双中子星并合事件的联合探测率和空间分布及其宇宙学应用

赵文

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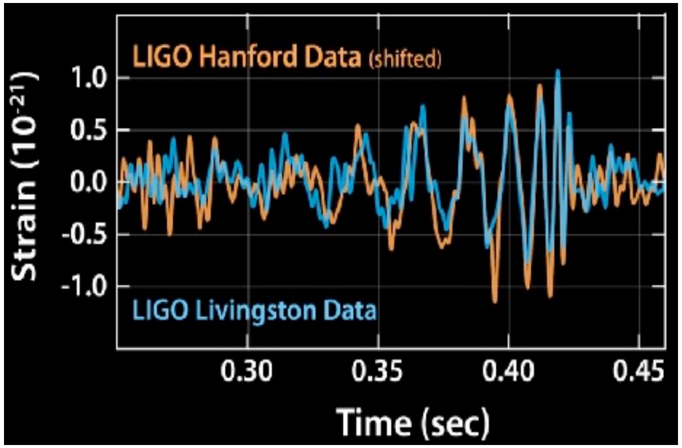
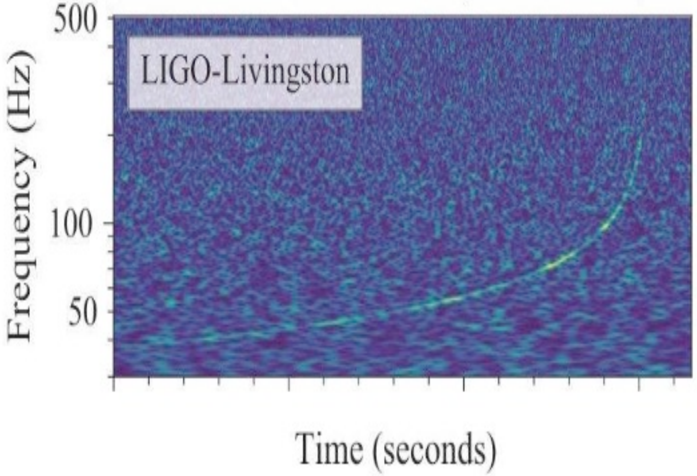
New era of GW astronomy

- Discovery of GW150914, produced by the binary black-hole merger, opens the windows of GW astronomy.
- Discovery of GW170817, produced by the coalescence of , marks the new era of multi-messenger of GW astronomy.
- In the near future, we expect the new breakthroughs in space-borne detection, pulsar-timing observations, and cosmic microwave background observations.





GW Sources as ‘Standard Sirens’

- **In 1986, Schutz found that the luminosity distance of the binary neutron stars (or black hole) can be independently determined by observing the G.W. generated by this system. If we can also find the EM counterpart, the redshift can also be determined. Thus the dL-z relation can be used to study the evolution of universe. This is the so-called: standard sirens. (Schutz,Nature,1986)**

  characters： 1. non-EM method to study the cosmology
  2. independent of “cosmic distance ladder”

*** Measurement of Hubble Constant**

[Ground-based] ALIGO，AVIRGO, LIGO A+ (BNS, NSBH)

*** Detection of Dark energy**

[Ground-based] Einstein Telescope, Cosmic Explorer (BNS, NSBH, BBH)

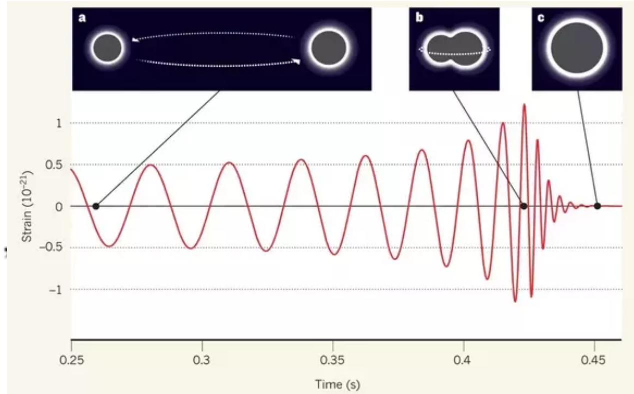
[Space-based] LISA, Taiji, TianQin (SMBBH)

[Pulsar Timing Array] SKA (SMBBH)

GW Sources as ‘Standard Sirens’

- How to determine the ‘distance’?

By amplitude and phase of GW (Schutz, 1986)



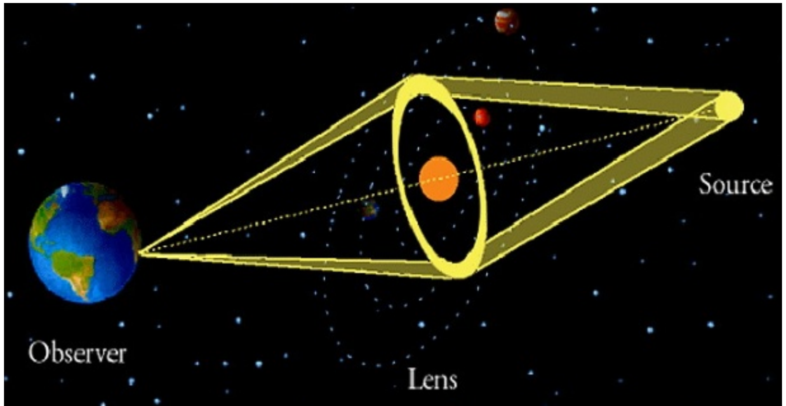
$$h_+(t) = 2\mathcal{M}_c^{5/3} d_L^{-1}(1+\cos^2(\iota))\omega^{2/3}(t_0-t)\cos[2\Phi(t_0-t;M,\eta)+\Phi_0],$$

$$h_\times(t) = 4\mathcal{M}_c^{5/3} d_L^{-1}\cos(\iota)\omega^{2/3}(t_0-t)\sin[2\Phi(t_0-t;M,\eta)+\Phi_0],$$

where ι is the angle of inclination of the binary’s orbital angular momentum with the line-of-sight

observed chirp mass   luminosity distance   observed mass

By lensed GW events (Liao et al. 2017)



Gravitational-wave standard siren and cosmology

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The discoveries of gravitational-wave (GW) event GW170817, caused by the coalescence of binary neutron-star, as well as the electromagnetic counterparts in multi-frequency bands, mark the coming of multimessenger GW astronomy. By observing the GW waveform of compact binary coalescence, one can independently determine its luminosity distance, which indicates that this kind of GW sources can be treated as “standard sirens” to study the expansion history of the Universe. This provides a novel method for the research of cosmology. In this article, we introduce the basic principle of GW sources as “standard sirens”, and focus on various methods to determine the distance and redshift of GW events. We also discuss the detection capabilities of constraining cosmological parameters for (second-generation and third-generation) ground-based GW detectors and space-based GW detectors. In particular, we investigate the potential constraints on the Hubble constant and equation-of-state of dark energy.

gravitational waves, compact binary coalescence, cosmological parameter

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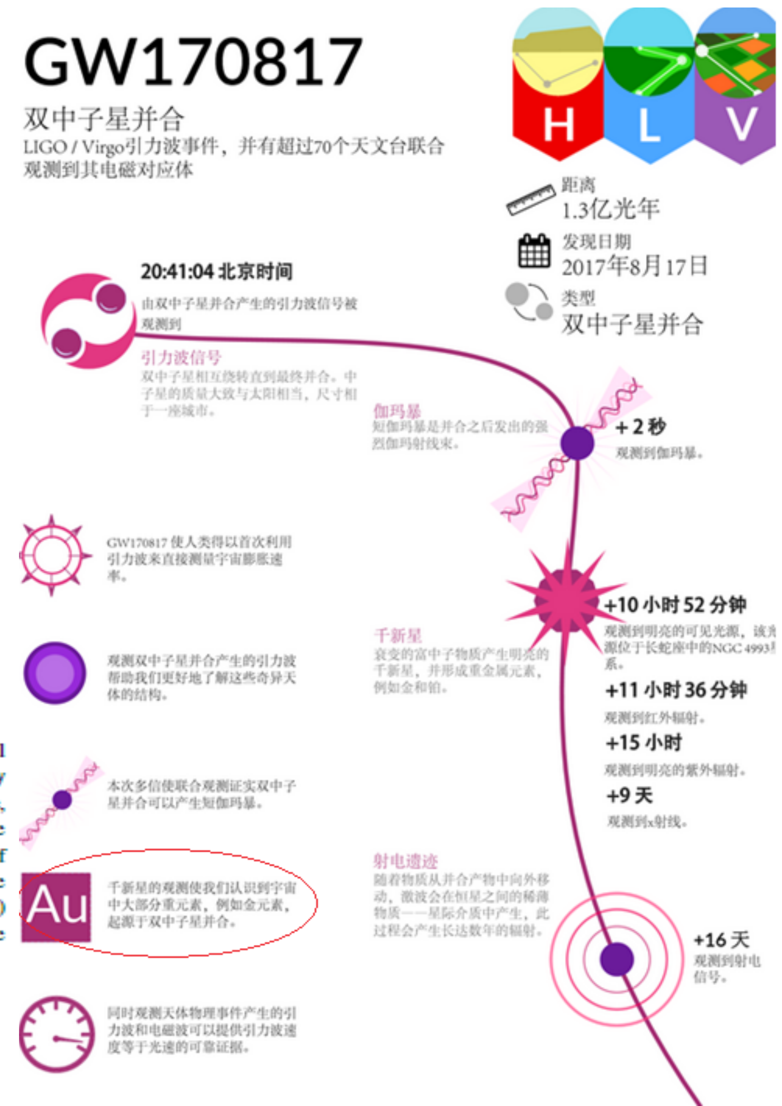
GW Sources as 'Standard Sirens'

❖ How to determine the 'redshift'?

- By observation of EM counterparts
- By fixing the host galaxies
- By redshift distribution of compact binaries
- By tidal effect on GW phases
- By mass distribution of compact objects



Gravitational-wave standard siren and cosmology

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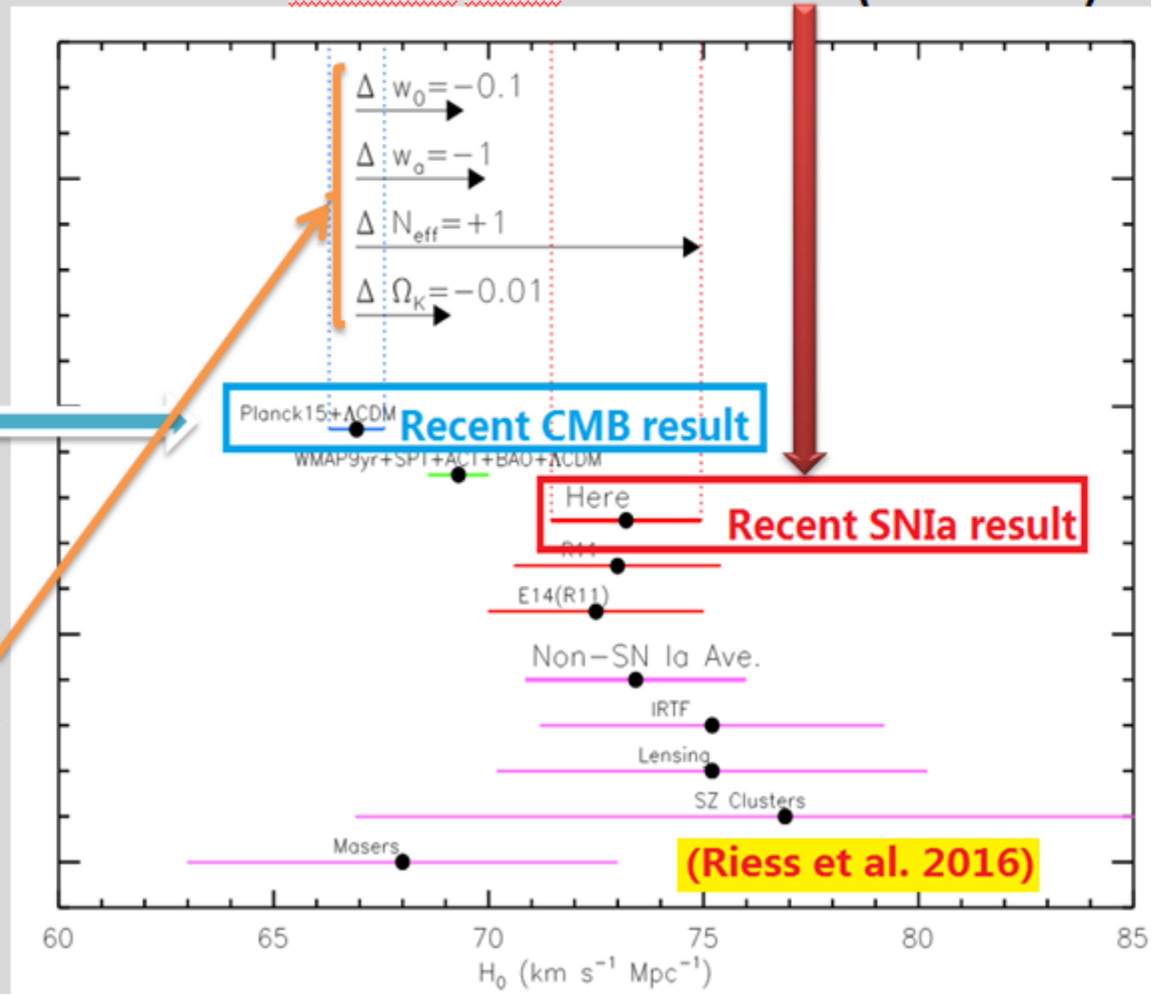
Measurement of Hubble constant

- The direct method to measure the Hubble constant is to use the Hubble law 'DL=z/H0', where DL is the luminosity distance, z is redshift, and H0 is Hubble constant. This law is satisfied at low redshift range for any cosmological model.

Recent result is derived from low-redshift SNIa observations (see below).

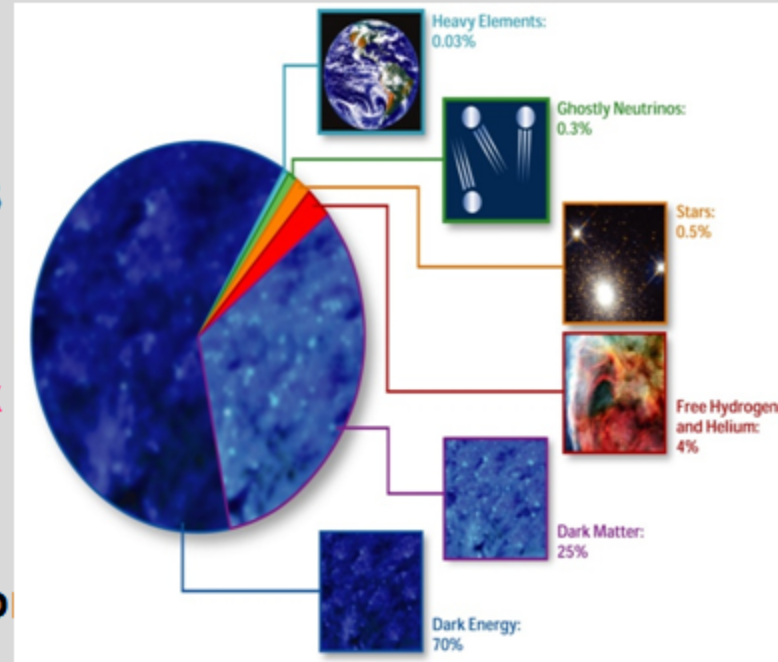
- The second indirect method is through the anisotropic power Spectra of CMB. Different H0 Follows different CMB spectra. **Recent result is derived from Planck observations, based on LCDM model (see right).**

PUZZLE: The tension between them exists at more than 3sigma level, which may indicate the new physics (e.g. dark energy, cosmic curvature neutrino, etc)



Determination of Dark Energy

- Since 1998, people discovered the an accelerating expansion of the universe by the observations of SNIa. Now the main observations include: SNIa, CMB, BAO, WL, GRB and so on, which all support the LCDM model.

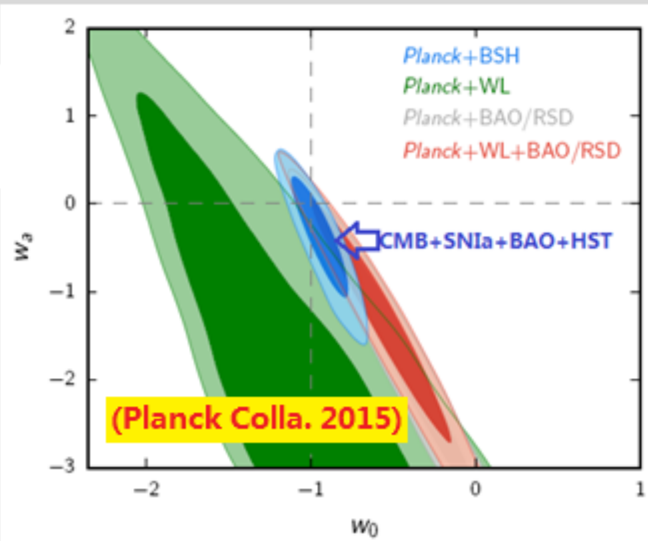


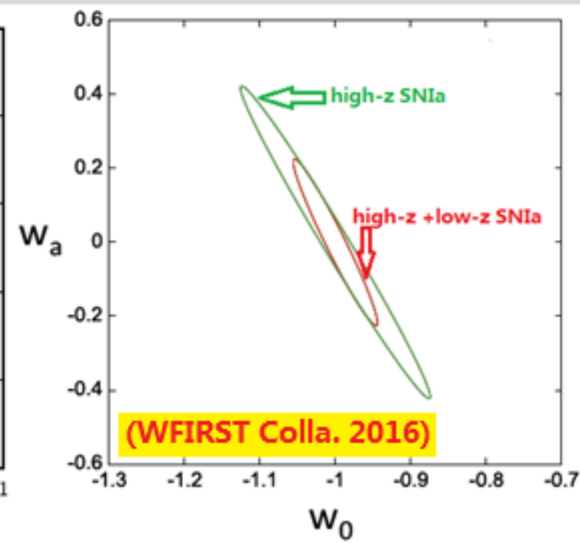
- In this model, ~70% energy is the so-called dark energy, mimic the cosmological constant.

- The key to distinguish various models is based on the observations of equation-of-state (EoS), which is parameterized as:

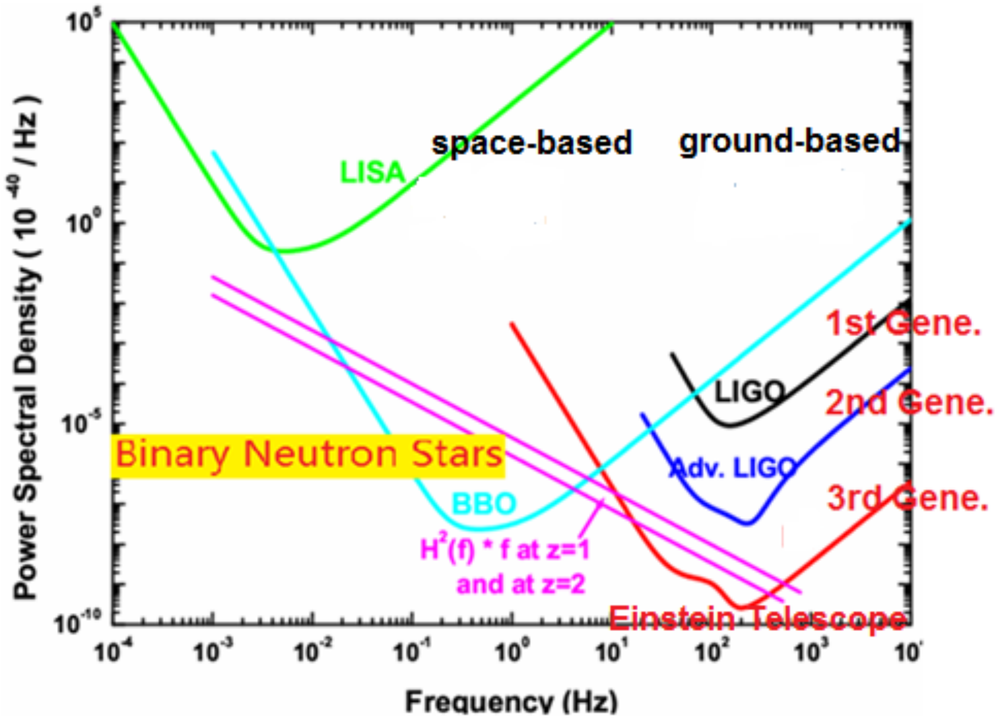
$$w(z) \equiv \frac{p_{\rm de}}{\rho_{\rm de}} = w_0 + w_a \frac{z}{1+z},$$

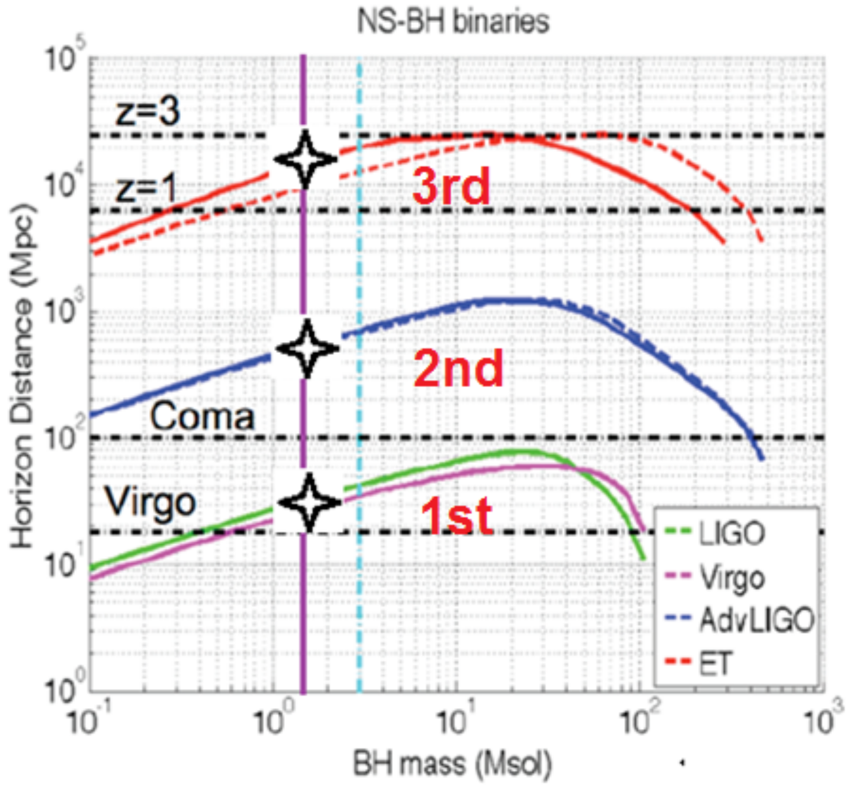
- Right figure presents the Current constraints and the potential constraints by WFIRST mission.





GW detectors





Event rate of BNSs and BBHs

- From current LHV observations, we have the event rate

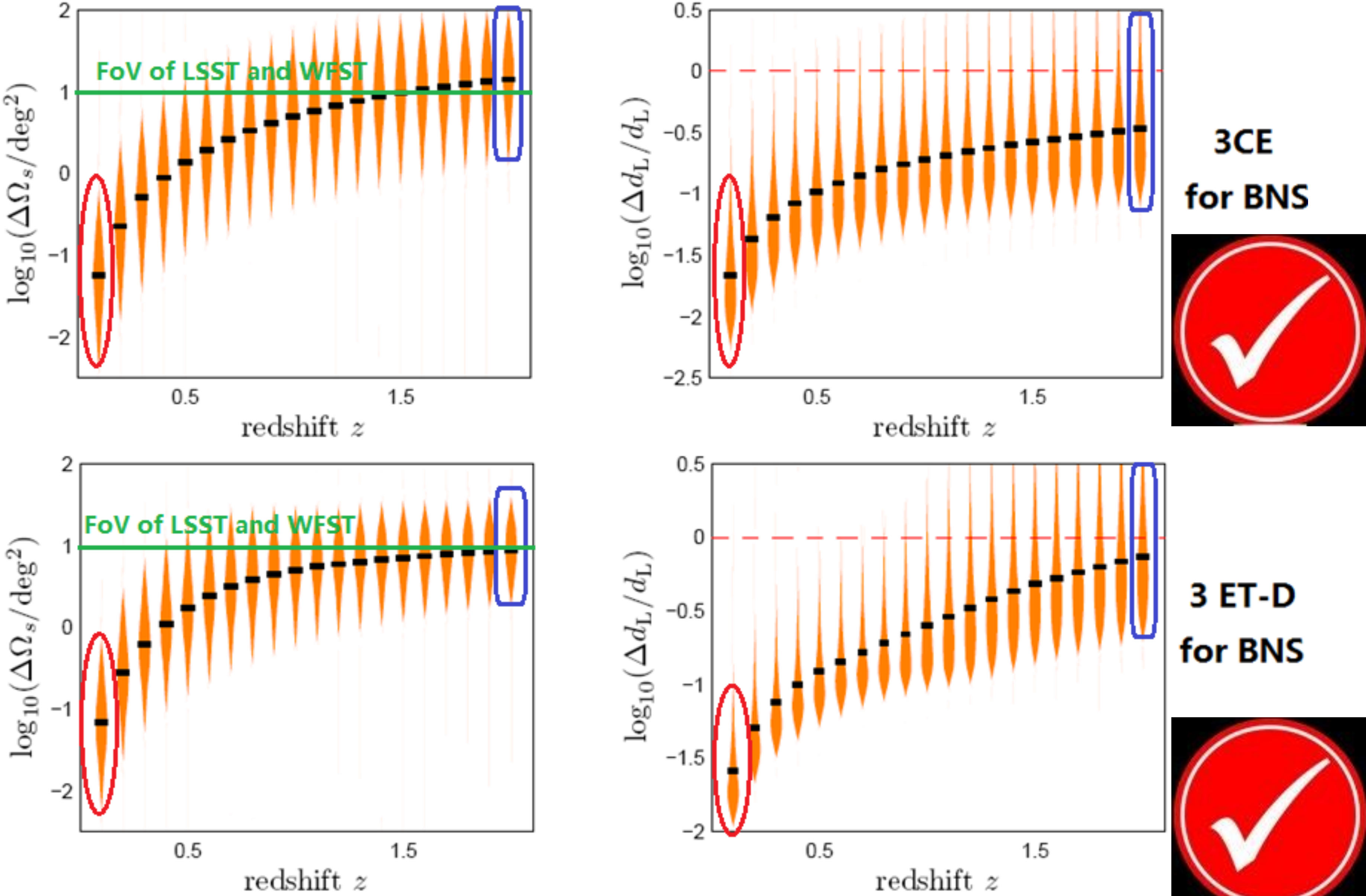
  * BBHs (12- 213)/Gpc^3/year,

  * BNSs (320 - 4720)/Gpc^3/year

- BBHs with $z<0.1$, the event rate is (3.7 - 66.5)/year;
  BBHs with $z<2$, the event rate is $(6.9*10^3 - 1.2*10^5)$/year.

- BNSs with $z<0.1$, the event rate is $(1.0*10^2 - 1.5*10^3)$/year;
  BNSs with $z<2$, the event rate is $(1.8*10^5 - 2.7*10^6)$/year.

Localization capabilities of 3-detector network



Electromagnetic counterparts and their detections (I)

- For BNS mergers, the primary EM counterparts are the kilonovas, gamma-ray burst and theirs afterglows.

- The emission of kilonovas are nearly isotropic, so for the low-z (i.e. $z<0.1$ or even lower) GW events, most events are expected to be discovered with kilonovas by LSST, WFST and so on, which can be treated as standard sirens to measuring Hubble constant.

For instance, WFST has FoV ~ 7 deg^2, and limiting magnitude r~23 (or 25). Note that the absolute magnitude of kilonova is -15 or -16.

- GW170817: $z=0.01$, $dL=(43.8^{+2.9}_{-6.9})$Mpc. According to Hubble law, the derived $h=(0.70^{+0.12}_{-0.08})$ (LVC collaboration 2017). The Hubble tension problem is expected to be sovled by GW observation in the near future.

Electromagnetic counterparts and their detections (II)

- For the high-z events, the expected EM counterparts are the short-GRBs and their afterglows.

- However, GRBs are believed to be beamed: the gamma radiation is emitted in a narrow cone more or less perpendicular to the plane of the inspiral. Therefore, only a small fraction of BNS mergers are expected to have observed GRBs and afterglows.

- In most previous works, we always roughly assume that ~ 1000 events in $z<2$ will be detected by both GW and GRB detections in 3G era. **The aim of our following work is to justify and quantify this assumption.**

Detection of “GW+sGRB+afterglow”

- **In this work, we investigate the detection rate and their distribution of BNS events, which can be jointed detected by GW, sGRB and afterglow.**

- **In this study, we consider the following detectors:**

  a. The GW detectors in 2G(LHV, LHVIK), 2.5G (LHVIK A+ networks), 3G (ET, CE, and 3G networks);

  b. The sGRB detectors (GECAM, EP, SVOM-ECLAIRS, Fermi-FBM, Swift-BAT and the similar detectors);

  c. The optical telescopes for afterglow detection (LSST, WFST et al.).

Binary neutron-star samples

- The event rate of BNS mergers with redshift **z** could be estimated as

$$N(z)dz = \frac{R_{\mathrm{BNSmergers},0} \times f(z)}{1+z} \frac{dV(z)}{dz} dz,$$

where R_{BNS} =(250-2810) /Gpc^3/year is the local BNS merger rate;
f (z) is the dimensionless redshift distribution function.

- The dimensionless redshift distribution function f (z) depends on the initial distribution of the BNS system and their delay time from generation to merger. In this work, we adopt the model derived in (Yuksel, H., Kistler, M. D., et al. ApJ., 683,L5, 2008).

- We simulate the random samples of BNSs accroding to this distribution.

GW detection

- For any given GW detector network, we estimate the detection SNR and the uncertainties of GW parameters (e.g. the luminosity distance d_L) with Fisher information matrix technique, developed in our previous work (Zhao & Wen, PRD, 2018).

- In this work, we choose SNR> 12 as GW signal's threshold.

- In order to estimate the uncertainties of d_L, we assume the redshift, event position and inclination angle can be fixed by their EM counterparts.

Short-hard GRB detection

- We assume all BNS mergers in our simulation has a relativistic jet with the Gaussian-shaped jet profile, which is derived from the observation of GW170817/GRB170817A event,

$$E(\iota) = E_0 \exp\left(-\frac{\iota^2}{2\iota_c^2}\right)$$

- In order to convent this energy profile to the luminosity profile, we assume that the burst durationT_{90} =2s (Abbott et al. 2017d) and the spectrum is flat with time during the burst. So the ray flux of each BNS mergers can be written as:

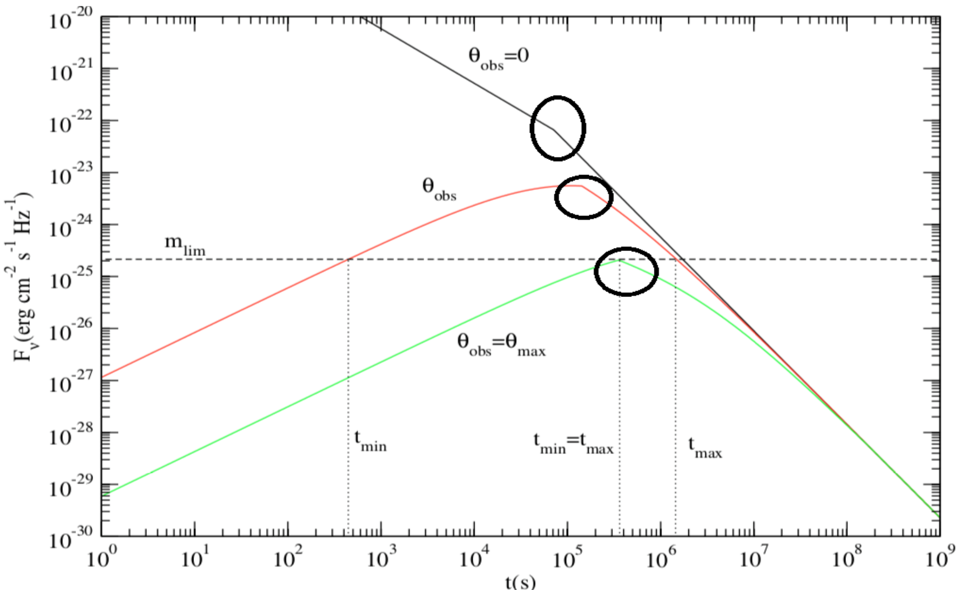
$$F_\gamma = \frac{E_0 \eta_\gamma}{4\pi D_L^2 T_{90}} \exp\left(-\frac{\iota^2}{2\iota_c^2}\right),$$

GRB afterglow detection

- The redshift of GRBs are usually measured through their optical afterglows.
- In this paper, we use the standard afterglow models (Sari et al. 1998) to estimate the afterglows on R band.
- The spectra and light curve is determined by the inclination angle (iota) , the half-opening angle (theta).
- We consider the models of

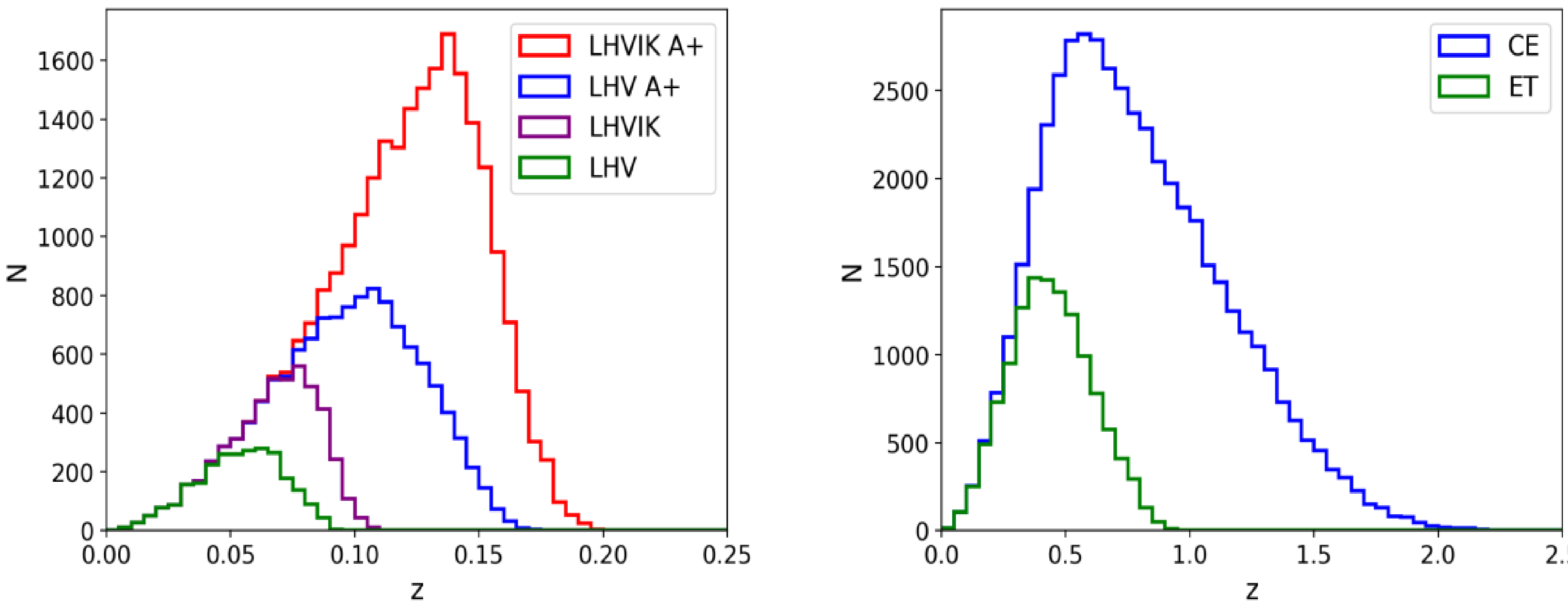
Theta=5deg, 10deg, 15deg.

The other parameters are adopted as the typical values.



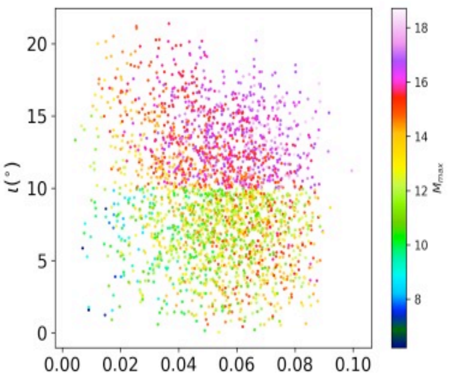
Event rate and redshift distribution

	Swift-BAT	SVOM-ECLAIRS	GECAM	Fermi-GBM	EP
LHV	0.131-1.473	0.226-2.538	0.870-9.784	0.620-6.970	0.092-1.032
LHVIK	0.264-2.486	0.452-5.084	1.727-19.420	1.230-13.824	0.183-2.058
LHV A+	0.679-7.634	1.169-13.145	4.281-48.116	3.007-33.794	0.464-5.218
LHVIK A+	1.390-15.628	2.394-26.911	8.571-96.335	5.958-66.972	0.940-10.568
ET	53.1-596.6	91.4-1027.3	251.7-2829.4	155.8-1751.6	33.5-376.5
CE	271.3-3049.9	467.2-5251.8	968.4-10884.8	538.5-6053.2	170.0-1911.4

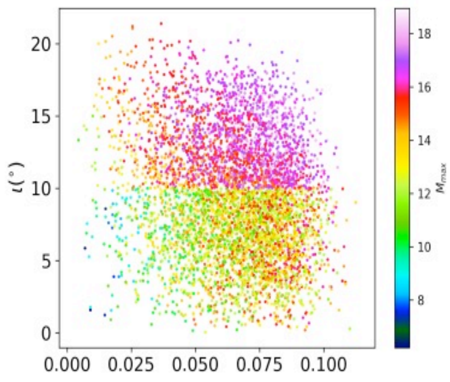


(a) 2G (b) 3G

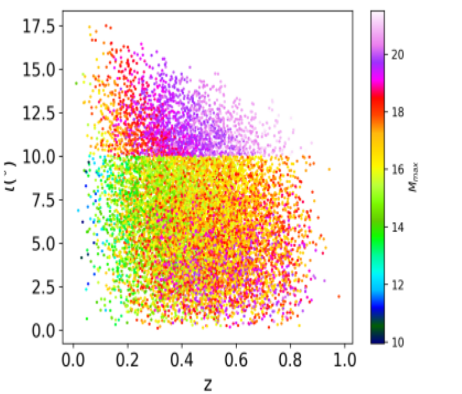
Distribution of “inclination angles” and “the magnitudes of afterglows”



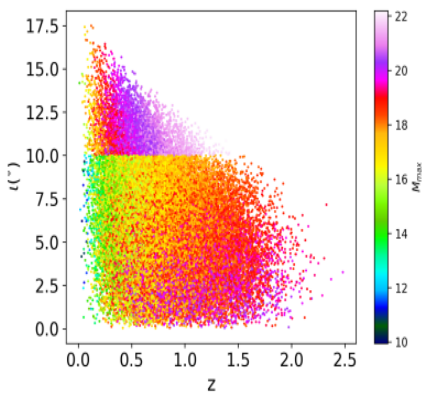
(a) LHV



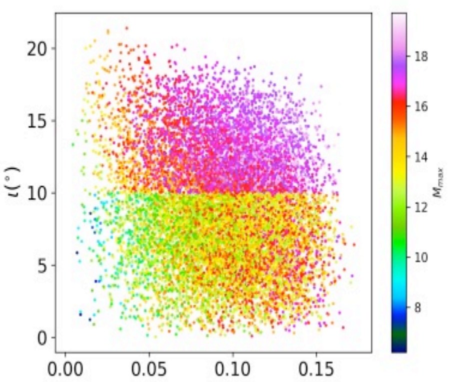
(b) LHVIK



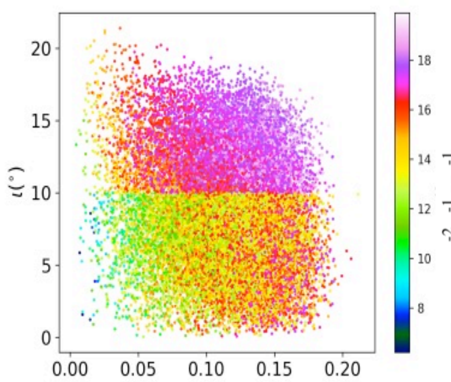
(e) ET



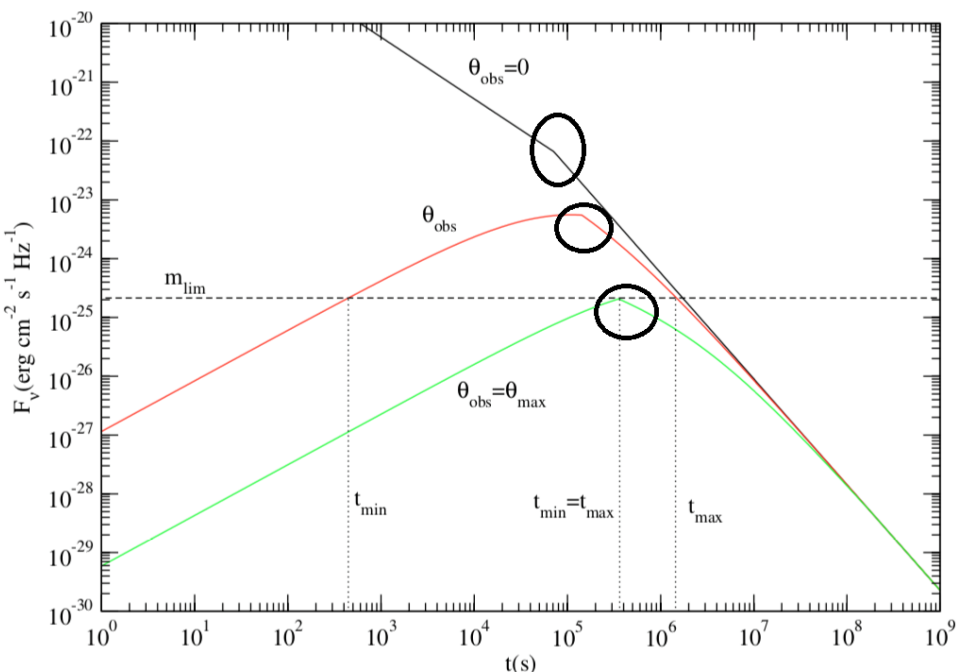
(f) CE



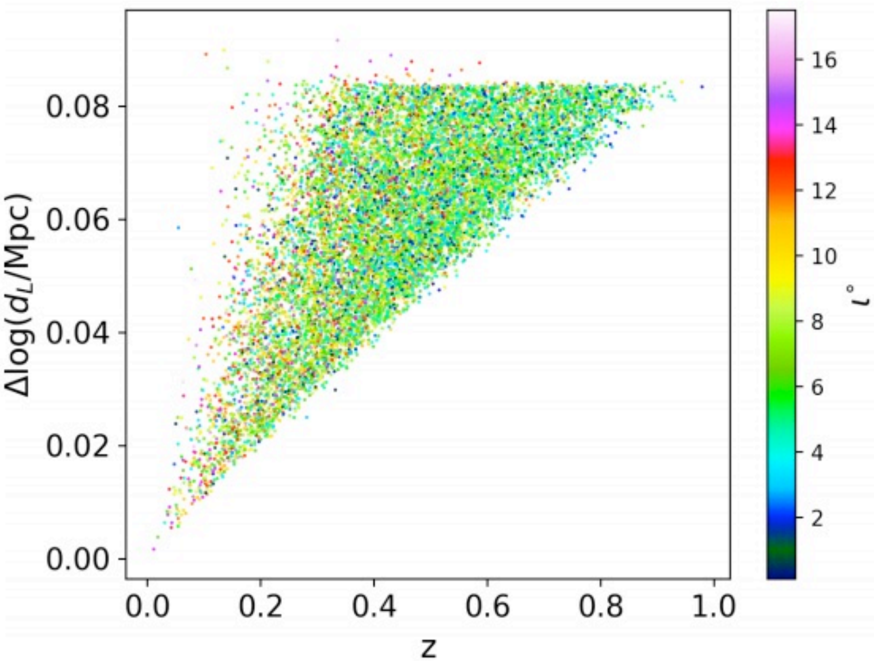
(c) LHVA+



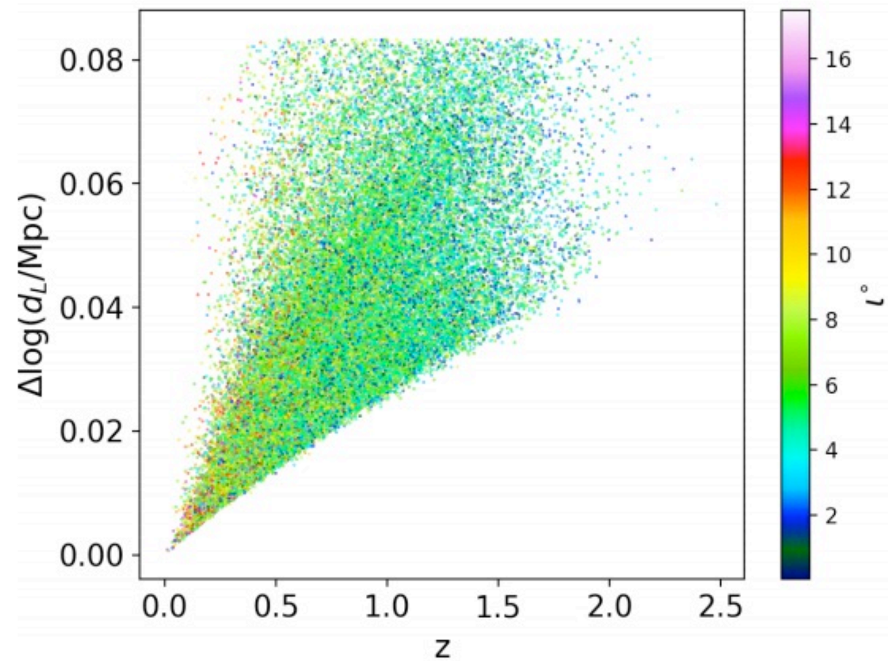
(d) LHVIKA+



Measurement of luminosity distance



(a) ET



(b) CE

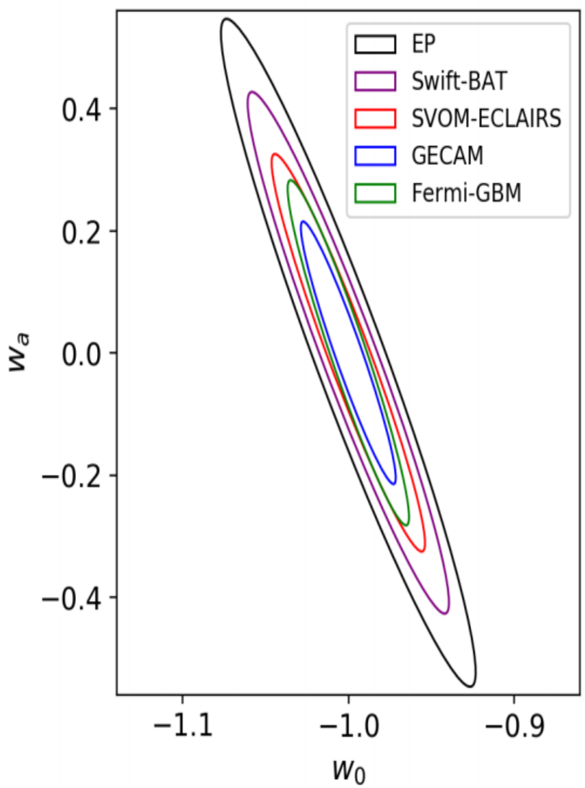
Total uncertainty of the luminosity distance is estimated by

$$\Delta \ln d_L = \sqrt{\sigma_o^2 + \sigma_l^2}$$

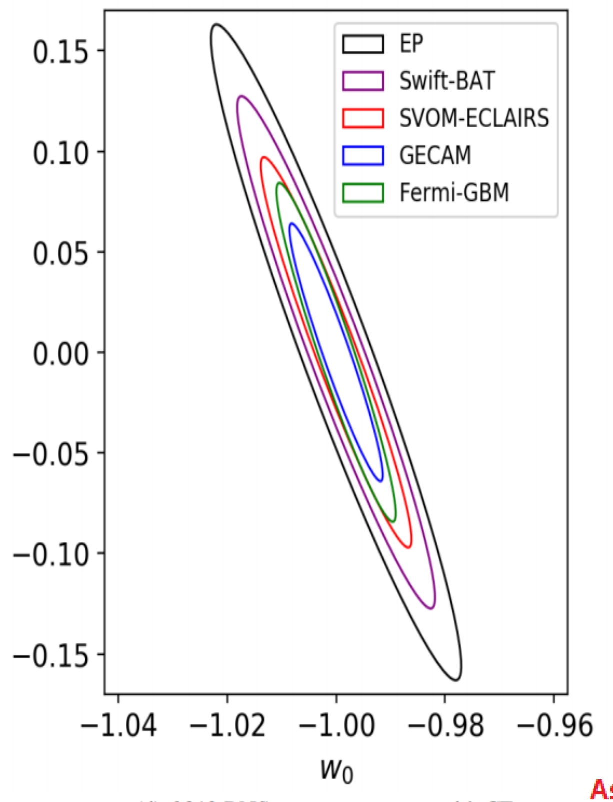
instrumental error σ_0 be estimated using a Fisher matrix

distance error from weak lensing to satisfy $\sigma_l = 0.05z$

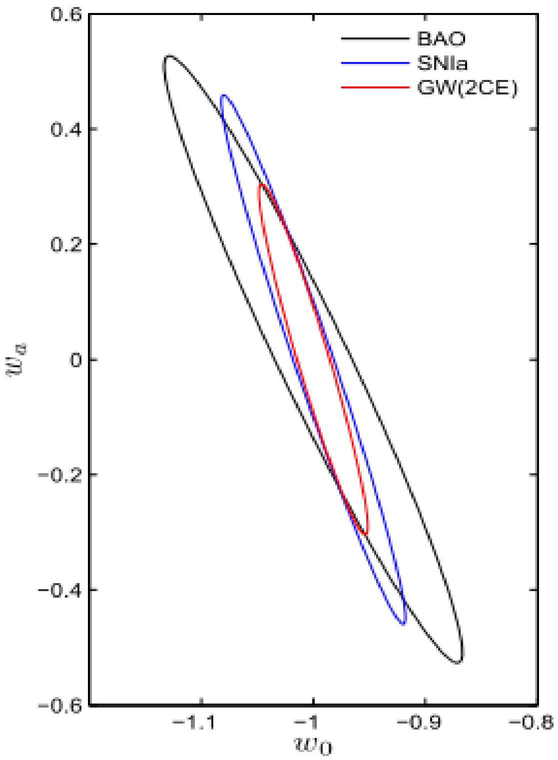
Potential constraints on dark energy



(c) 250 BNS mergers per year with CE.



(d) 2810 BNS mergers per year with CE.



Assuming 1000 face-on BNSs evenly distributed in z<2 (Zhao & Wen, PRD, 2018).

Conclusion

- 3G GW detectors + GECAM-like detectors can detect ~(200-10000)/year BNSs with detectable GRB afterglows. While, for 2G or 2.5G GW detectors, the detection rate is ~(1-100)/year.
- These souces distribute at $z<2$ for CE, and $z<1$ for ET, $z<0.2$ for 2.5G detectors, and $z<0.1$ for 2G detectors, with inclination angle < 20deg (nearly face-on).
- In 3G era, all these sources have excellent determination for luminosity distance, which can act as “standard sirens” for dark energy measurement.

Defect of standard sirens

- Similar to SNIa and BAO, in order to measure dark energy, GW standard sirens should be combined with CMB observations.

- The "inclination angle" of BNSs should be measuered by EM counterparts, which is crucial for distance measurement of BNSs by GW.

THANK YOU!