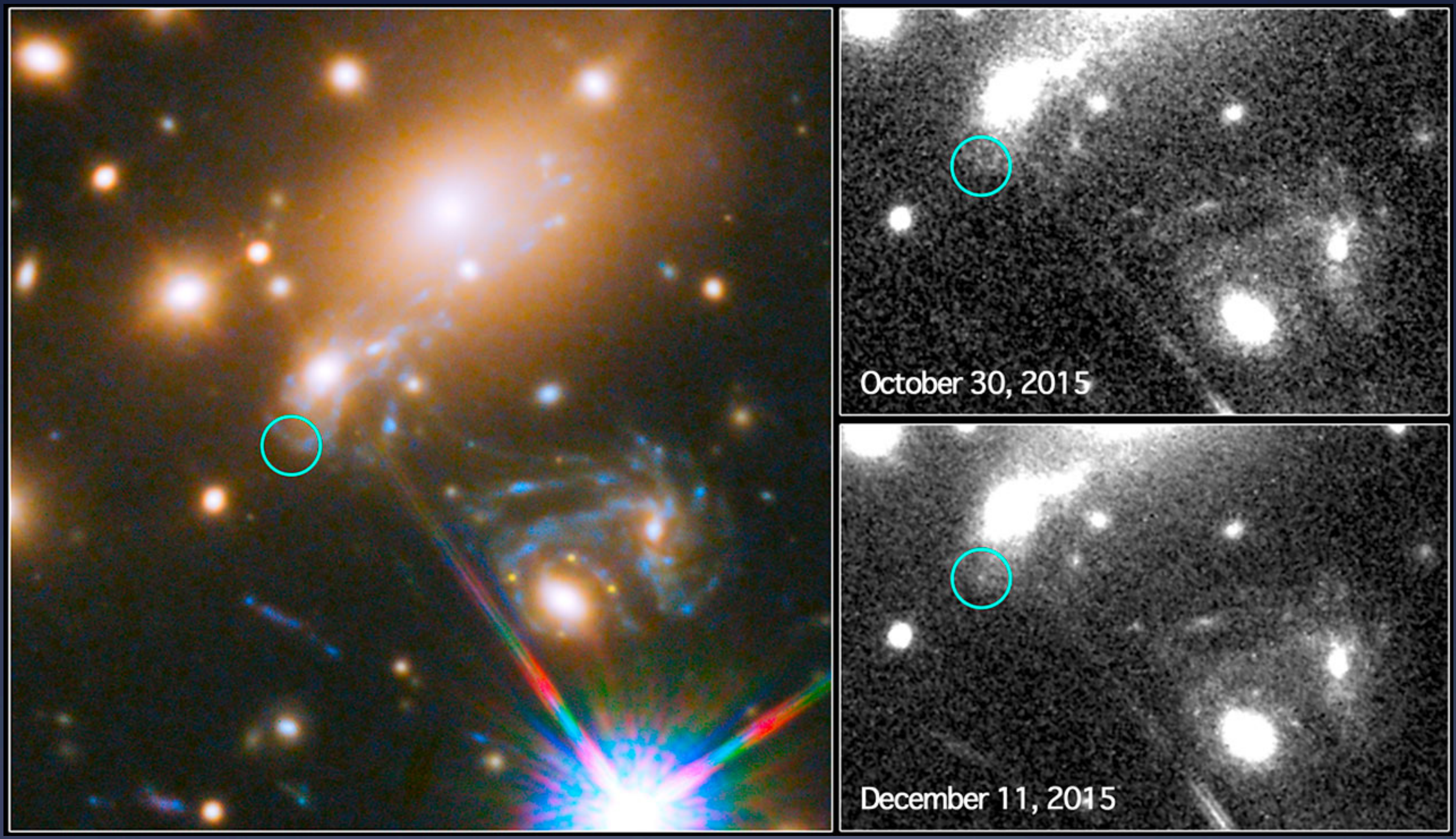
Strong lensing with WFIRST



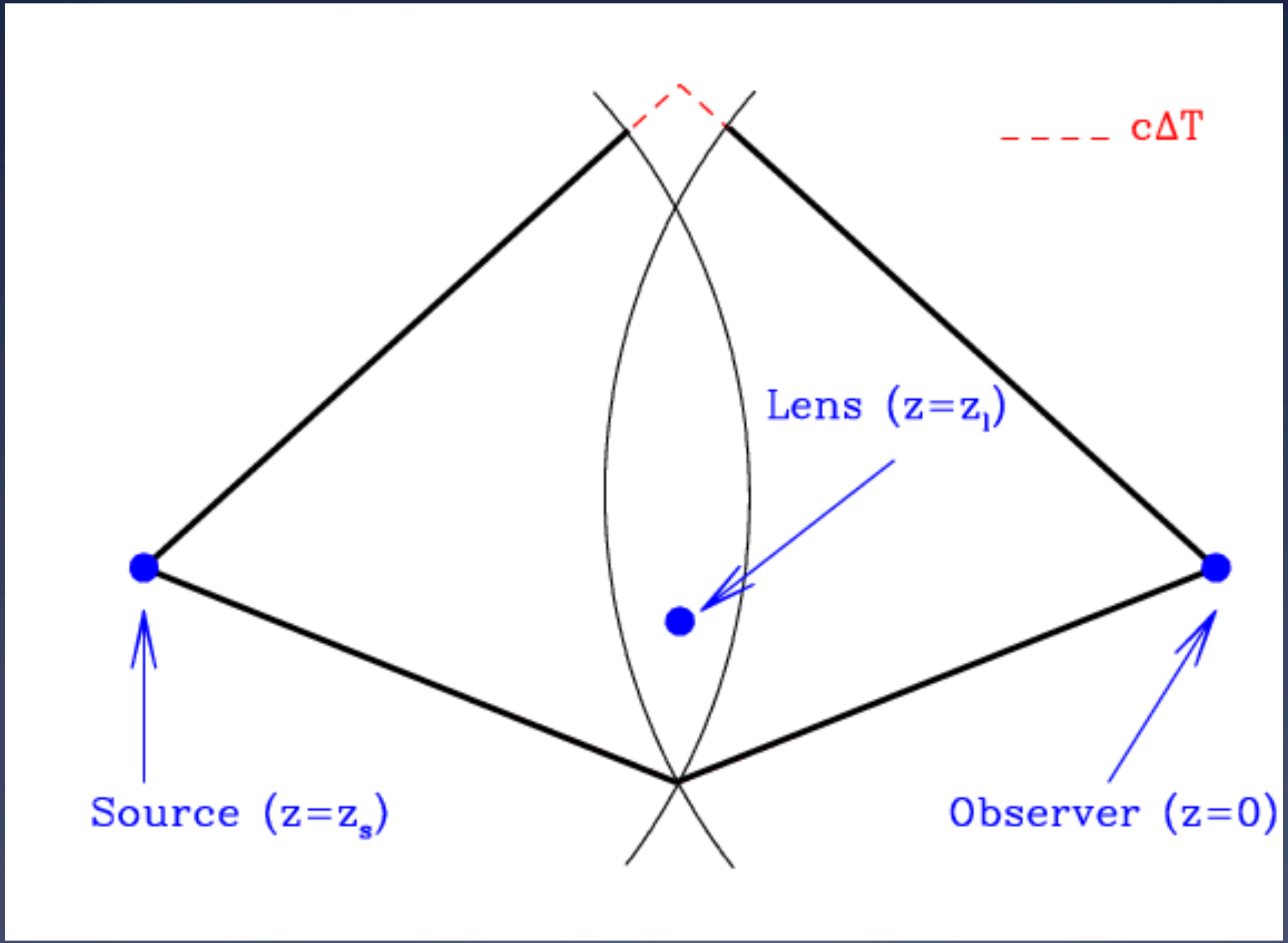
TOMMASO **TREU**
(University of California Los Angeles)

Outline

- Strong lensing as a probe of dark matter and dark energy
- Strong lenses as cosmic telescopes
- The role of WFIRST and ground based follow-up

Cosmography with gravitational lensing

Cosmography from time delays: how does it work?



Strong lensing in terms of Fermat's principle

Time delay distance

Shapiro delay

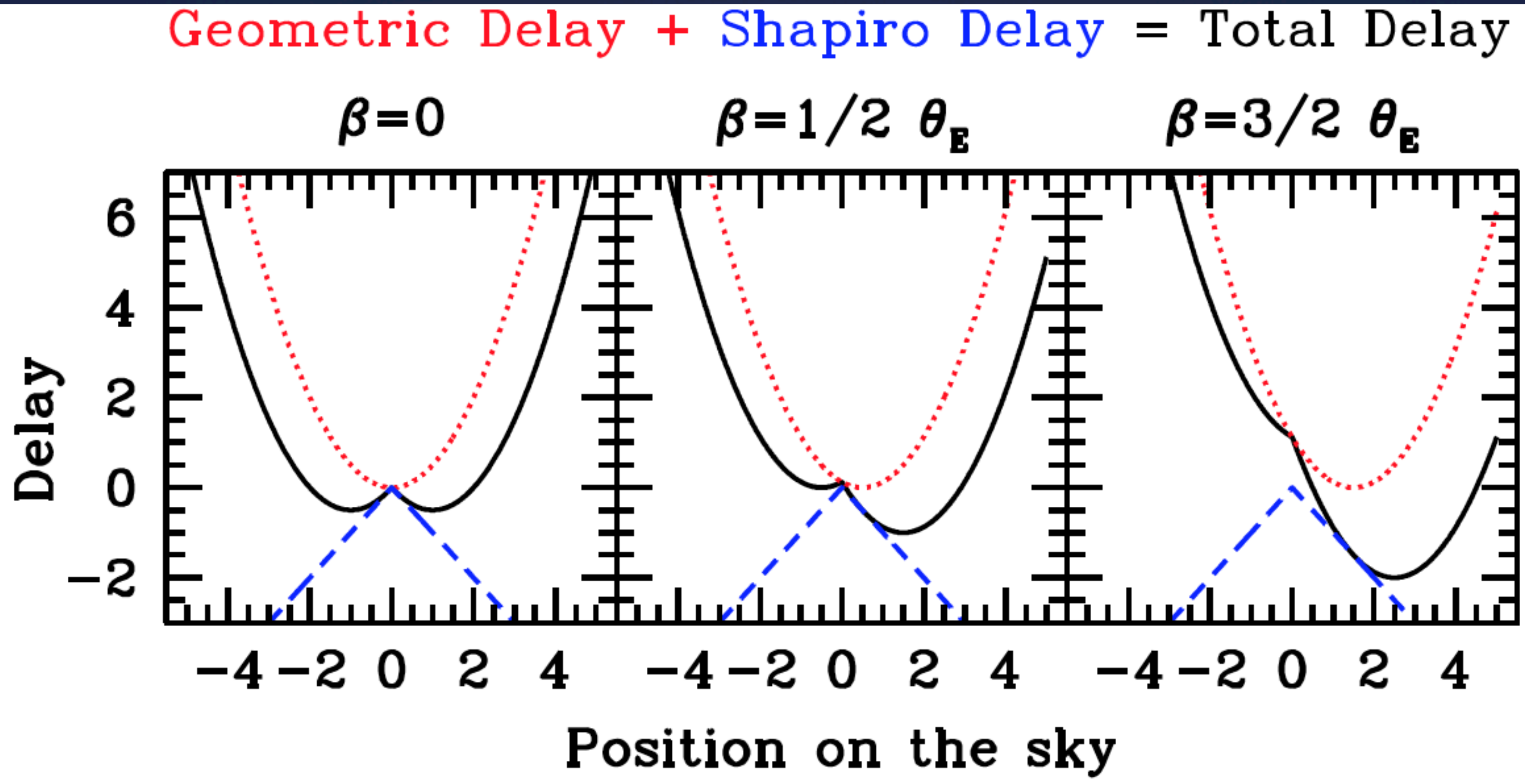
$$t(\vec{\theta}) = \frac{(1+z_{\rm d})}{c}\frac{D_{\rm d}D_{\rm s}}{D_{\rm ds}}\left[\frac{1}{2}(\vec{\theta}-\vec{\beta})^2 - \psi(\vec{\theta})\right]$$

Excess time delay

geometric time delay

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

Strong lensing in terms of Fermat's principle



Time delay distance in practice

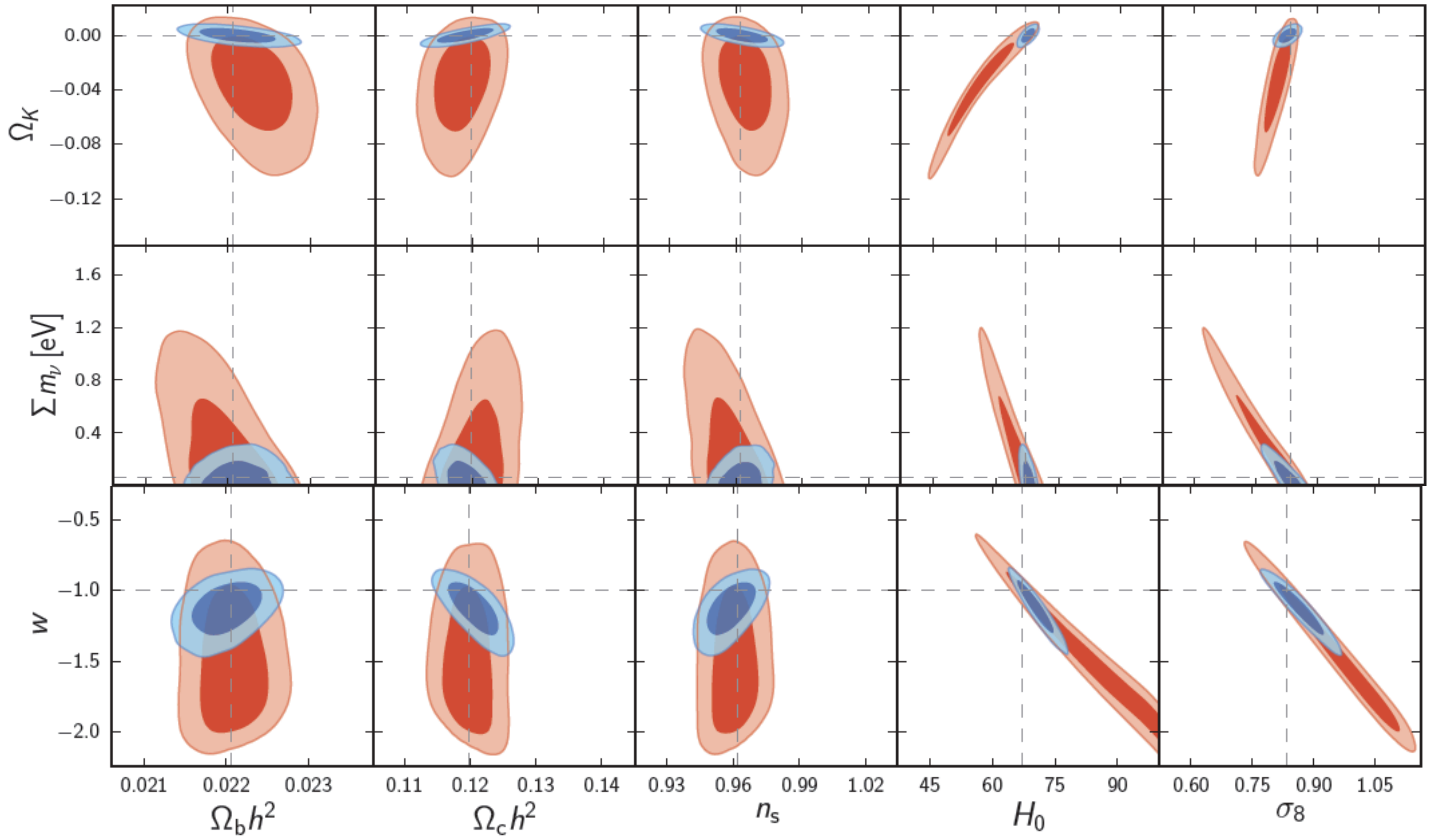
$$\Delta t \propto D_{\Delta t}(z_s, z_d) \propto H_0^{-1} f(\Omega_m, w, ...)$$

Steps:

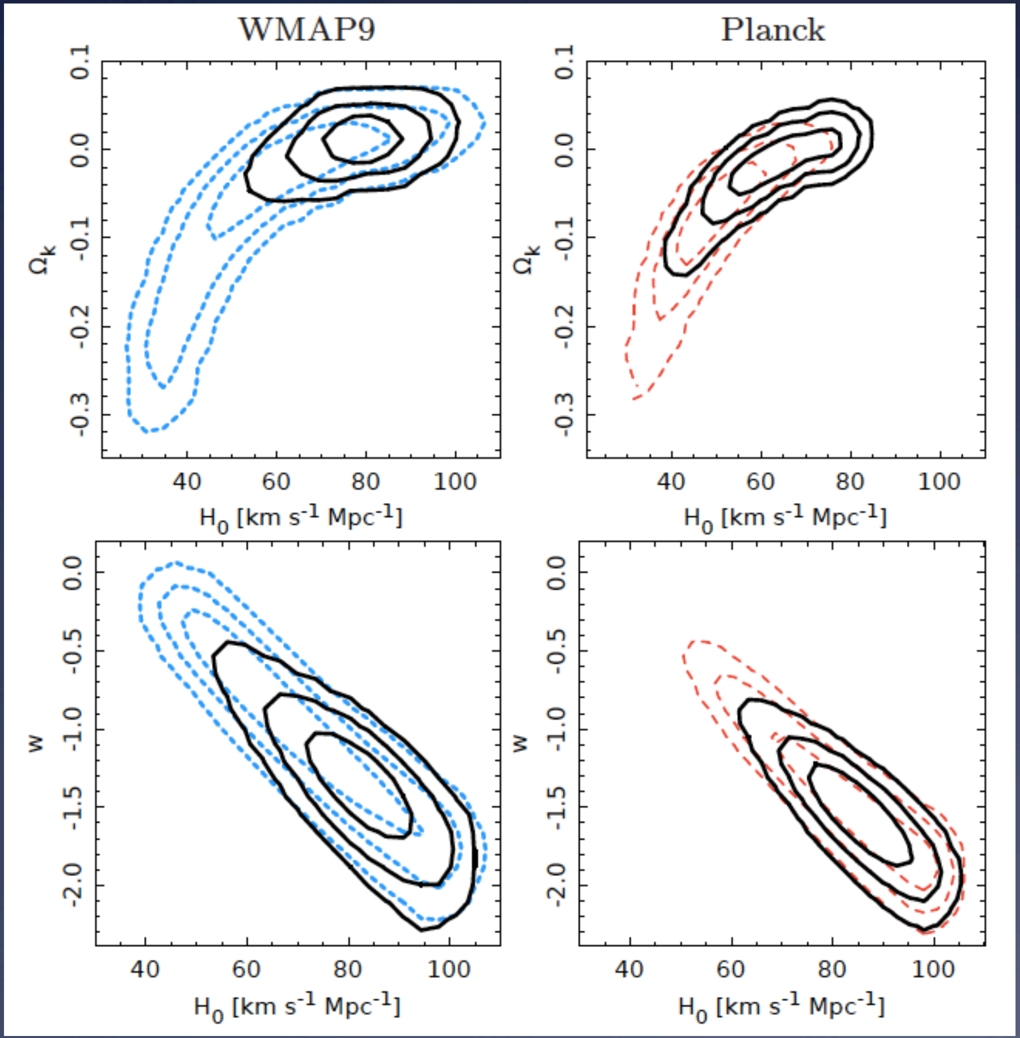
- Measure the time-delay between two images
- Measure and model the potential
- Infer the time-delay distance
- Convert it into cosmlogical parameters

Planck XVI

Low redshift measurements (like TD) are essential



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

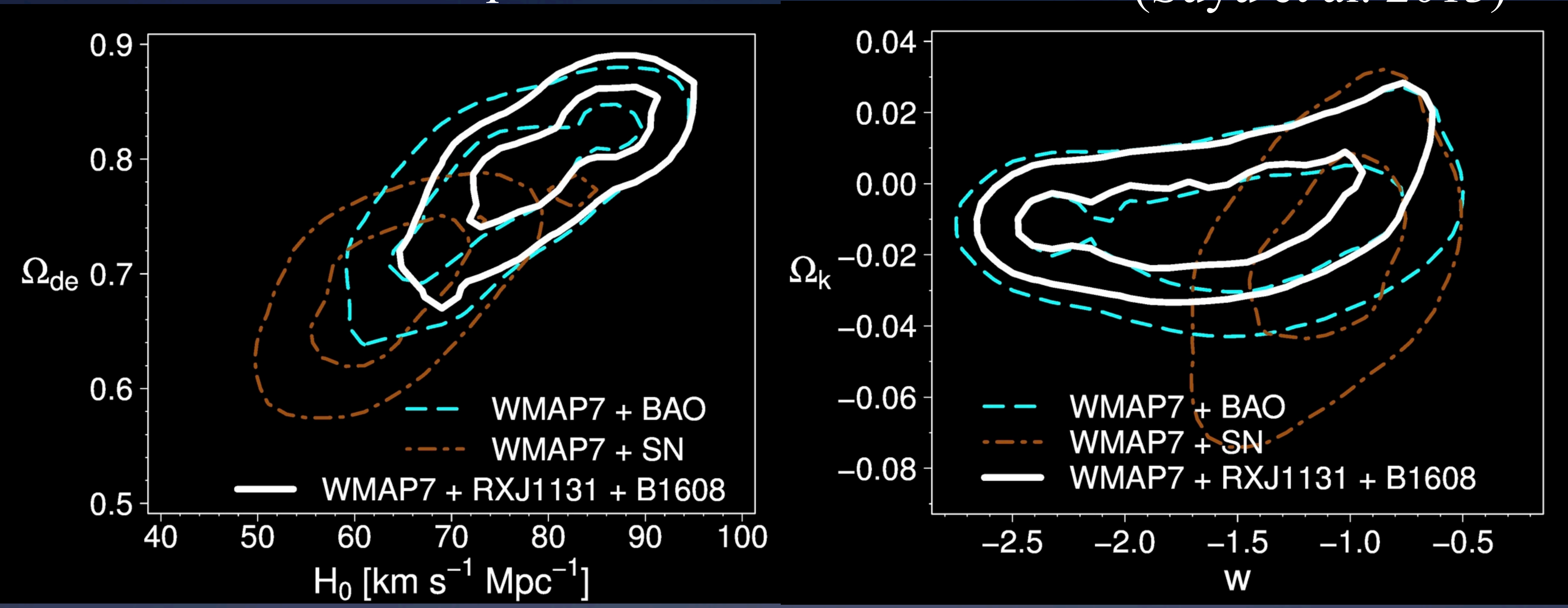


Suyu, Treu et al. 2014

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
- 9 systems currently being analyzed -> target ~2.3% on H_0

"REFSDAL" MEETS POPPER: COMPARING PREDICTIONS OF THE RE-APPEARANCE OF THE MULTIPLY IMAGED SUPERNOVA BEHIND MACSJ1149.5+2223

T. Treu[1,28], G. Brammer[2], J. M. Diego[3], C. Grillo[4], P. L. Kelly[5], M. Oguri[6,7,8], S. A. Rodney[9,10,29], P. Rosati[11], K. Sharon[12], A. Zitrin[13,29], I. Balestra[14], M. Bradač[15], T. Broadhurst[16,17], G. B. Caminha[11], A. Halkola, A. Hoag[15], M. Ishigaki[7,18], T. L. Johnson[12], W. Karman[19], R. Kawamata[20], A. Mercurio[21], K. B. Schmidt[22], L.-G. Strolger[2,23], S. H. Suyu[24], A. V. Filippenko[5], R. J. Foley[25,26], S. W. Jha[27], and B. Patel[27]

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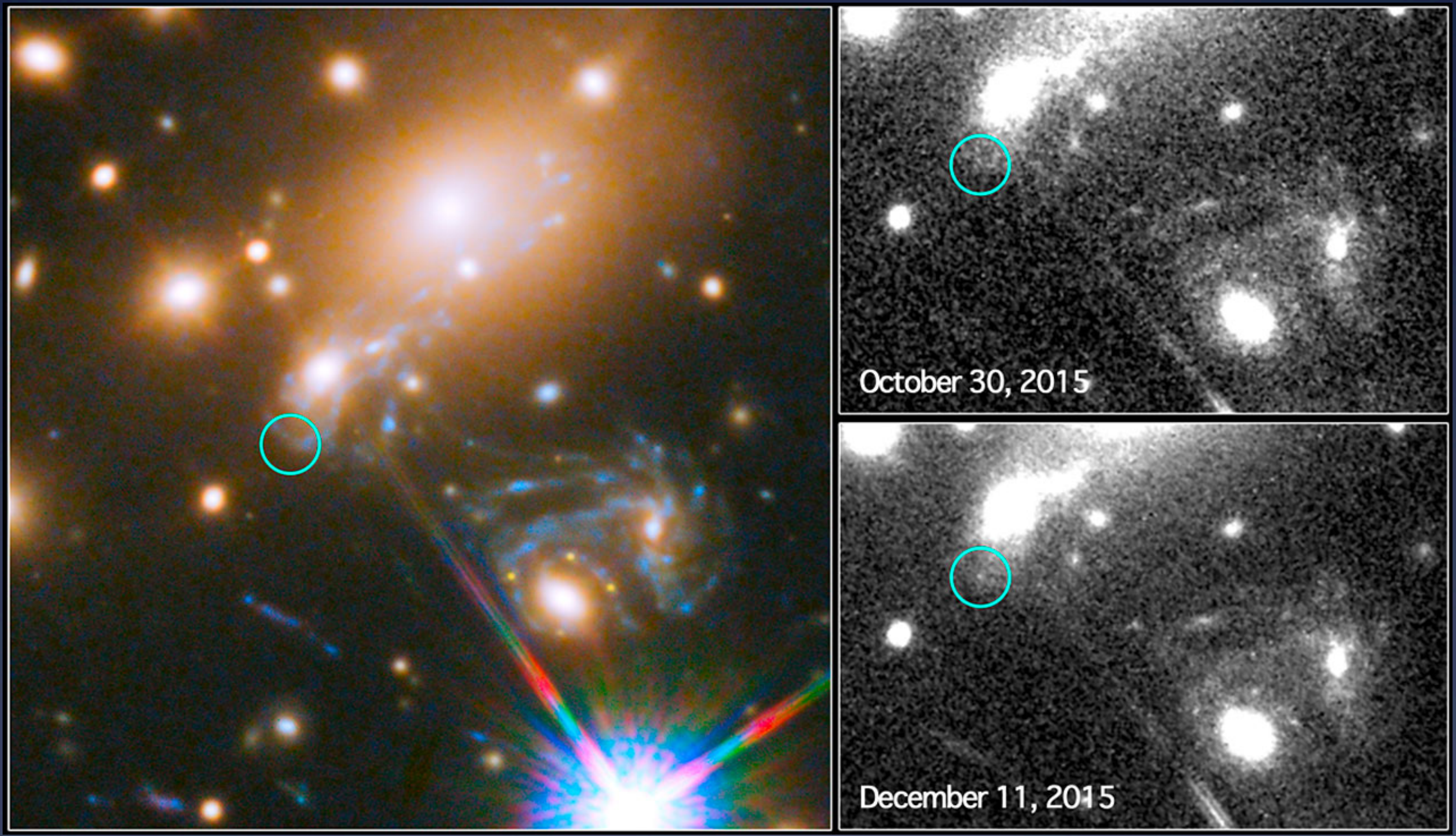
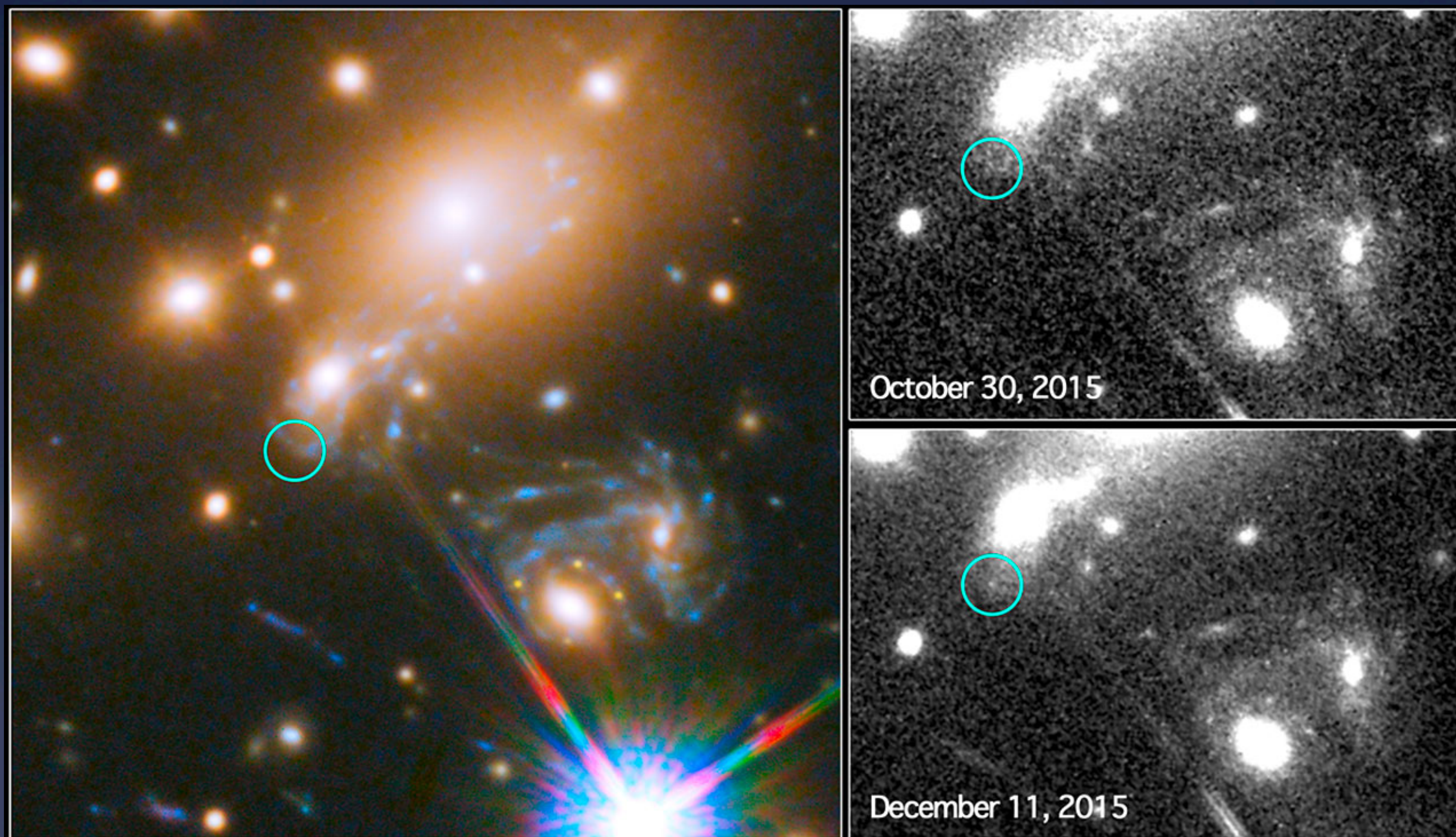


DÉJÀ VU ALL OVER AGAIN: THE REAPPEARANCE OF SUPERNOVA REFSDAL

P. L. Kelly[1], S. A. Rodney[2], T. Treu[3,4], L.-G. Strolger[5], R. J. Foley[6,7], S. W. Jha[8], J. Selsing[9], G. Brammer[5], M. Bradač[10], S. B. Cenko[11,12], O. Graur[13,14], A. V. Filippenko[1], J. Hjorth[9], C. McCully[15,16], A. Molino[17,18], M. Nonino[19], A. G. Riess[20,5], K. B. Schmidt[16,21], B. Tucker[22], A. von der Linden[23], B. J. Weiner[24], and A. Zitrin[25,26]

Draft version 2015/12/16



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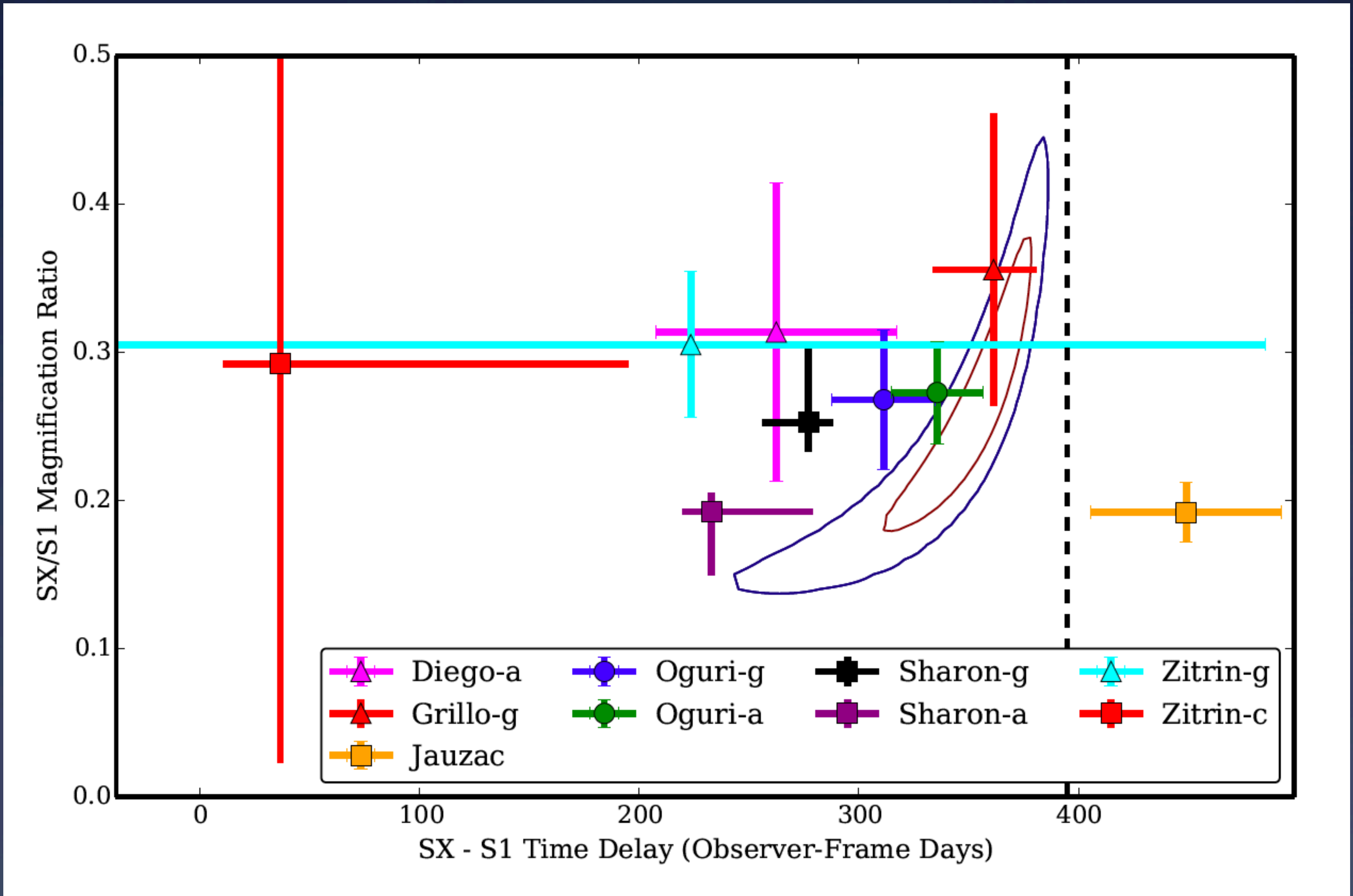
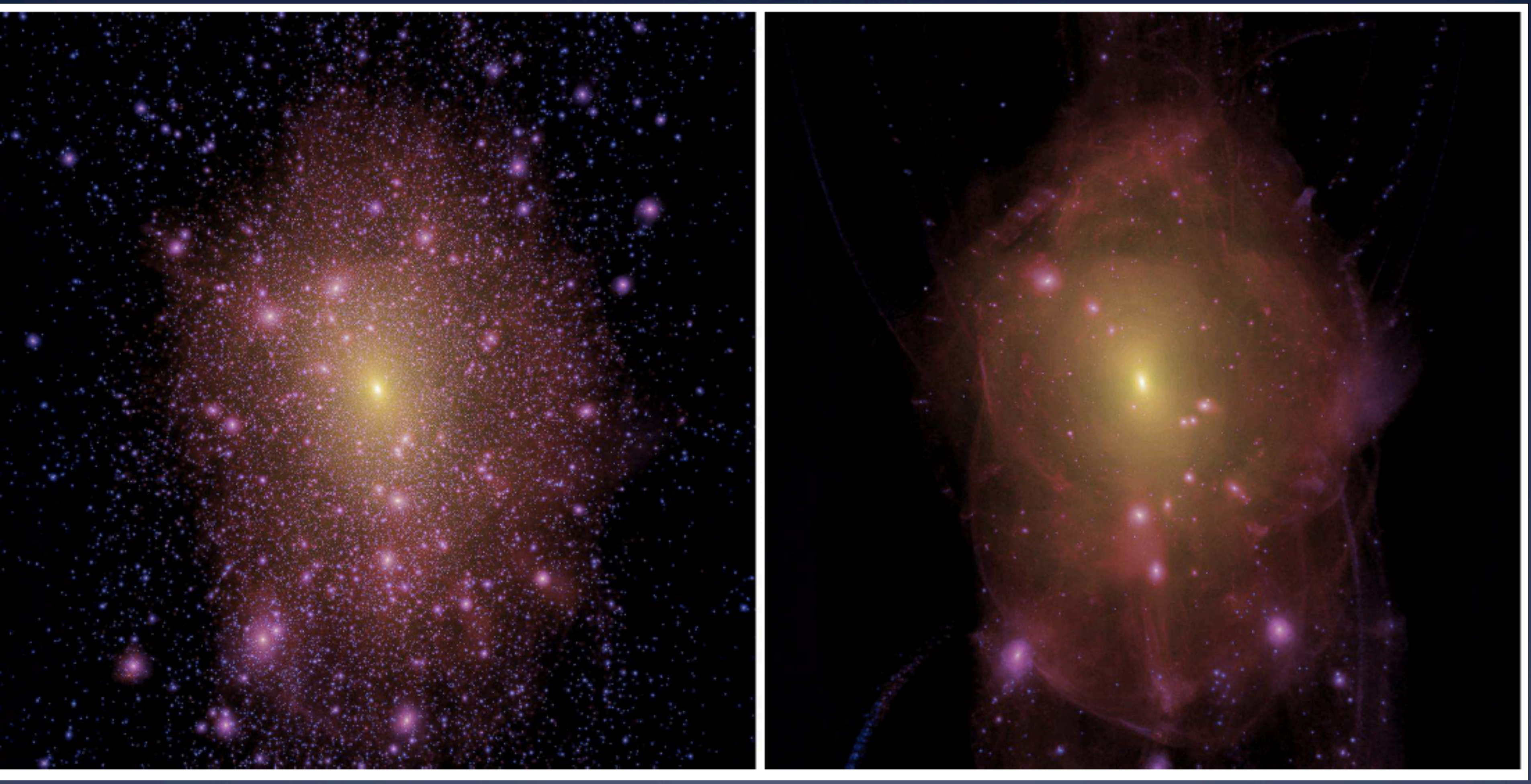


What’s the (dark) matter?

Cold or Warm Dark Matter?

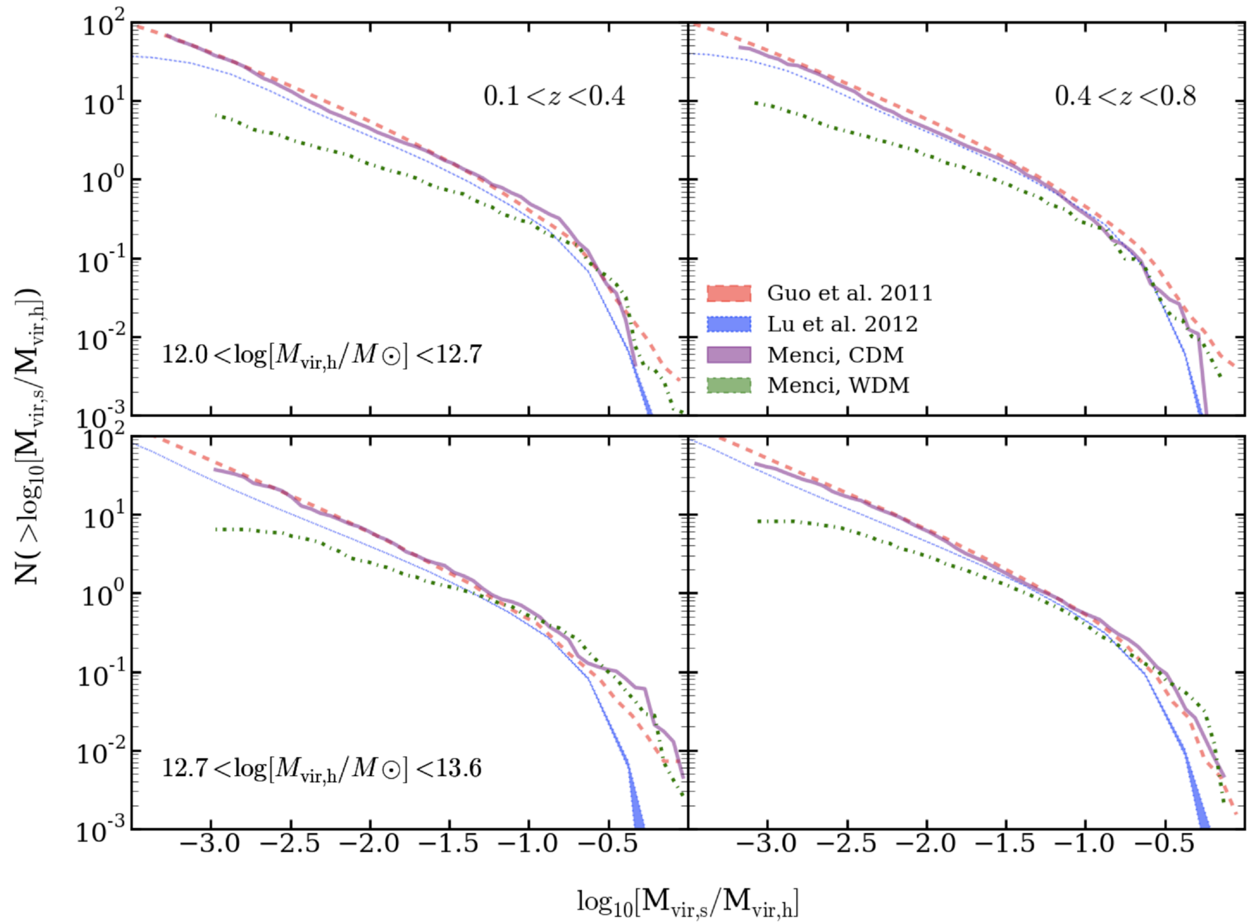


Free streaming ~kev scale thermal relic

Lovell et al. 2014

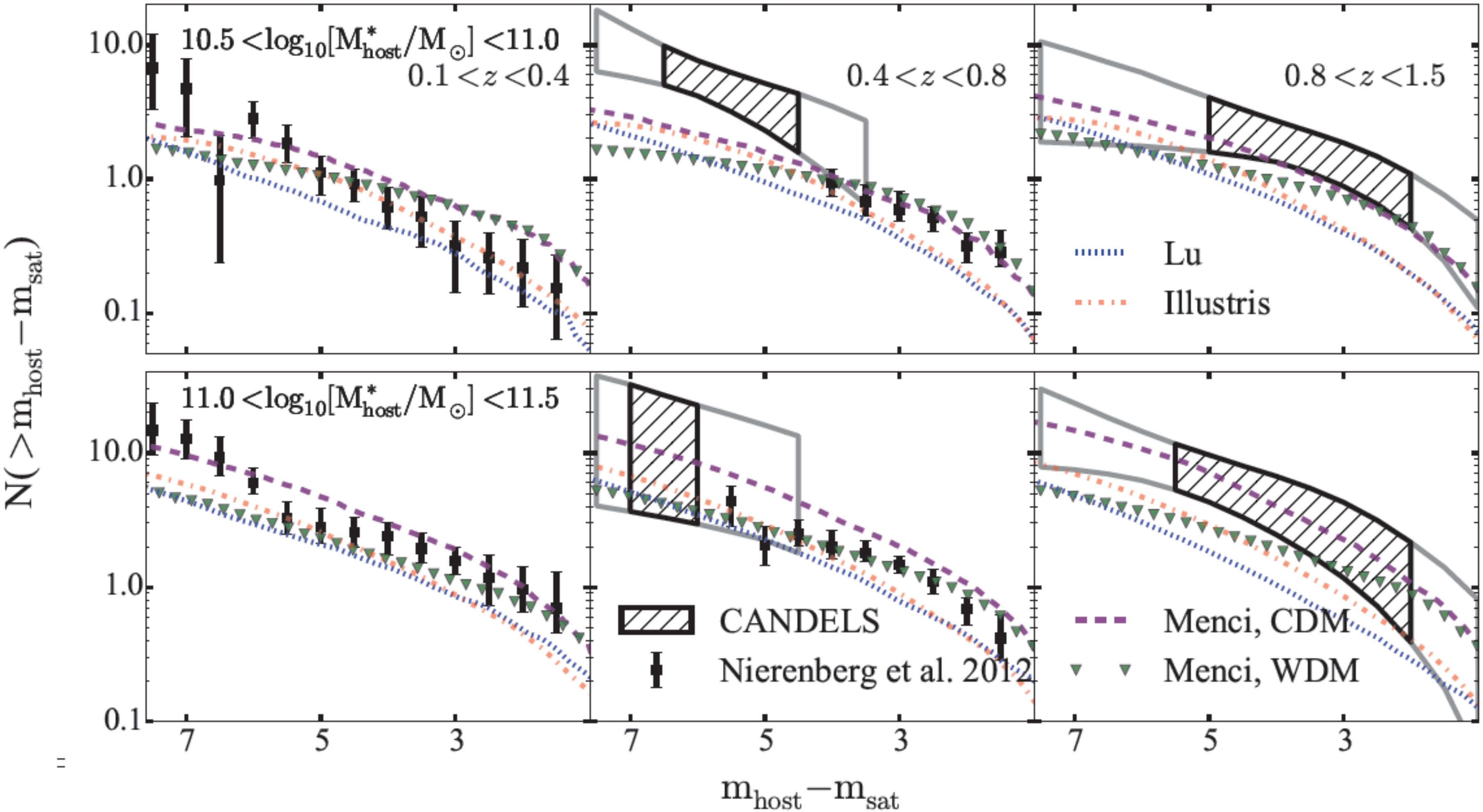
Satellites as a probe of dark matter “mass”

Dark Satellites in CDM vs WDM



Nierenberg, Treu, et al. 2013

Luminous Satellites in CDM vs WDM



Nierenberg, Treu et al. 2016

“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**

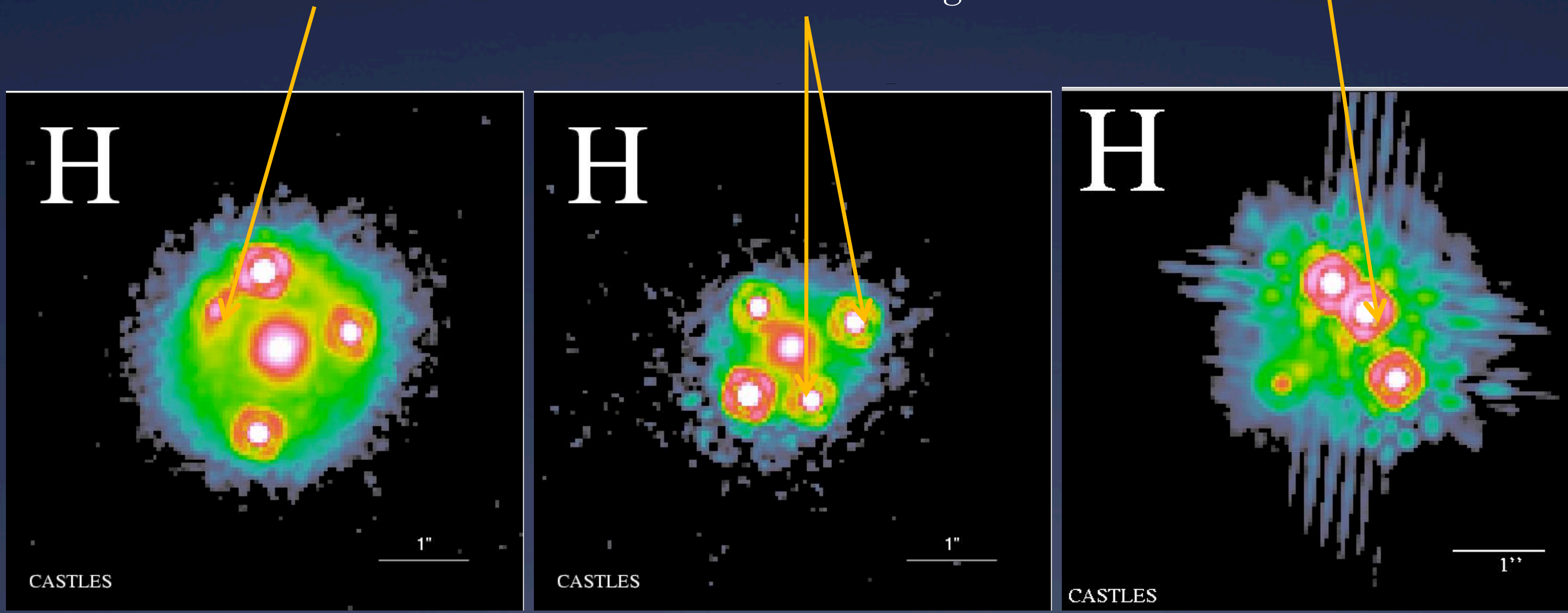
Flux Ratio Anomalies

A smooth mass distribution would predict:

This to be 100x brighter

These to be 2x brighter

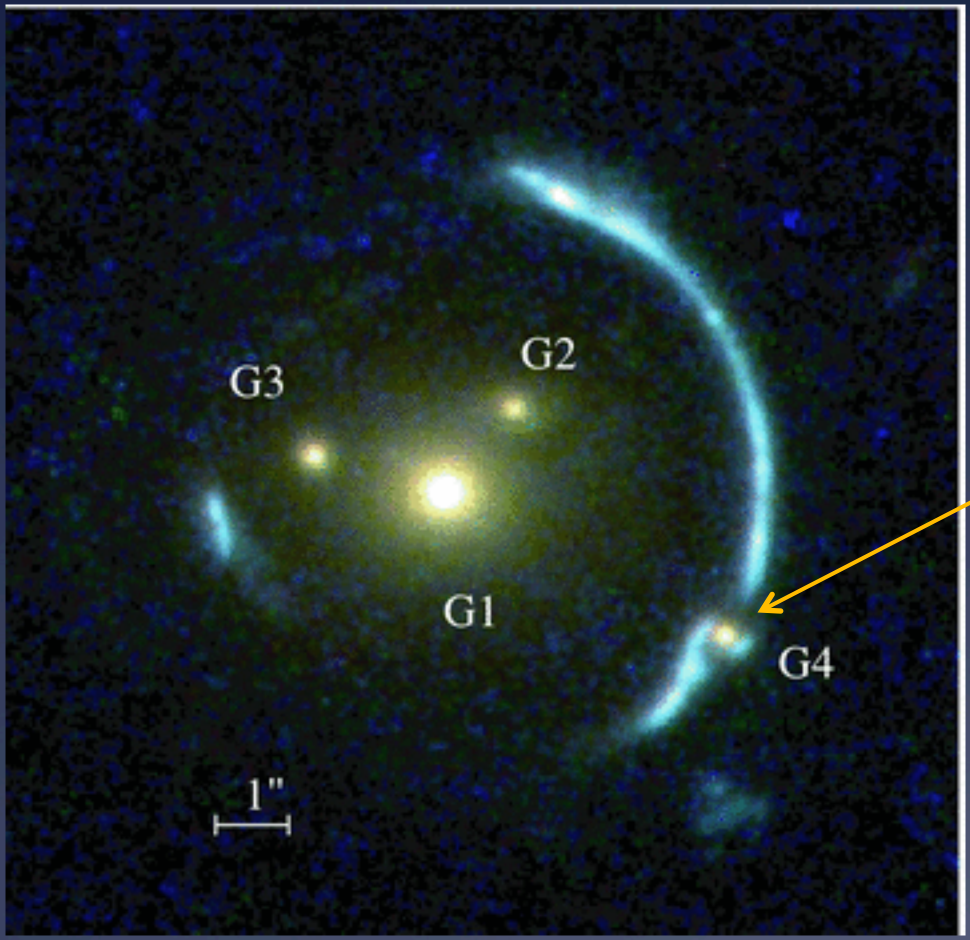
This to be 10% brighter



What causes this the anomaly?

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

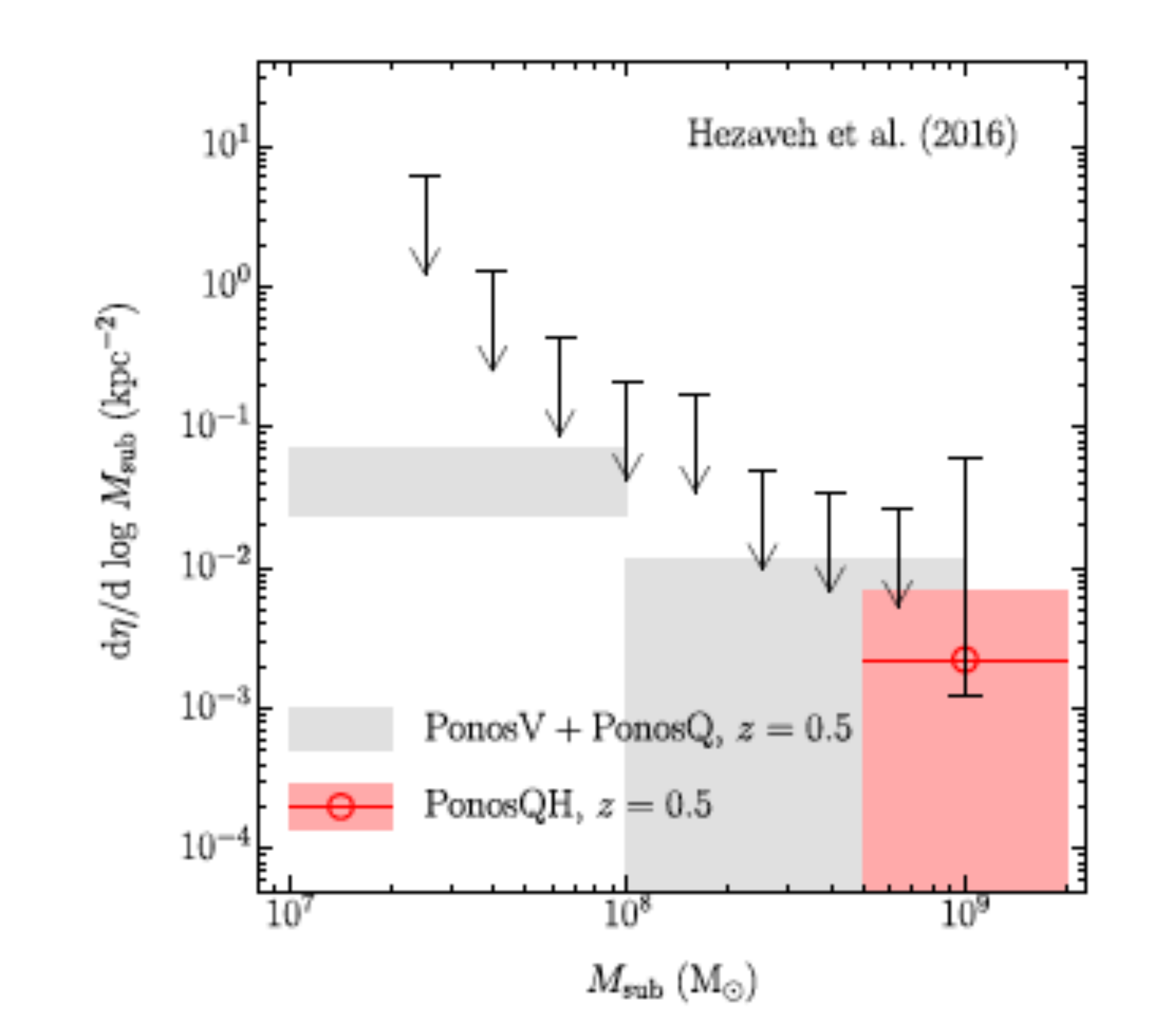
Astrometric perturbations: gravitational imaging



Mass substructure distorts extended lensed sources

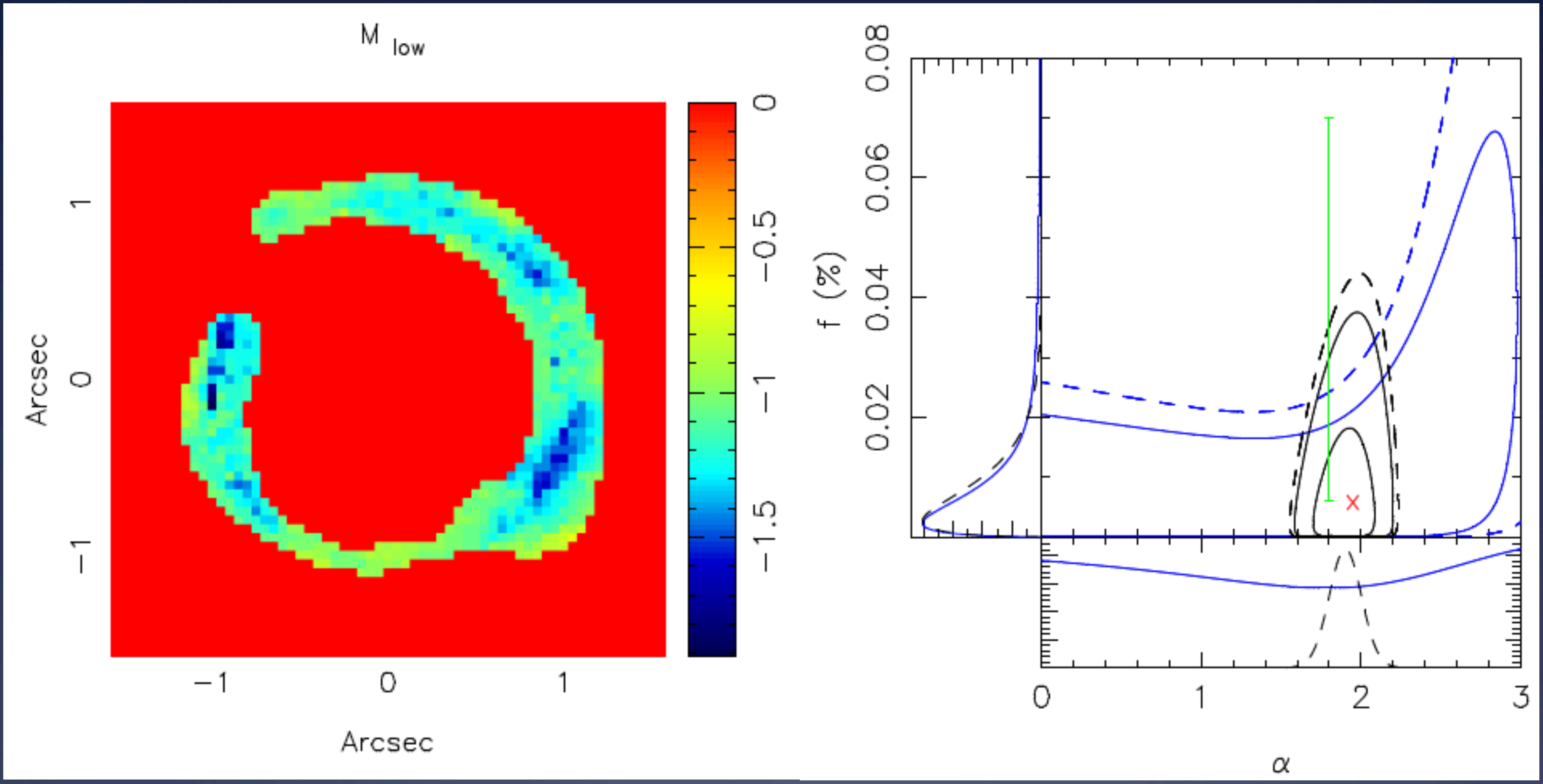
Vegetti et al. 2010

Radio Rings



Data from Hezaveh et al
Simulations from Fiacconi et al.

Statistics from gravitational imaging



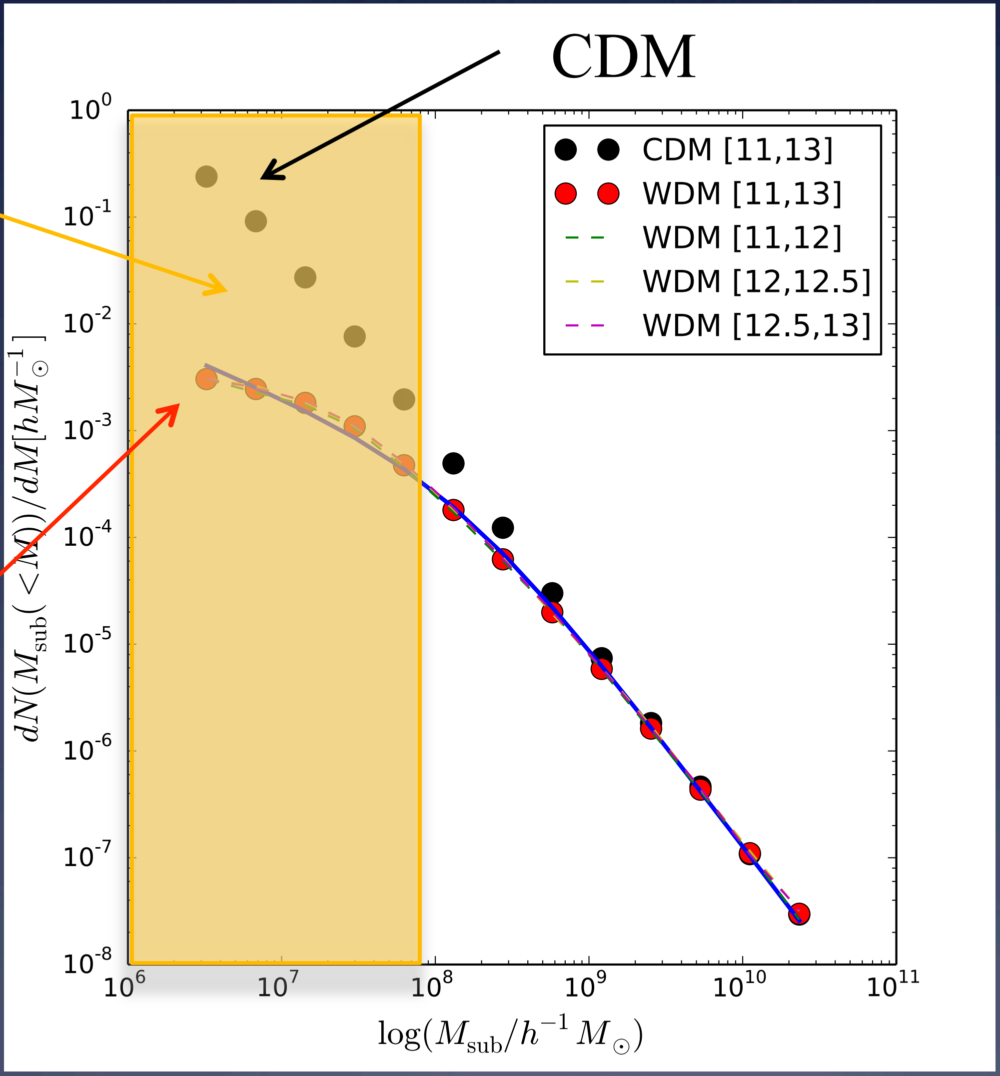
HST/AO can detect down to 3e8 Msun

Vegetti et al 2010, 2012, 2014

Dark Satellites in CDM vs WDM

Range accessible with lensing

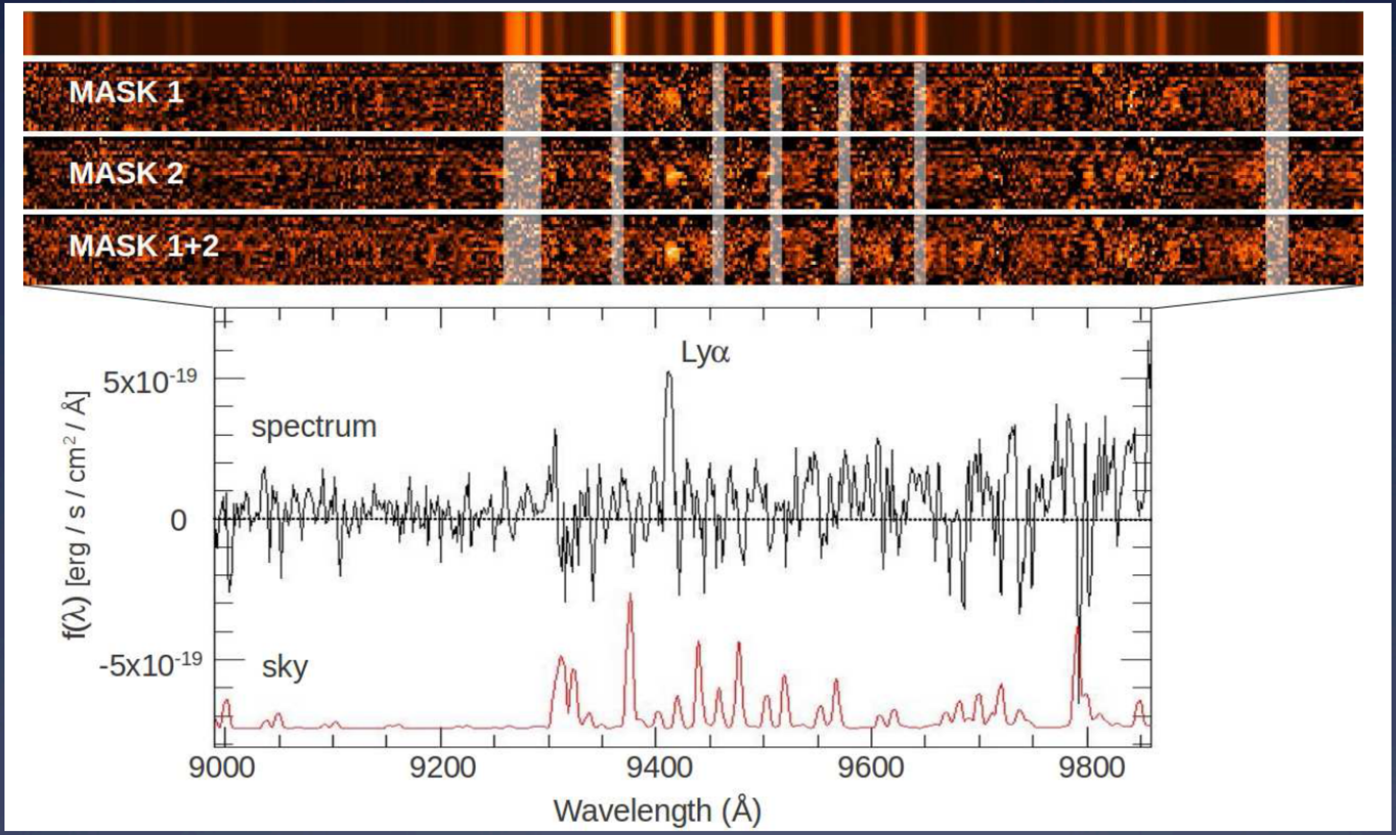
7 kev sterile neutrino



Li et al. 2015

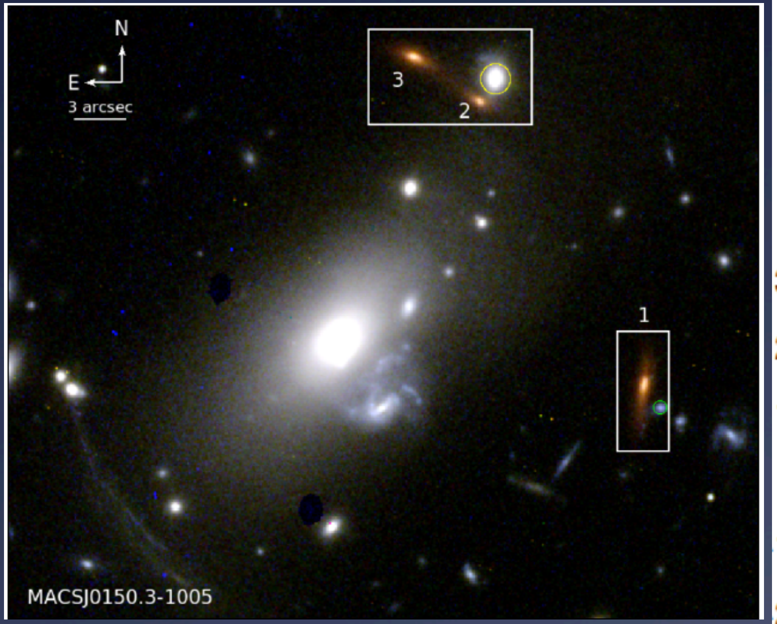
Clusters as cosmic telescopes

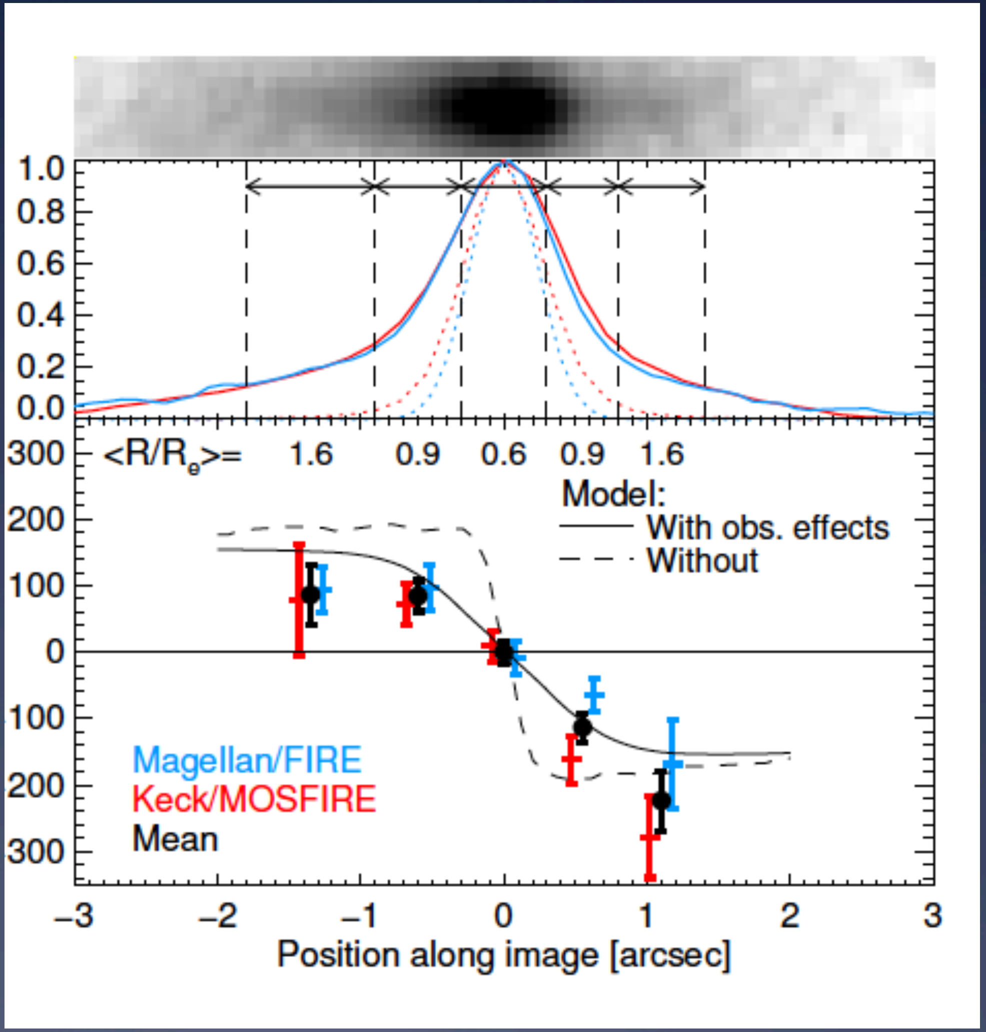
Bradac et al. 2012: flux 2e-18 cgs



Clusters of galaxies magnify background sources giving the unique to opportunity to study objects that are otherwise to faint and/or compact

Clusters as cosmic telescopes. II





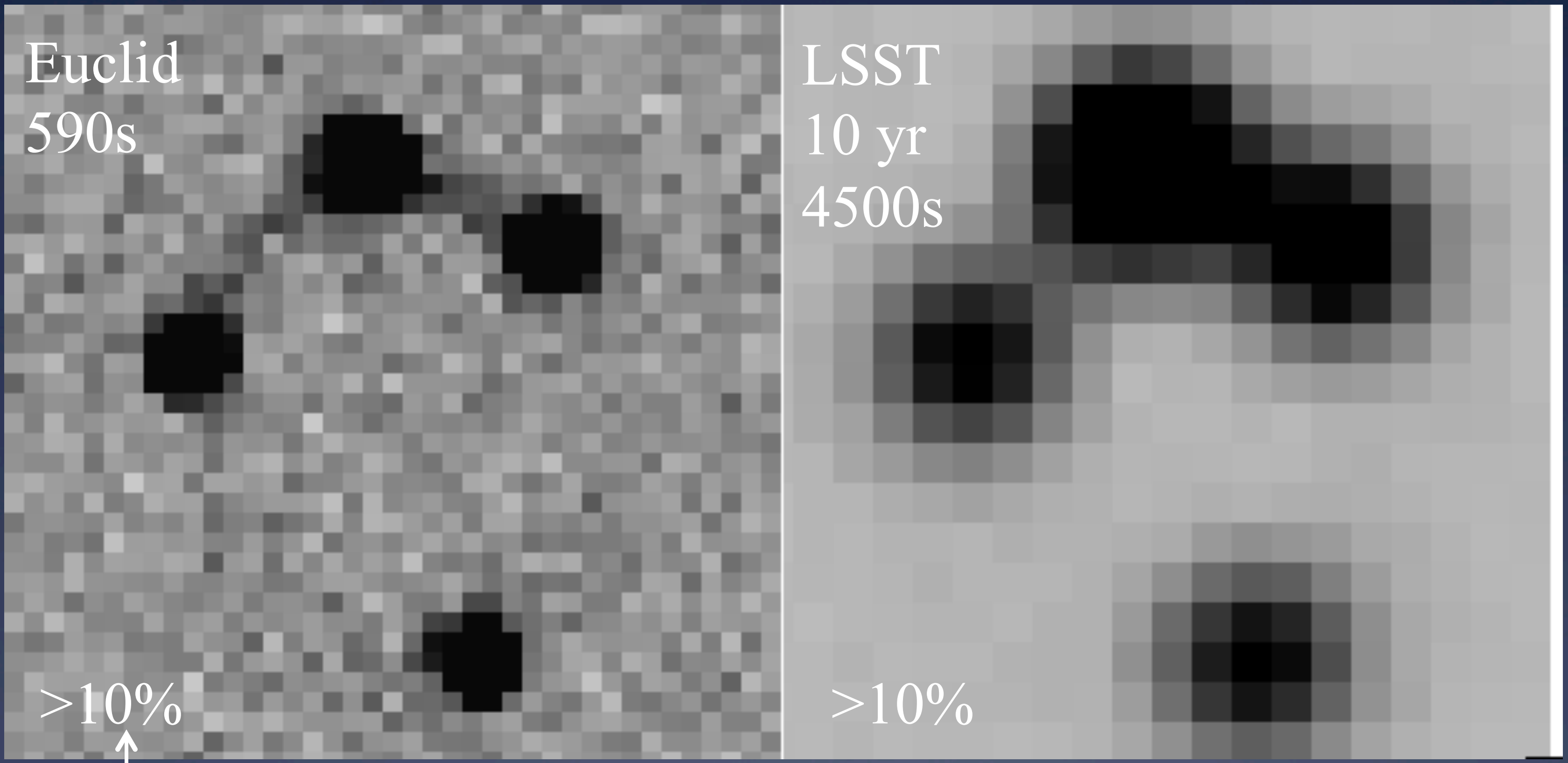
Newman et al. 2016

So, how do we learn about dark matter, dark energy and reionization?

Roadmap

- Find lenses: WFIRST-HLS
- Obtain high resolution imaging: WFIRST-HLS + Targeted follow-up with Adaptive Optics from Keck Next Generation AO and the Thirty Meter Telescope
- Obtain redshifts and detailed spectroscopy: the WFIRST grism Keck NGAO and TMT

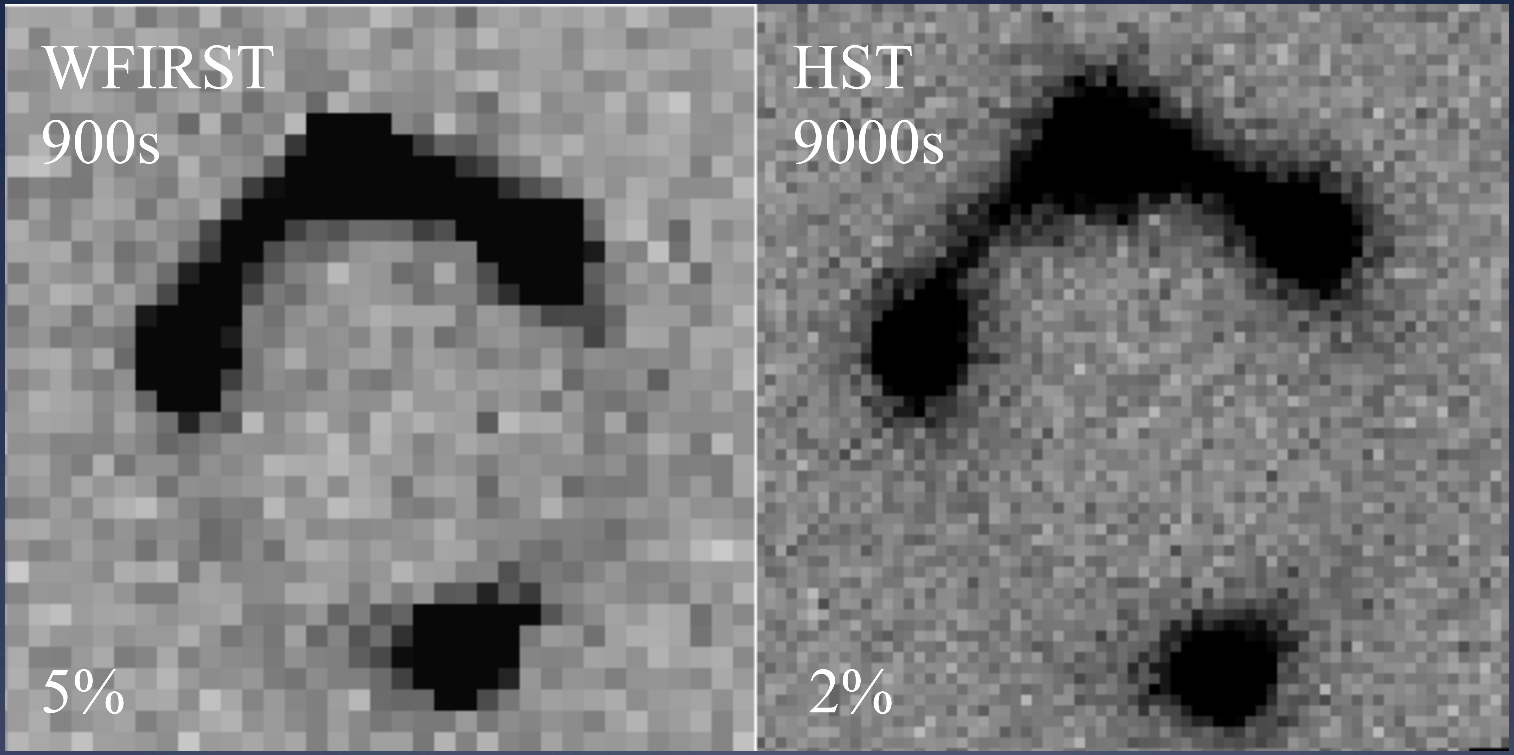
Euclid/LSST will be good for discovery but not for detail studies



Contribution of modeling error
To time delay distance

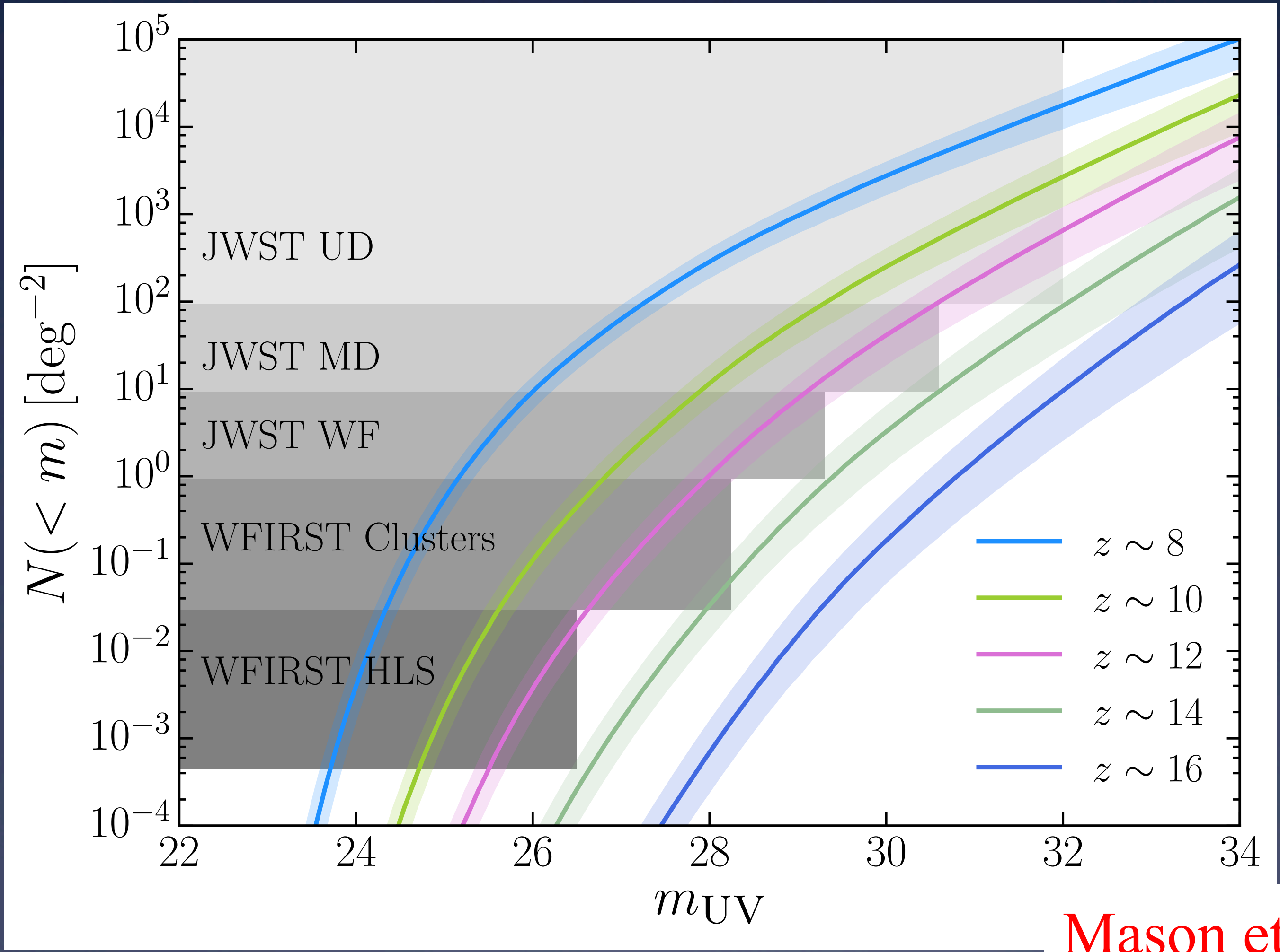
Meng, TT et al. 2015

WFIRST can find lenses AND provide sufficient high res info



Meng, TT et al. 2015

WFIRST will find magnified galaxies at z>10



Mason et al 2015

The problem of follow-up in the WFIRST ERA:

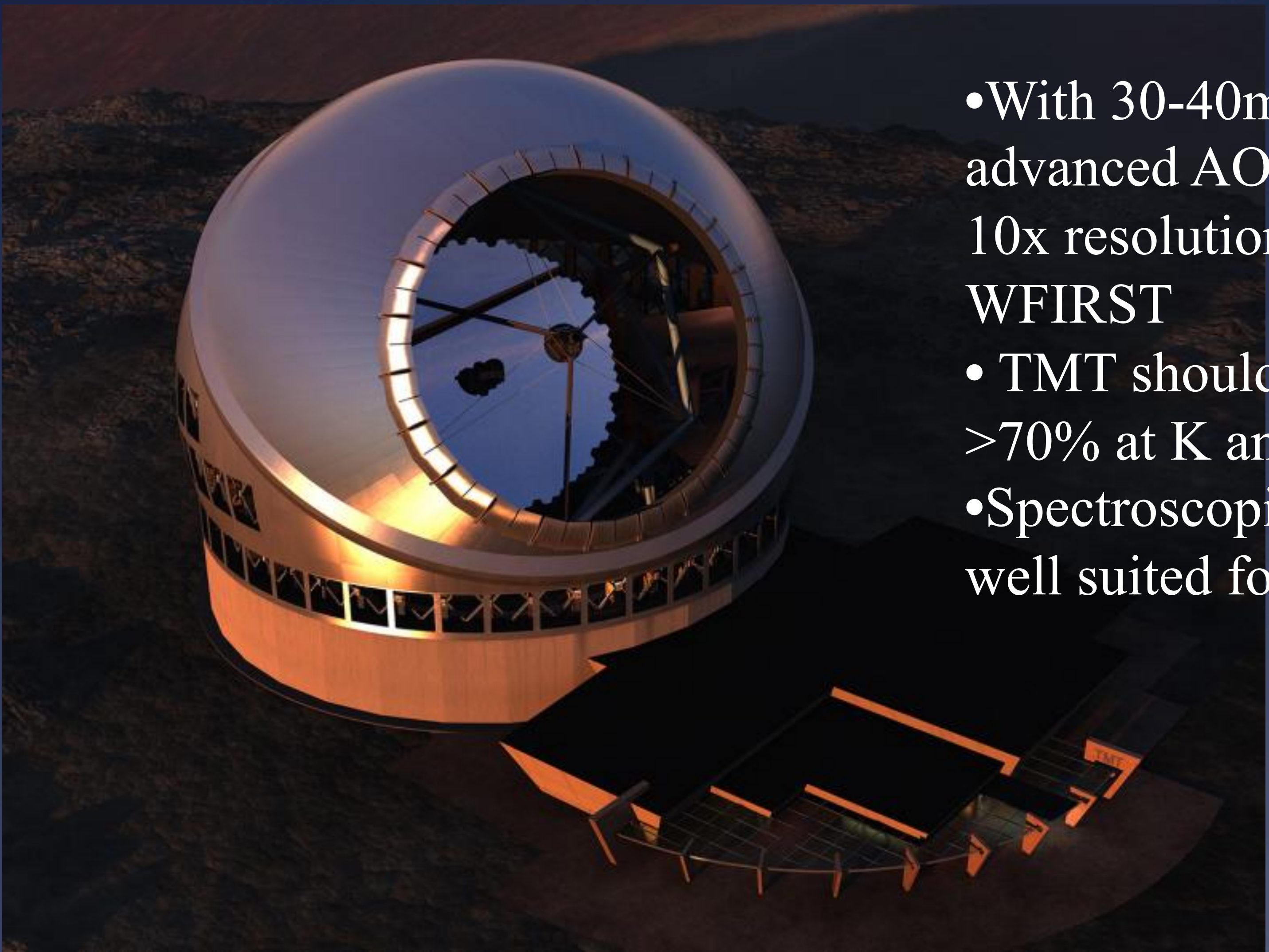
Where will the higher resolution imaging

and spectroscopy come from?

Keck Next Generation Adaptive Optics

- For strong lensing at galaxy scales and highly magnified sources we are interested in high-strehl small fov
- Keck-NGAO: 90% strehl at K, 60% at J (not funded yet; pathfinder KAPA currently being considered by NSF)
- It will provide high resolution imaging AND spectroscopy

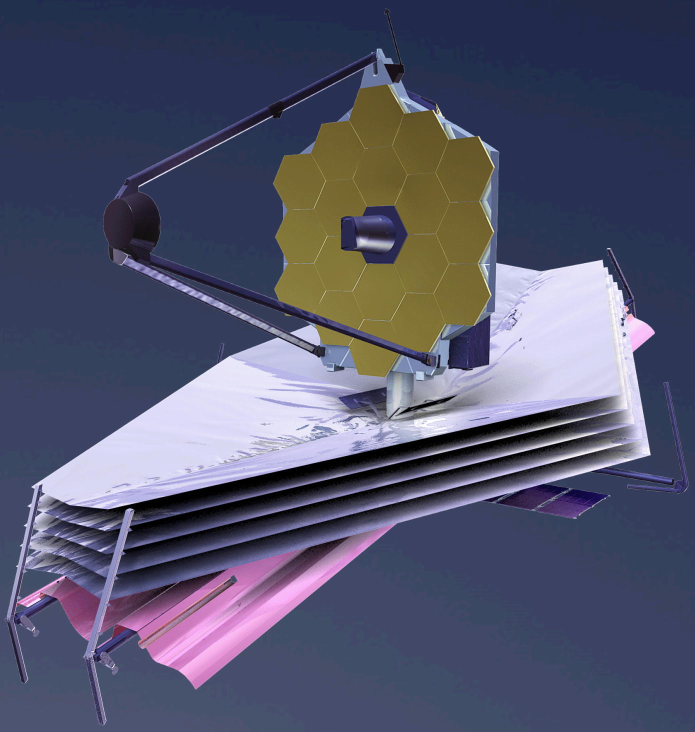
Extremely Large Telescopes



- With 30-40m apertures and advanced AO one can attain 10x resolution of HST/ WFIRST
- TMT should have strehl >70% at K and >30% at Y
- Spectroscopic capabilities well suited for (IRIS)

JWST if it overlaps

* JWST is 6.5m, diffraction limited beyond 2micron
* At best resolution equal to HST at ~0.7micron
* 0.032”/pix
* Ok down to 1micron or so, 0.65 strehl.
* Resolution ~HST
* Spectroscopy R~2700



Conclusions

- Strong gravitational lensing is a unique tool to study the universe
  - Time-delay cosmography 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
  - Cosmic telescopes are the ONLY way to study sources fainter and smaller than our observational limits
- WFIRST will be fantastic for these applications
- Follow-up from the ground will greatly enhance the power of WFIRST

The end

"That wraps it up --
the mass of the universe."