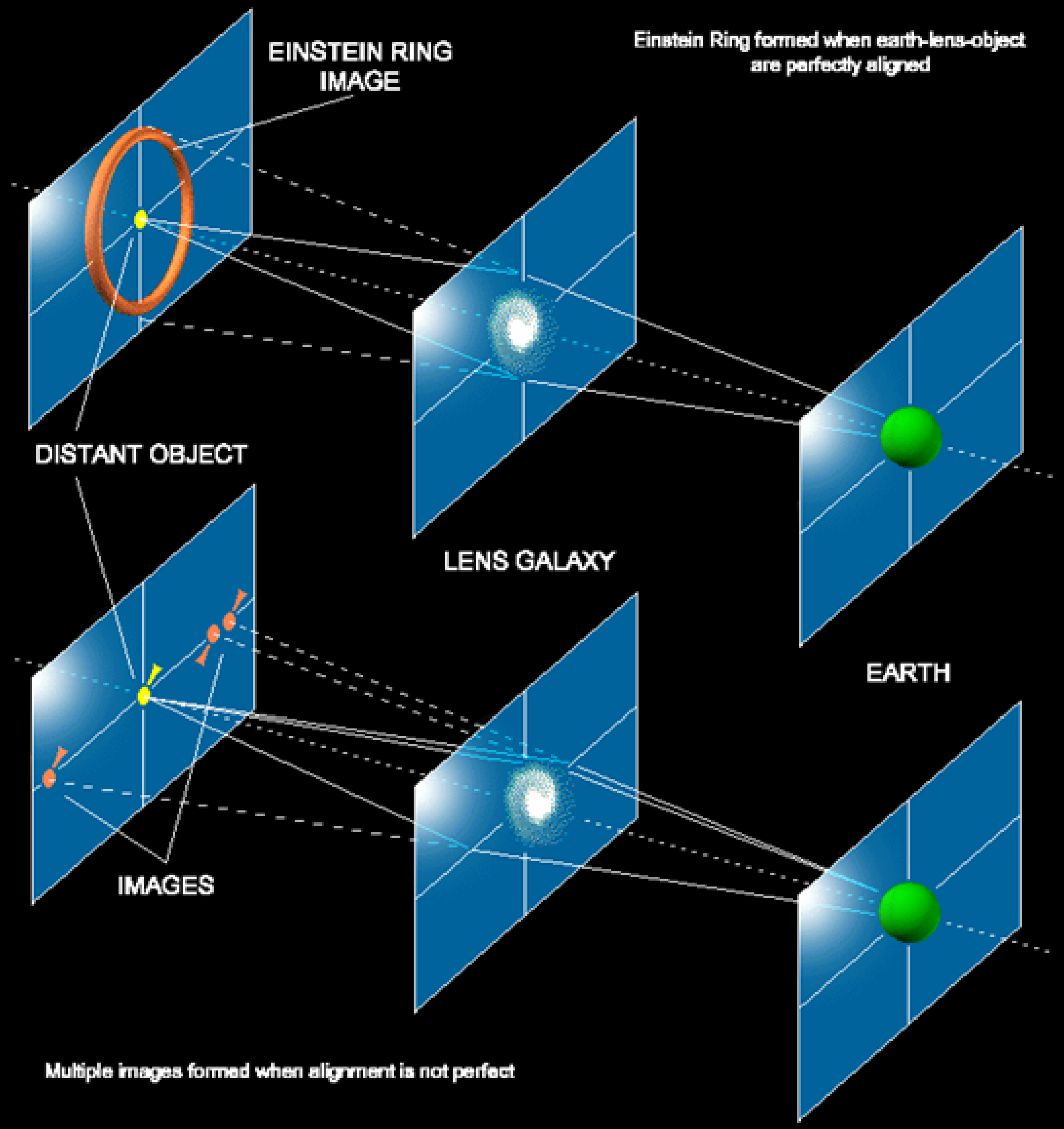
Gravitational Lensing with SDSS

1st KIAS International Workshop on Cosmology and Structure Formation
October 29, 2004

Myeong-Gu Park

Kyungpook National University

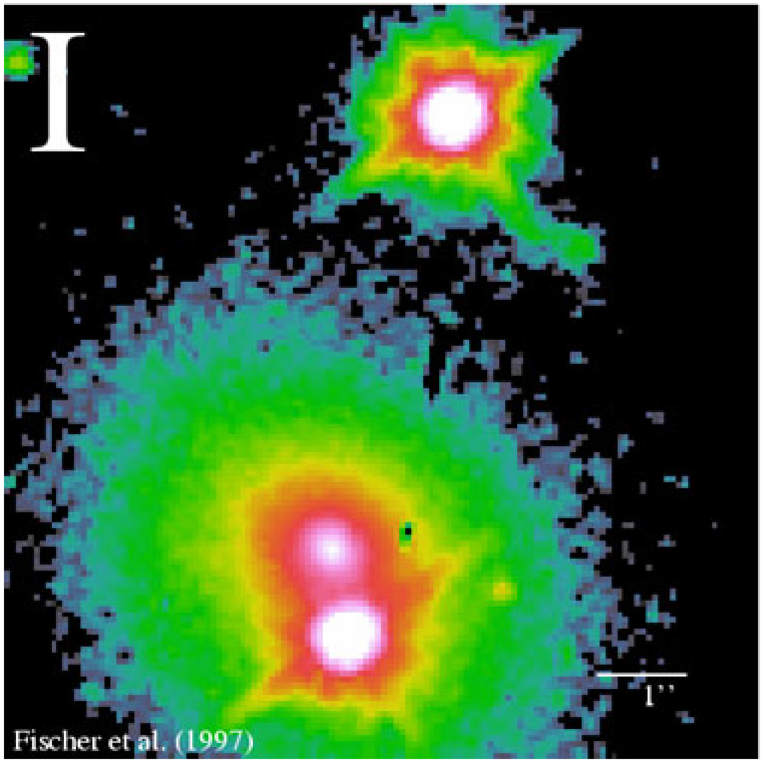

EINSTEIN RING IMAGE
Einstein Ring formed when earth-lens-object are perfectly aligned
DISTANT OBJECT
LENS GALAXY
EARTH
IMAGES
Multiple images formed when alignment is not perfect

Lensing Galaxy

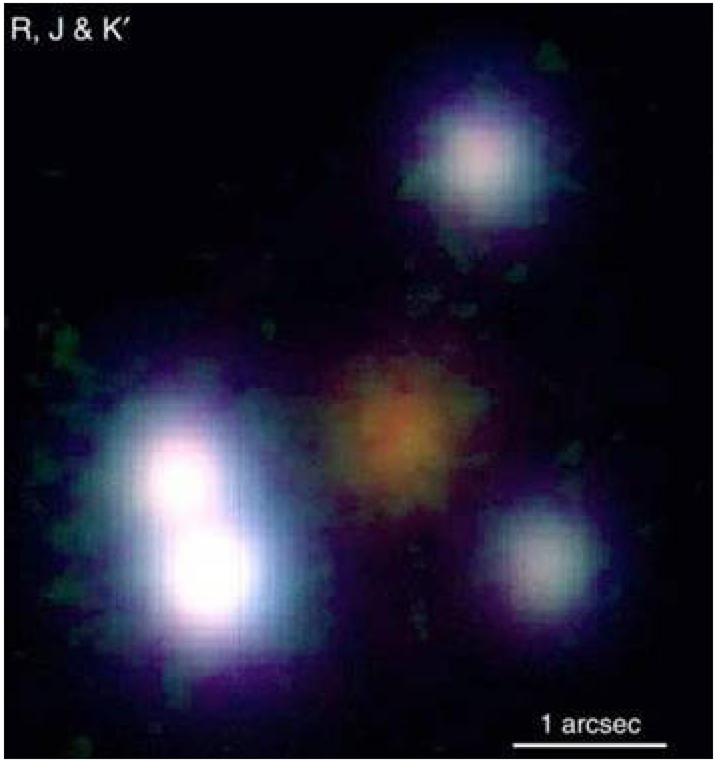
I. Gravitational Lensing & SDSS

- Strong lensing
  - Quasar-galaxy/cluster lensing
  - SDSS quasar sample
    - $\sim 10^{-3}$ lensing probability
    - 100 lens systems expected from spectroscopic sample of 10^5 SDSS quasars
    - 1000 lens systems plausible from 10^6 quasars expected in 10^4 deg^2
    - Well-defined sample
- Weak lensing

- Example



Q0957+561

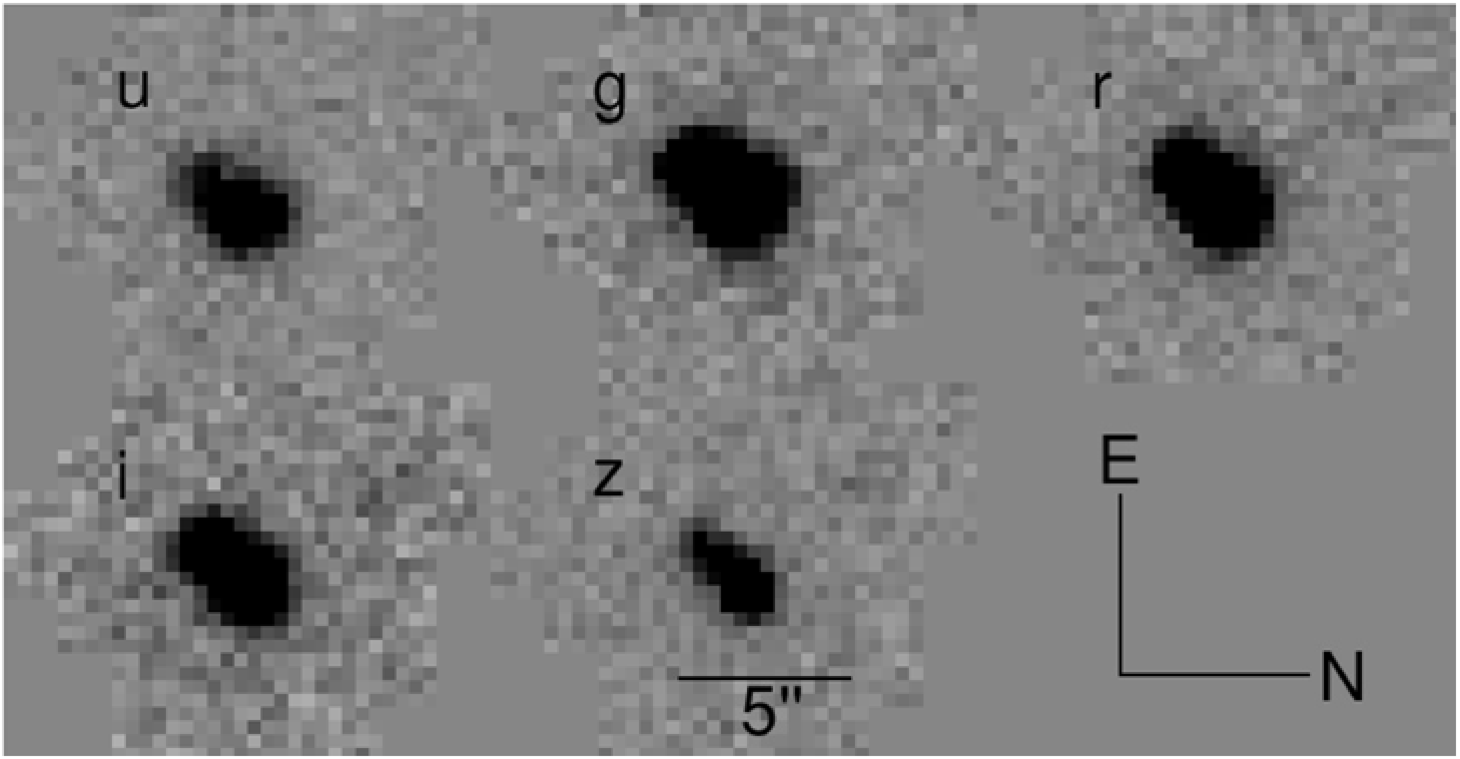


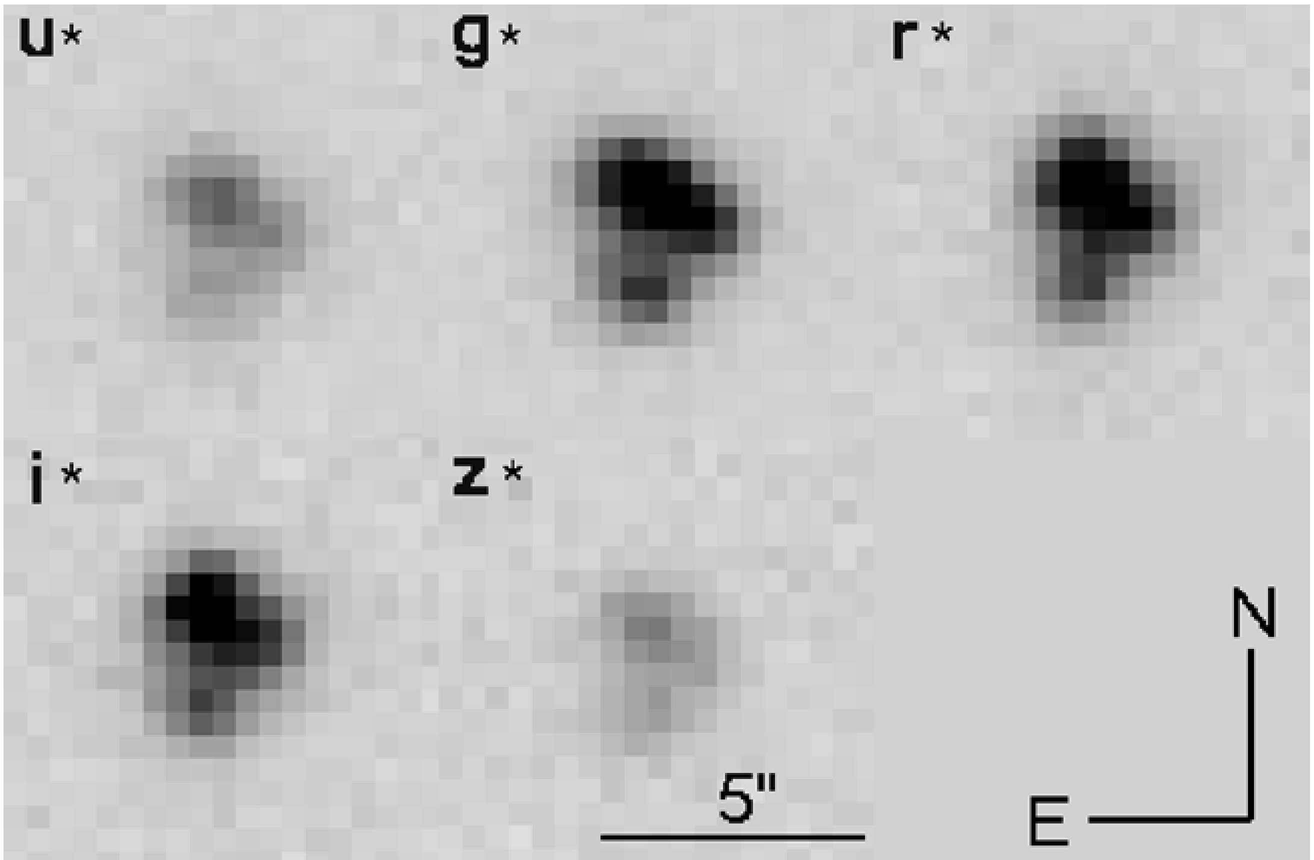
PG1115+080

II. How to find new lens?

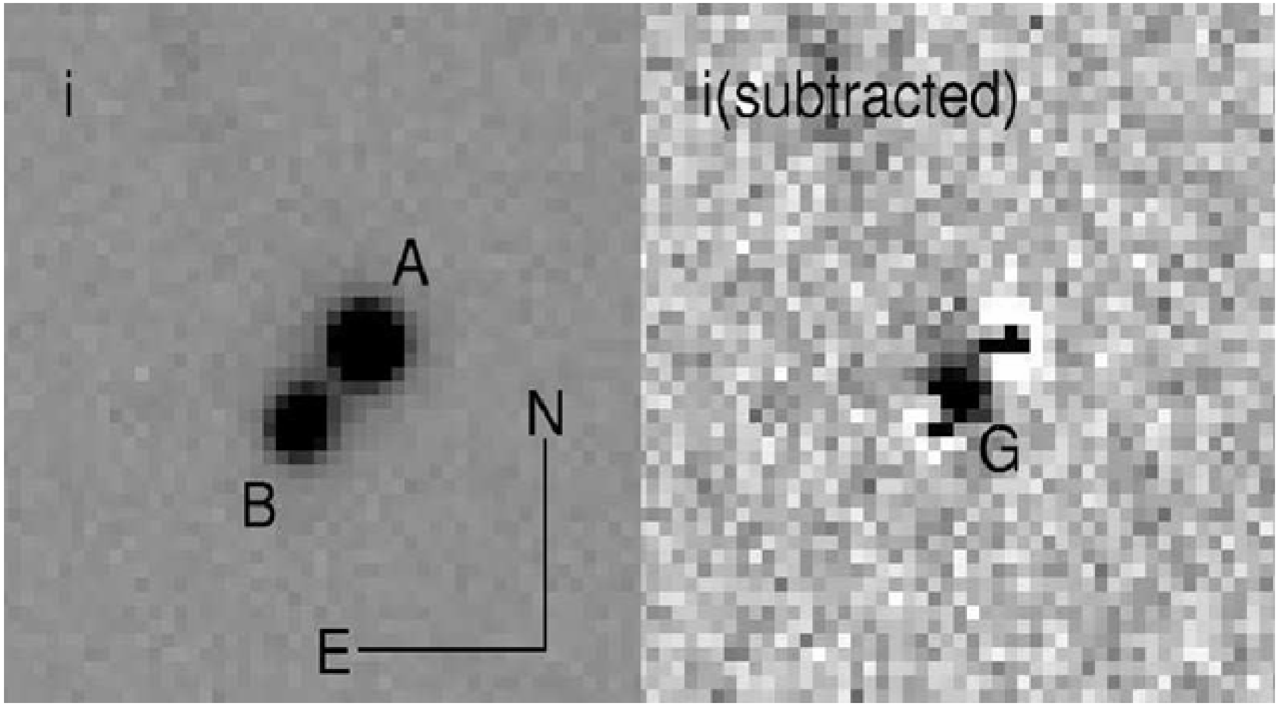
- Algorithm to select lens candidates from quasars
  - Pindor et al.; Inada, Oguri et al.
  - Typical FWHM for SDSS imaging data ≈ 1.”4
  - Small splitting pairs blended
  - Algorithm to identify unresolved pairs
  - Effective for 1.”0–2.”5 separation

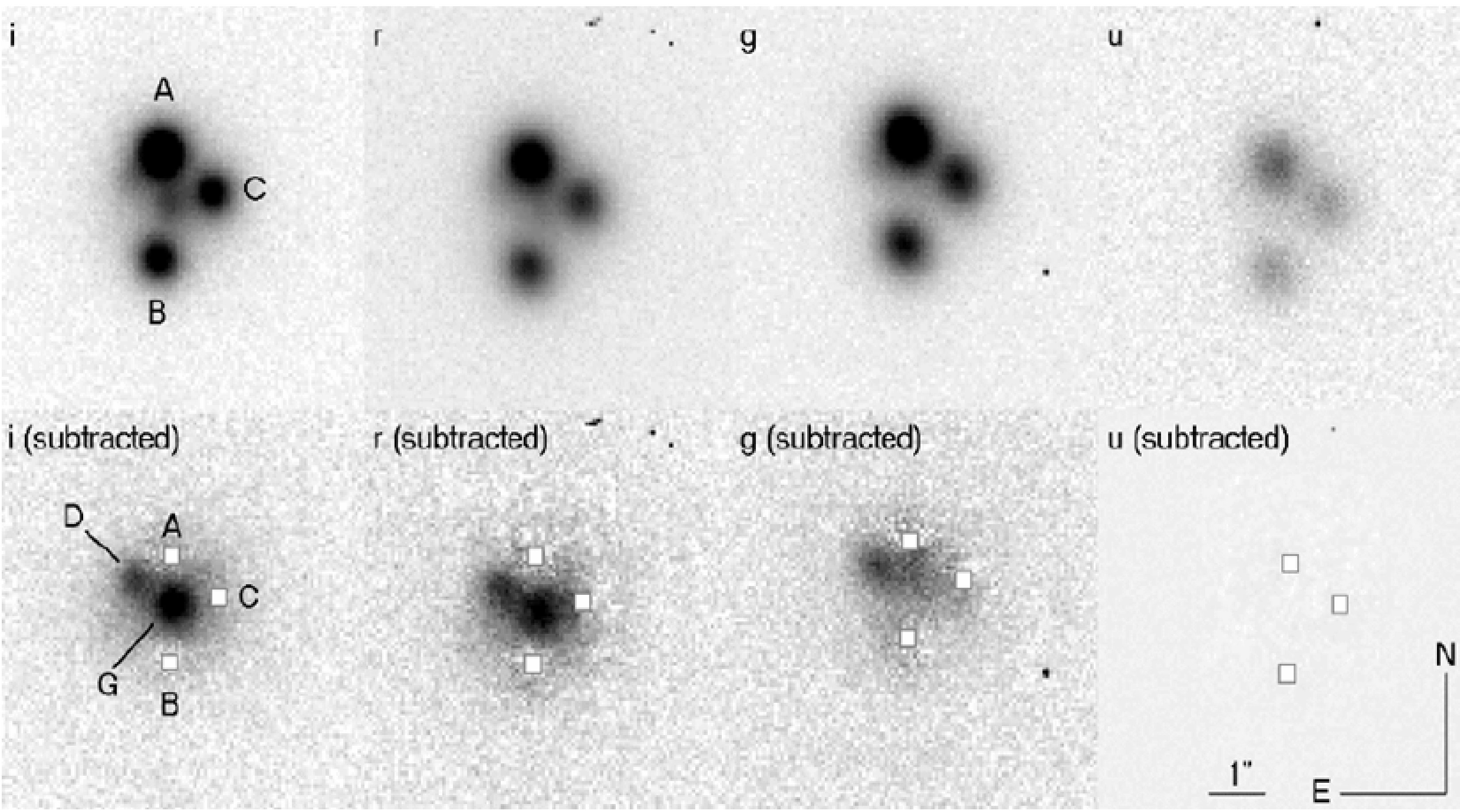
- SDSS image




u*
g*
r*
i*
z*
5"
N
E

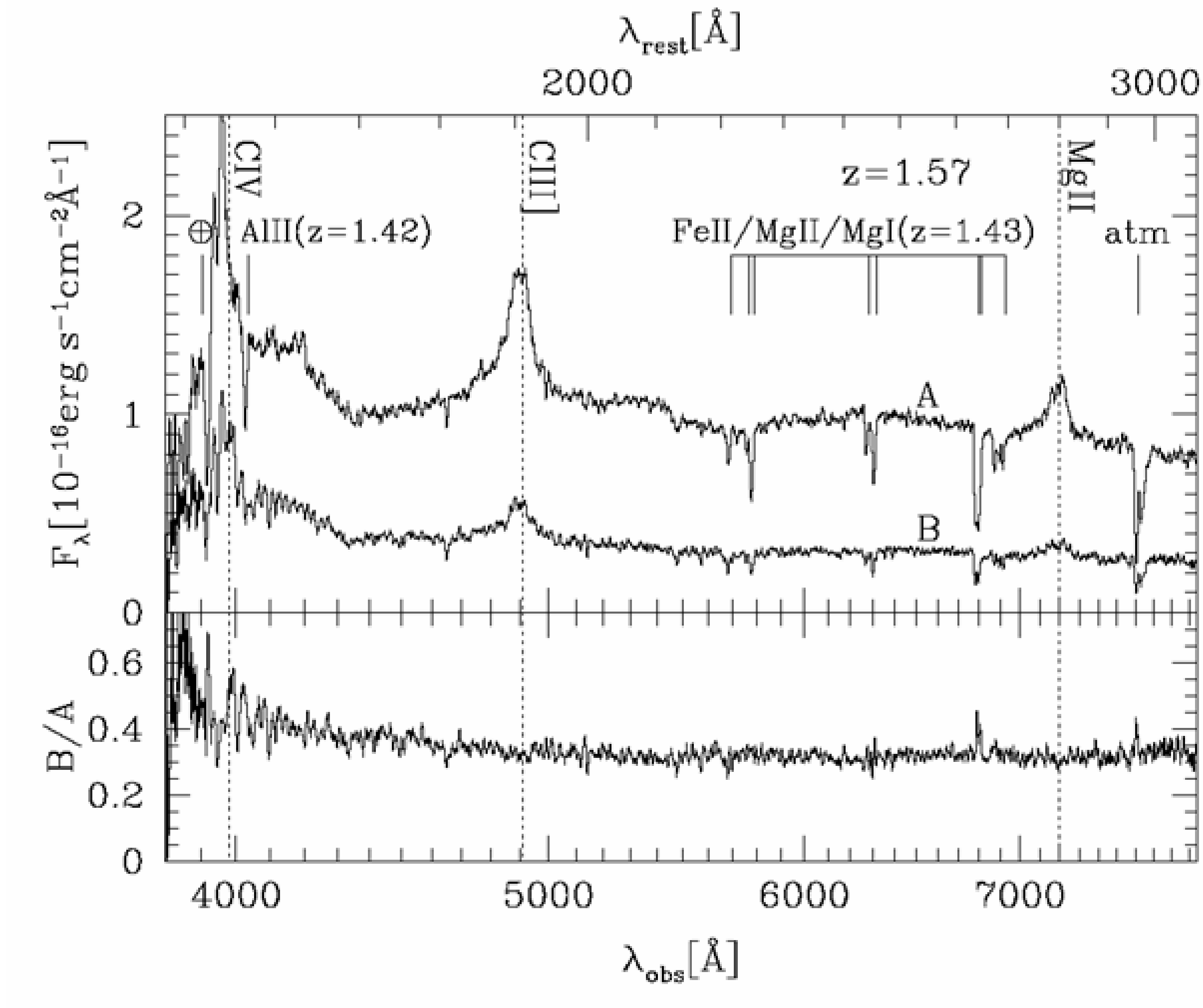
- Follow-up imaging





i
A
C
B
r
g
u
i (subtracted)
D
A
C
G
B
r (subtracted)
g (subtracted)
u (subtracted)
N
1"
E

Spectroscopic confirmation

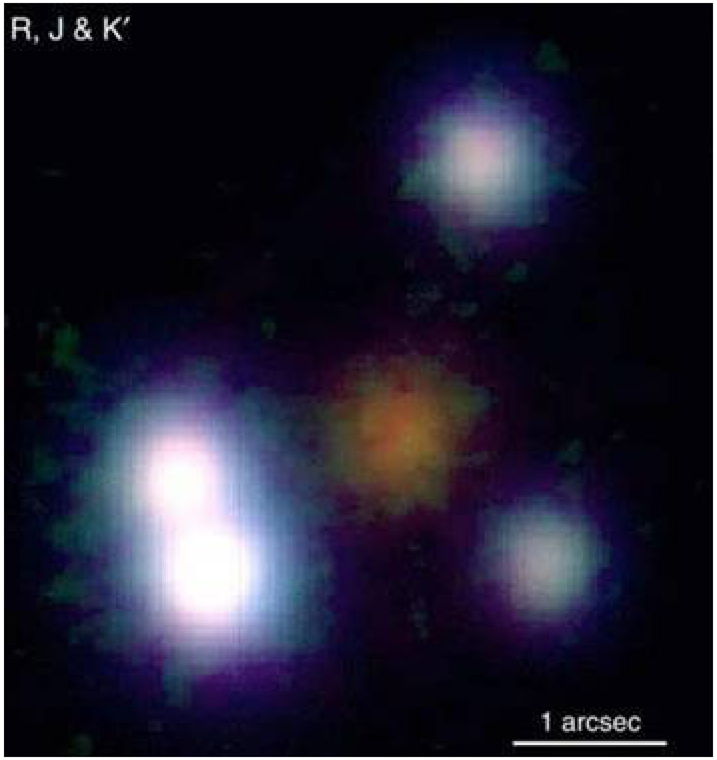


III. Current Lensed Quasars

- CASTLES (CfA-Arizona Space Telescope Lens Survey)
  - Class A: 63 cases
  - Class B: 10 cases
  - Class C: 8 cases
  - SDSS: 4 A, 1 B cases
  - Binary Quasars
    - Class A: 5
    - Class B: 13

IV. Information

- Total number of lens systems
- Number of Images
- Redshift
  - Source
  - Lens
- Position
  - Images
  - Lens
- Brightness Ratios
- Time Delay



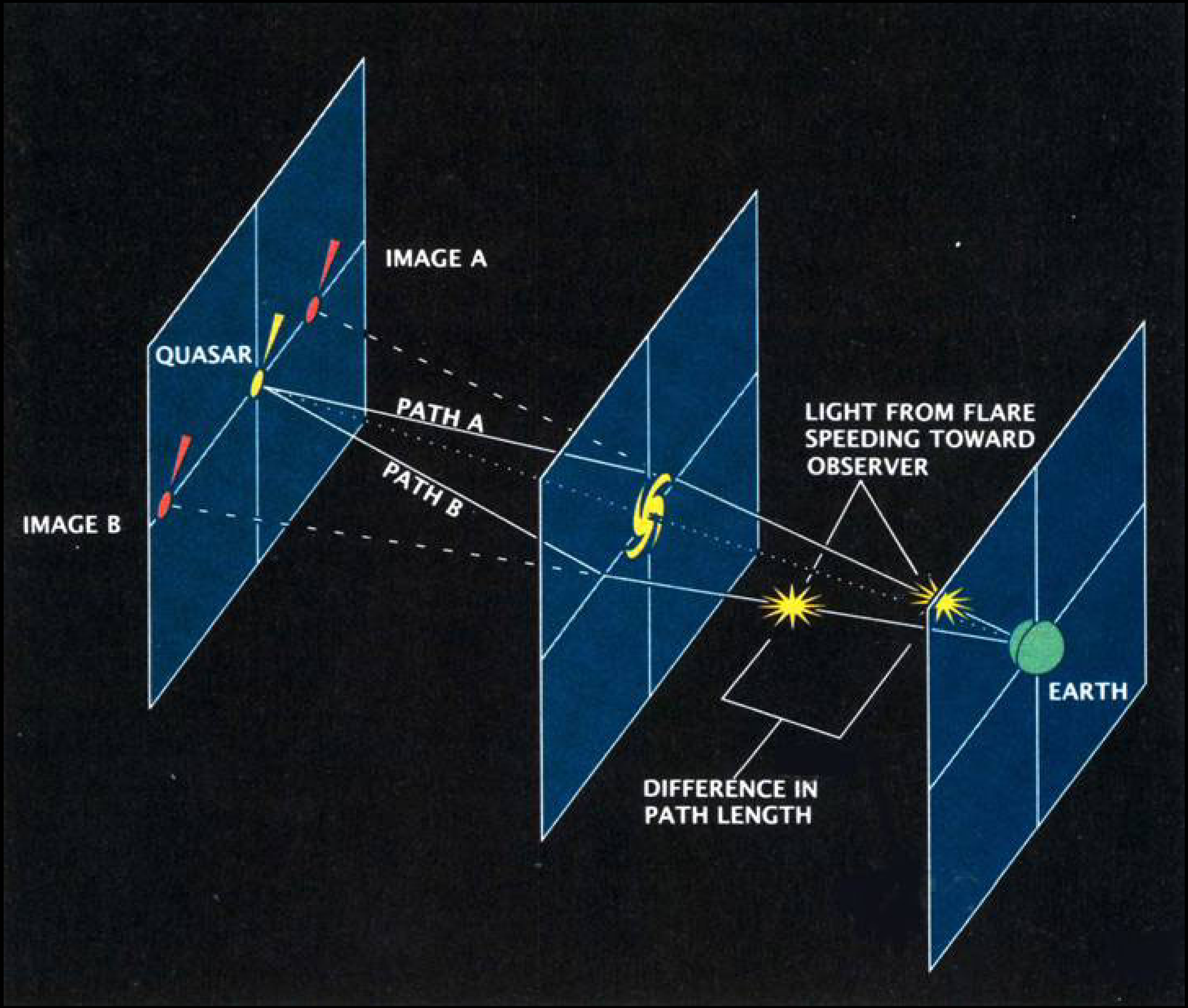


IMAGE A
QUASAR
PATH A
PATH B
IMAGE B
LIGHT FROM FLARE SPEEDING TOWARD OBSERVER
EARTH
DIFFERENCE IN PATH LENGTH

V. H_0

- Time delay between images
  - Direct determination of H_0 (Refsdal 1964)
  - Time delay =

    h^{-1} × 1 month

    × image separation in arcsec

    × $(1+z_{lens})$

    × weak dependence on z_{lens}, z_{QSO}, and cosmology

    × lens mass distribution–dependent factor

Observational Data for Time Delay Lenses

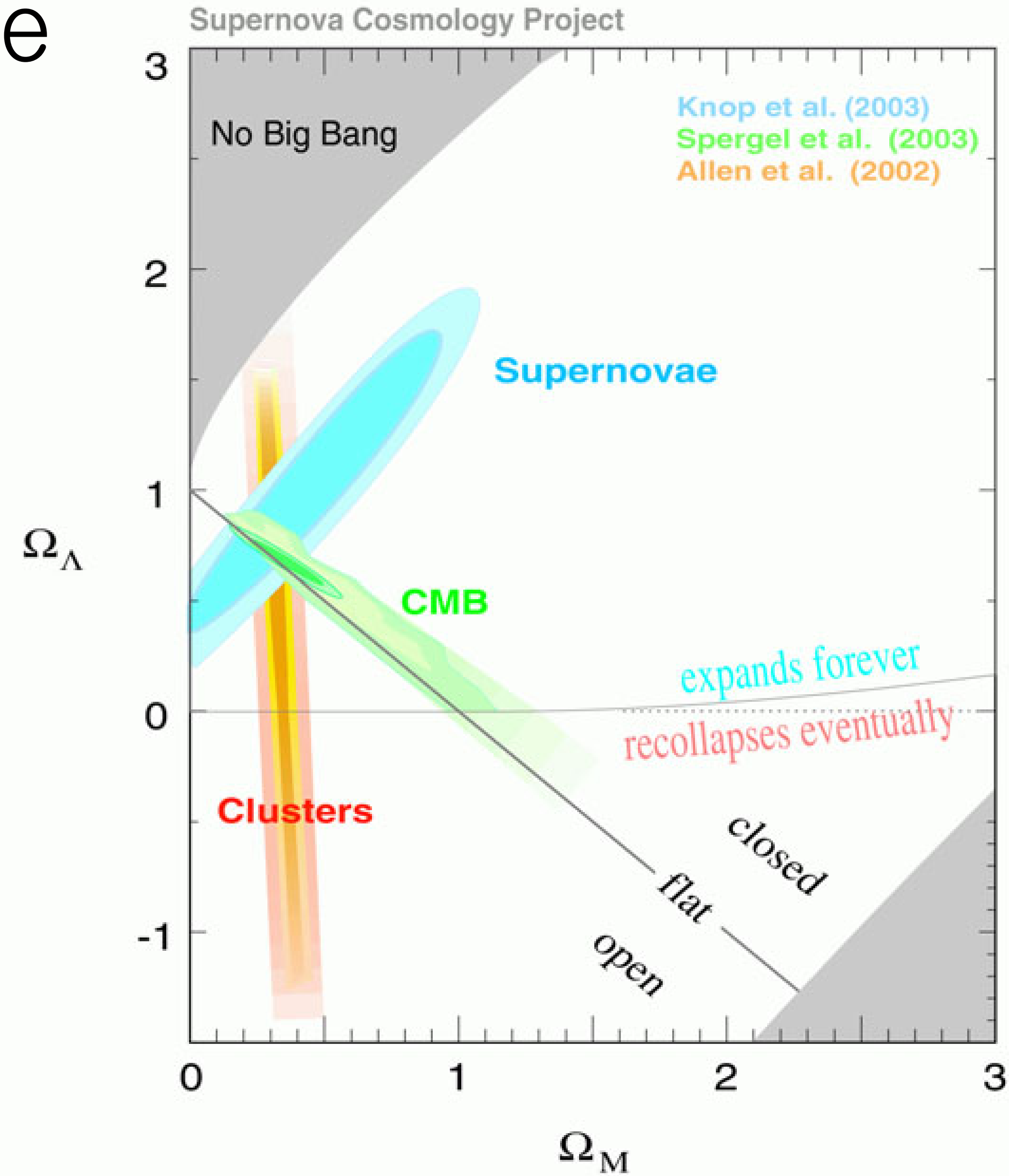
Lens/Components	z_d	z_s	$\Delta t_{i,j}$ (days)	r_j (arcsec)	r_i (arcsec)	$\lvert\theta_i - \theta_j\rvert$ (deg)	References
B0218+357/B−A	0.96	0.68	10.5 ± 0.2	0.24 ± 0.06	0.10 ± 0.06	176.4	3, 8, 10
Q0957+561/B−A	1.41	0.36	417 ± 3	5.2275 ± 0.0035	1.0340 ± 0.0035	154.2	2, 7
PG 1115+080/A−B	1.72	0.31	11.7 ± 1.2	1.147 ± 0.025	0.950 ± 0.004	115.5	1, 5
PG 1115+080/C−B	1.72	0.31	25.0 ± 1.6	1.397 ± 0.004	0.950 ± 0.004	114.6	1, 5
PG 1115+080/C−A	1.72	0.31	13.3 ± 1.0	1.397 ± 0.004	1.147 ± 0.025	130.1	1, 5
B1600+434/B−A	1.59	0.42	47 ± 6	1.14 ± 0.05	0.25 ± 0.05	179.4	4, 6
PKS 1830−211/B−A......	2.51	0.89	26 ± 5	0.67 ± 0.08	0.32 ± 0.08	160.5	8, 9

Note.—Observational data for five of the six time delay lenses. The remaining time delay system, B1608+656, is excluded because the presence of two lens galaxies clearly rules out the simple potential assumed in the text (Koopmans & Fassnacht 1999). For B0218+357, the position error bars include the systematic uncertainty in the lens galaxy position (see Lehár et al. 1999). For PG 1115+080, the time delay has been measured between B and the combined $A_1 + A_2$ components; the quoted position uncertainty includes the difference between A_1 and A_2. We do not give measurement uncertainties on the angle $\lvert\theta_i - \theta_j\rvert$ because they do not enter our calculations.

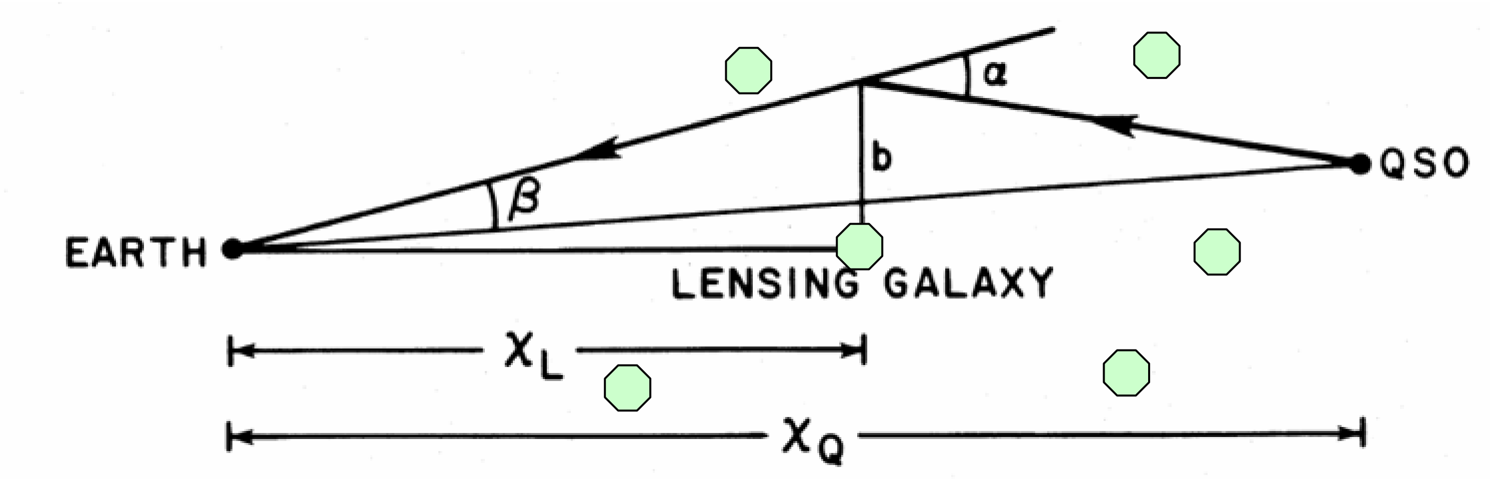
References.—(1) Barkana 1997; (2) Barkana et al. 1999; (3) Biggs et al. 1999; (4) Hjorth et al. 2000; (5) Impey et al. 1998; (6) Koopmans et al. 1998; (7) Kundić et al. 1997; (8) Lehár et al. 1999; (9) Lovell et al. 1998; (10) Patnaik et al. 1995.

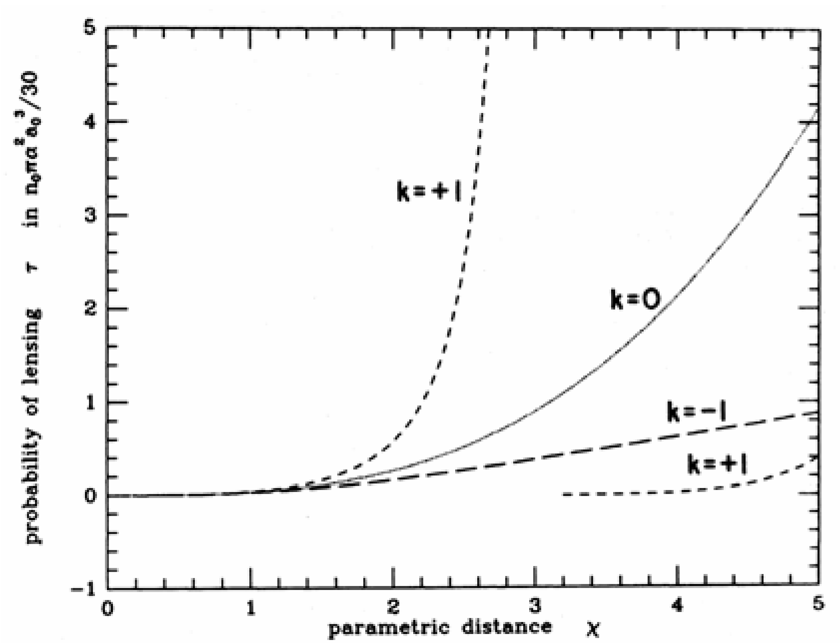
- H_0
  - Q0957+561: 64±13 km/s/Mpc
  - Others: 50 ~ 70 km/s/Mpc
- Limitations
  - Need to know the lens gravitational potential
    - Mapping lens mass distribution
    - Host galaxy images

VI. Curvature

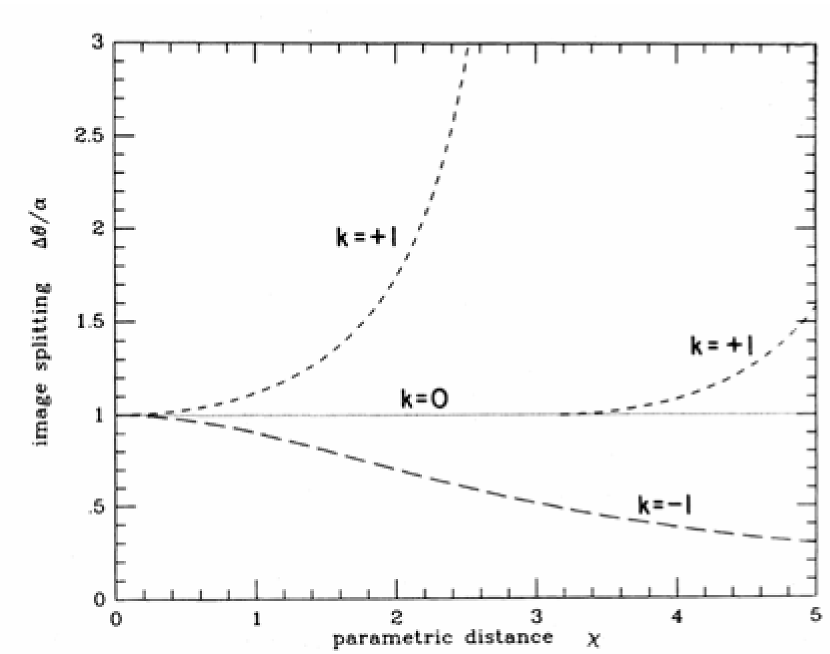


- Curvature and the lensing
  - Turner, Ostriker & Gott (1984)
  - Gott, Park & Lee (1989)
    - Image separation
    - Lensing probability

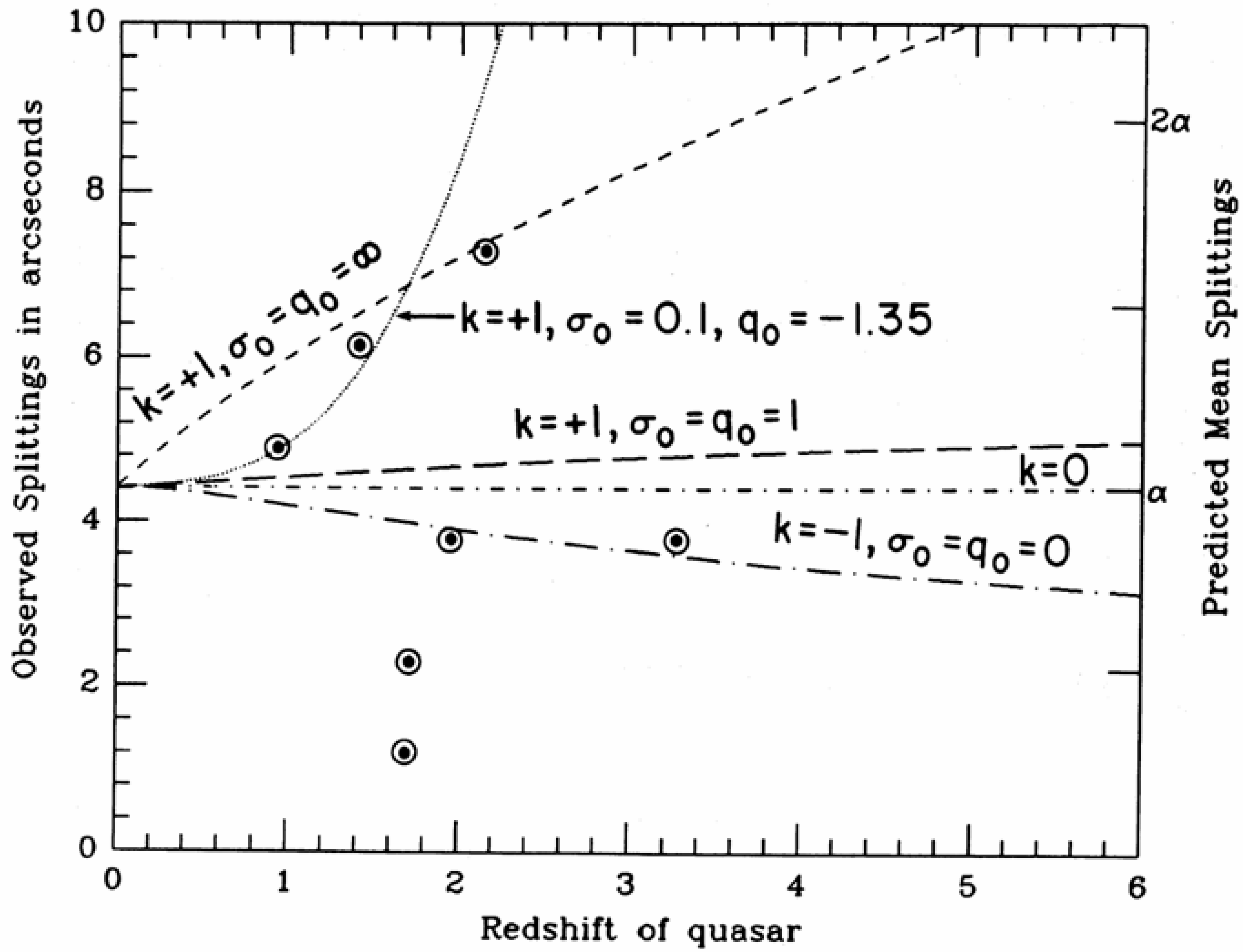




Lensing probability

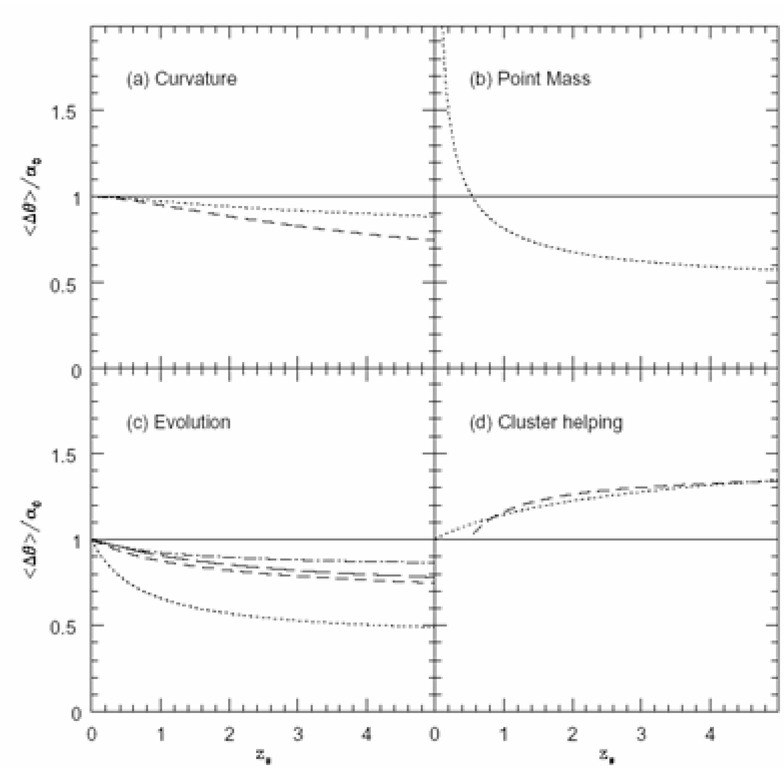


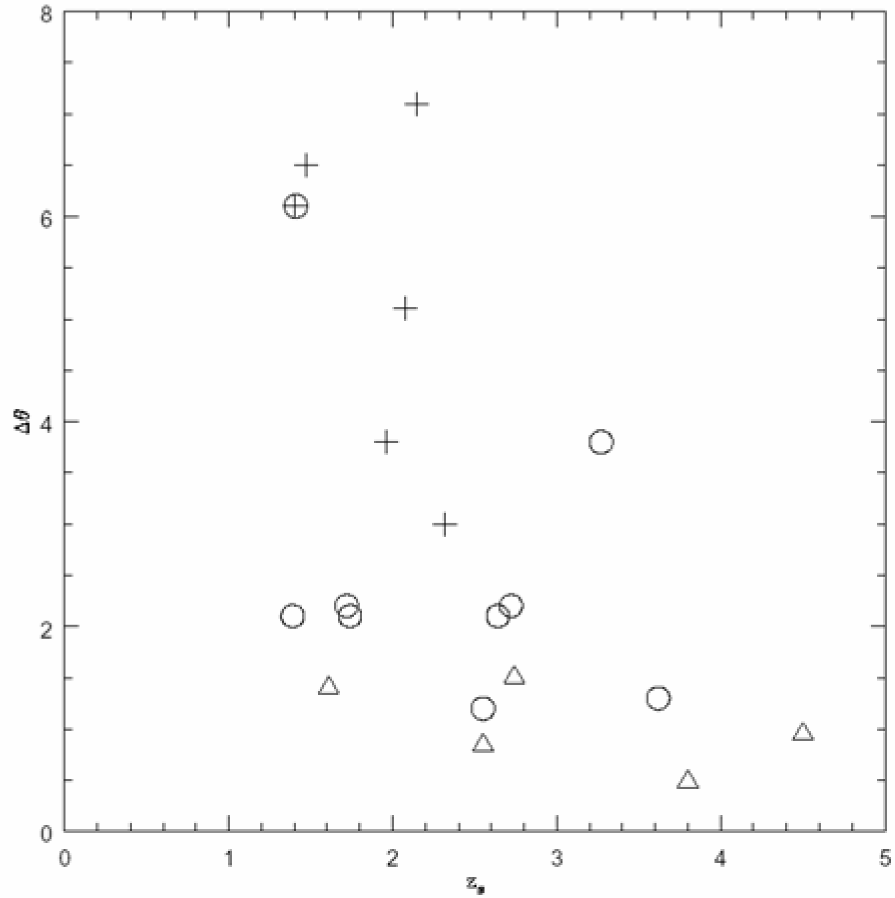
Mean image separation

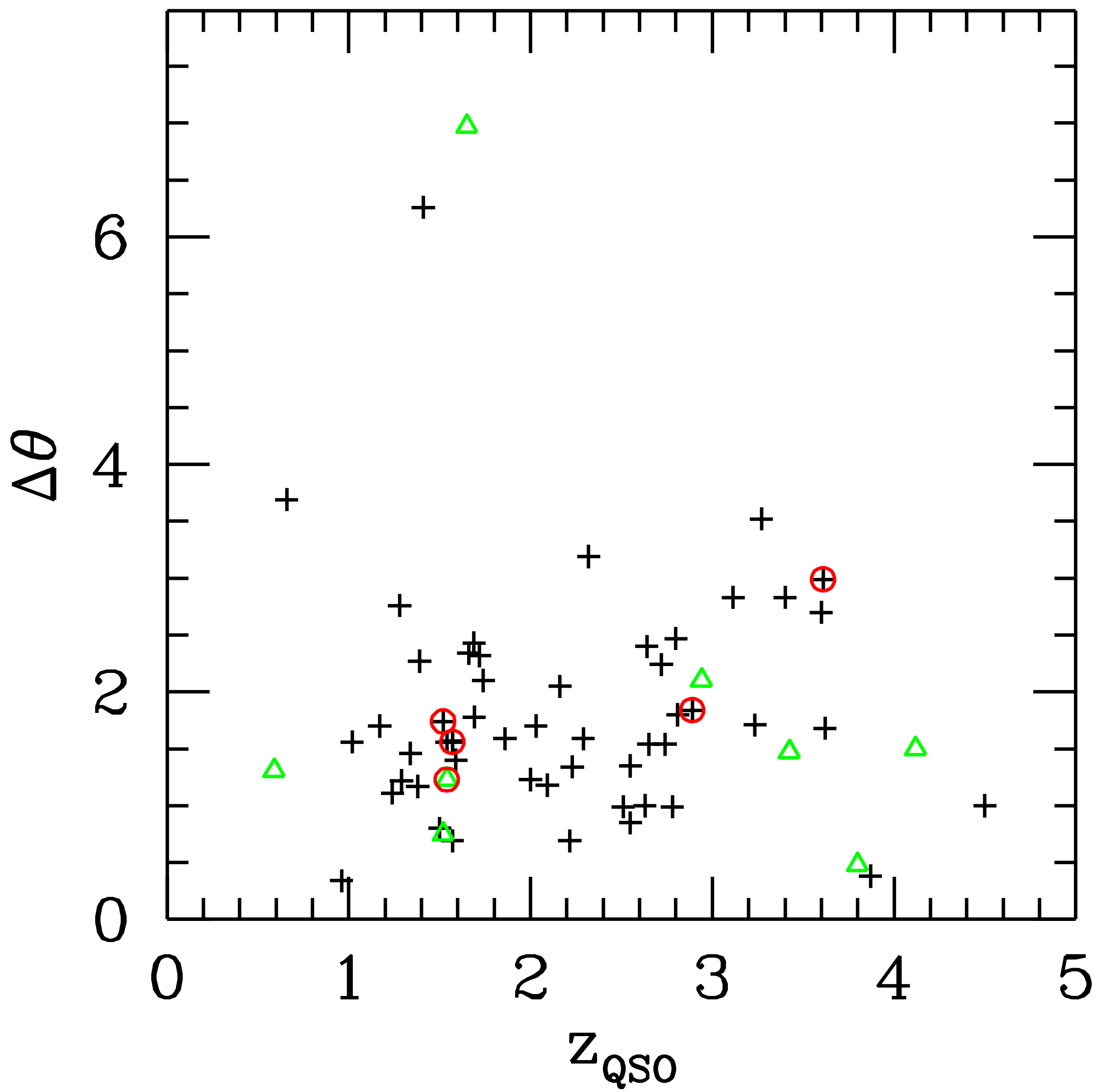


10
8
6
4
2
0
0
1
2
3
4
5
6
Redshift of quasar
Observed Splittings in arcseconds
Predicted Mean Splittings
2α
α
k=+1, σ0=q0=∞
k=+1, σ0 = 0.1, q0 = −1.35
k=+1, σ0=q0=1
k=0
k=−1, σ0=q0=0

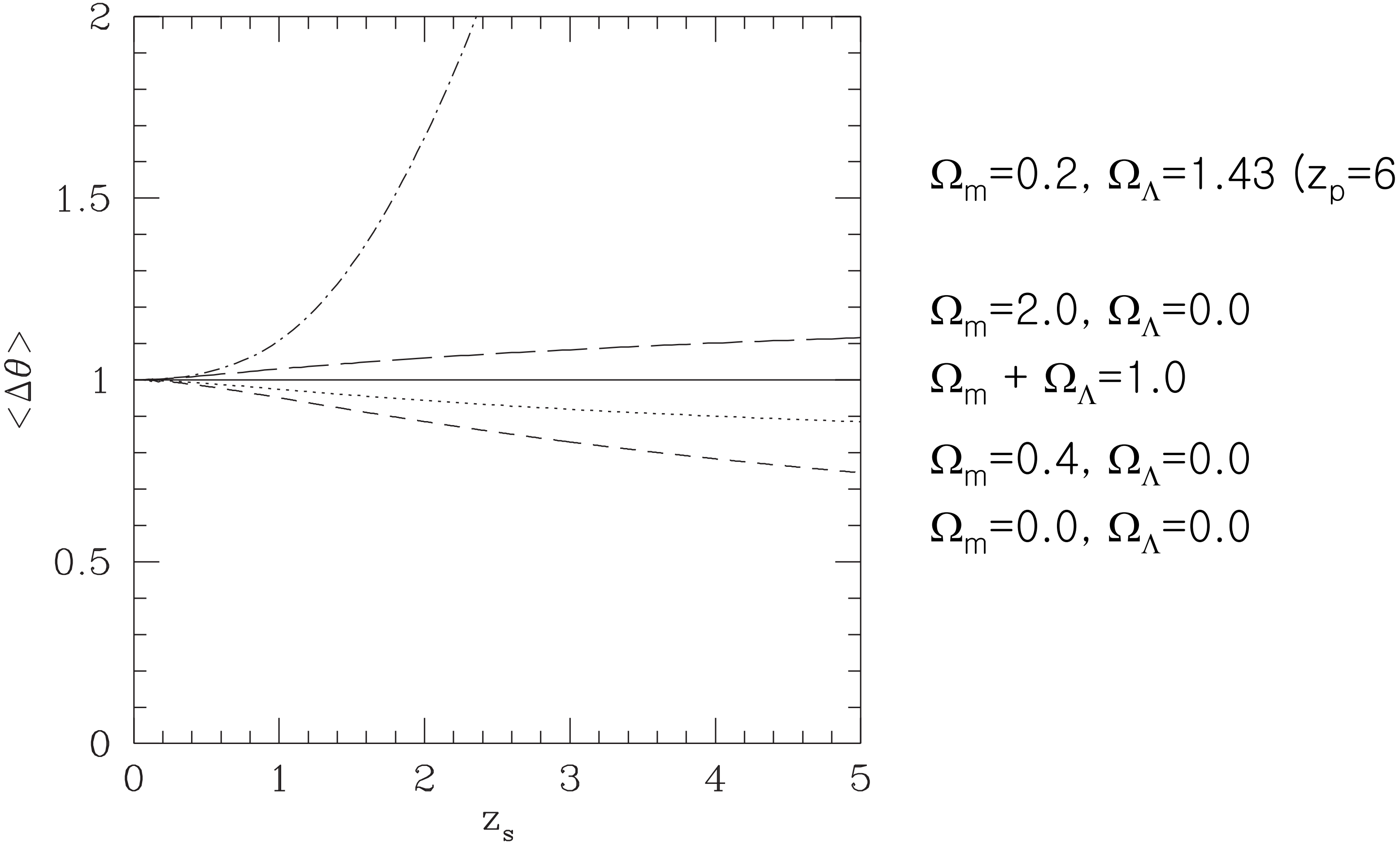
- Curvature Test
  - Park & Gott (1997)





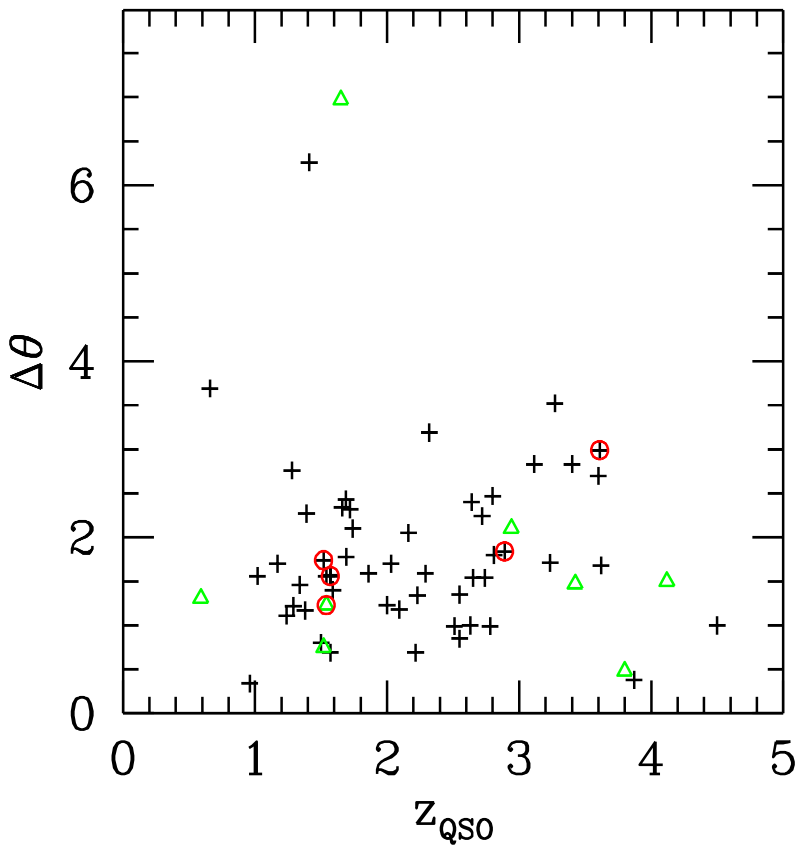


Δθ
0
2
4
6
0
1
2
3
4
5
z_{QSO}



2
1.5
1
0.5
0
0
1
2
3
4
5
z_s
$<\Delta\theta>$
Ω_m=0.2, Ω_Λ=1.43 (z_p=6)
Ω_m=2.0, Ω_Λ=0.0
Ω_m + Ω_Λ=1.0
Ω_m=0.4, Ω_Λ=0.0
Ω_m=0.0, Ω_Λ=0.0

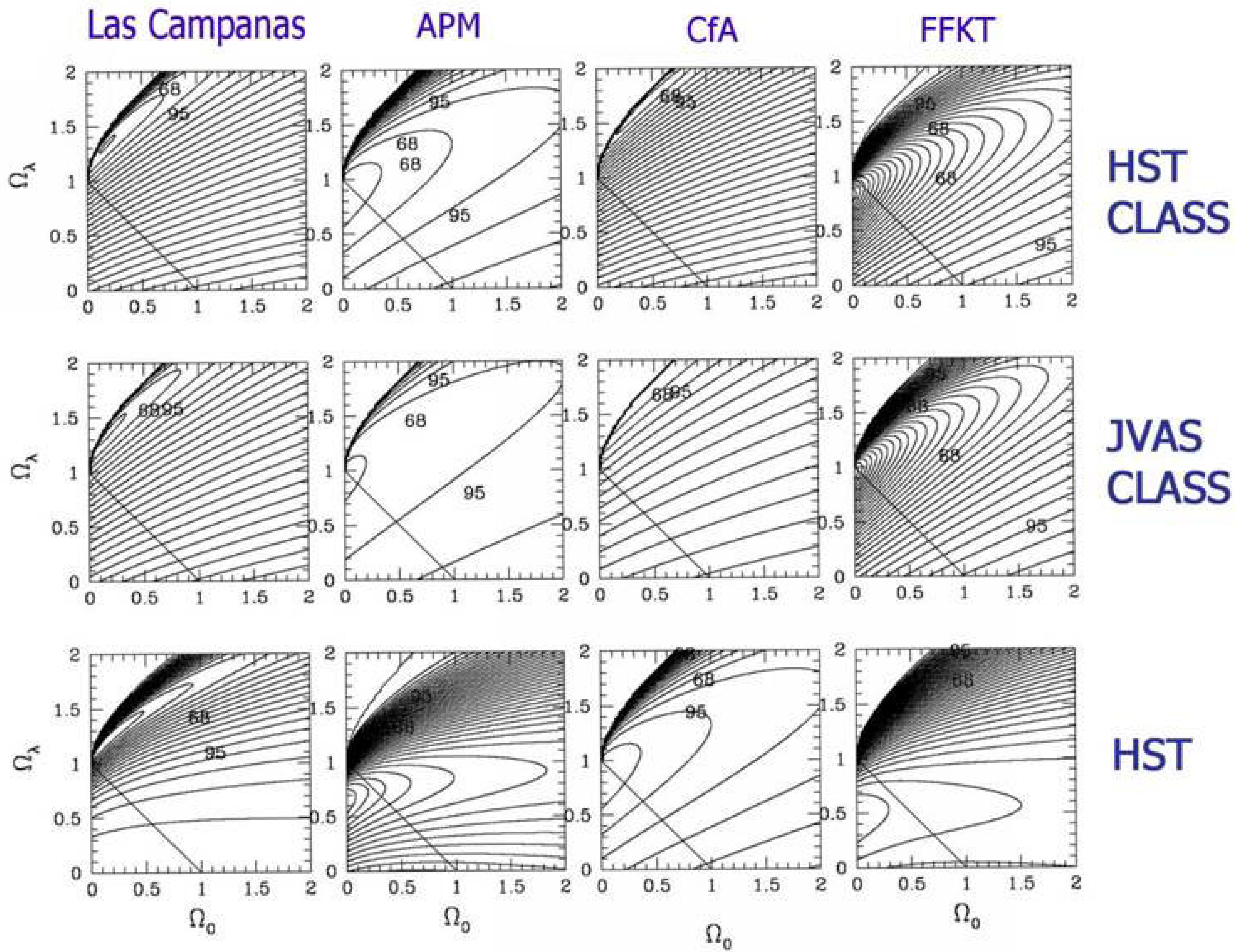
- Curvature Test (2004)
  - No difference between low z vs high z [K−S test]
  - Most of reasonable closed/flat/open models are not ruled out yet.
  - Cases needed to rule out at 95%CL
    - Ω_m=0.0, Ω_Λ=0 model: ~800 cases
    - Ω_m=0.4, Ω_Λ=0 model: >1000 cases



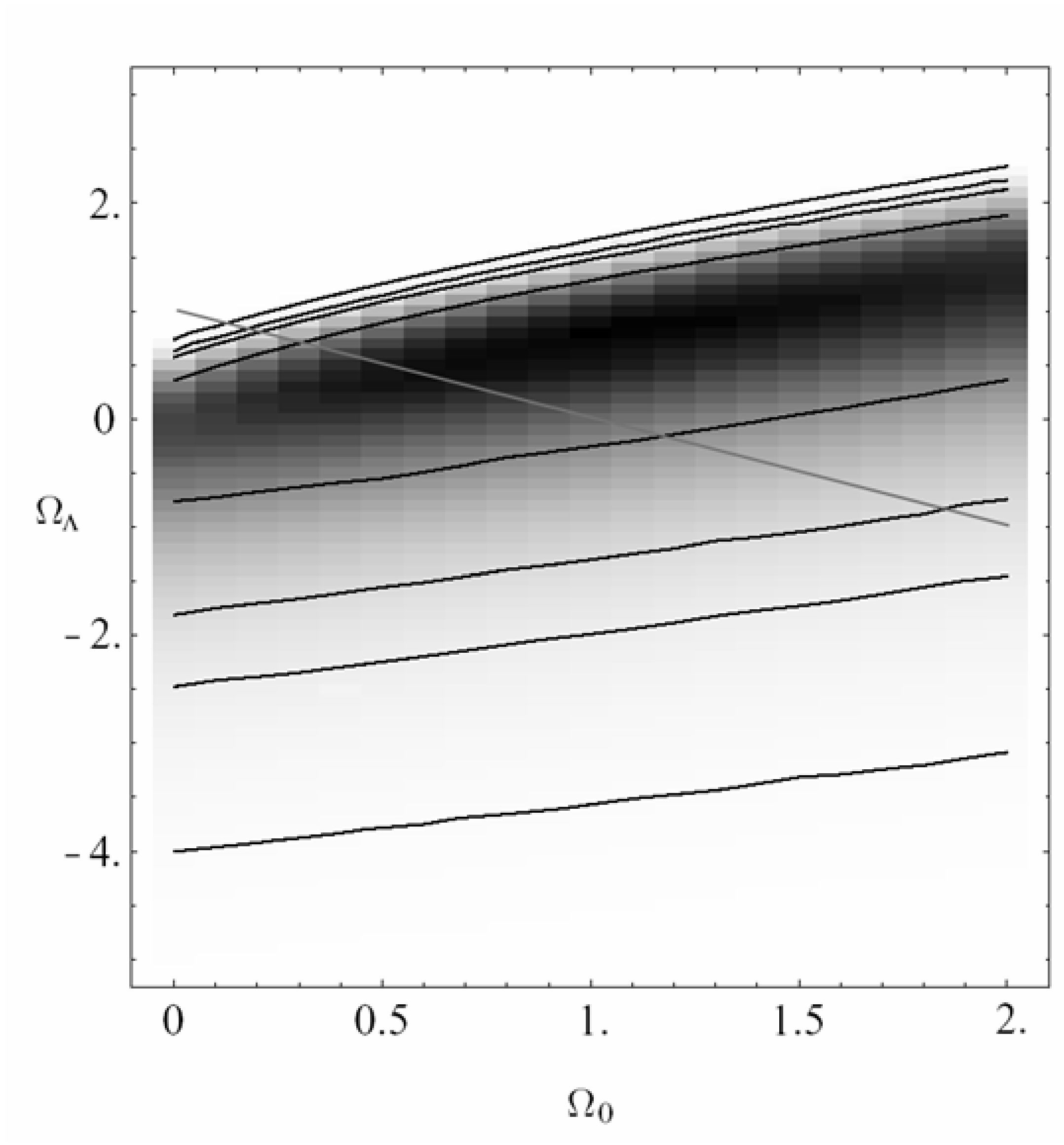
VII. Ω_0, Ω_Λ from lensing statistics

- Probability of Lensing Test
  - Fukugita & Turner (1991)
- Maximum Likelihood Test
  - Kochanek (1996): total number, redshifts, magnitudes, separations

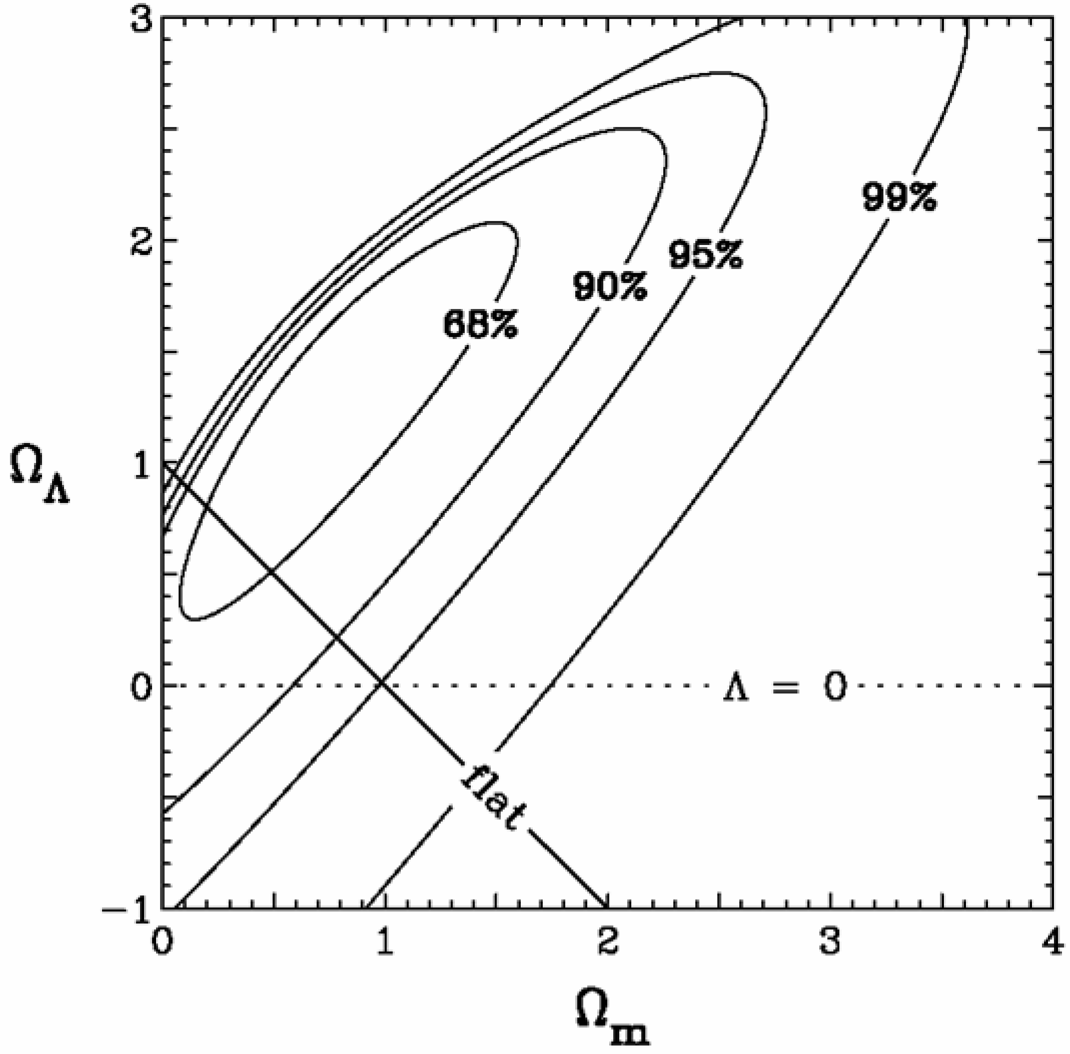
    $dP/dzd\Delta\theta \rightarrow$ $\Omega_\Lambda < 0.66$ (95% CL)
  - Lee & Park (1998): image separation only
    - Large Ω_Λ model favored
    - Depends on lens samples and galaxy parameters chosen



Lee & Park (1998)



JVAS: Helbig (1999)

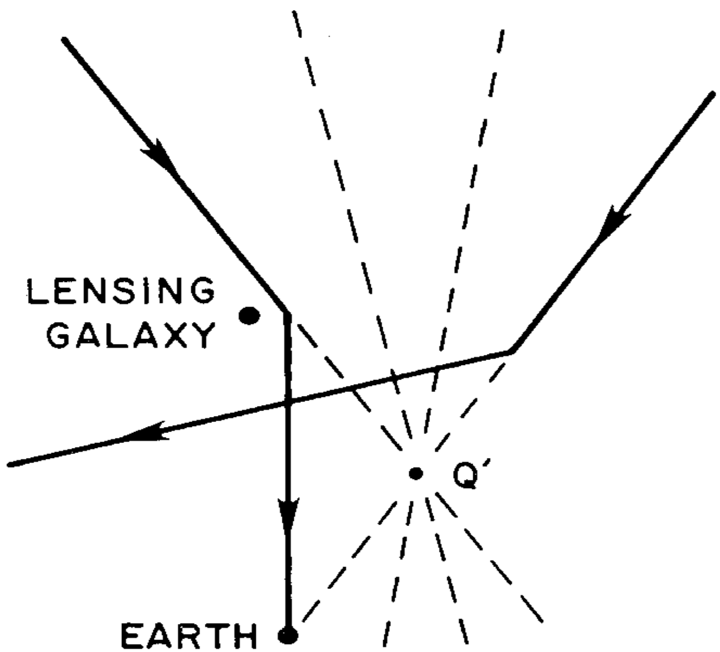


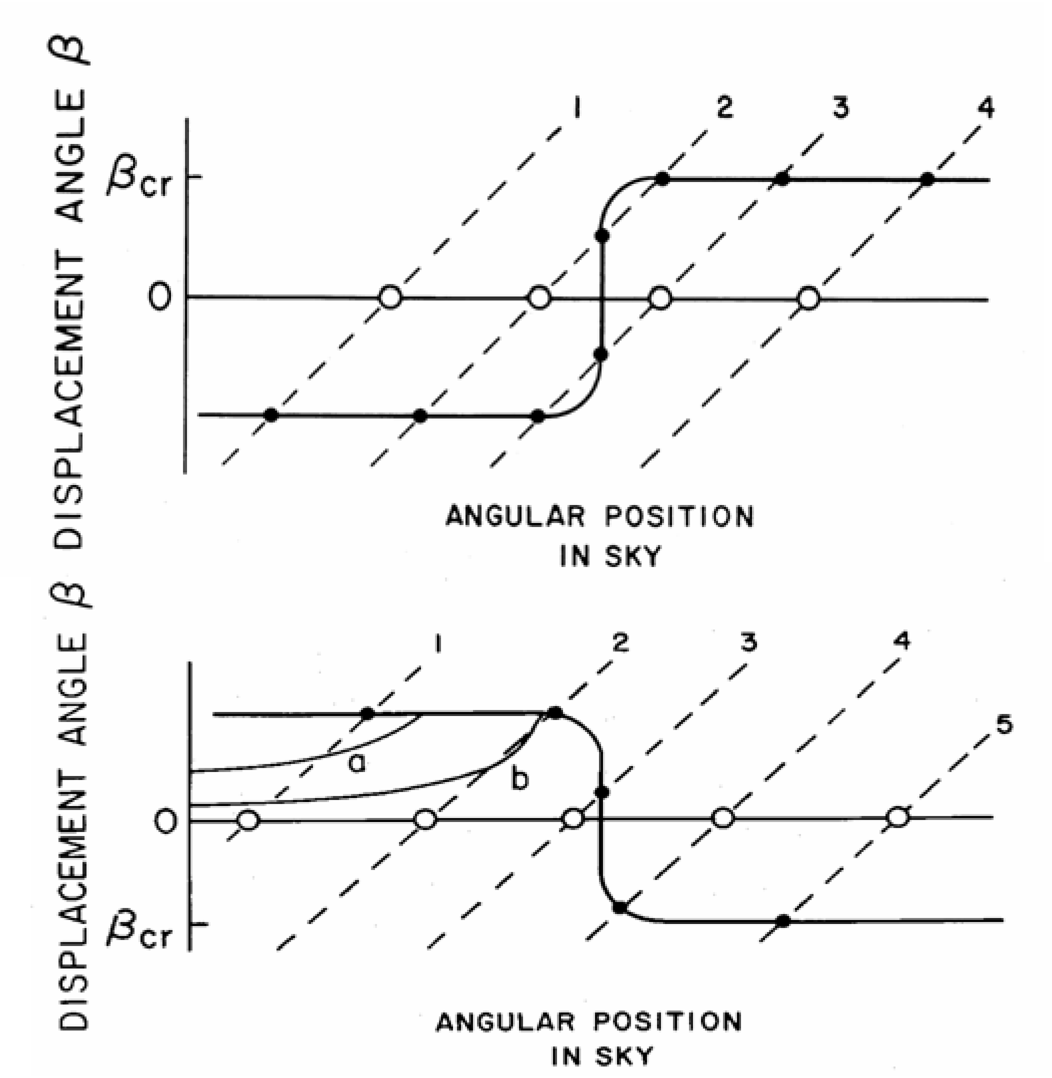
CLASS: Chae et al. (2002)

- Complications in lensing statistics
  - Potential of individual galaxy
  - Luminosity function of galaxies
  - Luminosity to mass conversion
  - Magnification bias
    - Faint sources get brightened and detected
    - Source distribution in luminosity and z needed

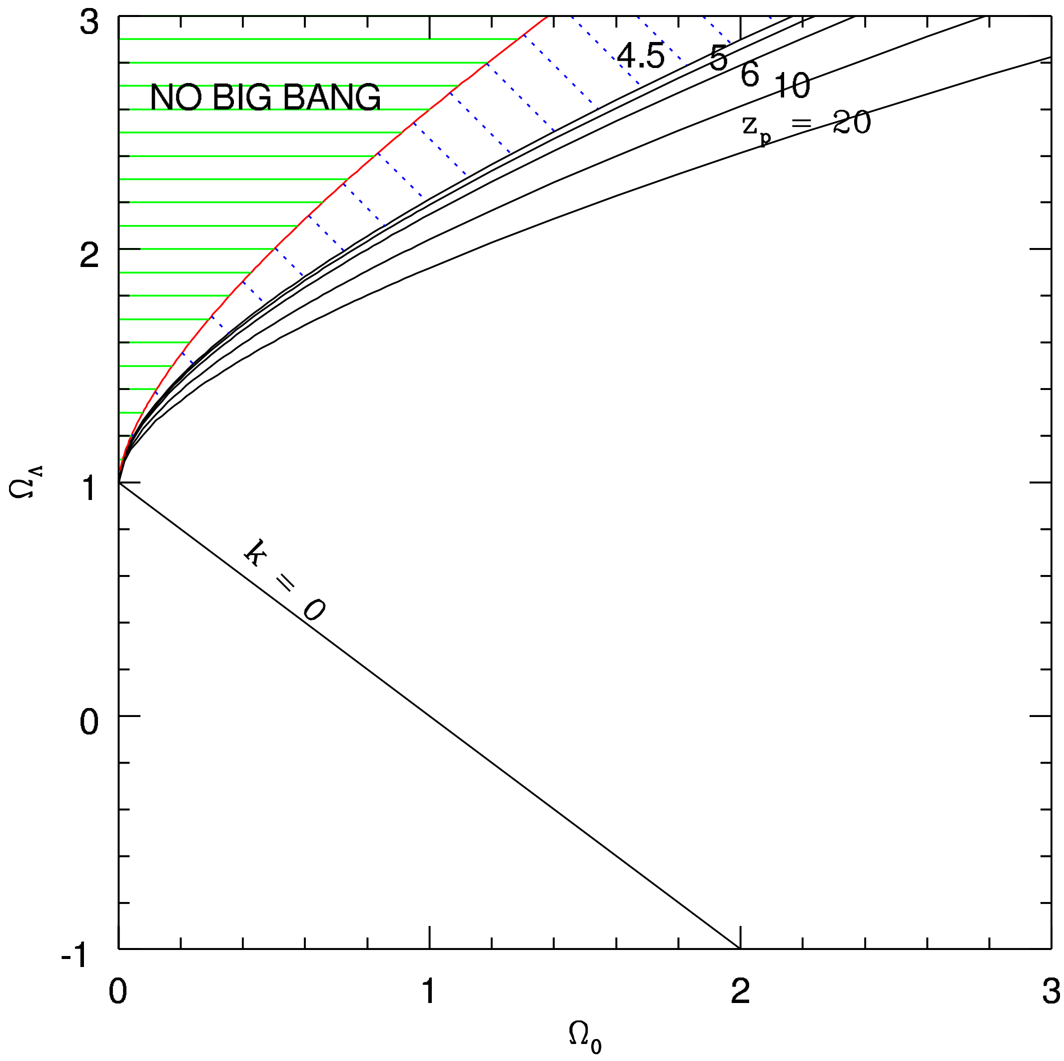
VIII. Over-focusing

- Over-focusing of quasar beyond the antipode

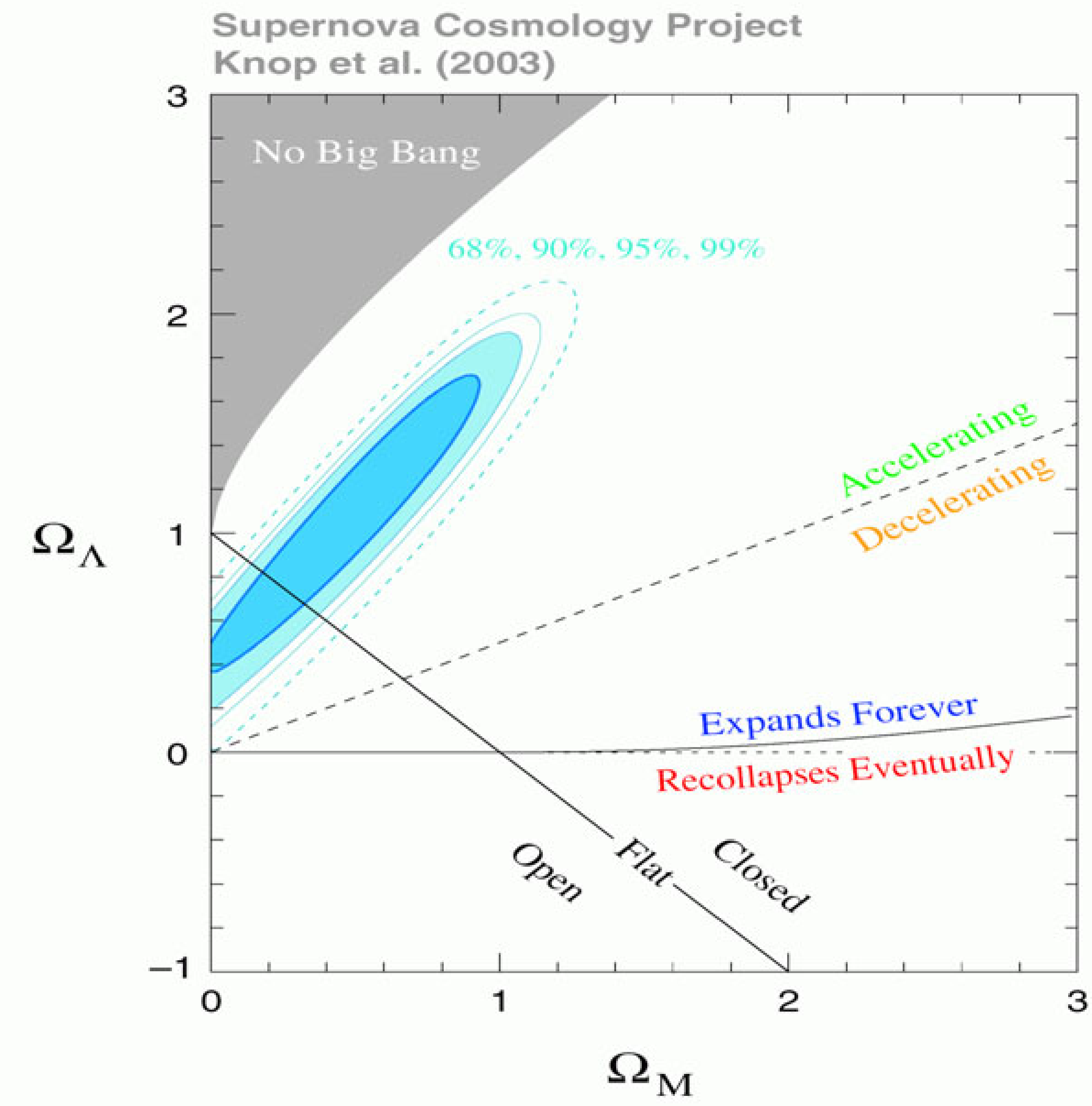




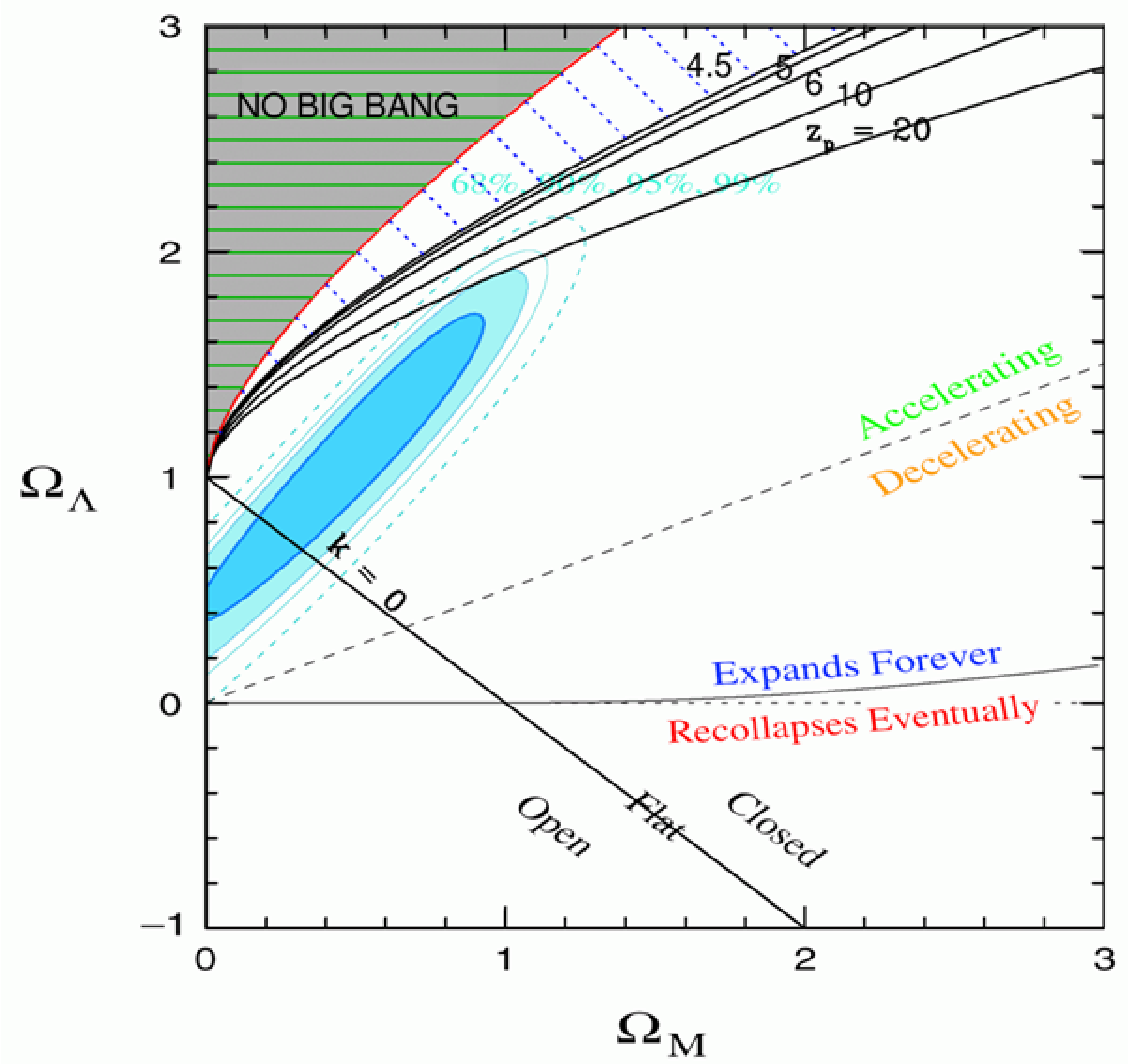
Over-focusing: no image or images on one side



Redshift of antipode



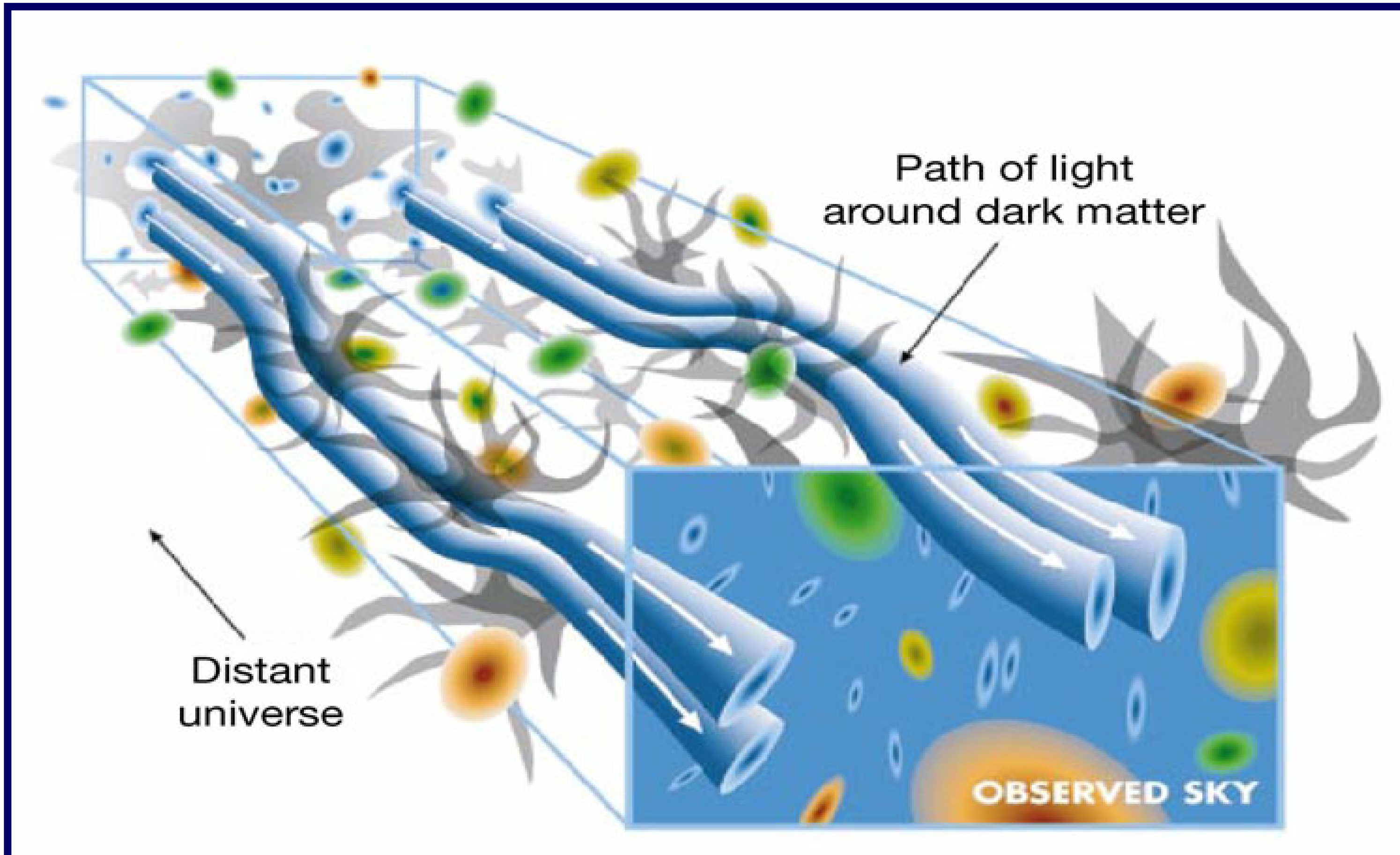
Supernova Cosmology Project
Knop et al. (2003)
No Big Bang
68%, 90%, 95%, 99%
Accelerating
Decelerating
Expands Forever
Recollapses Eventually
Open
Flat
Closed
Ω_Λ
Ω_M
3
2
1
0
−1
0
1
2
3



NO BIG BANG
4.5
5
6
10
z_b = 20
68%, 90%, 95%, 99%
Accelerating
Decelerating
$k = 0$
Expands Forever
Recollapses Eventually
Open
Flat
Closed
Ω_Λ
Ω_M

IX. Weak lensing with SDSS

- Galaxy-mass correlation function
- The power spectrum of the distribution of total mass
- The average size and distribution of the halo mass of galaxies
- Masses or mass profiles of nearby clusters
- Direct comparison of dark and luminous matter on cluster scales
- Statistical magnification of background QSOs


Path of light
around dark matter
Distant
universe
OBSERVED SKY