The lens redshift distribution –

Constraints on galaxy mass evolution

Eran Ofek, Hans-Walter Rix, Dan Maoz (2003)

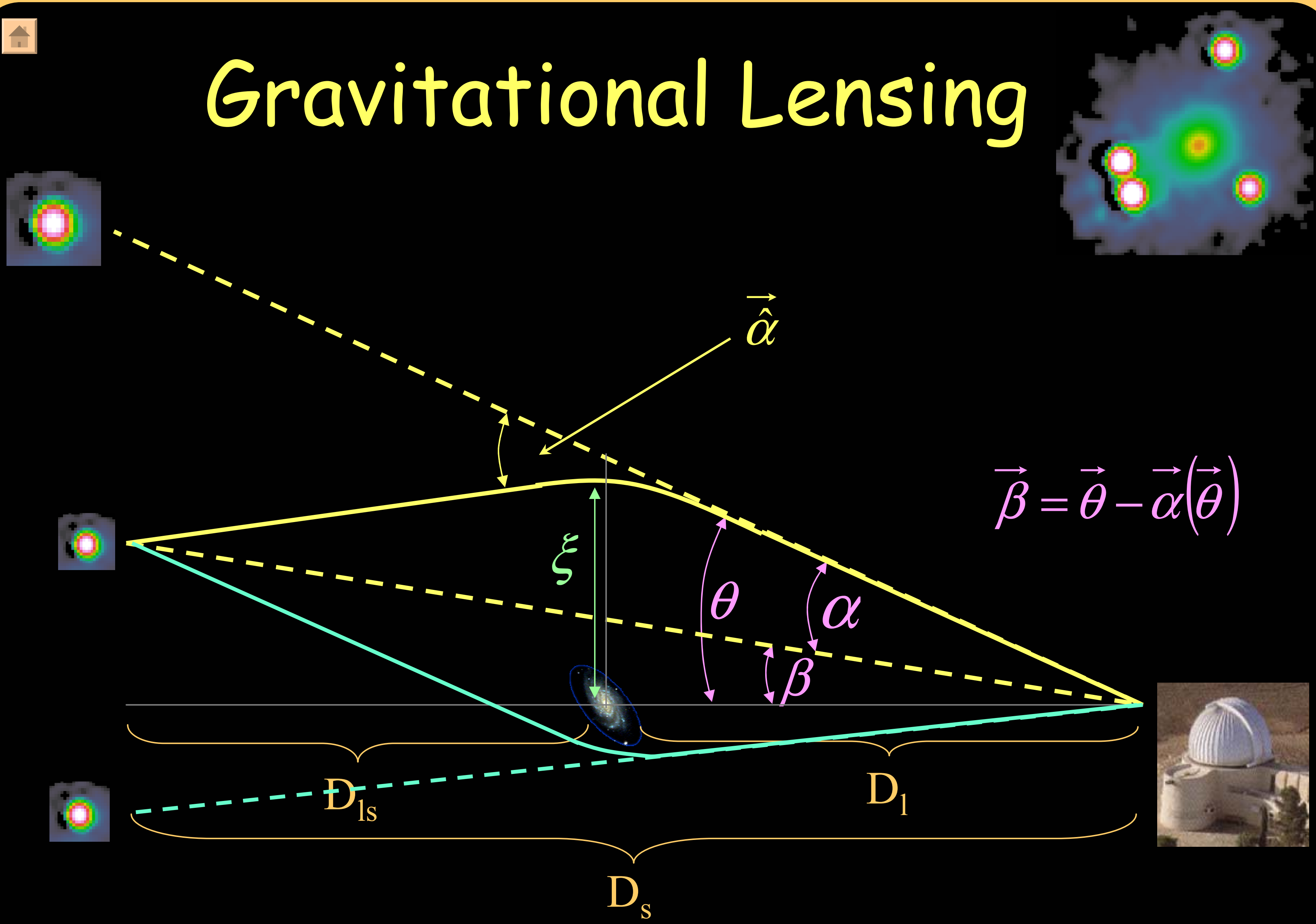
April 3, 2005

Talk layout

- Basics of gravitational lensing
- The lens redshift distribution test
- Sample selection
- Constraints on galaxy mass evolution

  The maximum likelihood and bias

Gravitational Lensing



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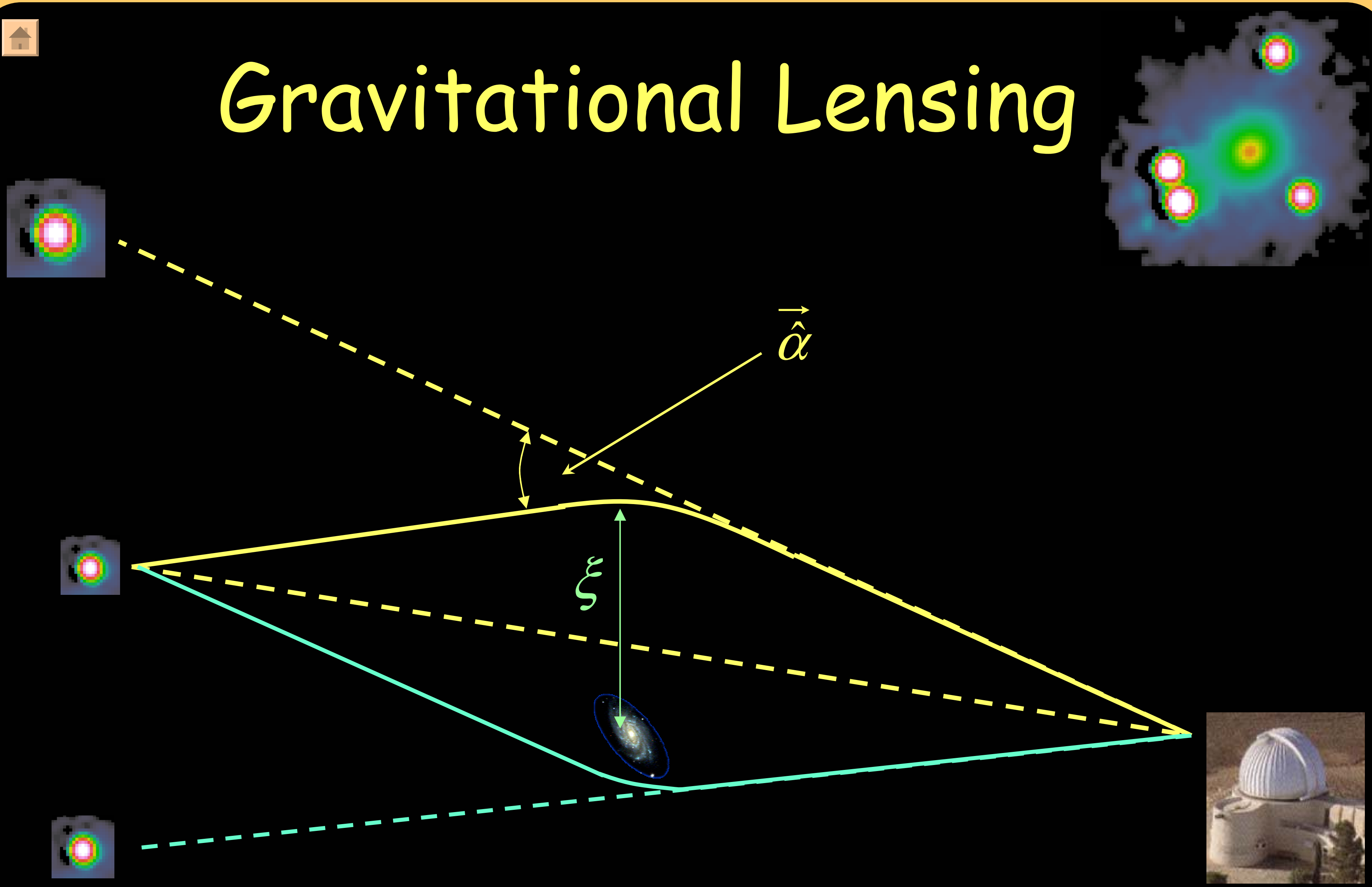
Gravitational Lensing



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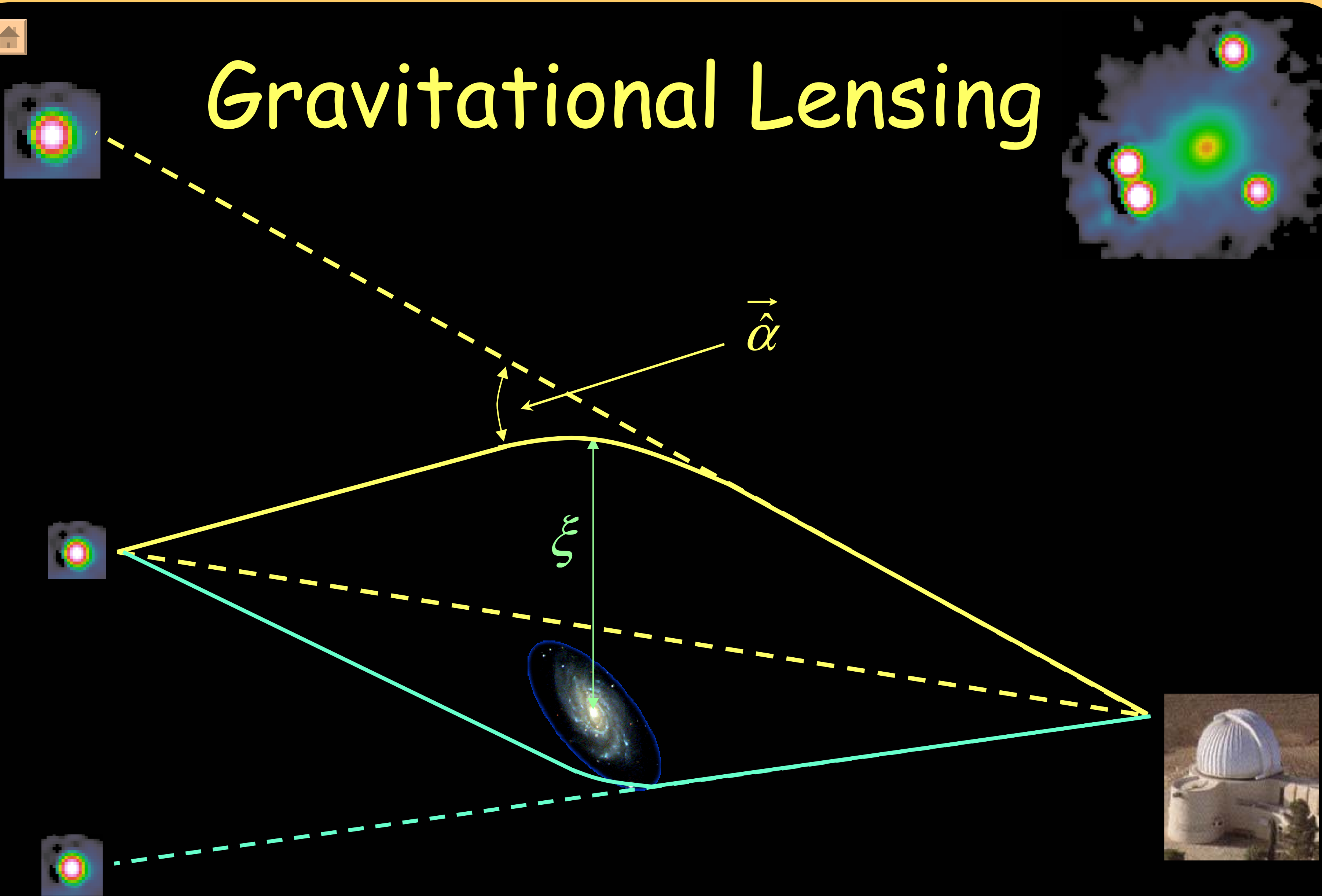
Gravitational Lensing



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Lens Redshift Distribution

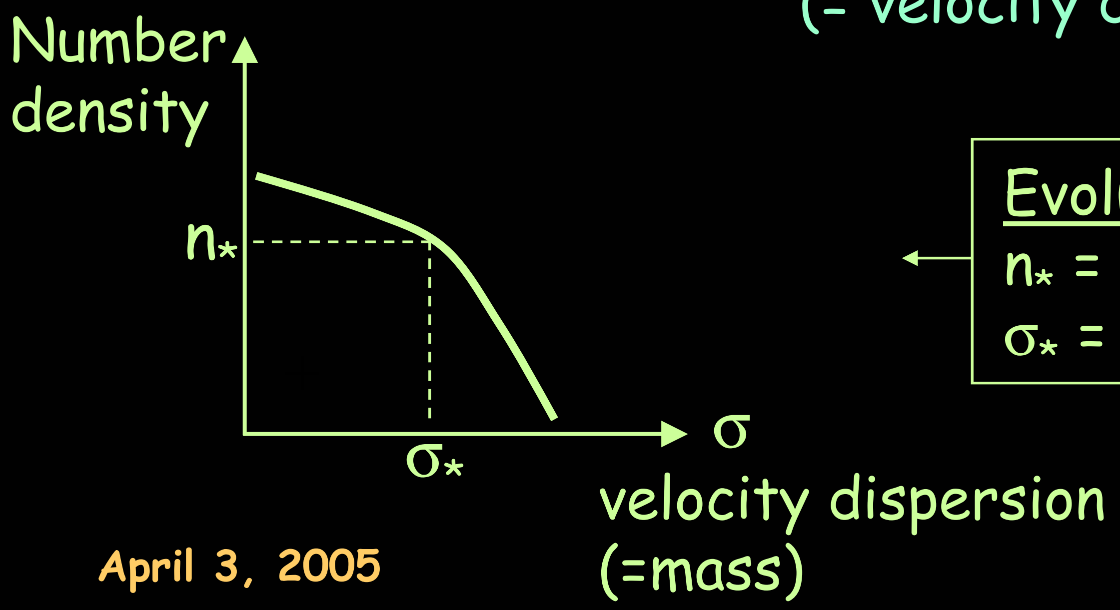
f/p

Probability for Lensing $P(z_l \mid z_s, \theta)$ ~ Number density of Lenses × Given Lens: probability of θ × Cosmology

Based on observations:

θ depends on lens mass (= velocity dispersion σ)

How much "distance" in redshift interval

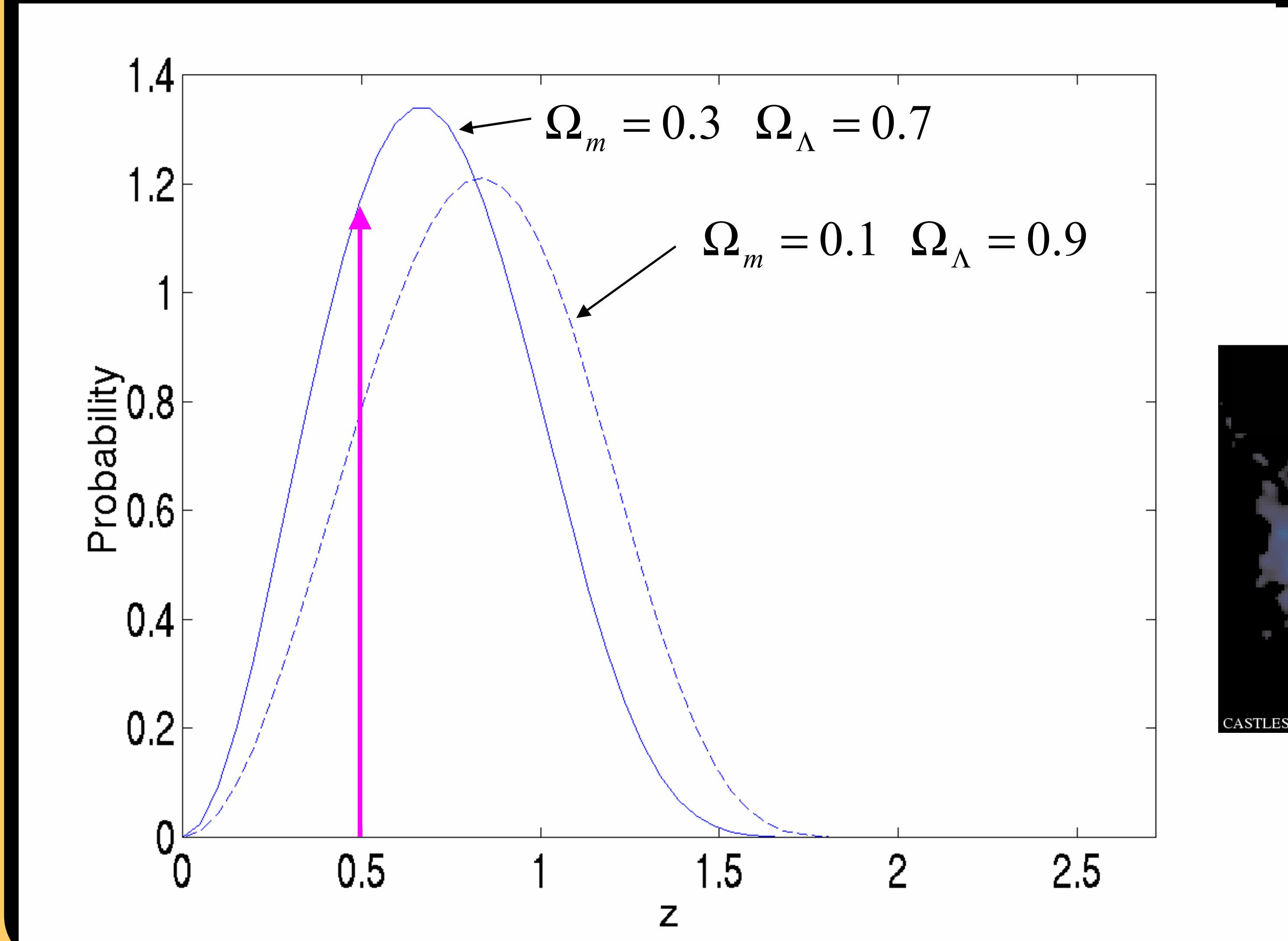


Evolution?

$n_* = n_*$ (redshift)

$\sigma_* = \sigma_*$ (redshift)

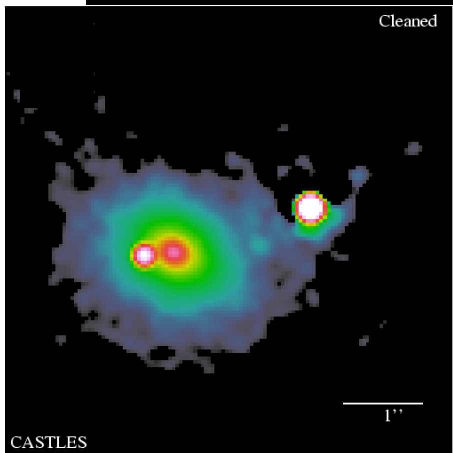
Lens Redshift Distribution - Example



$z_s = 2.72$

$z_l = 0.49$

$\theta = 1.12''$



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Selecting a sample

★ Image separation is prior

→ Doesn't depend on angular selection completeness

★ Missing redshift information?

→ Kochanek (1996):

truncated the redshift probability distribution beyond the redshift at which the lens galaxy become too faint to have its redshift measured

The Sample

- More than 80 gravitational lenses known
- We need lenses with complete redshift information
- Ignoring lenses without redshift information → Bias

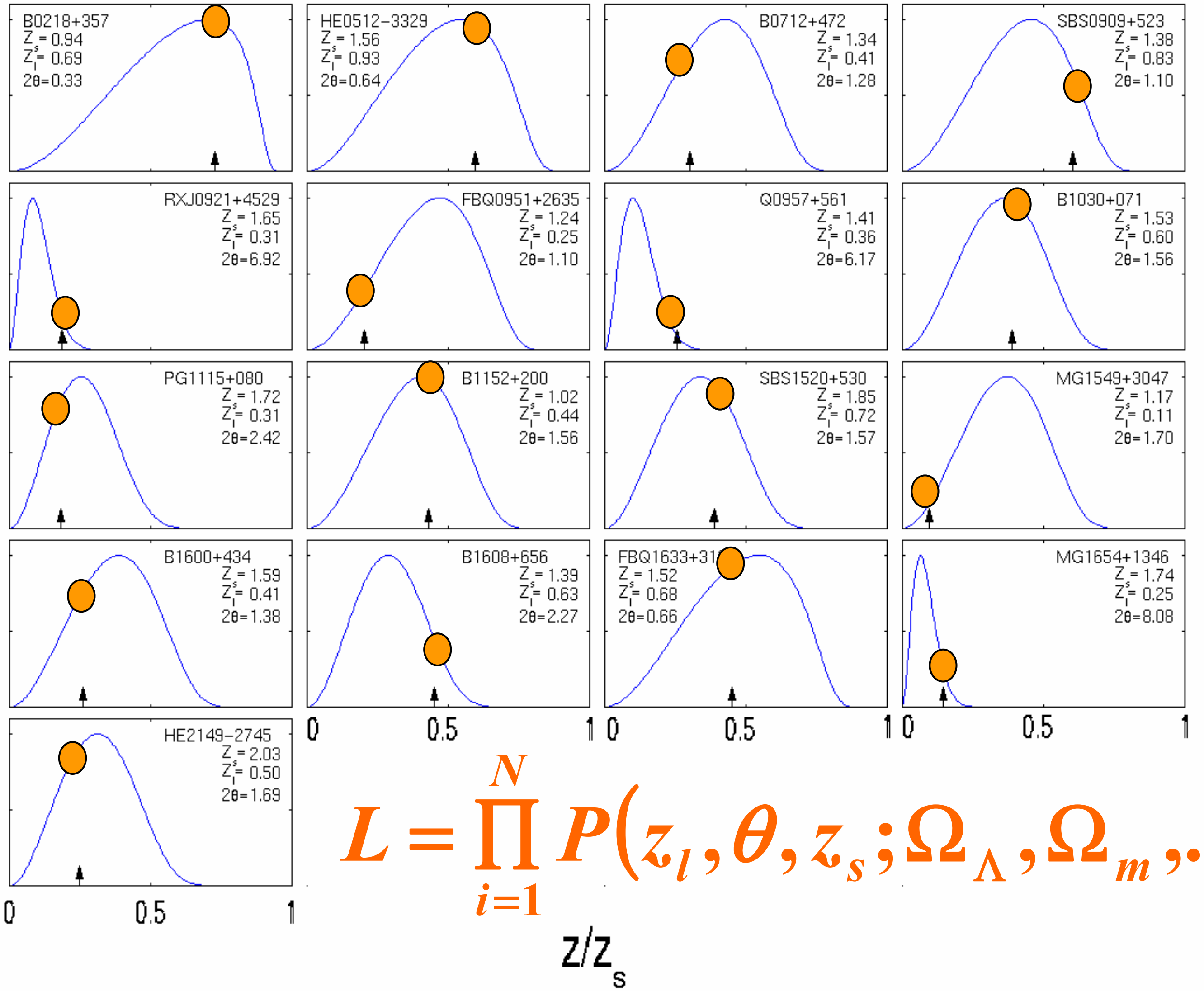
↓

Source redshift cut

Sample I	$z_s < 2.1$	**N=14**
Sample II	$z_s < 1.7$	**N=11**

JK

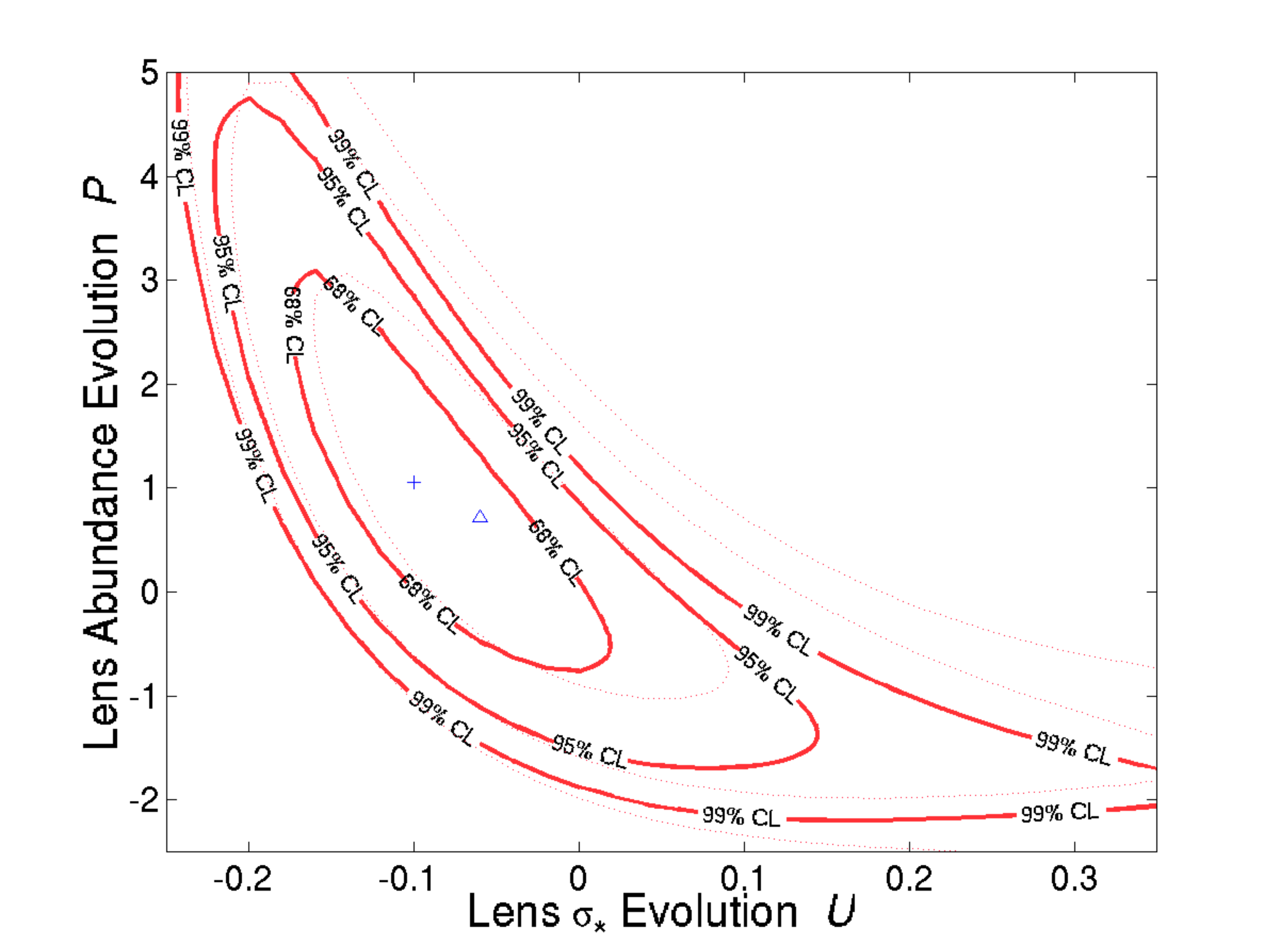
Probability vs. Lenses



$$L = \prod_{i=1}^{N} P\left(z_l, \theta, z_s; \Omega_\Lambda, \Omega_m, \ldots\right)$$

cos U/P/T

Galaxy Mass Evolution



$$\Omega_\Lambda = 0.7$$

$$\Omega_m = 0.3$$

$$P = +0.7^{+1.4}_{-1.2}$$

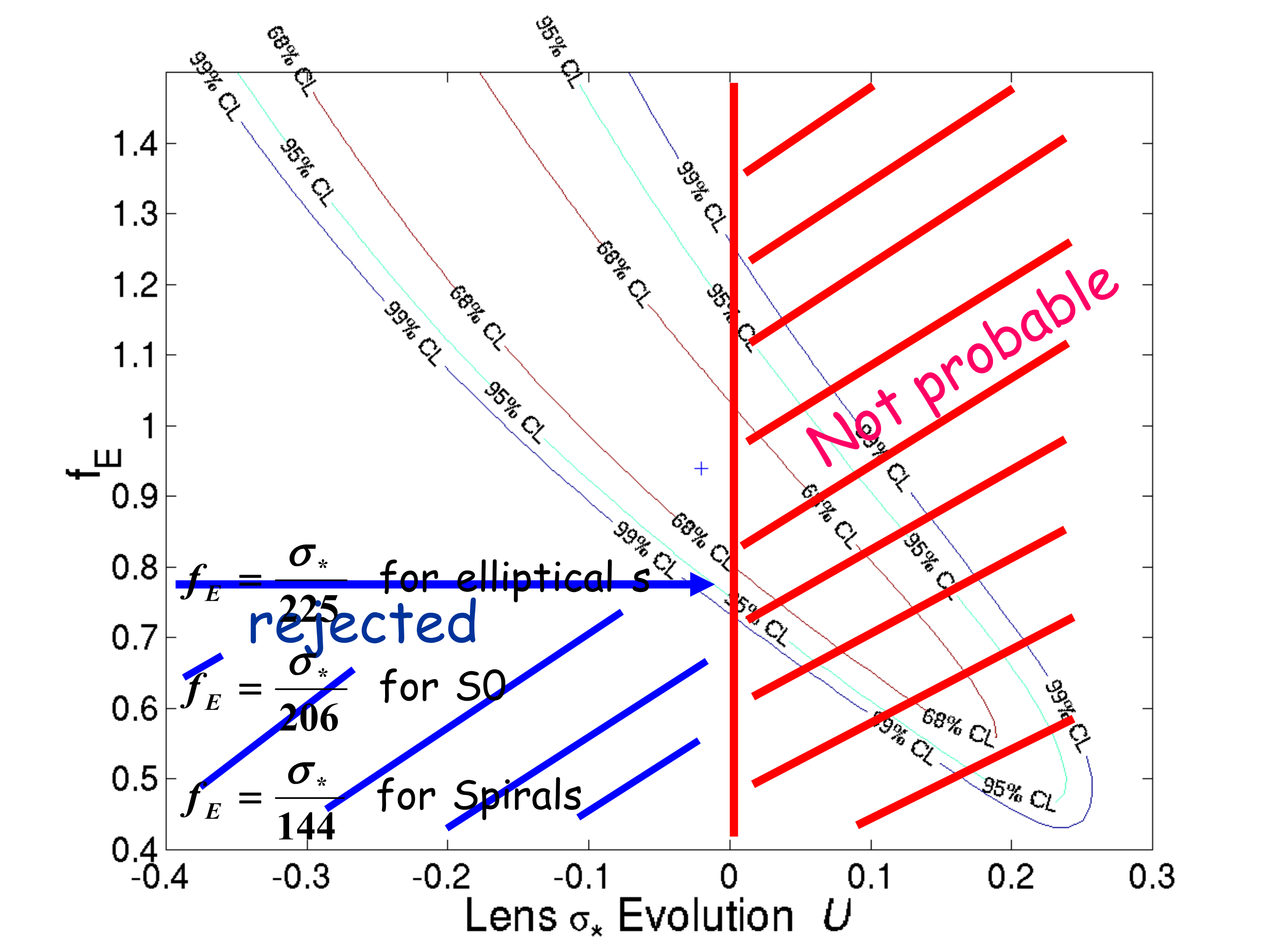
$$U = -0.10^{+0.06}_{-0.06}$$

definitions

$$n_*(z) = n_* 10^{Pz}$$

$$\sigma_*(z) = \sigma_* 10^{Uz}$$

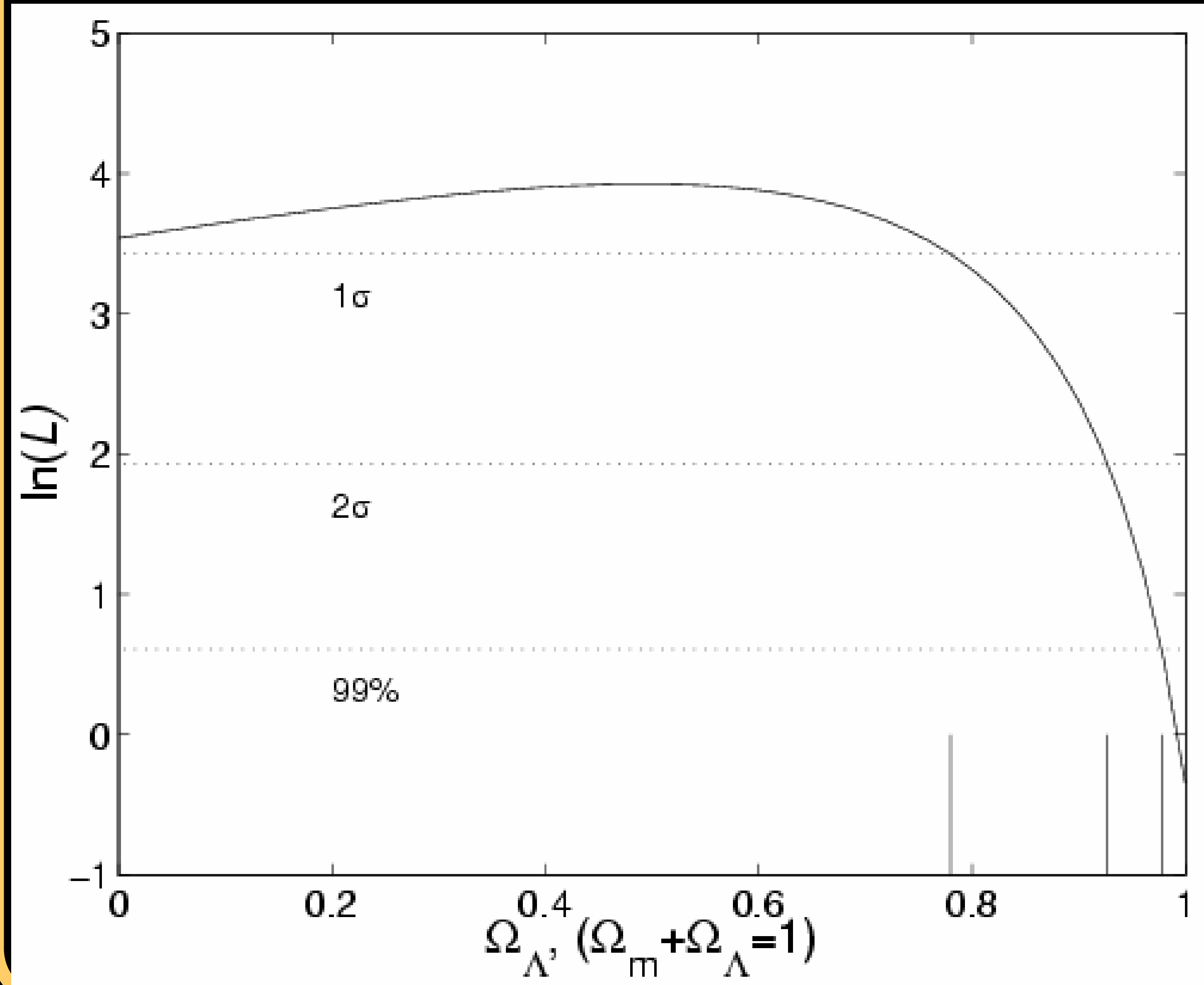
Galaxy Mass Evolution



$$\Omega_\Lambda = 0.7$$

$$\Omega_m = 0.3$$

Cosmology



No evolution
Flat Universe

$$\Omega_\Lambda = 0.49^{+0.29}_{-0.59}$$

Jackknife - bias and outliners

Given a sample $S_1, \ldots, S_n$: calculate statistic T

Drop point number k ($=S_k$).

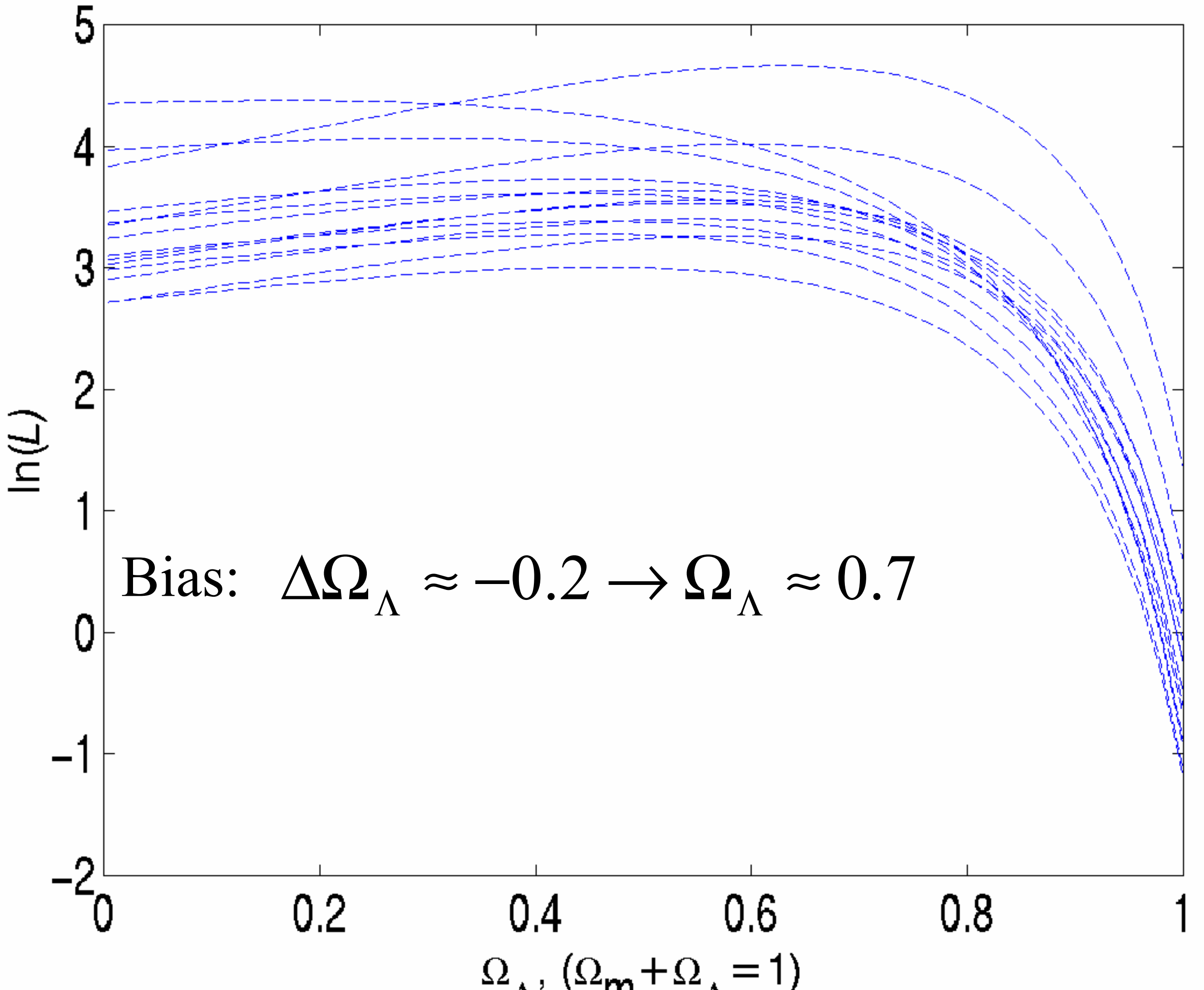
Calculate $T(S_1, \ldots, S_{k-1}, S_{k+1}, \ldots, S_n) = T_{i \neq k}$

$$StD = \sqrt{\frac{N-1}{N} \sum_{i}^{N} \left(T_{i \neq K} - \langle T_{i \neq K} \rangle \right)}$$

Quenouille-Tukey jackknife bias:

$$Bias = (N-1)\left(\langle T_{i \neq K} \rangle - \langle T_i \rangle \right)$$

Jackknife - bias and outliners



Summary

- Sensitive to galaxy mass evolution
- Assuming "standard cosmology"

  $\sigma_* @ z \sim 1 > 65\%$ of its current value (95% CL)

$$d\log[\sigma_*(z)]/dz = -0.10^{+0.06,+0.15}_{-0.06,-0.10}$$

$$d\log[n_*(z)]/dz = +0.7^{+1.4}_{-1.2}$$

- Assuming no evolution $\sigma_* > 175\, km\, s^{-1} @ 95\% CL$

$$f_E = 0.90^{+0.08,+0.19}_{-0.07,-0.12}$$

End

Lens Redshift Distribution

$$\frac{d\tau}{dz}(\theta, z_{source}) = n(\theta, z) \quad A(\theta) \quad \frac{cdt}{dz}$$

Number density of lenses

=

galaxy mass function

$\theta(\sigma)$

Lensing cross section

$\theta(\sigma)$

Proper distance interval

Schechter function

Faber-Jackson relation

$n(\sigma)$

$n_*(z) = n_* 10^{Pz}$

$\sigma_*(z) = \sigma_* 10^{Uz}$

Sensitivity

FJ Ω

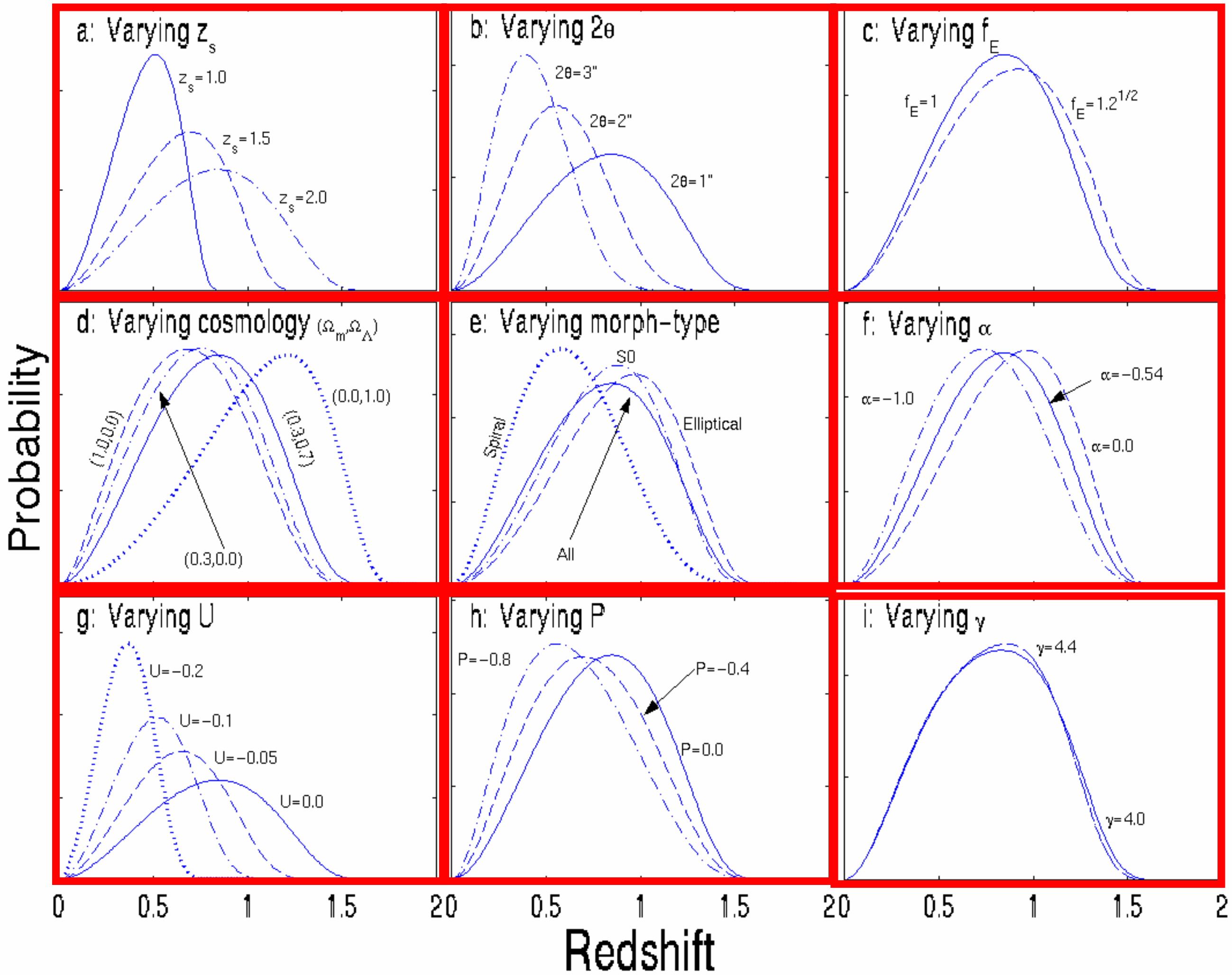
$z_s = 2.0$

$2\theta = 1''$

definitions

$n_*(z) = n_* 10^{Pz}$

$\sigma_*(z) = \sigma_* 10^{Uz}$



Future Work

- Obtain additional lens redshift

  Maoz, Rix, & Kochanek (@ VLT)

  Larger sample → Higher redshift (z~1.5)

- Use velocity dispersion function

  e.g., Sheth et al. (2003)

Spherical Isothermal Sphere $\rho \propto \frac{1}{r^2}$

★ SIS assumption is consistent with data:
- Galaxy dynamics (Rix et al. 1997)
- X-ray emission from ellipticals (Fabbiano et al. 1989)
- Lensing (Treu & Koopmans 2002)

★ SIS lenses ⟶ Einstein radius = $\frac{1}{2}$ image separation

★ For SIS the Einstein radius: $\theta_E = 4\pi \frac{\sigma^2}{c^2} \frac{D_{ls}}{D_s}$

Previous Work

	Sample size
◆ Kochanek 1992	N=4
◆ Helbig & Kayser 1996	N=6
◆ Kochanek 1996	N=8

↓

Weak constraints on cosmology

Lens Redshift Distribution

$$\frac{d\tau}{dz}(\theta,z)=\tau_N 10^{z[-U\gamma(1+\alpha)+P]} f_E^2(1+z)^3 \frac{D_{ls}}{D_s} D_l^2 \frac{cdt}{dz}\left(\frac{\theta}{\theta_*}\right)^{\frac{1}{2}\gamma(1+\alpha)+1} \exp\left[-\left(\frac{\theta}{\theta_*}\right)^{\frac{1}{2}\gamma} 10^{-zU\gamma}\right]$$

$$\tau_N = 4\pi^2 n_* \frac{\gamma}{2}\left(\frac{\sigma_*}{c}\right)^2$$

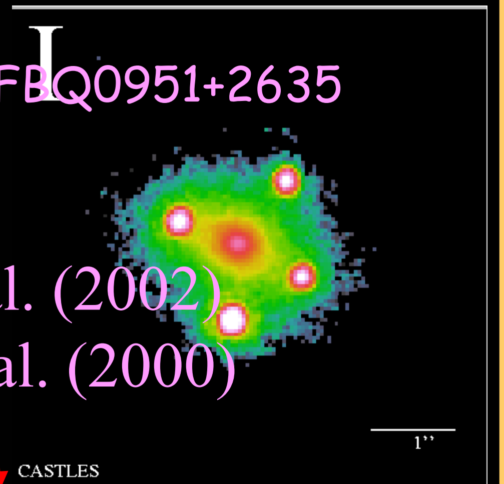
Parameters : 2dF - Madgwick et al. (2002)

	Spiral	S0	Elliptical
α	-1.16	-0.54	-0.54
$n_*[h^3\,\mathrm{Mpc}^3]$	1.46×10^{-2}	0.61×10^{-2}	0.39×10^{-2}
γ	2.6	4.0	4.0
$\sigma_*[\mathrm{km\,s^{-1}}]$	144	206	225

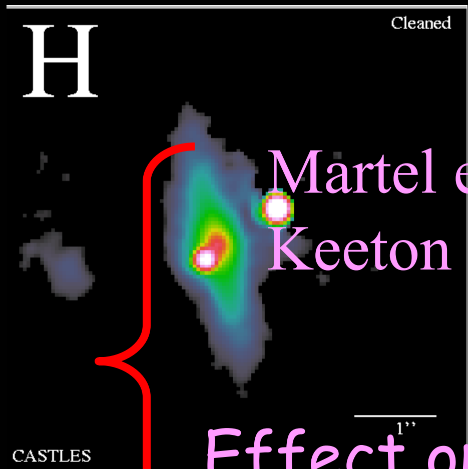
Problems

- ★ Lenses discovered based on lens-properties
- ★ Missing redshifts
- ★ Galaxy evolution
- ★ Clusters
- ★ Mass profile of galaxies

Q2237+0305



Photometric Redshift - FBQ0951+2635



Martel et al. (2002)

Keeton et al. (2000)

Effect on separation ± 20%

Kochanek (1996) - small effect

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Galaxy Evolution

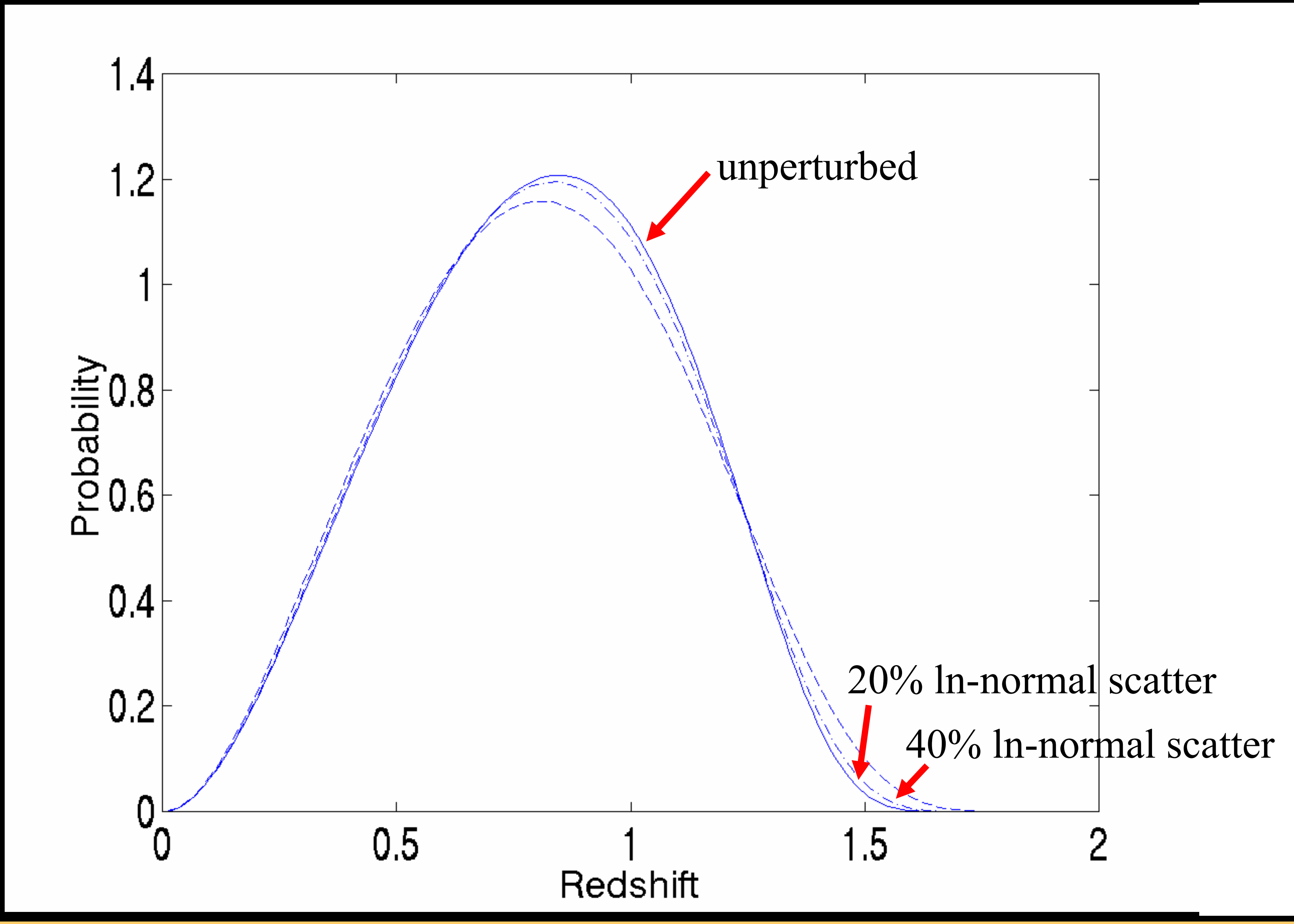
Van Dokkum et al. (1998)	0.83	$T \approx -0.45$
Keeton, Kochanek & Falco (1998)	~1	$T \approx -0.5$
Lin et al. (1999)	0.55	$P = -0.7 \pm 0.2$
		$Q = 0.8 \pm 0.2$
van Dokkum et al. (2001)	0.55	$T = -0.59 \pm 0.15$
Cohen (2002)	~1	$Q \approx 0.6$
Rusin et al. (2002)	~1	$T = -0.56 \pm 0.04$
Im et al. (2002)	~1	$Q = 0.8 \pm 0.3$
		$P = -0.26 \pm 0.20$

$$n_*(z) = n_* 10^{Pz}$$

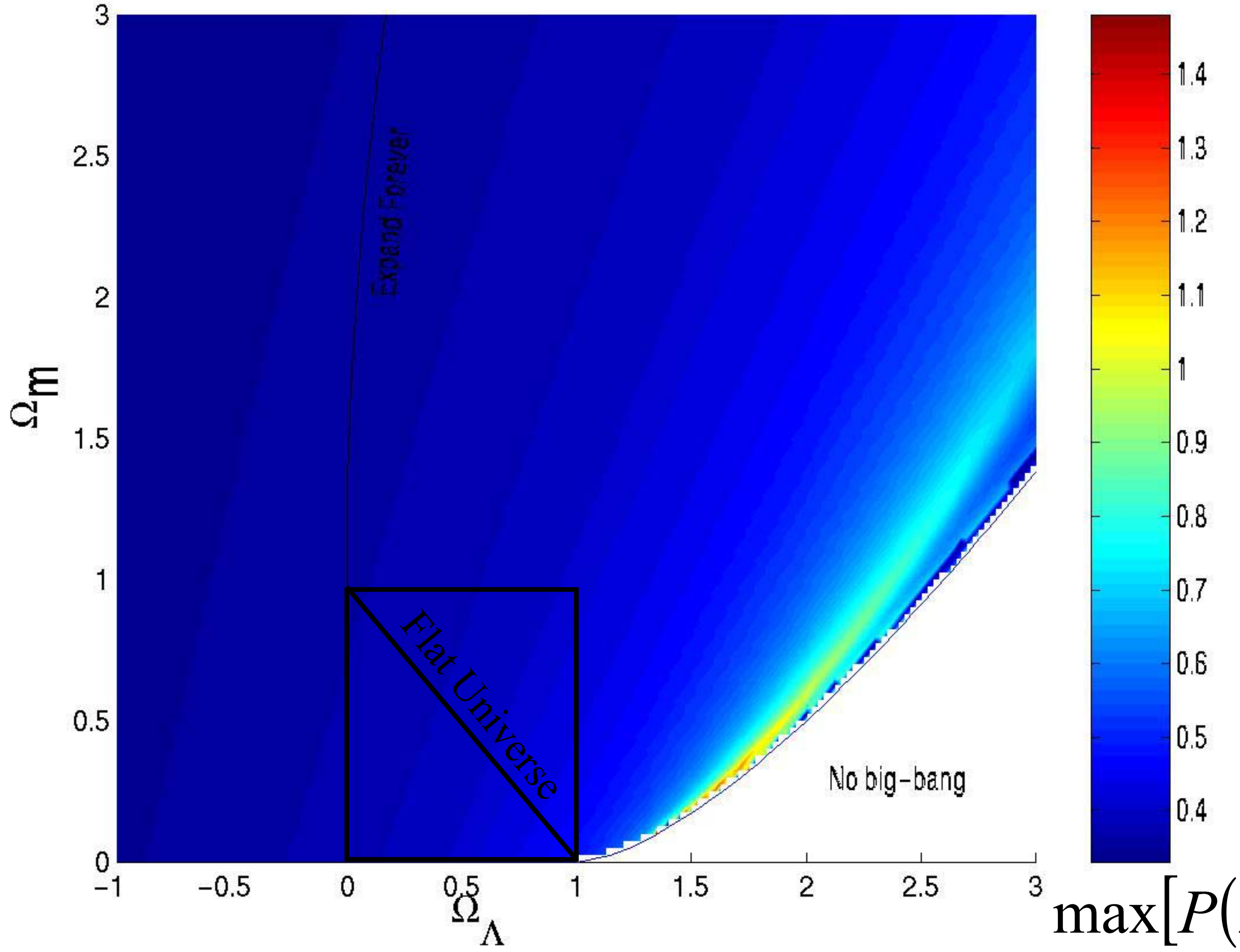
$$\sigma_*(z) = \sigma_* 10^{Uz}$$

$$\left(\frac{M}{L}\right)(z) = \left(\frac{M}{L}\right)_0 10^{Tz}$$

Scatter of the Faber-Jackson



Sensitivity - Cosmology

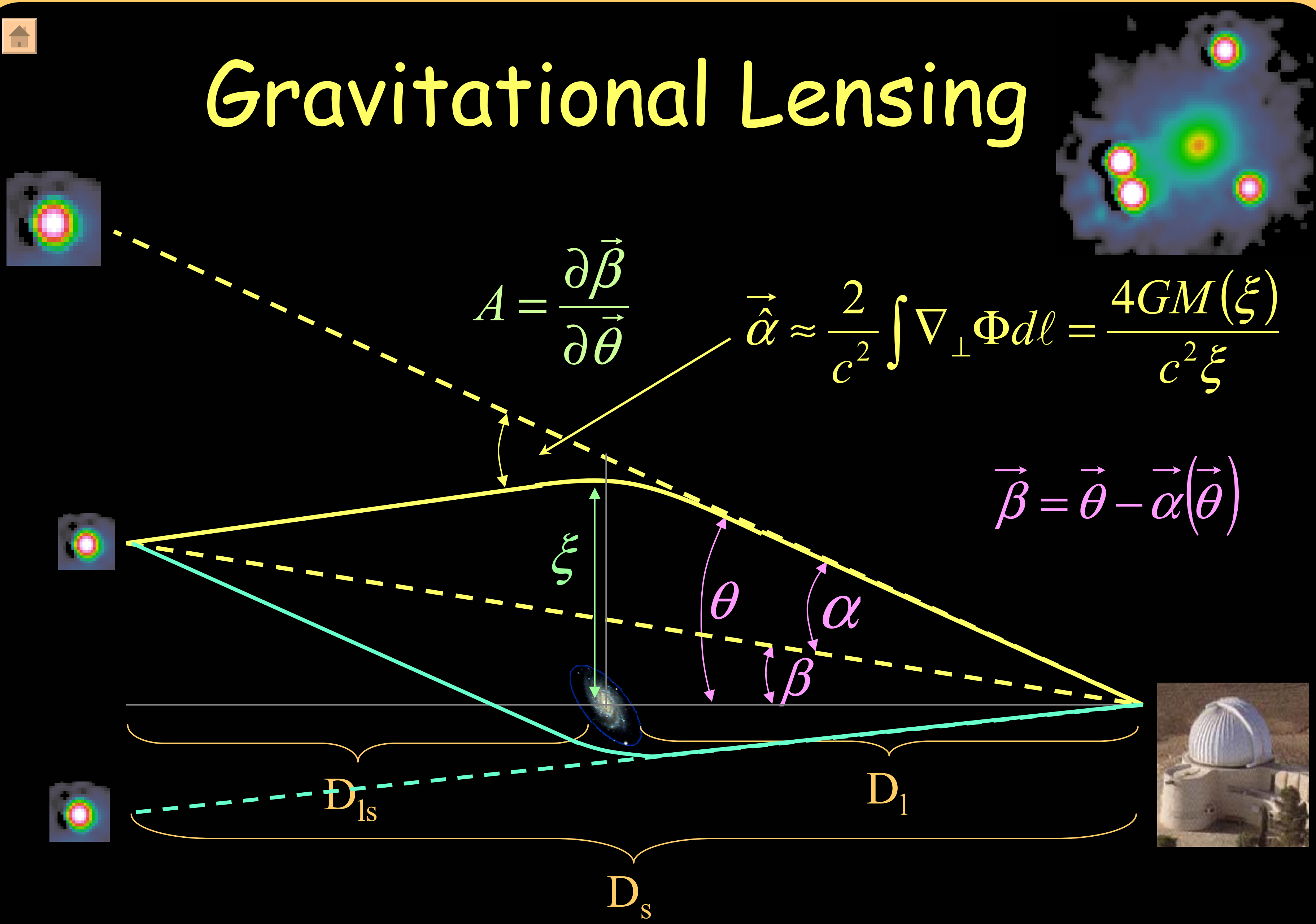


$\max[P(z_l)]$

$z_s = 2$

$\theta = 1''$

Gravitational Lensing



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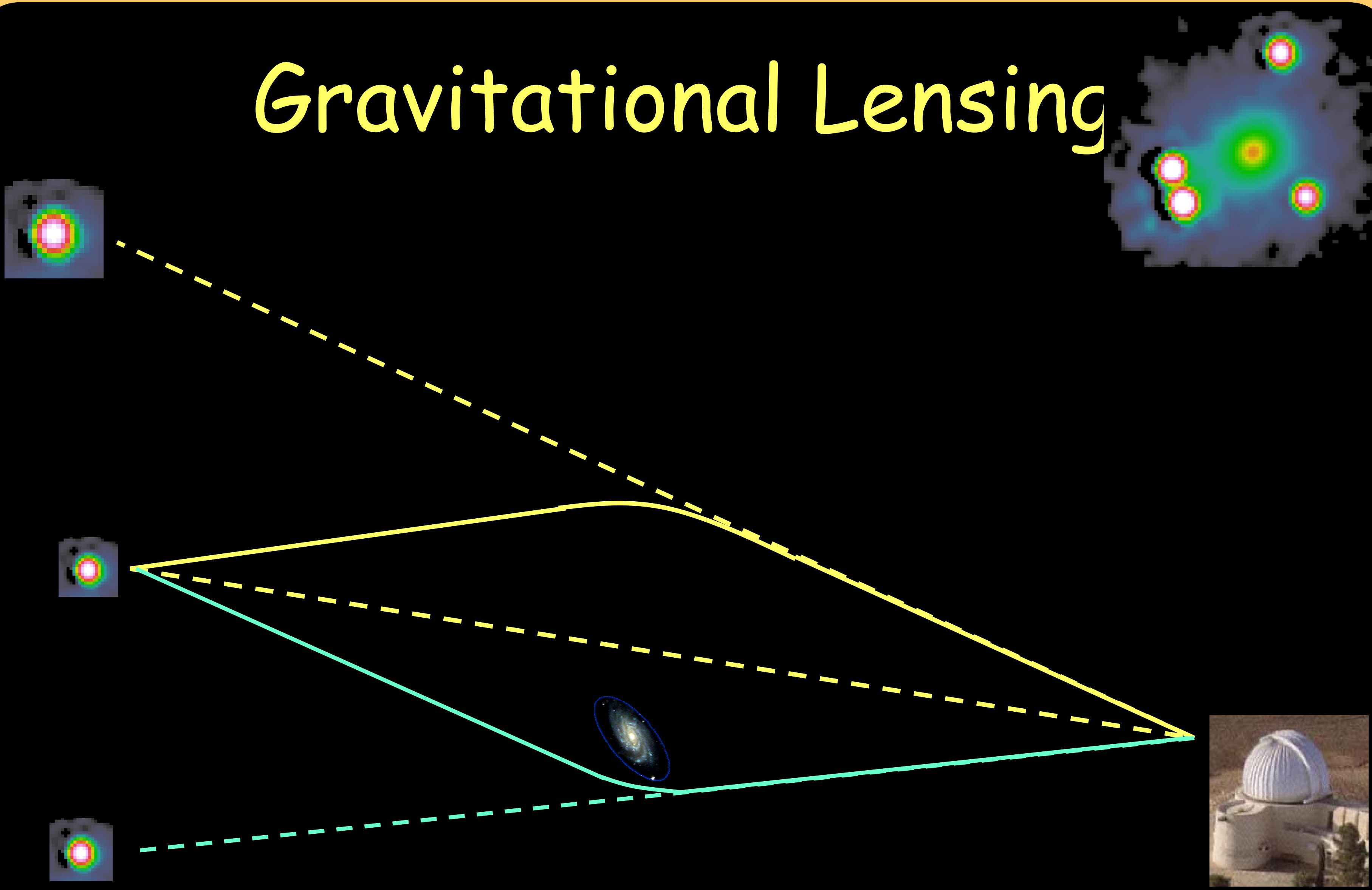
Gravitational Lensing



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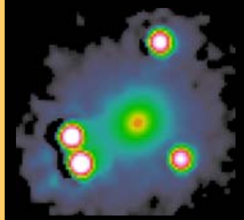
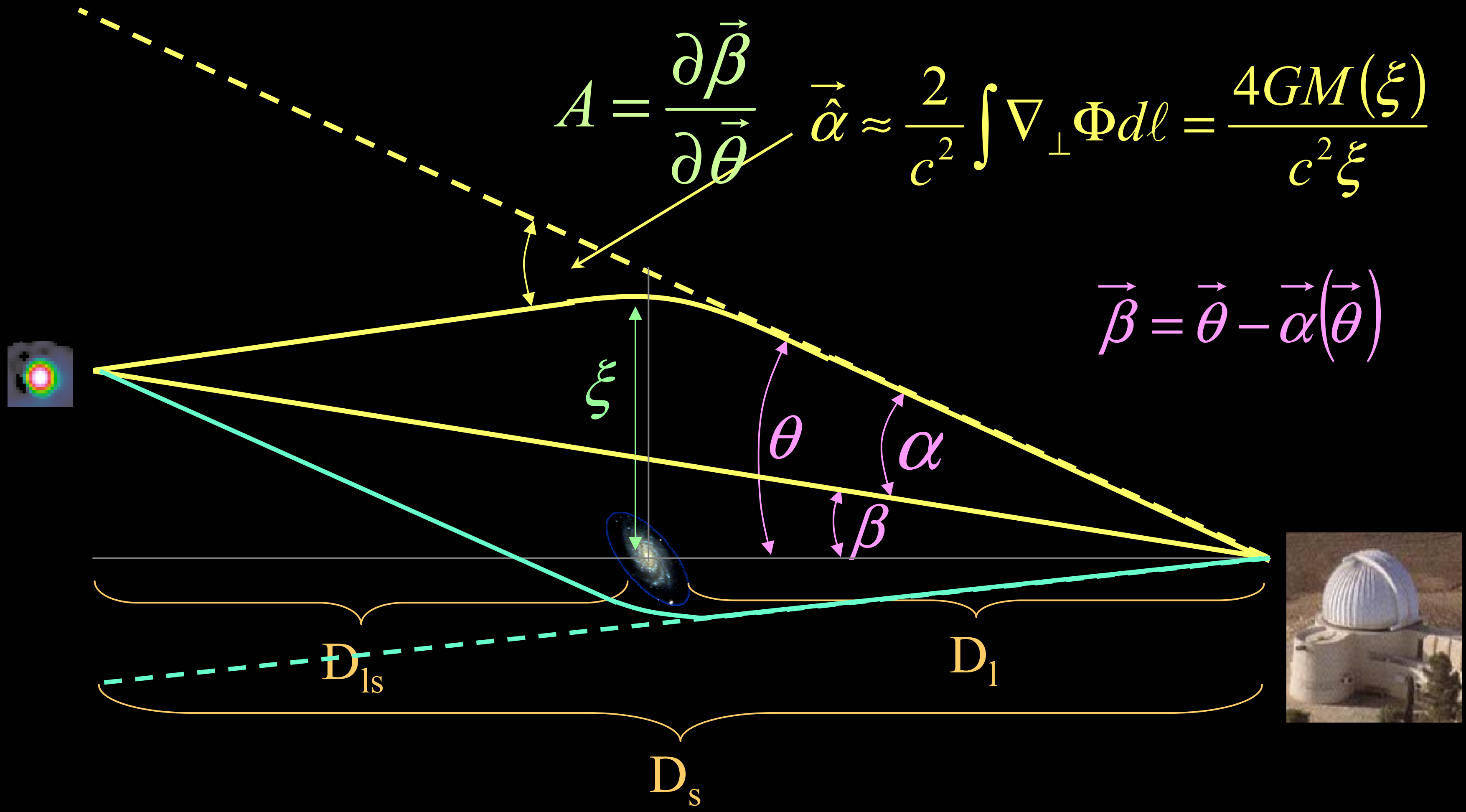
Gravitational Lensing





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