

SINS

SINFONI GTO science program on high redshift galaxies

*MPE-IR/Submm Group, USM/MPE Group, NOVA Group
and collaborations*

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Galaxy Formation and Evolution

Open issues...

- Angular momentum?
- Baryonic mass accretion?
- Inside-out?
- Connection between bulge and disk formation?
- Timescales?
- Star formation efficiency?
- Evolution as function of mass?
- Dissipation?
- Feedback? Environment?
- Relation between DM and baryons?
- Where do observed populations fit?

SINS

Survey of $z \sim 1 - 4$ galaxy populations from NIR integral field spectroscopy with SINFONI @ VLT

- spatially resolved kinematics, morphologies, metallicities, ionization
- dynamical masses, dynamical timescales, angular momentum
- evolution of dynamics, star formation, metallicity
- relationships between various high redshift samples
- role of feedback, role of environmental effects

To date: ~ 50 objects (BM/BX, BzK , K bright, LBGs, SMGs, ...)

SINFONI at the VLT

SPIFFI

(MPE/NOVA/ESO, P.I. F. Eisenhauer)

- Cryogenic integral field spectrometer with reflective image slicer
- HAWAII 2RG 2k² detector
- 3 pixel scales: 25, 100, 250 mas
FOVs 0.8"×0.8", 3.2"×3.2", 8"×8"
- 4 gratings: *J, H, K, H+K*
 $R \sim 2000 - 4500$
- Total throughput $\sim 30\%$



MACAO

(ESO, P.I. H. Bonnet)

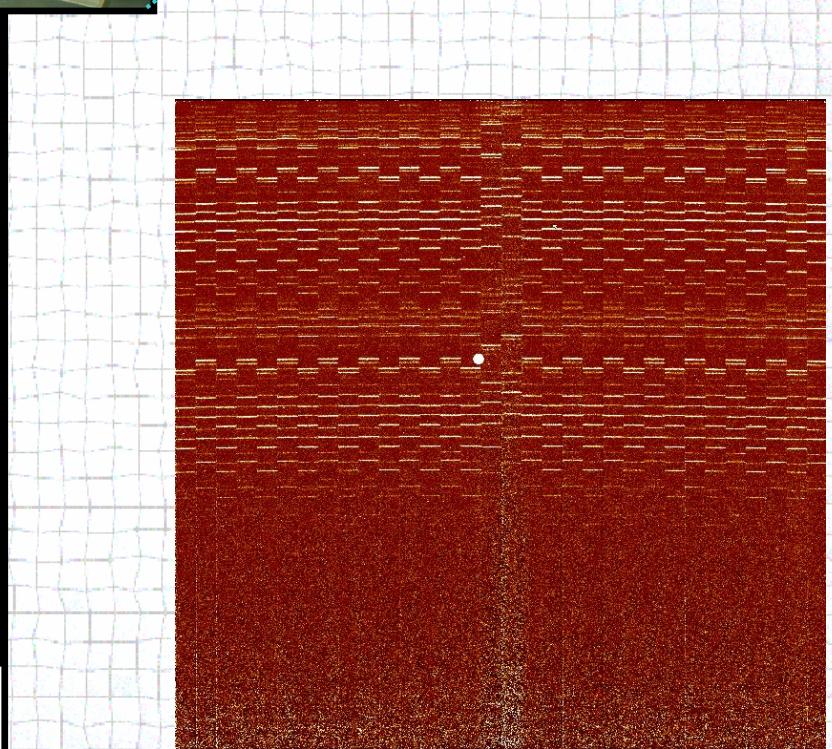
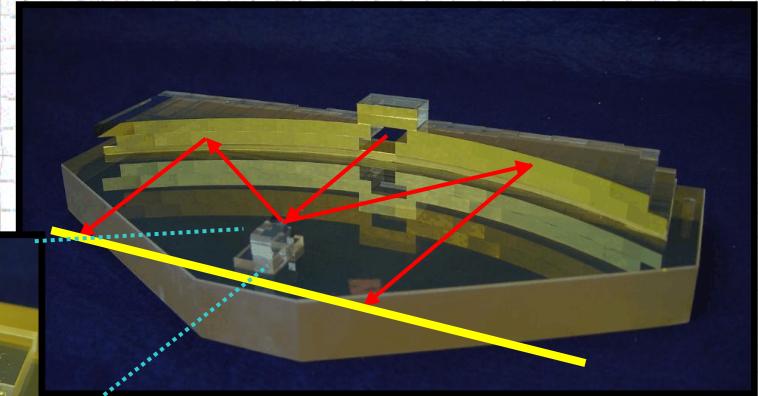
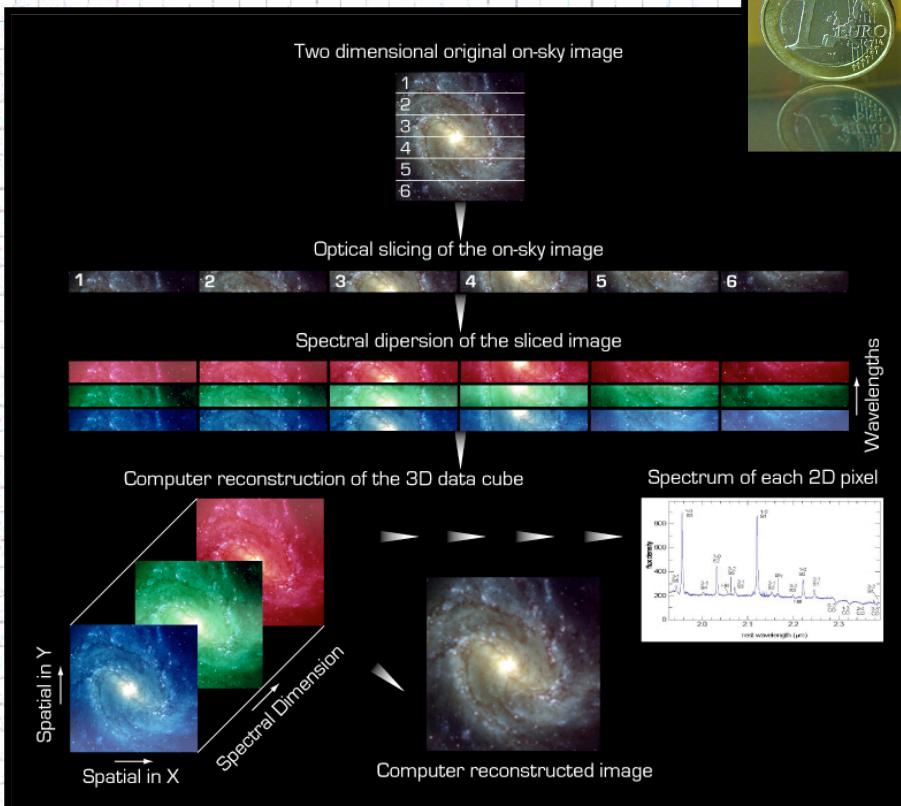
- 60-element curvature sensor AO system / bimorph mirror with APDs
- Natural & Laser Guide Star operations, seeing-limited mode



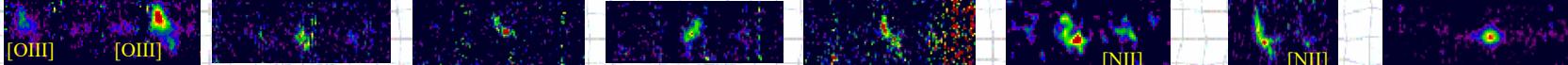
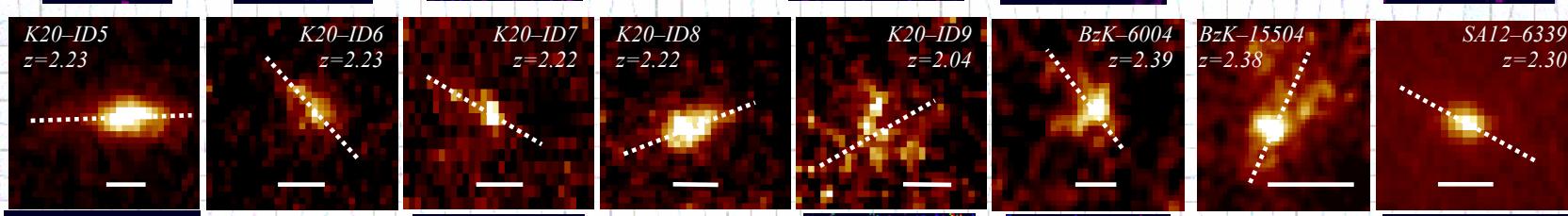
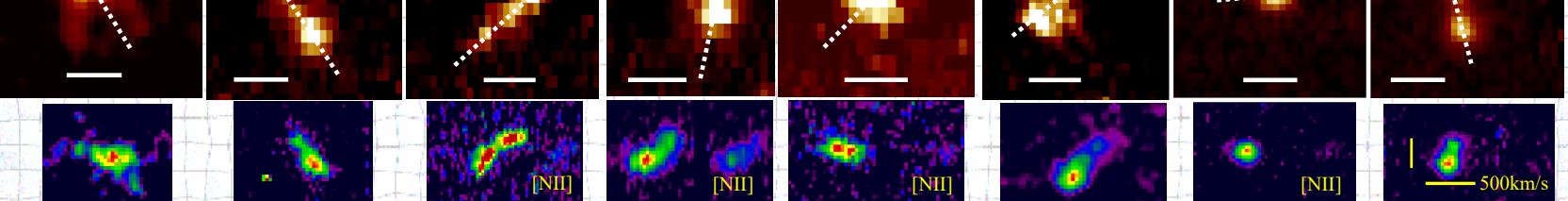
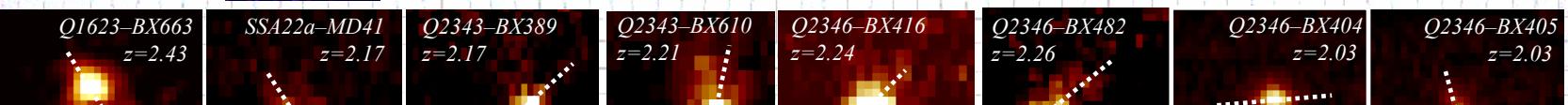
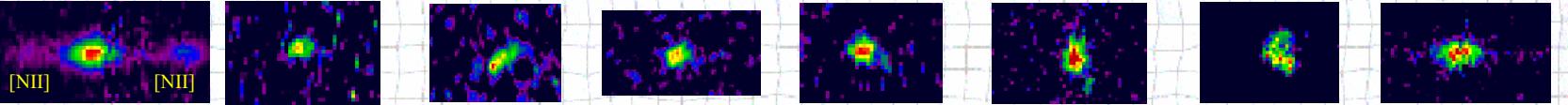
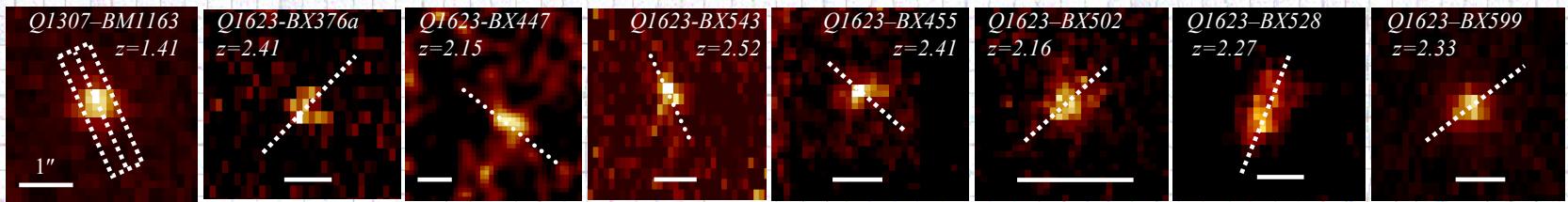
Eisenhauer et al. (2003) Bonnet et al. (2004)

ESO PR 24b/04

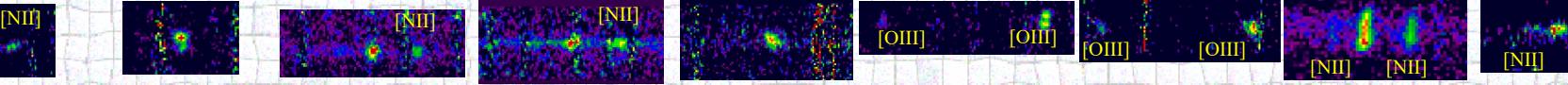
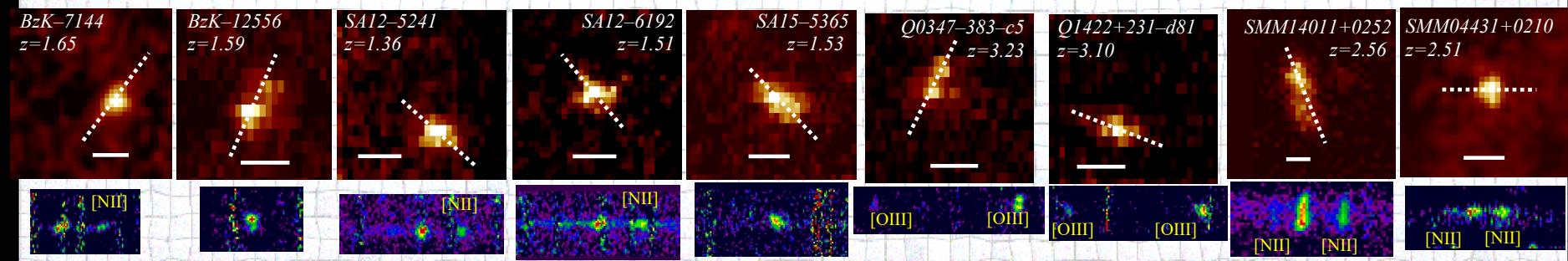
SPIFFI: 3D principle



The Principle of Integrated Field Spectroscopy (IFS)



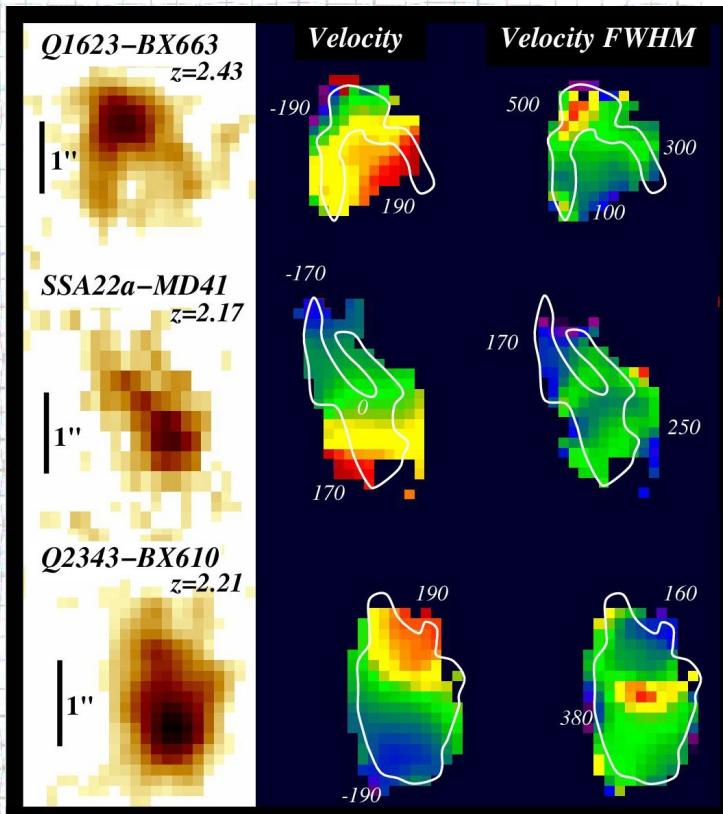
Top row: Q1307-BM1163 ($z=1.41$), Q1623-BX376a ($z=2.41$), Q1623-BX447 ($z=2.15$), Q1623-BX543 ($z=2.52$), Q1623-BX455 ($z=2.41$), Q1623-BX502 ($z=2.16$), Q1623-BX528 ($z=2.27$), Q1623-BX599 ($z=2.33$).
Second row: [NII] maps for the same eight quasars.
Third row: Q1623-BX663 ($z=2.43$), SSA22a-MD41 ($z=2.17$), Q2343-BX389 ($z=2.17$), Q2343-BX610 ($z=2.21$), Q2346-BX416 ($z=2.24$), Q2346-BX482 ($z=2.26$), Q2346-BX404 ($z=2.03$), Q2346-BX405 ($z=2.03$).
Fourth row: [NII] maps for the same eight quasars. A scale bar of 500 km/s is shown in the bottom right panel.
Fifth row: K20-ID5 ($z=2.23$), K20-ID6 ($z=2.23$), K20-ID7 ($z=2.22$), K20-ID8 ($z=2.22$), K20-ID9 ($z=2.04$), BzK-6004 ($z=2.39$), BzK-15504 ($z=2.38$), SA12-6339 ($z=2.30$).
Sixth row: [OIII] maps for the same eight quasars.



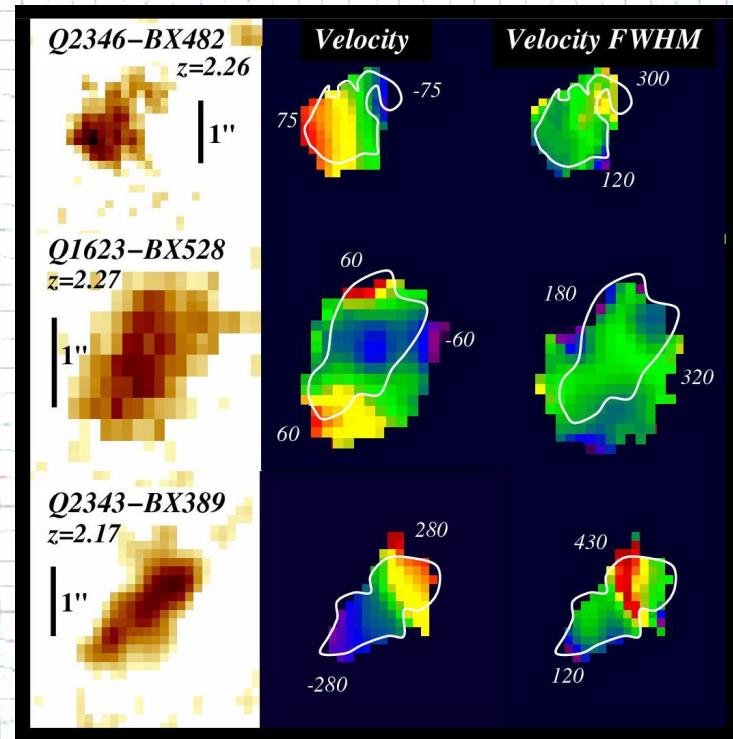
2D kinematics with SINFONI

Orbital motions at $z \sim 2$

BX galaxies



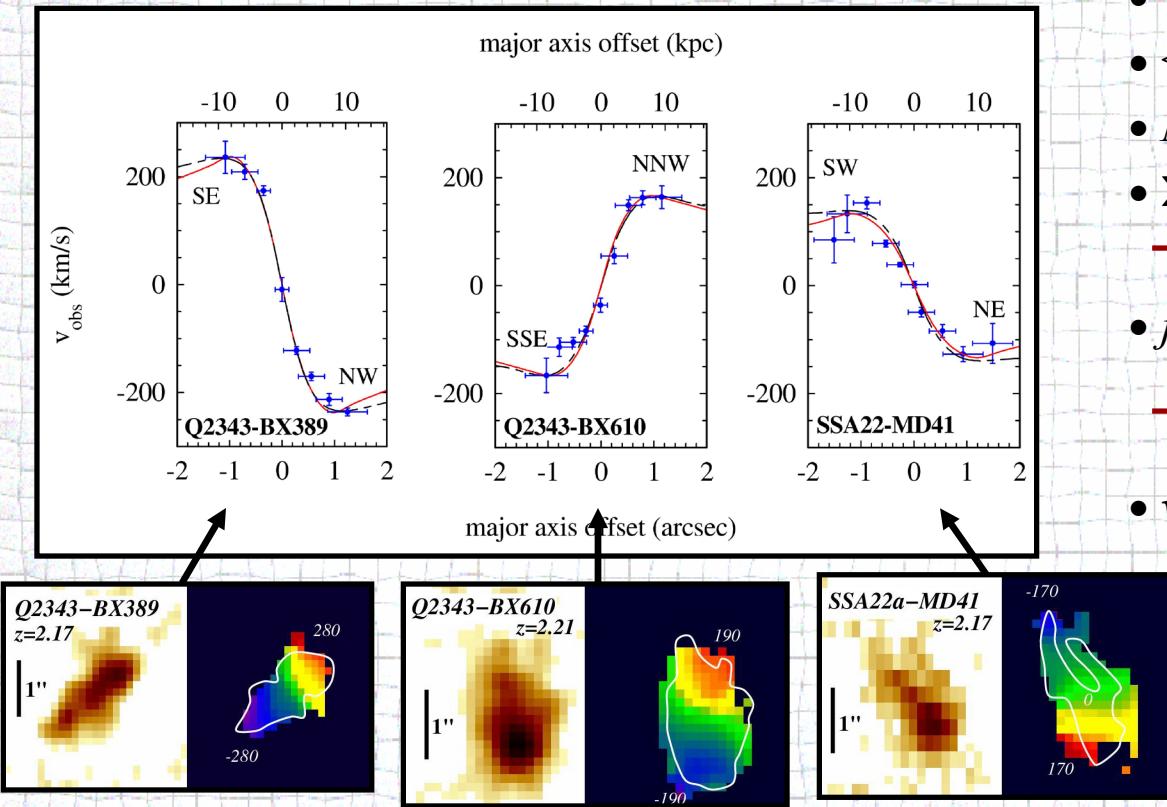
$\text{FWHM} \sim 0.5'' - 0.6'' \rightarrow \sim 4.5 \text{ kpc}$



Förster Schreiber et al. (2006)
(SINFONI sample drawn from Erb et al. 2006)

Properties of SINFONI BX sample

Rotation curves to $r \sim 10$ kpc at $z \sim 2$

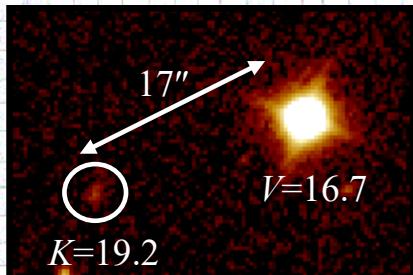


Förster Schreiber et al. (2006)

15 BX galaxies at $z \sim 2.2$

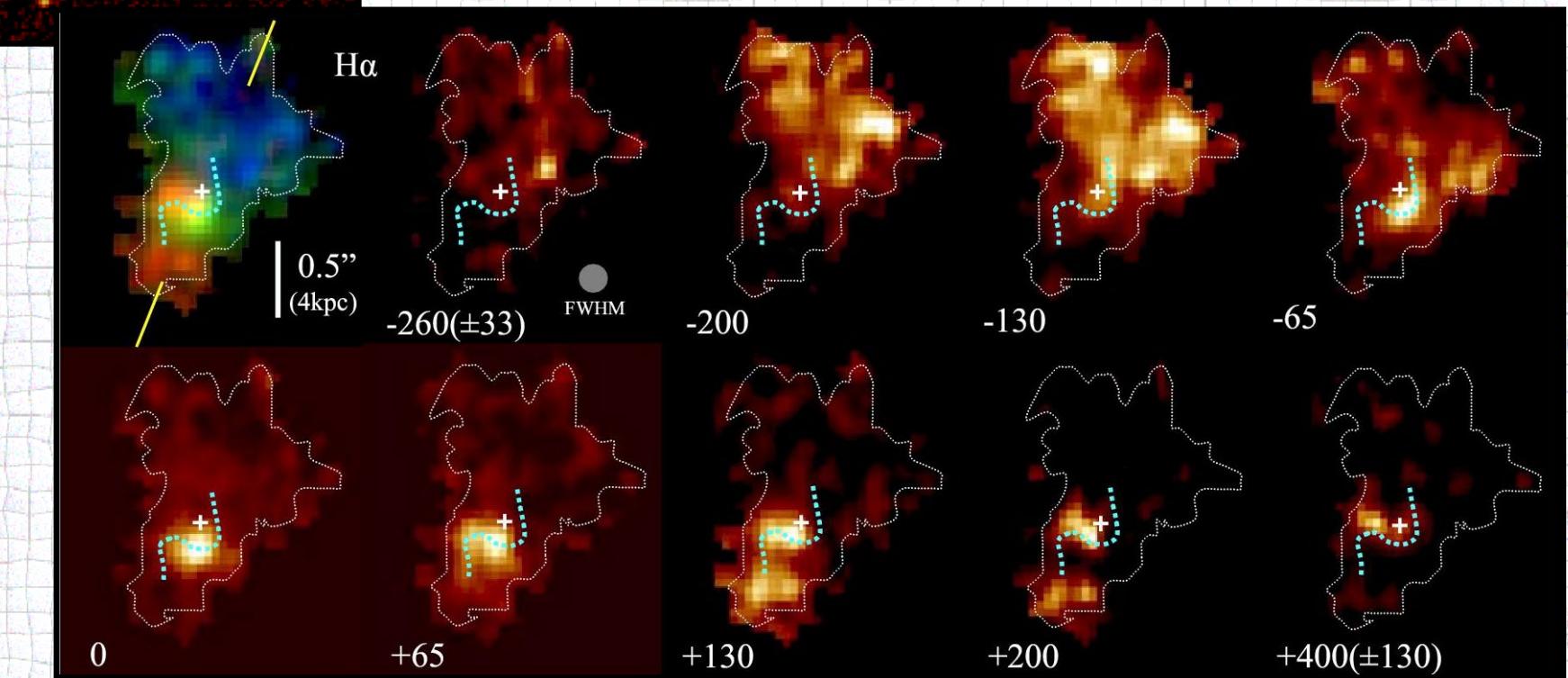
- $\langle v_c \rangle = 180 \pm 90 \text{ km s}^{-1}$
- $\langle r_{1/2} \rangle = 4.4 \text{ kpc}$ (range: 2–7 kpc)
- $M_{\text{dyn}} \sim (0.5 - 25) \times 10^{10} M_\odot$
- $\Sigma_{\text{dyn}} \sim 10^3 M_\odot \text{ pc}^{-2}$
- $j \sim 10^3 \text{ km s}^{-1} \text{ kpc}$ → *local late-type spirals*
- $v_c/\sigma \sim 2-4$ → *rapid accretion/gas exhaustion*
- $v_c/\sigma \sim 2-4$ → *gas-rich*

2D kinematics with SINFONI+AO



$BzK-15504$ at $z = 2.38$

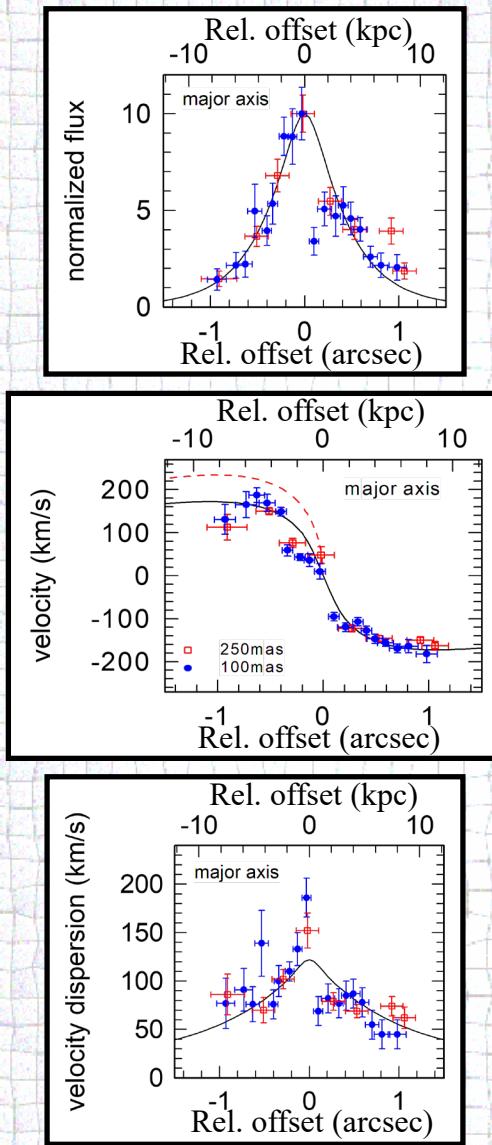
$\text{FWHM} \sim 0.15'' \rightarrow \sim 1.2 \text{ kpc}$



Genzel et al. (2006)

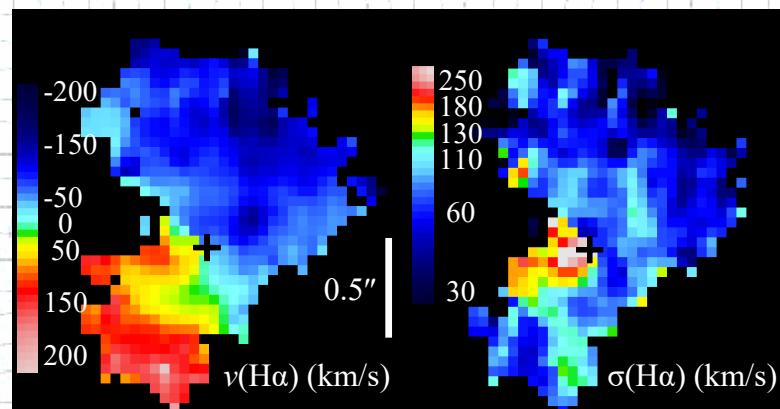
(Daddi et al. 2004; Kong et al. 2006)

A “Protodisk” at $z \sim 2$



BzK-15504 at $z = 2.38$

- *Large, massive, gas-rich disk*
- *Converting rapidly
a significant fraction of
its baryonic mass into stars*



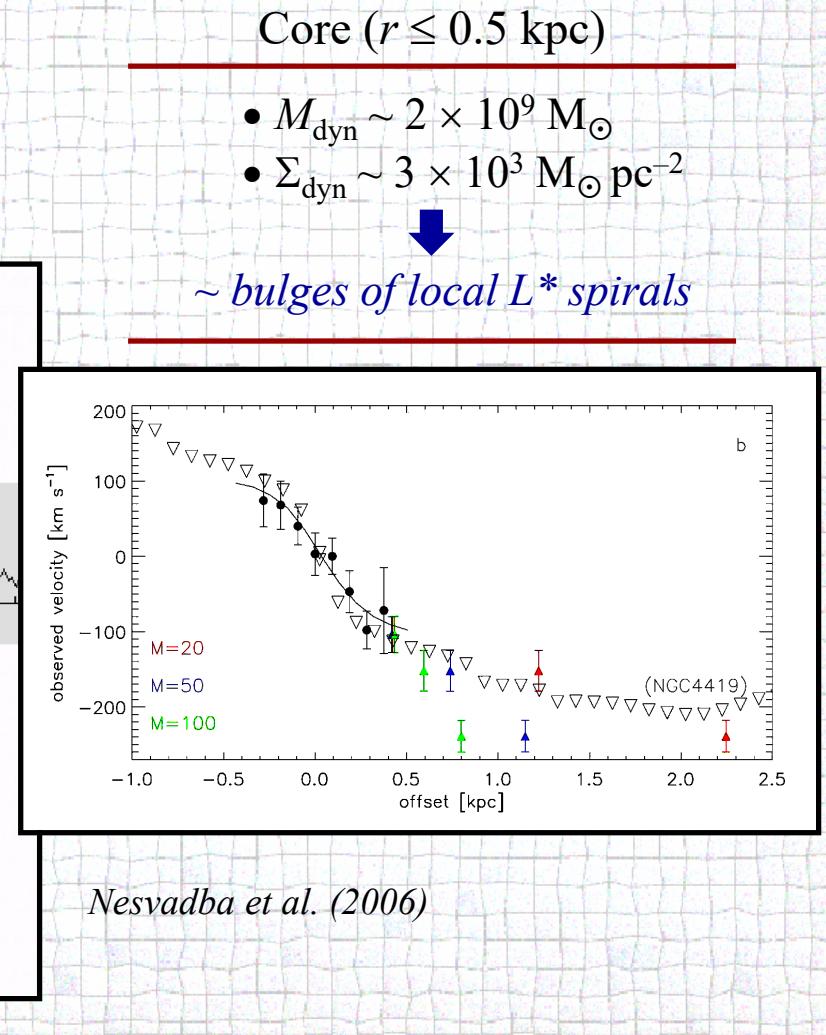
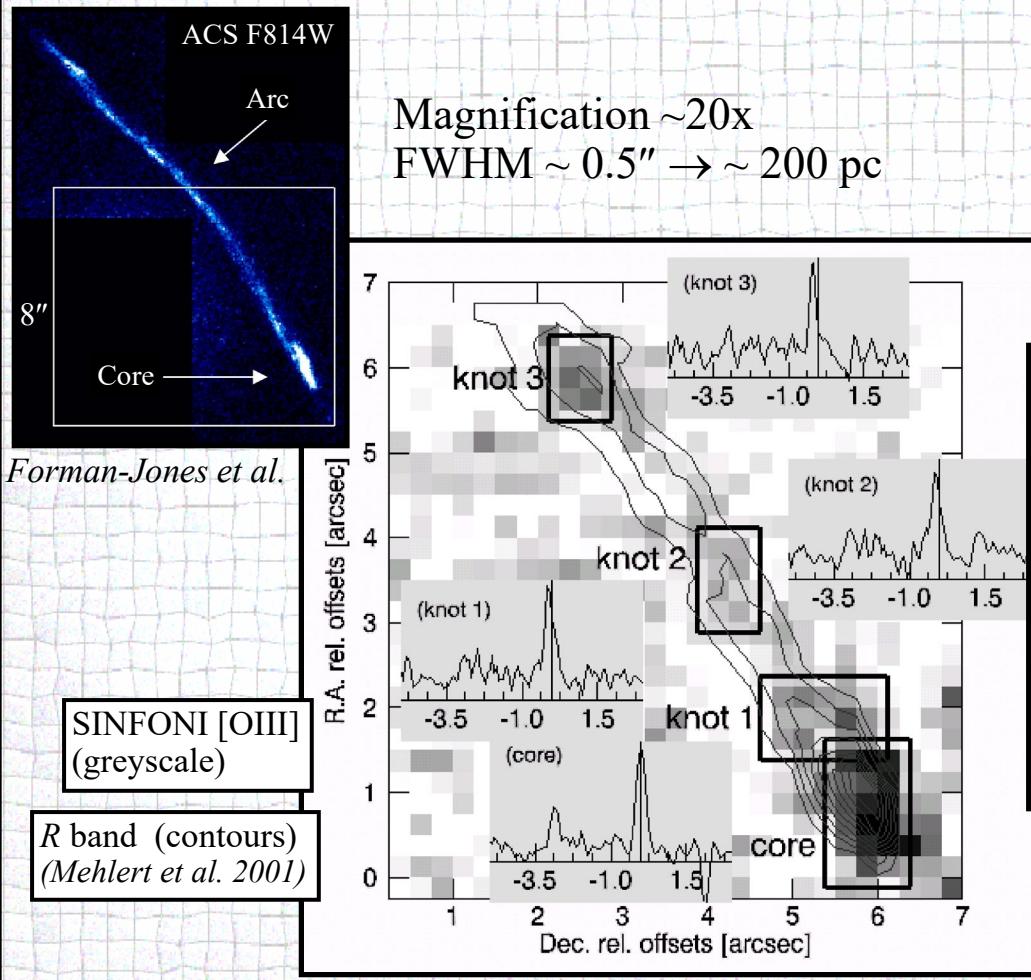
-
- $v_c = 230 \text{ km s}^{-1}$
 - $r_{1/e} \approx 4.5 \text{ kpc}$
 - $v_c/\sigma \approx 3$
-

- $M_{\text{dyn}} \approx 1.1 \times 10^{11} M_\odot$
 - $M_{\square} \approx 0.8 \times 10^{11} M_\odot$
 - $M_{\text{gas}} \approx 0.4 \times 10^{11} M_\odot$
 - $\Sigma_{\text{gas}} \sim 350 M_\odot \text{ pc}^{-2}$
-

- $\tau_{\square} \sim \tau_{\text{gas}} \sim 500 \text{ Myr}$
 - $\text{SFR} \sim 150 M_\odot \text{ yr}^{-1}$
 - $\Sigma_{\text{SFR}} \sim 1 M_\odot \text{ yr}^{-1} \text{ kpc}^{-2}$
-

Dynamics on small scales

1E0657-56 Arc+Core: strongly lensed LBG at $z = 3.24$



Summary

SINS: *spatially-resolved studies at $z \sim 1 - 4$ with SINFONI*



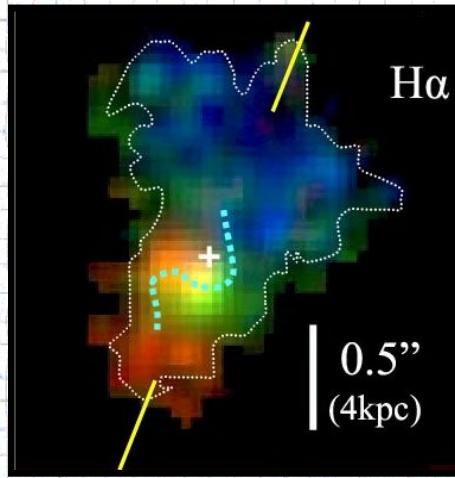
Witnessing galaxy mass assembly in detail

This talk:

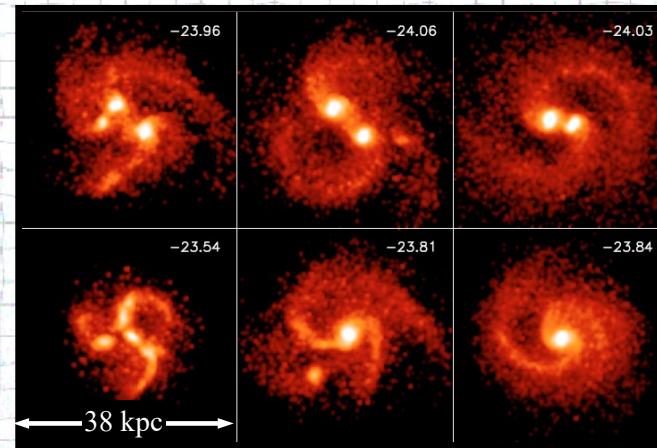
- ▶ Evidence for large, massive, gas-rich rotating disks at $z \sim 2 - 3$
- ▶ Significant amount of baryonic mass in central regions at $z \sim 2 - 3$



Inside-out scenario

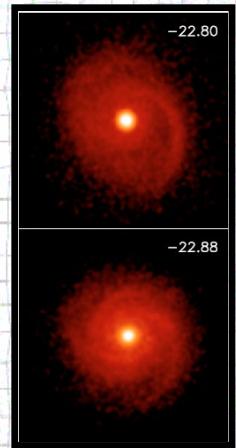


Genzel et al. (2006)



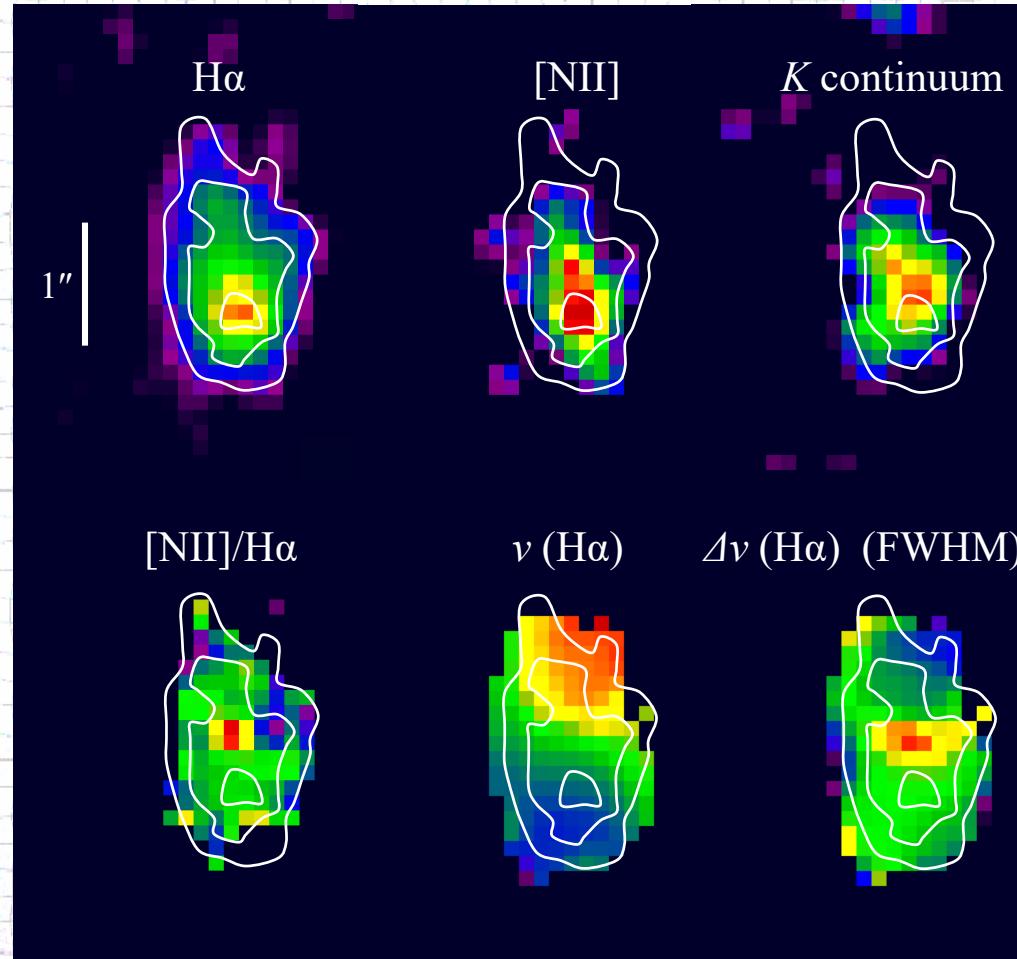
Immeli et al. (2004)

~2 Gyr



Spatially-resolved metallicity & SF

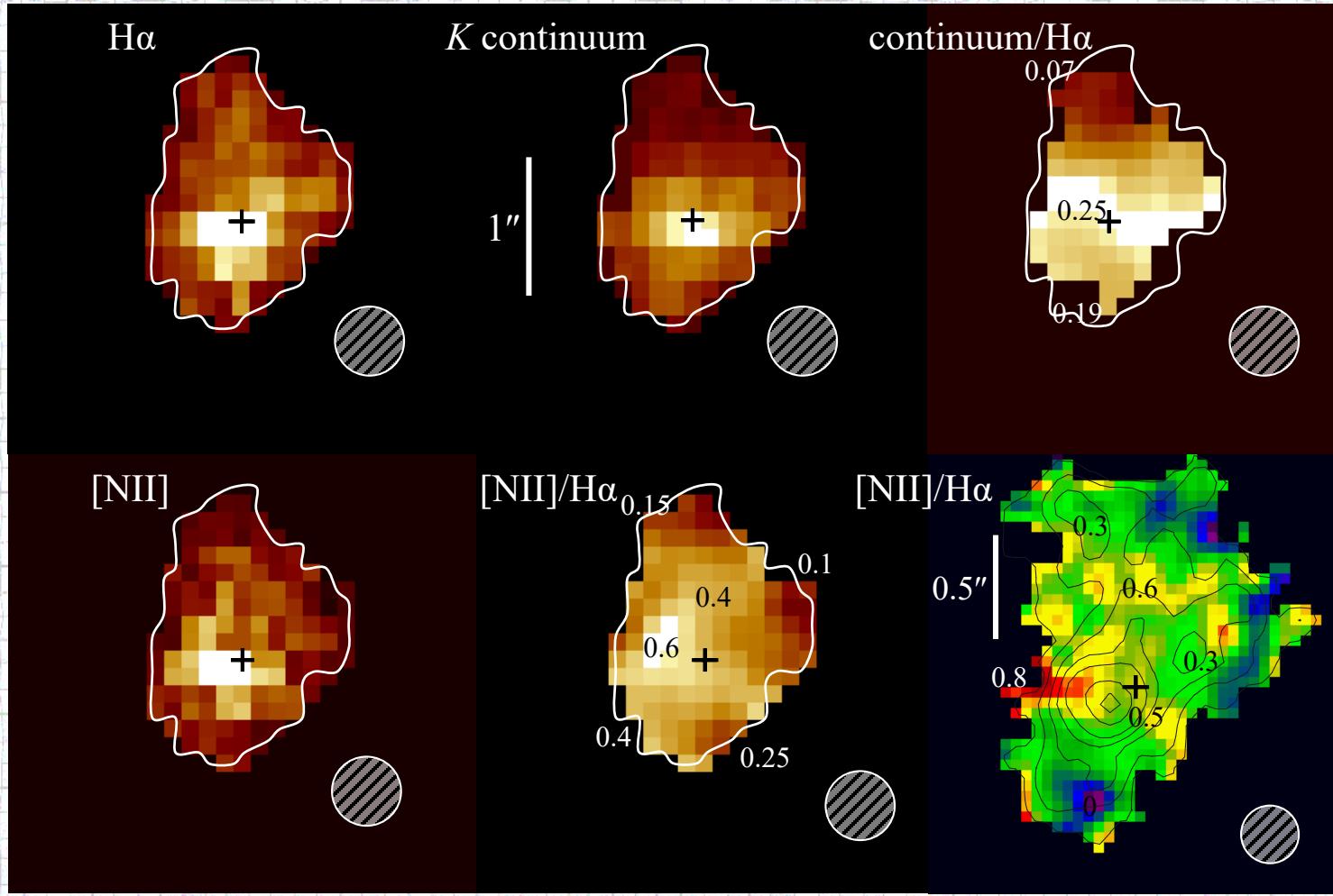
Q2343–BX610 at $z = 2.21$



Förster Schreiber et al. (2006)

Spatially-resolved metallicity & SF

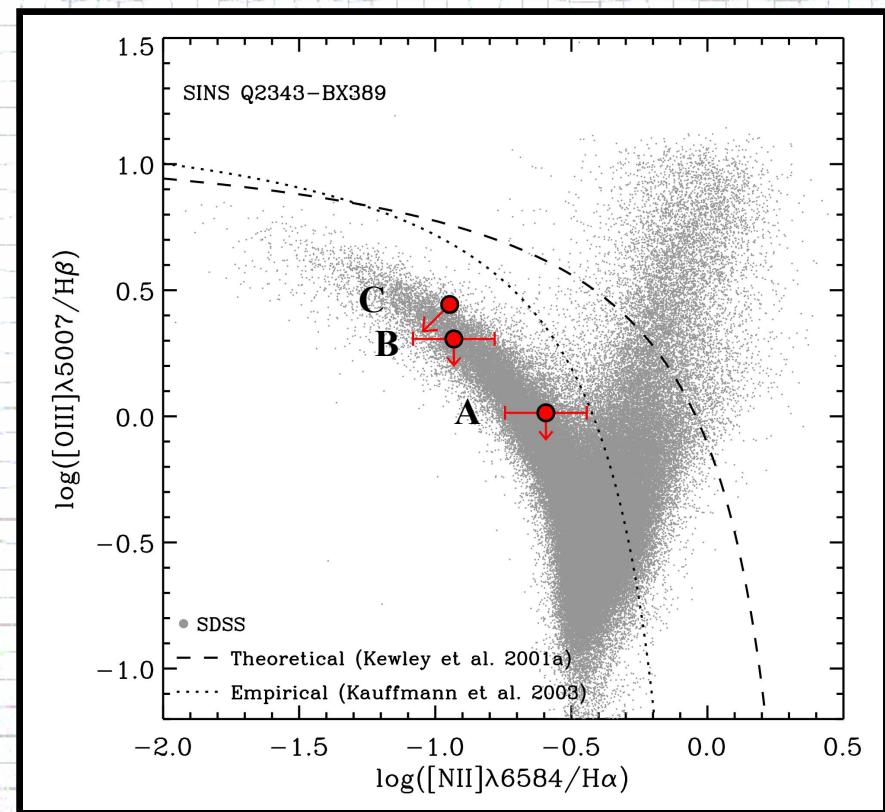
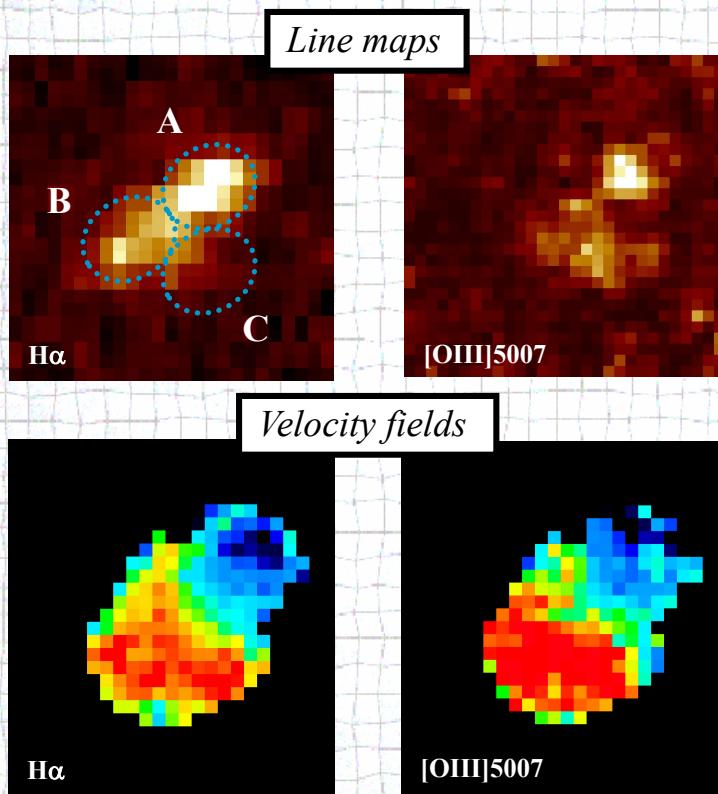
BzK-15504 at $z = 2.38$



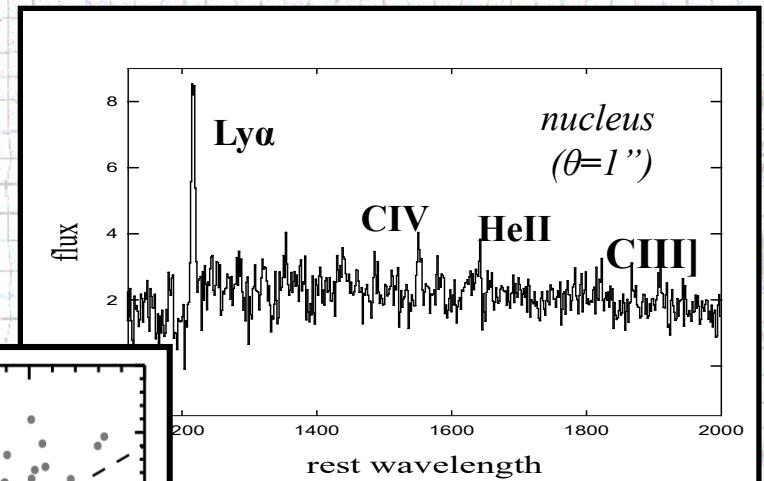
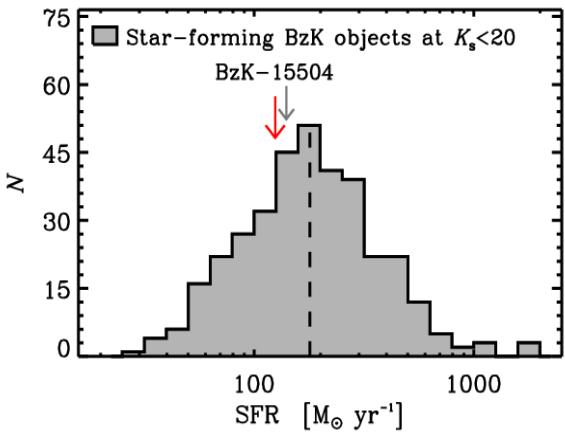
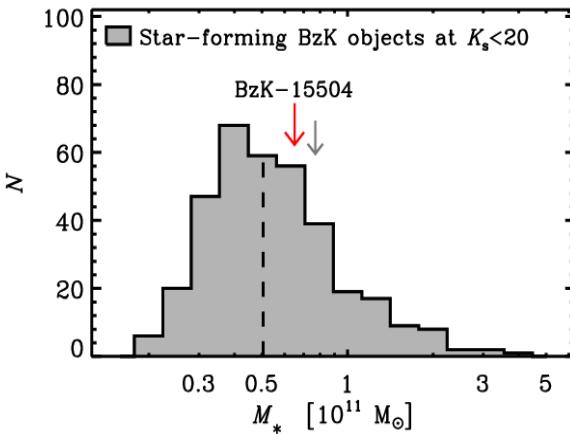
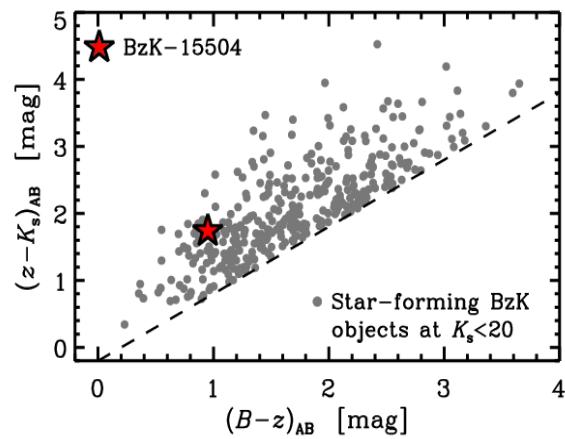
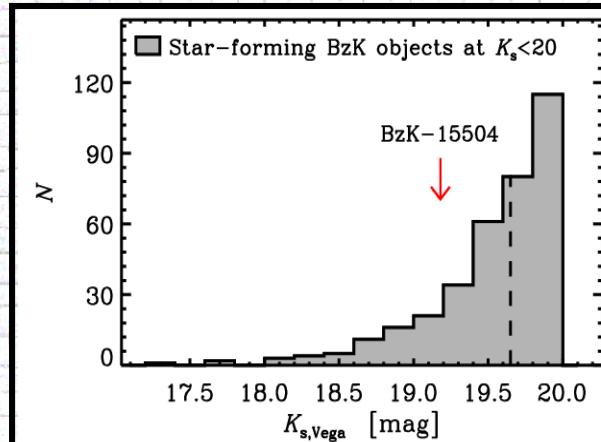
Genzel et al. (2006)

Spatially-resolved metallicity & SF

Q2343–BX389 at $z = 2.17$

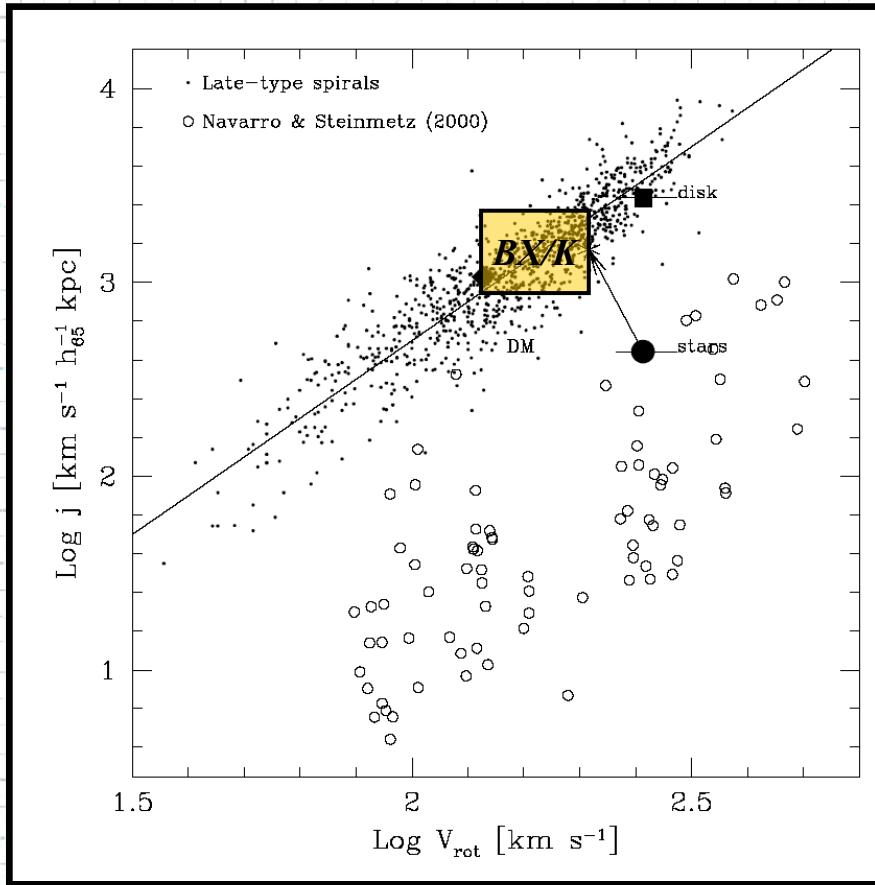


BzK-15504 ($z=2.38$)



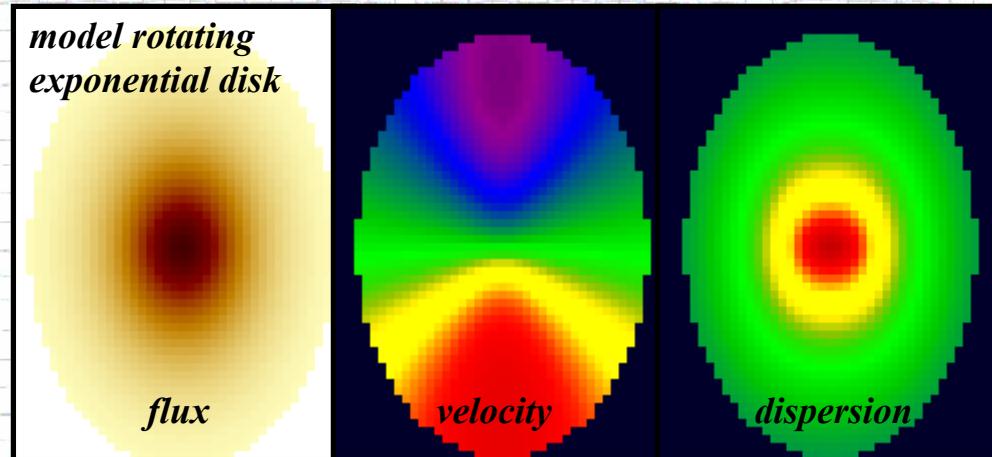
Kong et al. 2006
Daddi et al. 2003, 2004

Rotation and angular momentum



Abadi et al. 2003

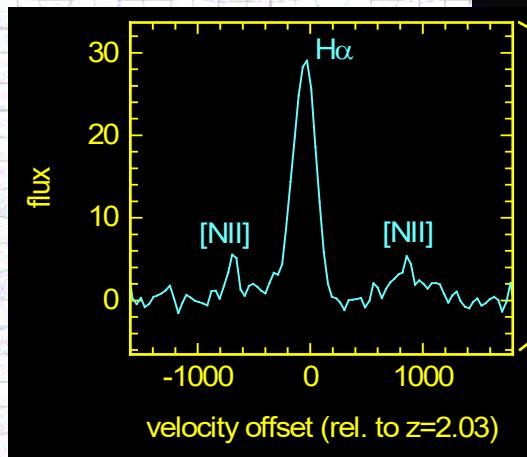
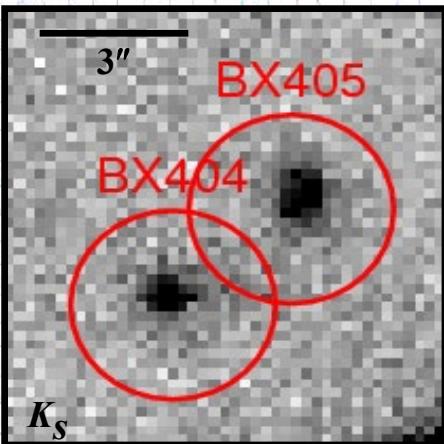
Model rotating disk



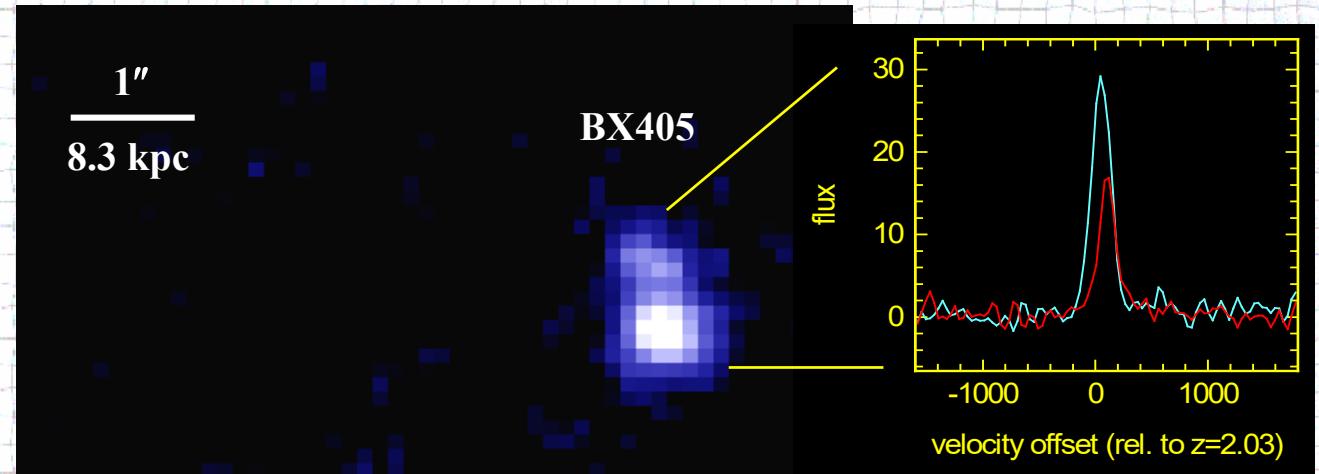
Characteristic signatures of a rotating disk

- maximum, smooth velocity gradient along morphological major axis
- velocity dispersion peaks at center of velocity gradient (and continuum peak if present)
- ‘spider’ diagram of iso-velocity contours = sinusoidal variation of velocities as a function of disk angle
- kinematic inclination = morphological inclination

BM/BX objects

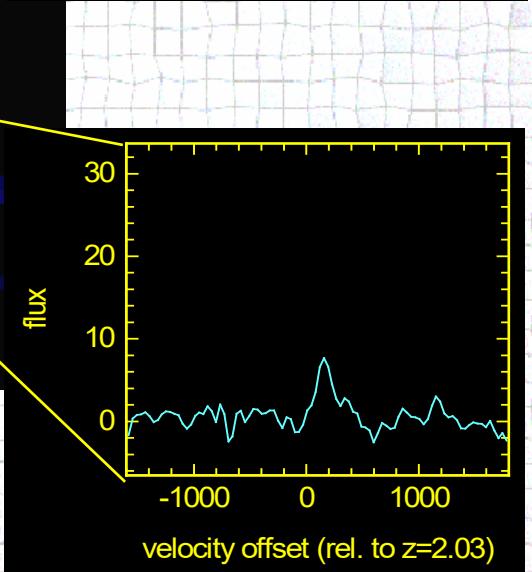


BX 404/405 $z = 2.03$



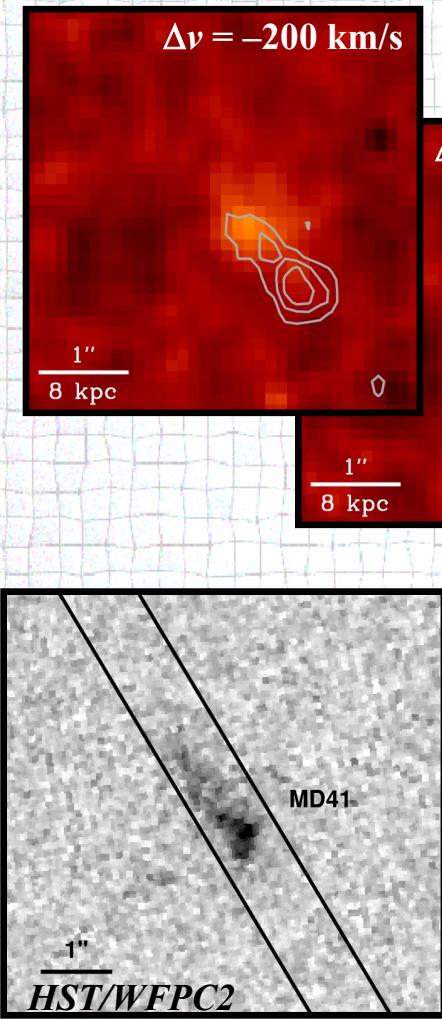
*Shapley et al. 2004; Erb et al. 2003, 2004
Förster Schreiber et al. 2006*

SINFONI H α ($2h$ K-band)

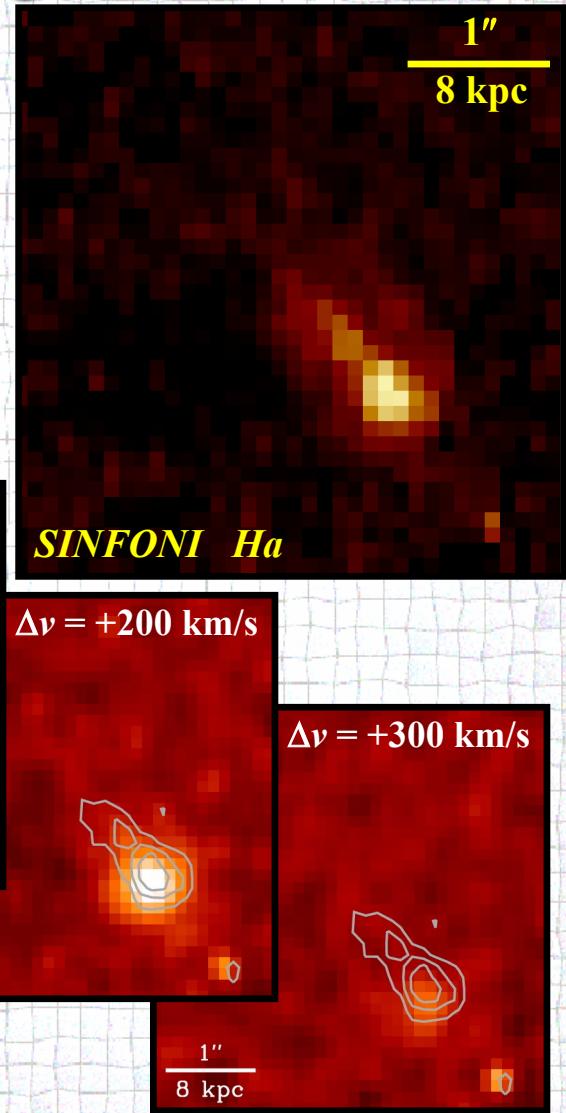


BM/BX objects

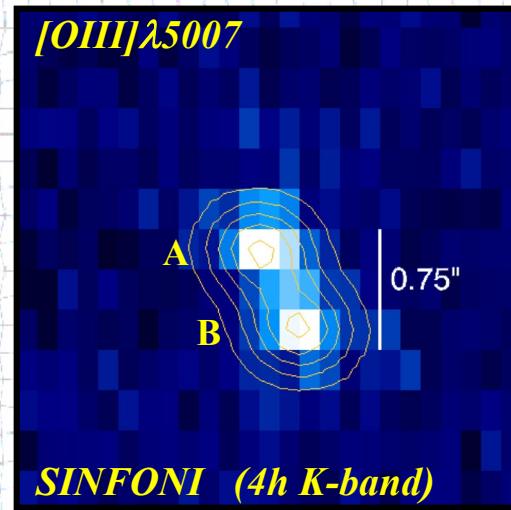
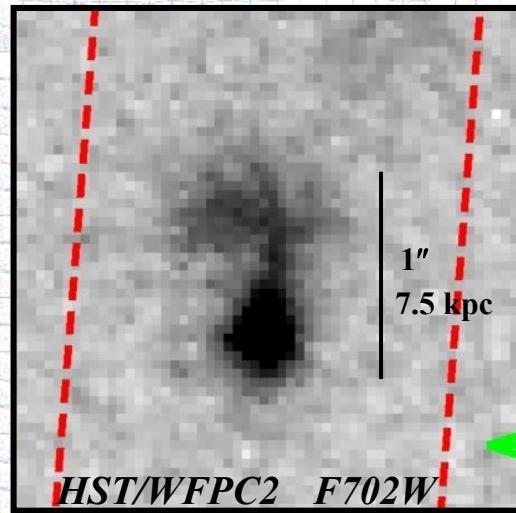
MD41 $z = 2.17$



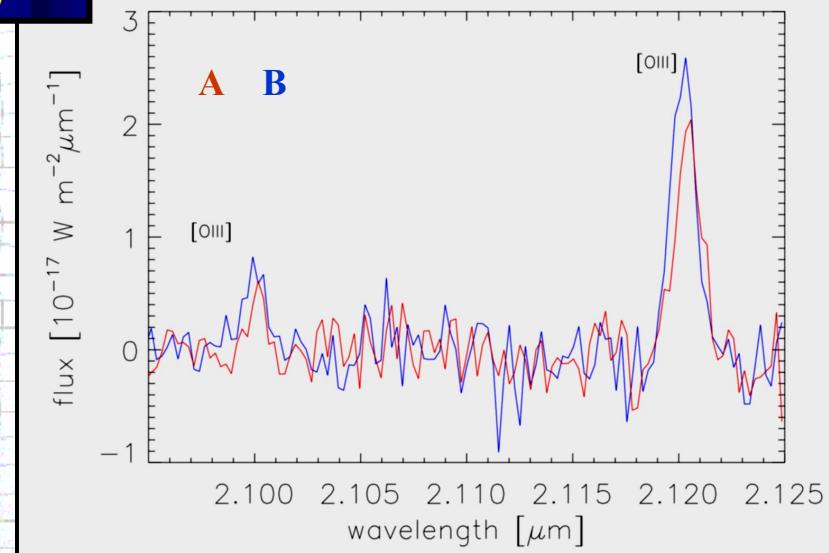
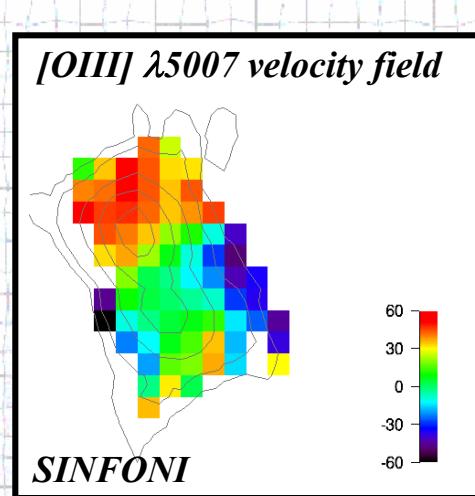
*Shapley et al. 2004; Erb et al. 2003, 2004
Förster Schreiber et al. (in prep.)*



Lyman-Break Galaxies



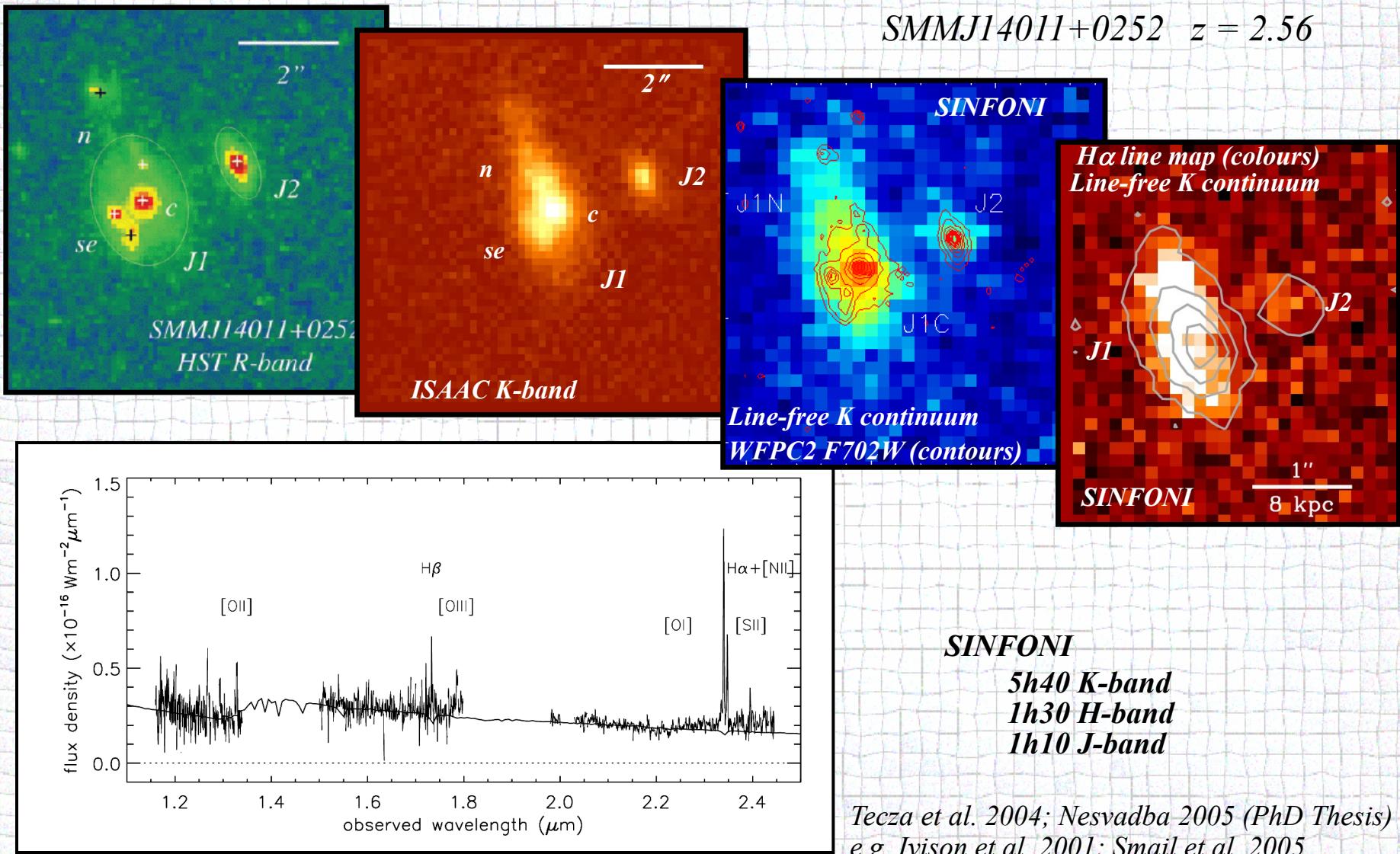
Q0347-383 C5 $z = 3.23$



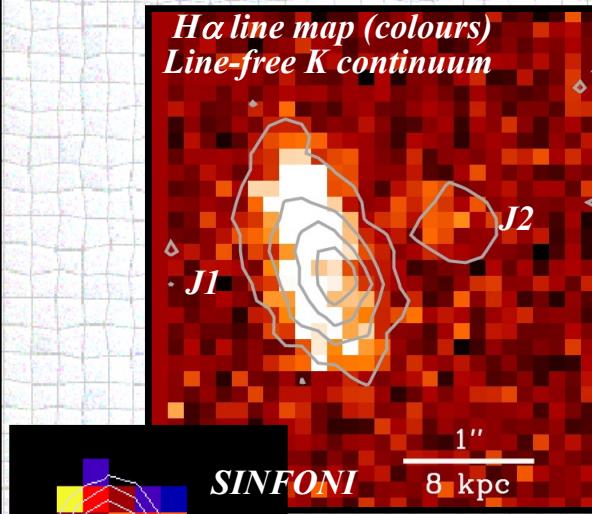
Pettini et al. 2001

Nesvadba 2005 (PhD Thesis)

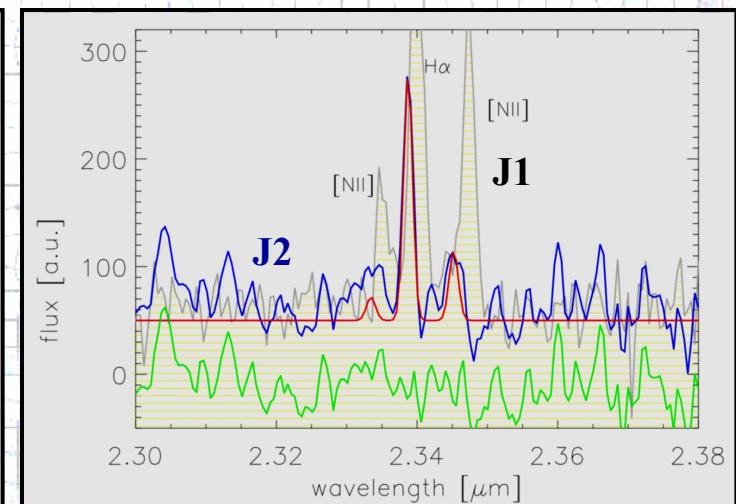
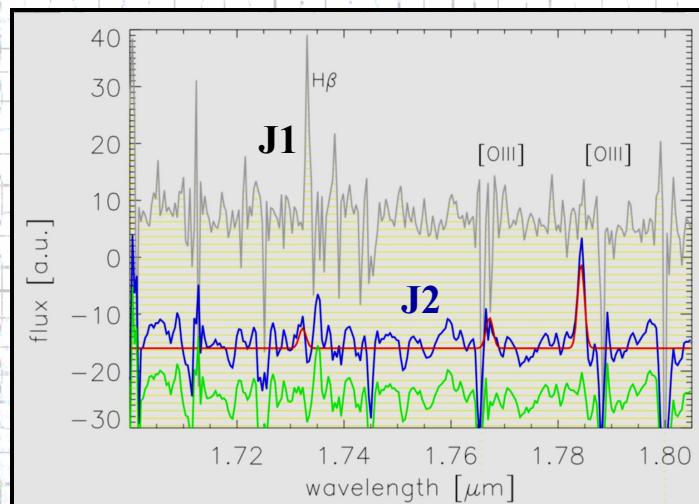
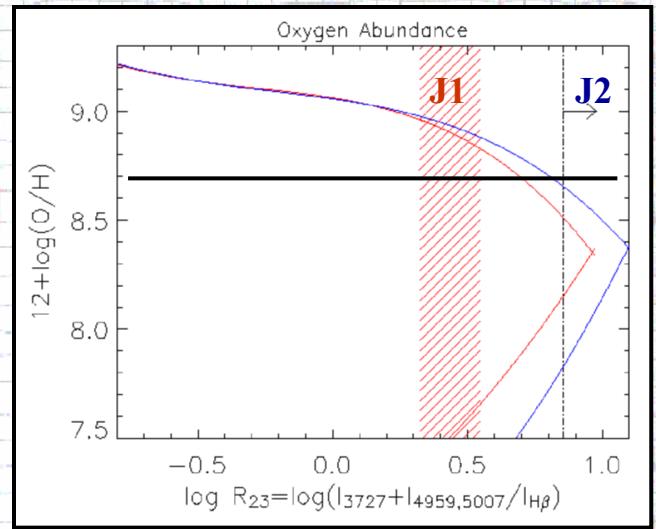
Submm-selected Galaxies



Submm-selected Galaxies

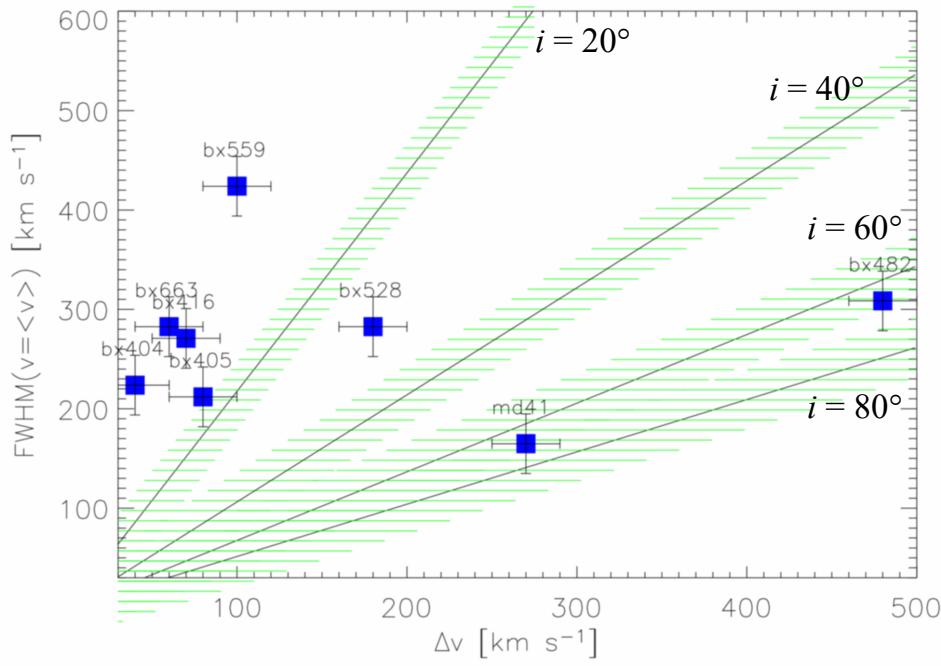


SMMJ14011+0252 $z = 2.56$



Tecza et al. 2004; Nesvadba 2005 (PhD Thesis)

Modelling



Model + noise

$$i = 80^\circ$$

$$\text{SNR(peak)} = 7$$



Exponential disk model

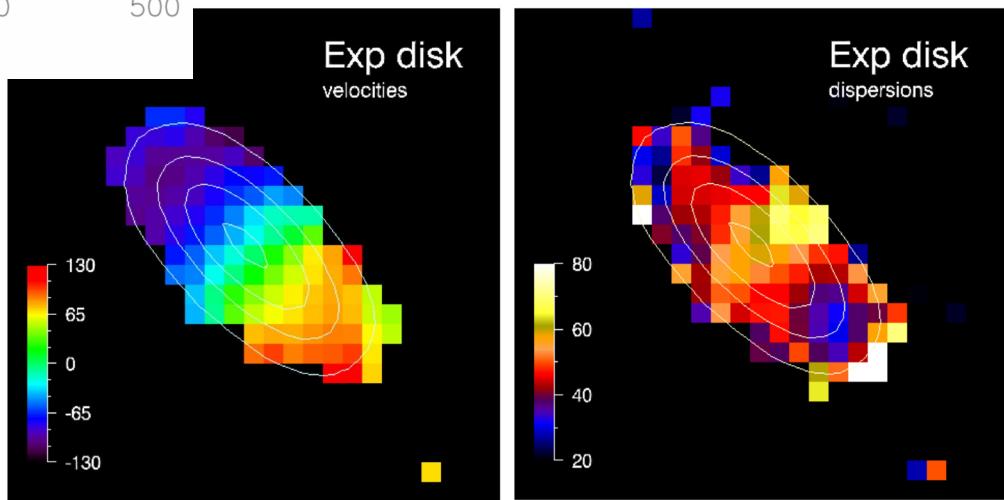
$$M = 3 \times 10^{10} M_\odot$$

$$i = 20^\circ - 80^\circ$$

$$\text{scale length} = 1''$$

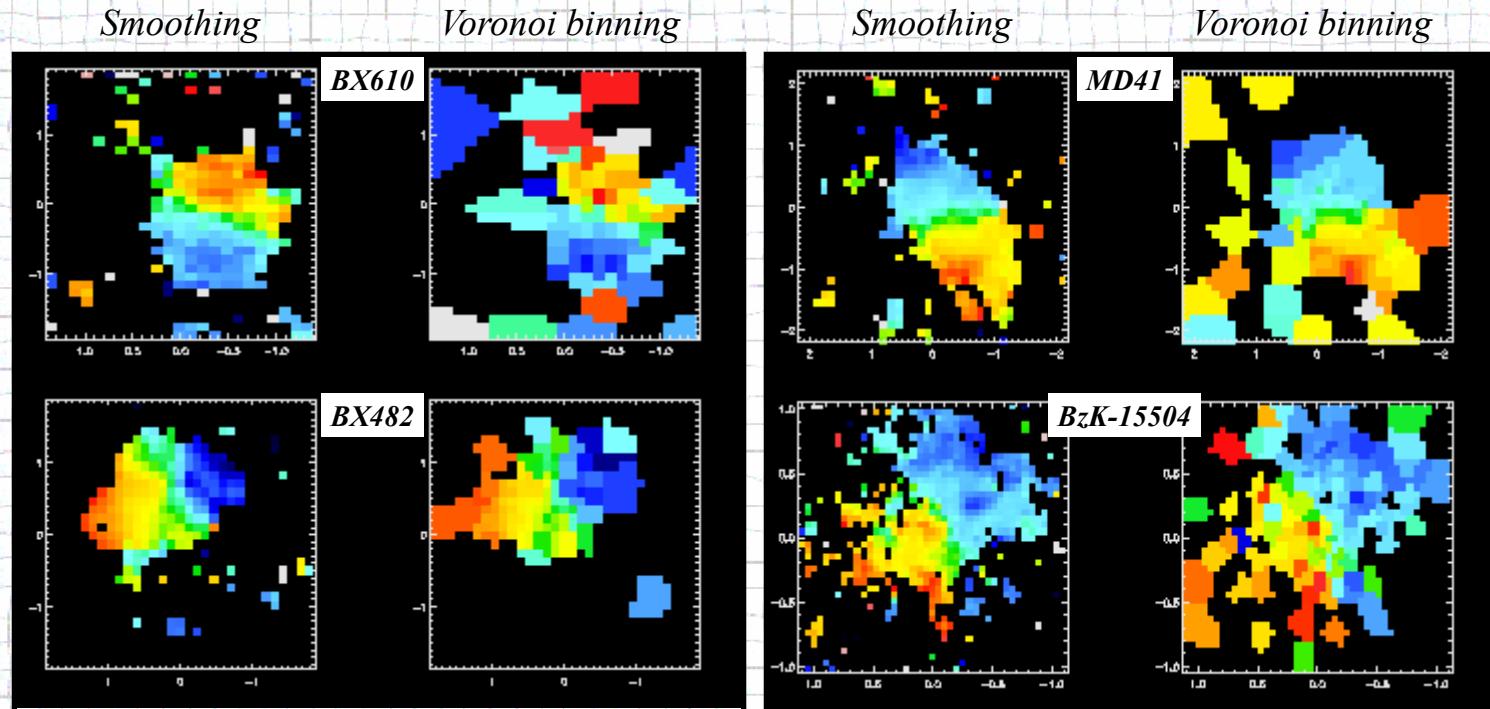
$$\text{thickness} = 0.2$$

$$\text{seeing} \approx 0.5''$$



Extracting robust 2D kinematics

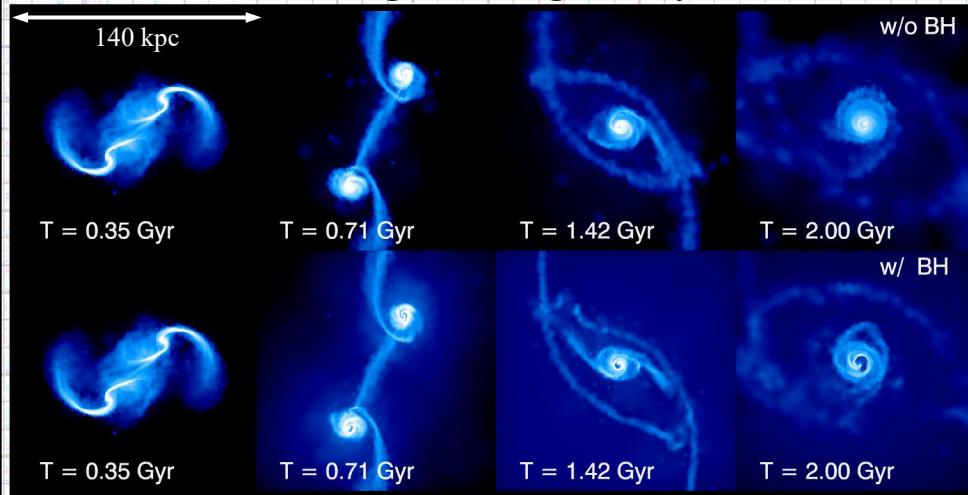
... from IFS of $z \sim 2$ galaxies



Shapiro 2006 (PhD Thesis)
Cresci et al.

Galaxy Formation and Evolution

Gas-rich mergers + vigorous feedback



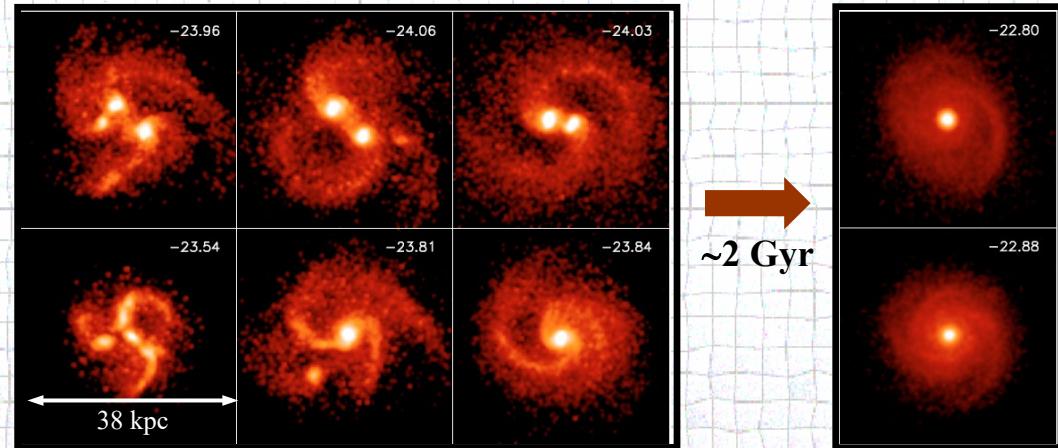
Robertson et al. (2005)

Baryonic component

complex physical processes

(angular momentum exchange/loss,
cooling, feedback, ...)

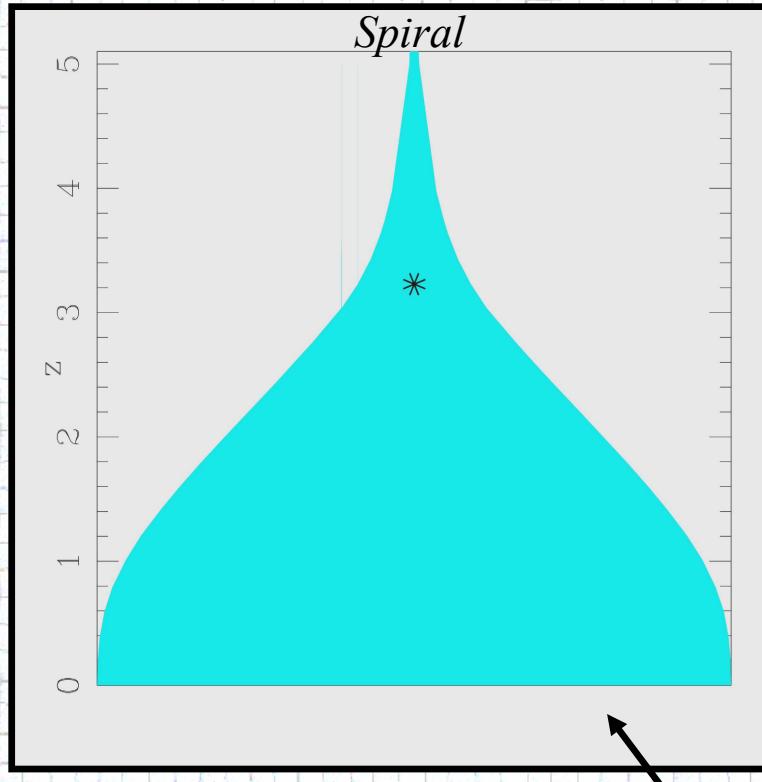
Gas-rich star-forming disk: disk fragmentation + bulge formation



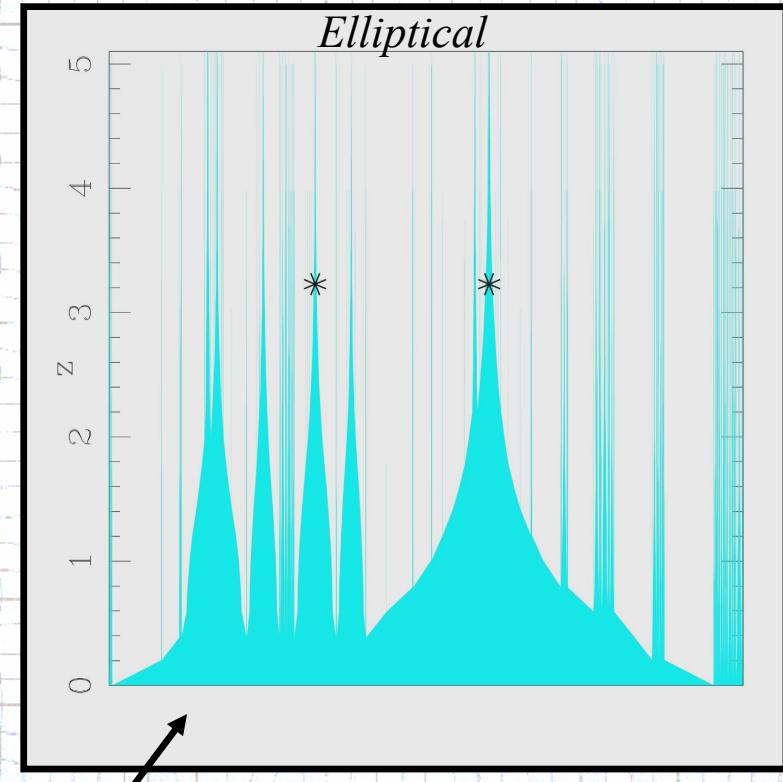
Immeli et al. (2004)

Galaxy Formation from Simulations

Mass accretion and star formation process



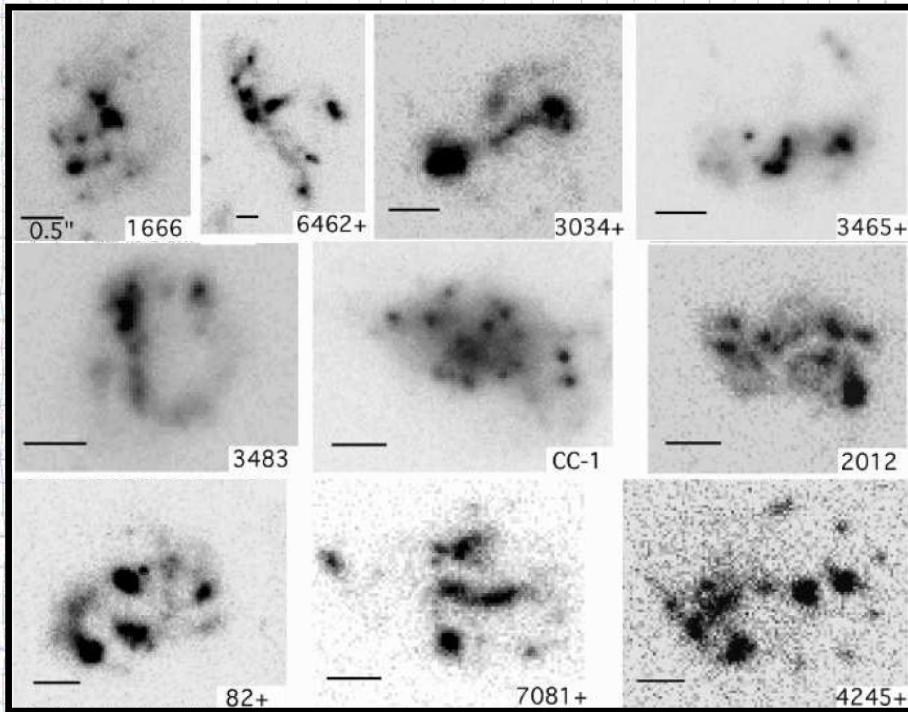
Frenk, Baugh, & Cole (1996)



smooth vs complex accretion...
angular momentum ...
dissipative vs non-dissipative collapse

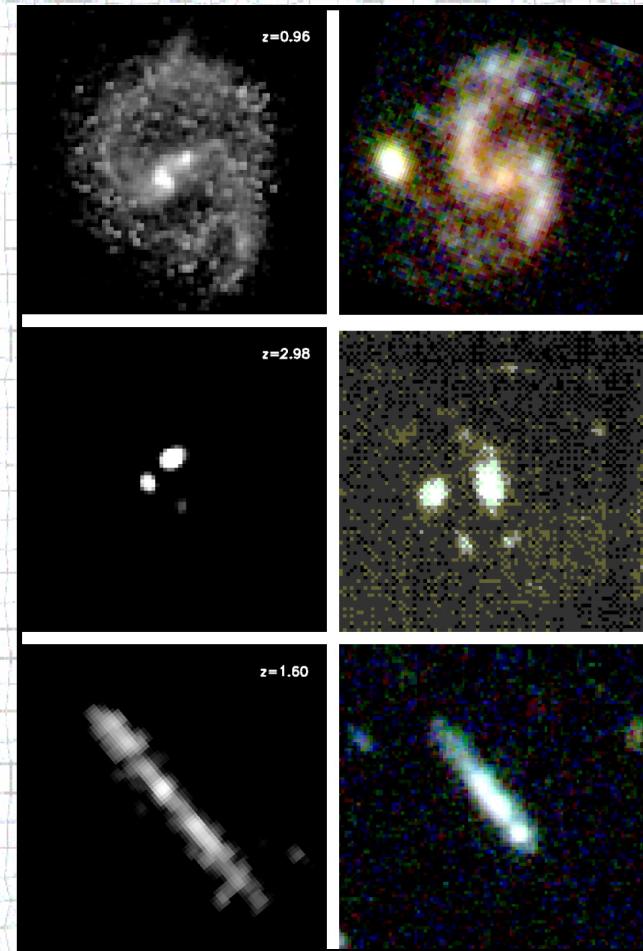
Observations vs Simulations

Complex X-band morphologies in UDF



Elmegreen & Elmegreen (2005)

V-band morphologies: models vs data



Immeli et al. (2004)
van den Bergh et al. (1996)