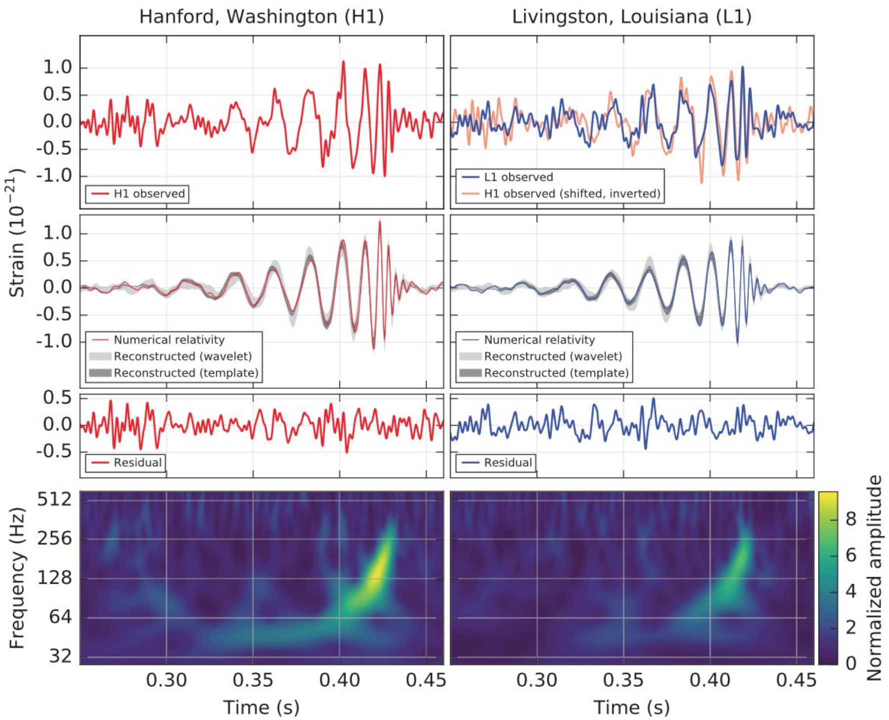
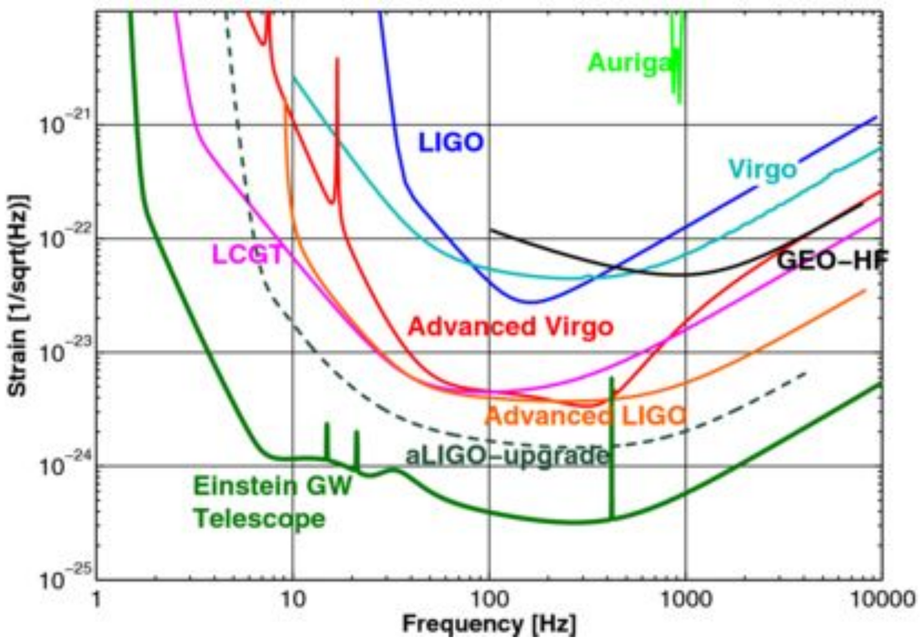
Gravitational waves from binary black holes

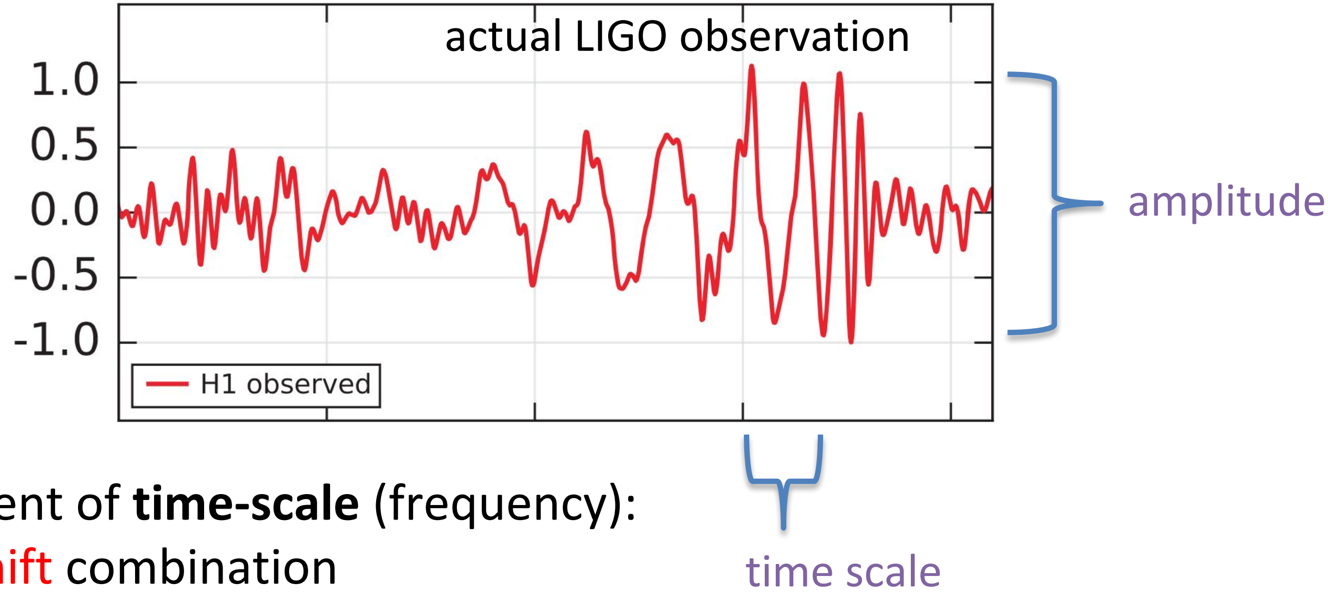




from ET conceptual design paper

Potential to detect a lot of massive binary (BH) mergers from far away

Gravitational wave observables



- Measurement of **time-scale** (frequency):
  mass-redshift combination

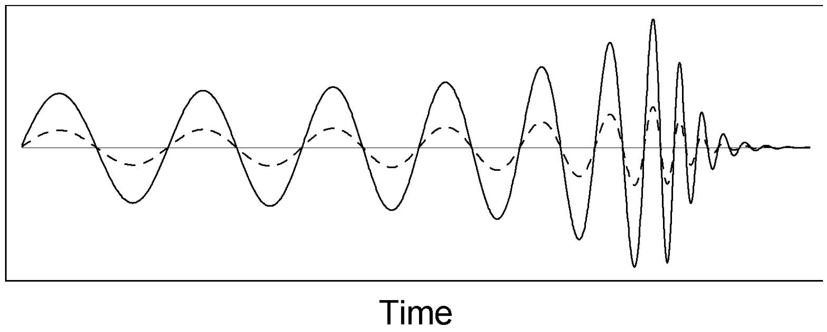
$$M(1+z)$$

- Measurement of **strain amplitude**: (multiple detectors for orientation)
  Luminosity distance-magnification combination

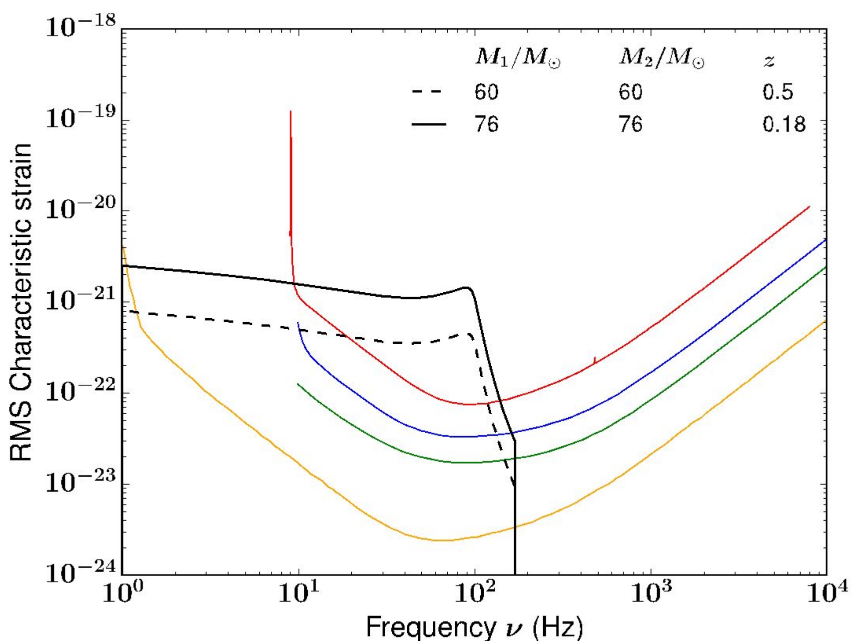
$$\frac{\sqrt{\mu}}{d_L(z)}\left(\frac{dE}{df_s}\right)^{1/2}_{M,f_s=f_o(1+z)}$$

- **Detailed shape**: mass ratio, spin, etc.

Gravitational lensing and GW parameter estimation



Consider an event with physical mass scale M, source redshift z, lensing magnification μ



Assume ignorance about magnification: Inferred mass scale $\tilde{M}$, inferred source redshift $\tilde{z}$

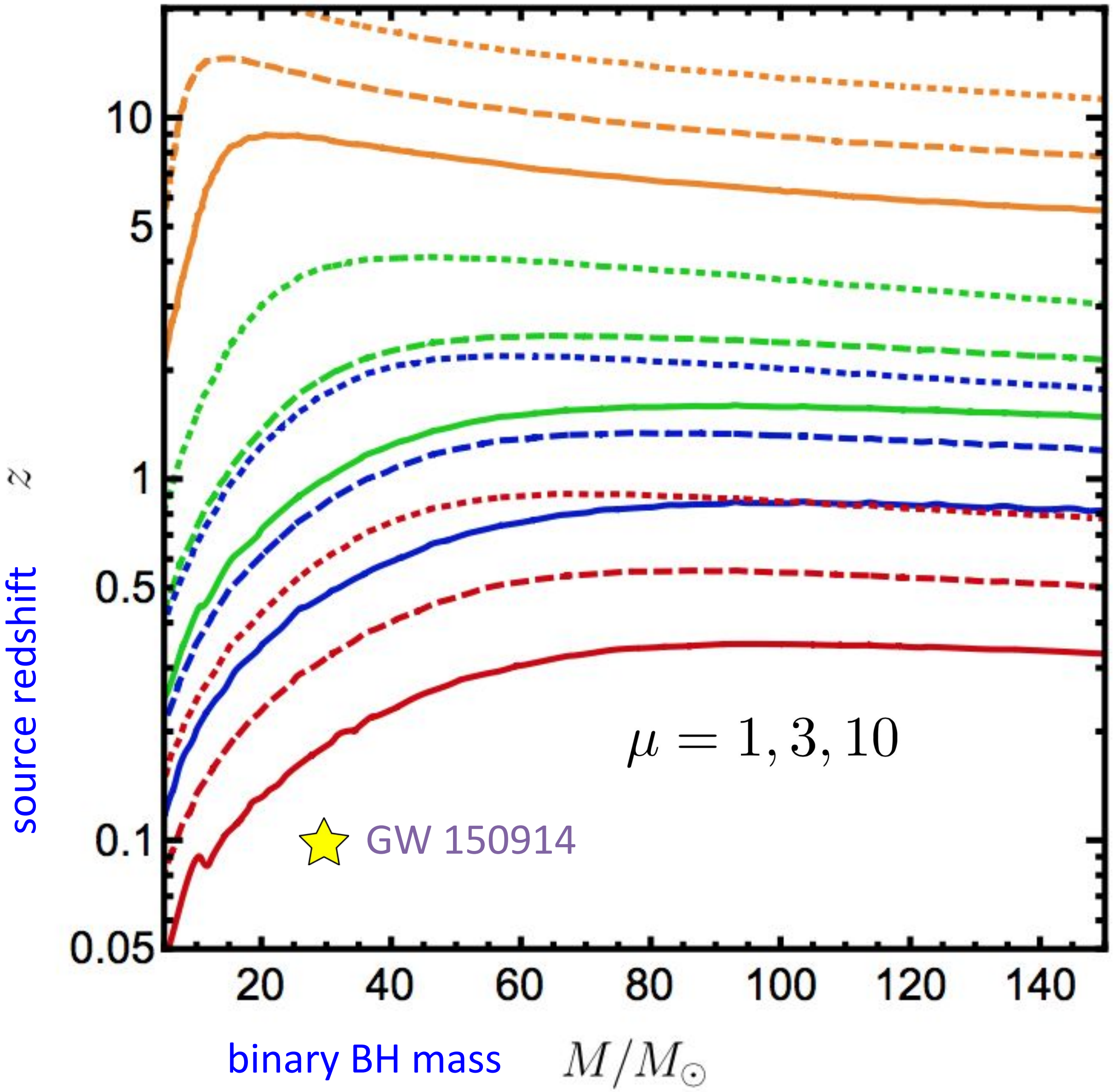
$$M(1+z) = \tilde{M}(1+\tilde{z})$$

$$d_L(\tilde{z}) = d_L(z)/\sqrt{\mu}$$

Availability of redshift information vs. lensing

	w/o lensing (de-)magnification	w/ lensing (de-)magnification
w/ EM counterpart or host identification	Independently measure M, z, d_L; **standard sirens** for measuring $d_L(z)$ (Holz & Hughes 05)	assuming **fiducial cosmology** $d_L(z)$; measure M, z and magnification μ
w/o EM counterpart or host identification (probably BH-BH merger)	assuming **fiducial cosmology** $d_L(z)$; still able to fix M, z (e.g. GW 150914)	Cannot uniquely determine M, z, μ **DEGENERACY**

High magnification tail

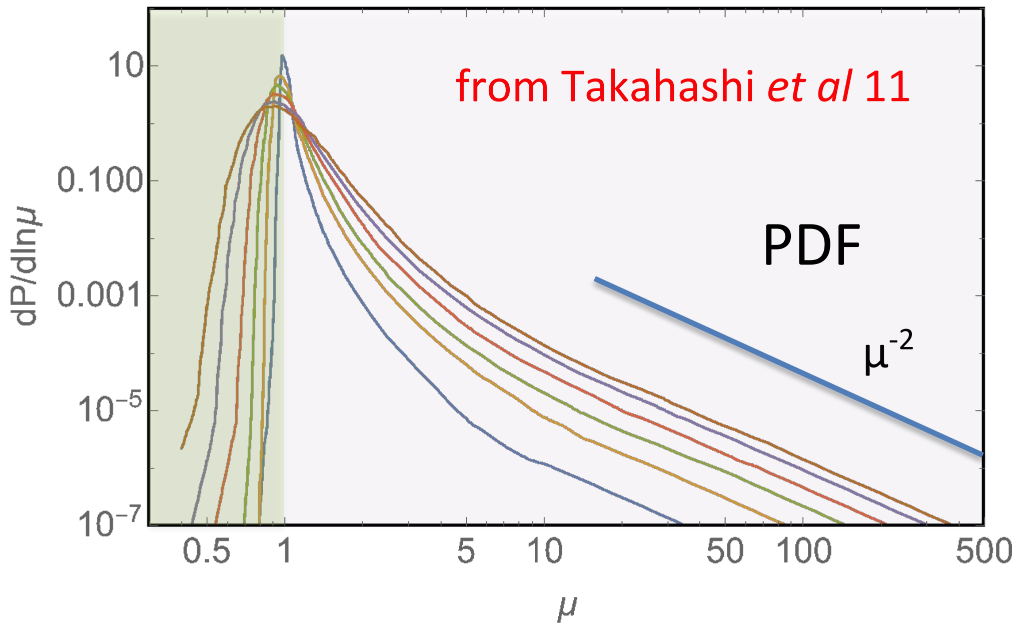


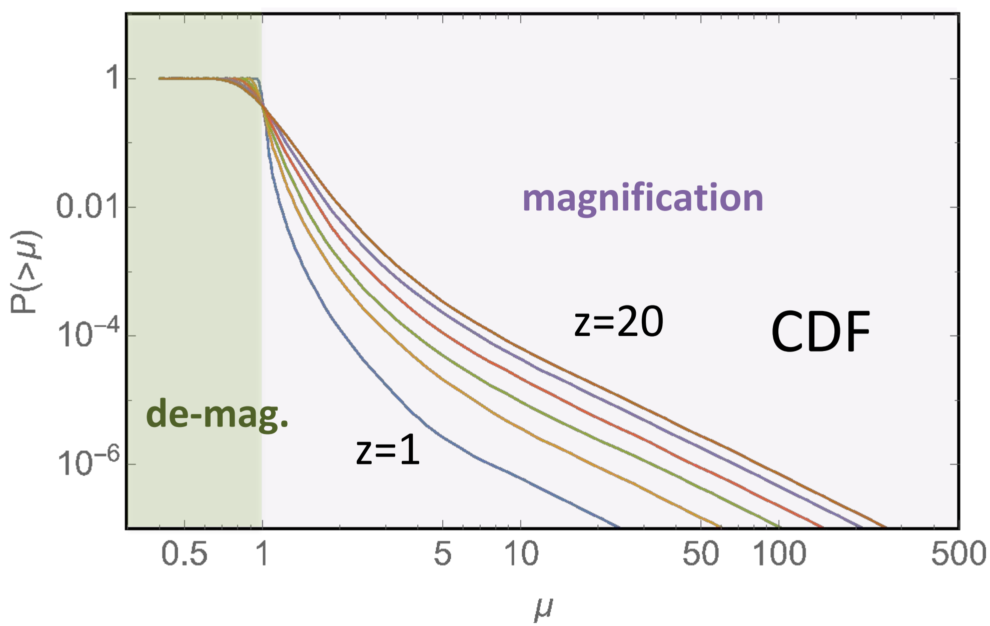
current LIGO
design LIGO
ultimate LIGO
Einstein Telescope

$$h' = \sqrt{\mu}\, h$$

S/N ~ 8

Lensing probability in ΛCDM





normalization

$$\int d\ln\mu \, \frac{dP(\mu, z)}{d\ln\mu} = 1$$

conservation of solid angle

$$<\mu> = \int d\ln\mu \, \frac{dP(\mu, z)}{d\ln\mu} \, \mu = 1$$

- Strong lensing dominated by galaxies; cluster lensing subdominant. Li & Ostriker 03
- Stellar lens population: diffraction regime. Takahashi 03

Observed merger distribution

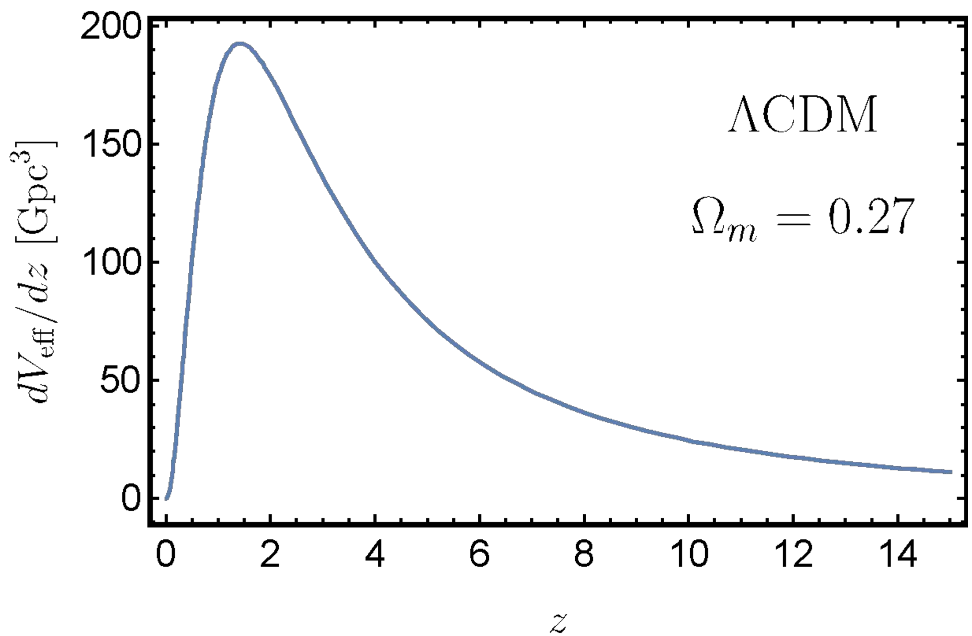
Only **inferred mass and redshift** are observable

$$\frac{d^3N\left(\tilde{M},\tilde{z}\right)}{d\tilde{M}\,d\tilde{z}\,dt} = \int d\ln\mu \frac{dP\left(\mu,z\right)}{d\ln\mu}\frac{d^3N\left(M,z\right)}{dM\,dz\,dt}\left[\frac{\partial\left(M,z\right)}{\partial\left(\tilde{M},\tilde{z}\right)}\right]_\mu$$

- Observed rate in terms of M' and z'
- lensing probability
- unlensed rate in terms of M and z
- mapping Jacobian

$$\frac{d^3N(M,z)}{dM\,dz\,dt} = \frac{d^2n(M,z)}{dM\,dt_s}\frac{4\pi c\,\chi^2(z)}{(1+z)\,H_0\,E(z)}$$

- intrinsic rate astrophysics models
- effective volume



Amplification bias

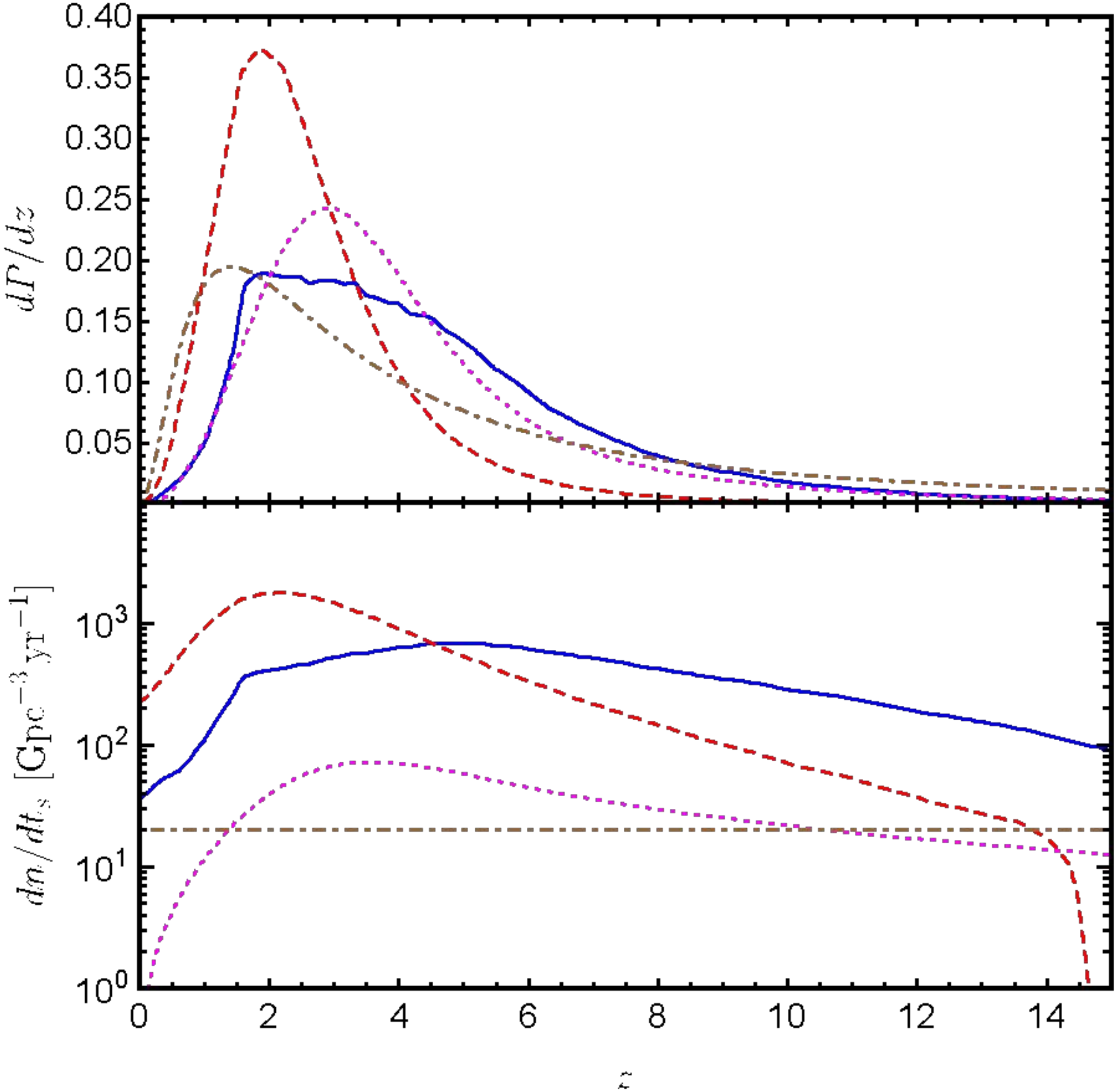
Sensitivity cut

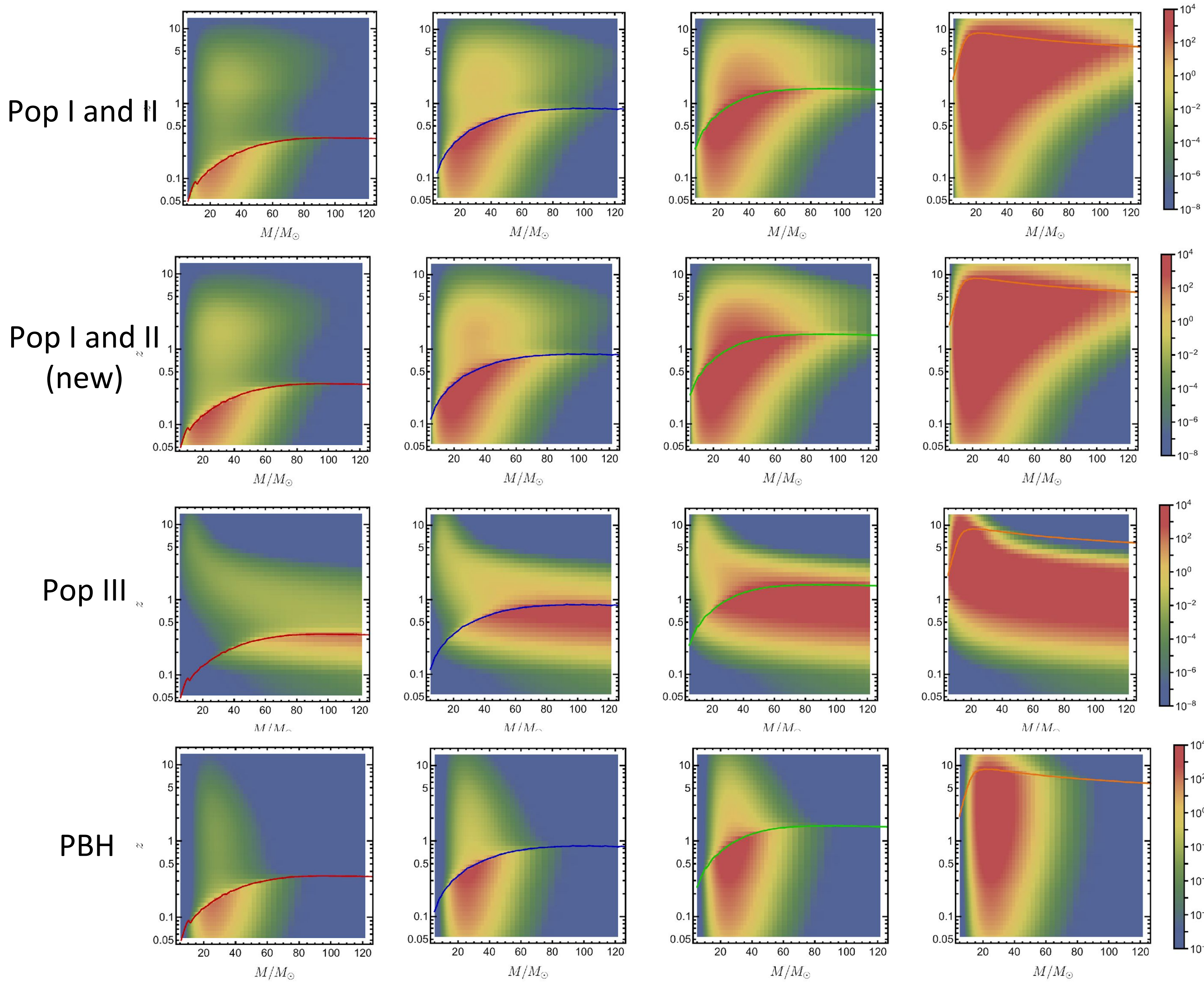
$$\frac{dN_{\mathcal{D}}}{dt}\left(\tilde{M} > M_{\min}\right) = \int_{M_{\min}}^{+\infty} d\tilde{M} \int d\tilde{z}\,\Theta\left(\mathcal{S}_{\mathcal{D}}(\tilde{M},\tilde{z}) - \mathcal{S}_0\right)$$

$$\times \int d\ln\mu\,\frac{dP(\mu;z)}{d\ln\mu}\,\frac{d^3N(M,z)}{dM\,dz\,dt}\,\left|\frac{\partial(M,z)}{\partial(\tilde{M},\tilde{z})}\right|_{\mu}.$$

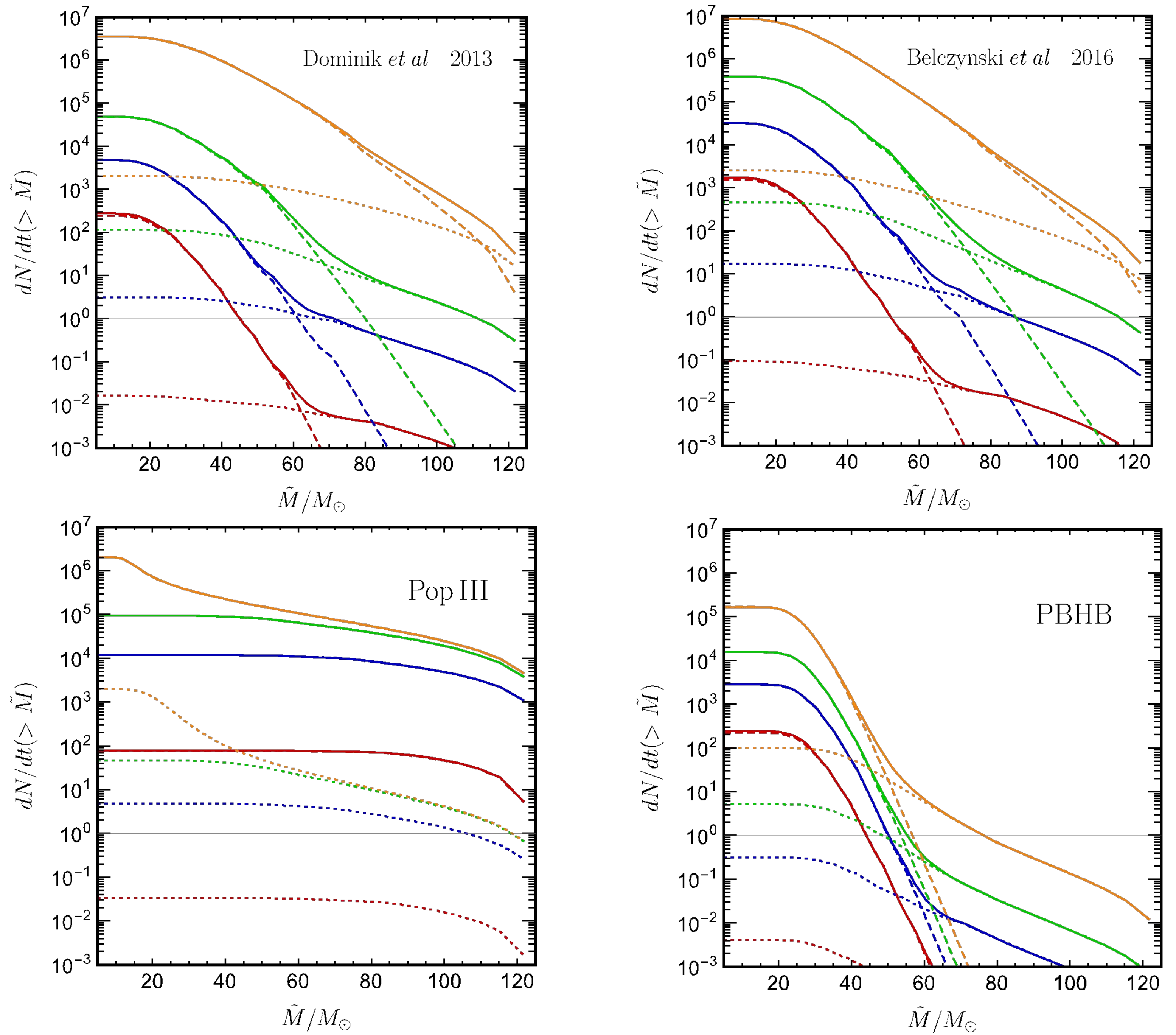
- Detector-dependent
- Increases the strongly lensed fraction for given parameters

Origin of massive BH binaries?





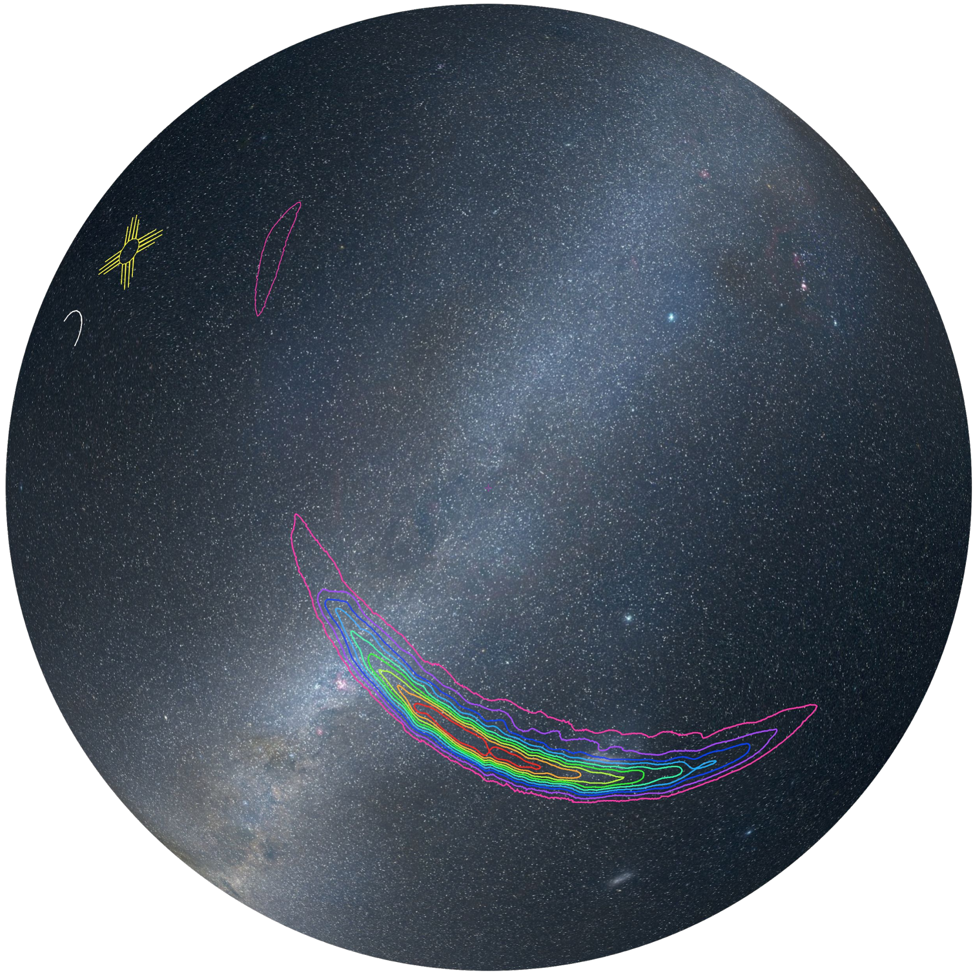
Pop I and II
Pop I and II
(new)
Pop III
PBH
$M/M_\odot$
z



Dominik *et al* 2013
Belczynski *et al* 2016
Pop III
PBHB
$dN/dt(>\tilde{M})$
$\tilde{M}/M_\odot$

What can we learn from multiple images?

With two detectors, localization is a function of orientation.
Multiple orientations -> improved location.



GW150914 Localization

See also Seto (14)