3D spectroscopy and galaxy physics

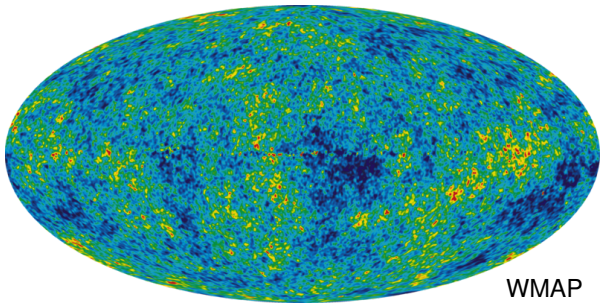
Benoît Epinat

Laboratoire d'Astrophysique de Marseille

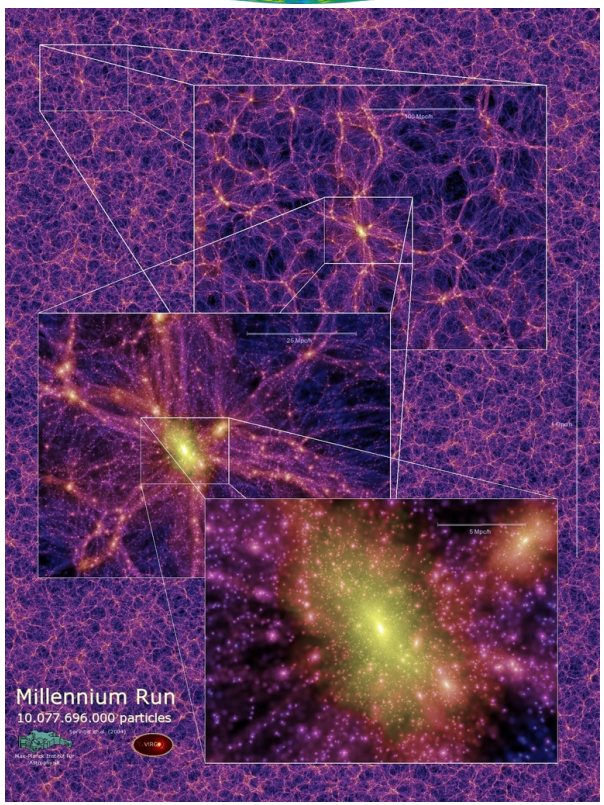


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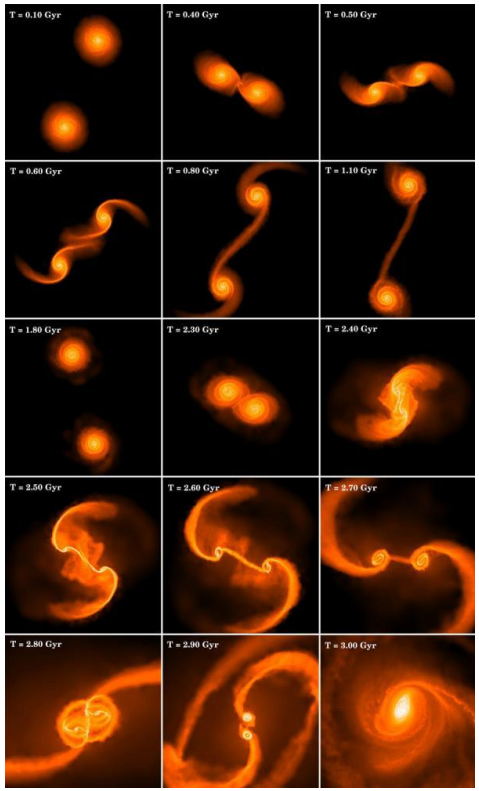
Galaxy formation and evolution processes

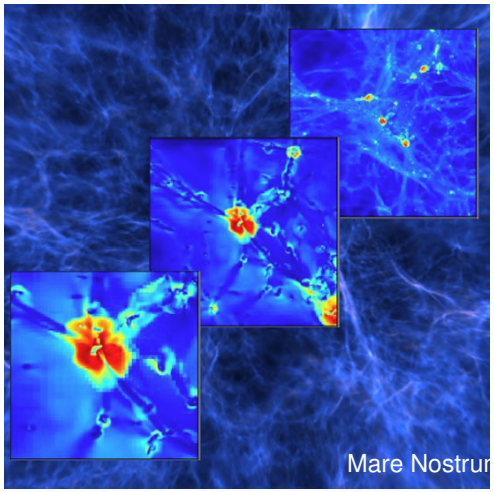


WMAP



Physics of baryons





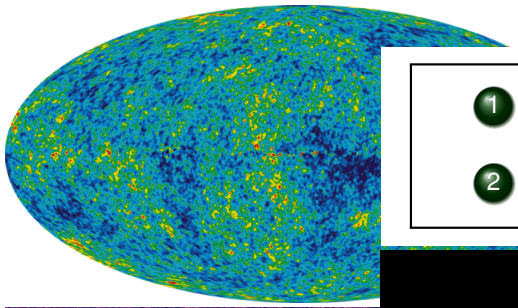
Galaxy mergers VS Diffuse gas accretion

&

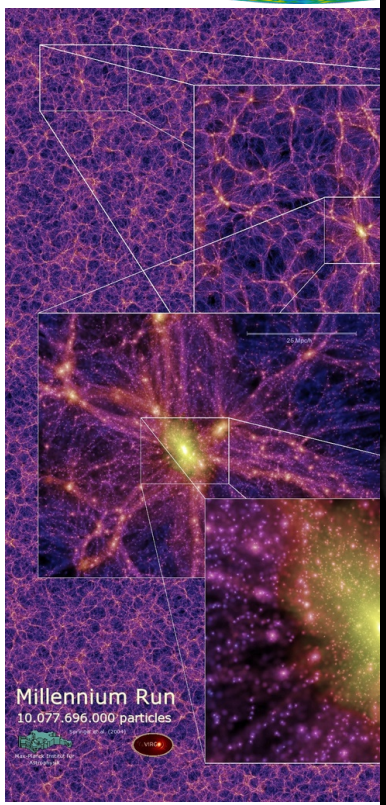
Secular evolution VS Environmental effect

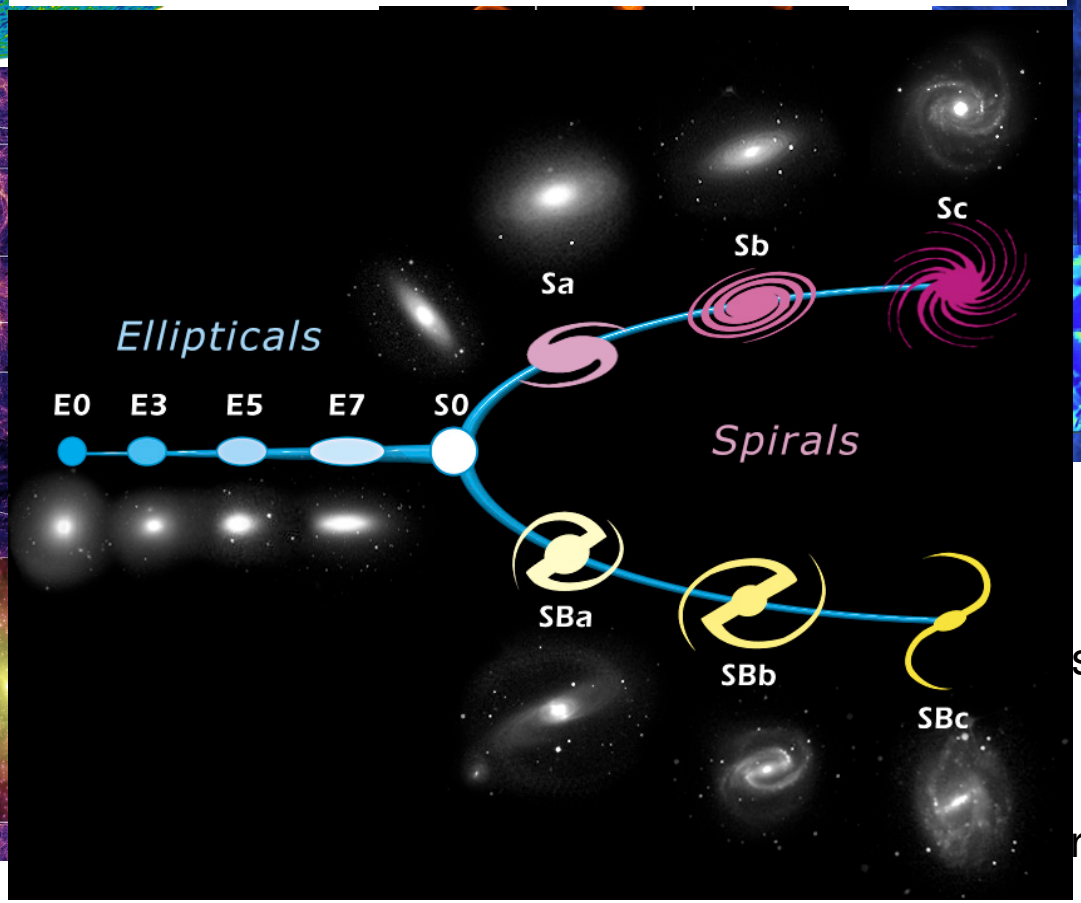
Galaxy formation and evolution processes

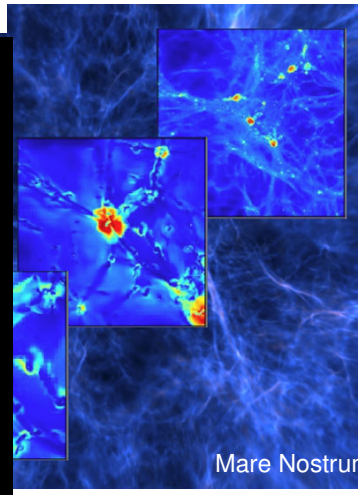
Physics of baryons



1. **Contribution of these processes**
2. **Hubble sequence build-up**







se gas accretion

ronmental effect

Spectro 3D vs long slit spectroscopy

Spatially resolved galaxy physics

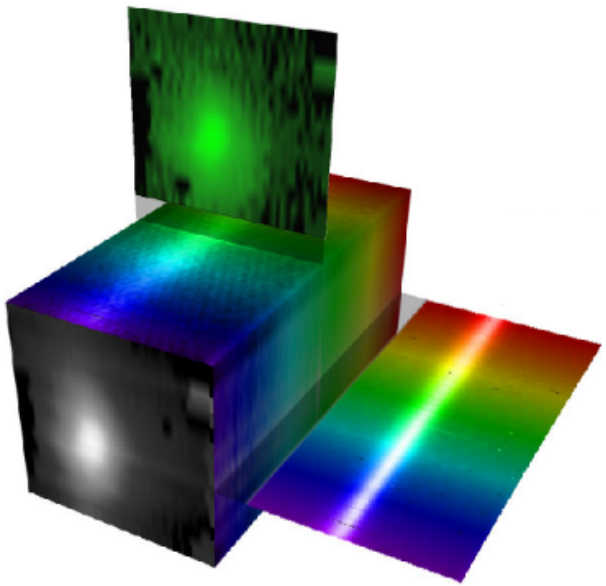
- Information over the whole 2D field of view
- No a priori on the projection parameters
- Non circular motions can be studied (e.g. kinemetry, Krajnović et al. 2006)
- Detection of off axis regions / companions

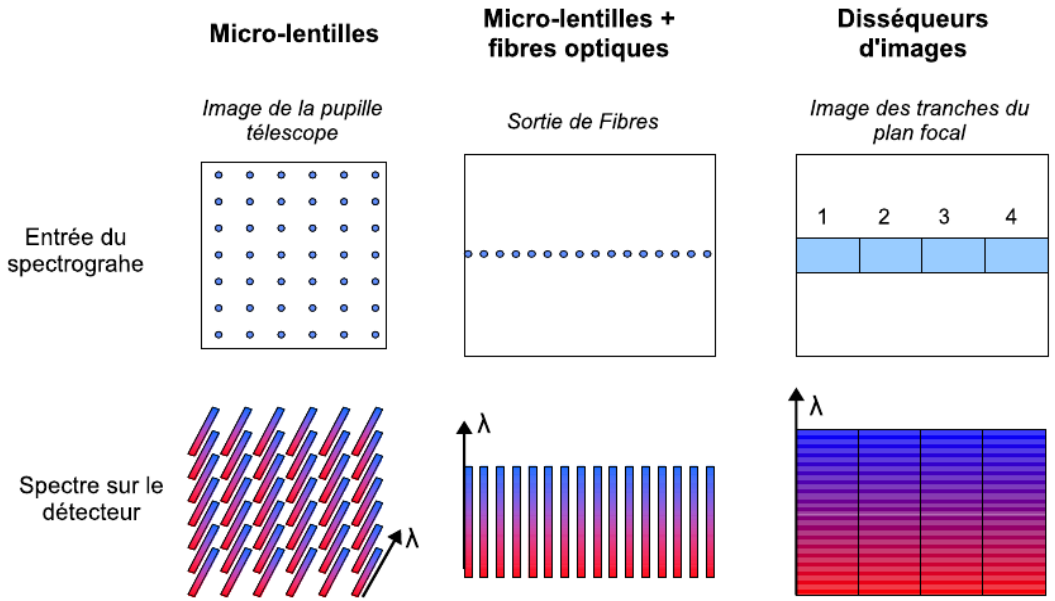
Blind surveys

- No a priori selection (e.g. MUSE)
- Emission line flux limited samples (e.g. groups or clusters)
- Lα at high redshift : tracing structures, luminosity functions of first galaxies

Various instrument concepts

- Splitting spectral information : Fabry-Perot, Tunable Filters, Fourier Transform Spectrometers
- Splitting of spatial information : image slicers + gratings (e.g. SINFONI, MUSE)
- No splitting : micro lens + grating instruments (e.g. SAURON)



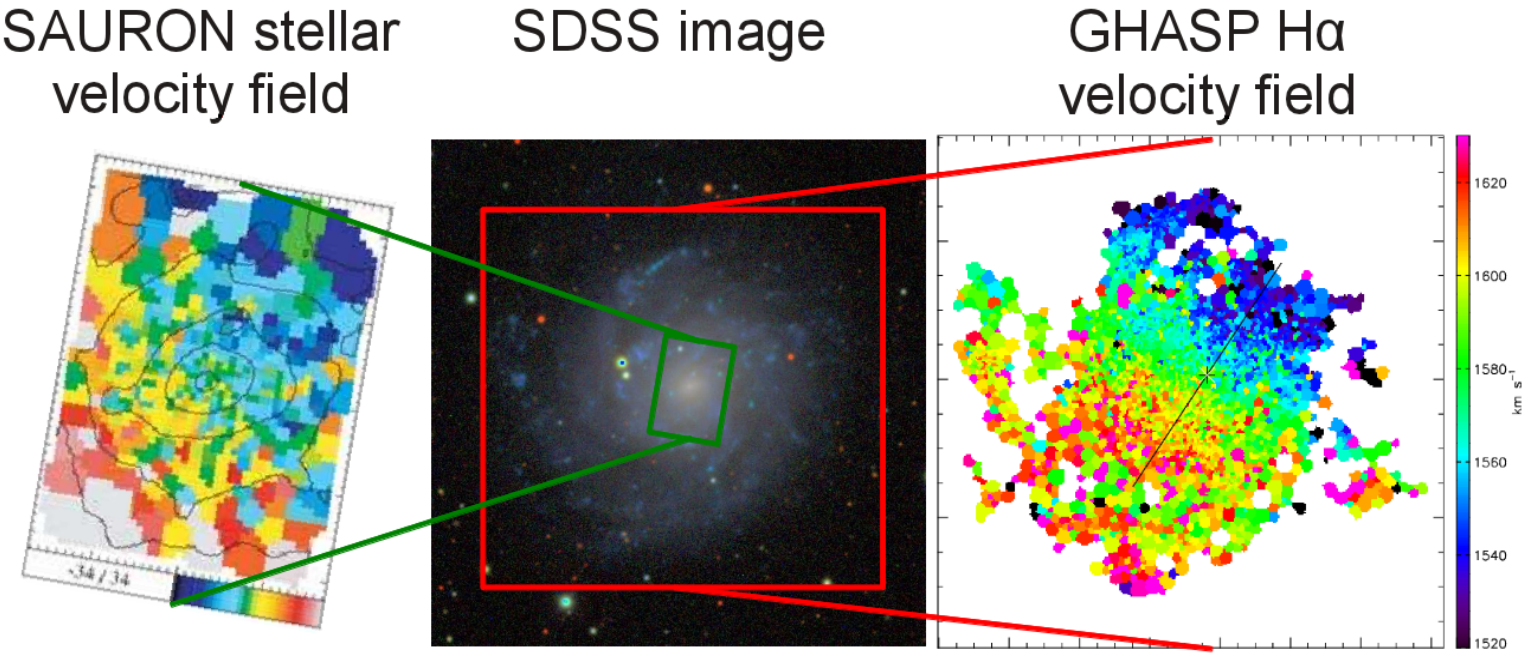


Data Reduction methods/difficulties are different to reconstruct the spatial + spectral information.

Various instrument setups

For a constant number of pixels :

- Large field of view and small spectral range
- Large spectral range and small field of view
- Tune spectral and spatial resolution
  $\Rightarrow$ depending on the scientific goals and targets



NGC5668 : SAURON (Ganda et al. 2007) spectral range : 300 *Å*.
GHASP (Epinat et al. 2008) spectral range : 10 *Å*.

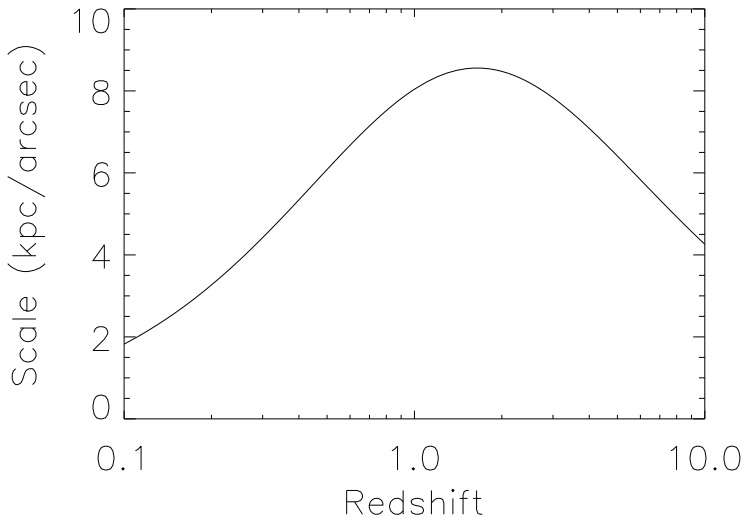
Main surveys

Low redshift

- Large spatial resolution
- Stars/early types : ATLAS3D, SAURON
- Gas/late types : Fabry-Perot (GHASP, SINGS, ...), CALIFA
- Single case studies
- High-z analogues (e.g. ULIRGS)

High redshift

- Low spatial resolution
- Stars : difficult to observe
- Ionized gas : IMAGES, MASSIV, SINS, LSD/AMAZE, OSIRIS
- Lensed galaxies, etc.



Physical scale

Resolution effects have to be taken into account in the analysis.

Main surveys

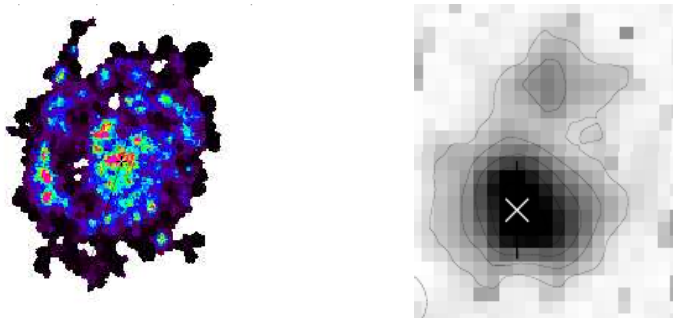
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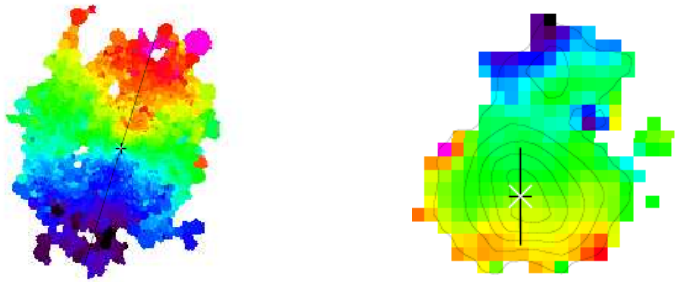
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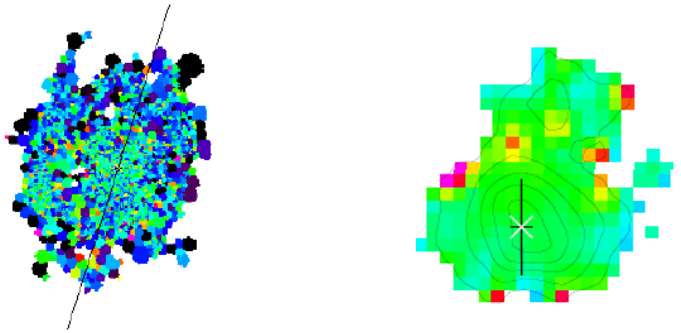
z=0 (GHASP) **z∼1 (MASSIV)**



Hα flux



Velocity fields

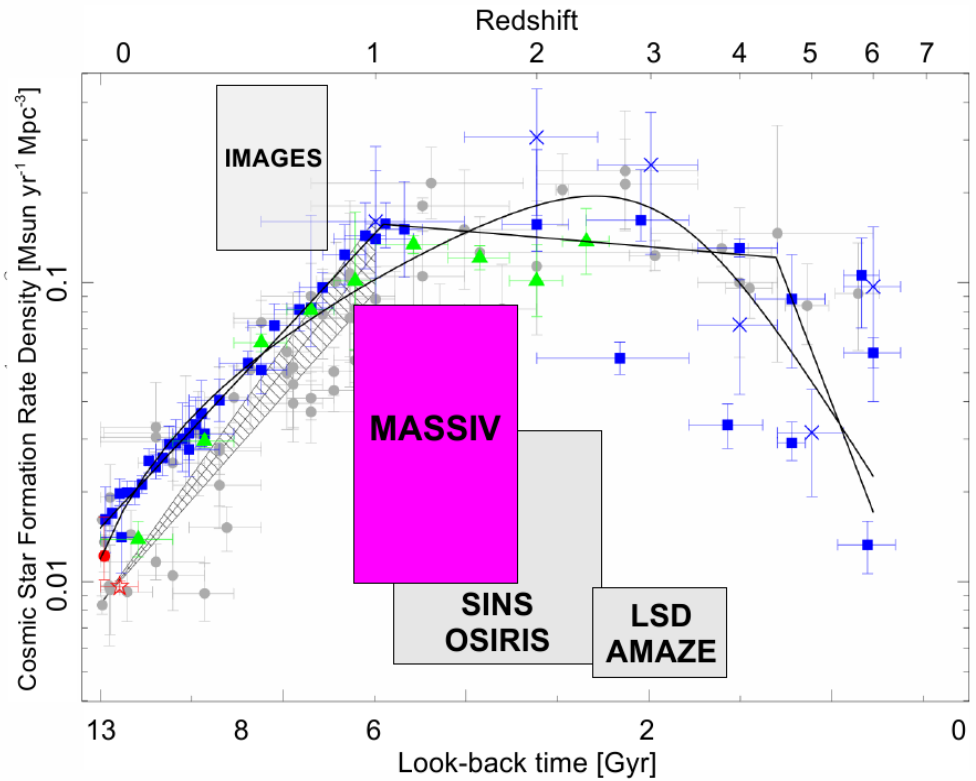


Velocity dispersion maps

3D spectroscopy surveys at high redshift

Samples at $0.5 < z < 3$

- Peak of cosmic star formation activity
- Morphological transition
- Only emission lines can be studied due to current instrument sensitivity
- Surface brightness dimming : $\propto (1+z)^4$
- Various observational setups
- Various selection functions



Contini et al. (2012) – adapted from *Hopkins (2006)*

Example of observations with SINFONI

Only emission lines can be studied due to current instrument sensitivity

General observational features

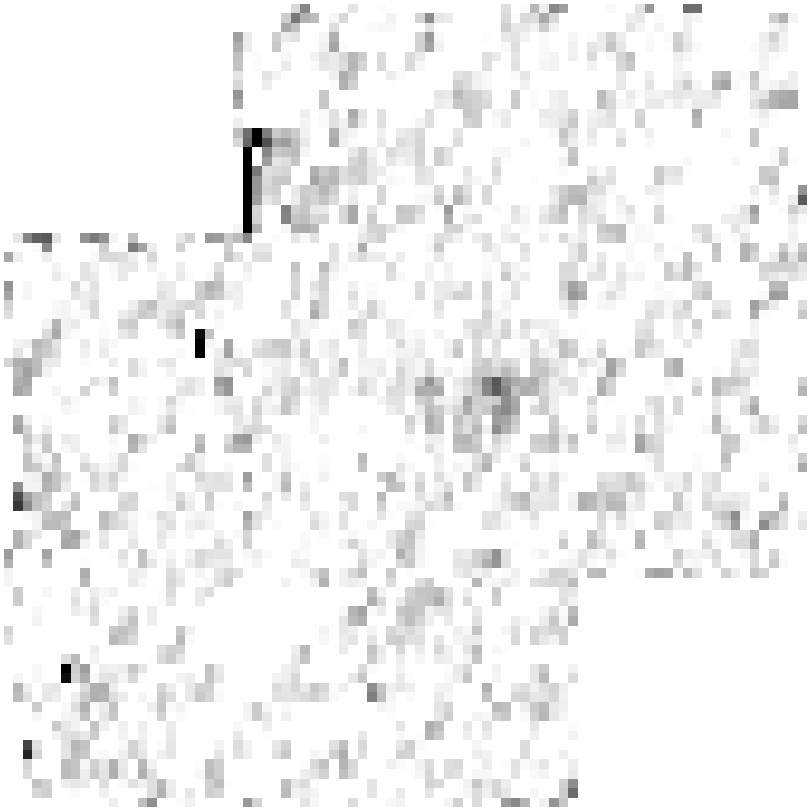
- Hα or [OIII] in J-band, H-band or K-band
- $R \sim 2000$ in J-band, $R \sim 3000$ in H-band, $R \sim 4000$ in K-band

Seeing limited observations

- Seeing $\sim 0.65''$
- Pixel size : $0.125'' \times 0.250''$
- FOV : $8'' \times 8''$

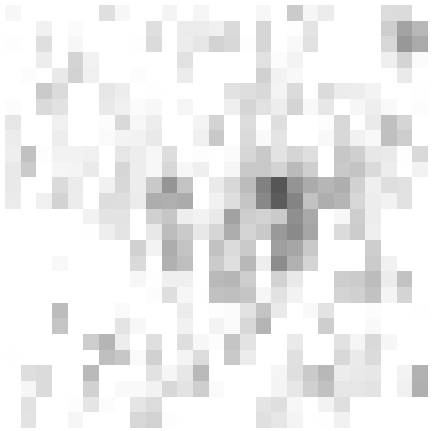
Observations using Adaptive Optics

- FWHM $\sim 0.2''$
- Pixel size : $0.05'' \times 0.10''$ or $0.125'' \times 0.250''$
- FOV : $3'' \times 3''$



Seeing limited observation

From 3D-spectroscopy observations to kinematic maps



Cube around Hα line

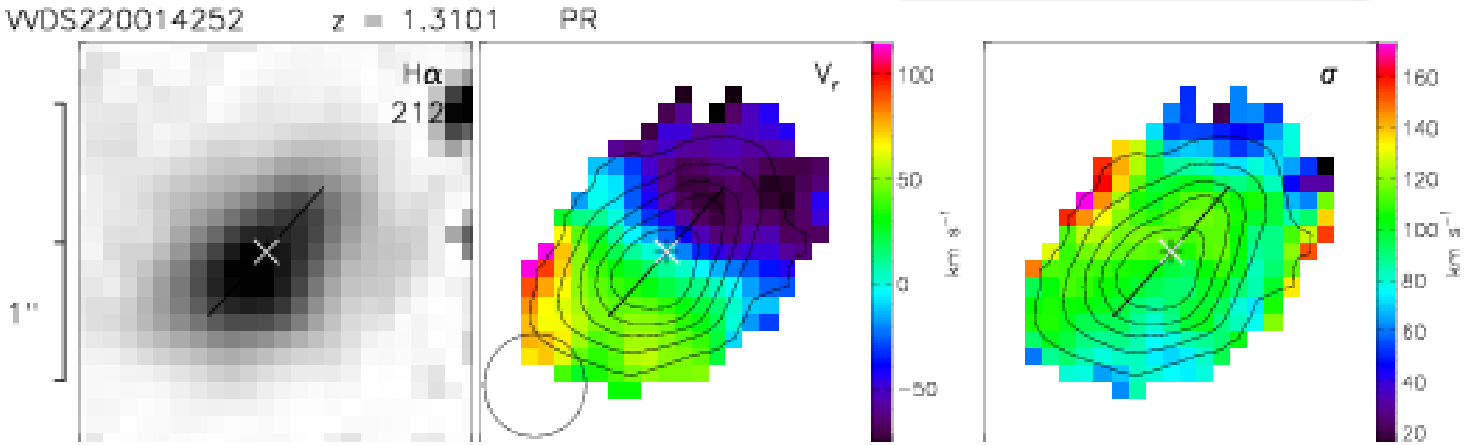
Doppler-Fizeau

$$z = \frac{\lambda - \lambda_0}{\lambda_0}$$

$$v = c\frac{(z+1)^2 - 1}{(z+1)^2 + 1}$$

$$v_r = \frac{v - v_{sys}}{1 - v \times v_{sys}/c^2}$$

$$\sigma \approx c\frac{d\lambda}{\lambda}$$



Hα flux map | Hα velocity field | Hα velocity dispersion

Resolution vs. sensitivity

$0.7 < z < 4$: small variation of the physical scale ($\sim$ 8.5 kpc/")

Seeing limited vs. AO

- Seeing limited : $\sim 0.6 - 1.0$"
- AO : $\sim 0.1 - 0.4$"

Higher sampling with AO $\Longrightarrow$
Lower sensitivity (extended sources)

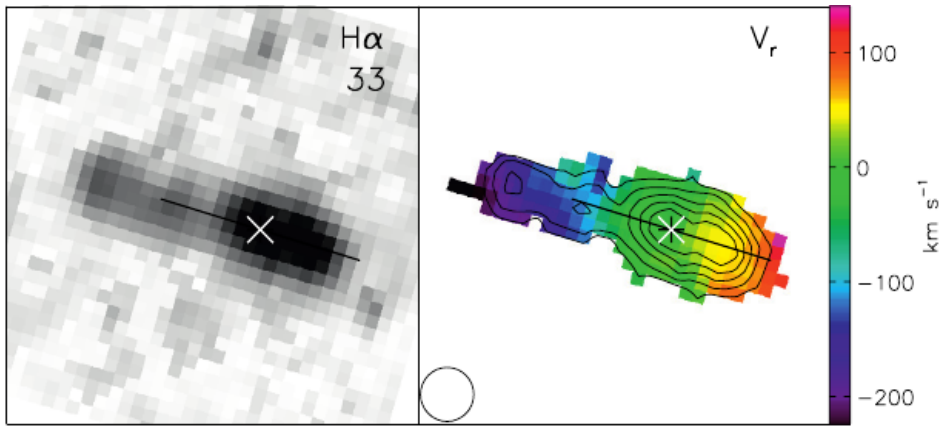
Current solution : lensed surveys

- Spatial magnification
- Flux magnification

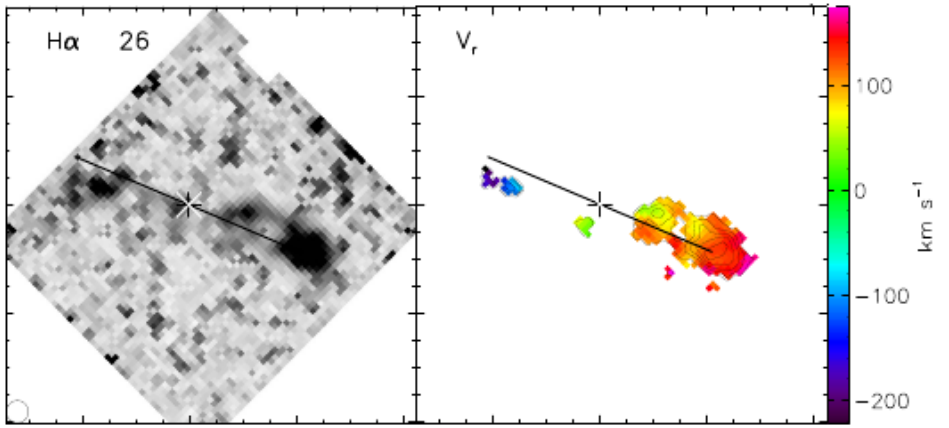
$\Longrightarrow$ Can target smaller and fainter sources + use AO
BUT difficulties to build statistical samples (*Stark et al., 2008 ; Jones et al., 2010*)

More complex PSF

Seeing limited : resolution $\sim$ 6 kpc



AO : resolution $\sim$ 2 kpc



Contini et al. (2012)
$z = 1.27$
$M_* \sim 5.5 \times 10^{10} M_\odot$

Resolution vs. sensitivity

$0.7 < z < 4$: small variation of the physical scale ($\sim$ 8.5 kpc/")

Seeing limited vs. AO

- Seeing limited : $\sim 0.6 - 1.0$"
- AO : $\sim 0.1 - 0.4$"

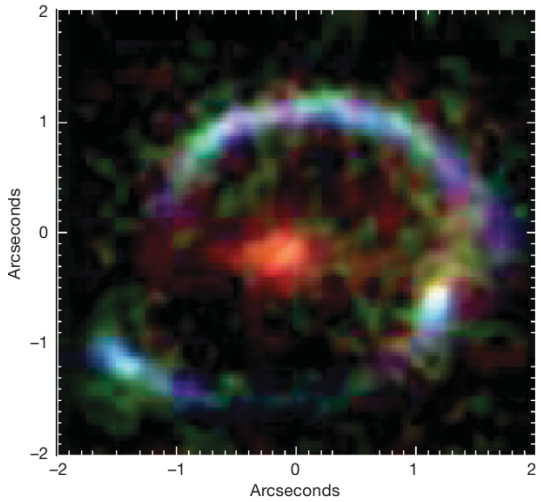
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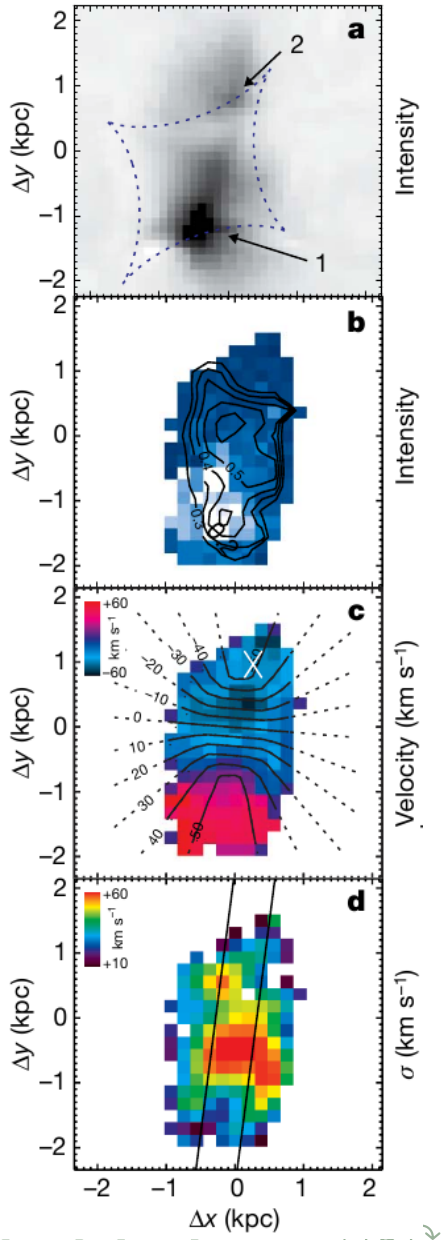
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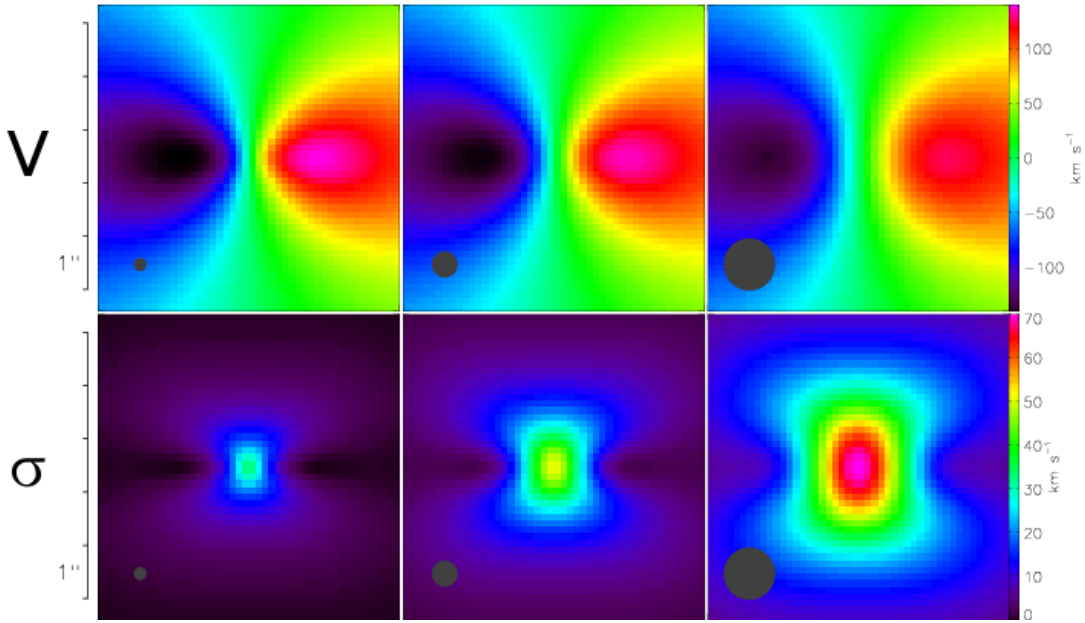
More complex PSF



Stark et al. (2008)
$z = 3.07$
resolution $\sim$ 100 pc
$M_* \sim 6 \times 10^9 M_\odot$



Effect of beam smearing on kinematical maps



Epinat et al. (2010)

Simulation of a rotating disk

- Seeing increasing from $0.125''$ to $0.5''$
- Null local velocity dispersion

Results

- Velocity gradient decreases
- Velocity dispersion has a peak

Rotating disk modeling

- Gas in rotation in a plane : $V_{los} = V_{sys} + V_\theta \cos\theta \sin i$
- Modeling allows to recover the parameters (e.g. Epinat et al. 2010 ; Davies et al. 2011)

Kinematics classifications

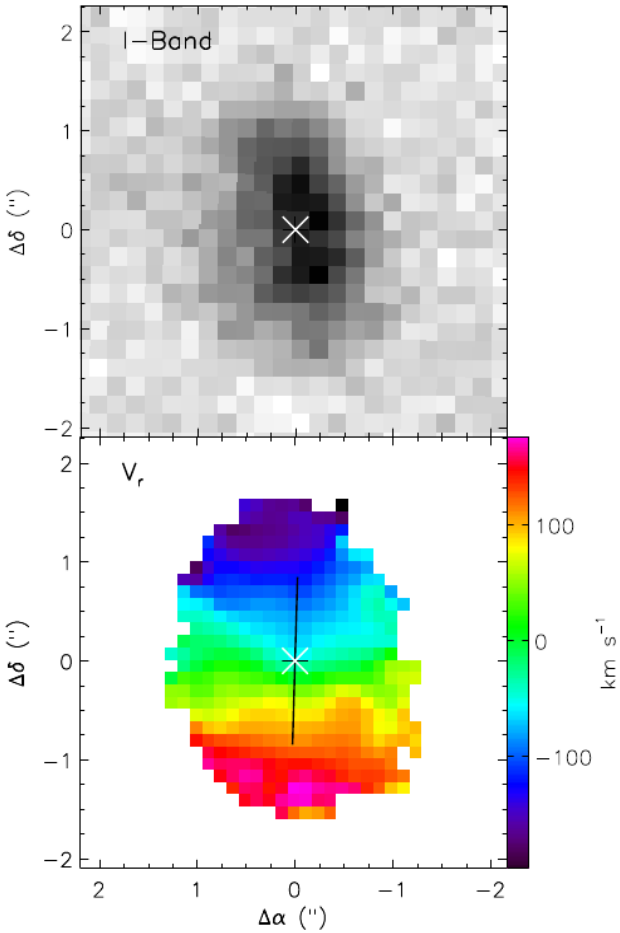
Goals

- Which galaxies are regular rotating disks (gas expected in a plane)
- Merger rate
- Rate of galaxies with other kinematics (irregular, non rotating galaxies, dispersion dominated disks, etc.)

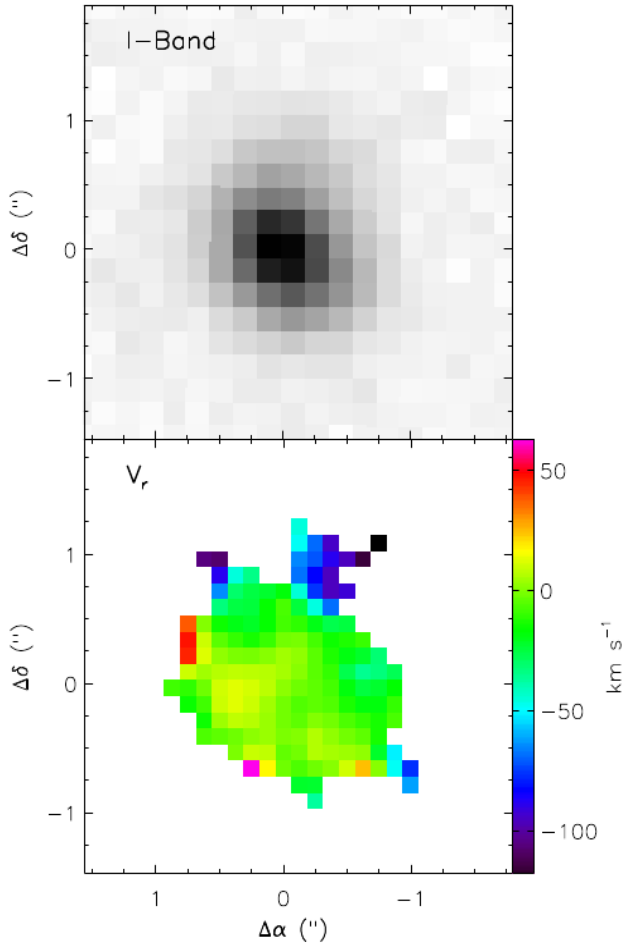
MASSIV classification

Based on agreement between morphology and kinematics

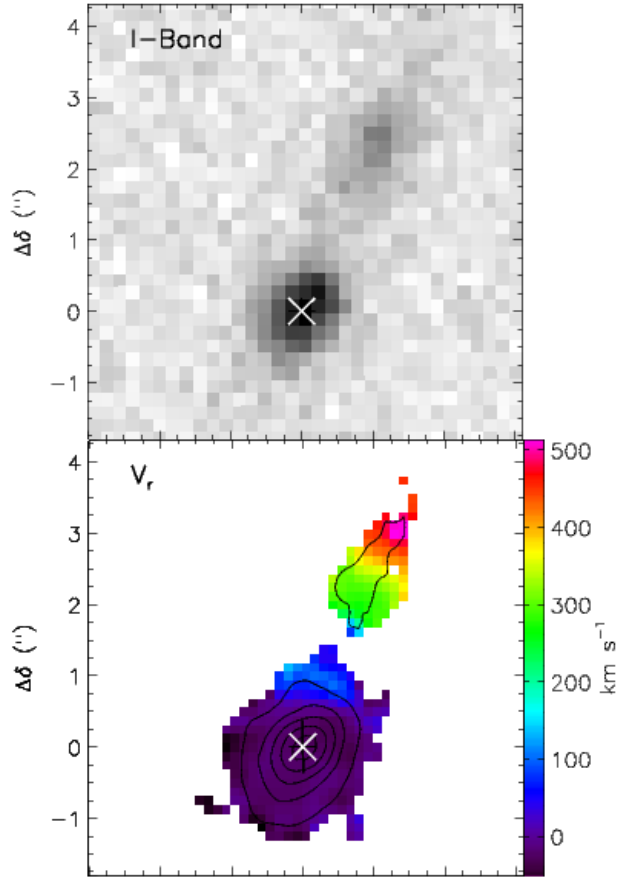
Rotators



Non-rotating galaxies



Interacting galaxies



Epinat et al. (2012)

Classification comparison

Classification results and interpretations

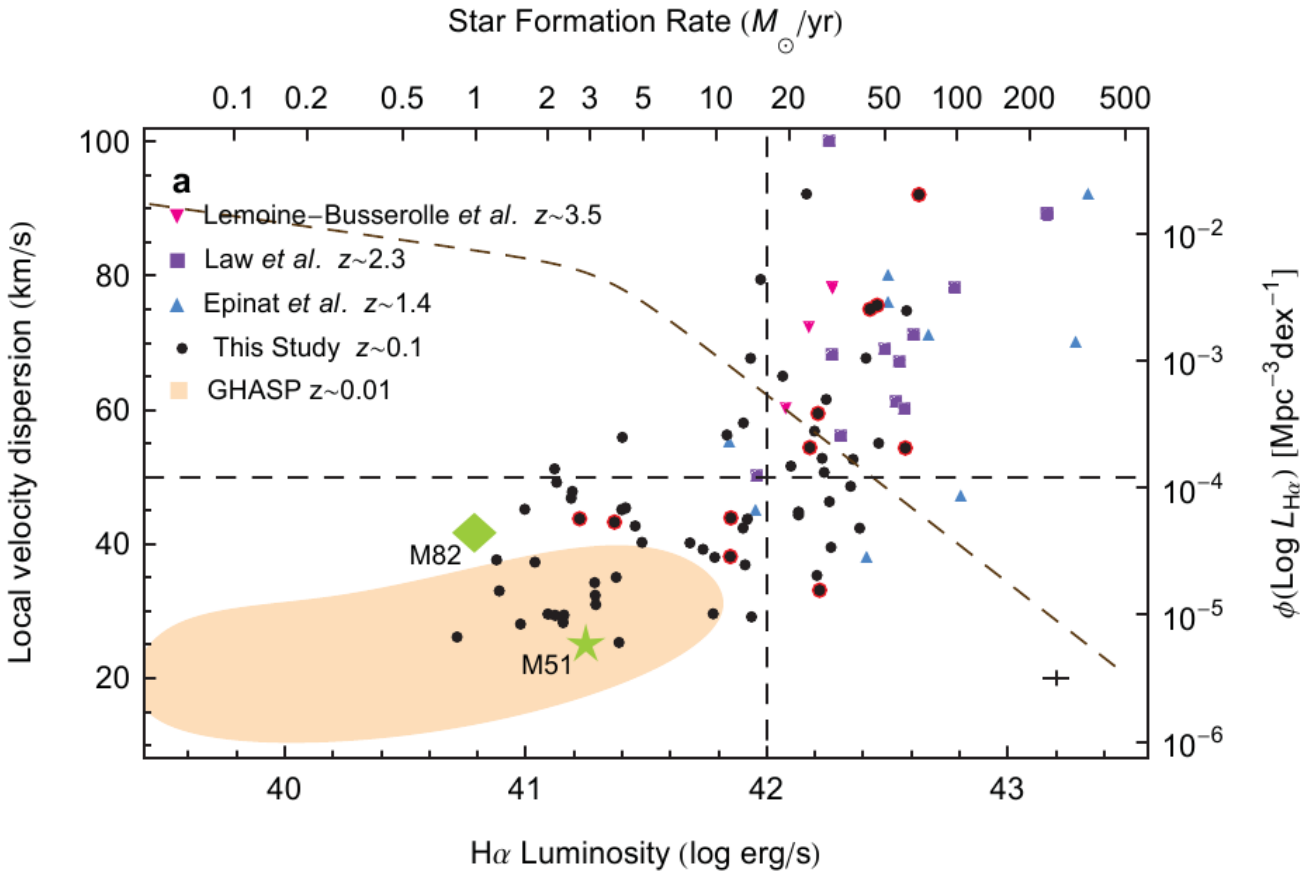
- $z \sim 0.6$
  IMAGES (*Puech et al., 2009*) : anomalous kinematics in at least 41% of the galaxy population
  $\Rightarrow$ rapid evolution of kinematics most probably induced by merging
- $z \sim 1.3$
  MASSIV (*Epinat et al., 2012*) : at least 30% of interacting galaxies (mainly minor mergers)
  + at least 35% of dispersion dominated objects or with no rotation
  + some stable disks similar to low-z disks
  $\Rightarrow$ Still several processes in action at $z > 1$ in contrast with $z \sim 0.6$
- $z \sim 2$
  SINS (*Forster-Schreiber et al., 2009*) : Evidence for cold gas accretion due to 1/3 of dispersion dominated disks
  + Significant fraction of mergers ($\sim 1/3$)
  OSIRIS (*Law et al., 2009*) : non rotating objects support cold gas accretion

Coherent scenario can be built but a consensus is not reached on the interpretation of the kinematics.

One clear evidence : high redshift galaxies have higher local velocity dispersion on average

High velocity dispersions at high-z

- Local galaxies are not in the same star formation regime than high-z galaxies
- *Green et al. (2010), Gonçalves et al. (2010)* found local counterparts with both high σ and SFRs



Green et al., 2010

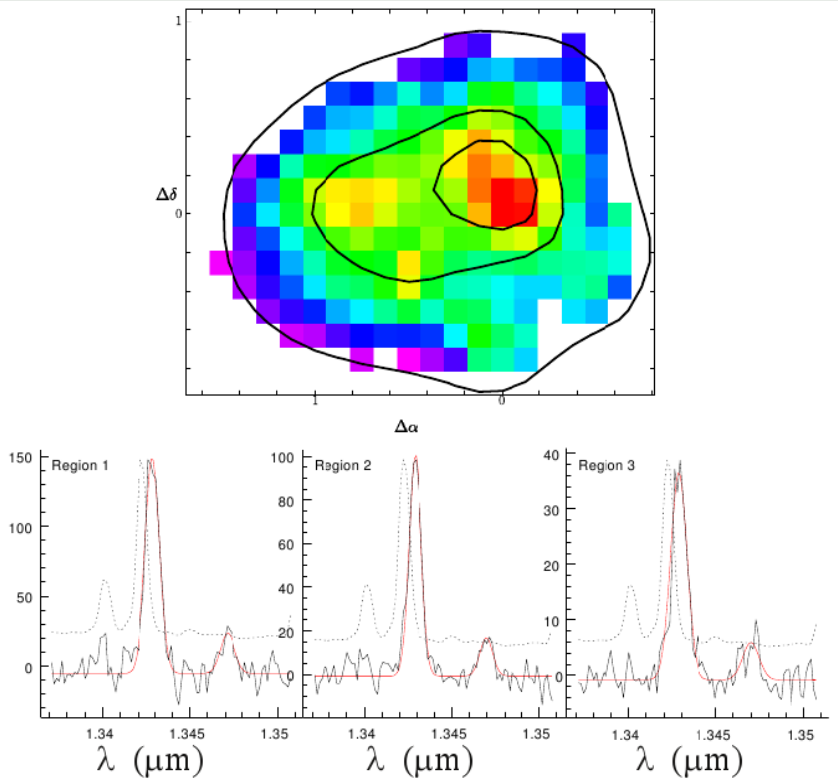
Gaseous velocity dispersion may be powered by star formation (e.g. Lehnert et al. 2009)

Abundance estimators

MASSIV

Calibration by *Pérez-Montero & Contini (2009)* :

$$12 + \log \frac{O}{H} = 9.07 + 0.79 \times \log \frac{[NII]}{H\alpha}$$

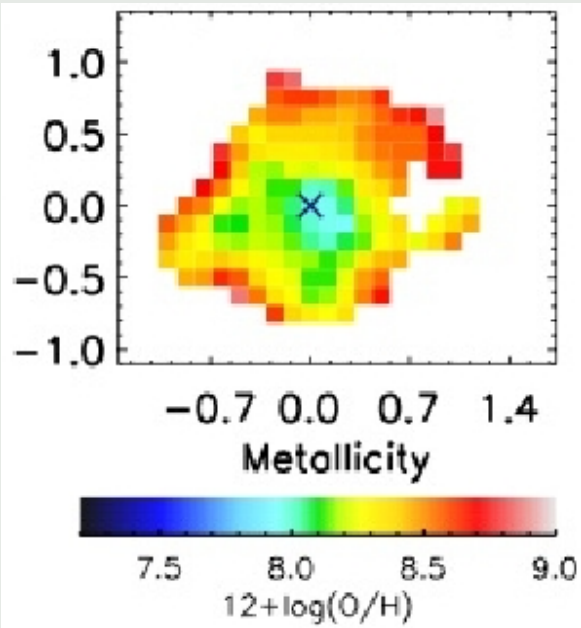


Queyrel et al. (2012)

LSD/AMAZE

Three diagnostics (from SINFONI data) :

- $[OIII]\lambda5007/H\beta$
- $[OIII]\lambda5007/[OII]\lambda3727$
- $[NeIII]\lambda3870/[OII]\lambda3727$



Cresci et al. (2010)

Positive metallicity gradients

MASSIV

Study of abundance gradients in 29 galaxies at $z \sim 1.3$:

- Positive abundance gradients in half the sample
- 7 unambiguous positive gradients : majority of interacting galaxies

Interpretation : Fresh gas accreted in the center due to interaction tidal tails

Queyrel et al. (2012)

LSD/AMAZE

Discovery of positive abundance gradients in 3 rotationally supported galaxies at $z \sim 3$

Interpretation : Cold flows along cosmic filaments toward the center

Cresci et al. (2010)

Conclusions

Different mass assembly mechanisms

$z \sim 0.6$ **: merging main driver (IMAGES)**

- Kinematics analysis + Clumpy galaxies + Baryonic Tully-Fisher relation (gas content is already there)

$z > 2$ **: cold gas accretion substantial driver (SINS, LSD/AMAZE, OSIRIS)**

- Existence of dispersion-dominated disks + Positive abundance gradients in disks + Clumpy galaxies

Transition around $z \sim 1-2$ **(MASSIV, OSIRIS)**

- Positive abundance gradients in merging systems + High fraction of interacting galaxies
- Stable disks in place
- But also dispersion dominated disks : cold gas accretion ?

Neutral and molecular gas observations of high-z galaxies

Need to constrain molecular and neutral gas content in high-z galaxies : existence of gas reservoirs ? continuous gas accretion ?

First observations : Plateau de Bures Interferometer

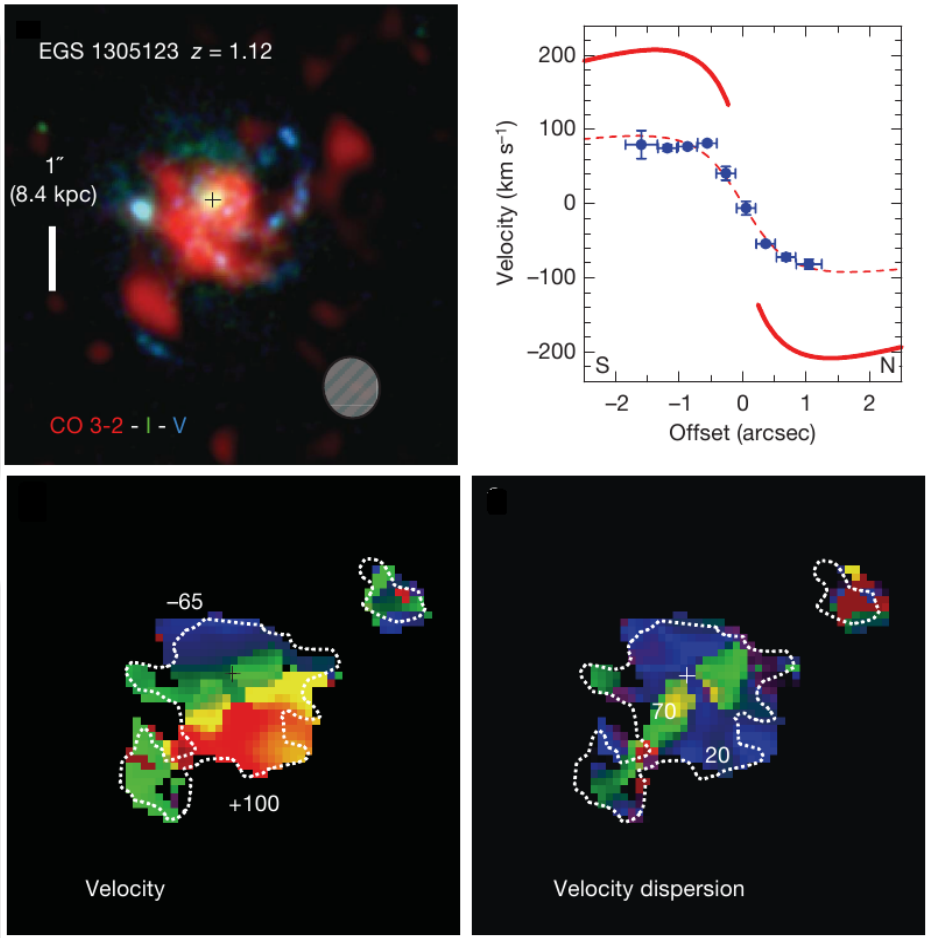
- CO observations of 3 ULIRGs : Bothwell et al. (2010)
- CO observations of 4 + 19 $z \sim 1.2$ & $z \sim 2.5$ galaxies : Taconni et al. (2008, 2010)

The future

- ALMA
- E-VLA
- SKA + precursors (ASKAP, MEERKAT)

$\Longrightarrow$ **Improved sensitivity, resolution and field**

Molecular gas content + kinematics



Tacconi et al. (2010)

Various 3D spectroscopy data are complementary

New generation of optical and infrared 3D spectrometers

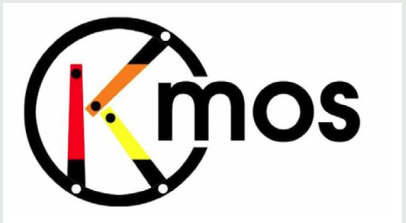
Need for better sensitivity and statistics

New instrumentation : slicers

- Large IFU in optical : MUSE / VLT



- Multi-IFU in IR : KMOS / VLT



- HARMONI / E-ELT



- EUCLID

New instrumentation : tunable filters / Fabry-Perot

- OSIRIS / GRANTECAN
- RSS Fabry-Perot / SALT
- 3D-NTT
- BTFI / SOAR

Future projects

- Explore new redshift ranges
- Effect of environment
- Target specific populations (most massive galaxies, less massive galaxies, AGN hosts, etc.)

Conclusions

Need to compare high and low redshift galaxies

- Spatial resolution has to be taken into account
- High resdhift galaxies have larger velocity dispersion but are observed with a lower spectral resolution
- Need to understand how spectral + spatial resolution impact these comparisons
- Numerical simulation are a good tool to understand the effect of resolution
- Local reference samples have to be compared with the same resolution
- Samples are not selected with the same criteria
- Blind surveys can help in having comparable selection criteria