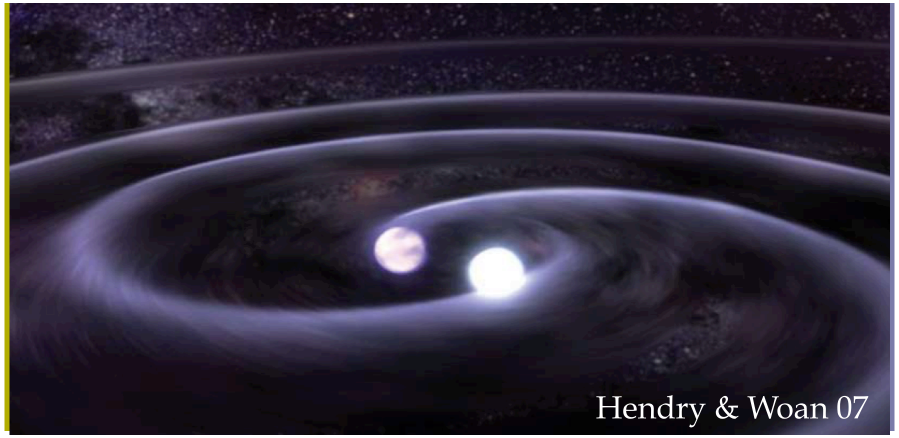
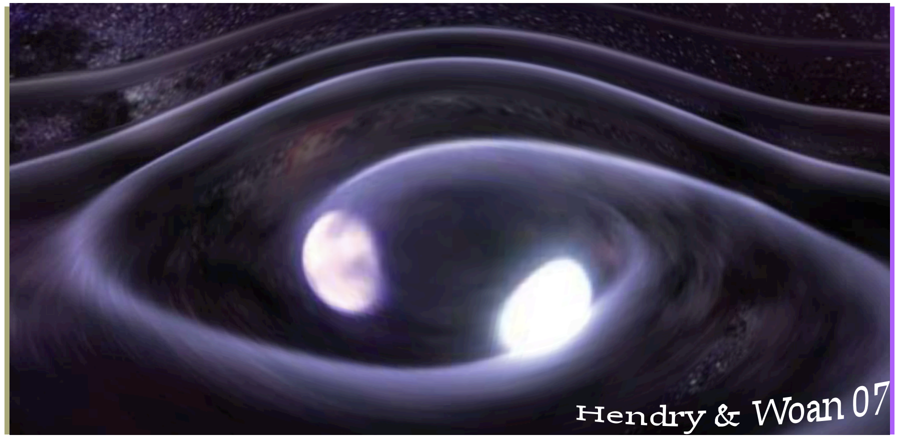
Are Gravitational Wave Standard-Sirens Ruined by Gravitational Lensing?





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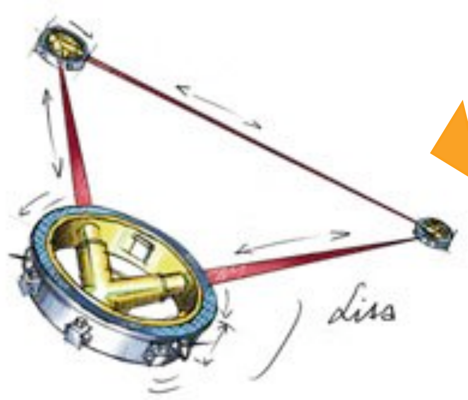
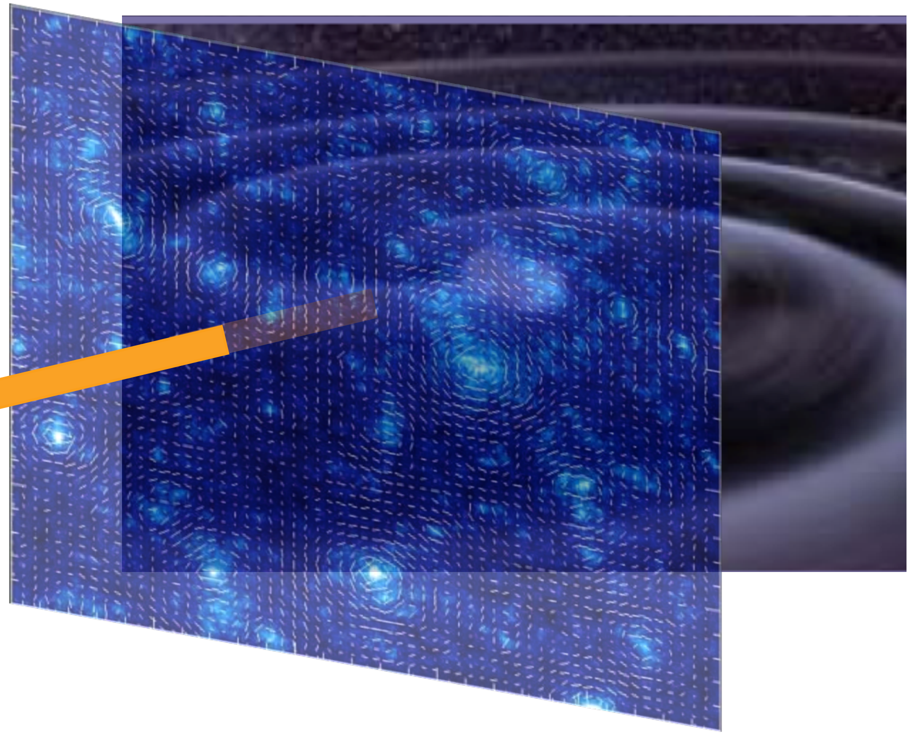
+ The Problem of Lensed Gravitational Wave Sirens



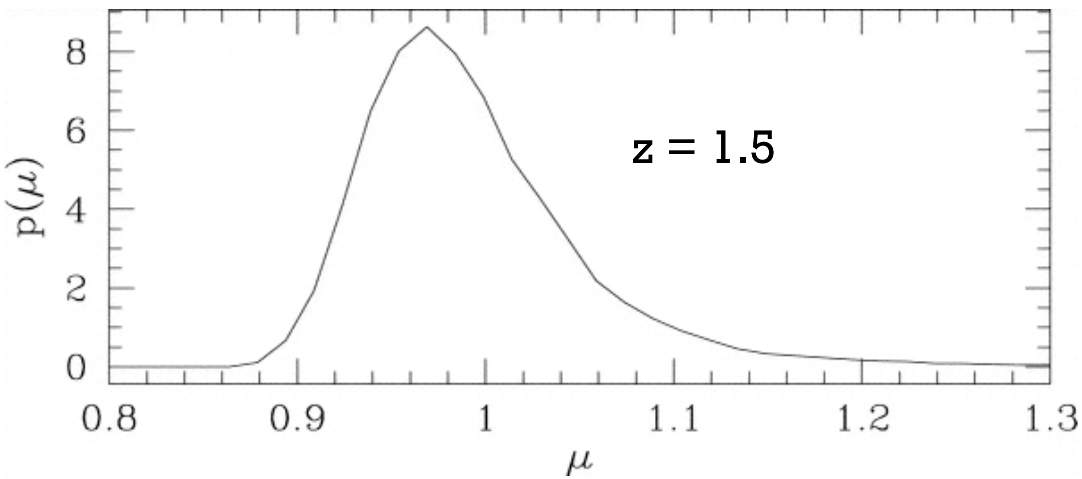


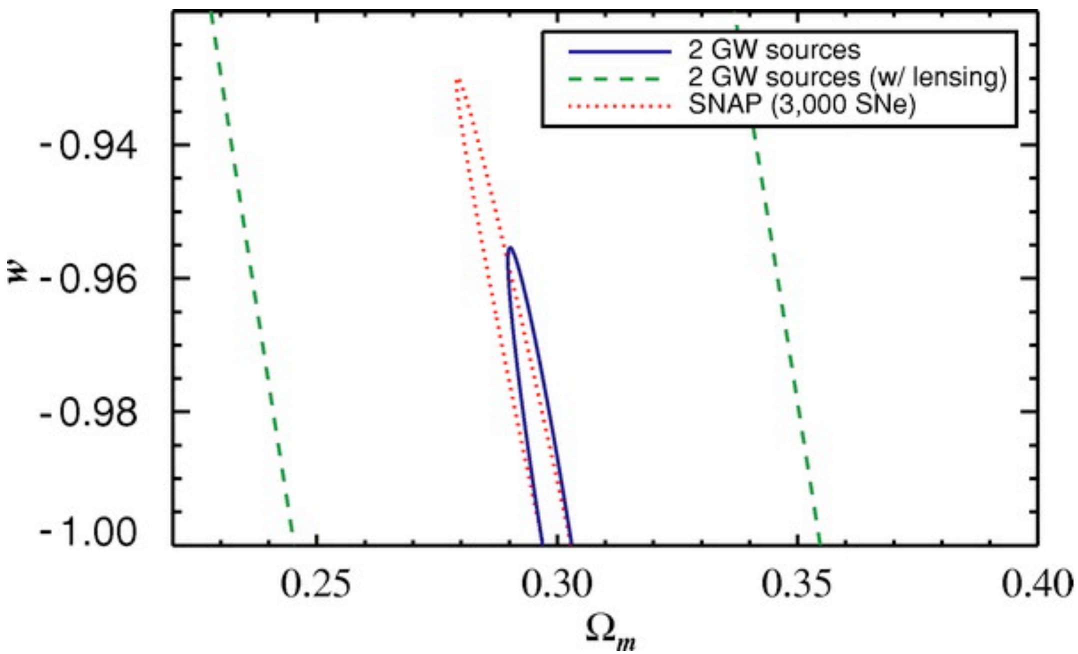
- Binary black holes (BBH) are precise "standard sirens." Gravitational waves (GW) measured by LISA could determine BBH distances to < 1%.
- If redshifts of EM counterparts are found, we can constrain cosmological parameters with the distance-redshift relation.
- But large-scale structure lenses GWs! From a (de)magnified signal, we can only measure

$$D_L^{\mathrm{obs}} = D_L^{\mathrm{true}}\, \mu^{-1/2}$$

- Lensing blows up distance uncertainty to ~5% at z=2.

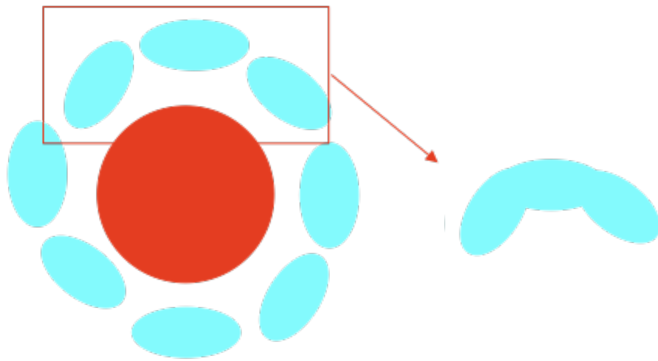
+ BBH distances are uncertain due to an unknown GW magnification





- Holz & Hughes (2005)
- All parameters fixed except 2
- Expect ~few BBH/year
- Oh, cruel Universe!

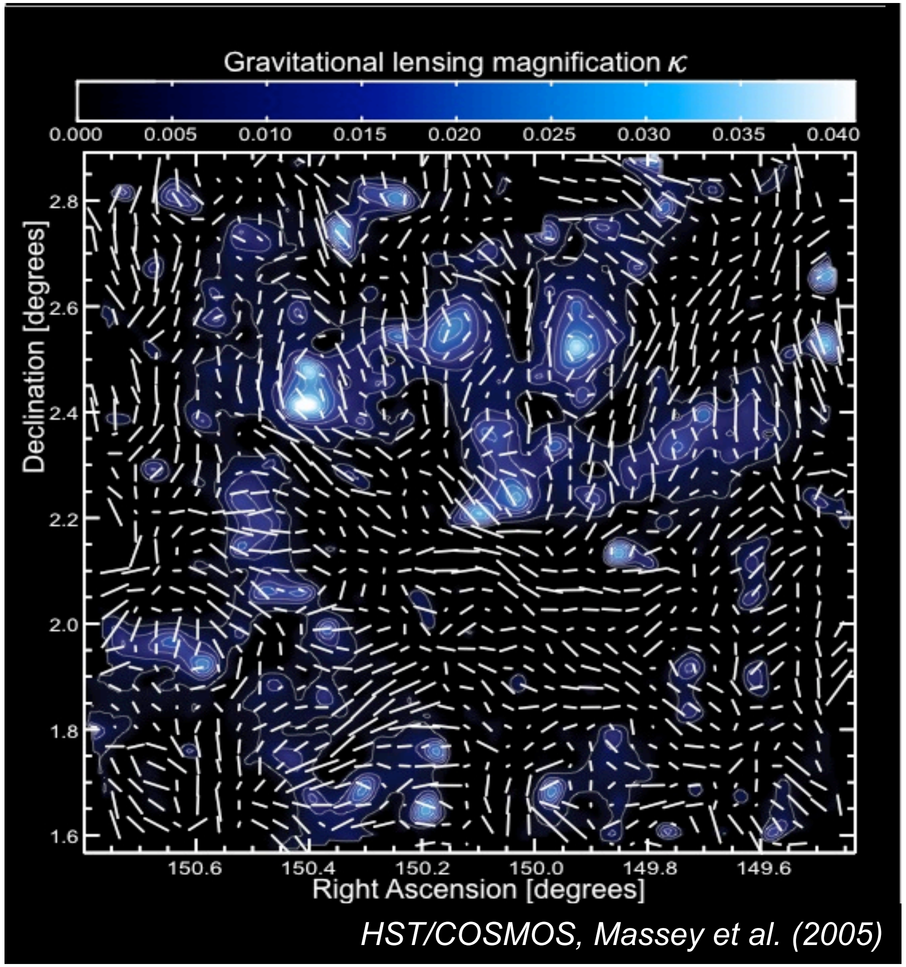
+ Solution: Can We Map the Magnification?



- Not a new idea
- A map of μ can be reconstructed from weakly lensed galaxy images ($\mu \approx 1\text{-}2\kappa$)
- Measure shear and **flexion**

- Flexion is the weak "arc-iness" or "bananification" of lensed galaxies
- Maps are noisy due to intrinsic galaxy shapes and finite sampling (we must smooth)
- Dalal et al. (2006): The fraction of σ_μ^2 that can be removed by mapping μ is

$$r^2 = \frac{\langle \kappa\kappa_\theta \rangle^2}{\langle \kappa^2 \rangle [\langle \kappa_\theta^2 \rangle + C_P(\theta)]}$$



HST/COSMOS, Massey et al. (2005)

+ The Power of Flexion

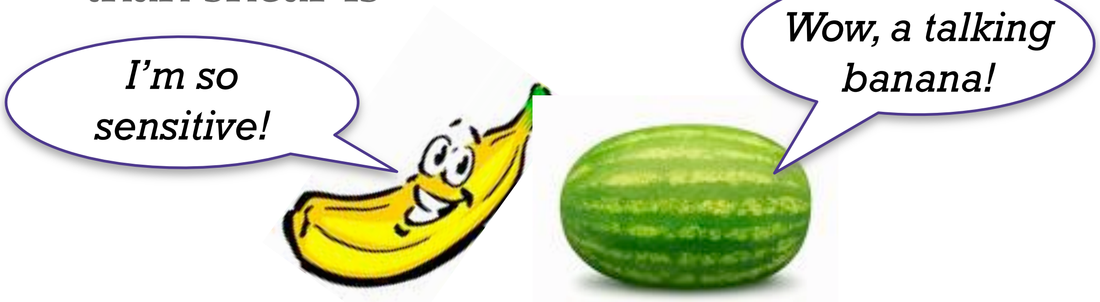
- Flexion is (informally)

  F ~ grad(κ) or G ~ grad(γ)

- High S/N galaxies have small intrinsic flexion

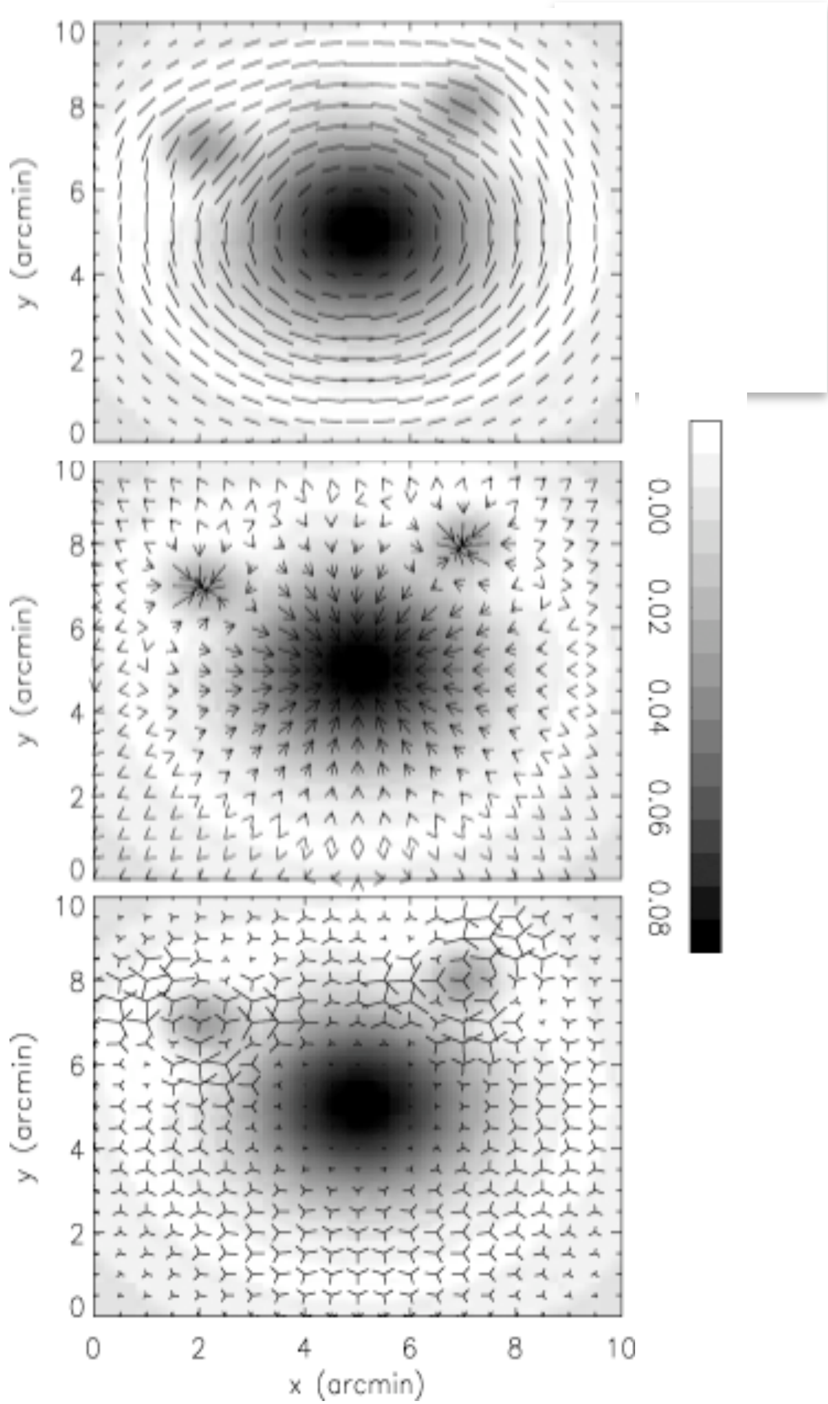
  $\gamma_{\rm int}$ = 0.2 – 0.4 $F_{\rm int}$ < 0.1/arcmin

- Flexion is more sensitive to **substructure** than shear is



- Shape noise in μ map is independent of flexion smoothing scale (unlike shear):

$$C_p(\theta) = \frac{F_{\rm int}^2}{\pi\, n_{\rm gal}} \qquad C_p(\theta) = \frac{\gamma_{\rm int}^2}{\pi\, \theta^2\, n_{\rm gal}}$$



+ How well can we remove magnification uncertainty? **Assumptions:**

- Follow up on each BBH with pointed observations (we'll want to anyway!) Say, with an ELT:

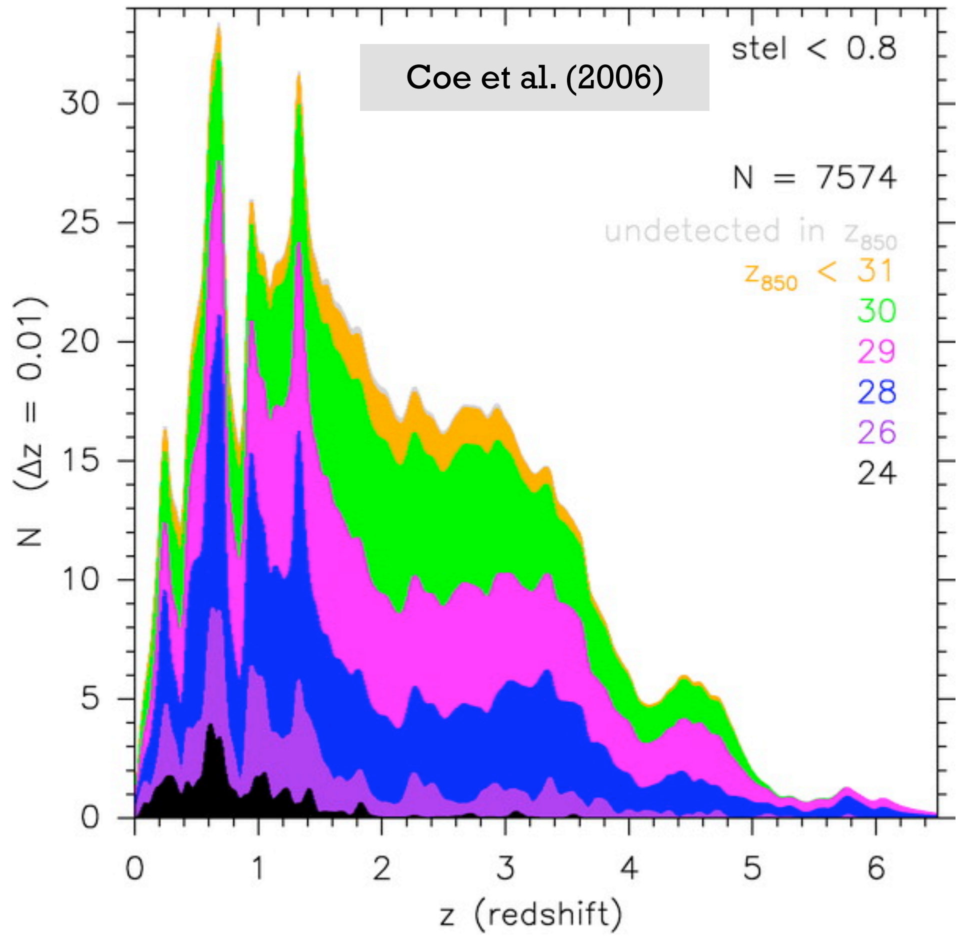
$$\gamma_{RMS} = 0.2 \qquad F_{RMS} = 0.04/\mathrm{arcmin}$$

- Assume images similar to Hubble Ultra Deep Field:

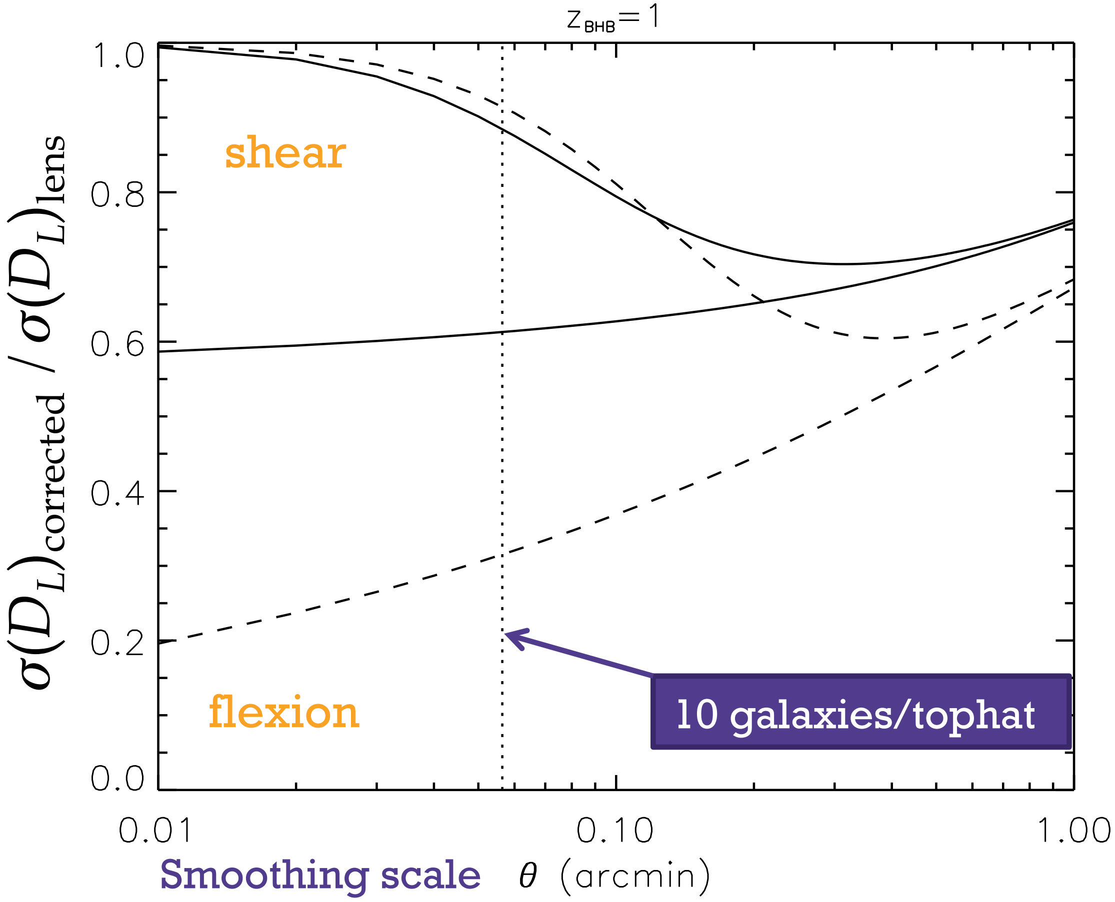
$$n_{gal}=1000/\mathrm{arcmin}^2 \qquad z_{med}=1.8$$

- Assume lensing fields are weak and Gaussian; no intrinsic correlations

- Concordance ΛCDM, σ_8=0.8, n_s=0.96, nonlinear power from Smith et al. fitting formula

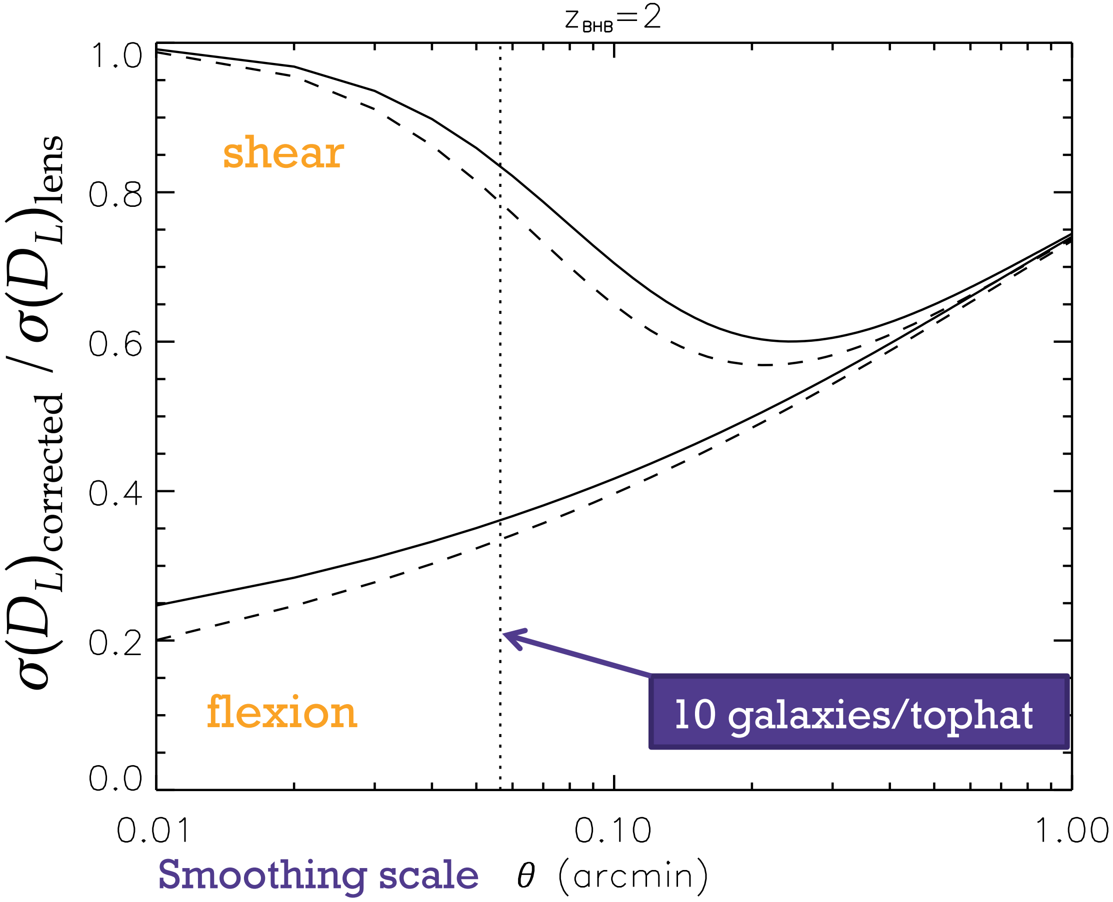


How well can we remove magnification uncertainty? $z = 1,\ \sigma(D_L)_{\rm lens} = 2\%$



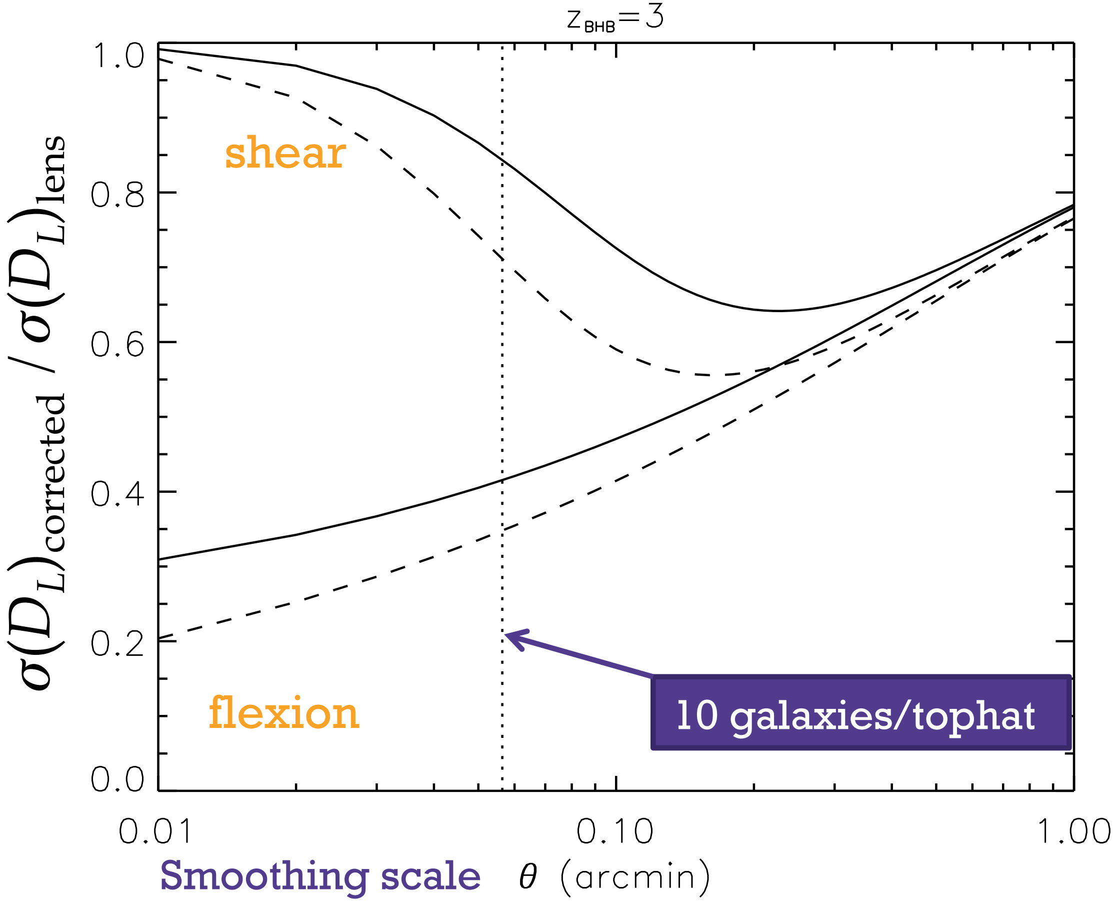
$$C_p(\theta) = \frac{F_{\rm int}^2}{\pi\, n_{\rm gal}} \qquad C_p(\theta) = \frac{\gamma_{\rm int}^2}{\pi\, \theta^2\, n_{\rm gal}} \qquad r^2 = \frac{\langle \kappa \kappa_\theta \rangle^2}{\langle \kappa^2 \rangle [\langle \kappa_\theta^2 \rangle + C_P(\theta)]}$$

+ How well can we remove magnification uncertainty? $z = 2,\ \sigma(D_L)_{\rm lens}$=4%



$$C_p(\theta) = \frac{F_{\rm int}^2}{\pi\, n_{\rm gal}} \qquad C_p(\theta) = \frac{\gamma_{\rm int}^2}{\pi\, \theta^2\, n_{\rm gal}} \qquad r^2 = \frac{\langle \kappa\kappa_\theta \rangle^2}{\langle \kappa^2 \rangle [\langle \kappa_\theta^2 \rangle + C_P(\theta)]}$$

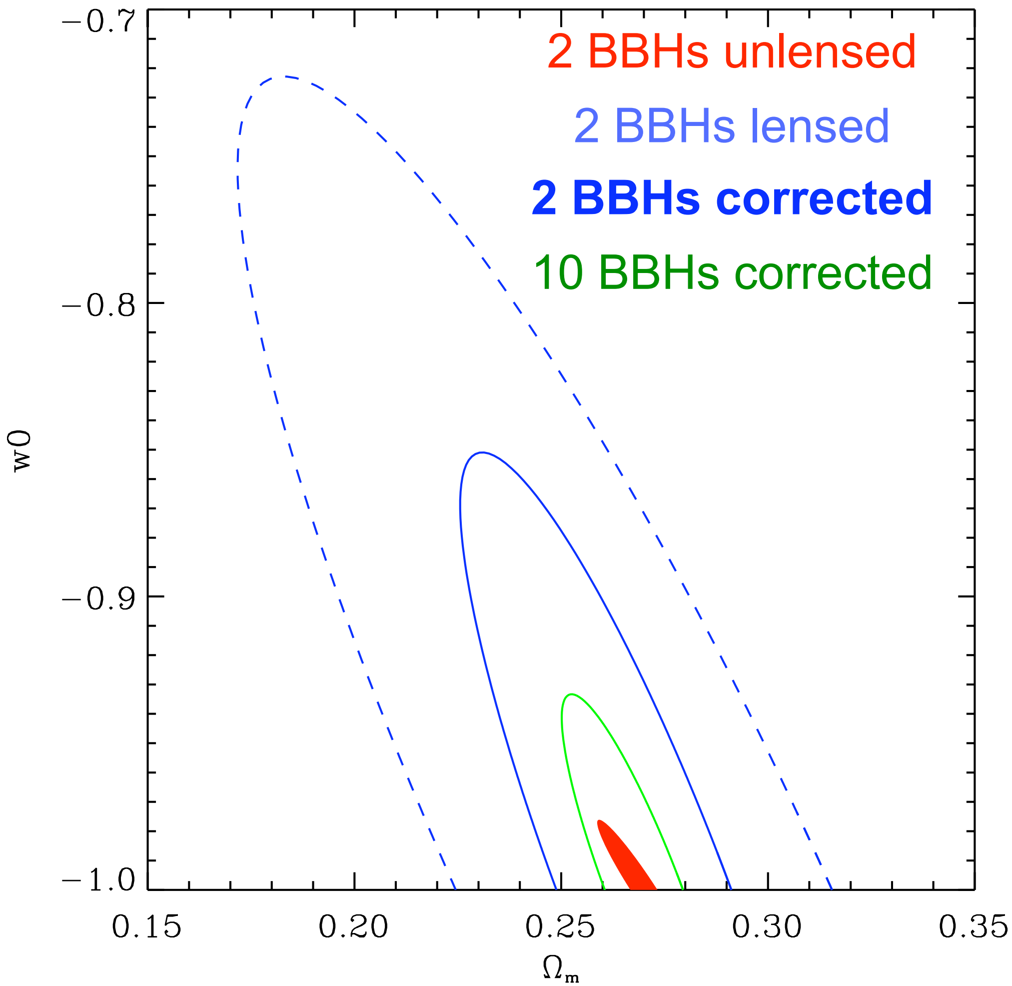
How well can we remove magnification uncertainty? $z = 3$, $\sigma(D_L)_{\rm lens}$=5.2%



$$C_p(\theta) = \frac{F^2_{\rm int}}{\pi\, n_{\rm gal}} \qquad C_p(\theta) = \frac{\gamma^2_{\rm int}}{\pi\, \theta^2\, n_{\rm gal}} \qquad r^2 = \frac{\langle \kappa\kappa_\theta\rangle^2}{\langle\kappa^2\rangle[\langle\kappa^2_\theta\rangle + C_P(\theta)]}$$

+ Impact on Dark Energy Parameters

- All parameters fixed except 2
- 2 BBHs are still not competitive with SNAP supernovae, but we have made good progress!



+ Summary

- Binary black holes are precise standard sirens, but gravitational lensing hampers distance measurements.
- Using deep images of BBH neighborhoods to make weak lensing maps, we can remove some uncertainty in BBH distances.
- Flexion maps from images like the from Hubble Ultra Deep Field could reduce distance errors by factors of 2 or 3.