Gas dynamics and angular momentum of star-forming galaxies

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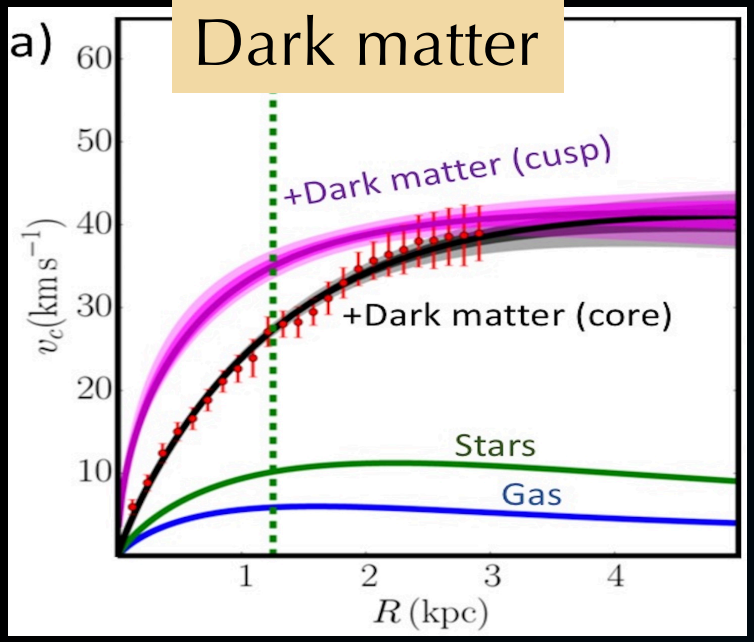
Importance of gas dynamics

Dark matter

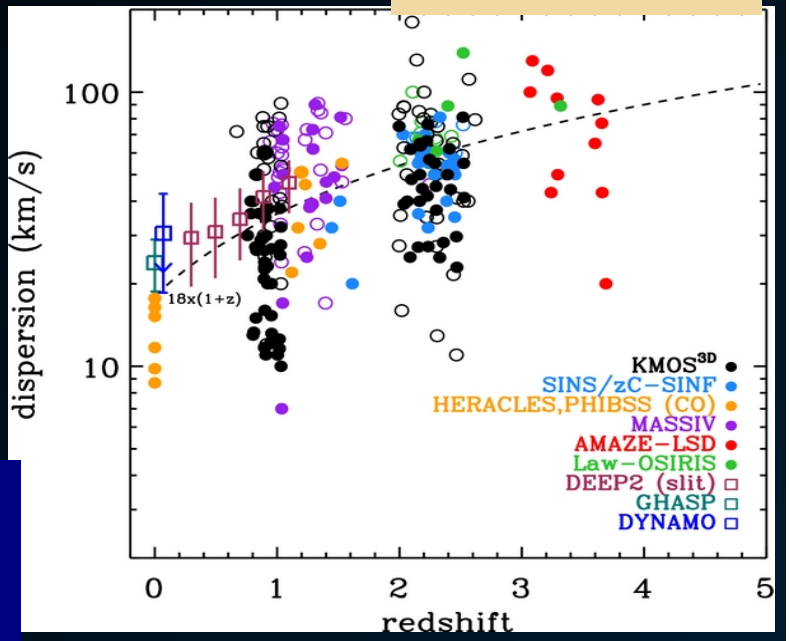


Read, Iorio, Agertz & Fraternali 2016

$$V_c^2(R) = -R\left(\frac{\partial \Phi(R,z)}{\partial R}\right)_{z=0}$$

van Albada et al. 1985

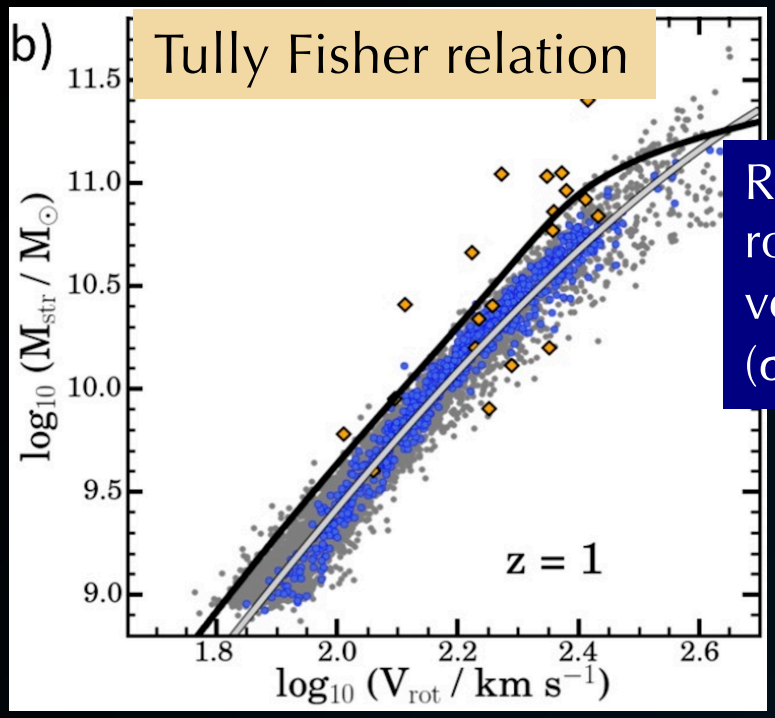
Turbulence



Wisnioski et al. 2015

Turbulent discs at high-z?
Formation of thick discs?

Tully Fisher relation



Ferrero et al. 2017

Reliable measures of rotation (v_c) and velocity dispersion (σ) needed!

Angular momentum

Di Teodoro & Fraternali, MNRAS, 2015

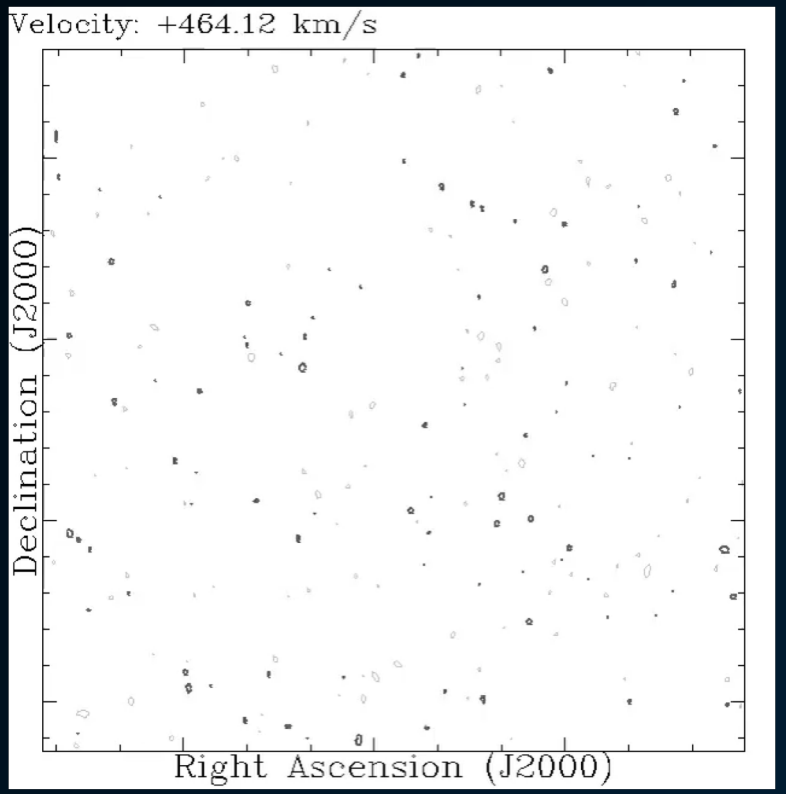
Enrico Di Teodoro
(ANU, Canberra)

BBAROLO

3D Based Analysis of Rotating Objects via Line Observations

- Generating 3D realization of the tilted ring model
- Convolves with PSF -> no beam smearing
- No parametric functions (like arctan)
- Source detection + Initial parameters estimate

V_{rot} (R)
σ (R)



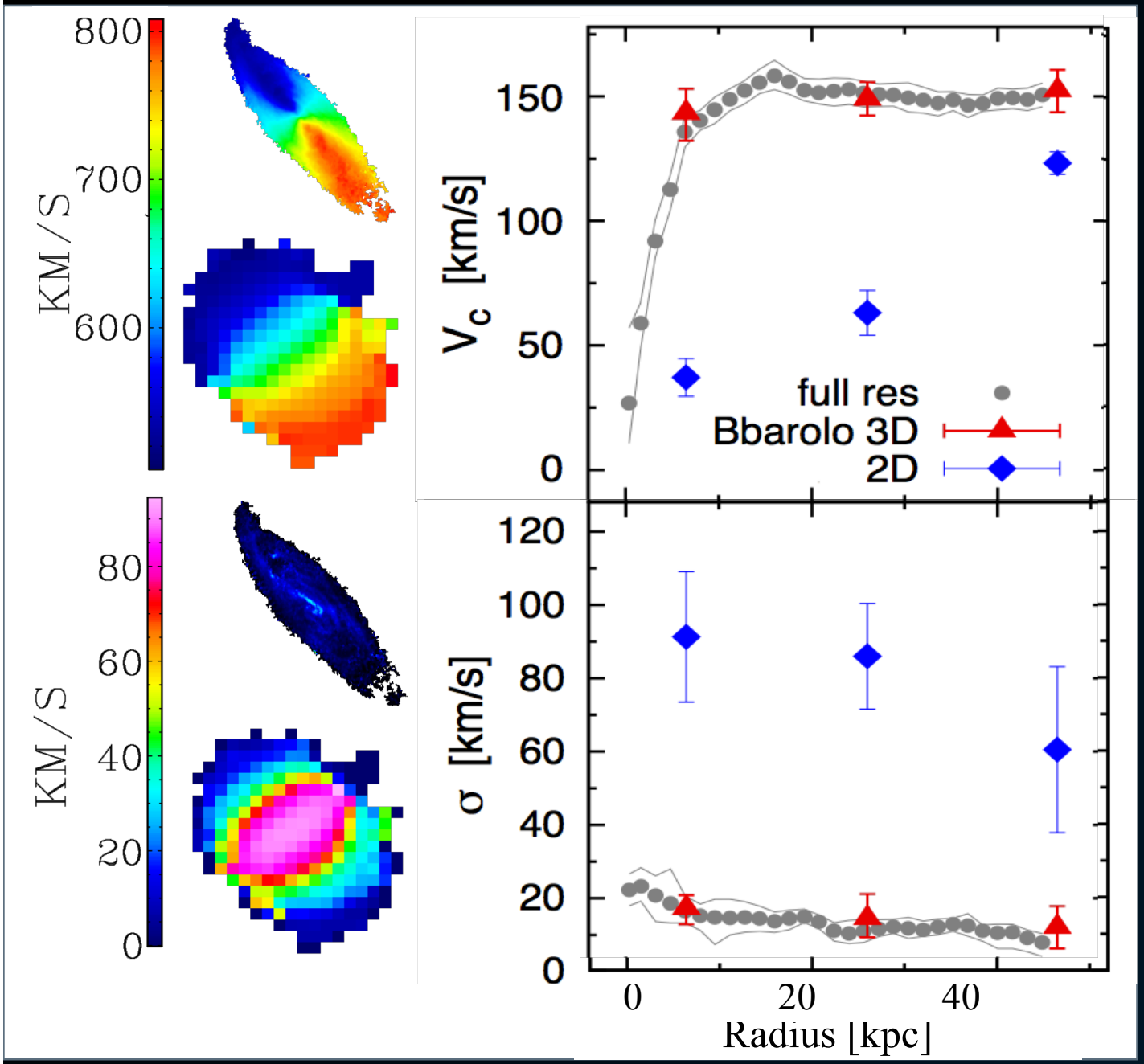
HI (VLA, WSRT…)
CO/[CI]/[CII] high-z (ALMA)
CO low-z (ALMA, VLA)
Ha, [OII], [OIII] (KMOS, SINFONI, MUSE)
Simulated galaxies (Apostle, RAMSES…)

Publicly available : http://editeodoro.github.io/Bbarolo/

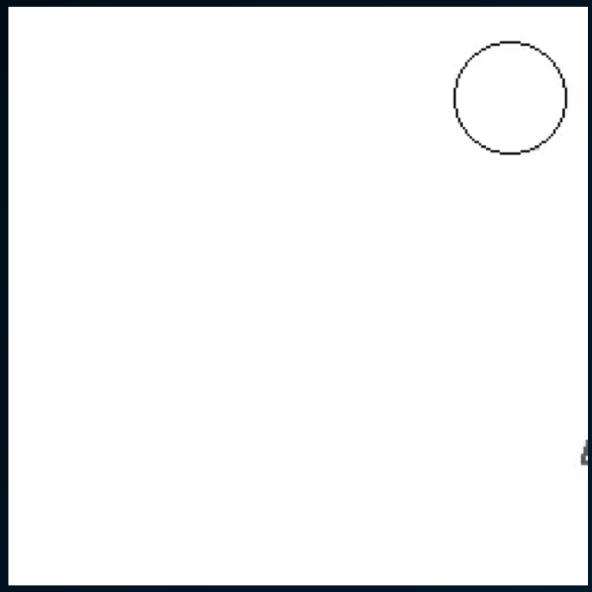
Filippo Fraternali (Kapteyn Institute)

University of Surrey, 23rd May 2019

^{3D}BAROLO AT VERY LOW RESOLUTION



NGC 3198
(Effelsberg)



Model

Data

^{3D}Barolo kills beam smearing

18 galaxies at z~1 with KMOS

Di Teodoro, Fraternali & Miller 2016, MNRAS, A&A 594, A77

Filippo Fraternali (Kapteyn Institute)

University of Surrey, 23rd May 2019

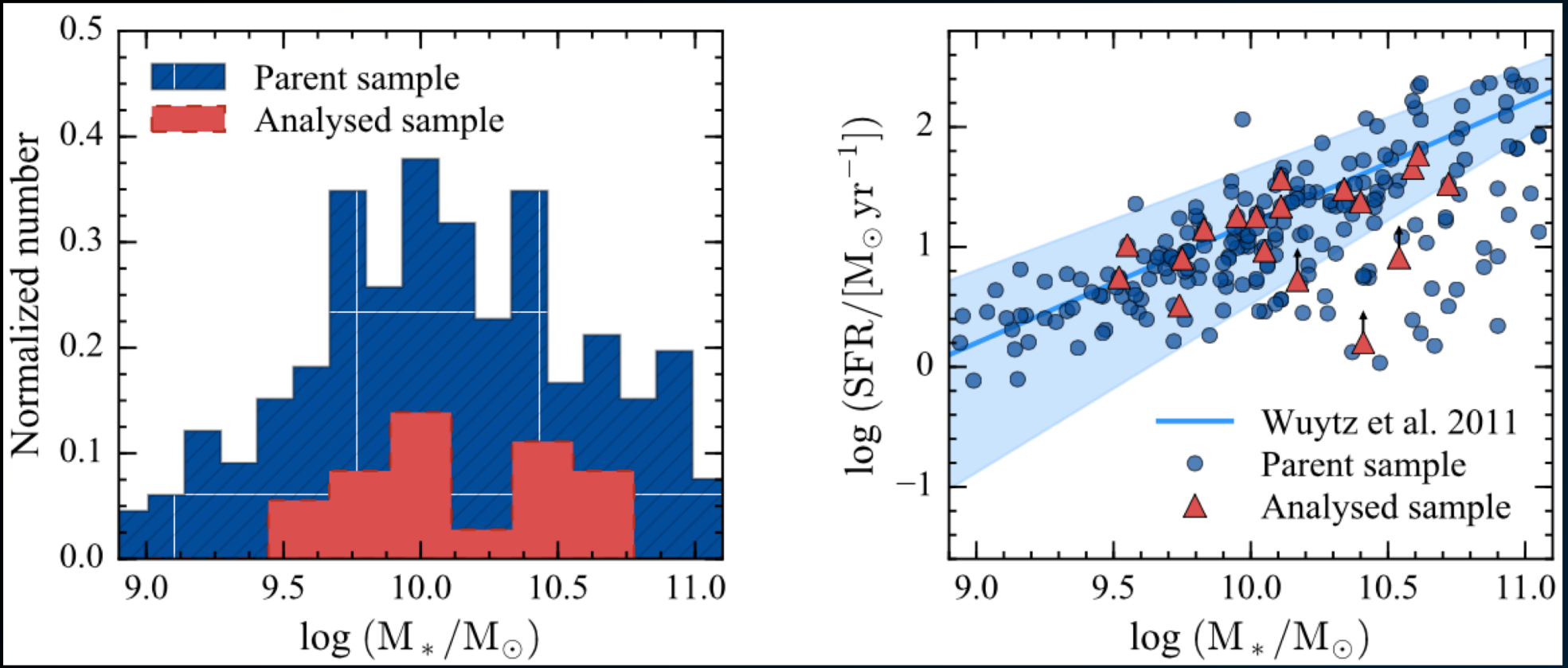
KMOS STAR-FORMING GALAXIES @ $z \sim 1$

18 galaxies observed with KMOS, Hα at $0.85 < z < 1$

From KROSS and KMOS^{3D} surveys (public data in the ESO archive)

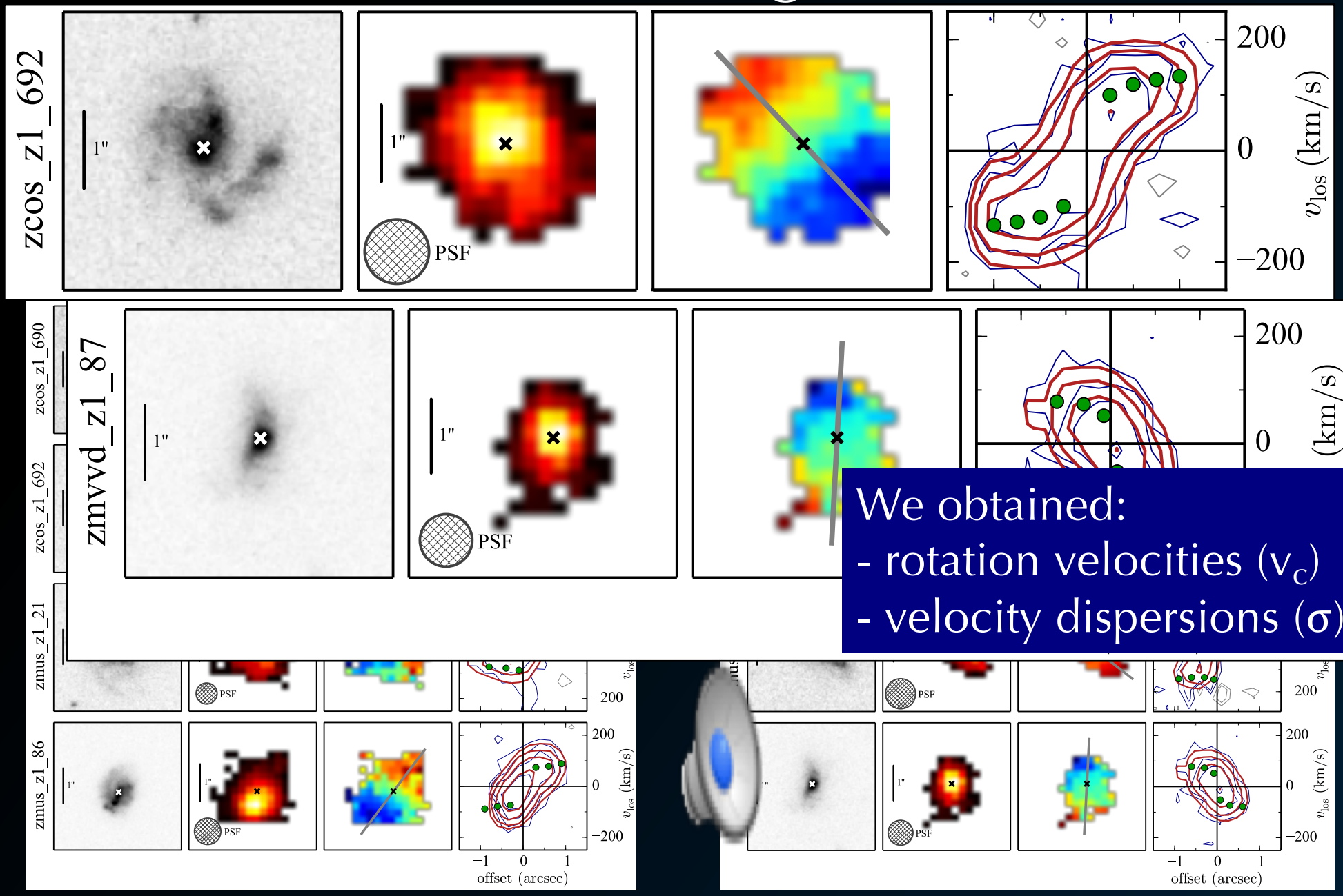
Stott et al. 2016, Wisnioski et al. 2015

Main sequence



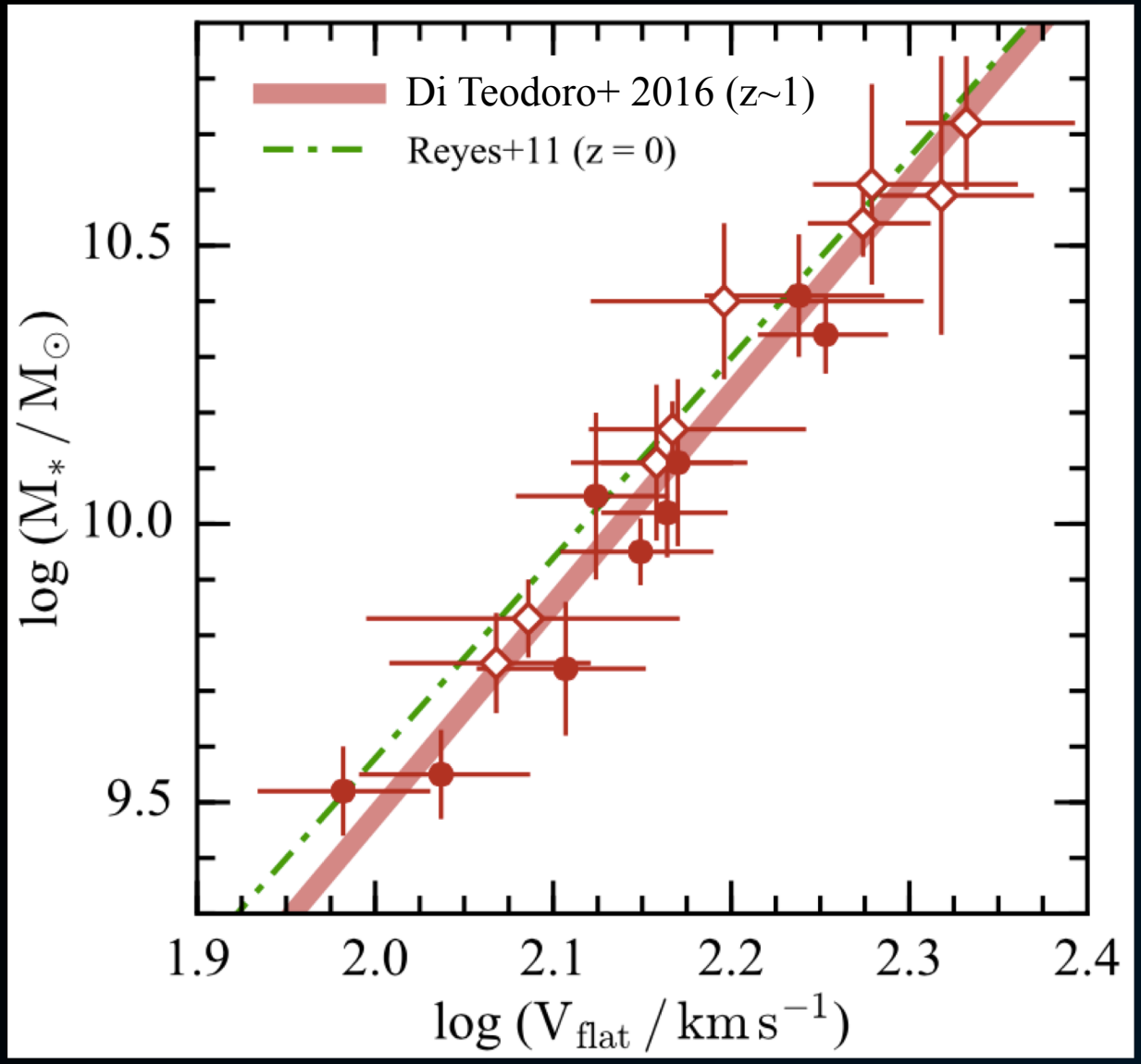
Di Teodoro, Fraternali & Miller 2016, A&A

OUR KMOS galaxies



We obtained:
- rotation velocities (v_c)
- velocity dispersions (σ)

OUR Tully Fisher relation at z~1



Full circles: inclination > 50º (very reliable)

-> No significant evolution

Slope ~ 3.8

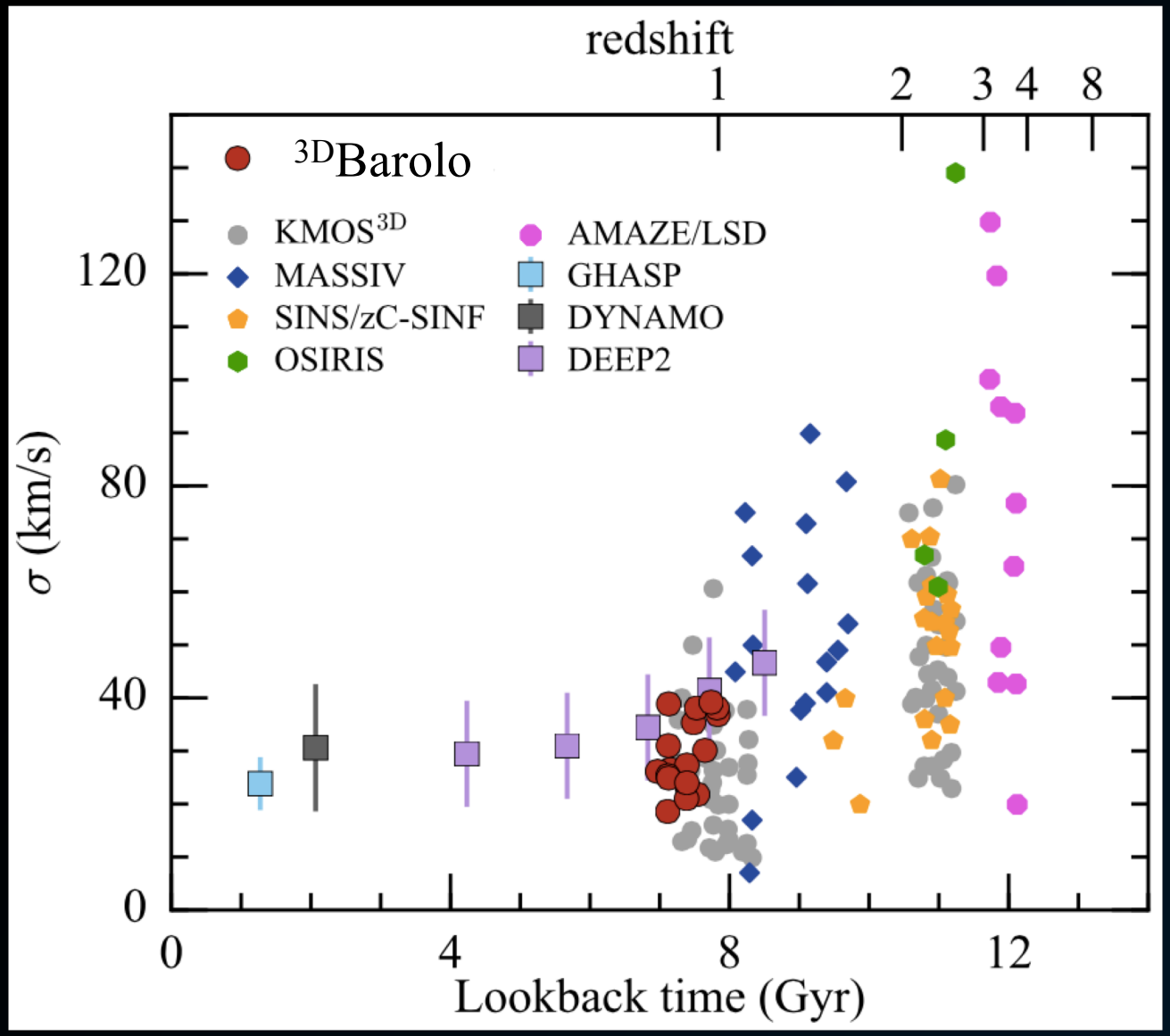
Different from *e.g. Simons et al. 2016; Tiley et al. 2016; Uebler et al. 2017*

In agreement with *e.g. Miller et al. 2011, Pelliccia et al. 2016, Harrison et al. 2017*

>~50-70% baryonic matter

Stellar masses from CANDELS (*Santini et al. 2015*) or COSMOS/3D-HST

Dispersion vs redshift



Same turbulence as local spirals

$\langle\sigma\rangle$ = 29 km/s

V/σ = 3-10

(thin?) disks settled at z~1

Di Teodoro, Fraternali+ 2016

Our σ are <u>averages</u> across the disc

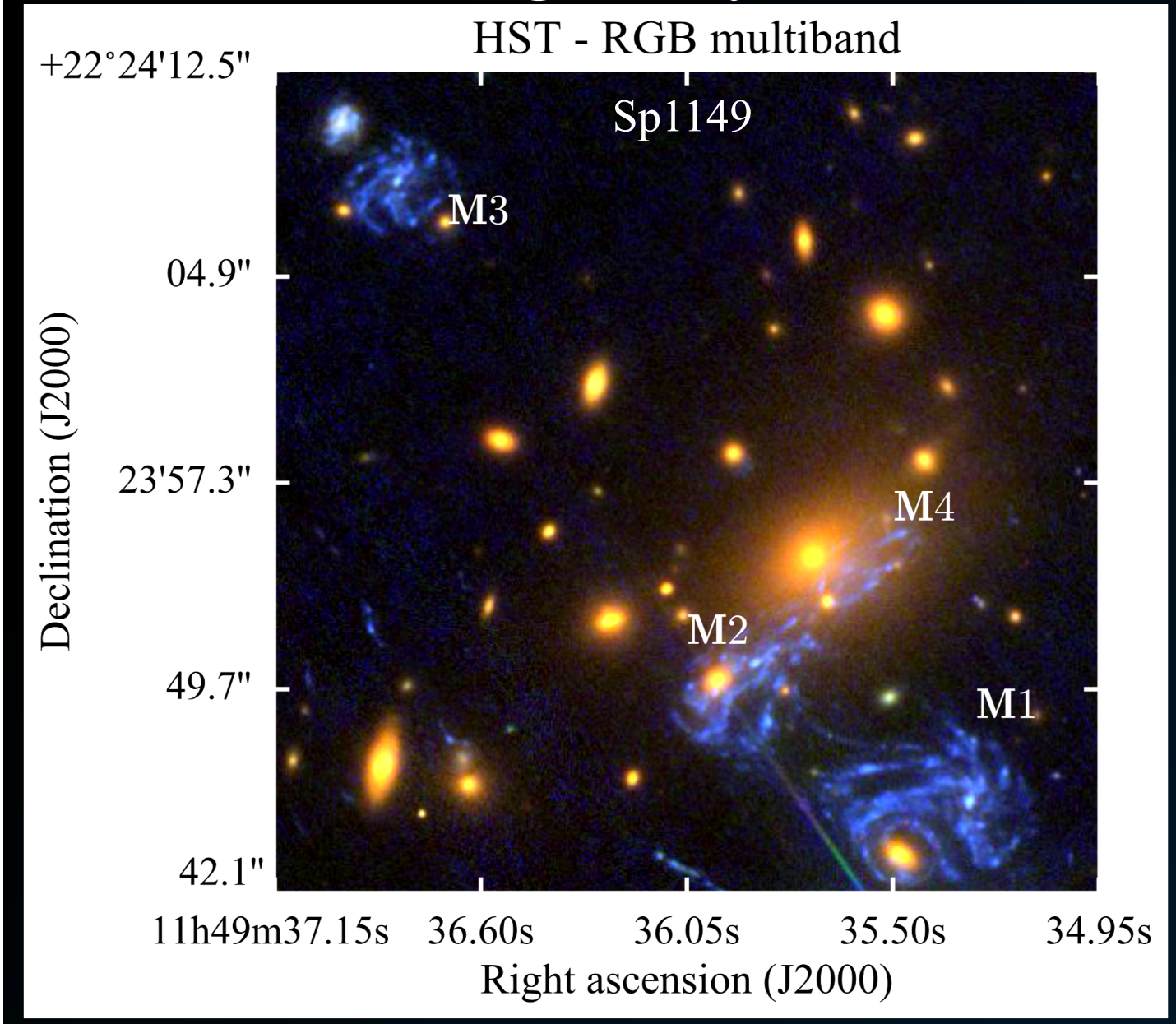
A wonder galaxy z=1.5 with MUSE

Di Teodoro, Grillo, Fraternali et al. 2018, MNRAS, 476, 804

Filippo Fraternali (Kapteyn Institute)

University of Surrey, 23rd May 2019

Lensed galaxy at z=1.49



Lensed by galaxy cluster MACS1149.5+2223 (z=0.544)

4 multiple images

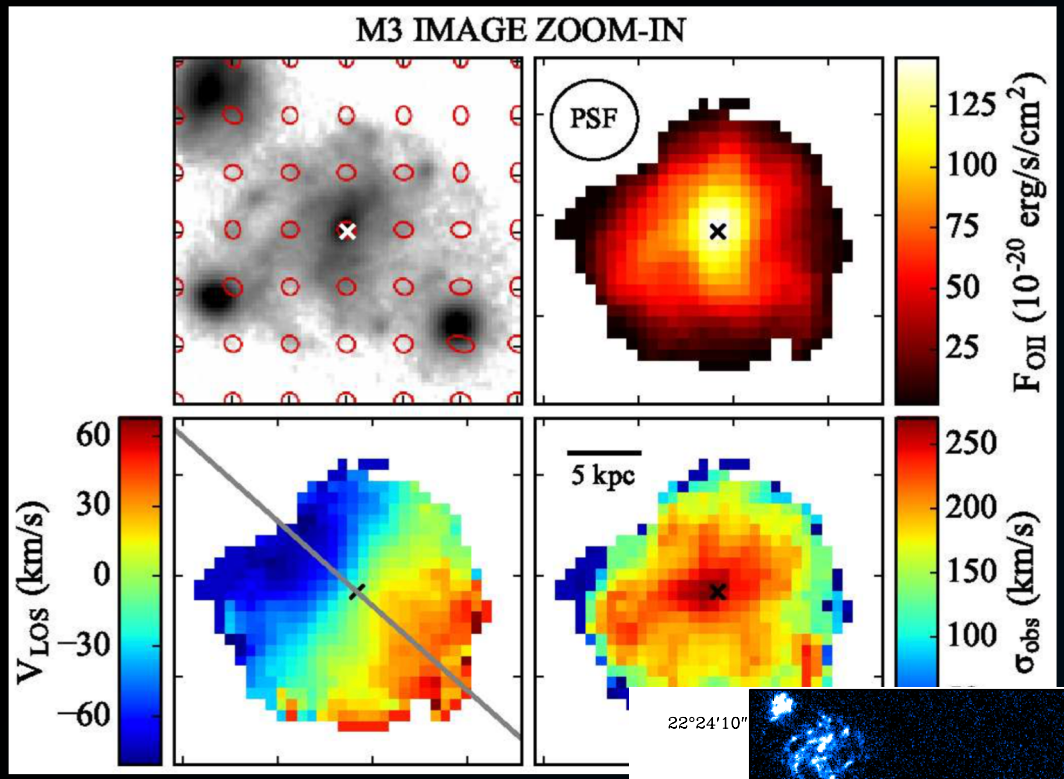
Global flux magnification ~ 20-25

Stellar mass 5×10^{10} $M_\odot$
SFR = 1-6 $M_\odot$/yr

Progenitor of the MW!

Zitrin & Broadhurst 2009; Grillo et al. 2016; Karman et al. 2016; Di Teodoro et al. 2018

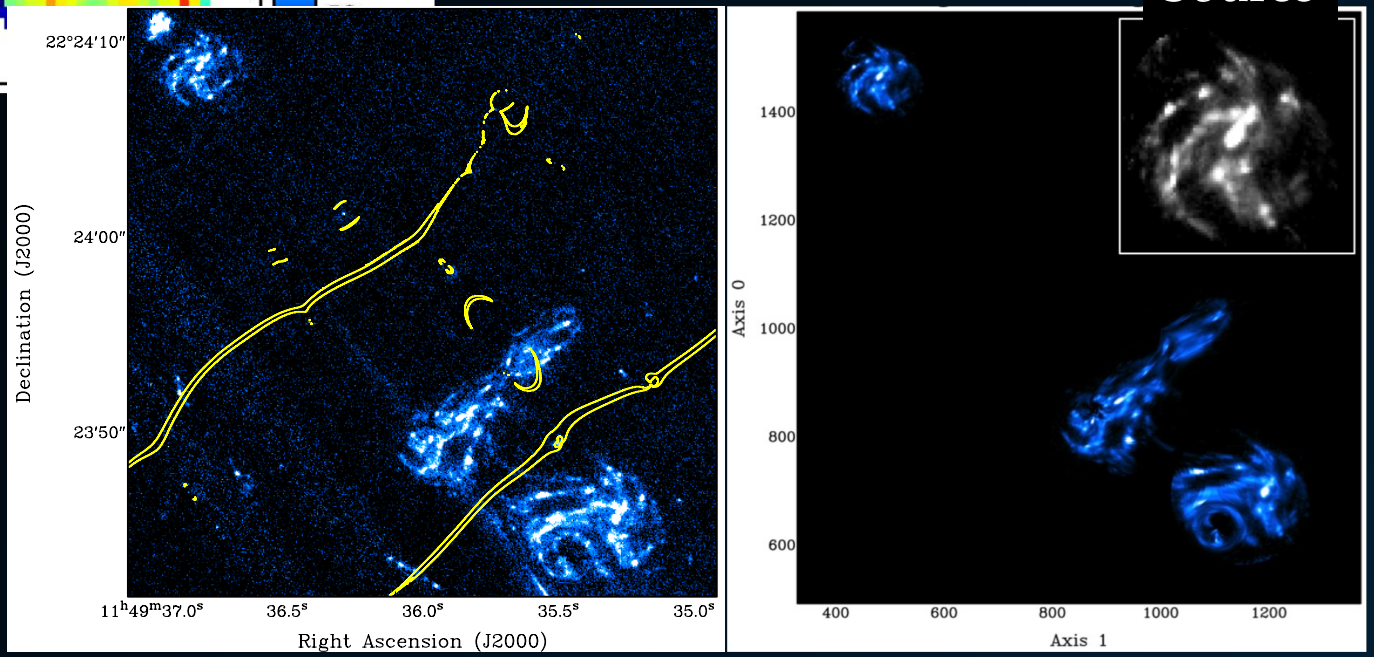
MUSE data of M3 image



[OII] doublet

Highly magnified:
Flux factor 4
Size factor 2
-> less beam smearing!

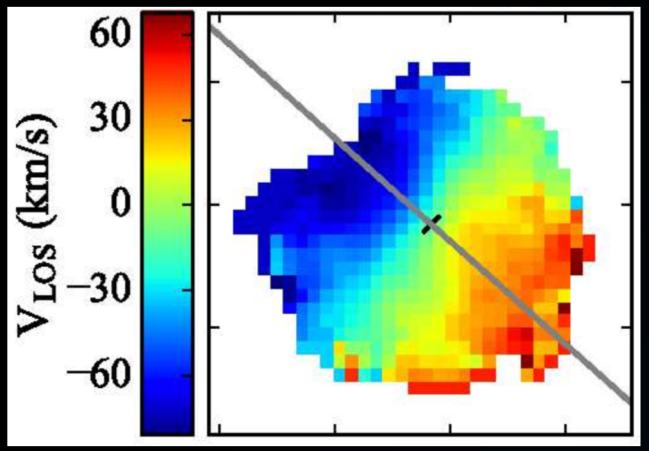
Lens model



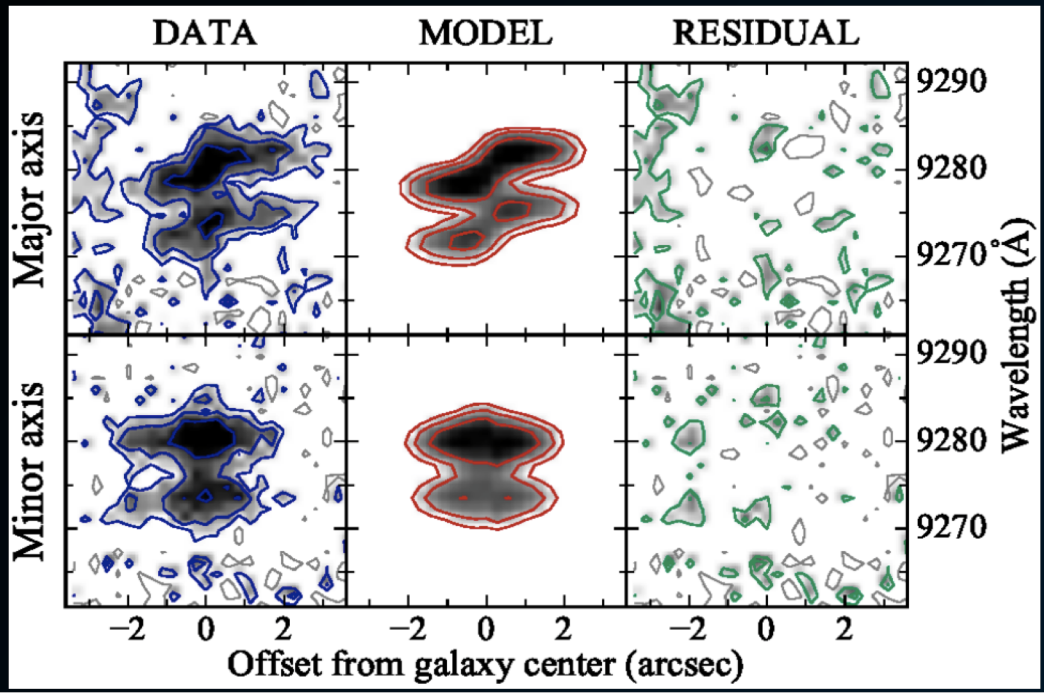
Essentially no distortion
-> work on image plane

Grillo et al. 2016

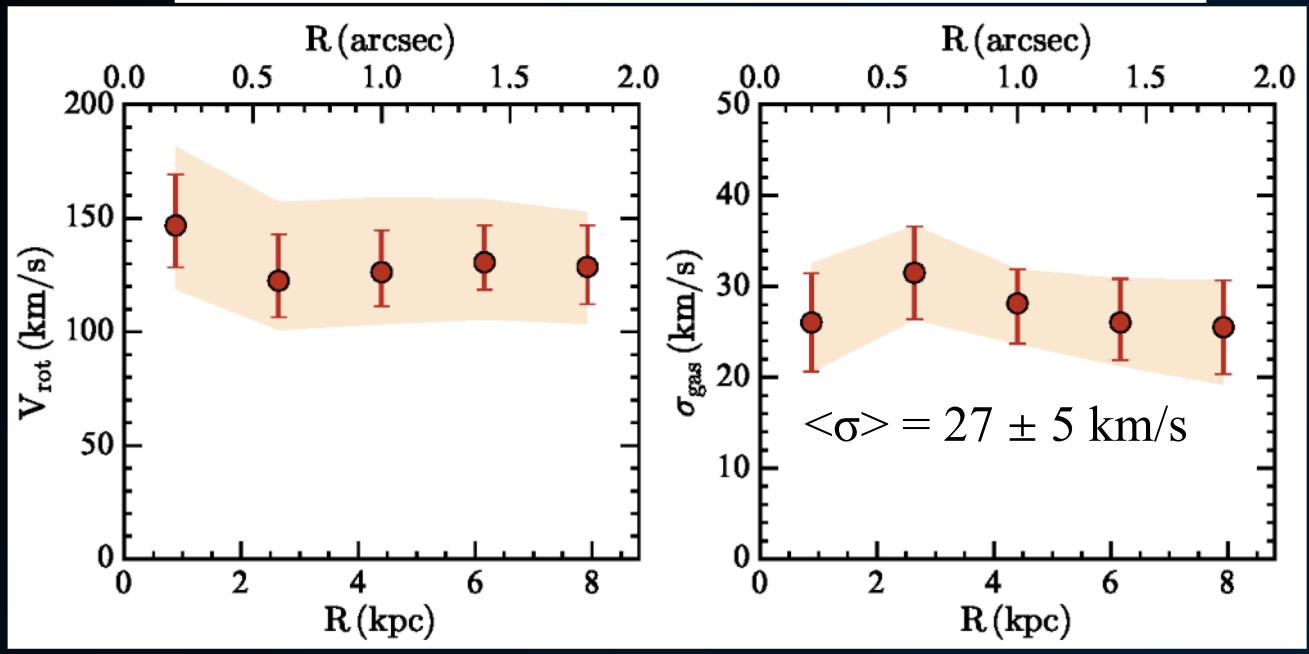
Rotation and dispersion in sp1149



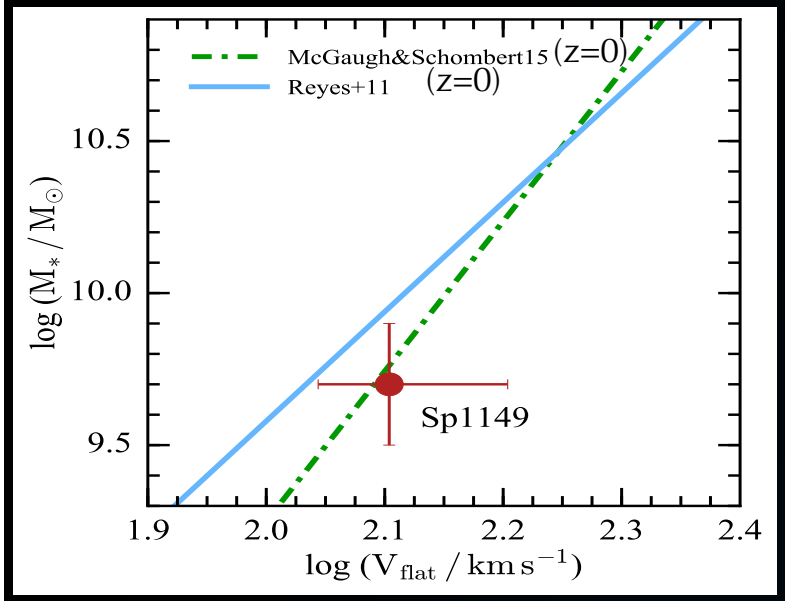
Di Teodoro, Grillo, Fraternali et al, MNRAS



Low inclination ~ 35°
->
Uncertain v_{rot}
Good vel dispersion!



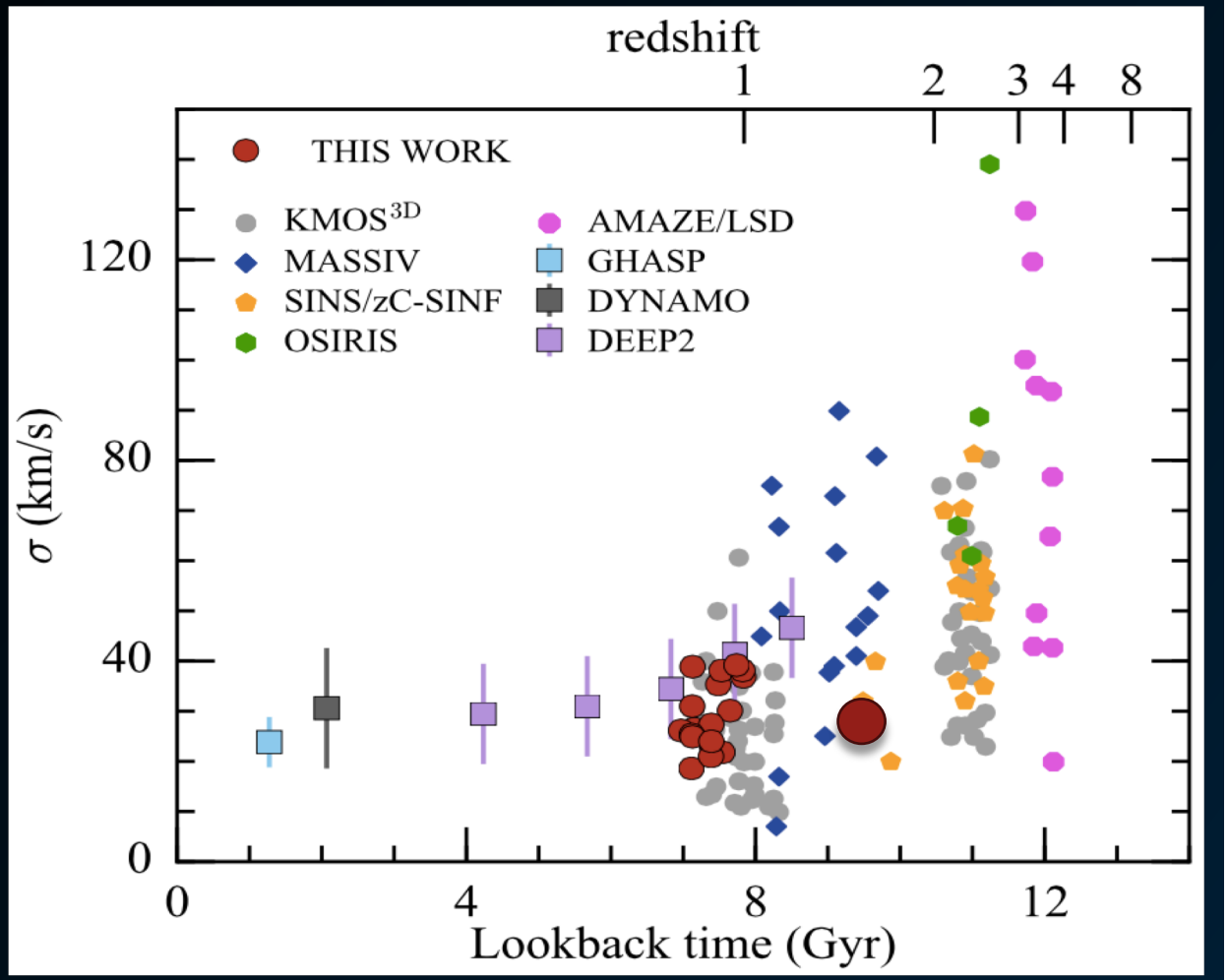
Tully-Fisher & σ-z relations



Tully-Fisher

Note uncertainties also at z=0

High-z discs not so turbulent if you measure the intrinsic velocity dispersion



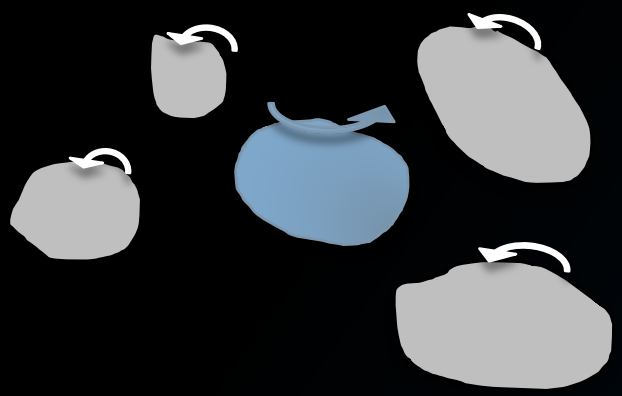
Our σ are averages across the disc

Angular momentum in galaxies

Filippo Fraternali (Kapteyn Institute)

University of Surrey, 23rd May 2019

Tidal torques and dissipative collapse



At turnaround (before virialization)
External tidal field -> torques -> angular momentum

Peebles 1969

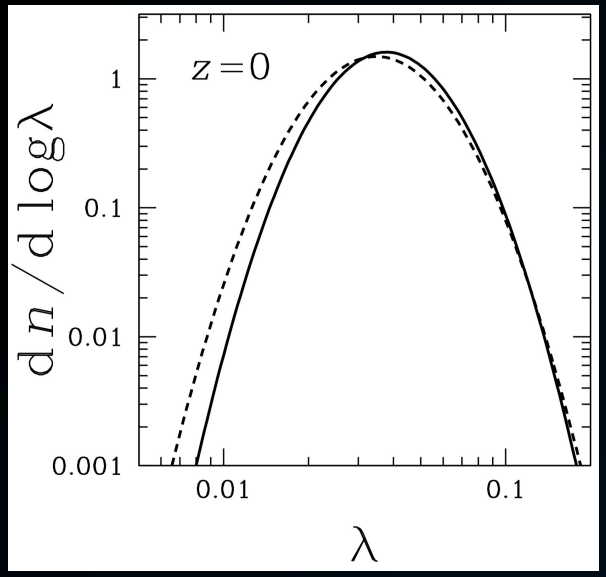
Dark matter and baryons experience the same torques

Same specific angular momentum: *j*

Lambda parameter

$$\lambda \equiv \frac{J|E|^{1/2}}{G\mathcal{M}_{\Delta}^{5/2}} \quad \rightarrow \quad \lambda = \frac{j_{\rm DM}}{\sqrt{2}\, r_{\rm vir} v_{\rm vir}}$$

If $\lambda << 1$ -> no rotational support



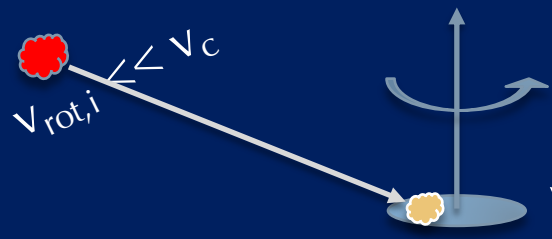
Cimatti, Fraternali & Nipoti 2019, CUP

$\lambda \sim 0.035$

From DM-only simulations

Constant with mass and *z*

BUT gas cools! -> Dissipative collapse

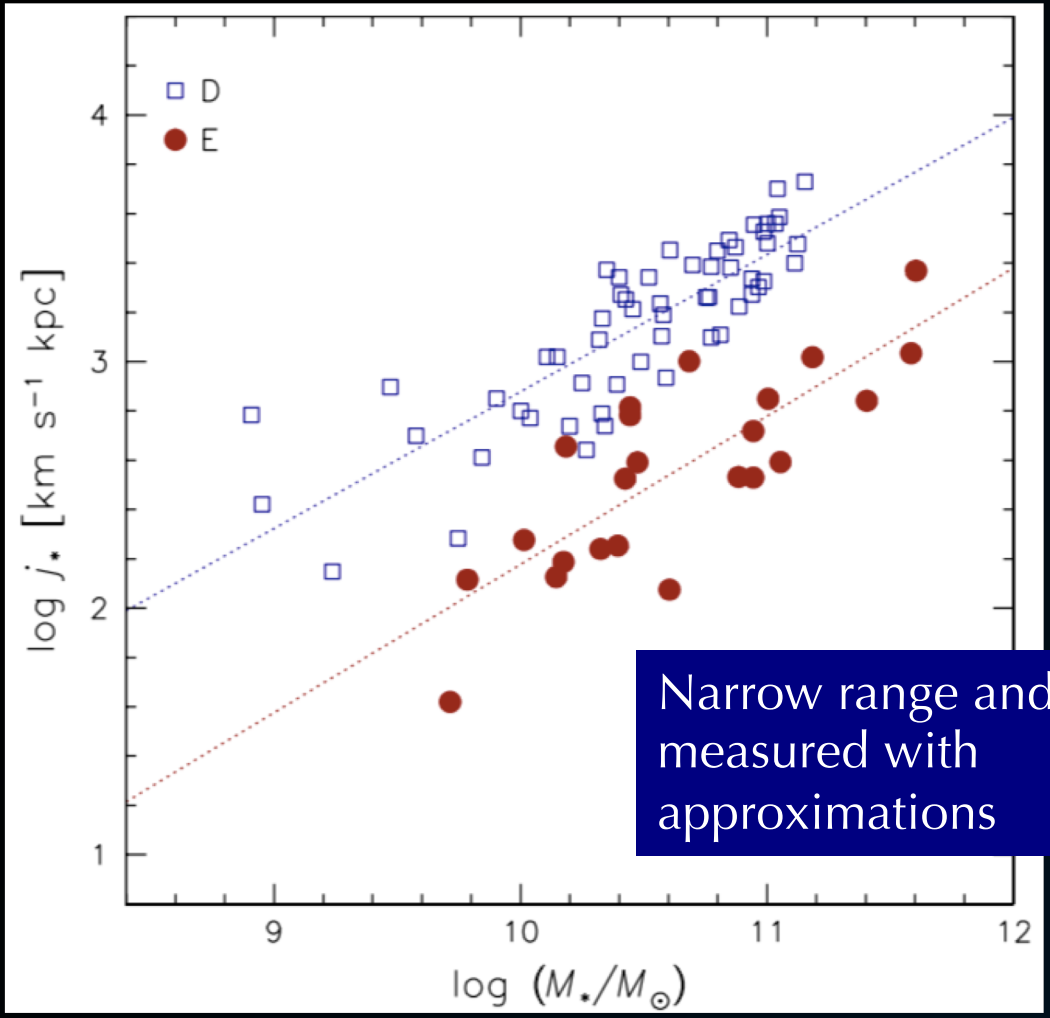


Works if

1) Ri >> Rf ($j = v_{rot} R$)
2) gas conserves angular momentum

Fall & Efstathiou 1980

j-M (Fall) relation



Fall & Romanowsky 2013

Narrow range and j measured with approximations

Slope ~ 0.6
Normalization Ellipticals ~1/5 Discs

$$\lambda = \frac{j_{\rm DM}}{\sqrt{2}\, r_{\rm vir} v_{\rm vir}}$$

$$r_{\rm vir} = A \mathcal{M}_{\rm vir}^{1/3}$$

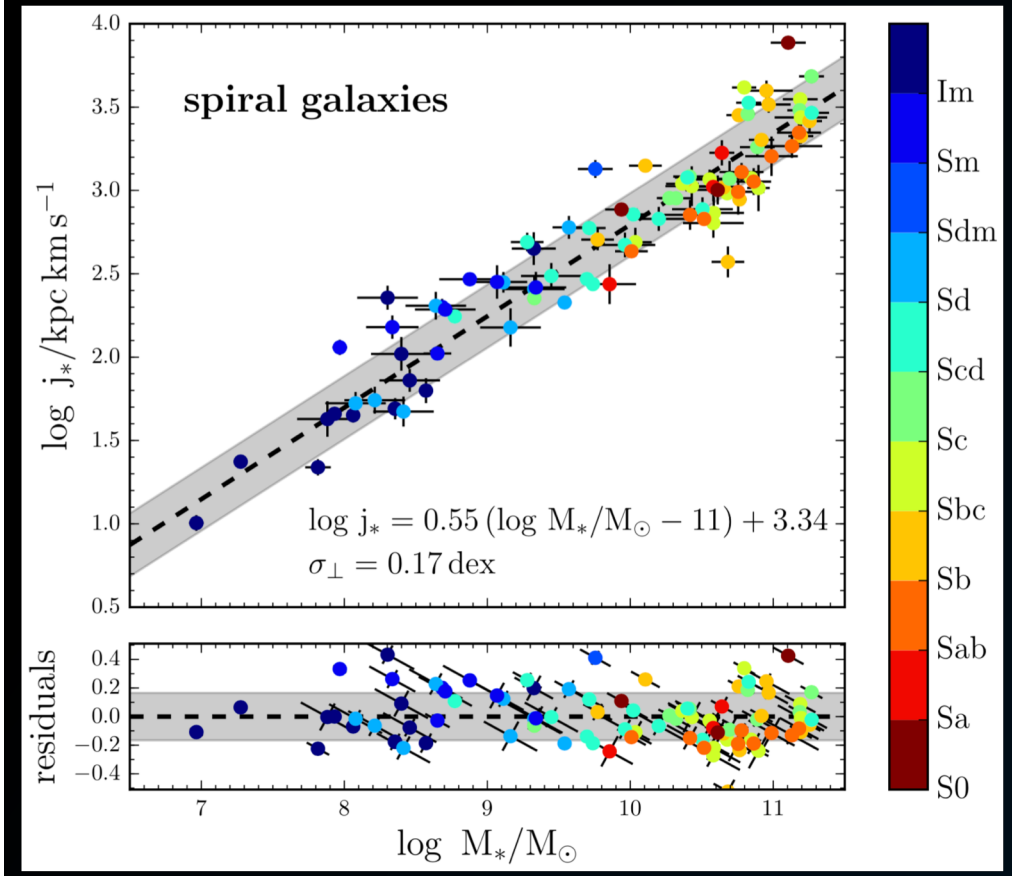
$$A(z) = \left[\frac{4\pi}{3}\Delta_{\rm c}(z)\rho_{\rm crit}(z)\right]^{-1/3}$$

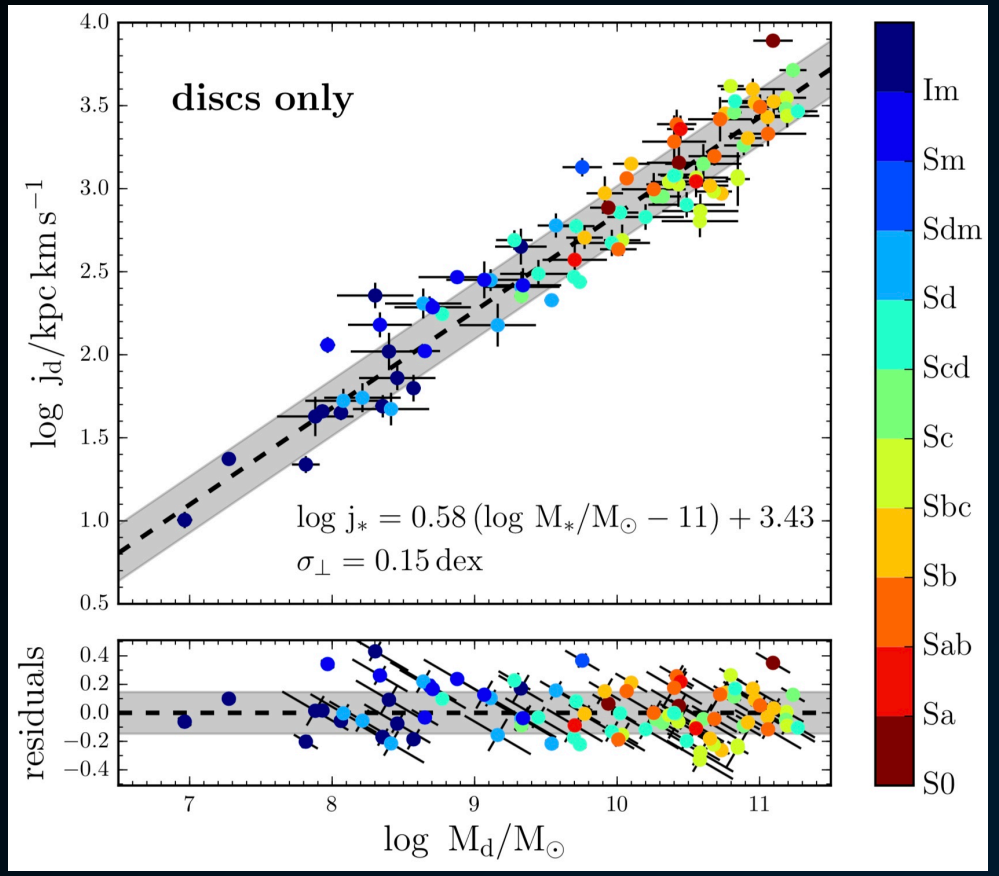
$$v_{\rm vir} = B \mathcal{M}_{\rm vir}^{1/3}$$

$$j_{\rm DM} = \frac{\lambda}{[\Delta_{\rm c}(z) H(z)^2]^{1/6}} (2G\mathcal{M}_{\rm vir})^{2/3}$$

Similar slope as the stars!

$j - M$ relation at z=0



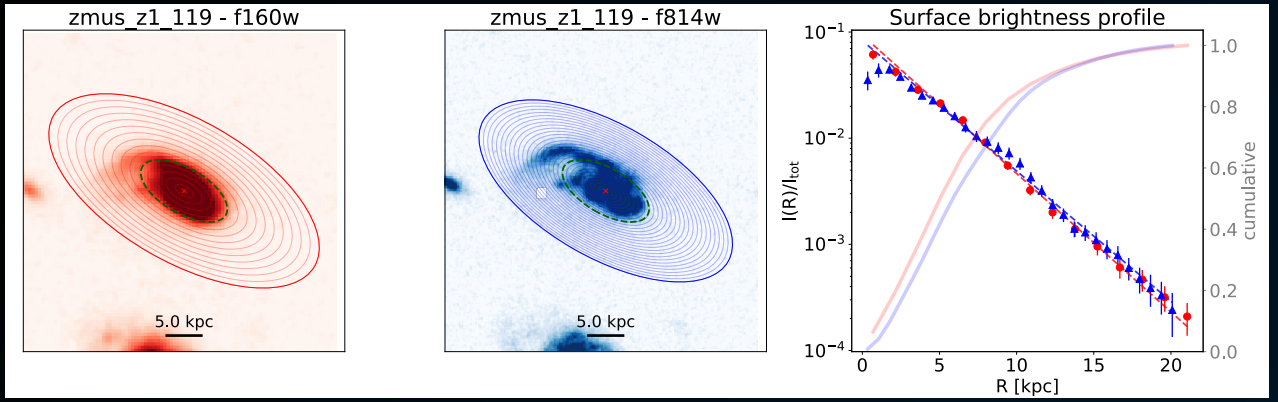


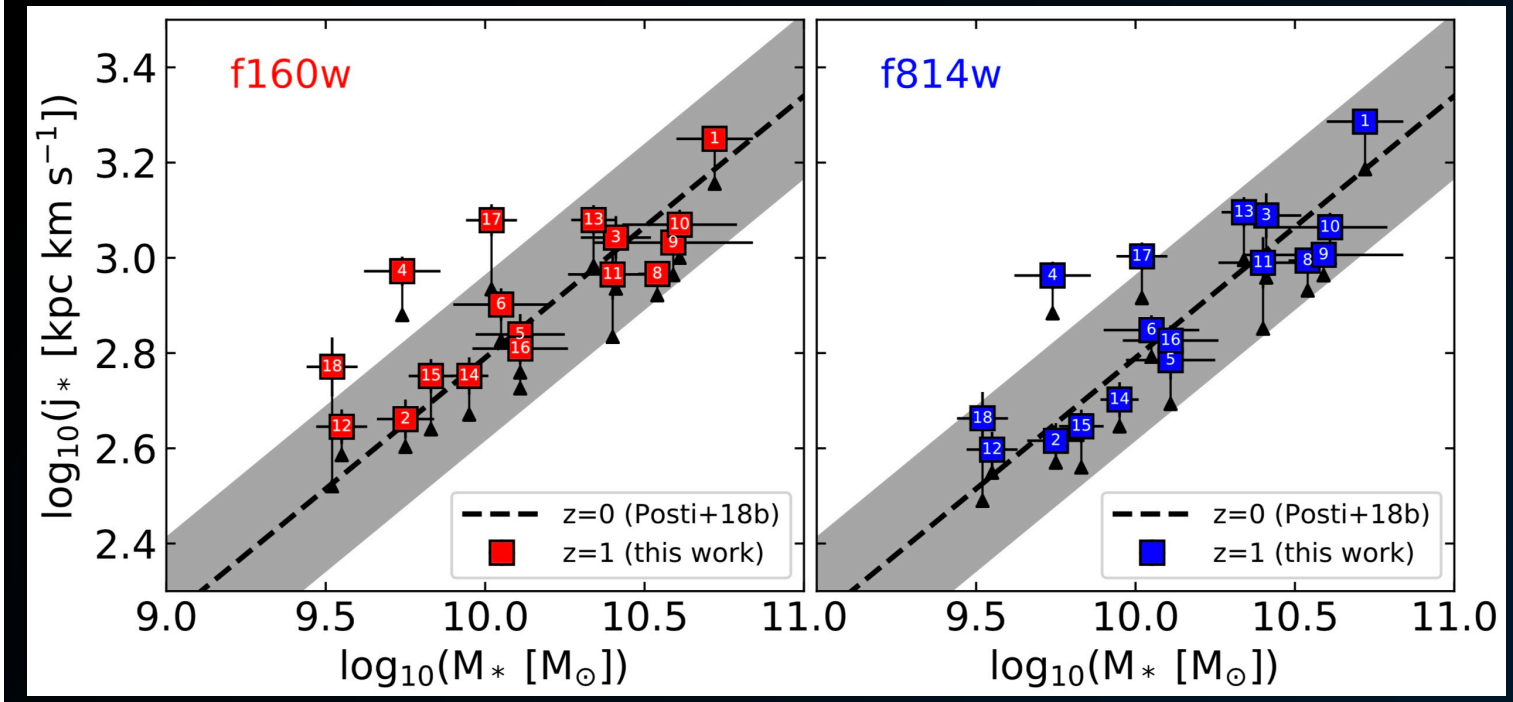
Posti, Fraternali et al. 2018

1) Slope & normalization compatible with *Romanowsky & Fall 2012, Fall & Romanowsky 2013*
2) One single power law down to 10^7 M_o

j – *M* relation at z=1

KMOS sample:
18 galaxies with
- Ha rotation curves
  ^{3D}Barolo, *Di Teodoro & Fraternali 2015*
- HST photometry





No evolution!

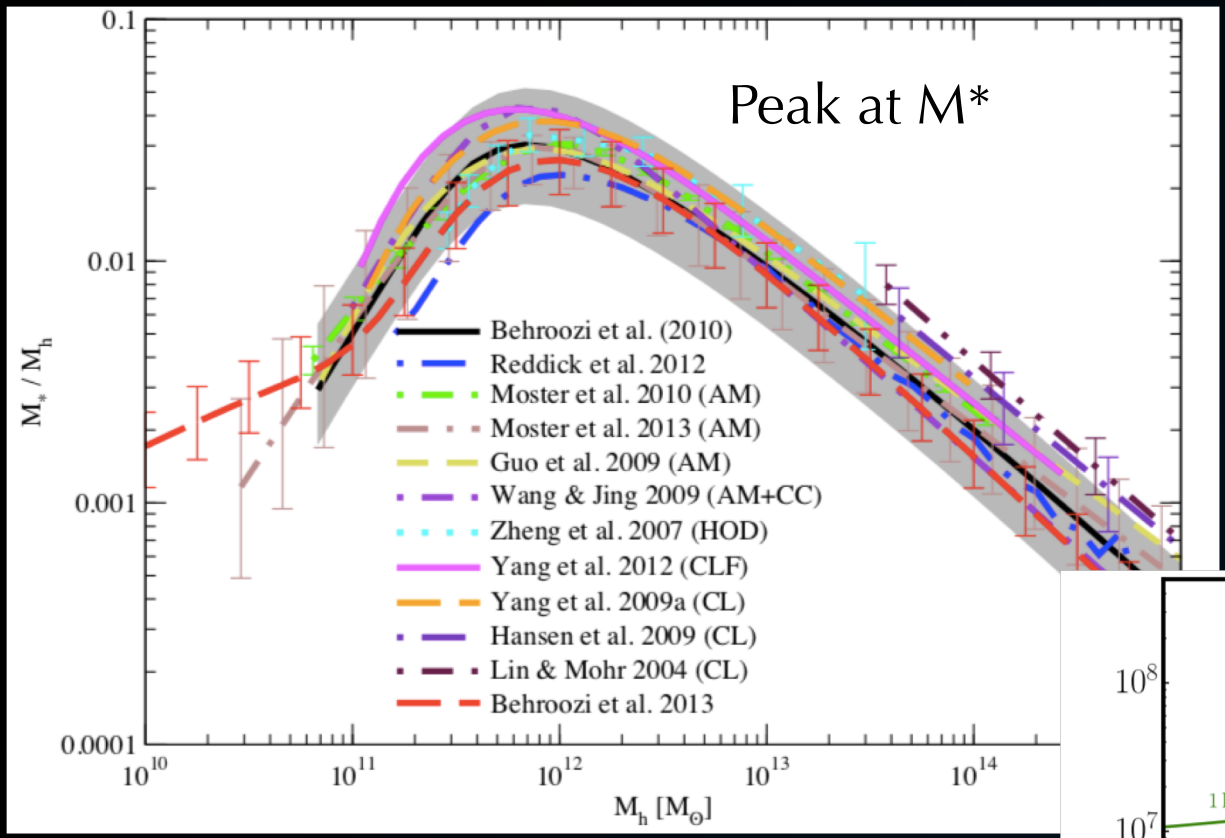
Different from *Harrison et al 2017*
-> evolution of 0.2-0.3 dex
Contini et al. 2016
-> continuum from spirals to Es

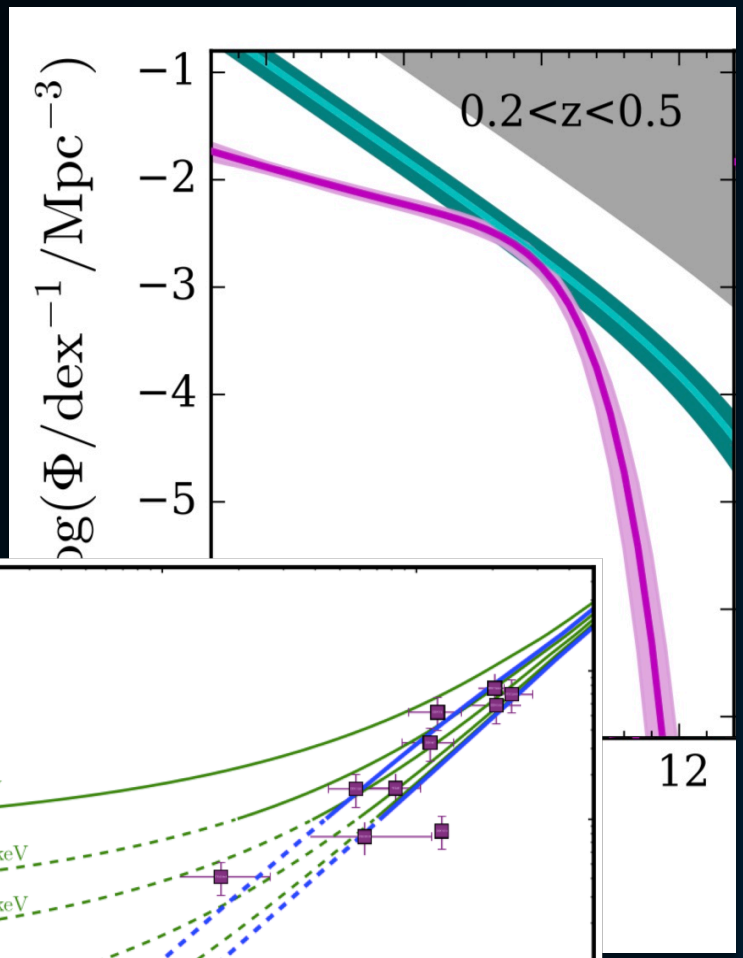
Marasco, Fraternali, et al. 2019

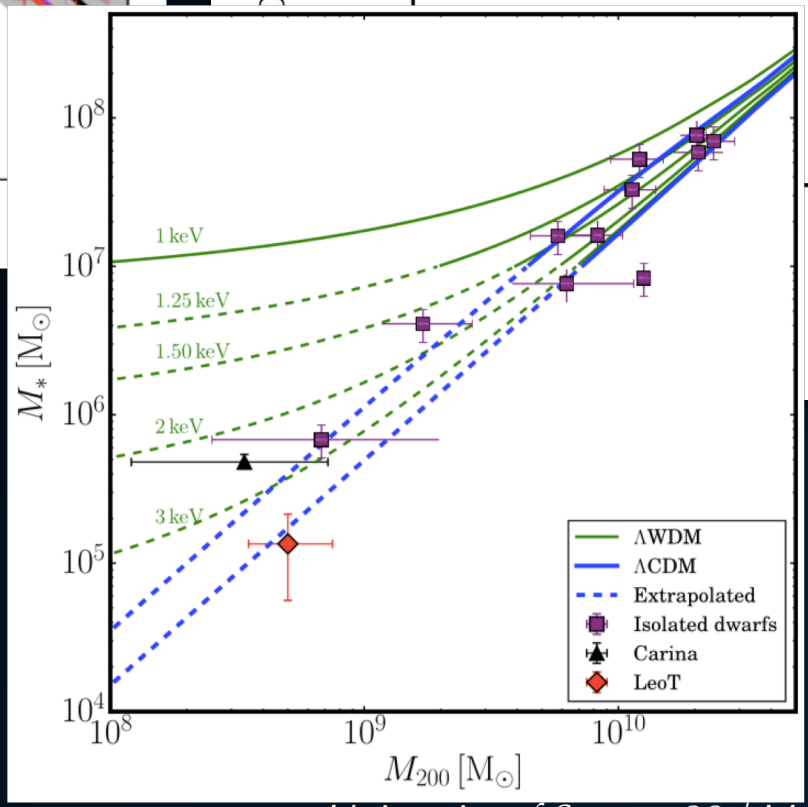
Stellar-to-halo mass relation

Filippo Fraternali (Kapteyn Institute)

Stellar-to-halo mass relation







$$f_{\mathrm{m},\star} \equiv \frac{\mathcal{M}_\star}{\mathcal{M}_{\mathrm{vir}}}$$

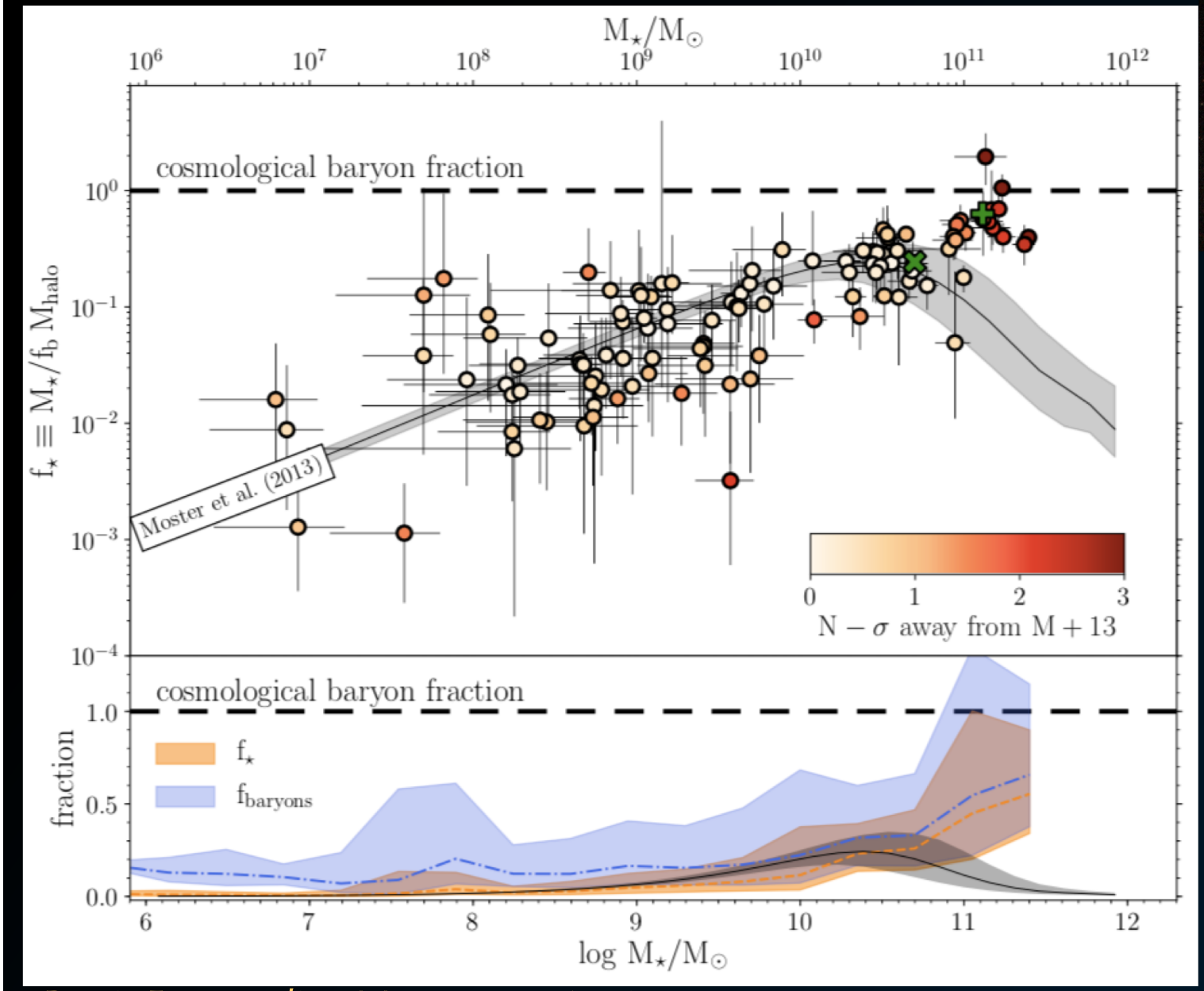
Behroozi et al.

Strong function of M_*

Rotation curve fitting

Read et al. 2017

Stellar-to-halo mass ratios



Peak is not at M*
There is no peak!

Large spirals have
– SF efficiencies up to 50-100%
– No missing baryons

Evolution of spirals not halted beyond a threshold mass of $M_{halo} \sim 6 \times 10^{11}$ (e.g. *Dekel+2009*)

Posti, Fraternali & Marasco 2019, in press

Conclusions

1. Galaxies at z =1.0-1.5 have high V/σ and lie close to z = 0 Tully-Fisher relation
2. SMGs at z = 4.5 rotating at 500 km/s
3. j-M relation one power-law, slope in agreement with TTT
4. Stellar-to-halo mass relation for spirals does not peak at M*