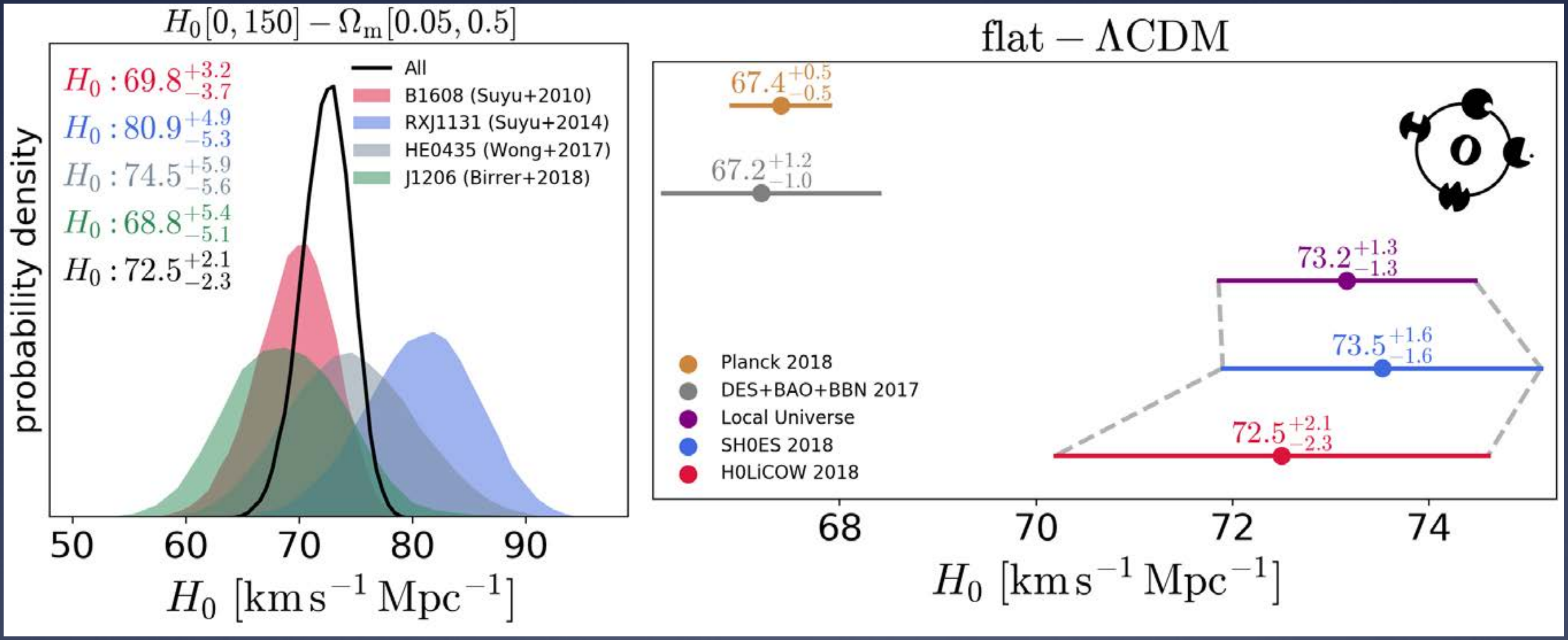
Exploiting the power of TMT to probe the dark universe via strong lensing



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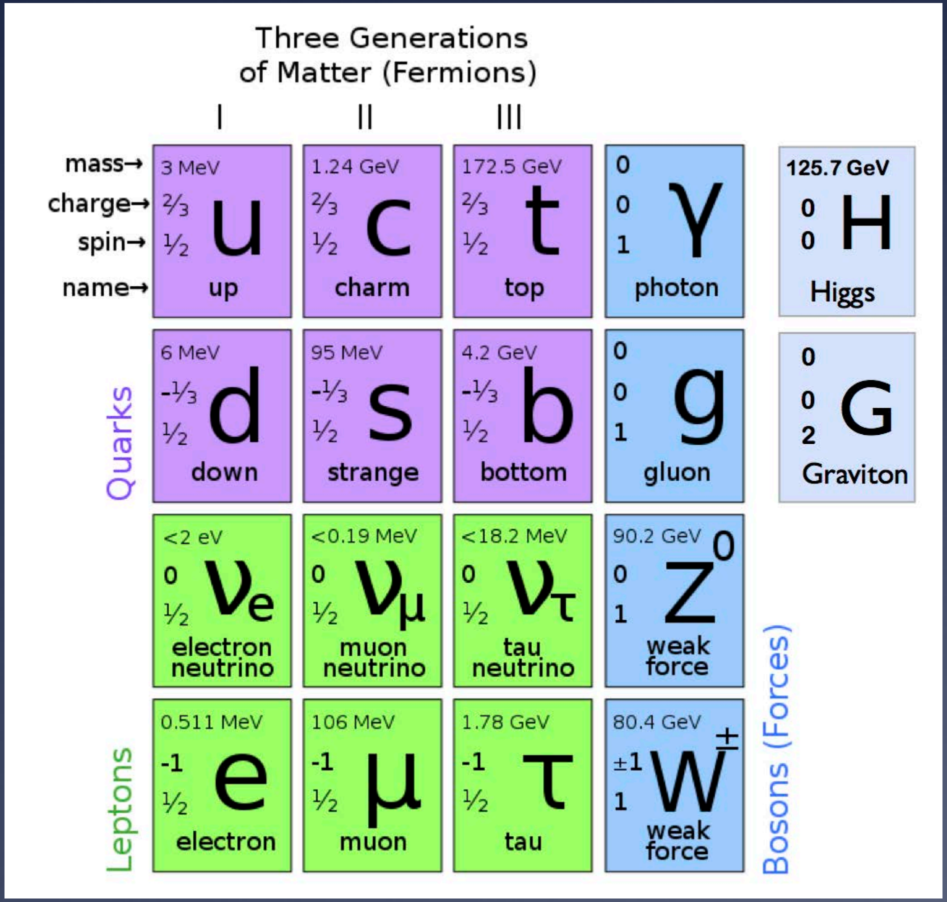
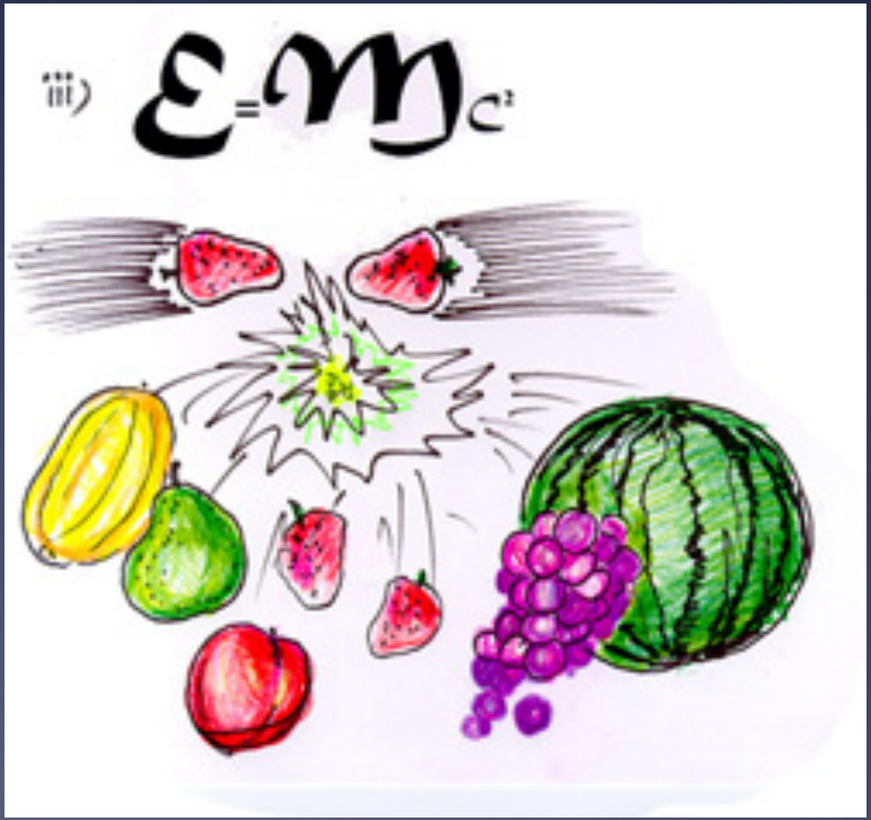
Outline

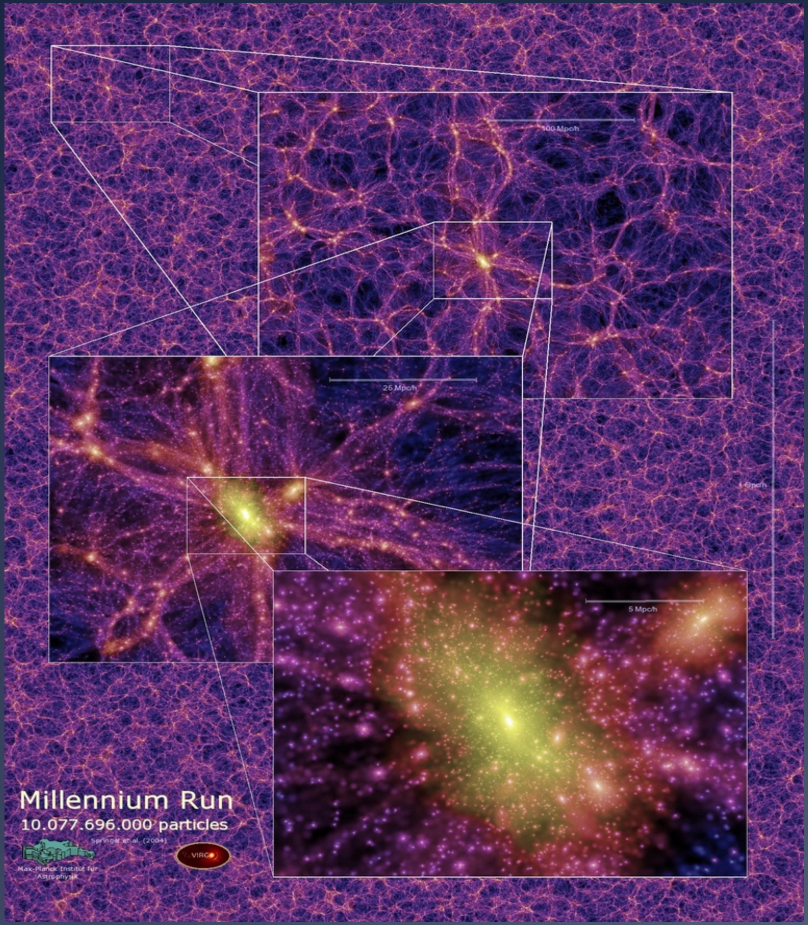
- Introduction. The view from Earth:
  - The standard model of particle physics
- The view from the Universe
  - Gravitational time delays and Dark energy
  - Strong lensing and dark matter
- A roadmap for the future: the role of ELTs

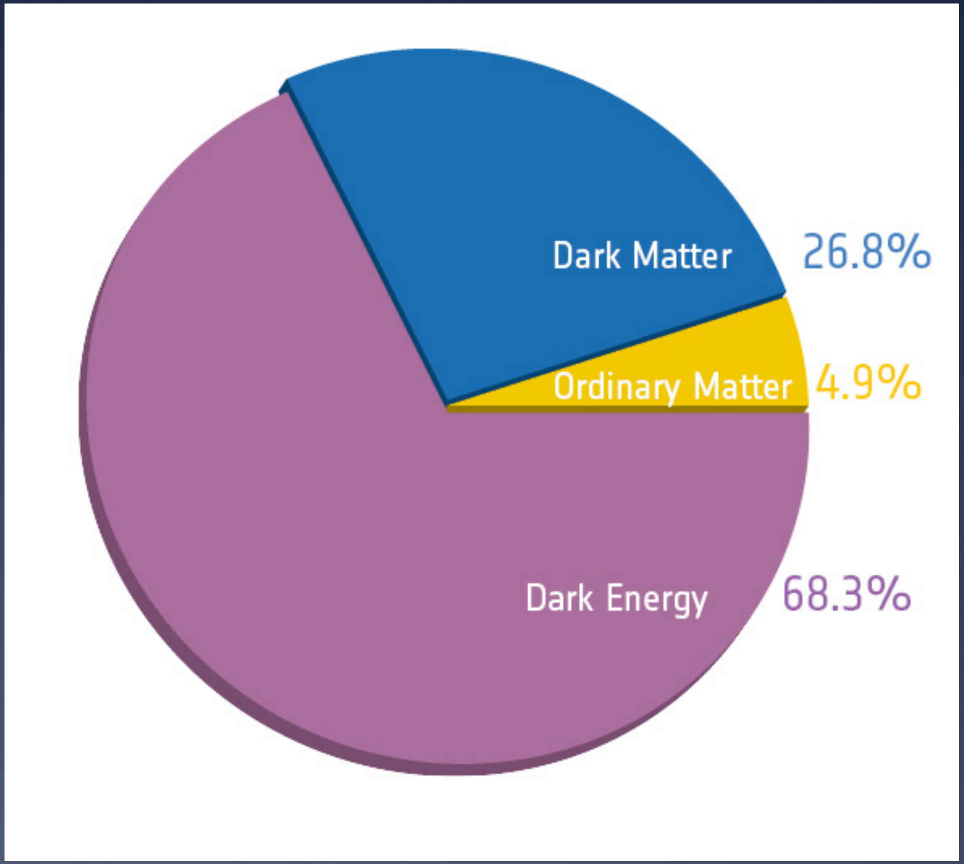
The view from Earth: standard model of particle physics





The Dark Universe





Most of the universe is dark matter and dark energy.

But what are they?

Dark matter and dark energy are invisible: we need to learn about them using gravity

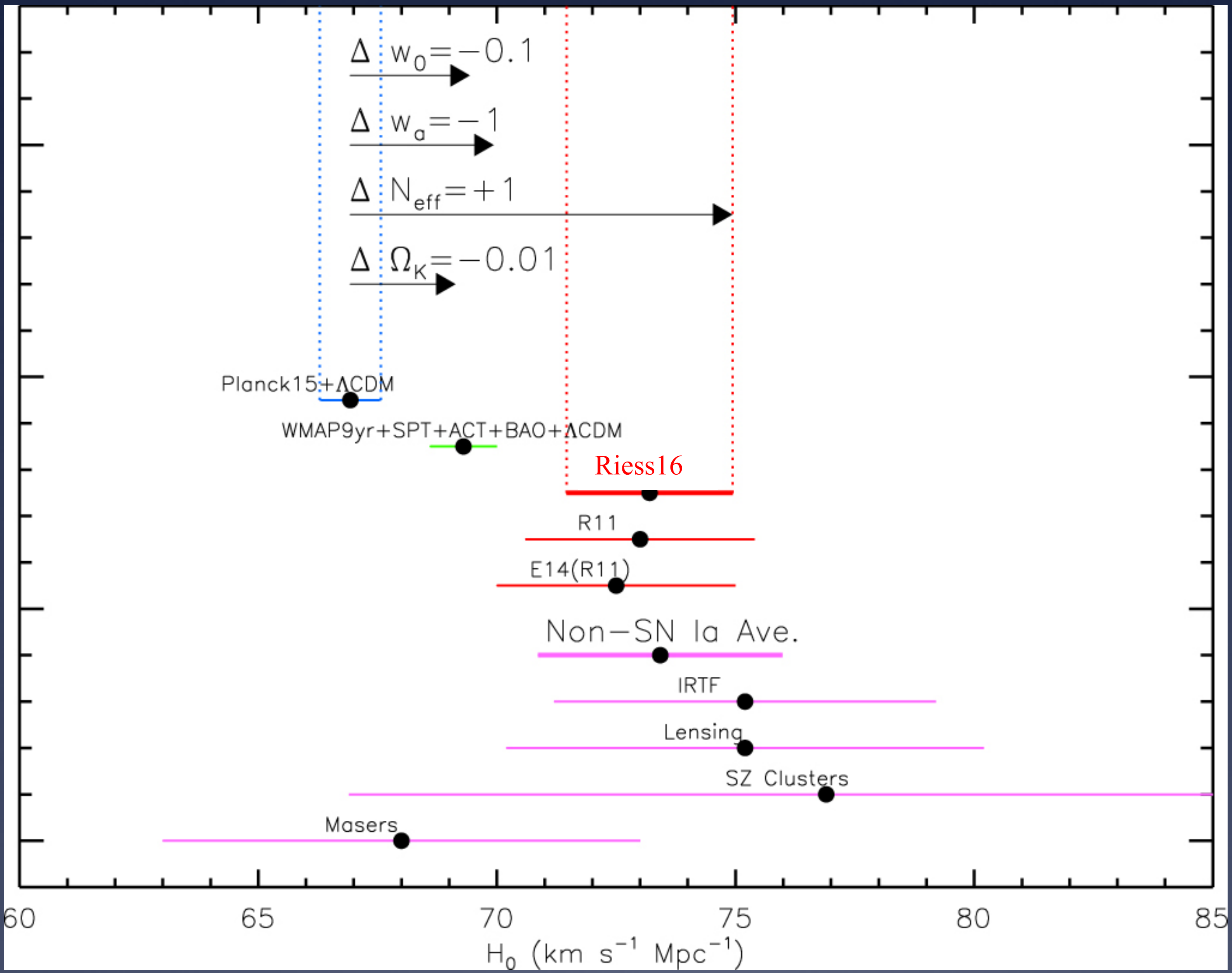
Strong gravitational lensing requires high angular resolution and sensitivity

What is Gravitational Lensing?

Movie courtesy of Y. Hezaveh

The H_0 tension and Dark energy

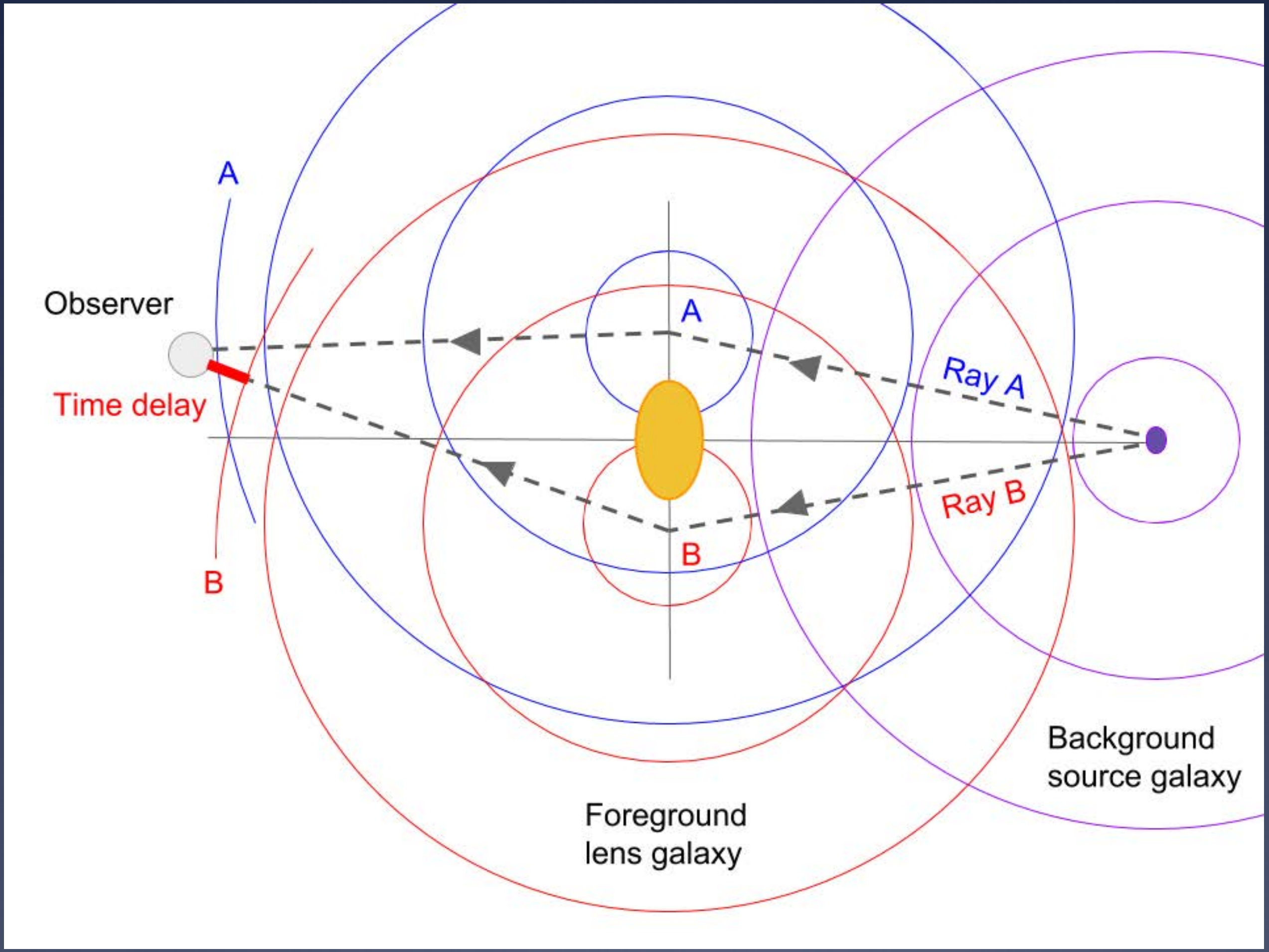
Systematic errors or new physics?



Riess et al. 2016

Cosmography with gravitational lensing

Cosmography from time delays: how does it work?



Treu & Marshall 2016

Time delay distance in practice

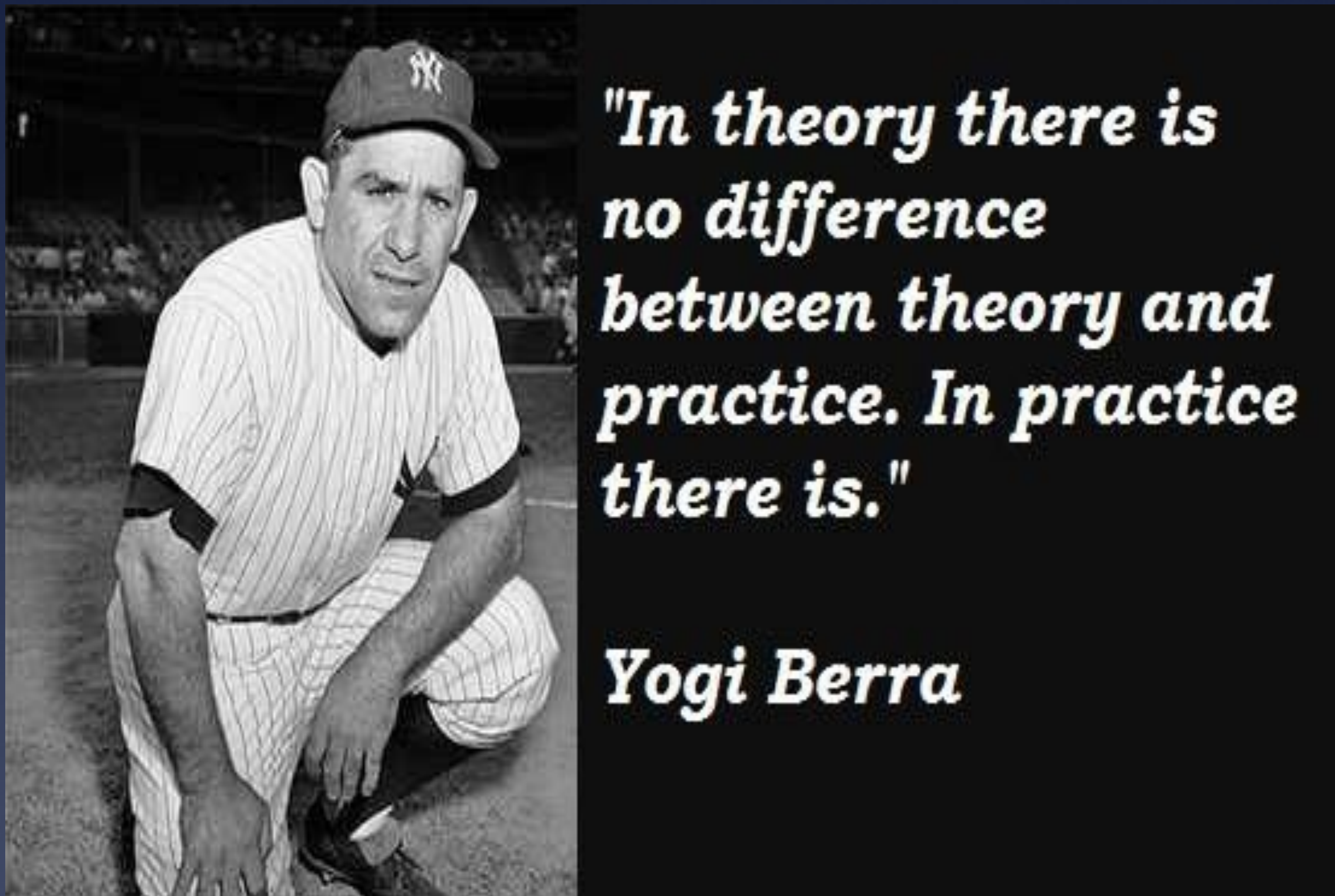
$$\Delta t \propto D_{\Delta t}(z_s, z_d) \propto H_0^{-1} f(\Omega_m, w, ...)$$

Steps:

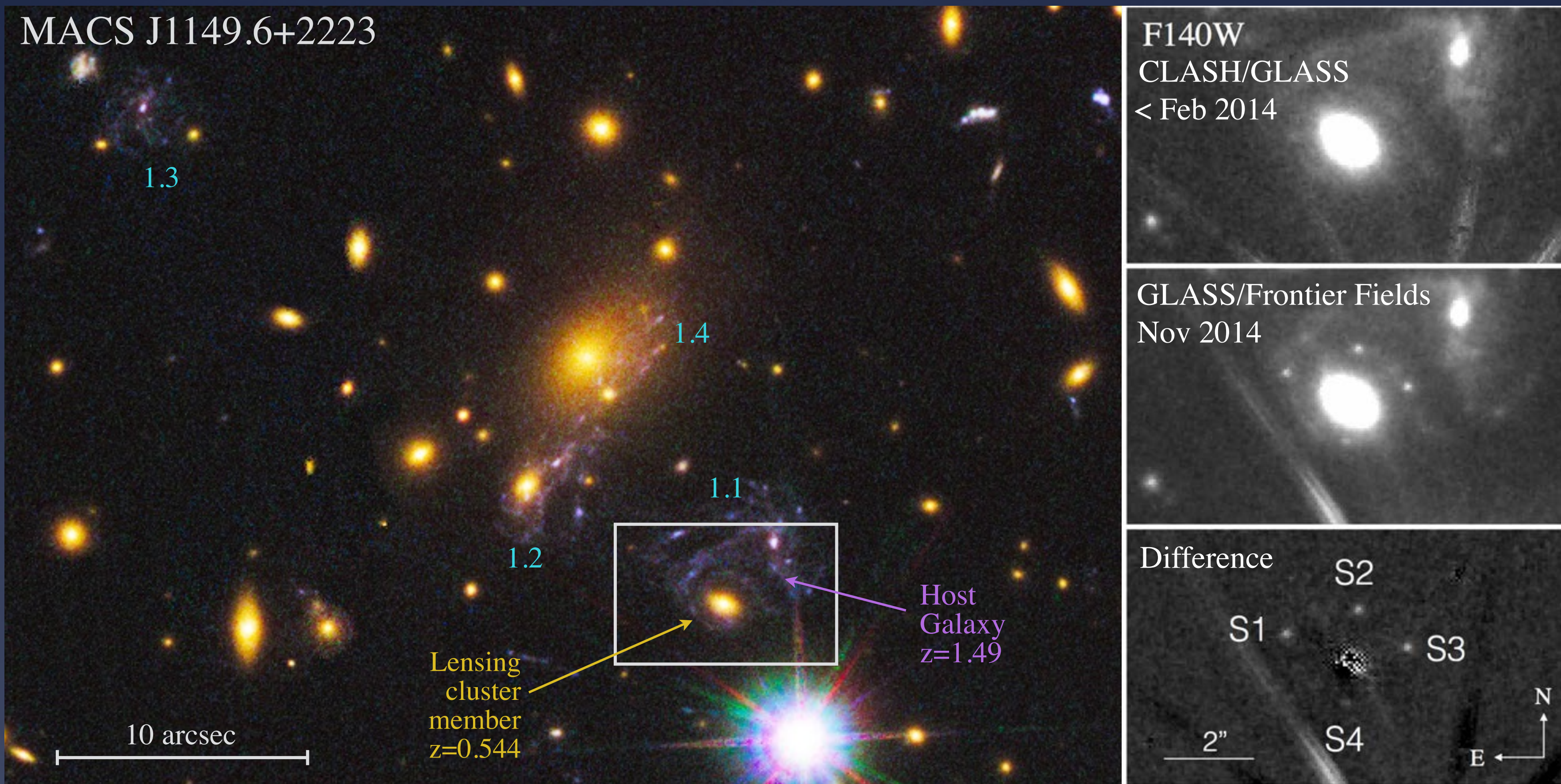
- Measure the time-delay between two images
- Measure and model the potential
- Infer the time-delay distance
- Convert it into cosmlogical parameters

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)


"In theory there is no difference between theory and practice. In practice there is."
Yogi Berra

A real life example



Kelly, Rodney,Treu et al. 2015

“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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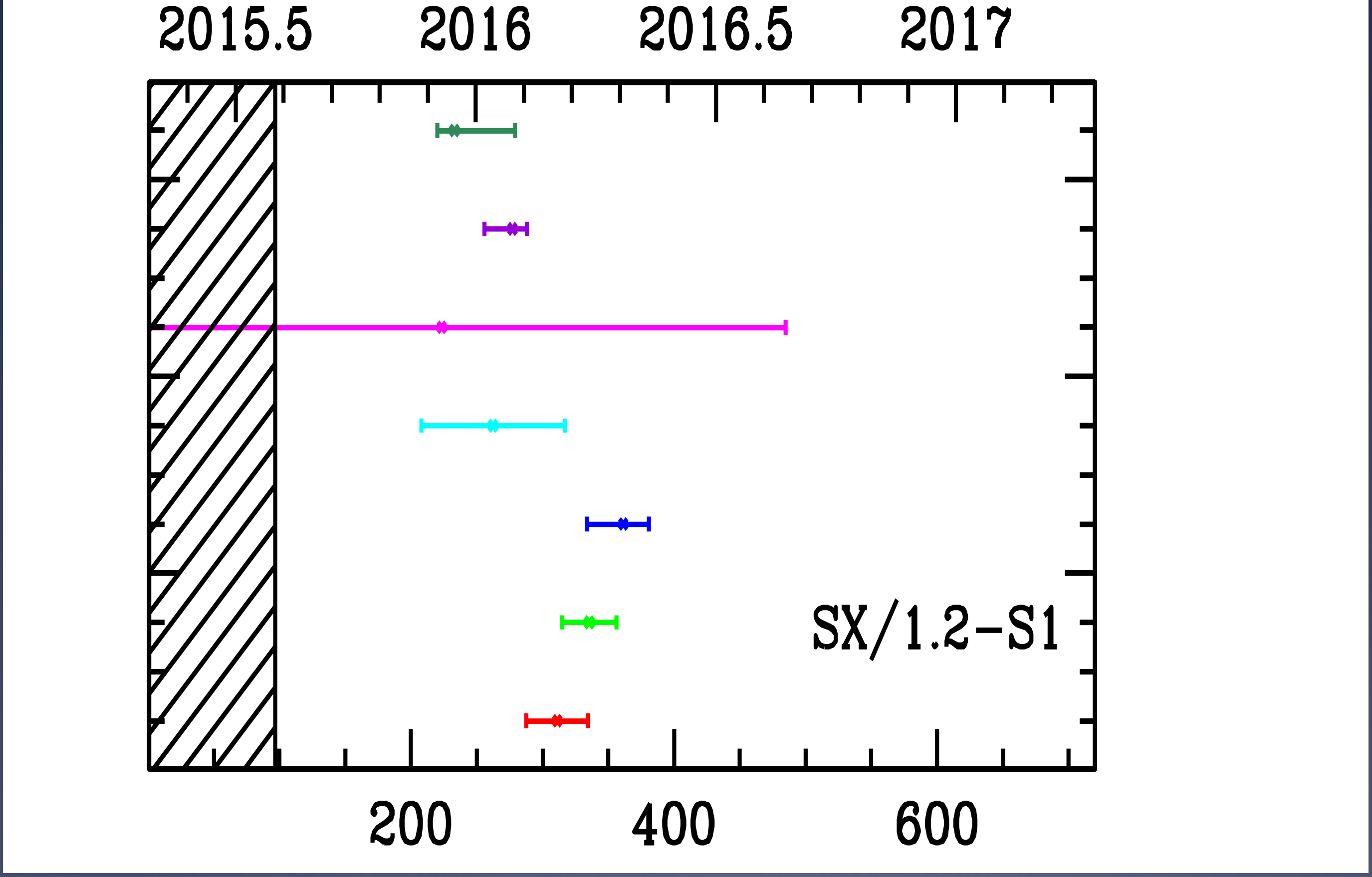
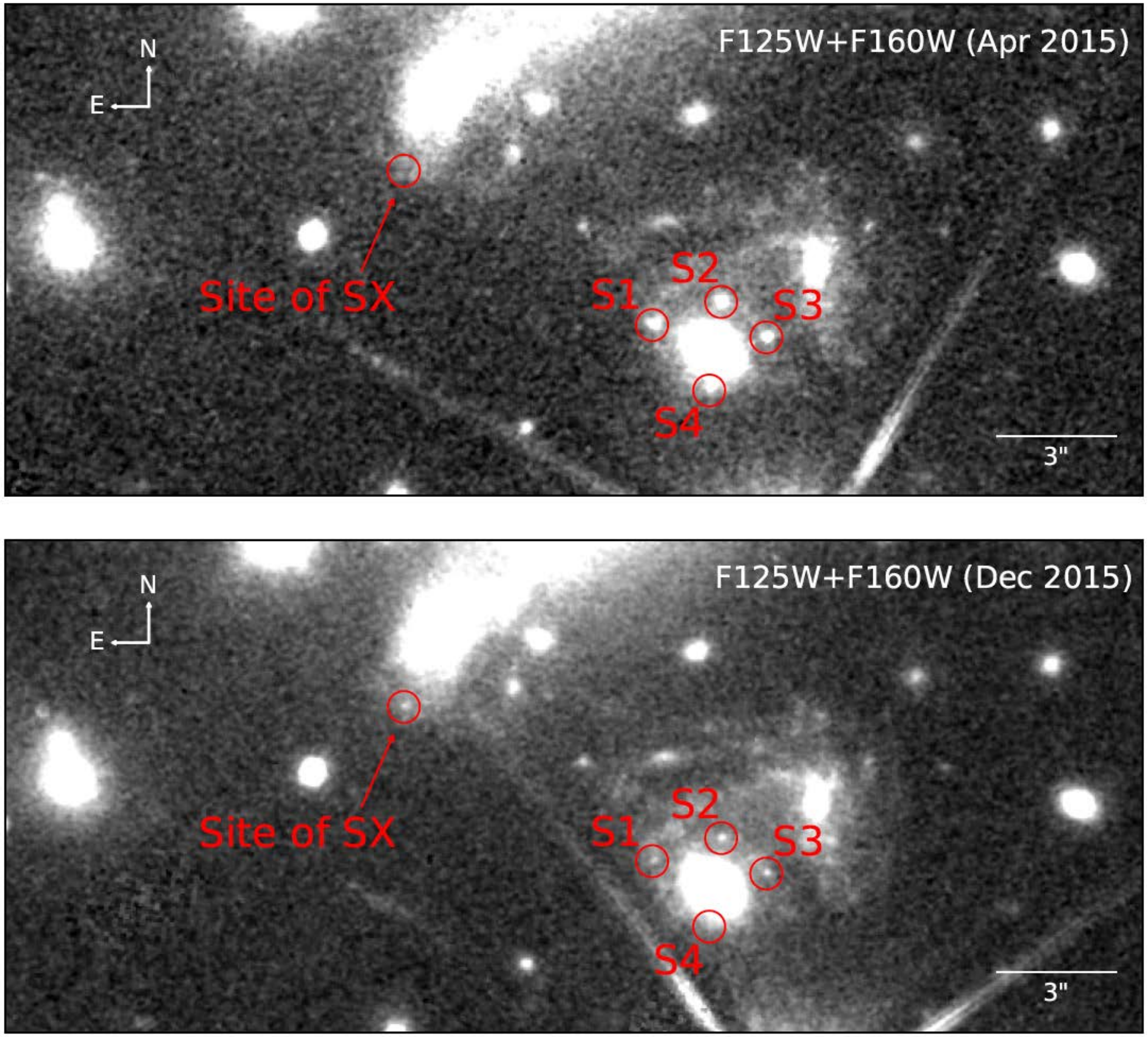


DÉJÀ VU ALL OVER AGAIN: THE REAPPEARANCE OF SUPERNOVA REFSDAL

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]



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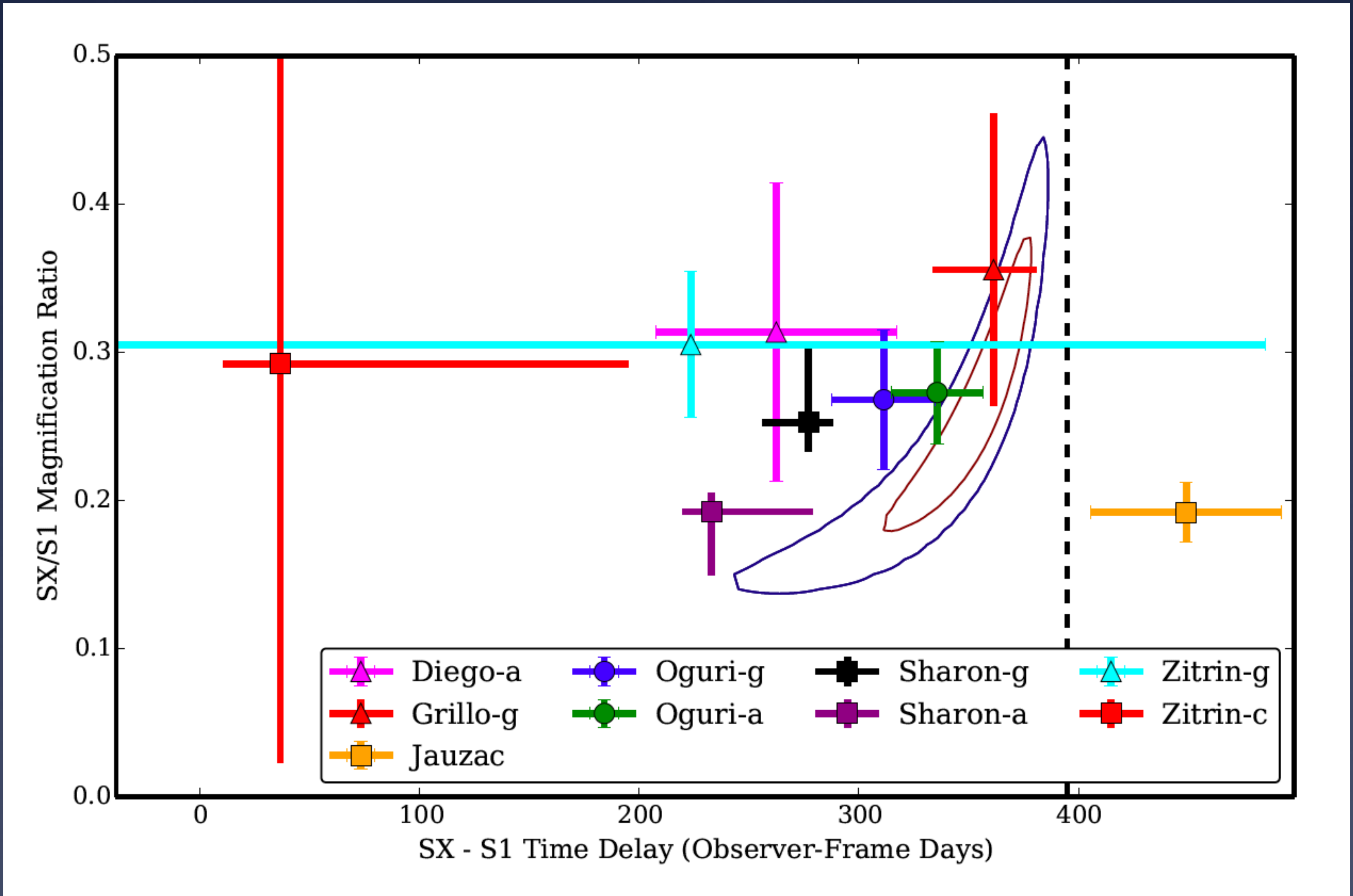
Draft version 2015/12/16



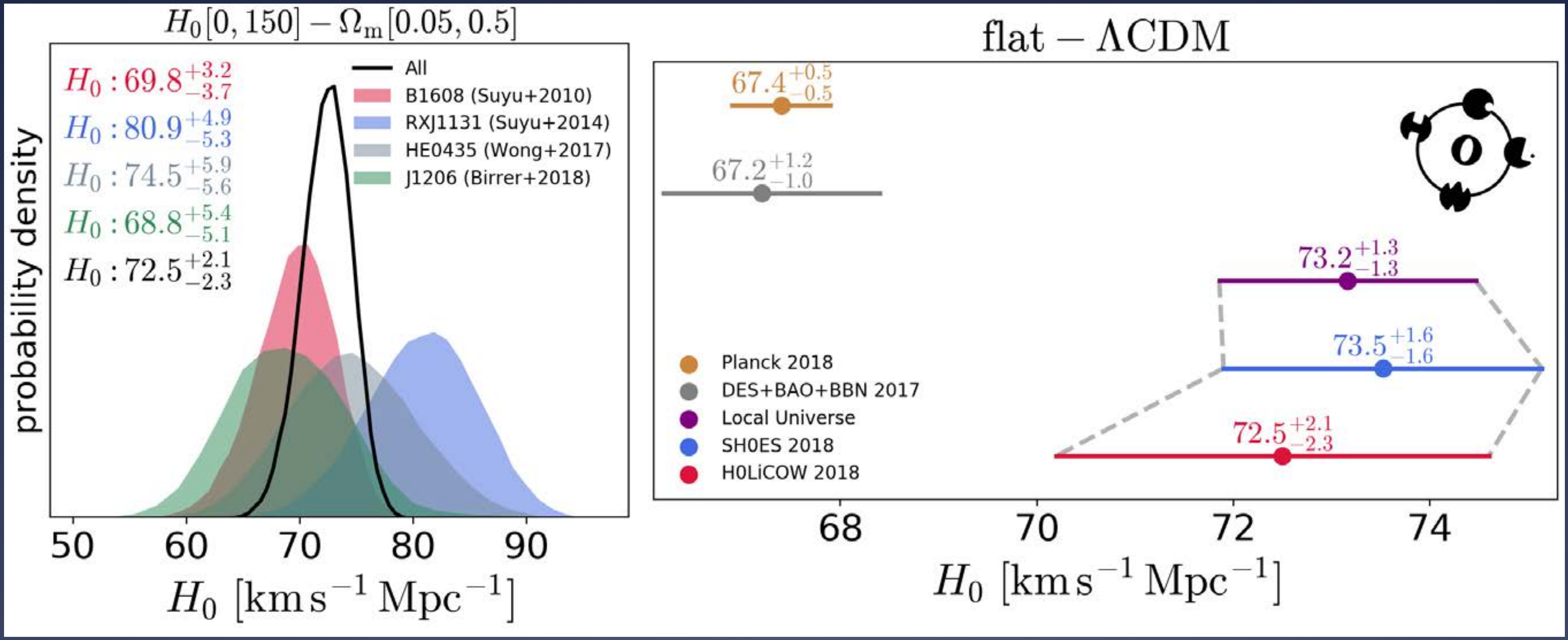
Cosmography with strong lenses: the 4 problems solved

* 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. 2010)
  * Stellar kinematics (Koopmans et al. 2003)

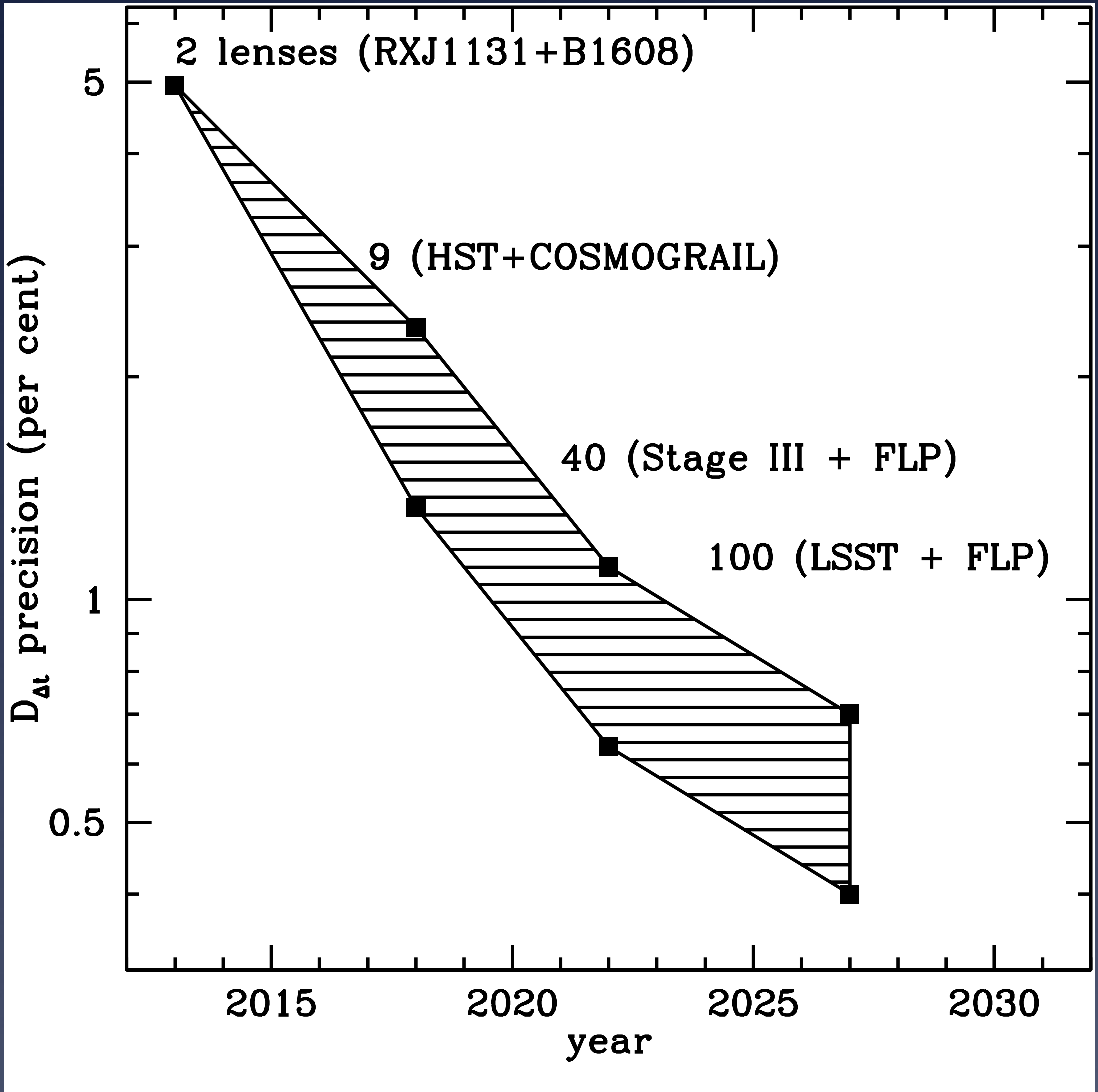
Blindness

- Blinding is the most effective way to avoid experimenter bias and discover unknown unknowns
- Only rarely true blindness can be achieved in astronomy (Refsdal is a rare example)
- When true blindness cannot be achieved it is of paramount importance to “blind” the results, especially when trying to test specific theoretical predictions or measure cosmological parameters
- “Blindness” can be achieved for example via software, by removing the average of the posterior pdf during the measurement and only revealing the average/peak just prior to publication. Unblinded results should be published without correction.
- Fortunately, blinding is becoming more and more popular, e.g., talks on time delay cosmography, cluster lensing, weak lensing…

Current state of the art

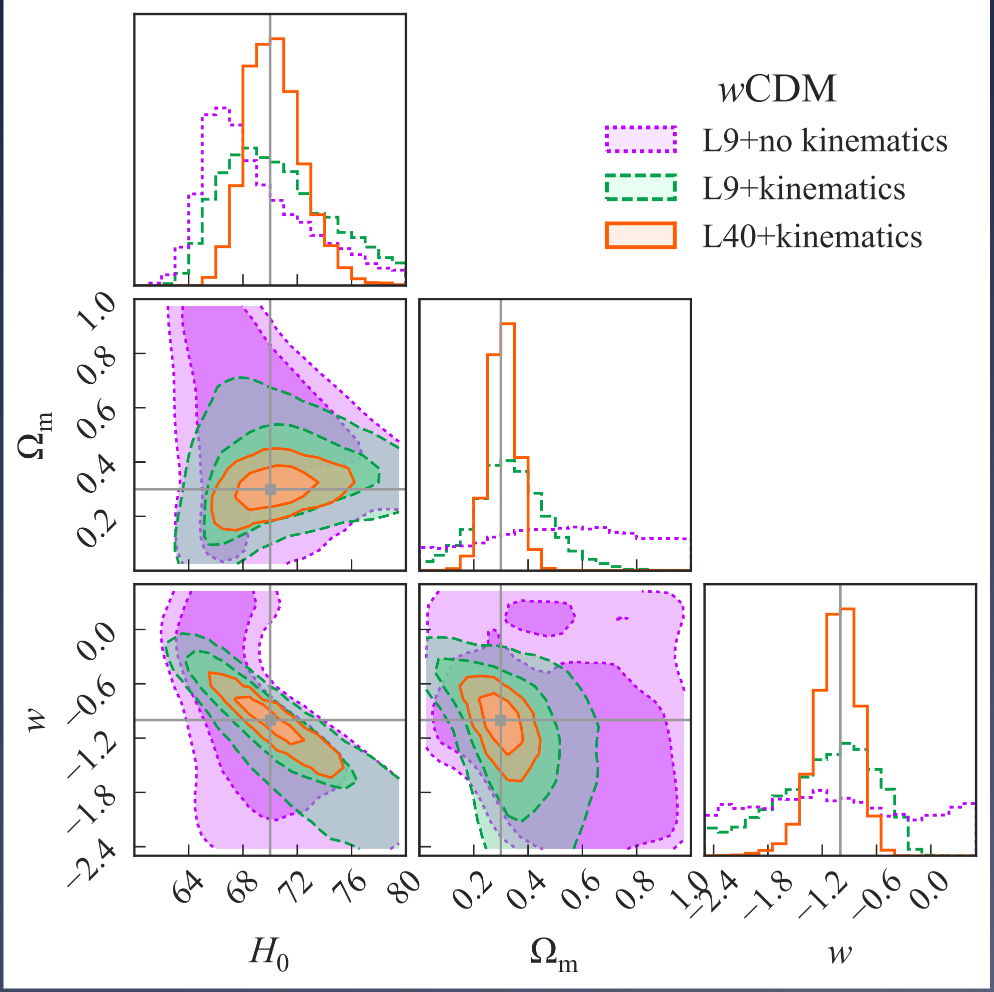


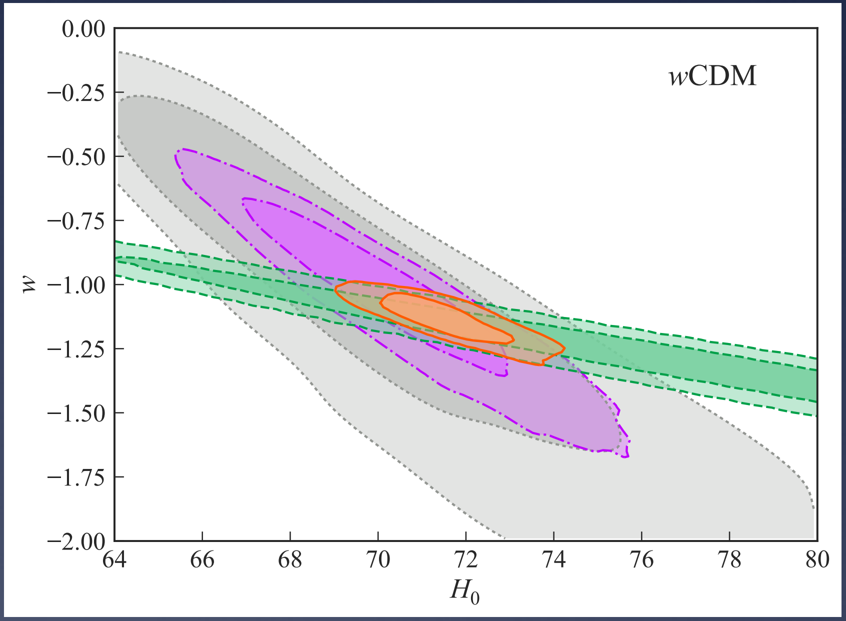
Future Prospects



Treu & Marshall 2016

Spatially resolved kinematics breaks the mass-anisotropy degeneracy





Shajib et al. 2018a

Where will ~40 TD lenses be?

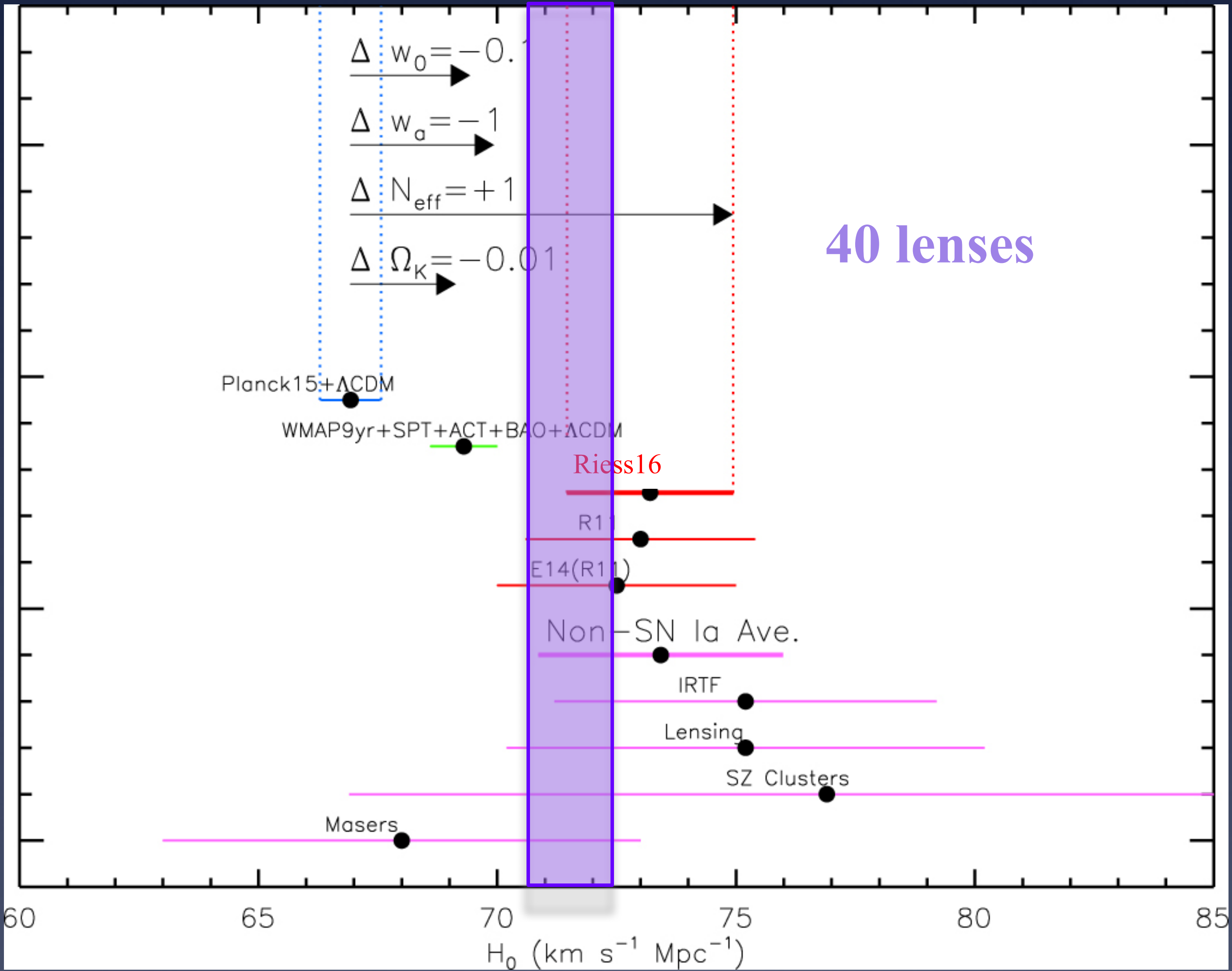
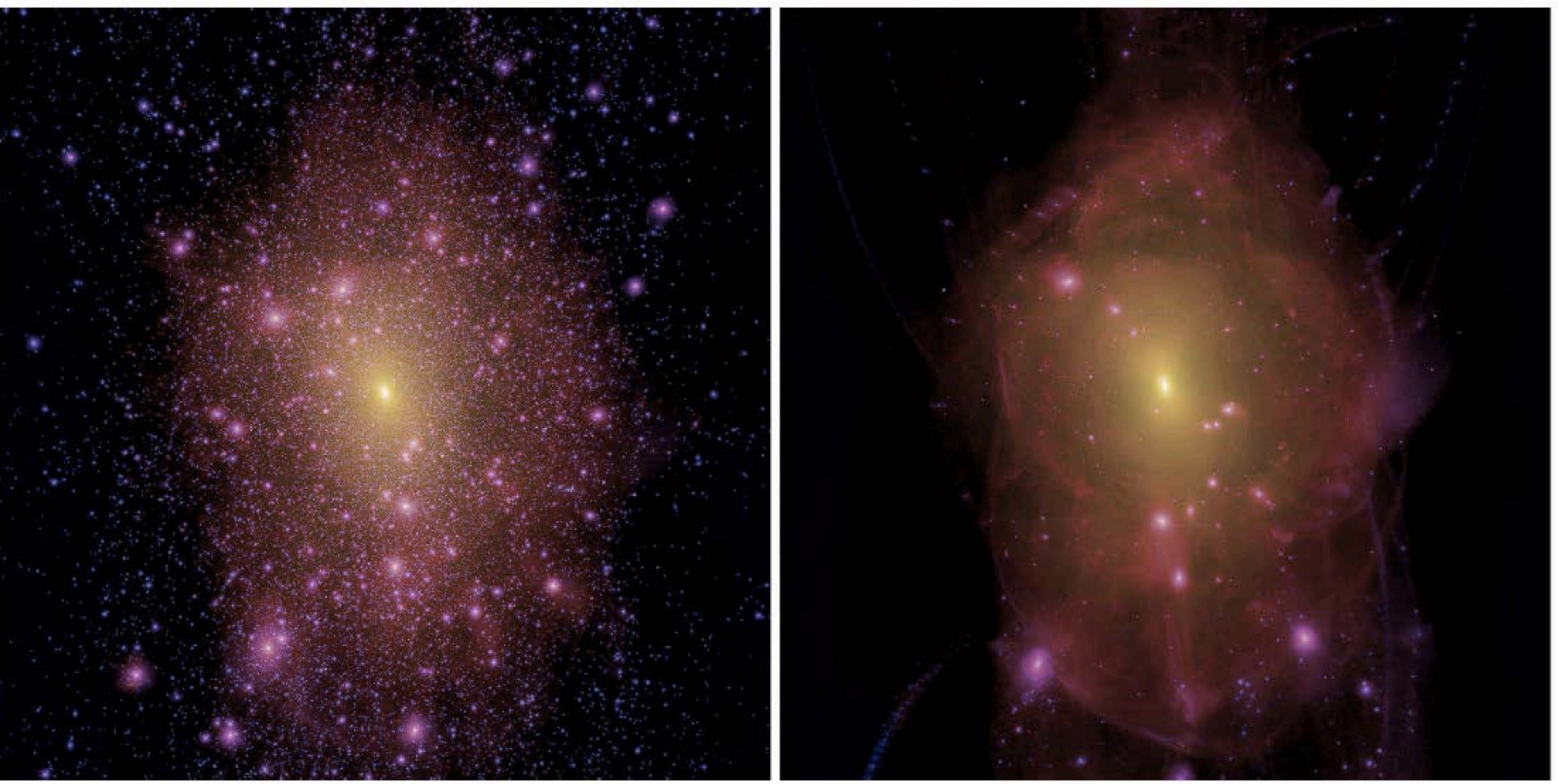


Figure adapted from Riess et al. 2016; Forecast by Shajib et al. 2018a

What’s the dark matter?

(I just showed it’s not light neutrinos)

Warm Dark Matter

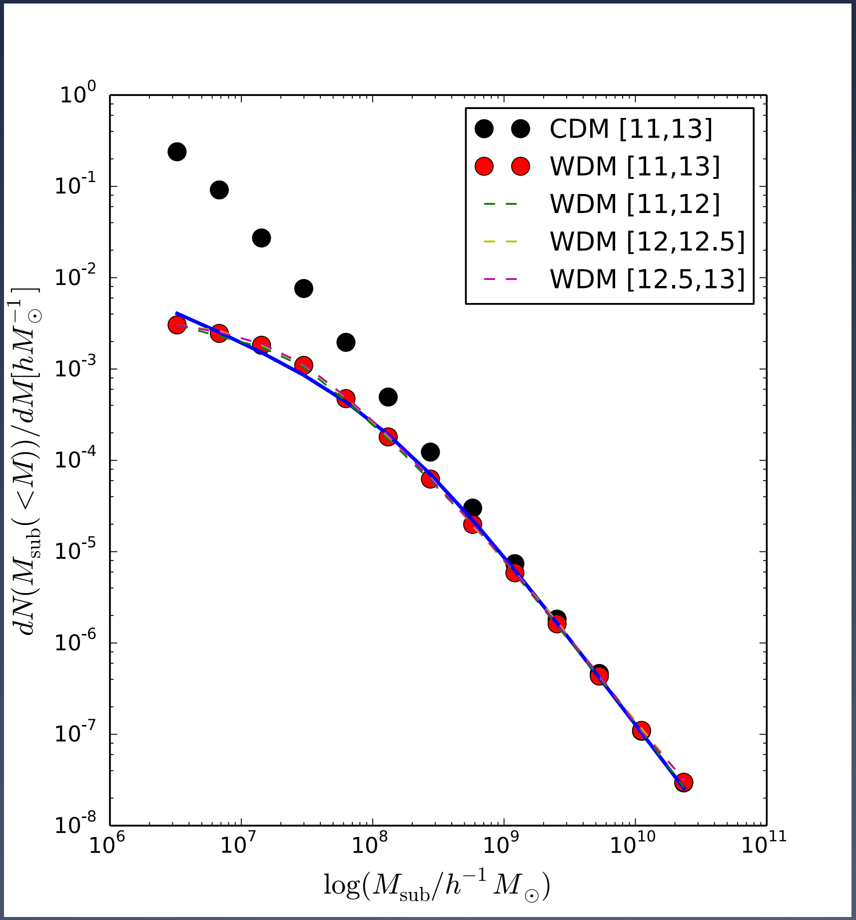


Free streaming ~kev scale thermal relic

Lovell et al. 2014

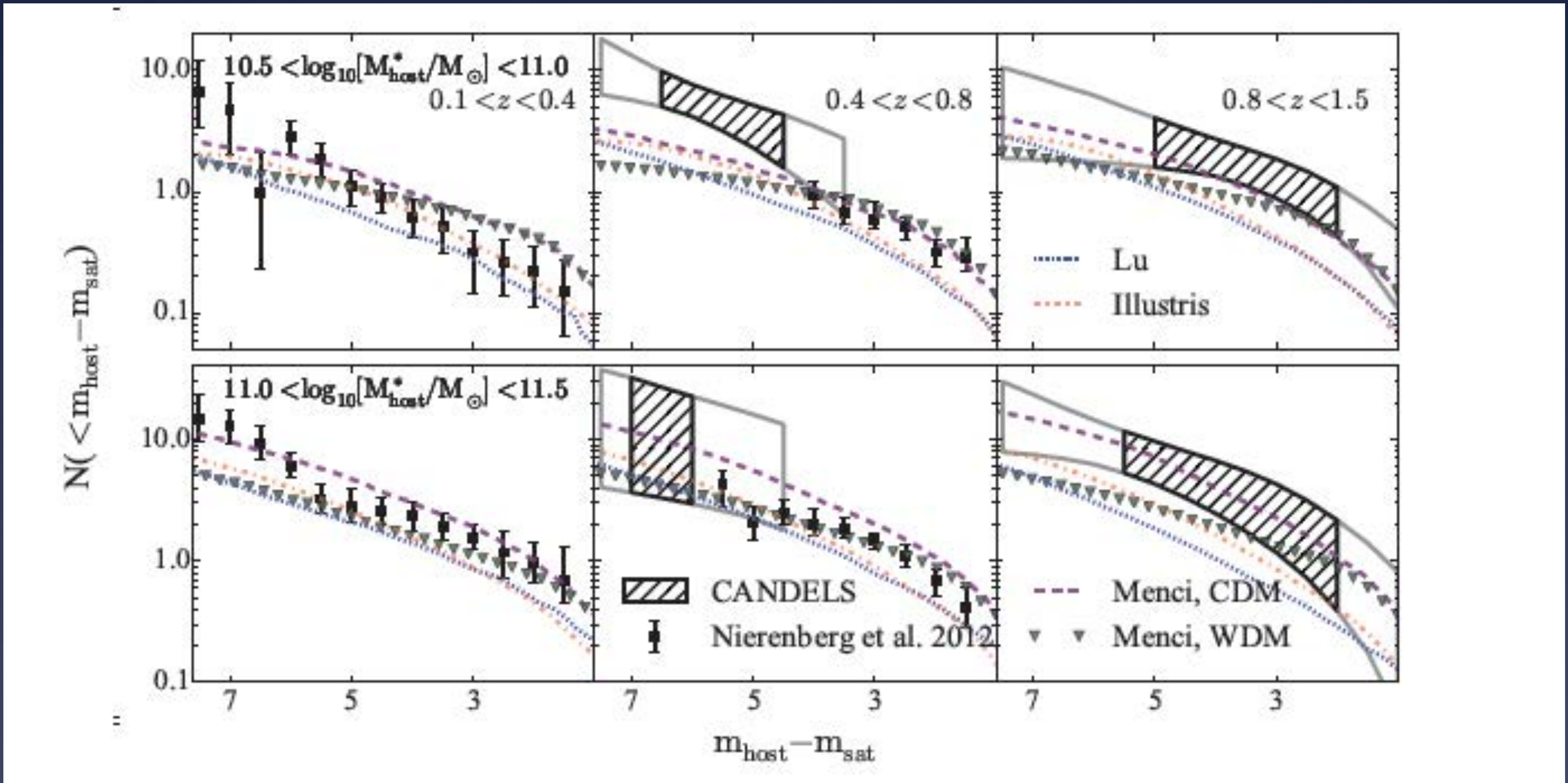
Satellites as a probe of dark matter “mass”

Dark satellites in CDM vs WDM



Li et al. 2016; Nierenberg et al. 2013

Luminous Satellites in CDM vs WDM



Nierenberg, Treu, Menci 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**

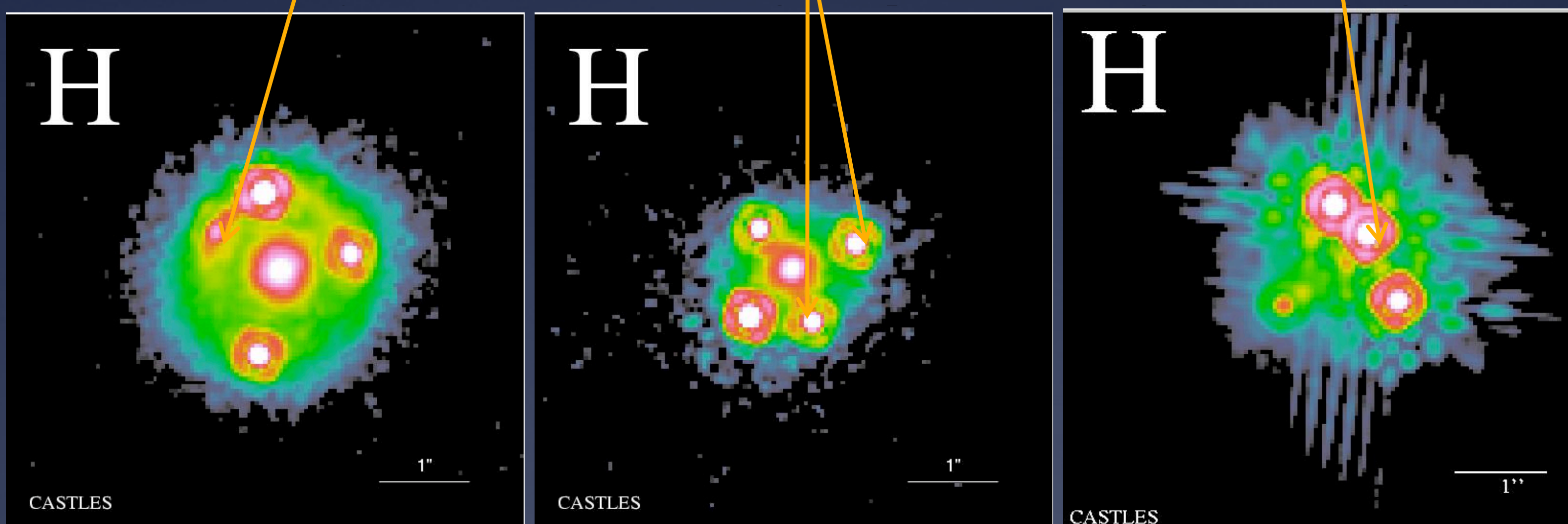
Flux Ratio Anomalies

A smooth mass distribution would predict:

This to be 100x brighter

These to be 2x brighter

This to be 10% brighter



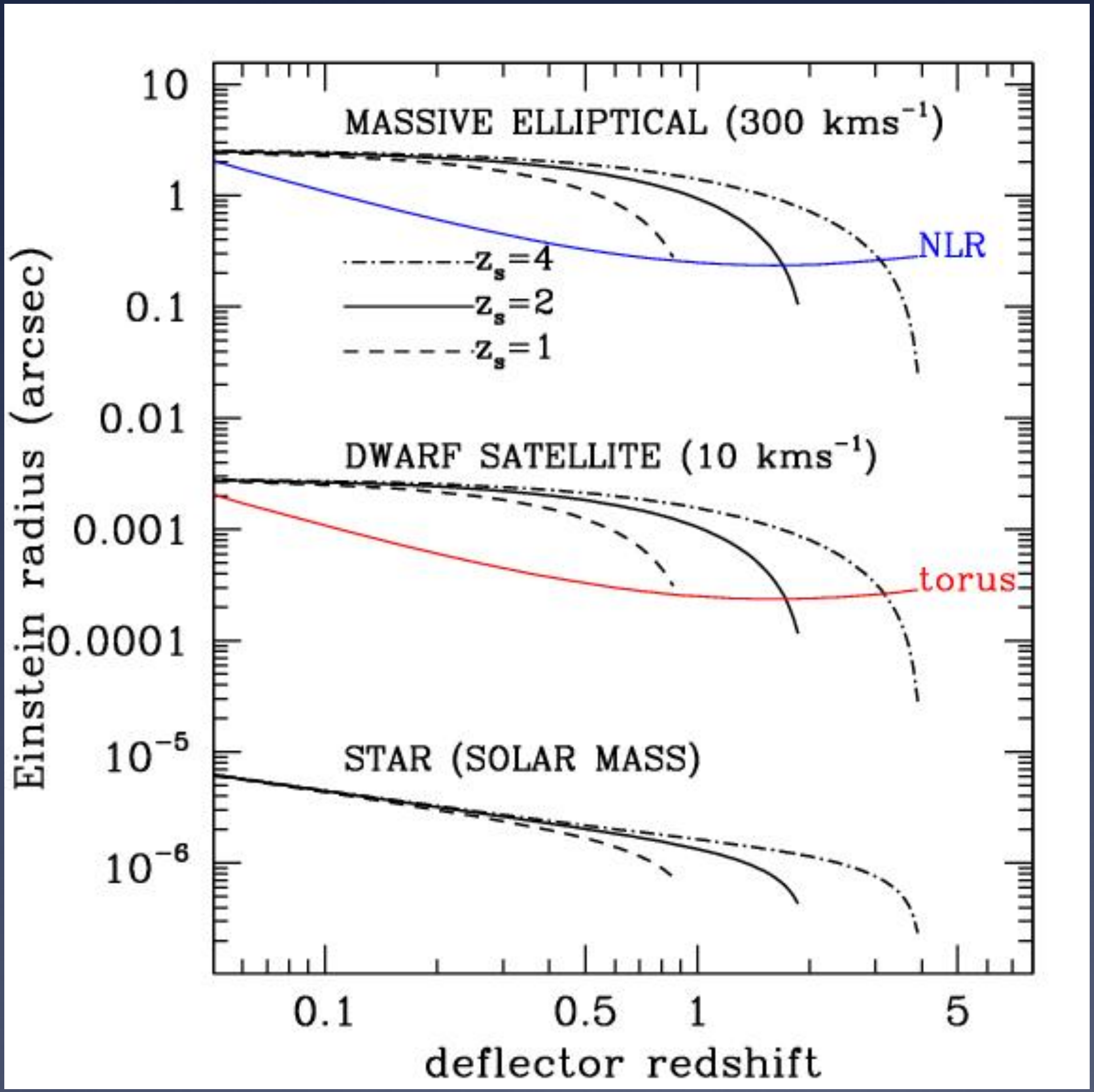
What causes this the anomaly?

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

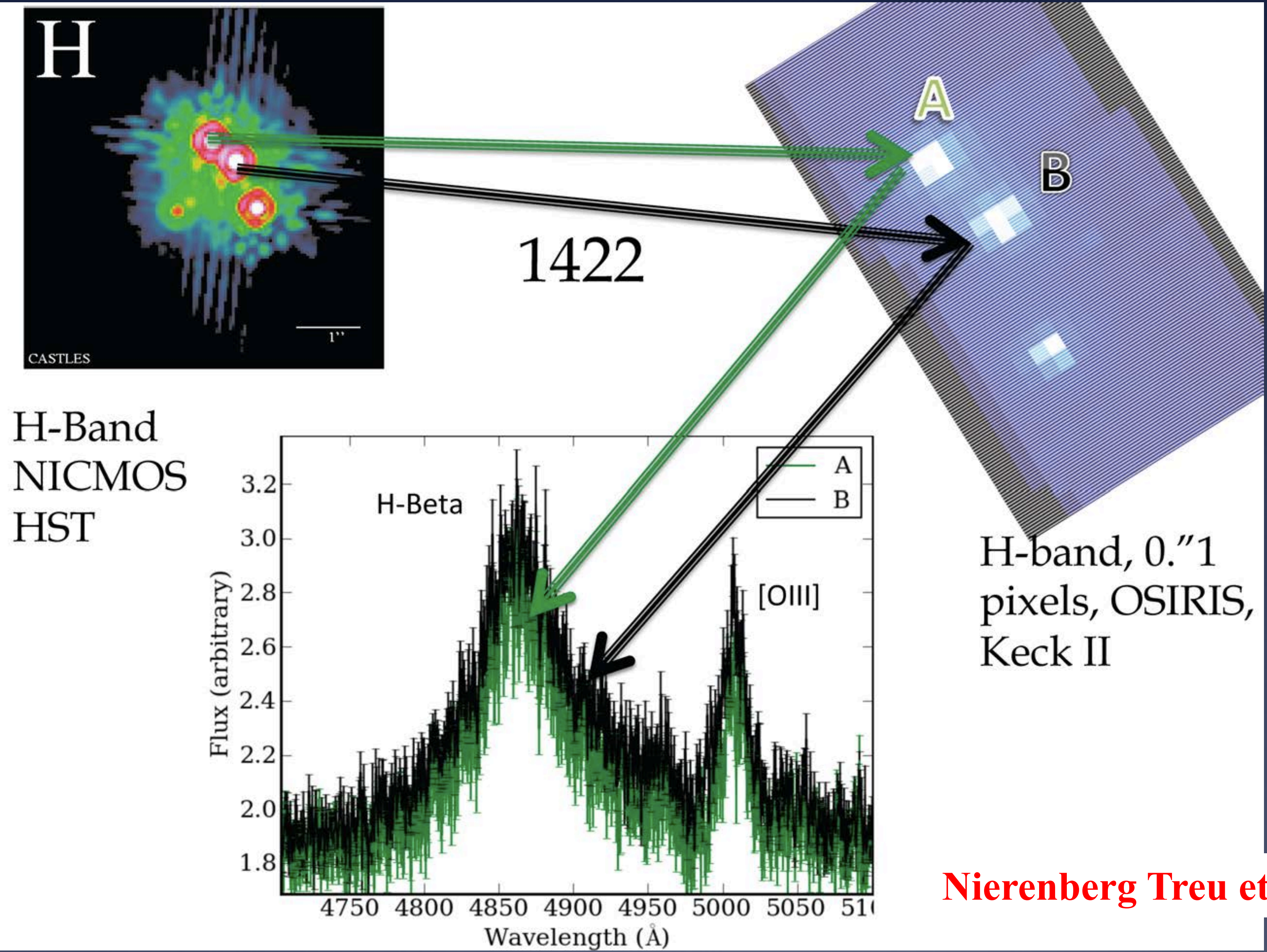
What do need?

1. Larger samples
2. High precision photometry and astrometry
3. Avoid microlensing and other baryonic features

Dusty Torus and Narrow Line Region Are not affected by microlensing

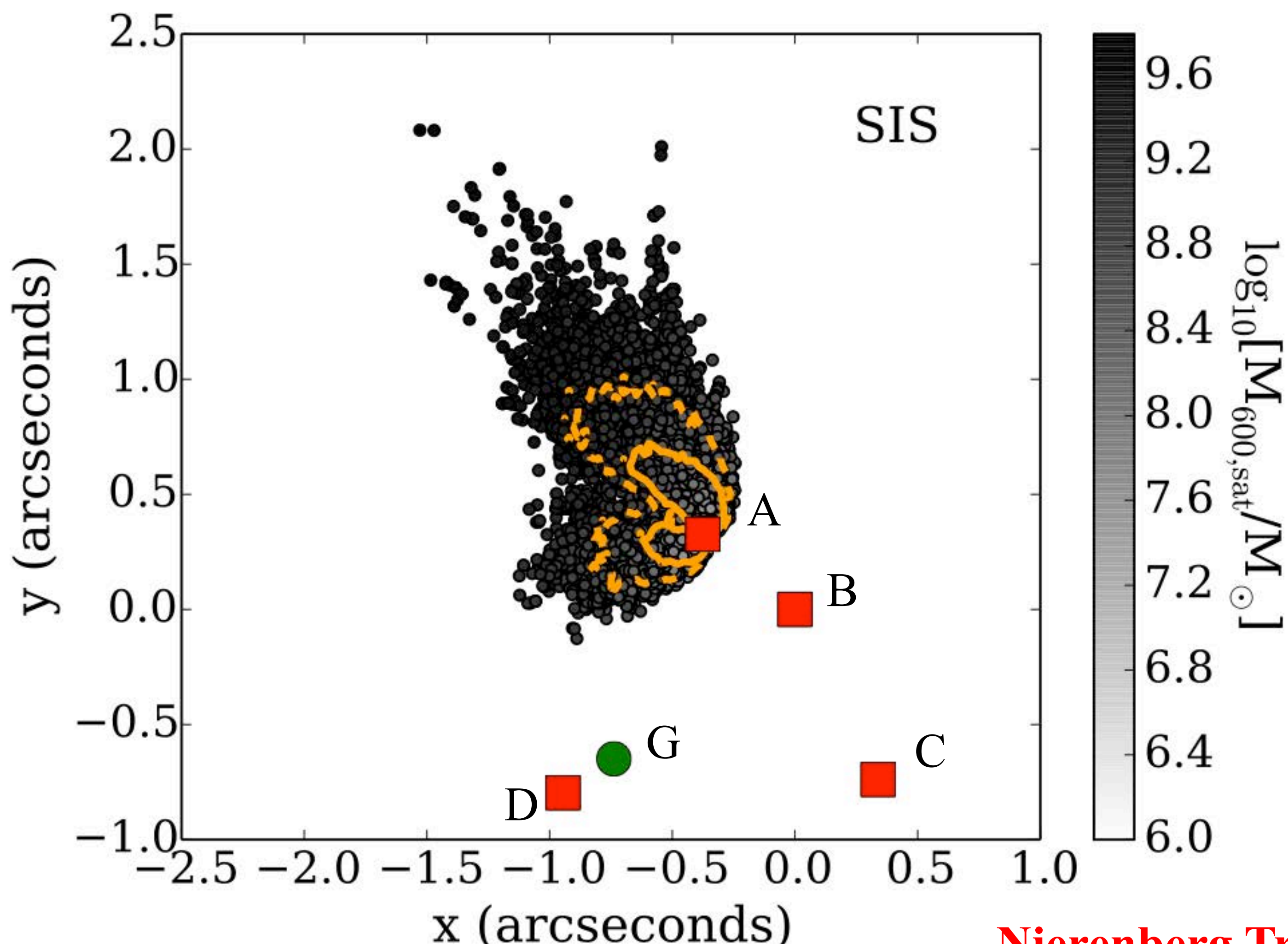


OSIRIS detection of substructure



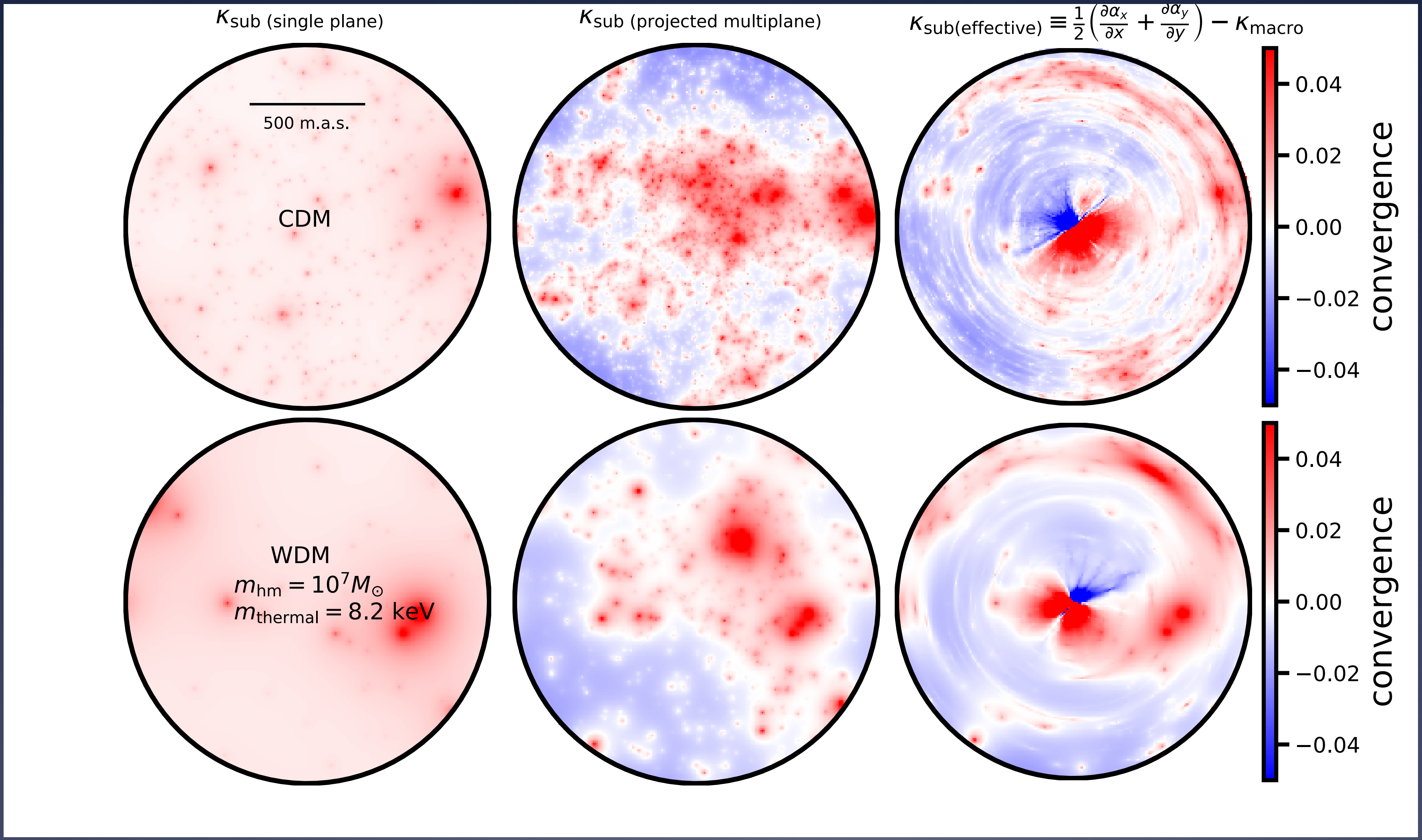
Nierenberg Treu et al 2014

OSIRIS detection of substructure



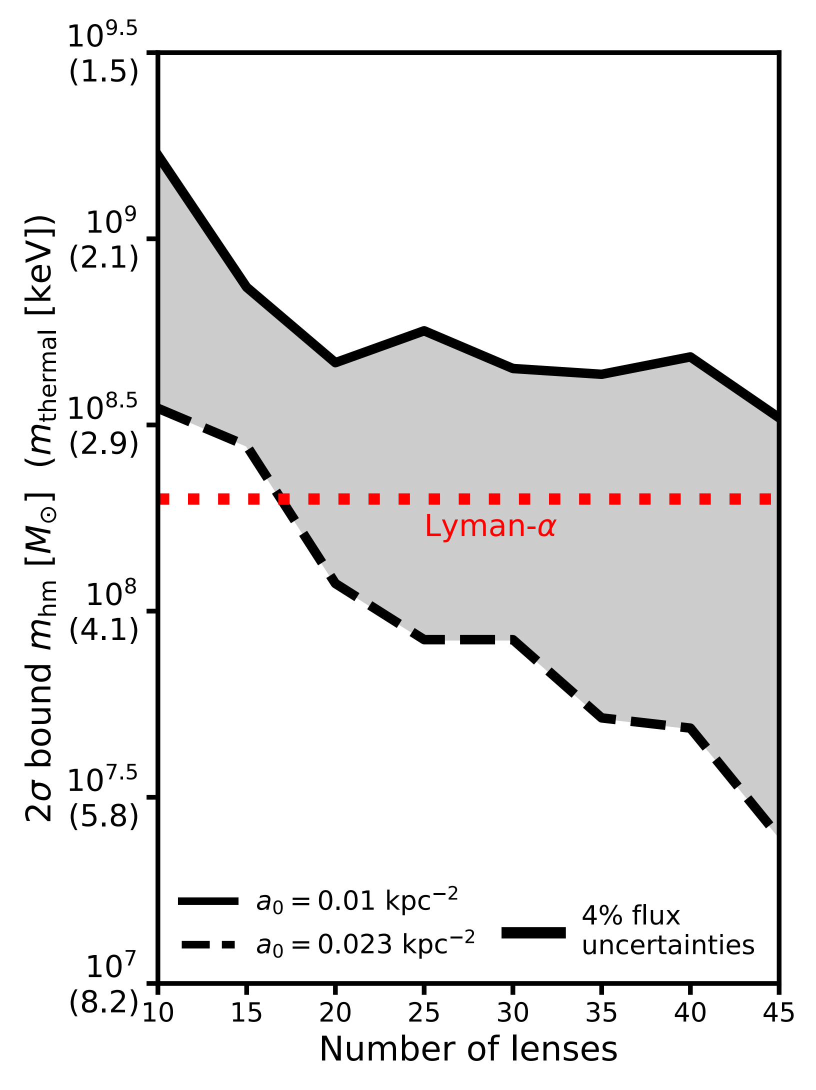
Nierenberg Treu et al 2014

The nature of dark matter: Future Prospects



See talk by Gilman

The nature of dark matter: Future Prospects



See talk by Gilman

Flux ratio anomalies: Future Prospects

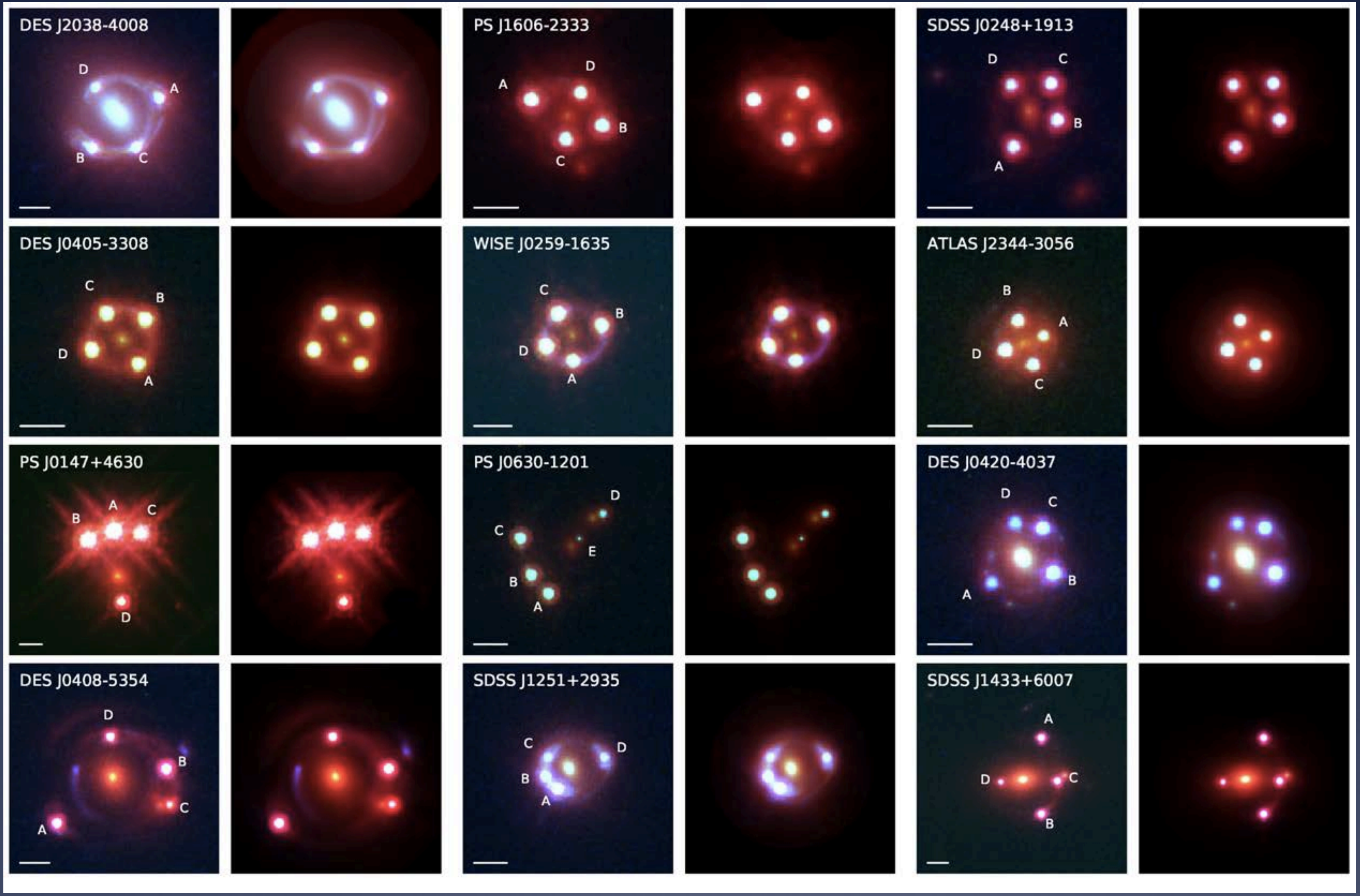
- Narrow line flux ratio anomalies can currently be studied for 20 systems
- Future surveys will discover thousands of systems
- TMT will provide spectroscopic follow-up and emission line flux ratios

100 quasar lenses with Flux ratios and time-delays. How do we do this in practice?

Roadmap. I. Find Lenses

- Carry out large imaging survey.
  - QSO forecasts by Oguri & Marshall (2010)
    - DES (~1000 lensed QSOs, including 150 quads)
    - LSST (~8000 lensed QSOs, including 1000 quads)
    - Euclid/WFIRST many more!
- Find lenses:
  - Different strategies for lensed QSOs and galaxies (Marshall+, Gavazzi+,Kubo+,Belokurov+,Kochanek+,Faure+,Pawase+,Agnello+) and under development (Marshall, Treu, LSST collaboration)
  - **Successfully demonstrated**

Voila'



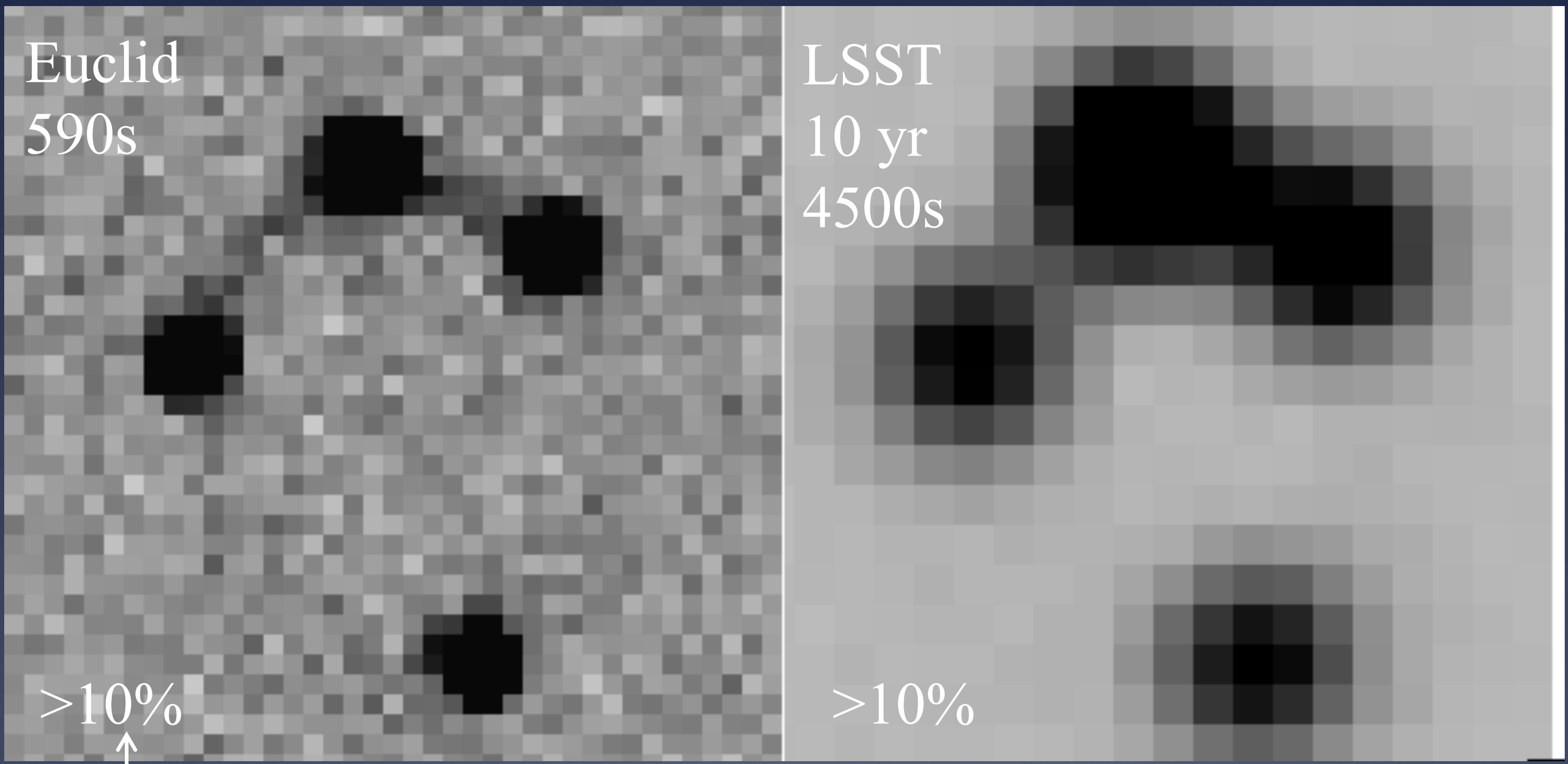
Shajib et al. 2018b

Roadmap. II. Follow-up

- High resolution imaging: space or Adaptive Optics (TMT)
- Time delays: dedicated monitoring in the optical or radio
- Deflector mass modeling: redshifts and stellar velocity dispersions (TMT) Shajib et al. 2018

High resolution information. Where will it come from?

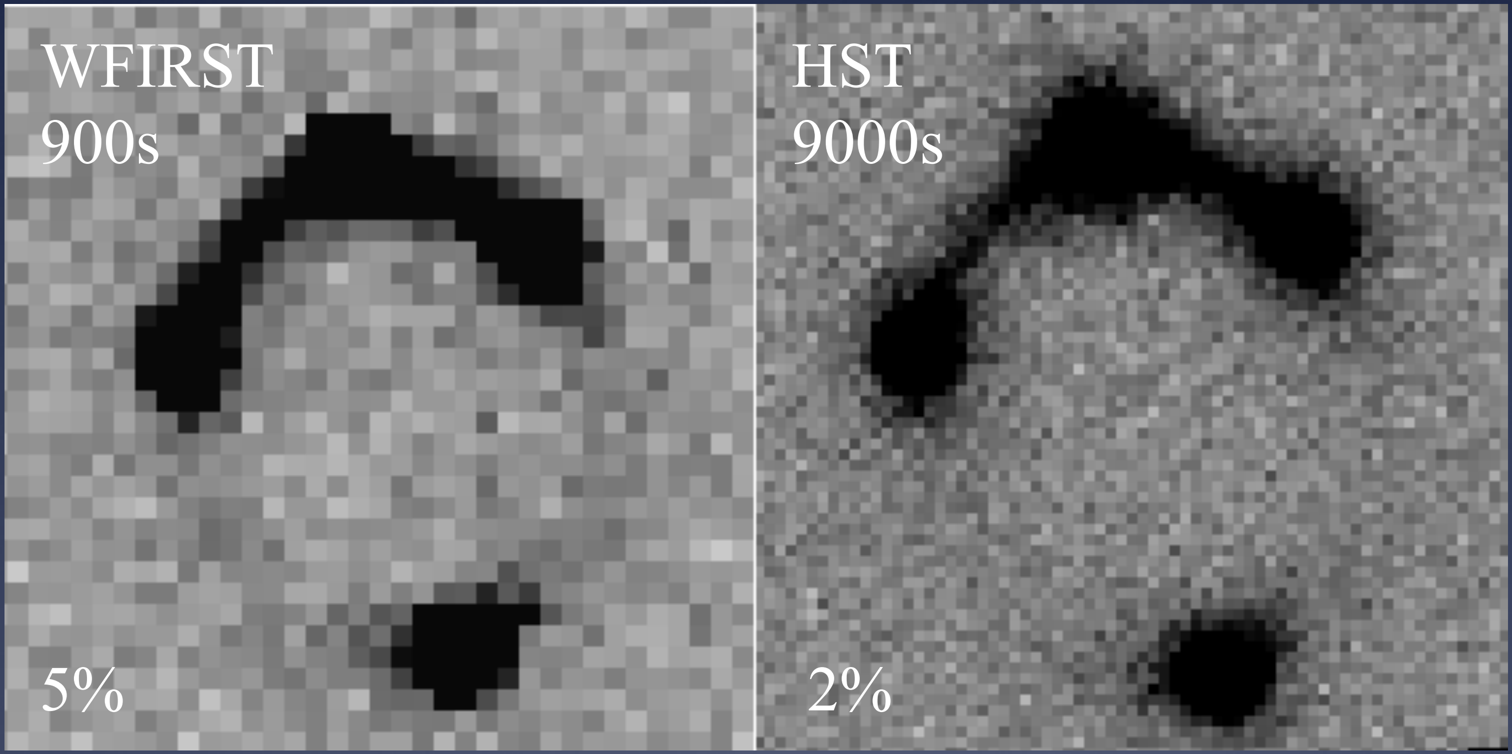
Euclid/LSST will be great for discovery but not for cosmography



Contribution of modeling error
To time delay distance

Meng, TT et al. 2015

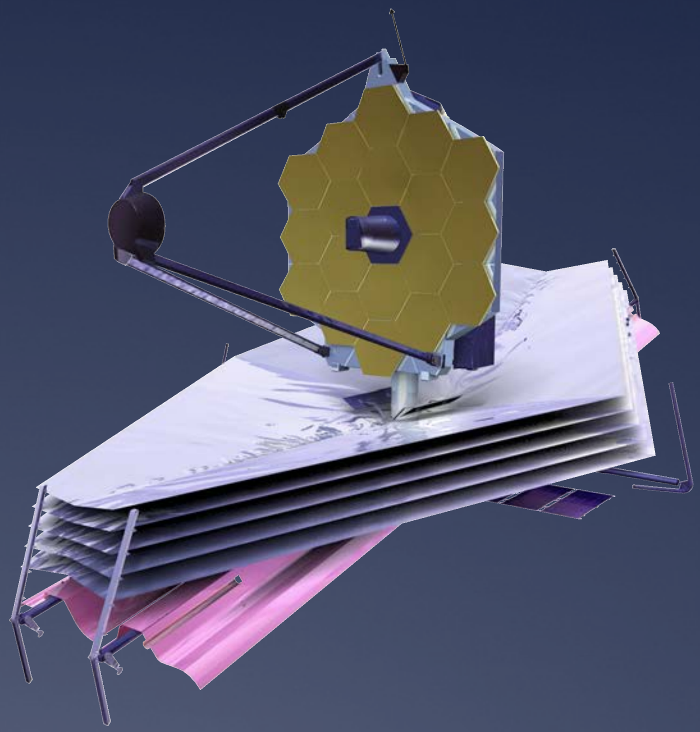
WFIRST will be probably good enough for the brighter lenses



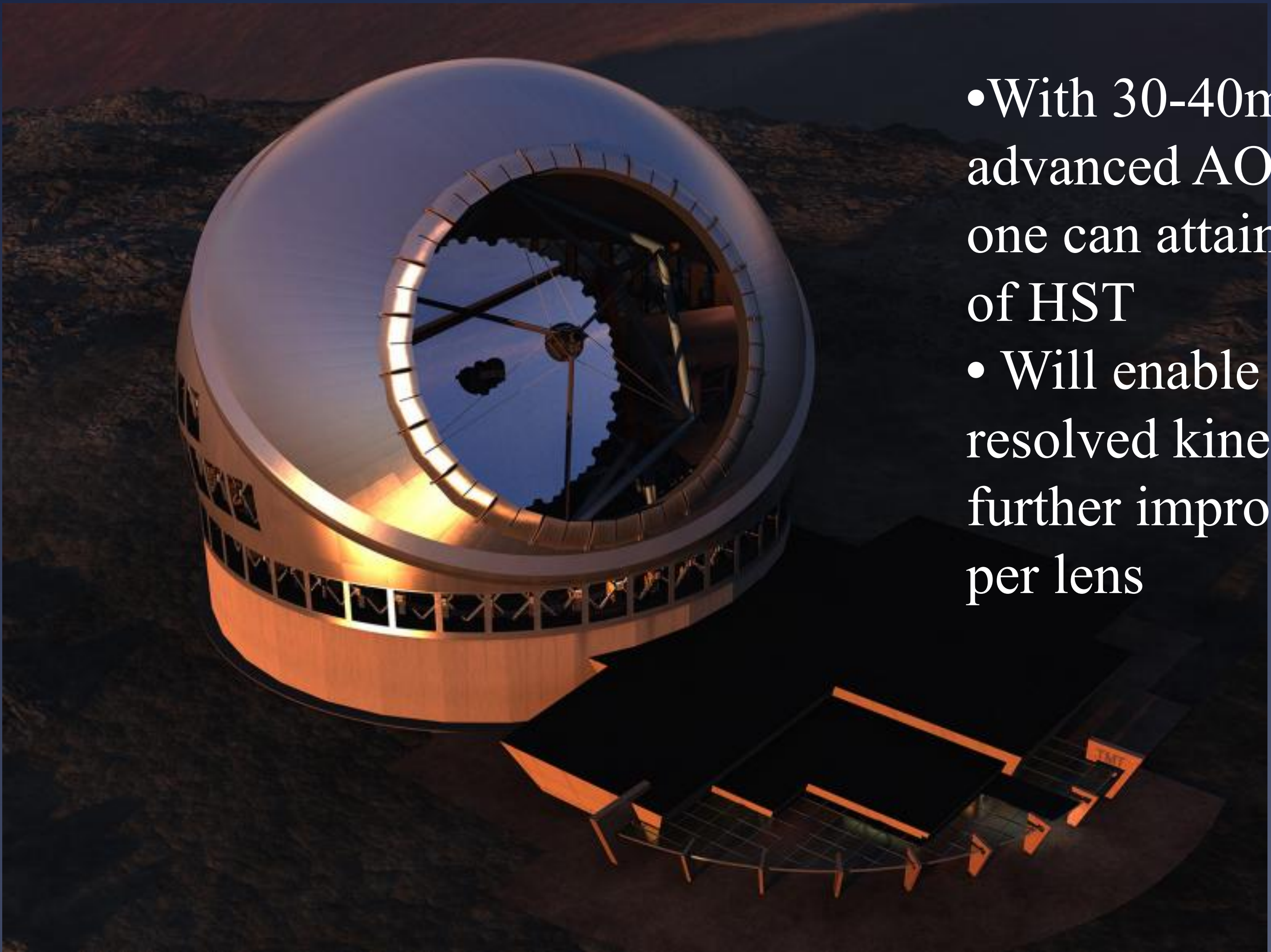
Meng, TT et al. 2015

JWST

* 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
* Spatially resolved spectroscopy very hard



Extremely Large Telescopes



- With 30-40m apertures and advanced AO, in principle one can attain 10x resolution of HST
- Will enable spatially resolved kinematics to further improve constraints per lens

Imaging lenses with Extremely Large Telescopes

Table 6. Exposure time requirements

Instrument	double		quad	
	faint	bright	faint	bright
HST	6×10^3s	360 s	3×10^3s	150 s
JWST	690s	180 s	210s	<60 s
Keck (LGSAO)	105×10^3s	3600 s	75×10^3s	2400 s
Keck (NGAO)	18×10^3s	180 s	12×10^3s	150 s
TMT	1200s	—	1080s	—

TMT will image any known lens to the required precision within 10-20 minutes! Meng, TT et al. 2015

Spectroscopy of lenses with Extremely Large Telescopes

Table 4. Uncertainties of D_d and $D_{\Delta t}$ for a single lens with different observational setups

Model	Kinematics data	σ_{D_d} (per cent)	$\sigma_{D_{\Delta t}}$ (per cent)
Baseline	No	-	6.5
	Integrated	19.8	6.5
	Resolved	9.6	5.8
Conservative	Integrated	27.0	7.8
	Resolved	16.7	7.5
Futuristic	Resolved	7.7	5.3

Shajib et al. 2018

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 feasble using TMT to follow-up quasar lenses discovered in LSST and other imaging surveys

The end

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

Roadmap. III. Modeling

- Extended sources
  - At the moment each lens requires months of work by an expert modeler, and months of CPU (e.g. Suyu+, Vegetti+).
  - Need to get investigator time down to hours/lens
  - Massive parallelization is required (GPUs?) for efficient posterior exploration and analysis of systematics