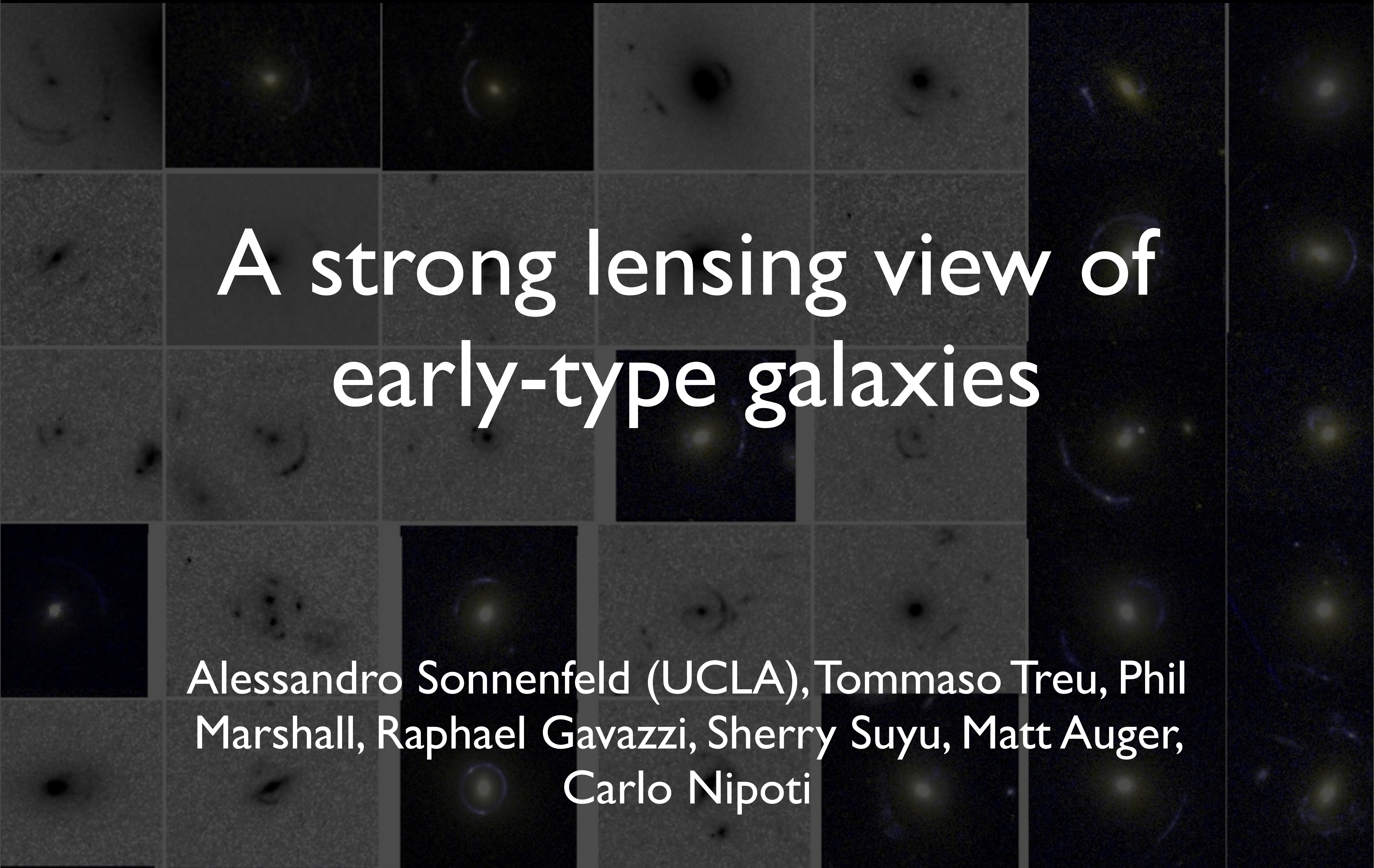


A strong lensing view of early-type galaxies

Alessandro Sonnenfeld (UCLA), Tommaso Treu, Phil Marshall, Raphael Gavazzi, Sherry Suyu, Matt Auger, Carlo Nipoti

Strong lensing

$$\theta_{\rm Ein} = \sqrt{\frac{4GM_{\rm Ein}}{c^2}\frac{D_{ds}}{D_d D_s}}$$

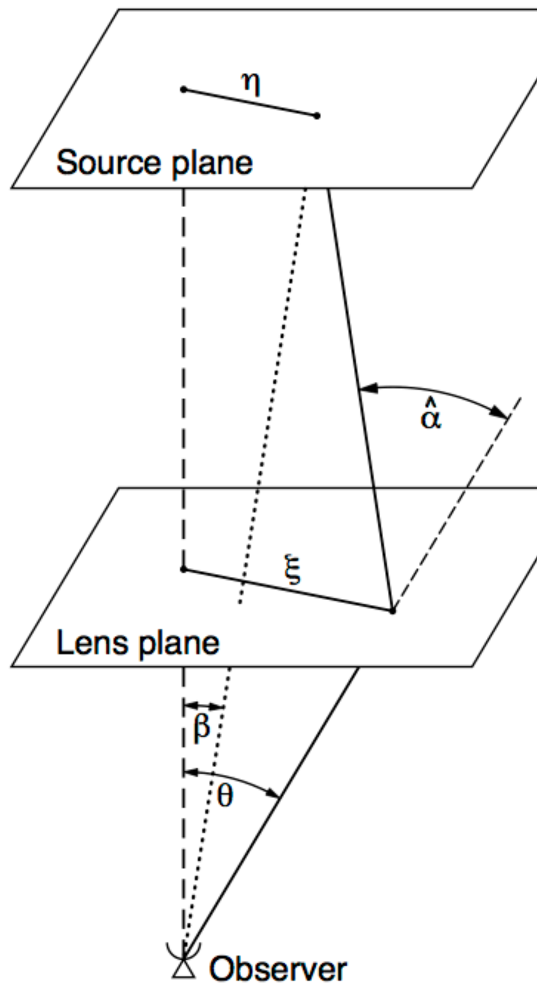


Fig. 11. Sketch of a typical gravitational lens system.

Bartelmann & Schneider 2001

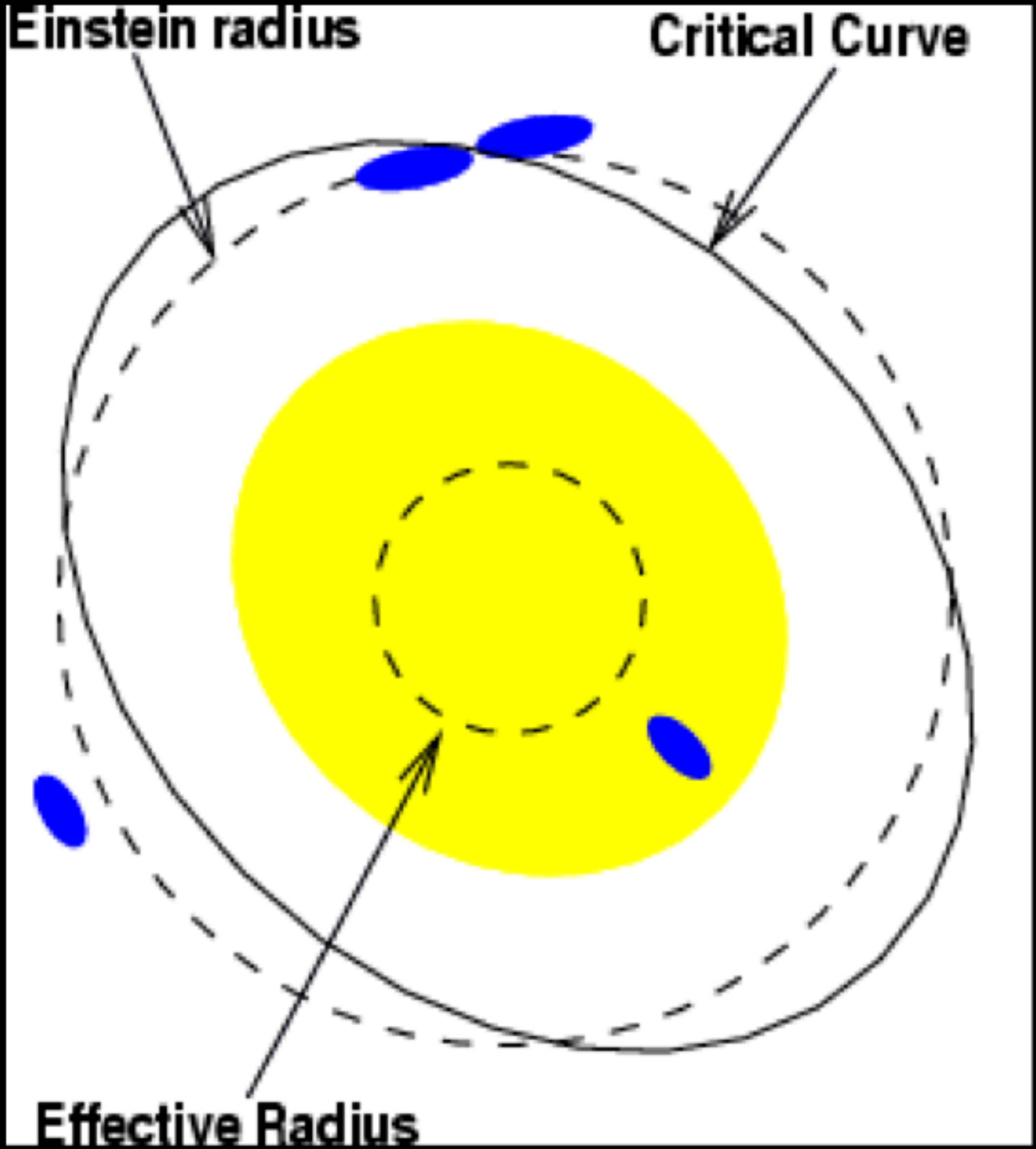
Outline

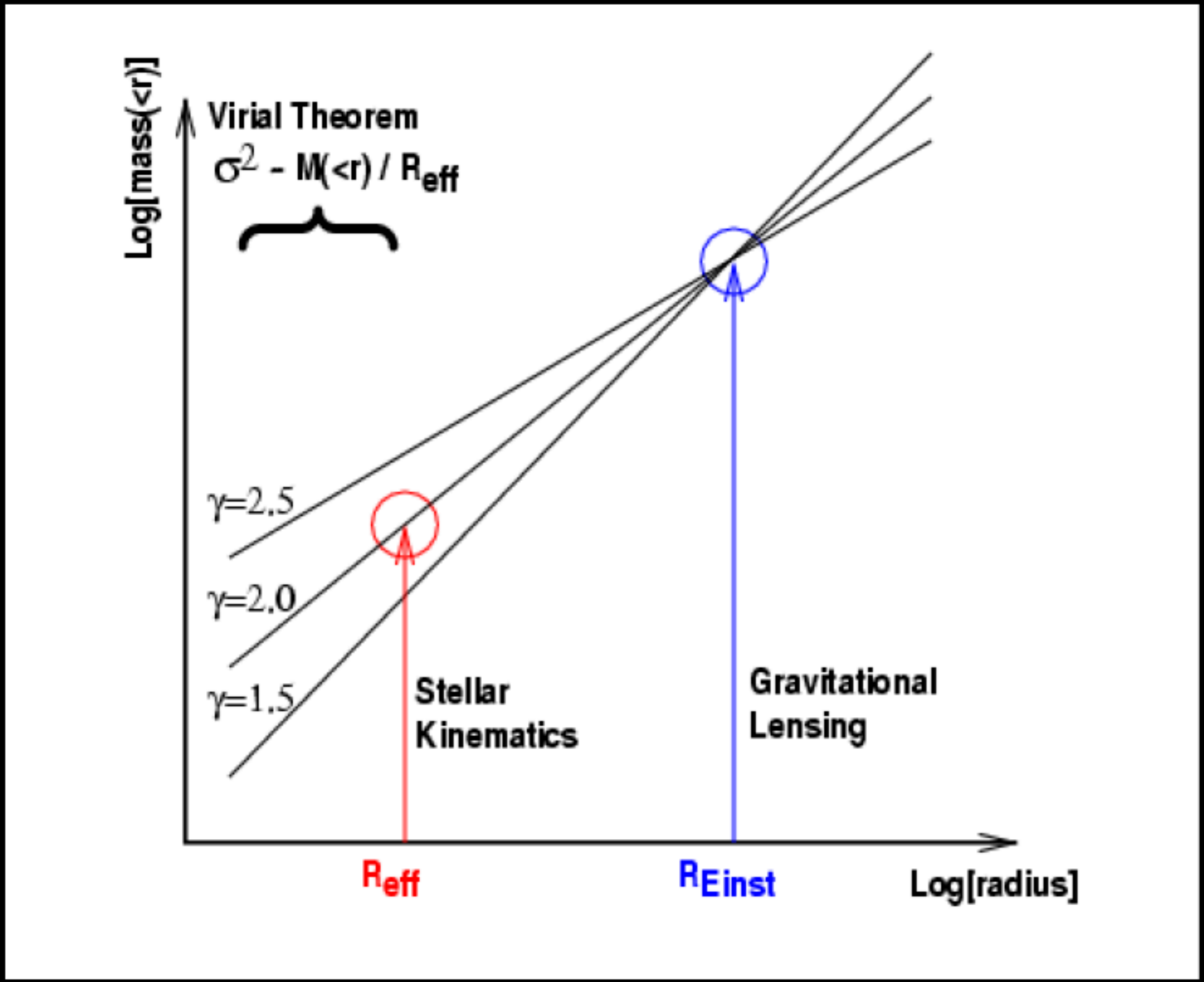
- The mass structure of early-type galaxies
  - Evolution
  - Size dependence

Part I: the total density profile and its evolution

The slope of the density profile

$$\rho(r) \propto r^{-\gamma'}$$

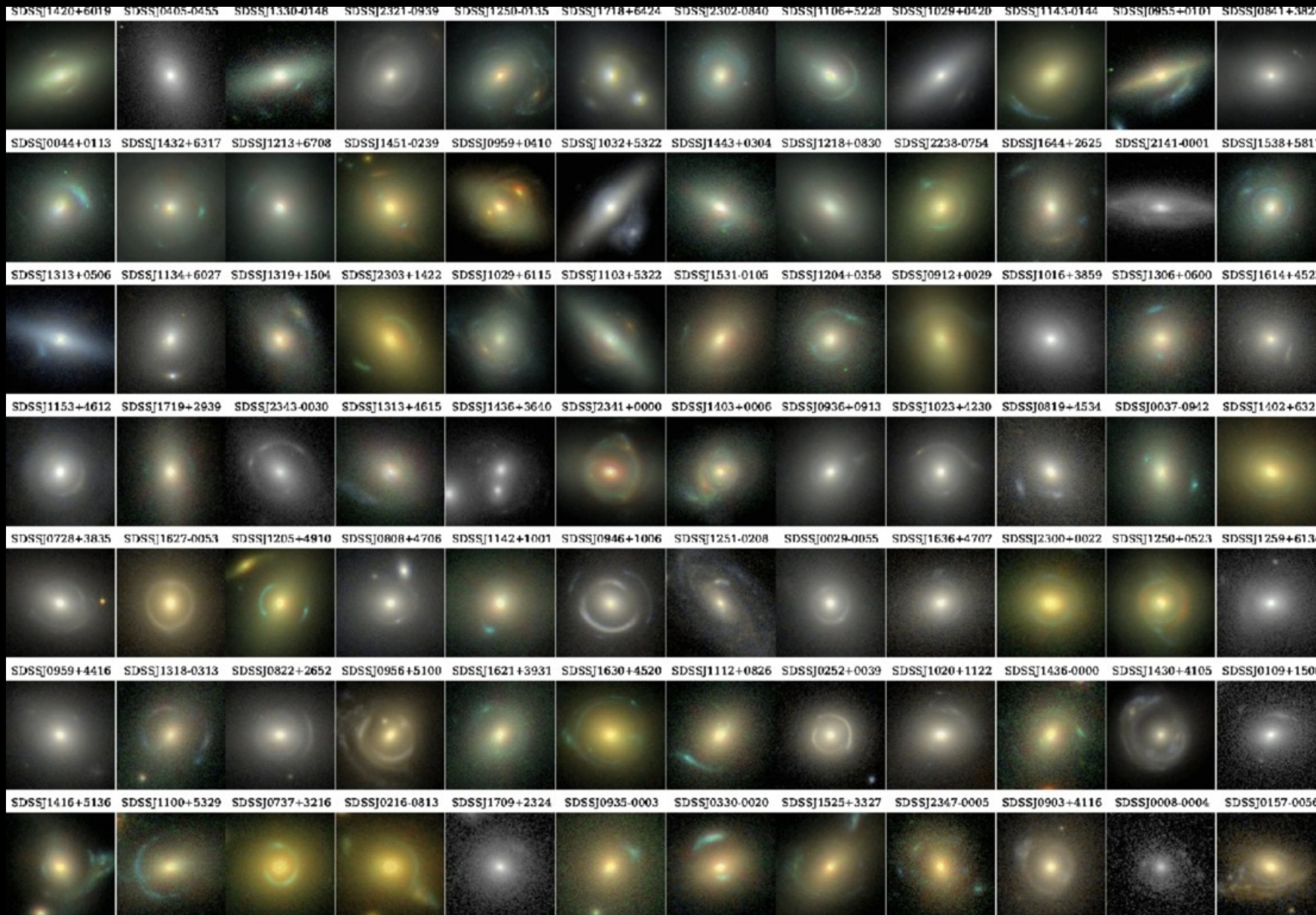




What about evolution?

- The evolution of the density slope could tell us about what physical processes are going on during the late ($z<1$) history of ETGs
- Dry mergers make the density profile shallower
- Wet mergers make the density profile steeper

The SLACS survey

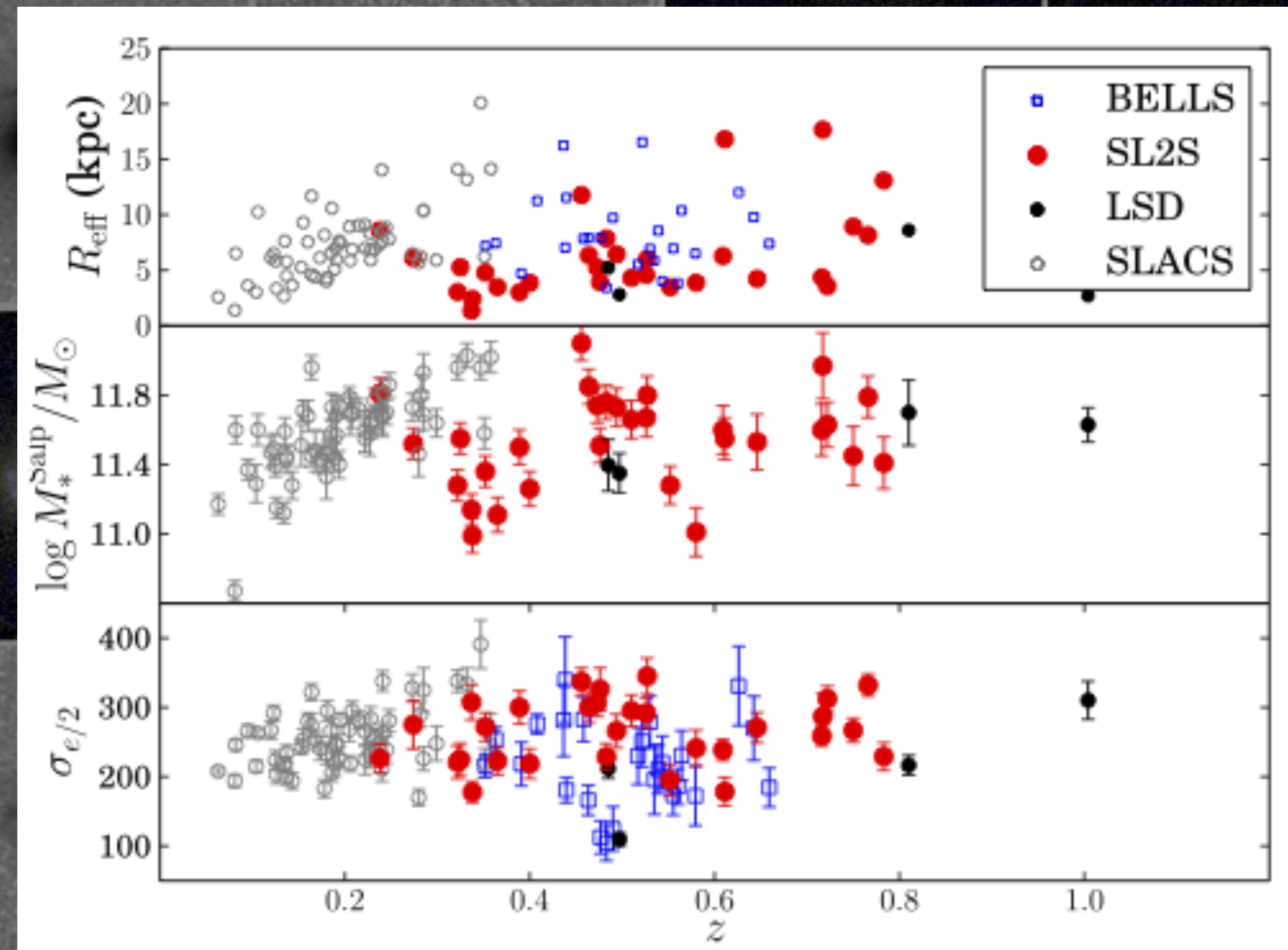


The SL2S survey

TABLE 1
CENSUS OF SL2S LENSES.

Grade	A	B	C	X	Total
With high-res imaging	30	3	13	21	67
With spectroscopy	36	15	2	5	58
High-res imaging and spectroscopy	27	3	0	0	30
Total with follow-up	39	15	15	26	95

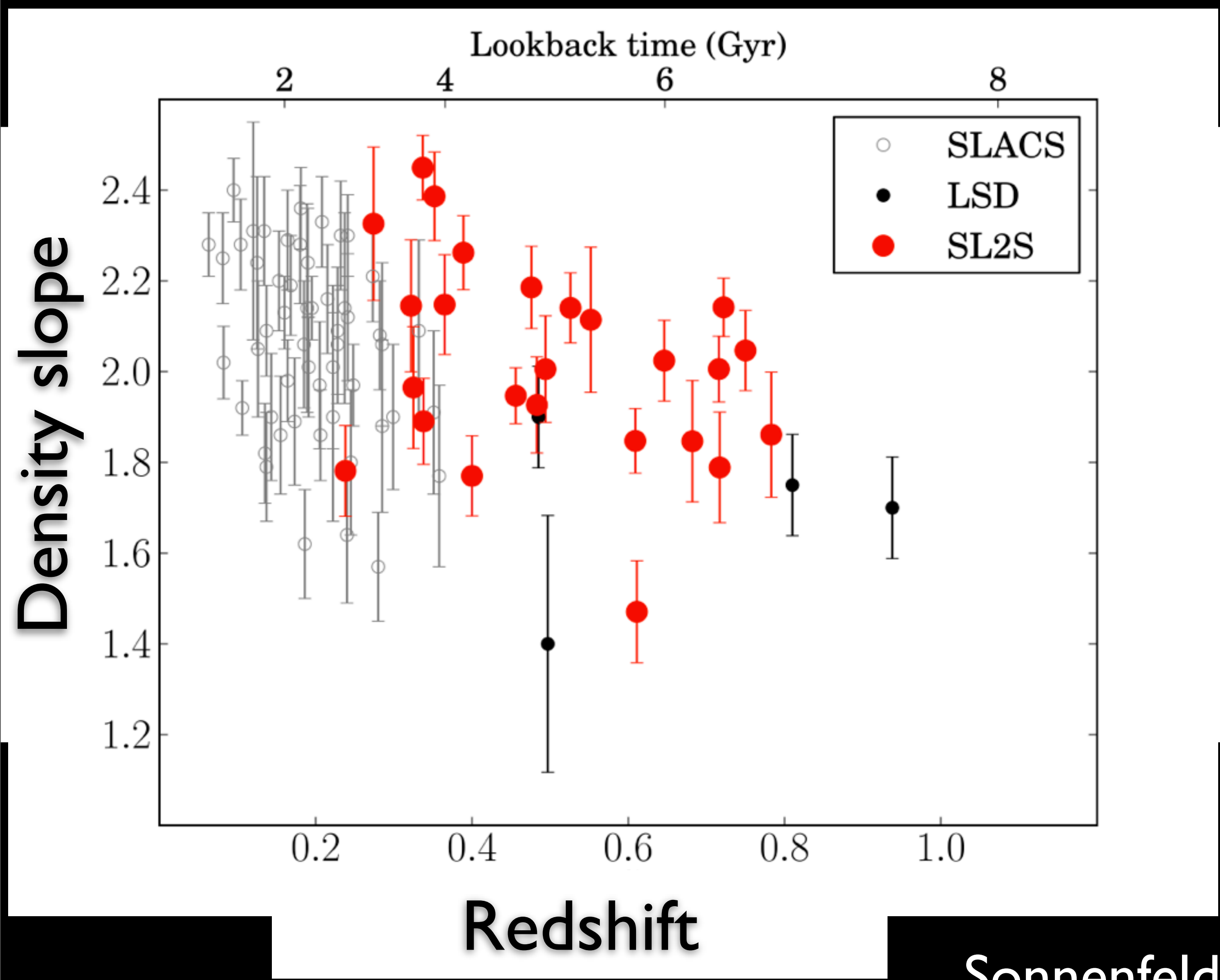
Ruff et al. (2011)
Gavazzi et al. (2012)
Sonnenfeld et al. (2013a)
Sonnenfeld et al. (2013b)
Gavazzi et al. (2014)
Sonnenfeld et al. (2015)

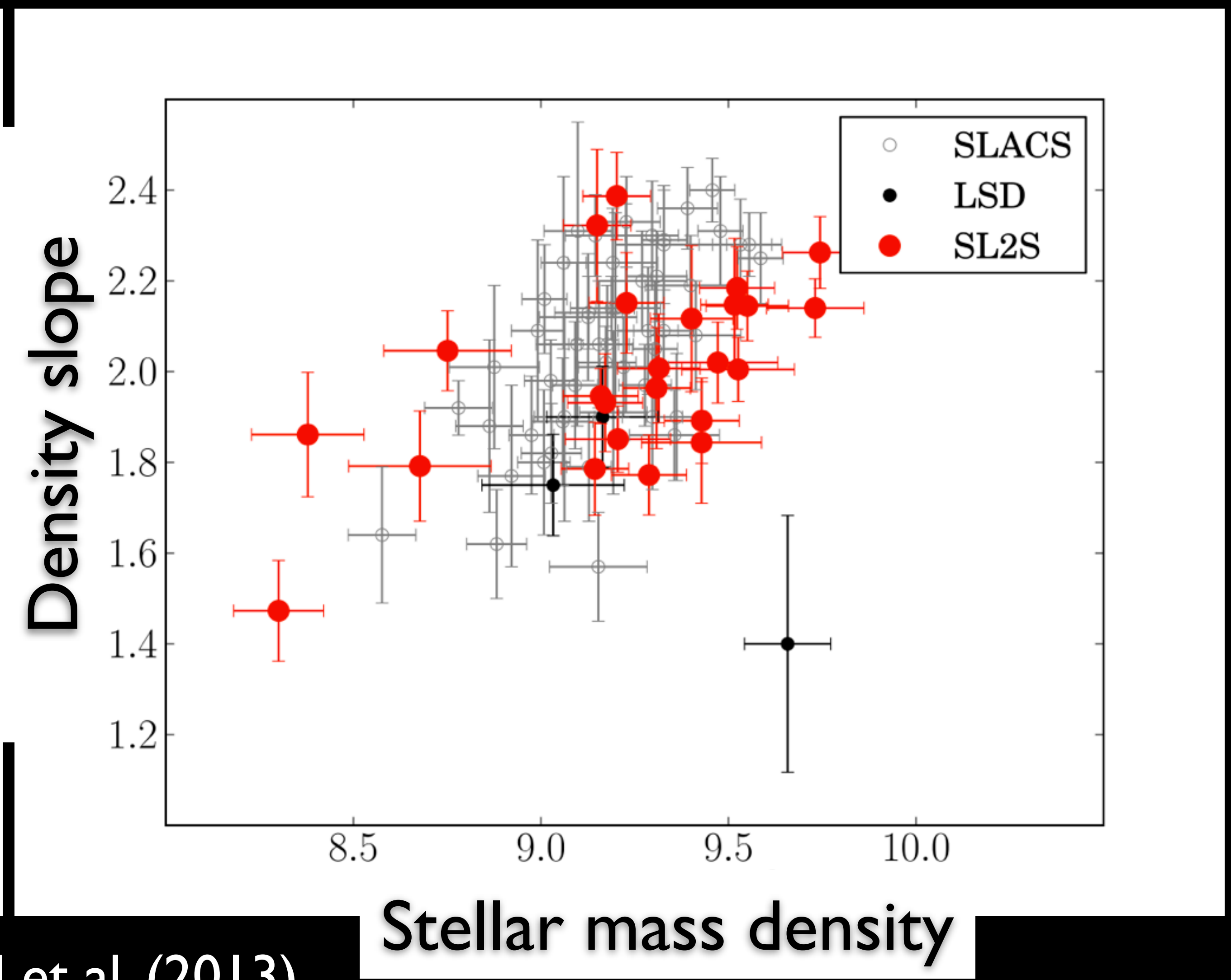


Sonnenfeld et al. (2013)

Evolution

$$\rho(r) \propto r^{-\gamma'}$$

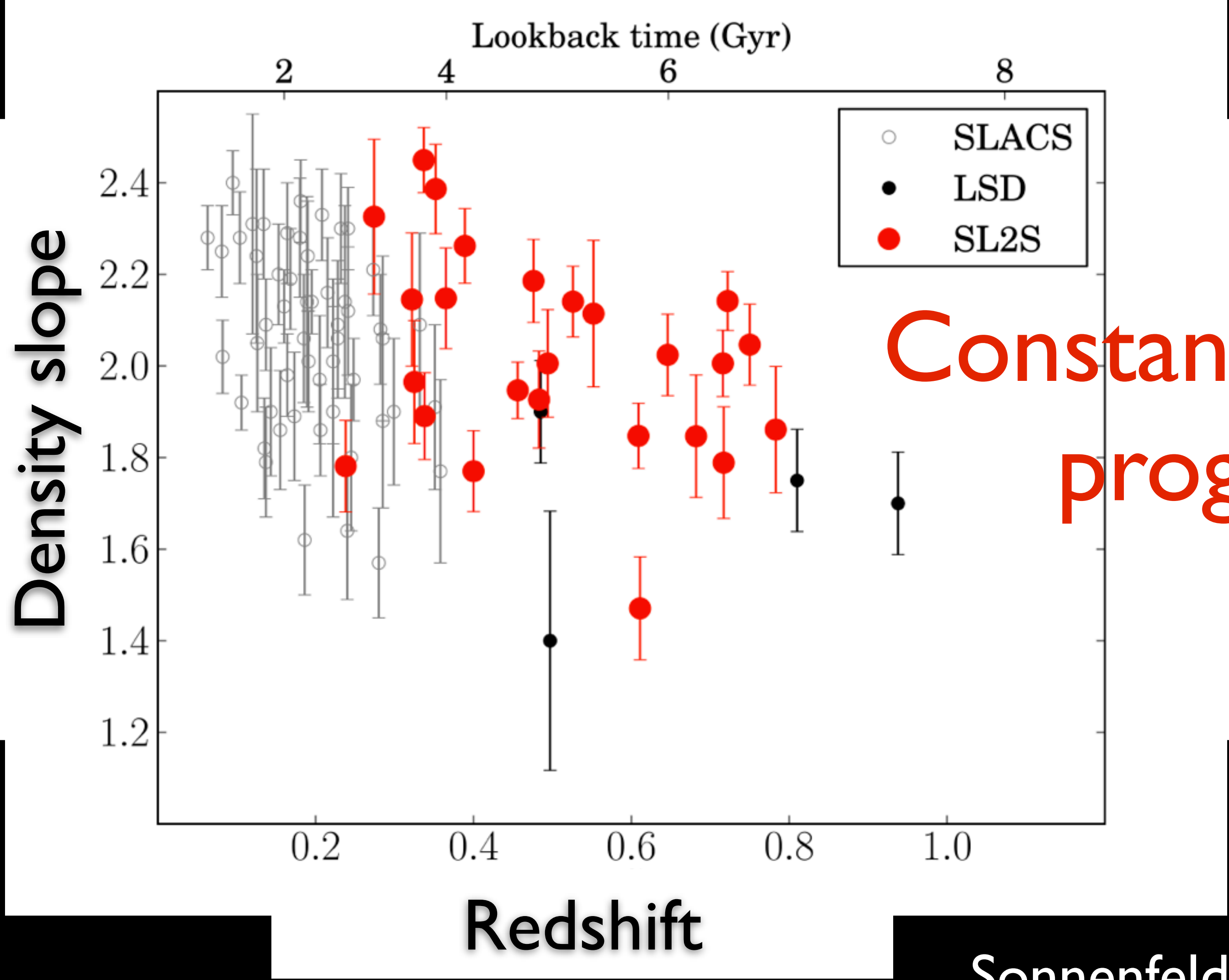


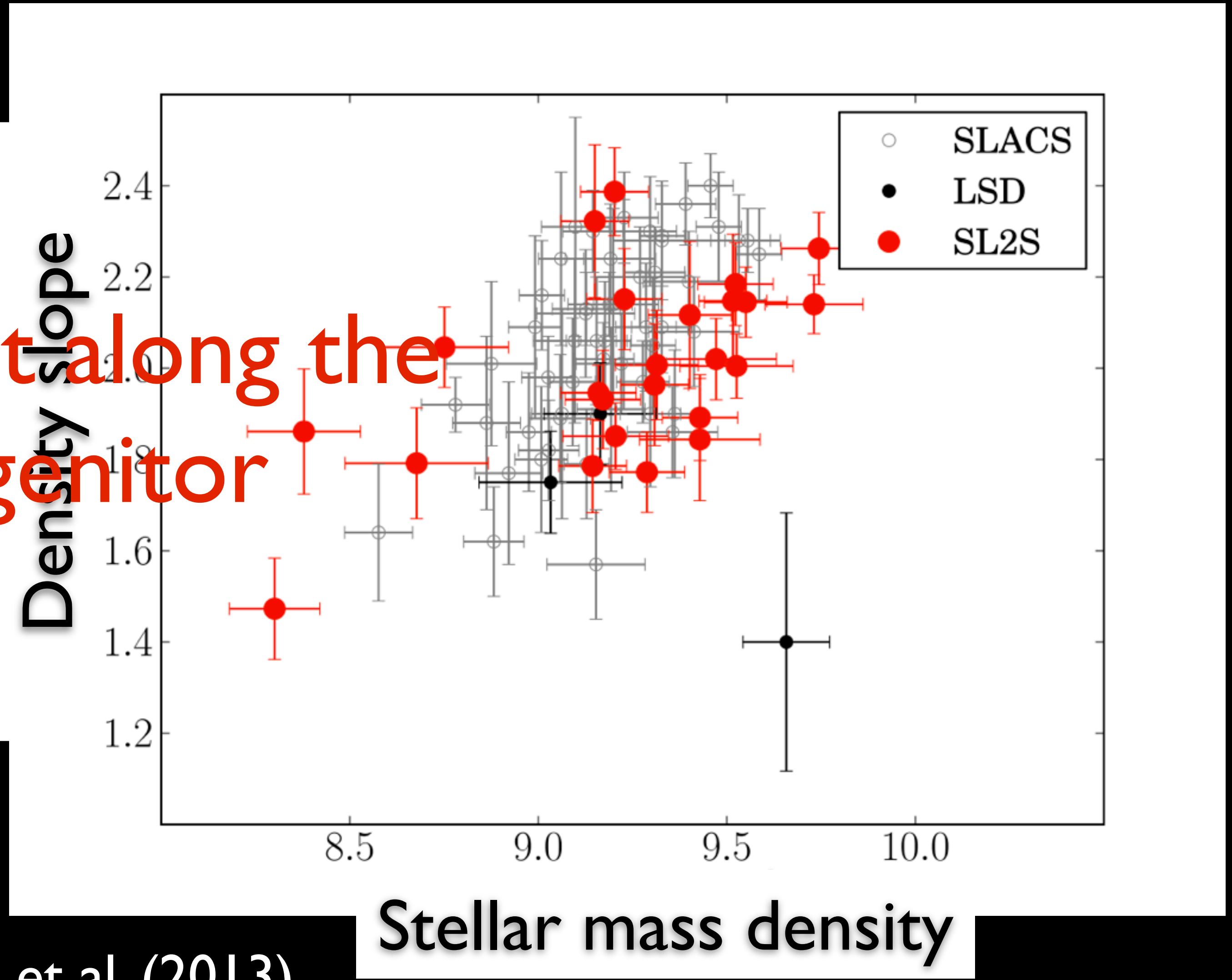


Sonnenfeld et al. (2013)

Evolution

$$\rho(r) \propto r^{-\gamma'}$$





Constant along the progenitor

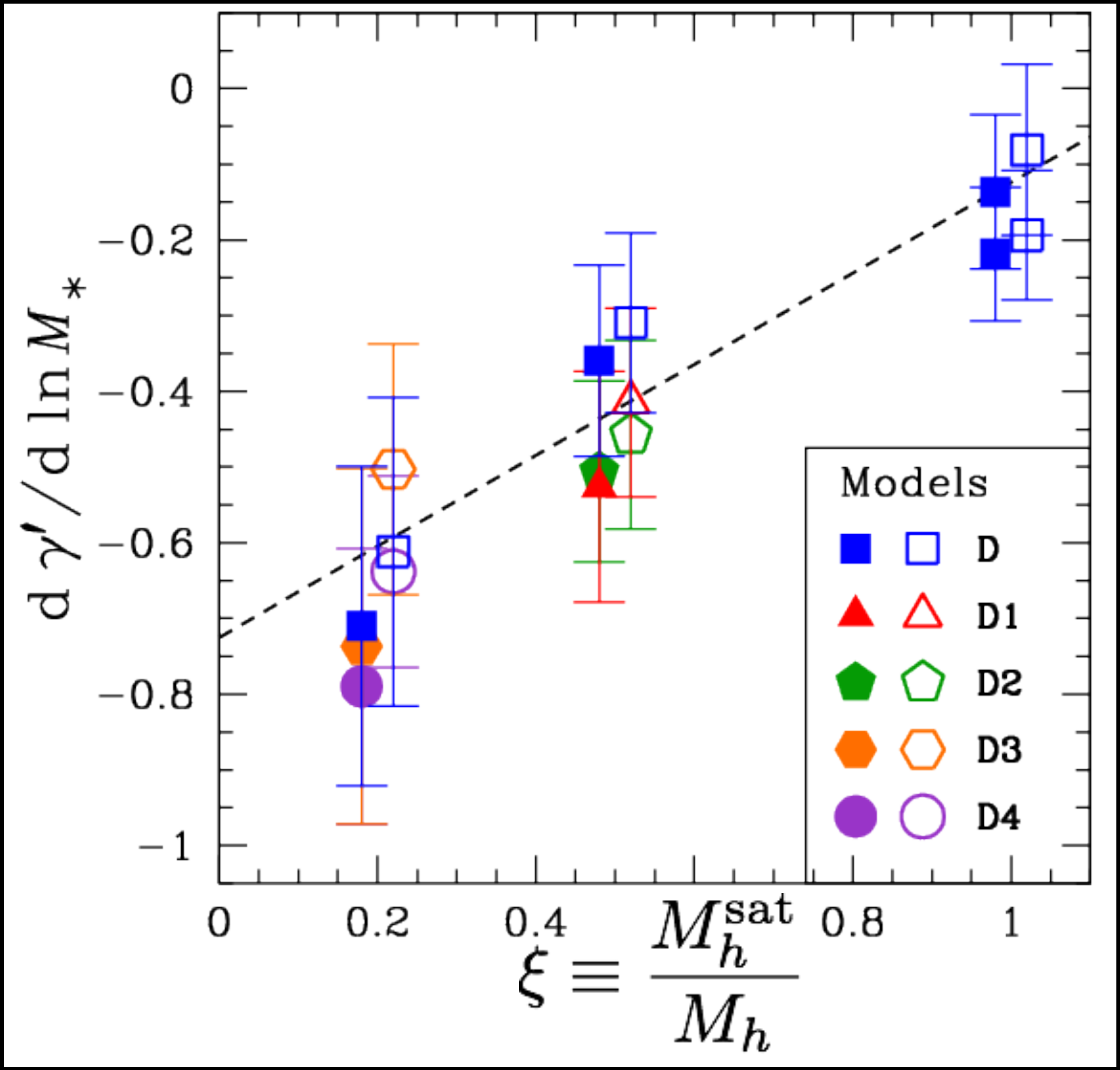
Sonnenfeld et al. (2013)

Testing a dry merger evolution scenario

- Dry mergers are able to reproduce the observed size evolution (at $z<1$)
- What about the evolution in the density profile?

Testing the dry merger scenario

- Assign stellar masses to halos with abundance matching
- Grow halos through mergers, with rates from Millennium simulation
- Effect of dry mergers on density profile taken from high resolution merger simulations
- Density slope is measured in simulations with same method used in lensing



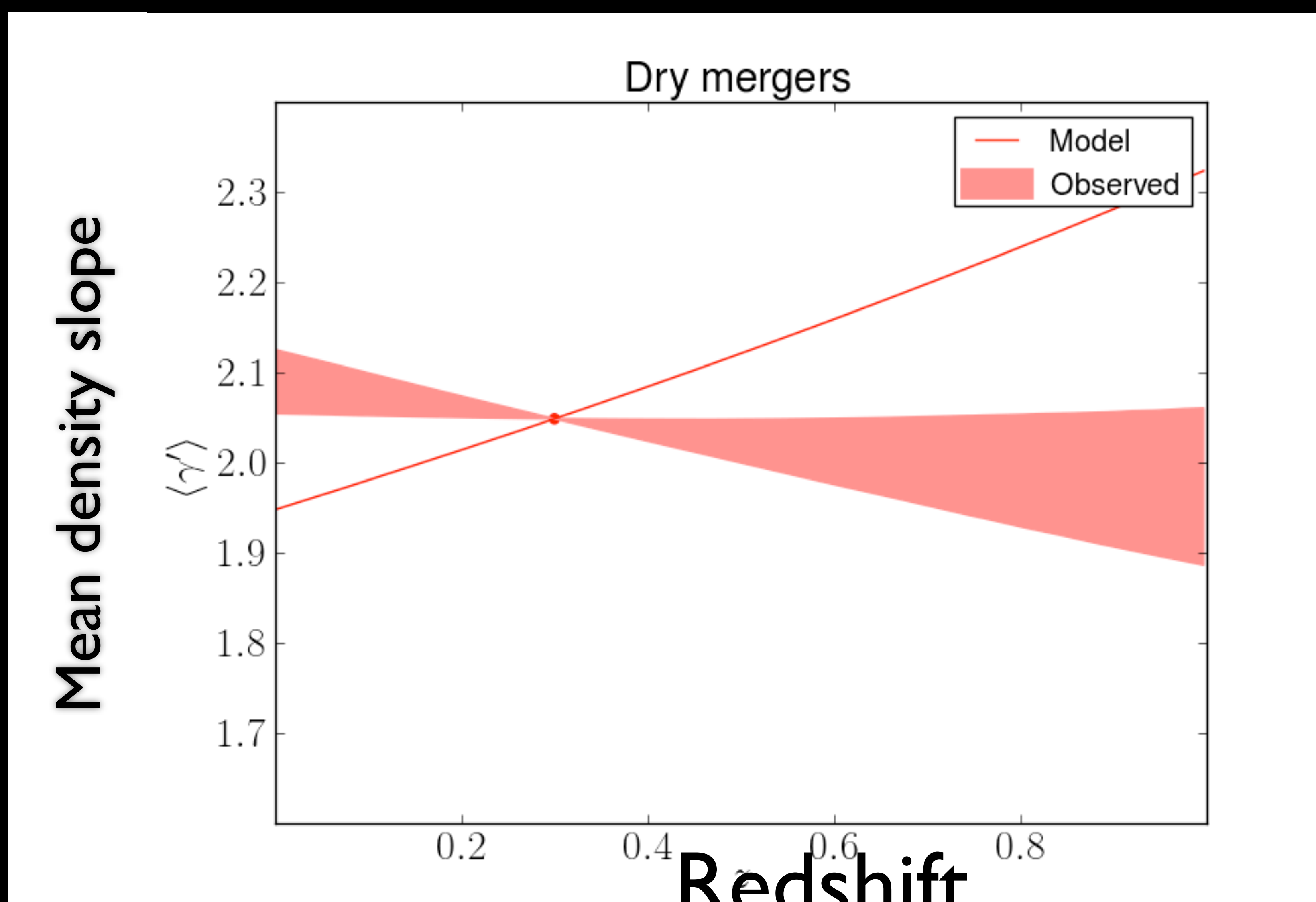
Sonnenfeld et al. (2014)

Testing the dry merger scenario

PURELY DRY MERGERS DO NOT EXPLAIN THE OBSERVED EVOLUTION OF MASSIVE EARLY-TYPE GALAXIES SINCE $Z \sim 1$

ALESSANDRO SONNENFELD[1*], CARLO NIPOTI[2], AND TOMMASO TREU[1†]

Draft version December 12, 2013



Sonnenfeld , Nipoti & Treu (2014)

Testing the dry merger scenario

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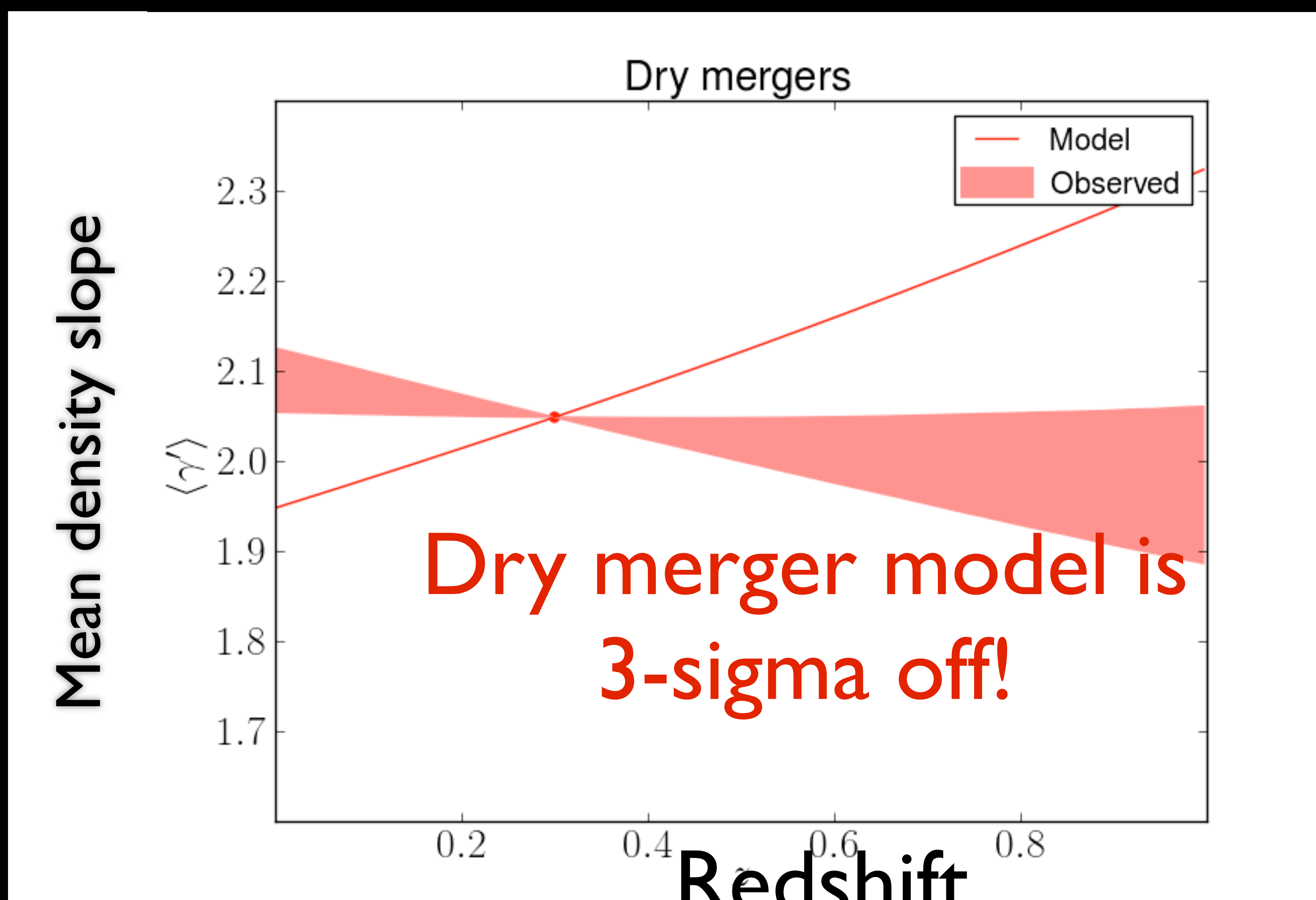


Sonnenfeld , Nipoti & Treu (2014)

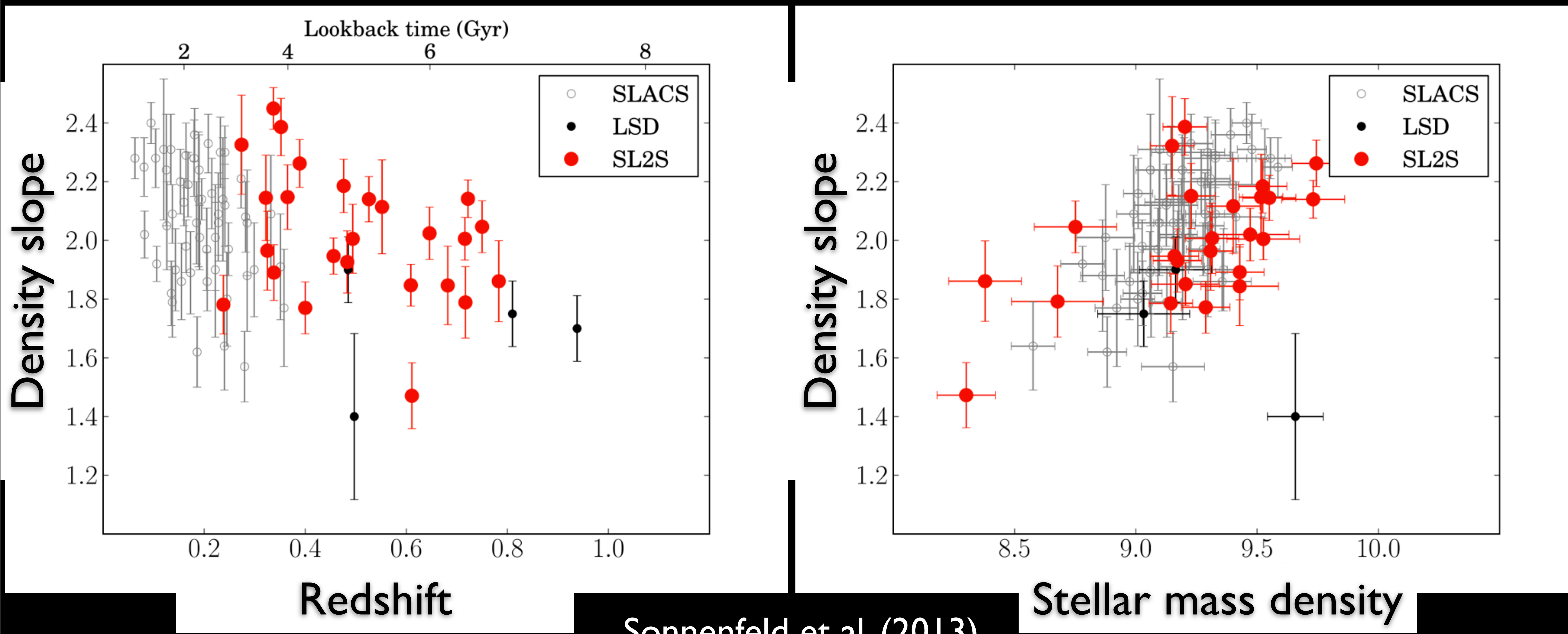
Part I: summary

- The mass-weighted density slope of early-type galaxies is close to isothermal
- The slope scales with stellar mass density and redshift
- Evolution (or lack thereof) of the density slope is in tension with a purely dry merger evolution

Part II: size dependence

Evolution

$$\rho(r) \propto r^{-\gamma'}$$

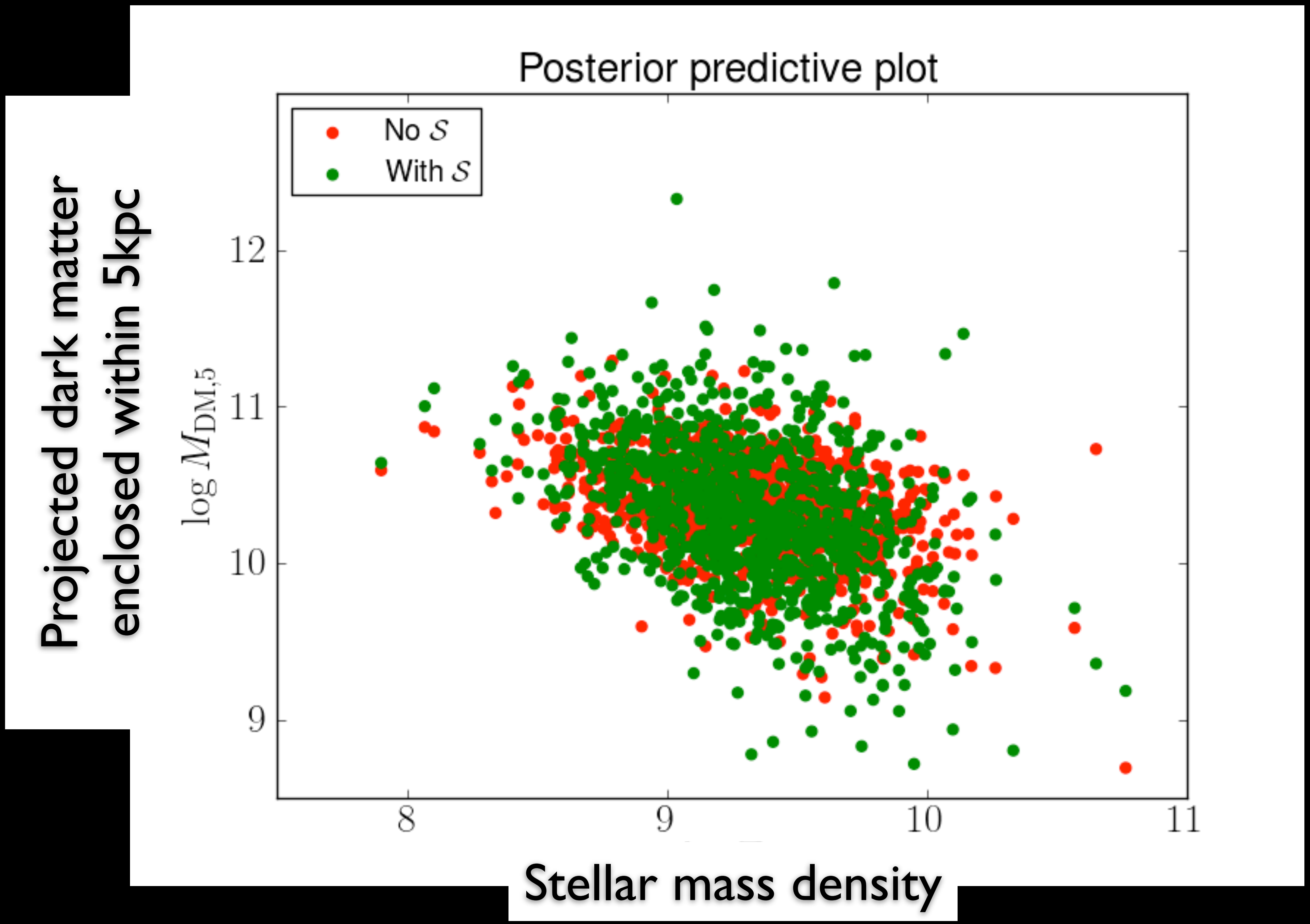


Sonnenfeld et al. (2013)

A two-component model

- Stellar bulge + gNFW dark matter halo
- Free parameters: stellar mass (IMF), projected dark matter mass, dark matter slope
- Hierarchical Bayesian fit: model parameters describe the properties of the population of massive ETGs

Dark matter content depends on size



- Dark matter mass anti-correlates with stellar mass density: at fixed stellar mass, more compact objects live in smaller dark matter halos

- Could also be that the dark matter content in the inner few kpcs is driving the trend (for example as a result of feedback)

Conclusions

- We know little about dark matter in ETGs
- Current sample of ~80 lenses gives competitive constraints on dark matter masses (hence halo masses)
- Lots of potential with future surveys

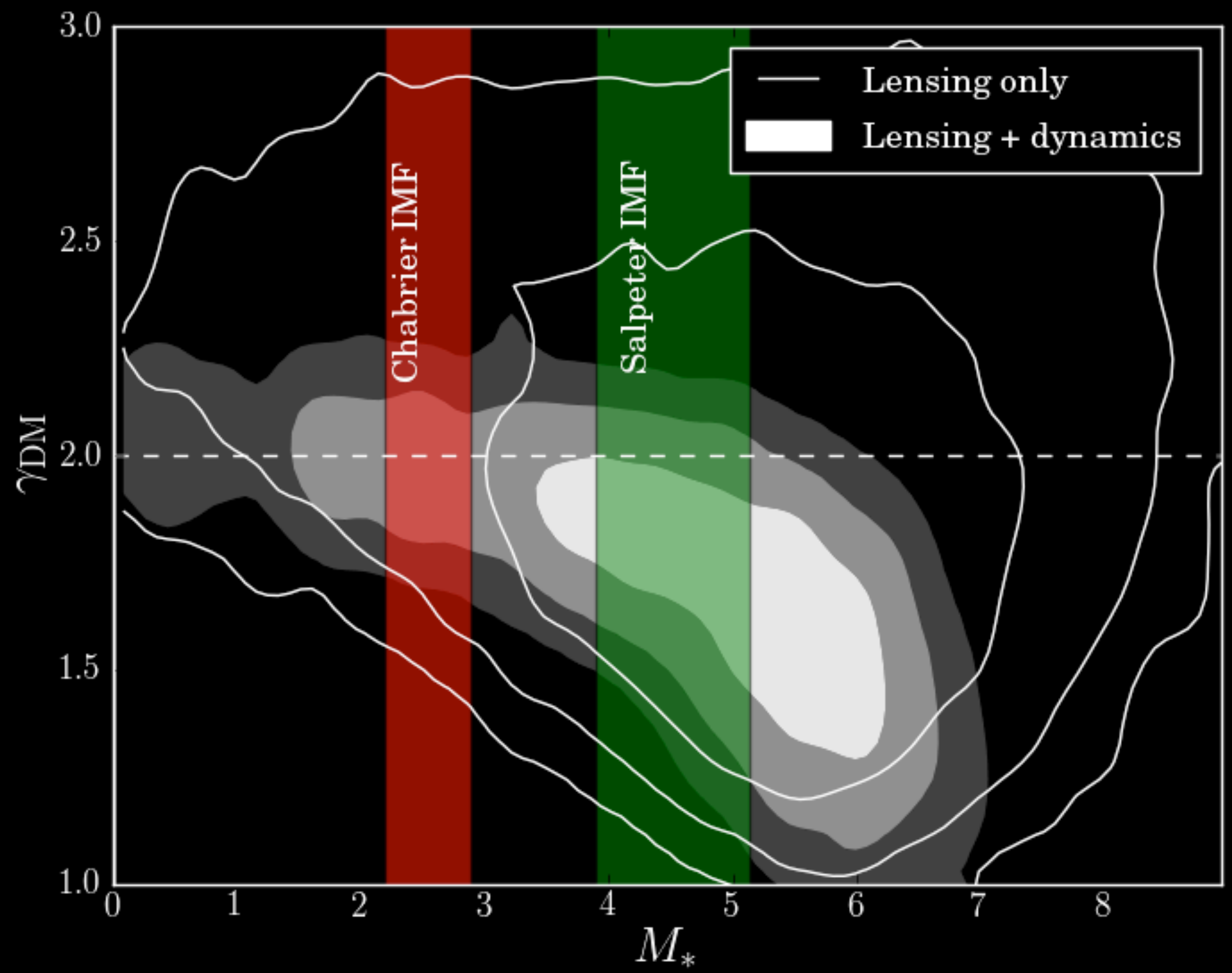
Questions

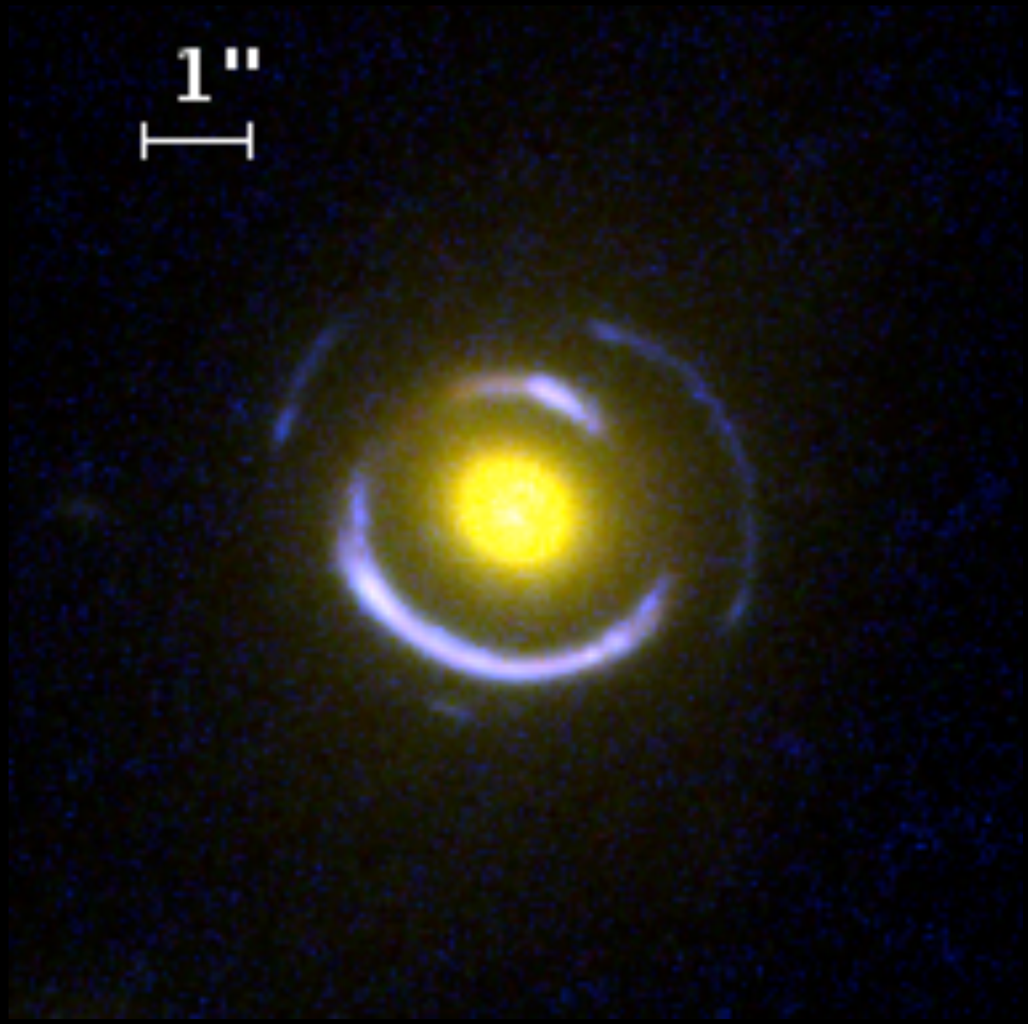
- What are some other observables that can be tested vs. size?

Thank you!

Extra slides

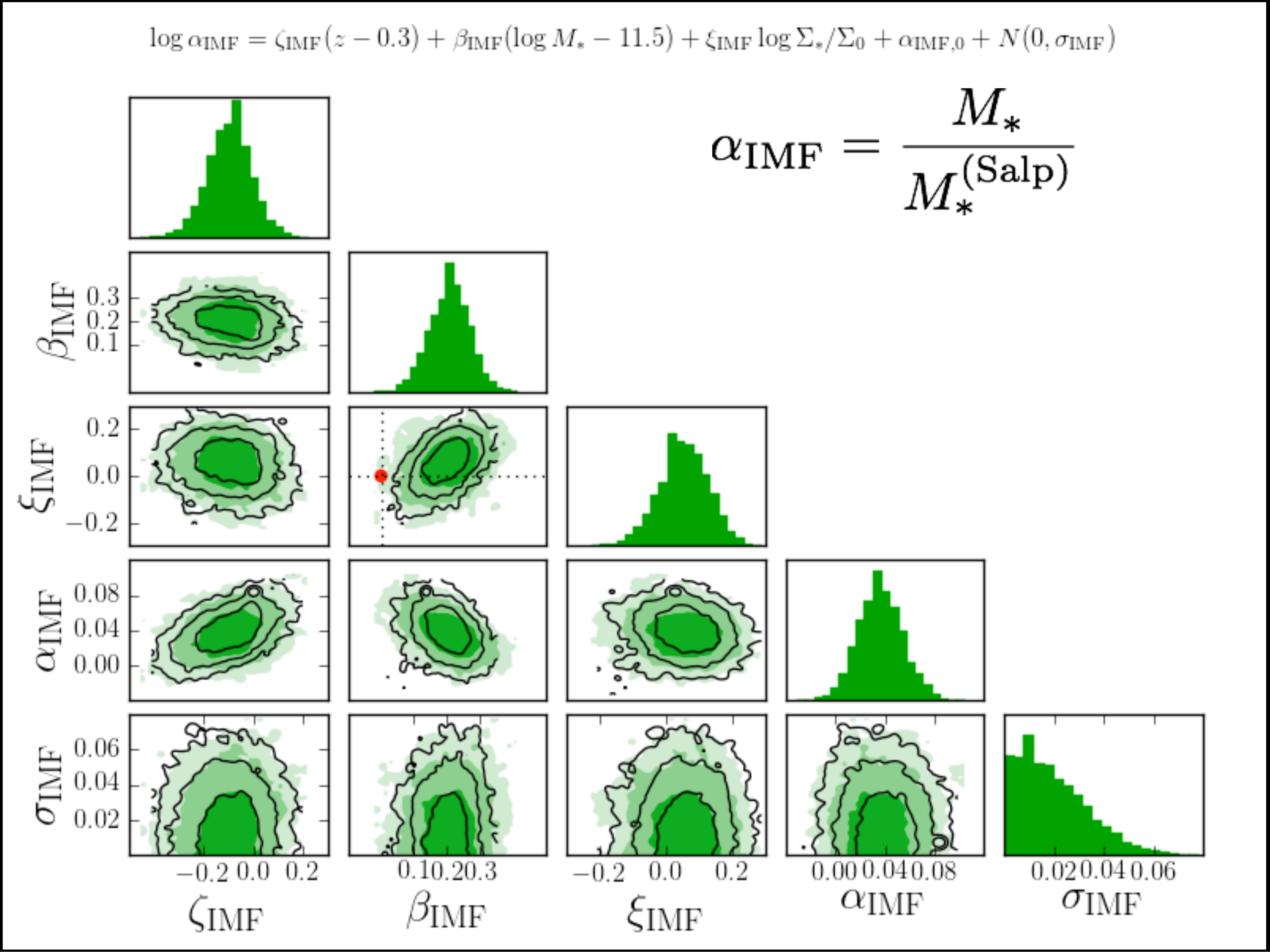
Measurements on individual galaxies



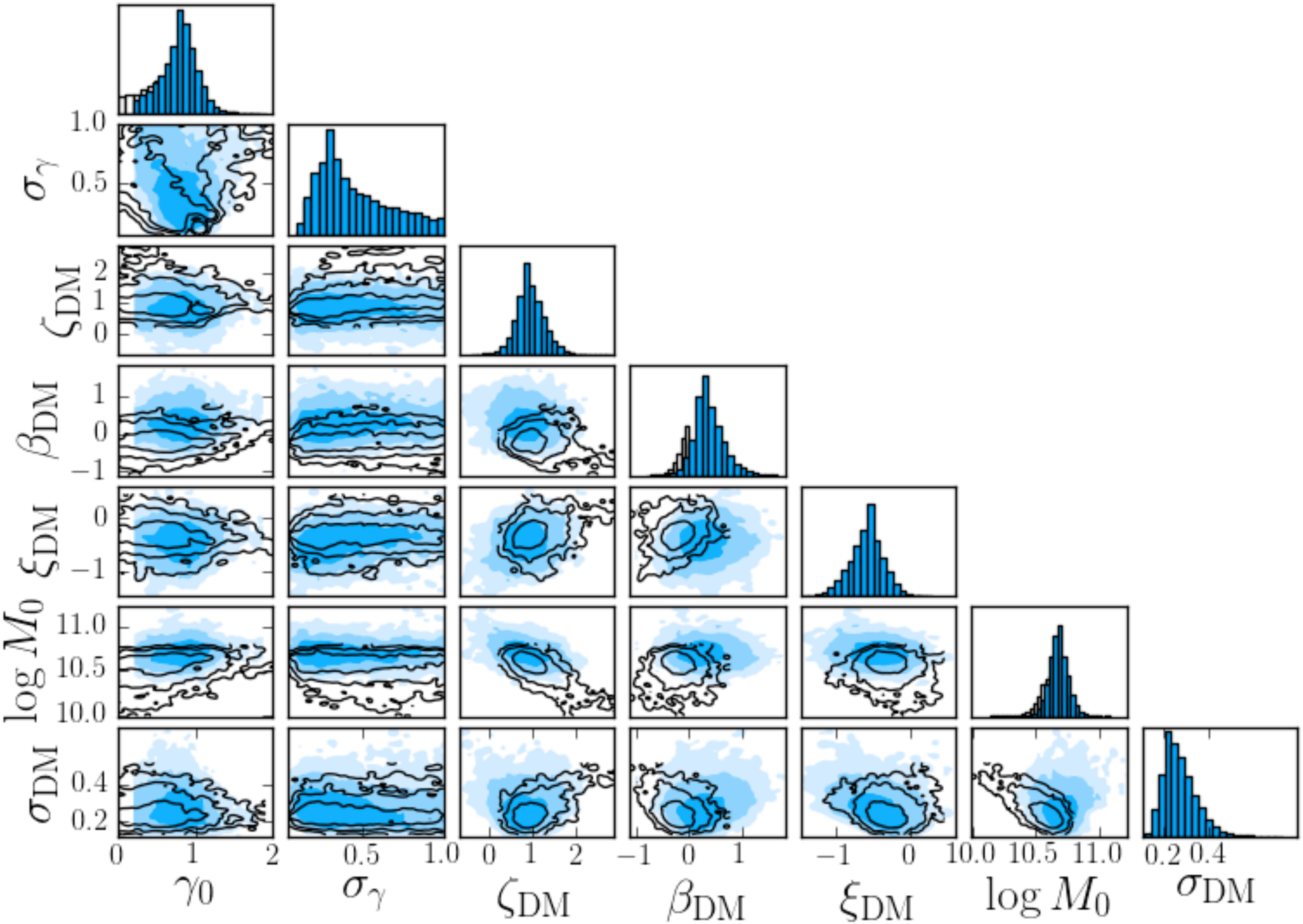


Sonnenfeld et al. (2012)

Statistically combining ~80 lenses

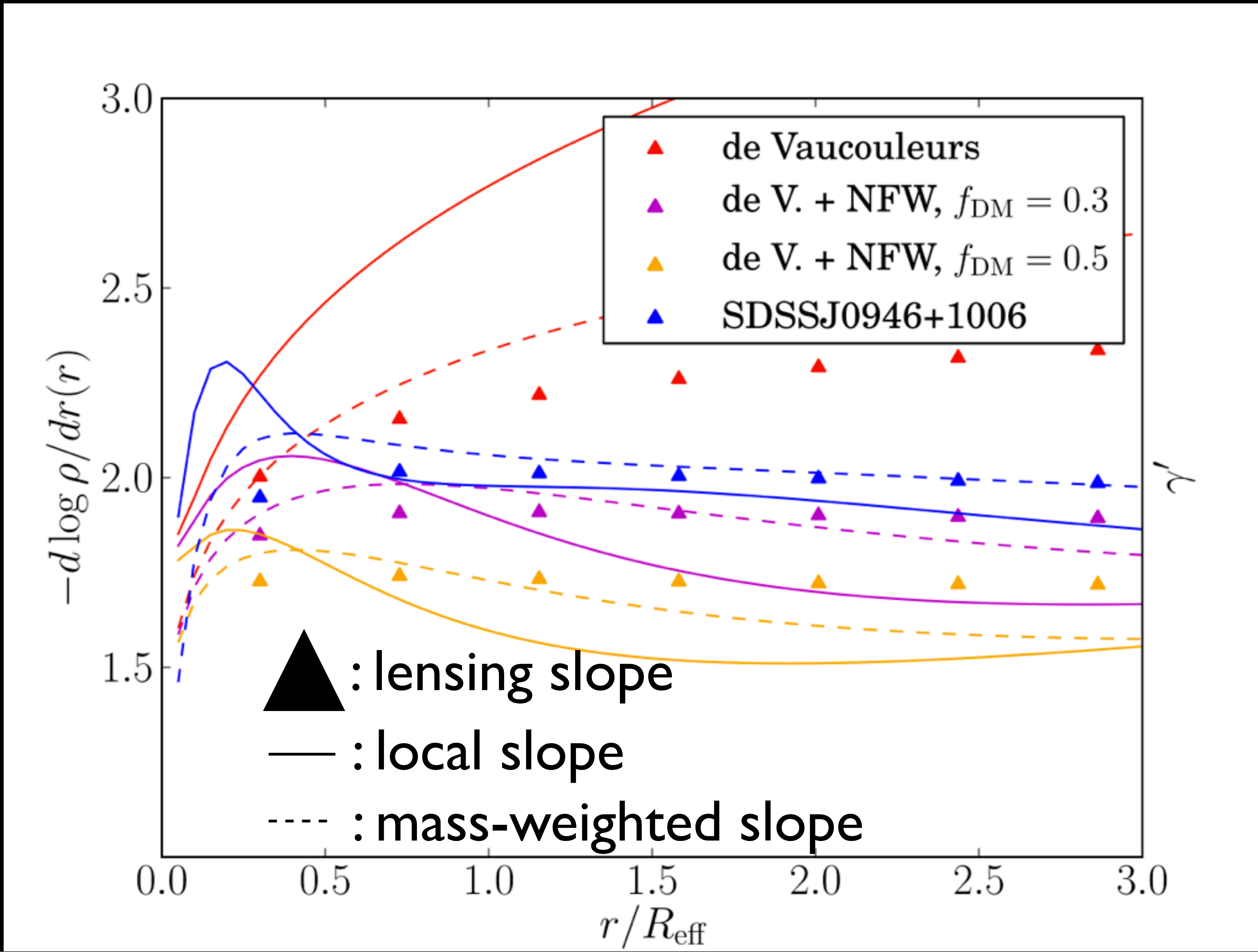


$\gamma_{\rm DM} = \gamma_0 + N(0, \sigma_\gamma) \quad ; \quad \log M_{\rm DM} = \zeta_{\rm DM}(z - 0.3) + \beta_{\rm DM}(\log M_* - 11.5) + \xi_{\rm DM} \log \Sigma_*/\Sigma_0 + \log M_0 + N(0, \sigma_{M_{\rm DM}})$



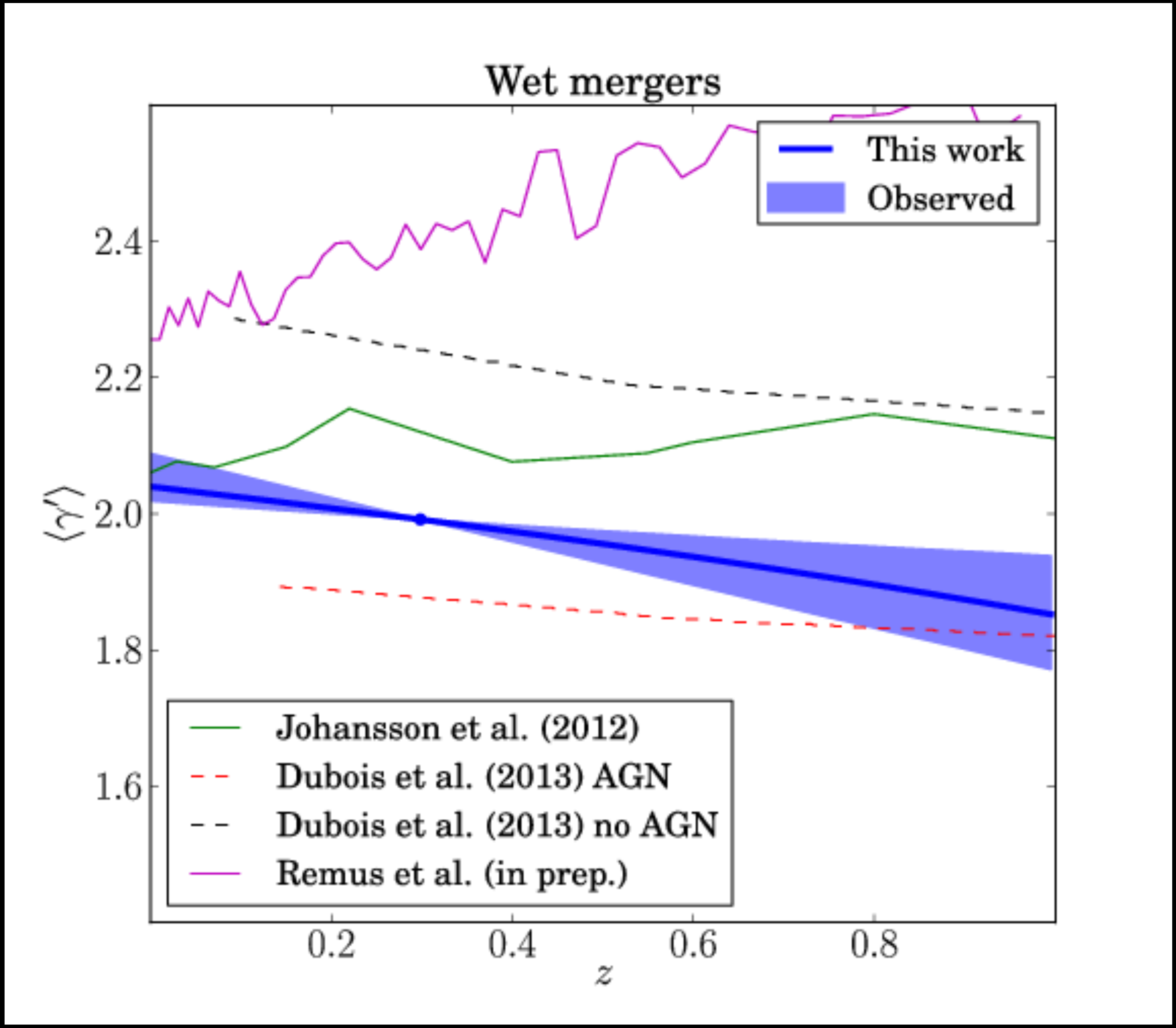
Sonnenfeld et al. (2015)

What are we measuring?



A wet merger toy model

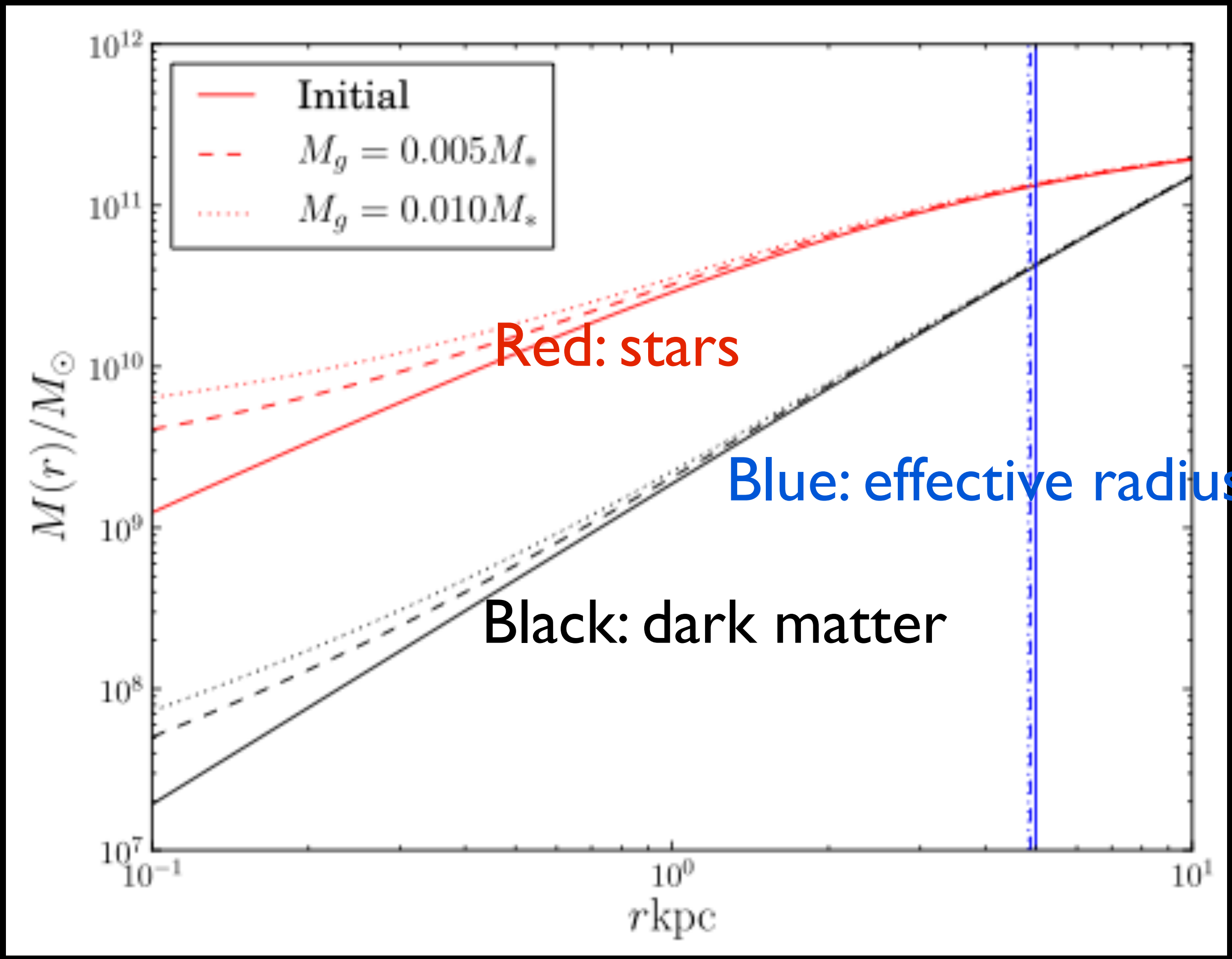
- Adding 10% of baryons in gas does the job
- Gas makes it harder to match observed size evolution
- Overall, the wet merger model provides a better fit to both size and density slope measurements
- Only a toy model: cosmological simulations are necessary to confirm or rule out this scenario



A wet merger toy model

- A fraction of the accreted baryonic mass is gas
- Gas falls to the center (r=0)
- The mass profile adiabatically contracts, following Blumenthal (1986, i.e. circular orbits)

$$r_i M(r_i) = r_f M(r_f)$$



Selection effects

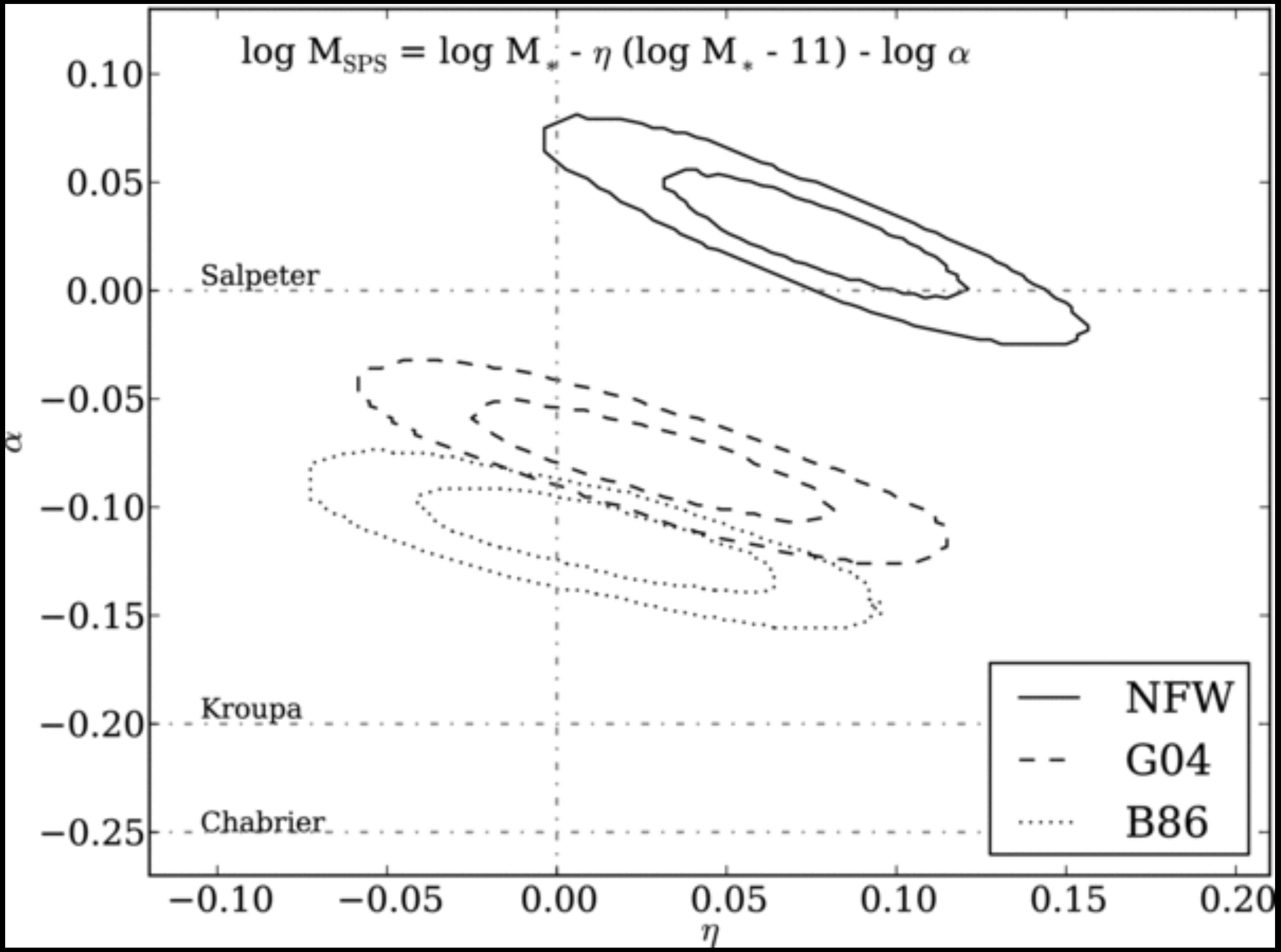
- SLACS and SL2S lenses are both magnitude-limited samples

$$\log M_{*,i} \sim N(\log M_{*,0} + \alpha_*(z - 0.3), \sigma_*)$$

- Lenses with too small (or large) Einstein radii are more difficult to observe
- Galaxies with larger lensing cross-section are more likely to be lenses

$$P(\psi_i|\eta) \propto S(R_{\rm Ein}(\psi_i))\sigma_{\rm lens}(\psi_i)$$

Degeneracy with stellar mass



Auger et al. (2010b)