Cosmology with Strong Lensing

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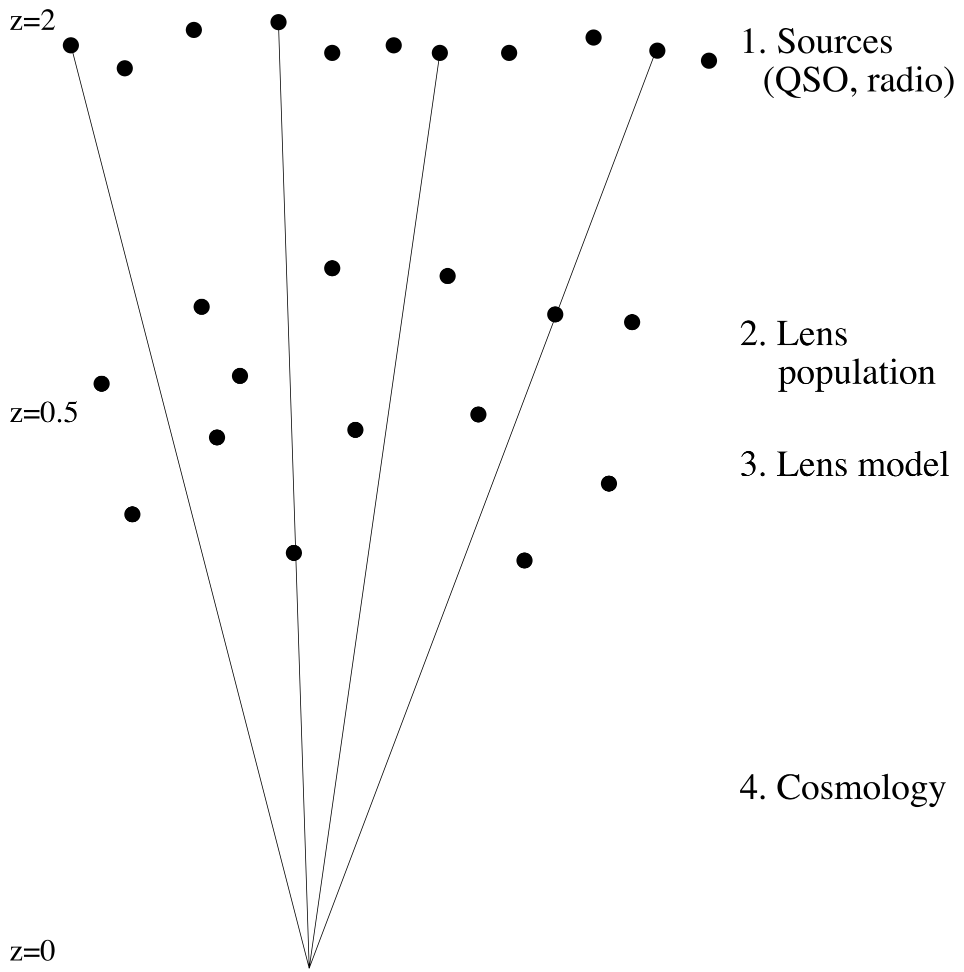


Flavors

	Direct	*Indirect*
Then	cosmography	
Now		evolution
When?	lensing Hubble diagram	
	$\longleftarrow$ alternative cosmologies $\longrightarrow$	

Lens Statistics

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

Lensing rate

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

Volume test!

Depending on what you know, use

$$\frac{\partial \tau}{\partial(\Delta\theta)} \quad \text{or} \quad \frac{\partial^2 \tau}{\partial z_l \, \partial(\Delta\theta)}$$

Note: redshift distribution

$$p(z_l|z_s) \; = \; 30 \, \frac{D_{ol}^2 D_{ls}^2}{D_{os}^5} \, \frac{dD_{ol}}{dz_l}$$

1. Source Population

Optical QSOs

- flux and redshift distributions known
- lens selection effects
  - seeing
  - extinction
  - lens galaxy luminosity
- $N = 4$ (pre-SDSS)

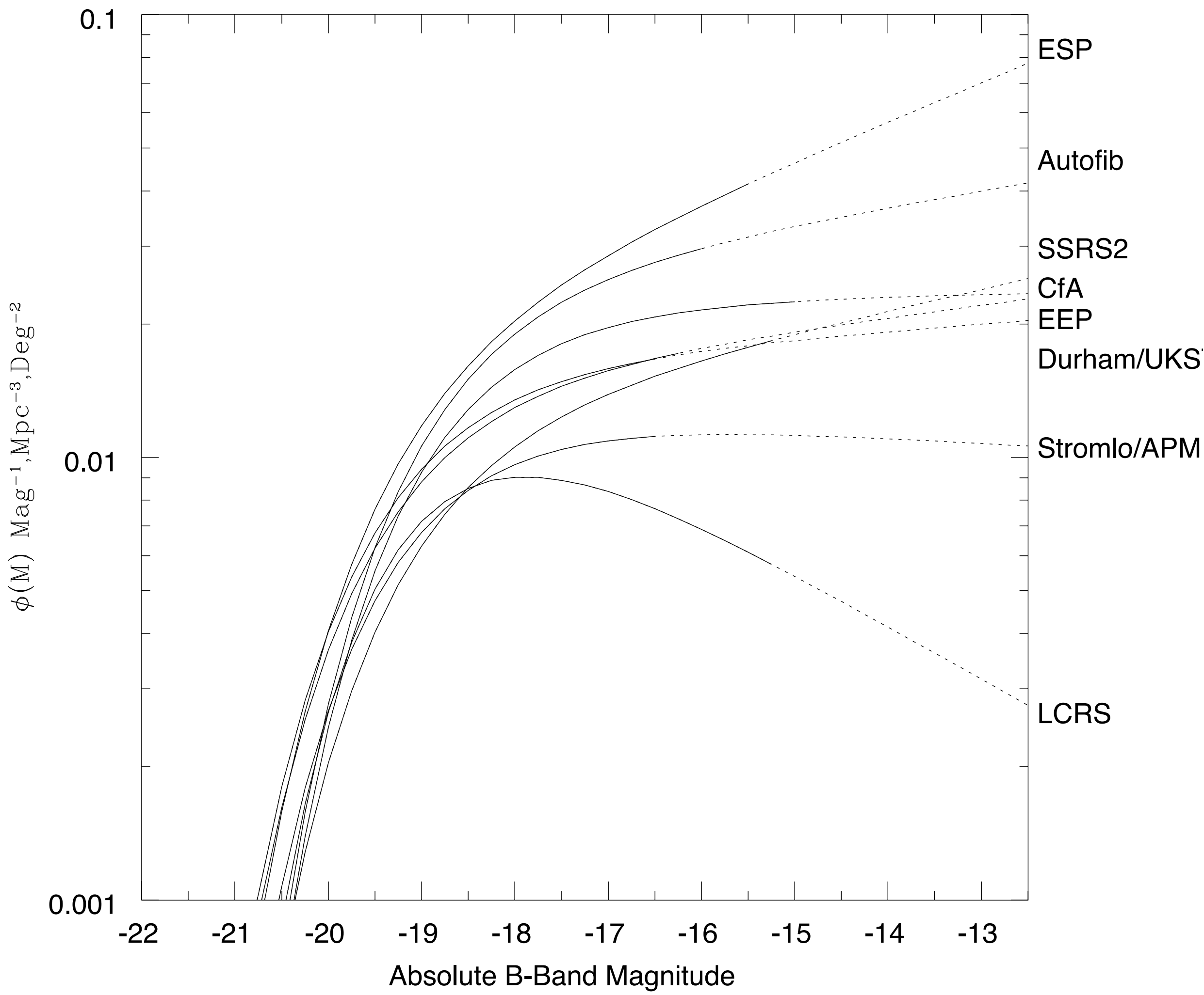
Radio sources

- flux distribution known
- redshift distribution *not* well known
- selection effects less important
- $N = 13$ from CLASS

2. Deflector Population: Velocity Dispersion Function

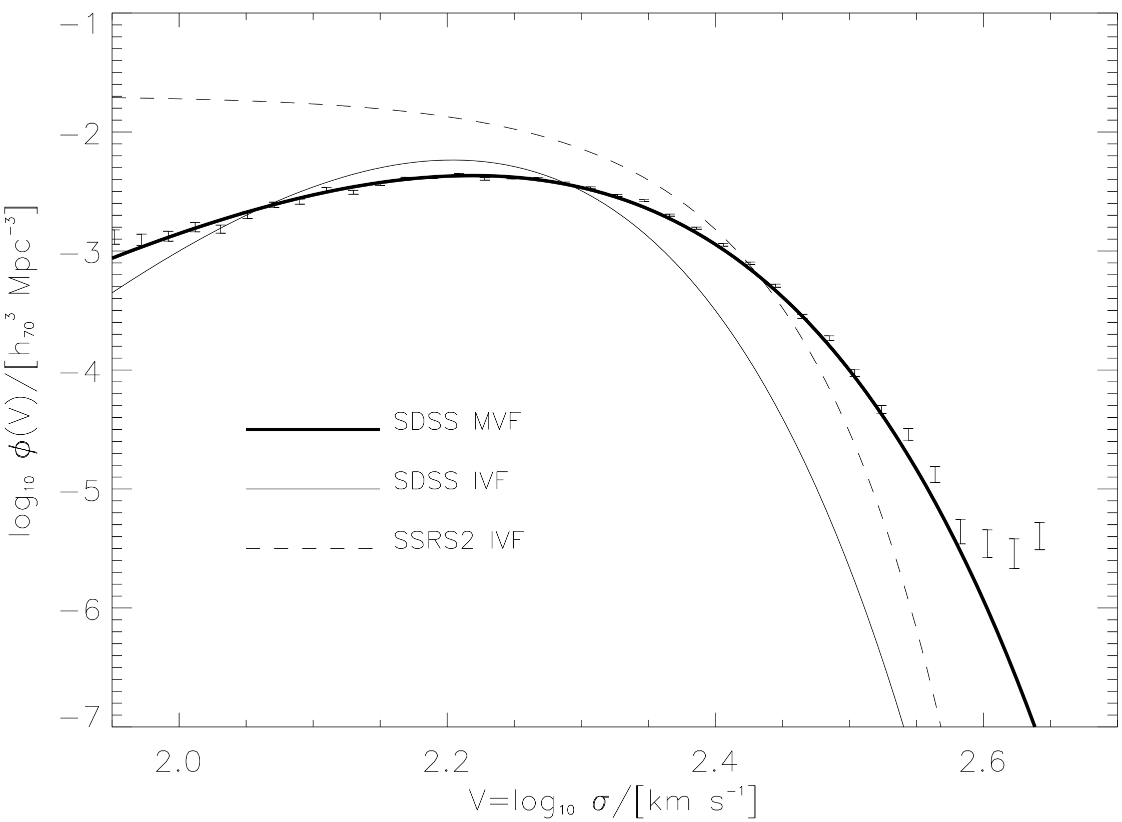
Inferred velocity function (IVF): luminosity function + Faber-Jackson

Study	Lens Sample	LF	Ω_Λ (if flat)
Kochanek (1996)	Opt+Rad	$\equiv$ K96	< 0.66
Falco et al. (1998)	Opt/Rad	K96	< 0.73 / 0.62 / 0.74
Helbig et al.	Rad	K96	< 0.65
Waga & Miceli (1999)	Opt	K96	< 0.55 / 0.76 / 0.91
Cooray et al. (1999)	HDF	HDF	< 0.72—0.79
Cooray (1999)	Rad	ESP	< 0.79
		EEP	$\simeq 0.5$
Chiba & Yoshii (1999)	Opt+Rad	APM	$\simeq 0.7$
		CfA	$\simeq 0.8$

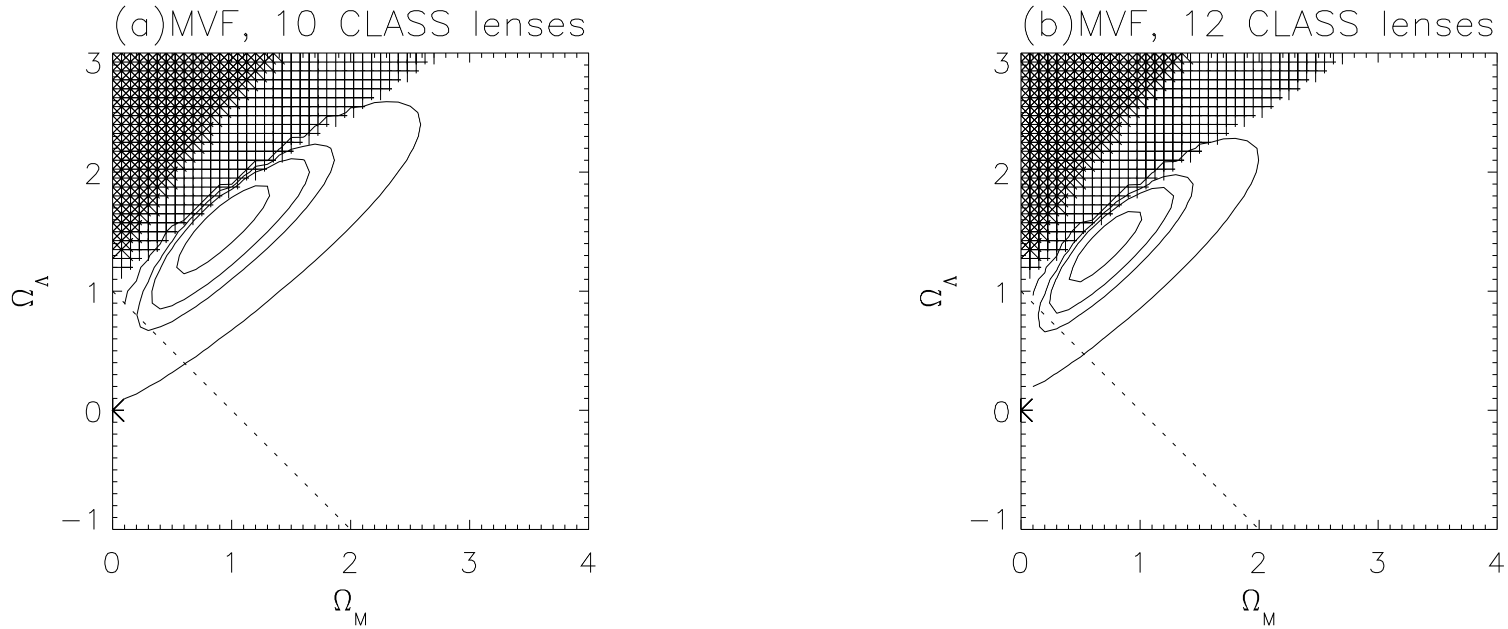


Cross et al. (2001)

Measured velocity function (MVF)



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



Chae (2003) finds similar results.

Agreement with SNe (not forced).

Evolution has little effect (fortuitous).

“Plus ça change ...”

Deflector population:

- Chae (2005) suggests the SDSS MVF undercounts early-type galaxies
  ⇒ general interest

Source population:

- Radio parent population is poorly characterized *(Maoz 2005)*
  ⇒ hard work
- Reconsider optical lens samples *(Maoz; Inada, Oguri, et al.)*
  ⇒ selection functions, extinction, ...

Lens model:

- Ellipticity not so important *(Huterer et al. 2005)*
  ⇒ can be incorporated *(e.g., Chae 2003)*
- Environment can boost image separation, magnification *(CRK & Zabludoff 2004)*
  ⇒ environments being surveyed *(talks by Zabludoff, Fassnacht)*

Evolution?

Direct cosmography: ϕ_* and σ_* degenerate with volume

One man's noise ... is another man's signal.

Indirect cosmology:

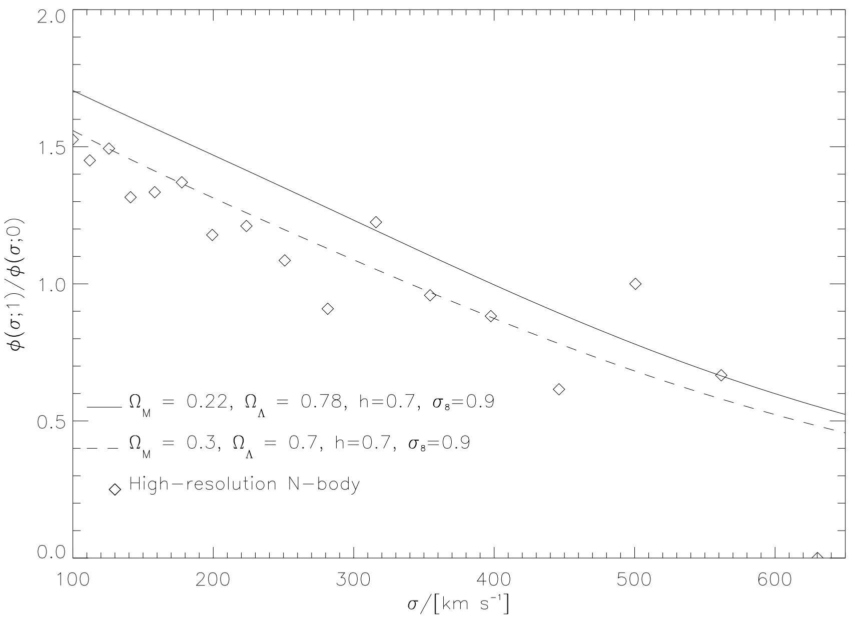
- number, mass evolution — growth of structure
- luminosity evolution — epoch of galaxy formation

Mass Evolution I

Build an evolution model into lens statistics . . .

If mergers preserve Fundamental Plane $\Rightarrow$ little effect on τ, more on $p(\Delta\theta)$.
(Rix et al. 1994; Mao & Kochanek 1994)

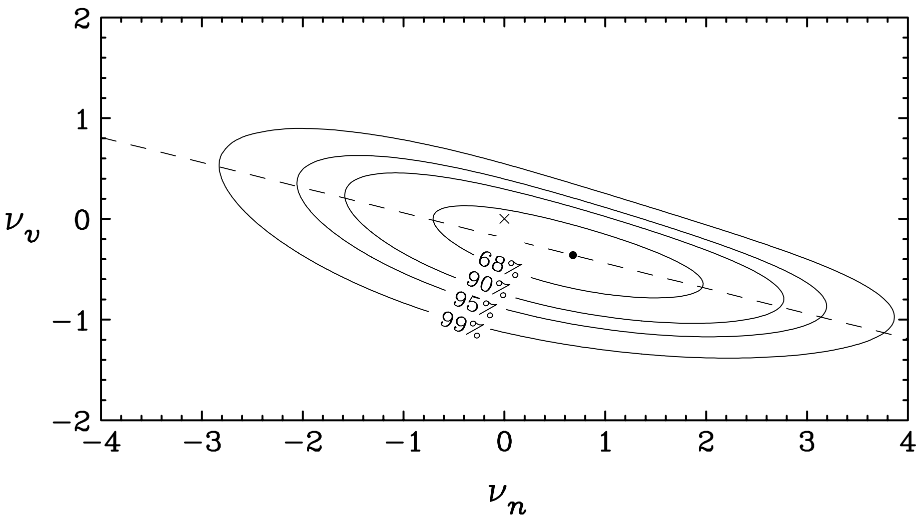
Use extended Press-Schechter theory to predict $\phi(\sigma, z)/\phi(\sigma, 0)$.

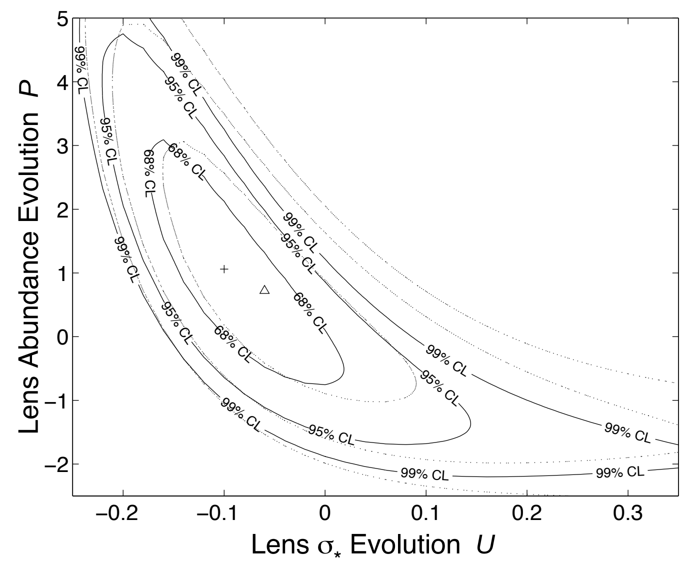


Mass Evolution II

Use statistics to constrain a phenomenological evolution model:

- Chae & Mao (2003): $n_*(z) = n_* \, (1+z)^{\nu_n}$, $\sigma_*(z) = \sigma_* \, (1+z)^{\nu_v}$
- Ofek et al. (2003): $n_*(z) = n_* \, 10^{Pz}$, $\sigma_*(z) = \sigma_* \, 10^{Uz}$





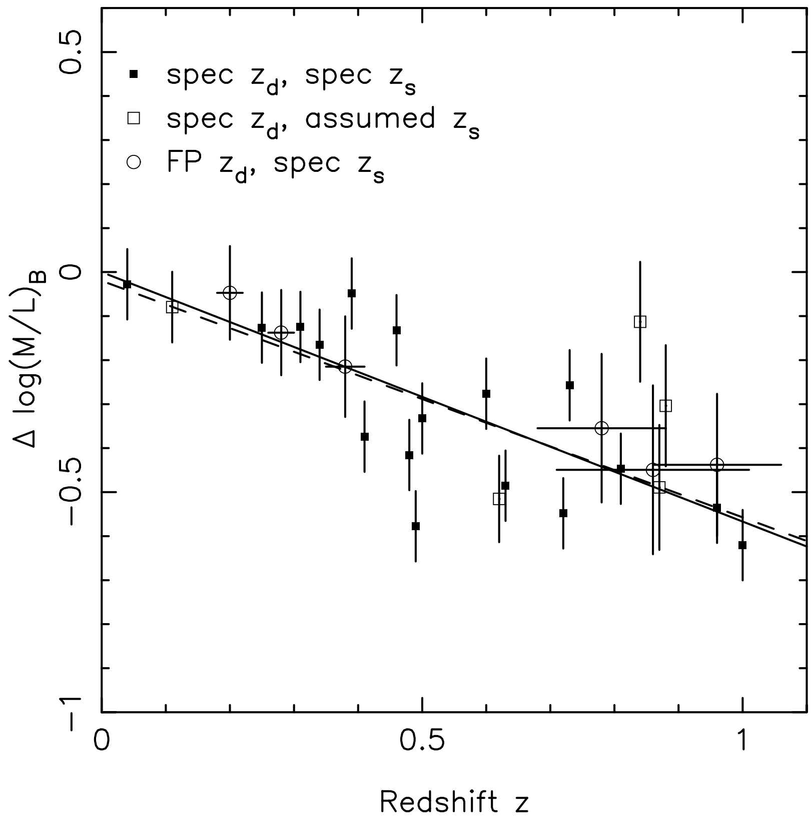
Stronger constraints on mass evolution than number evolution.

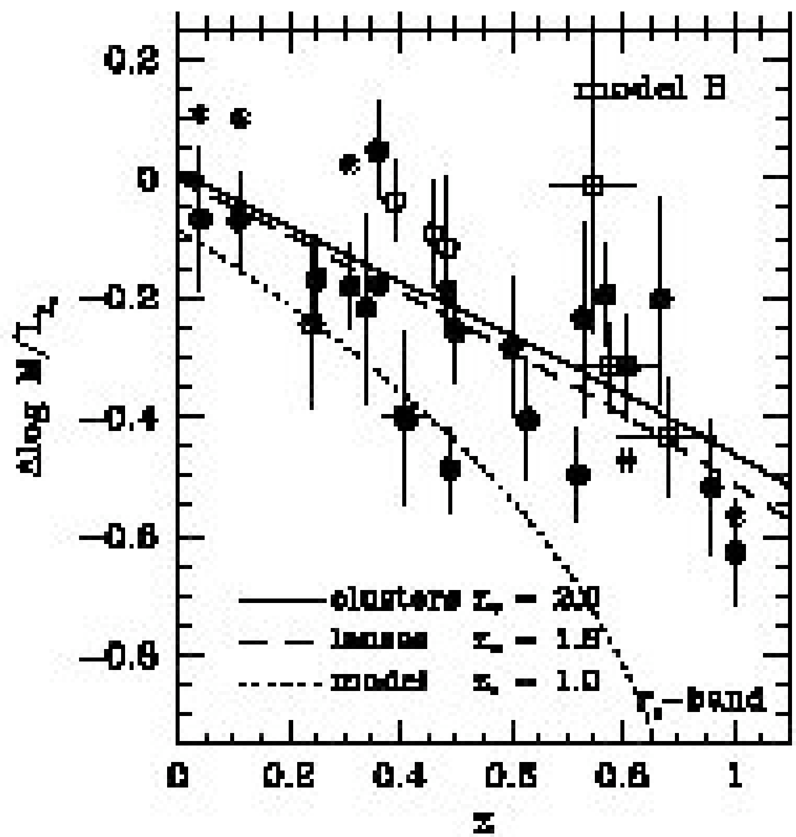
Ofek et al.: resurrect redshift test, expand sample.

Luminosity Evolution

Measure M/L vs. z.

(CRK et al. 1998; Treu & Koopmans; Rusin et al.; van de Ven et al.)





Luminosity Evolution

Can be applied to an ensemble.

Constrains star formation histories of E/S0 lens galaxies.

- stars are old: $\langle z_f \rangle > 1.5$
- evidence for a range of z_f

(Some debate over the details ...)

E/S0 galaxies in "low-density" environments not much younger than in clusters — challenge to CDM galaxy formation models.

Lensing and Dark Energy

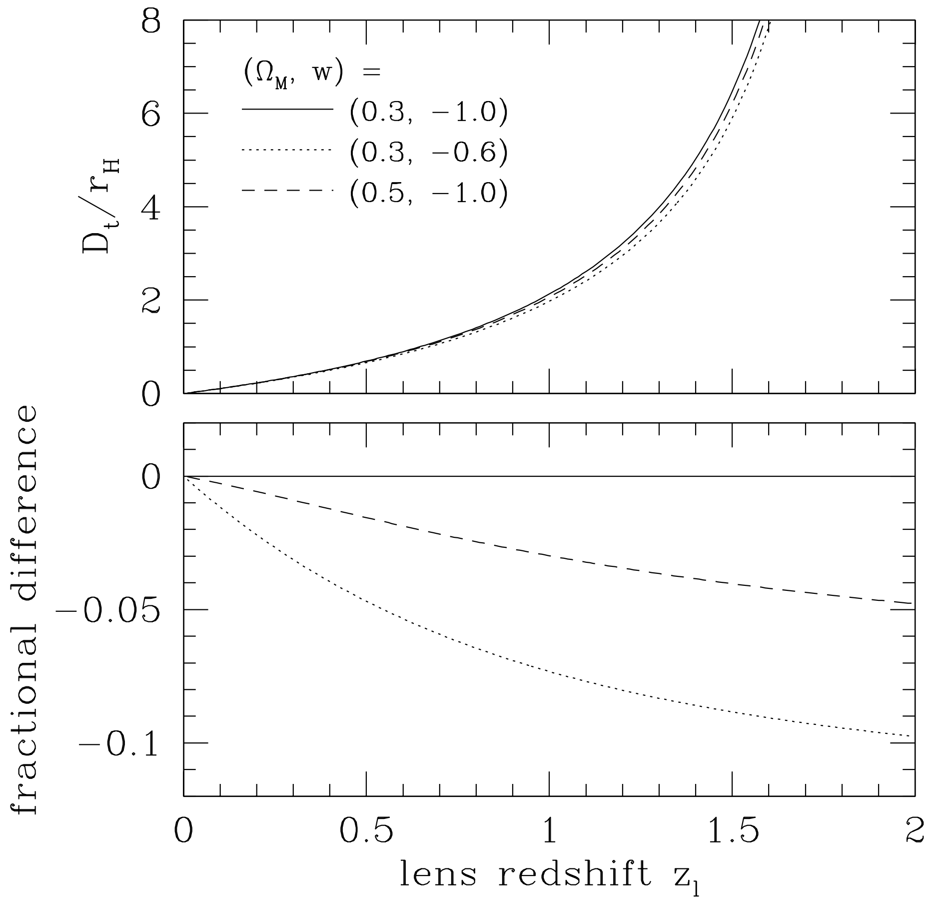
w is all the rage.

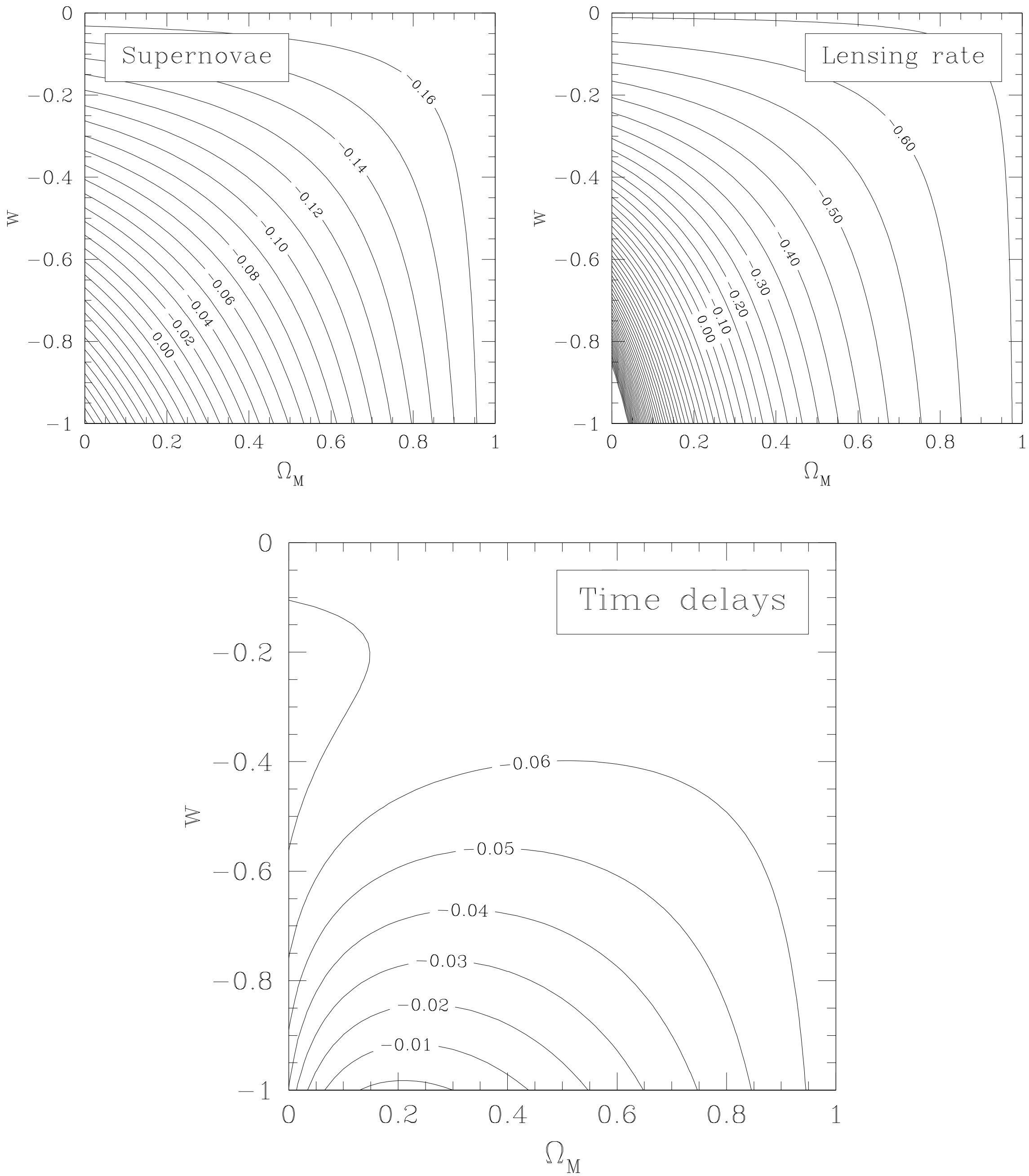
Lensing rate: Waga & Miceli (1999), Cooray (1999), Cooray & Huterer (1999)

Time delays and image separations: Lewis & Ibata (2002), Linder (2004)

Lensing Hubble Diagram

"time delay distance" $$D_t = \frac{D_{ol} D_{os}}{D_{ls}}$$





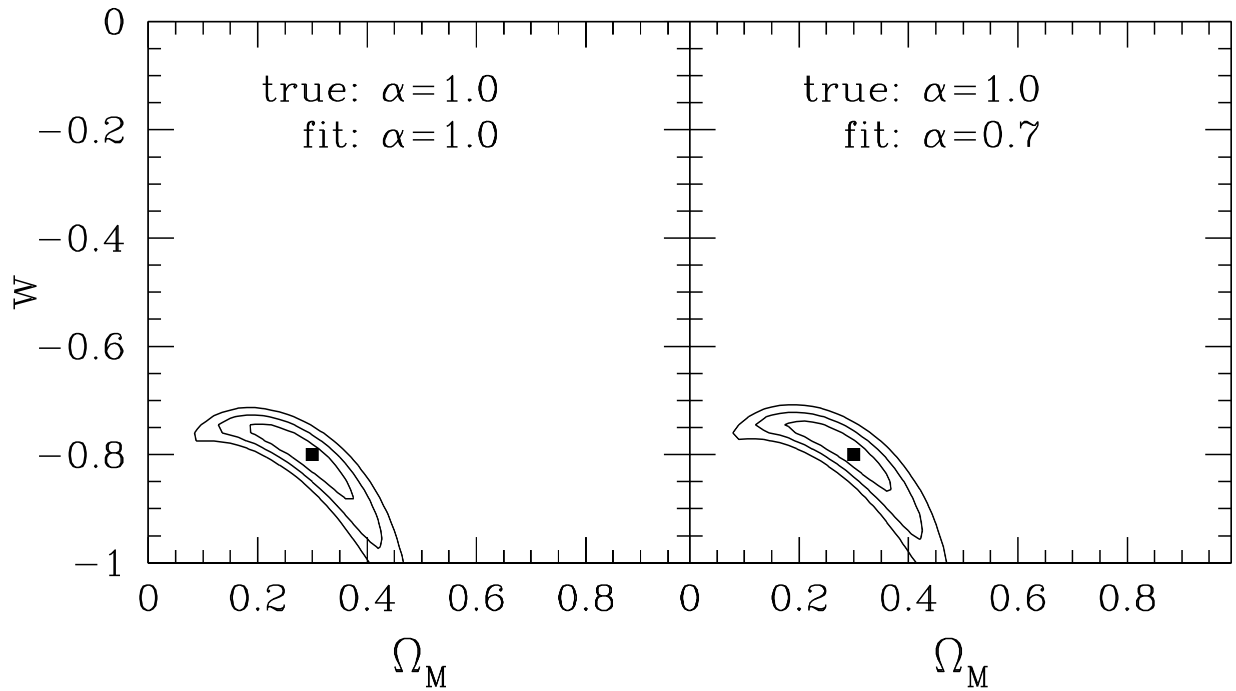
Supernovae
0.00
−0.02
−0.04
−0.06
−0.08
−0.10
−0.12
−0.14
−0.16
w
Ω_M
Lensing rate
0.00
0.10
0.20
0.30
0.40
0.50
0.60
w
Ω_M
Time delays
−0.01
−0.02
−0.03
−0.04
−0.05
−0.06
w
Ω_M

Practical?

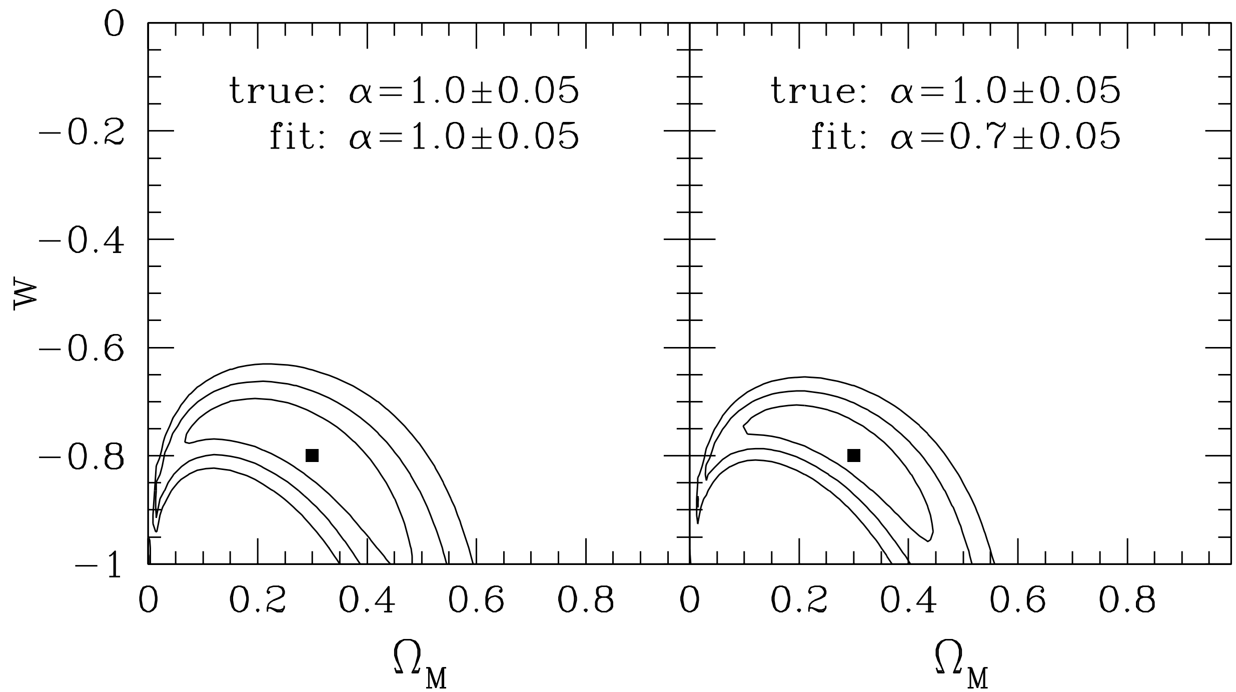
Future: 1000 lenses, to beat down random noise

Use as an ensemble, exactly like SNe.

Finesse radial profile degeneracy: $\mathcal{H} = H_0 (1 - \langle\kappa\rangle)$ is a nuisance parameter.



What Matters is Scatter



- profiles
- shapes
- environments

Lensing cosmology is dead. Long live lensing cosmology!

Lens ~~statistics~~ ensembles still have something interesting to say.

Now: evolution

Future: lensing Hubble diagram???

(Ask me about alternative cosmologies ...)

Alternative Cosmologies

Change gravity. Some modifications may be amplified near black holes.

CRK & Petters: framework for testing theories of gravity with black hole lensing.

Galactic black hole:

	weak-field	higher-order
image positions	0.01–0.1 arcsec	few microarcsec
time delay	minute	tens of millisec

A lensed millisecond pulsar?

Randall-Sundrum Braneworld Gravity

- primordial black holes $\leftrightarrow$ gamma-ray inteference
- "attolensing" of gamma-ray bursts