Probing dark matter with strong gravitational lensing

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Outline

- Introduction
  - What is gravitational lensing and why do we need it?
- Small-scale problems
  - The inner regions of dark matter halos and the self-interaction cross section
    - The core/cusp problem
    - Colliding clusters
  - Dark matter substructure and the dark matter free streaming length
- Dark matter substructure: a roadmap for the future

What’s the dark matter?

Let’s use gravity to find out

What is Gravitational Lensing?

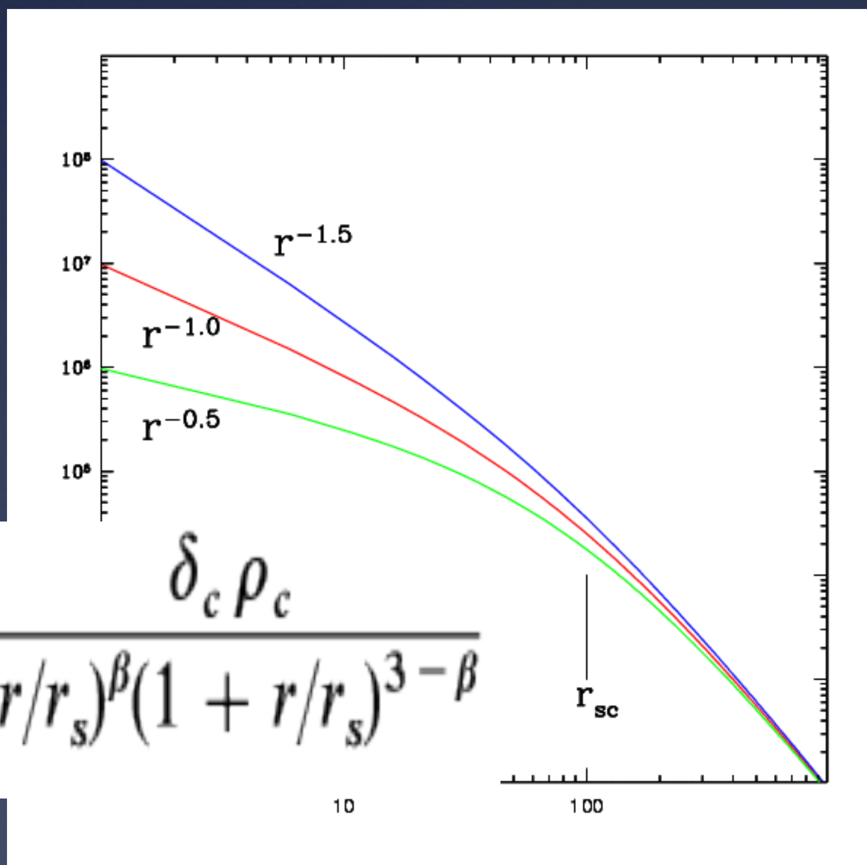
Movie courtesy of Y. Hezaveh

Self-interaction cross section

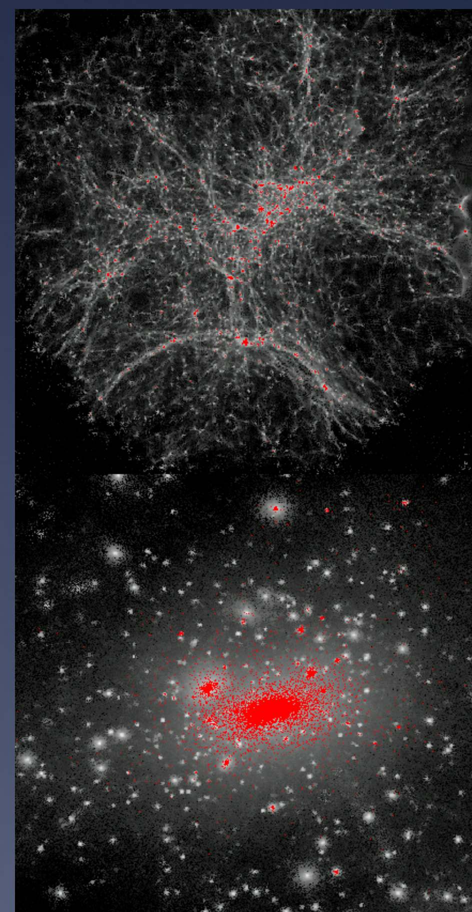
The inner regions of dark matter halos

Cold dark matter predictions

•How is matter distributed in clusters?
•Do clusters (and galaxies) follow a universal dark matter profile?



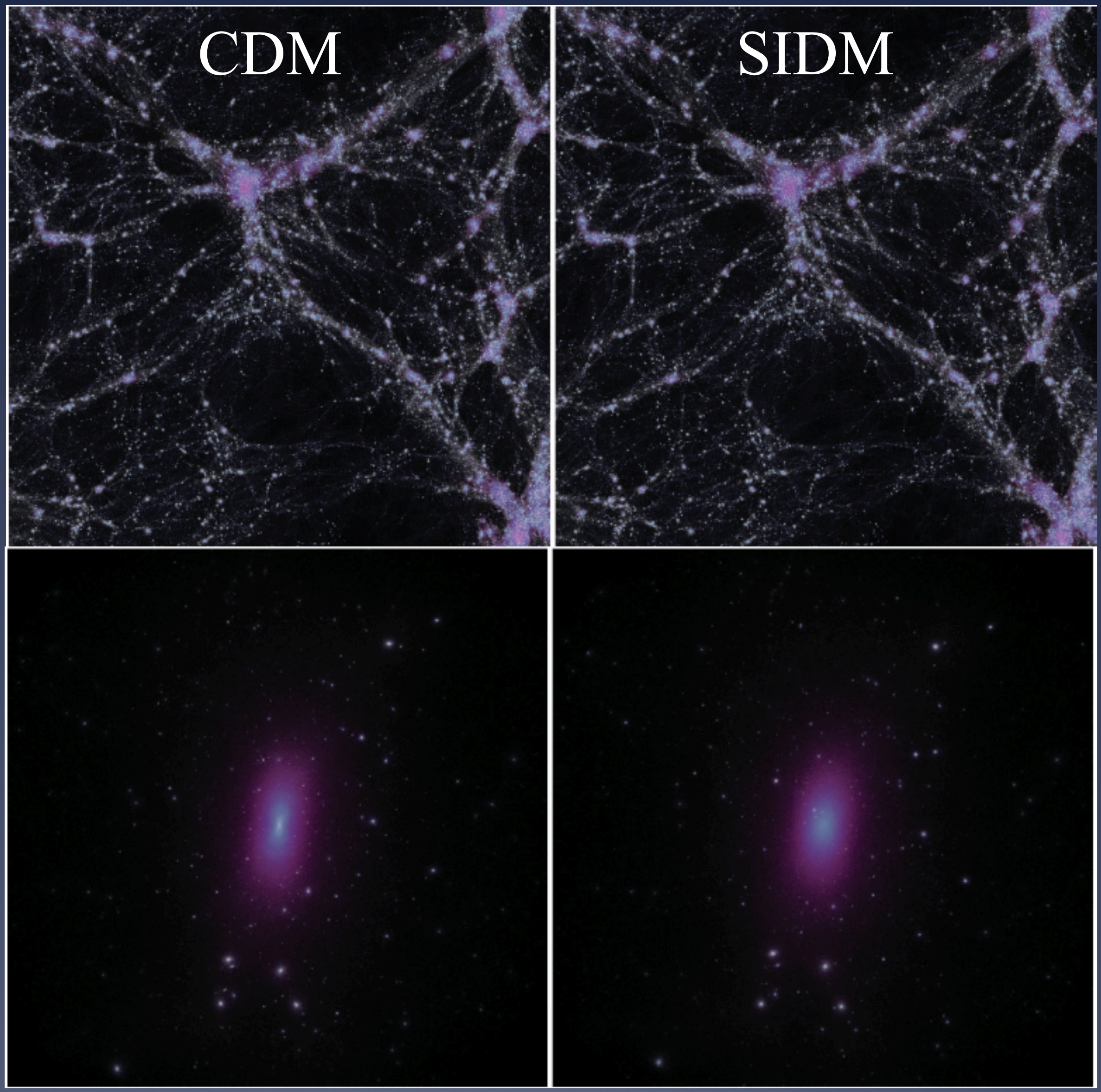
$$\rho(r) = \frac{\delta_c \rho_c}{(r/r_s)^{\beta}(1 + r/r_s)^{3-\beta}}$$



Navarro, Frenk & White 1996,1997; Moore et al. 1998; Navarro et al. 2007

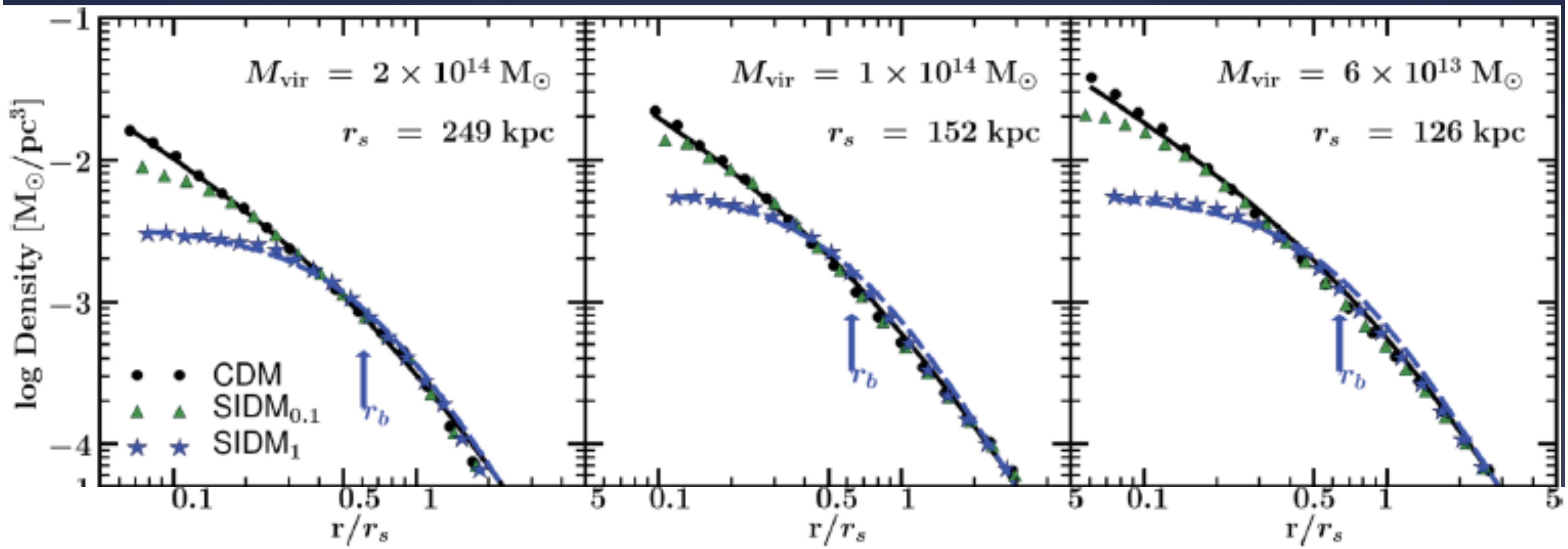
Self-Interacting dark matter

- LSS are same
- Centers of clusters are flatter and rounder



Rocha et al. 2013

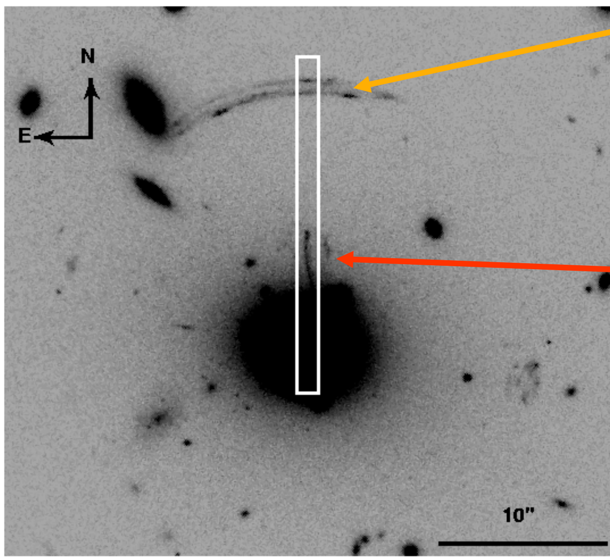
Self-Interacting dark matter



Only a limited range of (large) cross-sections has implications for clusters

Rocha et al. 2013

Methodology: critical lines and lensing constraints



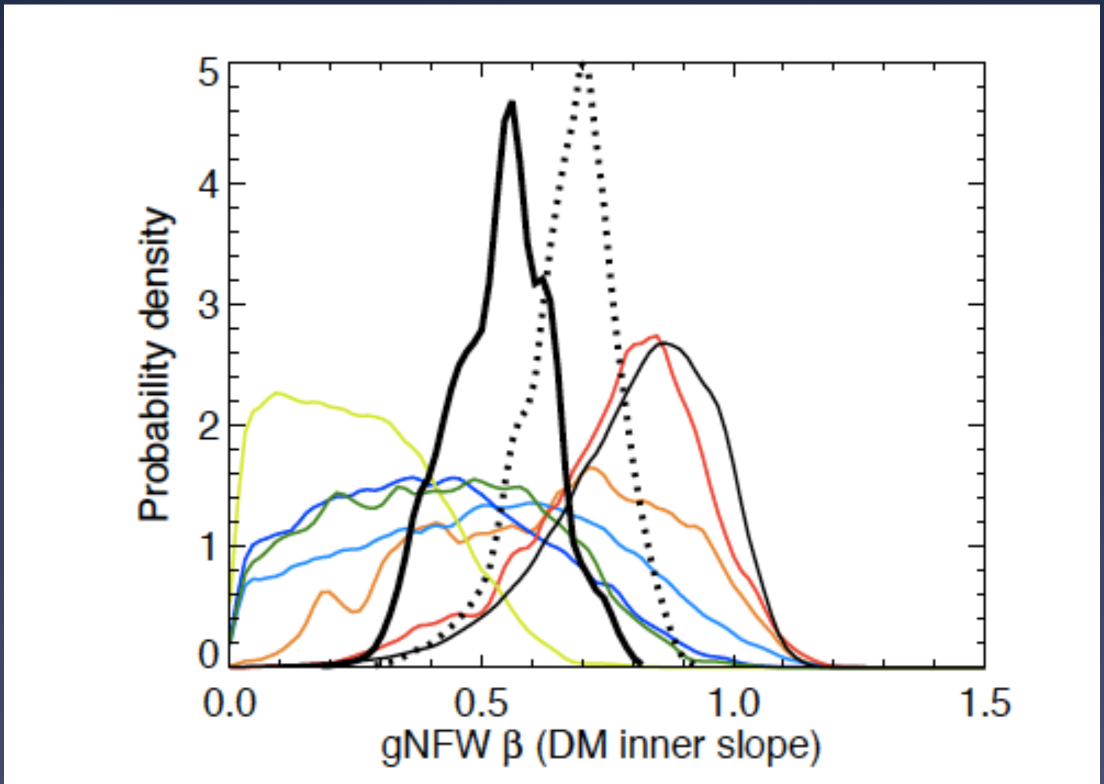
Tangential arc

Radial arc

$$1 - \frac{d}{dx}\frac{m(x)}{x} = 0 \quad 1 - \frac{m(x)}{x^2} = 0$$

Sand, Treu & Ellis 2002

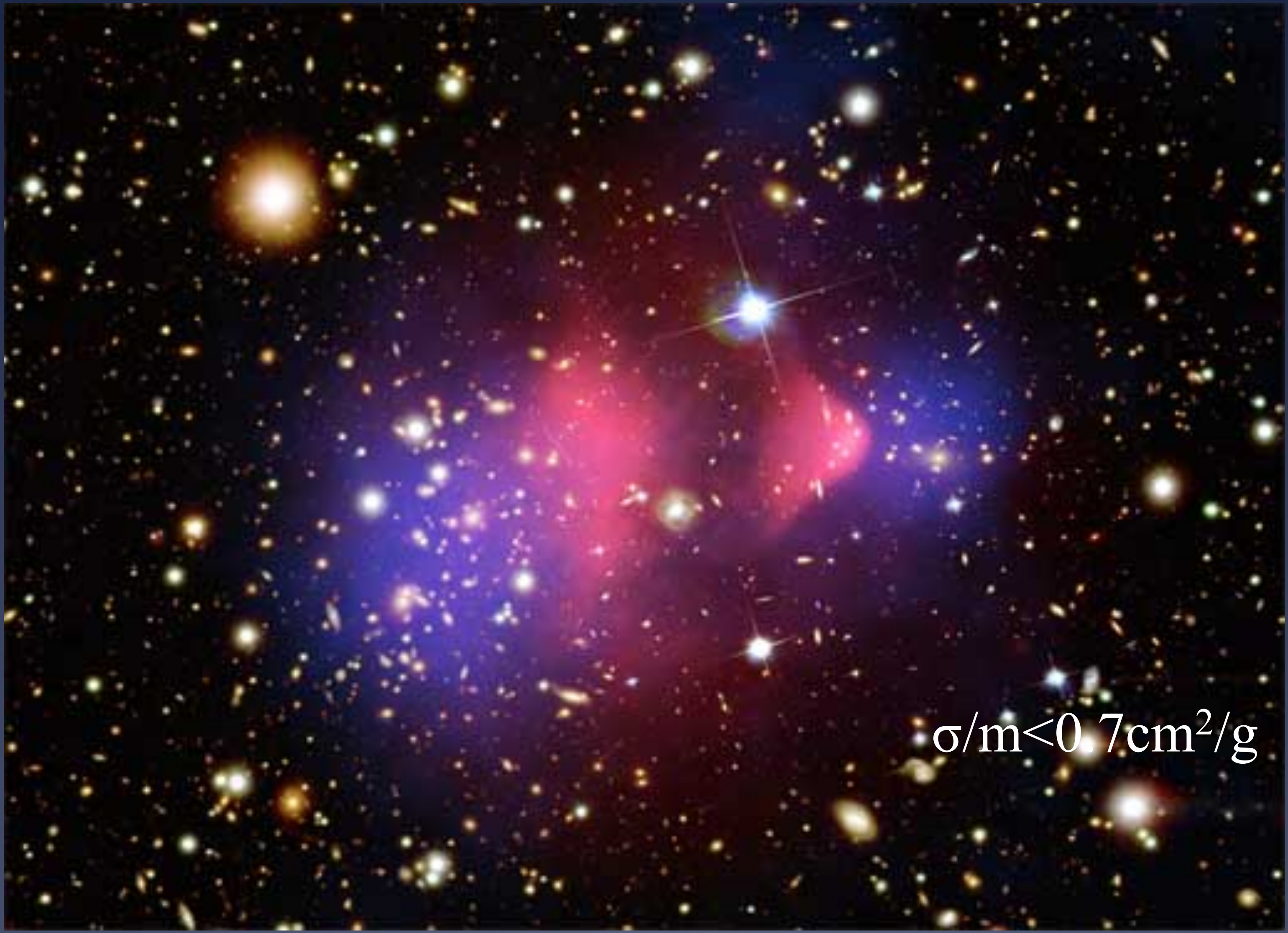
Results from lensing and dynamics work



Newman et al. 2013

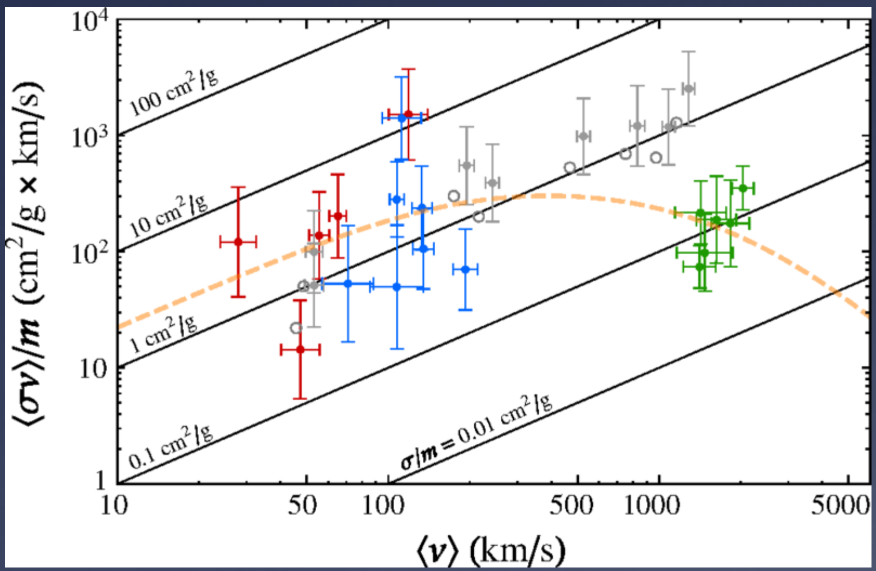
Colliding clusters

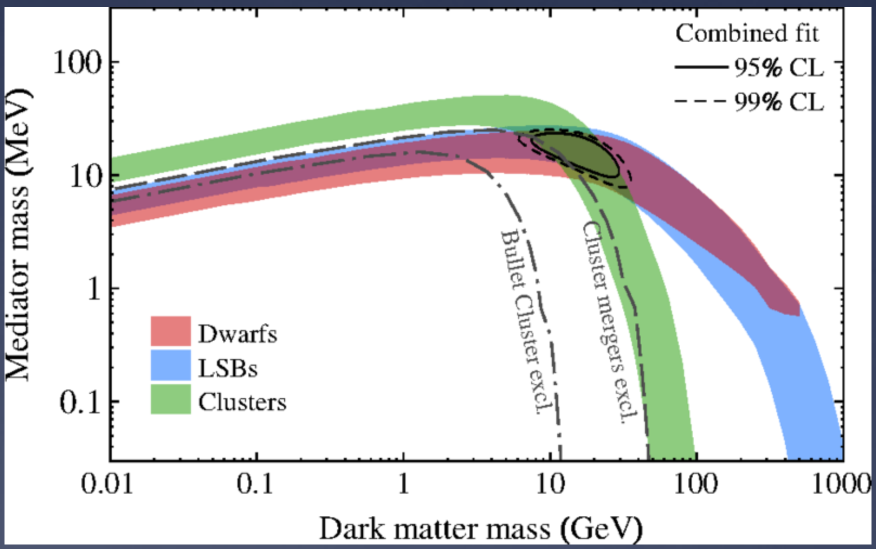
The bullet cluster



Clowe et al. 2006; Bradac et al 2006; Randall et al. 2008 see also Bradac et al. 2008

A possible explanation

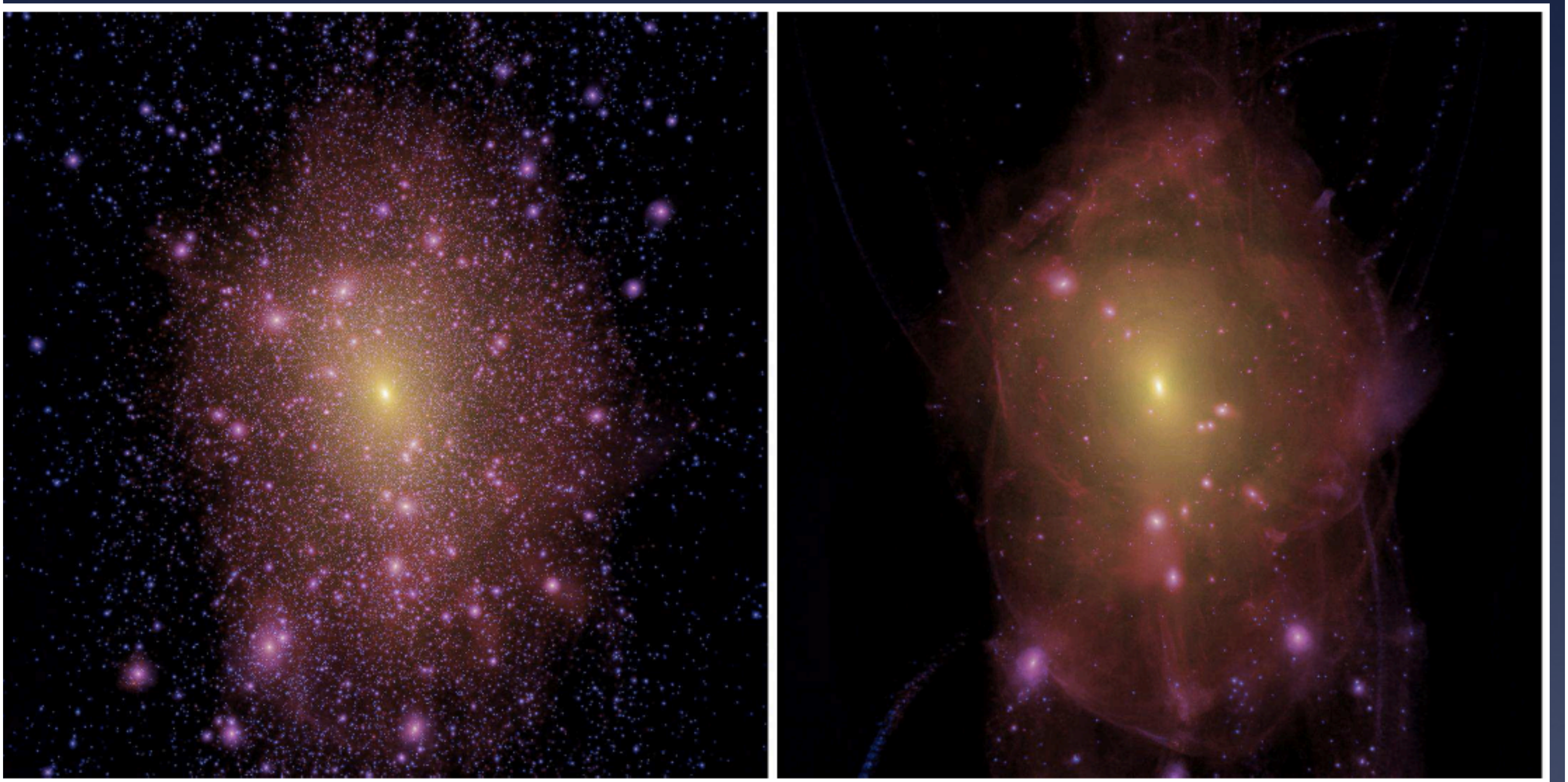




Kaplinghat et al. 2016

Satellites as a probe of dark matter free streaming length

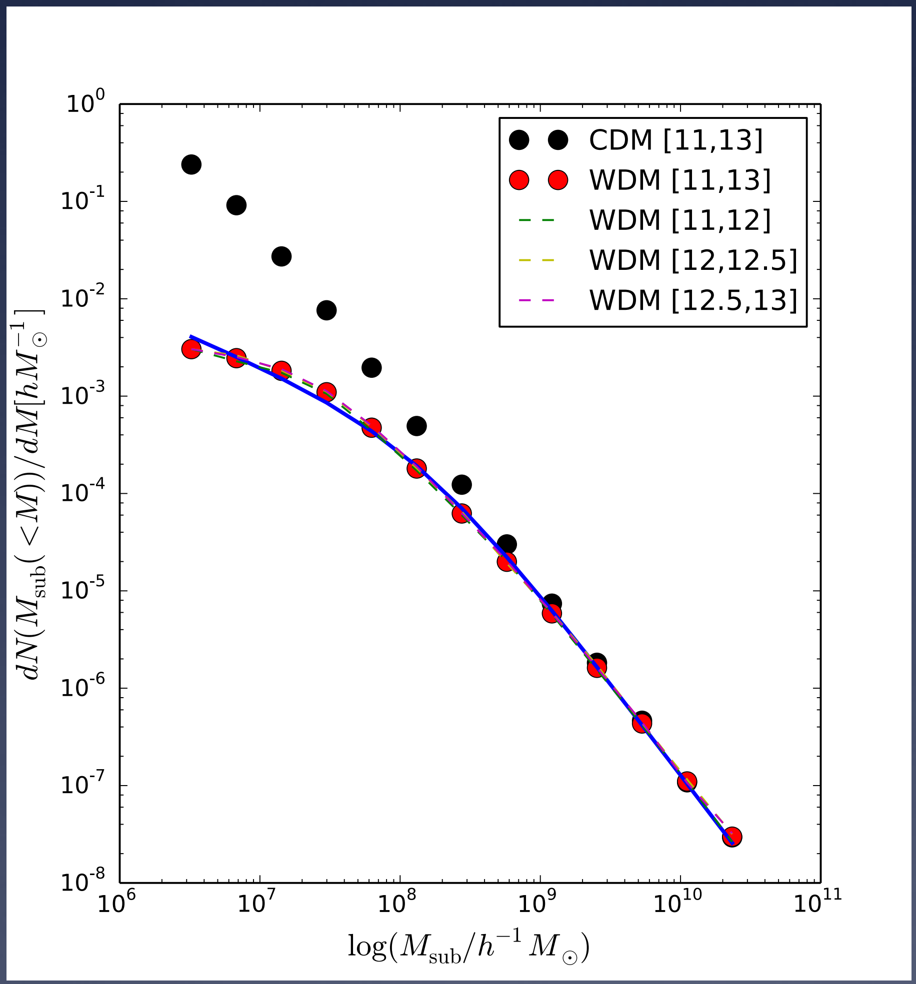
Warm Dark Matter



Free streaming ~kev scale thermal relic

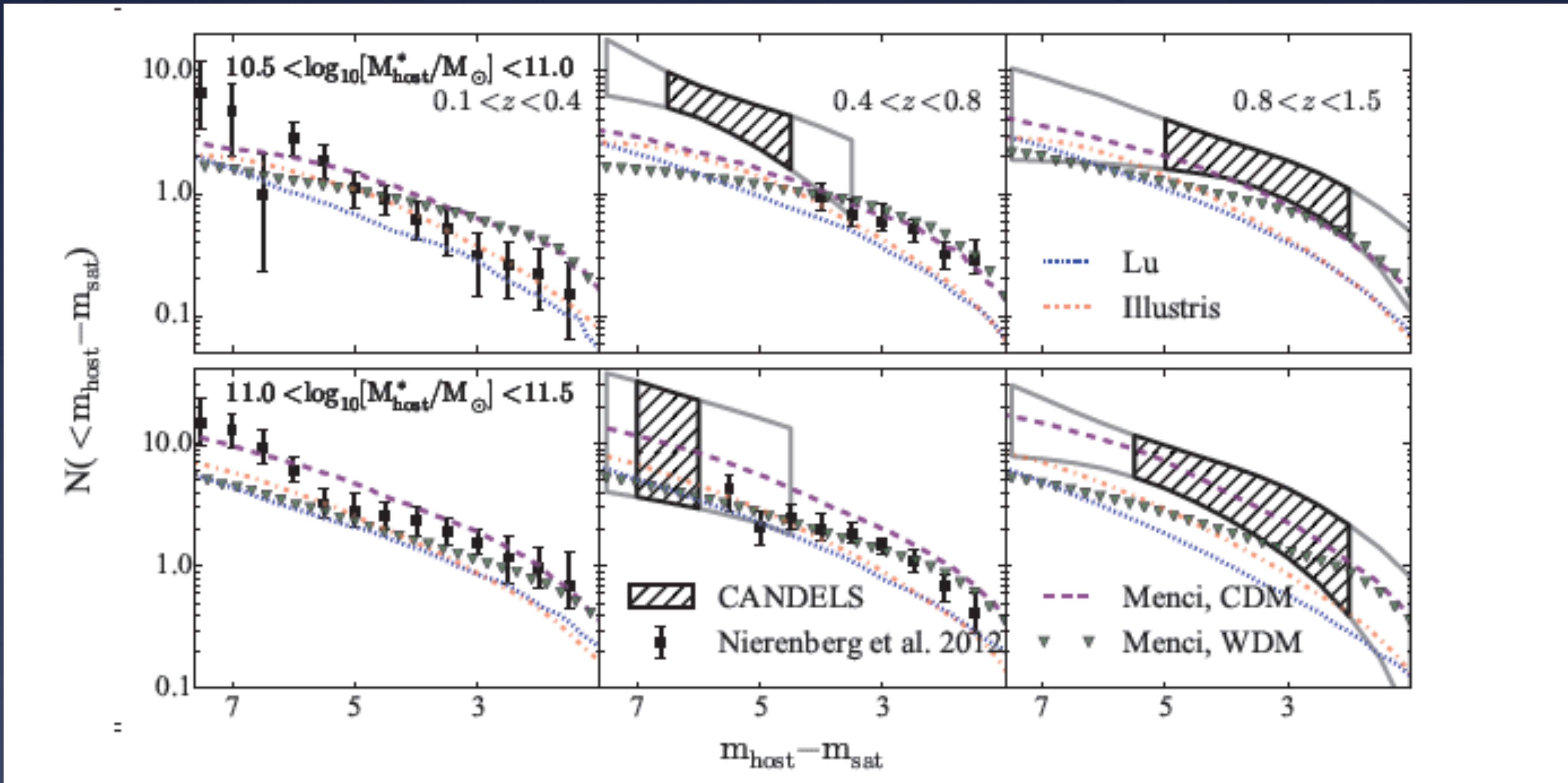
Lovell et al. 2014

Dark satellites in CDM vs WDM



Li et al. 2016; Nierenberg et al. 2013

Luminous Satellites in CDM vs WDM

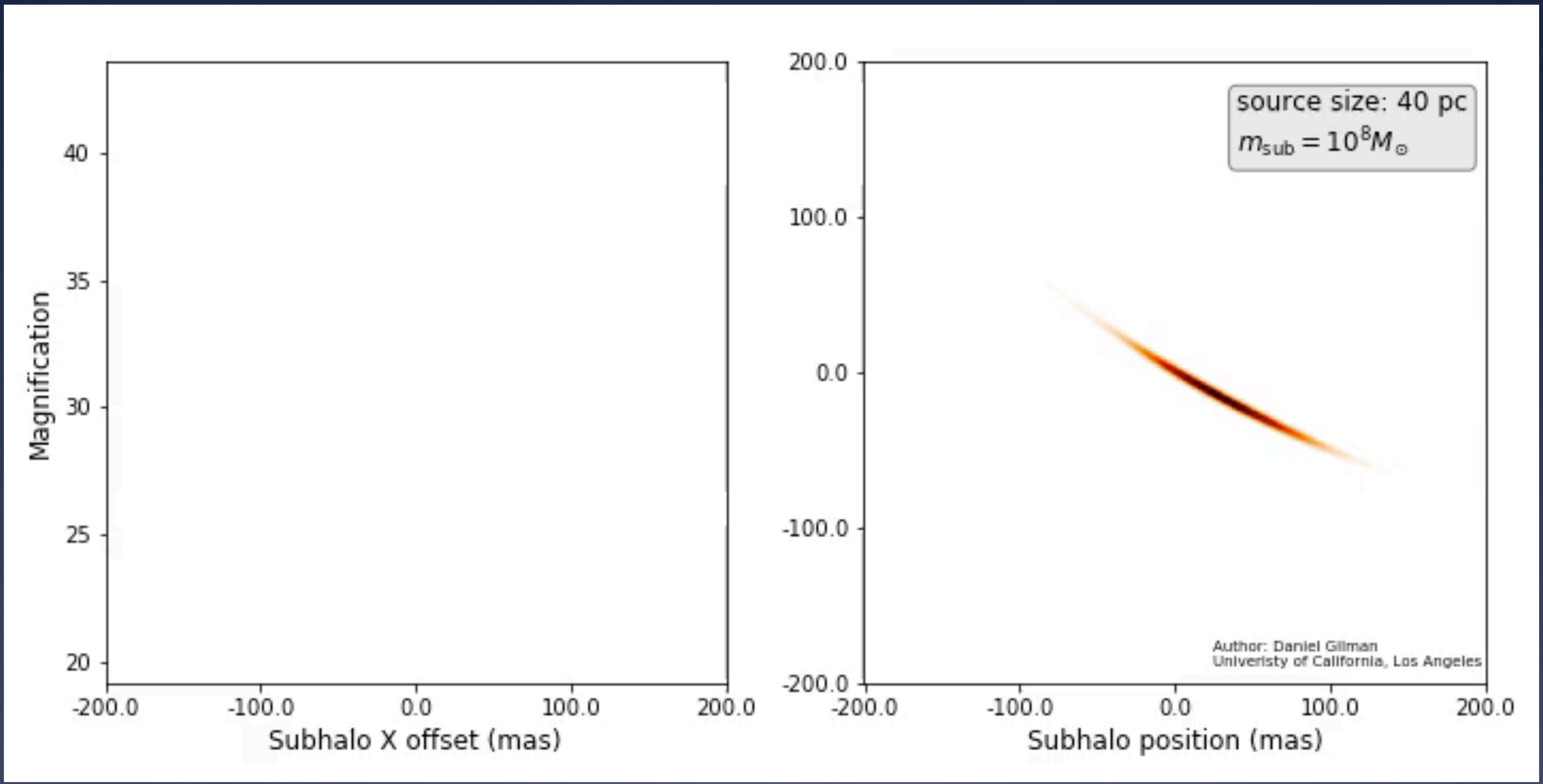


Nierenberg, Treu, Menci et al. 2016

"Missing satellites" and lensing

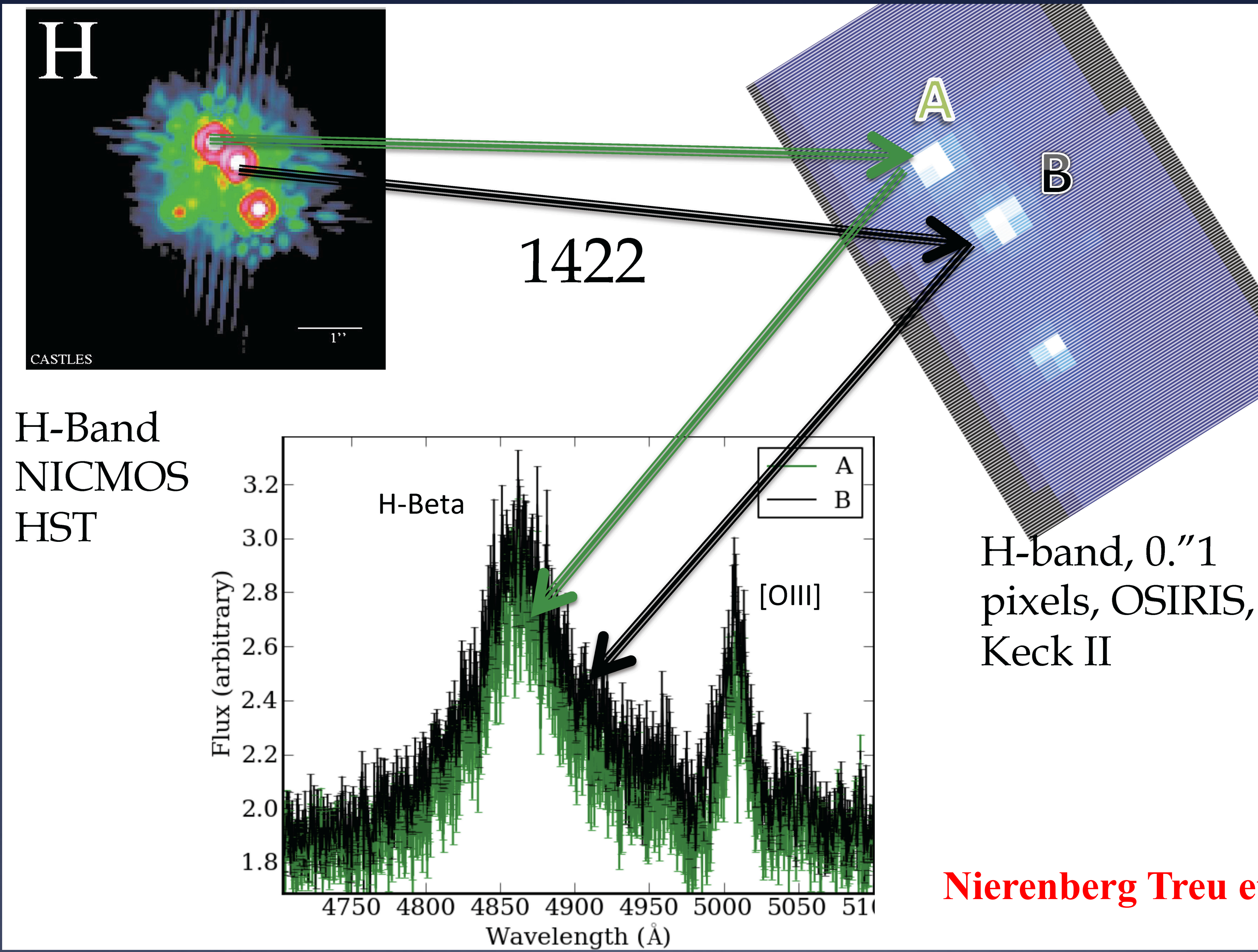
- Strong lensing can detect satellites based solely on mass!
- Satellites are detected as "anomalies" in the gravitational potential ψ and its derivatives
  - ψ'' = Flux anomalies
  - ψ' = Astrometric anomalies
  - ψ = Time-delay anomalies
- **Natural scale is a few milliarcseconds. Astrometric perturbations of 10mas are expected**

"Missing satellites" and lensing



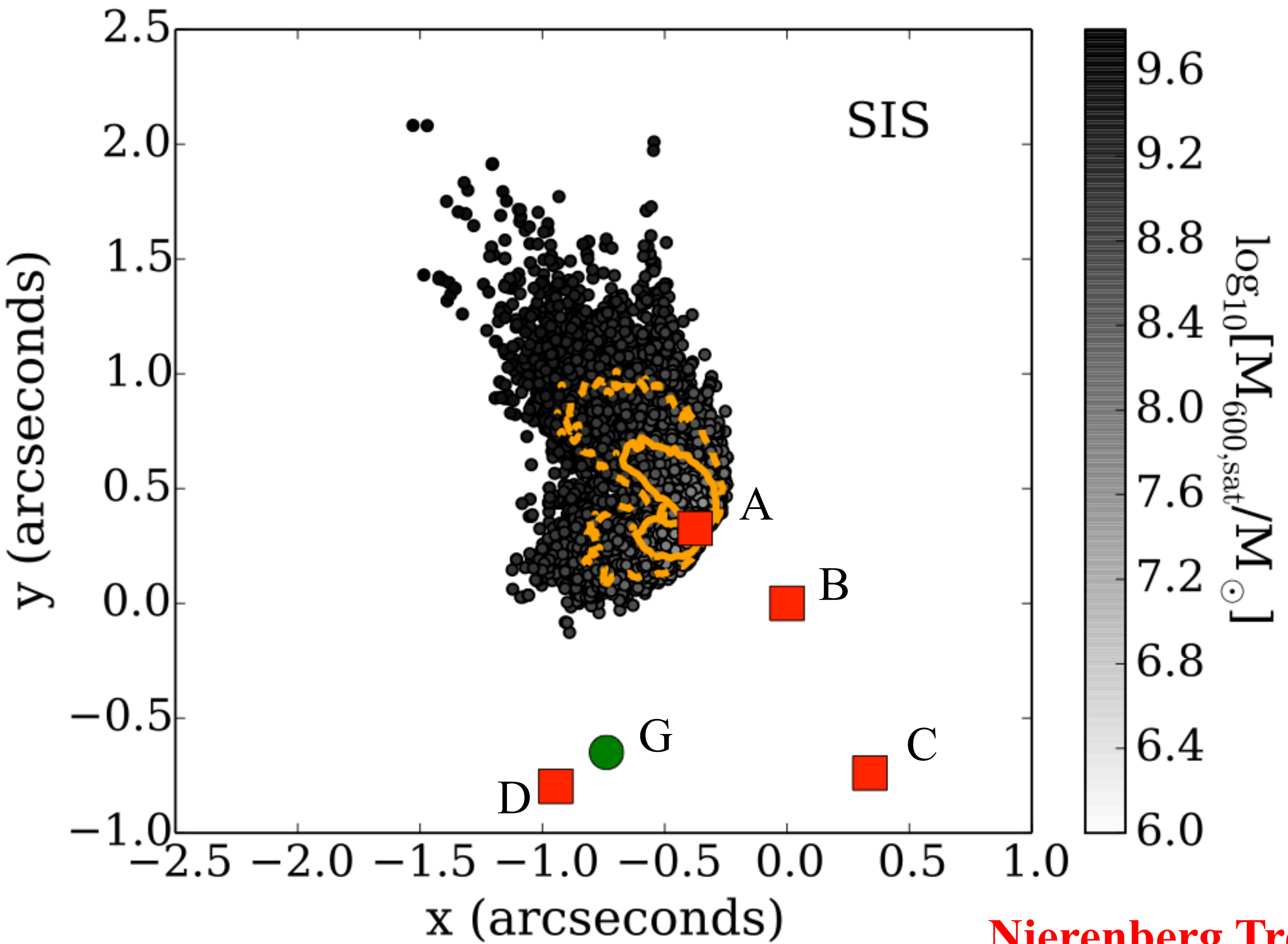
Courtesy of D.Gilman

OSIRIS detection of substructure



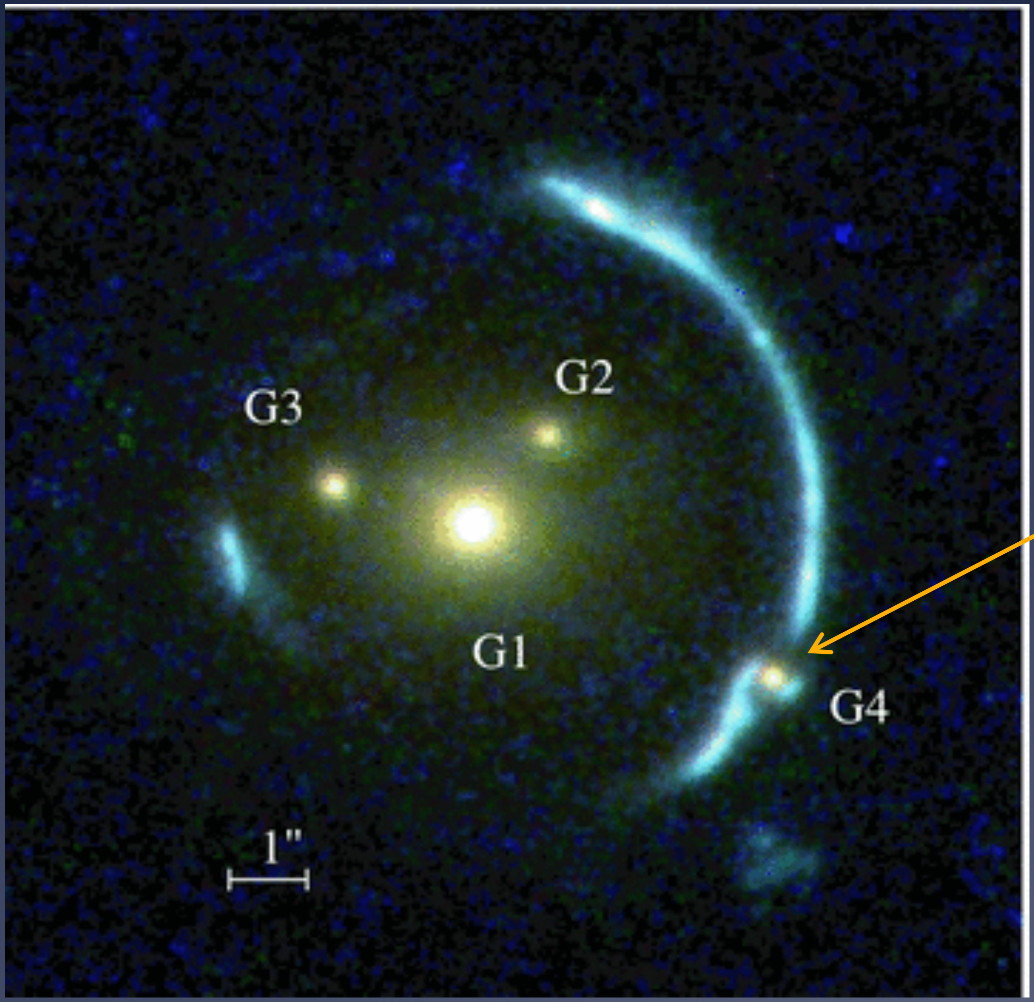
Nierenberg Treu et al 2014

OSIRIS detection of substructure



Nierenberg Treu et al 2014

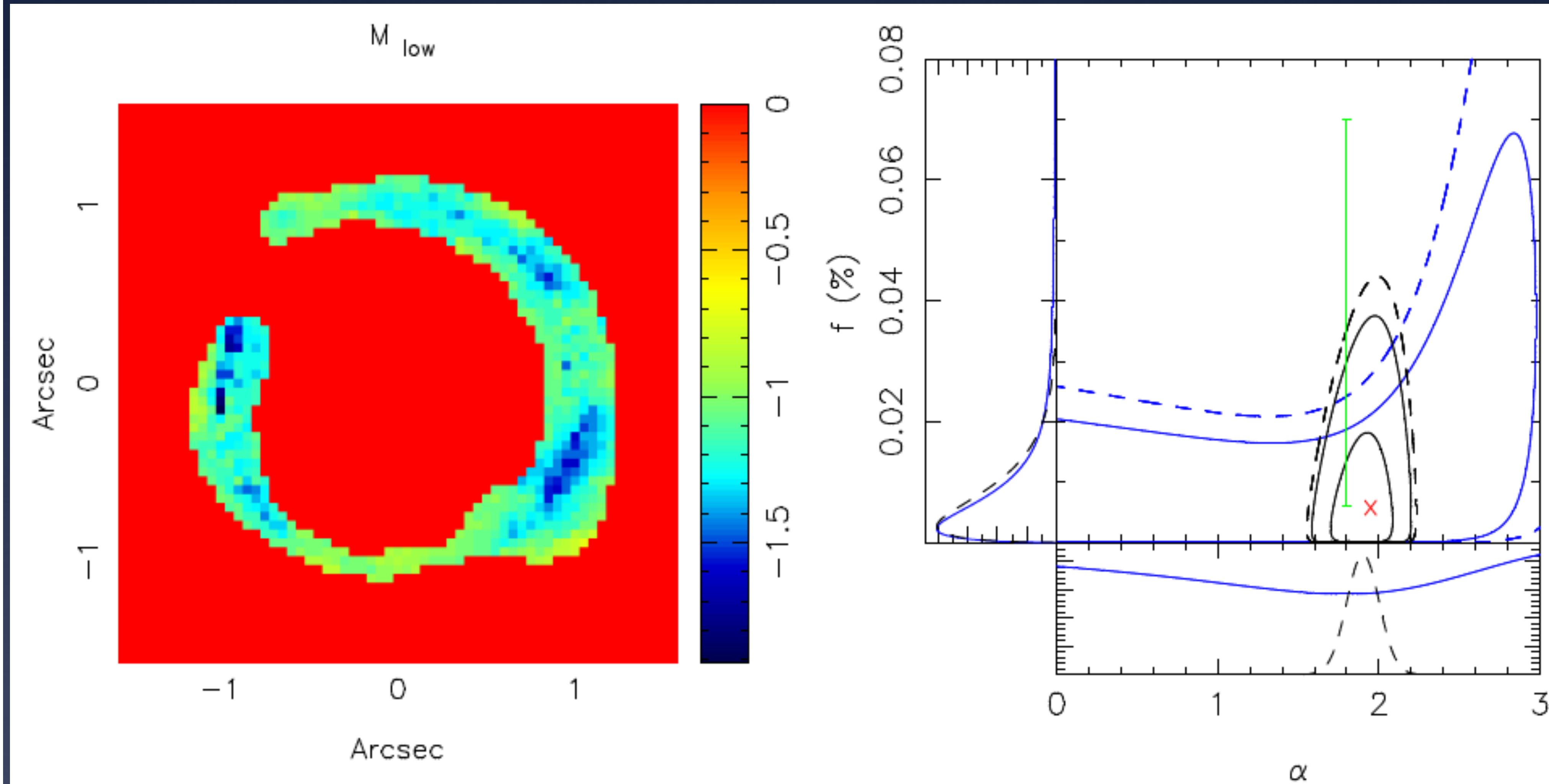
Astrometric perturbations: gravitational imaging



Mass substructure distorts extended lensed sources

Vegetti et al. 2010

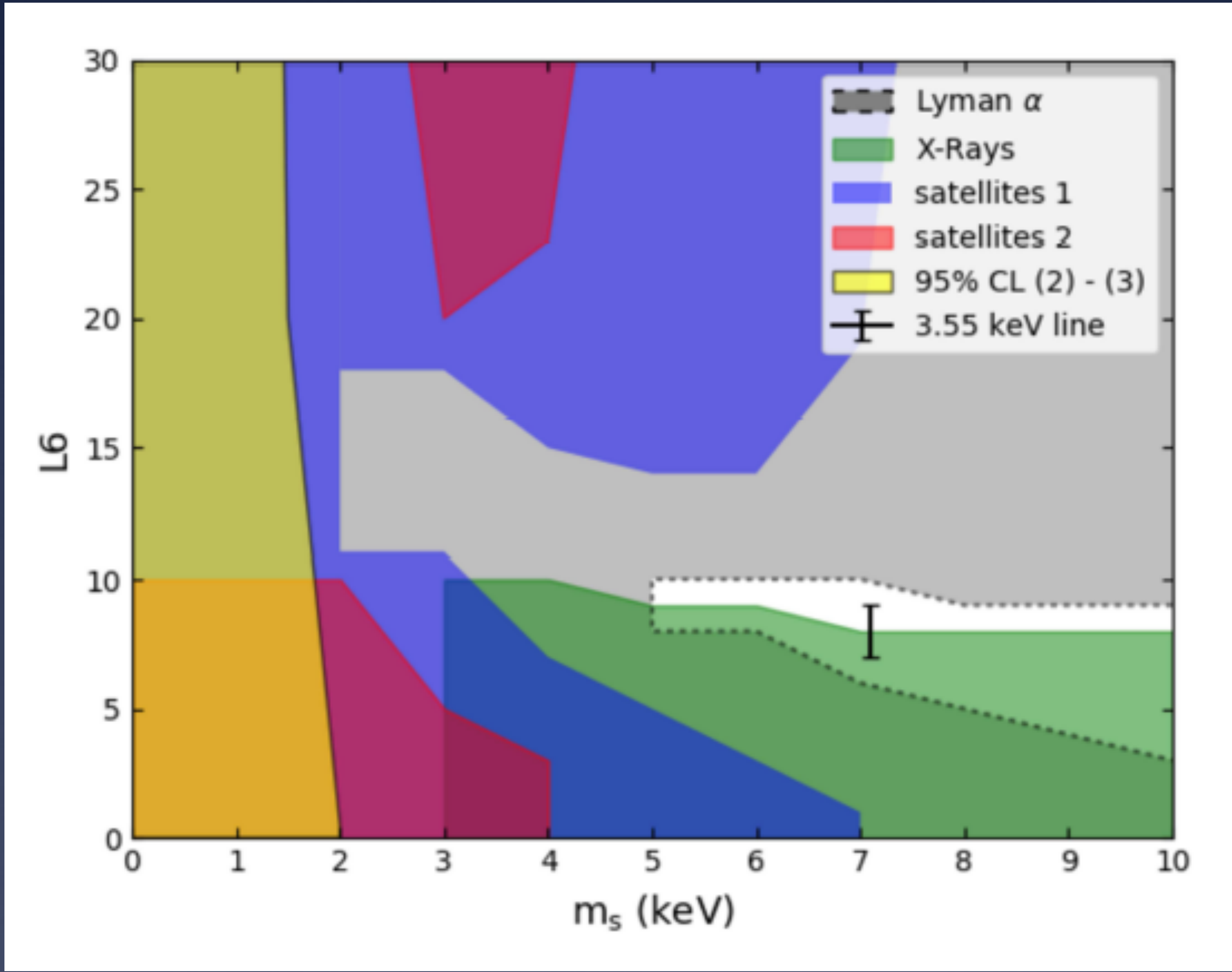
Statistics from gravitational imaging



HST/AO can detect down to 3e8 Msun

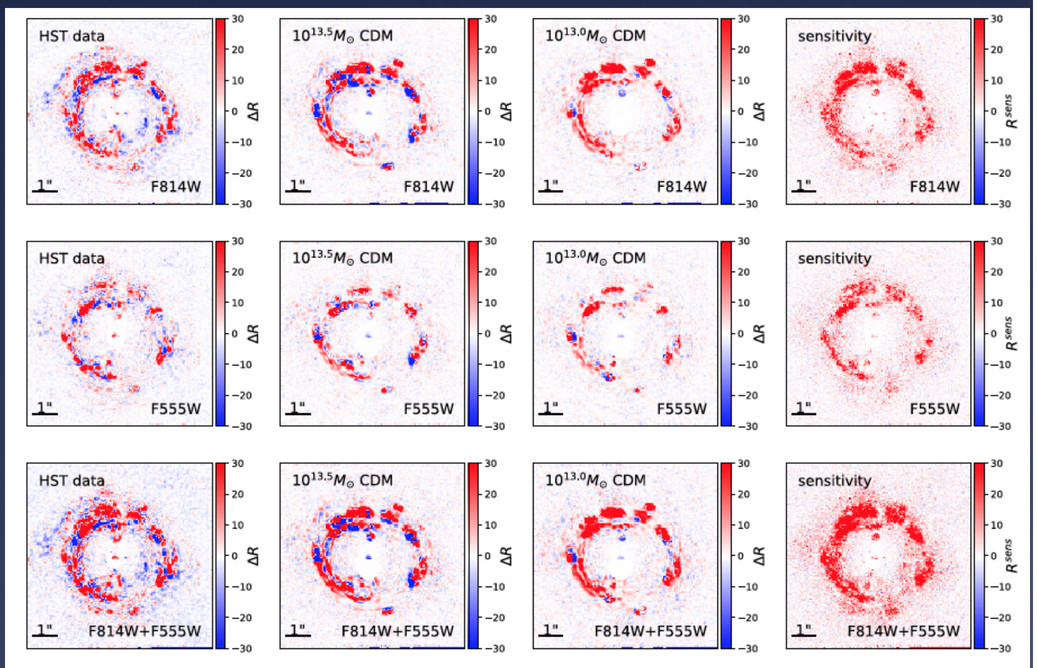
Vegetti et al 2010, 2012, 2014

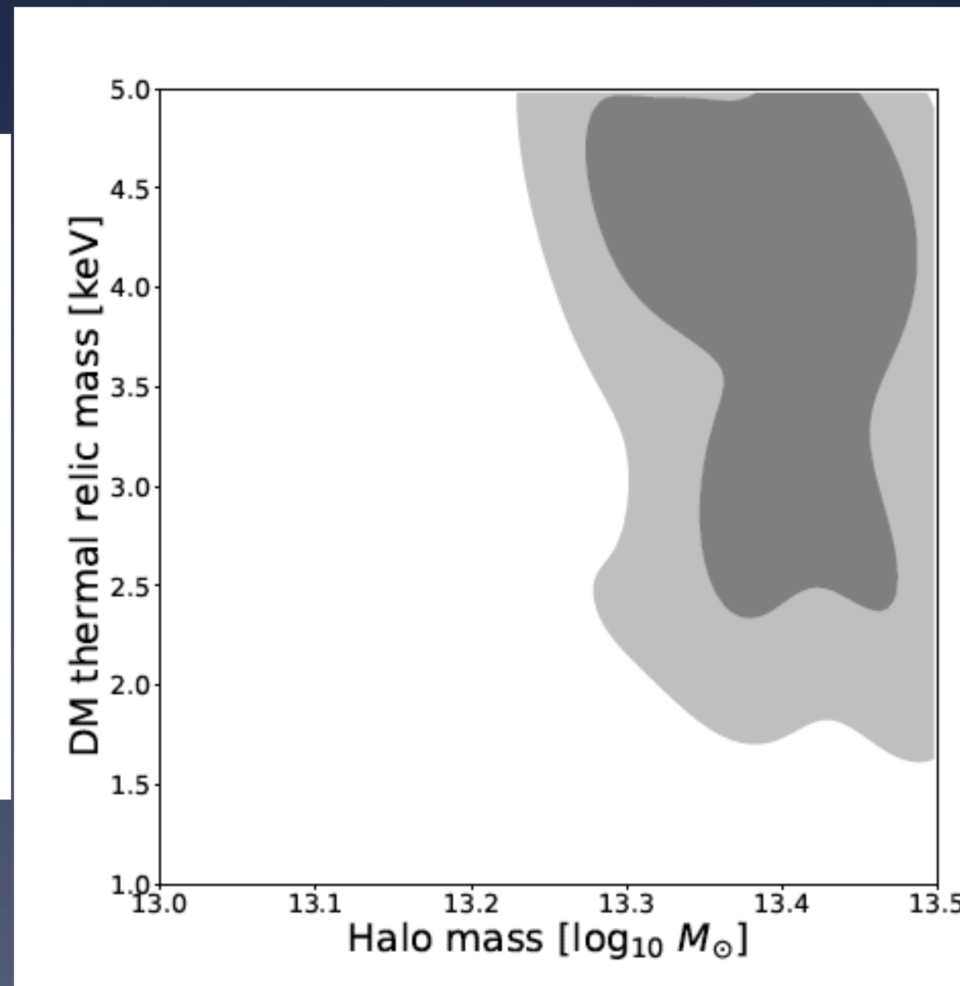
Limits on sterile neutrinos from gravitational imaging



Vegetti et al 2018

Statistical gravitational imaging



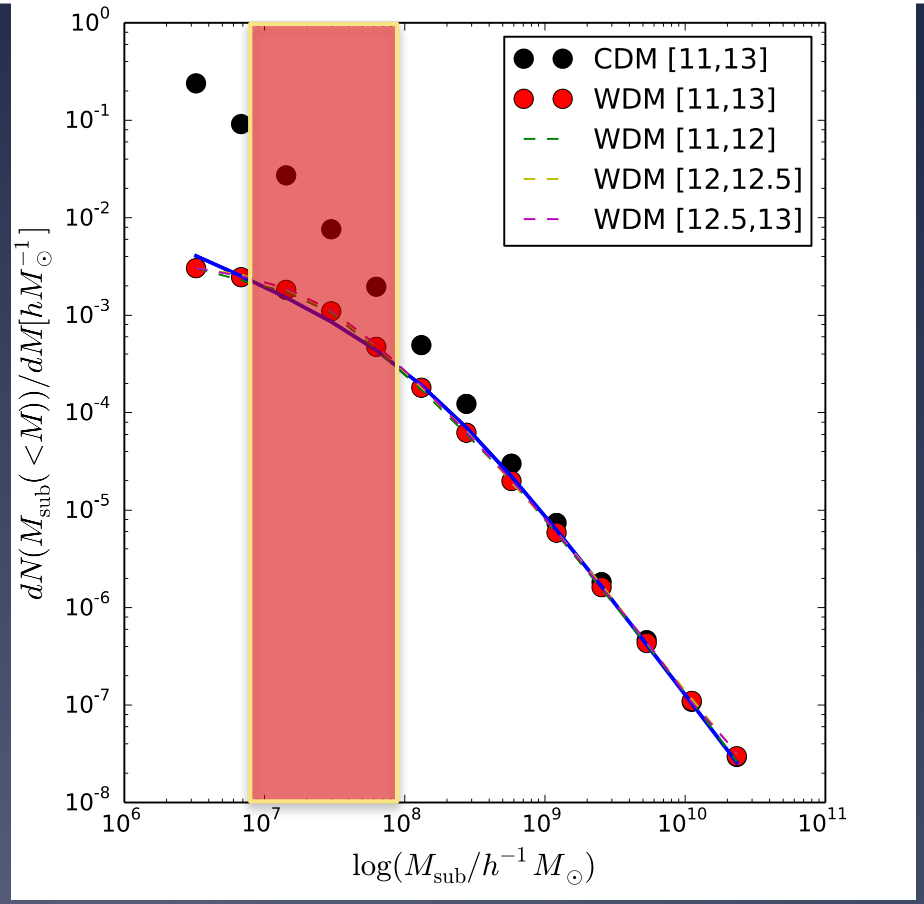


Birrer et al. 2017

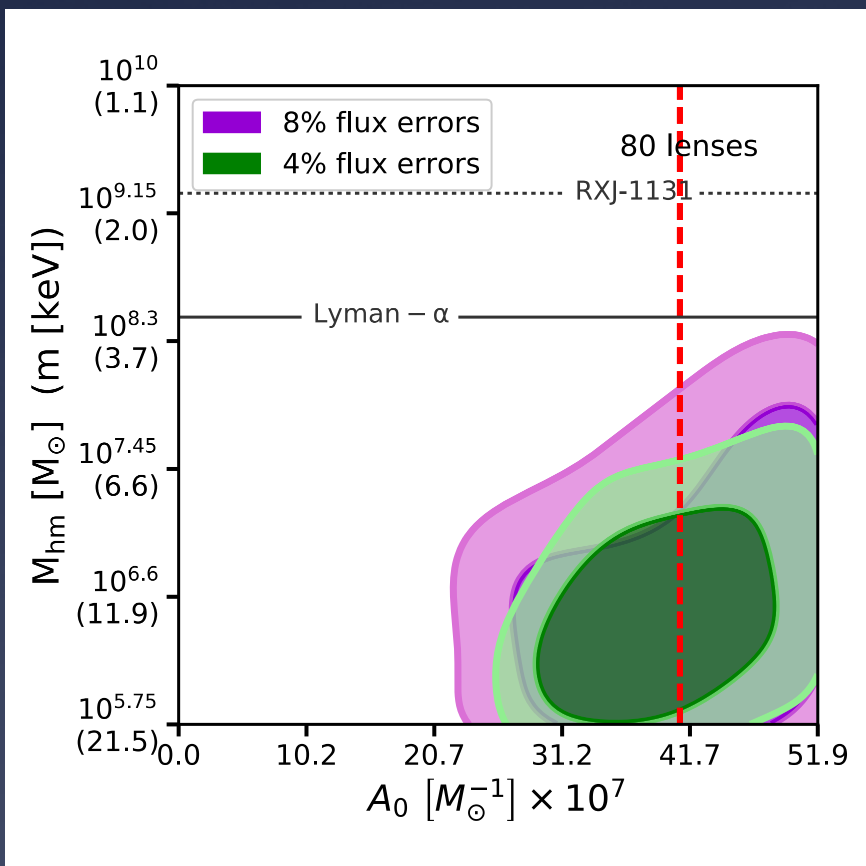
Gravitational imaging: Future Prospects

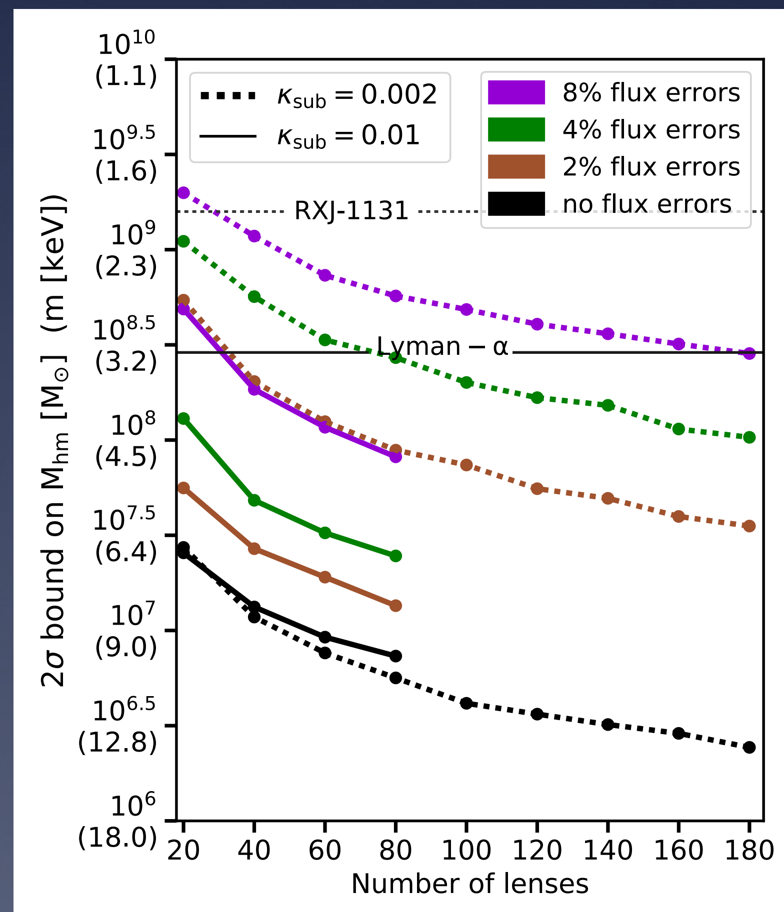
- Current limit is 10^8 msun (Vegetti et al. 2012, 2014)
- With Next Generation Adaptive Optics and then TMT we should reach 10^7 solar masses and below, where the discrepancy with theory is strongest
- LARGE SAMPLES WITH SUFFICIENT SENSITIVITY WITHIN REACH

Range accessible with Adaptive Optics



Flux ratio anomalies: Future Prospects





Gilman, Birrer, Treu et al. 2018

Flux ratio anomalies: Future Prospects

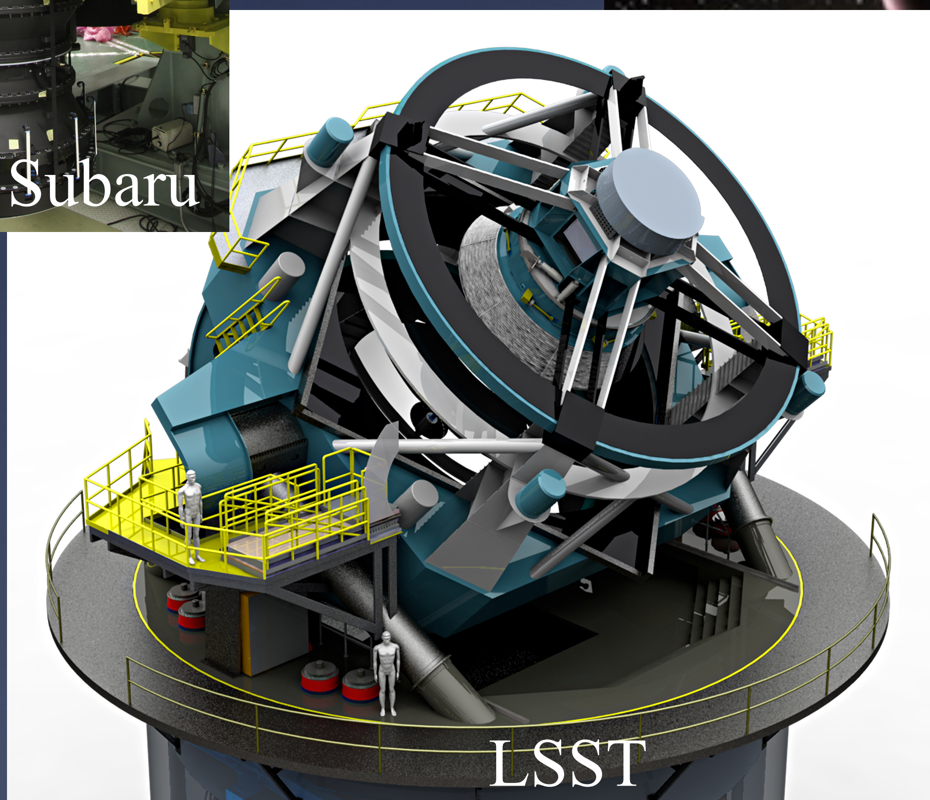
- Narrow line flux ratio anomalies can currently be studied for 20 systems
- Future surveys will discover thousands of systems
- NGAO/TMT will provide spectroscopic follow-up and emission line flux ratios

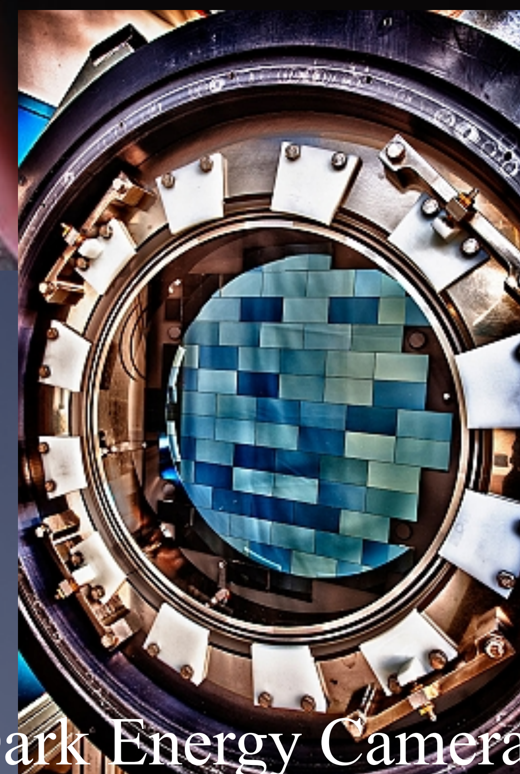
100 quasar lenses with Flux ratios. How do we do this in practice?

Roadmap. I. Find Lenses

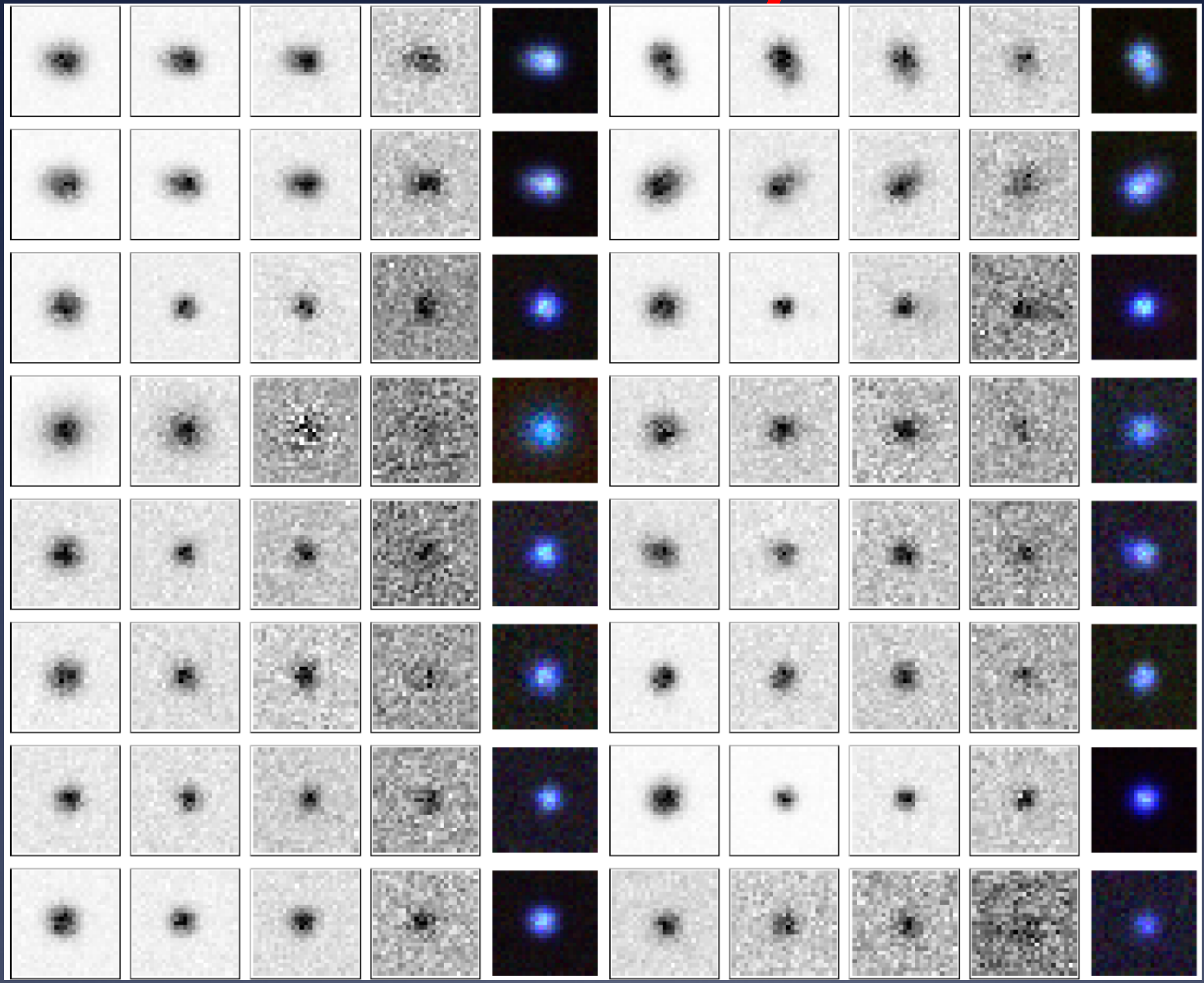
- Carry out large imaging survey.
  - QSO forecasts by Oguri & Marshall (2010)
    - DES (~1000 lensed QSOs, including 150 quads)
    - LSST (~8000 lensed QSOs, including 1000 quads)
    - Euclid/WFIRST many more!
- Find lenses:
  - Different strategies for lensed QSOs and galaxies (Marshall+, Gavazzi+,Kubo+,Belokurov+,Kochanek+,Faure+,Pawase+,Agnello+)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

In large imaging surveys



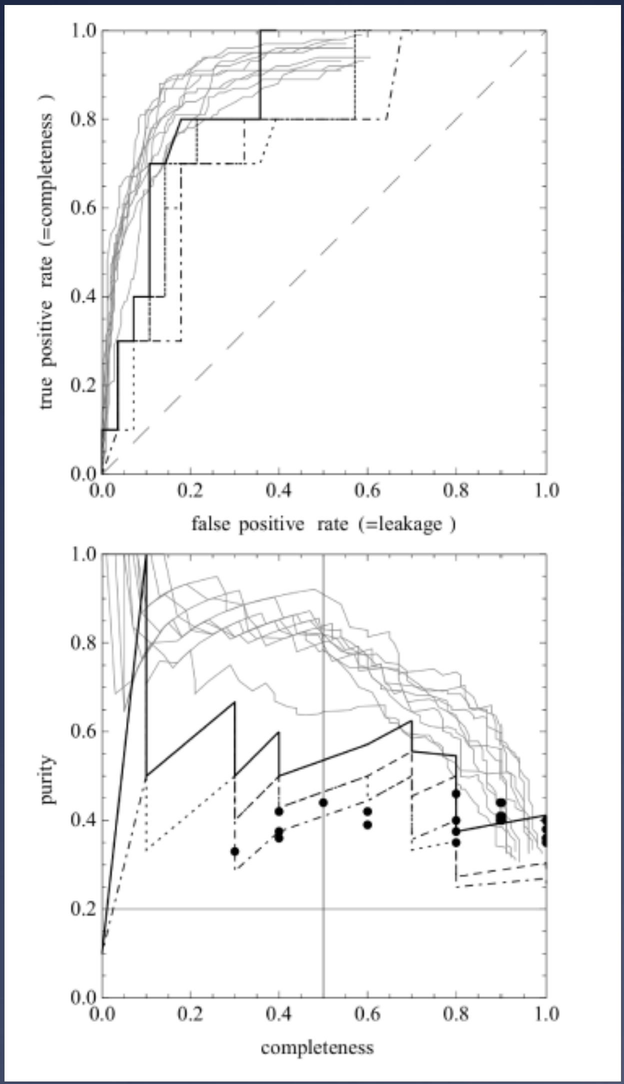


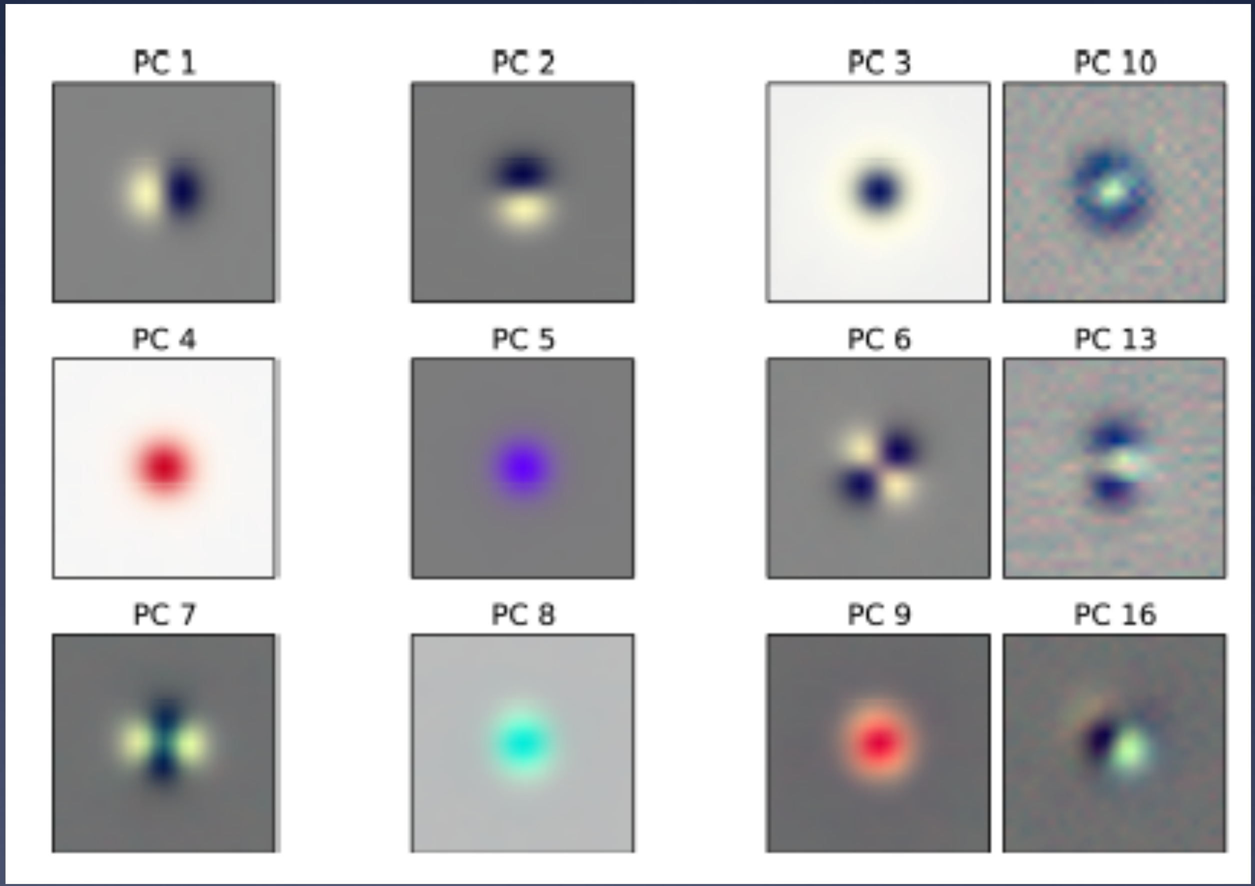
Needle in a haystack!



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

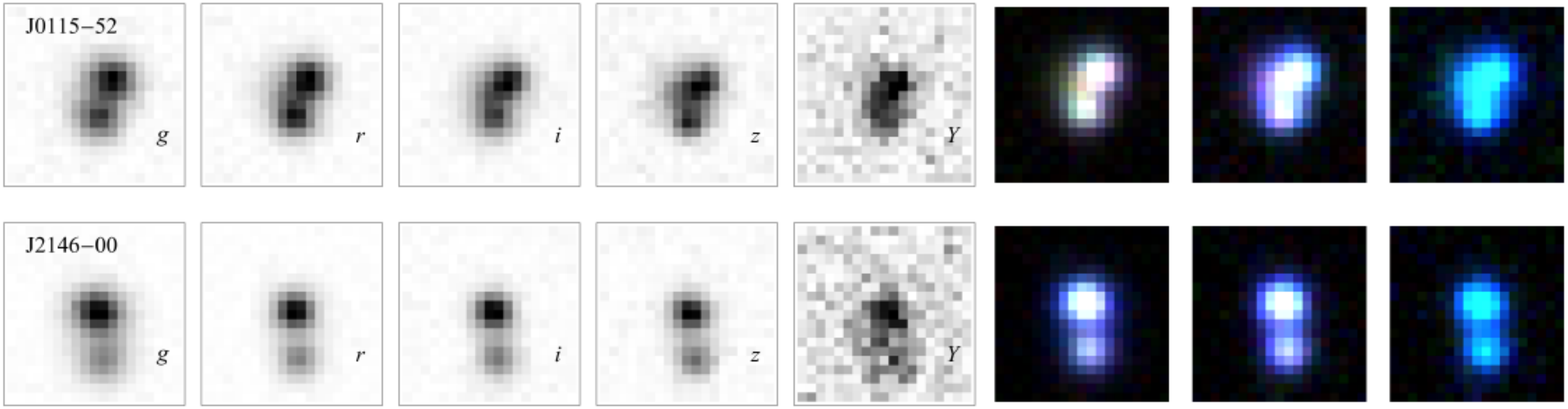
We can find them using machine learning techniques

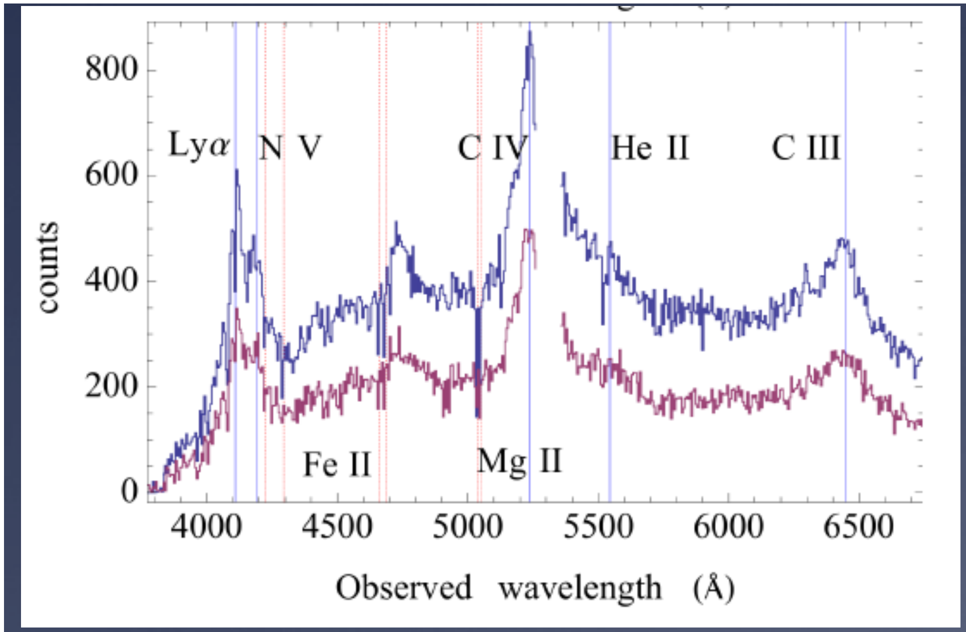




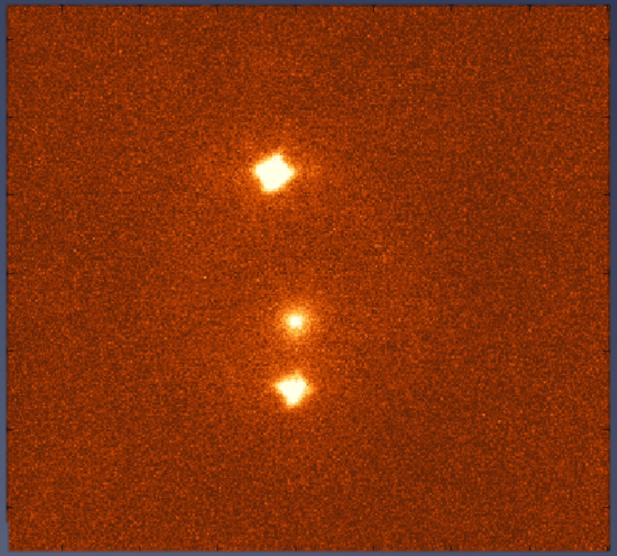
Agnello et al. 2015a; Williams et al. 2016

And here they are!



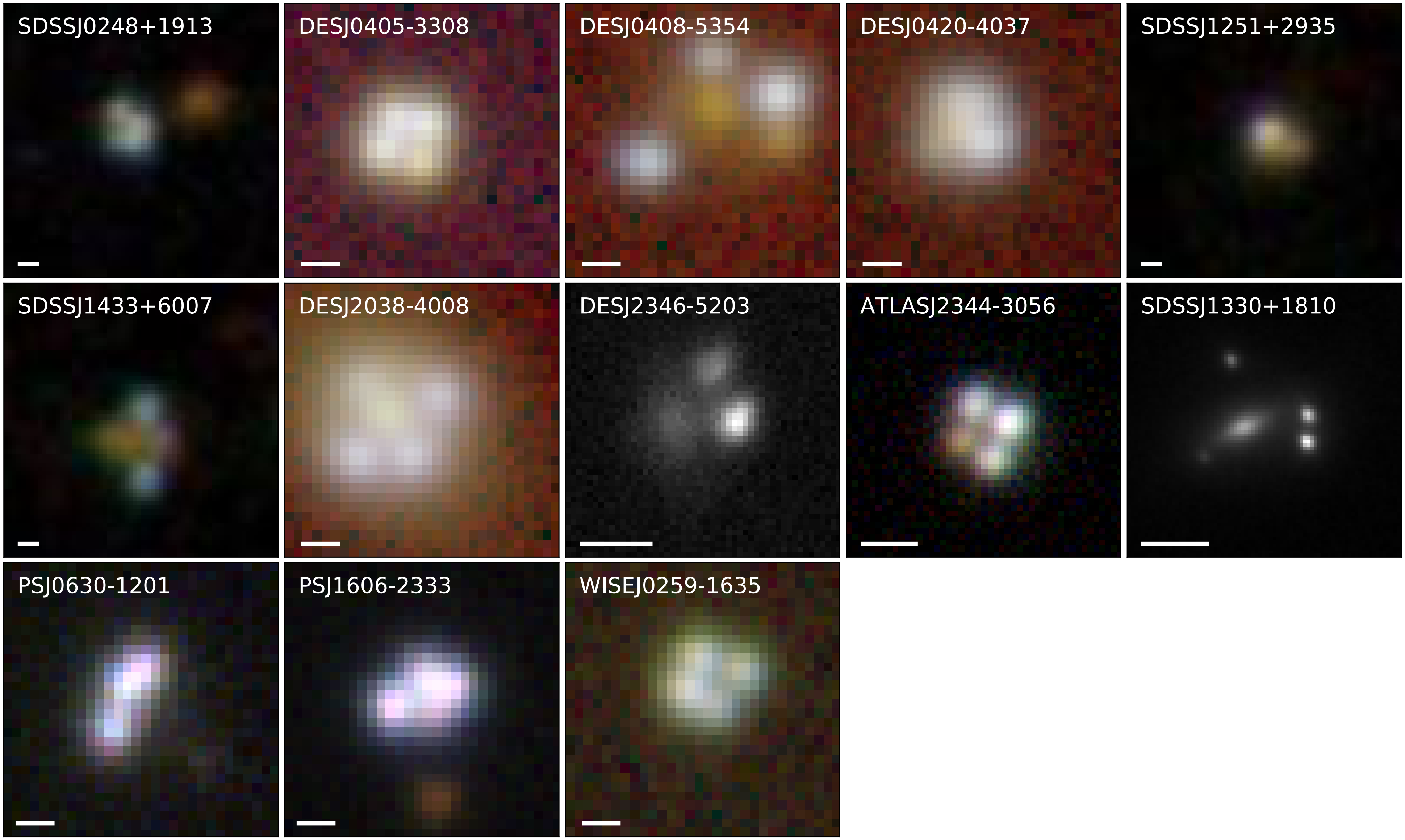


Agnello et al. 2015b

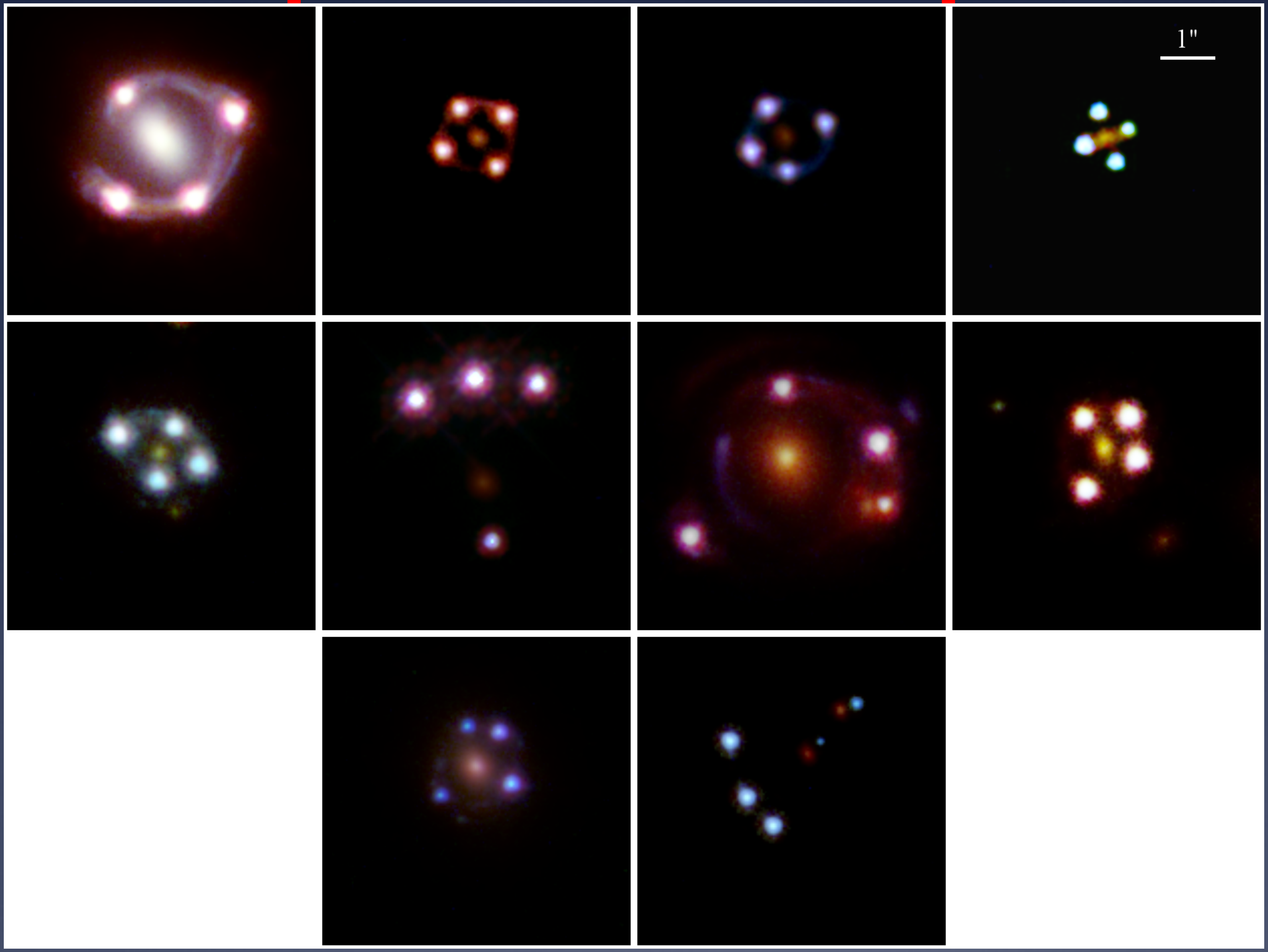


strides.astro.ucla.edu

Here are some more!



As viewed with the Hubble Space Telescope

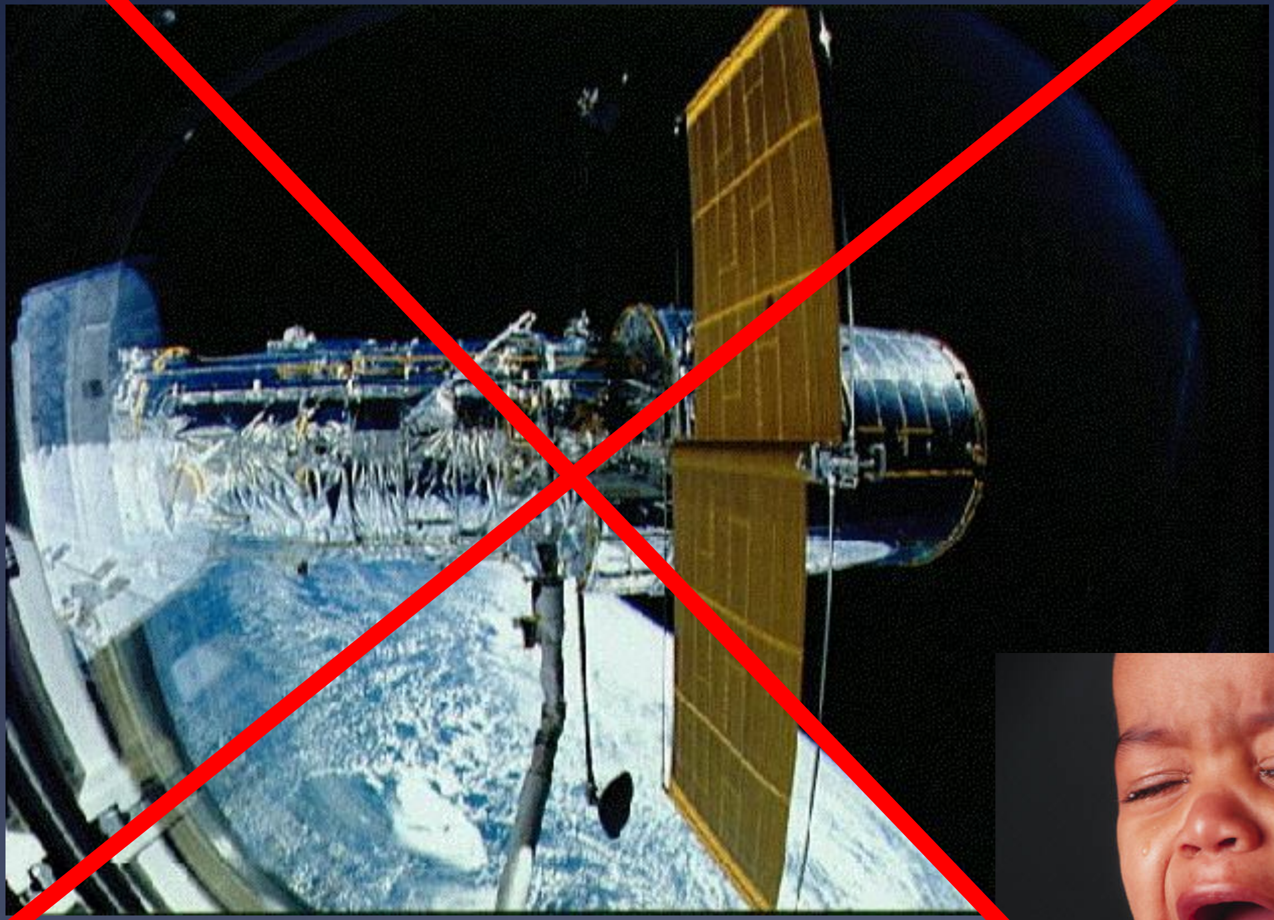


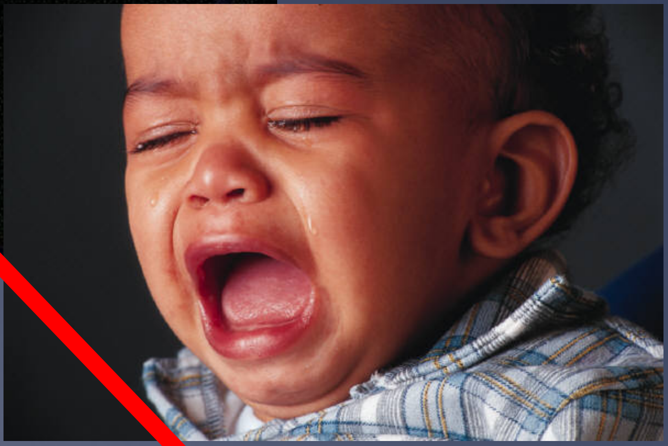
Roadmap. II. Follow-up

- High resolution imaging: space or Adaptive Optics
- Deflector mass modeling: redshifts and stellar velocity dispersions (Keck/TMT)

High resolution information. Where will it come from?

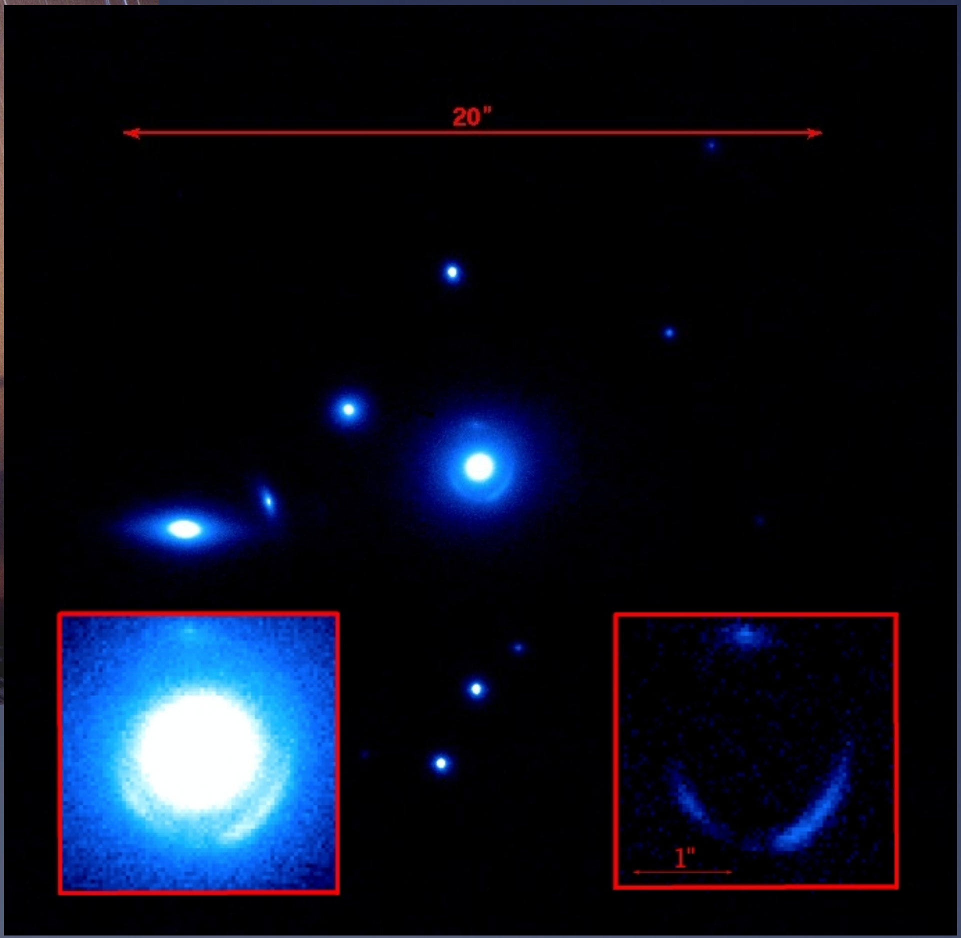
Imaging landscape after HST





Imaging landscape after 2018: Adaptive Optics

2012: 0.3-0.4 strehl at 2micron; improvements under way: PSF/TT

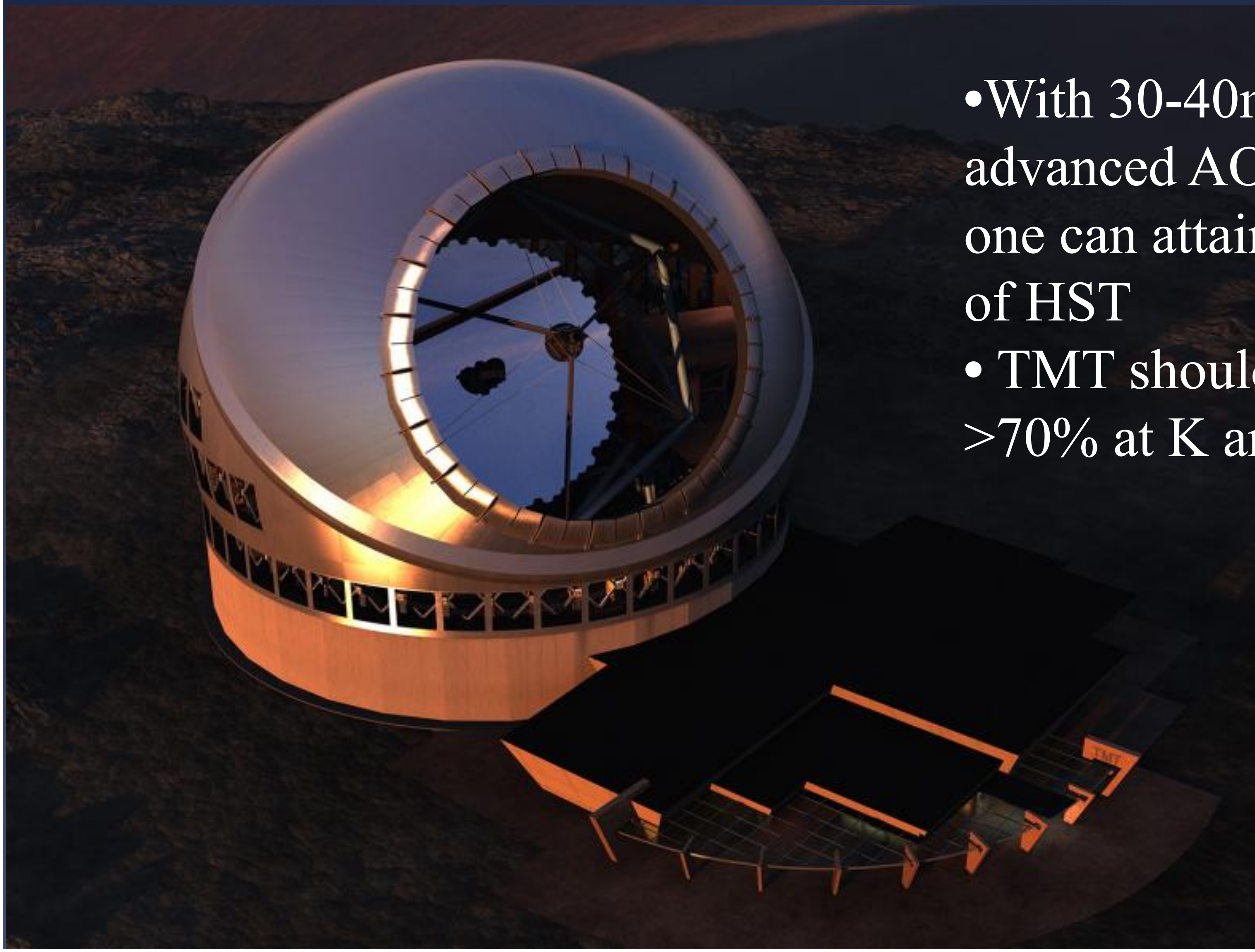


Marshall et al. 2007; Fassnacht

Imaging landscape after 2020: Next Generation Adaptive Optics

- For strong lensing at galaxy scales interested in high-strehl small fov:
    - Keck-NGAO: 90% strehl at K, 60% at J (not funded yet)
    - Gemini,VLT, Subaru etc are all developing AO+
- Resources spread between large fov and high strehl

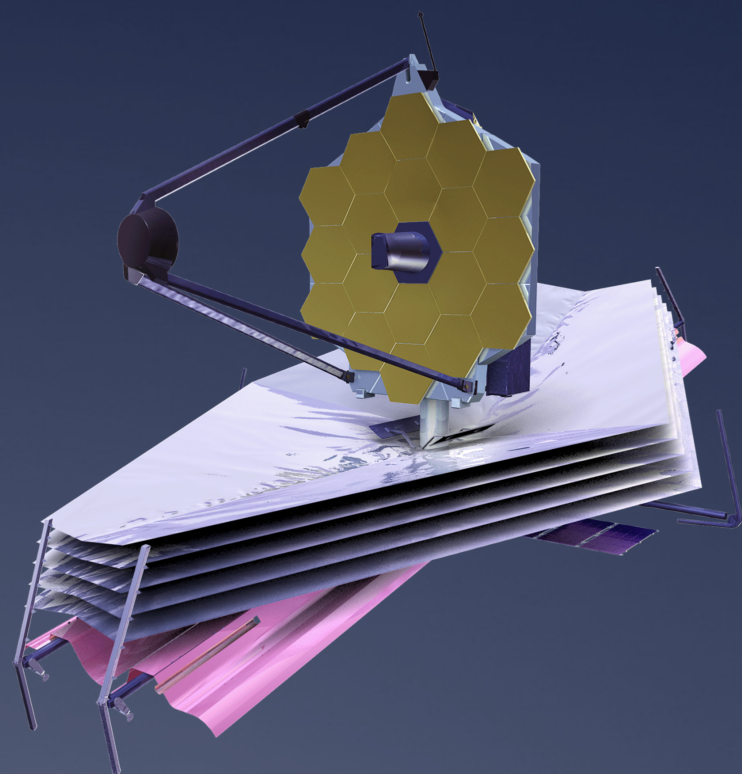
Imaging landscape after 2025: Extremely Large Telescopes



- With 30-40m apertures and advanced AO, in principle one can attain 10x resolution of HST
- TMT should have strehl >70% at K and >30% at Y

Imaging landscape after 2019: 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



The bill

- 100 gravitationally lensed AGN with deep images of host galaxies at 100mas resolution or better; ~200-300 orbits with HST; 4 nights with Keck NGAO; very fast with TMT/ELT
    - ALMA?
- Redshifts of source and deflector: ~2 weeks of Keck; a few days of TMT / ELT. Easy with ALMA.

Conclusions

- Strong gravitational lensing is a cost-effective tool to study the composition of the universe:
- Lensing is probing the self-interaction cross sections that are relevant for astronomy. Hints of self-interaction are present, but are difficult to disentangle from baryonic effects
- 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

The end