The Stellar Initial Mass Function of Massive Galaxies

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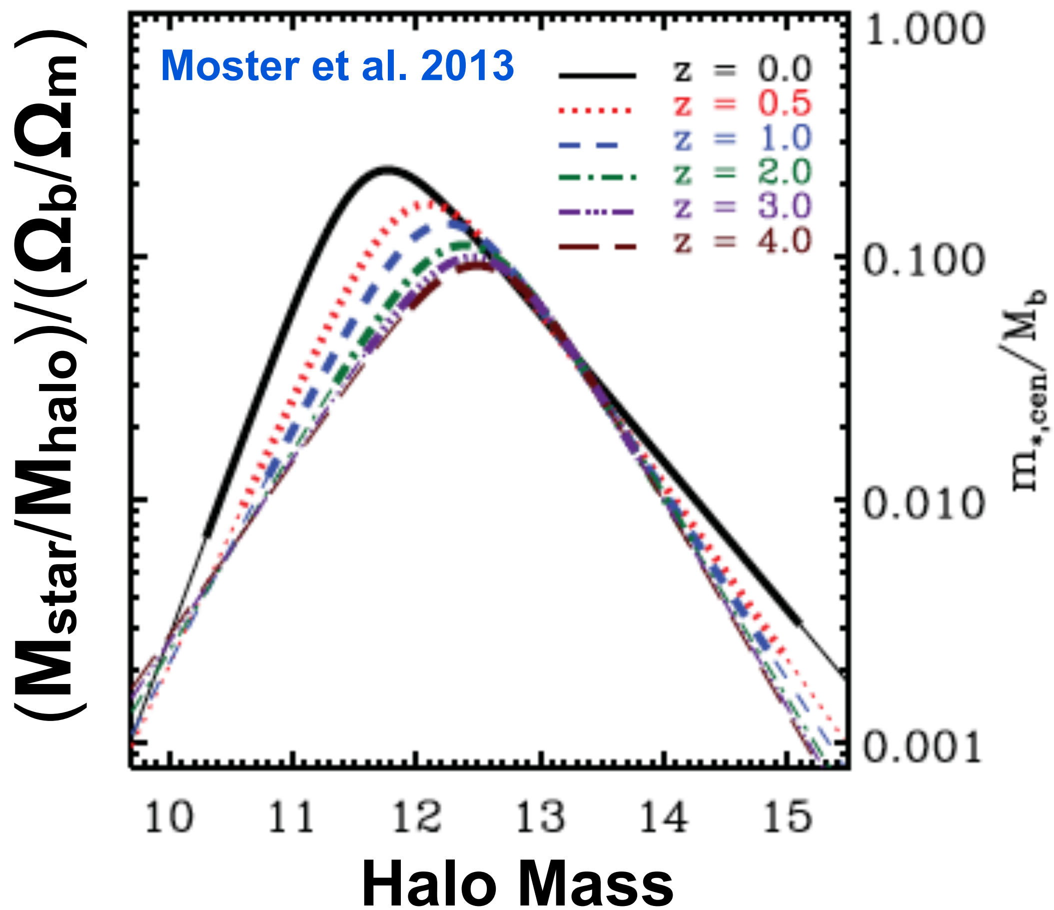
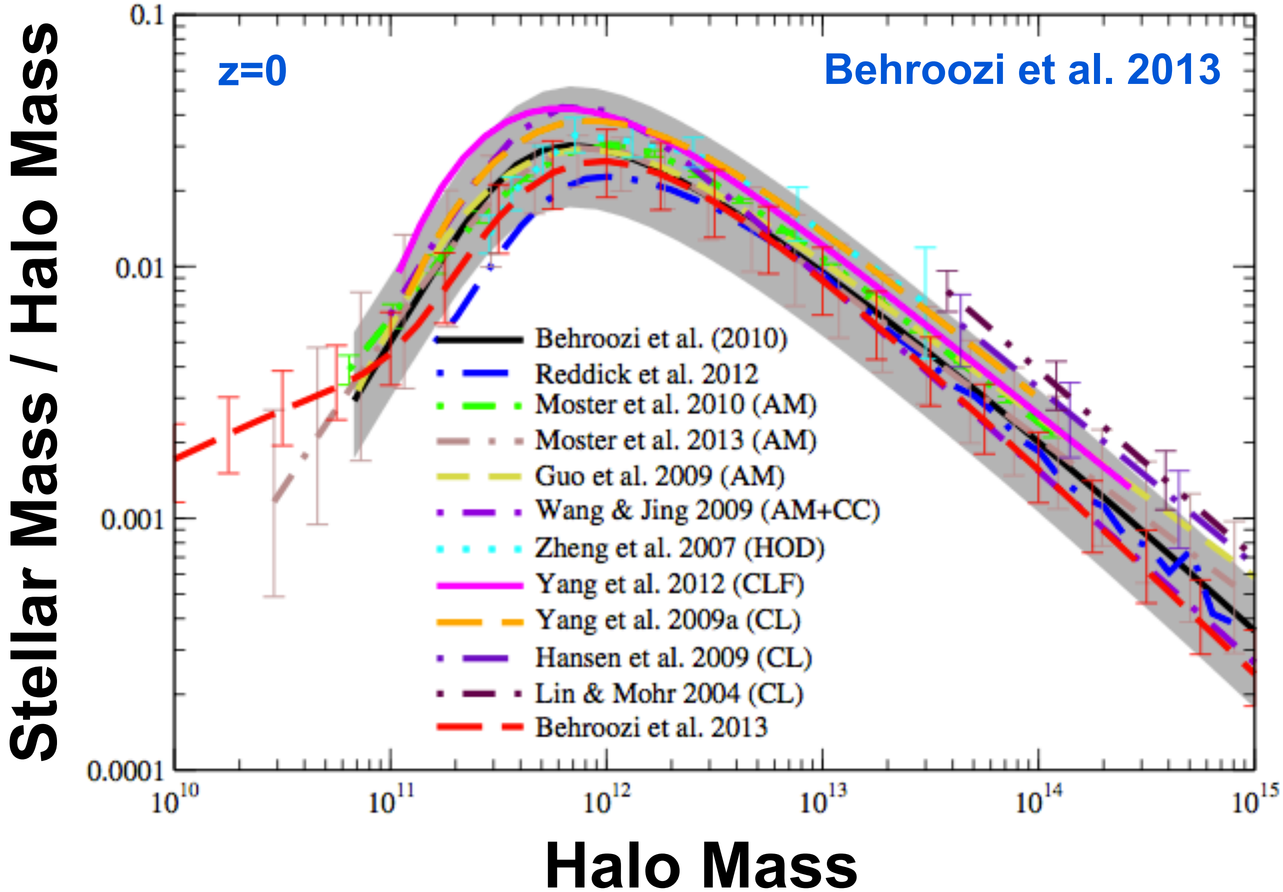
Motivation

- What is the (integrated) efficiency of star formation in massive dark matter haloes?



Motivation

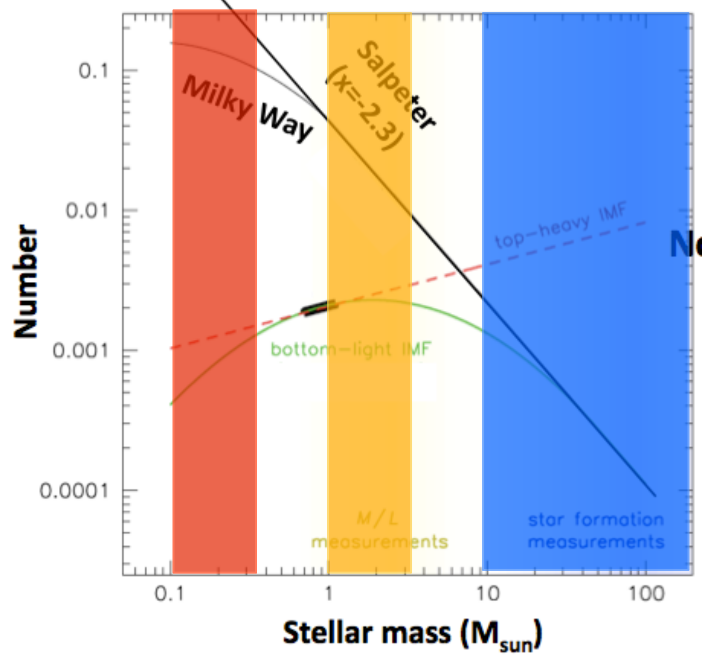
- Different studies agree, but all assume a universal stellar Initial Mass Function (IMF)



Why the IMF is important for galaxy masses

- Light comes from ~2 M_{sun} stars
- Mass comes from low mass stars, or stellar remnants of massive stars
- Feedback
  - Supernova rates
  - Gas recycling

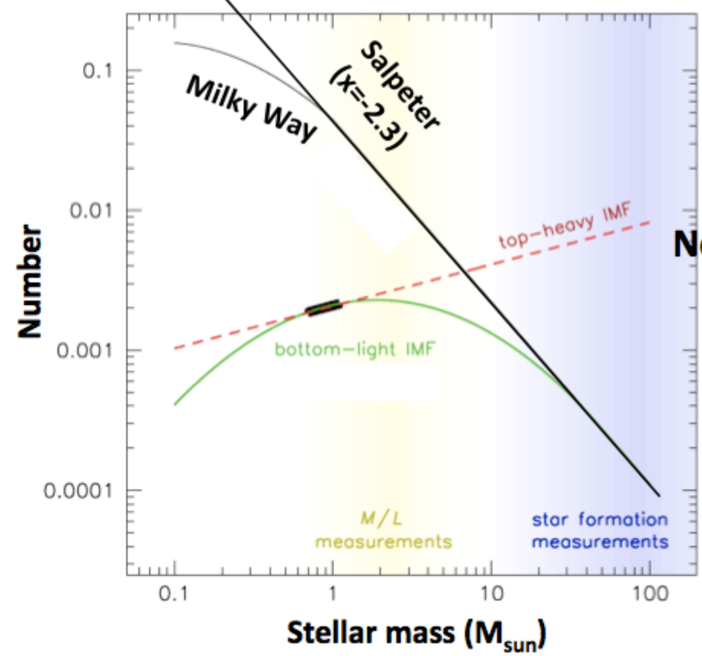
$dN / dM \propto M^{-x}$



Van Dokkum 2008

What do we know about the Stellar IMF?

$dN / dM \propto M^{-x}$



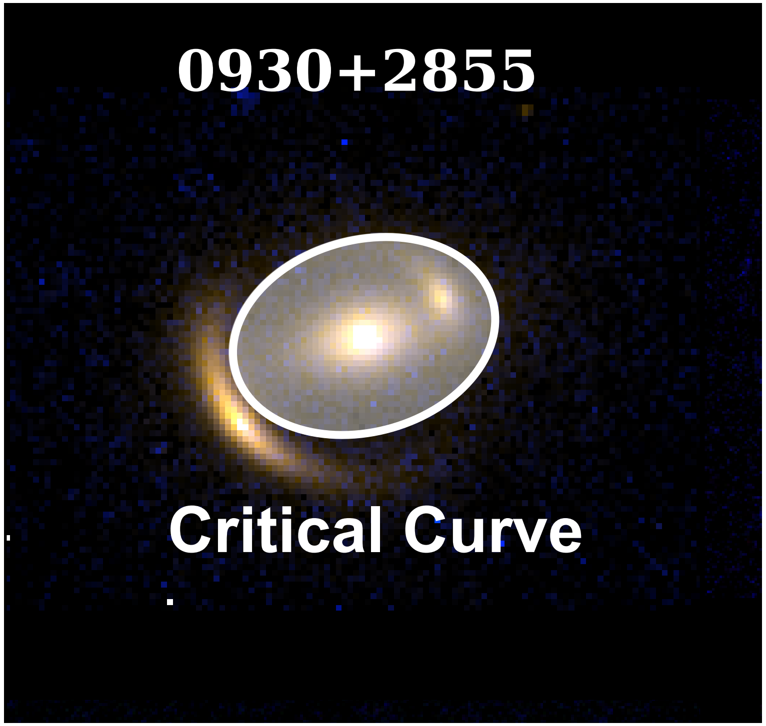
Van Dokkum 2008

- ***Star Counts in the Milky Way***
  - Power-law at high masses (Salpeter 1955)
  - Turn over at low masses (Kroupa 2001, Chabrier 2003
- ***Galaxy Dynamics: Upper limits to M/L***
  - Salpeter too "heavy" for spiral galaxies and fast rotating early-type galaxies (Bell & de Jong 2001; Cappellari et al. 2006)

Consistent with a universal IMF

Upper limits: Strong Gravitational lensing

Brewer et al. 2012



✦ **Strong lensing:**
projected total mass with critical curve: $\mathbf{M_{lens}}$

✦ **Stellar Pop Synthesis:**
projected stellar mass within critical curve, assuming an IMF: $\mathbf{M_{SPS}}$

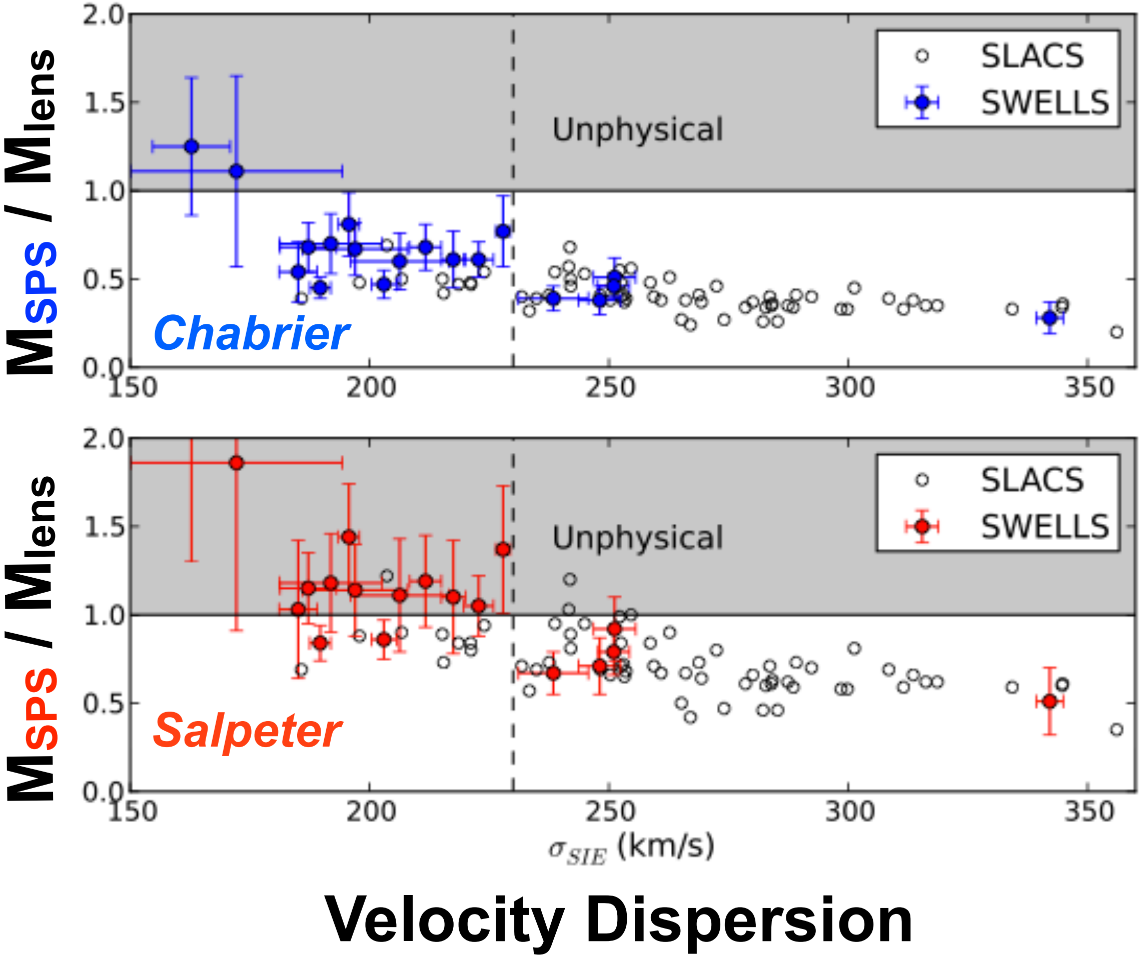
$$f_* = M_{SPS} / M_{lens}$$

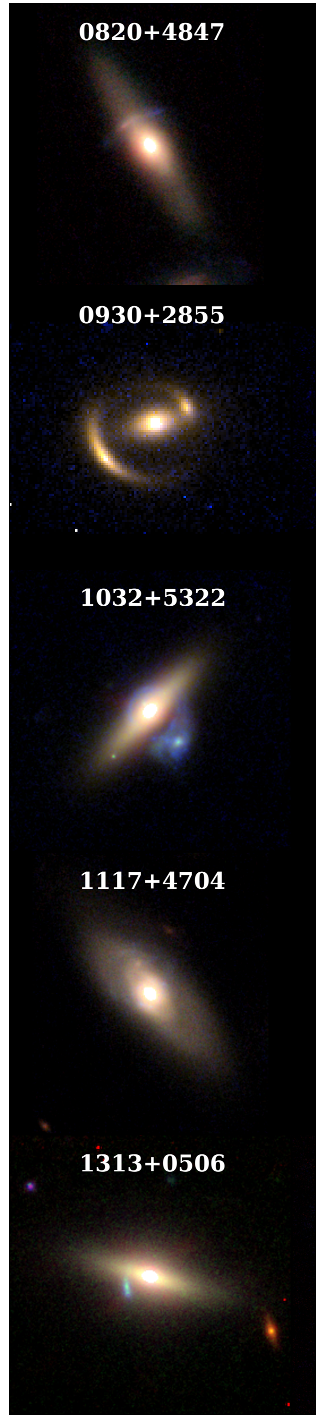
A physical IMF has $f_* < 1$

Upper limits: Strong Lensing

- ✦ *IMF is **lighter than Salpeter** in massive **spirals***
- ✦ *IMF can be **~2 x heavier than Salpeter** in most massive galaxies*

Brewer et al. 2012

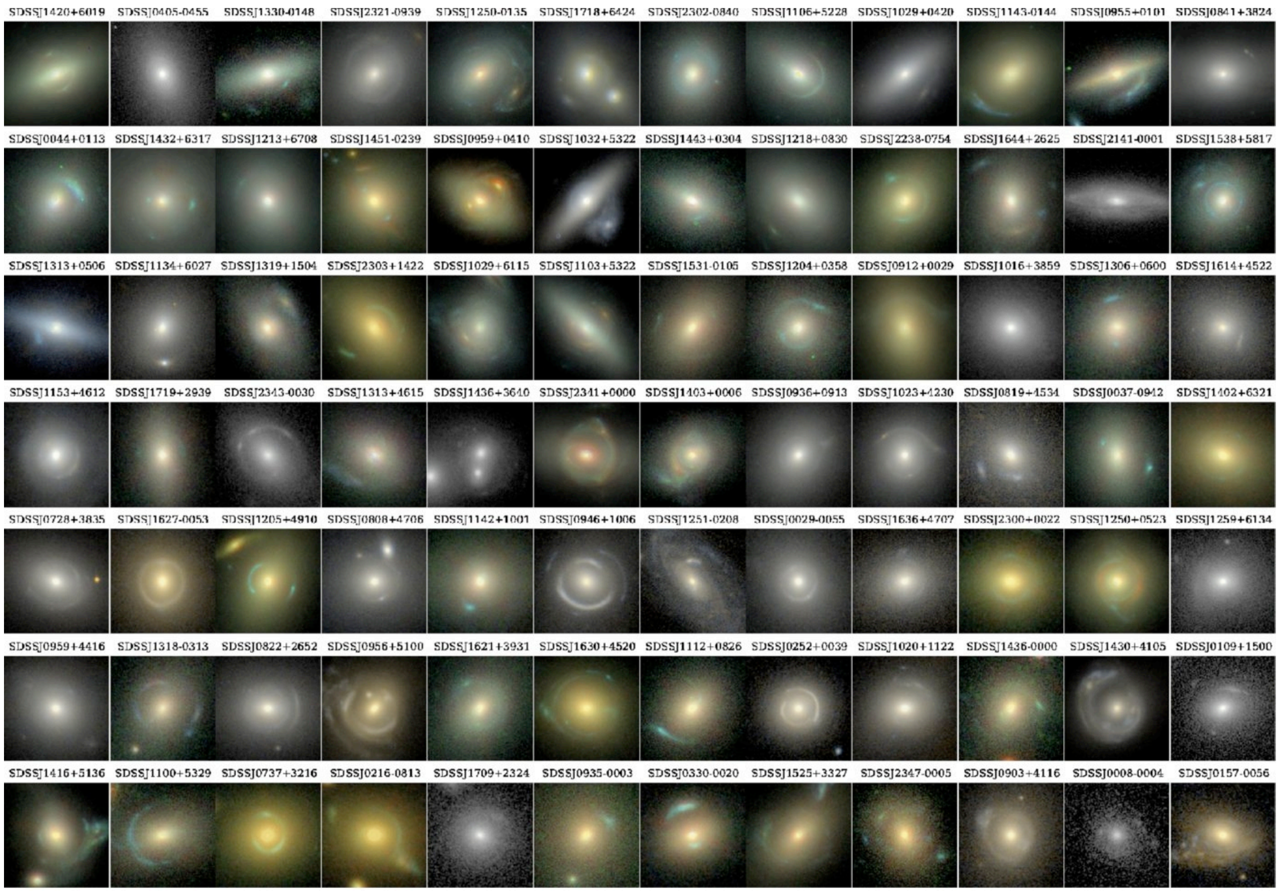




Lensing+Dynamics Scaling Relations

Massive Early-Type Galaxies σ~250 ± 40 km/s

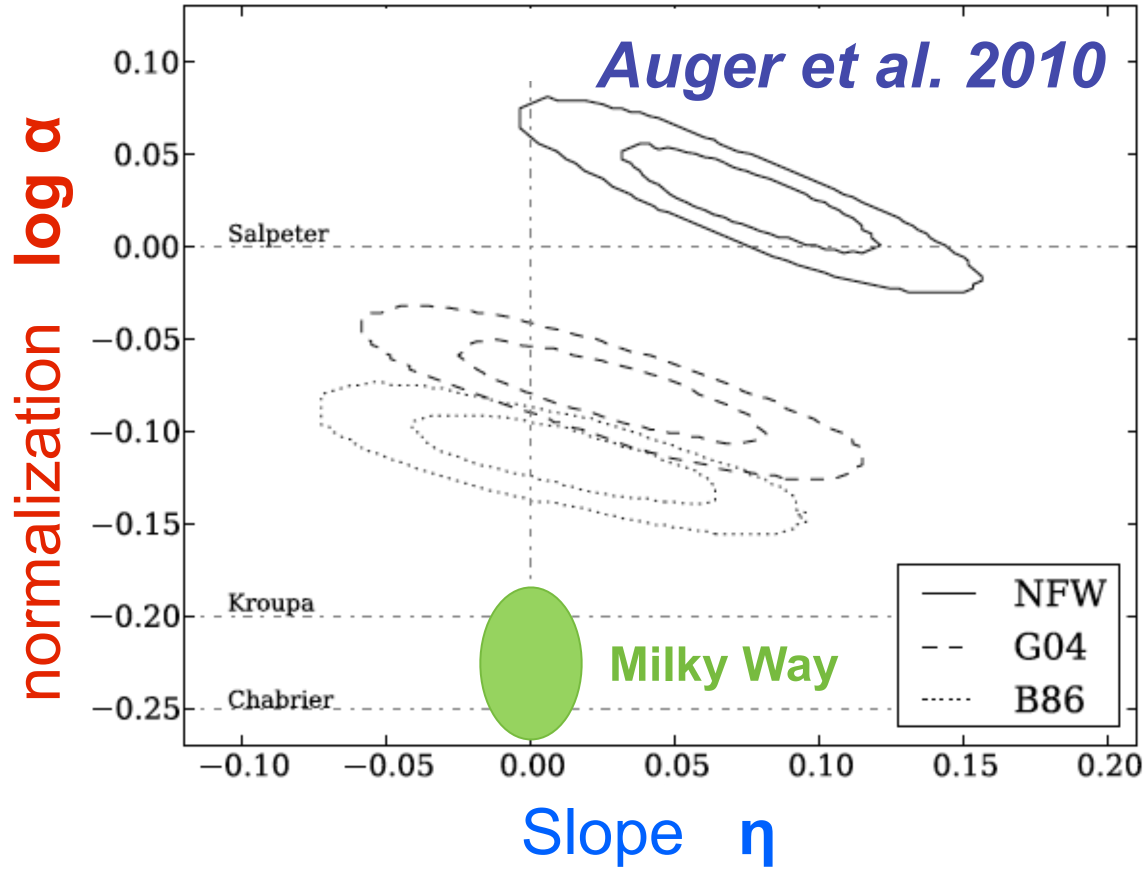
SLACS - Sloan Lens ACS Survey



Bolton et al. 2006, 2008; Auger et al. 2009

Lensing+Dynamics with Dark Matter Halo

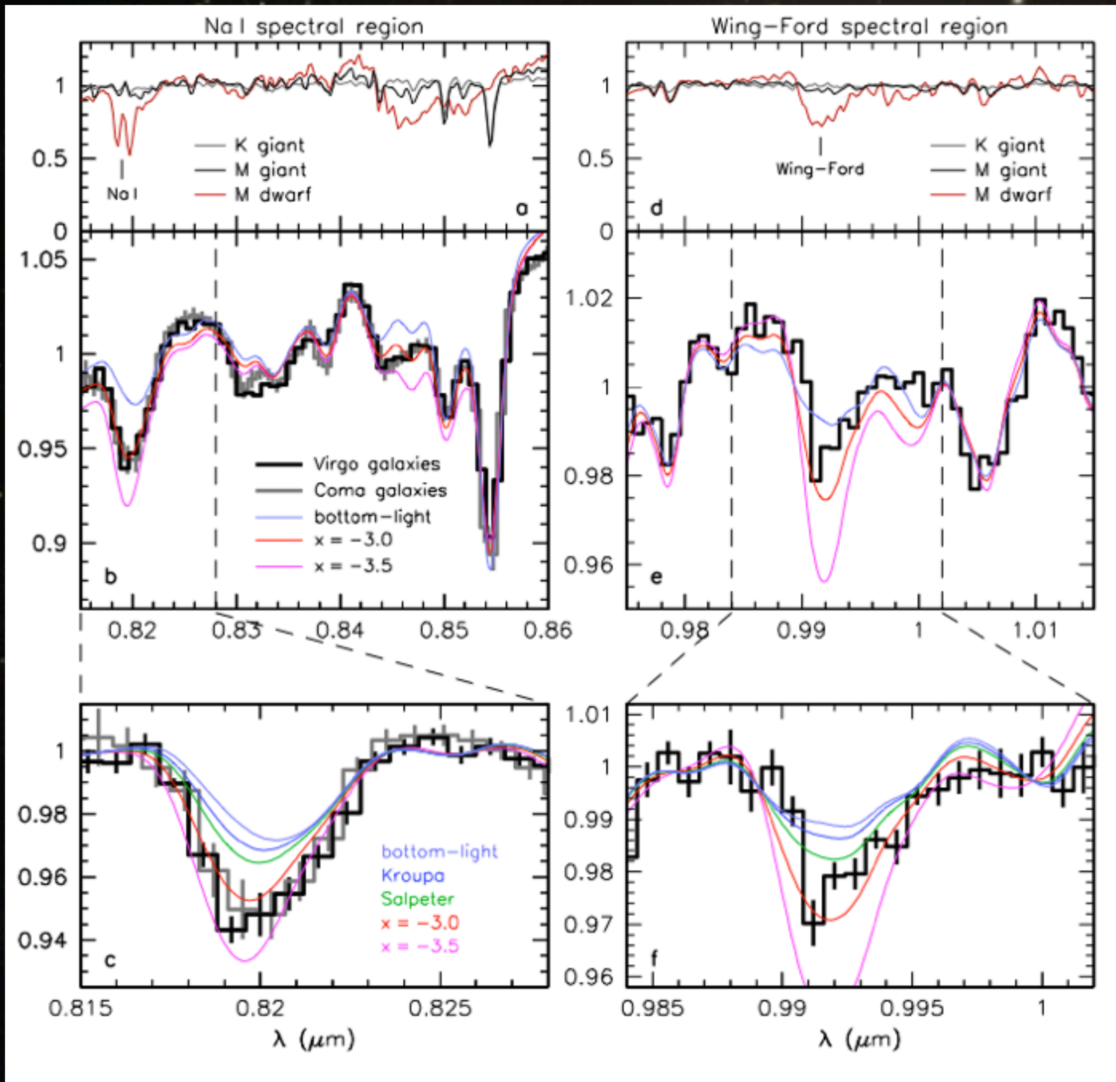
$$\log M_{star} / M_{SPS} = \log \alpha + \eta (\log M_{star} - 11)$$



All reasonable choices of DM halo result in non-MW IMF

A bottom heavy IMF in massive ellipticals

A bottom heavy IMF in massive ellipticals



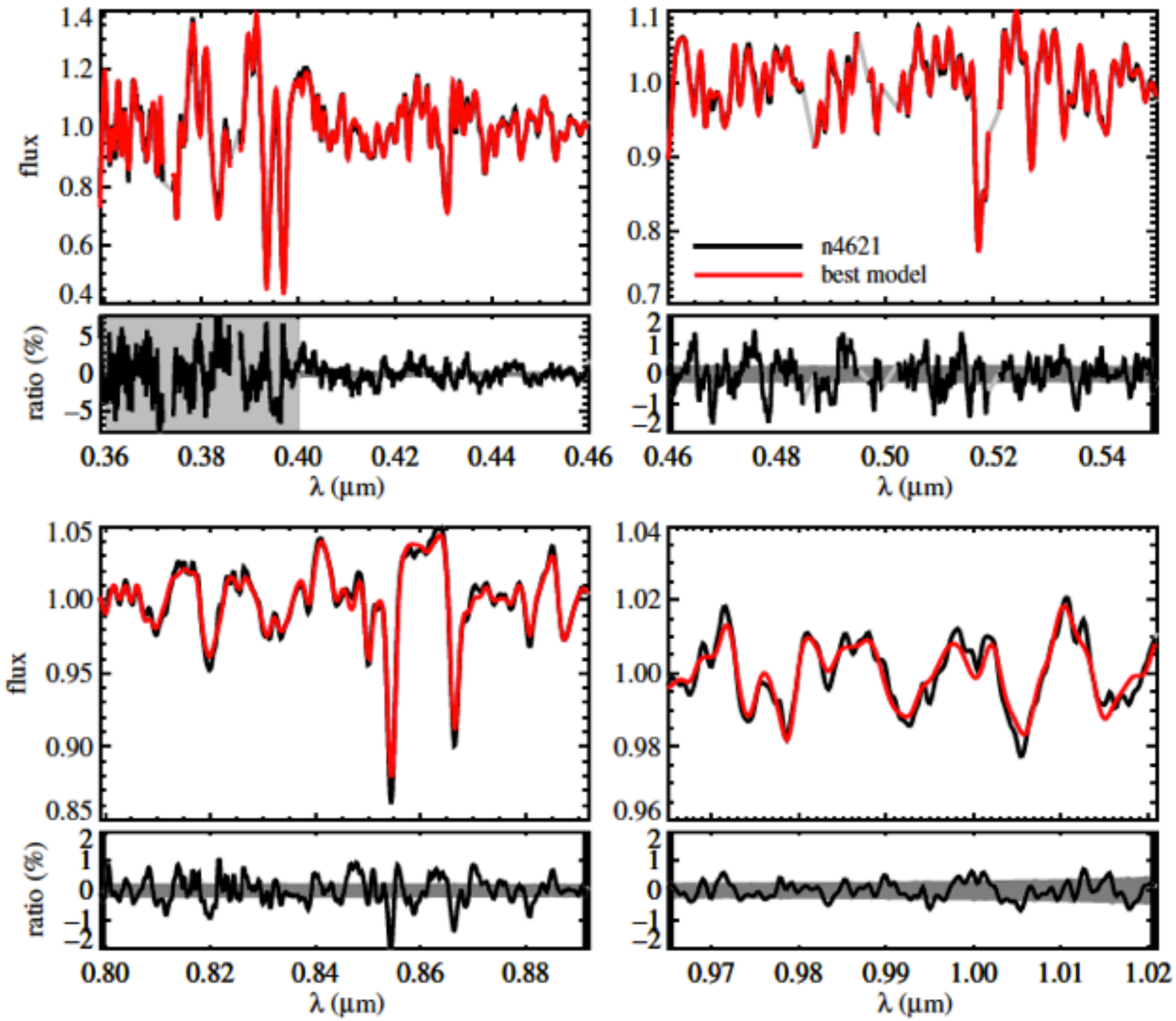
Dwarf sensitive stellar absorption lines (NaI, Wing-Ford)

IMF is > 2 times heavier than Milky Way (Chabrier / Kroupa)

Van Dokkum & Conroy 2010

Full Spectral Fitting

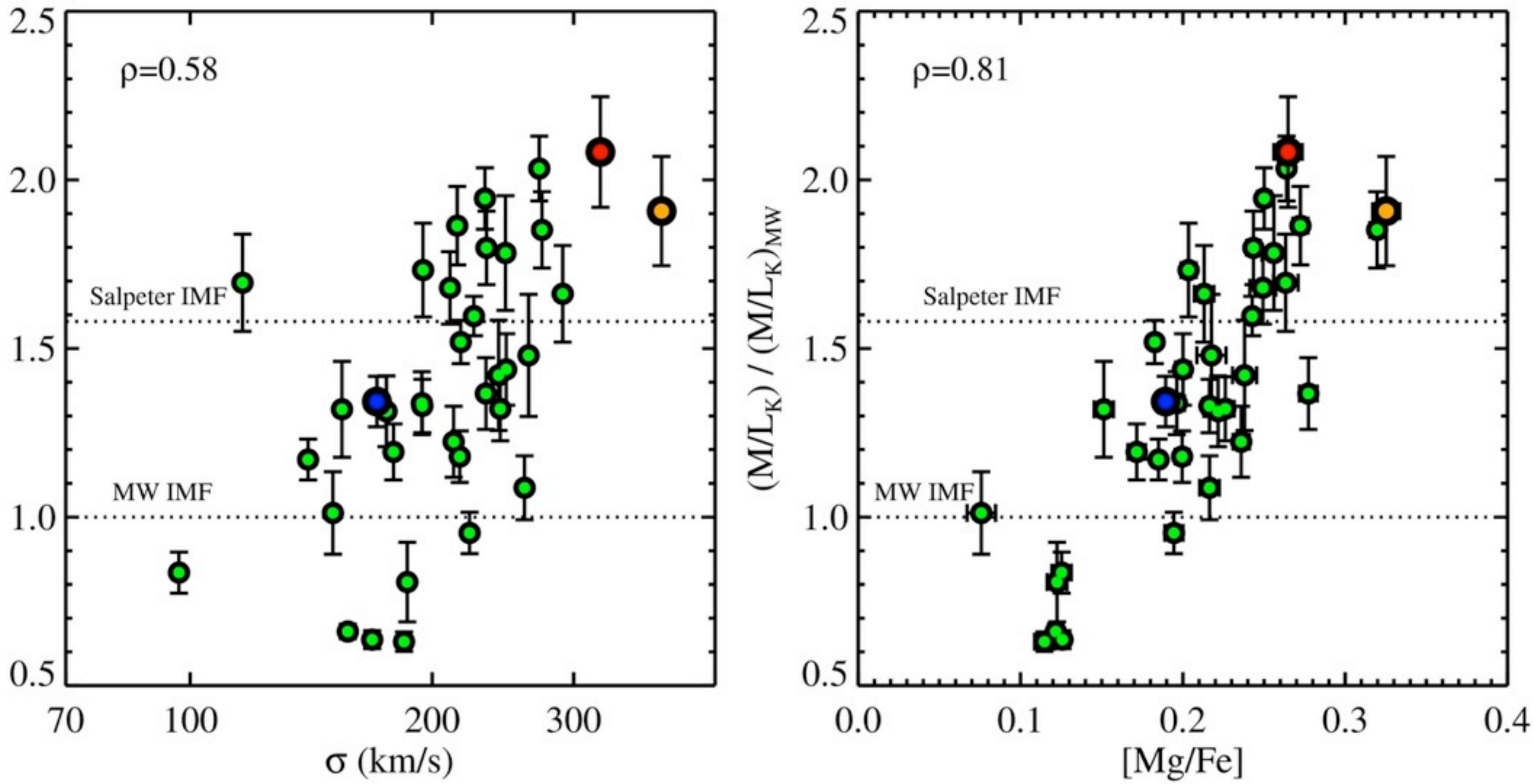
Conroy & van Dokkum 2012



Correlation with dispersion, alpha abundance

Conroy & van Dokkum 2012

M_{star}/M_{kroupa}



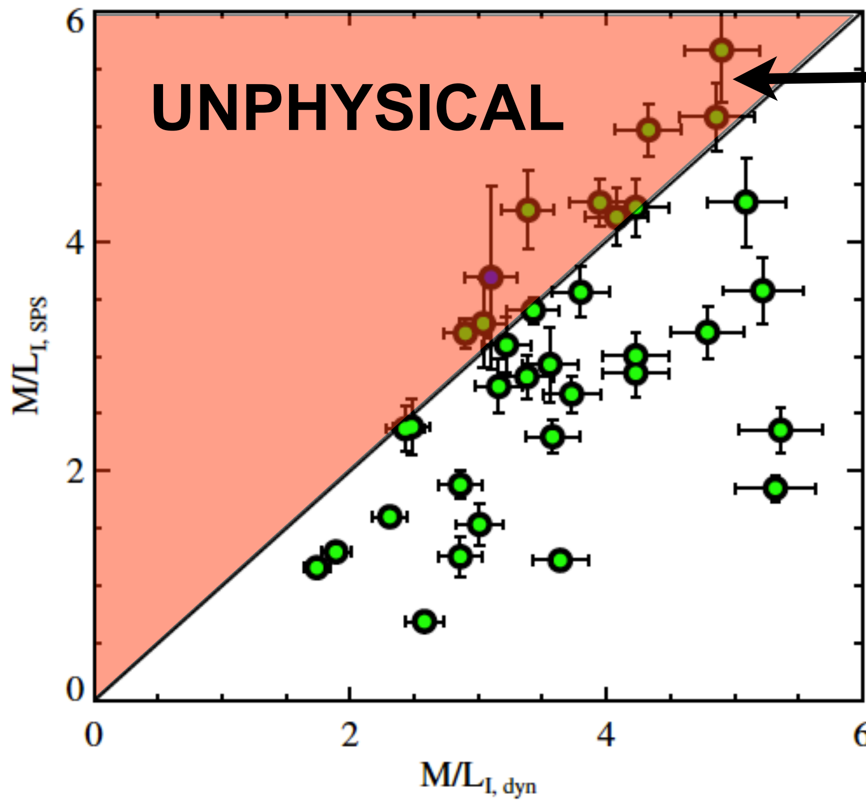
velocity dispersion

alpha abundance

Consistency check: spectral masses vs total dynamical masses

$M/L_{SPS} < M/L_{dyn}$

Conroy & van Dokkum 2012



spectral stellar mass / light

We expect some galaxies to be scattered here due to measurement errors.

total dynamical mass / light

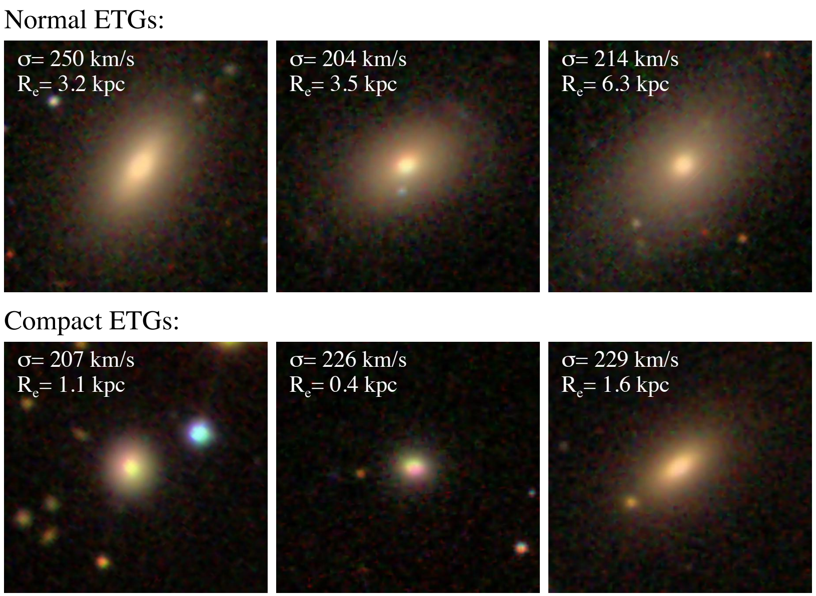
(SAURON)

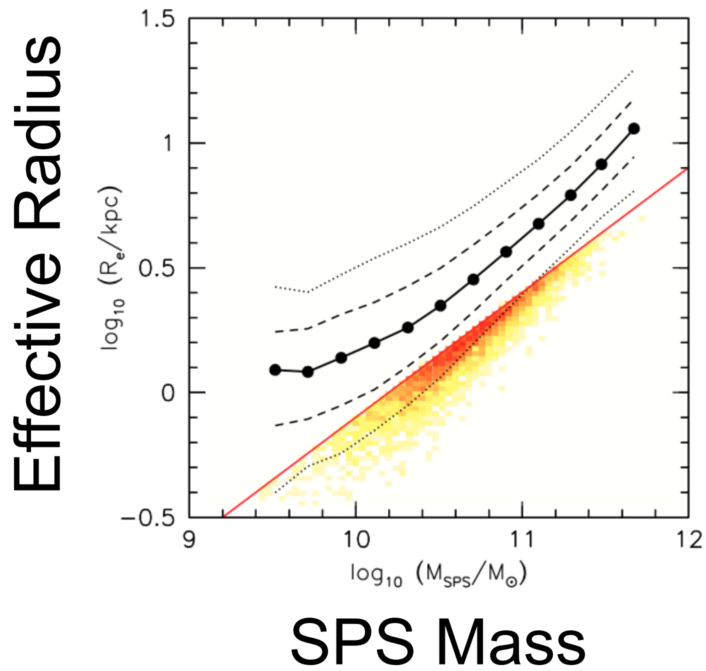
Consistency Check: Dense Galaxies

- **high density** galaxies expected to have **low dark matter** fractions
- Select early-type galaxies from SDSS with surface densities

Σ_e > 2500 M_{sun}/pc^2 (Chabrier IMF)

Dutton, et al. 2012



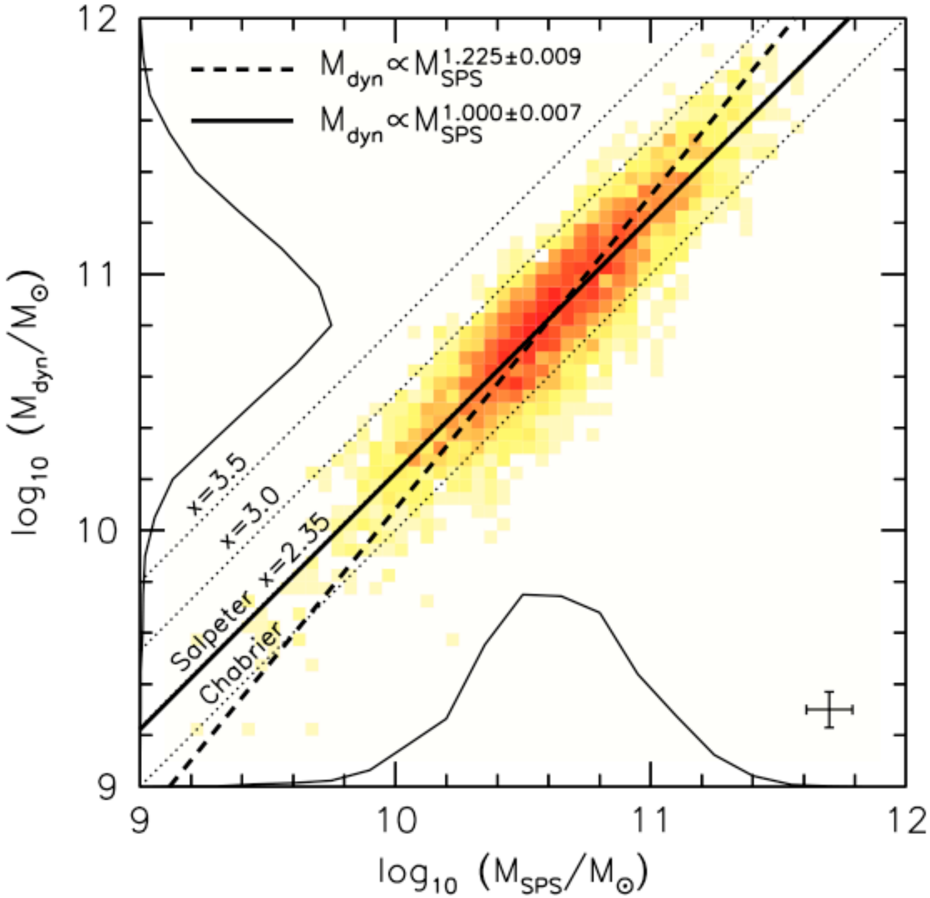


(SPS masses from MPA/JHU: ugriz, BC03, Chabrier IMF)

Dynamical Mass vs SPS Mass

- Dynamical masses from Spherical Jeans equations
- Only mild (5%) dependence on anisotropy (since $R_{ap} > R_e$)

Dynamical Mass (β=0)



Stellar Mass (Chabrier IMF)

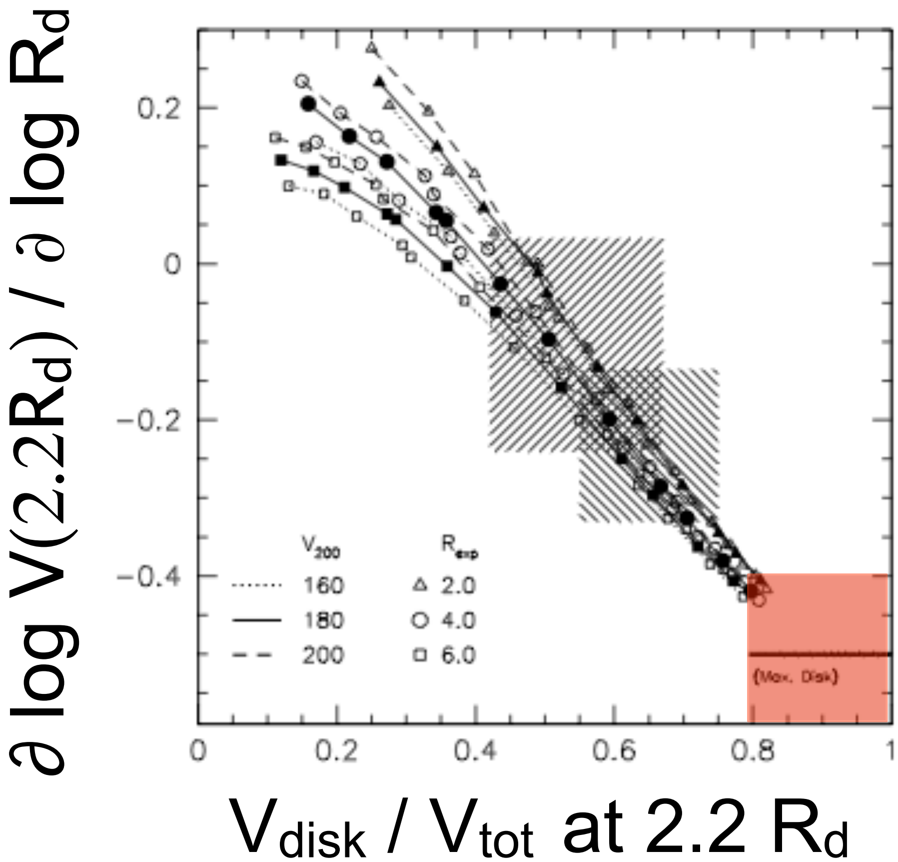
Normalization:
Salpeter

Slope:
1.00 to **1.23**
(depends on errors)

most likely **~1.1**

Evidence for Mass-Follows-Light

Relation between offsets of VM (Δ log V) and RM (Δ log R) relations depends on dark matter fraction (Courteau & Rix 1999)



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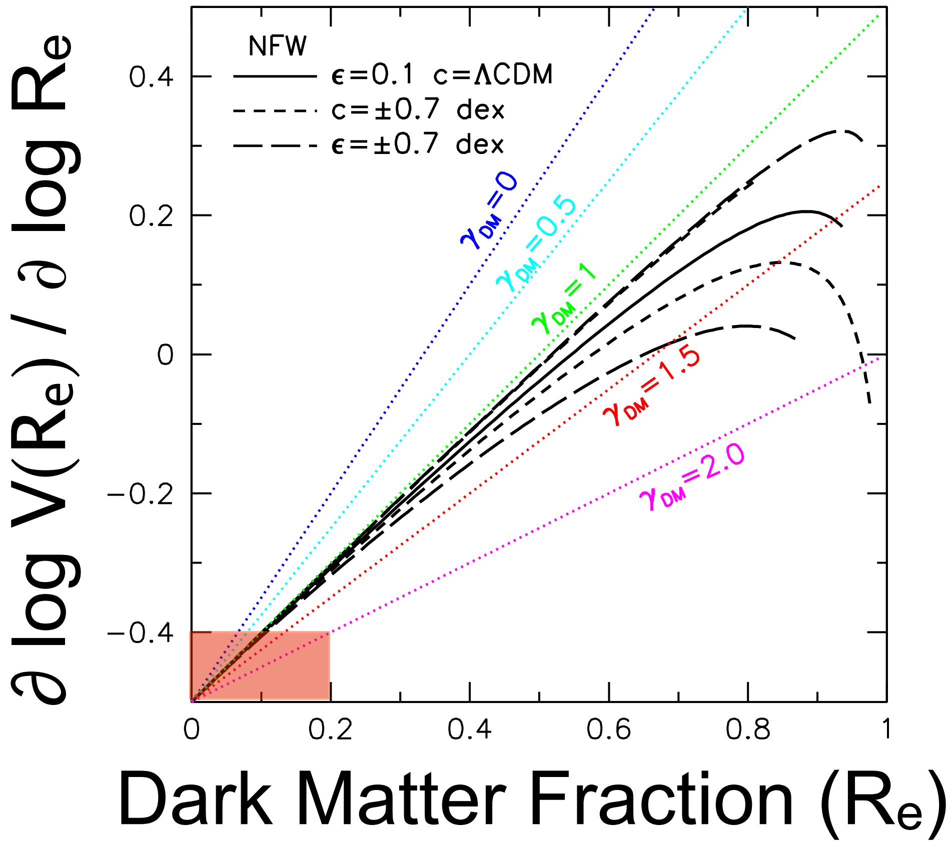
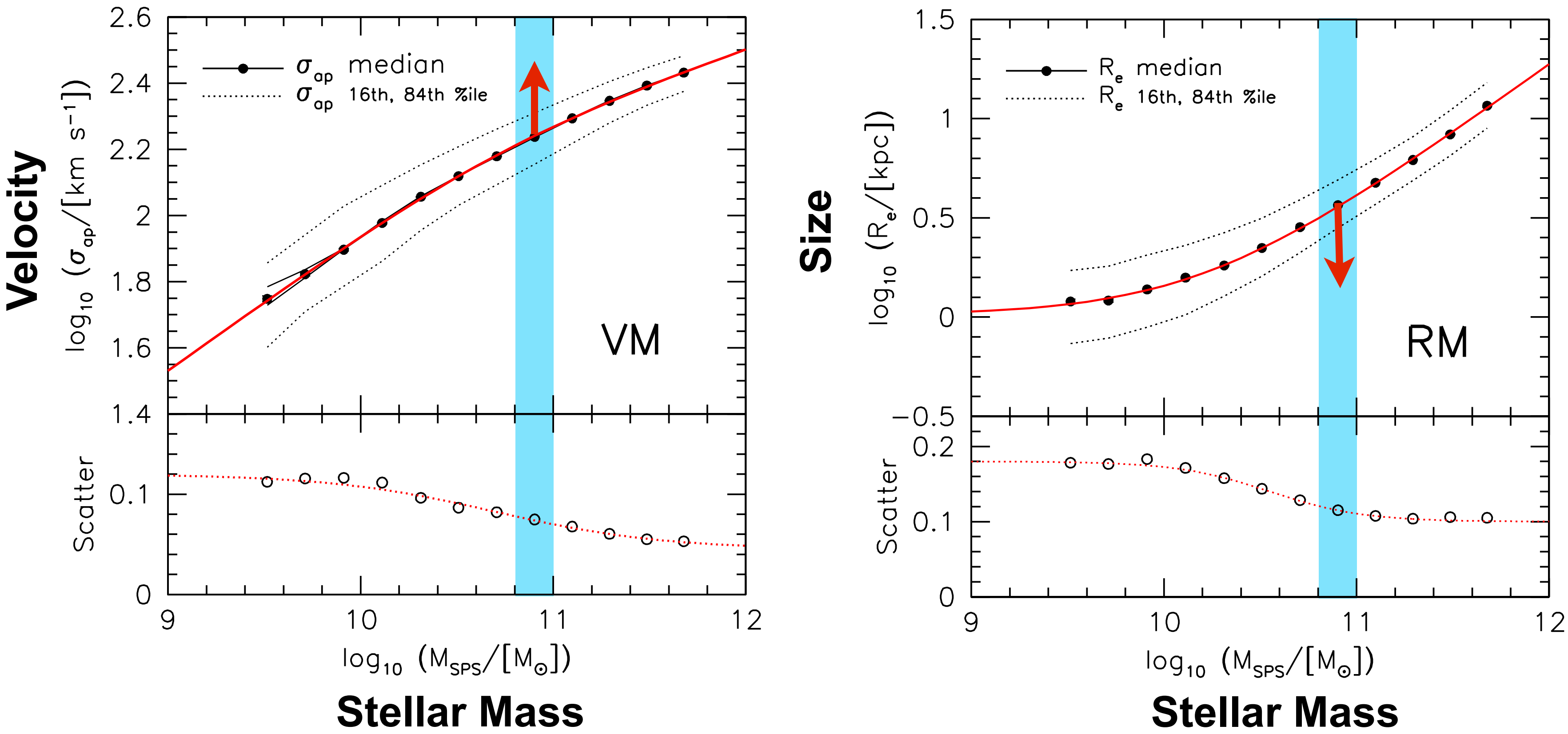


Correlation between aperture velocity dispersion (σ_{ap}), and size (R_e) at fixed stellar pop mass (M_{SPS})

(150 000 early-type galaxies from SDSS - Dutton et al. 2013)



Evidence for Mass-Follows-Light

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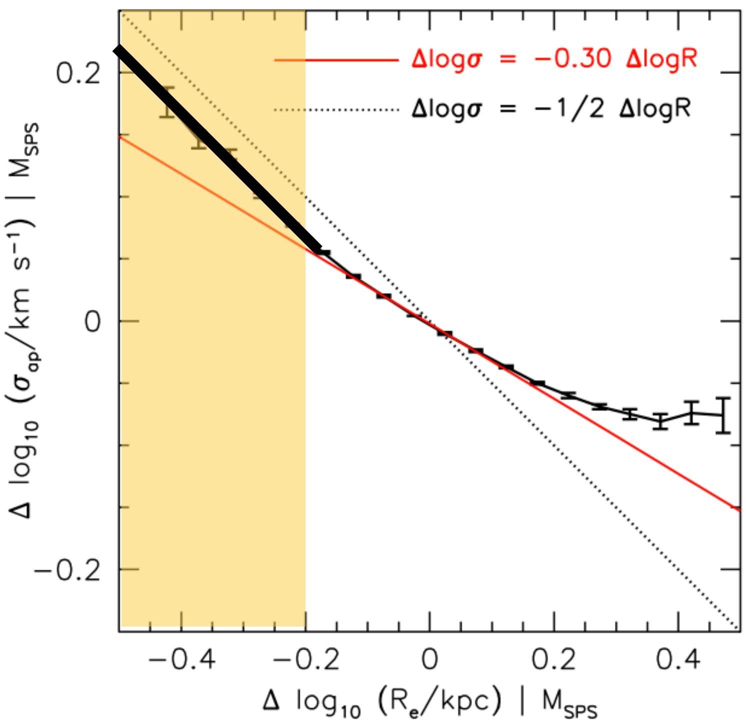
Δ log σ



Δ log R

Full Sample

$\Delta \log \sigma = \mathbf{-0.3}\ \Delta \log R$

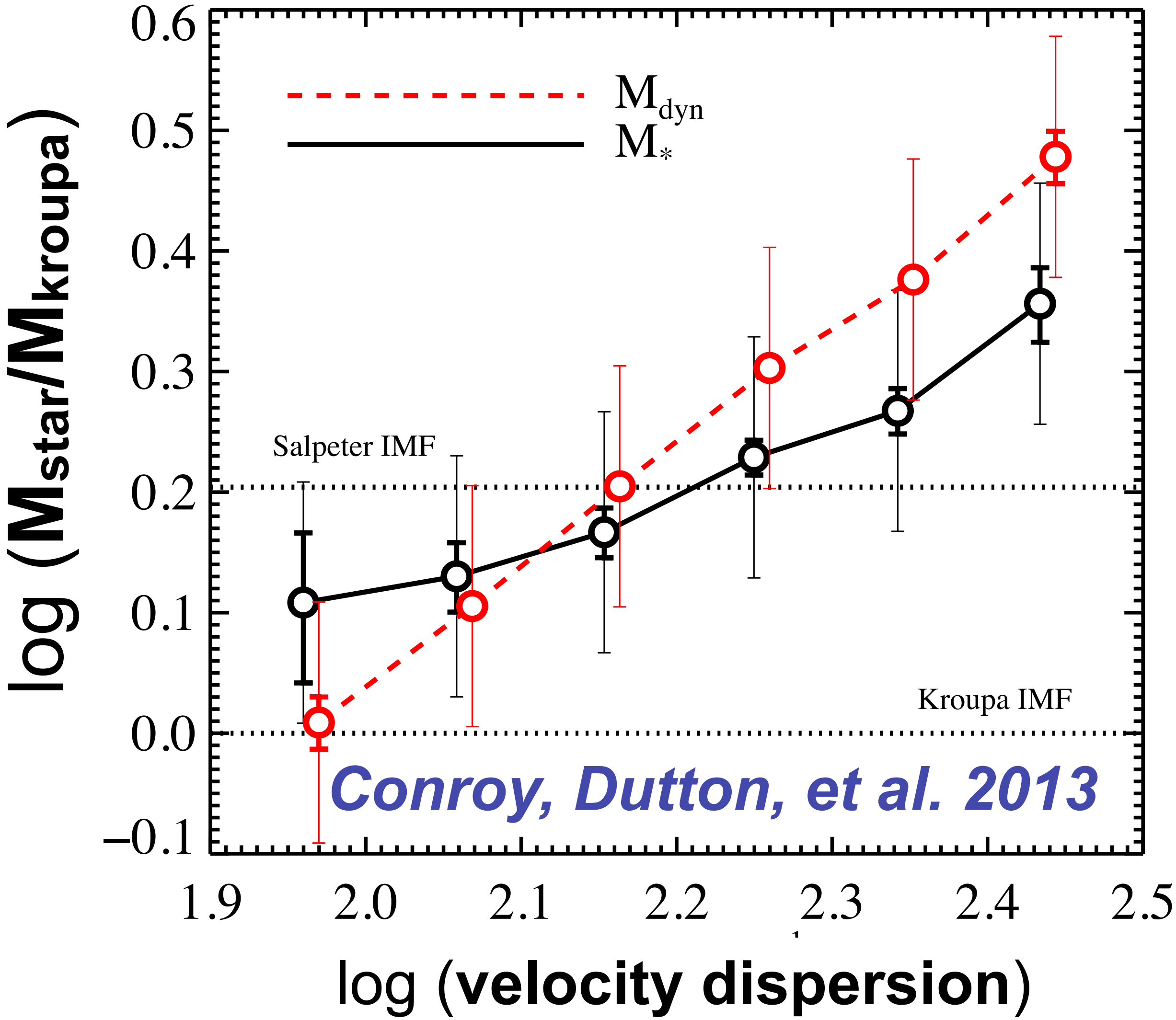
Tilt of the Fundamental Plane

Dense galaxies follow the virial FP:

$\Delta \log \sigma = \mathbf{-0.5}\ \Delta \log R$

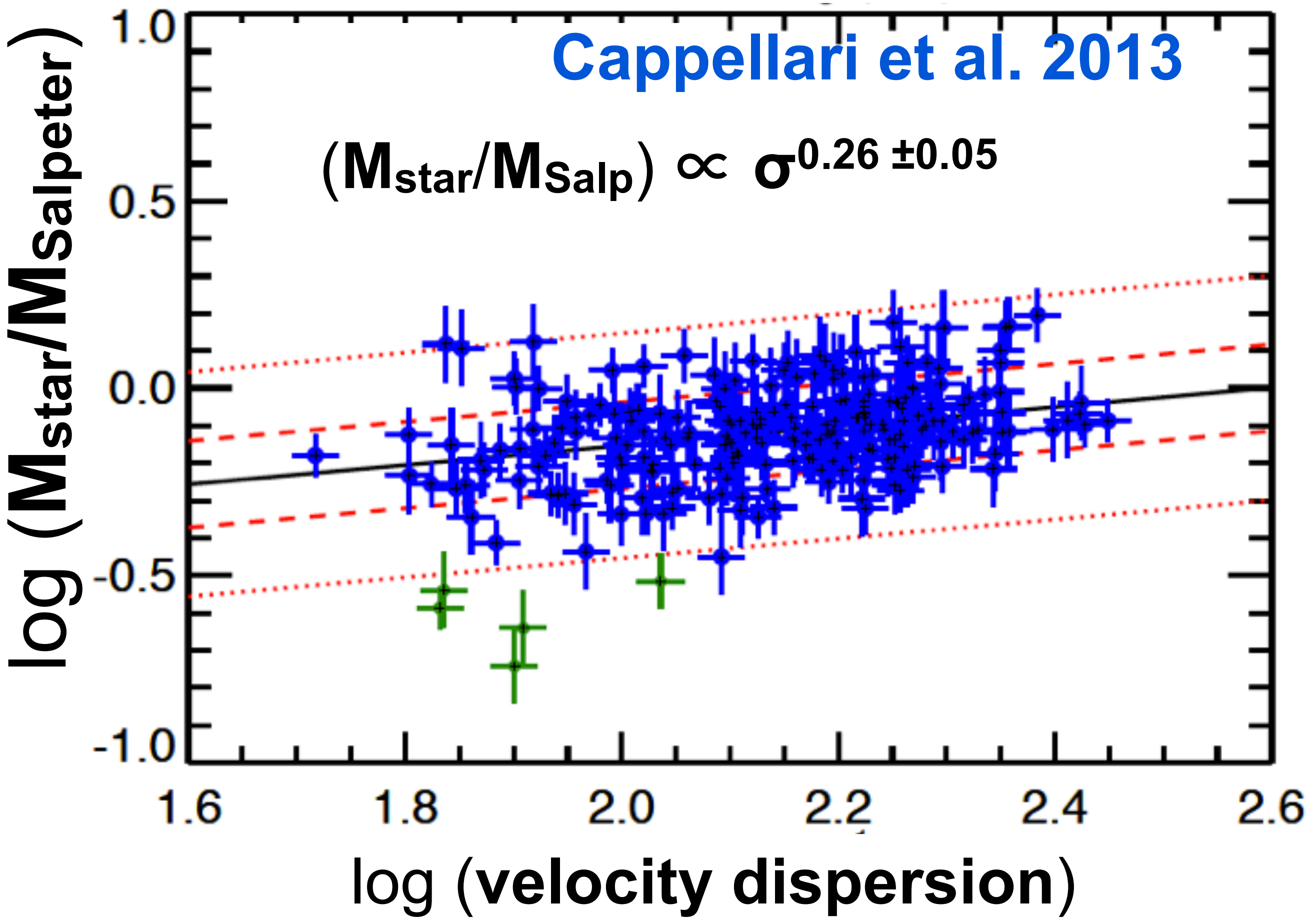
Implies mass follows light

Spectra and dynamics agree!



Correlation with dispersion

ATLAS3D, 260 nearby early-types



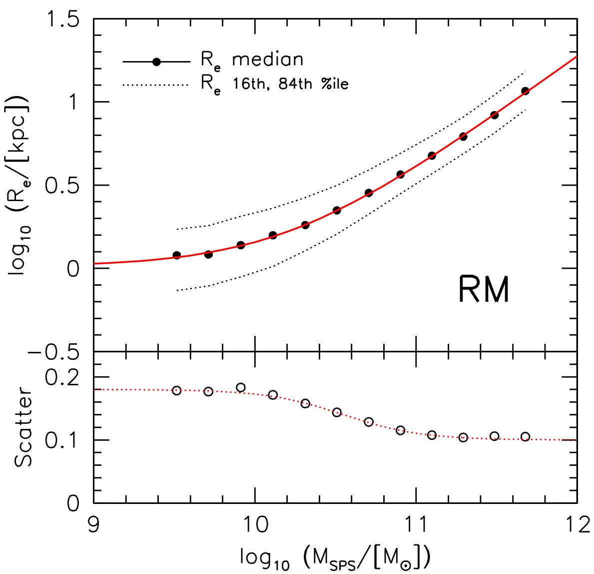
ΛCDM based models of Early-Type Galaxies

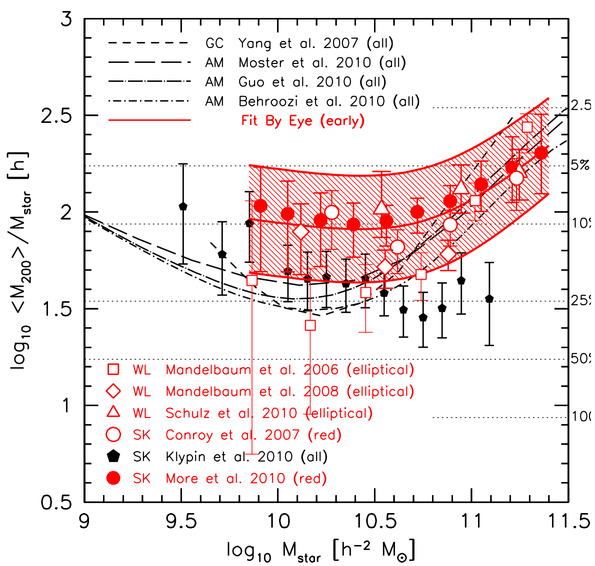
- ✦ **Stars** (4 parameters: R_{exp} , R_{dev} , f_{dev} , **Δ_{IMF} - stellar mass normalization**)
- ✦ **Dark Matter** (3 parameters: M_{vir}; c; **ν - dark halo response**)

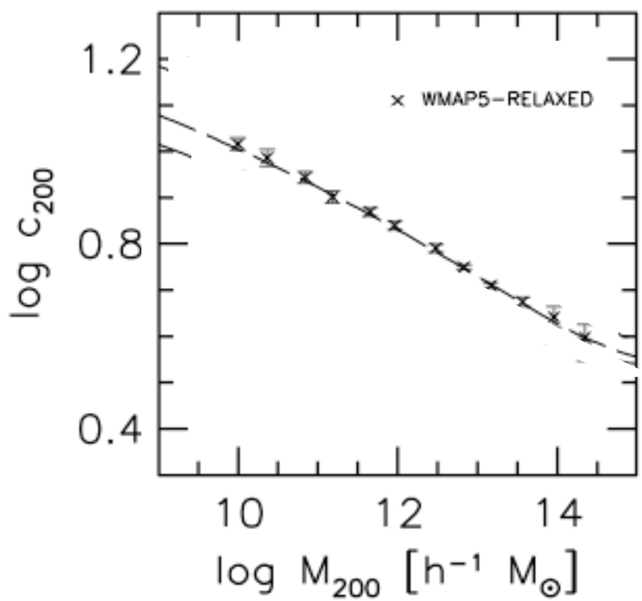
Galaxy Structure:
SDSS
Simard et al. (2011)

Halo masses:
WL+SK
Dutton et al. (2010)

Halo structure:
N-body sims
Macciò et al. (2008)







ΛCDM based models of Early-Type Galaxies

ASSUMPTIONS:

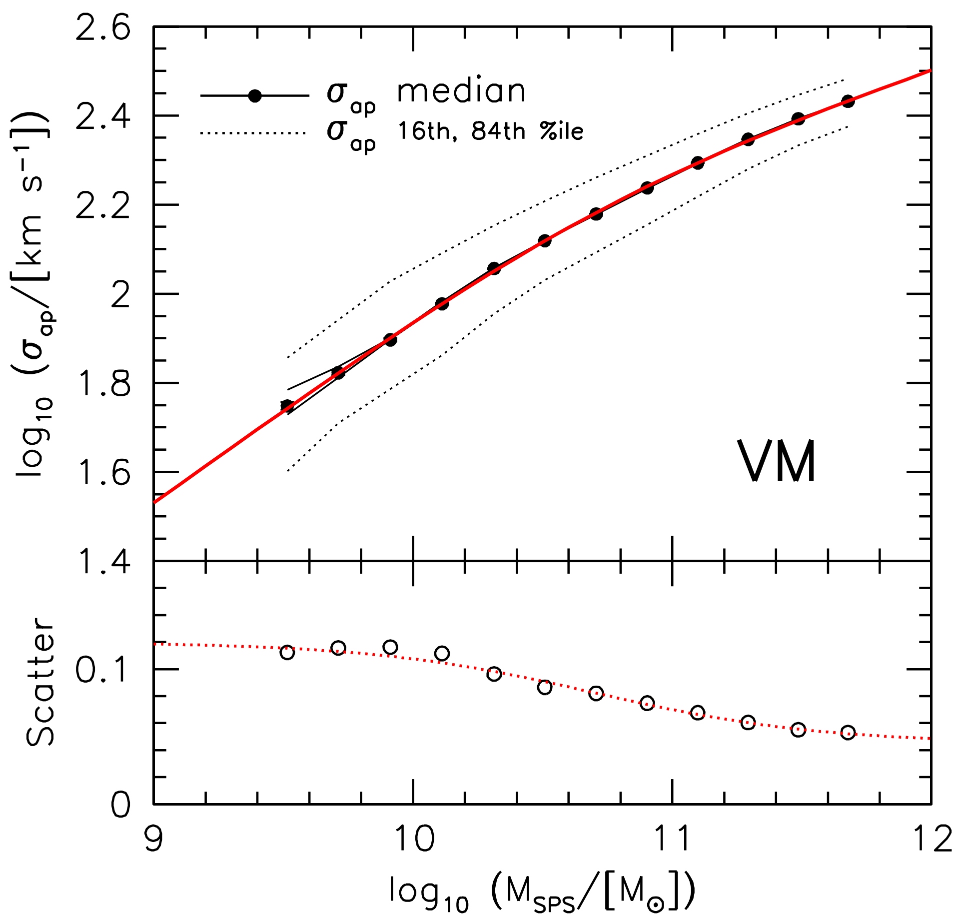
- Spherical Jeans equation to predict SDSS aperture velocity dispersions

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

- No stellar M/L gradients
- Constant anisotropy
- Scatter in galaxy size is UNCORRELATED with:
  - dark halo response;
  - scatter in halo mass;
  - scatter in halo concentration.

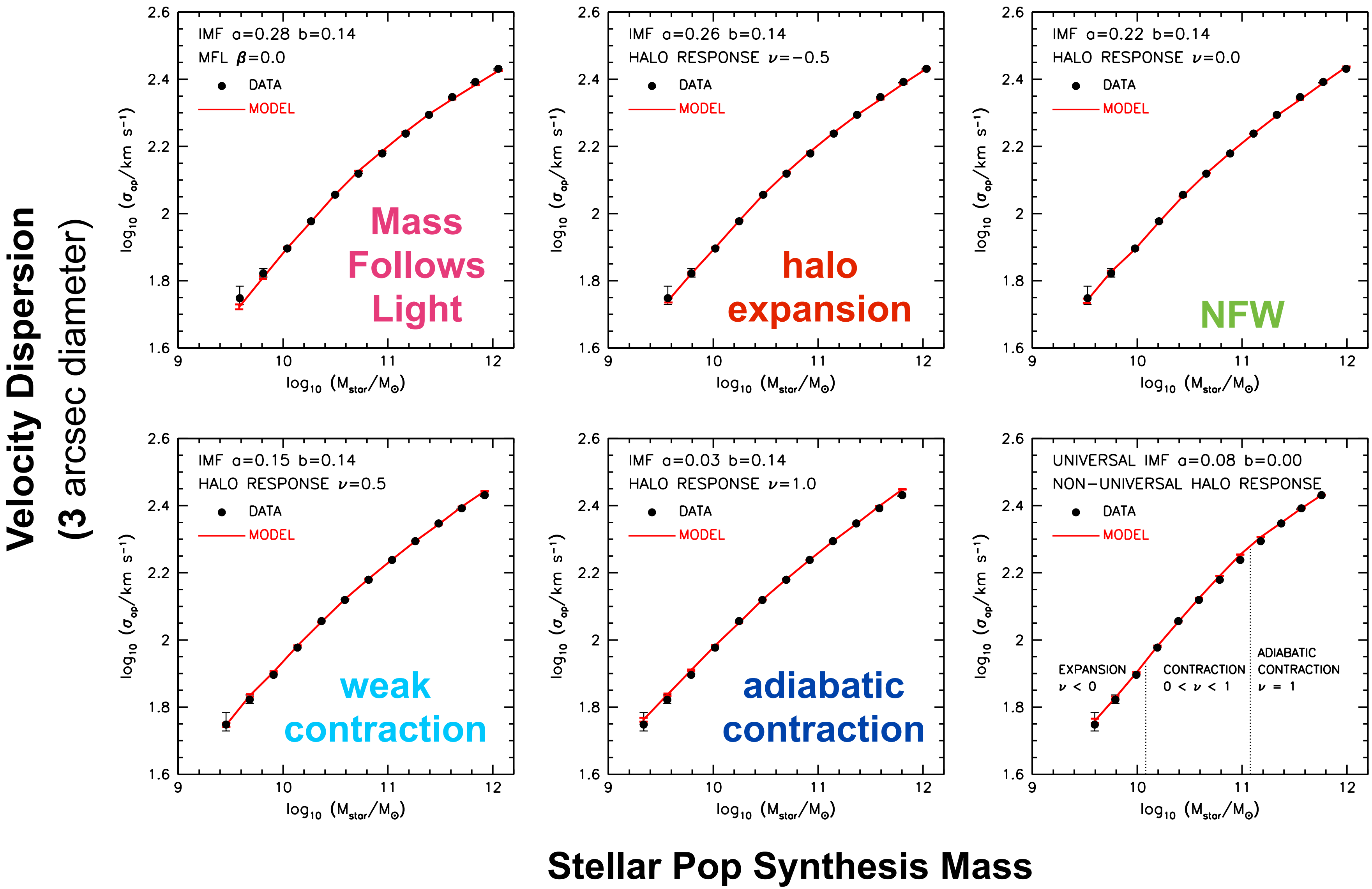
STEP 1:
Use the Faber-Jackson relation to constrain allowed combinations of halo response and IMF

Velocity Dispersion

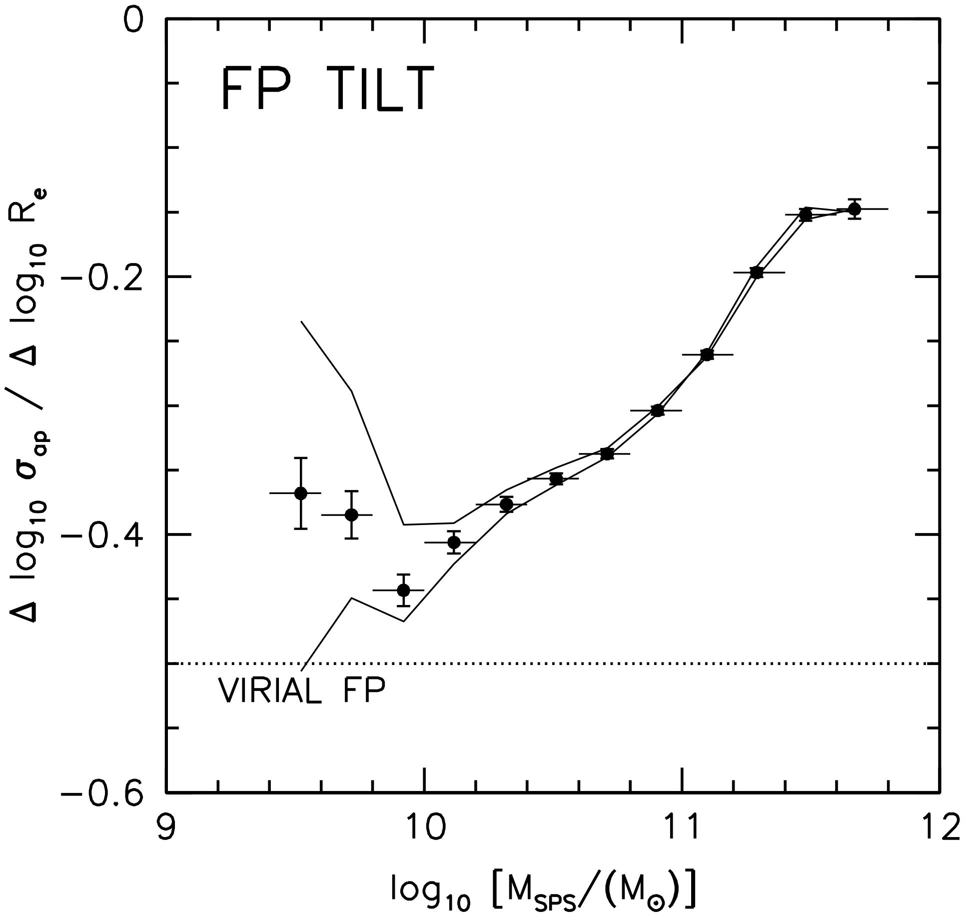


Stellar Mass

Degeneracy between IMF and dark matter



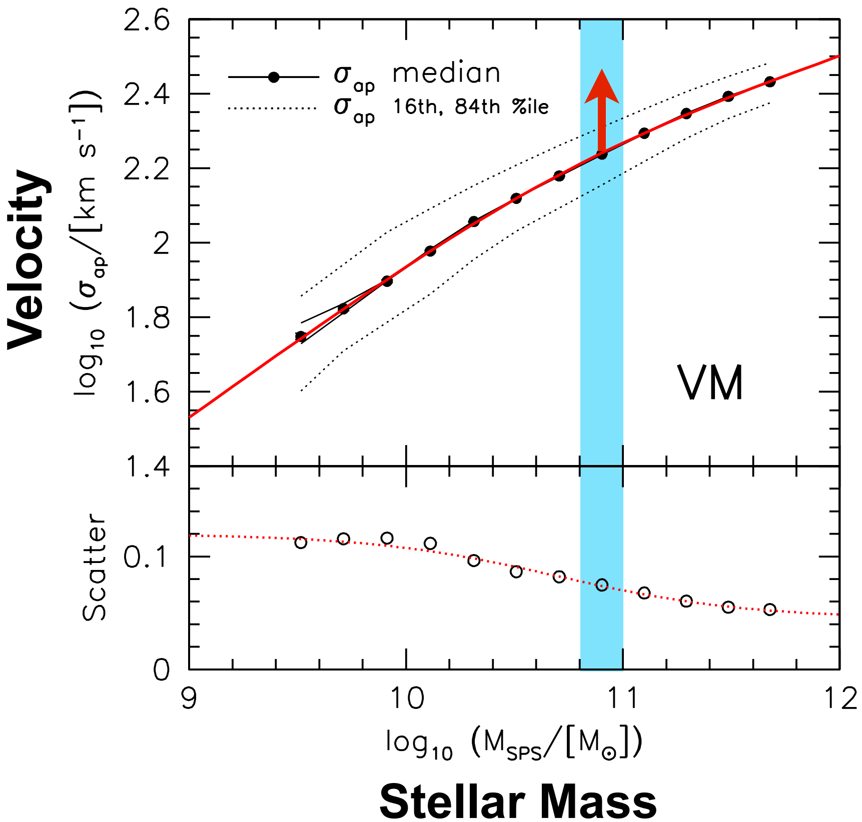
STEP 2:
Use the Fundamental Plane to break the halo response - IMF degeneracy

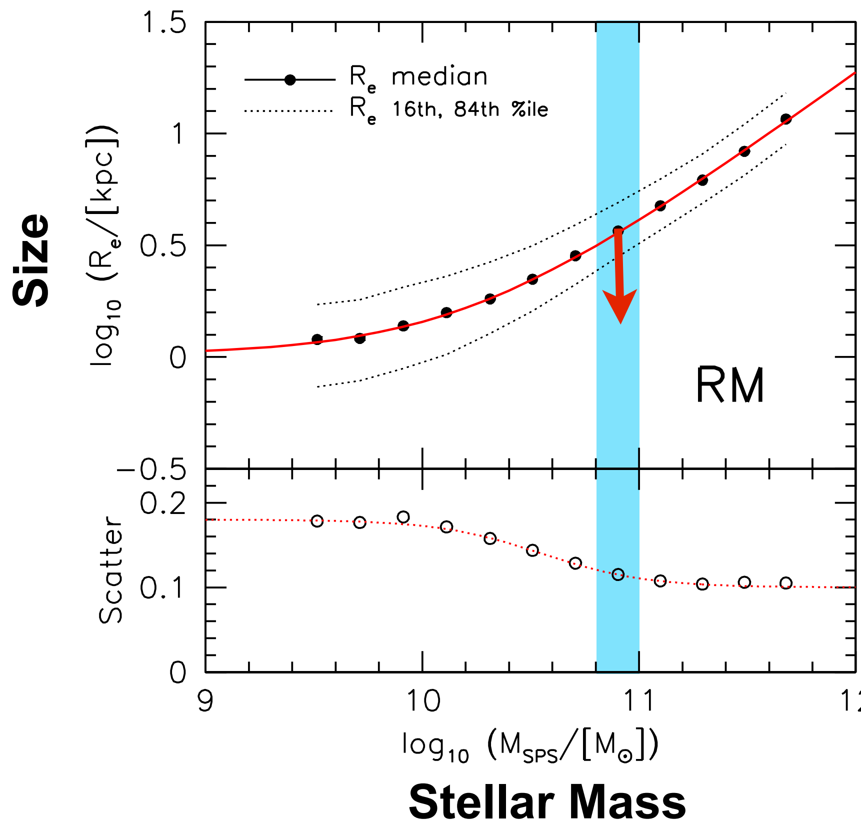


Stellar Mass

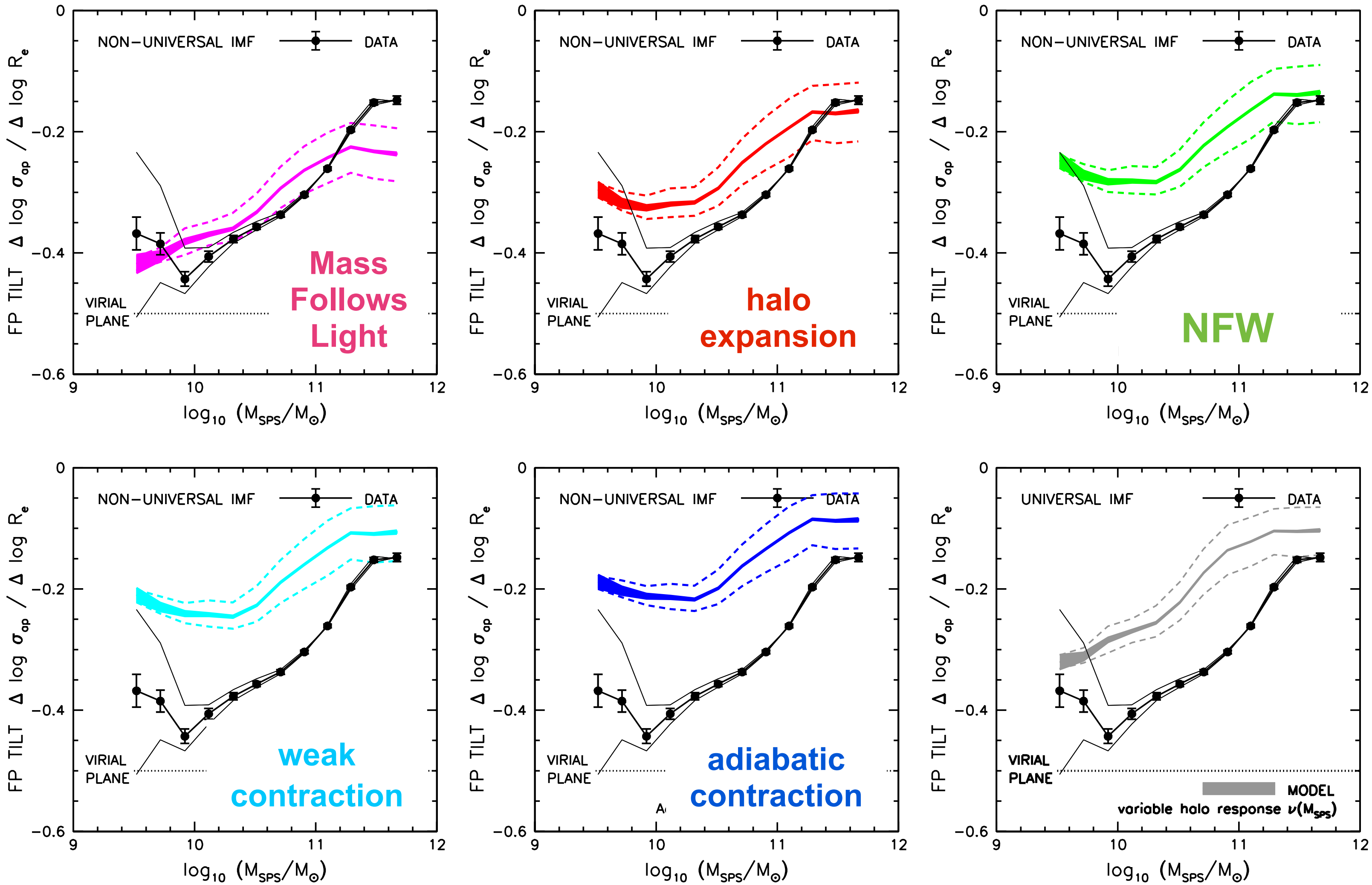
Correlation between aperture velocity dispersion (σ_{ap}), and size (R_e) at fixed stellar pop mass (M_{SPS})

(150 000 early-type galaxies from SDSS - Dutton et al. 2013)

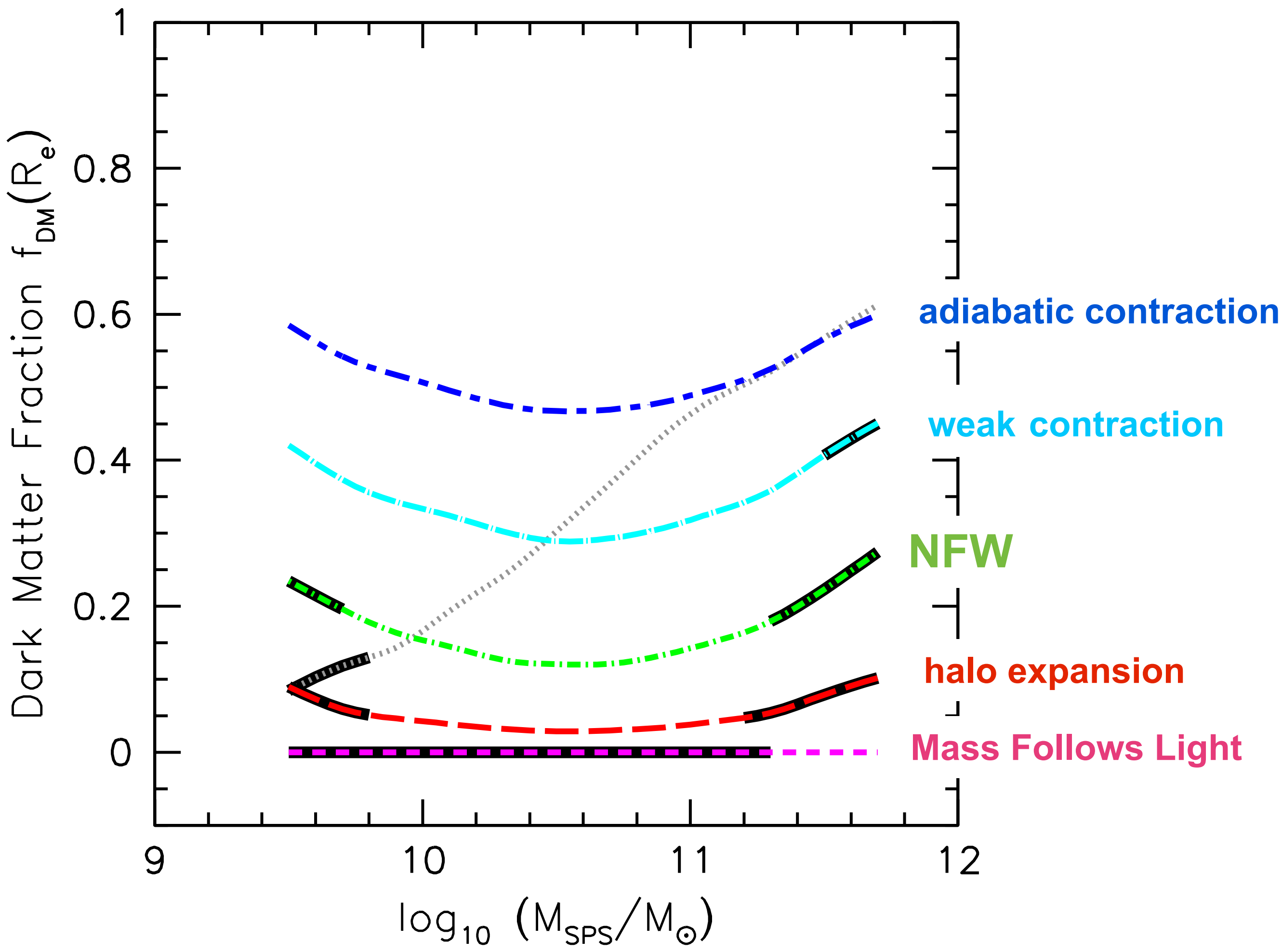




Fundamental Plane breaks the degeneracy



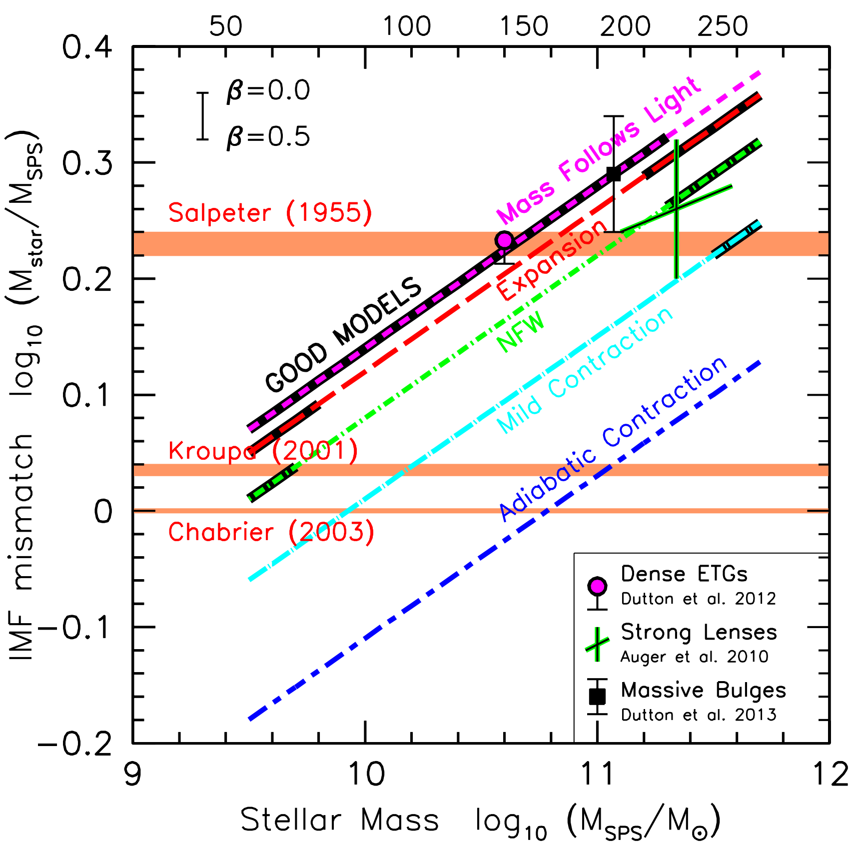
Why? Dark Matter dampens the FP



Thick black lines = acceptable model

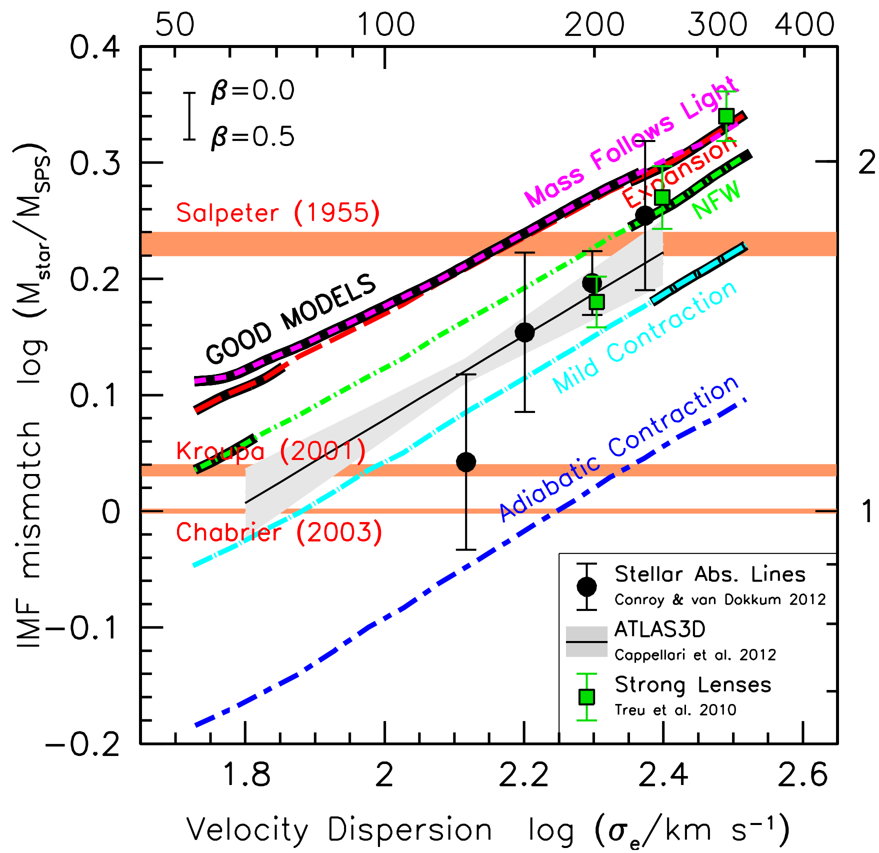
More “Massive” Early-Type Galaxies have “Heavier” IMFs

$(M_{star}/M_{MW}) \propto M_{MW}^{0.14}$



SPS Stellar Mass

$(M_{star}/M_{MW}) \propto \sigma^{0.3}$

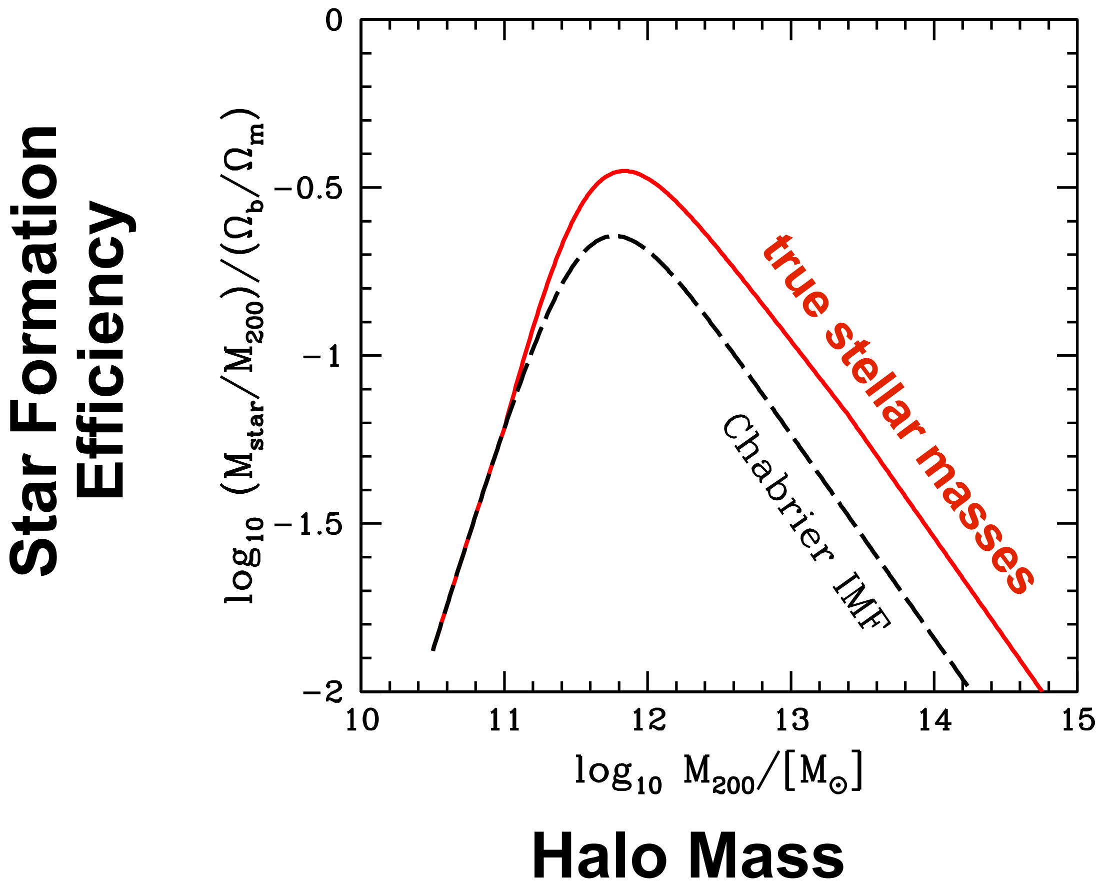


Velocity Dispersion

Dutton, Macciò , Mendel, Simard 2013

Summary

✦ Stellar mass-to-light ratios of massive galaxies are a factor ~ 2 higher than predicted by a Milky Way IMF

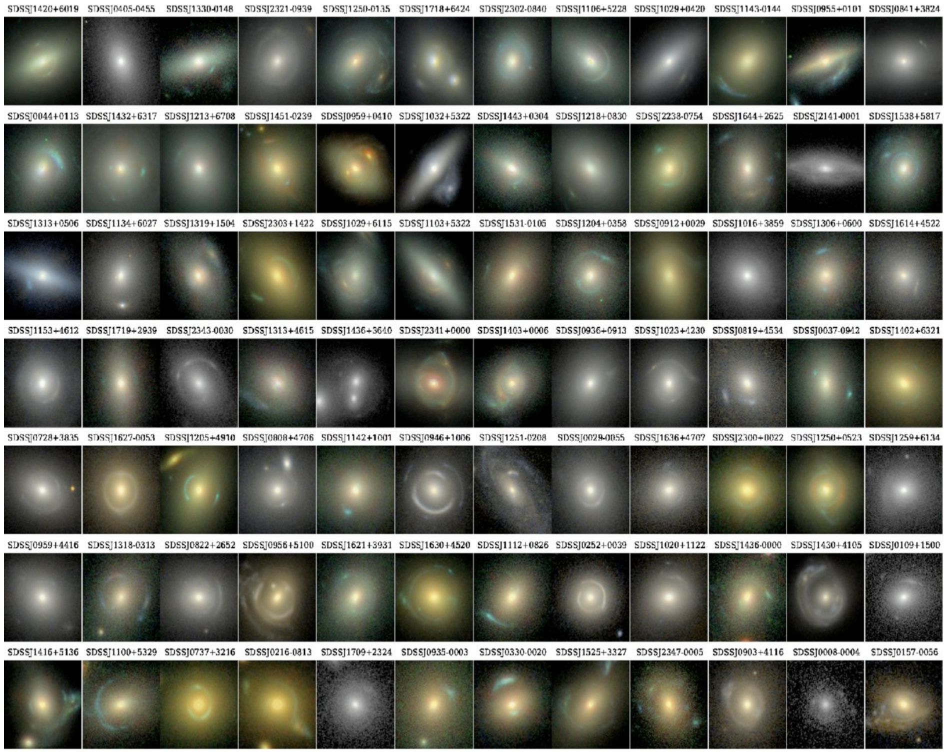


Auger et al. 2010;
van Dokkum & Conroy 2010;
Conroy & van Dokkum 2012;
Cappellari et al. 2013;
Dutton et al. 2012, 2013b;

Testing the model assumptions

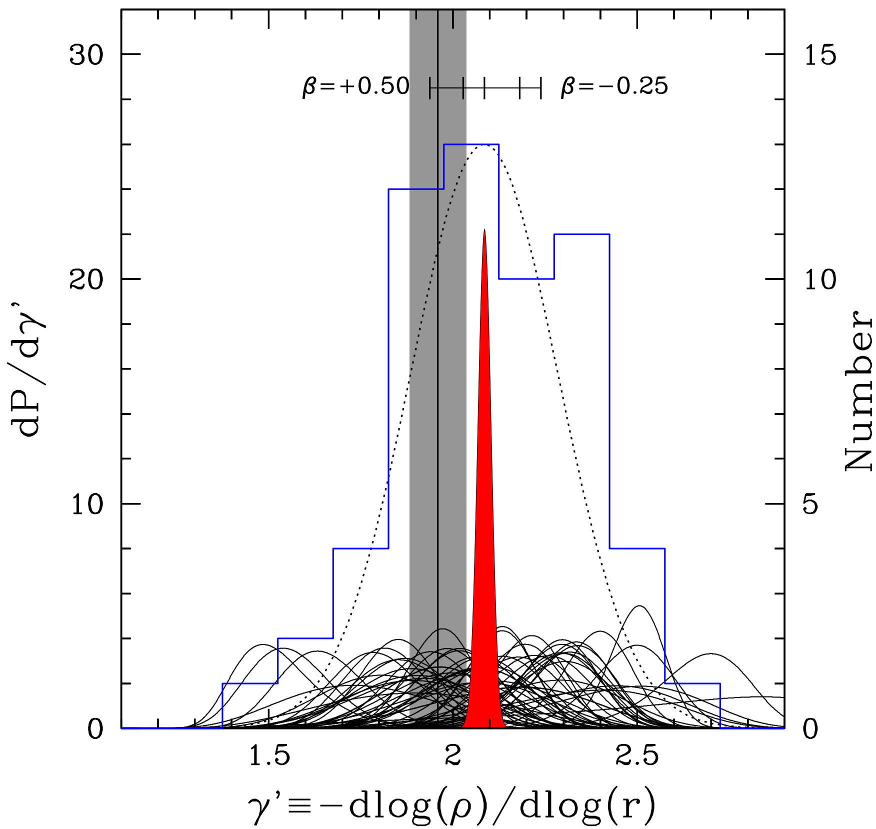
Strong lensing enables robust measurement of average mass density slope inside ~ half-light radius

SLACS - Sloan Lens ACS Survey



Bolton et al. 2006, 2008; Auger et al. 2009

Koopmans et al. 2009

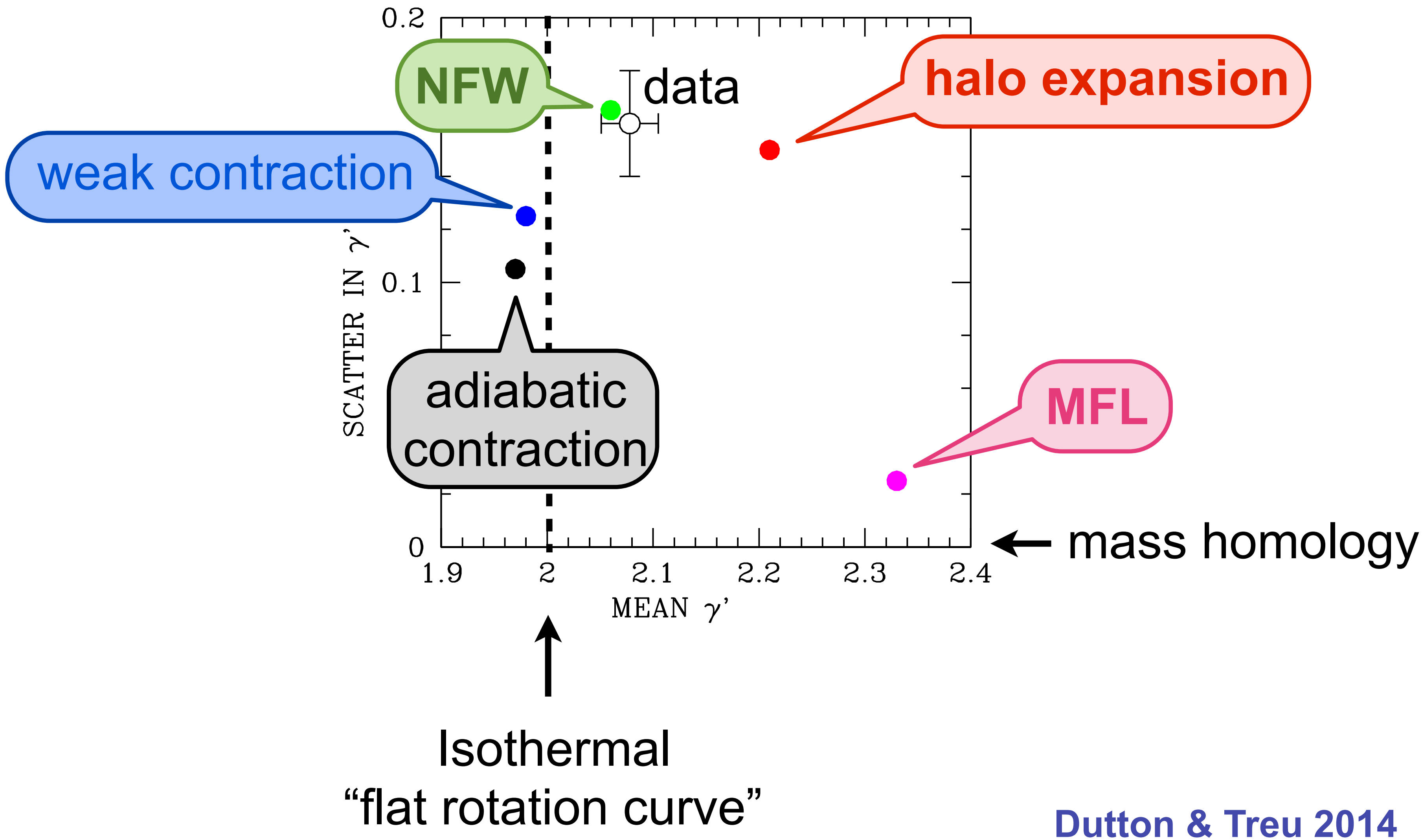


Monday, July 14, 2014

Testing the model assumptions

Select a sub-sample of galaxies with σ~250 ± 40 km/s

Lensing gives same result as fundamental plane!

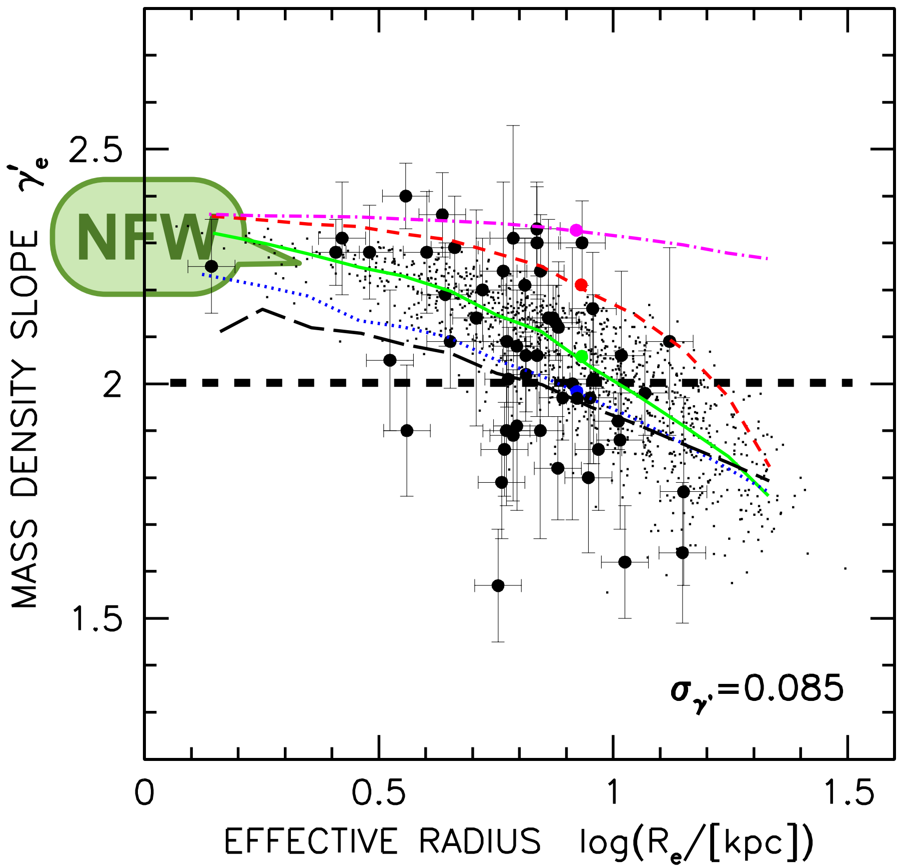


Dutton & Treu 2014

It gets better:

Select a sub-sample of galaxies with σ~250 ± 40 km/s

NFW model matches correlations as well!



Isothermal
“flat rotation curve”

Dutton & Treu 2014