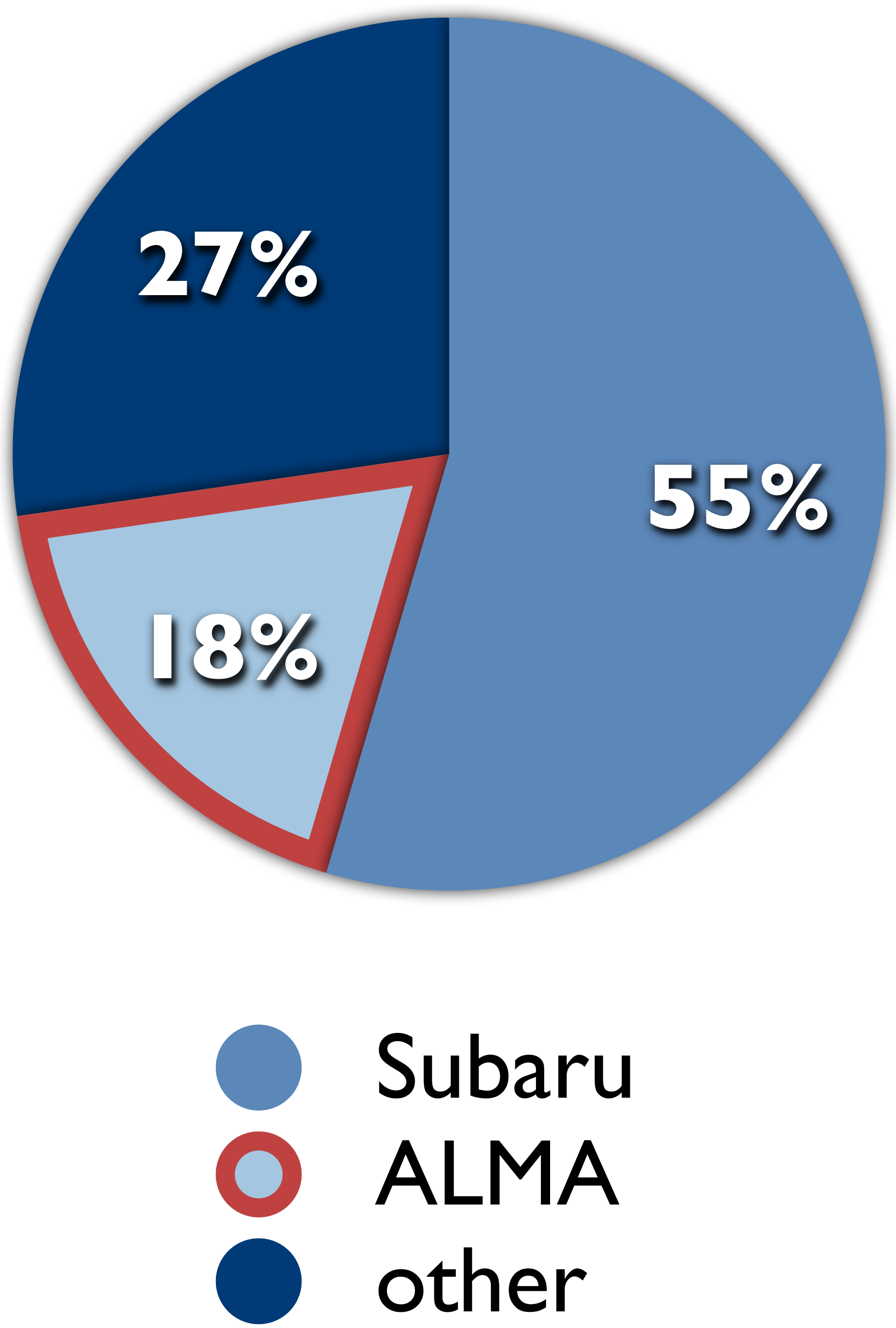
銀河進化研究会、６月７−９日、大阪大学

遠方銀河におけるガスの運動学

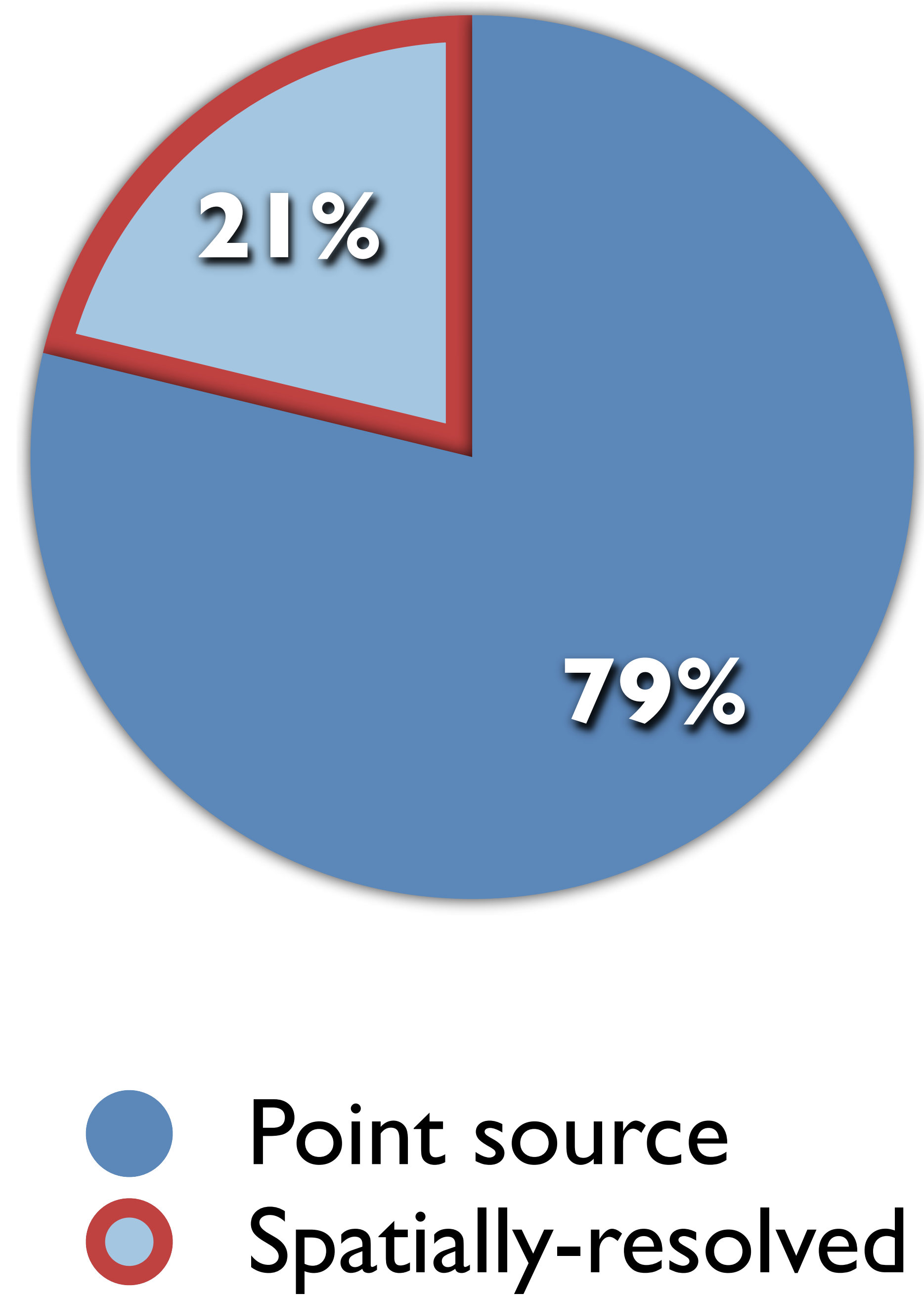
但木謙一（国立天文台）

銀河進化研究会2017の講演内容（遠方銀河観測）

望遠鏡

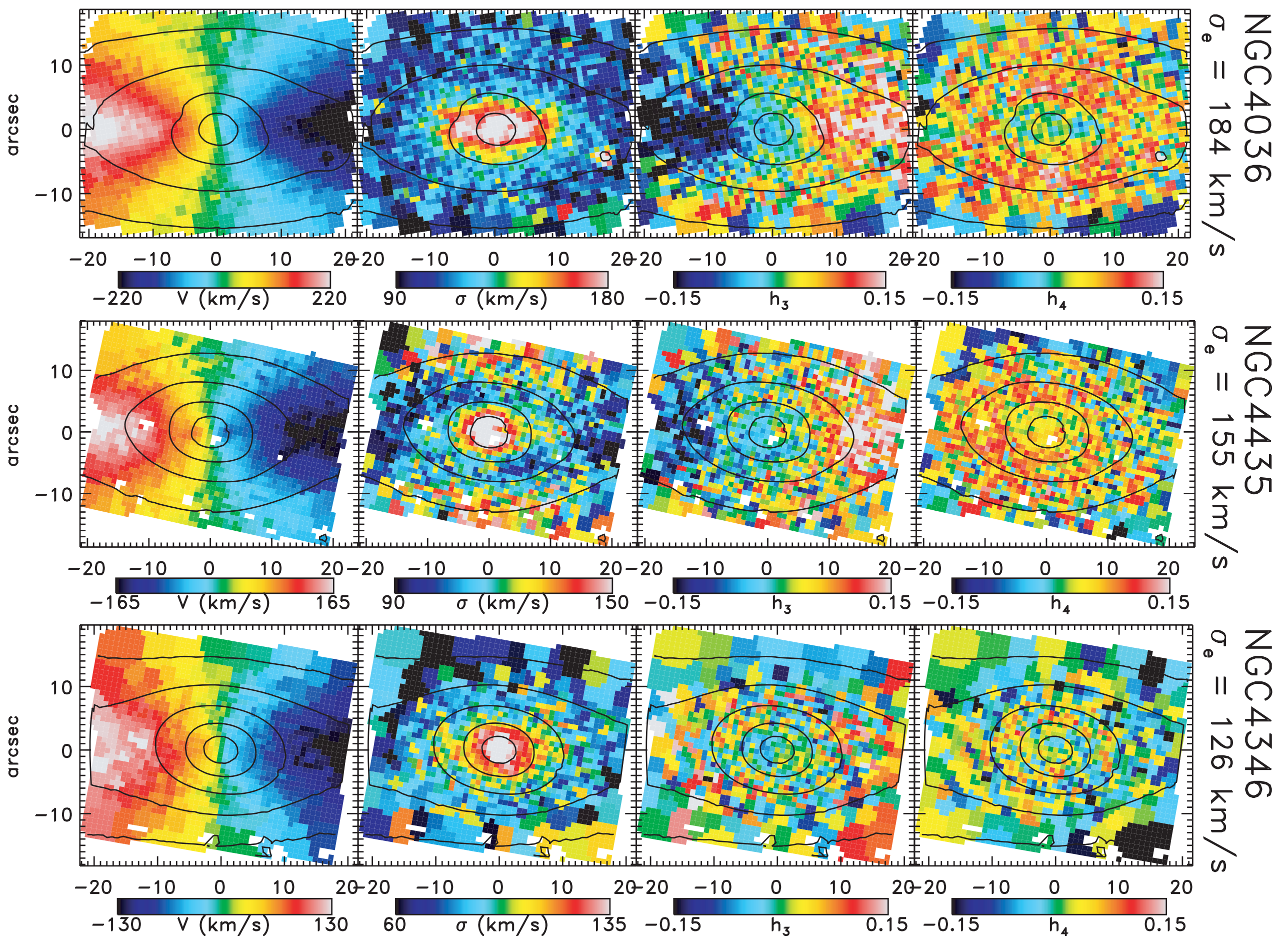


空間分解能



近年の運動学的研究におけるマイルストーン

ATLAS^{3D}



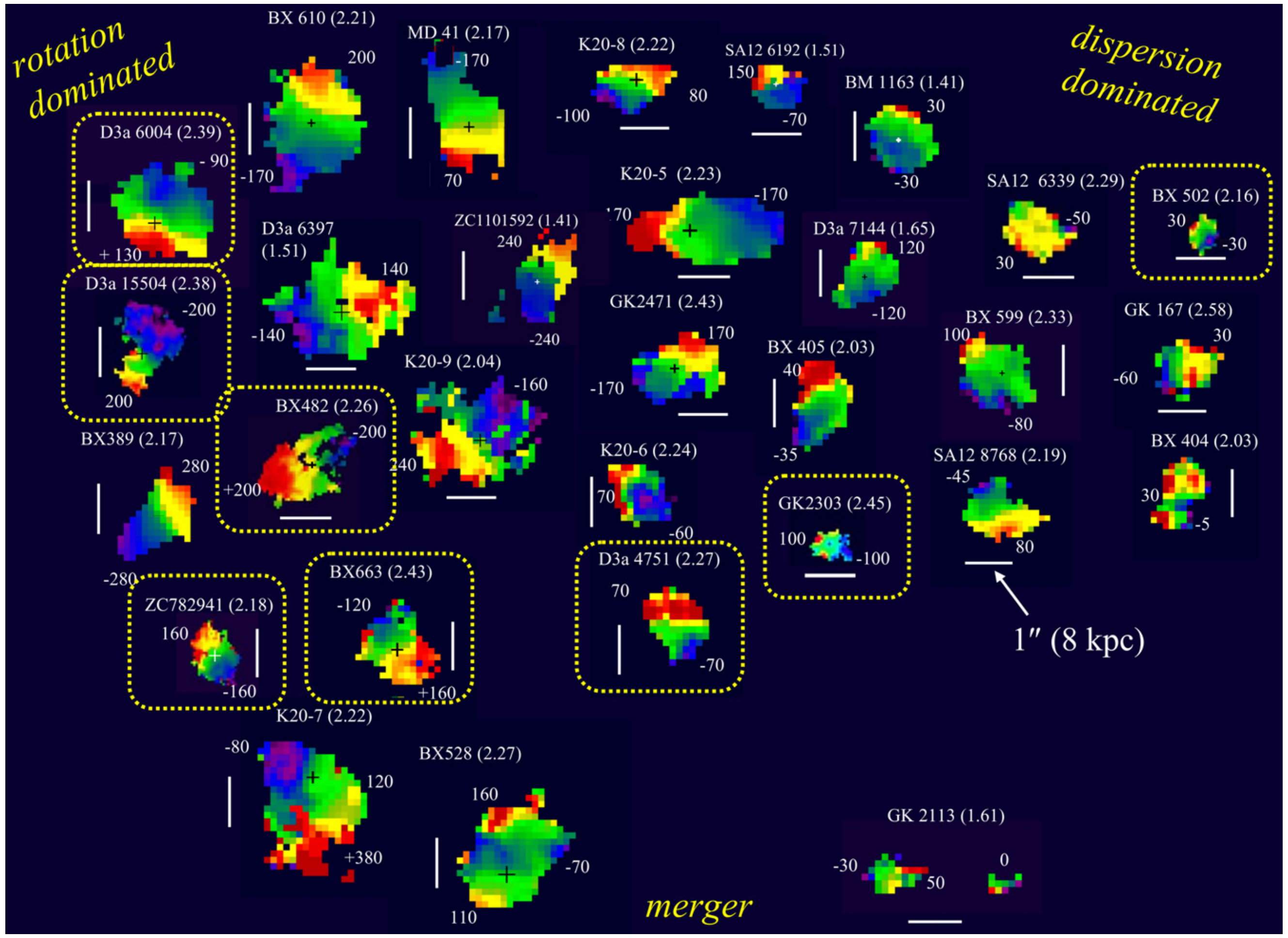
Cappellari+11

近傍早期型銀河

↓

slow rotator
fast rotator

SINS



Foerster Schreiber+09

遠方星形成銀河

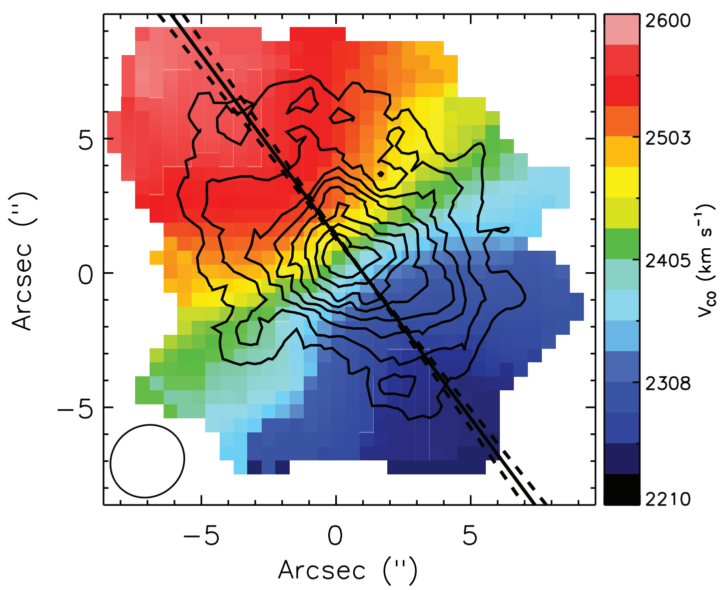
↓

merger -> 回転円盤銀河

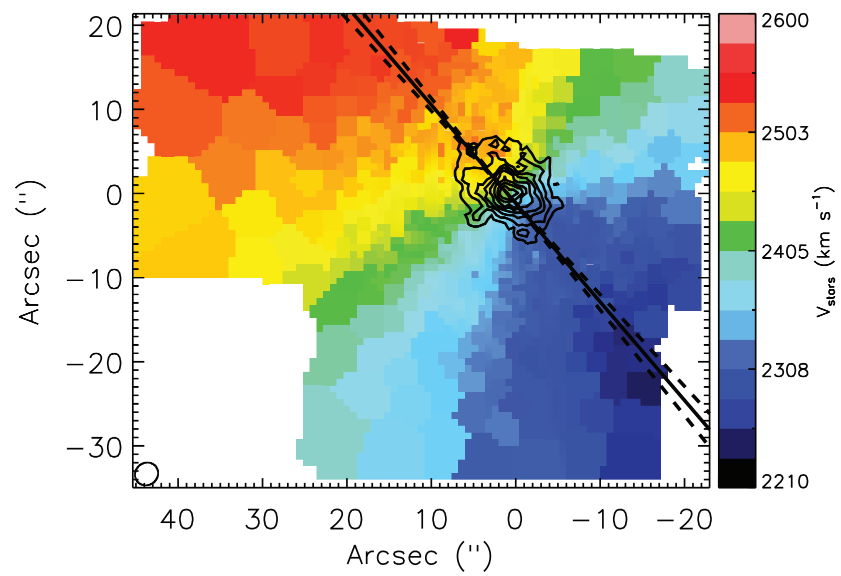
運動学のトレーサー

ATLAS^{3D}銀河の例

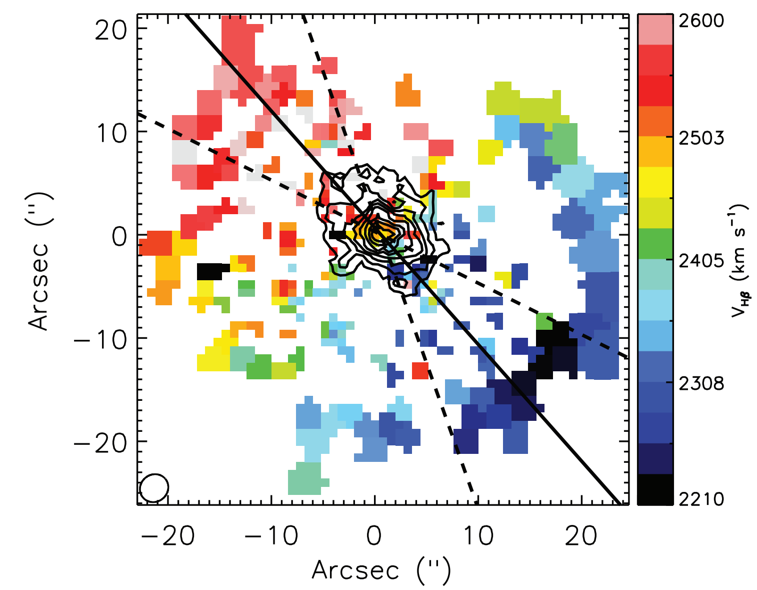
CO（分子ガス）



連続光吸収（星）



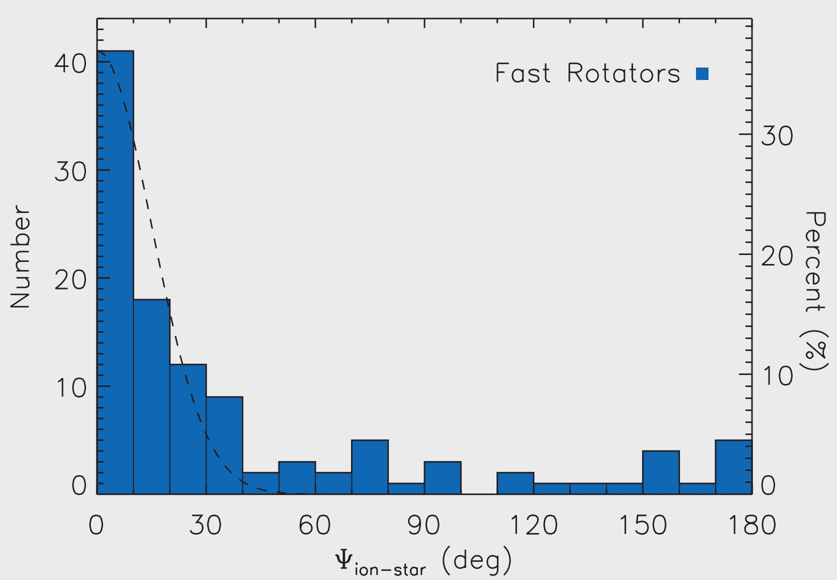
Hβ（電離ガス）



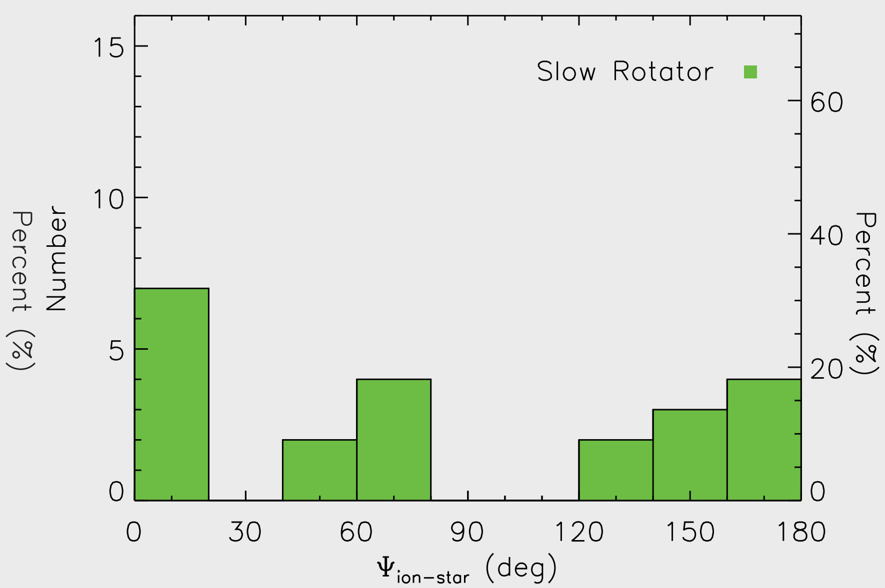
Davis+11

電離ガスと星の運動

fast rotator

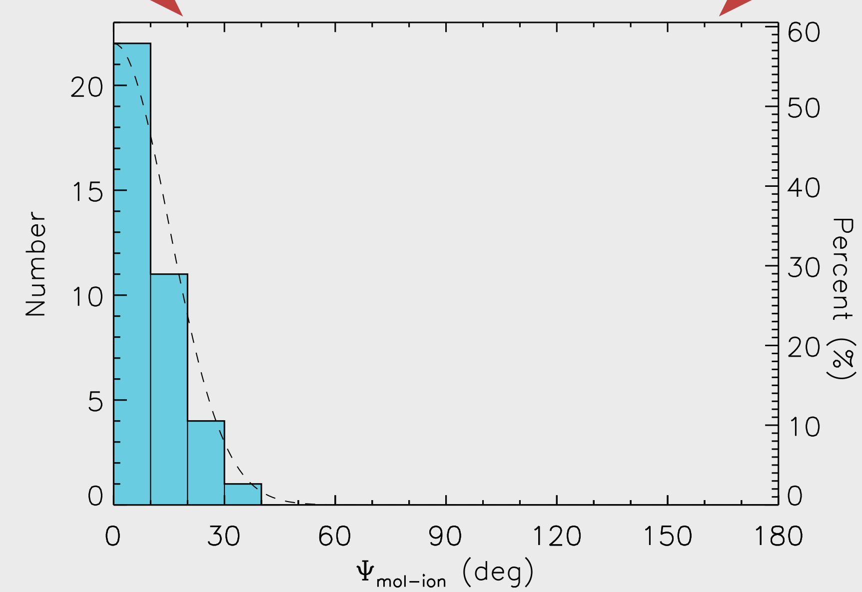


slow rotator



電離ガスと分子ガスの運動

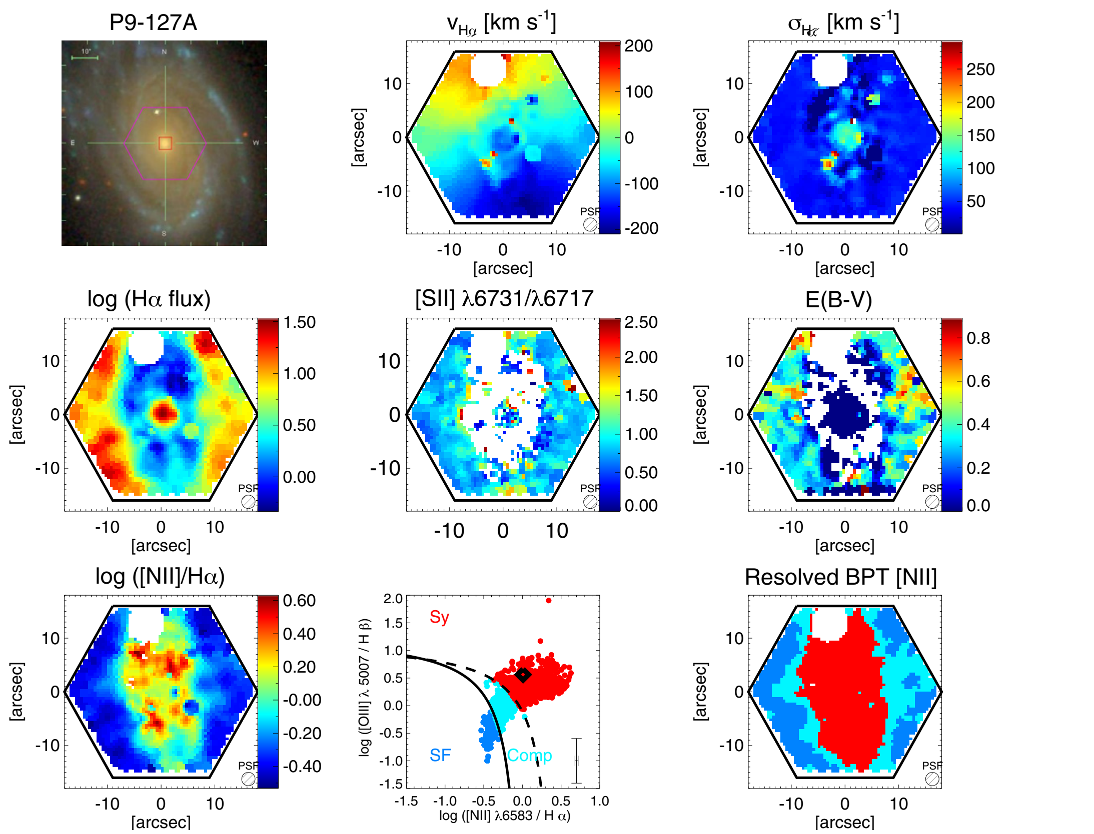
一致 ⟷ 不一致



横軸：kinematic misalignment angle

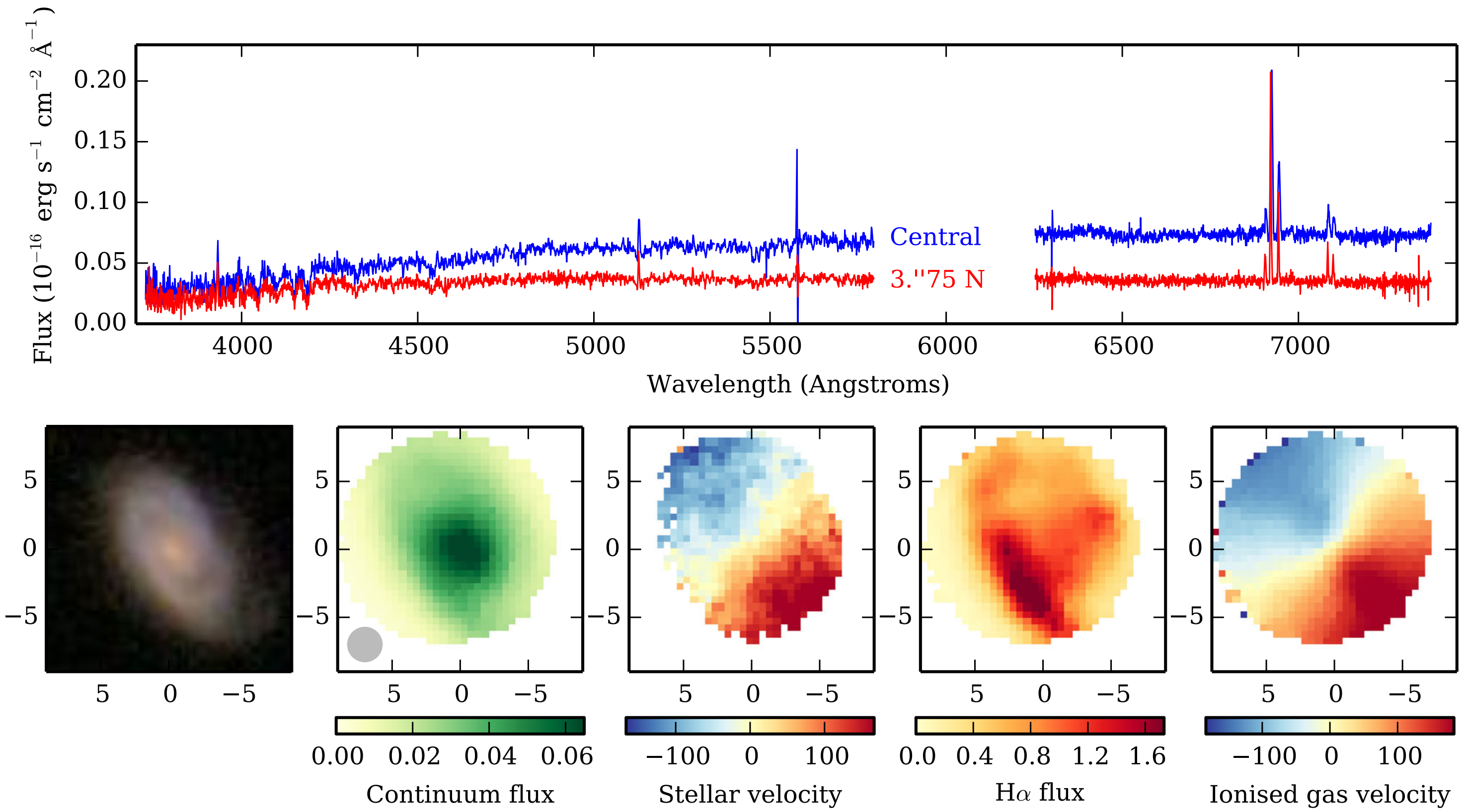
最近の大規模探査（電離ガス・星）

MaNGA (~10k galaxies)



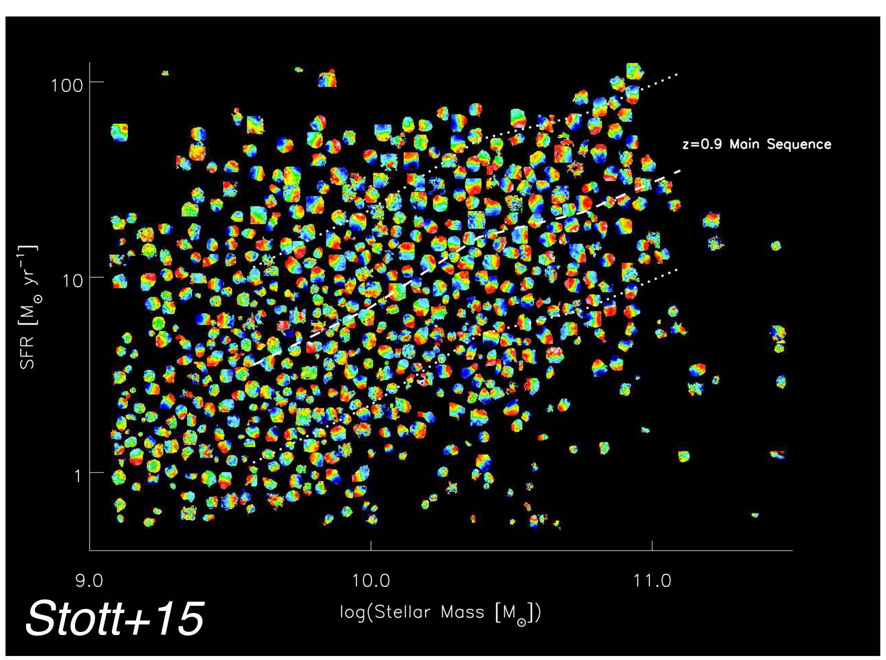
Bundy+15

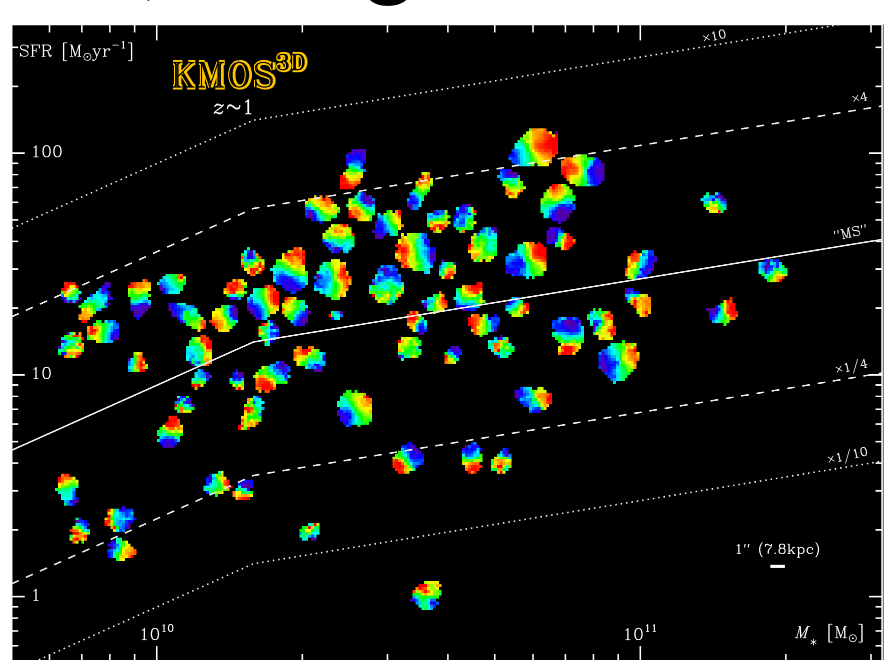
SAMI (~3k galaxies)

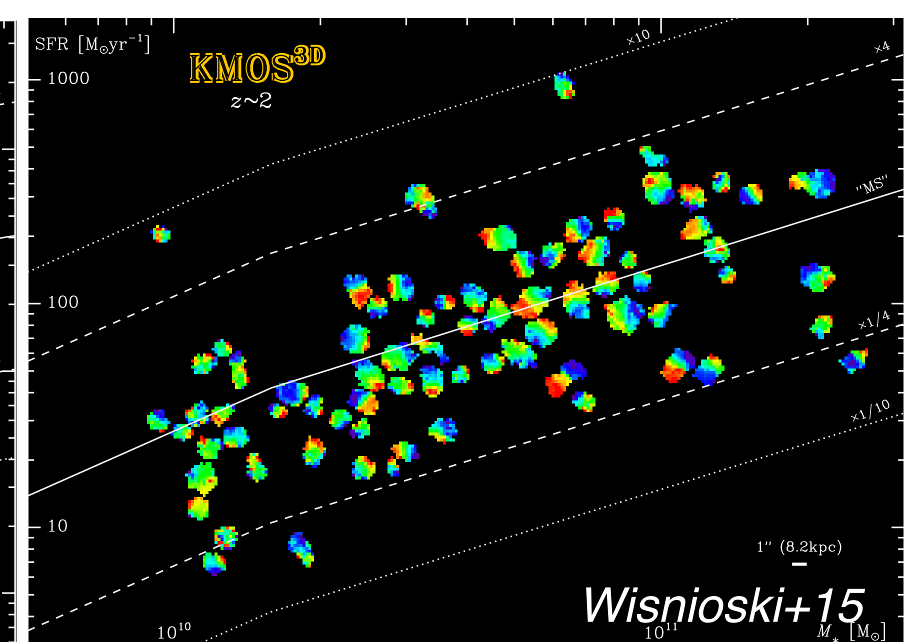


Bryant+15

KMOS (~1k galaxies at z>0.5)



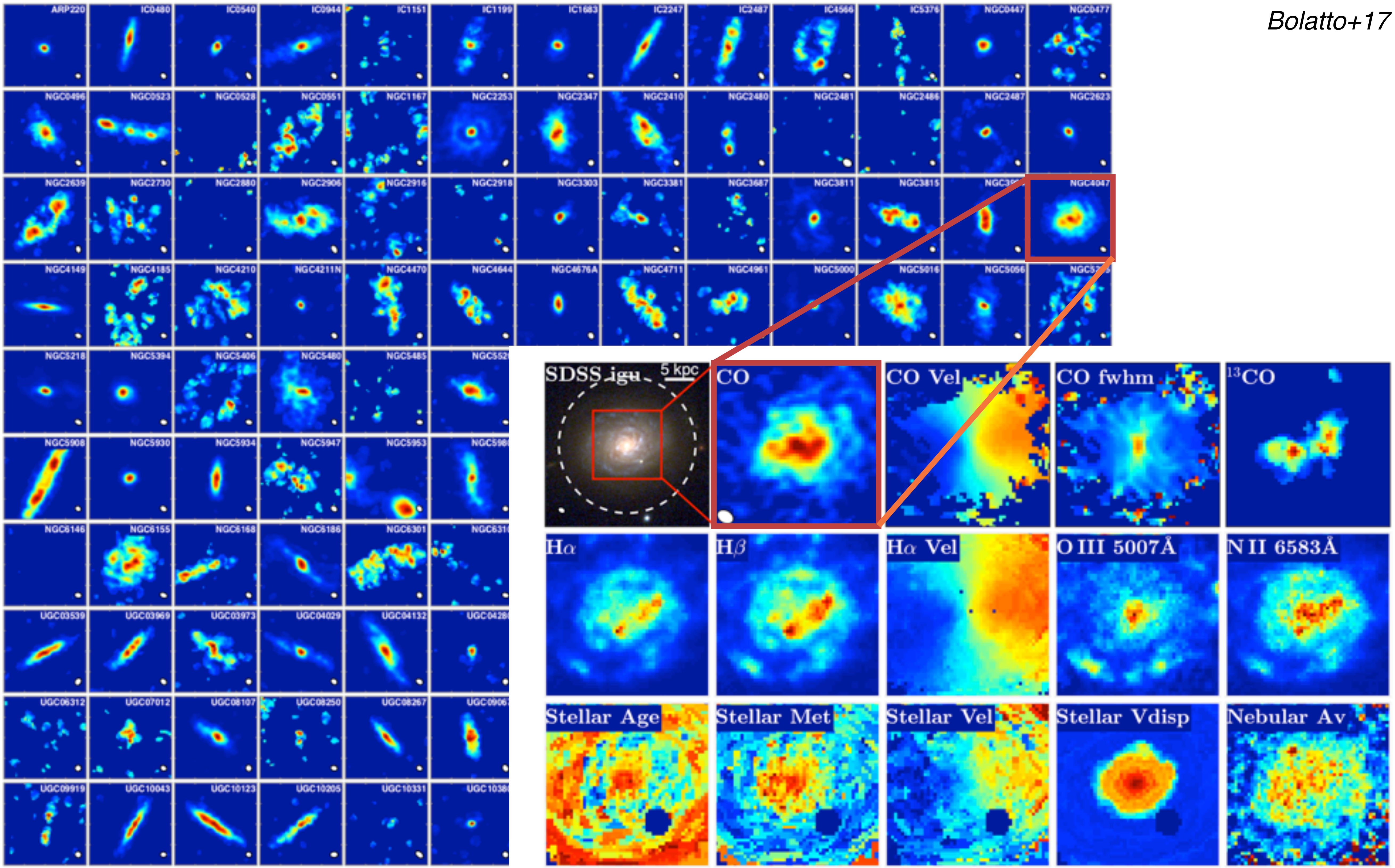




最近の大規模探査（分子ガス）

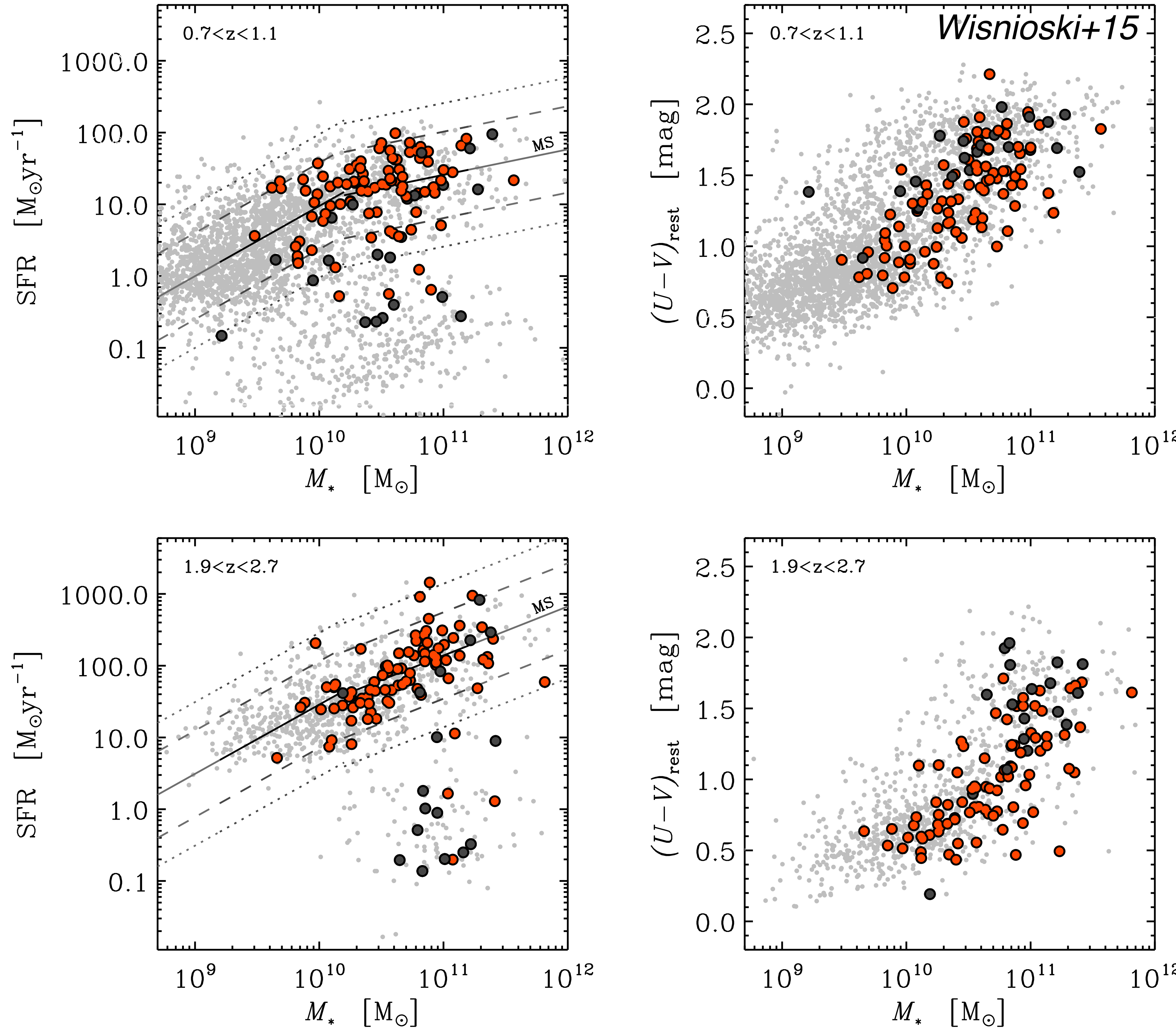
CARMA EDGE-CALIFA (125 galaxies at z=0.006-0.03)

Bolatto+17



KMOS^{3D} survey

VLT/KMOS



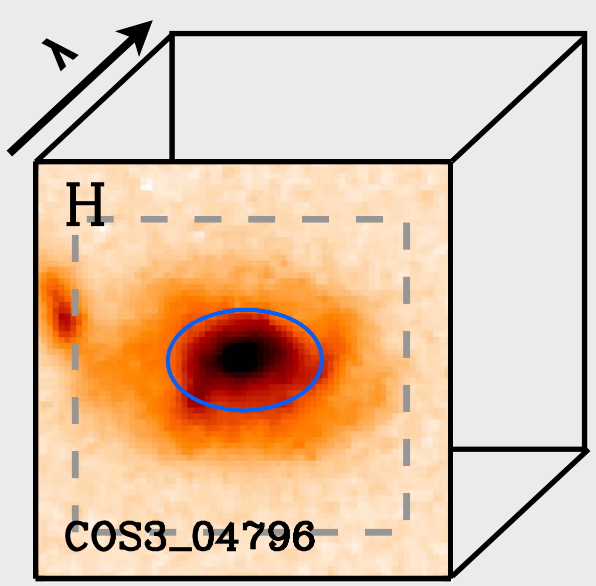
Hα IFU survey in an unbiased sample of >600 galaxies at 0.7<z<2.7

IFUデータの解析

生データ

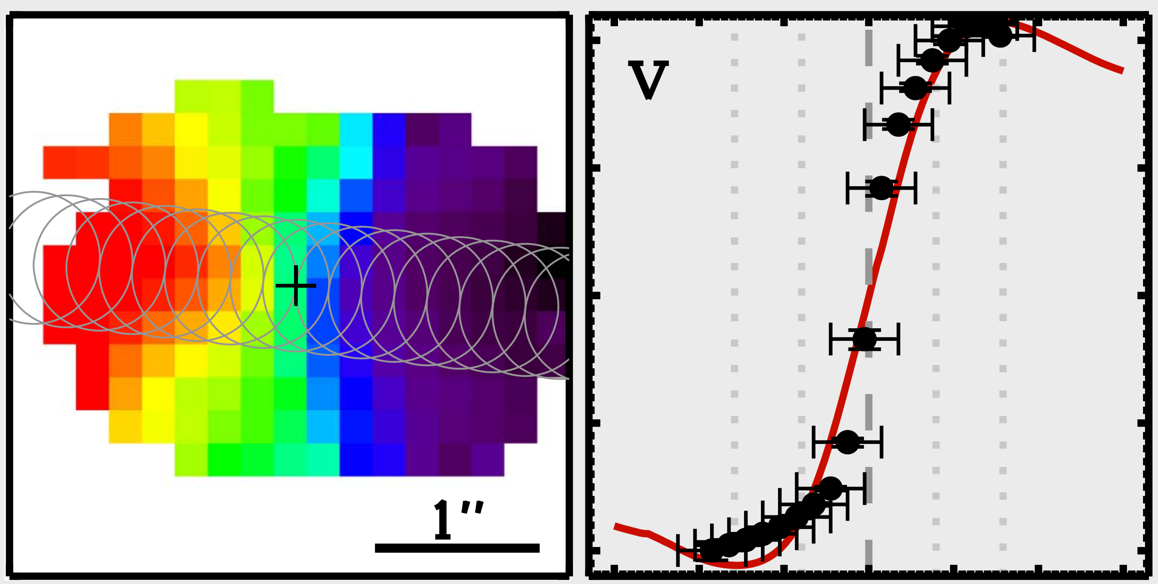
パイプライン

3D CUBE



ガウシアン
フィッティング

velocity map

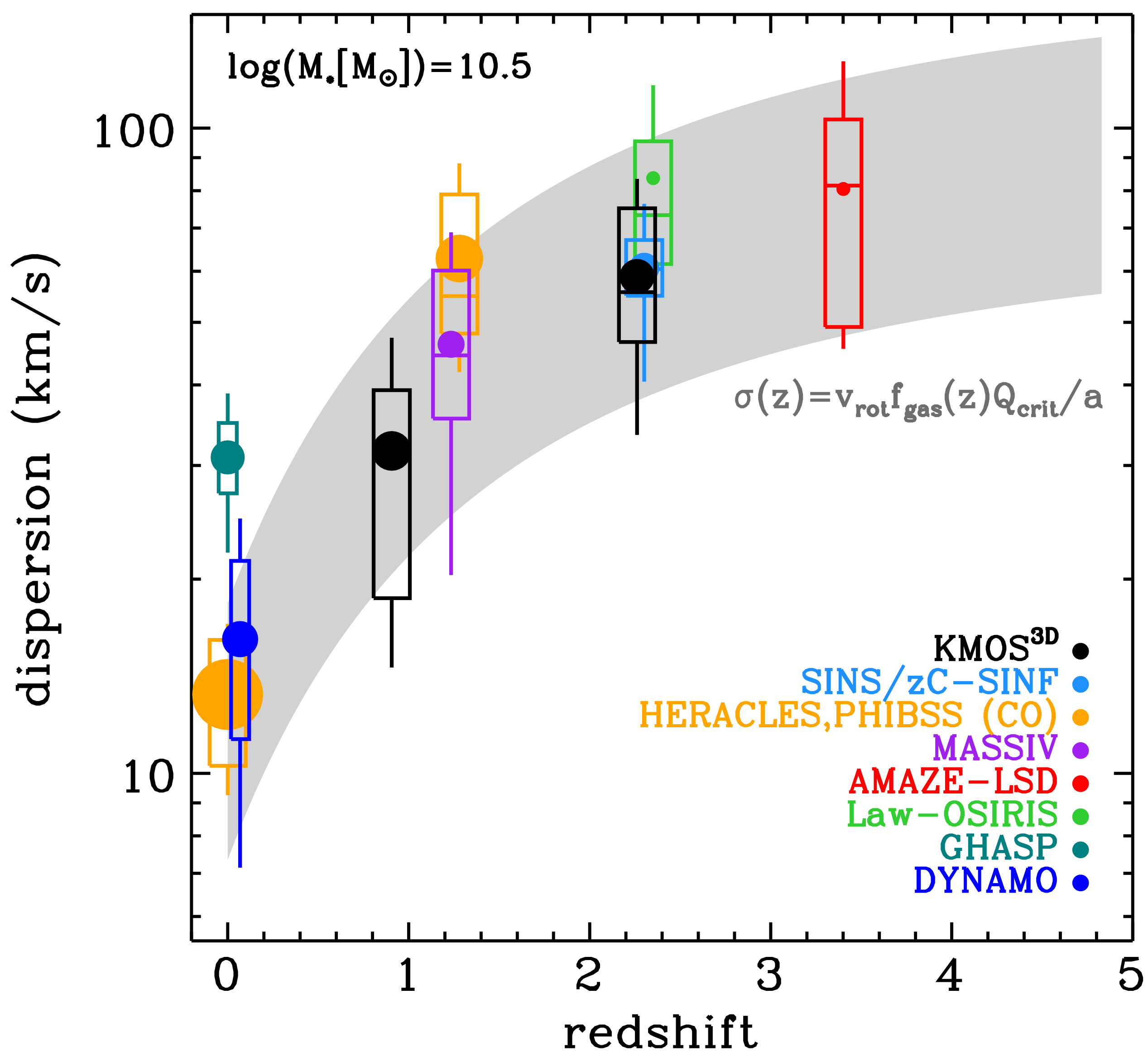


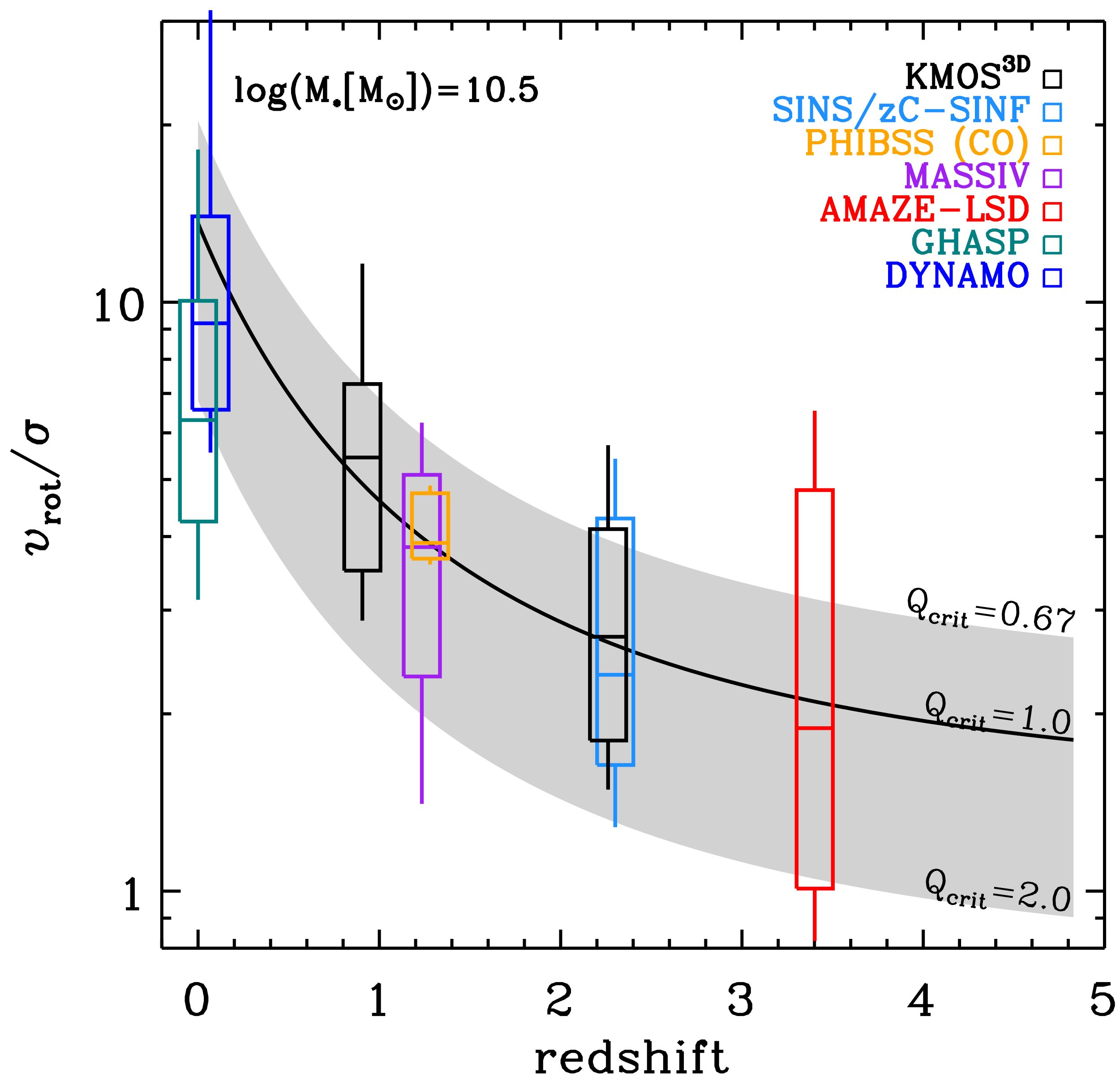
ディスクモデリング

V_{cir}, σ_0, M_{dyn},
(M_{halo}, λ)

σ、v/σの赤方偏移進化

z=0-4にある星形成銀河





a gas-rich, marginally unstable disk (Genzel+11)

$$Q_{\rm gas} = \frac{\sigma_0 \kappa}{\pi G \Sigma_{\rm gas}} = \left(\frac{\sigma_0}{v_c}\right)\left(\frac{a\left(v_c^2 R_{\rm disk}/G\right)}{\pi R_{\rm disk}^2 \Sigma_{\rm gas}}\right)$$

$$= \left(\frac{\sigma_0}{v_c}\right)\left(\frac{a M_{\rm tot}}{M_{\rm gas}}\right) = \left(\frac{\sigma_0}{v_c}\right)\left(\frac{a}{f_{\rm gas}}\right).$$

Disk modeling in KMOS^{3D}

in Wuyts+16 paper,
we derive $\mathbf{M_{dyn}}$ and $\boldsymbol{\sigma_0}$ by contrasting the data with convolved disk models

data

LINEFIT code
(Davies+09, Forster Schreiber+09)

1. extracting spectra in each spatial pixel or aperture
2. Gaussian fitting to derive rotation velocity and velocity dispersion

contrast

disk model

DYSMAL code
(Davies+11, Cresci+09)

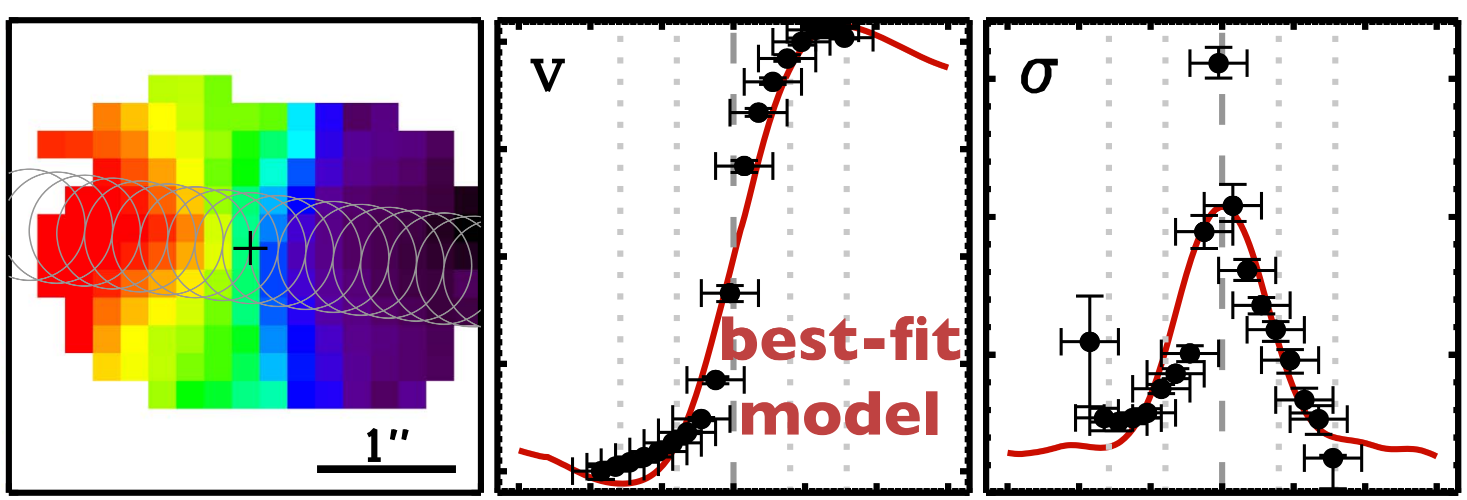
characterizing morphology

r_e: effective radius
n: Sersic index
h: scale height
i: inclination
PA: position angle

from HST 0.2″-resolution map (applies to r_e, n, h, i)

characterizing kinematics

v : rotation velocity (M_{dyn})
σ: velocity dispersion



high-z disks are highly turbulent

pressure support (asymmetric drift)

Burkert+10

hydrostatic equation

$$\frac{v_{\rm rot}^2}{r} = f_g(r) + \frac{1}{\rho}\frac{dp}{dr}, \qquad (1)$$

gravitational force　pressure gradient (thermal pressureは無視できる)

$v_0^2 \equiv f_g \times r$ (zero-pressure)

$$v_{\rm rot}^2 = v_0^2 + \frac{r}{\rho}\frac{dp}{dr} = v_0^2 + \frac{1}{\rho}\frac{d}{dlnr}\left(\rho\sigma^2\right). \qquad (2)$$

exponential disk
(see Burkert+10 and Binney&Tremaine 08)

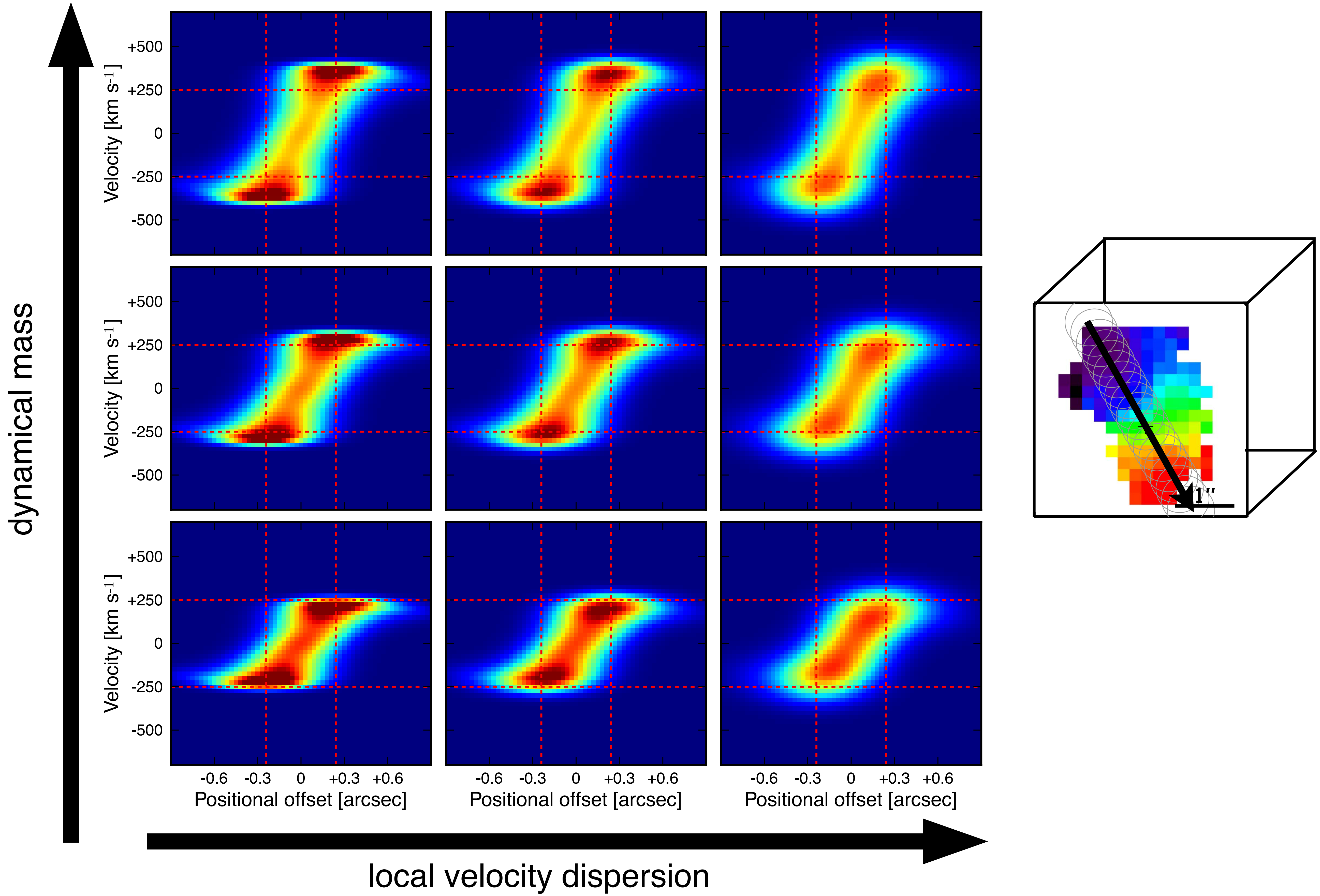
circular velocity

$$v_{\rm rot}^2 = v_0^2 - 2\sigma^2\left(\frac{r}{r_d}\right). \qquad (11)$$

observed rotation velocity　**pressure support**

σが大きいほど見かけの回転速度が遅くなる

Position-velocity diagram

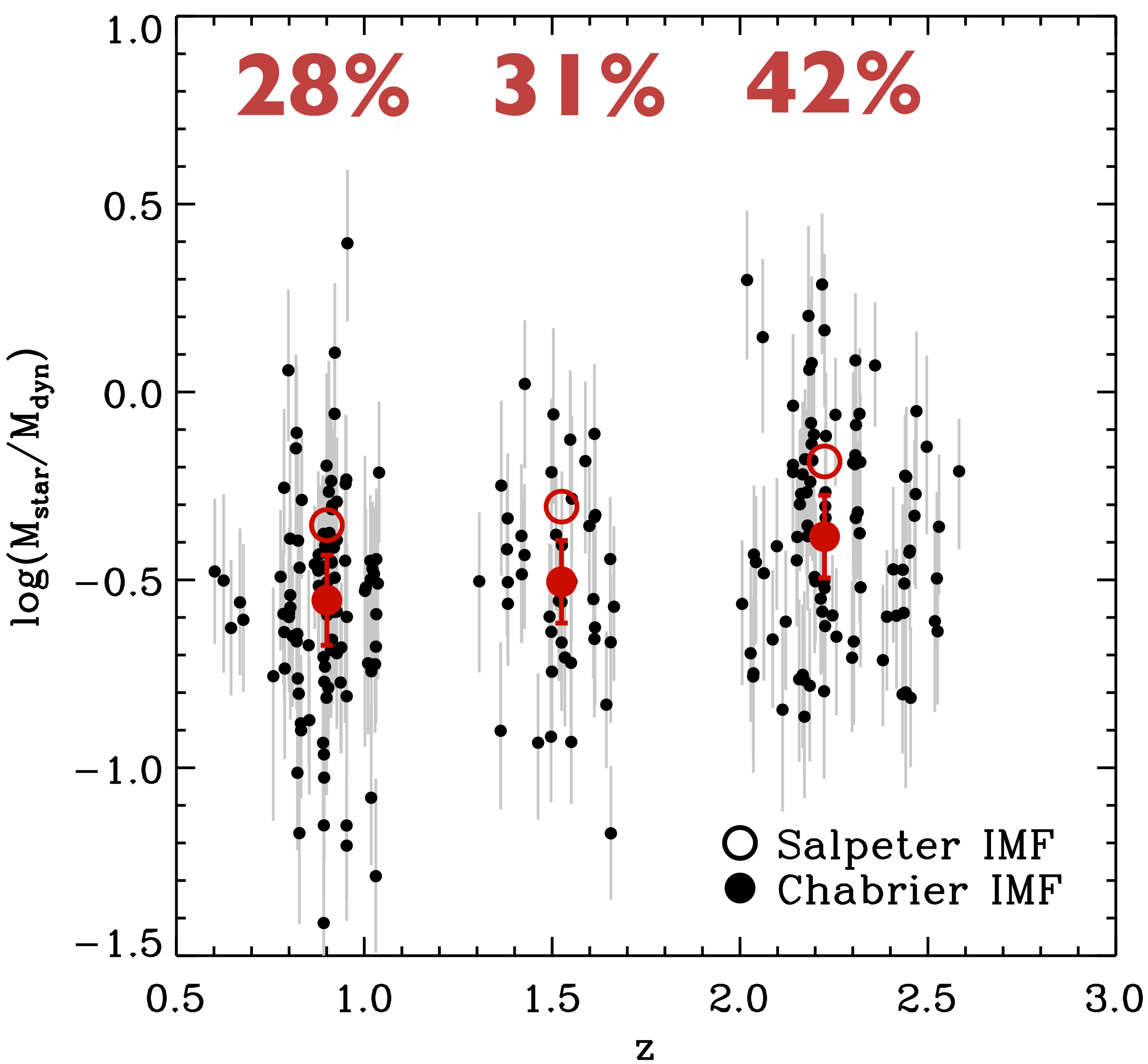


Dynamical mass

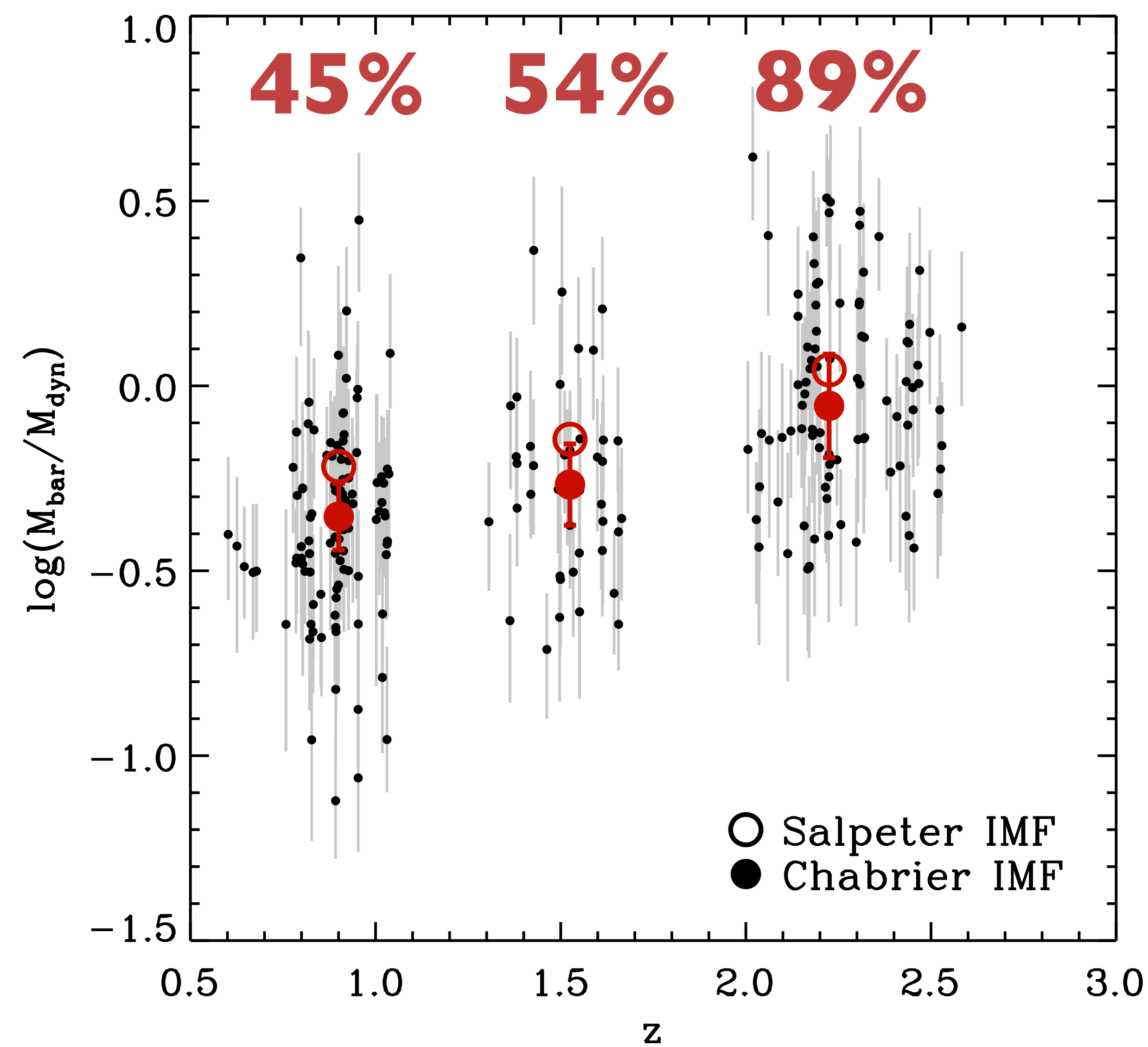
Wuyts+16

240 star-forming galaxies at 0.6<z<2.6

stellar mass fraction



baryonic mass fraction



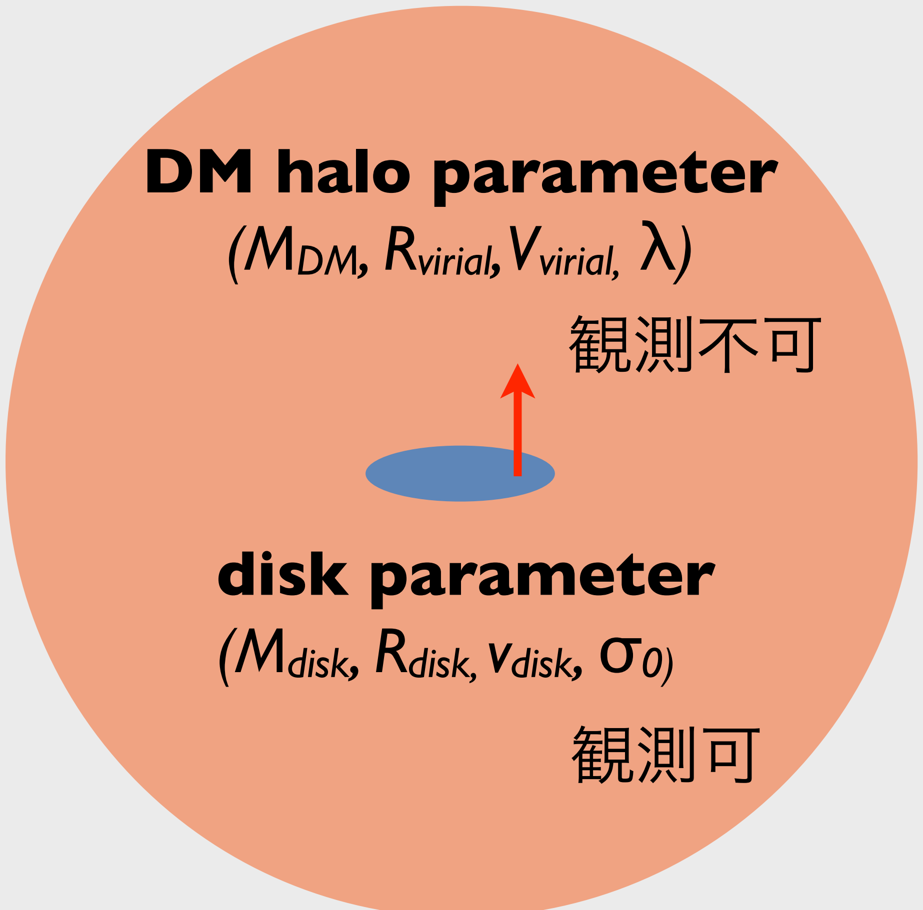
遠方銀河の内側（R<R_e）では、

ほとんどの質量はバリオン（星＋ガス）が担っている

DM halo mass

Exponential Disk within an NFW Dark Matter Halo (Mo+98)

Burkert+16



NFW Dark Matter Halo (Navarro+97)

$$\rho_{DM}(r) = \frac{4\rho_c}{(r/r_s)(1+r/r_s)^2}$$

$$v^2_{DM}(r) = V^2_{200}\left(\frac{r_{200}}{r}\right)\frac{ln(1+r/r_s)-(r/r_s)/(1+r/r_s)}{ln(1+c)-c/(1+c)}$$

Exponential thin disk (Freeman+70)

$$\Sigma(r) = \Sigma_0 \times \exp\left(-\frac{r}{r_d}\right)$$

$$v^2_{\rm disk}(r) = 4\pi G\Sigma_0\, r_d y^2[I_0(y)K_0(y) - I_1(y)K_1(y)]$$

$$v^2_{\rm circ} = v^2_{\rm disk} + v^2_{\rm DM},$$

IFU観測データ ($v^2_{\rm circ}$)　HST観測データ ($v^2_{\rm disk}$)

観測された回転速度において、diskで説明できない分はDMからの寄与と考える

原理的には観測データからhalo massとhalo spin parameterが得られる

halo mass

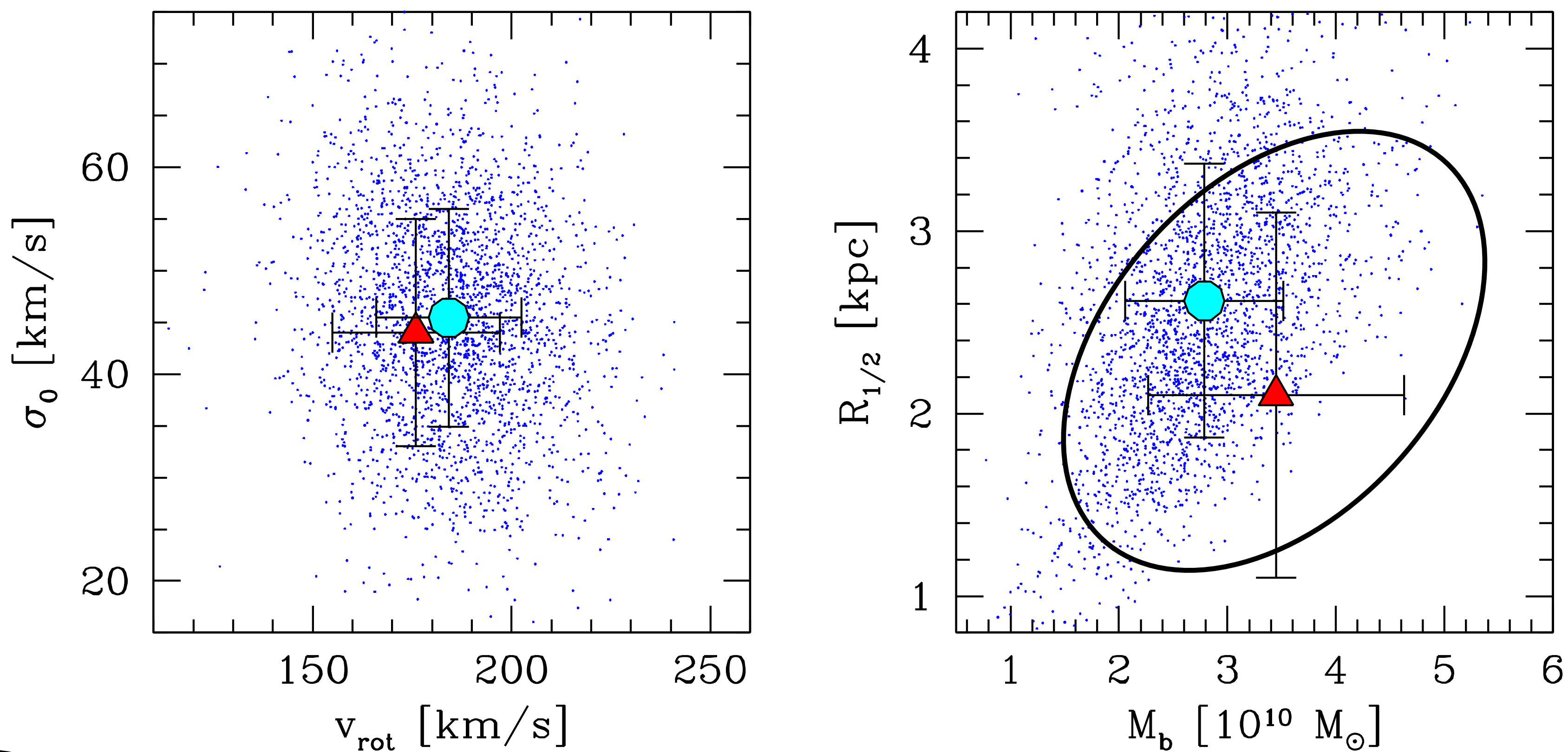
$$M_{\rm DM} = \frac{v^2_{\rm virial}R_{\rm virial}}{G} = \frac{v^3_{\rm virial}}{10GH(z)}$$

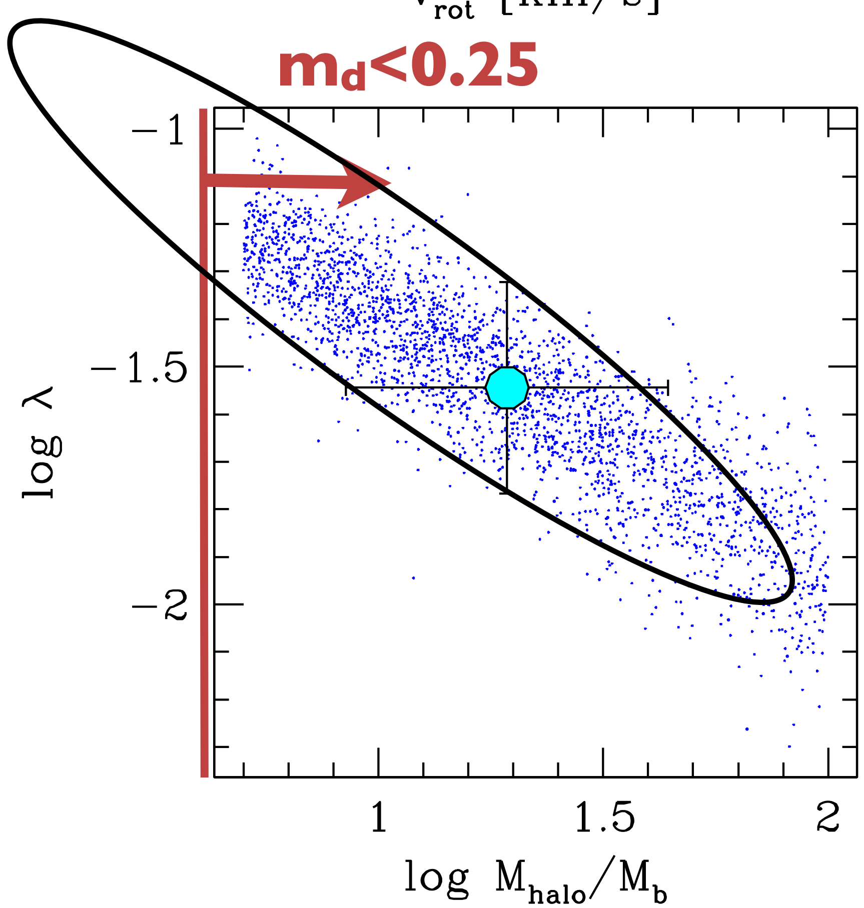
halo spin parameter

$$\lambda = \sqrt{2}\times\left(\frac{R_d}{R_{\rm virial}}\right)\times\left(\frac{j_d}{j_{\rm DM}}\right)^{-1}$$

Monte-Carlo search of halo parameter

Burkert+16





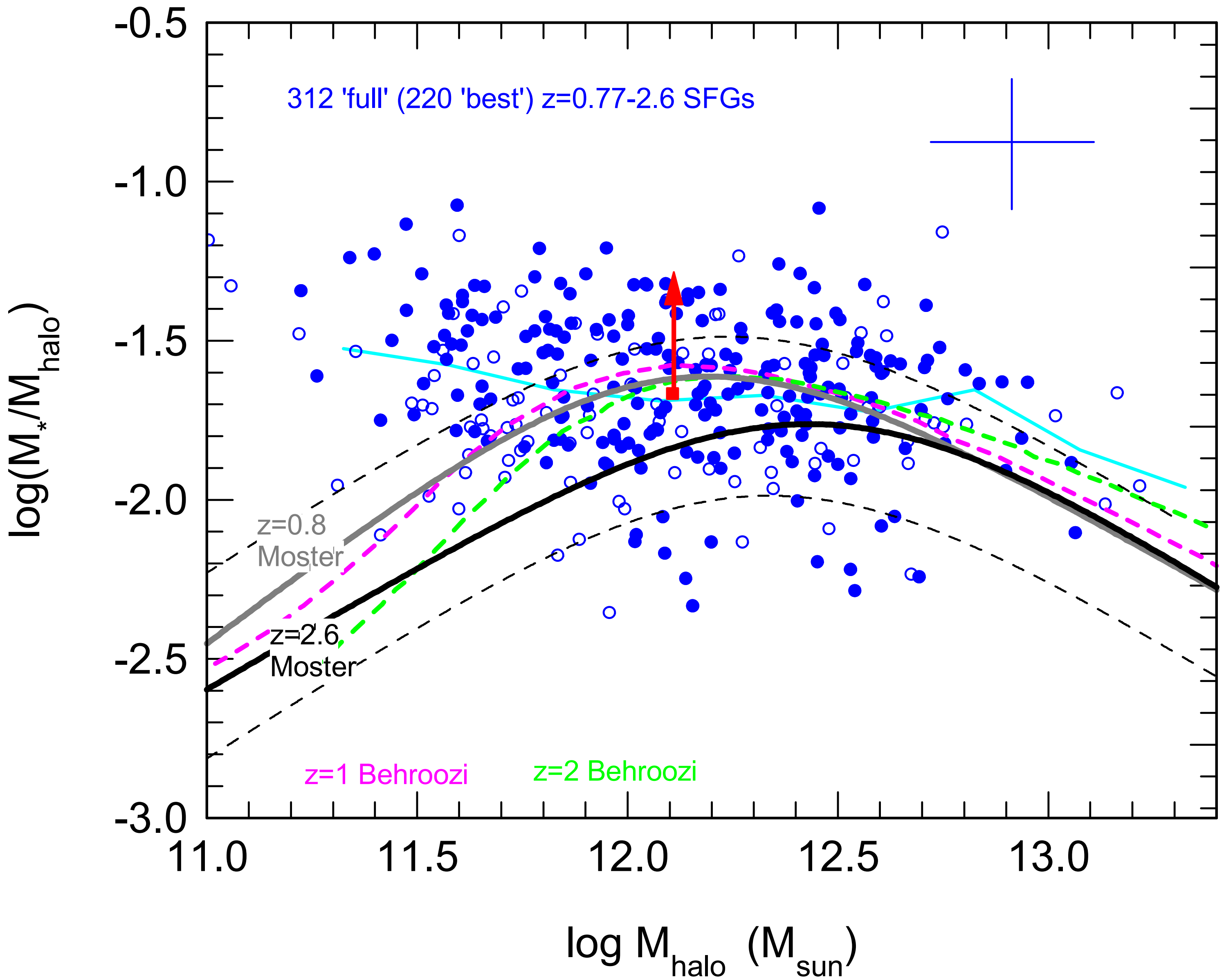
red: observed properties and uncertainties
cyan: mean of <u>**converged**</u> disk-halo models

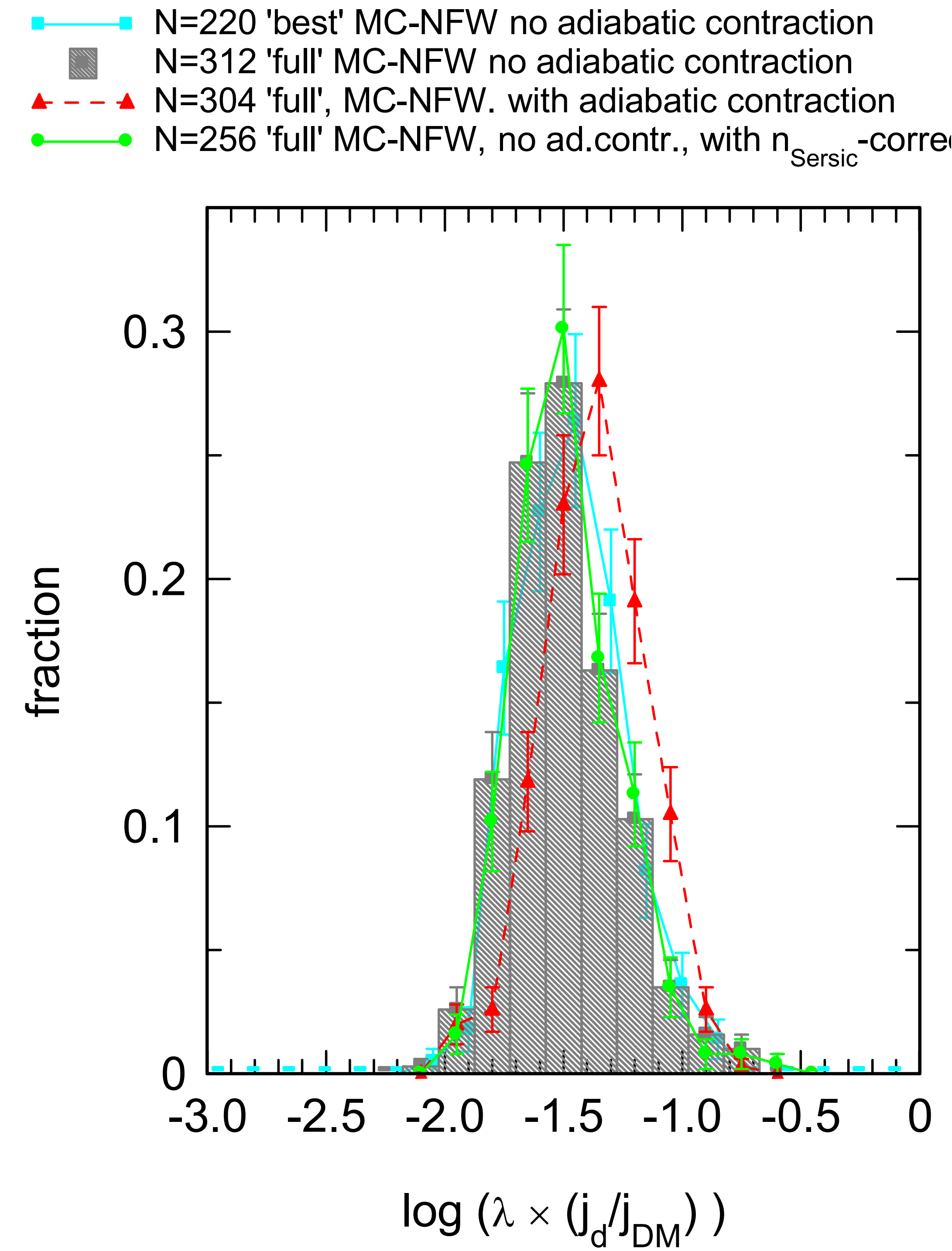
m_d<0.25

(cosmic baryonic fraction, 0.17)

Monte-Carlo search of halo parameter

Burkert+16





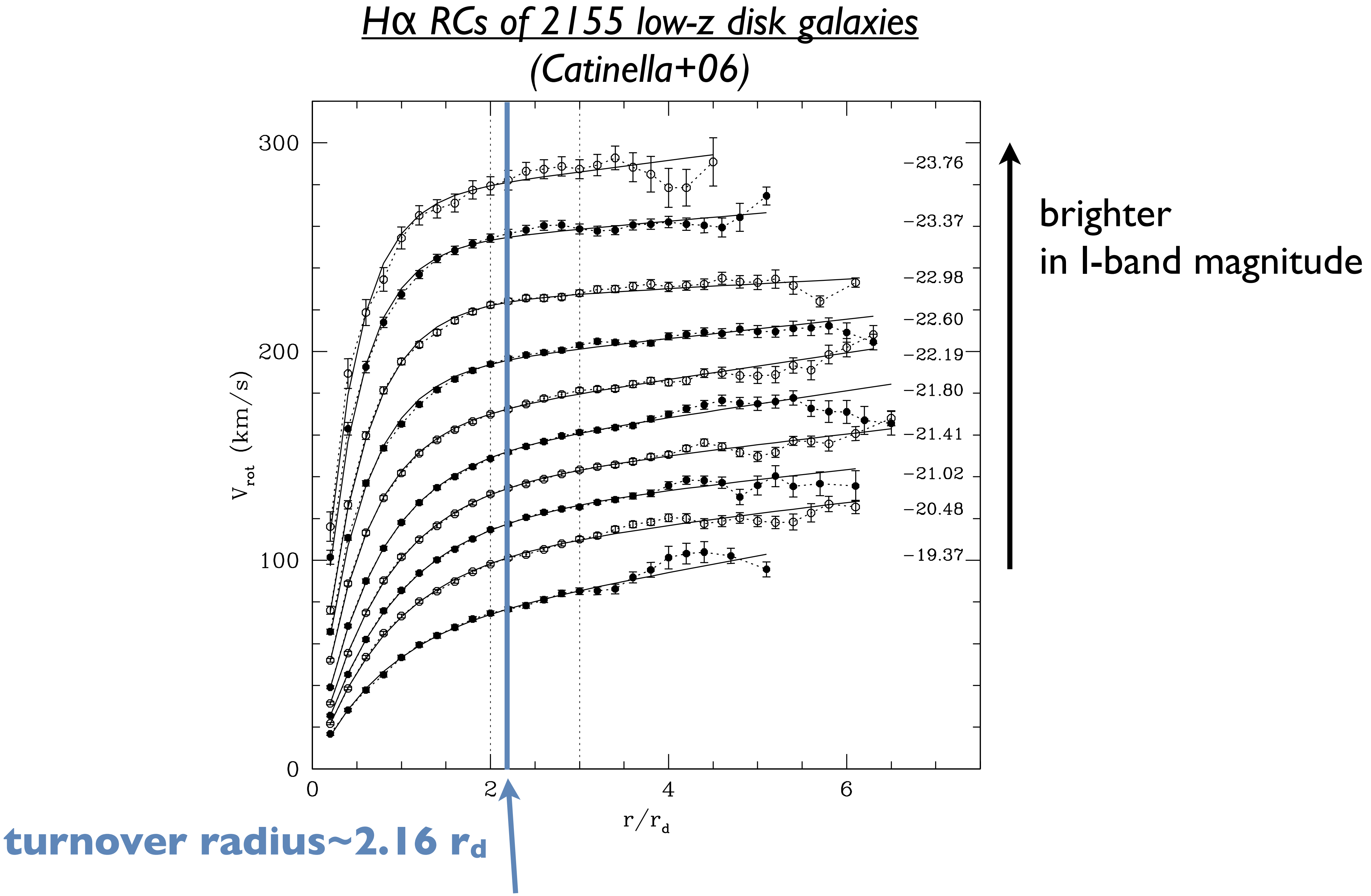
halo mass

$$M_{\rm DM} = \frac{v_{\rm virial}^2 R_{\rm virial}}{G} = \frac{v_{\rm virial}^3}{10GH(z)}$$

halo spin parameter

$$\lambda = \sqrt{2} \times \left(\frac{R_d}{R_{\rm virial}}\right) \times \left(\frac{j_d}{j_{\rm DM}}\right)^{-1}$$

Outer rotation curves



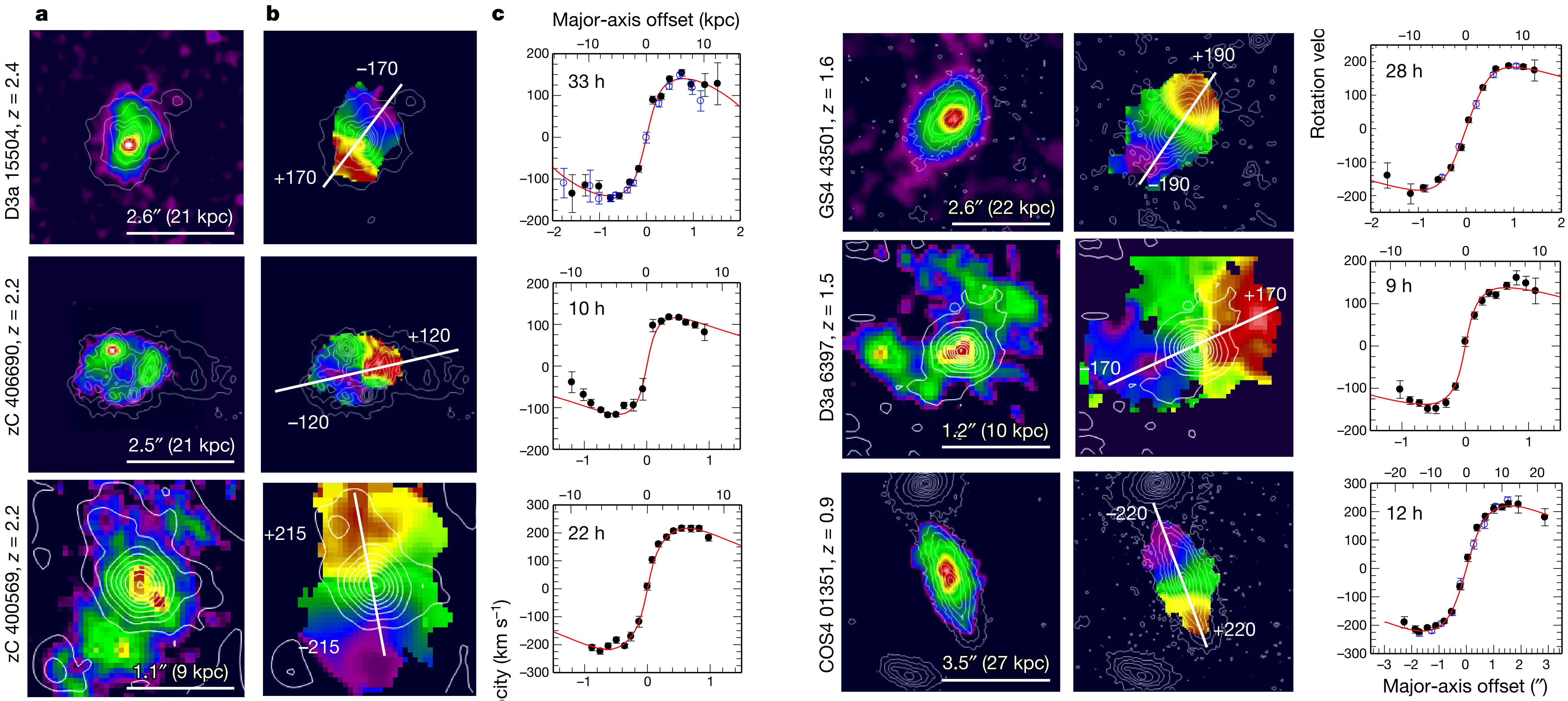
Exponential thin disk (Freeman+70)

$$\Sigma(r) = \Sigma_0 \times \exp\left(-\frac{r}{r_d}\right)$$

$$v_{\rm disk}^2(r) = 4\pi G \Sigma_0\, r_d\, y^2 [I_0(y)K_0(y) - I_1(y)K_1(y)]$$

Outer rotation curves

Genzel+17

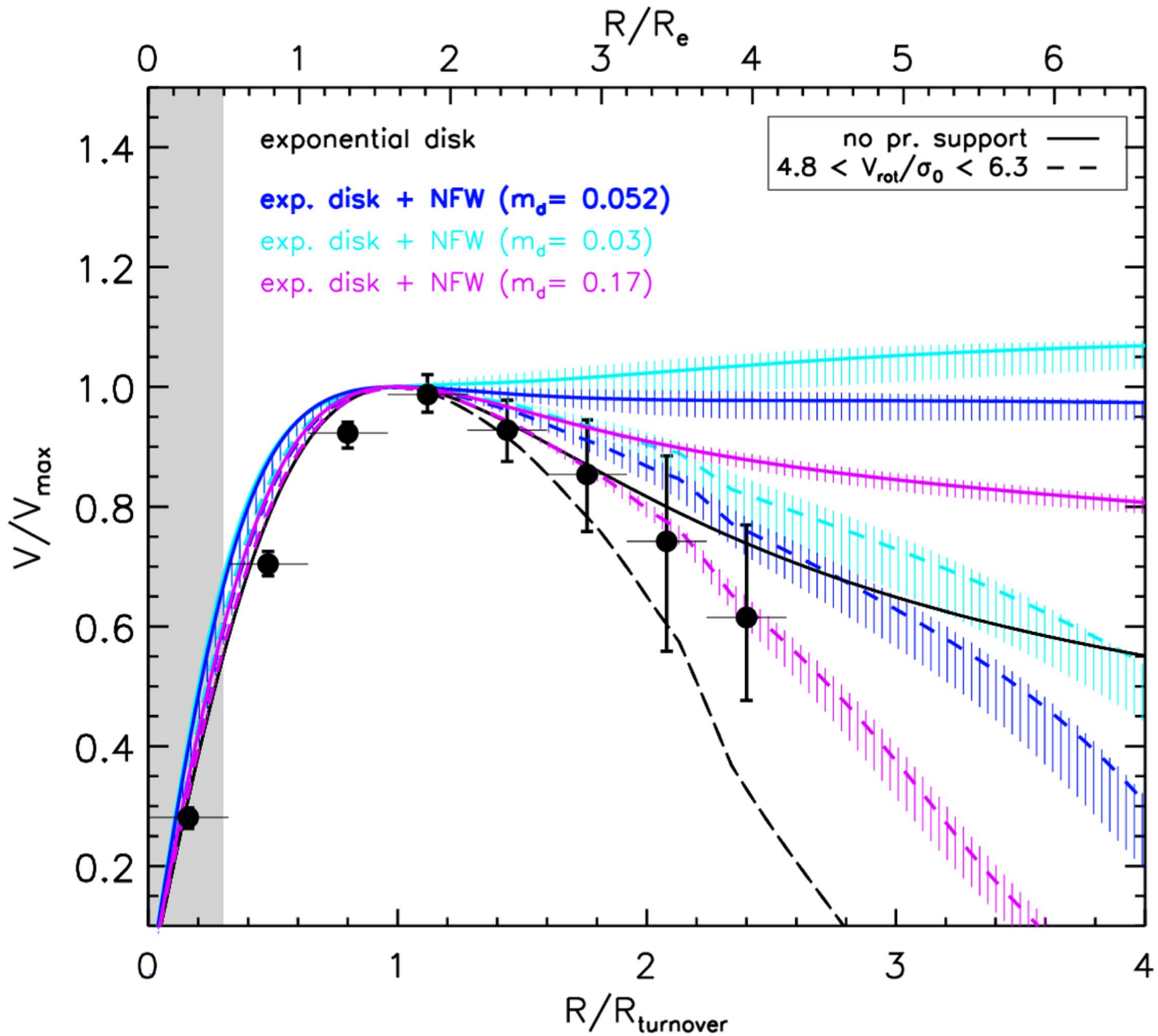


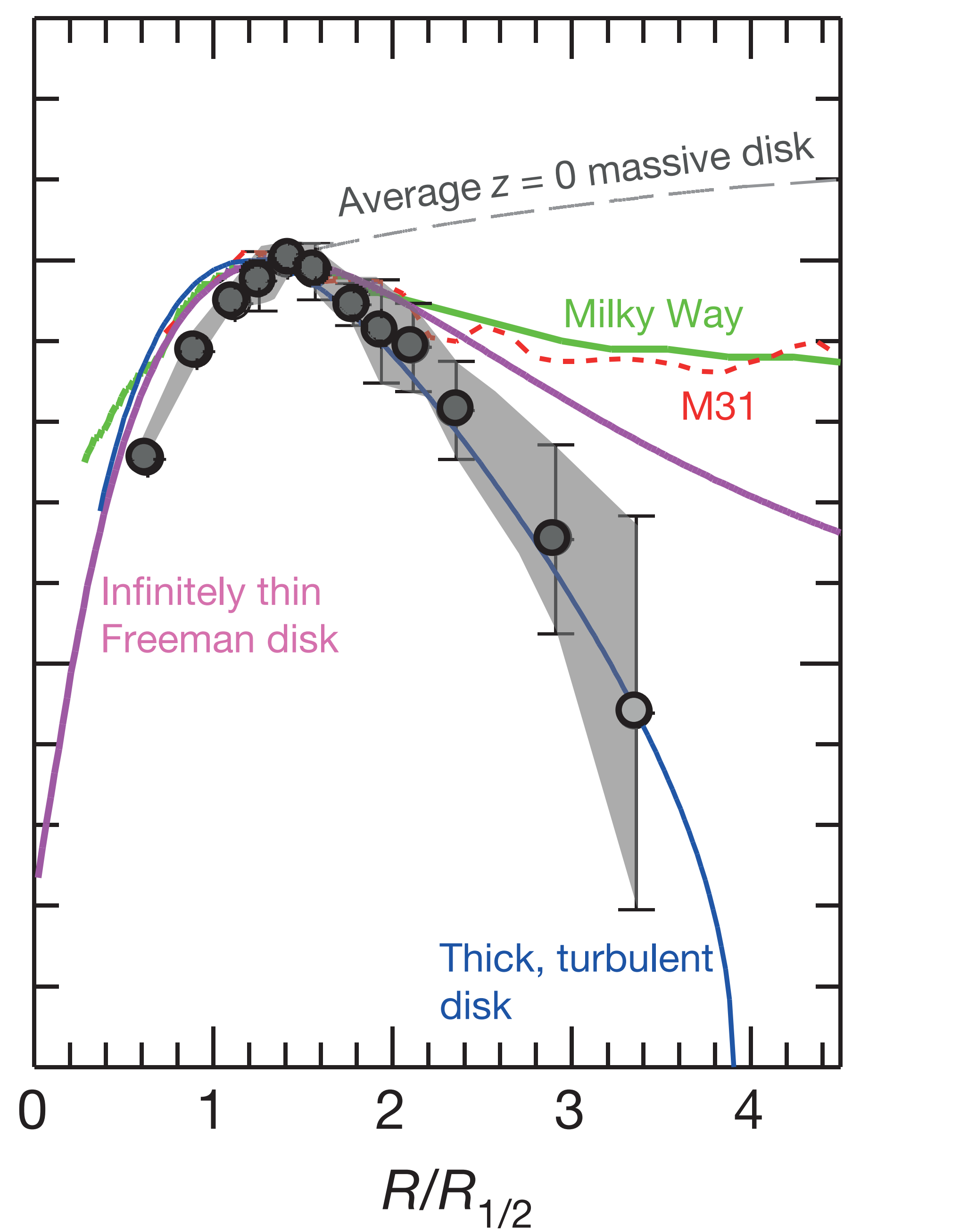
- outer rotation curves drop beyond the turnover radius

are they representative of high-z SF galaxies?

Outer rotation curves

Lang+17 ***stacking of 101 high-z SFGs*** *Genzel+17*

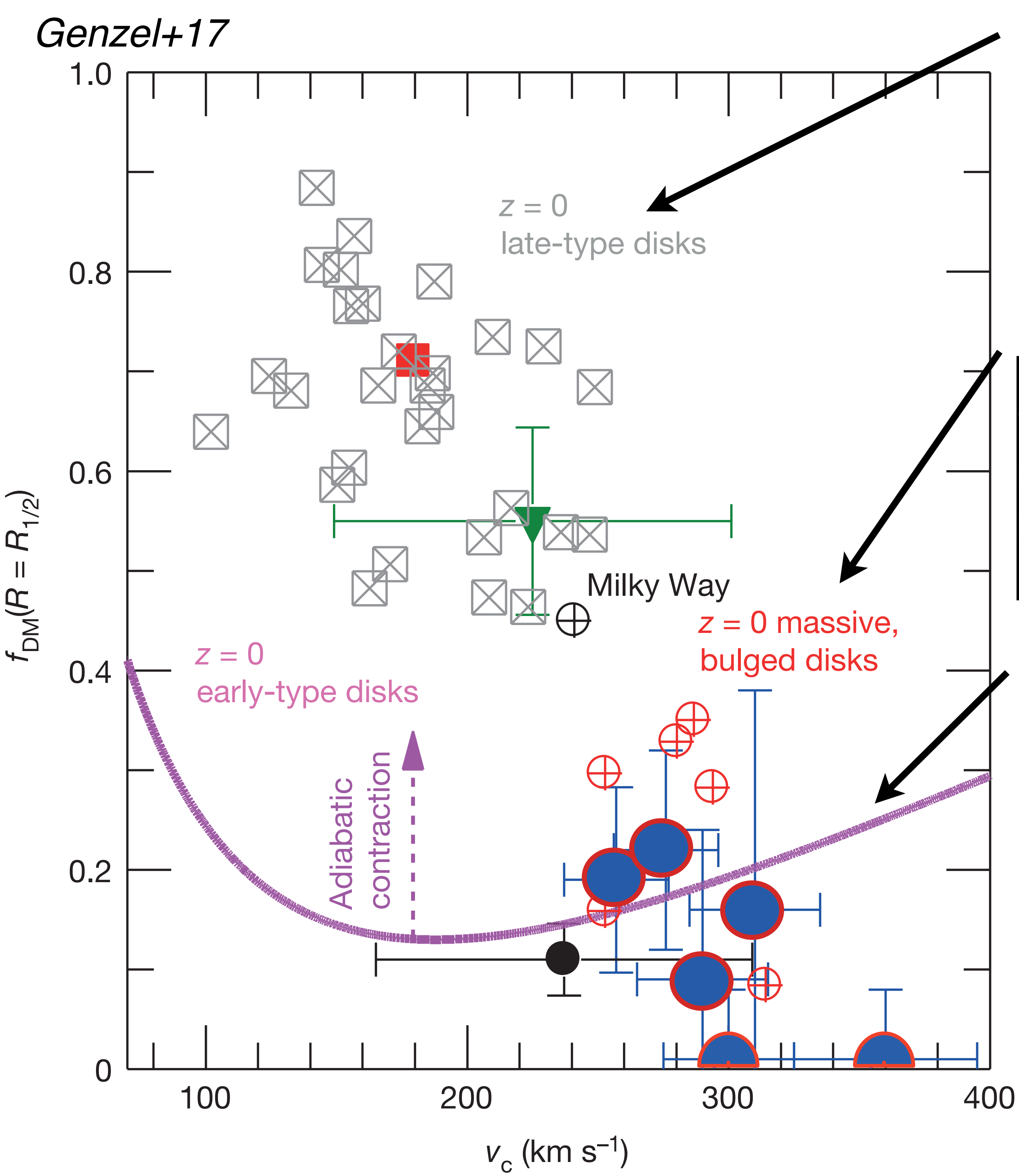




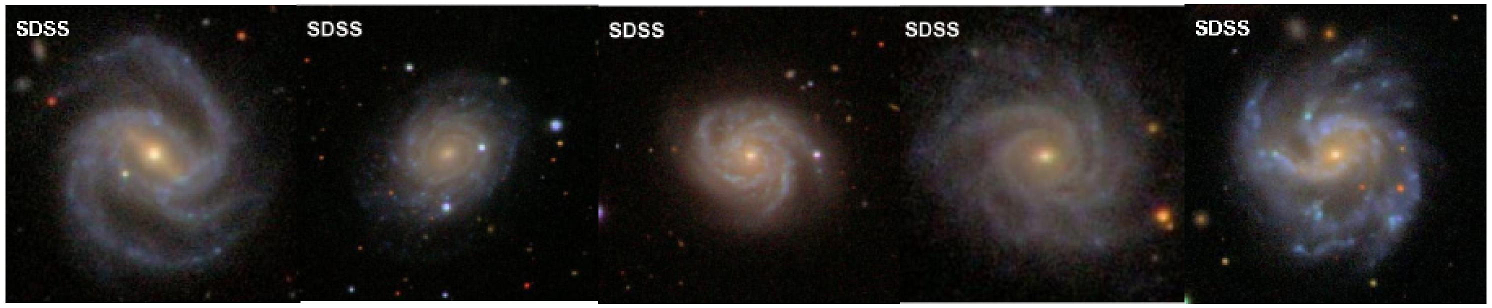
- falling rotation curves can be explained by two affects

1. high baryonic fraction
2. pressure support

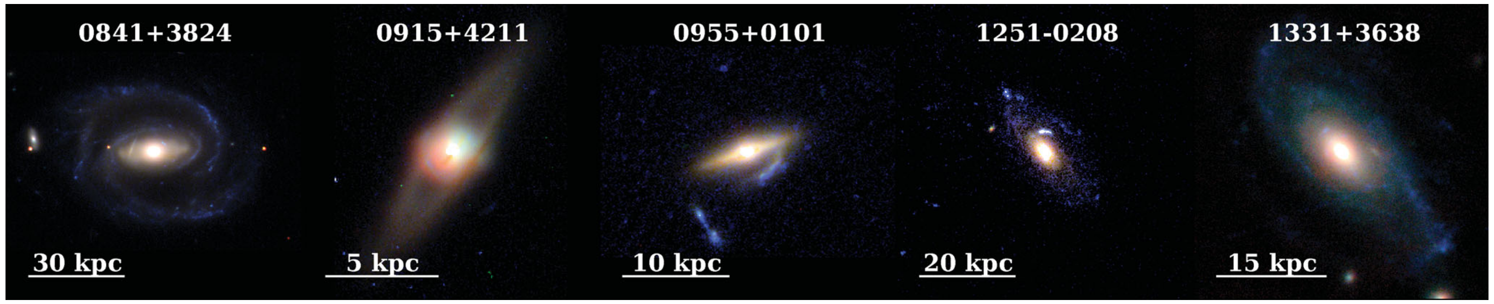
Comparisons with low-redshift results



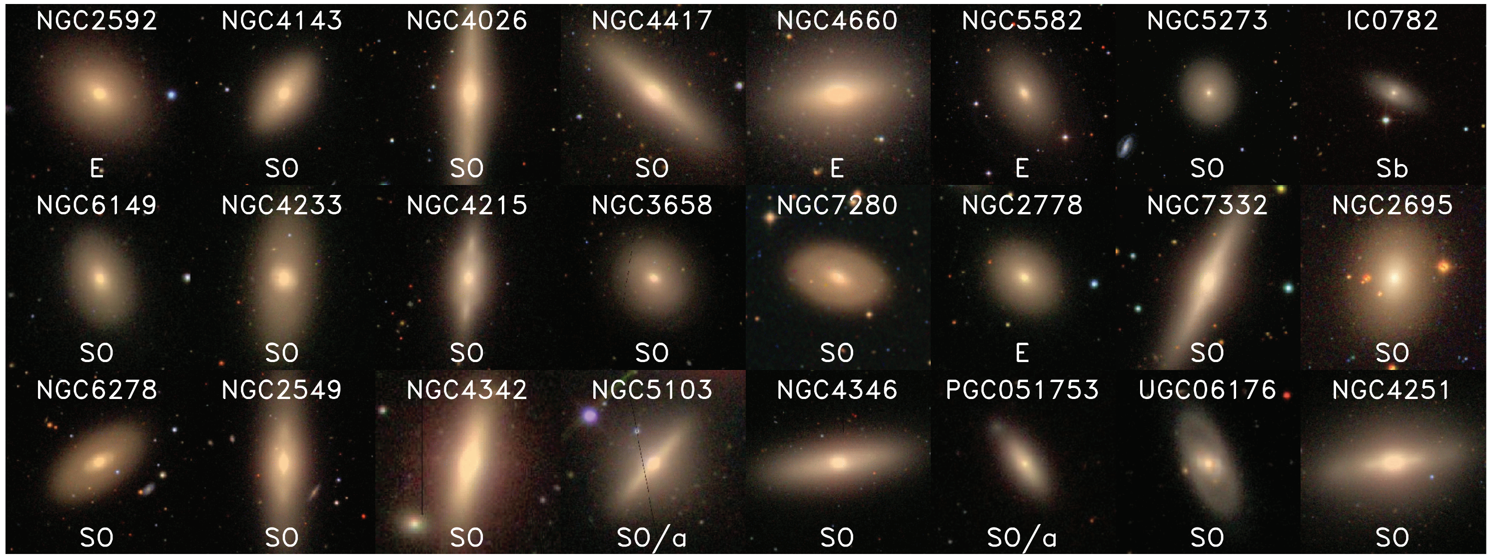
DiskMass survey (Martinsson+13, Bershady+10)



SWELLS survey (Dutton+13)



ATLAS3D (Cappellari+11)

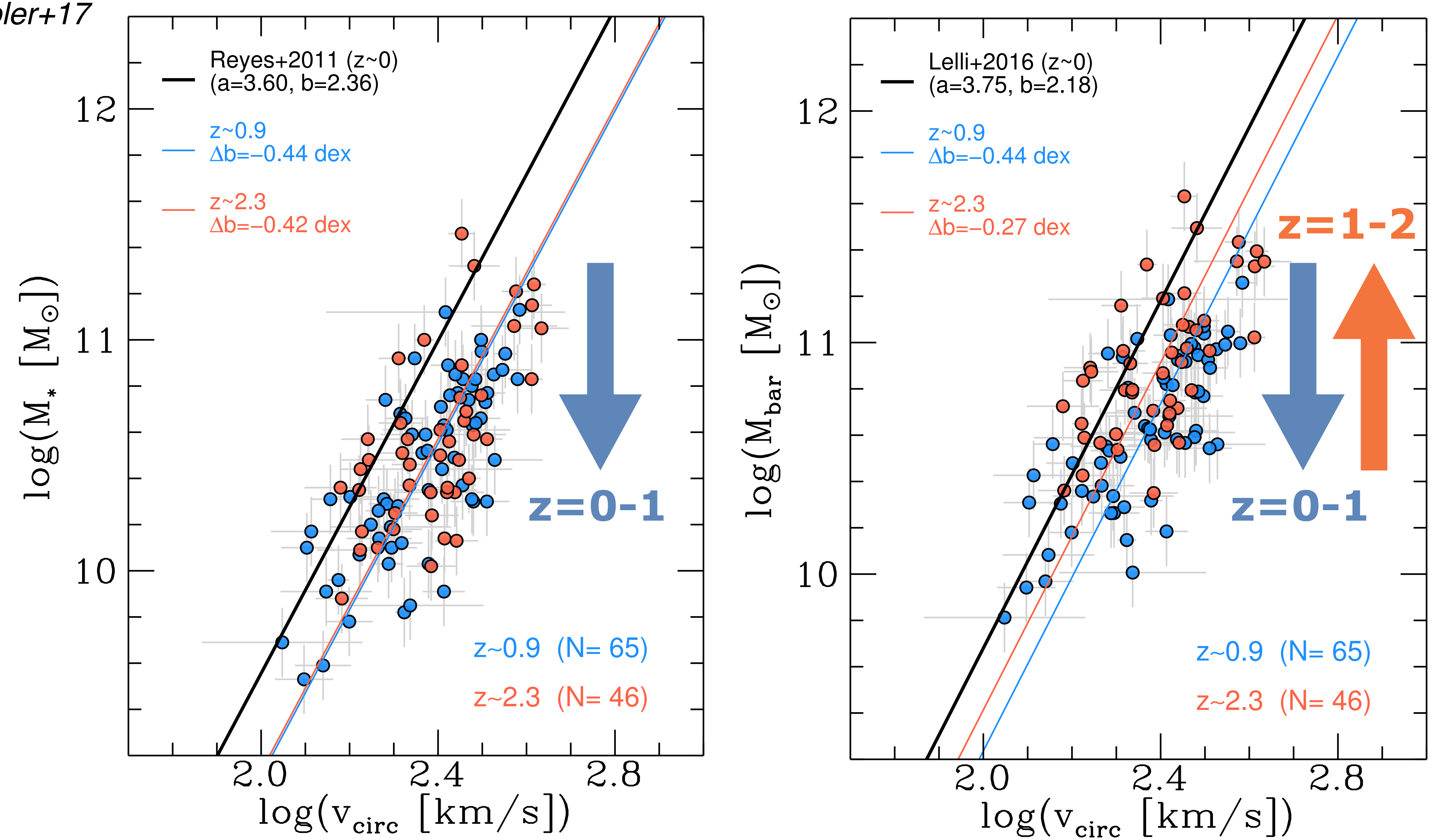


- passive galaxies are probably the descendants of massive star-forming galaxies

- the low dark-matter fractions may be preserved in the properties of the local passive population

Tully-Fisher relation (TFR)

Uebler+17



- at fixed velocity, higher baryonic mass and similar stellar mass at z~2.3 as compared to z~0.9
- zero point offset is not monotonic

Toy model of baryonic TFR

1. DM Halo (Mo+98)

$$M_h = \frac{V_h^3}{10G \cdot H(z)} \quad ; \quad R_h = \frac{V_h}{10H(z)} \qquad (3)$$

$$M_{\rm bar} = m_f \cdot M_h \quad ; \quad R_{\rm bar} = \underline{r_f} \cdot R_h$$

constant

$$\boldsymbol{M_{bar}/m_d = C_1 \times R_d^3 H(z)^2}$$

2. Exponential disk (Freeman+70)

$$v_{\rm circ}(r) = \sqrt{v_{\rm bar}^2(r) + v_{\rm DM}^2(r)}. \qquad (D4)$$

$$f_{\rm DM}(r) = v_{\rm DM}^2(r)/v_{\rm circ}^2(r).$$

$$\boldsymbol{v_{bar}^2 = (1 - f_{DM}) v_{cir}^2}$$

$$v_{\rm bar}^2(r) = 4\pi G \Sigma_0 R_d y^2 [I_0(y)K_0(y) - I_1(y)K_1(y)], \qquad (D5)$$

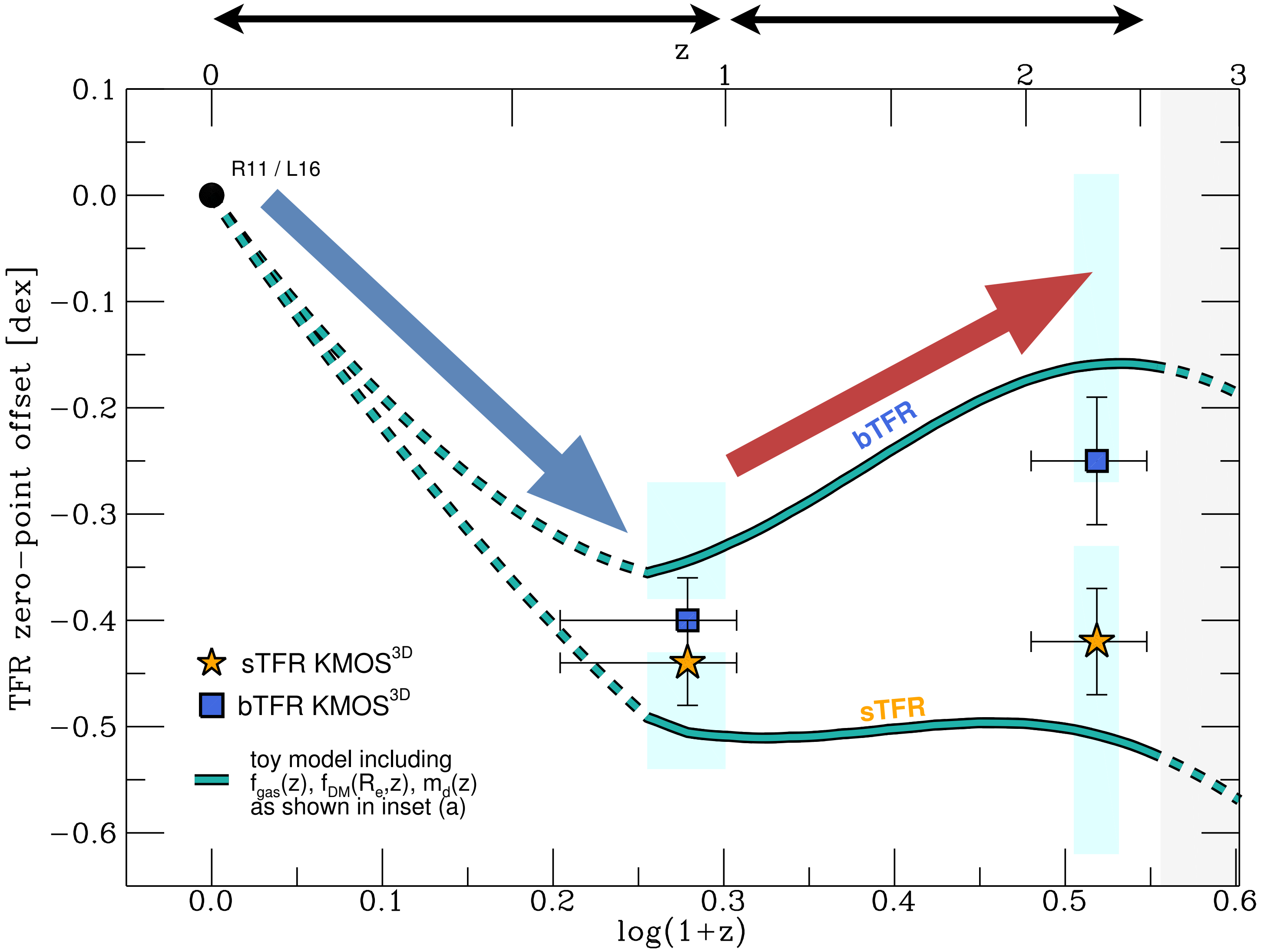
$$\propto M_{bar}/R_d$$

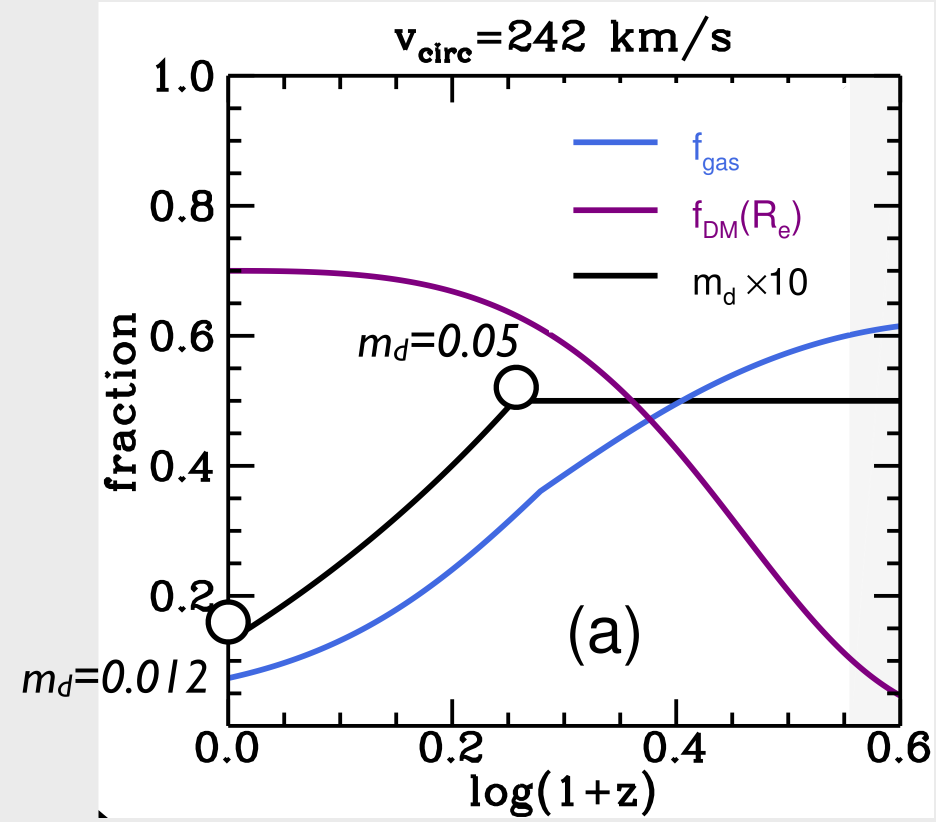
$$\boldsymbol{M_{bar}/R_d = C_2 \times (1 - f_{DM}) v_{cir}^2}$$

$$M_{\rm bar} = \frac{v_{\rm circ}^3(R_e)}{H(z)} \cdot \boxed{\frac{[1 - f_{\rm DM}(R_e, z)]^{3/2}}{m_d^{1/2}(z)} \cdot C} \qquad (4)$$

Interpretation of TFR zero-point offset

Uebler+17 **m_d is a dominant factor** **f_{DM} is a dominant factor**





Baryonic TF relation **zero-point offset term →**

$$M_{\rm bar} = \frac{v_{\rm circ}^3(R_e)}{H(z)} \boxed{\frac{[1 - f_{\rm DM}(R_e, z)]^{3/2}}{m_d^{1/2}(z)}} C \qquad (4)$$

Stellar TF relation

$$M_* = \frac{v_{\rm circ}^3(R_e)}{H(z)} \boxed{\frac{[1 - f_{\rm DM}(R_e, z)]^{3/2}\,[1 - f_{\rm gas}(z)]}{m_d^{1/2}(z)}} C', \quad (5)$$

1. gas fraction (M_{gas}/M_{star})

$$\log\left(\frac{M_{\rm gas,mol}}{M_*}\right) \approx 0.12 - 3.62\cdot[\log(1+z) - 0.66]^2 - 0.33\cdot[\log(M_*\,[M_\odot]) - 10.7]\,. \qquad (D8)$$

Tacconi+17

2. disk mass fraction (M_{bar}/M_{DM})

m_d=0.012 at z=0: Moster+13
m_d=0.05 at z=0.8<z<2.6 Burkert+16

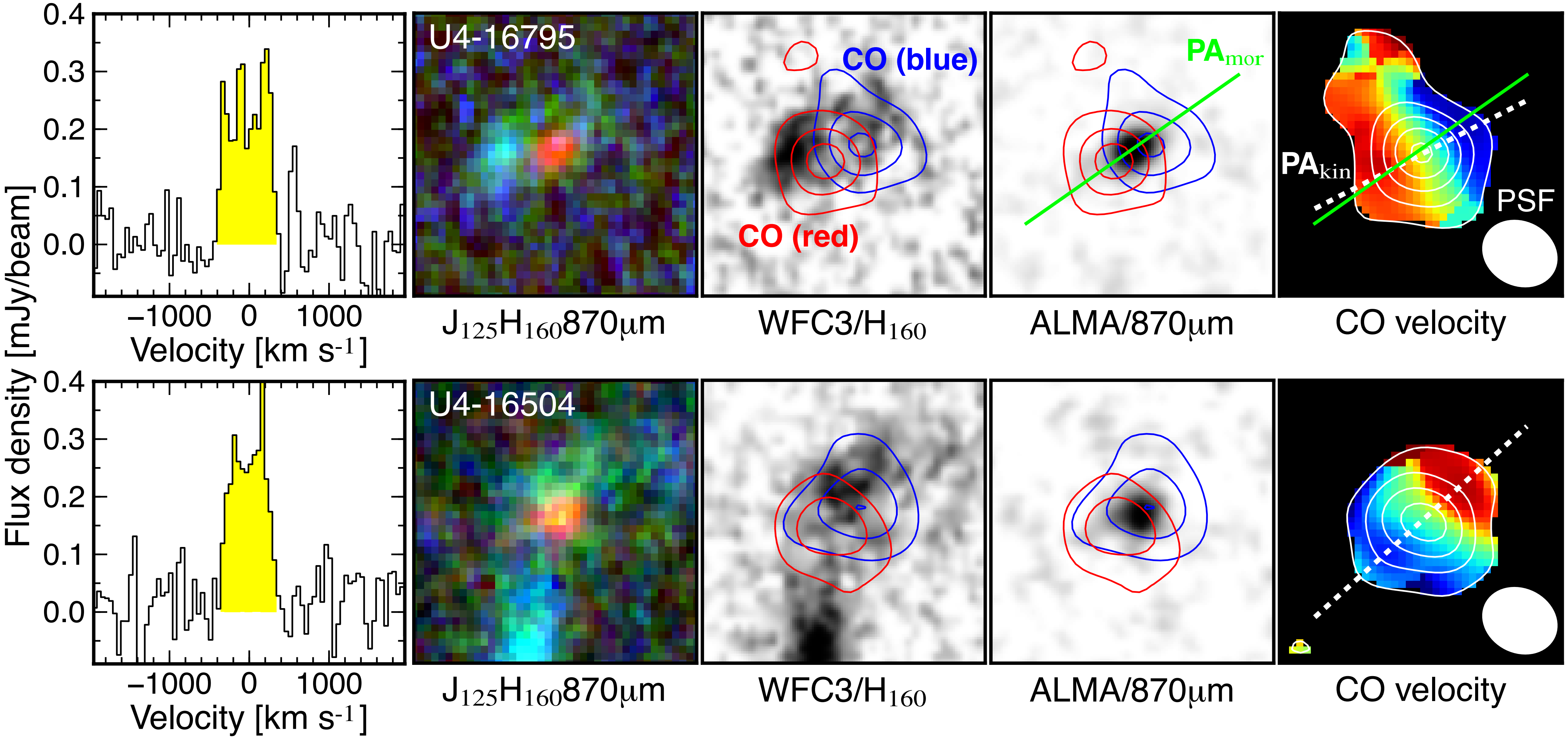
3. dark matter fraction (M_{DM}/M_{bar} **at R_e**)

$$f_{\rm DM}(R_e) = 0.7\cdot\exp[-(0.5\cdot z)^{2.5}]$$

z=0: Courteau&Dutton 2015
z=0.9,2.3: Wuyts+16

CO observations with ALMA

CO(3-2) observations in ***the most massive galaxies*** *at z=2.5 (Tadaki+17)*

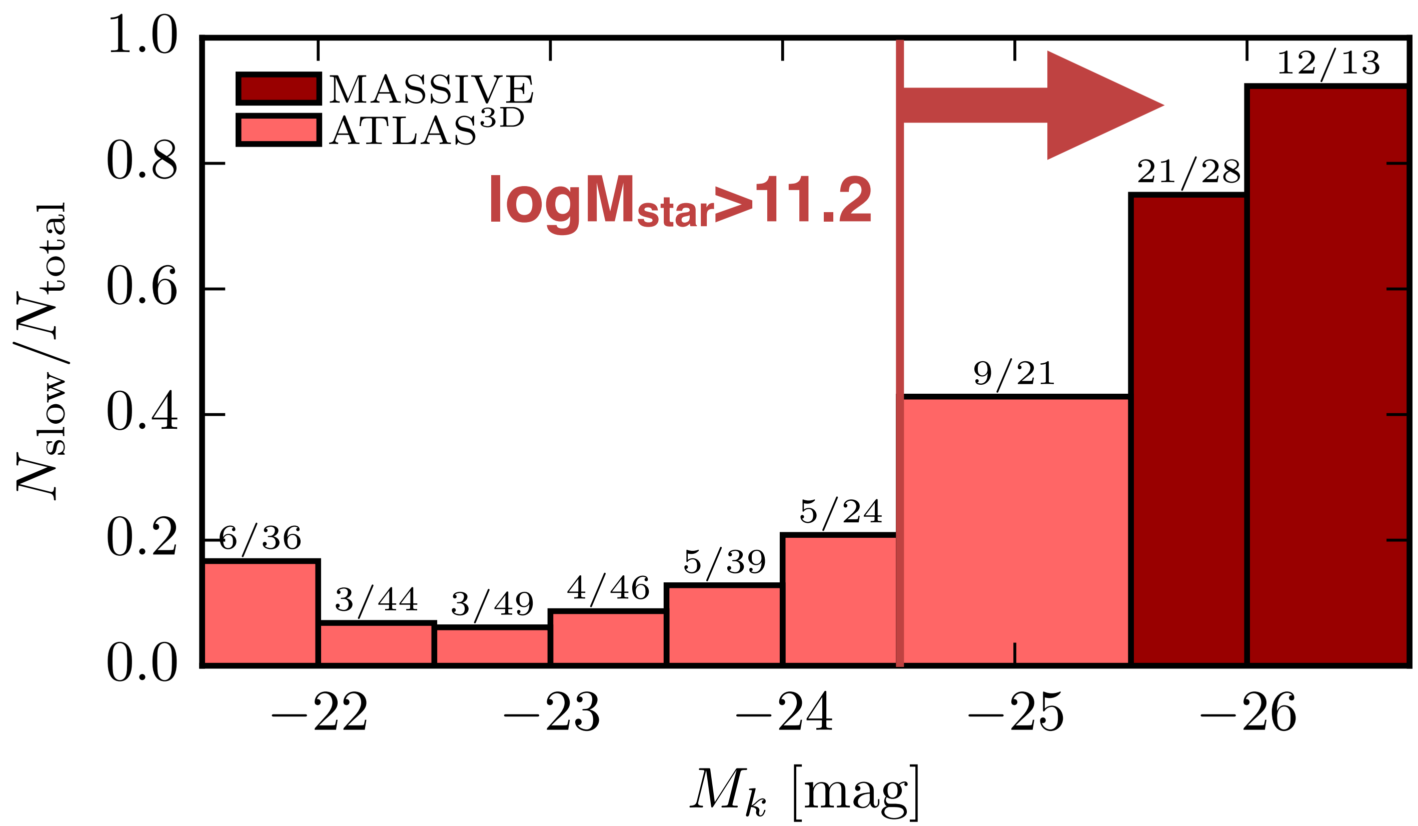


v/σ=7.0

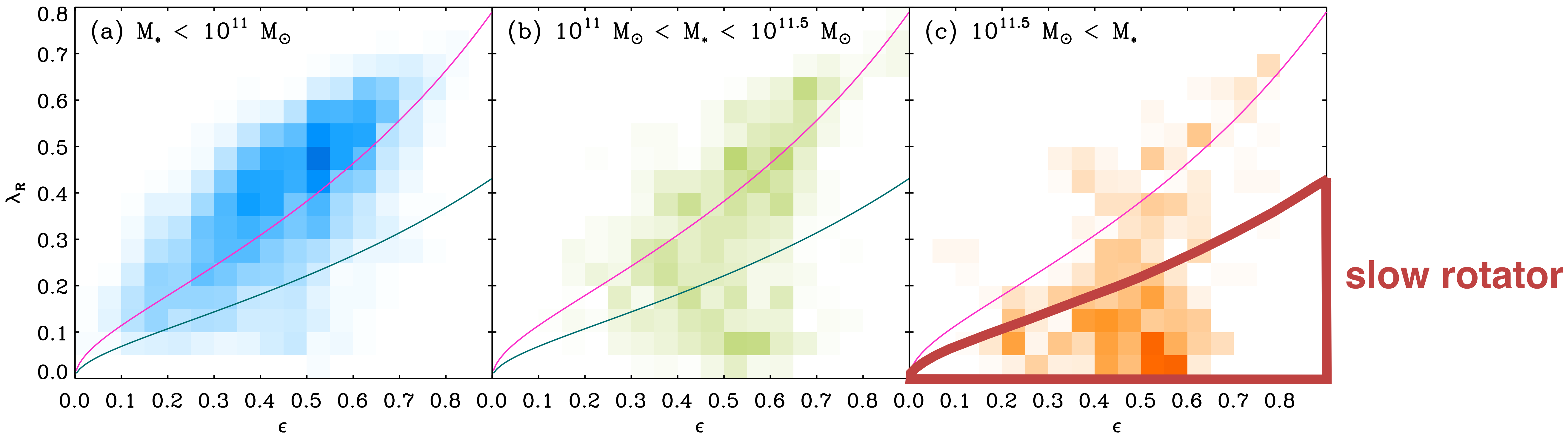
v/σ=4.1

z=2にある重い銀河はslow rotatorになる？

Observations (Veale+16)



Simulations (Penoyer+17)



何が銀河の回転を止めたのか？

the most massive star-forming galaxies at high-z

V/σ>>1

quenching

quiescent galaxies at high-z

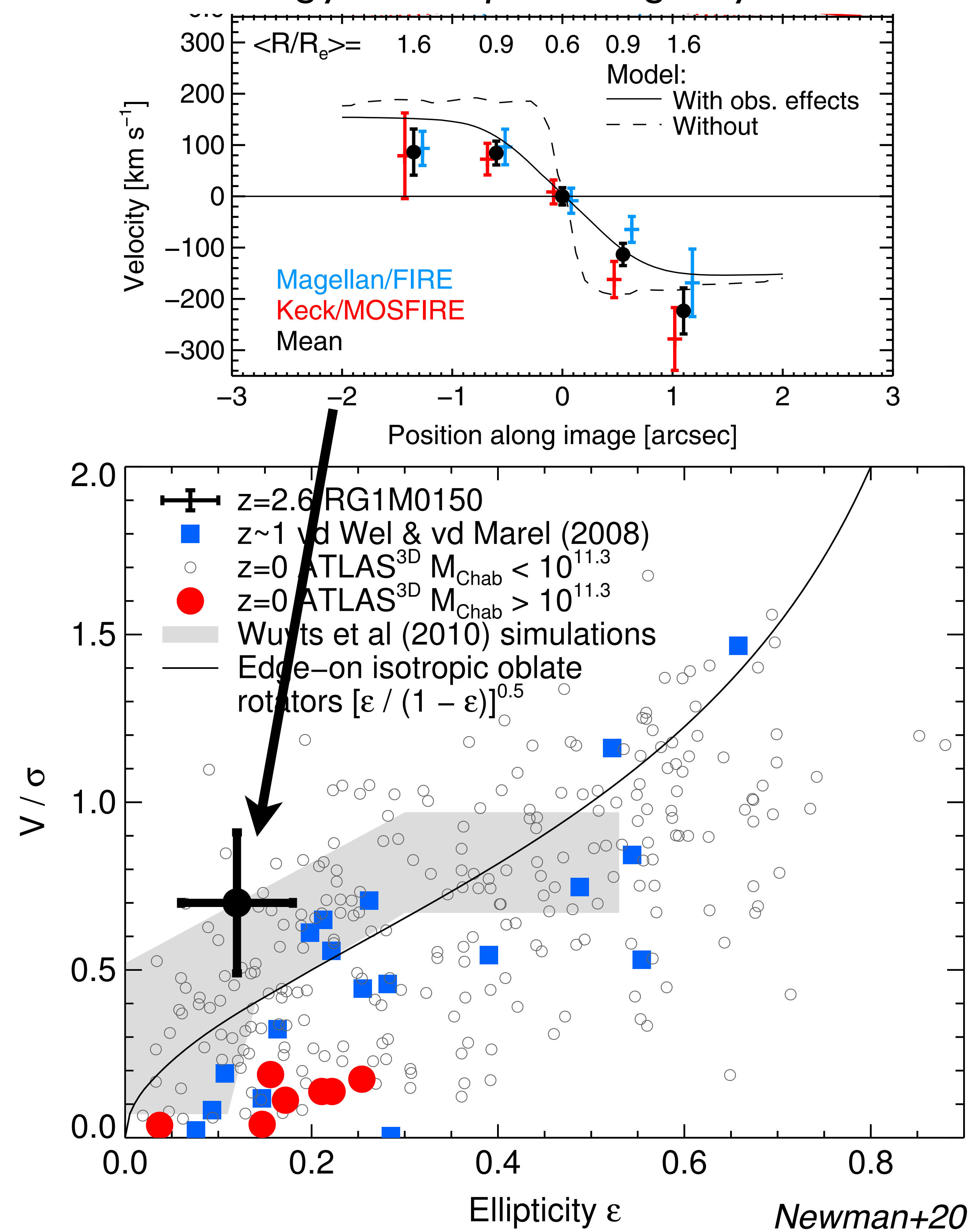
V/σ~1

size evolution

slow rotators at z=0

V/σ<<1

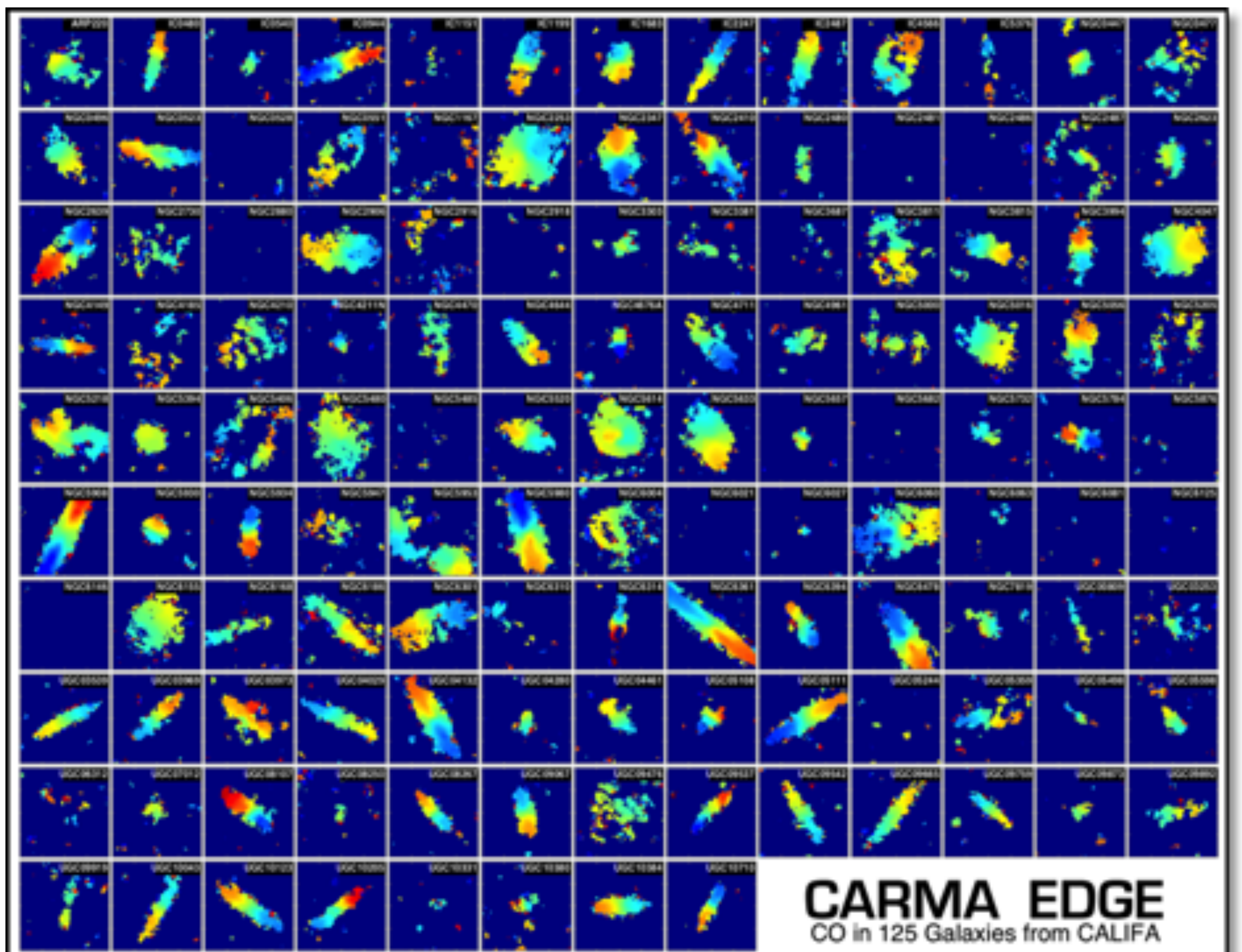
a strongly-lensed quiescent galaxy at z=2.6



Newman+2015

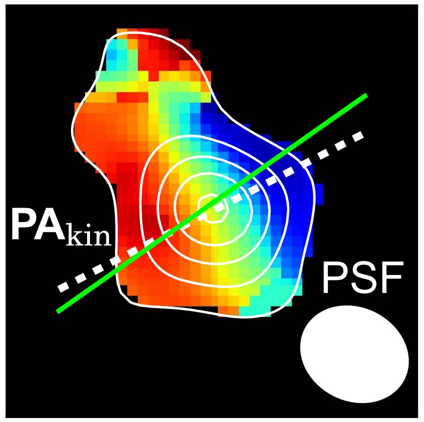
まとめ

CO(J=1-0)

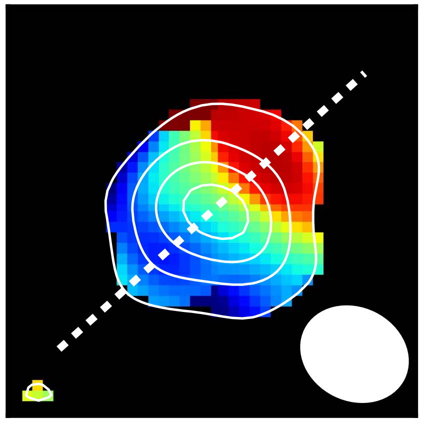


Bolatto+2017

CO(high-J)

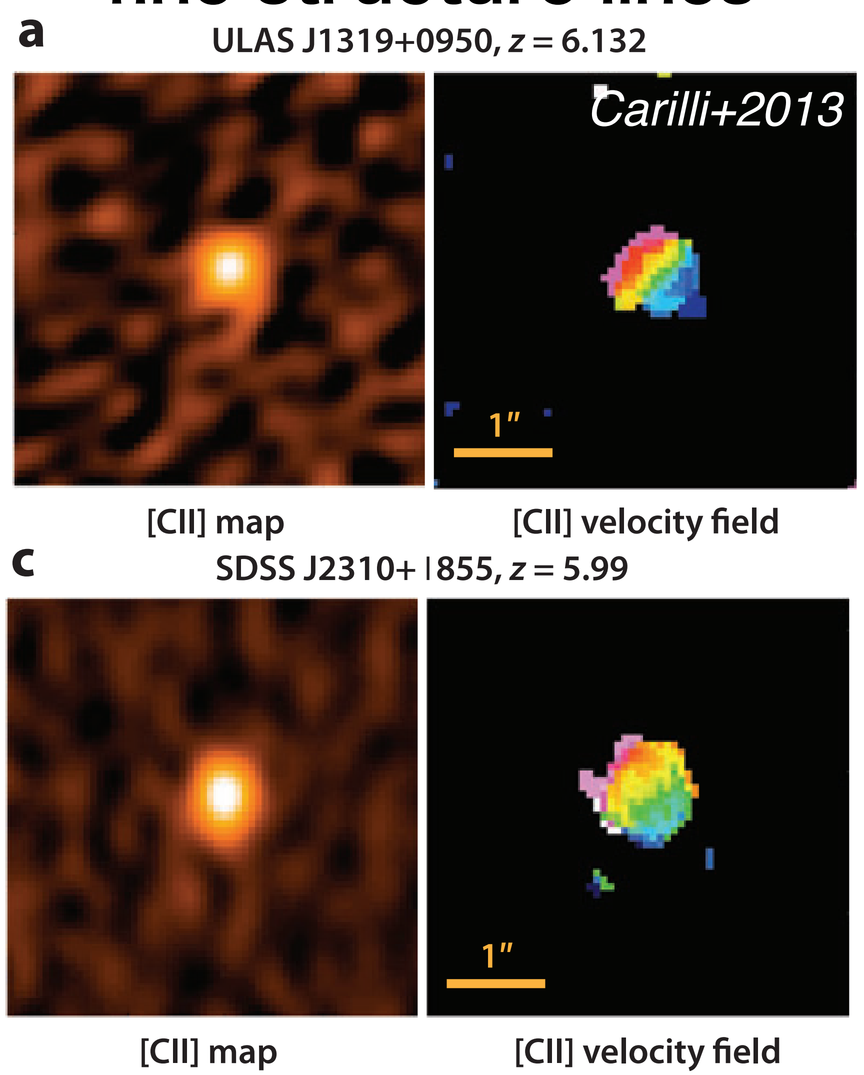


CO velocity



CO velocity

fine structure lines



redshift