

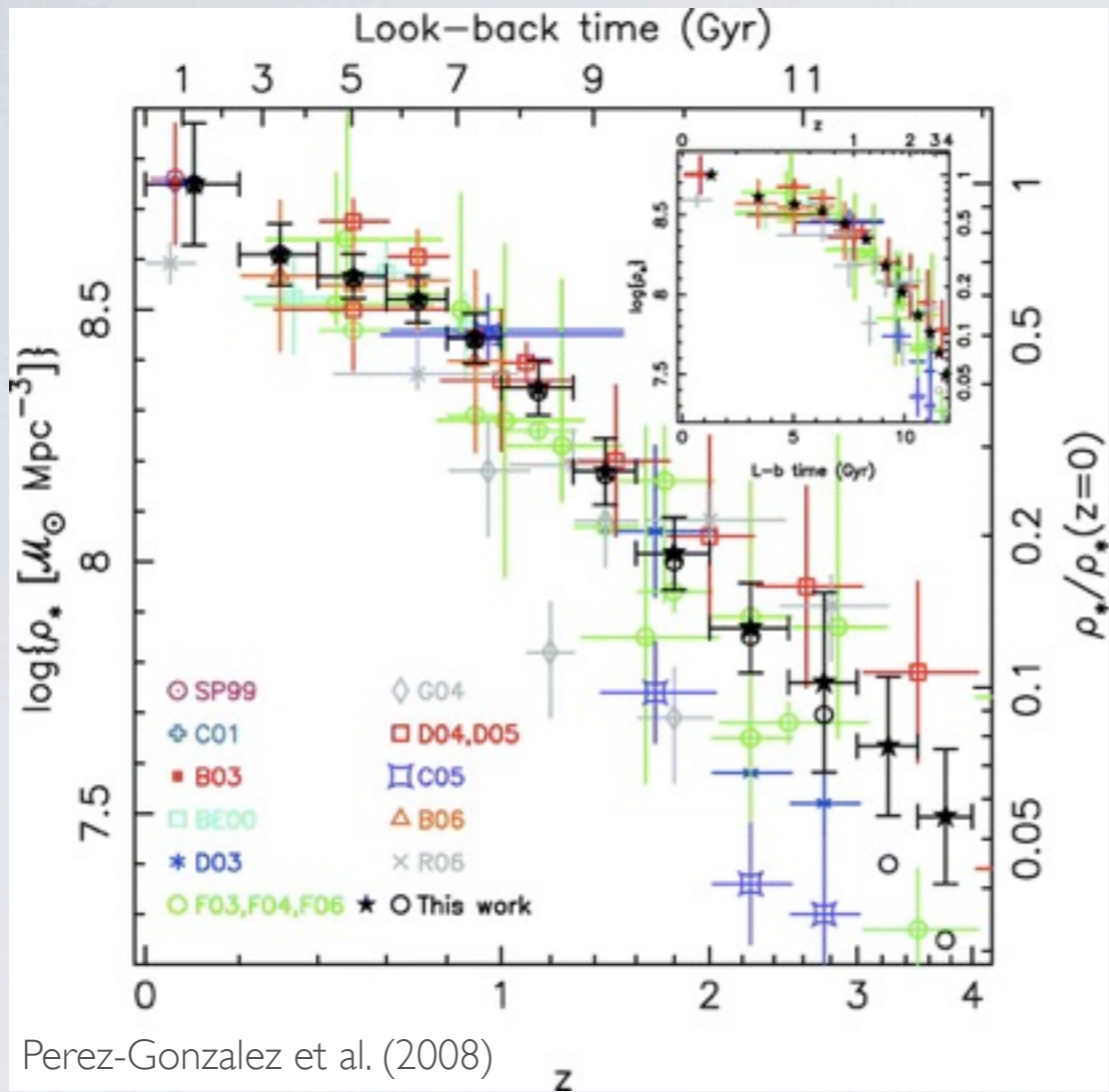
GALAXY EVOLUTION

insights from
High-Resolution Imaging and Deep Spectroscopy

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Max Planck Institute for Astronomy
Heidelberg, Germany

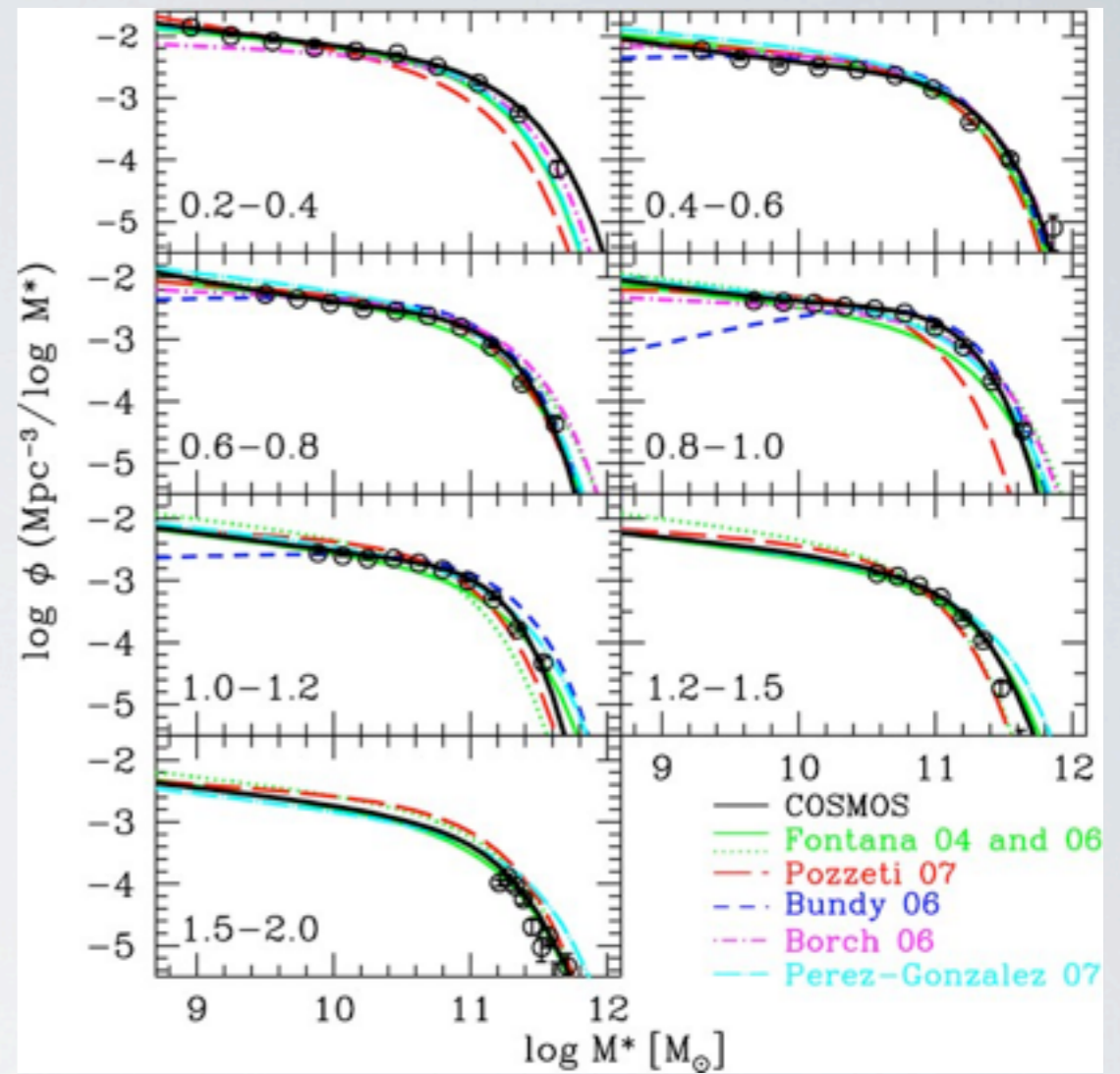
of stars



Perez-Gonzalez et al. (2008)

Redshift

of galaxies



Mass in stars

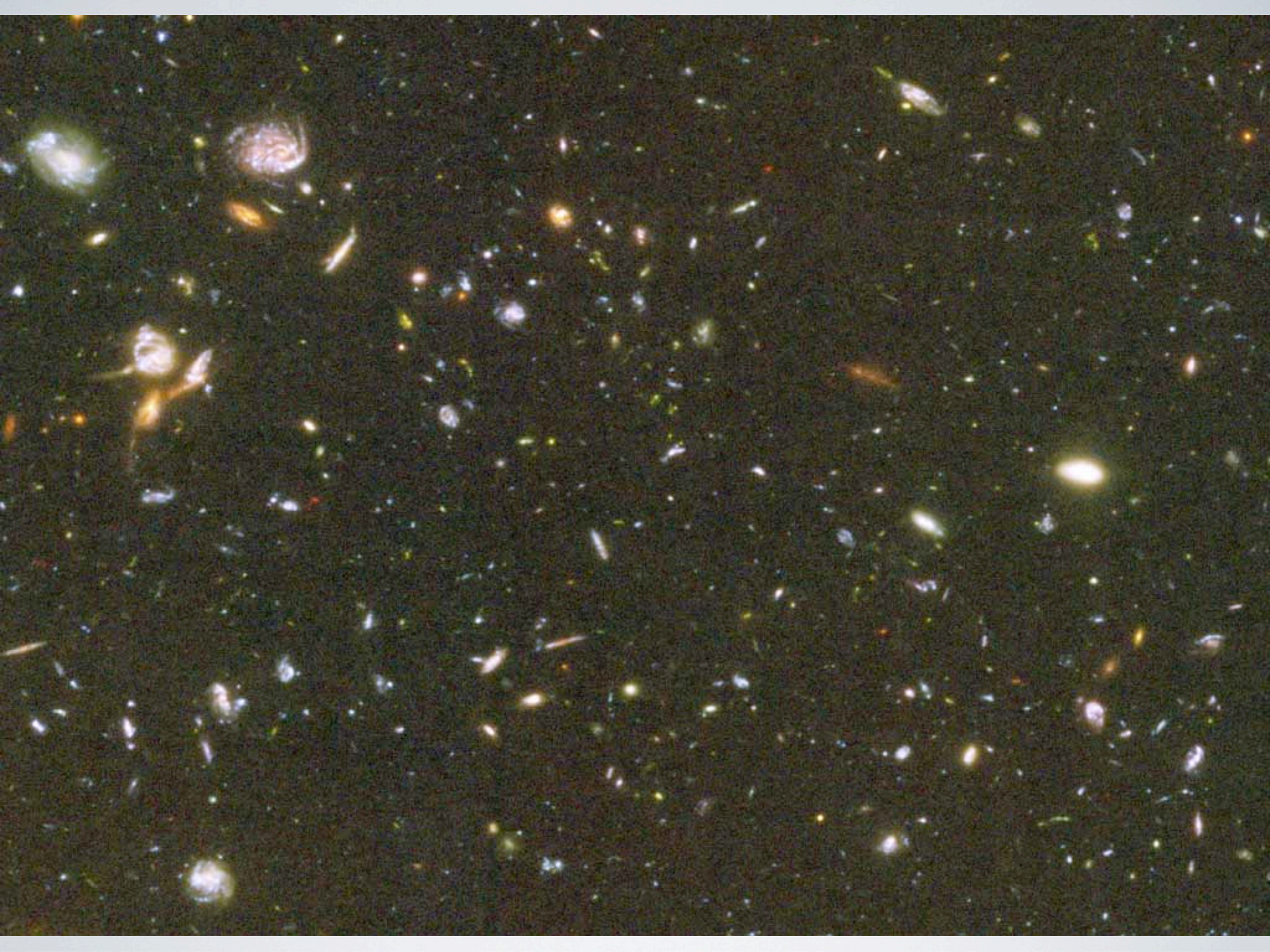
What we know...

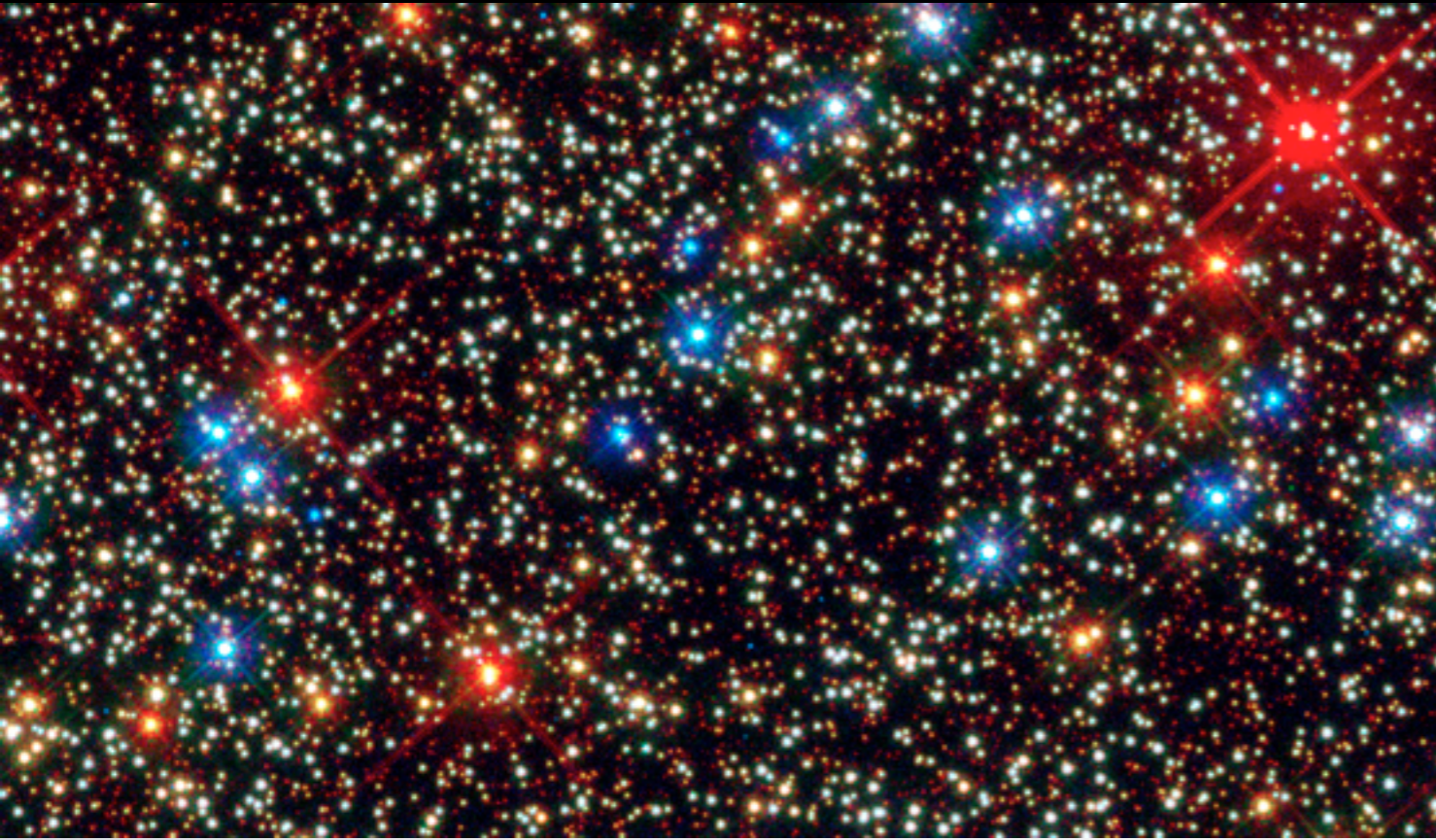
- how the number of stars evolves
- how those stars are distributed over different galaxies

This talk

- How was this formation history measured?
- Why do we believe it?
- Along the way: a few recent results

- Bonus part





Estimating galaxy masses ...

Stellar Population Synthesis modeling

- **Single/simple stellar populations (SSPs):** Slide from C. Conroy

$$S(t, Z) = \int_{M_i^l}^{M_i^u(t)} \Phi(M_i) \Lambda[L(M_i, Z, t), T(M_i, Z, t), Z] dM_i$$

IMF x spectra(stellar mass)

└─→ star clusters

Widely used models:

Bruzual & Charlot (2003); Maraston (2005); PEGASE (Fioc & Rocca-Volmerange (1999);
Starburst99 (Leitherer 1999); Vazdekis (1999)

Estimating galaxy masses ...

Stellar Population Synthesis modeling

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IMF \times spectra(stellar mass)

└─→ star clusters

- **Composite stellar populations (CSPs):**

$$F_\lambda(t, Z) = \int_0^t \Psi(t-t') S_\lambda(t', Z) e^{-\tau_\lambda(t')} dt'$$

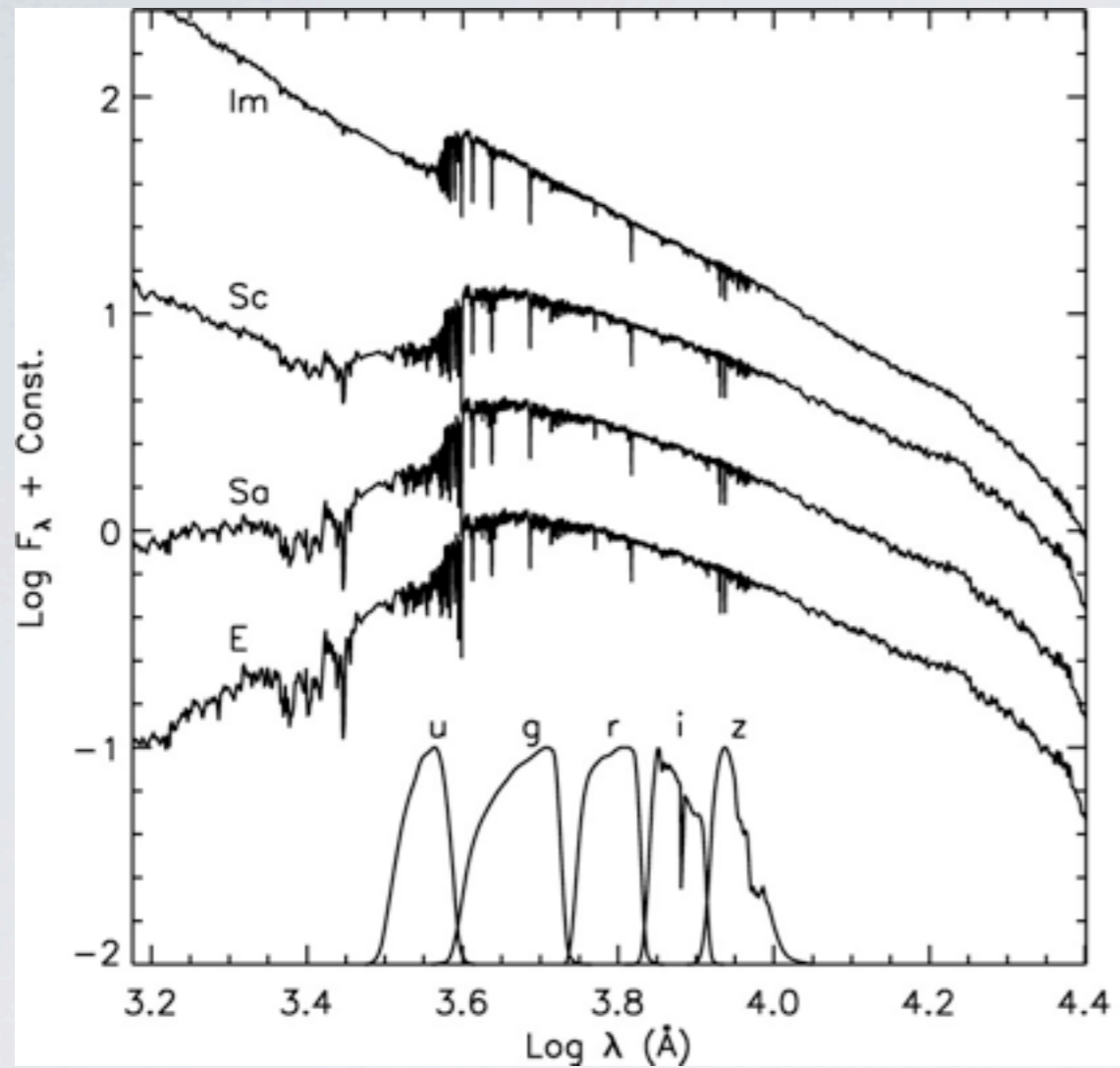
SFR \times SSP \times dust

└─→ galaxies

Integrate over stellar ages t'

Widely used models:

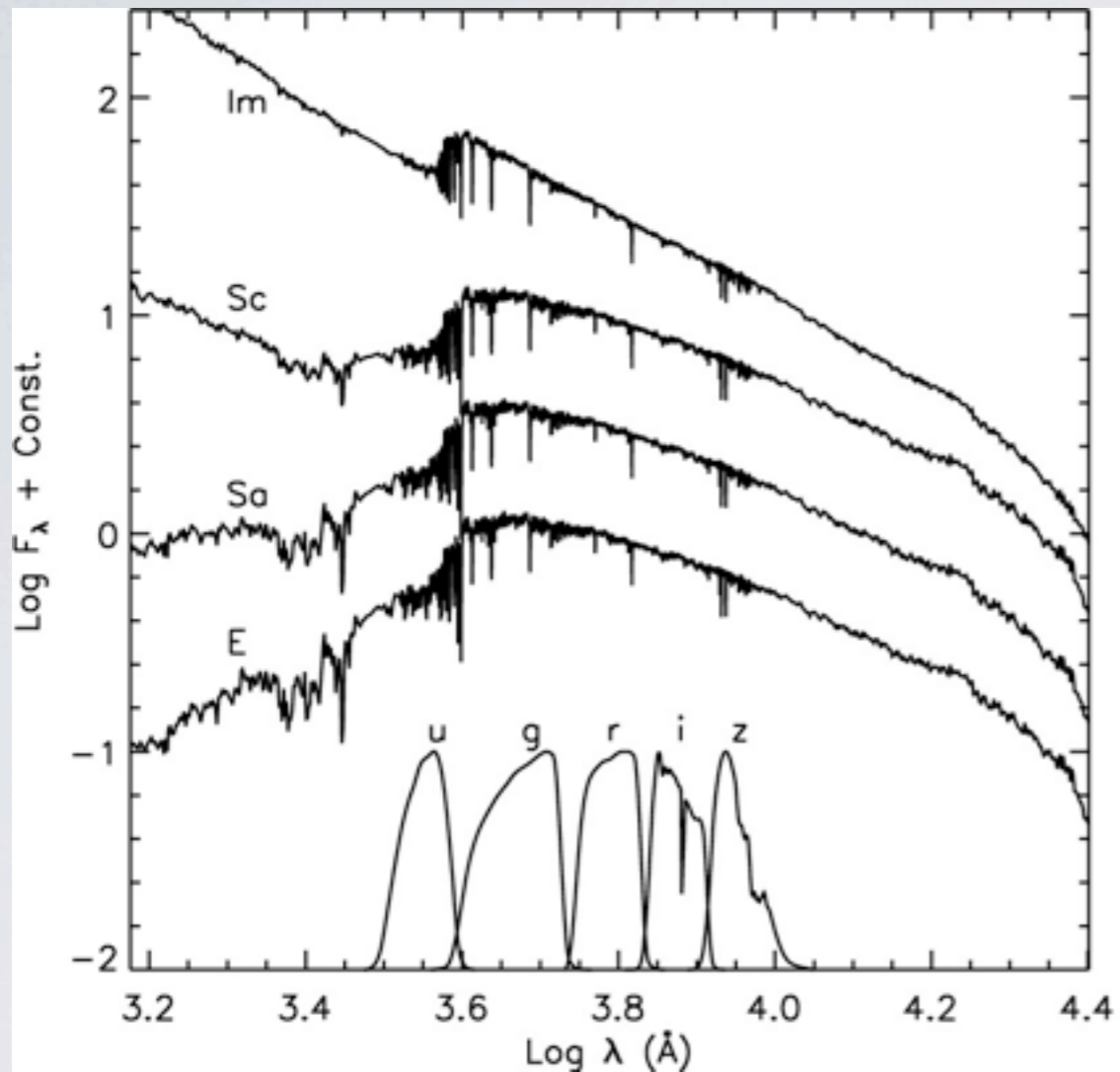
Bruzual & Charlot (2003); Maraston (2005); PEGASE (Fioc & Rocca-Volmerange (1999); Starburst99 (Leitherer 1999); Vazdekis (1999)



Colors



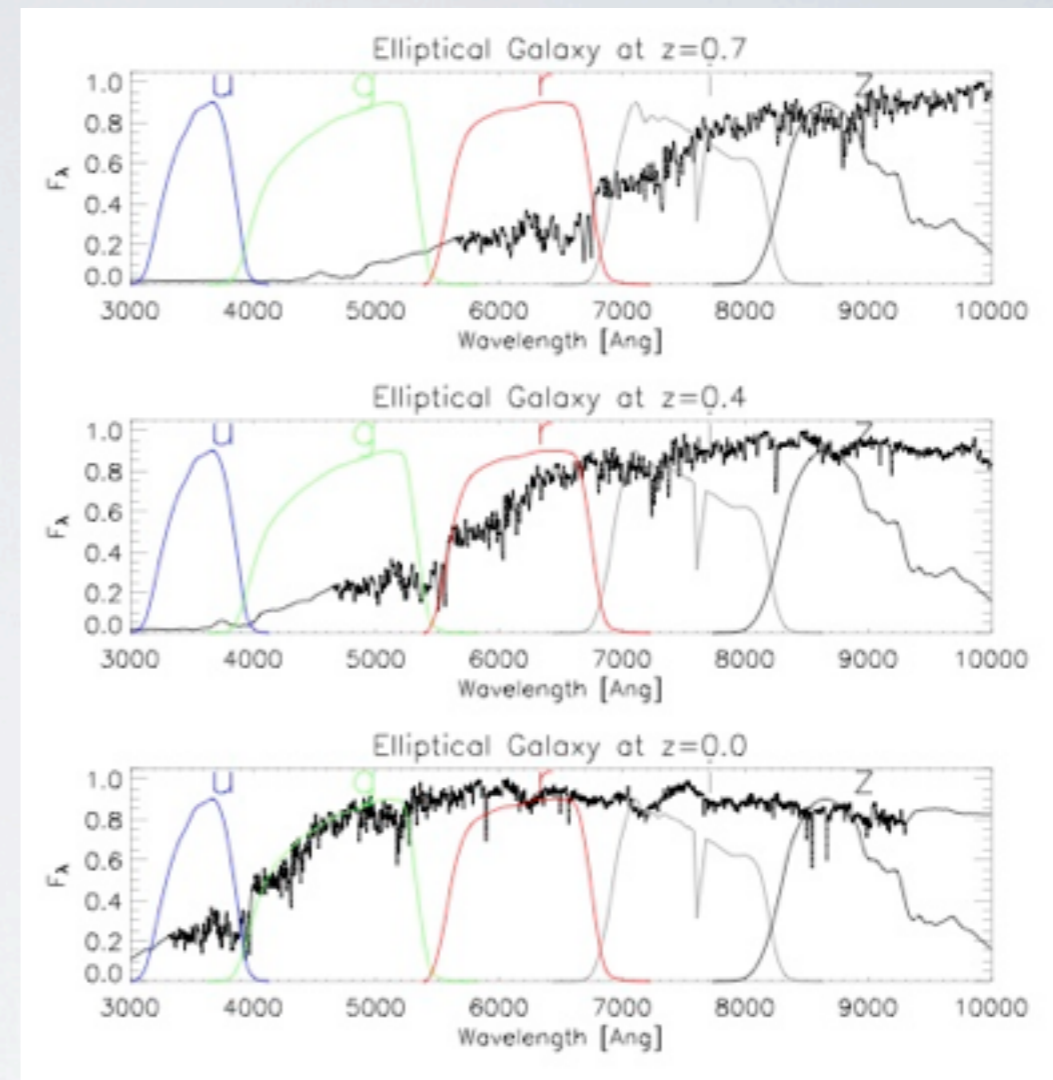
Stellar population (mass, age, Z , ...)



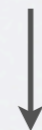
Colors




Stellar population (mass, age, Z, ...)



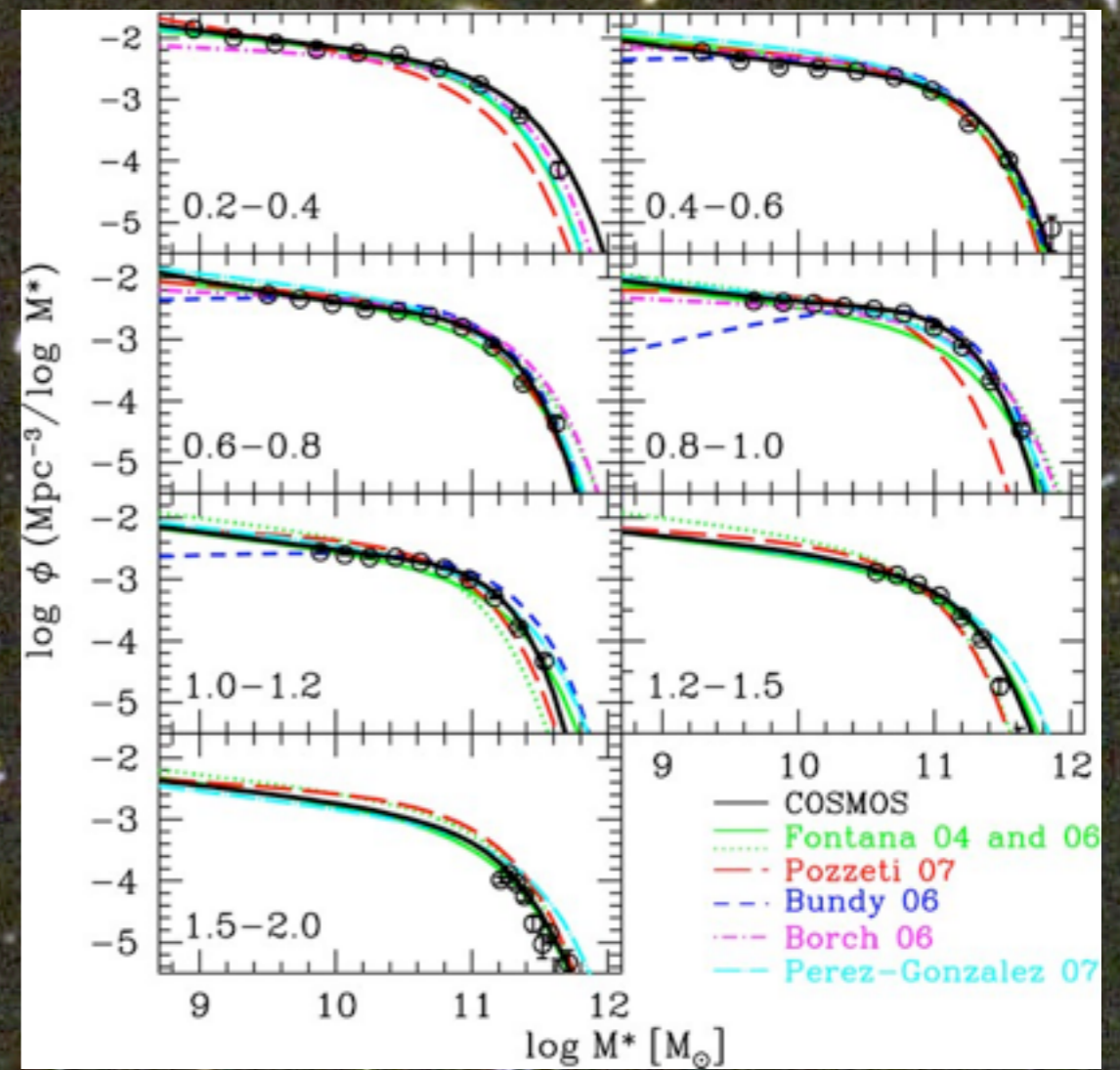
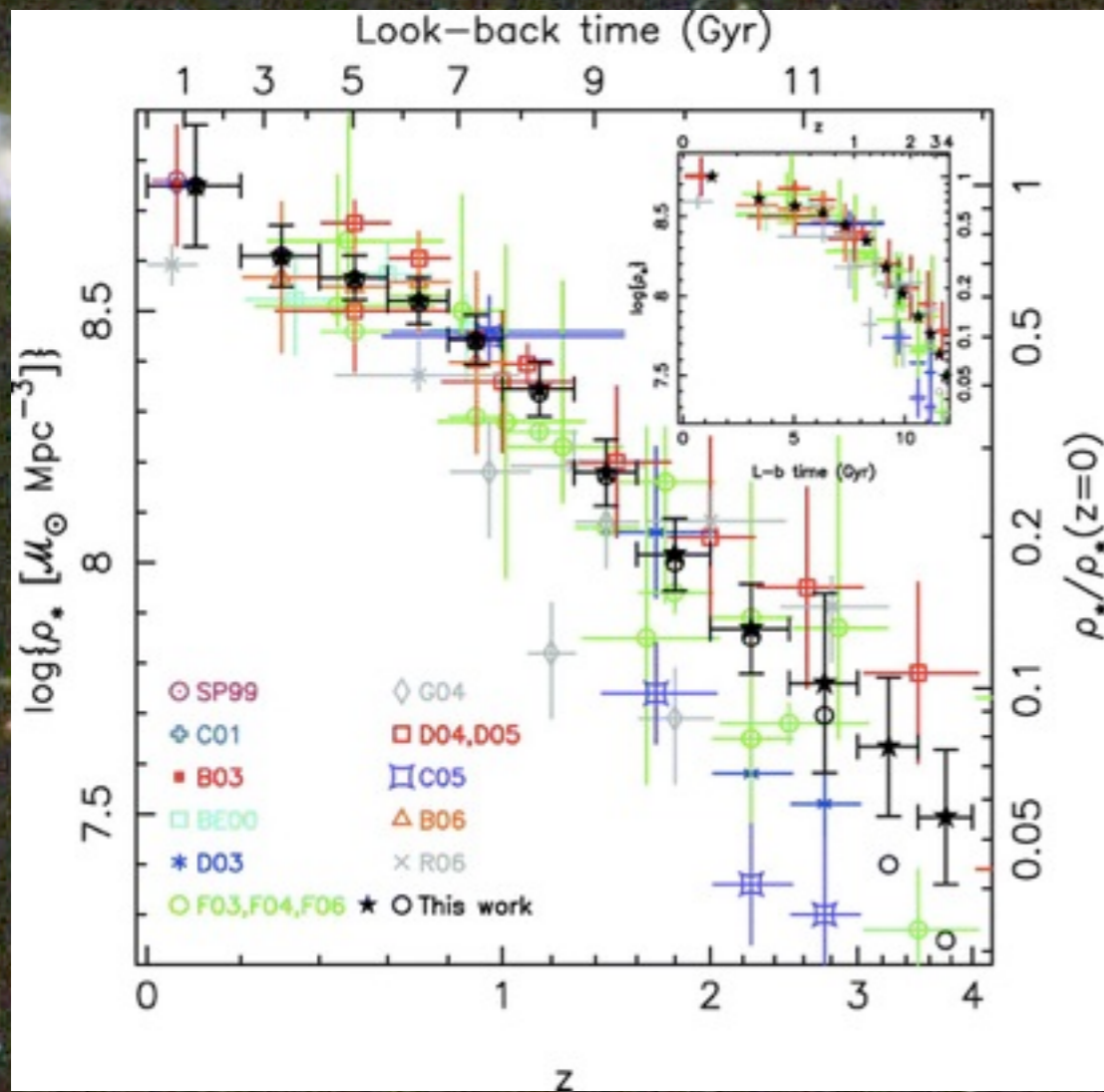
Colors



Photometric redshift

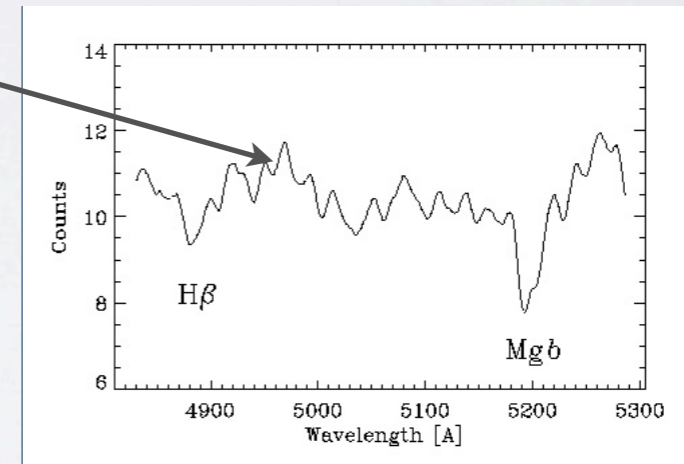
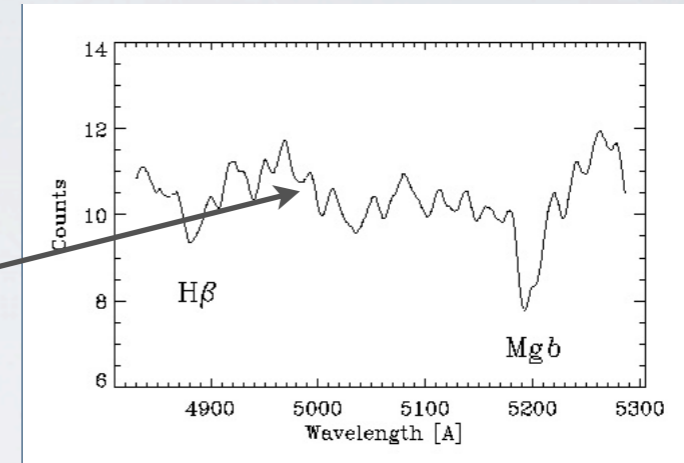
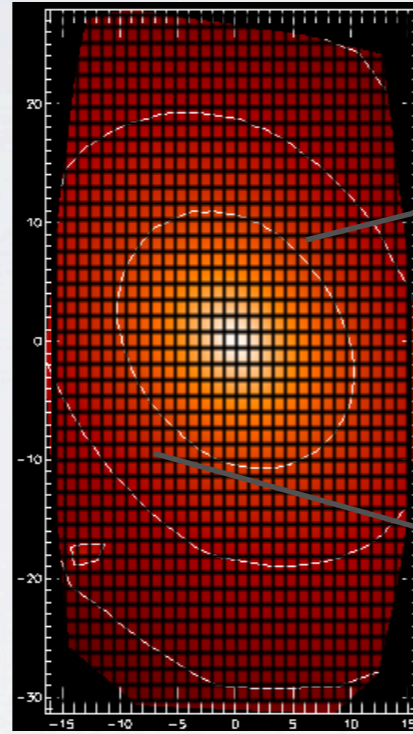
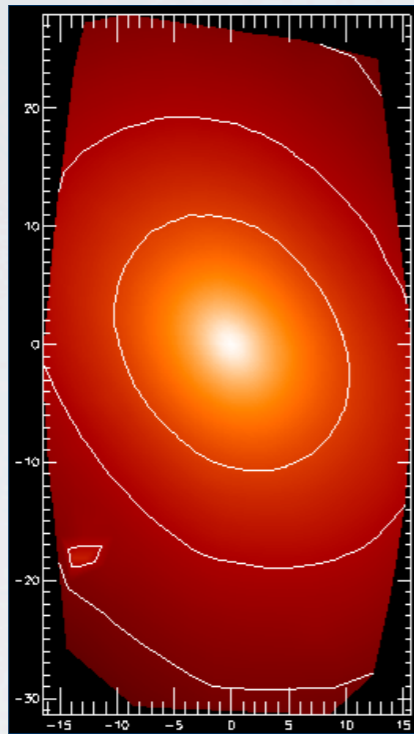


Uncertainties in the SPS models
Uncertainties from fitting/degeneracies



Uncertainties in the SPS models
 Uncertainties from fitting/degeneracies

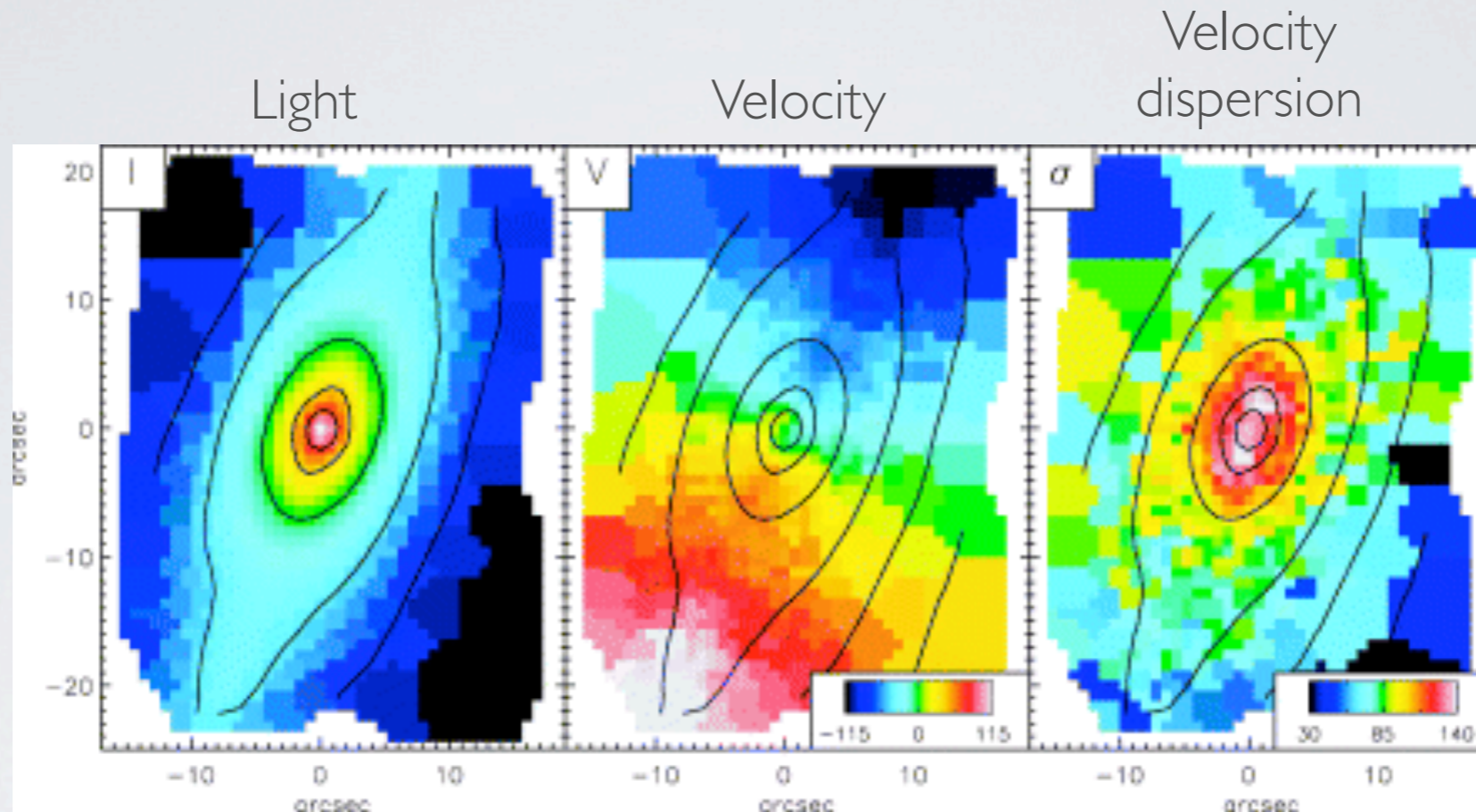
Estimating galaxy masses ... from kinematic measurements



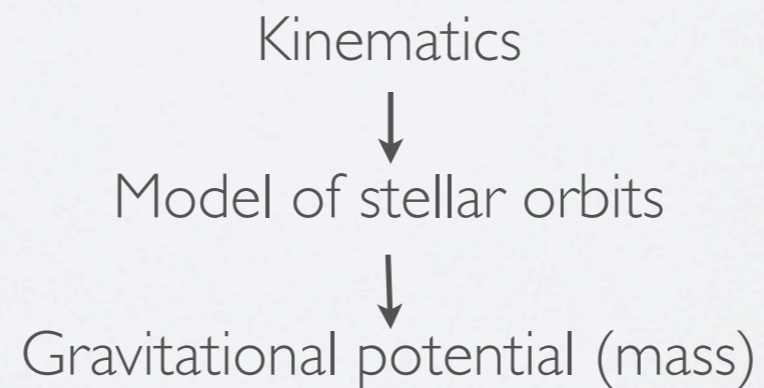
taken from R. Davies' slide

Estimating galaxy masses ...

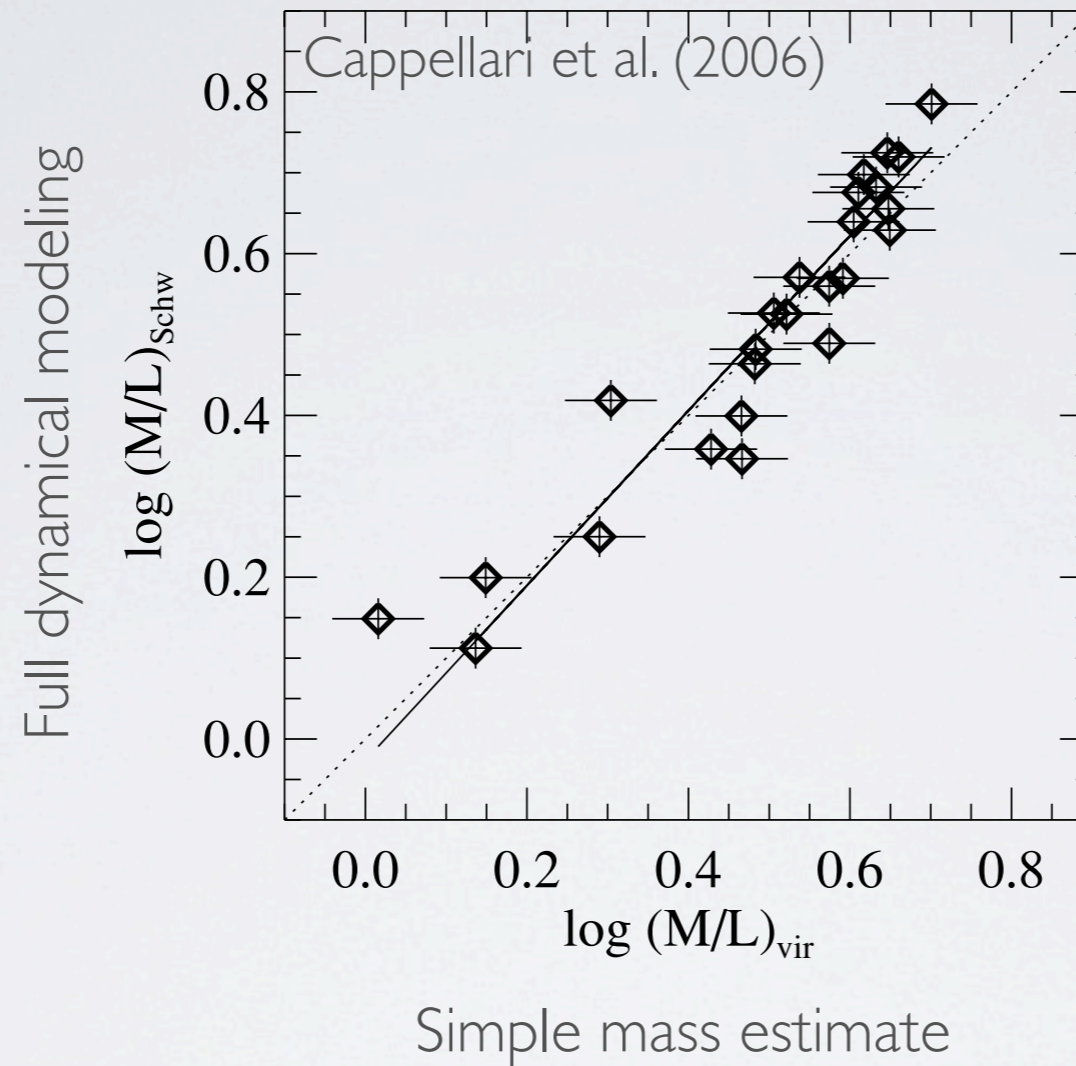
Dynamical modeling



NGC7332; Falcon-Barroso et al. (2004)

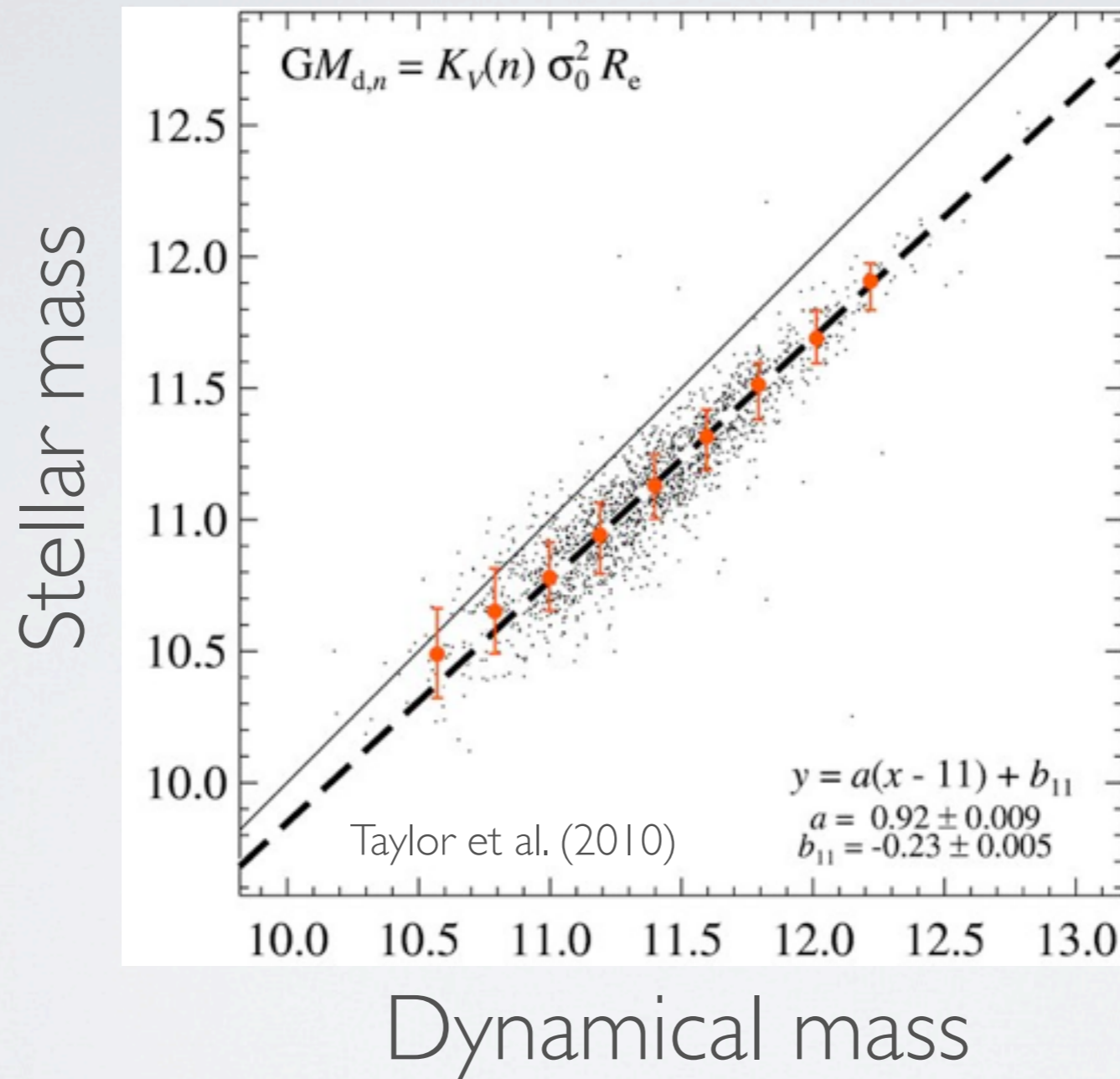


It doesn't have to be complicated...

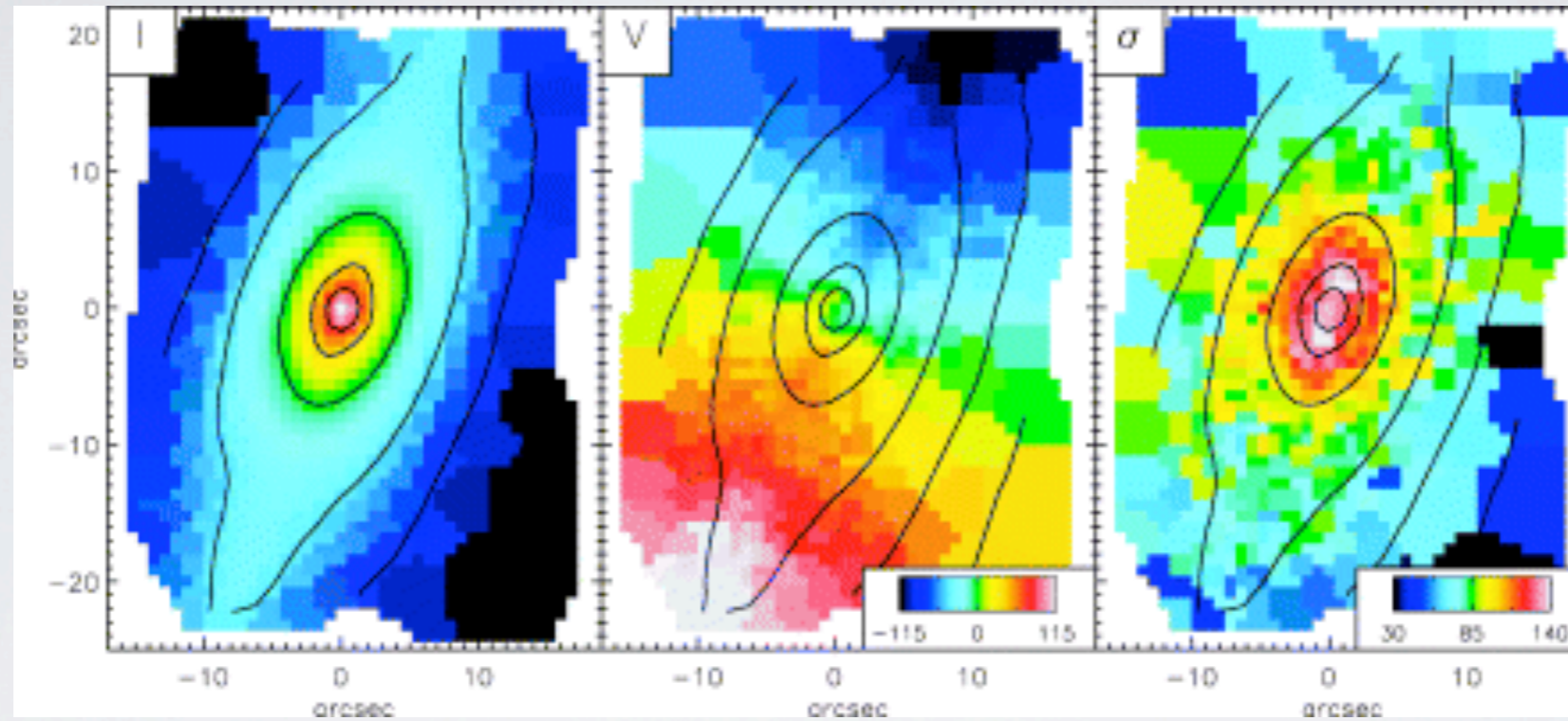


$$M \sim \beta r_{1/2} \sigma^2 / G$$

The ultimate test...
comparing dynamical and stellar mass estimates

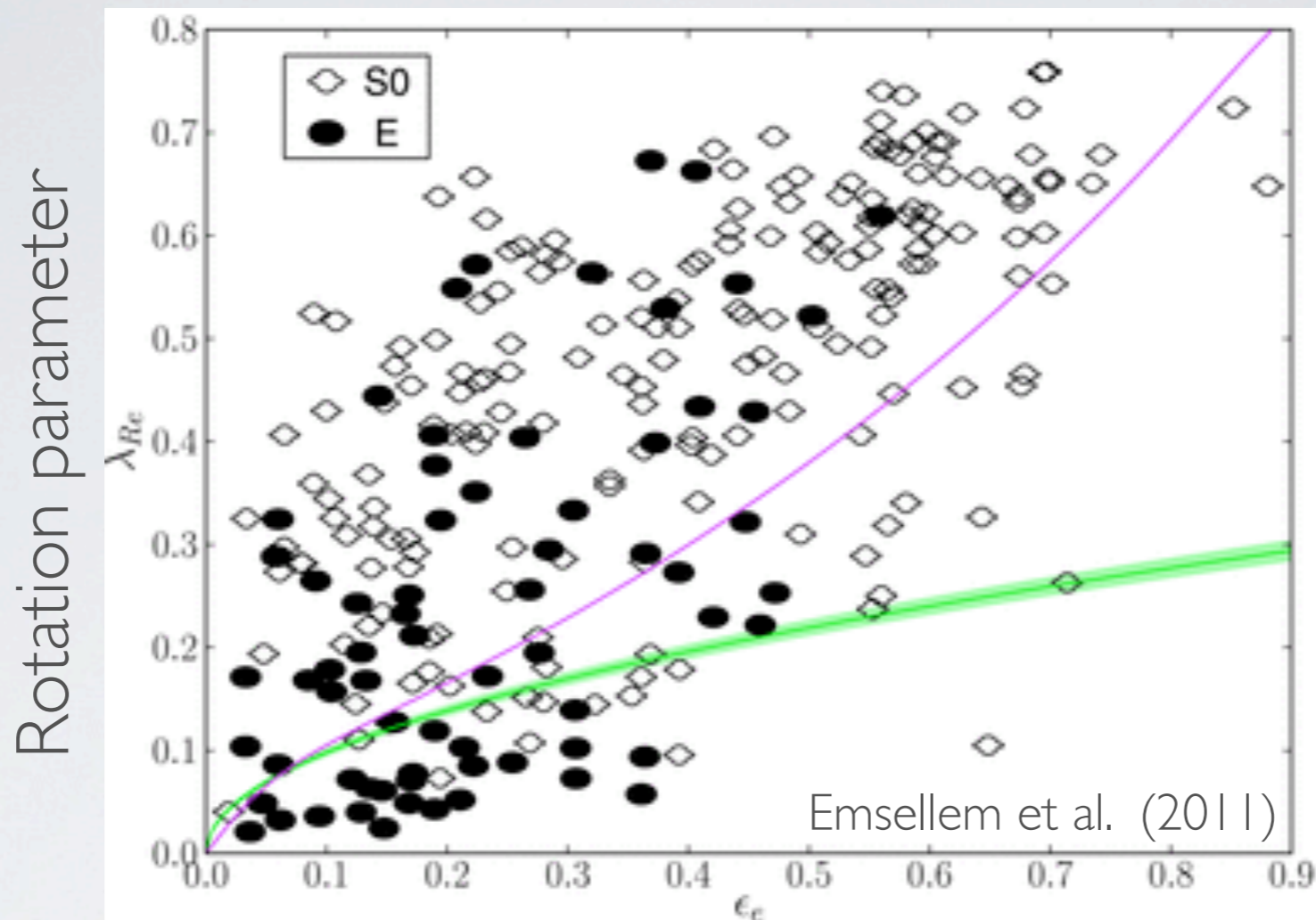


Dynamical structure



Shape \sim rotation/'diskiness'

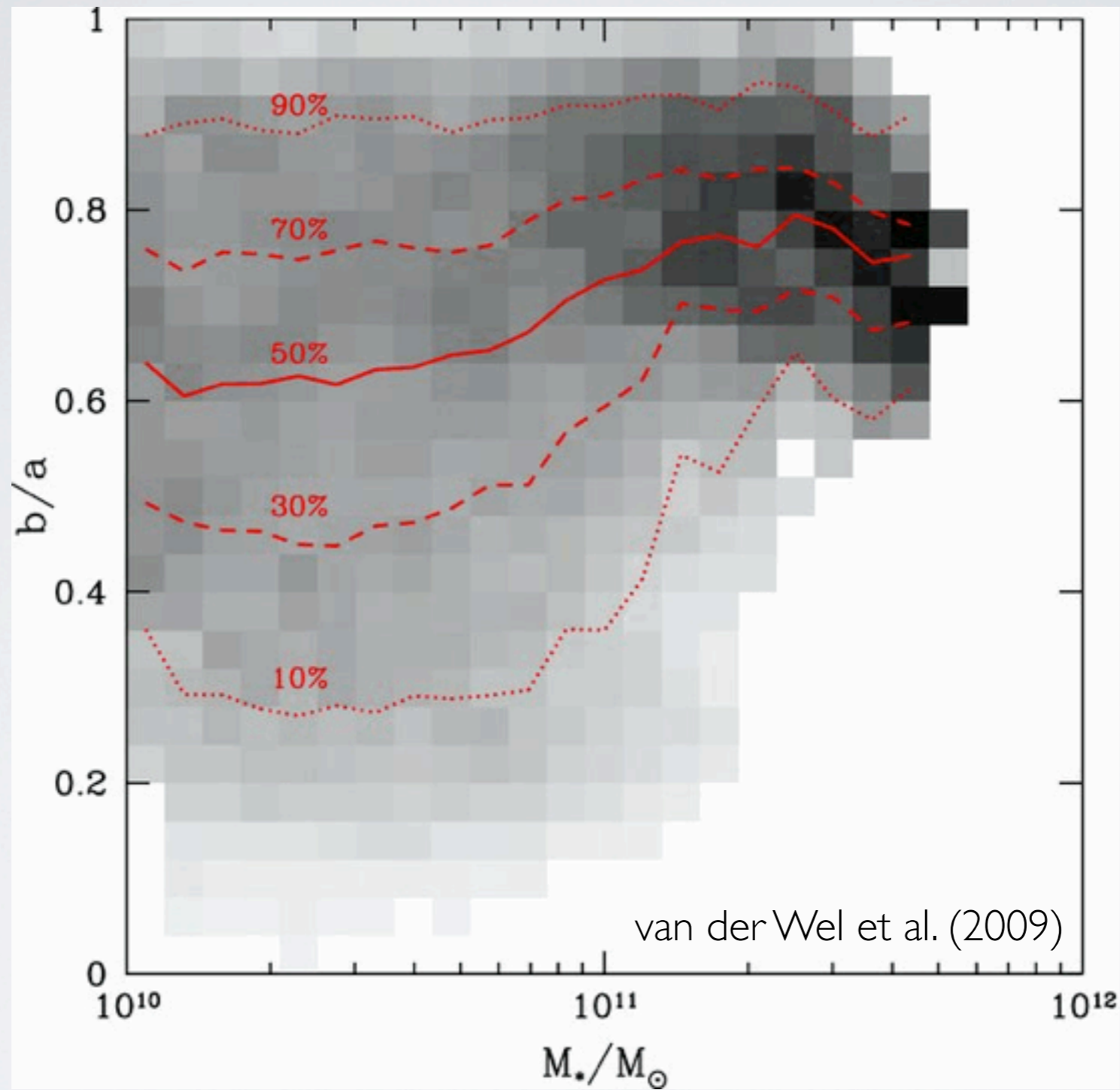
Dynamical structure



Ellipticity: Projected shape on sky

Shape \sim rotation/'diskiness'

The shape distribution of early-type galaxies

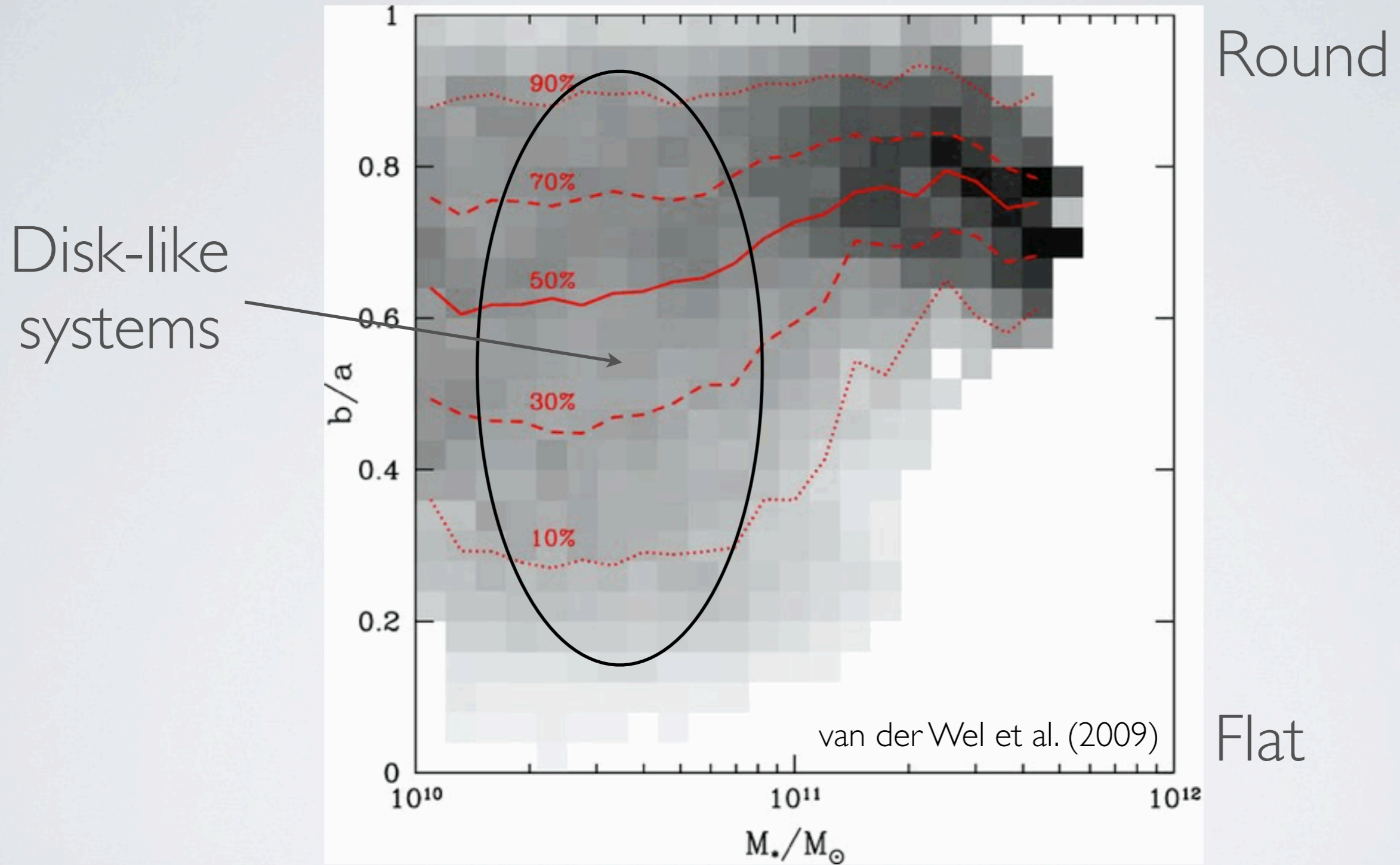


Round

Flat

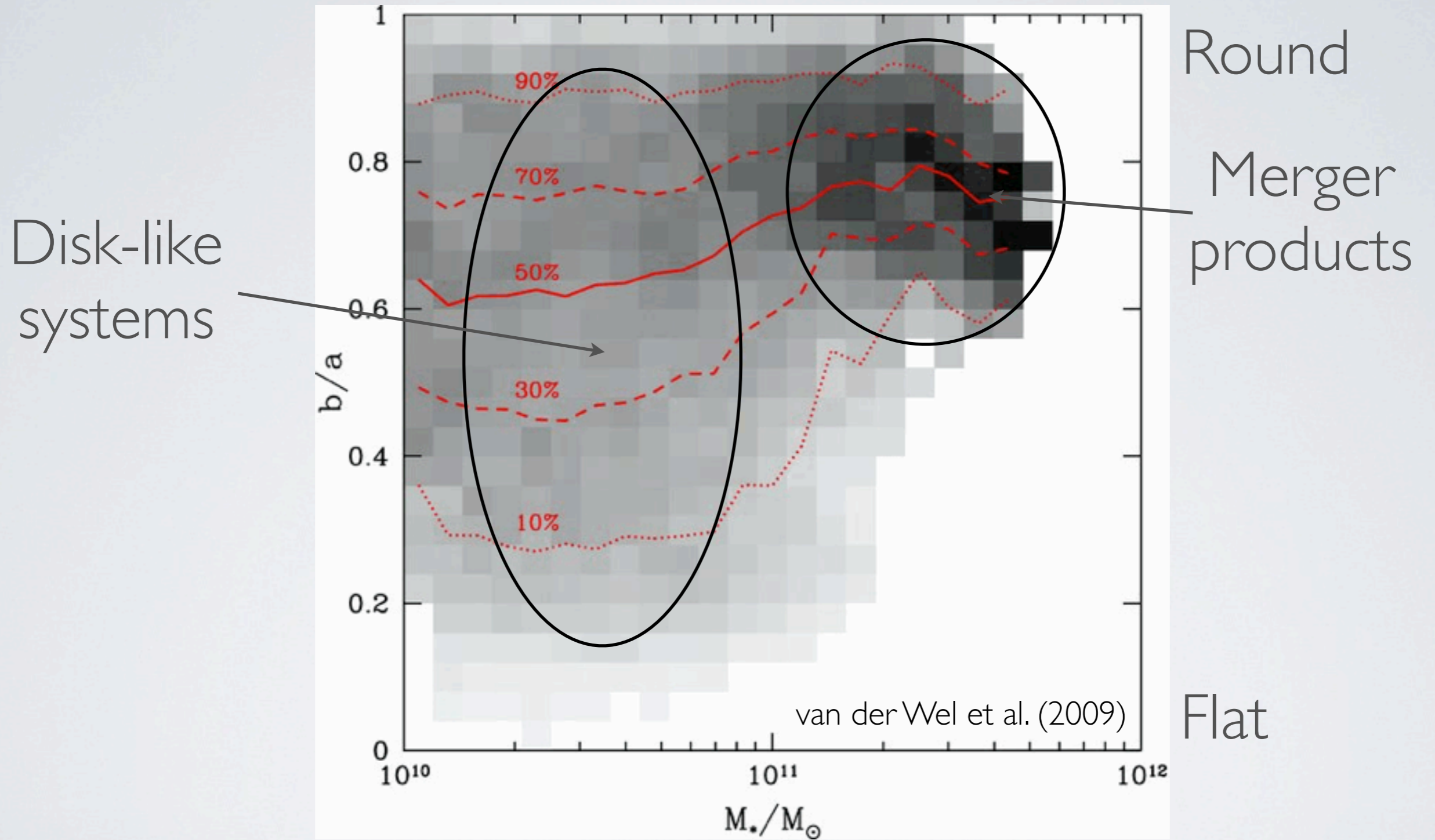
~ 10k SDSS galaxies at $0.04 < z < 0.08$ w/o emission lines

The shape distribution of early-type galaxies

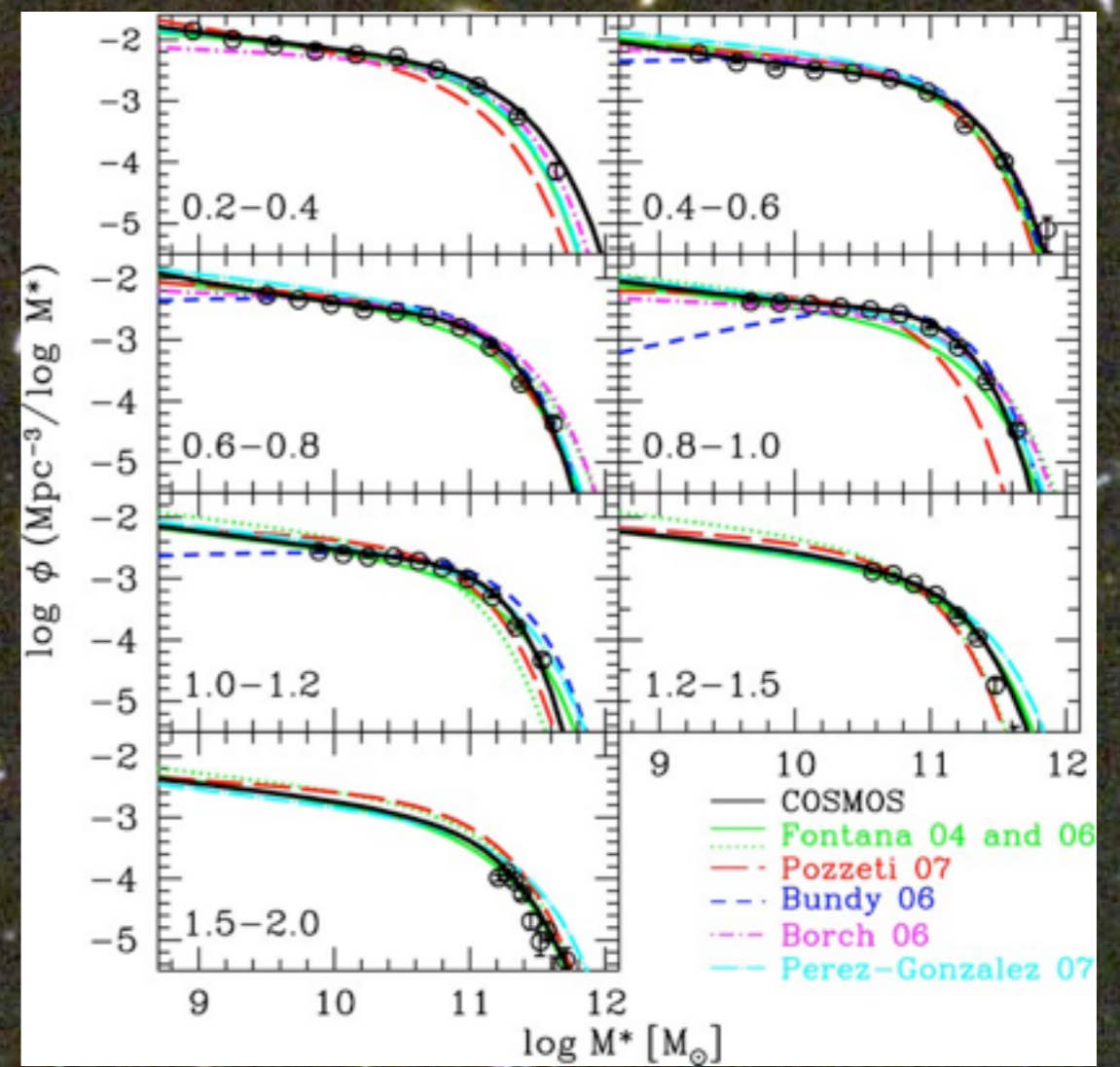
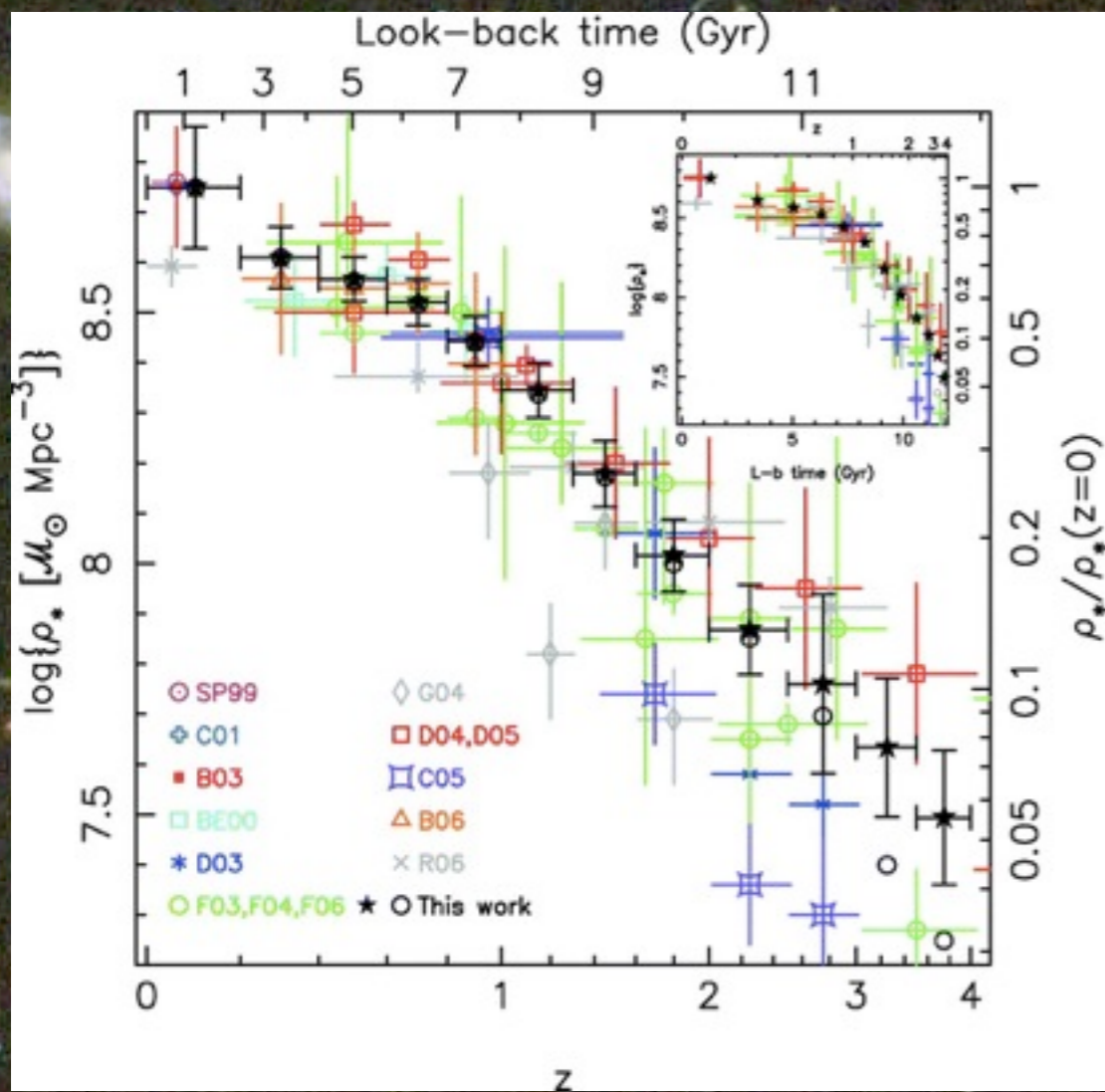


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The shape distribution of early-type galaxies

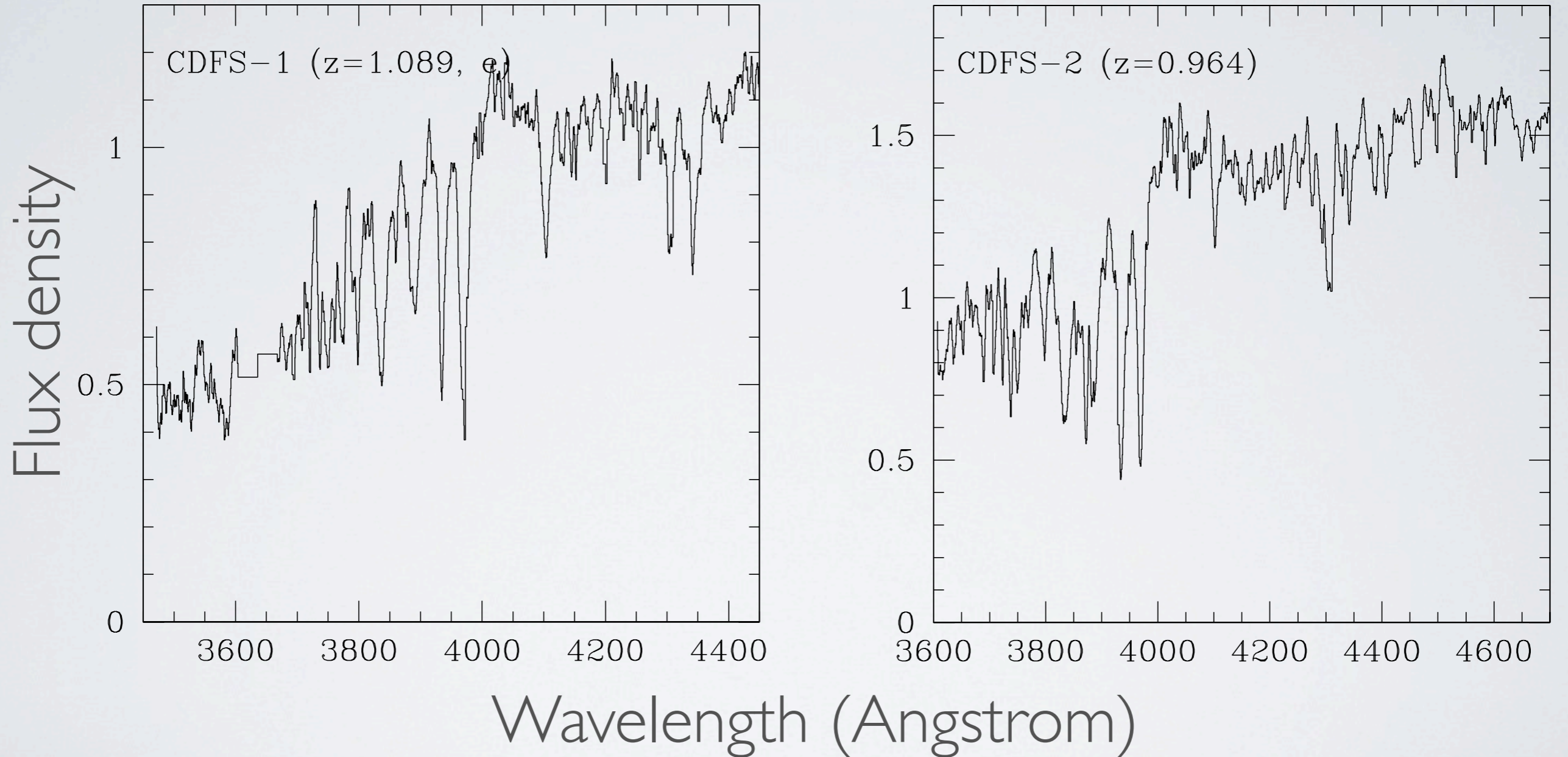


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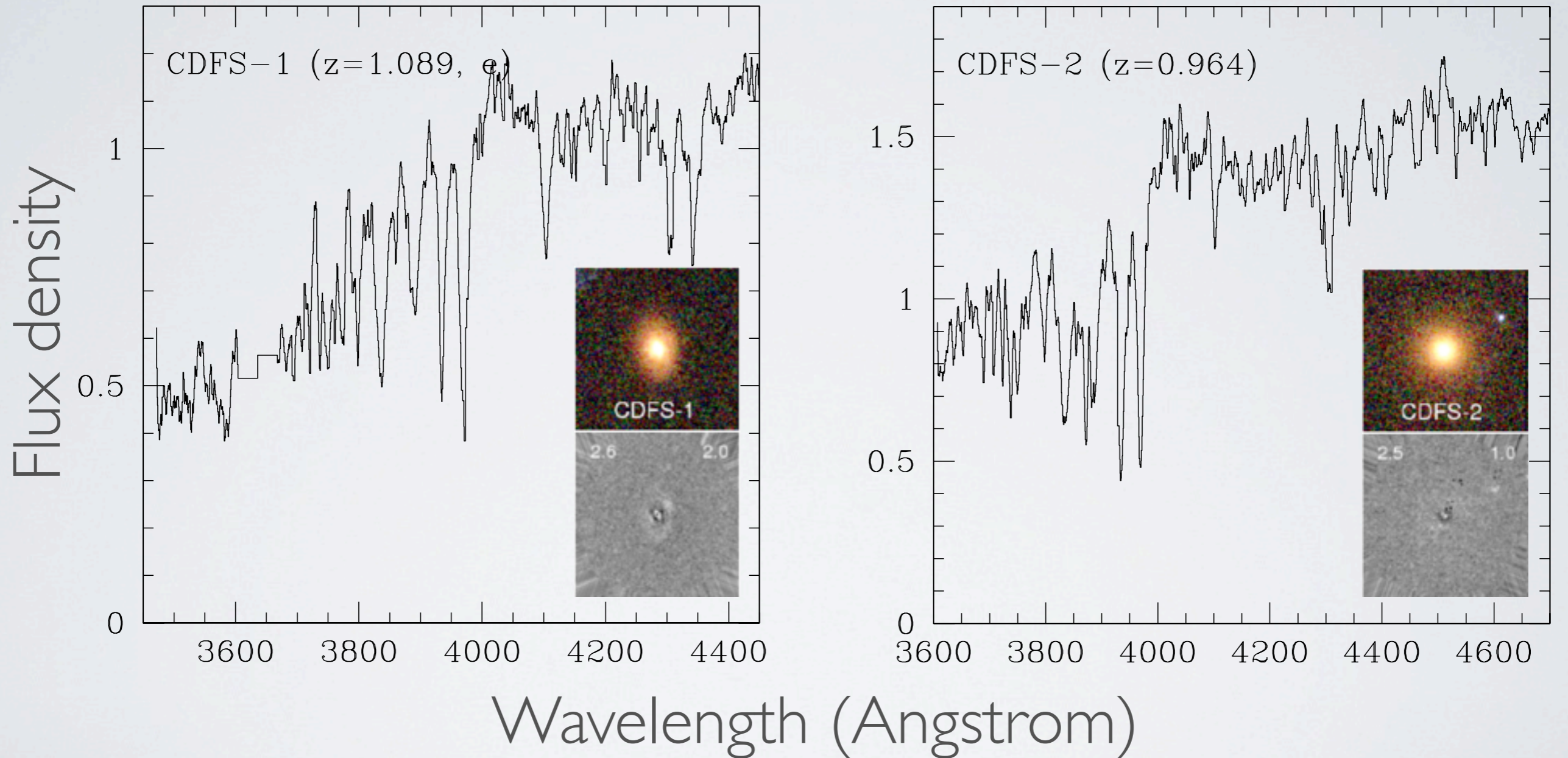
How about masses at high redshift?

Deep spectroscopy from ESO's VLT and high-resolution imaging from HST/ACS:

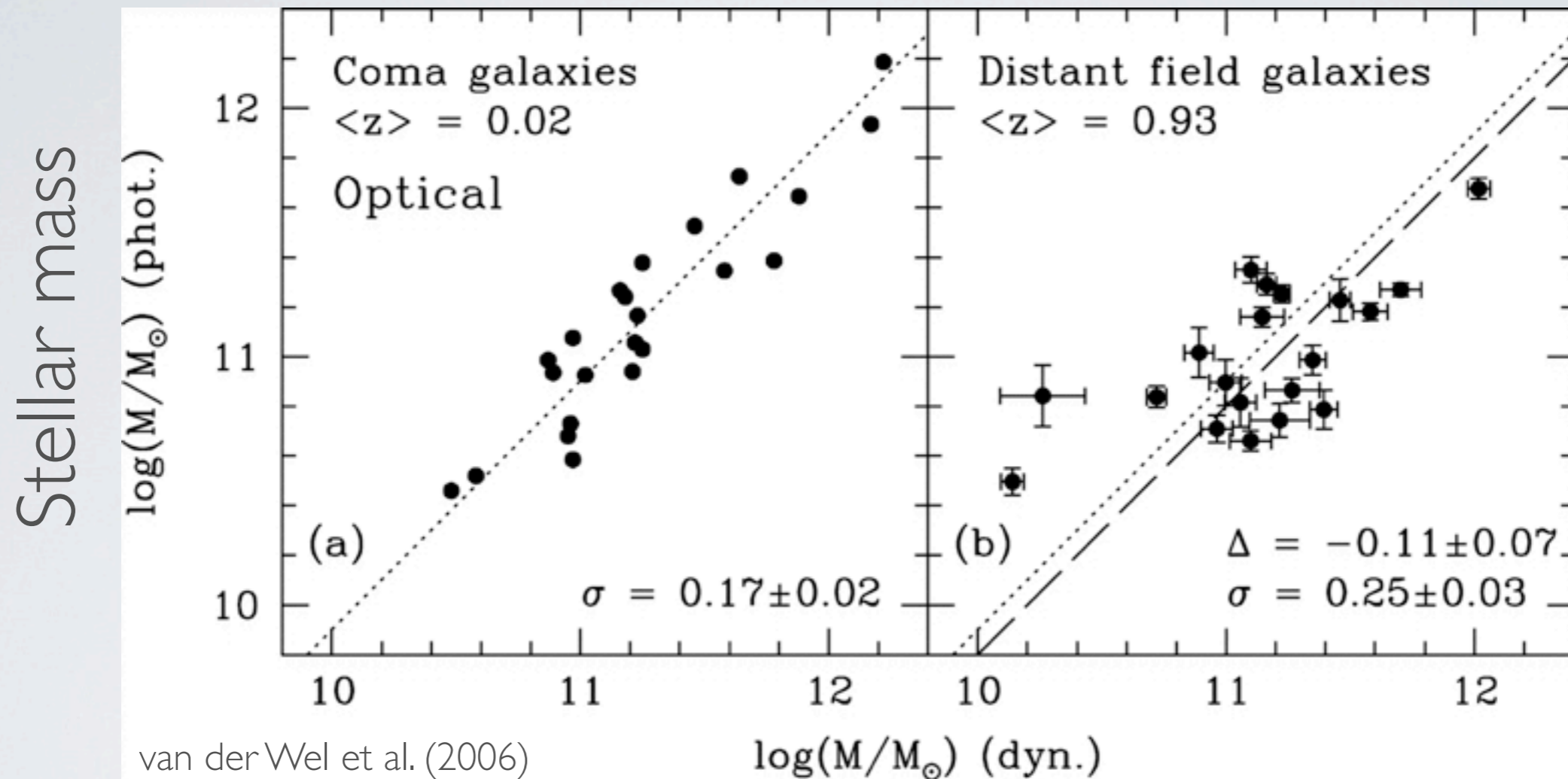


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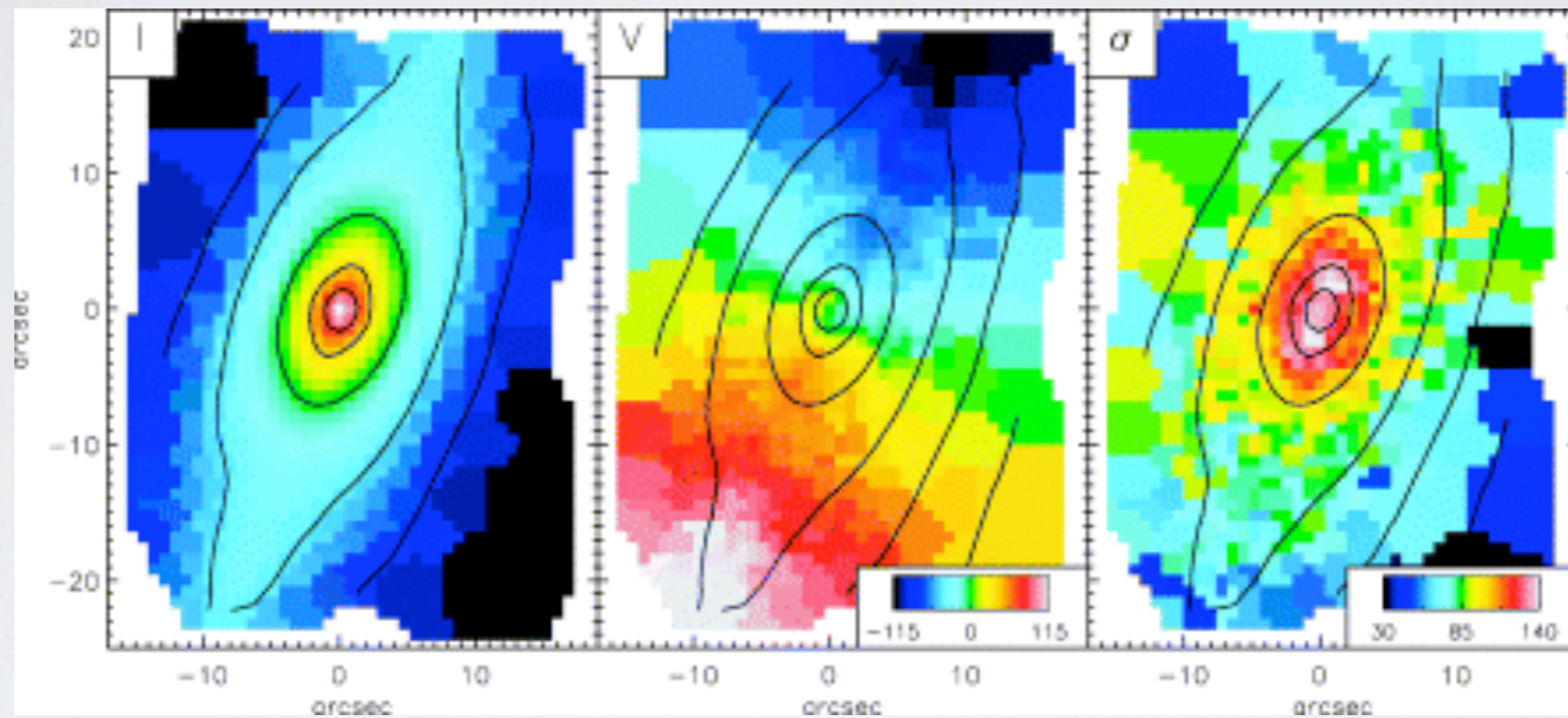


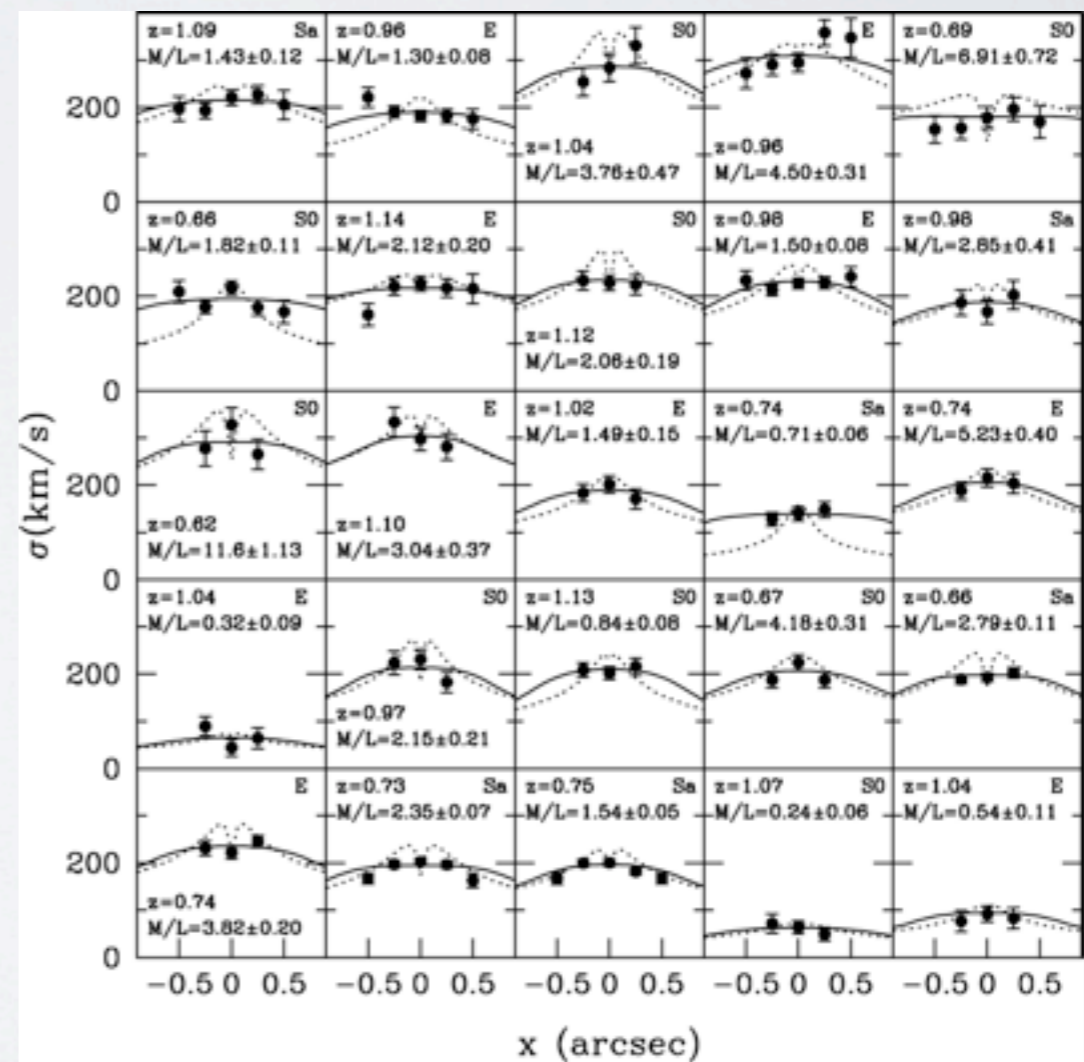
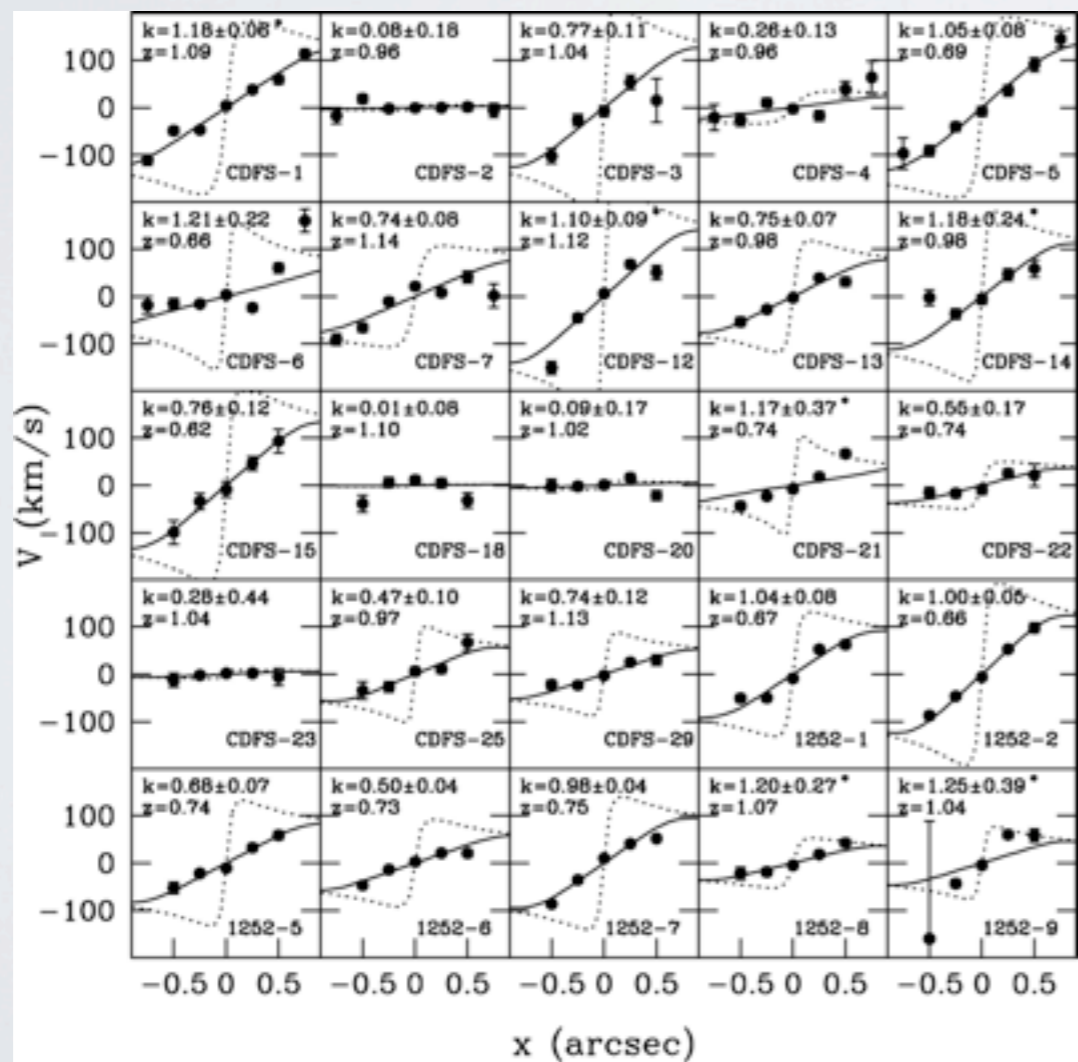
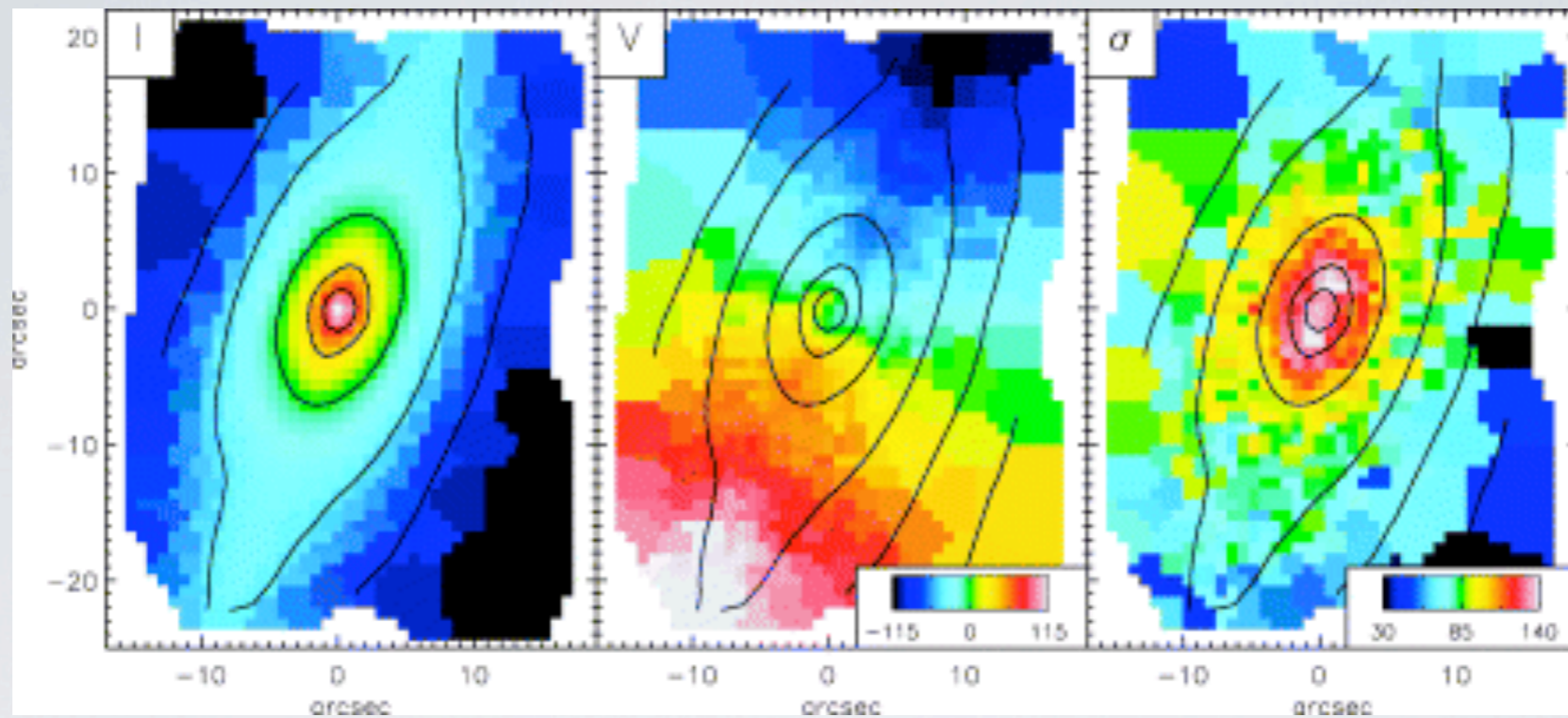
Stellar masses vs. dynamical masses at $z = 1$



Dynamical mass

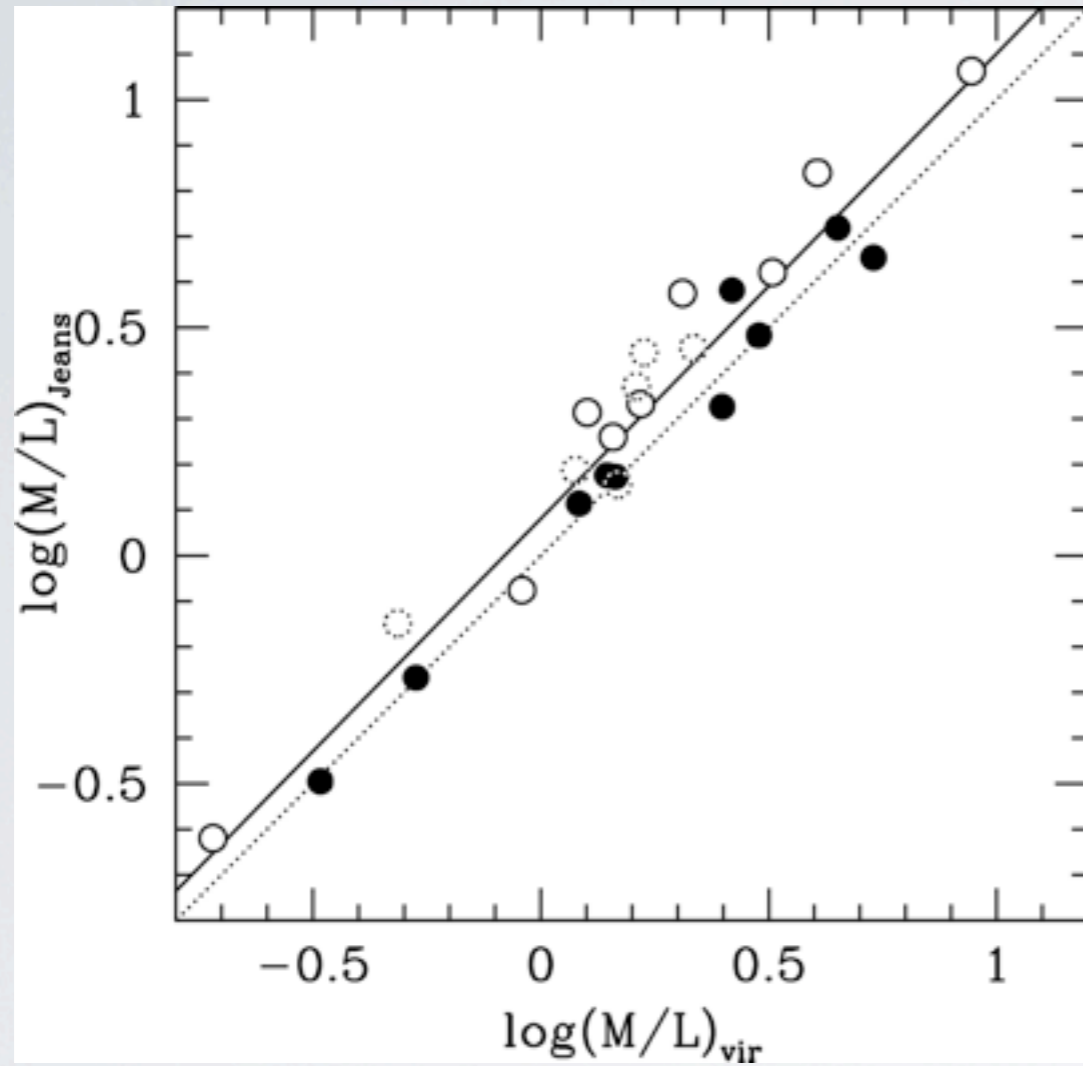
Is $M \sim \beta r_{1/2} \sigma^2 / G$ valid at higher z ?





van der Wel & van der Marel (2008)

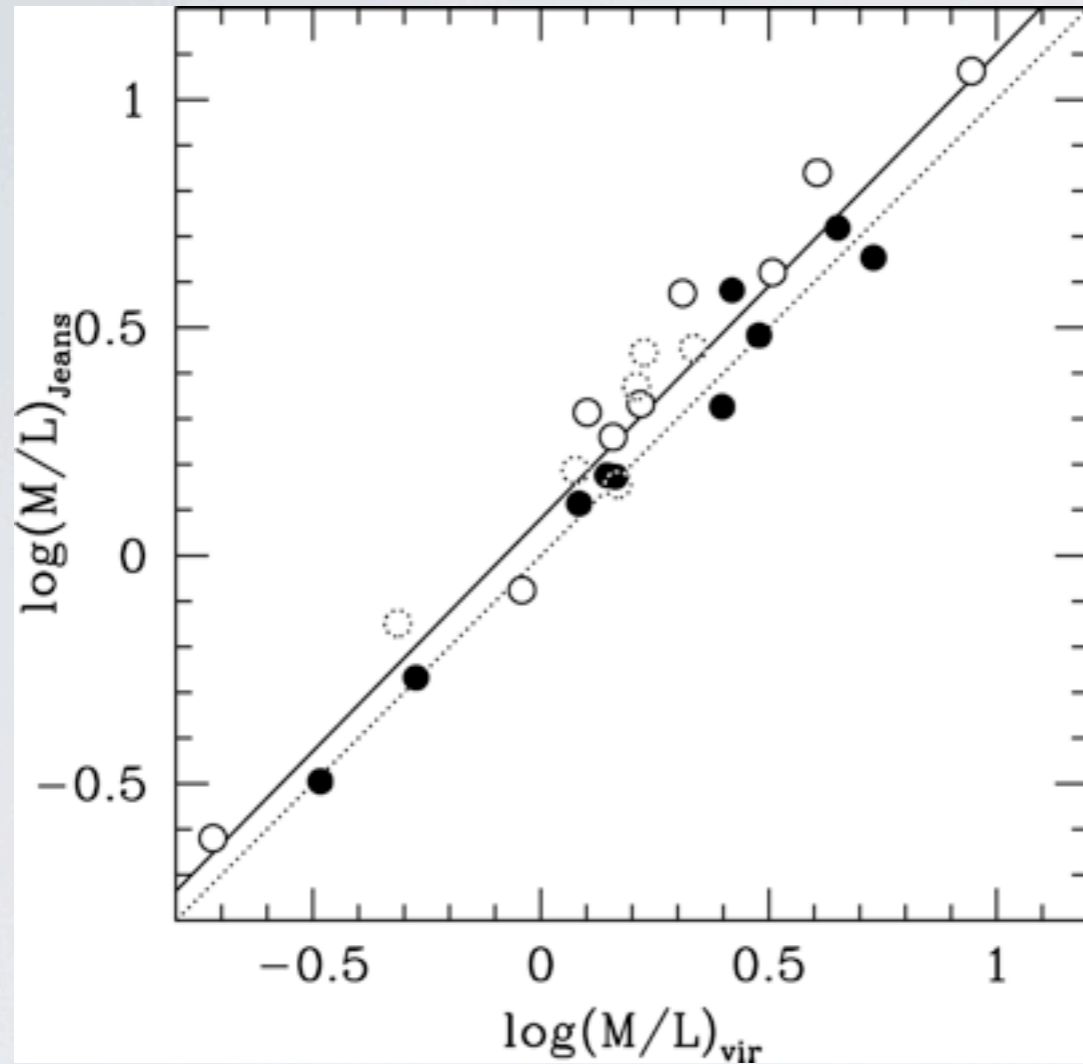
At $z = 1 \dots$



$$M \sim \beta r_{1/2} \sigma^2 / G$$

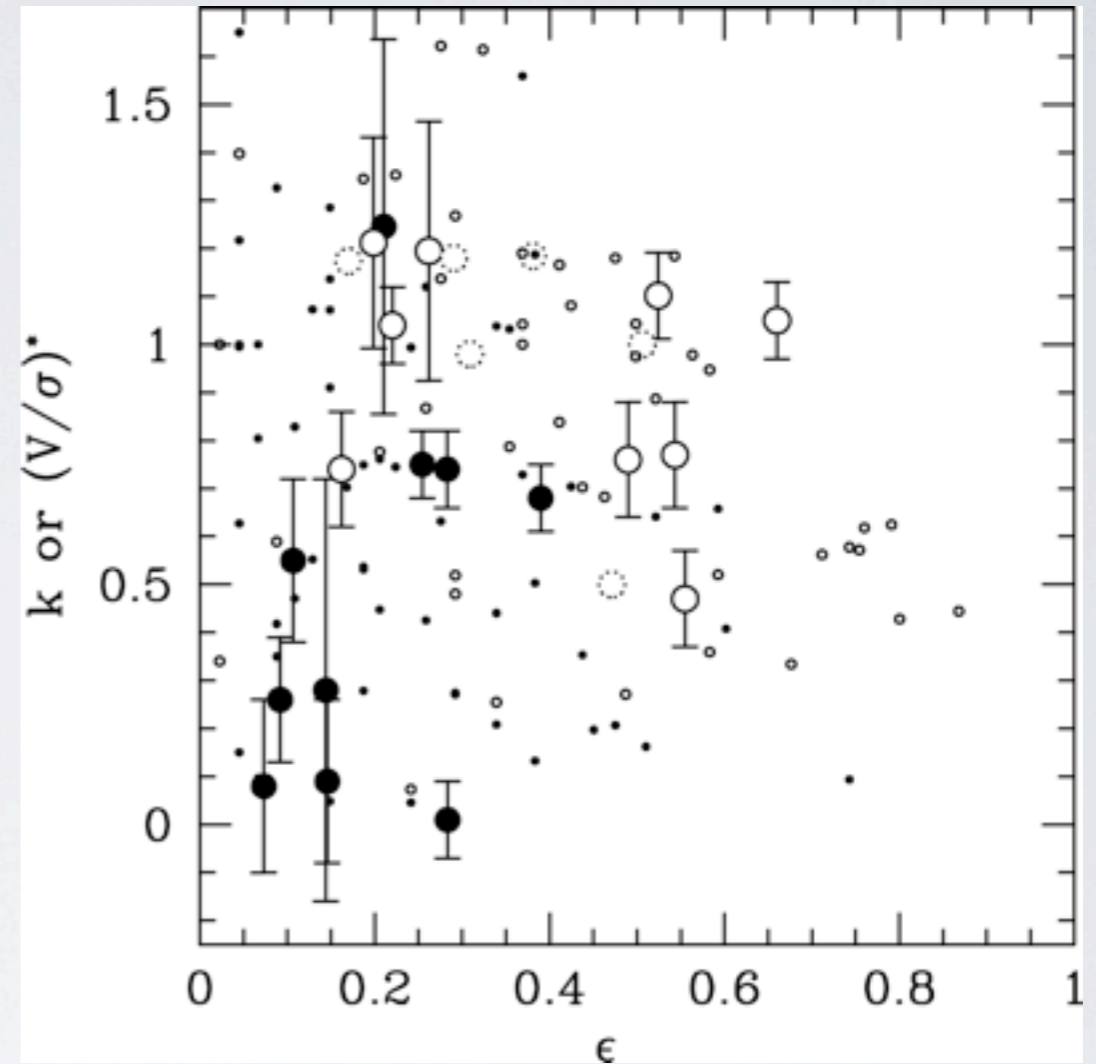
still valid

At $z = 1$...



$$M \sim \beta r_{1/2} \sigma^2 / G$$

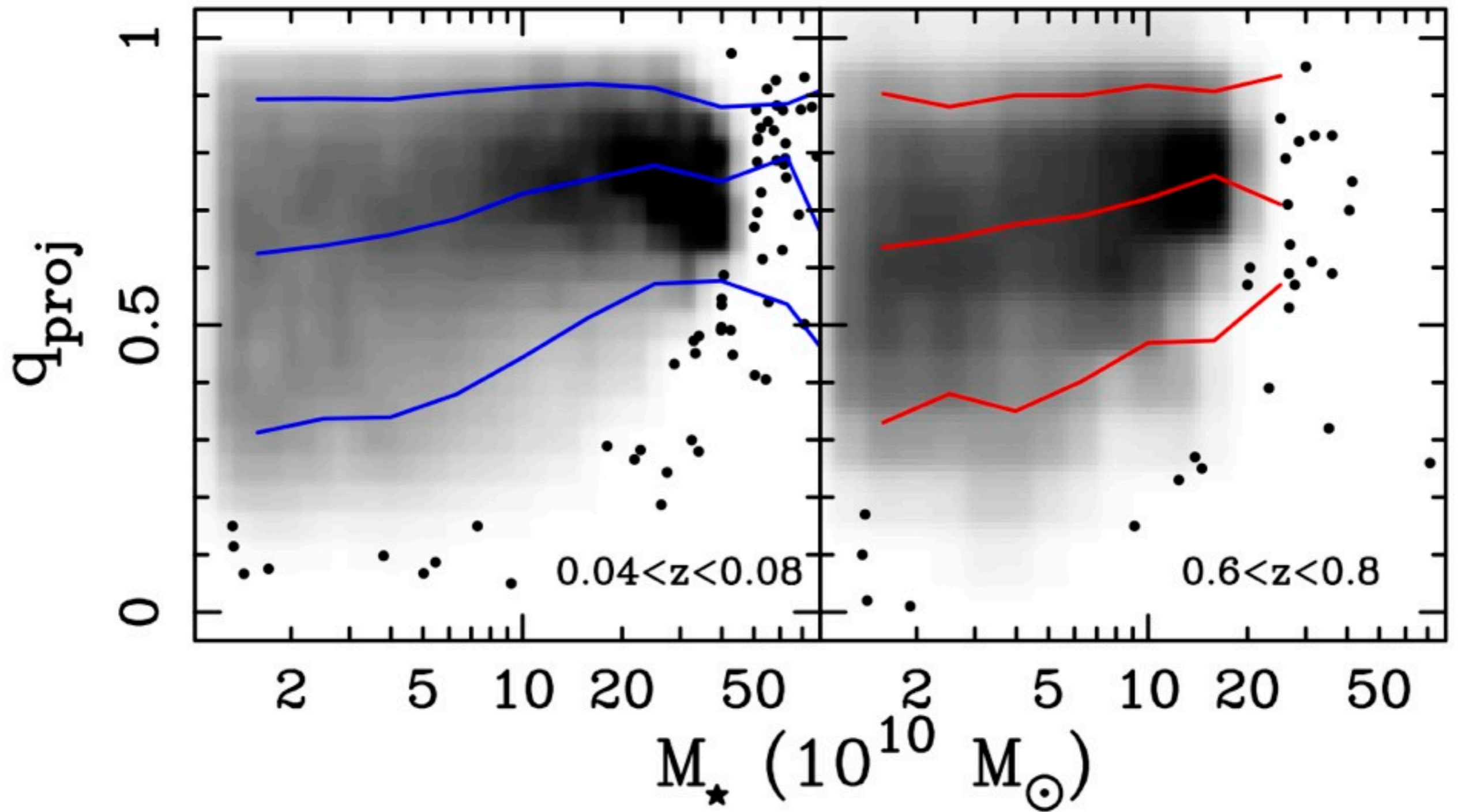
still valid



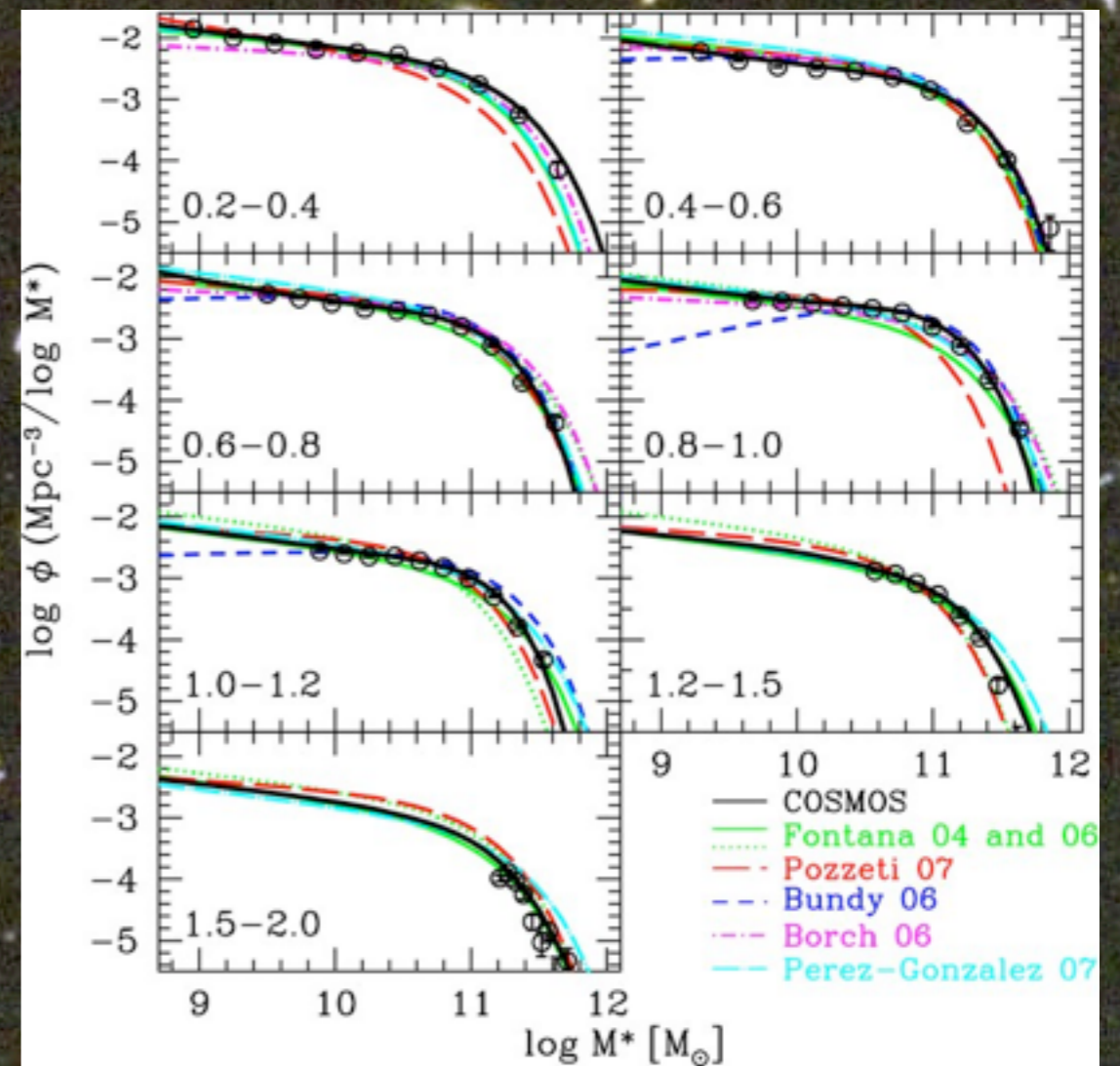
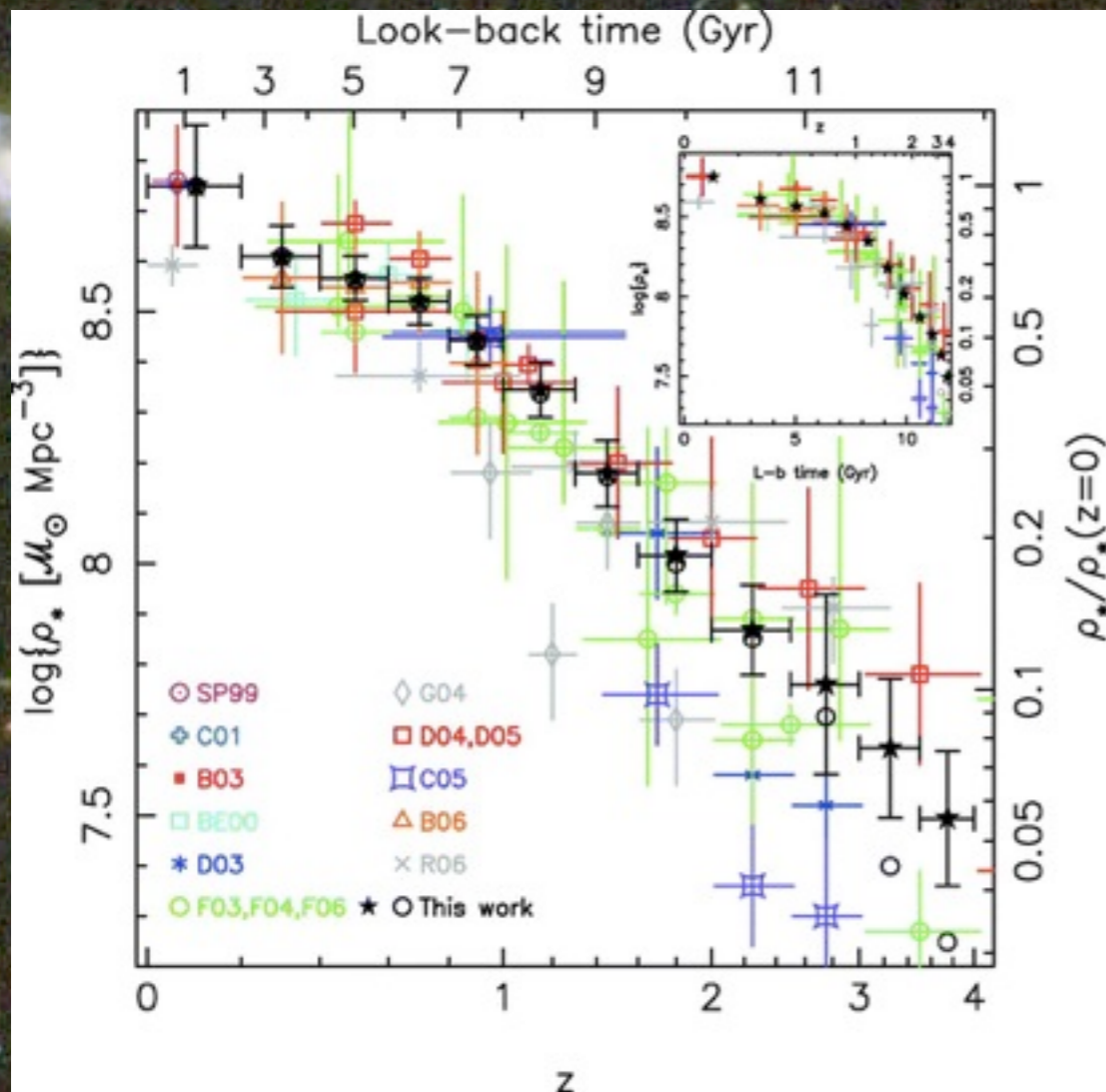
Shape \sim rotation/'diskiness'

still valid

No evolution in shape distribution of early-types at $z < 1$

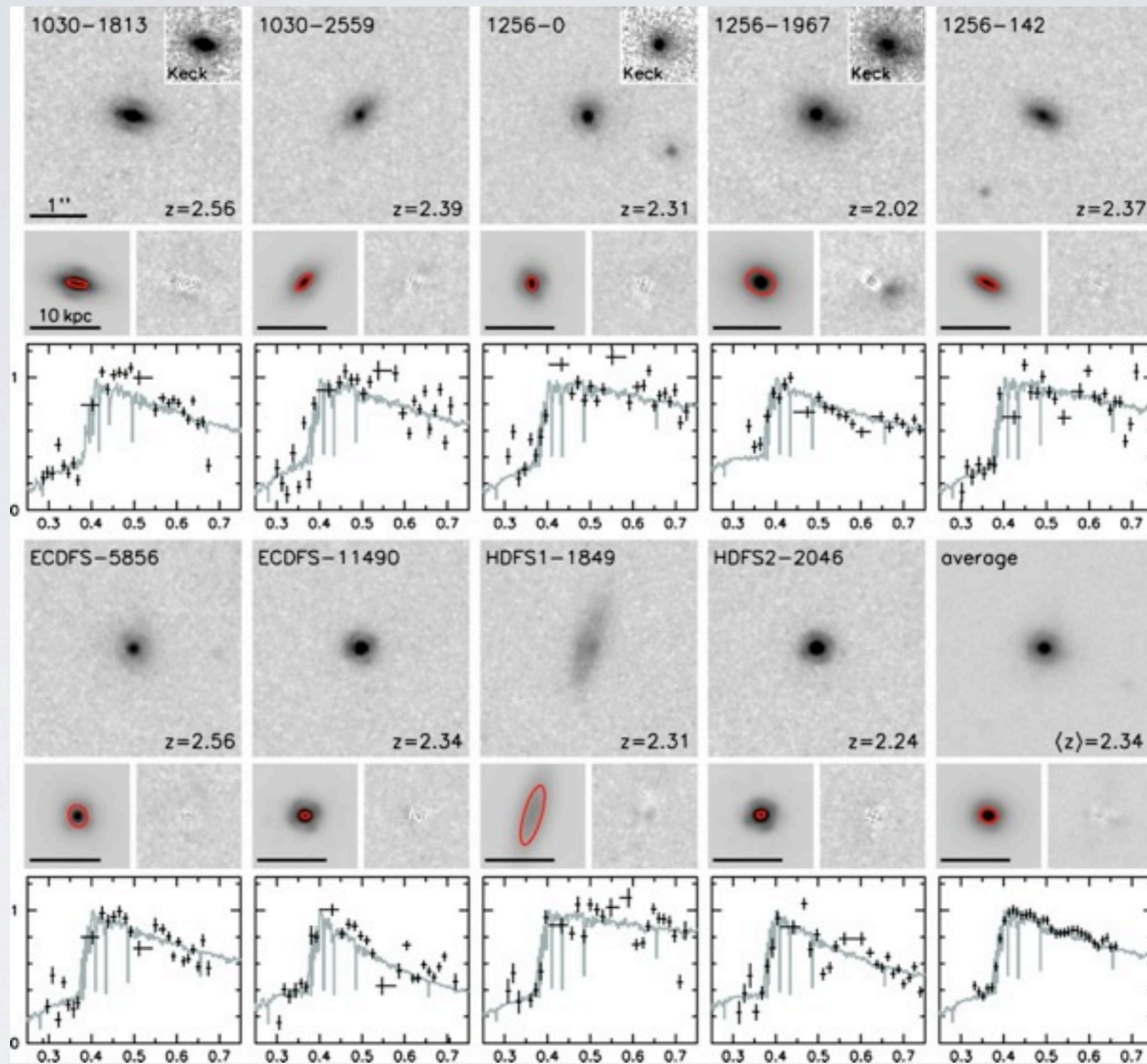


Holden et al. (2011)



$z > 1$ work: near-infrared observations

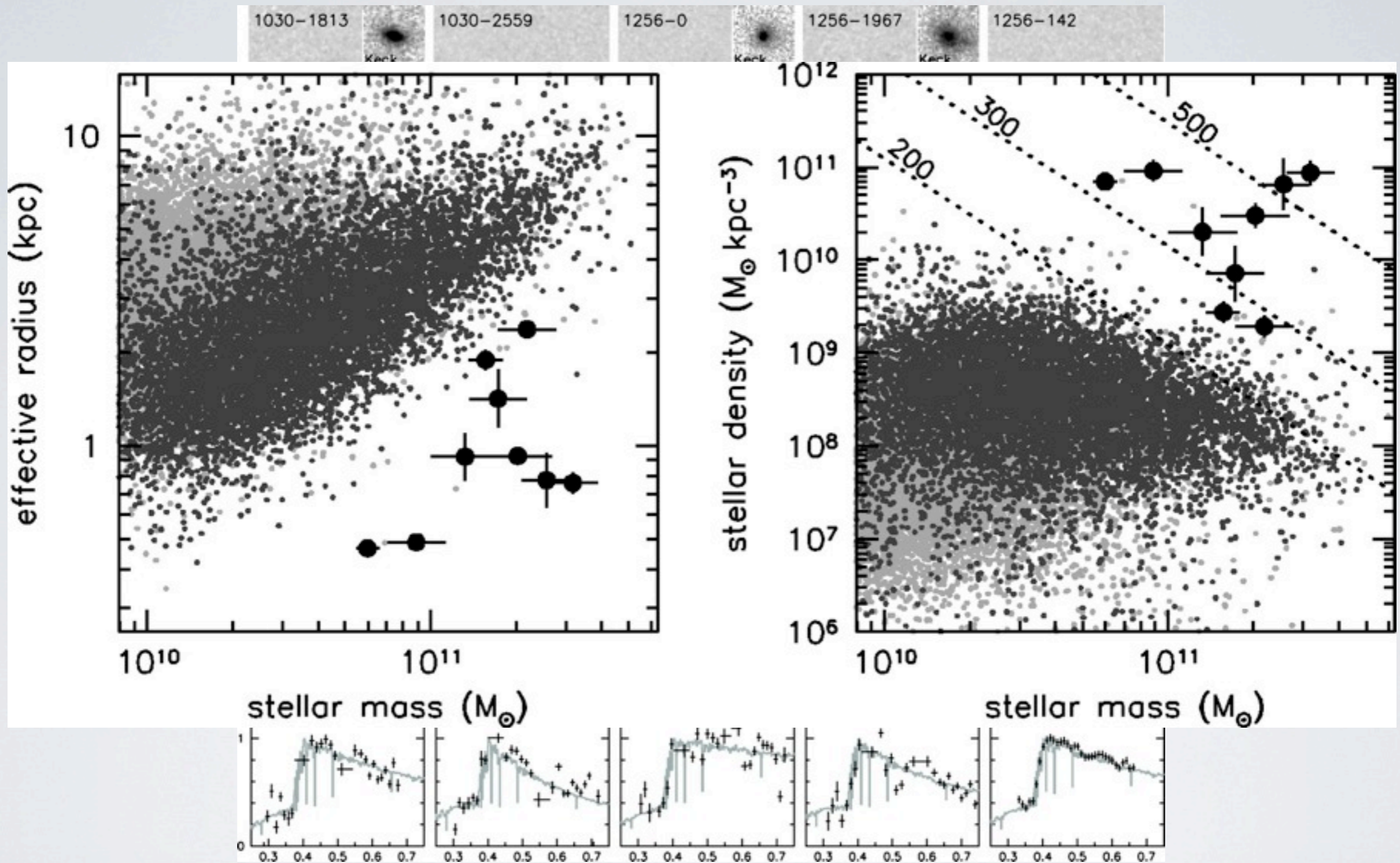
Massive early-type galaxies at $z \sim 2$ are small



HST/NICMOS imaging + Gemini/GNIRS spectroscopy: Kriek et al. (2007); van Dokkum et al. (2008)

also see, e.g., Daddi+05; Trujillo+06; Zirm+07; Toft+07

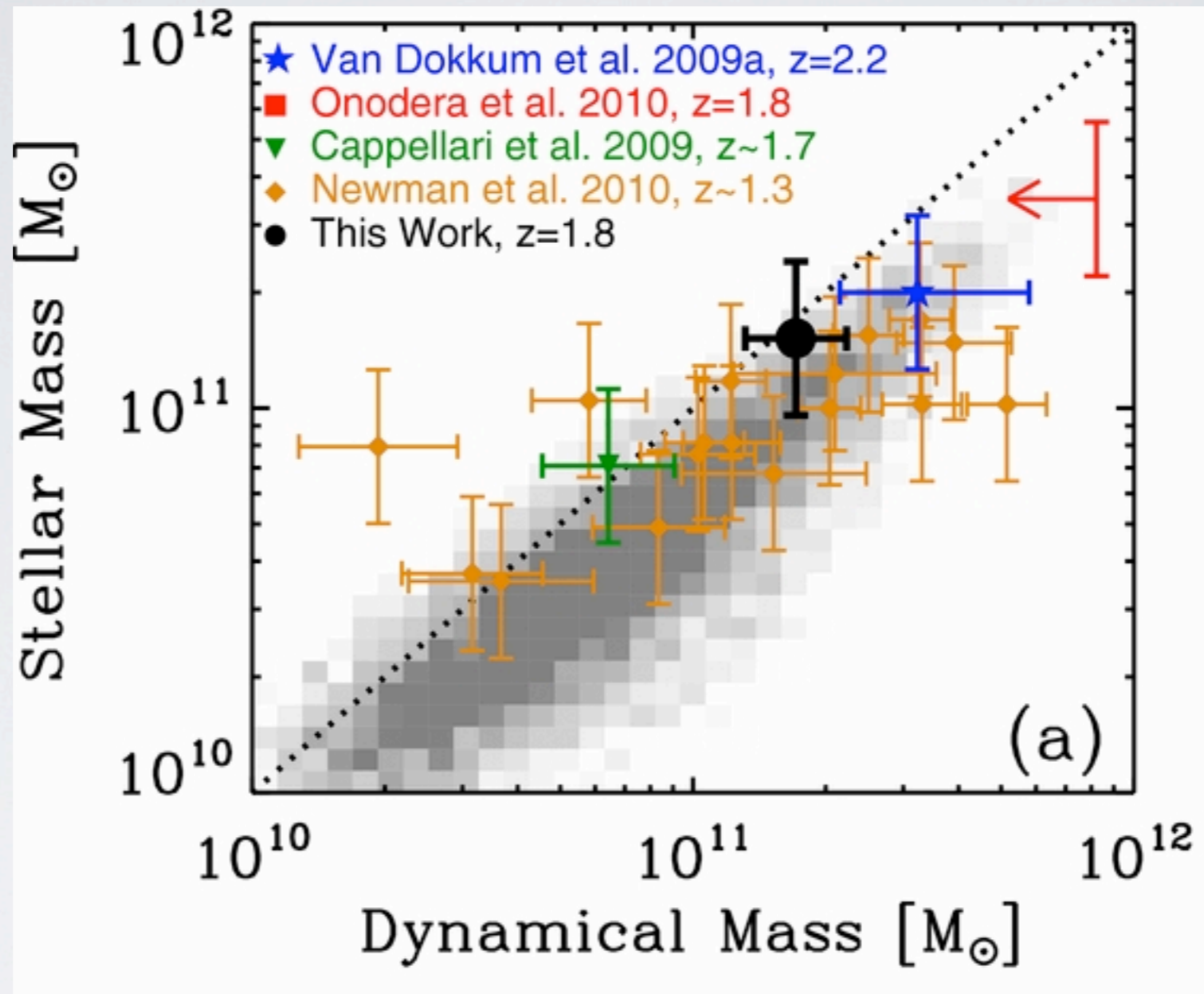
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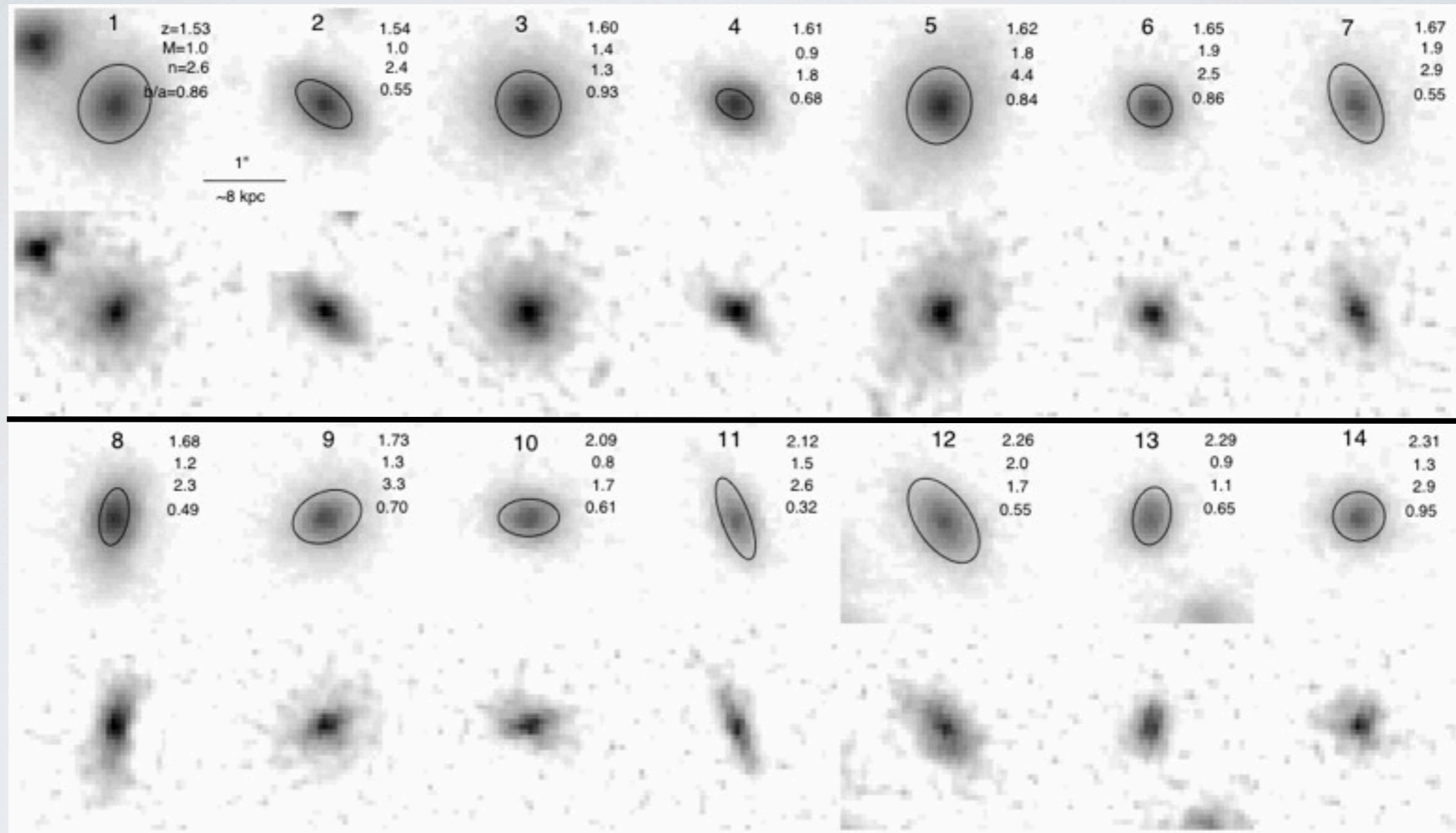
also see, e.g., Daddi+05; Trujillo+06; Zirm+07; Toft+07

Stellar masses vs. dynamical masses at $z = 2$



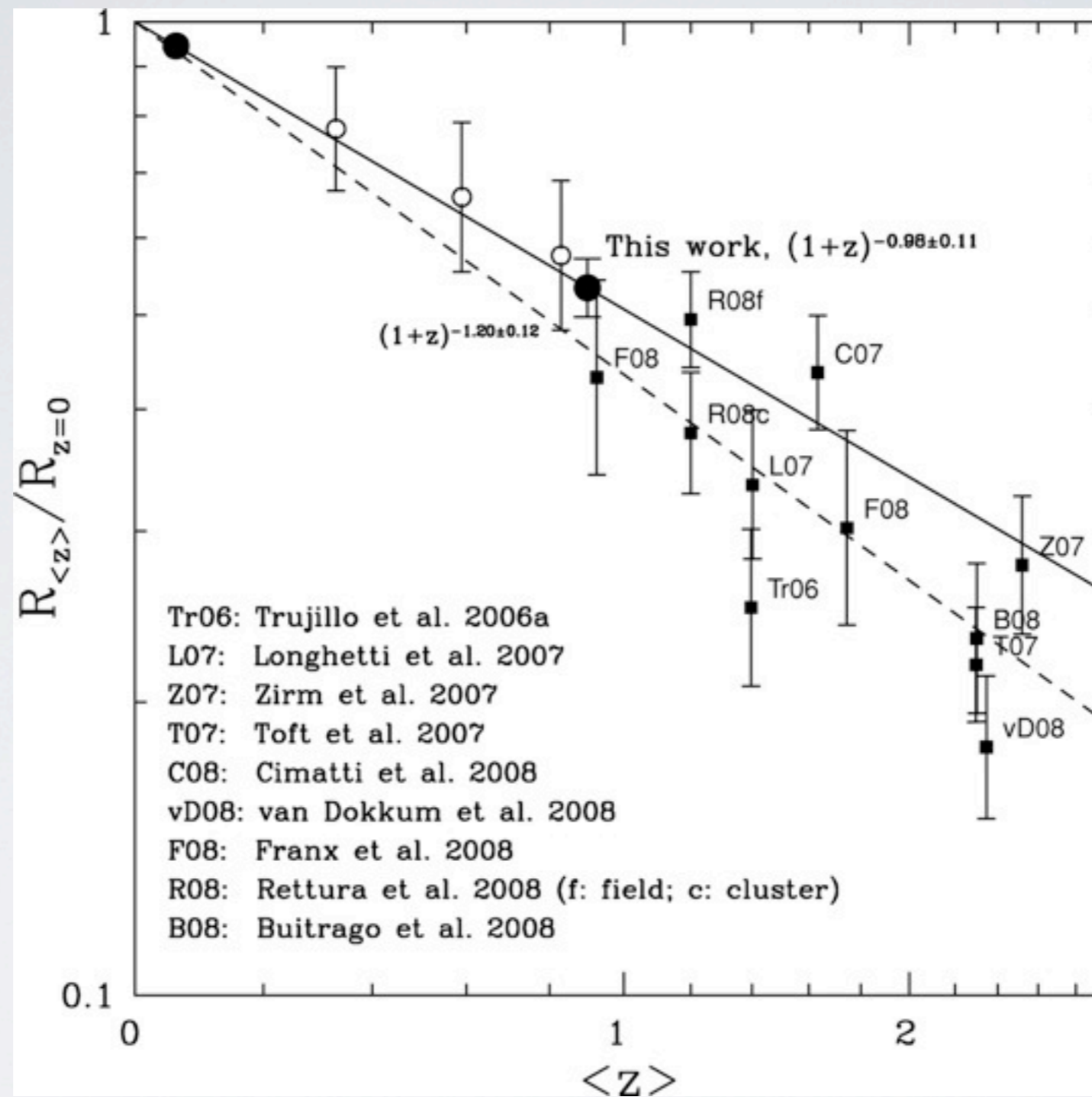
van de Sande et al. (2011)

Compact, massive early-type galaxies at $z \sim 2$ often have prominent disks



HST/WFC3 imaging: van der Wel et al. (2011)

Early-type galaxies evolve in size gradually



van der Wel et al. (2008)

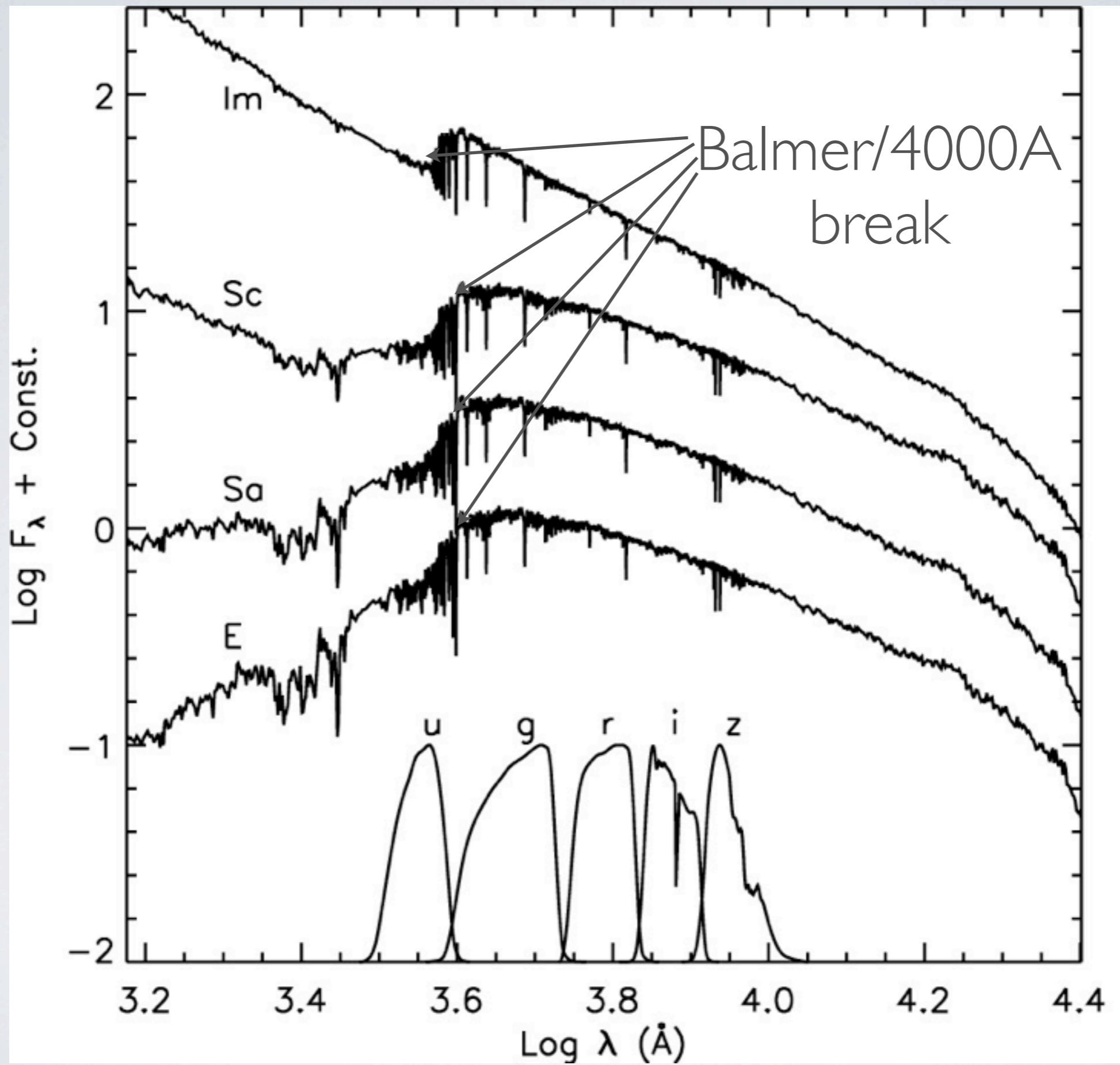
Summarizing ...

- Interpretation of high- z galaxy observations is robust
- This is thanks to the complementary approaches of dynamical measurements and observationally cheaper photometric measurements

Bonus part:

STARBURSTING DWARF GALAXIES

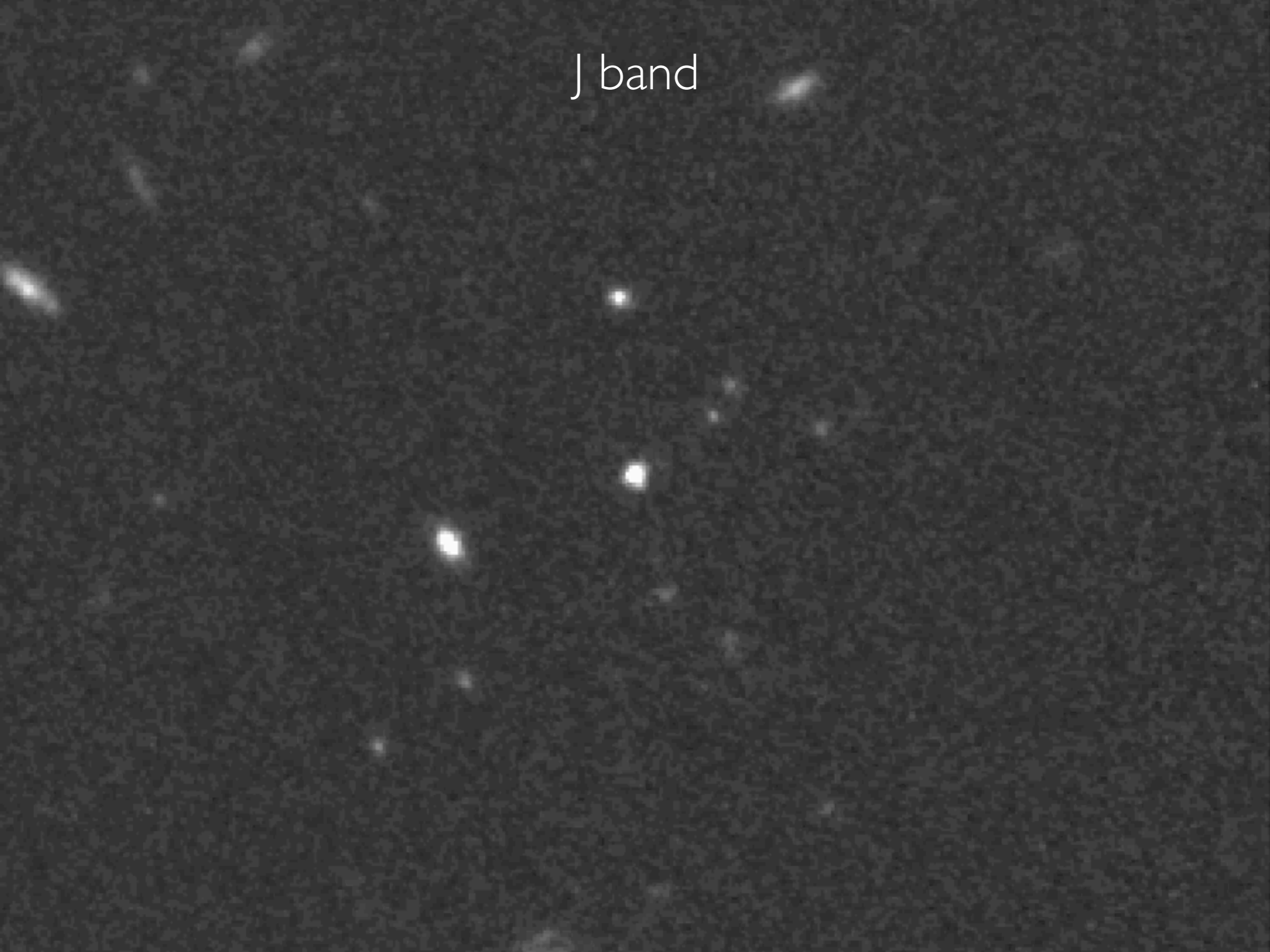
a recent result based on
HST imaging/spectroscopy
(van der Wel et al. 2011)



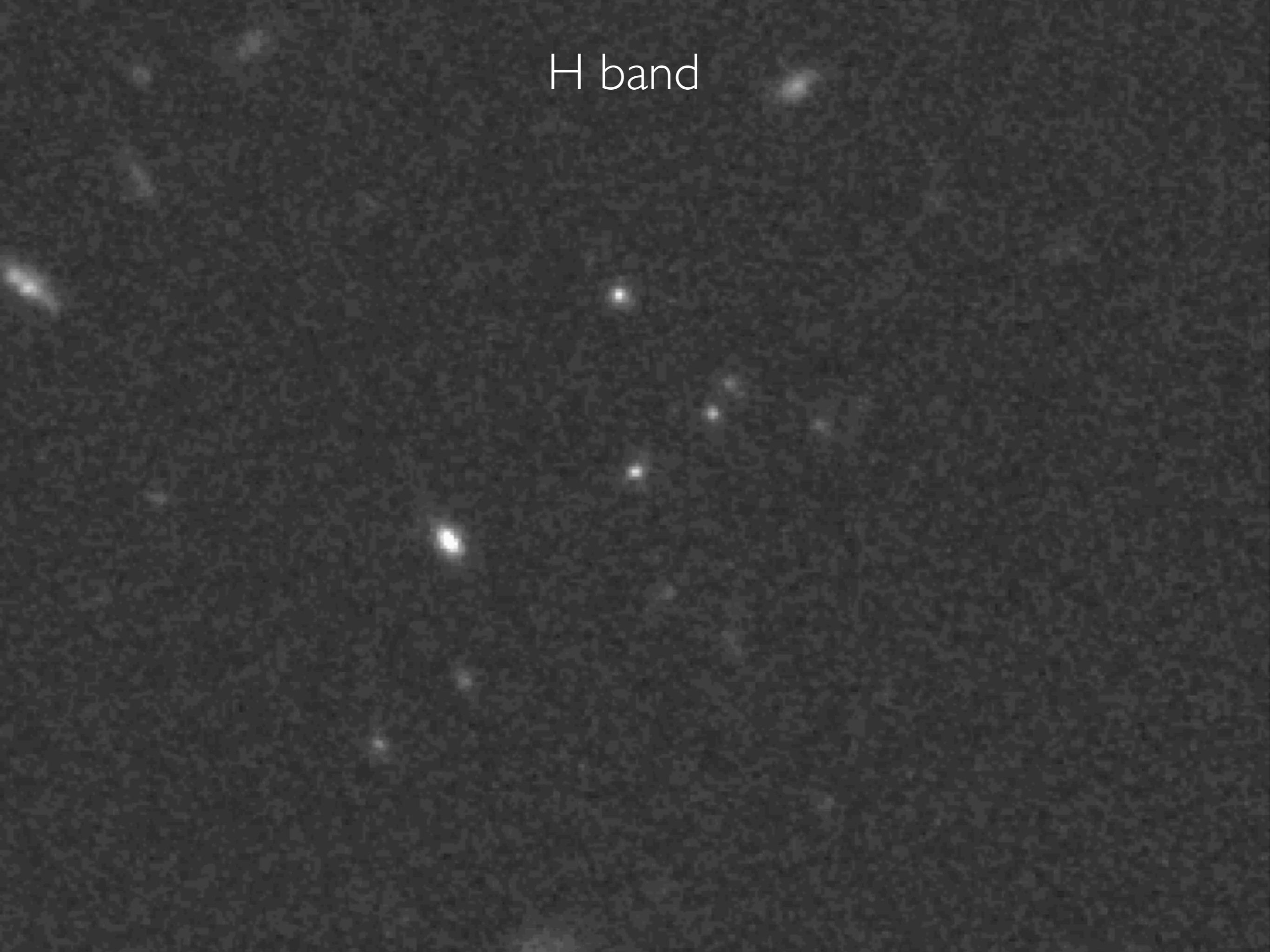
i band



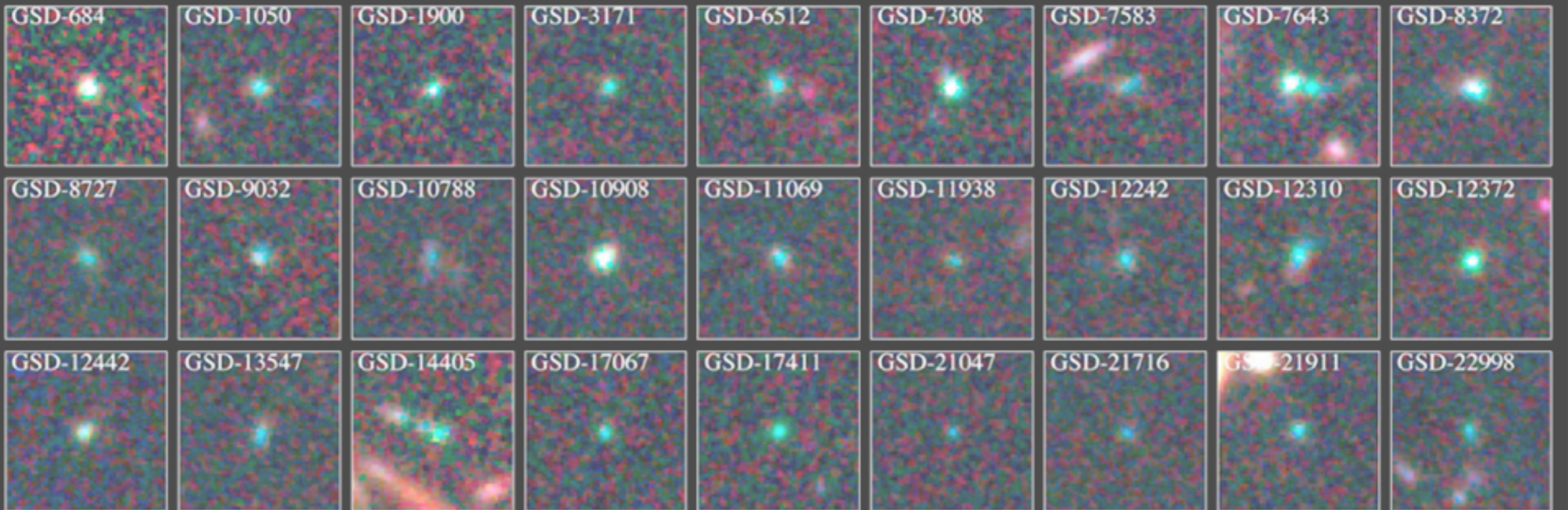
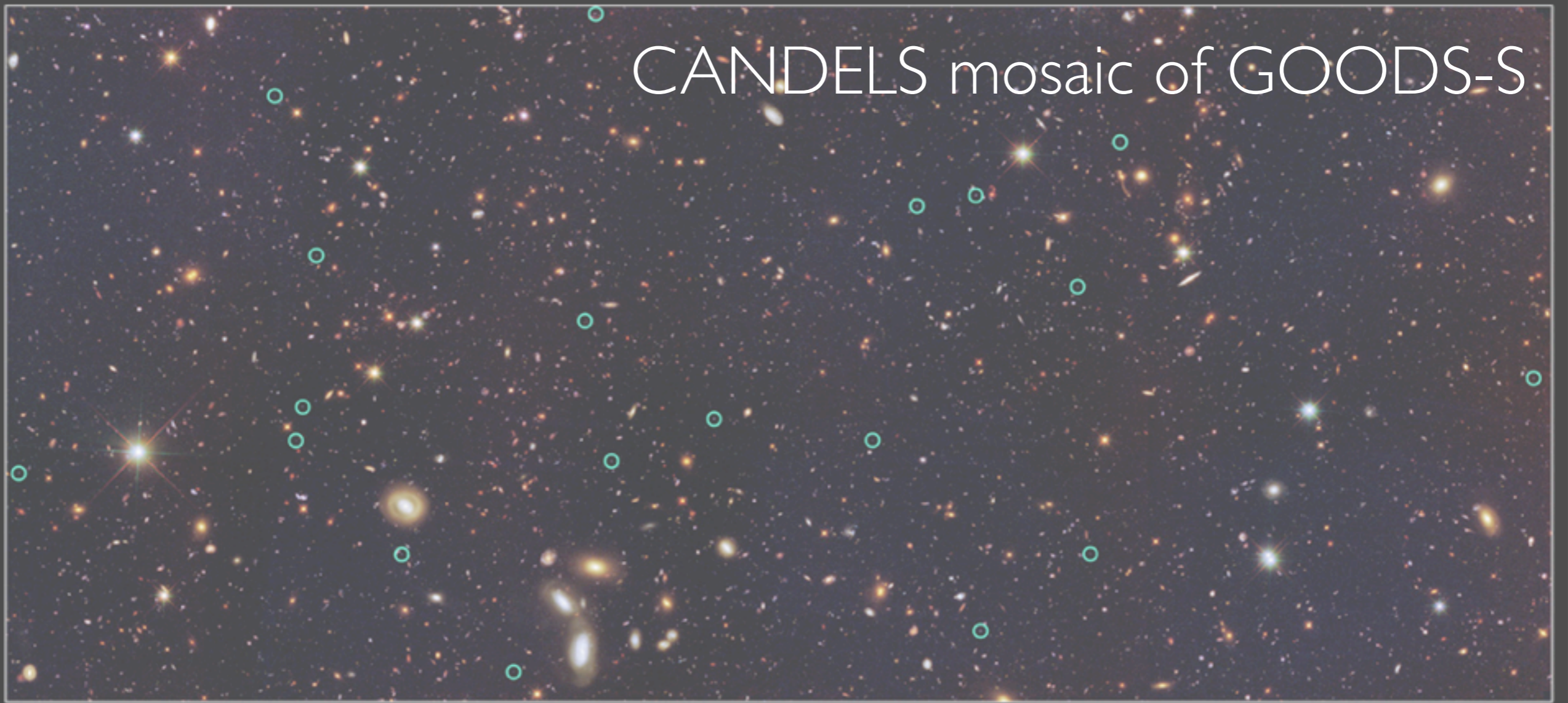
J band



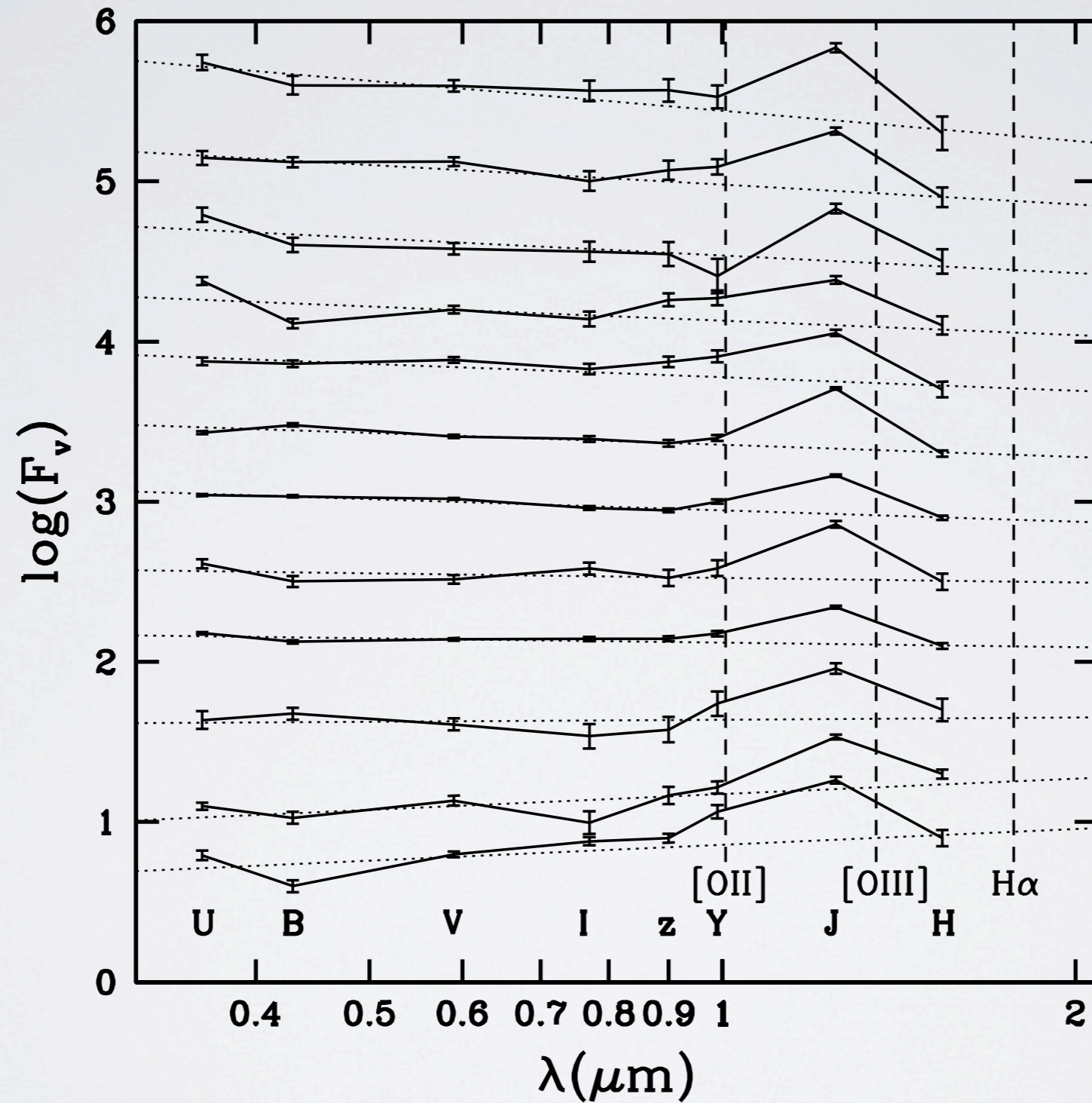
H band



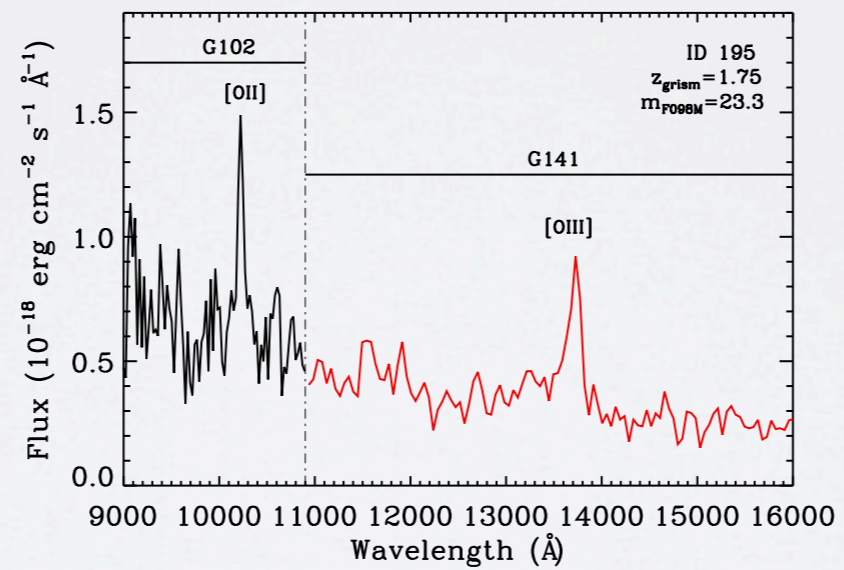
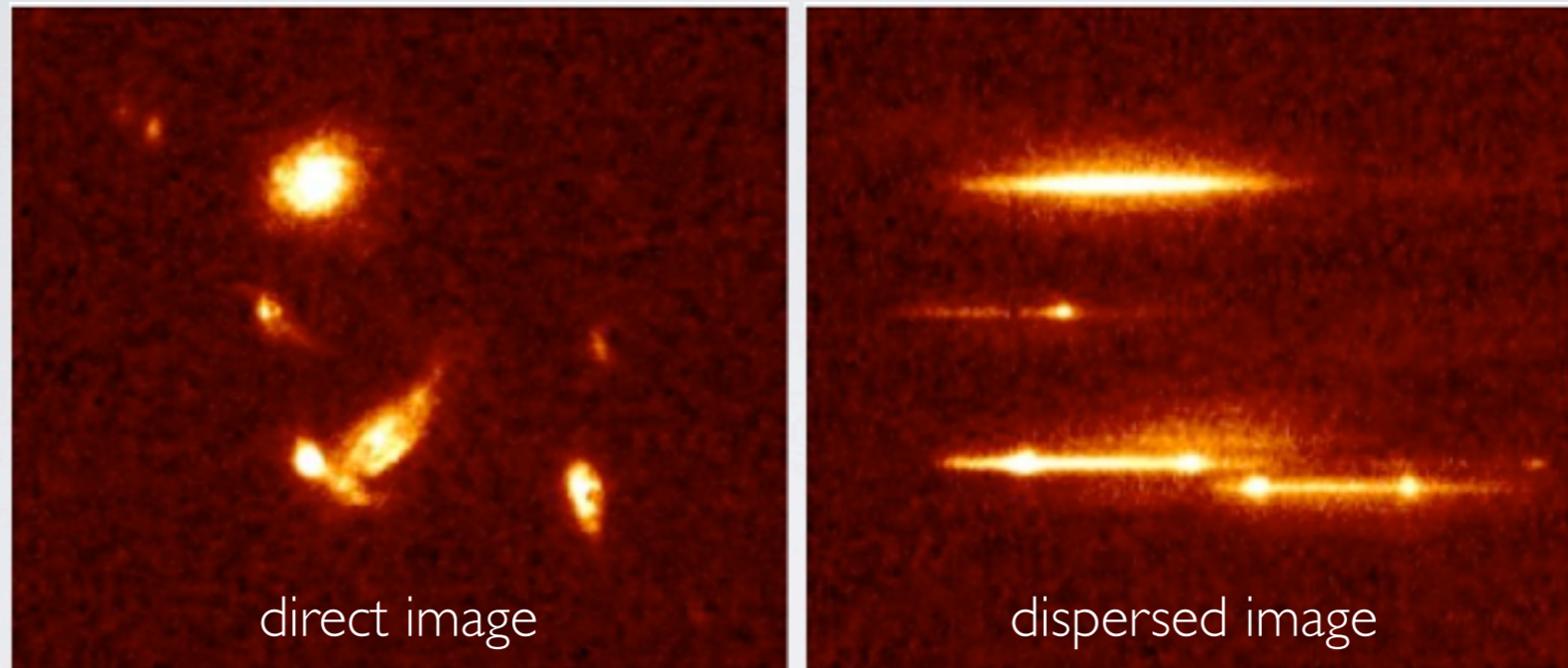
CANDELS mosaic of GOODS-S



69 candidates in 280 sq. arcmin

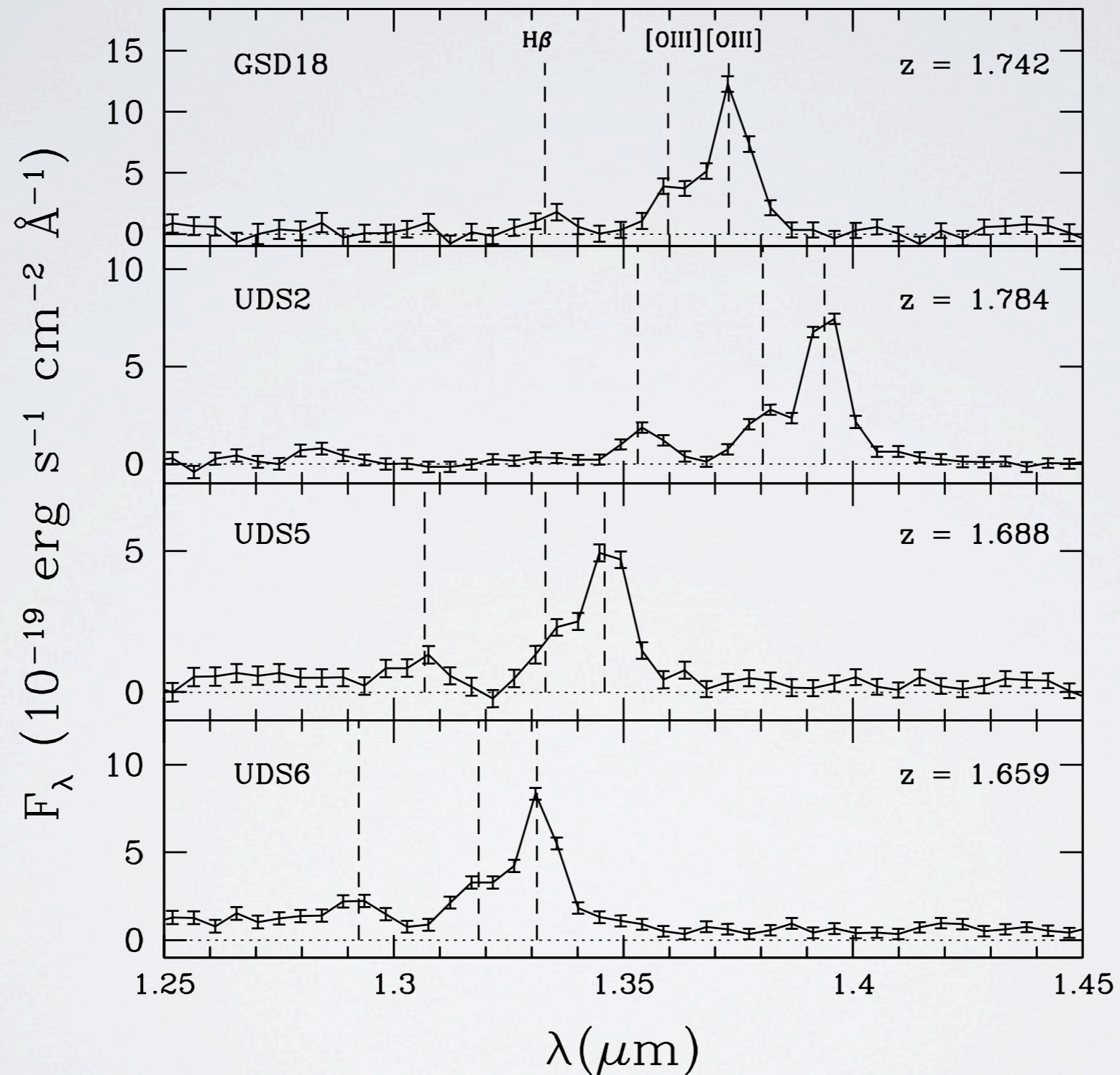


Slitless grism spectroscopy

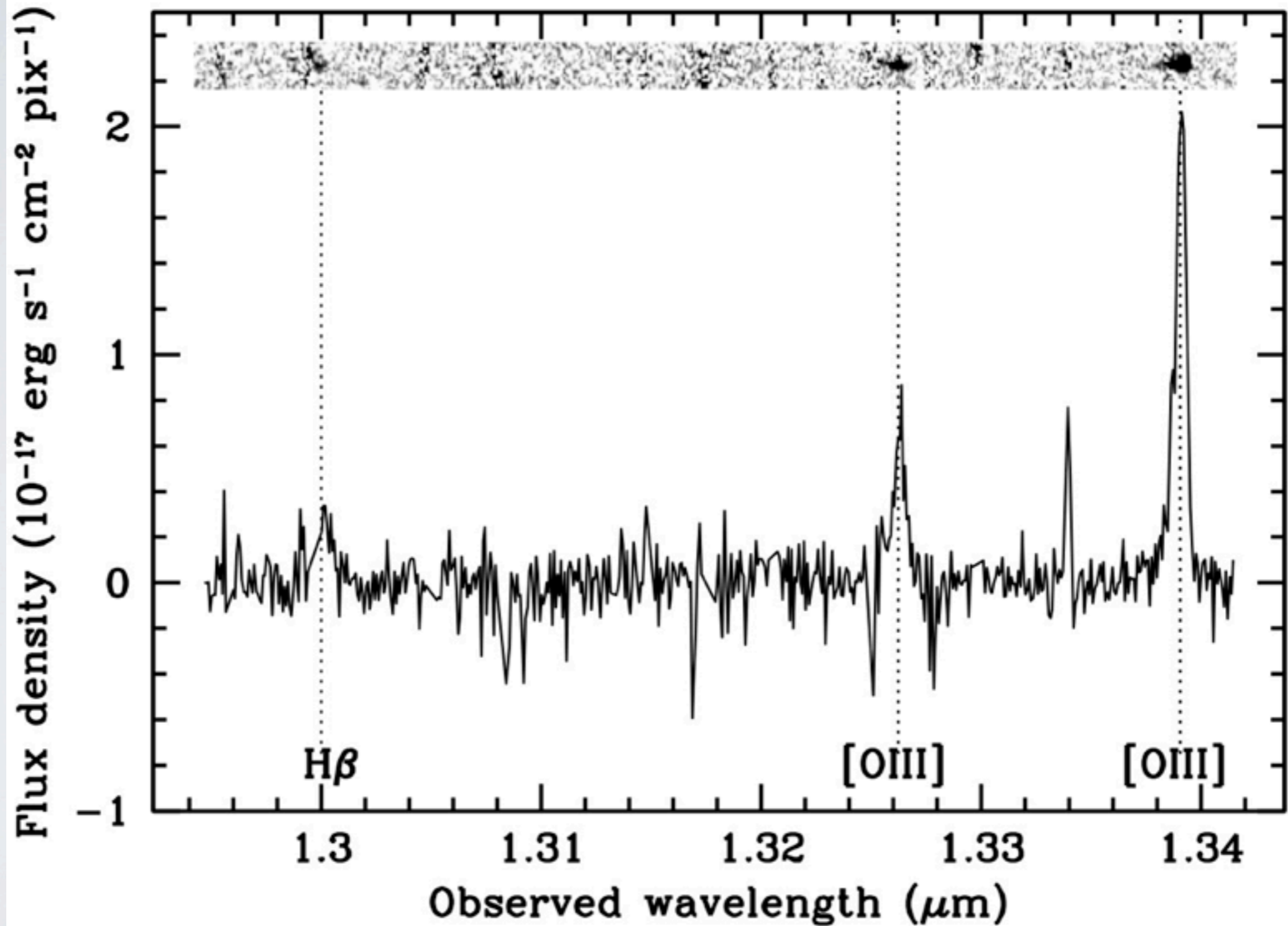


Extracted spectrum

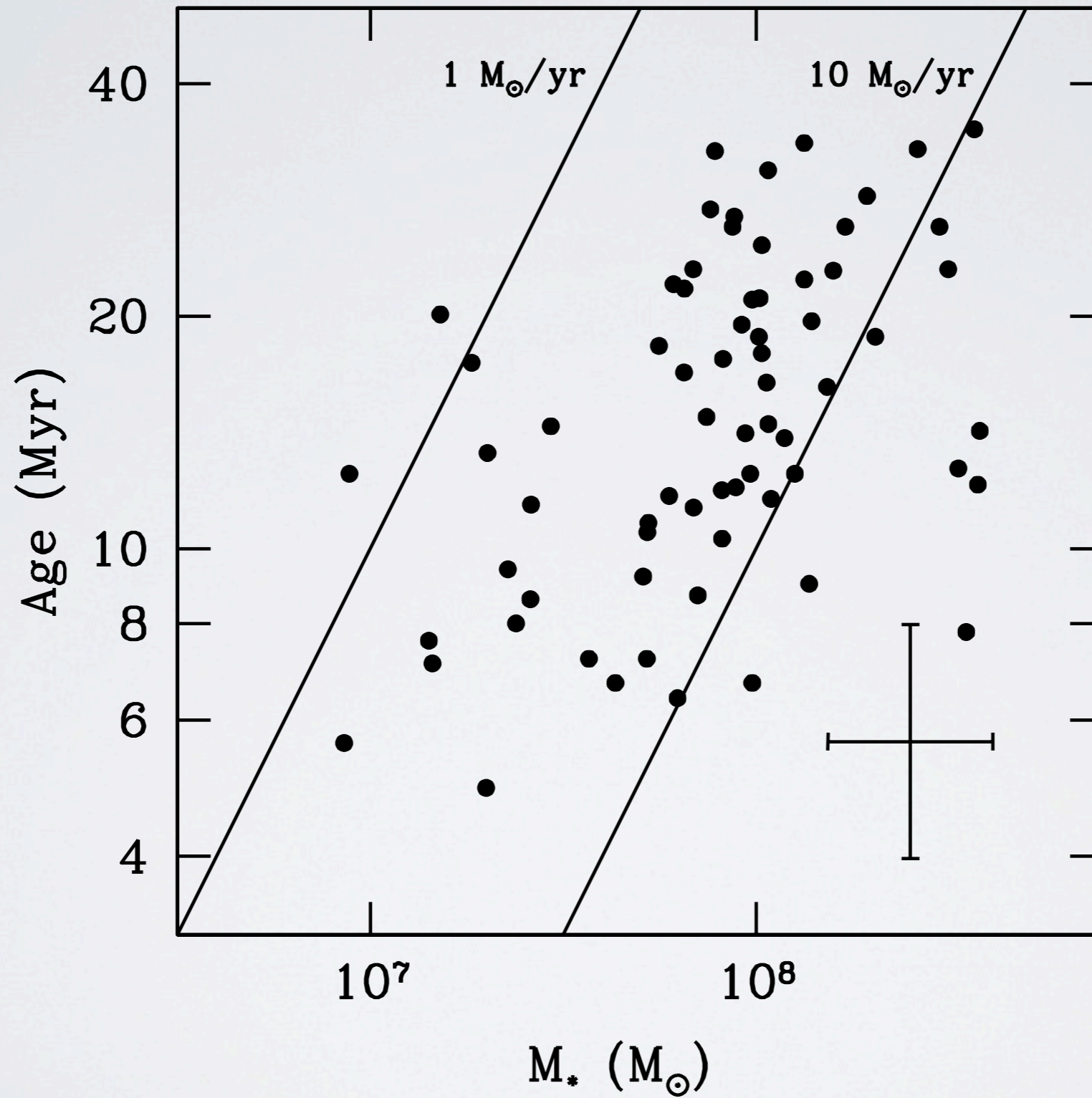
4 confirmed with WFC3 grism spectroscopy



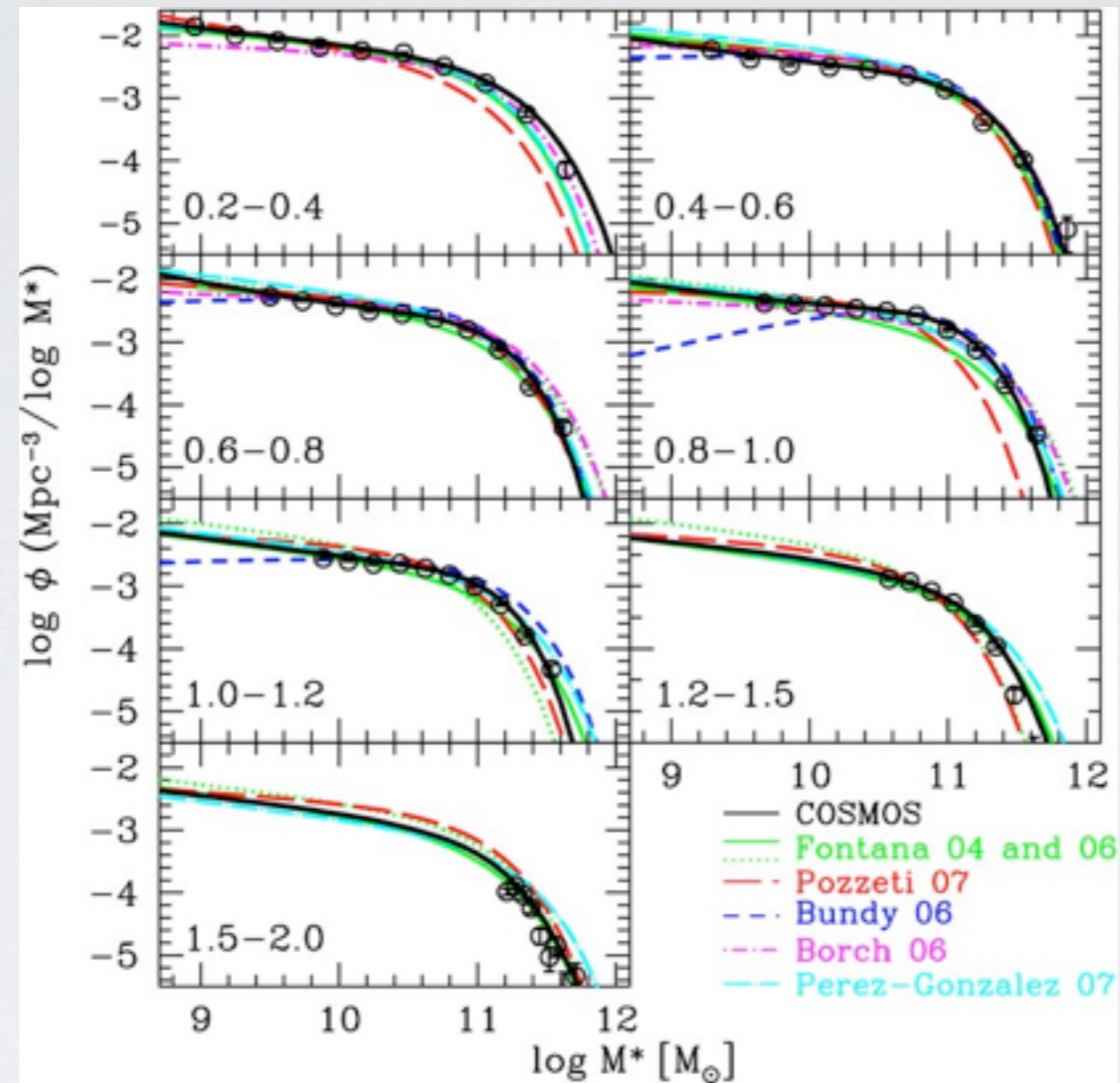
4 confirmed with WFC3 grism spectroscopy



mass $\sim 10^{7-8.5} M_{\odot}$; age 5 - 40 Myr

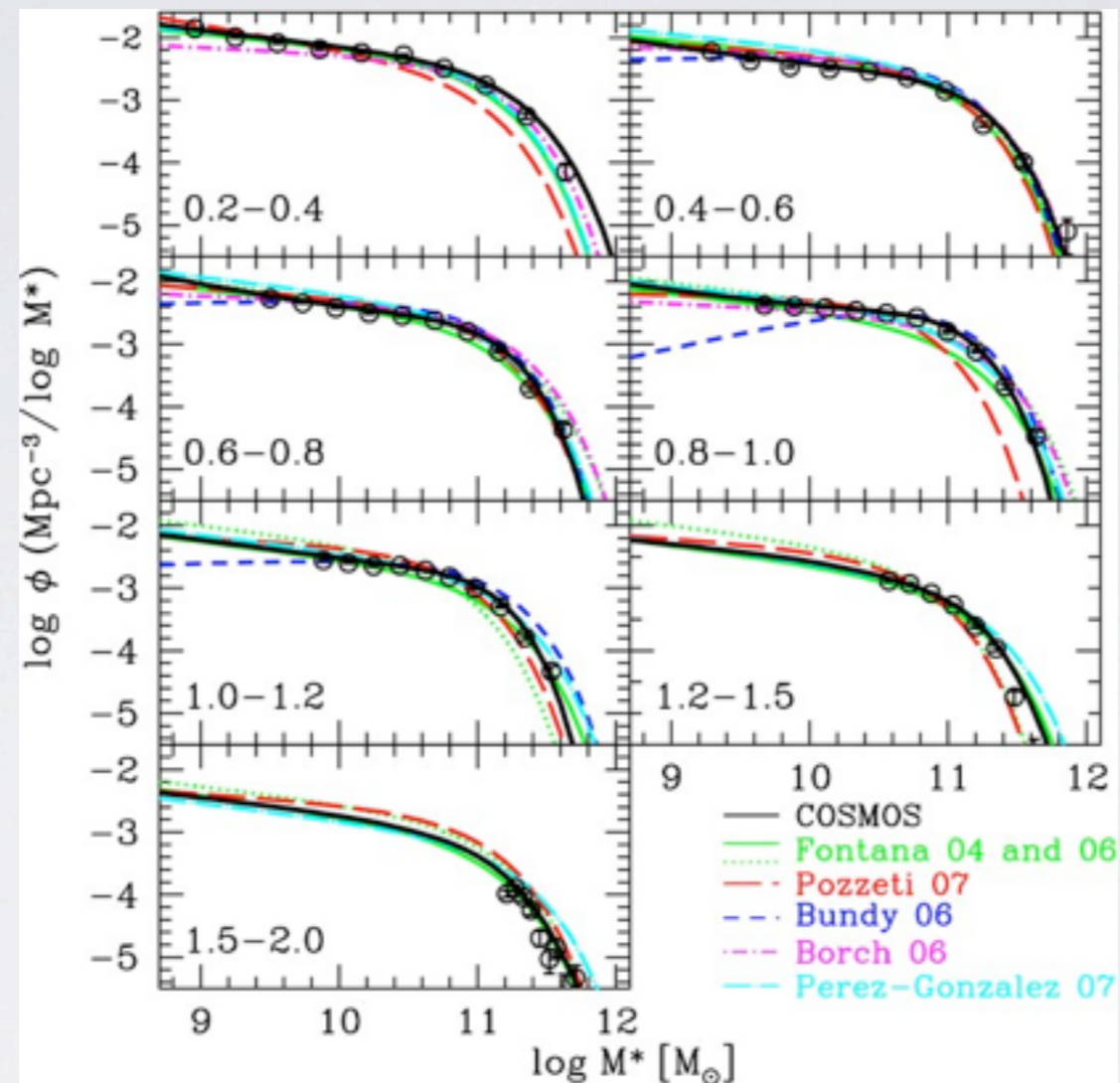


Why are these interesting?



First census of dwarf galaxies at any redshift $z > 0.1$

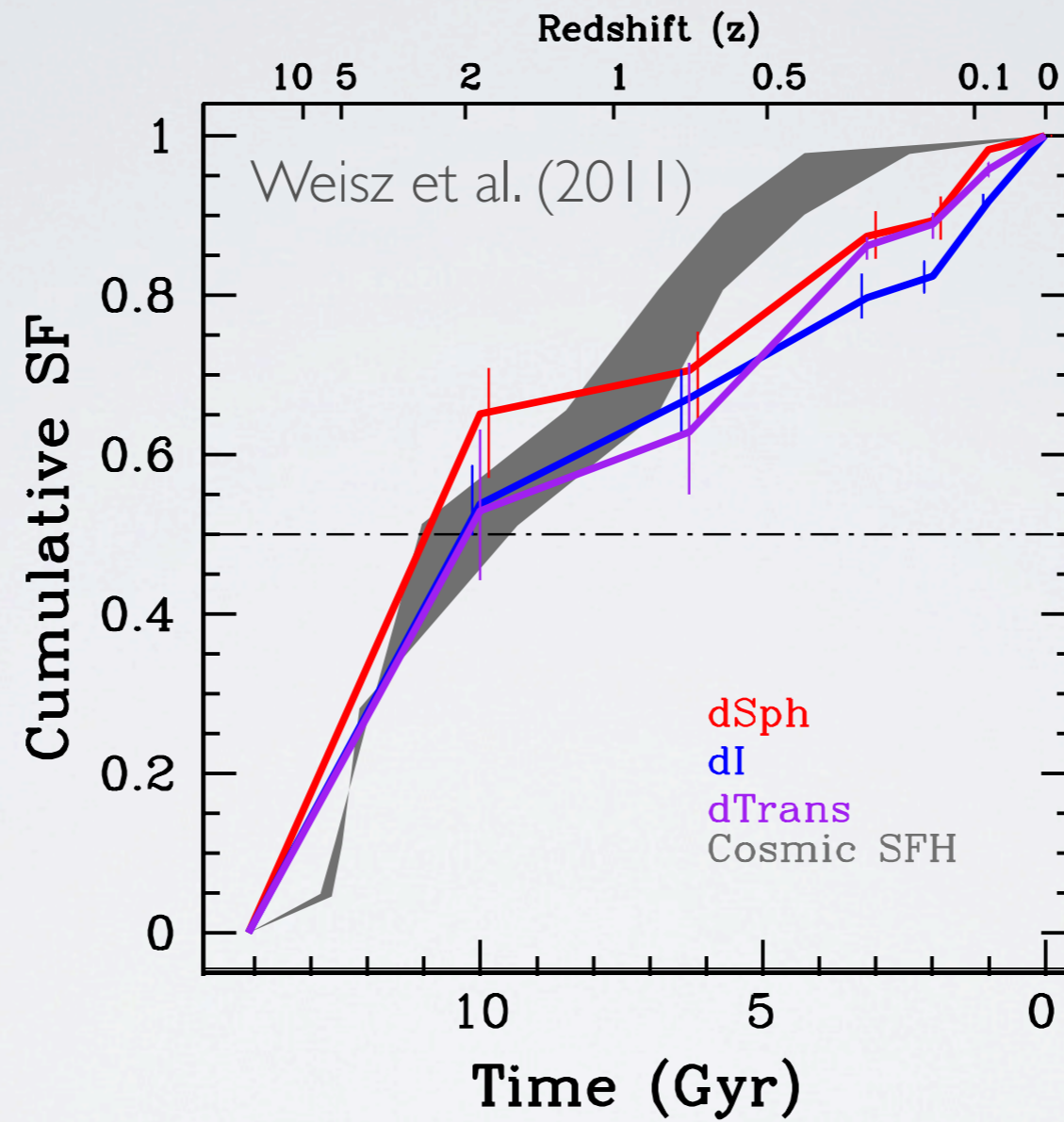
Why are these interesting?



First census of dwarf galaxies at any redshift $z > 0.1$

Significant contributors to SF in dwarf galaxies

Studies of local dwarf galaxies:



The new observations imply ...



Many or even most stars in present-day dwarf galaxies may have formed in strong, short-lived bursts at $z > 1$

Thank you!