# Anisotropies of Gravitational-Waves from BH Binaries as a Tracer of Dark Matter

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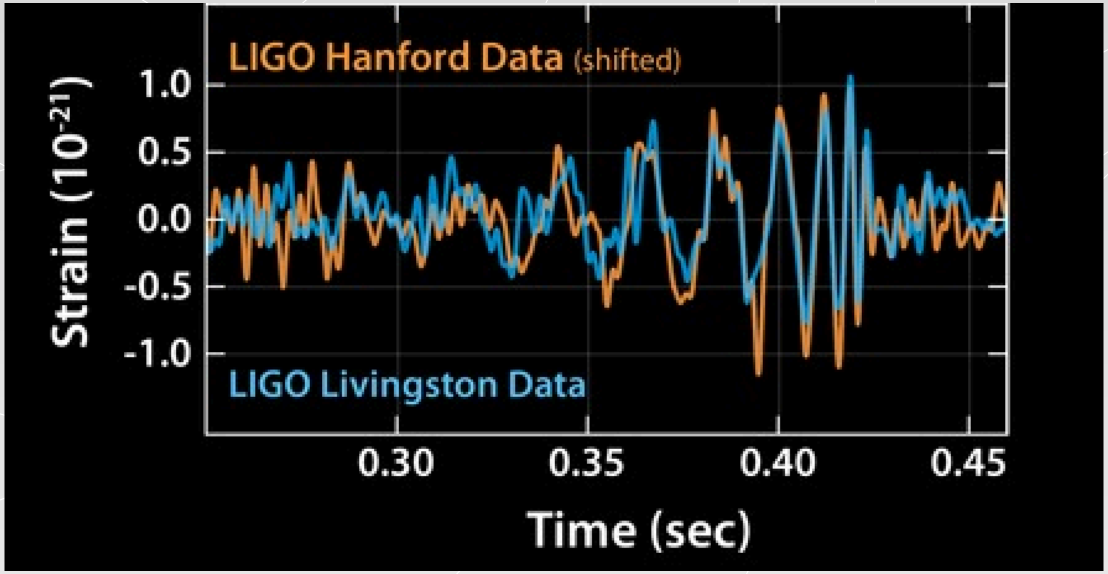
# Gravitational Waves

- GWs have been detected! (GW150914, GW151226)
  [ Abbott et al. 2016 ]




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

# What is the origin of BBH?

many possibilities for astrophysical formation scenarios

(i) pop II field binaries, (ii) binaries in globular cluster,
(iii) binaries near galactic nuclei, (iv) pop III stars,
(v) primordial BH, etc...

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- What kind of galaxies are BBH associated with?
- Do BBH trace dark matter? Baryon? Something else?

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To distinguish their origins, anisotropic clustering of BBH merger events on the sky is important information.

# angular cross-power spectrum

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

$$C_\ell^{sg} = 4\pi \int_0^\infty d\ln k \int_0^\infty d\chi\, j_\ell(k\chi) \int_0^\infty d\chi'\, j_\ell(k\chi')$$

$$\times W^s(k,\chi) W^g(k,\chi') \underline{\Delta_{\rm m}(k;\chi,\chi')}$$

matter density power spectrum

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$$\times \underbrace{W^s(k,\chi) W^g(k,\chi')}_{\text{weight function}} \underbrace{\Delta_{\rm m}(k;\chi,\chi')}_{\text{matter density power spectrum}}$$

weight function — matter density power spectrum

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

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

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weight function    matter density power spectrum

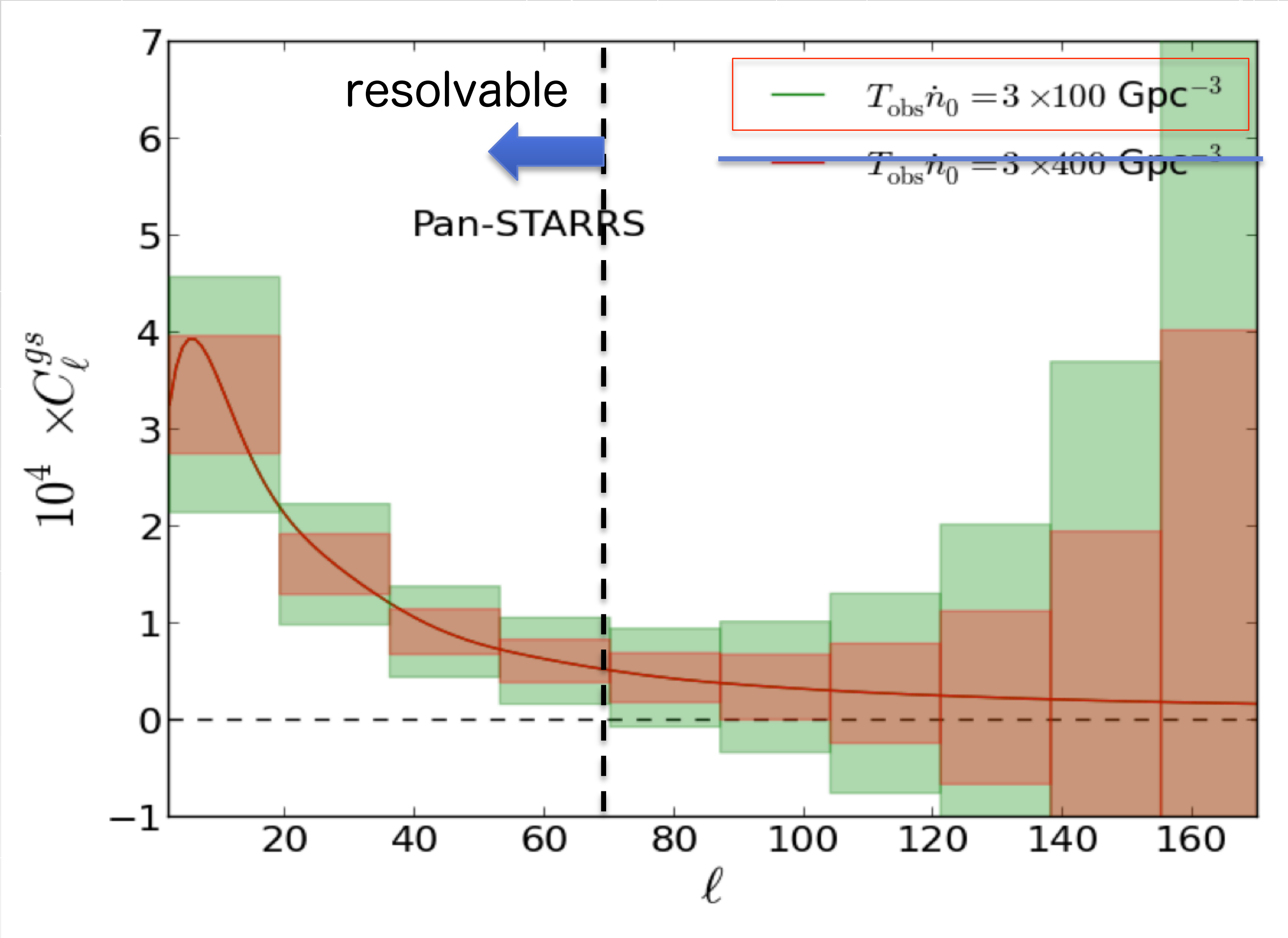
$$W^s(\chi) = \frac{dn_{\rm BH}}{d\chi}(\chi) \underline{b_{\rm BH}(\chi)}$$ for GW

→ clustering strength of BBH

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

# power spectrum: GW x galaxy

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



# detection significance of clustering

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

GW x Euclid

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

GW x Pan-STARRS

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

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

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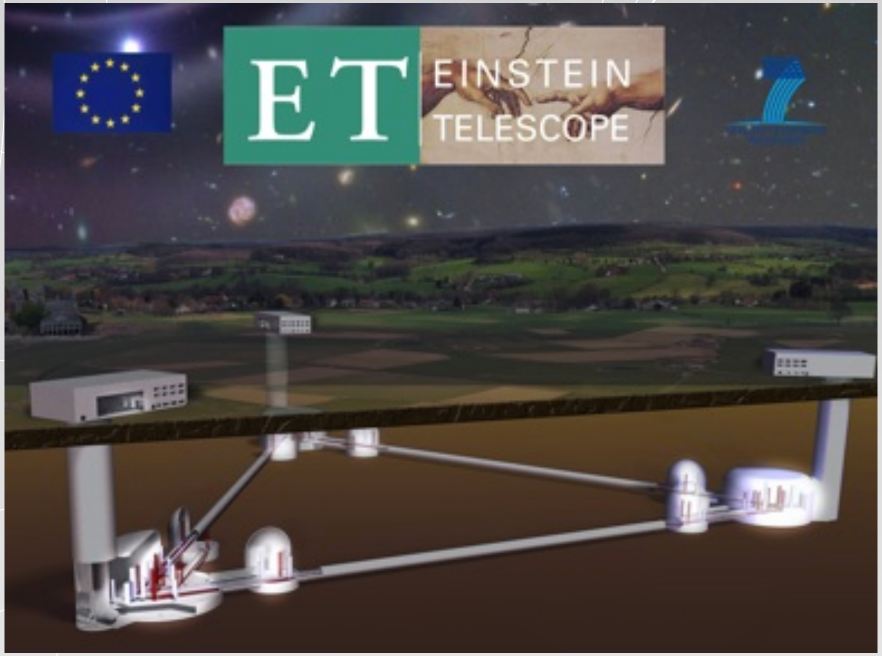
BBH clustering $b_{\rm BH,0}$ can be detected unless BBH merger rate is so small.

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.

# cosmology with GWs from BBH

Einstein Telescope (ET) is planned to start observation after aLIGO in 2026 or later.



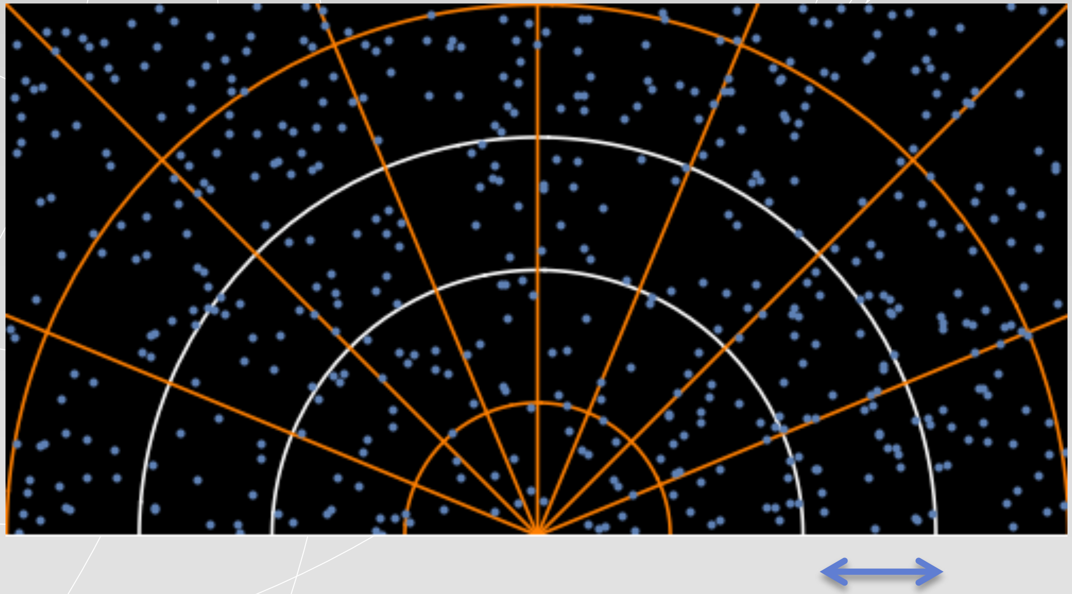

ET has x10 better sensitivity than aLIGO and will detect a million of BBH out to z~20.

With ET, we can extend the previous method including distance information.

→ cosmography

# anisotropy of luminosity distance

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



i-th distance bin

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

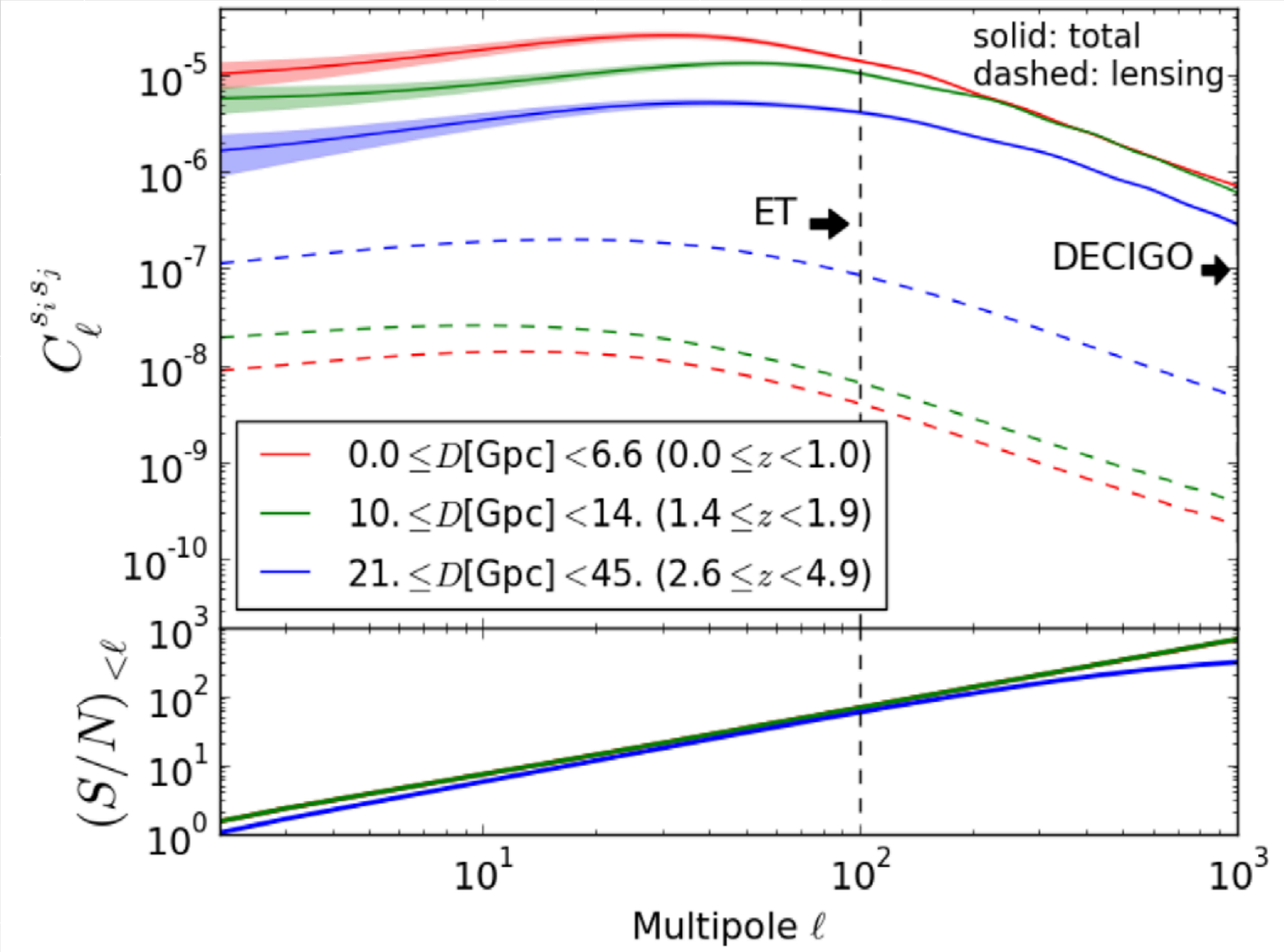
$$= \frac{1}{\bar{d}_i} \int_{D_i^{\min}}^{D_i^{\max}} dD\, \bar{n}(D) \{ \delta(\mathbf{x}) + \gamma(D)\kappa(\mathbf{x}) \}$$

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

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

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

# auto-correlation power spectrum



# cosmological implications

- non-Gaussianity of large-scale structure

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

- cross-correlation of clustering

GW x Planck S/N~31

GW x CMB stage IV S/N~43

- cross-correlation of weak lensing

GW x Euclid S/N~16

- A lot of applications of GW observations to cosmology

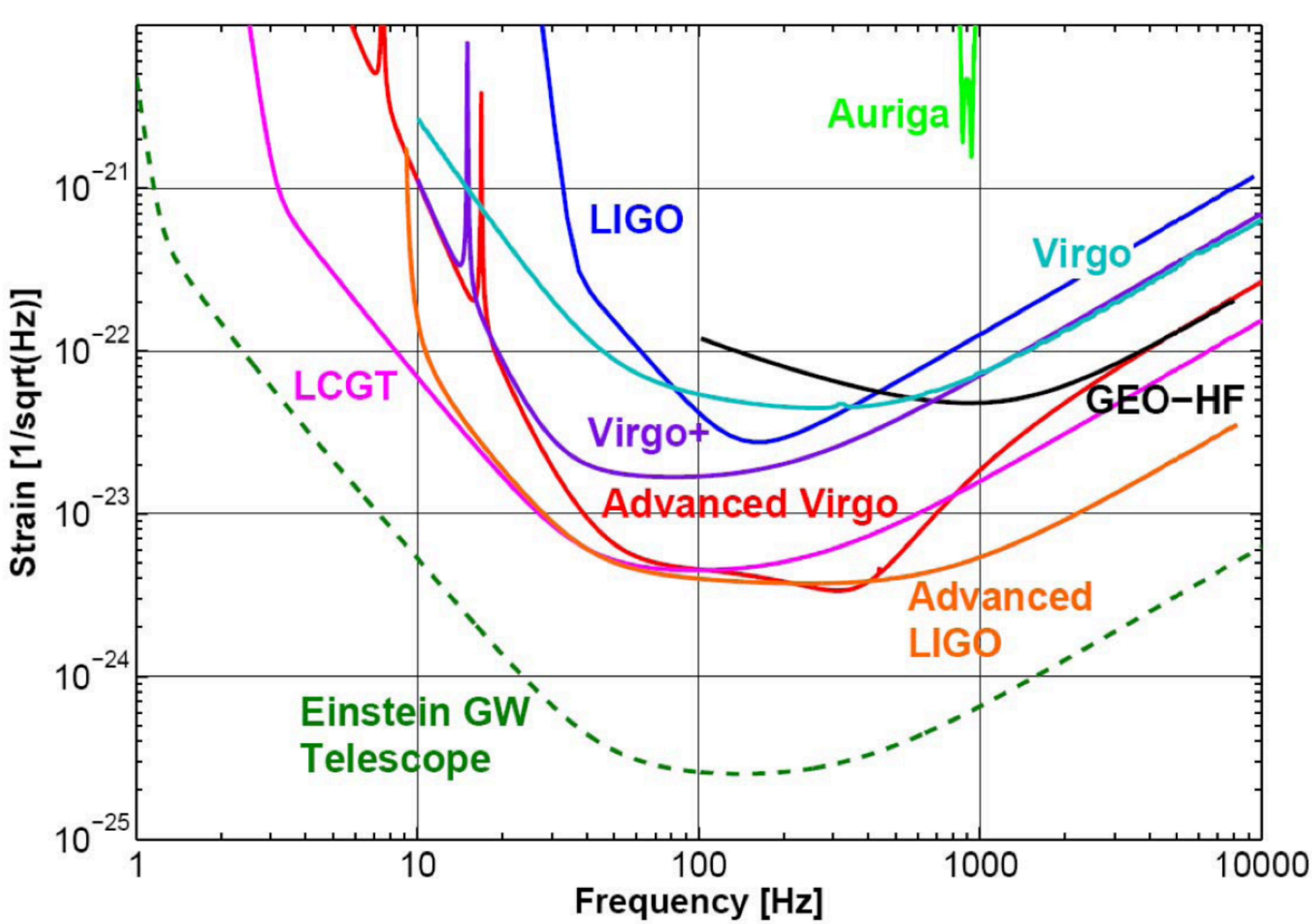
# Summary

- aLIGO-like detector network can measure BBH clustering, which may trace dark matter inhomogeneities.

- Einstein Telescope-like detector network can measure non-Gaussianity of large-scale structure via BBH clustering.

- By cross-correlating with future galaxy surveys and CMB observations, there are a lot of cosmological applications to be investigated.

Namikawa, Nishizawa, Taruya,
PRL 116, 121302 (2016);  PRD 94, 024013 (2016).



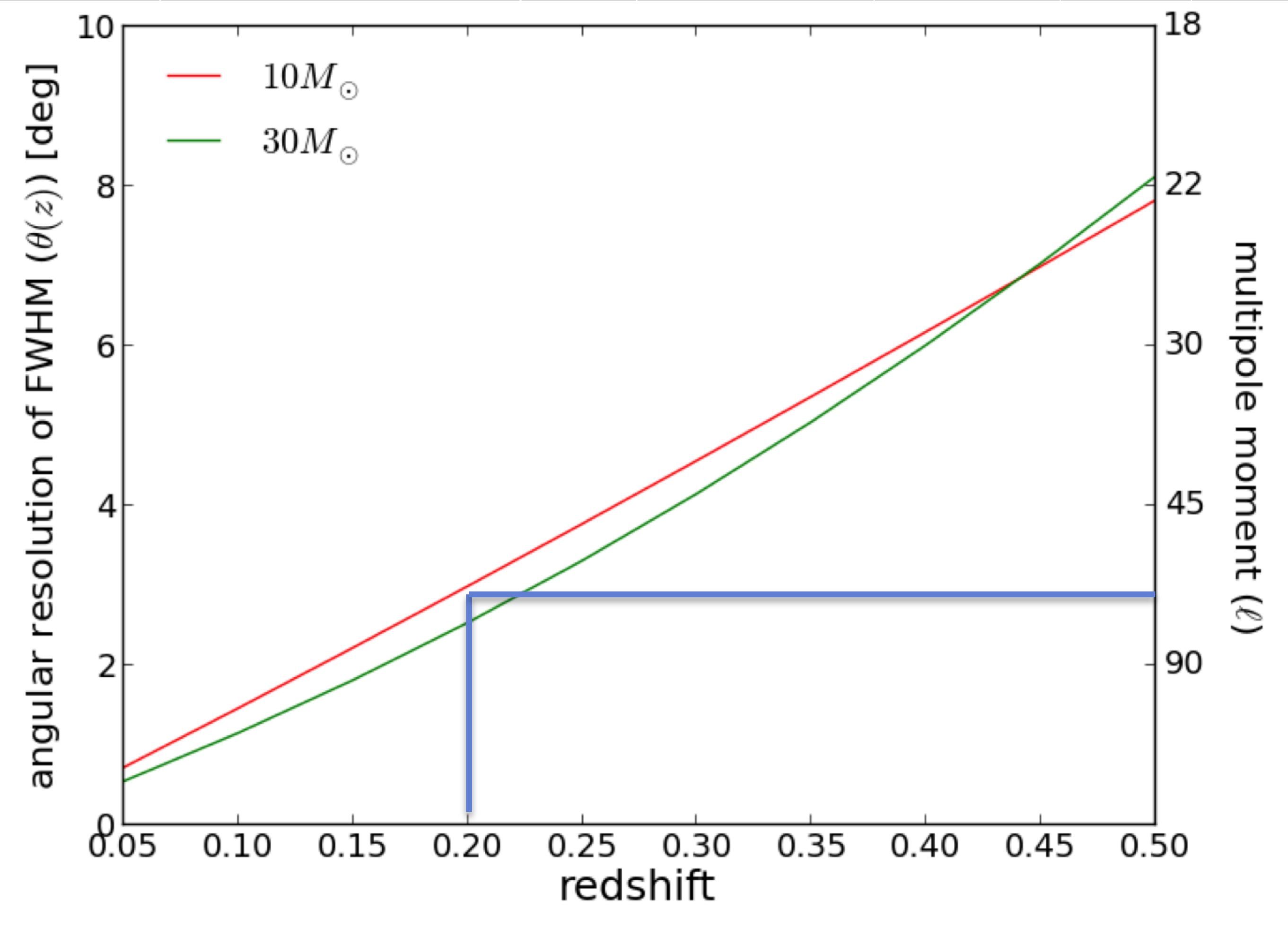
Auriga
LIGO
Virgo
GEO−HF
LCGT
Virgo+
Advanced Virgo
Advanced LIGO
Einstein GW Telescope
Strain [1/sqrt(Hz)]
Frequency [Hz]
$10^{-21}$
$10^{-22}$
$10^{-23}$
$10^{-24}$
$10^{-25}$
1
10
100
1000
10000

# galaxy surveys

| | $N_{\rm gal}$ [arcmin$^{-2}$] | $z_{\rm m}$ | $f_{\rm sky}$ |
|---|---|---|---|
| DES | 12 | 0.68 | 0.125 |
| Euclid | 30 | 0.90 | 0.500 |
| Pan-STARRS | 1 | 0.50 | 0.750 |

# angular resolution of GW obs.

aLIGO x2 + aVIRGO observations (at design sensitivity) of BBH, taking into account its angular resolution




$$z_{\rm max} = 0.2$$

$$\ell_{\rm max} \sim 70$$

$$N_\ell^{ss}(z) \propto \frac{1}{N_{\rm BH}}$$

# What limits the sensitivity

- GW observation

aLIGO x2 + aVIRGO observations (at design sensitivity) of BBH, taking into account its angular resolution

$$N_\ell^{ss}(z) \propto \frac{1}{N_{\rm BH}}$$ x (angle dependent factor)

$z_{\rm max} = 0.2$ ⟺ $\mathrm{SNR} \gtrsim 20$ ⟺ $\ell_{\rm max} \sim 70$

- galaxy survey

We consider galaxy surveys, DES, Euclid, and Pan-STARRS.

$$N_\ell^{gg}(z) = \frac{1}{N_{\rm gal}}$$

wide-field, dense survey is better.

# SNR formula

$$\left(\frac{\mathrm{S}}{\mathrm{N}}\right)^2 = \sum_{\ell}^{\ell_{\max}} \frac{2\ell+1}{2} \left(\frac{C_\ell^{s_i s_j}}{\sigma_i^2/N_i + C_\ell^{s_i s_j}}\right)^2$$