Near-IR IFU observations of high-redshift

Giovanni Cresci

INAF- Arcetri Observatory

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The SINS zC-SINS collaboration

N. Forster-Schreiber, R. Genzel, L.J. Tacconi, N. Bouché, P. Buschkamp, R.I. Davies, F. Eisenhauer, S. Genel, E.K.S. Hicks, J. Kurk, D. Lutz, S. Newman, K.L. Shapiro, A. Sternberg, S. Wuyts

A. Renzini, S. Lilly, C.M. Carollo, C. Mancini, Y. Peng, D. Vergani, G. Zamorani, A. Cimatti, E. Daddi, A.E. Shapley, D.K. Erb, C.C. Steidel

A. Burkert, T. Naab, P. Johansson, A. Dekel, D. Ceverino, O. Gerhard, S. Khochfar, F. Bournaud et al.

z~2.2

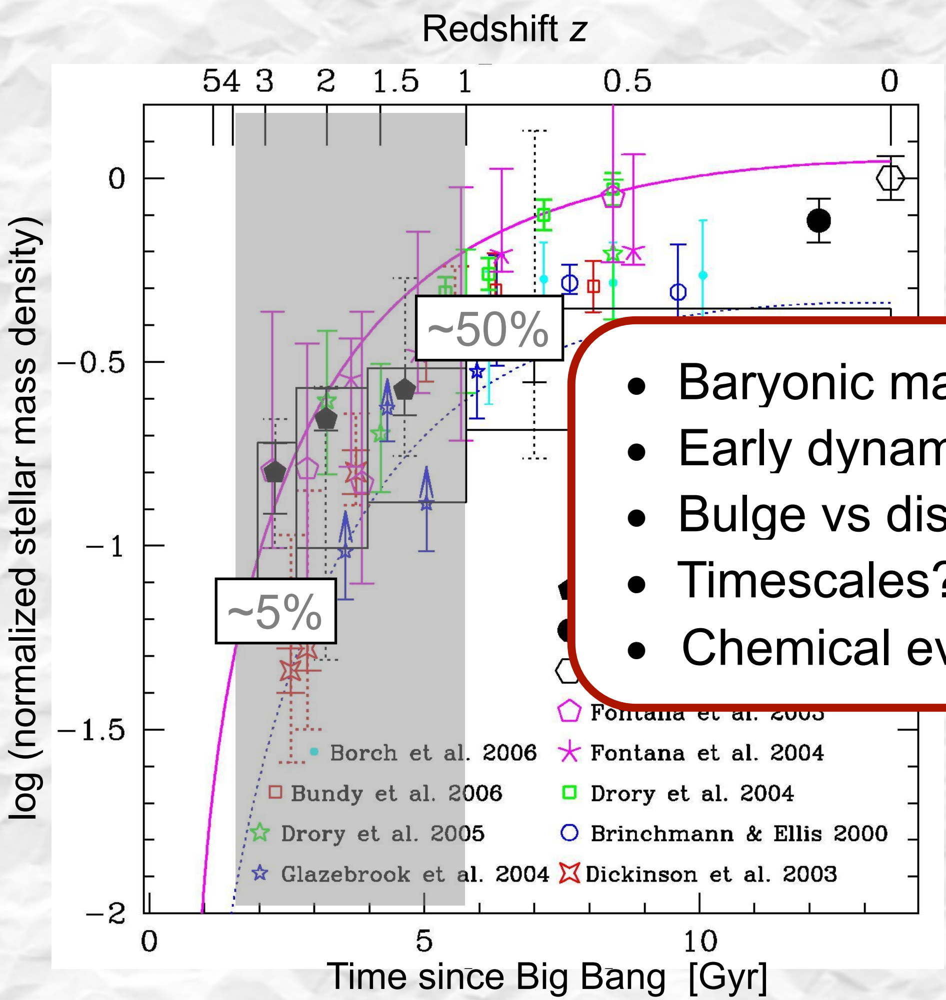
The AMAZE/LSD team

R. Maiolino, F. Mannucci, A. Marconi, T. Nagao, V. Sommariva, P. Troncoso, A. Gnerucci, A. Baroni, L. Magrini, A. Grazian, F. Cocchia, G. Risaliti, M. Salvati, A. Cimatti, A. Fontana, F. Matteucci, A. Pipino et al.

z~3

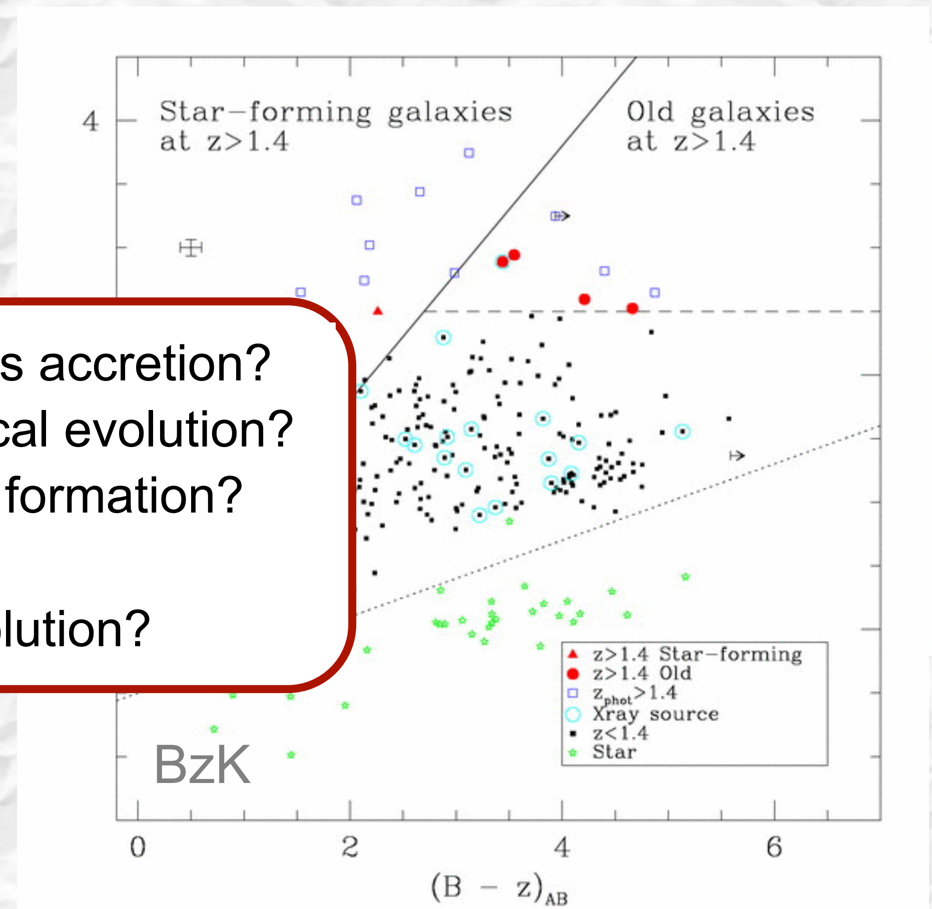
Star Forming Galaxies in the high-z Universe

Rapid growth of galaxies at z ~ 1 – 4:



Rudnick et al. (2006)

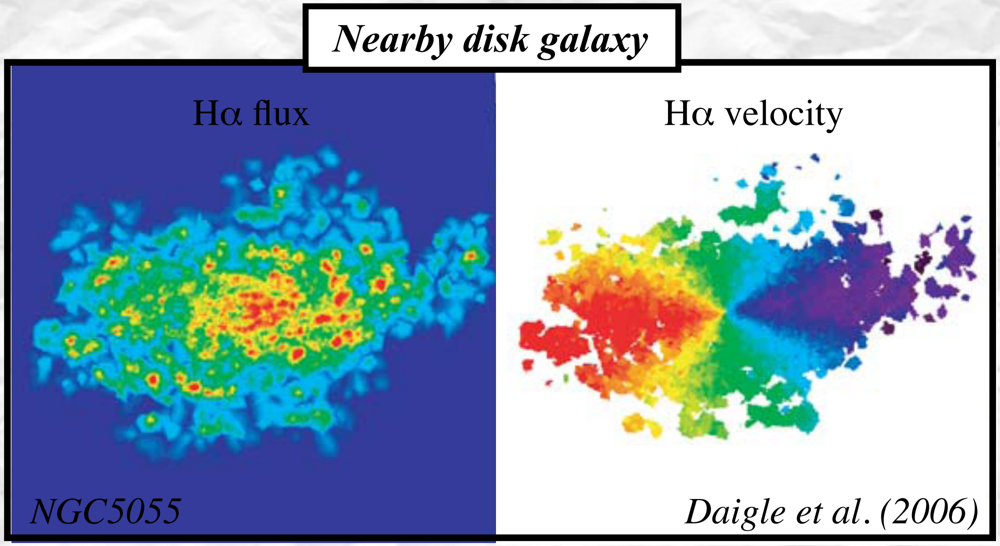
Well defined samples of z=1-6 starforming galaxies now available



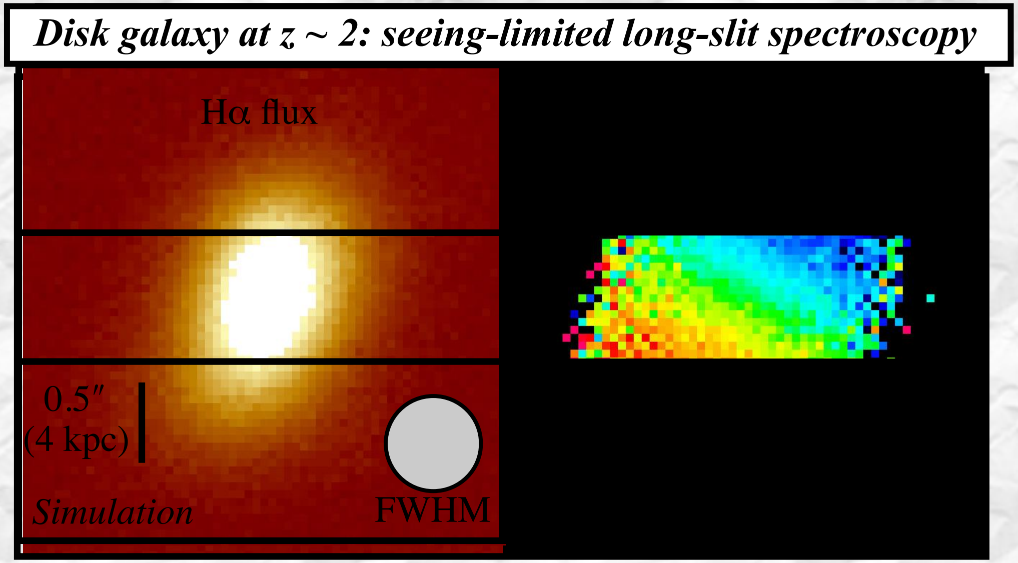
SMG — Chapman et al. (2005)

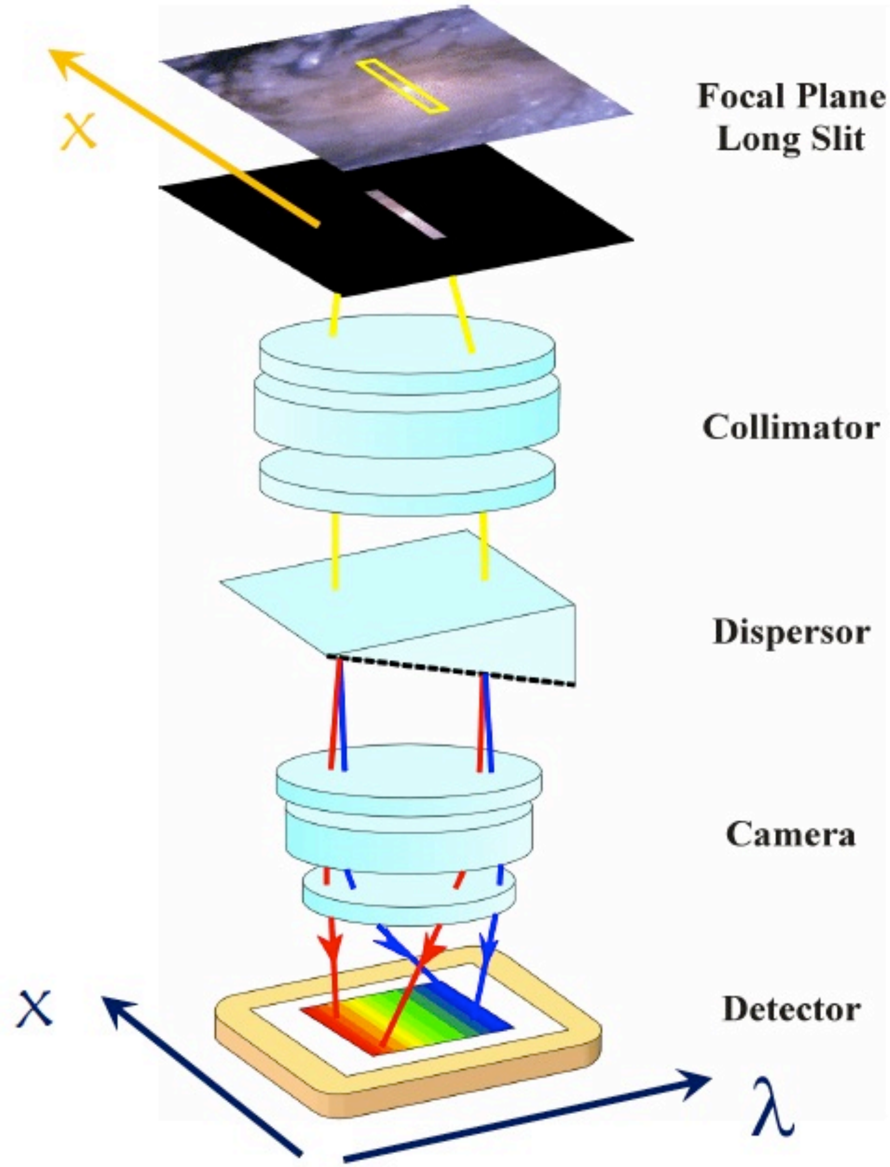
Daddi et al. (2004)

- Baryonic mass accretion?
- Early dynamical evolution?
- Bulge vs disk formation?
- Timescales?
- Chemical evolution?



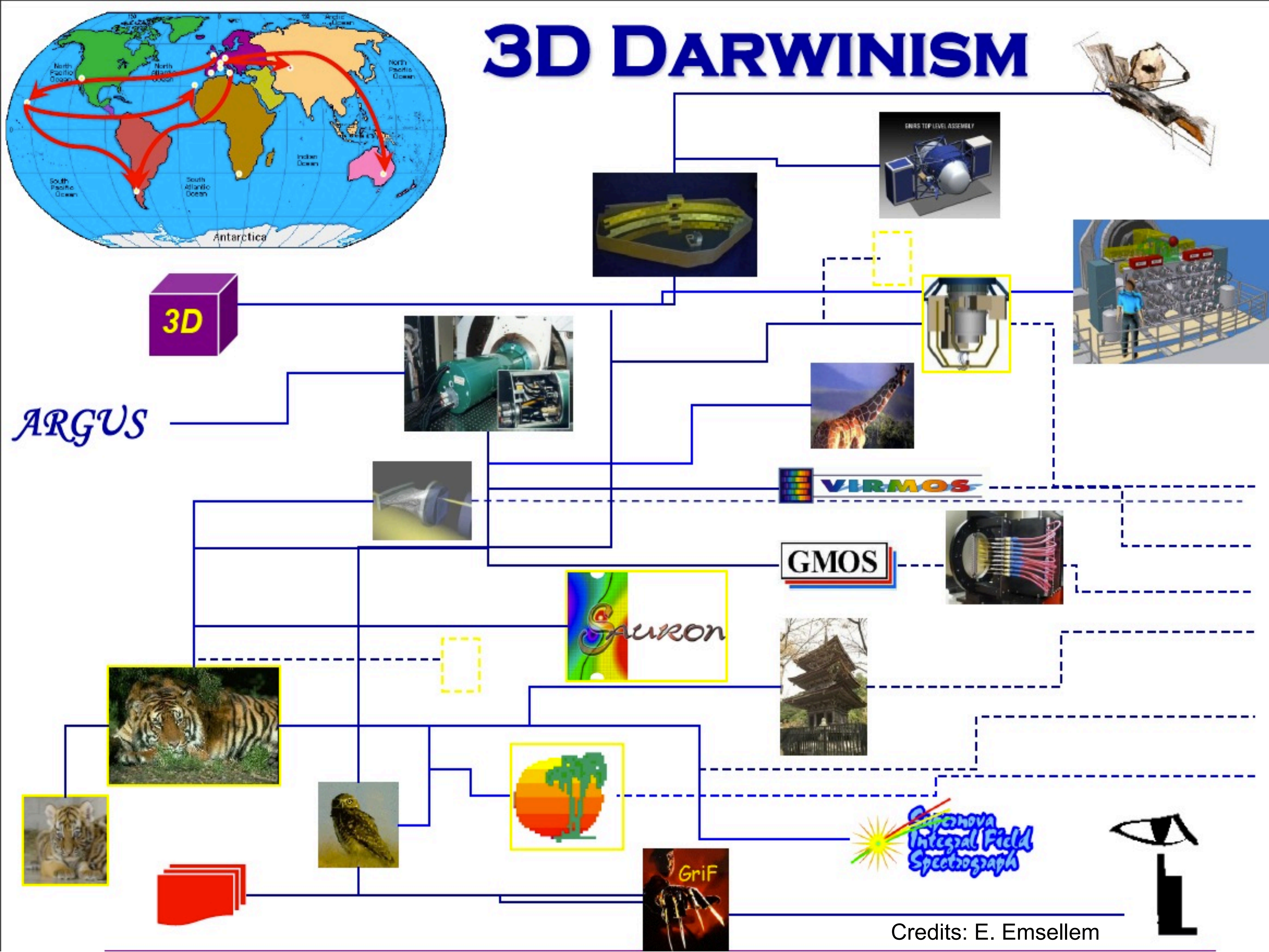
Is it possible to get close at high-z (waiting for JWST)?





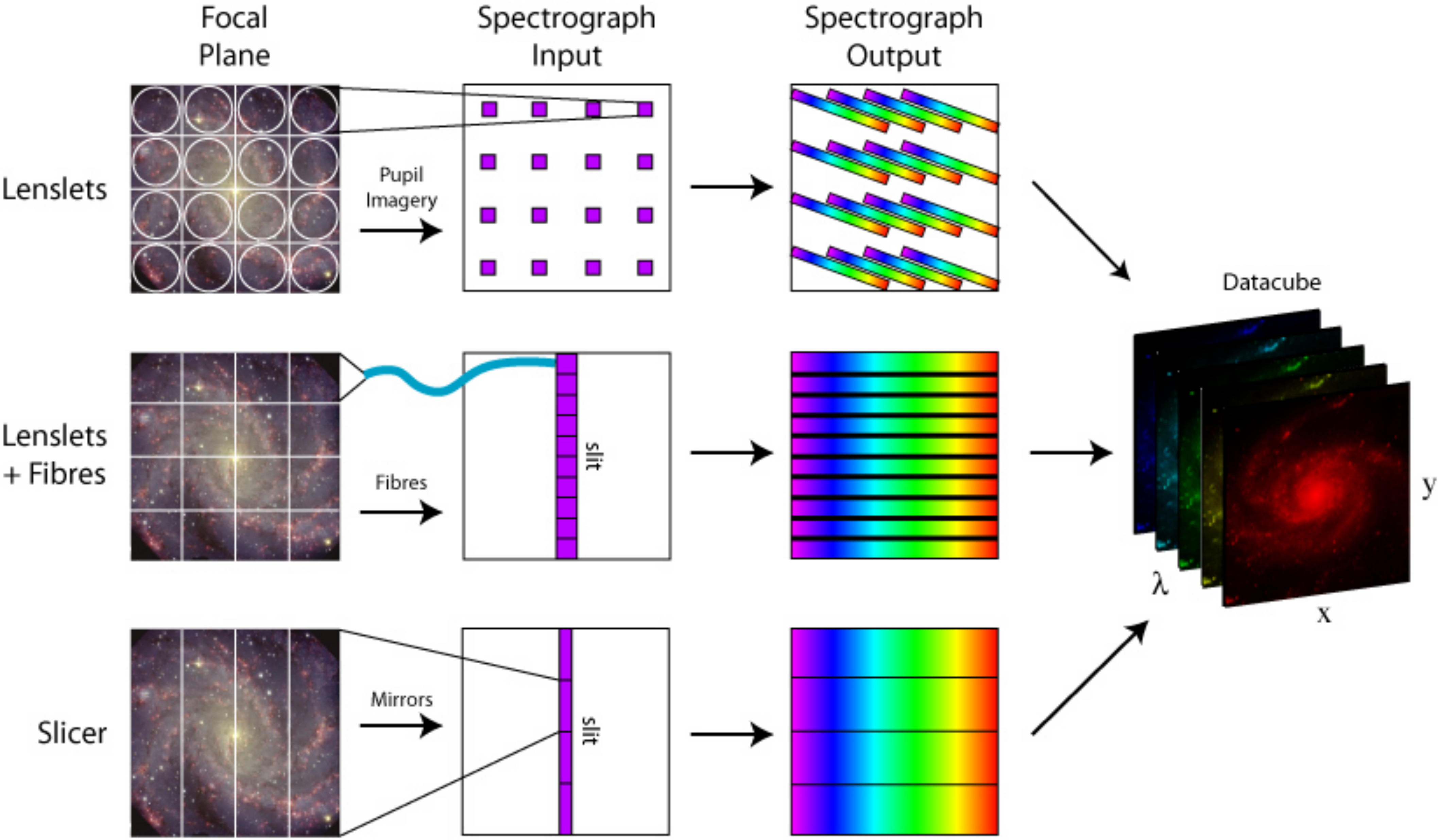
- Morphology of real objects do not follow the slit
- Light losses
- Resolution depends on slit itself…
- Limited angular resolution (~0.5″)

3D Darwinism



Credits: E. Emsellem

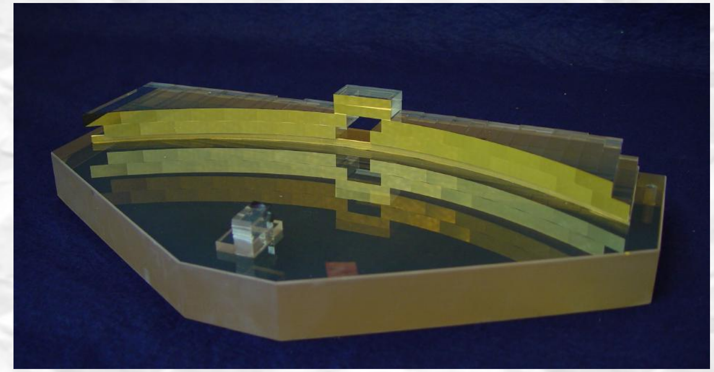
IFU families



Lenslets: OSIRIS, SAURON…; Lenslets+Fibers: GMOS, VIMOS, FLAMES…
Slicer: SINFONI, MUSE, KMOS, NIRspec…

SINFONI

The image slicer of SINFONI converts the two-dimensional field-of-view into an one-dimensional slit that is dispersed



It is re-arranged in a cube during data reduction: you get at the same time multiple images of the field of view at any wavelength and the full spectra of each “spaxel” of the image

The 0.250”x0.125” pixel scale (f.o.v. 8”x8”) is used for seeing limited observations, with an average resolution ~0.6”

For AO-assisted observation the 0.100”x0.050” scale (f.o.v. 3.2”x3.2”), with a typical resolution of 0.1”-0.2”

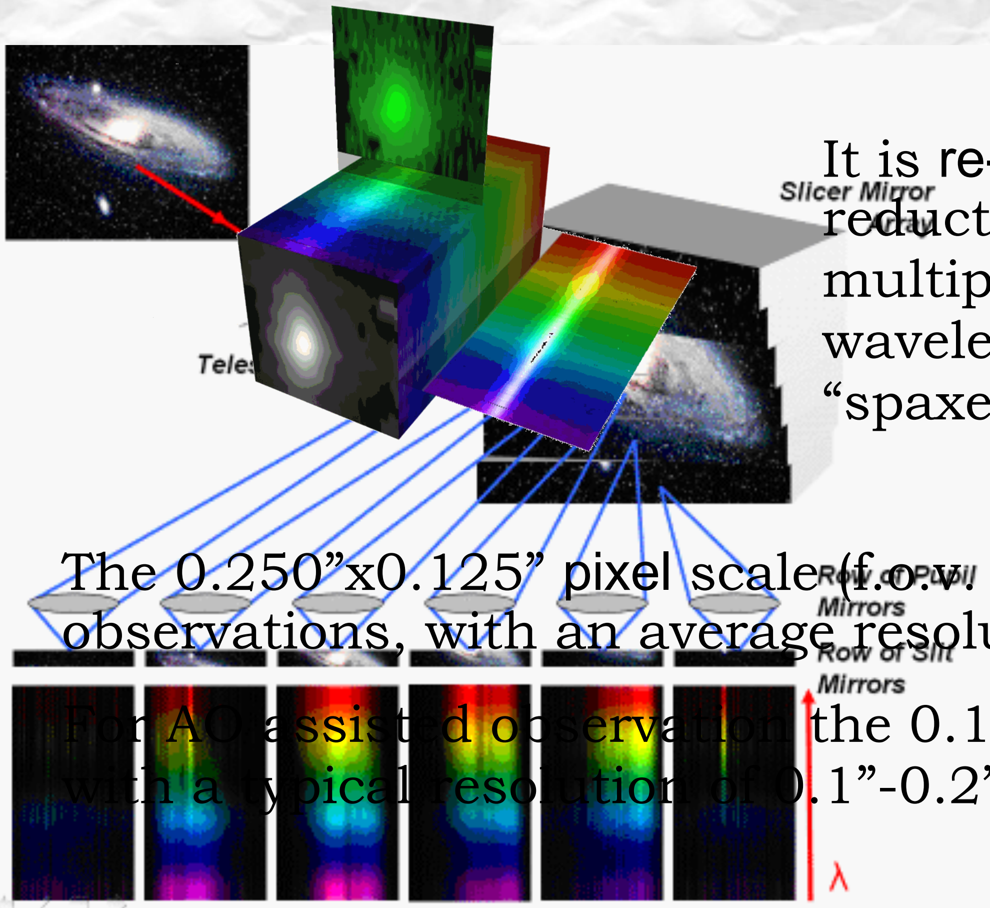
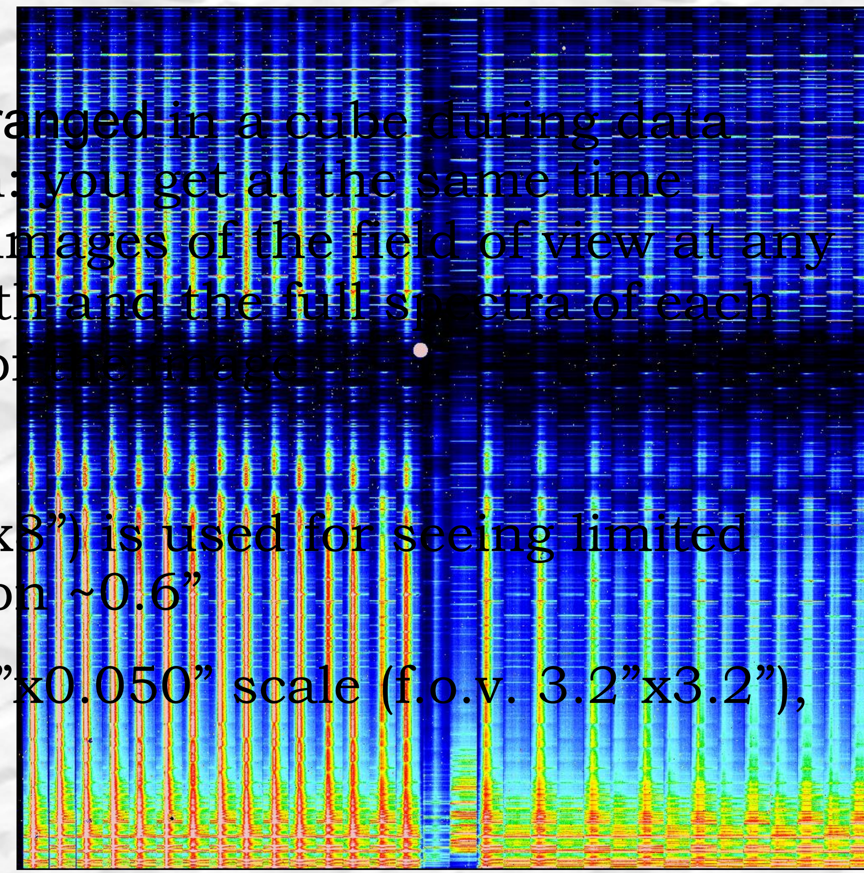


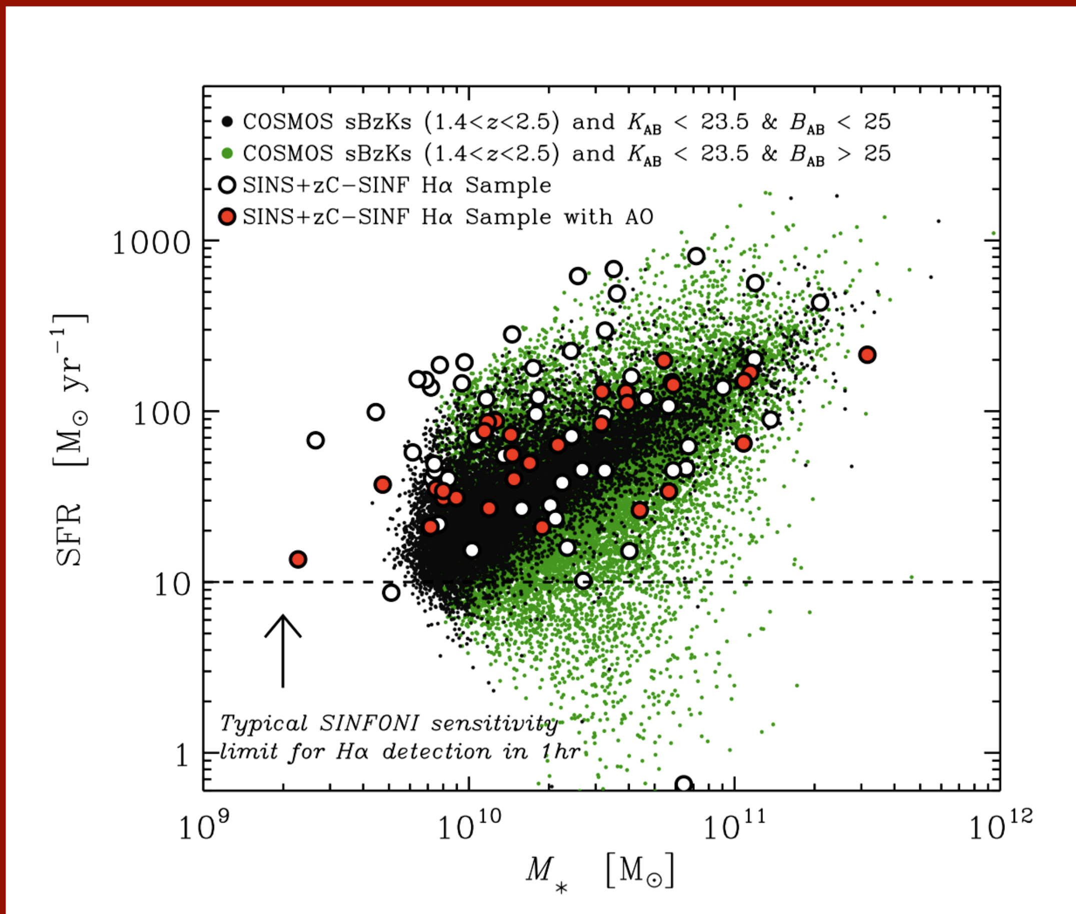
Image slicer



SINFONI raw frame

SINS+zC-SINF Survey of >100 z~2 Ga

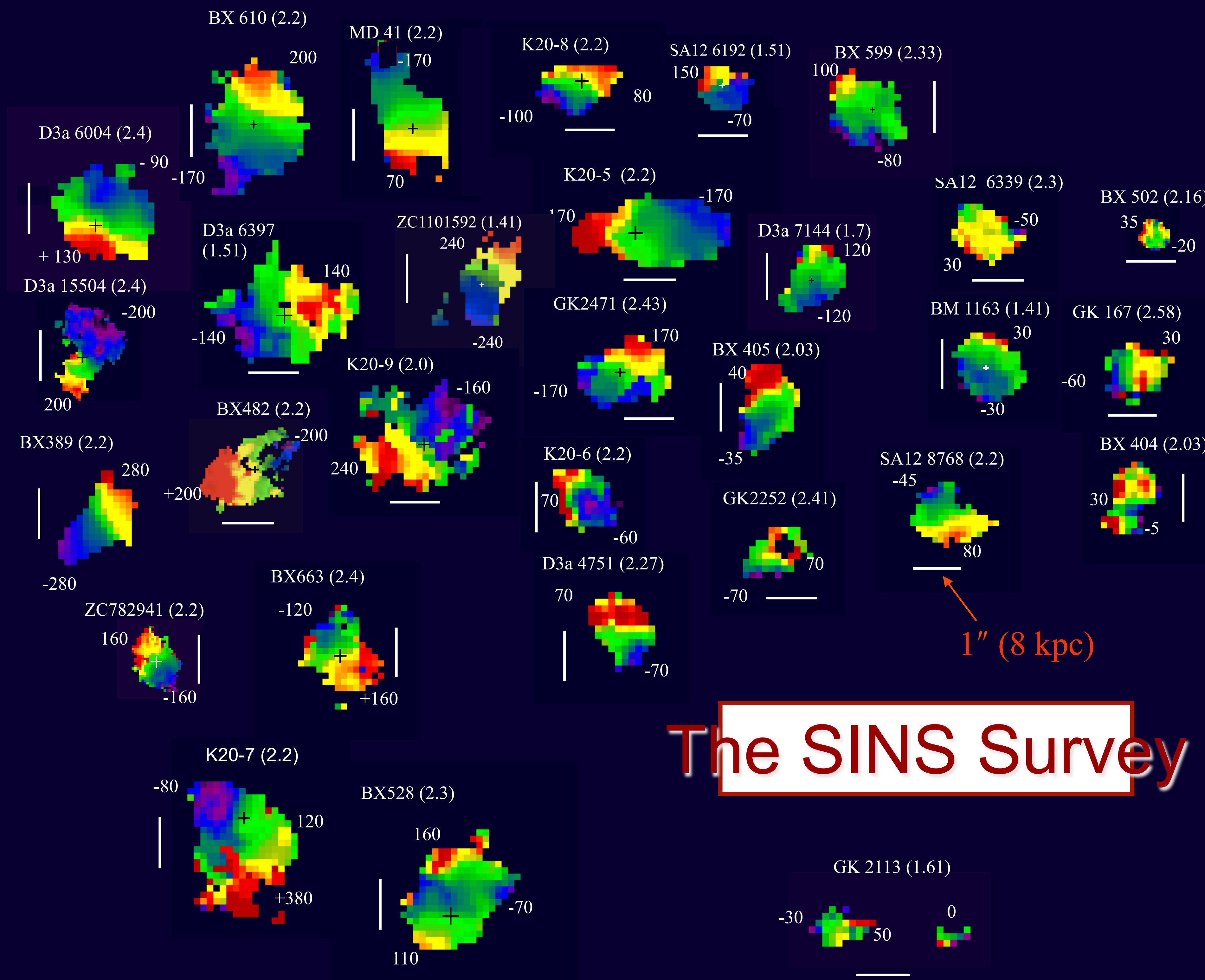
Largest survey of spatially-resolved kinematics at high z



- 113 star-forming galaxies at z ~ 1 – 3
- 30 with deep AO-assisted observations

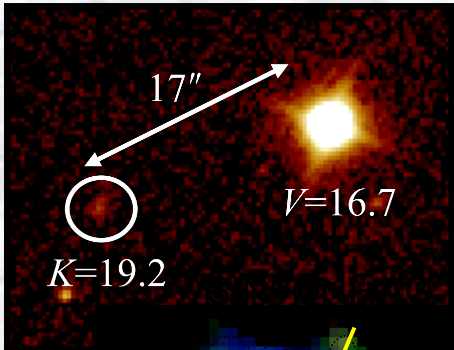
Other IFU samples at z~1-3: e.g., Law+07/09; Wright+07/09/10; Épinat+09; Jones+10; Gnerucci+10/11; Cresci+09/10; Wisnioski+11; Contini+11

NMFS et al. (2009); Mancini et al. (2011); and refs. therein



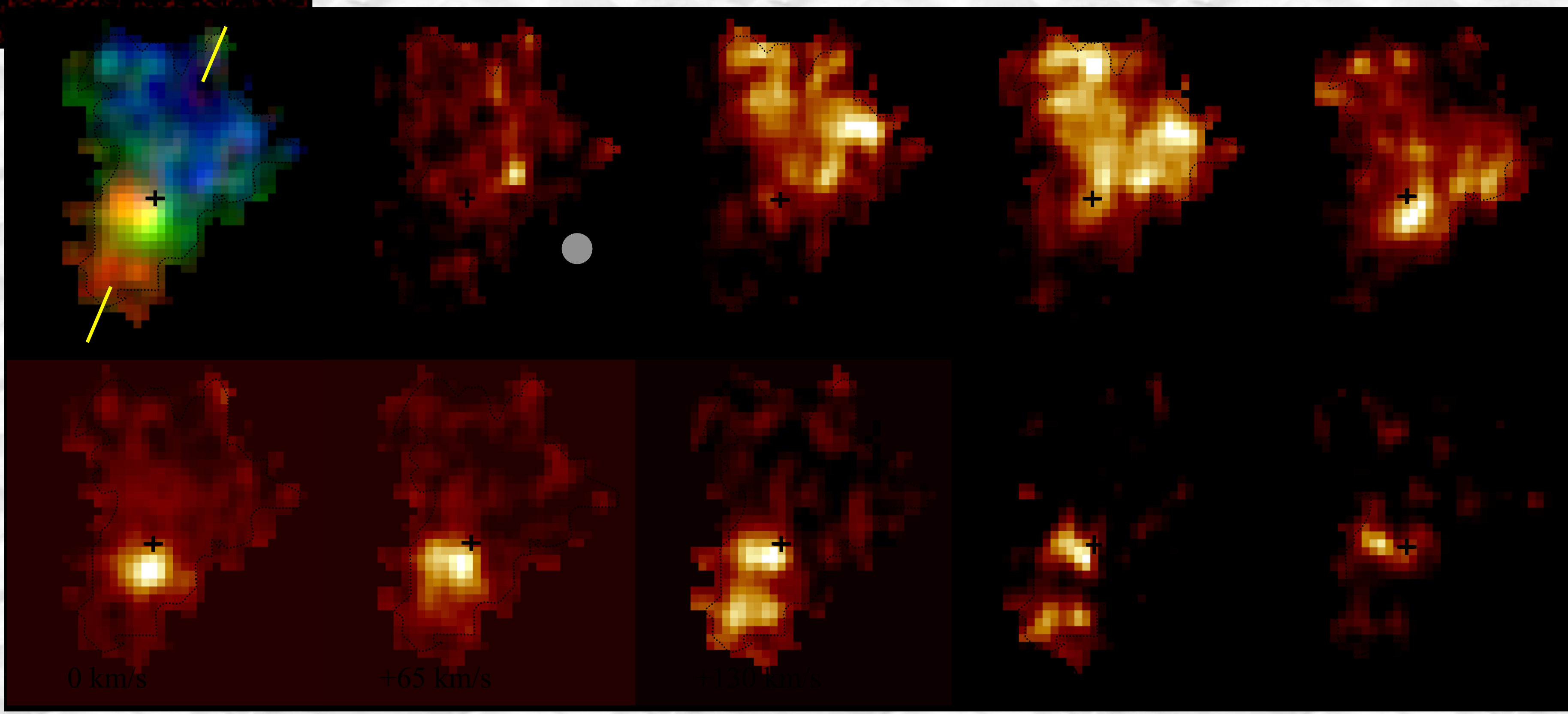
BX 610 (2.2)
MD 41 (2.2)
K20-8 (2.2)
SA12 6192 (1.51)
BX 599 (2.33)
D3a 6004 (2.4)
K20-5 (2.2)
SA12 6339 (2.3)
BX 502 (2.16)
D3a 6397 (1.51)
ZC1101592 (1.41)
D3a 7144 (1.7)
D3a 15504 (2.4)
GK2471 (2.43)
BM 1163 (1.41)
GK 167 (2.58)
K20-9 (2.0)
BX 405 (2.03)
BX482 (2.2)
BX389 (2.2)
K20-6 (2.2)
SA12 8768 (2.2)
BX 404 (2.03)
GK2252 (2.41)
D3a 4751 (2.27)
BX663 (2.4)
ZC782941 (2.2)
1″ (8 kpc)
The SINS Survey
K20-7 (2.2)
BX528 (2.3)
GK 2113 (1.61)

1st Detailed View of a z~2 Galaxy with Integral Field Spectroscopy + AO



BzK–15504 at $z = 2.38$

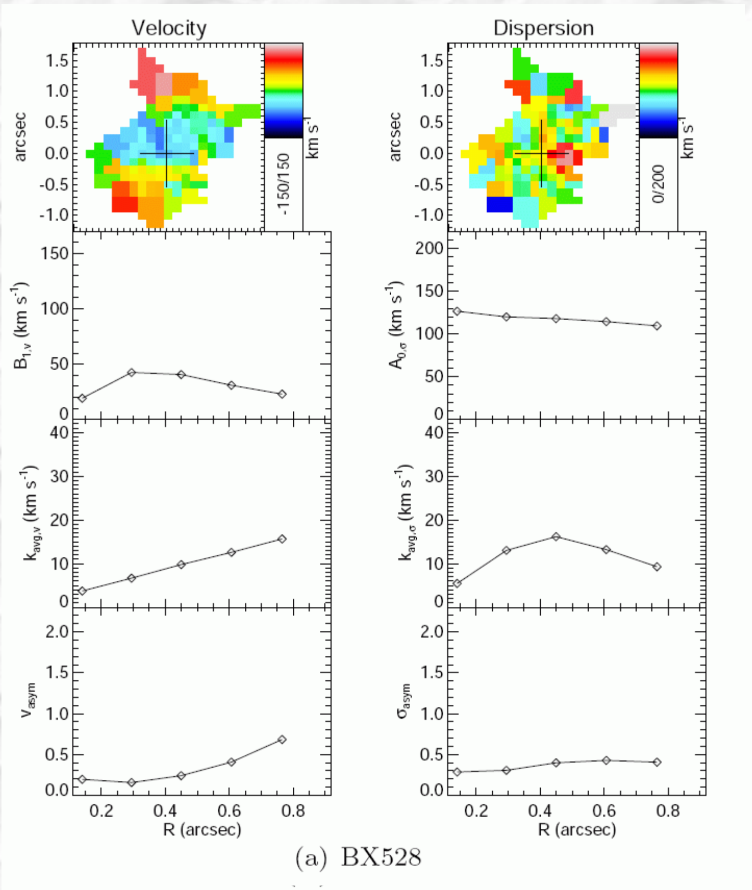
FWHM ≈ 0.15″ → ≈ 1.2 kpc

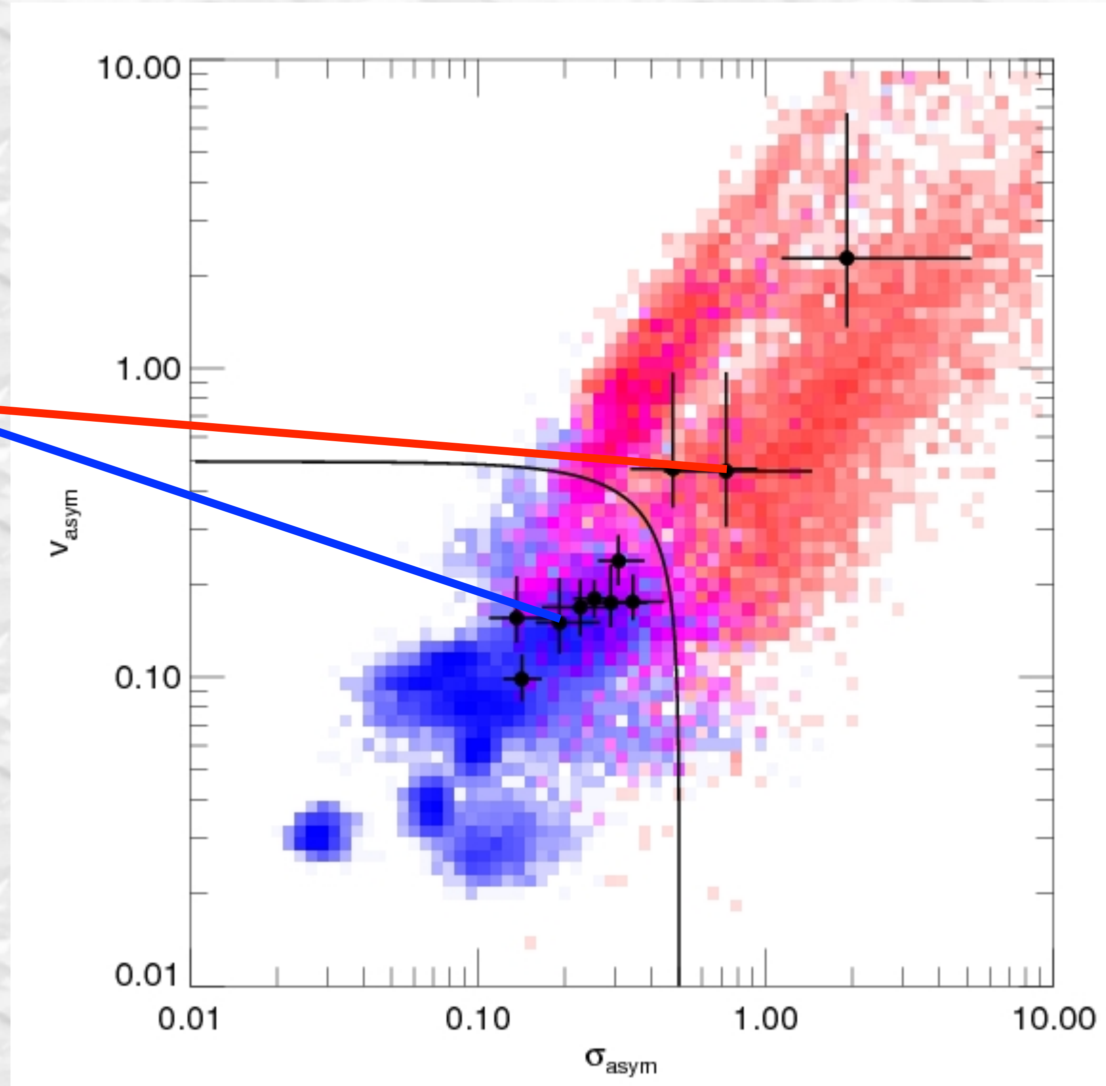


Genzel et al. (Nature, 2006)

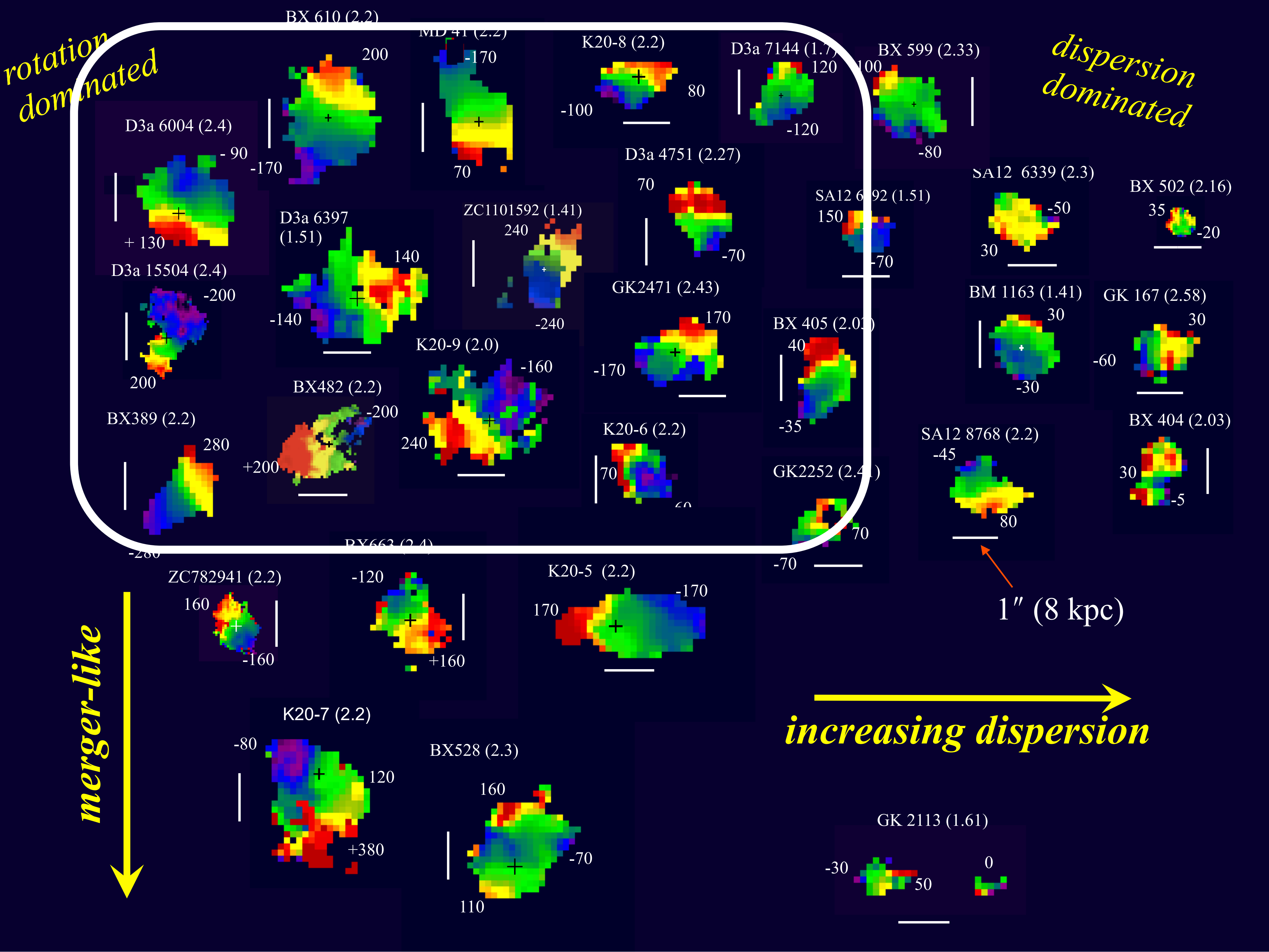
Disks vs Mergers

We use Kinemetry to evaluate the asymmetries in the velocity and dispersion fields and quantitative discriminate between rotating system and mergers:





Shapiro et al. (2008); Kinemetry: Krajnović et al. (2006)
Template data: Daigle et al. (2006), Colina et al. (2005), Naab et al. (2007), Johansson et al. (2008).


rotation dominated
dispersion dominated
merger-like
increasing dispersion
1″ (8 kpc)
BX 610 (2.2)
MD 41 (2.2)
K20-8 (2.2)
D3a 7144 (1.7)
BX 599 (2.33)
D3a 6004 (2.4)
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K20-5 (2.2)
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BX528 (2.3)
GK 2113 (1.61)

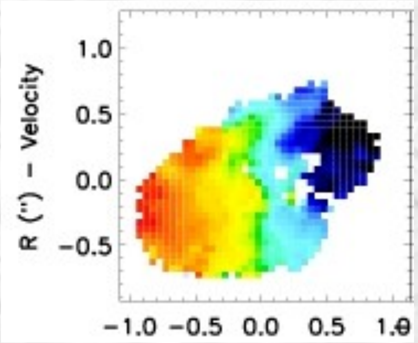
Dynamical modeling of SINS galaxies

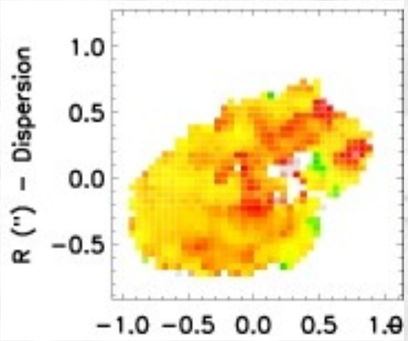
- We measure automatically (i.e. robustly and fast) with a χ^2 minimization genetic algorithm the main dynamical properties of z~2 galaxies with prominent rotation signatures using the full 3D dynamical information:

  - *Inclination and Position angle*
  - *Maximum rotational velocity*
  - *Total dynamical mass*
  - σ_0*, the dispersion term not due to rotation*

- To minimize the number of free parameters, we assume that all the mass is distributed in a simple thin exponential disk model

- The disk model is compared with both the observed Velocity and Dispersion maps of the Hα line emission





Large, turbulent disks in place at z=2

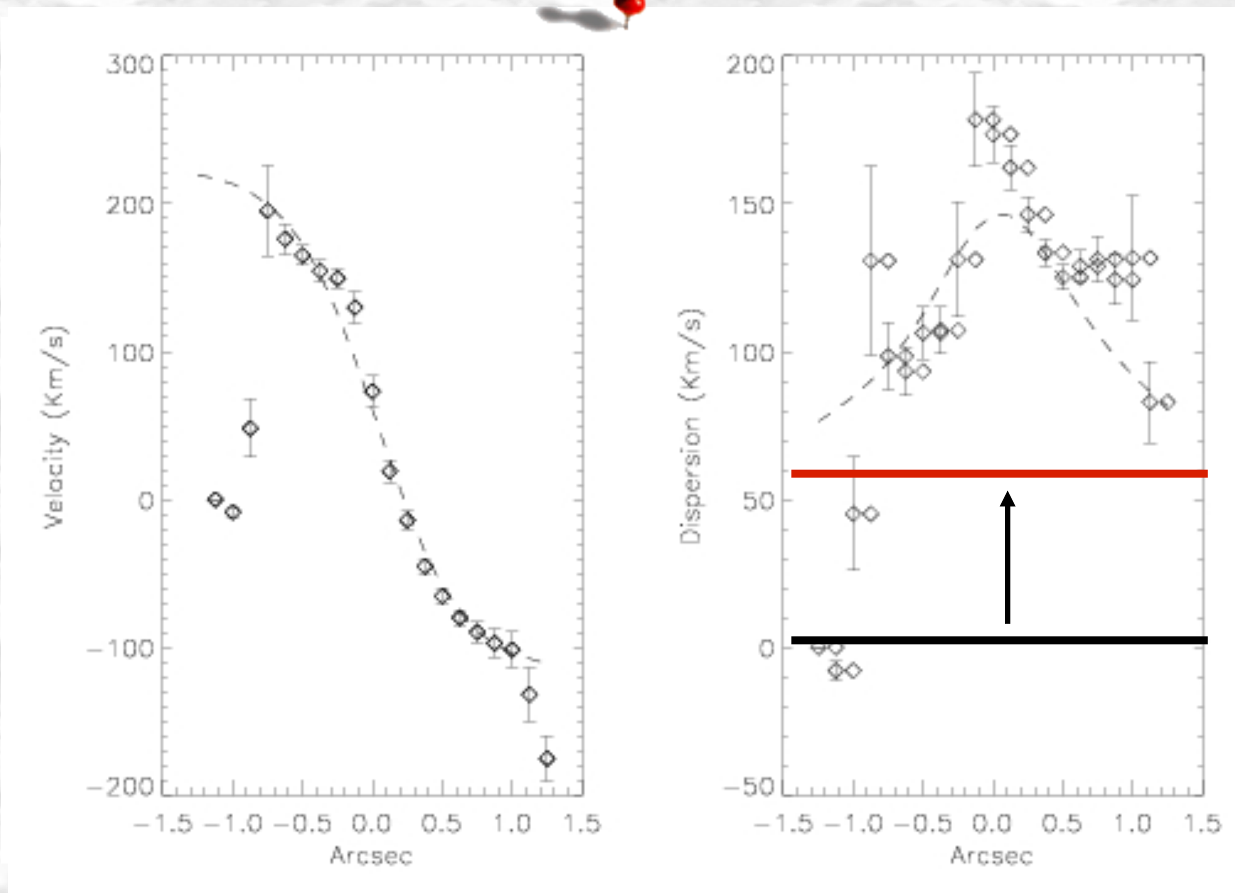
Even carefully accounting for beam smearing effects, an isotropic, **constant dispersion term σ_0 throughout the disk is required** to match the observed dispersions in the galaxies

In this sample the median **$\langle V/\sigma_0 \rangle$ = 4.7** much lower than in local spirals (V/σ_0=10-20)

Dynamical Modeling example: BzK-6004

z=2.4; R_d=6.6 kpc; i=30°; M_{dyn}=16·10^{10} $M_\odot$; V_{max}=273 km/s; σ_0=58 km/s

This **high-z disks are turbulent**, probably due to the ongoing star formation activity and/or gas accretion from the halo (see Cresci et al. 2009, Genzel et al. 2008)

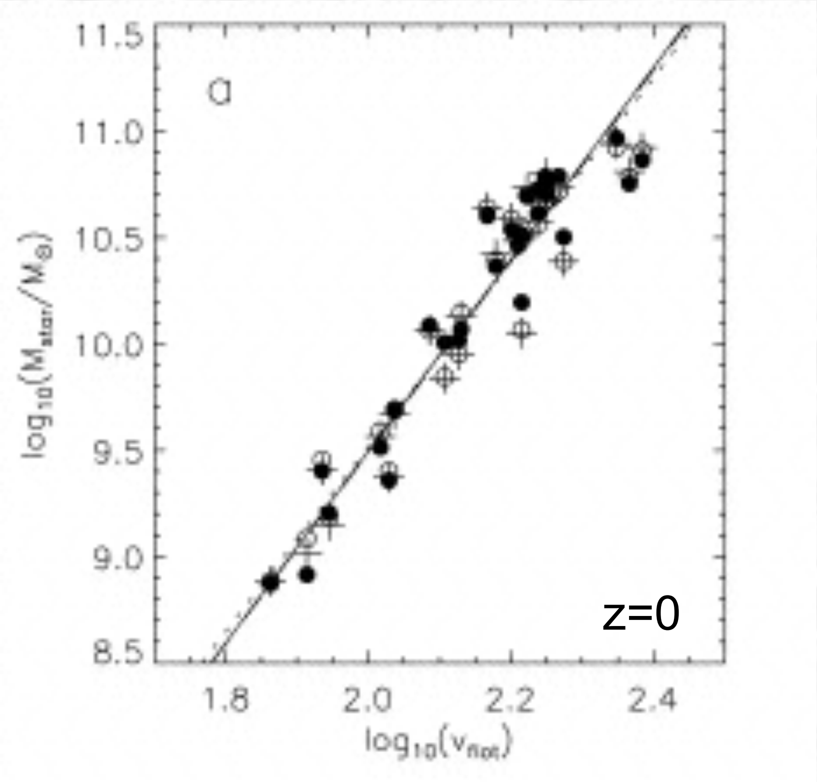


Cresci et al. (2009)

The Tully-Fisher relation

Fundamental to place observational constraints on the assembly history of galaxies and of their stellar and dark masses:

the T-F relation directly links the angular momentum of the dark halo with the stellar population of its disks.



Bell & de Jong (2001)

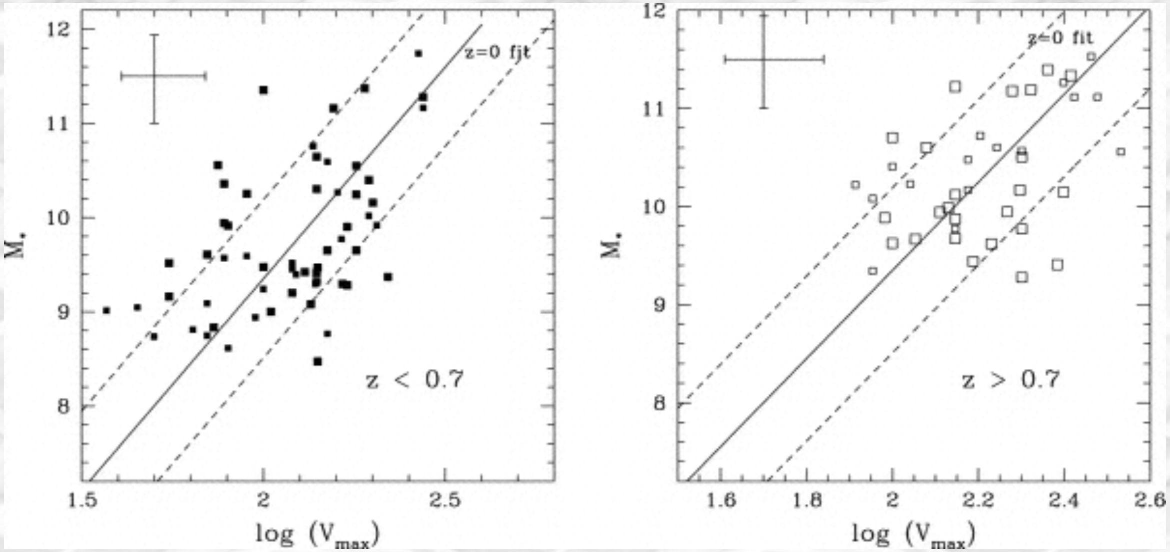
The interpretation of the evolution of a luminosity based T-F is difficult: luminosity and angular momentum are evolving at the same time:

Stellar Mass T-F

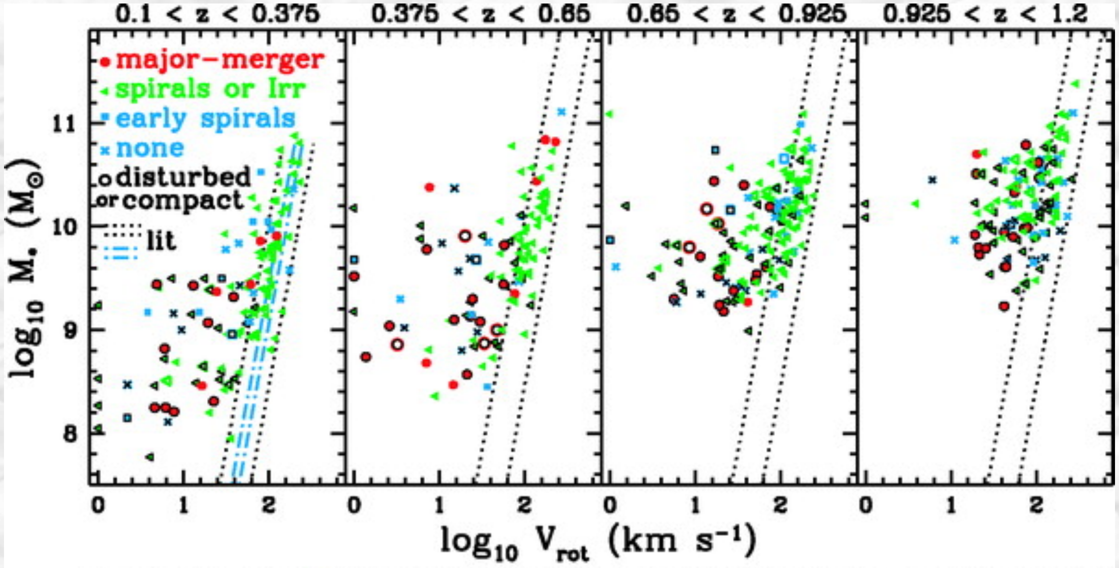
(e.g. Bell & de Jong 2001, McGaugh et al. 2005, Pizagno et al. 2005, Meyer et al. 2008, Torres-Flores et al. 2011)

The stellar mass T-F relation evolution

The limited data at higher redshift suggest that the zero-point of the relation evolves only modestly at higher redshift



Conselice et al. (2005)



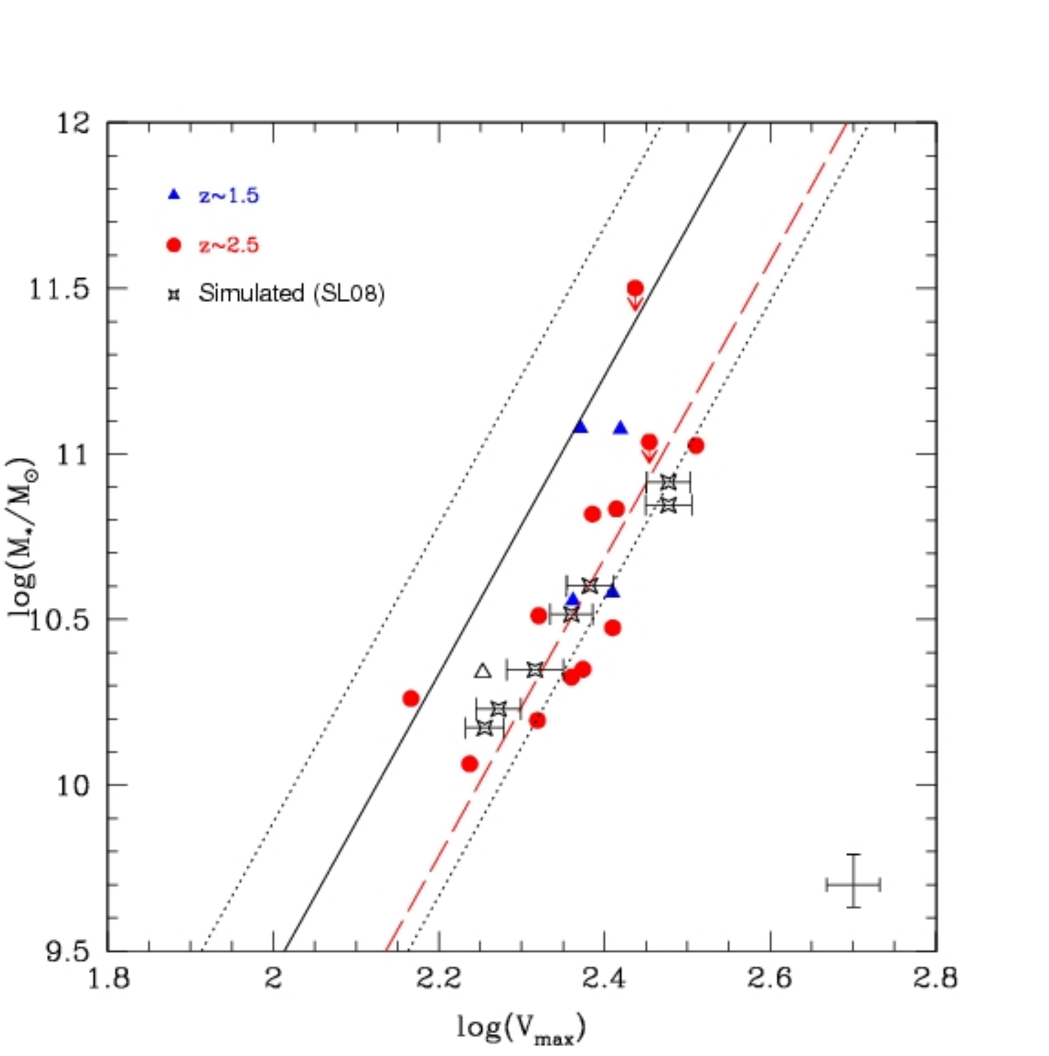
The evolution of individual galaxies up to z~1.2 occurs mainly along the relation

Kassin et al. (2007)

see also Puech et al. (2008), Meyer et al. (2008), Gnerucci et al. (2011)

The z=2.2 Tully-Fisher relation

With our data we can push for the first time the study of the evolution of scaling relations **up to z~2.2** for a sizeable sample:



Cresci et al. (2009)

Thanks to our selection and full 3D coverage of the dynamics, a **remarkably low scatter** is observed

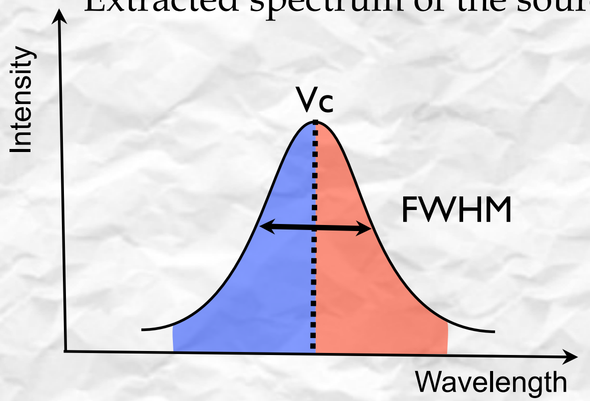
$$\log(M_*) = -0.09 + 4.49 \times \log(V_{max})$$

We detect a significant (3.6σ) **evolution of the zero point** of the relation respect to z=0

Cosmological SPH simulations by Sommer-Larsen et al. (2008) predict a **zero-point shift** of the relation at z~2, as observed.

Improved Virial masses with Spectroastrometry

Extracted spectrum of the source

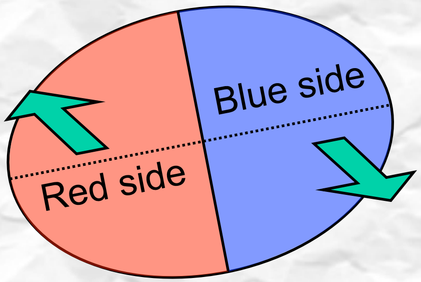


"Classical" virial mass estimator

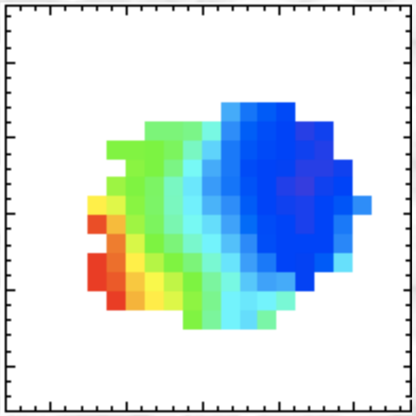
$$M(r_e) = f\frac{r_e V_{circ}^2}{G}$$

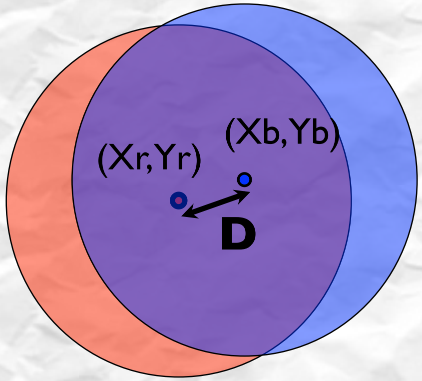
"Spectroastrometric" virial mass estimator

$$M(r_e) = f\frac{r_{spec} FWHM^2}{G}$$



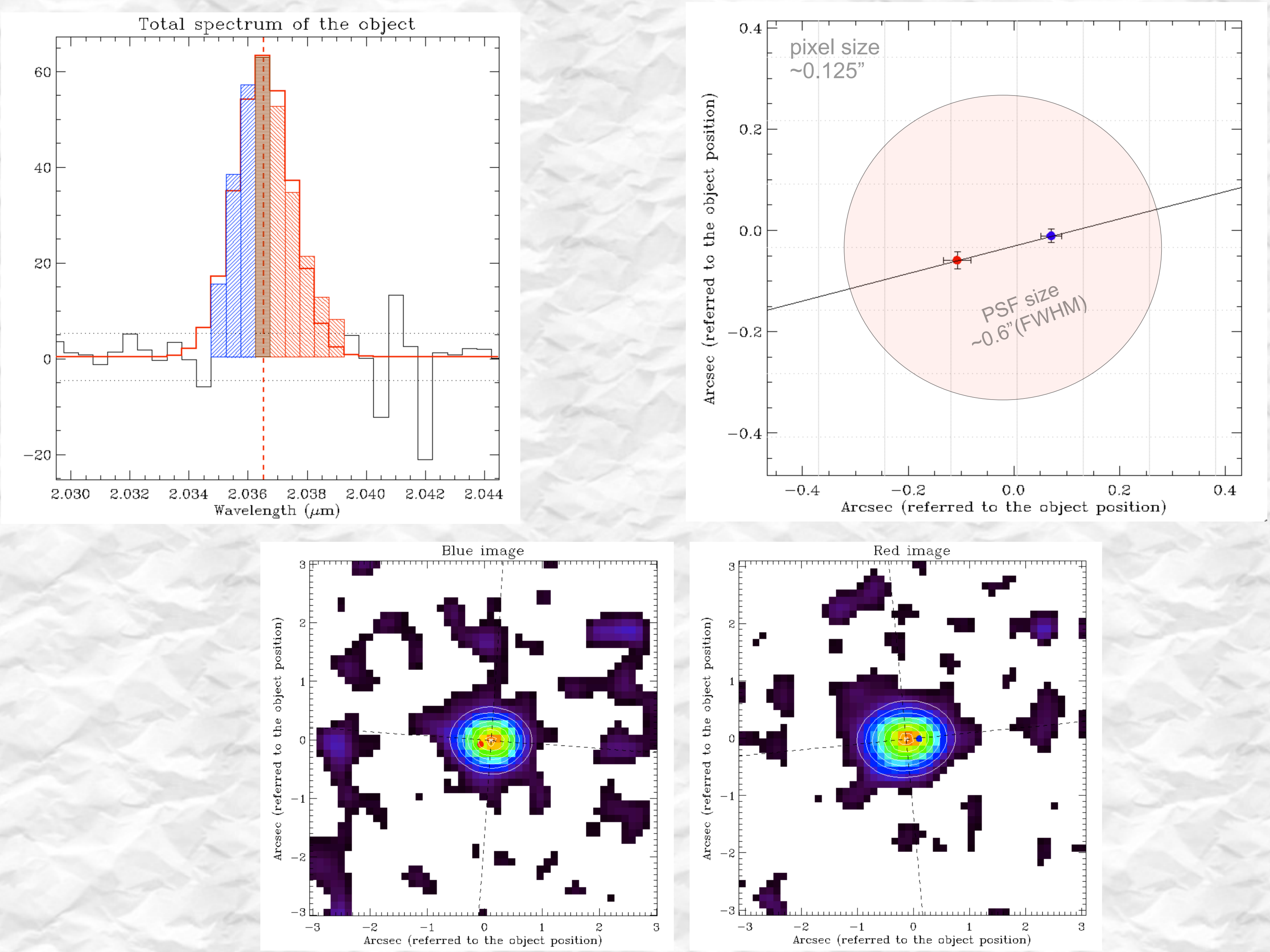
Velocity map





$$r_{spec} = D/2$$

Spectroastrometric mass estimator



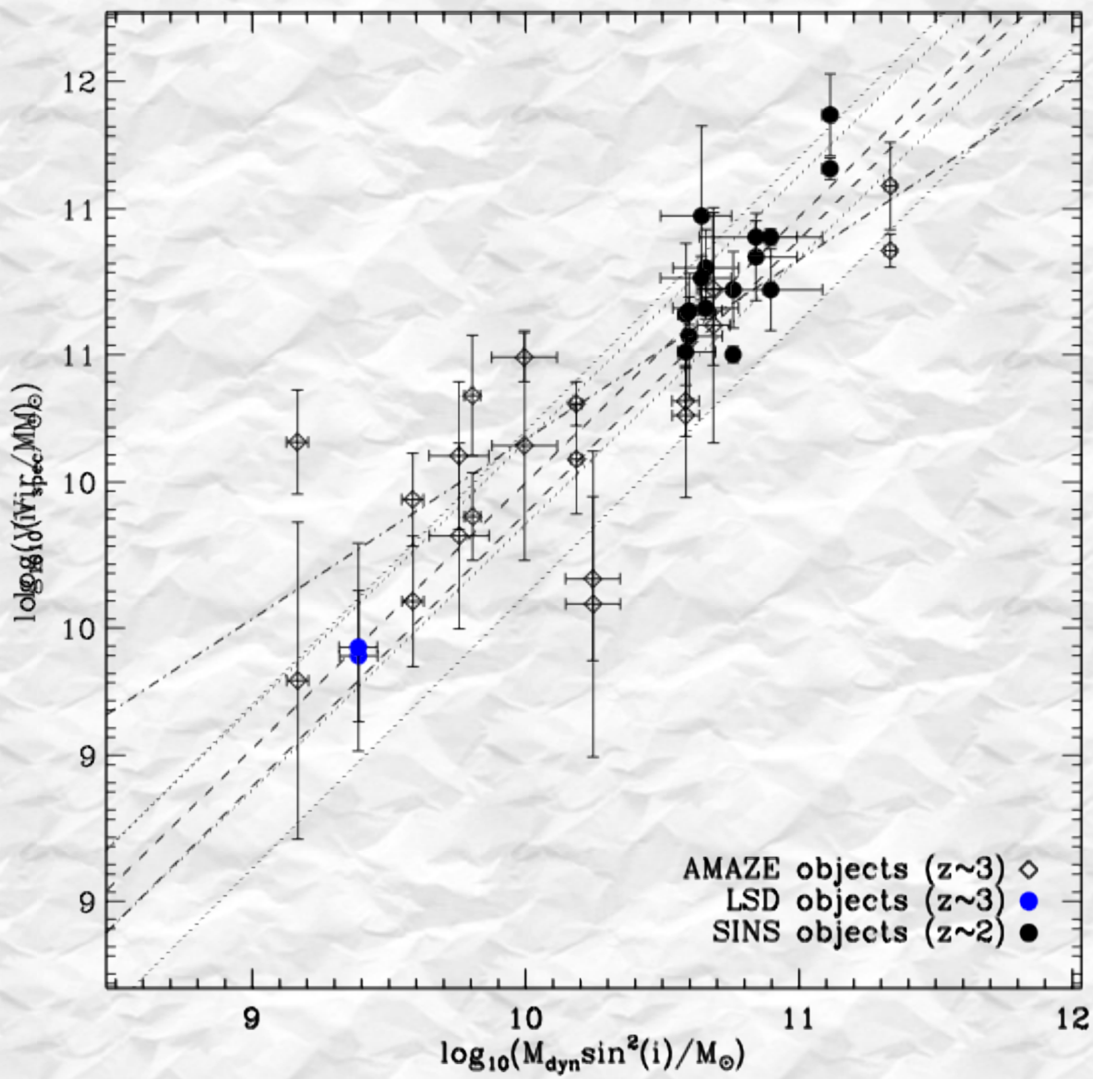
Calibration of the mass estimator

$$M_{dyn} sin^2 i = f_{spec} \frac{FWHM^2 r_{spec}}{G} = f_{spec} Vir_{spec}$$

Calibrated using
19 high S/N rotating galaxies

from the AMAZE, LSD (z~3) e SINS (z~2) samples

$$M_{dyn} sin^2 i \quad = \quad (1.0 \pm 0.1)\, 2.3 \times 10^9\, M_\odot \left(\frac{V}{100\, km/s}\right)^2 \left(\frac{r_{spec}}{1\, kpc}\right)$$
$$(\pm 0.15\, dex - \text{systematic})$$



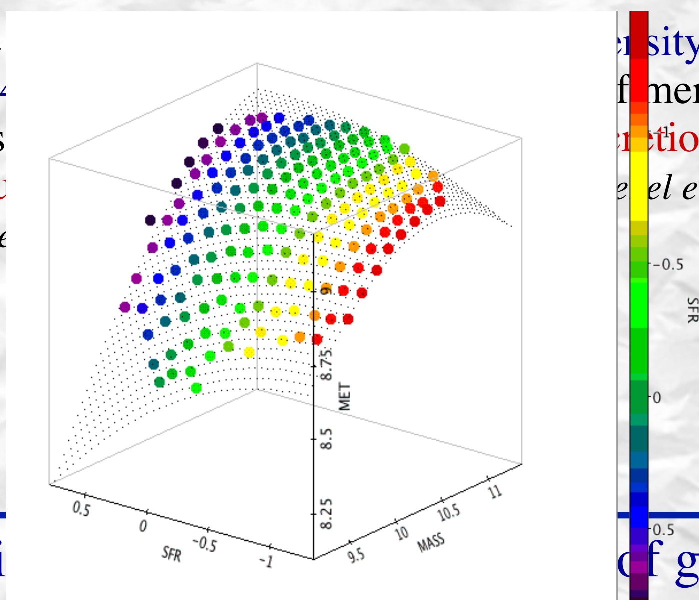
Gnerucci et al. 2011

Dynamical Evolution of Gas-rich Disks

- Massive (M_*~10^{10}-10^{11} $M_\odot$), high star-forming (SFR~100 $M_\odot$/yr), gas rich disks in place at z~2 incompatible with being major merger remnants *(Shapiro et al. 2008, Cresci et al. 2009, but also Wright et al. 2007, Bournaud & Elmegreen 2009, van Starkenburg et al. 2008, Genzelet al. 2010, Tacconi et al. 2010)*

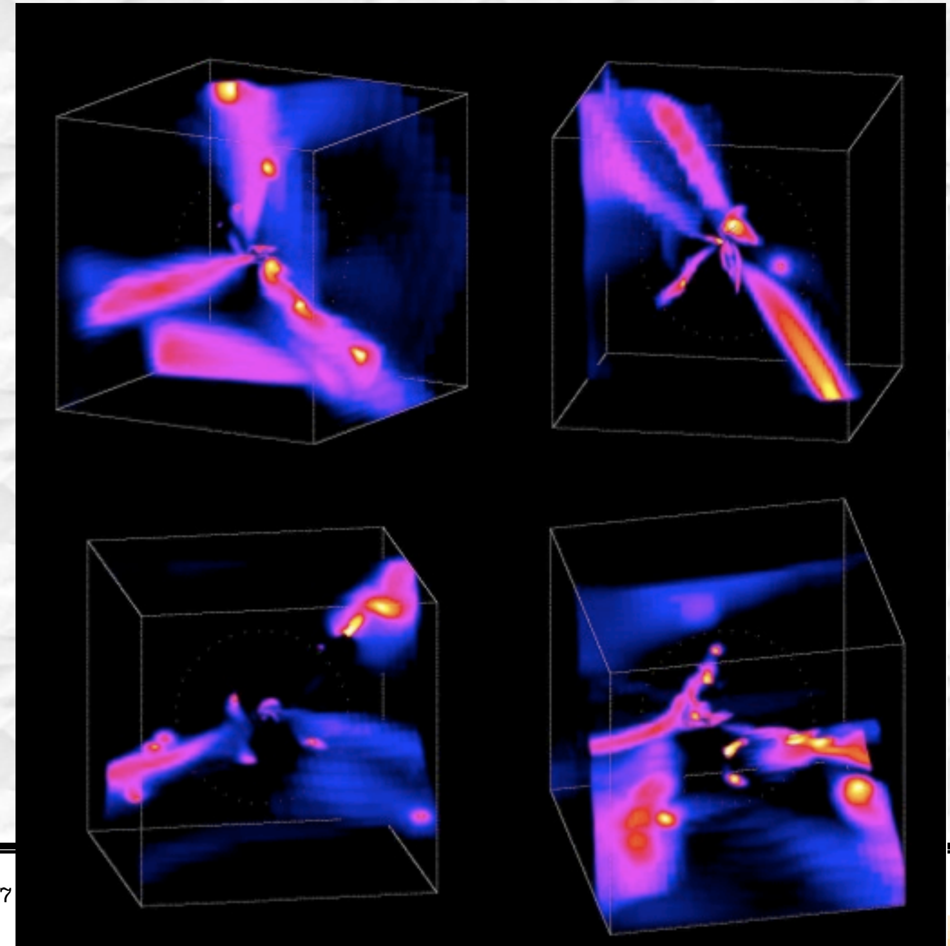
- Tight correlation between M_*, SFR (and metallicity) for star forming galaxies up to z=1-2.5: small space for short duty cycle merger events *(Elbaz et al. 2007, Daddi et al. 2008, Pannella et al. 2009, Förster Schreiber et al. 2009, Mannucci et al. 2010)*

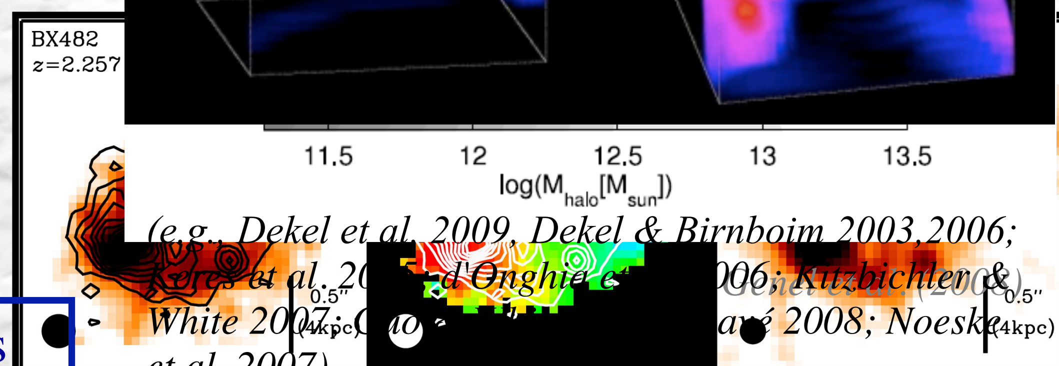
- Massive ... sity a factor of ... f merger induced s... tion rate high enou... el et al. 2009, Elme...



Mannucci et al. (2010)

Conti... f gas rather than violent mergers?

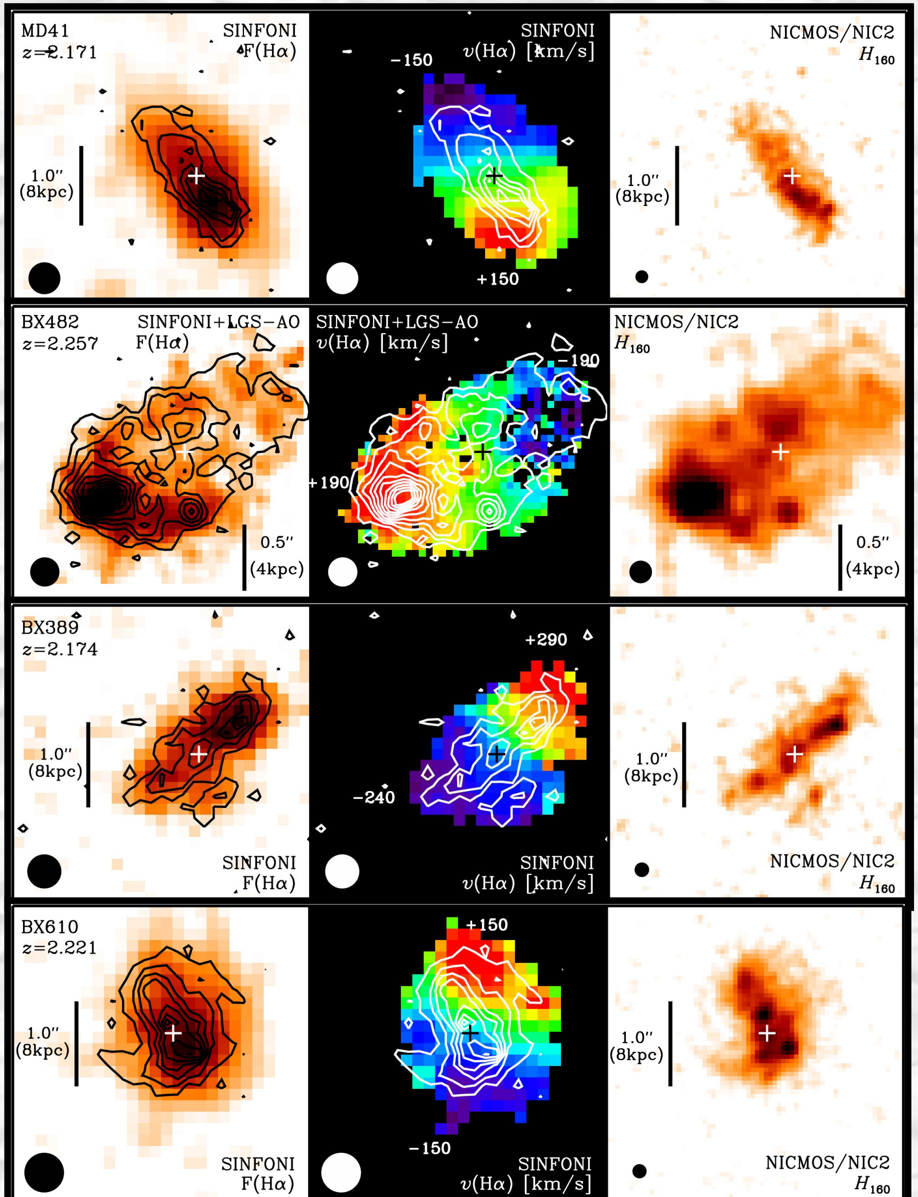




11.5 12 12.5 13 13.5
log(M_{halo}[M_{sun}])

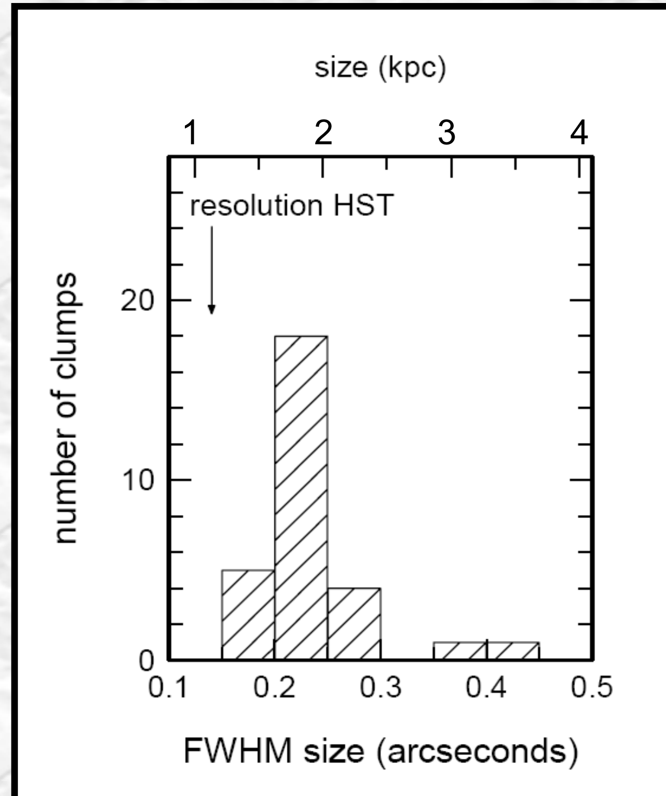
(e.g., Dekel et al. 2009, Dekel & Birnboim 2003,2006; Keres et al. 20... d'Onghia e... 006; Kitzbichler & White 2007; C... avé 2008; Noeske et al. 2007)

Star formation in large clumps



Förster Schreiber et al. (2011); Genzel et al. (2008)

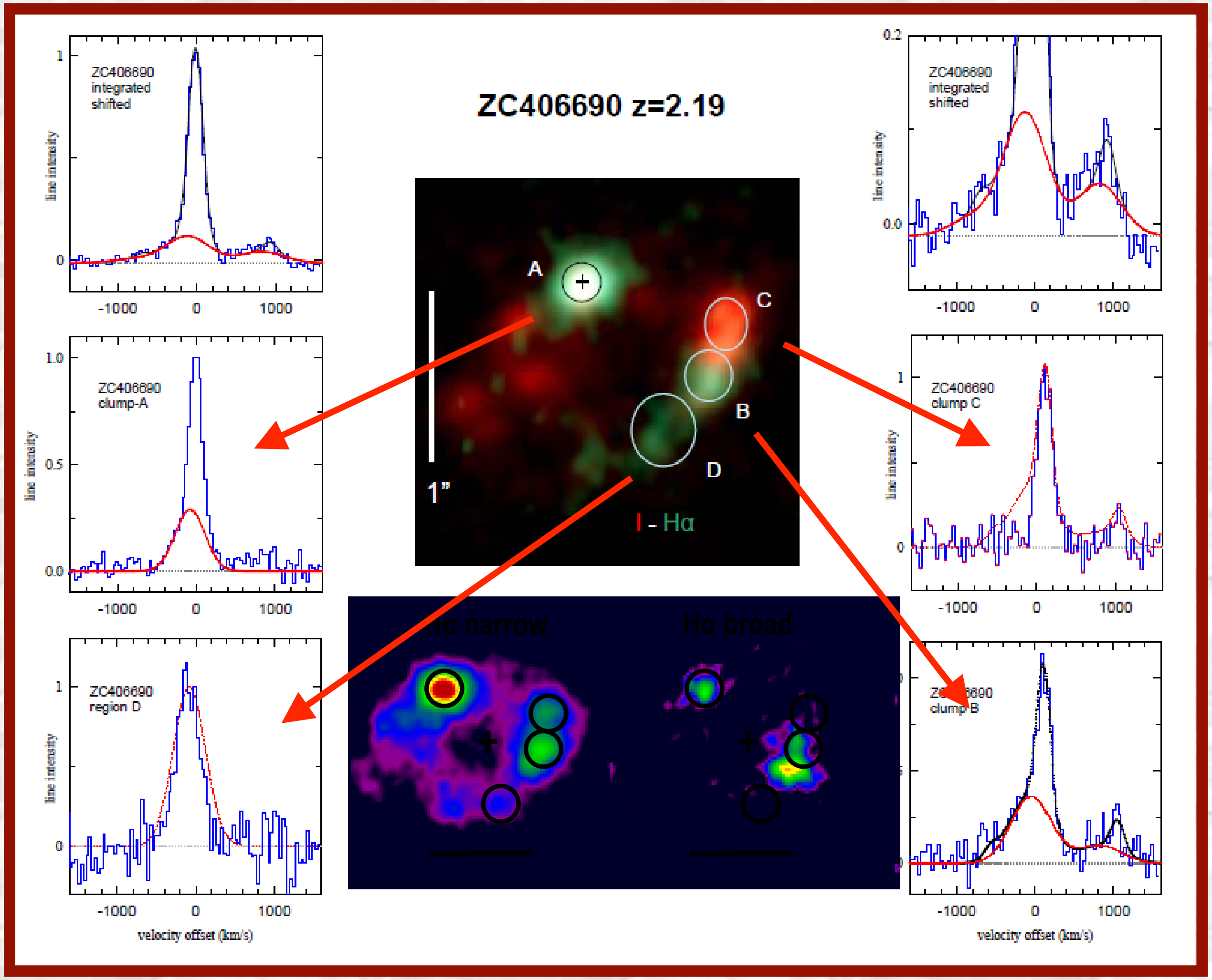
Clump size 0.15”-0.4” comparable to the Jeans length for these gravitationally instable disks (~0.3”)

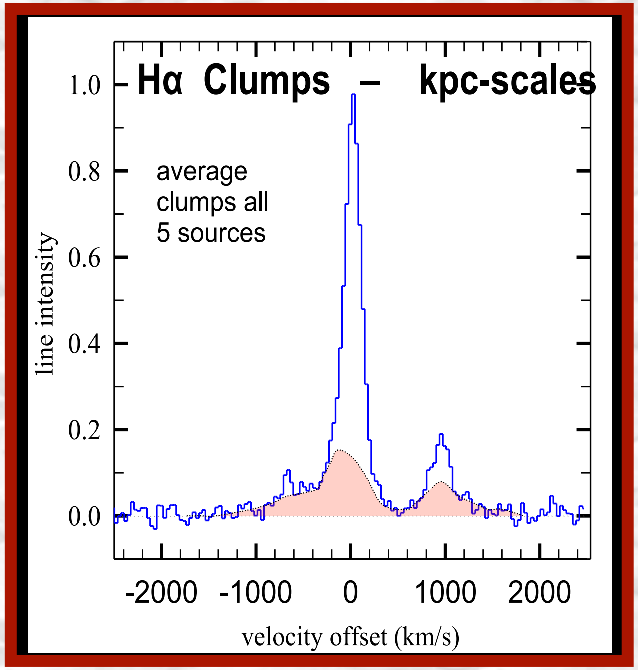


(Also, Cowie et al. 1995; van den Bergh et al. 1996; Giavalisco et al. 1996; Conselice et al. 2004; Lotz et al. 2004; Papovich et al. 2005; Toft et al. 2007; Law et al. 2007; Elmegreen, Elmegreen, et al. 2004-2008; and others)

Vigorous Stellar Feedback in Clumps

- Clump mass outflow rates ~ 1 – 10 x SFRs
- Lifetimes of most actively star-forming clumps limited to a few 100 Myrs



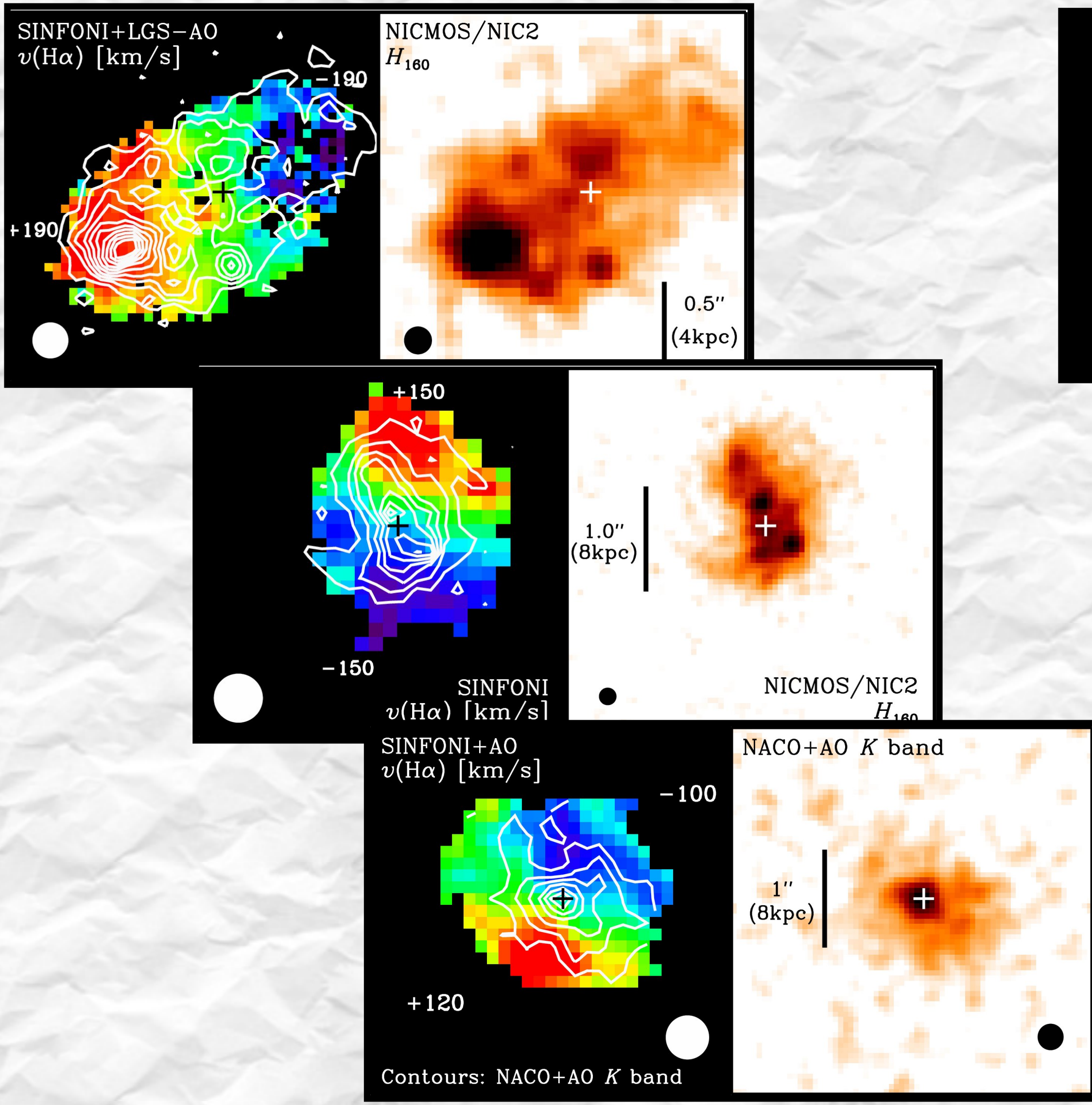


Genzel et al. (2011); Newman et al. (in prep.)

Large-scale galactic winds at high z: e.g., Pettini et al. (2000); Shapley et al. (2003); Erb et al. (2006/08); Shapiro et al. (2009); Weiner et al. (2010); Steidel et al. (2010); Law et al. (2011), Wisnioski et al. (2011)

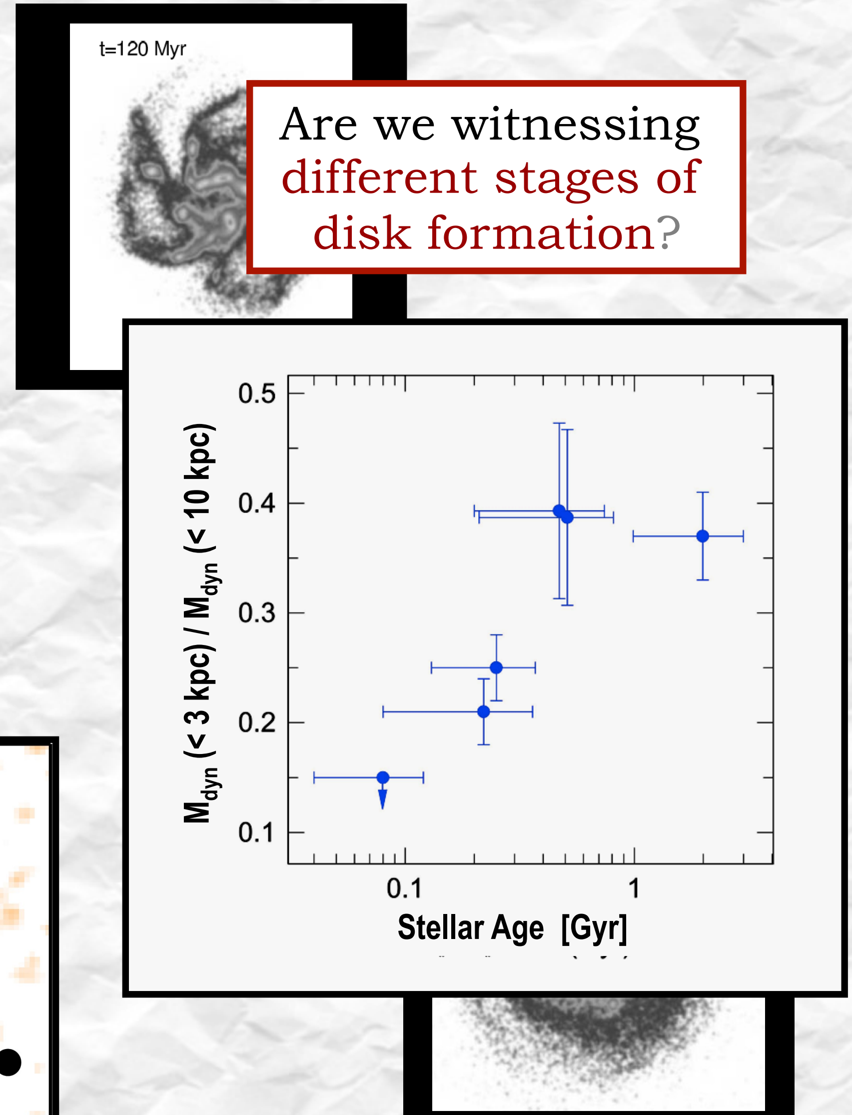
Bulge Formation in Gas-rich High z Disks

In-situ Observations



Genzel et al. (2008/11); NMFS et al. (2011b)

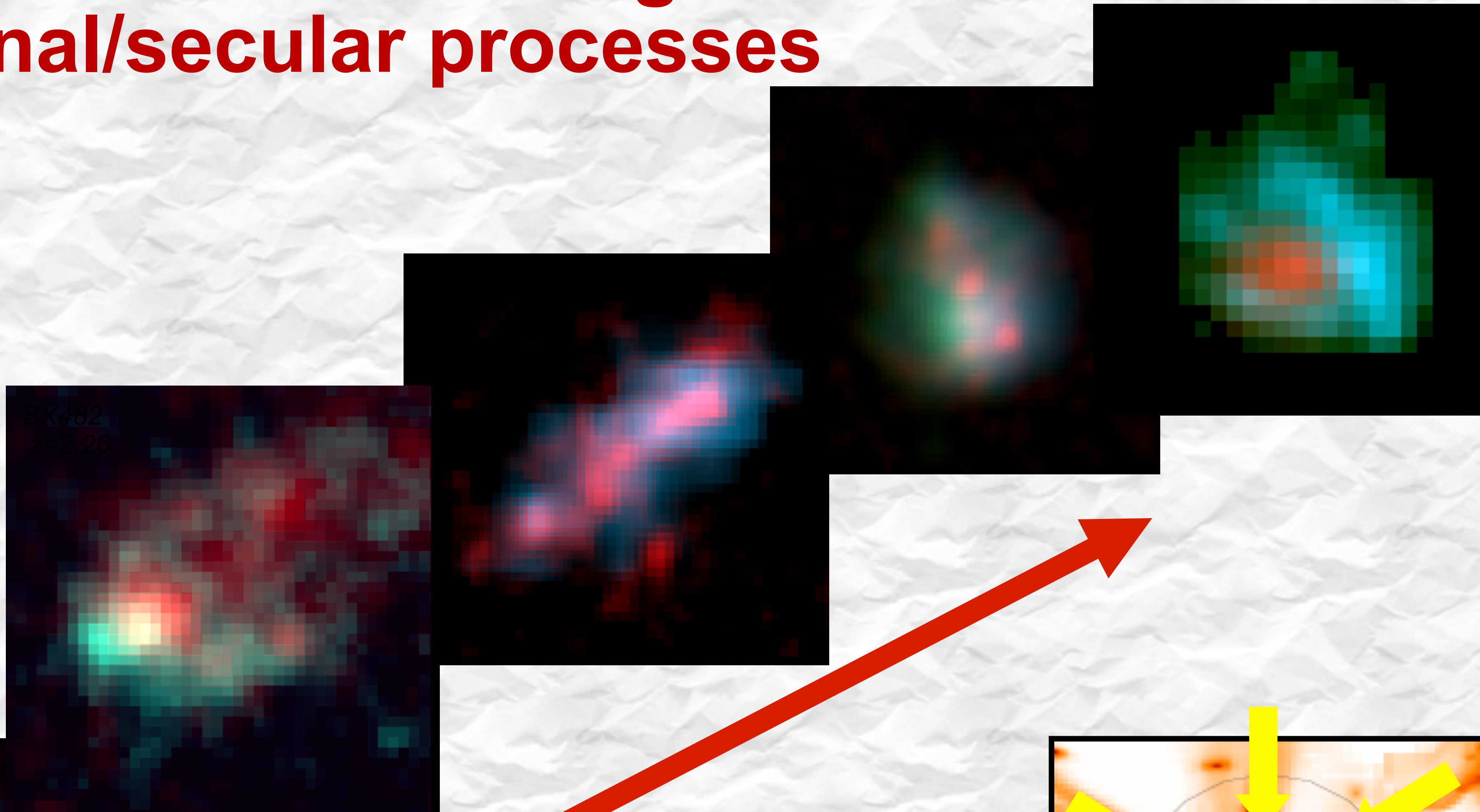
Numerical Simulations

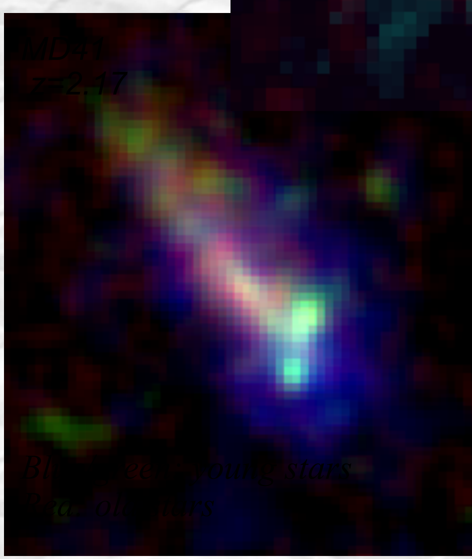


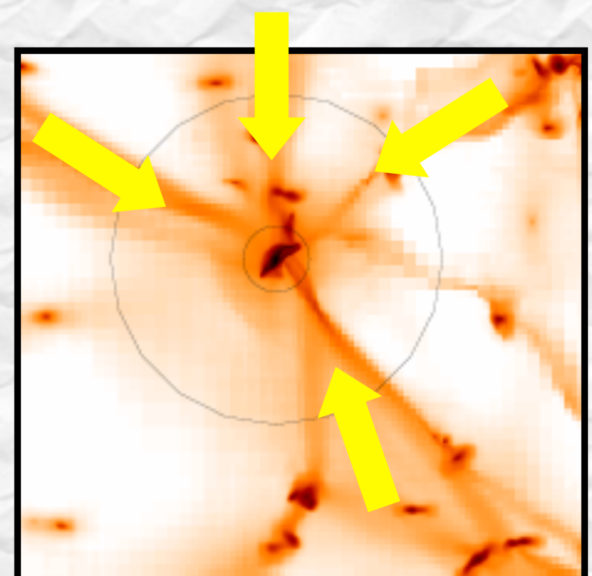
Bournaud et al. (2007-2009)

Also, e.g., Noguchi99; Immeli+04; Governato+06/07; Carollo+07; Burkert+09; Dekel+09; Aumer+10; Ceverino+10; Genel+11

Cold flows/minor mergers
Internal/secular processes

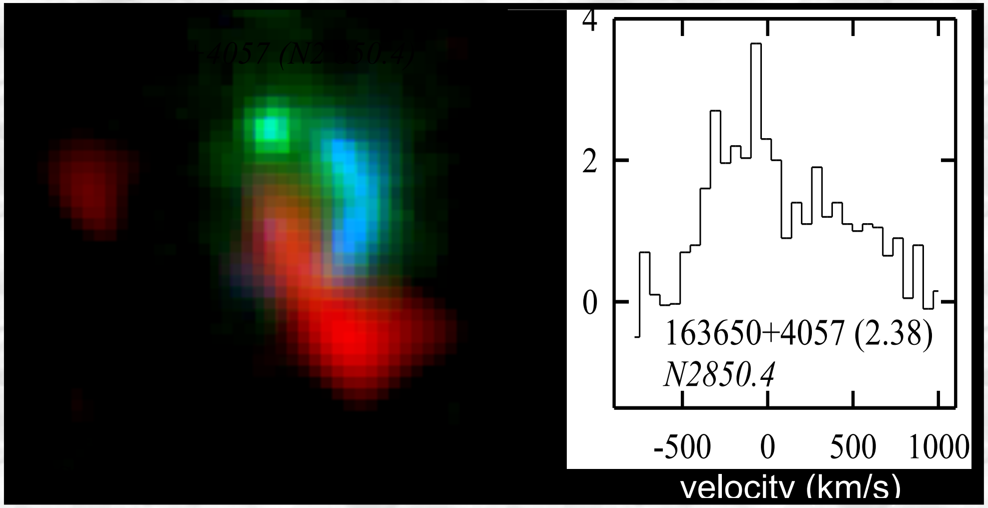


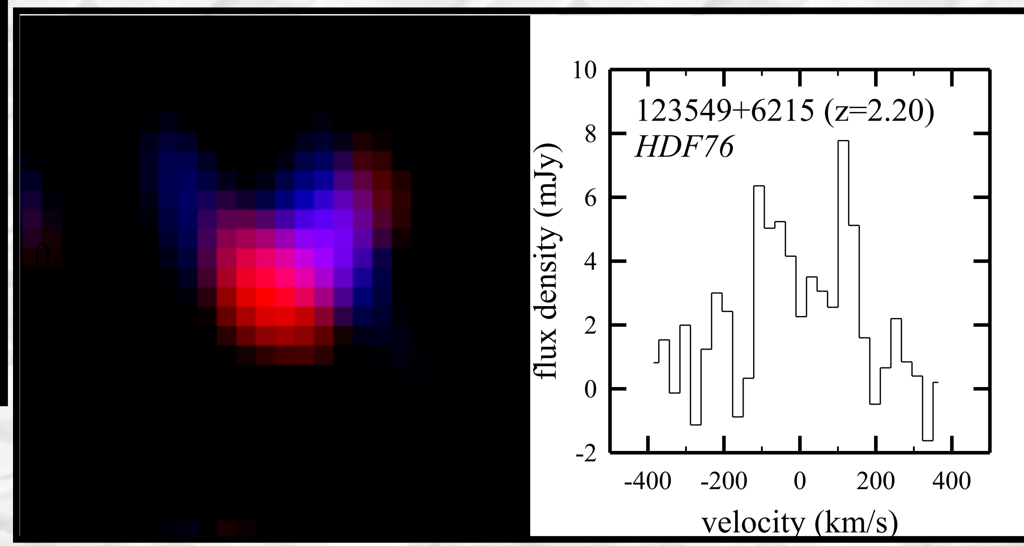




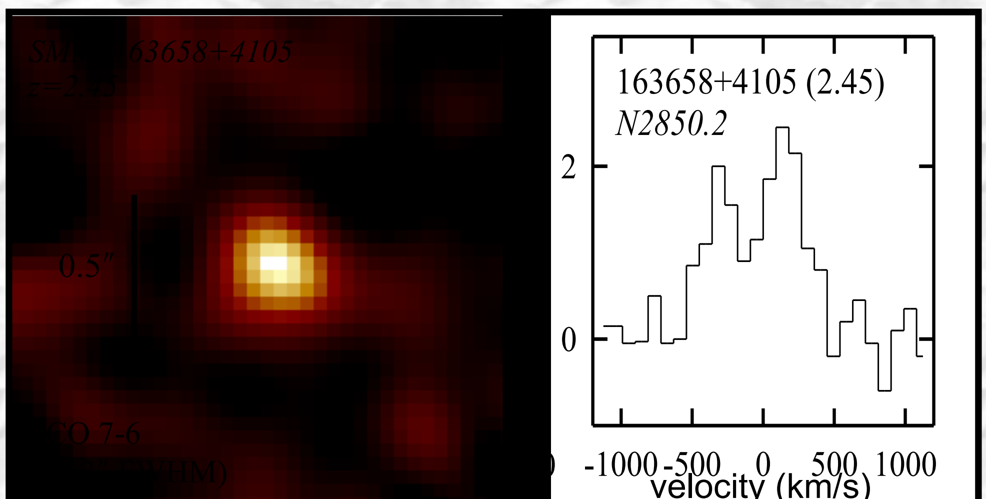
*(e.g., Dekel & Birnboim 2003, 2006;
Kereš et al. 2005; d'Onghia et al. 2006;
Noguchi 1999; Immeli et al. 2004; Bournaud et al. 2007;
Dekel et al. 2009)*

IRAM Interferometry of SMGs Reveal Compact Mergers





Molecular Gas Imaging Spectroscopy at z~1-3

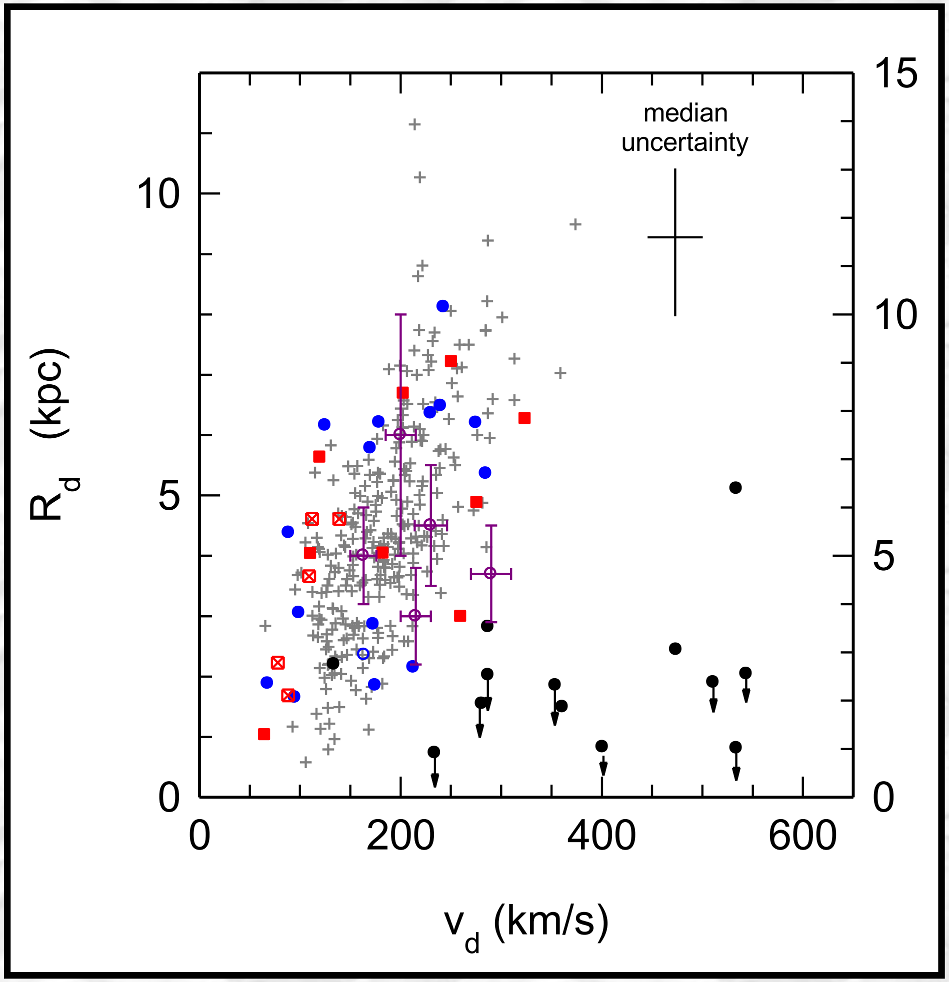


$M_{dyn} \sim 10^{10}\ M_{\odot}$

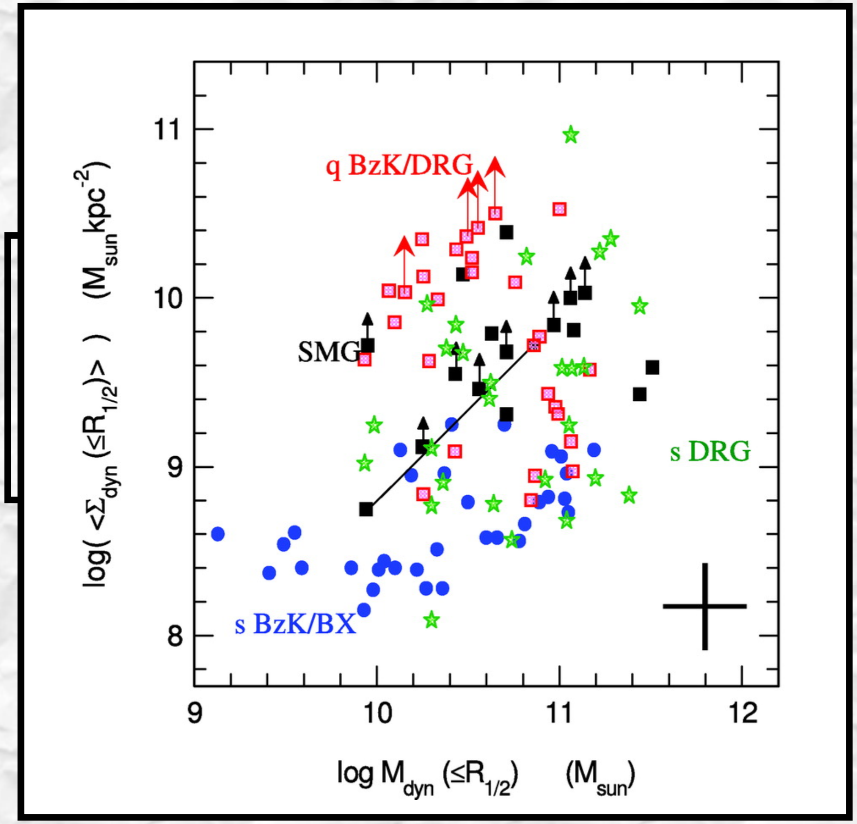
Re~0.2" (1.6 kpc)

Tacconi et al. (2006, 2008)
(also: Swinbank et al. 2006)

Velocity-Size Correlation: High-z Disks vs Dissipative Mergers



Bouché, Cresci et al. (2007); Tacconi et al. (2006)

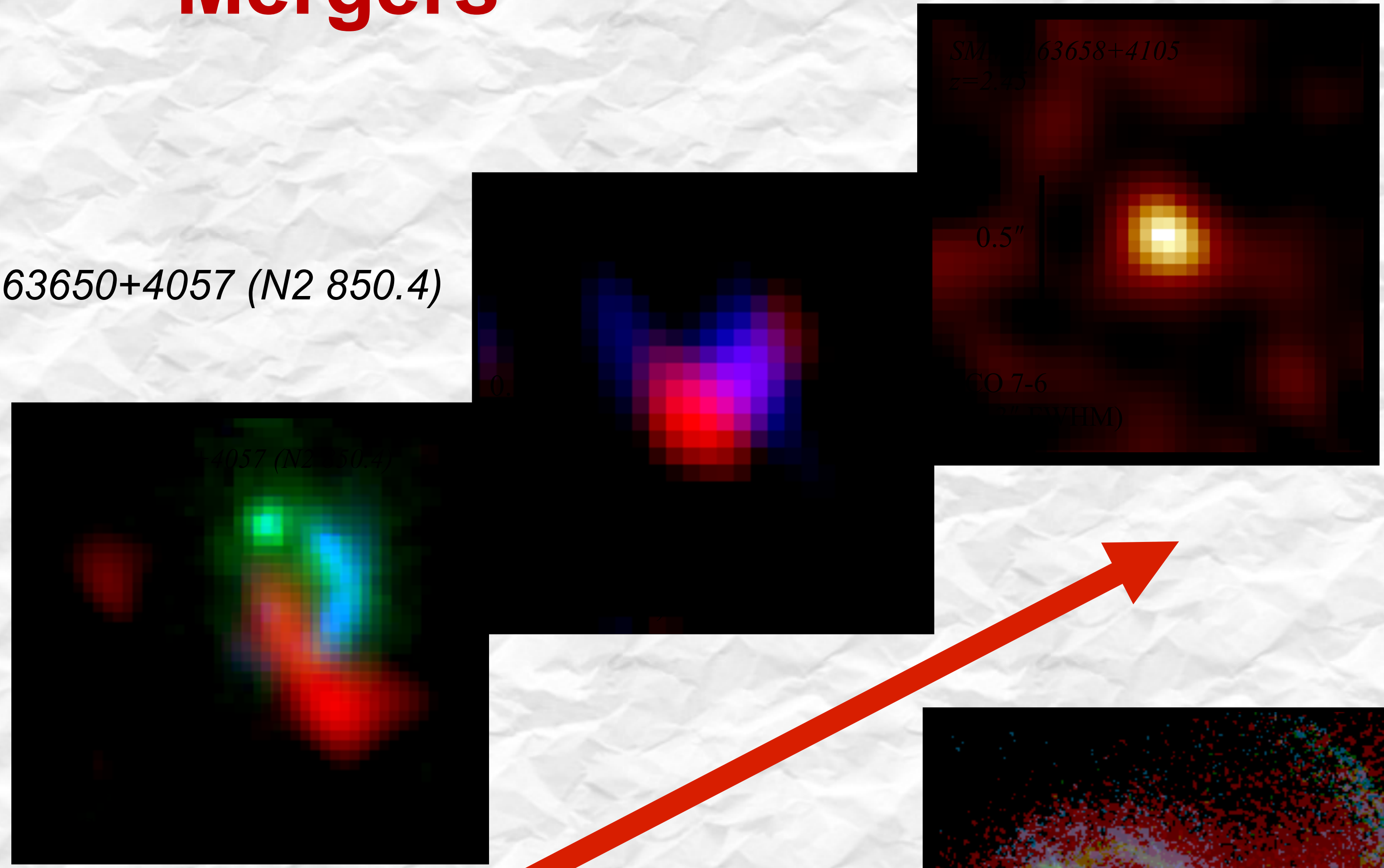


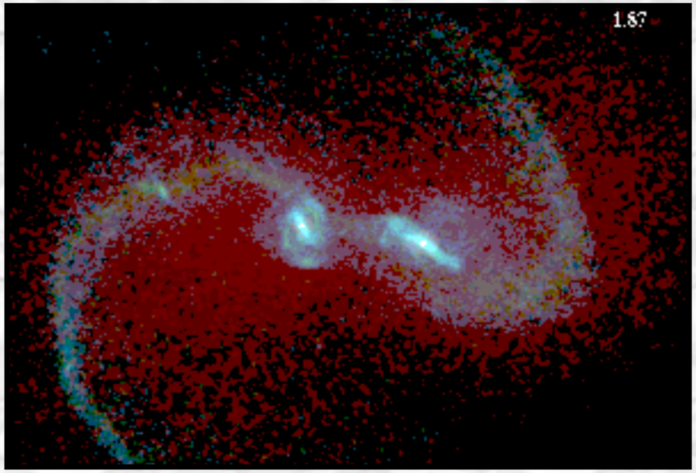
Tacconi et al. (2008); Smail et al. (2007)

(see also: Courteau et al. 1996; 1997; 2007, Daddi et al 2005; Trujillo et al 2006; Toft et al 2007; 2008; Zirm et al 2007; Cimatti et al 2008; van Dokkum et al 2008)

Gas-Rich Major Mergers

SMMJ163650+4057 (N2 850.4)
z=2.39





(e.g., Toomre & Toomre 1972; Barnes & Hernquist 1996; Springel & Hernquist 2005; di Matteo et al. 2005; Naab & Burkert 2003, 2006)

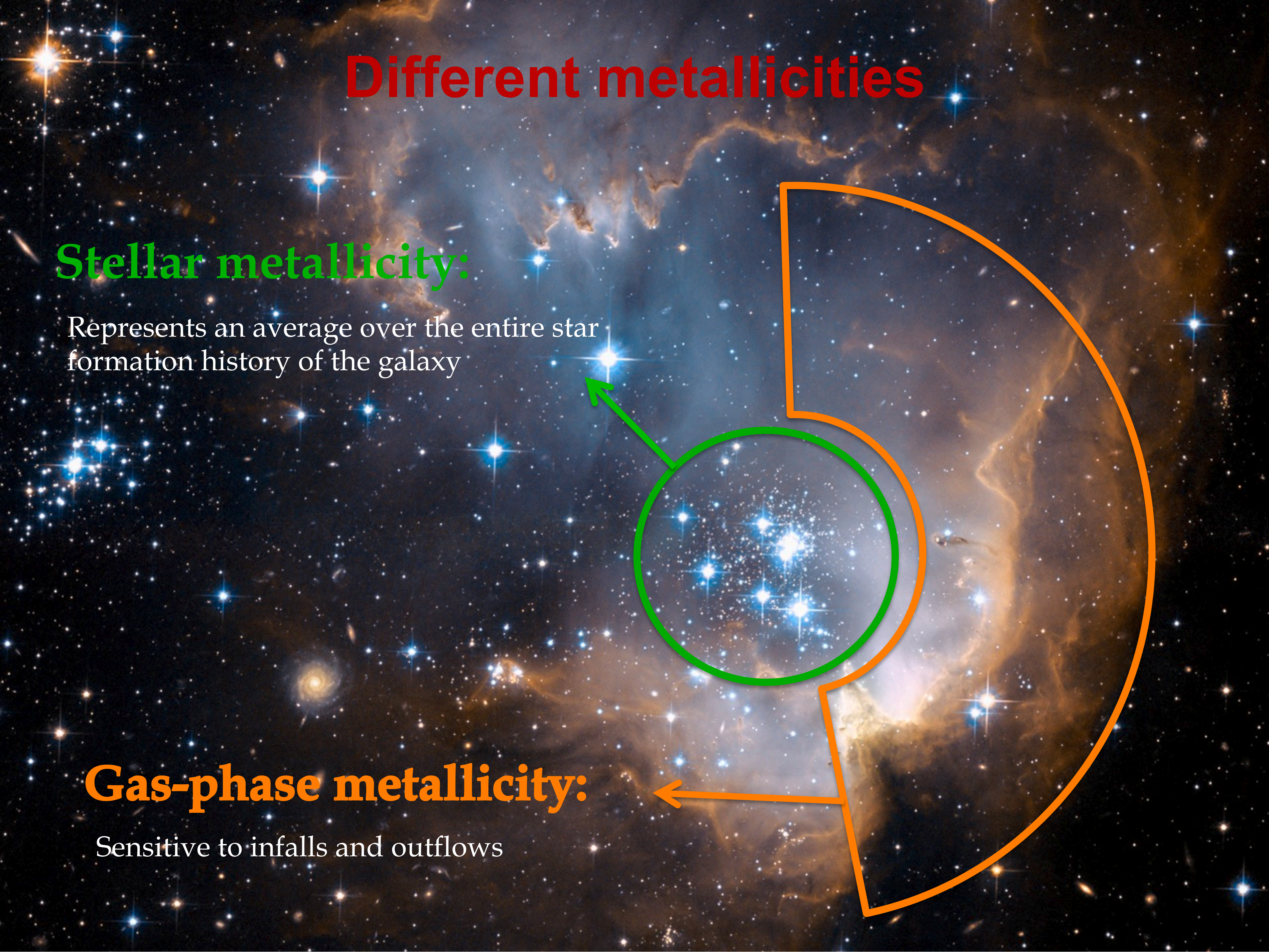
metallicity: a fundamental parameter

⋆ **Dynamics** and Star Formation Rate reveal the ***current*** status of galaxies, linking baryonic physics to dark matter and cosmological simulations.

⋆Metallicity and relative element abundances indirectly traces the ***integrated*** galaxy SFH, not only the current SFR, reflect the cycling of gas through stars, and any exchange of gas between galaxy and its environment (infall/outflows)

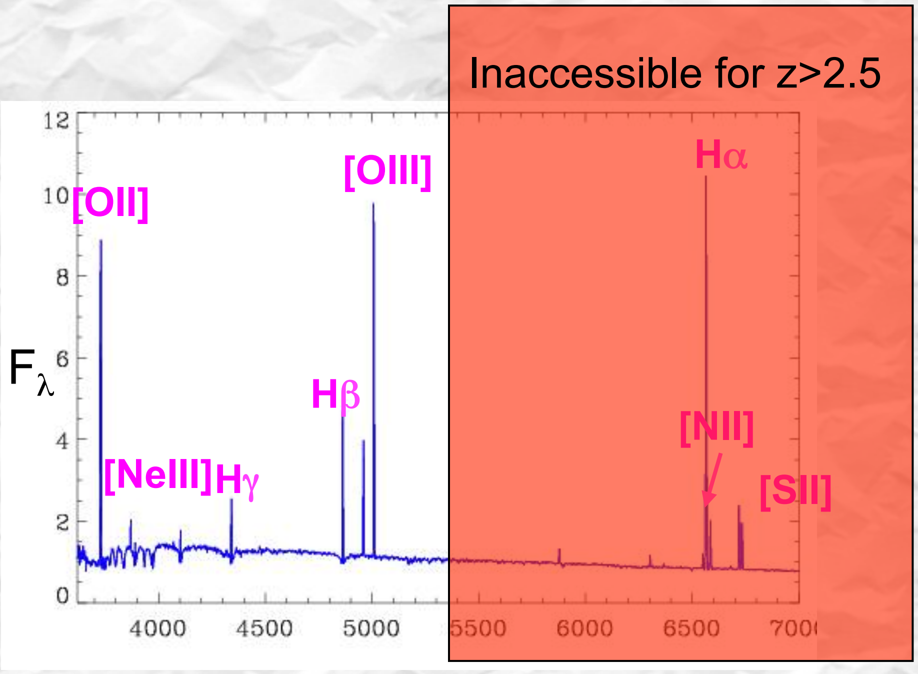
↓

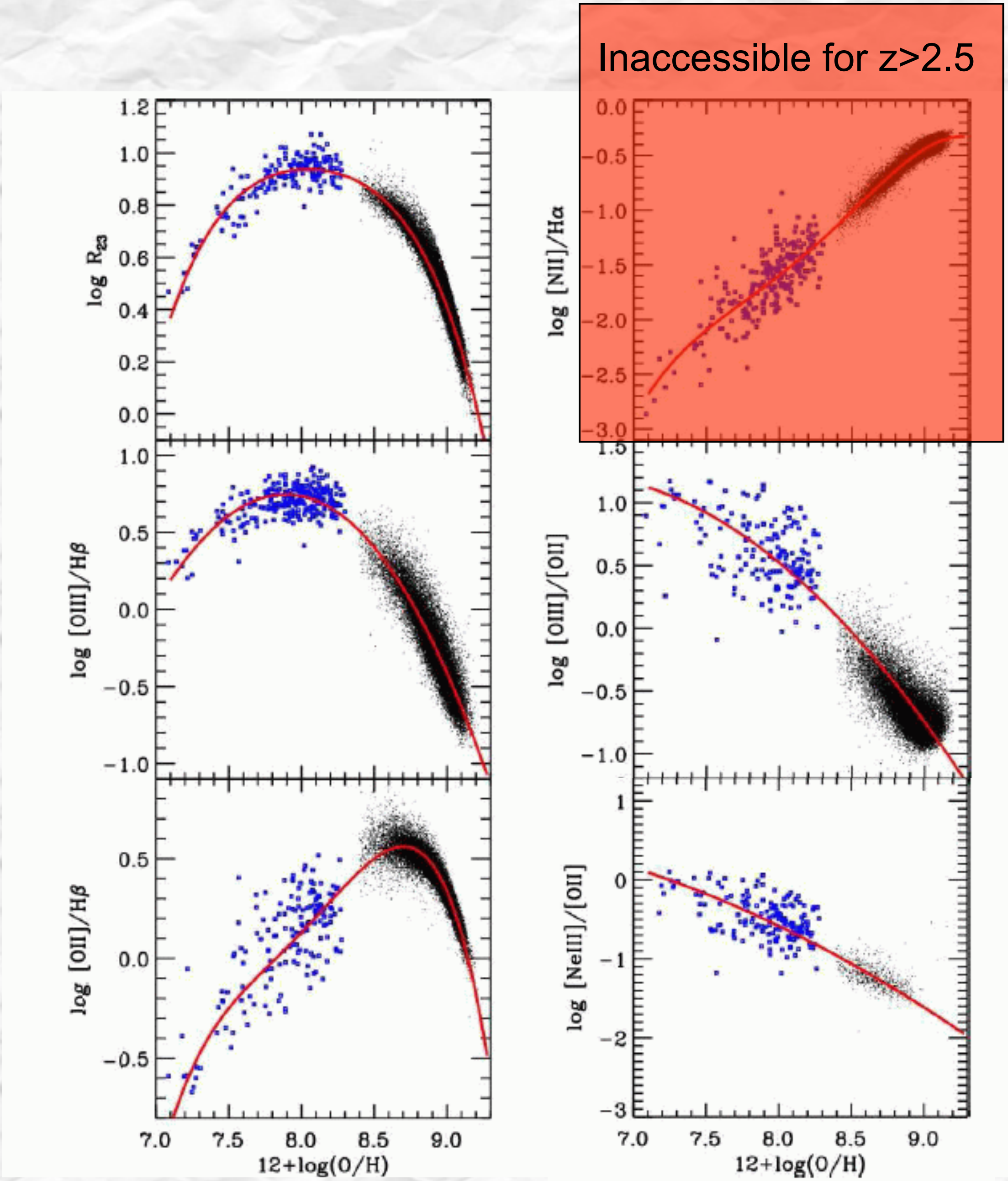
Together, spatially-resolved metallicity and dynamics constrain the evolutionary status of galaxies and isolate the physical mechanisms that drive Star Formation


Different metallicities
Stellar metallicity:
Represents an average over the entire star formation history of the galaxy
Gas-phase metallicity:
Sensitive to infalls and outflows

Measuring metallicities

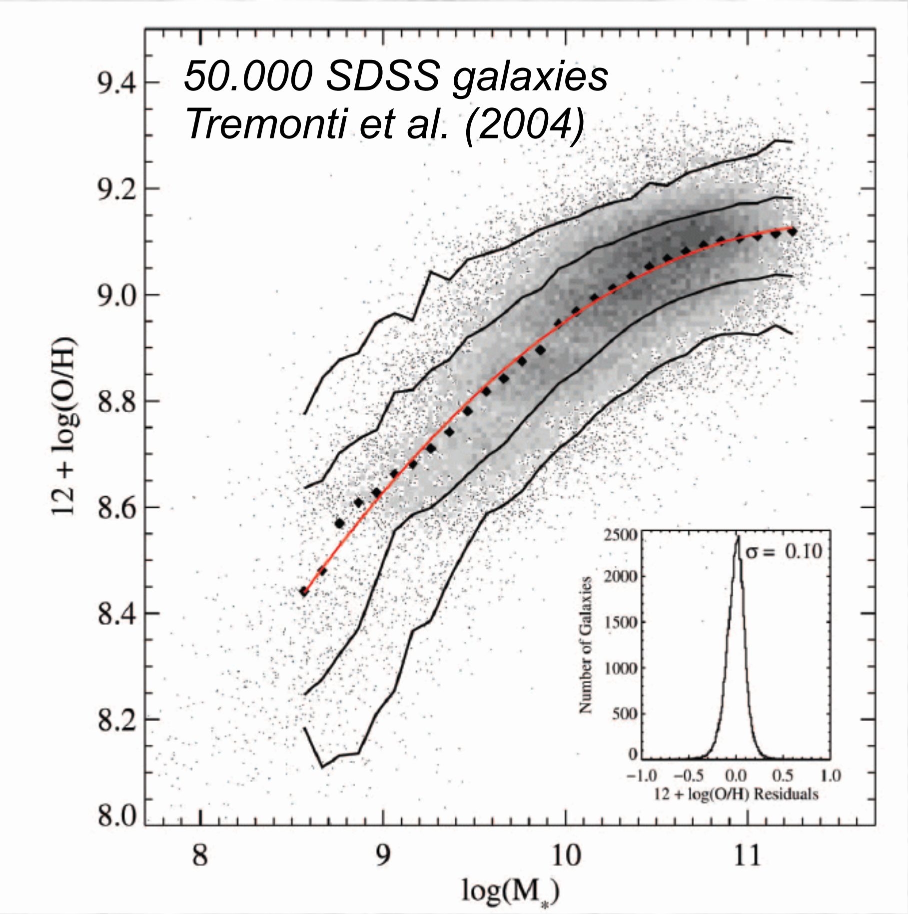
Gas phase metallicity from strong optical lines redshifted in the NIR





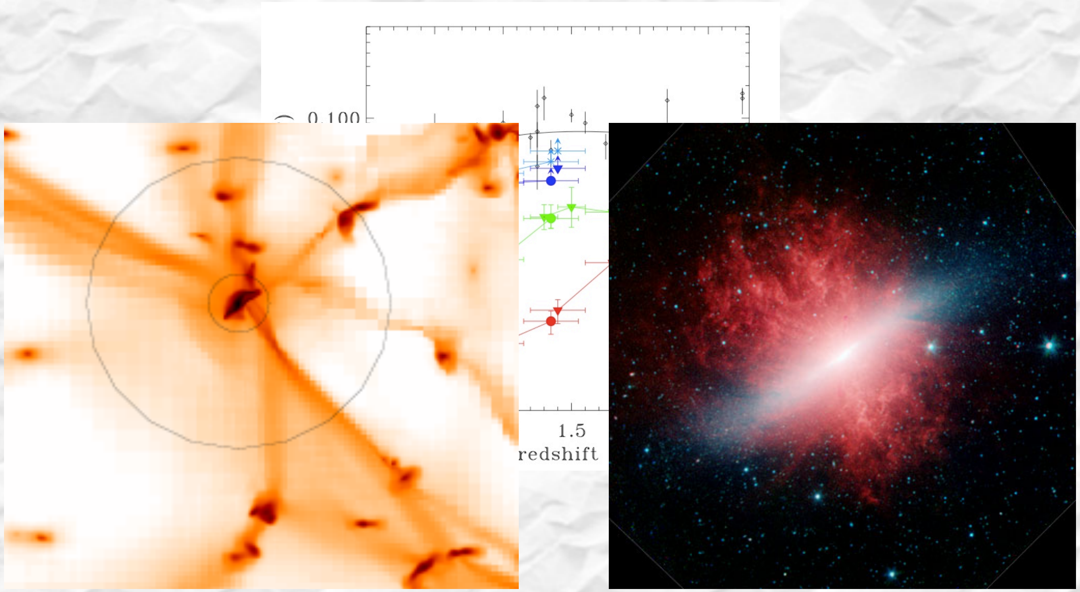
Nagao et al. 06, Maiolino et al. 2008: improved calibrations with low metallicity samples

The mass-metallicity relation



Possible Drivers:

- ✓ star formation history and mass lost
- ✓ downsizing
- ✓ inflows and merging
- ✓ outflows and feedback (AGN, SNe)
- ✓ evolution in IMF
- ✓…

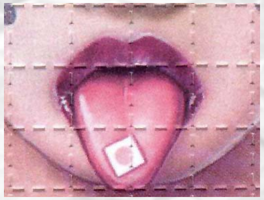


Crucial test for models!

Expecially at high-z, where the predictions of different models diverge more

See Kobayashi+ 2007; Brooks+ 2007; de Rossi+ 2007;Dave' & Oppenheimer 2007; Dalcanton, 2007; De Lucia+ 2004; Tissera+ 2005; Koppen+ 2007; Cid Fernandes+ 2007; Finlator & Dave', 2008, Panter+ 2008, Governato+ 2008, Sakstein+ 2009; Calura+ 2009, Save', Finlator & Oppenheimer 2011…

AMAZE… …with LSD

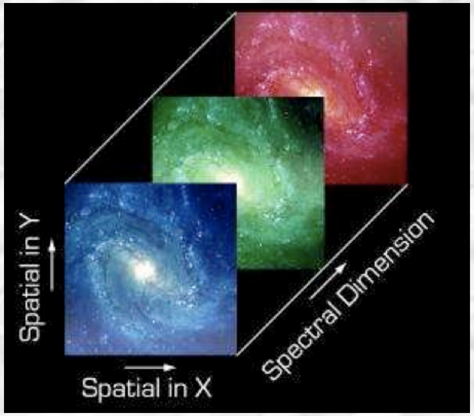


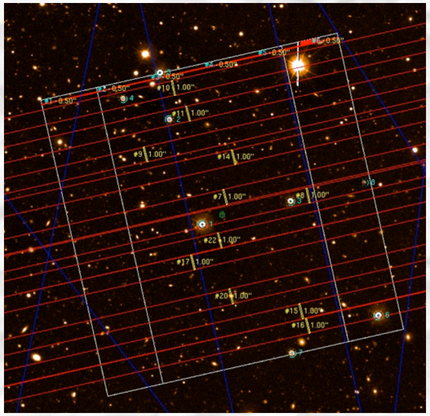
1. Near-IR Integral Field Spectroscopy with SINFONI@VLT

AMAZE (Assessing the Mass-Abundance redshift(Z) Evolution):
- seeing limited, a sample of 30 LBGs at 3<z<5
- 180h (PI: Maiolino) Maiolino et al. 2008, Cresci et al. 2010, Troncoso et al. 2011

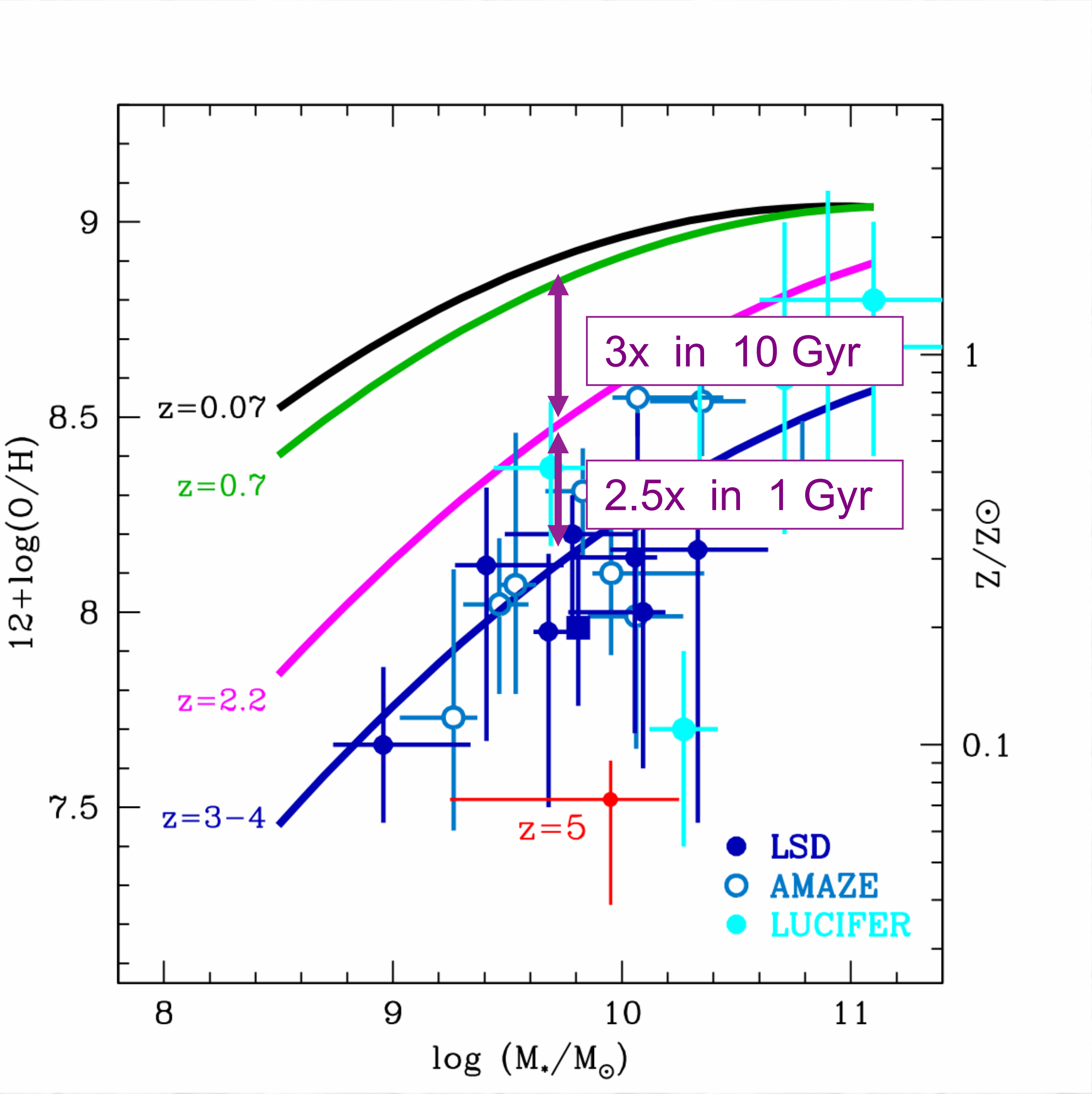
LSD (Lyman-break galaxies Stellar populations and Dynamics):
- diffraction limited with AO, an unbiased sample of 10 LBGs at 3<z<4
- 70h (PI: Mannucci) Mannucci et al. 2009, Gnerucci et al. 2010, Sommariva et al. 11

2. Near-IR Multi Object Spectroscopy with LUCIFER@LBT
- 4 Steidel fields, ~10 z=3 LBGs/field
- 40h (PI: Cresci) observations ongoing…





Evolution of the mass-metallicity relation



z~0.07 SDSS

z~0.8-1 GDSS+CFRS (Savaglio+05),
GOODS (Cowie & Barger 09)
VVDS (Lamareille+09, Perez-Monteiro+09))
IMAGES (Rodrigues+08)
DEEP2 (Zahid+10)

z~2.2 LBG (Shapley+04, Erb+06)
BzK (Hayashi+11)
Lenses (Richard+10)

z~3.3 ○ AMAZE (Maiolino+08, Troncoso+11))
● LSD (Mannucci +09)
● LUCIFER (Cresci+11)

z~5 ● AMAZE

M-Z relation already in place at z~3.5

Strong and fast evolution of the M-Z relation beyond z~2?

(BUT: it is not tracing the evolution of individual galaxies)

Inflows and Outflows

In a "*closed box model*" with instantaneous recycling, instantaneous mixing, and low metallicities:

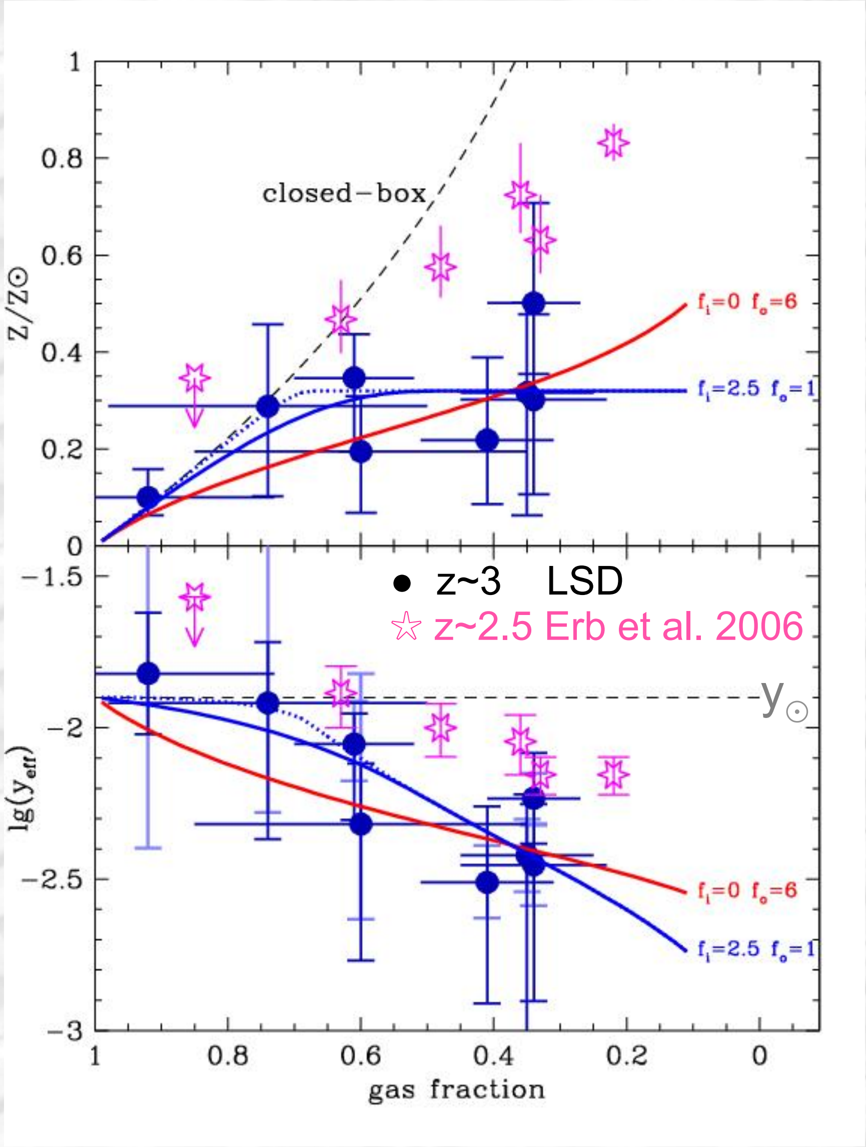
$$Z = y_{true} \cdot \ln(1/f_{gas})$$

y_{true} = stellar yield, i.e., the ratio between the amount of metals produced and returned to the ISM and the mass of stars.

The measured values of $y_{eff} = Z/\ln(1/f_{gas})$ could differ from the true stellar yields y if some of the assumptions do not hold, in particular if the system *is not a closed box*

↓

Inflows and outlows



Mannucci et al. 2009

Metallicity Gradients

Interplay between in- and out-flows, redistribution of mass within galaxies, radially dependent SFH, mixing due to a stellar bar, clump migration, etc

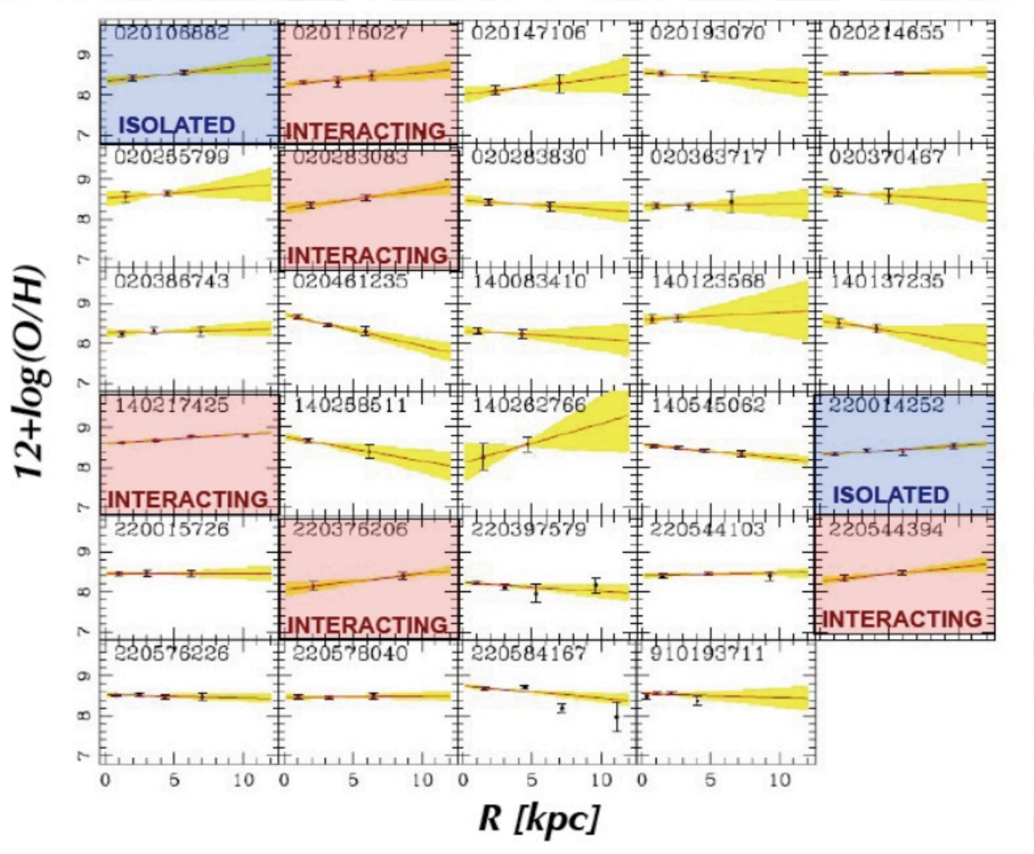
→ ***Fingerprints of galaxy evolution!***

Negative radial metallicity gradient in local spiral galaxies: the central disk region is more metal-enriched than the outer regions.

At higher redshift, steeper gradients measured in two gravitationally lensed galaxies at z~1.5 and z~2 with near-IR IFU spectra, supporting "inside-out formation"

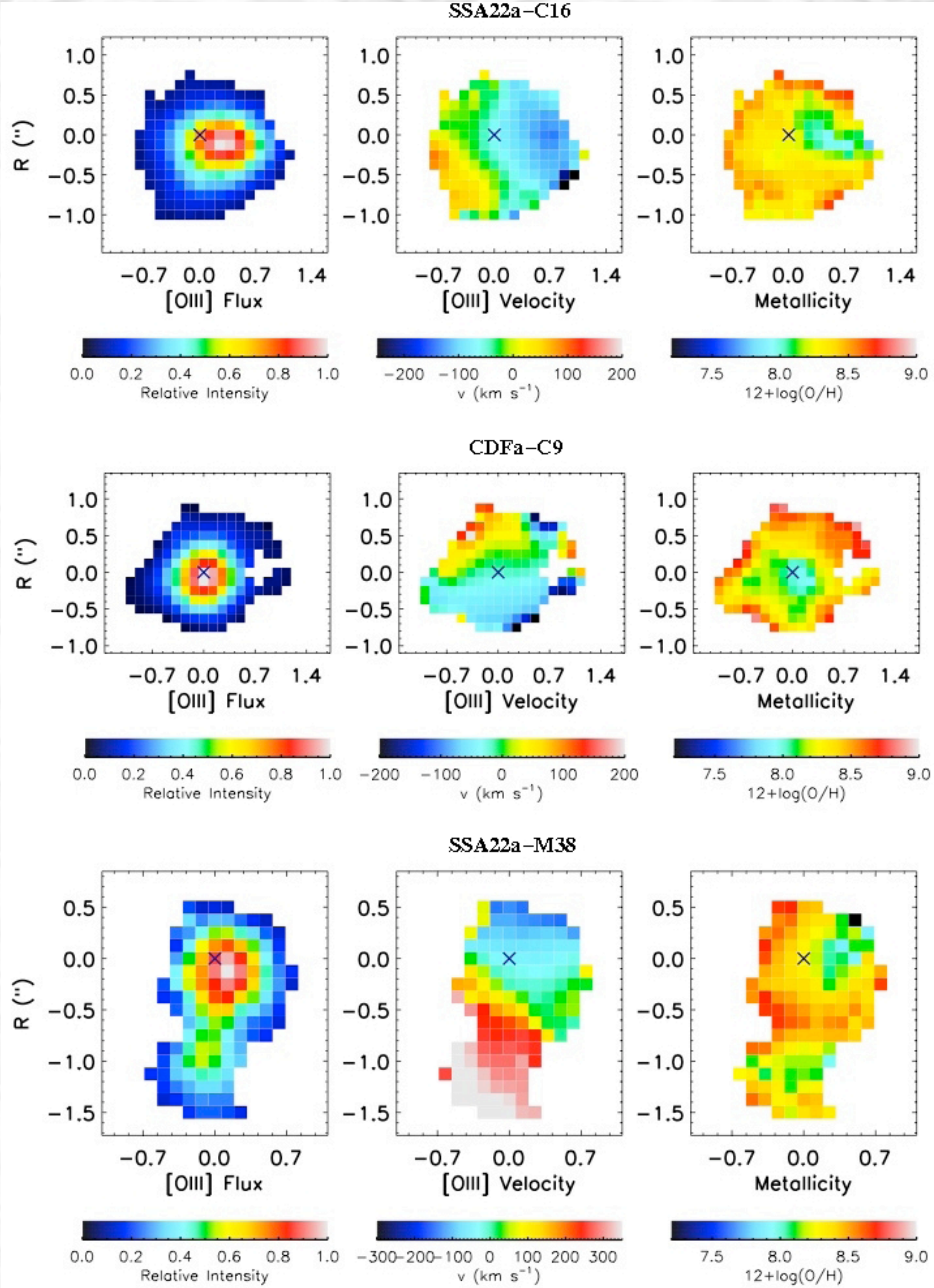
But more complex situation in larger samples: even positive "inverted" gradients at z~1.5 in MASSIV galaxies

(but see also Werk et al. 2010 at z=0)



Contini et al. 2011

Metallicity Gradients



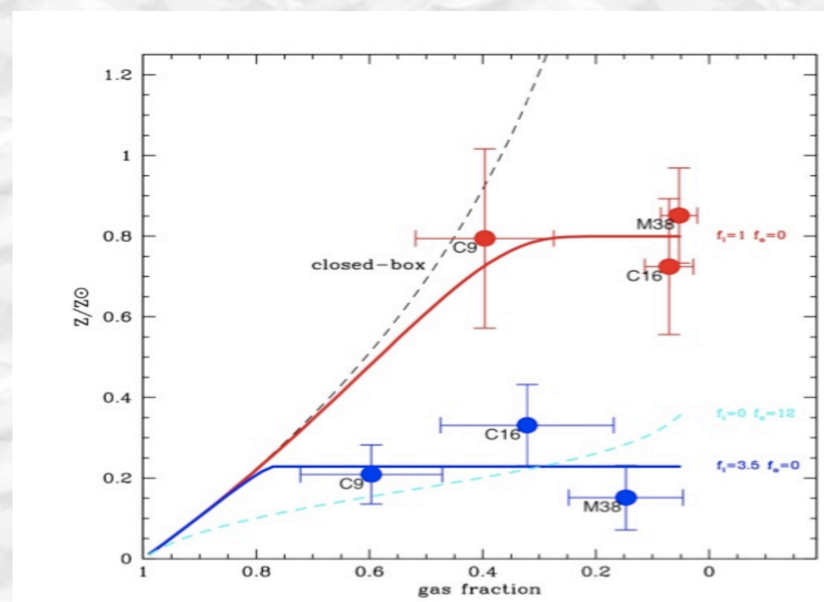
Cresci et al. 2010, Nature

Thanks to the IFU near-IR data

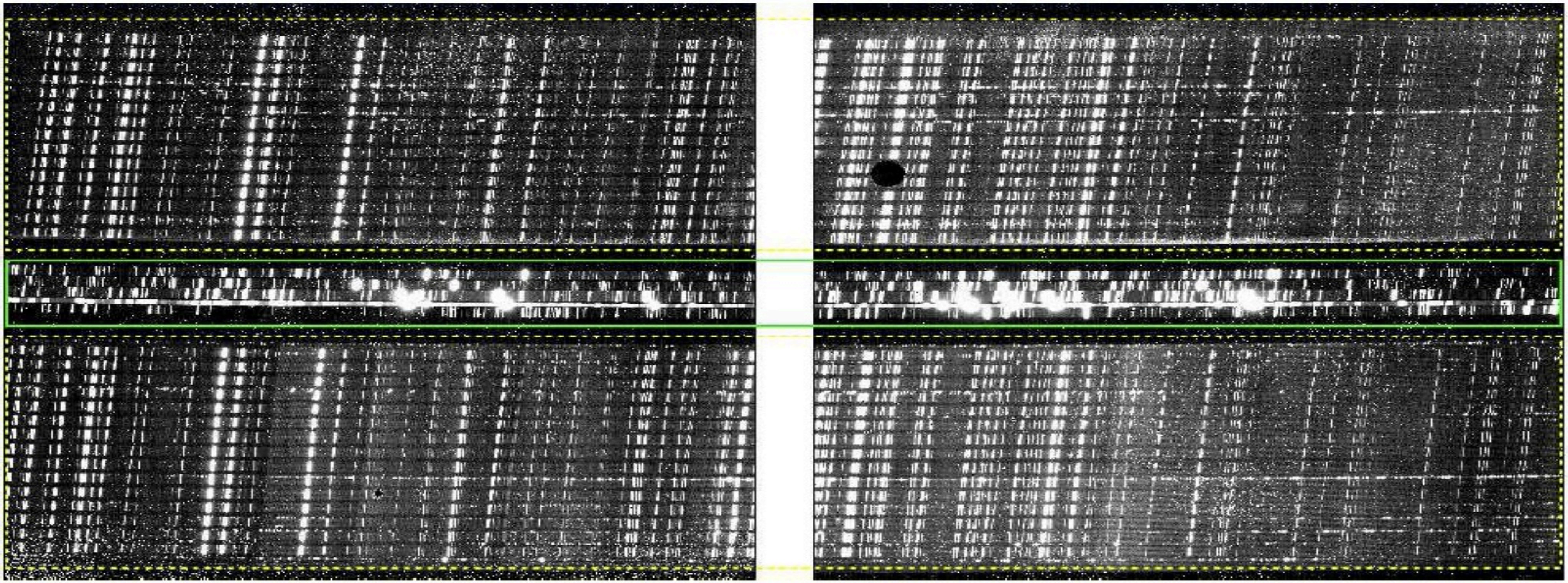
First metallicity maps at z~3:

- Three undisturbed disks
- Well defined regions close to the SF peak are less metal enriched than the disk

Direct evidence for massive infall of metal poor gas feeding the star formation



NIRspec IFU

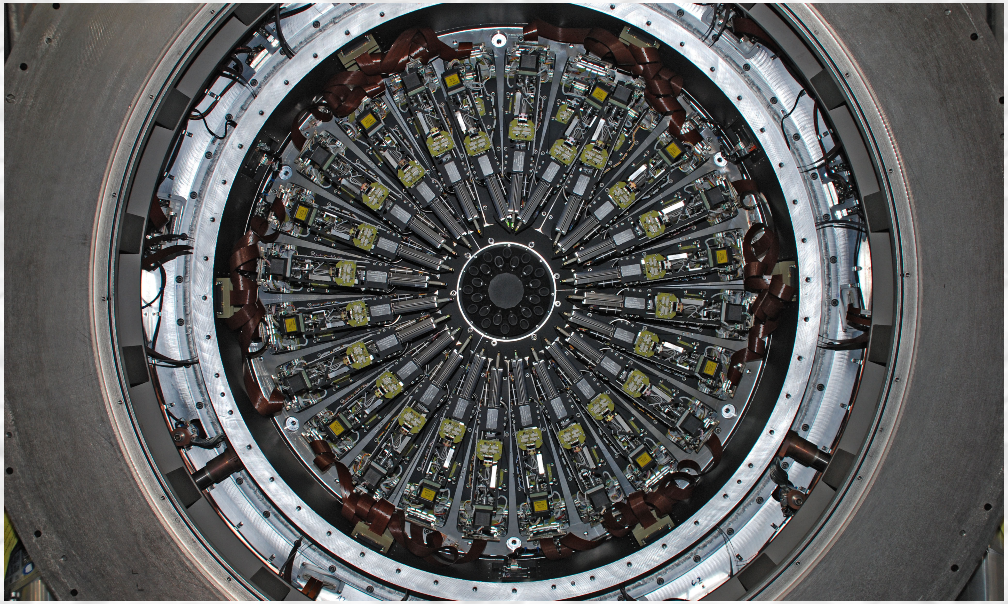


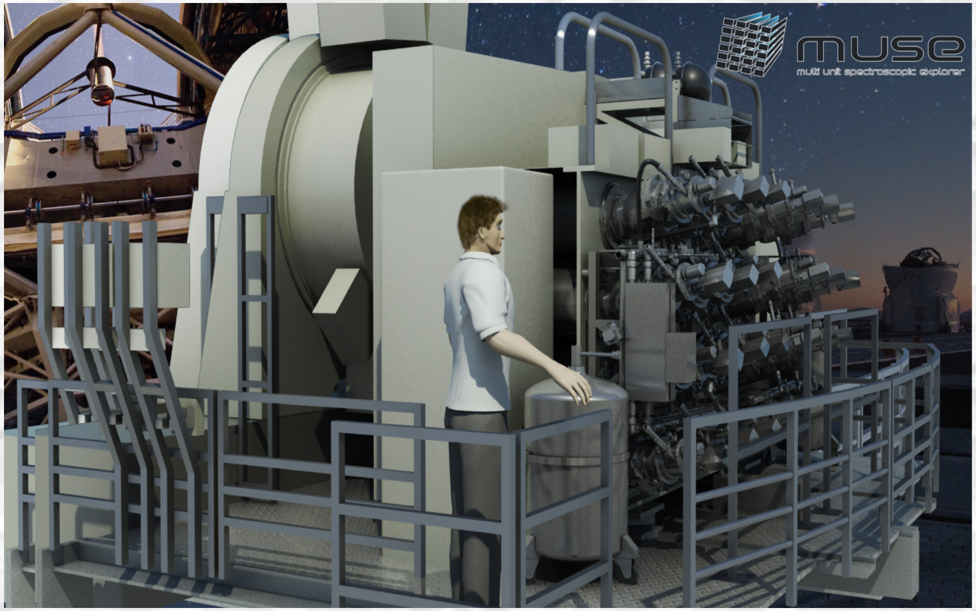
CLS Argon lamp taken with the Band II high resolution grating and the target acquisition filter

- λ< 2.3μm: no atmosphere (OH lines & bandpasses)
- λ> 2.3μm, unique facility (sensitivity and wavelength, e.g. Hα at *z*>2.5)

Perfectly matched with MOS: large samples and detailed studies of key targets

While waiting…





KMOS

24 cryogenic pick-up arms
Each 2.8″x2.8″ IFU (0.2″ sampling)
coverage 0.8-2.5μm (Iz, YJ, H, K, HK)
resolution ~3500

MUSE

24 identical IFUs covering contiguous field
λ=465-930nm with R=1700-3500
7.4”×7.4” at 0.025”
or 60”×60” at 0.2”

Summary

- **IFU Spectroscopy is an unique tool: looking forward to NIRspec**

  Fundamental insights on the physical mechanisms responsible for galaxy formation and evolution

- **Dynamics in high-z galaxies:**

  Majority of disk-like systems among rest frame UV selected galaxies at z~2

  Significantly more turbulent and gas rich rthan local disks

  Large clumps with significant feedback

- **Chemical evolution in high-z star-forming galaxy:**

  Evidence for rapid metal enrichment and significant inflows/outflows at high-z;

  Resolved metallicity gradients provide evidence of pristine gas accretion in star forming disks at high redshift;

  First measure of stellar metallicity in high-z star forming galaxies