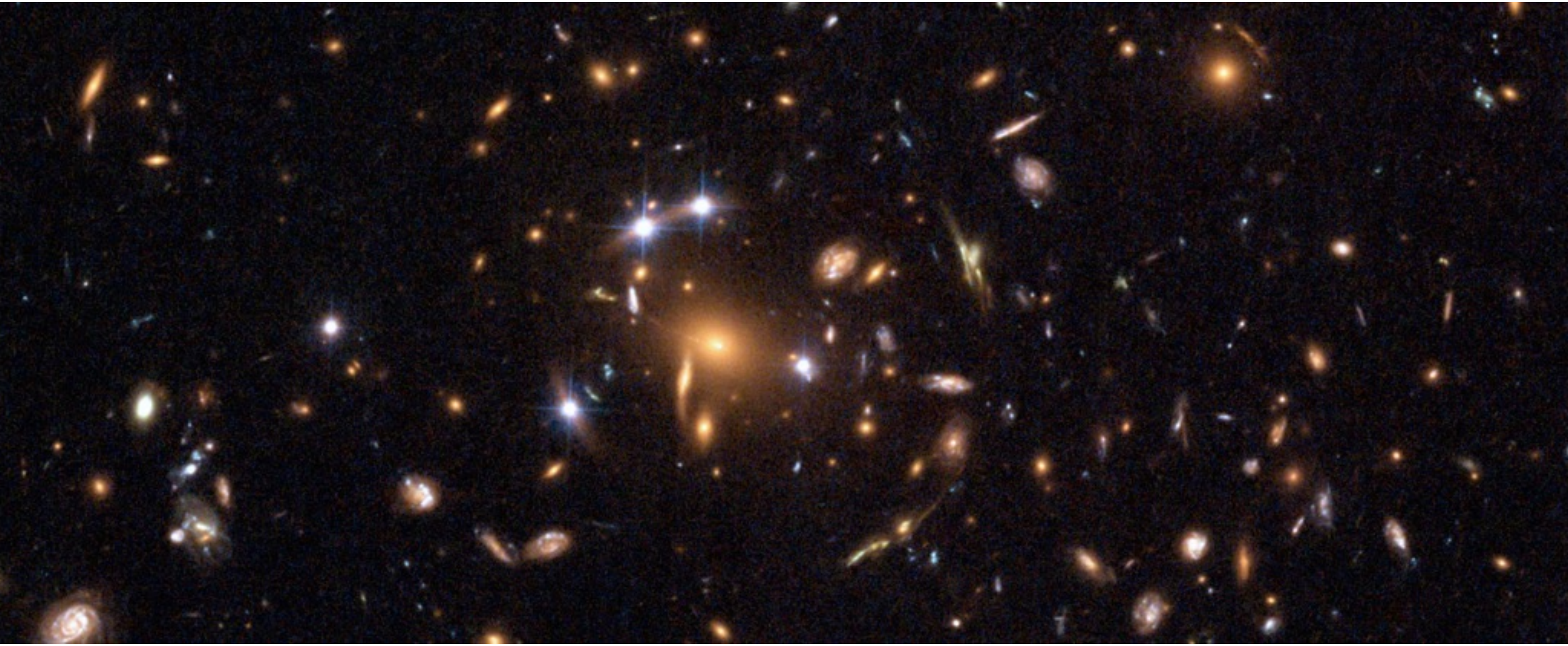
Quasar lenses as a cosmological probe



Masamune Oguri (NAOJ)

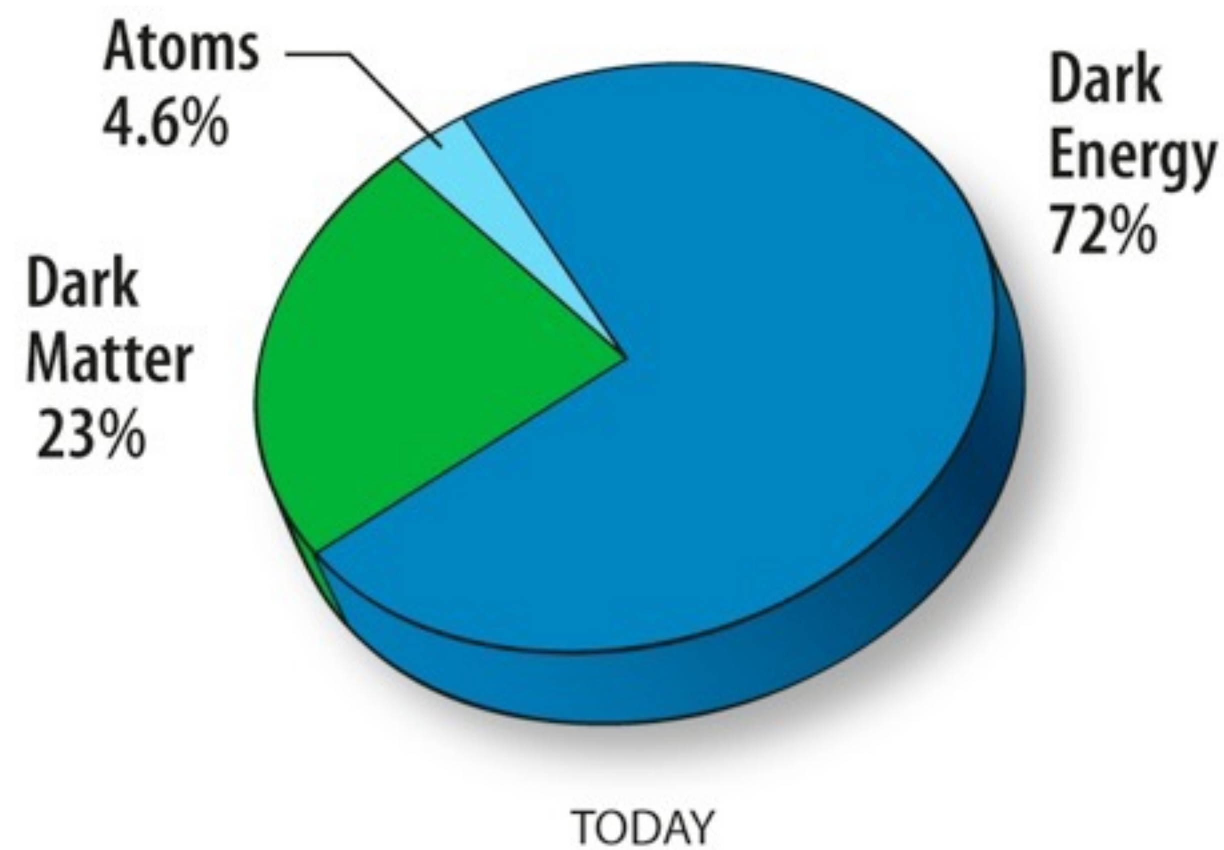
10/02/2010, QGC2010@Daejeon

Dark energy

Mysterious energy that accelerates the universe

Modified gravity? Void?

Now, only astronomical observations provide a clue to its nature



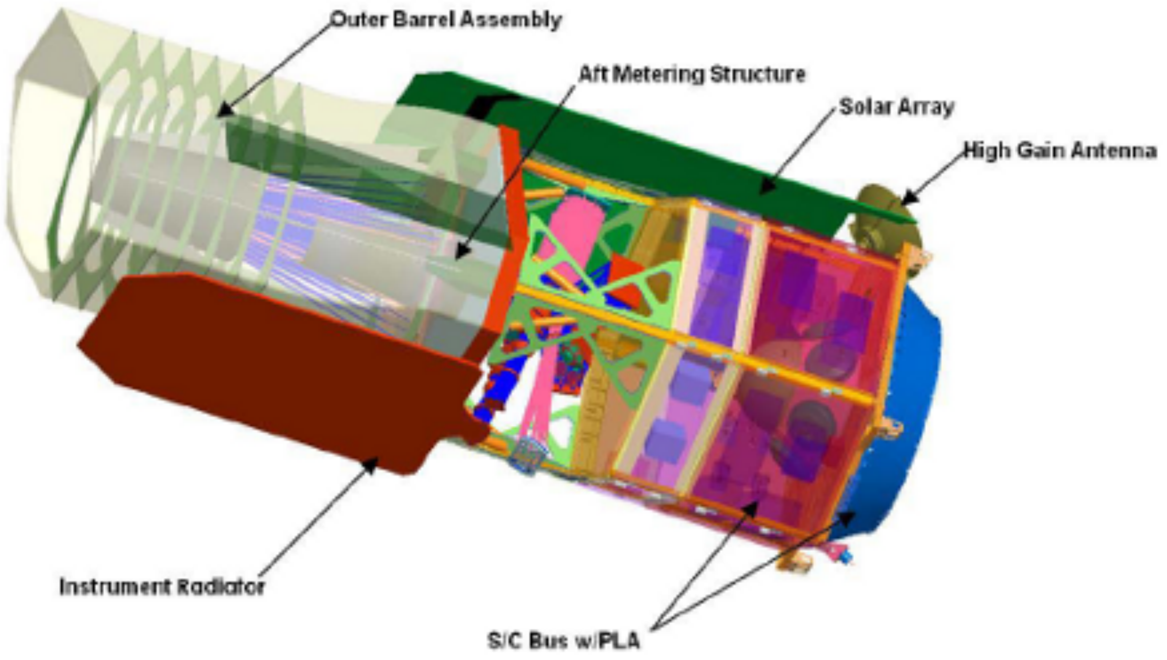
http://map.gsfc.nasa.gov/

Astro2010: next 10yr science in the US

ground #1 – LSST

Dark energy, dark matter, time-domain astronomy

space #1 – WFIRST

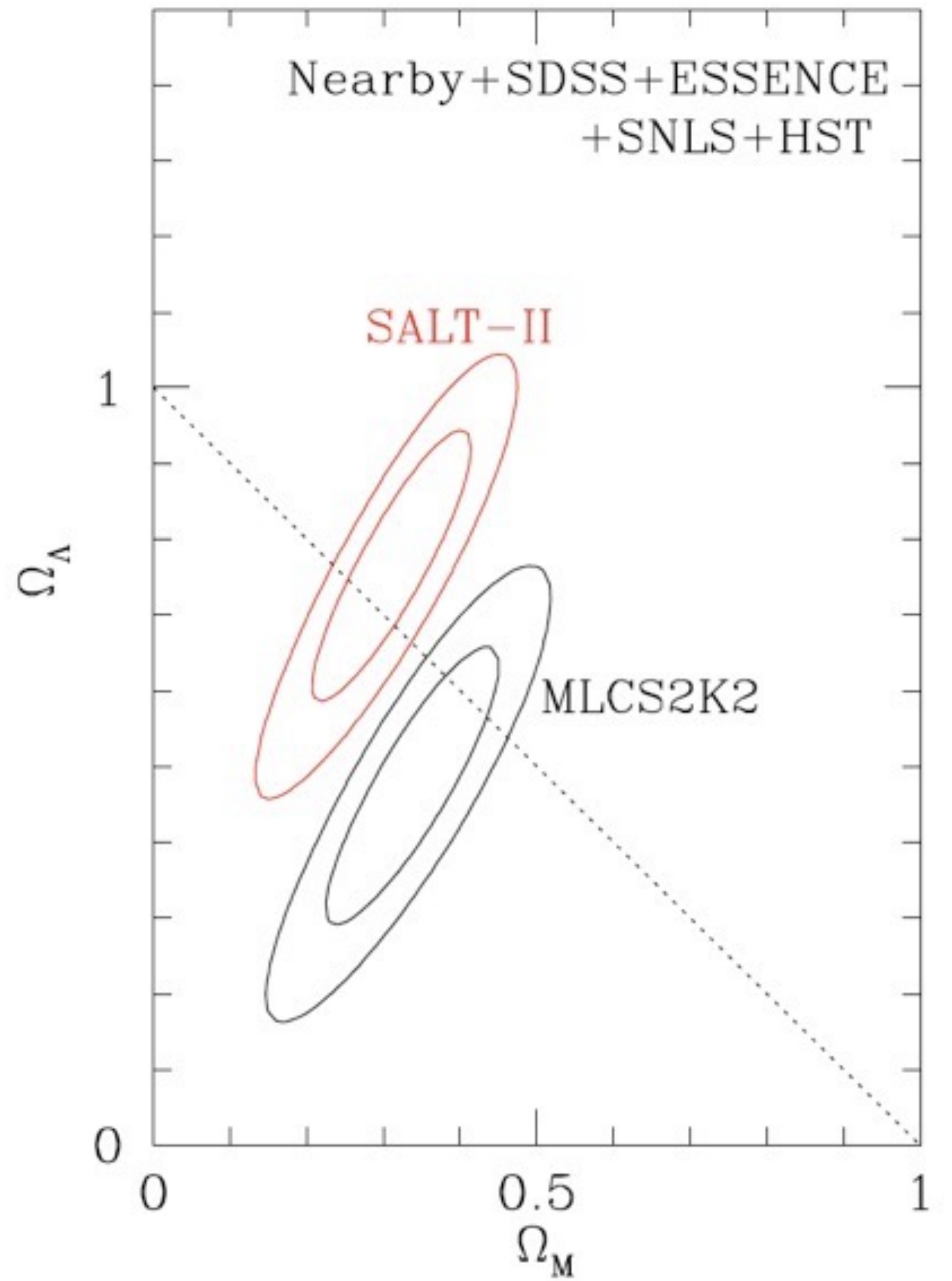


Dark energy, extra-solar planet

Probing dark energy

Method	Probe
CMB anisotropy	$D_A(z=1091)$
Supernova Ia	$D_L(z)$
Baryon Acoustic Oscillation	$D_A(z)$, $H(z)$
Weak lensing	$G(z)$ (growth rate)
Cluster of galaxies	$G(z)$ (growth rate)

Know systematics: example



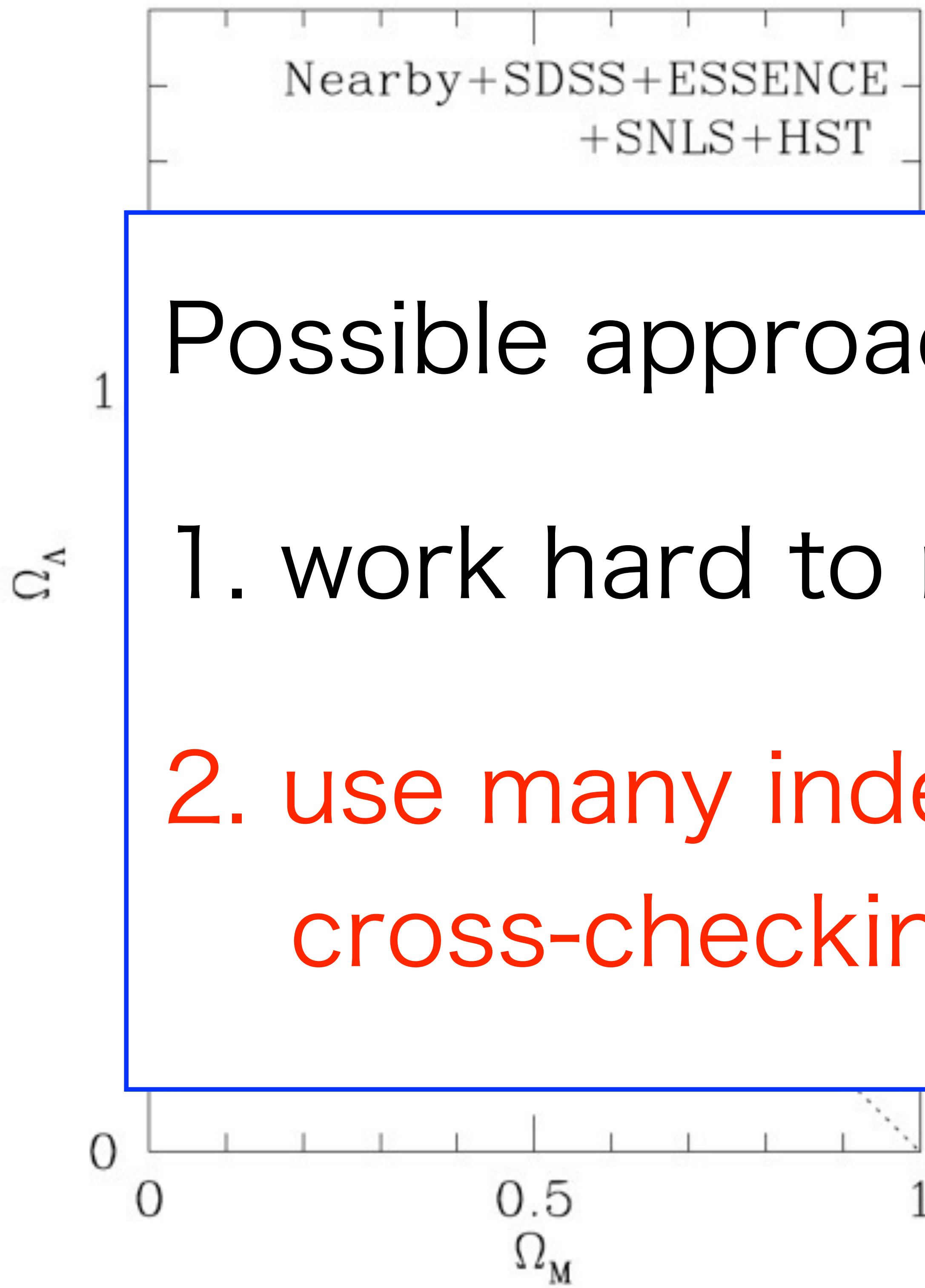
based on Kessler et al. (2009)

Cosmological constraint from type-Ia supernovae

Different light-curve fitting methods yield inconsistent results

→ Results are already systematics-limited !

Know systematics: example



based on Kessler et al. (2009)

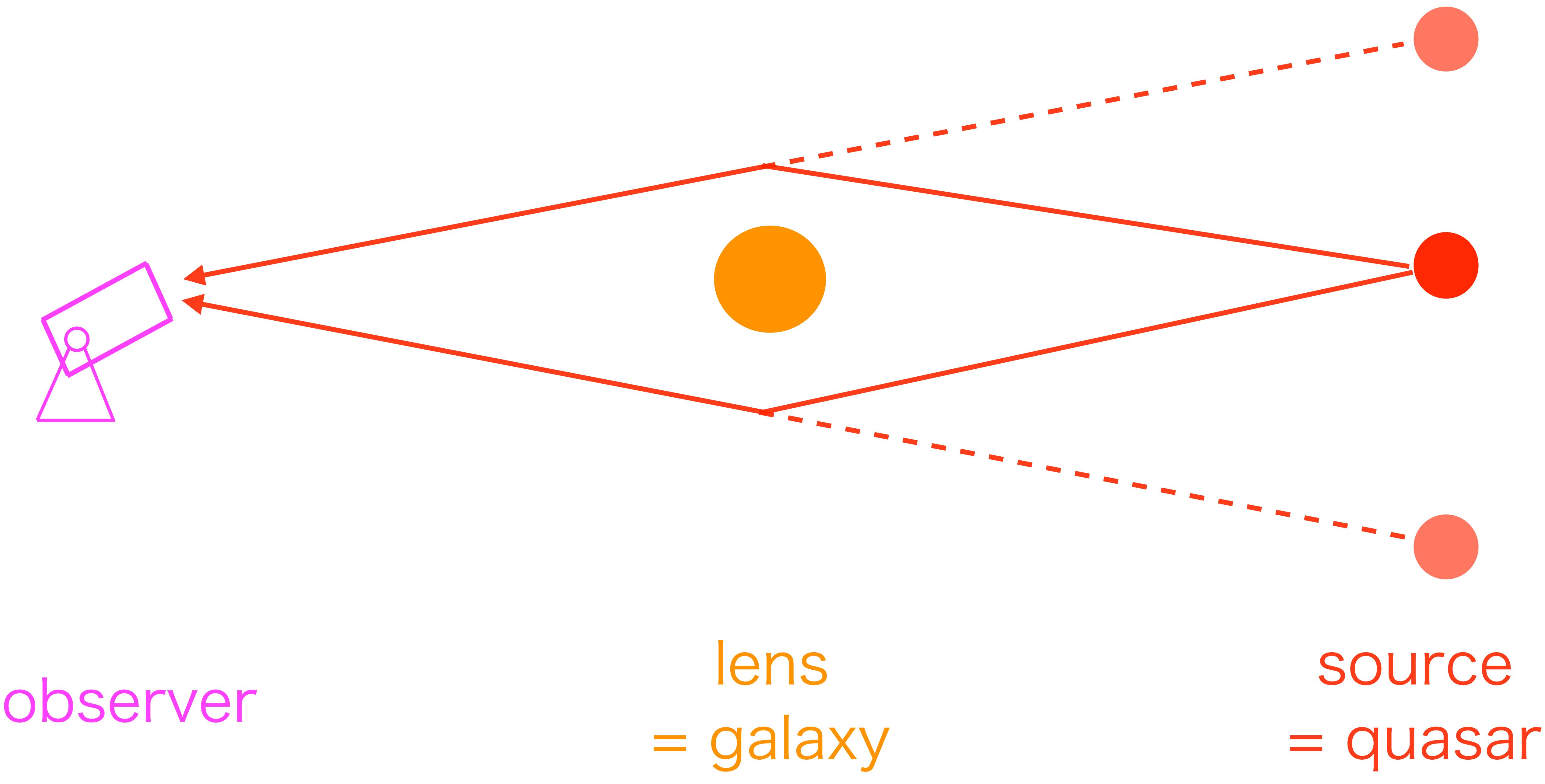
Cosmological constraint
from type-Ia supernovae

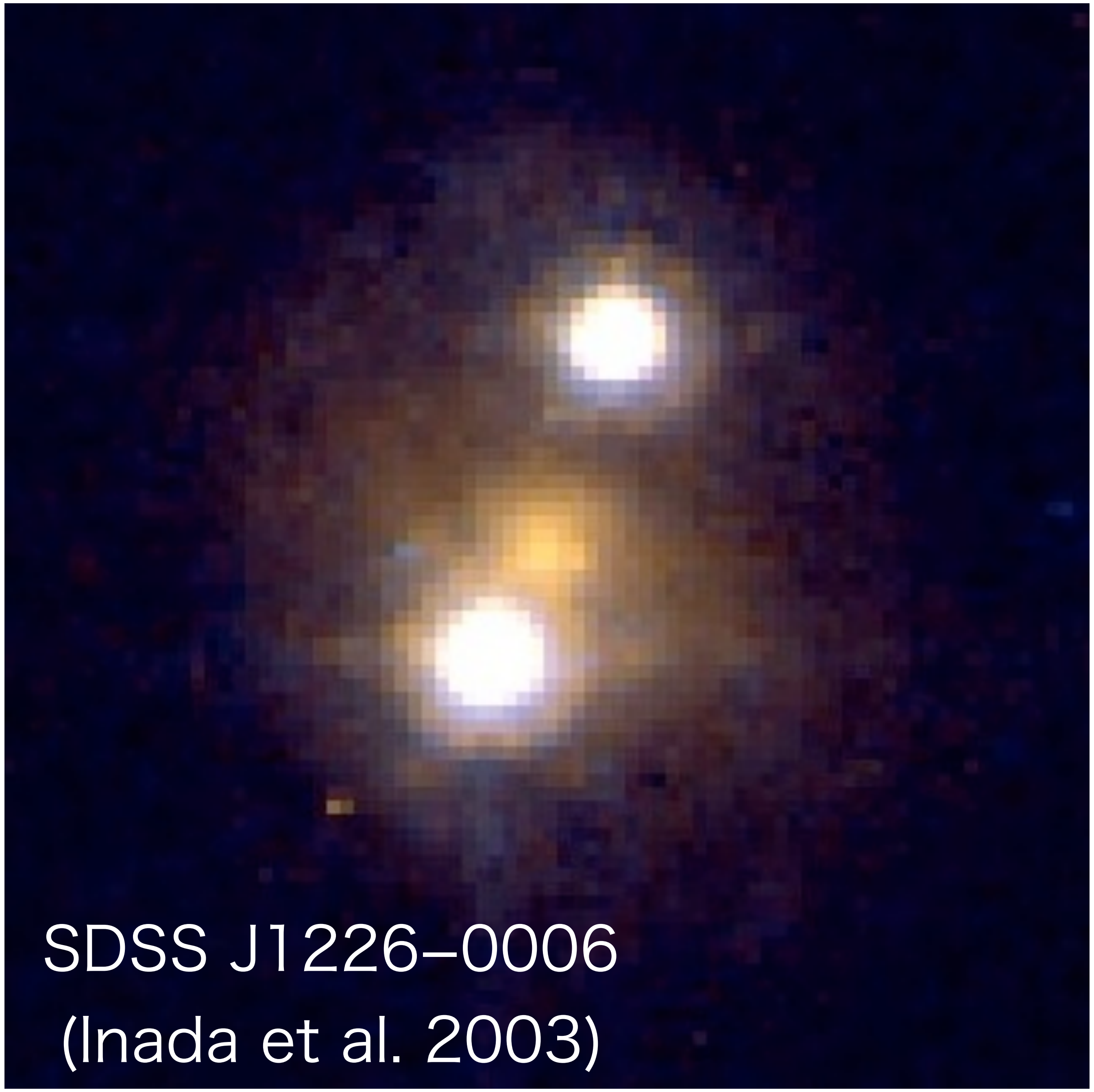
Possible approaches?

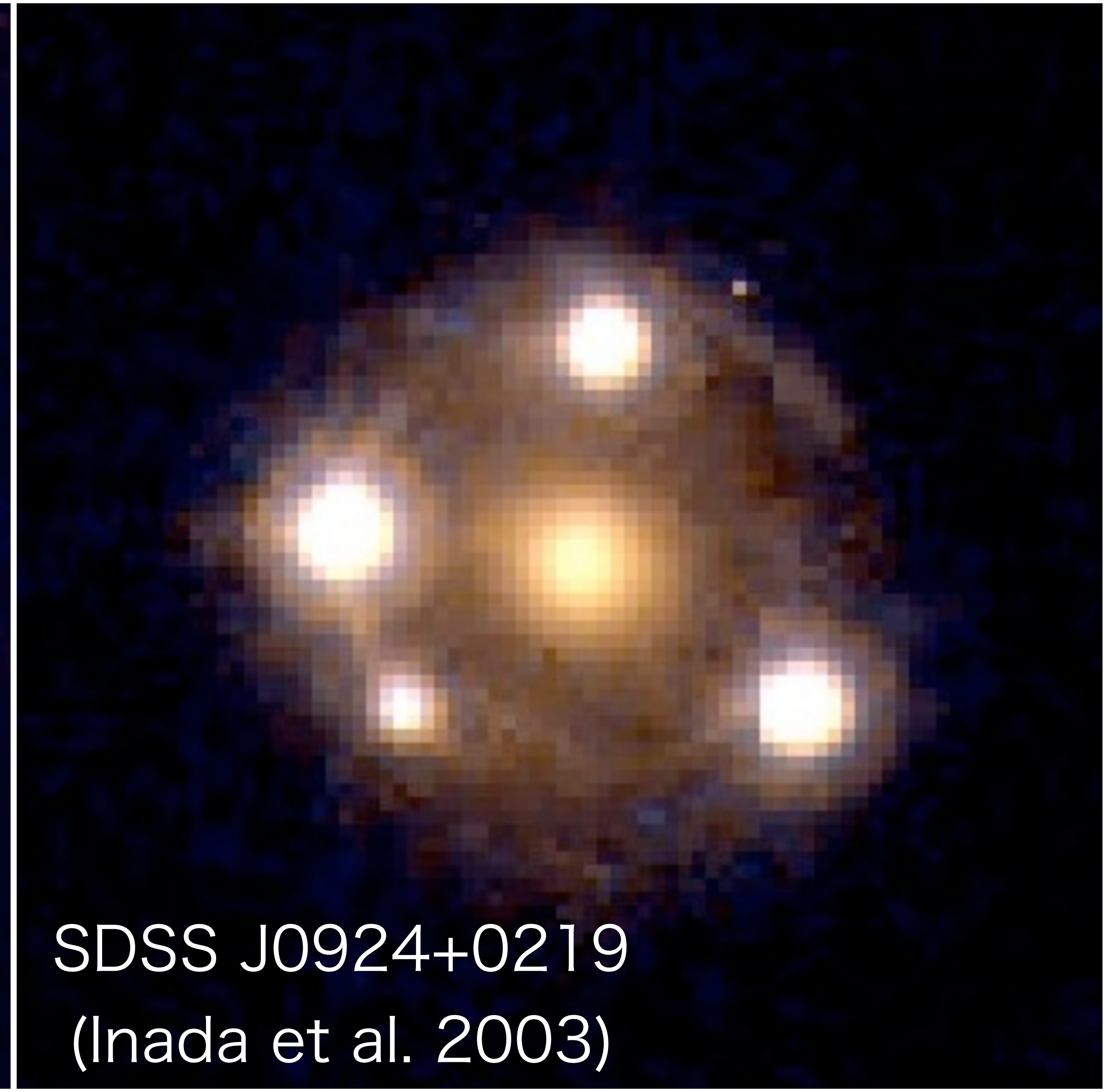
1. work hard to reduce systematics

2. use many independent methods for cross-checking

Quasar lensing







HST images (NASA/ESA/M. Oguri)

Cosmology w/ quasar lenses

1. Strong lensing probability
   → cosmic volume $D_A(z)^2 H(z)^{-1}$

2. Time delays between quasar images
   → Hubble constant H_0
   + distance ratio $D_A(z)D_A(z_s)/D_A(z,z_s)$

Cosmology w/ quasar lenses

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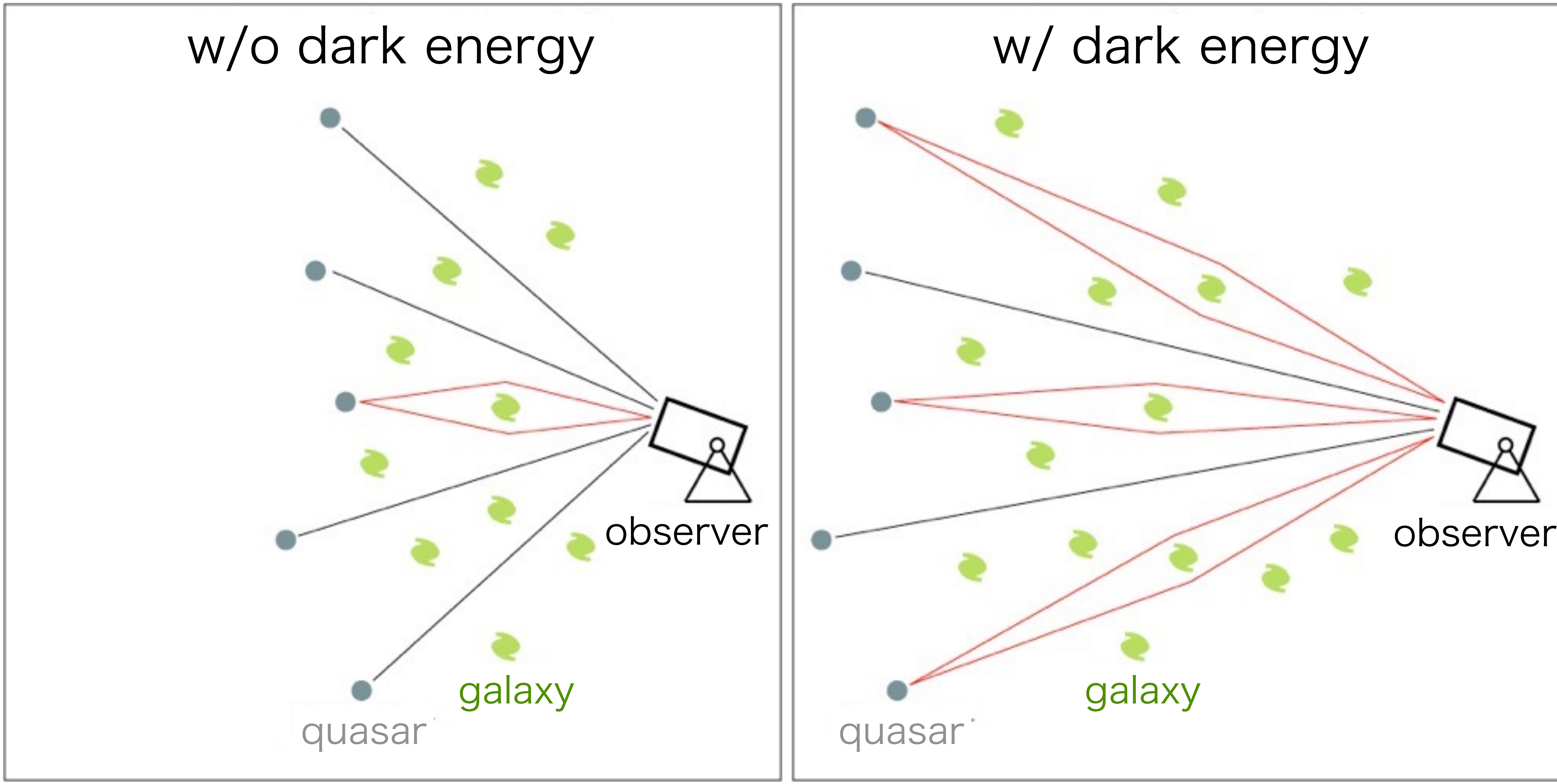
“Classical” lensing test

Fukugita et al. (1990), Turner (1990)



“standard volume”

Lensing test of dark energy

The probability that a quasar at z_s is lensed

velocity function = galaxy number density (observed)

lensing cross section (depend on galaxy profile)

$$p = \int_0^{z_s} dz \int dv \, \frac{dn_{\rm gal}}{dv} \sigma_{\rm lens} \frac{dr}{dz} \phi_{\rm sel}$$

selection function

∝ cosmological volume $D_A(z)^2 H(z)^{-1}$

× lensing power $[D_A(z,z_s)/D_A(z_s)]^2$

→ dark energy!

Sloan Digital Sky Survey

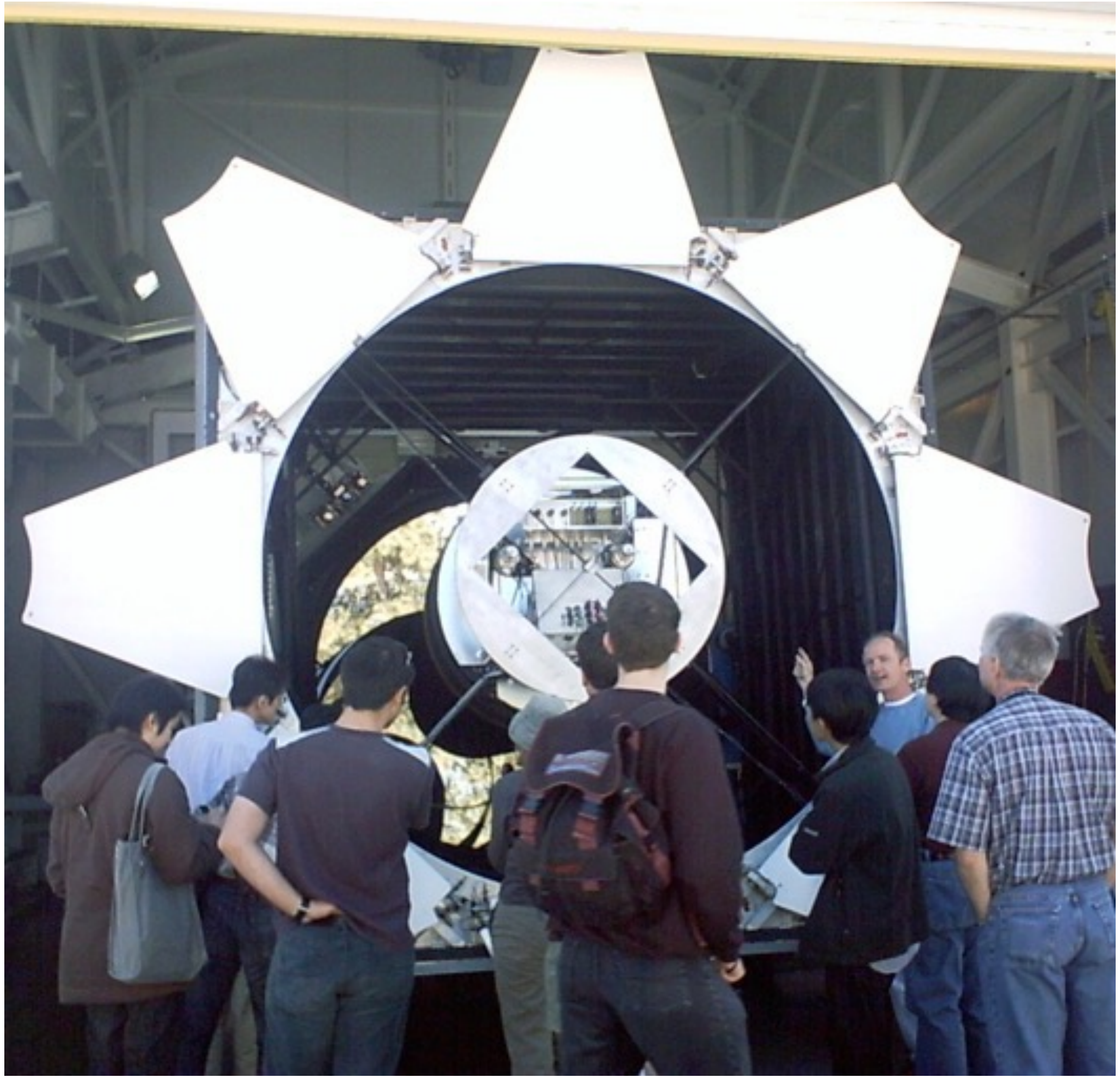
SDSS-I (2000-2005) & SDSS-II (2005-2008)

Imaging

8000 deg^2 in five optical bands

Spectroscopy

galaxies/quasars selected from imaging data



SDSS quasar lens search (SQLS)

- Survey of lensed quasars using the SDSS spectroscopic quasar catalog
- Select candidates from morphology/color
- Follow-up observations for confirmation

Team

Bob Becker (UC Davis)
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Issha Kayo (IPMU)
Chris Kochanek (OSU)
Tomoki Morokuma (U Tokyo)

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Bart Pindor (Melbourne)
Gordon Richards (Drexel)
Don Schneider (PSU)
Min-Su Shin (Michigan)
Michael Strauss (Princeton)
+ many others...

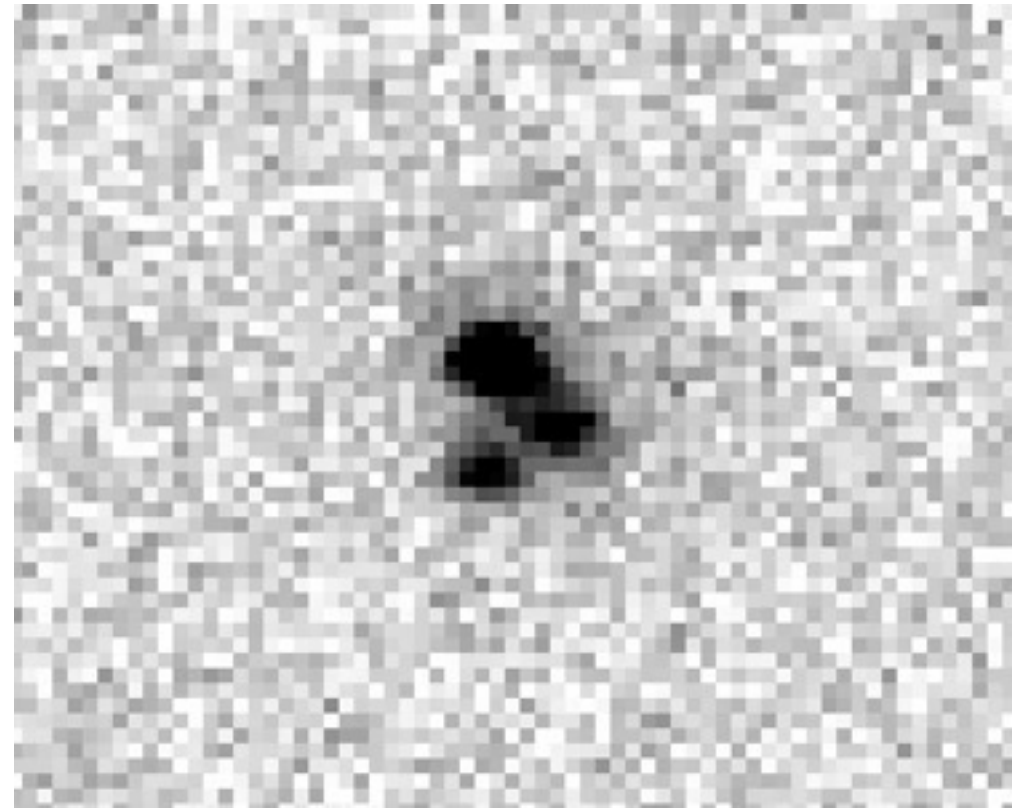
SDSS quasar lens search (SQLS)

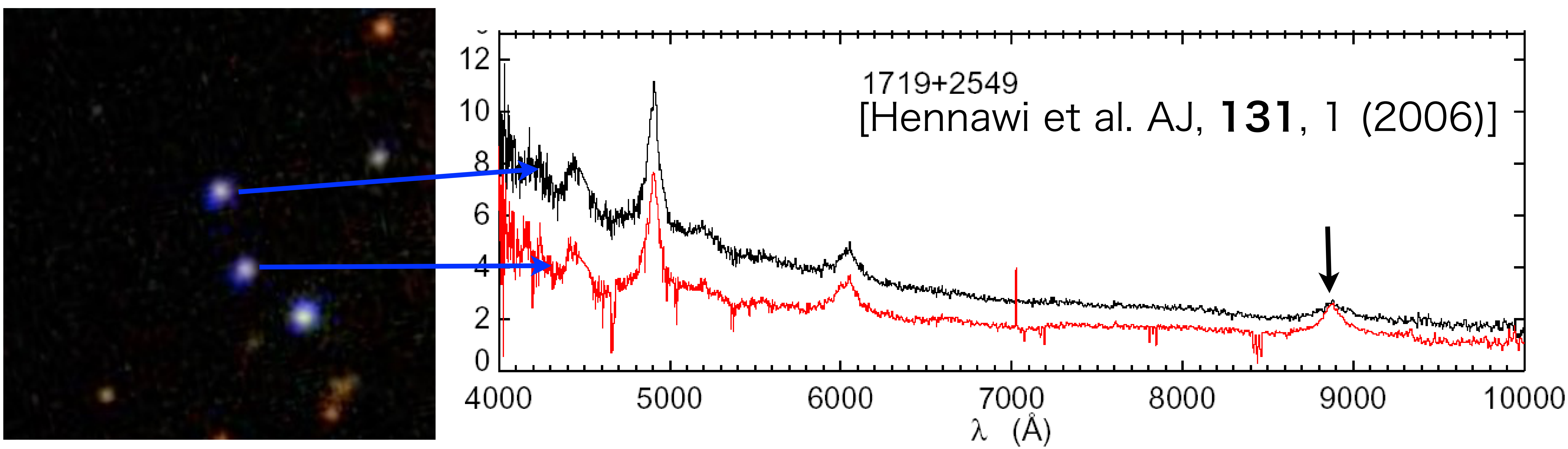
Public web page, up-to-date info on SQLS

http://www-utap.phys.s.u-tokyo.ac.jp/~sdss/sqls/

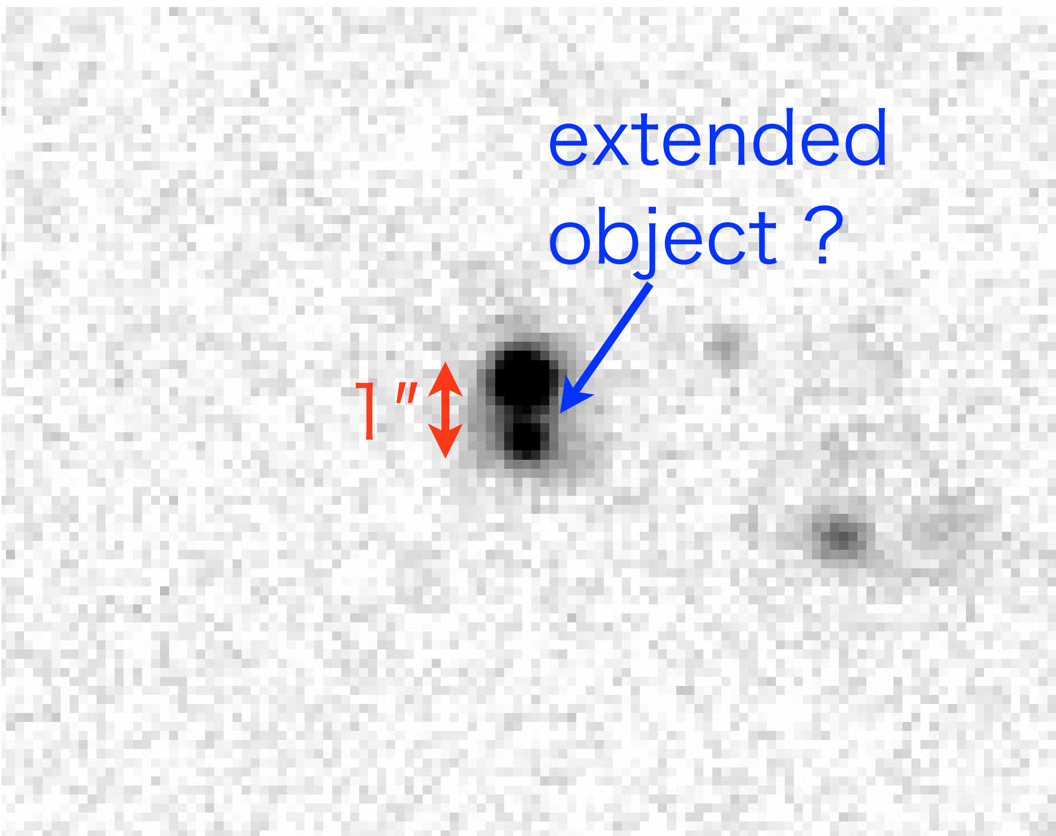
(Search "SDSS quasar lens search" on google/yahoo/bing/...)

It's never easy...

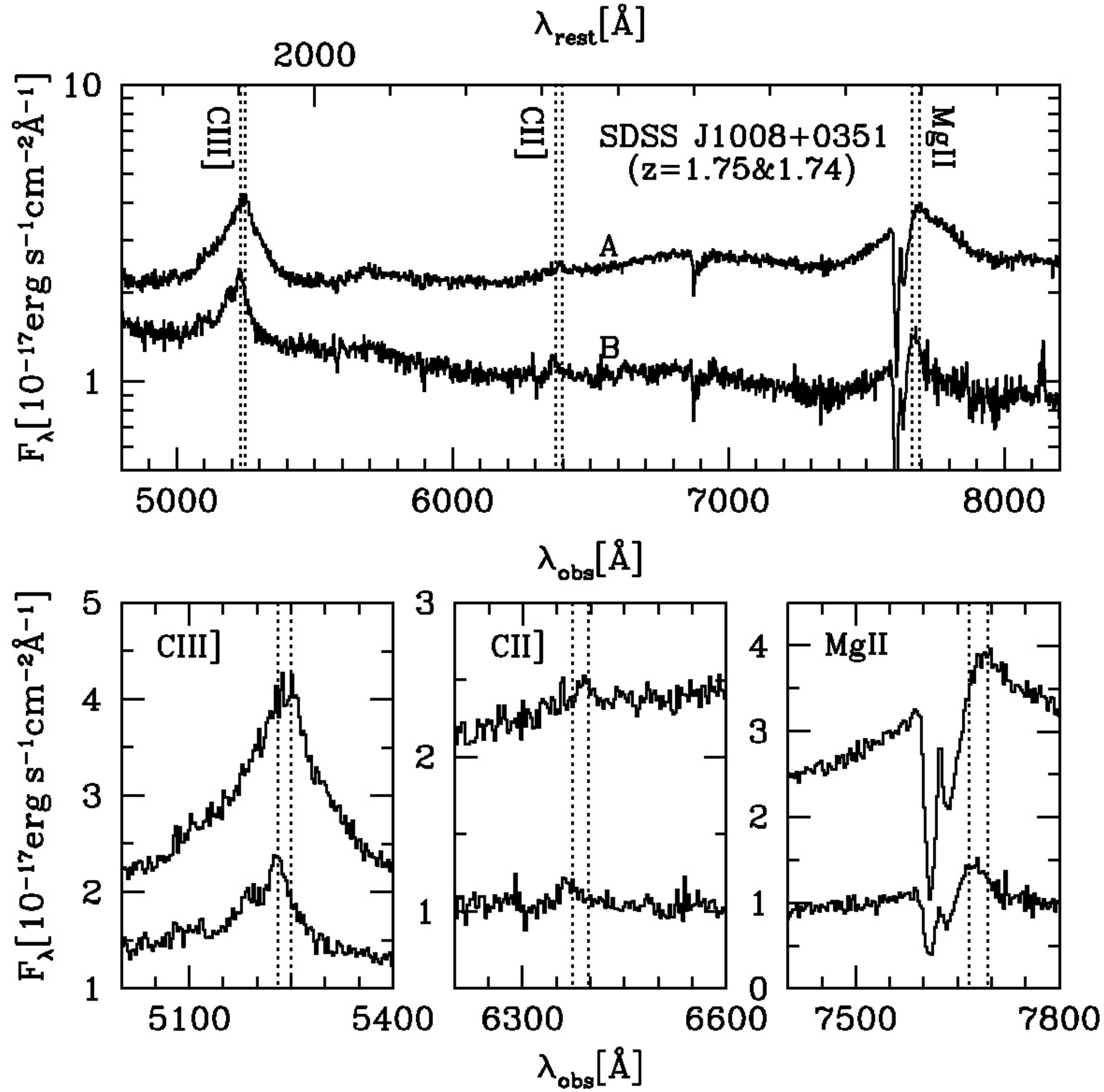




It's never easy...



Binary quasar...



[Inada et al. AJ, **135**, 496 (2008)]

SDSS quasar lens search (SQLS)

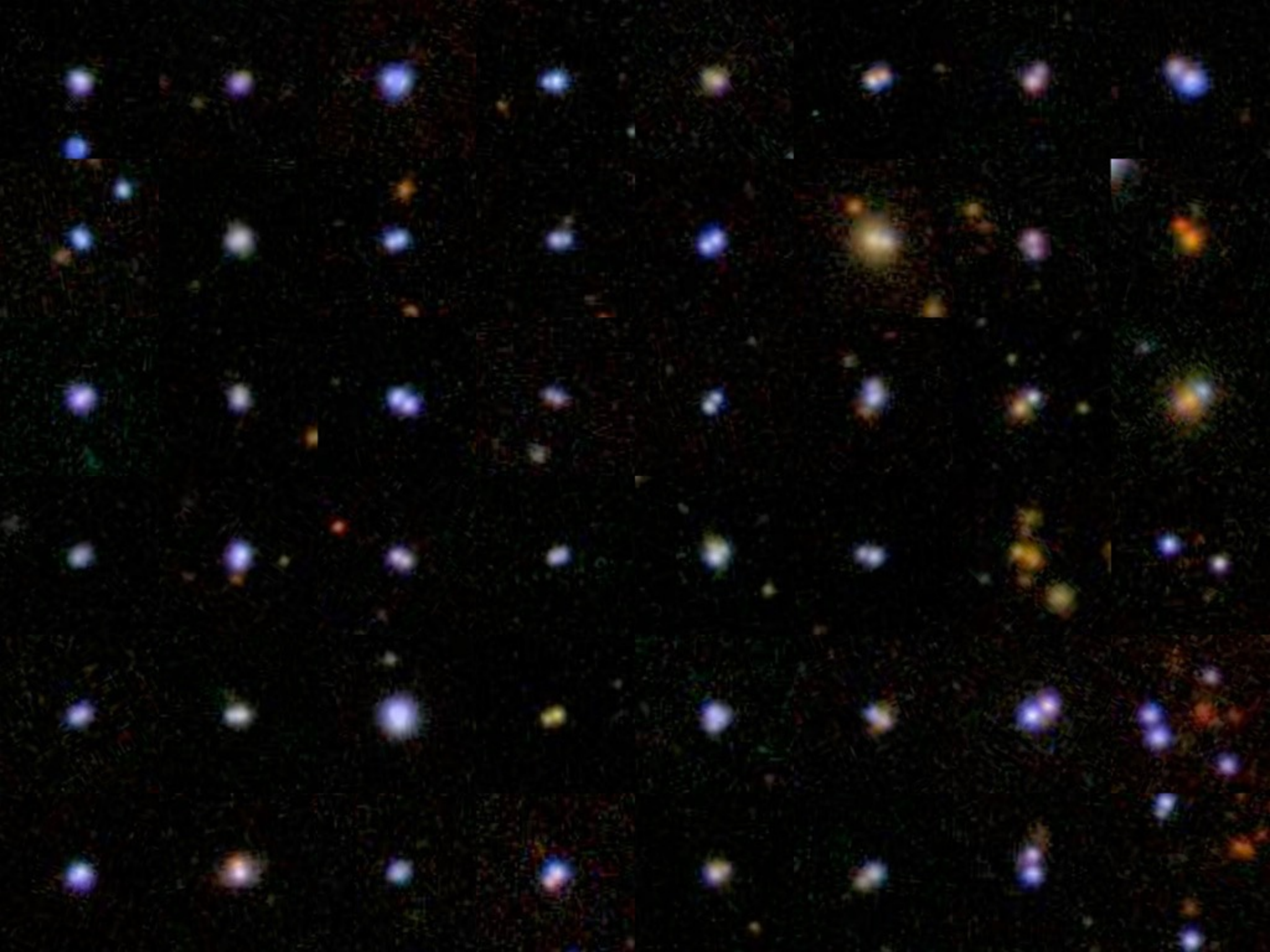
Current Status

>98% of the survey done

46 confirmed new lensed quasars
2 probable new lensed quasars
13 previously known lensed quasars

→ 61 lensed quasars !

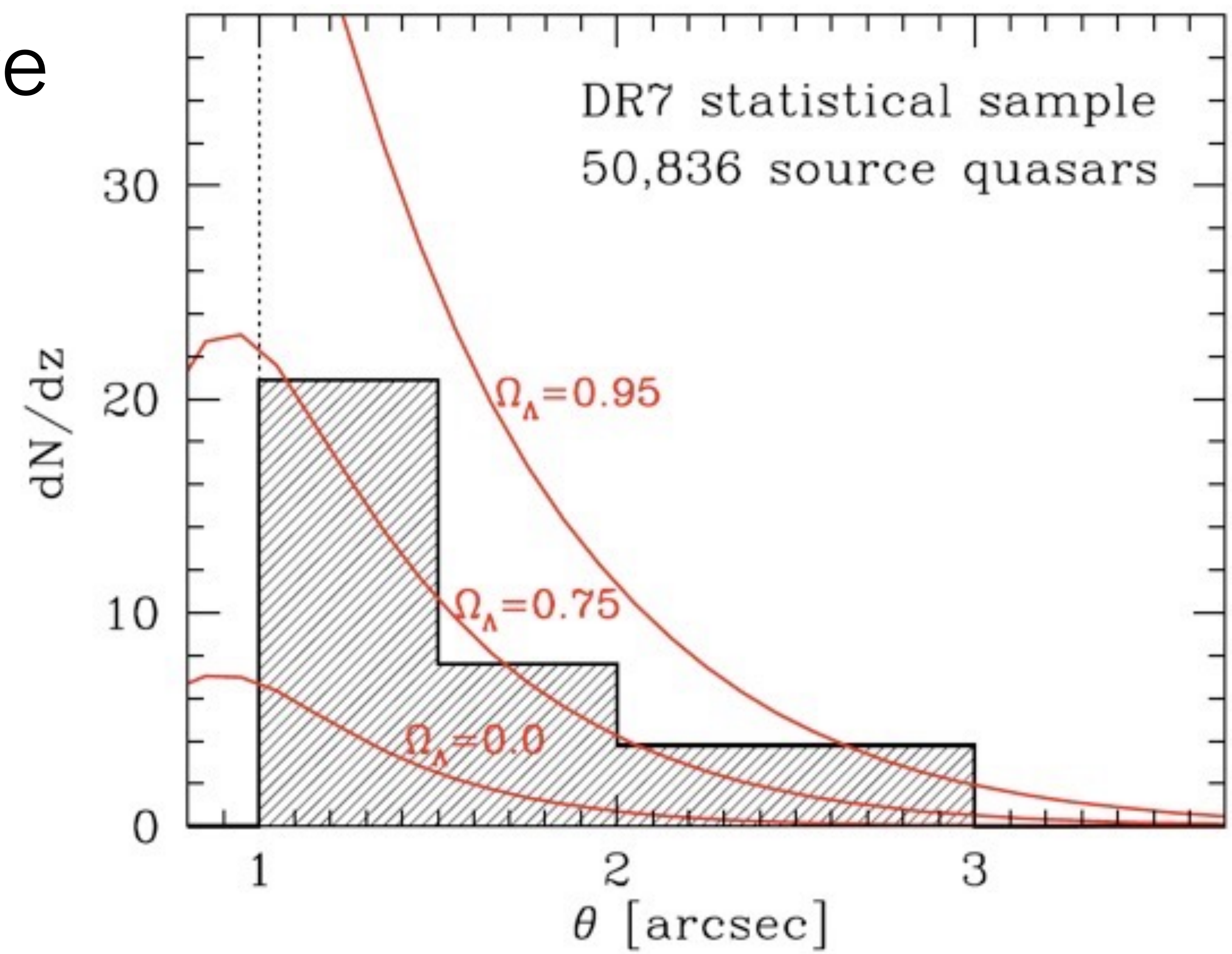
(cf. ~120 lensed quasars known to date)



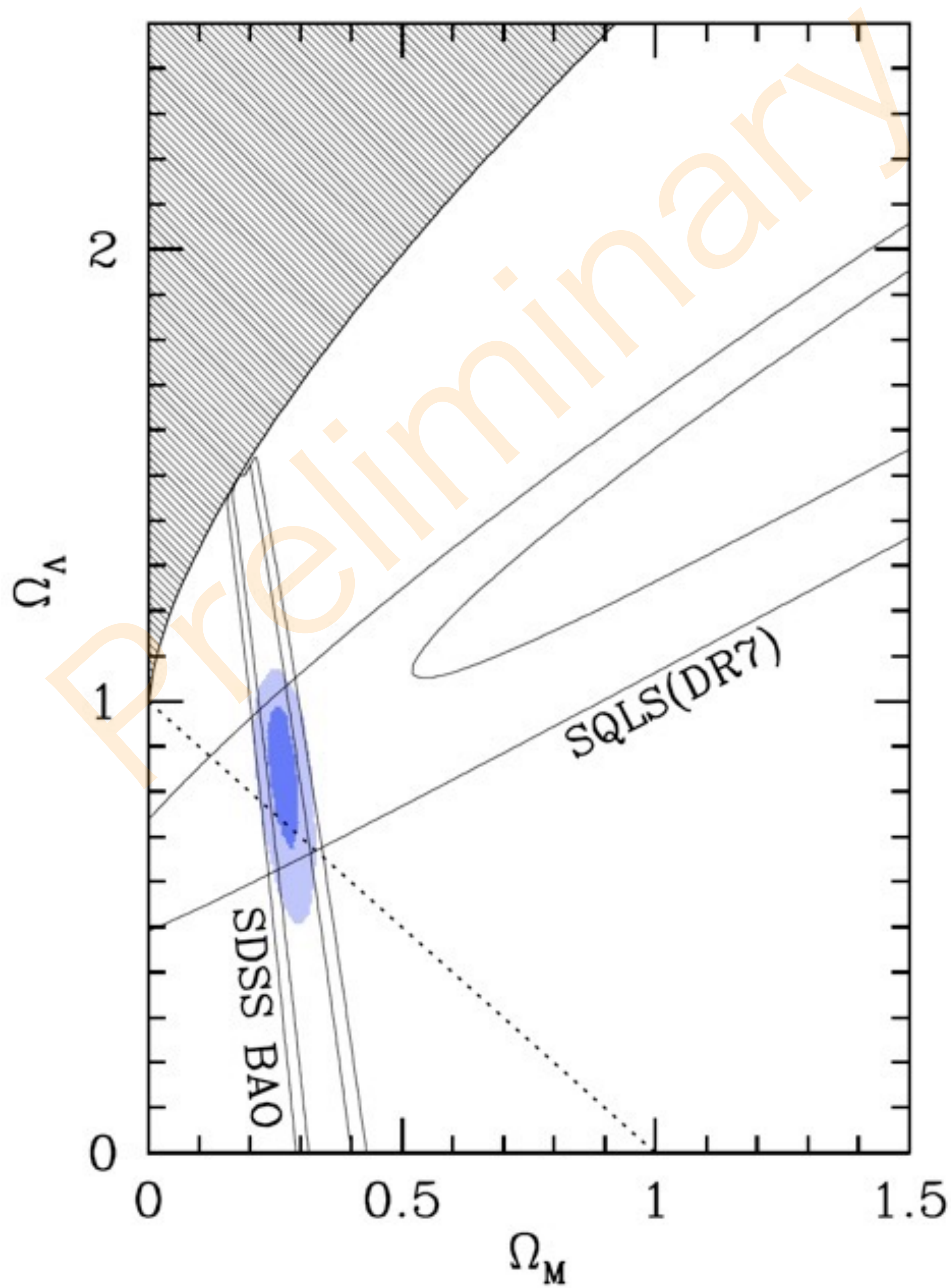
Constraining dark energy

of lenses as a function of image separation θ
vs. model predictions with different Ω_Λ (assume flat)

The number is sensitive to dark energy, with larger Ω_Λ being more lenses



Result from DR7: Ω_M-Ω_Λ



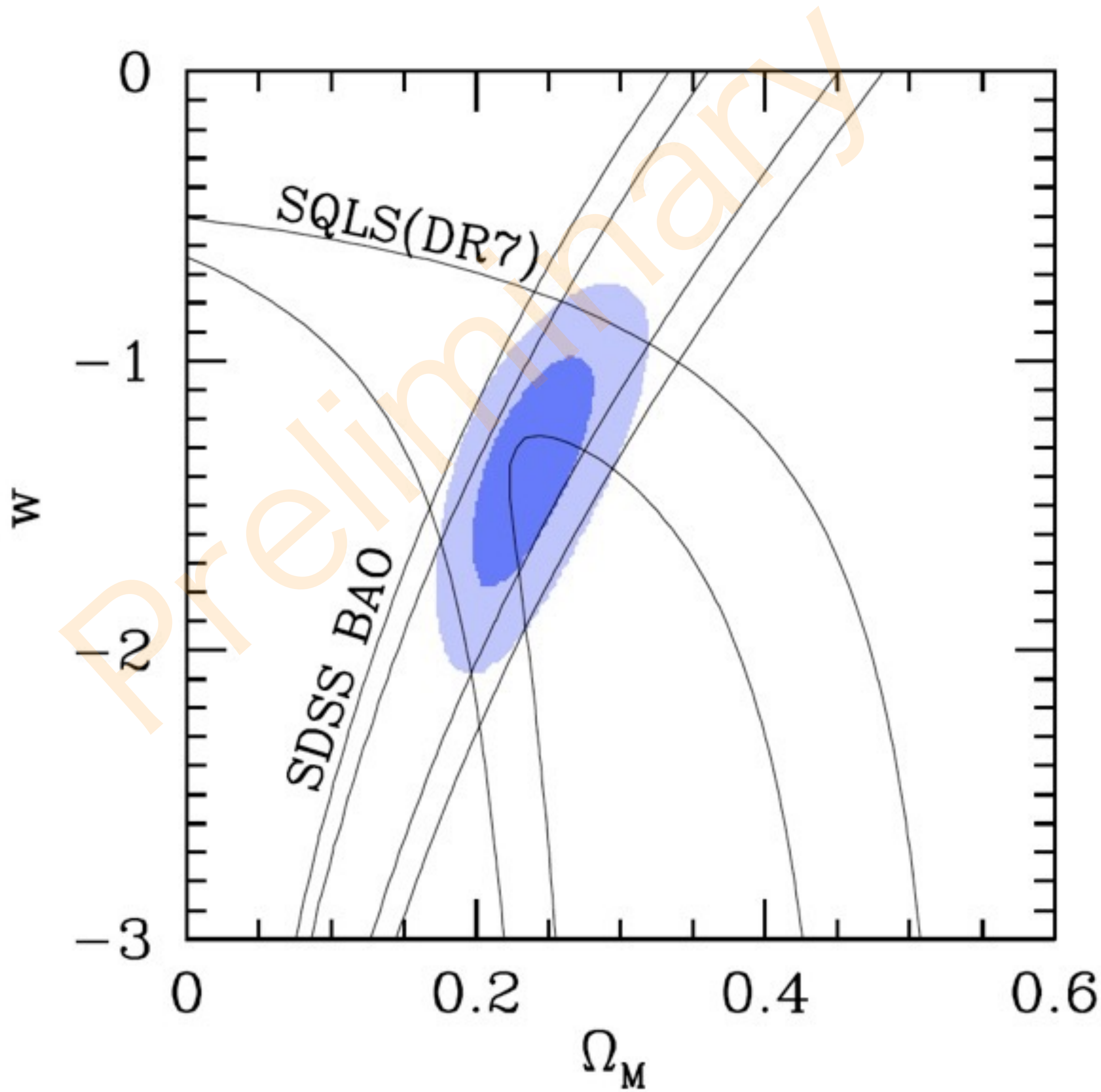
Combine lens result with SDSS BAO
(Eisenstein et al. 2005)

$$\Omega_M = 0.26^{+0.03}_{-0.02}$$

$$\Omega_\Lambda = 0.86^{+0.09}_{-0.12}$$

Consistent with "standard" model

Result from DR7: dark energy



Assume a flat universe

SQLS+BAO:

$\Omega_M = 0.24^{+0.03}_{-0.02}$

$w = -1.40^{+0.30}_{-0.25}$

Lens probability: summary

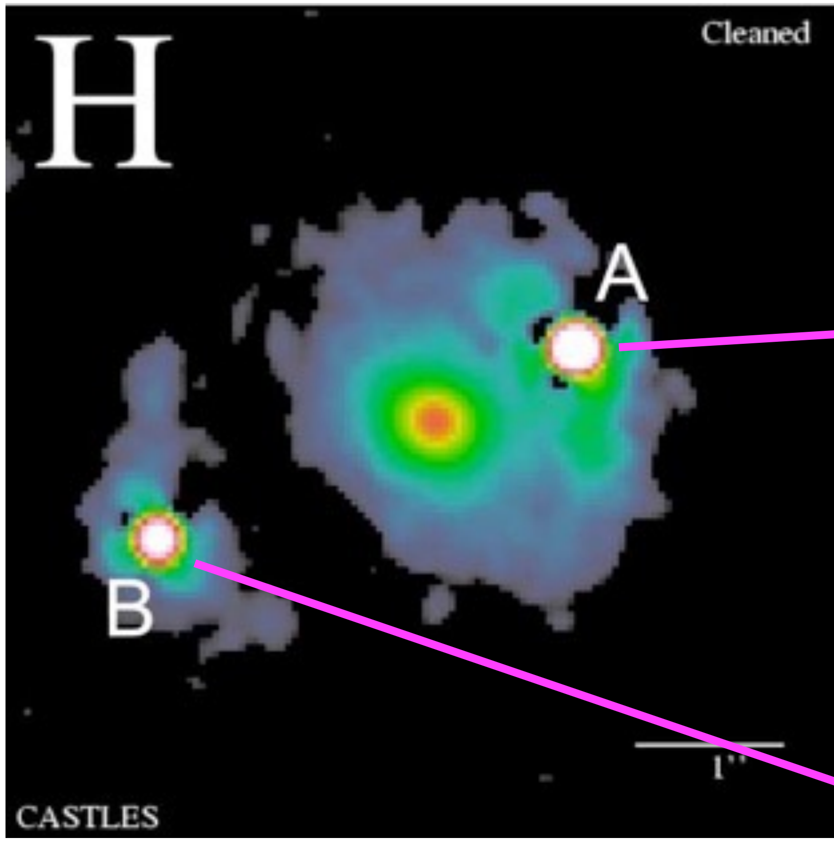
- Strong lensing probability of quasars is sensitive to the evolution of cosmic volume, and hence to dark energy
- We (SQLS) have construct the largest sample of quasar lenses appropriate for statistical studies
- The result is consistent with the current standard cosmological model, providing independent confirmation of dark energy

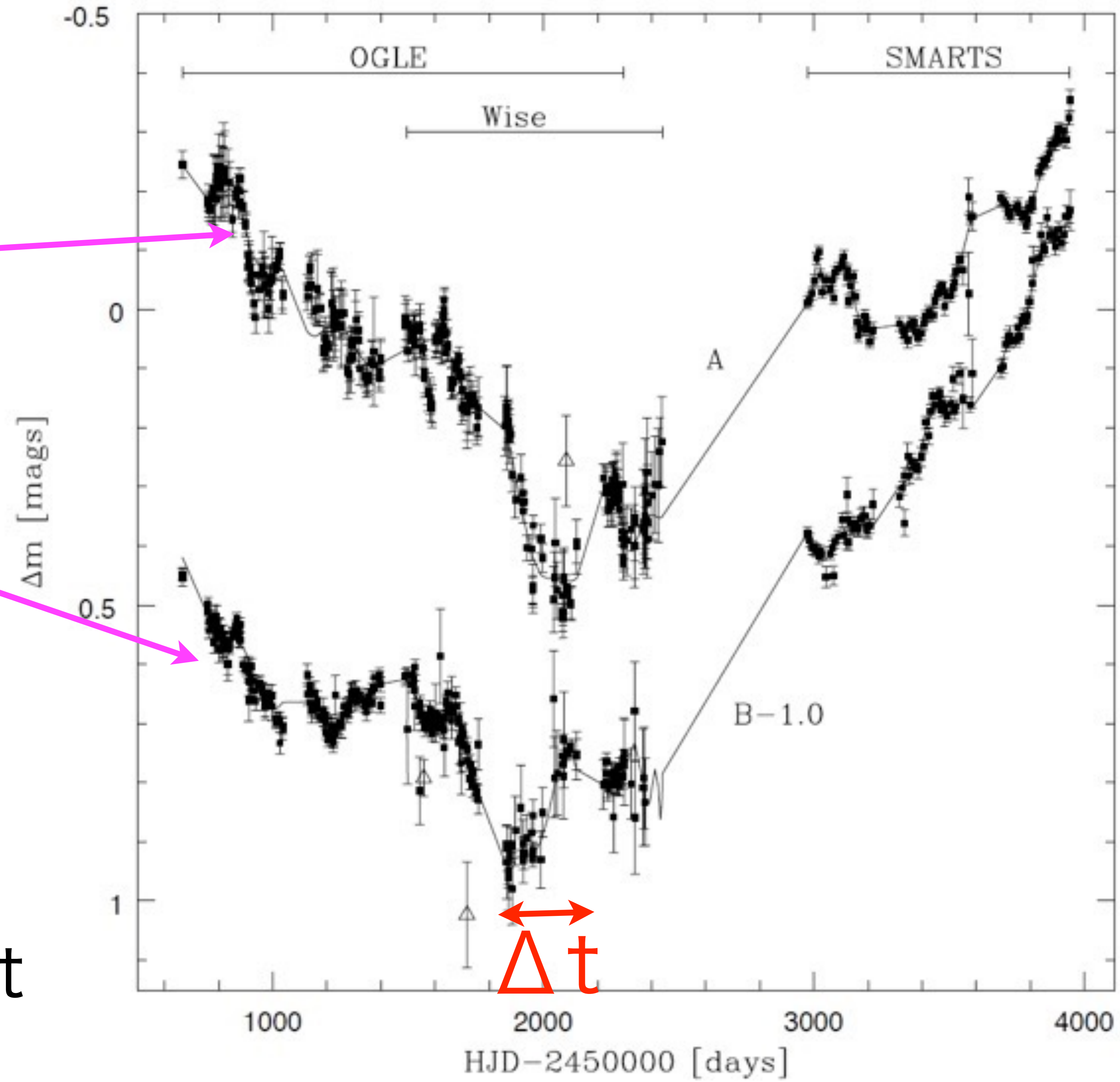
Cosmology w/ quasar lenses

1. Strong lensing probability
   → cosmic volume $D_A(z)^2 H(z)^{-1}$

2. Time delays between quasar images
   → Hubble constant H_0
   + distance ratio $D_A(z) D_A(z_S) / D_A(z, z_S)$

Time delay



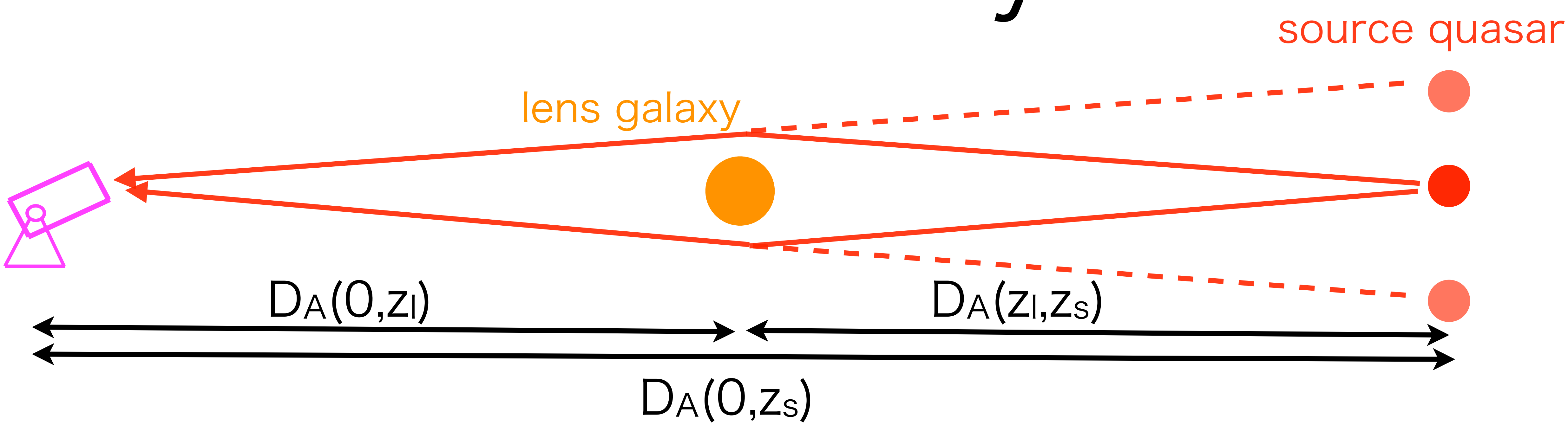


Arrival time difference due to geometrical + gravitational effect

(observed for ~20 lenses so far)

Poindexter et al. (2007)

Time delay



$$\Delta t_{ij} = (1+z_l)\frac{D_A(0,z_l)D_A(0,z_s)}{D_A(z_l,z_s)}(\phi_i - \phi_j)$$

measure this

Fermat potential (Blandford & Narayan 1986)
(depend on image config. and lens potential)

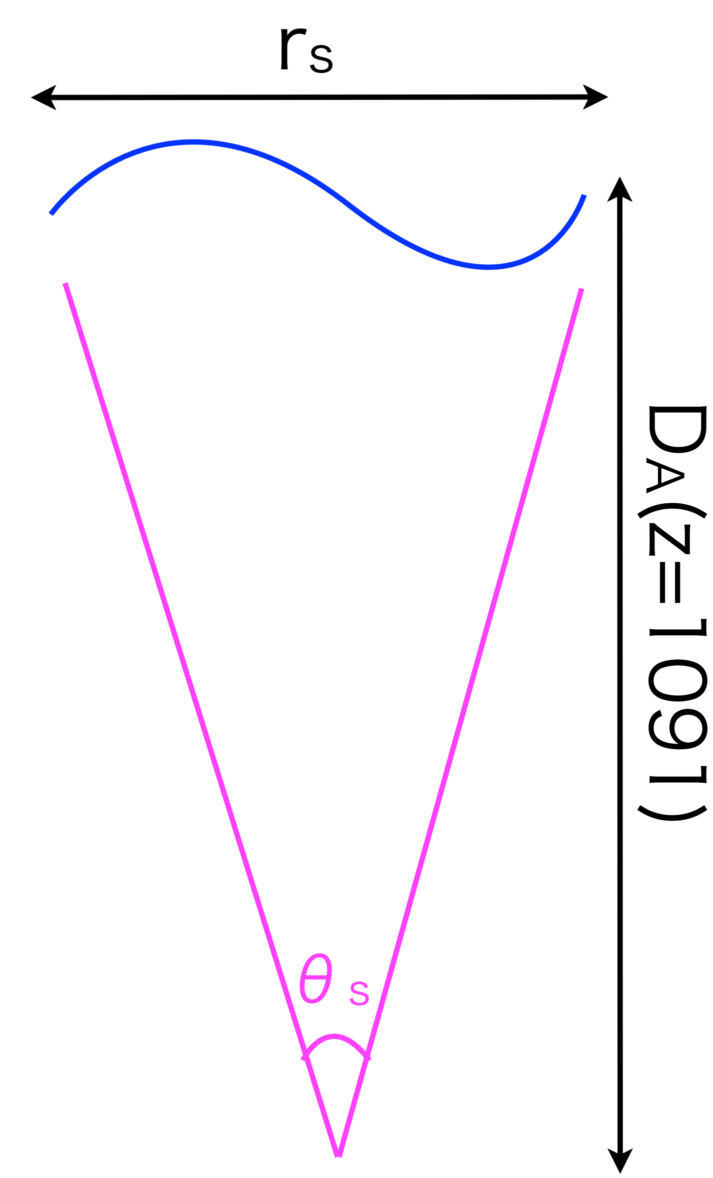
probing the distance ratio $\propto H_0^{-1}$

H_0 and dark energy

The characteristic scale of CMB is sound horizon at recombination (r_s ~150 Mpc in comoving)

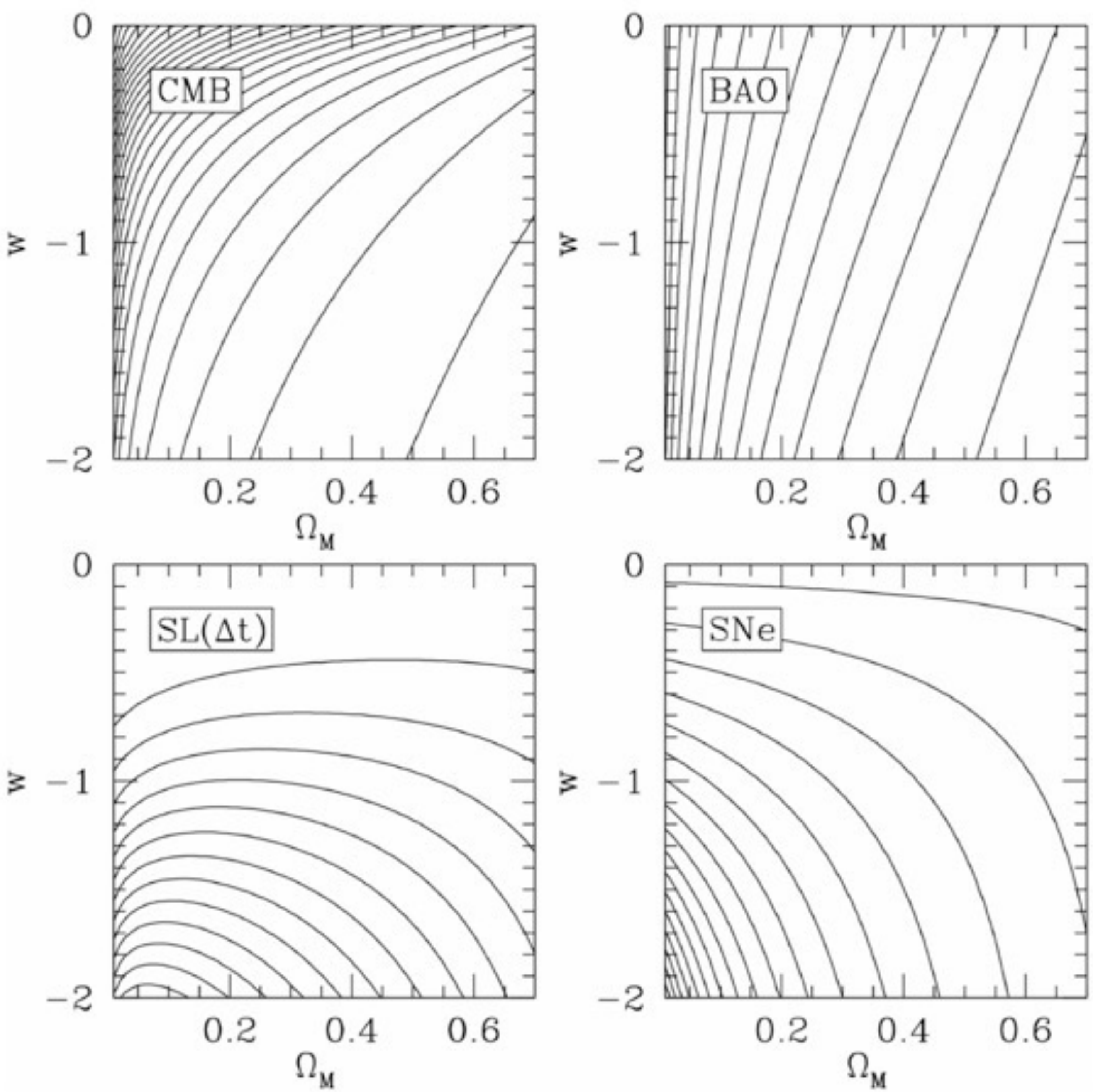
What we really measure is the angle subtended by r_s, i.e., $\theta_s = r_s / D_A(z=1091)$

Constraint on dark energy from CMB is only through this (→D_A), meaning that H_0 and dark energy are always degenerate



→ accurate H_0 is a key to improve DE constraint!

Distance ratio cosmography



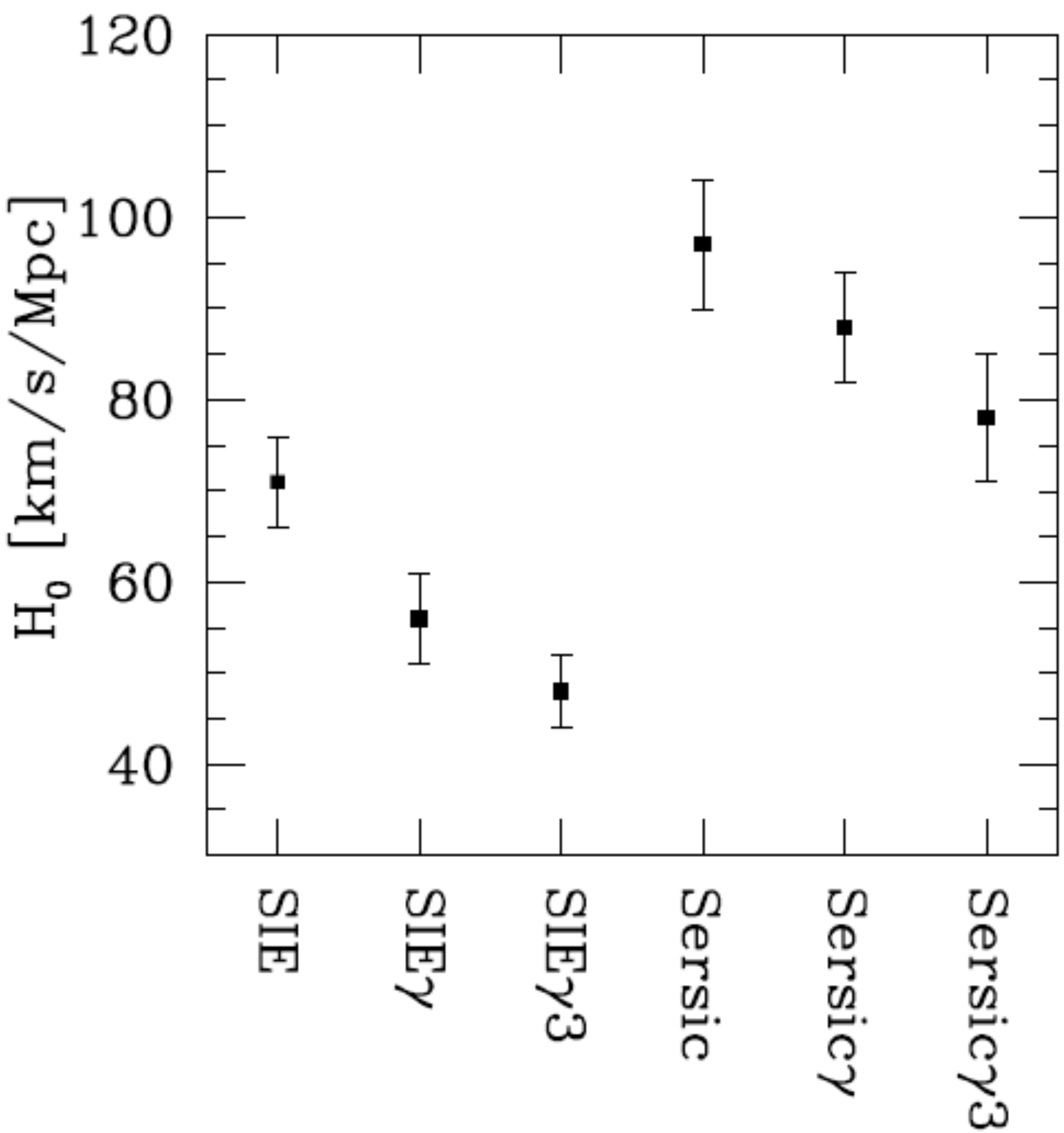
Time delays also probe dark energy directly through distance ratio $D_A(z_l)D_A(z_s)/D_A(z_l,z_s)$

The unique distance combination lead to the unique degeneracy direction, making it valuable DE probe

(see also Linder 2004)

LSST Science Book (arXiv:0912.0201)

However, ...



The biggest problem:
lens mass model

The resulting constraint on H_0 depends strongly on assumed mass model!

(example for 4-image lens PG1115+080)

Two approaches

1. “Golden lens” approach

   Investigate a singe lens in great detail to constrain its mass profile, and then use it to constrain cosmological parameters

   (e.g., Suyu et al. 2010)

2. “Ensemble of lenses” approach

   Combine many lenses to average out the lens mass model uncertainty

Two approaches

1. “Golden lens” approach

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   Combine many lenses to average out the lens mass model uncertainty

Statistics of time delays

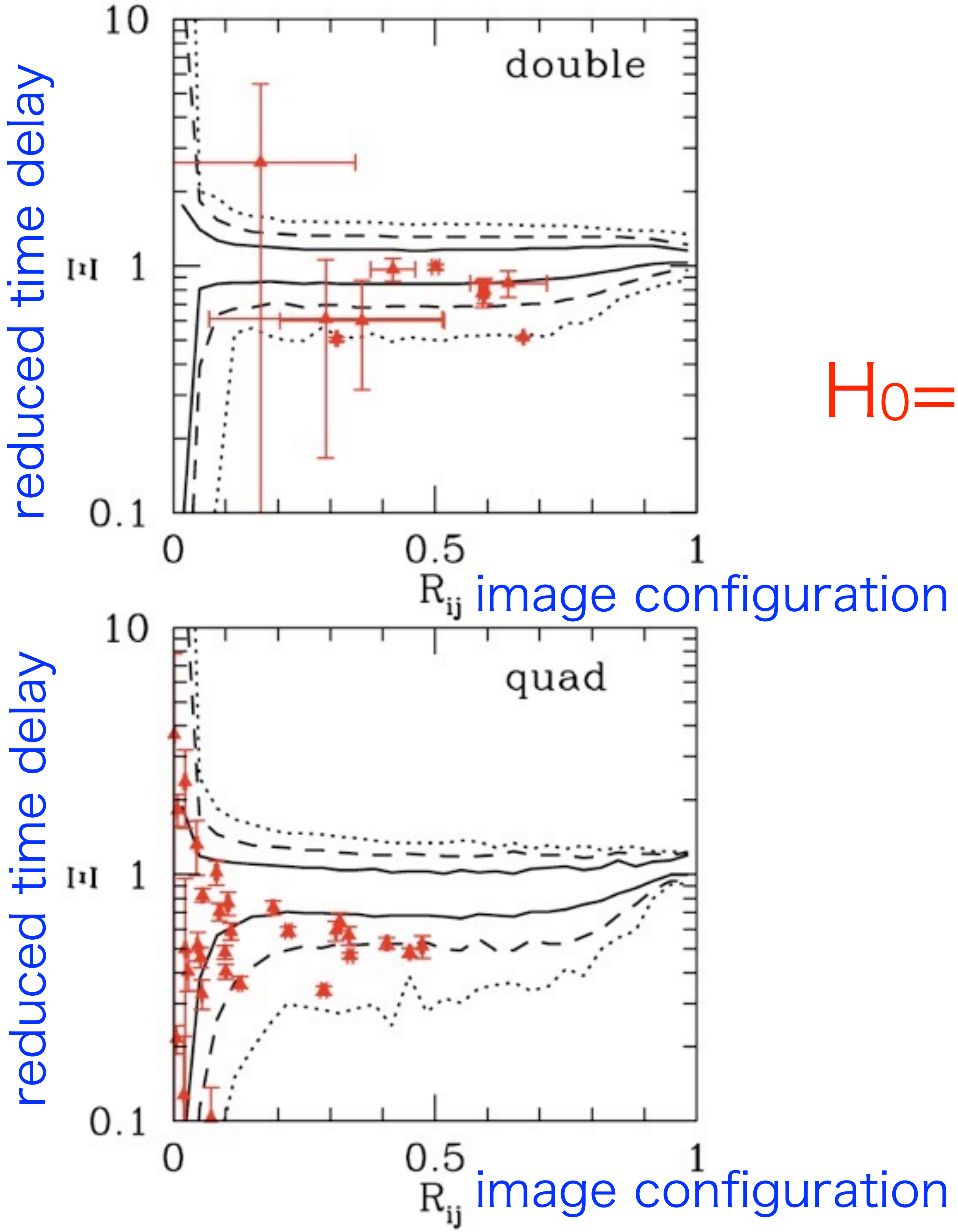
Oguri ApJ, **660**, 1 (2007)

A new statistical technique to combine many time delay measurements

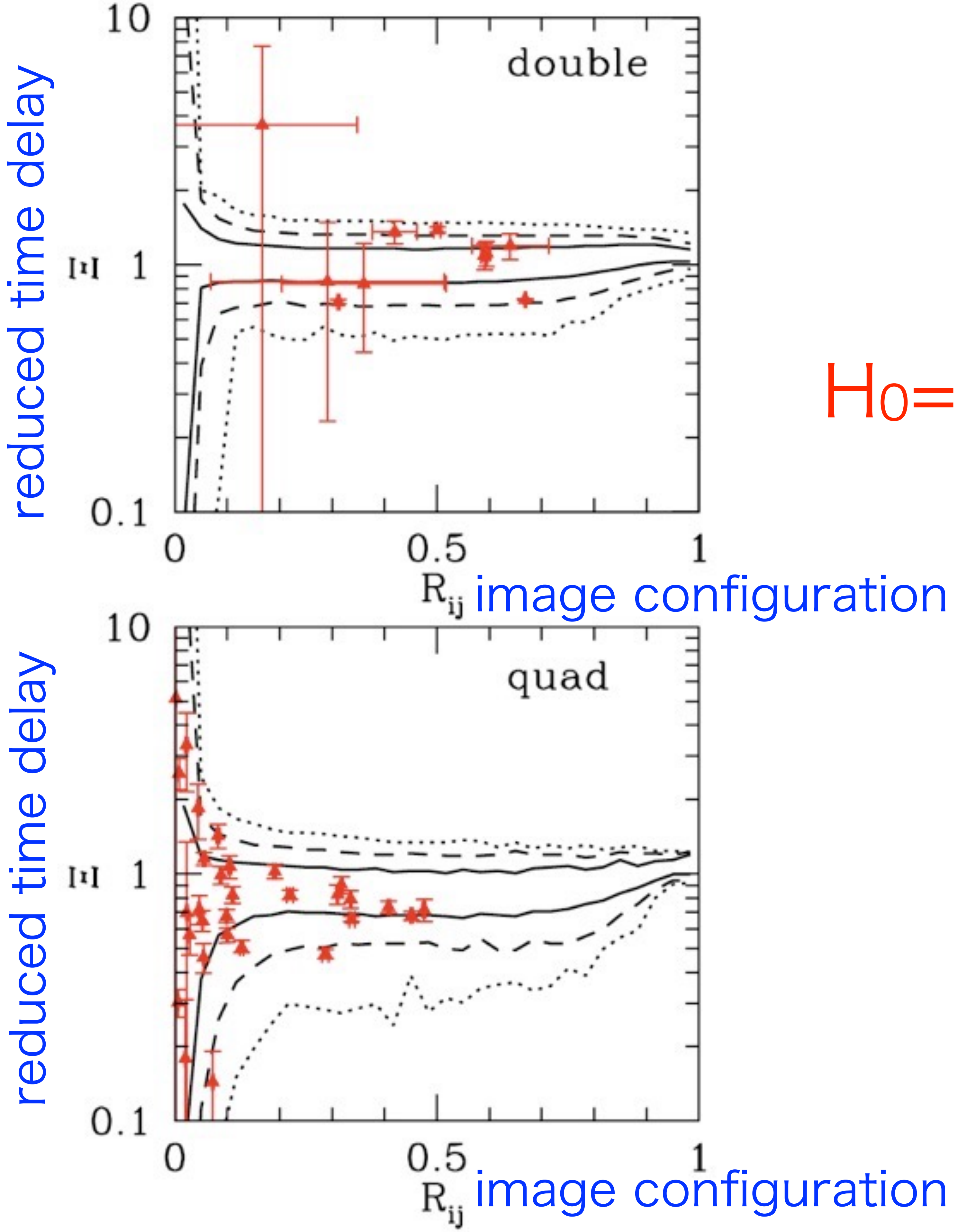
1. Define "reduced time delay" that quantifies the complexity of the lens potential

2. Derive reduced time delays as a function of image configurations and construct p(delay|image config.)

3. Compare it with observed delays to get constraints on cosmological parameters

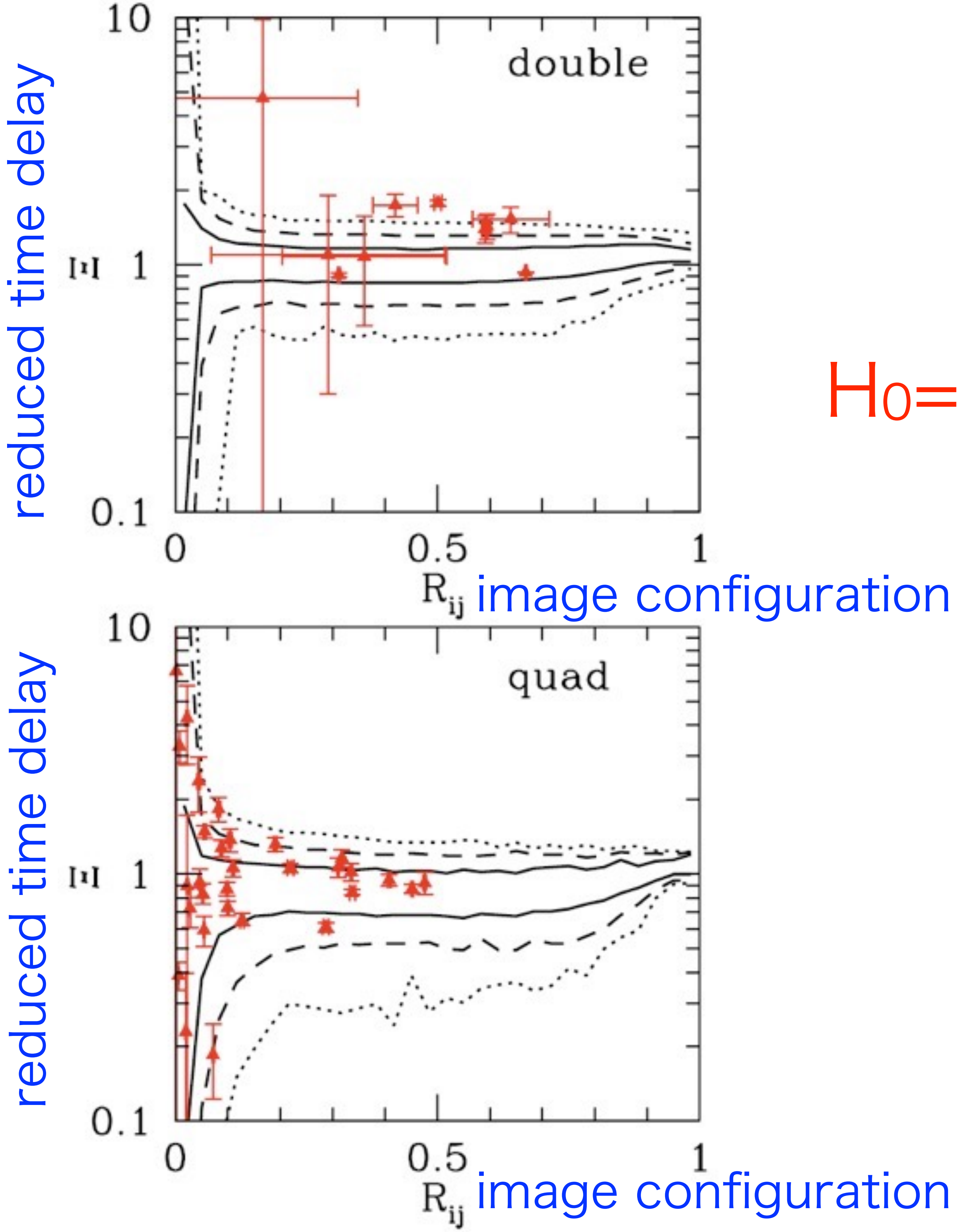

double
quad
reduced time delay
reduced time delay
Ξ
Ξ
10
1
0.1
10
1
0.1
0
0.5
1
0
0.5
1
R_ij image configuration
R_ij image configuration

H_0=50 km/s/Mpc



reduced time delay
double
quad
Ξ
10
1
0.1
0
0.5
1
R_ij image configuration
reduced time delay
Ξ
10
1
0.1
0
0.5
1
R_ij image configuration

H_0=70 km/s/Mpc



double
quad
reduced time delay
reduced time delay
Ξ
Ξ
10
1
0.1
10
1
0.1
0
0.5
1
0
0.5
1
R_ij image configuration
R_ij image configuration

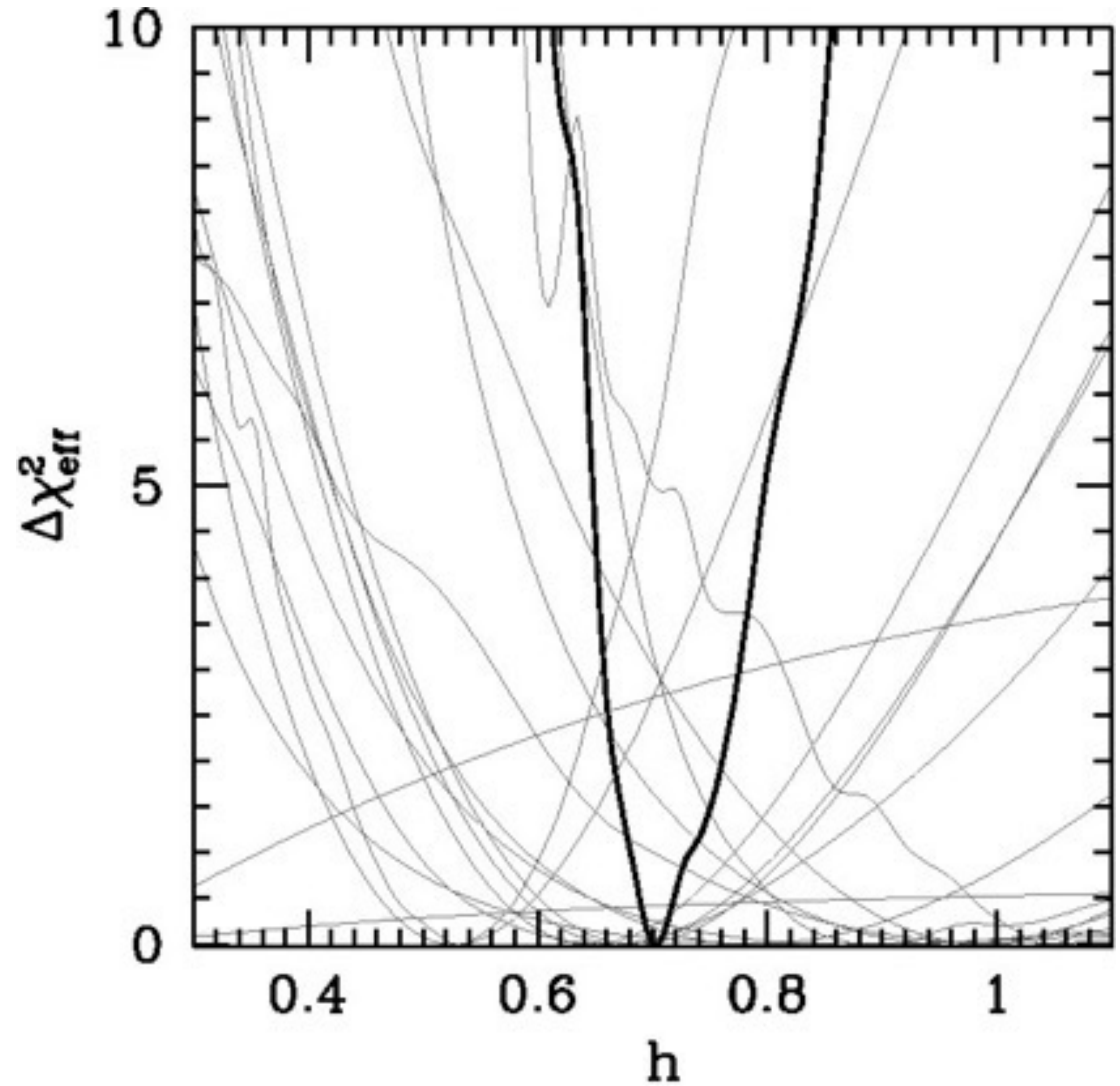
H_0=90 km/s/Mpc

Statistical constraint on H_0

Oguri ApJ, **660**, 1 (2007)

- Combined analysis of time delays for 18 lenses

- Fixing other cosmological parameters, the Hubble constant is constrained to H_0=70±6 km/s/Mpc



Future: LSST

(Large Synoptic Survey Telescope)

http://www.lsst.org

#1 in Astro2010

8.4-m telescope in Chili

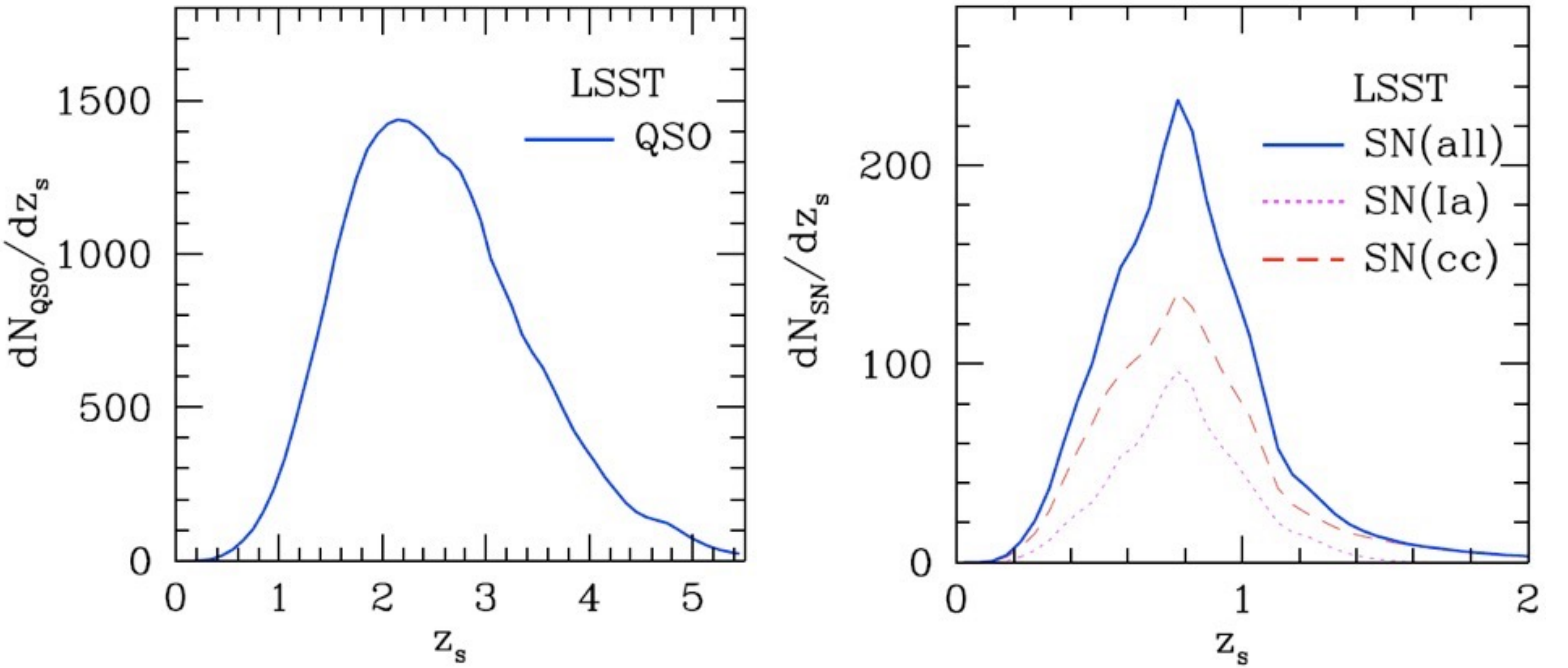
Survey from ~2017

Cover the entire visible sky every few days

→ Time-domain data for 1/2 of the whole sky!

Lensed QSOs/SNe in LSST

Oguri & Marshall MNRAS, **405**, 2579 (2010)



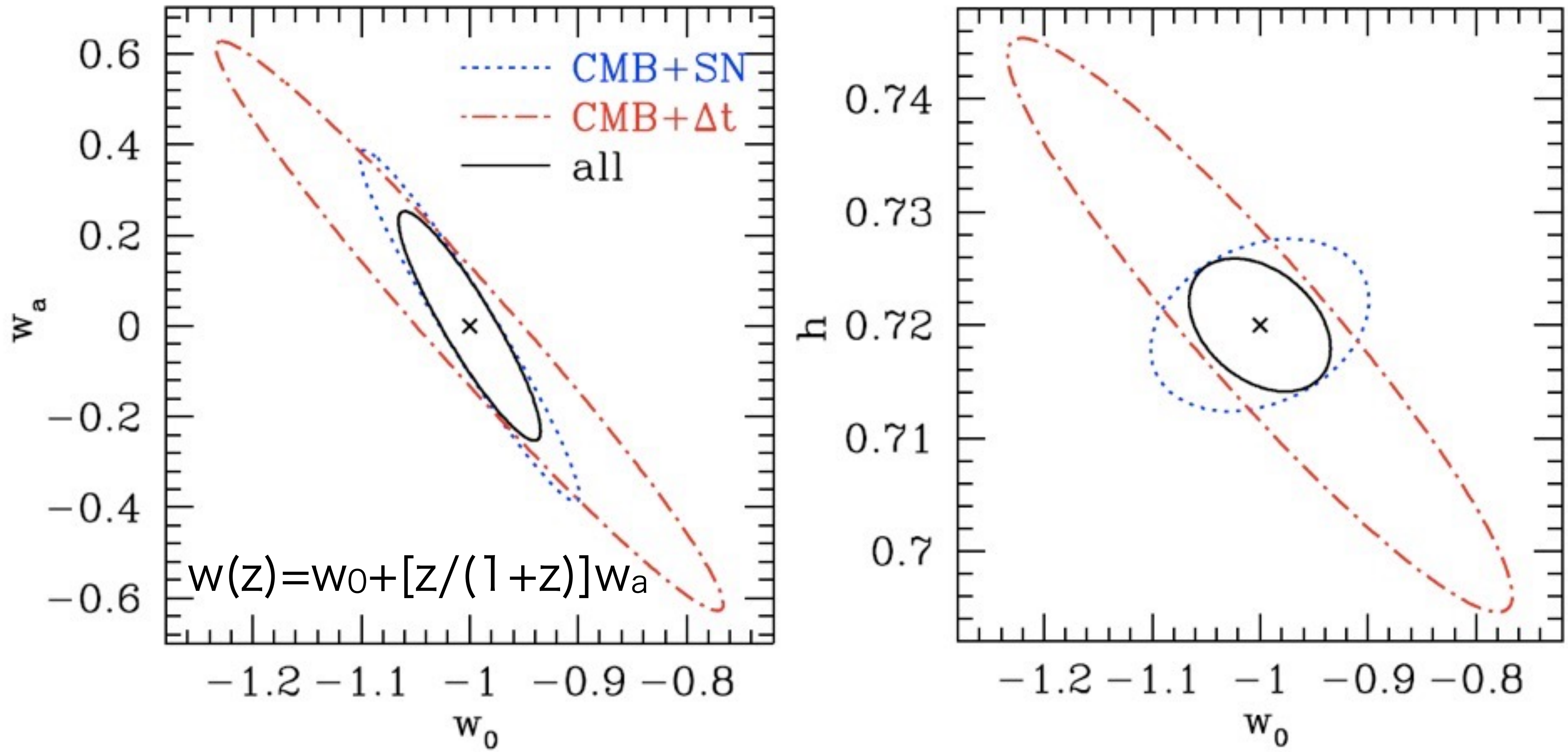
~3,200 lensed quasars

~130 lensed SNe
(~35% is Ia)

Time delays will be measured for **all** of these!

Forecasting DE measurement

Oguri & Marshall MNRAS, **405**, 2579 (2010)



(CMB - Planck, SN - JDEM, Δt - LSST)

Future time delays can help to constrain w(z)

Time delay: summary

- Time delays can be a unique probe of dark energy, through H_0 and distance ratio $D_A(z_l)D_A(z_s)/D_A(z_l,z_s)$
- The current limiting factor is the mass distribution in lensing galaxy; we can get around this using novel statistical technique
- Currently time delays are already putting interesting cosmological constraints
- In the future, statistics of time delays can be a powerful cosmological probe thanks to planned time-domain surveys (e.g., LSST)

Thank you!

감사합니다!