Gravitational Wave and Large-Scale Structure

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based on
S. Camera & AN, PRL 110, 151103 (2013)
T. Namikawa, AN, & A. Taruya, PRL 116, 121302 (2016)
T. Namikawa, AN, & A. Taruya, PRD 94, 024013 (2016)

Gravitational Waves and Cosmology
Oct. 17-21, 2016 @ DESY, Hamburg, Germany

Standard siren

GW from a compact binary can be a cosmological tool to measure distance to a source. [Schutz 1986, Holz & Hughes 2005]

GW phase

$$\dot{f}(t) \propto \{(1+z)M_c\}^{5/3} f^{11/3}$$

GW amplitude

$$h(t) \propto \frac{\{(1+z)M_c\}^{5/3} f^{2/3}}{D_L}$$

From observational data,

$$h,\ f,\ \dot{f}$$

⇓

$$M_z \equiv (1+z)M_c$$

⇓

luminosity distance

$$D_L$$

Standard siren as a probe of cosmic expansion and beyond

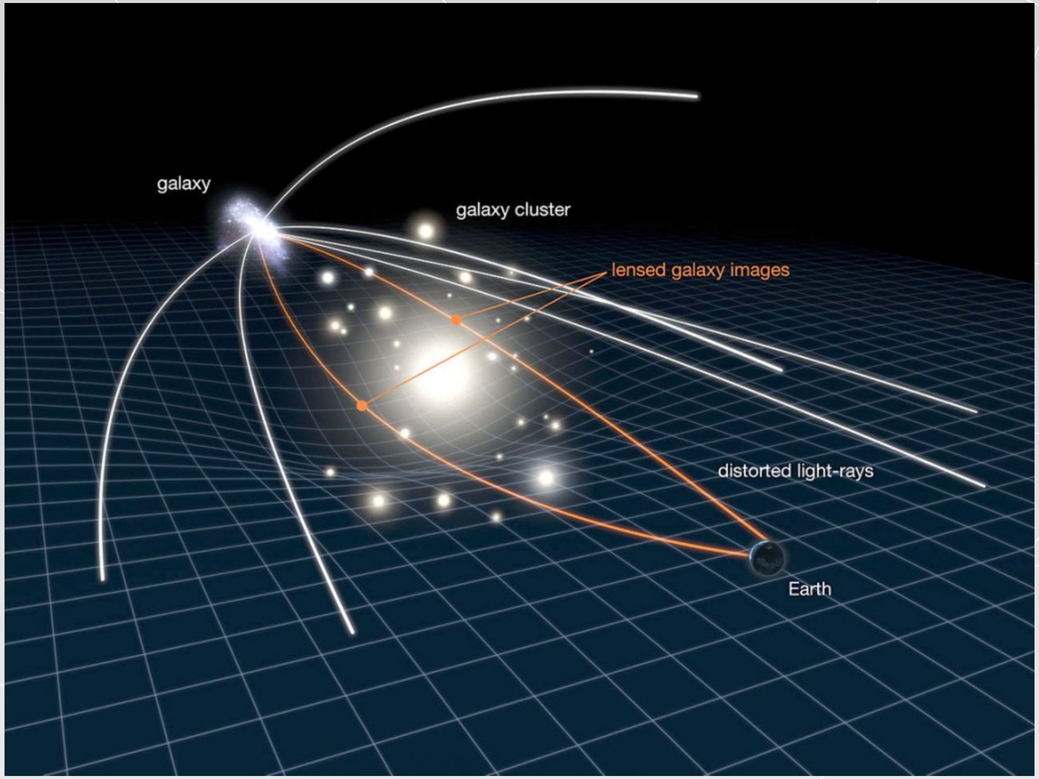
Taruya-san's talk yesterday

- With a standard siren, one can measure luminosity distance to a source directly without any distance ladder.
- Combining the luminosity distance with redshift information, cosmic expansion is measured.
- Even without redshifts, GW source clustering allows us to extract cosmological information.

In this talk, I will focus more on GW and large scale structure, and its cosmological applications.

Gravitational lensing of GW

[Wang, Stebbins & Turner 1996, Holz & Wald 1998]



- GW traces its null geodesic and is lensed by galaxies and galaxy clusters.

- Source is a compact binary.

⇓

No shear (too small image), but "brightness" of GW is magnified or demagnified.

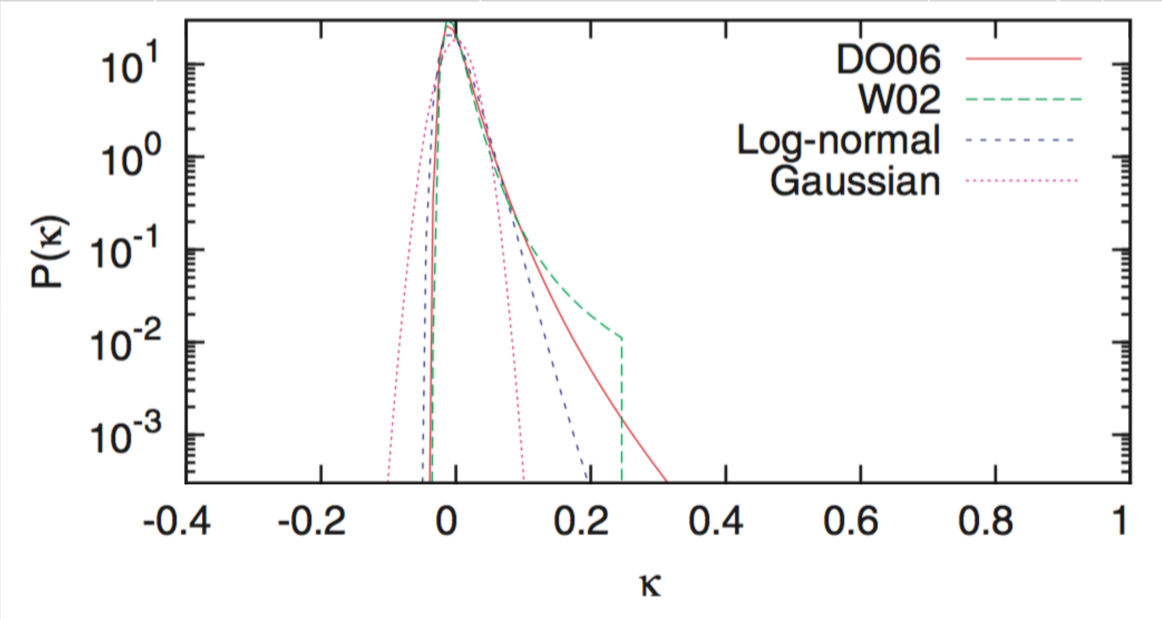
- Apparent luminosity distance

$$D(\mathbf{x}) = \bar{D}\left\{1 + \underline{\kappa(\mathbf{x})}\right\}$$

"magnification"

Standard siren at cosmological distance

➢ lensing PDF



[Shang & Haiman 2011]

lensing PDF is non-Gaussian, long-tailed.

luminosity distance error is monotonically increasing

$$\sigma_{\rm lense}(z) = 0.066 \left(\frac{1-(1+z)^{-0.25}}{0.25} \right)$$

[Hirata, Holz, & Cutler 2010]

➢ impact on GW observations

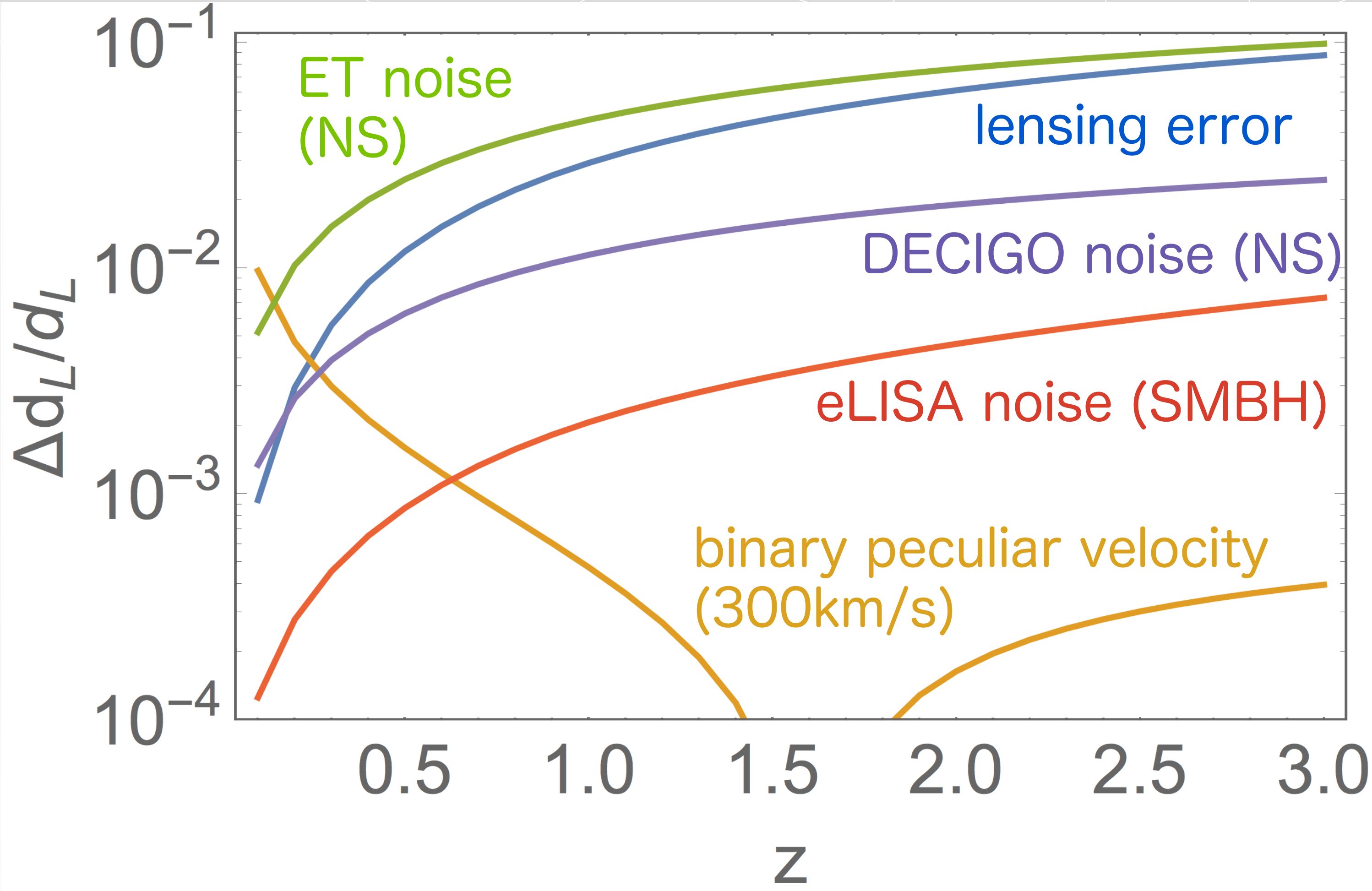
current ground-based detectors
NS: < ~300 Mpc,   BH: < z~0.1 ⟷ local universe

ET, LISA, DECIGO   z~1-10 ⟷ cosmological distance

Measurement accuracy of distance

$$\frac{\Delta d_L(z)}{d_L(z)} = \sqrt{\sigma^2_{\rm inst}(z) + \sigma^2_{\rm lens}(z) + \sigma^2_{\rm pv}(z)}$$

for a single binary, 3yr obs



The determination accuracy is limited by lensing error at almost all z.

Random error can be reduced by observing a large # of binaries, but may still contribute.

Beyond background cosmology

- Lensing is not noise but signal [Cutler & Holz 2009]

  Variance in luminosity distance carries information about cosmic expansion and matter clustering, depending on cosmological parameters.

- models for cosmic accelerating expansion

  dark energy (scalar field etc.) vs modification of gravity

  Current observational data (SNe + BAO + CMB + …) are consistent with the cosmological constant.

  The problem is that most models can mimic the LCDM as a special case by tuning their model parameters.

⇓

To discriminate the models, need to go to a perturbative level.
(growth of matter power spectrum, gravitational lensing, etc.)

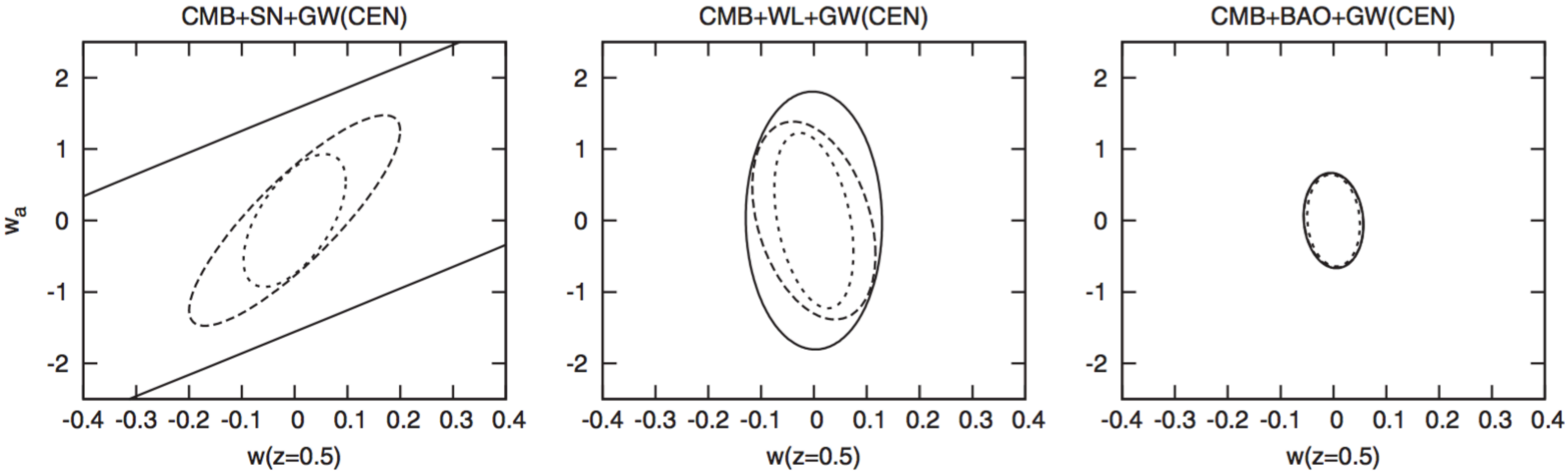
GW lensing cosmology with redshift information

1D cosmology from lensing PDF

Lensing magnification PDF depends on cosmological parameters.

[Hirata, Holz, & Cutler 2010]

LISA case



solid : CMB + (SN or WL or BAO) [DETF stage-III]
dashed: adding 10 SMBH GW events with LISA
dotted: adding 30 SMBH GW events with LISA

Brief summary of 2D method

[Cutler & Holz 2009, Camera & AN 2013]

1. For each NS binary,

$$D(\mathbf{x}) = \bar{D}\{1 + \kappa(\mathbf{x})\}$$

GW observation ($D(\mathbf{x})$)

z from EM observations ($\bar{D}$)

$\longrightarrow$ κ is given as a function of cosmo. parameters.

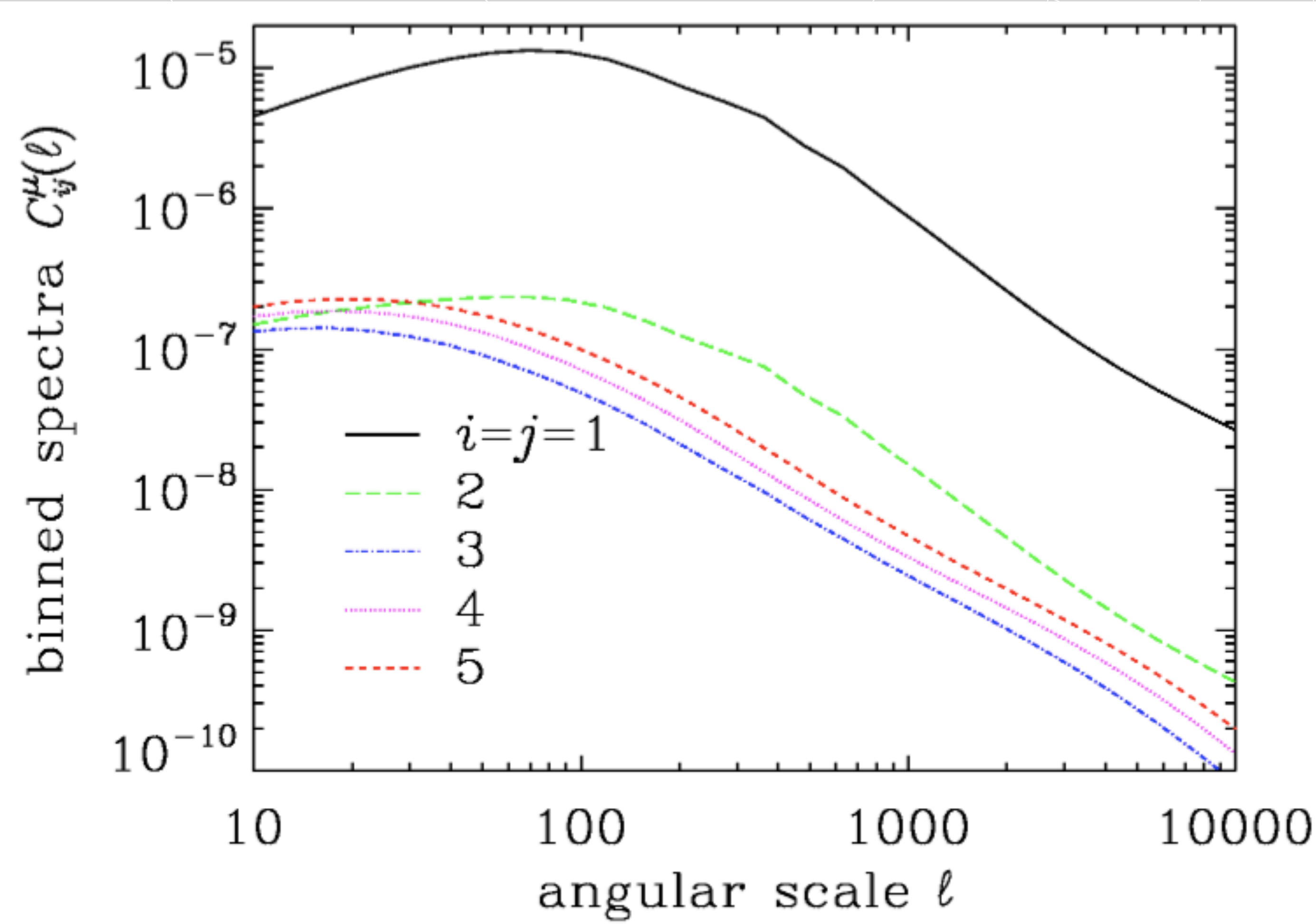
⇓

2. Combining all NS binaries, construct magnification sky map

⇓

3. Compute a magnification angular power spectrum
and estimate cosmological parameters

Magnification angular power spectrum



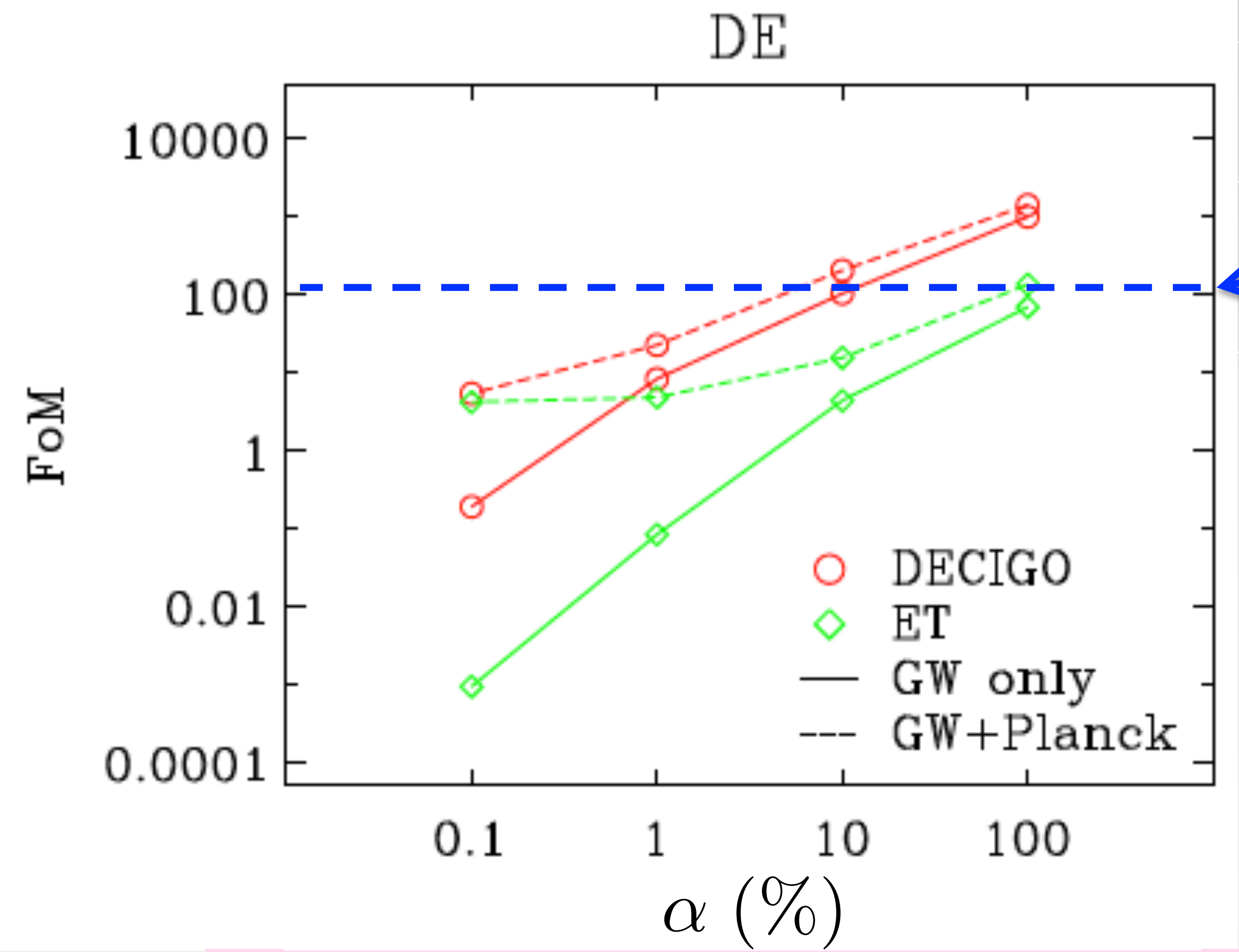
- 5 redshift bins in the range $z = 0.1 - 2$

$$\Delta z = 0.38$$

- power spectrum from each redshift bin can be measured with tomographic method.

Sensitivity to EOS of dark energy

3yr observation, $\mathrm{FoM} \sim (\Delta w_0 \Delta w_a)^{-1}$



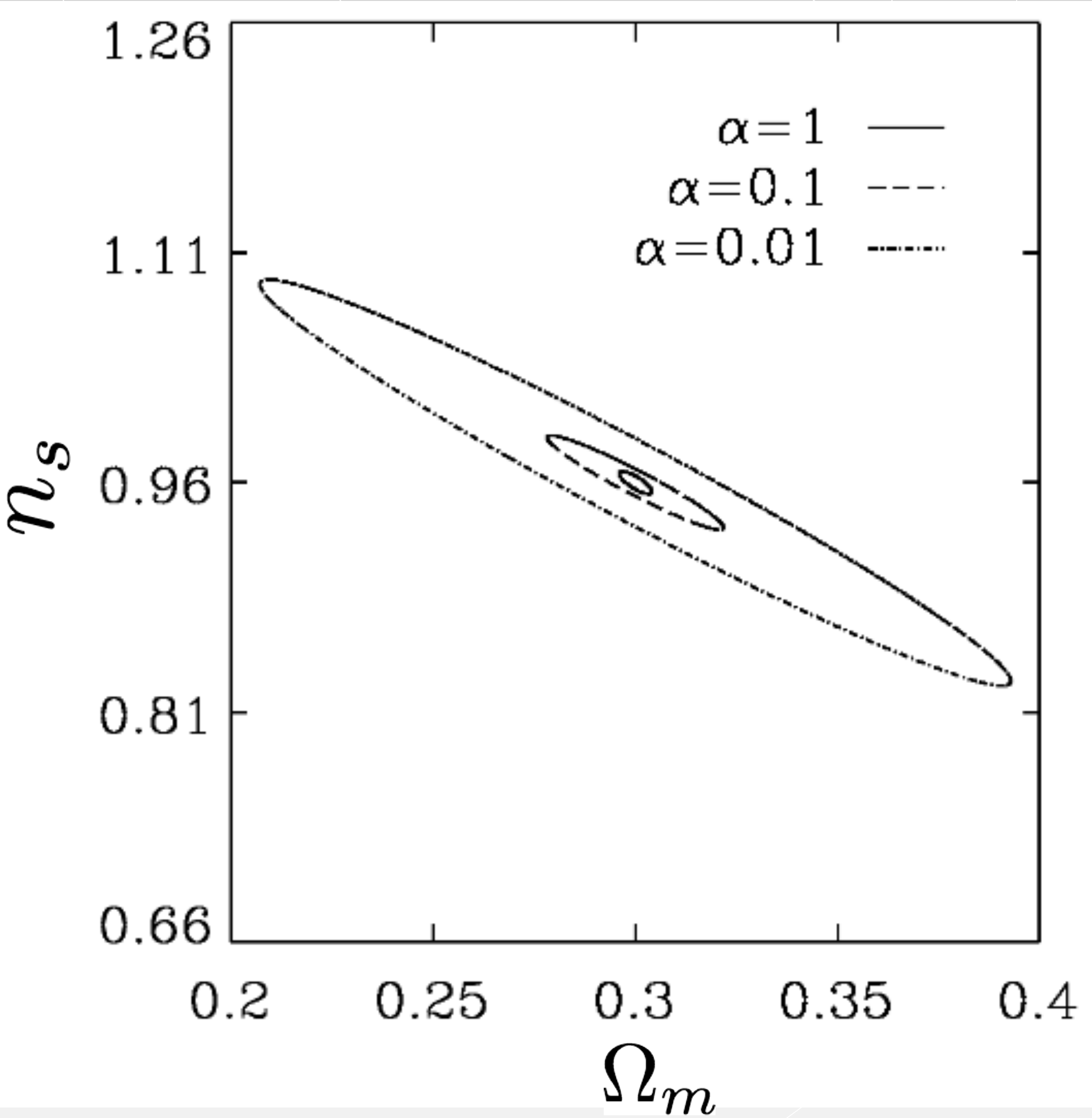
Fraction of sourfce redshift identification

EM observations in early 2020's (DETF stage-III)

ET exceeds Planck when $\alpha \geq 1\%$

DECIGO exceeds Planck when $\alpha \geq 0.1\%$

Other cosmological parameters



α : fraction of redshift-identified sources

- GW observations can also extract information about matter inhomogeneities.
- What can be measured is $n_s, \sigma_8,$ growth rate etc.
- useful to distinguish DE and modified gravity

only if nearly complete redshift identification is assumed

Redshifts are really obtained?

- using galaxy catalog

Future galaxy surveys (JDEM, WFIRST, Euclid etc.) will observe 10^8 galaxies at 0.5 < z < 2. But these are a part of host galaxies for GW events.

$\alpha \sim 10^{-4}$ with DECIGO, $\ll 10^{-4}$ with ET and LISA

The method to treat redshift distribution statistically may be biased too much. More careful study is necessary.

If GW sources are limited to NS binaries

- using short GRB – NS binary association

Given the half-opening angle of a jet is 10 deg, $\alpha \sim 2 \times 10^{-3}$

- narrow distribution of NS mass

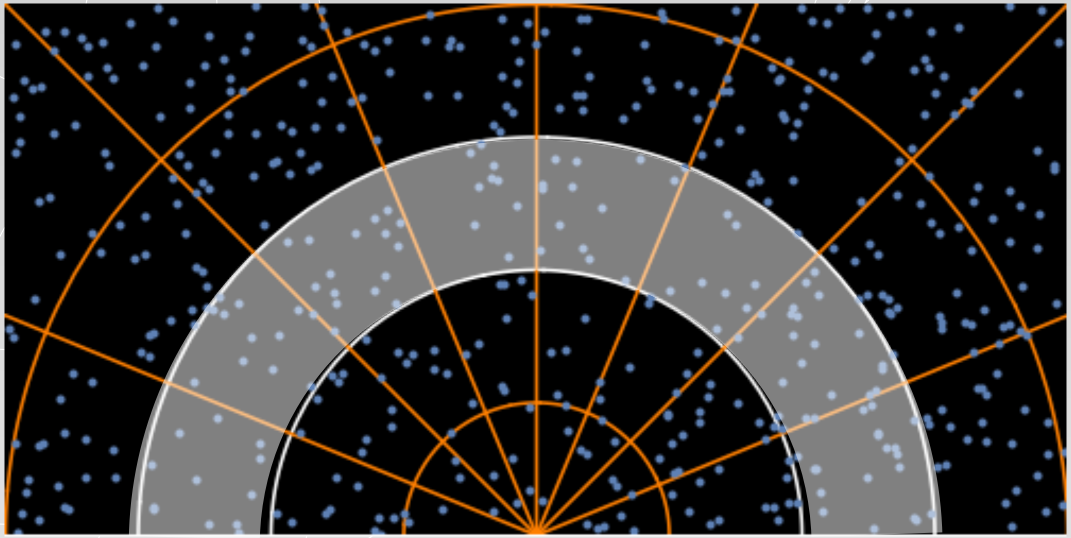
- tidal deformation of NS with known EOS

GW cosmology without redshift information

anisotropy of luminosity distance

[Namikawa, AN, Taruya 2016 (PRL)]

deviation of luminosity distance
from the averaged one
in i-th distance bin



i-th distance bin

$$\hat{s}_i(\Omega) = \frac{\hat{d}_i(\Omega) - \hat{d}_i}{\hat{d}_i}$$

$$= \frac{1}{\bar{\bar{d}}_i} \int_{D_i^{\mathrm{min}}}^{D_i^{\mathrm{max}}} dD\, \bar{n}(D)\{\delta(\mathbf{x}) + \gamma(D)\kappa(\mathbf{x})\}$$

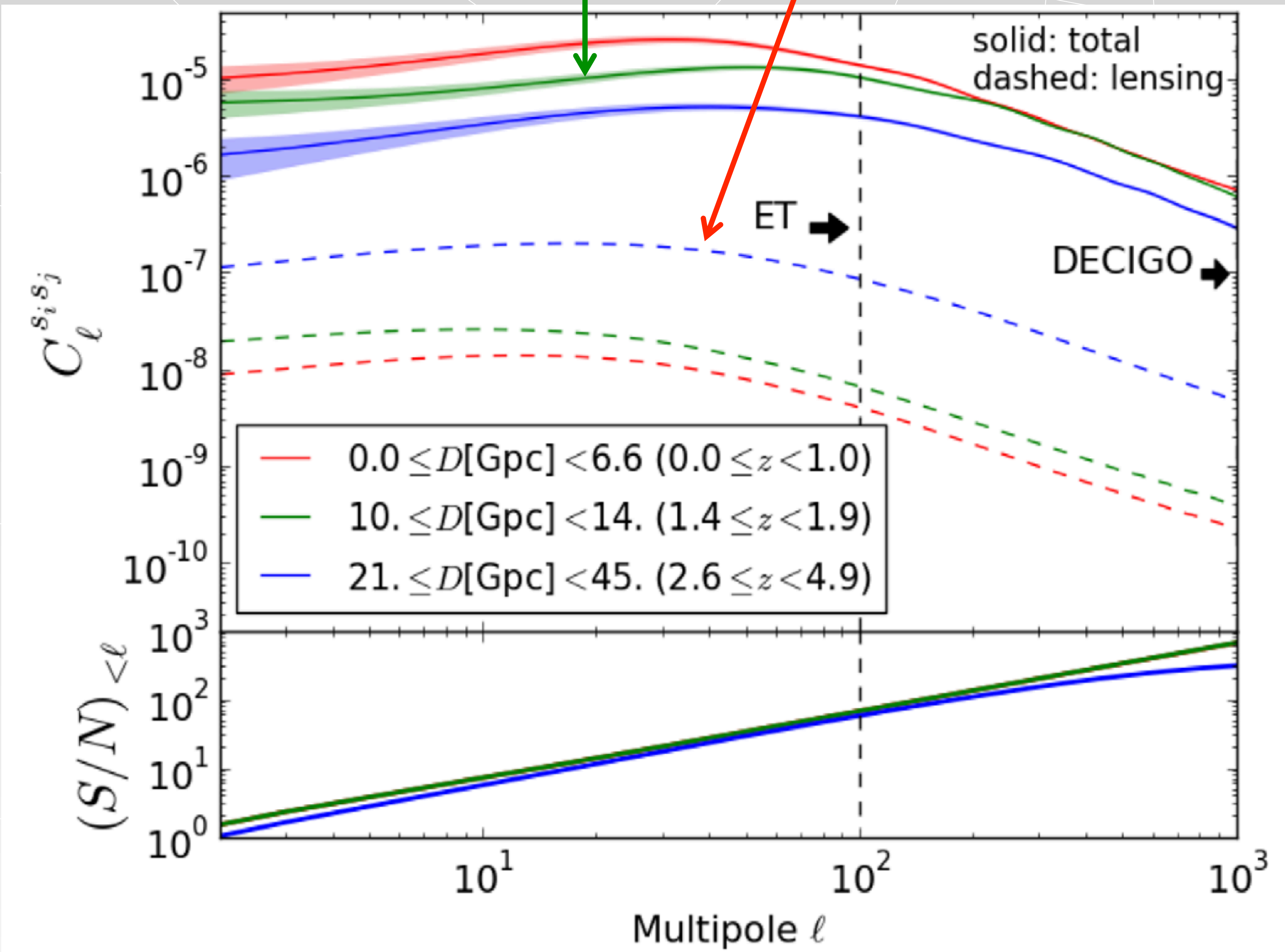
average number density ($\bar{n}(D)$)

clustering ($\delta(\mathbf{x})$)

weak lensing ($\kappa(\mathbf{x})$)

angular power spectrum

$$C_\ell^{s_i s_j} = C_\ell^{\delta_i \delta_j} + C_\ell^{\kappa_i \kappa_j} + C_\ell^{\delta_i \kappa_j} + C_\ell^{\kappa_i \delta_j}$$



Clustering spectrum dominates the signal.

Lensing spectrum is a small contribution.

Angular resolution of GW observation limits maximally observable ℓ .

cosmological implications

- non-Gaussianity of large-scale structure with ET

$$\sigma(f_{\rm NL}) \approx 0.54$$

comparable or better than Euclid

- cross-correlation of clustering

GW (ET) x Planck S/N~31

GW (ET) x CMB stage IV S/N~43

- cross-correlation of weak lensing

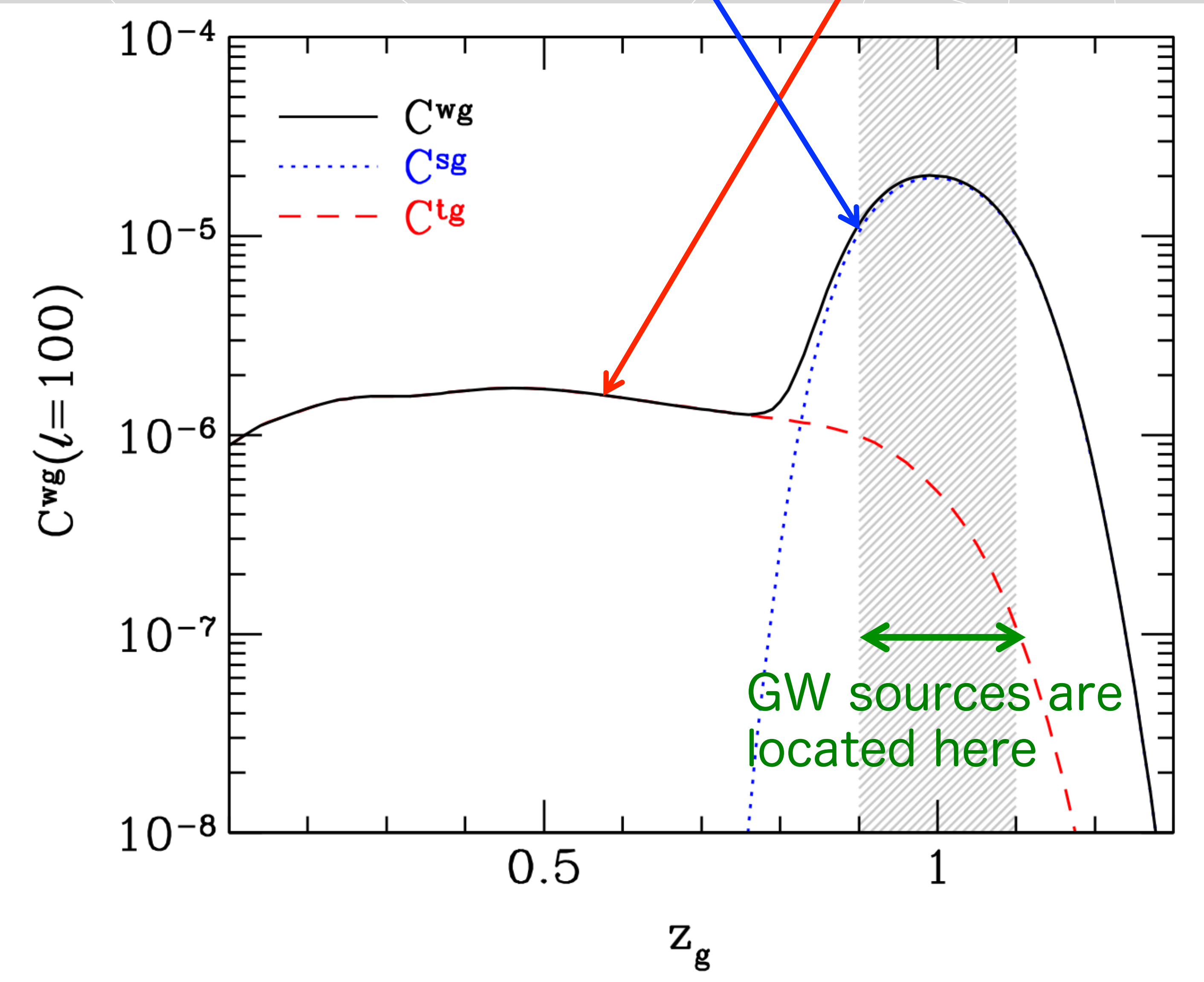
GW (ET) x Euclid S/N~16

- A lot of applications of GW observations to cosmology

galaxy cross-correlation

$$C_\ell^{s_i g_j} = C_\ell^{\delta_i g_j} + C_\ell^{\kappa_i g_j}$$

[Oguri 2016]



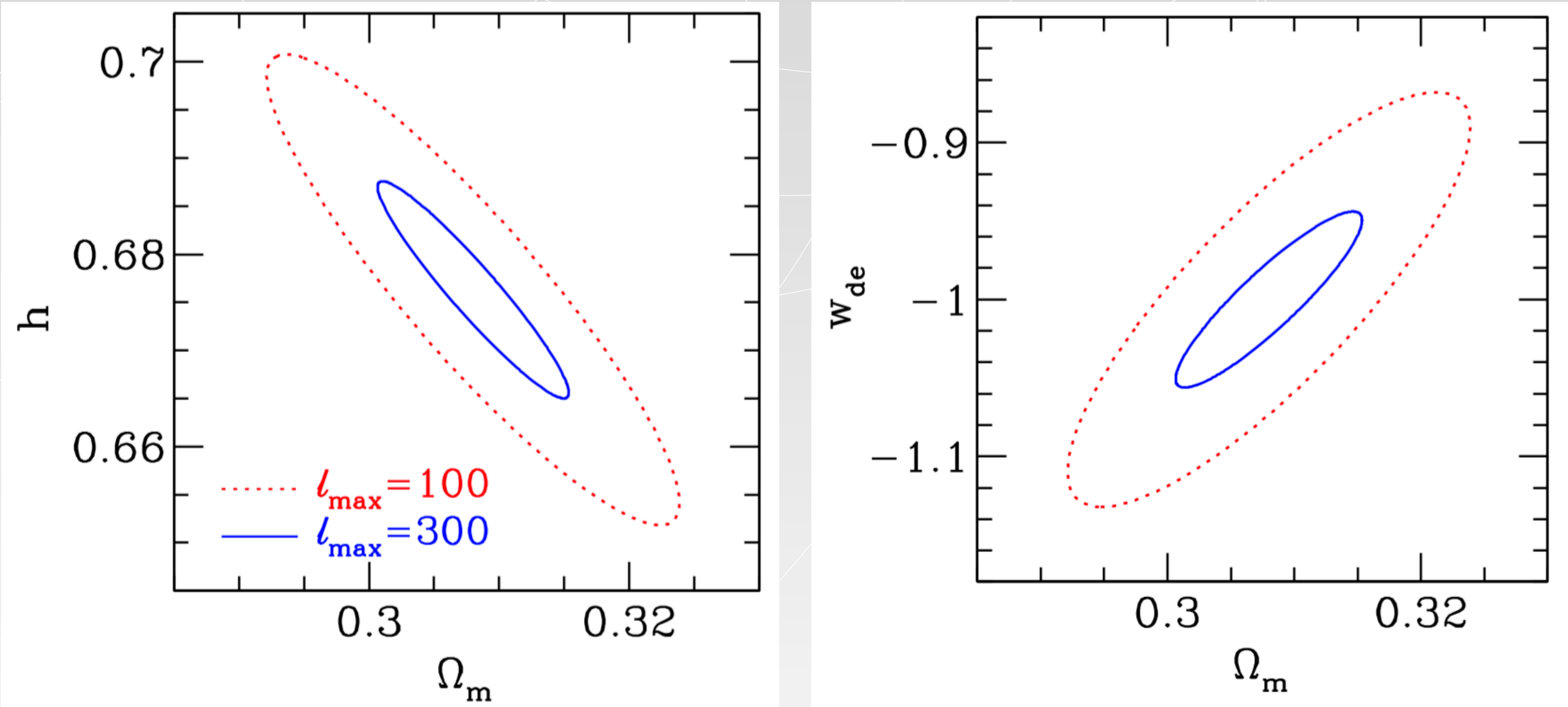
A peak shows up at true redshift range of GW sources.

statistical redshift ($z - D$ relation in a statistical sense)

constraints on cosmological parameters

GW (ET) x galaxy survey (Euclid) $0.3 < z < 1.5$

$T_{\rm obs}\dot{n}_{\rm GW} = 3\times 10^{-6} h^3 {\rm Mpc}^{-3}$ including BH-BH & NS-NS



Summary

- Lensing is not noise but signal

  Variance in luminosity distance carries information about cosmic expansion and matter clustering.

- GW lensing cosmology with redshift information

  Not only cosmic expansion but matter clustering are sensitively probed. However, redshifts would be problematic.

- GW cosmology without redshift information

  Redshift information is unnecessary.
  The measurement of non-Gaussianity would be one of most powerful applications. By correlating with galaxy or CMB data, a lot of cosmology would be possible. Need more investigations.