Gravitational Wave Cosmology

A new arena to test the dark universe

Nicola Tamanini

L2IT

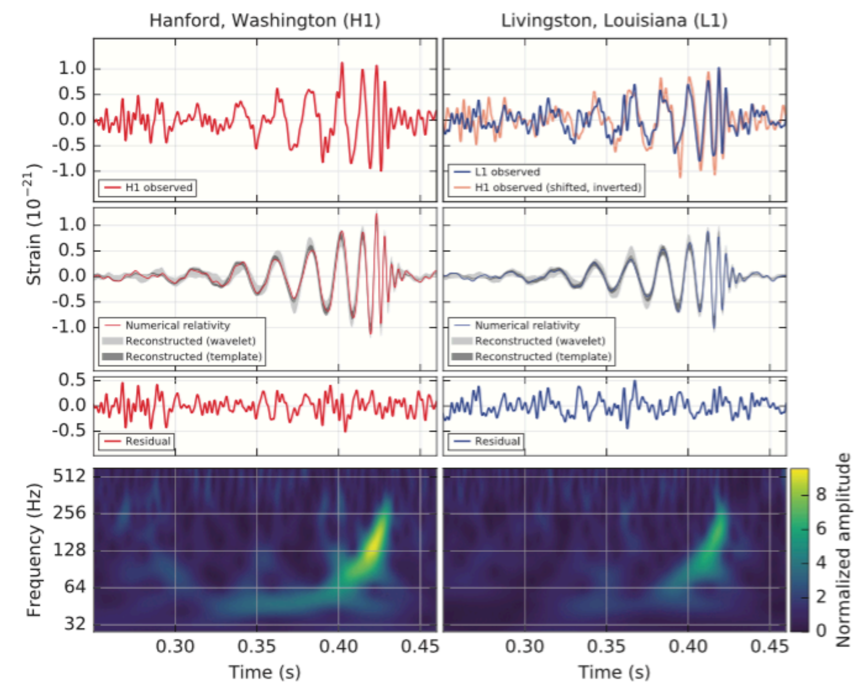
Laboratoire des 2 infinis - Toulouse
CNRS / IN2P3 / Univ. Paul Sabatier

Introduction

6 years of observing GWs

2015: first direct detection of GWs from a BBH merger

Kick-off of GWs as an observational science!



GW150914

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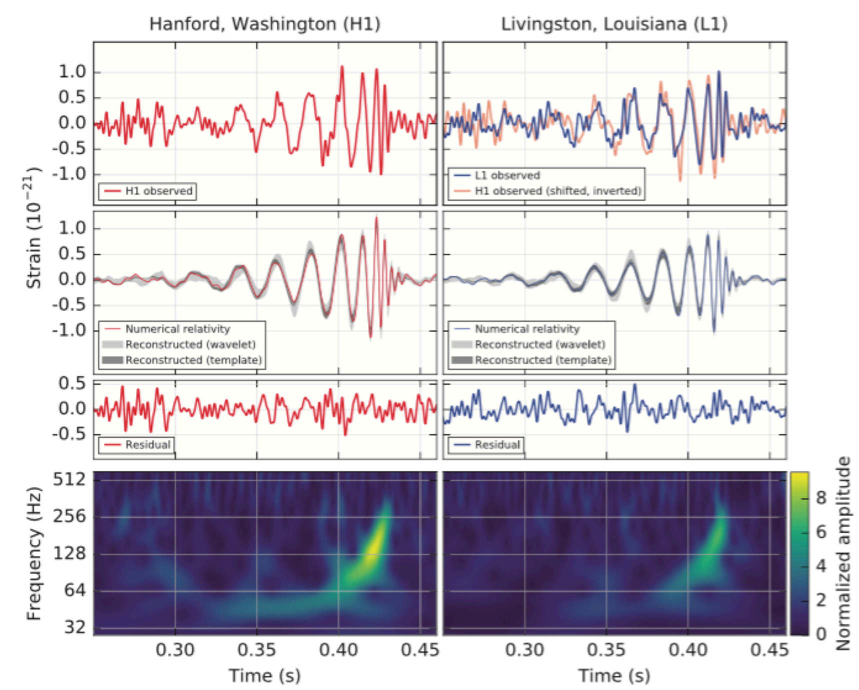

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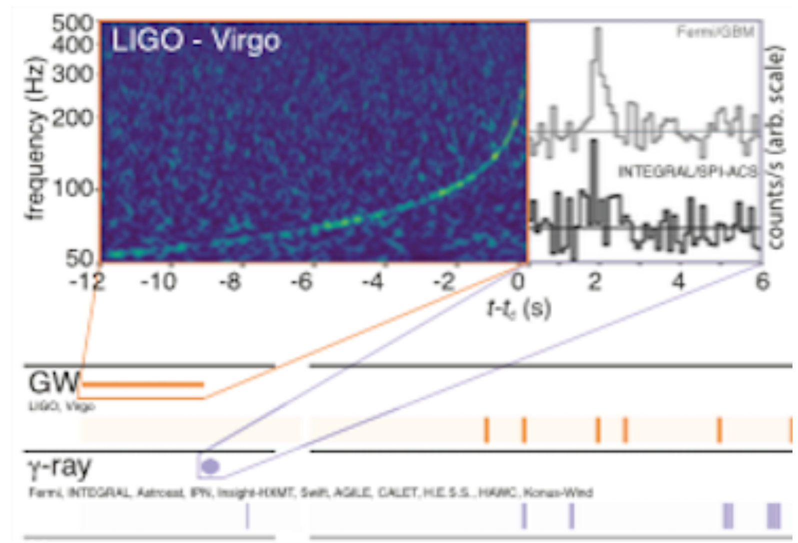

GW170817

Introduction

<u>6 years of observing GWs</u>

2015: first direct detection of GWs from a BBH merger

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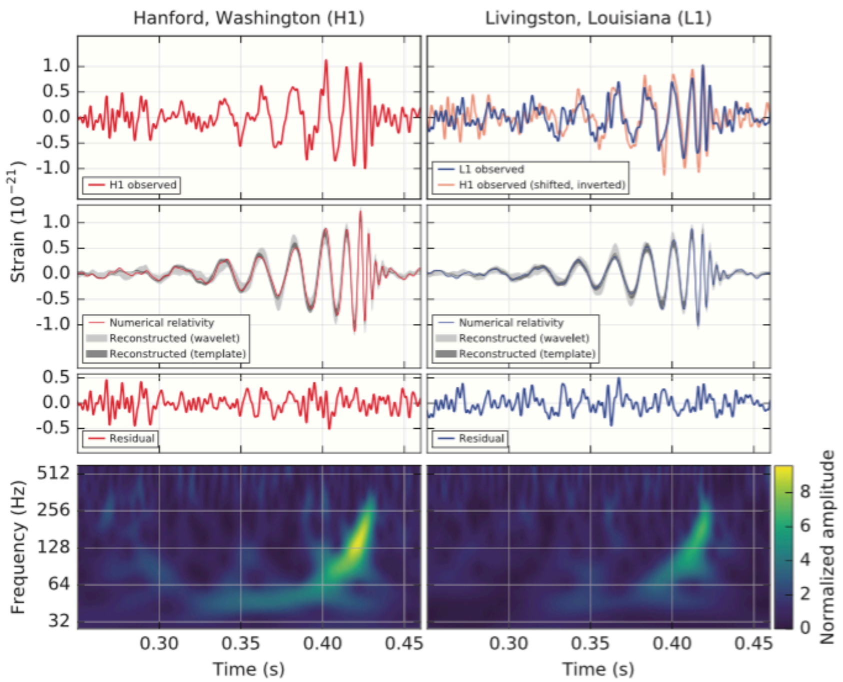
2020: 50 GW signals detected so far, GW astronomy is a new, established, and fast-expanding research field



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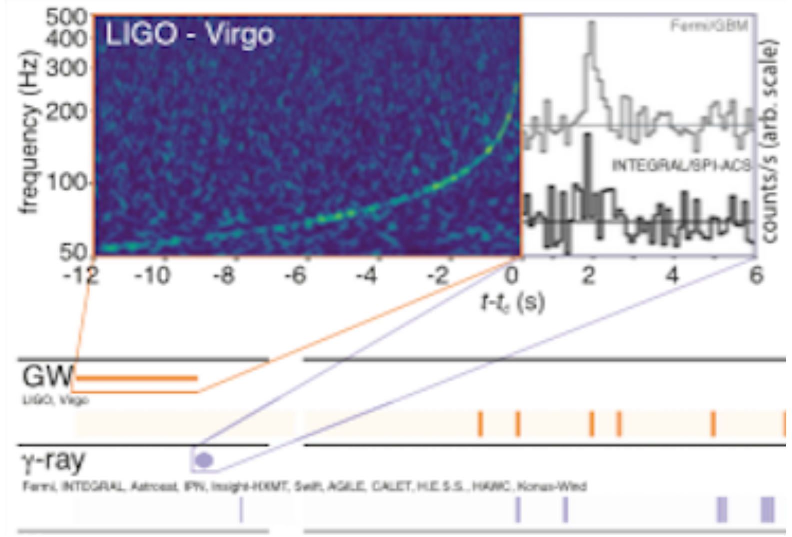
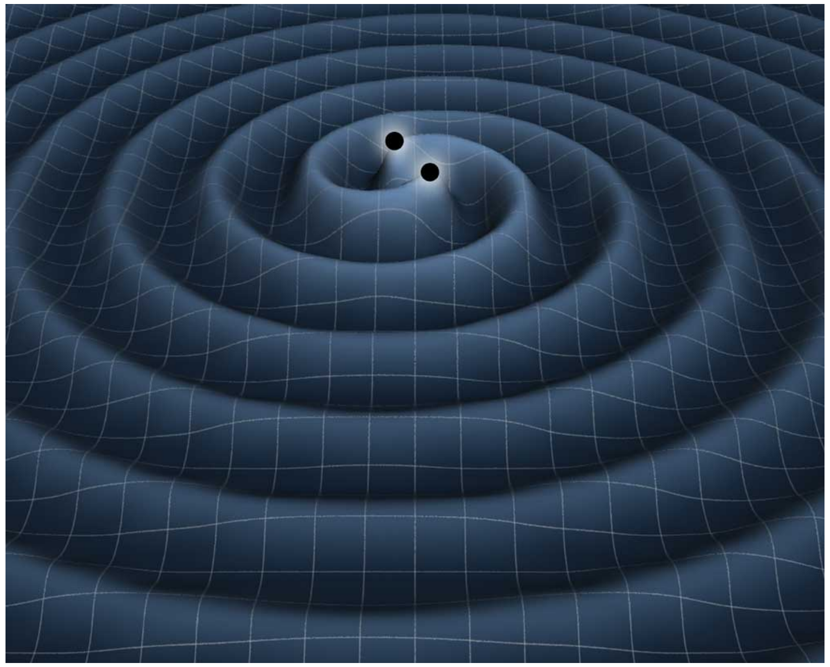


GW170817

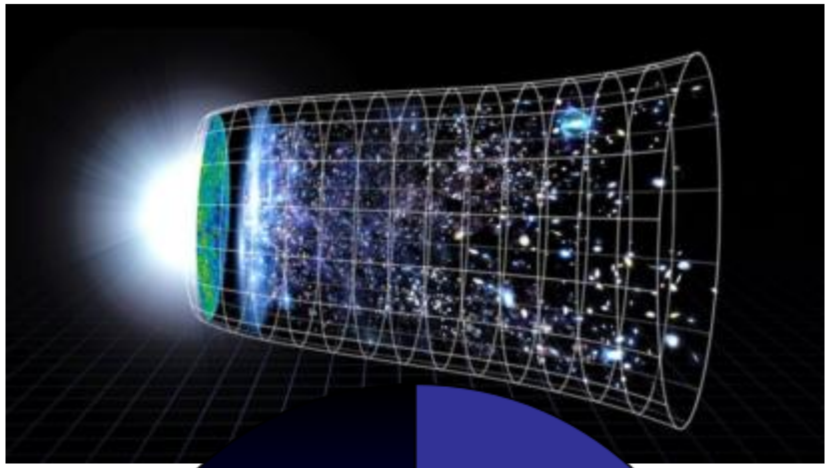
Introduction

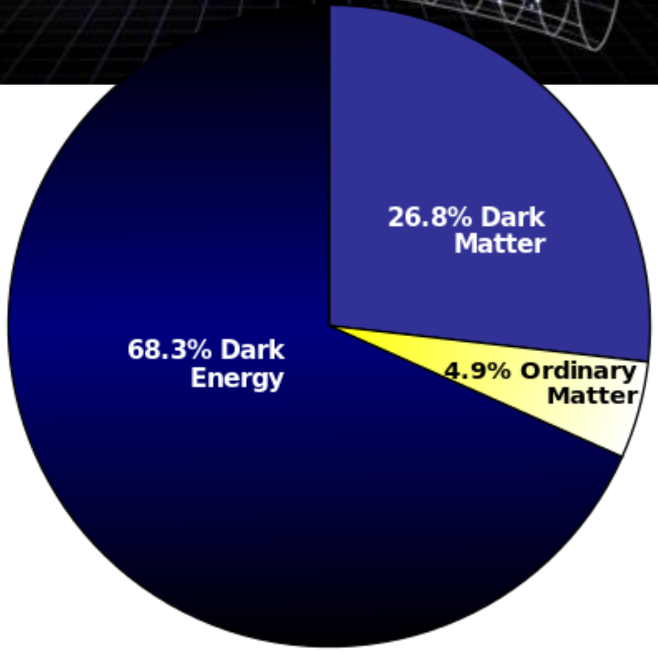
How can we use GW observations to probe the cosmic expansion and test cosmological theories/models?



Standard

Sirens





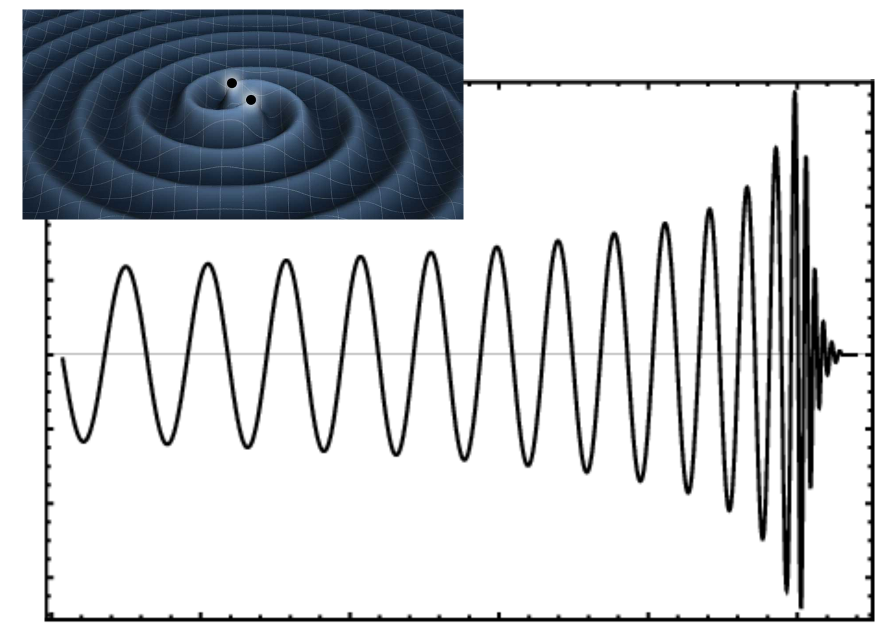
Outline:

- **What are standard sirens?**
- **What are their theoretical foundations?**
- **How can they be used to test cosmological theories/models?**
- **GW cosmology and IN2P3**

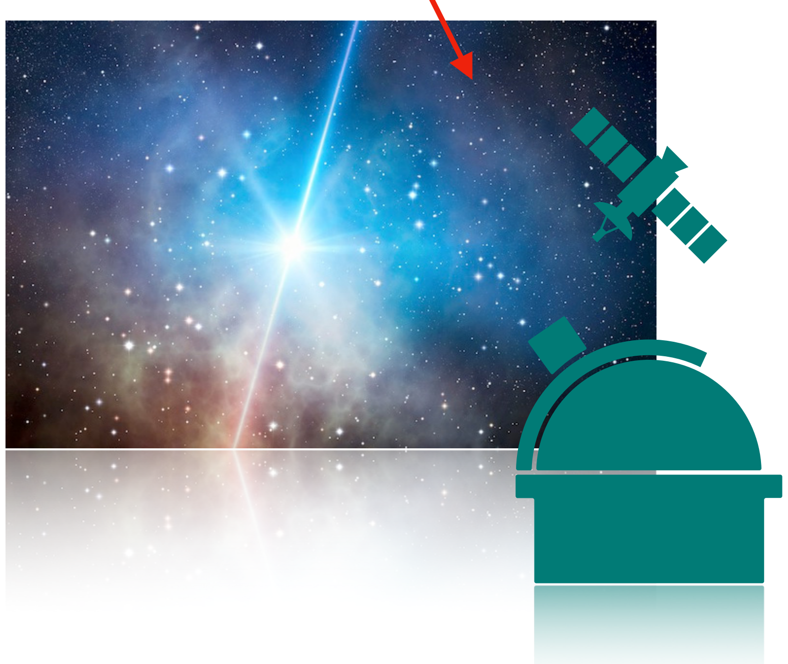
What are standard sirens?

Standard sirens are GW events that can be used as absolute cosmological distance indicators

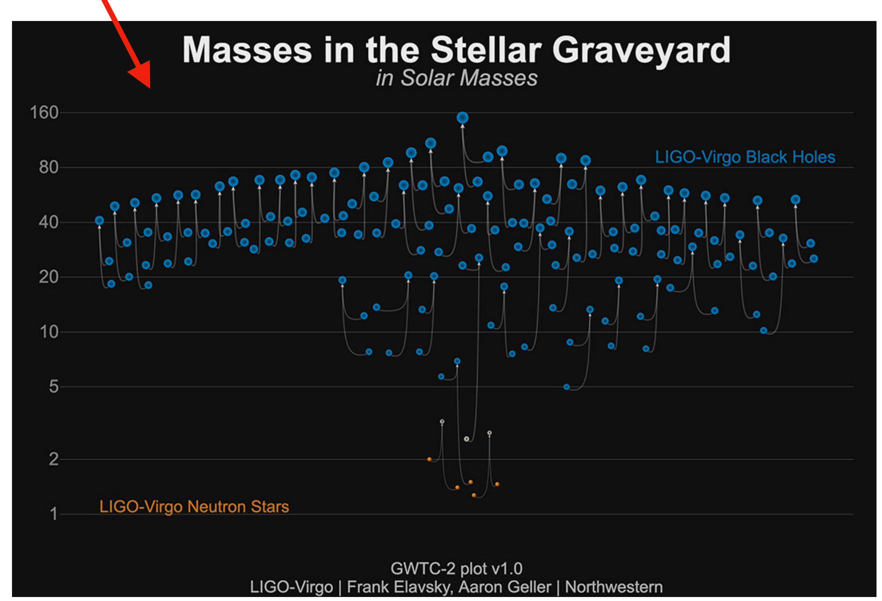
- **Luminosity distance** estimated from GW signal
- **Redshift** obtained from EM observations or features in the mass distribution of GW sources



$$h_\times = \frac{4}{d_L}\left(\frac{GM_c}{c^2}\right)^{\frac{5}{3}}\left(\frac{\pi f}{c}\right)^{\frac{2}{3}} \cos\iota \sin\Phi(t)$$



[Schutz, *Nature* (1986)]



[Mastrogiovanni+, arXiv:2103.14663]

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- **Luminosity distance** estimated from GW signal
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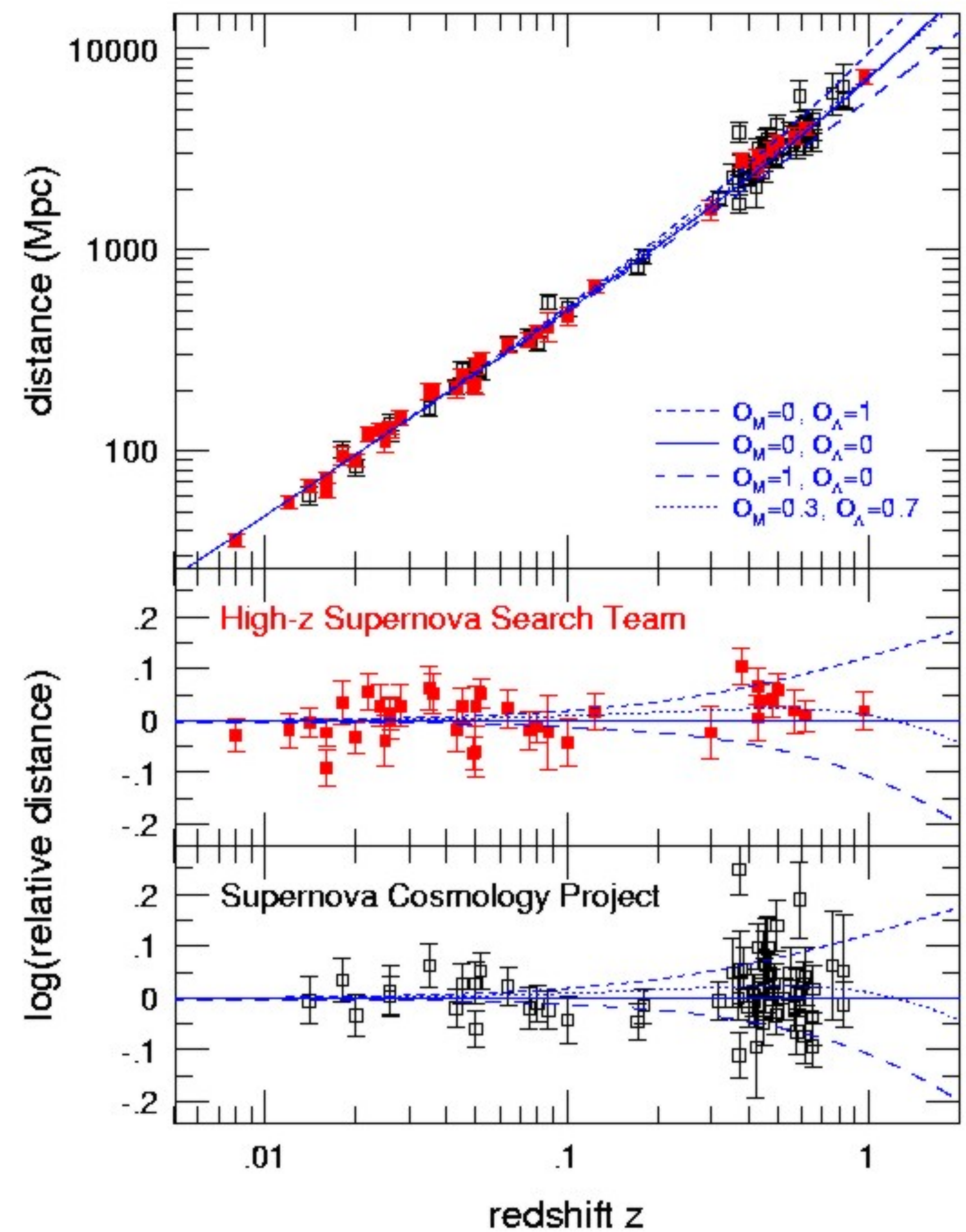
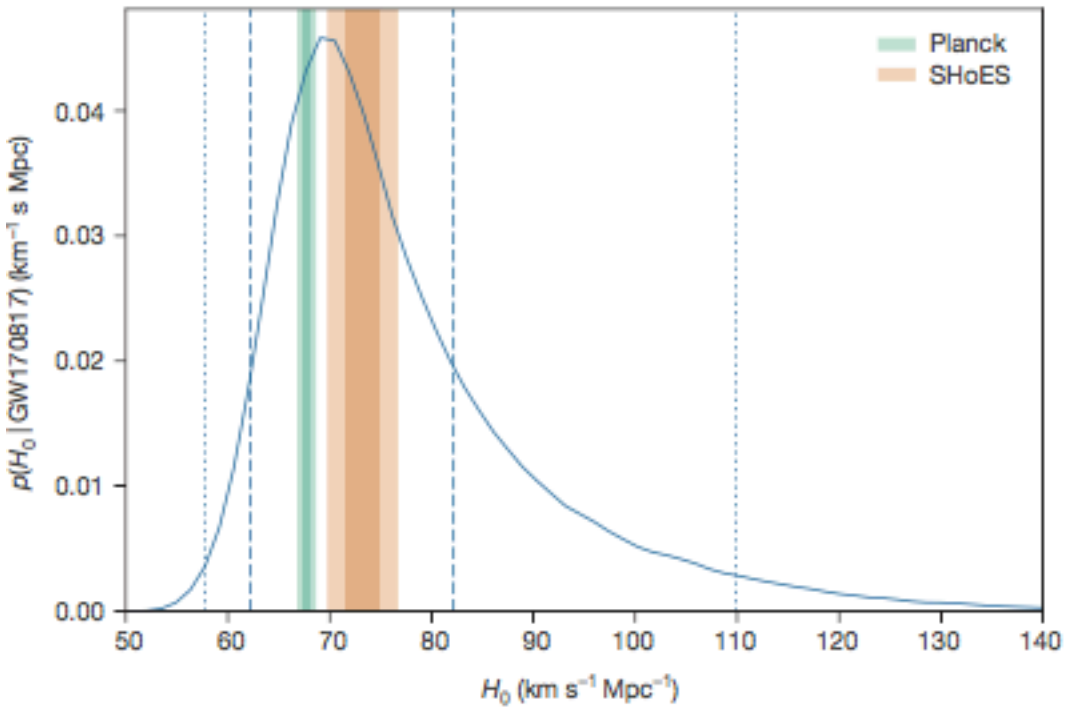
With these two measurements one can then fit the **distance-redshift relation** and obtain constraints on the **cosmological parameters** (similarly to *standard candles* ⇒ type-Ia SNs)

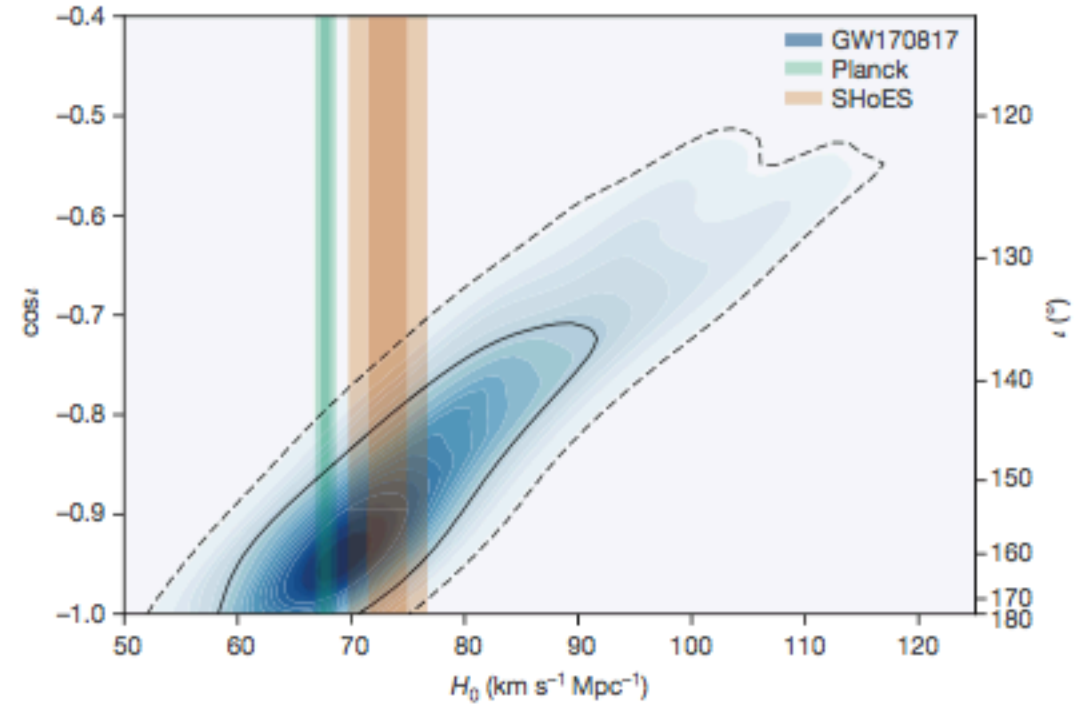
$$d_L(z) = \frac{c}{H_0}\frac{1+z}{\sqrt{\Omega_k}}\sinh\left[\sqrt{\Omega_k}\int_0^z \frac{H_0}{H(z')}dz'\right]$$



What are standard sirens?

GW170817: the first ever standard siren





The identification of an EM counterpart yielded the <u>first cosmological measurements with GW standard sirens</u>

$$H_0 = 69^{+17}_{-8}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

[LVC+, *Nature* (2017)]
[LVC, *PRX* (2019)]

Low-redshift event ($z = 0.01$): only H_0 can be measured (Hubble law)

Future GW observations will yield more numerous and more accurate data:

- Better measurements of H_0
- Measurements of other cosmological parameters

Connecting cosmo theory with GW observations

By assuming GR and an homogeneous and isotropic universe, GW propagates according to the equation:

$$h''_{ij} + 2Hh'_{ij} + c^2k^2h_{ij} = 0$$

Which implies: $h \propto \frac{1}{d_L^{\mathrm{GW}}}$ and $v_{gw} = c$

- h_{ij} = GW amplitude
- H = Hubble rate
- c = speed of light
- k = wave number
- $'$ = derivative w.r.t. (conformal) time

- What if GR is no longer valid at cosmological distances?
- What if we consider cosmic inhomogeneities?

Connecting cosmo theory with GW observations

If homogeneity holds (very large scale) but GR is modified, the most general GW propagation equation reads:

$$h''_{ij} + 2H(1+\nu)h'_{ij} + ({c_T}^2k^2 + a^2\mu^2)h_{ij} = a^2\Gamma\gamma_{ij}$$

$$h \neq \frac{1}{d_L^{\rm GW}} \qquad v_{gw} \neq c \qquad m_{gw} \neq 0$$

$h_{\times,+}$ mixing, birefringence, oscillations, …

- h_{ij} = GW amplitude
- H = Hubble rate
- c = speed of light
- k = wave number
- $'$ = derivative w.r.t. (conformal) time
- ν, c_T, μ, Γ are all spacetime functions
- γ_{ij} = source of anisotropic stresses

Different modifications of the GW propagation equation correspond to different physical effects

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$h \neq \frac{1}{d_L^{\rm GW}}$ $\quad$ $v_{gw} \neq c$ $\quad$ $m_{gw} \neq 0$ $\quad$ $h_{\times,+}$ mixing, birefringence, oscillations, …

Can be tested with GW+EM multi-messenger events (or population analyses)

Can be tested with GW-only matched-filtered searches

Can be tested with GW polarisation measurements

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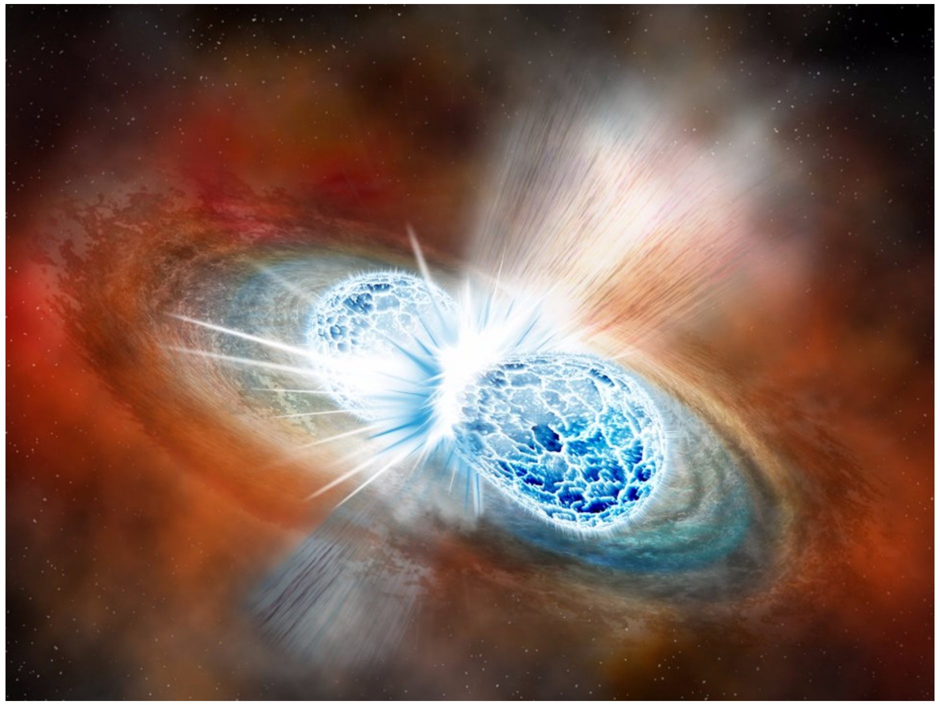
Example: GW170817



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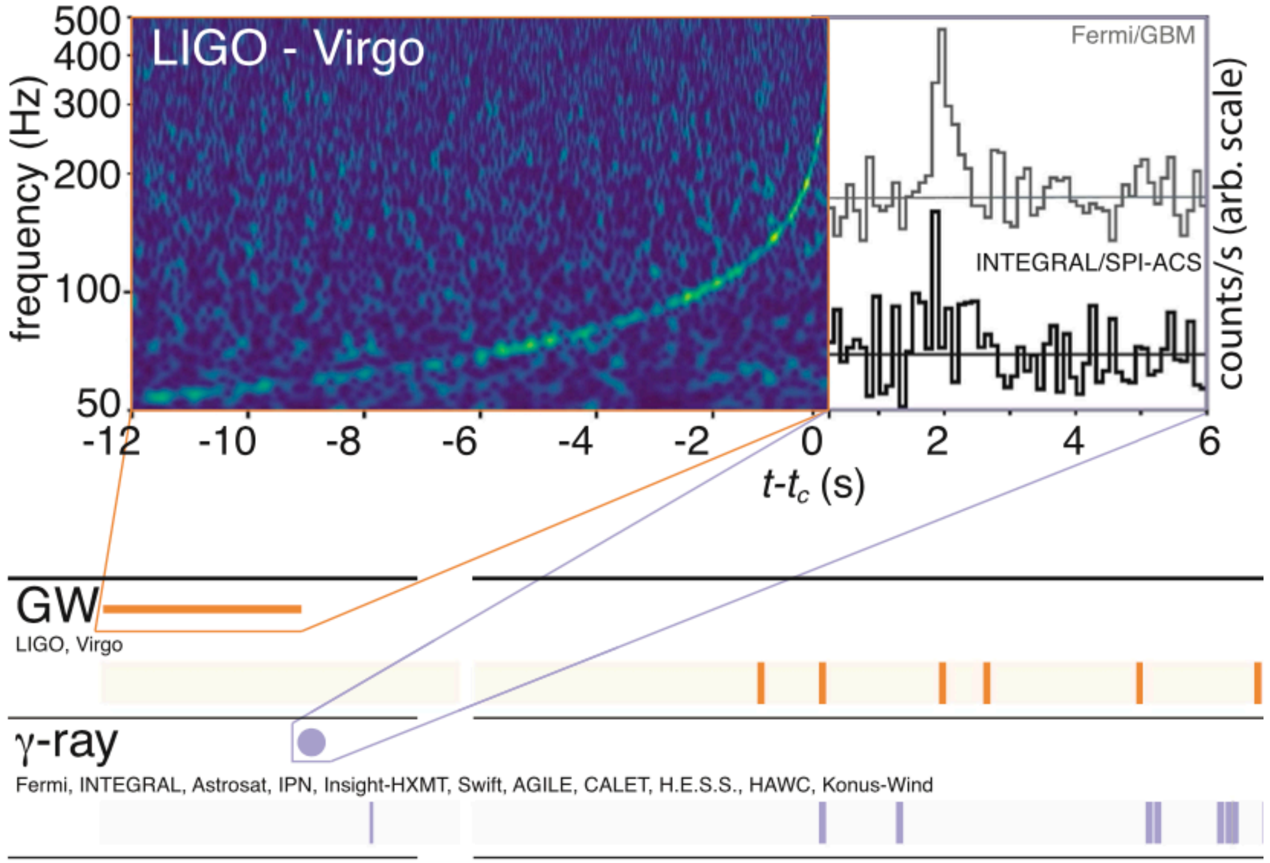

[LVC+, *ApJL* (2017)]

The coincident GW-EM detection of **GW170817** puts stringent constraints on the speed of GW:

$$v_{\rm gw} = c^{+7\times10^{-16}}_{-3\times10^{-15}}$$

This observation rules out several modified gravity models of dark energy predicting $v_{\rm gw} \neq c$

[Ezquiaga & Zumalacuarregui, *Front. Astron. Space Sci.* (2018)]

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UV modification of GR can efficiently be tested with GWs

↕

New phenomenology and observational tests of dark energy theories

Connecting cosmo theory with GW observations

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New phenomenology and observational tests of dark energy theories

Much theoretical work still needed to characterise beyond-GR effects on GW propagation and connect them to fundamental theories

Much theoretical work needed to fully define and refine the statistical framework (Bayesian) used to infer cosmological constraints with GW standard sirens, including assessment of all systematic effects

Connecting cosmo theory with GW observations

If GR holds but the universe is inhomogeneous, GW propagation will be dictated by full GR equations:

$$\Box h_{ij} + R_{kijl} h^{kl} = 0$$

Inhomogeneous terms will yield:

- GW weak lensing
- GW strong lensing
- Wave optics effects
- Polarisation state changes
- …

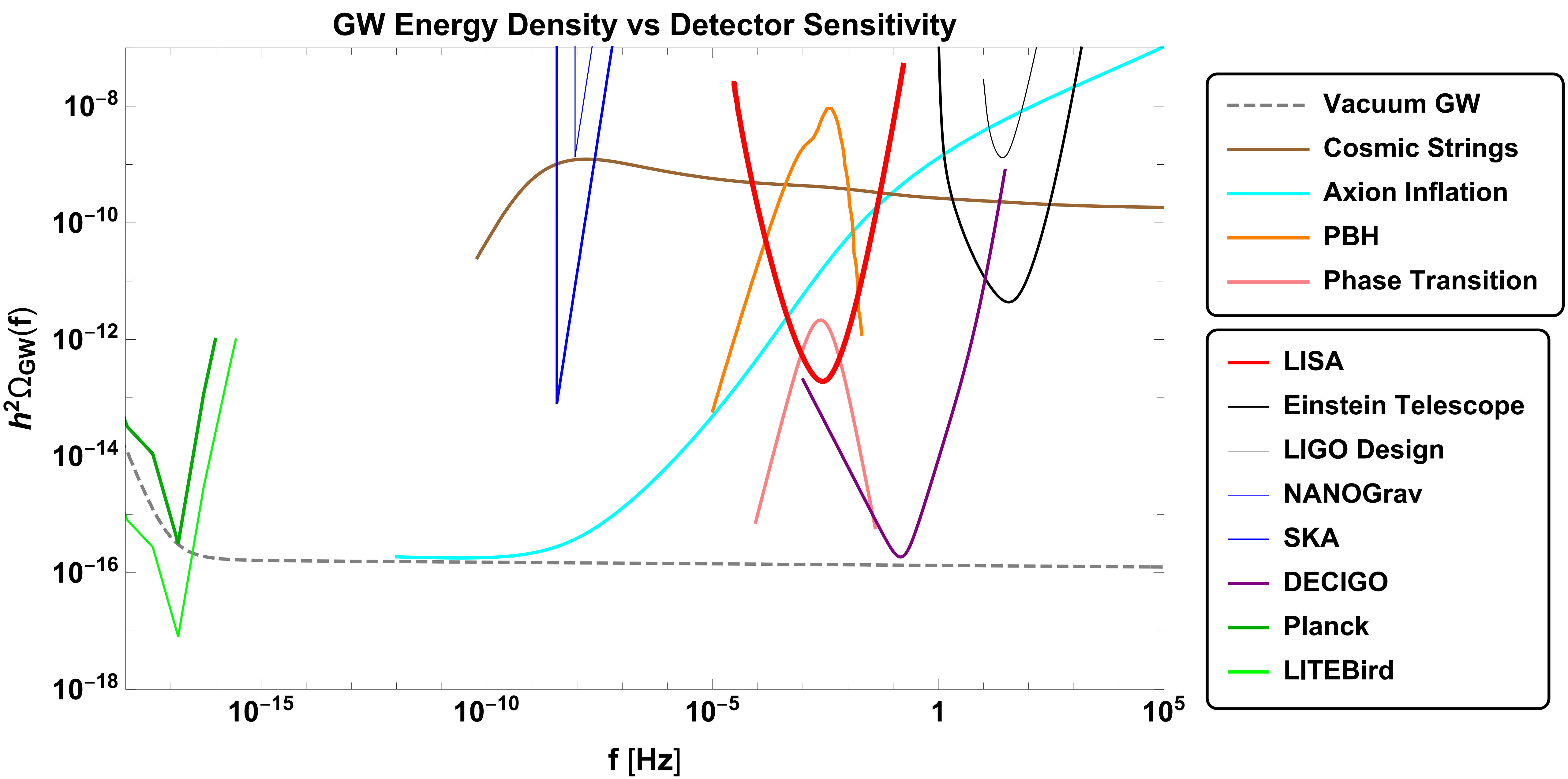
→

Future GW observations can be used to test cosmic structures and dark matter

Again much theoretical work still needed to fully determine GW propagation through cosmic structures

Connecting cosmo theory with GW observations

Finally a stochastic background of GWs can also be connected to different cosmic phenomena in the early universe:



GW cosmology and IN2P3

GW cosmology is flourishing with many institutes setting up dedicated research groups worldwide:

- Chicago
- Geneva
- Amsterdam
- Glasgow
- AEI Potsdam
- Padova …

The French community is showing strong interest with many institutes already involved or interested:

- APC - Paris
- IAP - Paris
- L2IT - Toulouse
- CPT - Marseille
- …

IN2P3 can become a major player in the new field of GW cosmology:

- Strong involvement in Virgo and LISA (GW cosmology important part of science case)
- Astro/cosmo expertises already present
- Solid experience on GW data analysis
- Relevance for many IN2P3 experiments: Virgo - LISA - ET - LSST - Euclid - …

Need to invest on theory now to prepare analyses for future experiments and be in a position of advantage once future data will come!

Conclusion

- GW cosmology is a new and fast-expanding field between GW and EM astronomy
- New opportunities to develop cosmological theories and test them through new phenomenology
- Direct connection to future experiments and observational data
- Strong interest in the French scientific community
- Important relevance for several current and future IN2P3 large projects/experiments