Dark matter in early-type galaxies: a strong lensing view

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Part I: Introduction

What do the dark matter halos of early-type galaxies look like?

Why is DM distribution important?

- Test hierarchical growth scenario: are halos growing the way we expect?
- Much more straightforward comparison with numerical simulations
- Test for effects of baryonic physics: adiabatic contraction vs. feedback
- Test for non-standard dark matter
- Predict DM annihilation signal

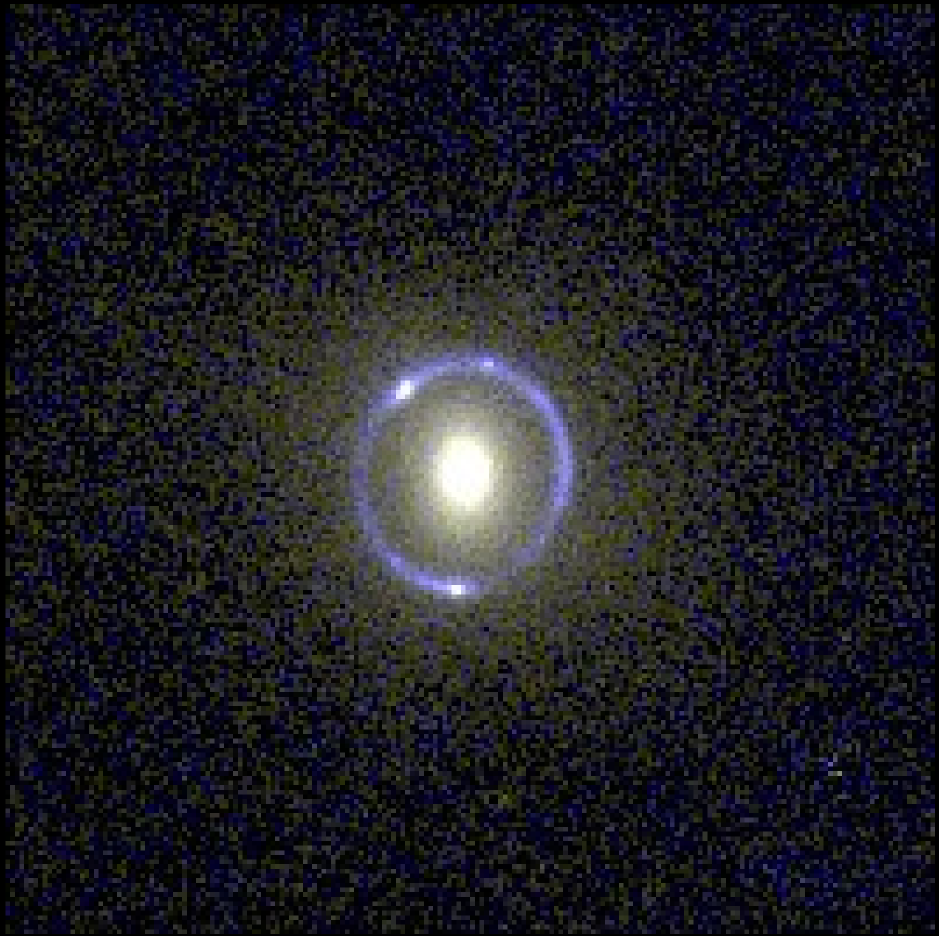
Measuring dark matter

- Observationally, dark matter (in early-type galaxies) is whatever mass does not follow the light

Measuring dark matter

$$R_{Ein} = \sqrt{\frac{4GM}{c^2}\frac{D_d D_{ds}}{D_s}}$$

$$\frac{1}{\rho_*}\frac{d\rho_*\sigma_r^2}{dr} + 2\frac{\sigma_\theta^2}{r} = -\frac{GM(r)}{r^2}$$



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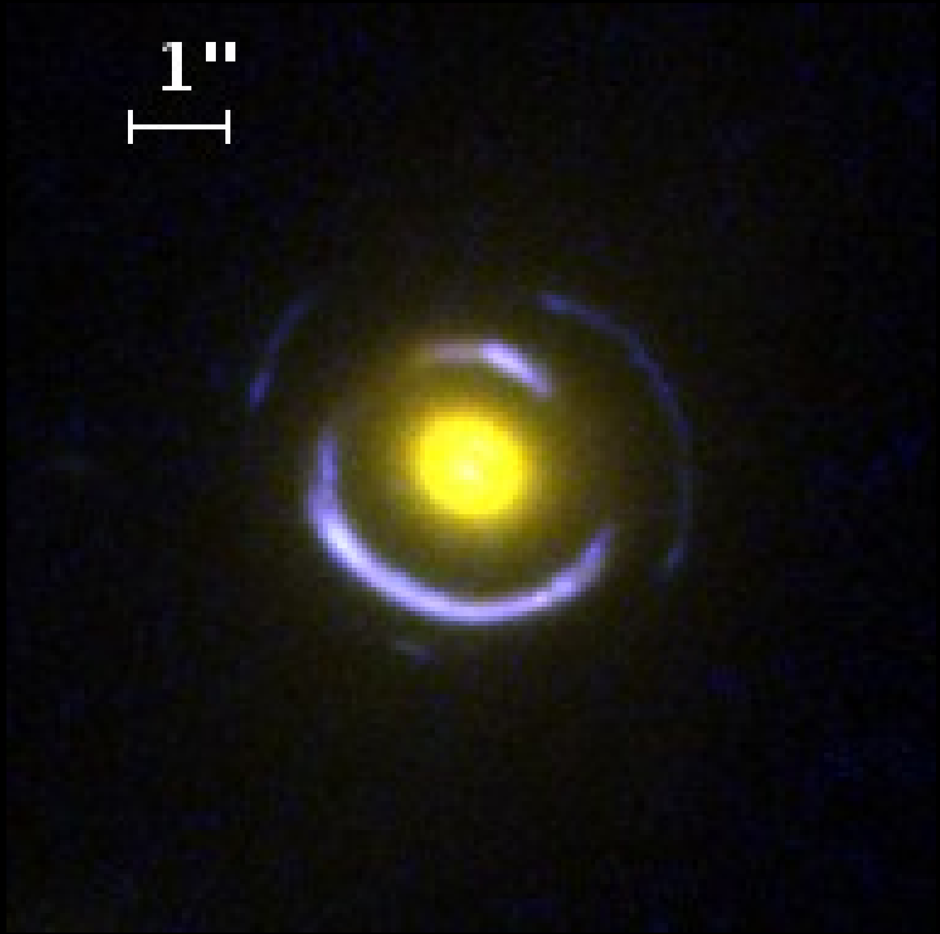
Part II: The “Jackpot”

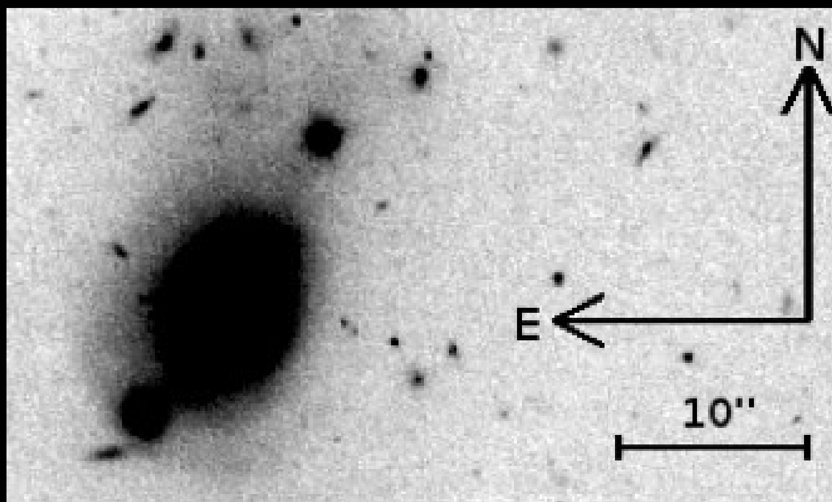
The “Jackpot”

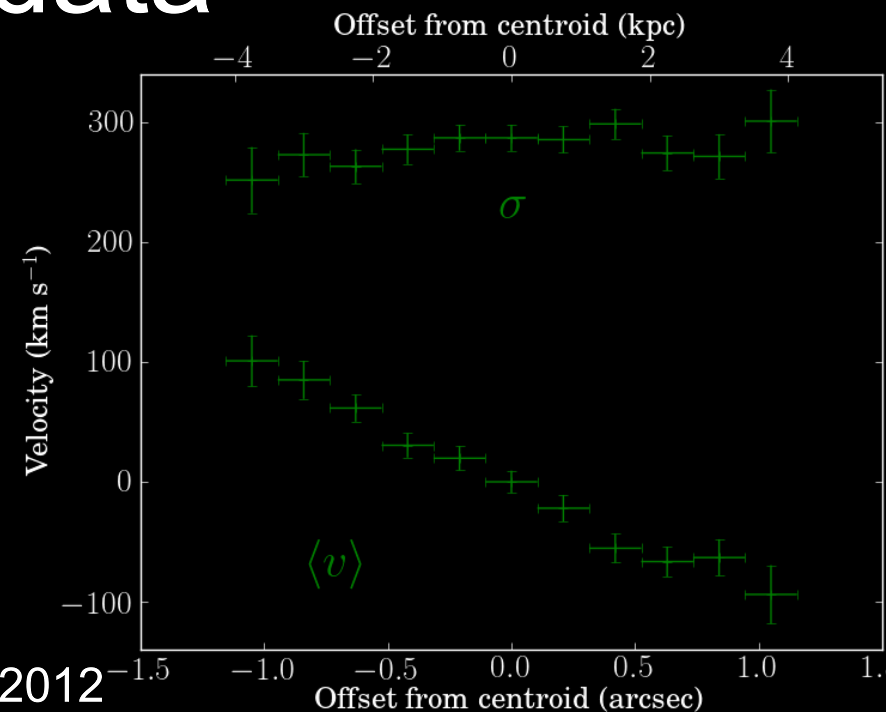
- Massive early-type galaxy at z = 0.222 (Gavazzi et al. 2008), V = -22.5
- Two lensed rings: more constraints than typical lenses
- Deep Keck spectroscopy



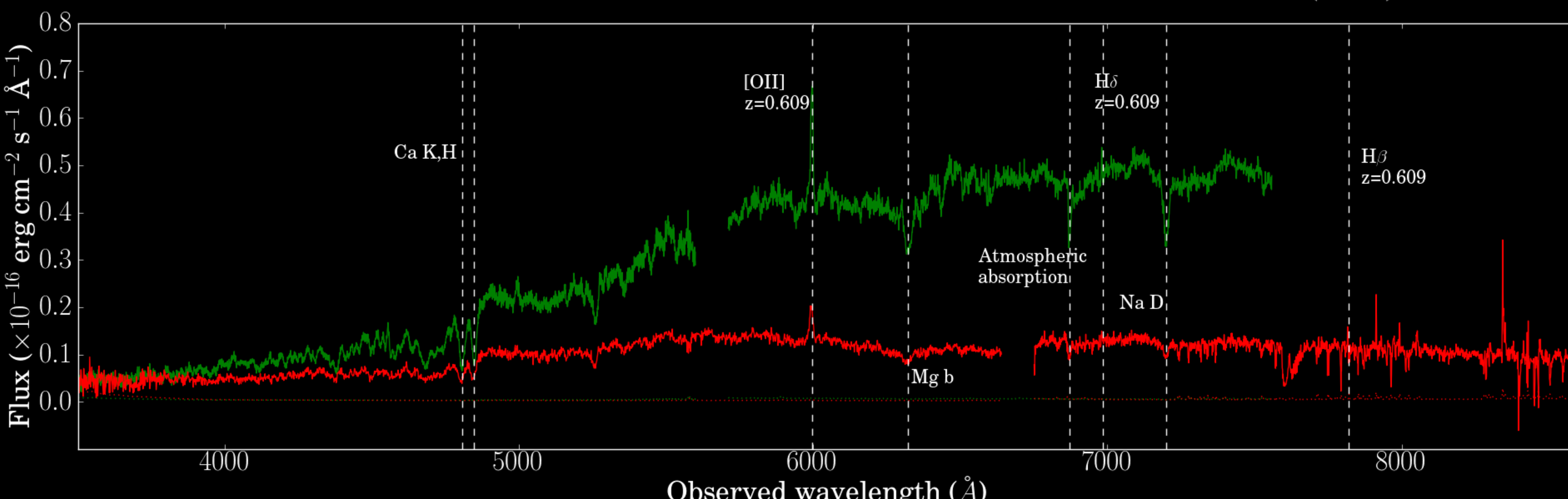
Sonnenfeld et al. 2012

The data





Sonnenfeld et al. 2012



The model

- Light: two tPIEMD

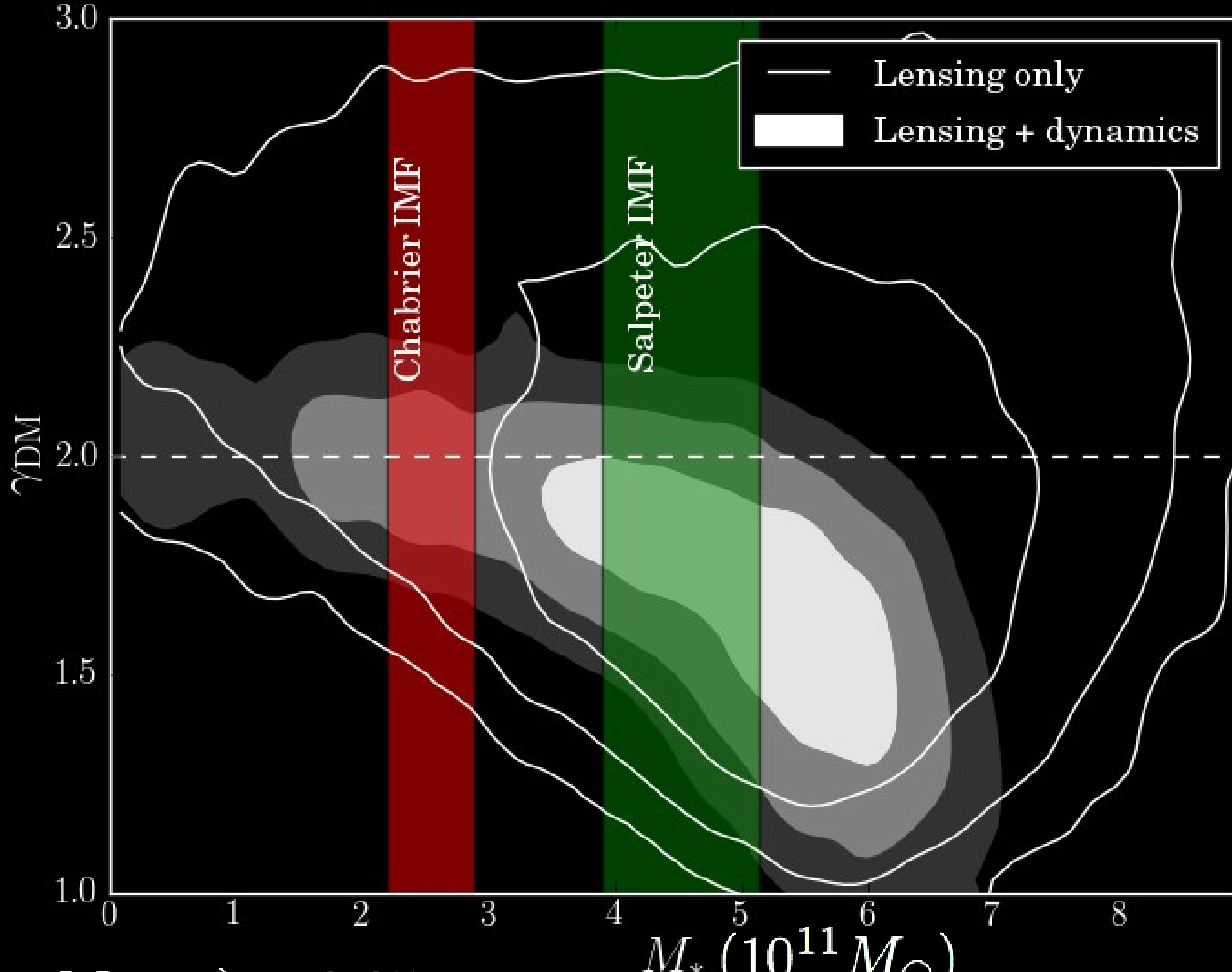
$$\rho(r) = \rho_c r_c^2 \left[\frac{1}{r_c^2 + r^2} - \frac{1}{r_t^2 + r^2} \right].$$

- Dark matter: power-law

$$\rho(r) \propto r^{-\gamma_{DM}}$$

- Osipkov-Merritt anisotropy $\frac{\sigma_\theta^2}{\sigma_r^2} = 1 - \frac{r^2}{r_a^2 + r^2}$

Results



$P(M_* > M_{Chab}) = 0.95$

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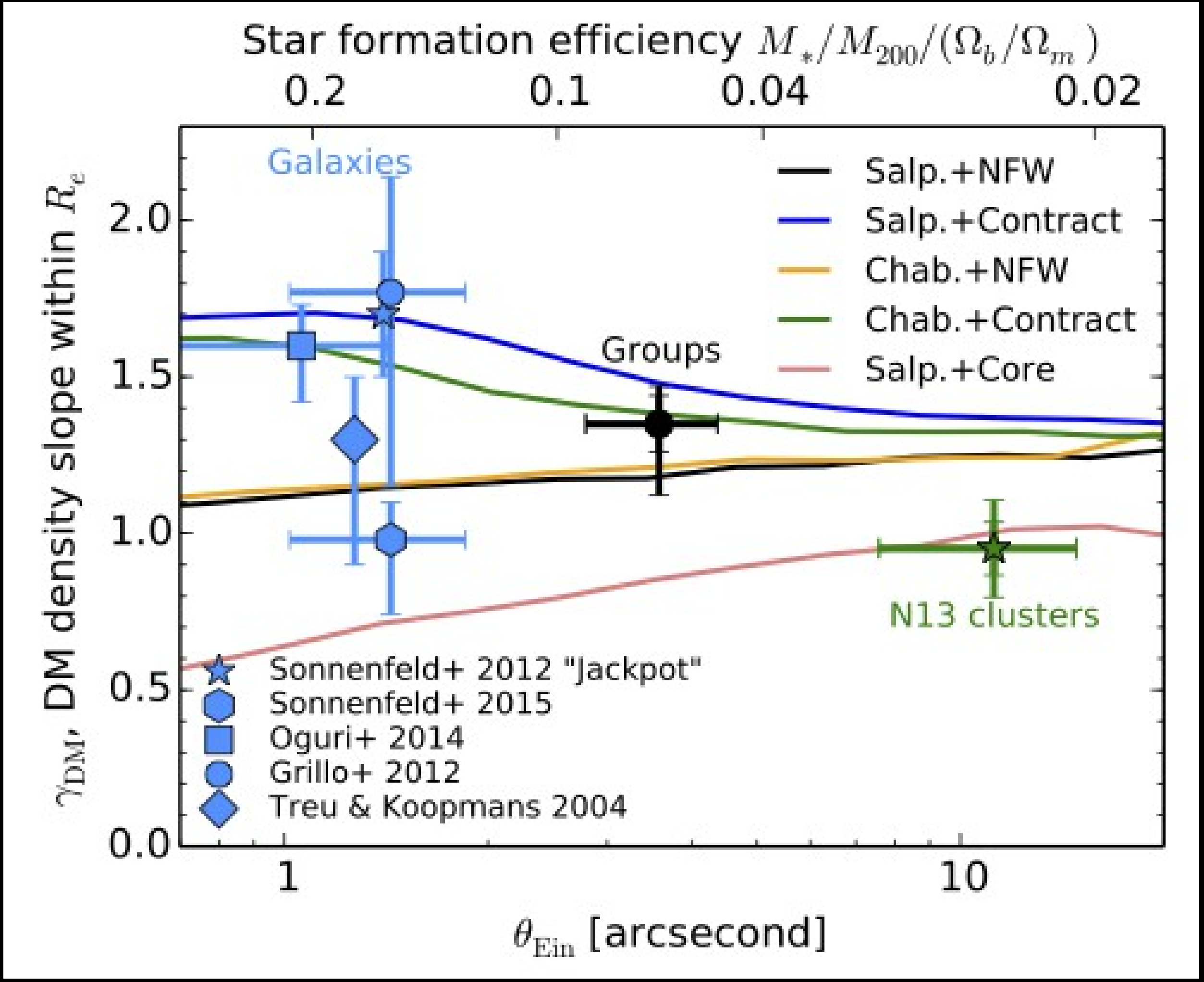
Sonnenfeld et al. 2012

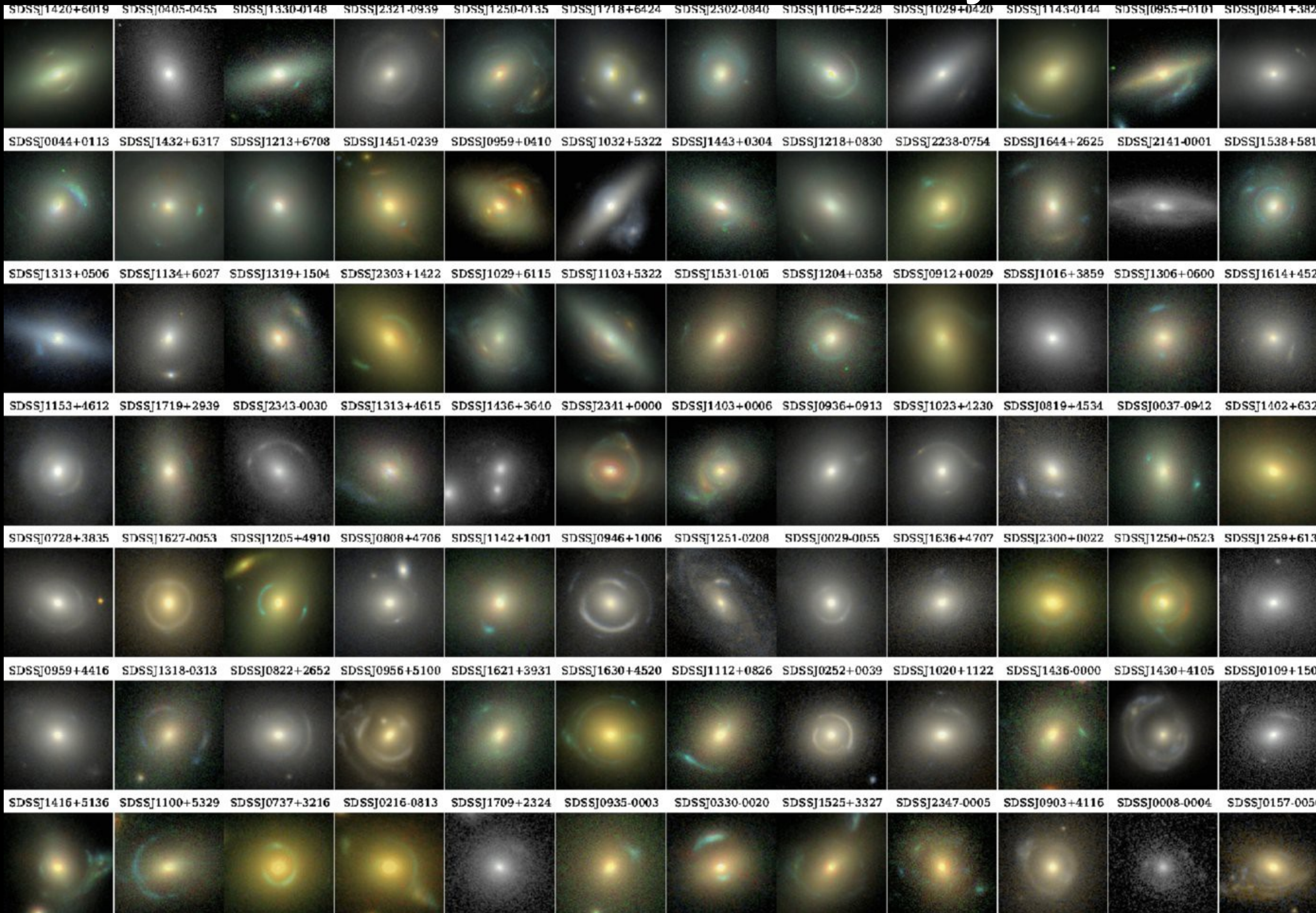
Results at higher halo masses



Newman et al. 2015

Part III: ensemble measurements

The SLACS survey



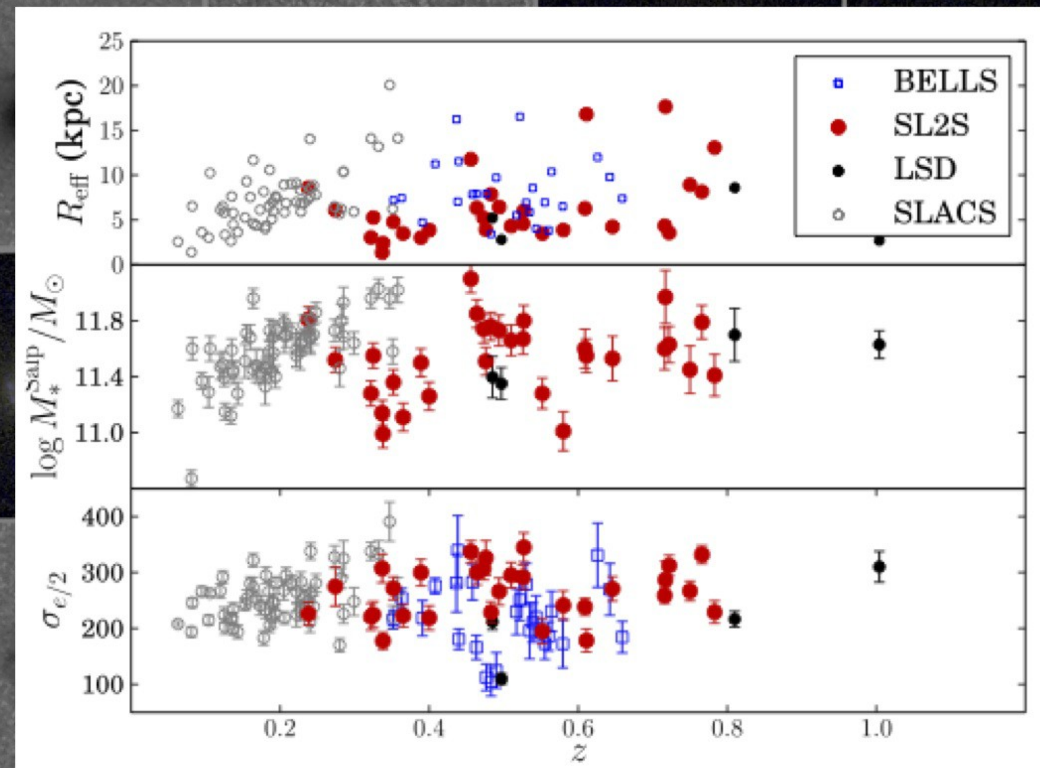
Auger et al. 2009

The SL2S survey

TABLE 1
Census of SL2S lenses.

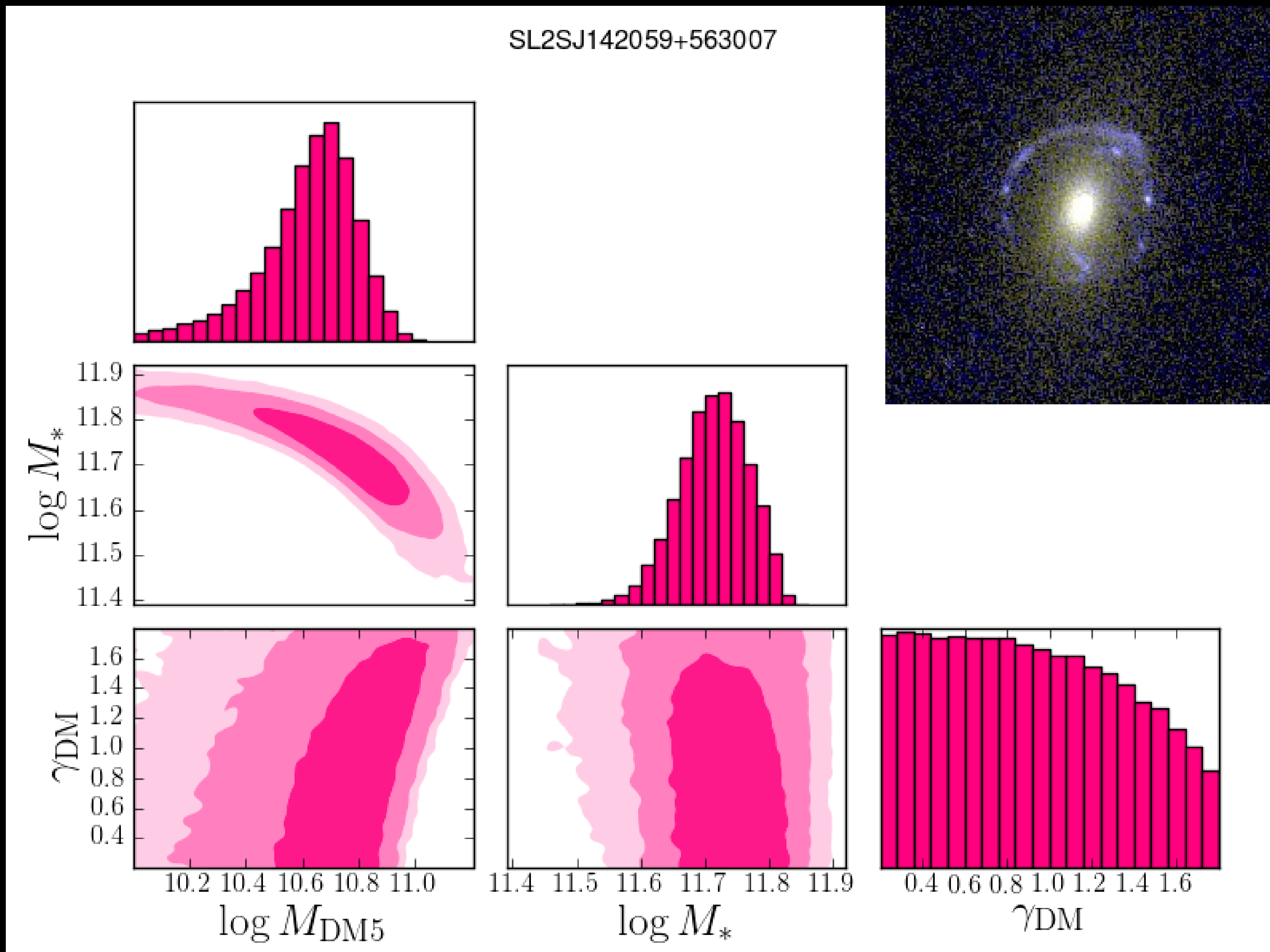
Grade	A	B	C	X	Total
With high-res imaging	30	3	13	21	67
With spectroscopy	36	15	2	5	58
High-res imaging and spectroscopy	27	3	0	0	30
Total with follow-up	39	15	15	26	95

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)

Dark and luminous matter decomposition in “standard” lenses



Sonnenfeld et al. 2015

Hierarchical Bayesian inference

- Density profile of individual lenses is described by a set of parameters, e.g.

$$\psi_i = \{M_{*,i}, M_{\mathrm{DM},i}, \gamma_{\mathrm{DM},i}, R_{\mathrm{e},i}, \alpha_{\mathrm{IMF},i}\}$$

- Individual lens parameters are drawn from a distribution describing the general population of strong lens galaxies. The population distribution is described by hyperparameters

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

$$\log M_{\mathrm{DM},i} \sim N(\log M_{\mathrm{DM},0} + \alpha_{\mathrm{DM}}(z-0.3) + \beta_{\mathrm{DM}}(\log M_* - 11.5) + \xi_{\mathrm{DM}}(\log \Sigma_* - \log \Sigma_0), \sigma_{\mathrm{DM}})$$

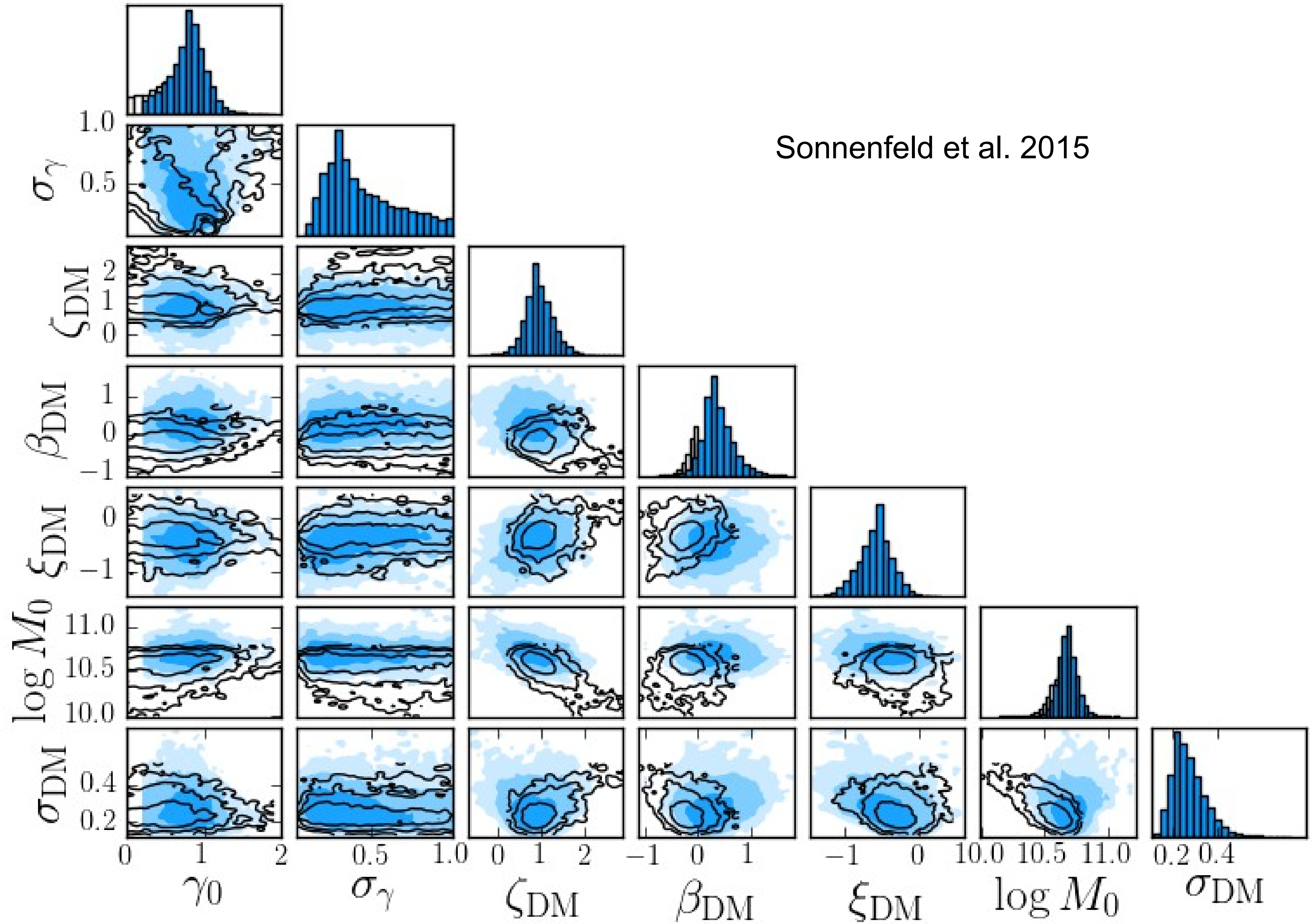
$$\gamma_{\mathrm{DM}} \sim N(\gamma_0, \sigma_\gamma)$$

$$\log \alpha_{\mathrm{IMF},i} \sim N(\log \alpha_{\mathrm{IMF},0} + \zeta_{\mathrm{IMF}}(z-0.3) + \beta_{\mathrm{IMF}}(\log M_* - 11.5) + \xi_{\mathrm{IMF}}(\log \Sigma_* - \log \Sigma_0), \sigma_{\mathrm{IMF}})$$

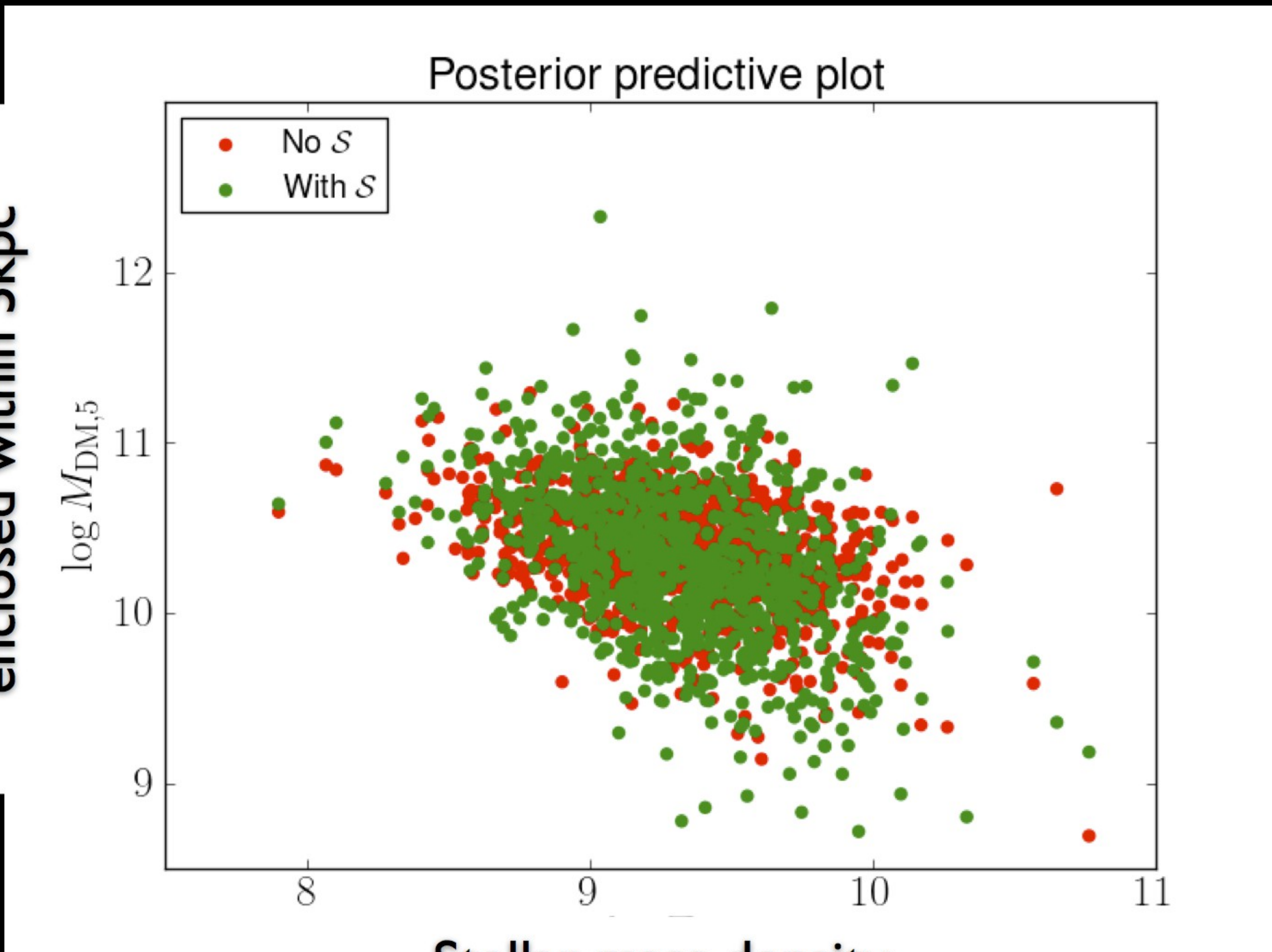
- Fit using Bayes formalism

$$P(\eta|d) = P(\eta)P(d|\eta) = P(\eta)\prod_i \int d\psi_i P(d|\psi_i)P(\psi_i|\eta)$$

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



Dark matter content depends on size



Projected dark matter enclosed within 5kpc

Stellar mass density

- 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)

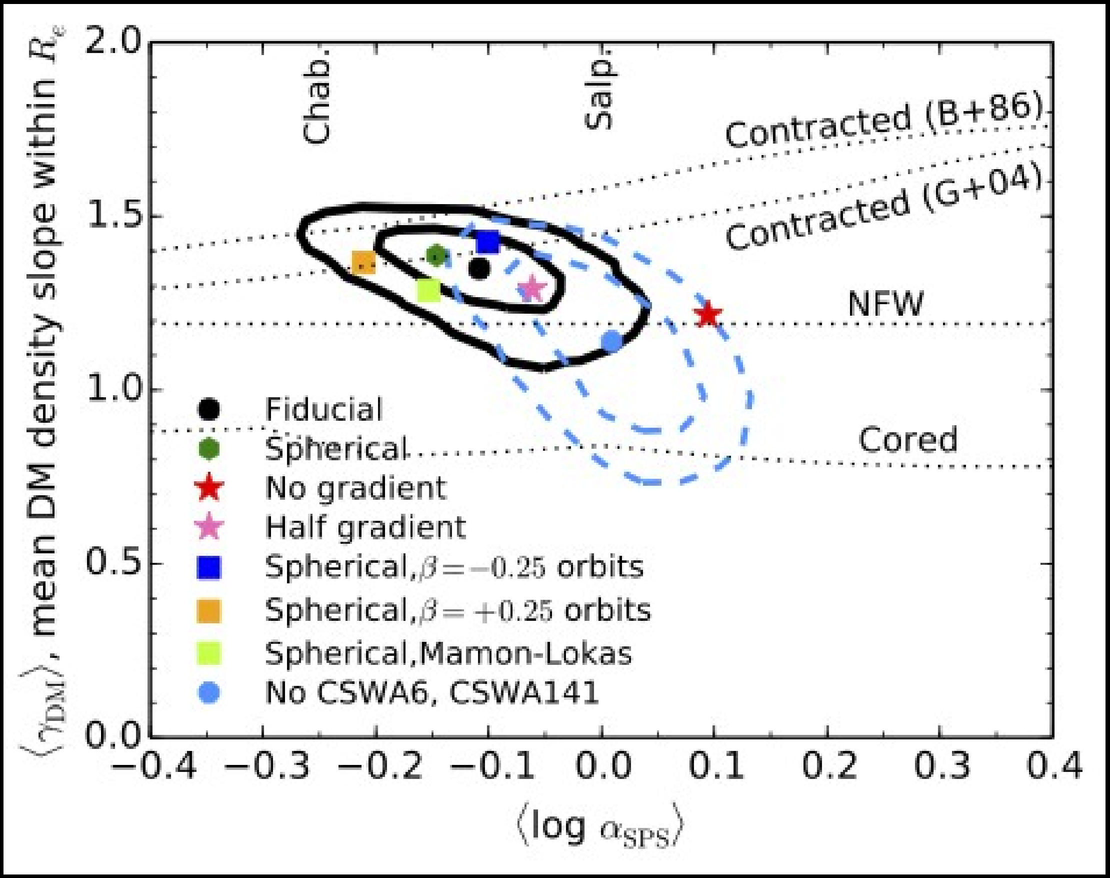
Conclusions

- We still 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

Thank you!

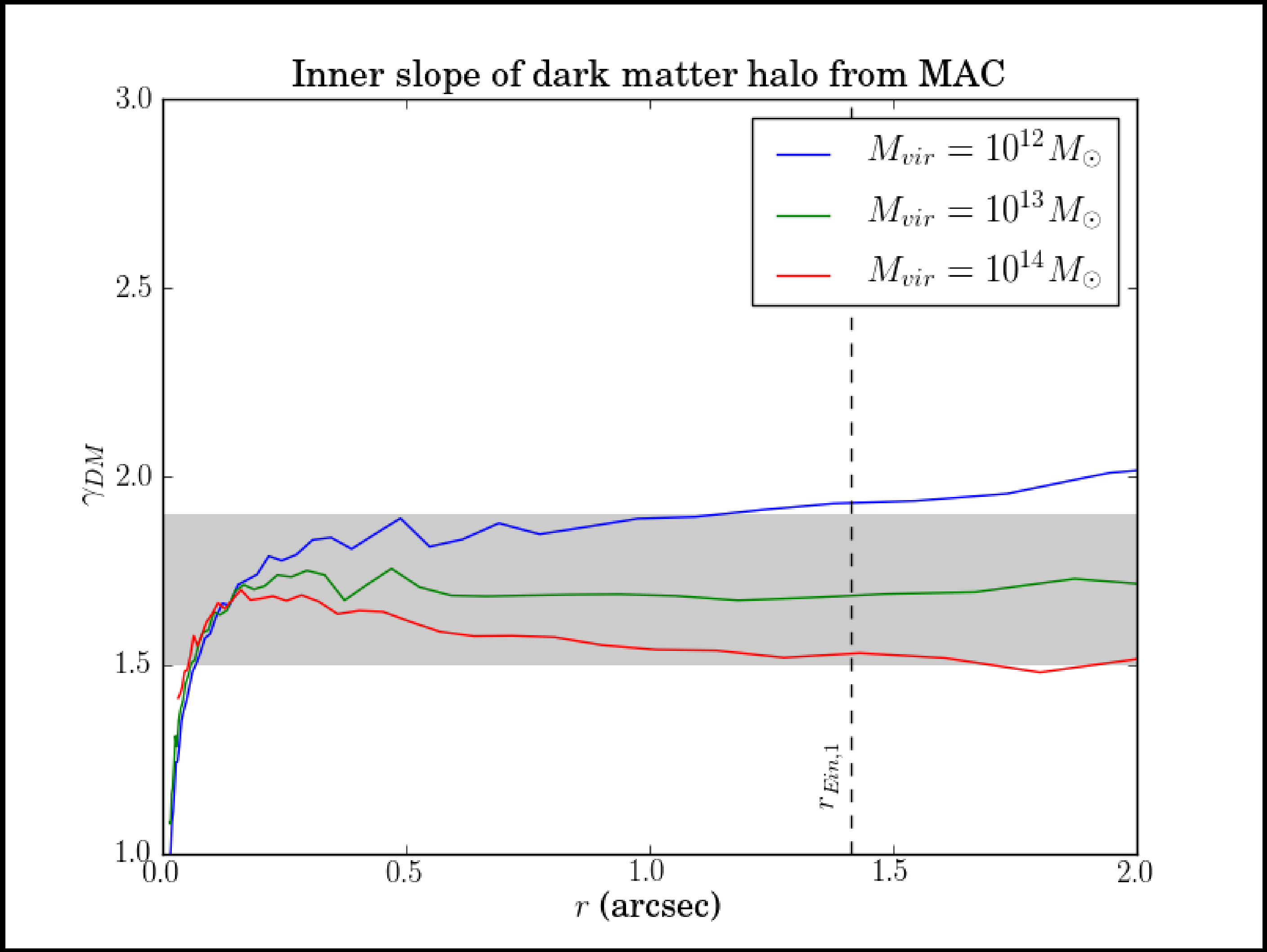
Extra

Caveats



Newman et al. 2015

Dark matter contraction



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