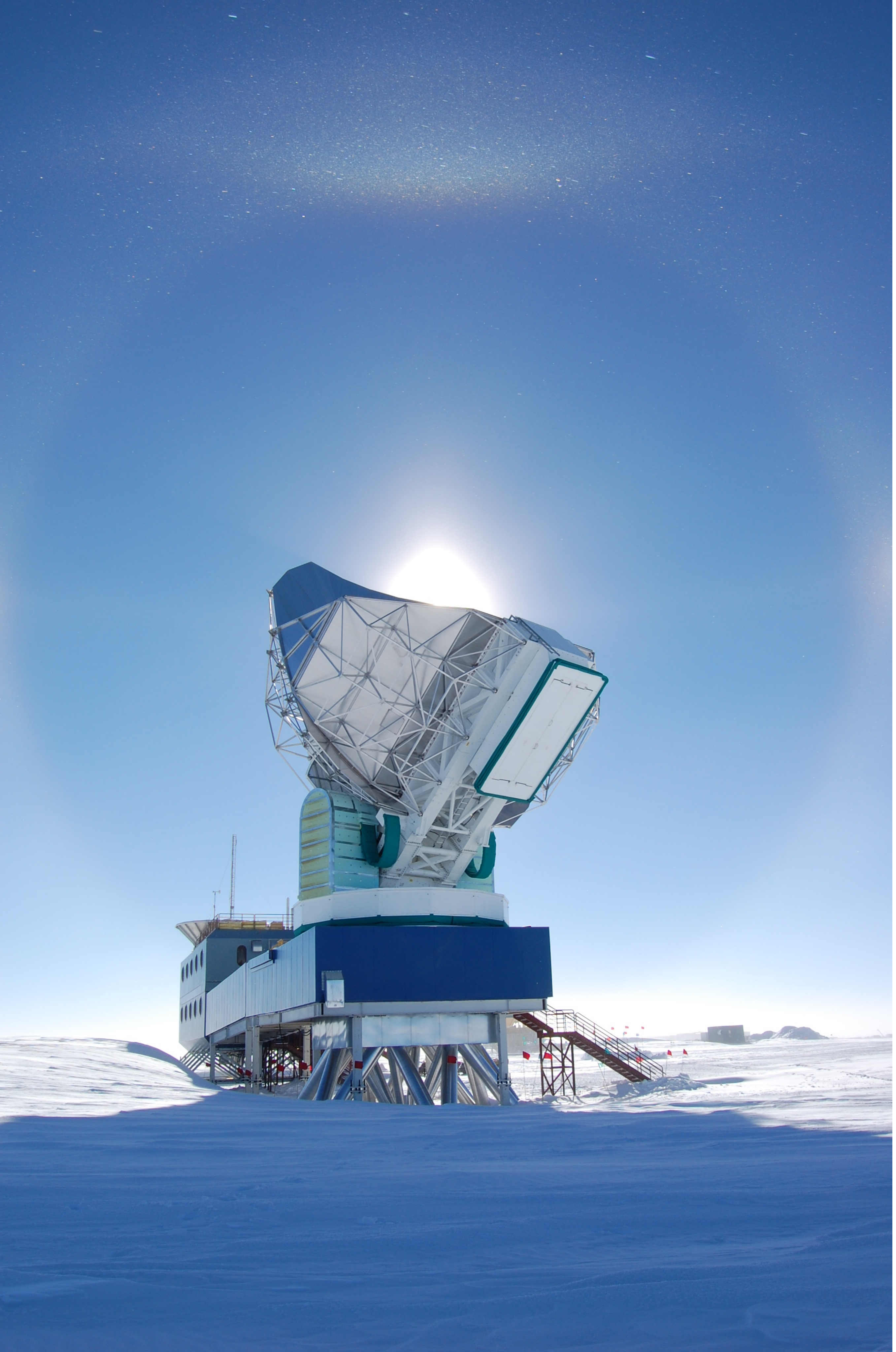


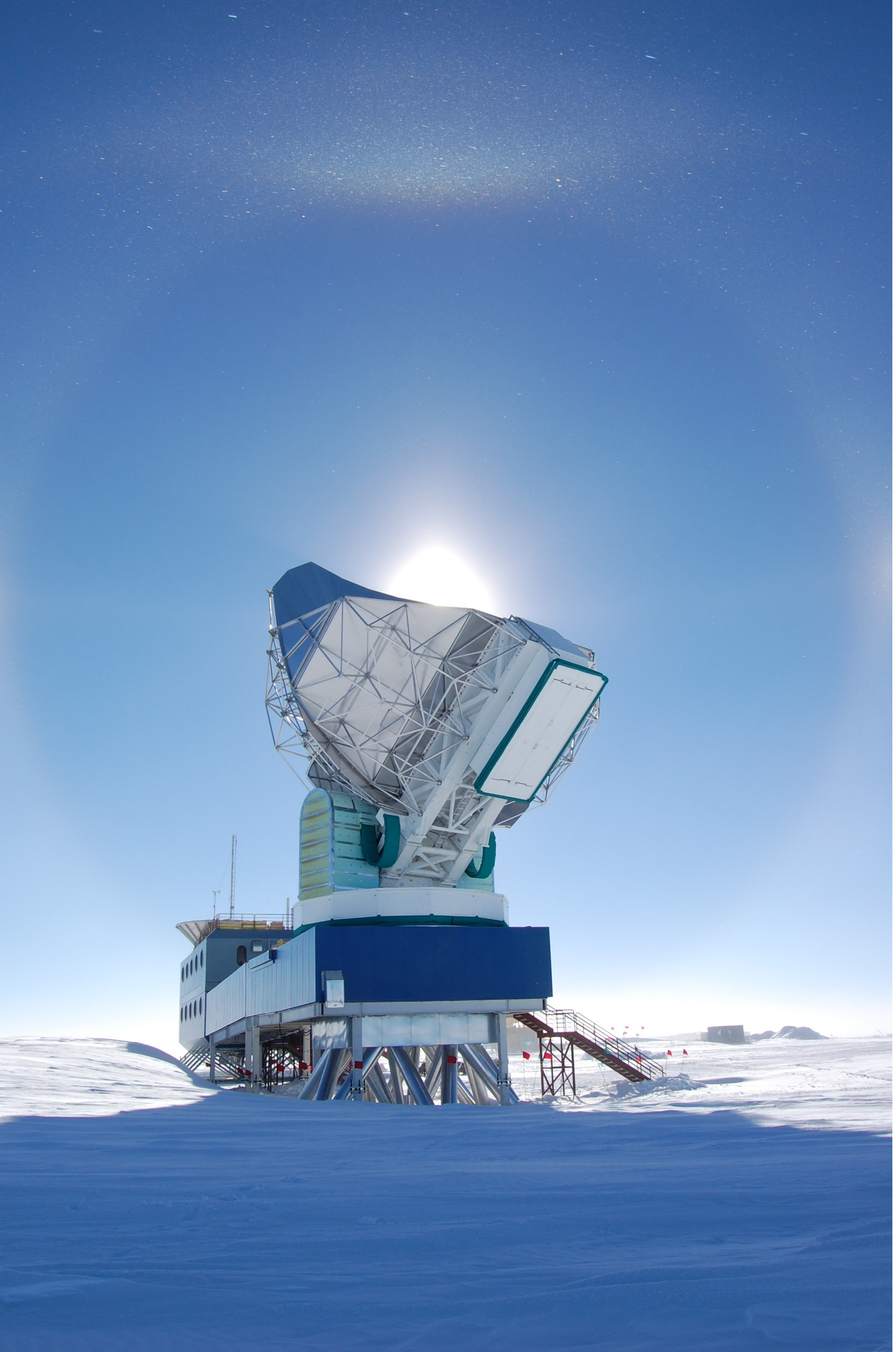
The South Pole Telescope Strong Lensing Cluster Sample

Lindsey Bleem

June 30, 2023

mm Universe 2023

Argonne NATIONAL LABORATORY



The South Pole Telescope Strong Lensing Cluster Sample

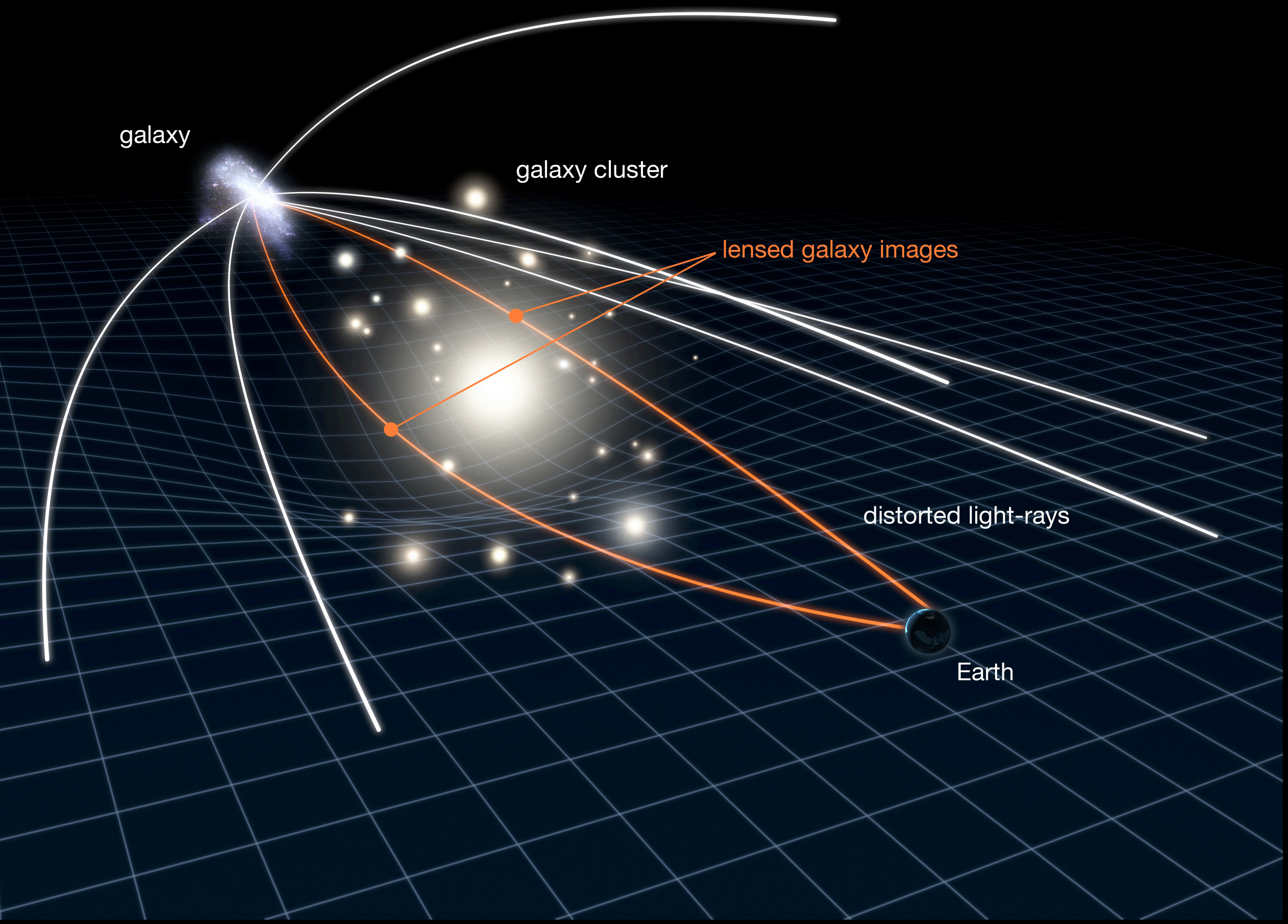
(with Matt Bayliss, Michael Florian, Mike Gladders, Juan Remolina Gonzalez, Salman Habib, Katrin Heitmann, Nan Li, Guillaume Mahler, Kate Napier, Keren Sharon, Brian Stalder, Tony Stark)

mm Universe 2023

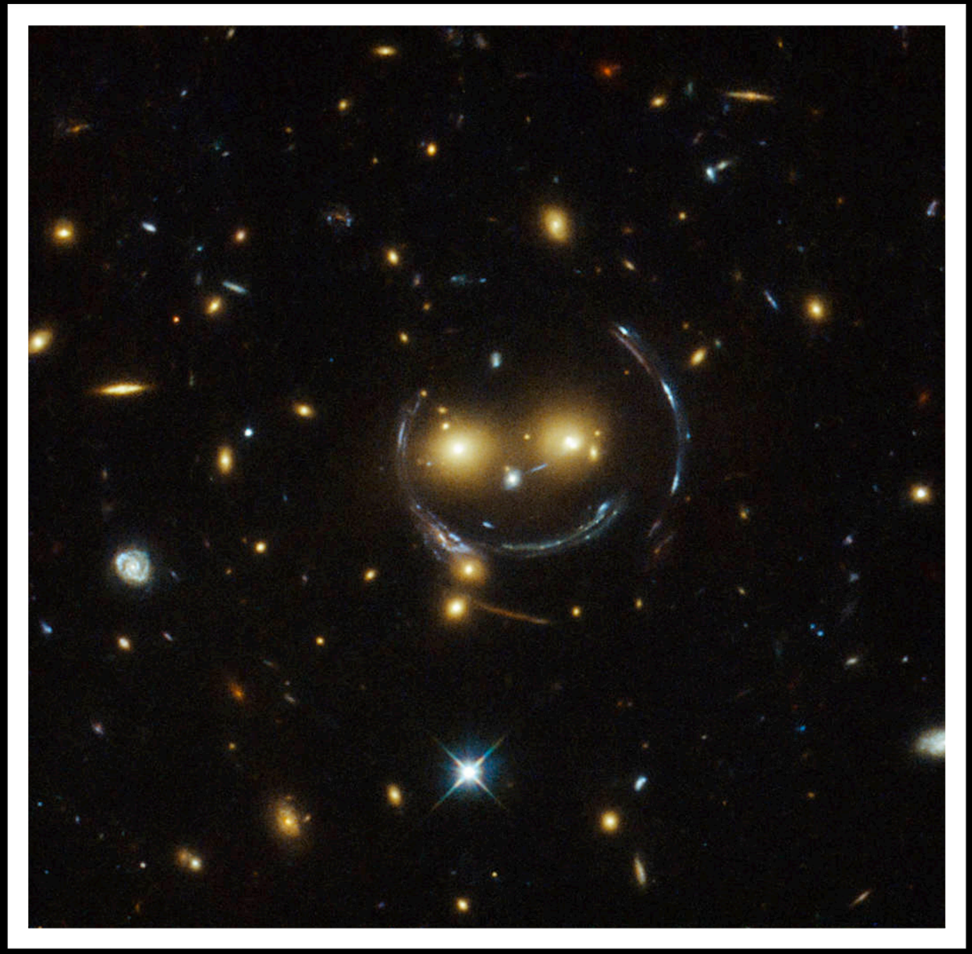
Argonne NATIONAL LABORATORY

Outline

- Introduction
- The SPT Sample and Followup Observations
- Simulation Efforts
- First results
- Next Steps



NASA, ESA & L. Calçada



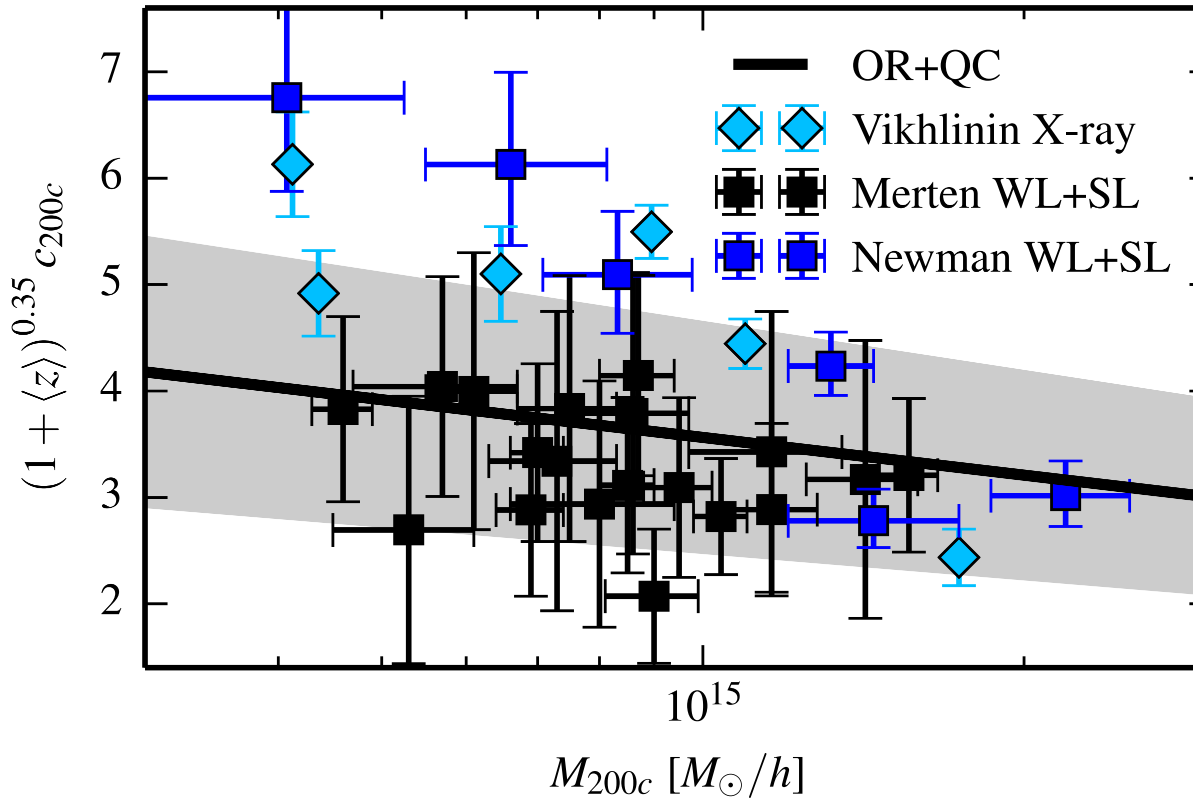
NASA/ESA

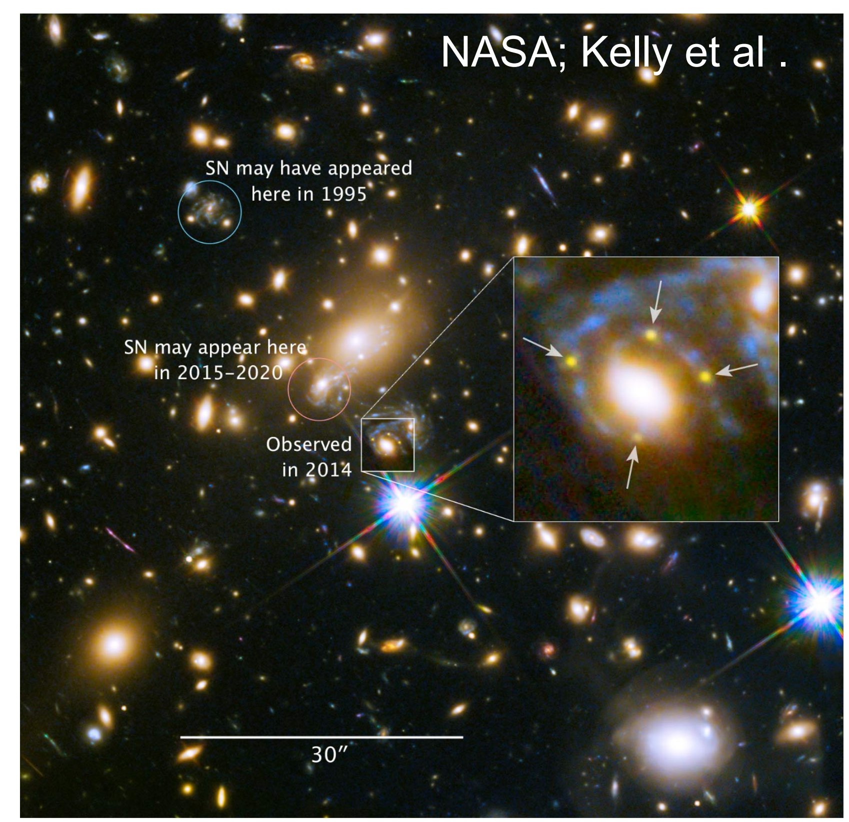
Argonne
NATIONAL LABORATORY

Strong Lensing Science

- **Direct test of structure formation:** Large N-body simulations provide predictions for the properties of Dark Matter haloes that are directly testable by using Strong Lensing as a probe the cores of massive systems
- **Improved Dark Energy Constraints from Cluster Surveys:** Joint Strong + Weak Lensing provides the best constraints on cluster masses
- **New Tests of LCDM**
- **Cosmic Telescopes** - Strong lensing is a powerful tool with which to study the distant Universe
  - *Earliest galaxies (reionization!)*
  - *Expansion Rate of the Universe (e.g., SN Refsdal)*
  - *Dark Matter Substructure (SPT + ALMA)*

Child+ ApJ 859, 55C 2018

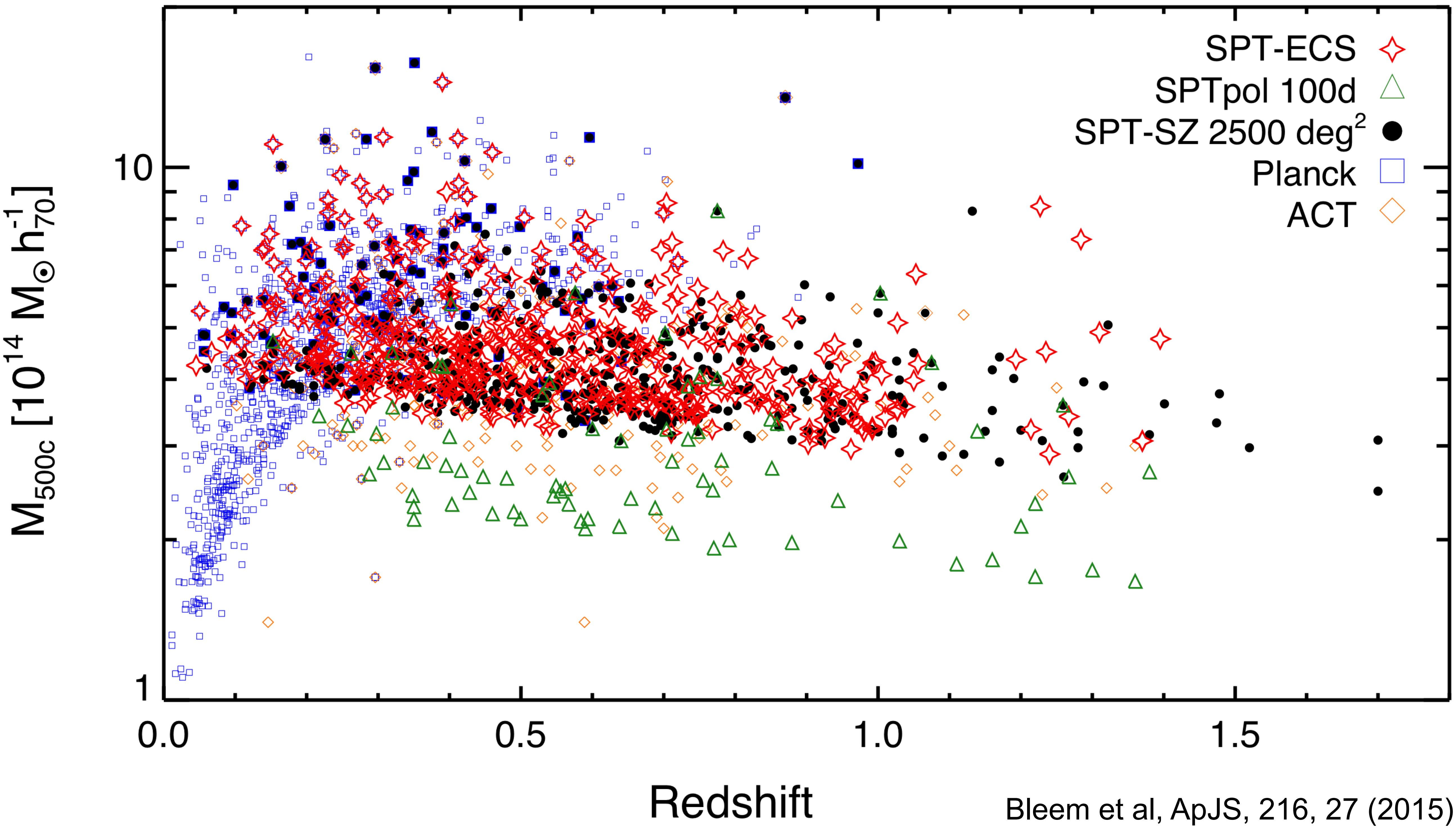




The Program

- Identify a well-characterized and cleanly-defined cluster sample
- Obtain uniform depth observations of this entire sample and characterize its strong lensing properties
- In parallel develop a simulation program to enable us to interpret our results.

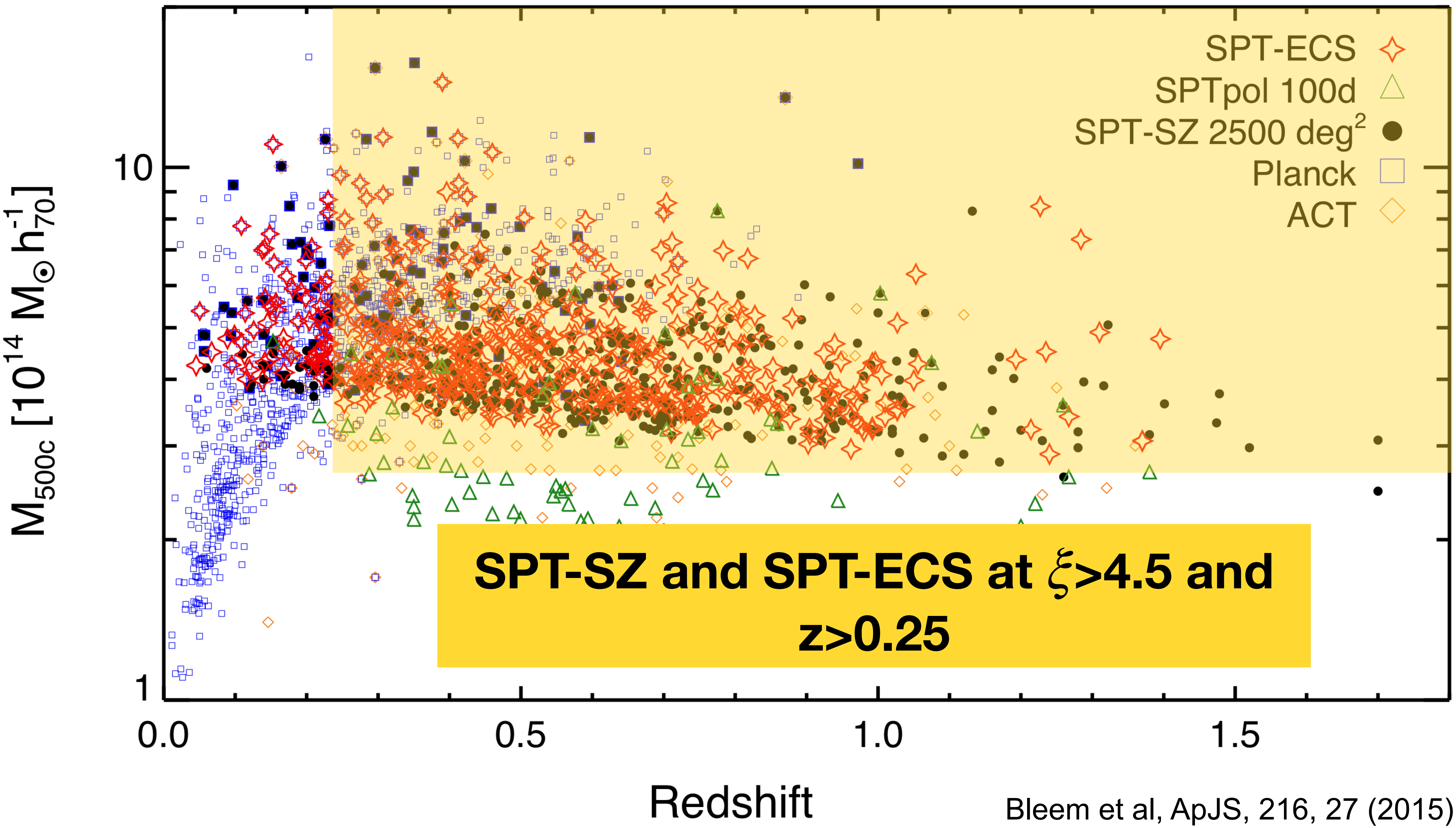
The SPT Cluster Samples



Bleem et al, ApJS, 216, 27 (2015)
Huang, LB et al. AJ, 195, 110, 2020
Bleem et al. ApJS 247,25, 2020

Argonne NATIONAL LABORATORY

The SPT Strong Lensing Program: The Sample



Bleem et al, ApJS, 216, 27 (2015)
Huang, LB et al. AJ, 195, 110, 2020
Bleem et al. ApJS 247,25, 2020

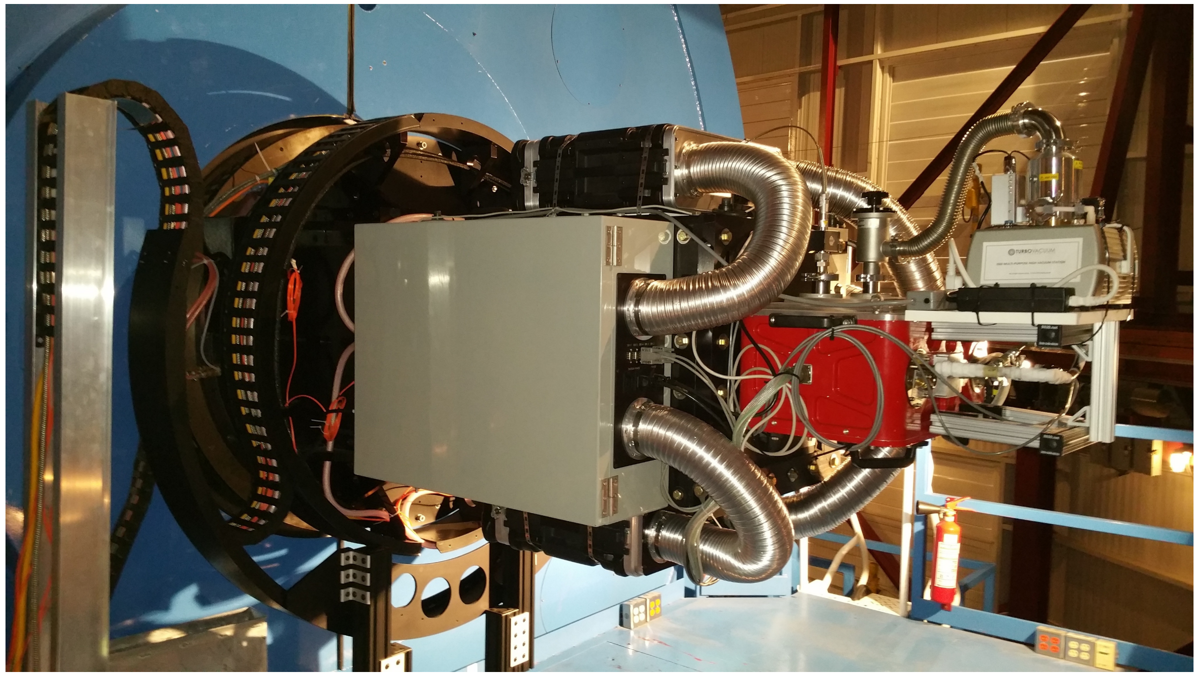
Argonne NATIONAL LABORATORY

The SPT Strong Lensing Program: Observations

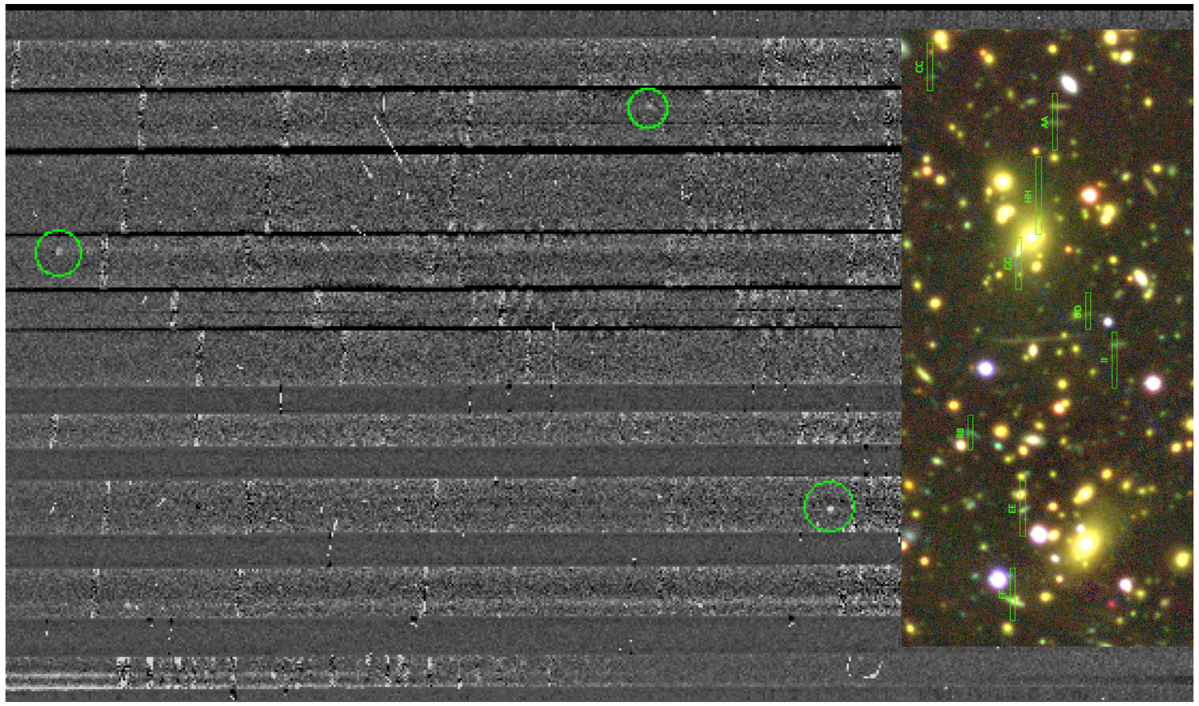
- **Uniform** coverage of this **uniformly-**selected sample

- Imaging Program with PISCO
  - simultaneous ***griz'*** imager installed on Magellan/Clay
  - Adaptive exposures strategy compensating for airmass, seeing, lunar brightness
  - Fast cadence; broad RA range of SPT enables optimization of target ordering
    - 120 clusters in a good night!

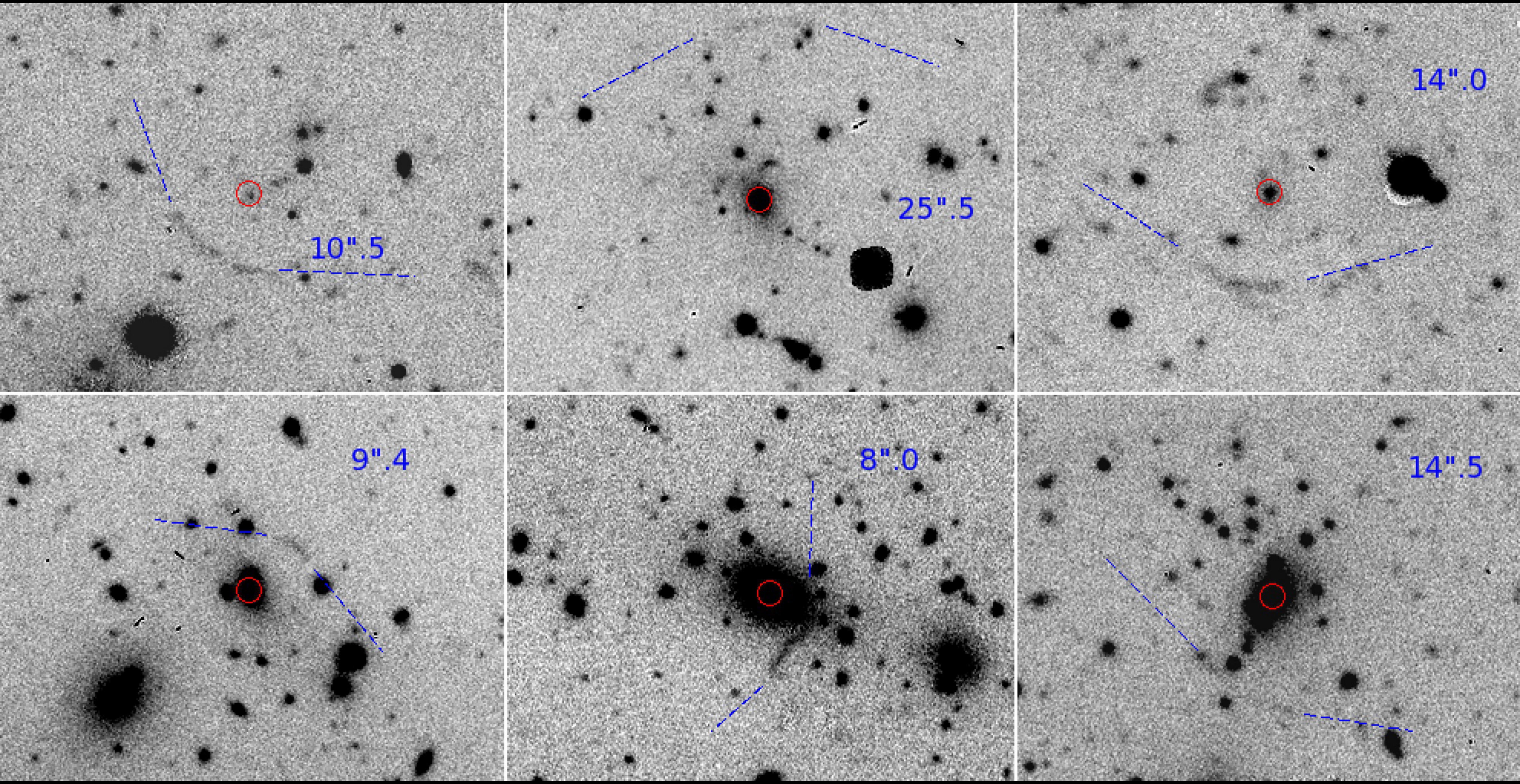
- Spectroscopic Campaign targeting lensed galaxies; followed up over 100 SL systems
(K. Sharon, J Remolina Gonzalez)



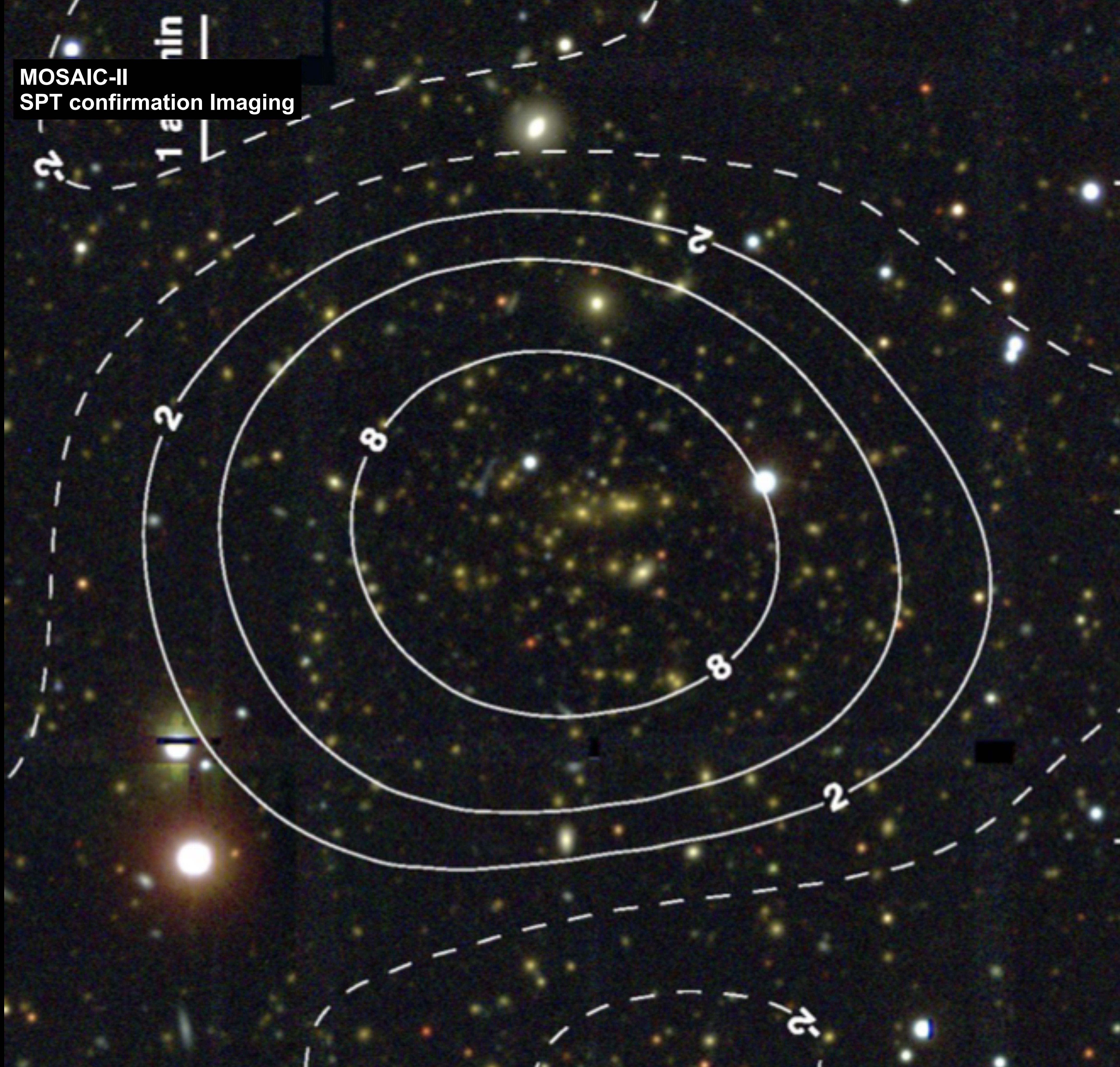
PISCO imager



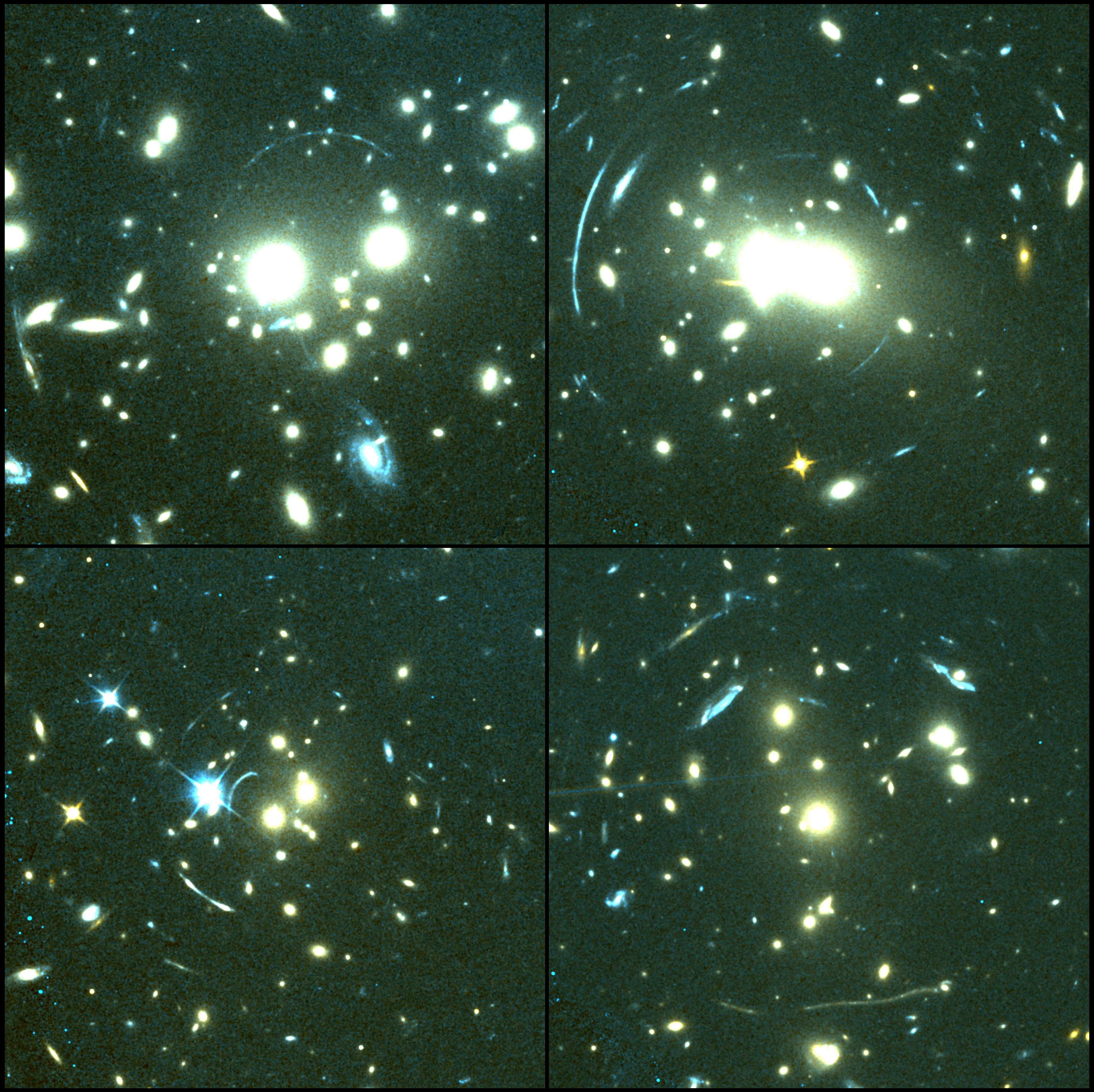
Emission line search IMACs



>450 clusters observed with Magellan/PISCO with <0.9” seeing

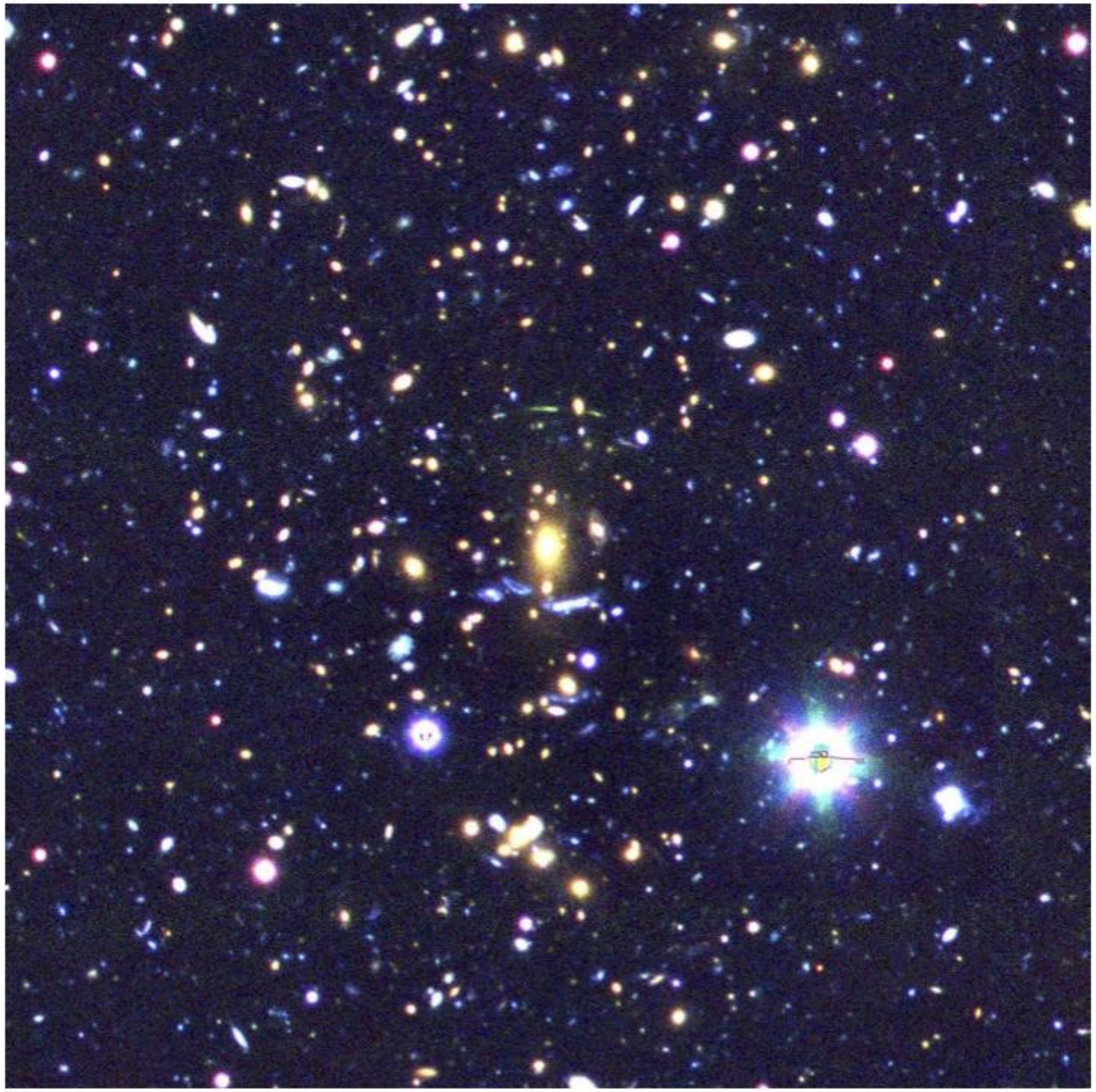

MOSAIC-II
SPT confirmation Imaging
1 arcmin
2
8
8
2
2
-2
-2

PISCO - 300 s



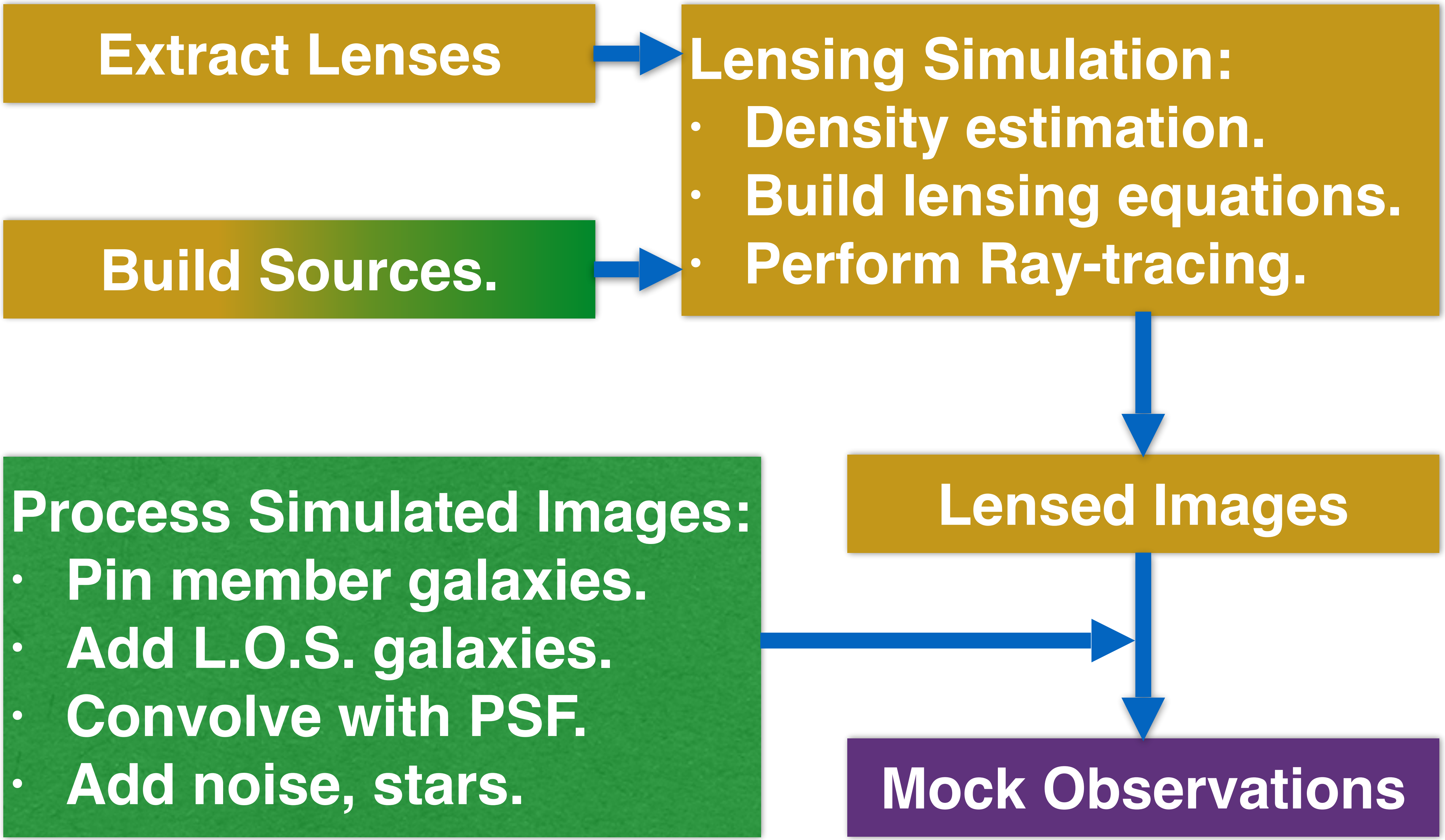
> 200 SPT Clusters with HST imaging including 130 from HST SNAP (PI Gladders)

Contrasting Simulations with Observations:
Cluster-scale Strong Lensing

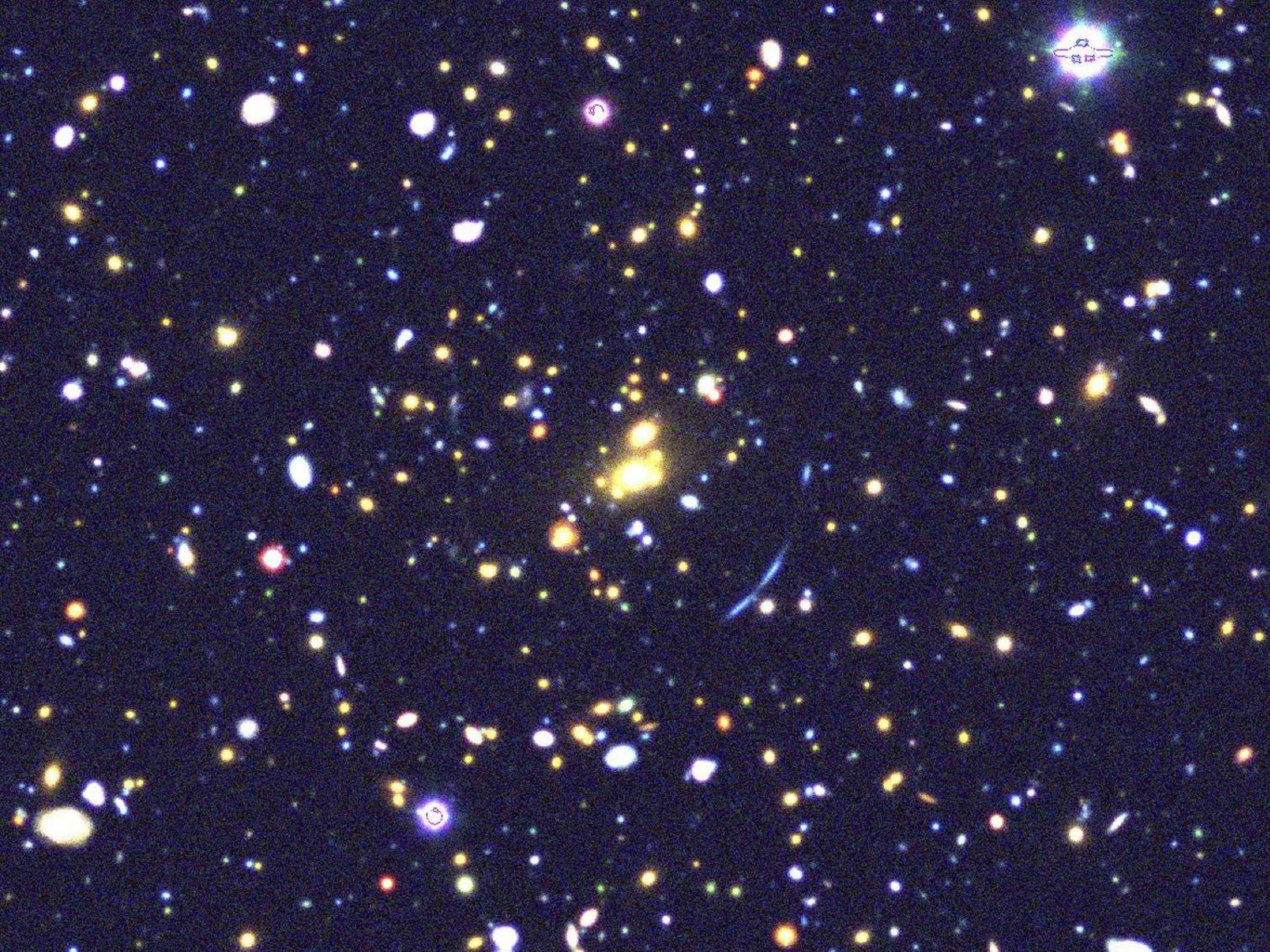


Li et al.
ApJ 828,1, 54 (2016)
ApJ 878, 122L (2019)

Strong Lensing Pipeline



Nan Li et al.
ApJ 828,1, 54 (2016)



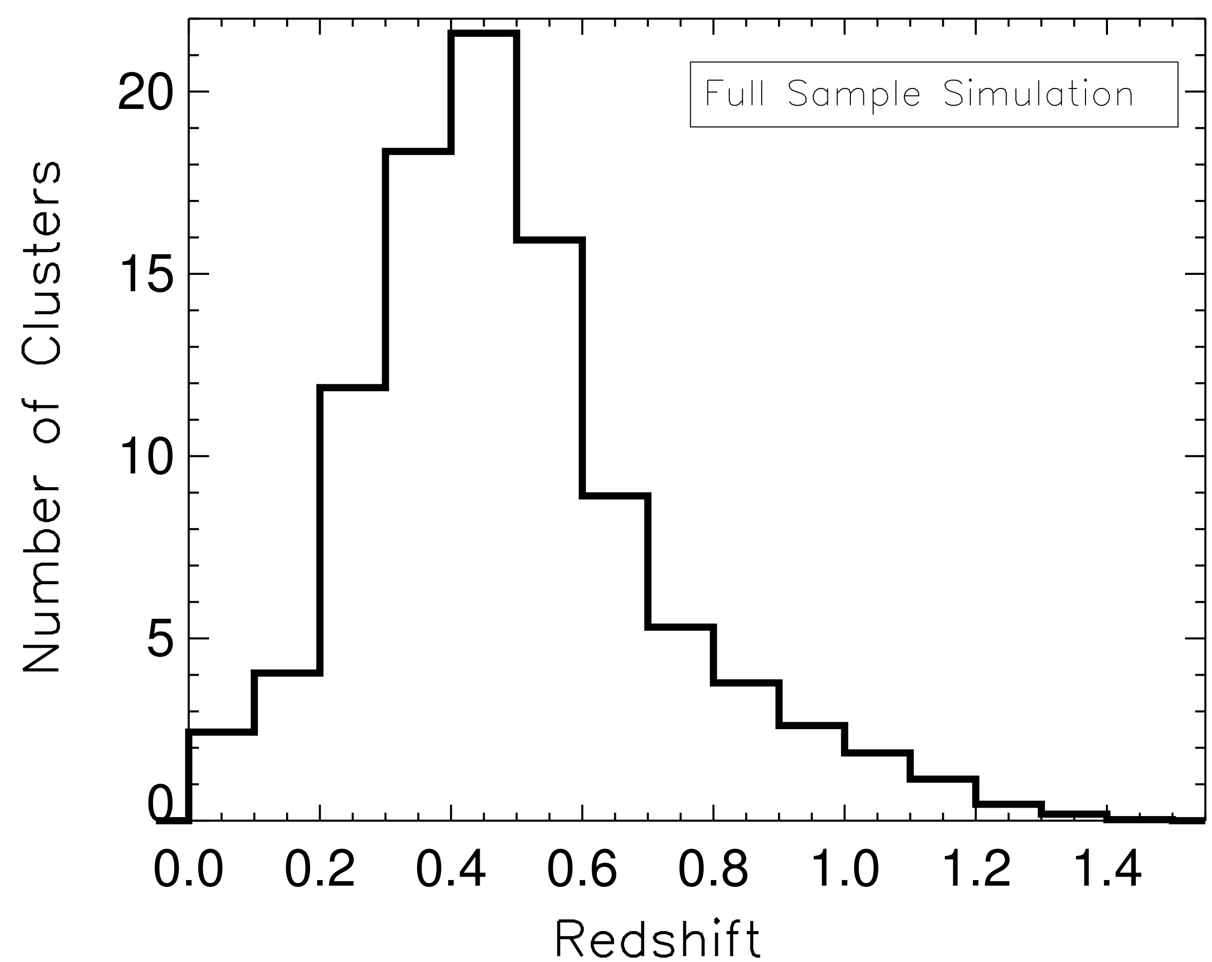
The SPT Strong Lensing Program: Simulations

- On-going simulation efforts to interpret observations:
  - “Outer Rim” simulation (HACC code; Habib+16, NewAst,42,49H)
  - 1.1 trillion particles with mass $2.6 \times 10^9 M_\odot$
  - (4.225 Gpc)^3 Volume

- Expect >100 strong lenses to be detected in SPT-SZ cosmology sample with reasonable (<0.90”) ground-based imaging.

- Objective: to measure the mean mass-concentration relation of massive halos to ~5%, and constrain its scatter to ~10% precision ***(statistical)***.

Preliminary Predicted Lens Redshift Distribution



Efficient Strong Lensing Mass Estimates Using the Einstein Radius

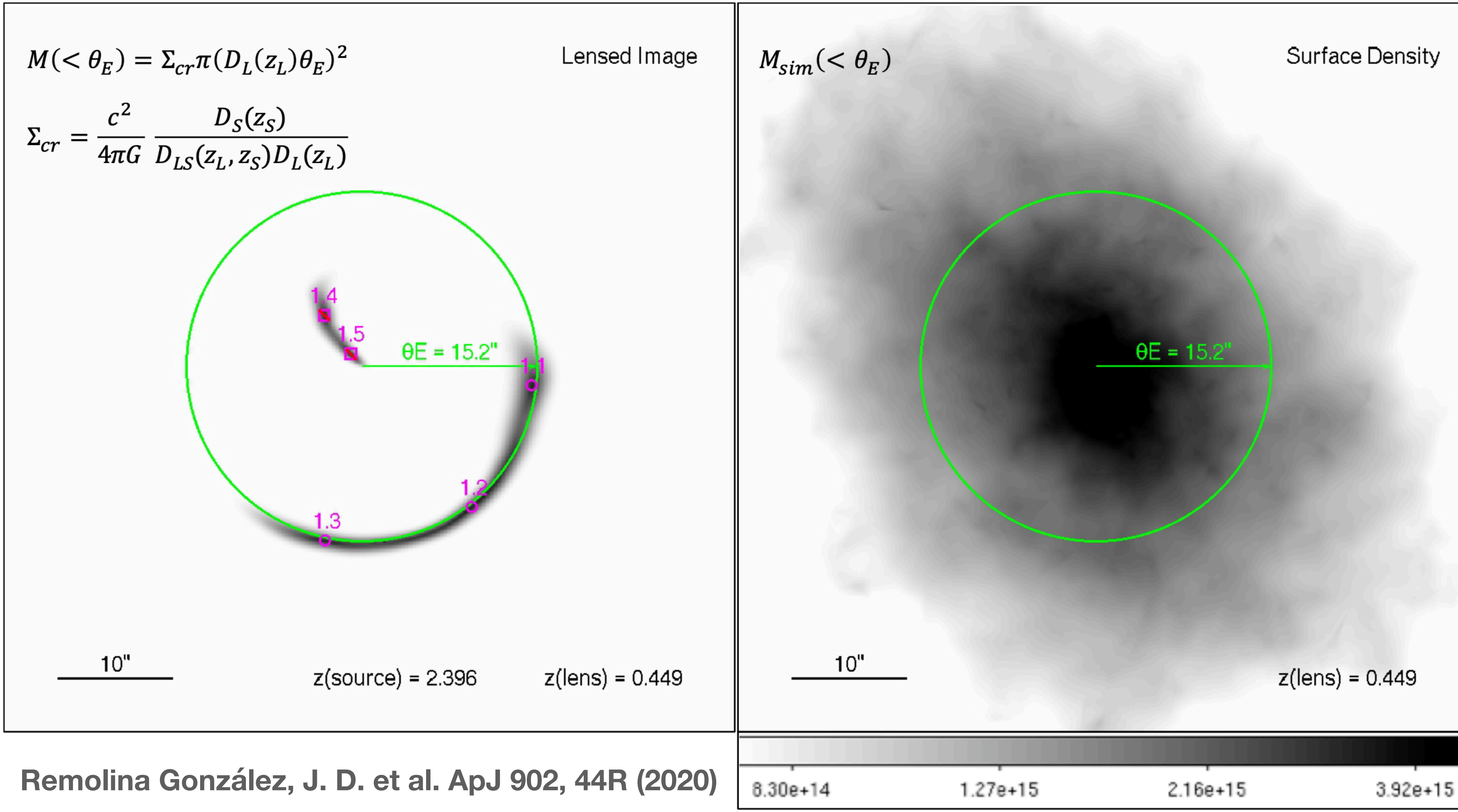
- For many of our clusters, we have minimal strong lensing information so detailed lens models are impossible.
- Used simulated clusters from the Outer Rim to validate the accuracy and scatter in using the Einstein Radius to estimate mass in the cluster core.
- Study used 74 strong lensing systems at $M_{500} > 2 \times 10^{14}\ M_{sun}$ in the Outer Rim simulation, generate 5-24 mock observations per halo.

Juan Remolina González

Efficient Strong Lensing Mass Estimates Using the Einstein Radius

$$M(<\theta_E) = \Sigma_{cr}\pi(D_L(z_L)\theta_E)^2$$

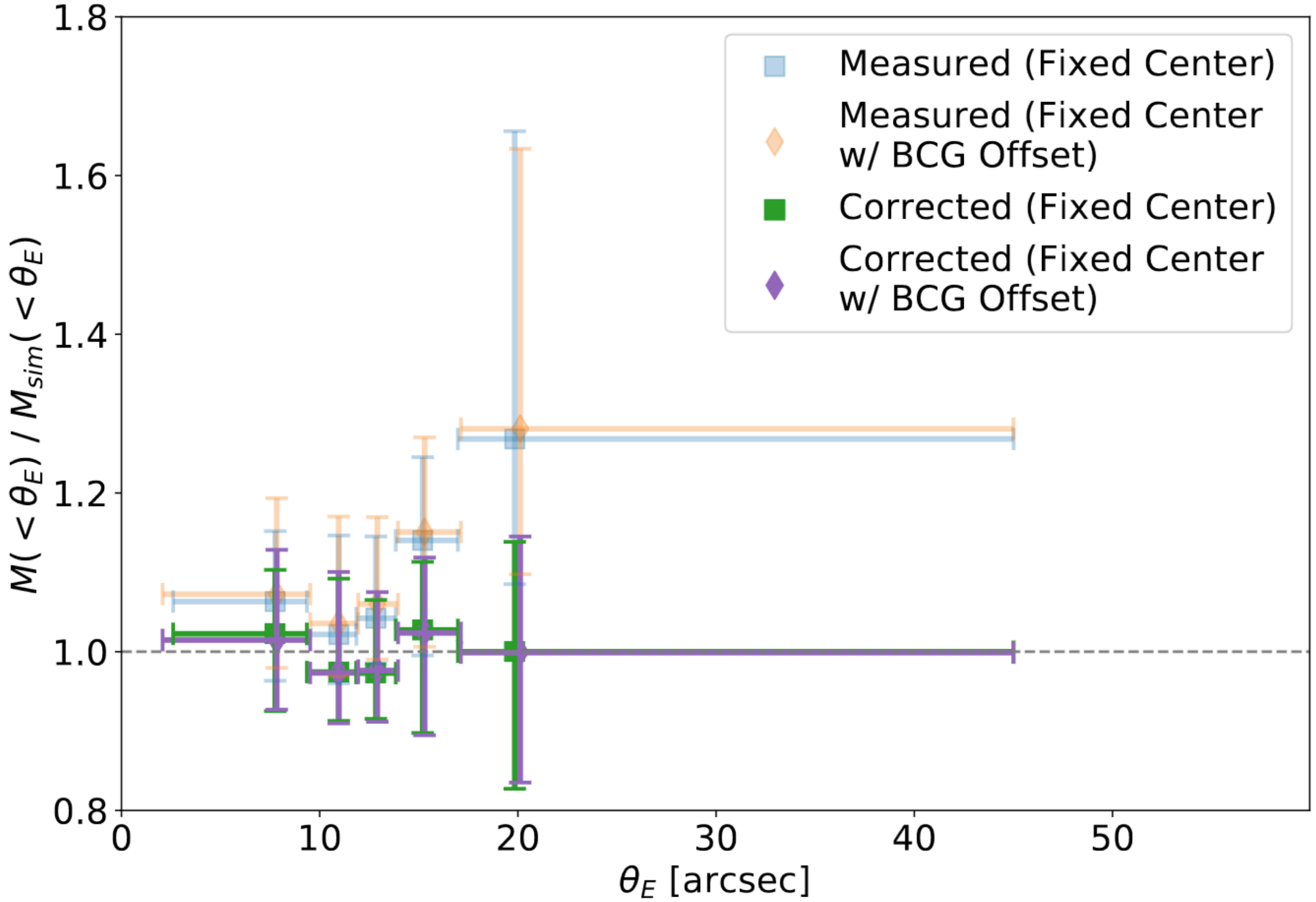
$$\Sigma_{cr} = \frac{c^2}{4\pi G}\frac{D_S(z_S)}{D_{LS}(z_L, z_S)D_L(z_L)}$$

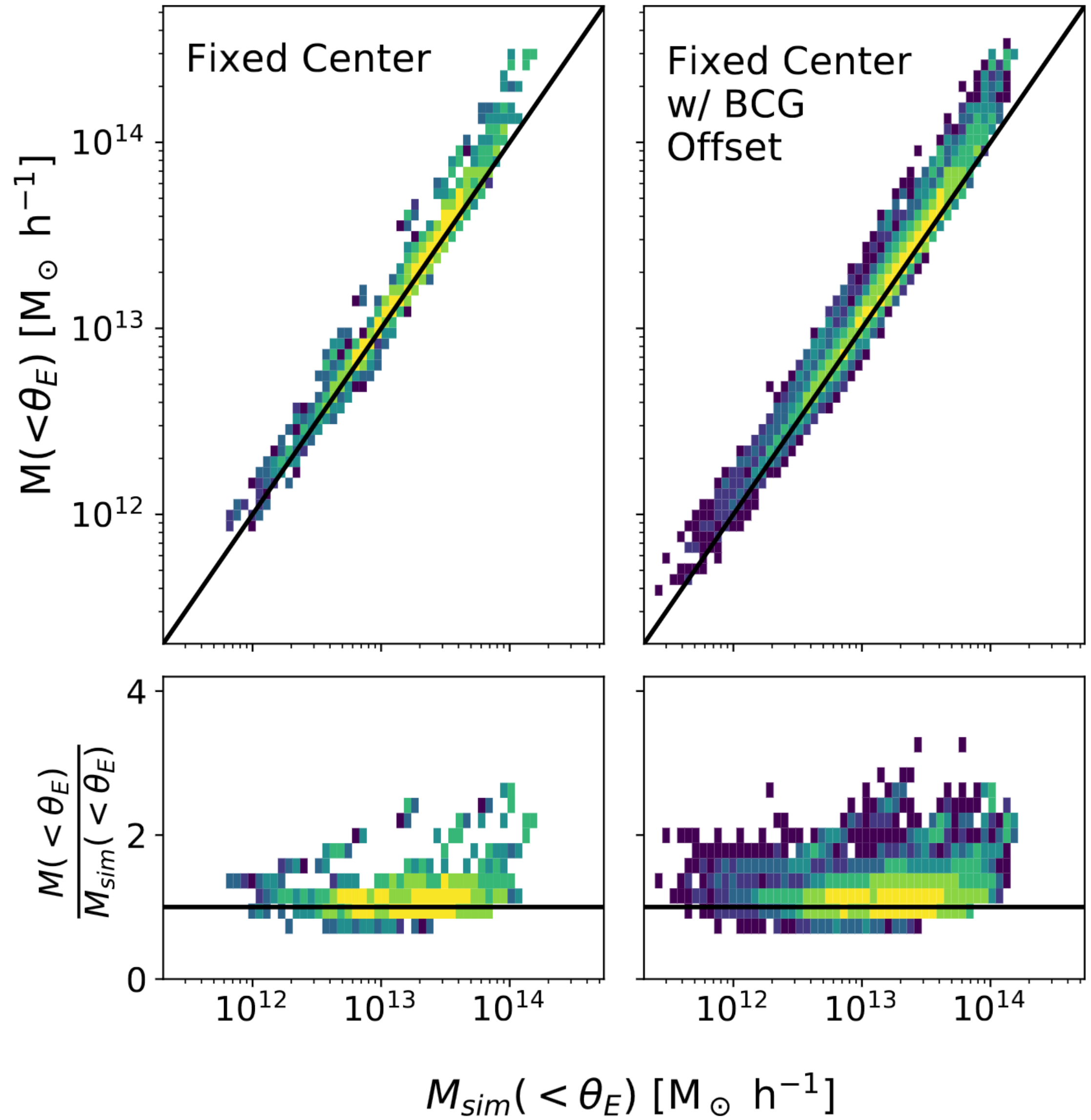


Remolina González, J. D. et al. ApJ 902, 44R (2020)

Efficient Strong Lensing Mass Estimates Using the Einstein Radius

Measured v/s True Mass





Remolina González, J. D. et al. ApJ 902, 44R (2020)

See also:
Remolina González, J. D. et al. ApJ 910, 146R (2021)
Remolina González, J. D. et al. ApJ 920, 98R (2021)

First results c-M relation

$$\rho_{\mathrm{NFW}}(r) = \frac{\rho_{\mathrm{s}}}{r/r_{\mathrm{s}}\left(1 + r/r_{\mathrm{s}}\right)^2}$$

$$M_{\Delta} = 4\pi \rho_{\mathrm{s}} r_{\mathrm{s}}^3 \left(\ln\left(1 + c_{\Delta}\right) - \frac{c_{\Delta}}{1 + c_{\Delta}} \right)$$

$$c_{\Delta} = \frac{r_{\Delta}}{r_s}$$

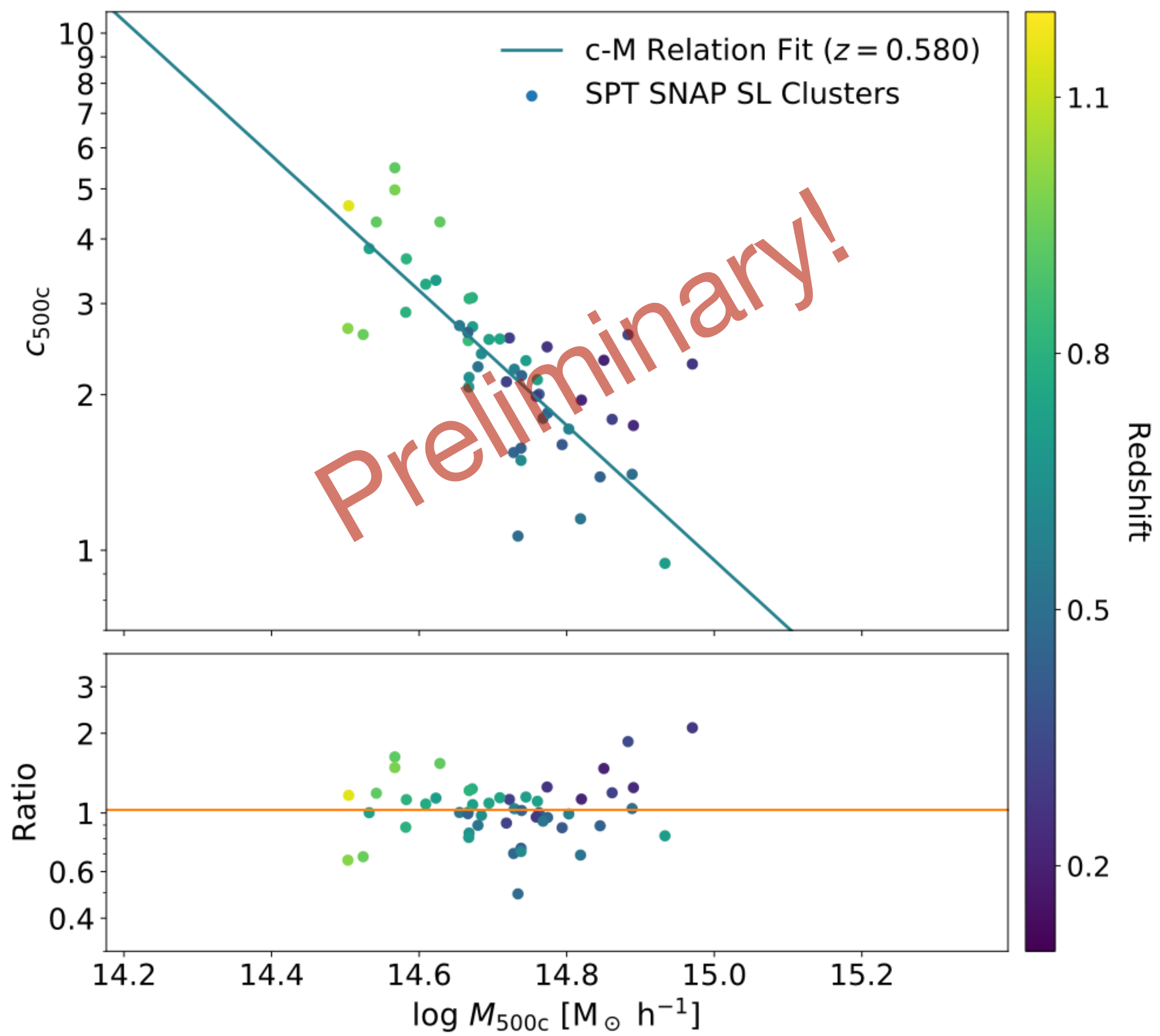
First results c-M relation

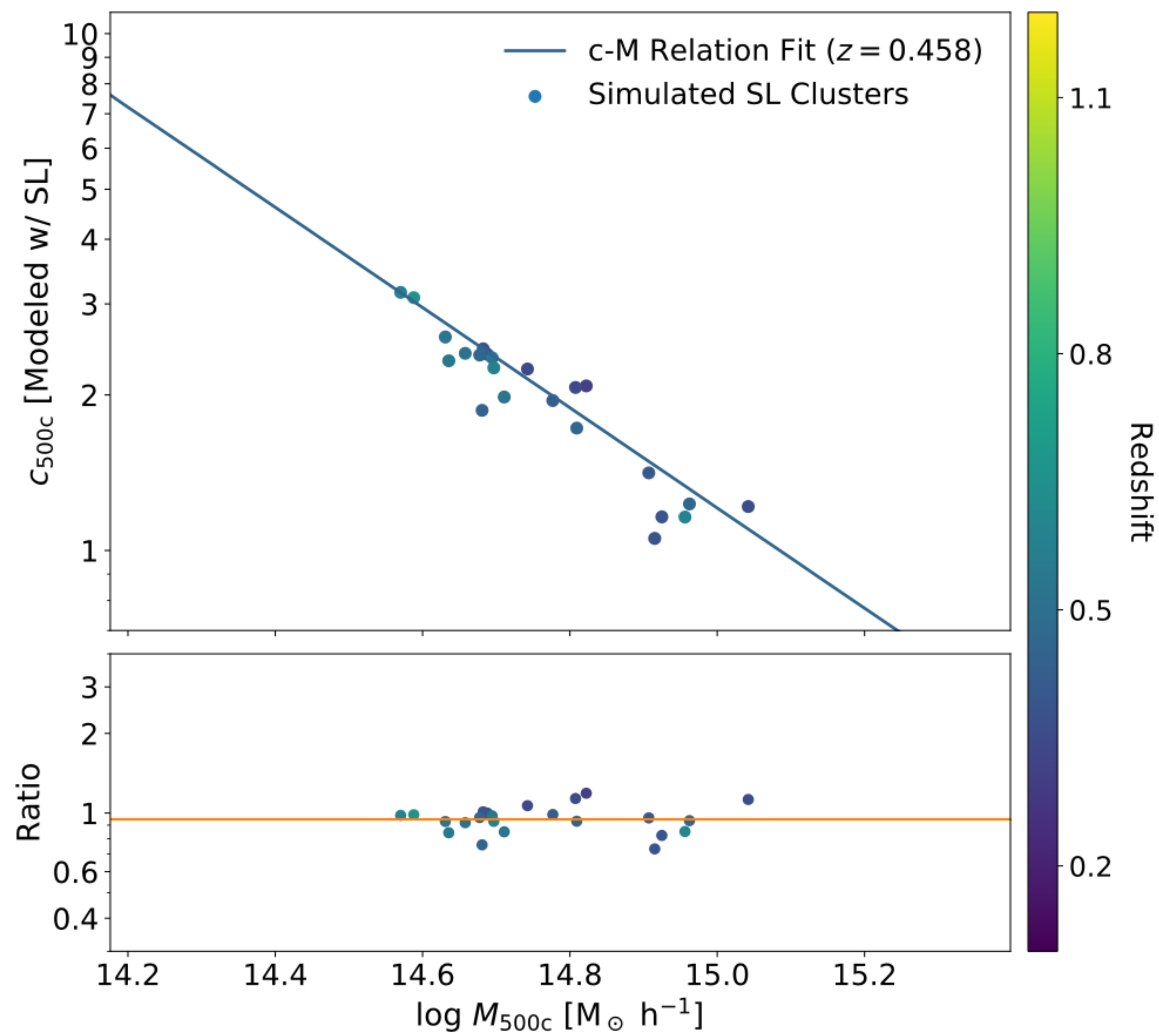
$$\rho_{\mathrm{NFW}}(r) = \frac{\rho_s}{r/r_s\,(1 + r/r_s)^2}$$

$$M_\Delta = 4\pi\rho_s r_s^3 \left(\ln(1 + c_\Delta) - \frac{c_\Delta}{1 + c_\Delta}\right)$$

$$c_\Delta = \frac{r_\Delta}{r_s}$$

$$c^*_{\Delta c}(M_{\Delta c}, z) = \alpha \left(\frac{M_{\Delta c}}{M_{\mathrm{pivot}}}\right)^\beta \left(\frac{1 + z_{\mathrm{pivot}}}{1 + z}\right)^\gamma$$





$\alpha = 2.30 \pm 0.21$; $\beta = -0.97 \pm 0.21$; $\gamma = -0.24 \pm 1.44$

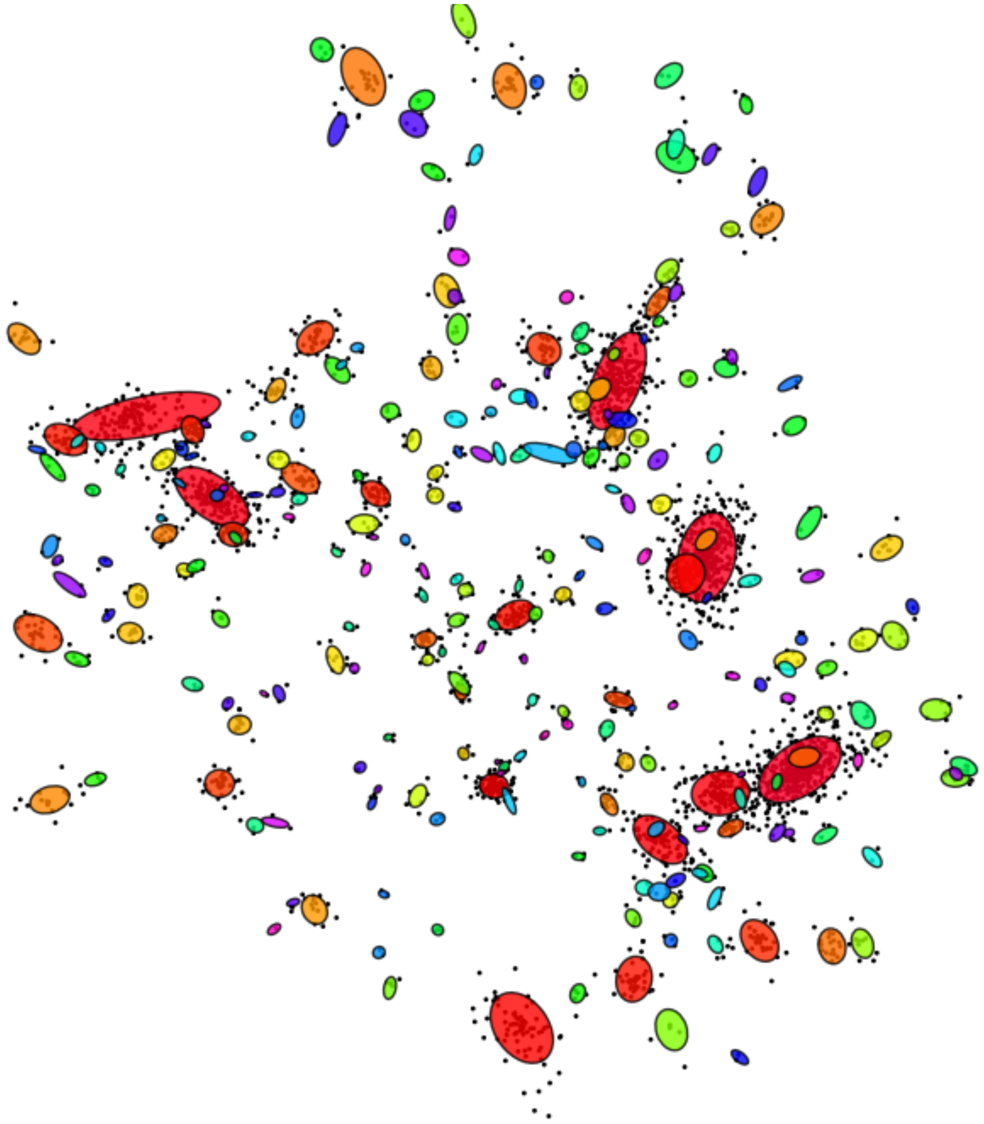
$M_{\mathrm{pivot}} = 5.14 \times 10^{14}\ M_\odot h^{-1}$; $z_{\mathrm{pivot}} = 0.458$

Remolina González, J. D. et al. (in prep)

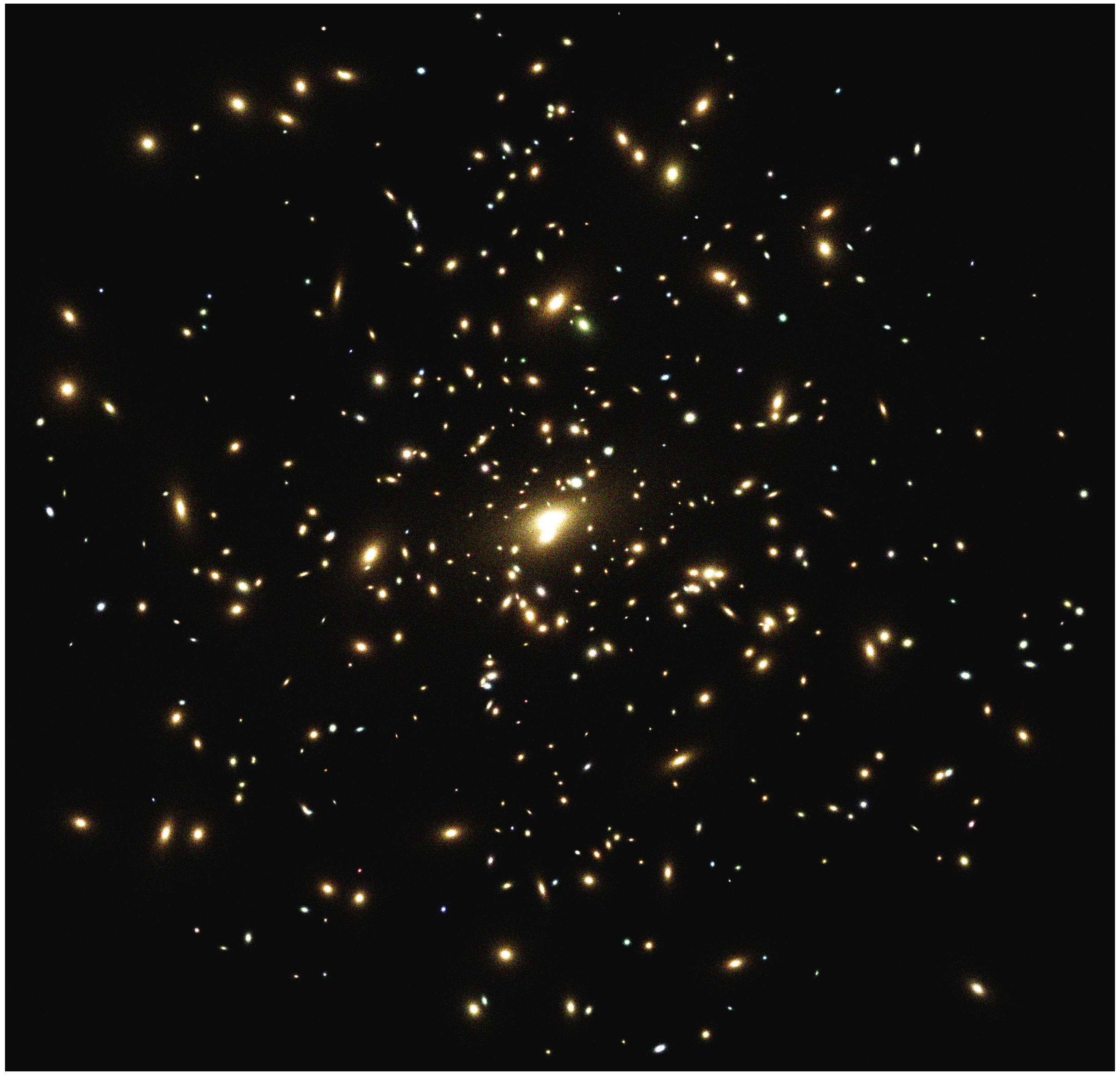
Conclusions and Next Steps

- With our uniform follow-up of the SPT SZ cluster sample we have identified >150 cluster scale strong lenses.
- We have an ongoing simulation campaign to help us interpret these results.
- First results on the mass-concentration relation of strong lensing clusters agree well with predictions (paper coming soon!)
- Our next steps are to incorporate data from our spectroscopic observations to improve our observational constraints and to improve our predictions by better modeling the impact of the SPT-selection function (see F. Kéruzoré's BP talk!) as well as the role of feedback (hydrosims) on strong lensing observables.

Building Cluster Member Galaxies



(main halo removed)



(not the same halo)

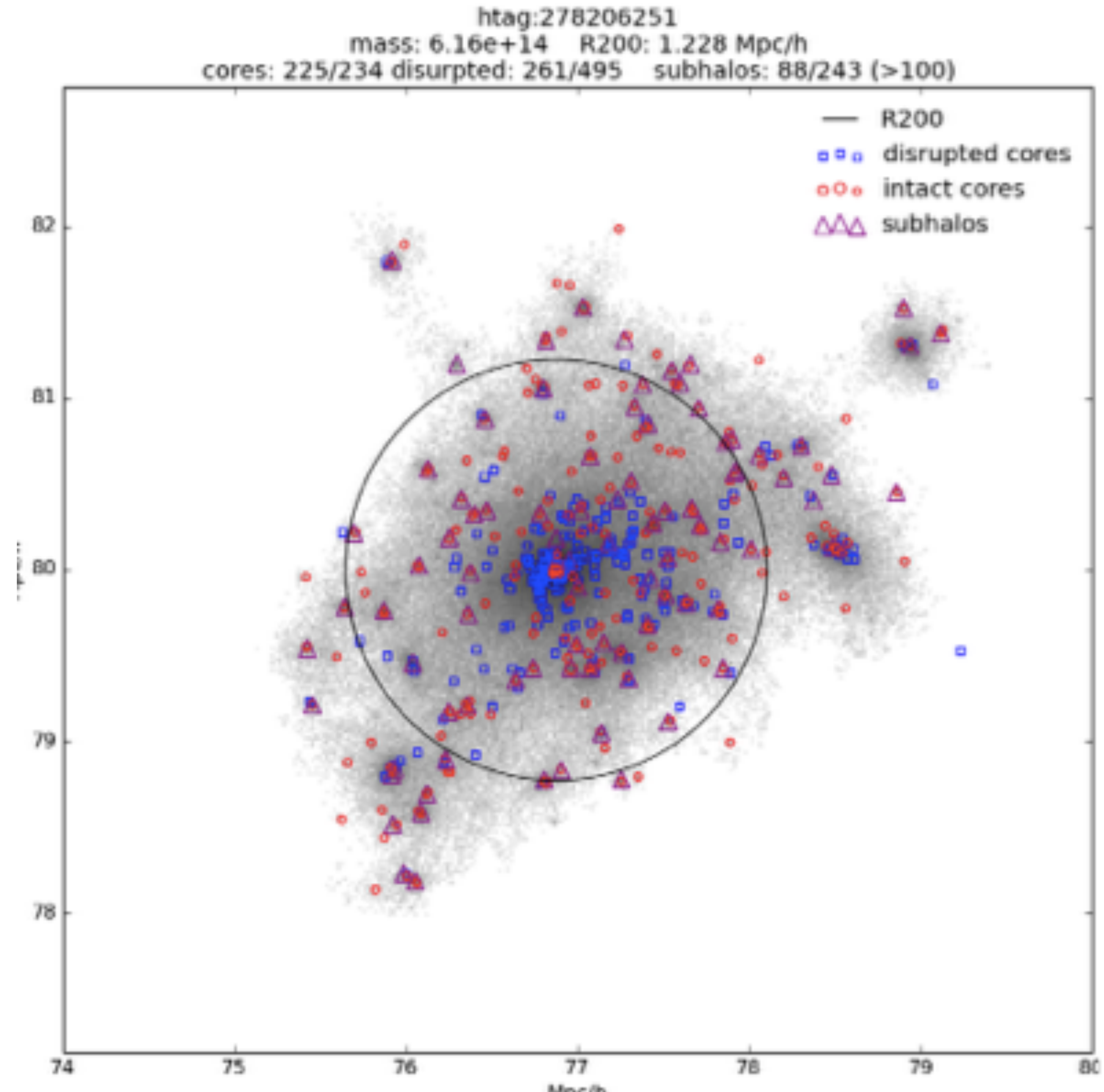
Core Tracking - Placing Satellite Galaxies in Halos

Basic Assumptions

- Galaxies form at the centers of small DM halos and, once formed, experience primarily gravitational forces
- Simulation particles from the center of halos should follow the same paths as galaxies

Simple Model Parameters

- When does a halo get a core?
- Does the core stay intact?
- When does a core "merge"?



Galaxy Placement in halos

[D. Korytov+ arXiv:2302.04194 (accepted by OJA)]

Core Tracking - Placing Satellite Galaxies in Halos

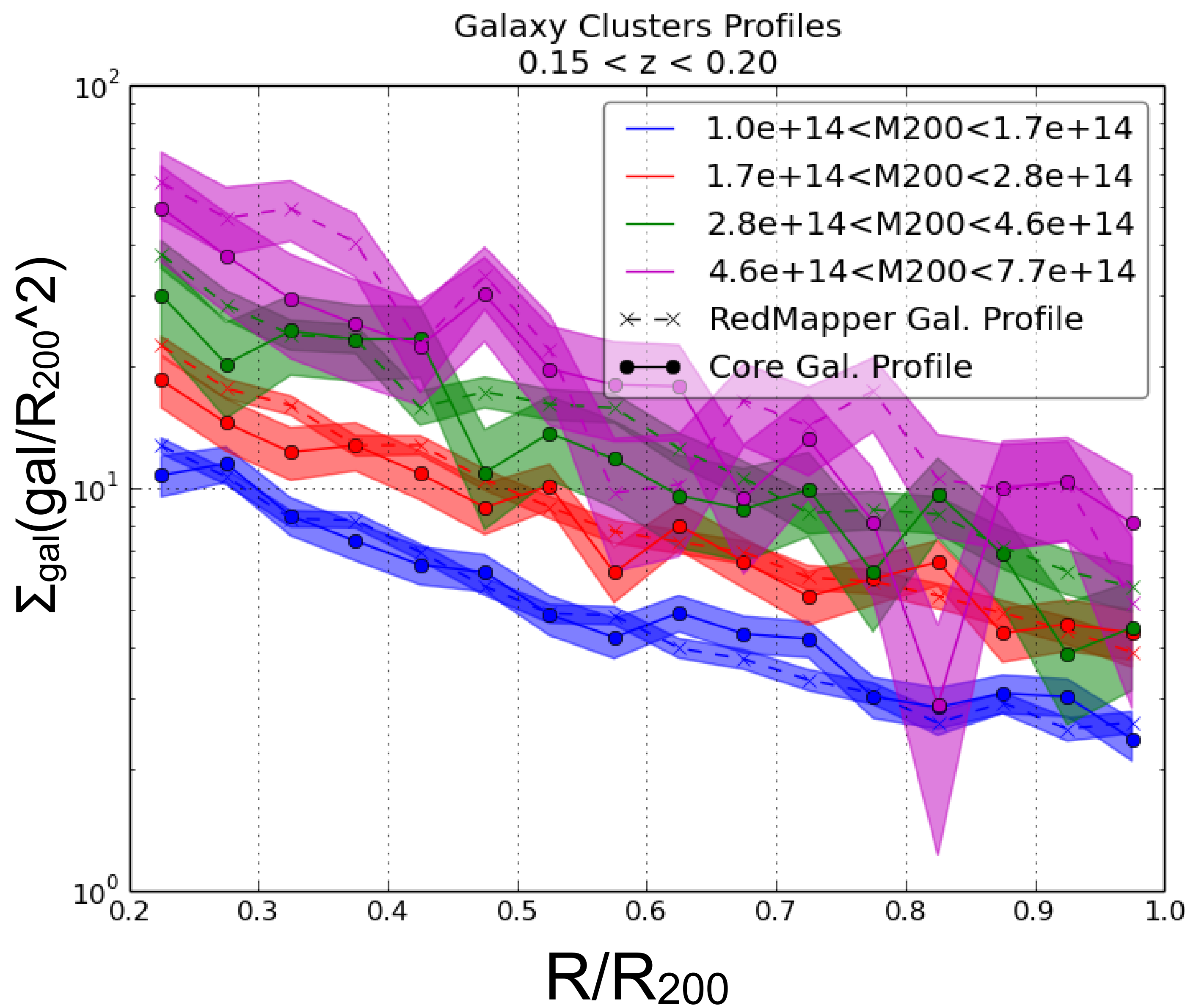
Basic Assumptions

- Galaxies form at the centers of small DM halos and, once formed, experience primarily gravitational forces
- Simulation particles from the center of halos should follow the same paths as galaxies

Simple Model Parameters

- When does a halo get a core?
- Does the core stay intact?
- When does a core "merge"?

Matching to RedMapper SDSS



[D. Korytov+ arXiv:2302.04194