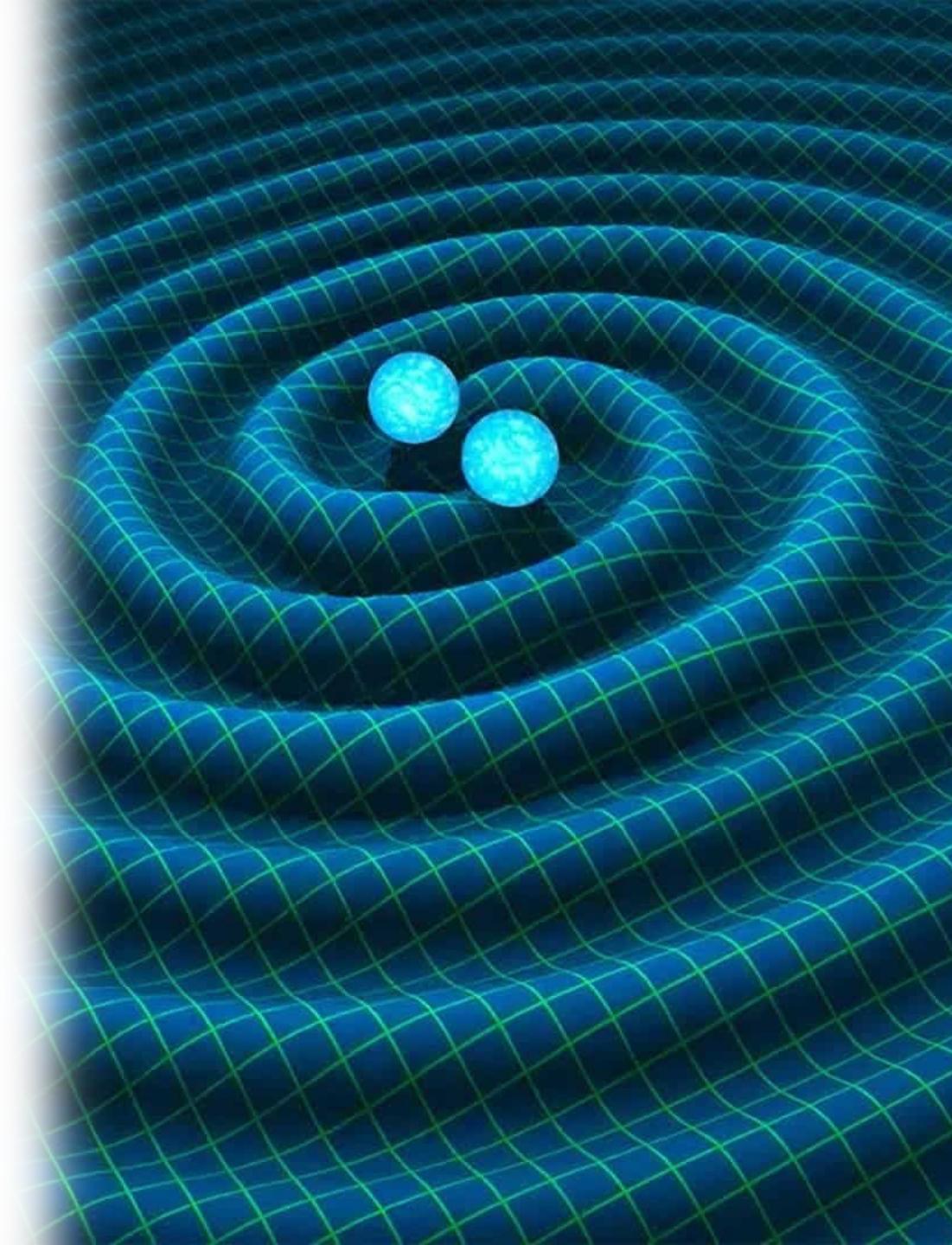


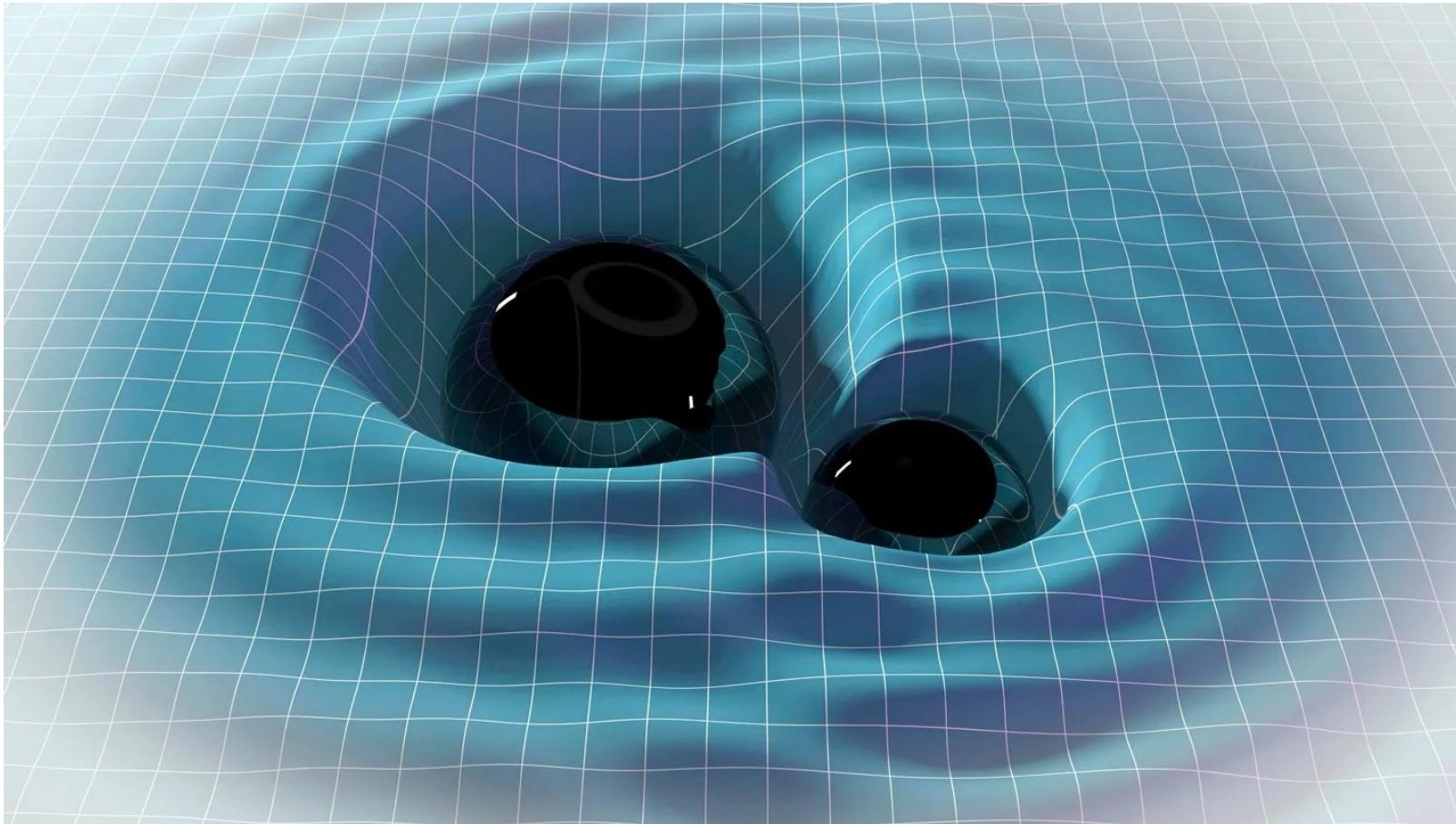
Measuring the expansion of the Universe with gravitational waves : Constrain the H_0

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2019135007 Hyunho Lee
2021135006 Joon Young Lee
2021135035 Seojin Kim



Introduction

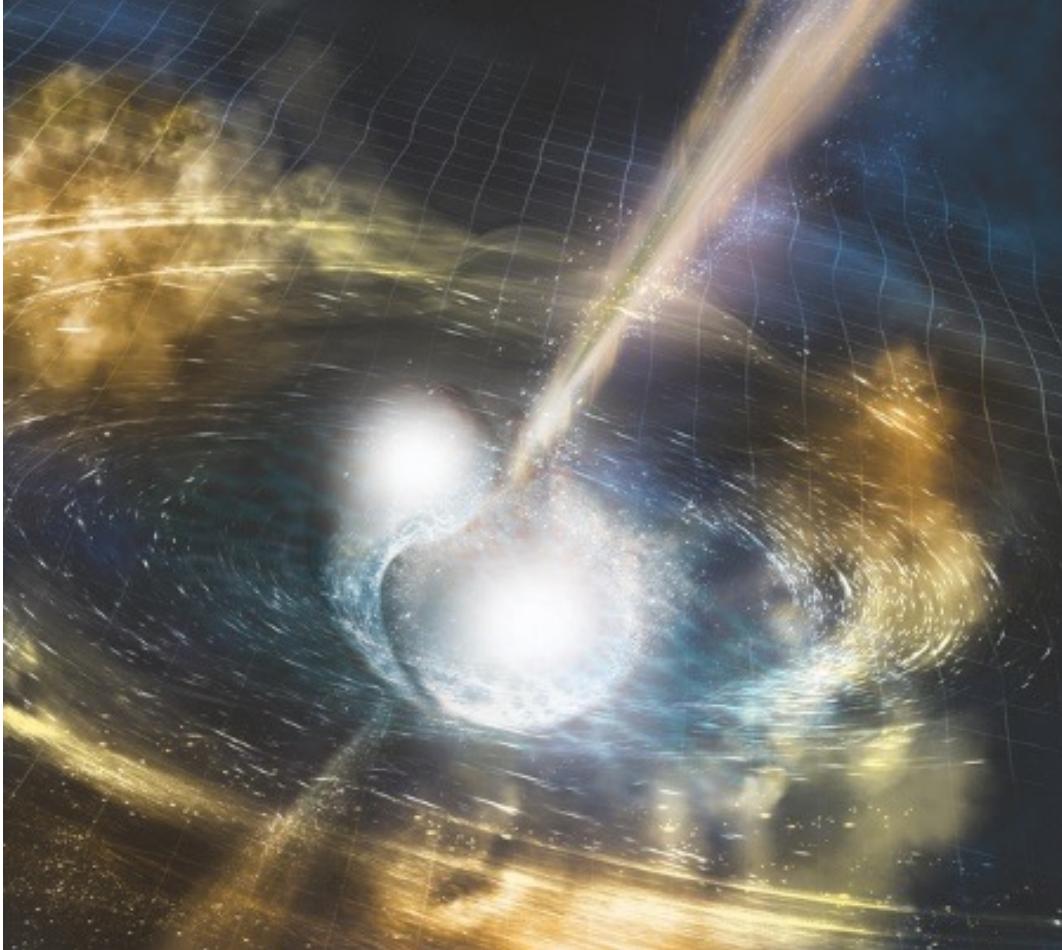
Gravitational Waves



<https://www.sciencenews.org/article/gravitational-waves-detection-lasers-atoms>

Introduction

Constrain the Hubble Constant, H_0



<https://www.ligo.caltech.edu/image/ligo20171016d>

Object: GW170817

GW
↓ 1.7s
EM

Introduction



<https://science.nasa.gov/mission/hubble/observatory/>

HST

LIGO + VIRGO



<https://www.ligo.caltech.edu/news/ligo20170927>

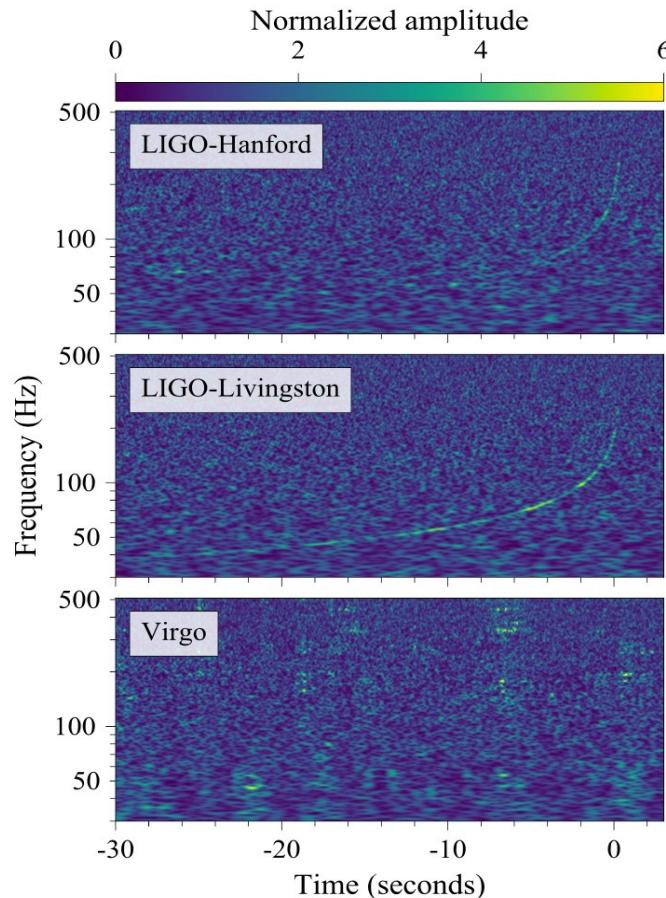


<https://www.virgo-gw.eu/about/scientific-collaboration/>

- Fermi-GBM, INTEGRAL
- Swope
- VLT, Keck

Introduction

GW170817



<https://ligo.org/science-summaries/GW170817BNS/>

Hubble's law : $v_H = H_0 d$

GW data

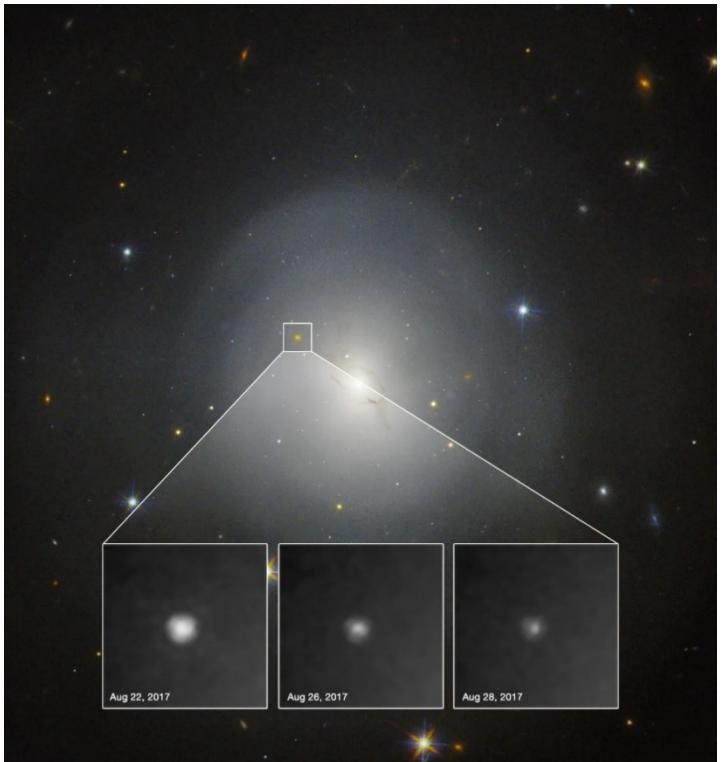
→ standard siren (amplitude & waveform)

→ d : luminosity distance

- uncertainty of about 15%
- independent of the Cosmic Distance Ladder

Introduction

GW170817



NGC 4993

<https://science.nasa.gov/image-detail/hubble-observes-first-kilonova/>

$$\text{Hubble's law : } v_H = H_0 d$$

Identification on NGC 4993

1. position $\rightarrow d$

2. redshift $\rightarrow v_H$

- consideration of peculiar velocity
- By means of redshift-distance relation

Method

Bayesian Statistics

Bayes Rule

$$P(A|B) = P(A) \times \frac{P(B|A)}{P(B)}$$

posterior prior marginality

$$P(A|B) \propto P(A) \times P(B|A)$$

Posterior Probability on H_0 from N_{det} GW events

$$p(H_0 | \{x_{GW}\}, \{D_{GW}\}) \propto p(H_0) p(N_{det} | H_0) \prod_i^{N_{det}} \frac{p(x_{GW_i} | D_{GW_i}, H_0)}{p(D_{GW_i} | H_0)}$$



 Priority of H_0
 (log normal function)

Likelihood for each event
 $= \frac{p(x_{GW} | H_0)}{p(D_{GW} | H_0)}$

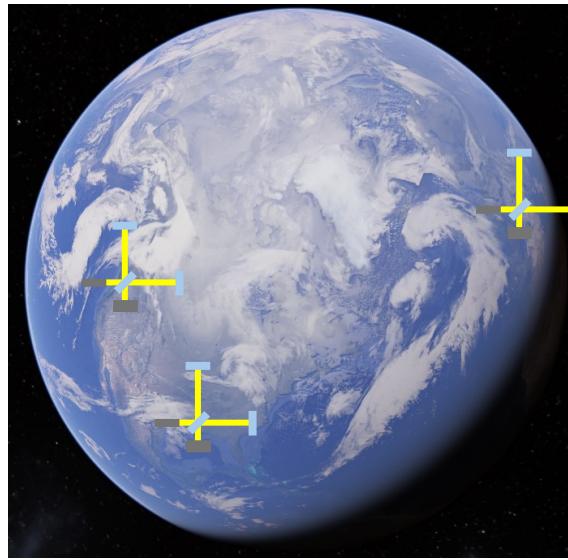
Method

Priors: Redshift from the galaxy

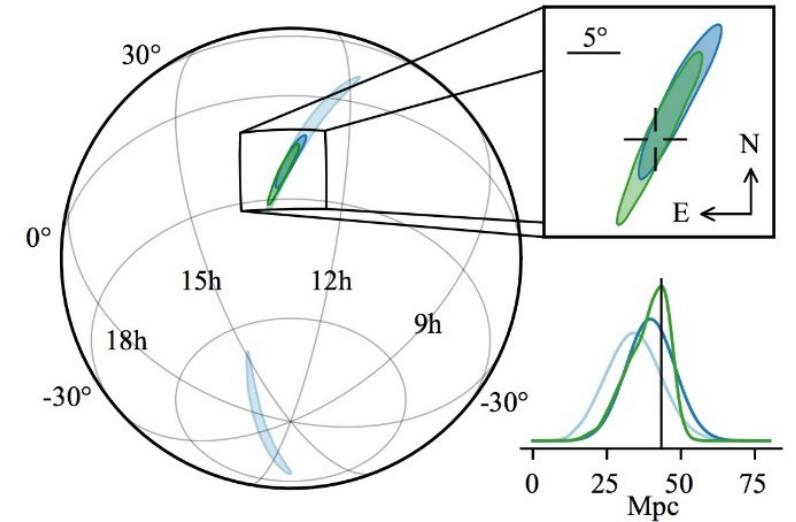
We can constrain cosmologic parameters such as the Hubble parameter from luminosity distance, which is a function of Redshift (z) $d_L(z) \approx cz/H_0$

When the EM counterpart is unknown…

Abbott et al. (2017). *Physical review letters*, 119(16), 161101.



<https://www.google.com/intl/earth/>



- 1) possibility that each galaxy from the region can be the source
- 2) possibility that the source galaxy is unknown due to luminosity biases

Method

Priors: Redshift from the Galaxy

We can constrain cosmologic parameters such as the Hubble parameter from luminosity distance, which is a function of Redshift (z) $d_L(z) \approx cz/H_0$

When the EM counterpart is known...

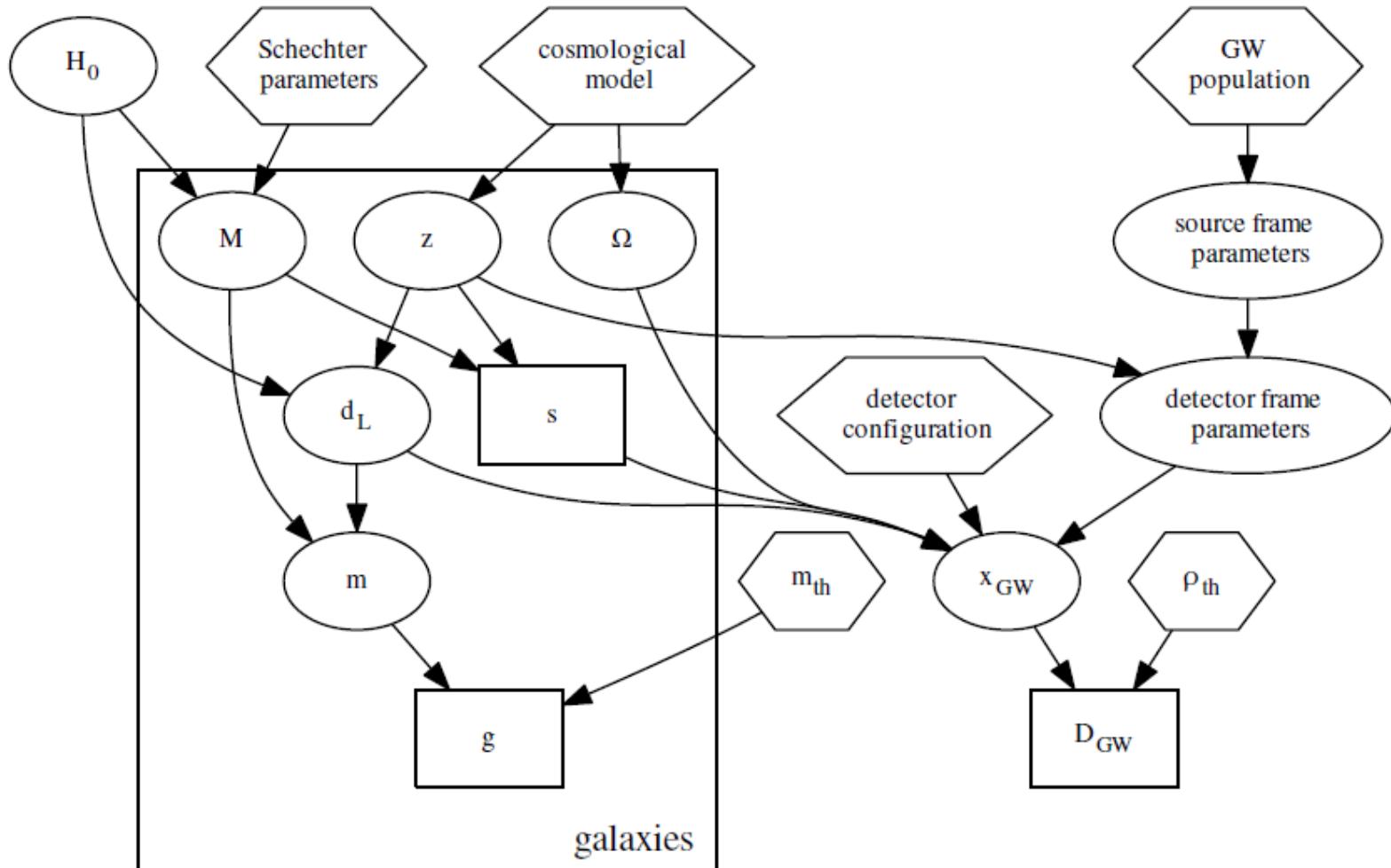


we only need to consider the distance the given galaxy!

$$z_{NGC4993} = 0.009727$$

Method

Flow Chart of the Priors



Method

GWcosmo

This work makes use of gwcosmo which is available at <https://git.ligo.org/lscsoft/gwcosmo>.



Python Package distributed from
LIGO GitLab

Result

Methodology

- F-L-R-W universe $H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda}$
- We assumed a flat universe, so $\Omega_k = 0$, and $\Omega_m + \Omega_k + \Omega_\Lambda = 1$
- Luminosity Distance $d_L(z) = c(1+z) \int_0^z \frac{1}{H(z')} dz' \approx \frac{cz}{H_0} \propto \frac{1}{h} \rightarrow h \propto H_0$
- Where h is the amplitude of the gravitational wave and $z \ll 1$ region.
- So, a bigger H_0 makes it easier to detect GW events, a smaller H_0 makes it harder to detect GW events.
- This is related to the probability of detection we are going to use in our Bayesian analysis.

Result

Probability of Detection

Monte Carlo Integration

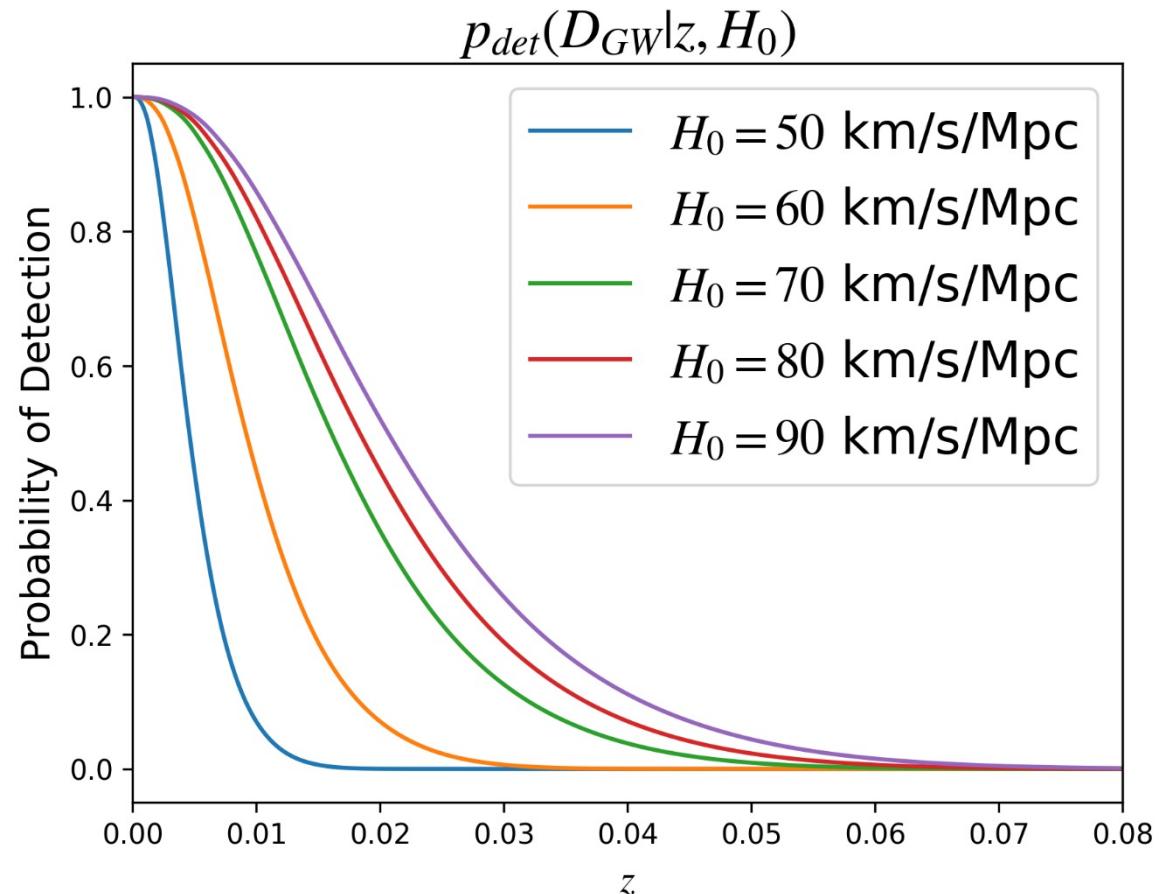
$$p_{det}(D_{GW}|z, \Omega, H_0) = \frac{1}{N_{samples}} \sum_{i=1}^{N_{samples}} p(D_{GW,i}|x_{GW,i}, z, \Omega, H_0)$$

$N_{samples} = 2000$

$SNR \rho_{th} = 12$

Dependency of Ω is smoothed out with many samples.

* Gray et al., 2020



Result

Likelihood of NGC 4993

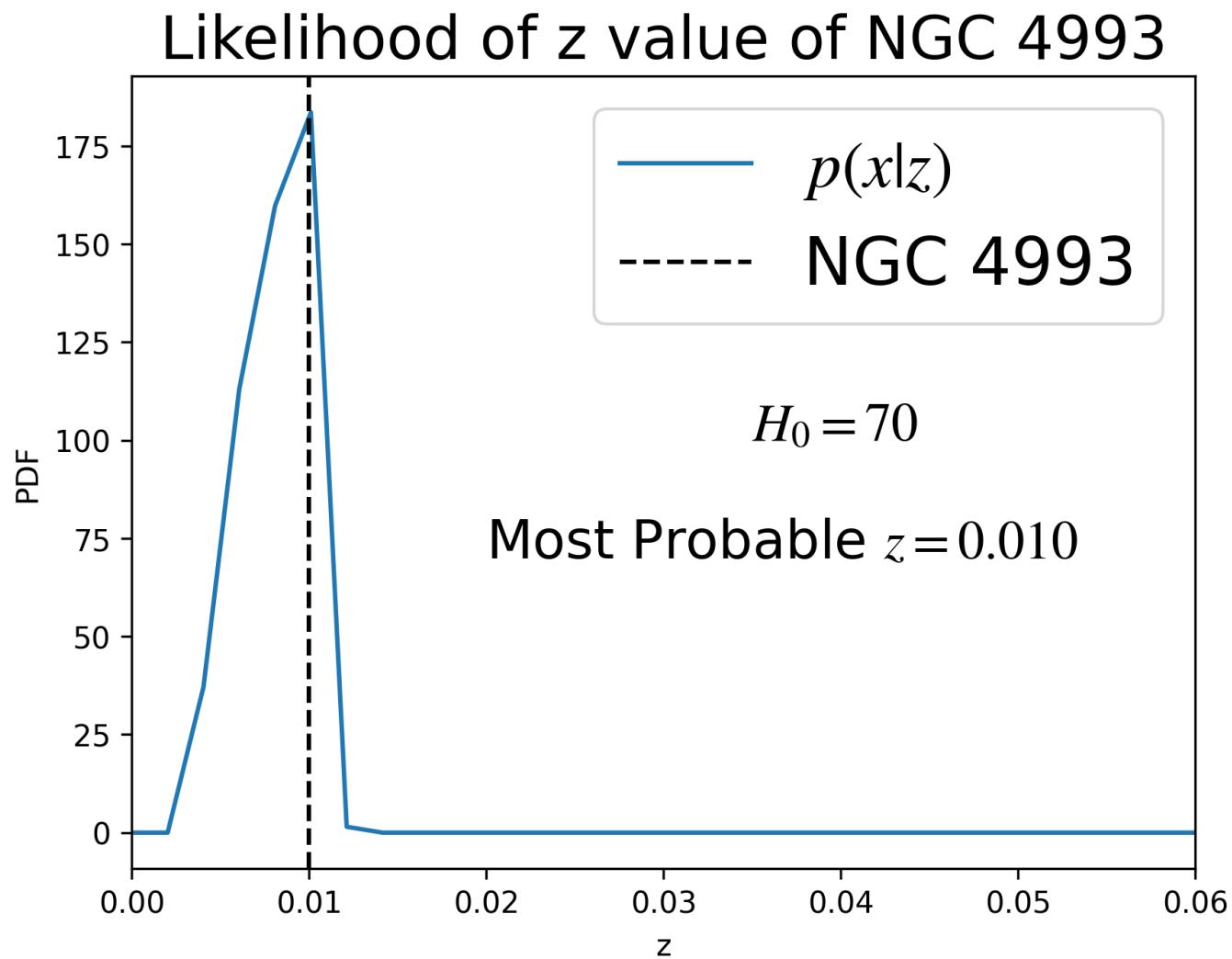
- Likelihood of z value of NGC 4993 from the Luminosity distance obtained by GW170817, assuming $H_0 = 70$

Host Galaxy of GW170817 Event

Tully–Fisher distance: 41.1 ± 5.8 Mpc (Sakai et al. 2000, Freedman et al. 2001)

Redshift (J. Hjorth et al., 2017)

- $z_{\text{helio}} = 0.00978 \pm 0.000023$
- $z_{\text{cosmic}} = 0.00980 \pm 0.000079$



Result

Calculation of the Posterior

Likelihood of redshift of NGC 4993

$$p(H_0 | x_{GW}) = \frac{p(x_{GW} | H_0) p(H_0)}{\beta(H_0)}$$

Posterior of H_0

Prior of H_0

Selection Bias: $\beta(H_0) = \int p_{det}(z, H_0) p(z) dz$ from probability of detection.

Result

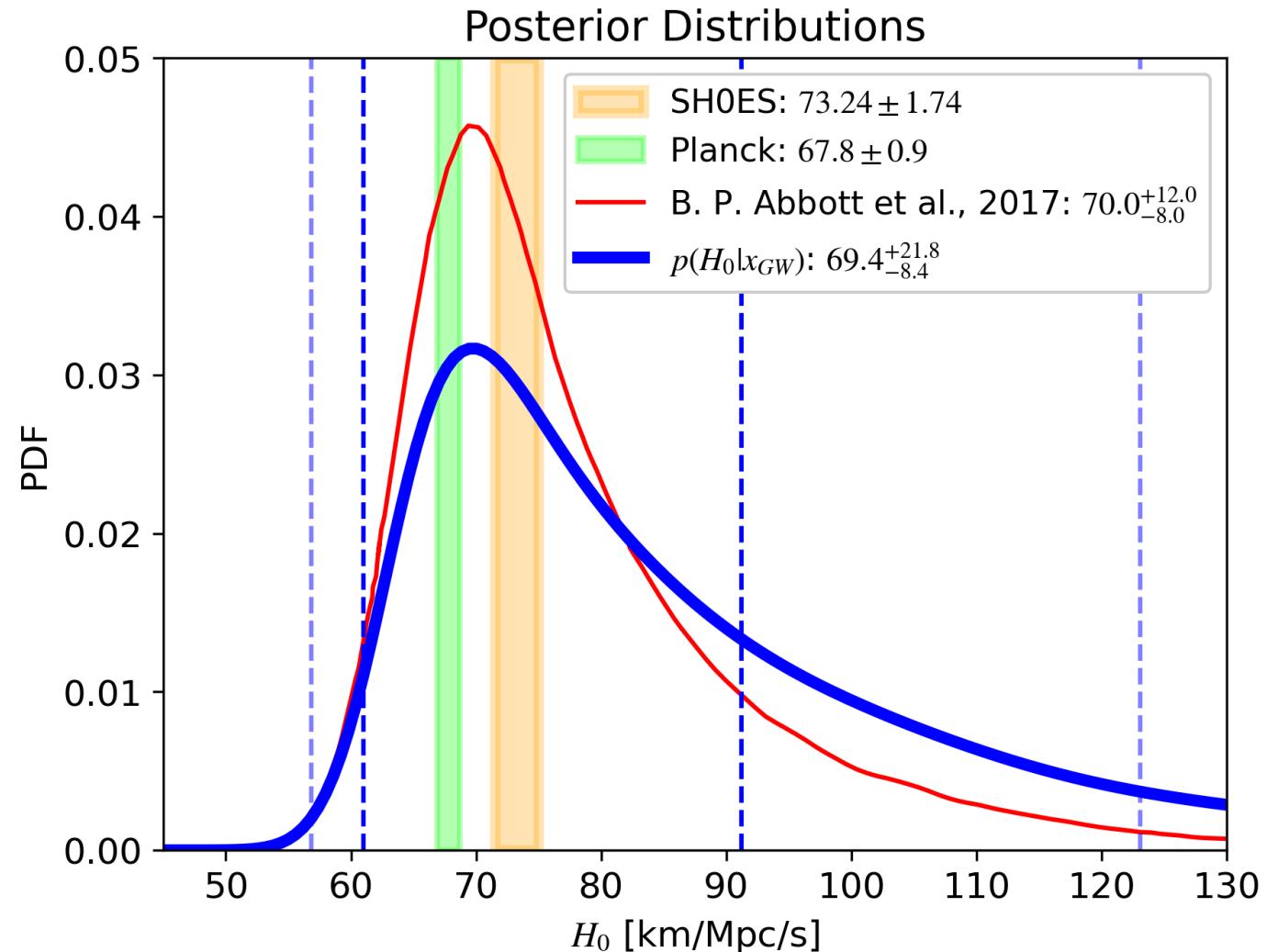
Posterior

Posterior Distribution

- $p(H_0|x_{GW}) = 69.4^{+21.8}_{-8.4}$
- Roughly consistent with other independent calculations.
- We should all be happy with the consistency, but they still are about 4σ away.

*SH0ES: Riess et al., 2016

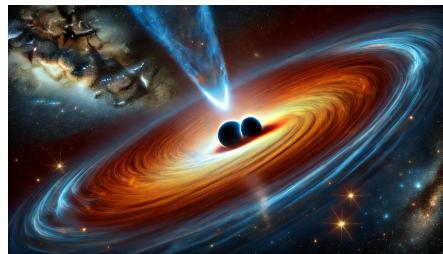
*Planck: Planck Collaboration et al., 2016



Discussion

Problems

GW



GW + EM



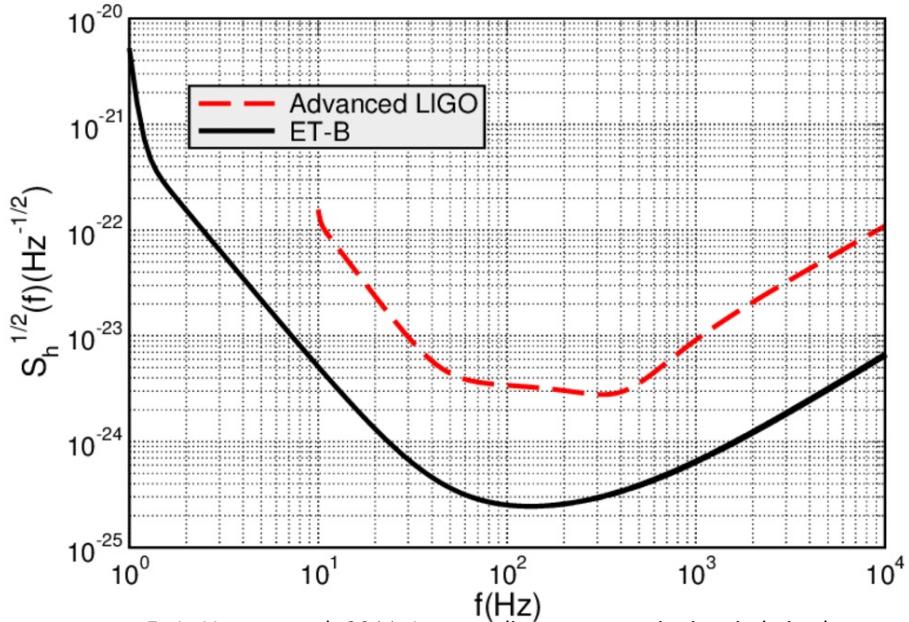
But GW detection's SNR is too low!

So, for more precise estimation of H_0 ,

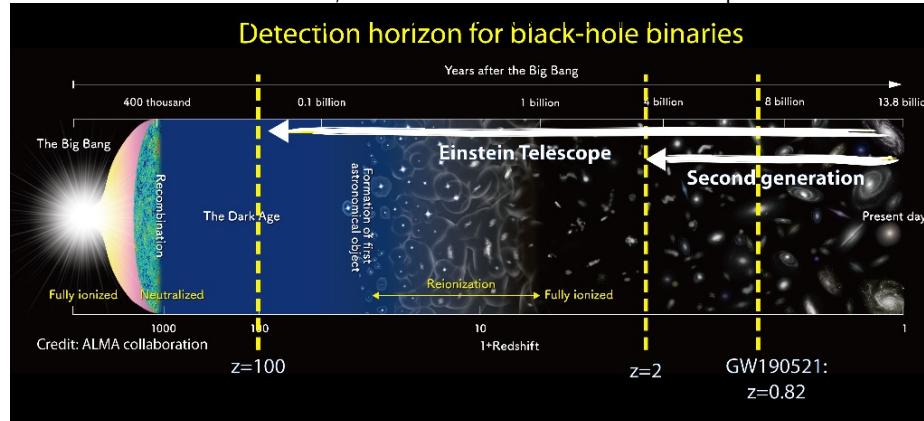
It is essential to use much more advanced detector.

Discussion

Advanced Plan



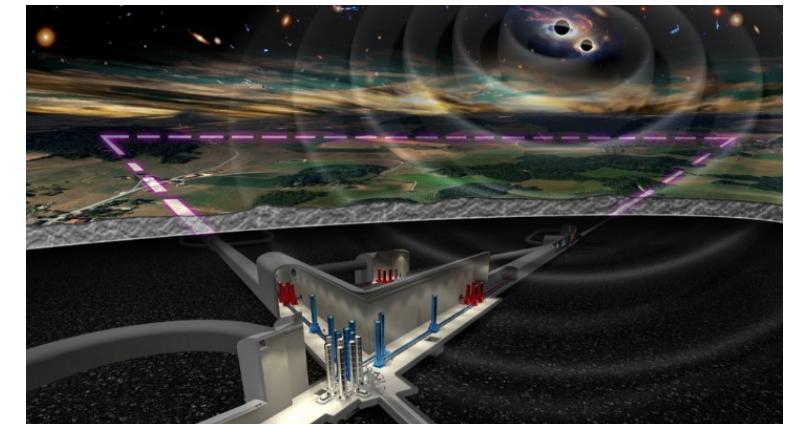
E. A. Huerta et al, 2011. Intermediate-mass-ratio-inspirals in the



<https://www.et-gw.eu/>

Einstein telescope

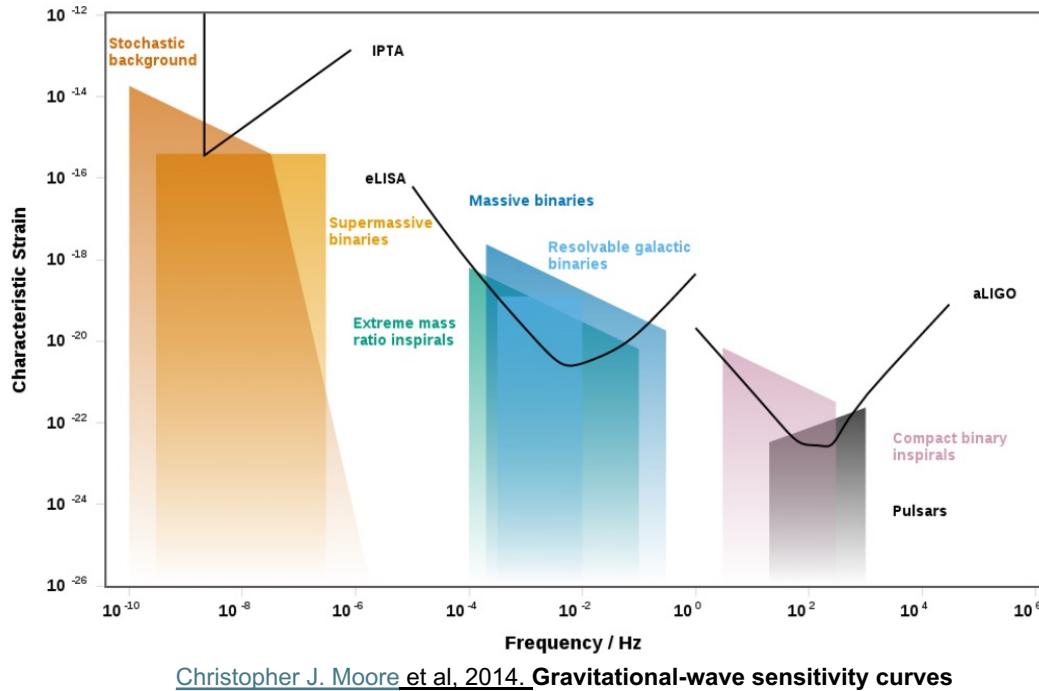
- long arm(10km)
- 60° arm angle * 3arms
- Detect Farther GW
- More sensitive



<https://www.et-gw.eu/>

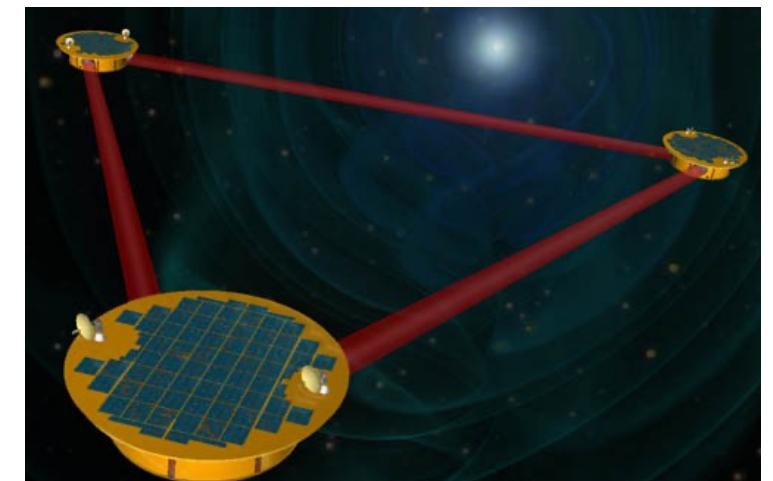
Discussion

Advanced Plan

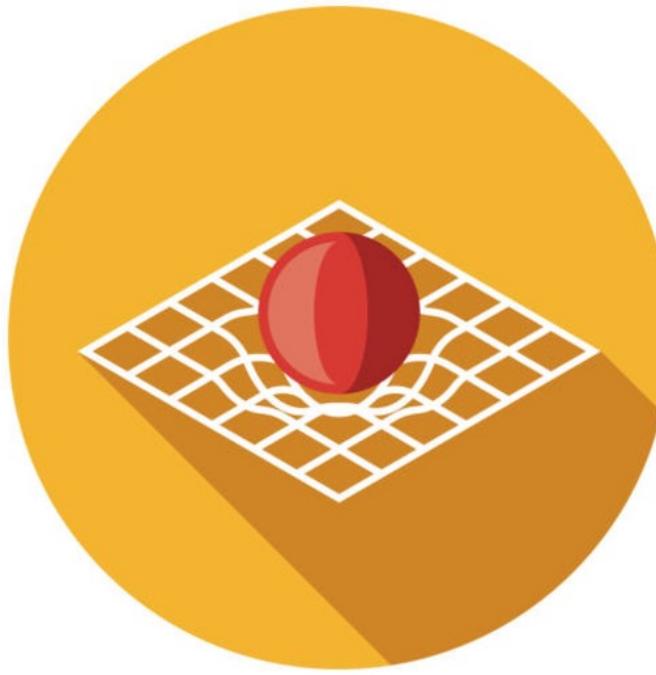


eLISA

- Space based
- arm length: $2.5 * 10^6$ km
- detect other source



<https://lisa.nasa.gov/archive2011/>



Thank you for your attention !

A-1 : About GW170817

- Luminosity distance $\sim 44\text{Mpc}$
- uncertainty of about 15% due to instruments noise and the fact that we don't know precisely the inclination of the orbital plane
- Hubble velocity $\sim \text{over } 3000 \text{ kms}^{-1}$
- correct peculiar velocity (large uncertainty of 150 kms^{-1})
 - still have uncertainty of about 15% in the estimation of H_0
- Mass
 - (1) $2.26 \& 0.86$ solar masses
 - (2) $1.60 \& 1.17$ solar masses (when the objects are spinning slowly)
 - these masses are consistent with the masses of all known neutron stars : the reason they think is a binary neutron stars system.
- Tidal deformation : it's determined by mass and equation of state
 - but does not definitively tell us the equation of state might be

A-2 : GW170817, after Merged

Two possibilities

(1) the largest neutron star

(2) the lightest black hole

→ data isn't good enough to tell us one way or the other.

→ All we know is the object, whatever it is, has a mass around 3 solar masses