GW propagation as a probe for cosmology and beyond

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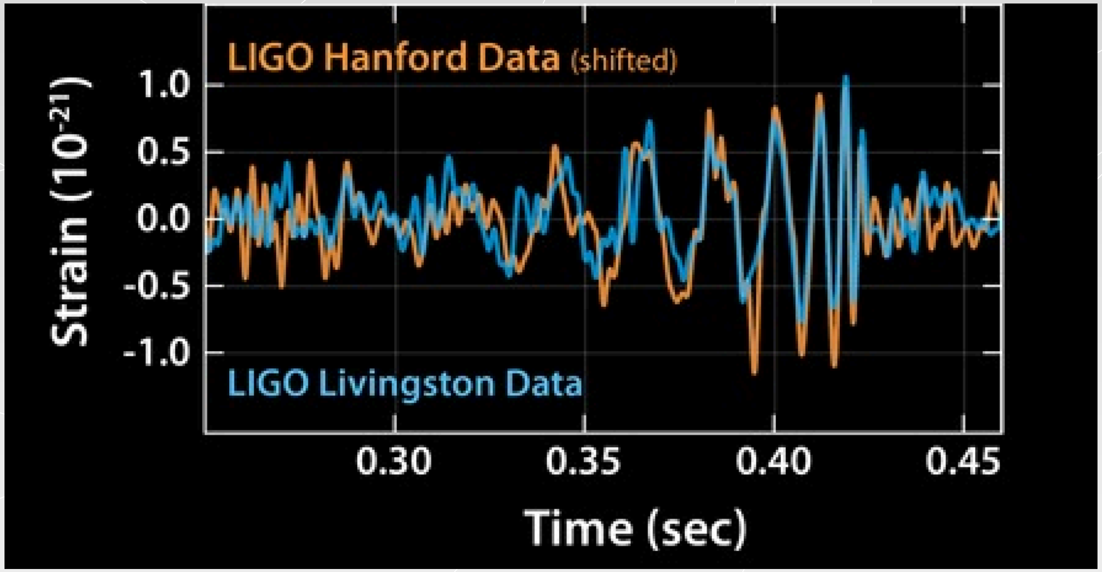
Gravitational Waves

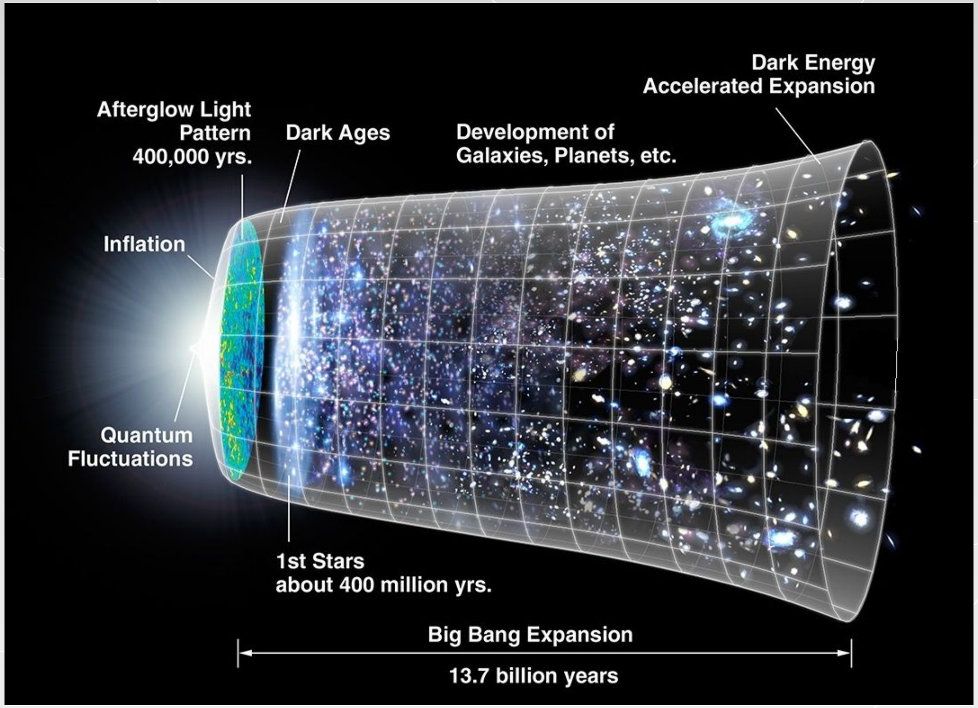
- GWs have been detected! (GW150914, GW151226)
  [LIGO Scientific Collaboration 2016]



- BBH merger rate $9 - 240\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$
- aLIGO is expected to detect more events $\sim 100\,\mathrm{yr}^{-1}$

This opens new windows to astronomy, cosmology, and gravity.

GW and late-time cosmology



- Cosmic expansion changes distance to a GW source and adds extra GW phase.
- Large scale structure deforms a GW waveform, mainly in amp. (gravitational lensing)
- GW source location clusters and may trace matter dist.

GW as a probe for cosmic expansion

Standard siren (1)

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

GW phase

from $L_{\rm gw} = -\dfrac{dE_{\rm orbit}}{dt}$

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

GW amplitude

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

From observational data,

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

↓

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

↓

luminosity distance

$$D_L$$

Standard siren (2)

In principle, redshift and chirp mass are degenerated.

Assuming the redshift is determined by EM observation of a host galaxy or an EM counterpart,

M_c is separately determined.

$z - D_L$ relation is obtained.

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Advantages of cosmological-expansion measurement by GWs

- No need of distance ladder.
- Consistency test of Ia-type SNe observation.
- Accurate cosmological probe (less systematic err)

identifying a host galaxy

[AN 2016]

If a host galaxy for a GW event is uniquely identified,
the redshift is obtained from EM obs of the galaxy.

No need to prepare a complete galaxy catalog.

Applicable not only to NS binaries but also to BH binaries.

Ability to identify a host galaxy strongly depends on sky localization error.

Statistical study of parameter estimation

Parameter error estimation with a Fisher information matrix

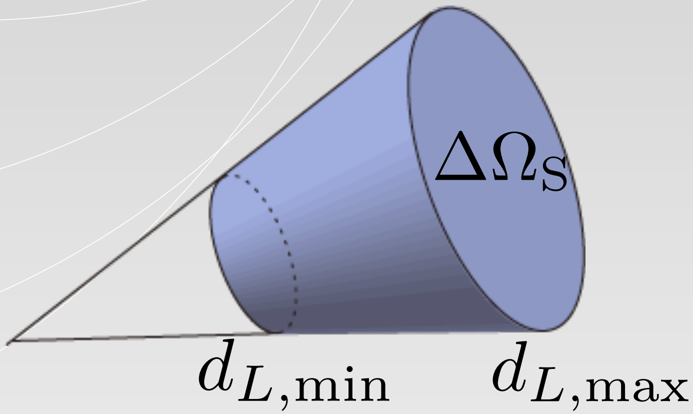
- log-flat mass distribution (1/m) with
  $5\,M_\odot < m_1, m_2 < 100\,M_\odot$ and $M < 100\,M_\odot$
- constant merger rate
- 10^4 nonspinning binaries with S/N > 8
- orbital inclination: uniformly random
- sky position: uniformly random
- phenomenological IMR GW waveform [Khan et al. 2016]
- detector network: aLIGOx2 + aVIRGO (HLV)
  aLIGOx2 + aVIRGO + KAGRA (HLVK)

Error volume

For each GW event, 3D sky error volume $(\Delta d_L, \Delta\Omega_{\rm S})$ is obtained.

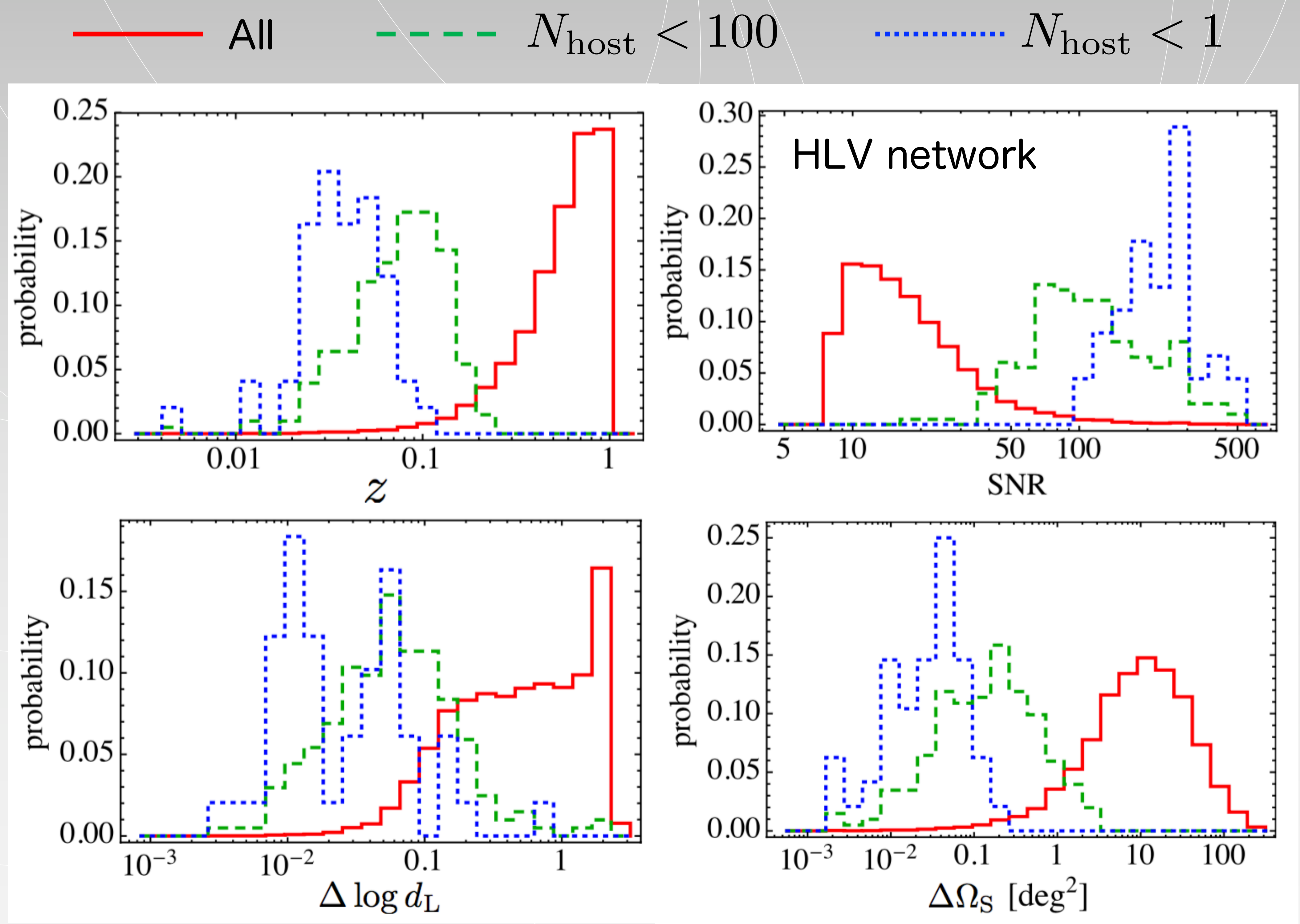
# of host galaxies in the error volume

$$N_{\rm host} \equiv n_{\rm gal} \{V(d_{L,{\rm max}}) - V(d_{L,{\rm min}})\} \frac{\Delta\Omega_{\rm S}}{4\pi}$$

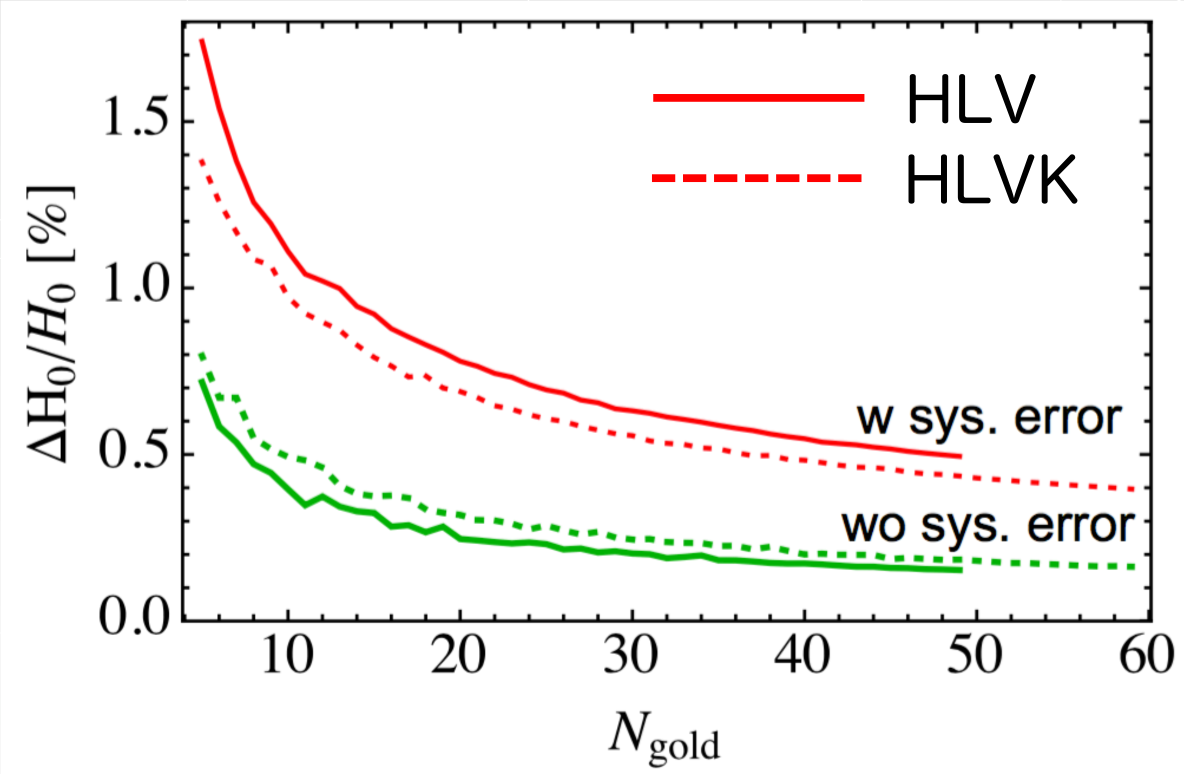


$n_{\rm gal} = 0.01\,{\rm Mpc}^{-3}$ galaxy number density (covering 90% total luminosity in B-band)

source selection	source catalog	$70\,{\rm Gpc}^{-3}\,{\rm yr}^{-1}$	$30\,{\rm Gpc}^{-3}\,{\rm yr}^{-1}$	$10\,{\rm Gpc}^{-3}\,{\rm yr}^{-1}$
HLV (SNR>8, $z < 1$)	10000	4512 ${\rm yr}^{-1}$	1934 ${\rm yr}^{-1}$	645 ${\rm yr}^{-1}$
HLV (SNR>8, $z < 1$), $N_{\rm host} < 1$	49	22 ${\rm yr}^{-1}$	9 ${\rm yr}^{-1}$	3 ${\rm yr}^{-1}$
HLVK (SNR>8, $z < 1$)	10000	5122 ${\rm yr}^{-1}$	2195 ${\rm yr}^{-1}$	732 ${\rm yr}^{-1}$
HLVK (SNR>8, $z < 1$), $N_{\rm host} < 1$	59	30 ${\rm yr}^{-1}$	13 ${\rm yr}^{-1}$	4 ${\rm yr}^{-1}$


All
$N_{\rm host} < 100$
$N_{\rm host} < 1$
probability
z
HLV network
SNR
$\Delta \log d_L$
$\Delta\Omega_S$ [deg^2]

measurement precision of Hubble const



After a few yrs observation, 20-30 golden events will be observed.

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~0.8% measurement of H_0

Currently, calibration error ~8%.

Can be reduced to 1%.

[Tuyenbayev et al. 2017]

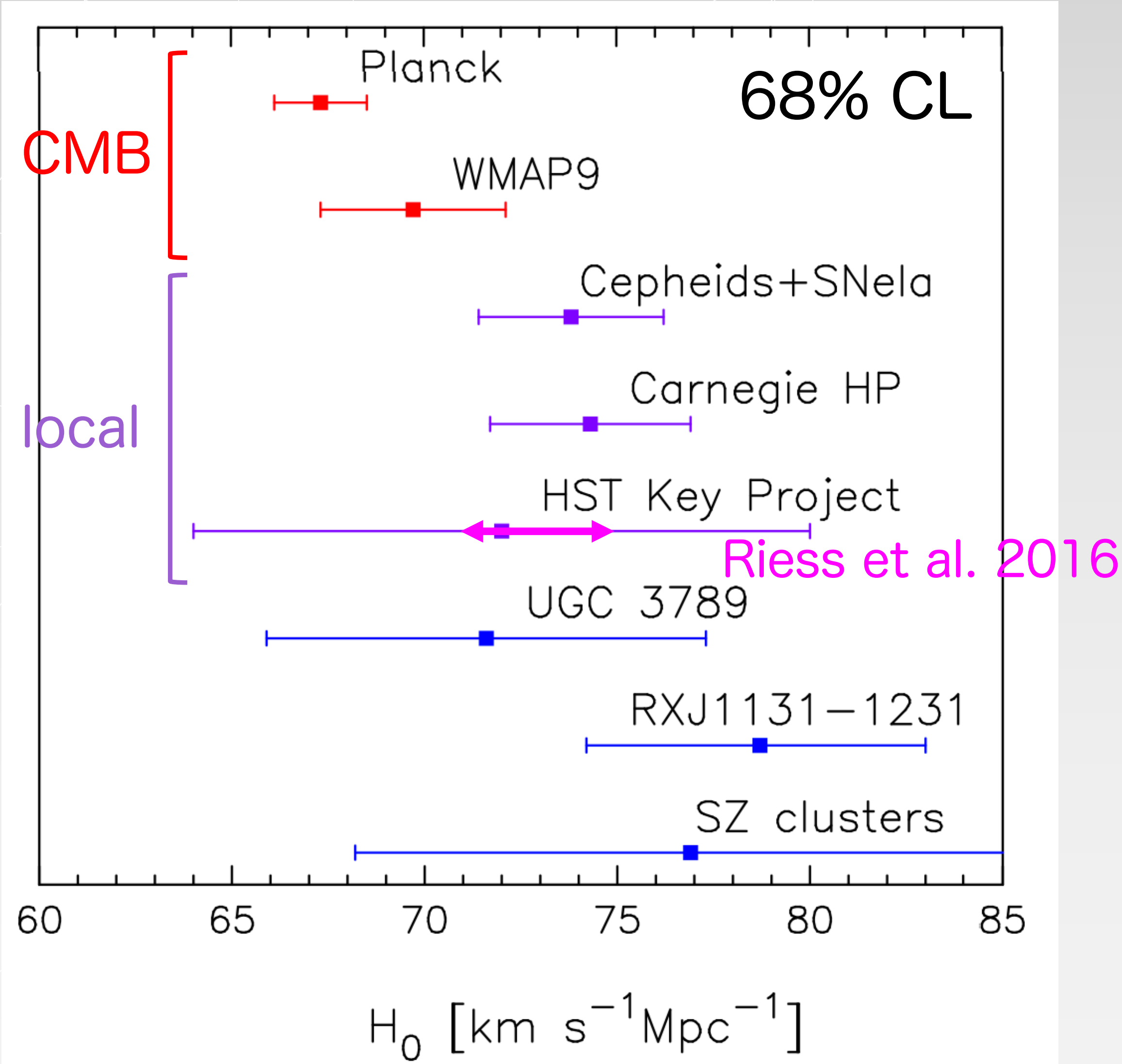
H_0 value discrepancy problem

There is still some discrepancy between observations of H_0 .

GW from BH binaries allows us to measure H_0 at precision of 0.8%.

Importantly, GW obs is completely independent way to measure cosmic expansion.

[Planck Collaboration 2013]



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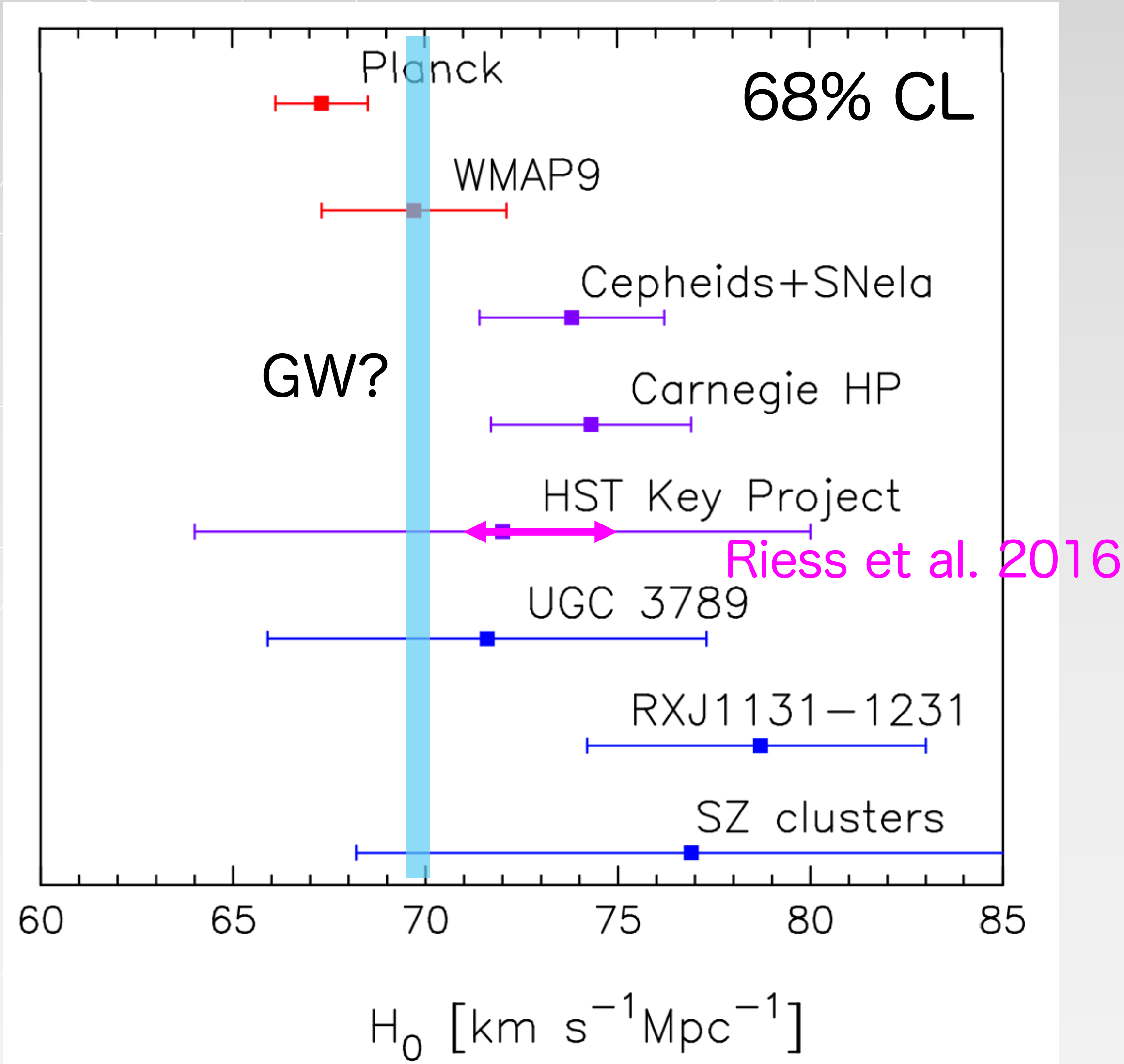

GW as a probe for matter inhomogeneities in the universe

Beyond background cosmology

- With a standard siren, one can measure luminosity distance to a source directly. Combining the luminosity distance with redshift information, cosmic expansion is measured.

- models for cosmic accelerating expansion

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

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

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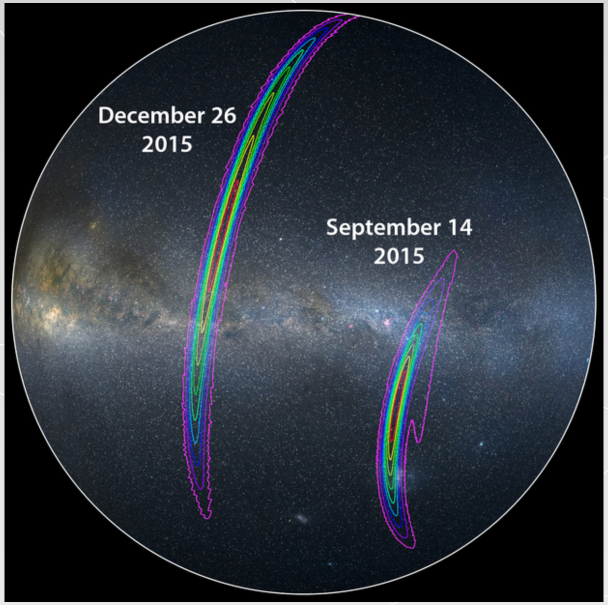
  To discriminate models, need to go to a perturbative level. (matter clustering, gravitational lensing, etc.)

angular clustering

cross-correlating sky maps



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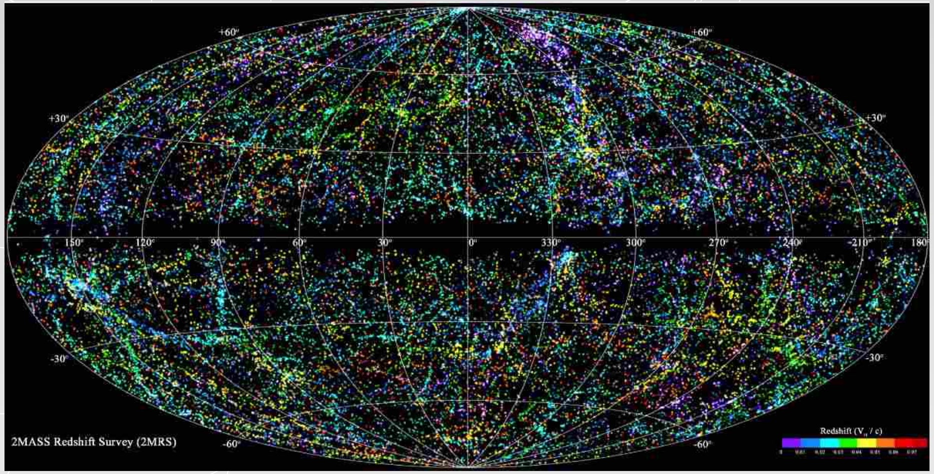


GW events

galaxy survey
(2MASS redshift survey)

- How strongly are GW events correlated with galaxies?
- What kind of galaxies are associated with BBH?

angular cross-power spectrum

[Namikawa, AN, Taruya 2016]

cross-correlation between the probes, GW (s) and galaxy (g)

$$C_\ell^{sg} = 4\pi \int_0^\infty d\ln k \int_0^\infty d\chi\, j_\ell(k\chi) \int_0^\infty d\chi'\, j_\ell(k\chi')$$
$$\times \underbrace{W^s(k,\chi) W^g(k,\chi')}_{\text{weight function}} \underbrace{\Delta_\mathrm{m}(k;\chi,\chi')}_{\text{matter density power spectrum}}$$

weight function — matter density power spectrum

$$W^s(\chi) = \frac{dn_\mathrm{BH}}{d\chi}(\chi) b_\mathrm{BH}(\chi)$$ for GW

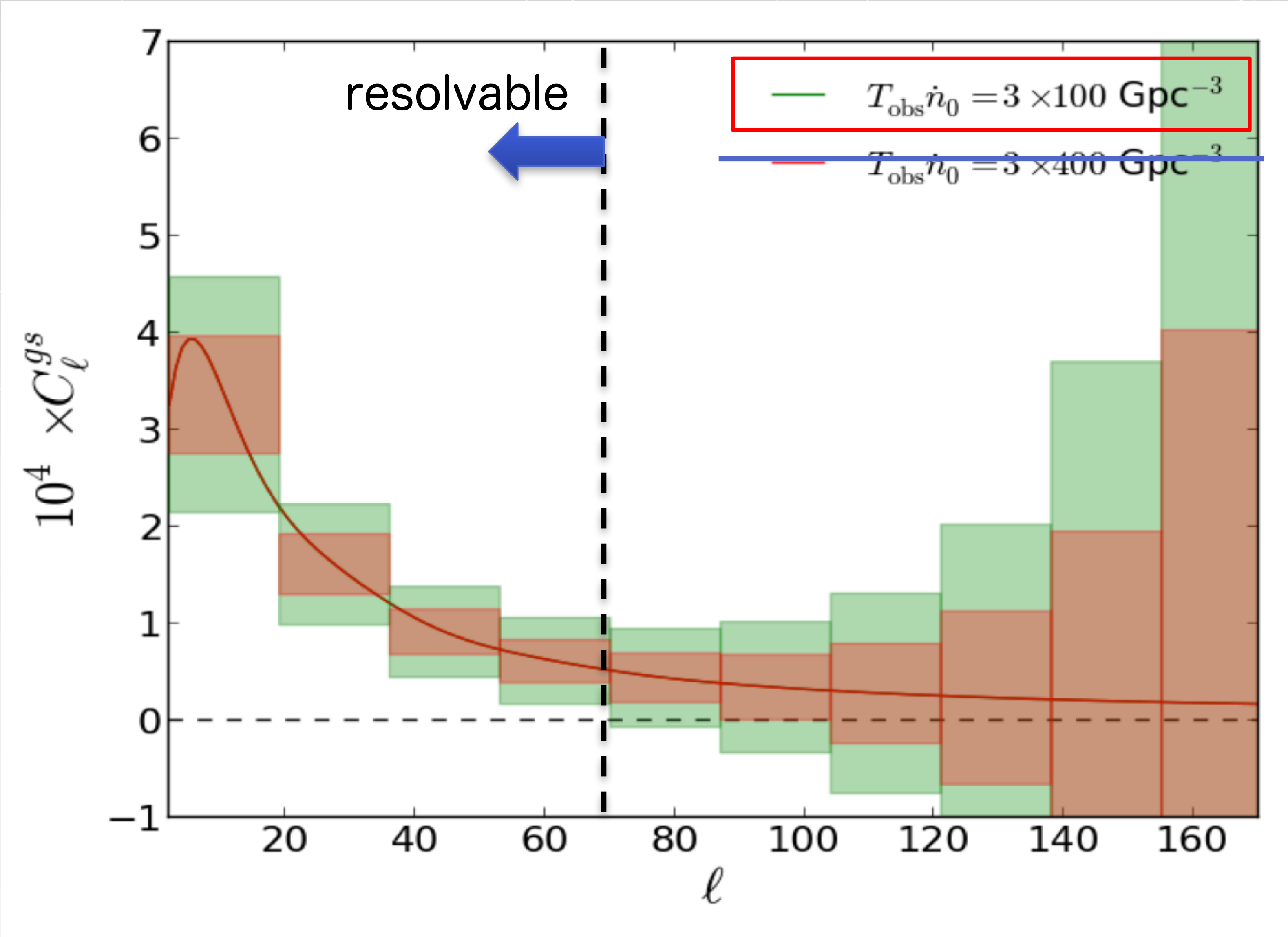
→ $b_\mathrm{BH}(\chi)$: clustering strength of BBH

$$W^g(\chi) = \frac{dn_\mathrm{gal}}{d\chi}(\chi) b_\mathrm{gal}(\chi)$$ for galaxy

→ $b_\mathrm{gal}(\chi)$: clustering strength of galaxy

power spectrum: GW x galaxy

aLIGO x2 + aVIRGO observations (at design sensitivity) & Pan-STARRS



detection significance of clustering

$$\alpha_{sg} = \alpha_{sg}^{0} \left(\frac{b_{\rm BH,0}}{1.5} \right) \left(\frac{T_{\rm obs} \dot{n}_0}{3 \times 100\,{\rm Gpc}^{-3}} \right)^{1/2}$$

GW x Euclid

$$\alpha_{sg}^{0} = 3.6$$

GW x Pan-STARRS

$$\alpha_{sg}^{0} = 4.5$$

BBH clustering $b_{\rm BH,0}$ can be detected
unless BBH merger rate is so small.

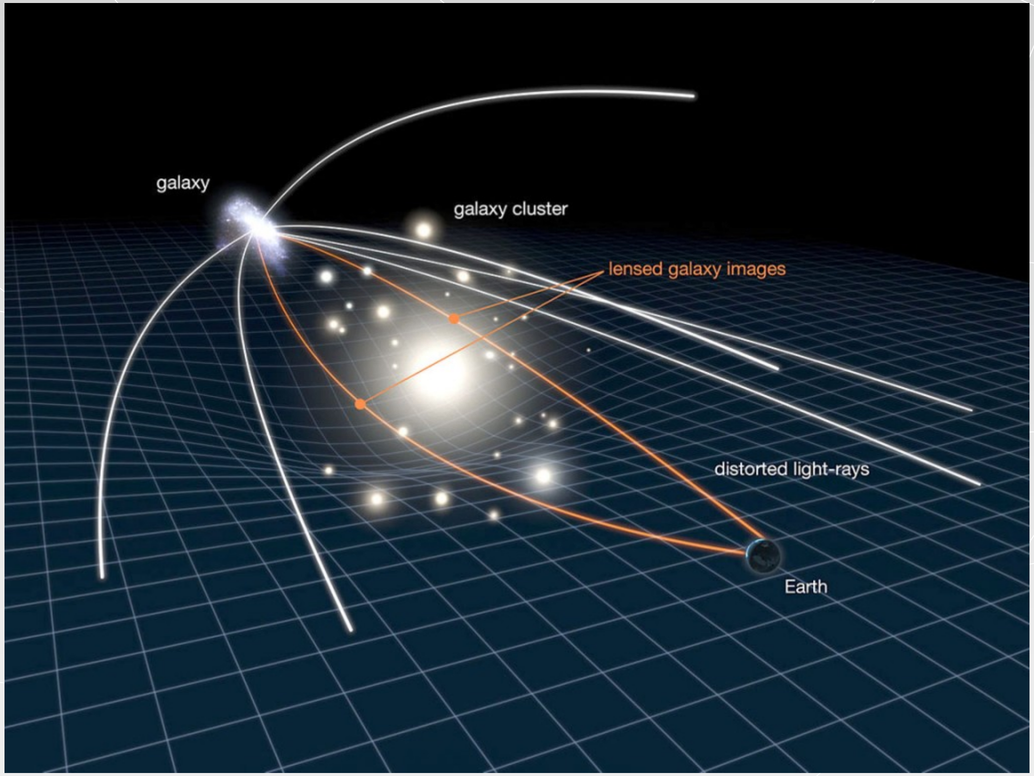
If $b_{\rm BH,0} \approx b_{\rm gal,0}$, BBH are likely to trace a baryon distribution and star formation.

If not, a nonstandard scenario (e.g. PBH) may be preferred.

gravitational lensing

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.

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

- Apparent luminosity distance

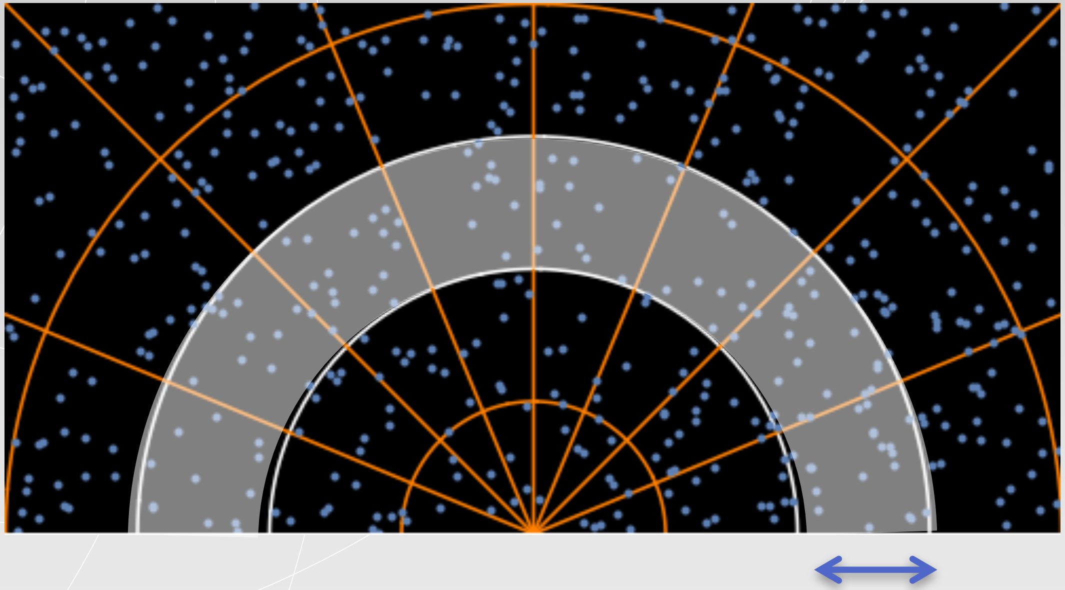
$$D(\mathbf{x}) = \bar{D}\,\{1 + \underline{\kappa(\mathbf{x})}\}$$

"magnification"

anisotropy of luminosity distance

[Namikawa, AN, Taruya 2016]

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



i-th distance bin

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

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

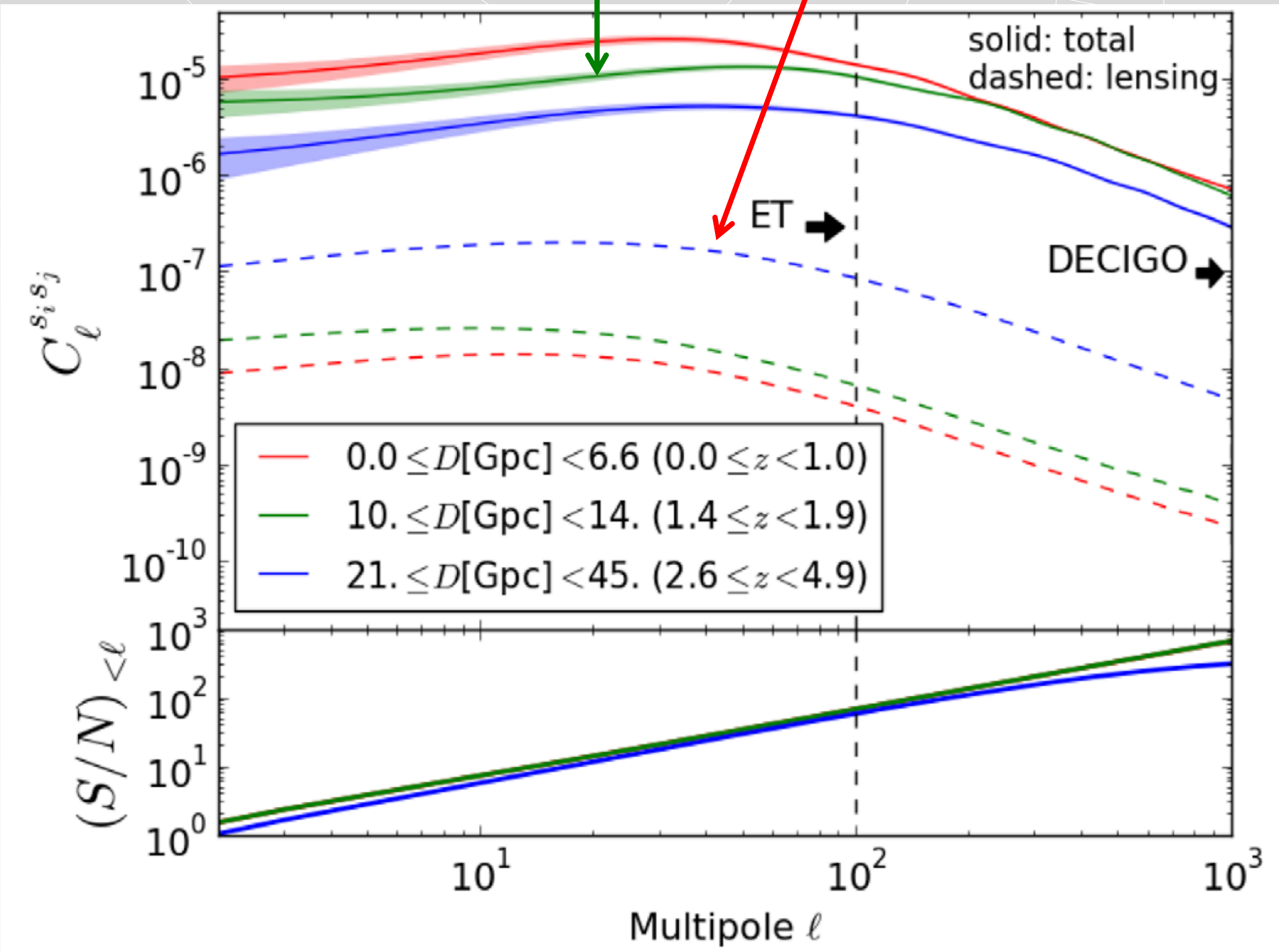
average number density

clustering

weak lensing

angular power spectrum

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



Angular resolution of GW observation limits maximally observable ℓ .

With ET, SNR for clustering signal reaches ~50.

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 SNR ~ 31
GW (ET) x CMB stage IV SNR ~ 43

- cross-correlation of weak lensing

GW (ET) x Euclid SNR ~ 16

- A lot of applications of GW observations to cosmology

Open questions

- With BBH observed with aLIGOx2 + aVIRGO, Hubble constant can be measured at 1% level.

  How realistic is this method? Any more systematic error?

- Angular clustering of GW from BBH gives information about what type of galaxies are associated with them.

  Any robust prediction in astrophysical side?

- Gravitational lensing of GW offers many cosmological applications by correlating with CMB and galaxy surveys.

  Sensitivity to cosmological parameters? Any systematic bias?