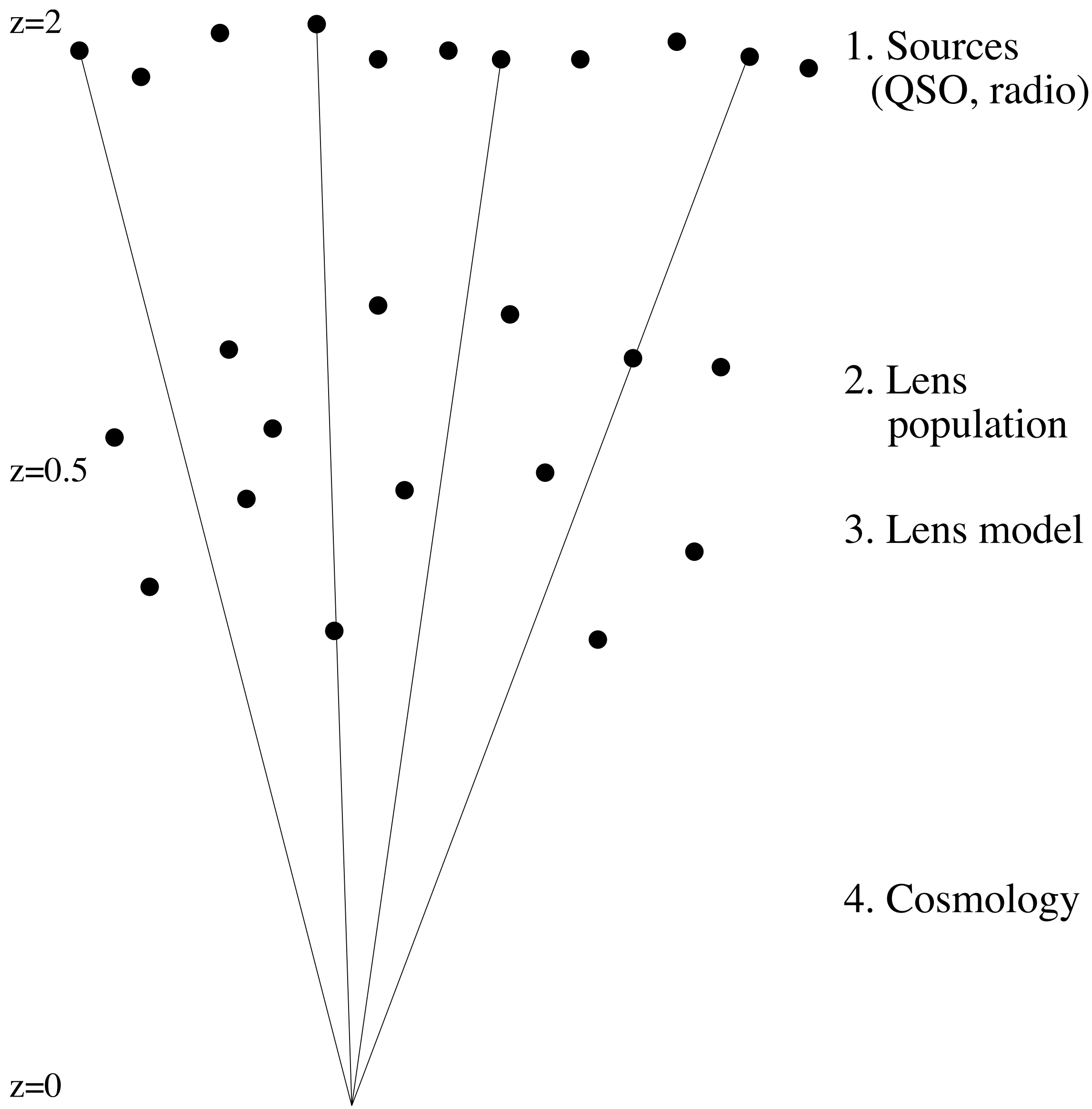
Strong Lensing and Cosmology

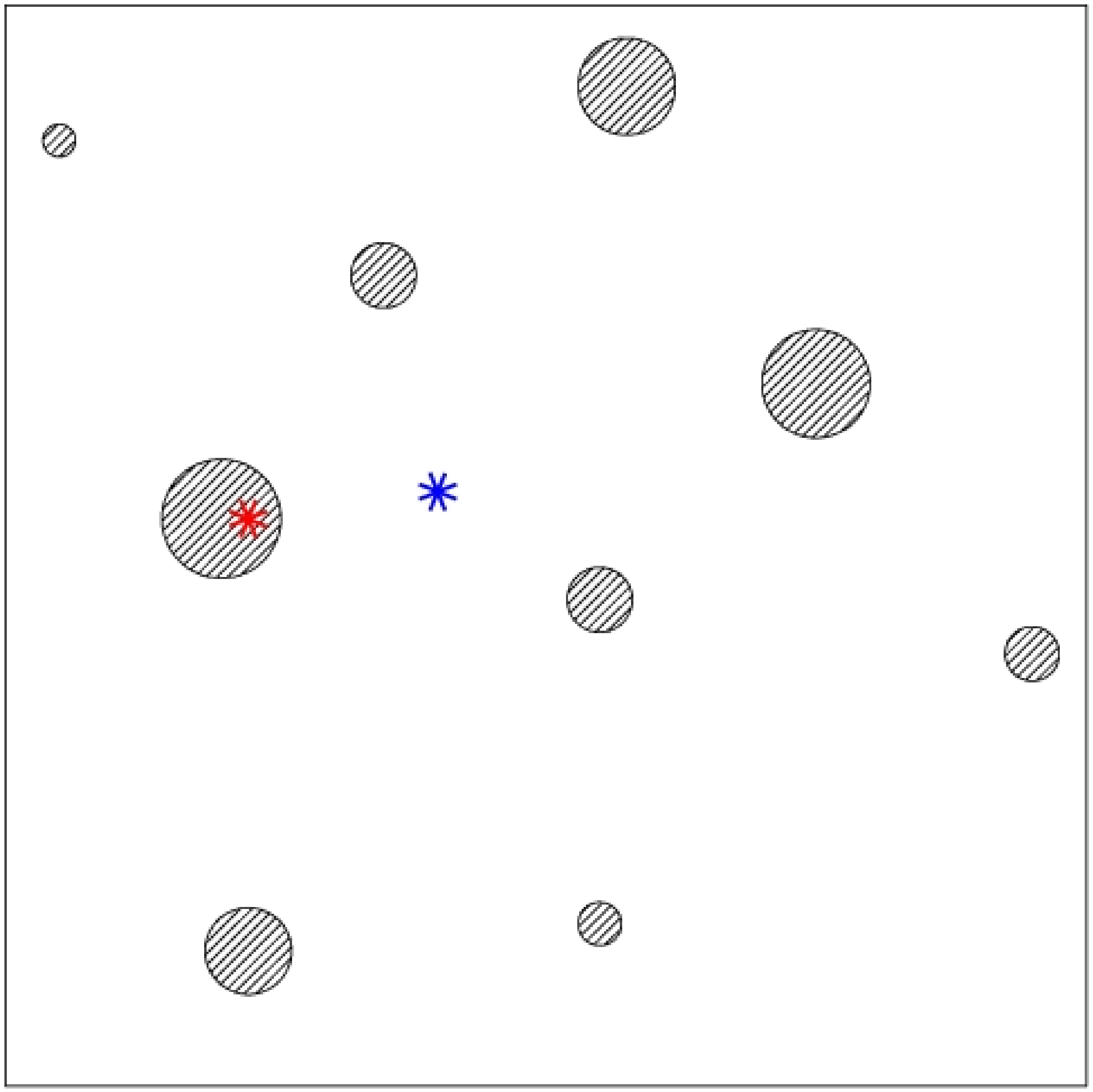
Chuck Keeton *(Rutgers)*

- lens statistics and $(\Omega_M, \Omega_\Lambda)$
- dark energy
- evolution
  - *number, mass evolution probe growth of structure*
  - *luminosity evolution probes epoch of galaxy formation*
- H_0 with time delays

Know your systematics!



z=2
z=0.5
z=0
1. Sources
(QSO, radio)
2. Lens
population
3. Lens model
4. Cosmology



Basic Theory

Non-evolving population of isothermal spheres. *(e.g., Turner; Kochanek)*

Einstein radius:

$$\theta_E = 4\pi \left(\frac{\sigma}{c}\right)^2 \frac{D_{ls}}{D_s}$$

Velocity dispersion function: *(e.g., Sheth et al. 2003)*

$$\frac{dn}{d\sigma} = \frac{n_*}{\sigma_*}\left(\frac{\sigma}{\sigma_*}\right)^{\alpha} e^{-(\sigma/\sigma_*)^{\beta}}$$

Lensing optical depth to redshift z_s:

$$\tau(z_s) = \frac{1}{4\pi}\int_0^{z_s} dz_l \frac{dV}{dz_l}\int d\sigma \frac{dn}{d\sigma} \times \pi\theta_E^2$$

$$= n_* \sigma_*^4 f(\alpha,\beta) \times \boxed{D(z_s)^3}$$

Measure lensing rate $\Rightarrow$ infer volume of universe!

Refinements

Magnification bias.

Various probabilities:

- lensing, $p(z_s)$
- lensing with particular image separation, $p(z_s|\Delta\theta)$
- lensing with particular image separation, by galaxy at particular redshift, $p(z_s|\Delta\theta, z_l)$

Then build likelihood:

$$\mathcal{L} = \prod_{\mathrm{lenses}} p \times \prod_{\mathrm{non-lenses}} (1 - p)$$

Alternative statistic: redshift test, $p(z_l|z_s, \Delta\theta)$. *(Kochanek 1992; Ofek et al. 2003; Capelo & Natarajan 2007)*

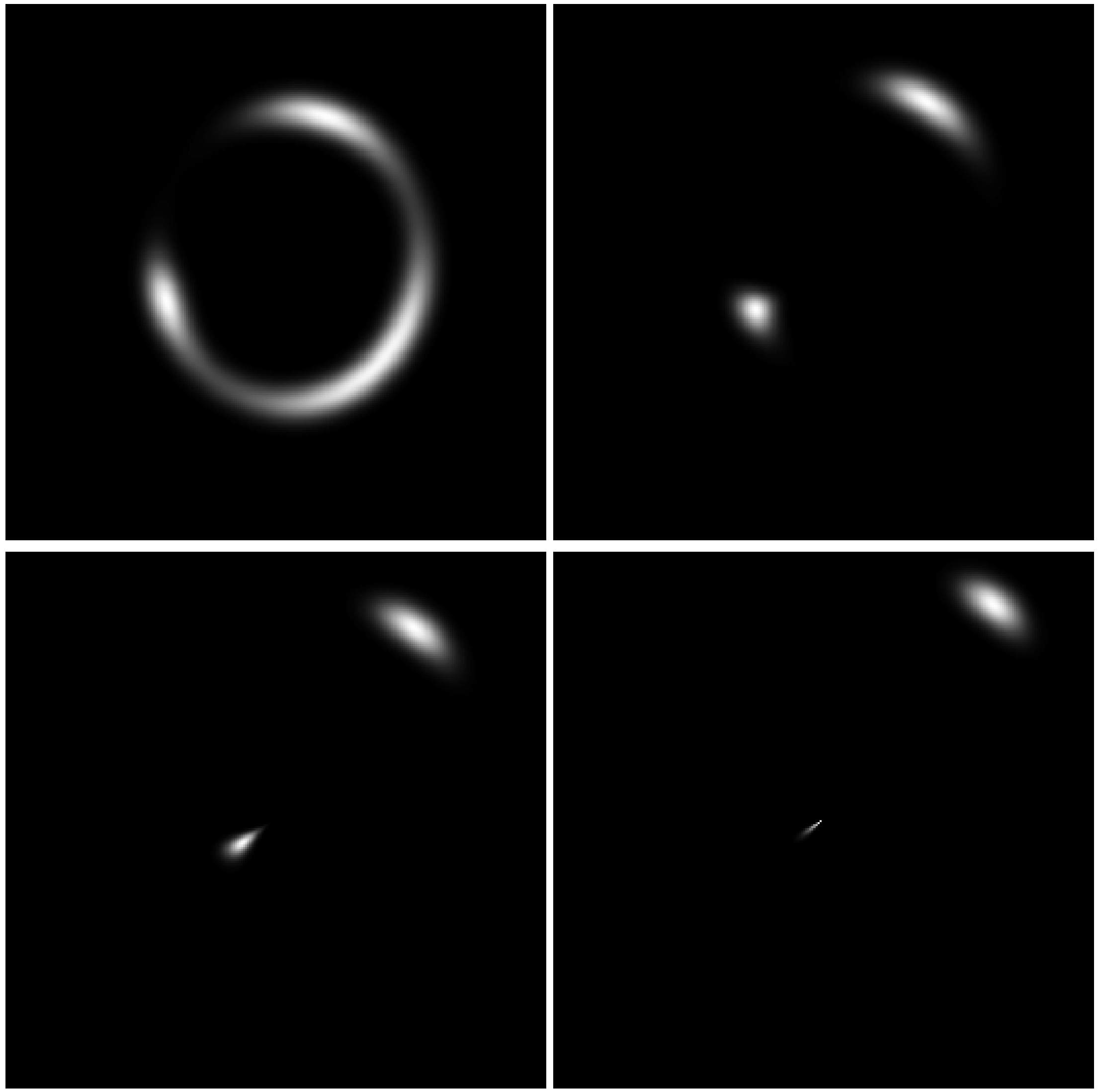
1. Source Population

	Optical QSOs	Radio Sources	Galaxies
source fluxes	Y	Y	Y
redshifts	Y	N	?
sizes	—	—	?
selection effects	(Y)	(—)	?

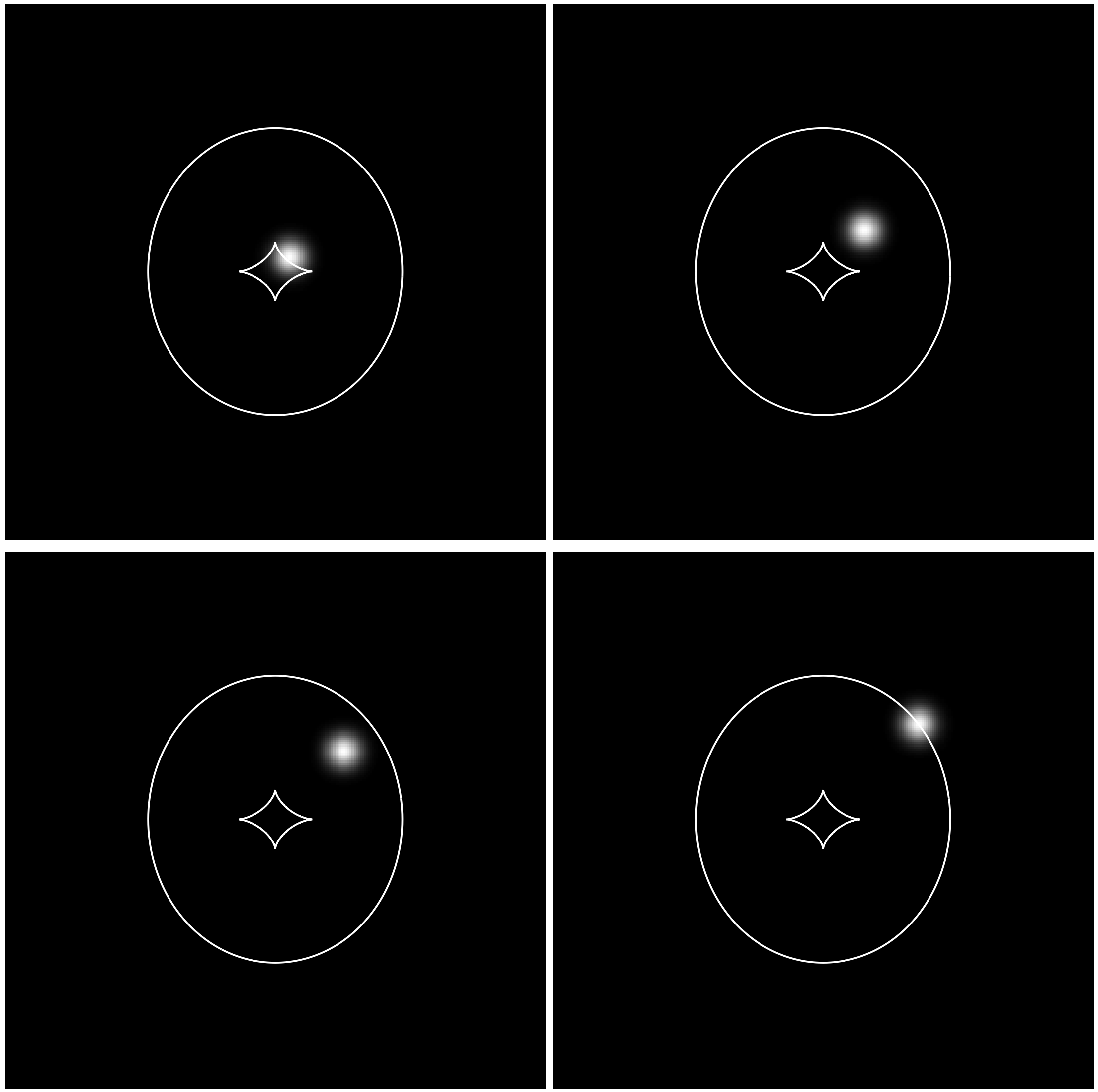
Selection effects:

- seeing
- extinction
- lens galaxy luminosity

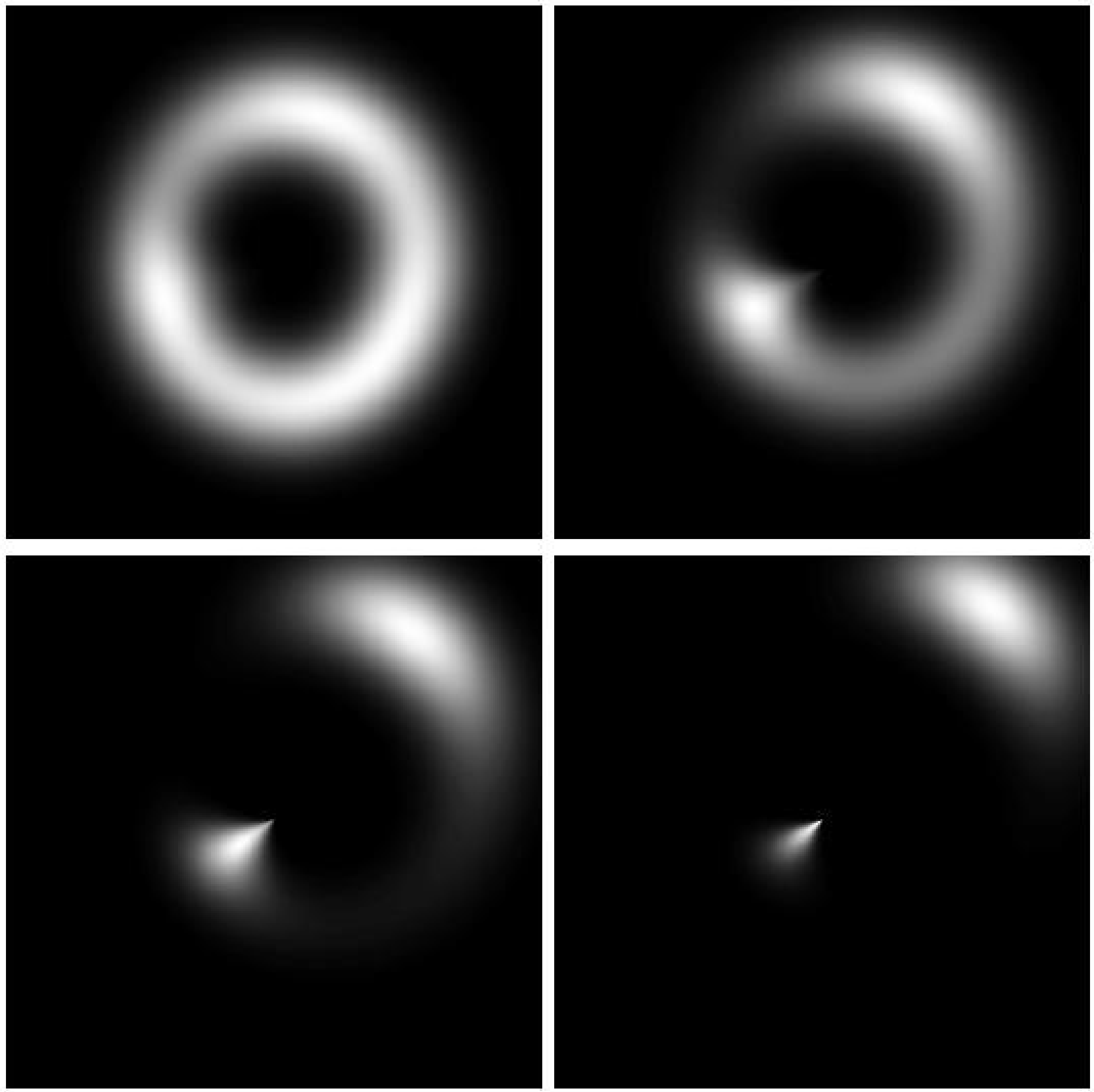
Galaxy Source: Morphological Selection



Galaxy Source: Morphological Selection

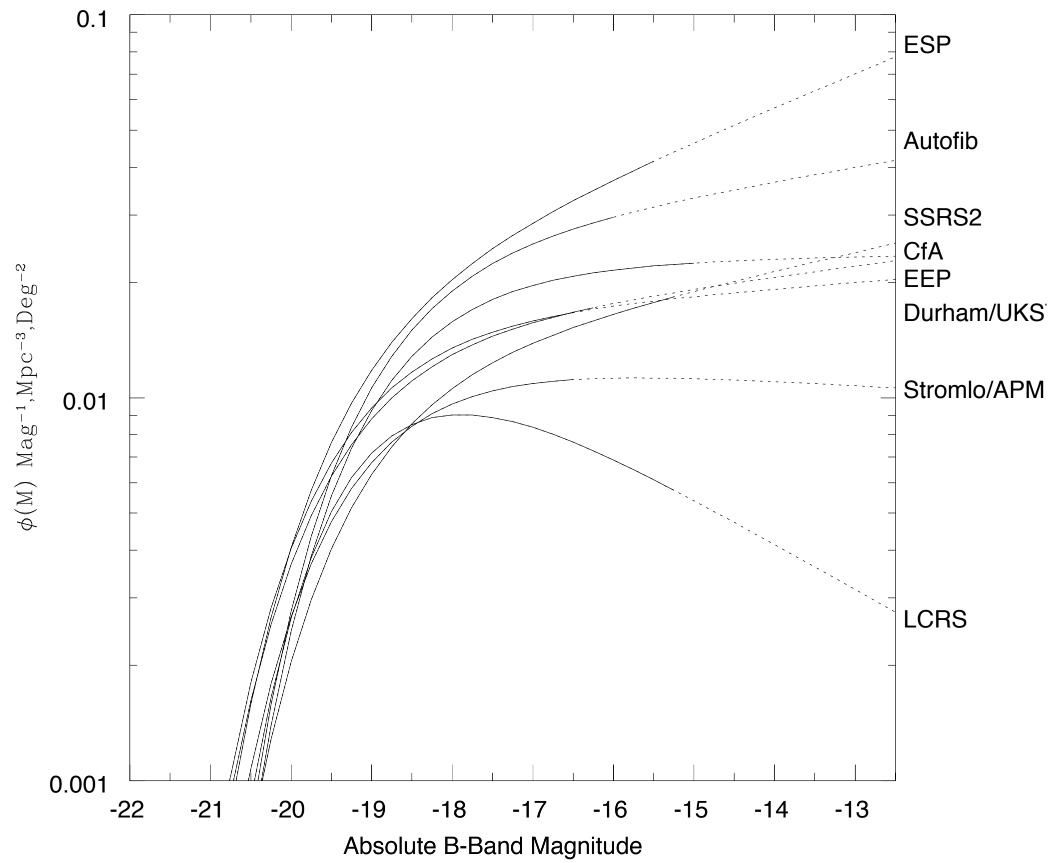


Galaxy Source: Morphological Selection



2. Deflector Population: Velocity Dispersion Function

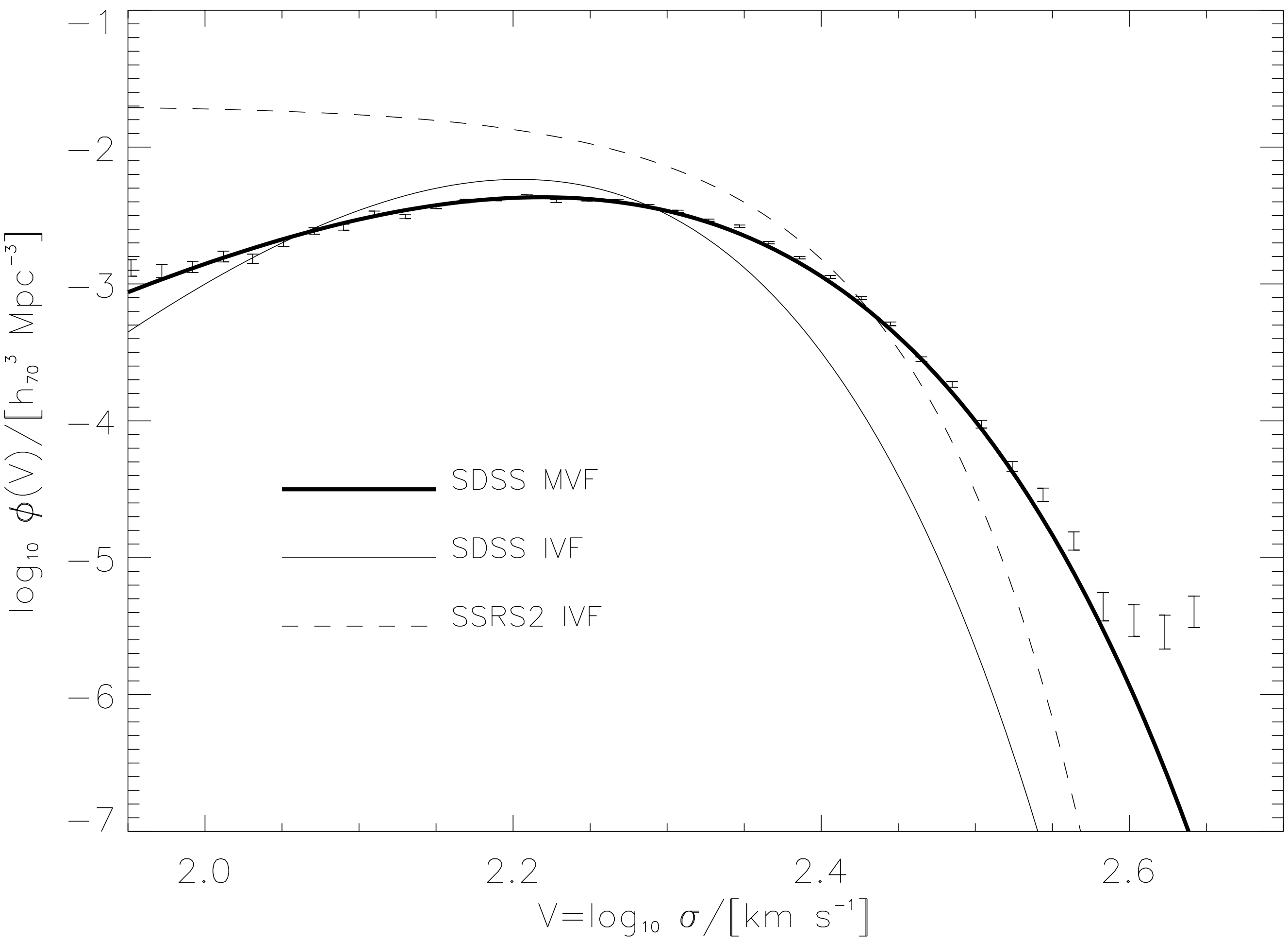
Inferred velocity function = luminosity function + Faber-Jackson relation



Cross et al. (2001)

⇒ Diverse conclusions from lensing. *(e.g., Kochanek 1996; Falco et al. 1998; Helbig et al.; Waga & Miceli 1999; Cooray et al. 1999; Chiba & Yoshii 1999)*

Measured velocity function



Sheth et al. (2003); Mitchell et al. (2005)

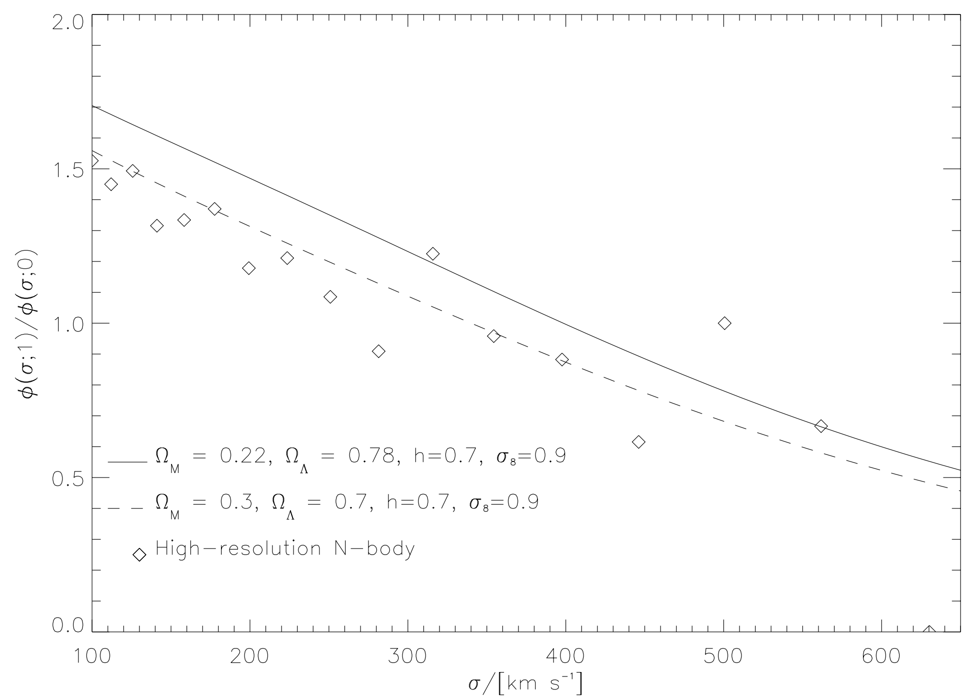
Mass Evolution (I)

If mergers preserve Fundamental Plane ⇒ little effect on lensing optical depth.

(Rix et al. 1994; Mao & Kochanek 1994)

Use extended Press-Schechter theory to predict $\mathrm{VF}(\sigma, z)/\mathrm{VF}(\sigma, 0)$.

(Mitchell et al. 2005)



3. Lens Model

Isothermal looks surprisingly good, at least on average.
(e.g., Rusin & Kochanek; Koopmans, Treu, et al.; etc.)

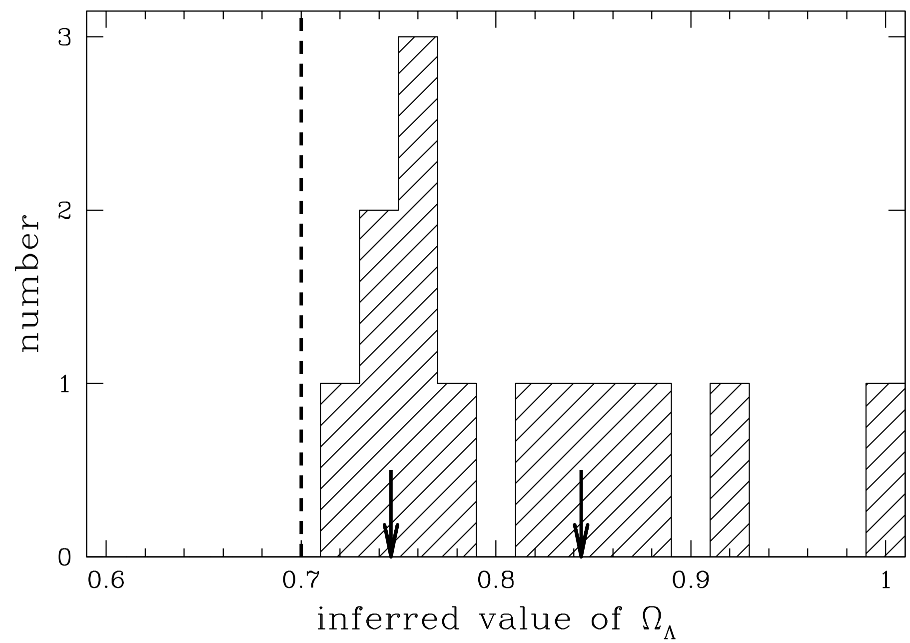
Ellipticity:

- not so important *(Huterer et al. 2005; Dobler et al. 2007)*
- can be incorporated *(e.g., Chae 2003)*

Lens Environments

Many lens galaxies lie in groups of galaxies.

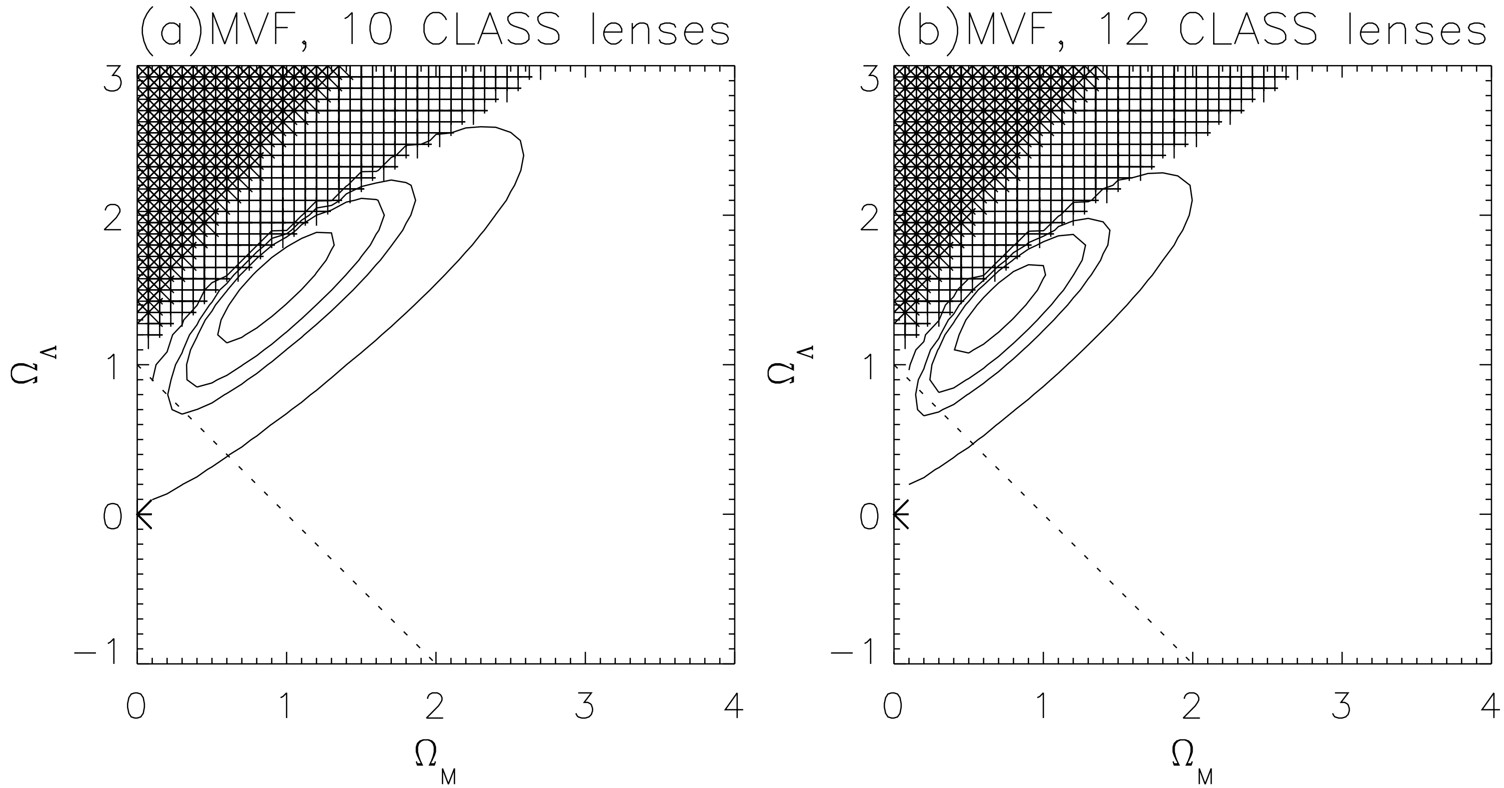
- contribute shear
- boost lensing probability (through magnification bias)



(CRK & Zabludoff 2004)

Need to survey lens environments! *(CRK, Zabludoff, et al.; Fassnacht, Lubin, et al.)*

4. Cosmological Constraints



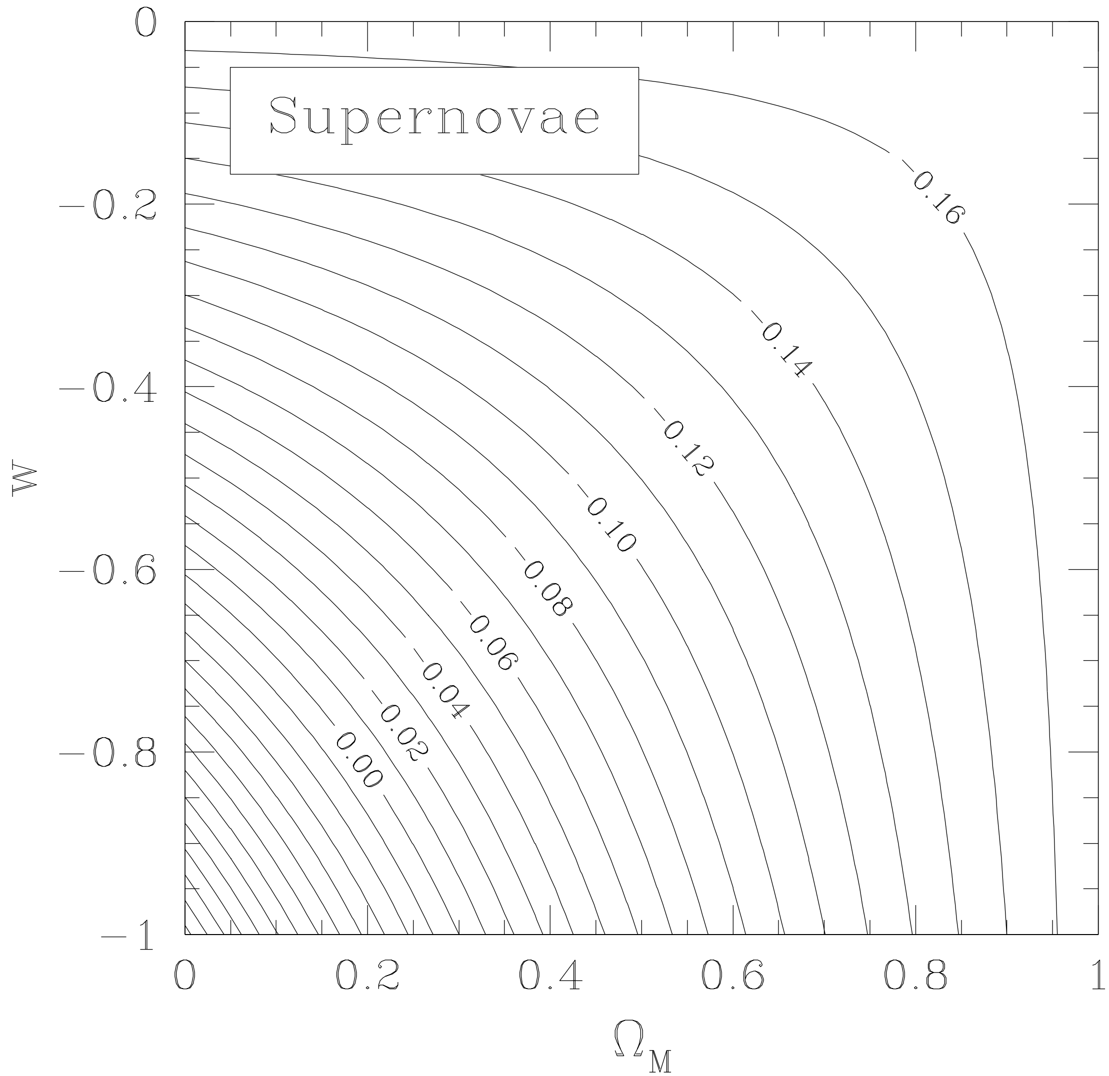
Mitchell et al. (2005)

- Chae (2003) finds similar results.
- Agreement with SNe (not forced).
- Mass evolution has little effect (fortuitous).

Dark Energy

Enough with Ω_Λ.
What about w, $\dot{w}$?

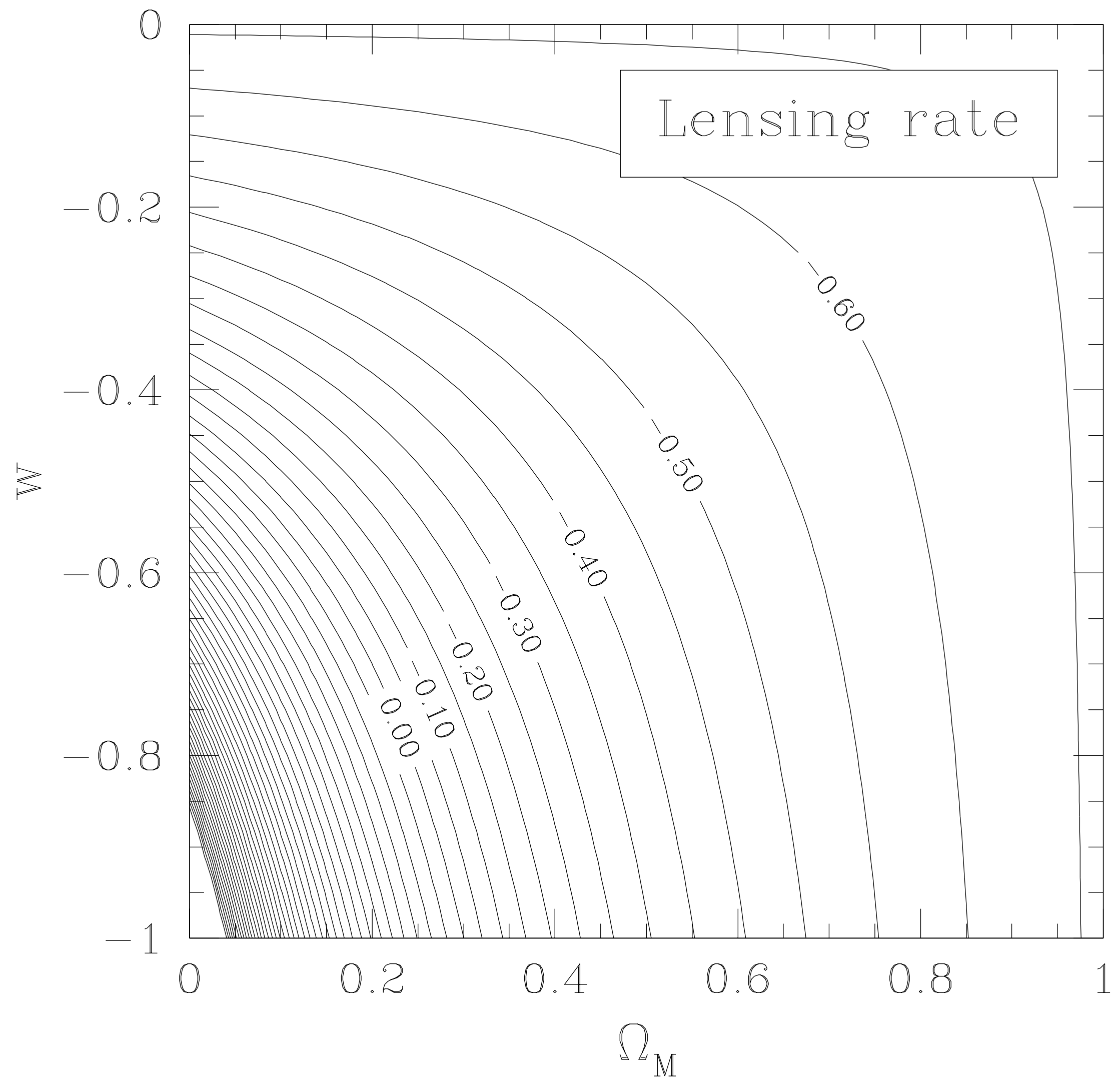
Supernovae measure
$D(z)$ to $z \gtrsim 1$.



Dark Energy and Lensing (I)

Lensing rate measures $D(z_s)$ to $z_s \sim 1-4$.

See Waga & Miceli (1999), Cooray (1999), Cooray & Huterer (1999).



Anything Else?

Image separation:

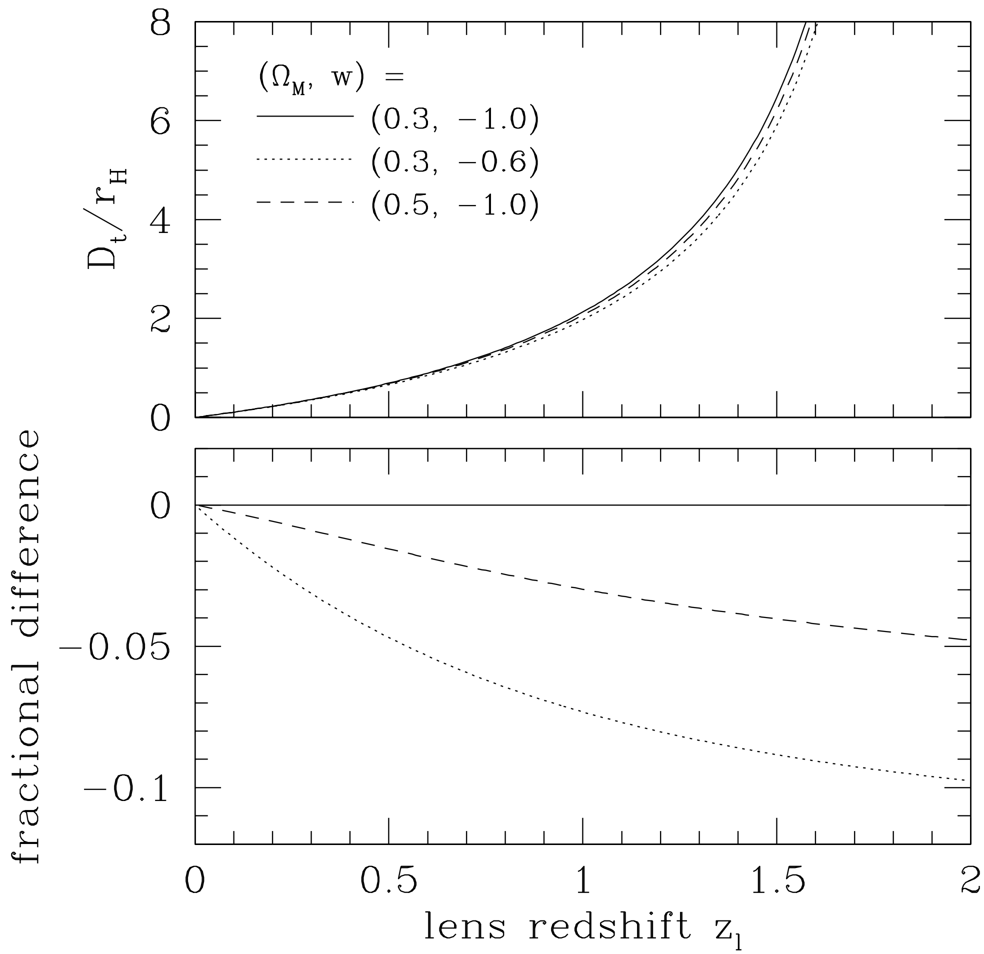
$$\Delta\theta = 8\pi \left(\frac{\sigma}{c}\right)^2 \frac{D_{ls}}{D_s}$$

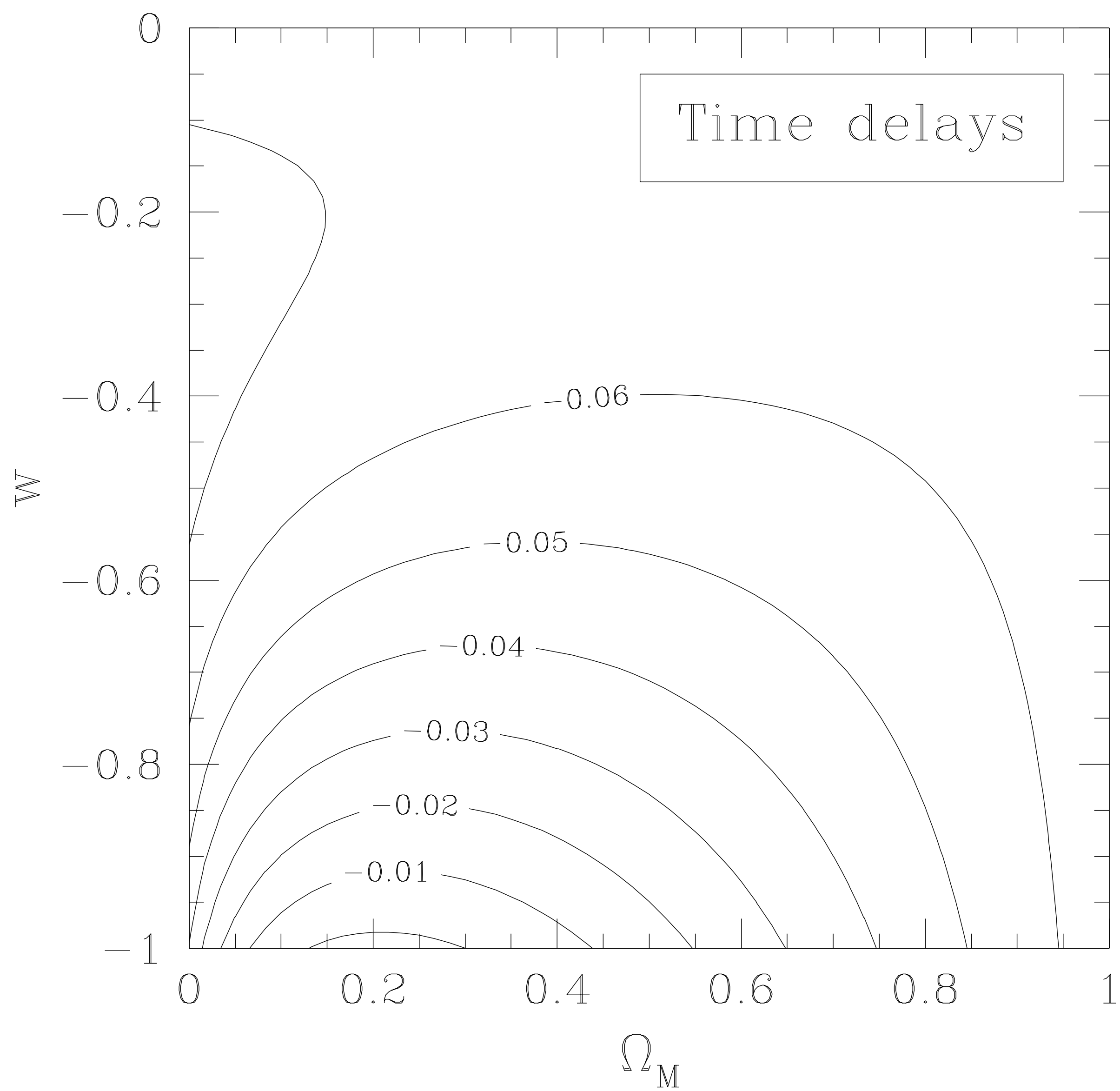
Time delay:

$$\Delta t = \frac{D_l D_s}{D_{ls}} \times [\text{lens model}]$$

Can apply to ensembles.

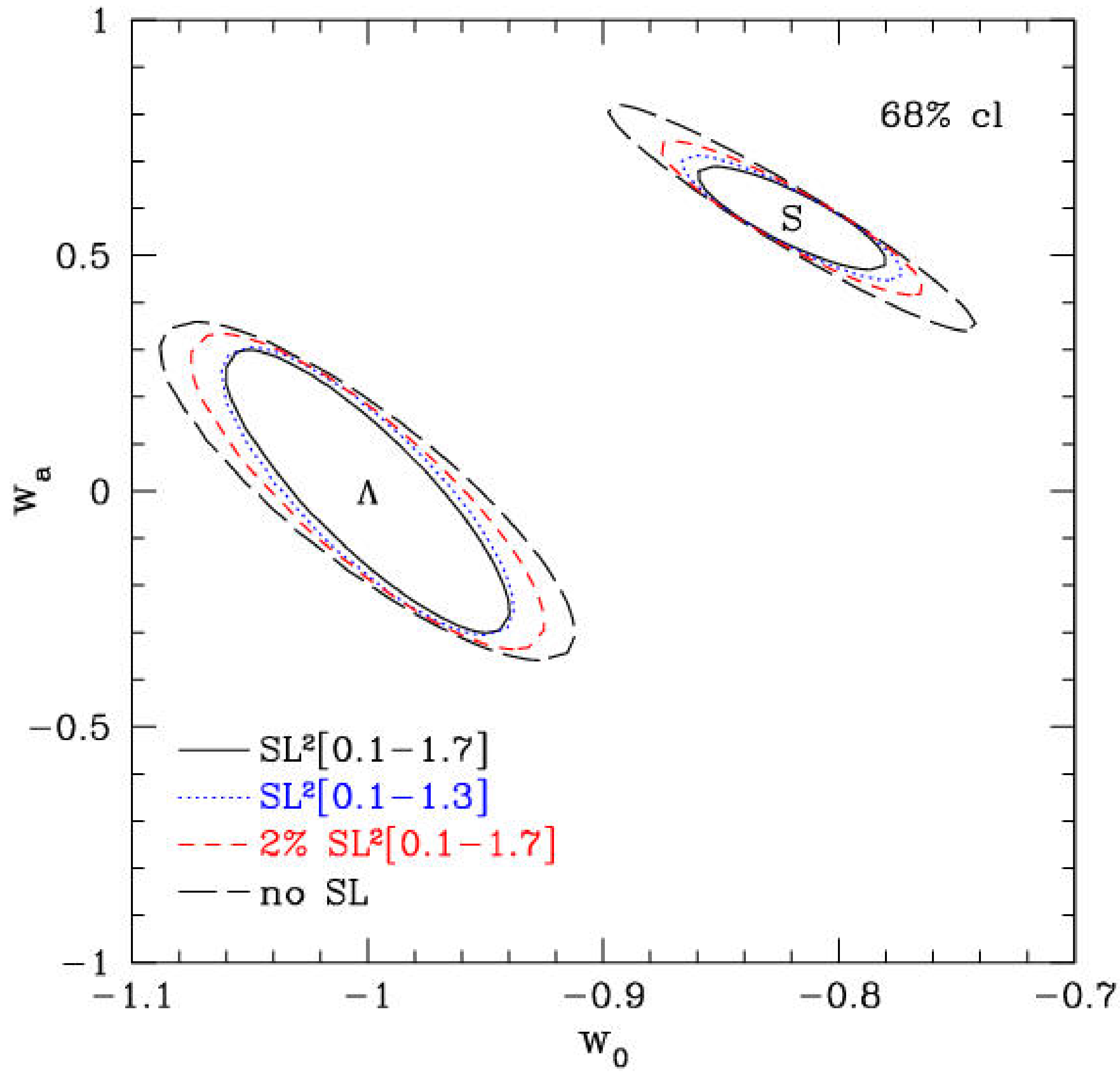
(See Lewis & Ibata 2002; Linder 2004.)





Time delays
−0.06
−0.05
−0.04
−0.03
−0.02
−0.01
w
Ω_M
0
−0.2
−0.4
−0.6
−0.8
−1
0
0.2
0.4
0.6
0.8
1

Linder (2004): 1% uncertainties in $\Delta z = 0.2$ bins



Cosmology with Strong Lensing

Future: (much) larger lens samples.

Still, know your systematics!

1. Source population, selection effects
2. Deflector population: evolution
3. Lens model: environments

Direct cosmology vs. evolution . . .

What do you do with 1000 lenses? Something new!

- lensing Hubble diagram?
- [your ad here]