Applications of gravitational lensing in astrophysics and cosmology

4. Cosmological applications

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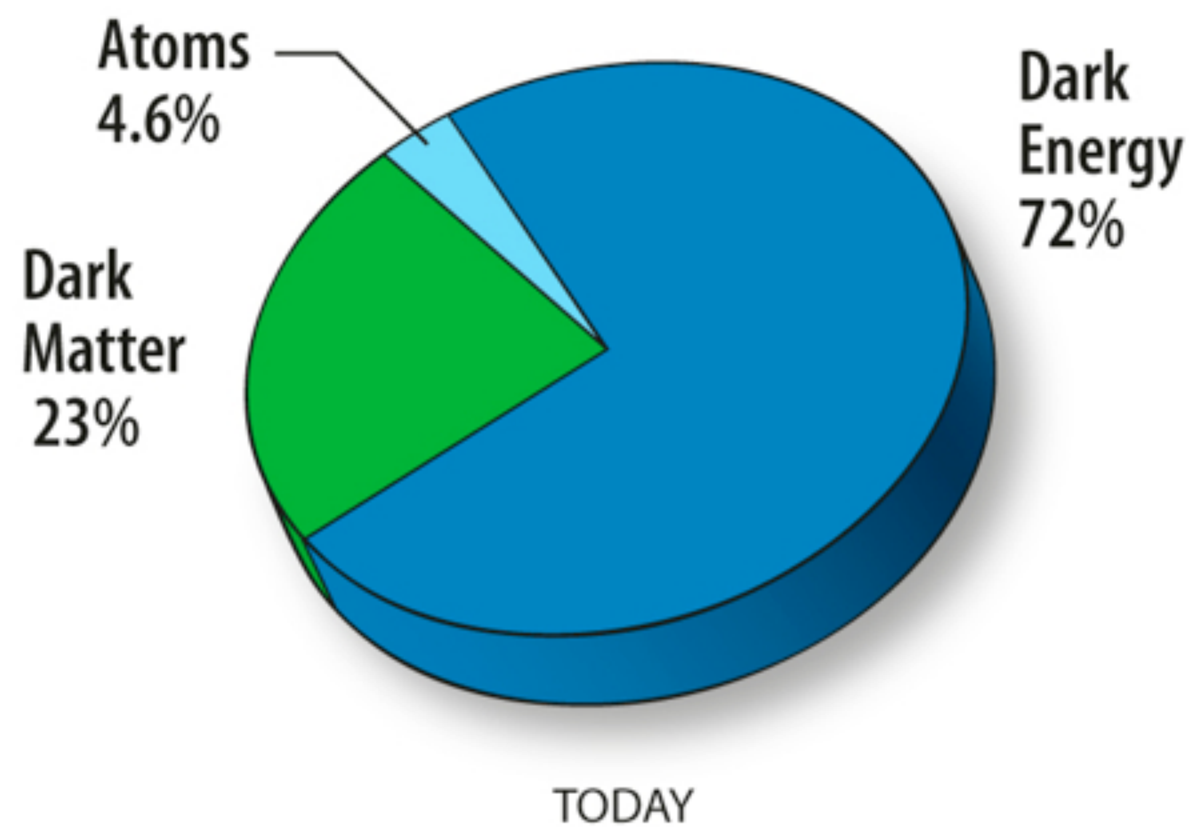
Outstanding issues

- Universe is dominated by unknown components called dark matter and dark energy



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

Dark matter: my (biased) view

- assumed to be cold and collision-less

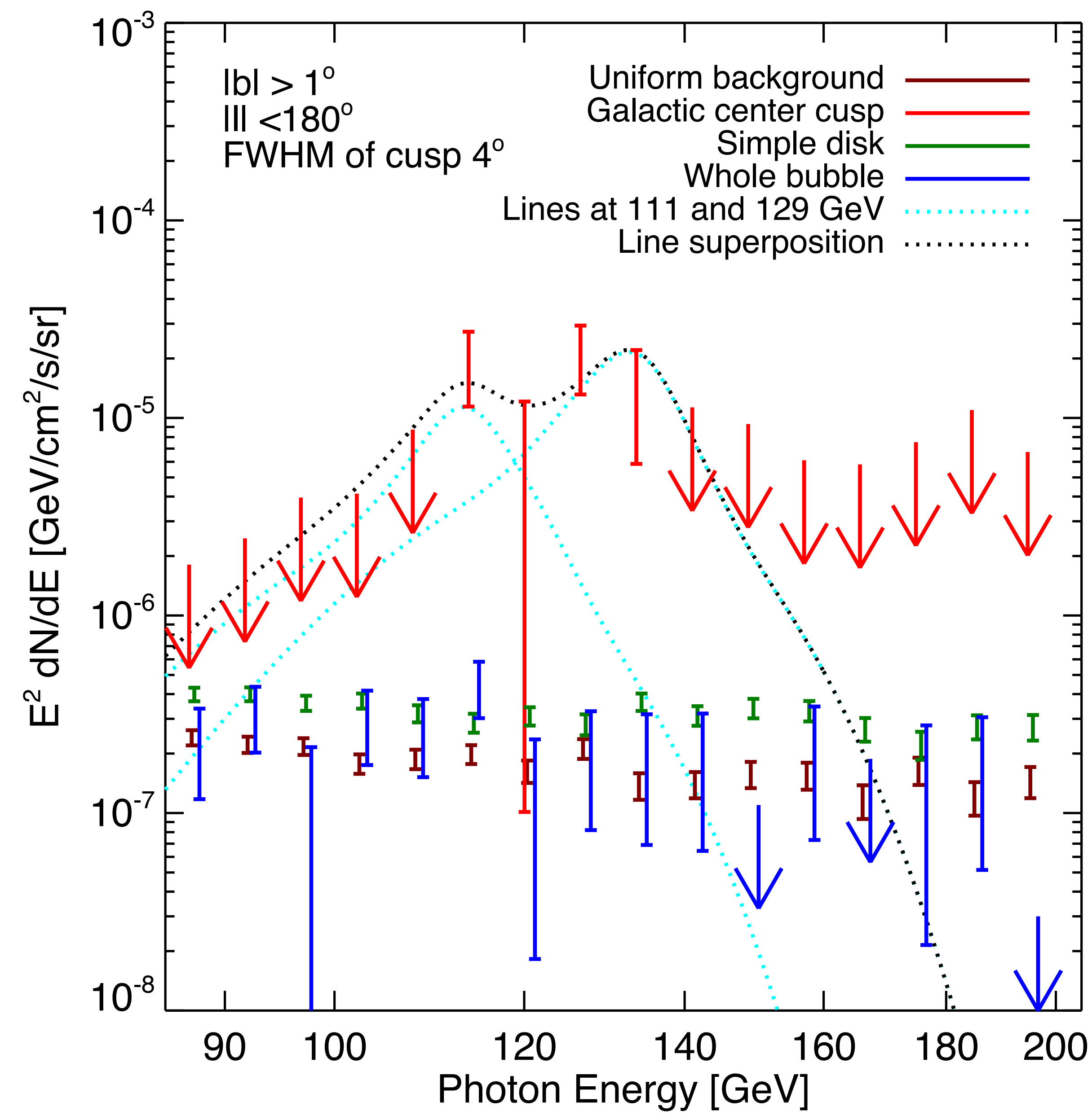
- it works remarkably well at cluster scale
  (e.g., Clowe et al. 2006; Oguri et al. 2012)

- currently, it looks ok at galaxy scale too
 (satellite/dwarf problems being resolved...)

- extensive efforts for direct/indirect detections

Dark matter detected??

- Su and Finkbeiner reported gamma ray line from Galactic center in the public Fermi satellite data
- it is consistent with WIMP annihilation at energy 127±3 GeV
- interestingly, LHC recently discovered "Higgs" at 126GeV!



Su & Finkbeiner arXiv:1206.1616

Dark energy: my (biased) view

- energy component that leads to accelerated expansion of the Universe

$$p_{\rm DE} = w(z)\rho_{\rm DE}$$ $w(z) \sim -1$: dark energy EOS

- currently no plausible physical model

- therefore no direct/indirect detection likely in the near future

- only astronomical observations provide clues

Or modified gravity?

- Einstein equation for usual dark energy model

$$G_{\mu\nu} = 8\pi G(T_{\mu\nu}^{\mathrm{matter}} + T_{\mu\nu}^{\mathrm{dark\,energy}})$$

- an alternative is to modify action and let the higher-order term to accelerate the Universe

$$G_{\mu\nu} + F_{\mu\nu} = 8\pi G T_{\mu\nu}^{\mathrm{matter}}$$

- lensing will provide a key to distinguish modified gravity with dark energy

Cosmological application

- constraints from geometrical tests
- constraints from growth of structure

Geometrical tests

- measure Hubble parameter (=expansion rate)

$$H^2(a) = H_0^2\left[\Omega_M a^{-3} + \Omega_K a^{-2} + \Omega_{\rm DE} e^{-3\int_1^a da'(1+w(a'))/a'}\right]$$

- or its integral (=distance)

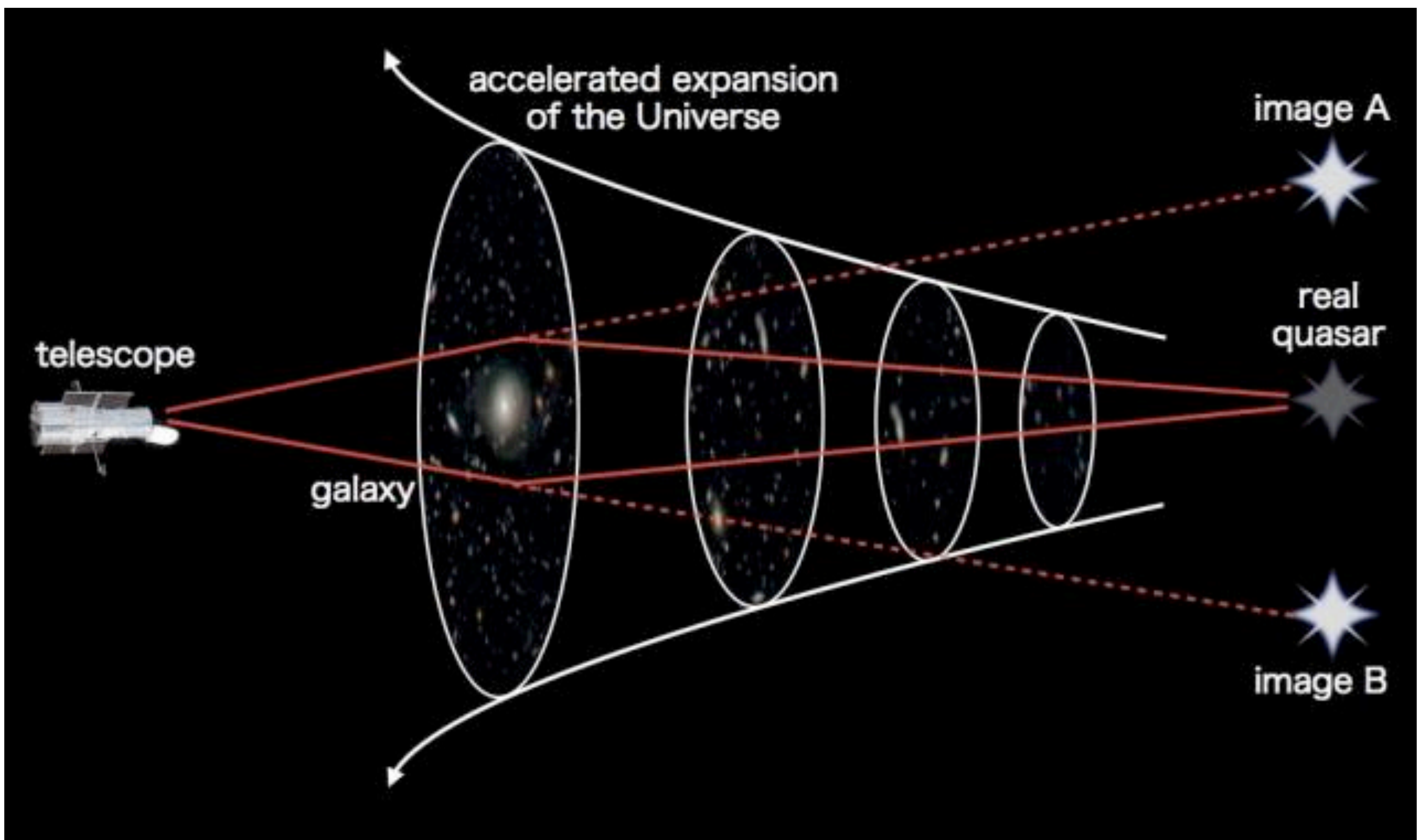
$$\chi = \int_a^1 \frac{c\,da'}{a'^2 H(a')}$$

Geometrical tests with lensing

- quasar lens statistics
- time delays between quasar images
- distance ratios from lensing

Quasar lens statistics

- acceleration of the Universe increases a chance of strong lensing for a distant quasar
  (Fukugita et al. 1990; Turner 1990)



How it works

- lensing objects of lensed quasars are dominated by early-type galaxies which formed early (z~2)

- assume that velocity dispersion function $dn/d\sigma$ does not evolve with redshift (up to z~1)

- then probability that a distant quasar is strongly lensed is proportional to the volume element $D_A(z)^2 H(z)^{-1}$, which is sensitive to dark energy

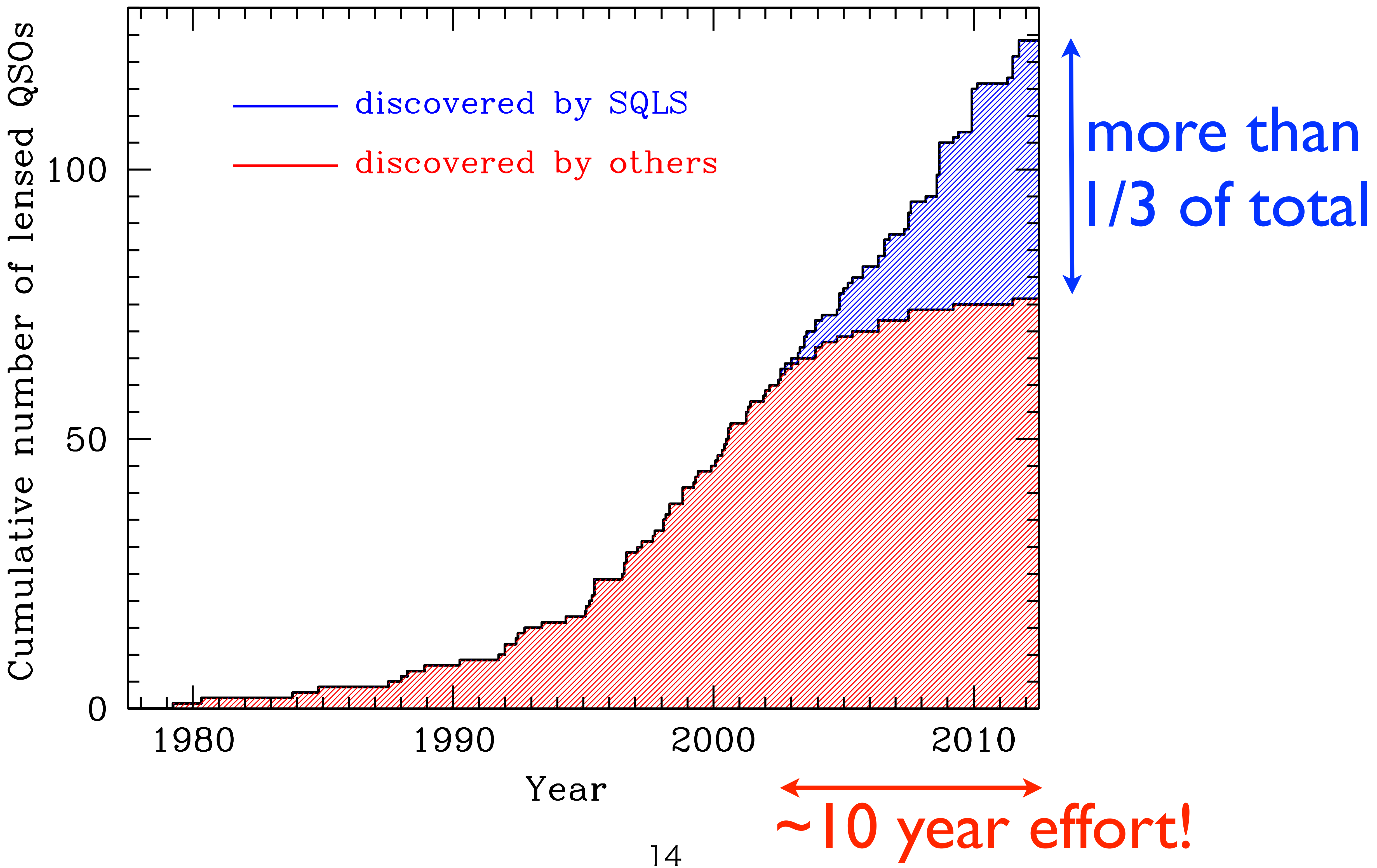
- a problem: samples of lensed quasars too small!

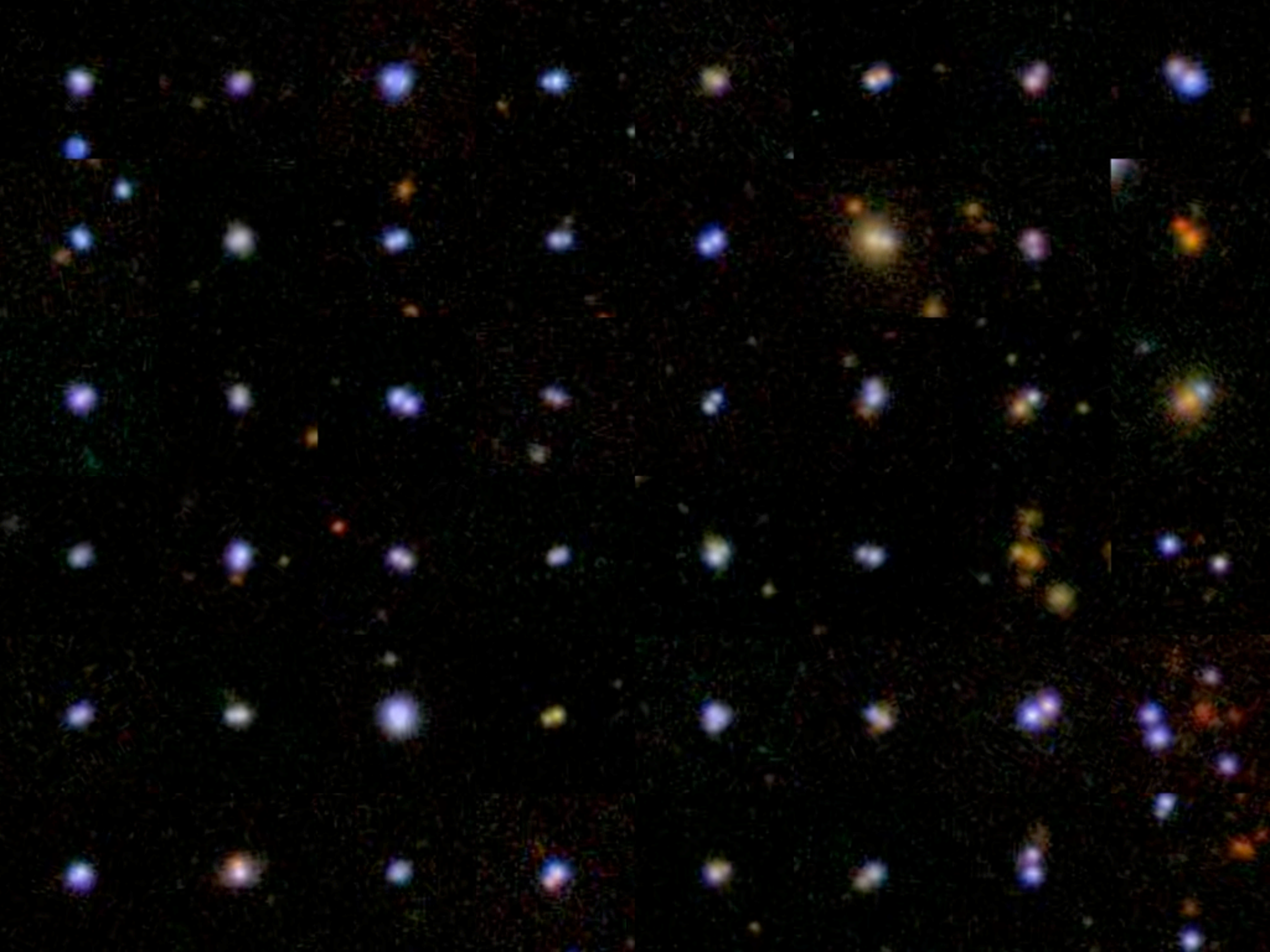
http://www-utap.phys.s.u-tokyo.ac.jp/~sdss/sqls/

SDSS quasar lens search (SQLS)

- project to search for strongly lensed quasars among spectroscopic SDSS quasars
- identify lens candidates using ugriz-band SDSS images, need extensive follow-up observations to confirm true lenses
- all the survey in DR7 already completed!
- co-PI: Naohisa Inada, Masamune Oguri

Number of lenses discovered



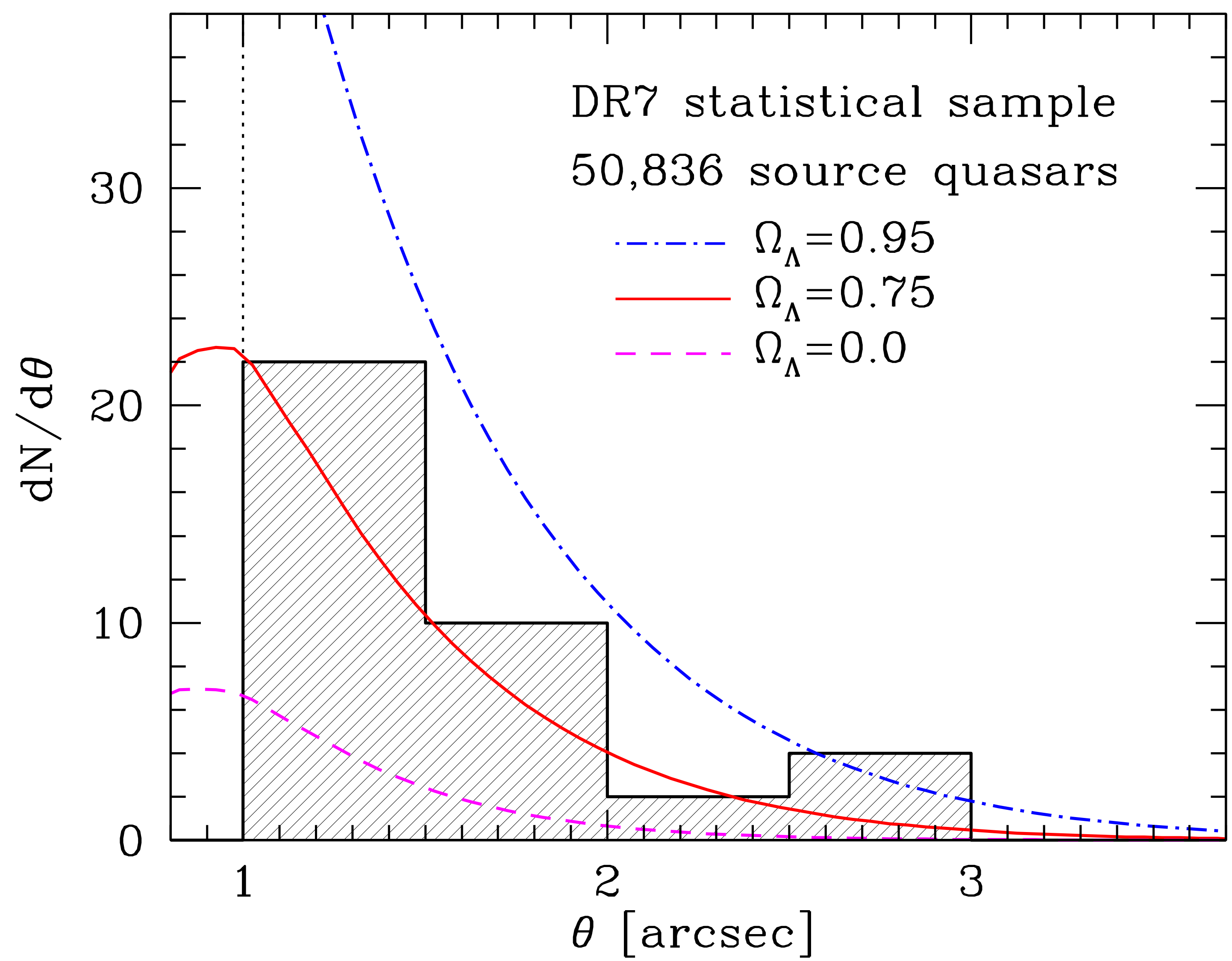


Oguri et al. AJ **143**(2012)120

Cosmological constrains from DR7

- use a statistically well-defined subsample of 19 lensed quasars from 50,836 quasars

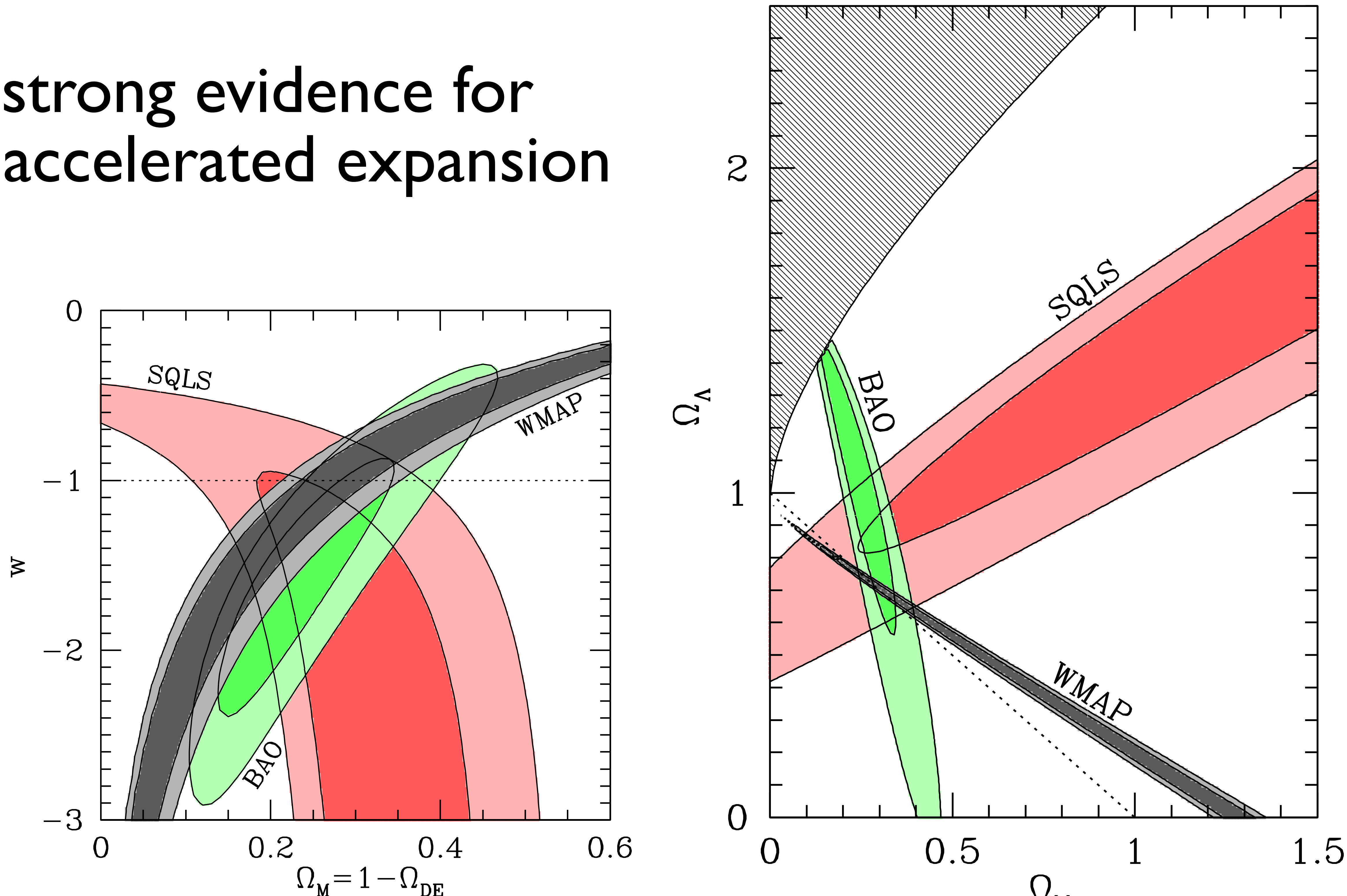
- also include lens redshifts, which help disentangle cosmology and galaxy evolution (also papers by Cao, Zhu+)



Oguri et al. AJ **143** (2012) 120

Cosmological constrains from DR7

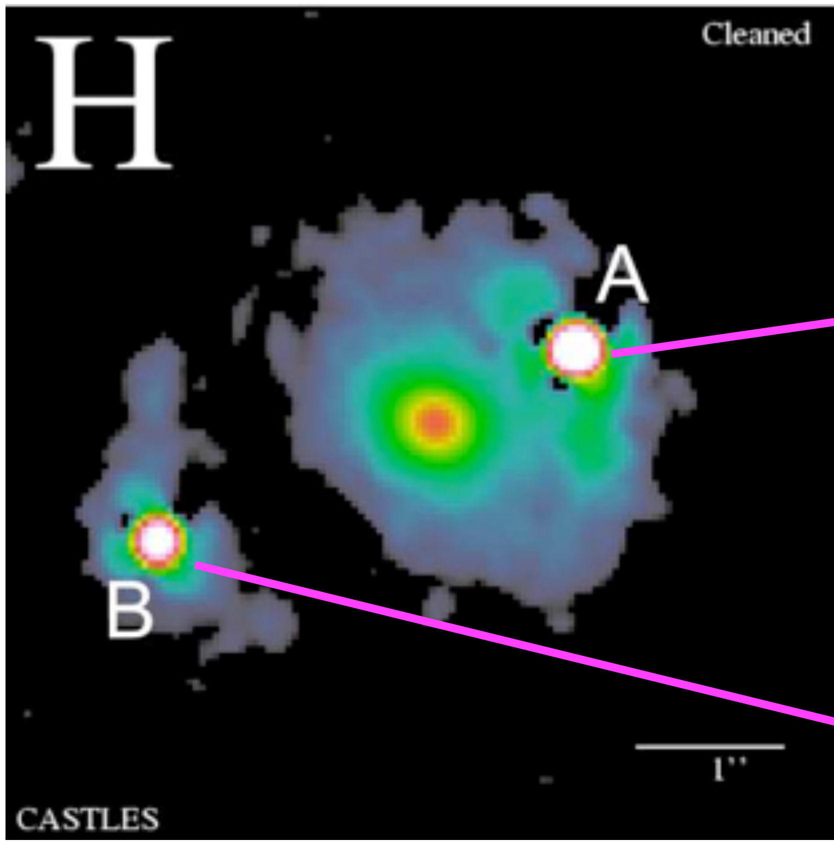
- strong evidence for accelerated expansion

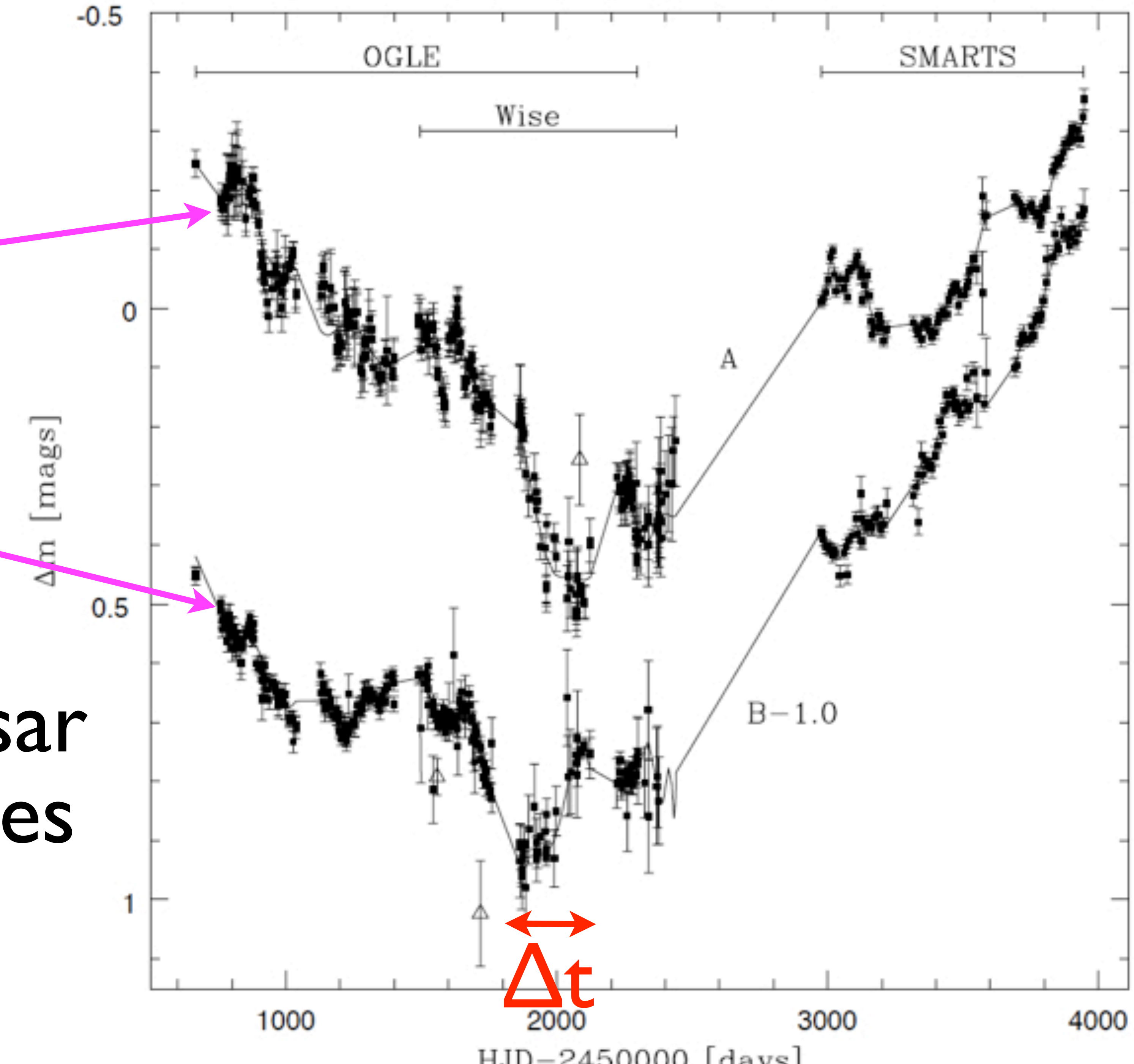


Quasar lens statistics: summary

- large SQLS lens sample confirmed dark energy
- the result becomes less significant if we allow velocity dispersion function to evolve, but still favor models with dark energy
- in SQLS, systematic errors (from the lens mass distribution and velocity dispersion function) are estimated to be comparable to statistical errors, suggesting that this method may not be very promising in the future

Time delays between quasar images





- monitoring of quasar lens systems enables measurements of time delays
  (~20 measurements so far)

Poindexter et al. (2007)

Time delay and H_0

- time delay is known to provide a unique probe of the *absolute* distance scale, H_0

$$c\Delta t_{\rm obs} = (1+z_l)\frac{D_A(z_l)D_A(z_s)}{D_A(z_l,z_s)}\left[\frac{1}{2}\left|\vec{\theta}-\vec{\beta}\right|^2-\psi\right]$$

observe (typically a few months)

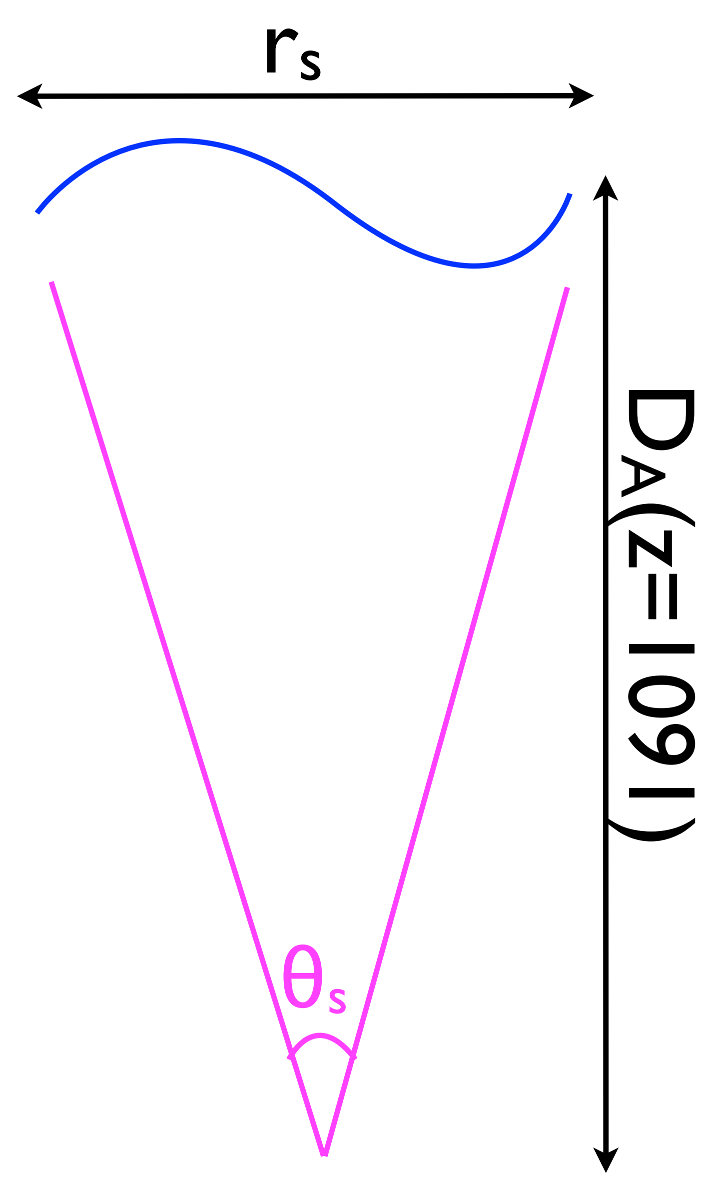
observe (θ) + mass modeling

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

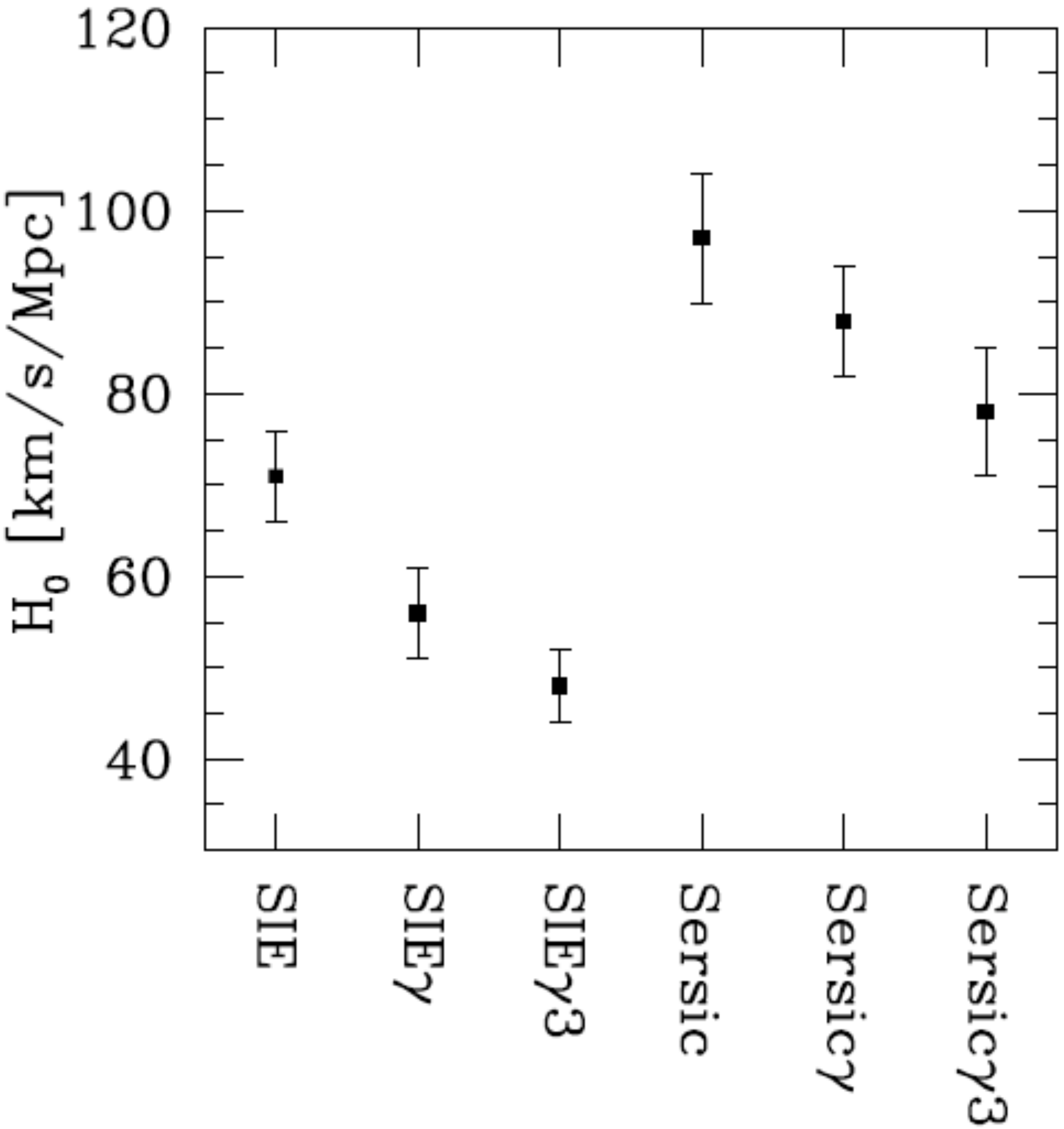
H_0 and dark energy

- a characteristic scale of CMB is sound horizon r_s at z=1091
- we measure an angle subtended by r_s, i.e., $\theta_s=r_s/D_A(z=1091)$
- constrains on dark energy from CMB comes through this, meaning H_0 and dark energy are always degenerate

(accurate H_0 is a key for dark energy!)



Challenge: lens model dependence



(names of lens model assumed)

- example from quadruple quasar lens PG1115+080
- resulting constraints on H_0 depends sensitively on assumed lens mass distribution

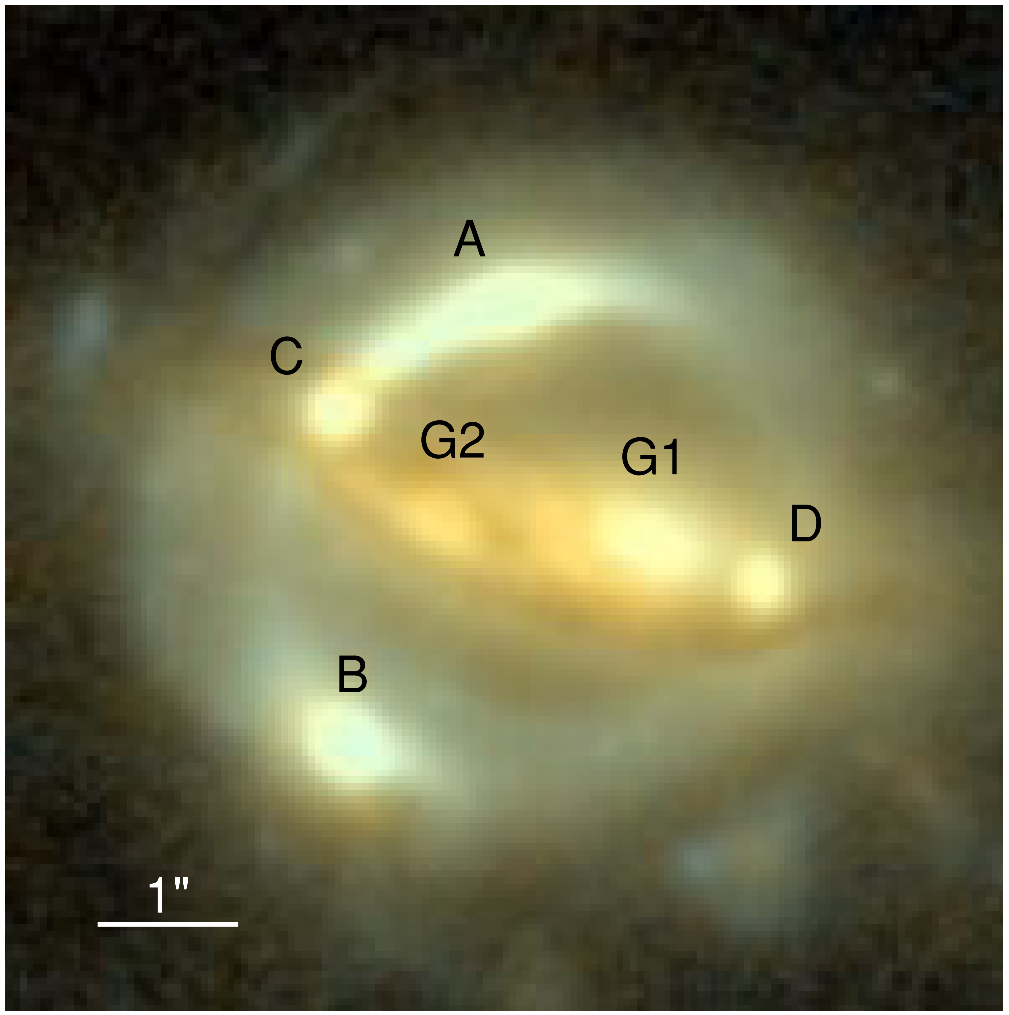
How to get around

(1) "golden lens" approach
add many observations (velocity dispersion, lensed host galaxy, ...) to constrain the lens potential and derive H_0 (e.g., Suyu et al. 2010)

(2) "ensemble of lenses" approach
combine many quasar lenses to average out complexity and perturbation on the lens potential, use our knowledge on average properties of lensing galaxies to derive H_0 (e.g., Oguri 2007)

Suyu et al. ApJ **711** (2010)201

"Golden lens" B1608+656

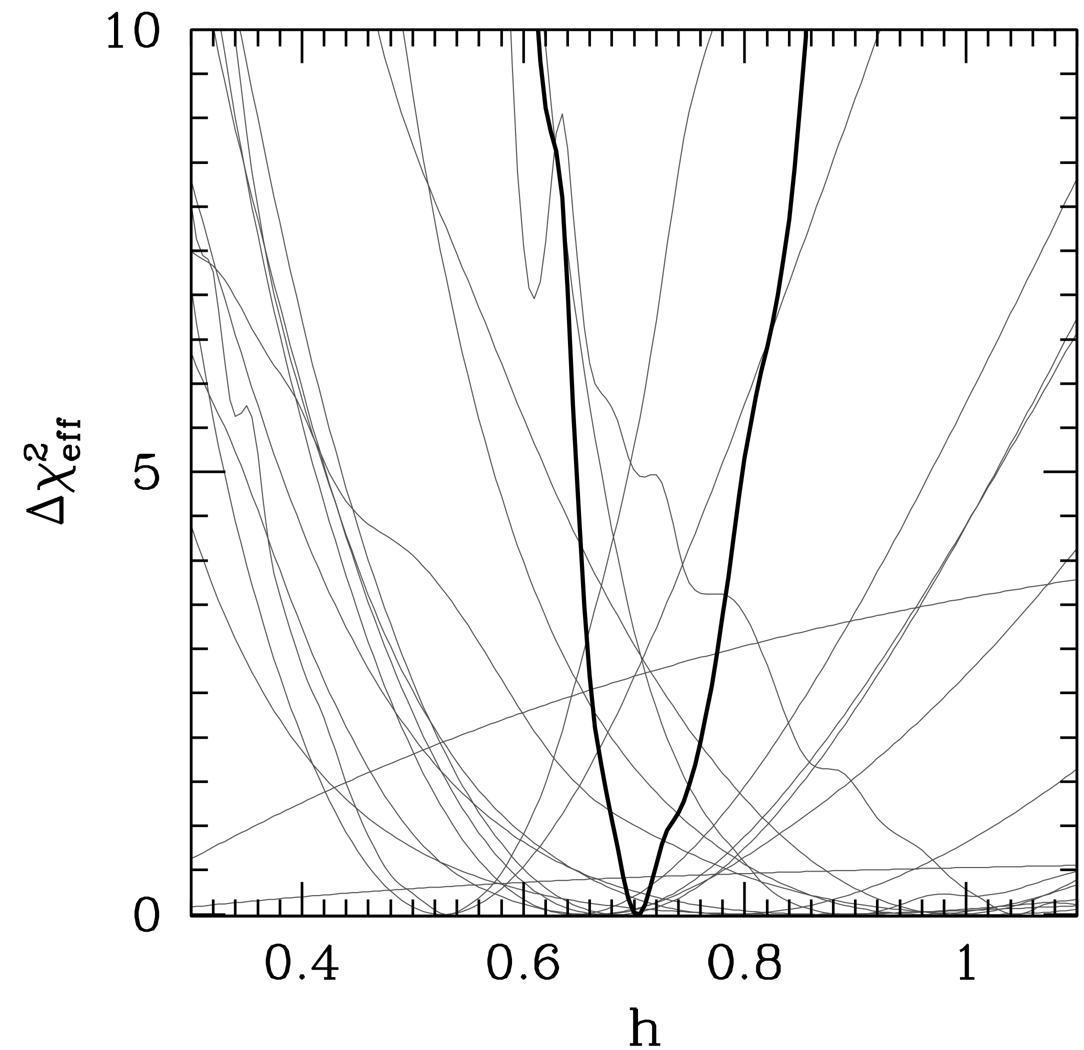


- four-image radio-loud lens system with extended source, velocity dispersion, ..
- H_0=70.6±3.1 km/s/Mpc for a fixed Ω_M and Ω_Λ
- uncertainty dominated by l.o.s. matter fluctuations (mass-sheet degeneracy), need several more golden lenses to average it out

Oguri ApJ **660**(2007)1

"Ensemble of lenses" approach

- concept: define dimension-less `reduced time delay' which quantifies complexity of lens potentials
- most perturbations are shown to be averaged out in this statistics
- by combining 16 lenses, H_0=68±6(stat.)±8(syst.)km/s/Mpc



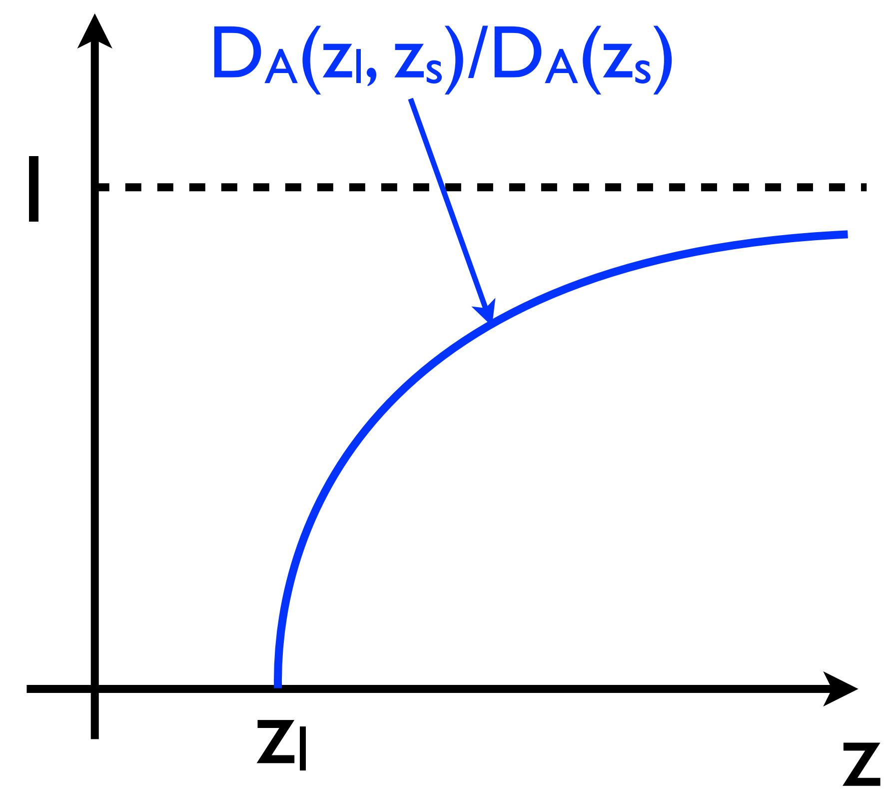
Time delays: summary

- time delays provide unique way to constrain H_0
- a challenge lies in degeneracy with lens mass distribution, which can be overcome by either very detailed observations and modeling or relevant statistical approaches
- future of time delays is bright, more data from time-domain surveys (LSST, Pan-STARRS, ...) and people are getting more interested in time delays these days

Distance ratio cosmography

- lensing signals proportional to Σ_{cr}^{-1}, so for a fixed lens redshift signals scale as

$$\alpha,\ \kappa,\ \gamma \propto \frac{D_A(z_l, z_s)}{D_A(z_s)}$$



- one can constrain dark energy by observing this evolution of lens signals as a function of z_s

Many approaches

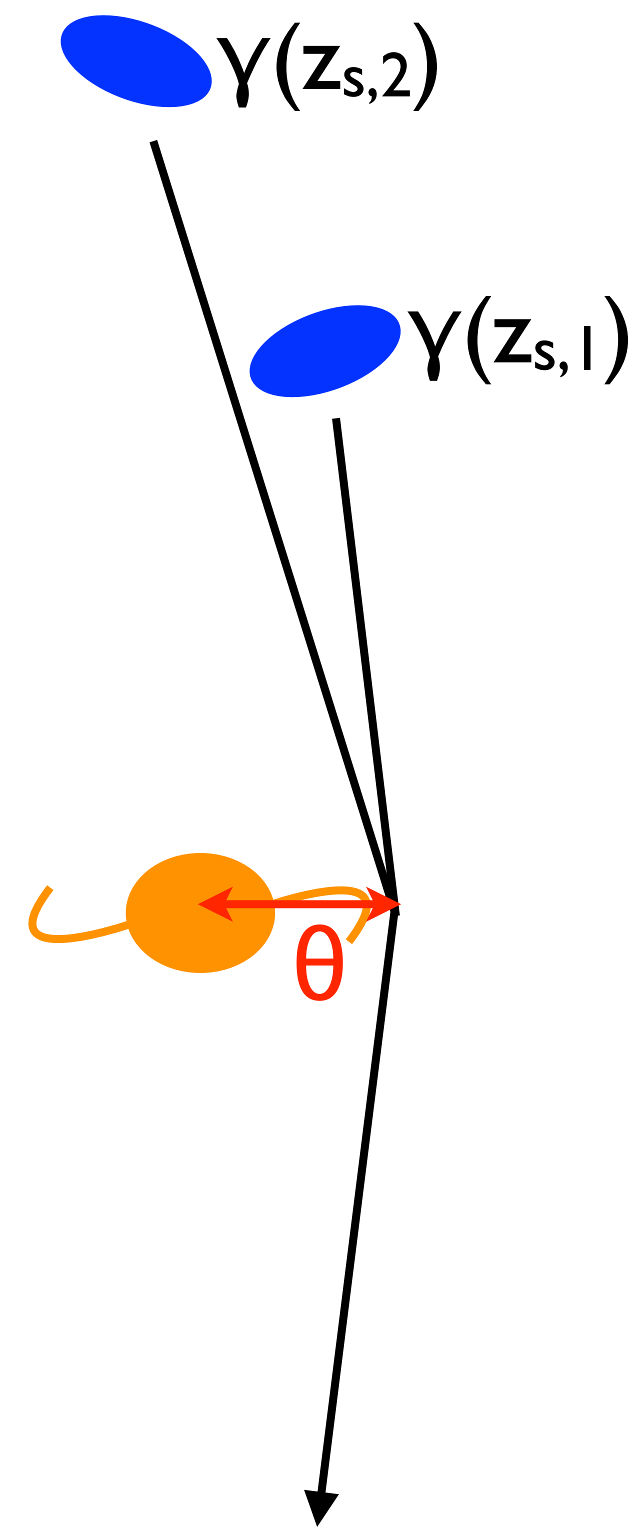
- the Einstein radius plus velocity dispersion (e.g., Grillo et al. 2007; Liao & Zhu 2012)
- double Einstein rings (e.g., Collett et al. 2012)
- many arcs in massive cluster (e.g., Jullo et al. 2010)
- again, degeneracy with the lens potential is the limiting factor

Shear ratio test

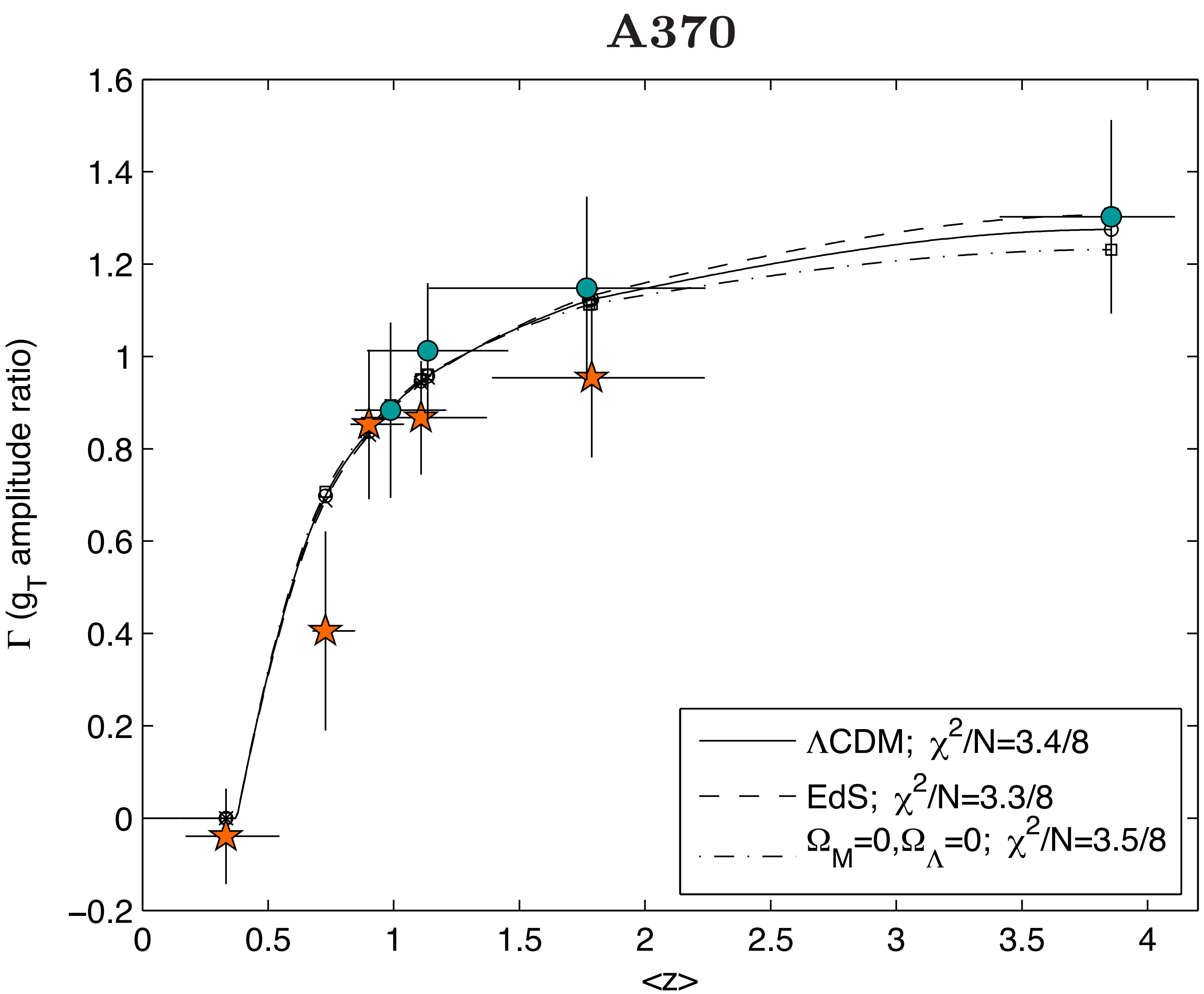
- for given lens(es), take a ratio of weak lensing shears at some fixed radius θ but at different z_s

$$\frac{\gamma(\theta; z_{s,1})}{\gamma(\theta; z_{s,2})} = \frac{D_A(z_l, z_{s,1})}{D_A(z_{s,1})} \frac{D_A(z_{s,2})}{D_A(z_l, z_{s,2})}$$

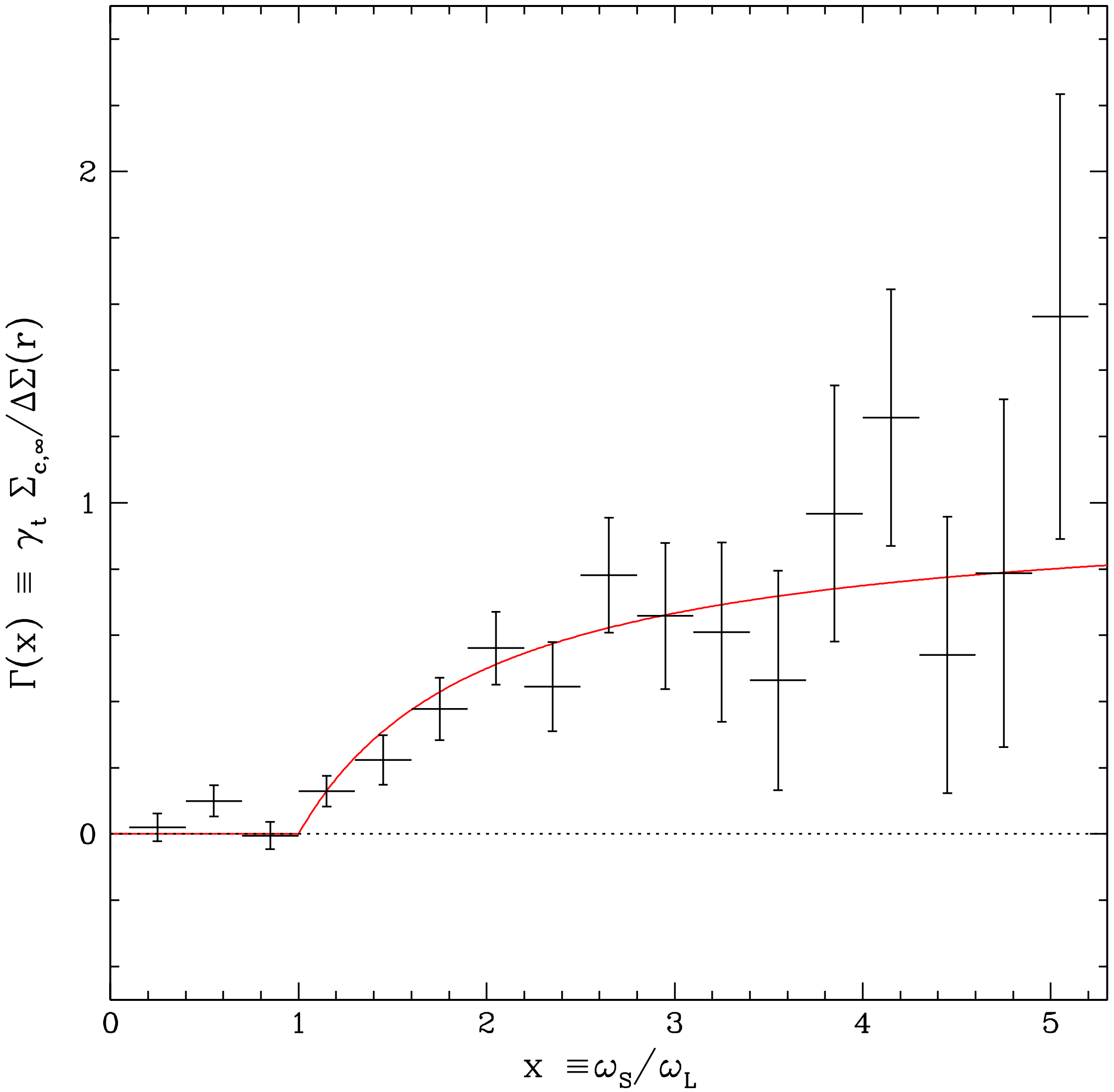
- advantage: lens mass distribution dependence ($\Sigma(\theta)$) cancels out! (Jain & Taylor 2003)



Shear ratios in observations



in massive clusters
(Medezinski et al. 2010)



in stacked groups
(Taylor et al. 2012)

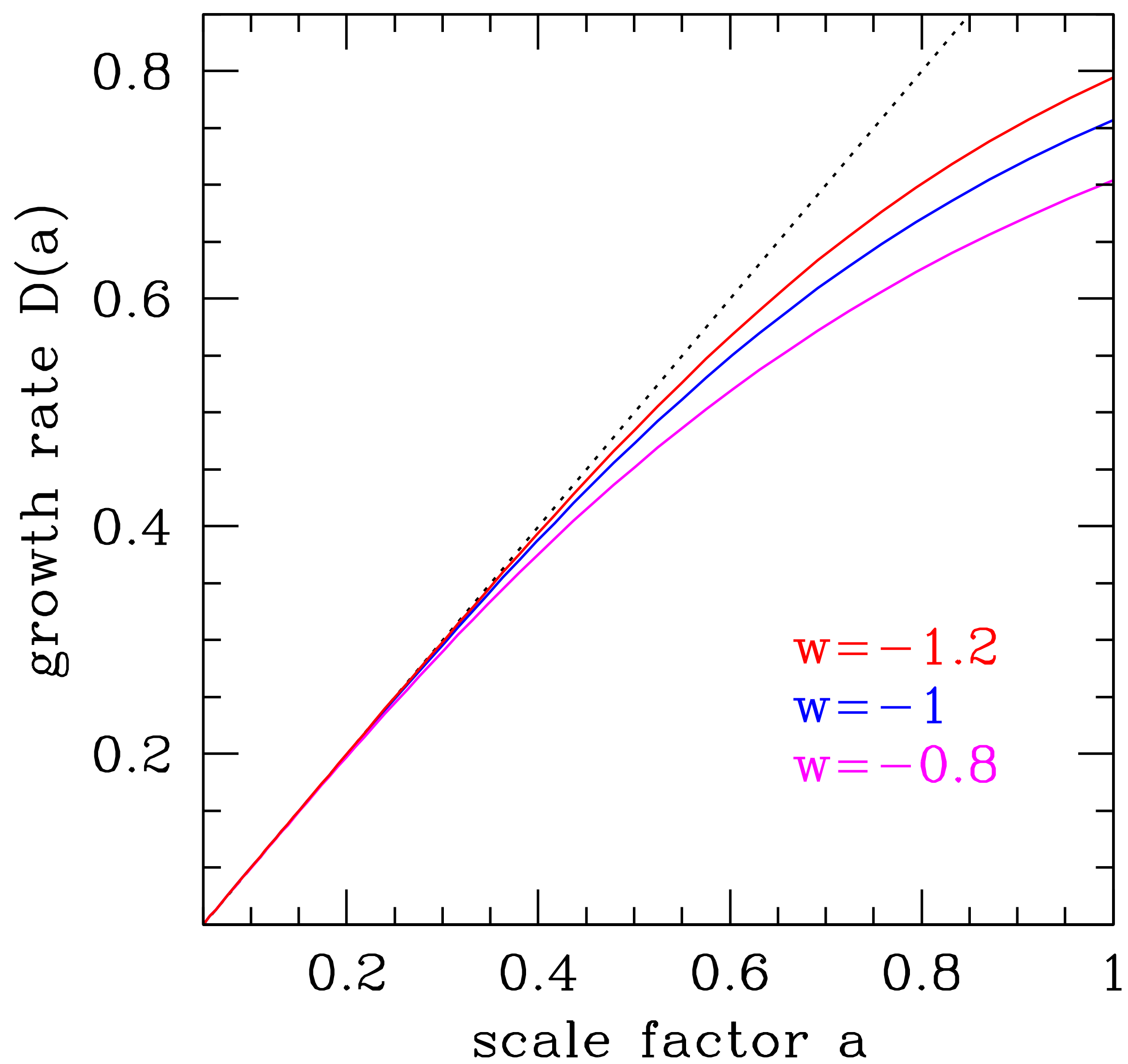
Distance ratio: summary

- there are many ways to measure distance ratios from strong and weak lensing
- again, degeneracy with lens mass distribution is a main source of systematics

Growth of structure

- density fluctuations grow as $\delta(a) \propto D(a)$ in the linear regime

- D(a)=a when Universe is matter dominated, but growth slows down due to the accelerated expansion

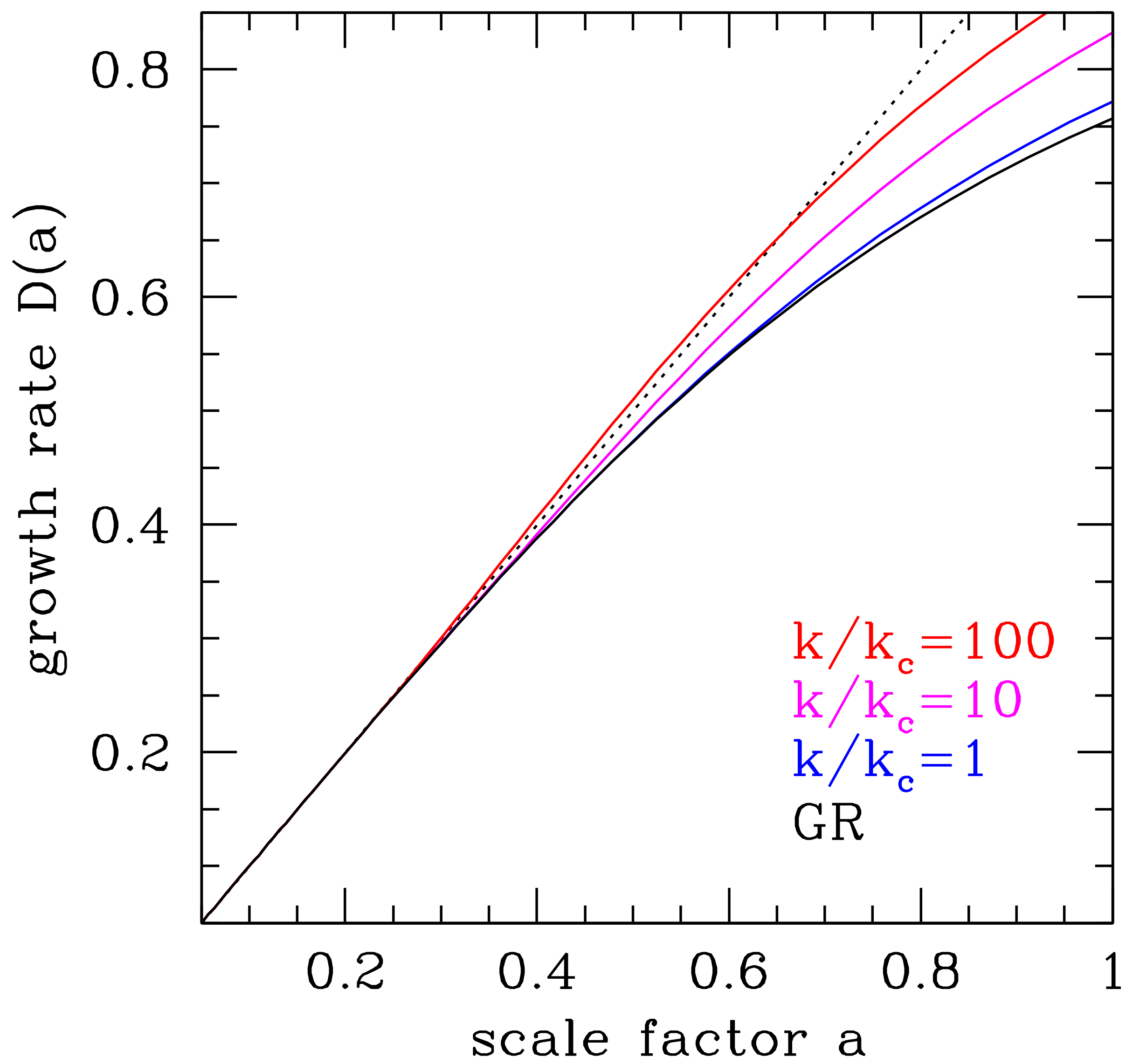


- provides another way to study dark energy

Growth in modified gravity

- in modified gravity theories, growth rate D(a) can be different from GR, even if the expansion history is exactly the same

- therefore growth of structure is a key to distinguish dark energy from modified gravity



(example from f(R) model)

Weak lensing

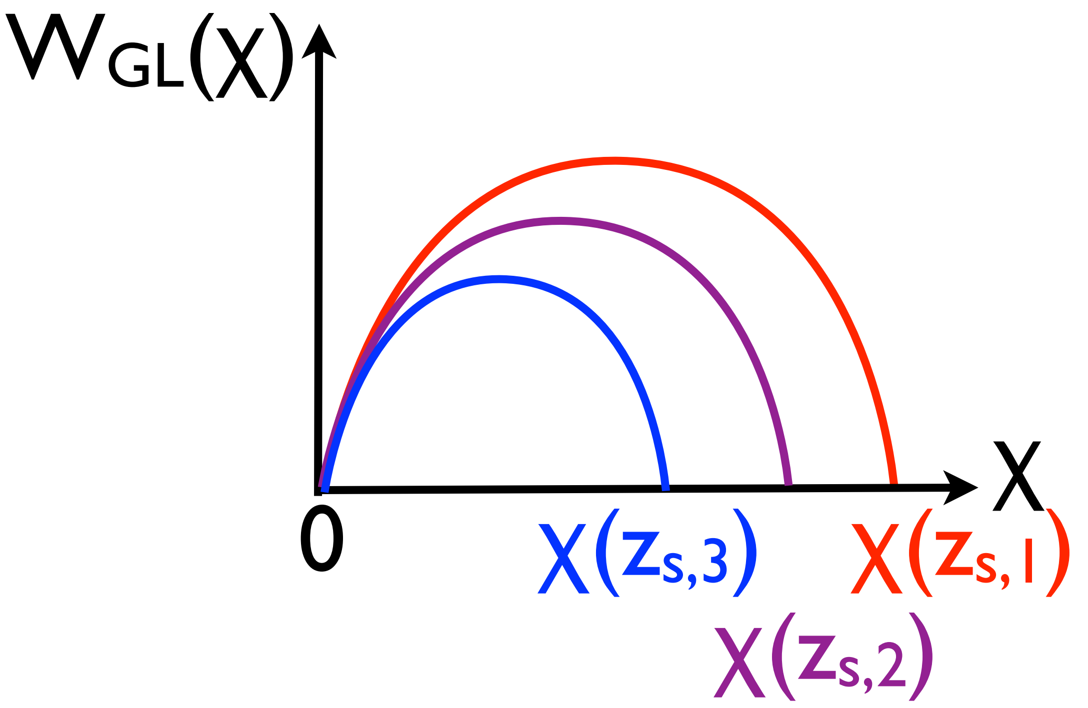
- weak lensing probes amplitude of density fluctuations *directly*

$$C^{\kappa\kappa}(\ell) = \int d\chi W^2_{\rm GL}(\chi)\frac{1}{f^2_K(\chi)}P(k=\ell/f_K(\chi))$$

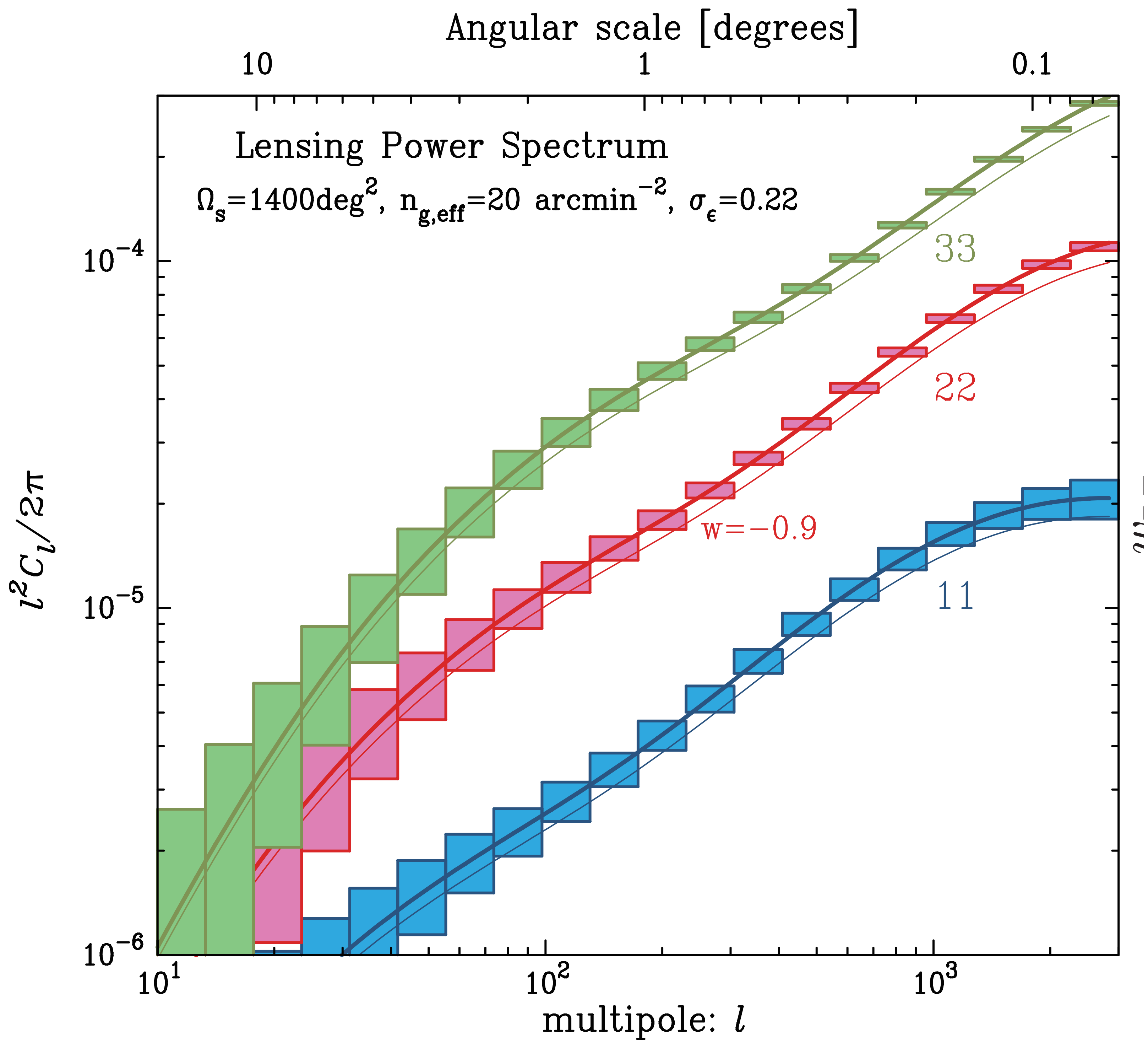
- however this gives you only projected (integrated) density fluctuations, i.e., need something more to study *growth* of fluctuations

Method (I): tomography

- use source galaxies at different redshift bins
- different z_s probe mass distribution at different z ranges (e.g., Hu 1999)
- note significant cross-correlation between different bins



Weak lensing tomography: example



predicted signal for Subaru/HSC

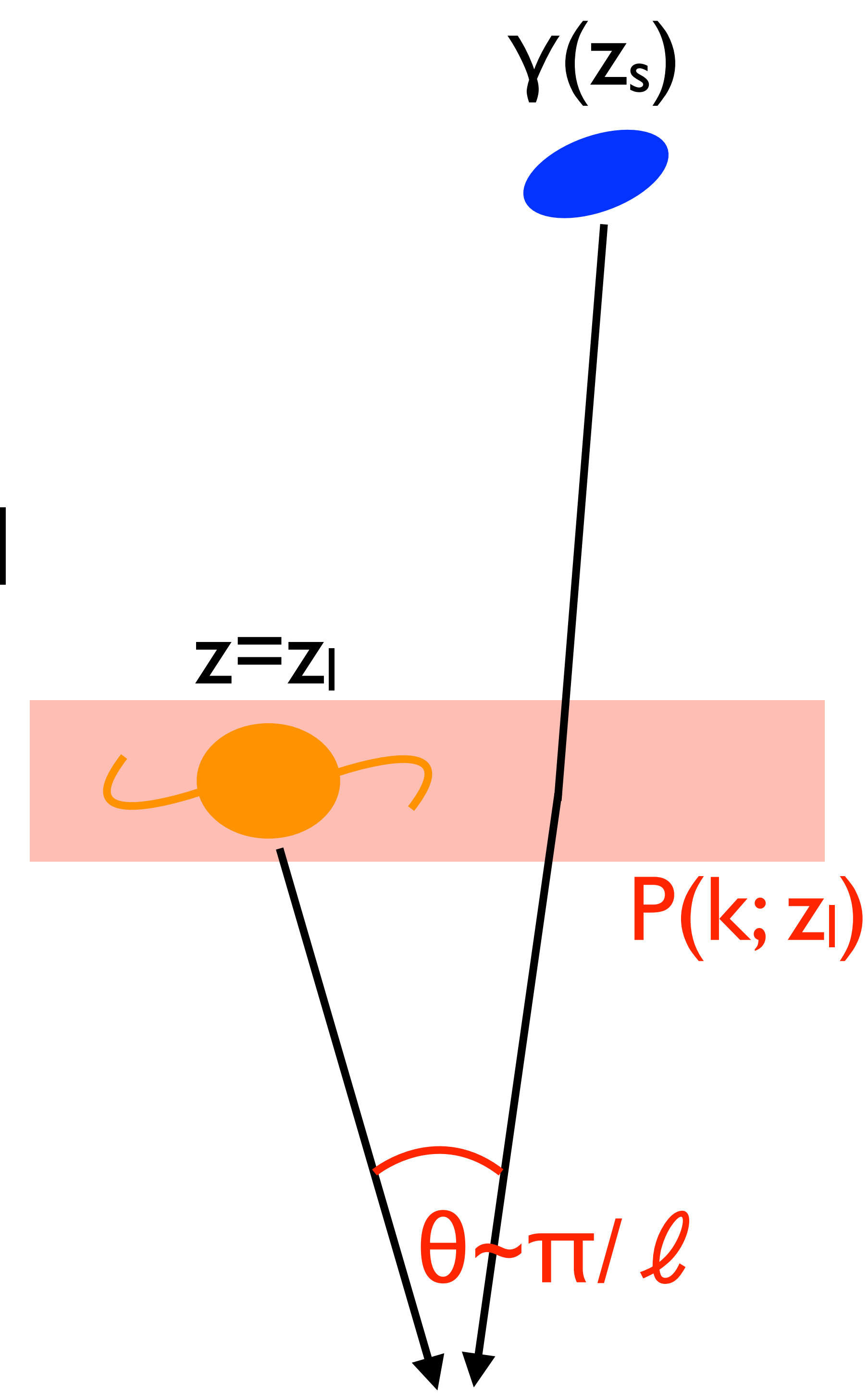
bin 1: $0<z_s<0.6$
bin 2: $0.6<z_s<1$
bin 3: $1<z_s$

(by Masahiro Takada)

Method (II): cross-correlation

- take cross-correlation of shear and foreground objects with known $z=z_l$
- at large scale, correlation signal is proportional to $P(k; z_l)$, and therefore can extract density fluctuations at $z=z_l$

$$C^{\delta\gamma}(\ell) \propto P(k = \ell/f_K(\chi_l);\, z_l)$$

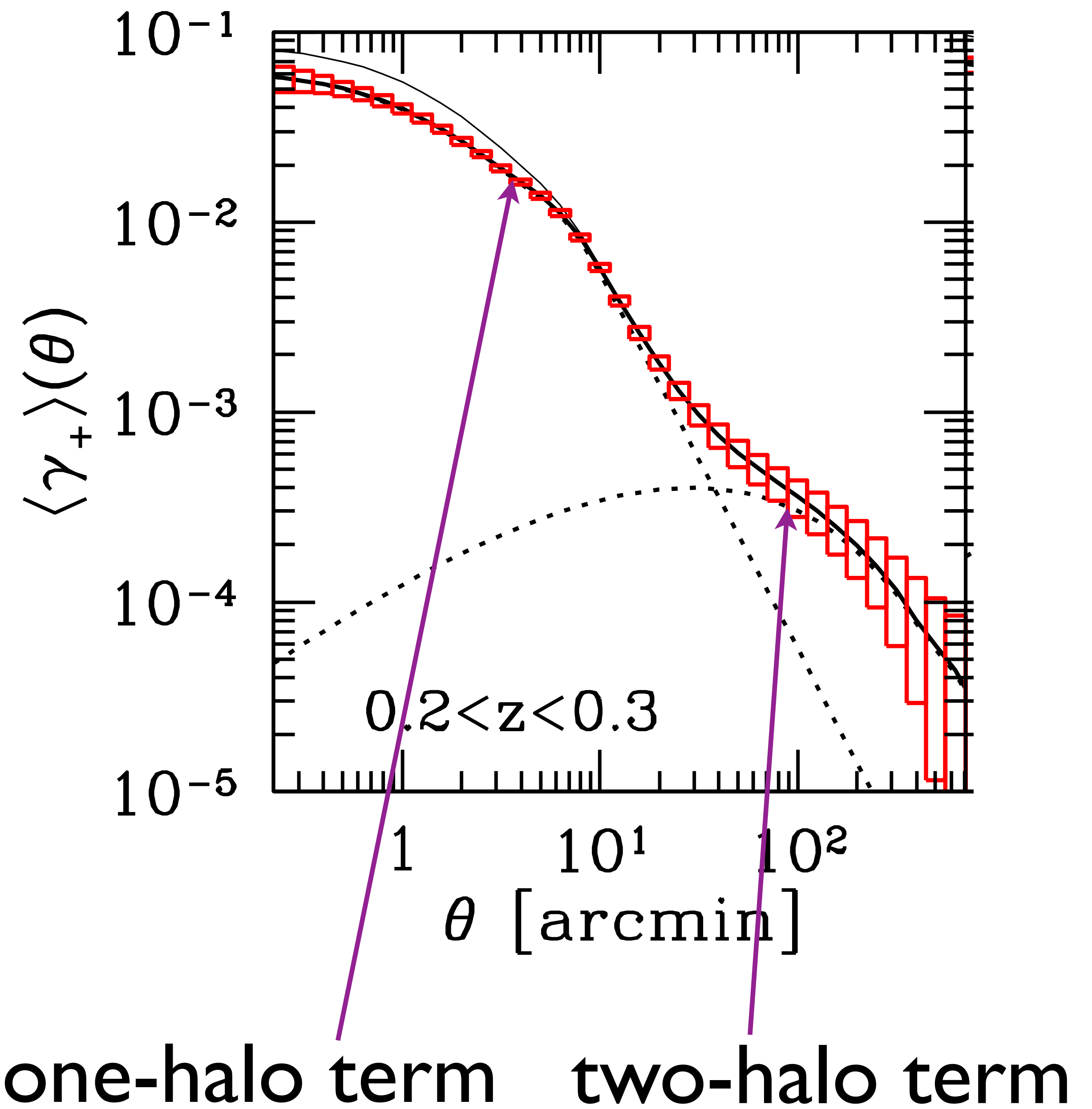


Oguri & Takada PRD **83**(2011)023008

Cross-correlation: example

- expected cross-correlation signal between shear and massive clusters in Subaru HSC survey

- “two-halo term” probes matter power spectrum at the cluster redshift

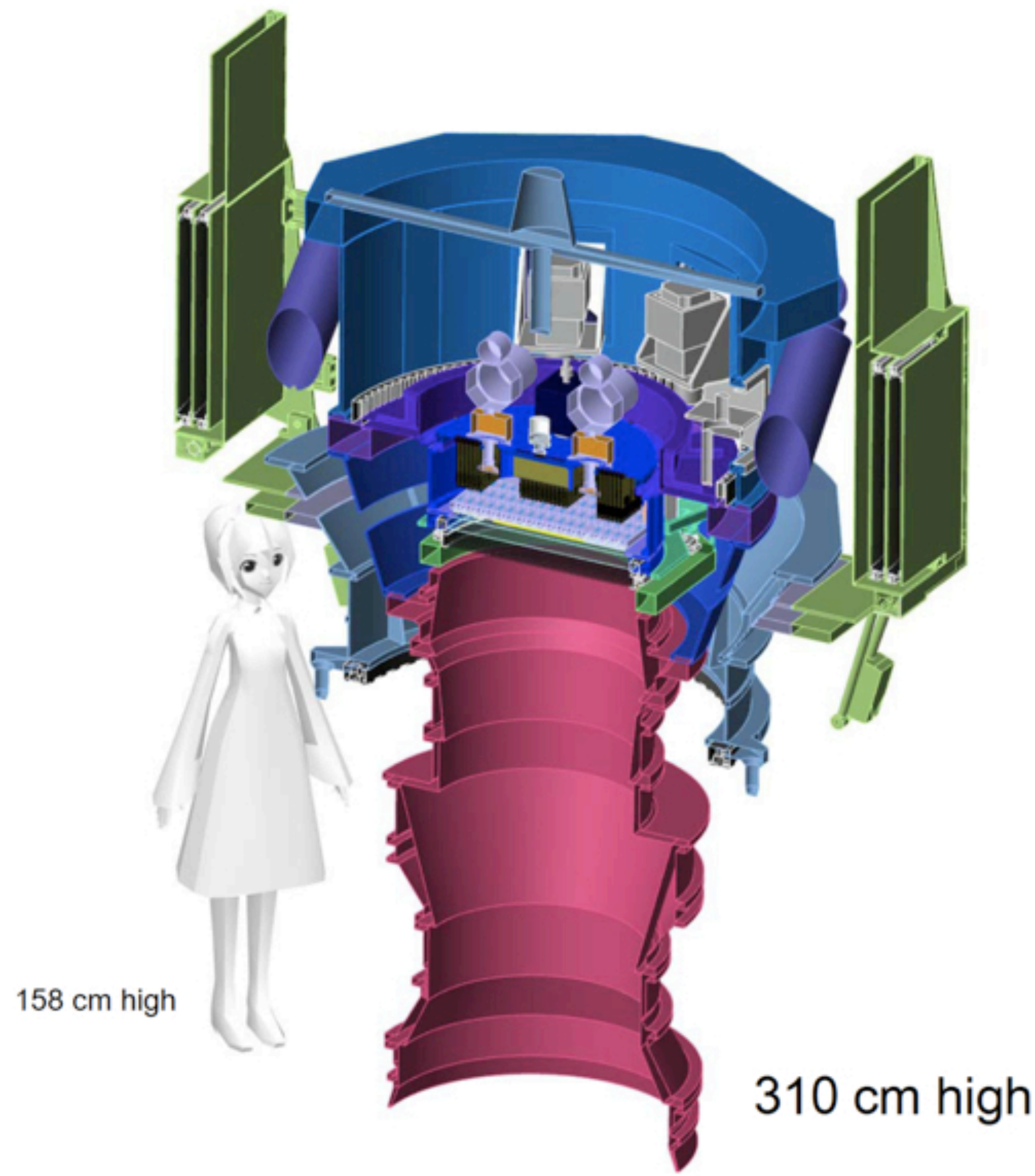


Weak lensing surveys

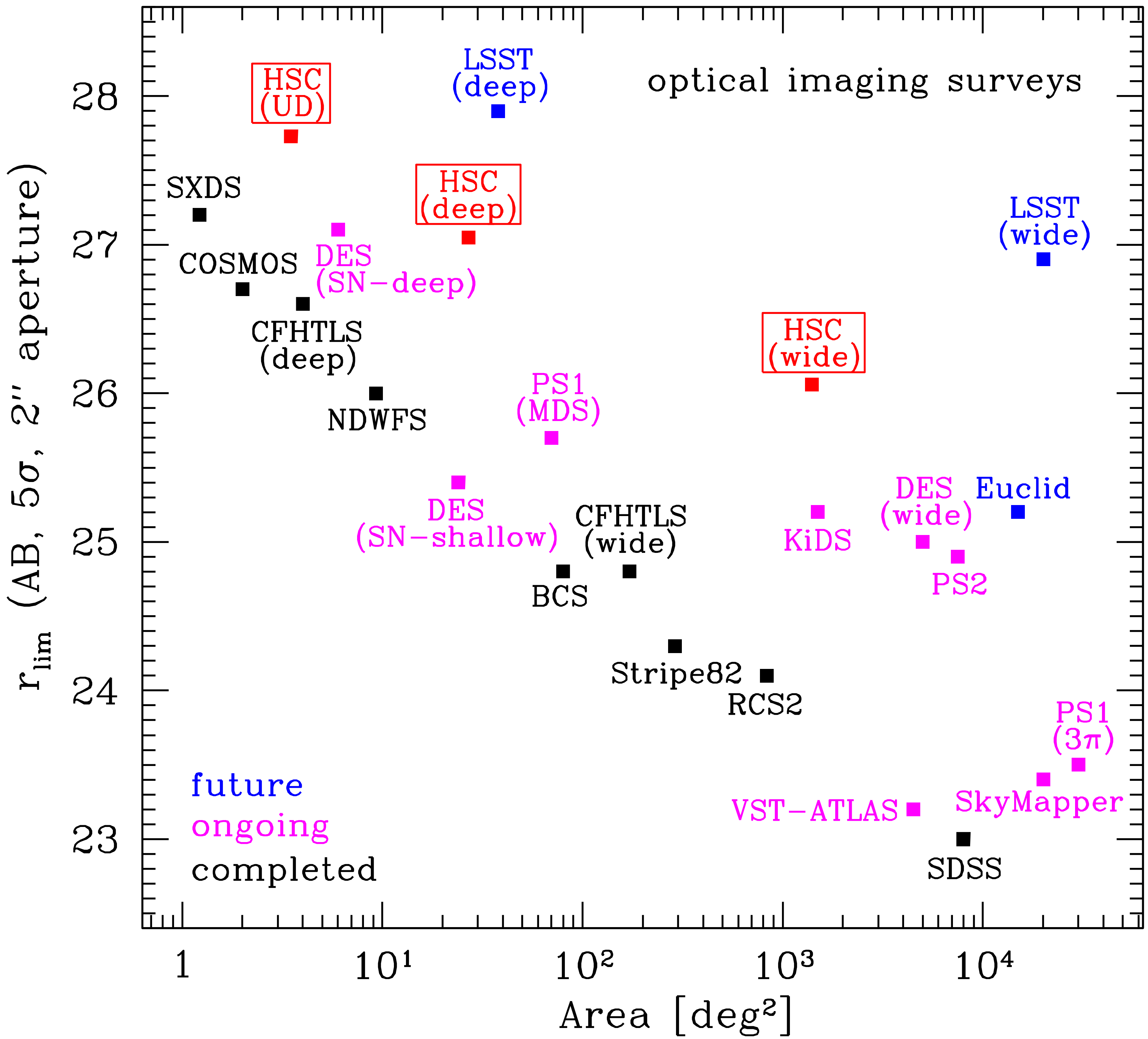
- weak lensing cosmology is one of the main drivers of ongoing optical imaging surveys
  - CFHTLenS (170 deg^2, r_{lim}~24.8) completed and results come out "soon"
  - KiDS (1500 deg^2, r_{lim}~25.2) survey started
  - Dark Energy Survey (5000 deg^2, r_{lim}~25.0) survey start end of this year?
  - Hyper Suprime-cam (1400 deg^2, r_{lim}~26.0) first light soon, survey from mid-2013

Hyper Suprime-cam

- wide-field optical imager at the Subaru telescope
- collaboration between Japan, Taiwan, Princeton
- 1.5deg diameter FOV while keeping good image quality for weak lensing



Comparison of surveys



HSC will be great and unique!

stay tuned for future updates!

Summary

- there are many approaches for cosmology with gravitational lensing
- gravitational lensing probes both geometry and growth of structure
- in many cases, degeneracy with lens mass distribution is main systematic error − need clever methods for future applications (there is plenty of room to explore!)