Constraining the IMF via galaxy mass determinations

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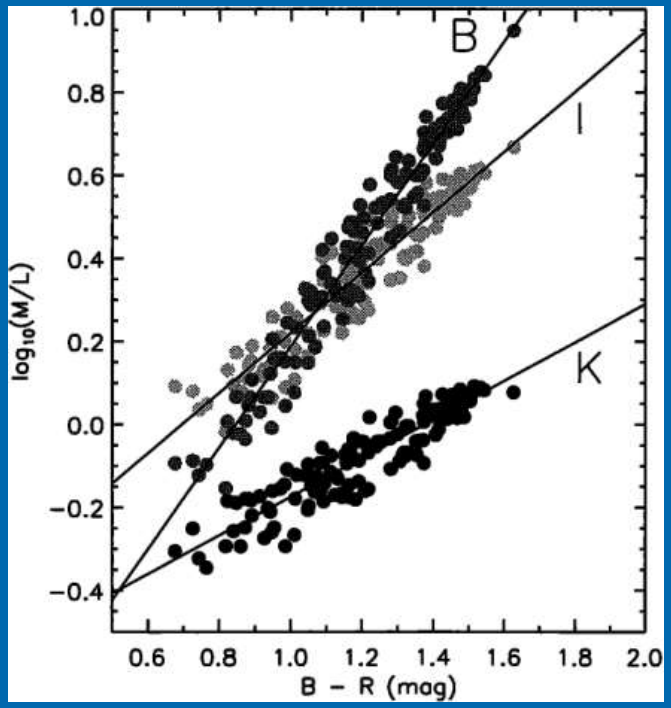
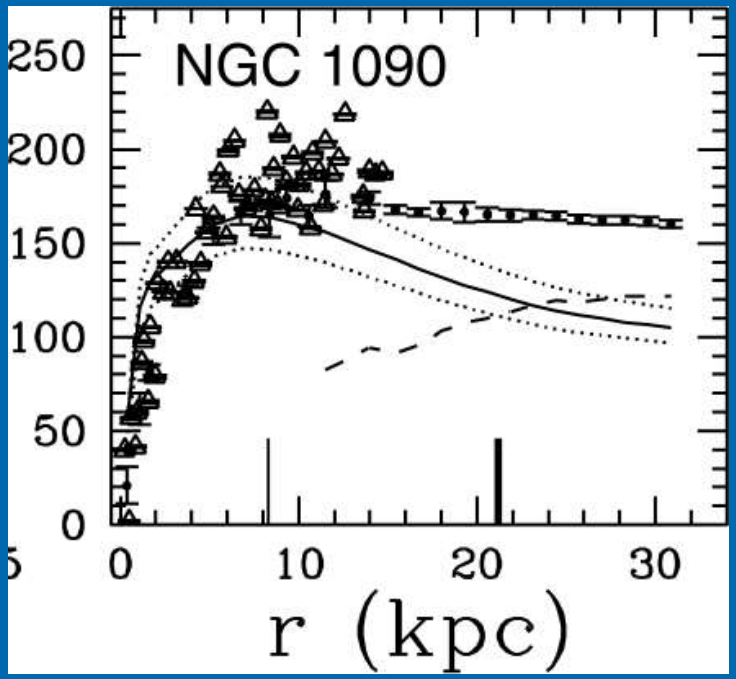
Preamble

- IMF = integrated mass normalization of IMF
- IMF measured comparing population & dynamics
- Equal-mass IMF are indistinguishable

Measuring central M/L in spirals



(Bell+deJong01)

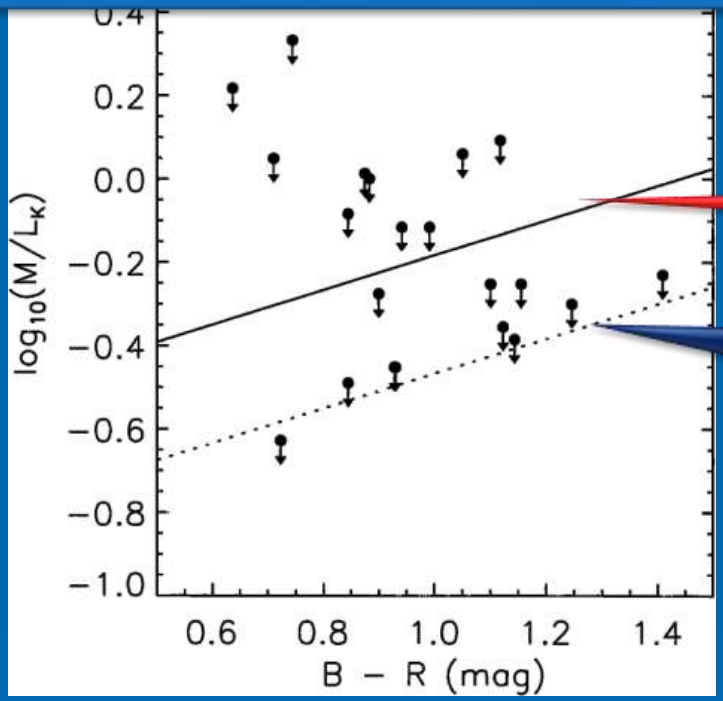


(Kassin+06)

- $(M/L)_{\mathrm{pop}}$ from galaxy colours
- $(M/L)_{\mathrm{stars}}$ from 34 HI+Hα rotation curves
- Assume maximum disk (=max stellar mass)

Need for Kroupa IMF in spirals

Maximum-disk rotation curves



$\xi(m) \propto m^{\alpha}$

$\alpha = 2.35$

diet-Salpeter
≈ Kroupa M/L

(Bell+deJong01;
Kassin+06)

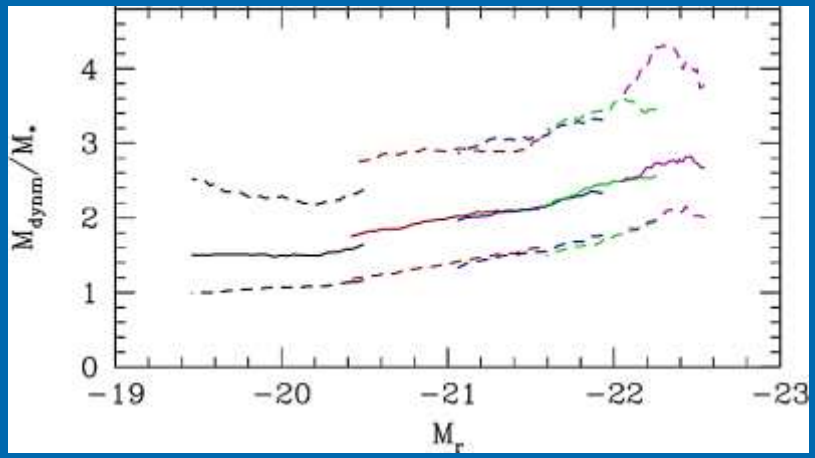
- If IMF universal → Must be light (Kroupa-type M/L)
- $(M/L)_{\mathrm{stars}}$ does not follow population $(M/L)_{\mathrm{pop}}$
- Many disks sub maximal or IMF not universal

(also Bershady+11; Dutton+11; Brewer+12)

$(M/L)_{\rm pop} \neq (M/L)_{\rm dyn}$

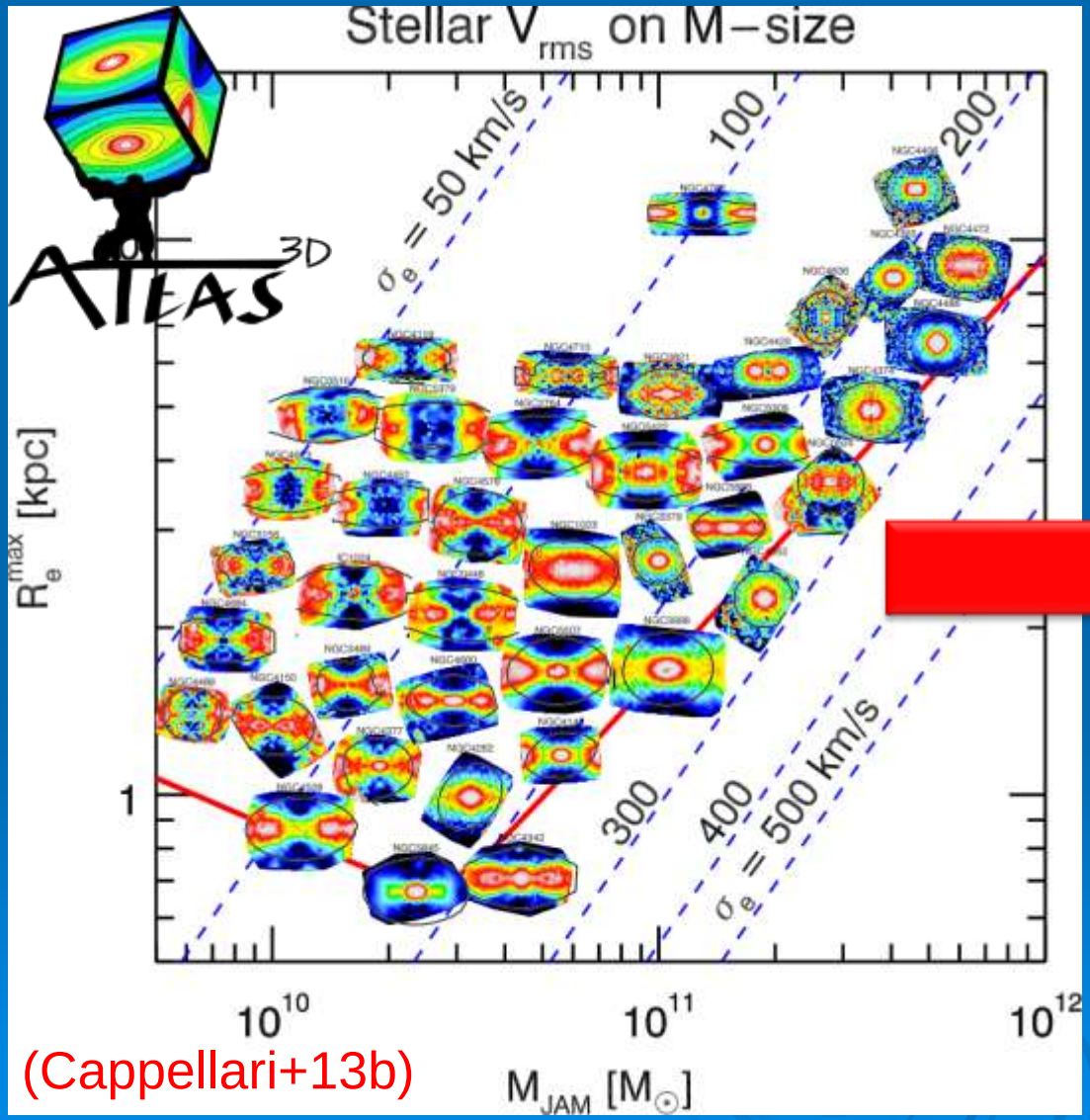
Padmanabhan+04

$$M_{\rm dyn} \equiv 5.5 \frac{R_{50}\,\sigma^2}{G}$$



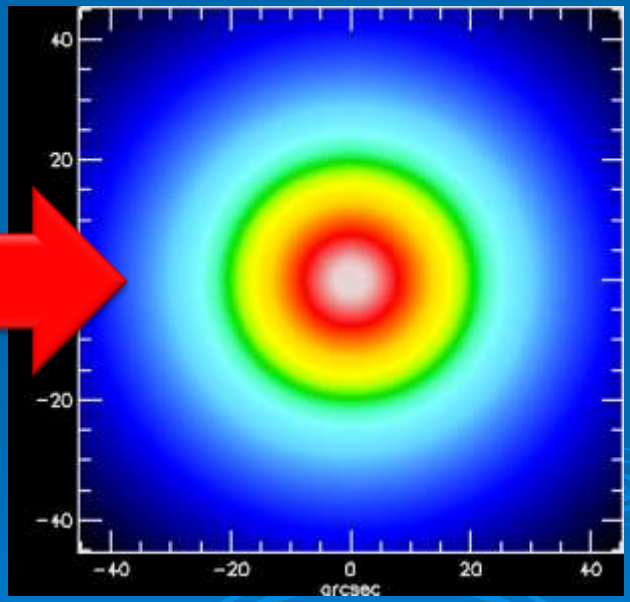
- $M_{\rm dyn}$ coeff. via spherical Hernquist + halo models
  - Assumes all galaxies spherical & homologous
  - Assumes anisotropy/rotation unimportant
- Interpreted as dark halo trend but can be
  - Massive ellipticals more concentrated
  - Massive ellipticals rotate less
  - Massive ellipticals have heavier IMF

But ETGs not spherical!



(Cappellari+13b)

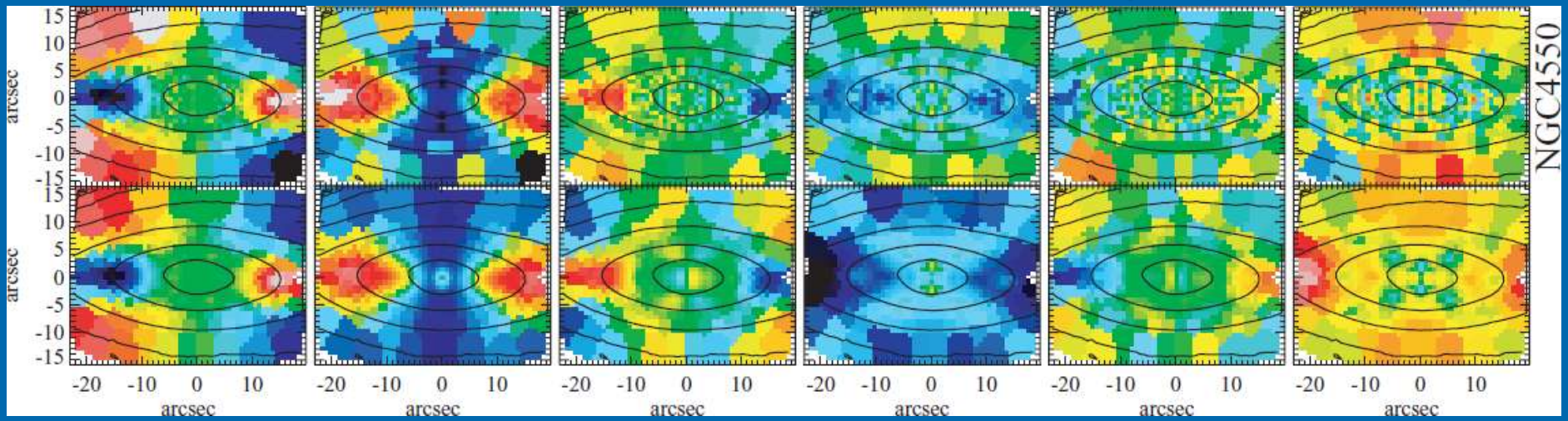
$$V_{rms} \equiv \sqrt{V^2 + \sigma^2}$$



Herquist model V_{rms}

Removing biases in $(M/L)_{\mathrm{dyn}}$

Schwarzschild's models (Cappellari+07)



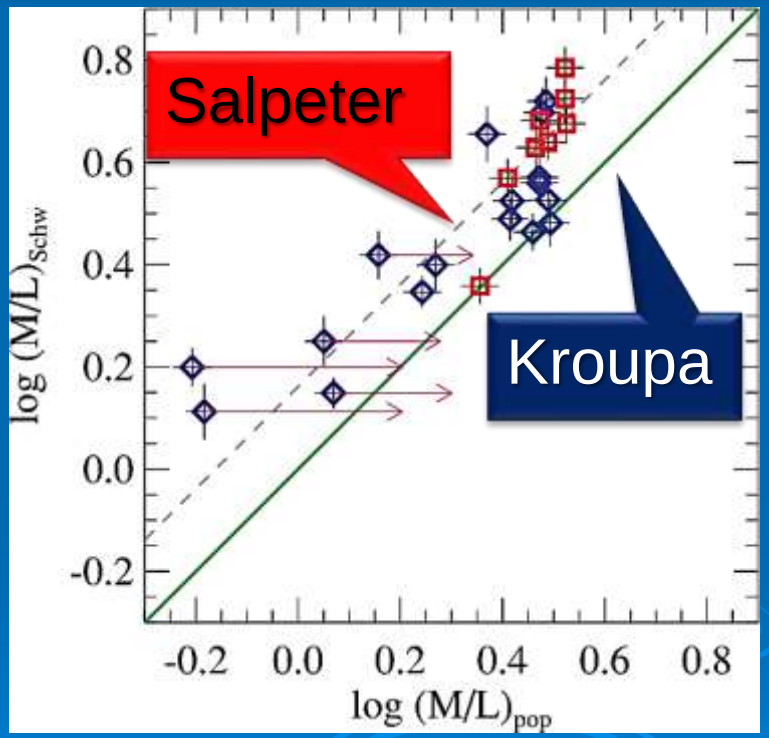
V σ h_3 h_4 h_5 h_6

- Light distribution matches individual galaxies
- Kinematics accurately fitted including anisotropy
- Strong constraint to dynamical models from IFU

Need for Kroupa IMF in ETGs

- Measure <u>total</u> $(M/L)_{\rm dyn}$
- Measure $(M/L)_{\rm pop}$ from spectra using SSP
- Total $(M/L)_{\rm dyn} \neq (M/L)_{\rm pop}$
- If IMF universal → Must be Kroupa-type (=Chabrier M/L)
- "Dark matter is needed to explain the differences in M/L (if the IMF is not varying)"

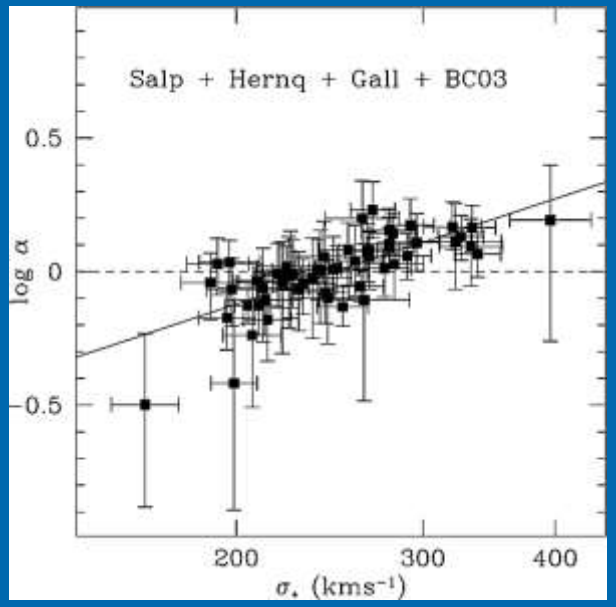
General dynamical models



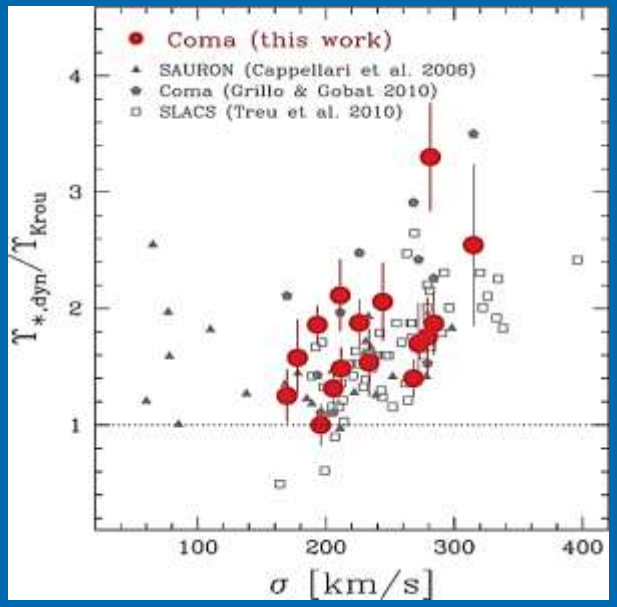
Cappellari+06

(also lensing study by Ferreras+08)

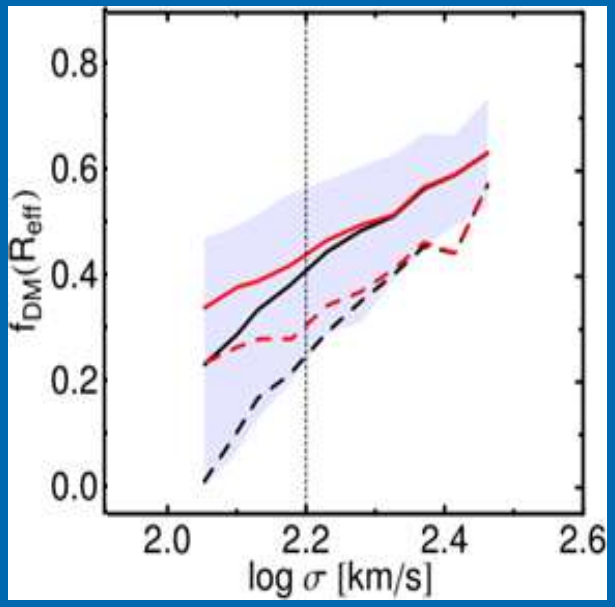
IMF or dark matter trend?



(Treu+10)



(Thomas+11)

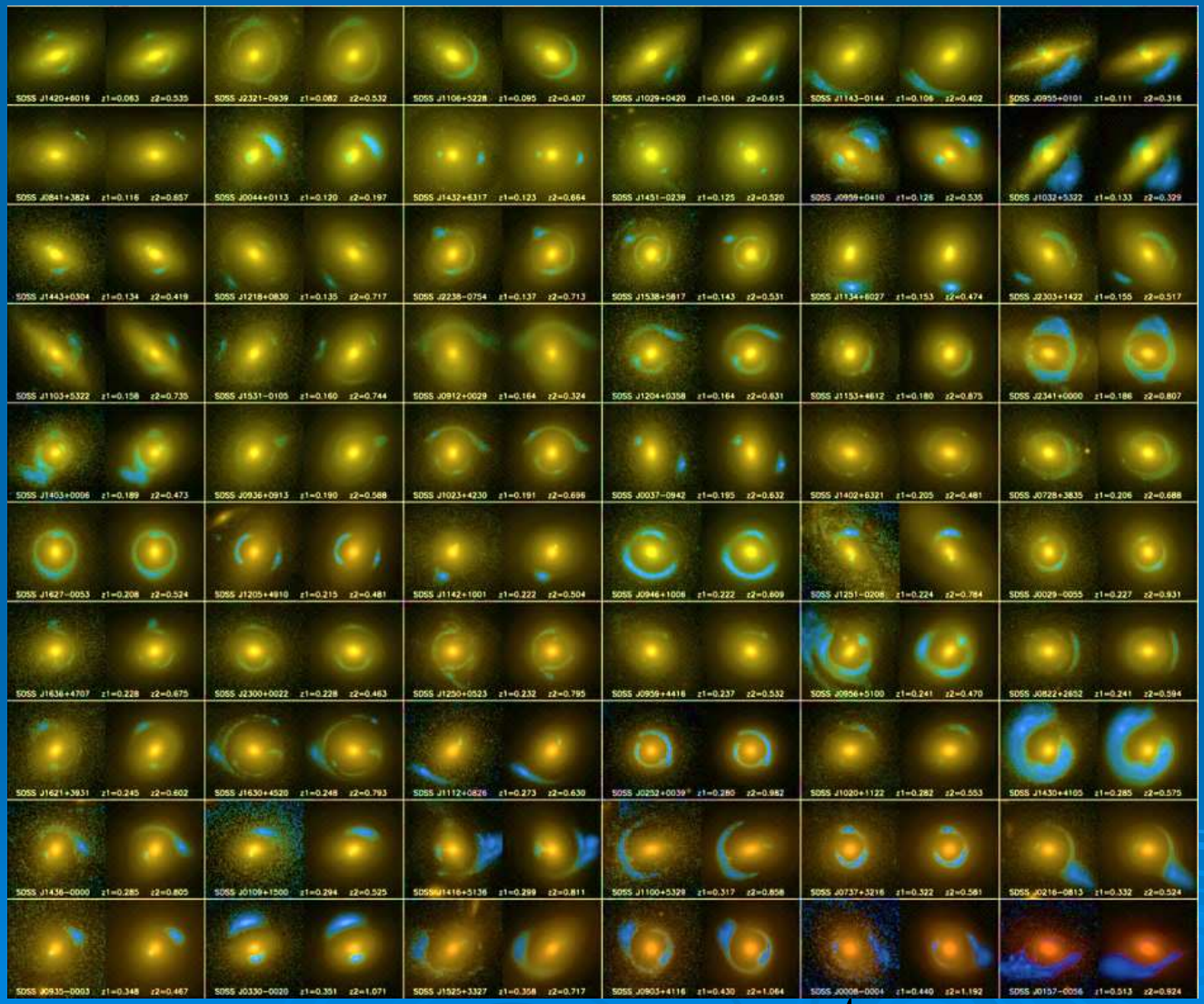


(Tortora+12)

(also Zaritsky+06; Tortora+09; Schulz+10; Graves+Faber10; Dutton+11; Barnabè+11; Deason+12)

- Agreement on mass-excess trend with mass or σ
- But none of the works can disentangle IMF and DM
- Key assumption: halo-slope is universal!

The Sloan Lens ACS Survey



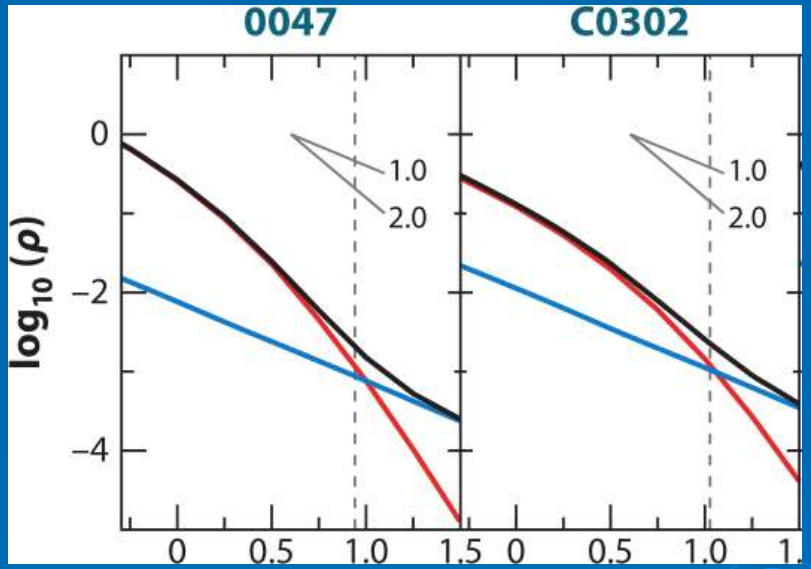
SLACS: Bolton+06 (figure from Koopmans+Czoske12)

IMF from lensing and dynamics

- Measured $M(R_{\mathrm{Ein}})$
- Measured σ
- Observed stellar profile
- Assume spherical shape
- Assume halo profile
- Fixed anisotropy

→ σ unique function of total mass profile

→ $(M/L)_{\mathrm{stars}}$



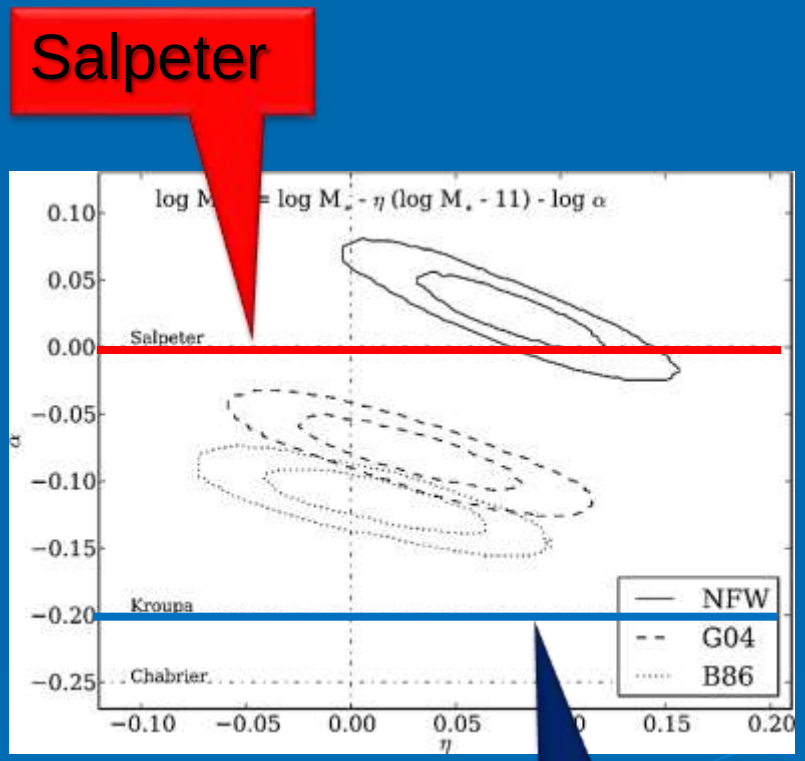
Treu+Koopmans-04

Salpeter IMF in massive ETGs

- Assume 53 homologous Hernquist galaxies
- Assume halo profile: either NFW or contracted
- Assume same halo mass but free normalization
- Assume same IMF but free normalization

→ Heavy IMF still needed

- No IMF trend with mass



Auger+10

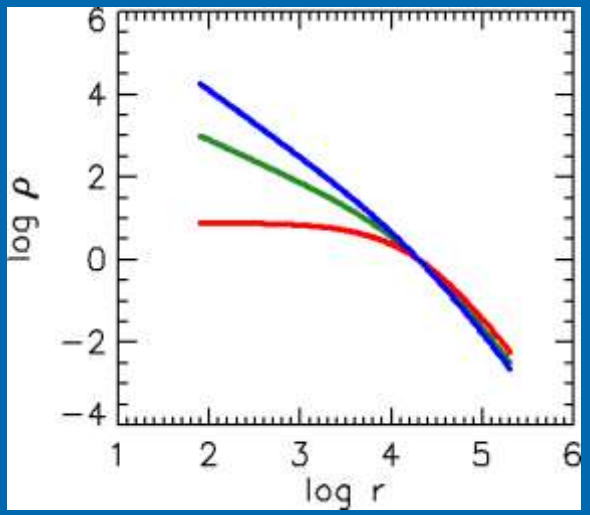
(also two galaxies by Spiniello+11 and Sonnenfeld+12)

Volume-limited sample of 260 ETGs

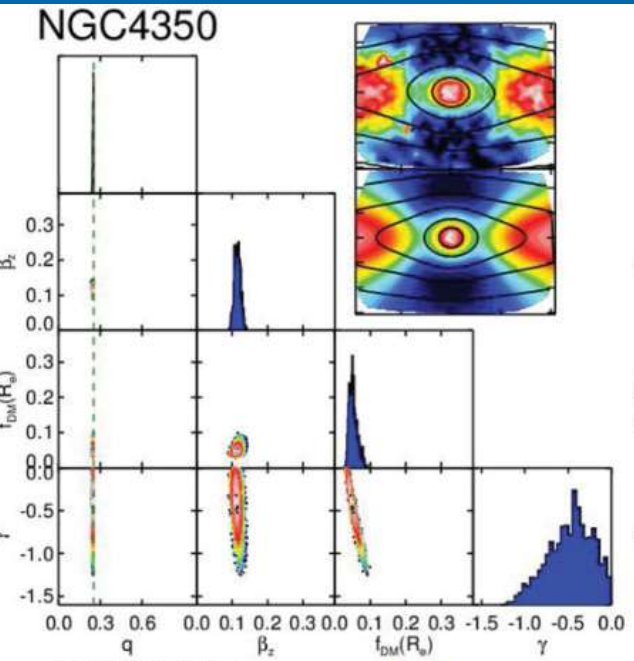
purl.org/atlas3d

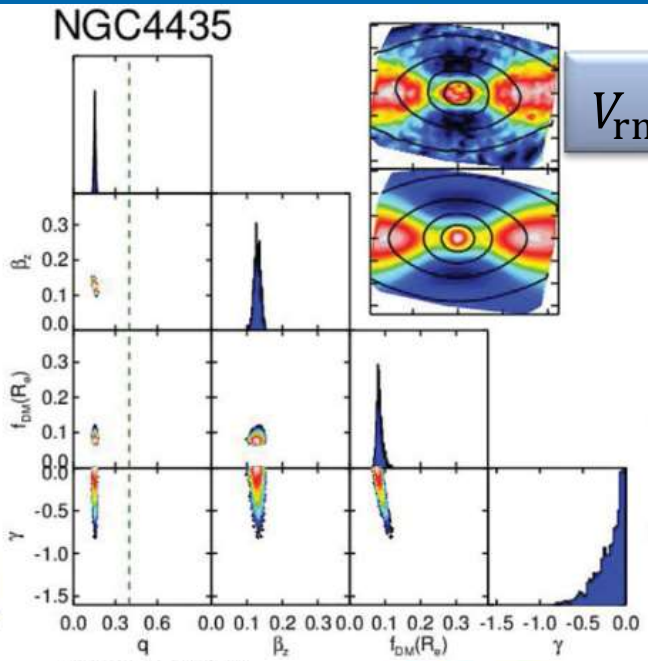
Sample (Cappellari+11a: P1) Stellar velocities (Krajnovic+11: P2)

Allowing for trends in halo slope

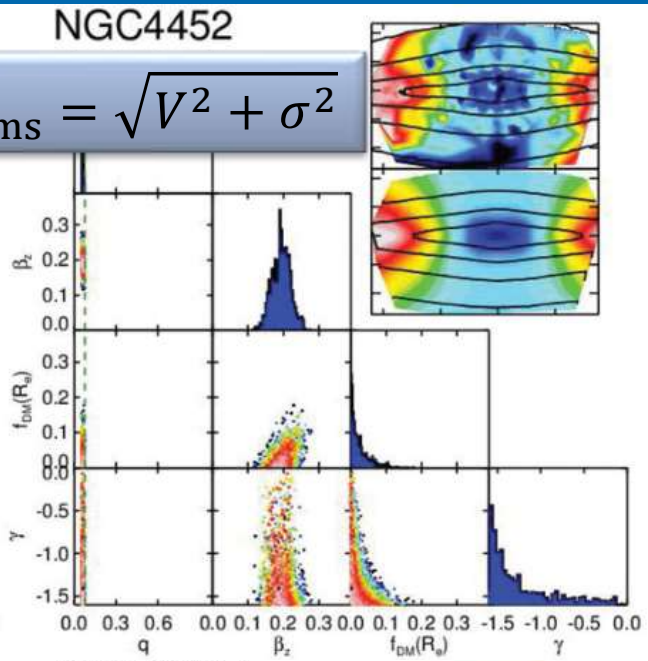


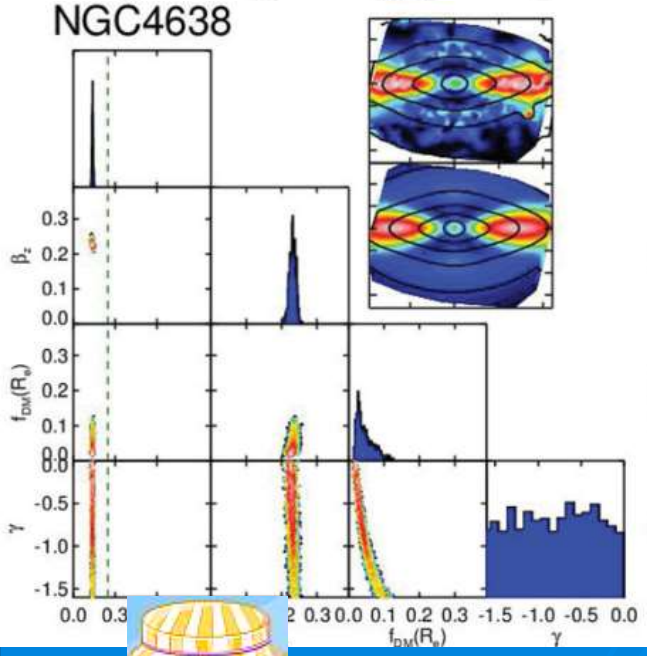
- Generalized NFW halo profile
  - $\rho_{DM}(r) = \rho_s \left(\frac{r}{r_s}\right)^{\gamma} \left(\frac{1}{2} + \frac{1}{2}\frac{r}{r_s}\right)^{-\gamma-3}$
- Reproduce individual galaxy images
- Axisymmetric models, free inclination
- Anisotropy free but <u>assume</u> constant per galaxy
- Halo slope free but <u>assume</u> $-1.6 < \gamma < 0$
- Sample $(i, \beta_z, \frac{M}{L}, f_{DM}, \gamma)$ via MCMC
- *non-informative* (constant) priors

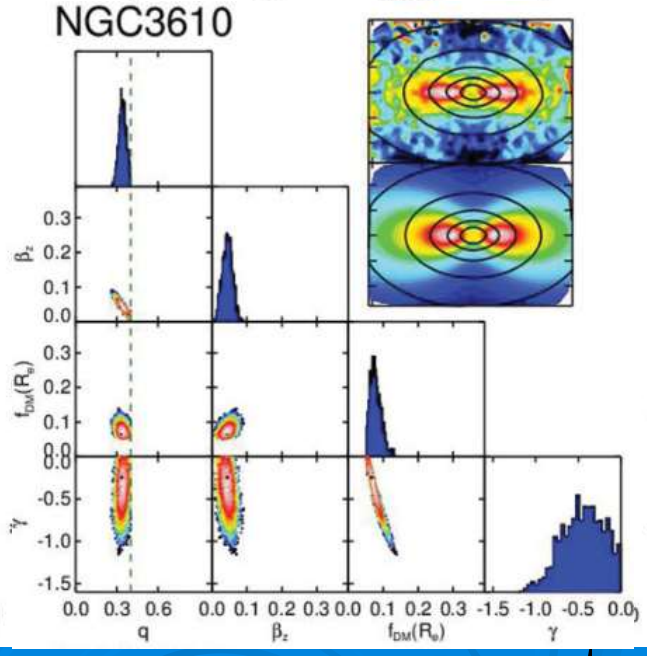


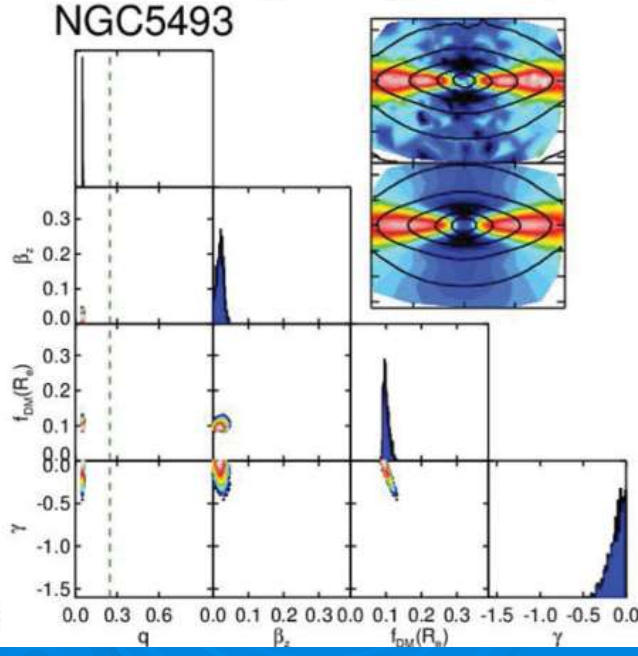


$$V_{\rm rms} = \sqrt{V^2 + \sigma^2}$$



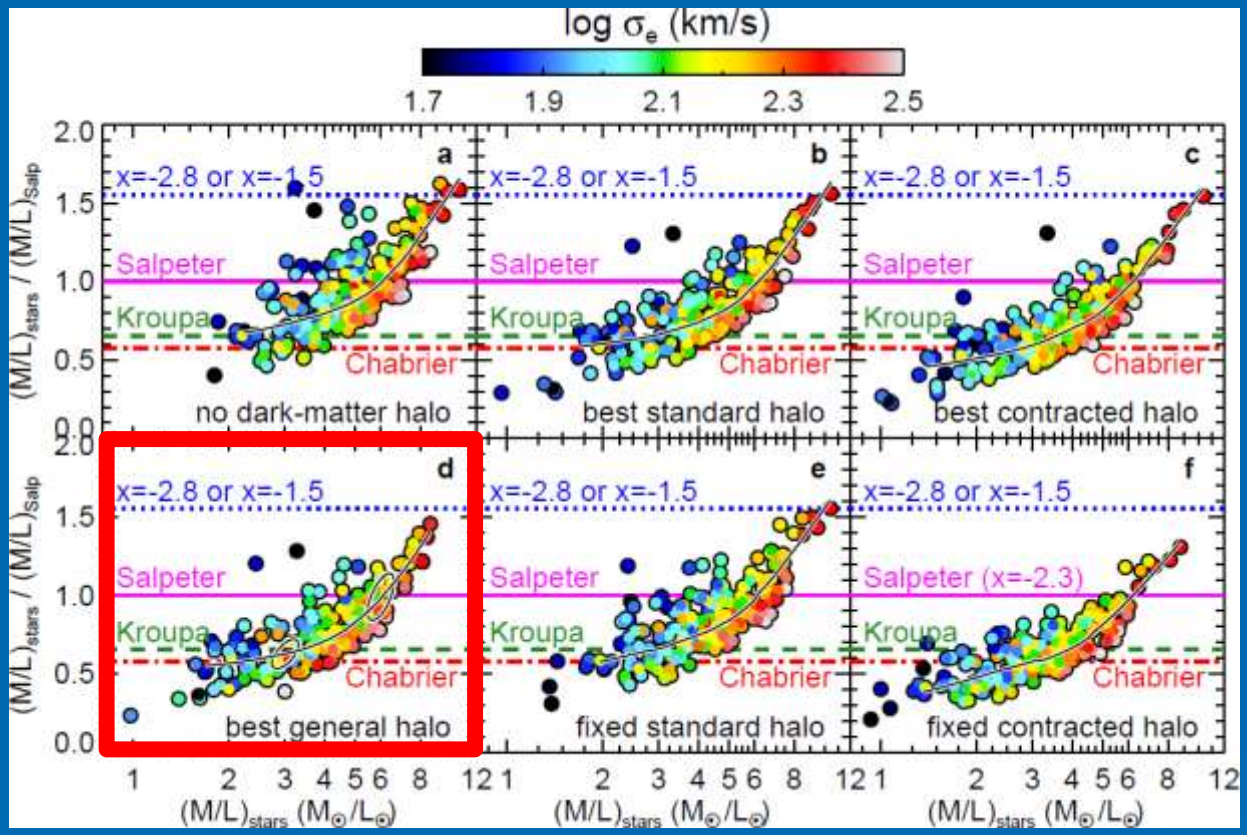






JAM models with MCMC (Cappellari+13a: P15)

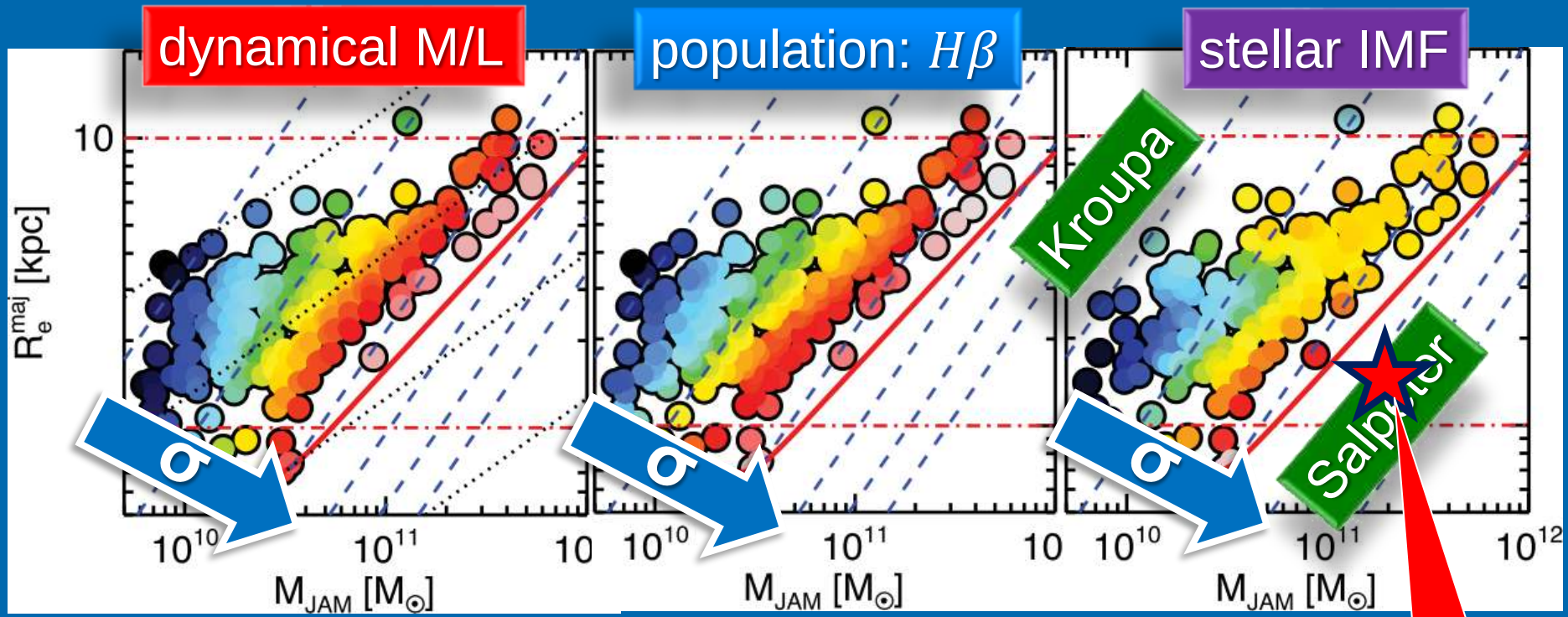
Systematic IMF variation in ETGs



(Cappellari+12, Nature)

- Most general halo still requires IMF variation
- But IMF variation consistent with standard ΛCDM halos
  (as Treu+10; Dutton+13; Tortora+13)
- Salpeter IMF also consistent with lensing (Auger+10)

IMF trends on mass-size

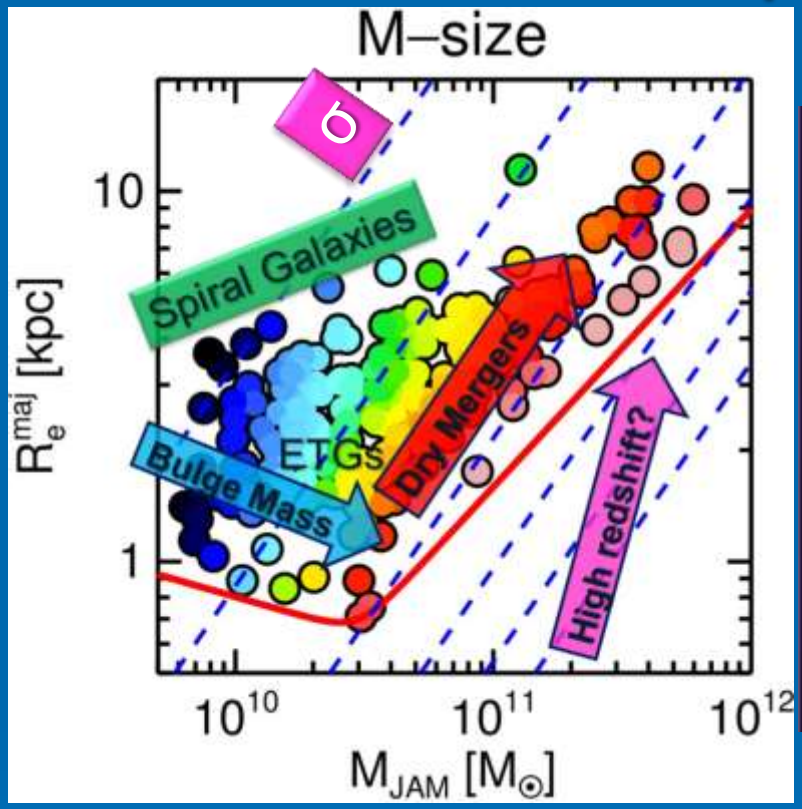


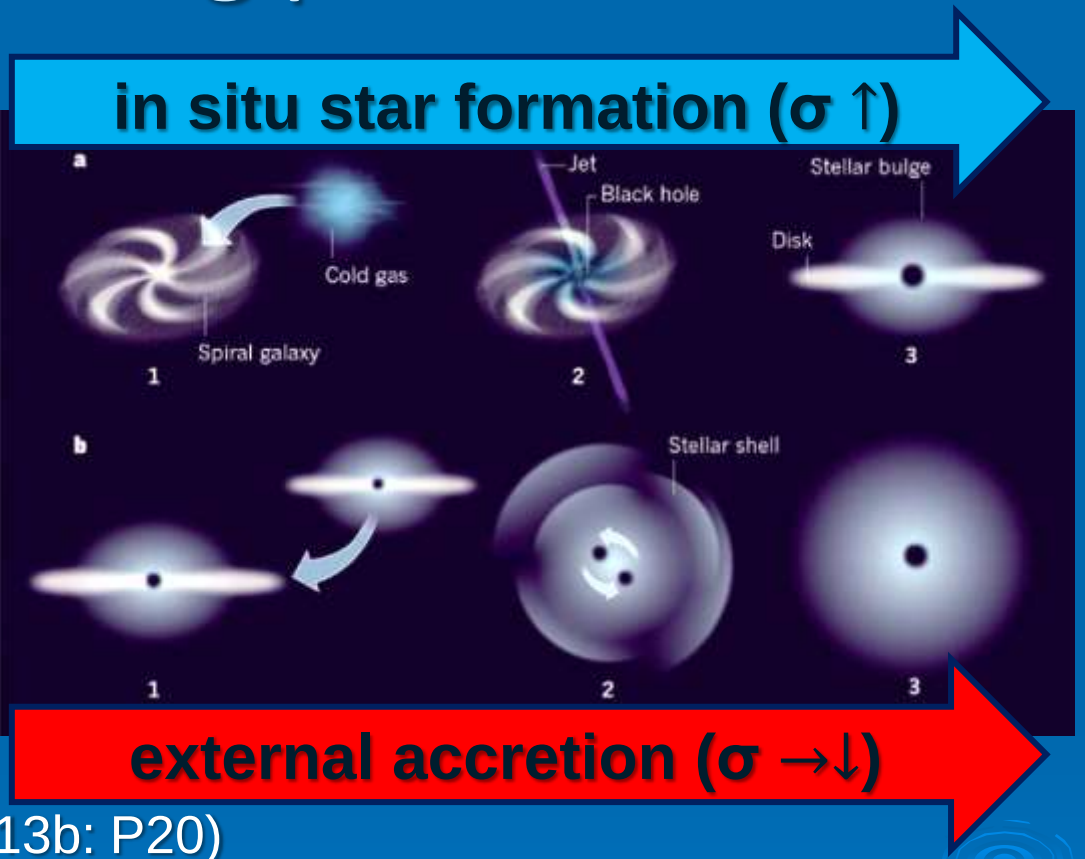
(Cappellari+13b: P20)

Läsker+13

- IMF traces dynamical M/L and stellar population
- Variation along lines of constant velocity dispersion σ
- At fixed mass σ traces bulge fraction

Two competing processes





(Cappellari+13b: P20)

- In situ star formation: accretion and bulge growth (e.g. Dekel+09)
- External accretion: dry mergers (e.g. Naab+09, Bezanson+09)
- Heavy IMF associated to bulge/spheroid formation
- IMF unchanged during dry mergers

Can IMF still be universal?

- No for non-trivial but predicted reasons
  - Variation in halo contraction/expansion
  - Variation of homology (shape, profile, kinematics)
  - Variation of $f_{DM}(R_e)$ with mass
  - Multiple stellar population or gradients
- Yes for trivial but dramatic reasons
  - Dark matter accurately follows light (unlike models)
  - Fundamental problem with all population models
- IMF spectral signature → abundance conspiracy