# Distance determination beyond the nearest galaxies (?)

Masamune Oguri (University of Tokyo)

2016/5/24 Astronomical Distance Determination@Beijing

# Gravitational wave standard sirens

Masamune Oguri (University of Tokyo)

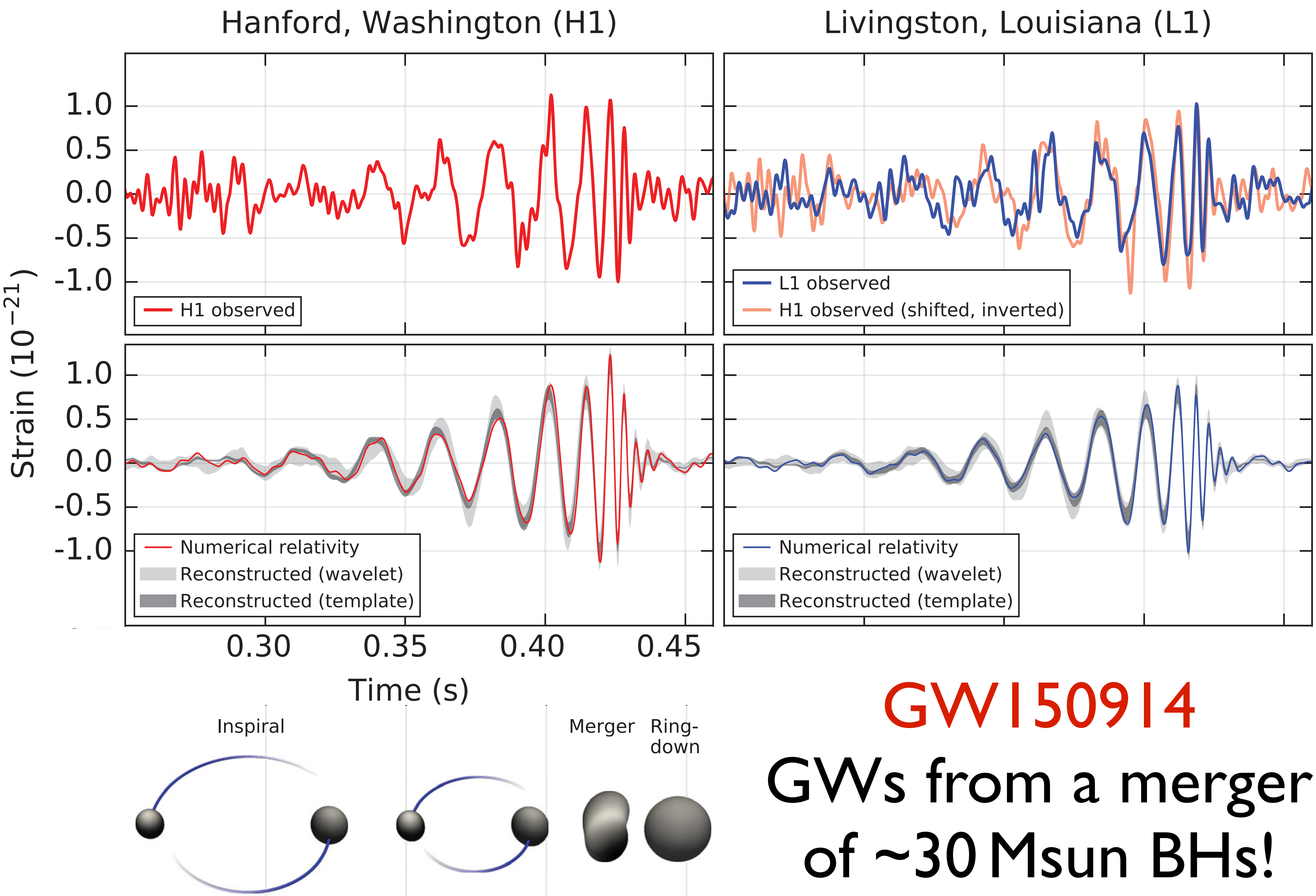
2016/5/24 Astronomical Distance Determination@Beijing

# February 11, 2016


Saul Loeb/Getty Images

Abbott et al. (2016)

# Gravitational waves detected!




GW150914

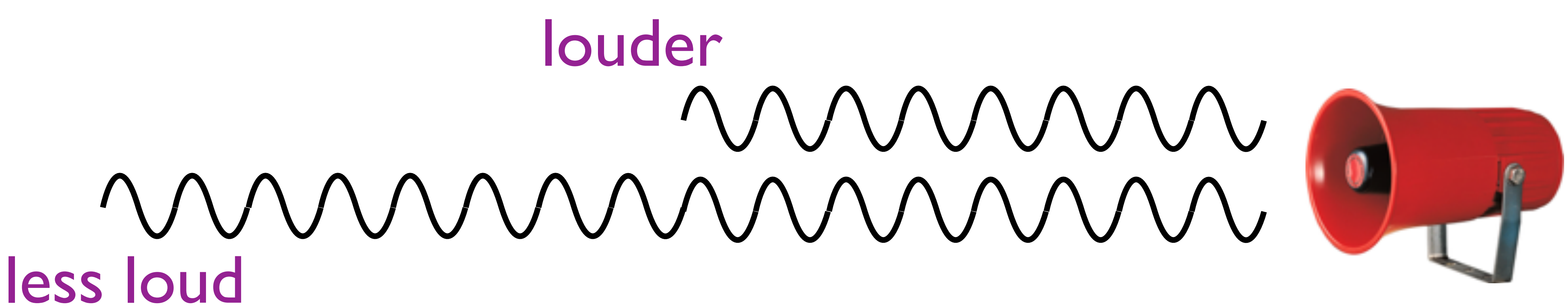
GWs from a merger of ~30 Msun BHs!

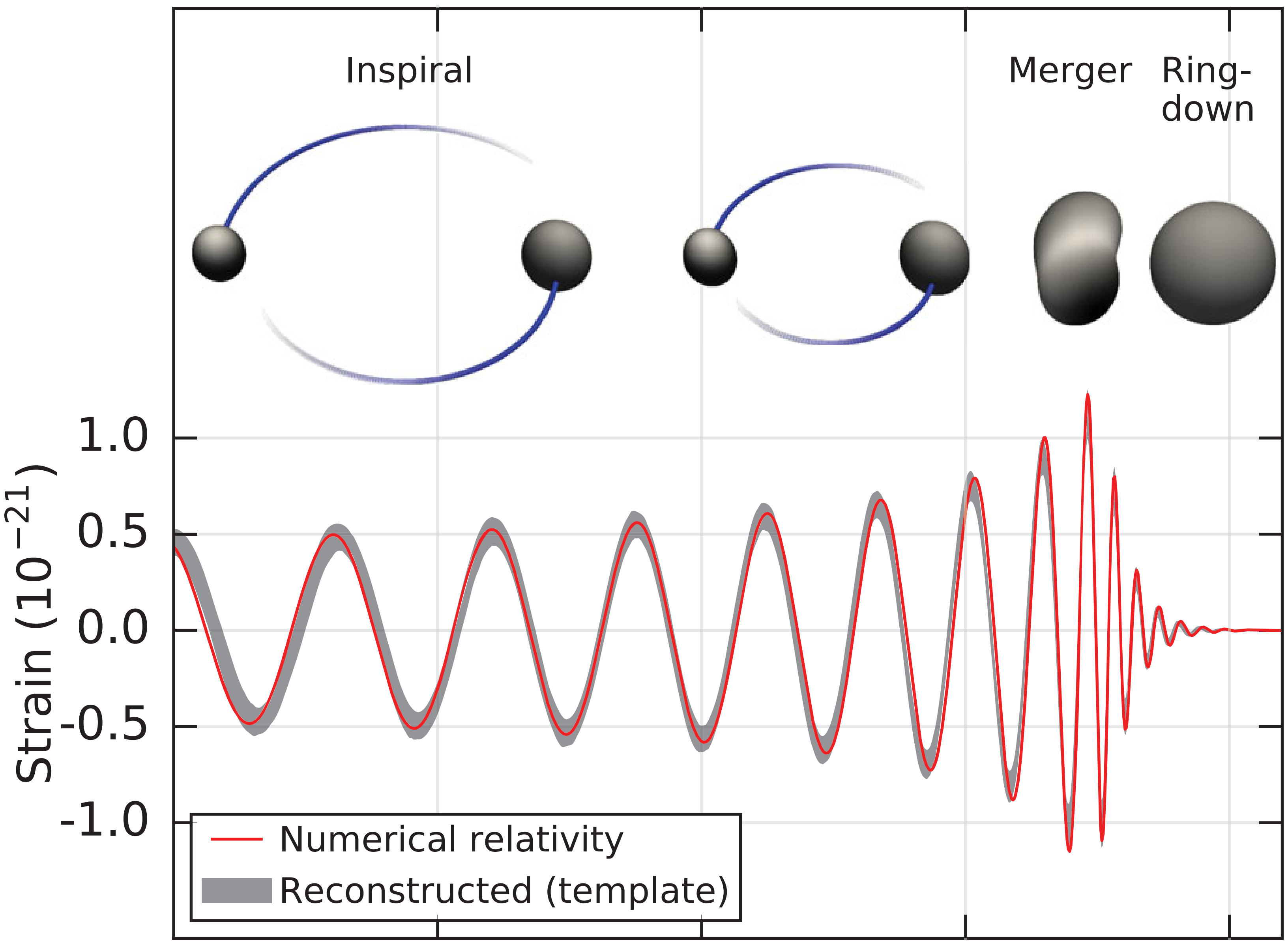
# GW150914 was "super-luminous"

- $3 M_{\odot} \sim 5\times10^{54}$ erg converted to the GW energy
- this was emitted within ~0.1 sec
- thus the peak luminosity was $\sim10^{56}$ erg/s, which was much more luminous than SNe/GRBs

# Gravitational wave standard sirens

- we can infer masses of inspiraling compact binaries from the waveform
- observed strain amplitude is inversely proportional to the luminosity distance to the source
- we can measure the luminosity distance directly, incld. absolute distance scale $H_0$ (Schutz 1986)






analytic (post-Newtonian) | numerical relativity | analytic (QNM)

## Inspiral

$$h \propto \frac{M_z^{5/3}}{D_L(z)} f^{2/3}$$

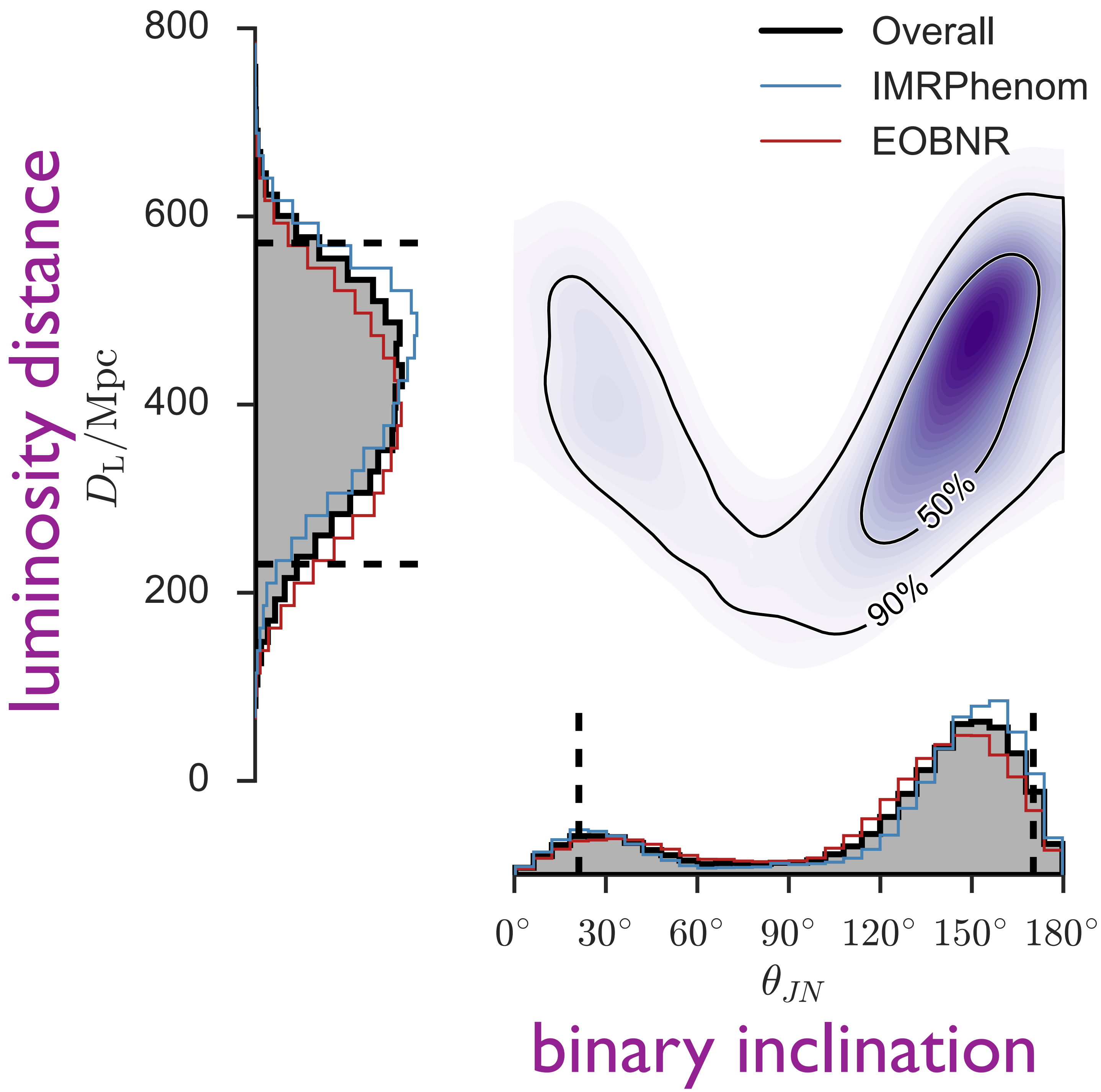
$$\dot{f} \propto M_z^{5/3} f^{11/3}$$

→ chirp mass $M_z$ and distance $D_L$

## Merger/Ringdown

→ final BH mass, spin, and distance $D_L$

# Standard siren at work




GW150914

observed waveform fitted to GR predicted waveforms

→ luminosity distance $D_L = 410^{+160}_{-180}$ Mpc

→ *inferred* redshift assuming standard cosmological model $z = 0.09^{+0.03}_{-0.04}$

# Cosmology with gravitational waves

- inspiraling compact binaries (BH-BH, NS-NS, BH-NS) are excellent standard sirens that allow us to measure absolute distances to the sources with gravitational waves

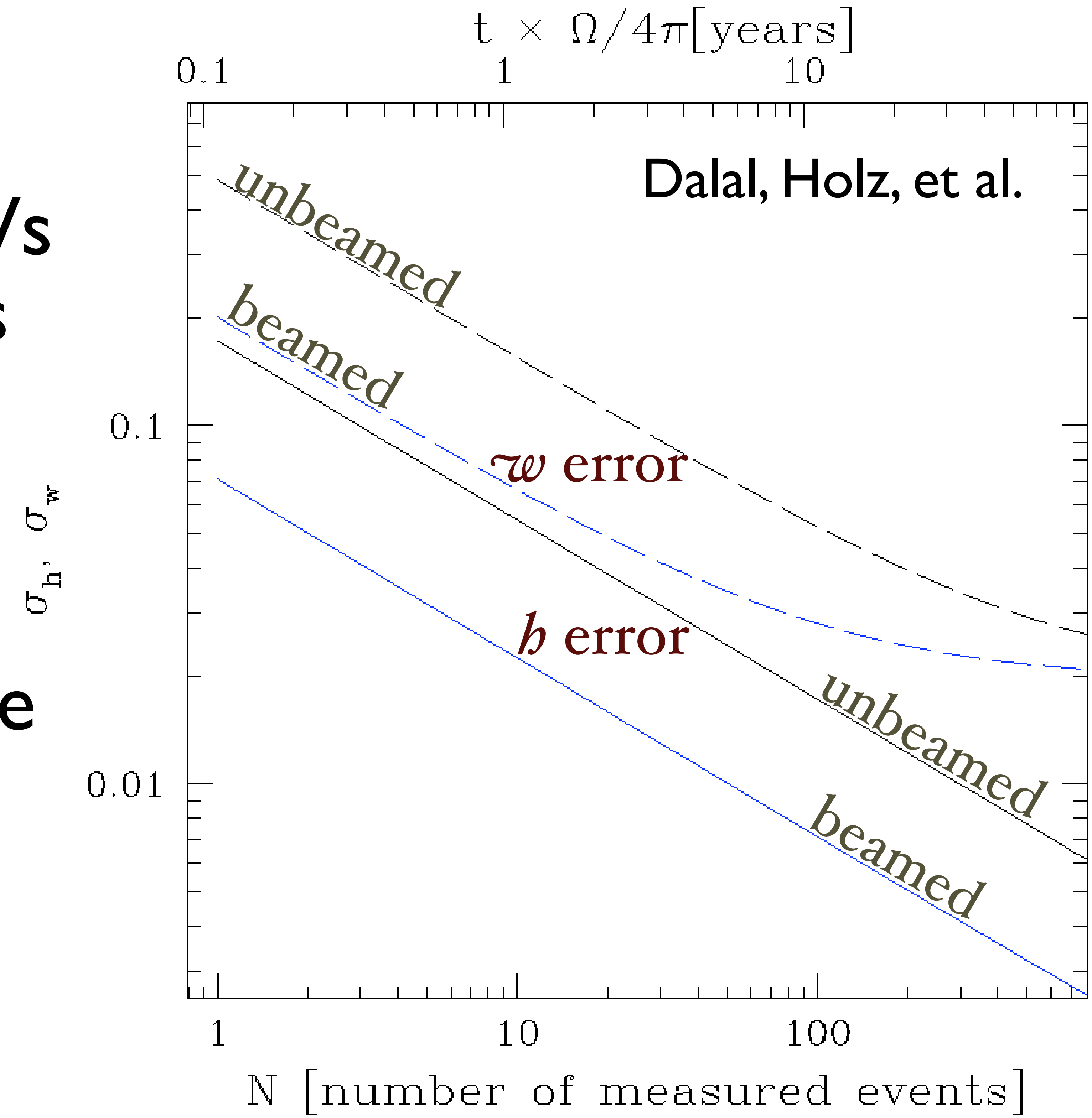
- *if* we get redshifts to the sources from other observations (electromagnetic counterparts) we can directly constrain the distance-redshift relation at cosmological distances
  → useful constraints on $H_0$, $\Omega_m$, $w$, ...

  (Holz & Hughes 2005; Dalal et al. 2006; Cutler & Holz 2009; Nissanke et al. 2010; ...)

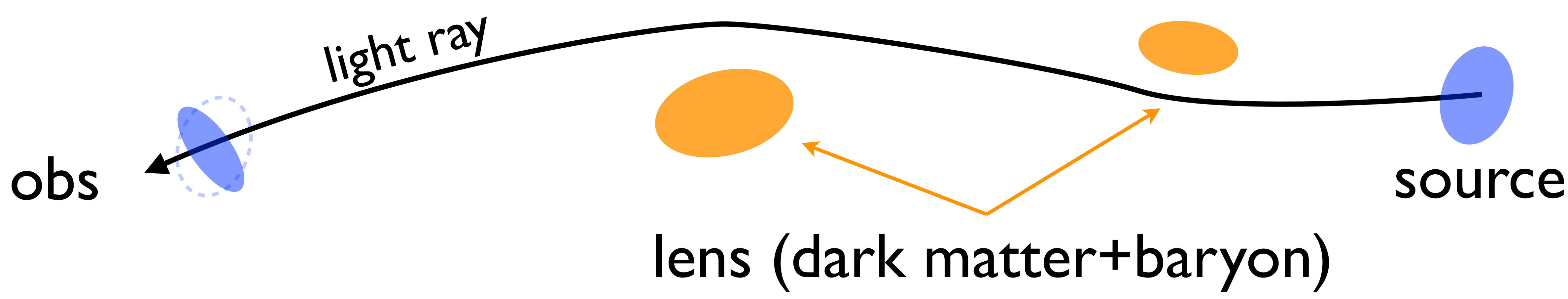
# Precision cosmology with GWs

even a small number of well-measured GWs with EM counterparts for z can constrain cosmology

information on the absolute distance scale $H_0$ is very precious



# Gravitational lensing as noise



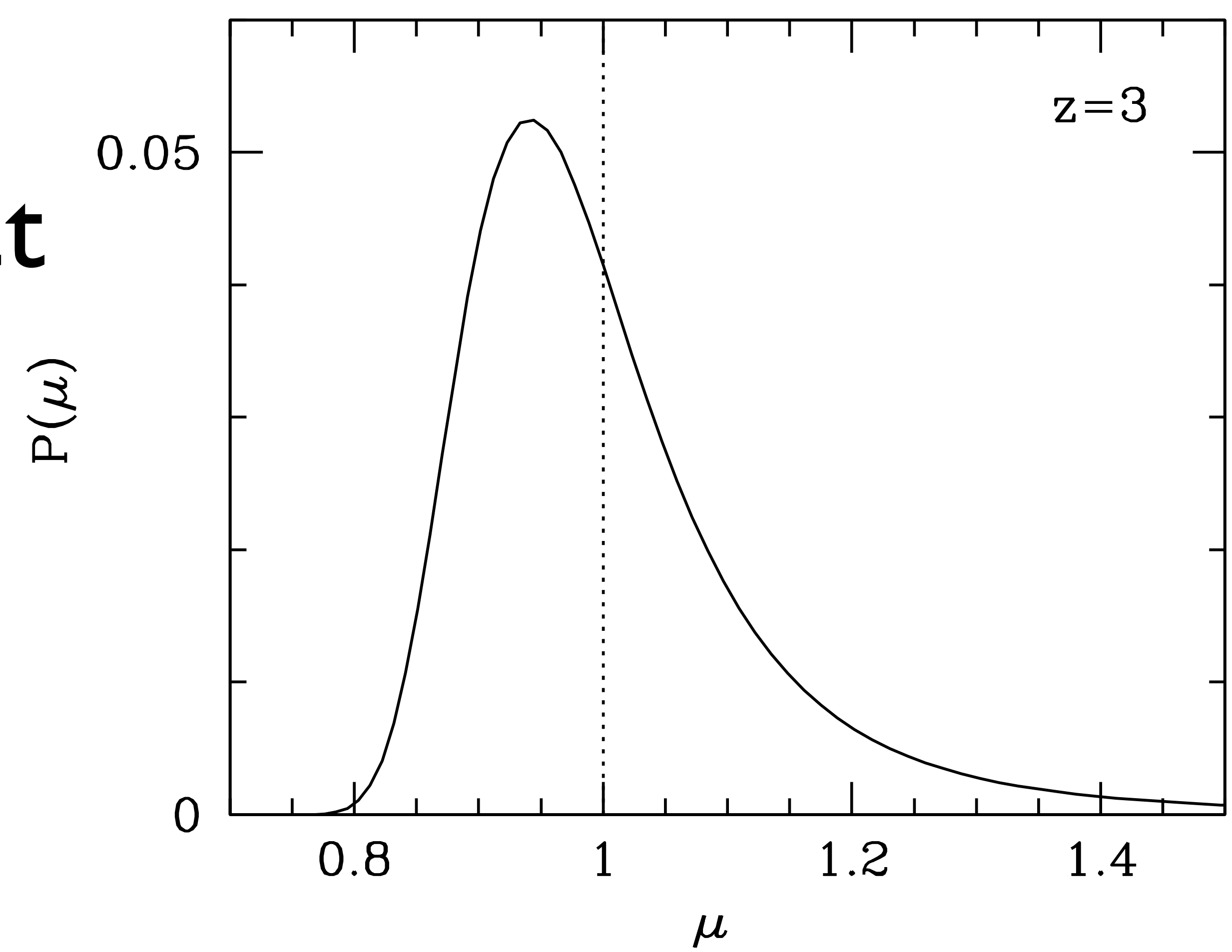

- deflection of light ray due to gravitational lensing changes apparent brightness of observed images
  → effectively changes the luminosity distance

$$D_{\rm obs} = \bar{D}\mu^{-1/2} \approx \bar{D}\left[1 - \kappa(\vec{\theta}, z)\right]$$

# Gravitational lensing as noise

- lensing is the most important source of errors in cosmology with GW standard sirens
  (also for high-z SNeIa, time delay cosmography, ...)
- effect is larger at higher-z
- can be averaged out, but beware that lensing effect is quite non-Gaussian

Takahashi, Oguri, et al. (2011)



# Gravitational wave detectors

- second generation (~2018) [~$10^2$–$10^3$ BH-BHs]
  Advanced LIGO, VIRGO, KAGRA, ...
- third generation (~2025?) [~$10^5$–$10^6$ BH-BHs]
  Einstein Telescope, LIGO Cosmic Explorer, ...
  (~10km underground)
- space (~2035?)
  LISA, DECIGO, ...

# Pros and cons

Pros

- clean physics, can easily/robustly predict signals from the first principle (assuming GR)
- can reach high-z relatively easily ($h \propto D_L^{-1}$)

Cons

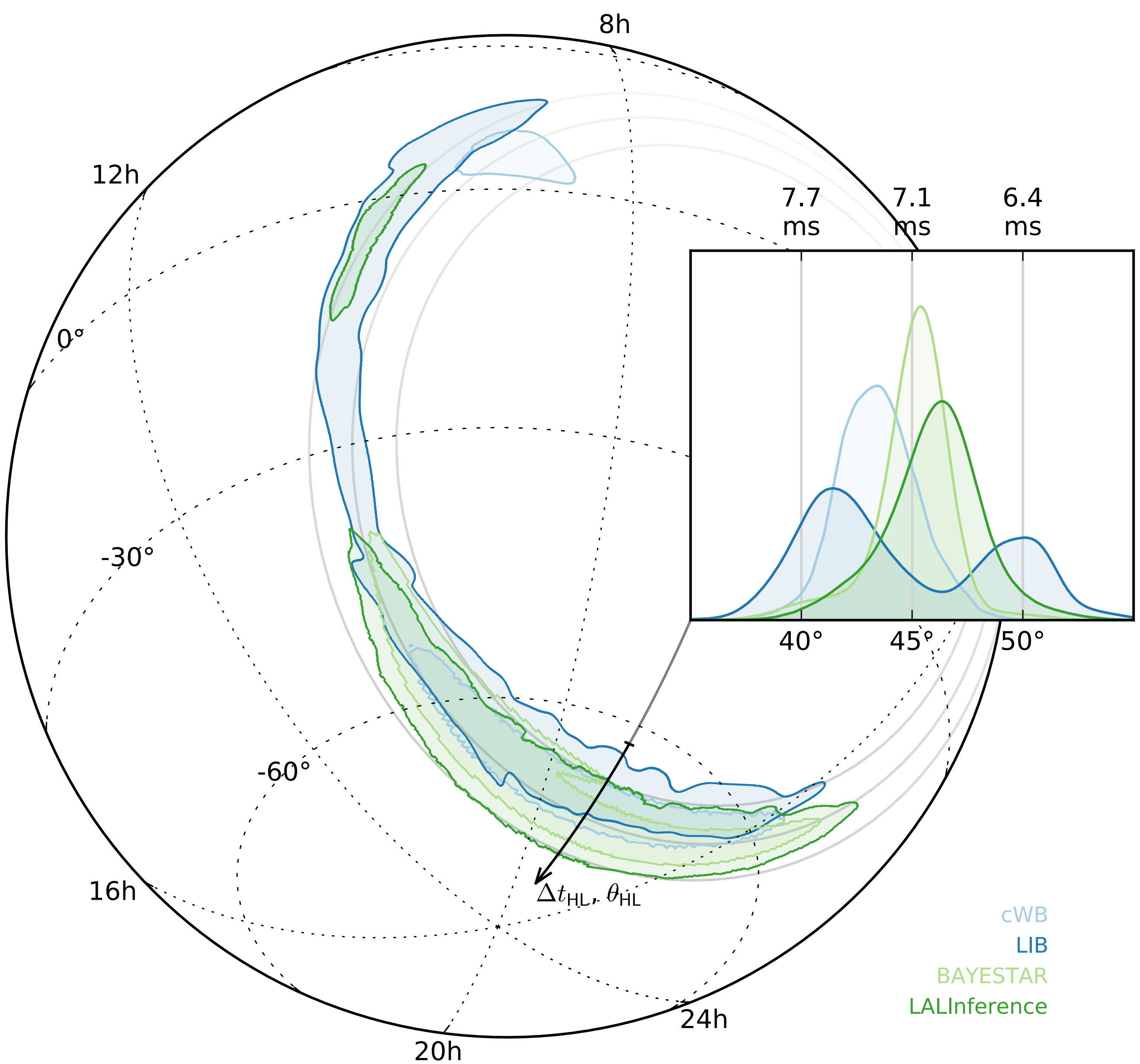
- GWs are hard to detect!
- need to identify electromagnetic counterparts for redshifts – how easy/secure??

# Localizing GWs

- it is essential to identify electromagnetic (EM) counterparts for measuring redshifts (necessary for cosmology)
- several challenges
  - angular resolution of GW observations is not great
  - not clear how bright EM counterparts are
  - for BH-BH mergers we usually don't expect EM counterparts

Abbott et al. (2016)

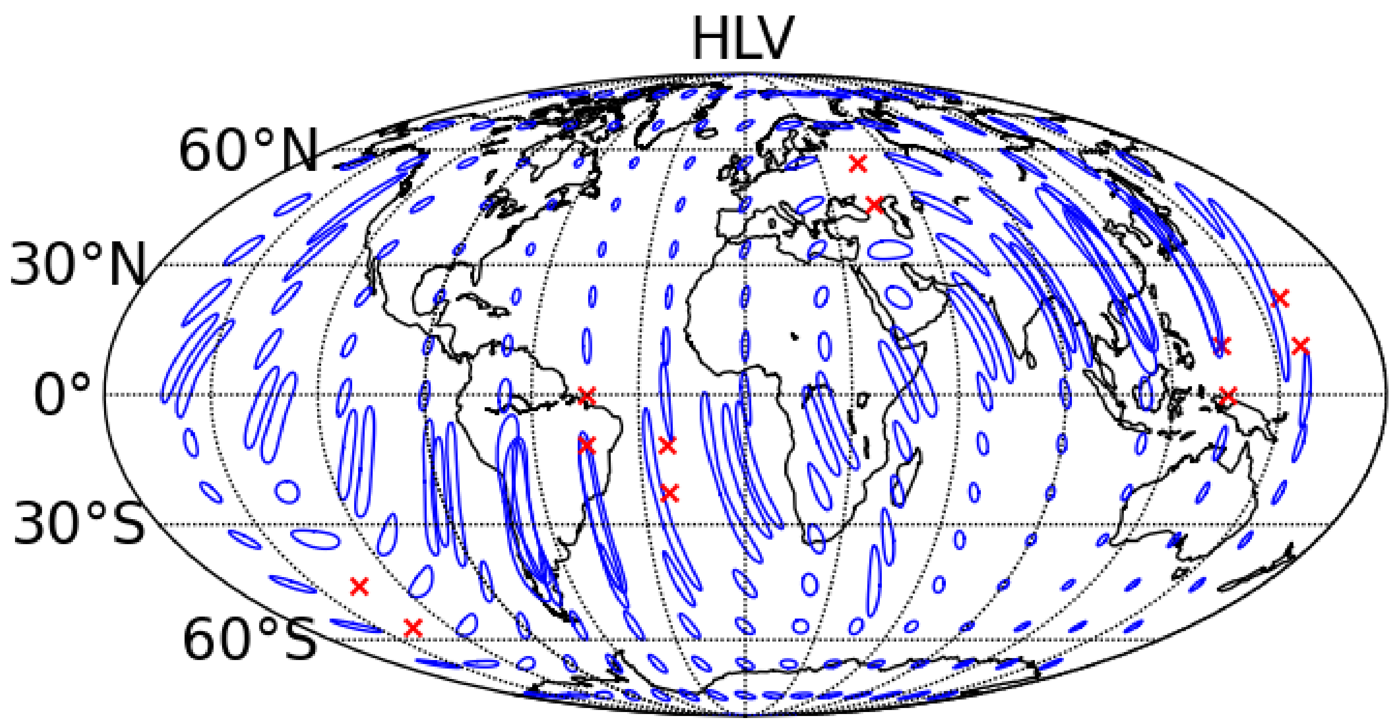
# Location of GW150914 on the sky




- expected direction of GW150914 is not well-constrained, with area ~600 deg$^2$
- more GW detectors will improve the accuracy

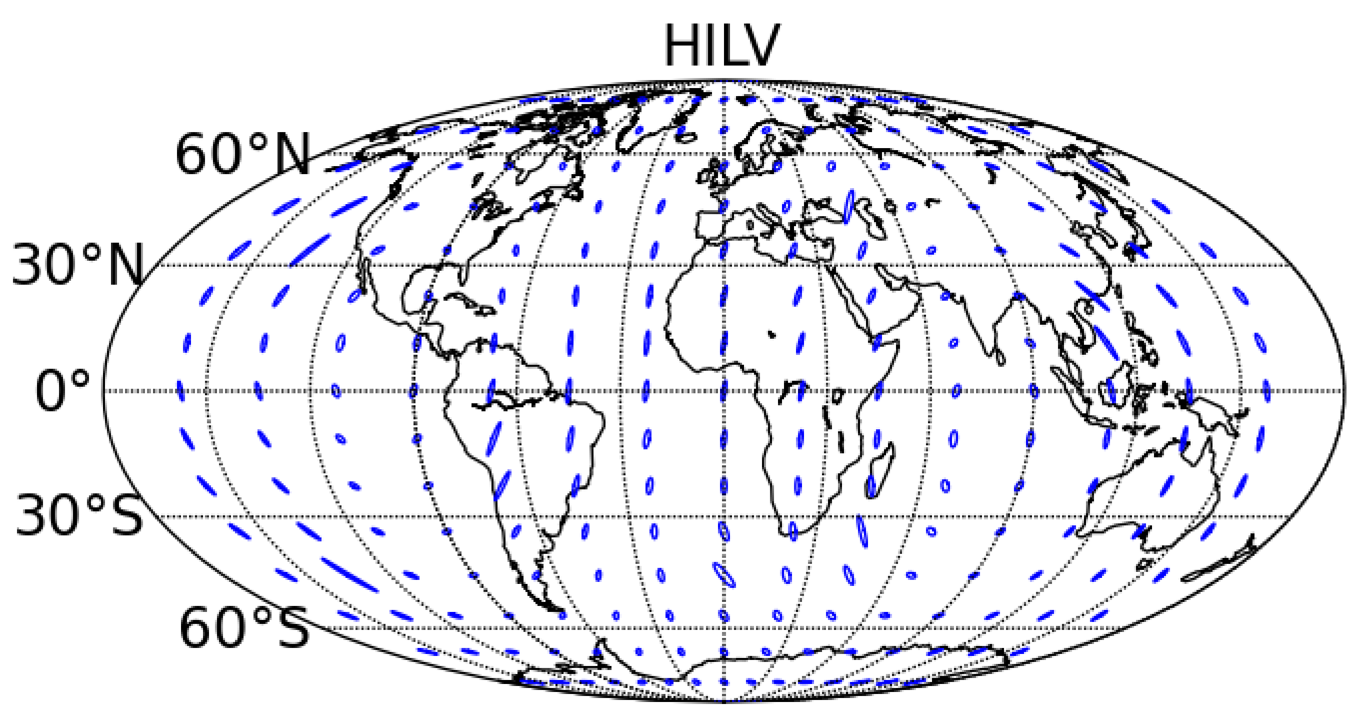
Abbott et al. (2016)

# Expected localization accuracy




3 detectors

→ ~100 deg$^2$




4-5 detectors

→ ~10 deg$^2$

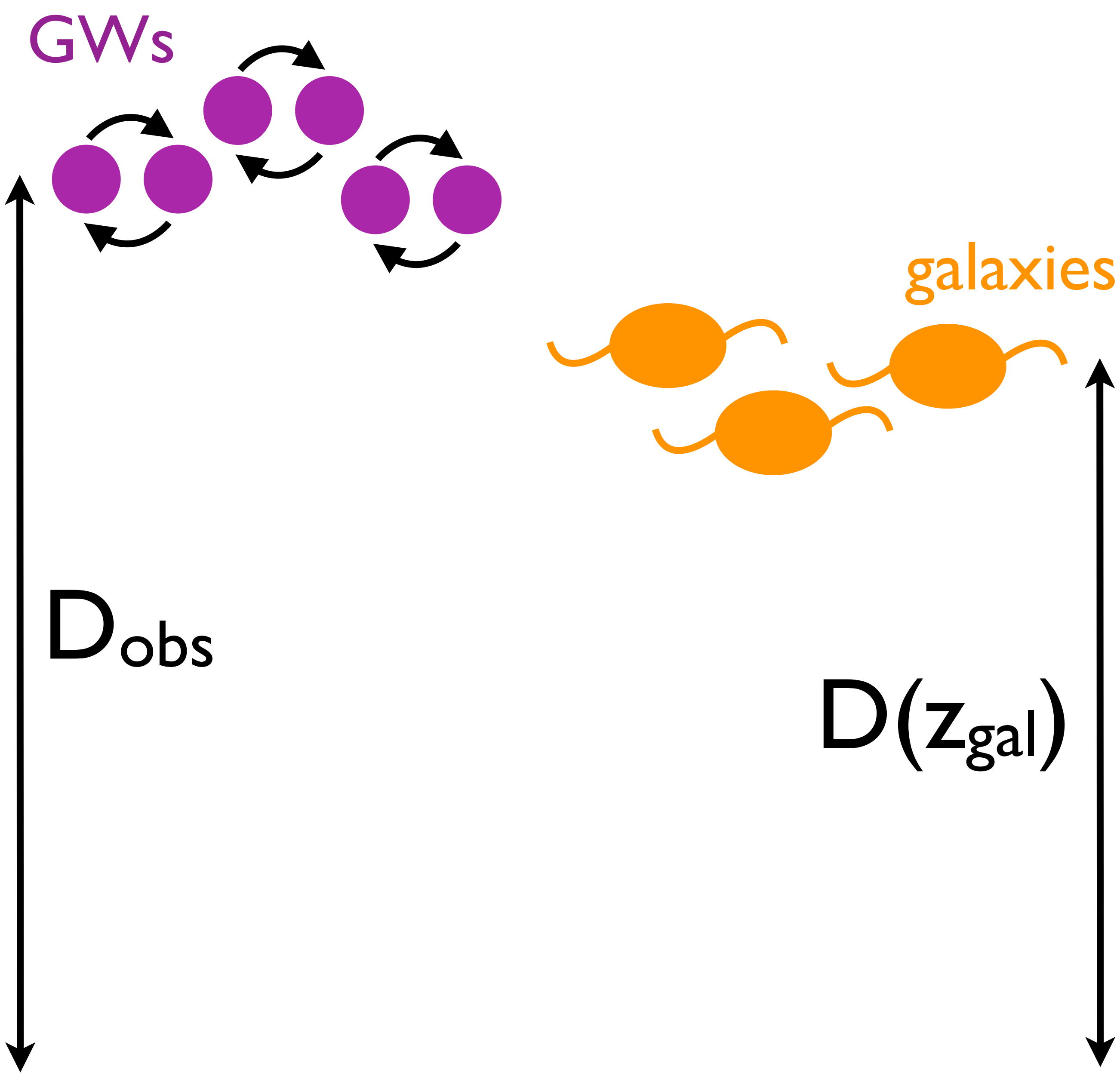
# Do we really need EM counterparts for cosmology with GW standard sirens?

Oguri Phys. Rev. D**93**(2016)083511

# Cross-correlation approach

- in the future we will have a bunch of burst GW events, possibly without EM counterparts
- idea: constrain distance-redshift relation with cross-correlation of GW sources (known $D_L$) and galaxies (known z)
- no need of follow-up observations for individual GW events!

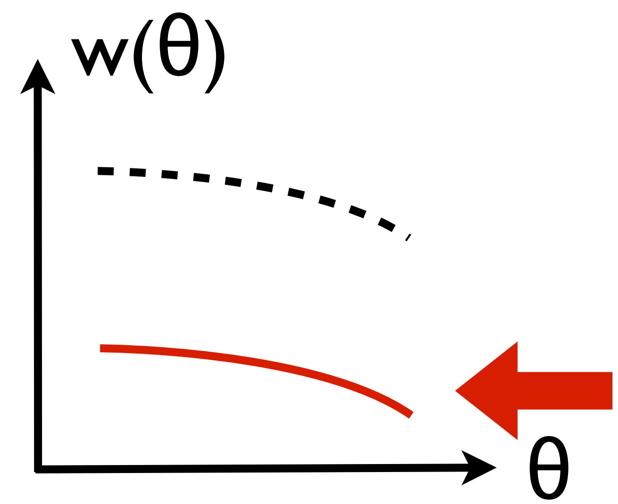
# Cross-correlation approach



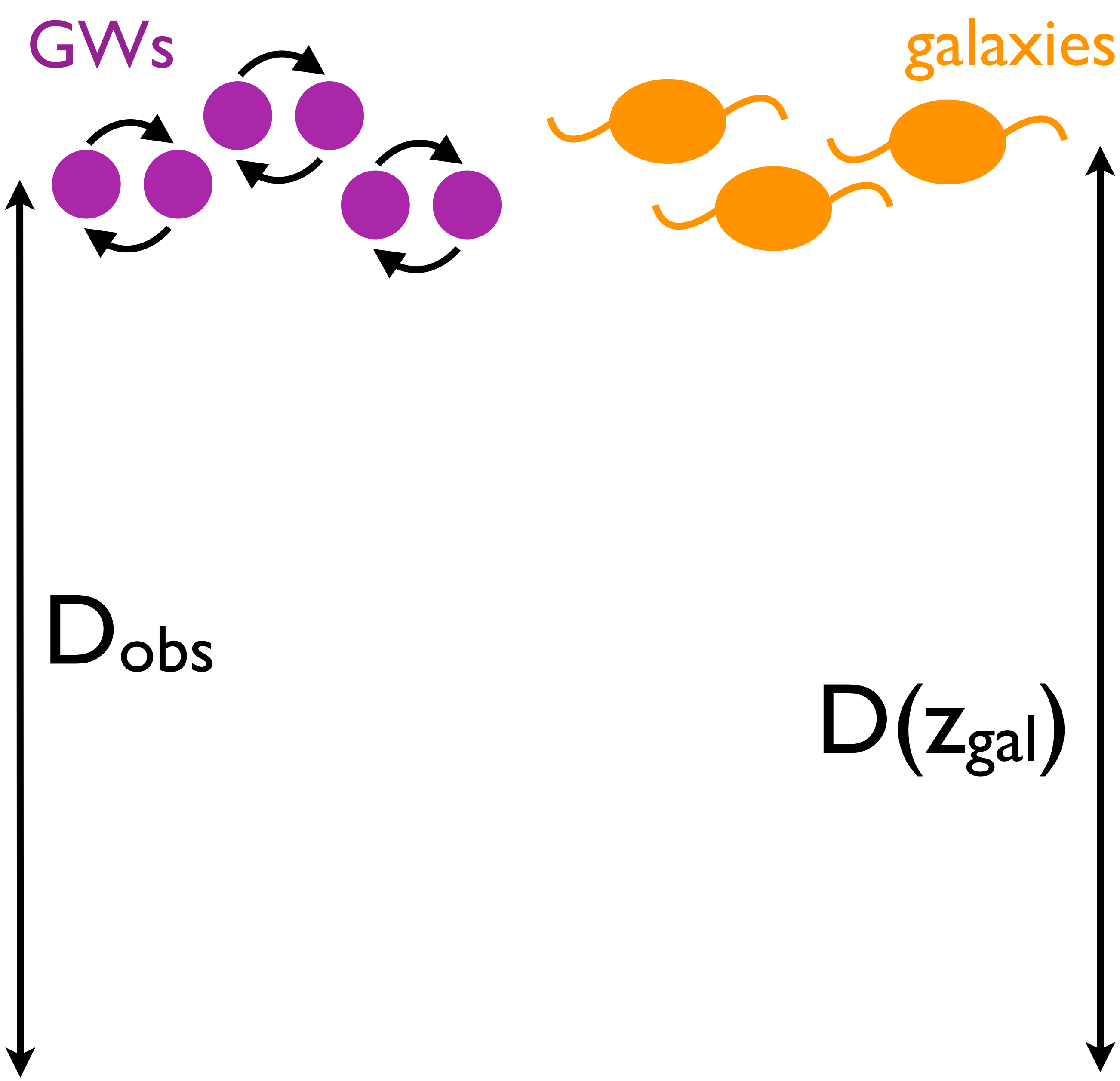

- cross-correlation of spatial distributions

$$w(\theta) = \langle \delta_{\rm GW}(\vec{\theta}')\delta_{\rm gal}(\vec{\theta}' + \vec{\theta})\rangle$$

- when $D_{obs} > D(z_{gal})$ cross-correlation is small



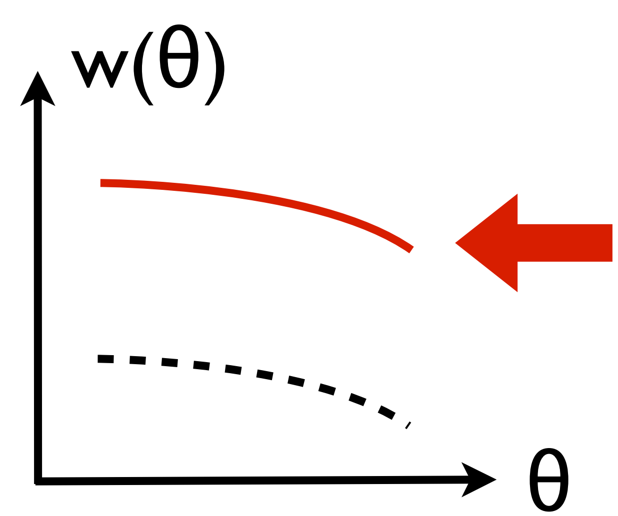
# Cross-correlation approach



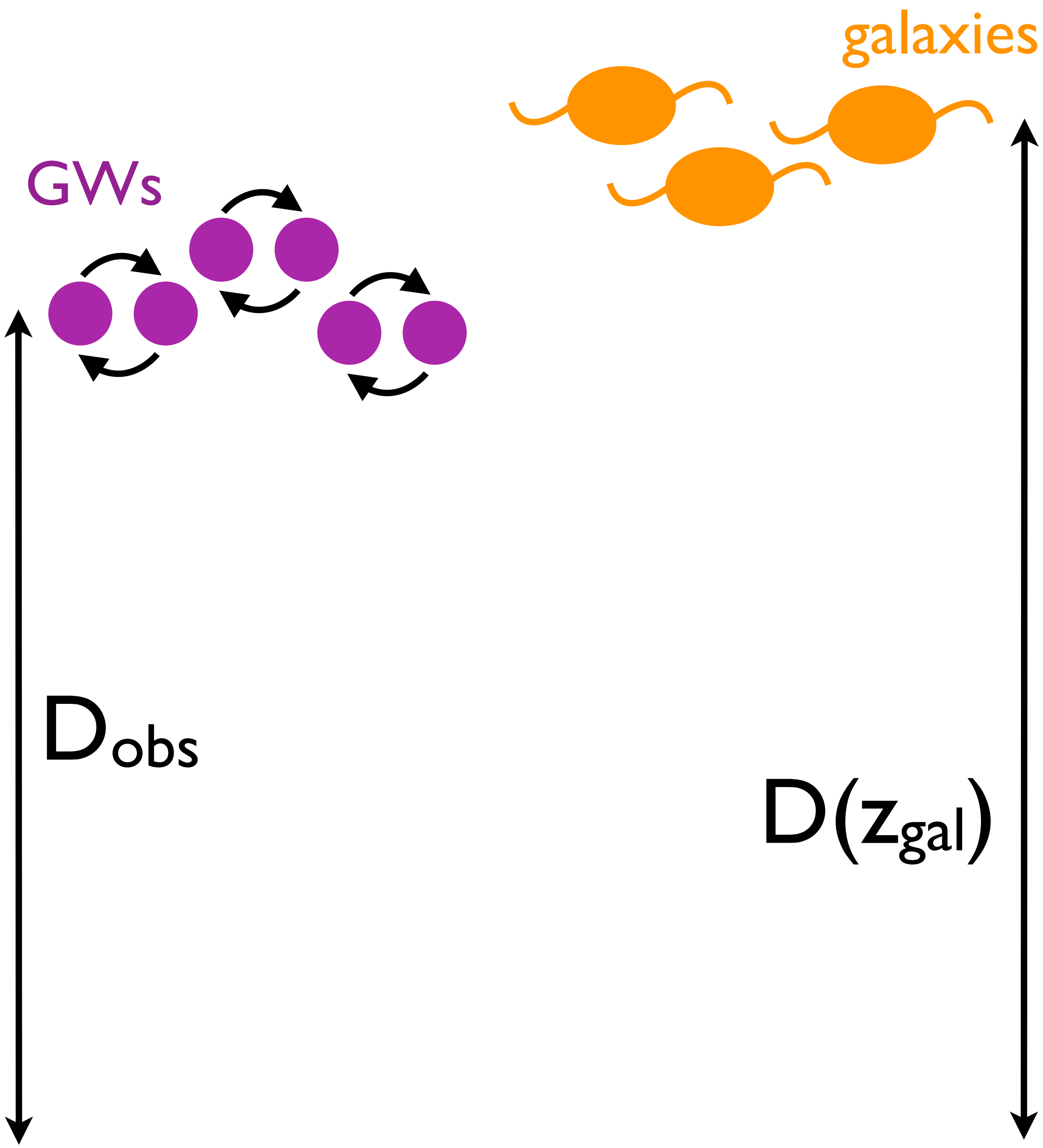

- cross-correlation of spatial distributions

$$w(\theta) = \langle \delta_{\rm GW}(\vec{\theta}')\delta_{\rm gal}(\vec{\theta}' + \vec{\theta})\rangle$$

- when $D_{\rm obs} \approx D(z_{\rm gal})$ cross-correlation is large



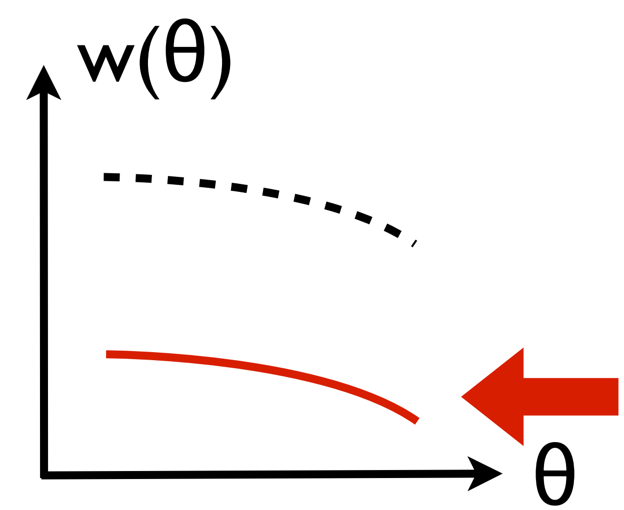
# Cross-correlation approach



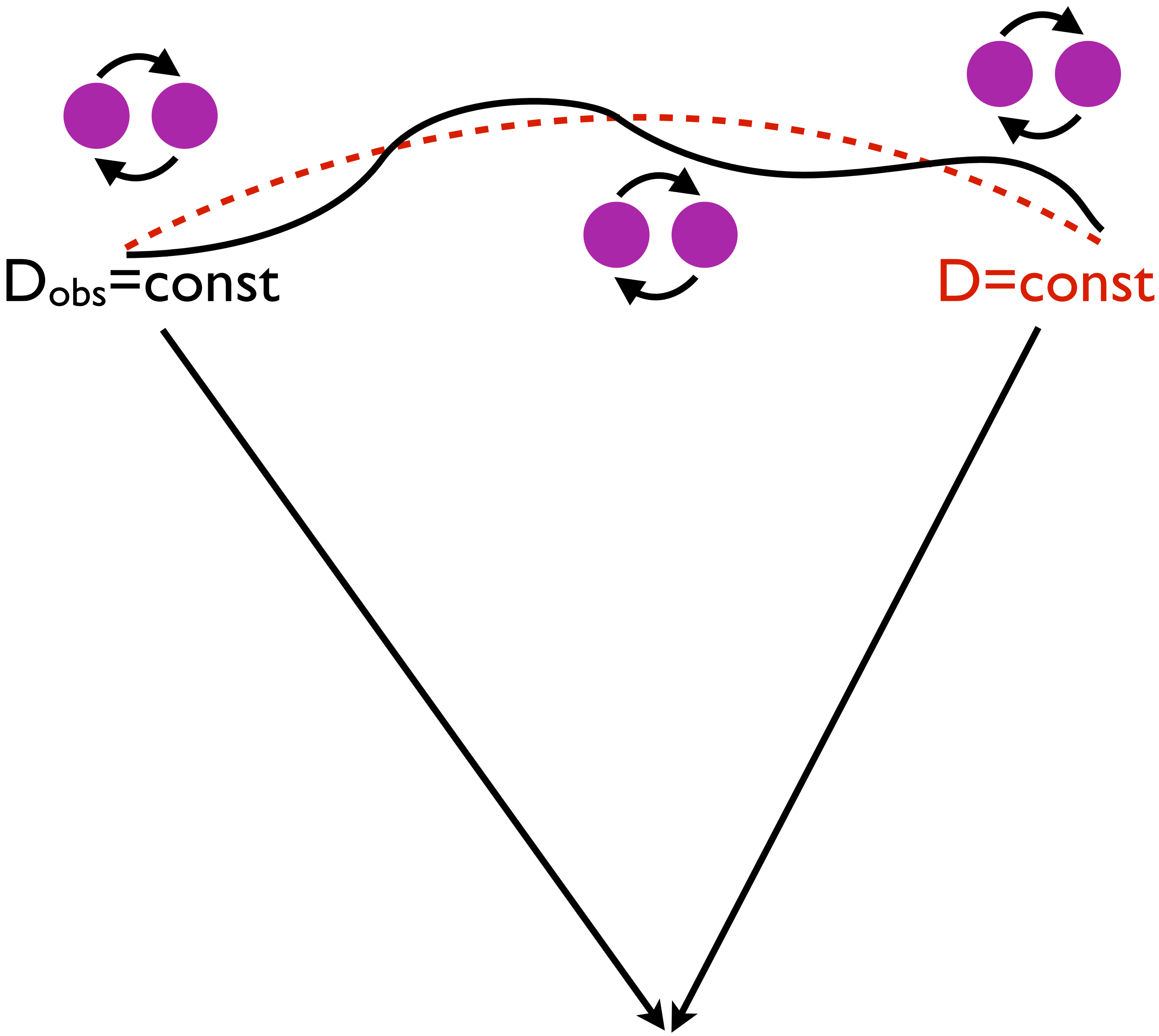

- cross-correlation of spatial distributions

$$w(\theta) = \langle \delta_{\rm GW}(\vec{\theta}')\delta_{\rm gal}(\vec{\theta}' + \vec{\theta})\rangle$$

- when $D_{obs} < D(z_{gal})$ cross-correlation is small



# Apparent clustering due to lensing




- weak lensing changes observed distance

$$D_{\rm obs} = \bar{D}\mu^{-1/2} \approx \bar{D}\left[1 - \kappa(\vec{\theta}, z)\right]$$

- since lensing effect is position-dependent it induces additional clustering pattern on the sky

Oguri Phys. Rev. D**93**(2016)083511

# Cross-correlation signals

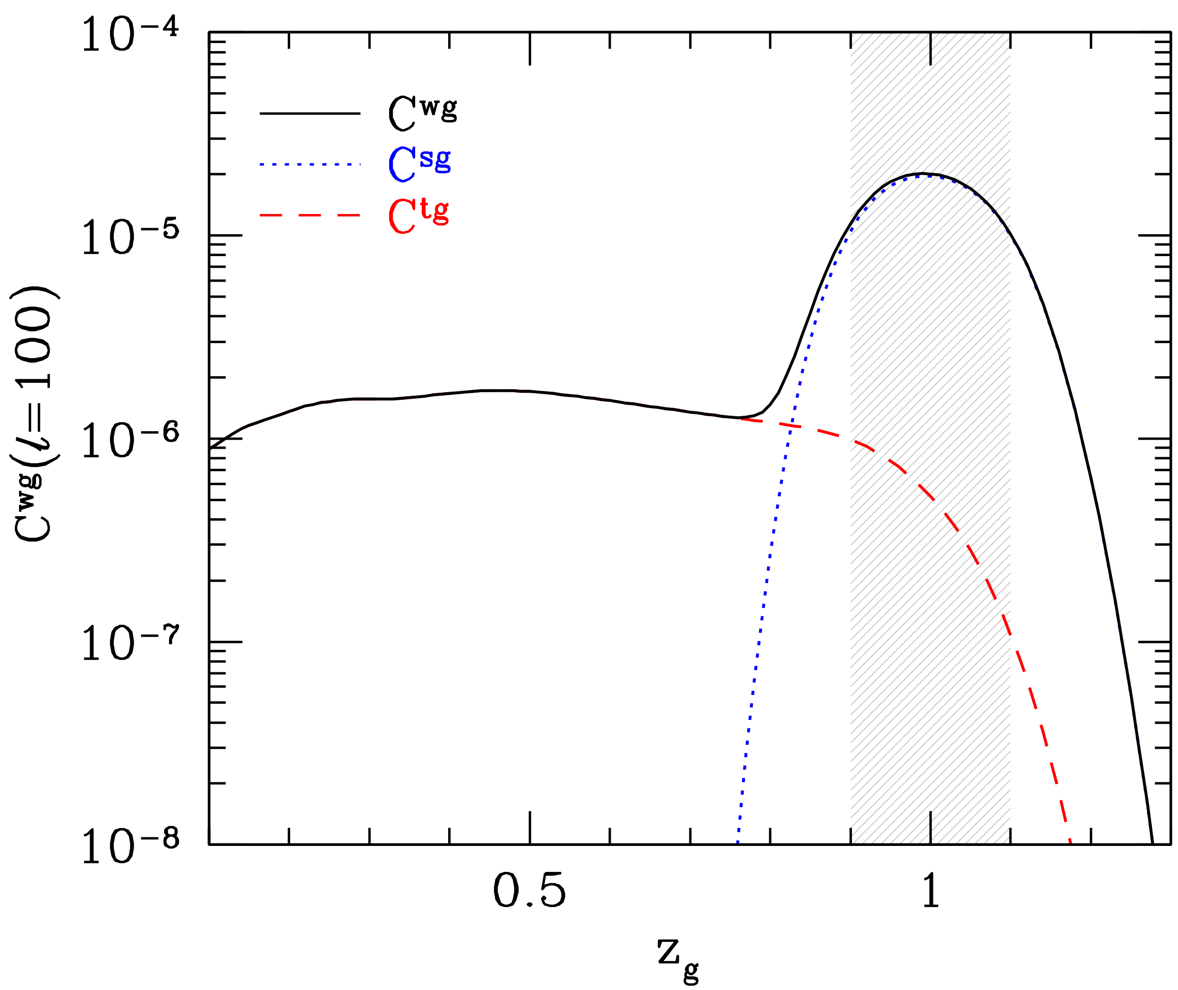
$$C^{\mathrm{w}_i\mathrm{g}_j}(\ell) = C^{\mathrm{s}_i\mathrm{g}_j}(\ell) + C^{\mathrm{t}_i\mathrm{g}_j}(\ell)$$

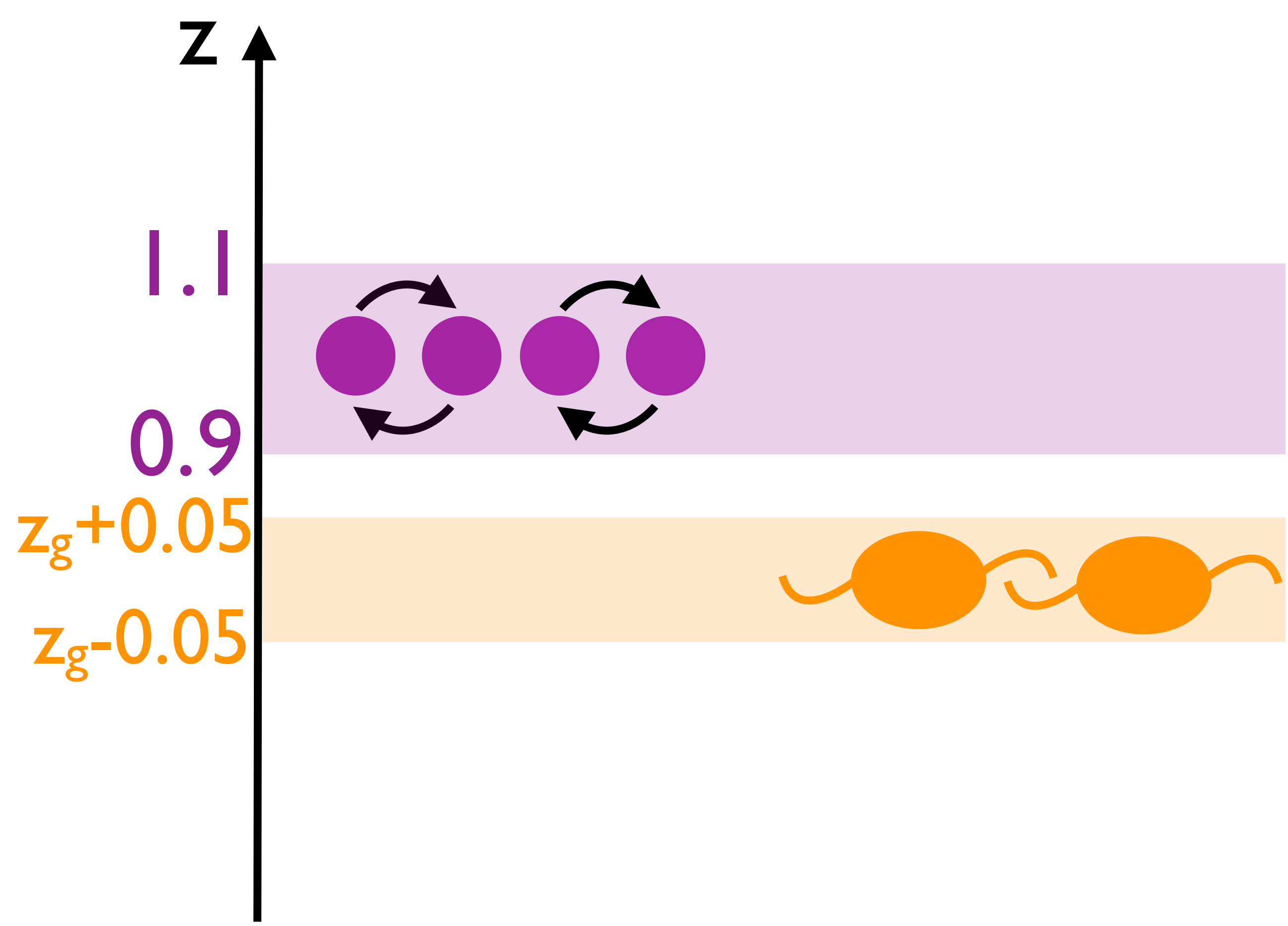
$$C^{\mathrm{s}_i\mathrm{g}_j}(\ell) = \int_0^\infty dz\, W_i^{\mathrm{s}}(z) W_j^{\mathrm{g}}(z) \frac{H(z)}{\chi^2} b_{\mathrm{GW}} b_{\mathrm{g}} P_{\mathrm{m}}\left(\frac{\ell+1/2}{\chi}; z\right)$$

physical spatial correlation

$$C^{\mathrm{t}_j\mathrm{g}_j}(\ell) = \int_0^\infty dz\, W_i^{\mathrm{t}}(z) \int_0^z dz' W_j^{\mathrm{g}}(z') W^{\kappa}(z';z) \frac{H(z')}{\chi'^2} b_{\mathrm{g}} P_{\mathrm{m}}\left(\frac{\ell+1/2}{\chi'}; z'\right)$$

apparent clustering due to weak lensing

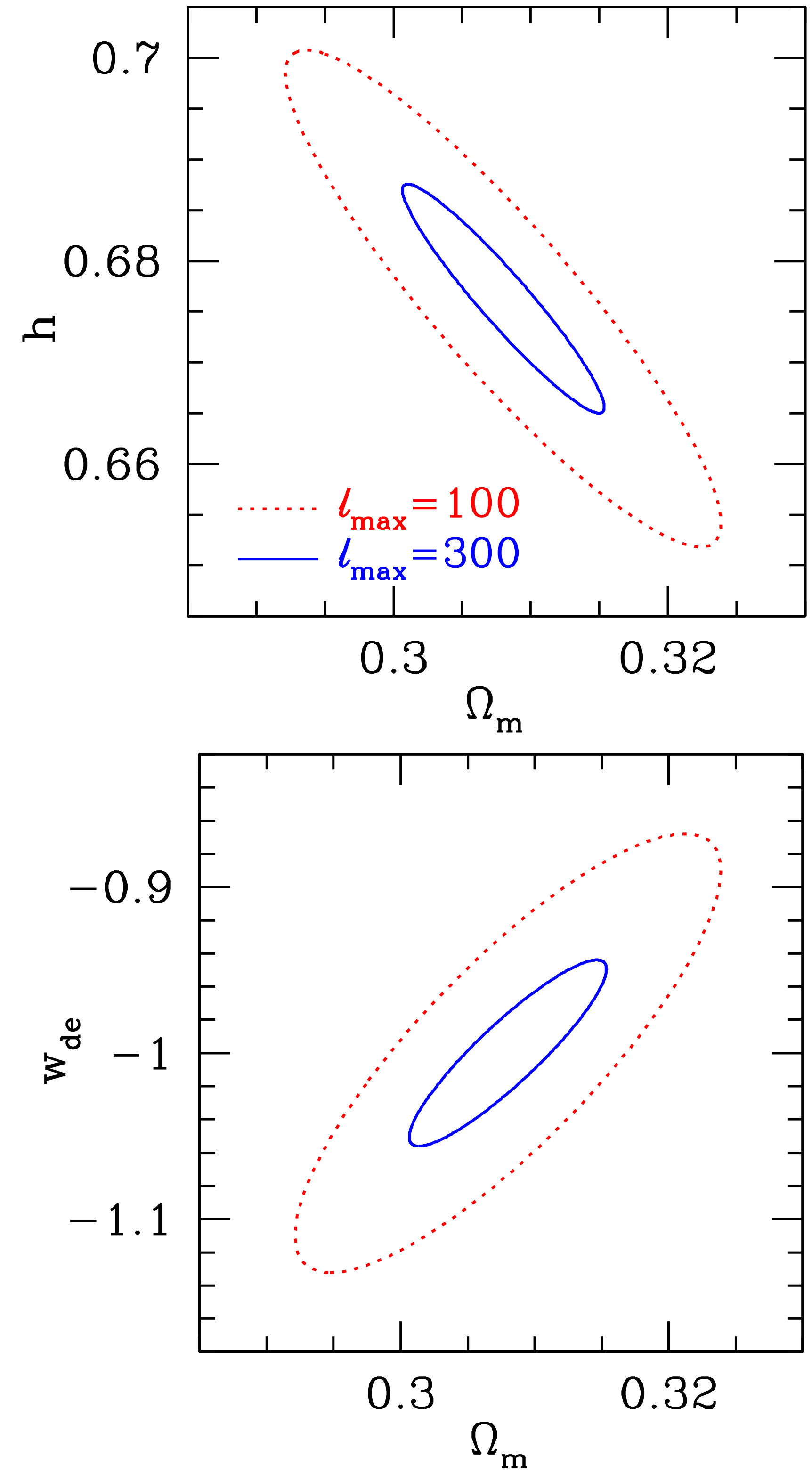


Oguri Phys. Rev. D**93**(2016)083511

# Forecast

- GWs from third-generation exp. + galaxies from Euclid (0.3<z<1.5)
- $l_{max}$ comes from accuracy of GW localizations
  fiducial: $l_{max}$ = 100 (→ ~1deg)
  optimistic: $l_{max}$ = 300
- tight constraints on $H_0$ and w possible with the cross-correlation approach (without any follow-up!)



# Summary

- gravitational waves from mergers of compact binaries are a promising, totally new absolute distance indicator at cosmological scale
- recent observation of GW150914 suggested its enormous potential
- usually identifications of EM counterparts are need to get redshifts and constrain distance-redshift relation
- a cross-correlation approach is proposed which enables GW cosmology without follow-up