Measuring the acceleration of the Universe with strong lens statistics

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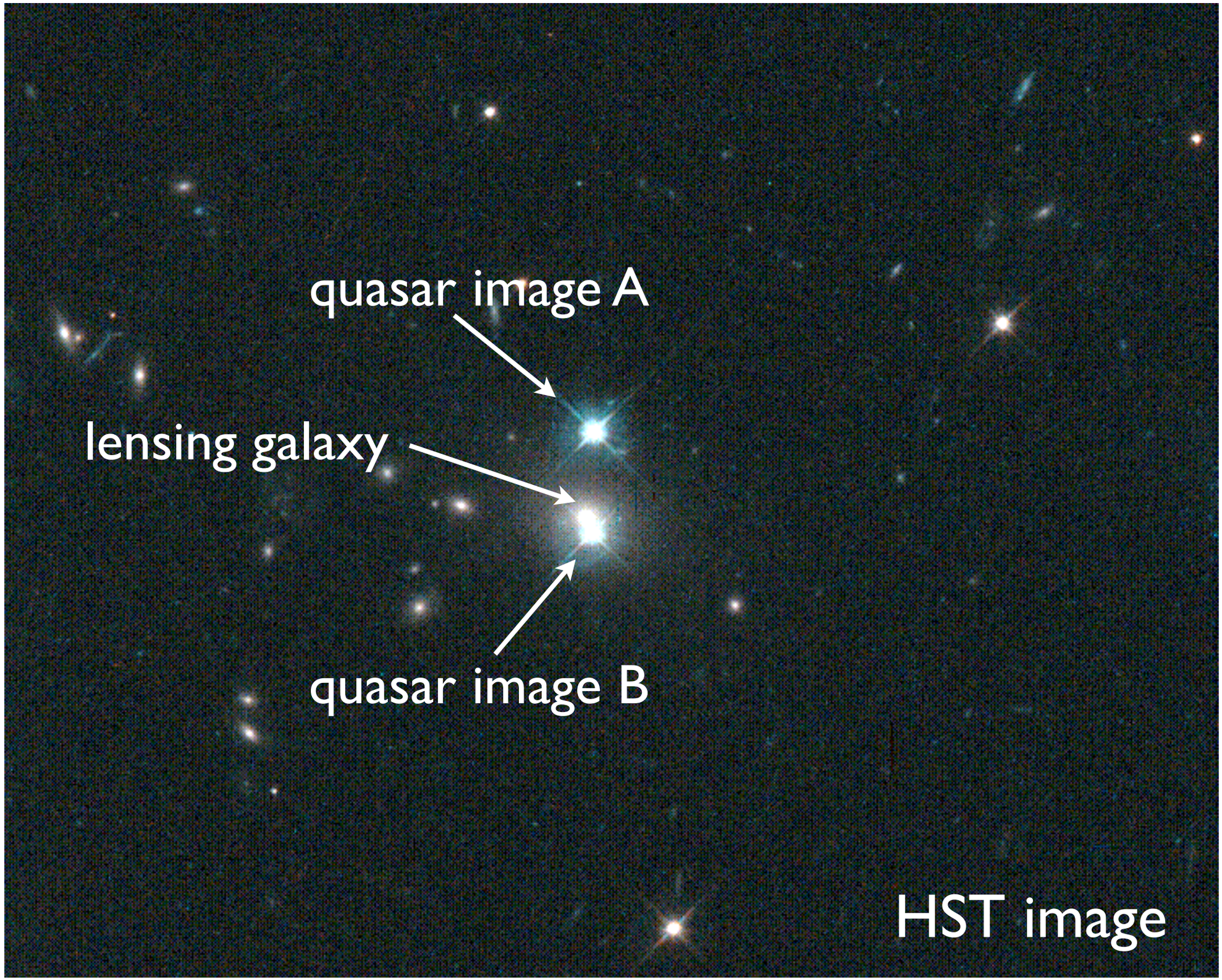
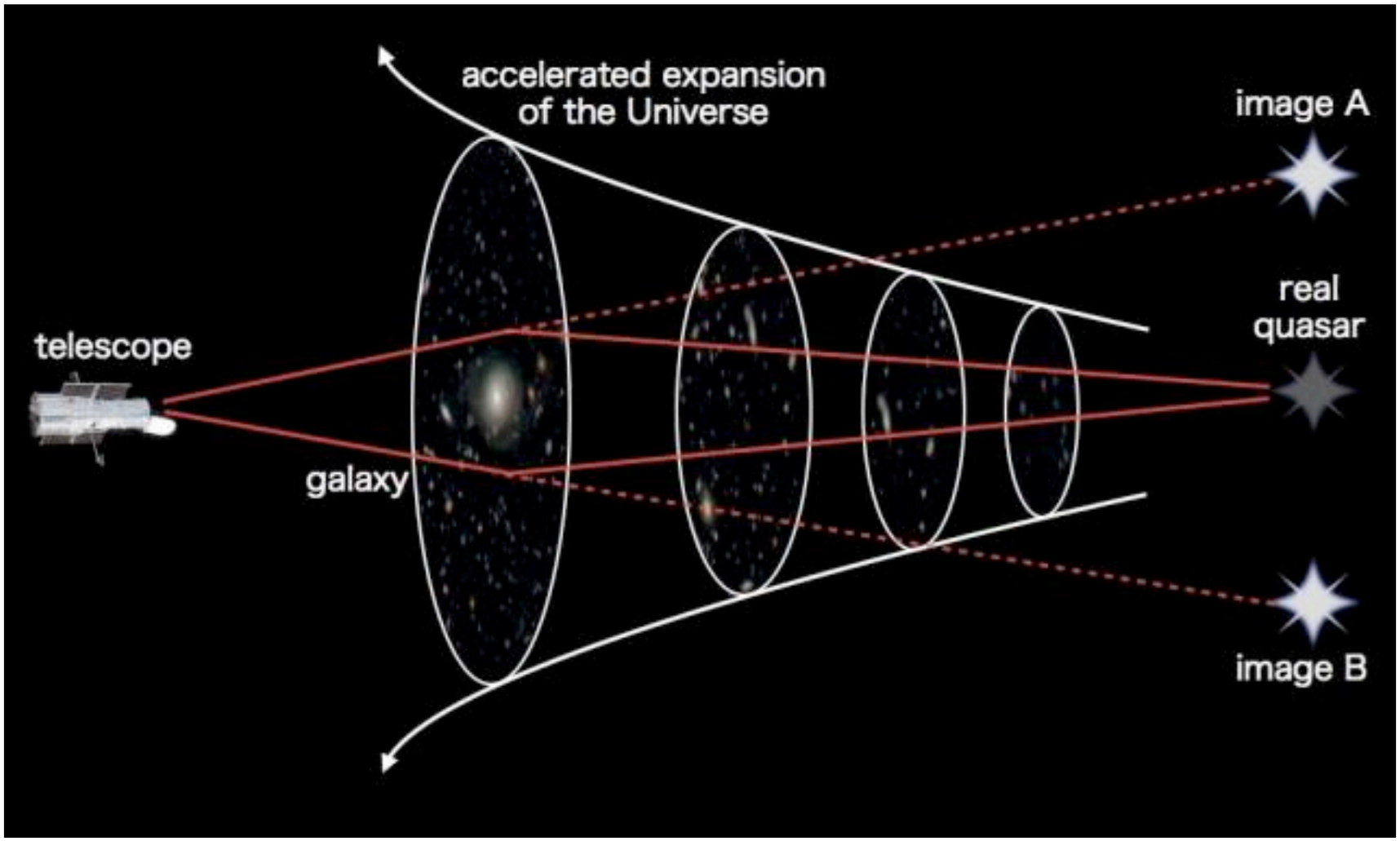
First strong lens: Q0957+561 (Walsh et al. 1979)



Quasar lens statistics

- acceleration of the Universe increases a chance of strong lensing for a distant quasar
  (Fukugita, Futamase & Kasai 1990; Turner 1990)



How it works

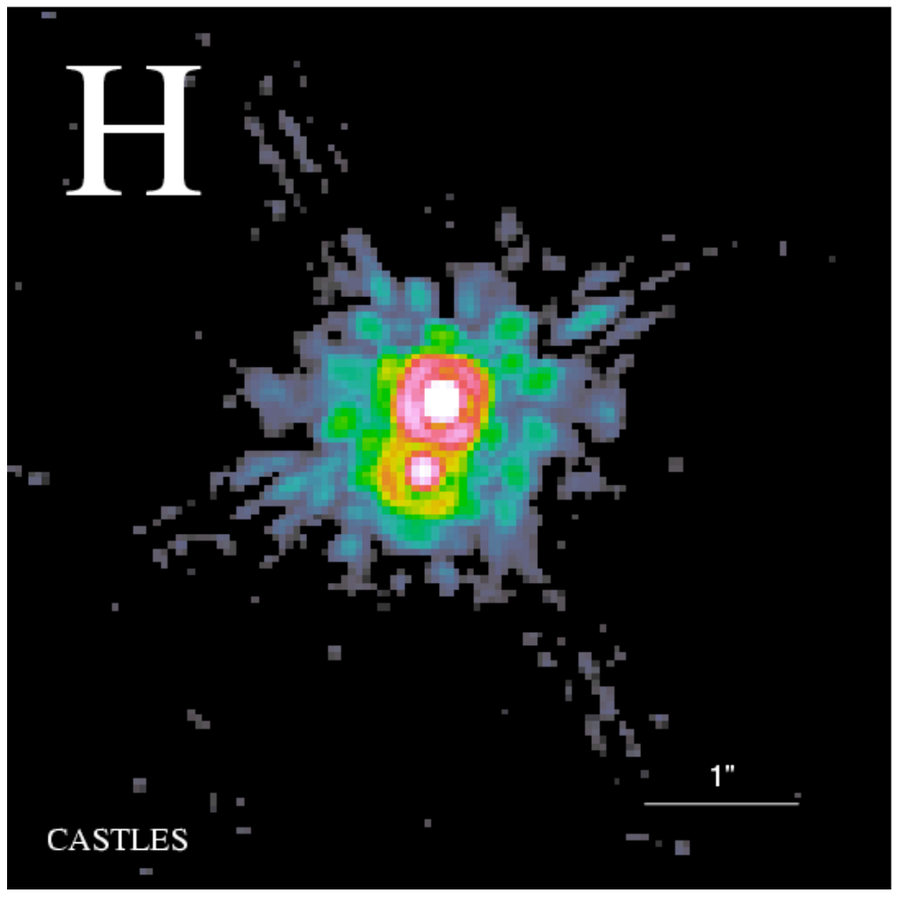
- lensing objects of lensed quasars are dominated by early-type galaxies which formed early (z~2)

- assume that velocity dispersion function dn/dσ 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 ("standard volume" method)

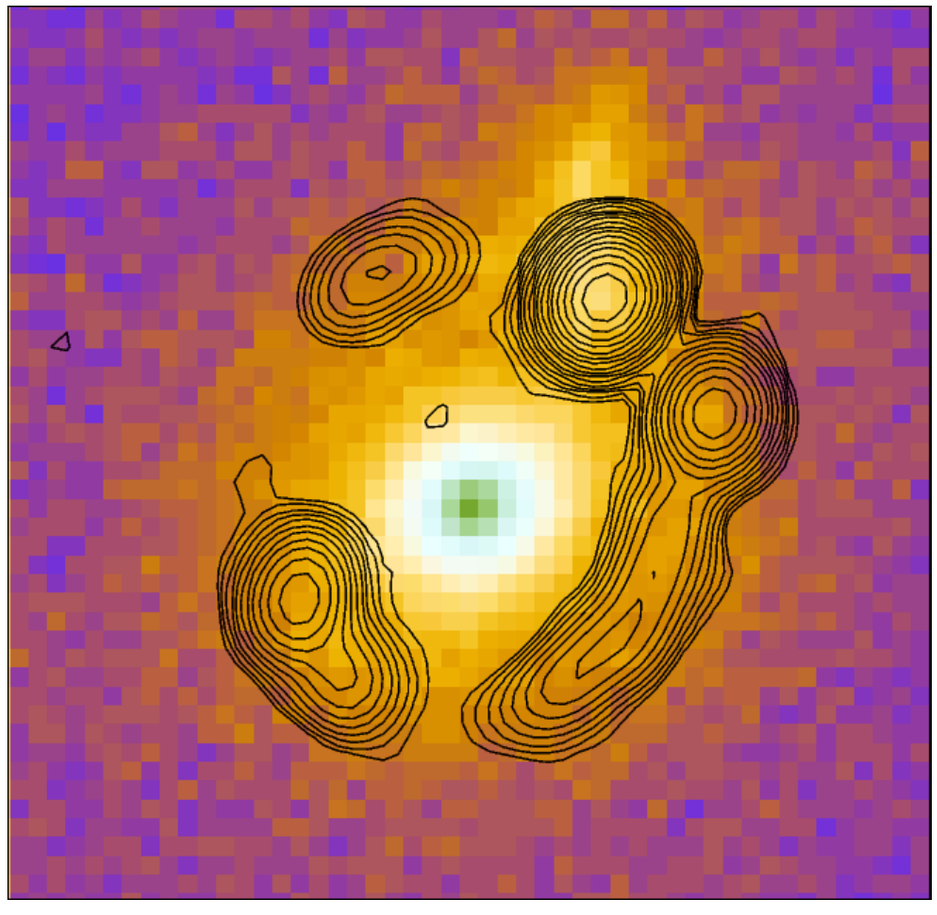
Old attempts

HST snapshot (optical)
(Maoz et al. 1993)



500 quasars, <3 lenses,
number too small

CLASS (radio)
(Browne et al. 2003)



22 lenses from 10k sources
redshift dist. uncertain

SDSS quasar lens search (SQLS)

- project to search for strongly lensed quasars among spectroscopic SDSS quasars

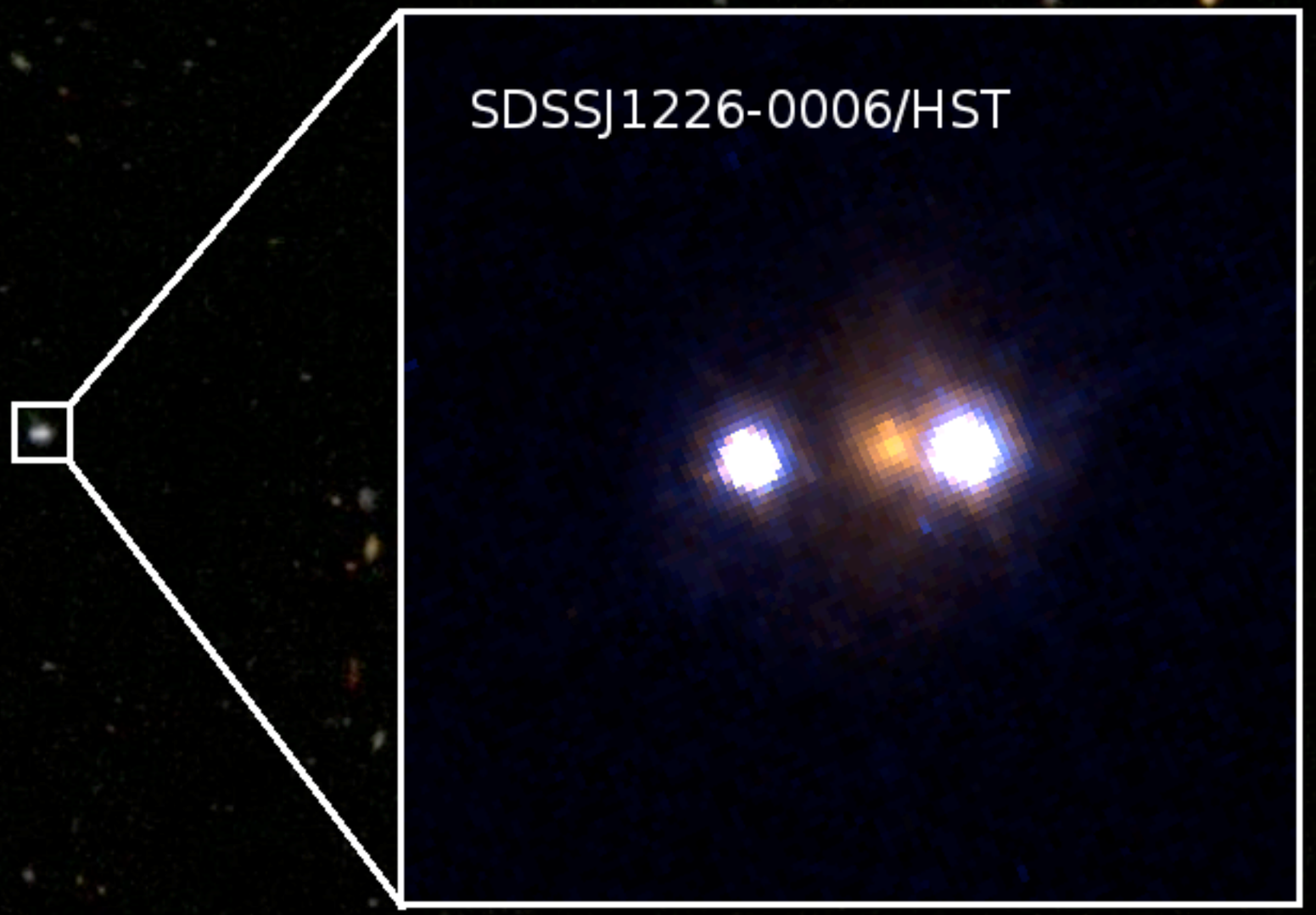
- identify lens candidates using ugriz-band SDSS images, need extensive follow-up observations to confirm true lenses

- all the survey in DR7 already completed!

- see the following URL for more details http://www-utap.phys.s.u-tokyo.ac.jp/~sdss/sqls/

SDSSJ1226-0006/SDSS

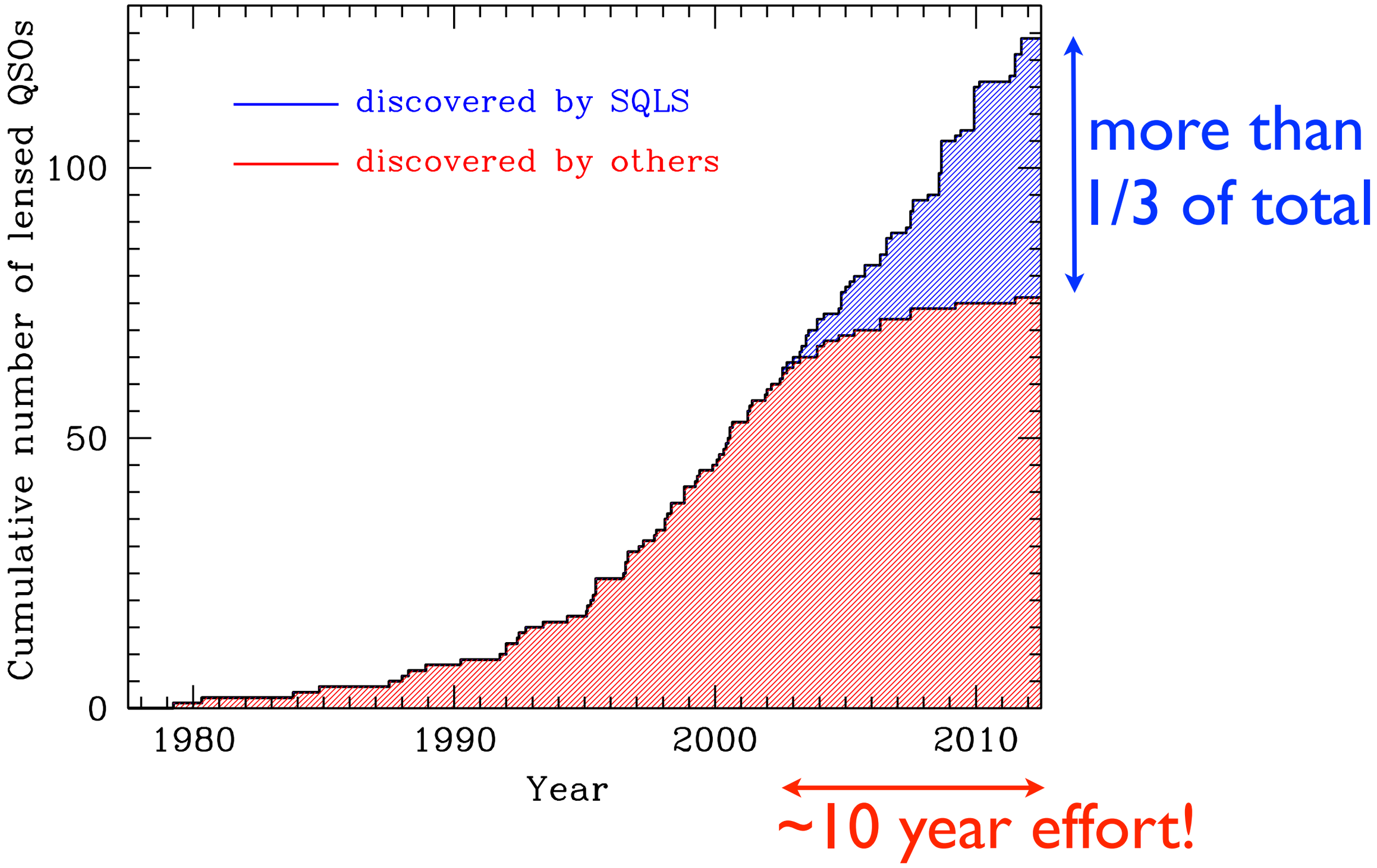
SDSSJ1226-0006/HST

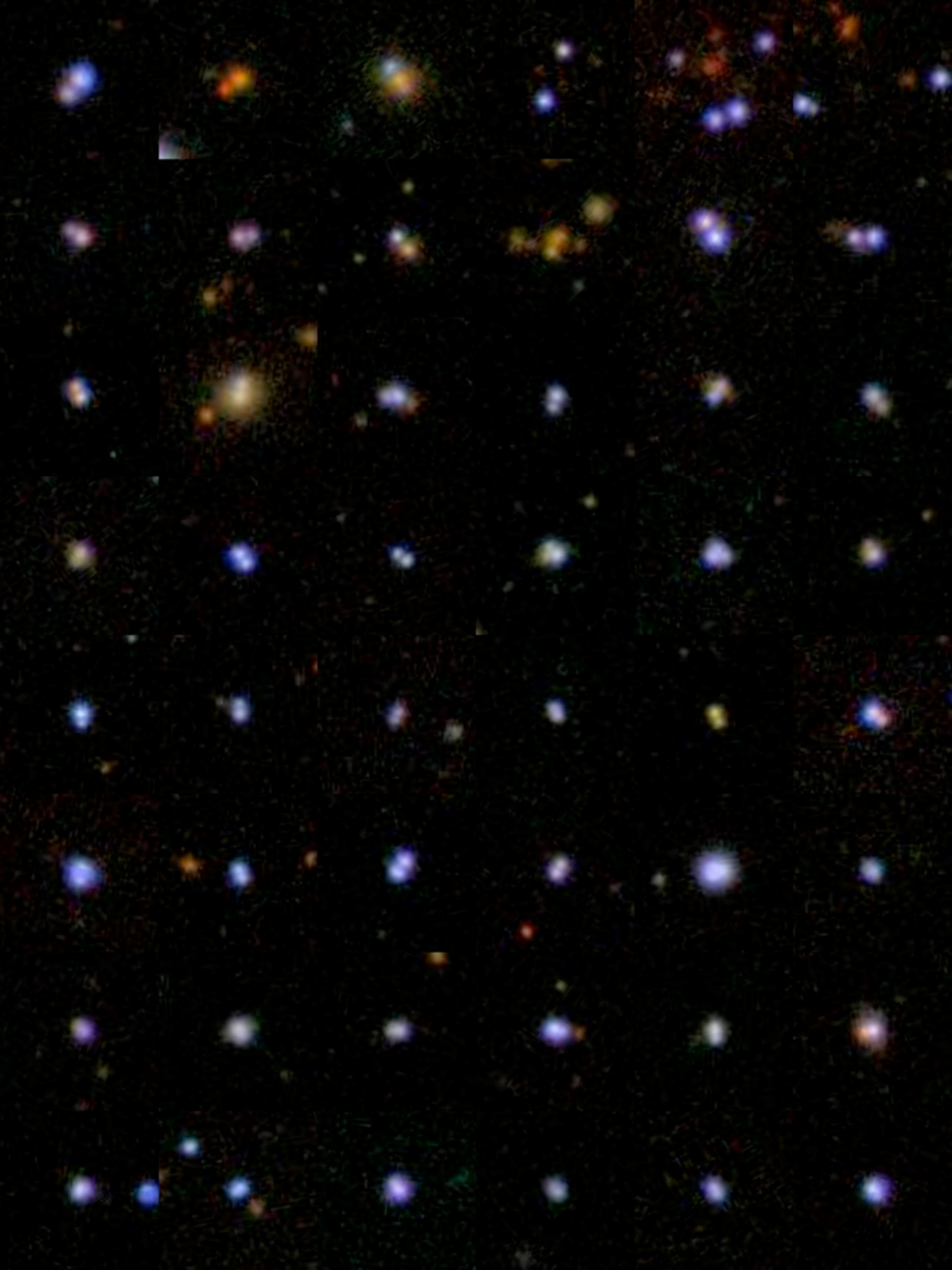


SQLS: main members

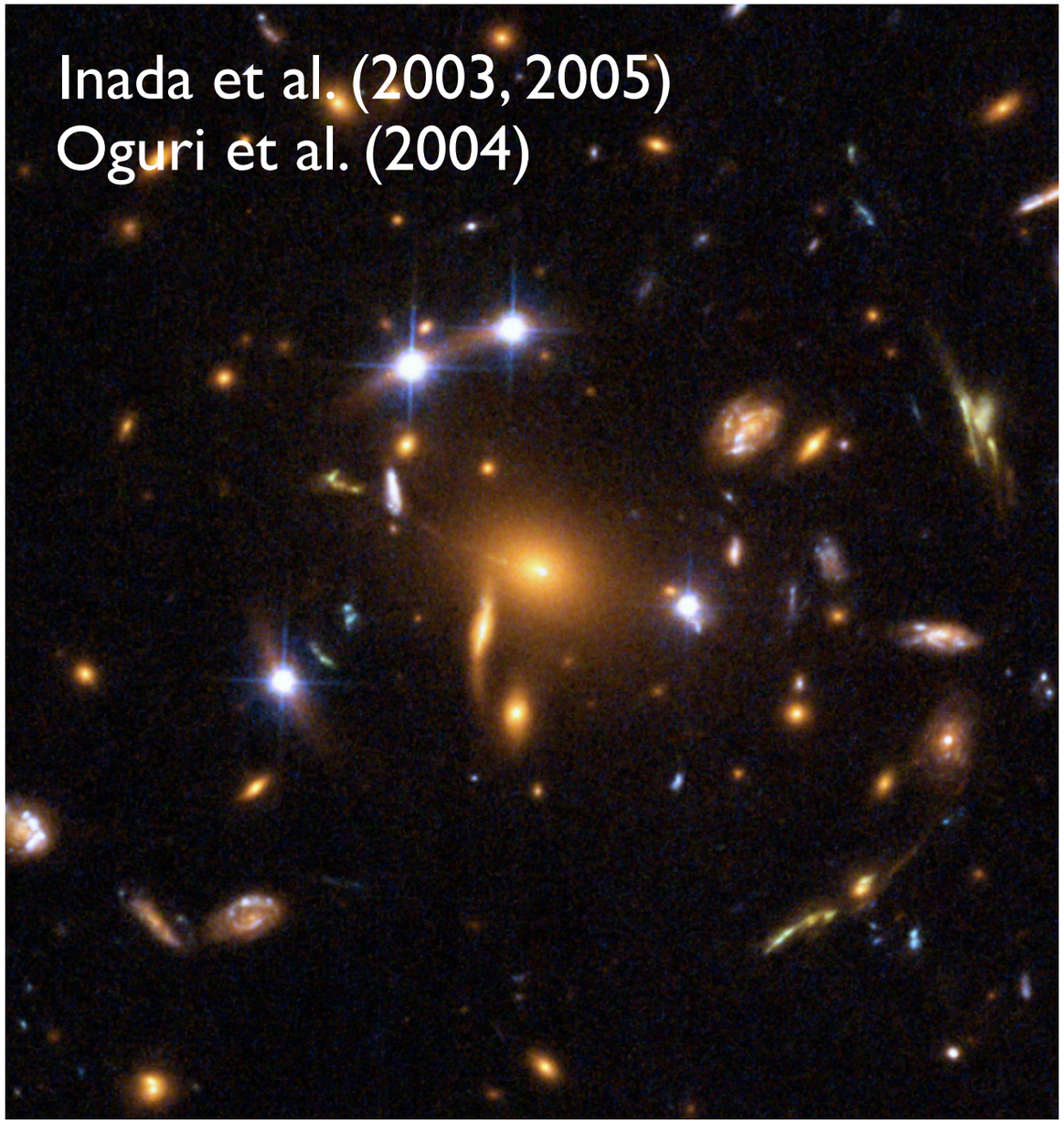
- Neta Bahcall (Princeton)
- Bob Becker (UC Davis)
- Francisco Castander (CSIC)
- Kuenley Chiu (Caltech)
- Alejandro Clocchiatti (PUC)
- Josh Frieman (Chicago)
- Masataka Fukugita (IPMU)
- J. R. Gott (Princeton)
- Michael Gregg (UC Davis)
- Pat Hall (York)
- Joe Hennawi (MPIA)
- Naohisa Inada (NNCT) [co-PI]
- Issha Kayo (Toho)
- Chris Kochanek (OSU)
- Tomoki Morokuma (Tokyo)
- Masamune Oguri (IPMU) [co-PI]
- Bart Pindor (Melbourne)
- Gordon Richards (Drexel)
- Cristian E. Rusu (Tokyo)
- Don Schneider (PSU)
- Min-Su Shin (Oxford)
- Michael Strauss (Princeton)
- Rick White (STScI)
- Don York (Chicago)

Number of lenses discovered

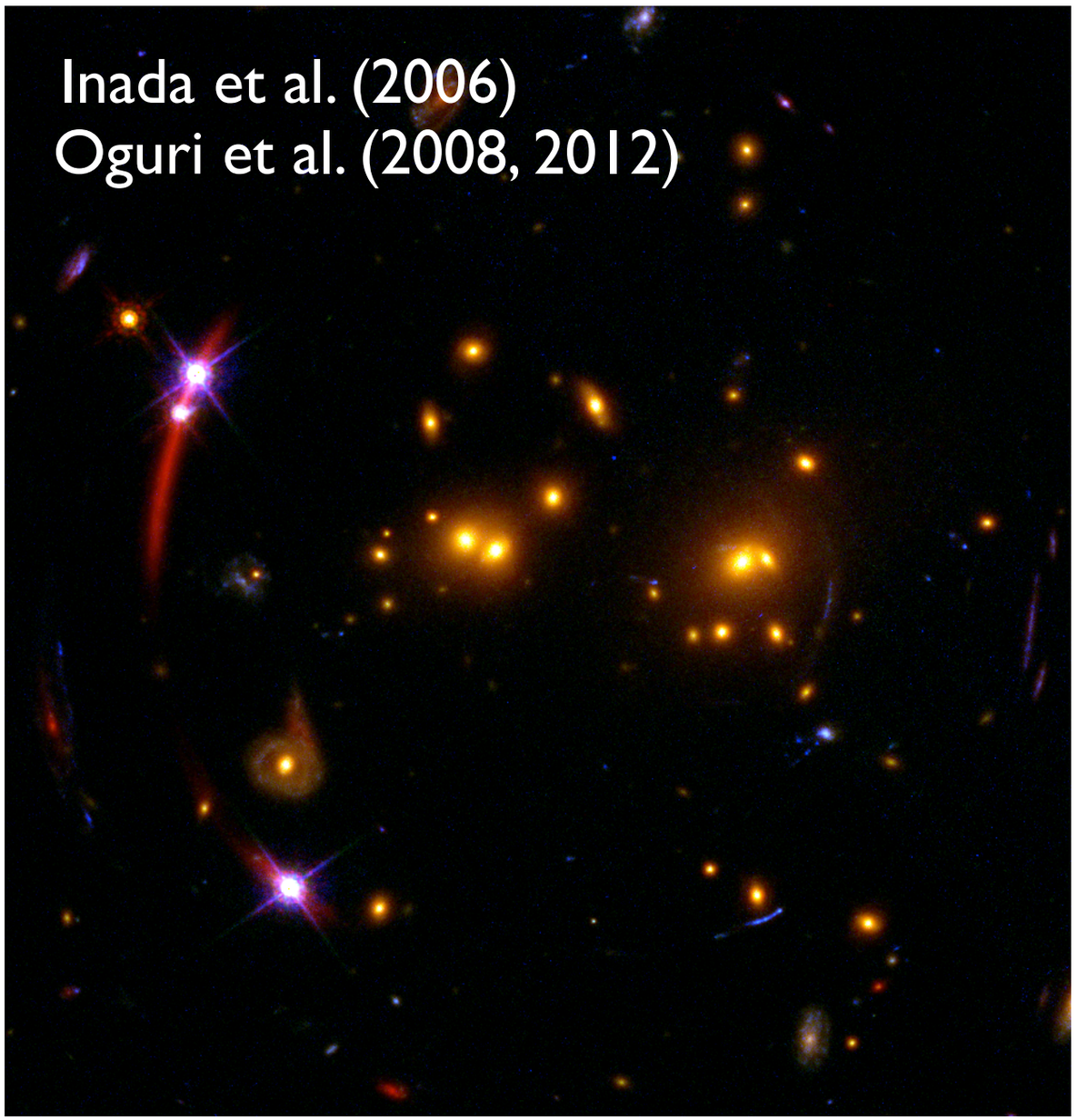




Rare large-separation quasar lenses



SDSS J1004+4112
(5 images, θ_{max}=14.7″)



SDSS J1029+2623
(3 images, θ_{max}=22.5″)

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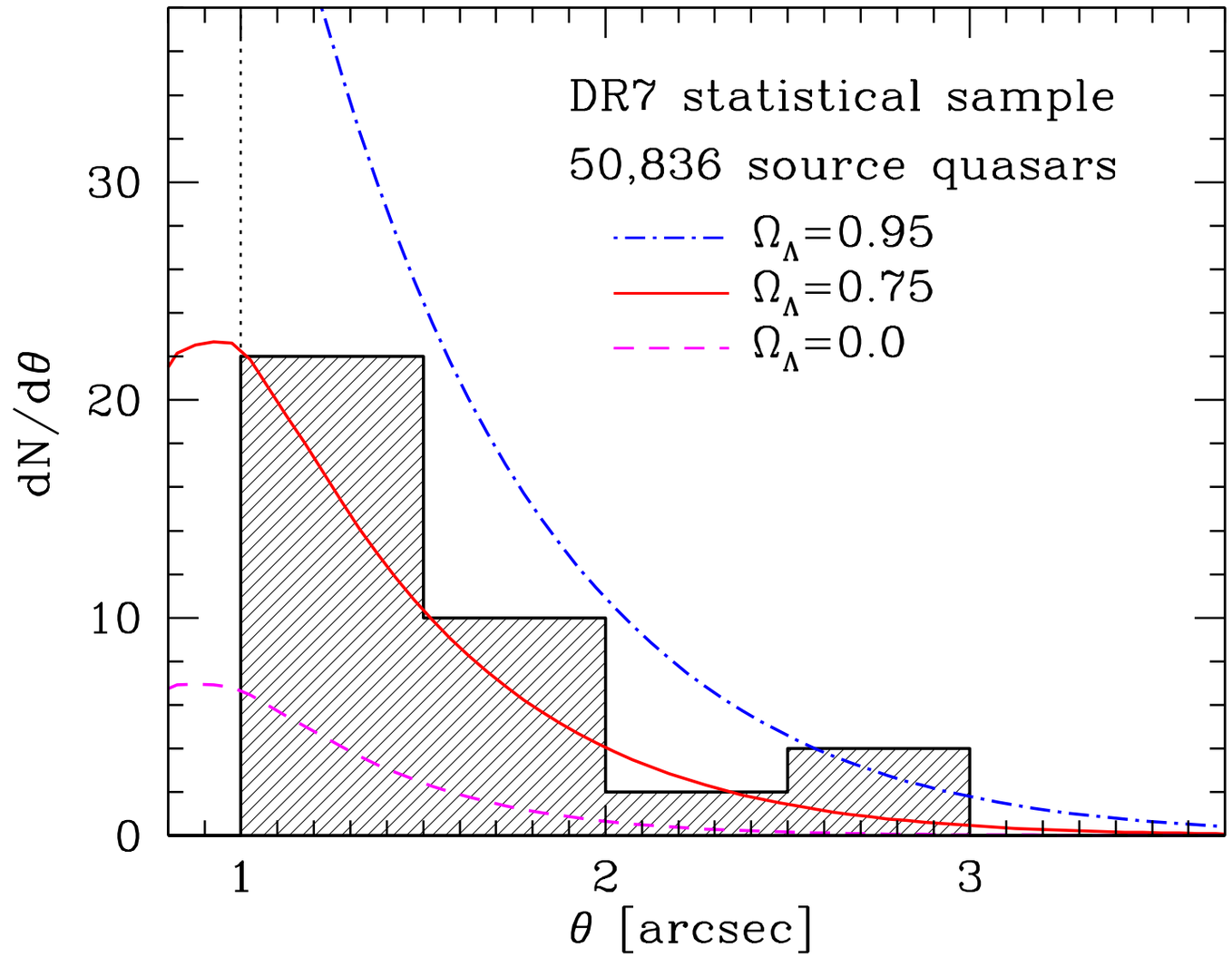
Cosmological constrains from DR7

- 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



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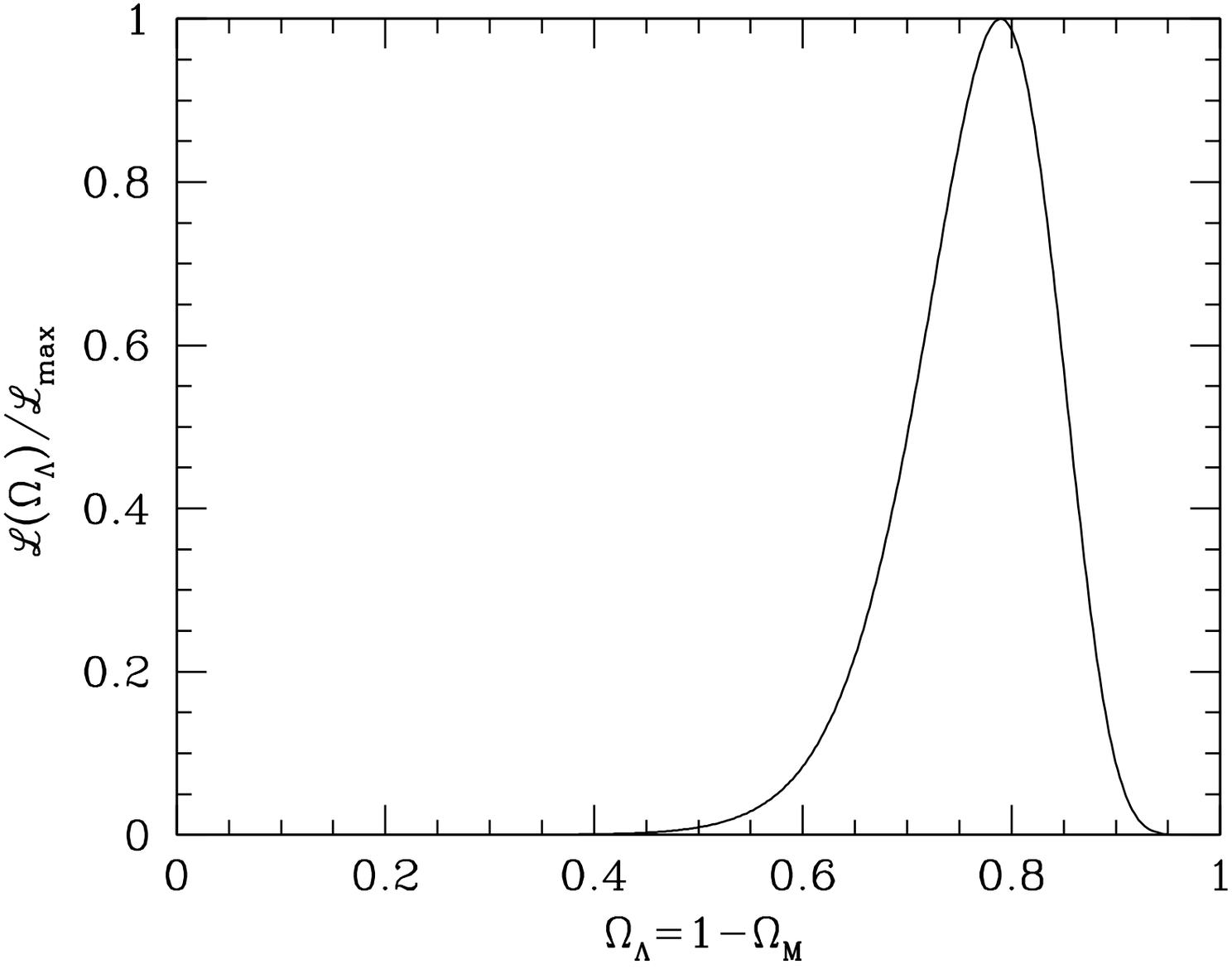
Result (I)



- constraint on Ω_Λ assuming flat
- SQLS only
- result: $\Omega_\Lambda = 0.79^{+0.06}_{-0.07}$ (stat.) $^{+0.06}_{-0.06}$ (syst.)
- $\Omega_\Lambda = 0$ rejected at 6σ (stat. only)

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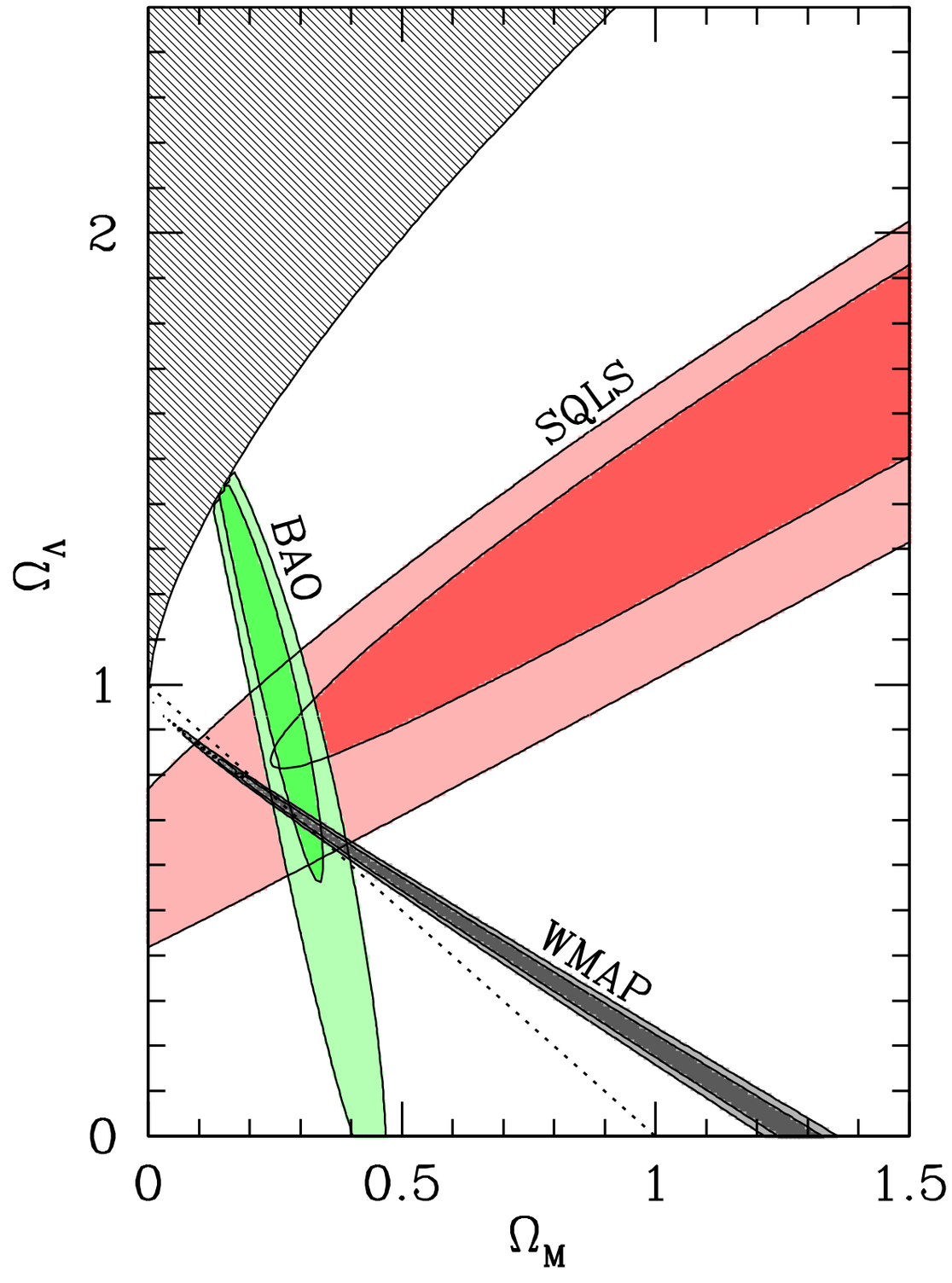
Result (II)

- non-flat Universe with cosmological constant
- $\Omega_\Lambda > 0$ still required at more than 4σ level



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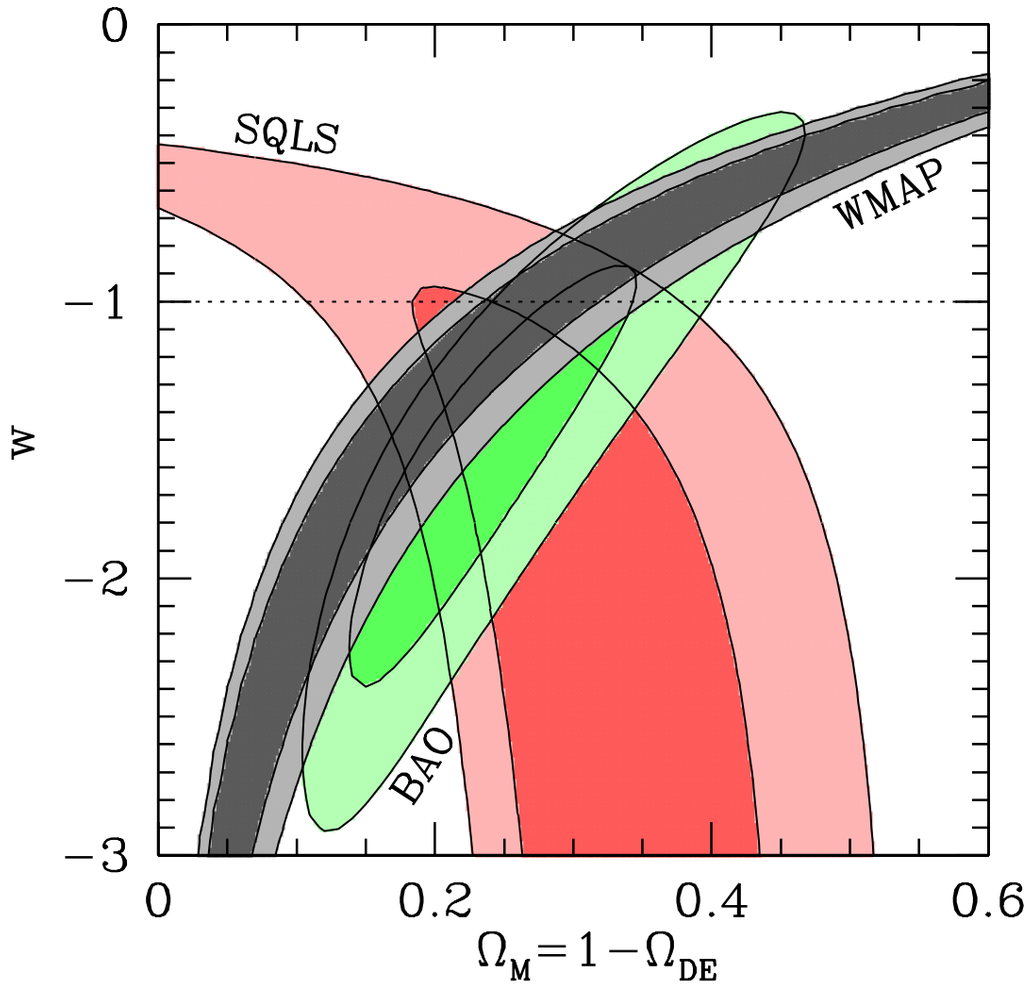
Result (III)



- flat Universe with constant DE EOS
- $w = -1.11^{+0.14}_{-0.17}\,(\text{stat.})^{+0.08}_{-0.10}\,(\text{syst.})$ from SQLS+BAO+WMAP

To summarize...

- statistics of SQLS quasar strong lenses indicate that the expansion of the Universe must be accelerated
- however this result relies on the assumption that the velocity function of (early-type) galaxies does not evolve
- what if we allow fully evolving velocity function?

$$\phi_* \longrightarrow \phi_*(1+z)^{\nu_n}$$

$$\sigma_* \longrightarrow \sigma_*(1+z)^{\nu_\sigma}$$

Simultaneous constraint

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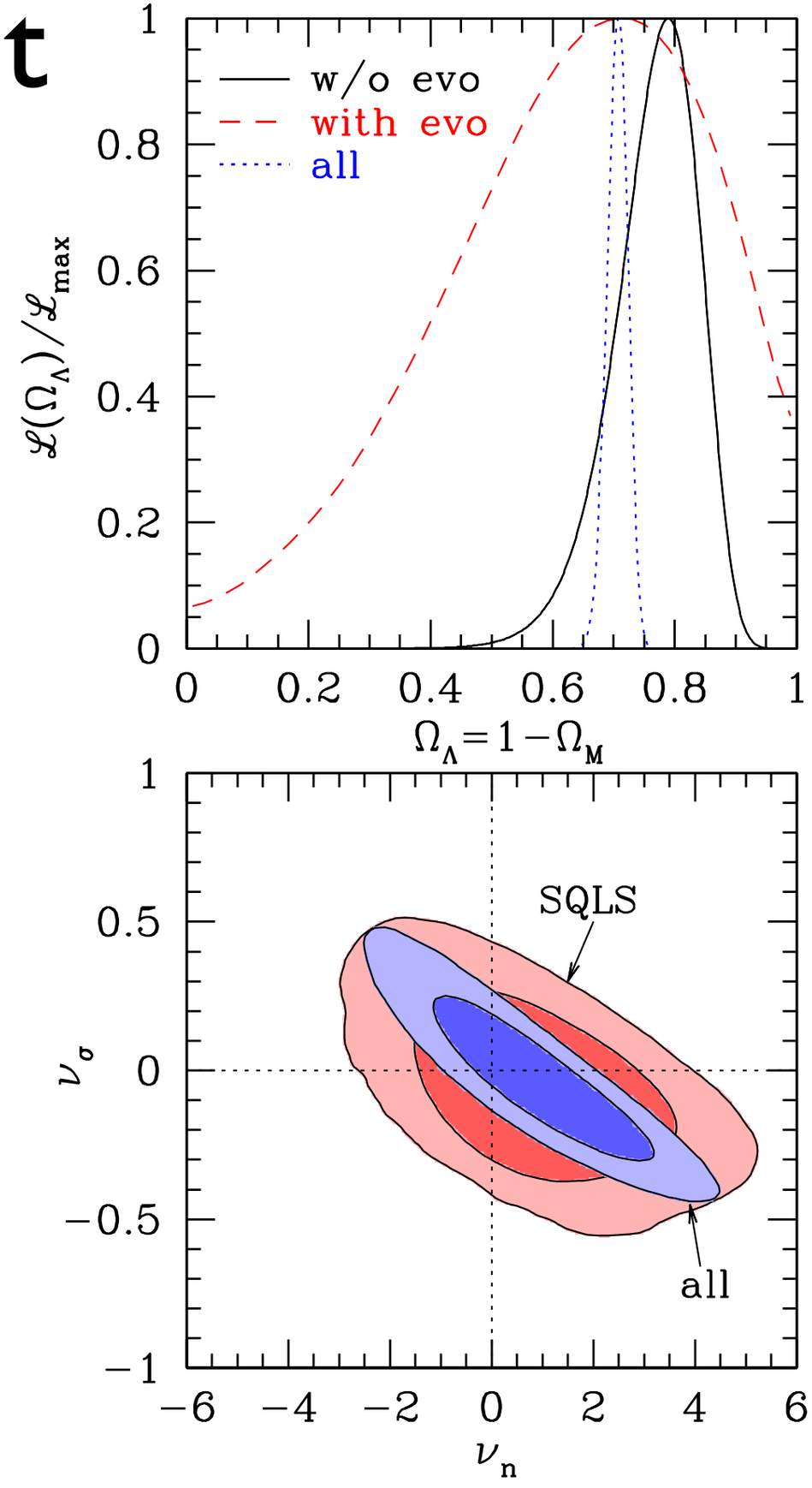
- constrain Ω_Λ and galaxy evolution simultaneously from the SQLS data
- $\Omega_\Lambda > 0$ still preferred at more than 2σ level
- consistent with non-evolving velocity function
- implying that conclusion is robust



Conclusion

- SQLS has drastically increased the number of strongly lensed quasars known
- the careful statistical analysis confirmed the acceleration of the Universe independently of type-Ia supernovae
- future? stay tuned for a new survey in SDSS-III!