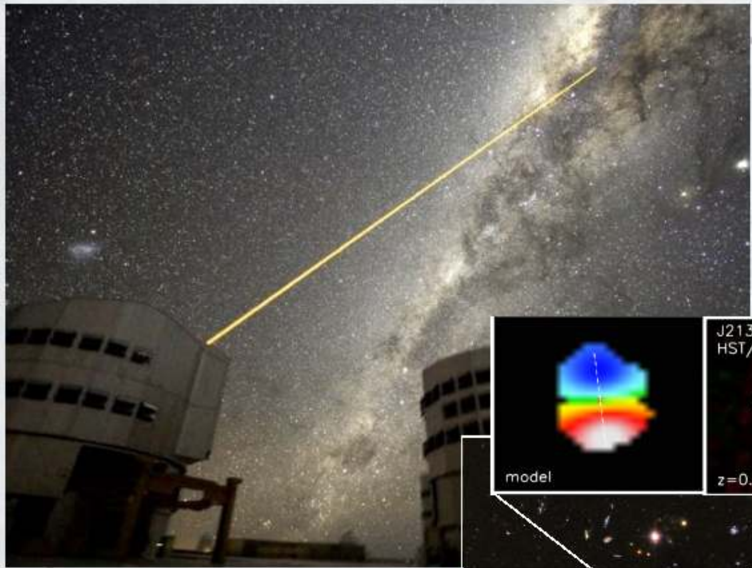
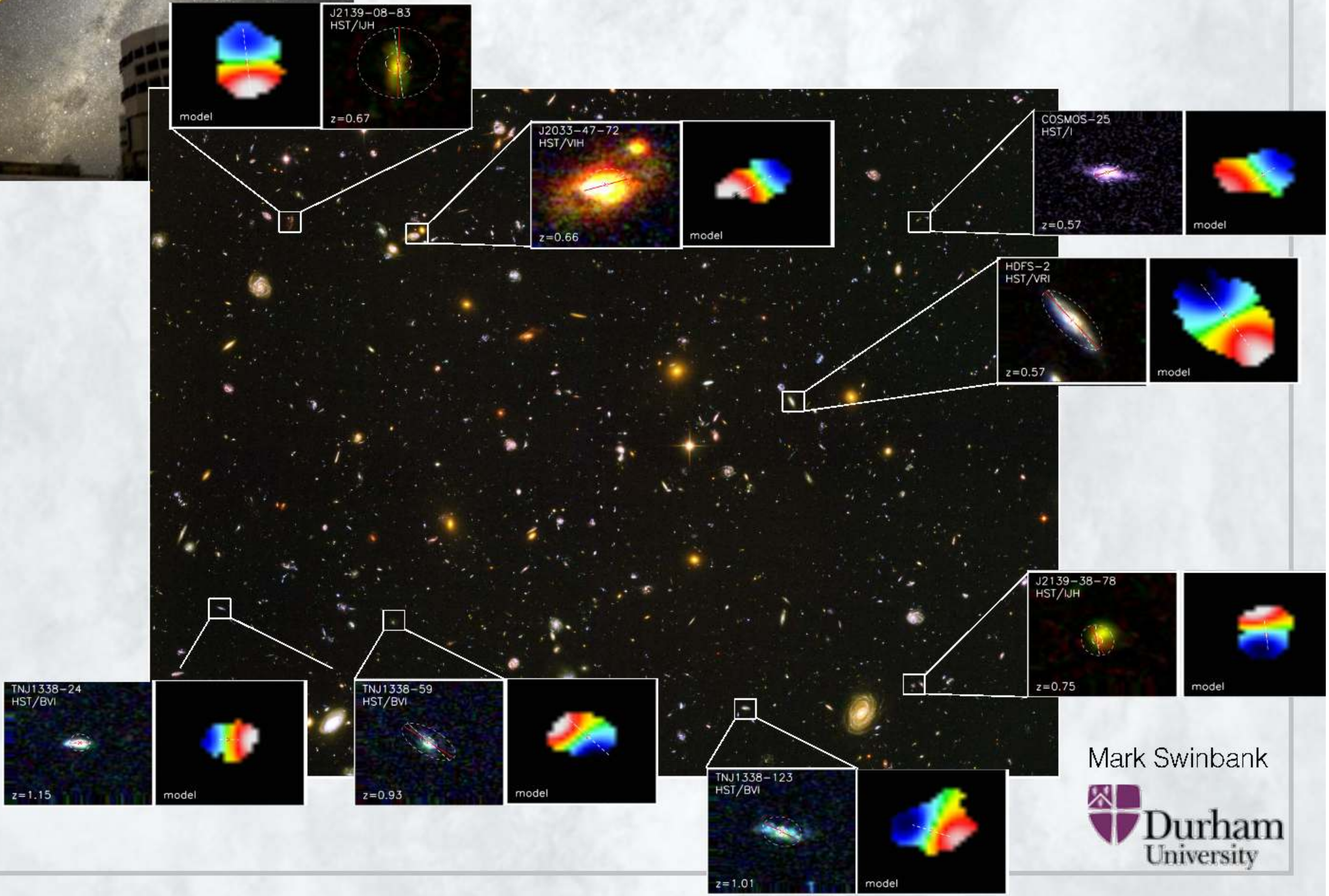
# Galaxy formation and evolution: an observational perspective






Mark Swinbank
Durham University

NAM 2016

Introduction

Studies of high-redshift galaxies

Detailed Studies of high-redshift galaxies

Very Detailed Studies of high-redshift galaxies

Extremely Detailed Studies of high-redshift galaxies

Summary

Introduction

Studies of high-redshift galaxies

Mapping the demographics of the star-forming population at z=1-3

Detailed Studies of high-redshift galaxies

Resolved spectroscopy of z=1-3 star forming galaxies on 4-8kpc scales

Very Detailed Studies of high-redshift galaxies

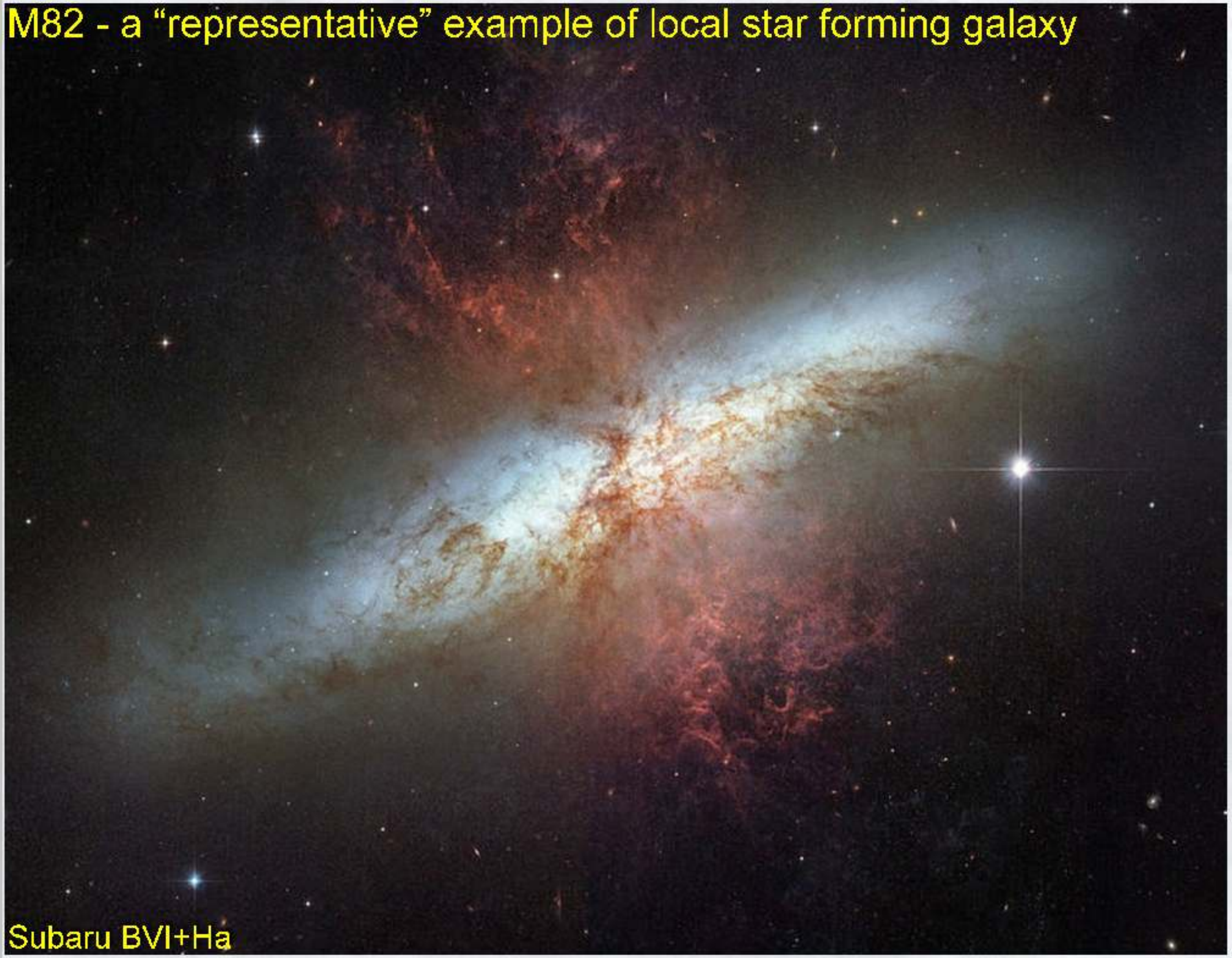
AO assisted observations to provide ~kpc resolution dynamical studies

Extremely Detailed Studies of high-redshift galaxies

AO assisted observations + gravitational lensing providing ~100pc resolution

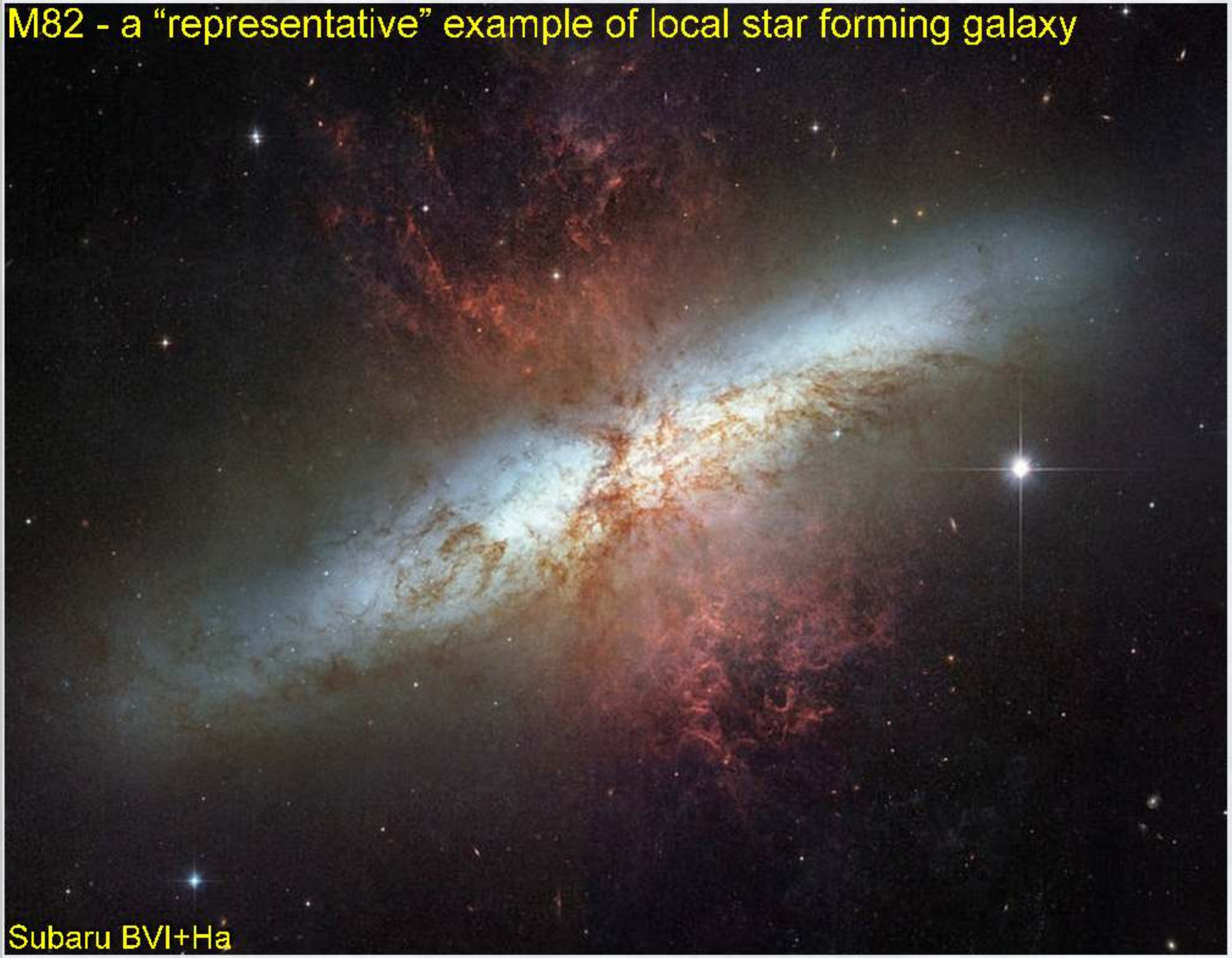
Summary

# Galaxy Formation:
## How do galaxies, like the Milky-Way form and evolve?




- Extent of filaments: 2kpc
- Velocity of outflow: 600km/s
- Most of wind is not seen directly
- $dM_{wind}/dt$ ~ SFR

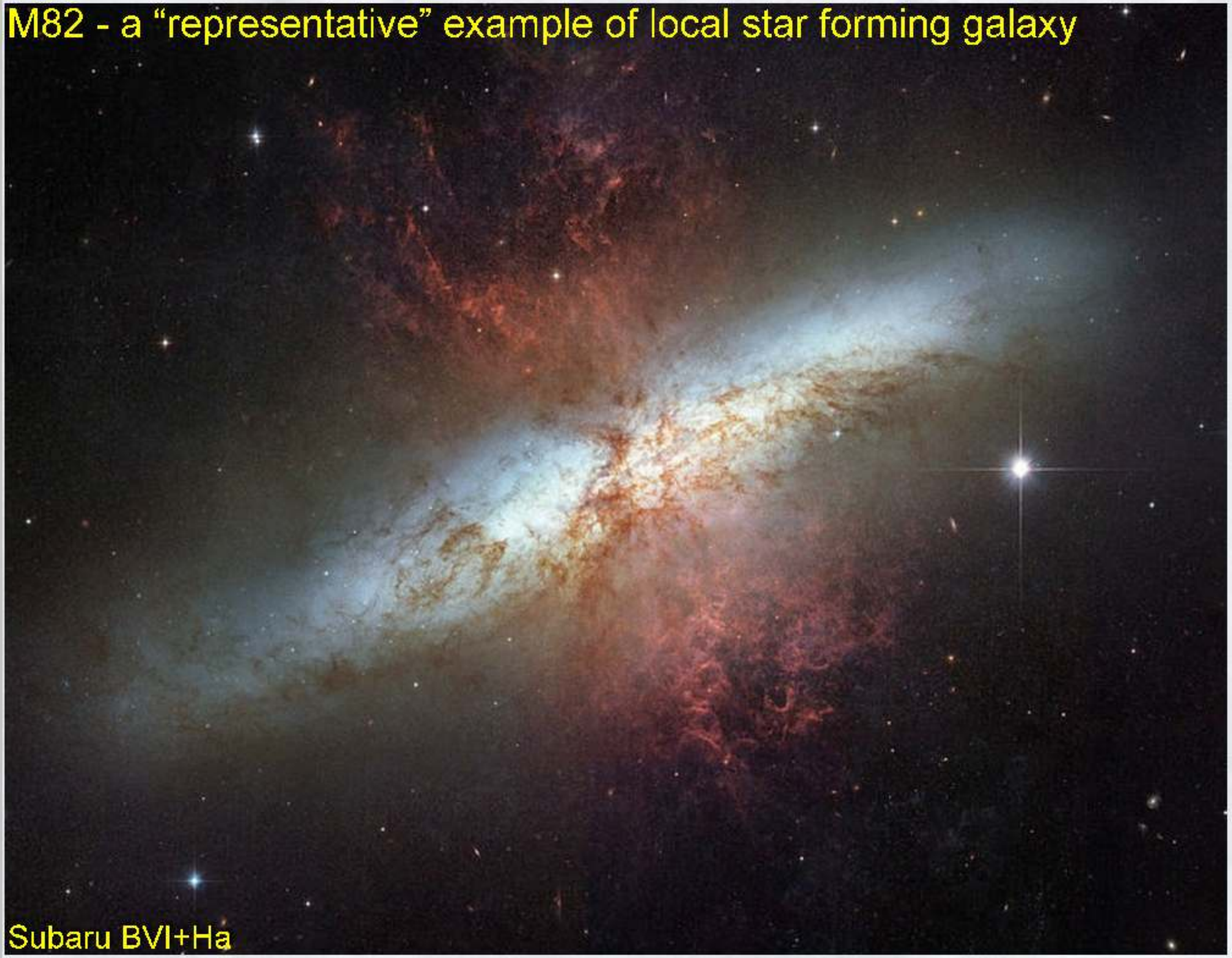
Galaxy Formation:
How do galaxies, like the Milky-Way form and evolve?




- Extent of filaments: 2kpc
- Velocity of outflow: 600km/s
- Most of wind is not seen directly
- $dM_{wind}/dt \sim SFR$

Ingredients:
- efficiency of star-formation
- energetics/mass-loading of winds
- metallicity
- stellar IMF
- growth of super-massive black holes
- frequency and impact of mergers

# Galaxy Formation:
How do galaxies, like the Milky-Way form and evolve?



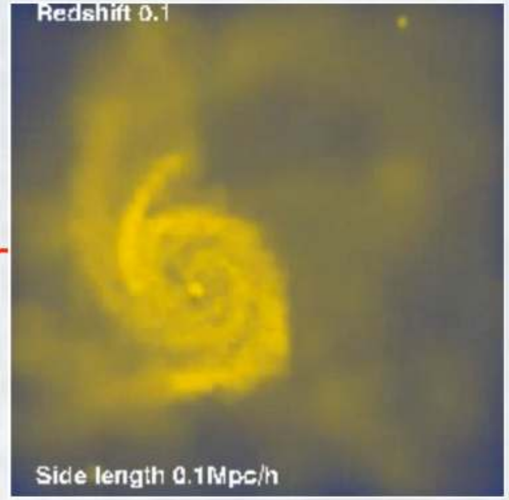

- Extent of filaments: 2kpc
- Velocity of outflow: 600km/s
- Most of wind is not seen directly
- $dM_{wind}/dt \sim SFR$

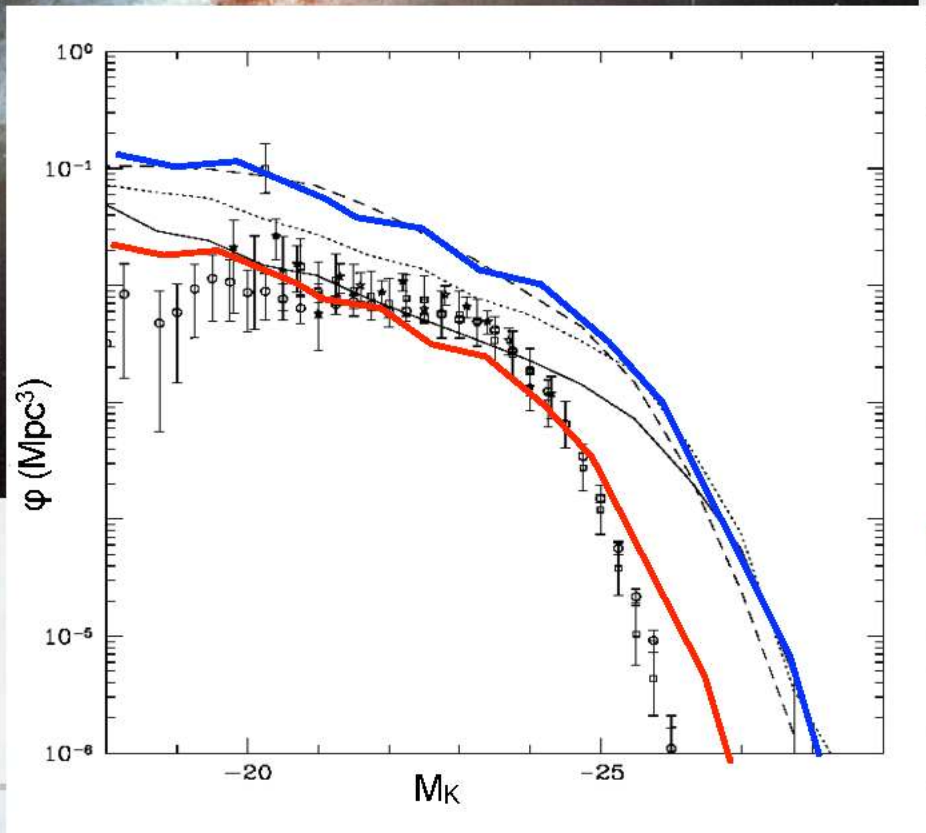
Ingredients:
- efficiency of star-formation
- energetics/mass-loading of winds
- metallicity
- stellar IMF
- growth of super-massive black holes
- frequency and impact of mergers

# Galaxy Formation:
# How do galaxies, like the Milky-Way form and evolve?

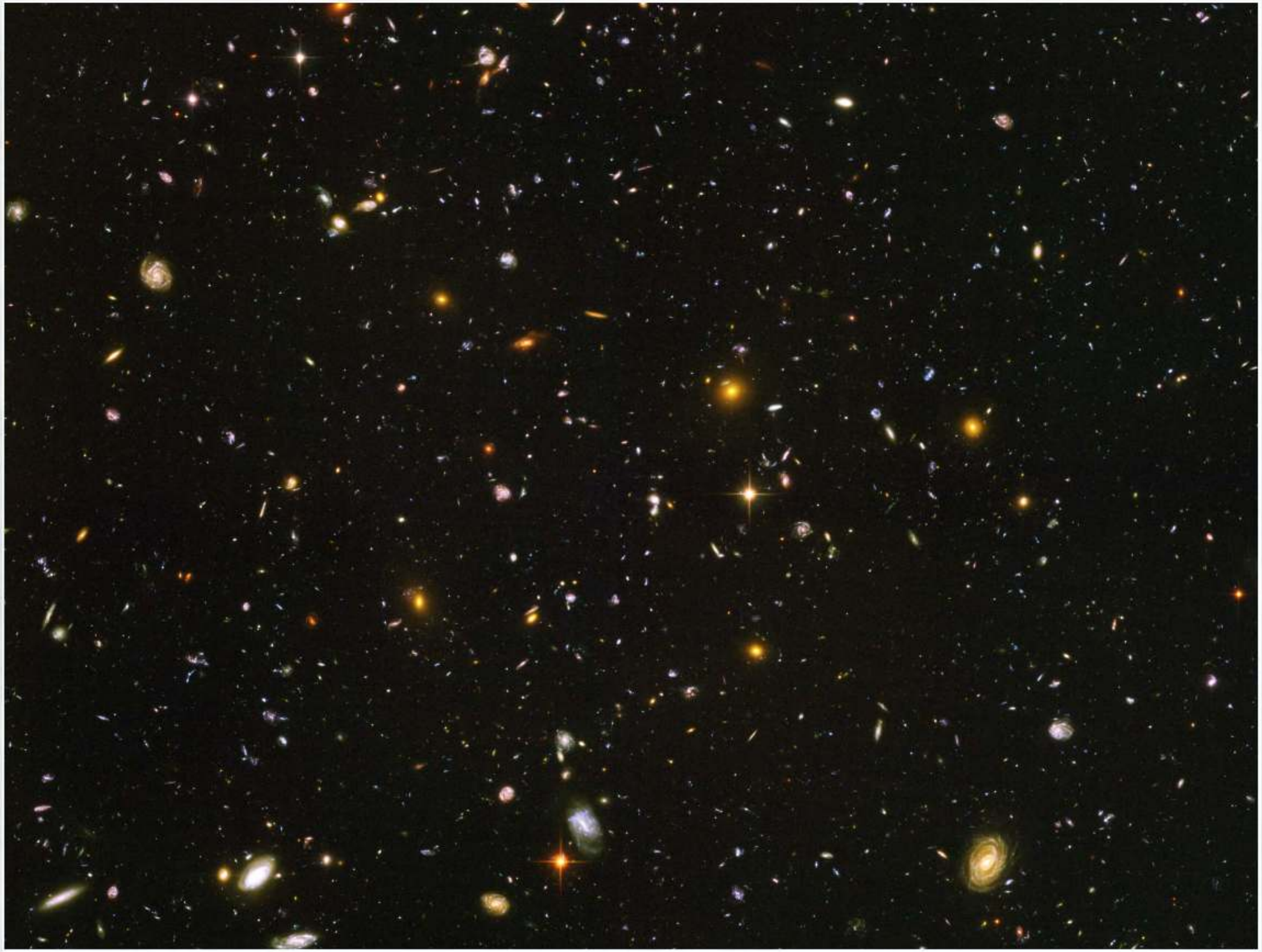

- Extent of filaments: 2kpc
- Velocity of outflow: 600km/s
- Most of wind is not seen directly
- $dM_{wind}/dt$ ~ SFR

Ingredients:
- efficiency of star-formation
- energetics/mass-loading of winds
- metallicity
- stellar IMF
- growth of super-massive black holes
- frequency and impact of mergers



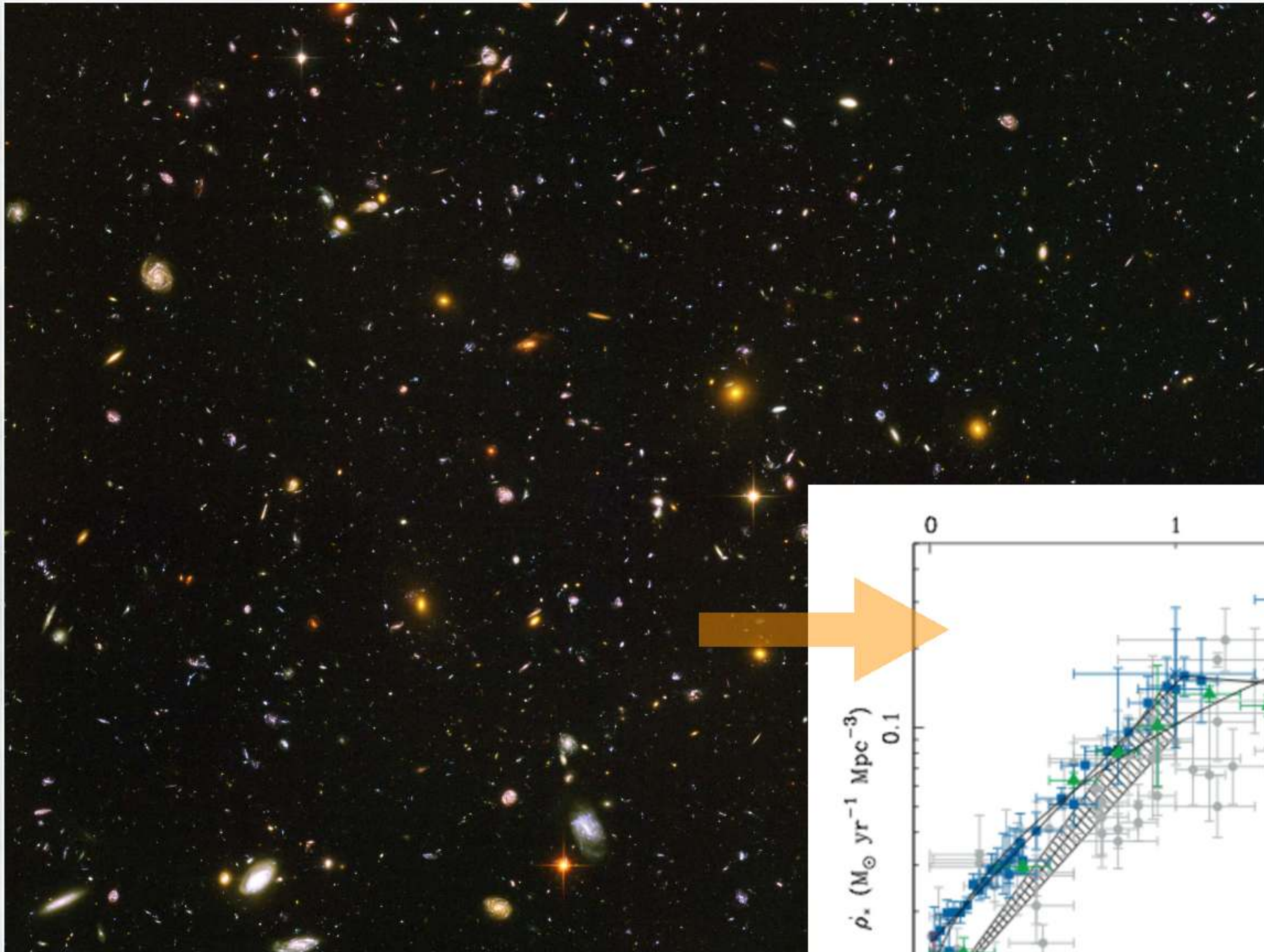



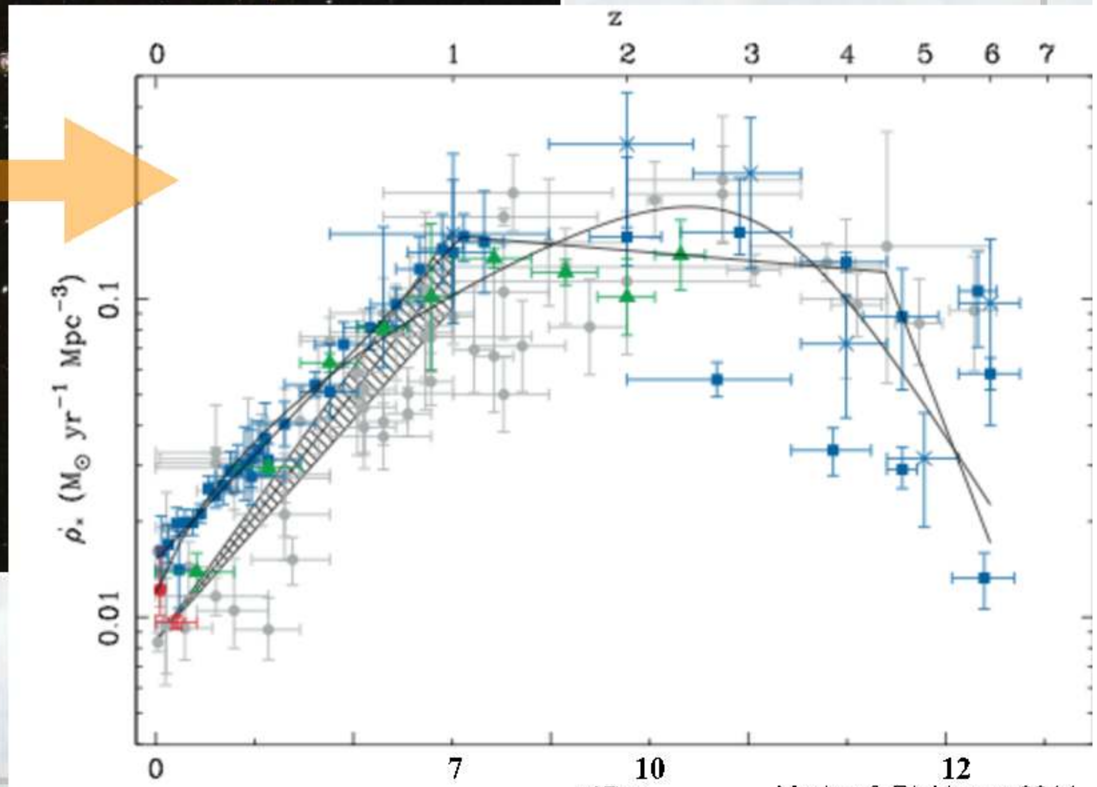
# Why observe distant galaxies?
# The Hubble Ultra Deep Field



# Why observe distant galaxies? The Hubble Ultra Deep Field

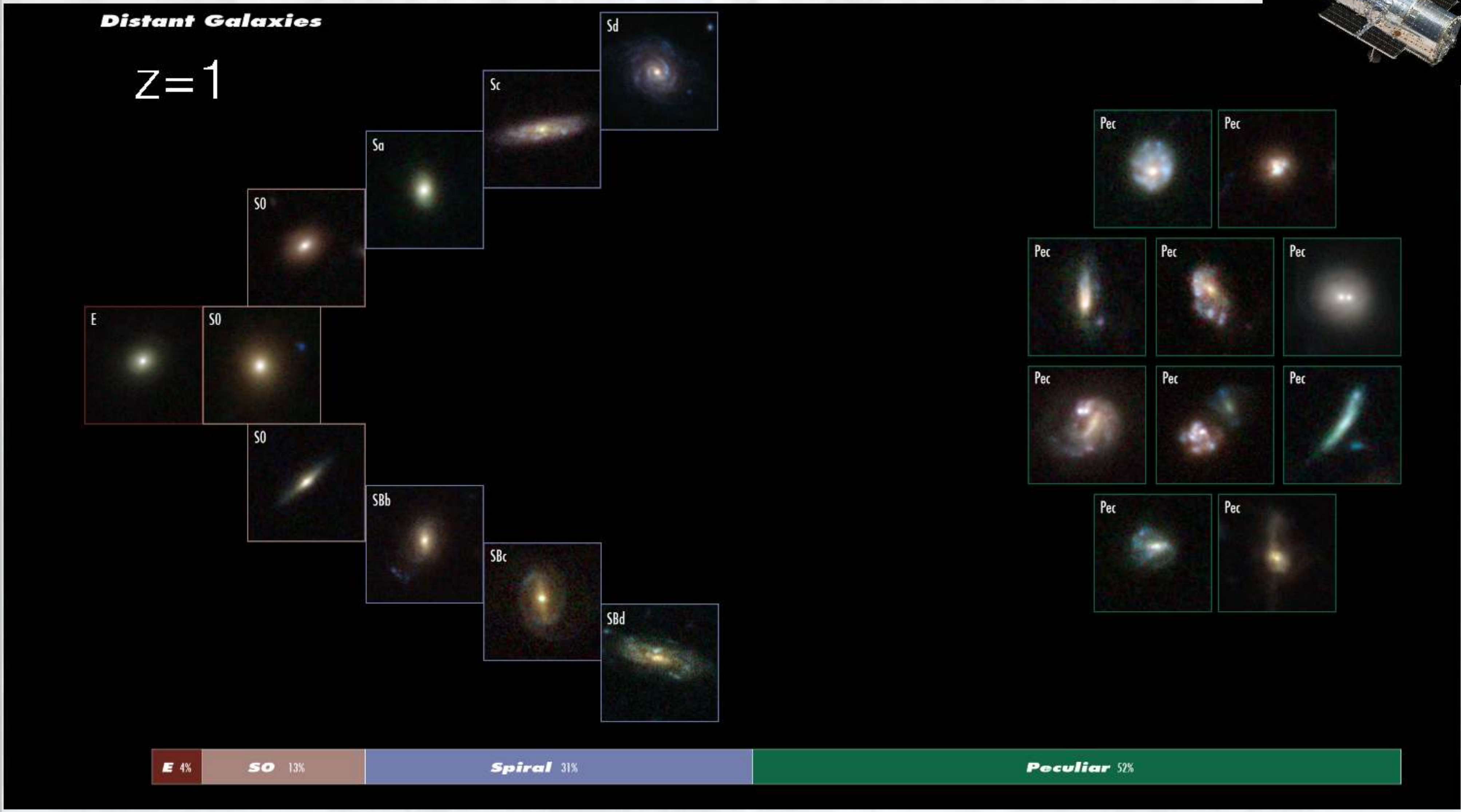
- The star formation rates of galaxies were much higher in the past.
- There are enough baryons to maintain high star formation rates today. What processes shut off star formation? Gas supply? Outflows? Mergers?
- Do to the "recipes" that are used to describe star formation in local galaxies apply in distant galaxies?
- Need to resolve star formation, dynamics and outflows of individual galaxies to compare to z=0






Madau & Dickinson 2014

## ‘Easiest’ way to study distant galaxies: look at them!




Around z~1.5 the Hubble sequence begins to emerge with the spirals and ellipticals becoming as common as peculiar galaxies.

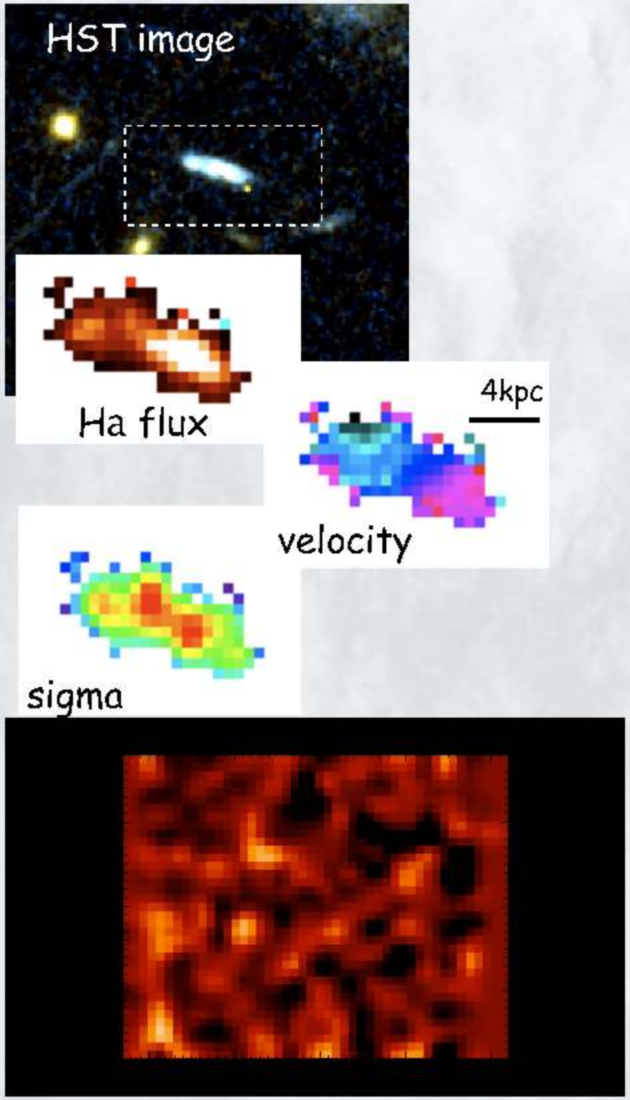
(e.g. Bell et al. 2004; Conselice et al. 2011; Buitrago et al. 2013; Mortlock et al. 2013)

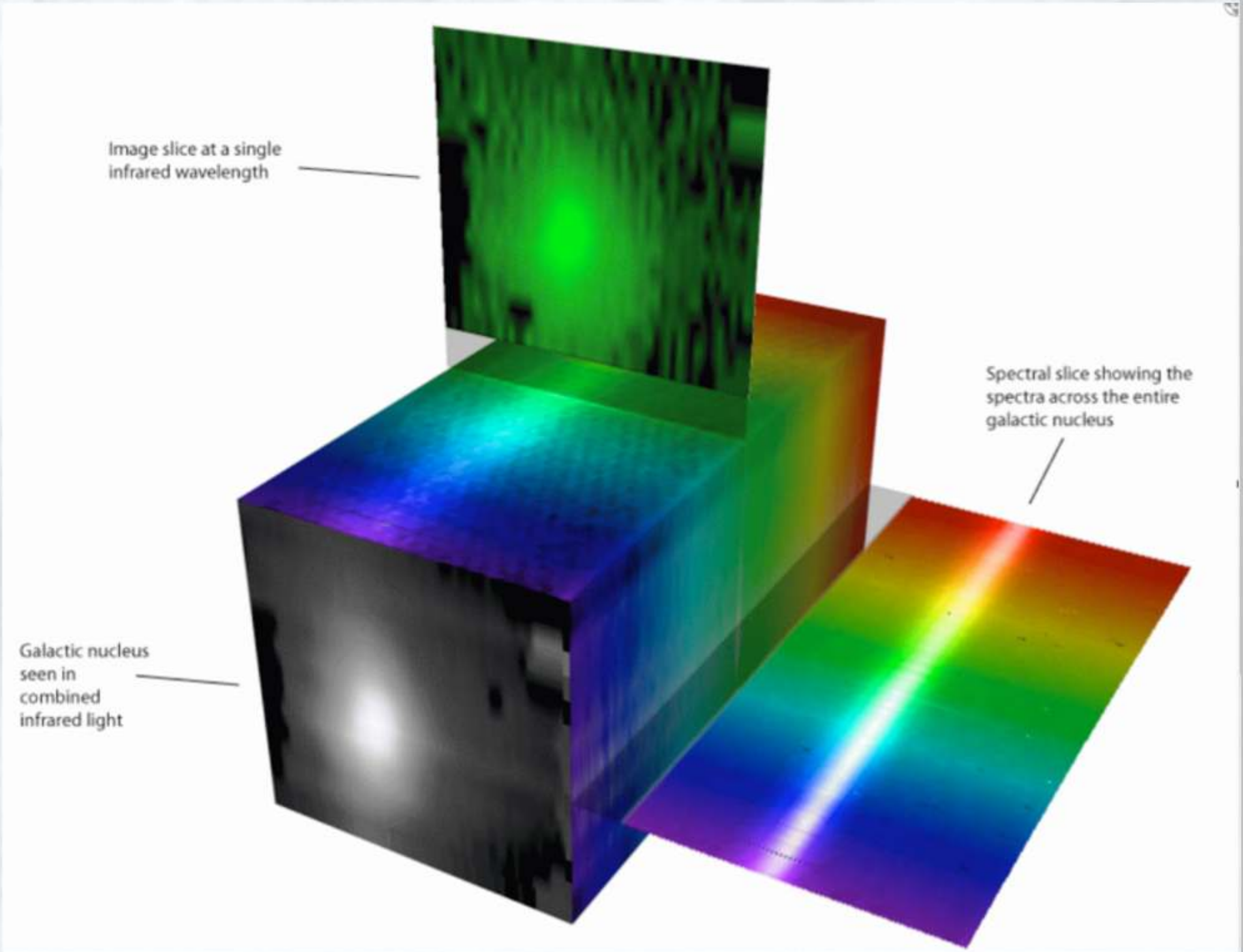
Can we learn about the dominant mode of mass assembly of high-redshift galaxies from their dynamics?

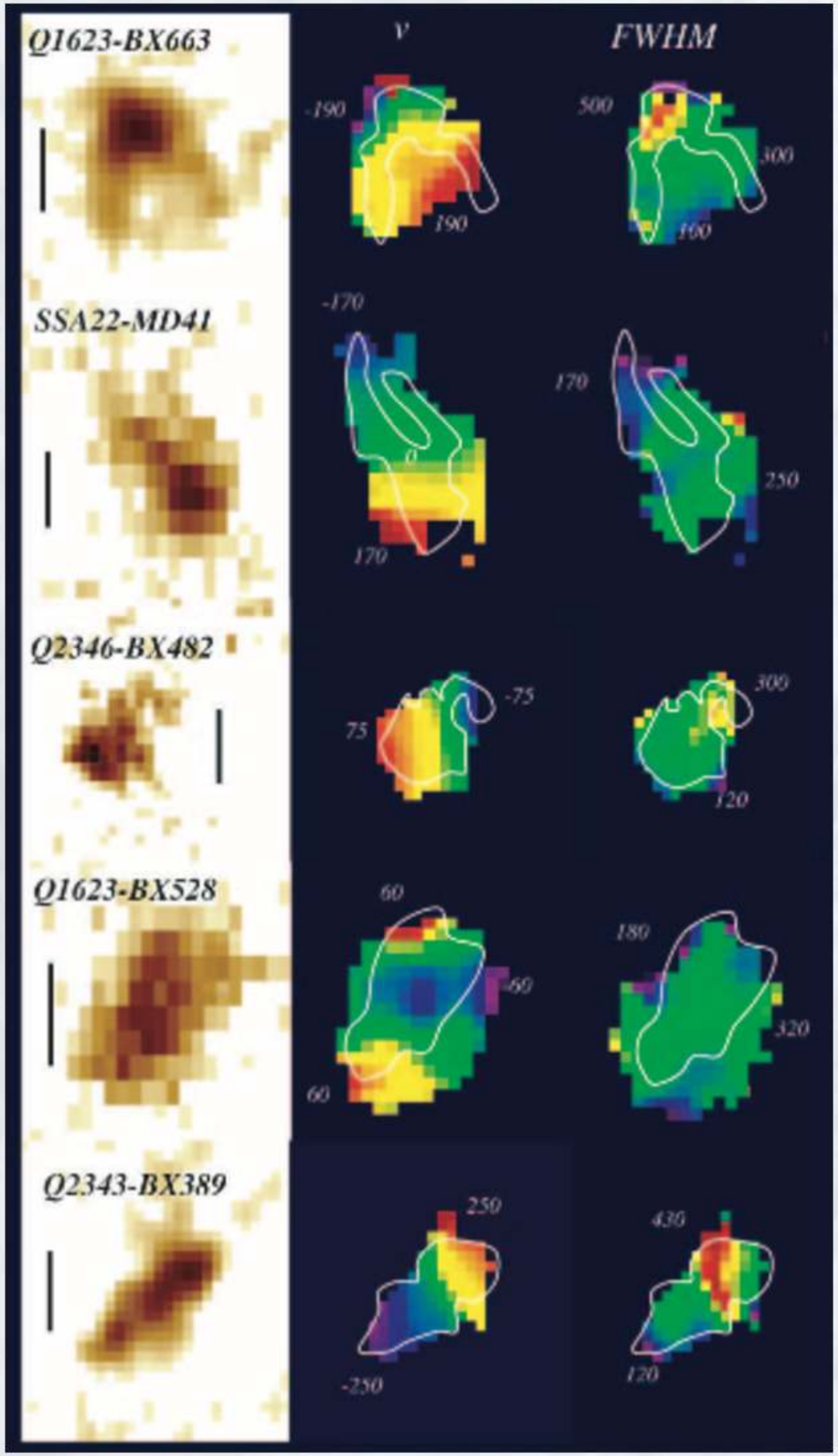
- At every wavelength you get an image

- At every pixel you get a spectrum

A quick aside: Integral Field Spectroscopy

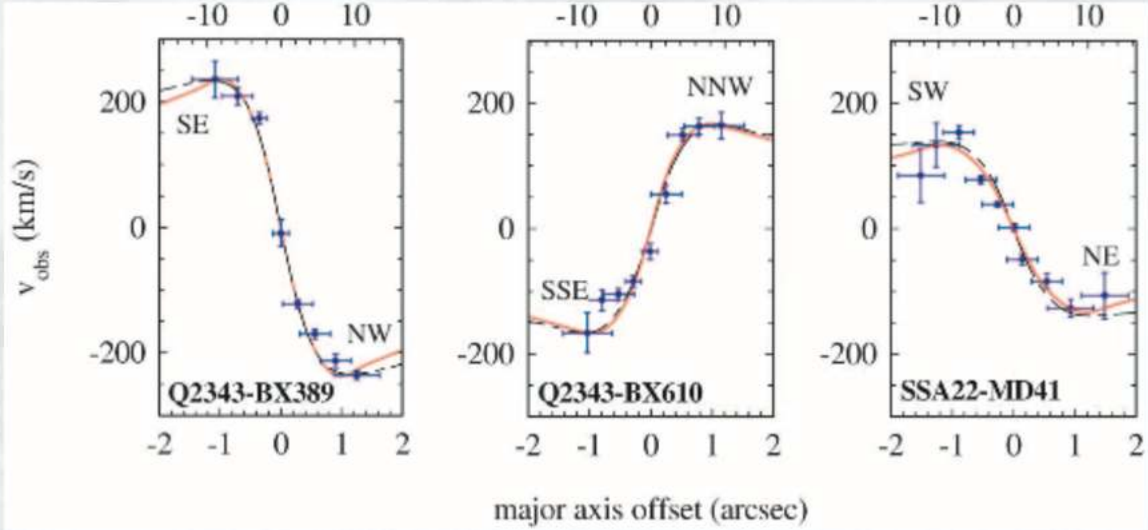


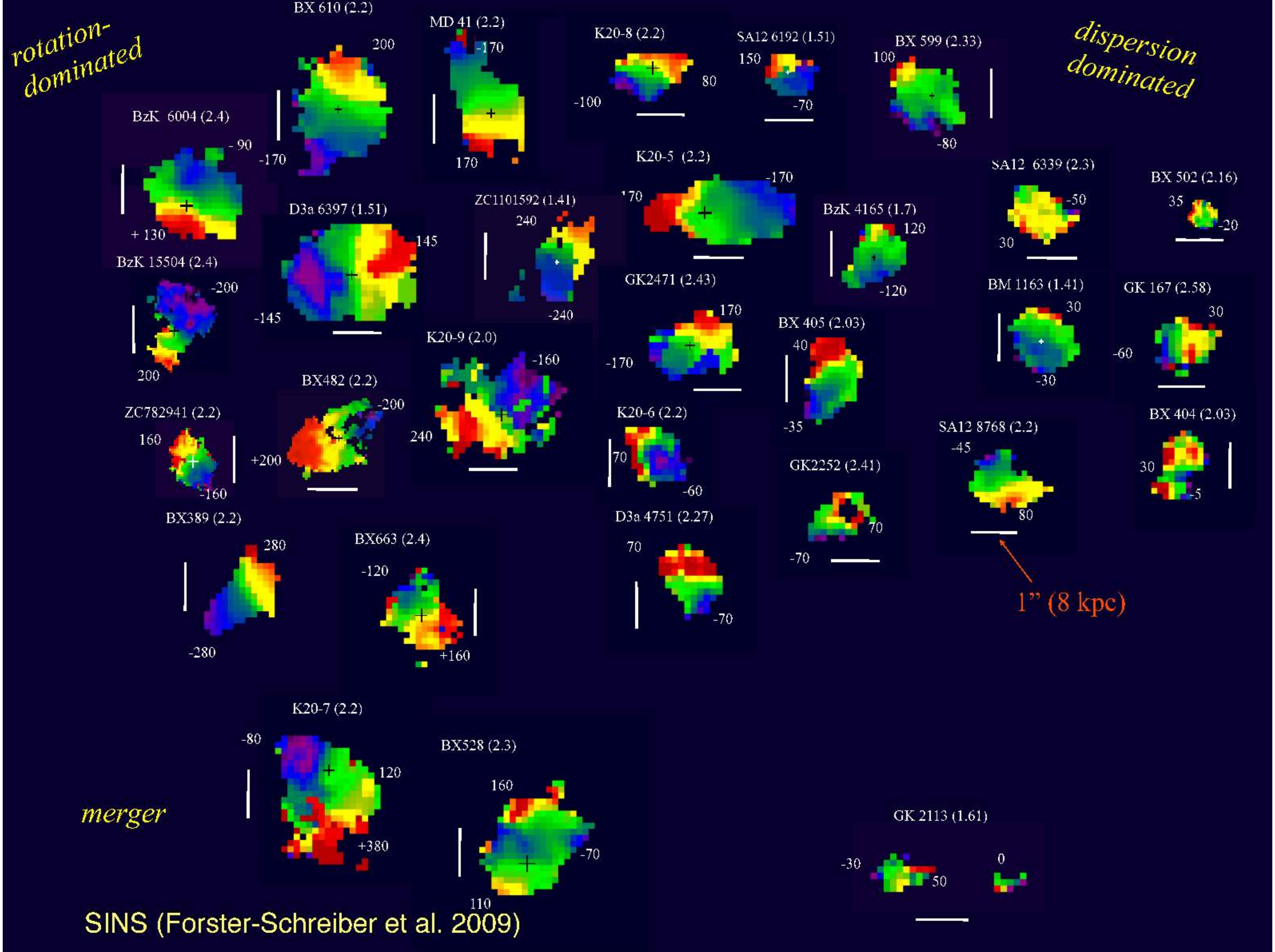





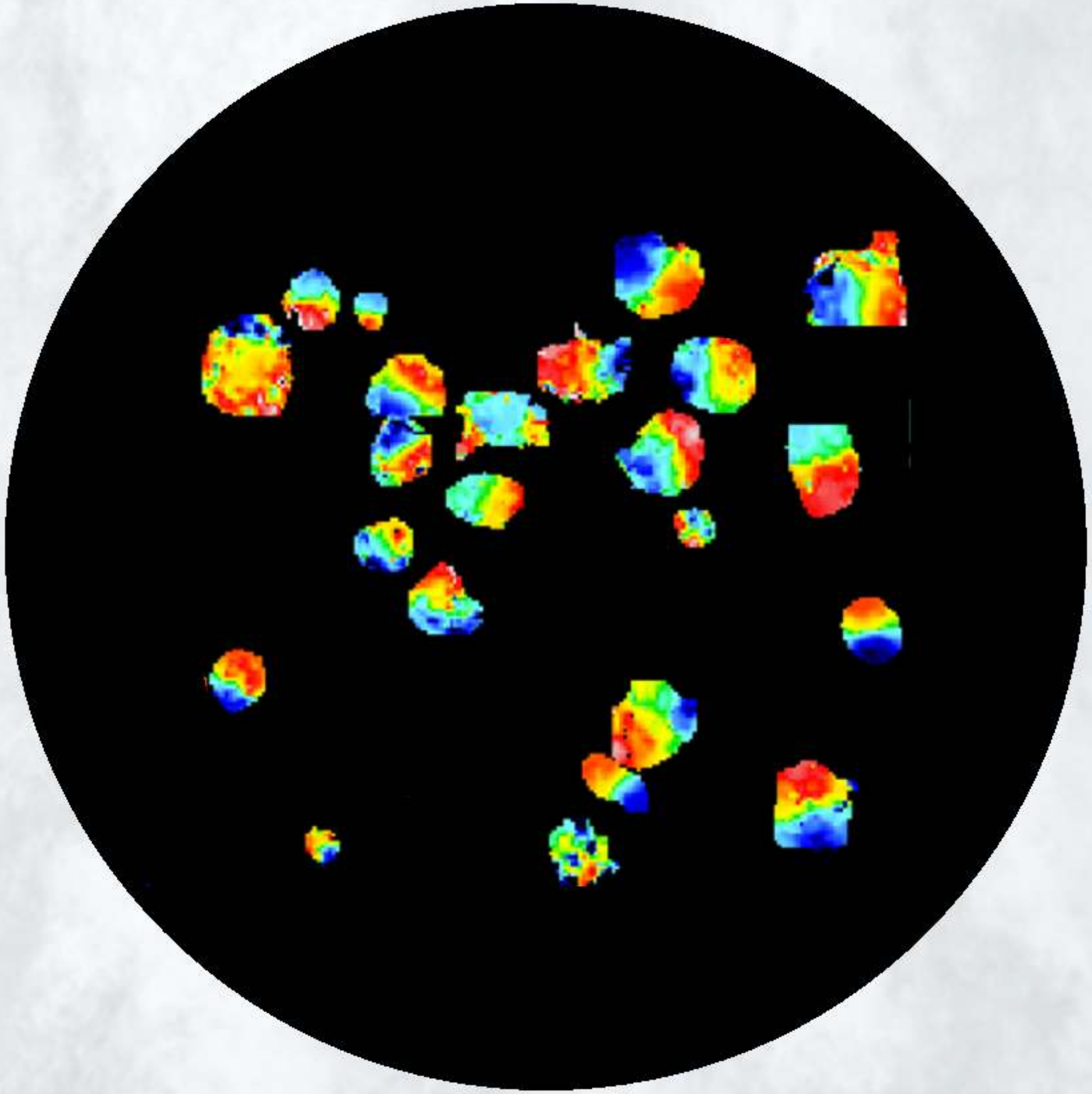

# "Detailed Studies"

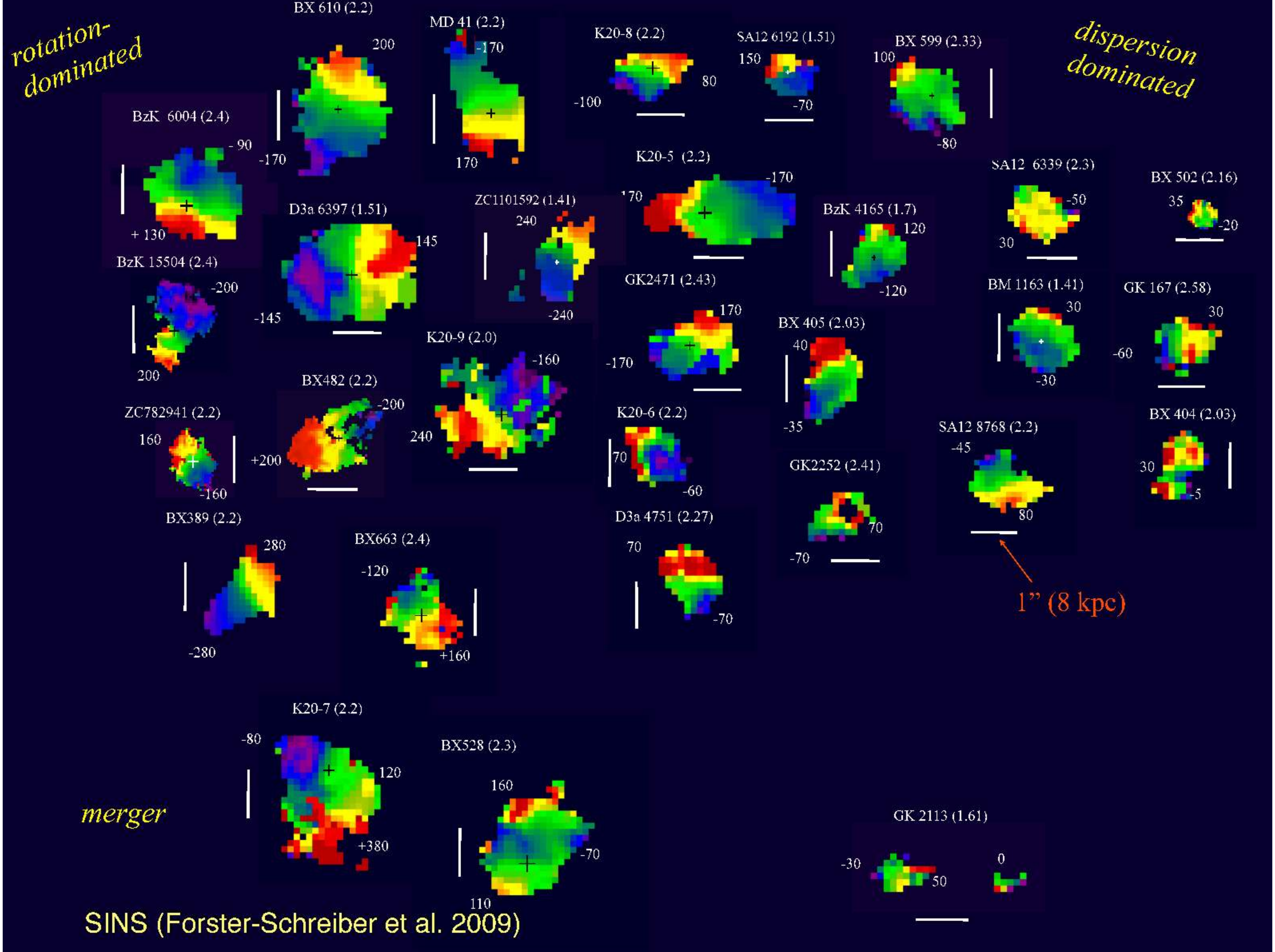
Forster-Schreiber et al. (2006) studied 14 star-forming galaxies at z~1.5–2 using SINFONI and found evidence for rotational support on ~4kpc scales in 12/14 galaxies.

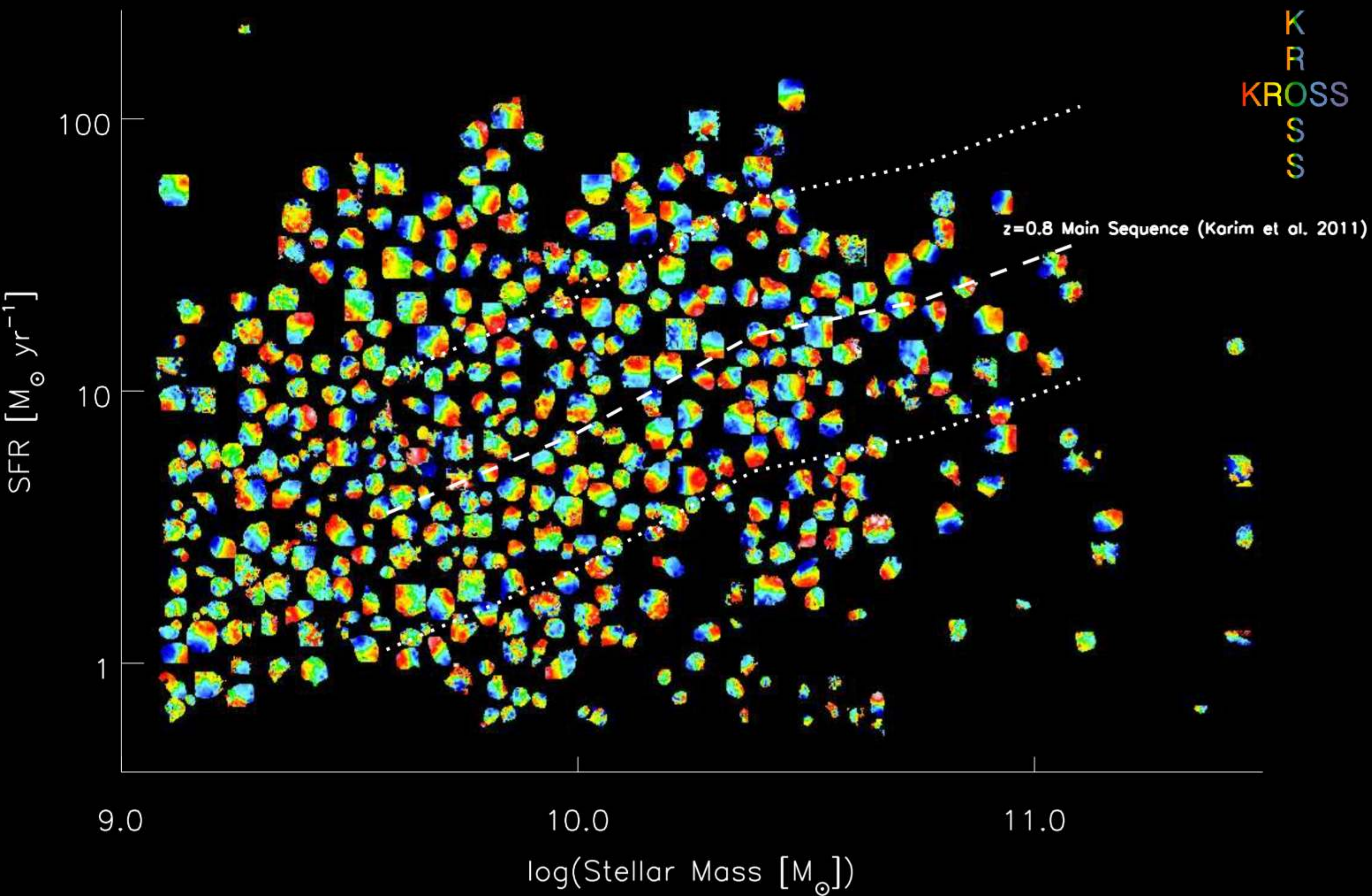



rotation-dominated
dispersion dominated
merger
BzK 6004 (2.4)
BX 610 (2.2)
MD 41 (2.2)
K20-8 (2.2)
SA12 6192 (1.51)
BX 599 (2.33)
BzK 15504 (2.4)
D3a 6397 (1.51)
ZC1101592 (1.41)
K20-5 (2.2)
BzK 4165 (1.7)
SA12 6339 (2.3)
BX 502 (2.16)
GK2471 (2.43)
BX 405 (2.03)
BM 1163 (1.41)
GK 167 (2.58)
ZC782941 (2.2)
BX482 (2.2)
K20-9 (2.0)
K20-6 (2.2)
SA12 8768 (2.2)
BX 404 (2.03)
GK2252 (2.41)
BX389 (2.2)
BX663 (2.4)
D3a 4751 (2.27)
1" (8 kpc)
K20-7 (2.2)
BX528 (2.3)
GK 2113 (1.61)
SINS (Forster-Schreiber et al. 2009)

The KMOS + MUSE integral field spectrographs on ESO VLT provides ~24x speed improvement over previous instruments.

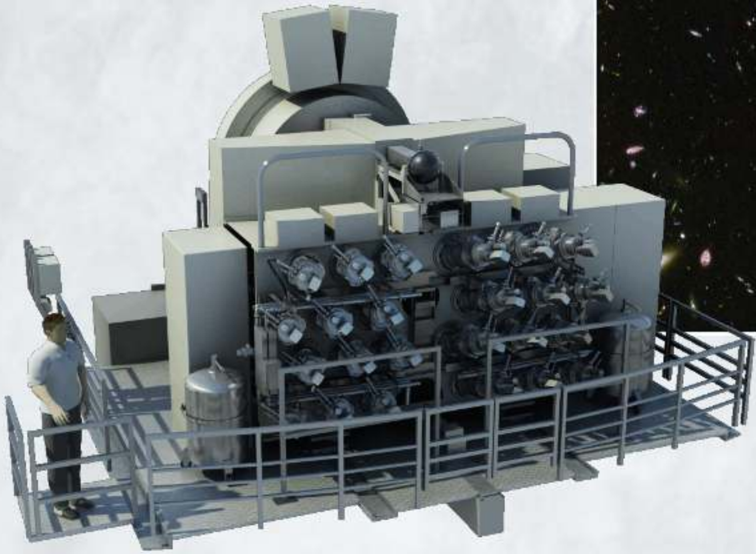


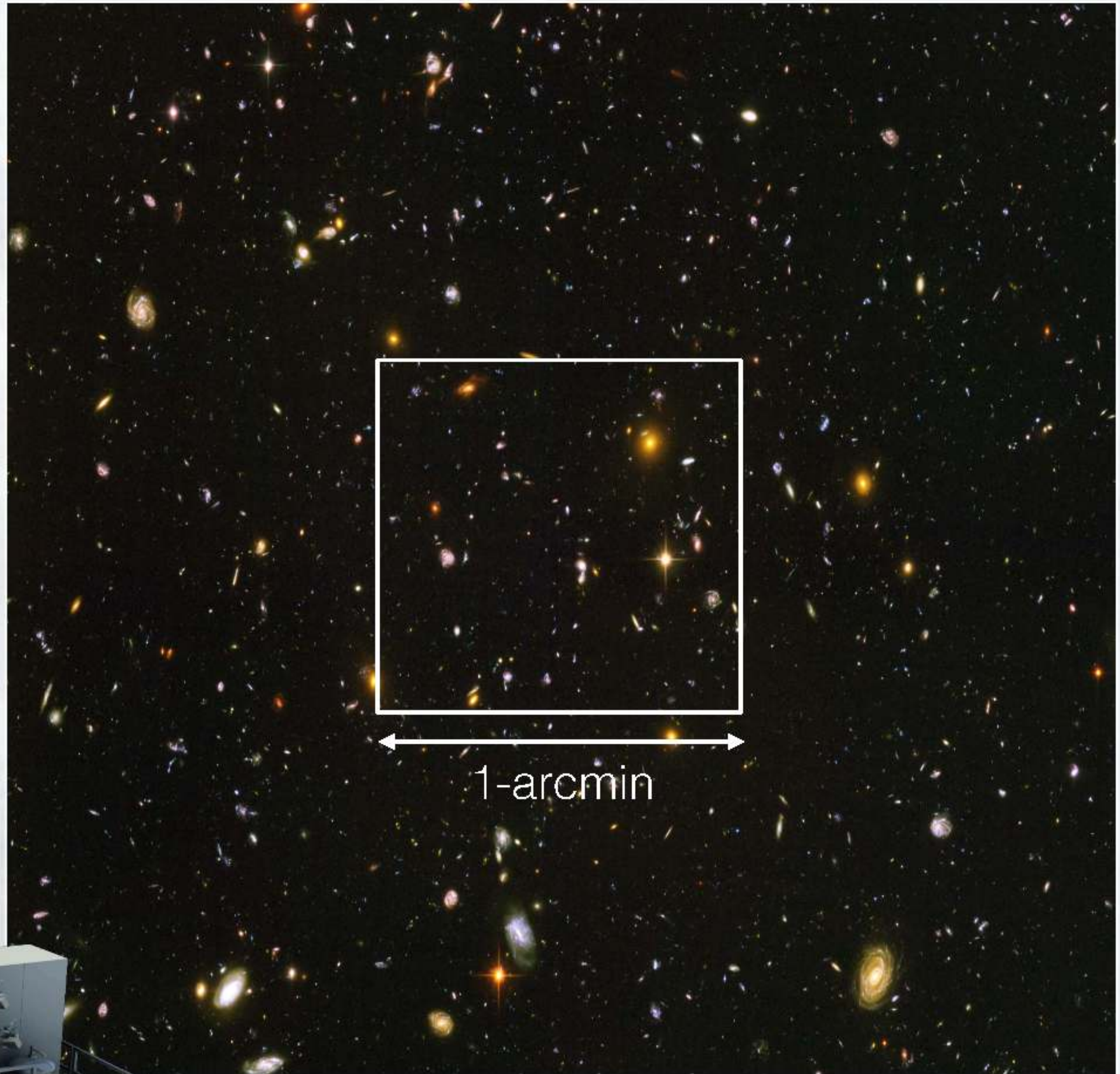

rotation-dominated
dispersion dominated
merger
BX 610 (2.2)
MD 41 (2.2)
K20-8 (2.2)
SA12 6192 (1.51)
BX 599 (2.33)
BzK 6004 (2.4)
K20-5 (2.2)
SA12 6339 (2.3)
BX 502 (2.16)
D3a 6397 (1.51)
ZC1101592 (1.41)
BzK 4165 (1.7)
BzK 15504 (2.4)
GK2471 (2.43)
BM 1163 (1.41)
GK 167 (2.58)
K20-9 (2.0)
BX 405 (2.03)
BX482 (2.2)
ZC782941 (2.2)
K20-6 (2.2)
SA12 8768 (2.2)
BX 404 (2.03)
GK2252 (2.41)
BX389 (2.2)
D3a 4751 (2.27)
BX663 (2.4)
1" (8 kpc)
K20-7 (2.2)
BX528 (2.3)
GK 2113 (1.61)
SINS (Forster-Schreiber et al. 2009)



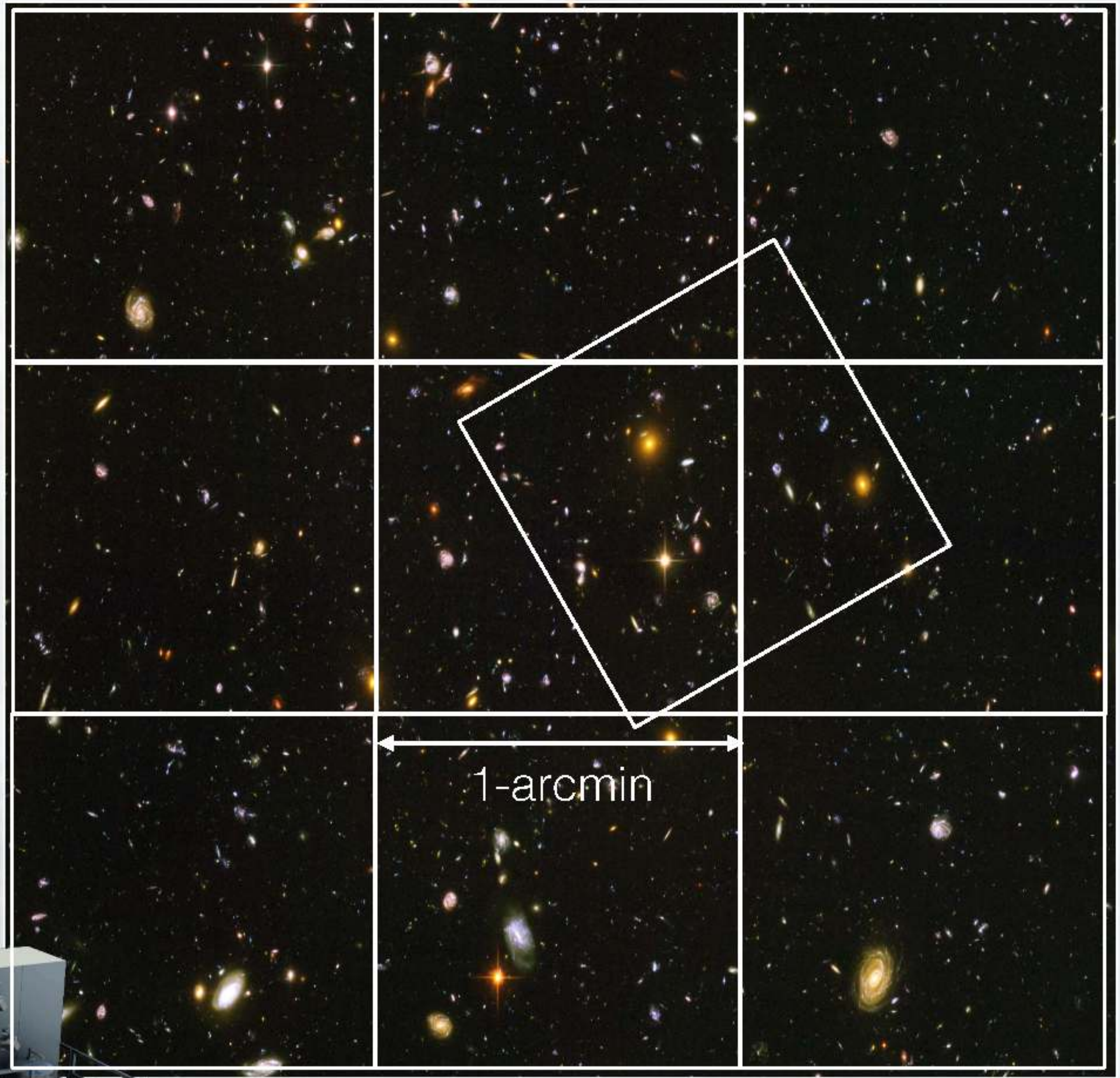

e.g. Stott et al. 2015

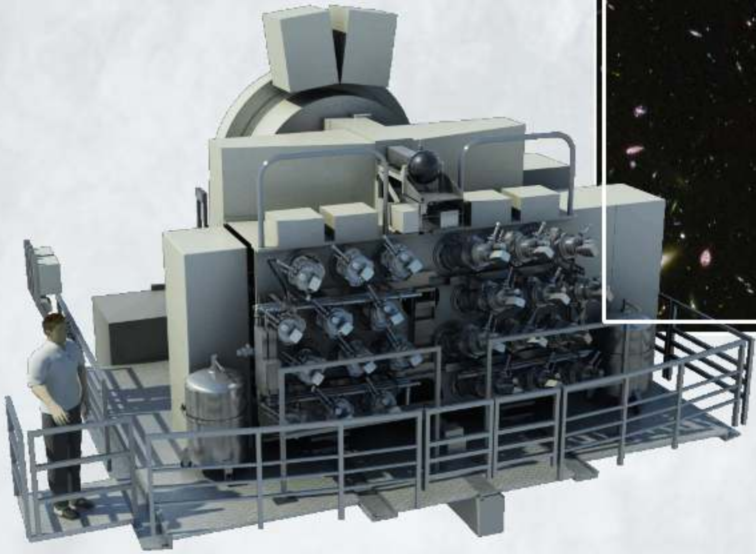
MUSE integral field spectrograph

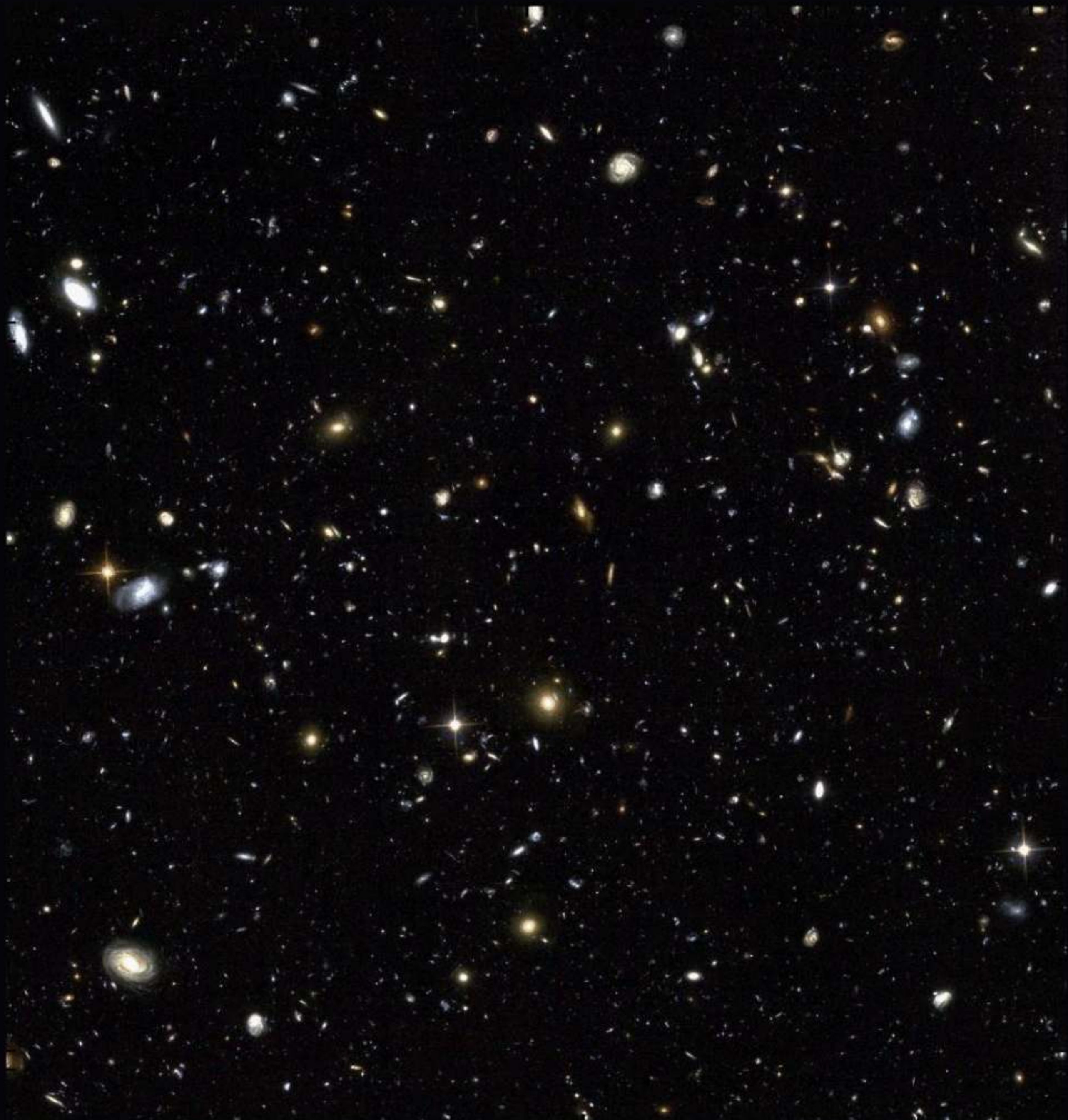


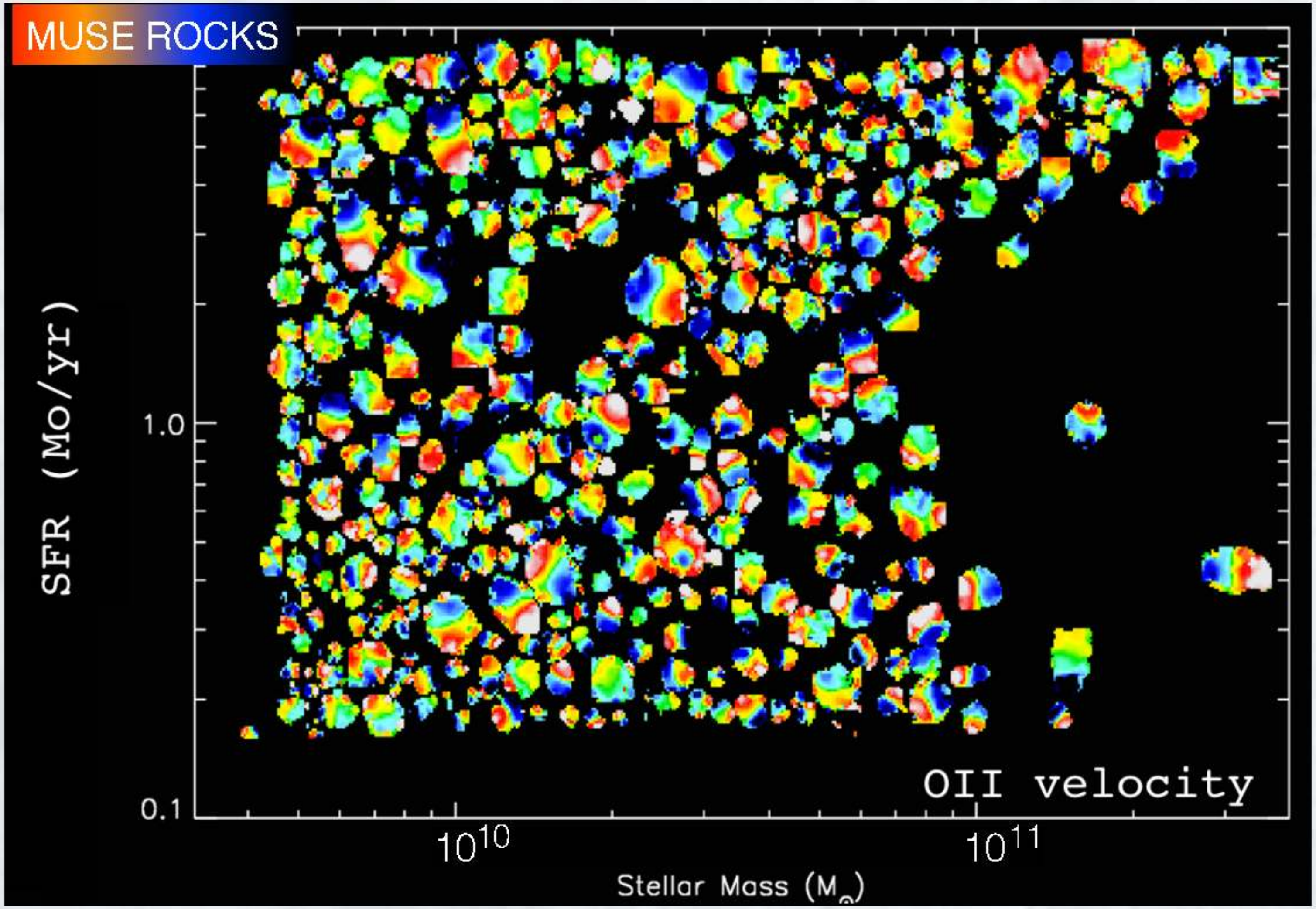


MUSE integral field spectrograph







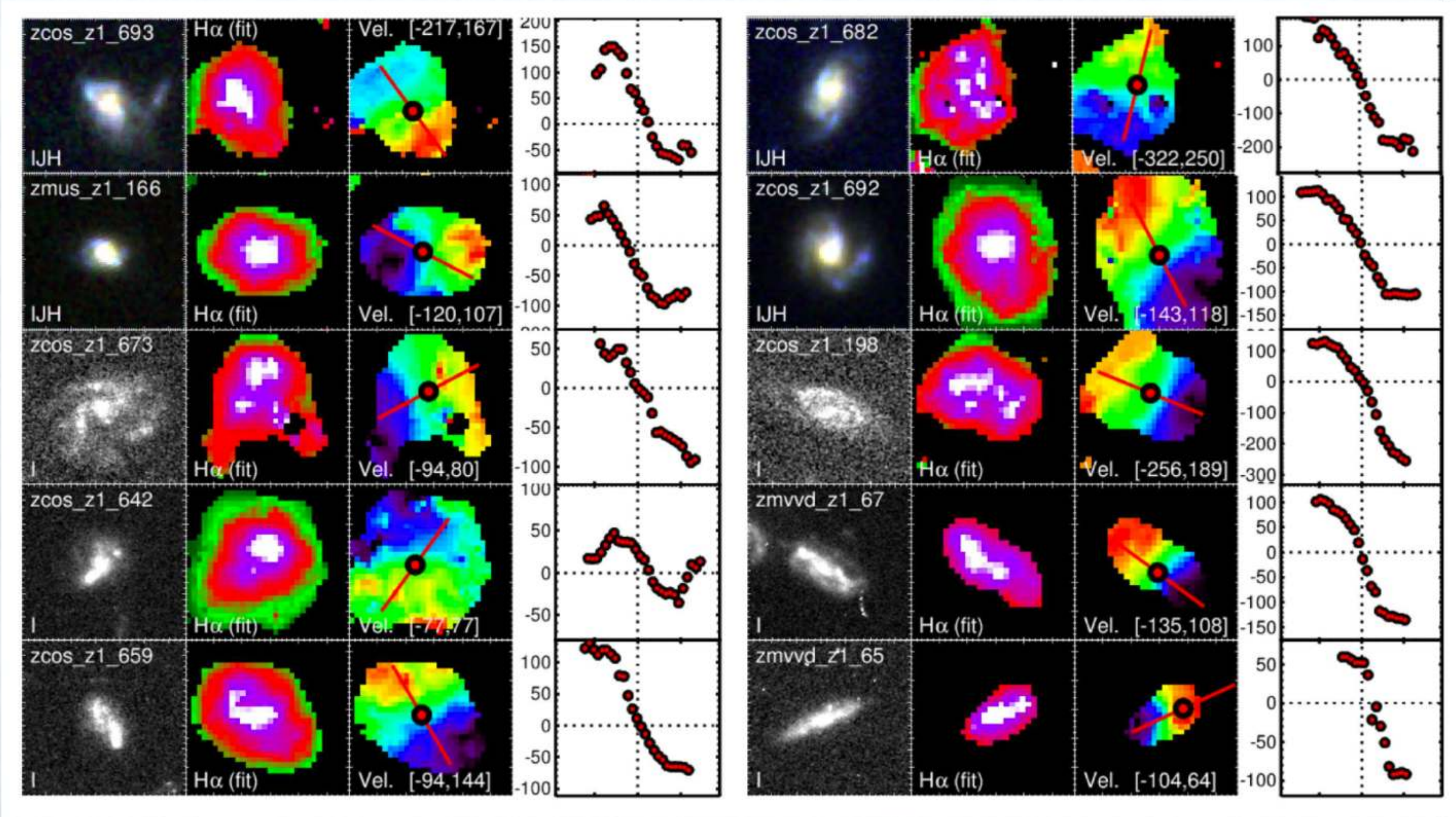

MUSE ROCKS + KROSS + 


(currently) yields ~1500 star-forming galaxies at z = 0.5 - 1.7

~75% of sample are spatially resolved (~1200 galaxies)

# The dynamics of high-z galaxies: what we get

HST Hα velocity rot curve HST Hα velocity rot curve



# Angular momentum of galaxy disks

Dynamical measurements of galaxies at z = 0

Angular momentum of disks appears to be related to the Hubble sequence (e.g. Fall 1980; Romanowski & Fall 2012).

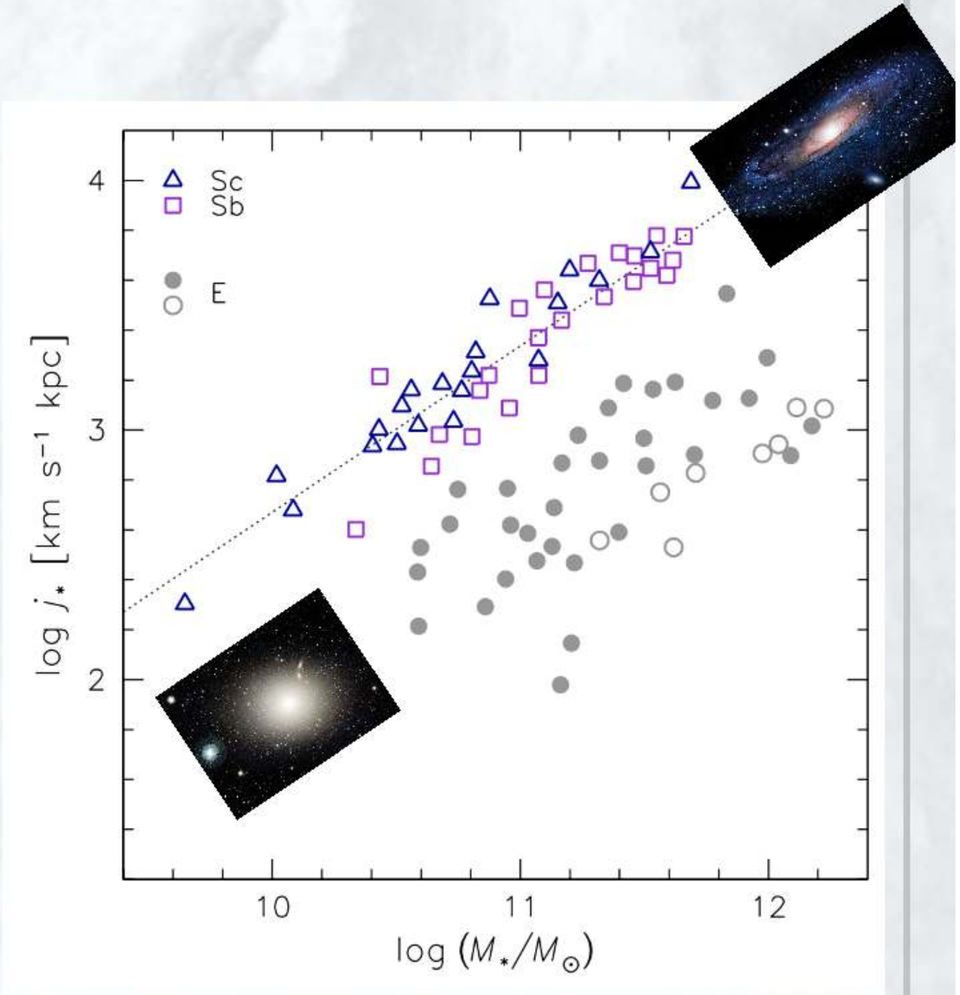
$$j_\star = \frac{J}{M_\star} = \frac{\int_{\mathbf{r}} (\mathbf{r} \times \bar{\mathbf{v}}) \rho_\star \, d^3\mathbf{r}}{\int_{\mathbf{r}} \rho_\star \, d^3\mathbf{r}}$$

for an exponential disk, this simplifies to

$$j_\star = 2 \, v_c \, R_d$$

circular velocity

disk effective radius




Fall & Efstathiou 1980
Romanowky & Fall 2012
Obreschkow & Glazebrook 2014

# Angular momentum of galaxy disks

Dynamical measurements of galaxies at z = 0

Angular momentum of disks appears to be related to the Hubble sequence (e.g. Fall 1980; Romanowski & Fall 2012).

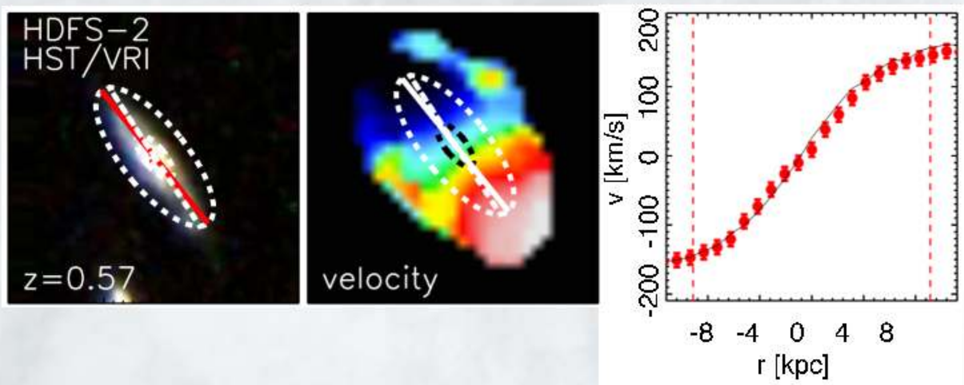
$$j_\star = \frac{J}{M_\star} = \frac{\int_{\mathbf{r}} (\mathbf{r} \times \bar{\mathbf{v}}) \rho_\star \, d^3\mathbf{r}}{\int_{\mathbf{r}} \rho_\star \, d^3\mathbf{r}}$$

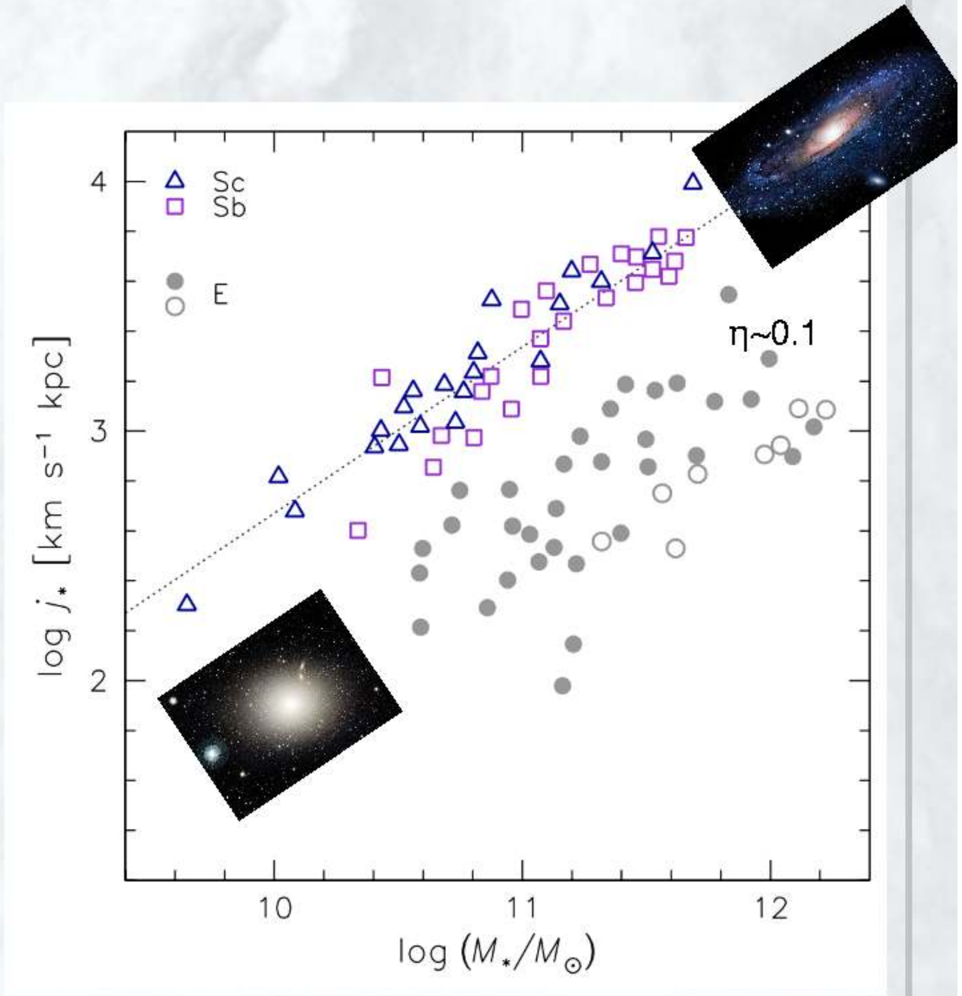
for an exponential disk, this simplifies to

$$j_\star = 2\, v_c\, R_d$$

circular velocity

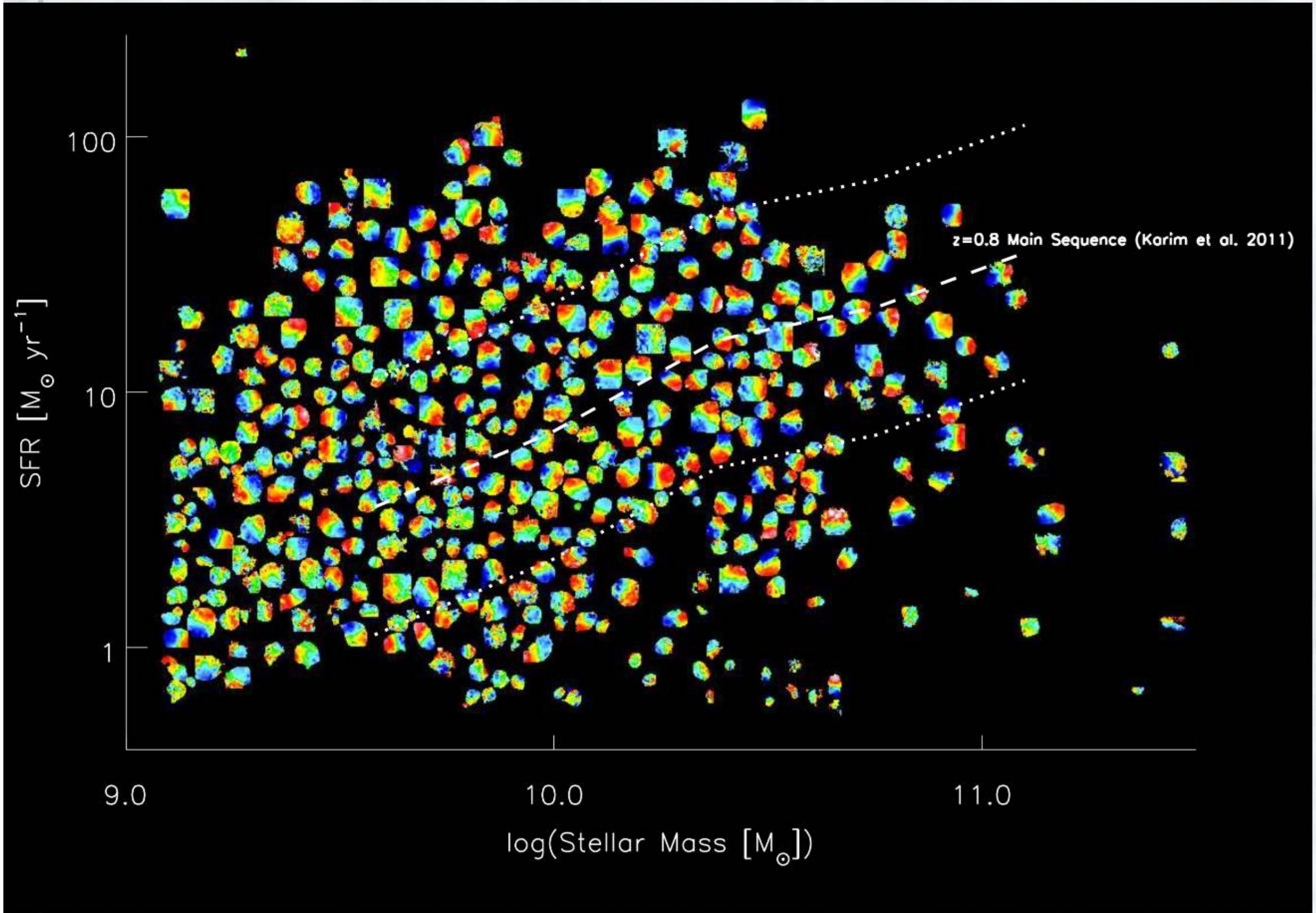
disk effective radius



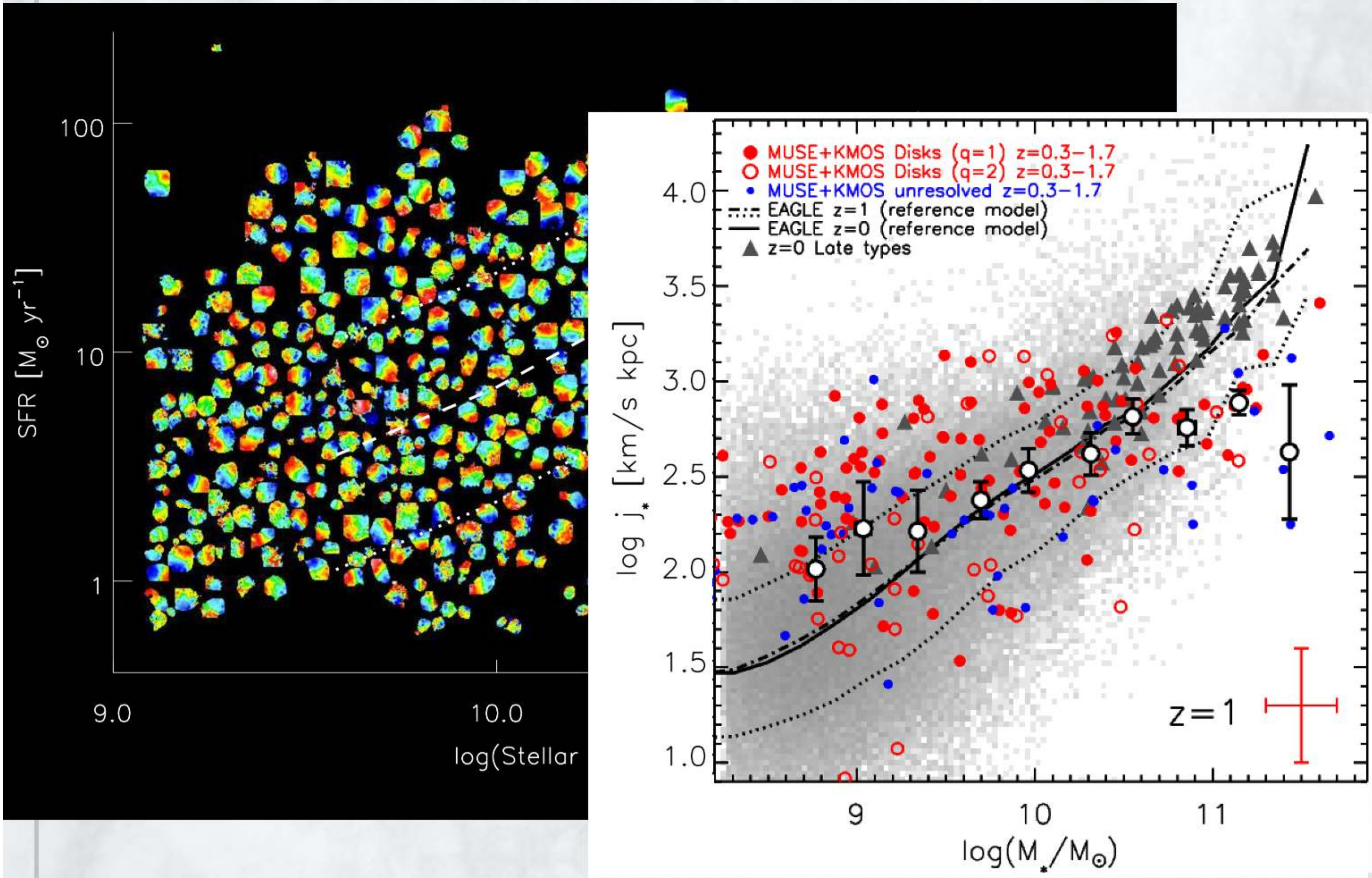

Fall & Efstathiou 1980
Romanowky & Fall 2012
Obreschkow & Glazebrook 2014

# Angular momentum of high-redshift star-forming galaxies



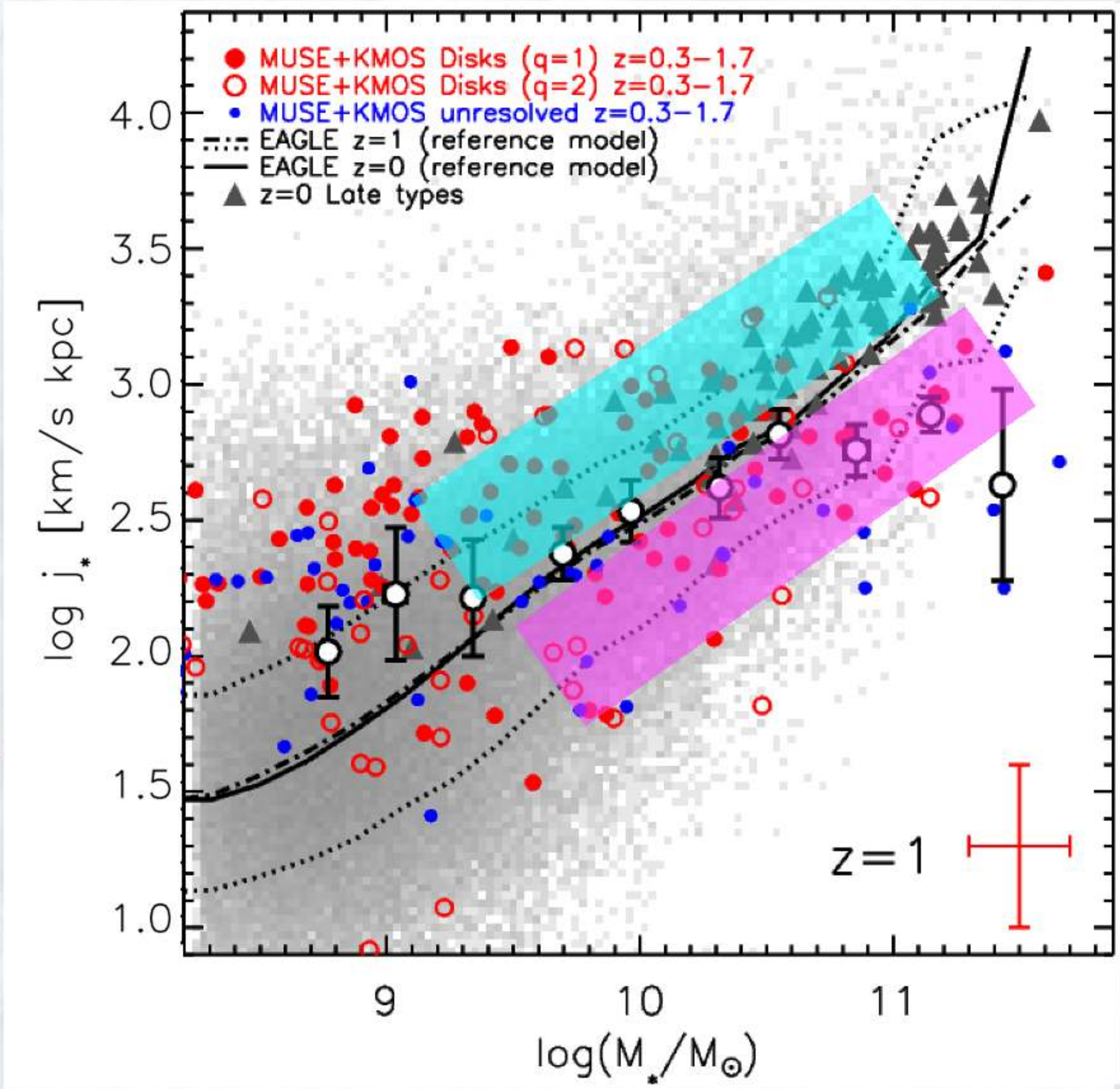
# Angular momentum of high-redshift star-forming galaxies

High-z data follow similar scaling of j* ~ $M^{2/3}$ as local spirals



# Angular momentum of high-redshift star-forming galaxies

High-z data follow similar scaling of j* ~ $M^{2/3}$ as local spirals



Star-Formation Scales within Disks: back of the envelope calculation

In rotating disk of gas and stars, perturbations smaller than critical wavelength ($\lambda_{max}$) are stabilised against gravity by velocity dispersion whilst those larger than $\lambda_{min}$ are stabilised by centrifugal force: Toomre parameter, $Q = \lambda_{min}/\lambda_{max}$.

## Star-Formation Scales within Disks: back of the envelope calculation

In rotating disk of gas and stars, perturbations smaller than critical wavelength ($\lambda_{max}$) are stabilised against gravity by velocity dispersion whilst those larger than $\lambda_{min}$ are stabilised by centrifugal force: Toomre parameter, $Q = \lambda_{min}/\lambda_{max}$.

Galaxies with Q<1 are unstable and will fragment into clumps.

For galaxies whose velocity field resemble rotation:

mass surface density

$$Q = \sigma_r \kappa \;/\; \pi G \Sigma$$

$1.5V_{max}/R$

## Star-Formation Scales within Disks: back of the envelope calculation

In rotating disk of gas and stars, perturbations smaller than critical wavelength ($\lambda_{max}$) are stabilised against gravity by velocity dispersion whilst those larger than $\lambda_{min}$ are stabilised by centrifugal force: Toomre parameter, $Q = \lambda_{min}/\lambda_{max}$.

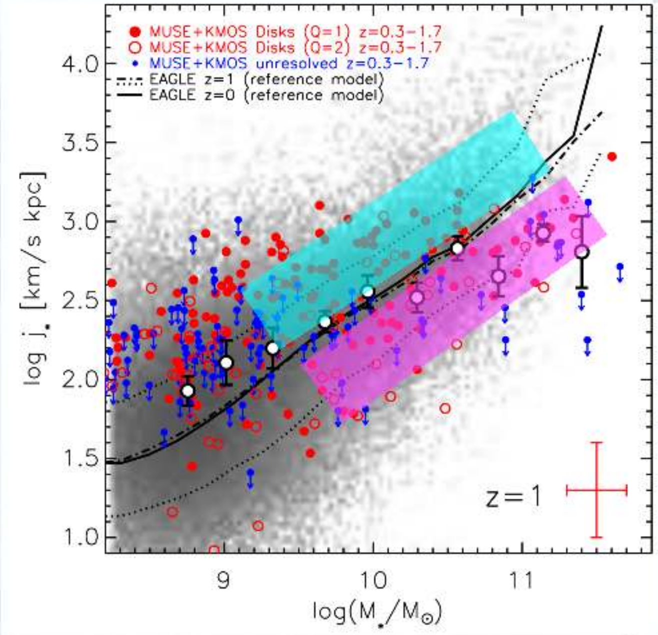
Galaxies with Q<1 are unstable and will fragment into clumps.

For galaxies whose velocity field resemble rotation:

mass surface density

$$Q = \sigma_r \kappa \,/\, \pi G \Sigma$$

$1.5V_{max}/R$



## Star-Formation Scales within Disks: back of the envelope calculation

In rotating disk of gas and stars, perturbations smaller than critical wavelength ($\lambda_{max}$) are stabilised against gravity by velocity dispersion whilst those larger than $\lambda_{min}$ are stabilised by centrifugal force: Toomre parameter, $Q = \lambda_{min}/\lambda_{max}$.

Galaxies with Q<1 are unstable and will fragment into clumps.

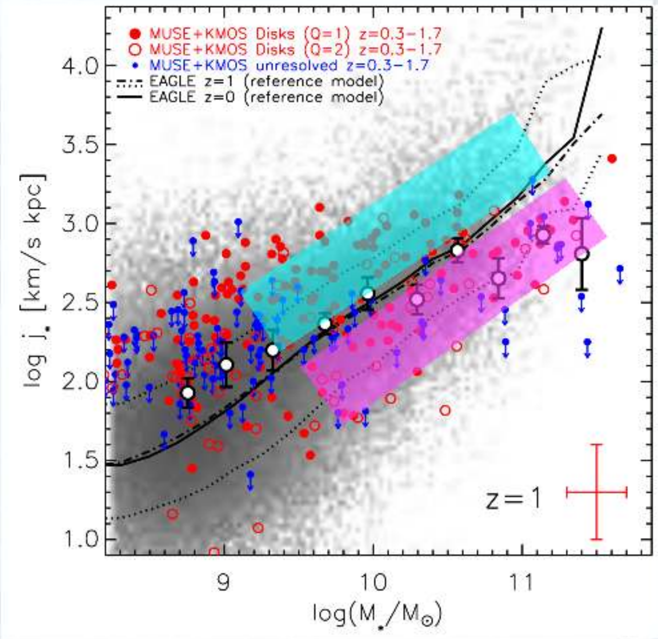
For galaxies whose velocity field resemble rotation:

mass surface density

$$Q = \sigma_r \kappa \, / \, \pi G \Sigma$$

$1.5 V_{max}/R$

For galaxies above relation, Q ~ 1.5 +/- 0.2
For galaxies below relation, Q ~ 0.6 +/- 0.2



# Star-Formation Scales within Disks: back of the envelope calculation

In rotating disk of gas and stars, perturbations smaller than critical wavelength ($\lambda_{max}$) are stabilised against gravity by velocity dispersion whilst those larger than $\lambda_{min}$ are stabilised by centrifugal force: Toomre parameter, $Q = \lambda_{min}/\lambda_{max}$.

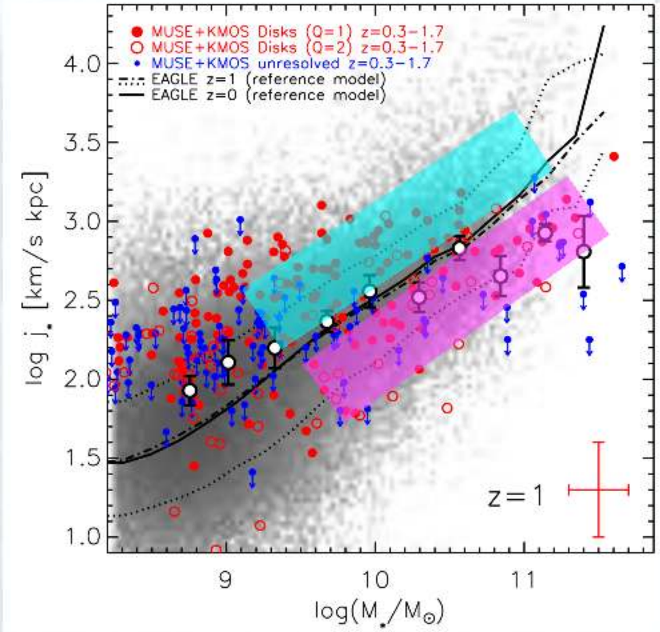
Galaxies with Q<1 are unstable and will fragment into clumps.

For galaxies whose velocity field resemble rotation:

mass surface density

$$Q = \sigma_r \kappa \,/\, \pi G \Sigma$$

$1.5V_{max}/R$




For galaxies above relation, Q ~ 1.5 +/- 0.2
For galaxies below relation, Q ~ 0.6 +/- 0.2

For Q~0.6, gas will fragment into massive clumps on scales of Jeans length for dispersion support. In uniform disk, the largest scale for which velocity dispersion stabilises against gravitational collapse is:

$$L_J = \pi\sigma^2 \,/\, 8G\Sigma$$

gives $L_J$ = 0.1–1kpc for all galaxies in our sample

## Star-Formation Scales within Disks: back of the envelope calculation

In rotating disk of gas and stars, perturbations smaller than critical wavelength ($\lambda_{max}$) are stabilised against gravity by velocity dispersion whilst those larger than $\lambda_{min}$ are stabilised by centrifugal force: Toomre parameter, $Q = \lambda_{min}/\lambda_{max}$.

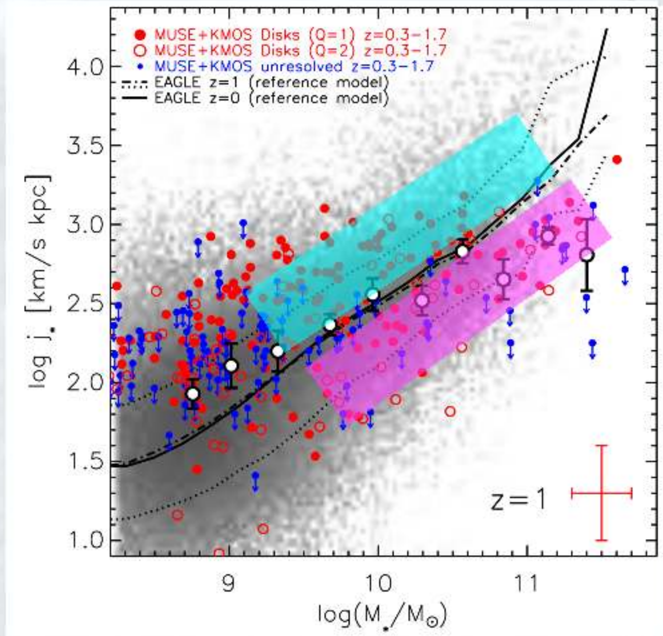
Galaxies with Q<1 are unstable and will fragment into clumps.

For galaxies whose velocity field resemble rotation:

mass surface density

$$Q = \sigma_r \kappa / \pi G \Sigma$$

$1.5V_{max}/R$




For galaxies above relation, Q ~ 1.5 +/- 0.2
For galaxies below relation, Q ~ 0.6 +/- 0.2

For Q~0.6, gas will fragment into massive clumps on scales of Jeans length for dispersion support. In uniform disk, the largest scale for which velocity dispersion stabilises against gravitational collapse is:

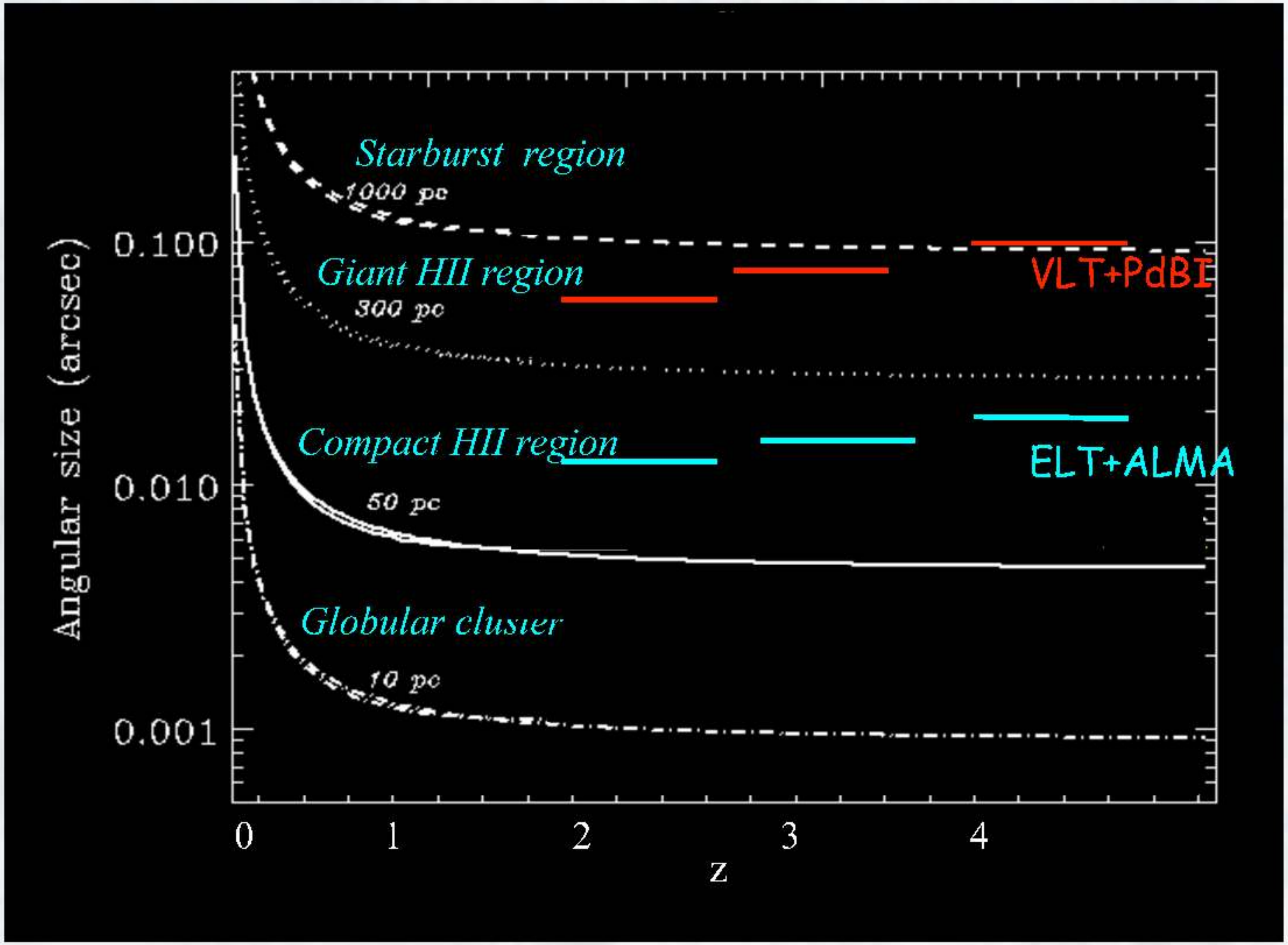
$$L_J = \pi\sigma^2 / 8G\Sigma$$

gives $L_J$ = 0.1–1kpc for all galaxies in our sample

Can we identify “clumps” on these scales and measure their dynamical properties?

## Internal star-formation: Clumpy Disks

On the smaller scales, we can resolve the giant star-forming clumps:
pseudo bulges in formation? formation epoch of local globular clusters?

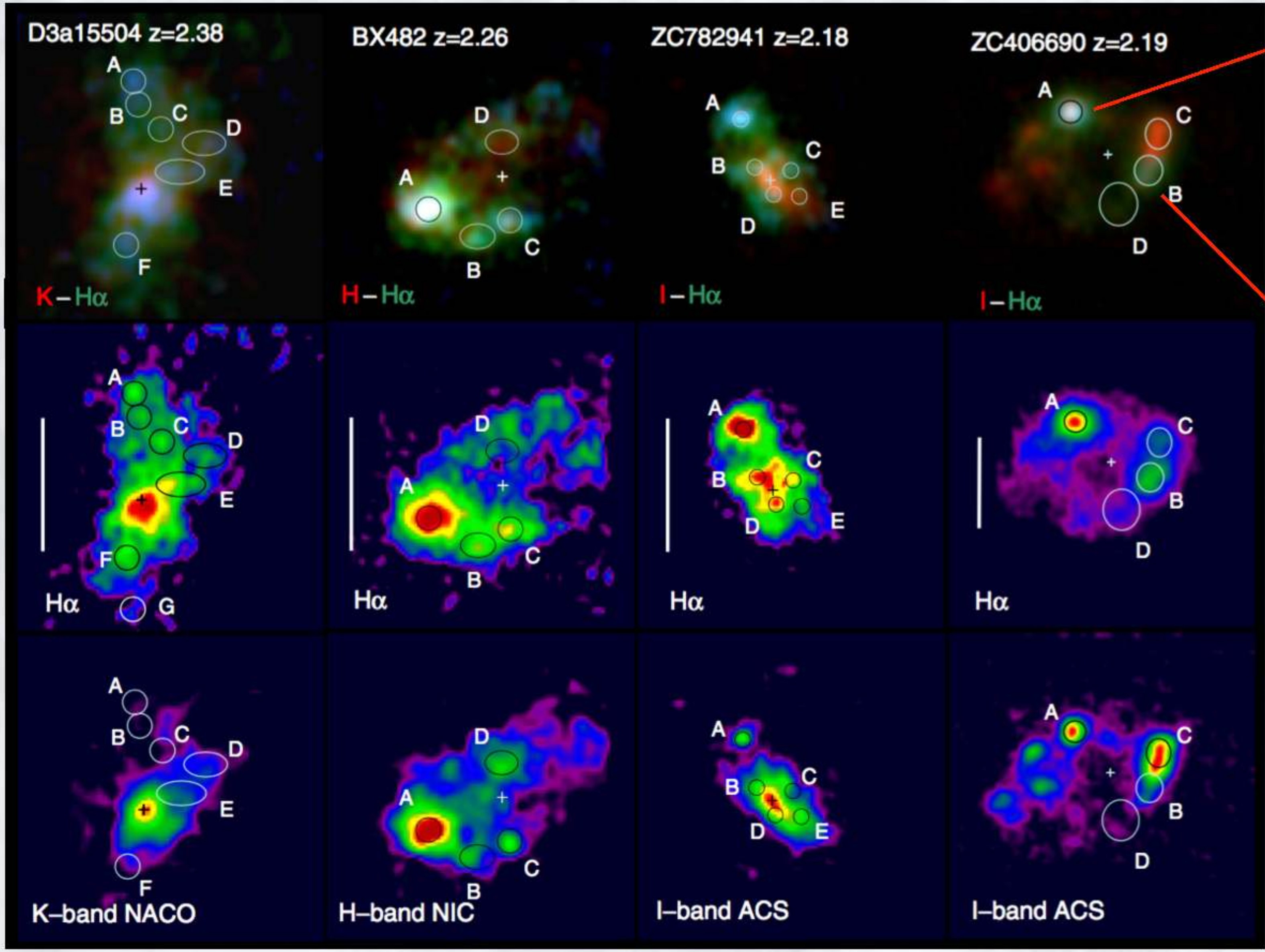


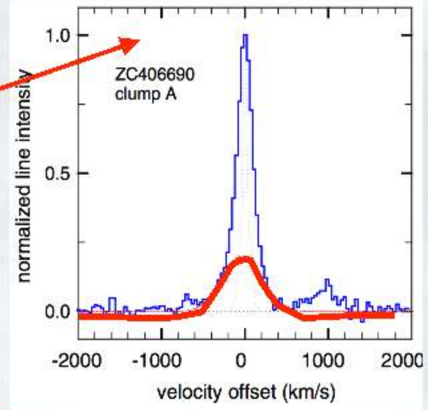
## Internal star-formation: Clumpy Disks

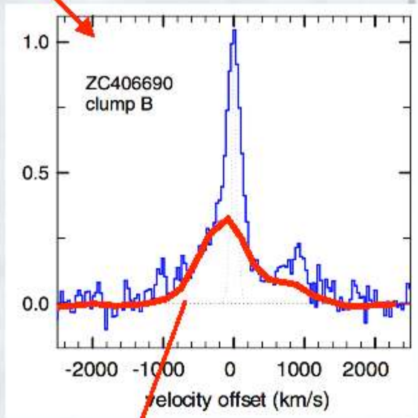
On the smaller scales, we can resolve the giant star-forming clumps:
pseudo bulges in formation? formation epoch of local globular clusters?

# "Very Detailed Studies": Internal star-formation

On the smaller scales, we can resolve the giant star-forming clumps: pseudo bulges in formation? formation epoch of local globular clusters?

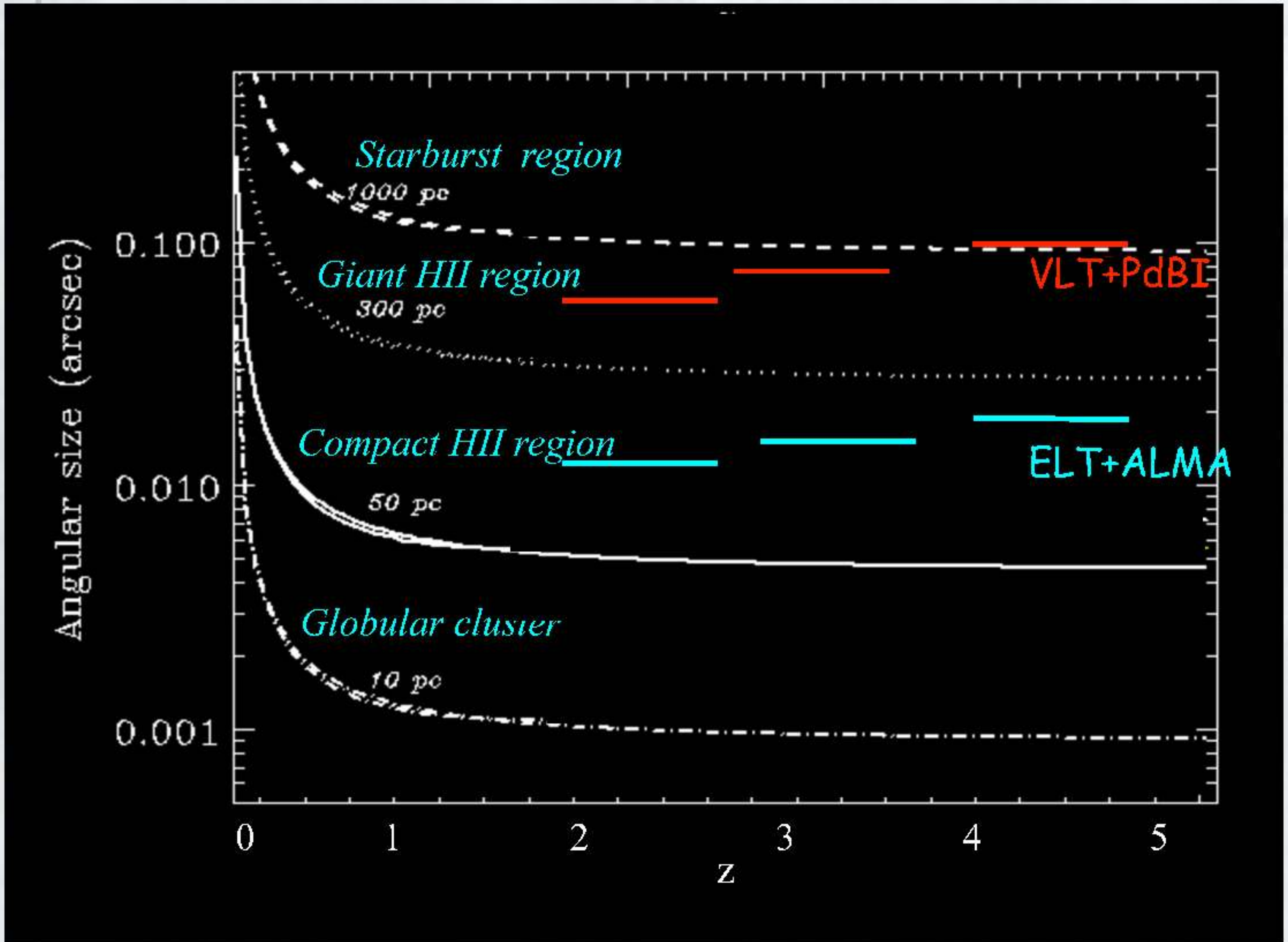



underlying Hα broad lines from clumps —> launch sites for powerful outflows $dM_{out}/dt > SFR$

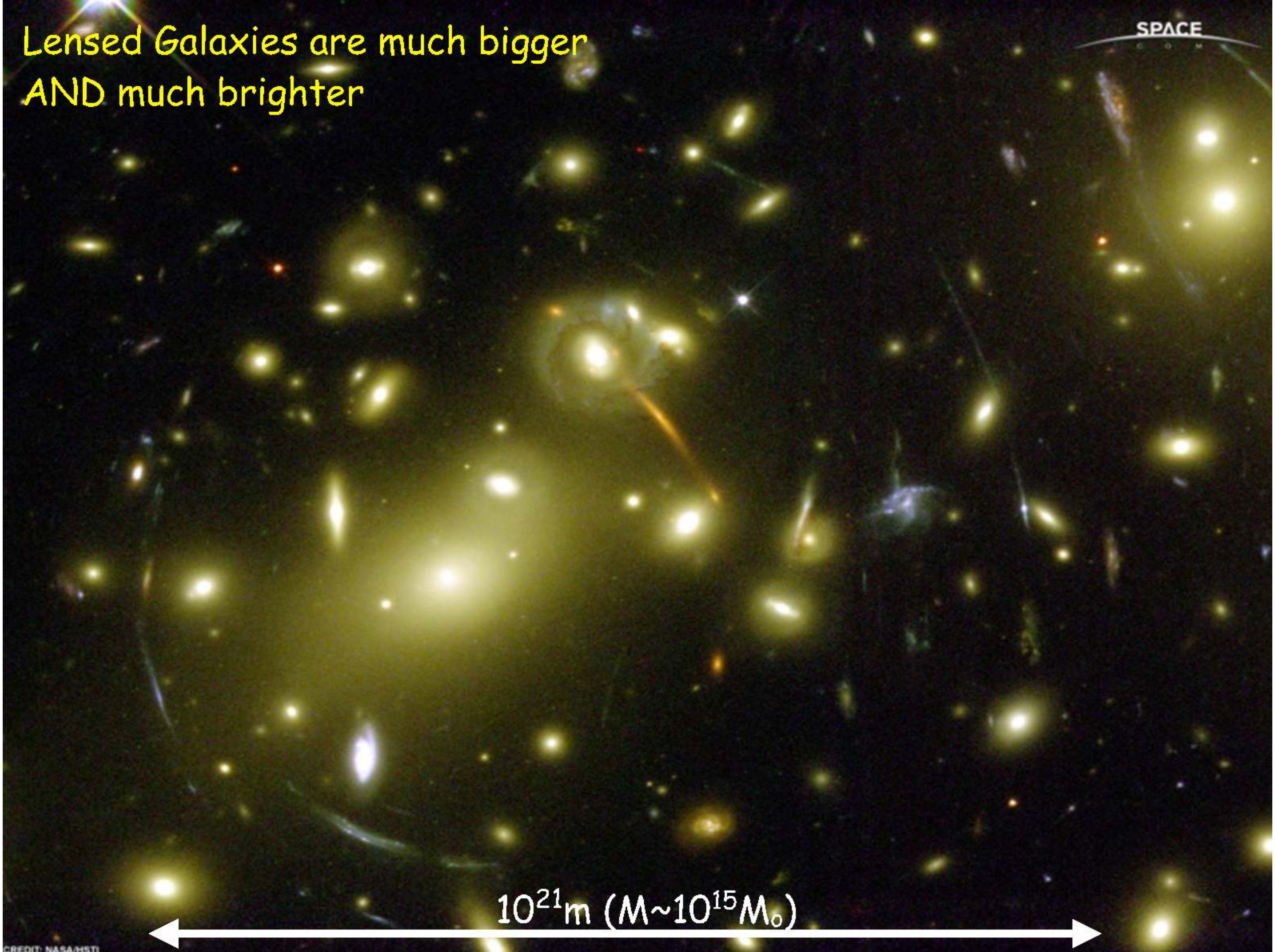
e.g. Genzel et al. 2011 733 101

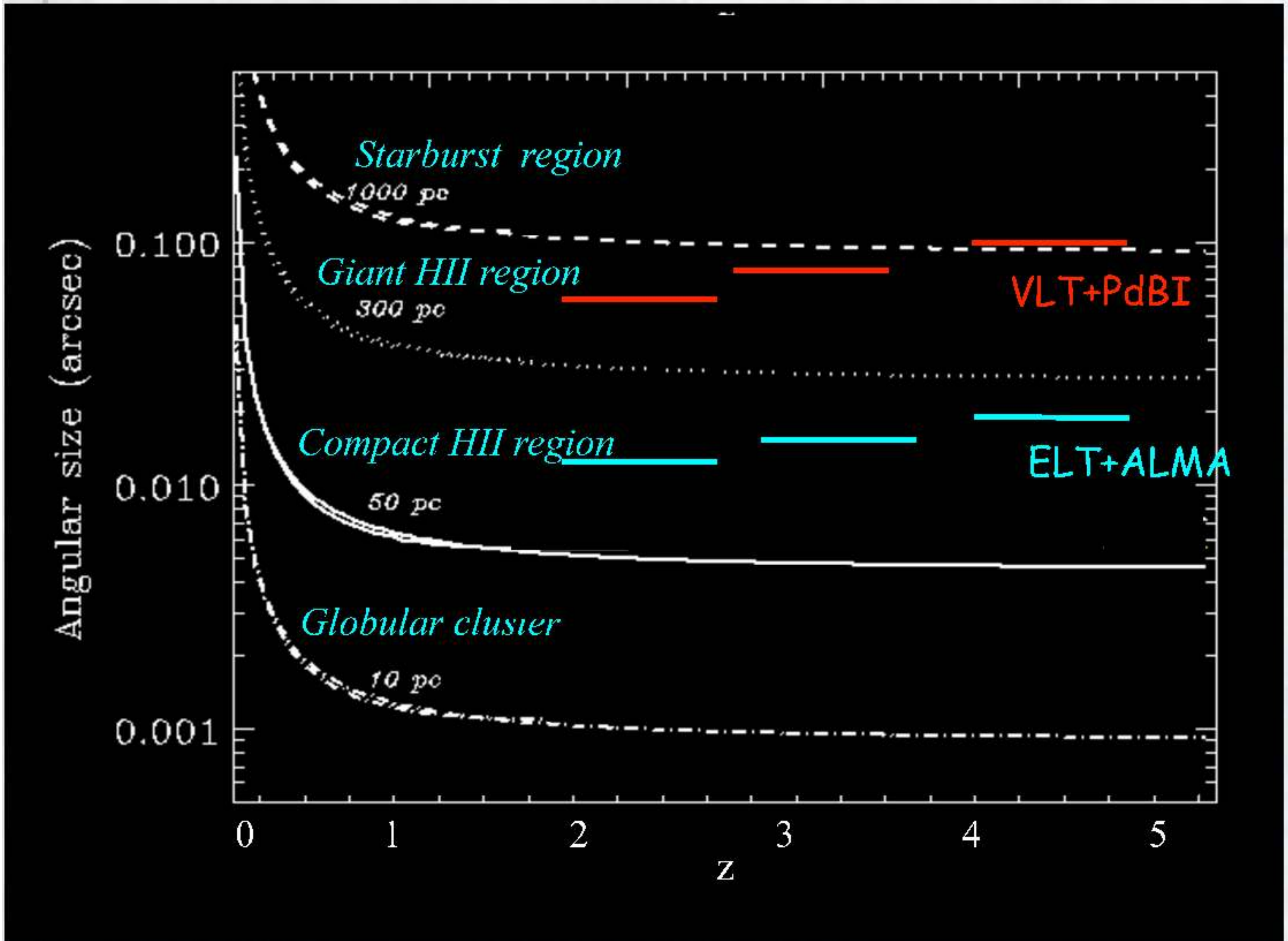

Starburst region
1000 pc
Giant HII region
300 pc
Compact HII region
50 pc
Globular cluster
10 pc
VLT+PdBI
ELT+ALMA
Angular size (arcsec)
0.100
0.010
0.001
0
1
2
3
4
5
z


VLT


ELT (2018)

Lensed Galaxies are much bigger
AND much brighter




Starburst region
1000 pc
Giant HII region
300 pc
Compact HII region
50 pc
Globular cluster
10 pc
VLT+PdBI
ELT+ALMA
Angular size (arcsec)
0.100
0.010
0.001
0
1
2
3
4
5
z

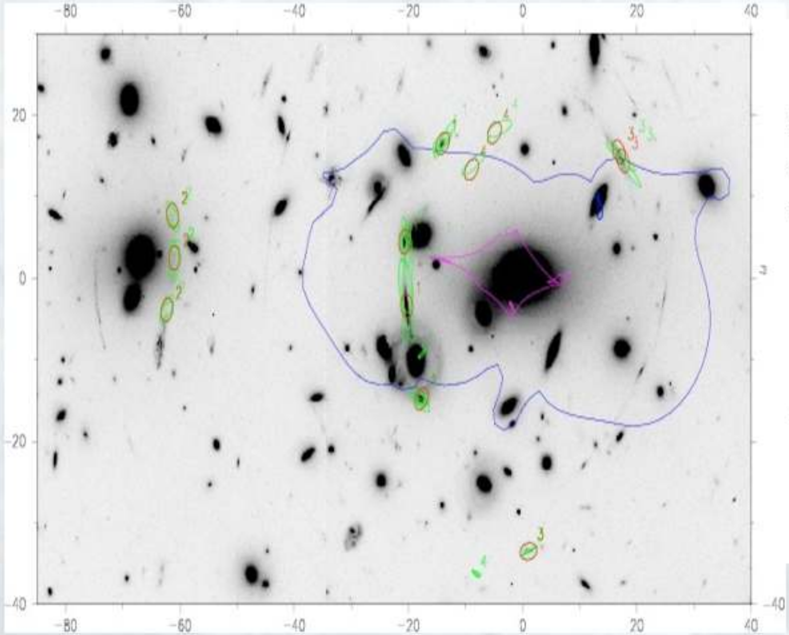

VLT

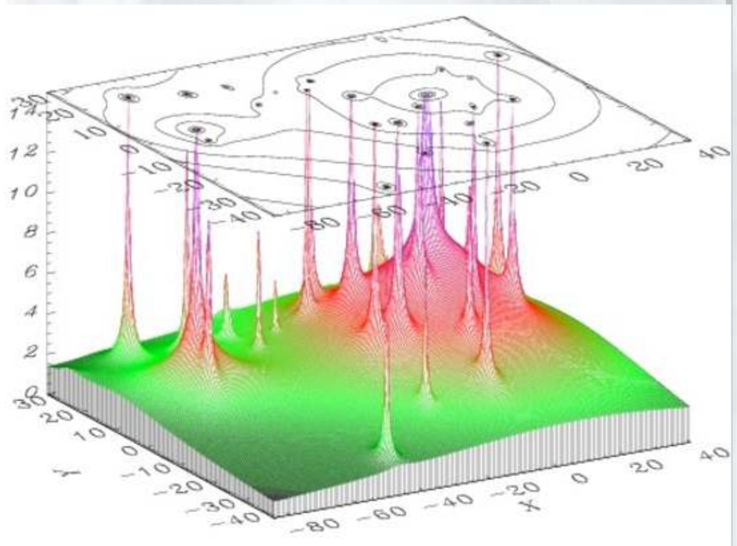

ELT (2018)


z~1
z~2-3
z~5
Abell 1689b
z = 3.04
MACS J0744
z = 1.28
MACS J1149
z = 1.49

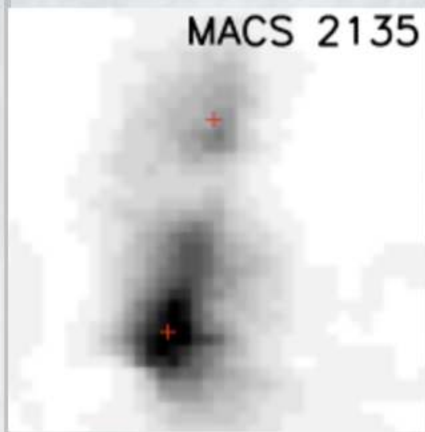
# Example: Mass modelling + source plane reconstruction of z=3 galaxy

Original image → Galaxy Cluster → Lens model

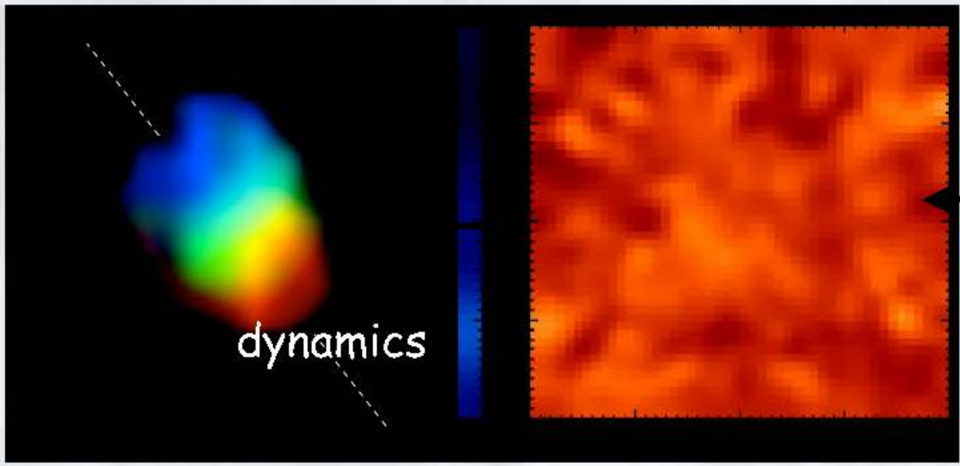


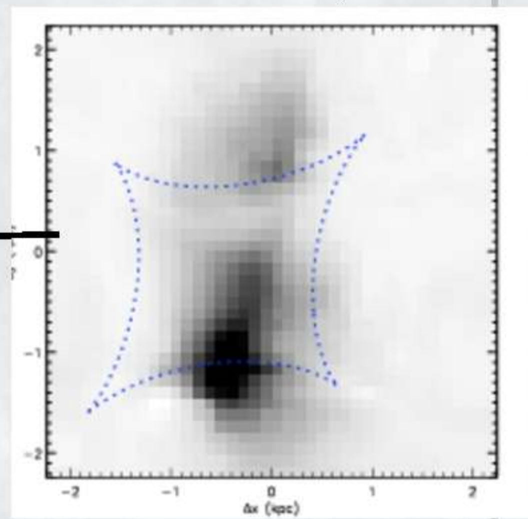



SF and dynamics maps with spatial scale of 100pc 15mas in non-lensed case!

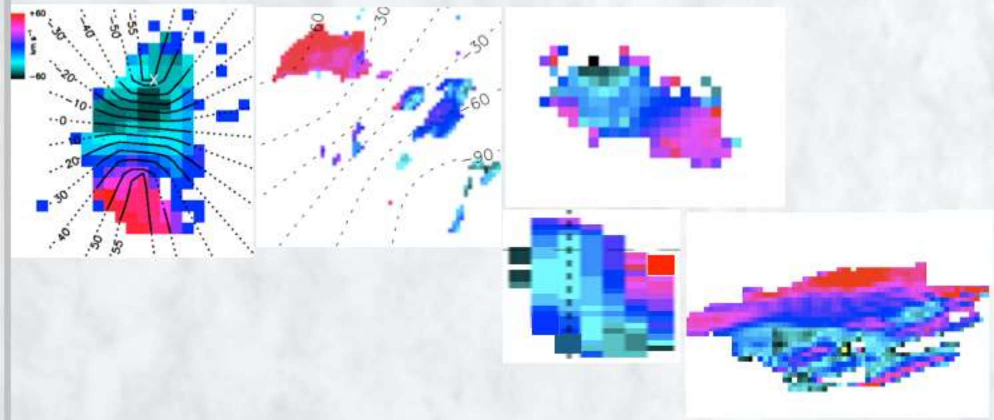



+



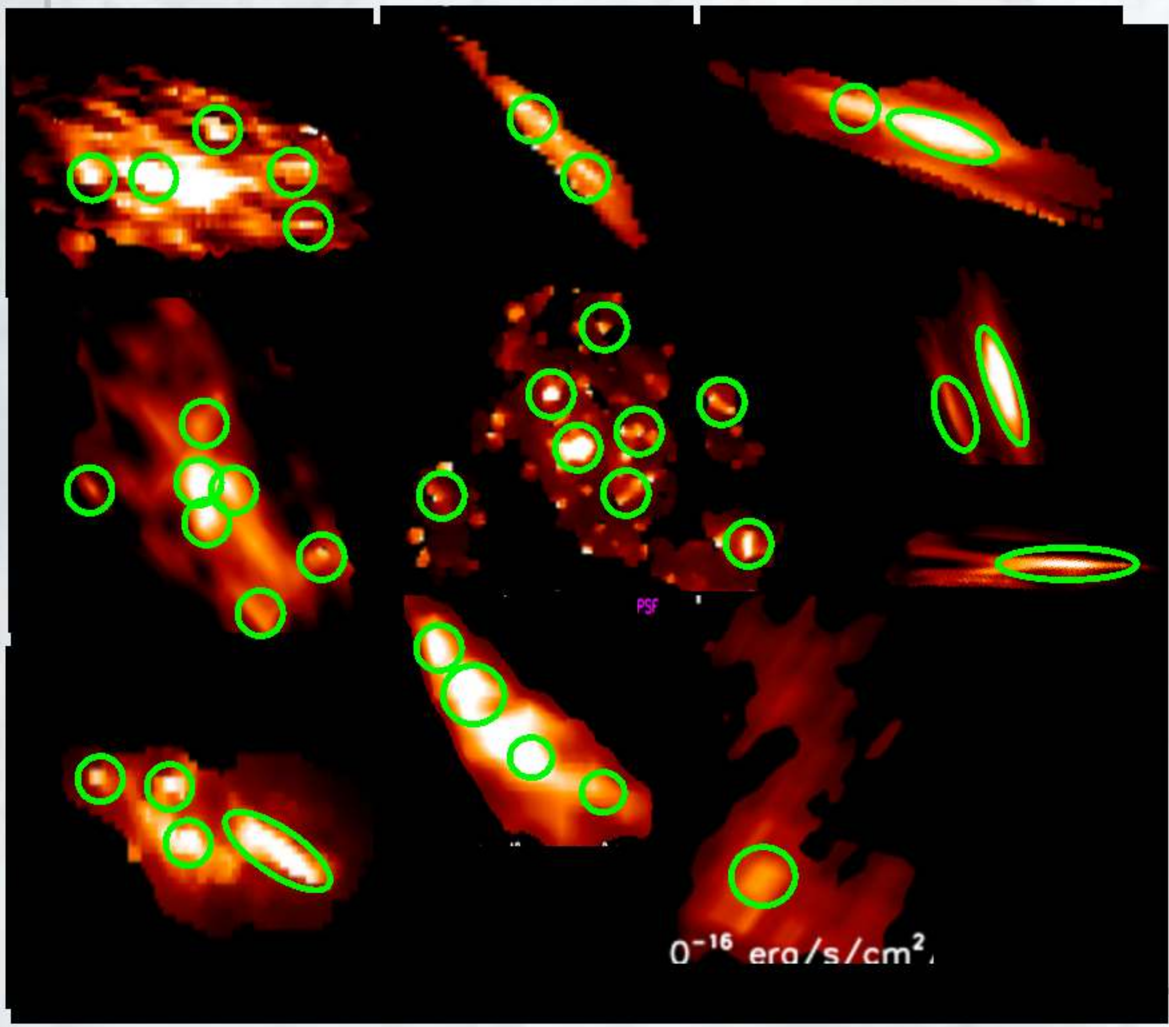
# Internal Star-Formation



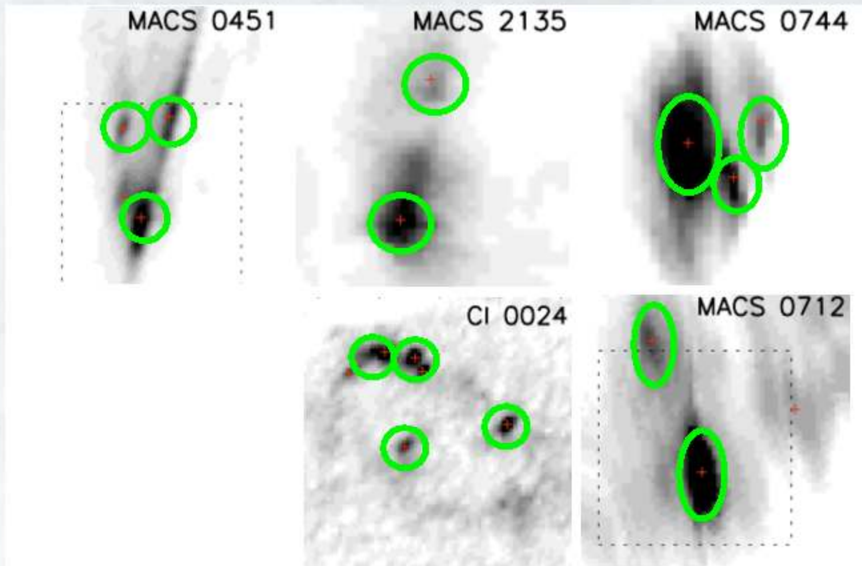
- 19 lensed galaxies observed with AO using VLT/SINFONI and Gemini/NIFS to reach 100-300pc resolution (source plane).

- 16/19 systems display 'coherent' velocity gradients across 2--10kpc in projection

- 15 consistent with rotation, 2 merger, 3 ambiguous.

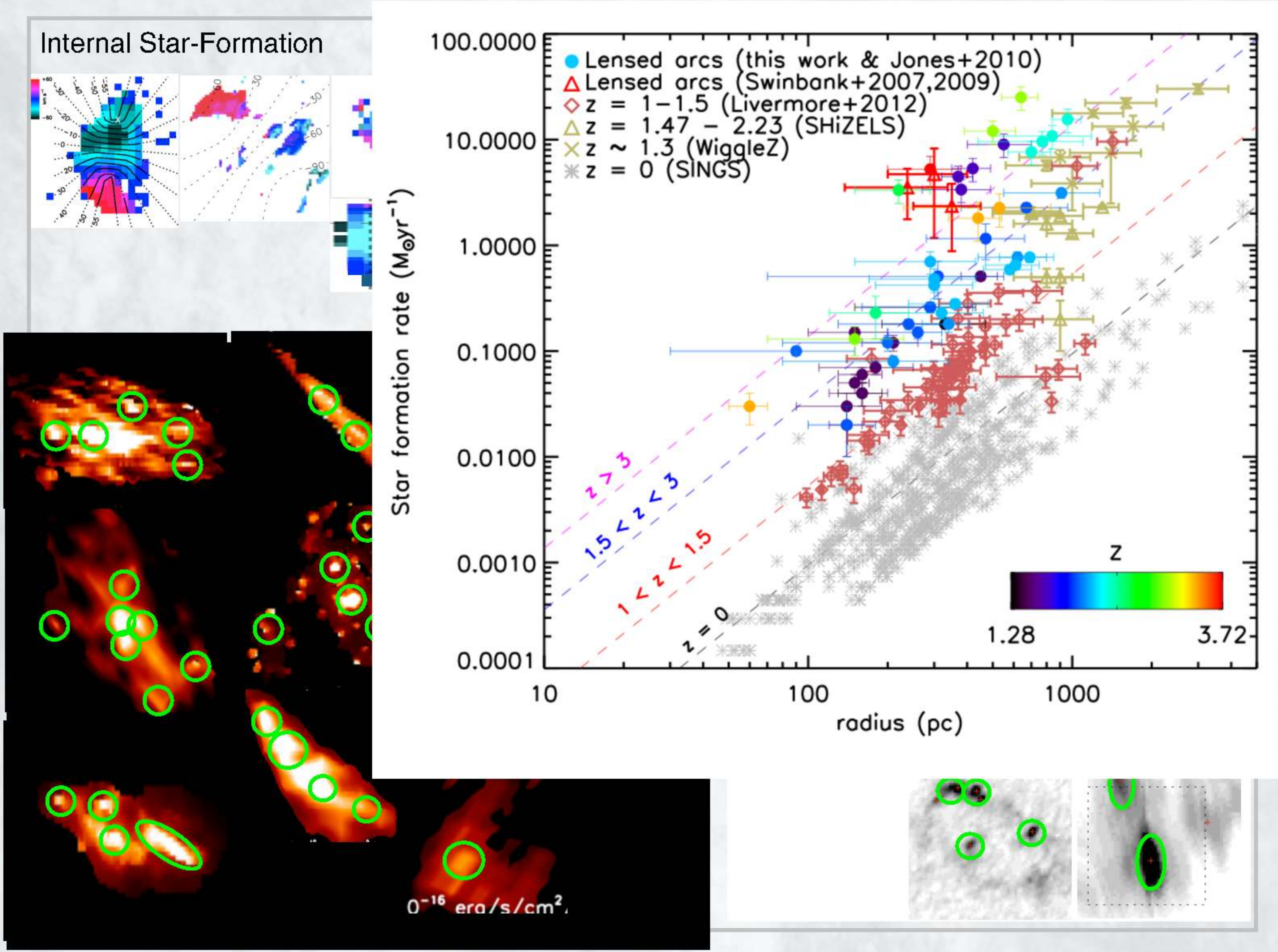



High-z galaxies display "clumpy" morphologies. The properties of the SF clumps reflect those of the underlying ISM.




Jones et al. 2010; Livermore et al. 2012; 2015

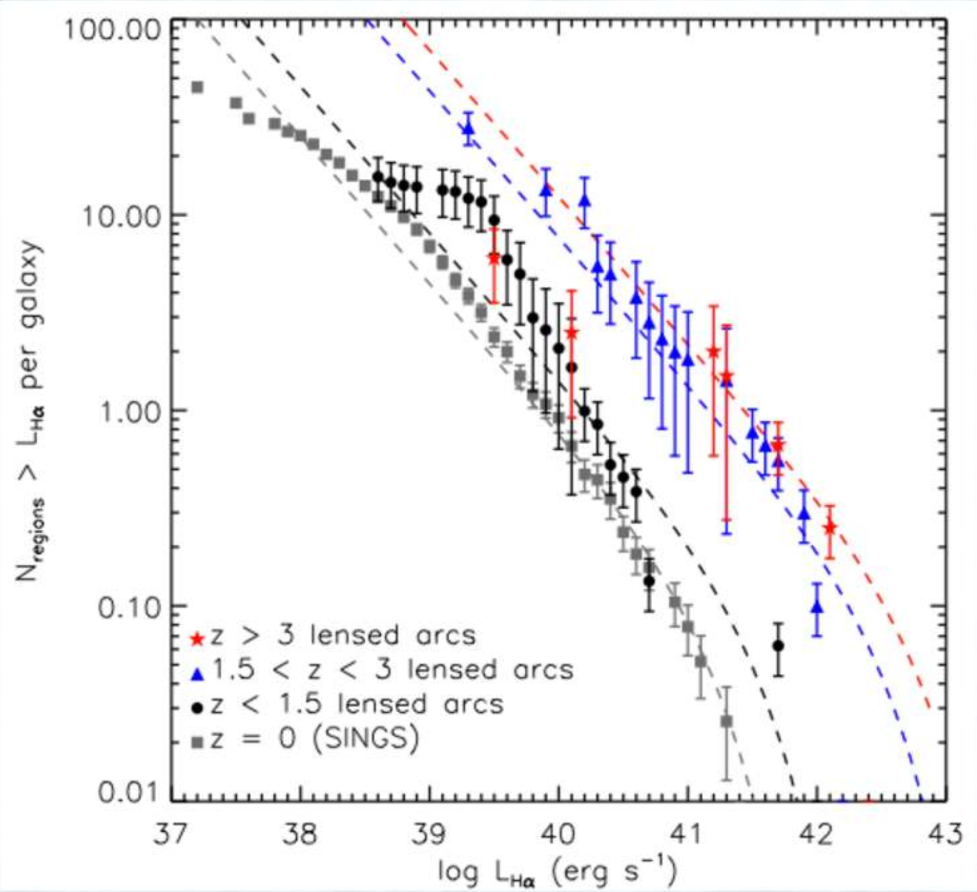
# Internal Star-Formation



Relating the SF clumps to the underlying disk

For marginally disk (Q=1) of finite thickness, density structures on scales >h will be stabilised by rotation, leading to exponential cut off in clump mass function with

$$M_0 \sim 8.6\times10^3 \left(\frac{\Sigma_{disk}}{10 M_\odot pc^{-2}}\right)^3 \times \left(\frac{\kappa}{100 km/s/kpc}\right)^{-4}$$




Hopkins et al. 2012MN 423 2016
Livermore et al. 2015 MN 450 1812
Livermore et al. 2012 MN 427 688

# Summary

1) Can we learn about the dominant mode of mass assembly of high-z galaxies from their dynamics?
e.g. How does the angular moment of gas disks evolve with time?
How is the evolution of angular momentum related to the formation of the Hubble sequence?

2) What is the physical properties (size/luminosity/σ) of star-forming regions in high-*z* galaxies?
How do global dynamics and gas properties of the ISM effect the size, luminosity, velocity dispersion of star-forming (HII) regions?

3) What are the energetics of starburst driven feedback?
e.g. How does the mass loading of winds depend on the mass and SFR at high-z?
How do winds on large scales relate to those on small scales (the "launch sites")?