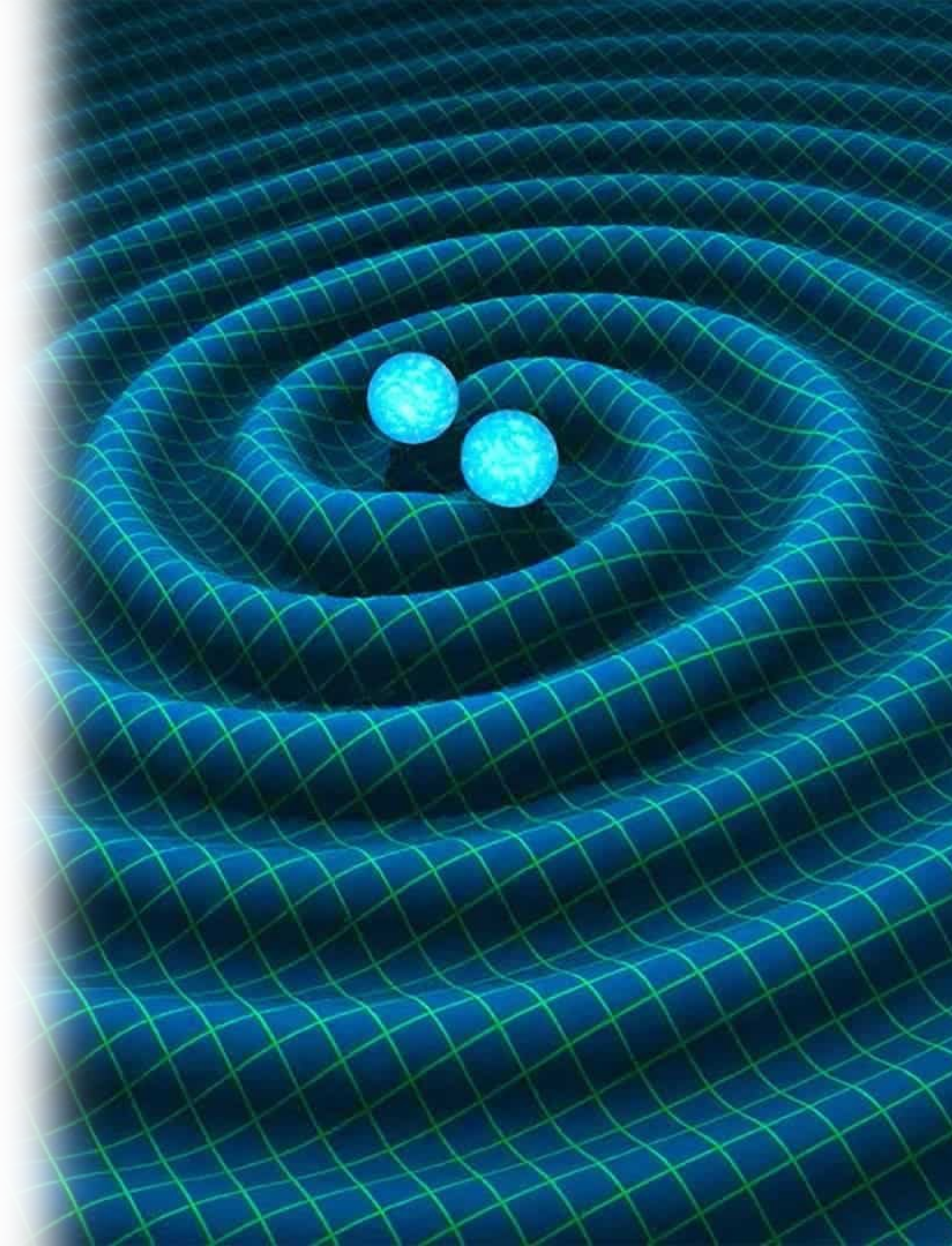
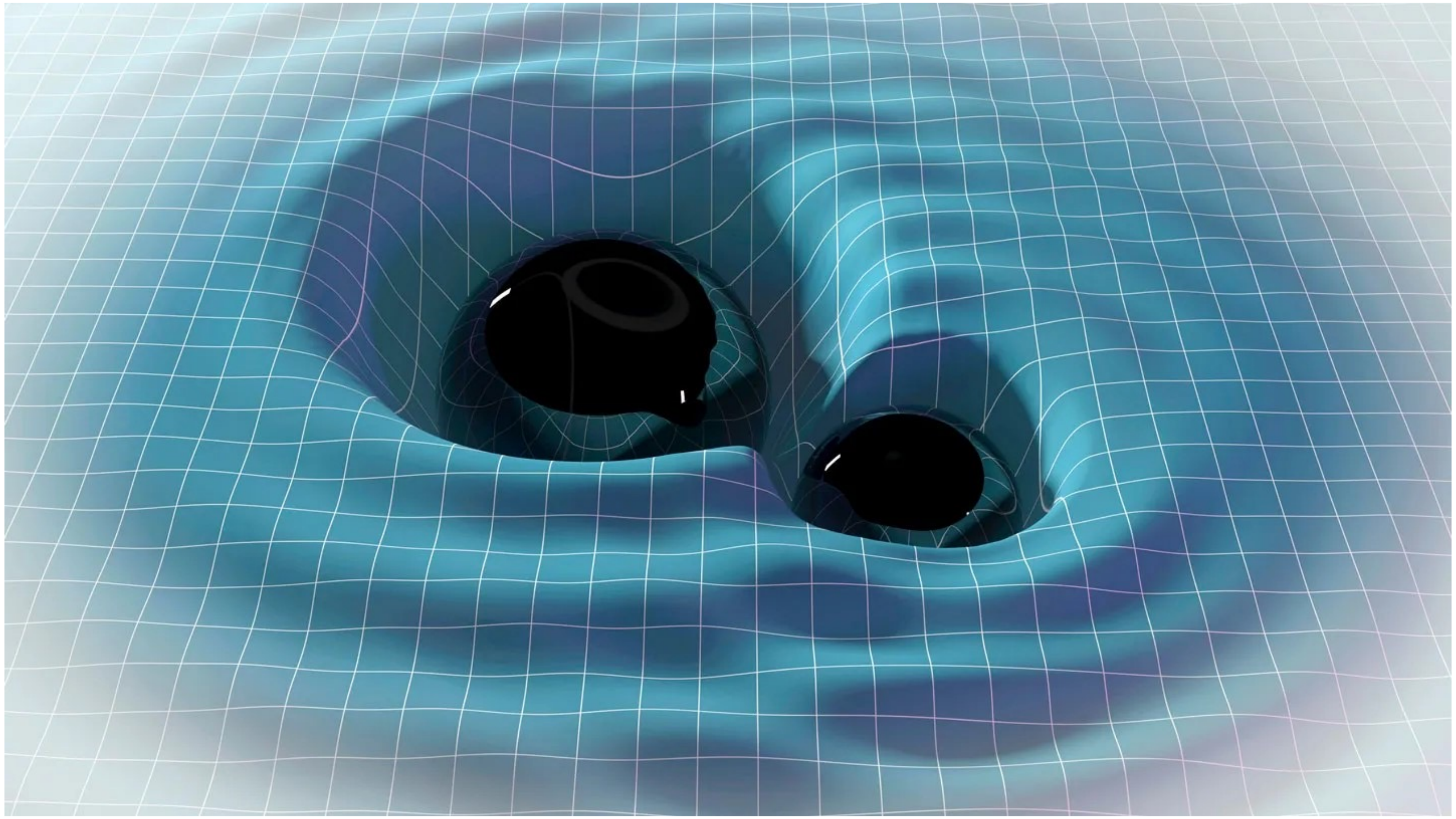
Measuring the expansion of the Universe with gravitational waves

：Constrain the H_0



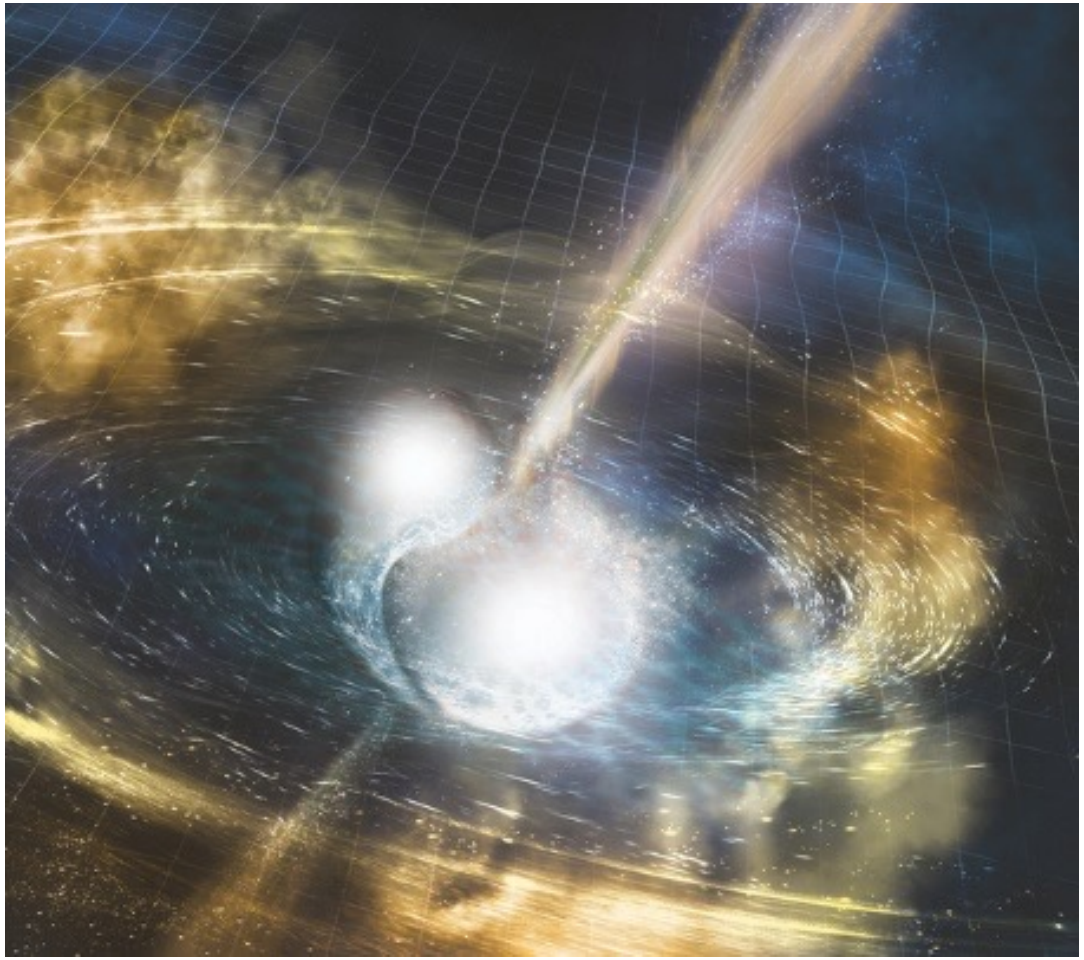
Gravitational Waves



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

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

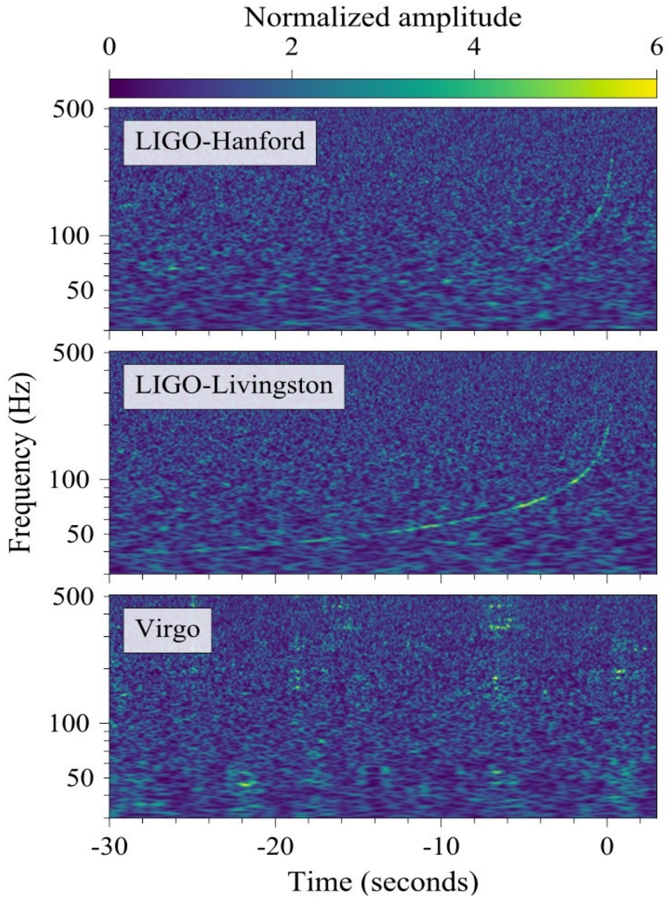
LIGO + VIRGO

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

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

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/

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

Identification on NGC 4993

1. position → d
2. redshift → $\boldsymbol{v_H}$

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

Method

Bayesian Statistics

Bayes Rule

$$\underbrace{\boxed{P(A|B)}}_{\text{posterior}} = \underbrace{\boxed{P(A)}}_{\text{prior}} \times \frac{\overbrace{\boxed{P(B|A)}}^{\text{likelihood}}}{\underbrace{\boxed{P(B)}}_{\text{marginality}}}$$

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

Posterior Probability on H_0 from N_{det} GW events

$$p(H_0|\{x_{GW}\},\{D_{GW}\}) \propto p(H_0)\underbrace{p(N_{det}|H_0)}_{=1}\prod_{i}^{N_{det}}\underline{p(x_{GW_i}|D_{GW_i},H_0)}$$

Priority of H_0
(log normal function)

Likelihood for each event

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

Gray et al. (2020). *Physical Review D*, *101*(12), 122001.

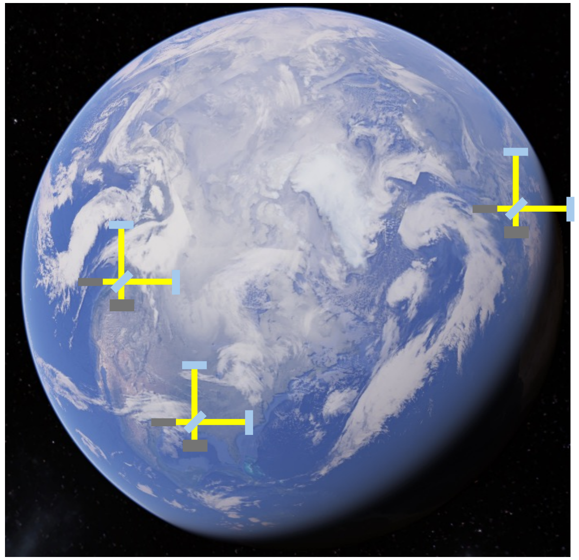
Method

Priors: Redshift from the galaxy

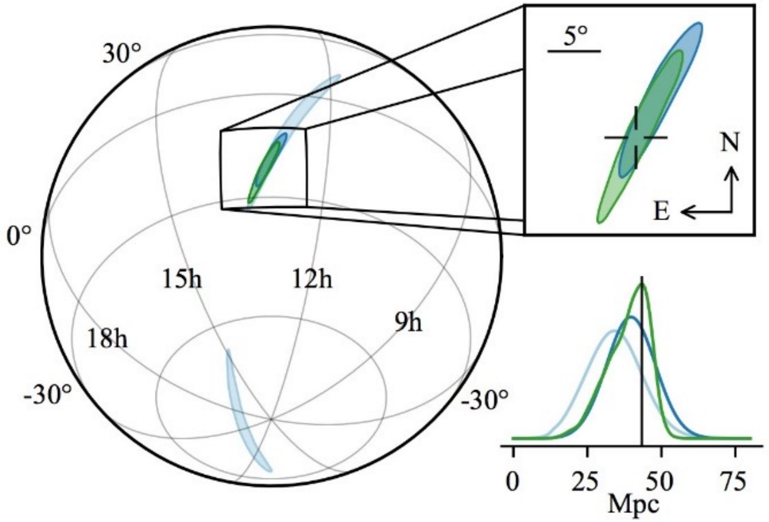
We can constrain cosmologic parameters such as the Hubble parameter from luminosity distance, which is a function of Redshift (z) $d_L(z) \approx cz/H_0$

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

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…

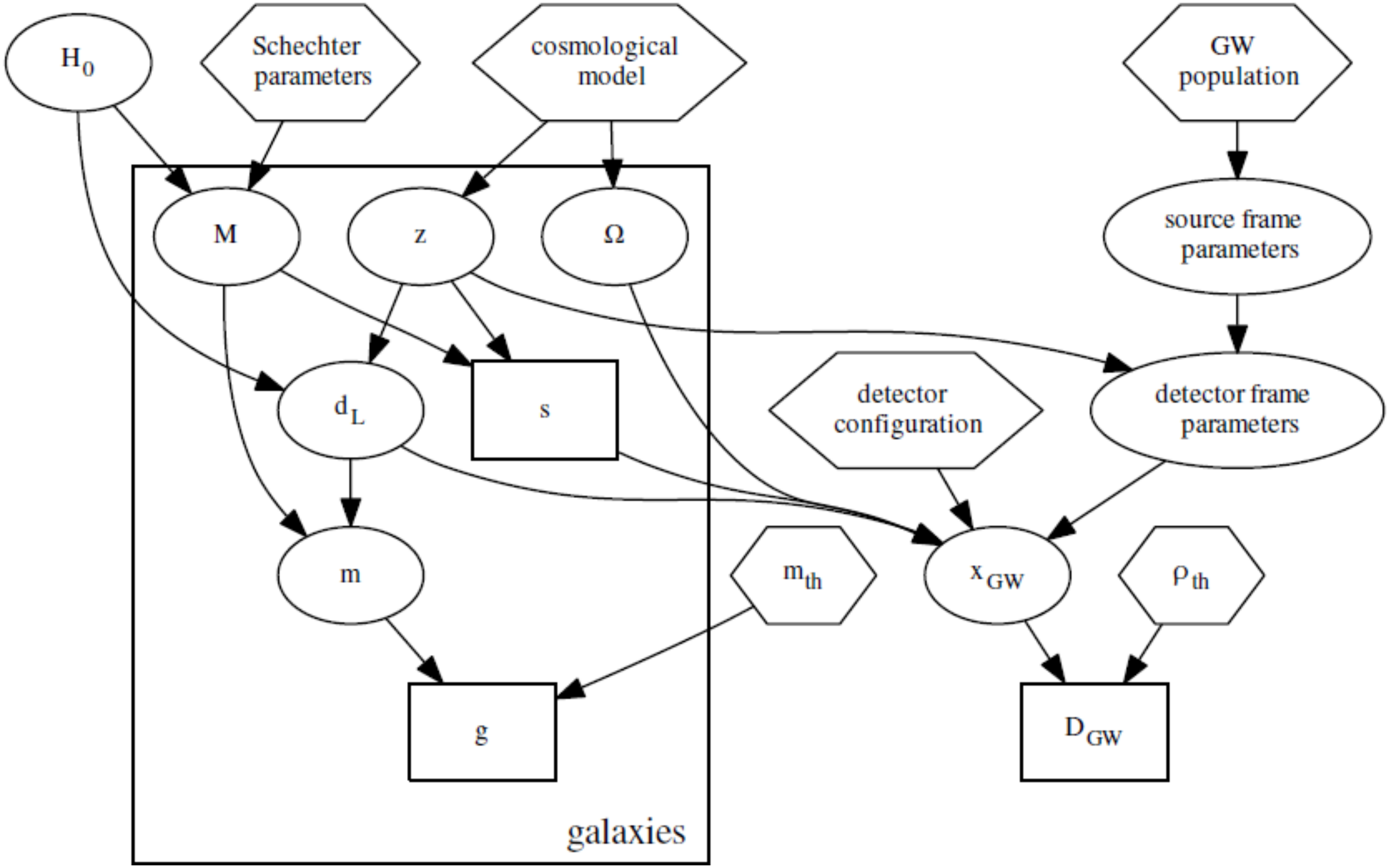
we only need to consider the distance the given galaxy!

$$z_{NGC4993} = 0.009727$$

https://hubblesite.org/contents/media/images/2017/41/4078-Image.html?news=true

Method

Flow Chart of the Priors



Gray et al. (2020). *Physical Review D*, *101*(12), 122001.

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 $d_L(z) = c(1+z)\int_0^z \frac{1}{H(z\prime)} dz' \approx \frac{cz}{H_0} \propto \frac{1}{h} \rightarrow h \propto H_0$
- 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 is 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

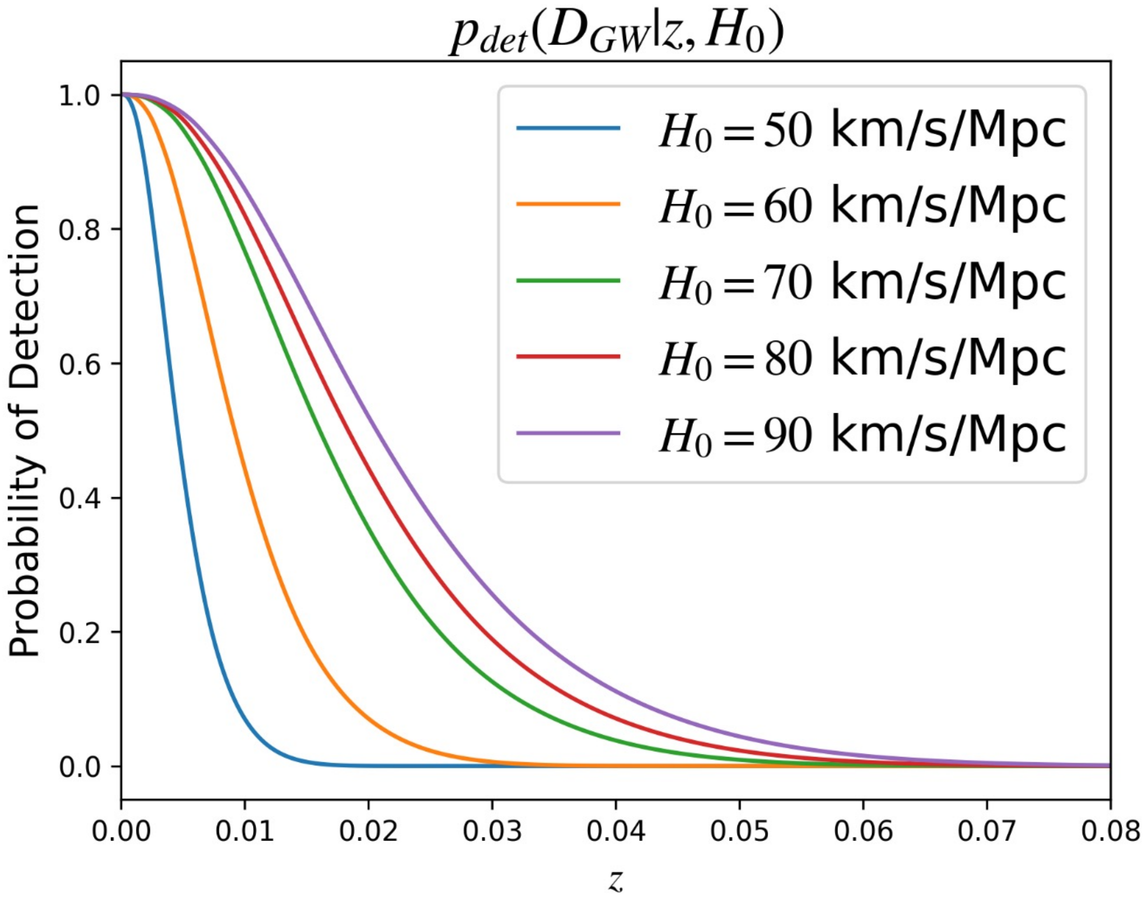
$$p_{det}(D_{GW}|z,\Omega,H_0) = \frac{1}{N_{samples}} \sum_{i=1}^{N_{samples}} p\left(D_{GW,i} \middle| x_{GW,i}, z, \Omega, H_0\right)$$

$$N_{samples} = 2000$$

$$SNR\ \rho_{th} = 12$$

Dependency of Ω is smoothed out with many samples.

* Gray et al., 2020



Result

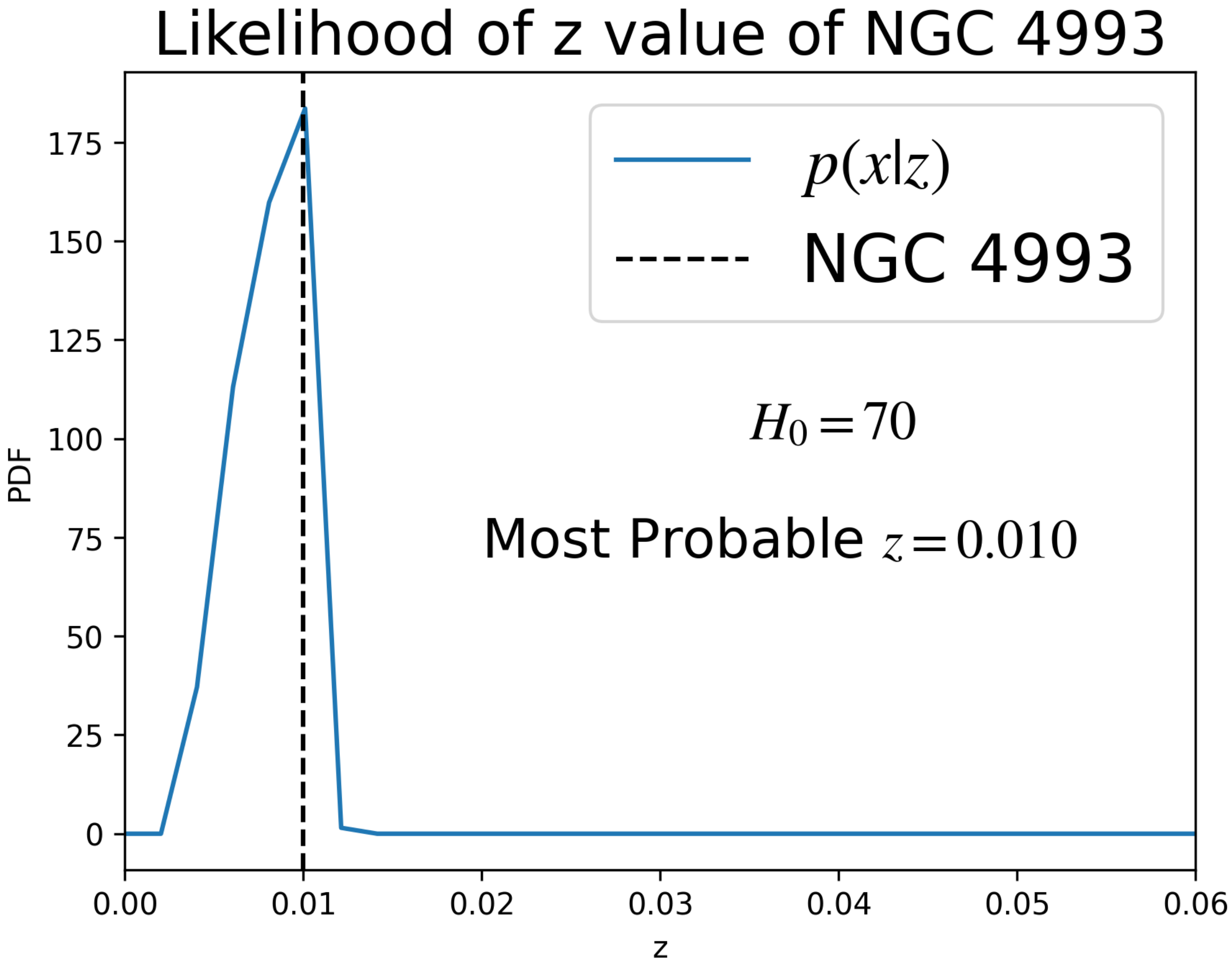
Likelihood of NGC 4993

- Likelihood of z value of NGC 4993 fro m 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. 2 000, Freedman et al. 2001)

Redshift (J. Hjorth et al., 2017)

- $z_{helio} = 0.00978 \pm 0.000023$
- $z_{cosmic} = 0.00980 \pm 0.00079$



Calculation of the Posterior

Likelihood of redshift of NGC 4993

Prior of H_0

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

Posterior of $\boldsymbol{H_0}$

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

Result

Posterior

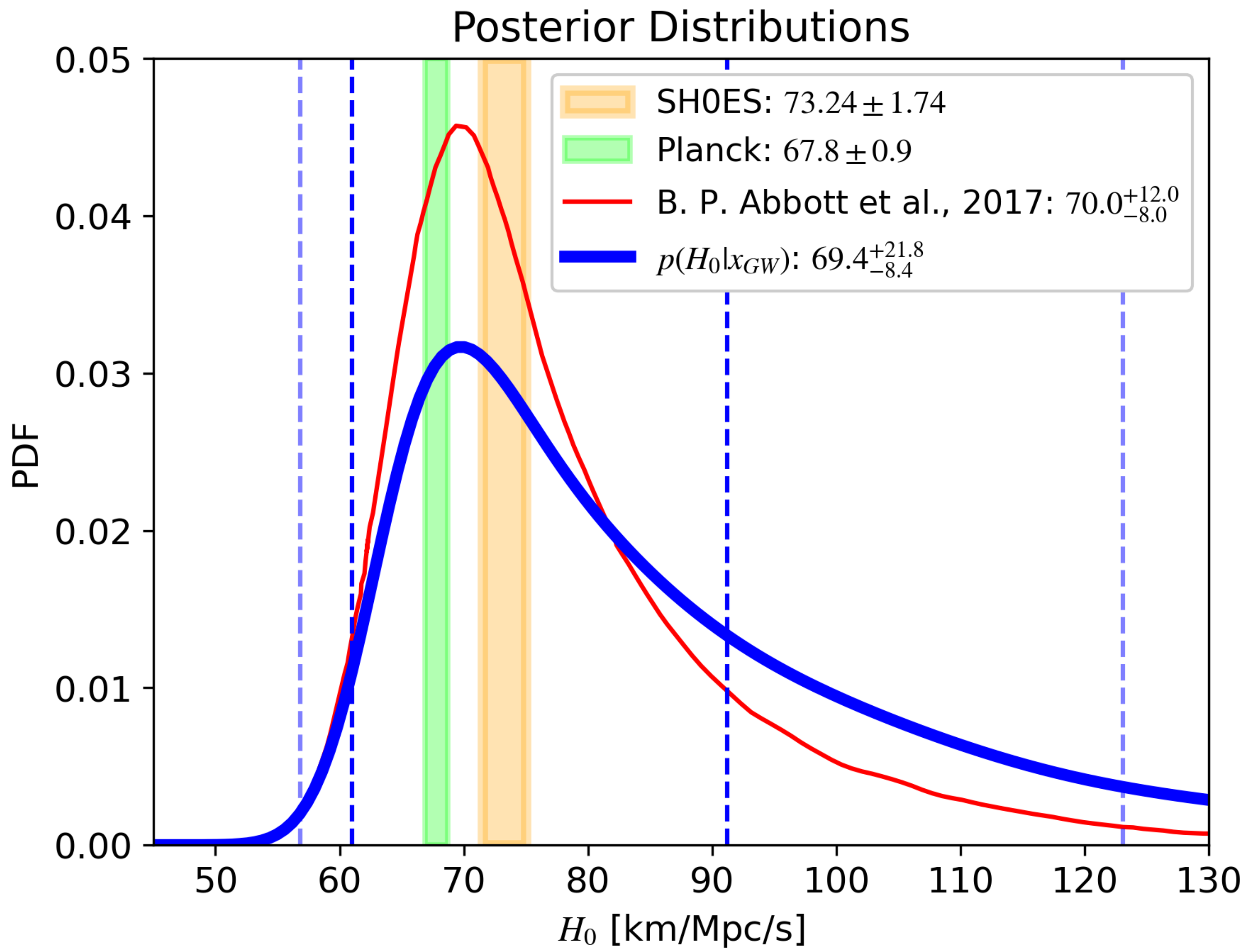
Posterior Distribution

- $p(H_0|x_{GW}) = 69.4^{21.8}_{-8.4}$

- Roughly consistent with other independent calculations.

- We should all be happy with the consistency, but they still are about 4σ away.

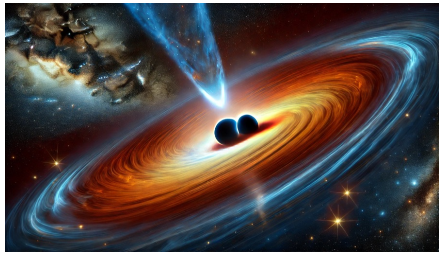
*SH0ES: Riess et al., 2016
*Planck: Planck Collaboration et al., 2016



Problems

GW

GW + EM

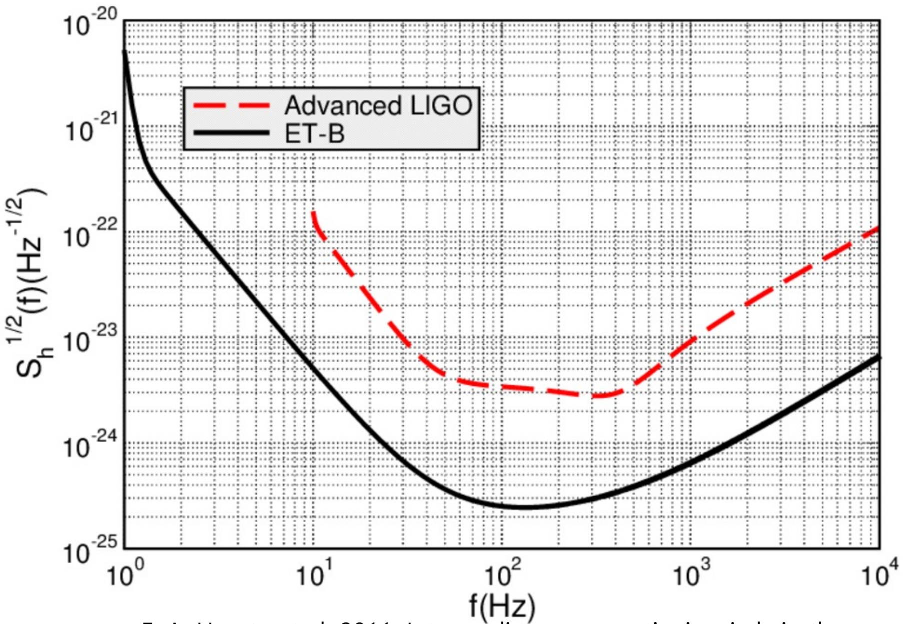


But GW detection's SNR is too low!

So, for more precise estimation of H_{0},

It is essential to use much more advanced detector.

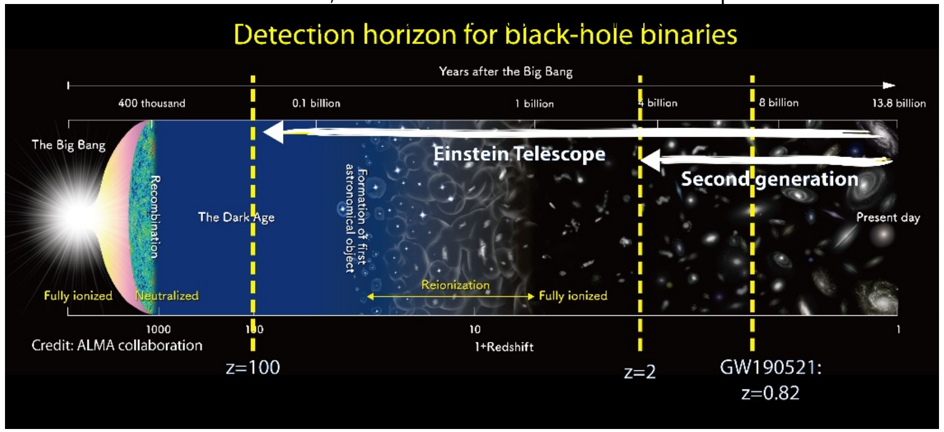
Advanced Plan



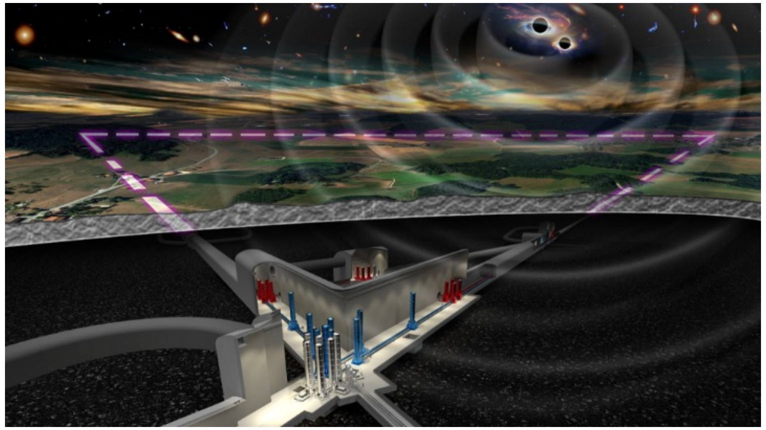
E. A. Huerta et al, 2011. Intermediate–mass–ratio–inspirals in the

Einstein telescope

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



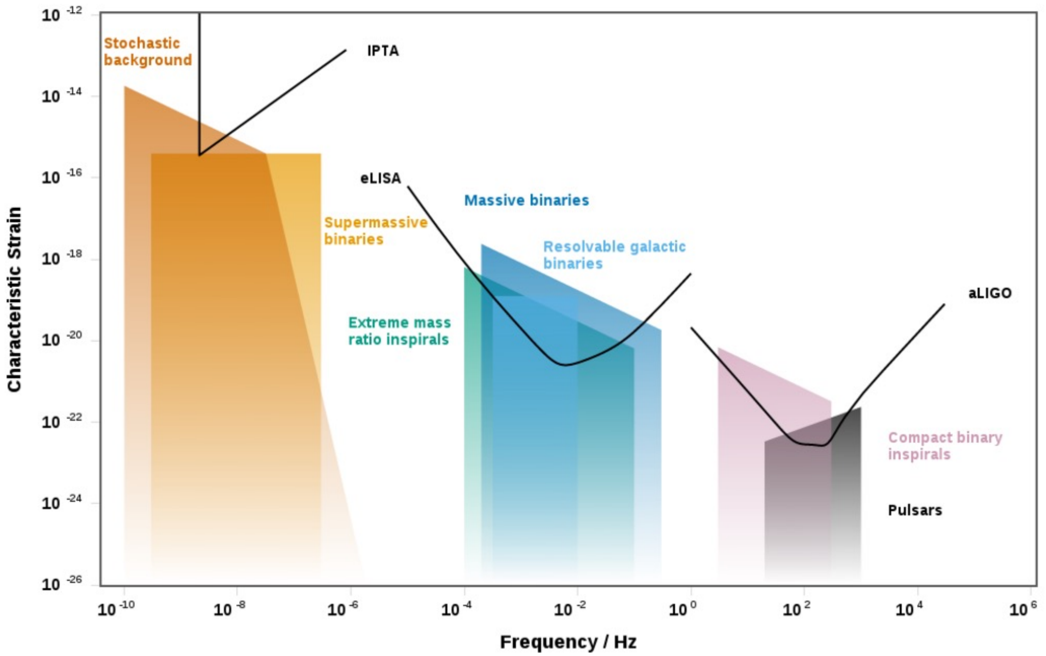
https://www.et-gw.eu/



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

Discussion

Advanced Plan



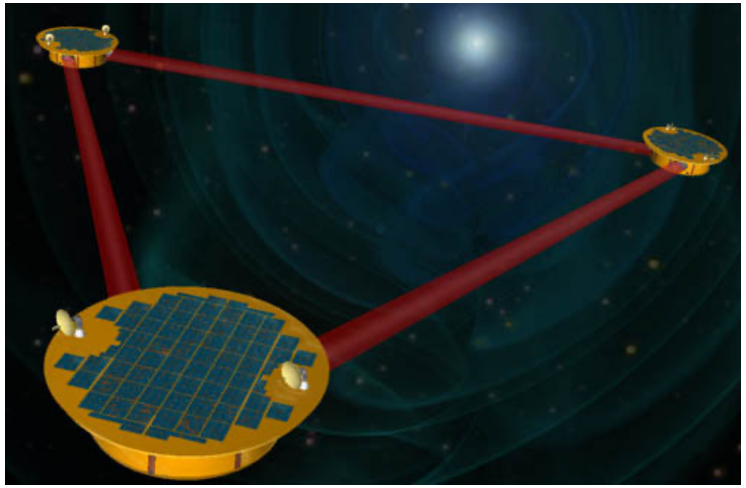
Christopher J. Moore et al, 2014. **Gravitational-wave sensitivity curves**

eLISA

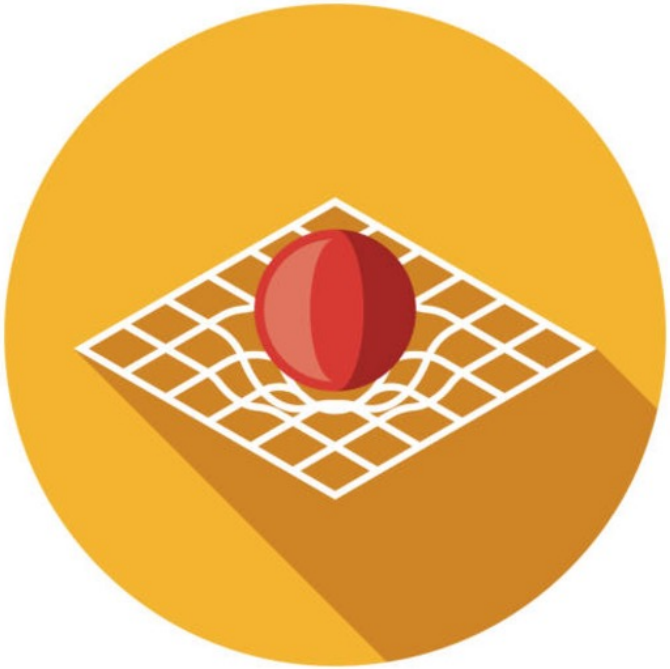
–Space based

–arm length: $2.5*10^6$ km

–detect other source



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



Thank you for your attention !

Advanced

A-1：About GW170817

- **Luminosity distance ~ 44Mpc**

– uncertainty of about 15% due to instruments noise and the fact that we don't know precisely the inclination of the orital plane

- **Hubble velocity ~ over 3000 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

Abbott, B. P., et al. (2017). A gravitational-wave standard siren measurement of the Hubble constant. *Physical Review Letters, 119*(3), 031102.

Advanced

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

Abbott, B. P., et al. (2017). A gravitational-wave standard siren measurement of the Hubble constant. *Physical Review Letters, 119*(3), 031102.