A high-z perspective on galaxy growth and star formation

Stijn Wuyts

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&
CANDELS, 3D-HST, SINS/zC-SINF, KMOS^{3D} and PHIBSS2 teams

UNIVERSITY OF BATH

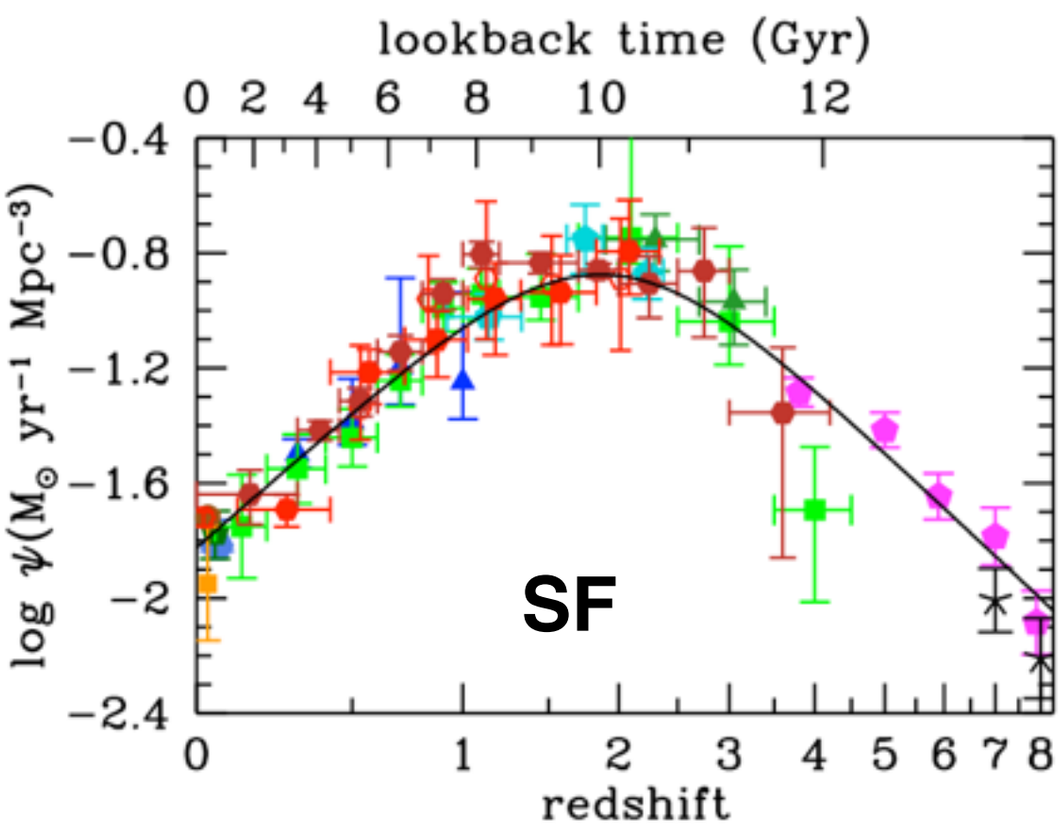
Mostly since 'cosmic noon' (z~2)

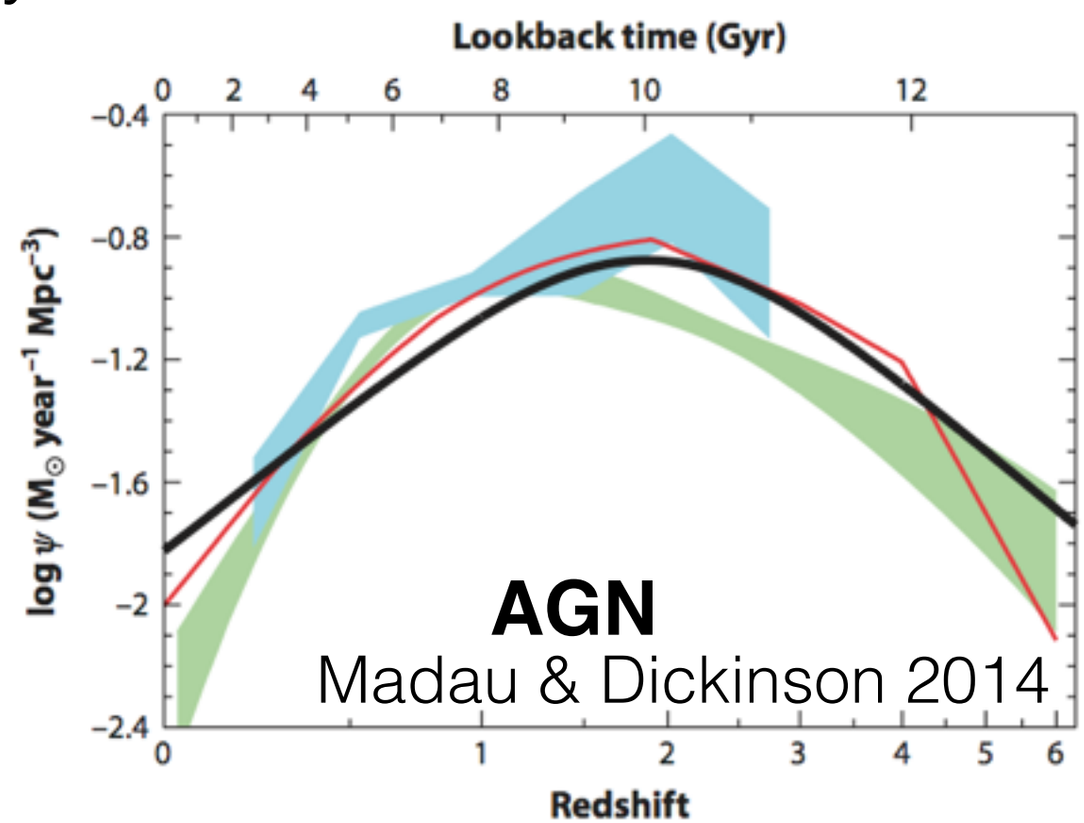
A high-z perspective on

Massive ($\gtrsim 10^{10}\ M_\odot$)

galaxy growth and star formation

Stijn Wuyts





Why study at high-z?

- Witness live where a lot of the ‘action’ happens
- Different conditions $\dot{M}_{gas} \sim M_{halo}^{1.15}\,(1+z)^{2.25}$
- Color information of fossil record saturates
- Star formation vs assembly

Outline

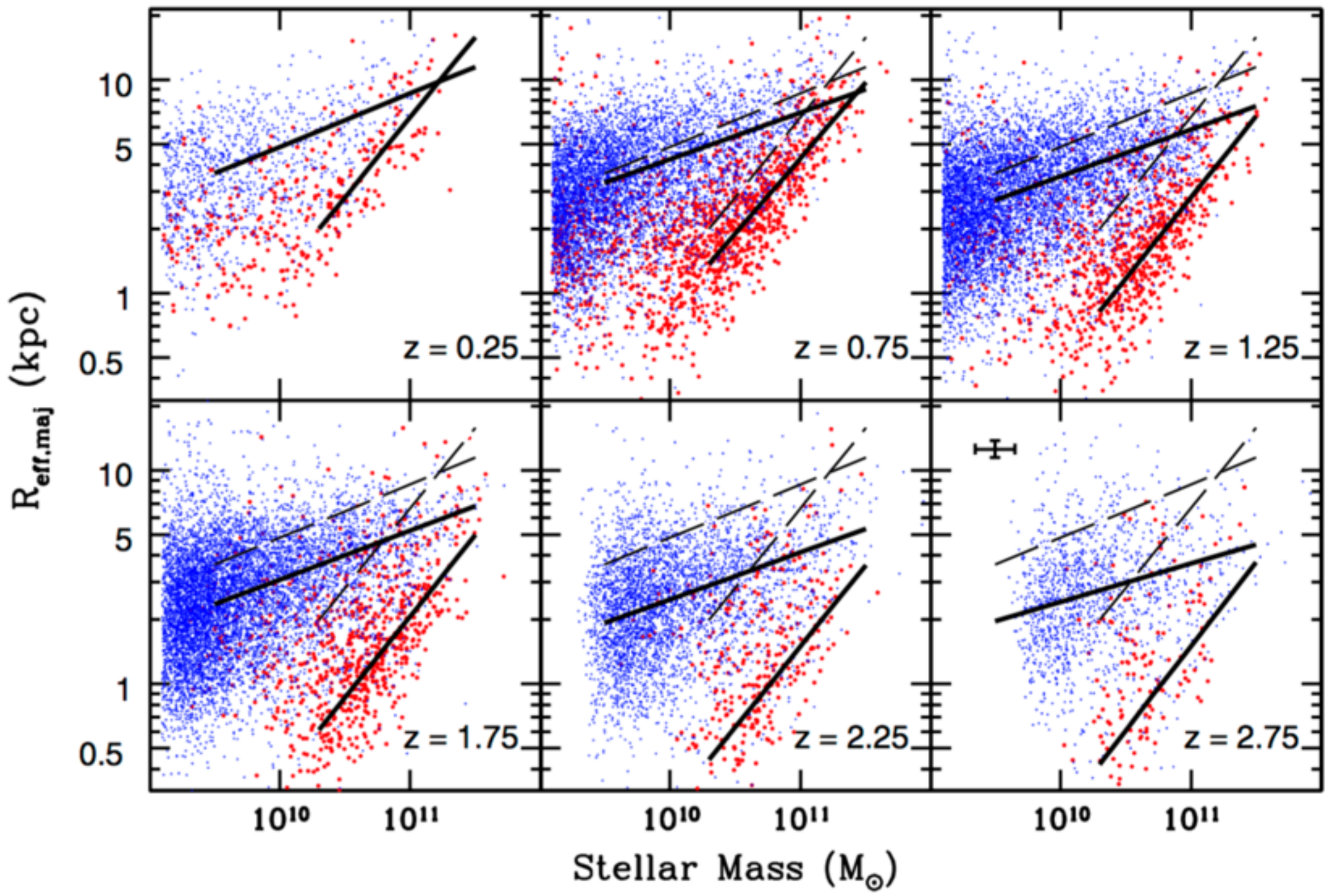
- **GLOBAL**
  In what galaxies do stars form?
  Disks, but unlike local disks
  → ubiquitous outflows
  → turbulent ISM
  → clumpy
  → gas-rich

  The mass budget of early disks: baryon-dominated at z>2

- **LOCAL**
  Combining multi-wavelength resolved tracers
  Where within galaxies do stars form?
  Inside-out growing exponential disks
  Parallel tracks vs compaction

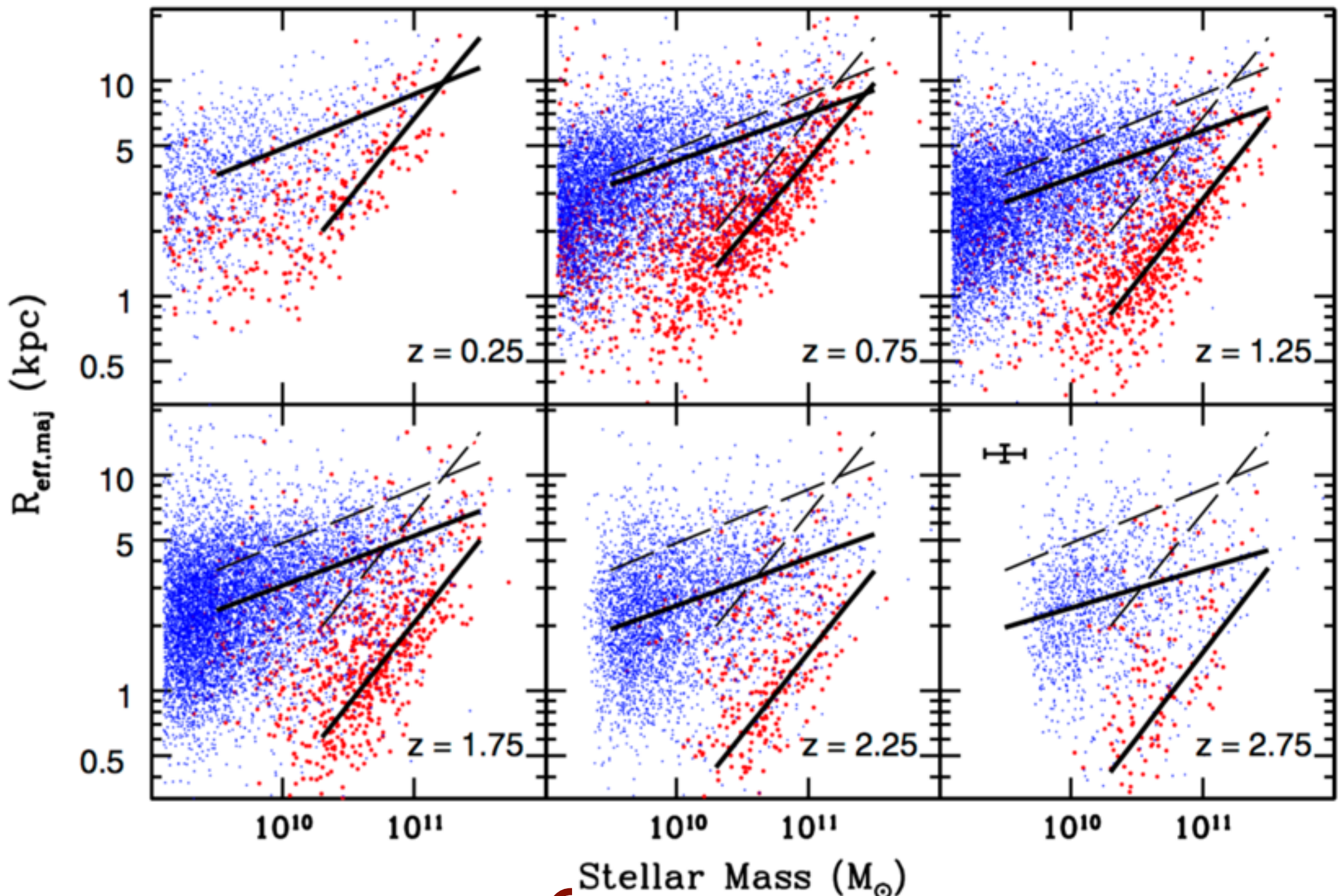
In what galaxies do stars form?

SFGs are <typically> larger than QGs (at same mass and redshift)



van der Wel+2014

SFGs are <typically> larger than QGs (at same mass and redshift)



van der Wel+2014

Halo mass → viral radius

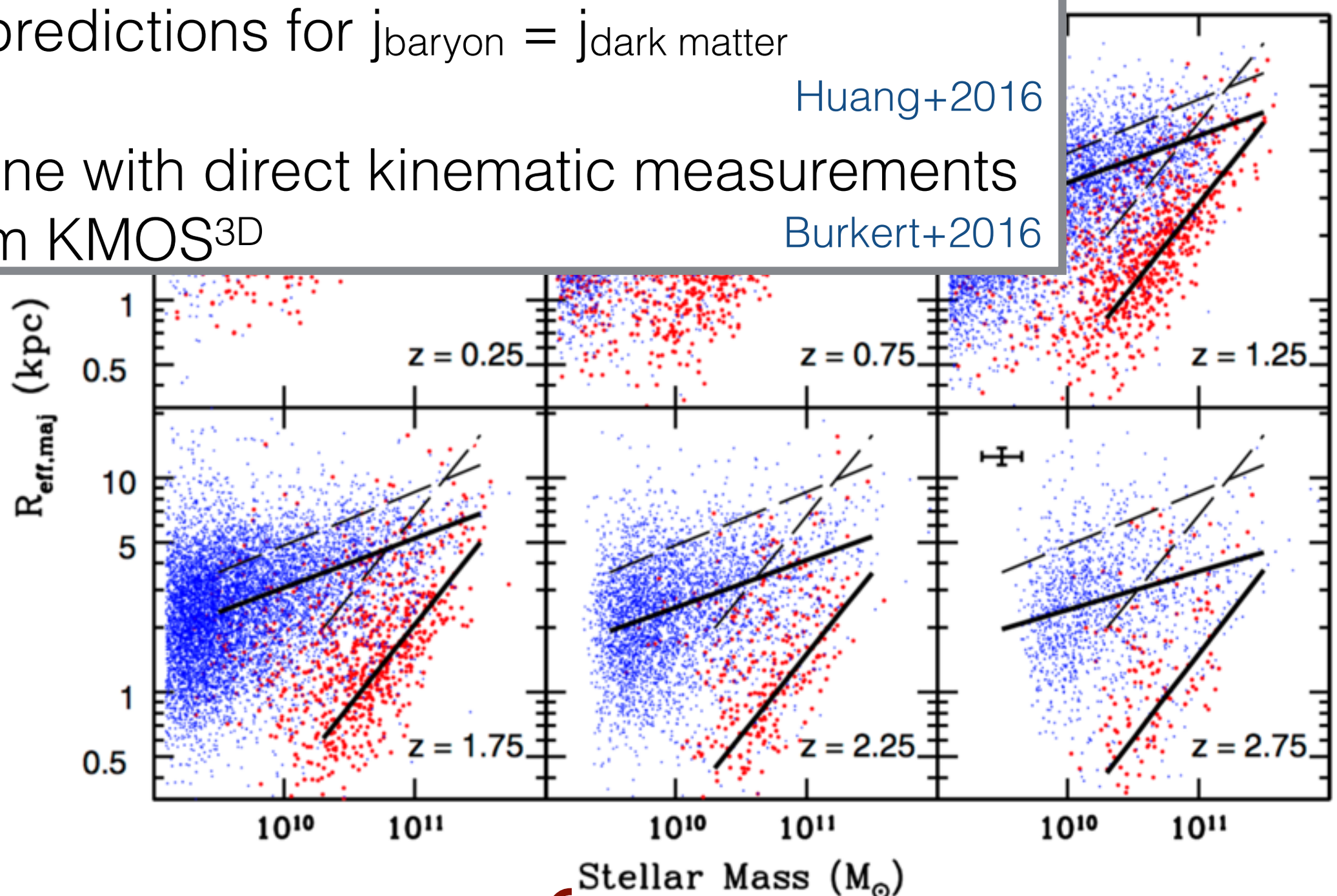
SFGs are <typically> larger than QGs (at same mass and redshift)

R_e - R_{vir} relation of SFGs within ≲ 0.1 dex of predictions for $j_{baryon} = j_{dark\ matter}$

Huang+2016

in line with direct kinematic measurements from KMOS^{3D}

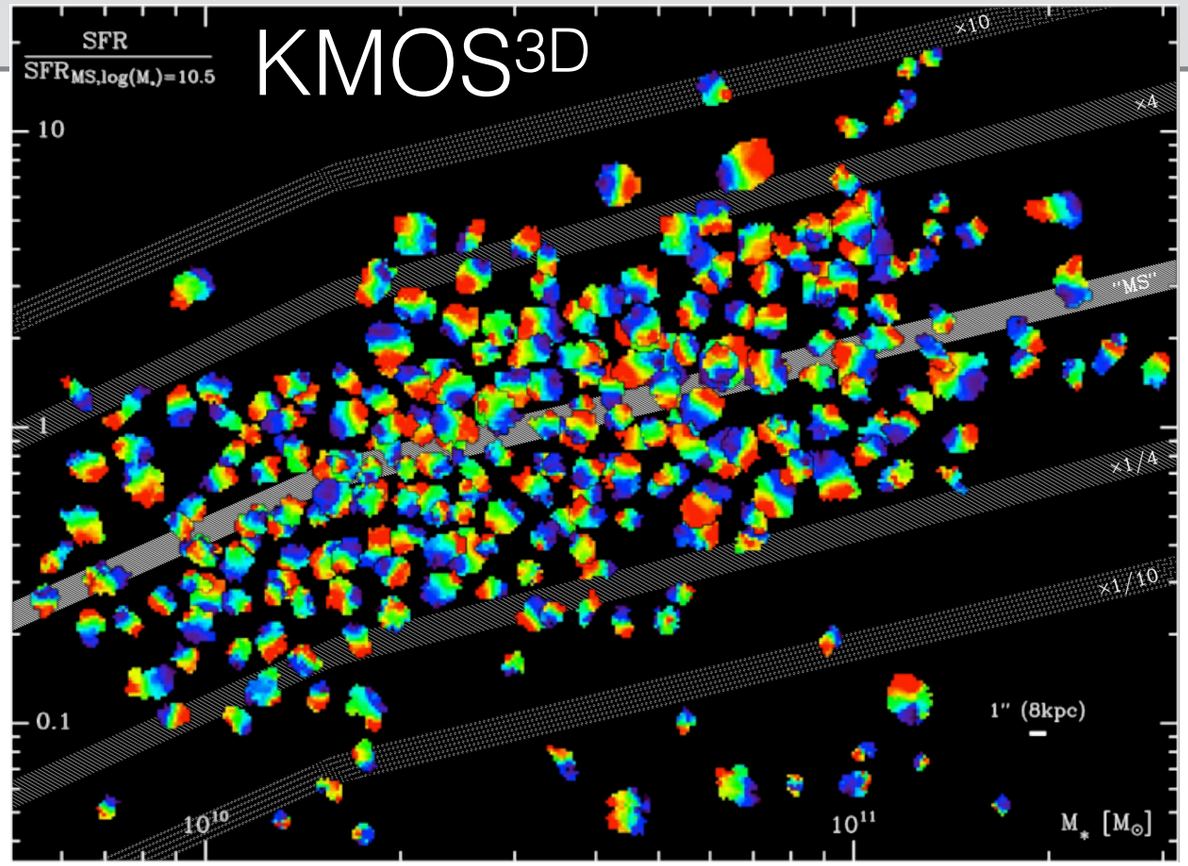
Burkert+2016



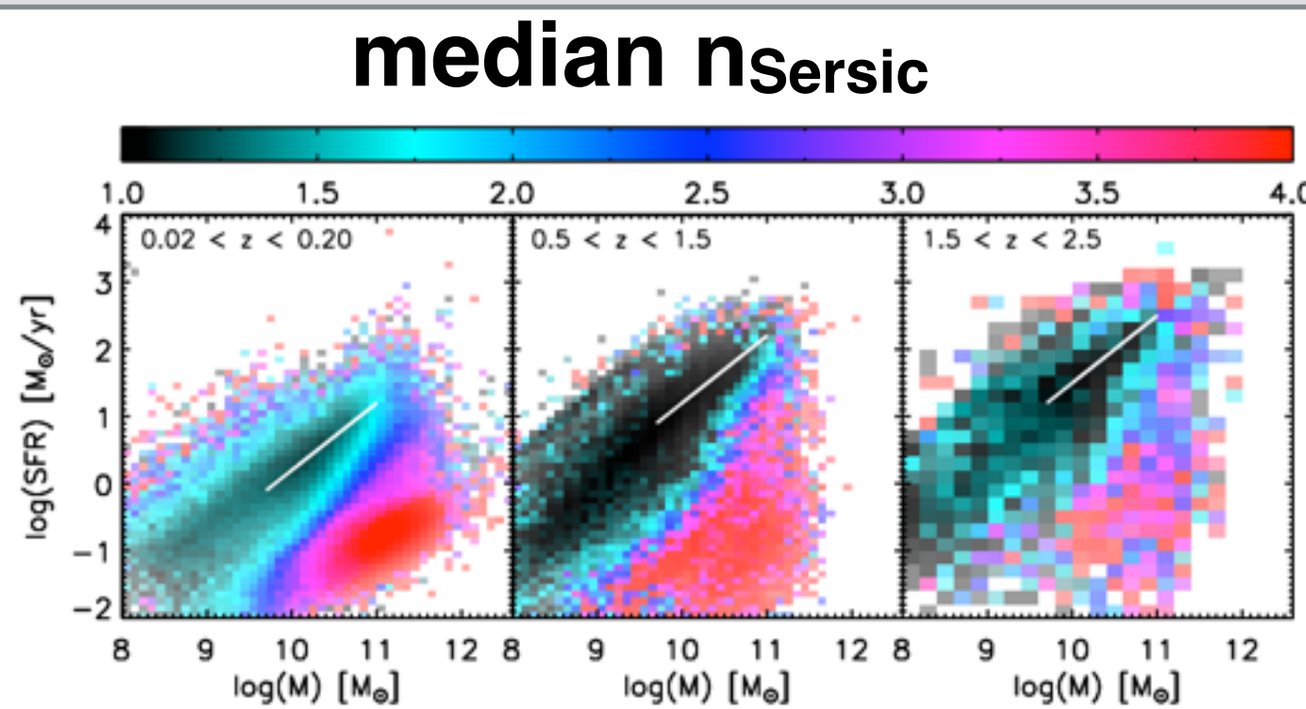
van der Wel+2014

Halo mass → viral radius

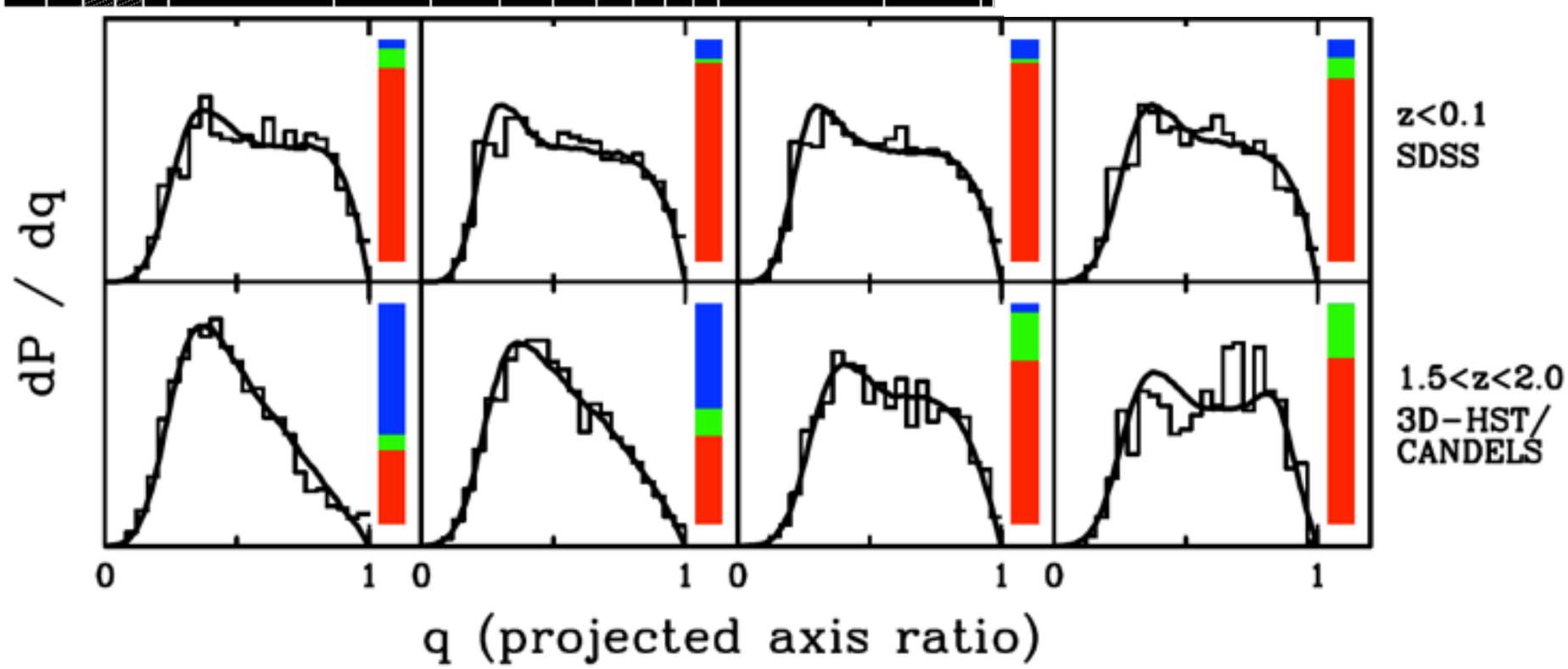
SFGs are <typically> disks (at least at ≳ 10^{10} $M_\odot$)



Wisnioski+2015



Wuyts+2011

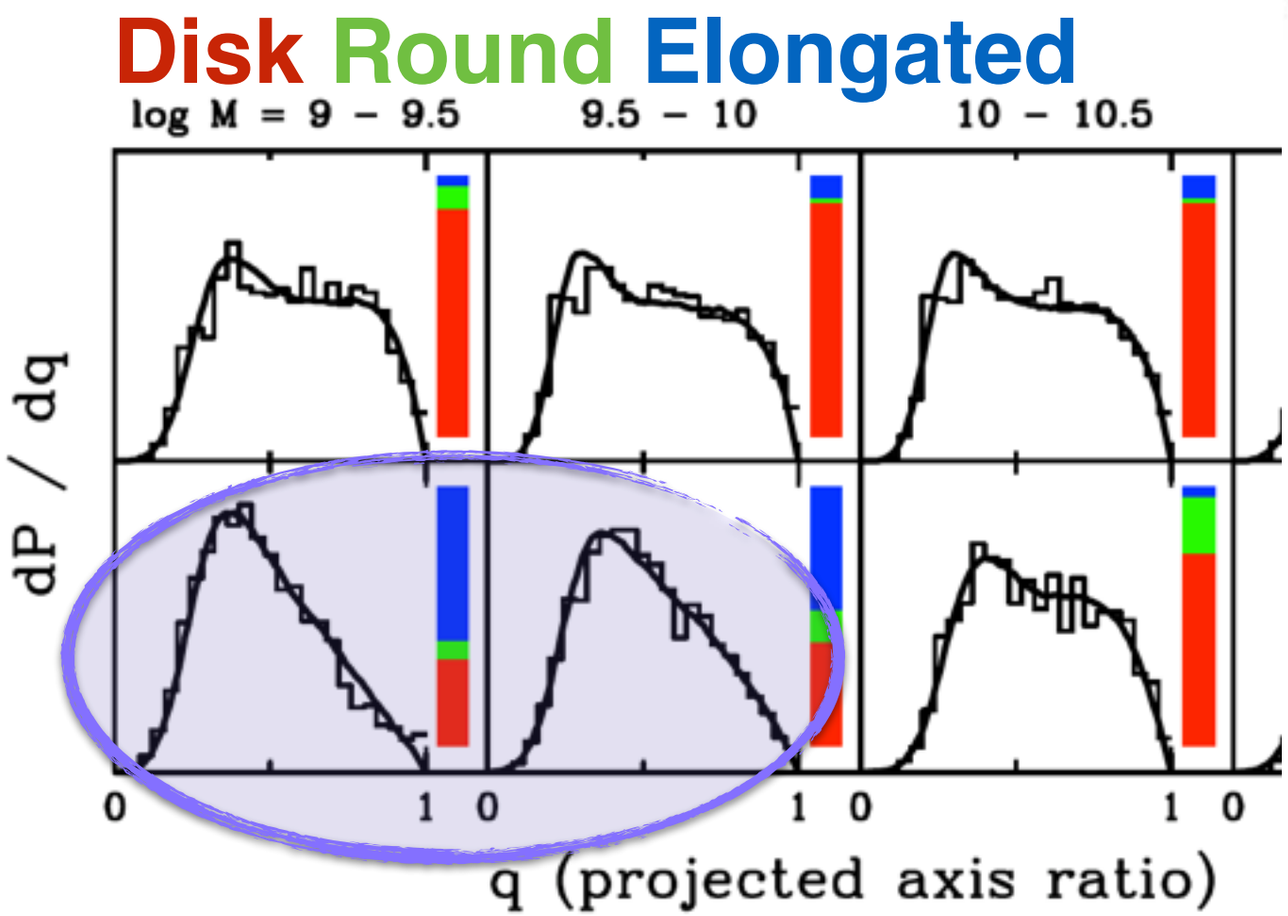


van der Wel+2014

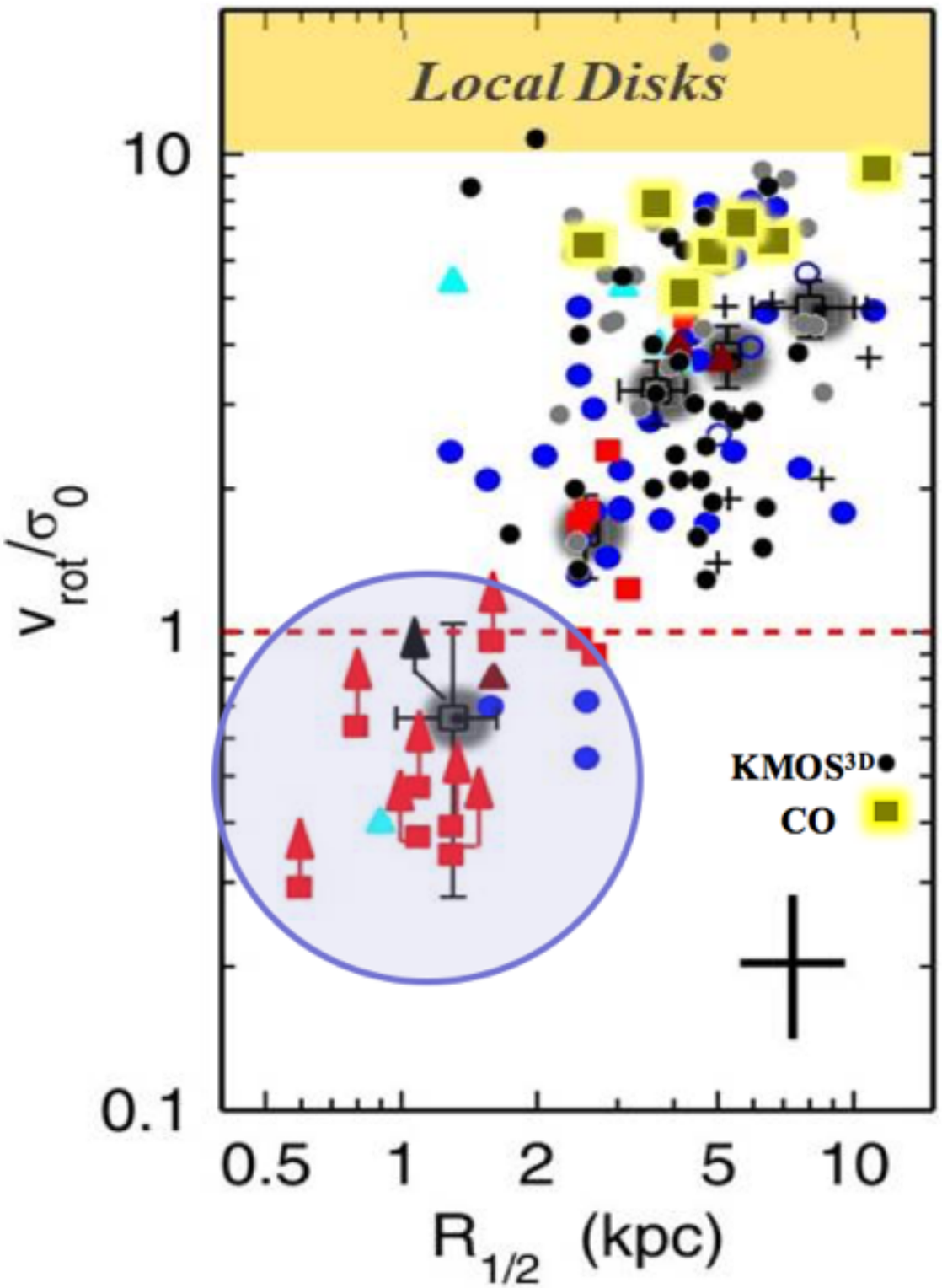
SFGs are <typically> disks (at least at ≳ 10^{10} $M_\odot$)

Dispersion-dominated disks: triaxiality & non-equilibrium

see also Simons+2015

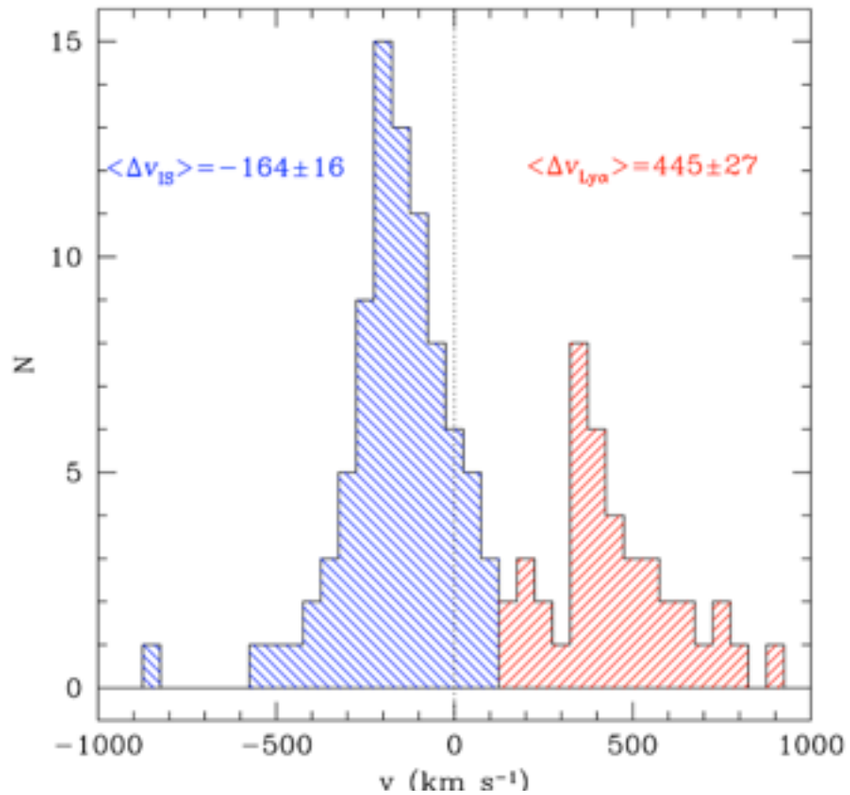


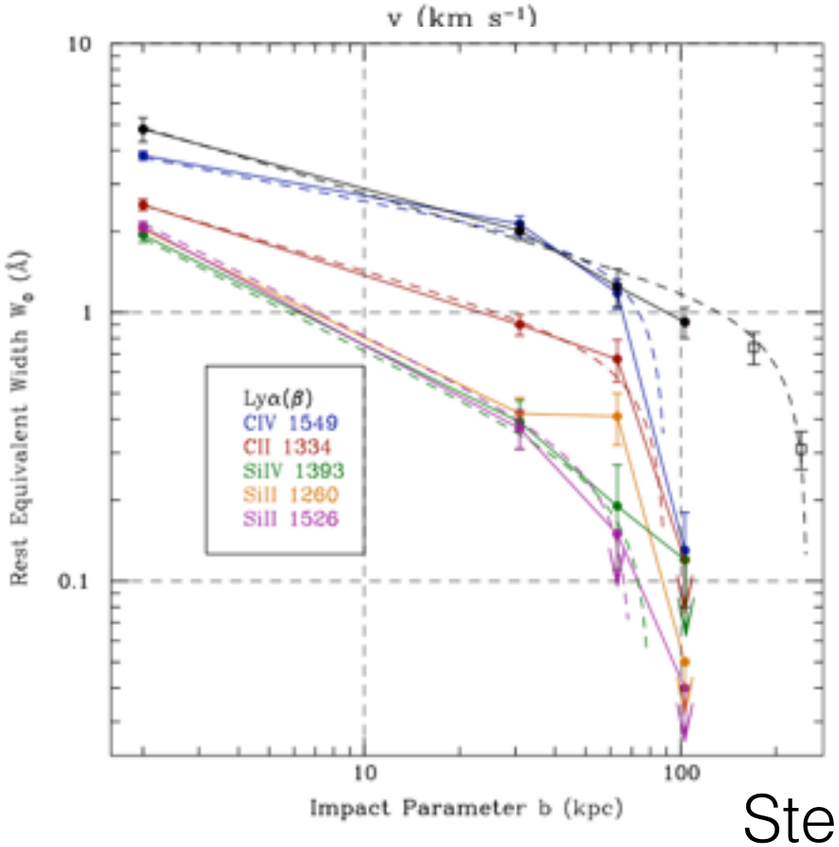
van der Wel+2014



Newman+2013

… but unlike local disks - Ubiquitous outflows

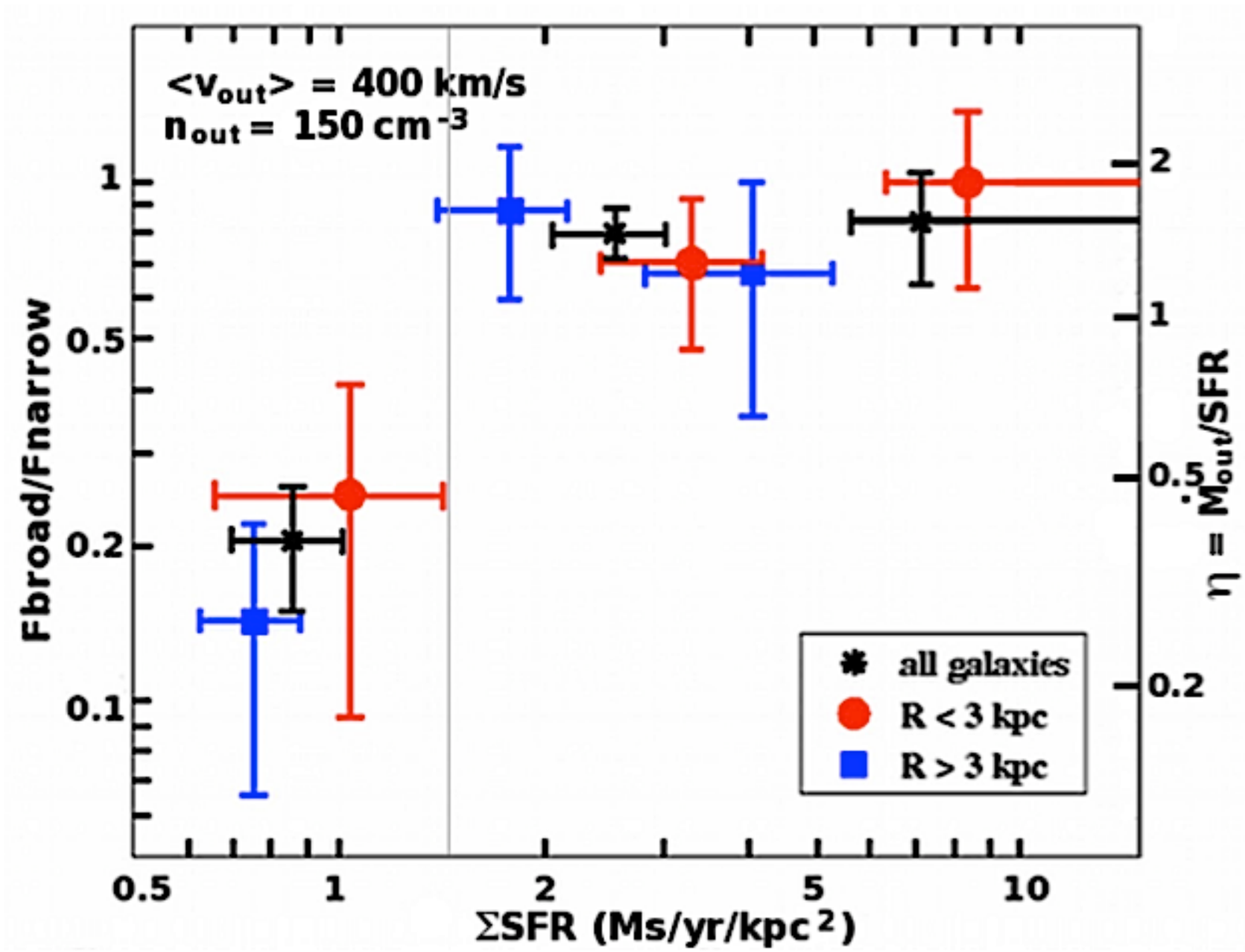




Steidel+2010

SINS, zC-SINF, KMOS^{3D}:

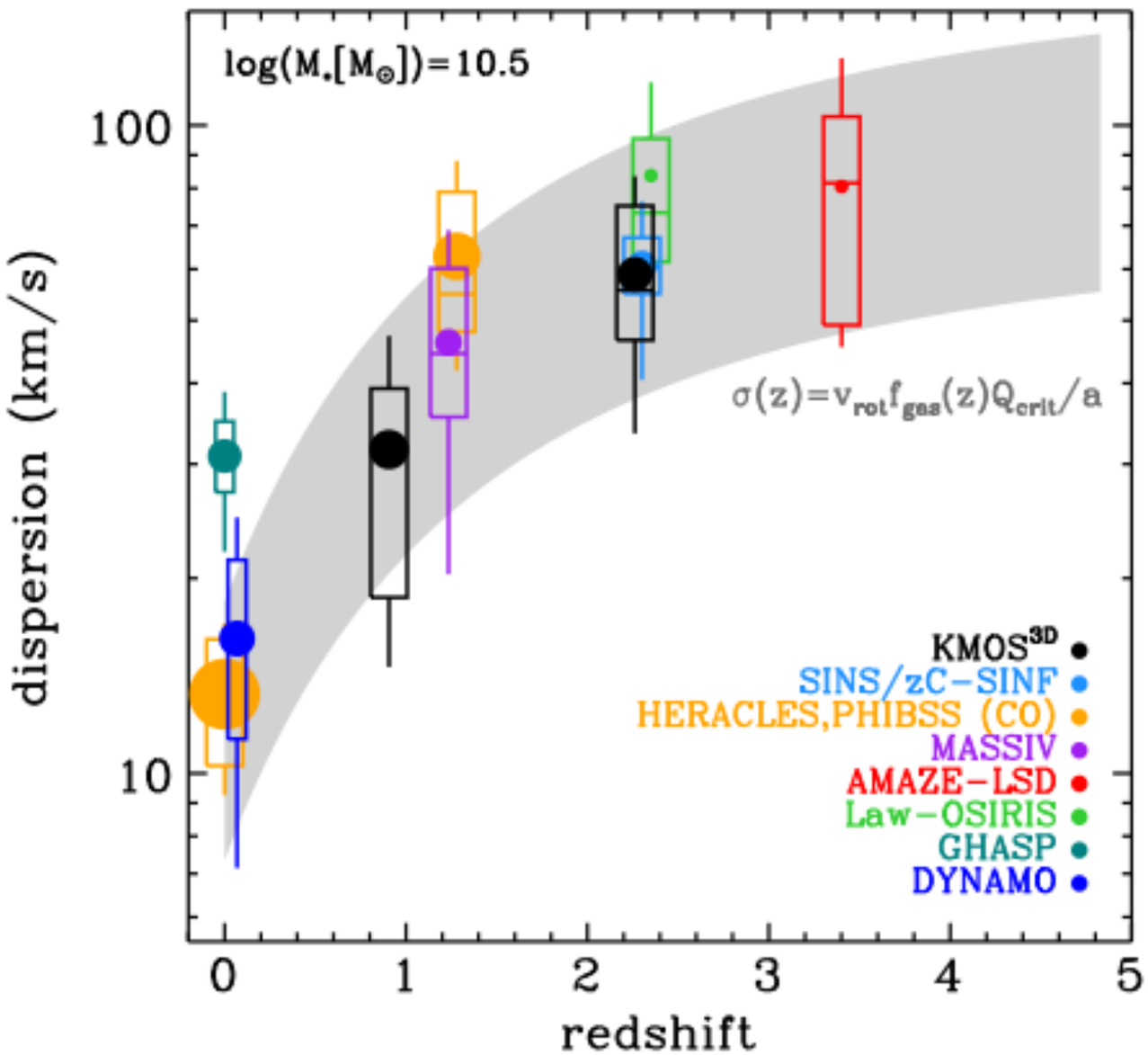
Outflows from emission line kinematics



Newman+2012

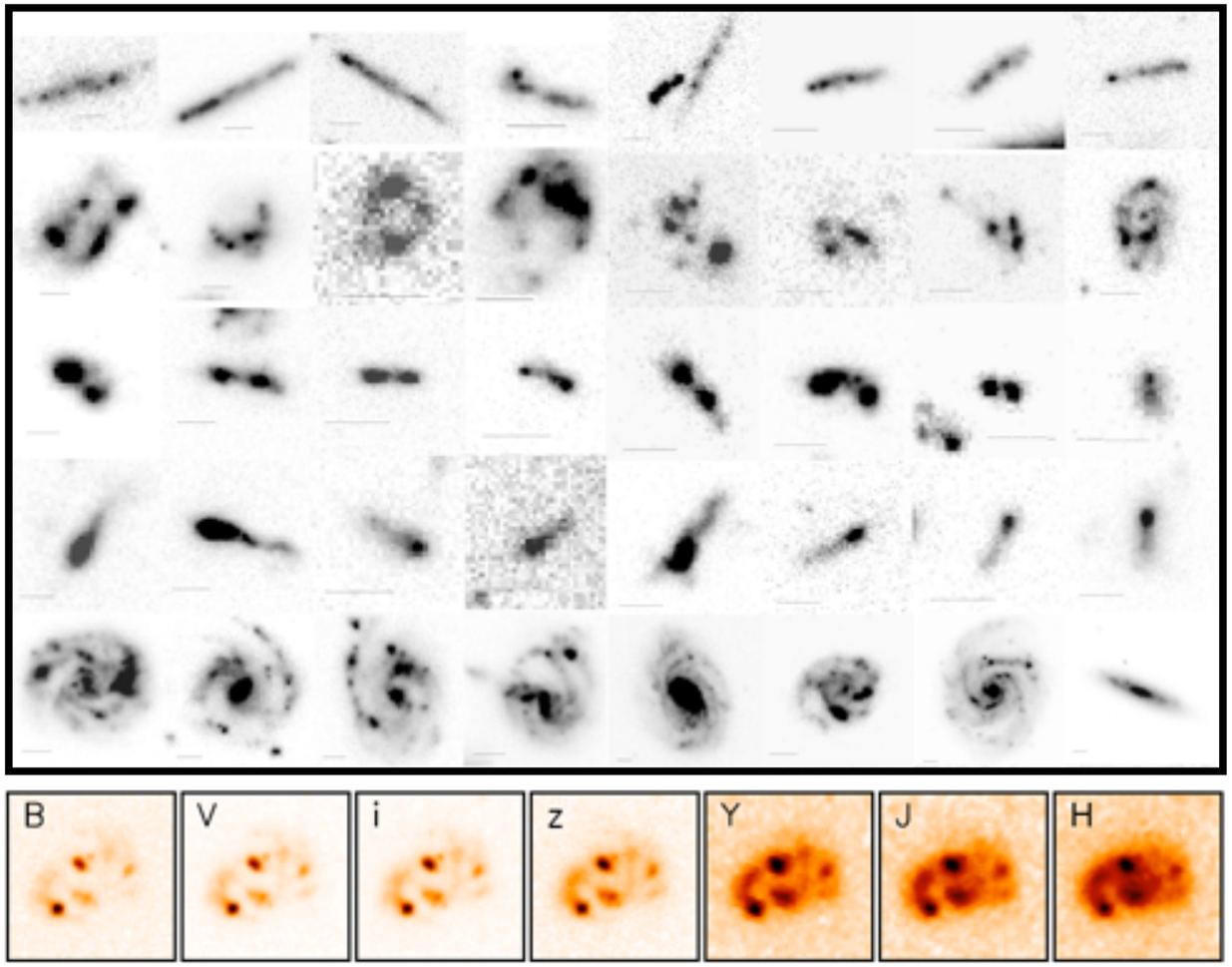
… but unlike local disks - Turbulent ISM

Increasing intrinsic dispersions



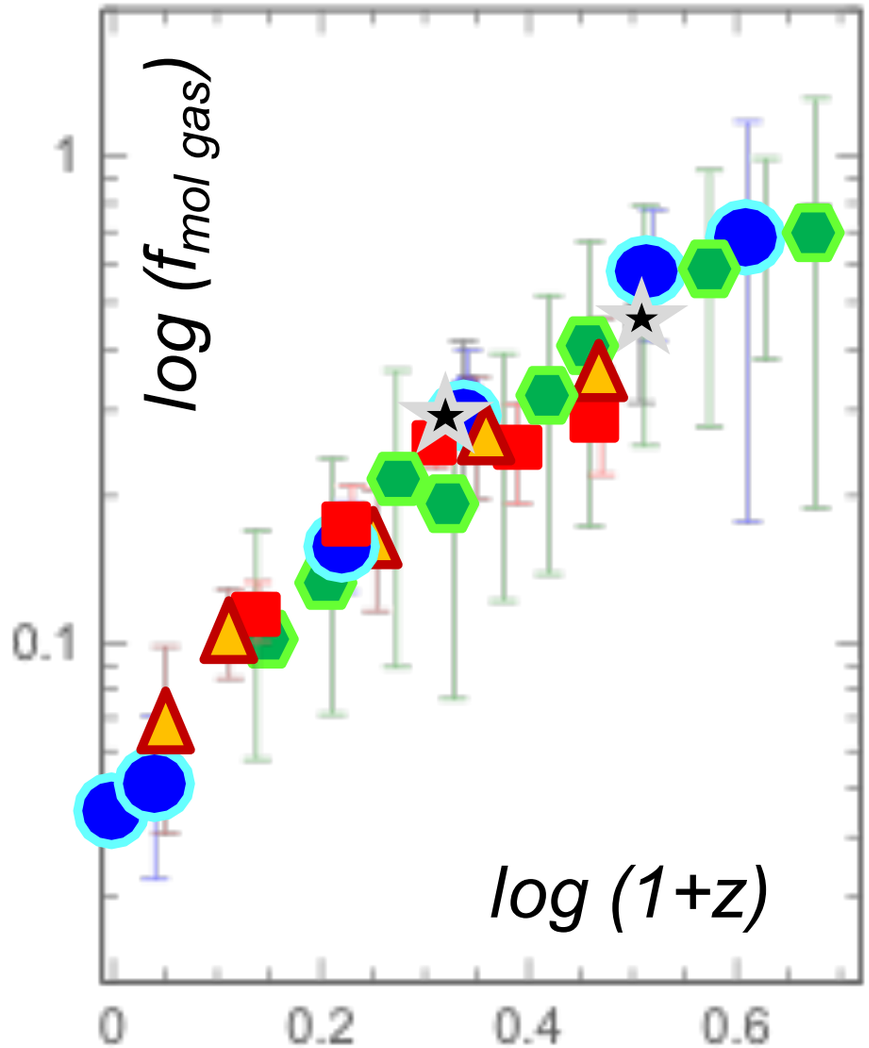
Kassin+2012; Wisnioski+2015

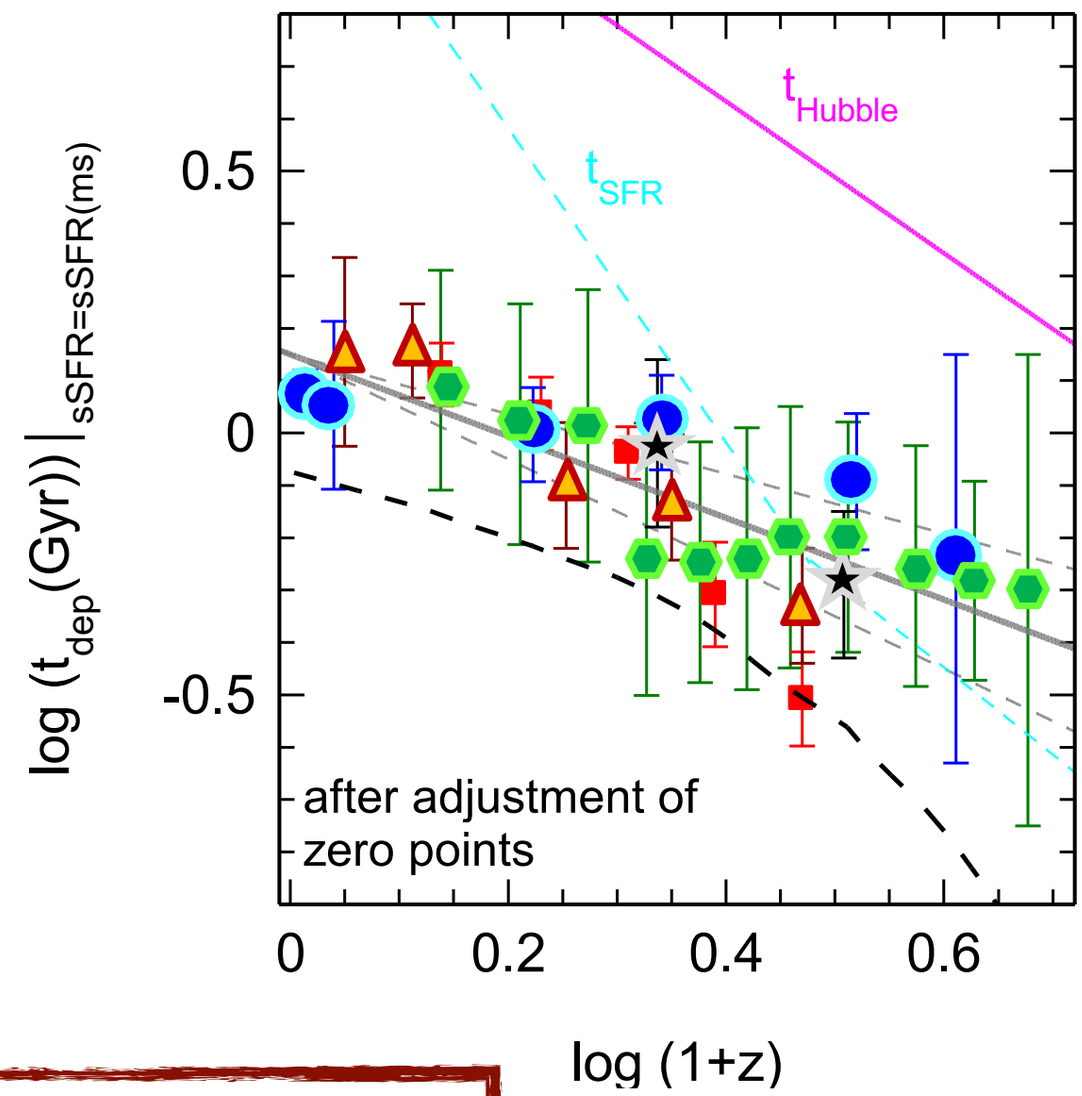
Clumpy morphologies



Elmegreen+05,09; Genzel+2011; Förster-Schreiber+2011; Wuyts+12,13; Guo+12,15

… but unlike local disks - Gas-rich





- $M_{gas} \approx M_{star}$ @ z~2
- High SFRs due to f_{gas} ↗ and SFE ↗
- $t_{dep} \ll t_{Hubble}$

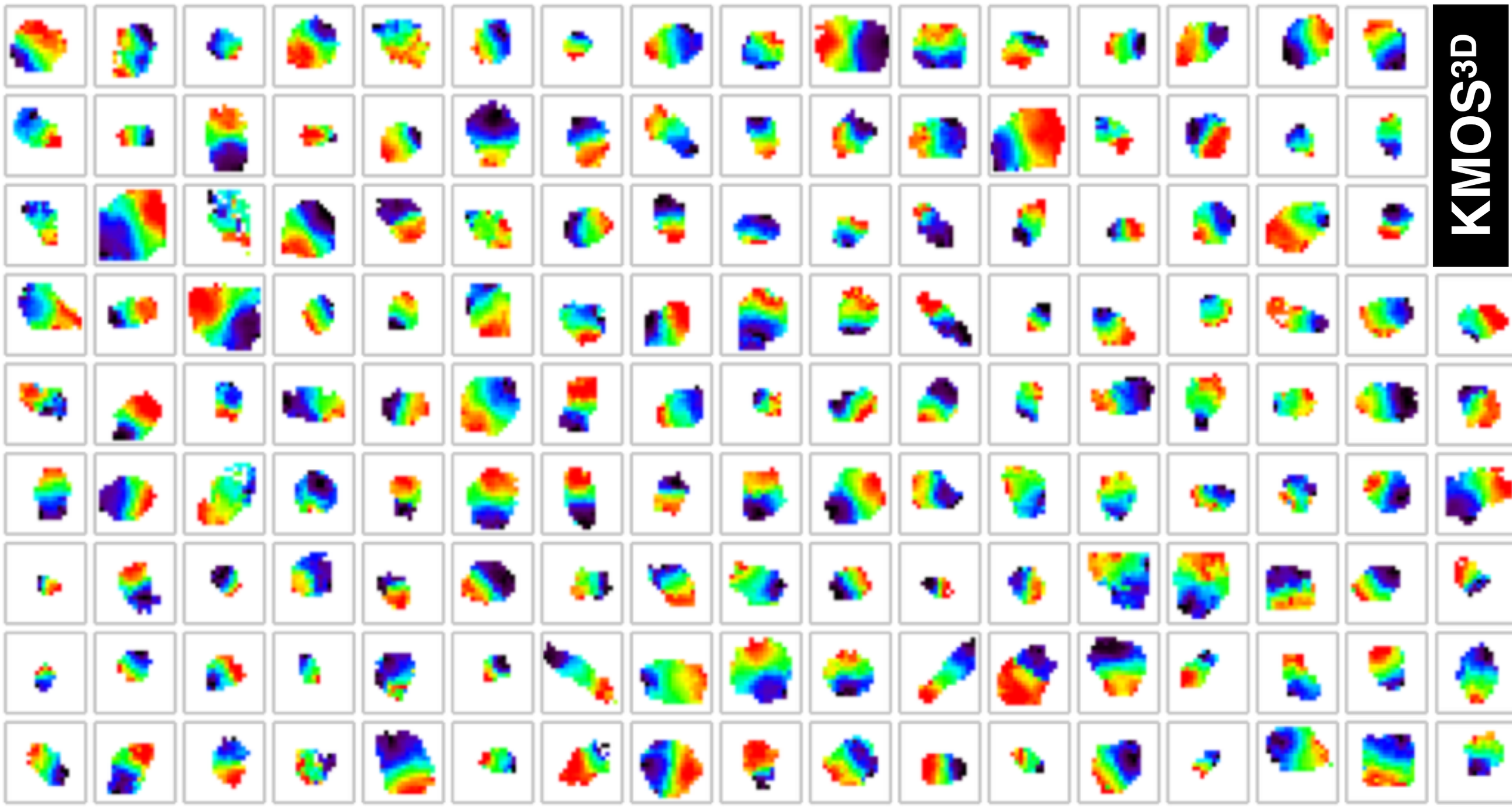
PHIBSS2 CO Survey (PIs L. Tacconi, F. Combes, R. Neri, S. Garcia-Burillo)
+ literature compilation

1200 SFGs; z = 0 - 4

- dust Bertermin+15
- dust Scoville+16
- dust Genzel+15, Berta+16
- dust Santini+14
- CO Saintonge+11,+13, Genzel+15,
- logt=0.15-0.78*log(1+z)
- Lagos+15

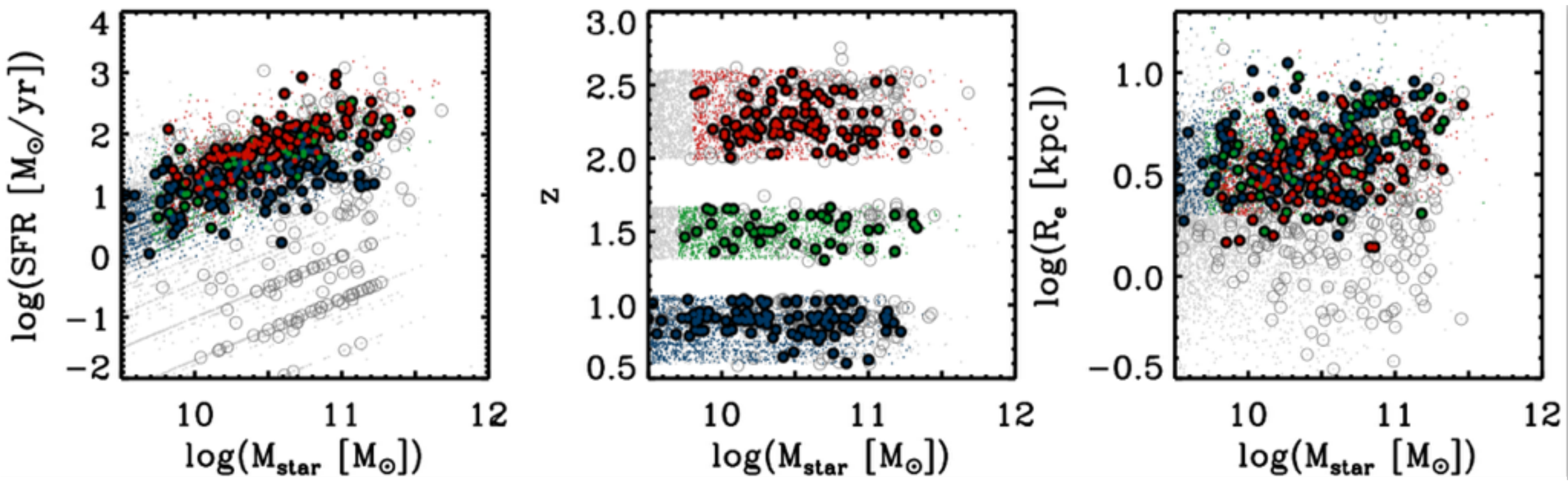
Mass budget in early disks

Wuyts+2016: Combine $\mathbf{M_{star}}$ from U-to-8μm SED modeling, $\mathbf{M_{gas}}$ from CO+dust-based gas scaling relations with $\mathbf{M_{dyn}}$ from structural + kinematic information to study breakdown of the mass budget within the disk regions of high-z galaxies



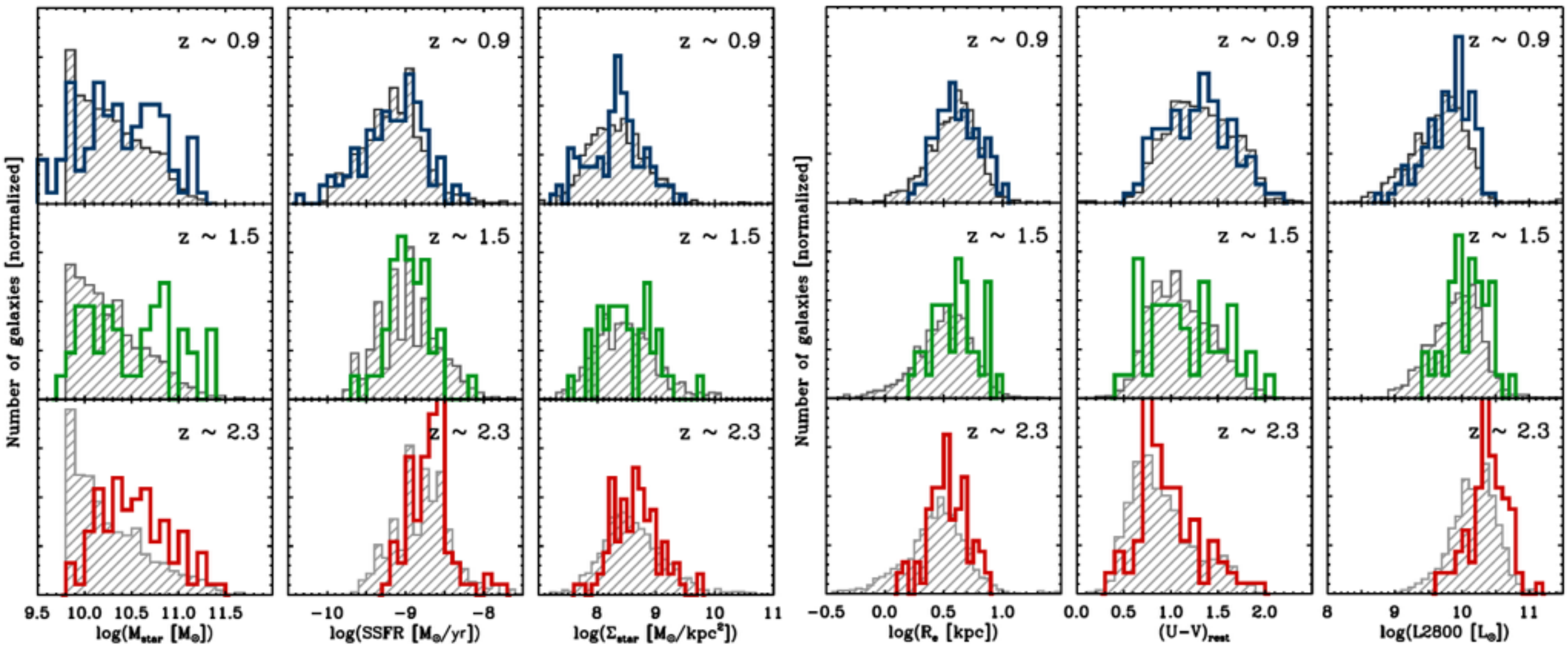
Mass budget in early disks

240 star-forming disks @ 0.6 < z < 2.6



Mass budget in early disks

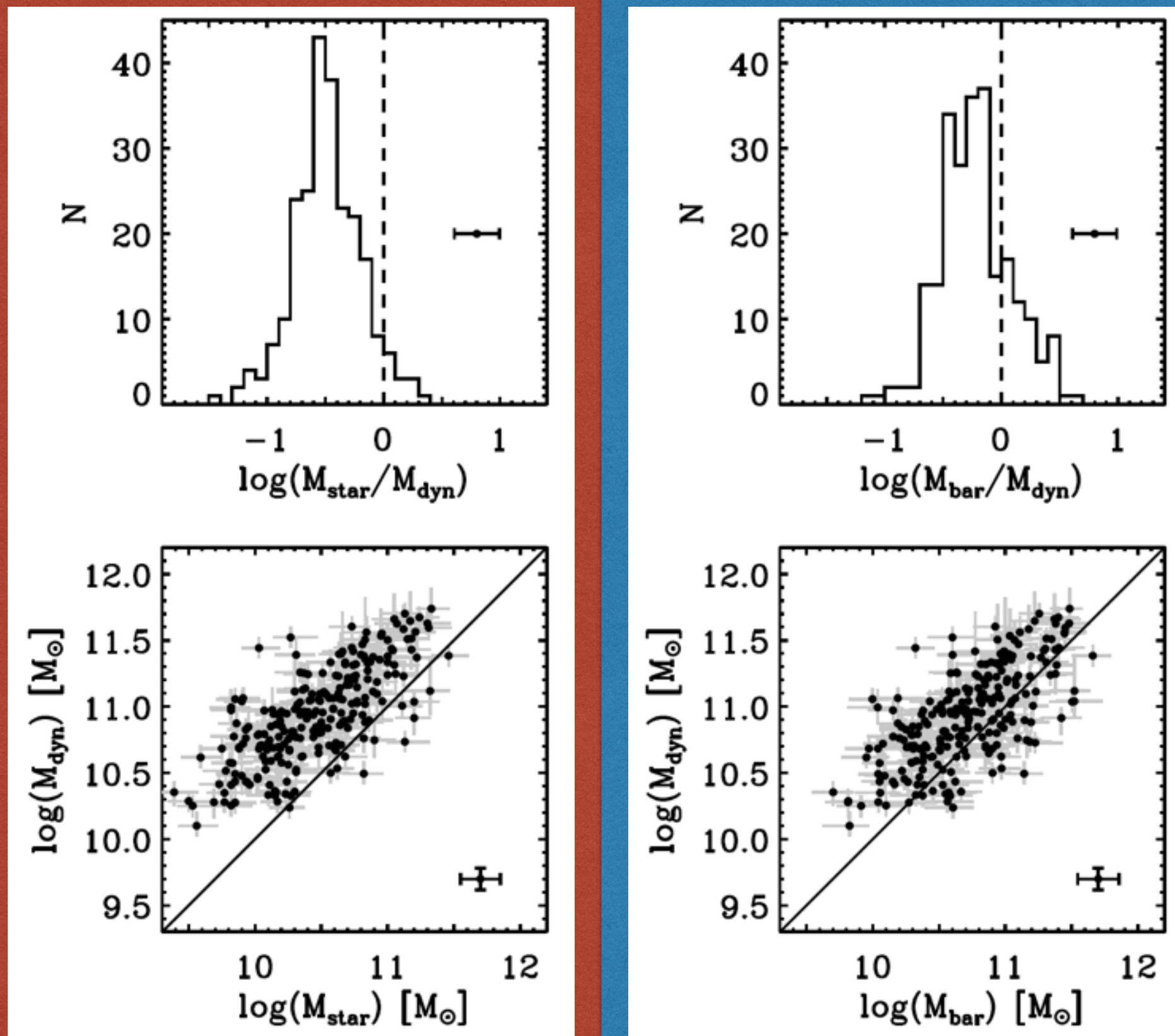
well characterised sampling from underlying population



Stars

Mass budget in high-z disks

Baryons



Wuyts+16

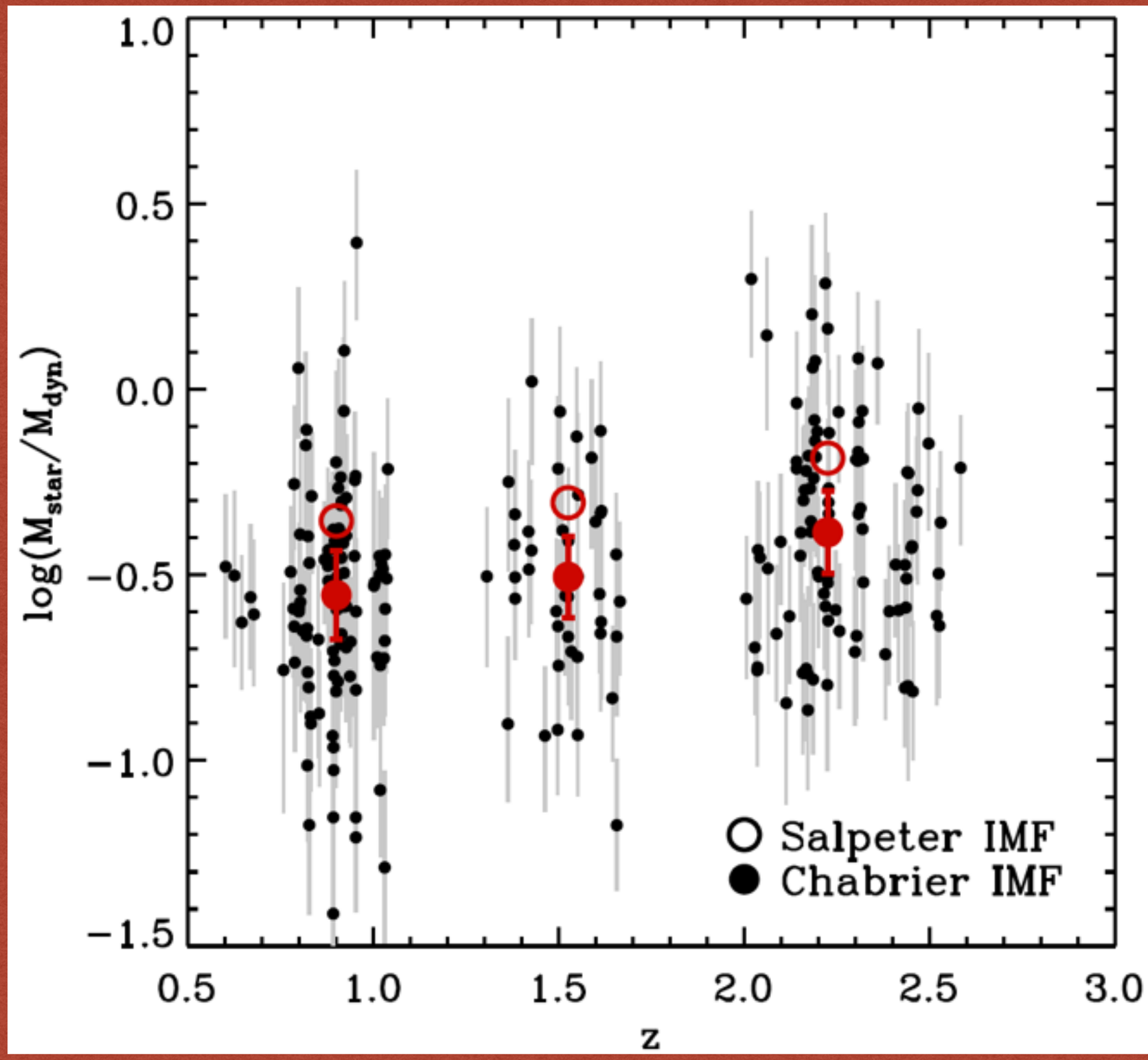
see also

Förster Schreiber+09; Barro+14; Burkert+16; Price+16; Stott+16; Contini+16; Lang+16

Redshift evolution

Stellar mass fraction

- Significant room for other mass components
- No decline M_{star}/M_{dyn} with increasing redshift, despite evolution in f_{gas}



Wuyts+16

see also
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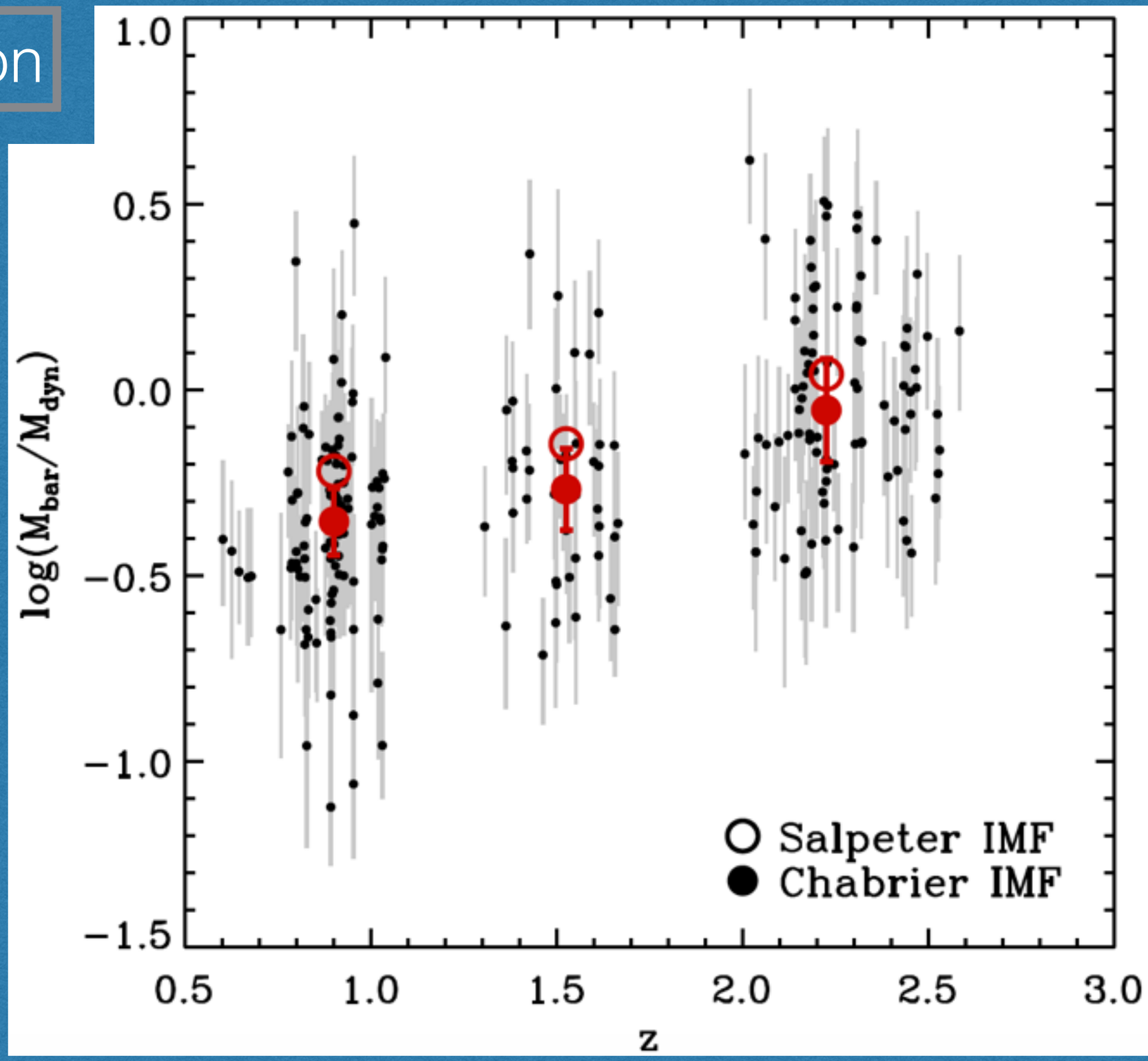
Redshift evolution

Baryonic mass fraction

- Fully baryon-dominated disks at z > 2



Wuyts+16

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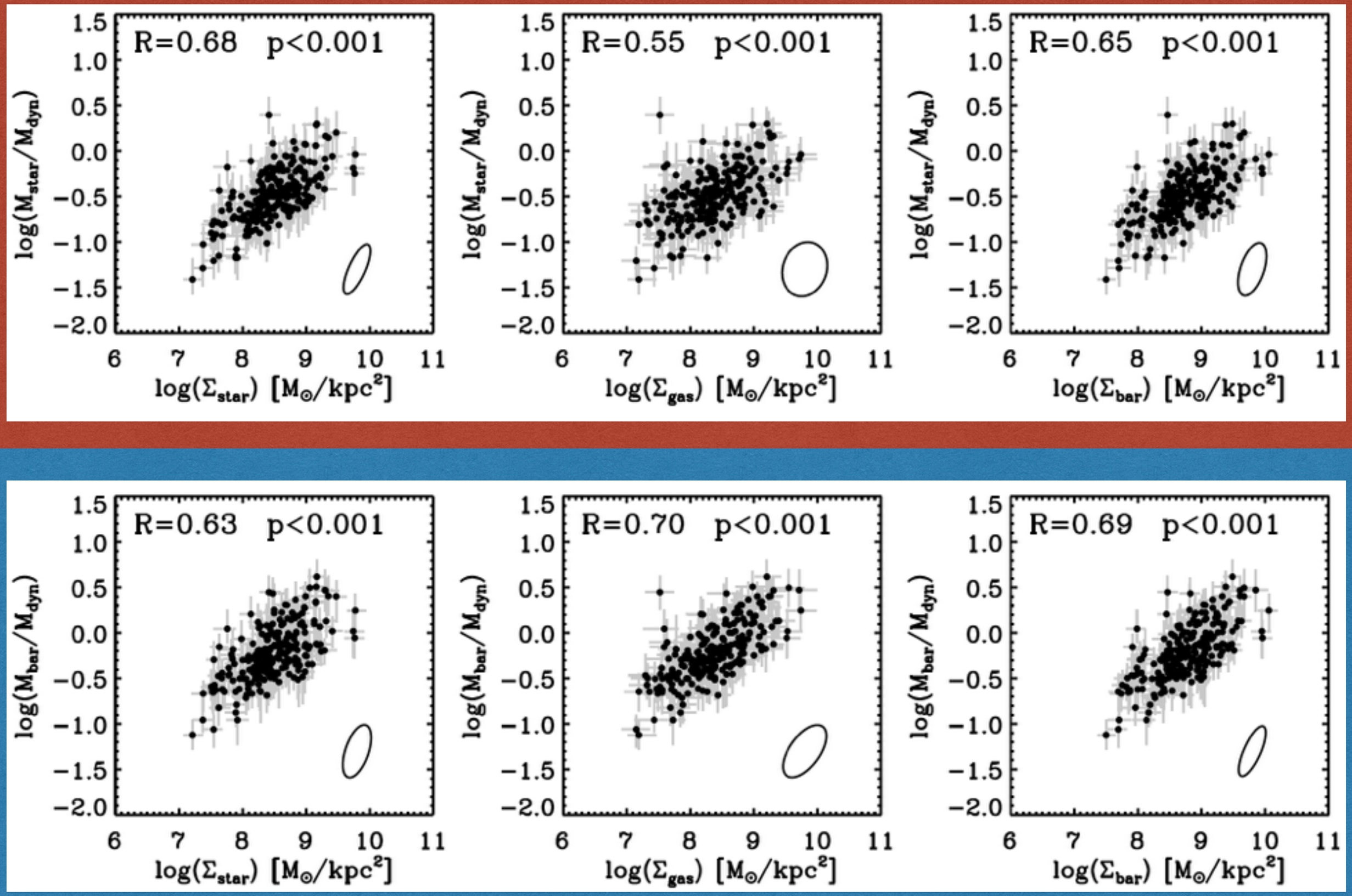
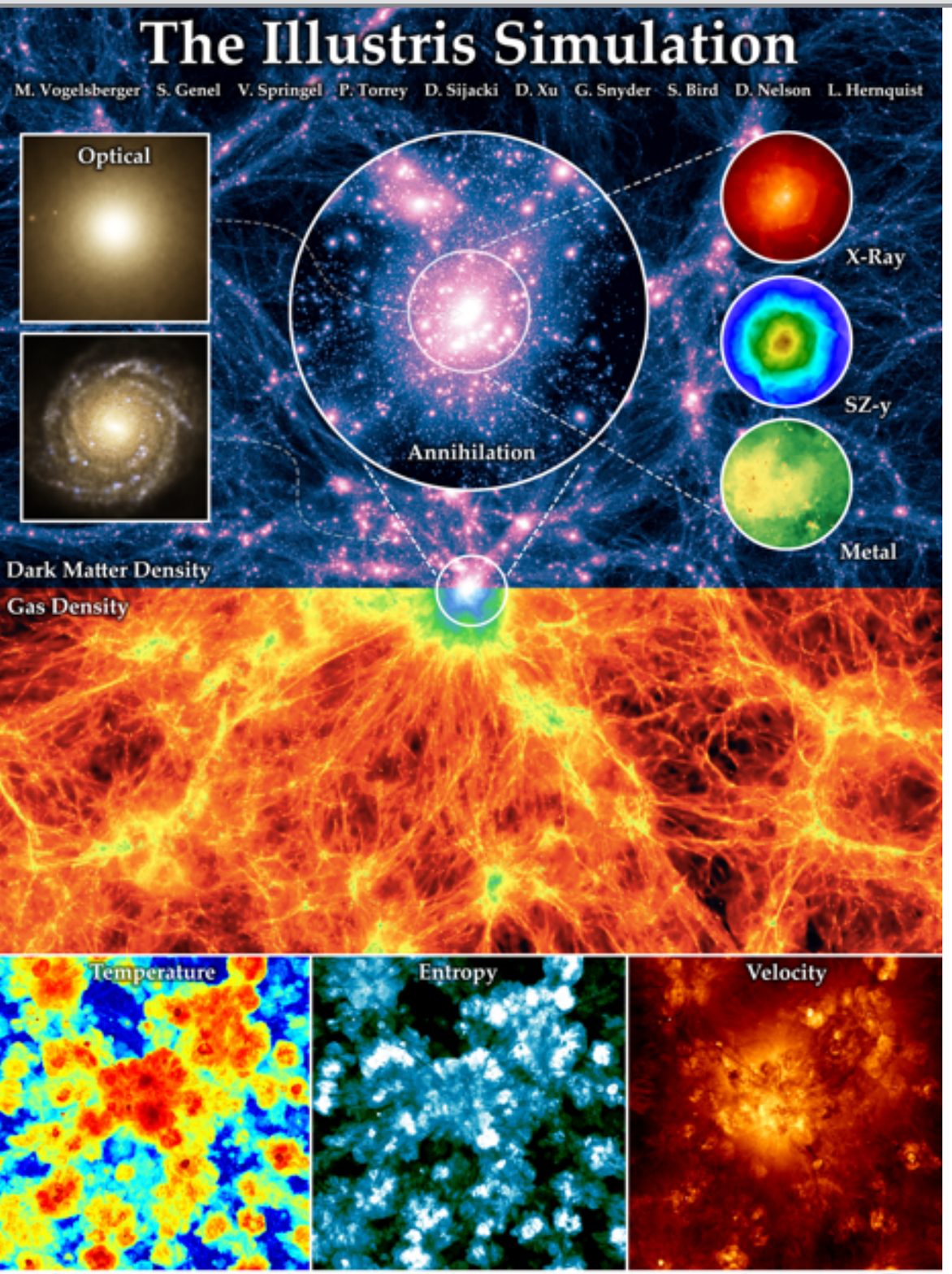
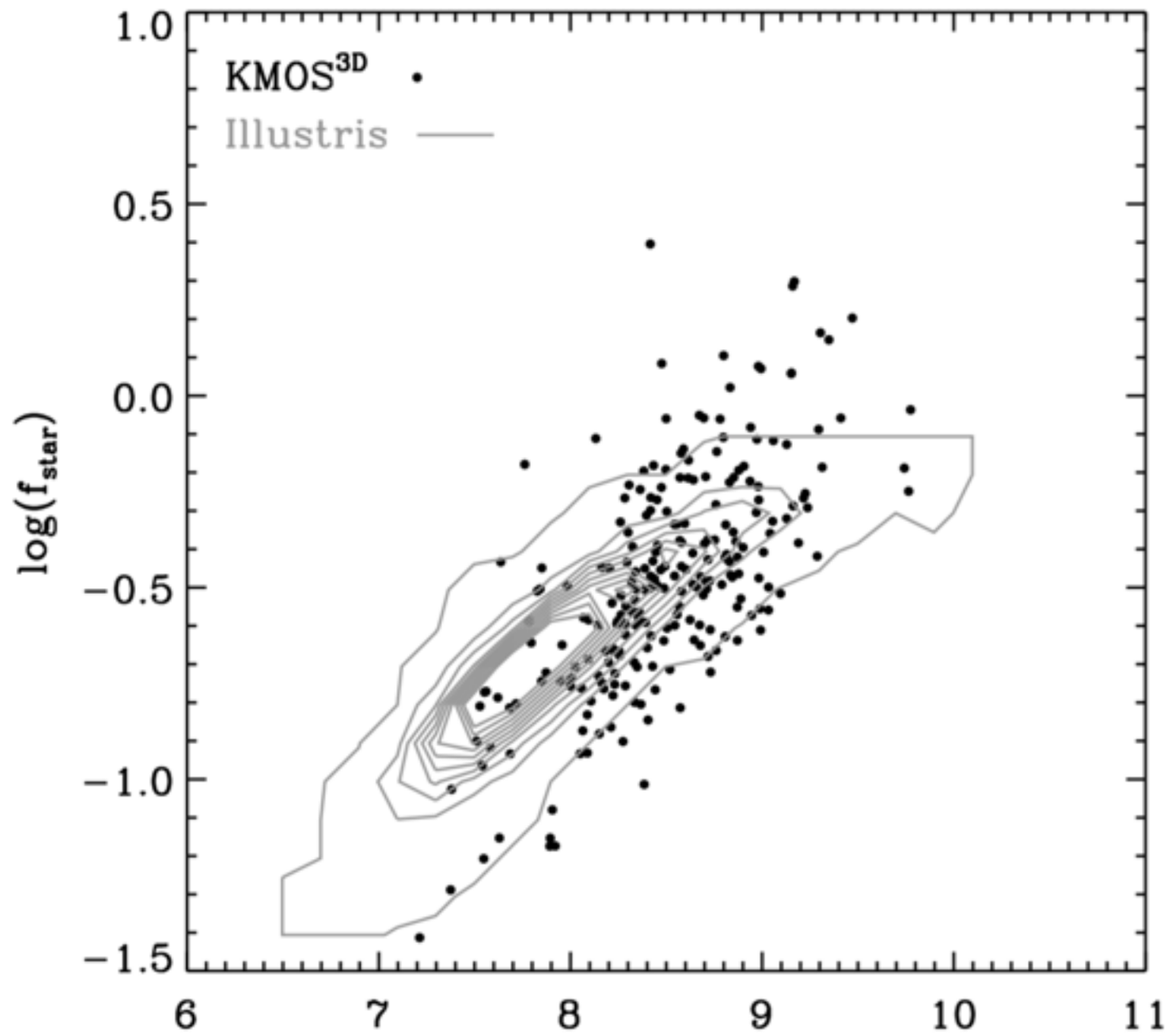
Σ-dependent breakdown of the mass budget



Mass fraction - surface density relation

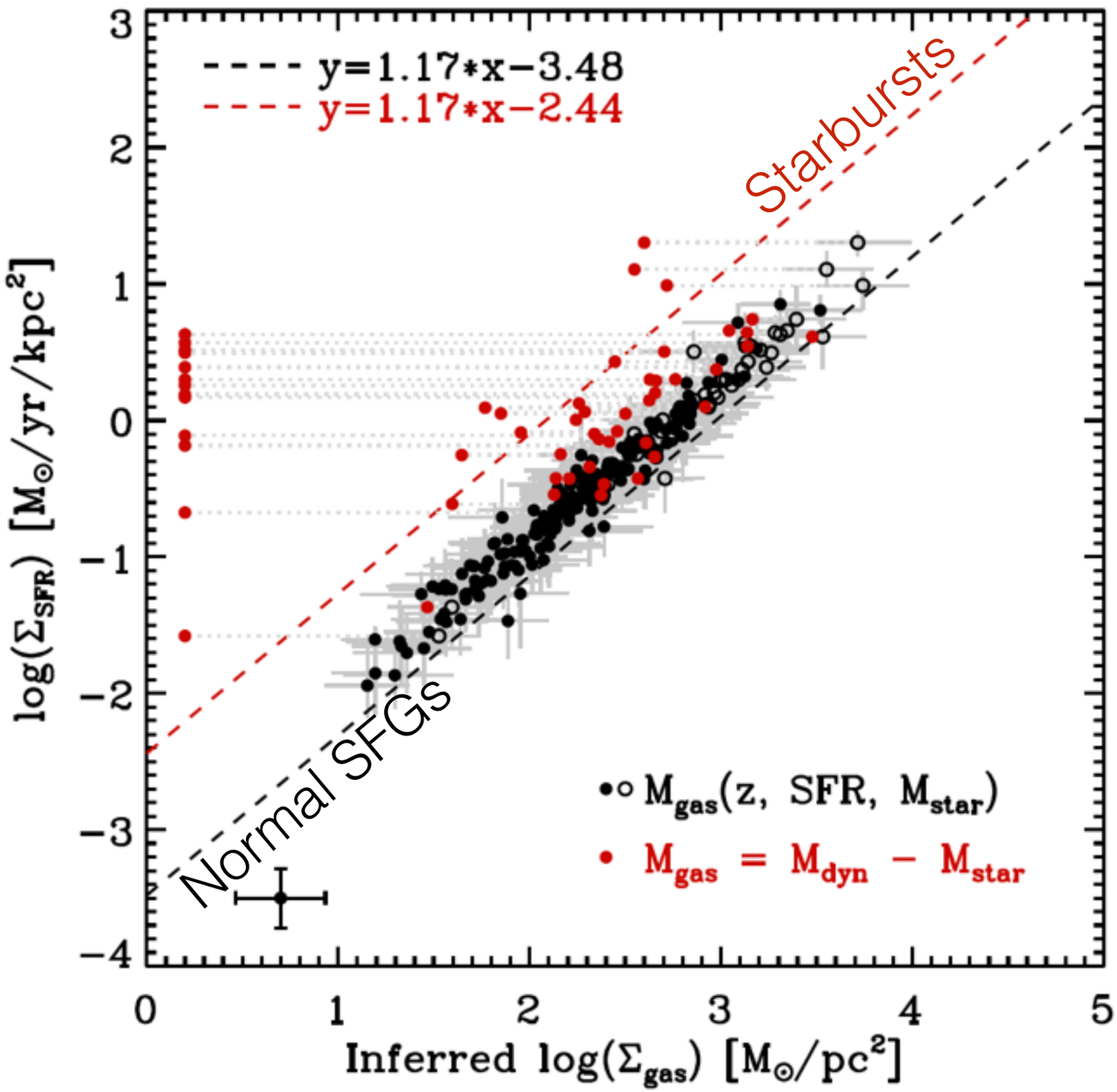




Wuyts+2016

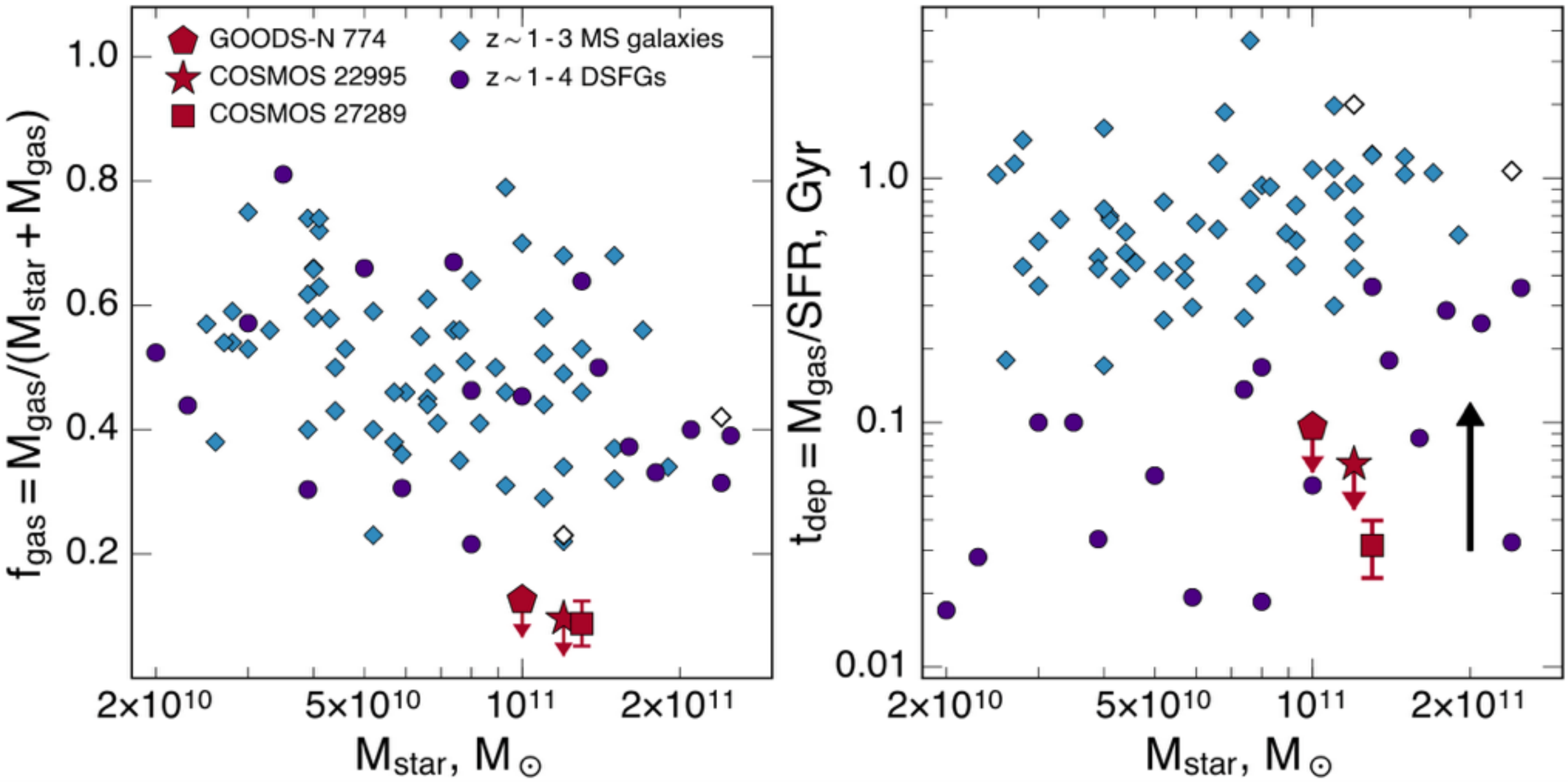
Illustris: Vogelsberger+2014; Nelson+2015; Pillepich+2014; Genel+2015

Kennicutt-Schmidt relation



Wuyts+2016

Low f_{gas} connect compact SFGs to their z~2 quiescent descendants

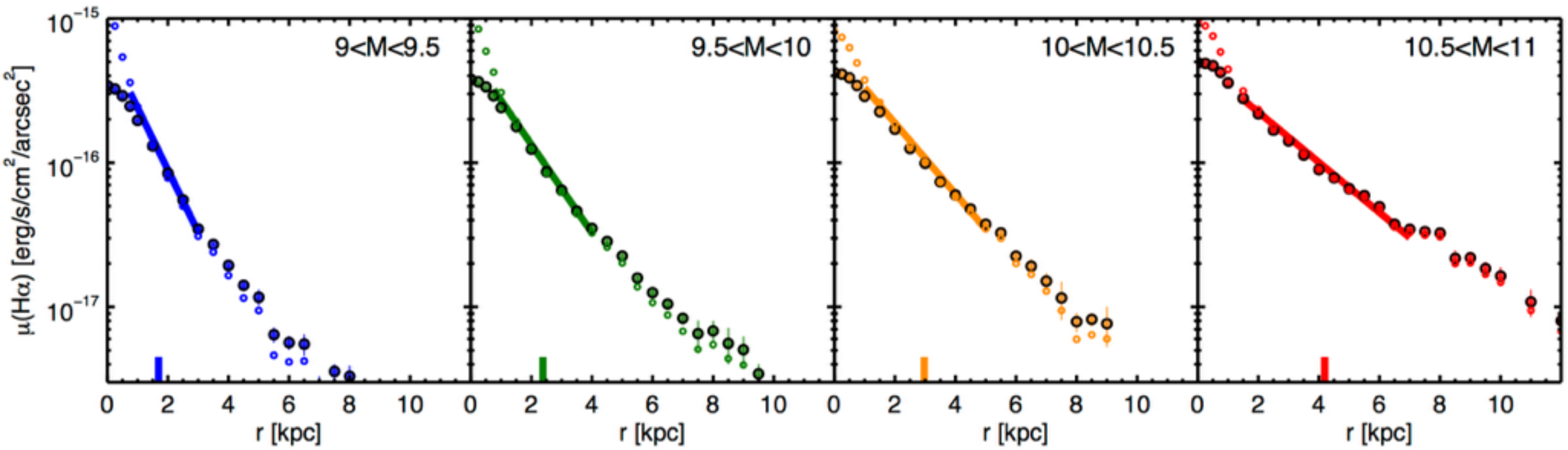


Spilker+2016

Where within galaxies do stars form?

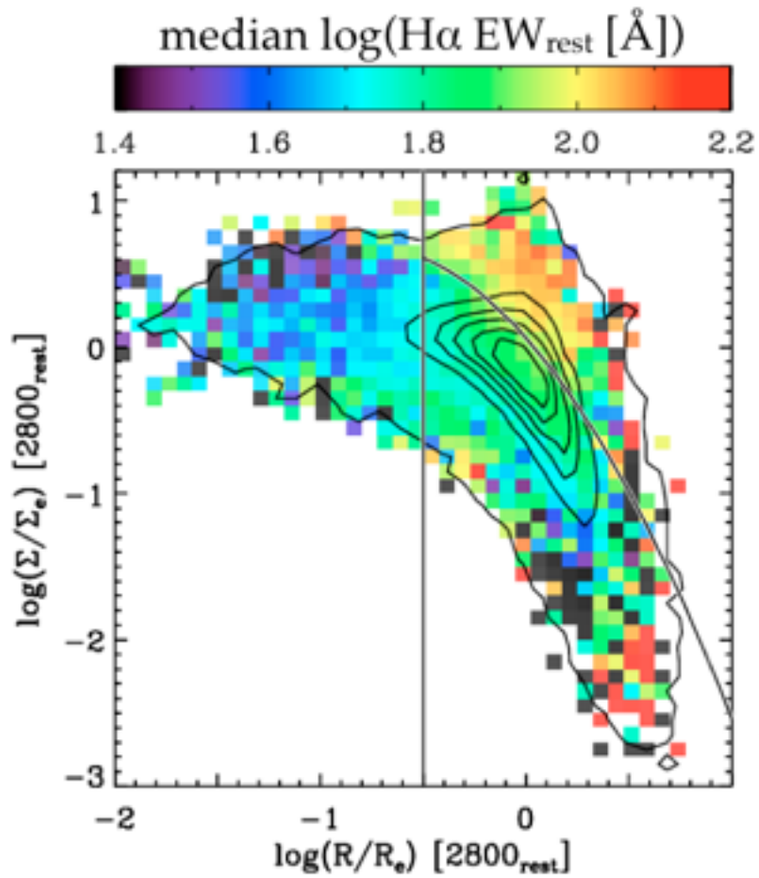
Hα in near-exponential disks

Over 2 orders of magnitude, from stacking of 2676 galaxies at z~1 with Hα maps from 3D-HST grism spectroscopy

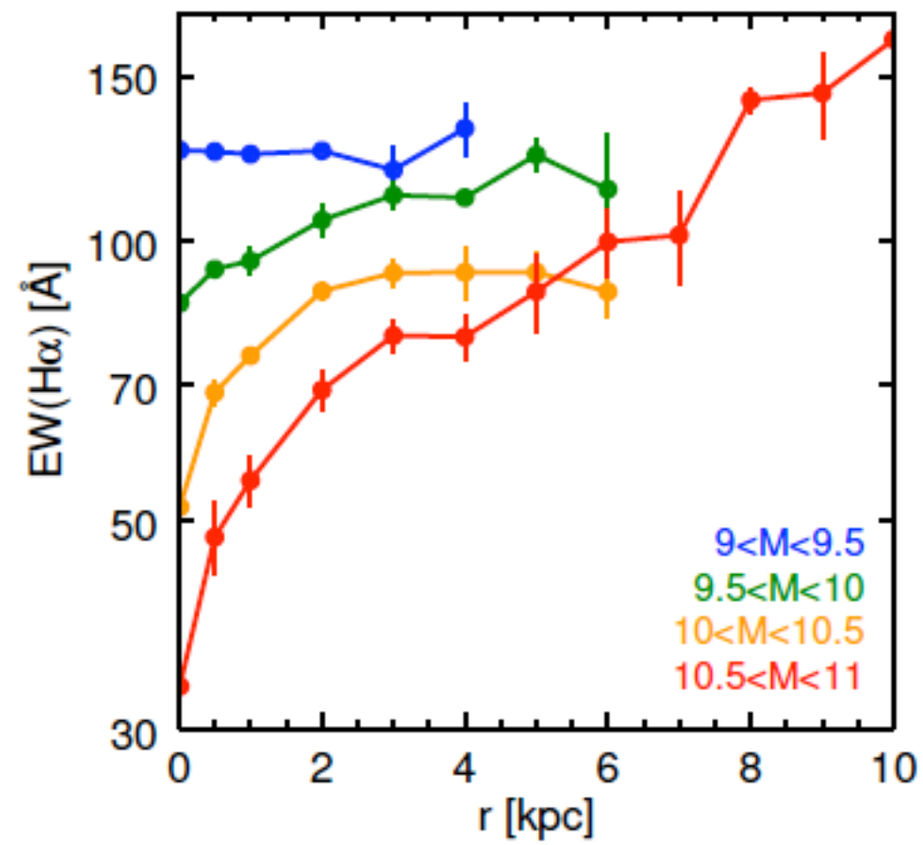


Nelson+2015

Central depression in Hα EW (of massive galaxies)

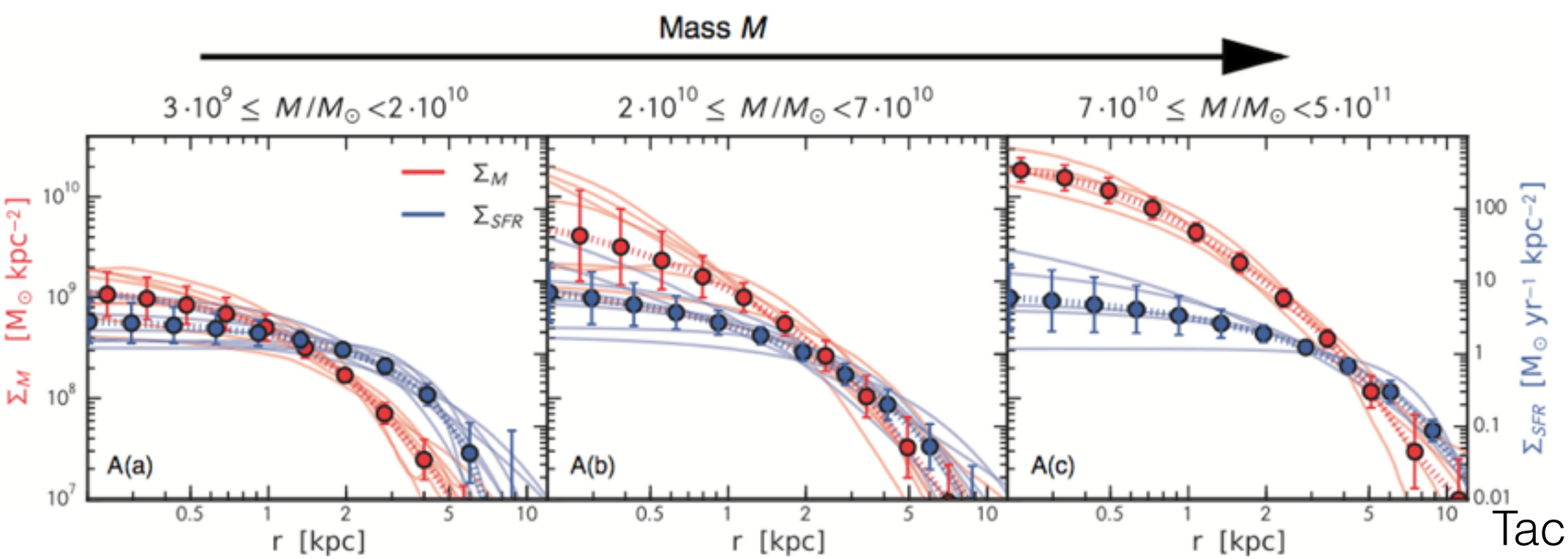


Wuyts+2013



z ~ 1

Nelson+2015

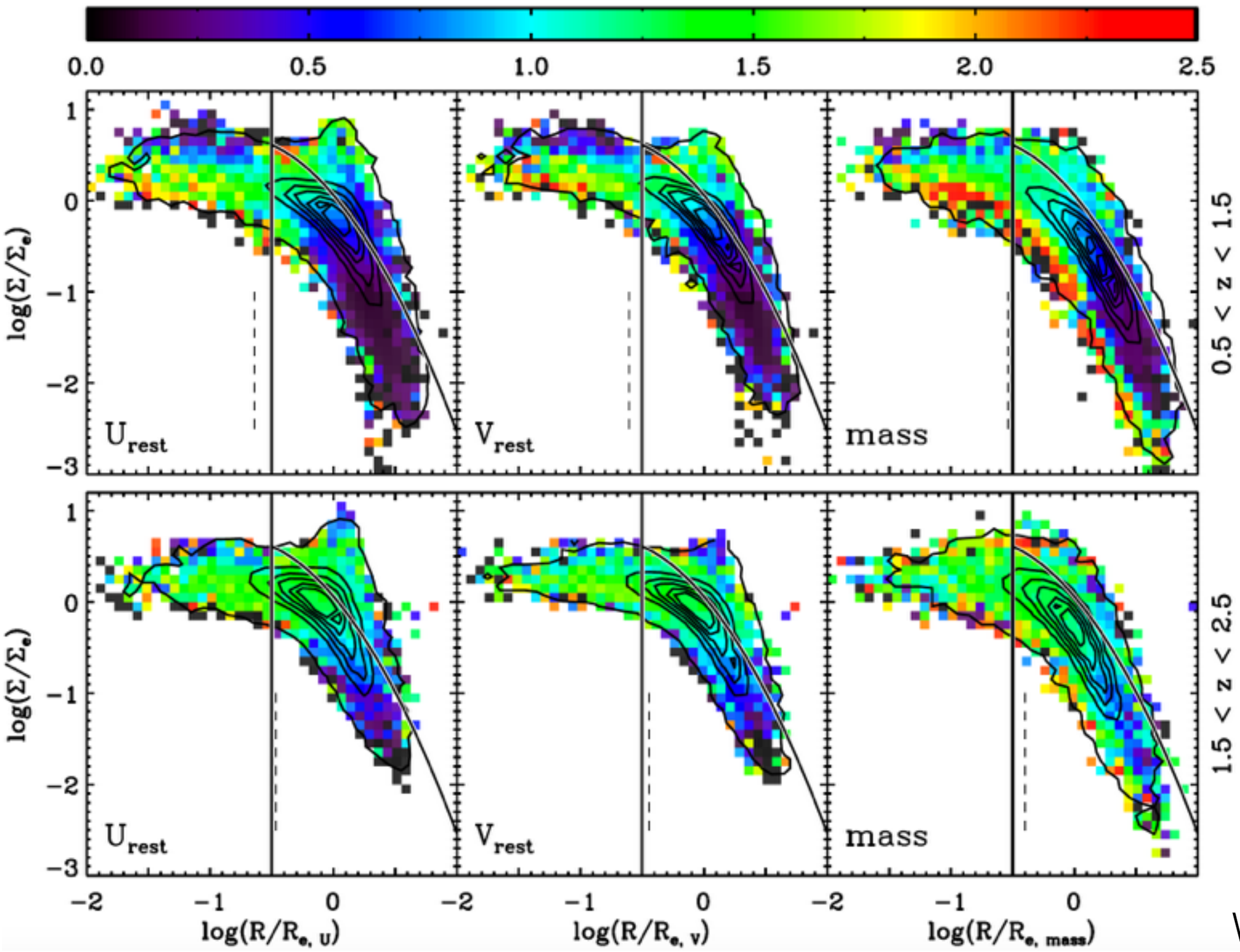


z ~ 2

Tacchella+2015

Dust gradients in high-z SFGs (1)

median A_V (from resolved SED modelling)

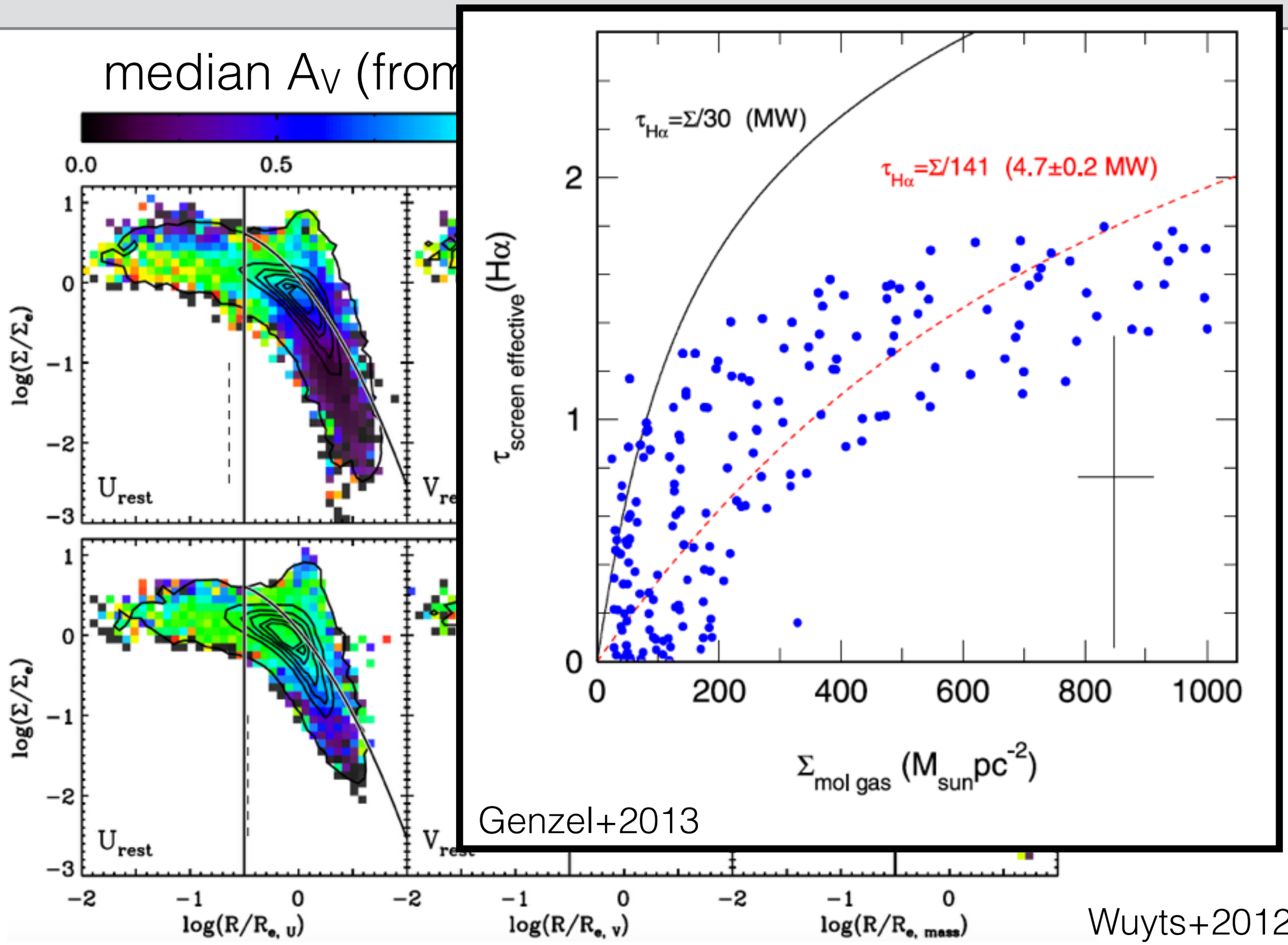


z ~ 1

z ~ 2

Wuyts+2012

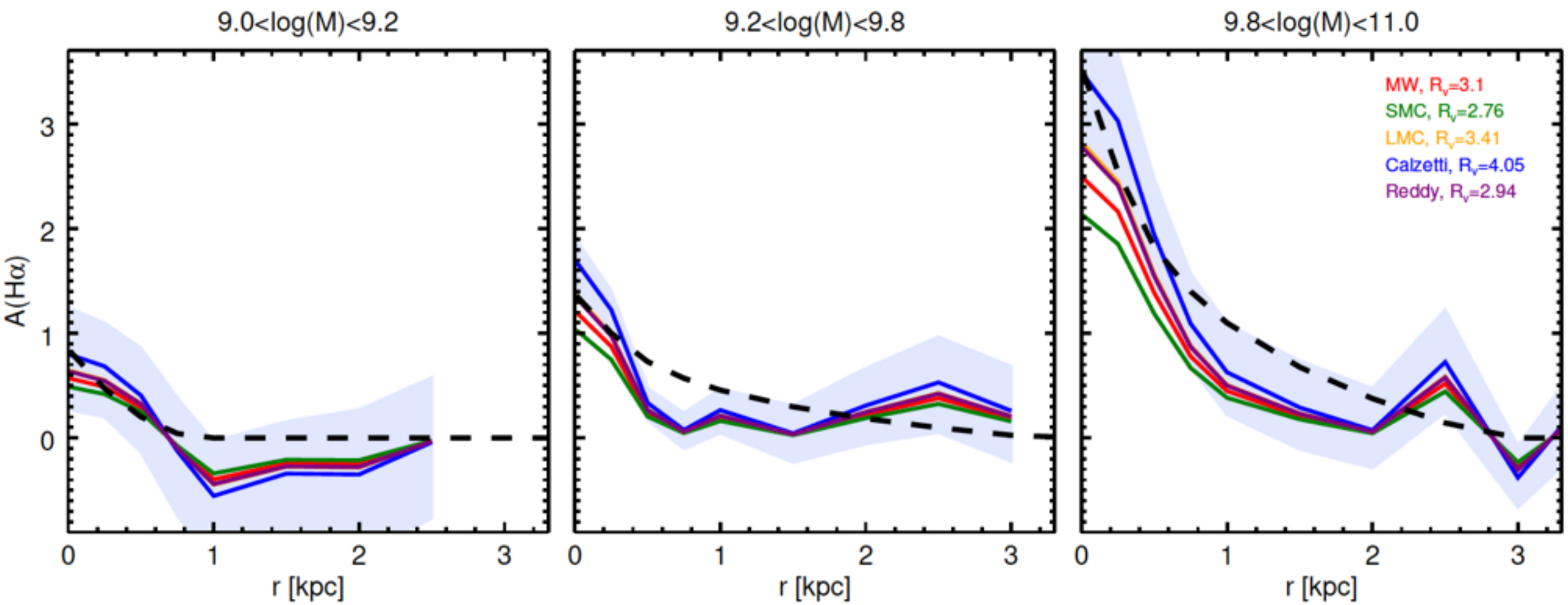
Dust gradients in high-z SFGs (1)



Dust gradients in high-z SFGs (2)

z ~ 1.4

$A_{H\alpha}$ (from resolved Balmer decrement)

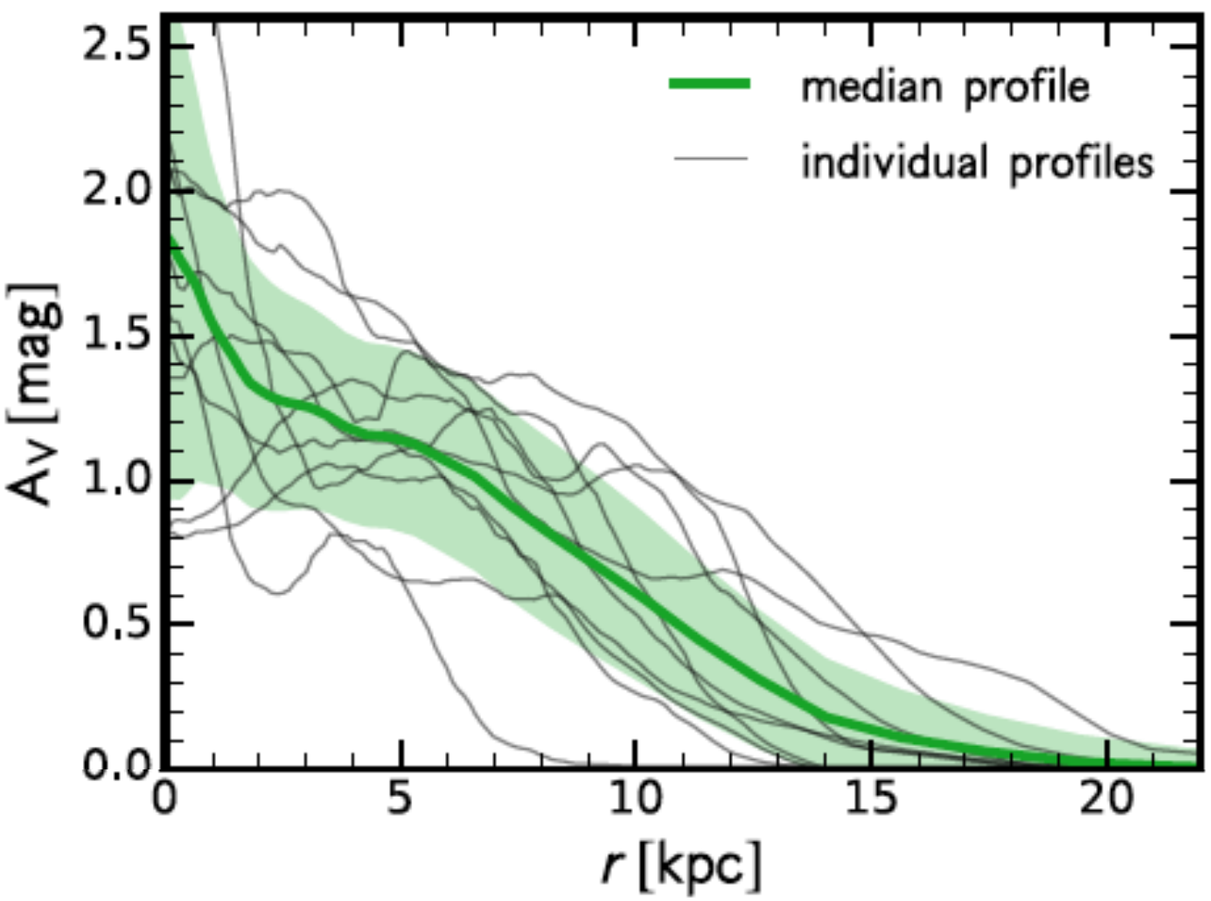


Nelson+2016

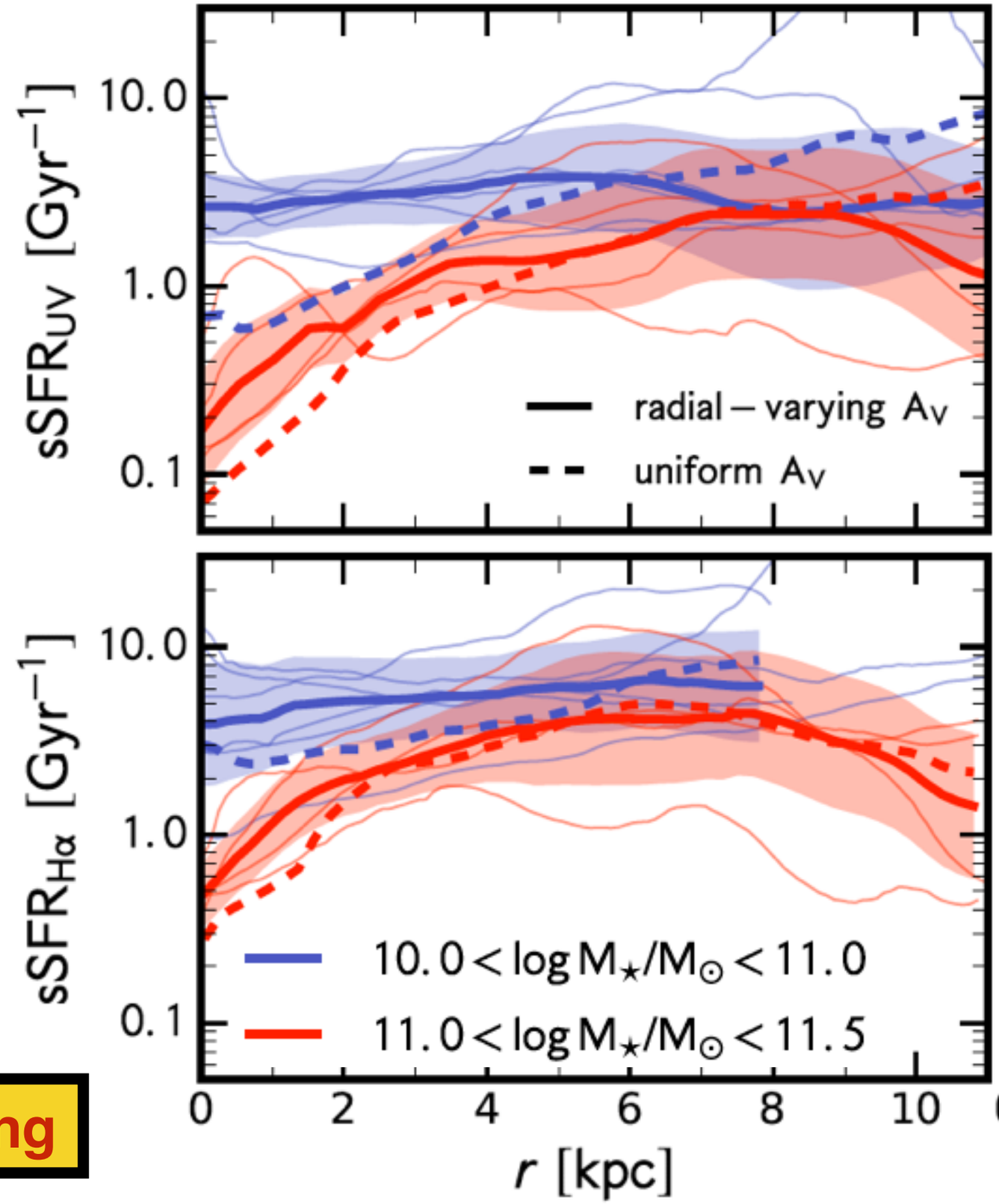
Dust gradients in high-z SFGs (3)

z ~ 2

A_V (from resolved FUV-NUV)

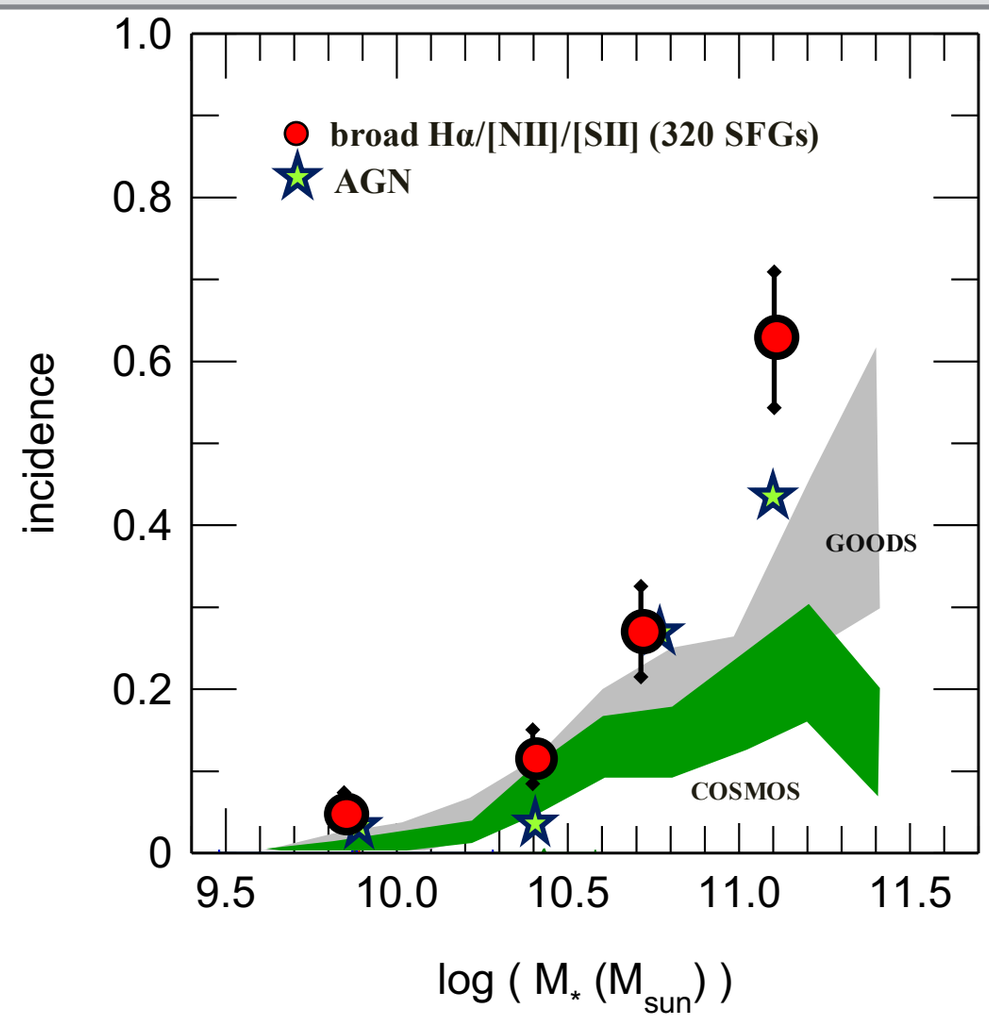


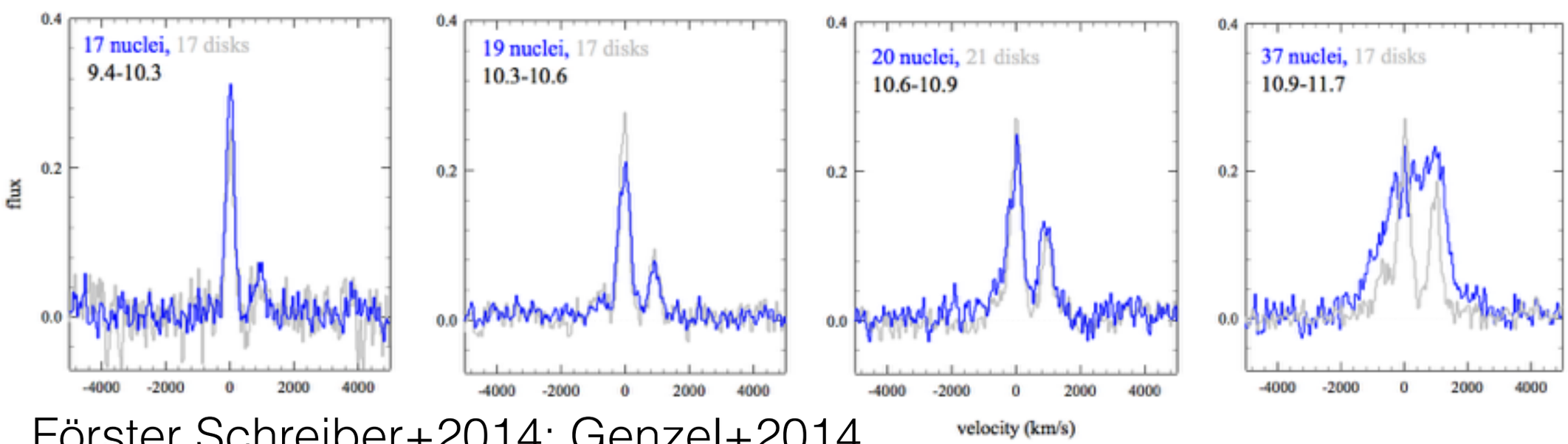
Tacchella+2016



Inside-out disk growth / quenching

Wide-spread nuclear outflows



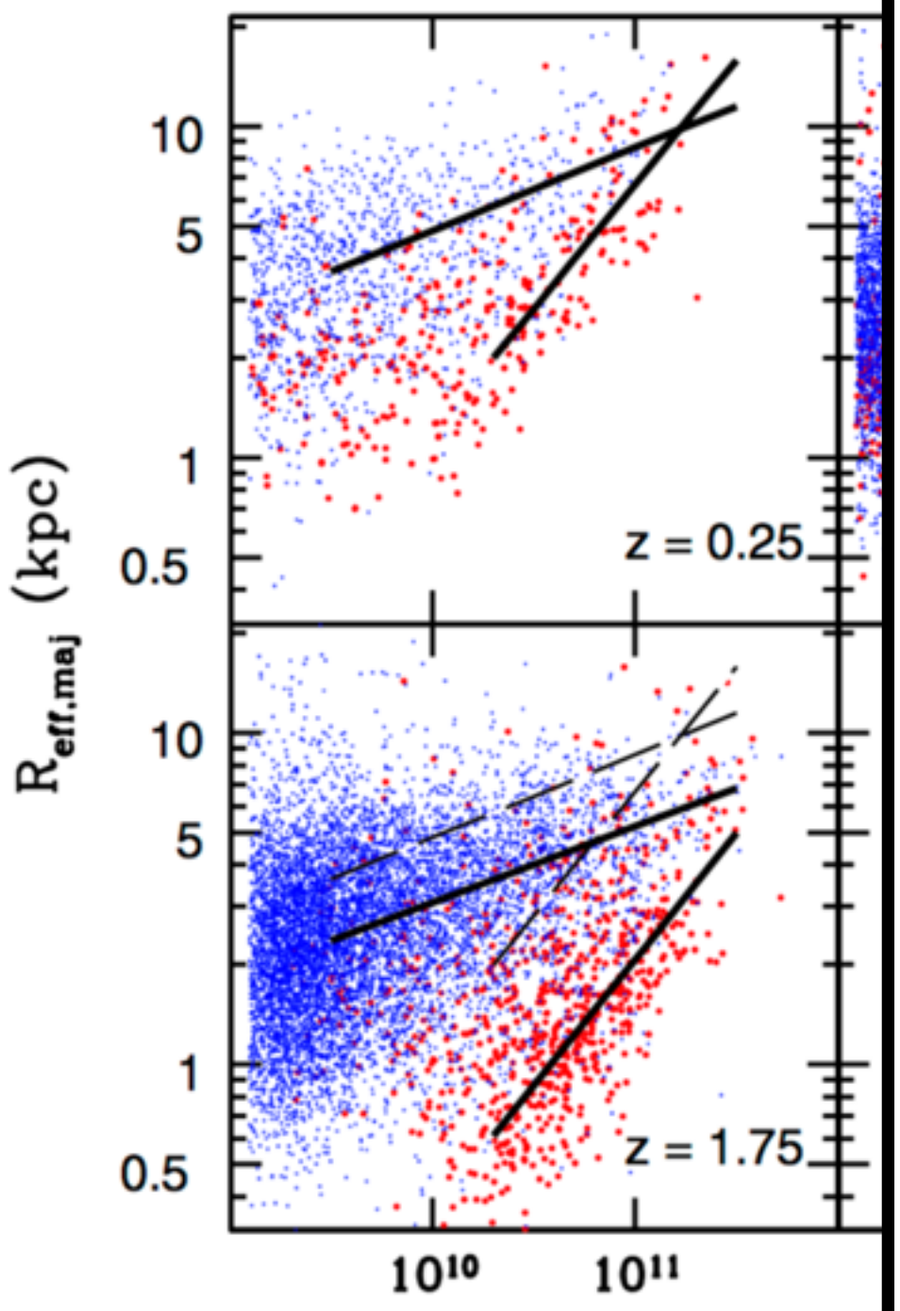


nucleus, narrow component removed,
grey= outer disk

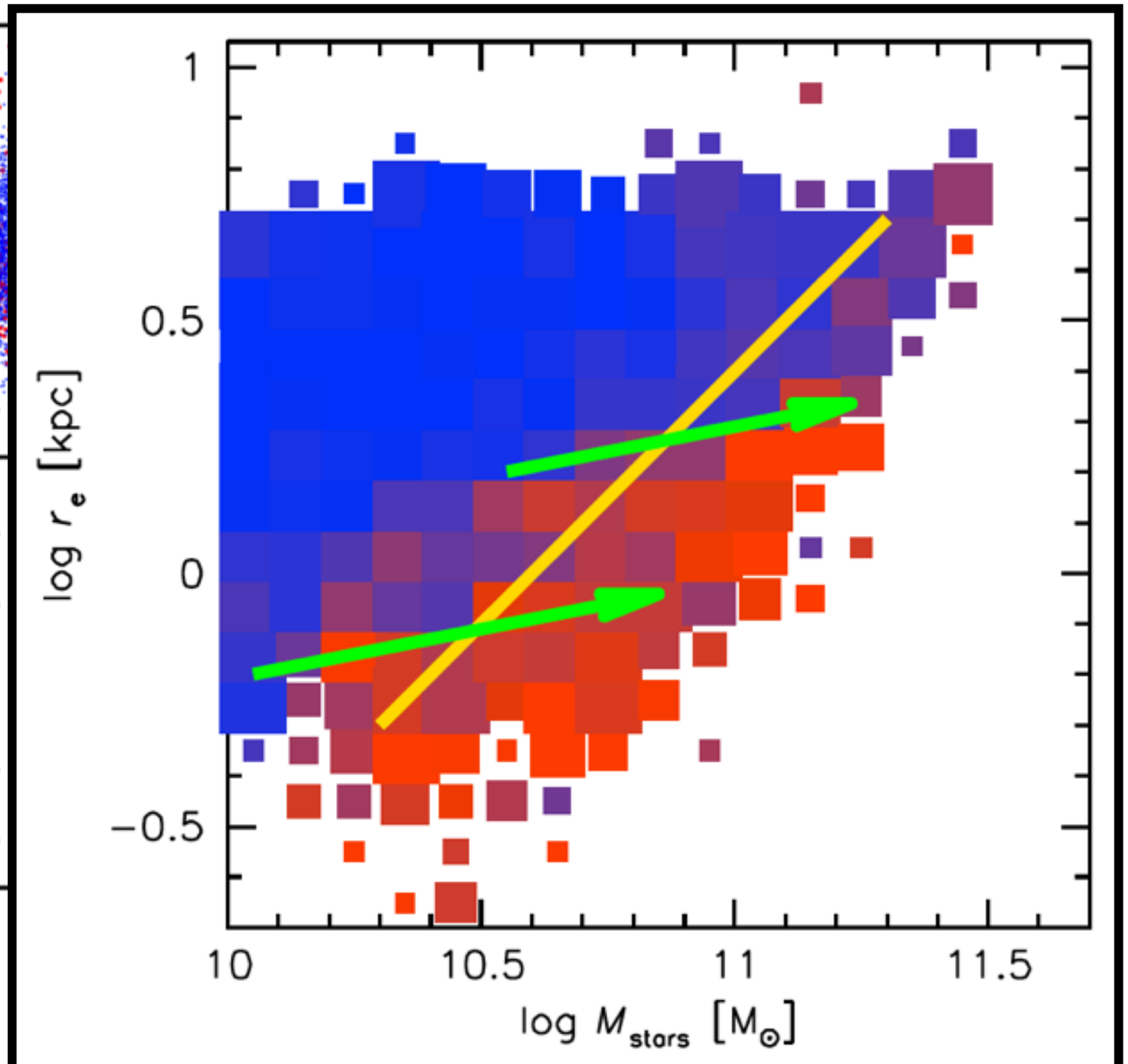
4000 km/s

Förster Schreiber+2014; Genzel+2014

Parallel tracks?

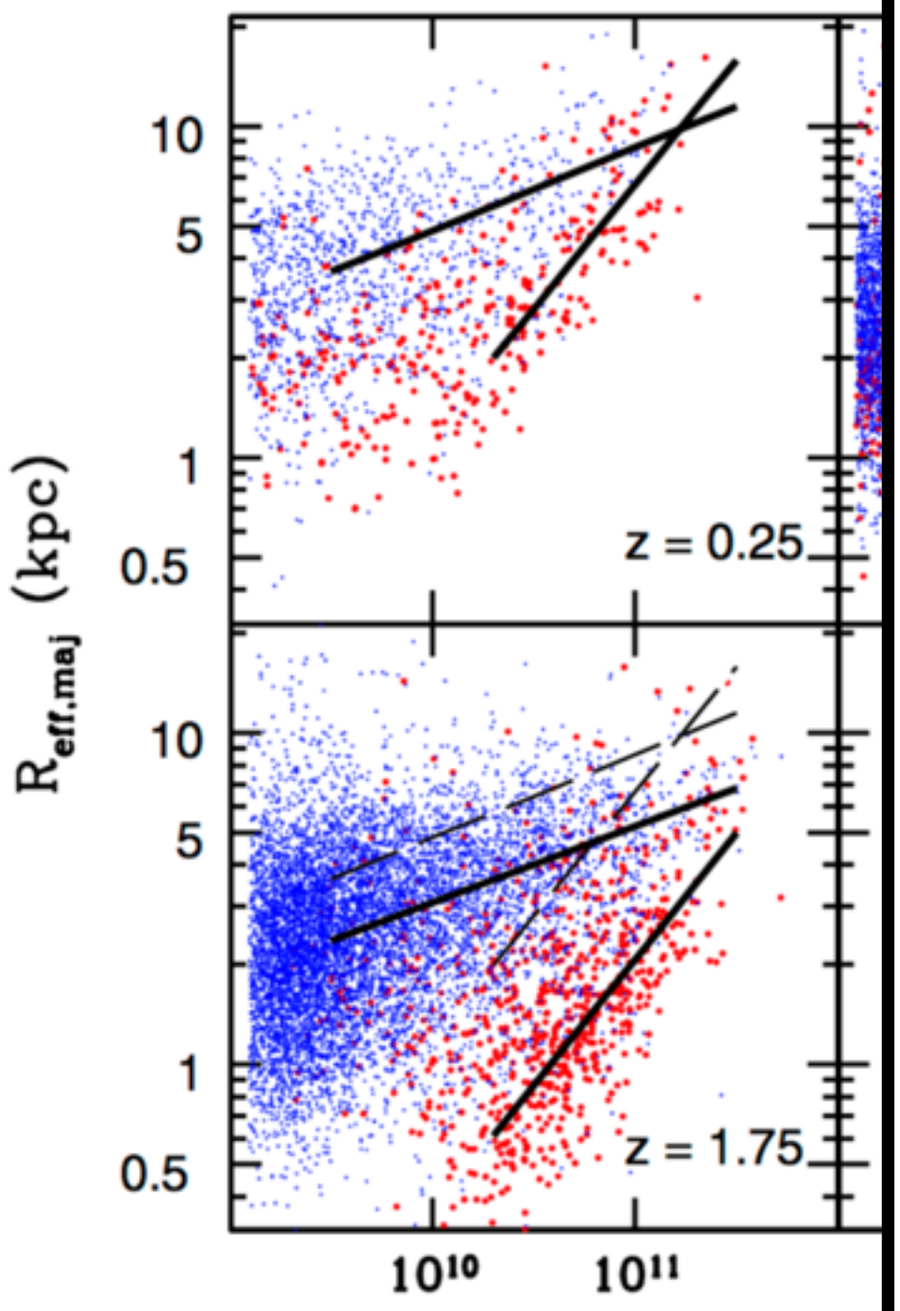


van der Wel+2014

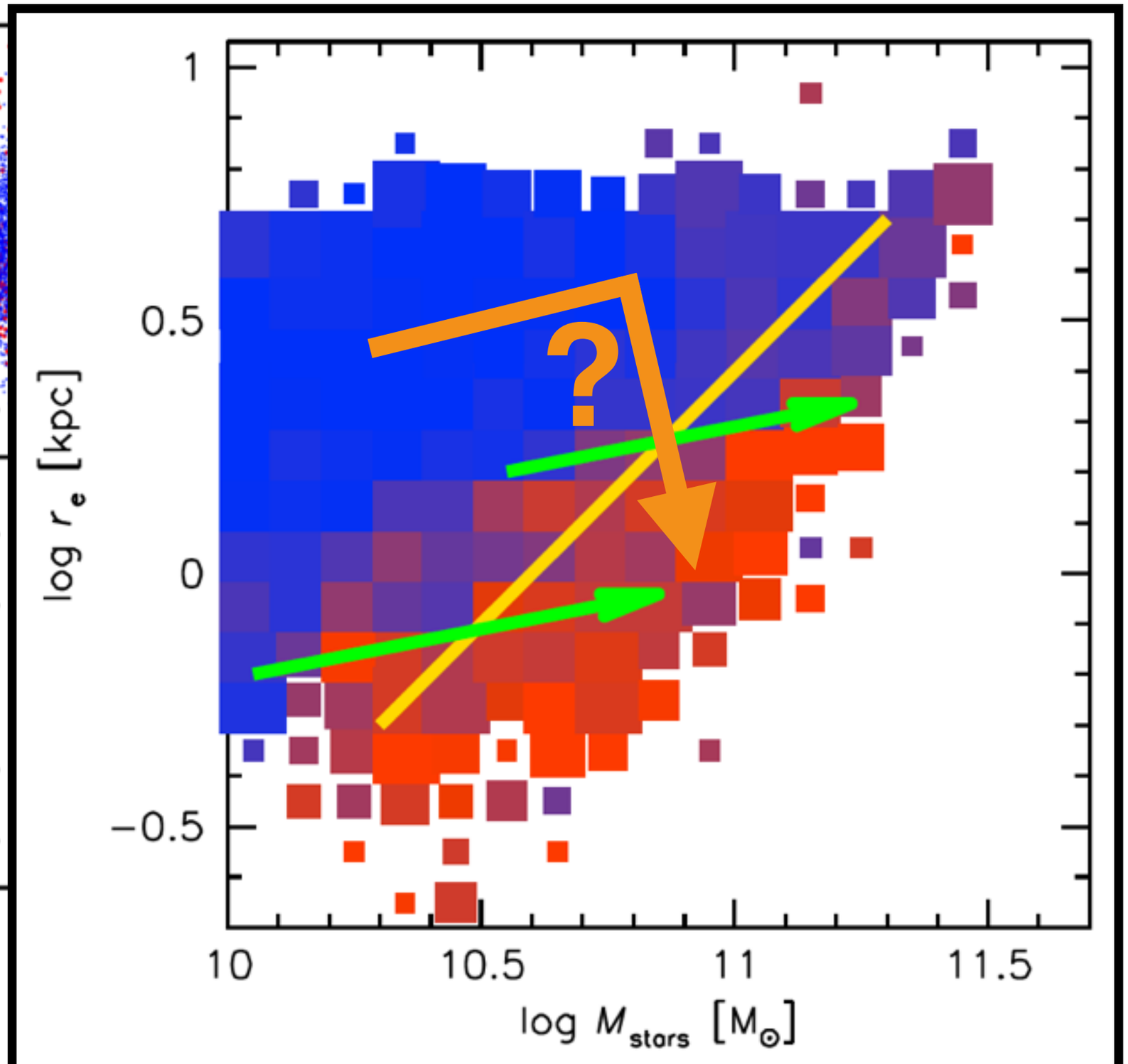


van Dokkum+2015

Parallel tracks? Or compaction?



van der Wel+2014



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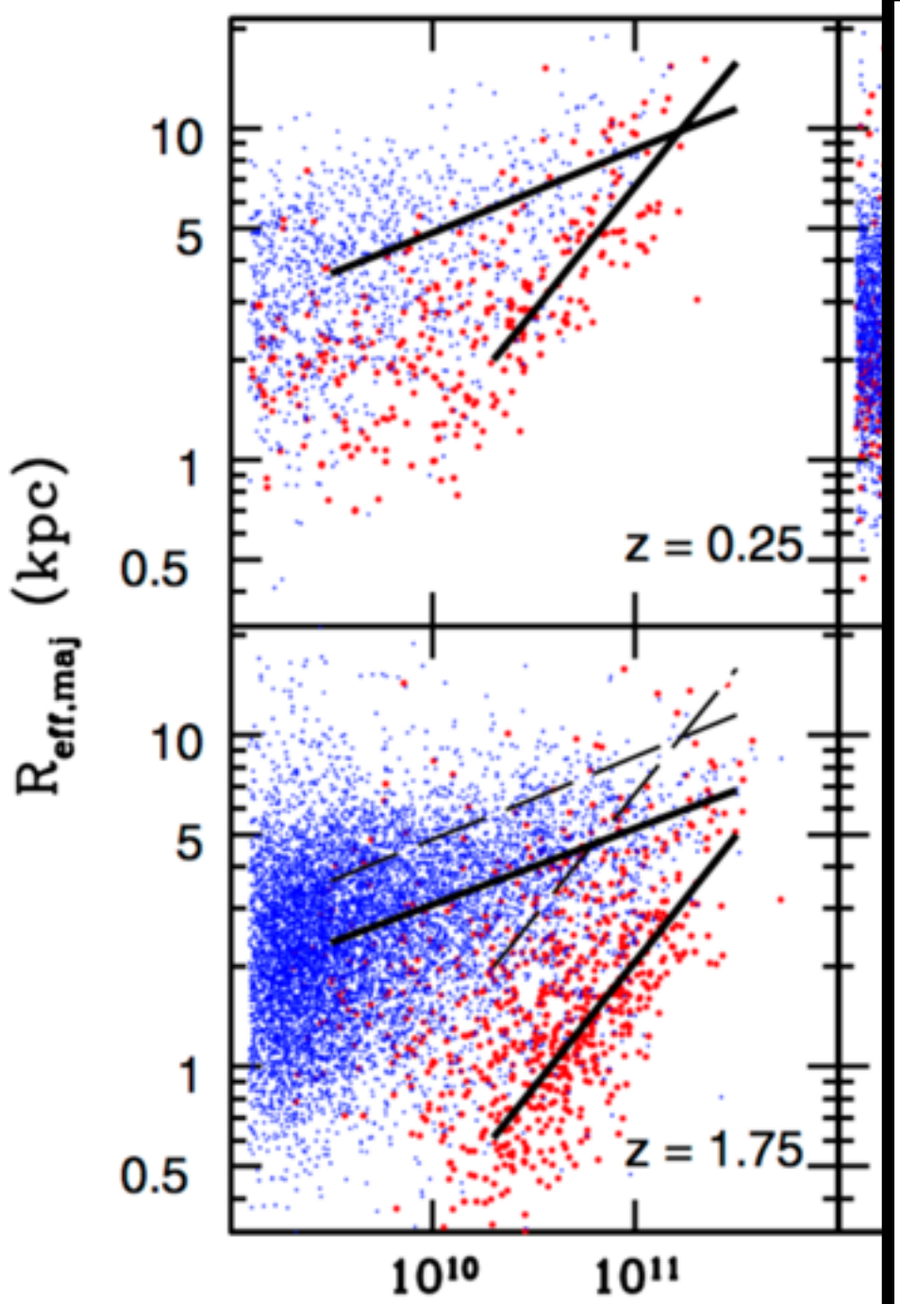
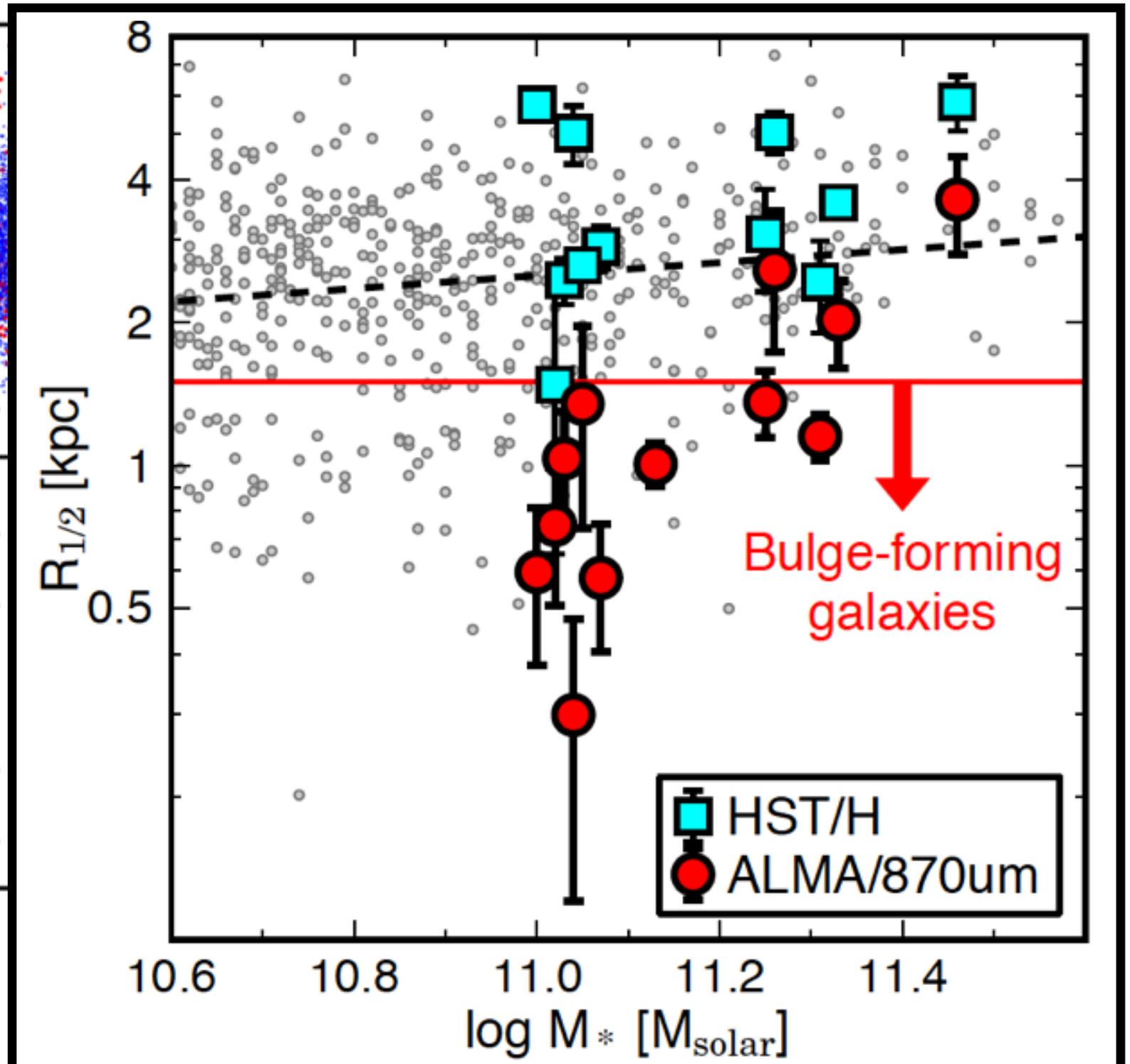
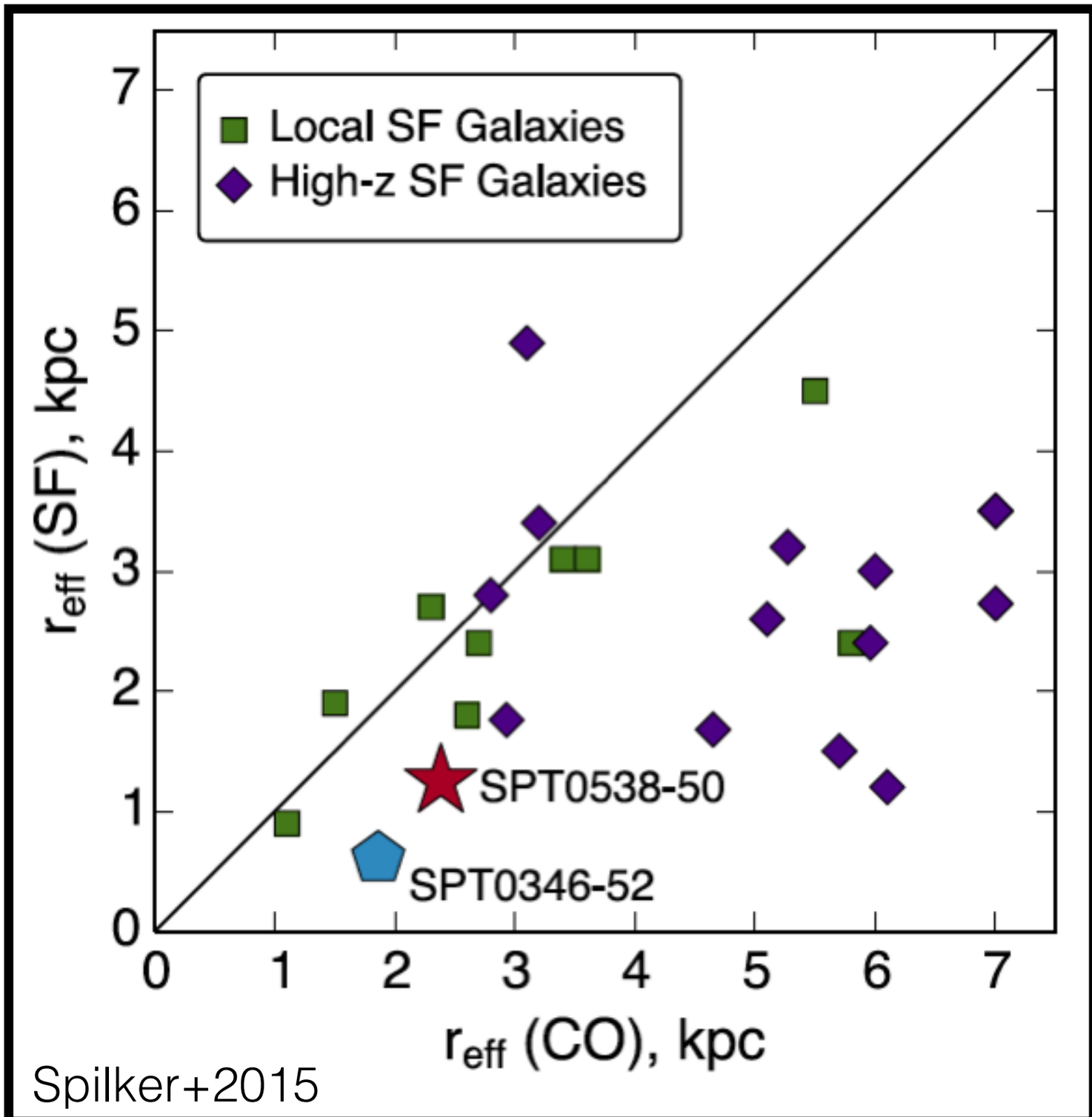


van der Wel+2014

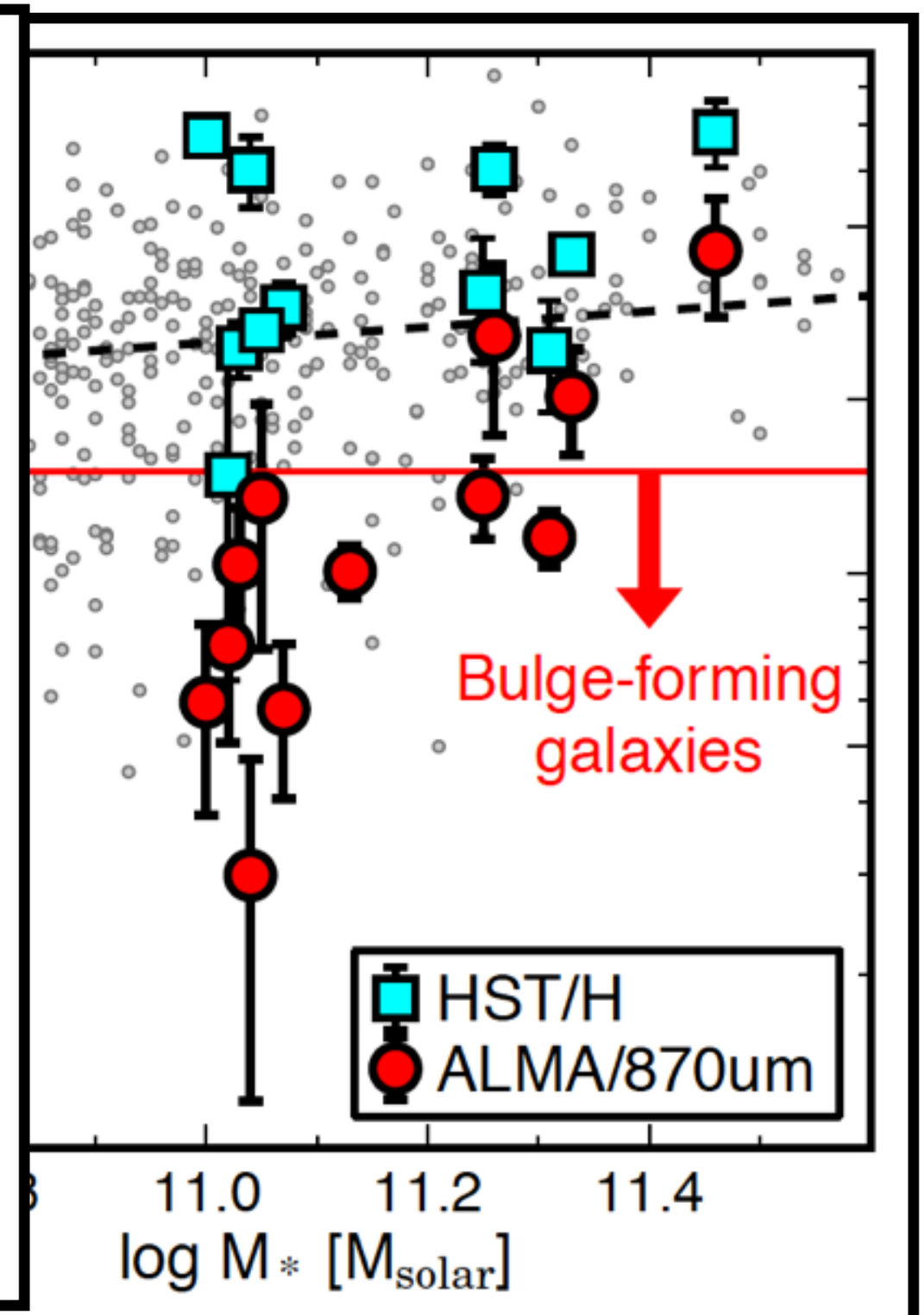


Tadaki+2016 (also Barro+2016 who target cSFGs)

Parallel tracks? Or compaction?



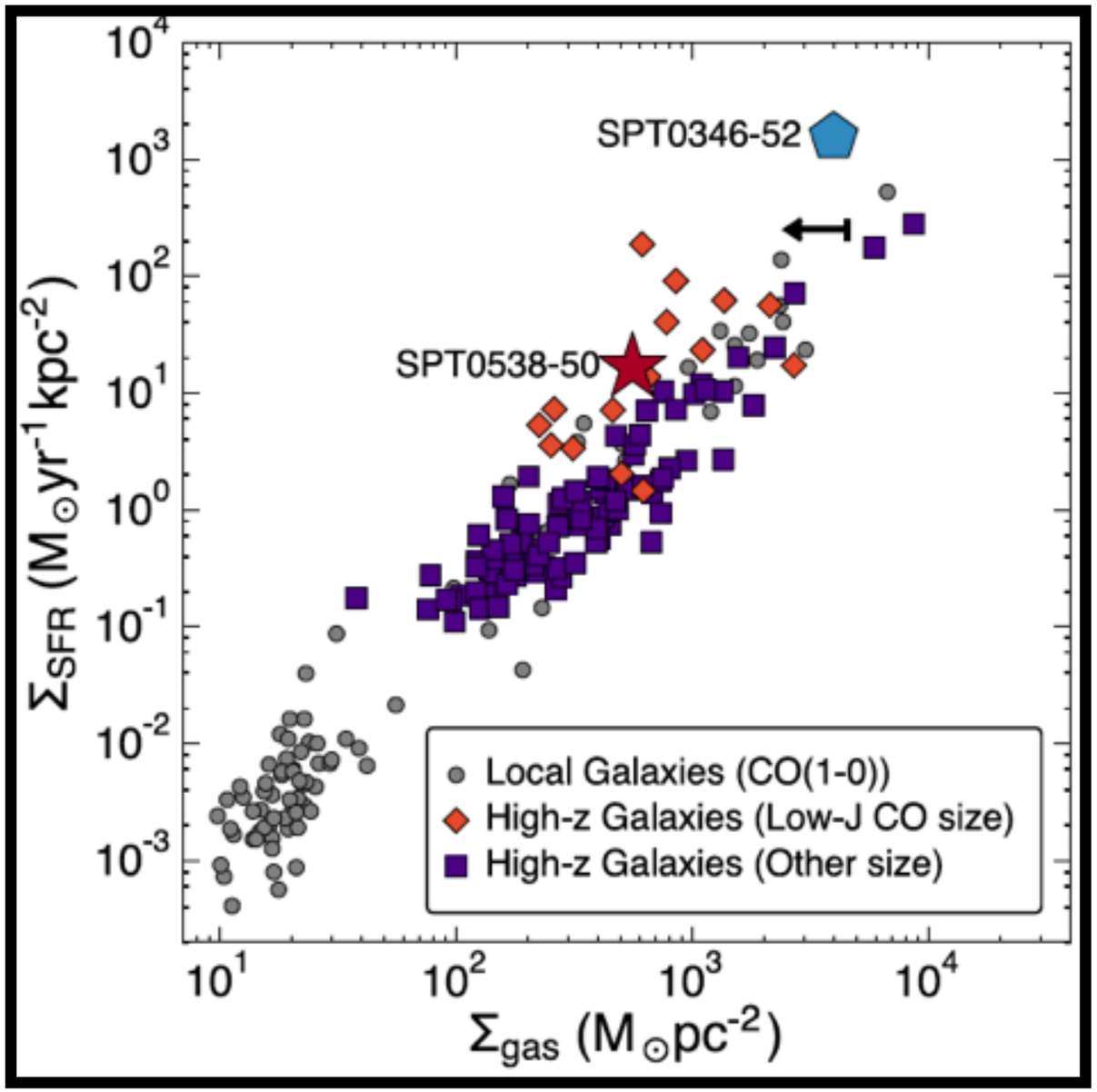
Spilker+2015



Tadaki+2016 (also Barro+2016 who target cSFGs)

(Resolved) KS relation at high z

Spilker+2015: caution when computing Σ with sizes measured at different wavelength
<one data point per galaxy>



(Resolved) KS relation at high z

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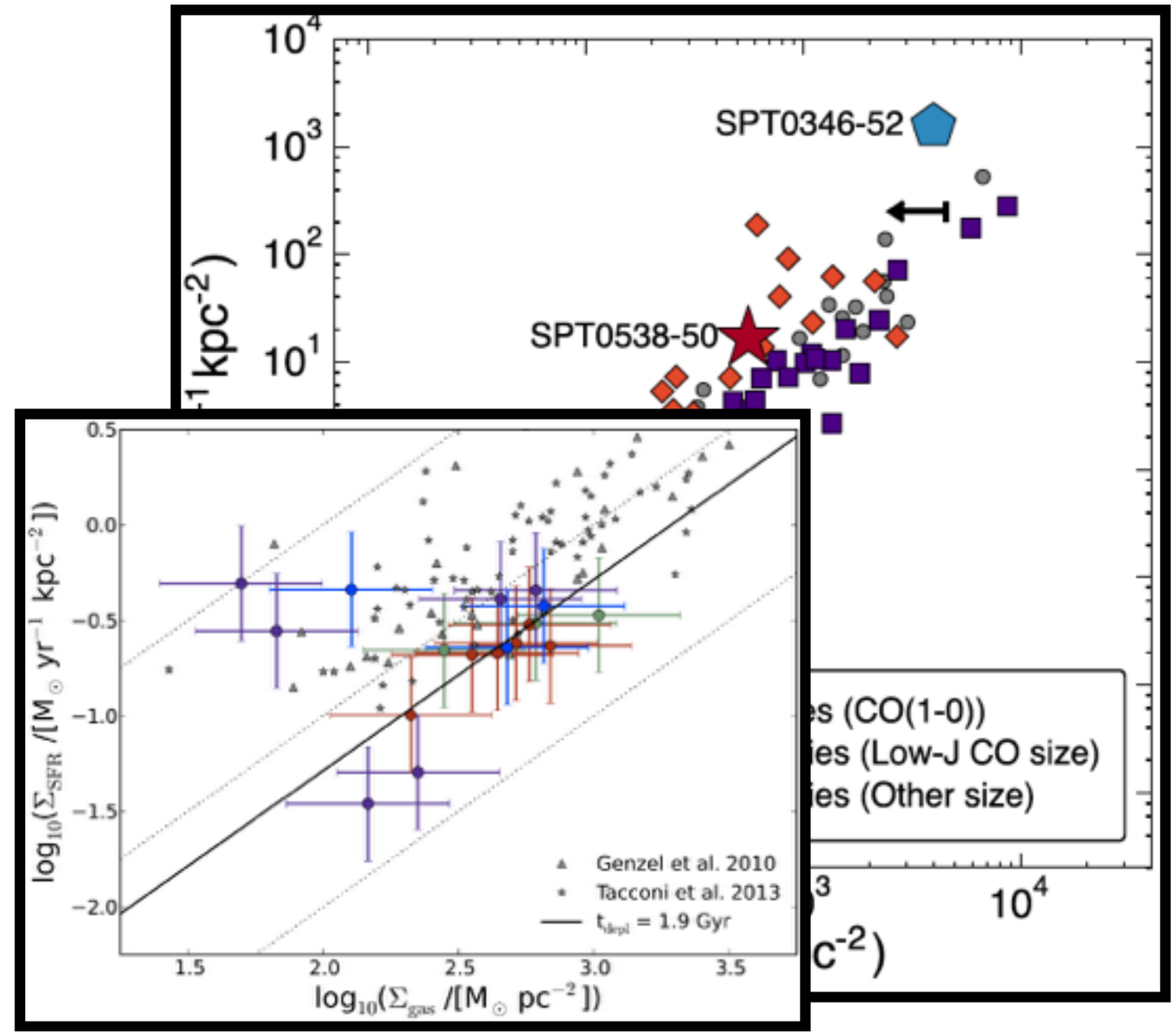
<one data point per galaxy>

Freundlich+2013: go below 1-1.5" resolution limit by identifying clumps in position-velocity diagram



(Resolved) KS relation at high z

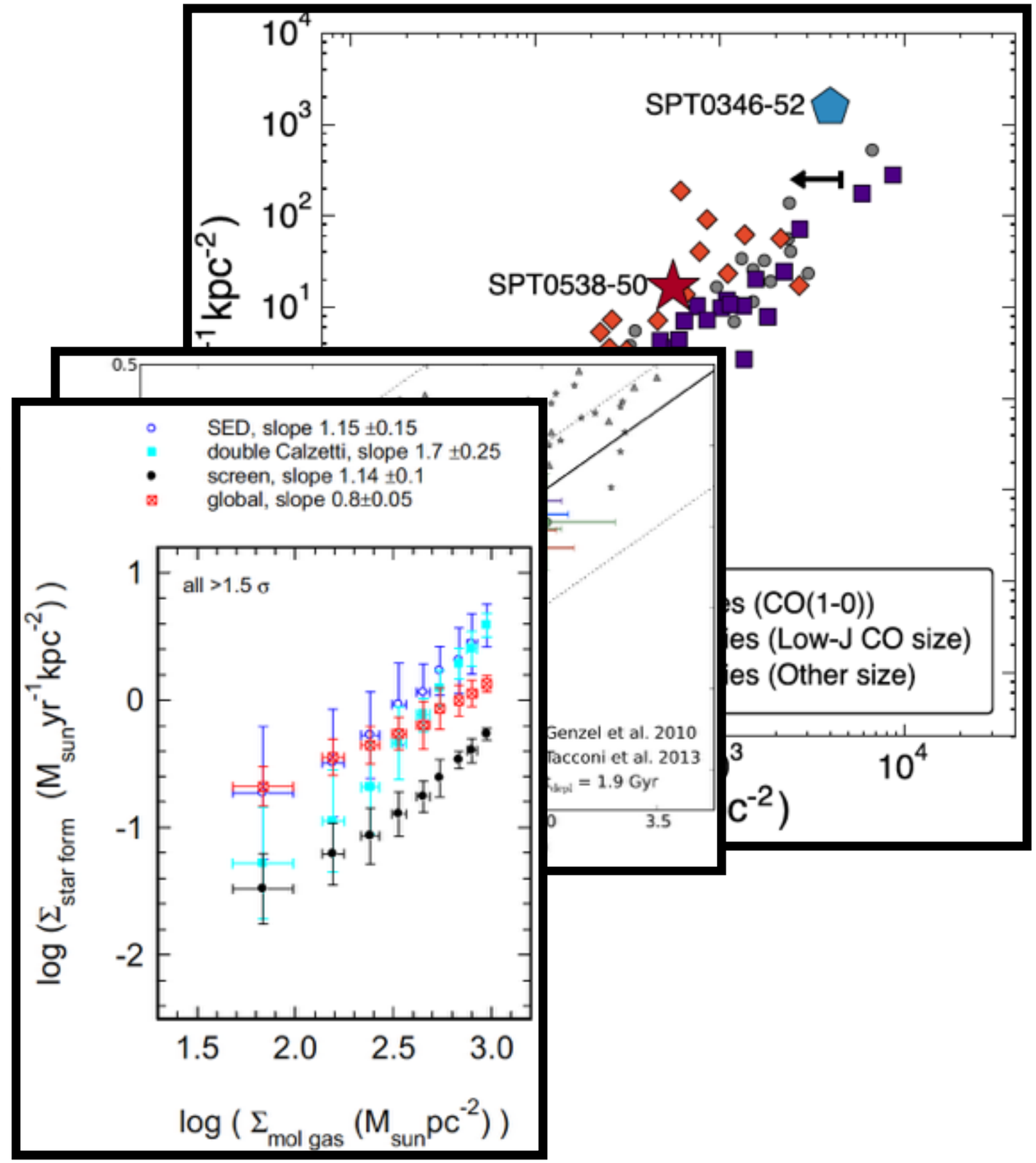
Spilker+2015: caution when computing Σ with sizes measured at different wavelength
<one data point per galaxy>

Freundlich+2013: go below 1-1.5" resolution limit by identifying clumps in position-velocity diagram

Genzel+2013: KS slope 0.8 - 1.7 depending on extinction correction

For high-z calibrations of
$A_{nebular}$ vs $A_{continuum}$:
Wuyts+2013; Price+2014; Reddy+2015

See Calzetti+2000 for z~0 calibration



Summary

- **GLOBAL**
  In what galaxies do stars form?
  Disks, but unlike local disks
  → ubiquitous outflows
  → turbulent ISM
  → clumpy
  → gas-rich

  The mass budget of early disks: baryon-dominated at z>2

- **LOCAL**
  Combining multi-wavelength resolved tracers
  Where in galaxies do stars form?
  Inside-out growing exponential disks
  Parallel tracks vs compaction