Strong Lensing Constraints on Dark Energy: A Critical Review

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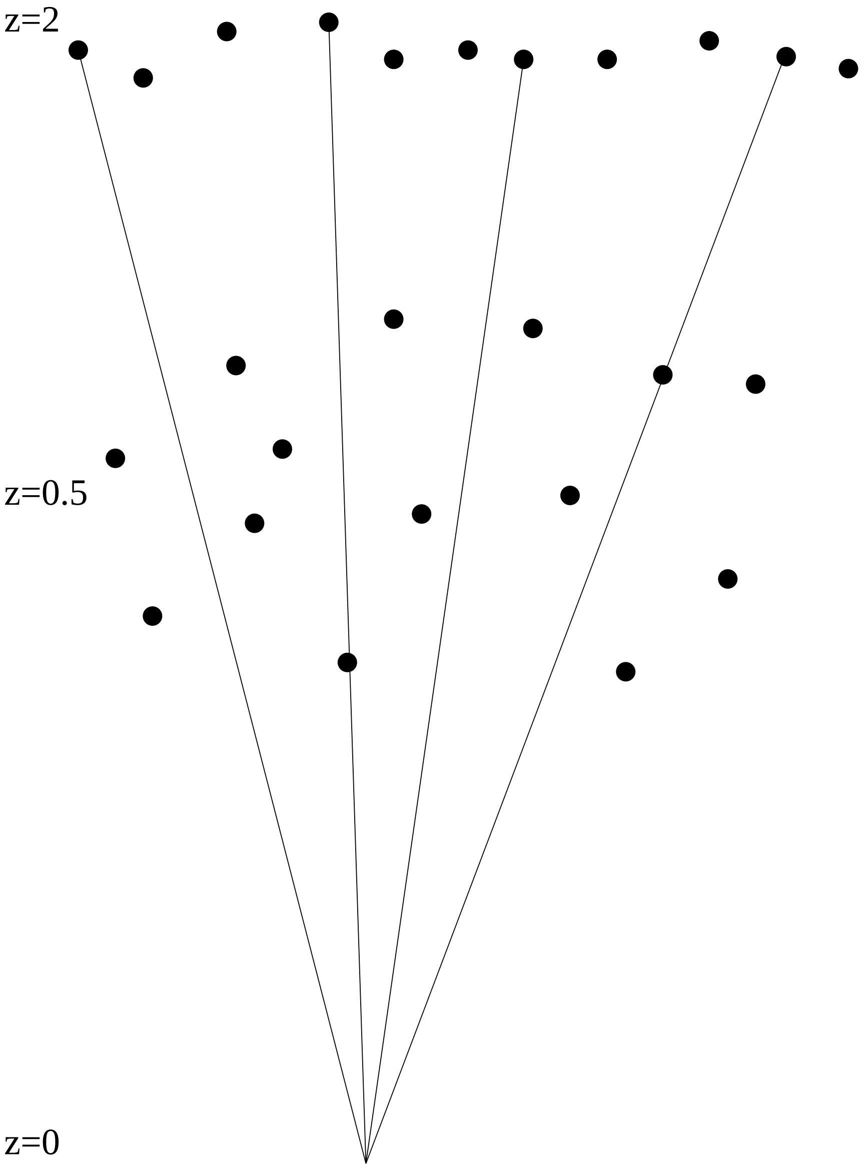
- Lens statistics probe the **volume** of the universe to $z \sim 1$–3.
- Current constraints on Λ.
- Systematics!
- Prospects for equation of state (w, $\dot{w}$).

Strong Lens Statistics: Ingredients



1. Sources
(QSO, radio)

2. Lens
population

3. Lens model

4. Cosmology

$$\text{Optical depth :} \quad \tau = \int dV \int dM \, \frac{dn}{dM} \, A_{lens}(M)$$

1. Source Populations

Optical QSOs:

- Flux and redshift distributions known.
- Lens selection effects are important:
  - Seeing $\sim$ typical lens size
  - Extinction in lens galaxy
  - Lens galaxy luminosity if $L(\text{gal}) > L(\text{QSO})$

Radio sources:

- Flux distribution known.
- Redshift distribution *not* well known.
- Lens selection functions unimportant.

Sample	# Lenses	# Sources
Optical	5	867
Radio	18	$\approx$ 12,000

2. Lens Populations

- Need mass function of lens galaxies out to $z \sim 1$.
- Focus on ellipticals.

2.1. Phenomenology Models

- (All) observed lenses are produced by normal galaxies.
  (Not by group or cluster halos.)
- Use observed Galaxy Luminosity Function (GLF).
- Use local GLF and assume constant comoving number density.
  (Okay for ellipticals?)
- Luminosity $\longleftrightarrow$ mass with Faber–Jackson:

$$\frac{L}{L_*} = \left(\frac{\sigma}{\sigma_*}\right)^{\gamma} \qquad \text{with } \sigma_* \simeq 220 \text{ km/s}, \; \gamma \simeq 4$$

- Optical depth (flat cosmology):

$$\tau(z_s) = \frac{8}{15}\,\pi^3\,R_H^3 \times \left(\frac{\sigma_*}{c}\right)^4 \phi_*\,\Gamma\left[1+\alpha+\frac{4}{\gamma}\right] \times D(z_s)^3$$

- Cosmology dependence: **volume**

2.2. Theory Models

Structure formation models predict a mass function.

- Press–Schechter
- Sheth–Tormen
- Jenkins et al.

These automatically include cosmology dependence and evolution.

Problem:

- Theoretical mass functions don't match observed luminosity functions. *(c.f. semi-analytic models of galaxy formation)*
- Baryons!
- It's the region around the baryons that matters for lensing.

Cosmology dependence: **volume, $\boldsymbol{\Omega}_{\mathrm{M}}$, growth factor**

3. Lens Model

Groups and clusters: NFW

$$\rho \propto \frac{1}{r(s+r)^2}$$

Galaxies: Singular Isothermal Sphere (SIS)

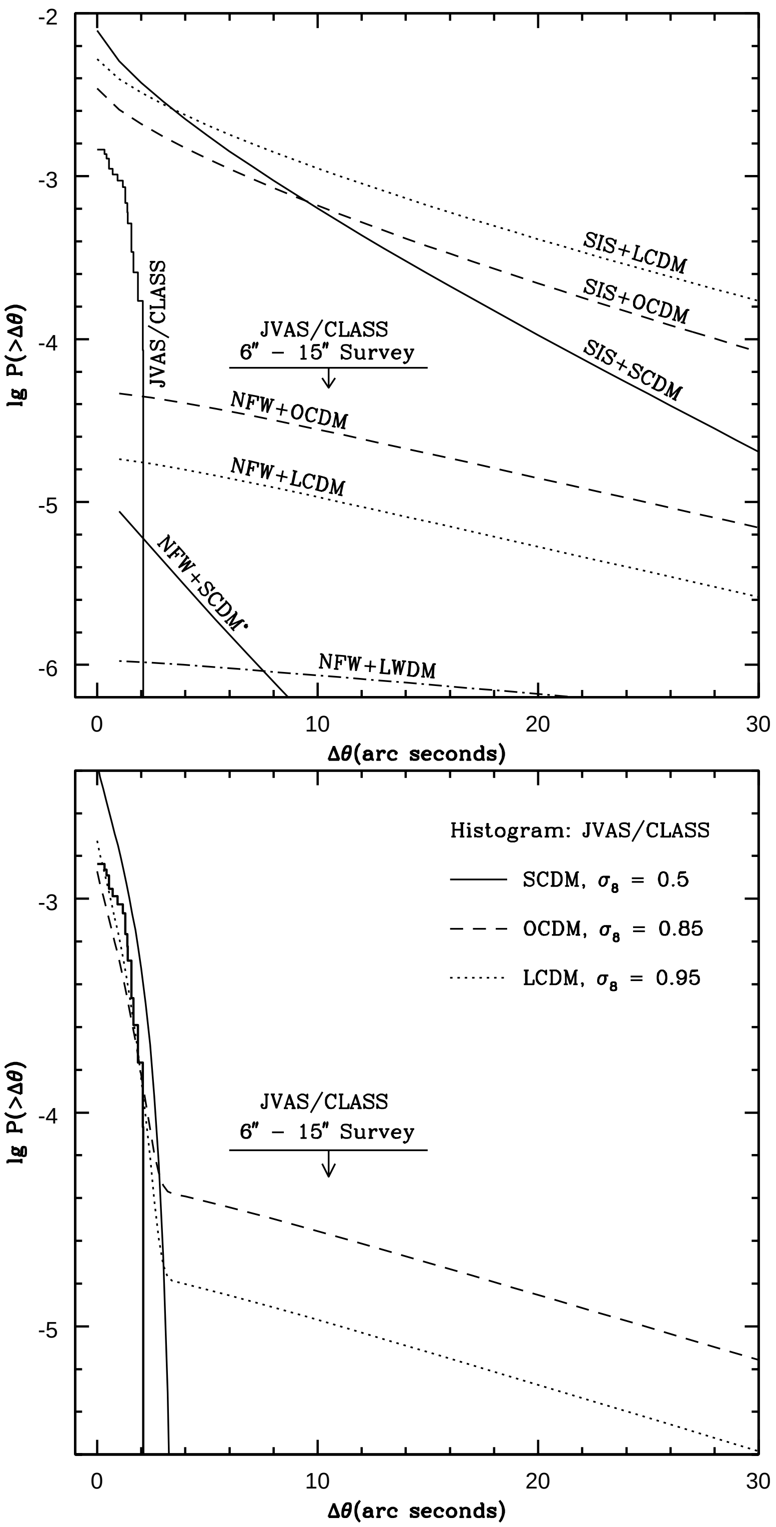
$$\rho \propto r^{-2} \qquad \text{(inside 5–10 kpc)}$$

Cross section $A \propto \sigma^4$.

The difference can be attributed to *cooling*:

- $M > M_{cool}$ — gas has not cooled, system remains NFW.
- $M < M_{cool}$ — gas has cooled and condensed into a galaxy, adiabatic compression has modified dark matter halo, result is SIS.
- $M_{cool} \sim 10^{13}\ M_\odot$ — scale for which the gas can cool in a Hubble time.

(See Kochanek & White 2001 ApJ 559:531.)



Li & Ostriker (astro-ph/0010432)

also Keeton (1998 thesis); Porciani & Madau (2000 ApJ 532:679)

Systematics

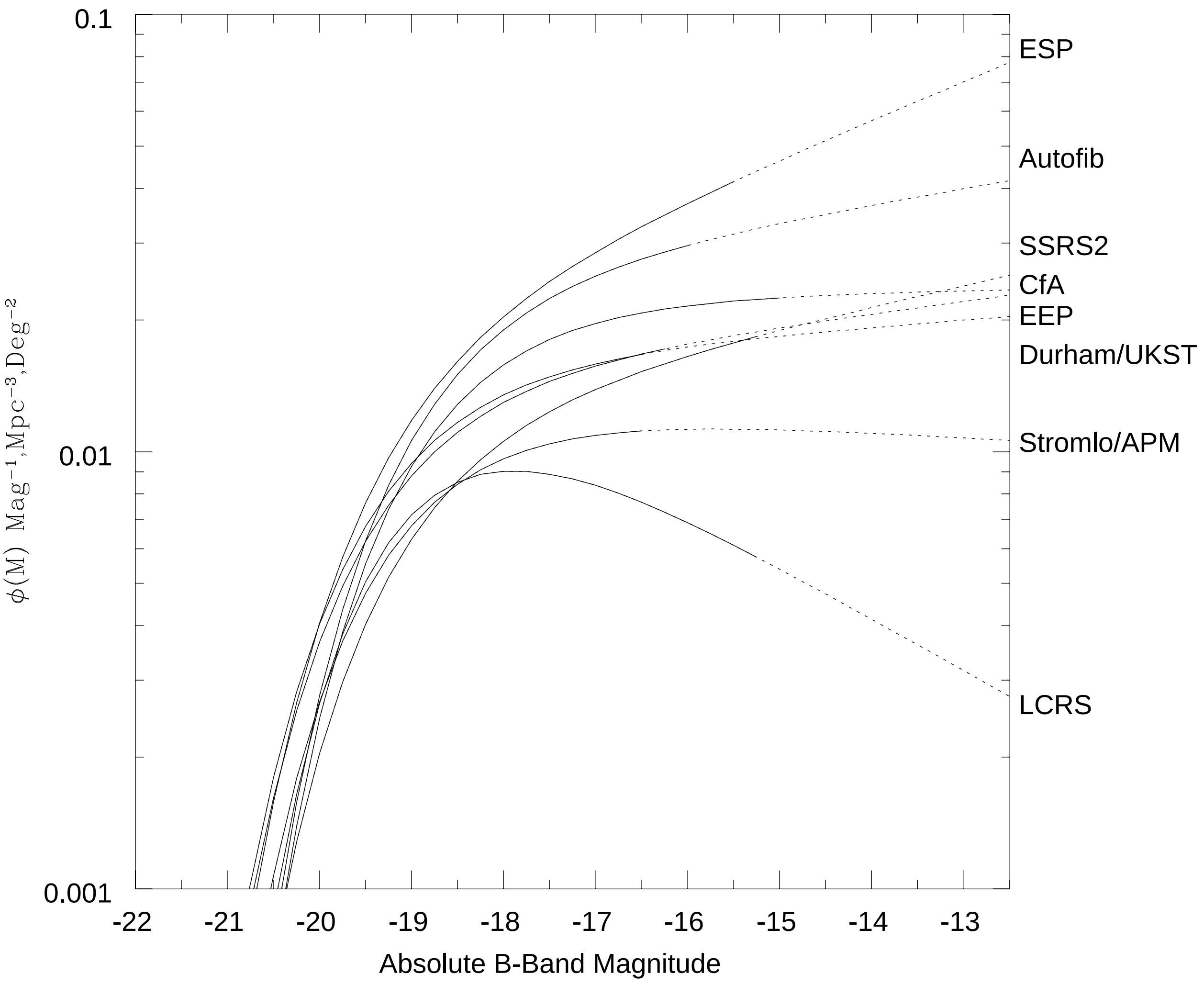
Models:

- Galaxy luminosity function (for phenomenology models)
- Phenomenology vs. theory mass function
- Evolution

Data:

- Radio: source redshifts
- Optical: Poisson statistics, selection effects

That Pesky Luminosity Function



Cross et al. (2001 MNRAS 324:825)

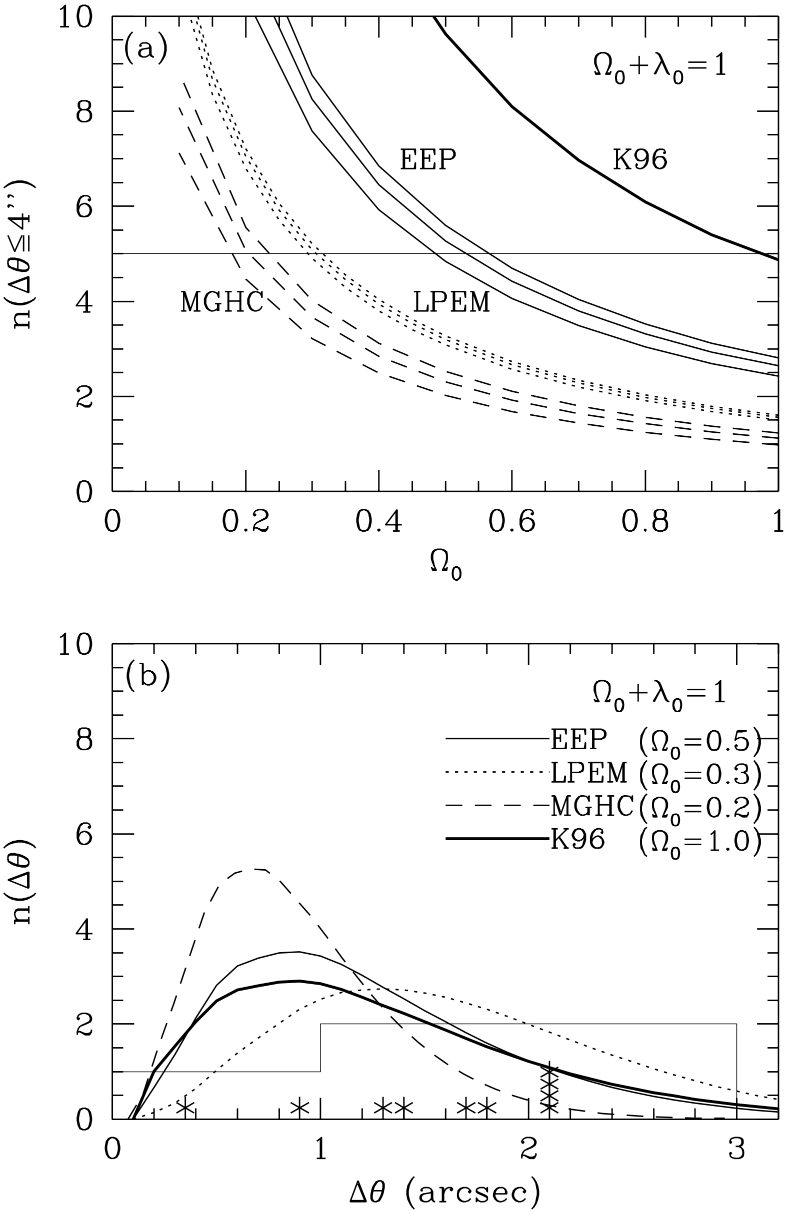
Phenomenology Models

Study	Sample	GLF	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	(sample/extinction)
Helbig et al.	Rad	K96	< 0.65	
Waga & Miceli (1999)	Opt	K96	< 0.55 / 0.76 / 0.91	(extinction)
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	$\simeq 0.8$	

"The uncertainties in the luminosity function of galaxies by type contribute as much to the uncertainties in the cosmological limits derived from lens statistitics as the Poisson errors arising from the small size of the samples."

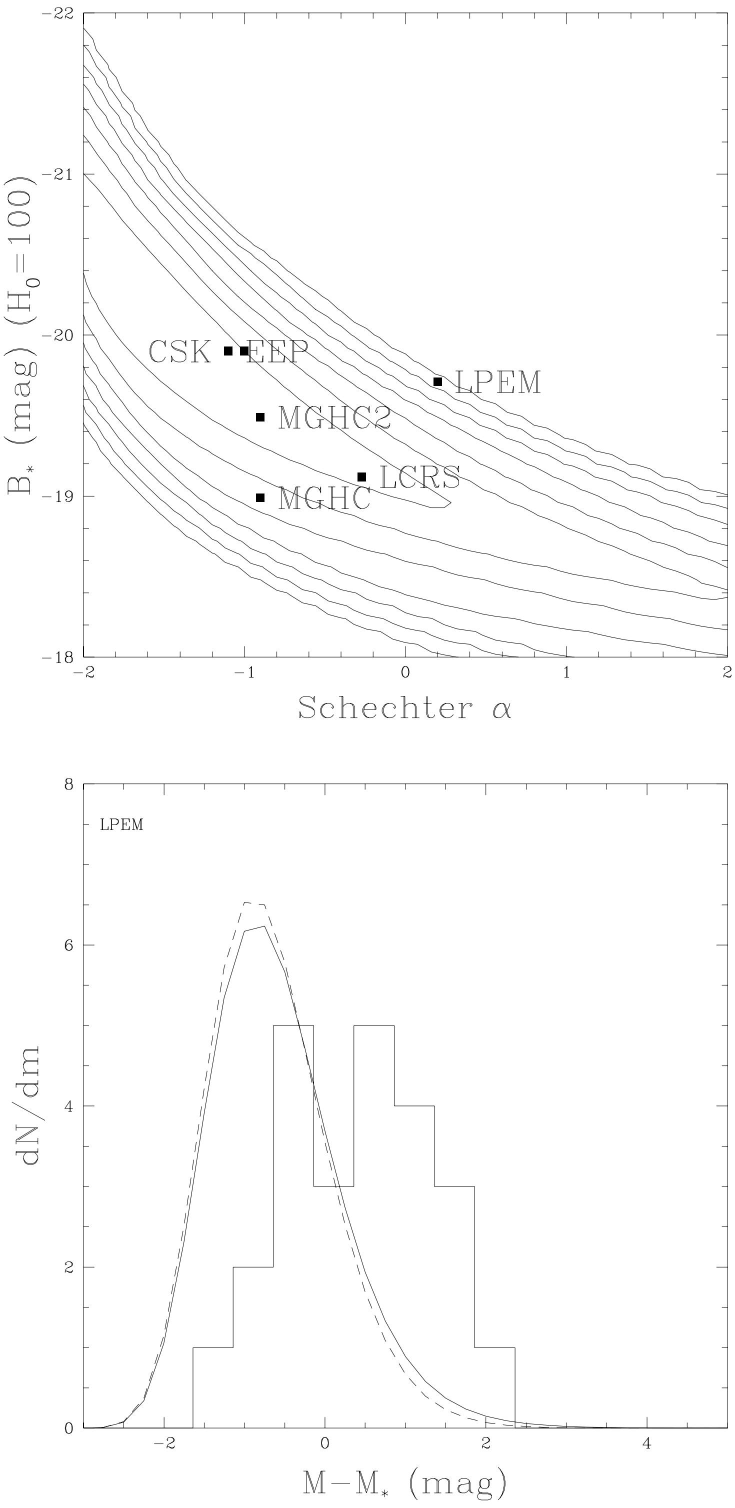
— Kochanek et al. (astro-ph/9811111)

Chiba & Yoshii (1999 ApJ 510:42)



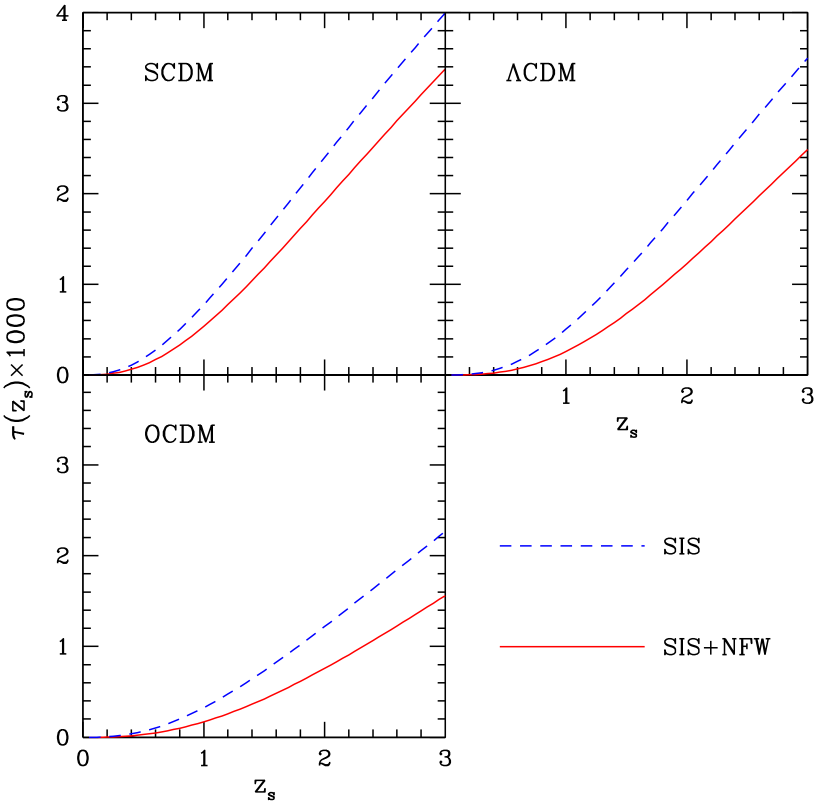
Note: increasing Ω_Λ increases N_{lens}.

Kochanek et al. (astro-ph/9811111)



Theory Models

Porciani & Madau (2000 ApJ 532:679)



Li & Ostriker (astro-ph/0010432): CLASS survey

SCDM	37
LCDM	16
OCDM	12
Observed	18

Higher $\Omega_M \Longrightarrow$ more galaxies $\Longrightarrow$ more lenses

Which Mass Function?

For normal lenses...

Phenomenology:	SCDM predicts	*fewer*	lenses than LCDM
Theory:	SCDM predicts	*more*	lenses than LCDM

Phenomenology:

+ (All) normal lenses are produced by normal galaxies.

− Uncertainties in luminosity function and its evolution.

Theory:

+ Automatically includes cosmology and evolution effects.

− But does it really describe galaxy populations?

Evolution and Phenomenology Models

Traditional models for lens statistics:

- Claim little evolution to $z \sim 1$ in early-type galaxies

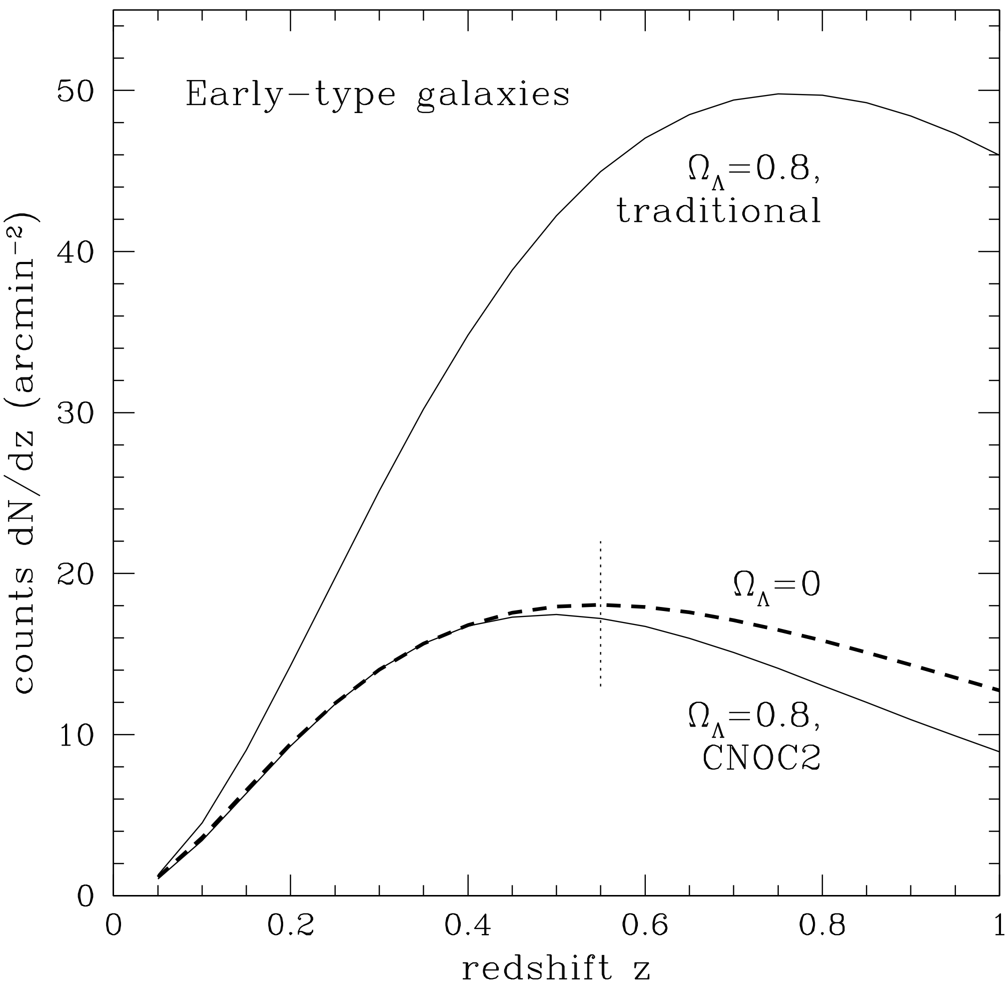
$\Rightarrow$ Assume constant comoving number density

$\Rightarrow$ $N_{lens} \propto N_{gal} \propto$ volume

CNOC2 redshift survey (H. Lin et al.):

- Observe sample $0.12 < z < 0.55$, derive evolving Schechter function
- See small, non-zero evolution in early-types
- Evolution rate depends on cosmology

Degeneracy between evolution and cosmology.



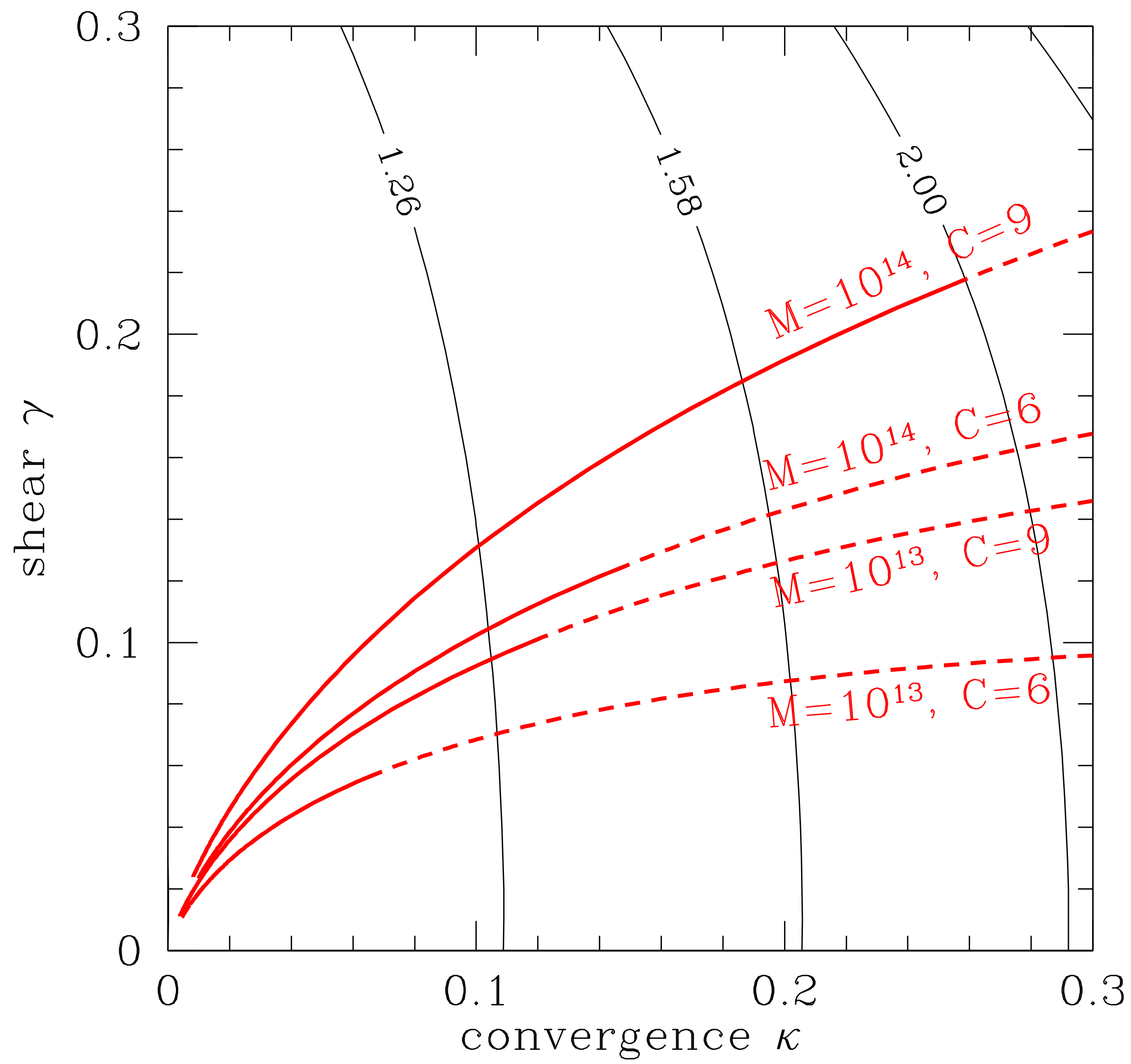
$$\frac{N_{lens}(\mathrm{LCDM})}{N_{lens}(\mathrm{SCDM})} = \begin{cases} 3.1 & \text{traditional models} \\ 1.1 & \text{CNOC2 models} \end{cases}$$

If you use models normalized by deep number counts,
do you lose most sensitivity to cosmology?

Need to measure evolving $dn/d\sigma$ (e.g., DEEP).

Lens Galaxy Environments

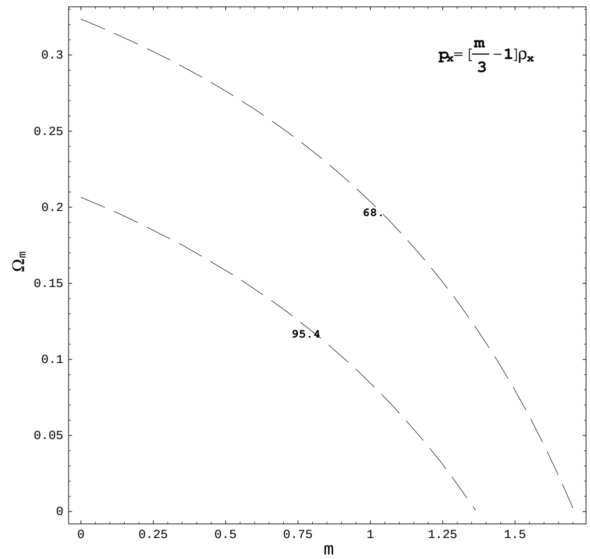
Many lens galaxies lie in groups, which add a convergence and shear.

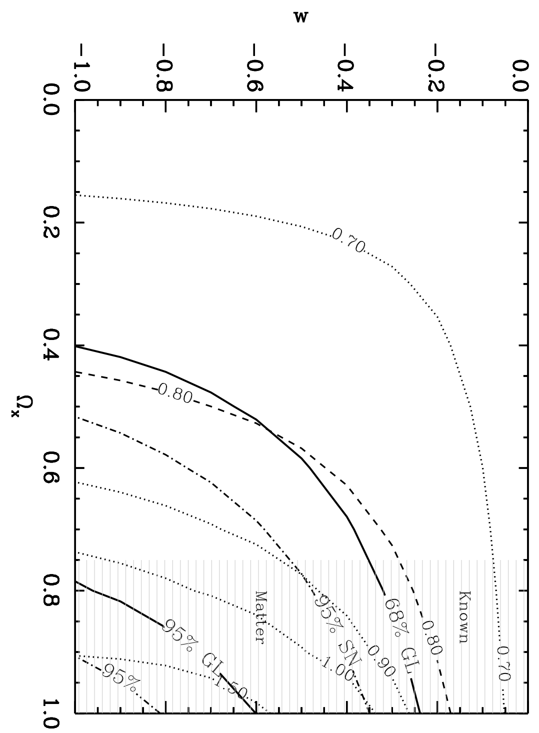


Keeton & Zabludoff (in prep.)

- Expect environments to affect the number of lenses by $\lesssim$10–20%
- Working to identify lens environments, study their properties

Phenomenology Models for w



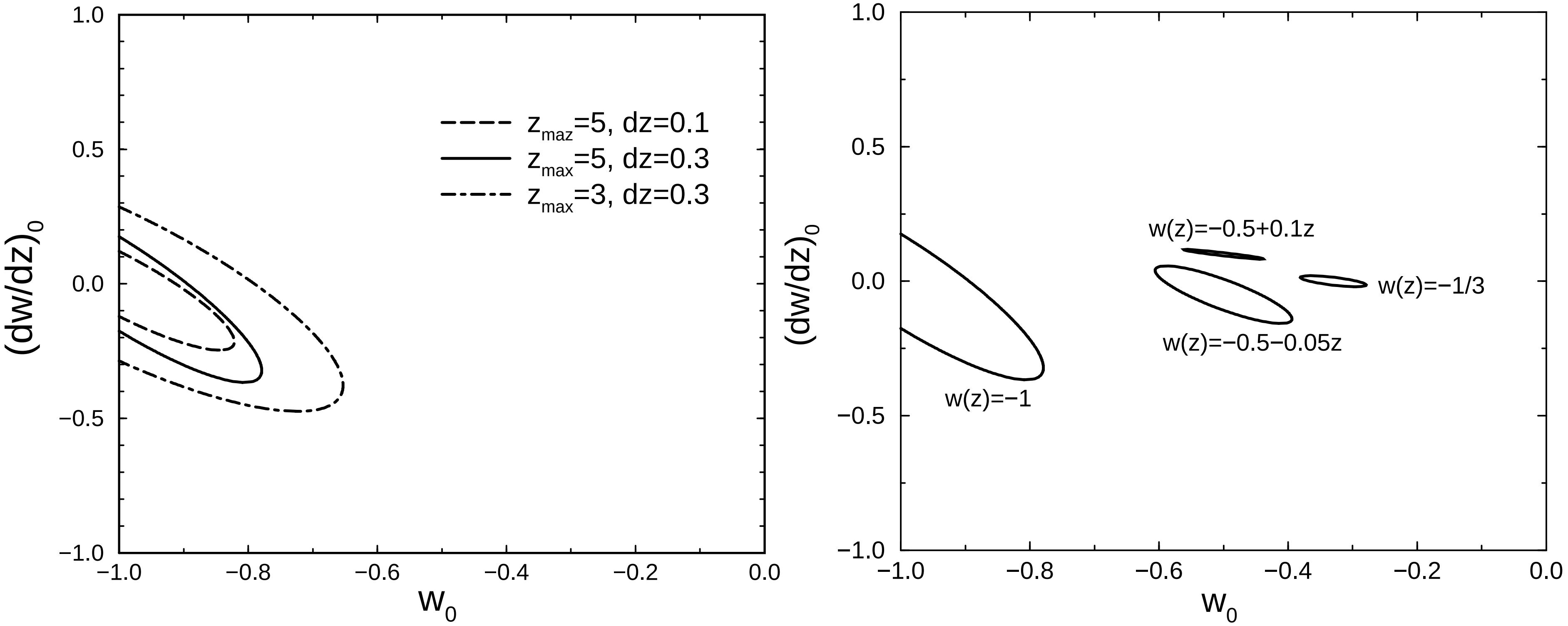


Waga & Miceli (1999 PRD 59:103507); Cooray (1999 A&A 342:353)

- Upper limits on Ω_X
- Lower limits on w
- (Increasing w reduces N_{lens}, allows higher Ω_X.)

Cooray & Huterer (1999 ApJL 513:L95)

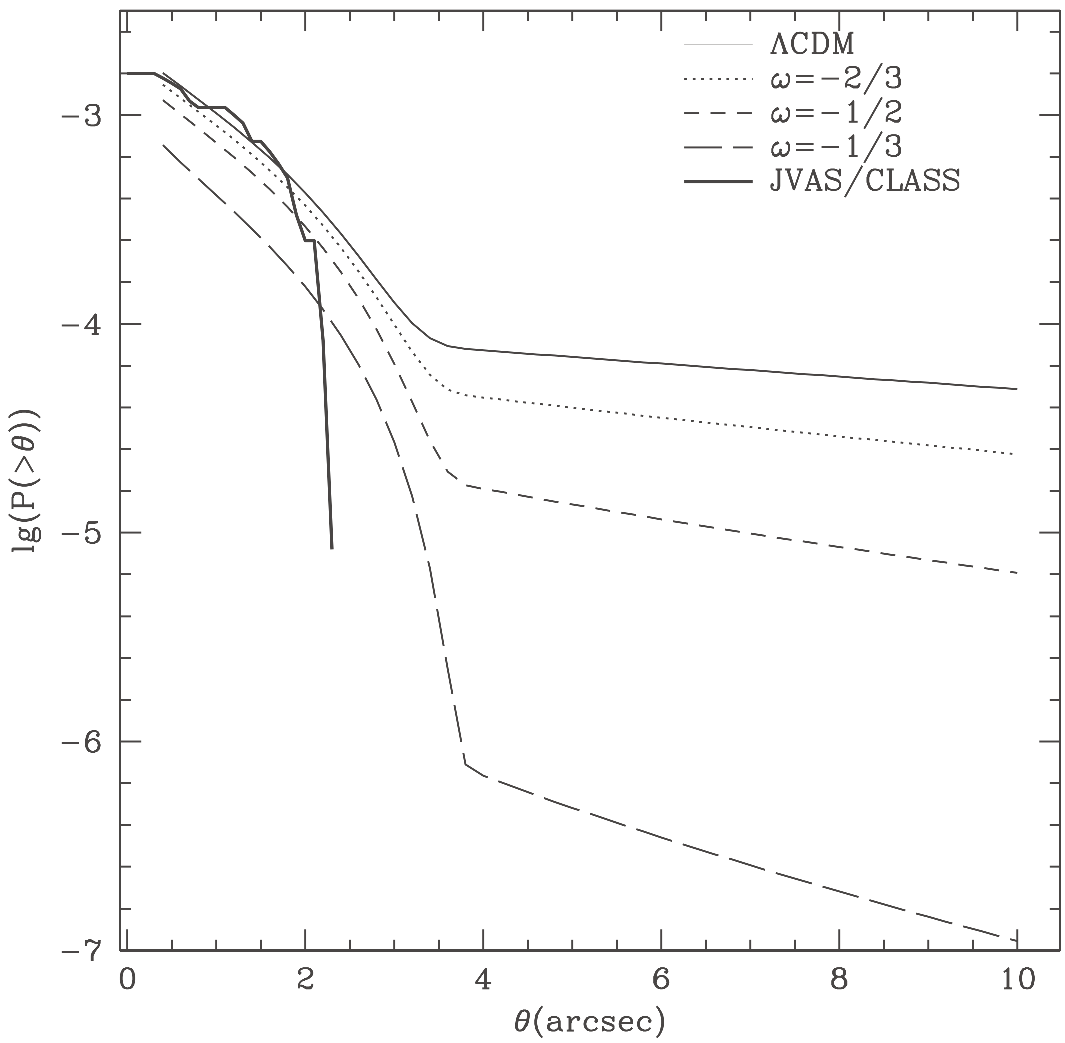
- Phenomenology models
- SDSS down to a limiting magnitude of 21, separation 1–6$''$
- project $\sim$2000 lenses in LCDM
- Redshifts known and binned: $z_{max} = 5$, $\sigma_z = \Delta z = 0.3$
- Flat universe, $\Omega_M = 0.3 \pm 0.1$ (marginalized)



1.0
0.5
0.0
−0.5
−1.0
(dw/dz)$_0$
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
w$_0$
z$_{maz}$=5, dz=0.1
z$_{max}$=5, dz=0.3
z$_{max}$=3, dz=0.3
w(z)=−0.5+0.1z
w(z)=−1/3
w(z)=−0.5−0.05z
w(z)=−1

Normal vs. Wide-Separation Lenses

(Theory models)

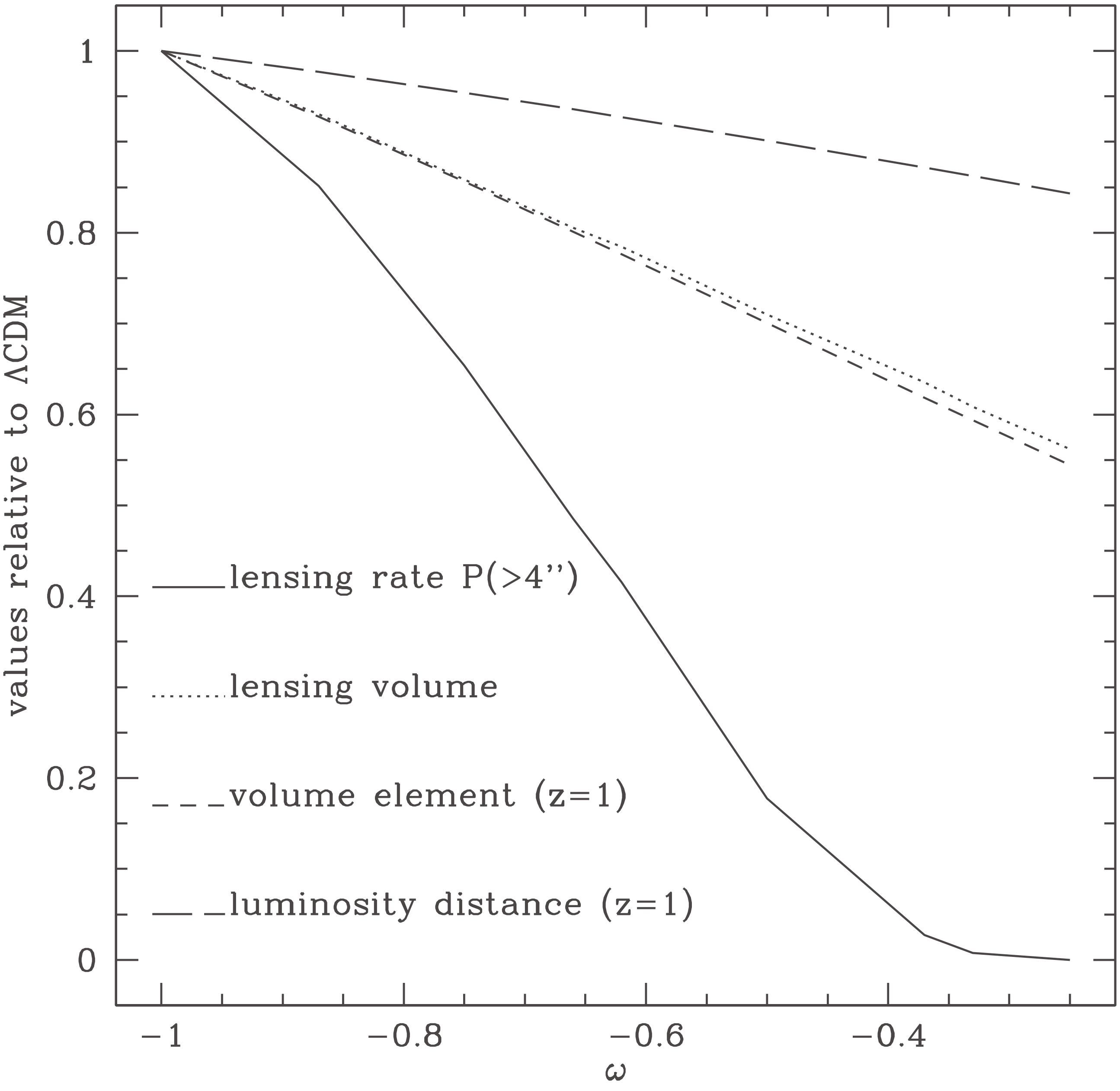


Sarbu, Rusin & Ma (2001 ApJL 561:L147)

- Normal: normal galaxies
- Wide-sep: groups/clusters — more sensitive to growth factor

Wide-Separation Lenses and w

(Theory models)



Sarbu, Rusin & Ma (2001 ApJL 561:L147)

Two Proposals for SDSS/2dF

1. Luminosity Function

- SDSS and 2dF seem to resolve many of the previous problems with the local GLF.
- SDSS has $dn/d\sigma$ for ellipticals.
- Compute robust optical depth (for normal lenses):

$$\tau = (\mathrm{const}) \int dV \, \left(\frac{D_{ls}}{D_{os}}\right)^2 \int d\sigma \, \frac{dn}{d\sigma} \, \sigma^4$$

- Use with existing lens samples.
- (Evolution?)

2. Wide-Separation Lenses

- Define a statistical sample. (Expect a few per 10,000 QSOs.)
- Know source population, selection functions.
- Different dependence on cosmology $\Longrightarrow$ complementary test.

Prospects

Models:

- Phenomenology vs. theory mass function?

  Define the sample (normal or wide-sep lenses)

- Galaxy luminosity function?

  Better data: SDSS, 2dF, etc.

- Evolution?

  Use the data: CNOC2, DEEP, etc.

Data:

- Larger optical samples?

  SDSS(?), SNAP, etc.

- Radio source redshifts?

  Hard work

Proposal: normal vs. wide-separation lenses as a consistency check.