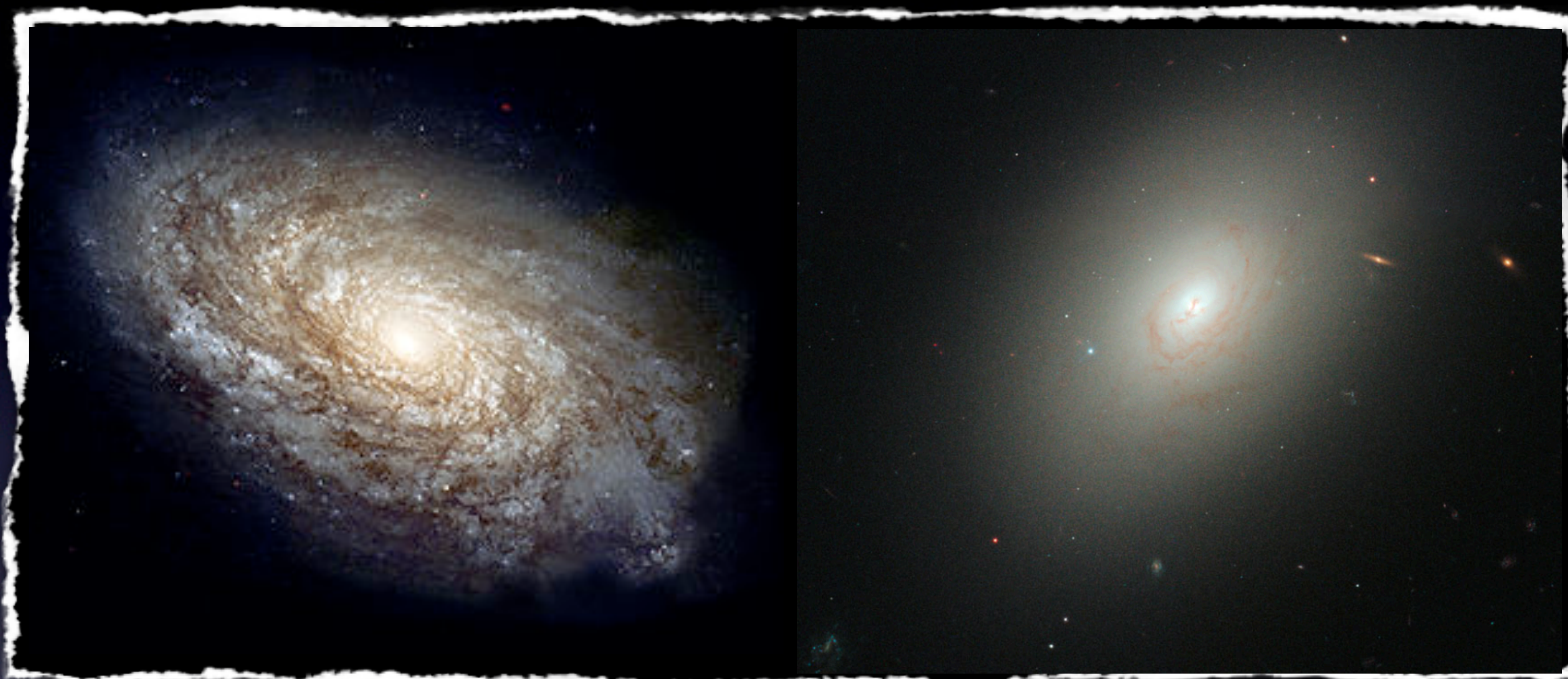
Dark Halo Response and the Stellar IMF in Early- and Late-Type Galaxies



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Scaling Relations

Both Late- and Early-Type Galaxies follow tight Scaling Relations

Tully-Fisher (TF) Relation

$$L \propto V_{\rm rot}^{\alpha} \qquad (\alpha \sim 3.5)$$

scatter NOT correlated with size

Faber-Jackson (FJ) Relation

$$L \propto \sigma^{\beta} \qquad (\beta \sim 4)$$

scatter correlated with size

↓

Fundamental Plane Relation

$$L \propto \sigma^{\beta} R_e^{\gamma}$$

These scaling relations can be used as distance indicators, but are also interesting for understanding galaxy formation

The Origin of Galaxy Scaling Relations

The origin of the TF and FJ relations is believed to be that all DM halos have same density, which implies that

$$V_{\rm vir} \propto R_{\rm vir} \propto M_{\rm vir}^{1/3}$$

Using that less massive halos are more concentrated, this becomes

$$V_{\rm max,h} \propto M_{\rm vir}^{0.29}$$

This scaling is similar to observed stellar mass TF & FJ relations

$$V_{2.2} \propto M_*^{0.28}$$

[Dutton et al. 2010]

$$\sigma_{\rm e} \propto M_*^{0.29}$$

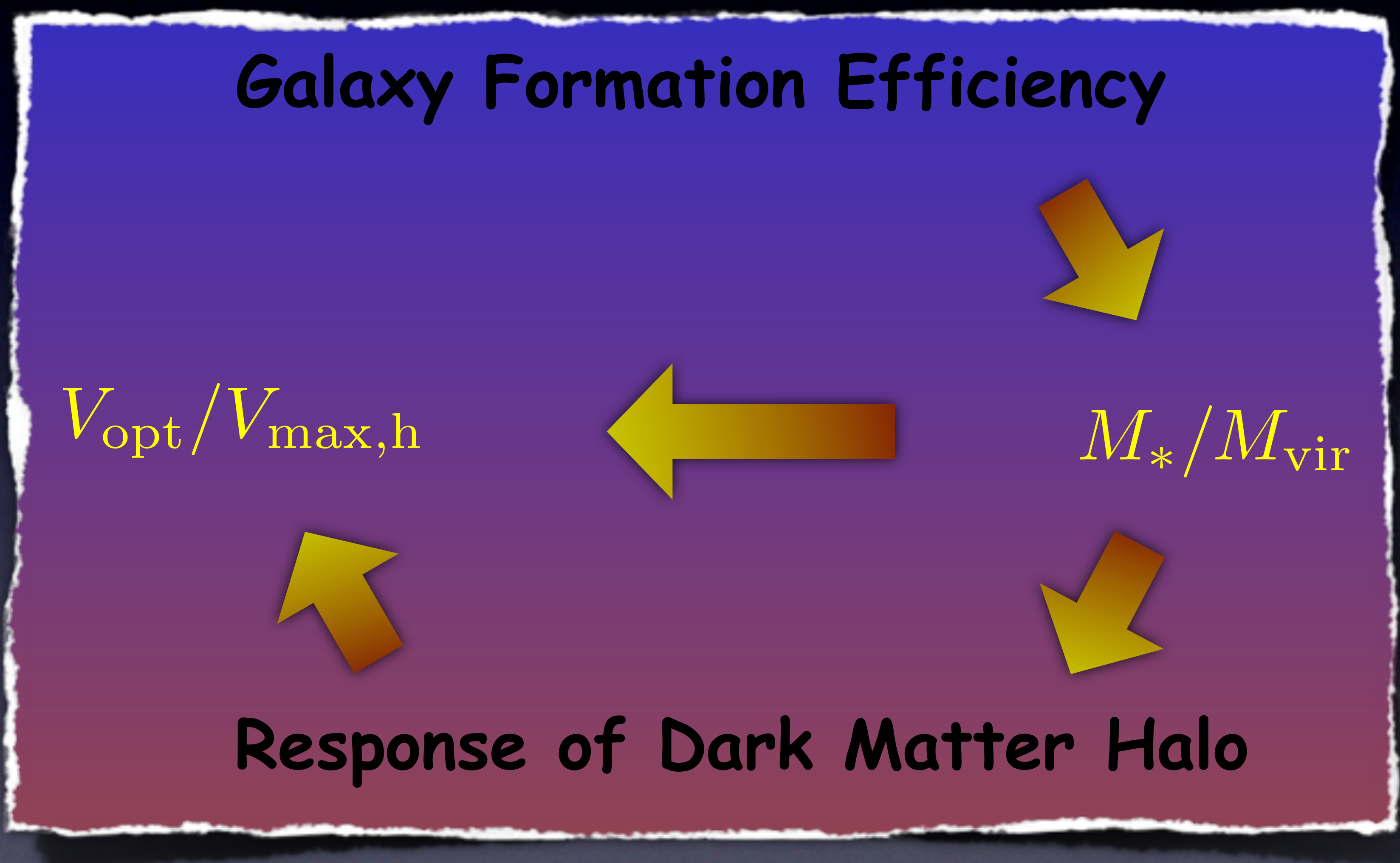
[Gallazzi et al. 2006]

$V_{2.2}$ is disk rotation velocity at 2.2 disk scale lengths

$\sigma_{\rm e}$ is velocity dispersion inside effective radius

The Origin of Galaxy Scaling Relations

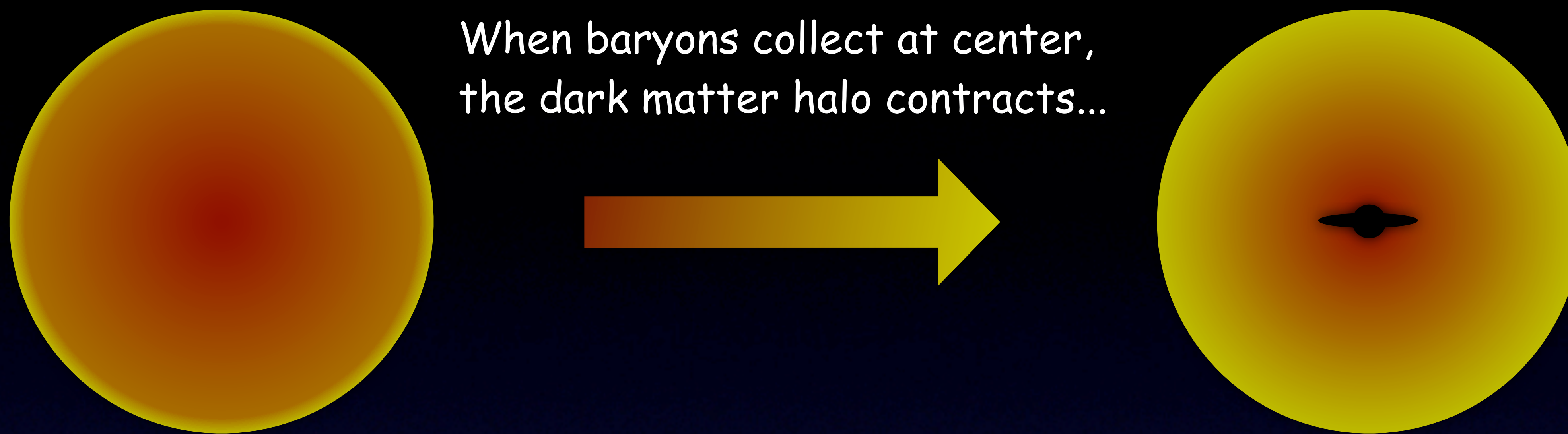
For the $V_{\rm max,h} - M_{\rm vir}$ relation to be the direct origin of the TF & FJ relations requires that $V_{\rm opt}/V_{\rm max,h}$ and $M_*/M_{\rm vir}$ are both constants! ✣



Hence, there is hope that the observed TF & FJ relations can shed light on Galaxy Formation and Halo Response.

✣ Here $V_{\rm opt} = V_{2.2}$ for late-types, and $V_{\rm opt} = \sigma_{\rm e}$ for early-types

Dark Halo Response



In the limit where the process is slow, the response is adiabatic

spherical symmetry: $r_{\rm i}\, M_{\rm i}(r_{\rm i}) = r_{\rm f}\, M_{\rm f}(r_{\rm f})$

no shell crossing: $M_{\rm h,i}(r_{\rm i}) = M_{\rm h,f}(r_{\rm f})$

initially well mixed: $M_{\rm b,i}(r_{\rm i}) = f_{\rm b} M_{\rm h,i}(r_{\rm i})$

$$\frac{r_{\rm f}}{r_{\rm i}} = \Gamma_{\rm AC} = \frac{M_{\rm h,i}(r_{\rm i})}{M_{\rm b,f}(r_{\rm f}) + (1 - f_{\rm b}) M_{\rm h,i}(r_{\rm i})}$$

Blumenthal et al. (1986)

In general, system is not spherically symmetric and the process of galaxy formation may not be adiabatic. We therefore adopt the more general form:

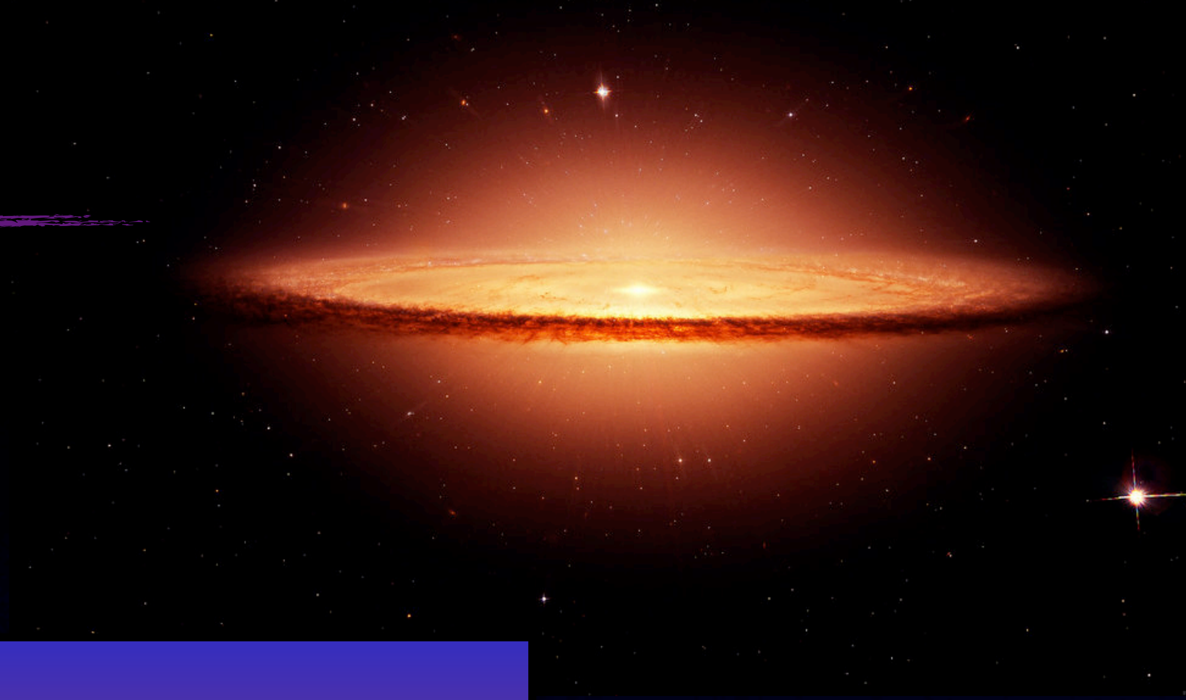
$$\frac{r_{\rm f}}{r_{\rm i}} = \Gamma_{\rm AC}^{\nu}$$

Here ν is a free parameter, to be constrained by the data:

- $\nu = 1$ standard AC
- $\nu = 0$ no contraction
- $\nu < 0$ expansion

[Based on cosmological, hydrodynamical simulations, Gnedin et al. (2004) suggest $\nu \simeq 0.8$]

Structural Models



Galaxies consist of three components:

Dark Matter Halo

Modelled as spherical NFW halo.
Concentration mass relation of Maccio et al. (2007)
Completely specified by its mass, $M_{\rm h}$

Stellar Component

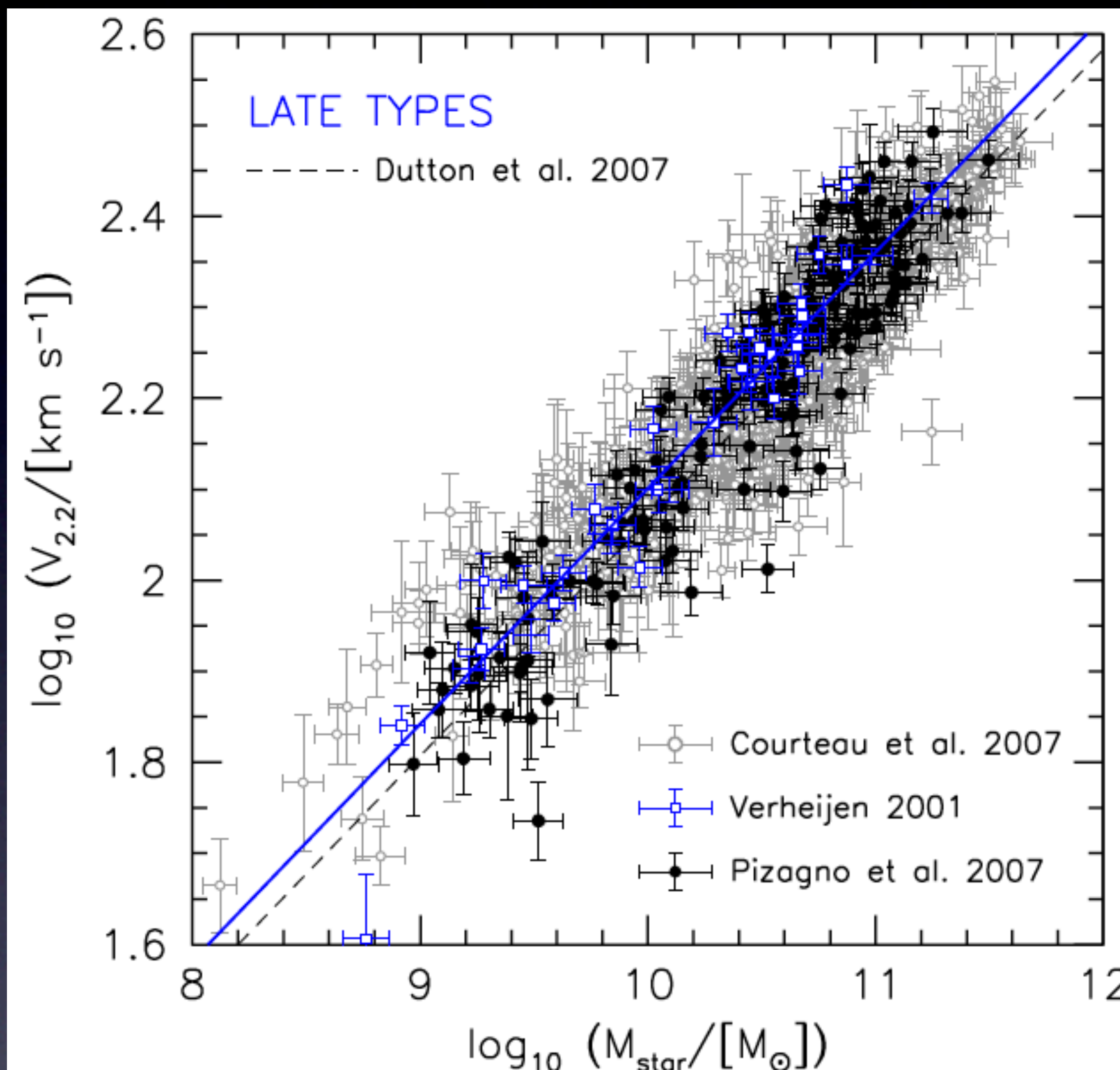
Modelled as sum of two Sersic profiles: n=1 plus n=4.
In case of late-type, n=1 component is thin disk.
In case of early-type, n=1 component is spherical.
Specified by four free parameters: $M_{\rm d}, M_{\rm b}, R_{\rm d}, R_{\rm b}$

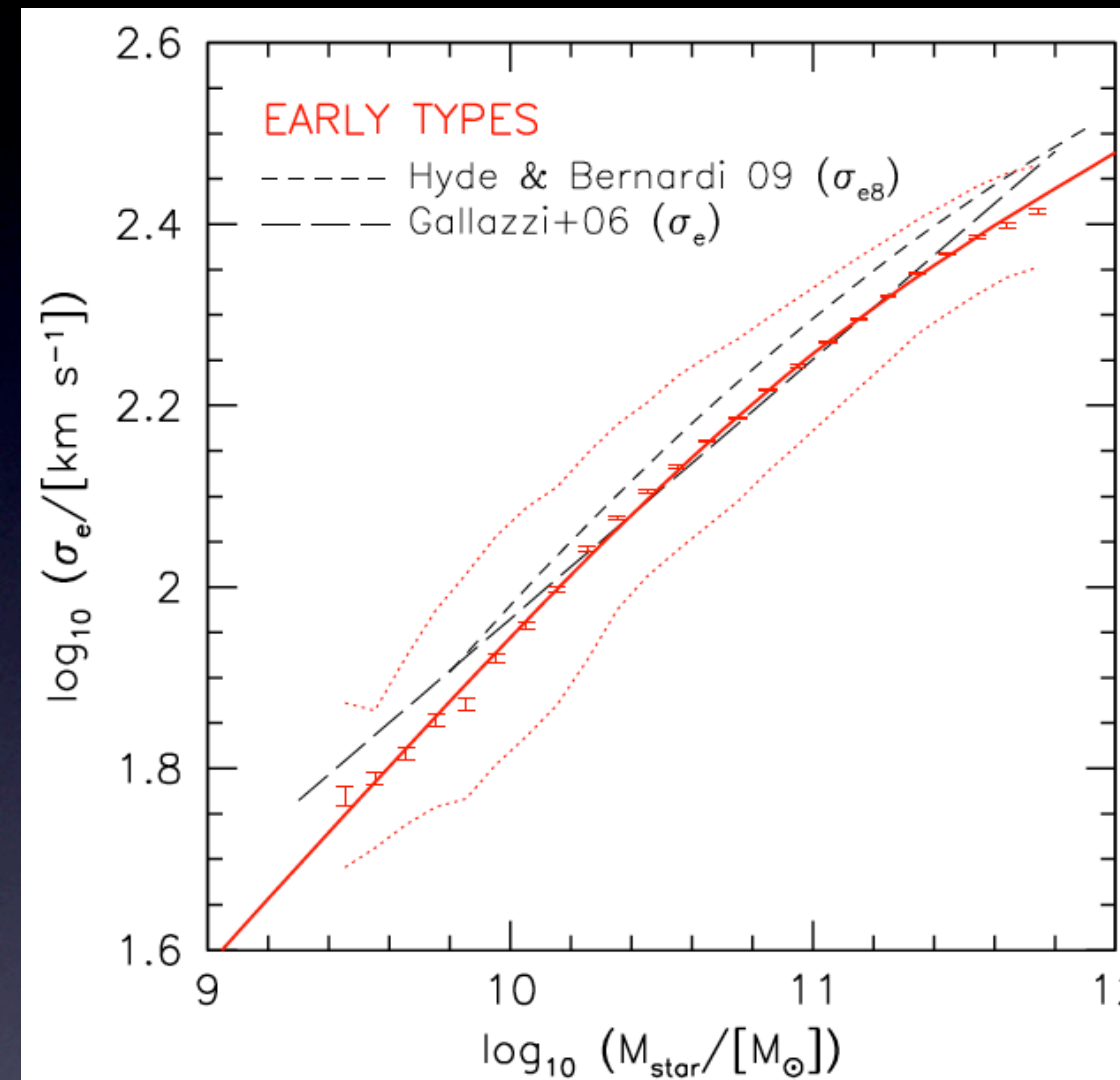
$$M_* \equiv M_{\rm d} + M_{\rm b}$$

Cold Gas Disk

Modelled as thin exponential disk.
Specified by two free parameters: $M_{\rm g}, R_{\rm g}$

Tully-Fisher and Faber-Jackson Relations



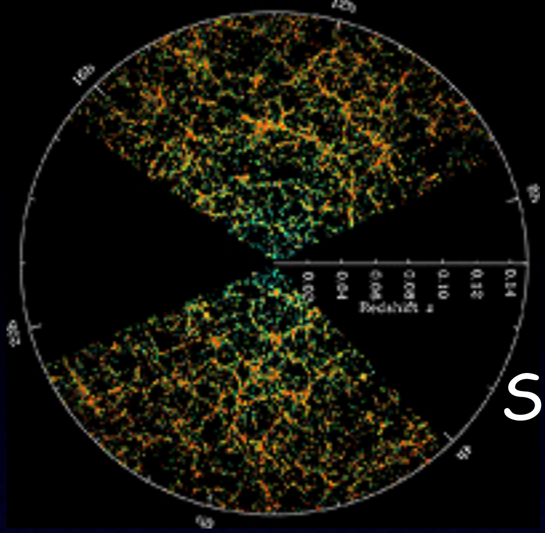


We use these relations as constraints for the models

Methodology

Observed Scaling Relations

M_h *vs.* M_*	R_d *vs.* M_*	B/D *vs.* M_*
M_g *vs.* M_*	R_b *vs.* M_*	R_g *vs.* R_d



SDSS

Model Parameters

$M_\mathrm{h}, M_\mathrm{d}, M_\mathrm{b}, M_\mathrm{g}$

$R_\mathrm{d}, R_\mathrm{b}, R_\mathrm{g}$

Δ_IMF ν

Rotation Curve

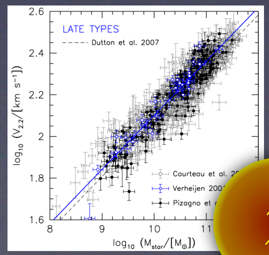
$$V_c(r) = \sqrt{V_\mathrm{h}^2 + V_\mathrm{d}^2 + V_\mathrm{b}^2 + V_\mathrm{g}^2}$$

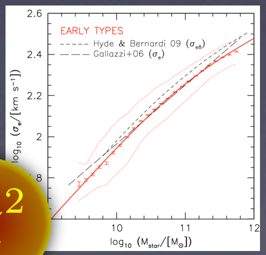
$V_\mathrm{c}(r_\mathrm{e})/\sigma_\mathrm{e}$

$V_{2.2}$ or σ_e

Sampling of M_h

TF & FJ relations





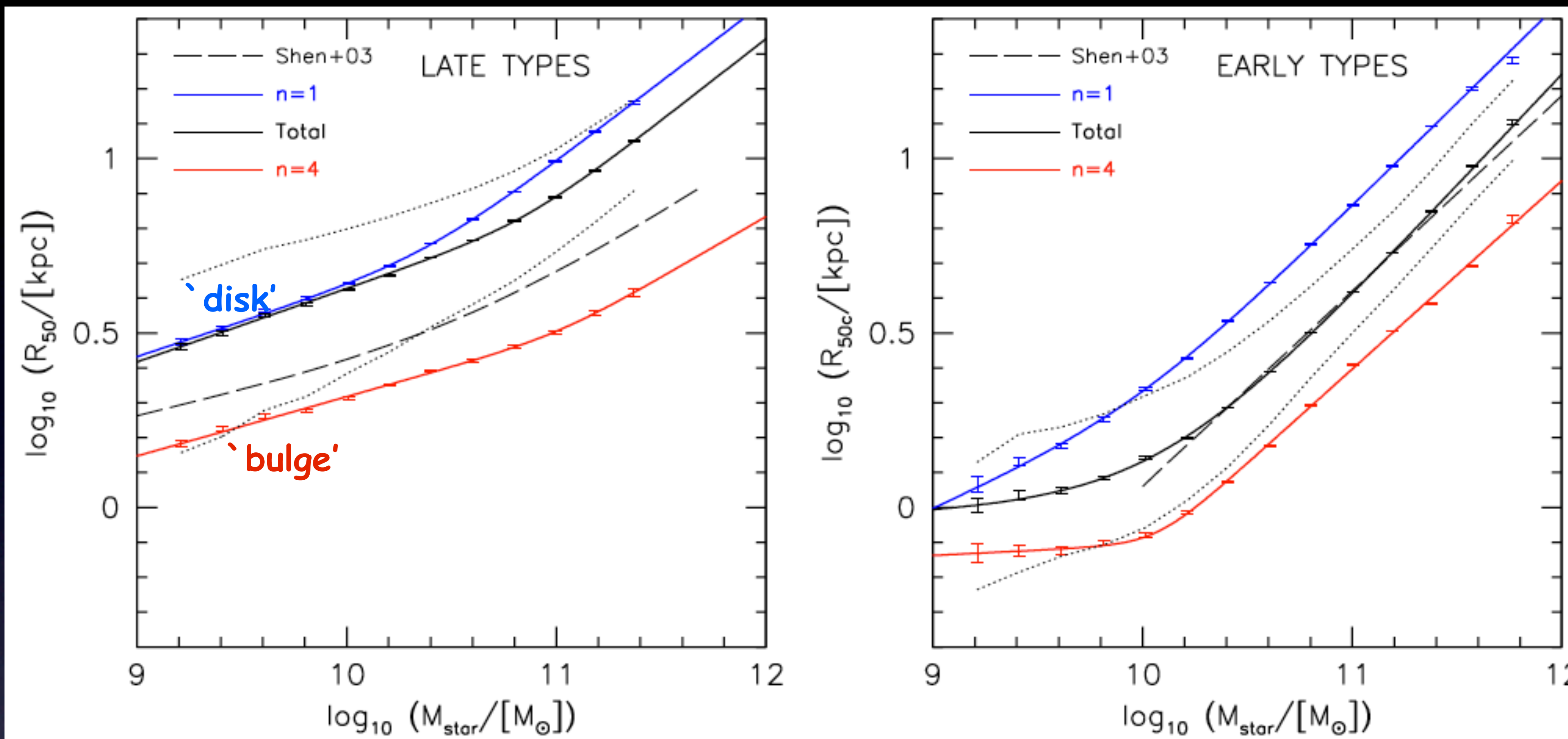
χ^2

compare to data

Constrain

Δ_IMF & ν

Galaxy Sizes and B/D Ratios



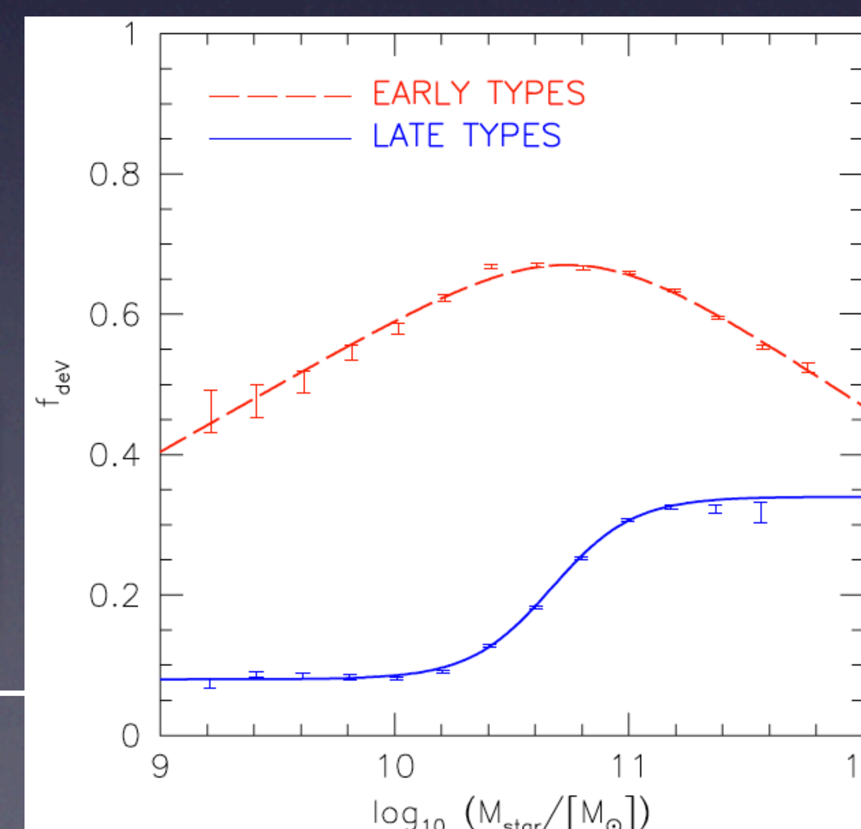
Sizes and B/D ratios obtained from GIM2D photometric analysis of ~270.000 SDSS galaxies.

Stellar masses obtained from SDSS *ugriz*-SED by MPA/JHU group, assuming a Chabrier IMF.

We can rescale these stellar masses to another IMF by adding $\Delta_{\rm IMF}$ to $\log(M_*)$

Chabrier: $\Delta_{\rm IMF} = 0.0$

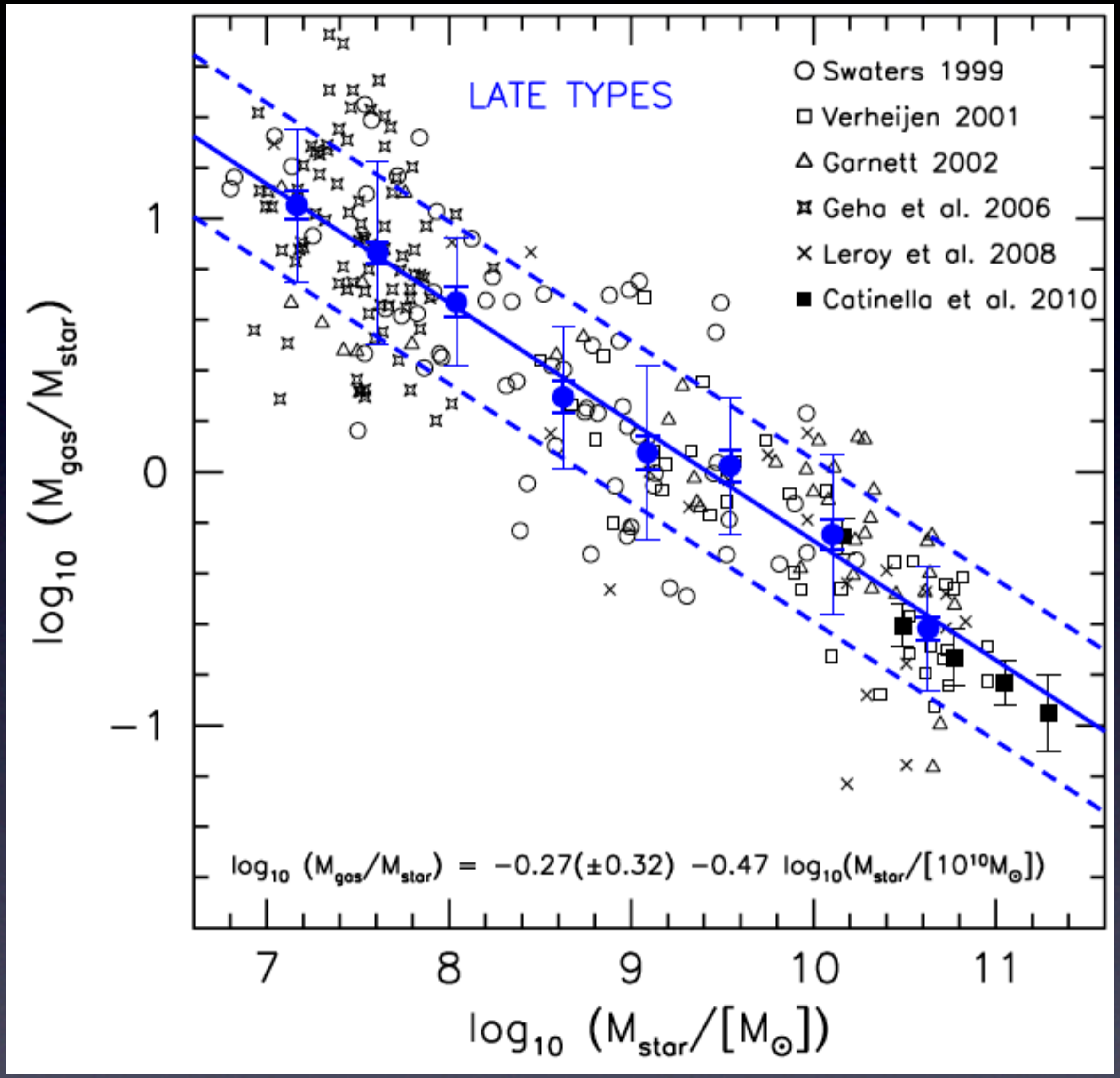
Salpeter: $\Delta_{\rm IMF} = +0.24$



Note: Our sizes for late-types are larger than those of Shen et al. (2003); This is due to fact that Shen et al used circular aperture photometry.

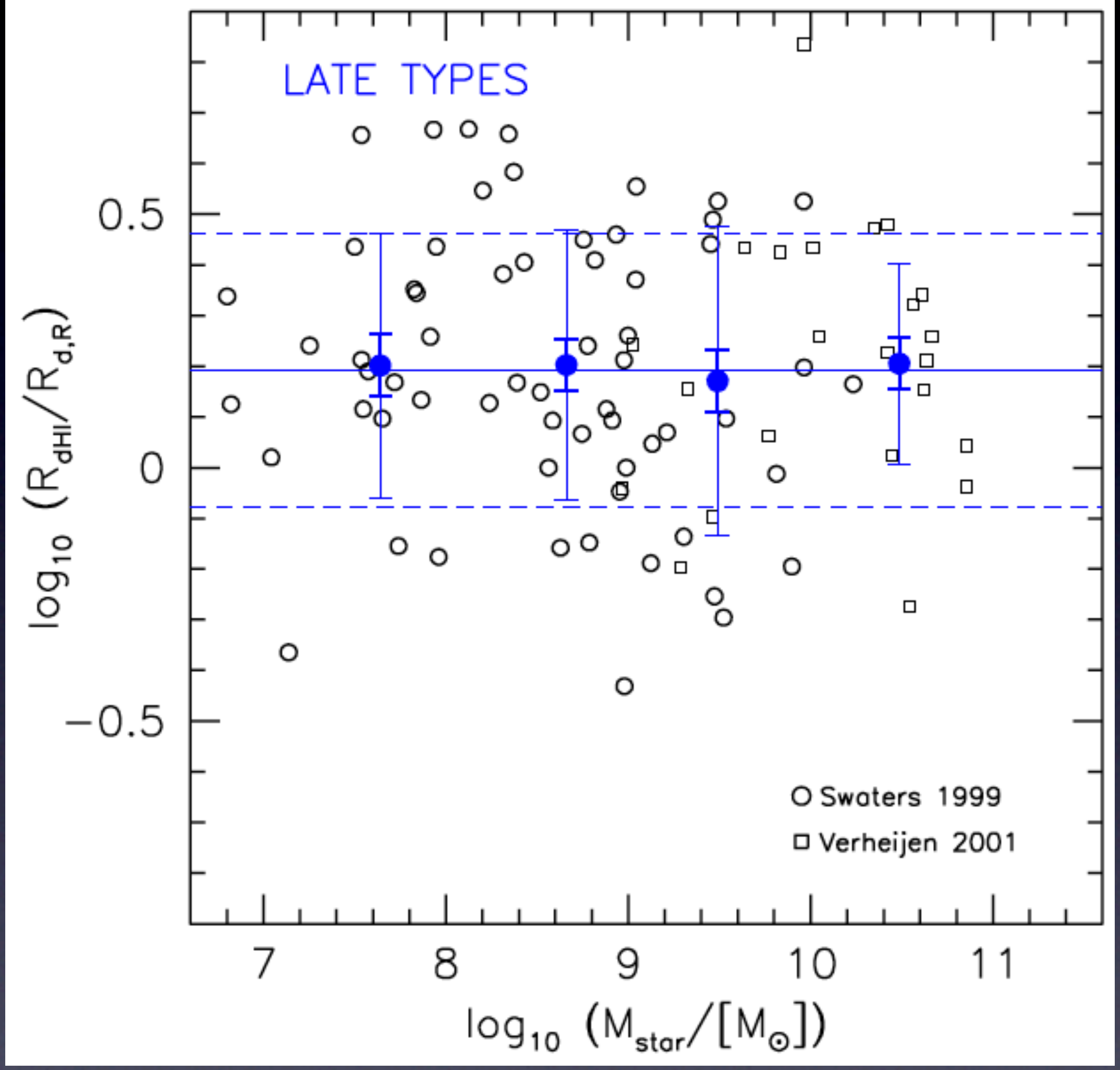
Properties of Cold Gas in Late-Type Galaxies

Gas Mass Fractions



$$\log\left(\frac{M_{\rm g}}{M_*}\right) = -0.27 - 0.47\log\left(\frac{M_*}{10^{10}M_\odot}\right)$$

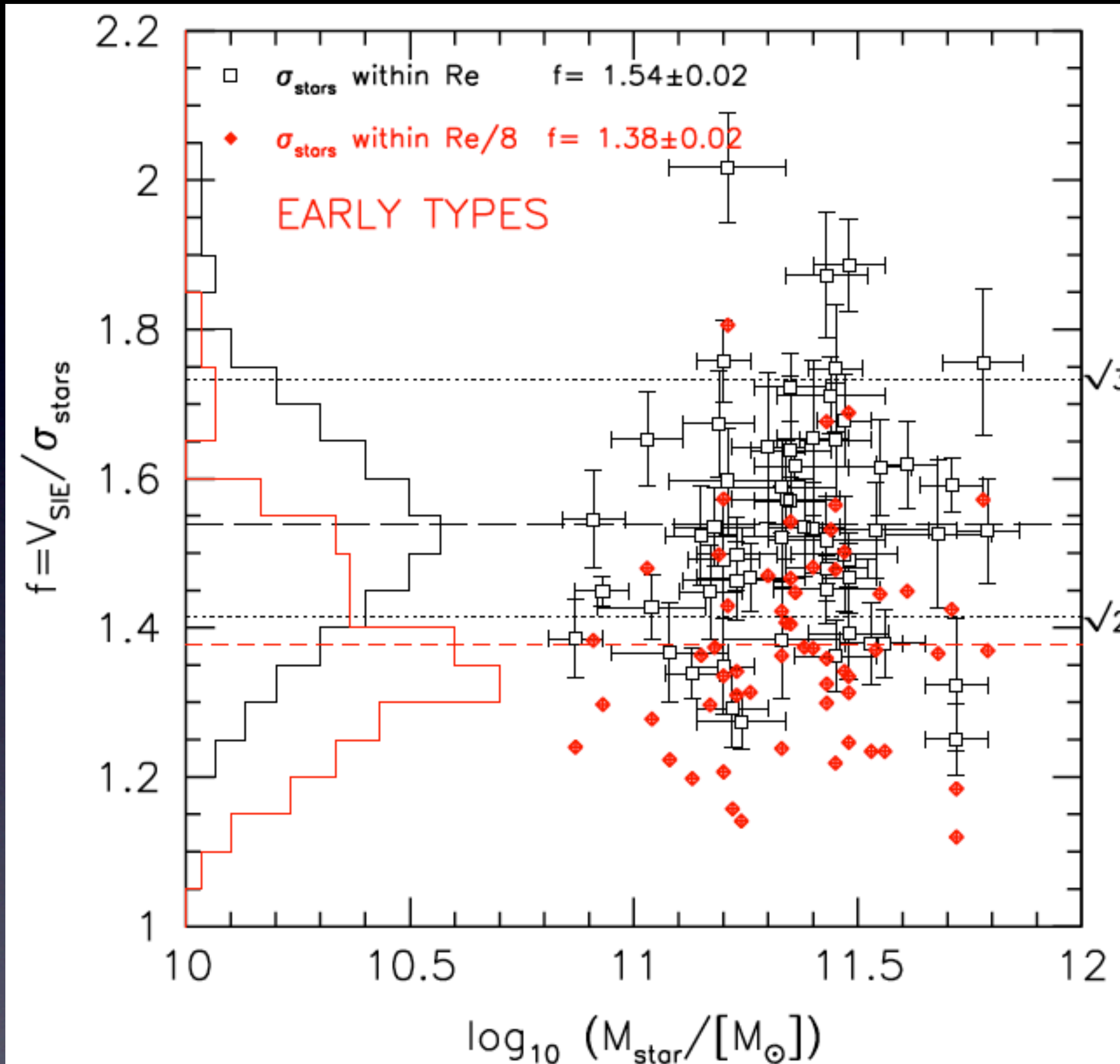
Gas Scale Lengths



$$\log\left(\frac{R_{\rm d}}{R_{\rm g}}\right) = 0.19$$

These two relations define the gas properties of late-types.

How to convert from V(r) to σ_e?



Data from SLACS survey (strong gravitational lensing sample). Taken from Auger et al. (2009)

Based on strong lensing data we infer that

$$\frac{V_c(R_e)}{\sigma_e} = 1.54$$

which is the value we adopt throughout.

Previous studies:

Padmanabhan et al. (2004)

$$\frac{V_c(R_e)}{\sigma_e} = 1.65$$

Cappellari et al. (2006)

$$\frac{V_c(R_e)}{\sigma_e} = 1.44$$

We adopt uncertainty of 0.03 dex

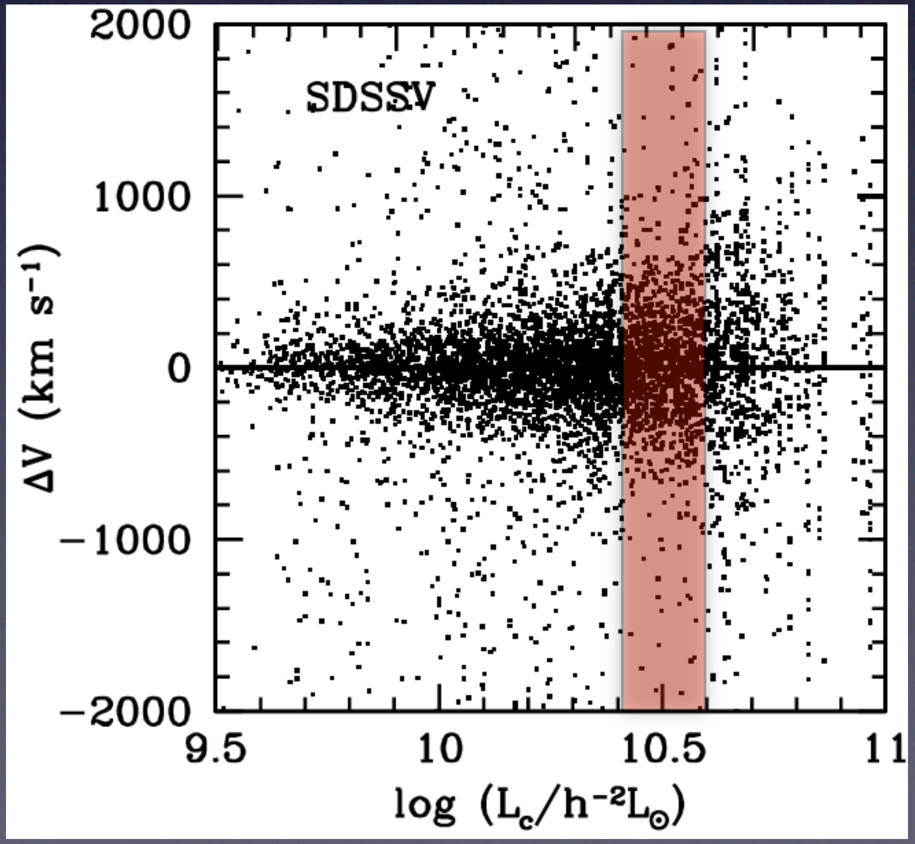
Satellite Kinematics

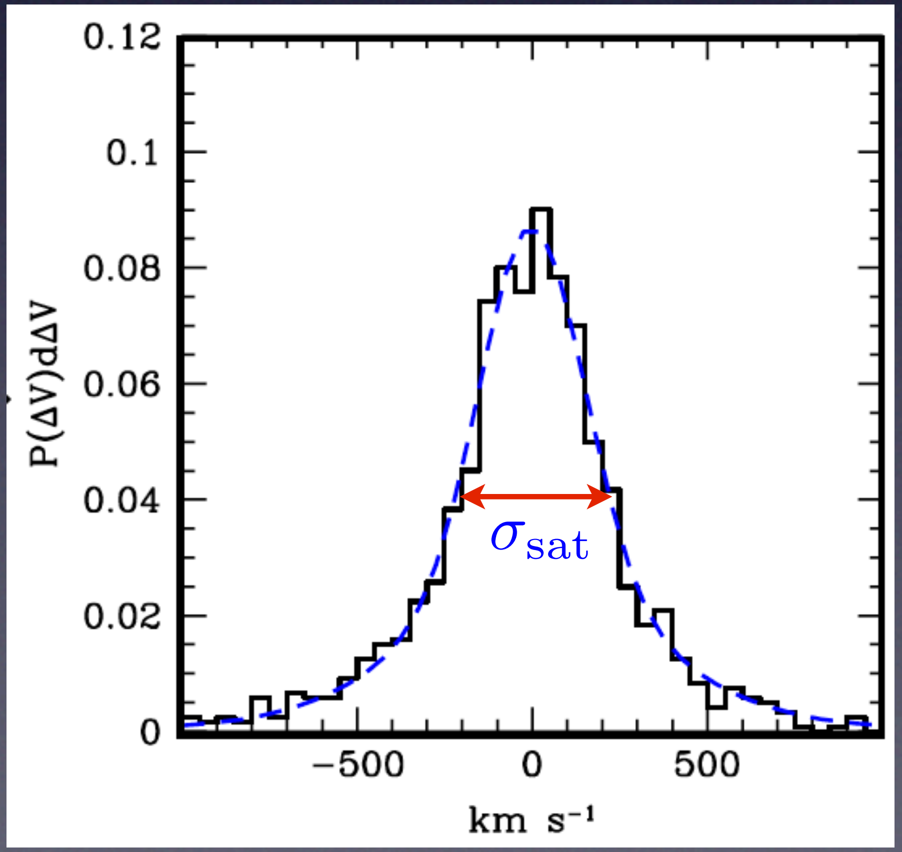
We use satellite kinematics in the SDSS to probe the relation between stellar mass and halo mass. Using virial equilibrium and spherical collapse:

$$\sigma^2 \propto \frac{GM_{\rm h}}{r_{\rm h}} \qquad M_{\rm h} \propto r_{\rm h}^3 \qquad \sigma \propto M_{\rm h}^{1/3}$$

On average, only ~2 satellites per central: → **stacking**

- select centrals and satellites from SDSS
- using redshifts, measure $\Delta V = V_{\rm sat} - V_{\rm cen}$ as function of M_*





Satellite Kinematics

Unless $P(M_\mathrm{h}|M_*)$ is a Dirac Delta function, stacking implies combining haloes of different masses. Consequently, distinguish two schemes:

satellite weighting:

$$\sigma^2_\mathrm{sw}(M_*) = \frac{\int P(M_\mathrm{h}|M_*)\,\langle N_\mathrm{s}|M_\mathrm{h}\rangle\,\sigma^2_\mathrm{sat}(M_\mathrm{h})\,\mathrm{d}M_\mathrm{h}}{\int P(M_\mathrm{h}|M_*)\,\langle N_\mathrm{s}|M_\mathrm{h}\rangle\,\mathrm{d}M_\mathrm{h}}$$

host weighting:

$$\sigma^2_\mathrm{hw}(M_*) = \frac{\int P(M_\mathrm{h}|M_*)\,\sigma^2_\mathrm{sat}(M_\mathrm{h})\,\mathrm{d}M_\mathrm{h}}{\int P(M_\mathrm{h}|M_*)\,\mathrm{d}M_\mathrm{h}}$$

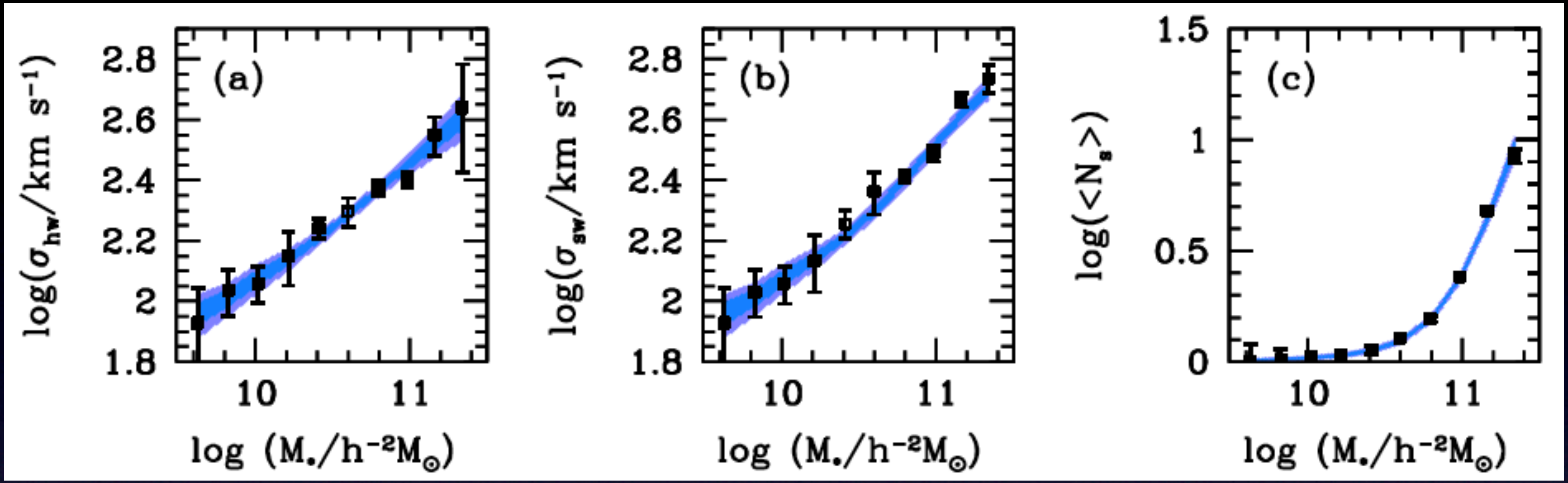
satellites per host:

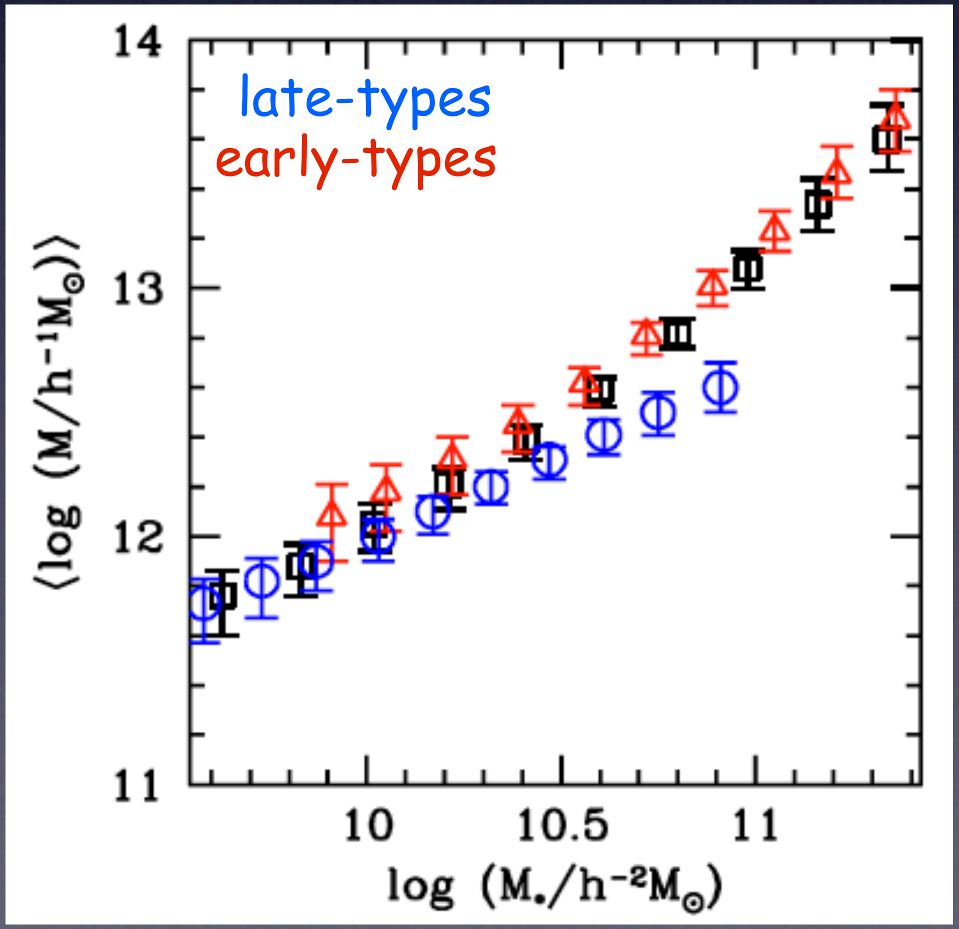
$$\langle N_\mathrm{sat}\rangle(M_*) = \frac{\int P(M_\mathrm{h}|M_*)\,\langle N_\mathrm{s}|M_\mathrm{h}\rangle\,\mathrm{d}M_\mathrm{h}}{\int P(M_\mathrm{h}|M_*)\,\mathrm{d}M_\mathrm{h}}$$

From the measurements of $\sigma^2_\mathrm{sw}(M_*)$, $\sigma^2_\mathrm{hw}(M_*)$, and $\langle N_\mathrm{sat}\rangle(M_*)$ one can determine $P(M_\mathrm{h}|M_*)$.

[More, vdB & Cacciato 2009]

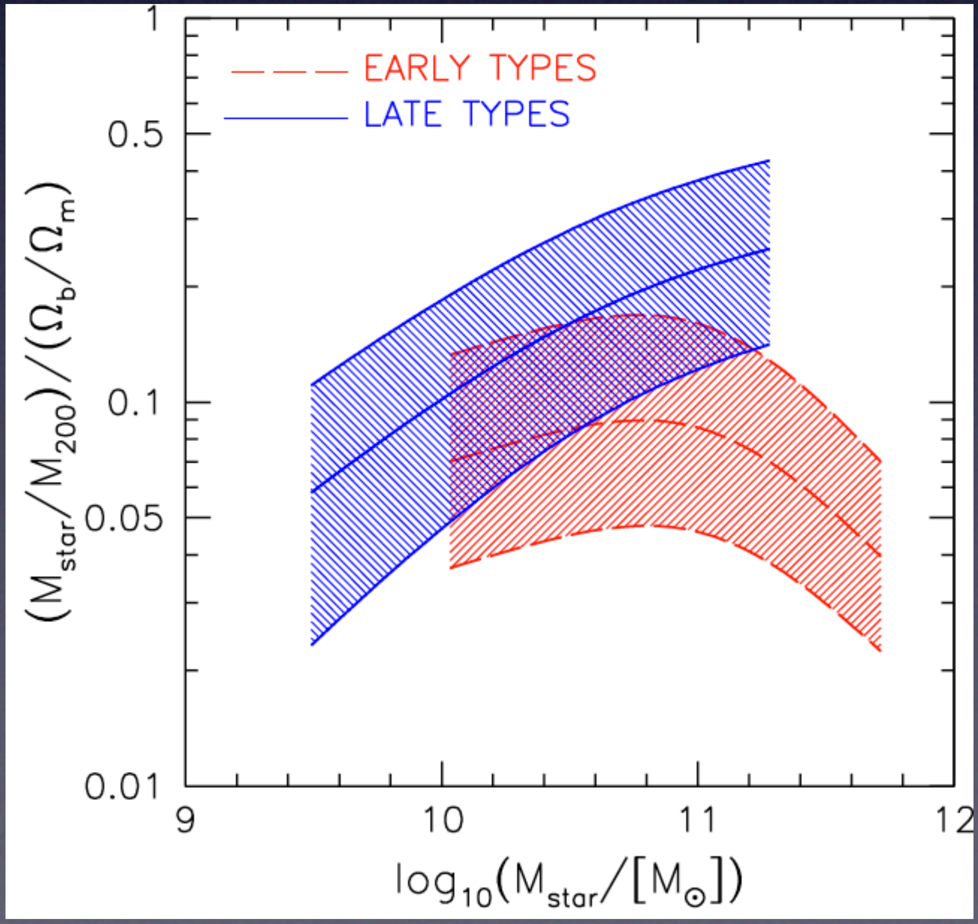
Satellite Kinematics: results



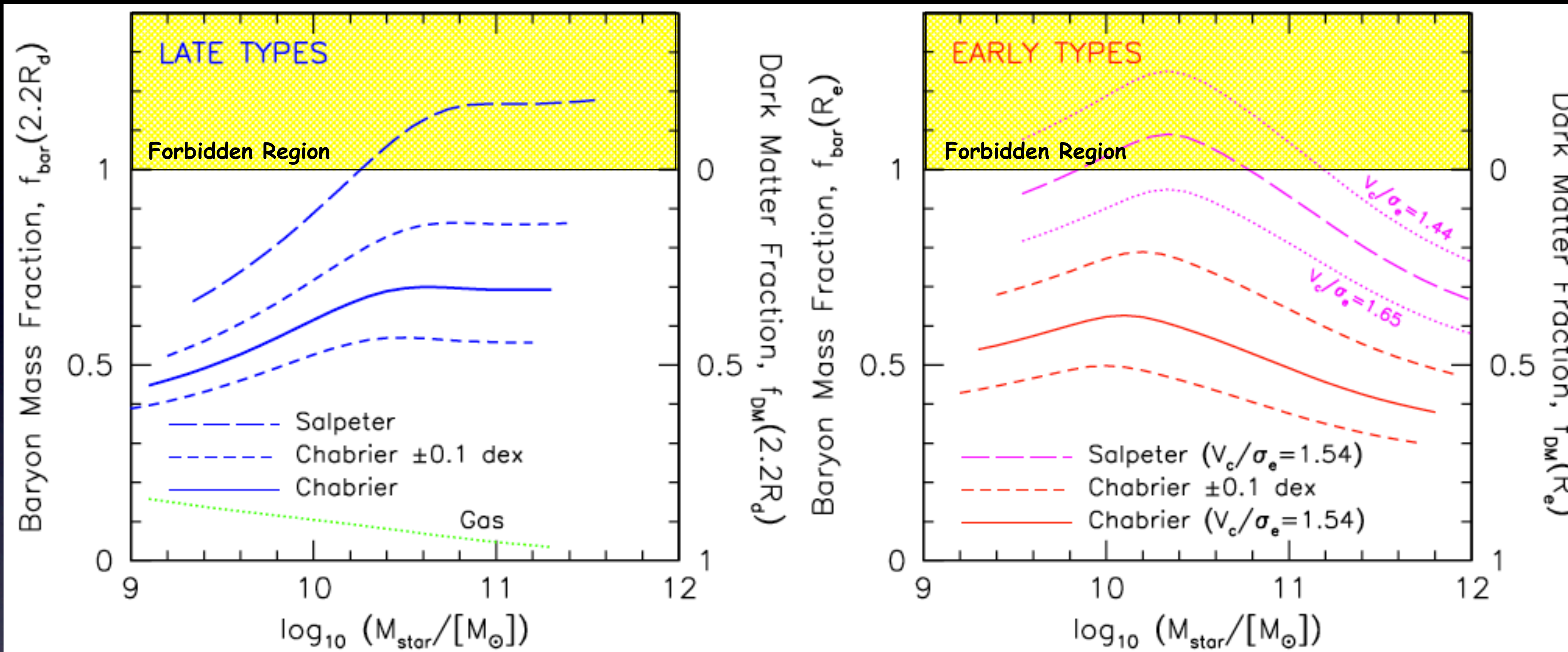


based on ~6300 satellites around ~3800 centrals

[More et al. 2011]



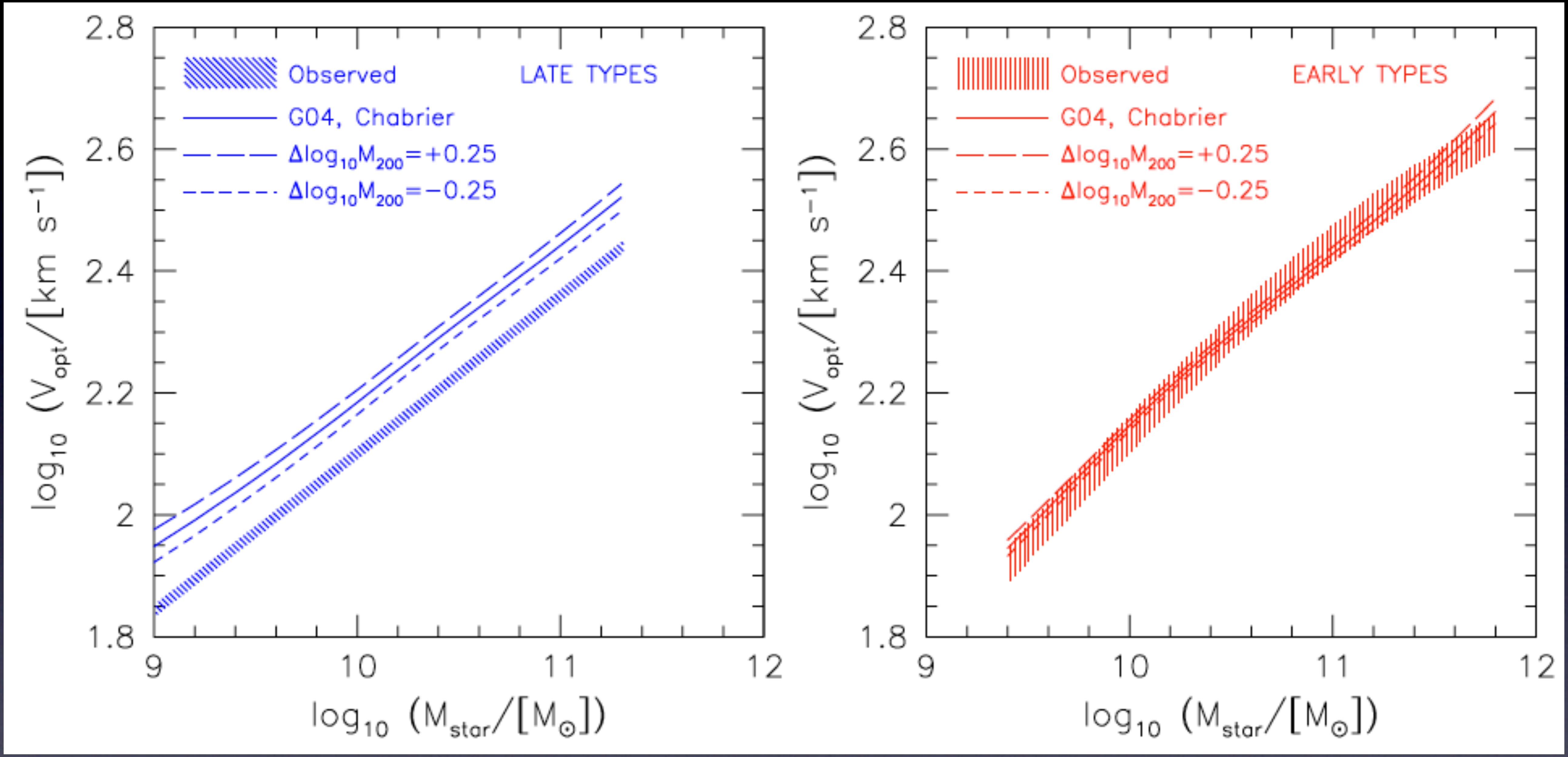
Baryonic Mass Fractions



Chabrier IMF consistent with all galaxies....

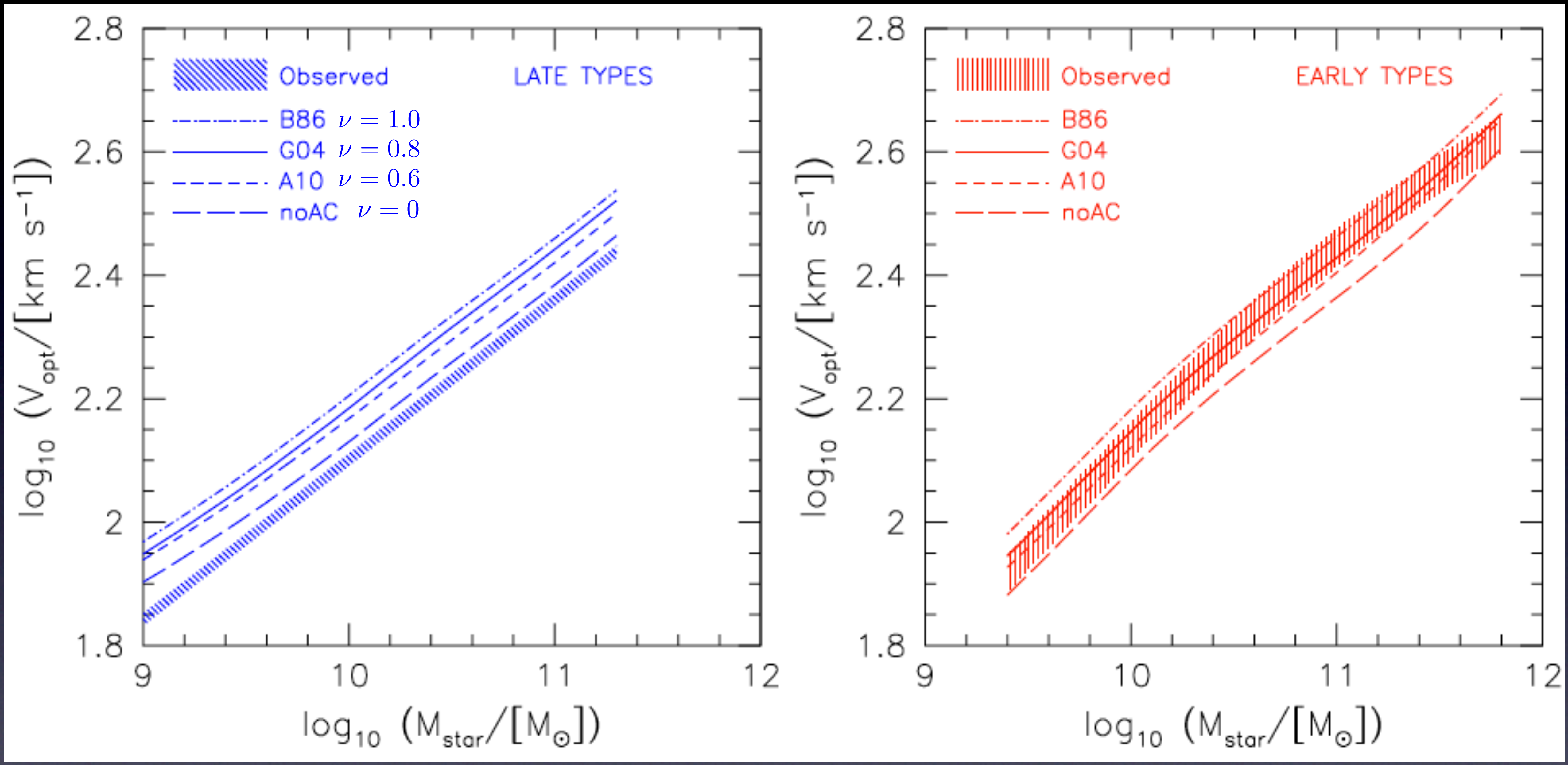
Salpeter IMF ruled out for massive late-types and for low mass early-types

Results



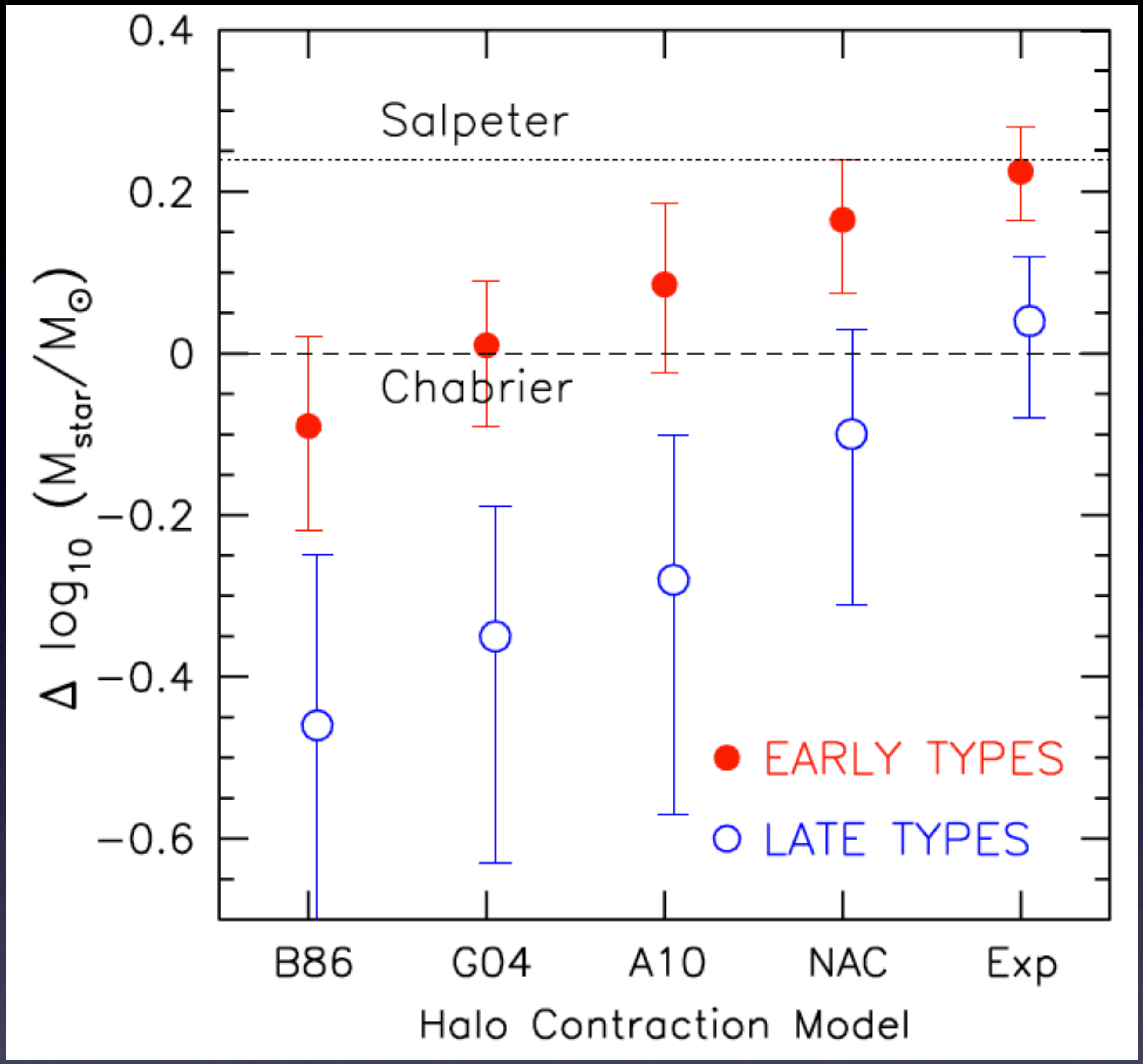
A model with Chabrier IMF ($\Delta_{\mathrm{IMF}} = 0.0$) and Gnedin contraction ($\nu = 0.8$) is in agreement with the FJ relation, but yields a TF zeropoint that is too high (too much rotation for given stellar mass).

Results



For a Chabrier IMF ($\Delta_{\rm IMF} = 0.0$), the zero-point of the TF relation requires halo expansion ($\nu < 0$). However, for the same IMF, the zero-point of the FJ relation requires contraction with $\nu = 0.8$.

Summary of Results



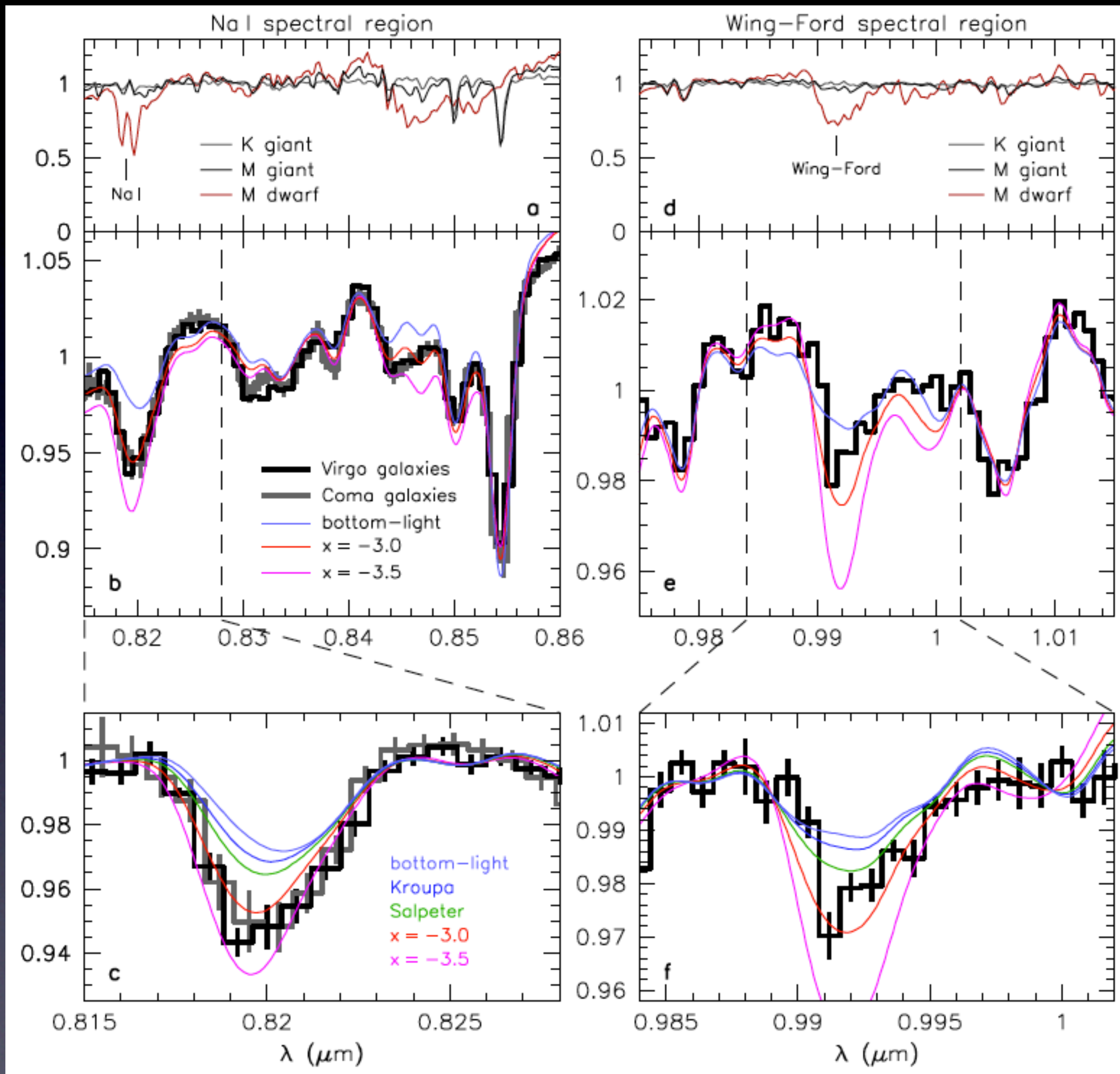
Early- and Late-type galaxies cannot have same IMF **and** have experienced the same amount of halo contraction!

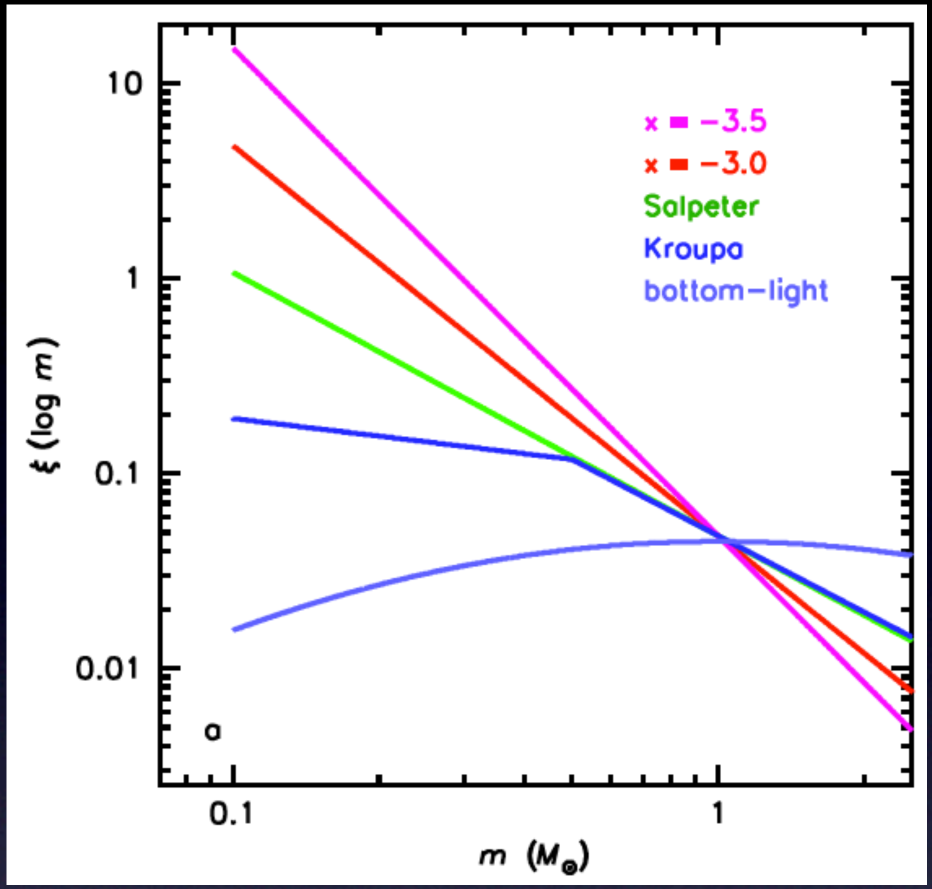
In case of universal IMF, early-types must have experienced more halo contraction than late types.

In case of universal contraction, early-types must have IMF that is less top-heavy than in case of late-types.

IMF is power-law which turns over at low mass. Turn-over mass set by Jeans mass at formation, which is expected to increase with redshift due to T_CMB (Larson 1998). Early-types have older stellar populations, yielding IMF that is more top-heavy.

A Bottom-Heavy IMF in Massive Ellipticals?



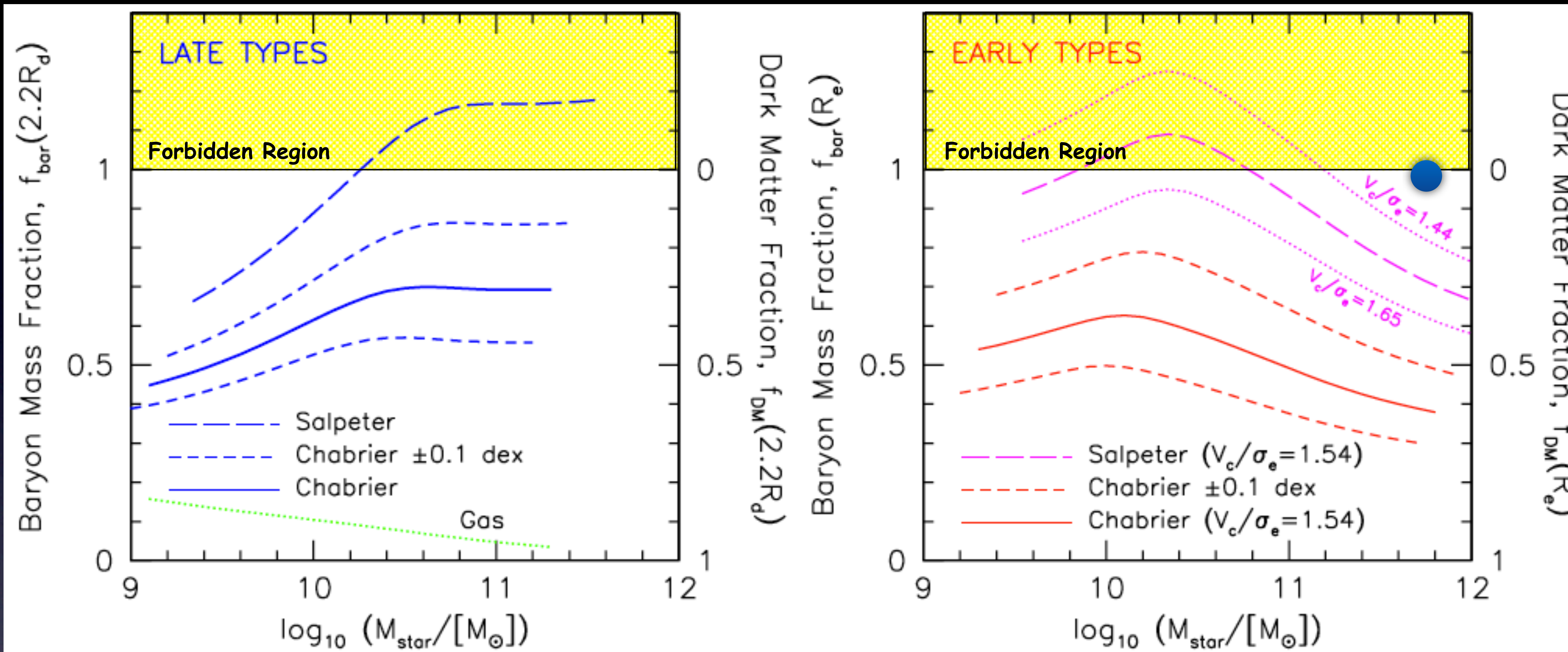


Sodium line and Wing-Ford band in spectra of nuclei of massive ellipticals reveal large population of low-mass stars; this suggests IMF that is more bottom-heavy than a Salpeter...

[van Dokkum & Conroy 2010]

Similar data of M31 globulars, which have similar age and metallicity, are consistent with Salpeter/Kroupa IMF [van Dokkum & Conroy 2011]

Baryonic Mass Fractions



Bottom-heavy IMF of Conroy & van Dokkum CANNOT be present in lower mass early-types!