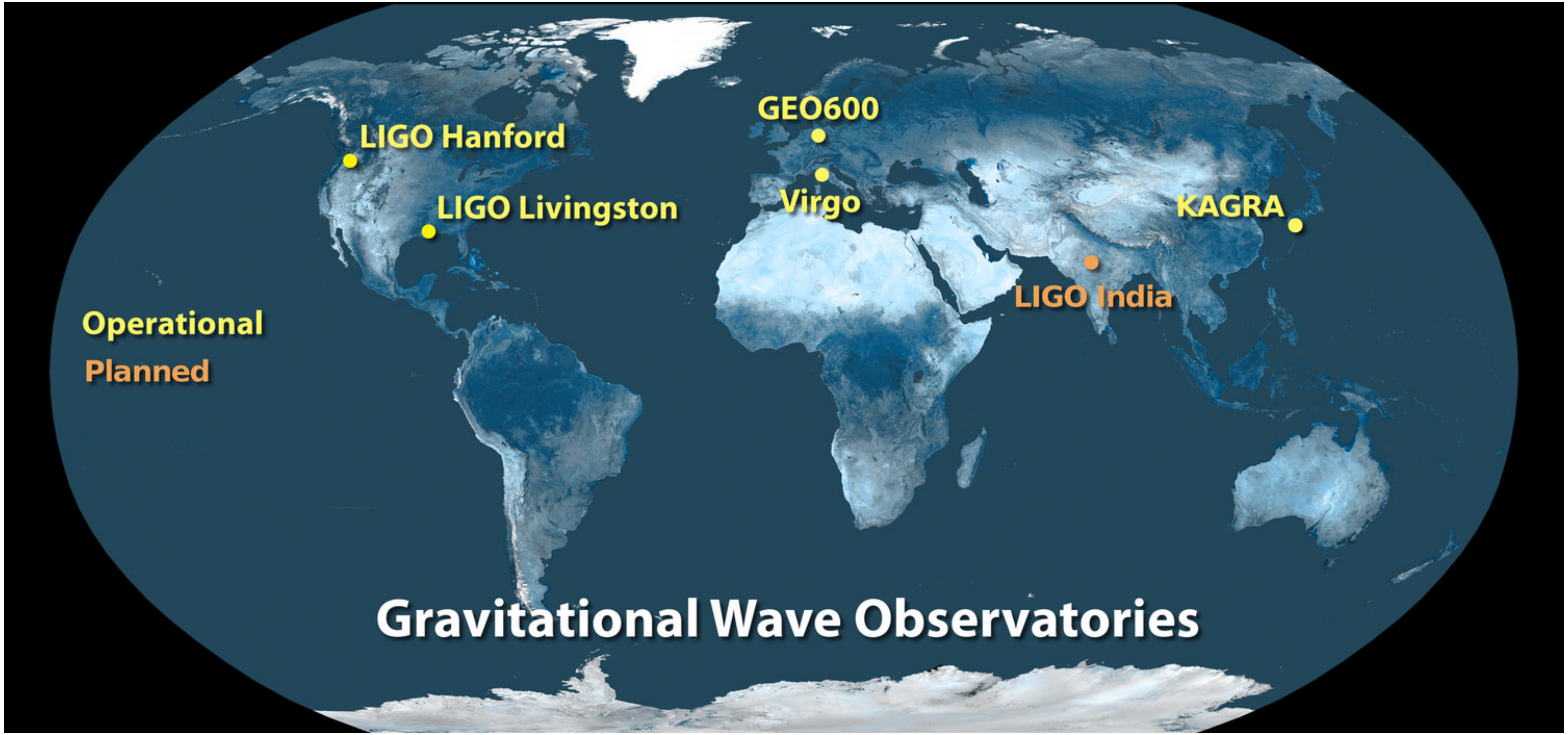
Luminosity distance d_L

Spins of black holes χ

Primary masses of black holes m_1, m_2

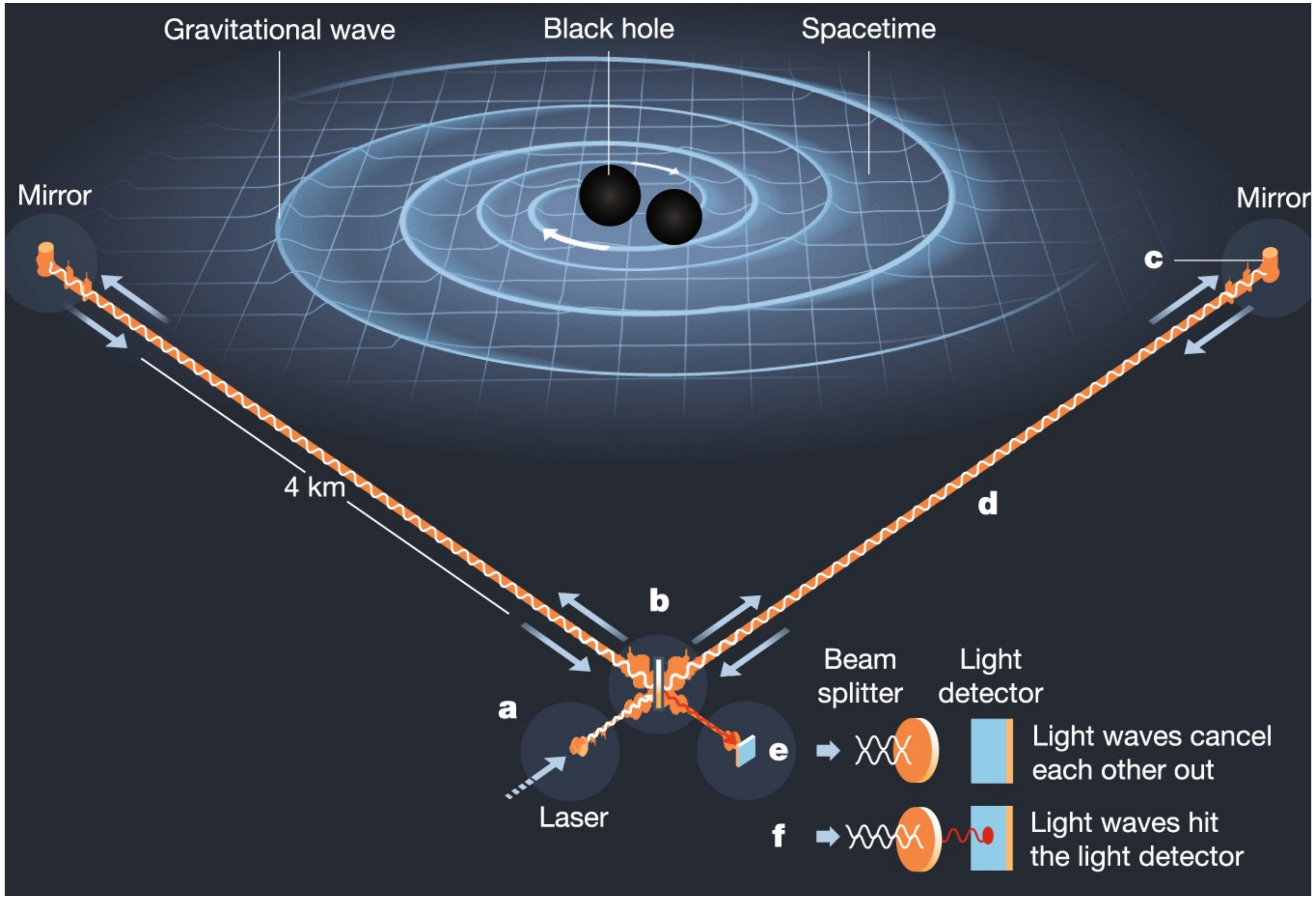


Detection of GWs



Detection of GWs

Detection of GWs



The new frontier of gravitational waves

Gws propagates across the Universe at $v = c$ and go through the detector on Earth

↓

The arms will be contracted/extended due to the waves

↓

Change in the light pattern

↓

GW detection

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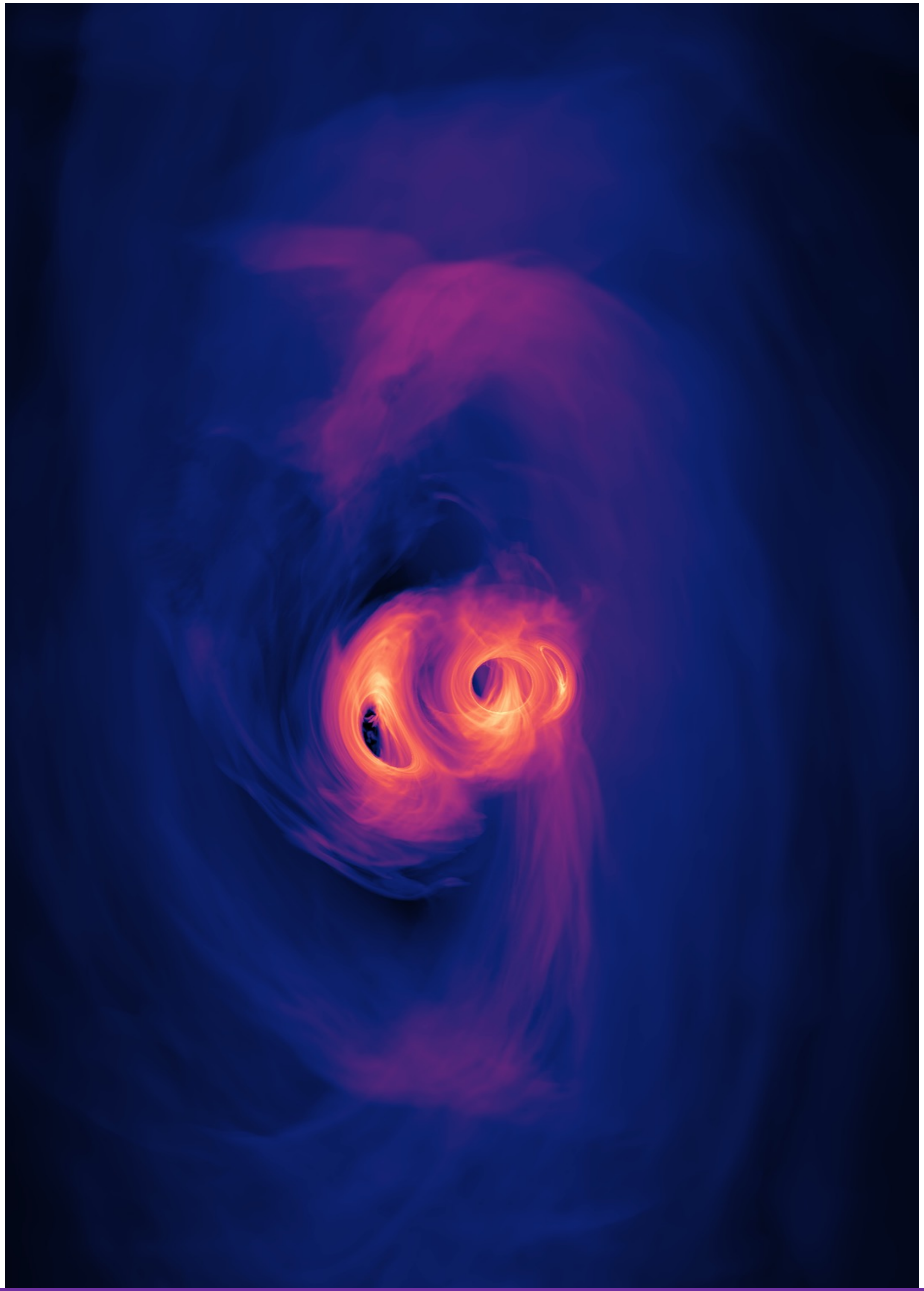
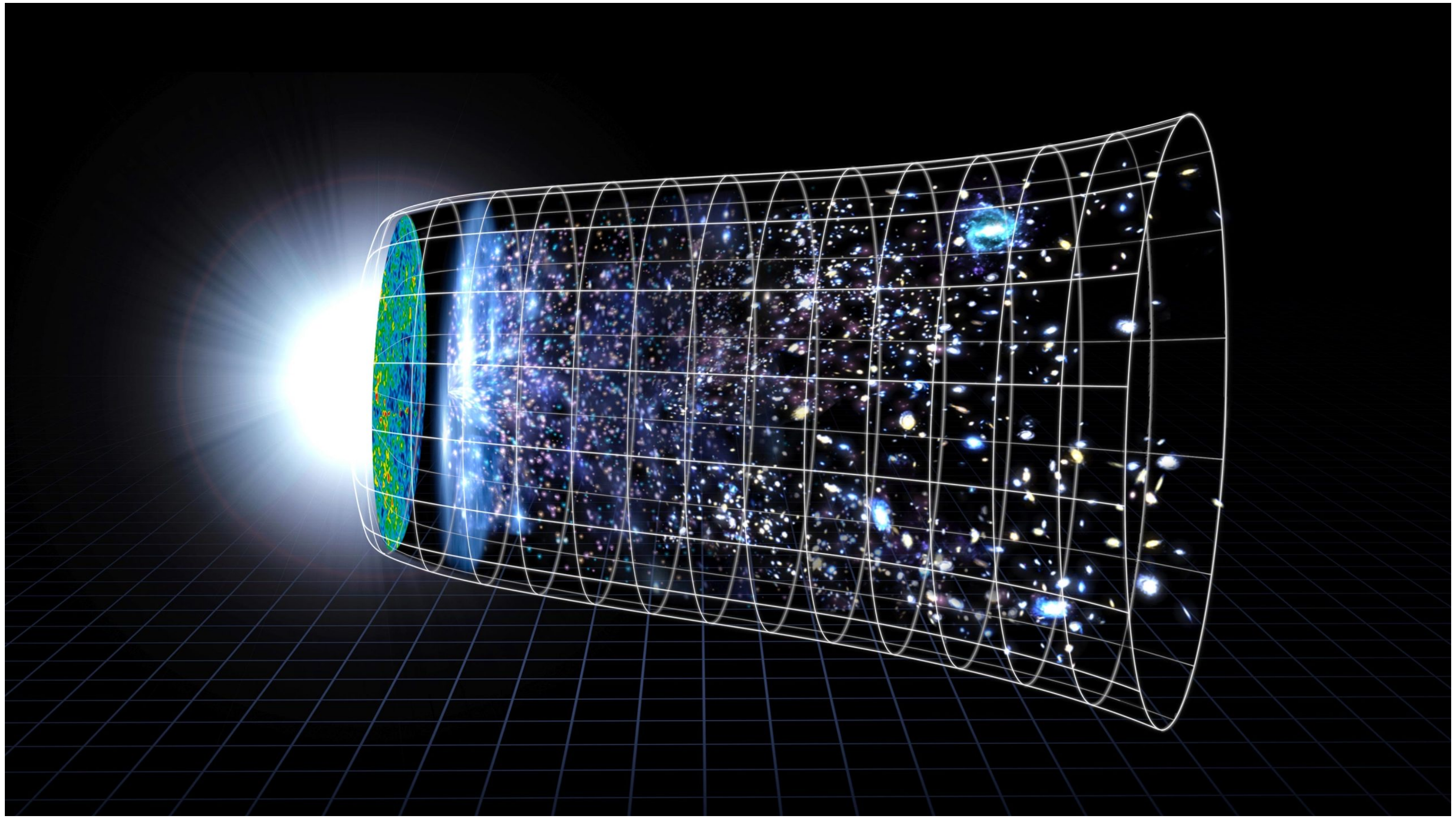


Hubble constant

H_0 = Expansion rate of the universe today in $km.s^{-1}.Mpc^{-1}$

$$\Leftrightarrow$$

How fast our universe is expanding



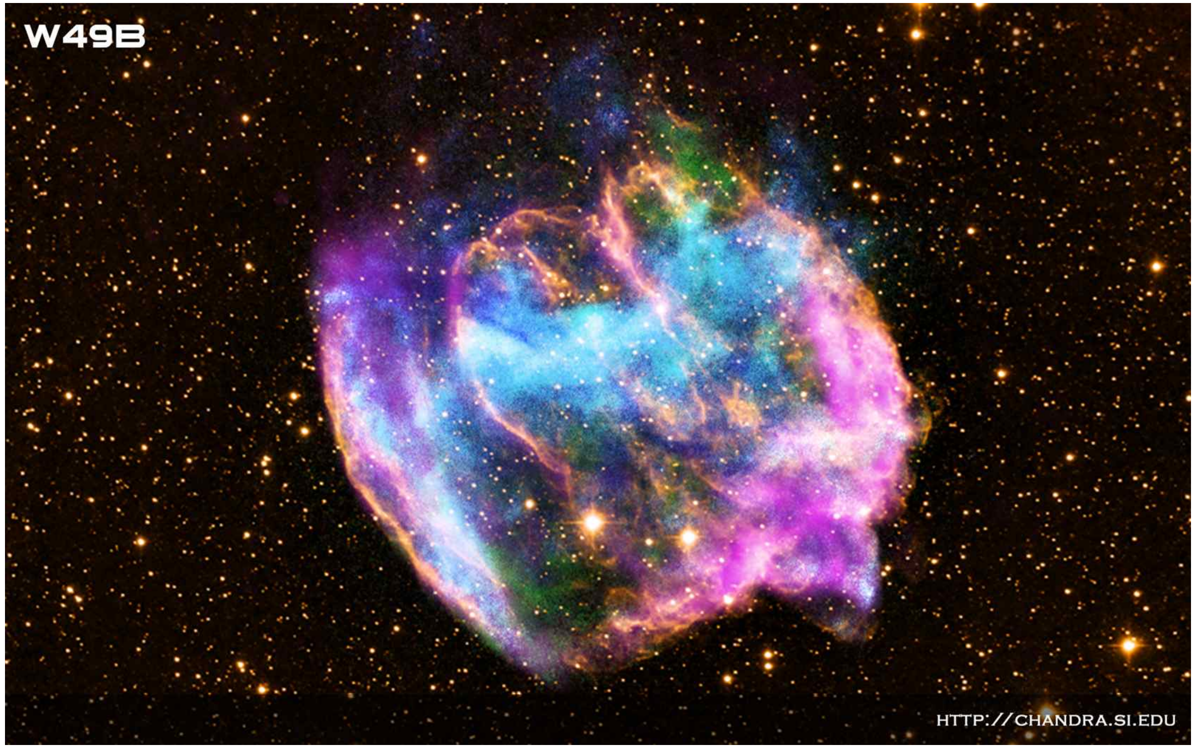
Hubble tension

H_0 = Expansion rate of the universe today
in $km.s^{-1}.Mpc^{-1}$

❖ Two measurements late & early universe :

Supernovae Ia

$H_0 = 74.03 \pm 1.42$



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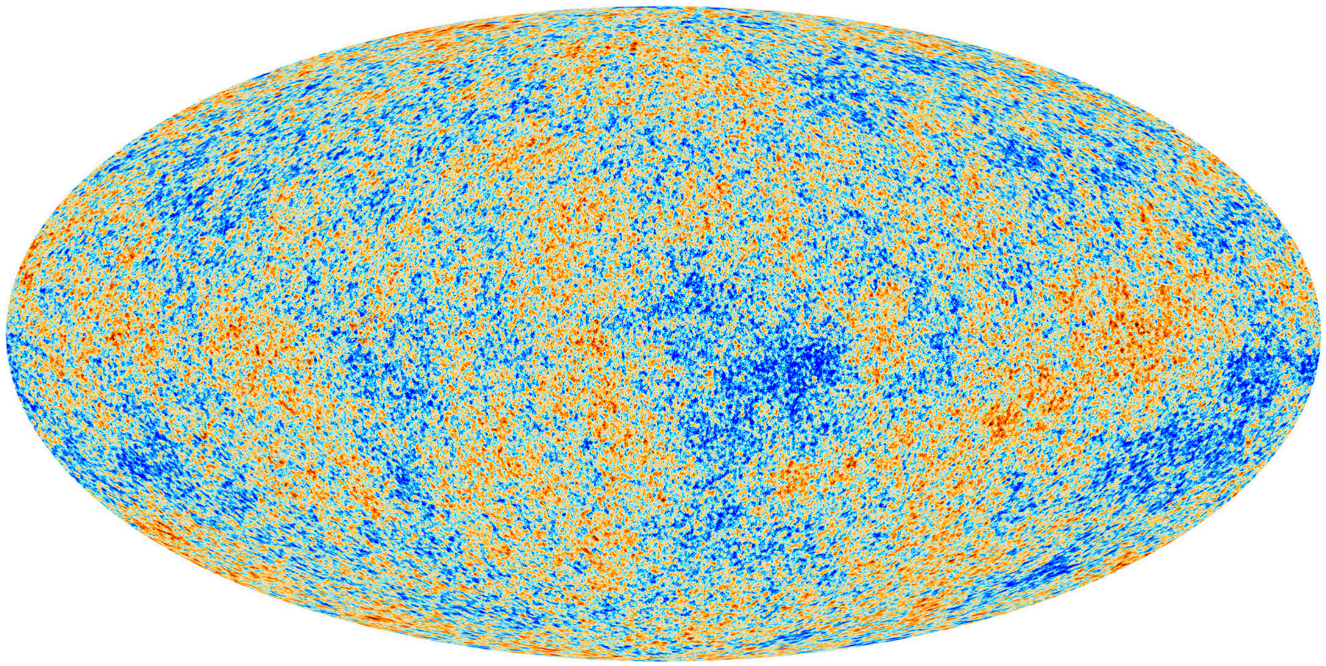
- Two measurements late & early universe :

Cosmic microwave background

$$H_0 = 67.4 \pm 0.5$$



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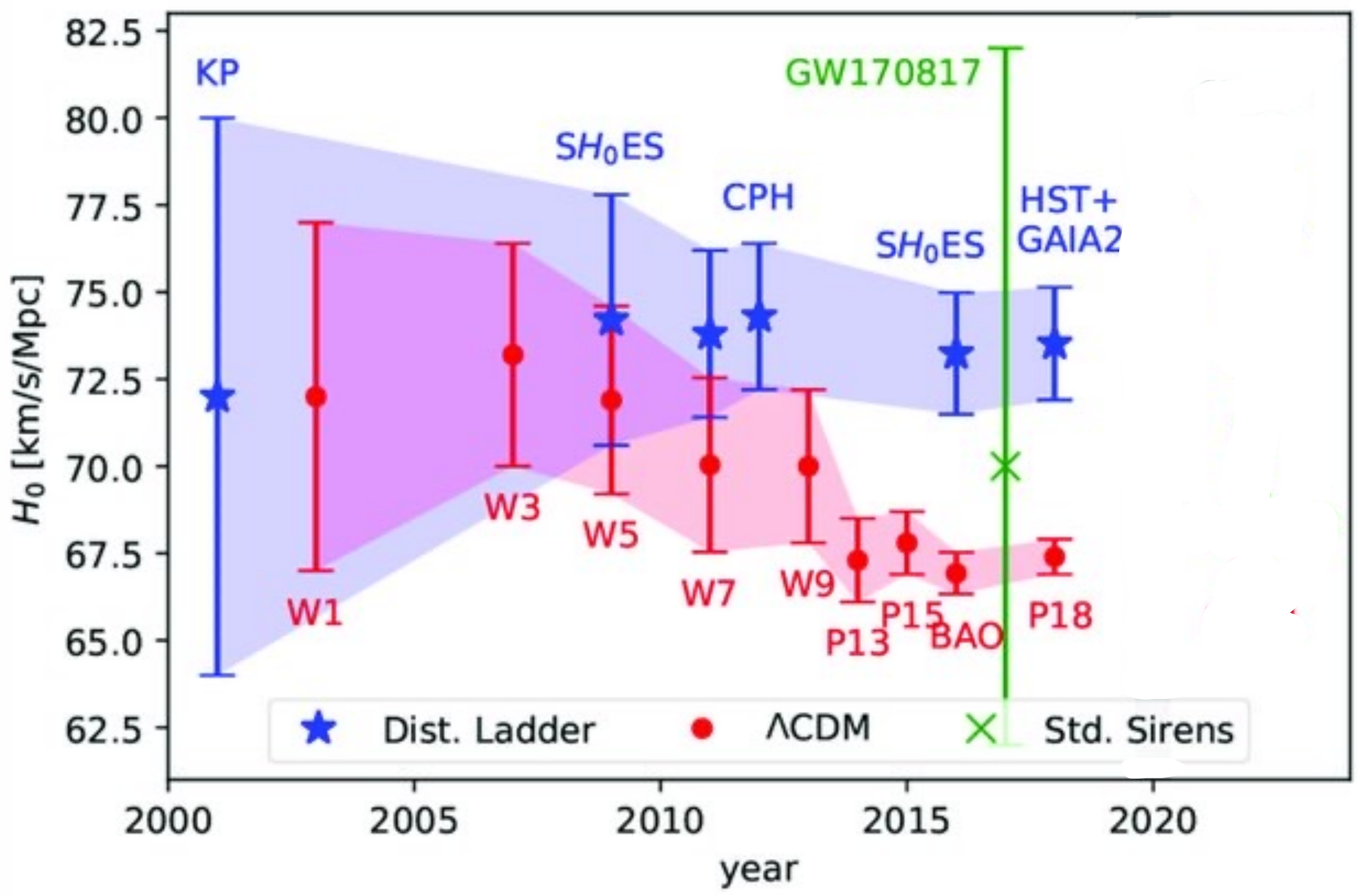


Dark Energy in light of multi-messenger gravitational-wave astronomy

Hubble tension

H_0 = Expansion rate of the universe today in $km.s^{-1}.Mpc^{-1}$

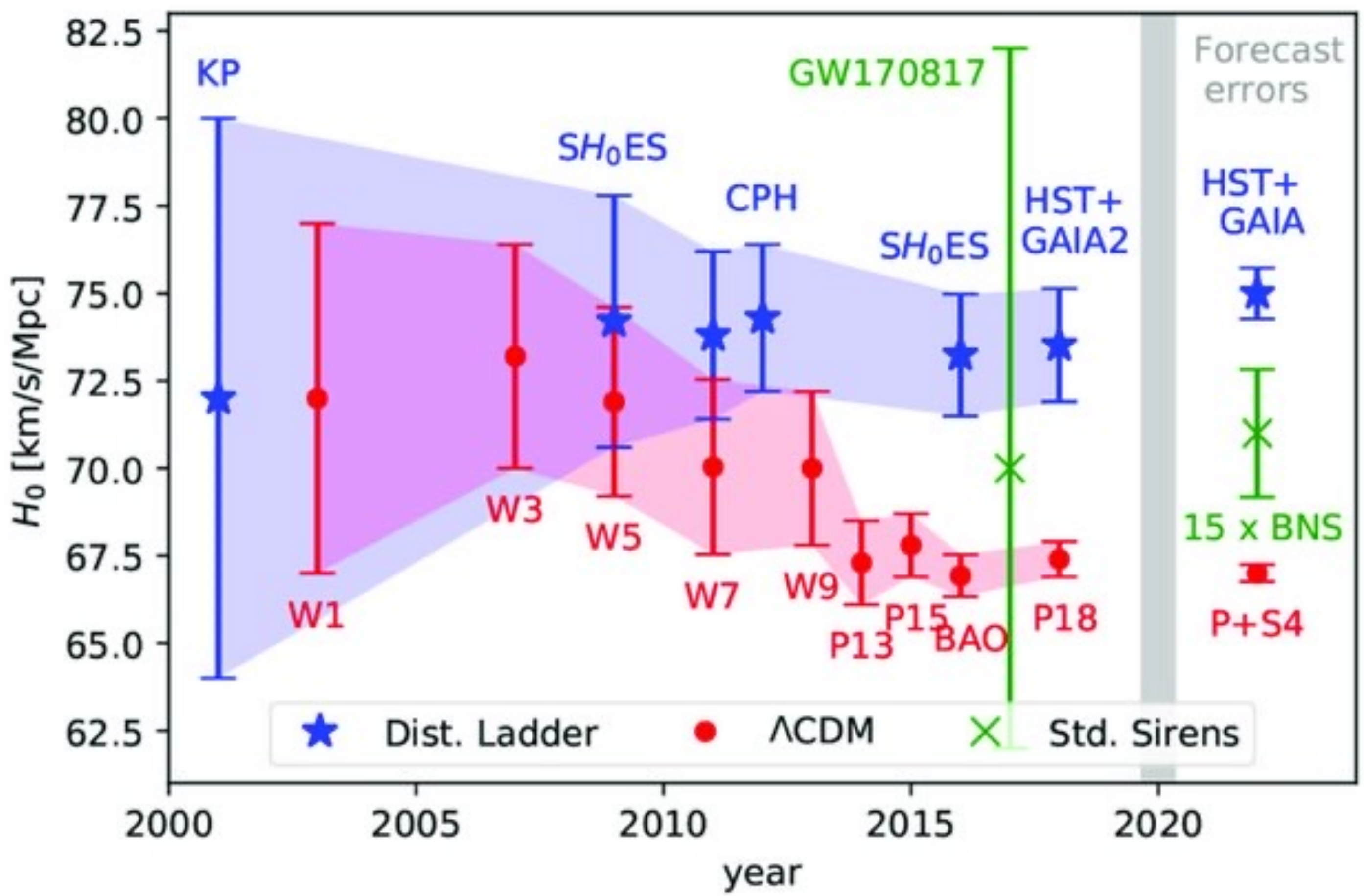
❖ Two measurements late & early universe :

Supernovae Ia

Cosmic microwave background

$H_0 = 74.03 \pm 1.42$ $H_0 = 67.4 \pm 0.5$

$\longrightarrow$ 4.4σ tension



Dark Energy in light of multi-messenger gravitational-wave astronomy

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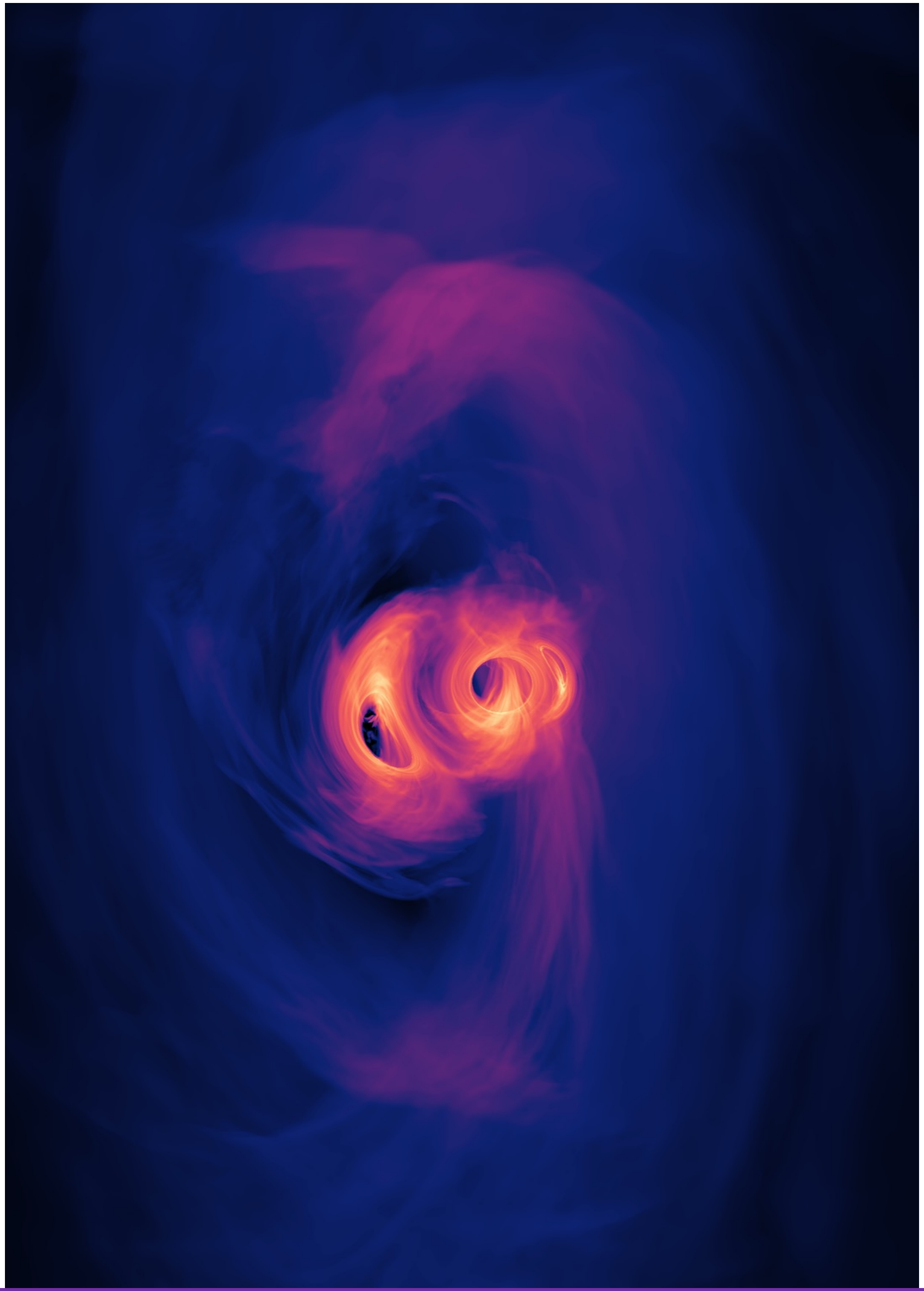


How do we measure H_0 ?

How to access H0 with GWs ?

- The redshift z and the luminosity distance d_L of a GW source are related through cosmology

$$d_L \simeq \frac{c}{H_0} z$$

(low redshift approximation)

d_L : Directly measurable the GW signal

z : Need to be found through other methods

- Access H0 by breaking this degeneracy

GW170817 : golden event

GW170817 is a **binary neutron stars** event

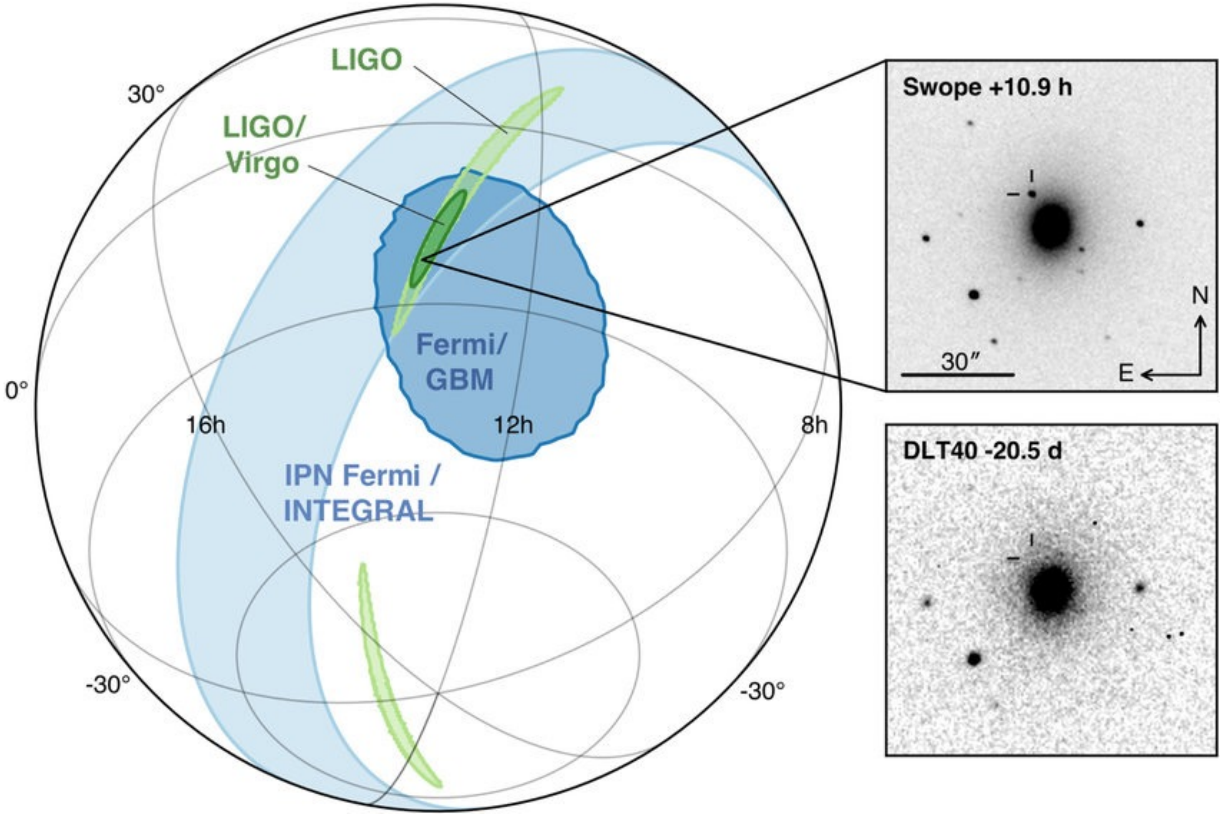
Two type of signals were emitted :

GWs → Luminosity distance

Gamma ray burst → Redshift

$$H_0 = 70.0^{+12.0}_{-8.0} \quad km.s^{-1}.Mpc^{-1}$$

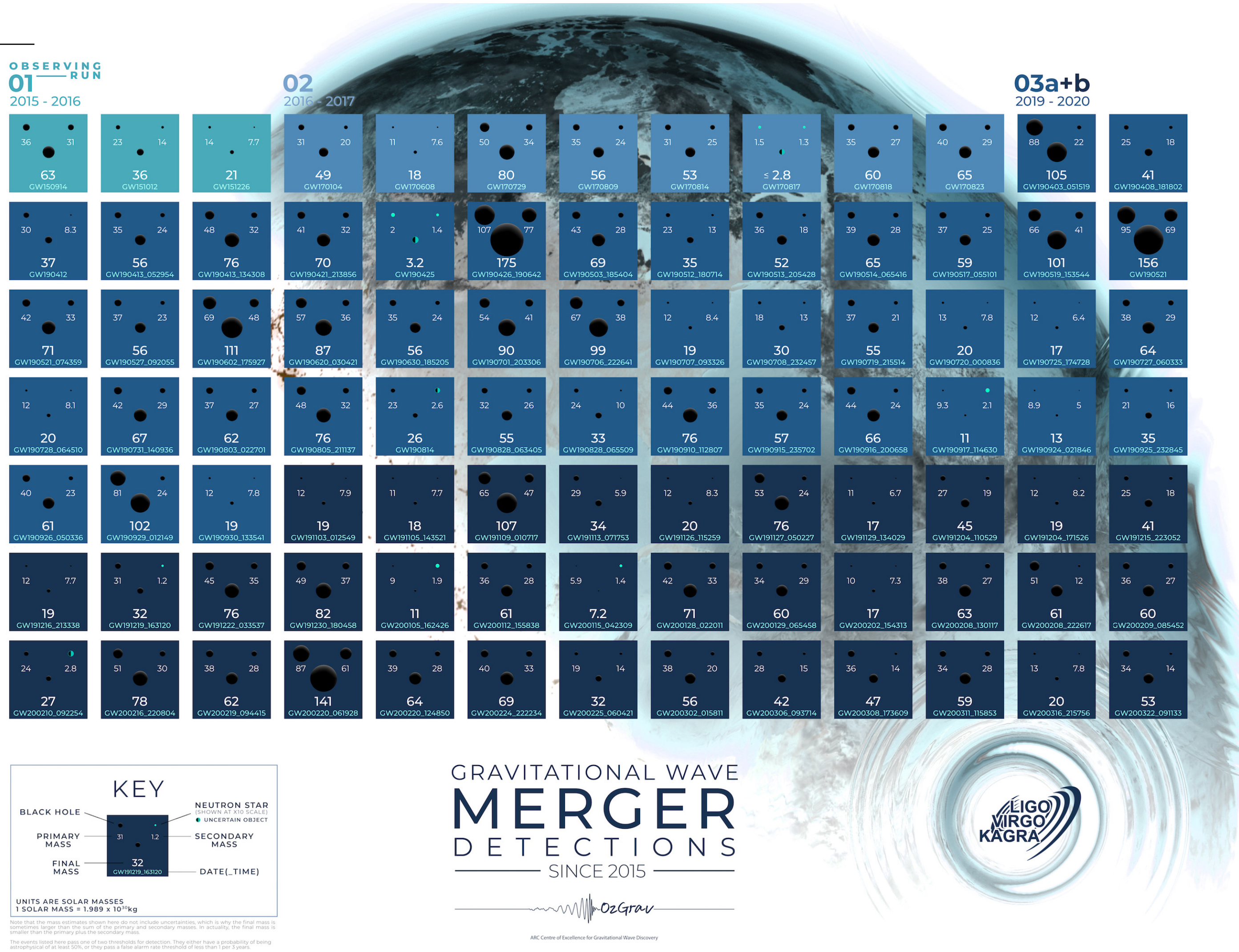
But still in agreement with the early and late universe values...



GWs state of the art

Since 2015, LIGO and Virgo had 3 observation runs

- ❖ 90 Compact binary mergers
- ❖ 89 of them are Dark-Sirens
  (no E.M. counterpart)

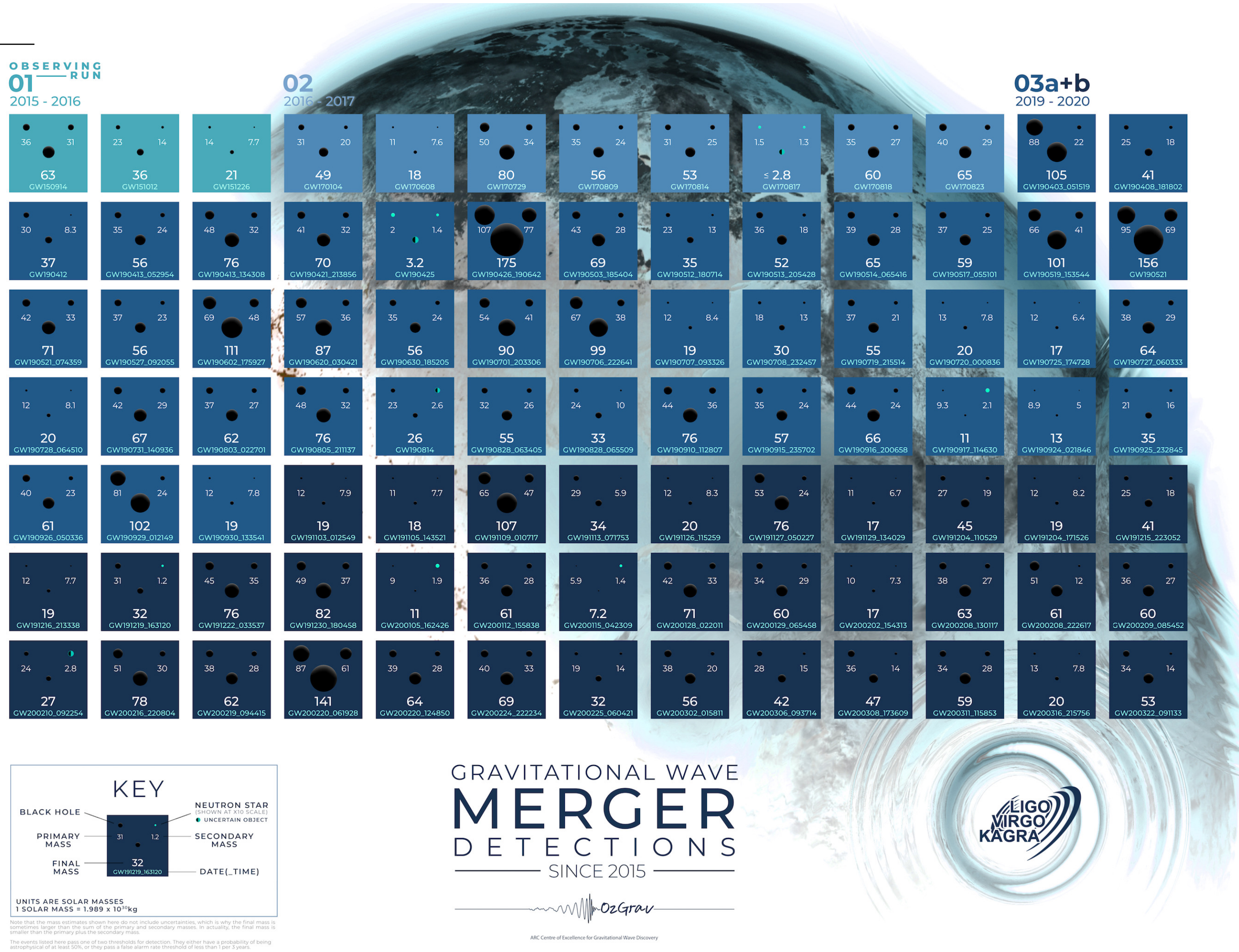


GWs state of the art

Need alternative methods to derive the redshift of GWs sources

Population inference using binary black-holes

Galaxy catalog inference



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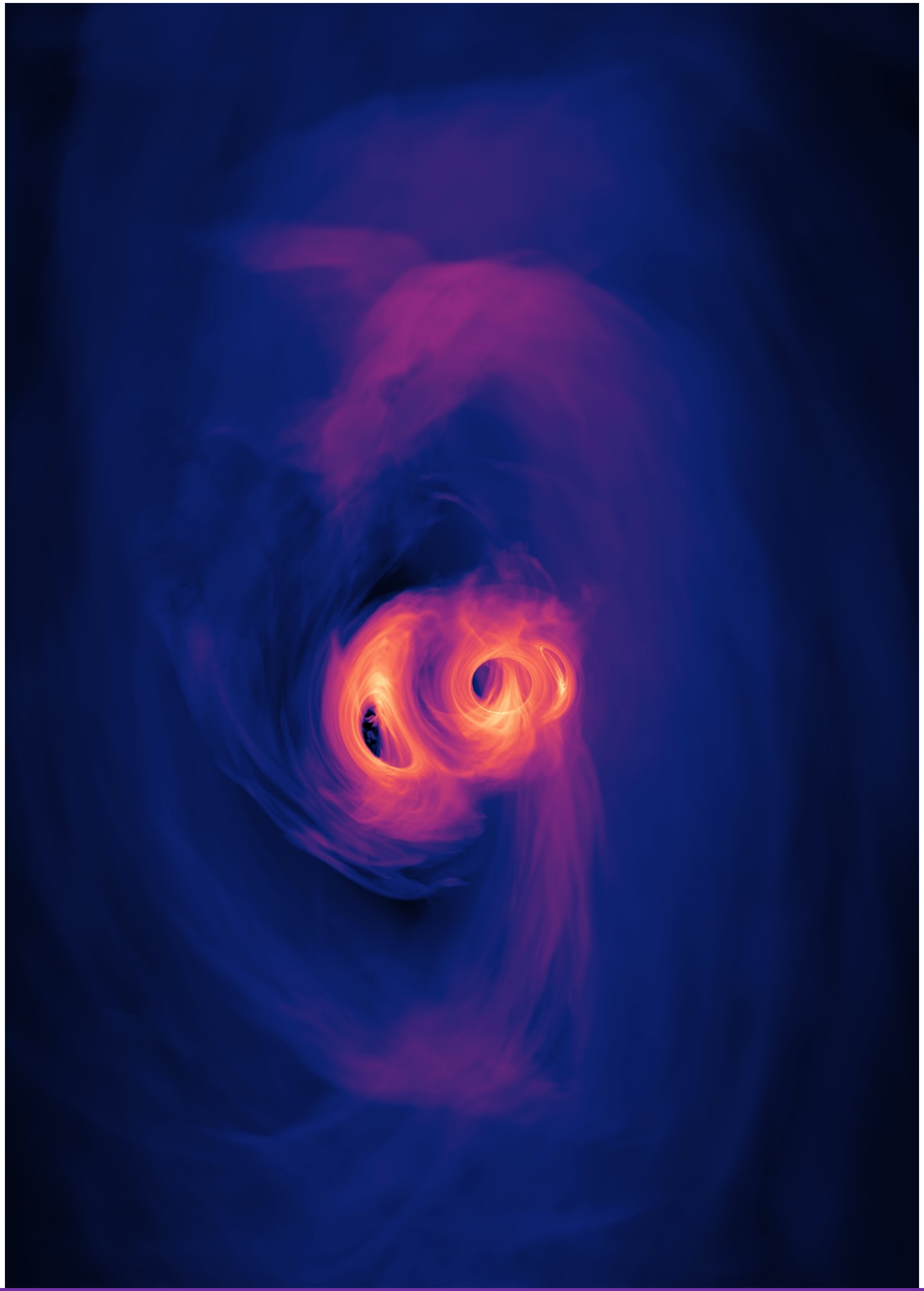
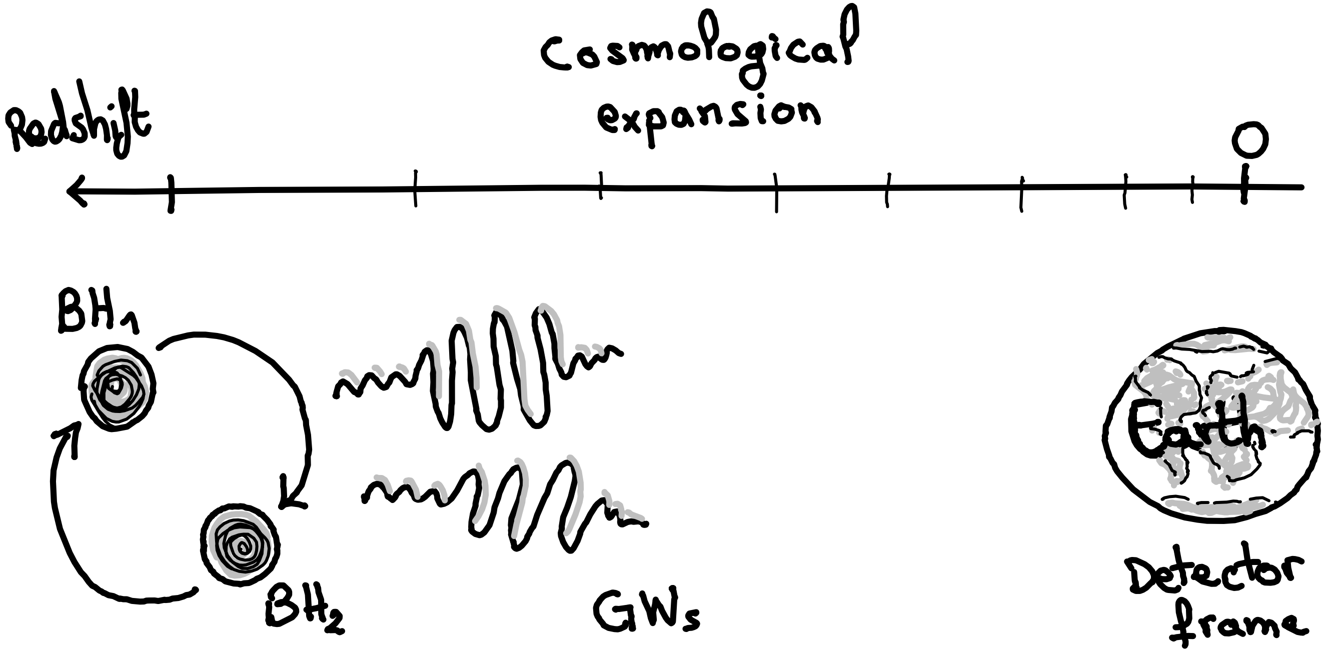


Dark-Sirens method

❖ GWs are redshifted due to cosmological expansion



❖ Degeneracy between the detected and the source mass of BBH : $m_i^{\mathrm{det}} = (1+z) m_i^{\mathrm{source}}$

Dark-Sirens method

ICAROGW : **I**nferring **C**osmology and **A**st**R**ophysics with **O**bservations of **G**ravitational **W**aves

- One of the two official pipelines in LVK for cosmology analysis.
  (main dev : S. Mastrogiovanni, G. Pierra et al.)

- Jointly infer the population parameters (masses, redshift, rate, spins) and the cosmological parameters (H0, Ω_m, w0)

- Hierarchical Bayesian inference method with Dark-Sirens events (no e.m. counterpart)

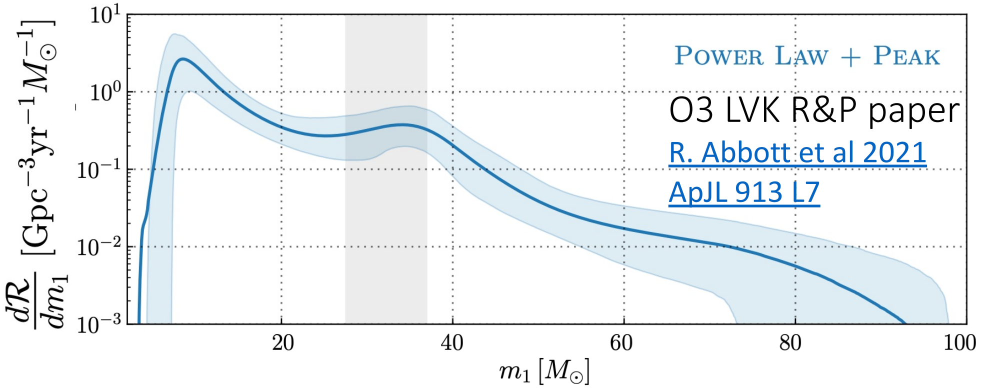
- Based on the mass-redshift degeneracy : $m_i^{\mathrm{det}} = (1+z)m_i^{\mathrm{source}}$

Dark-Sirens method

❖ By fixing the cosmology :

⟶ Deduce the true mass distribution of BBH

$$m_i^d = (1+z)m_i^s$$



Dark-Sirens method

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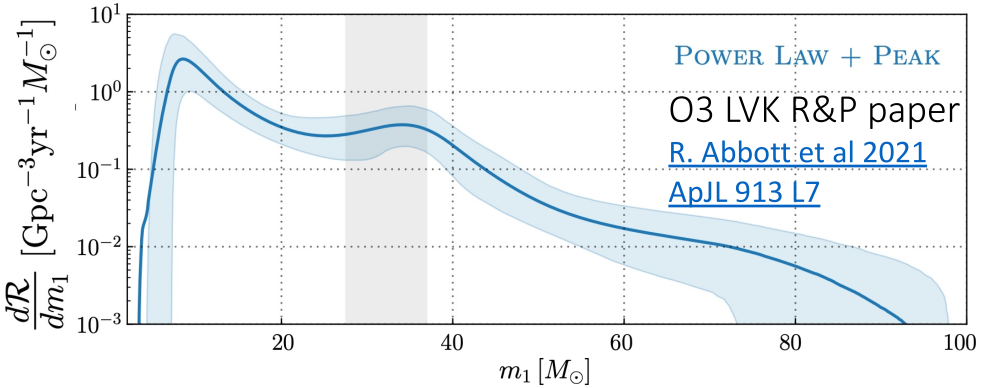

O3 LVK R&P paper
R. Abbott et al 2021
ApJL 913 L7

❖ By fixing the population :

⟶ Deduce the cosmology

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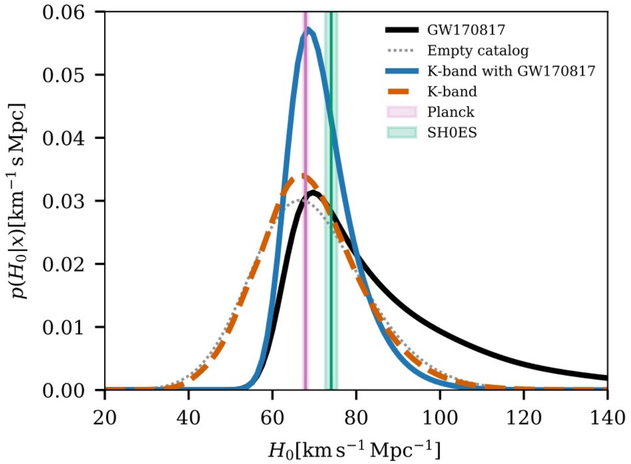


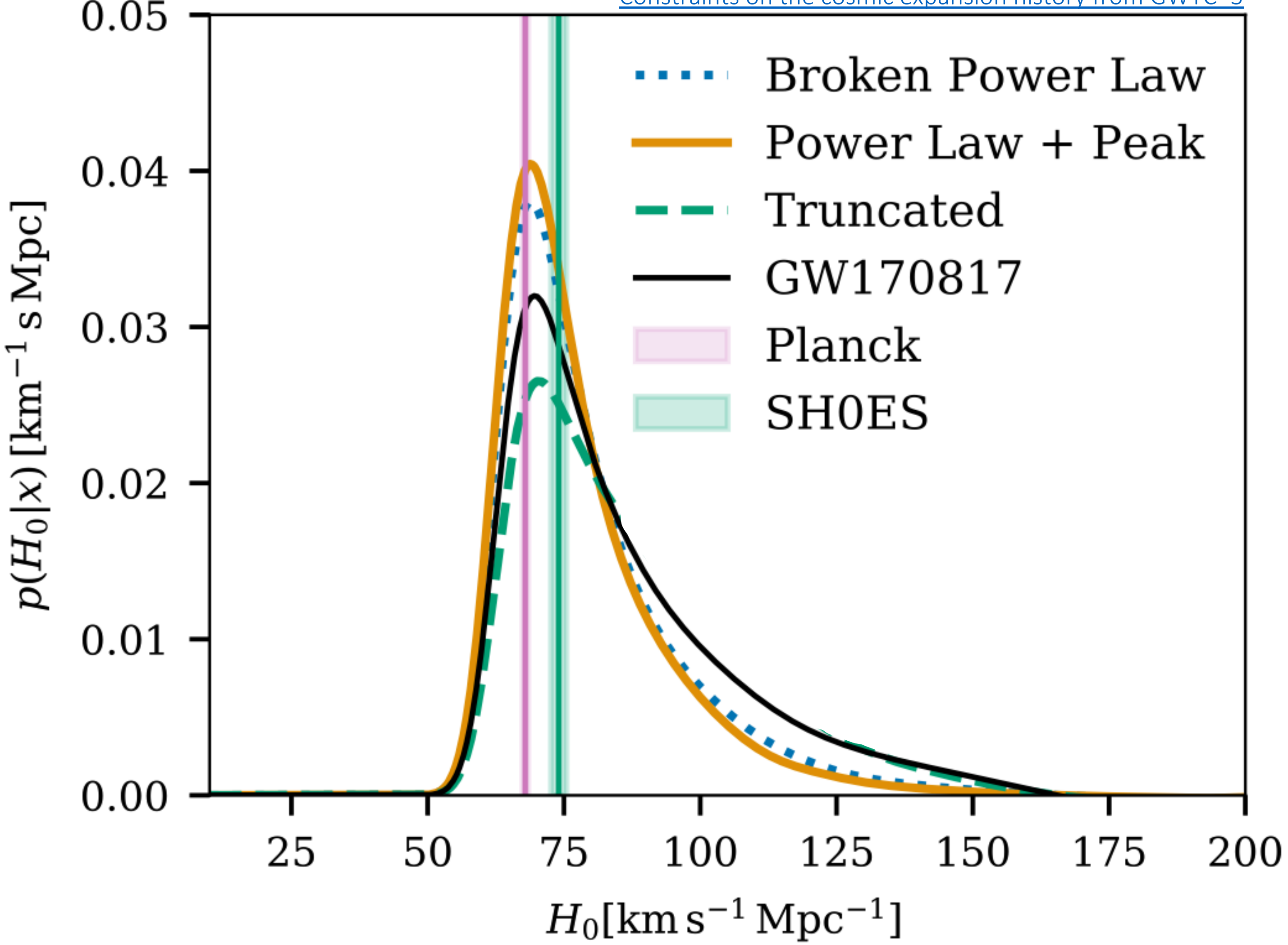
O3 LVK Cosmology paper
arXiv:2111.03604

Best measure so far

Combined with GW1708187 :

$$H_0 = 68^{+8}_{-6}\ \ km.s^{-1}.Mpc^{-1}$$

Constraints on the cosmic expansion history from GWTC–3



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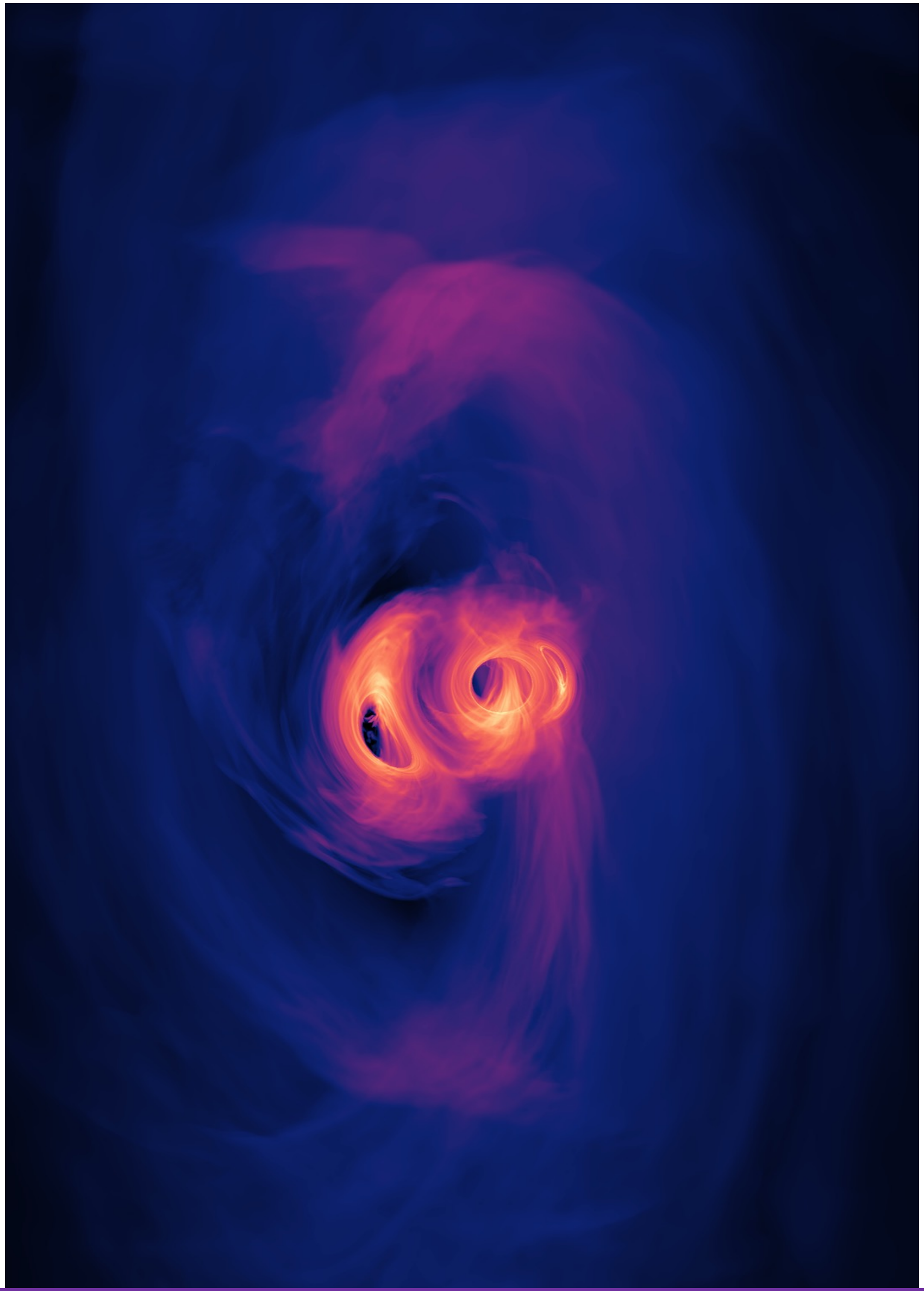


Inclusion of BBH spins for cosmology

Aim : Add BBH spin distributions to generalize the analysis :

- Development of two spin models for BBH

  Default spin model : First introduced by LSC collaboration arXiv:1811.12940

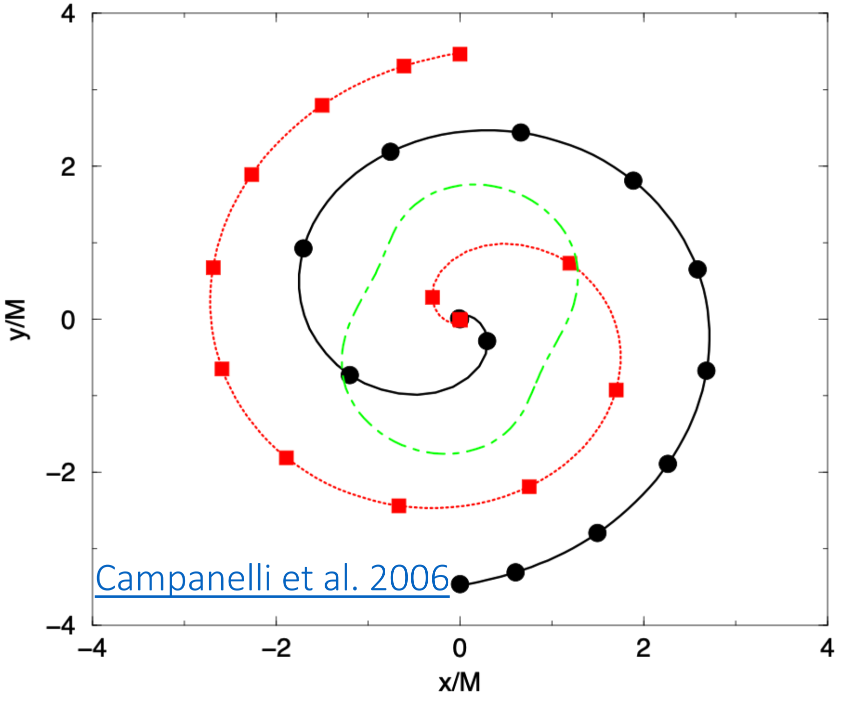
  Gaussian spin model : First introduced by Schmidt et al. arXiv:1408.1810

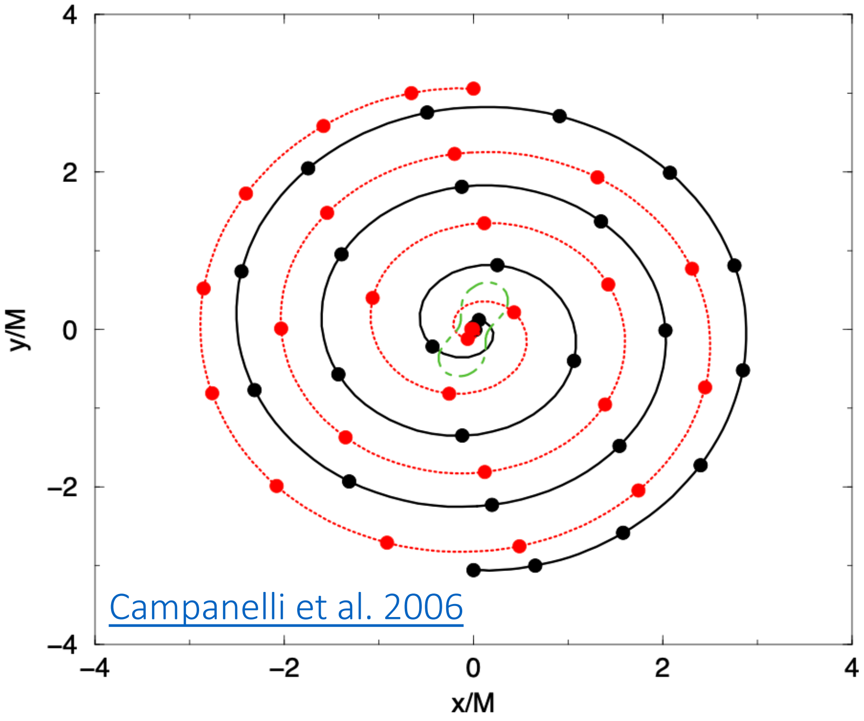
Motivations

- Generalize the analysis and be ready for future spins measurement
- Spins could correlate with the Hubble constant H_0
- BBH formation channels might prefer specific spin configurations

Impact of the spins

Number of orbits is impacted by the spin orientation of each BHs

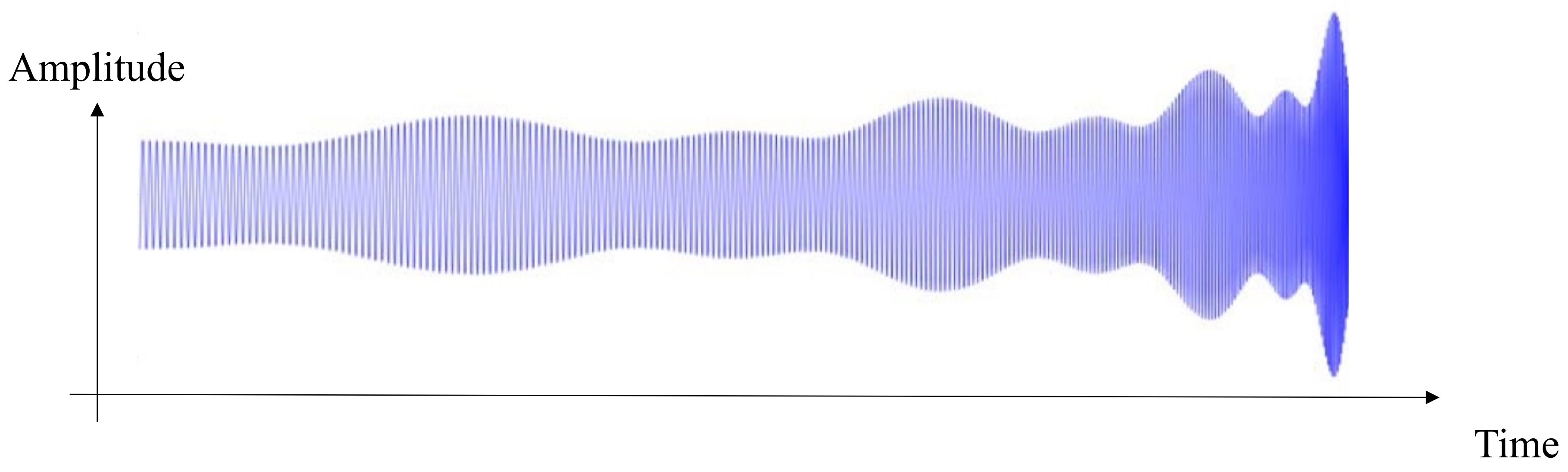




→ Direct effect on the amplitude of the GWs

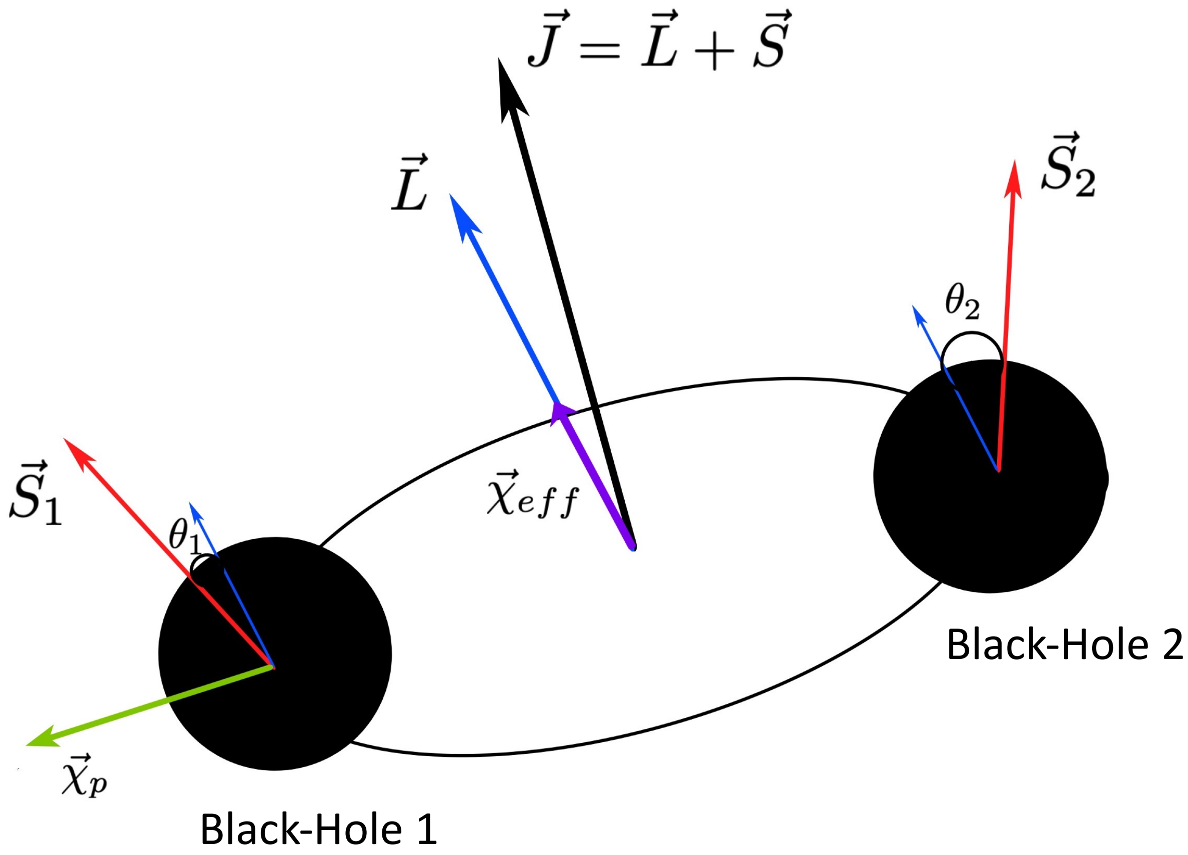
Impact of the spins

Modulation of the GW signal due to spin effect



→ Direct effect on the envelope of the GWs

Spin models of BBH



Default spin model

- ❖ Multiple formation channels
- ❖ Covers all 6 degrees of freedom

Gaussian spin model

- ❖ Sensitive to precession effects
- ❖ Sensitive to spin asymmetries

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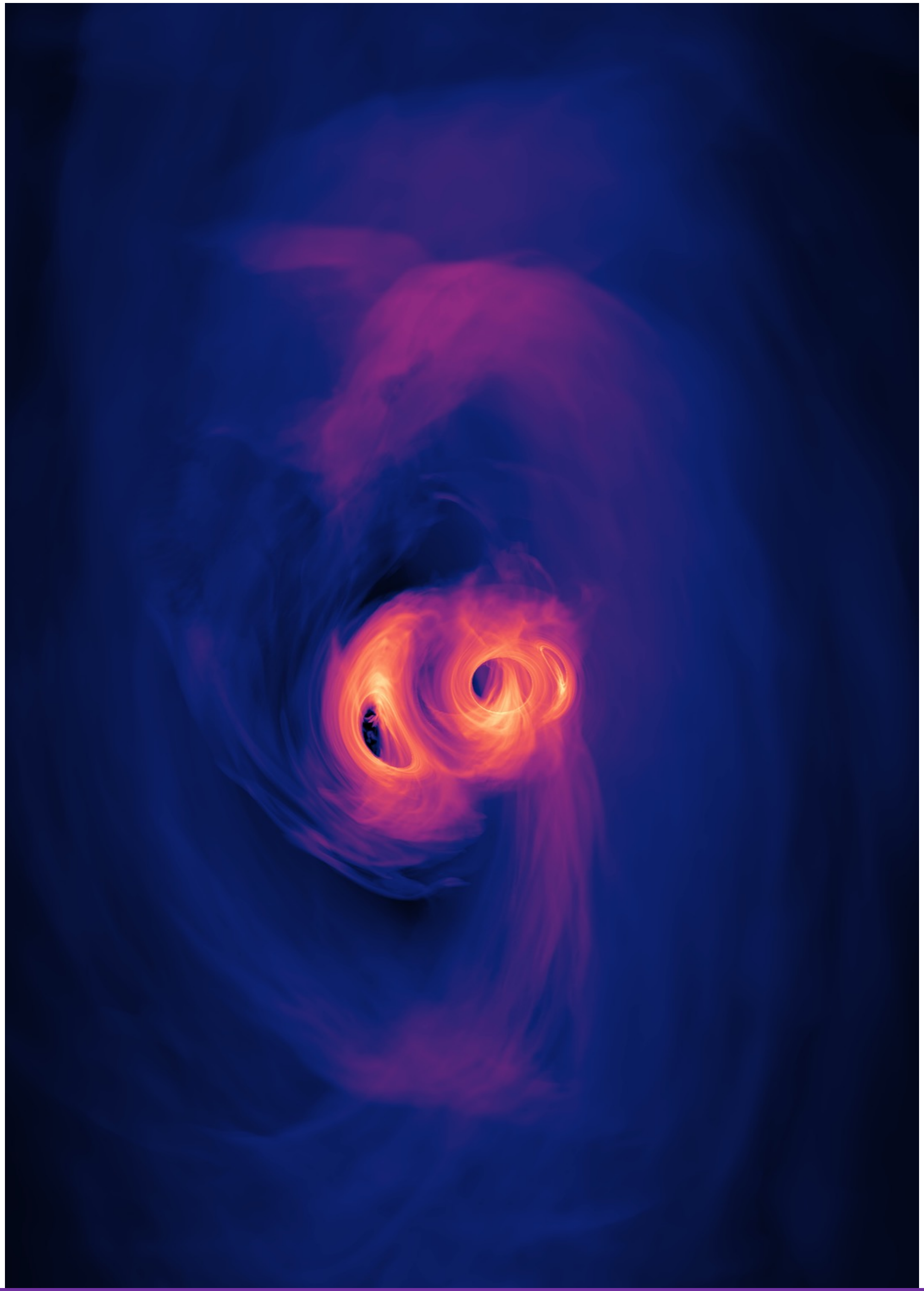


Set-up of the analysis

- First time analysis that jointly estimates the cosmology and spins parameters of black-holes !

- These results have been obtain using 42 BBHs events from the O3 run of LVK

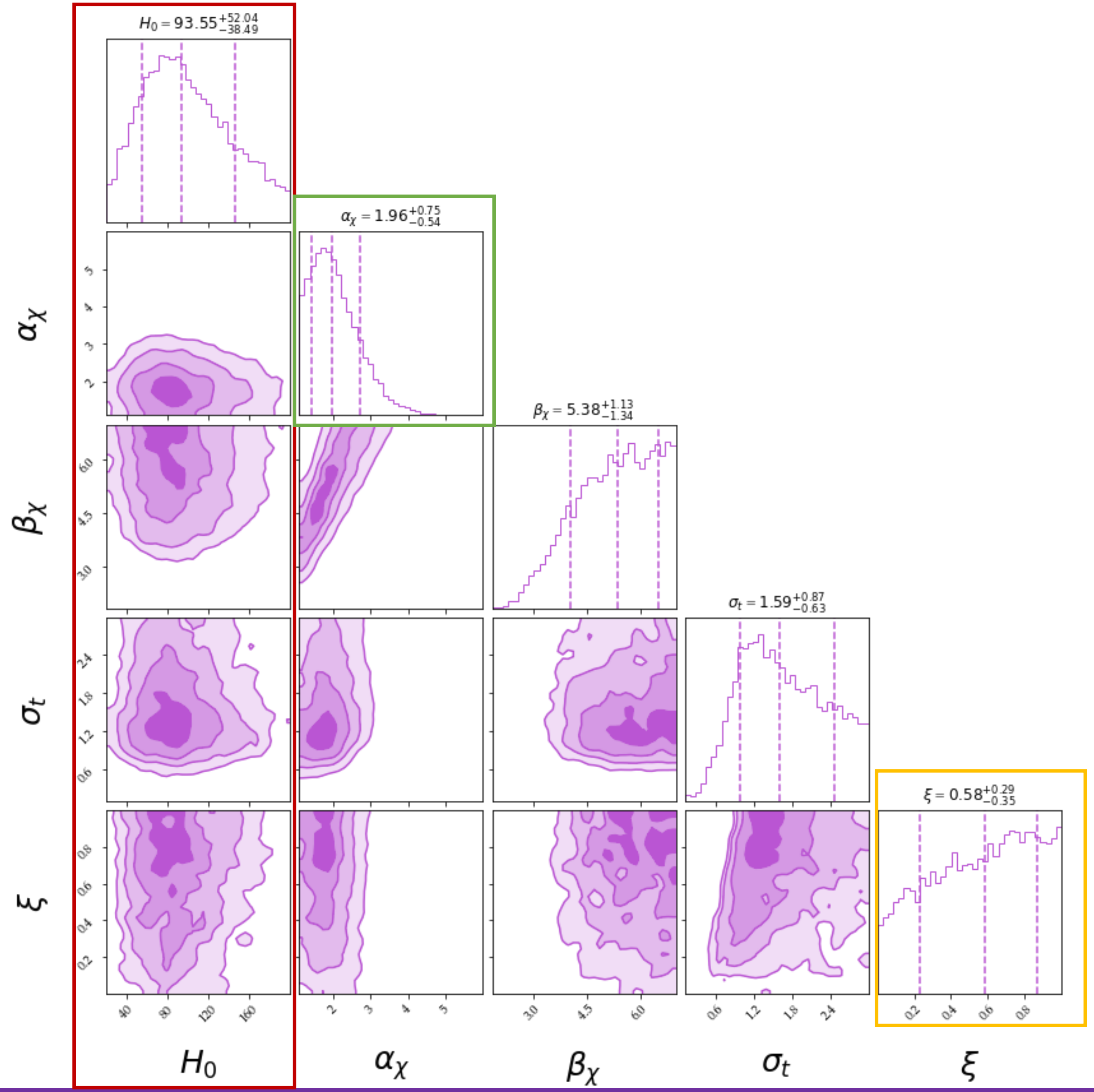
- We tested both spin models

Default model

$$\pi(\chi_{1,2}|\alpha_\chi, \beta_\chi) = Beta(\alpha_\chi, \beta_\chi)$$

$$\pi(cos\theta|\zeta, \sigma_t) = \zeta G_t(cos\theta|\sigma_t) + (1-\zeta)\mathcal{F}(cos\theta)$$

- ❖ No spin correlation with H_0 so far
- ❖ Preference for a slowly spinning black-hole population
- ❖ Mixed population between isolated and dynamical mergers



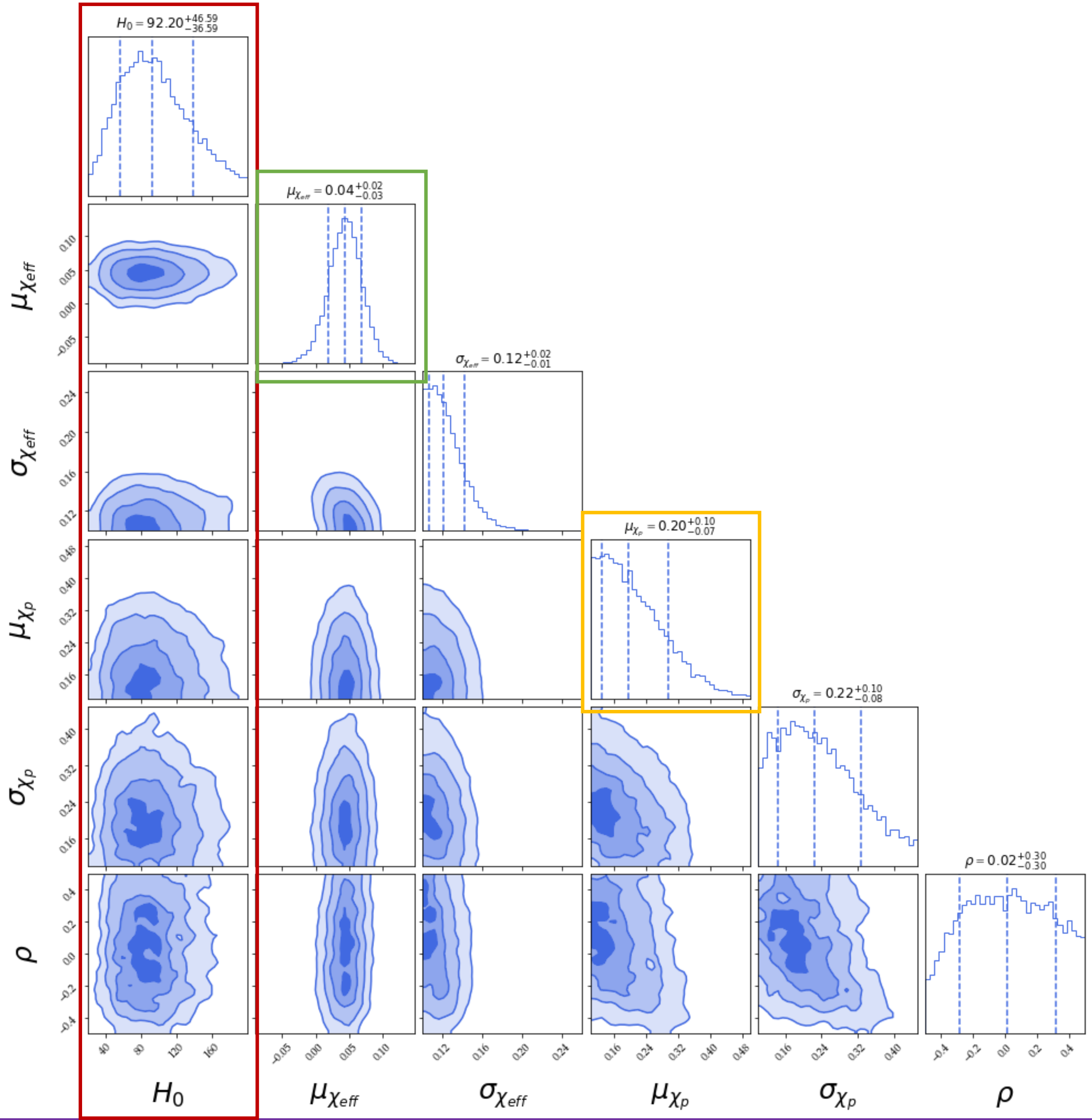
Gaussian model

$$\pi(\chi_{eff}, \chi_p | \mu_{eff}, \sigma_{eff}, \mu_p, \sigma_p) = G^{2D}_{[-1,1],[0,1]}(\chi_{eff}, \chi_p | \mu, \Sigma)$$

❖ No spin correlation with H_0

❖ Aligned spins are favoured

❖ Slowly precessing black-holes



Conclusion on spins

- Correlation BBH spins/cosmology not yet found

- Spin properties on the population of BBH :
  - Slowly spinning
  - No preferred channel of formation (isolated/dynamical)
  - Slowly precessing
  - Mostly aligned

- Current sensitivity too low to explore spin effects on GW signals

Perspectives

- Next run of LVK starting on 24th of may 2023 (hundreds of GWs events)
- IcaroGW2.0 with spins is officially reviewed
- IcaroGW will be used as one of the two cosmology codes in the LVK collaboration for the next observation run
- Constraints on cosmology and population parameters will get better and better with higher statistic

Thanks

BACK UP

Basic principle behind IcaroGW

❖ Infer jointly the population and cosmological parameters via hierarchical Bayesian inference :

$$p(\mathrm{cosmology}|\mathrm{GWs}) \propto \prod_{i}^{N_{\mathrm{obs}}} \frac{\int p(\mathrm{GW_i}|\theta, \Lambda)\pi(\theta|\Lambda)d\theta}{N_{\mathrm{eff}}}$$

Probability of estimating a certain cosmology given some GWs data

Galaxy catalog results

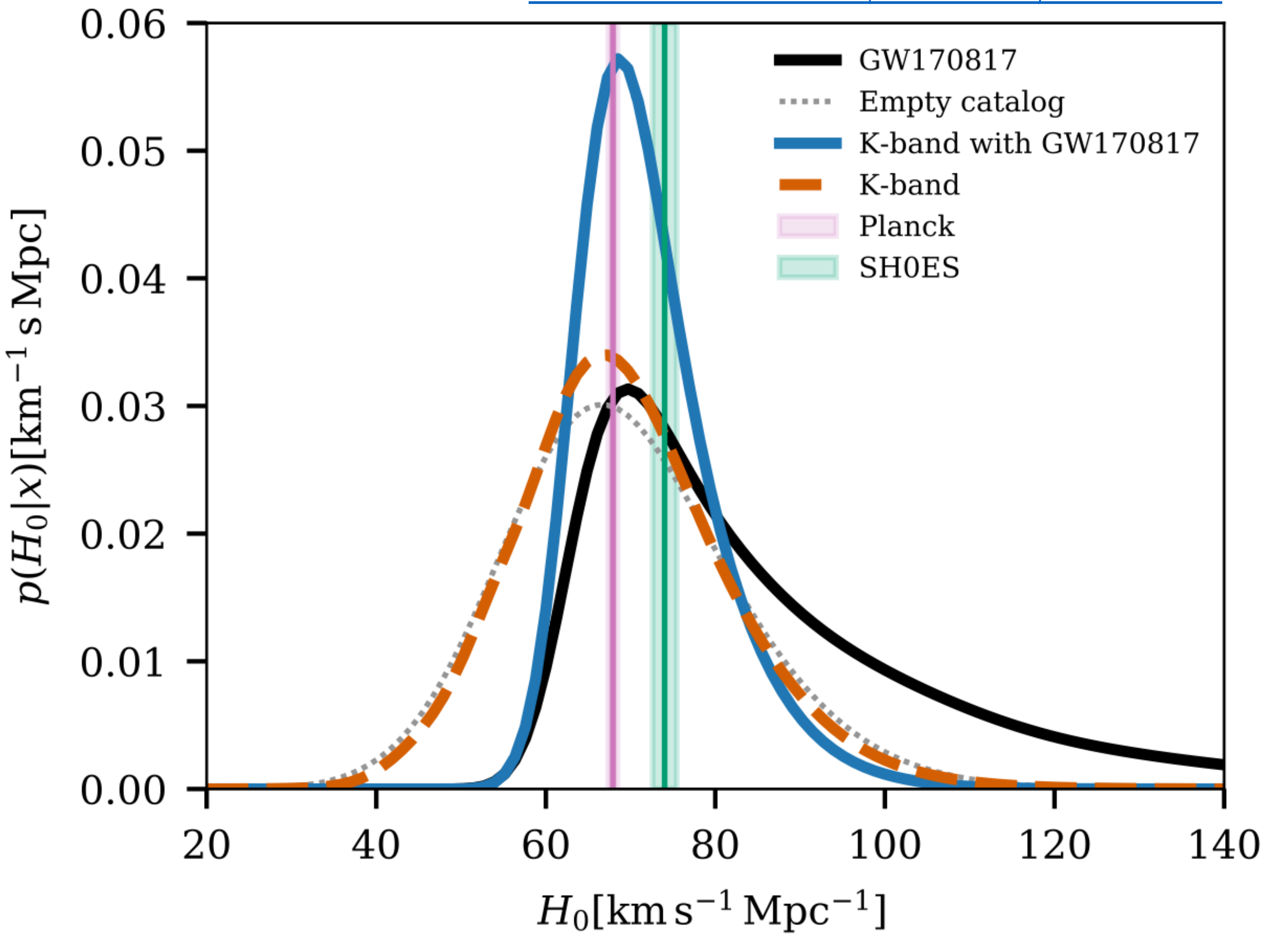
From the galaxy catalog only :

$$H_0 = 67^{+13}_{-12} \ \ km.s^{-1}.Mpc^{-1}$$

Combined with GW1708187 :

$$H_0 = 68^{+8}_{-6} \ \ km.s^{-1}.Mpc^{-1}$$

Constraints on the cosmic expansion history from GWTC–3

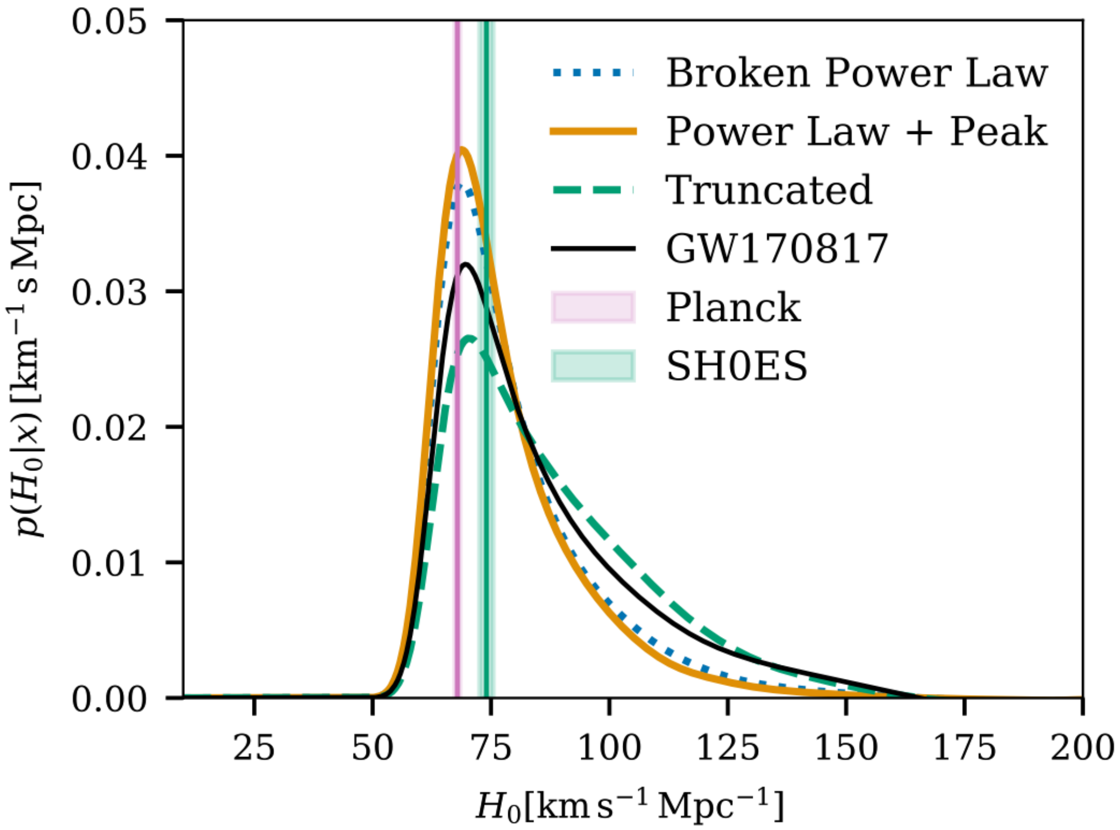


Back up

$$d_L(z) = \frac{1+z}{H_0} c \int_0^z \frac{dz}{(\Omega_m(1+z)^3 + \Omega_\Lambda)}$$

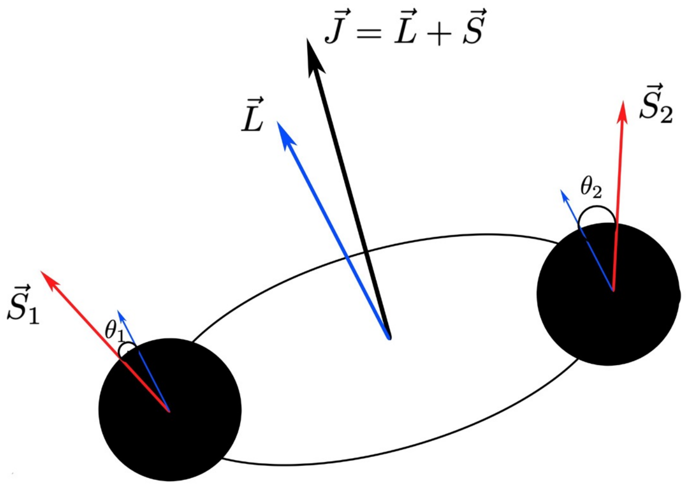
and

$$z = \frac{m^d}{m^s} - 1$$



Spin models of BBH

Default spin model



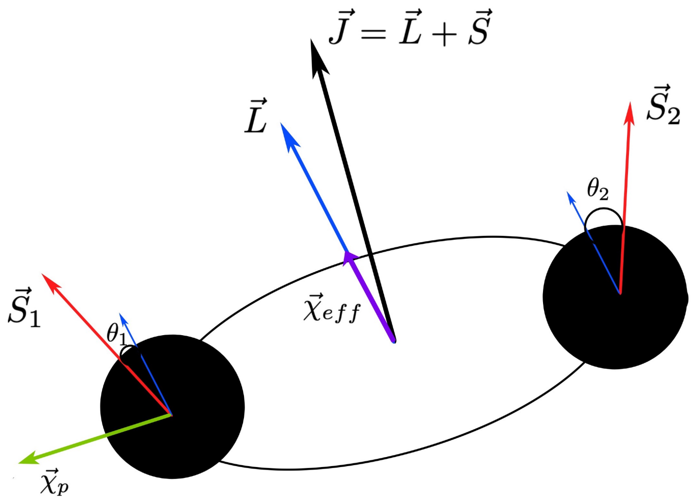
$$\chi_i = |\frac{\vec{S}_i}{m_i^2}|$$

Dimensionless spin magnitudes & tilt angle :

$$\pi(\chi_{1,2}|\alpha_\chi, \beta_\chi) = Beta(\alpha_\chi, \beta_\chi)$$

$$\pi(cos\theta|\zeta, \sigma_t) = \zeta G_t(cos\theta|\sigma_t) + (1-\zeta)\mathcal{F}(cos\theta)$$

Gaussian spin model



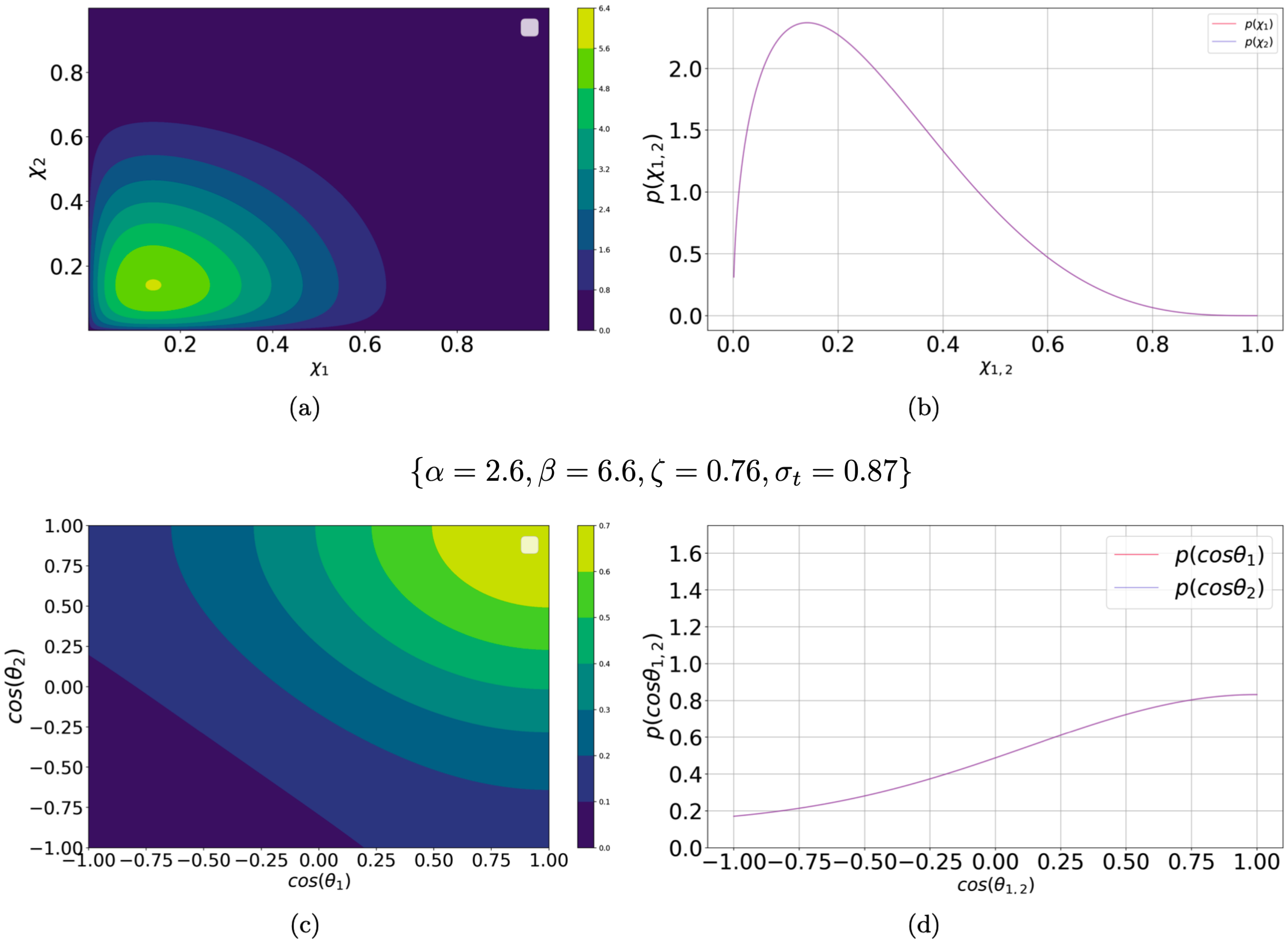
Effective & precession spin :

$$\pi(\chi_{eff}, \chi_p|\mu_{eff}, \sigma_{eff}, \mu_p, \sigma_p) = G^{2D}_{[-1,1],[0,1]}(\chi_{eff}, \chi_p|\mu, \Sigma)$$

$$\vec{\mu} = (\mu_{eff}, \mu_p)$$

$$\Sigma = \begin{pmatrix} \sigma_{eff}^2 & \rho\sigma_{eff}\sigma_p \\ \rho\sigma_{eff}\sigma_p & \sigma_p^2 \end{pmatrix}$$

Spin distributions : Default



(a) and (c) :
Joint 2D probability density functions

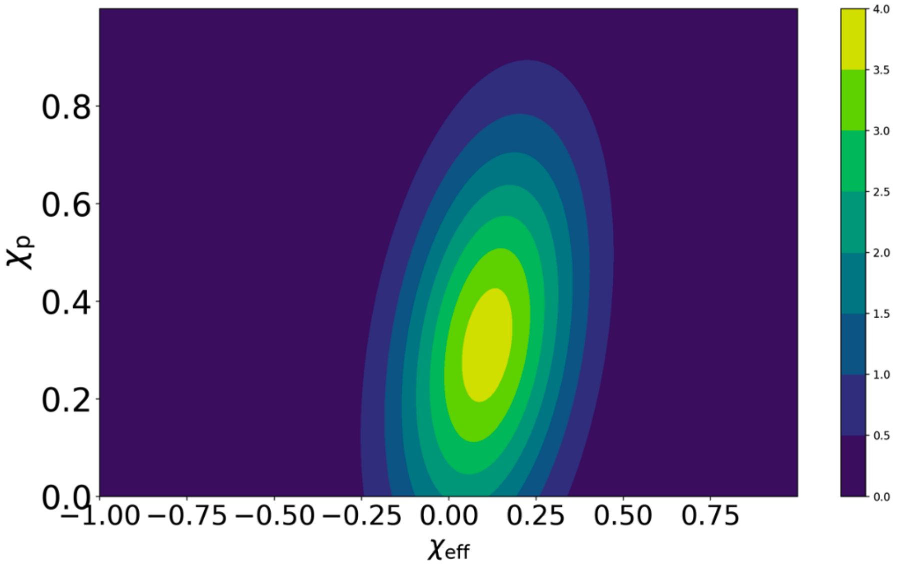
(b) and (d) :
Marginalized probability density functions

Described black-holes :

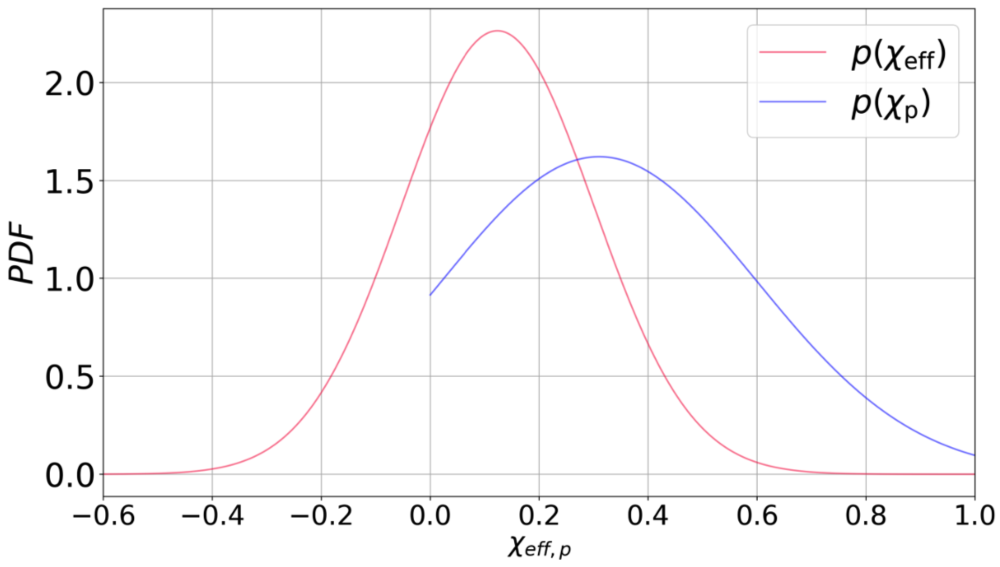
- Slowly rotating
- Mostly aligned with $\vec{L}$

Spin distributions : Gaussian

$\{\mu_{eff} = 0.11, \sigma_{eff} = -.18, \mu_p = 0.31, \sigma_p = 0.29, \rho = 0.32\}$



(a)



(b)

❖ (a) :
Joint 2D probability density functions

❖ (b) :
Marginalized probability density functions

Described black-holes :

- Slight asymmetry toward aligned spins
- Slowly precessing systems