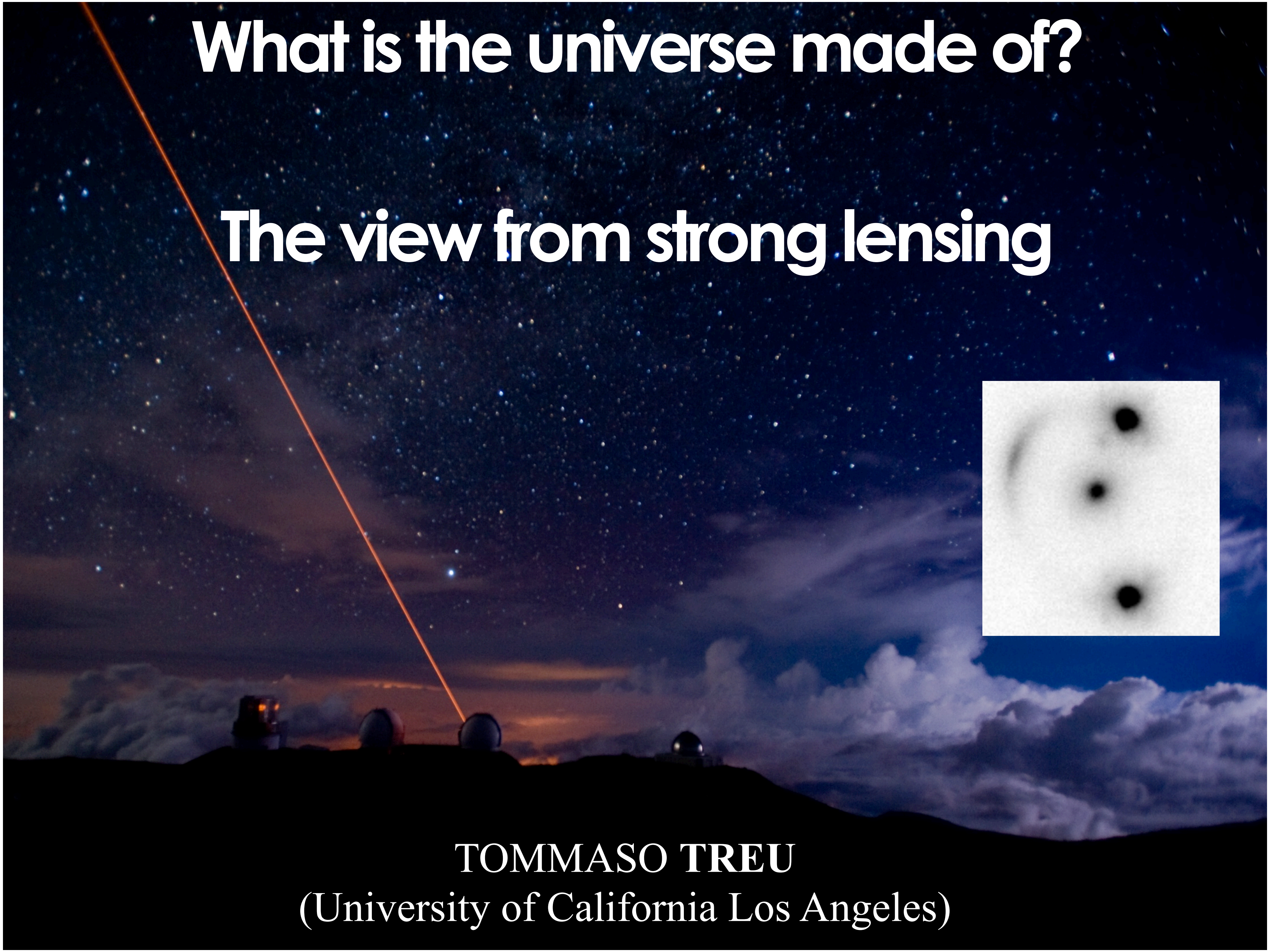
What is the universe made of?

The view from strong lensing

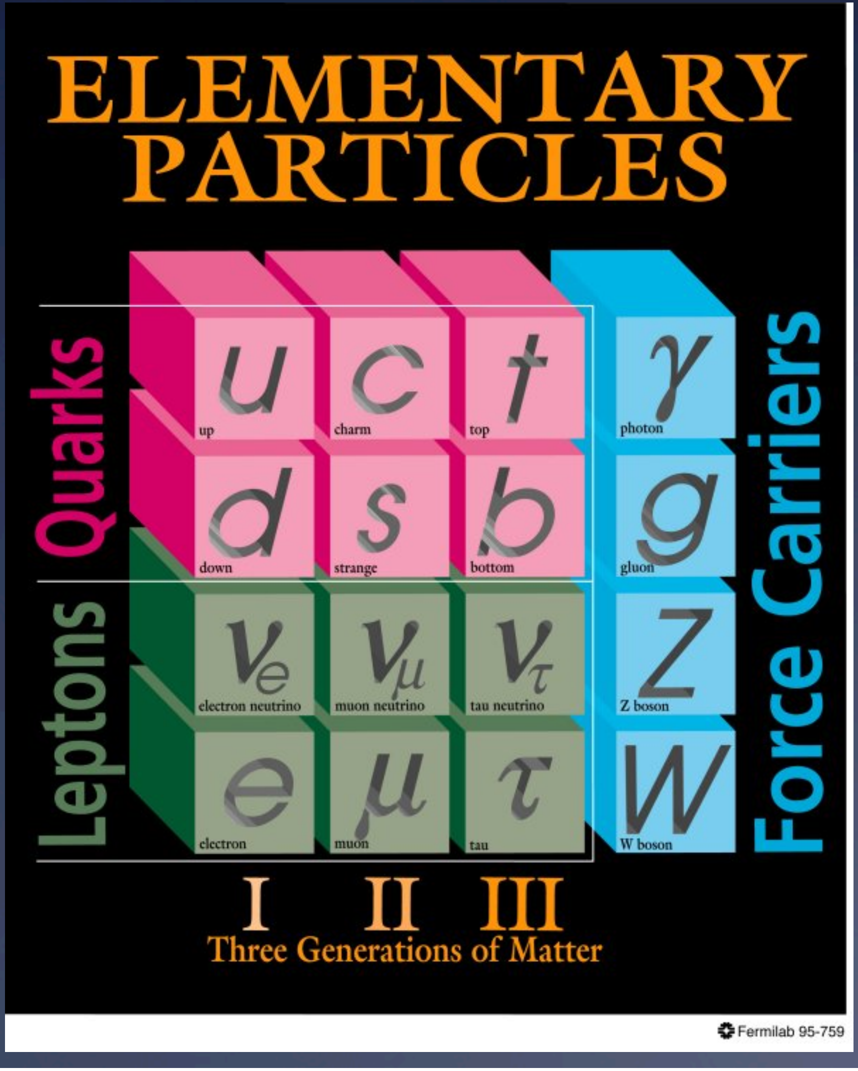


TOMMASO **TREU**
(University of California Los Angeles)

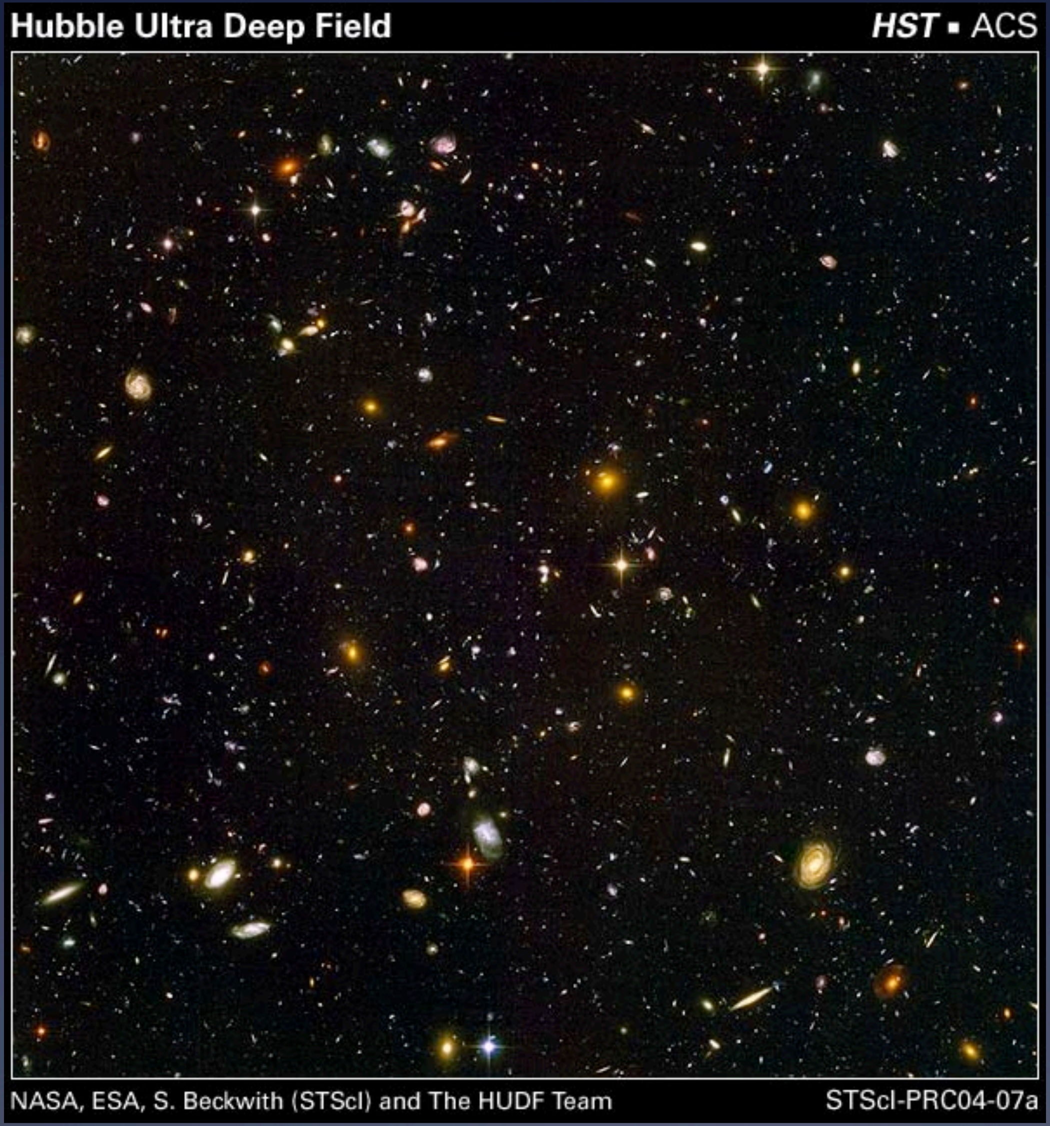
Outline

- Introduction. The view from Earth:
  - The standard model of particle physics
- The view from the Universe
  - Gravitational time delays and Dark energy
  - Strong lensing and dark matter
- The quest for more lenses

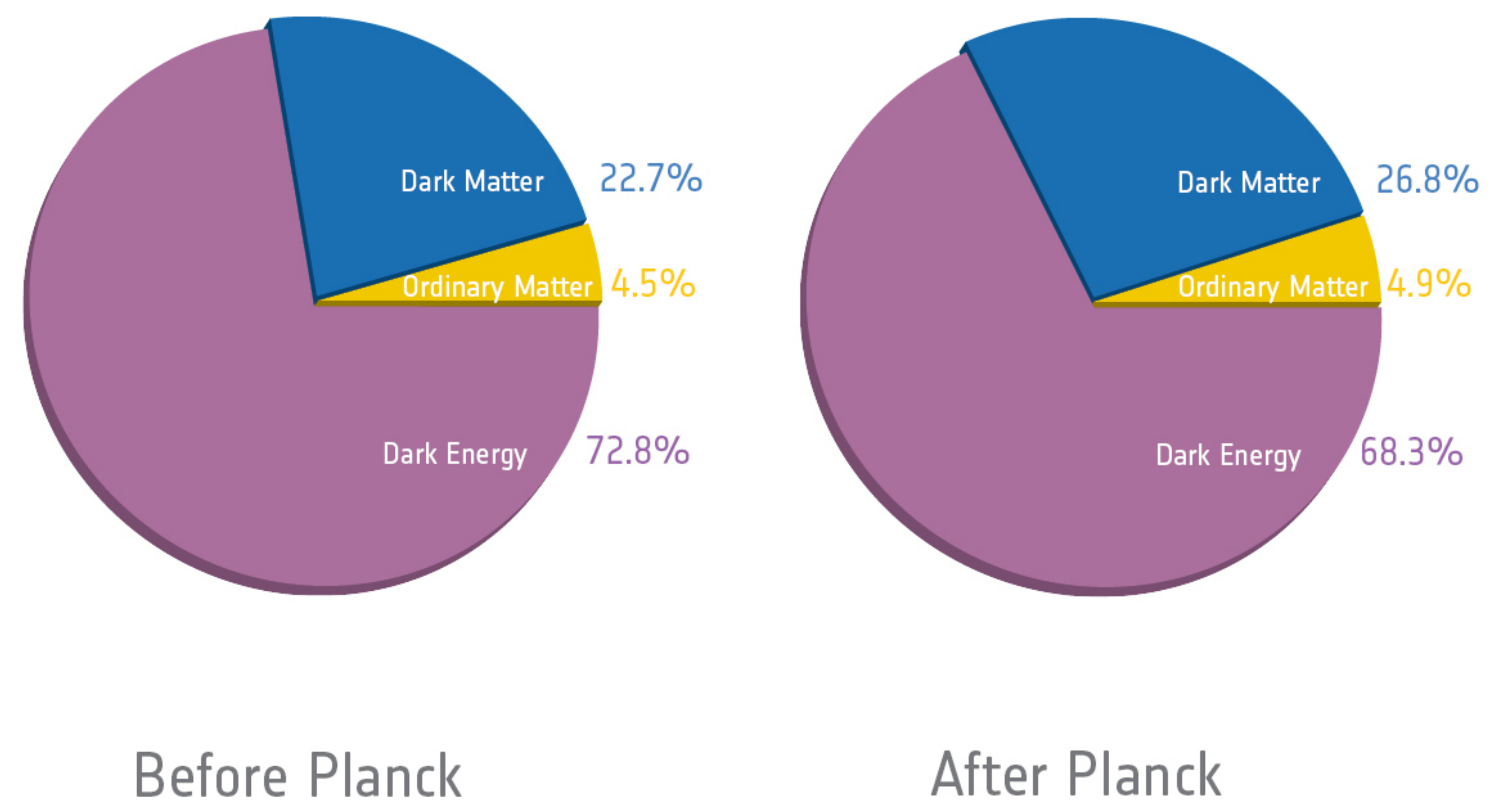
The view from Earth: standard model of particle physics



The view from the universe

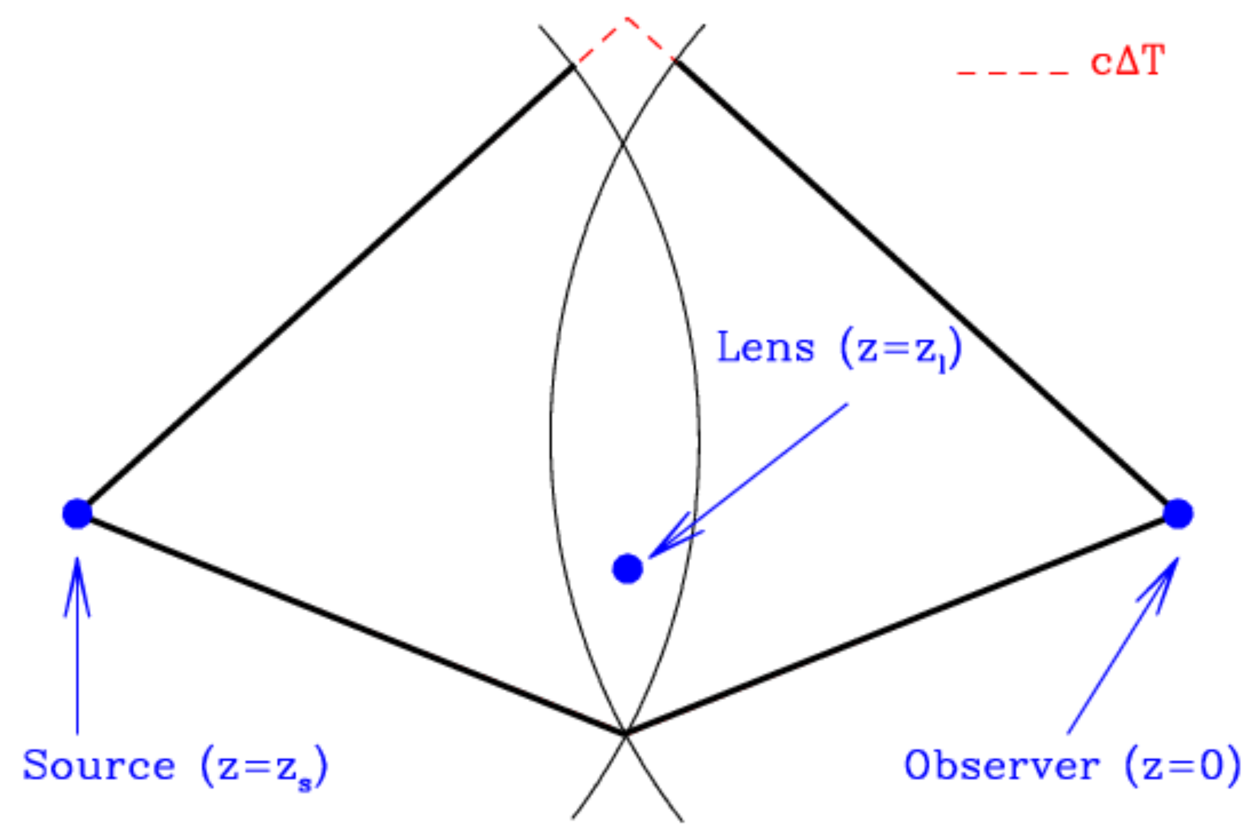


What is the universe made of? (2013-2015)



Cosmography with gravitational lensing

Cosmography from time delays: how does it work?



Strong lensing in terms of Fermat's principle

$$\underbrace{t(\vec{\theta})}_{\text{Excess time delay}} = \frac{(1+z_{\mathrm{d}})}{c}\overbrace{\frac{D_{\mathrm{d}}D_{\mathrm{s}}}{D_{\mathrm{ds}}}}^{\text{Time delay distance}}\left[\underbrace{\frac{1}{2}(\vec{\theta}-\vec{\beta})^2}_{\text{geometric time delay}} - \overbrace{\psi(\vec{\theta})}^{\text{Shapiro delay}}\right]$$

Observables: flux, position, and arrival time of the multiple images

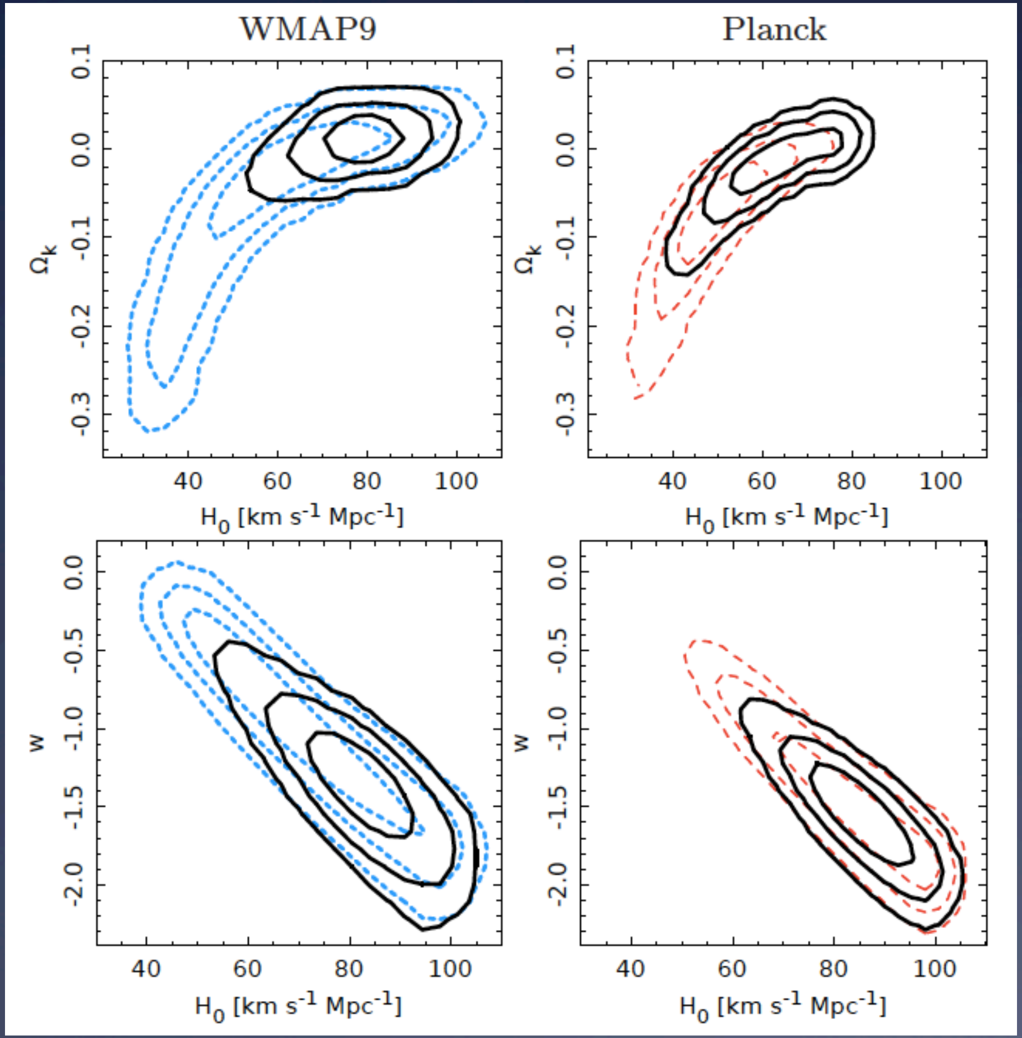
Time delay distance in practice

$$\Delta t \propto D_{\Delta t}(z_s, z_d) \propto H_0^{-1} f(\Omega_m, w, ...)$$

Steps:

- Measure the time-delay between two images
- Measure and model the potential
- Infer the time-delay distance
- Convert it into cosmlogical parameters

The power of time-delays (and other low-z probes)

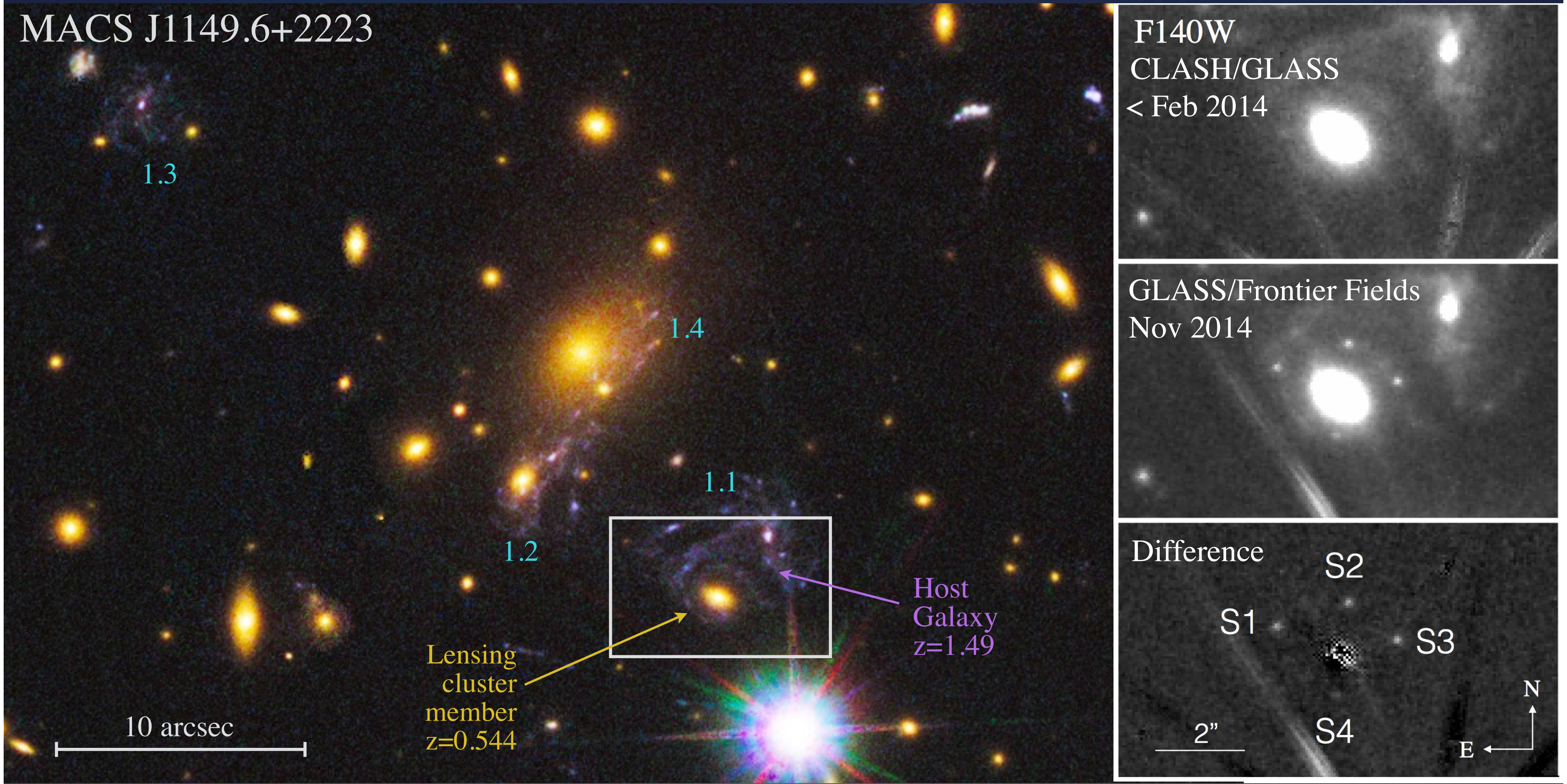


Suyu, Treu et al. 2014

Cosmography from time delays: A brief history

- 1964 Method proposed
- 70s First lenses discovered
- 80s First time delay measured
  - Controversy. Solution: improve sampling
- 90s First Hubble Constant measured
  - Controversy. Solution: improve mass models
- 2000s: modern monitoring (COSMOGRAIL, Fassnacht & others); stellar kinematics (Treu & Koopmans 2002); extended sources
- 2010s Putting it all together: precision measurements (6-7% from a single lens)
- 2014 first multiply imaged supernova discovered (50th anniversary of Refsdal's paper)

November 2014
Supernova ‘Refsdal’

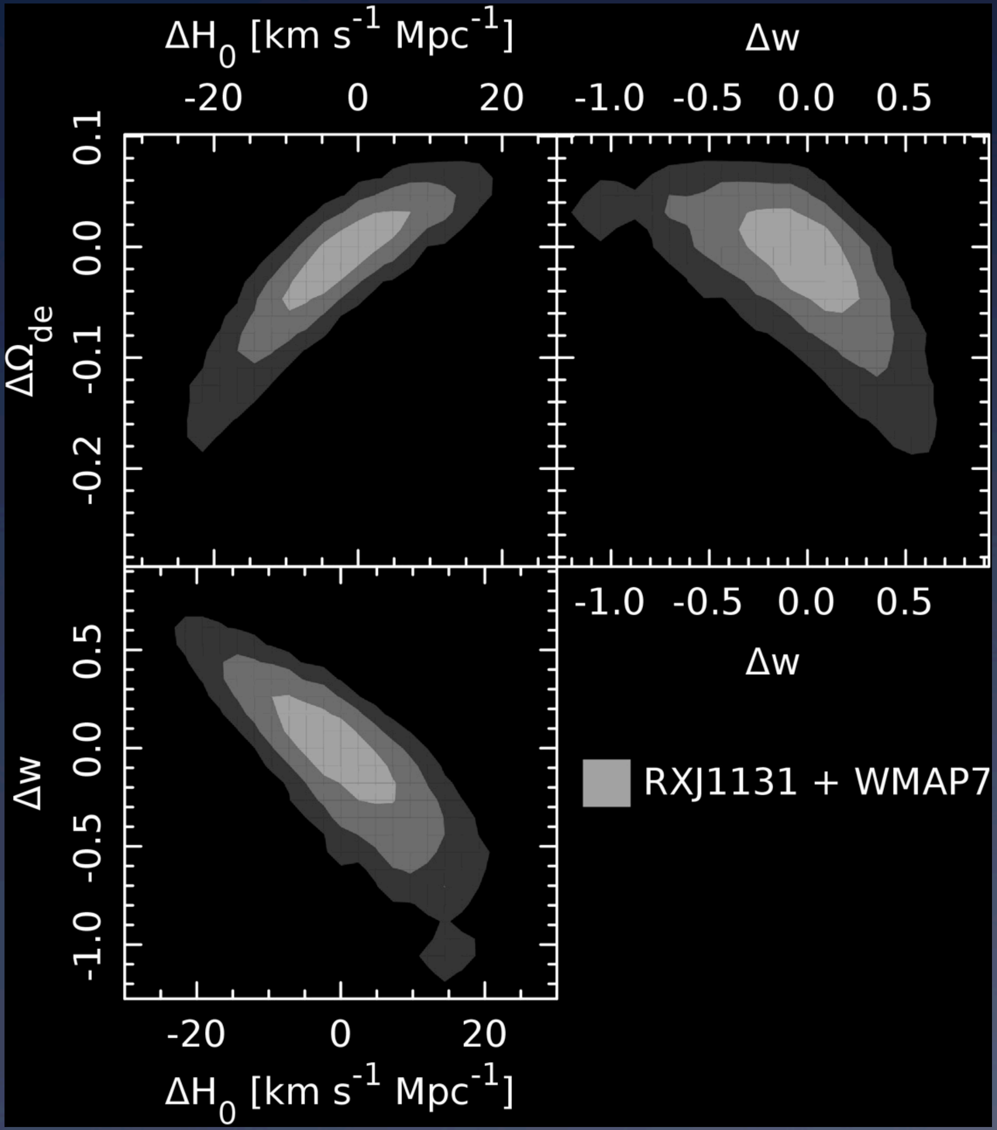


Kelly, Rodney, Treu et al. 2014

Cosmography with strong lenses: the 4 problems solved

- Time delay – 2-3 %
  - Tenacious monitoring (e.g. Fassnacht et al. 2002); COSMOGRAIL (Meylan/Courbin)
- Astrometry – 10-20 mas
  - Hubble/VLA/(Adaptive Optics?)
- Lens potential (2-3%)
  - Stellar kinematics/Extended sources (Treu & Koopmans 2002; Suyu et al. 2009)
- Structure along the line of sight (2-3%)
  - Galaxy counts and numerical simulations (Suyu et al. 2009)
  - Stellar kinematics (Koopmans et al. 2003)

Cosmological Results



Blinded

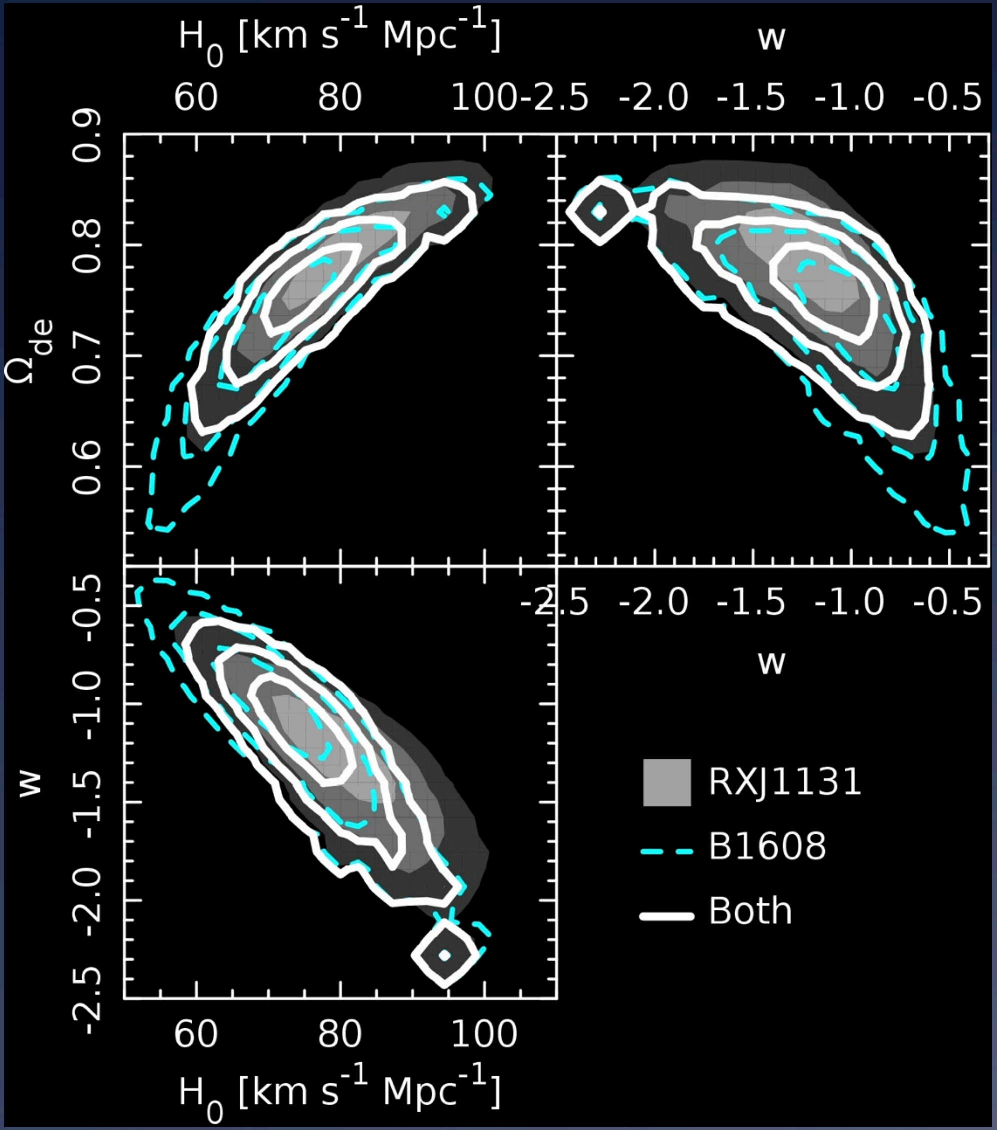
In combination with WMAP7 in flat wCDM cosmology

Precision comparable to that of B1608+656

Accuracy?

After completing the blind analysis and agreeing we would publish the results without modification once unblinded…

Constraints from Two Lenses



In combination with WMAP7 in wCDM cosmology:

$$H_0 = 75.2^{+4.4}_{-4.2}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

$$\Omega_{\rm de} = 0.76^{+0.02}_{-0.03}$$

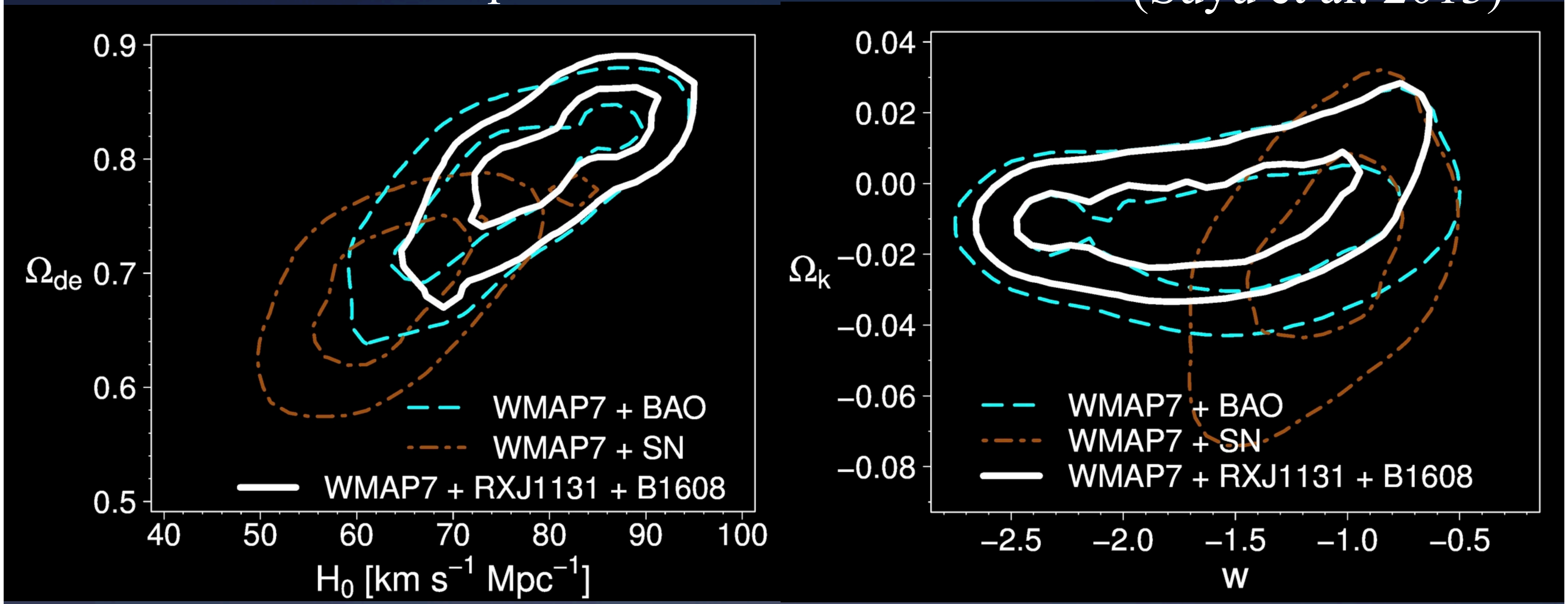
$$w = -1.14^{+0.17}_{-0.20}$$

(Suyu et al. 2013)

Cosmological Probe Comparison

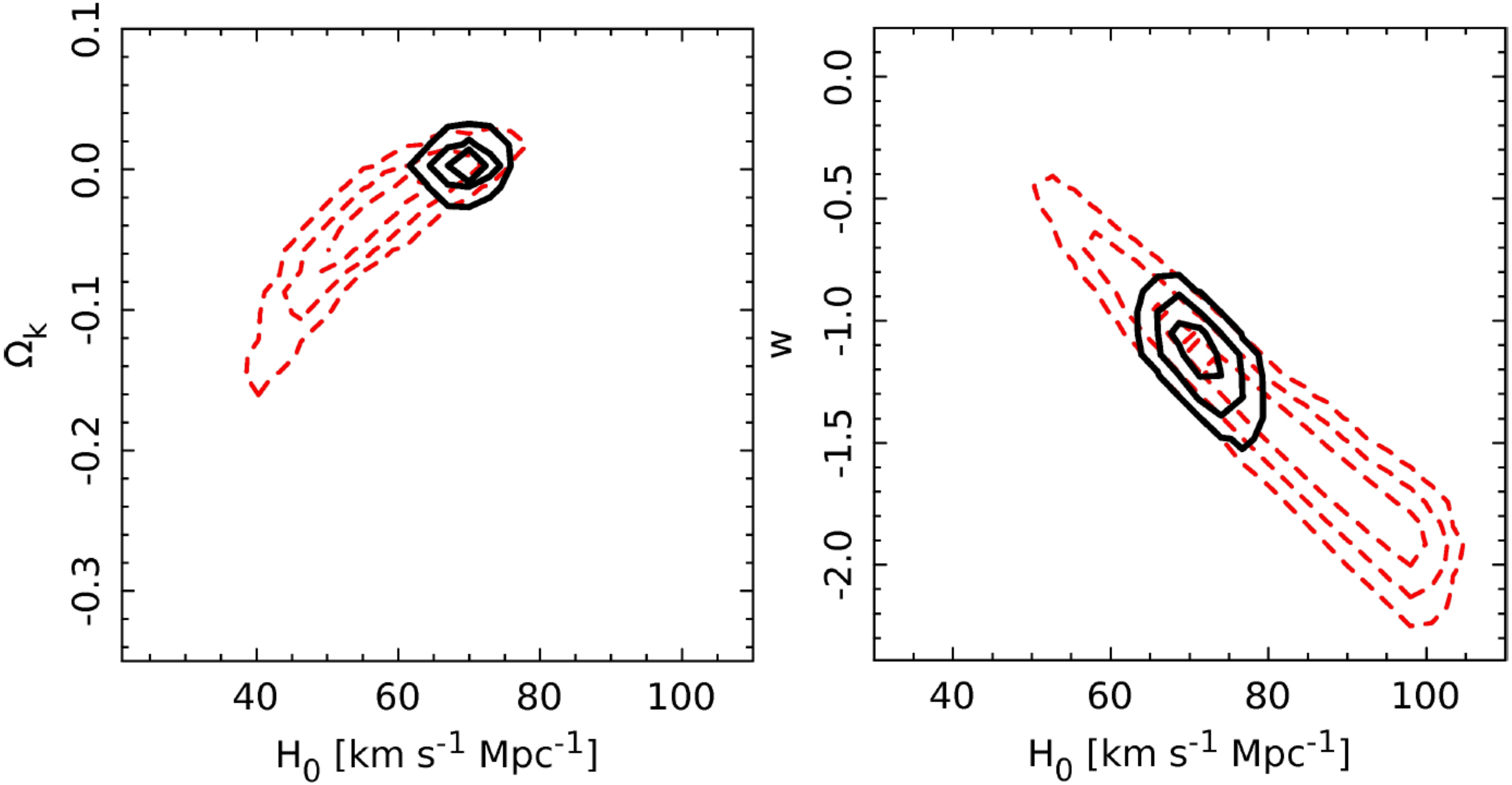
WMAP7owCDM prior

(Suyu et al. 2013)



- contour orientations are different: complementarity b/w probes
- contour sizes are similar: lensing is a competitive probe

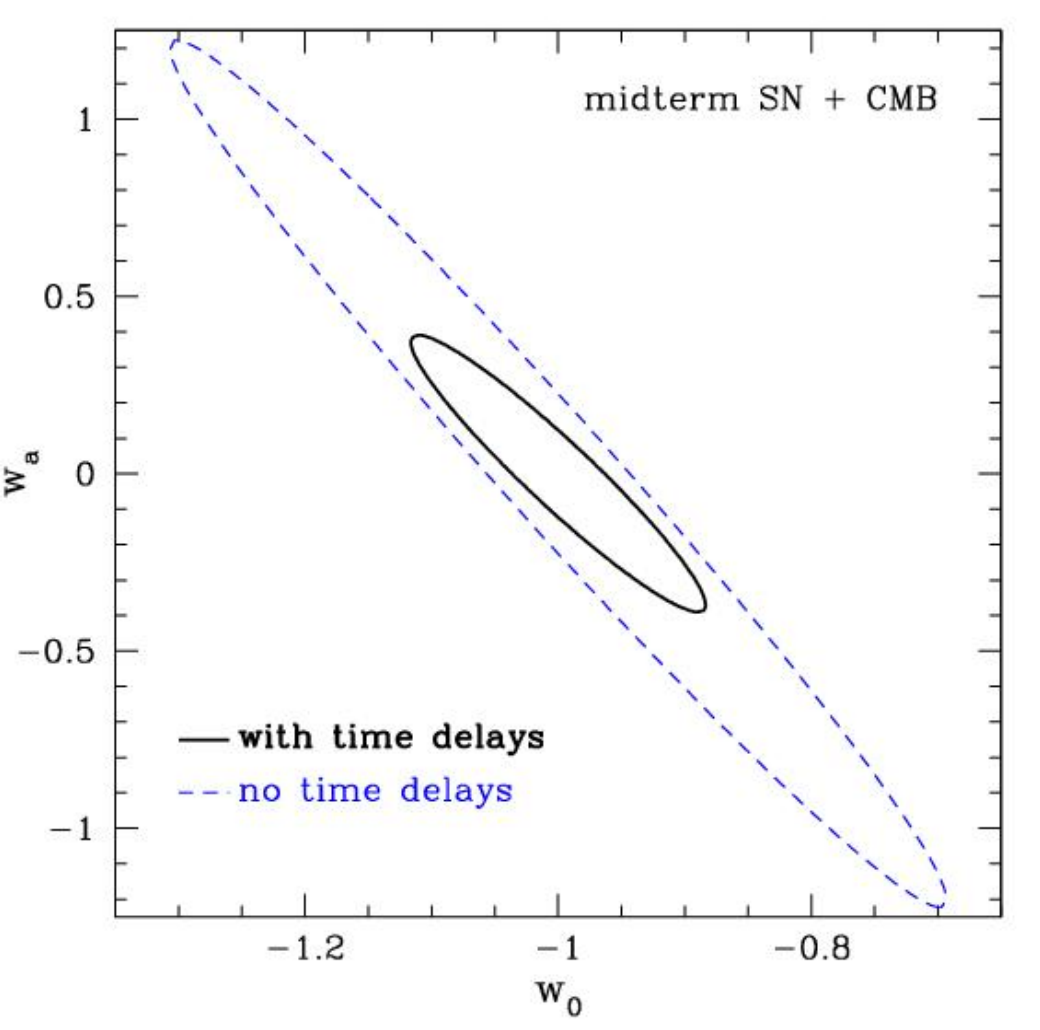
Immediate prospects



Currently working on 9 lenses

Future Prospects

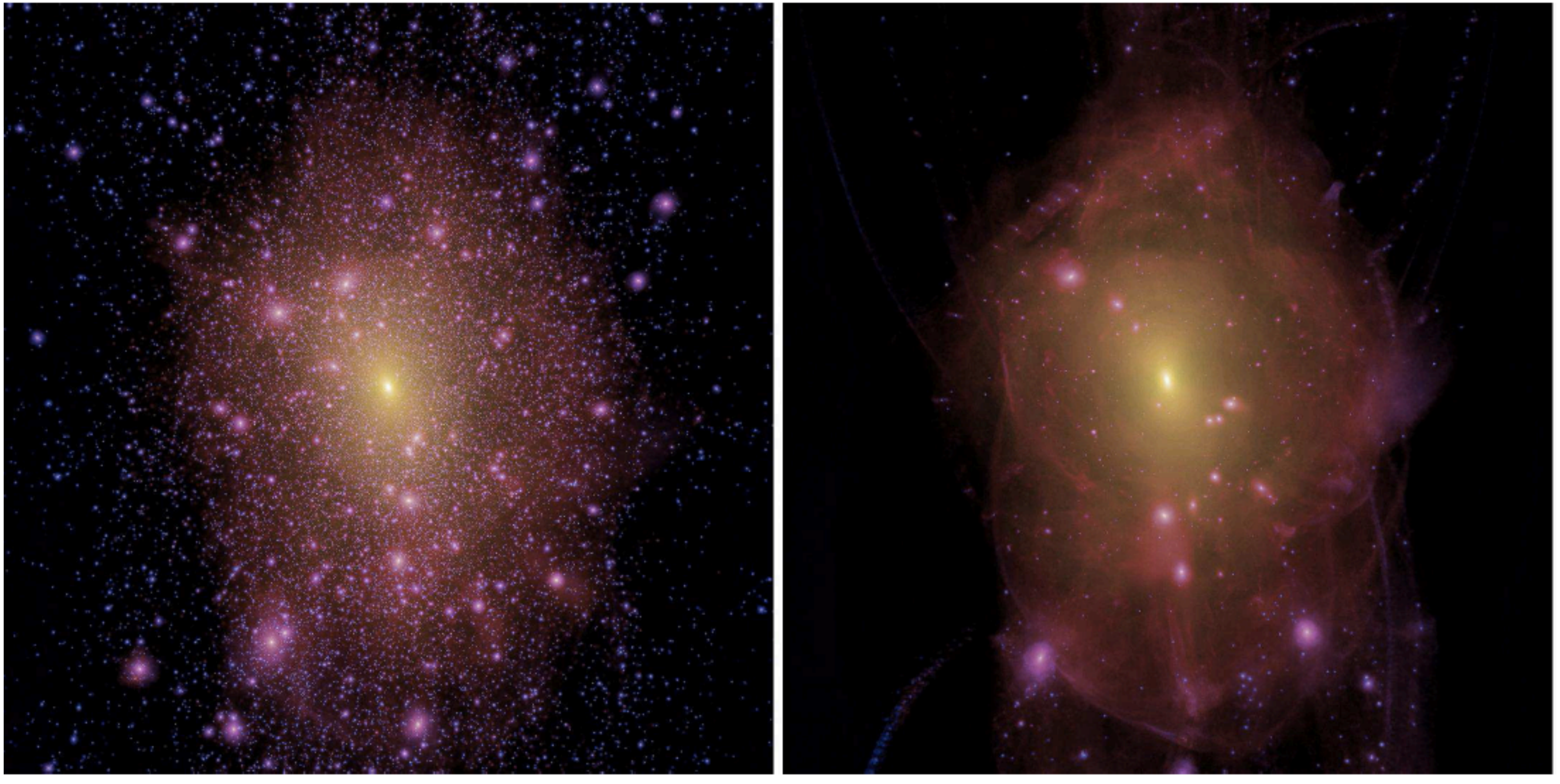
- Currently ~10 lenses have precise time-delays
- Future telescopes (e.g. LSST) will discover and measure 100s of time delays (Oguri & Marshall 2010; Treu 2010)
- A time delay survey could provide very interesting constraints on dark energy



Linder 2011

What's the (dark) matter?

Warm Dark Matter

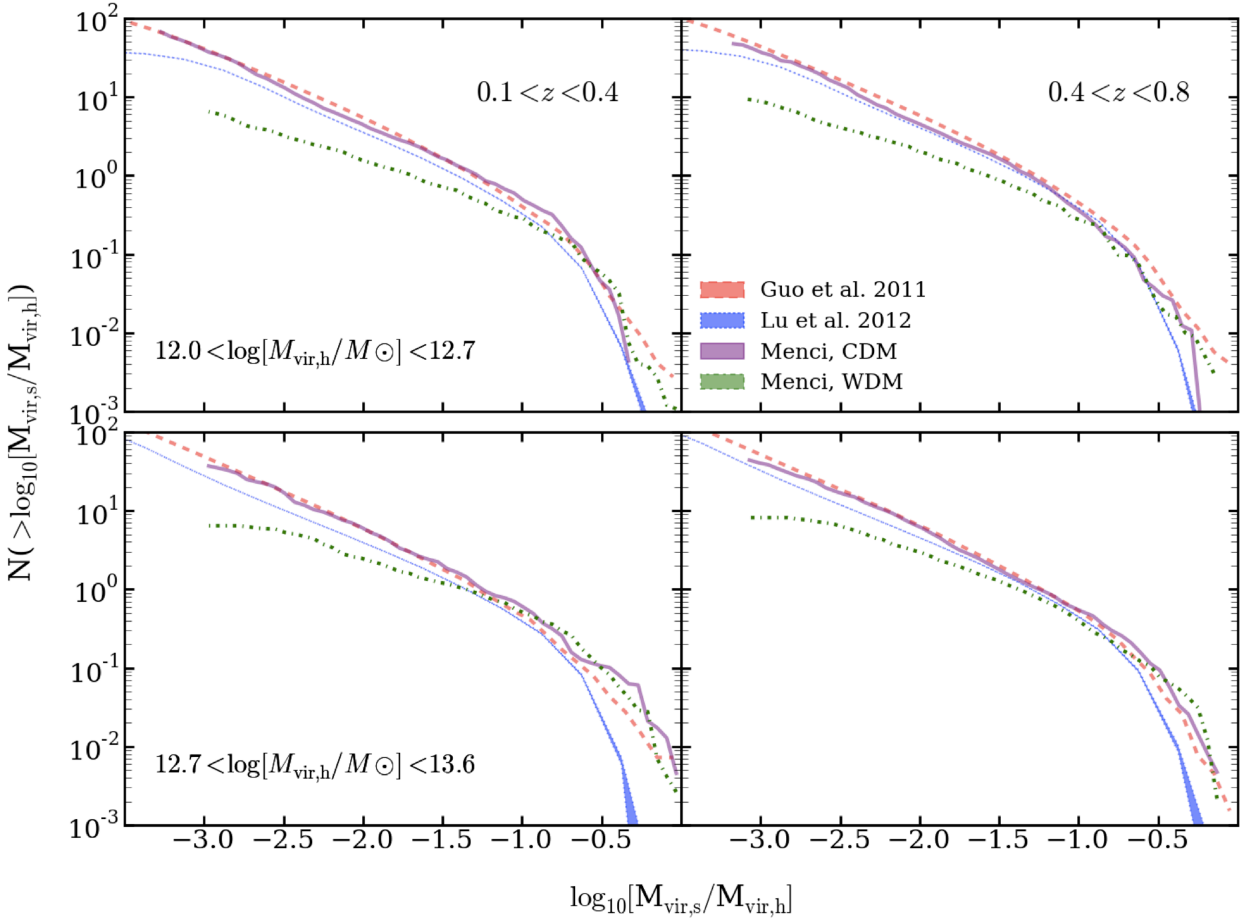


Free streaming ~kev scale thermal relic

Lovell et al. 2014

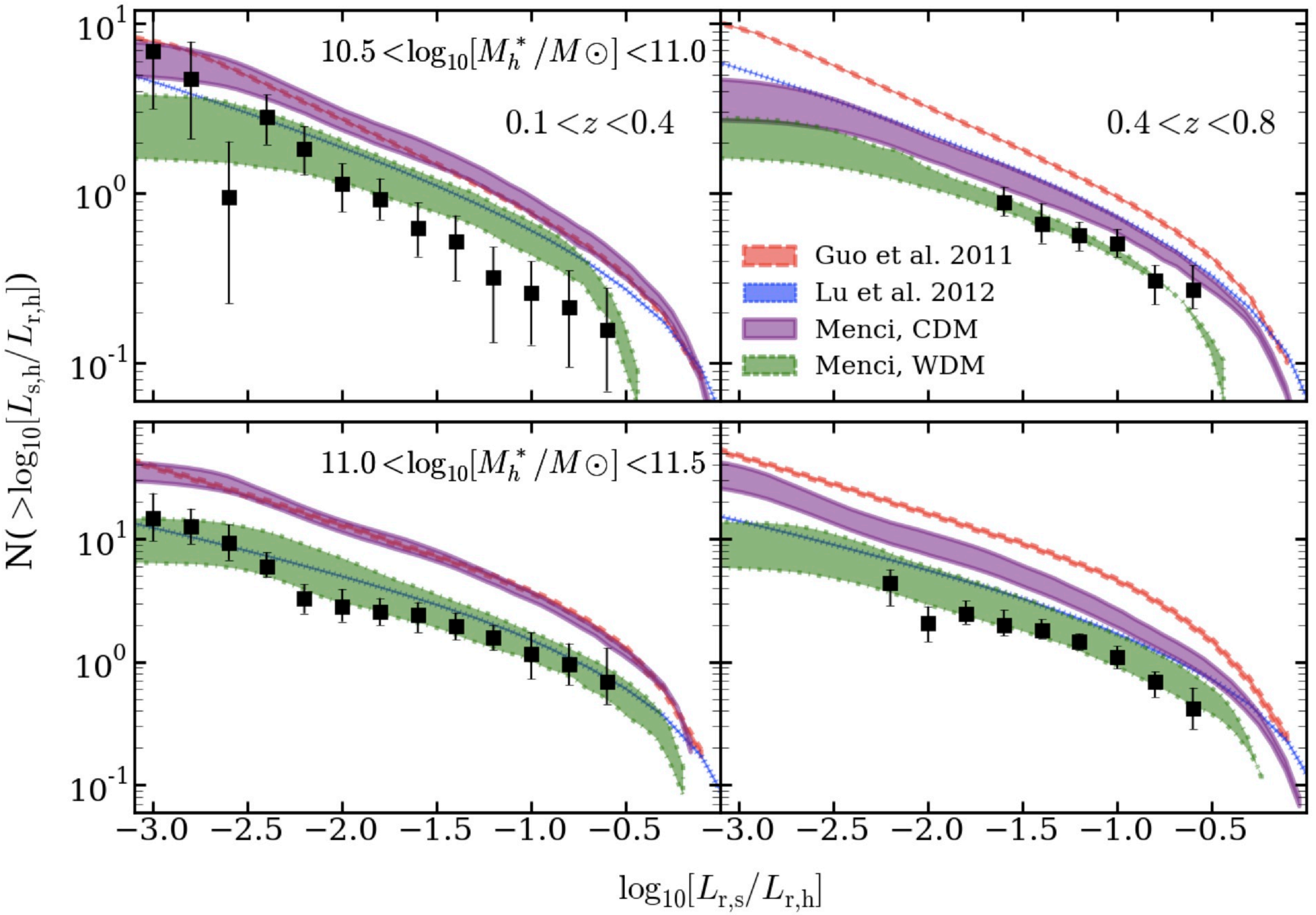
Satellites as a probe of dark matter “mass”

Dark Satellites in CDM vs WDM



Nierenberg, Treu, et al. 2013

Luminous Satellites in CDM vs WDM



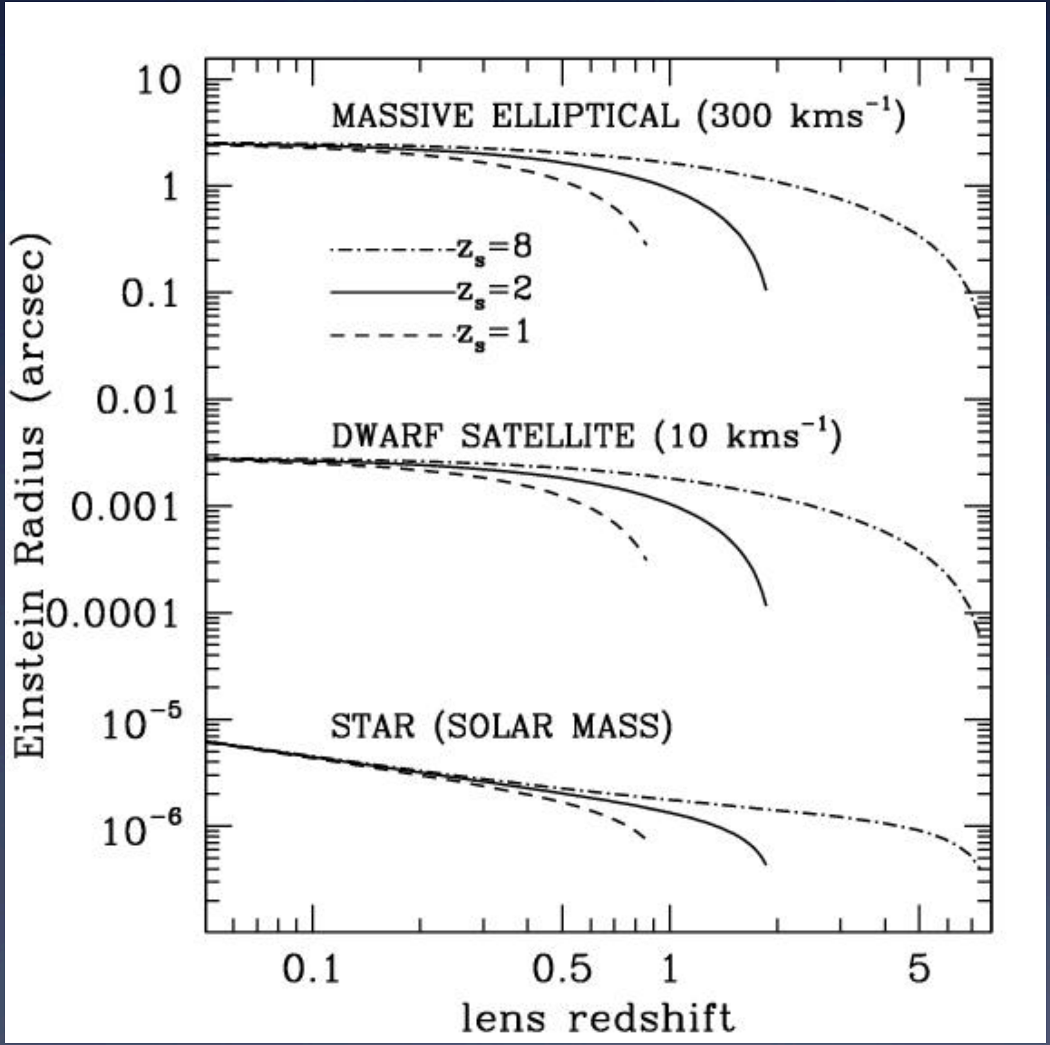
Nierenberg, Treu et al. 2013

“Missing satellites” and lensing

- Strong lensing can detect satellites based solely on mass!
- Satellites are detected as “anomalies” in the gravitational potential ψ and its derivatives
  - ψ'' = Flux anomalies
  - ψ' = Astrometric anomalies
  - ψ = Time-delay anomalies

– **Natural scale is a few milliarcseconds. Astrometric perturbations of 10mas are expected**

“Missing satellites” and lensing



Treu 2010

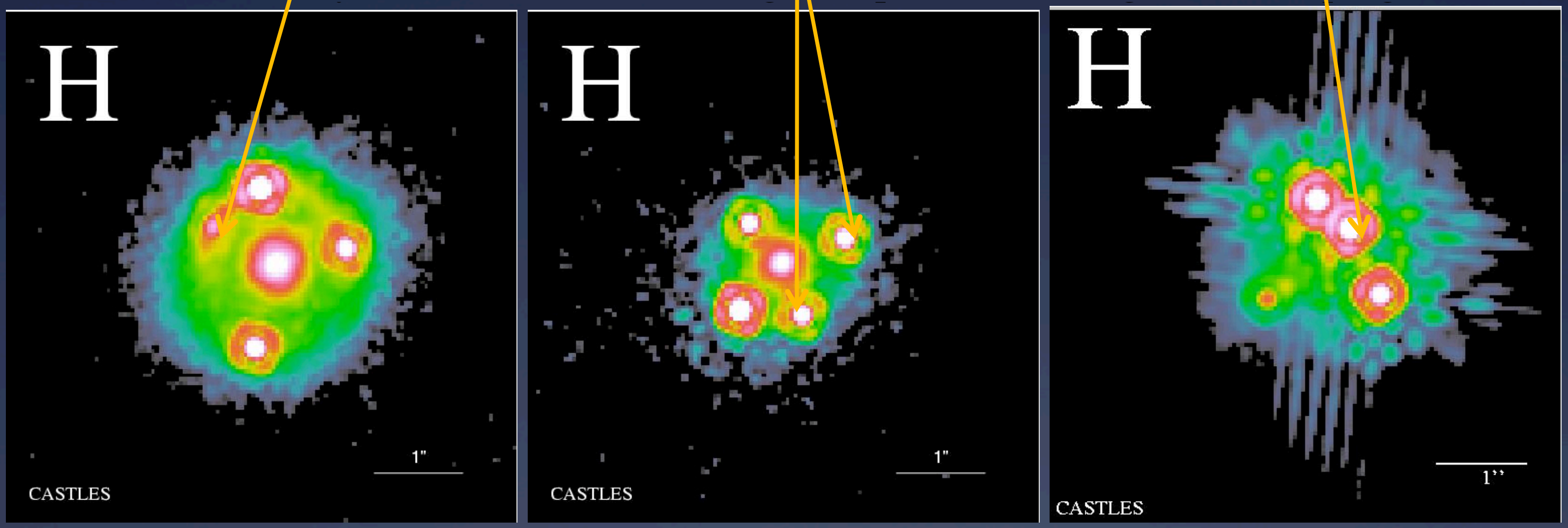
Flux Ratio Anomalies

A smooth mass distribution would predict:

This to be 100x brighter

These to be 2x brighter

This to be 10% brighter

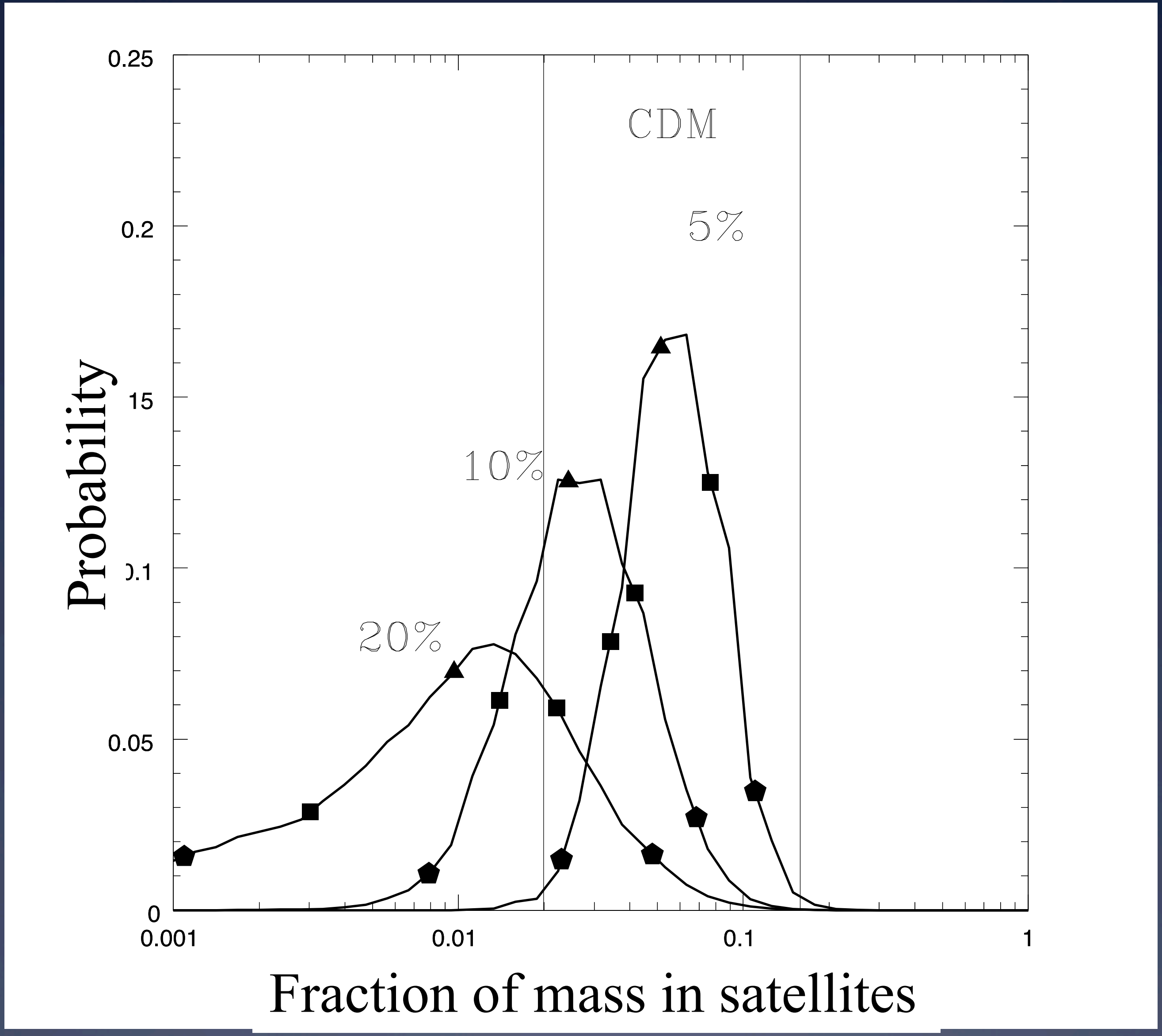


What causes this the anomaly?

1.Dark satellites?

2.Astrophysical noise (i.e. microlensing and dust)?

Anomalies detected in 7 radio lenses

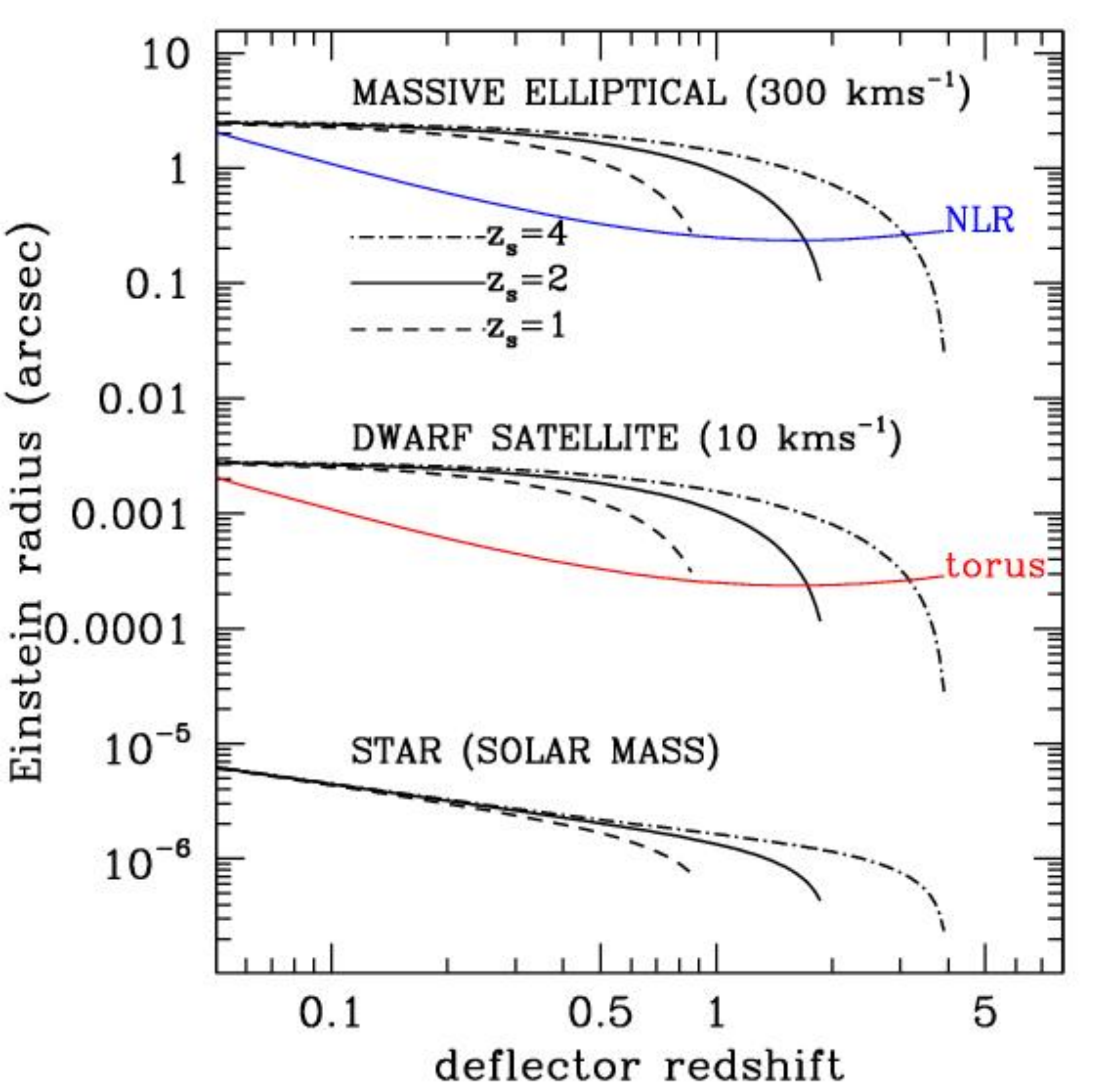


Dalal and Kochanek 2002

How do we make progress?

1. Larger samples
2. High precision photometry and astrometry
3. Avoid microlensing
4. Direct detection a.k.a. "gravitational imaging"

Dusty Torus and Narrow Line Region Are not affected by microlensing



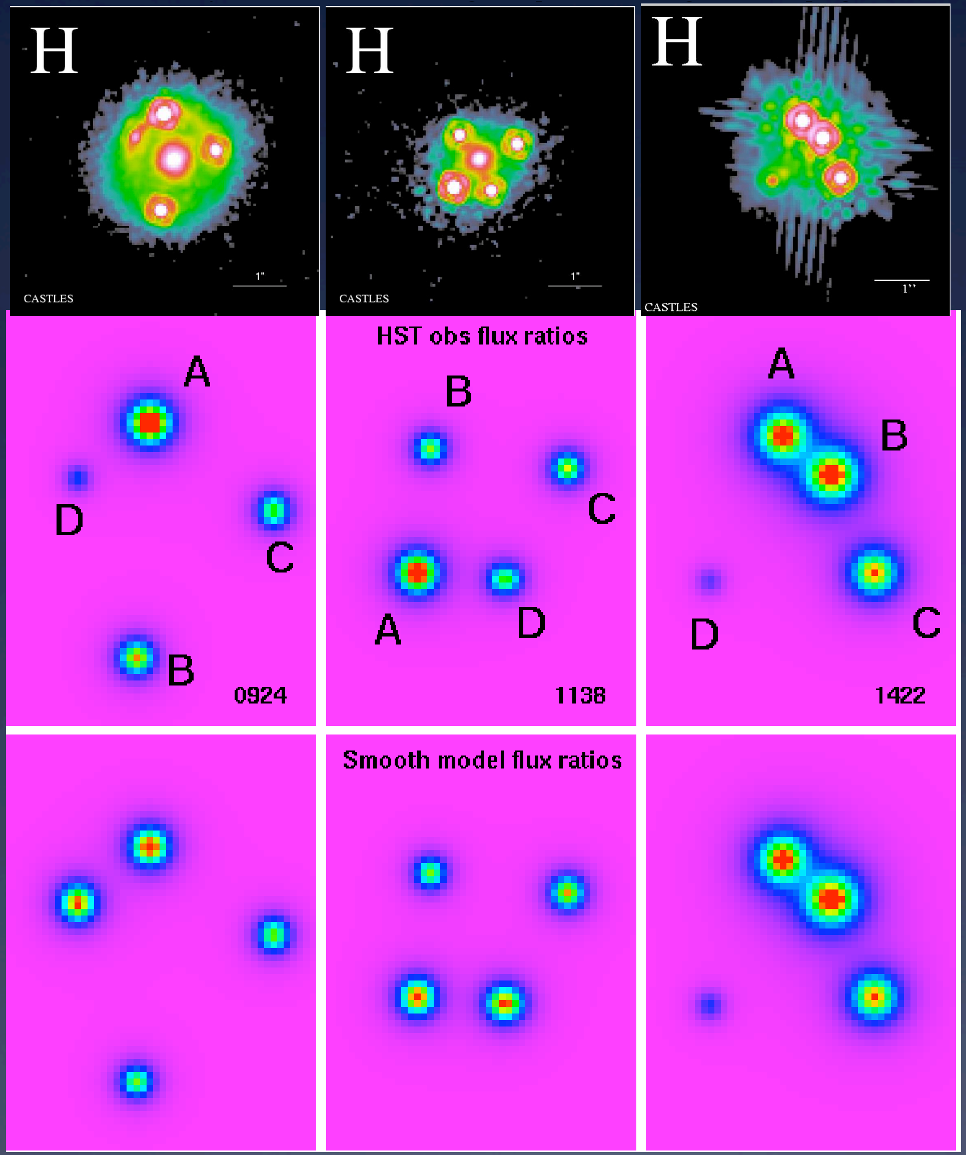
Narrow line flux ratios of lensed AGN

Benefits:

1. Confirm/ eliminate microlensing

2. High resolution spectroscopy rules out wavelength-dependent suppression (e.g. dust)

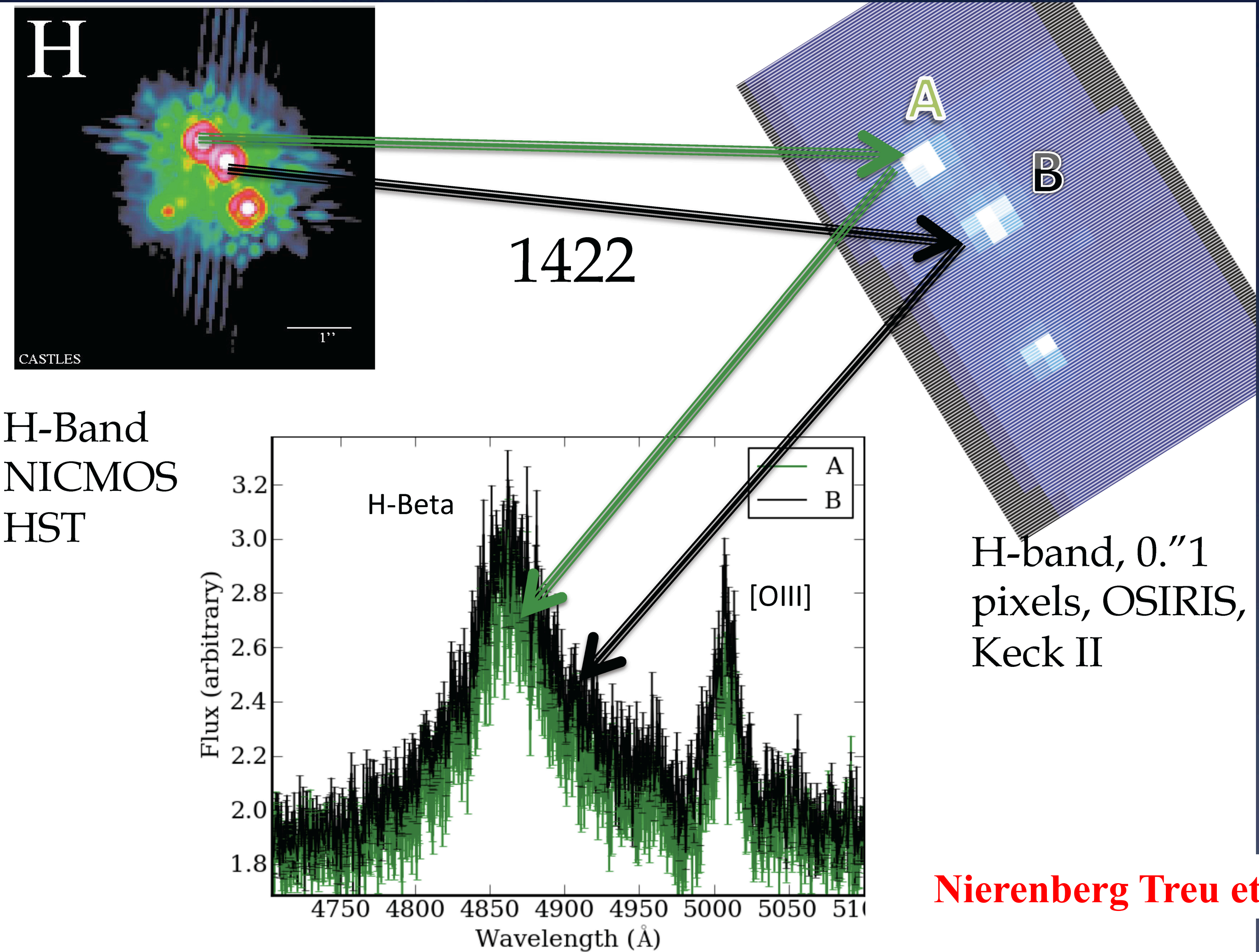
3. Excellent astrometry and photometry



If the anomaly is from substructure…

If the anomaly is from microlensing…

OSIRIS detection of substructure



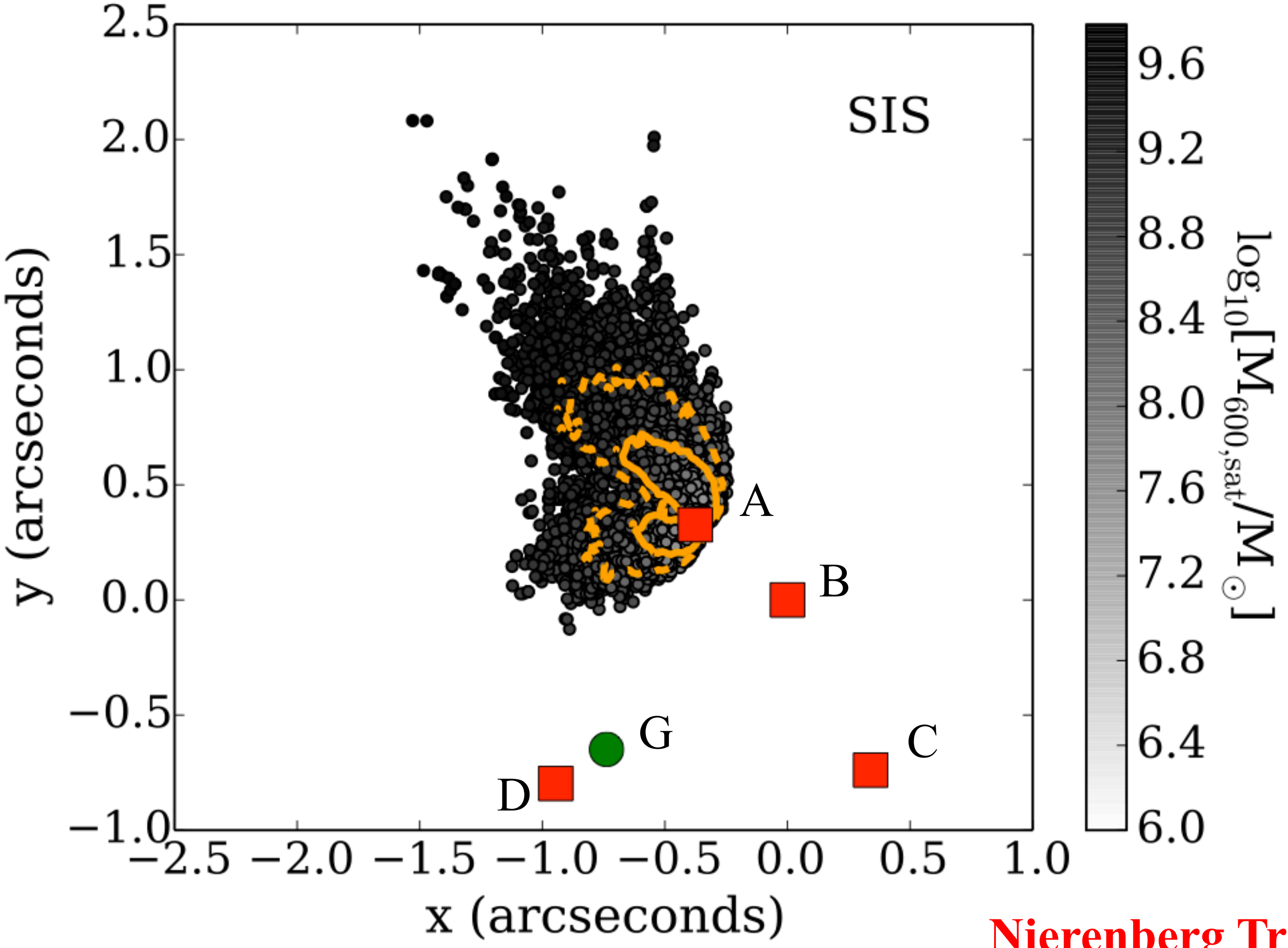
1422

H-Band
NICMOS
HST

H-band, 0.″1
pixels, OSIRIS,
Keck II

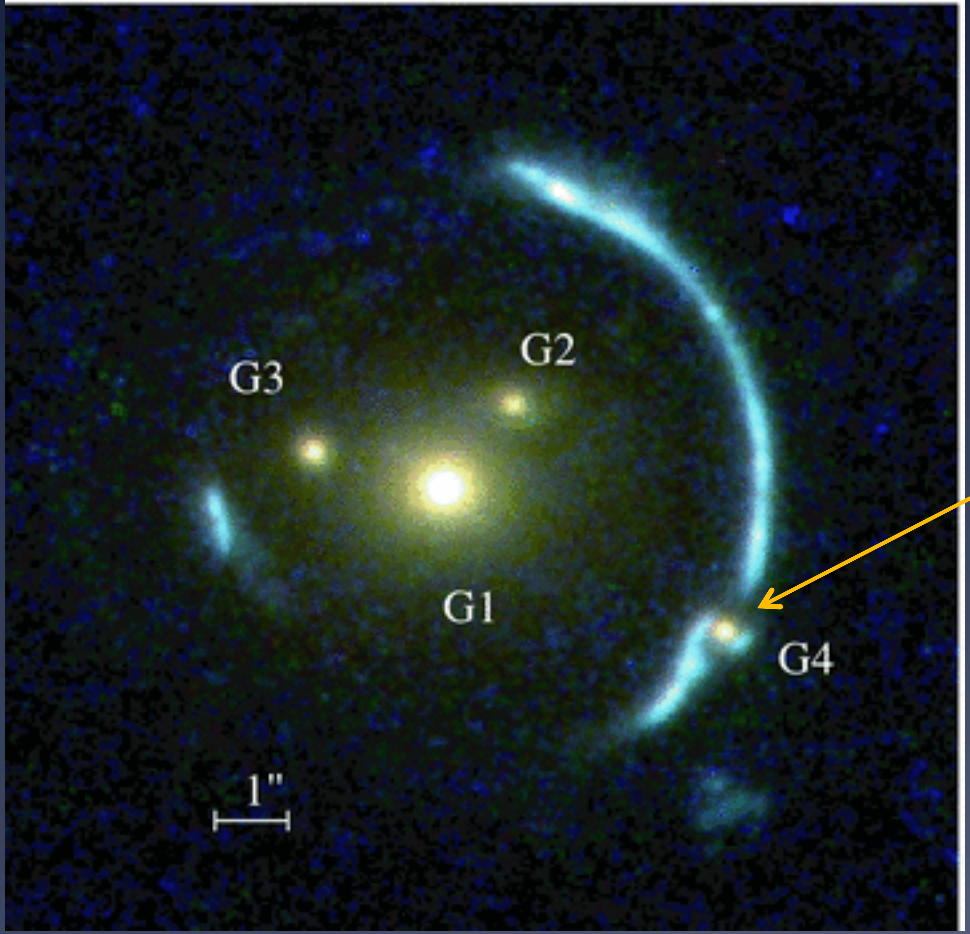
Nierenberg Treu et al 2014

OSIRIS detection of substructure



Nierenberg Treu et al 2014

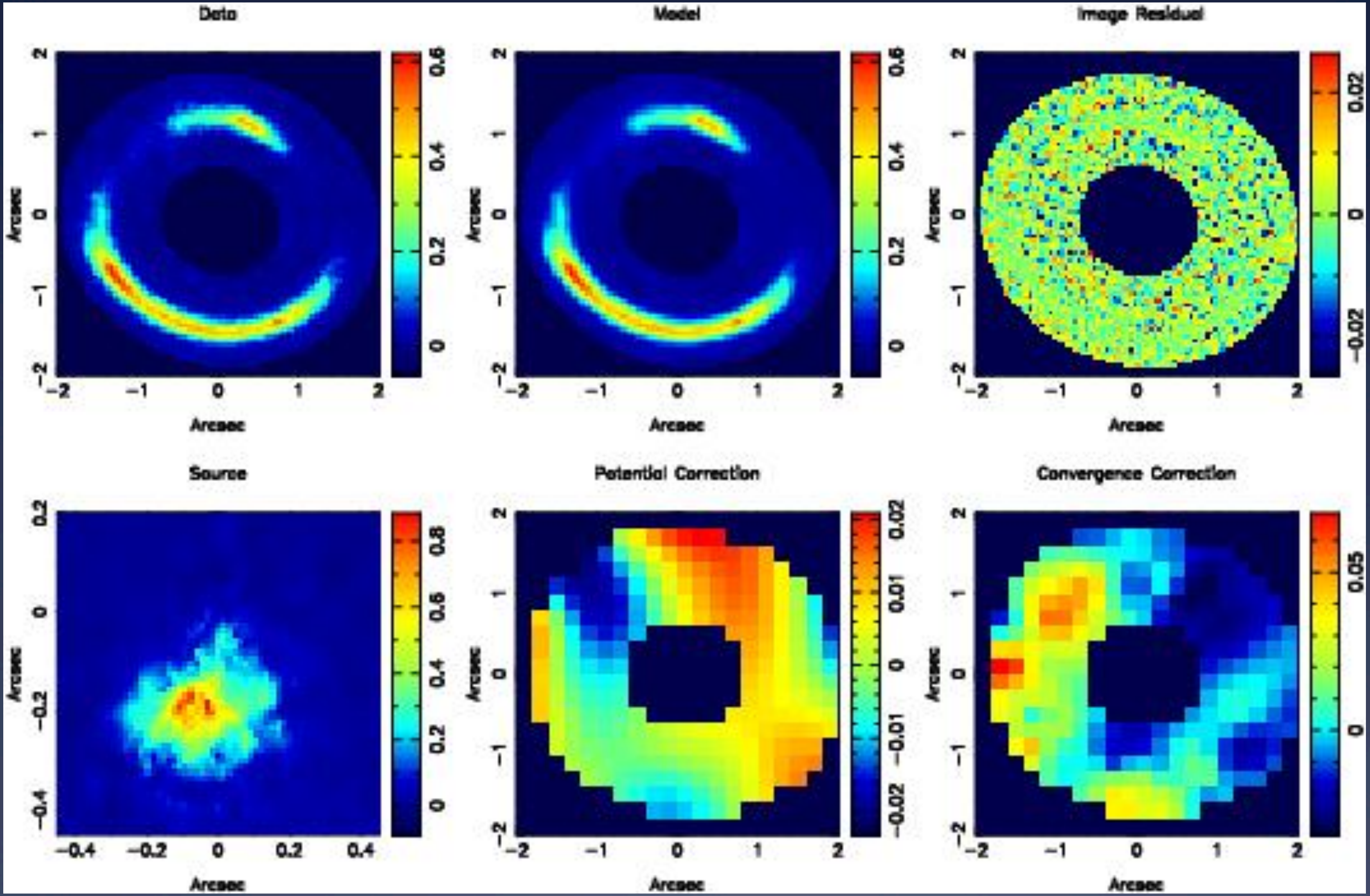
Astrometric perturbations: gravitational imaging



Mass substructure distorts extended lensed sources

Vegetti et al. 2010

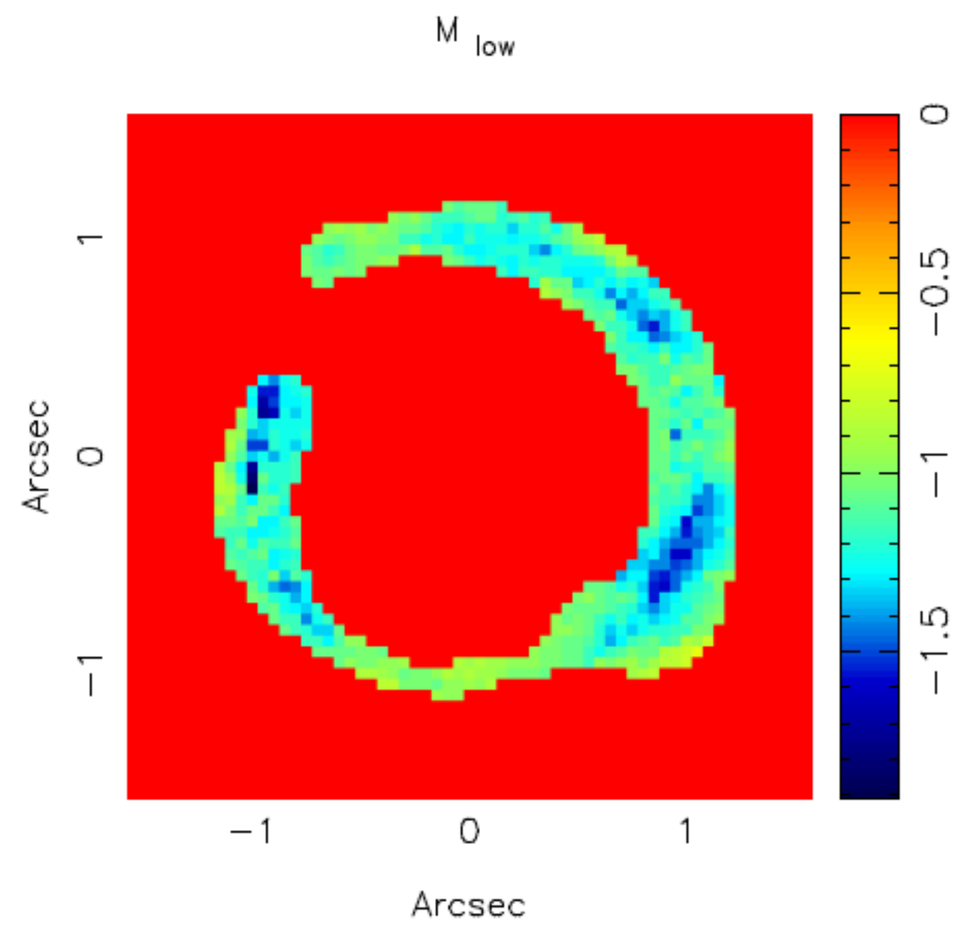
Direct detection of a dark substructure

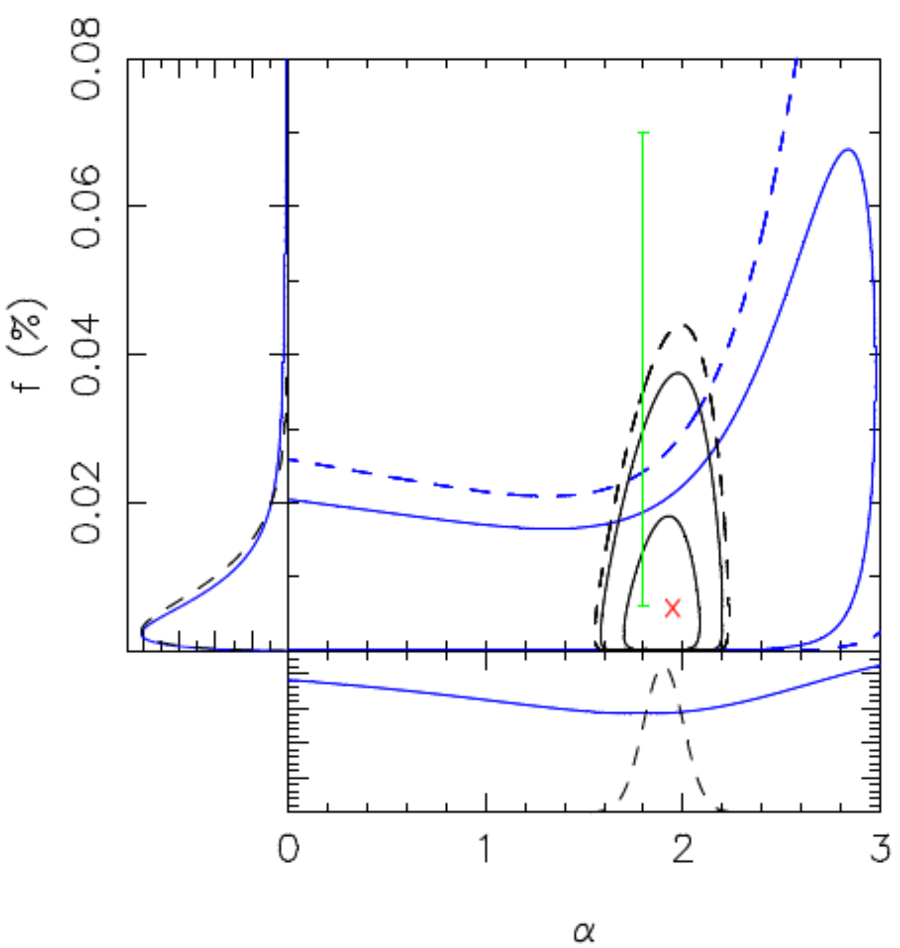


HST/AO can detect down to 1e8 Msun

Vegetti et al 2010, 2012

Statistics from gravitational imaging

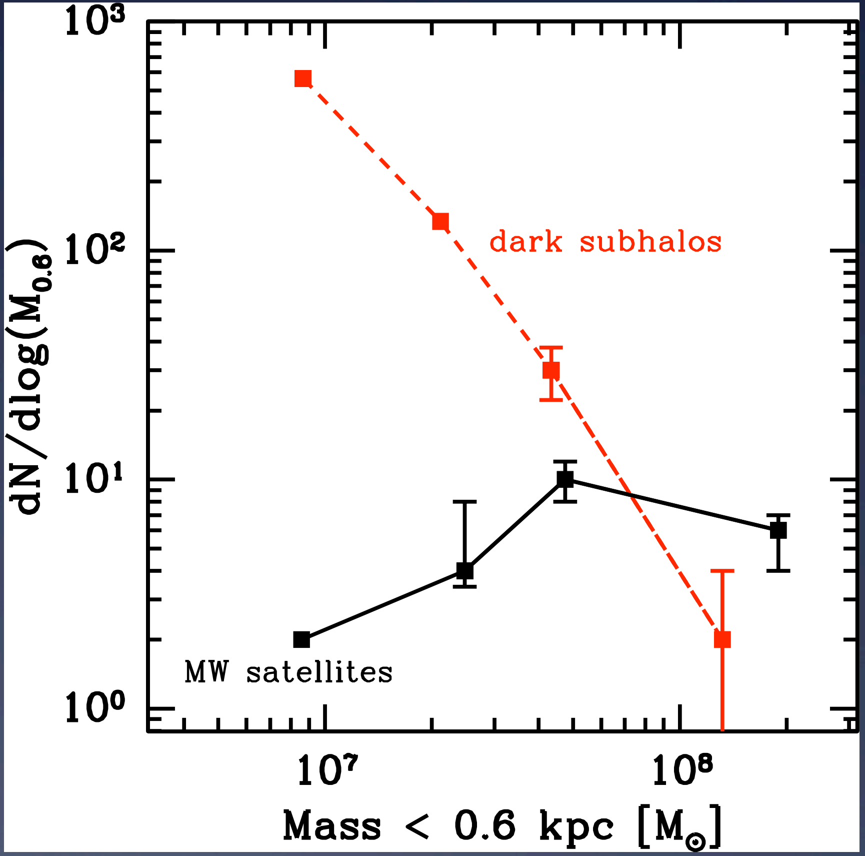




HST/AO can detect down to 3e8 Msun

Vegetti et al 2010, 2012, 2014

Gravitational imaging: Future Prospects



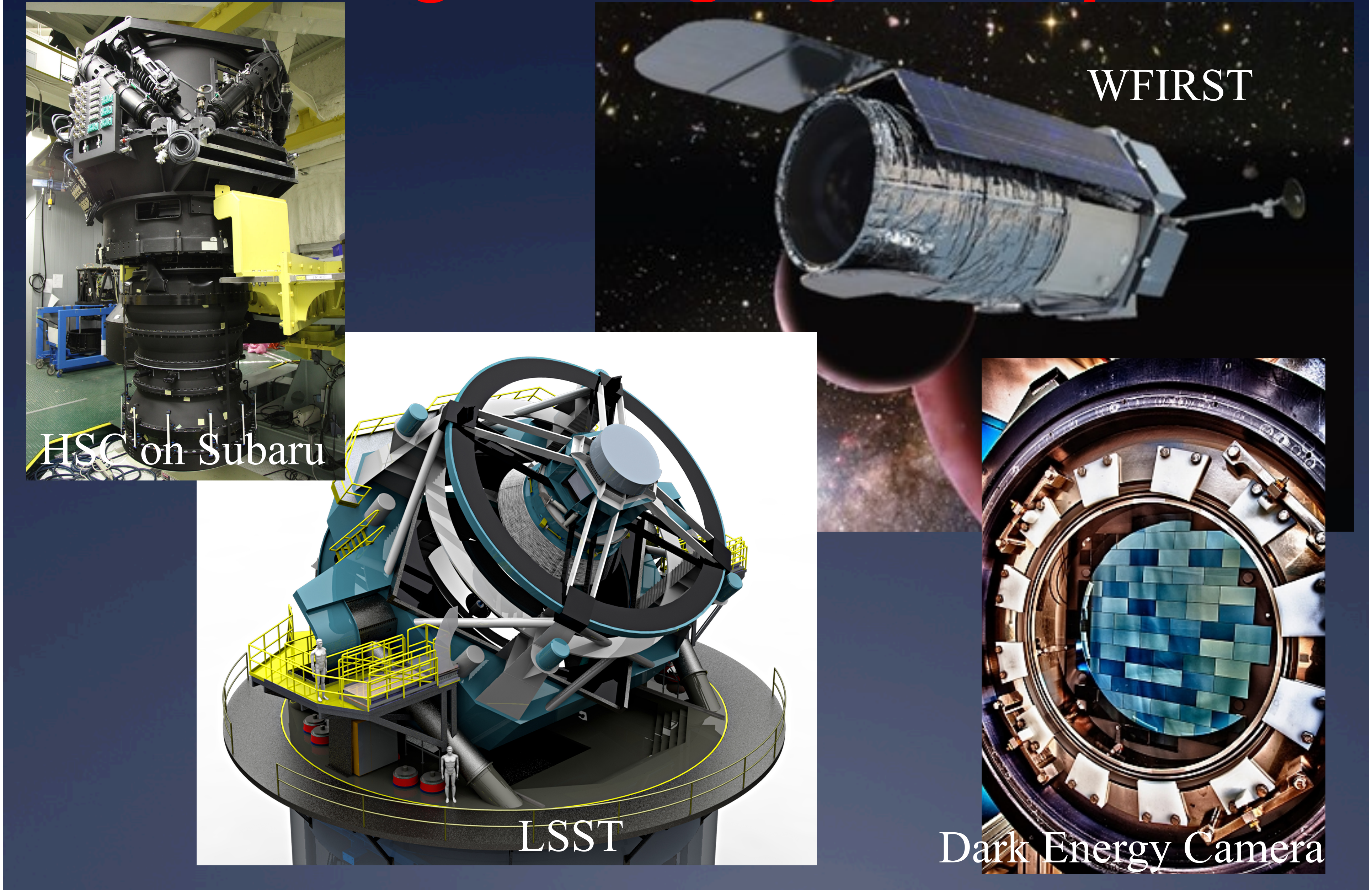
- Gravitational imaging can now reach ~10^8 solar mass sensitivity, limited by resolution and S/N (Vegetti et al. 2012, 2014)
- With Next Generation Adaptive Optics and then ELTs we should reach 10^7 solar masses, where the discrepancy with theory is strongest
- LARGE SAMPLES WITH SUFFICIENT SENSITIVITY WITHIN REACH

Flux ratio anomalies: Future Prospects

- Narrow line flux ratio anomalies can currently be studied for 15 systems
- Future surveys will discover thousands of systems
- ELTs will provide spectroscopic follow-up and emission line flux ratios

How do we find more lensed quasars?

In large imaging surveys



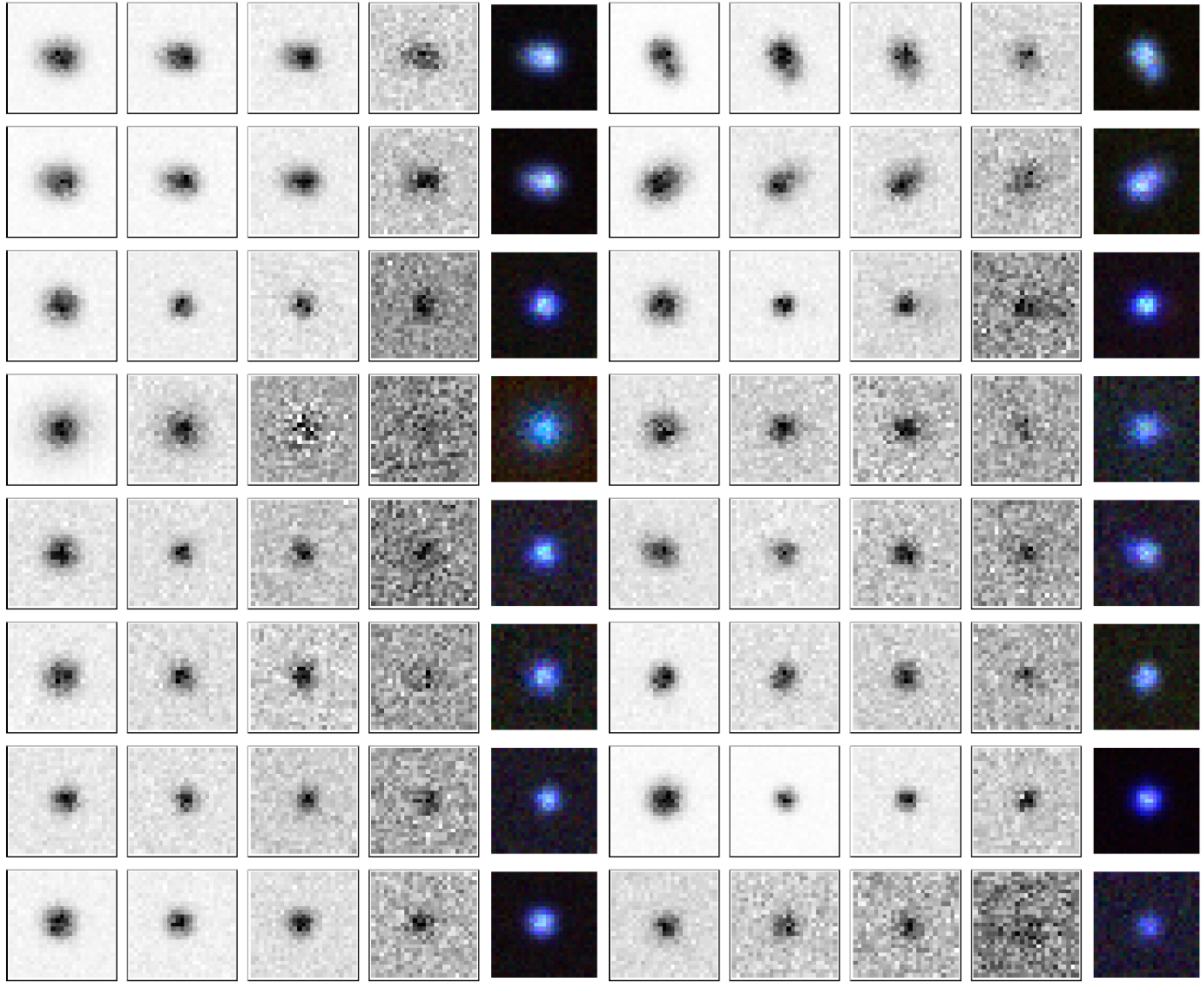
HSC on Subaru

WFIRST

LSST

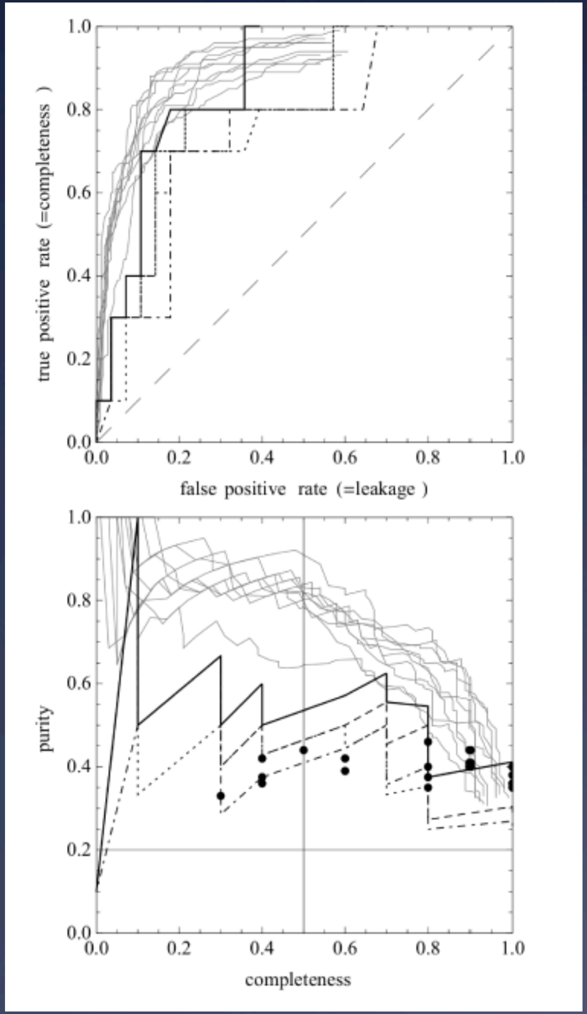
Dark Energy Camera

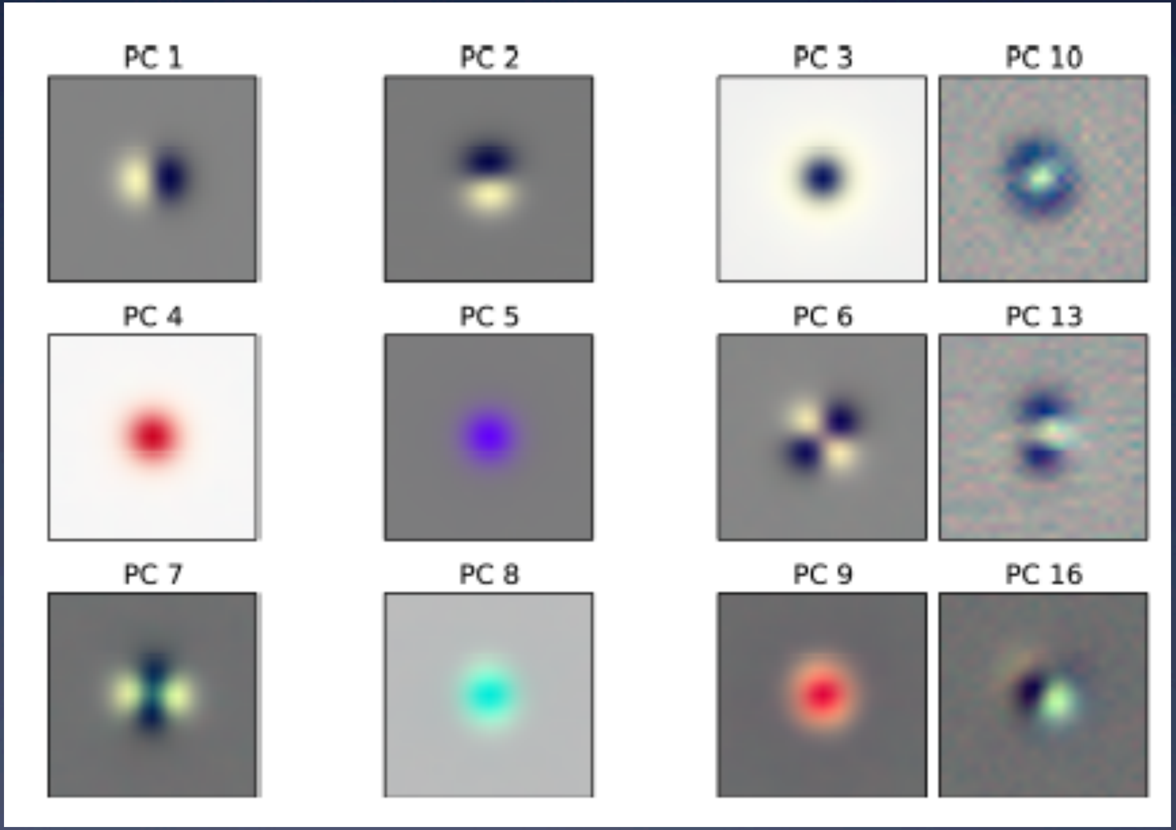
Needle in a haystack!



Which ones are lenses? Agnello, Kelly Treu & Marshall 2015

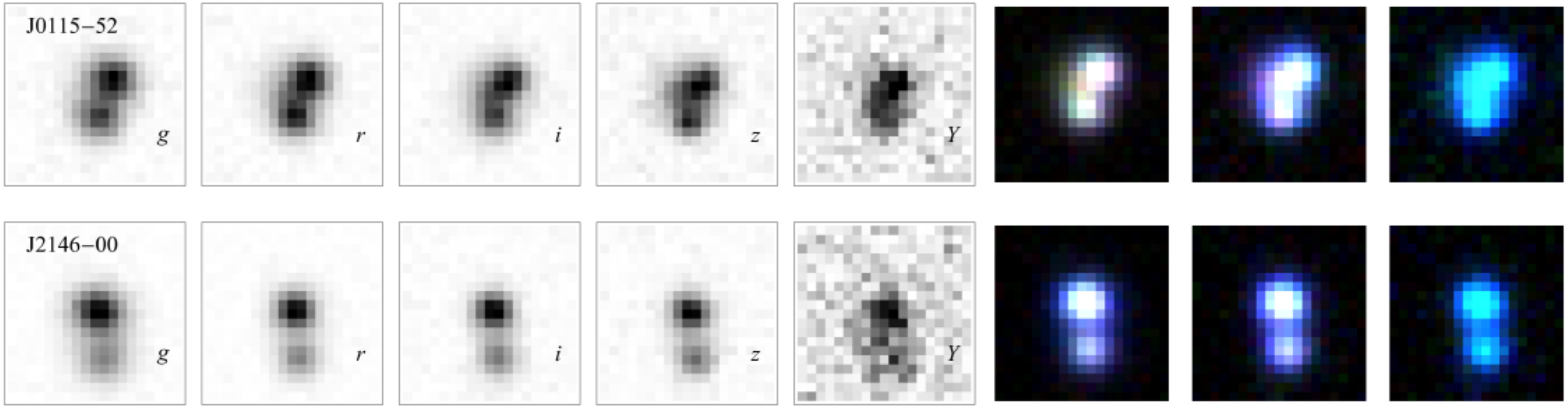
We can find them using machine learning techniques

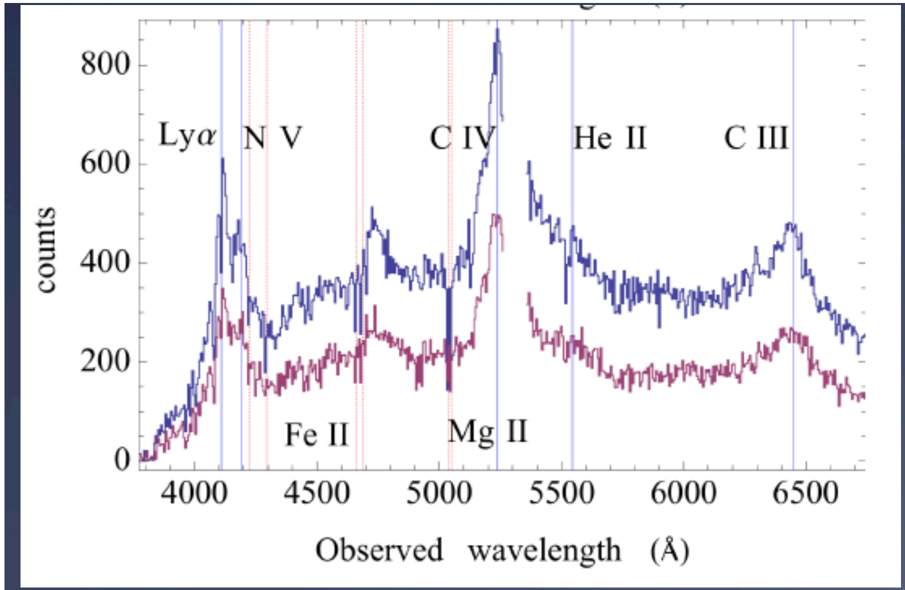


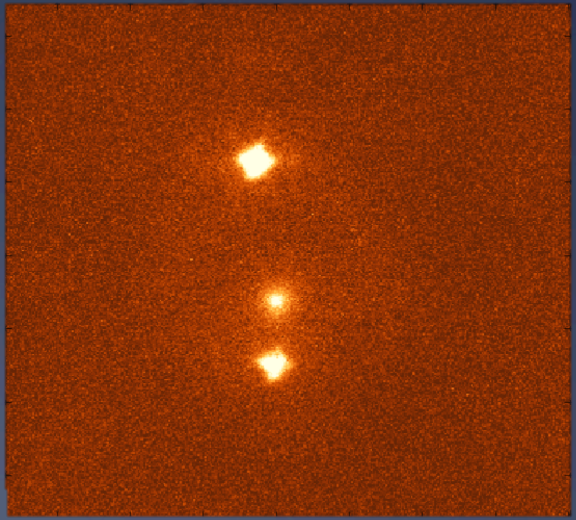


Agnello et al. 2015a

And here they are!







Agnello et al. 2015b

Conclusions

- Strong gravitational lensing is a cost-effective tool to study the composition of the universe:
  - A dedicated time-delay program can achieve sub-percent accuracy on H_0 and increase figure of merit of other dark energy experiments by x5 or more
  - Flux ratios and gravitational imaging can probe the subhalo mass function down to 1e7 solar masses and thus help rule out (or confirm) WDM
- This is feasible in the next five years with a concerted follow-up effort of quasar lenses discovered in DES and other imaging surveys