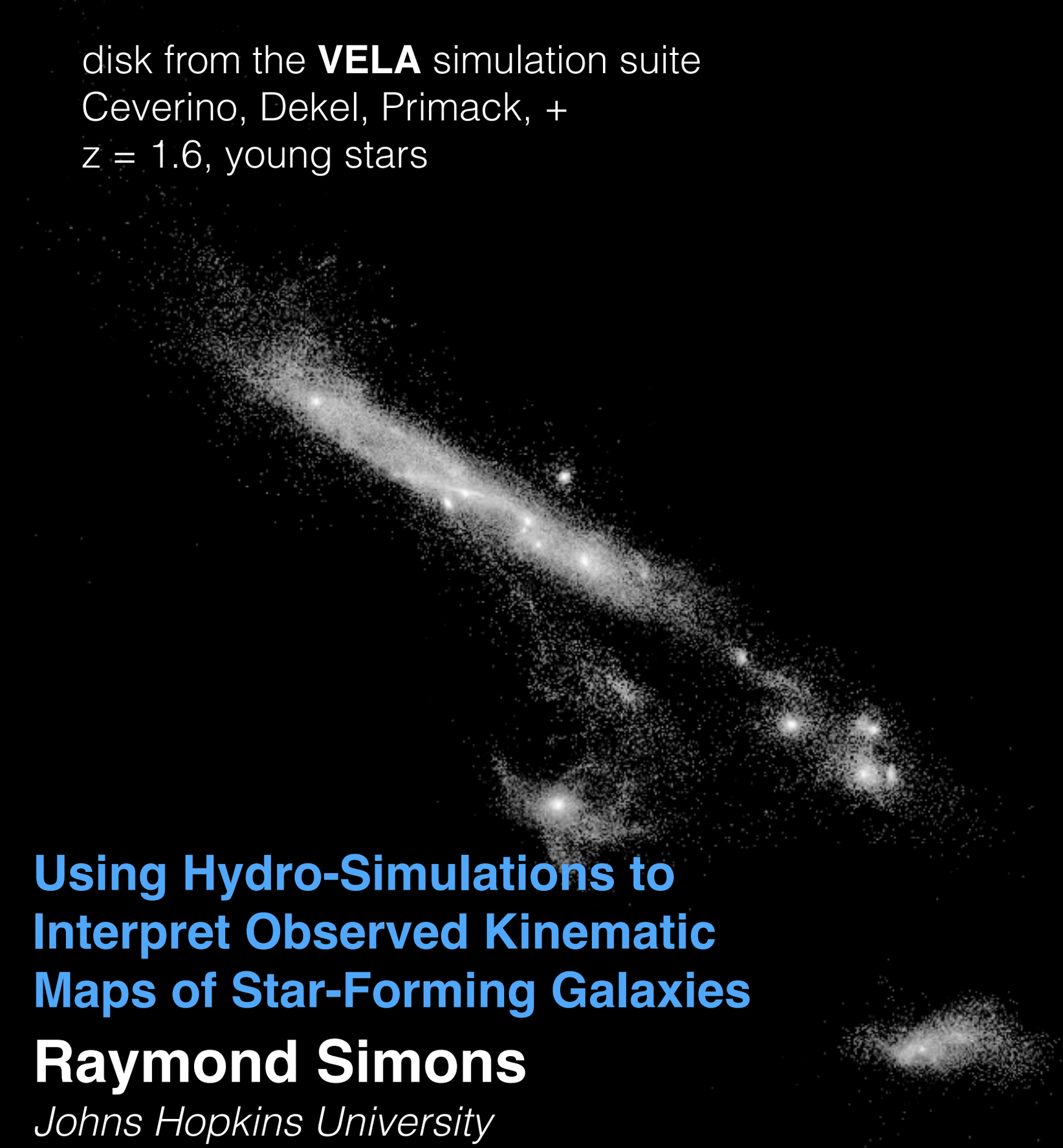
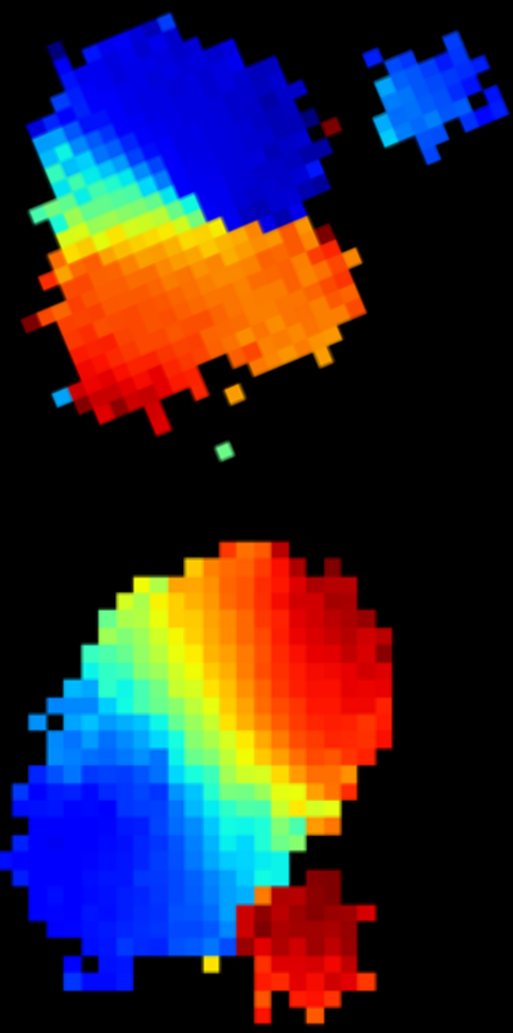
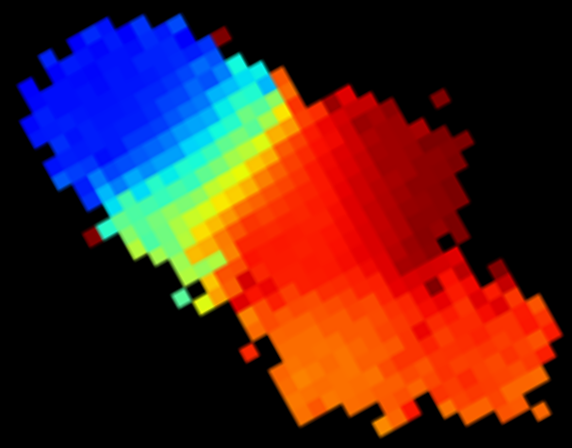
disk from the **VELA** simulation suite
Ceverino, Dekel, Primack, +
z = 1.6, young stars







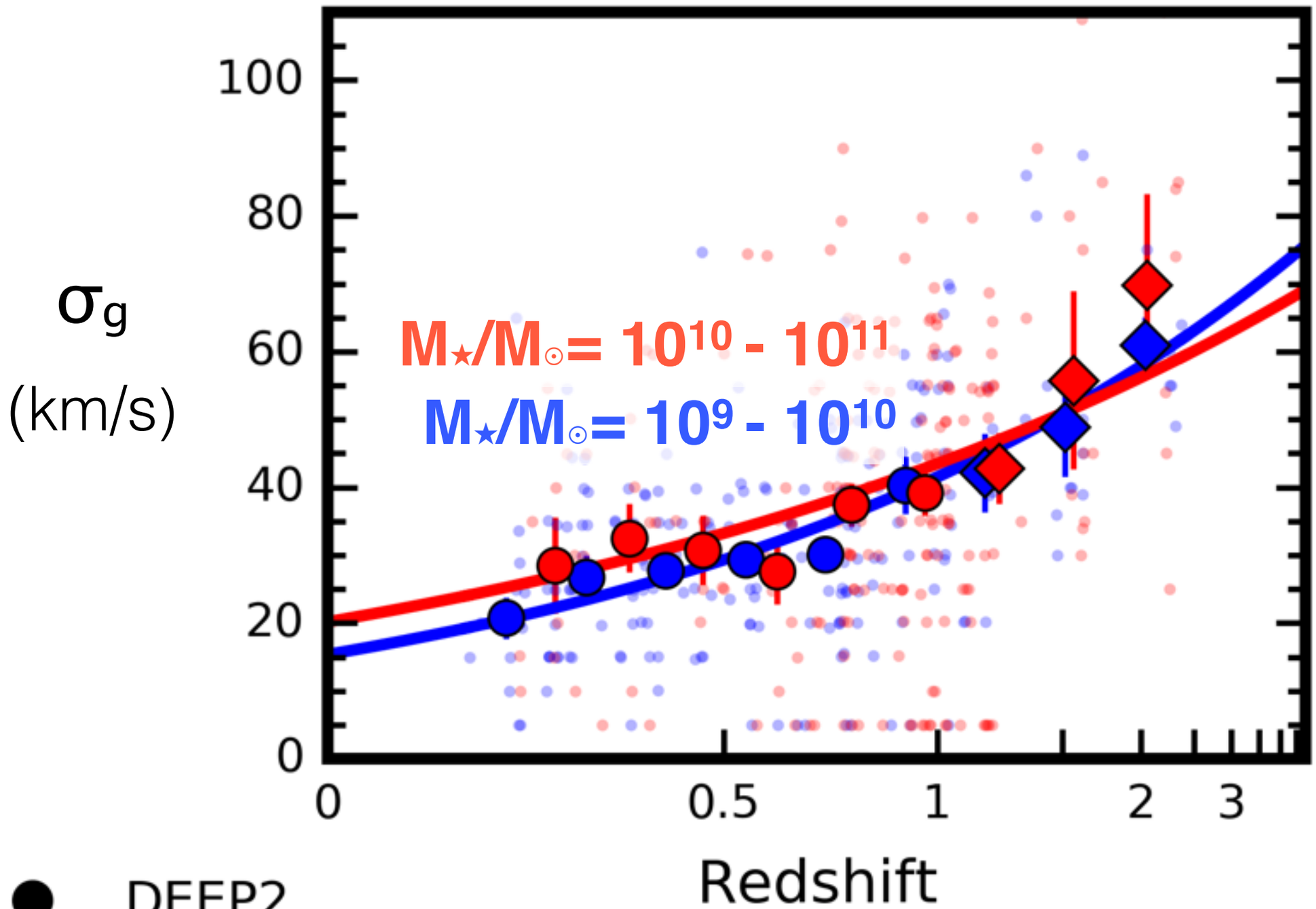
Using Hydro-Simulations to Interpret Observed Kinematic Maps of Star-Forming Galaxies

Raymond Simons
Johns Hopkins University
S. Kassin, G. Snyder, J. Primack, A. Dekel, D. Ceverino, B. Weiner, J. Trump
+ CANDELS + DEEP2 + SIGMA + VELA teams

What have we learned from observations of galaxy kinematics?

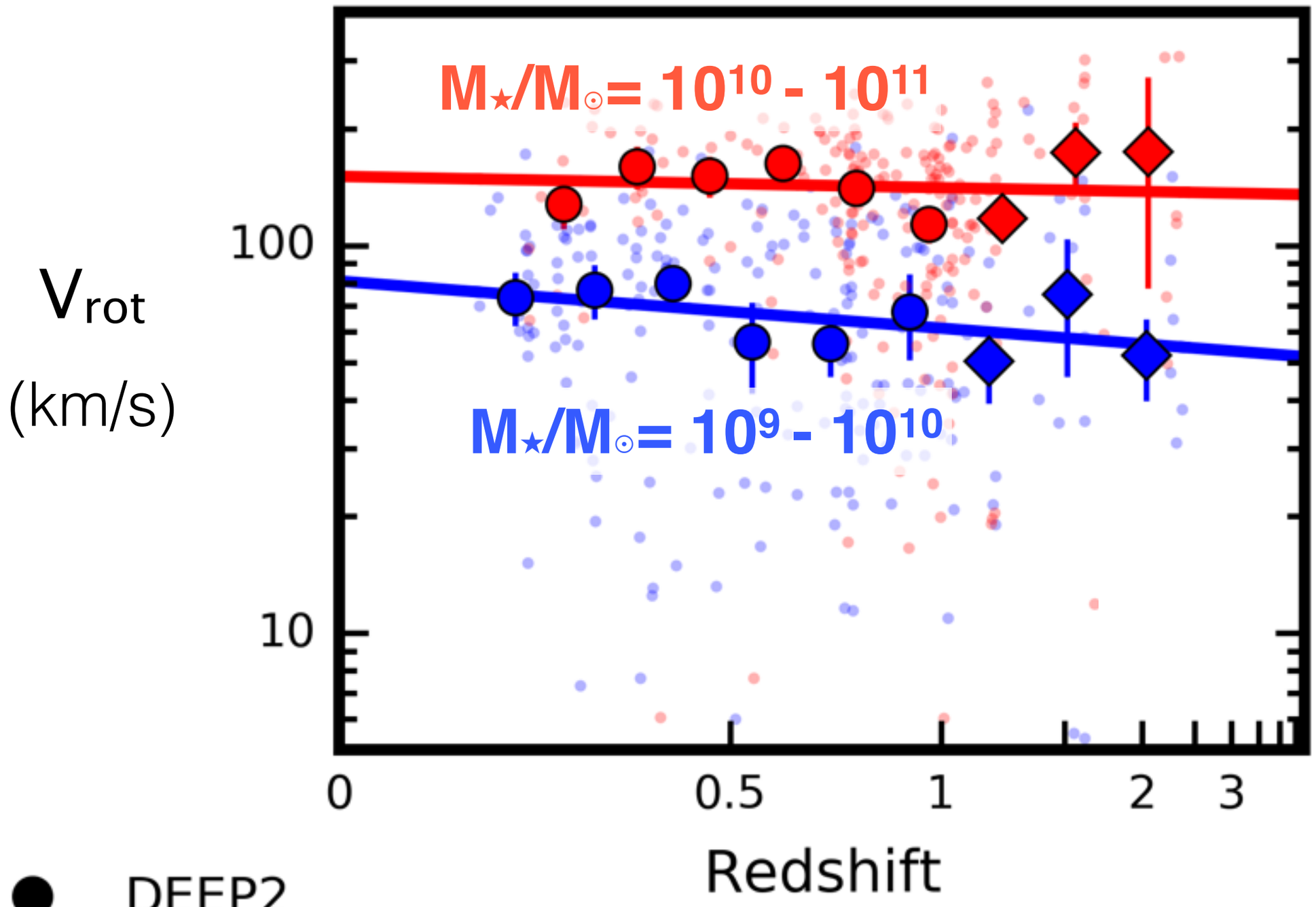
from z = 2.5 to now, star-forming galaxies…

disordered motions (σ_g) ***decline***



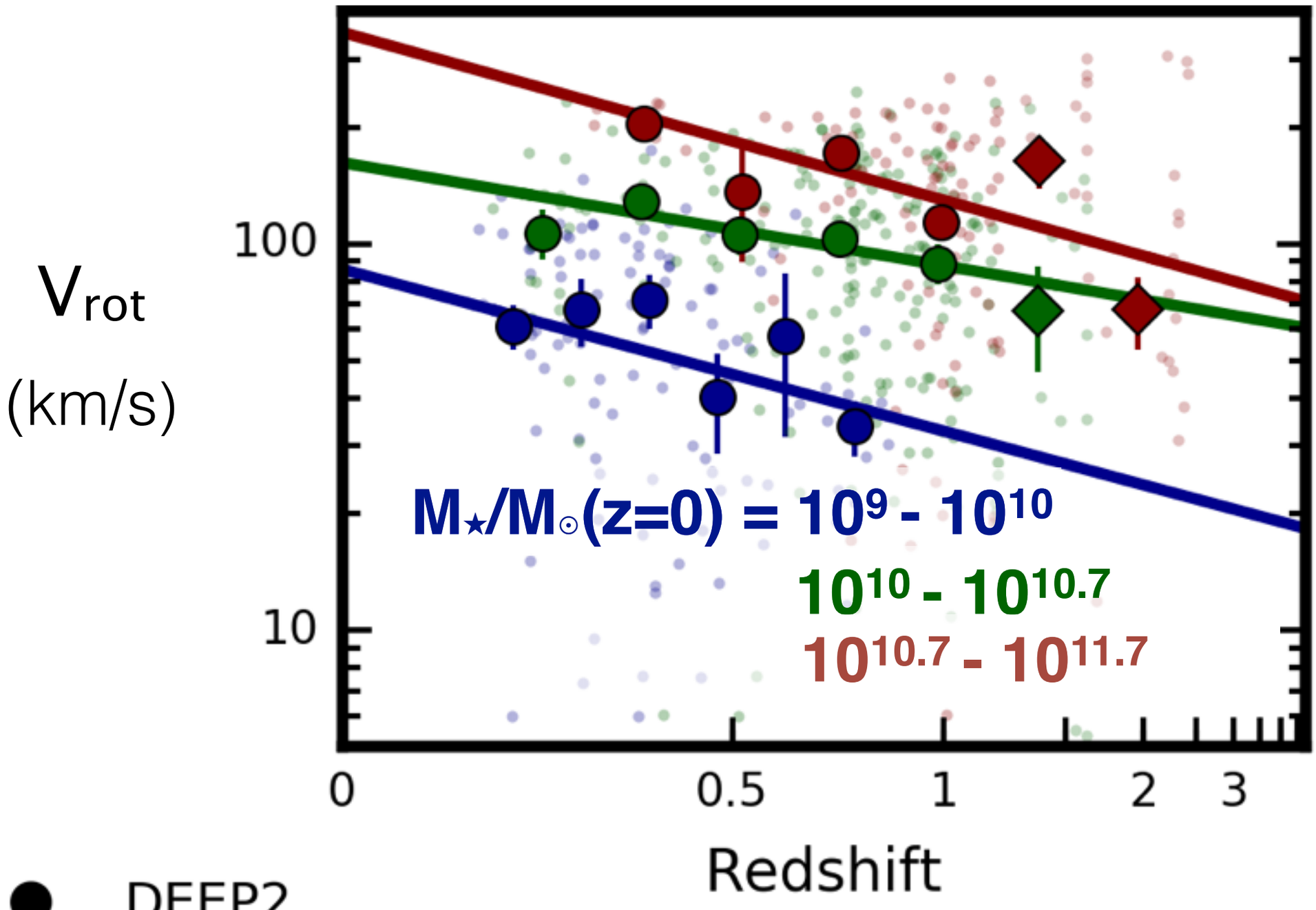
Kassin et al. 12
Simons et al. 16, 17

ordered motions (V_{rot}) ***increase*** *or* ***remain constant***



Kassin et al. 12
Simons et al. 16, 17

but, at fixed z = 0 mass, **all** populations of galaxies on average **increase** in V_{rot} with time



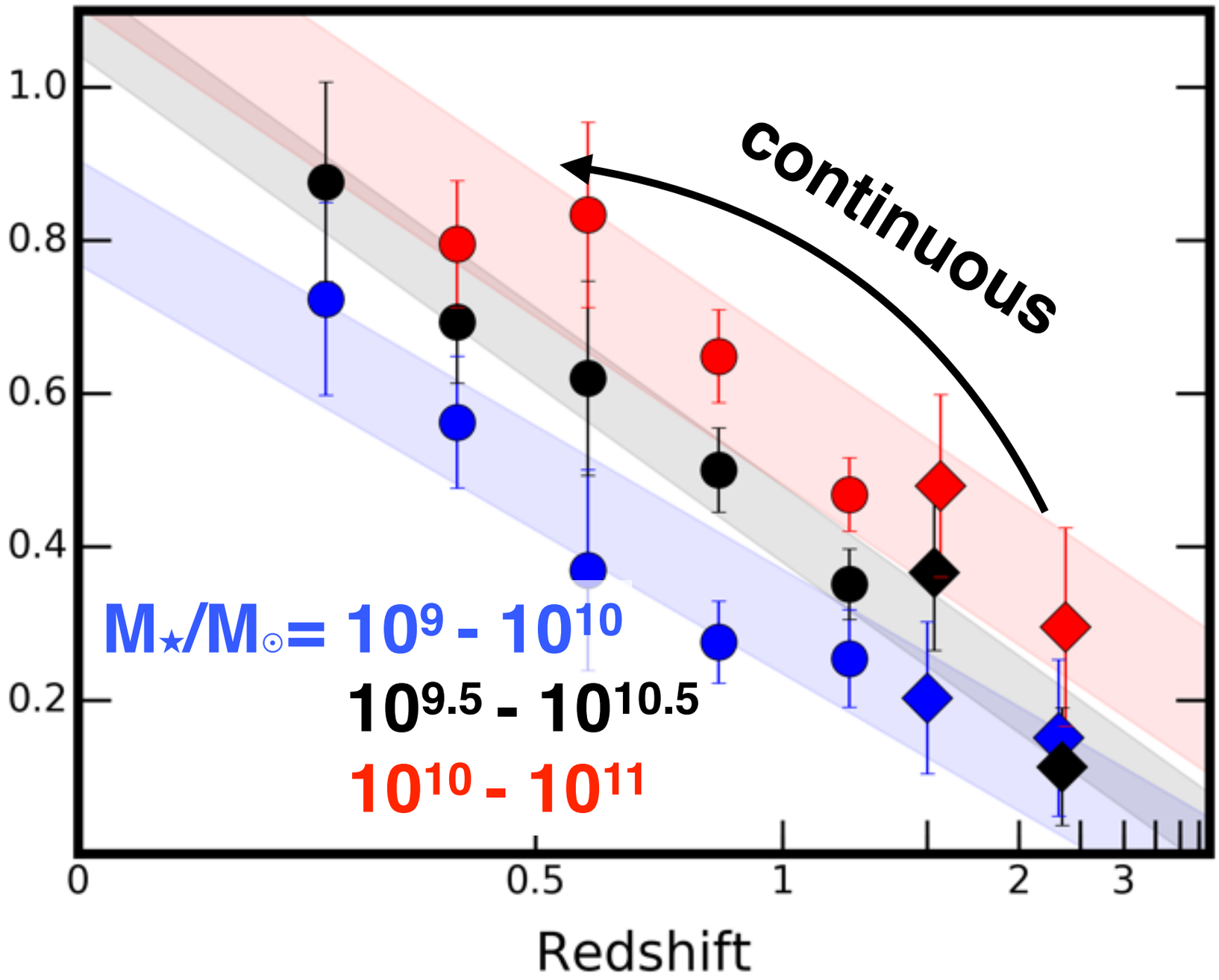
*using Moster+13 abundance matching

Kassin et al. 12
Simons et al. 16, 17

assemble and **settle** their disks

continuous

fraction of galaxies with $V_{rot}/\sigma_g > 3$



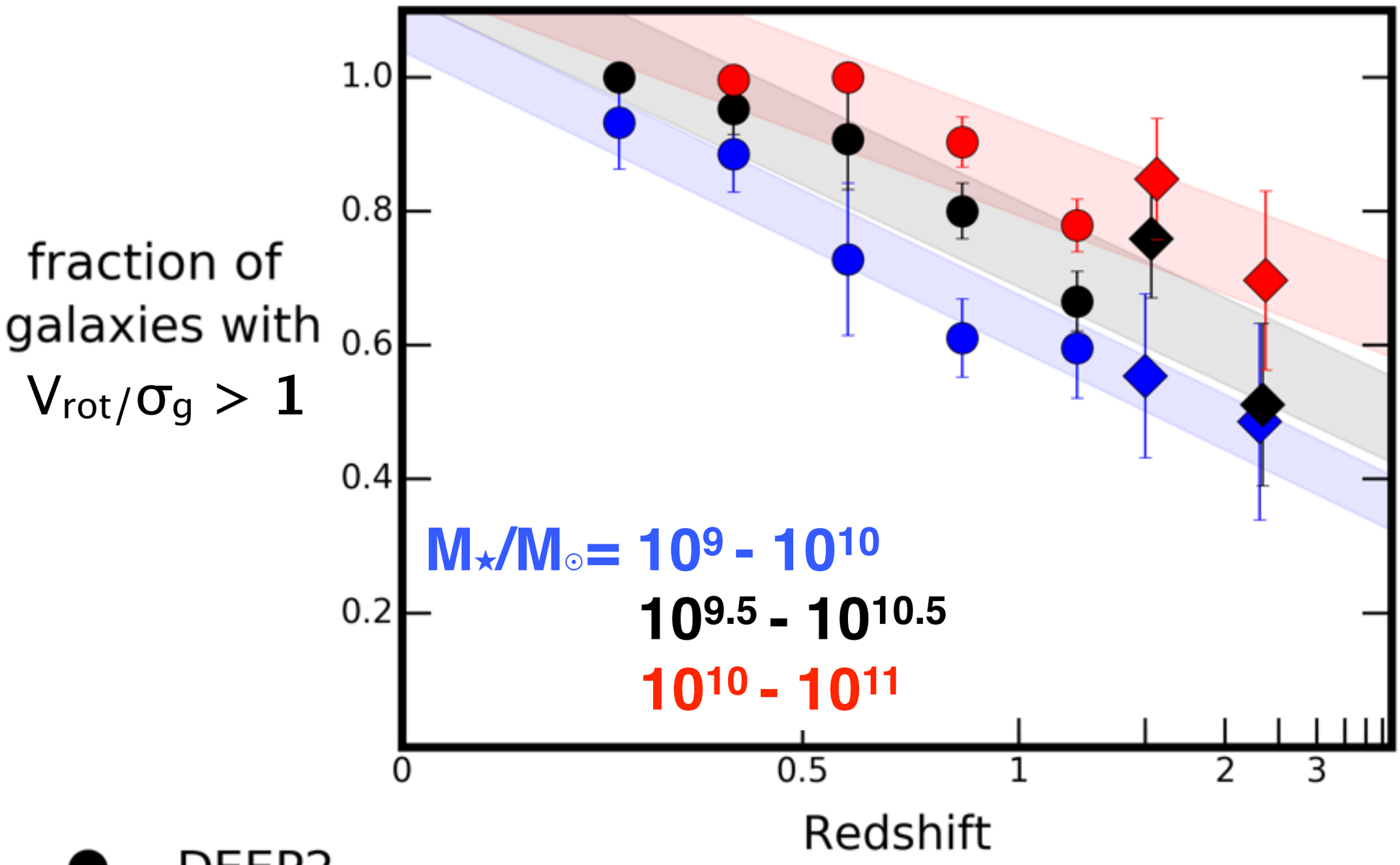
DEEP2

SIGMA

Kassin et al. 12

Simons et al. 16, 17

assemble and **settle** their disks

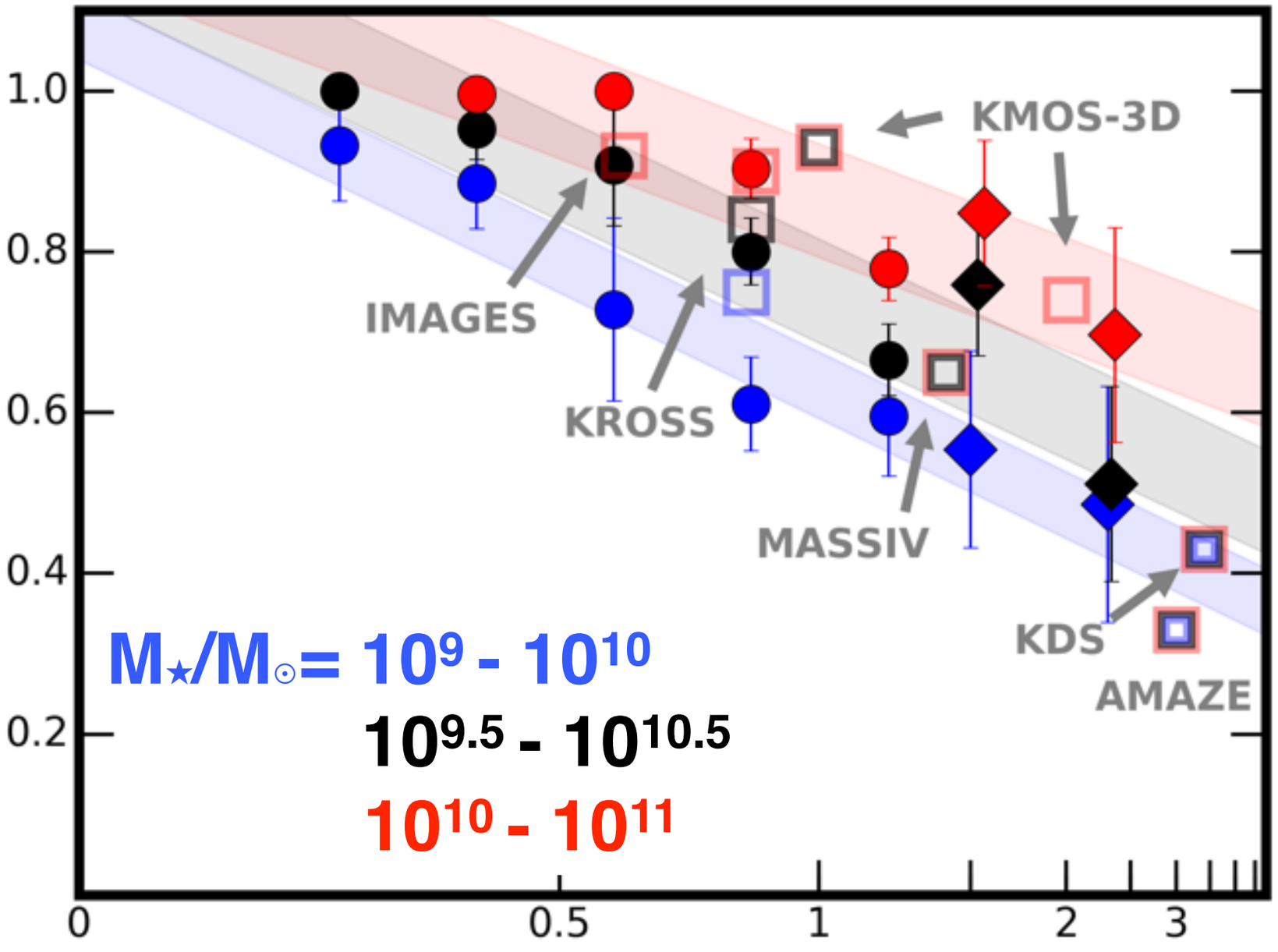


Kassin et al. 12
Simons et al. 16, 17

assemble and **settle** their disks

mass explains most discrepancies between surveys

fraction of galaxies with $V_{rot}/\sigma_g > 1$



● DEEP2

◆ SIGMA

IMAGES (Puech+ 07,08), KROSS (Harrison+ 17), KMOS-3D (Wisnioski+ 16), MASSIV (Vergani+ 12), AMAZE/LSD (Gnerucci+ 11), KDS (Turner+ 17)

Kassin et al. 12

Simons et al. 16, 17

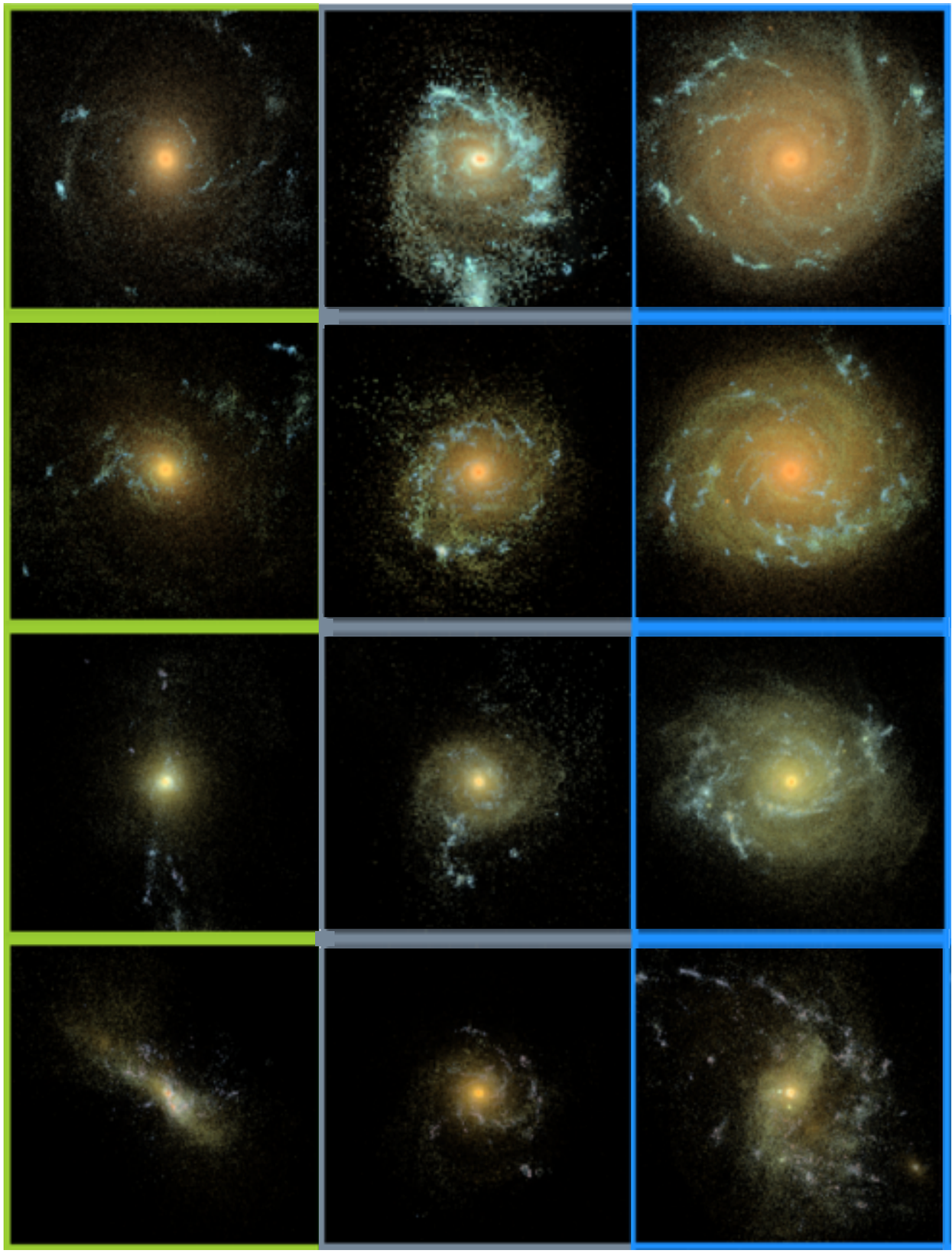
VELA Simulations

for details: Ceverino+10,14

- 35 high resolution (17-35 pc) zoom-in AMR cosmological simulations using the HYDRO-ART code (Ceverino & Klypin 09), down to z~1

- Relevant galaxy formation physics (gas cooling, radiation pressure, UV photoionization, thermal feedback from SNe, stellar winds)

- 11 < log halo mass < 12.3
  9.3 < log stellar mass < 10.7
  at z~1



idealized images from Snyder+15

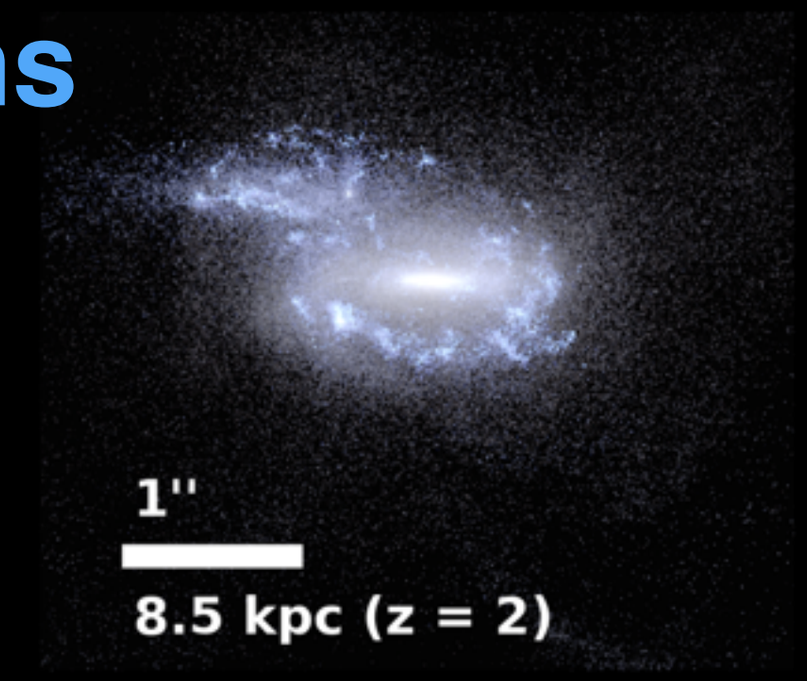
Mandelker+ 14,17, Moody+ 14, Danovich+ 15, Snyder+ 15, Zolotov+ 15, Inoue+ 16, Tacchella+16 a,b, Ceverino+ 14,15,16, Tomasetti+ 16

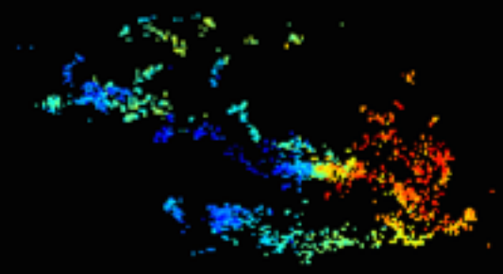
Mock Observations

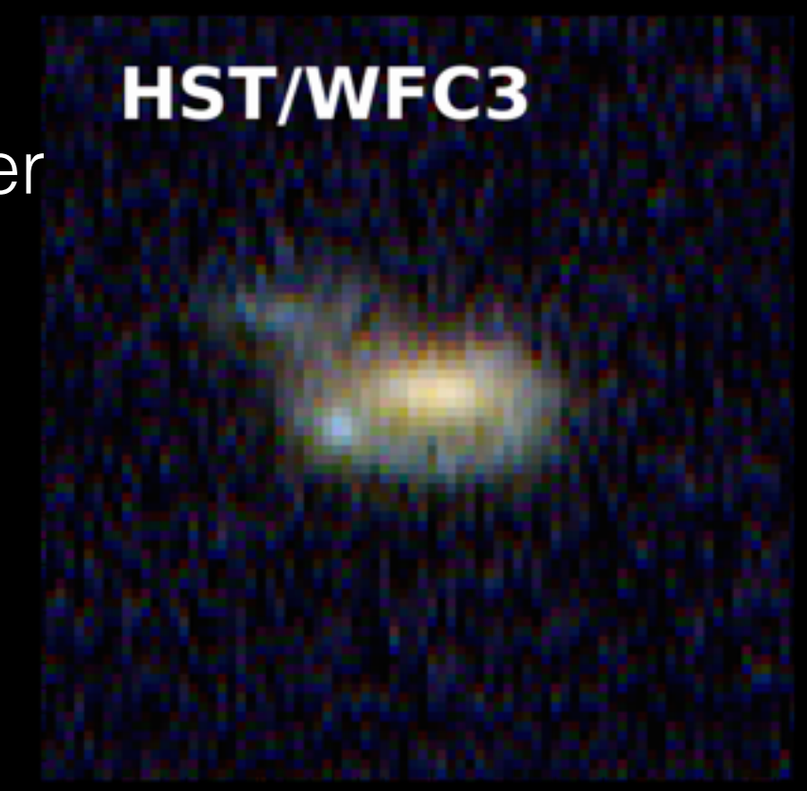
Mock images and kinematic maps for arbitrary telescope/ observing conditions

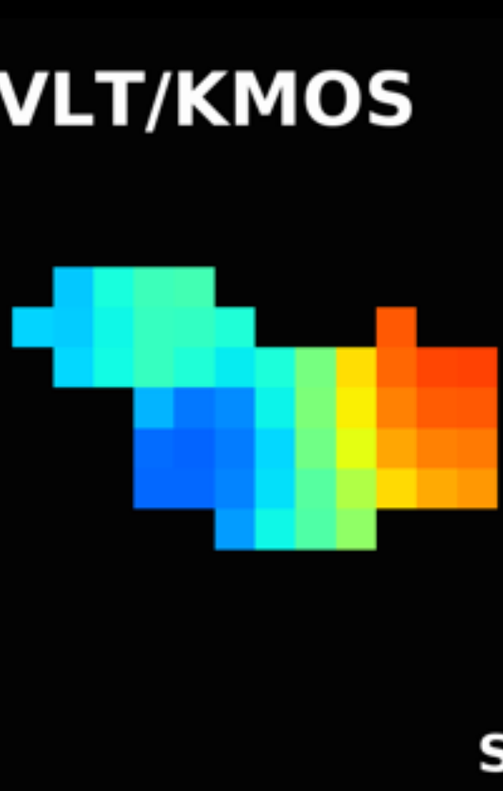
Without dust or with full SUNRISE dust radiative transfer

- MAPPINGS III model for star-forming regions
- Emission lines for gas
- Absorption lines for stars







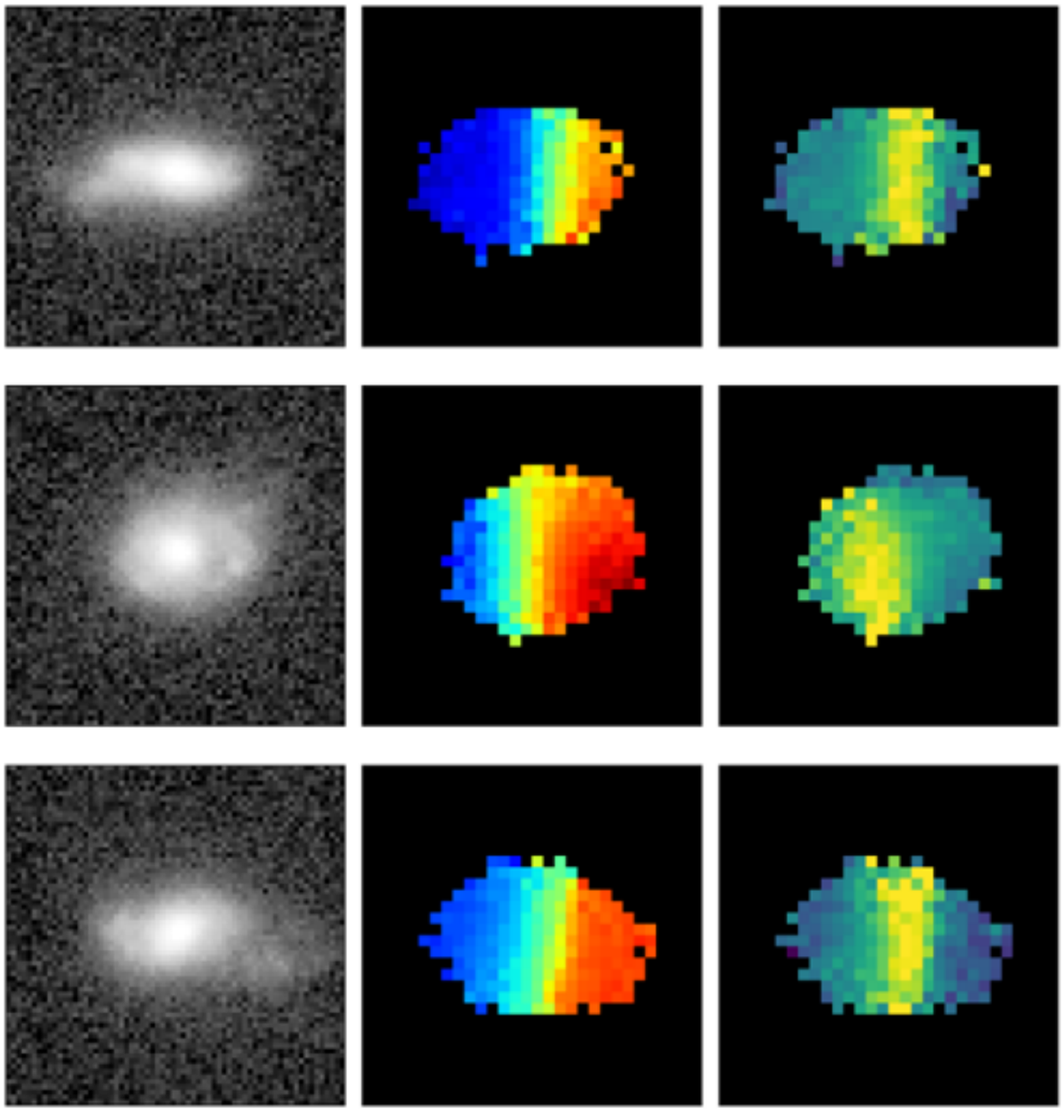


SUNRISE: Jonsson+ 06,10, Jonsson & Primack 10
MAPPINGS III: Groves+08

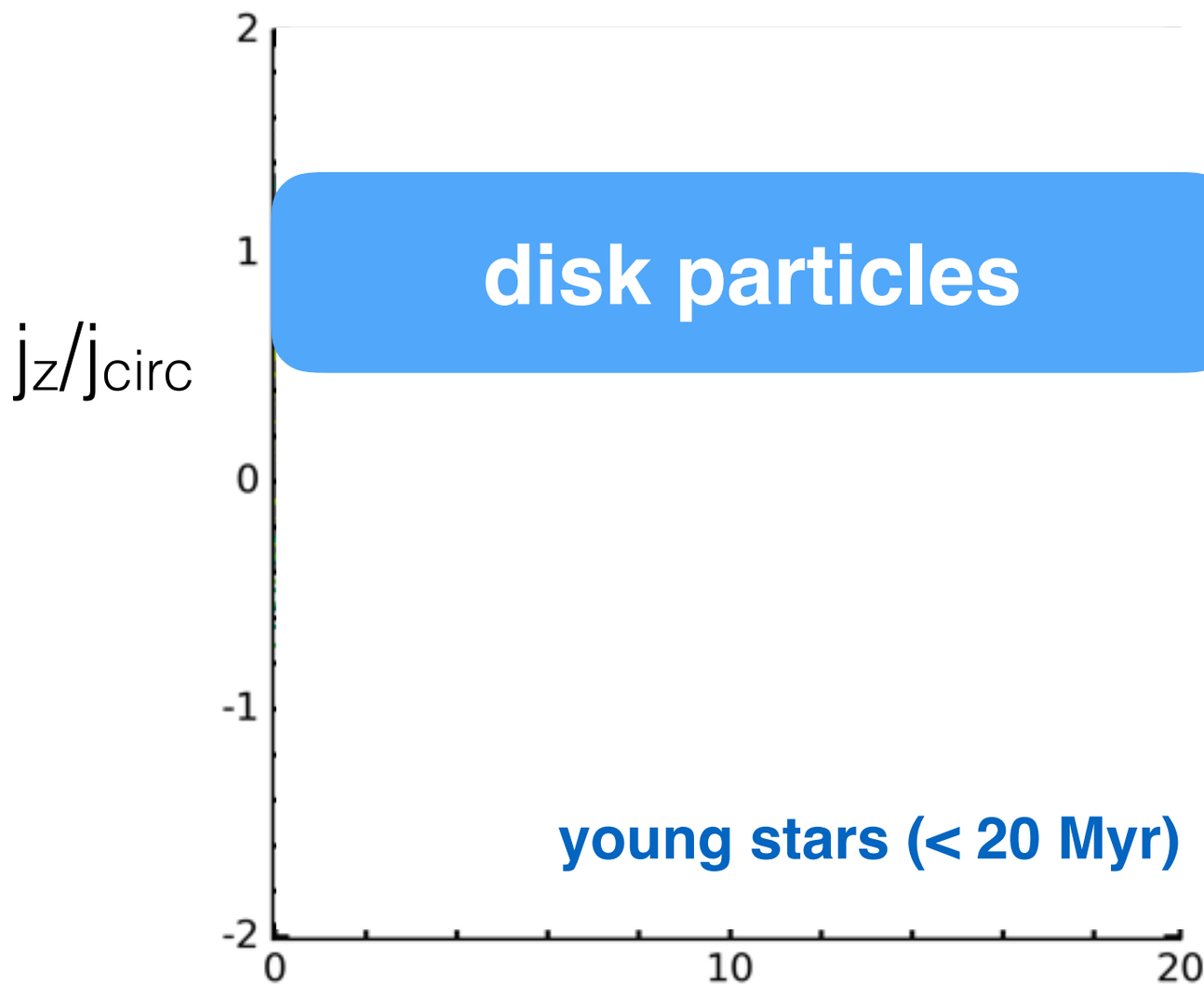
HST
H-band

KMOS
V

KMOS
σ



z = 1.7



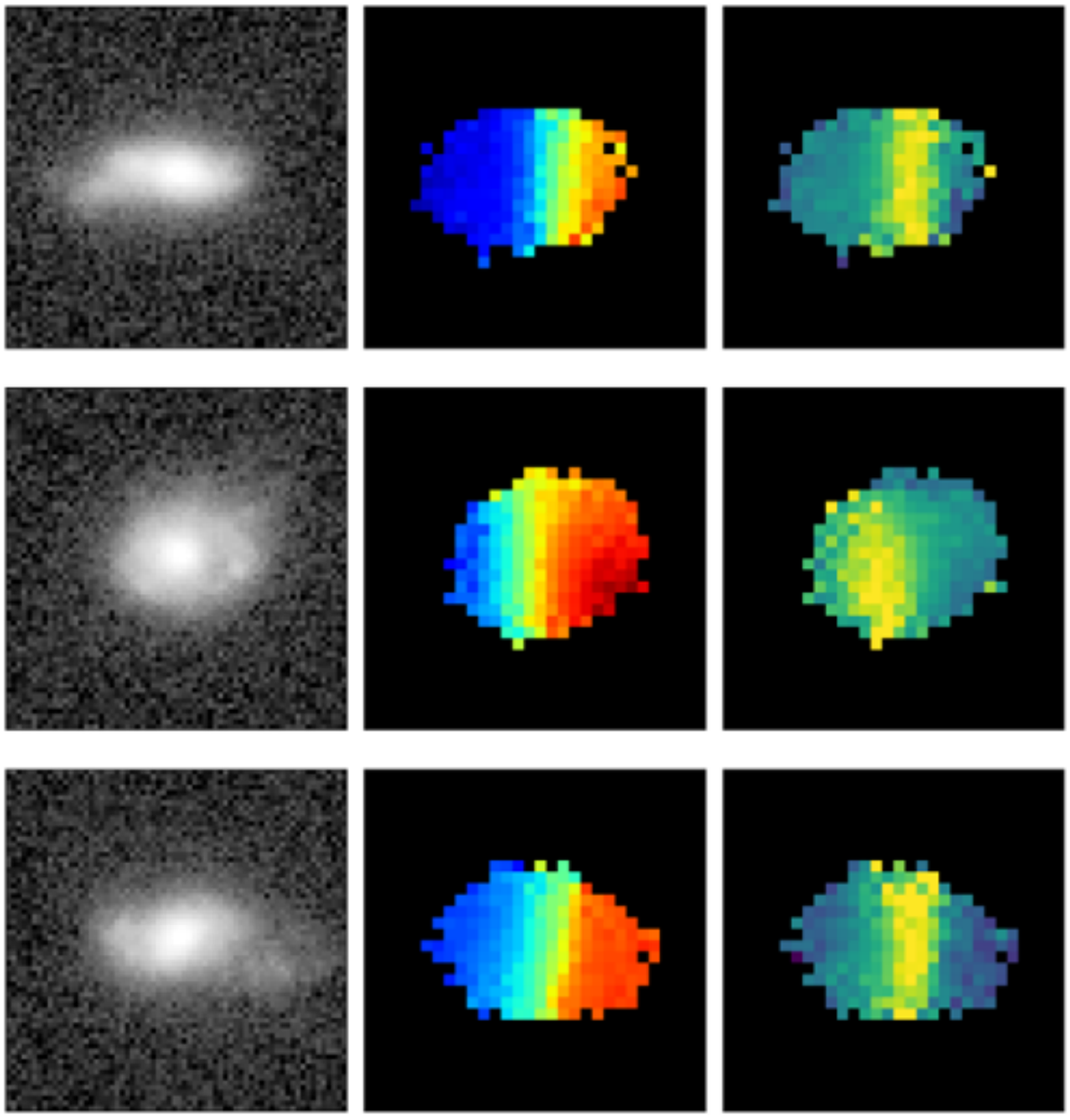
observed

intrinsic

HST
H-band

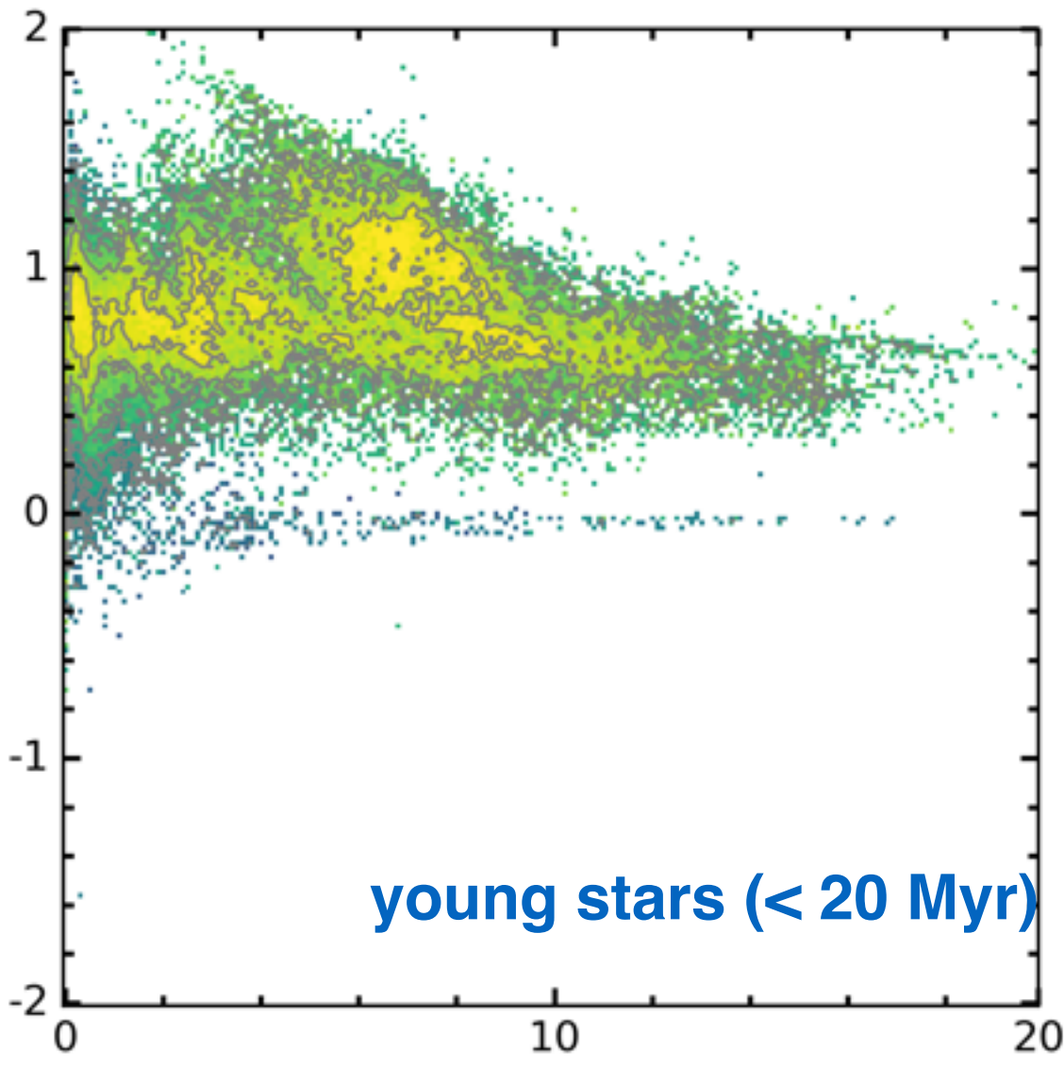
KMOS
V

KMOS
σ



z = 1.7

j_z/j_{circ}



radial distance (kpc)

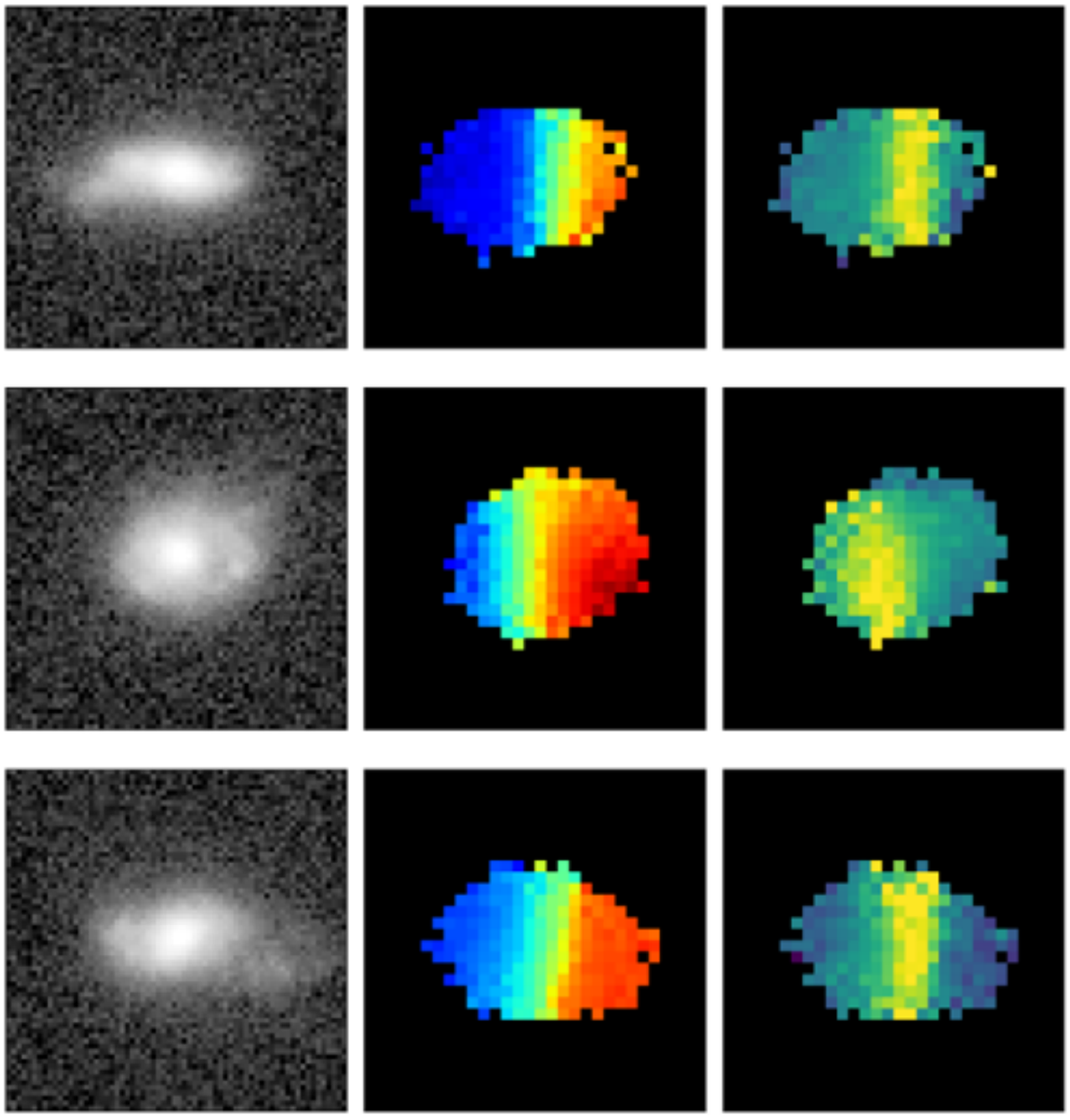
observed

intrinsic

HST
H-band

KMOS
V

KMOS
σ



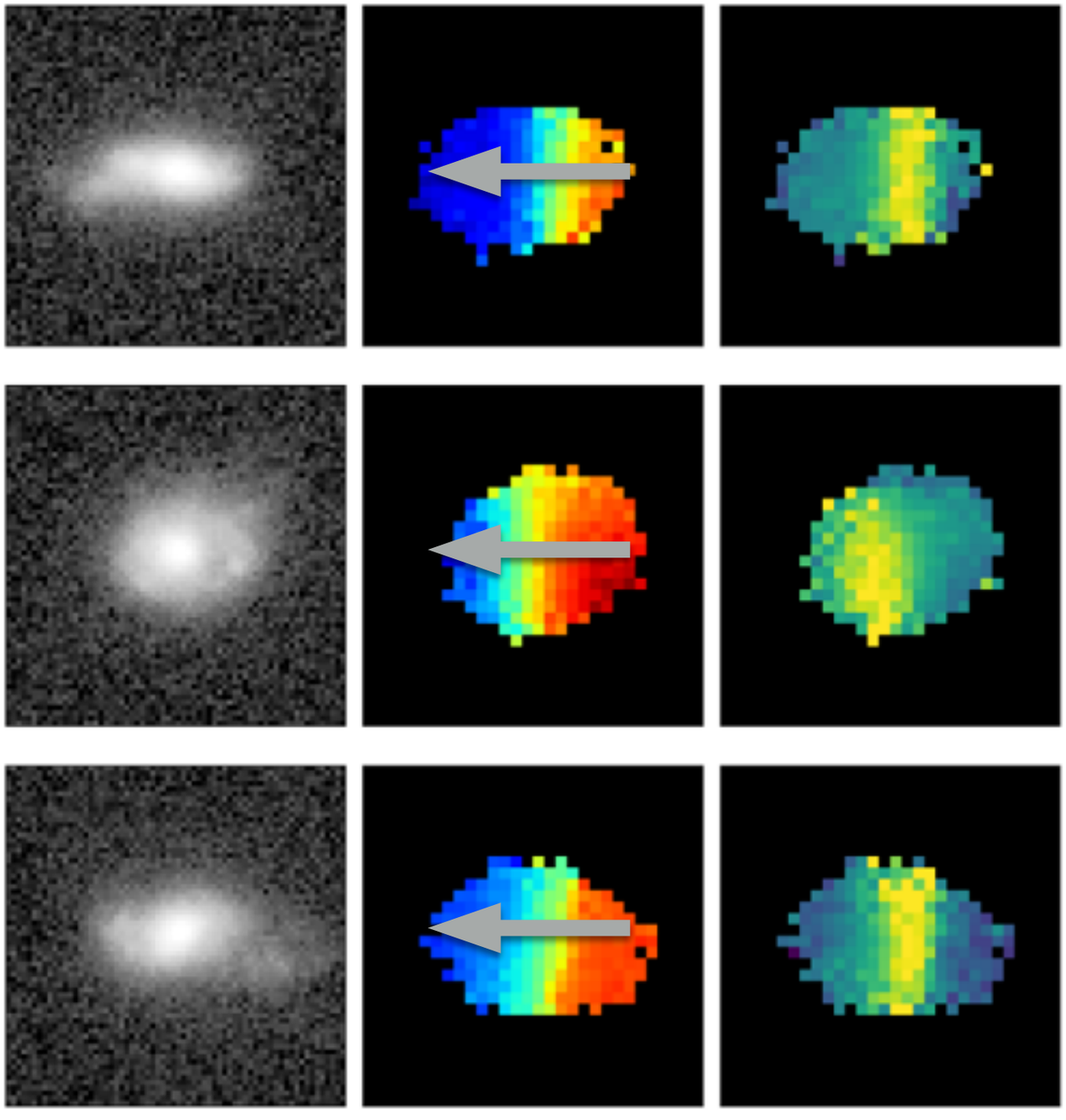
observed

observational disk criteria

HST
H-band

KMOS
V

KMOS
σ



observed

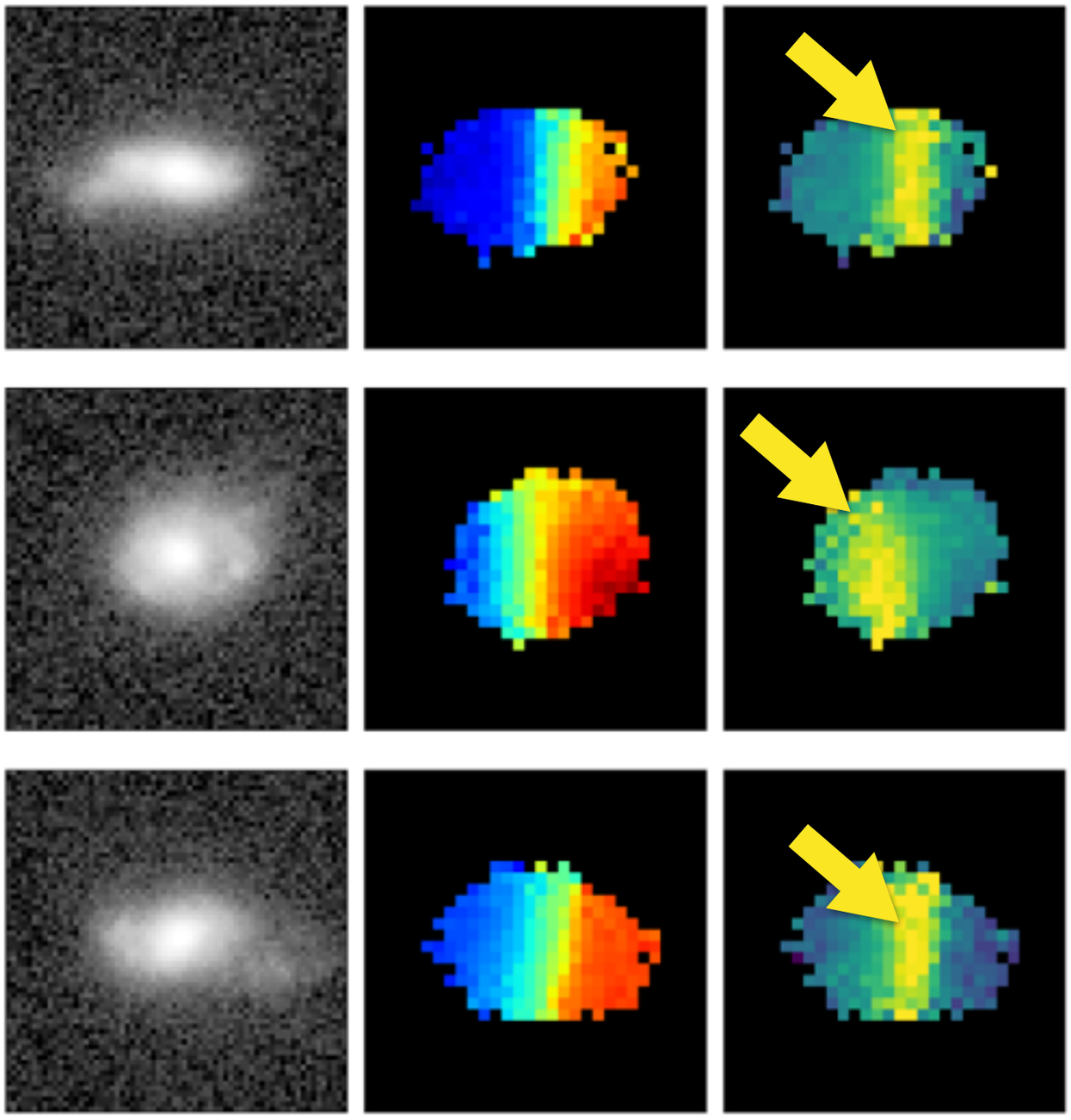
observational disk criteria

✓ continuous velocity gradient

HST
H-band

KMOS
V

KMOS
σ



observed

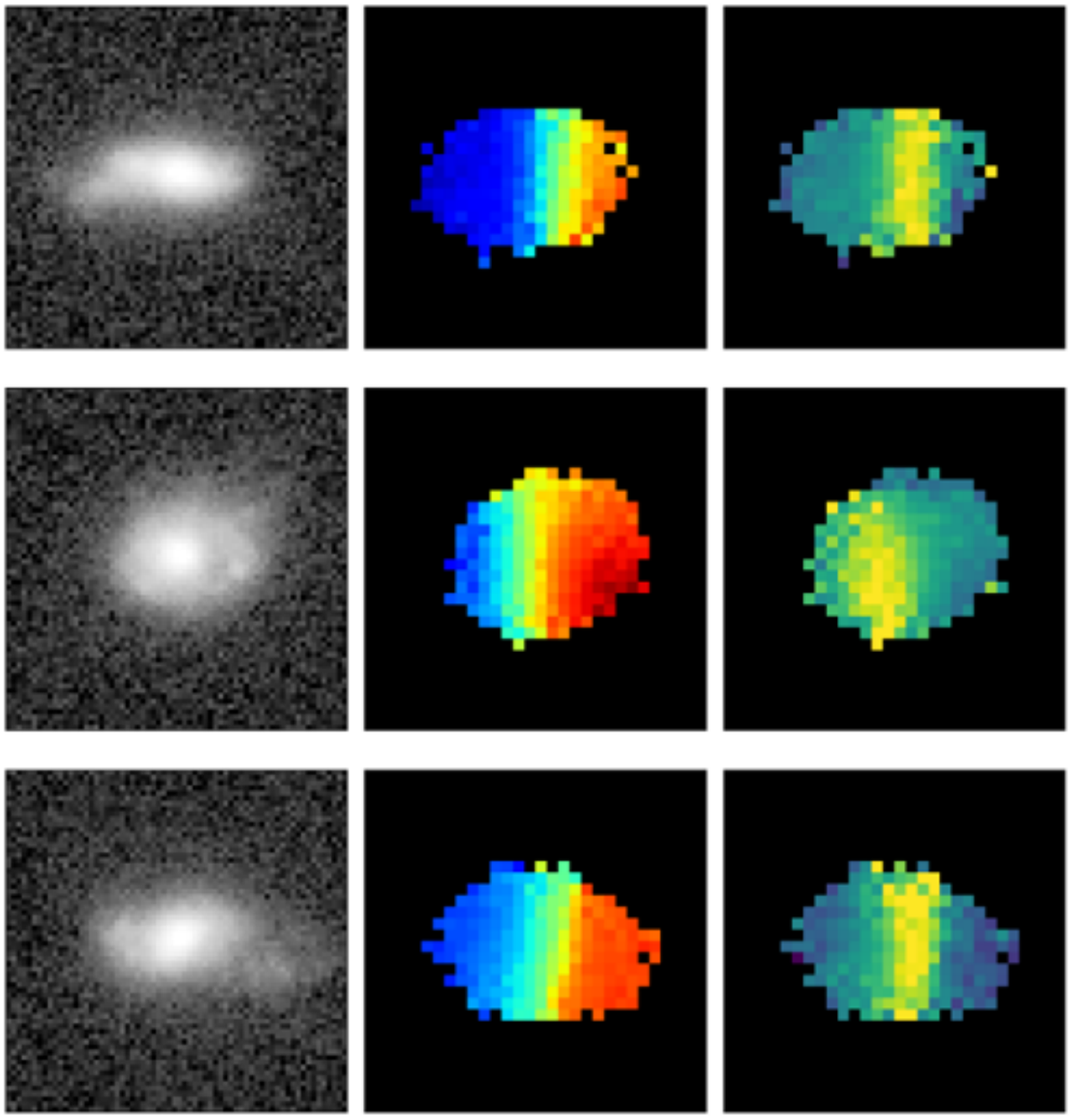
observational disk criteria

- ✓ continuous velocity gradient
- ✓ central peak in σ_g

HST
H-band

KMOS
V

KMOS
σ



observed

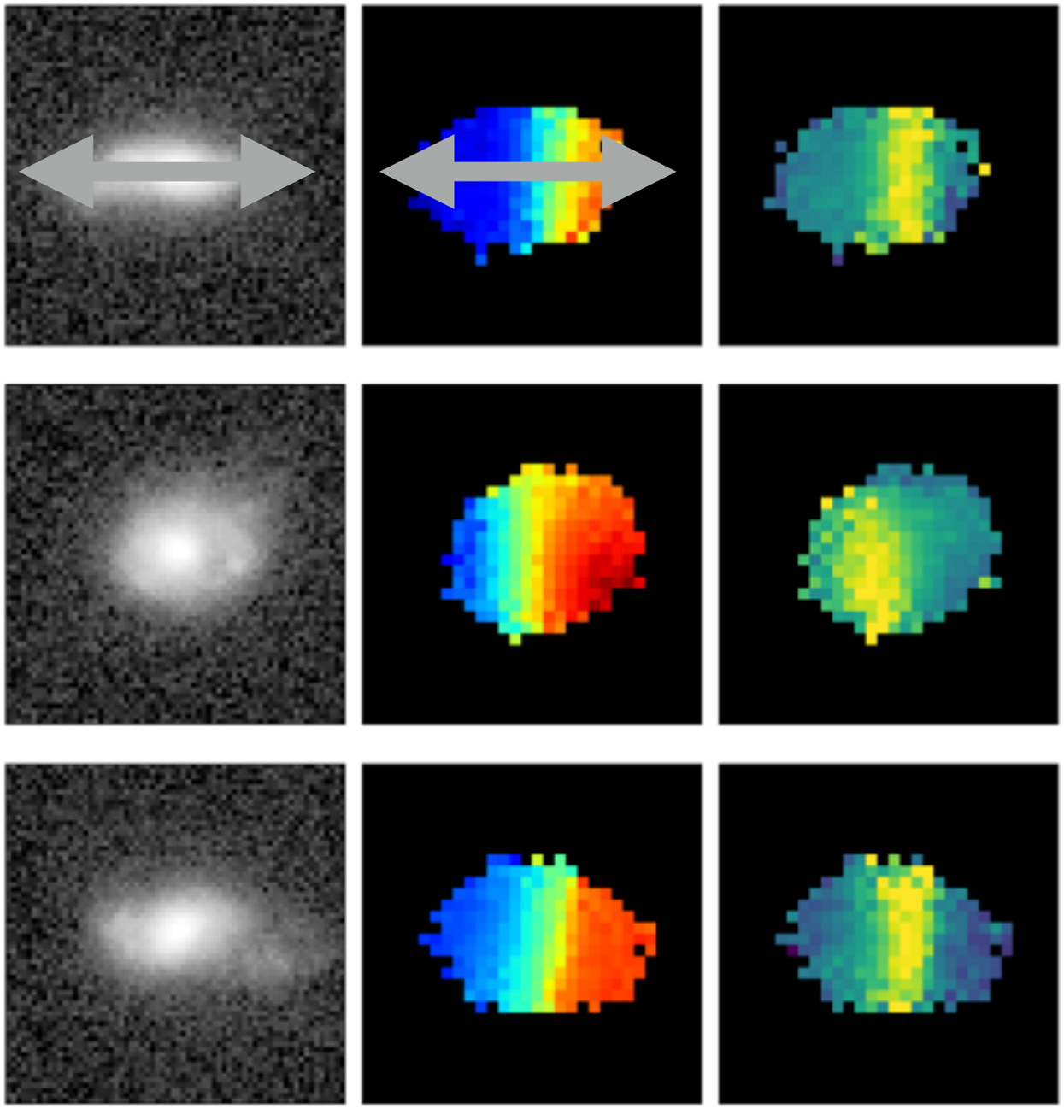
observational disk criteria

- ✓ continuous velocity gradient
- ✓ central peak in σ_g
- ✓ $V_{rot}/\sigma_g > 1$

HST
H-band

KMOS
V

KMOS
σ



observed

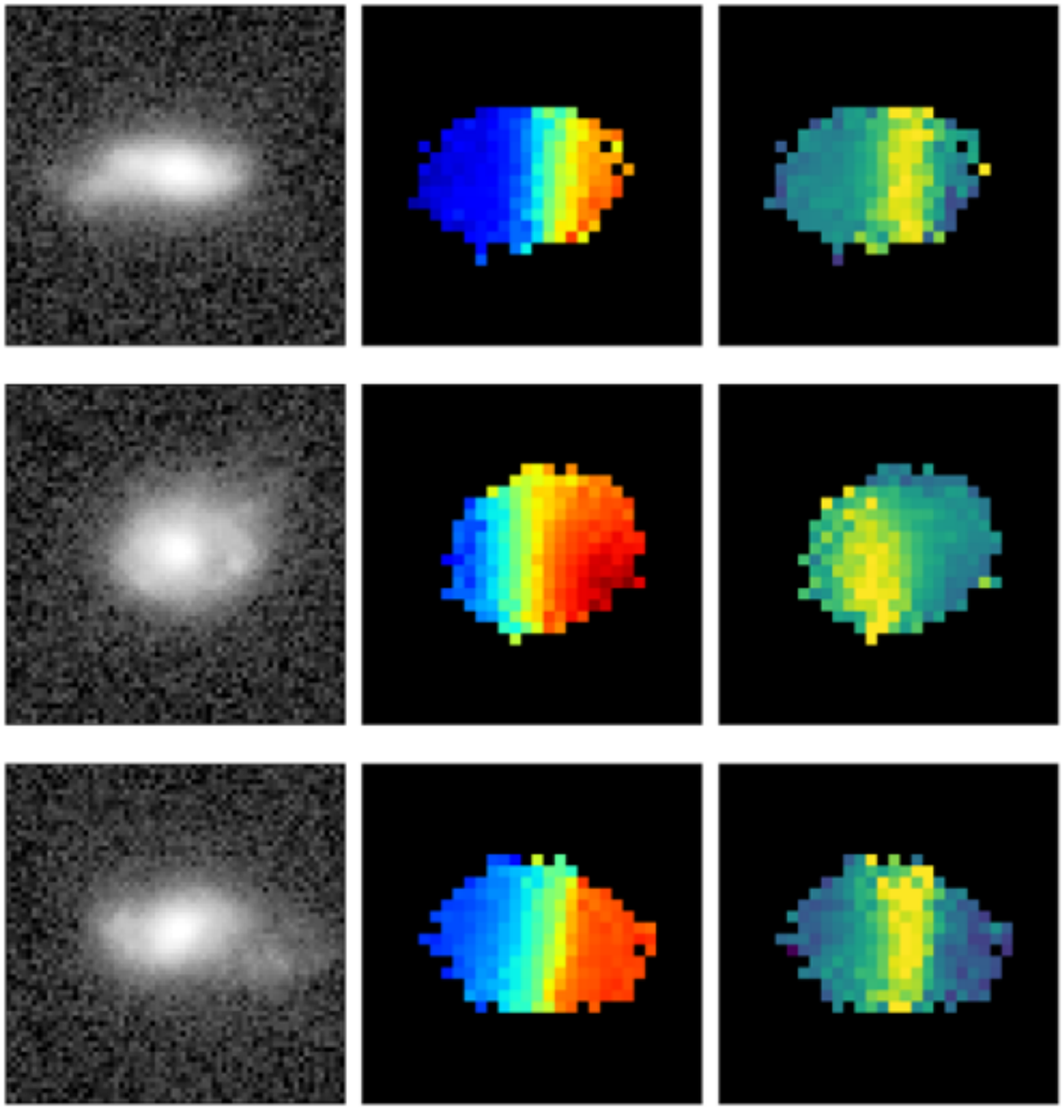
observational disk criteria

- ✓ continuous velocity gradient
- ✓ central peak in σ_g
- ✓ $V_{rot}/\sigma_g > 1$
- ✓ kinematic and photometric axis aligned

HST
H-band

KMOS
V

KMOS
σ

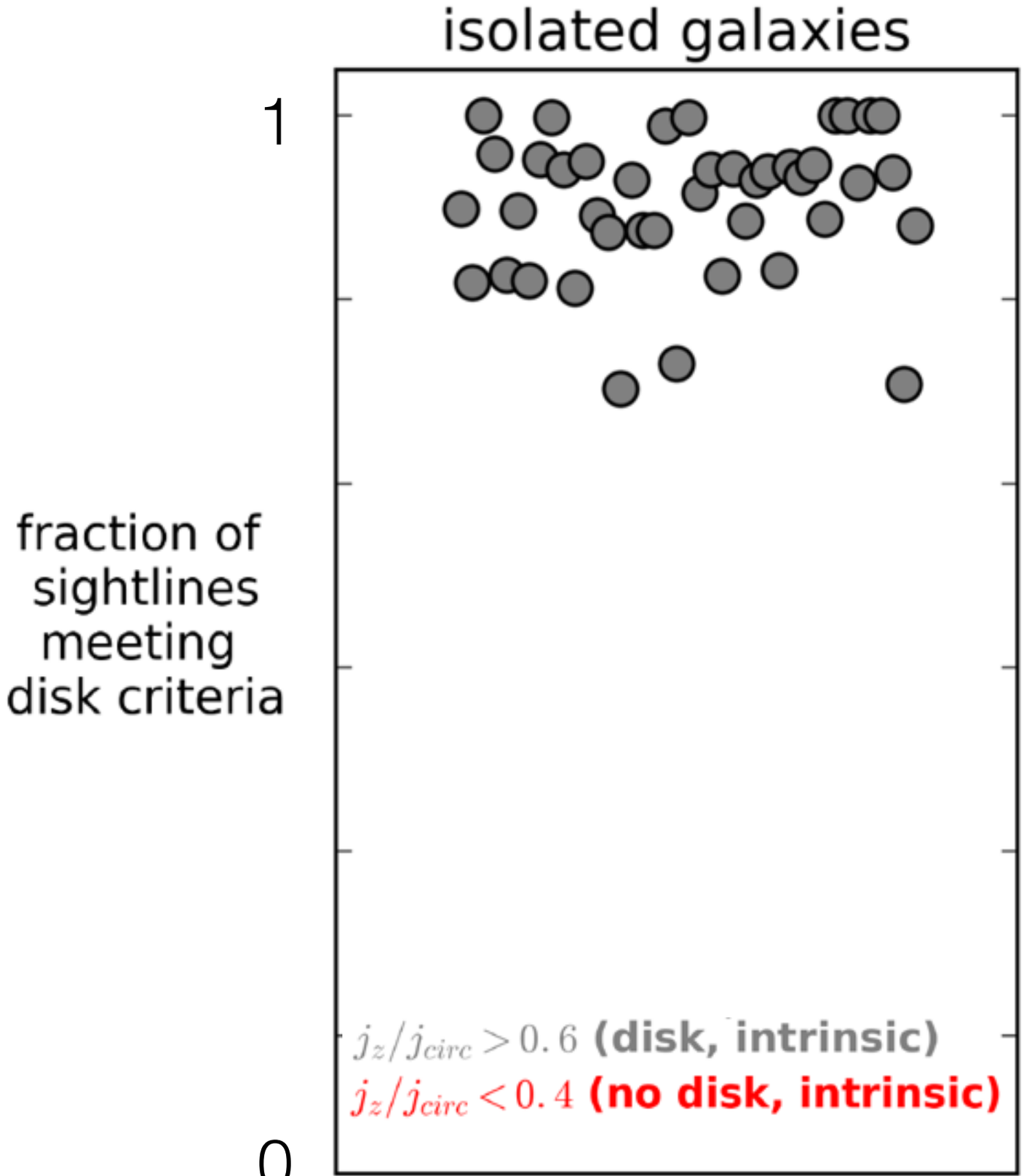


observed

observational disk criteria

- ✓ continuous velocity gradient
- ✓ central peak in σ_g
- ✓ $V_{rot}/\sigma_g > 1$
- ✓ kinematic and photometric axis aligned

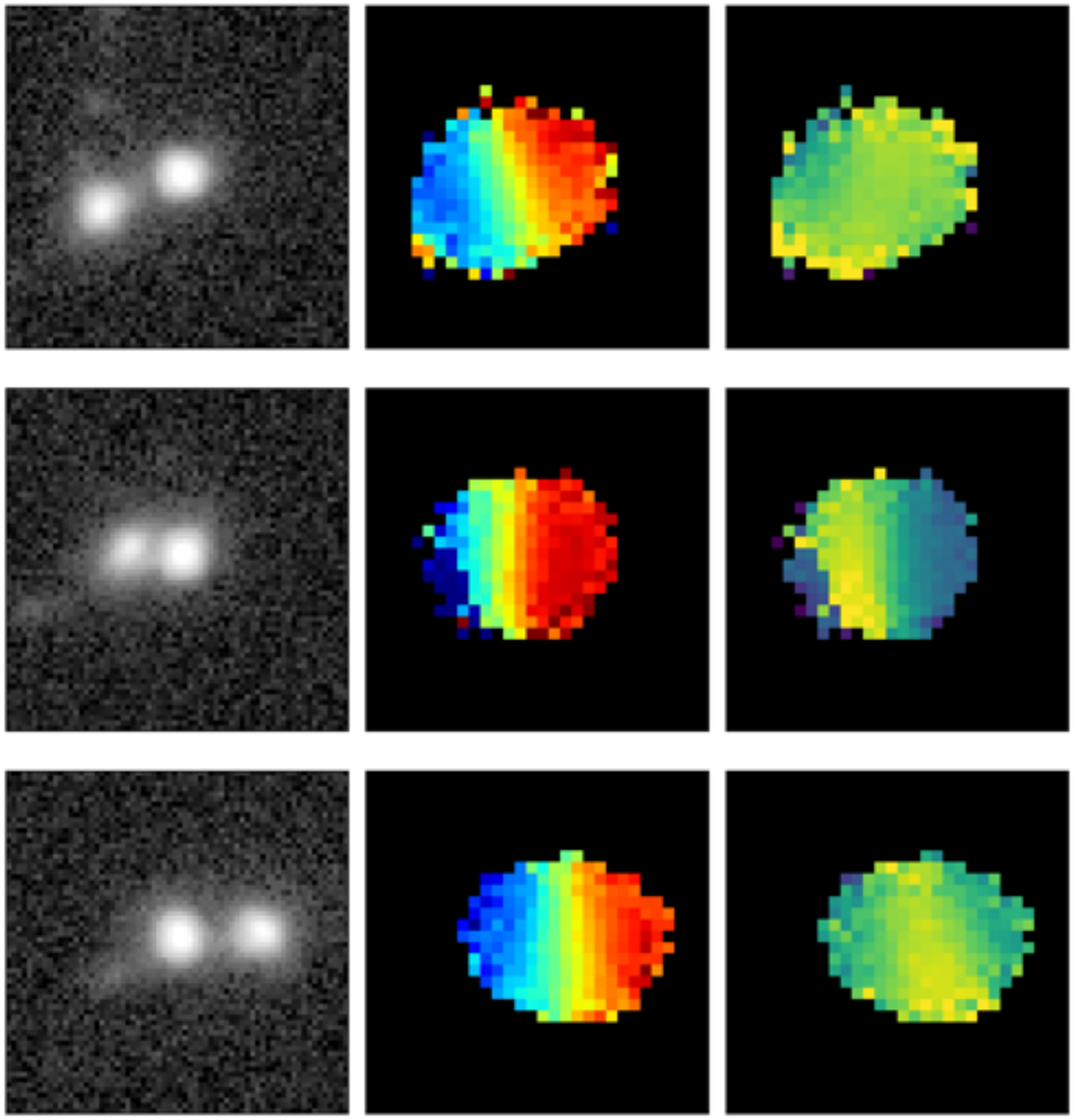
✓ **disk**


isolated galaxies
1
fraction of sightlines meeting disk criteria
$j_z/j_{circ} > 0.6$ (disk, intrinsic)
$j_z/j_{circ} < 0.4$ (no disk, intrinsic)
0

HST
H-band

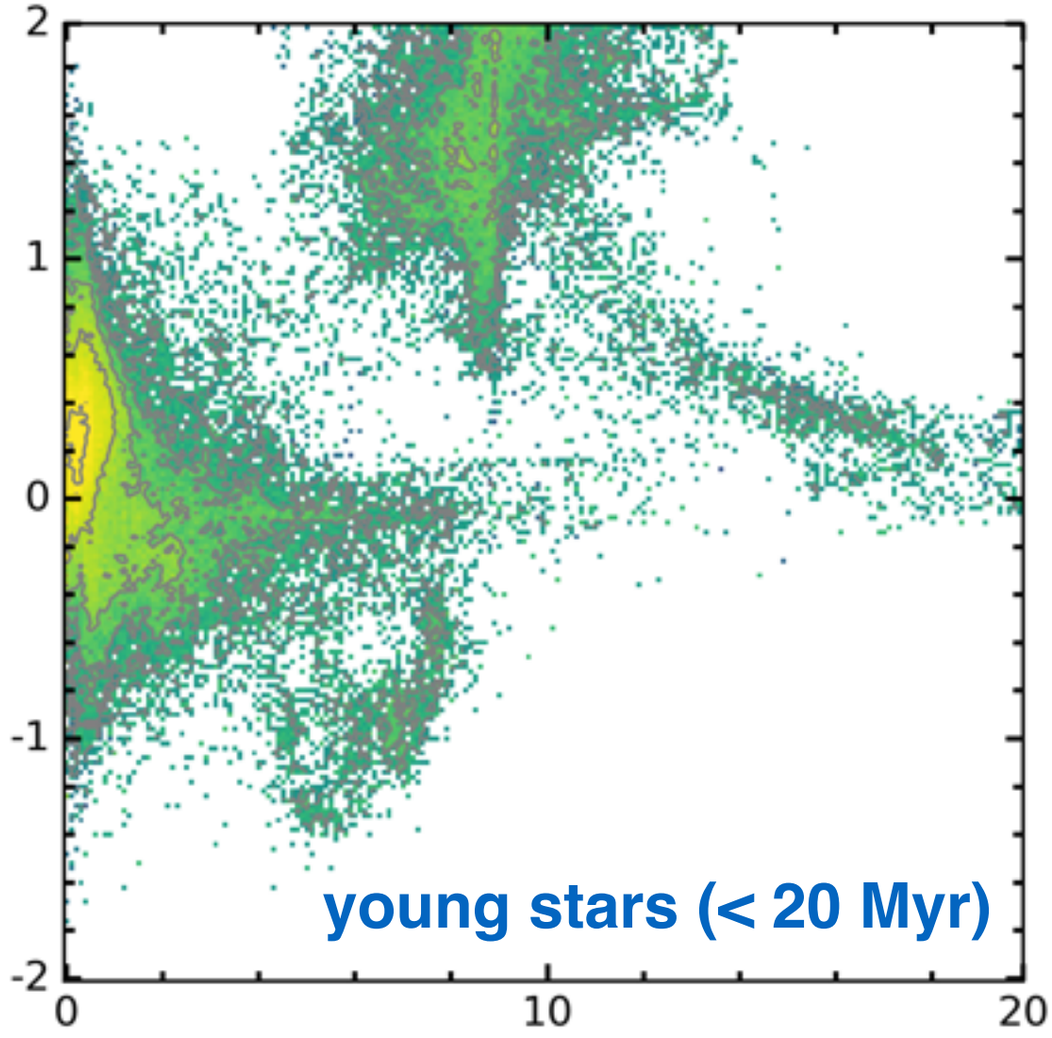
KMOS
V

KMOS
σ



j_z/j_{circ}

z = 1.7



radial distance (kpc)

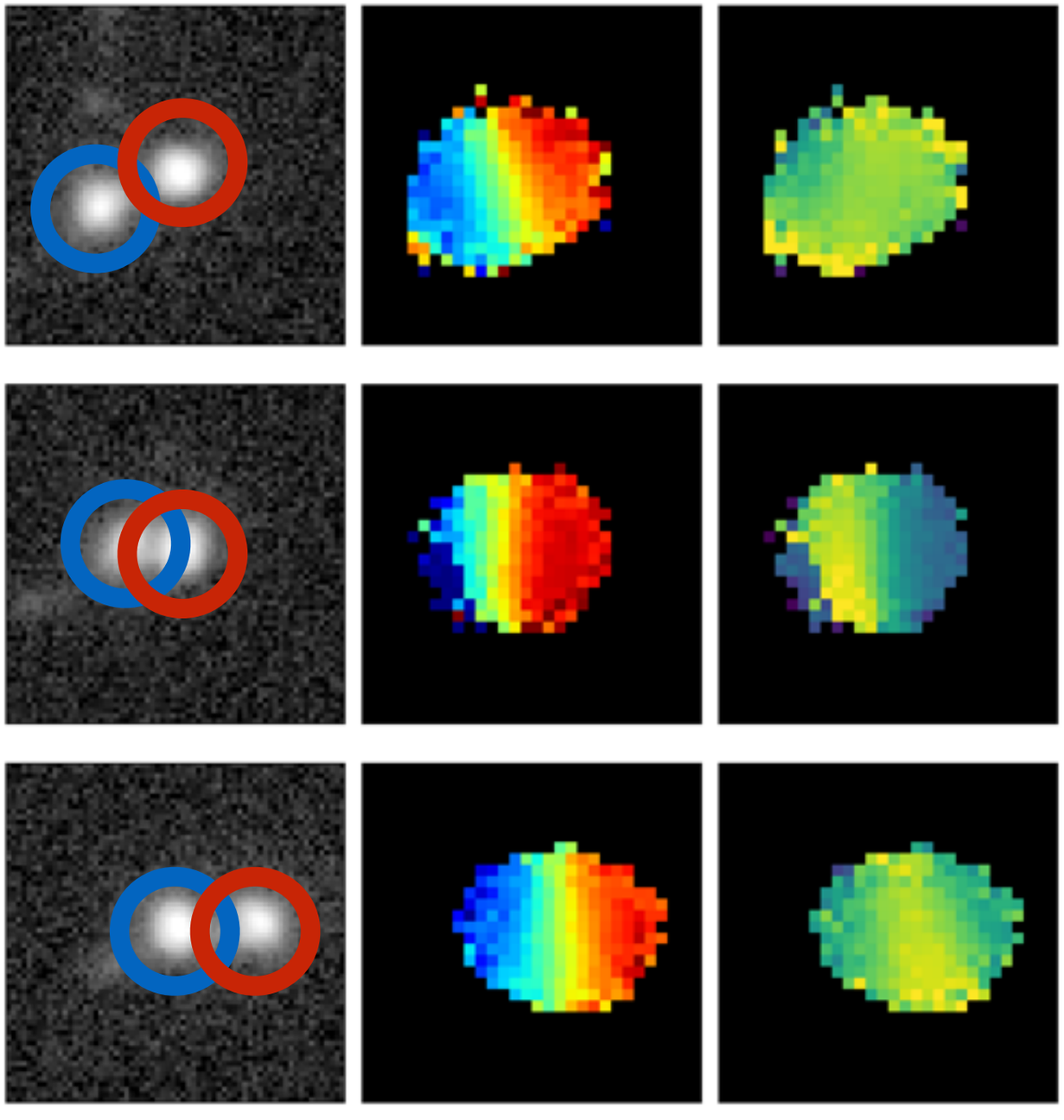
observed

intrinsic

HST
H-band

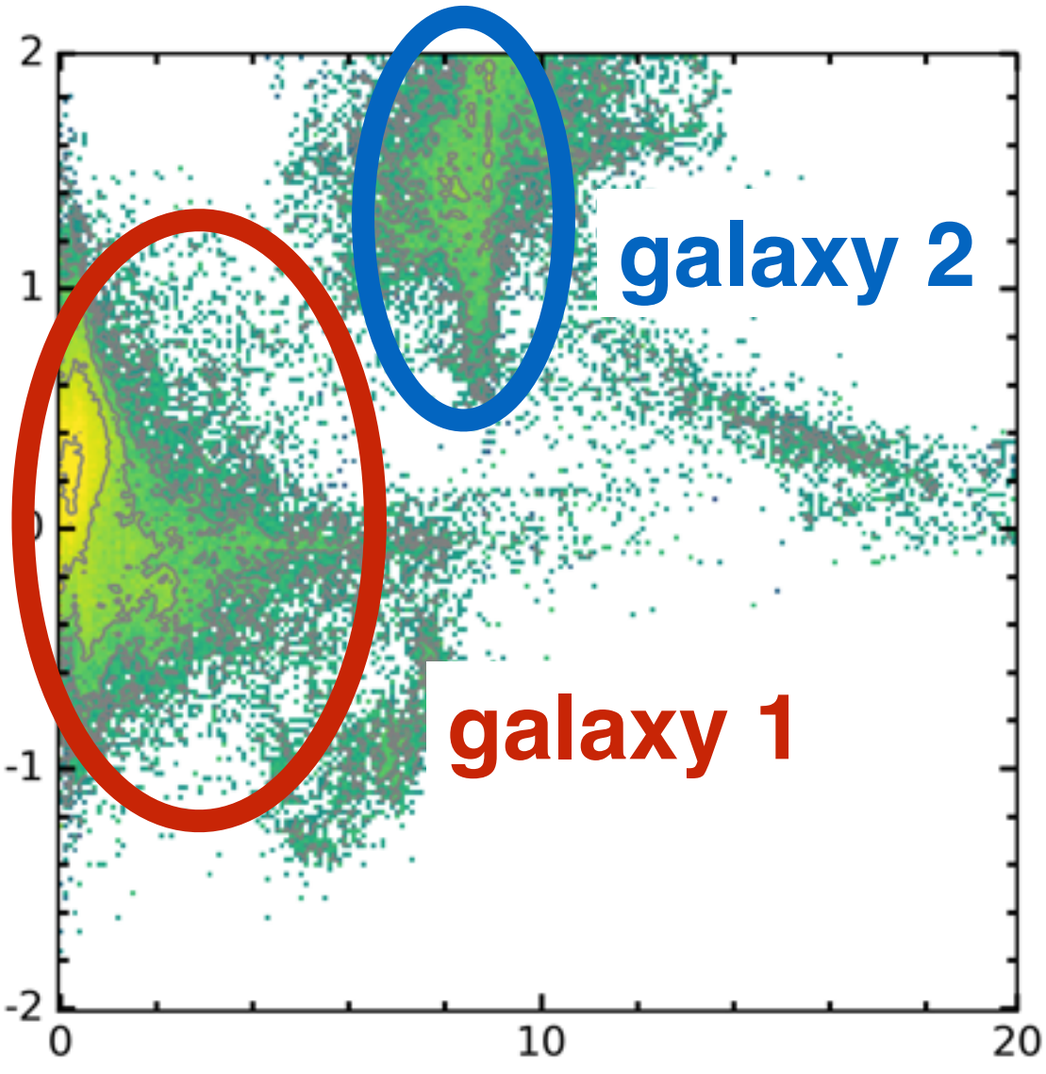
KMOS
V

KMOS
σ



j_z/j_{circ}

z = 1.7



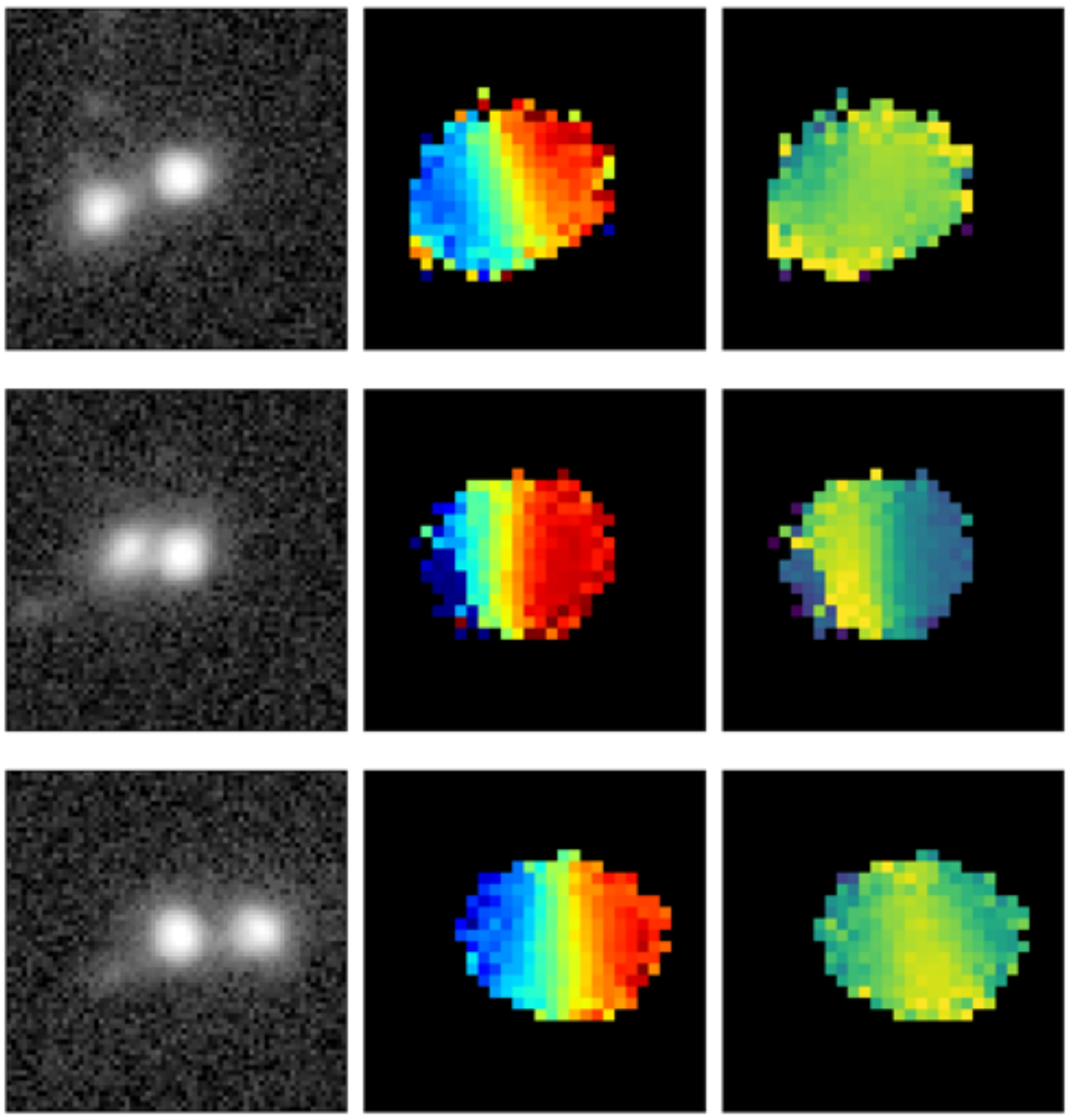
observed

intrinsic

HST
H-band

KMOS
V

KMOS
σ



observed

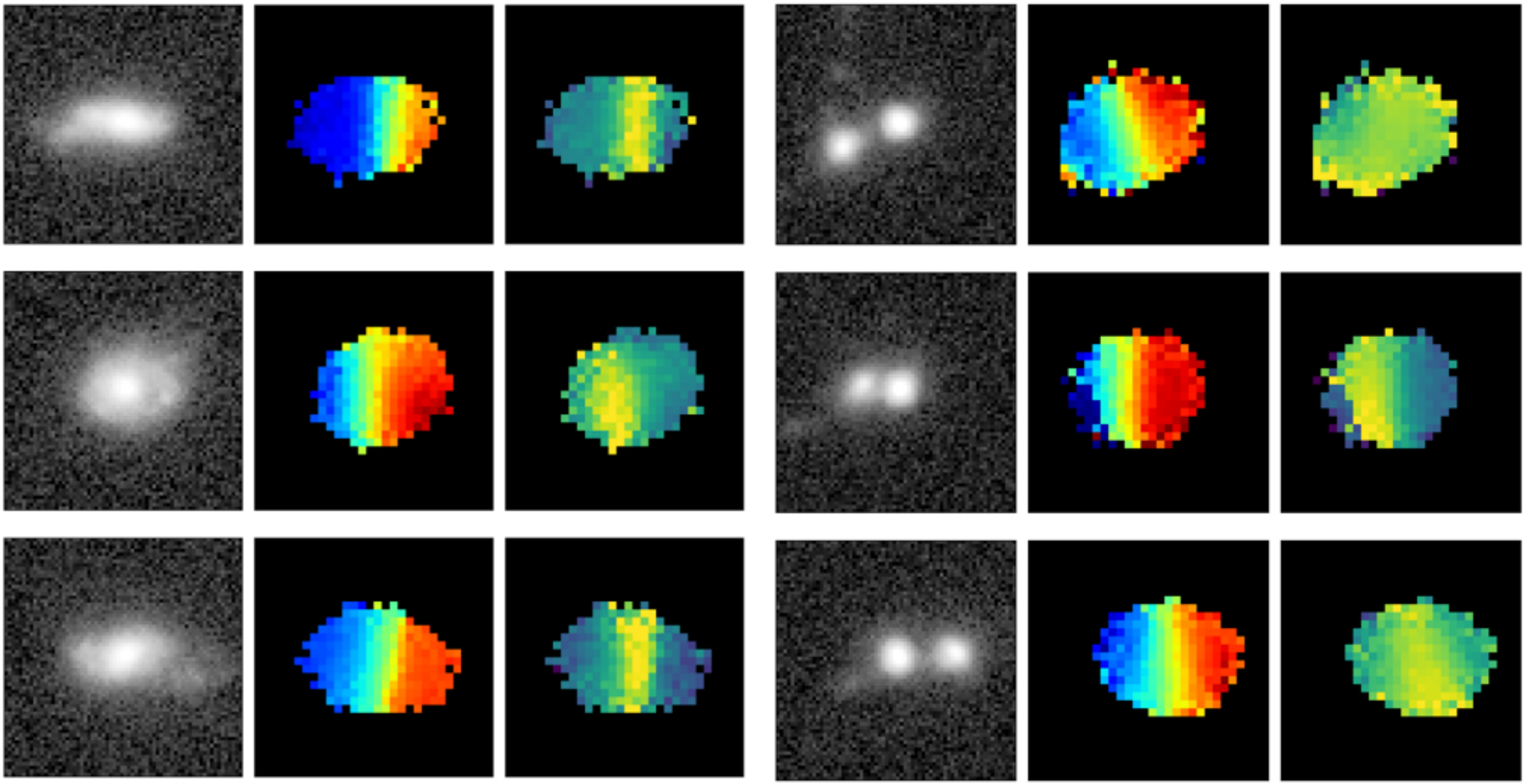
observational disk criteria

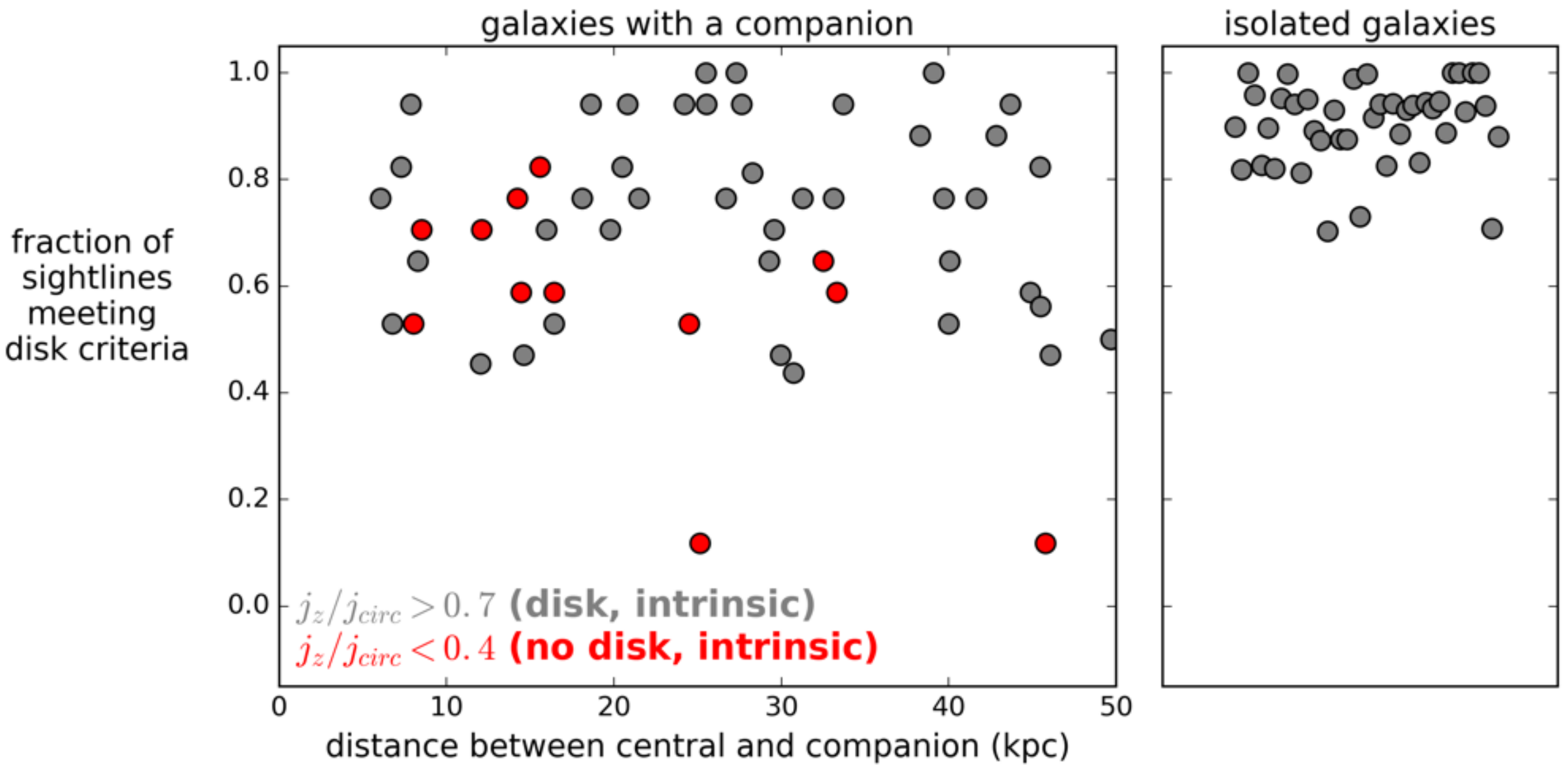
- ✓ continuous velocity gradient
- ✓ central peak in σ_g
- ✓ $V_{rot}/\sigma_g > 1$
- ✓ kinematic and photometric axis aligned

✓

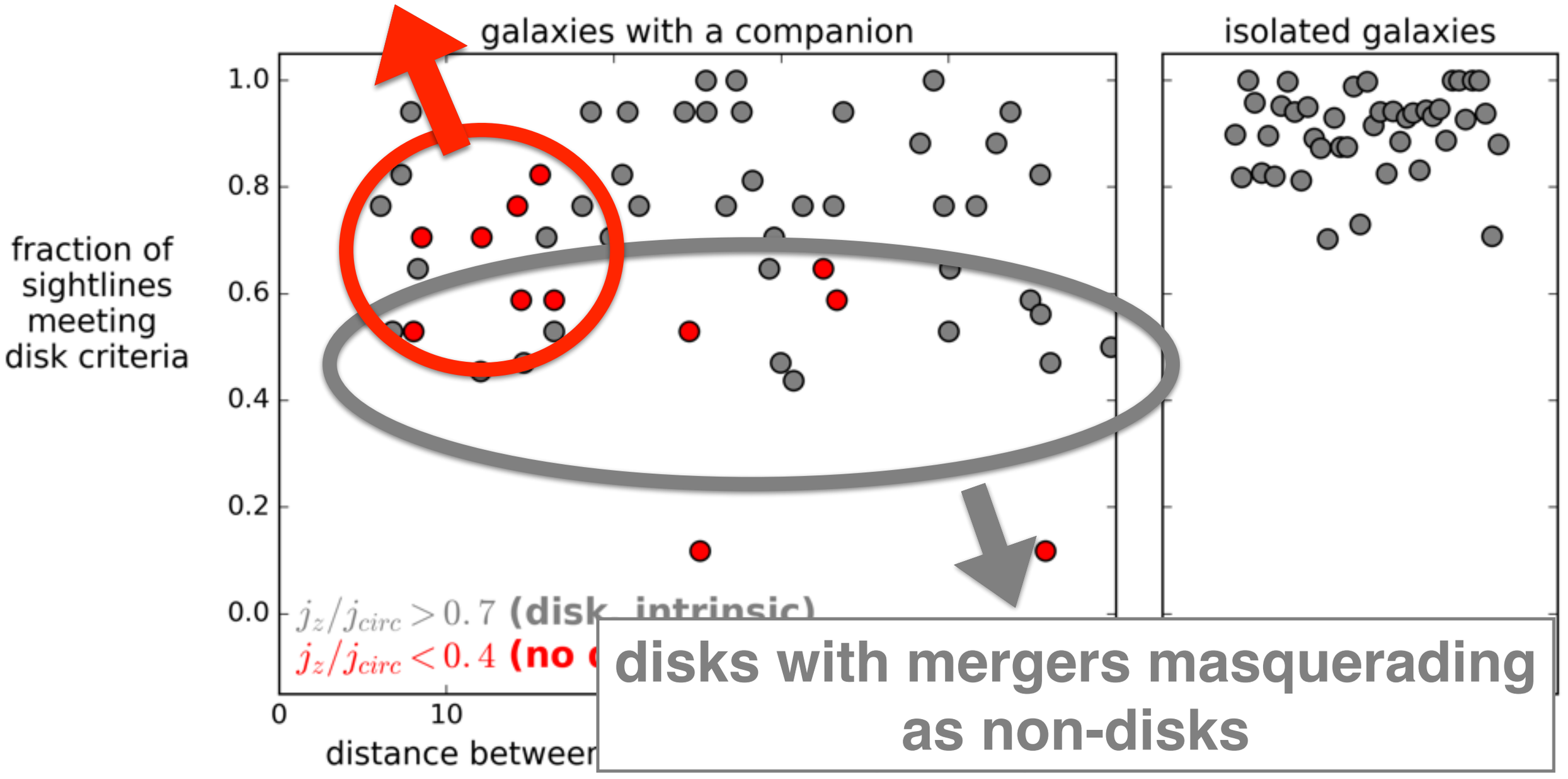
intrinsic disk

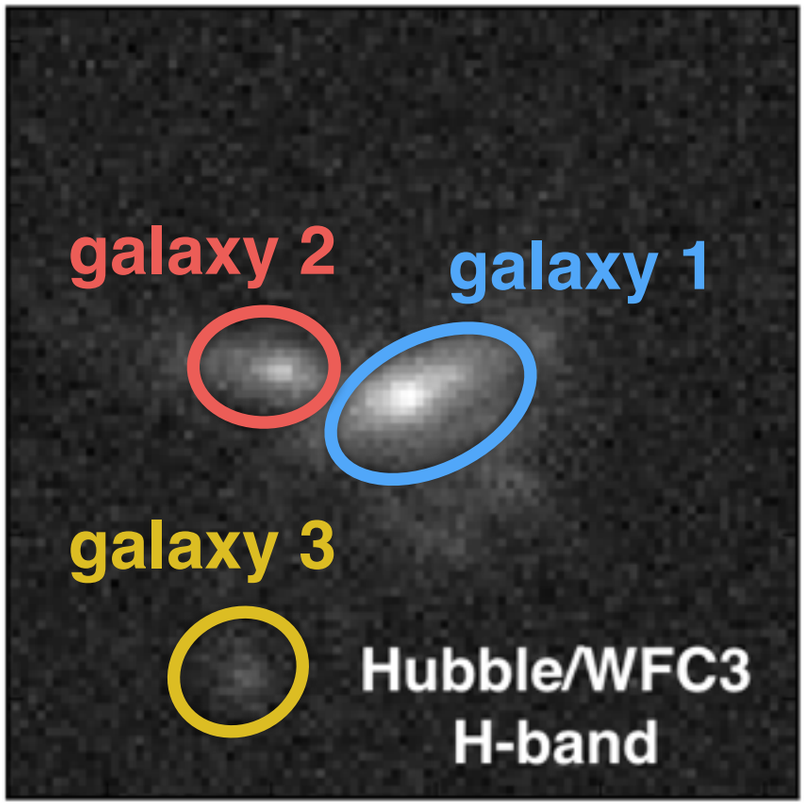
no intrinsic disk

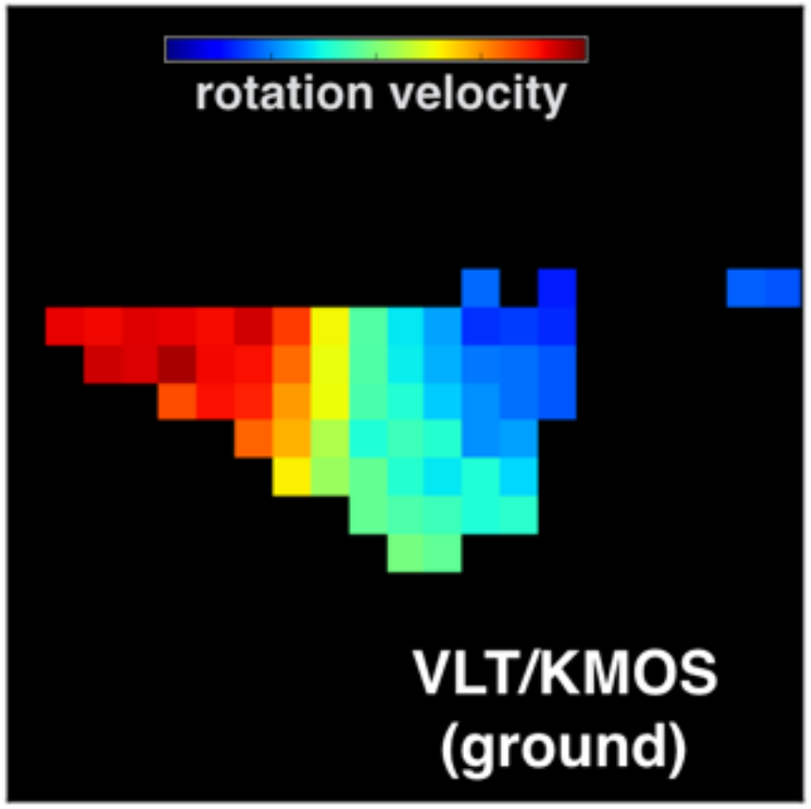


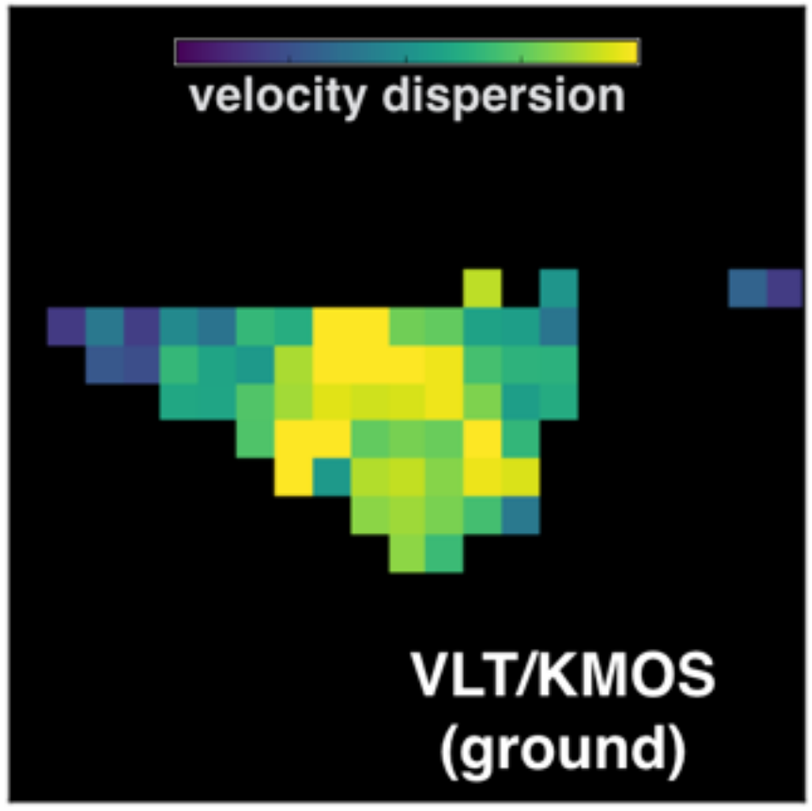

galaxies with a companion
isolated galaxies
fraction of sightlines meeting disk criteria
1.0
0.8
0.6
0.4
0.2
0.0
$j_z/j_{circ} > 0.7$ (disk, intrinsic)
$j_z/j_{circ} < 0.4$ (no disk, intrinsic)
0
10
20
30
40
50
distance between central and companion (kpc)

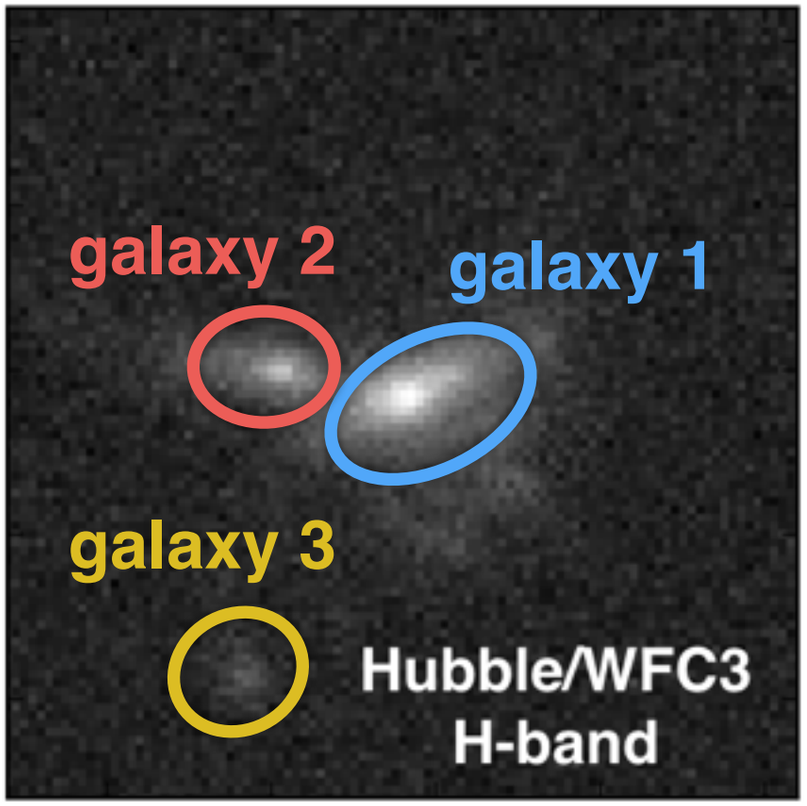
mergers masquerading as disks

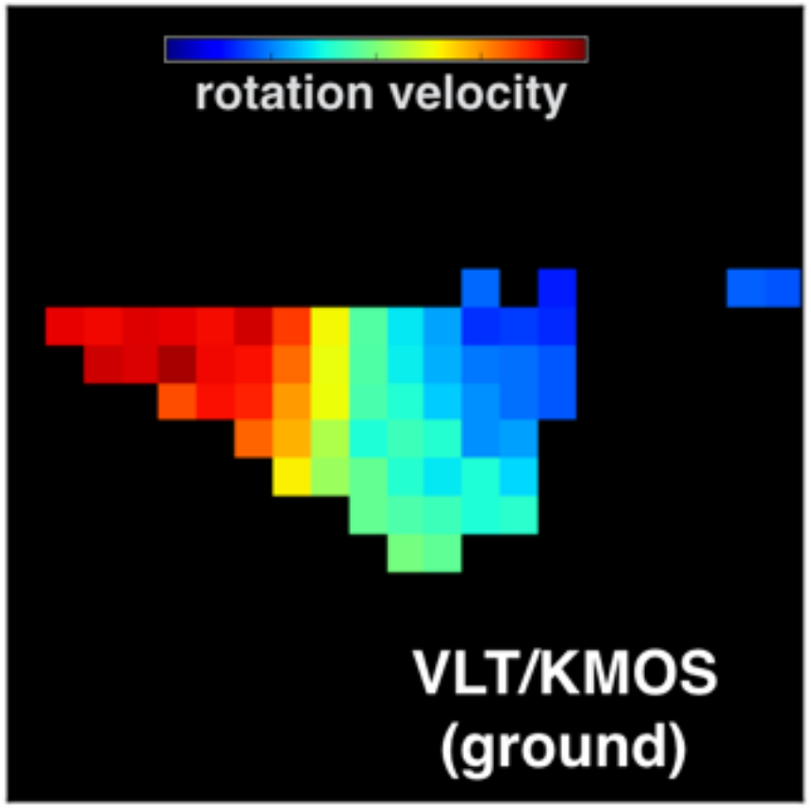


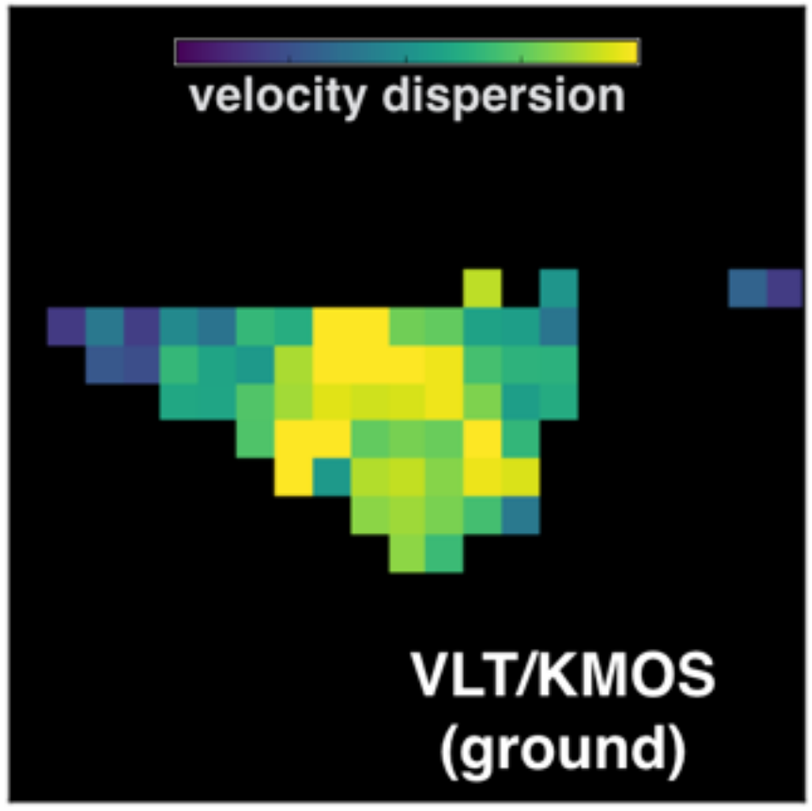

galaxy 2
galaxy 1
galaxy 3
Hubble/WFC3
H-band

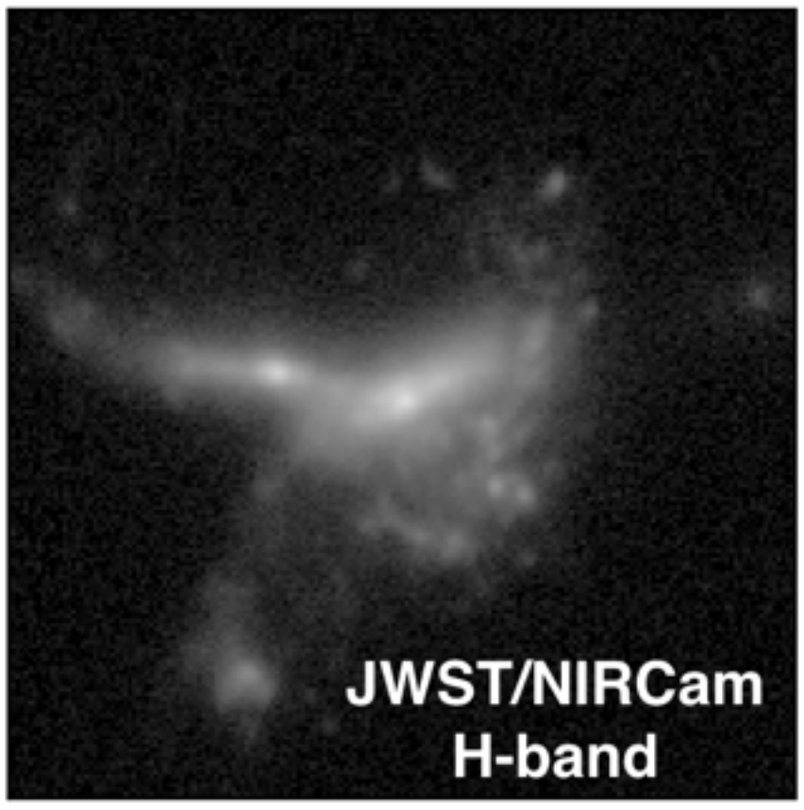

rotation velocity
VLT/KMOS
(ground)

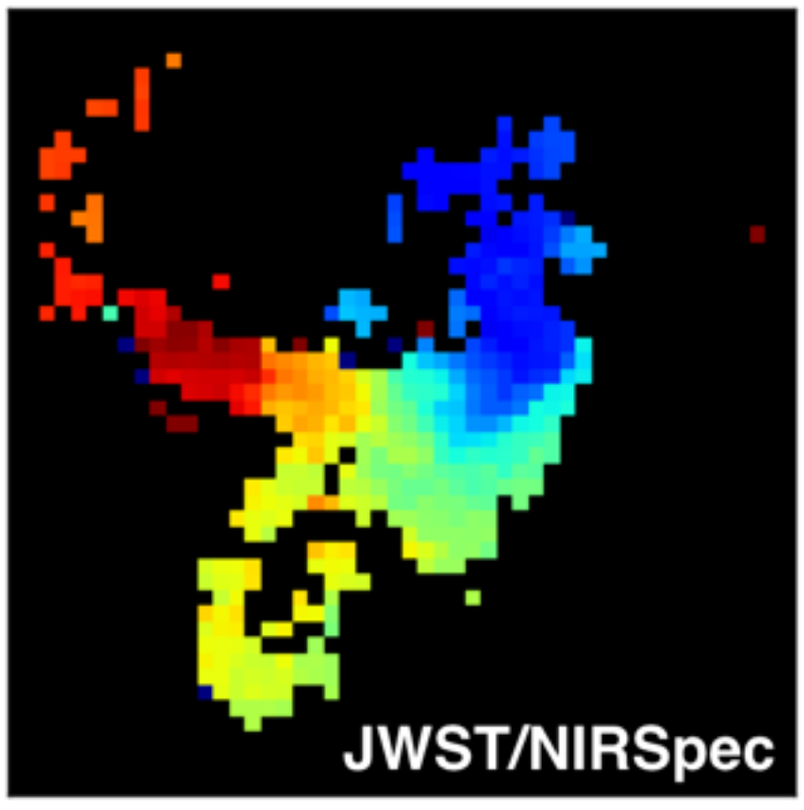

velocity dispersion
VLT/KMOS
(ground)

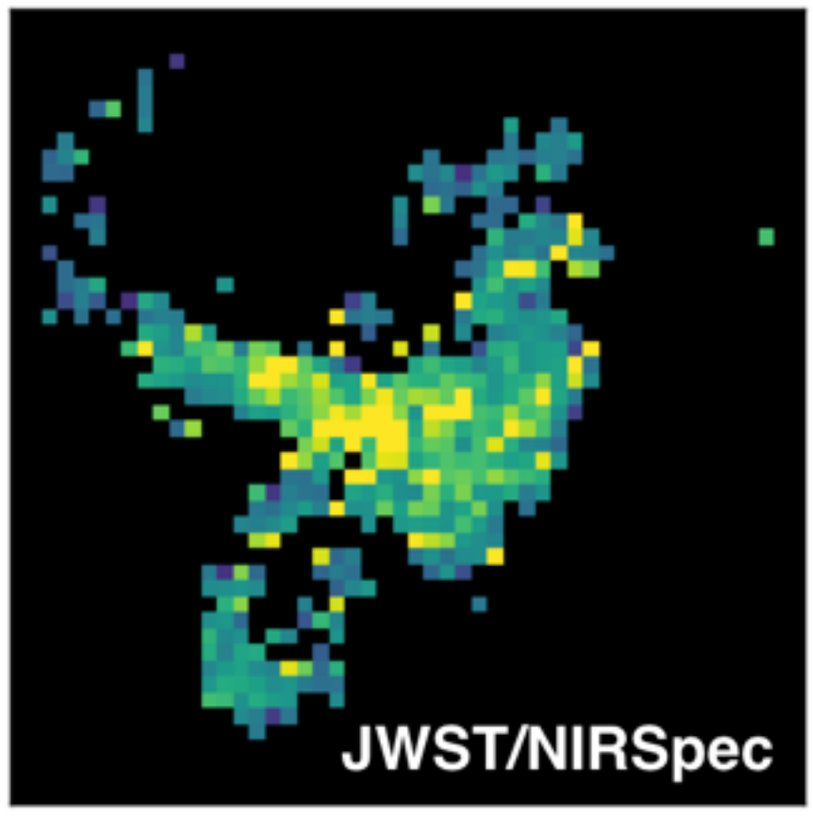

galaxy 2
galaxy 1
galaxy 3
Hubble/WFC3
H-band

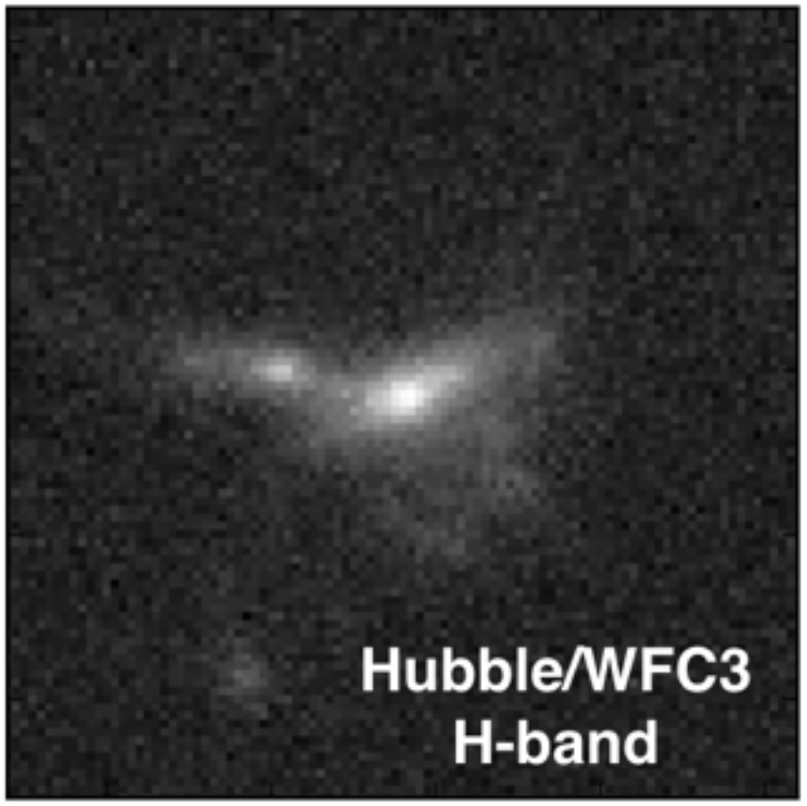

rotation velocity
VLT/KMOS
(ground)

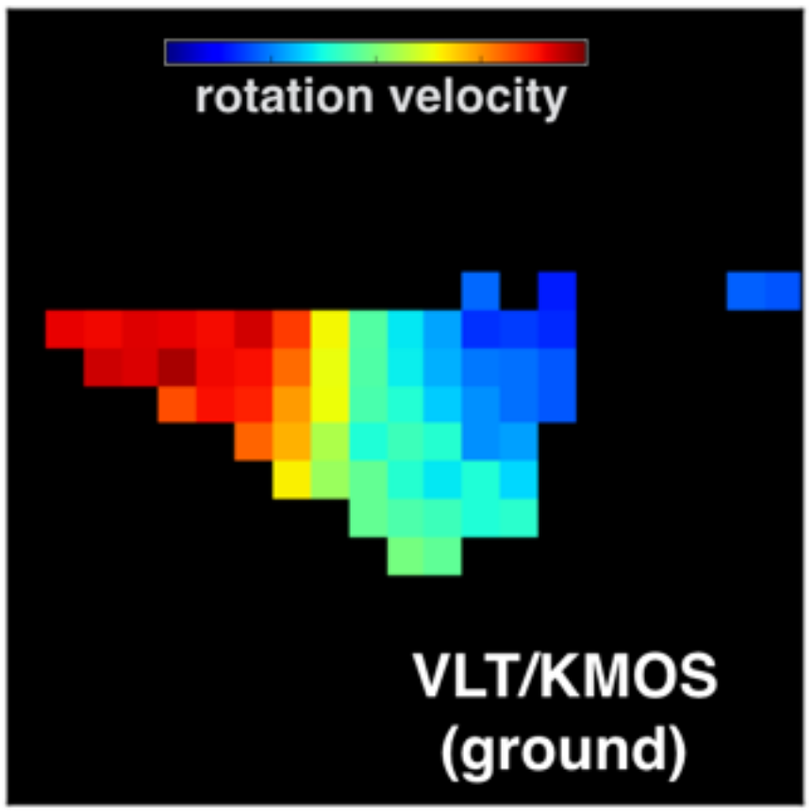

velocity dispersion
VLT/KMOS
(ground)


JWST/NIRCam
H-band

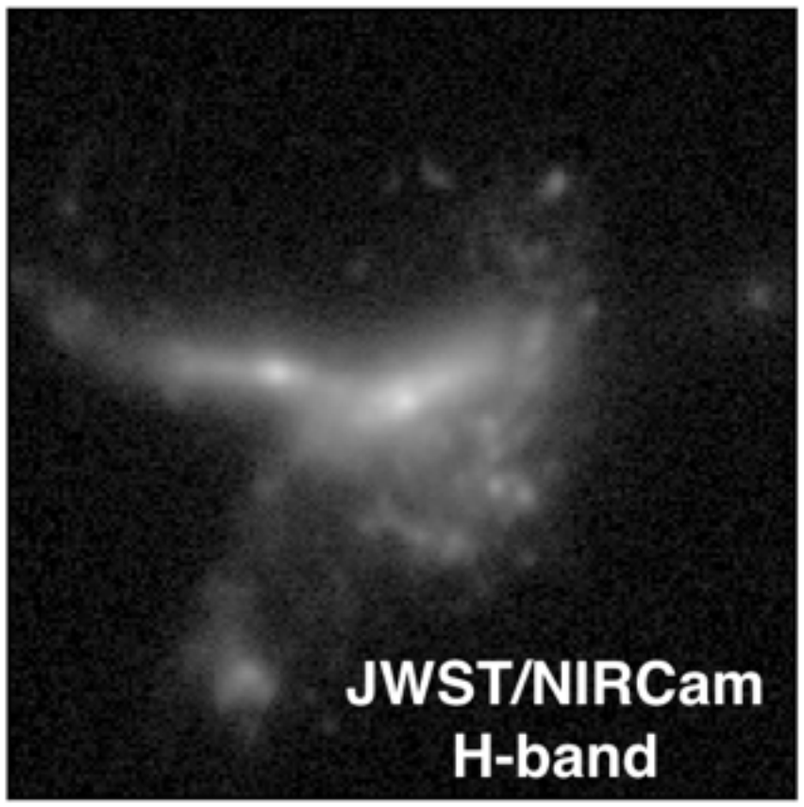

JWST/NIRSpec

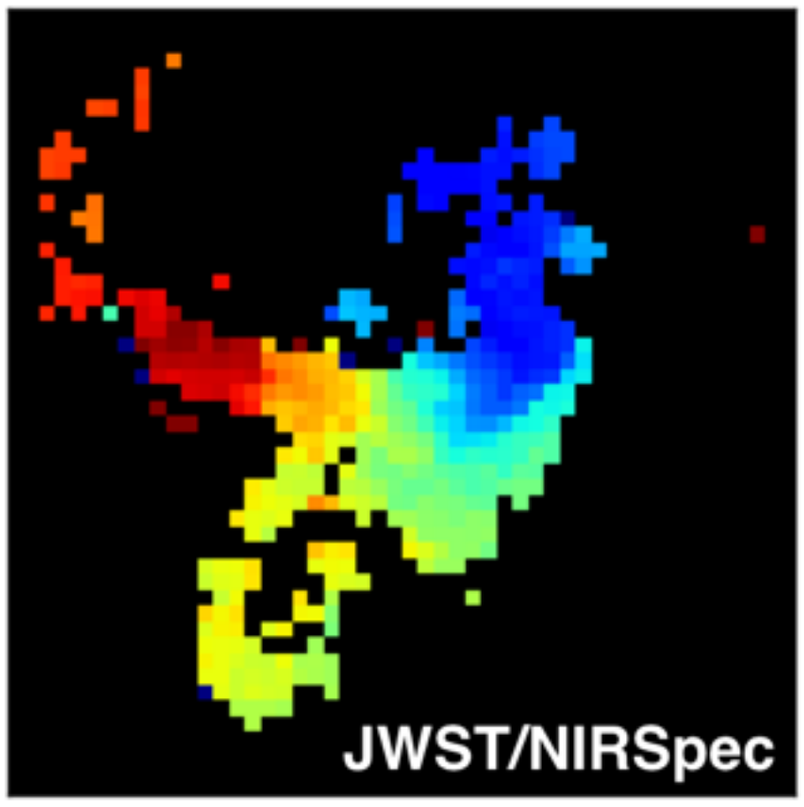

JWST/NIRSpec





single kinematic axis





complex
3 kinematic axes

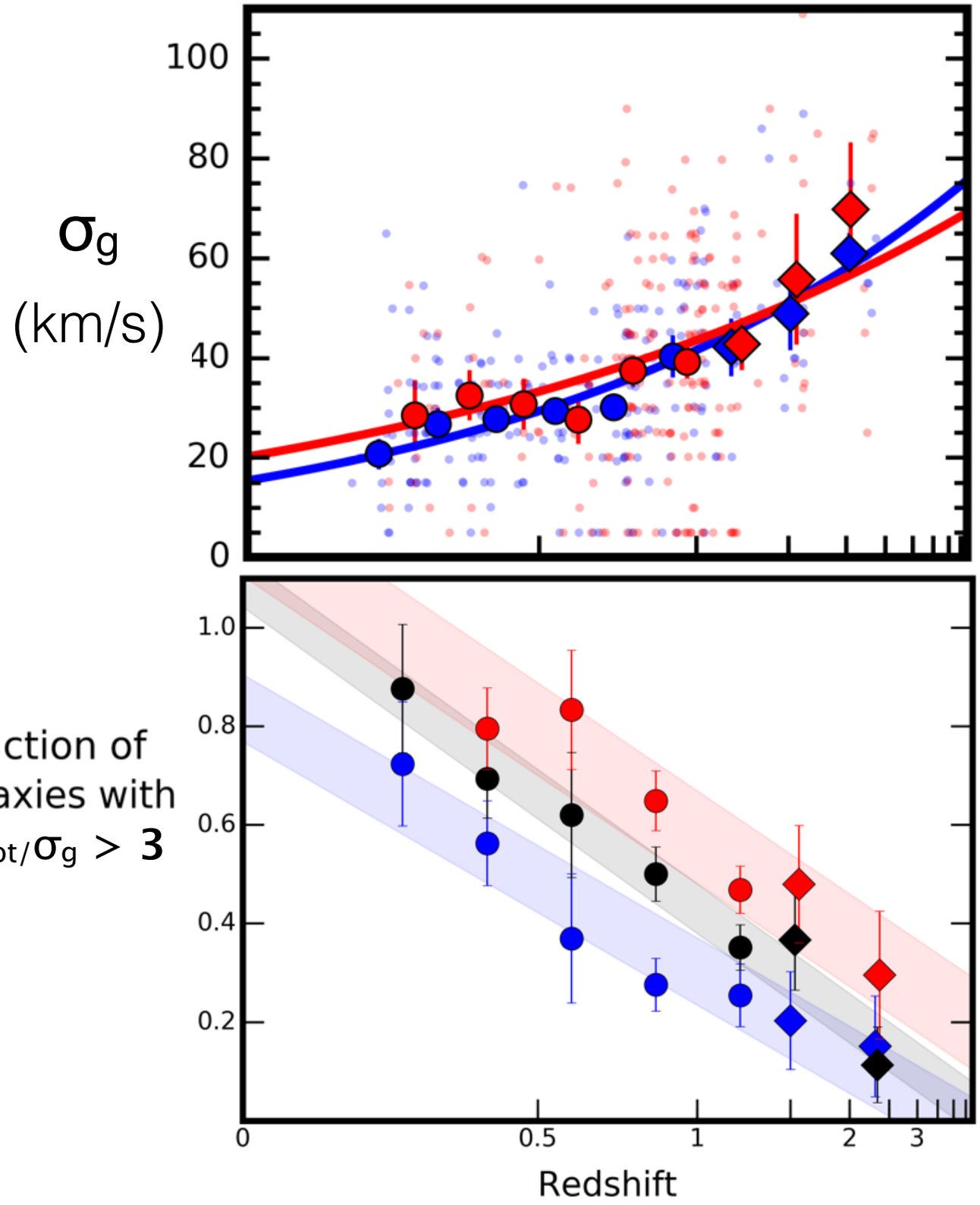
Summary

Observations of the motion of gas in **star-forming** galaxies indicate a:

- Shortage of well-ordered disks ($V_{rot}/\sigma_g > 3$) at z~2: epoch of "disk assembly".

- Build up of ordered gas disks through a mild increase in V_{rot} and dramatic decline in σ_g (factor of x3 since z~2), on average.

- happens first in high mass galaxies out to z~2 => "kinematic downsizing".



Typical global kinematics measurements, i.e. V_{rot}, σ_g, will underserve the rich details available in JWST/NIRSpec maps

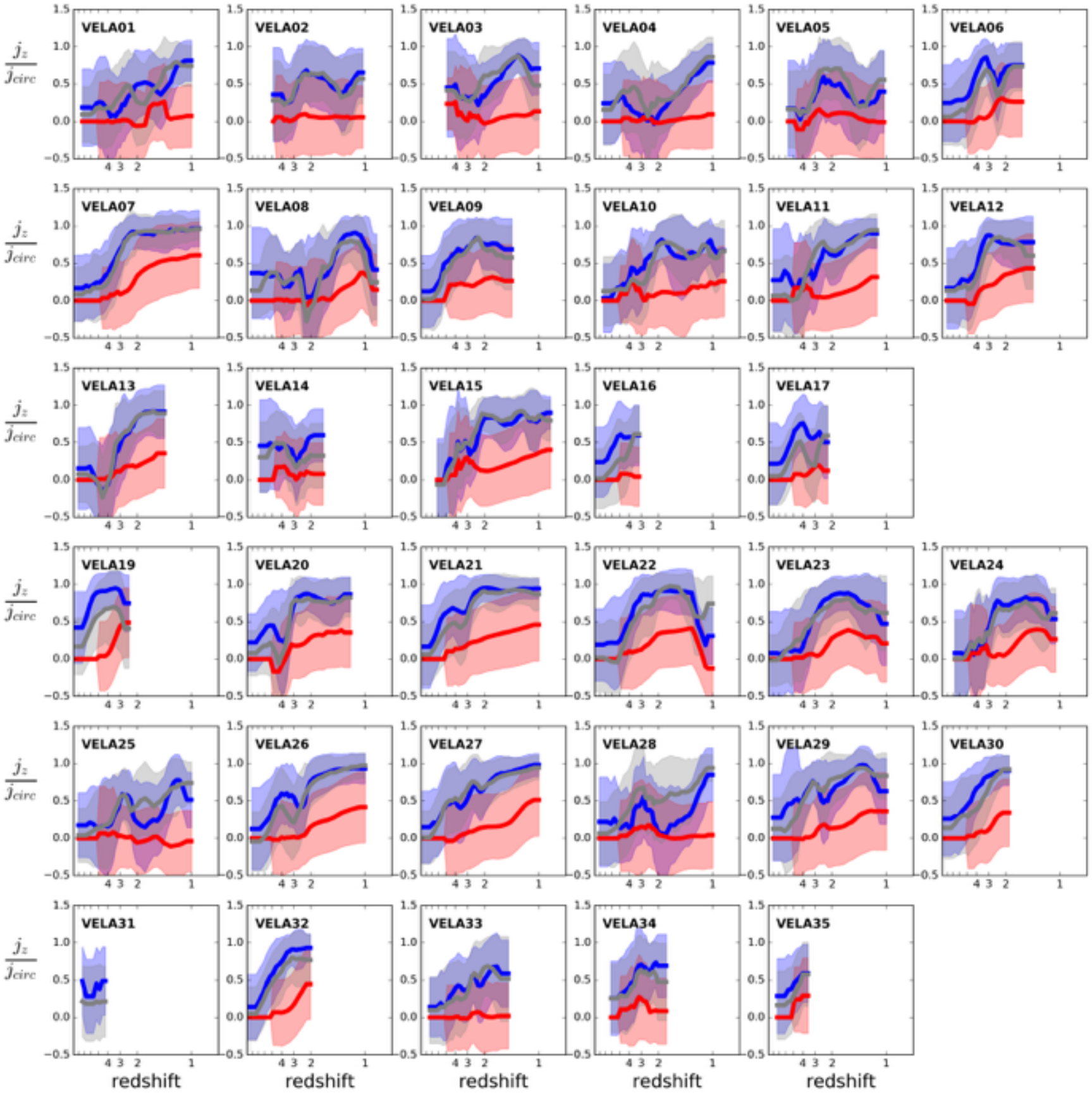
young stars
(age < 20 Myr)

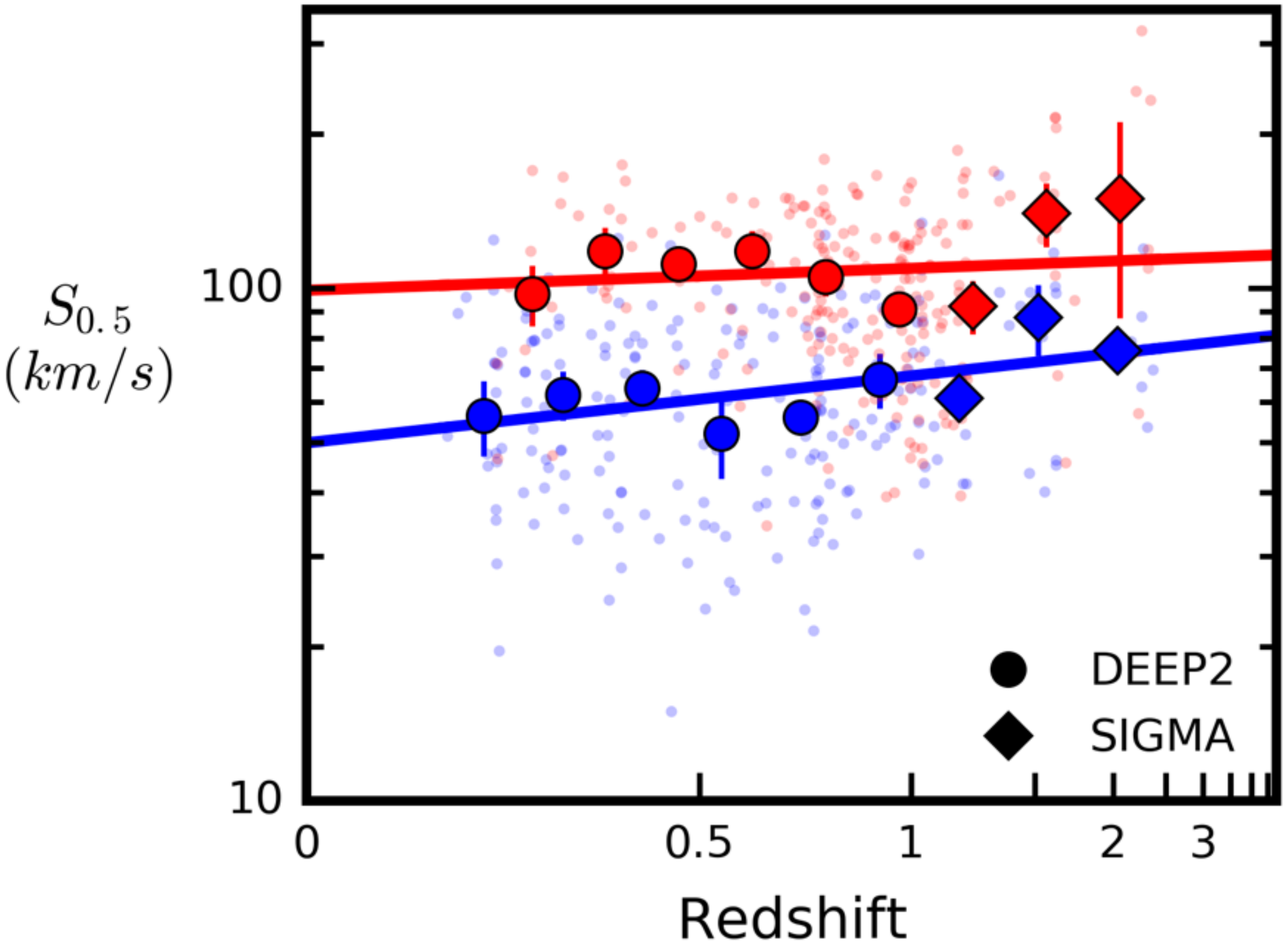
z = 1.5

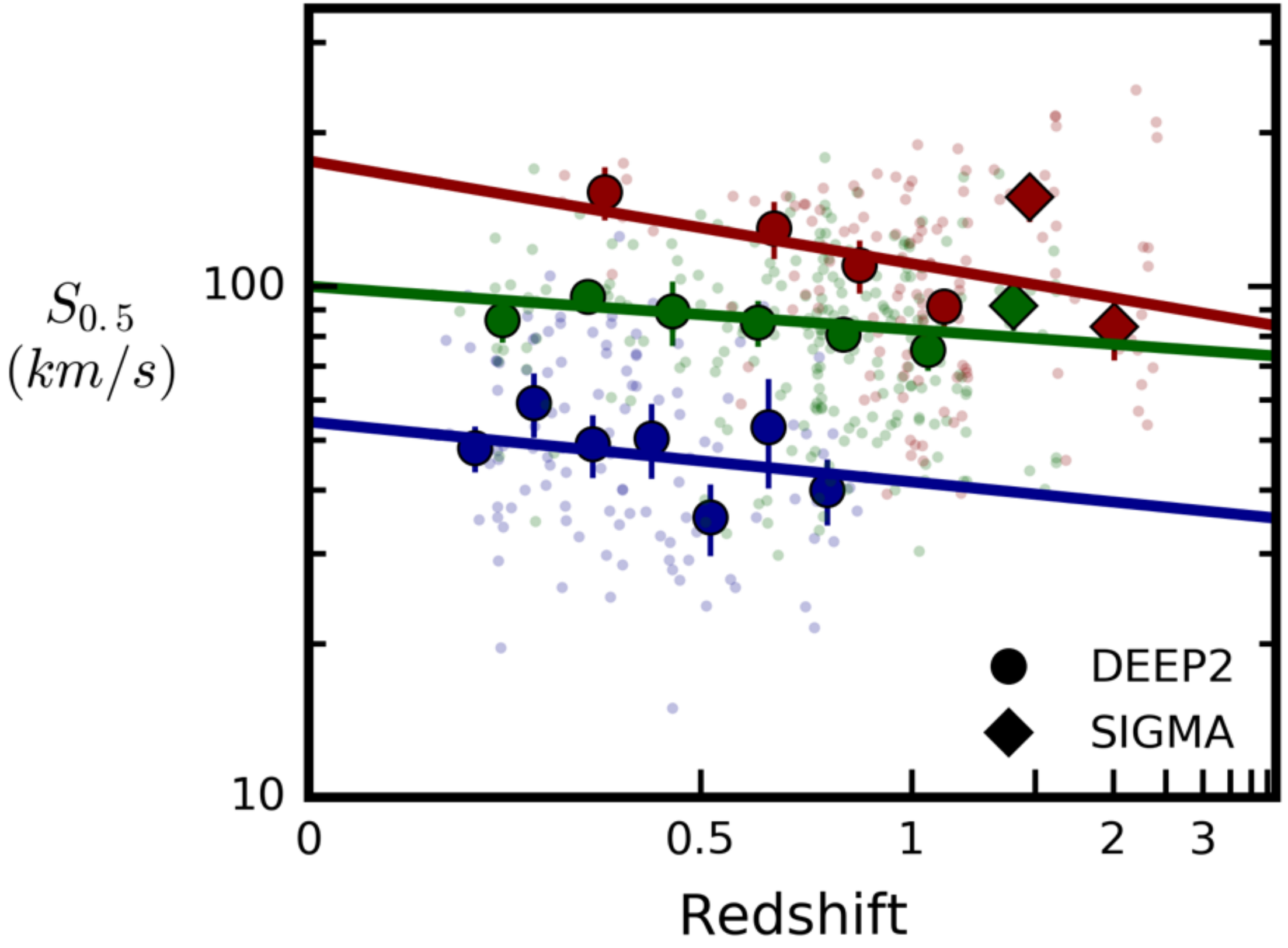
10 kpc

backup slides

Cold gas
Young Stars (< 20 Myr)
Old Stars (> 1 Gyr)




$S_{0.5}$
(km/s)
100
10
0
0.5
1
2
3
Redshift
DEEP2
SIGMA


$S_{0.5}$
(km/s)
100
10
0
0.5
1
2
3
Redshift
DEEP2
SIGMA