The dynamics of z~2 Star Forming galaxies in SINS

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and the SINS team

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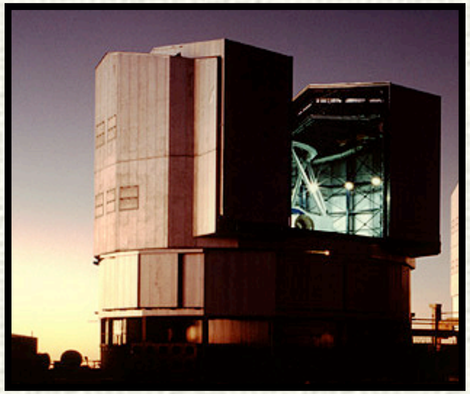
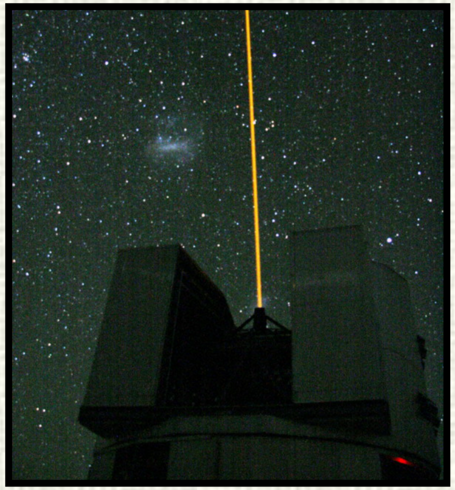
Spineta 7-7-09

The SINS Survey



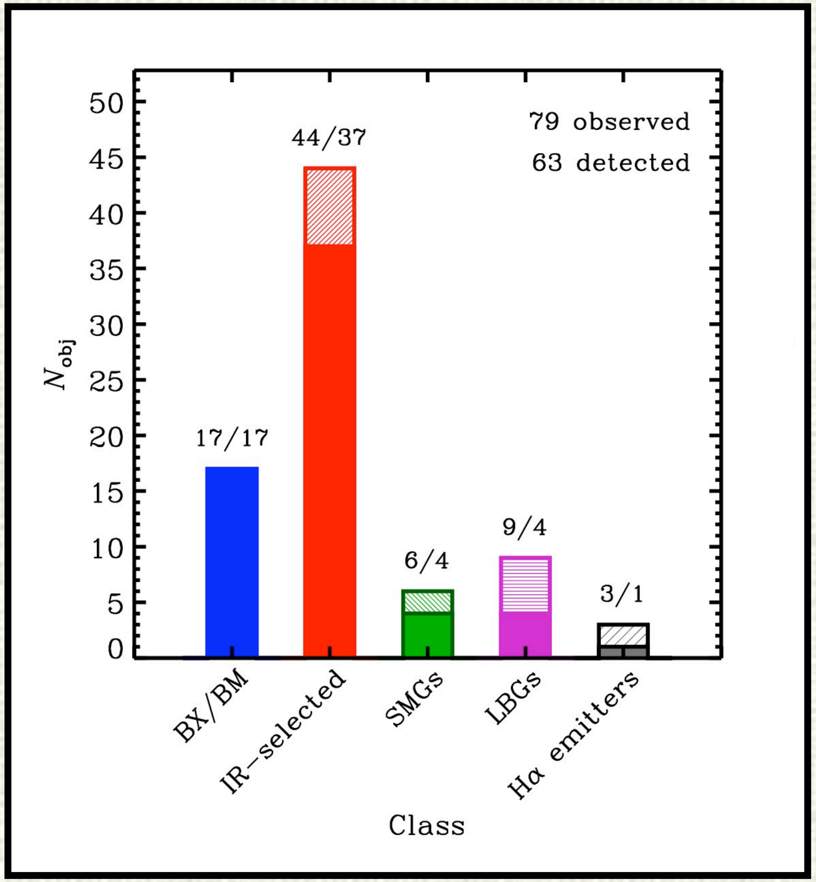
(high-z Spectroscopic Imaging survey in the NIR with SINFONI)



Near-IR
integral field spectroscopy
with SINFONI, +AO,
at the VLT

(15 w/ AO observations)

Complemented with near-IR imaging with HST/NICMOS-NIC2 and VLT/NACO+AO



High-z
(1.5 < z < 2.5)

Luminous
(L_{bol}~10^{11}-10^{12} $L_\odot$)

Massive
(M_*~10^9-$10^{11.3}$ $M_\odot$)

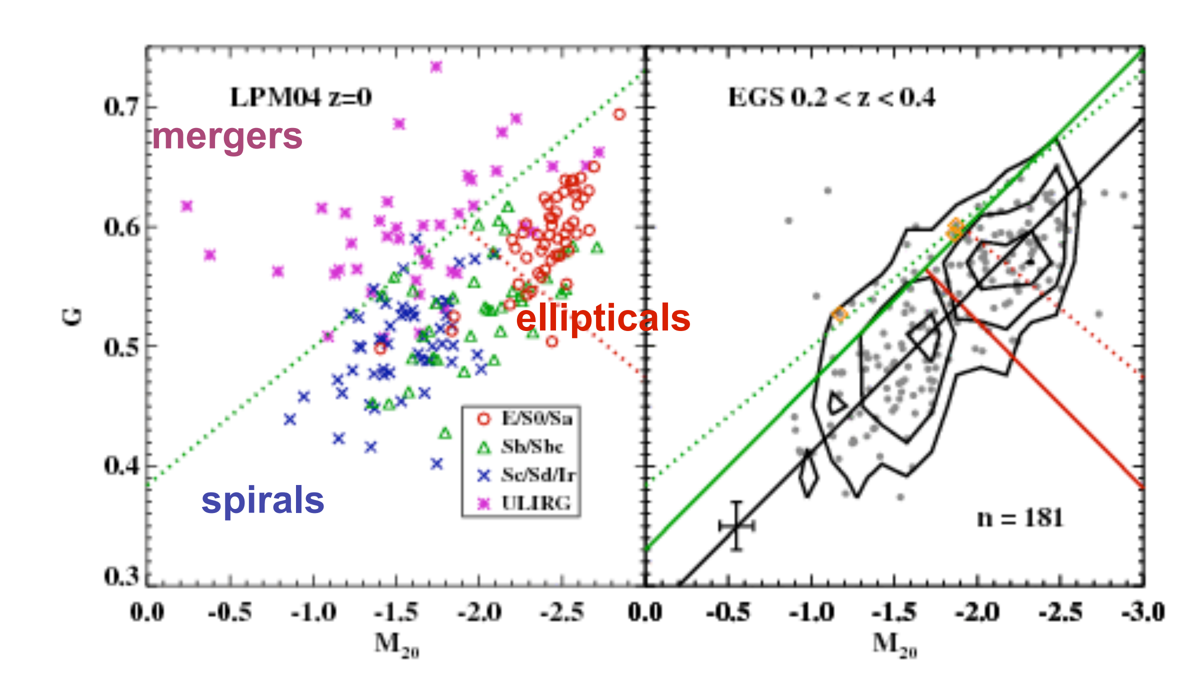
High SFR
(~10-100 $M_\odot$/yr)

Distinguishing rotating systems from major mergers

- **Very important to fully understand the evolution of both the baryons and the underlying dark matter distributions**

- **Which is the formation mechanism of massive galaxies at high-z? Is the star formation triggered by major mergers or by smooth accretion and/or minor mergers?**

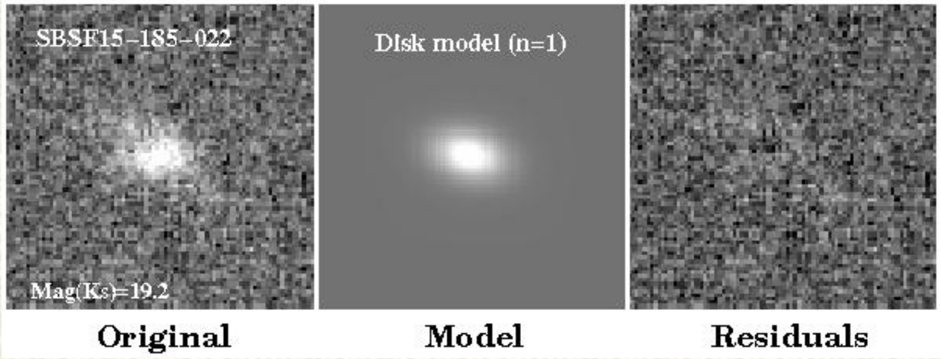
However, a morphological quantitative measurement is increasingly difficult at high-z, especially at rest frame UV wavelengths, due to severe K-correction, dust extinction, limited spatial resolution, low S/N…



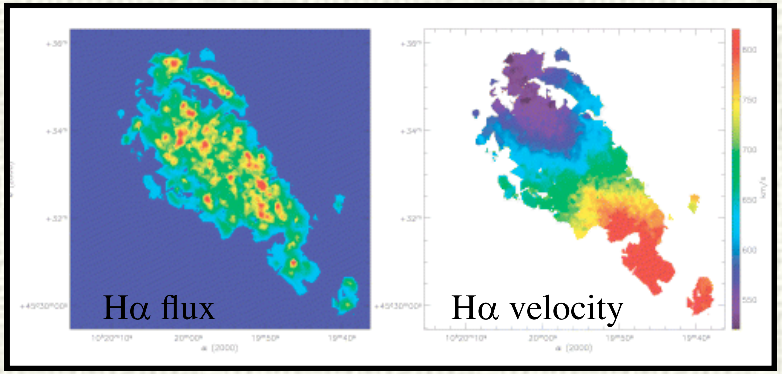
Lotz et al. (2007)

Distinguishing rotating systems from major mergers

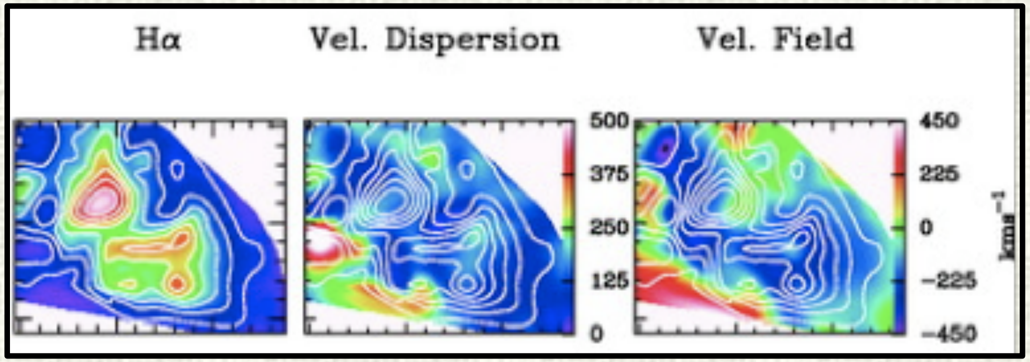
1. A possibility is using **AO assisted near-IR imaging**, sampling rest-frame optical at z~1-4 to study the morphologies of the galaxies



Cresci et al. (2006)



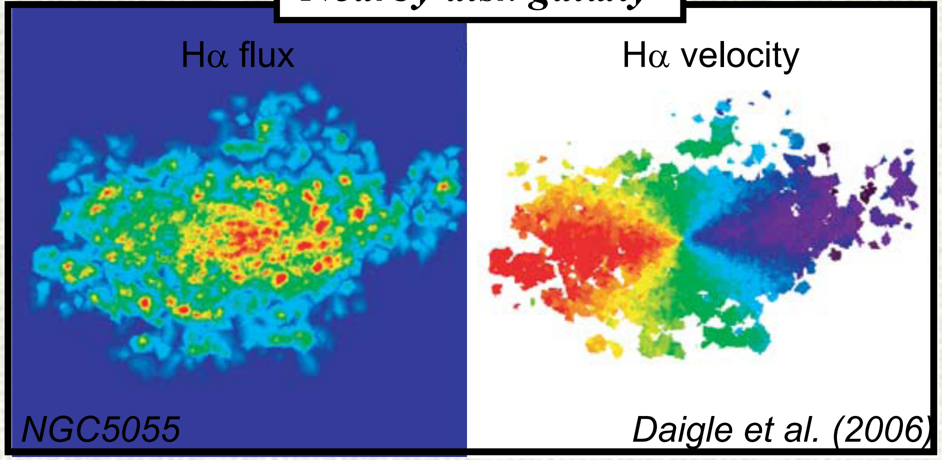
Daigle et al. (2006)



Colina et al. (2005)

2. **Integral Field Spectroscopy** provides spatial resolved kinematical information and thus ***directly probes the dynamics*** and total enclosed mass of the galaxies

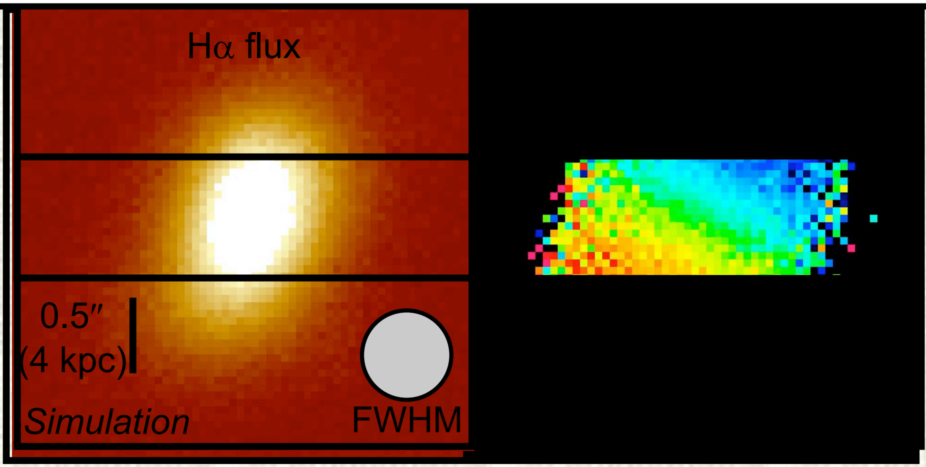
Nearby disk galaxy



Is it possible to get close at high-z?

+

Disk galaxy at z ~ 2: seeing-limited long-slit spectroscopy



Mergers vs Rotation: Kinemetry

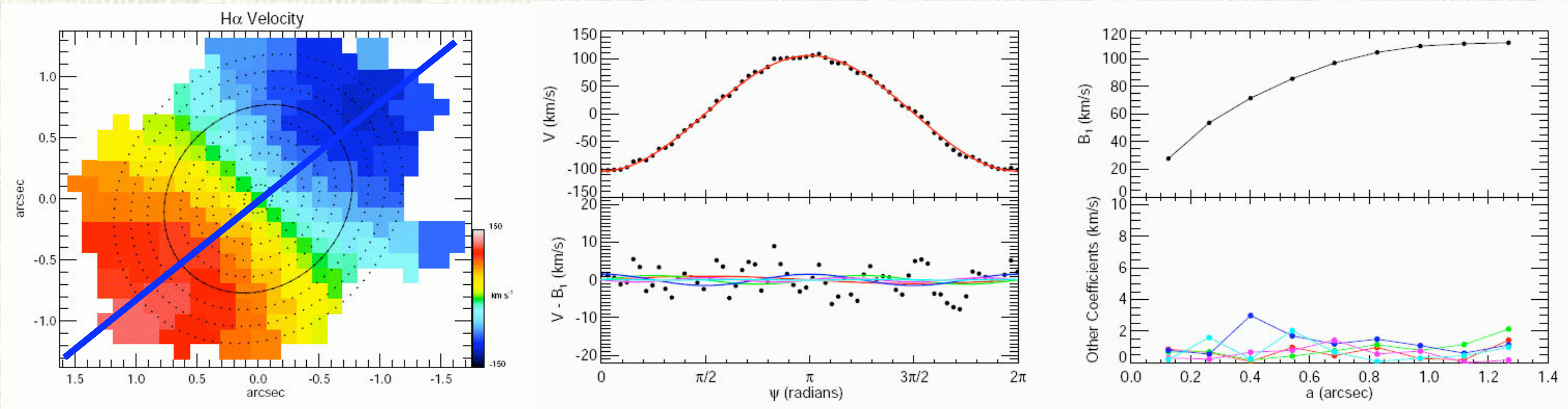
- ***Kinemetry*** (Kranjnovic et al. 2006) is an extension of surface photometry to the higher order moments of the velocity distributions, that we use to quantify asymmetries in the kinematics and differentiate between regular ordered motions and disturbed dynamics of major mergers.

- The SINFONI velocity and velocity dispersion maps of the **Hα emission** are described with concentric ellipses defined by the system center, position angle and inclination
- The moments of both the velocity and dispersion fields are decomposed as a function of the angle ψ into the Fourier series:

The dispersion is constant along each ring: *A_0 dominates σ*

$$K(\psi) = A_0 + A_1 \sin(\psi) + B_1 \cos(\psi) + A_2 \sin(2\psi) + B_2 \cos(2\psi) + \dots,$$

The velocity at each ring peaks on the major axis: *B_1 dominates V*



Testing the Kinemetry method

The method was tested for high-z galaxies using a sample of models, simulations and local galaxies, "observed" at z~2 adding noise, beam smearing and rebinning typical of SINS observations

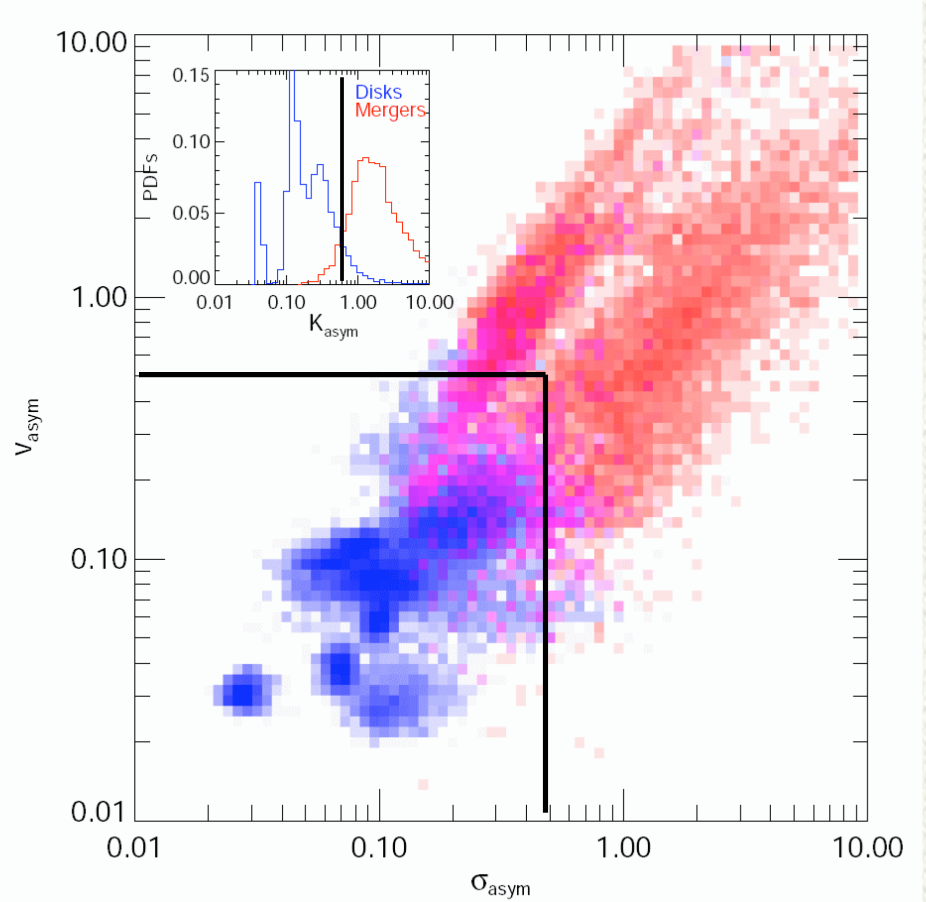
Local "redshifted" galaxies:

- **SINGS local disk galaxies from Daigle et al. (2006)**
- **Local ULIRG mergers observed by Colina et al. (2005)**

Model galaxies:

- **Disk models with clumpy knots**
- **Hydrodynamic simulations of z~2 galaxies by Naab et al. (2007)**
- **Simulated major mergers (<3:1) by Johansson et al. (2007) with different orbit geometry**

For each template, we use 1000 MonteCarlo realizations of the noise



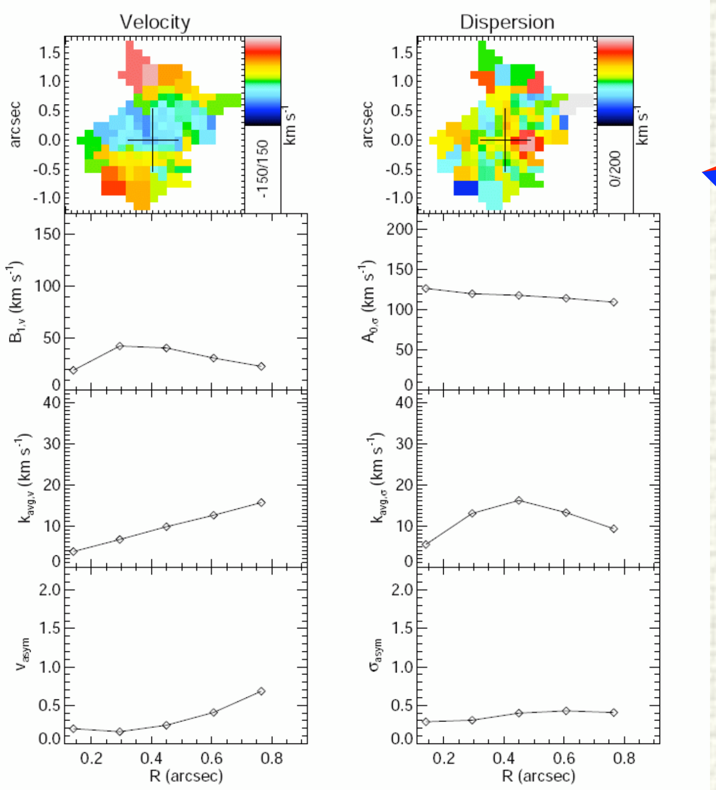
Shapiro et al. 2007

Applying the method to SINS galaxies

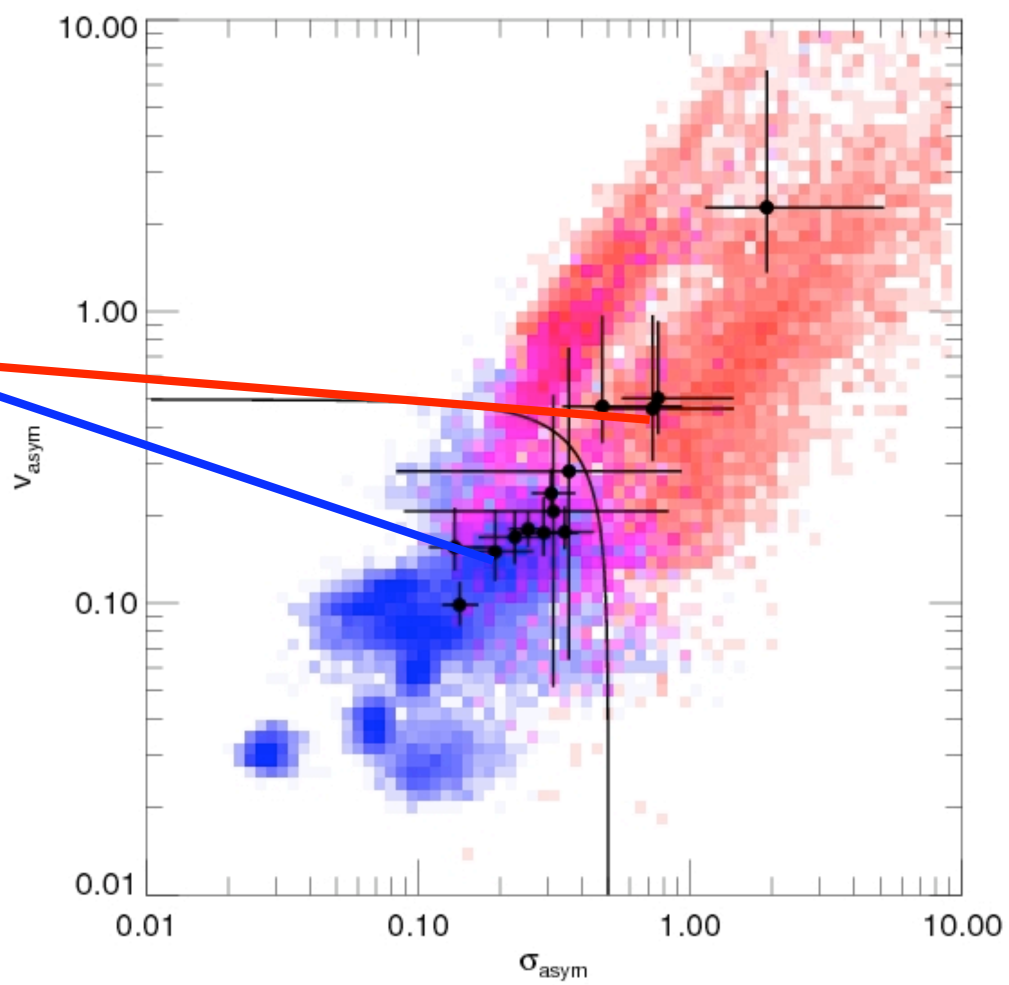
We first apply the method to the 14 galaxies with better S/N in the SINS sample, with higher quality data than the "redshifted" model galaxies:

We find 10 rotating systems

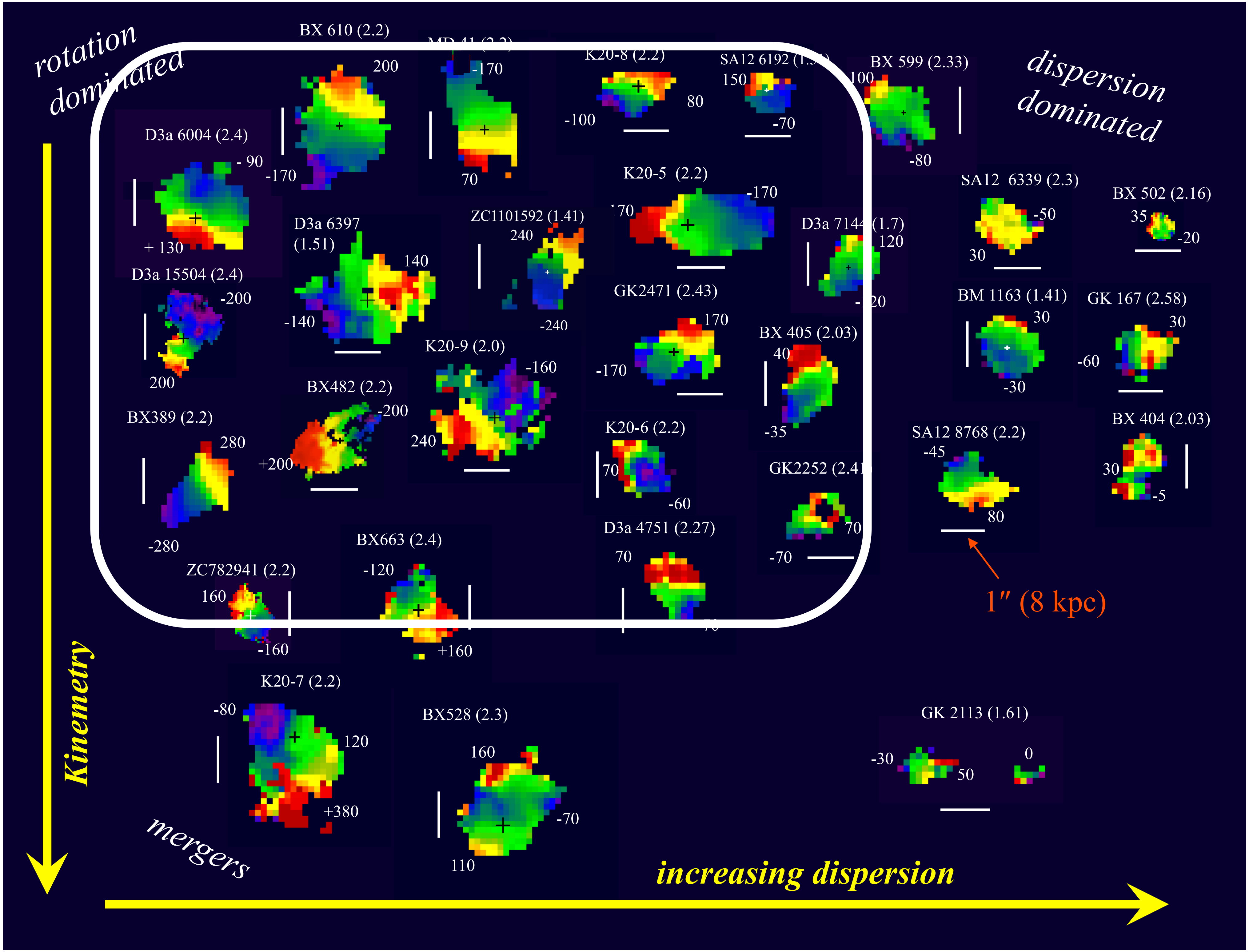
and 4 mergers



(a) BX528



Shapiro et al. 2007



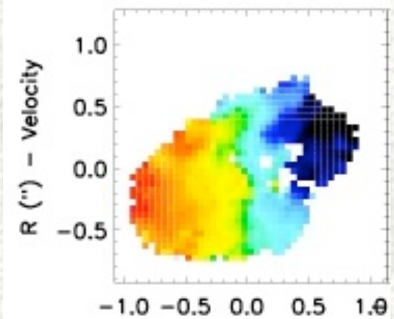
rotation dominated
dispersion dominated
Kinemetry
mergers
increasing dispersion
1″ (8 kpc)
BX 610 (2.2)
K20-8 (2.2)
SA12 6192
BX 599 (2.33)
D3a 6004 (2.4)
K20-5 (2.2)
SA12 6339 (2.3)
BX 502 (2.16)
D3a 6397 (1.51)
ZC1101592 (1.41)
D3a 7144 (1.7)
D3a 15504 (2.4)
GK2471 (2.43)
BM 1163 (1.41)
GK 167 (2.58)
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
D3a 4751 (2.27)
BX663 (2.4)
ZC782941 (2.2)
K20-7 (2.2)
BX528 (2.3)
GK 2113 (1.61)

Dynamical modeling of SINS galaxies

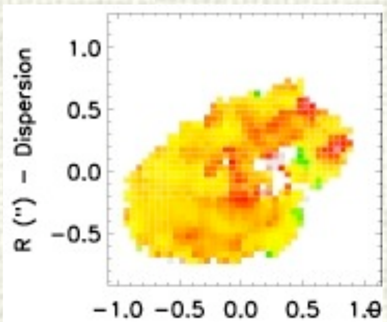
- **We measure with a χ^2 minimization the main dynamical properties of z~2 galaxies with prominent rotation signatures, using the full 3D dynamical information:**
  - ***Inclination and Position angle***
  - ***Total dynamical mass and maximum rotational velocity***
  - σ_0, ***the dispersion term not due to rotation***

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

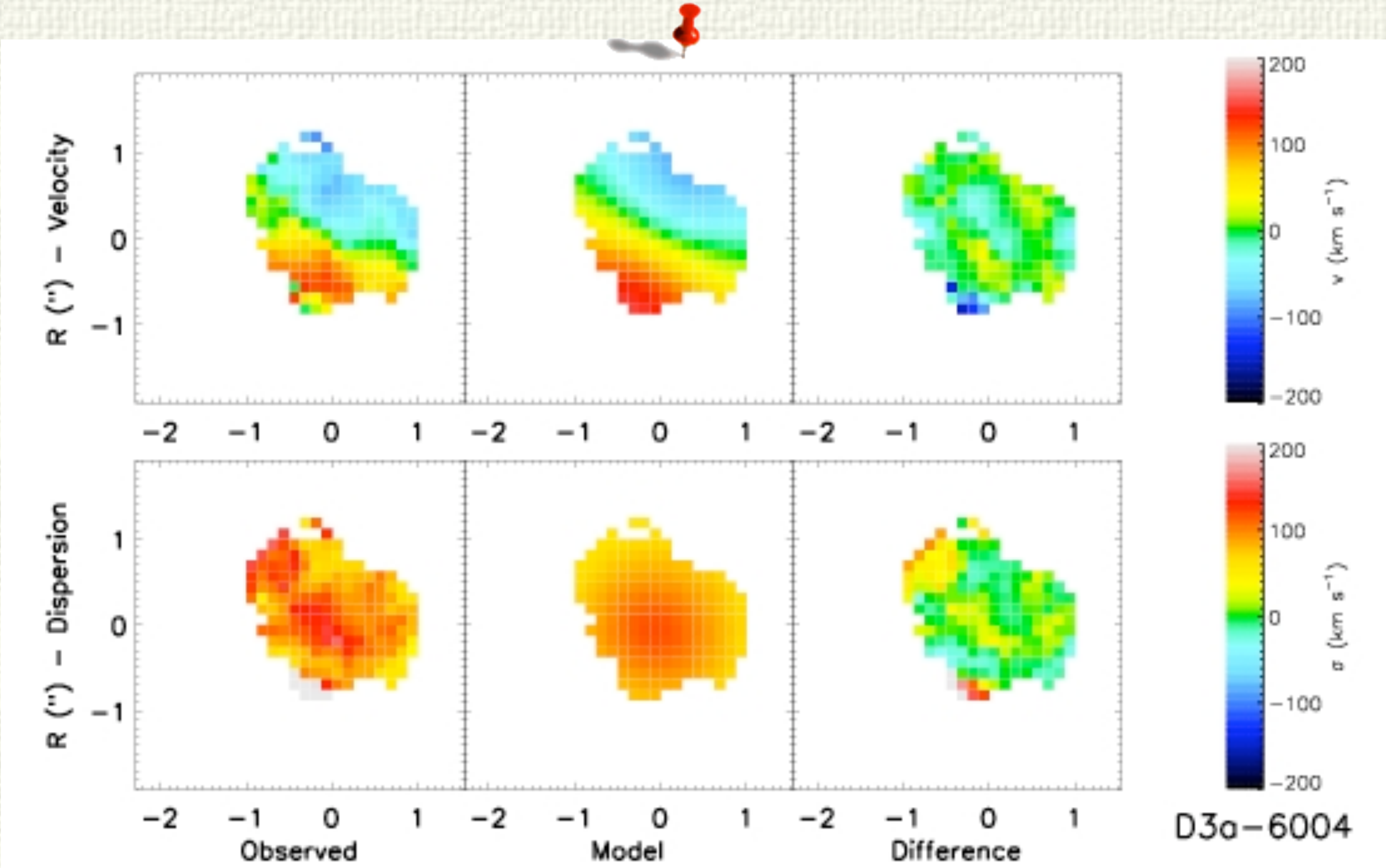
- **The disk model is convolved with the observed beam and reduced to the pixel sampling of the observations to carefully account for resolution effects**



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



Fitting example: D3a-6004



z=2.4; R_d=6.6 kpc; i=30°; $M_{dyn}=16\cdot10^{10}\ M_\odot$; V_{max}=273 km/s; σ_0=58 km/s

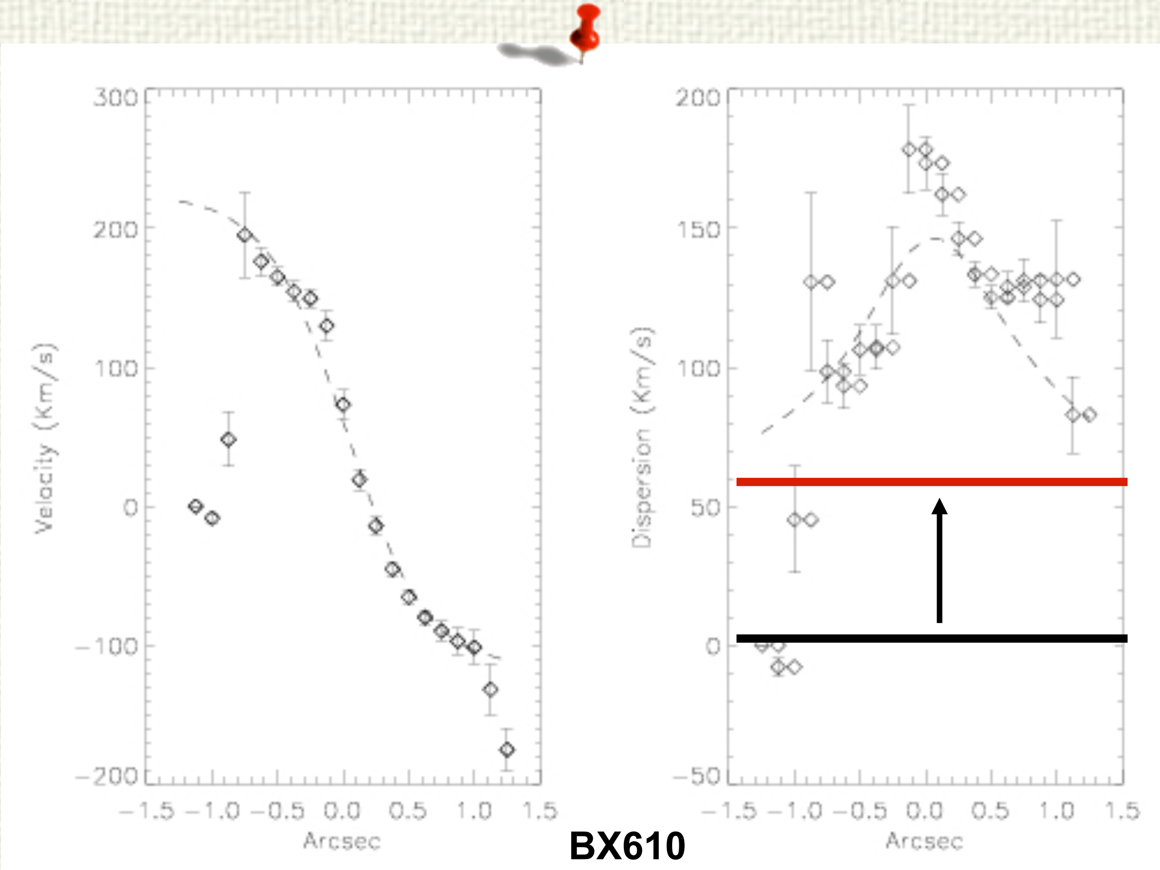
Cresci et al. (2009)

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 $<V/\sigma_0> = 4.3$ much lower than in local spirals (V/σ_0=10-20)

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)

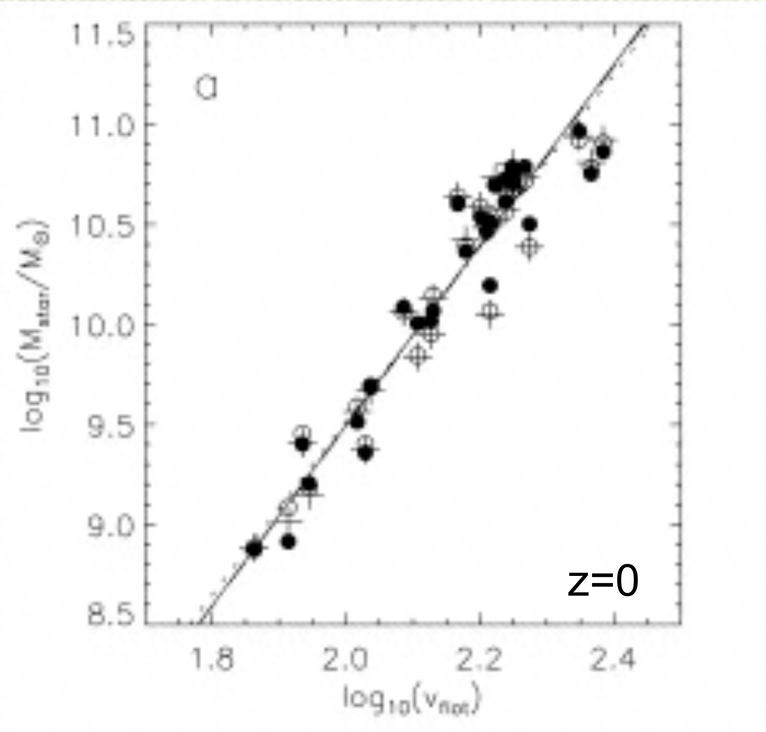


Cresci et al. (2009)

The Tully-Fisher relation

The evolution of scaling relation is fundamental to place observational constraints on the assembly history of stellar and dark masses in galaxies:

- **The T-F relation correlates the absolute magnitude of disk galaxies with their maximum rotational velocity. Therefore it directly links the angular momentum of the halo with the stellar population of its disks.**



Bell & de Jong (2001)

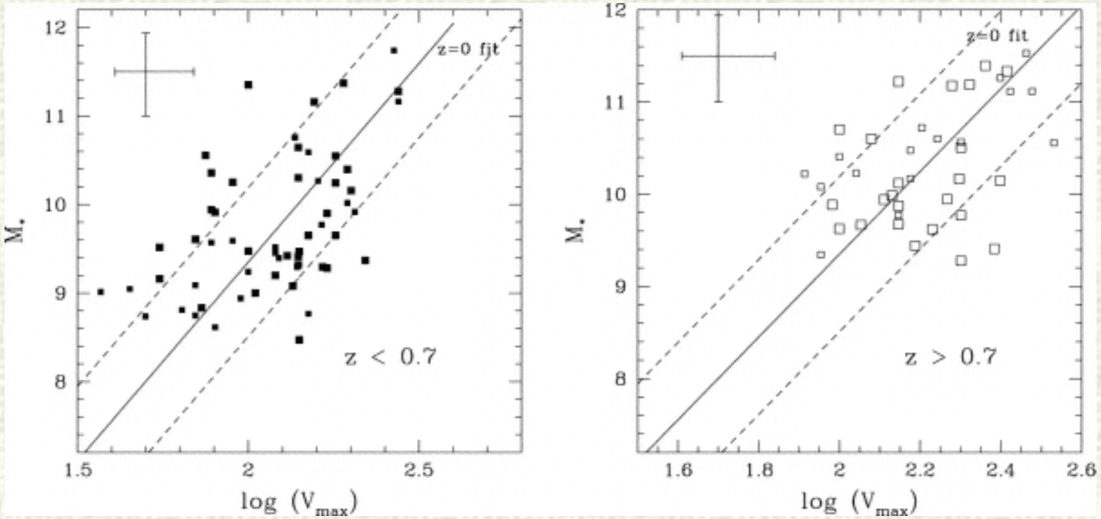
The interpretation of the evolution of a luminosity based T-F is difficult: luminosity and angular momentum are evolving at the same time:

Stellar Mass T-F

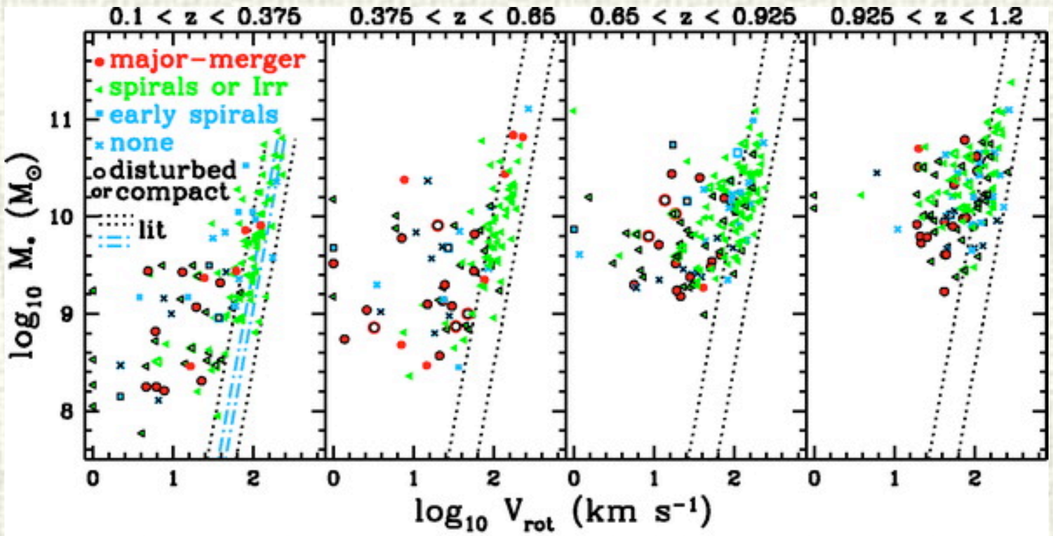
(e.g. Bell & de Jong 2001, McGaugh et al. 2005, Pizagno et al. 2005, Meyer et al. 2008)

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)



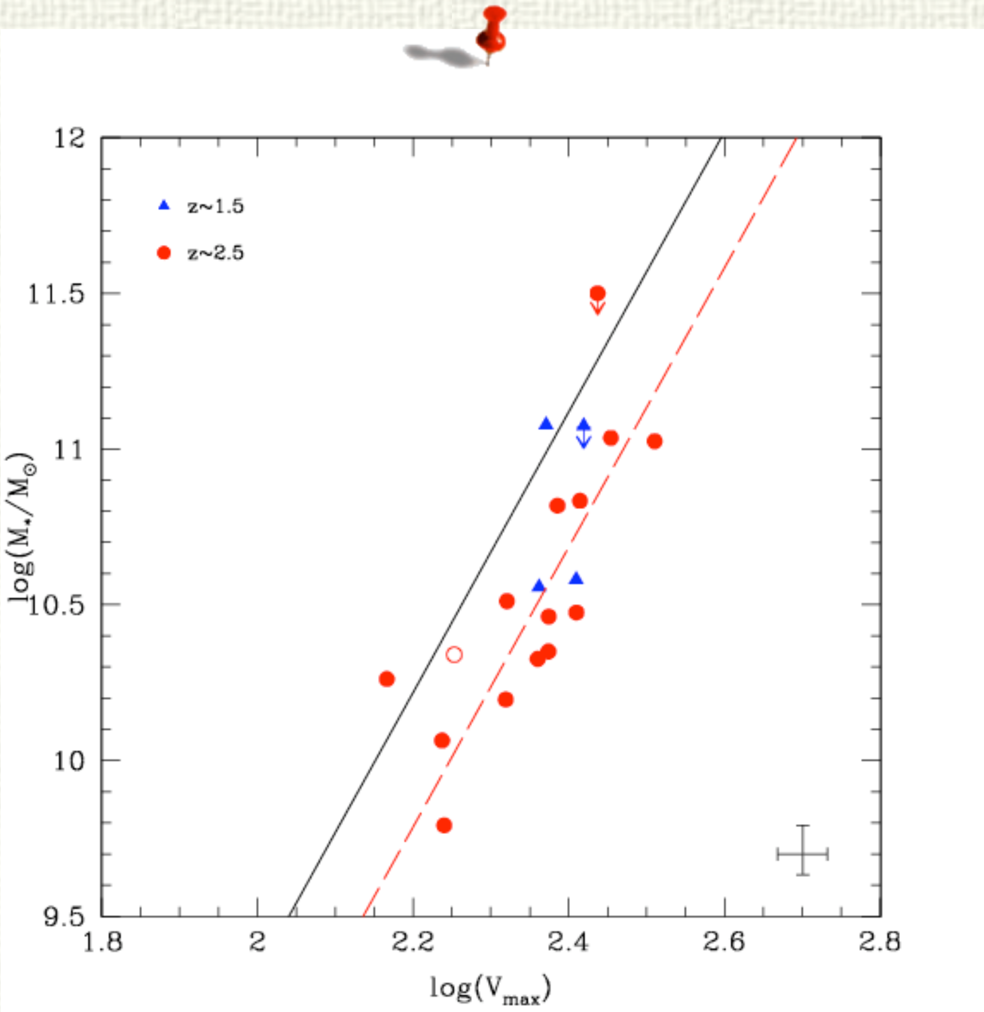
Kassin et al. (2007)

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

see also Puech et al. (2008), Meyer et al. (2008)…

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)

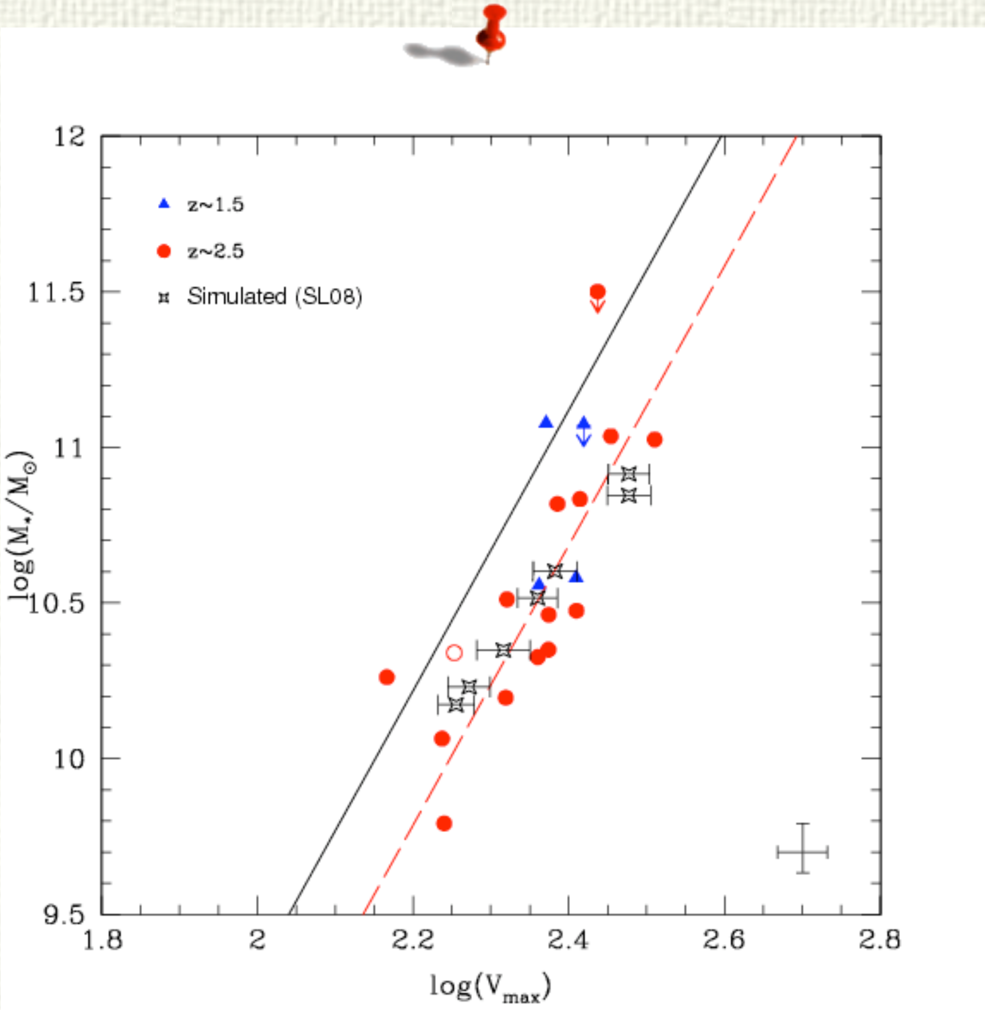
✓ **We detect a significant (3.6σ) evolution of the zero point respect to z=0**

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

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

Theoretical expectation for the TF evolution

The normalization, slope and evolution of the T-F depend strongly on the prescriptions used for star formation and feedback in the models, as well as the disk formation mechanism: it represent a crucial test for models



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

Smooth and continuous gas accretion is required in the model to preserve angular momentum and reproduce the observed disk properties

see also Burkert et al. (2009), Bouche' et al. in prep, Somerville et al. (2008)…

Going to even higher redshift: LSD & AMAZE

(see Roberto Maiolino's talk this afternoon)

AMAZE (Assessing the Mass-Metallicity Redshift Evolution) – Seeing limited (0.5-0.8")

- 30 *UV-selected LBGs*: 22 galaxies at 3.2<z<3.8, 8 galaxies at 4.5<z<5

LSD (LBG Stellar populations and Dynamics) – NGS AdOpt (~0.2")

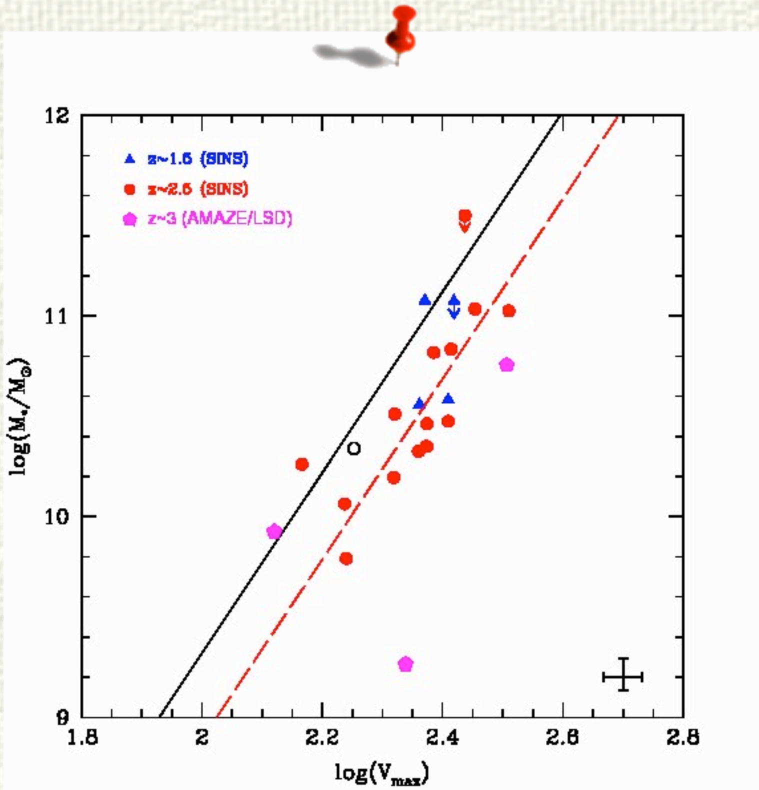
- 10 LBGs at z~3.1, R<25

↓

- Lower fraction of rotationally supported galaxies at z>3 (in contrast to SINS results at z~2)
- Many objects with complex morphology and dynamics detected in emission lines

SSA22a-C16:

z=3.065; $\log M_{dyn}$=10.34; V_{max}=139 km/s σ_0=89 km/s



Gnerucci et al., Cresci et al. in prep.

Conclusions

• We have developed robust tools to **discriminate between ordered rotating systems and major mergers** at high-z using the dynamical properties of the galaxies

• We found that massive, rotating disks were **already in place at z~2**, (~35% of the SINS sample), providing evidence for smooth+rapid mass accretion via cold flows/minor mergers

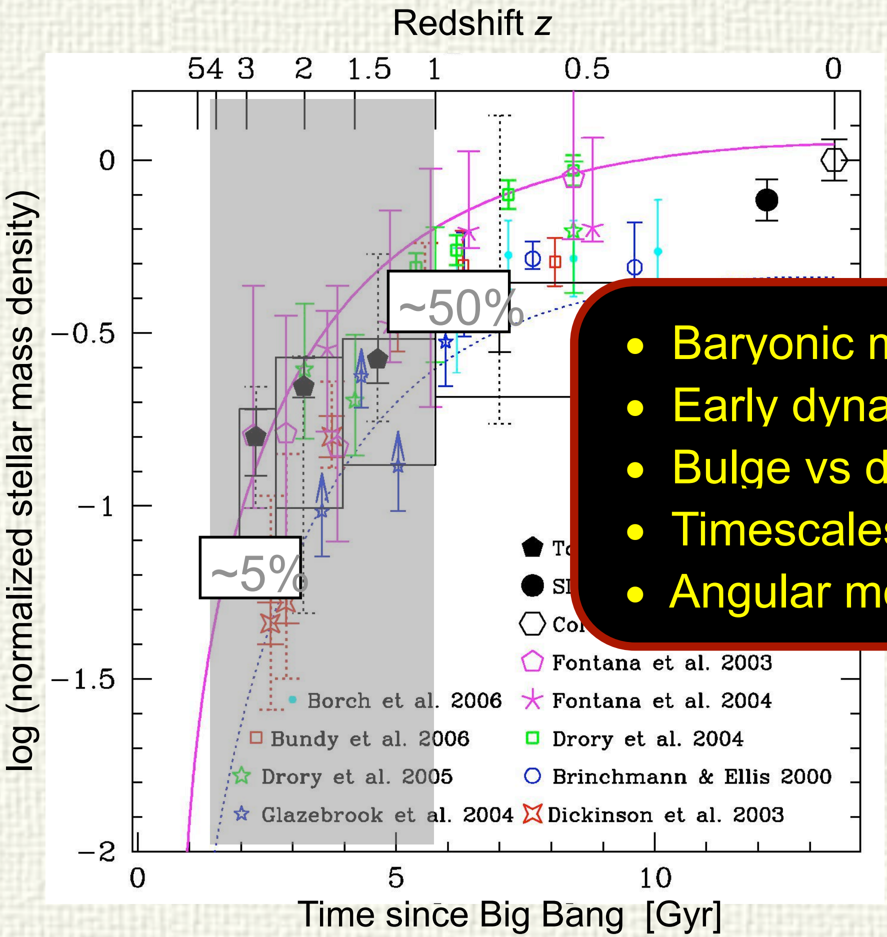
• Thanks to robust χ^2 minimization techniques, we can **measure the main dynamical parameters** of the galaxies, finding that high turbulent disks are required to reproduce the observations

• This allow us to study for the first time the **z~2 Tully-Fisher relation**, providing important constraints for galaxy evolution models

• The study of the dynamics of high redshift galaxies is starting to **explore the z>3** universe thanks to projects like LSD and AMAZE

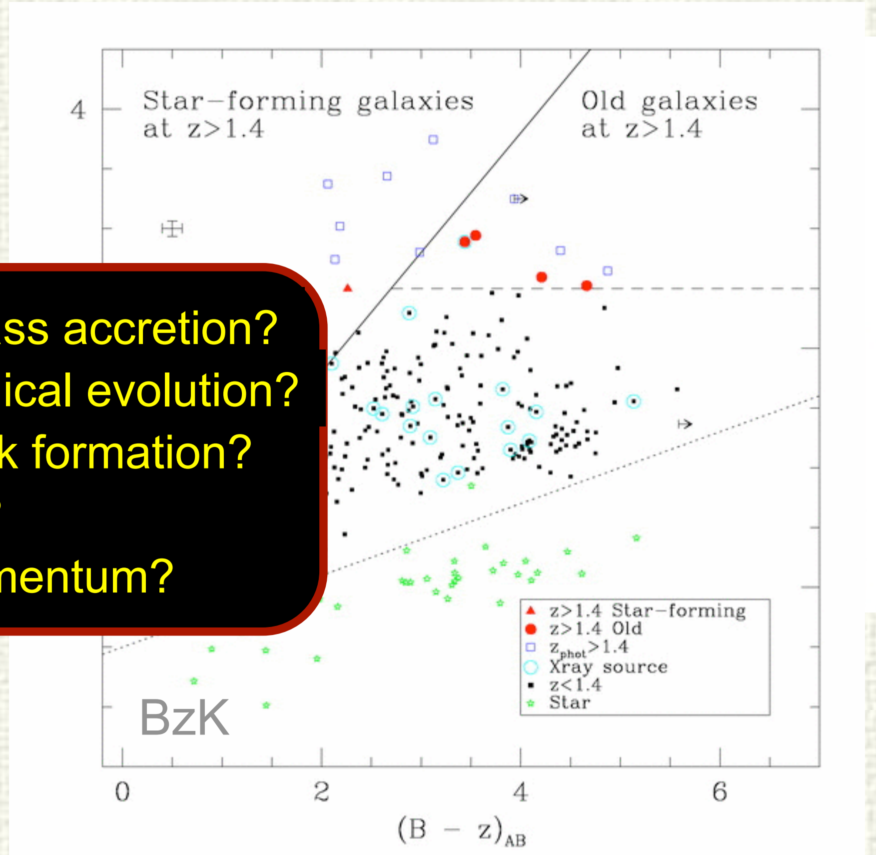
Galaxies in the high-z Universe

Rapid growth of galaxies at $z \sim 1 - 4$:



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?
- Angular momentum?

The SINS team and collaborations

N.M. Förster Schreiber, R. Genzel, N. Bouché, G. Cresci
K. Shapiro, L.J. Tacconi, D. Lutz, P. Buschkamp, R. Davies, S. Genel,
E.K. Strobel Hicks, A. Sternberg, F. Eisenhauer,
M.D. Lehnert, N. Nesvadba, A. Verma, R. Abuter, R. Bender, S. Seitz

MPE/Berkeley/Arcetri/Tel Aviv/Meudon/Oxford/USM

A.E. Shapley, D. K. Erb, C.C. Steidel
UCLA/CfA/Caltech

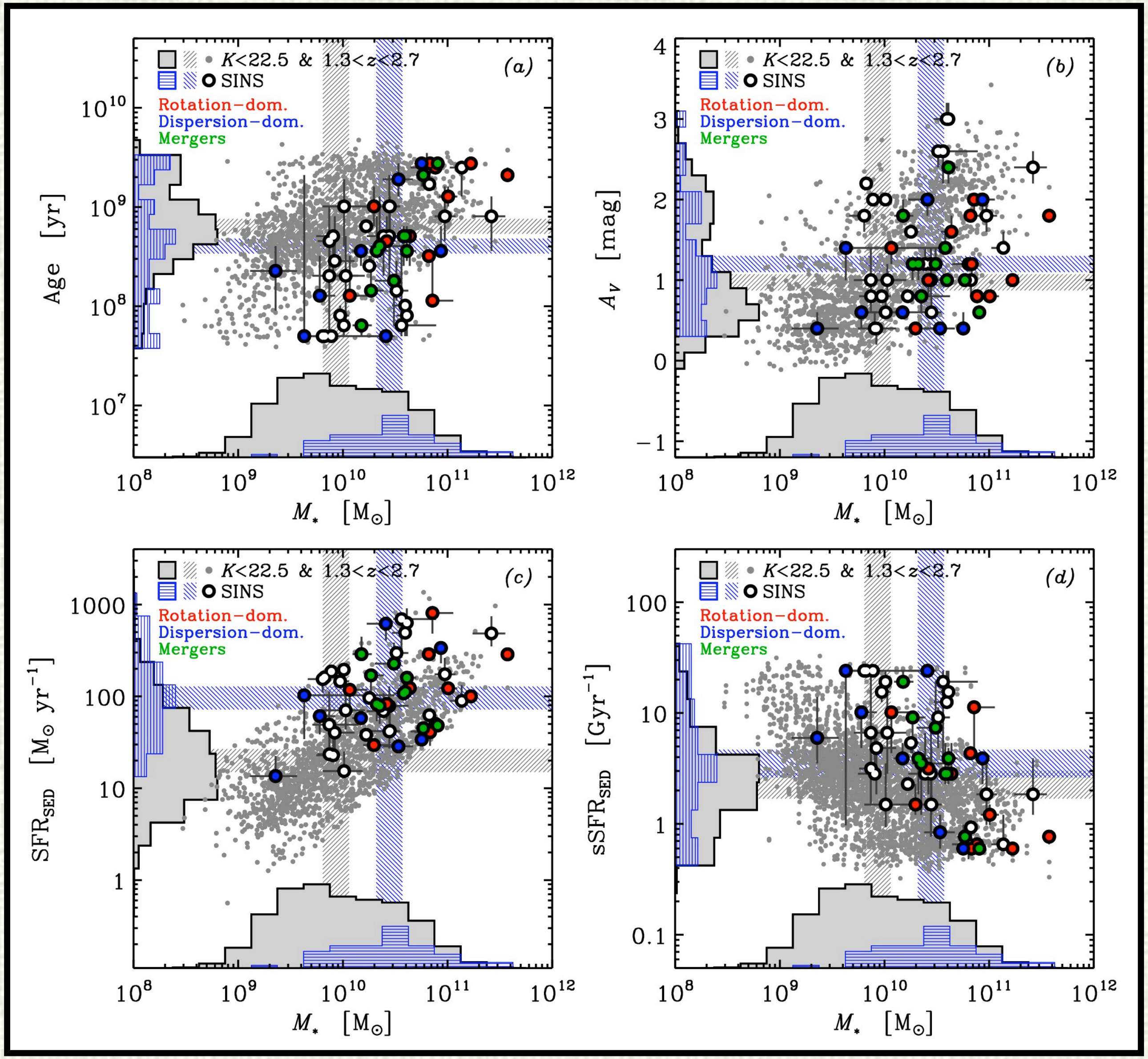
A. Cimatti, E. Daddi, J. Kurk, A. Renzini, S. Lilly, C. Maier, X. Kong, V. Mignoli, N. Arimoto

Bologna/CEA Saclay/MPIA/Padova/ETH Zürich/Hefei China/NAO Japan

A. Burkert, T. Naab, P. Johansson
USM

J. Sommer-Larsen
TUM

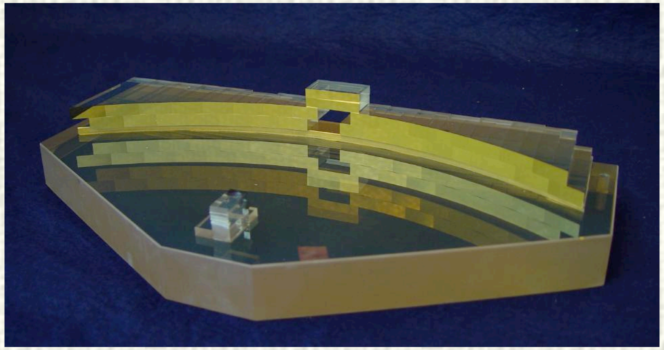
SINS Sample Properties



Förster Schreiber et al. (2009); FIREWORKS/CDFS data: Wuyts et al. (2008)

Observations: SINFONI

The image slicer of SINFONI converts the two-dimensional field-of-view on 32 one-dimensional slits that are dispersed



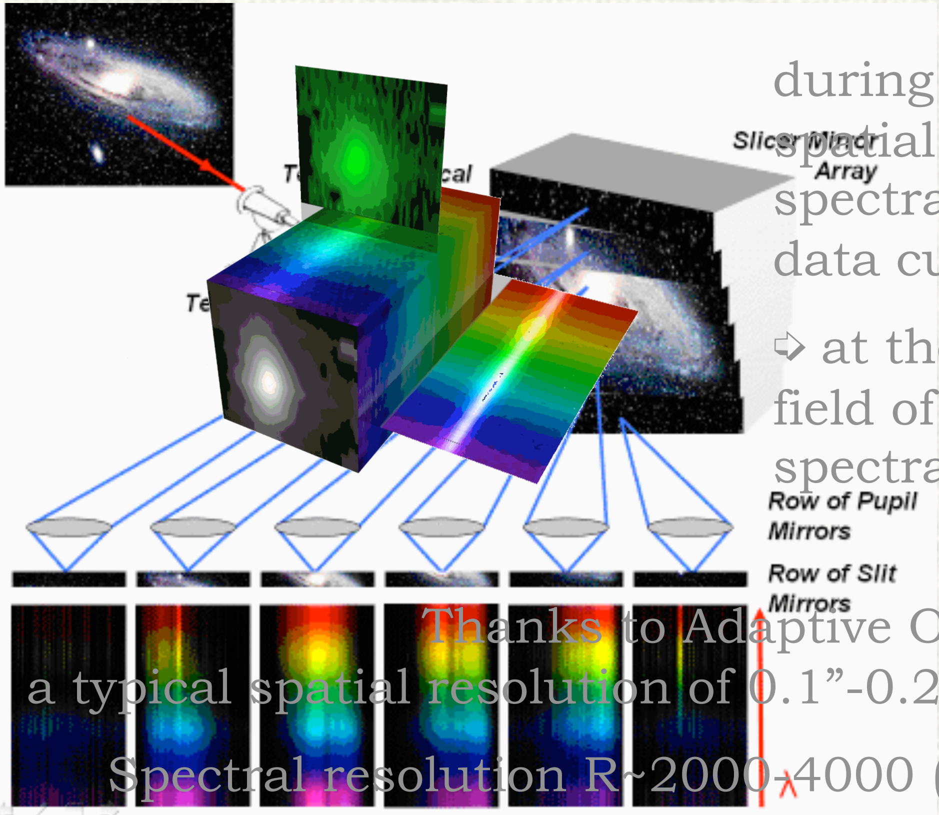
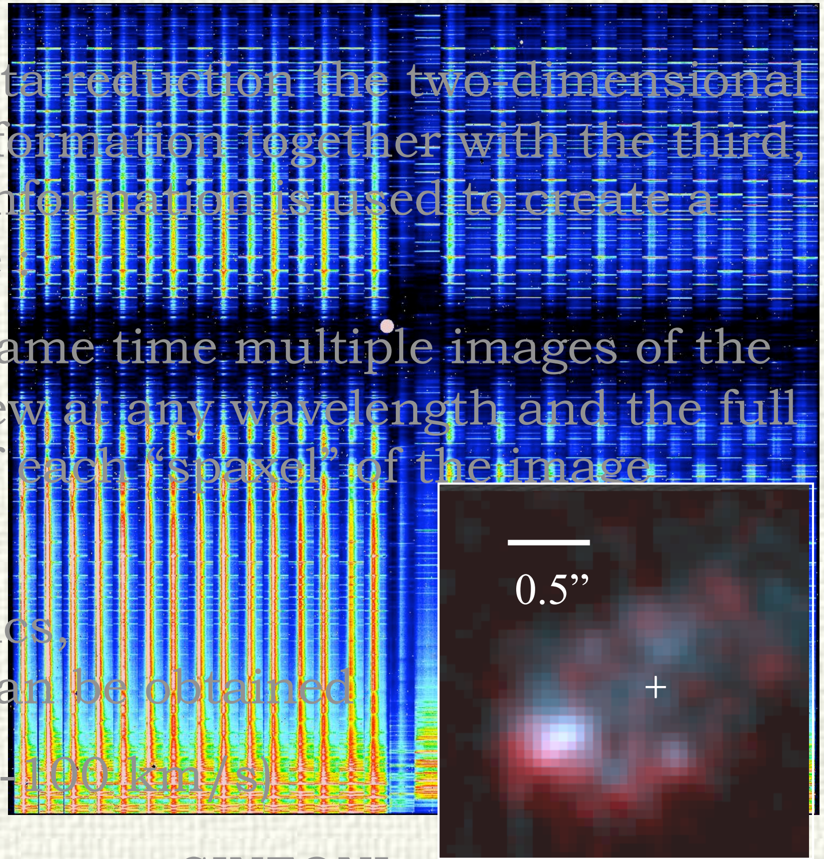


Image slicer

during data reduction the two-dimensional spatial information together with the third, spectral information is used to create a data cube

➪ at the same time multiple images of the field of view at any wavelength and the full spectra of each “spaxel” of the image



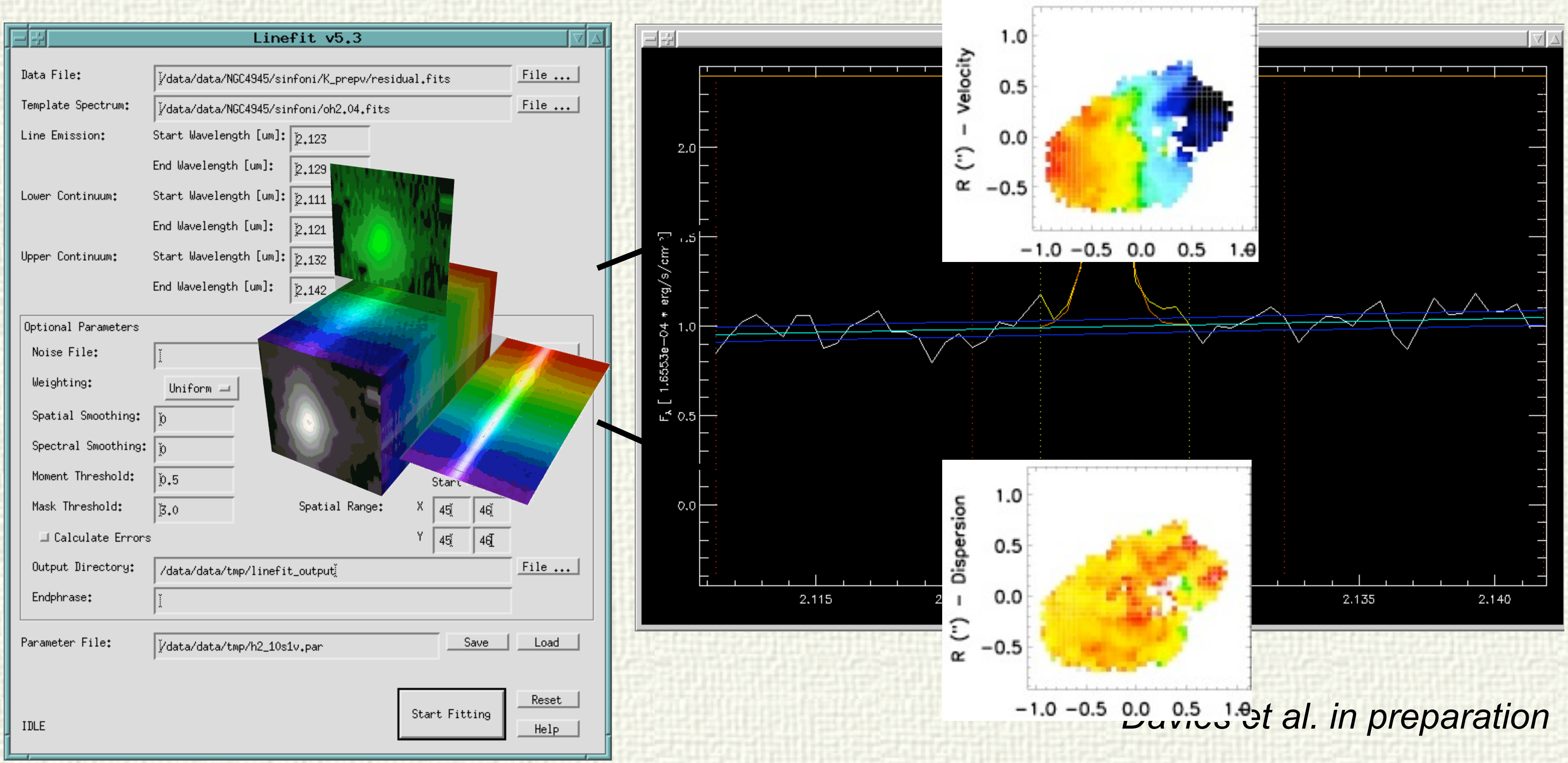
SINFONI raw frame

Thanks to Adaptive Optics,
a typical spatial resolution of 0.1”-0.2” can be obtained

Spectral resolution R~2000-4000 (65-100 km/s)

Emission line extraction: LINEFIT

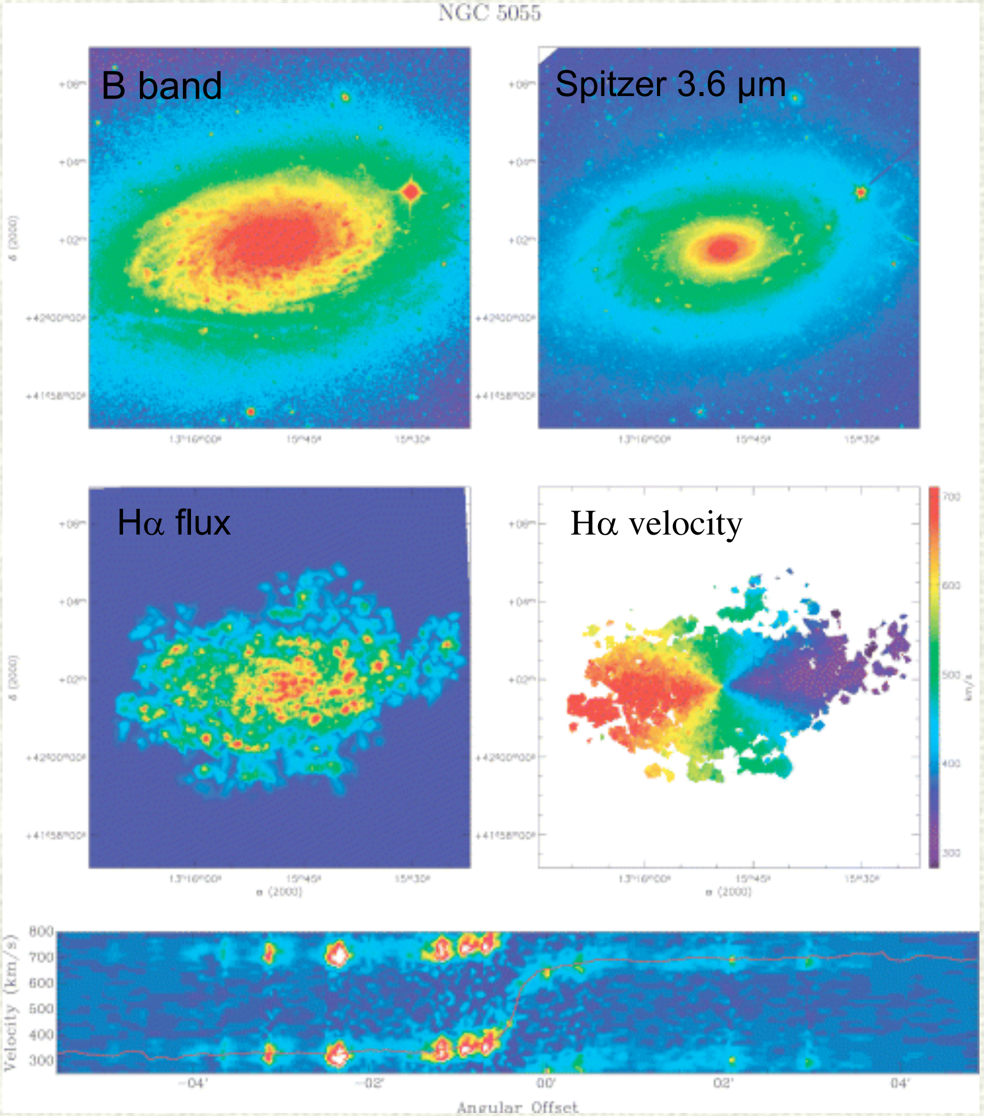
- Flux, velocity, & dispersion maps are calculated from the data fitting to the line profile a Gaussian convolved with an unresolved line profile
- Error maps are generated based on derived or input error cube using Monte Carlo techniques



Davies et al. in preparation

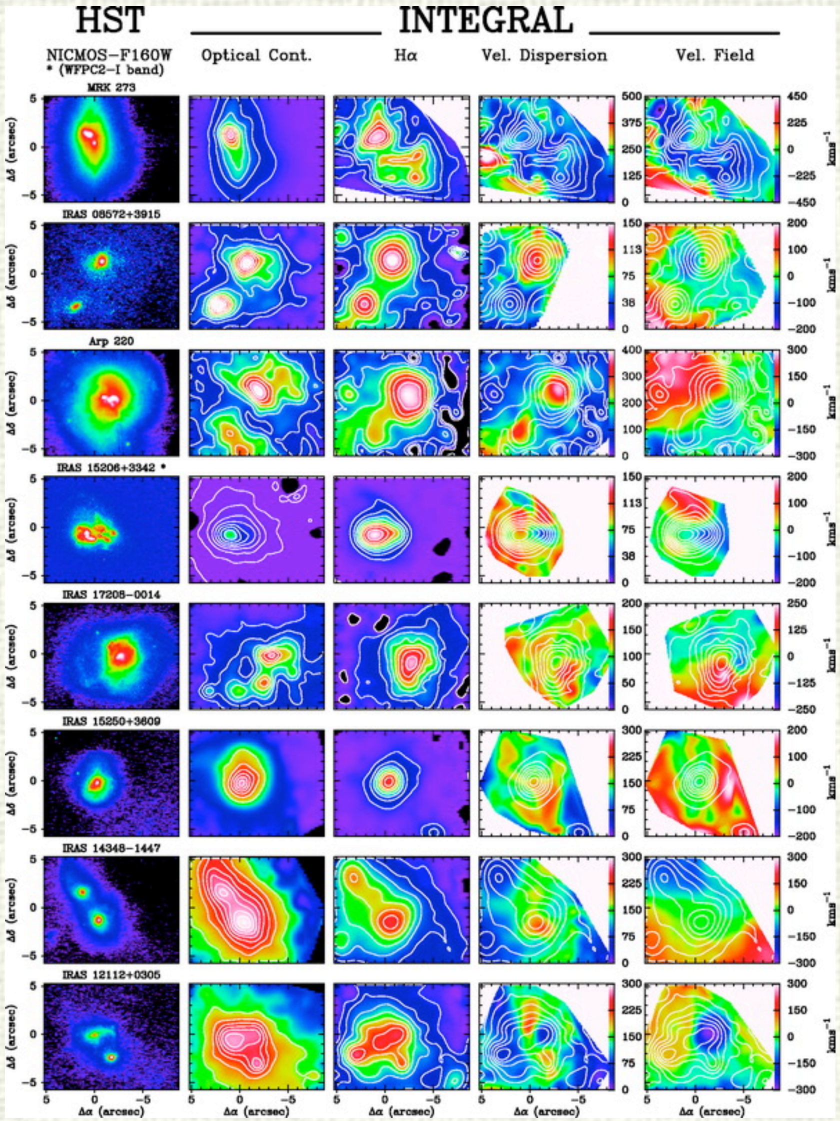
In the local Universe

Rotating systems



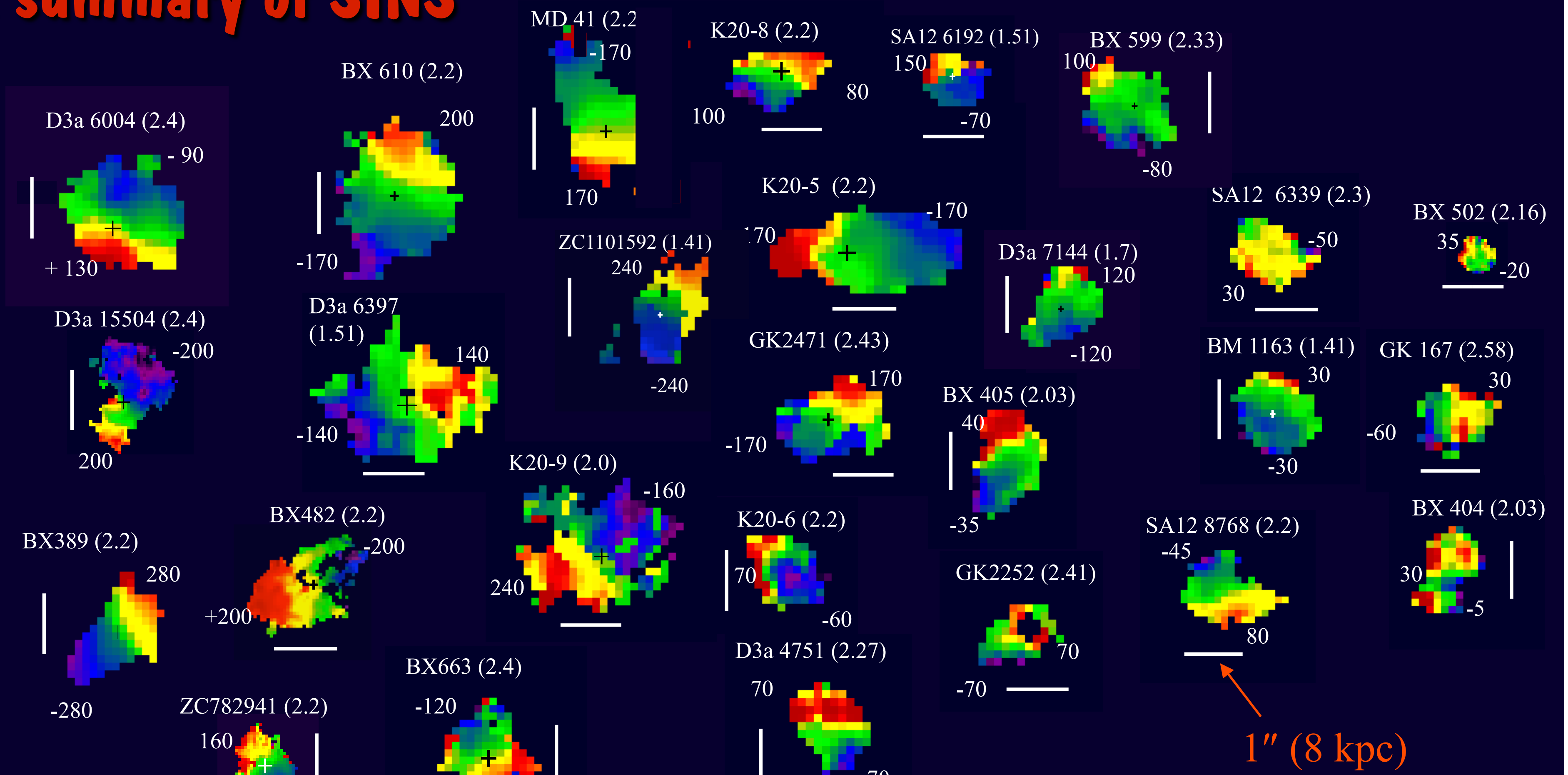
Daigle et al. (2006)

Merger like ULIRGS



Colina et al. (2005)

A summary of SINS



In order to derive robust and quantitative information from the data new tools have been developed:

- **to discriminate between disturbed system with recent major mergers signatures and rotating system at high-z**
- **to measure and model the dynamical properties of the galaxies**

In the high-z Universe: Kinemetry

- The method was used by Krajnovic et al. (2006) to measure dynamical feature of local, high S/N galaxies (such as bars, spiral structures...)
- In our high-z case this deviations are smaller than the noise, but we use Kinemetry to quantify the global asymmetry of the system **induced by major mergers**
- In an *ideal case*, all the power for the velocity field should be in the $B_{1,v}$ term, and for the dispersion in the $A_{0,d}$ term

$$K(\psi) = A_0 + A_1 \sin(\psi) + B_1 \cos(\psi) + A_2 \sin(2\psi) + B_2 \cos(2\psi) + \ldots,$$

- *Any power in the other A_n, B_n terms can thus be identified as a deviations from an ideal rotating case*:

If we define:

$$k_n = \sqrt{A_n^2 + B_n^2}$$

We can use the averages $k_{avg,v}$ and $k_{avg,\sigma}$ as measures of asymmetries:

$$v_{asym} = \left\langle \frac{k_{avg,v}}{B_{1,v}} \right\rangle_r$$

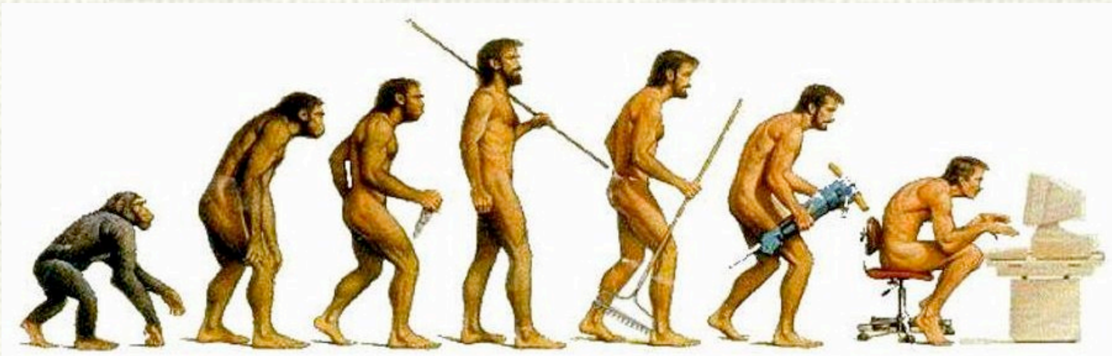
$$\sigma_{asym} = \left\langle \frac{k_{avg,\sigma}}{B_{1,v}} \right\rangle_r$$

Genetic fitting of the SINS galaxies

We search the disks model that better reproduces the features observed with a χ^2 minimization using a *genetic algorithm:*

- ***No good initial guesses needed***
- ***Efficient in finding the true absolute minimum even in a very complex topology***

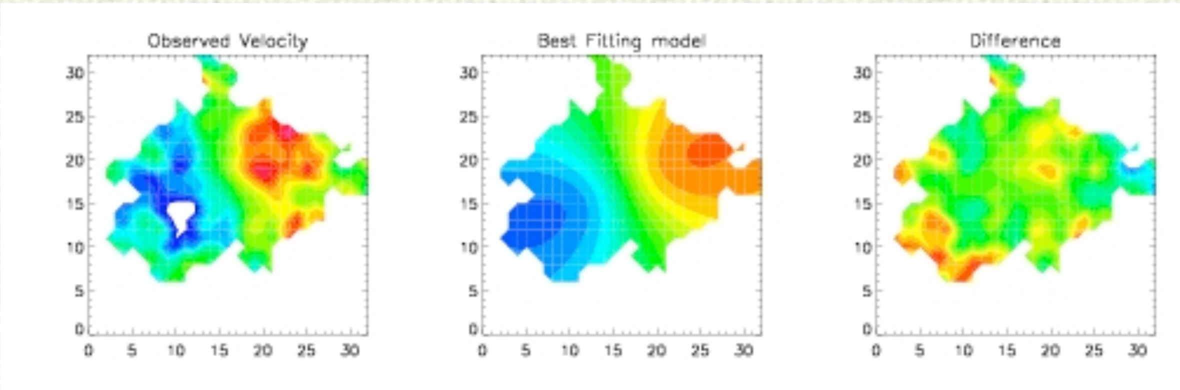
We start with a random initial population of parameters, and the "fitness" of each individual is evaluated in each iteration, so that only the best fitting individuals survive. The parameter space is sampled with random "*mutations*" and "*crossovers*" between pairs: *evolution by natural selection*



Genetic fitting of the SINS galaxies

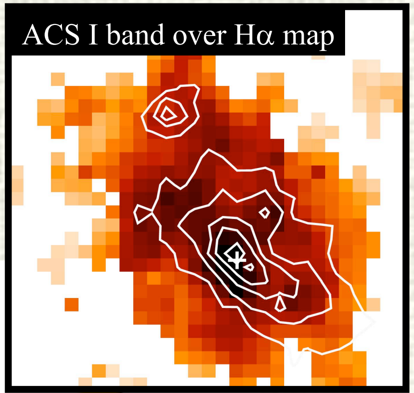
• The rotation centre is determined using the peak of the continuum emission, as for the Kinemetry analysis.
• The scale length is evaluated using the Half Light Radius of the galaxies, measured through the curve of growth of the line emission
• The dynamical mass, inclination, position angle and isotropic σ_0 are free parameters

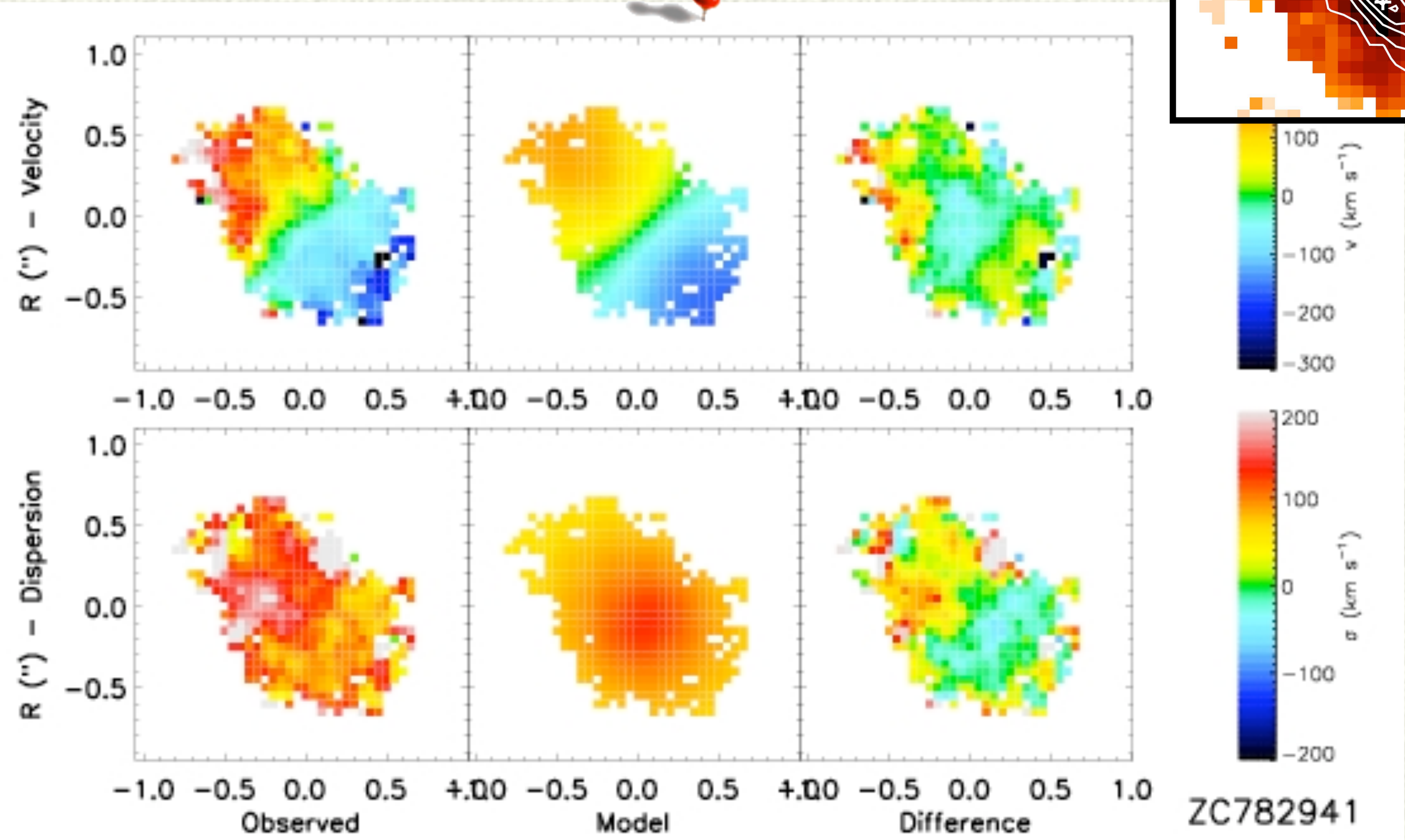
• The disk model is convolved with the observed beam and reduced to the pixel sampling of the observations to carefully account for resolution effects



• The difference is minimized, weighting each pixel using the uncertainty and masking out the pixel with low signal/noise

Fitting examples: AO scale





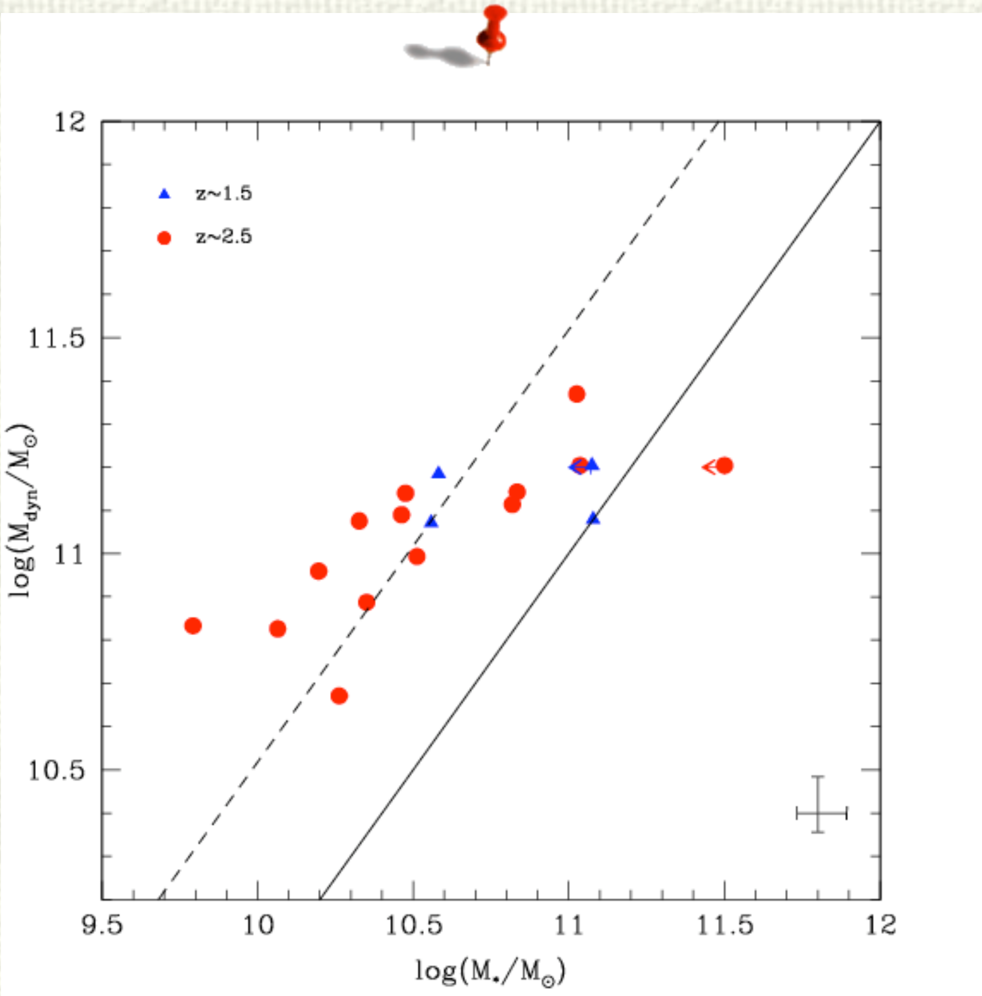
z=2.2; R_d=4.5 kpc; i=40°; $M_{dyn}=14\cdot10^{10}\,M_\odot$; V_{max}=257 km/s; σ_0=63 km/s

Comparing M_{dyn} and M_*

We can compare M_{dyn} (at R=10 kpc) as derived by the dynamical modeling with M_* derived from SED fitting of the galaxies

↓

We find good correlation between the two: $P=2\cdot10^{-5}$ that the two are uncorrelated



Cresci et al. (2009)

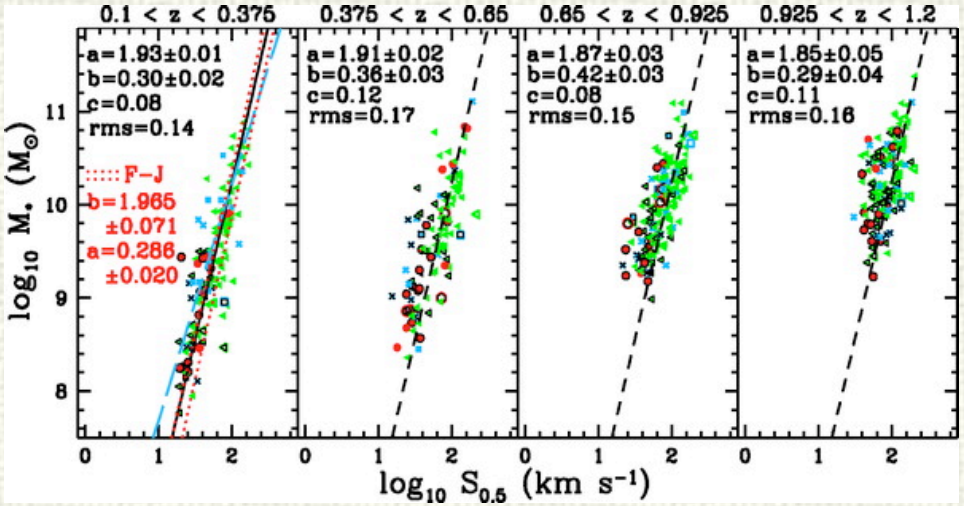
On average $\langle M_{dyn}\rangle = 3.3 \langle M_*\rangle$: very high gas mass fraction needed ($M_{gas} \approx M_*$, but large uncertainties! see also e.g. Daddi et al. 2008, Tacconi et al. 2009)

The S(0.5) Tully-Fisher relation

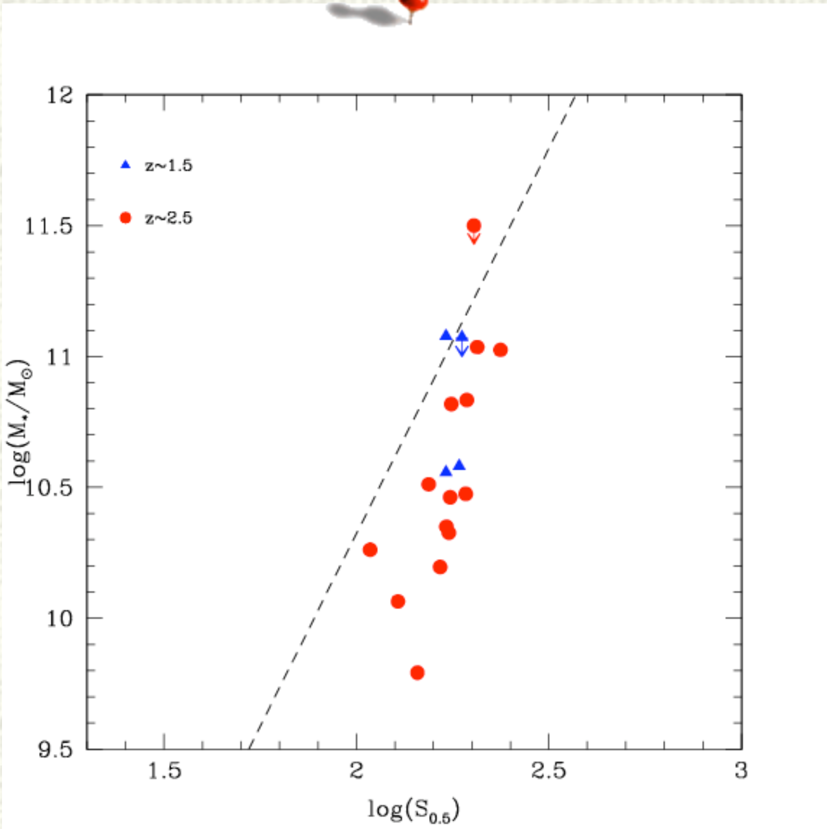
- **Kassin et al. (2007) introduced the quantity S(0.5) to reduce the scatter in the TFR, taking into account the effects of disordered motions**

$$S^2(0.5) = 0.5\,V_{max}^2 + \sigma_0^2$$

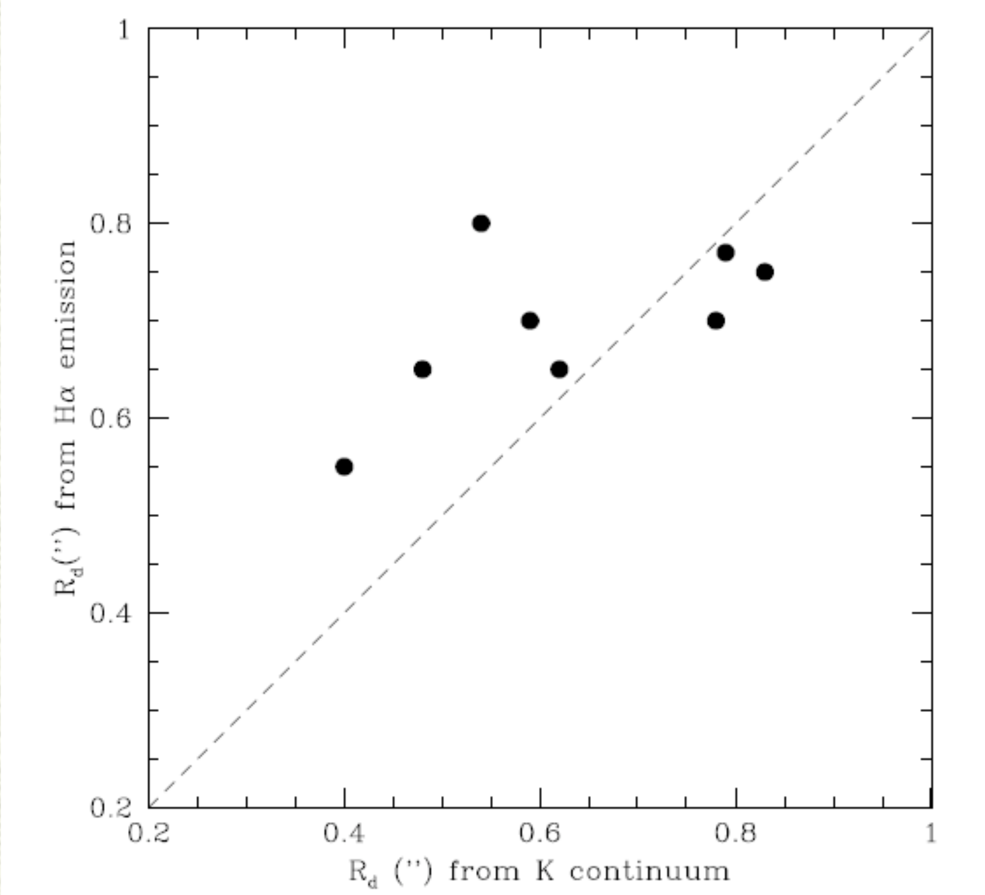
They found no evolution up to z~1.2:



Some evolution detected at z~2.2:



Halpha radius vs Continuum



The SINS Survey

Spatially-resolved Studies of z~1–3 Star-forming Galaxies:

Dynamics, morphologies, physical properties

Spectroscopic **I**maging survey of high redshift galaxies in the **N**ear-IR with **S**INFONI at VLT

GTO + open time program

Rest-frame UV/optically selected star-forming galaxies

Sub**M**m **G**alaxy **S**urvey with the IRAM Plateau de Bure mm-interferometer

Long-term program

Submillimeter-selected luminous dust-rich galaxies

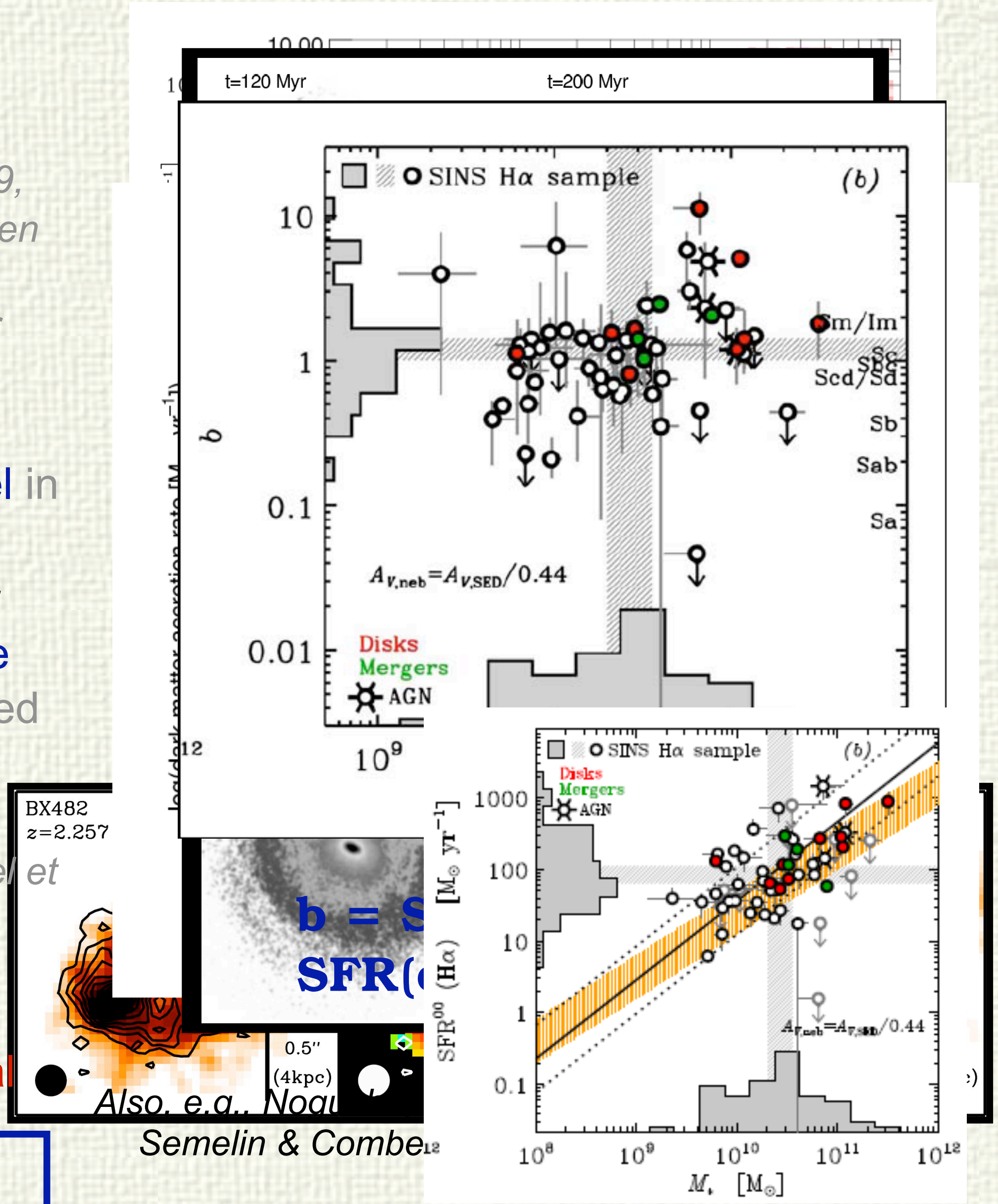
Dynamical Evolution of Gas-rich Disks

- Massive ($M_* \sim 10^{10}$-10^{11} $M_\odot$), high star-forming (SFR~100 $M_\odot$/yr), 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)*
- Tight correlation between M_* and SFR for star forming galaxies up to z=1-2.5: small space for short duty cycle merger events ...

… and constant Star Formation activity level in the SINS galaxies *(Elbaz et al. 2007, Daddi et al. 2008, Förster Schreiber et al. 2009)*

- Massive star-forming galaxies have space density a factor of 4 higher than the expected density of merger induced starburst of comparable SFR, but accretion rate high enough to sustain SF *(Genel et al. 2008, Dekel et al. 2009, Elmegreen et al. 2007)*
- Highly turbulent disks at high-z, with massive clumps: the simulations show that the clumps coalesce into a central "classical bulge"

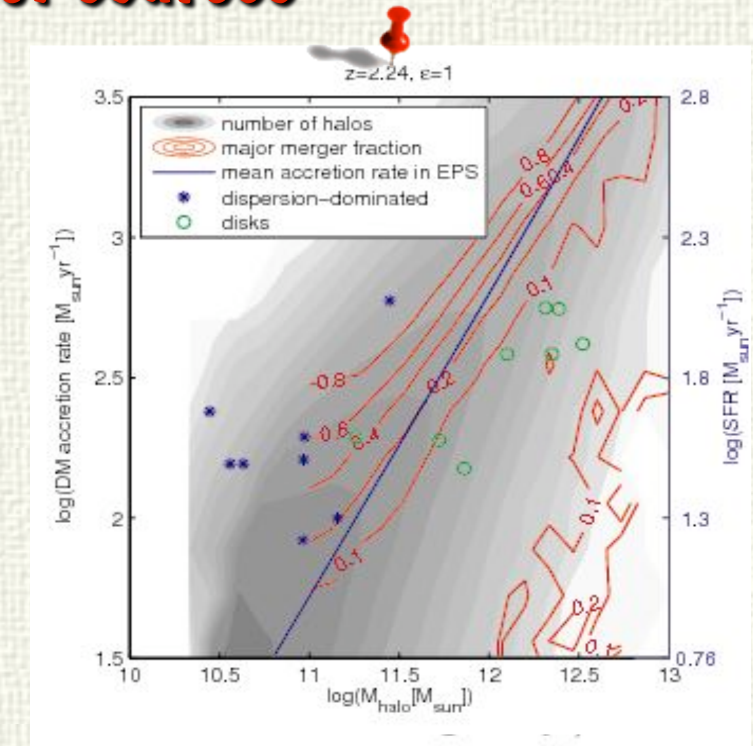
Smooth accretion and secular evolution?



Semelin & Combes

Forster-Schreiber et al. 2009

V/σ: dynamical support and compact sources

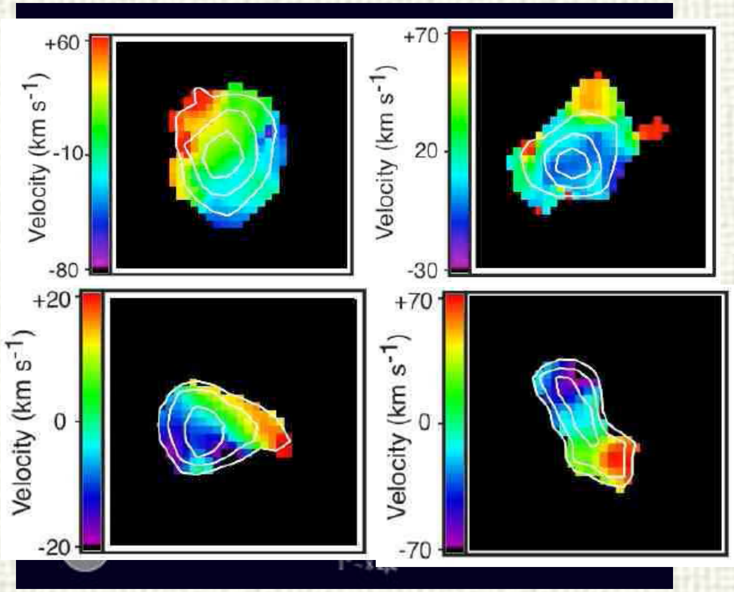


Genel et al. (2008)

- The sources that appear to be dominated by dispersion rather than rotation ($V/\sigma < 1$) are compact (2-4 kpc)

- These includes both the *youngest* as well as some of the *more evolved* sources in the sample

- If the observed V_c is a measure of the halo Mass, a merger interpretation would be favored



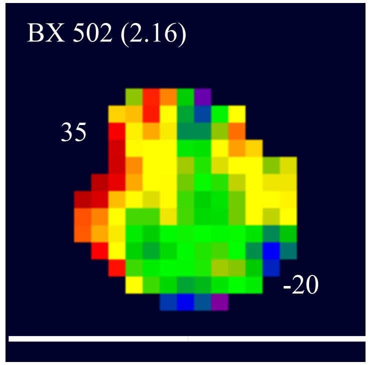
- However, due to beam smearing effect the true V_c might be underestimated, and/or size be underestimated due to surface brightness:

Law et al. (2008) observed 24 galaxies with OSIRIS at Keck. *Only 13 detected, all look compact (R<2kpc) and dispersion dominated ($V/\sigma<1$)*

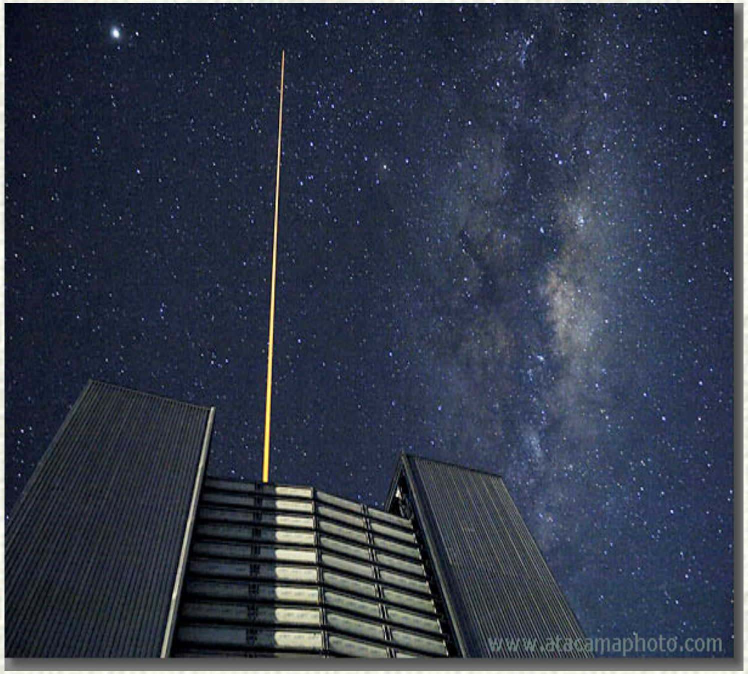
OSIRIS SFR surface density limit (1 $M_\odot$/yr/kpc^2) is more 10 times lower than SINFONI (0.03/0.1)

A larger sample with AO

Laser AO assisted observations are required to clarify how the compact, dispersion dominated galaxies fit in the general picture of galaxy formation:



- lower mass and compact objects with smaller velocity gradient?
- bursting mergers remnants?
- primordial systems undergoing the first major SF episode?



A larger sample with AO resolution will benefit also the study of the large disks and mergers:

- fraction of mergers/disks with kinemetry
- better sample of the diversity in physical properties
- compare the local deviation in the gas dynamics with the presence of clumps
- study spatially resolved gradients