Stellar and Dark Masses: IMF gradients in the era of big telescopes

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and
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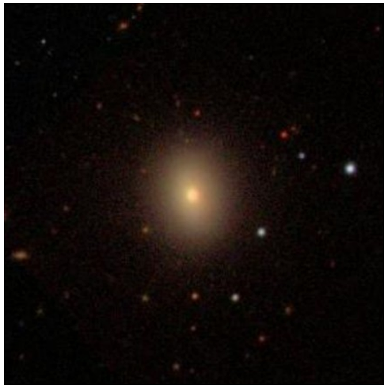
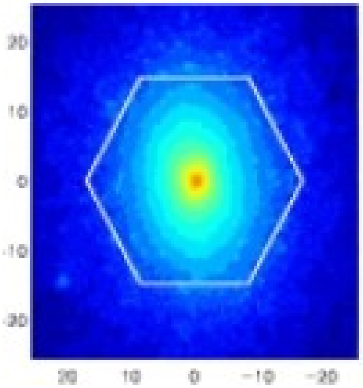
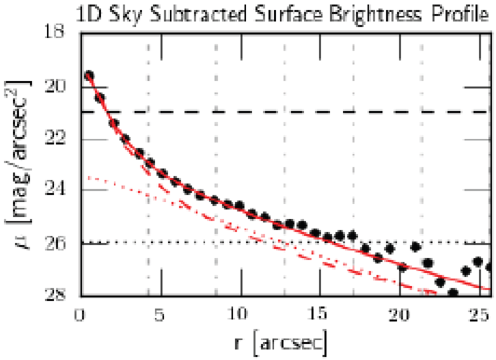
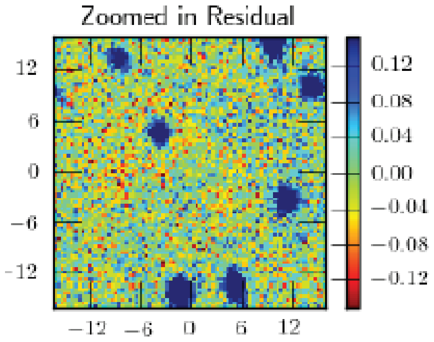
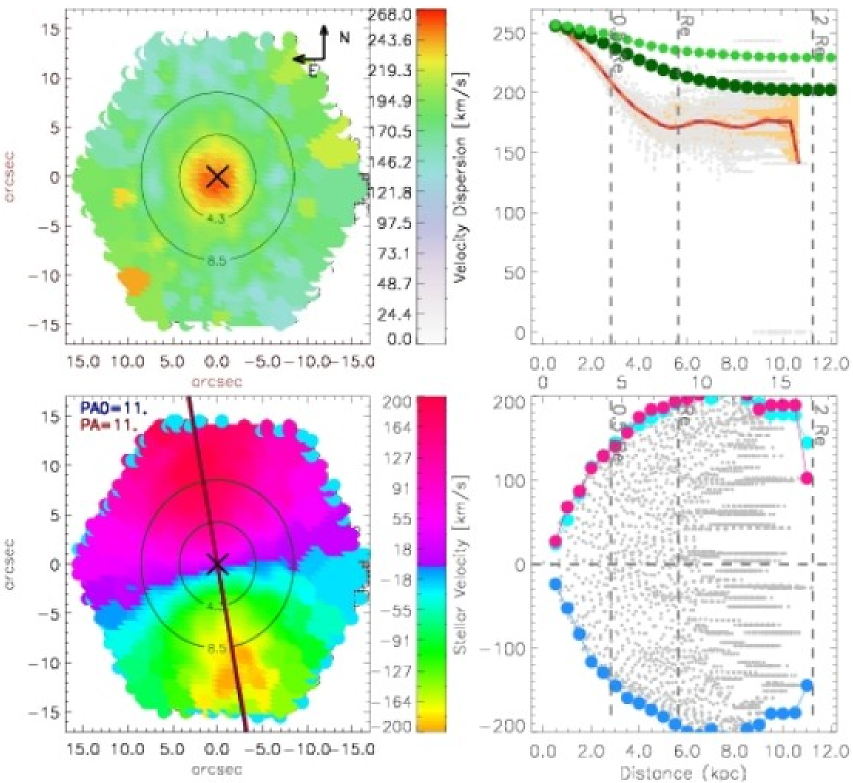










A galaxy is made of luminous + dark matter;

$$M_{tot}(<r) = M_{*+gas}(<r) + M_{DM}(<r)$$

Dark matter dominates at large r

- Estimate M_* as $(M_*/L) \times L$
  - must measure L well
  - typically determine M_*/L in a separate step
- Lensing from outer parts gives M_{tot} at large r.

– Check self-consistency using M_*^{dyn} from Jeans equation with observed L(<r) and σ(r), and with M_*^{dyn}/L determined by matching observed σ(r) at small r (where DM should matter less)

Outline

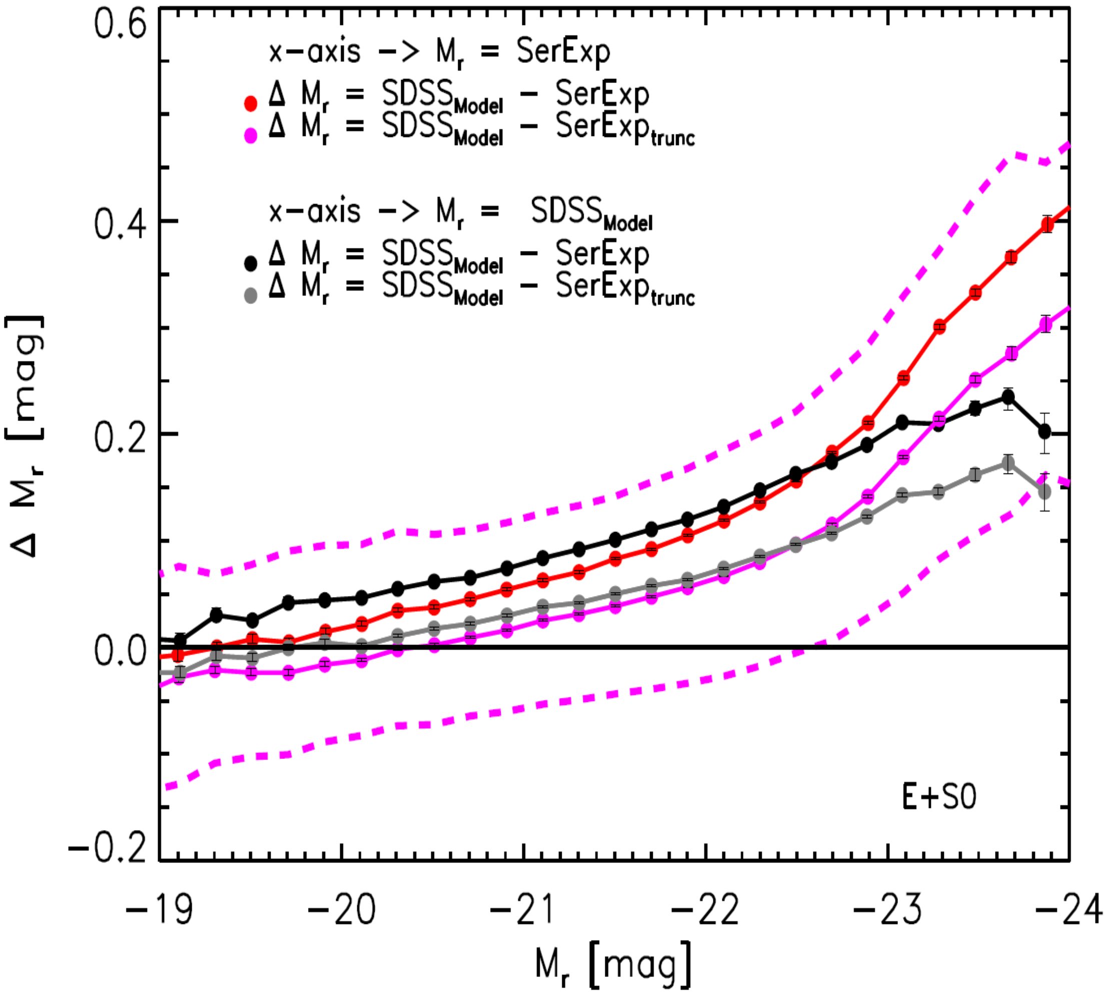
- Better photometry of SDSS galaxies → L
- IMF variation across population → M_*/L
- MaNGA (SDSS IV)
- IMF gradients → implications (e.g. M_*^{dyn}, f_{DM})

  - The need for ELT like telescopes

- Selection bias in SMBH samples having dynamically measured masses

  - The need for ELT like telescopes

PyMorph:
Better photometry of SDSS galaxies



- Dependence on sky
- Dependence on fitted model/truncation
- Dependence on ICL

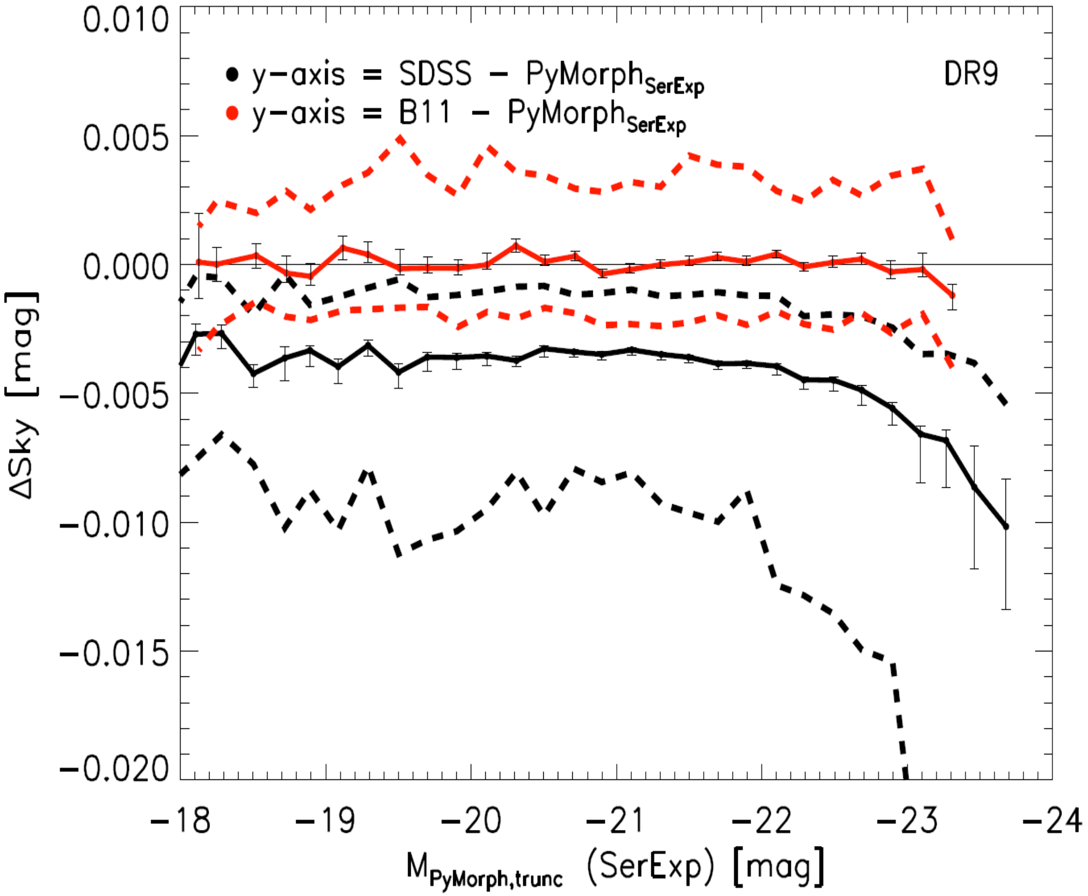
Bernardi et al. 2013 -- 2017

Meert et al. 2015a,b; 2016

UPenn SDSS Photom. Catalog

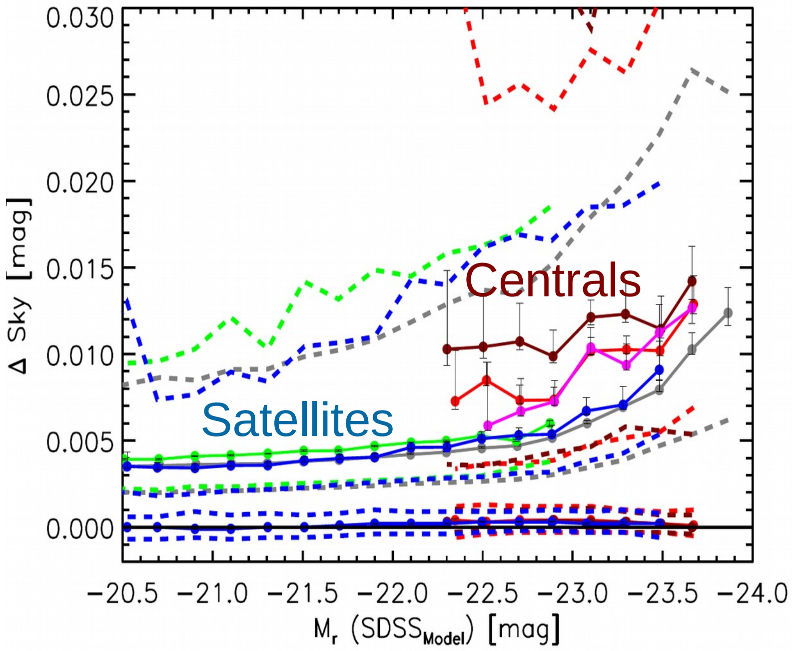
Alan Meert

Well known that SDSS sky is biased ….
…. It is more biased for Centrals than for Satellites



PyMorph sky in excellent agreement with Blanton+2011

Bernardi et al. 2017b

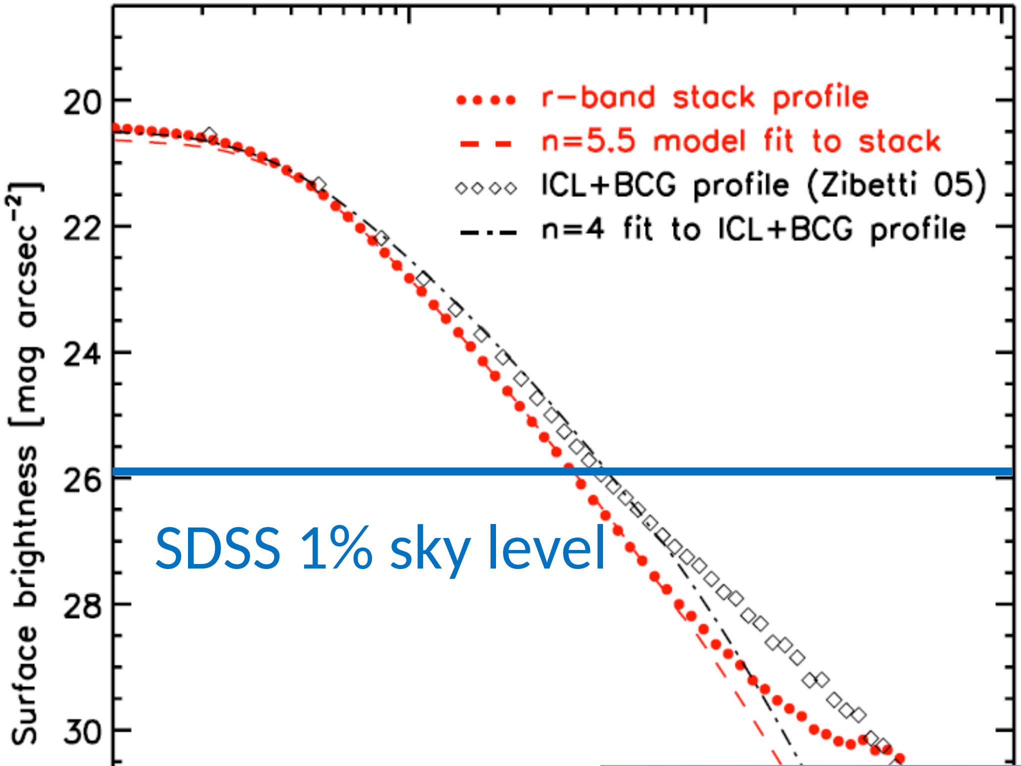


Fischer et al. 2017

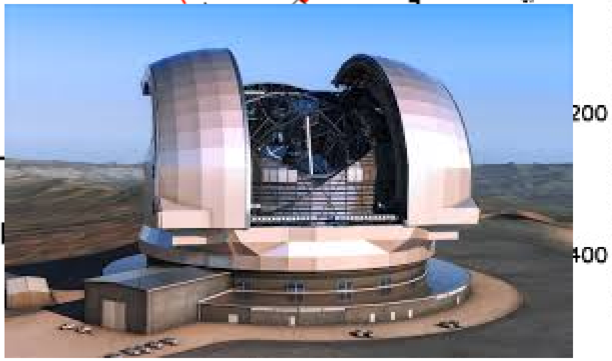
Bias is more than semantics …..

SDSS 1% of sky level is ~ 26 mag/arcsec^2

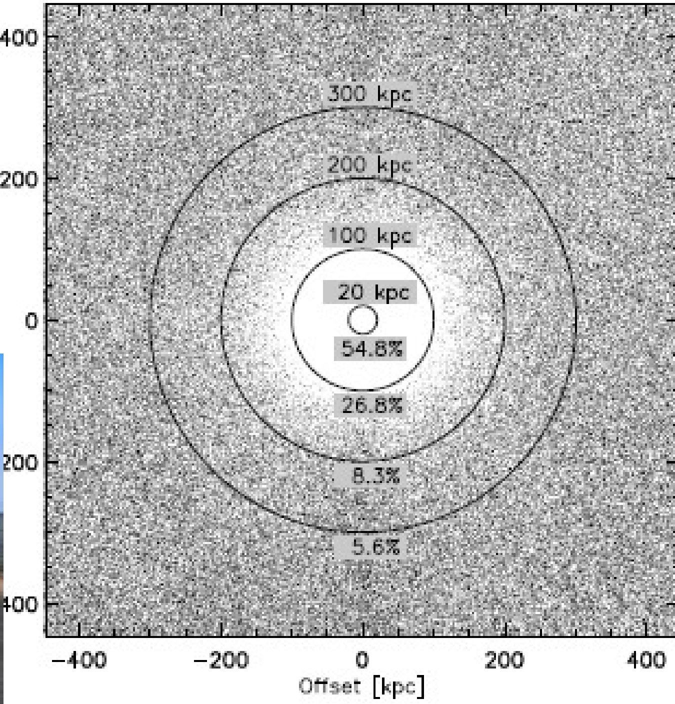
Individual SDSS galaxy profiles CANNOT be dominated by ICL

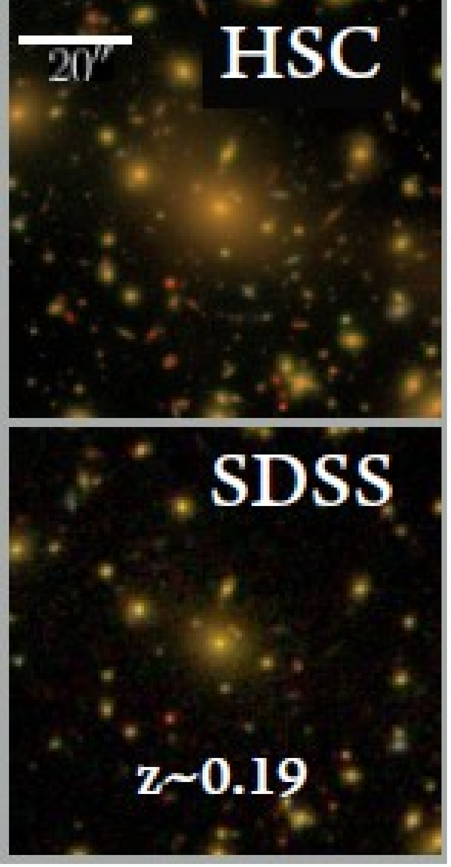


Tal & van Dokkum 2011



Stacking analysis of LRGs and BCGs





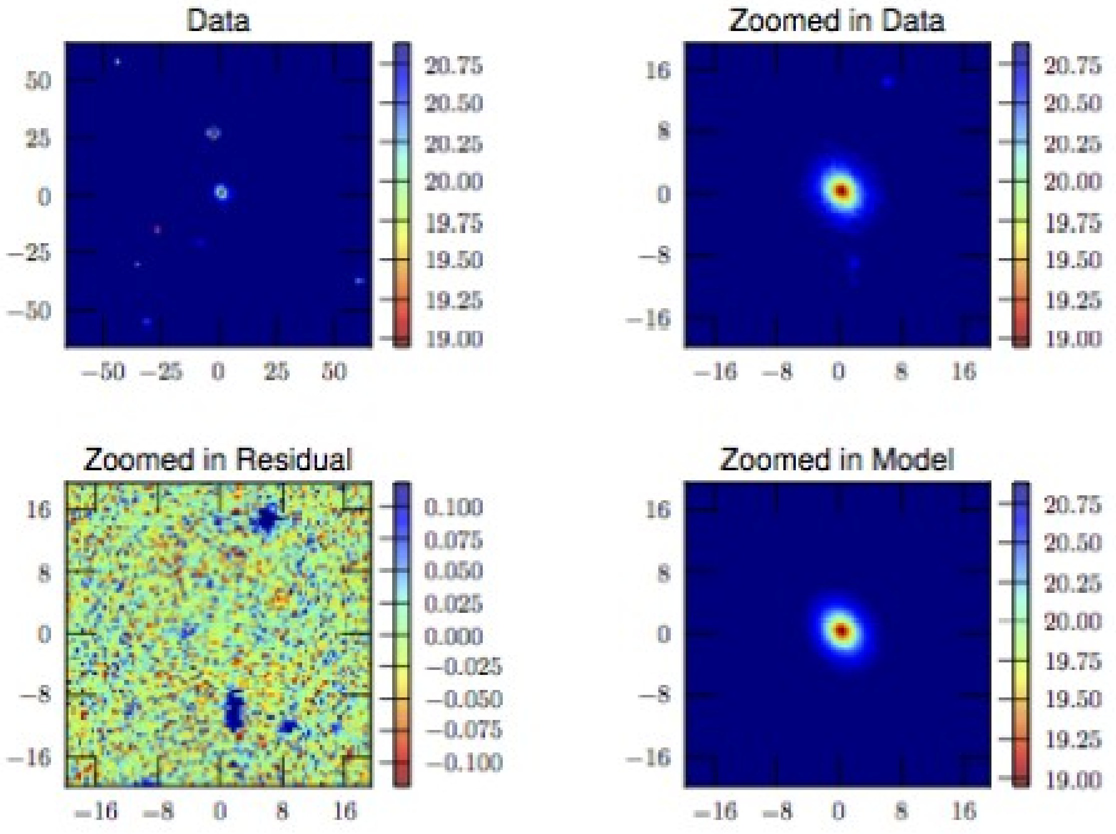
M_{serexp} = -23.649
m_{serexp} = 15.919
B/T_{serexp} = 0.71
n_{serexp} = 4.60
$r_{hl,cir,serexp}$ = 4.29
$r_{bulge,serexp}$ = 3.60
$r_{disk,serexp}$ = 4.42
$pa_{bulge,serexp}$ = 35.58
$pa_{disk,serexp}$ = -0.67
$ba_{bulge,serexp}$ = 0.69
$ba_{disk,serexp}$ = 0.89

FLAGS

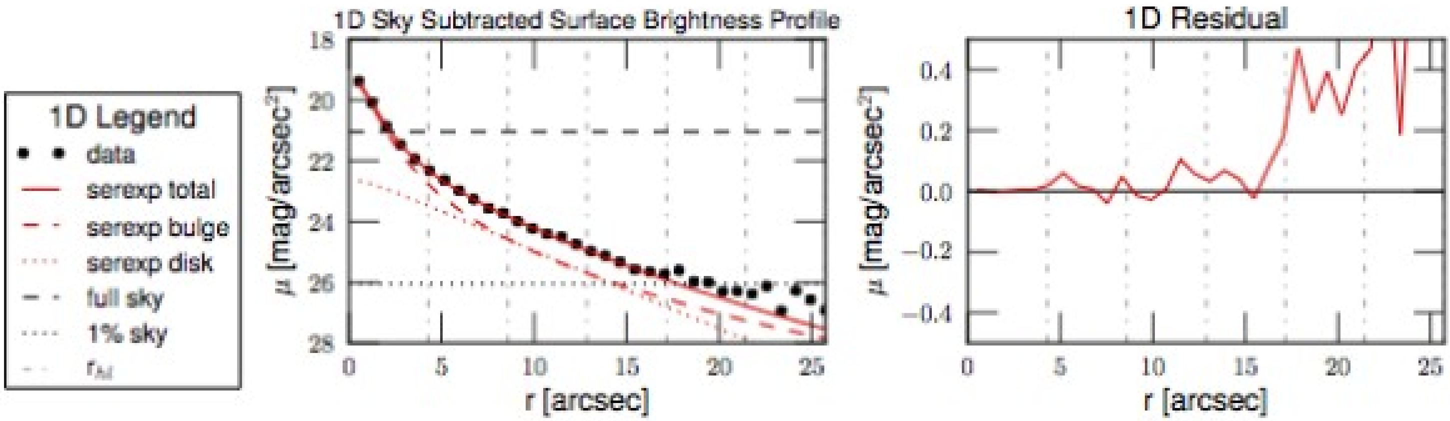
Good Total Magnitudes and Sizes

Two-Component Galaxies

No Flags



Z ~ 0.19
M_r ~ -23.6
R_{hl} ~ 13 kpc
$n_{Ser(Bulge)}$ ~ 4.5
n_{Ser} ~ 6.5

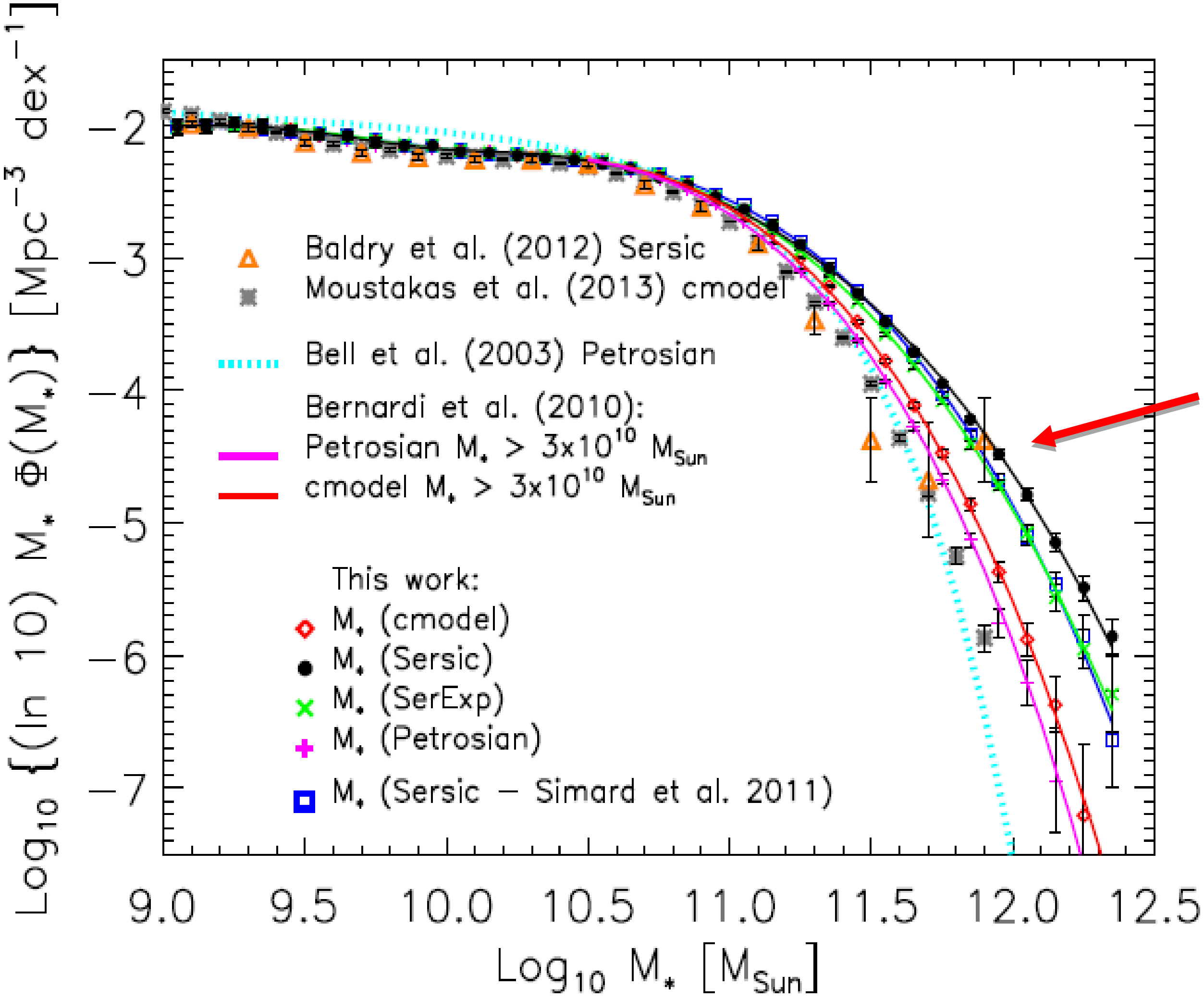


Bernardi et al. 2017b

M_*^{SP} Function

$M_*^{SP} = L \times (M_*^{SP}/L)$

Dependence on L (same M_*^{SP}/L)



At large M_*^{SP} choice of L matters greatly

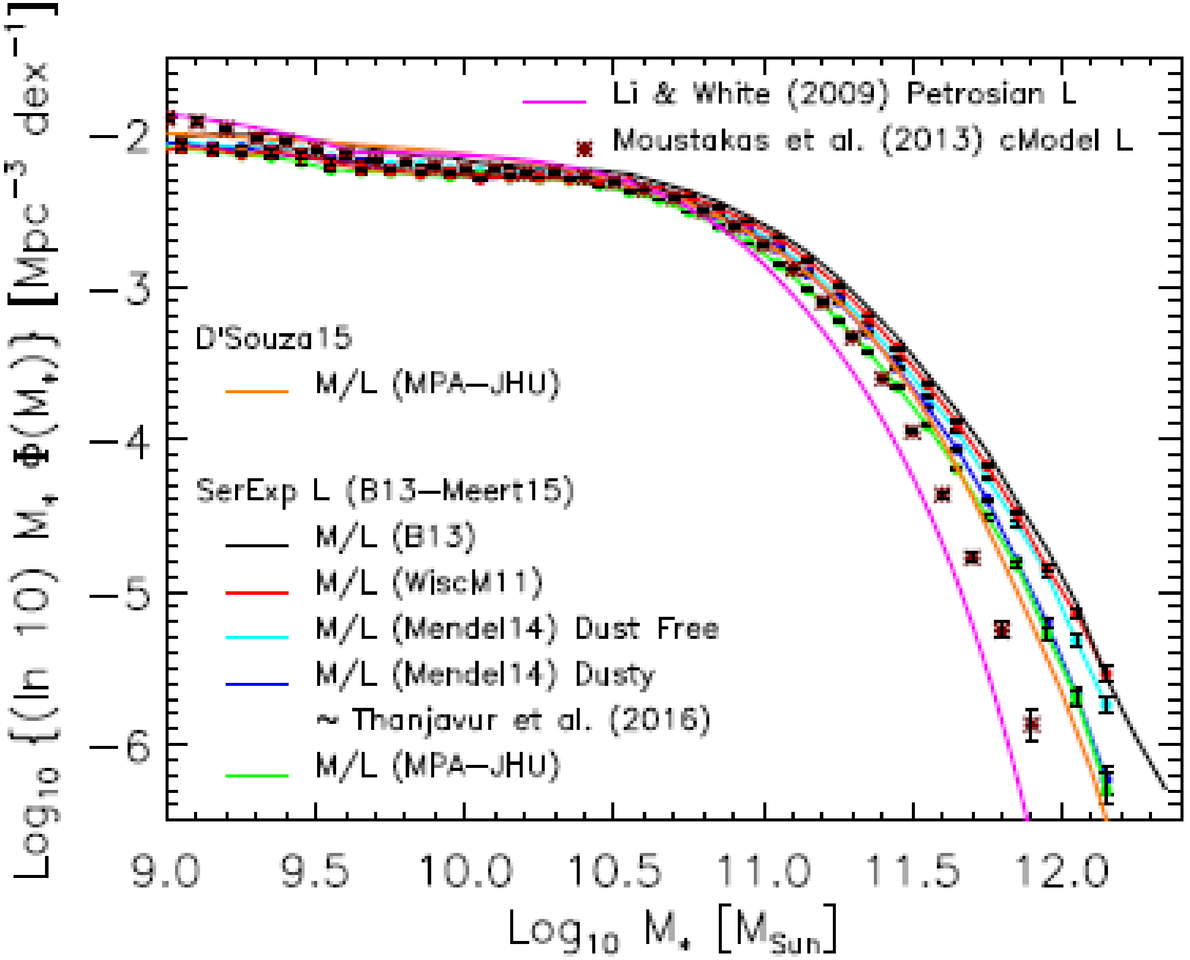
Bernardi et al. 2013

M_*^{SP} Function

$M_*^{SP} = L \times (M_*^{SP}/L)$

Dependence on M_*^{SP}/L (same L)

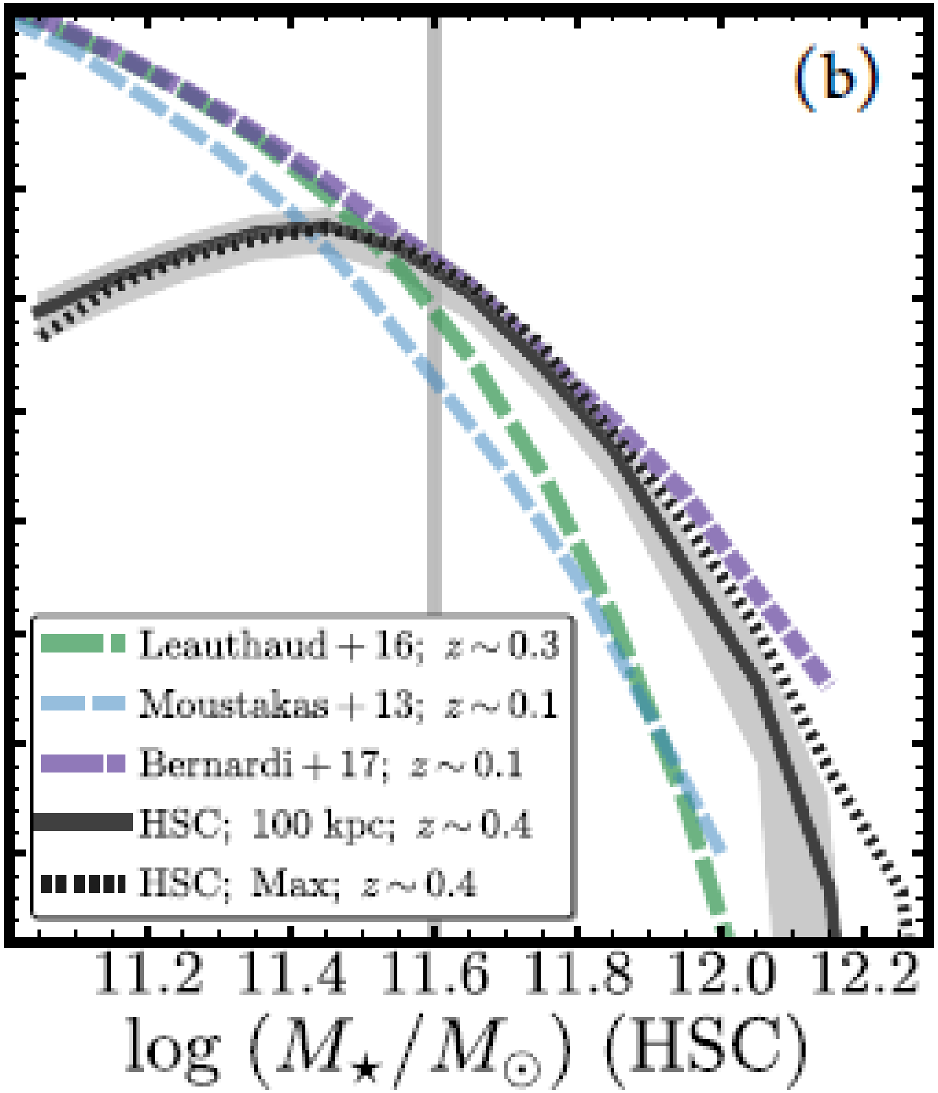
… but also same IMF

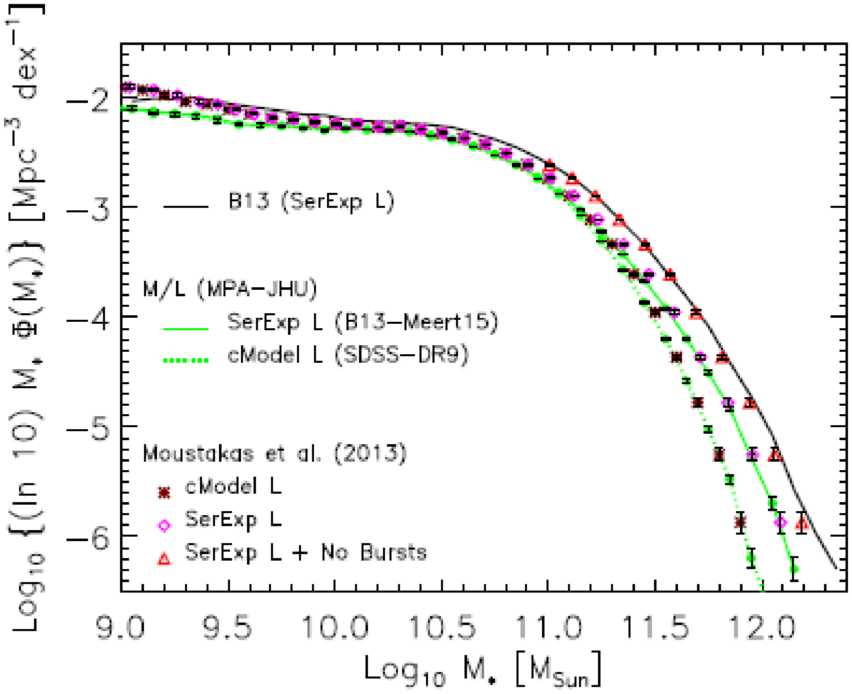


- SF History (burst)
- Dusty / no-dusty
- IMF

Bernardi et al. 2017a

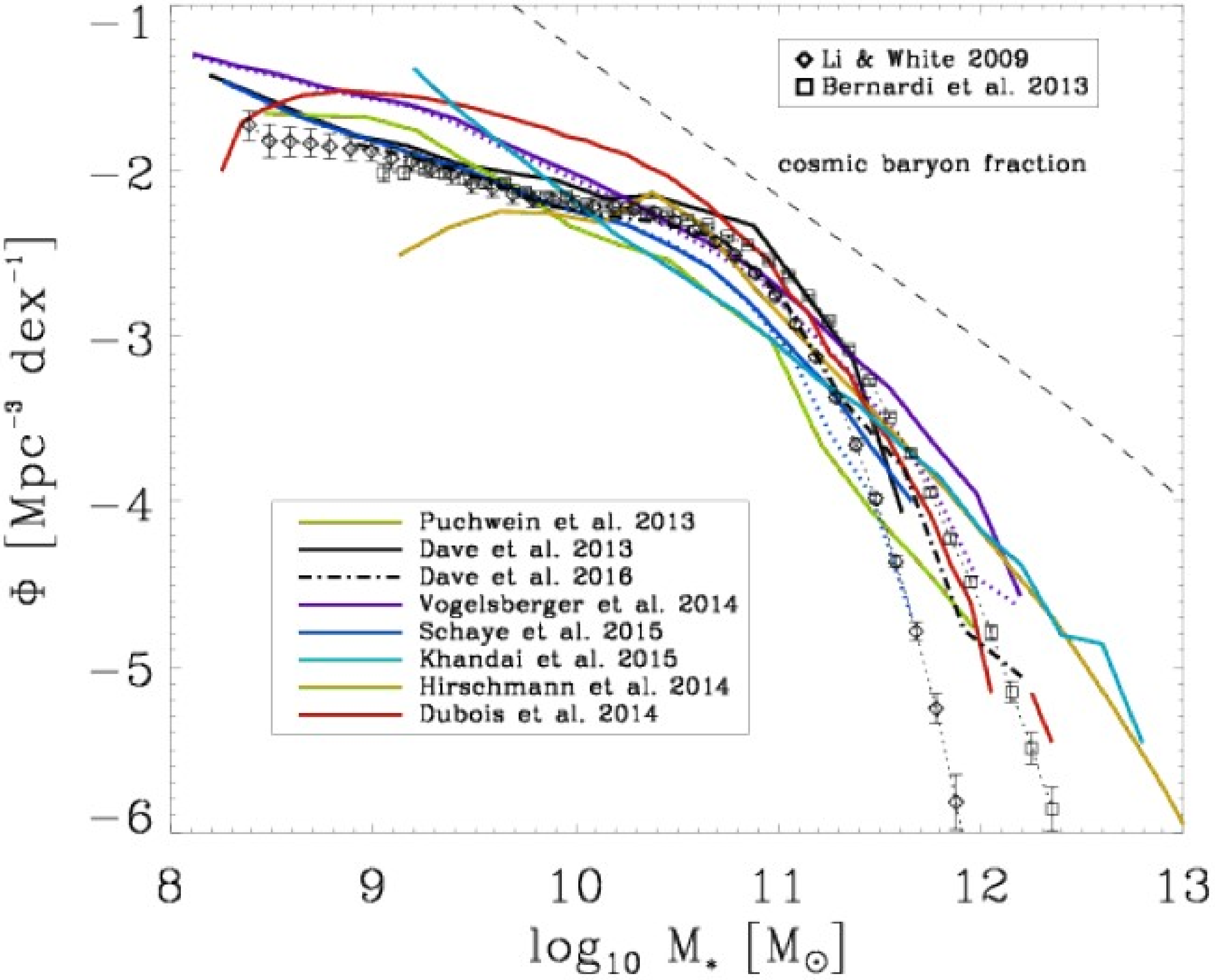
Confirmed by other groups





Bernardi et al. 2017a

Huang et al. 2017
(see also Kravtsov et al. 2014,
Thanjavur et al. 2016, D'Souza et al. 2015)



Required feedback at large M_* is reduced, in better agreement with models

Naab & Ostriker 2017 (see also Cattaneo et al. 2017)

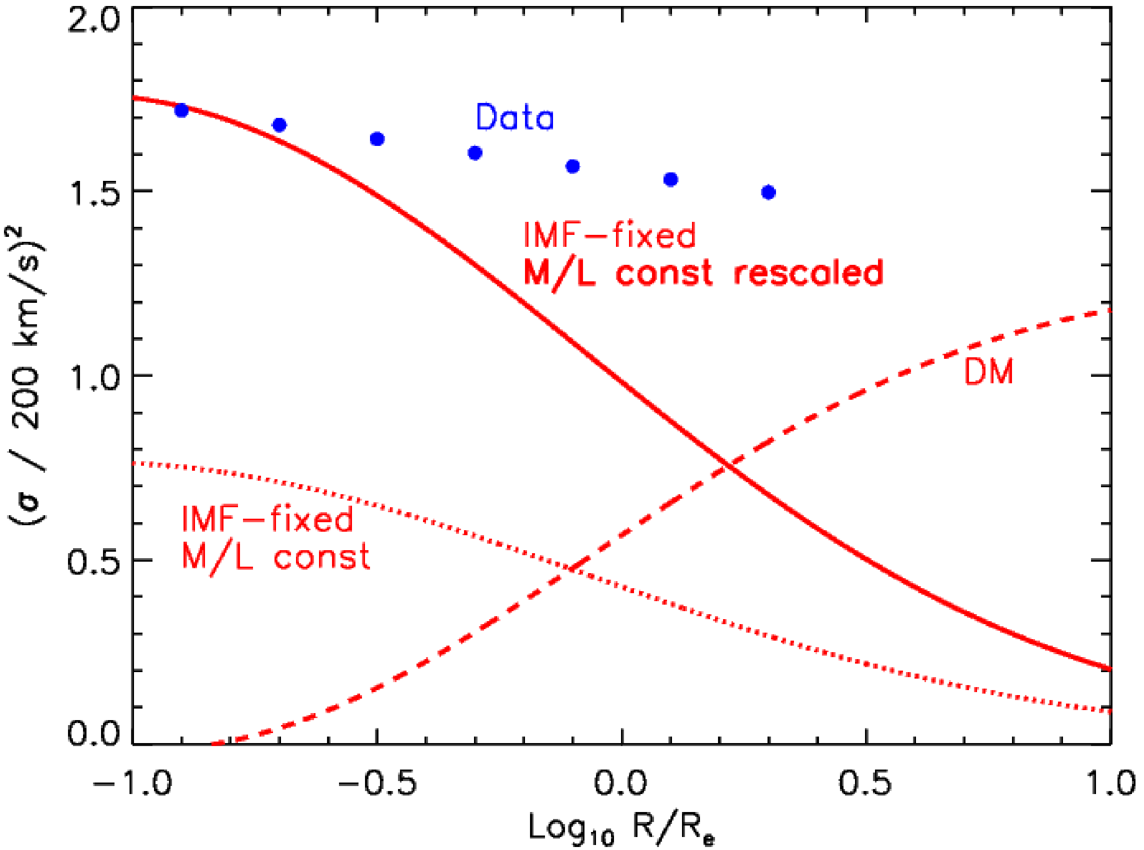
Consistency check using M_*^{dyn}

Crudely, M_*^{dyn} determined as follows:

$$\sigma^2(r) \sim G\, M_{tot}(<r)/r \sim G\, M_*^{dyn}(<r)/r \sim G\, (M_*^{dyn}/L)\, L(<r)/r$$

Stars dominate at small r + M*/L constant

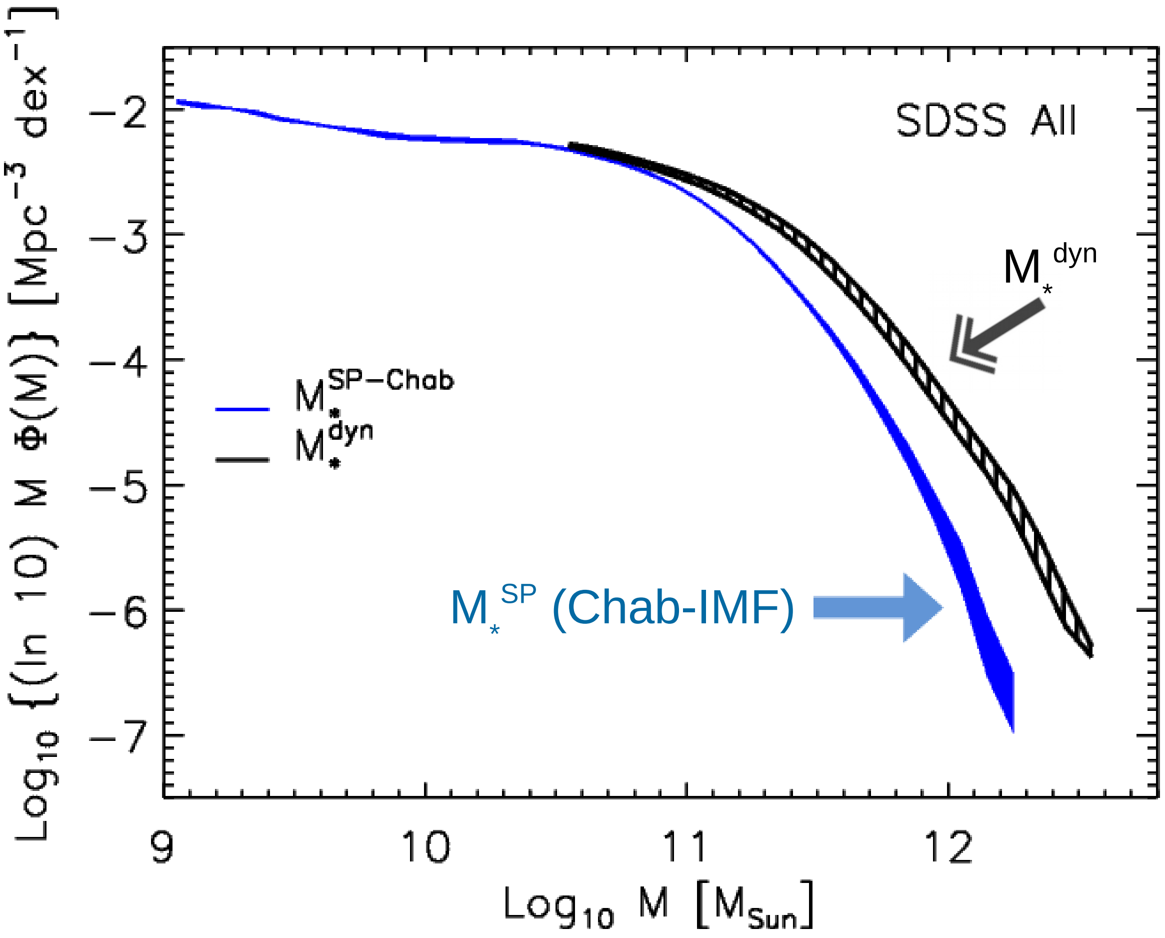
Matching σ determines M_*^{dyn}/L independent of stellar pop model!



In practice, allow for velocity anisotropy and dark matter, and for exactly how σ is measured (e.g. Sauron, ATLAS^{3D})

Bernardi et al. (2018a)

M_*^{SP}(Chab-IMF) ≠ M_*^{dyn}

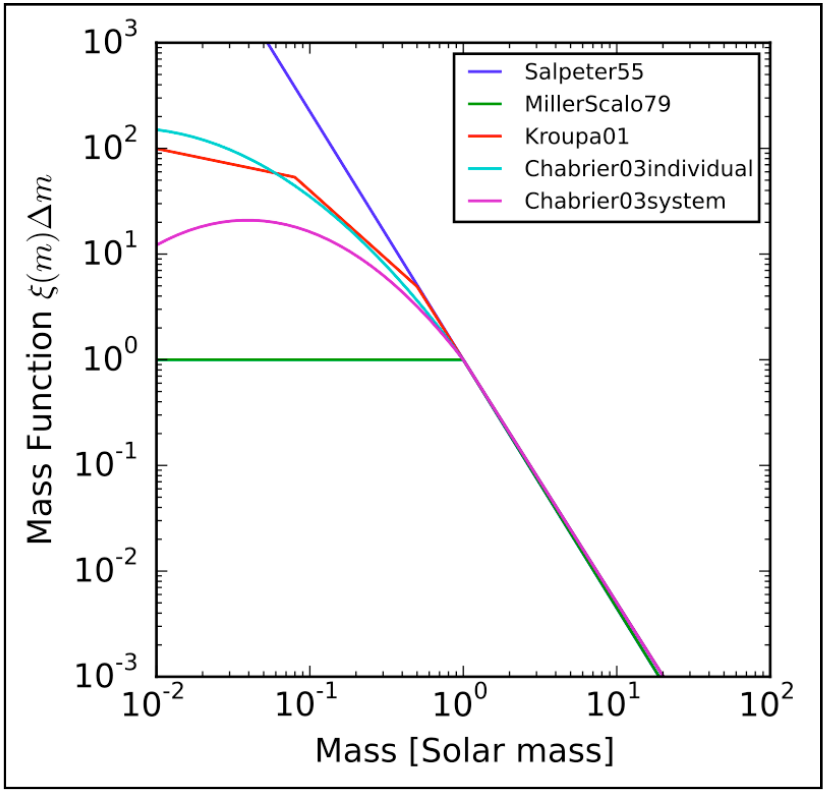


Bernardi et al. (2018a)

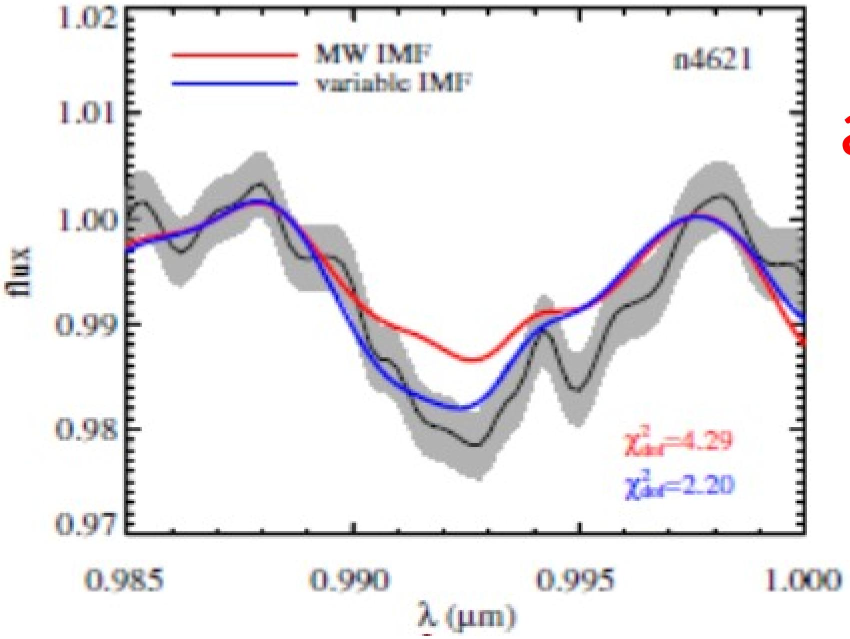
What is the IMF?

Initial Mass Function: initial distribution of masses for a population of stars. Fundamental for determining total mass of galaxies.

For convenience, assume same for all galaxies, and constant within a galaxy

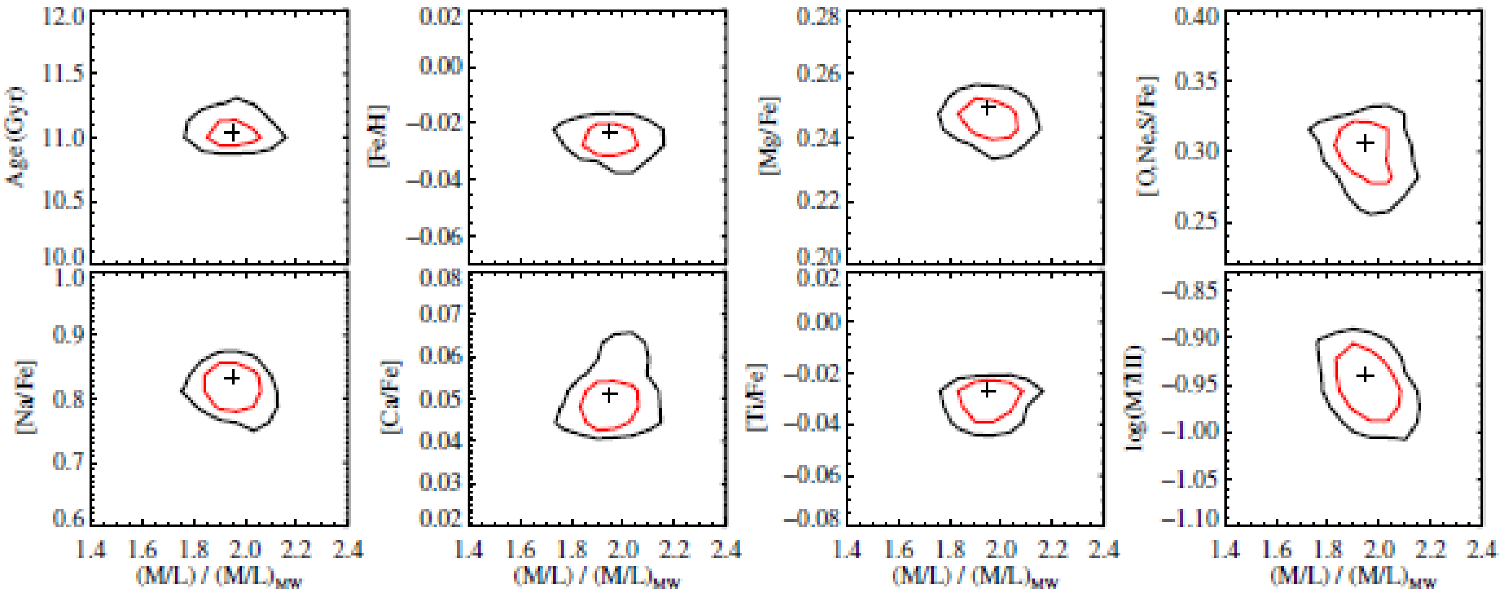


Evidence for IMF variations across the galaxy population

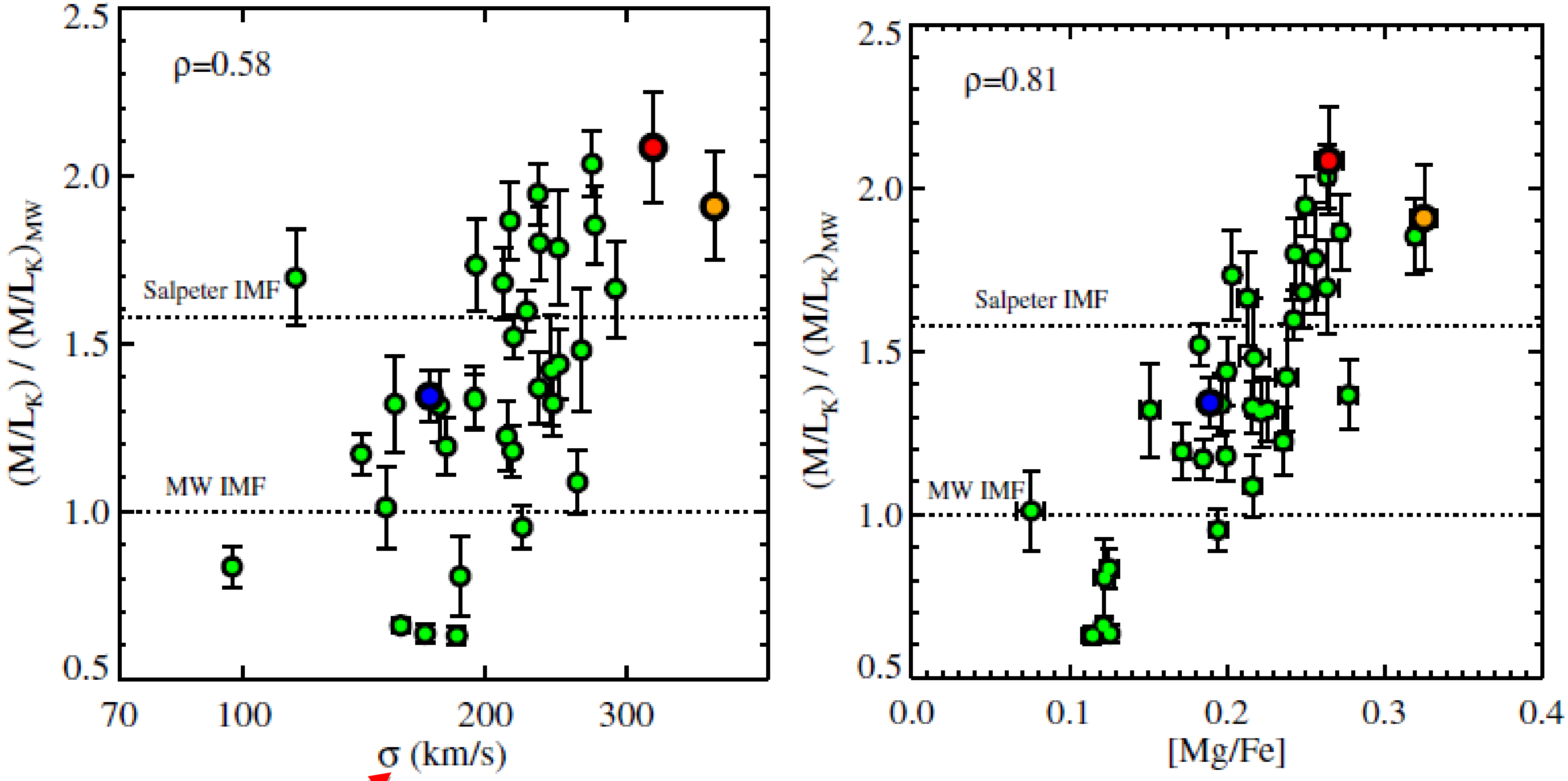


Conroy & van Dokkum 2012

La Barbera et al. 2013; Spiniello et al. 2014;
Lyubenova et al. 2016; Lagattuta et al. 2017



IMF correlates with galaxy properties

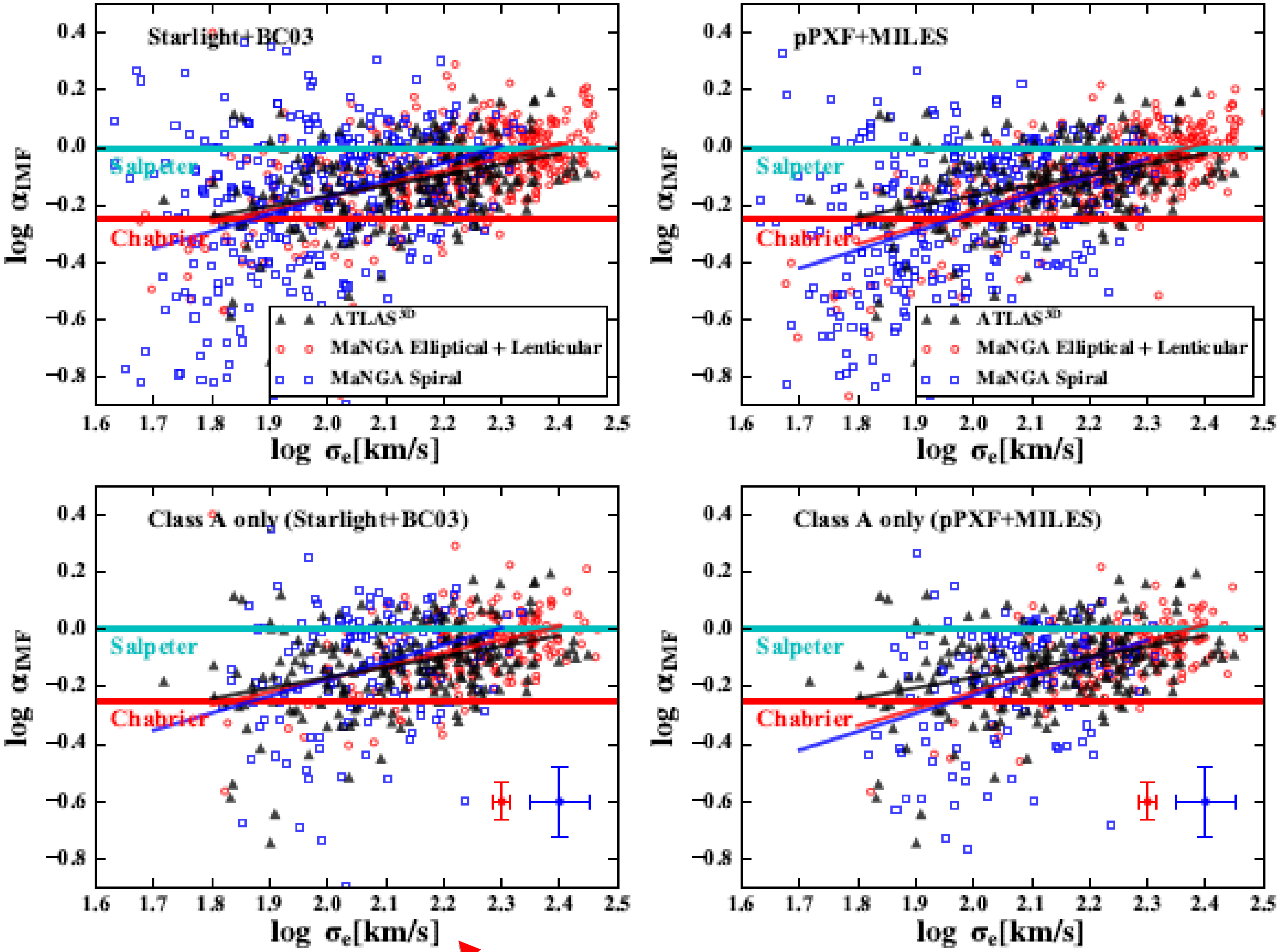


Conroy & van Dokkum 2012

Note: This is the central velocity dispersion

Assume difference between M_*^{SP} and M_*^{dyn} due to variable IMF (800 MaNGA galaxies)

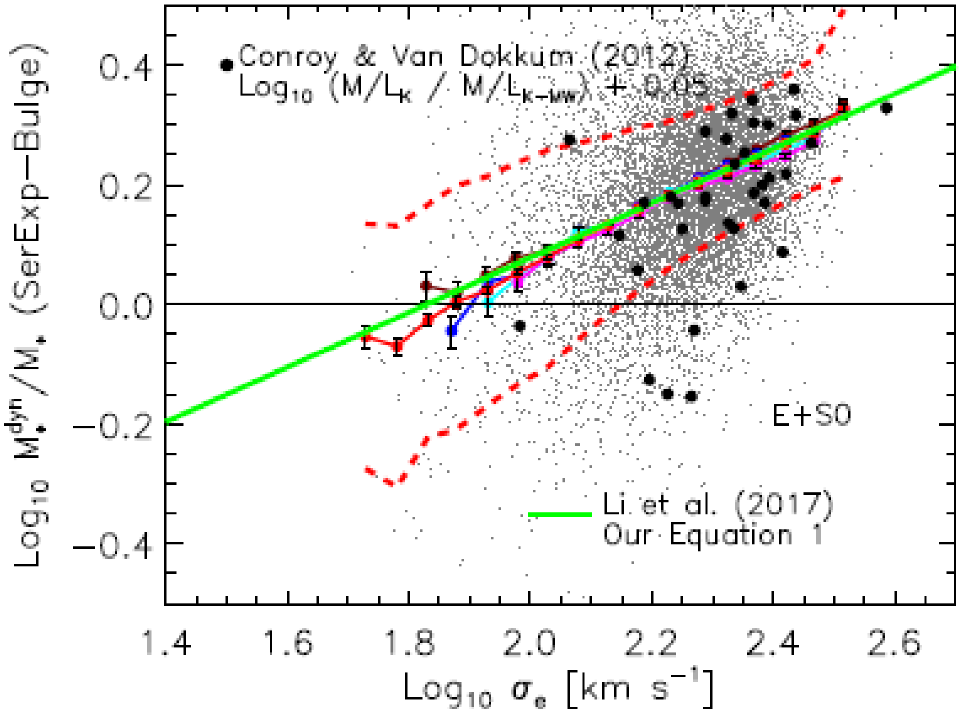
$\mathrm{Log}\ M_*^{dyn} / M_*$



Li et al. 2017

Note: This is velocity dispersion within R_e

If bottom heavy IMF at large σ then M_*^{SP}~ M_*^{dyn}

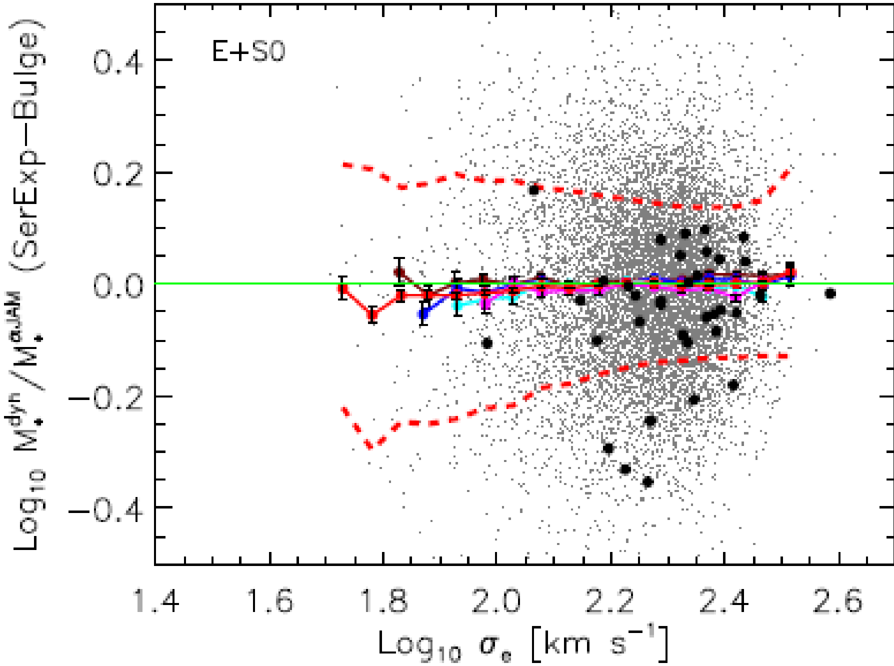


$$M^{\rm dyn}_{*+{\rm gas}} = k(n,t_a)\,\frac{R_e\sigma_a^2}{G}, \quad \text{where} \quad t_a \equiv \frac{\theta_a}{\theta_e}$$

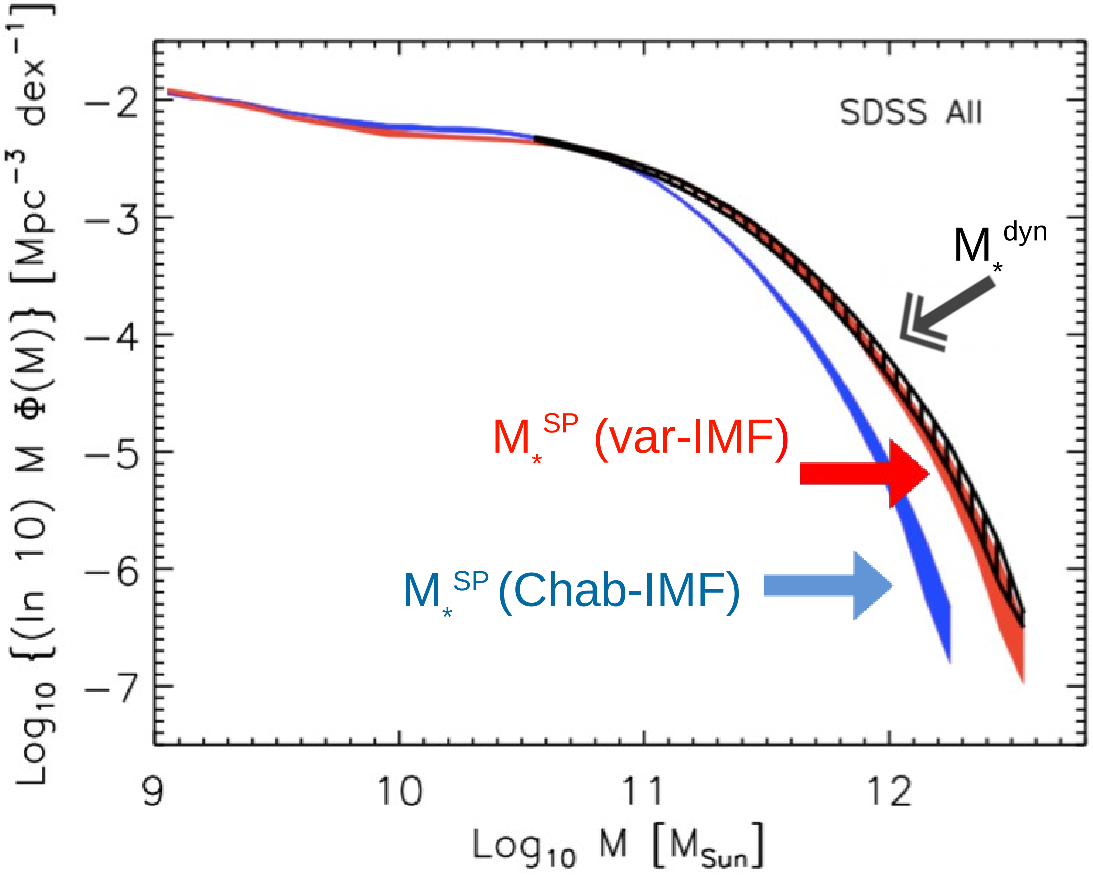
Bernardi et al. 2018a

$$\left\langle \log_{10}\frac{M_*^{\alpha {\rm JAM}}}{M_*}\middle|\log_{10}\sigma_e\right\rangle = a + b\,\log_{10}\frac{\sigma_e}{\rm km\ s^{-1}} + 0.25$$

$$(a, b, \Delta_{int}) = (-1.086, 0.457, 0.082)$$

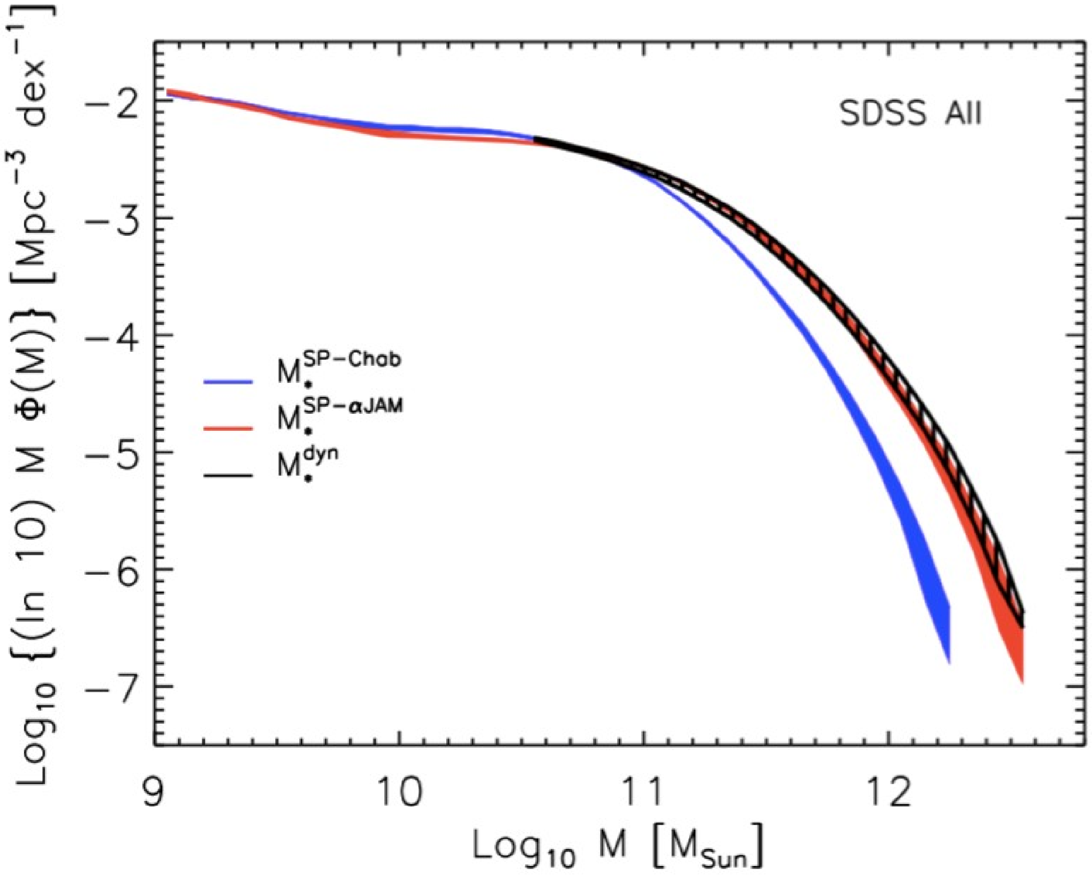


Good agreement between M_*^{SP}(variable-IMF) ~ M_*^{dyn}



Bernardi et al. (2018a)

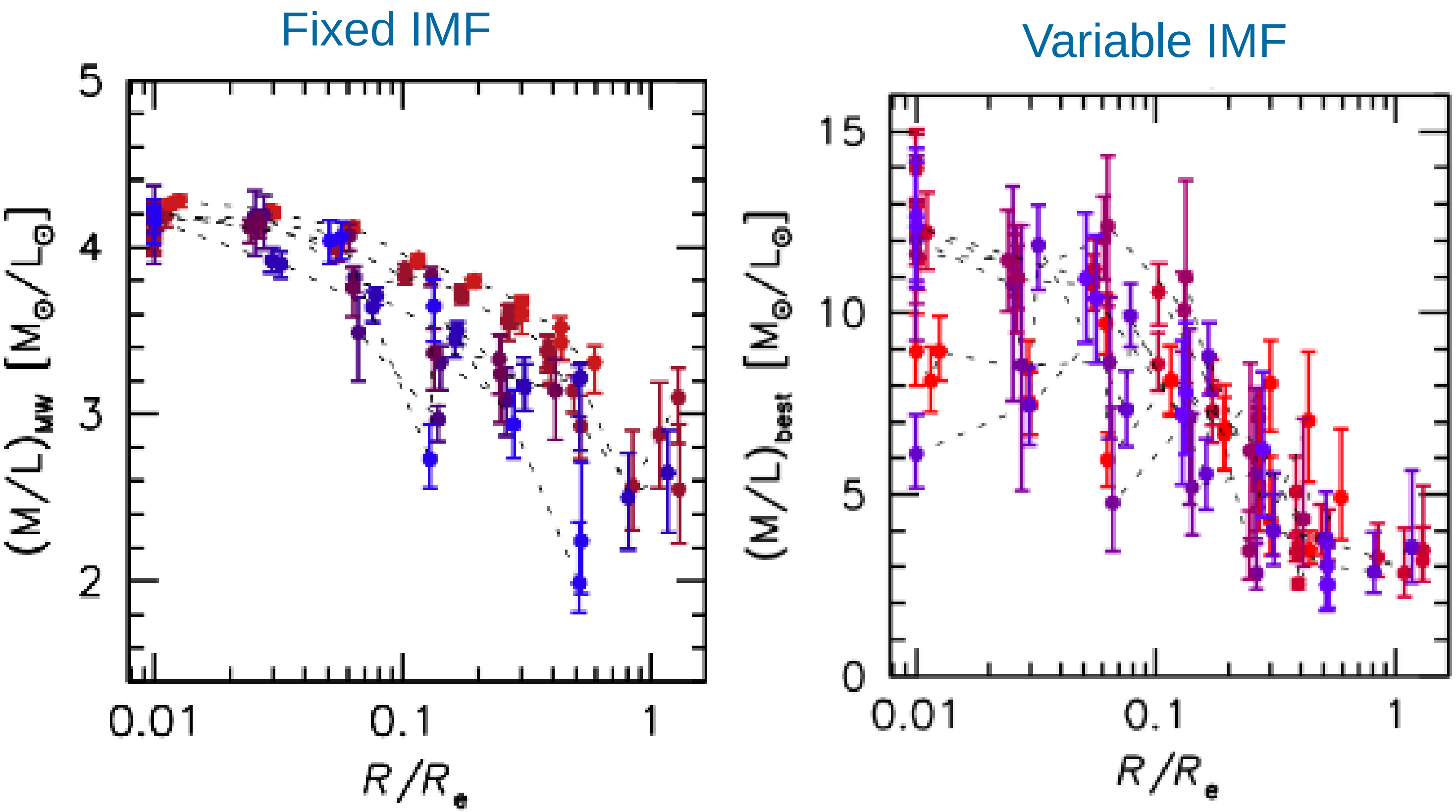
But … OK to ignore M/L gradient within each galaxy?



Bernardi et al. (2018a)

Gradients within a galaxy

Lyubenova et al. 2016; van Dokkum et al. 2017; La Barbera et al. 2017



6 galaxies

Van Dokkum+ 2017

Inferred M*/L gradient stronger when IMF allowed to vary with R: 50% effect in the left hand panel → factor of 3 in the right panel. Ignoring gradient not justified.

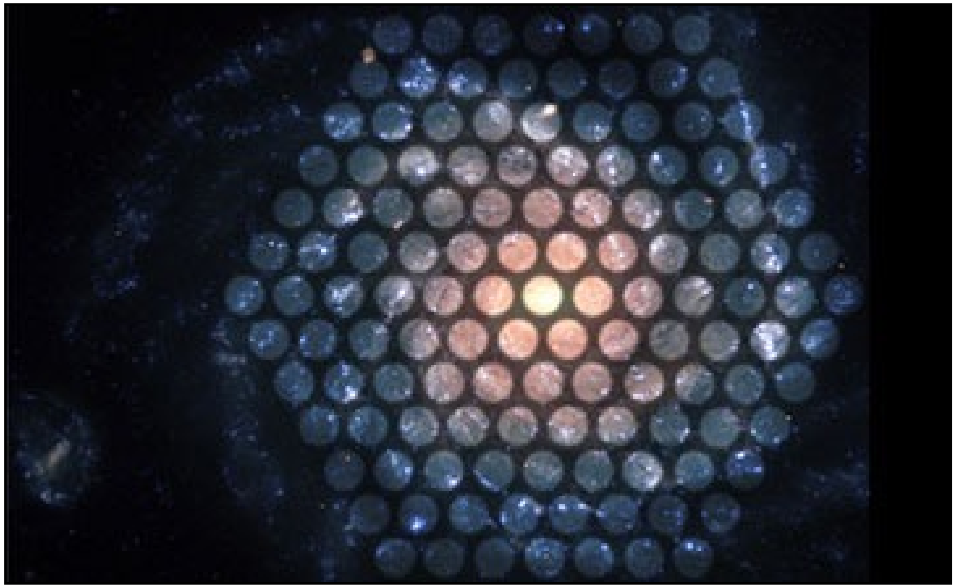
Why is IMF gradient so difficult to measure?

- Must distinguish imprint of dwarf stars in spectral features.
- Very high SN spectra required (> 100).
- Single aperture spectroscopic observations prevent study of IMF gradients within galaxies.
- MaNGA is a great data set for overcoming these limitations.

MaNGA Survey

Mapping Nearby Galaxies at APO

Integral Field Unit (IFU)



4,600 (10,000) nearby galaxies

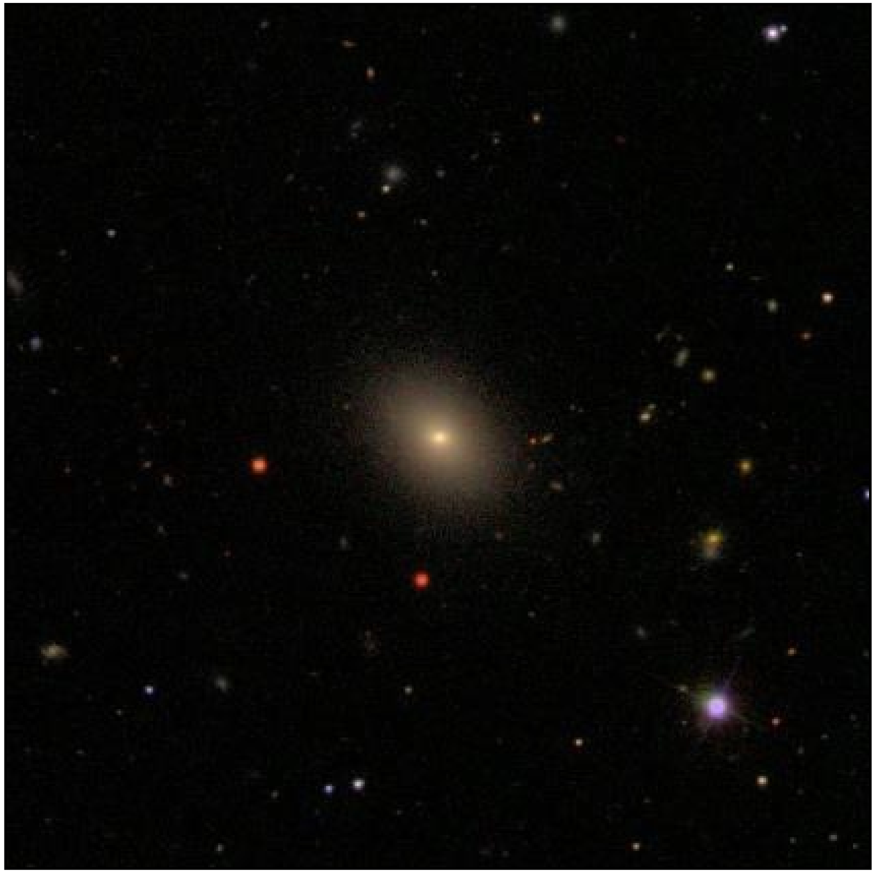
z~0.03, ~2700 deg^2

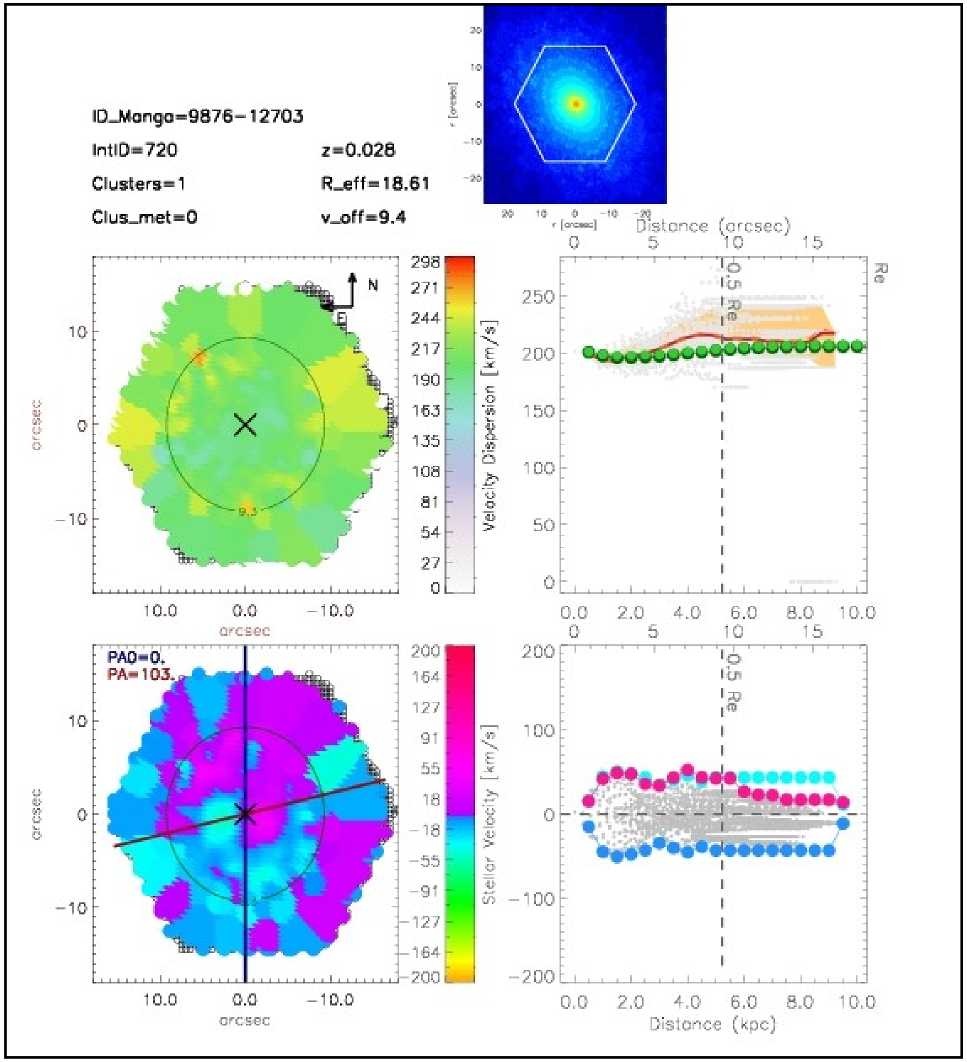
- ✓ Wavelength: 360-1000 nm
- ✓ Resolution R~2000

- ✓ Spatial sampling of ~ 1 kpc
- ✓ S/N=4-8 (per angstrom) at 1.5 Re

Elliptical galaxies: slow rotators

- T-Type = -2.1
- P_S0 = 0.3

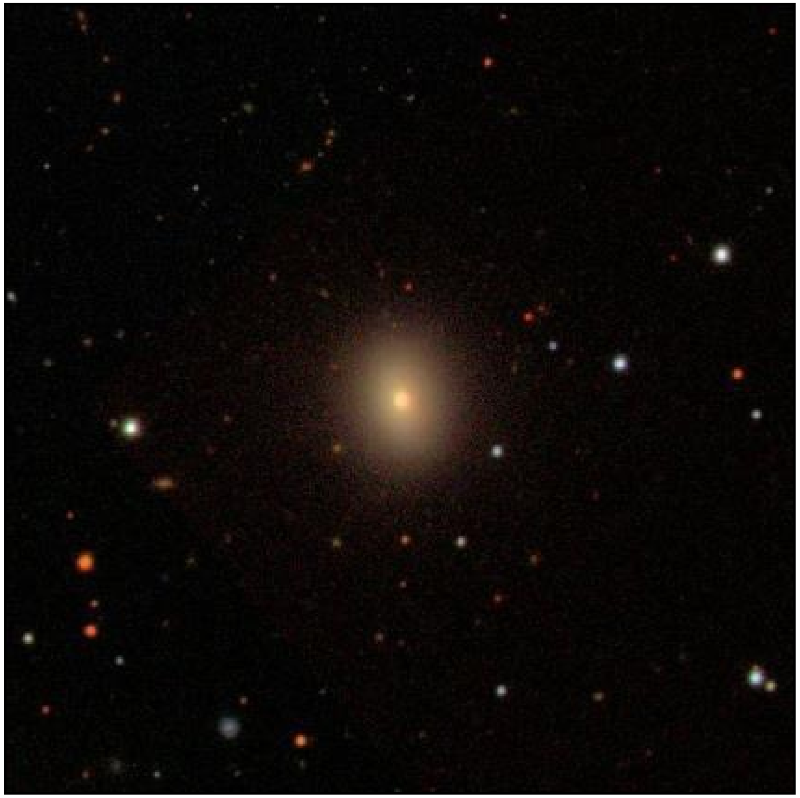


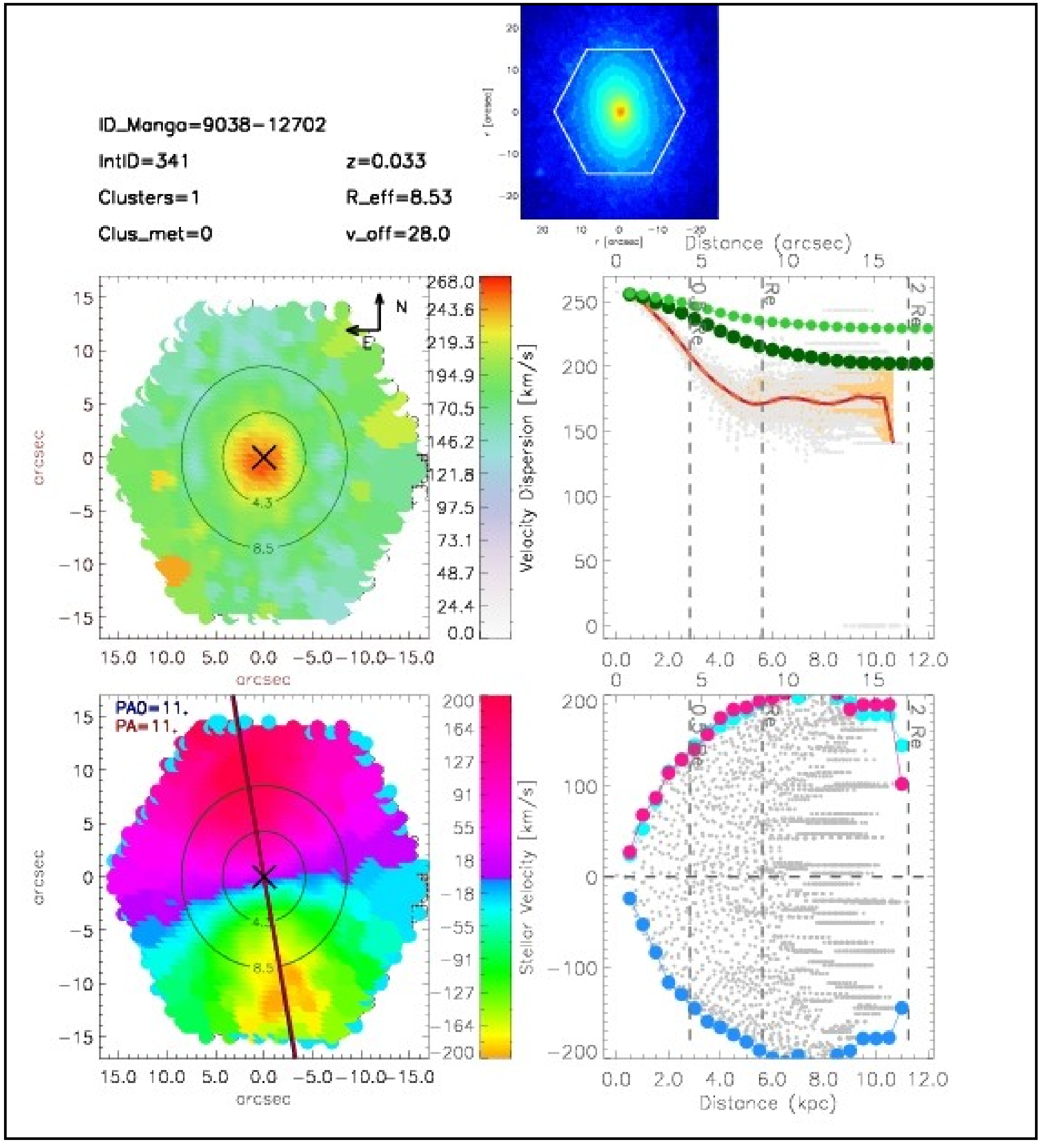


ID_Manga=9876-12703
IntID=720 z=0.028
Clusters=1 R_eff=18.61
Clus_met=0 v_off=9.4

Elliptical galaxies: fast rotators

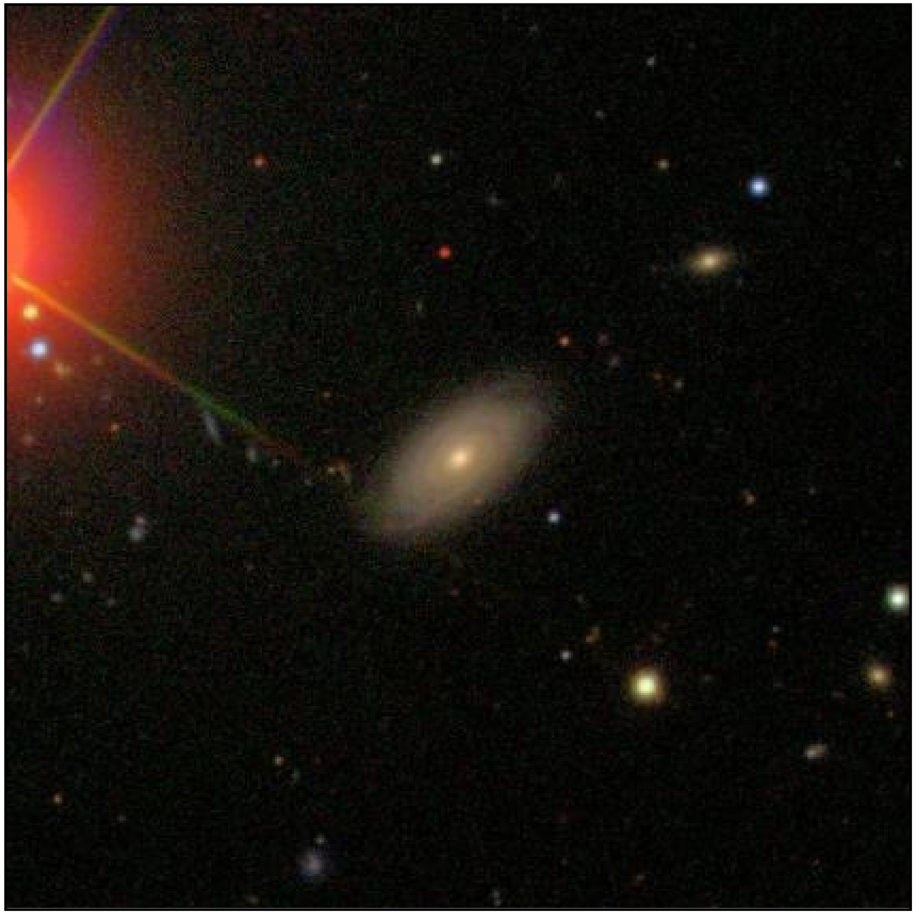
- `T-Type = -2.3`
- `P_S0   = 0.17`

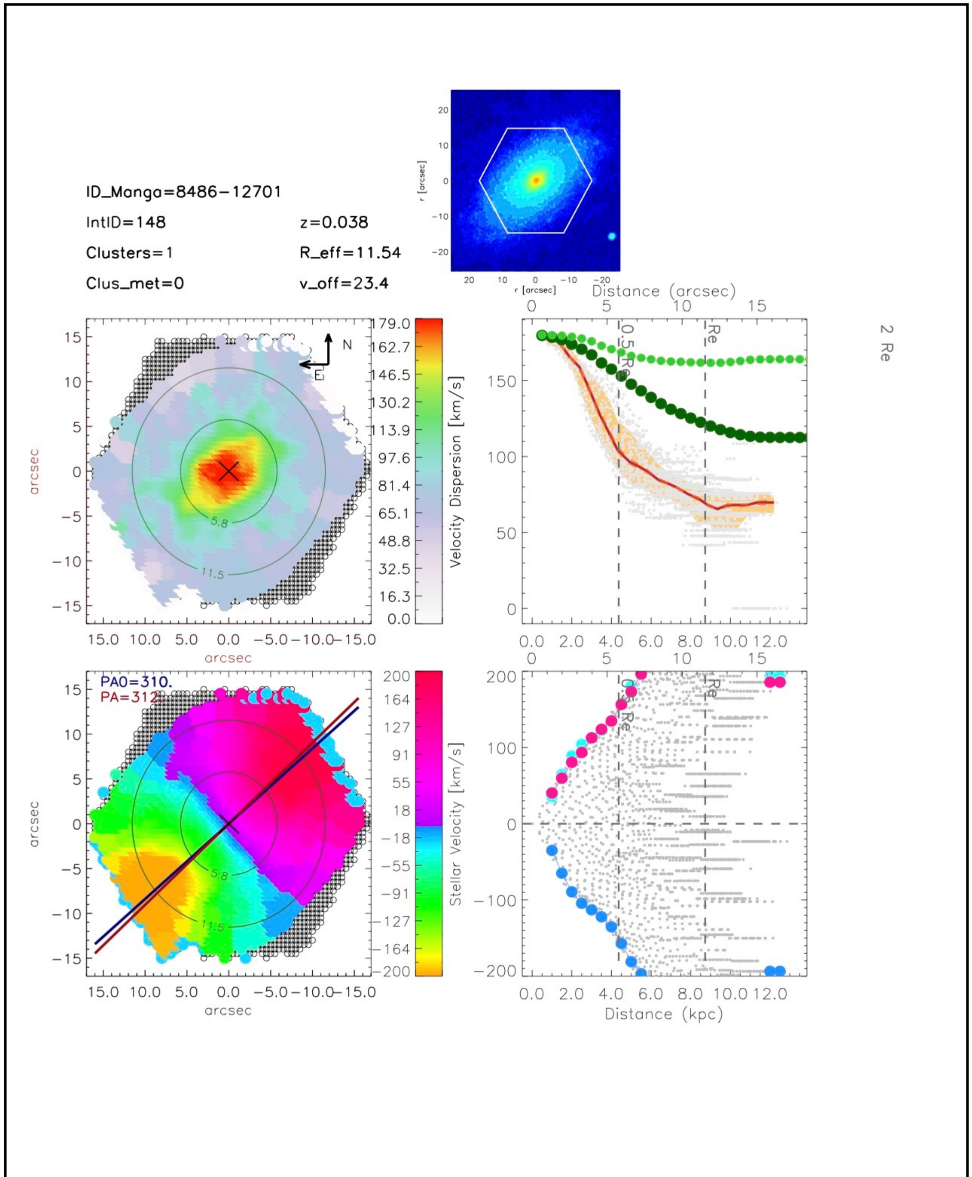




Late Type galaxies

- T-Type = 4.2
- P_bulge = 0.6





ID_Manga=8486−12701

IntID=148 z=0.038

Clusters=1 R_eff=11.54

Clus_met=0 v_off=23.4

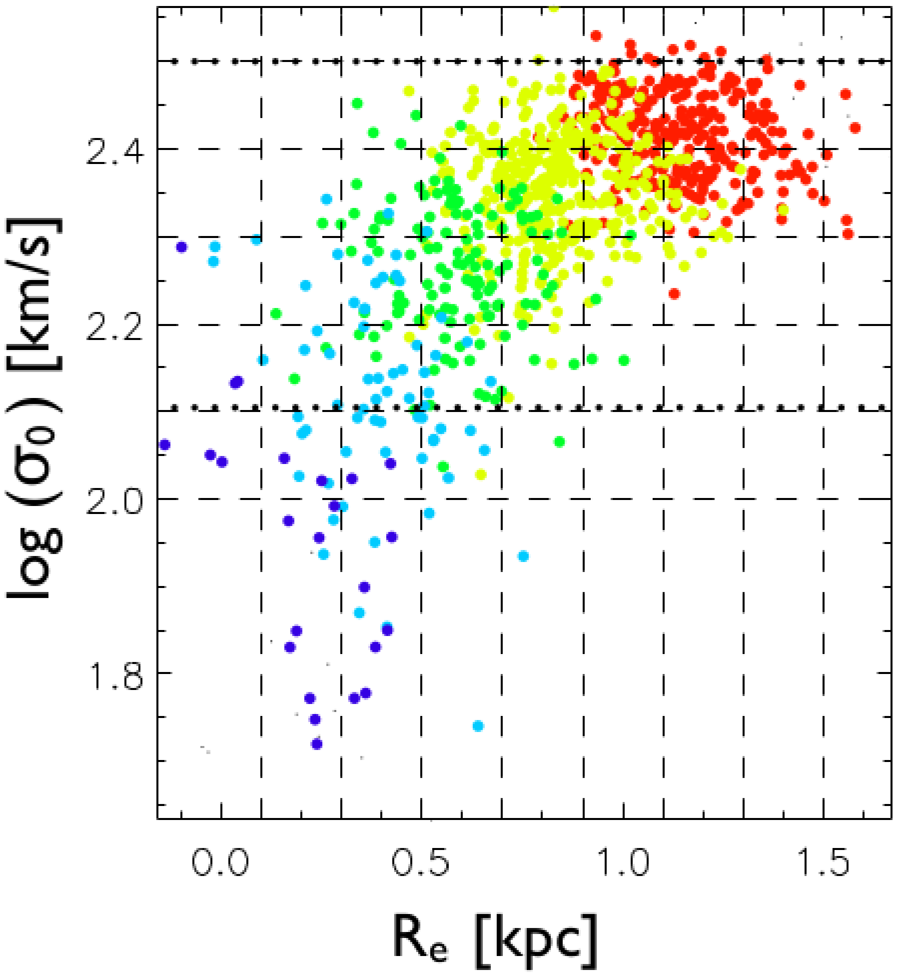
Helena Dominguez-Sanchez

Measuring IMF gradients: Methodology

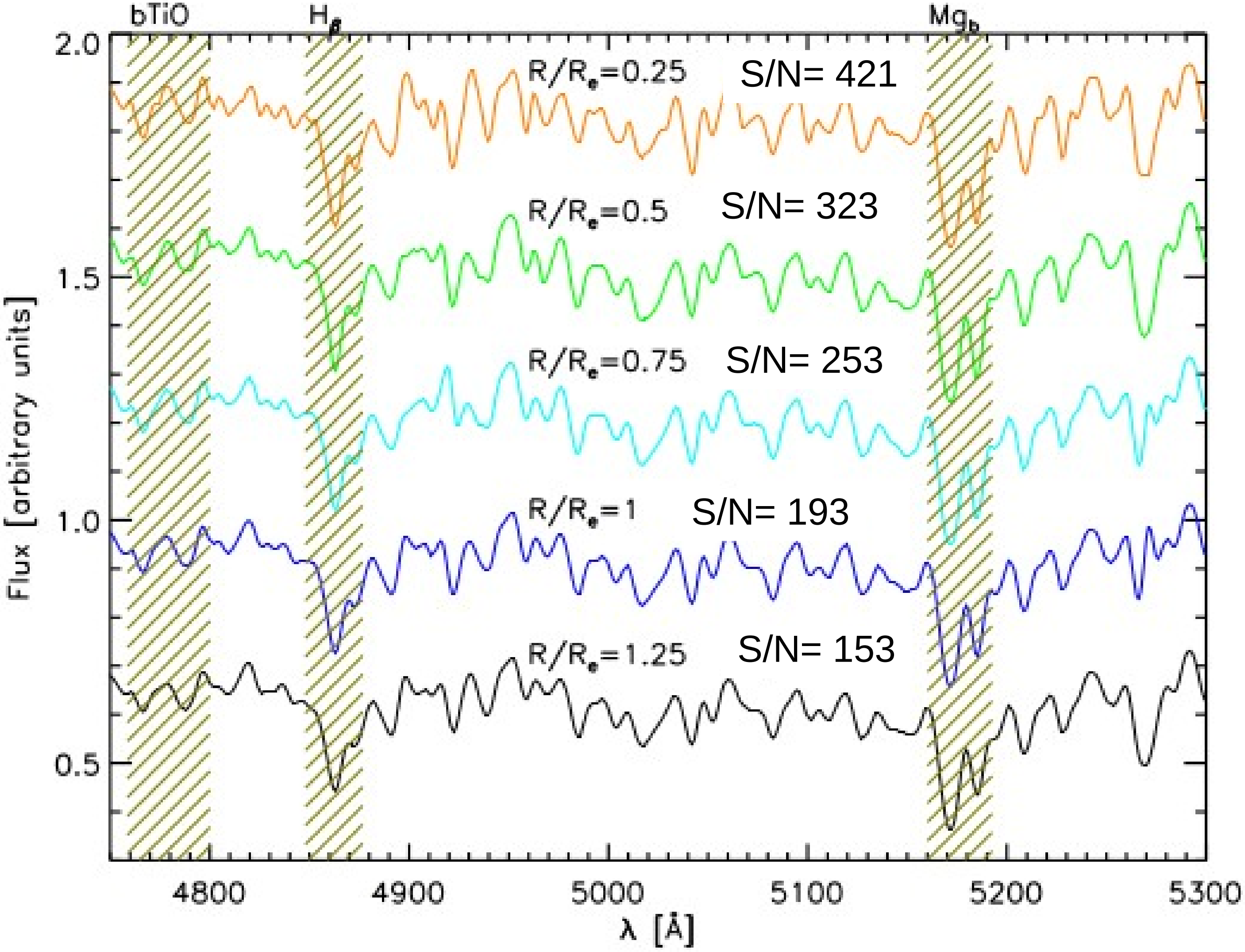
- Select ~ 900 MaNGA elliptical galaxies using our Morphological Deep Learning-VAC:
- T-Type ≤ 0 & P_S0 < 0.5 (Dominguez-Sanchez et al. 2018)

- Construct stacked spectra for different σ_0 bins at different R/R_e

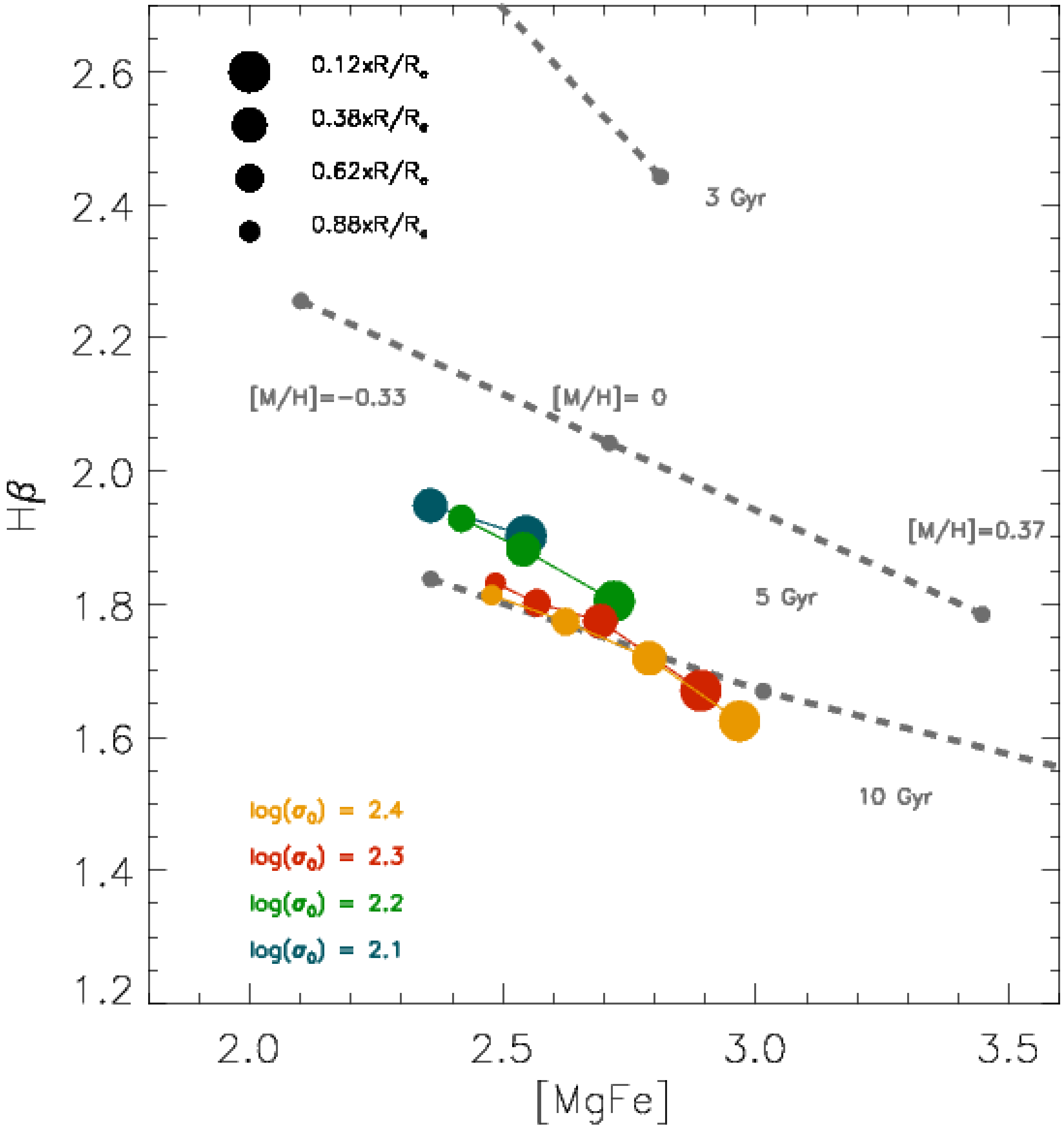
- Study radial gradients of lick indices (H_β, NaD, TiO2, bTiO, etc.) following *Tang & Worthy (2017)*



Example of composite Spectra



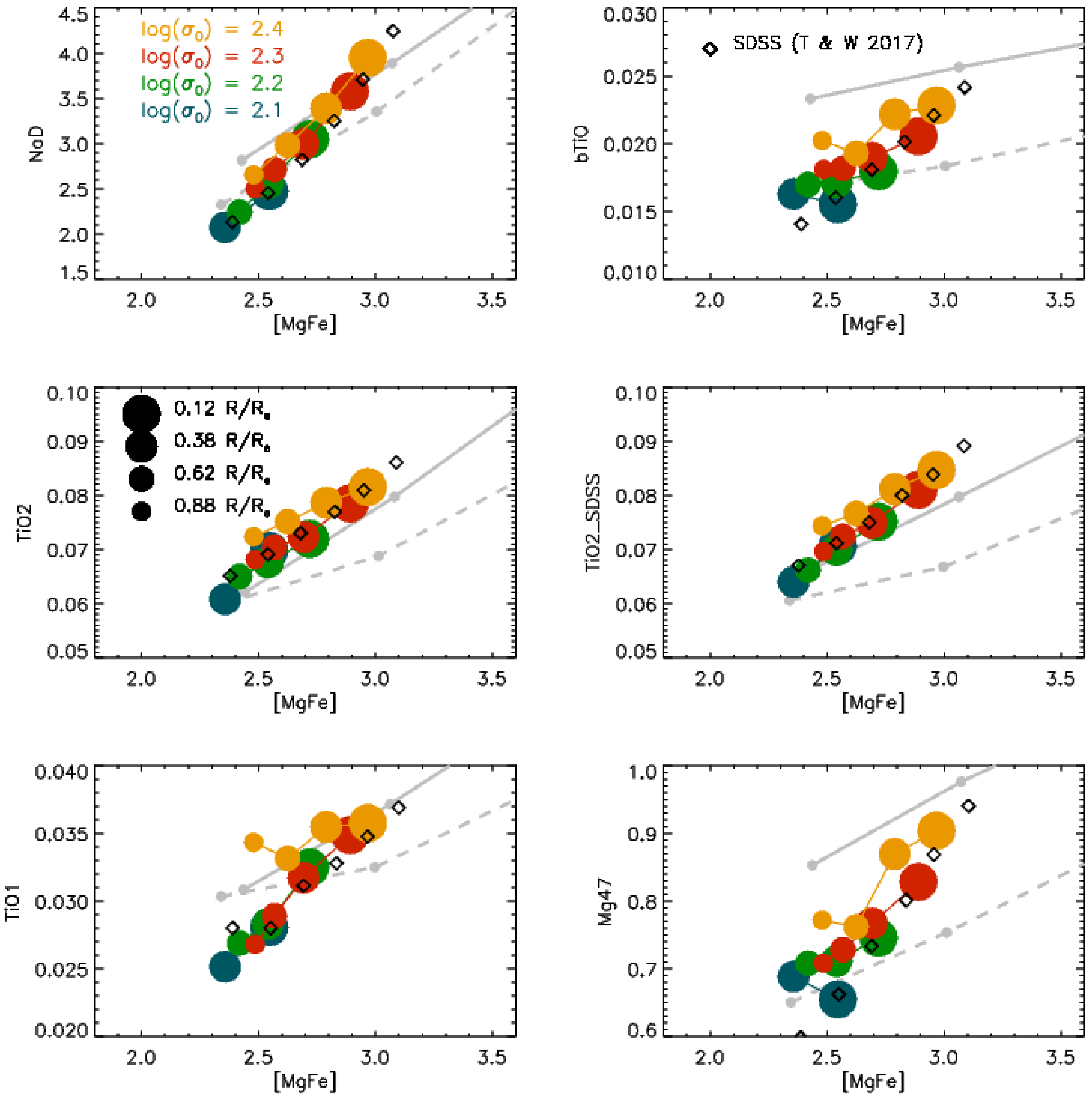
Results: Ages



- Consistent with old stellar populations (> 8 Gyr)
- Dependence on central velocity dispersion
- Radial gradient related to metallicity

Dominguez-Sanchez, MB et al. 2018

Results: IMF Index gradients



Bottom-heavy(α=3)IMF

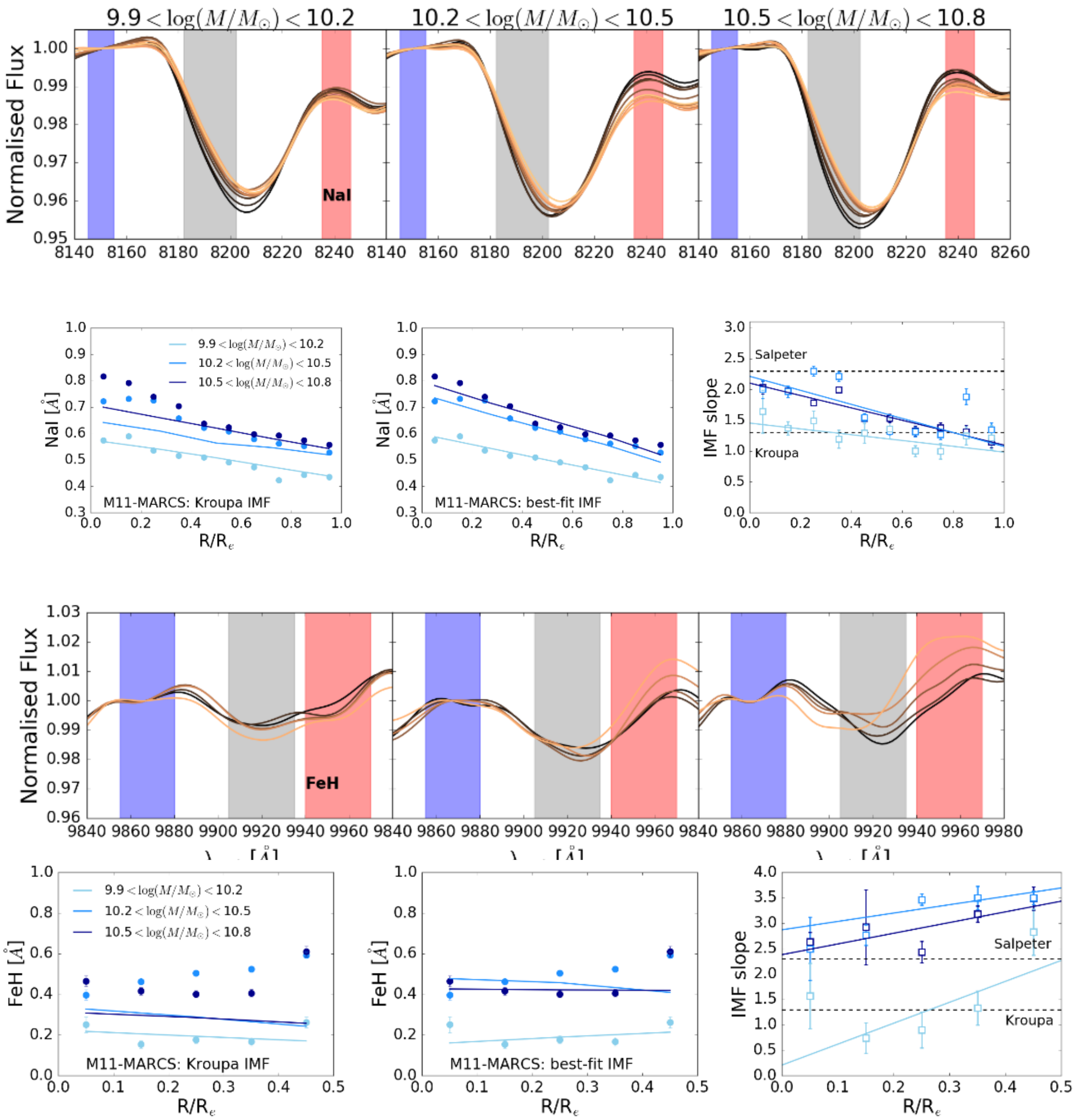
Kroupa IMF

Indices favor bottom-heavy IMF in central regions!

Also:

- dependence on metallicity
- dependence on central velocity dispersion

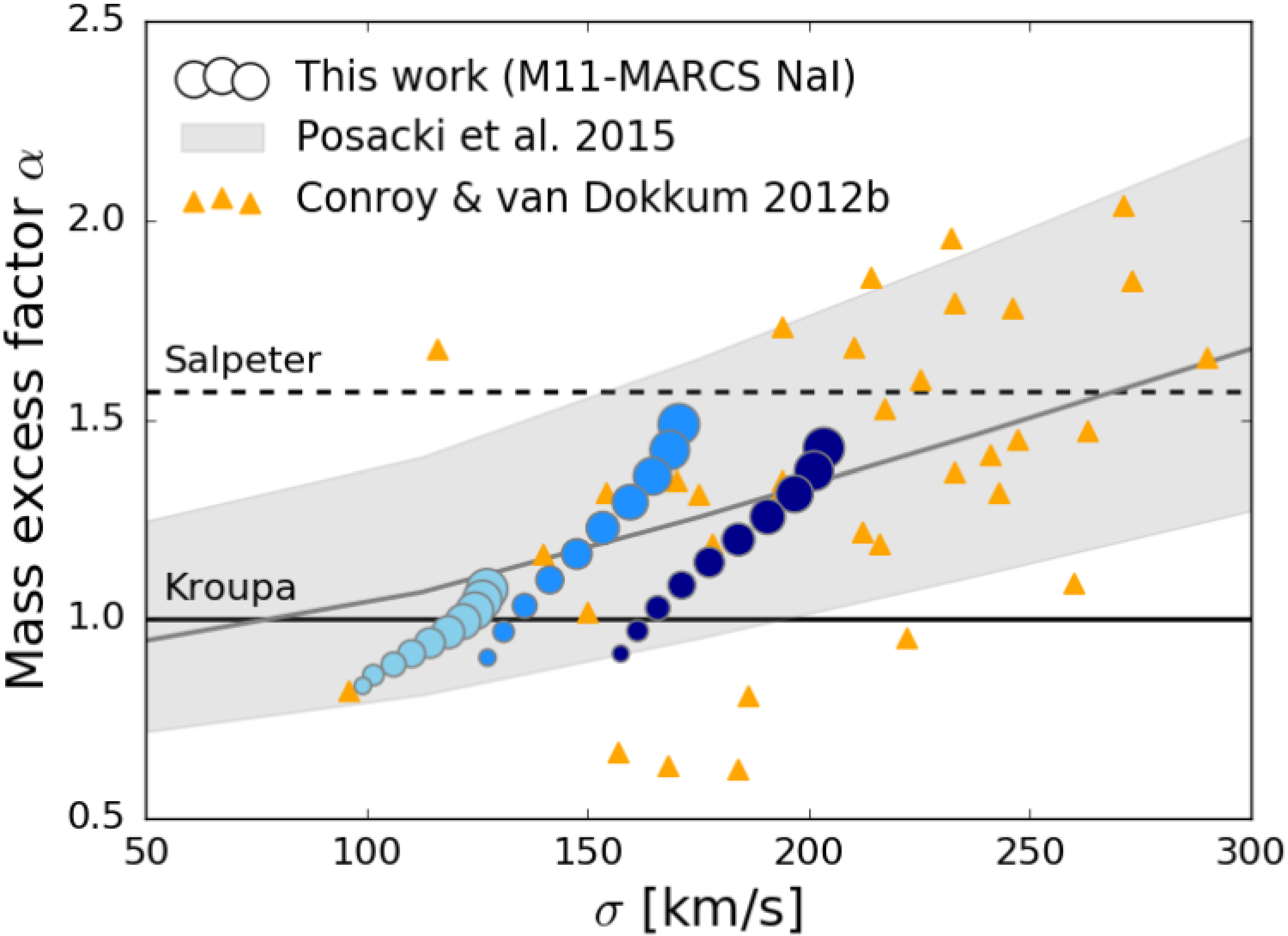
Dominguez-Sanchez, MB et al. 2018



Parikh et al. 2018

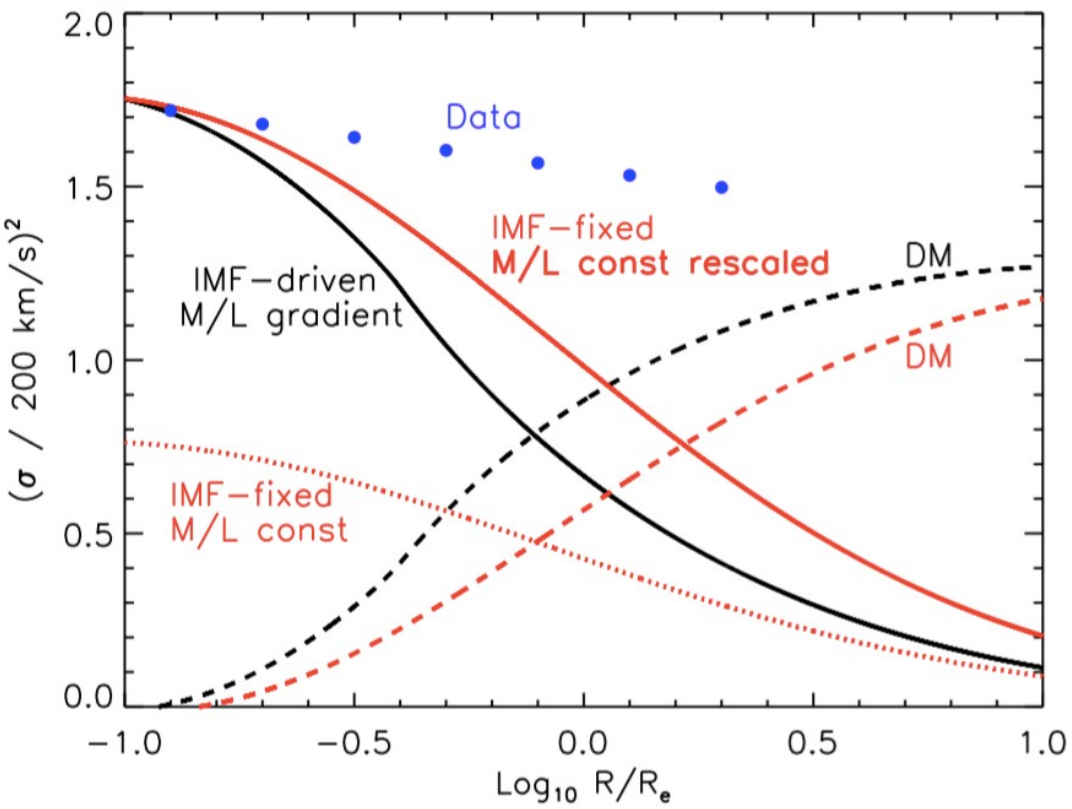
Constructed composite spectra from a sample of ~400 MaNGA ETGs

Used longer λ indices



Parikh et al. 2018

IMF gradients have a large effect on M_*^{dyn}



- Large effect on M_*^{dyn}

  because it is calibrated to match the velocity dispersion at the center

- Inferred dark matter at small r ~2x larger

IMF (M_*/L) gradient important for deriving both M_*^{SP} and M_*^{dyn}

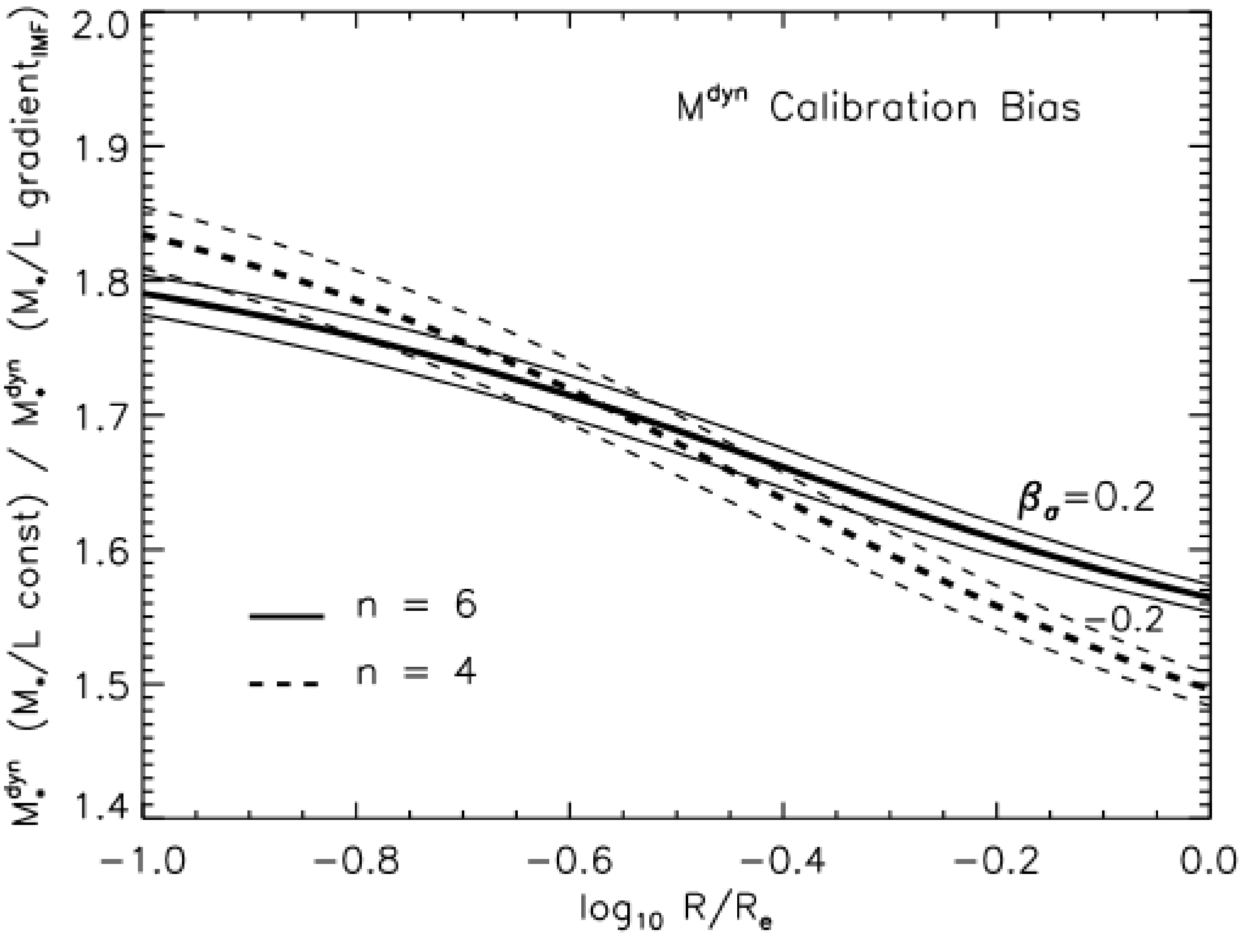
Bottom-heavy IMF in central regions

→ stellar mass more centrally concentrated than light

→ dark matter matters at smaller r (adiabatic contraction etc.)

Bernardi et al. (2018b)

M_*^{dyn} decrease by ~2x if IMF gradients are considered

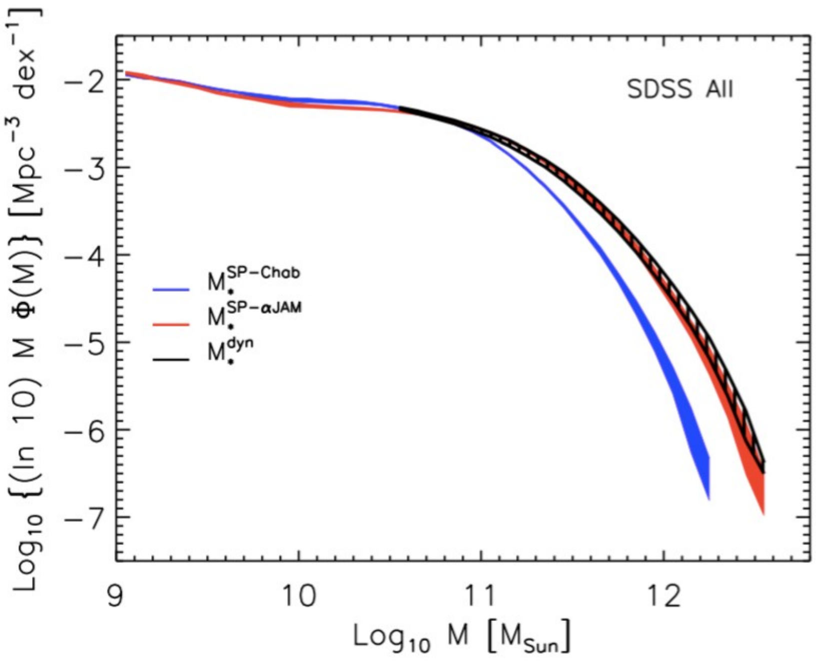


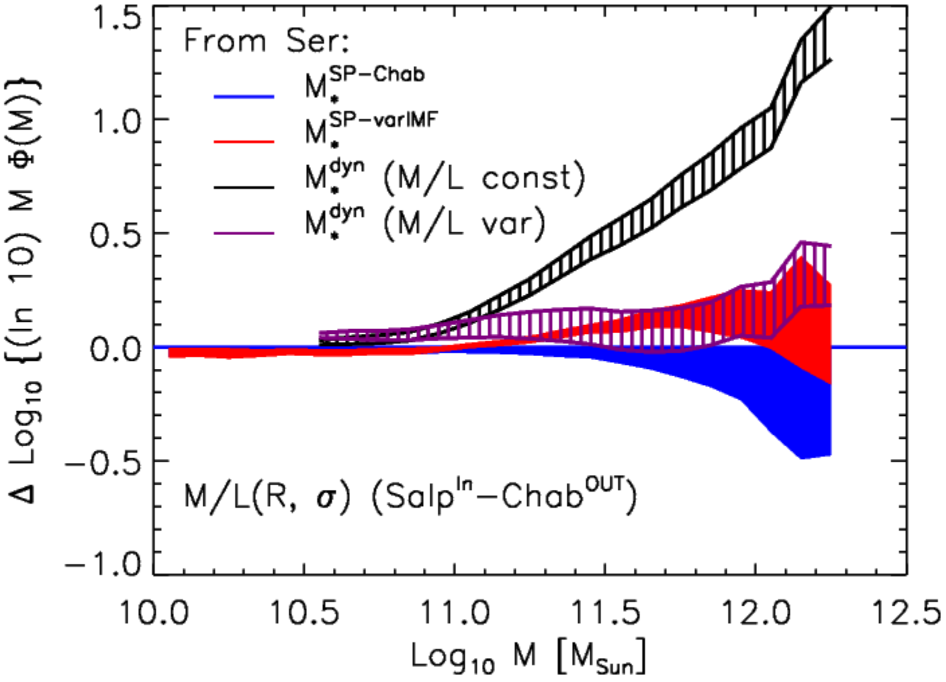
Bernardi et al. (2018b)

Conclusions:

Accounting for IMF gradients within galaxies reconciles M_*^{SP} and M_*^{dyn}

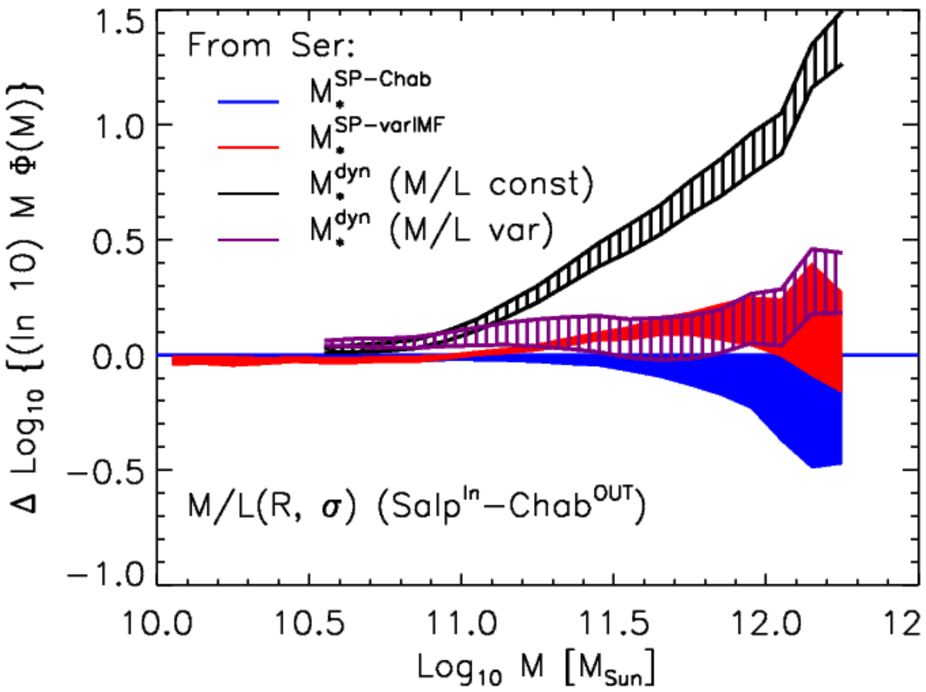
-> M_*^{dyn} decreases rather than M_*^{SP} increases





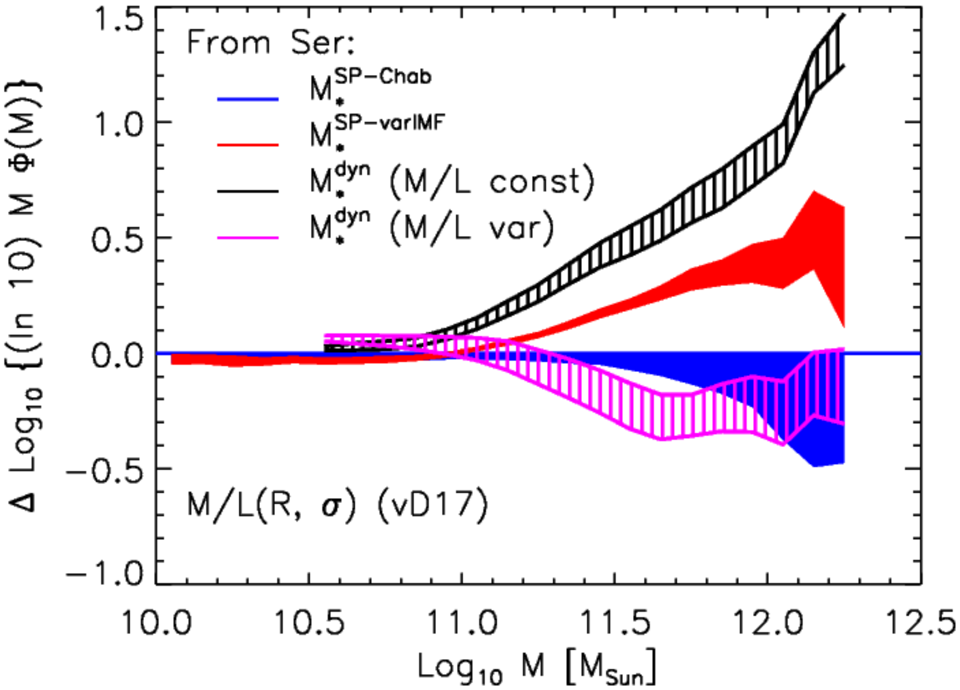
Gradient Strength

Salpeter Inside – Chabrier Outside

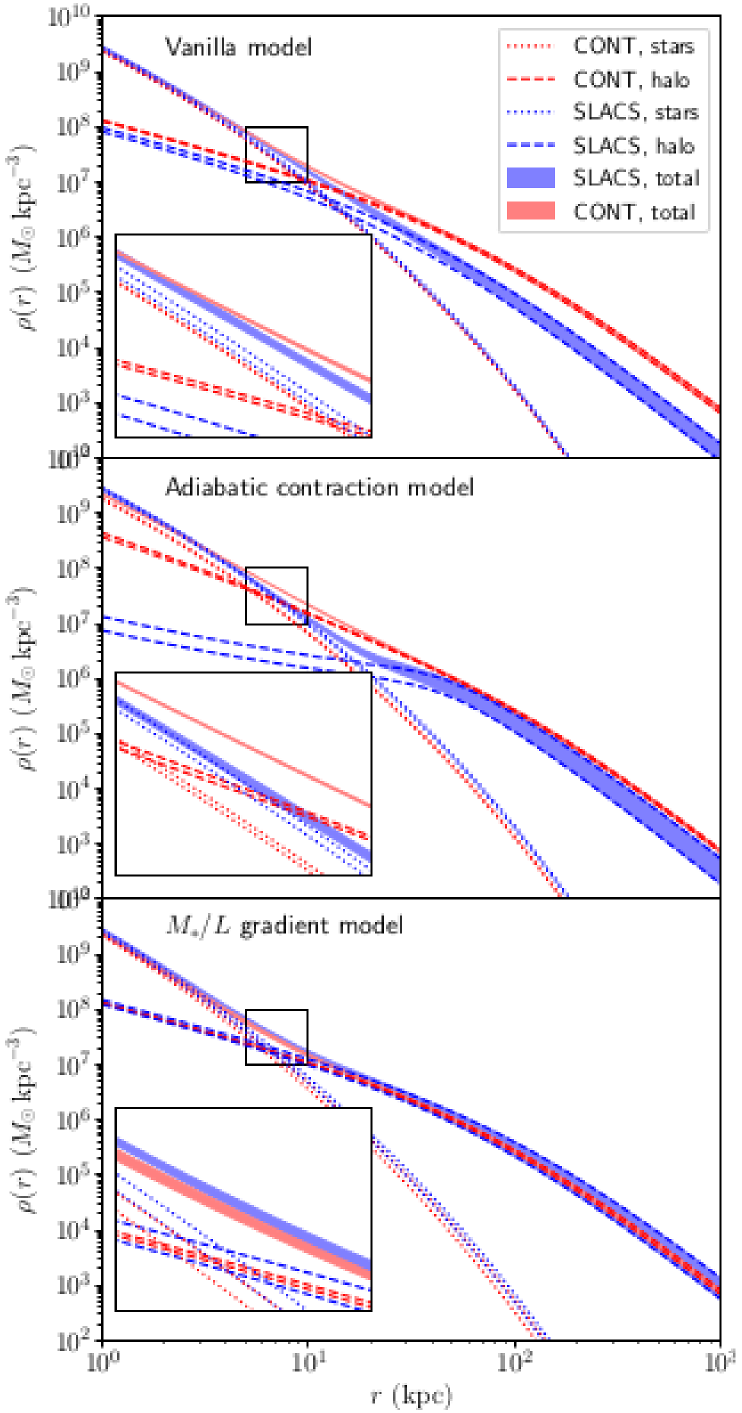


OK

Van Dokkum et al. 2017



Too large



Different approach ➡ Same conclusion

Fit strong lensing & stellar kinematics on small scales

+

weak lensing on large scales

- Vanilla: deV + constant M/L + NFW
- Adiabatic contraction: modify DM only
- M/L gradient: modify stars only

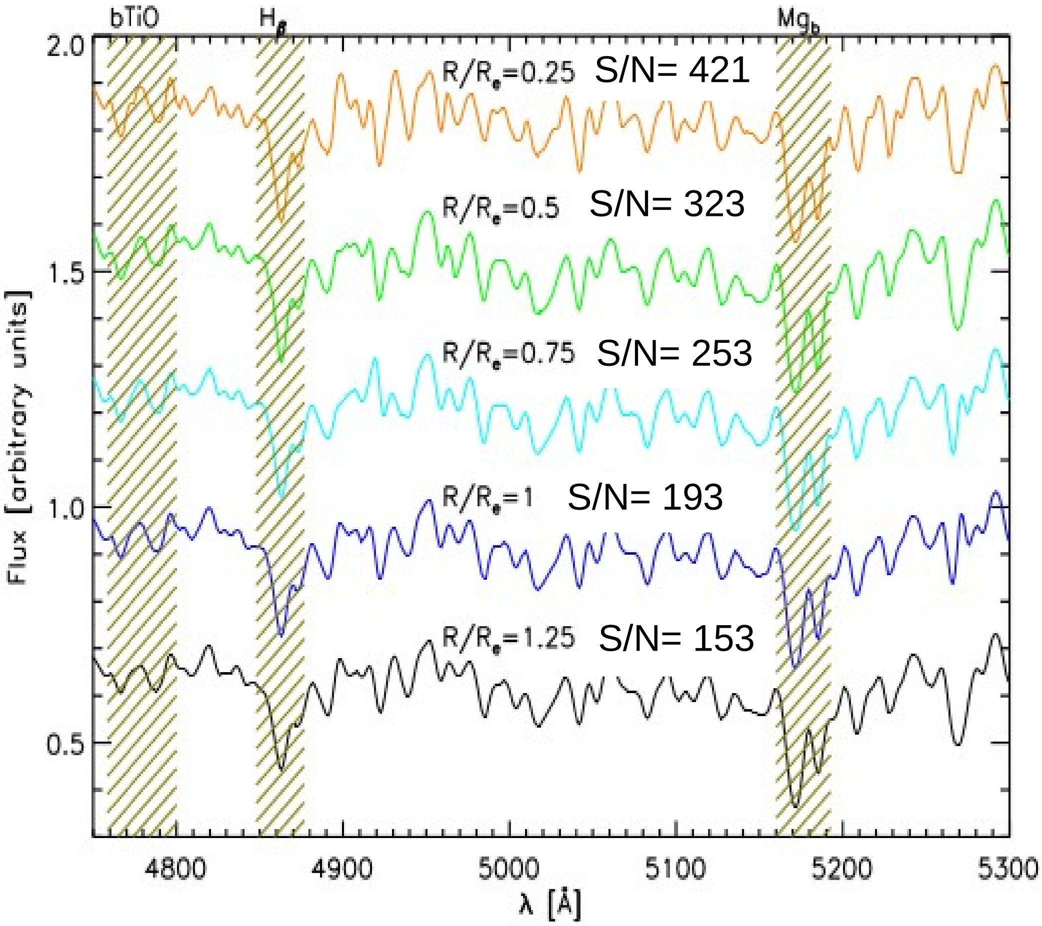
Agreement between SLACS and CONTROL only in bottom panel (M/L gradient model)

Cannot say if required gradient IMF-driven

Sonnenfeld et al. 2018

IMF gradients in the era of big telescopes

No Stacked Spectra



ELT

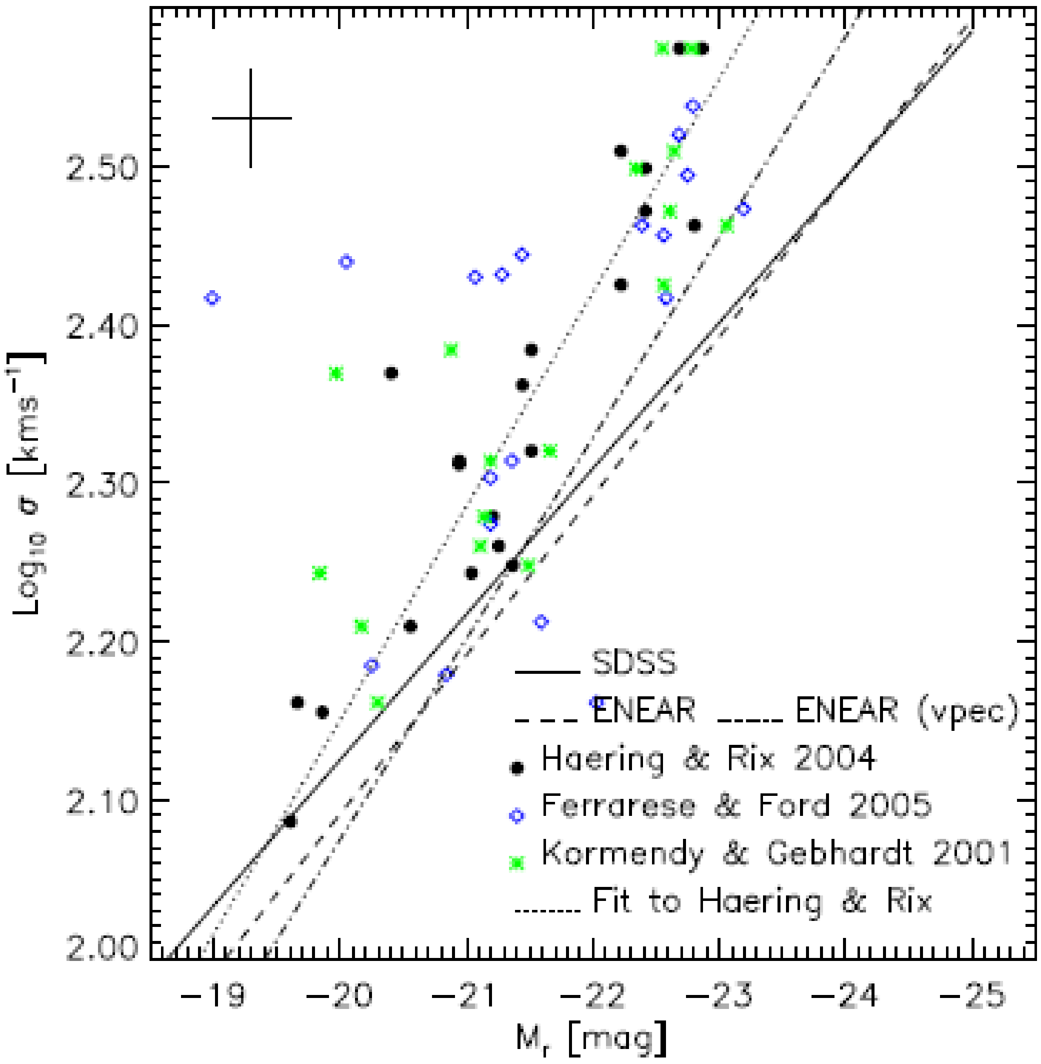
- individual galaxies
- larger radii
- evolution

Outline

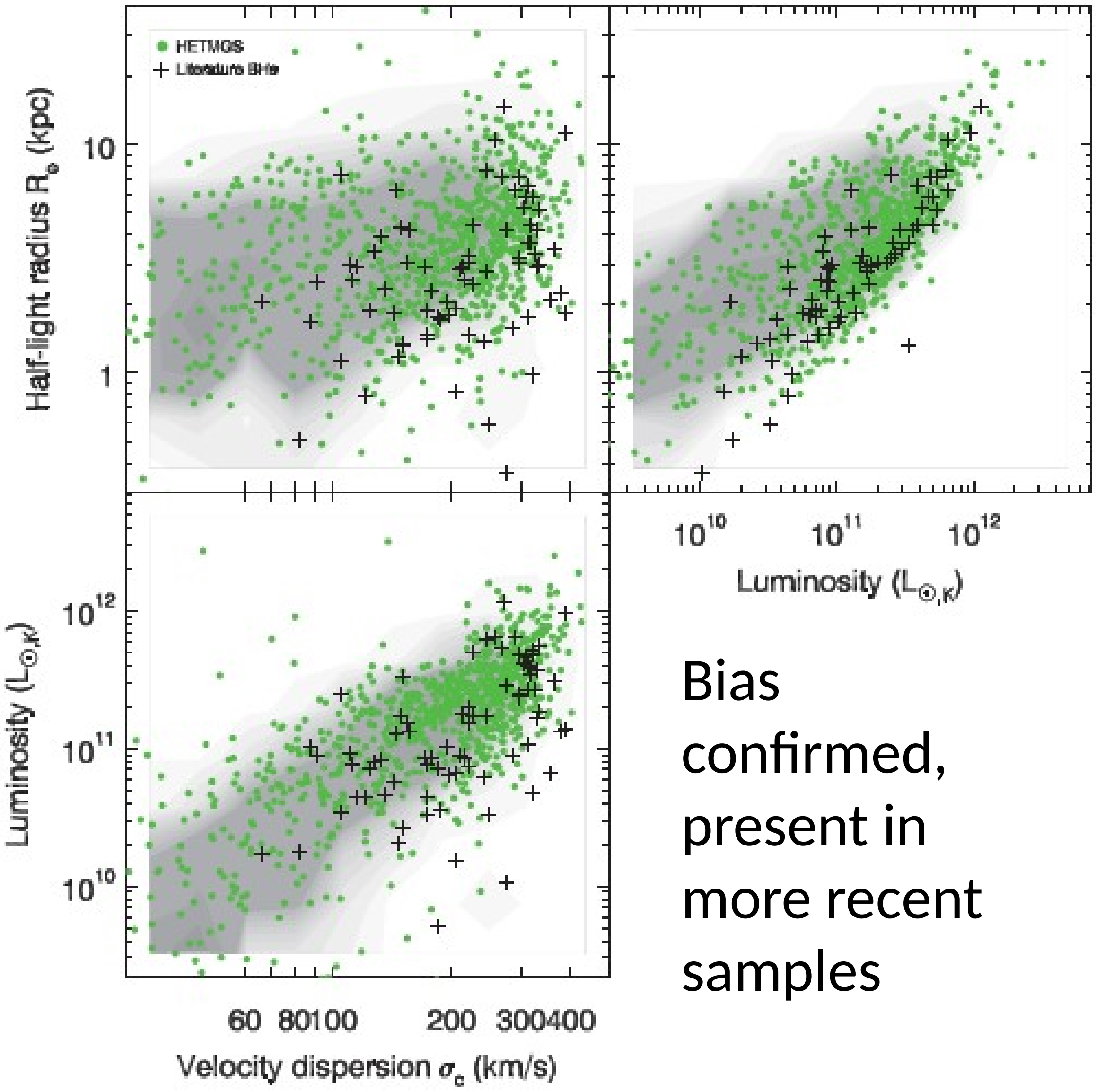
- Better photometry of SDSS galaxies → L
- IMF variation across population → M_*/L
- MaNGA (SDSS IV)
- IMF gradients → implications (e.g. M_*^{dyn}, f_{DM})

- Selection bias in SMBH samples having dynamically measured masses

Bias in SMBH samples



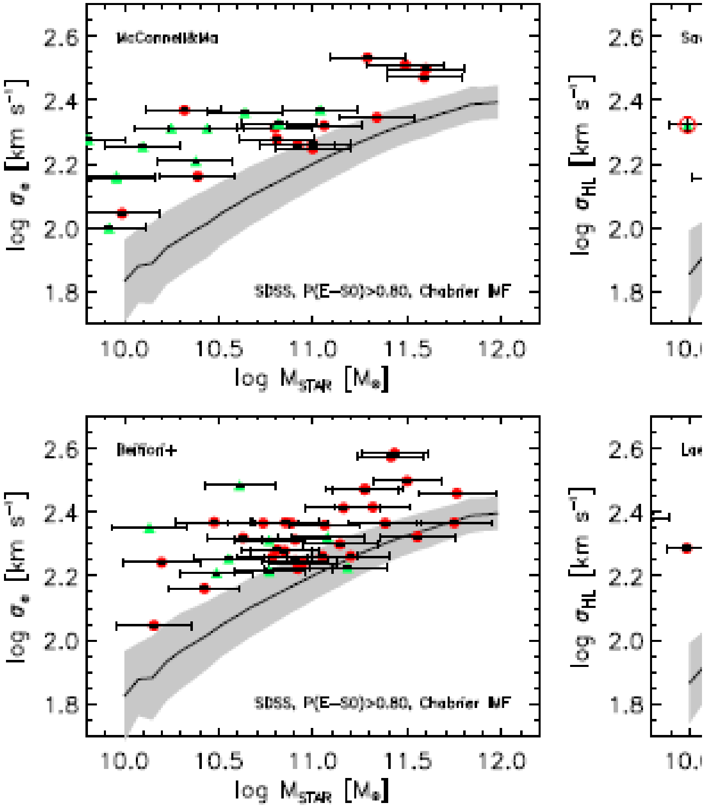
Bernardi et al. 2007

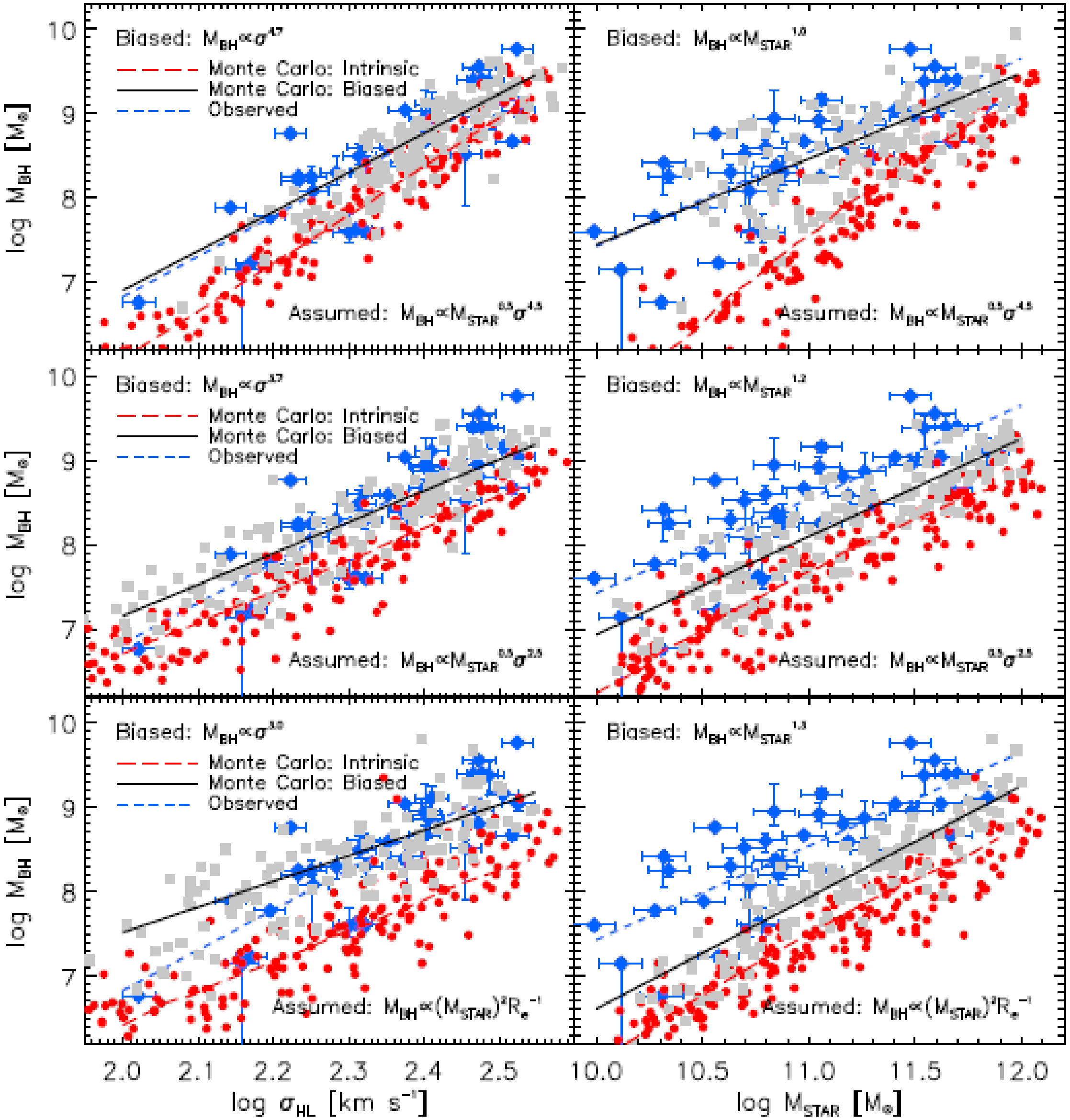


Bias confirmed, present in more recent samples

Van den Bosch et al. 2015

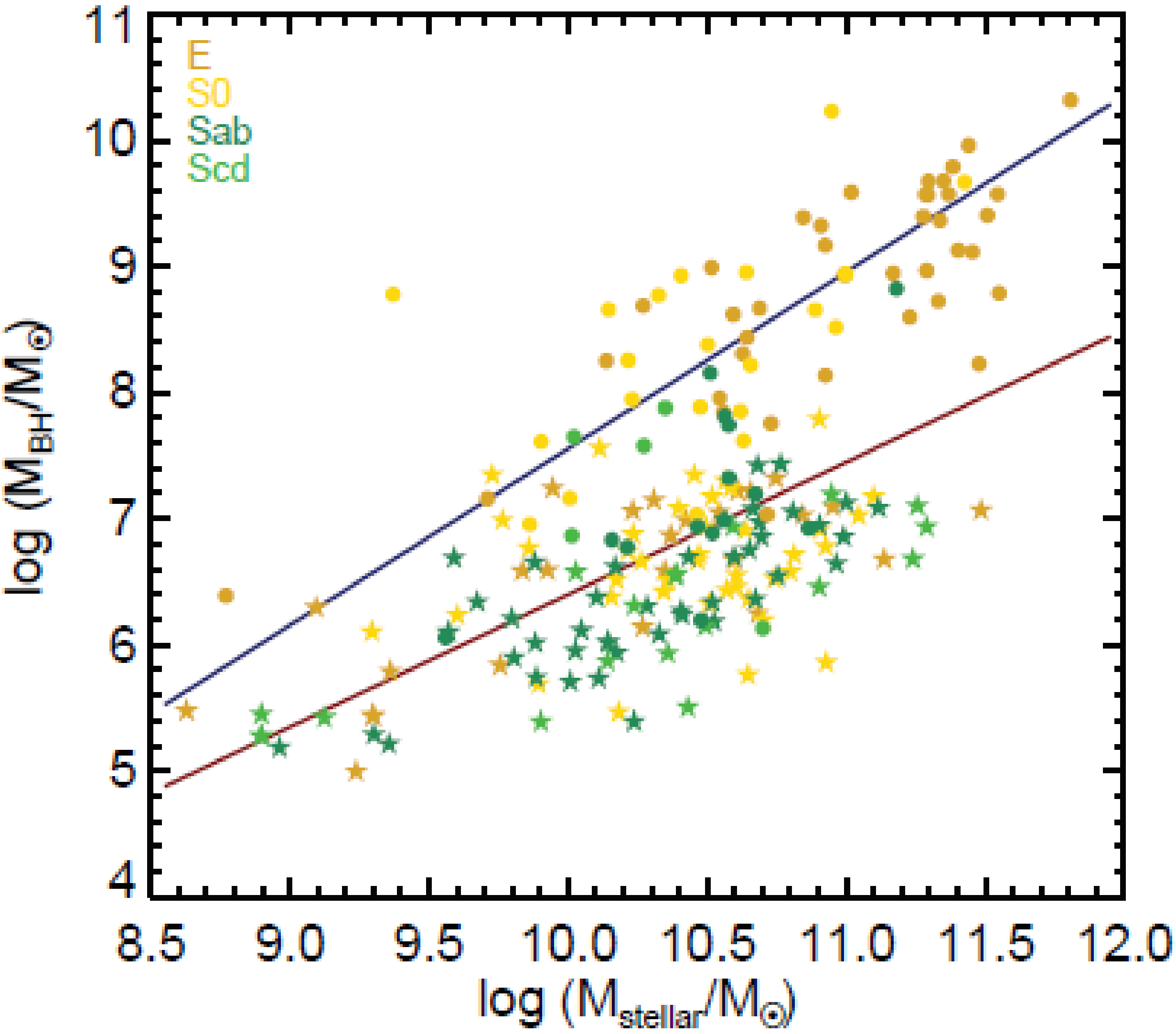
Data + Simulations





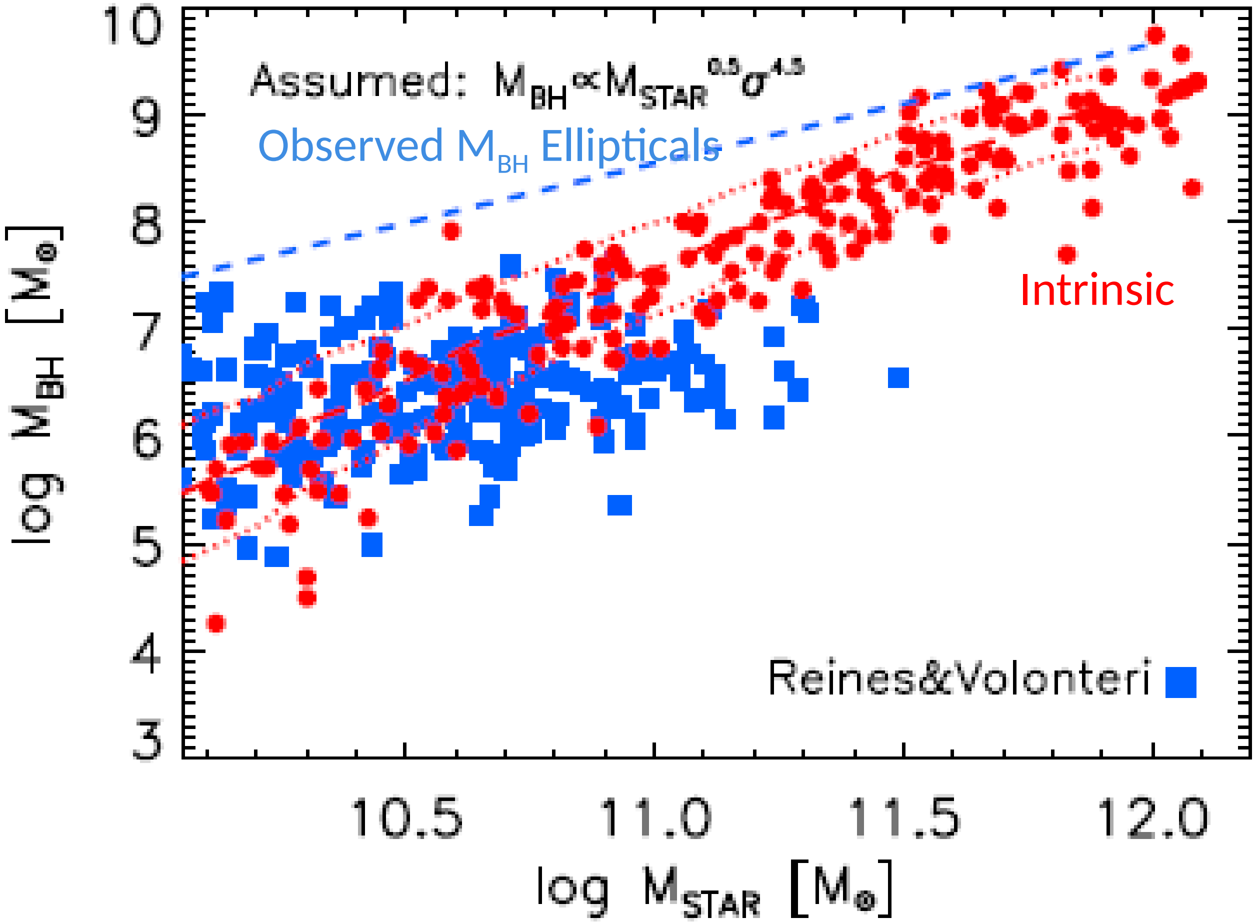
Shankar, MB et al. 2016

Discrepancy between dynamical and AGN measured M_{BH}



Reines & Volonteri 2015

Due to selection bias!

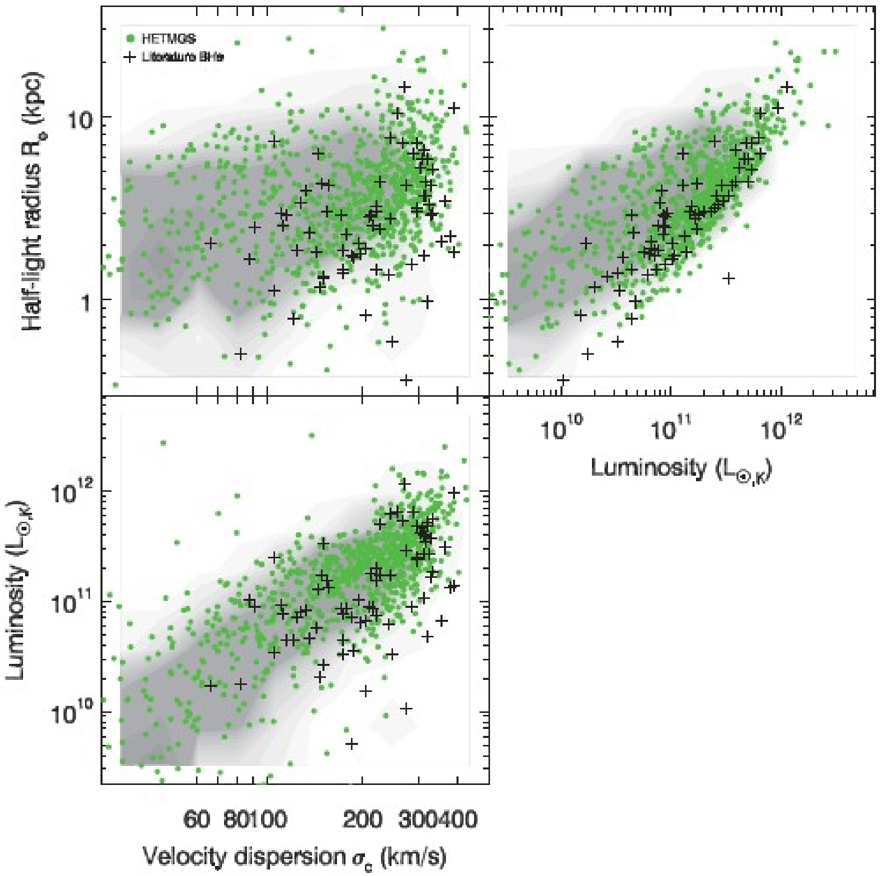


Shankar, MB et al. 2016

Implications

- Black hole masses and abundances have been overestimated
- Accounting for this brings SMBH scaling relations into better agreement with those for AGN
- Smaller M_{BH} → smaller AGN feedback

  → consistent with higher M_*?
- Predicted Pulsar Timing Array (PTA) gravity wave signal 3x smaller



Need larger telescopes to remove bias from observed samples of SMBH

Conclusions

- Sky-subtraction + Sersic/SerExp fits suggest more massive galaxies than previously thought:
  - impacts HOD/SHAM M_*-M_{halo} relations
  - reduces required feedback at high M
  - ELTs will give (low surface-brightness) → ICL/evolution
- IMF gradients bring M_*^{dyn} and M_*^{SP} into agreement by decreasing M_*^{dyn}
  - ELTs will allow analysis of IMF gradients for individual galaxies + evolution
- Bias in SMBH samples having dynamically measured masses leads to overestimate of M_{BH}
  - ELTs will return bigger samples with fewer selection effects