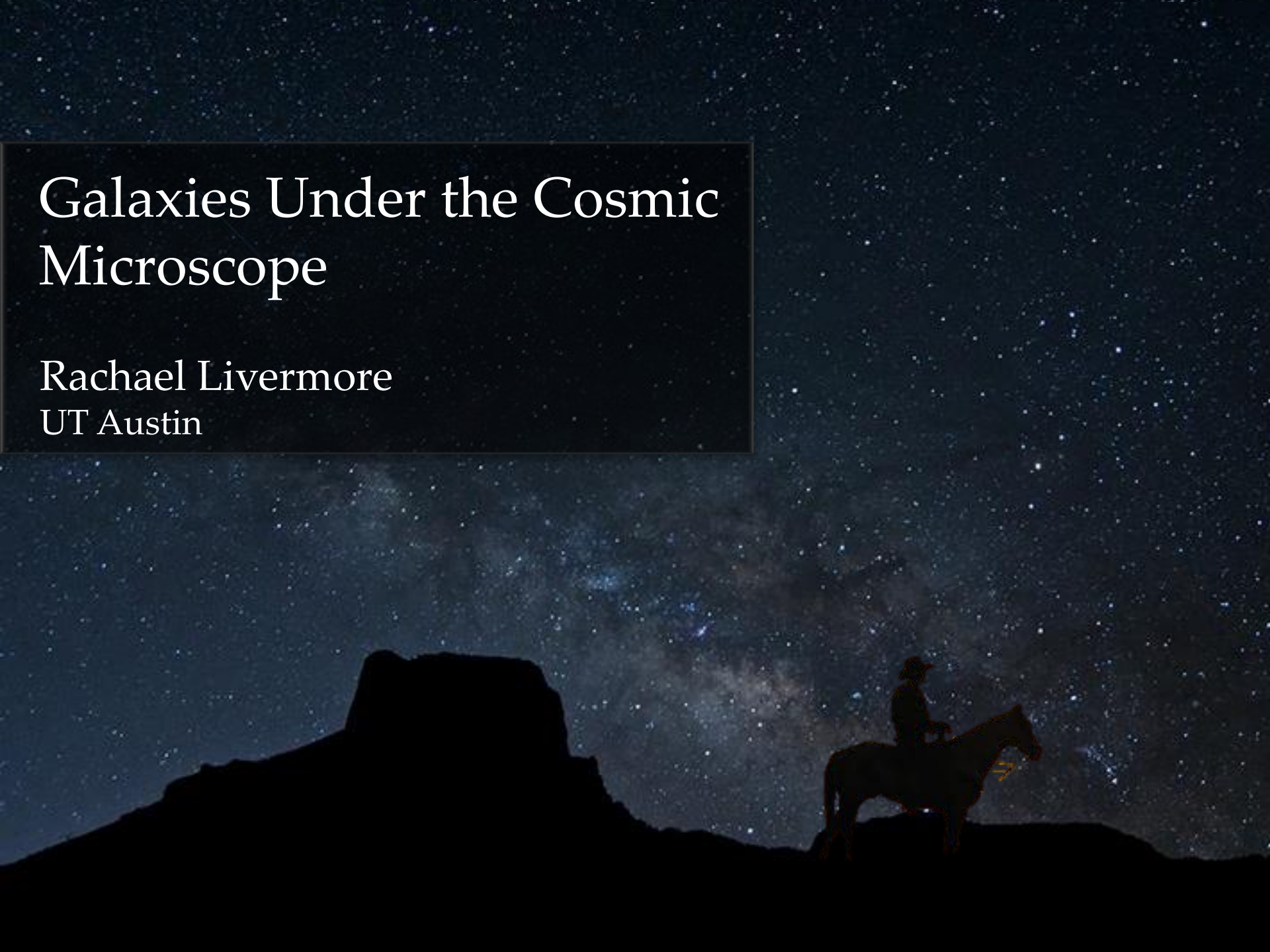


Galaxies Under the Cosmic Microscope

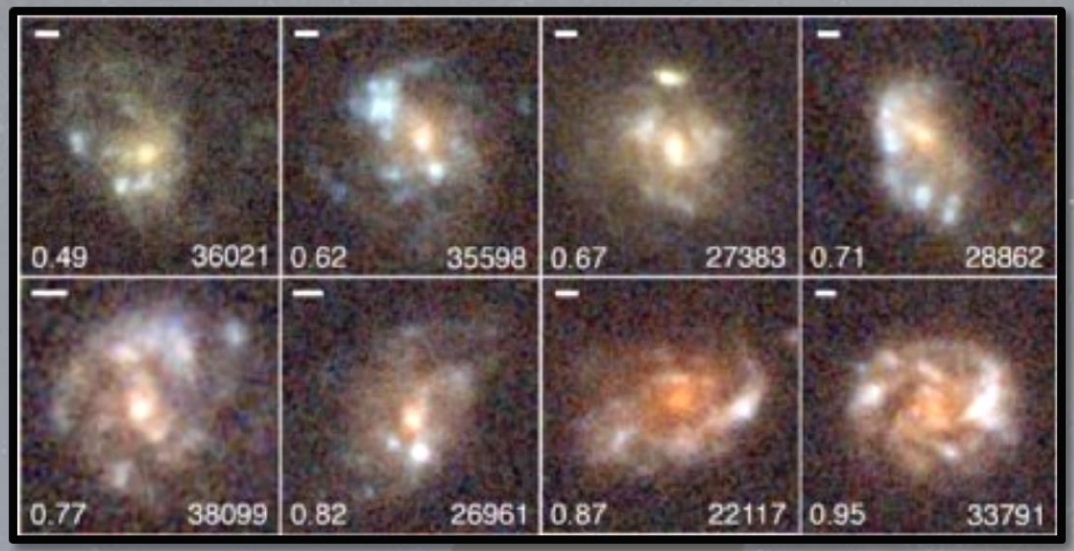
Rachael Livermore
UT Austin

Summary

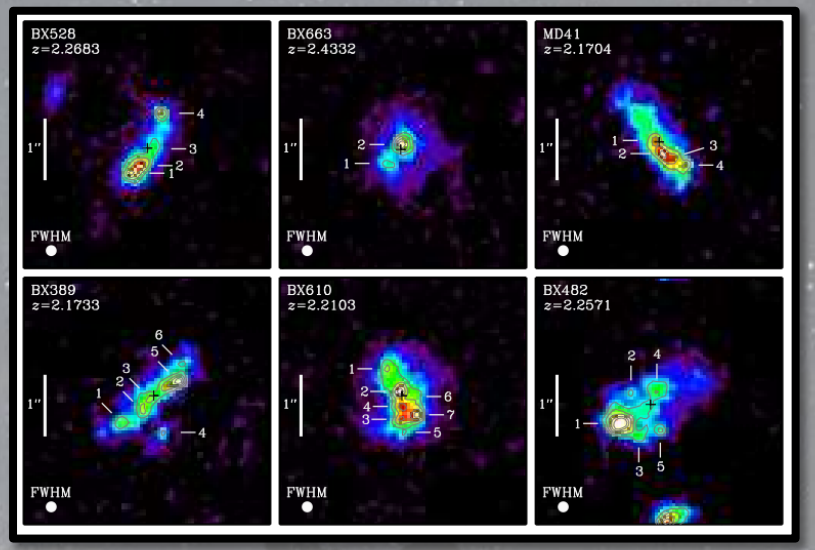
- Why do we need high spatial resolution?
- A brief introduction to gravitational lensing
- Imaging galaxies at $1 < z < 1.5$
- Molecular gas at $z = 5$
- Clumps at $1 < z < 4$

High-redshift galaxy morphologies

Elmegreen et al. 2009



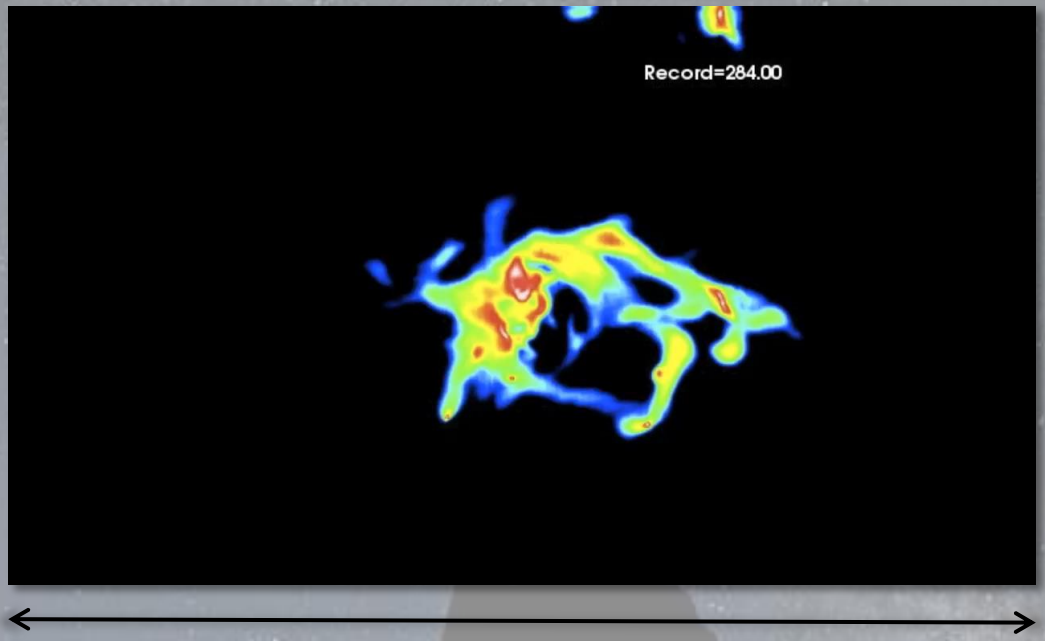
Förster Schreiber et al. 2011



kpc-scale clumps are ubiquitous at high-z, but barely resolved.

Clump origins: cold flows?

Ceverino et al. 2011



20 kpc

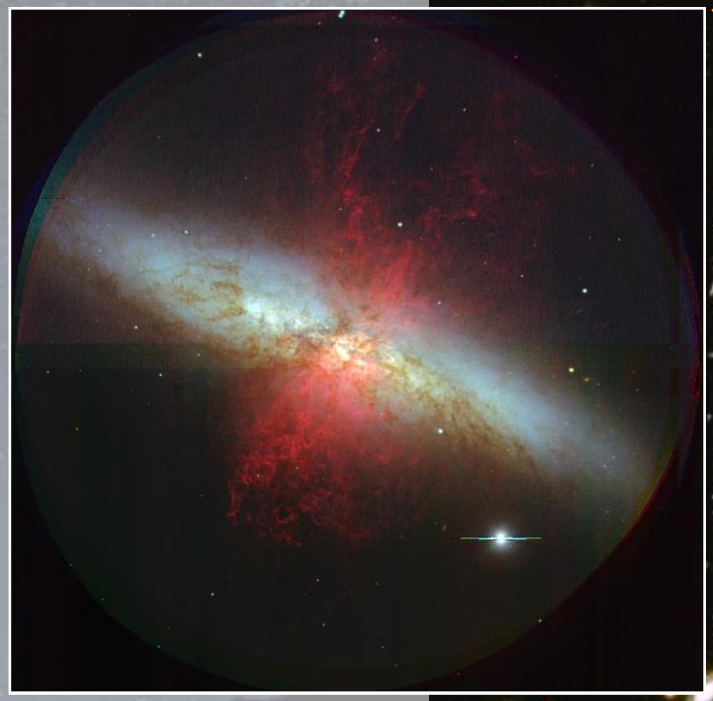
Gravitationally unstable disk fragments into clumps

Clumps migrate to center of galaxy to form bulge

Steady state maintained by accretion through cold streams

N.B.: Cold flows have never been observed

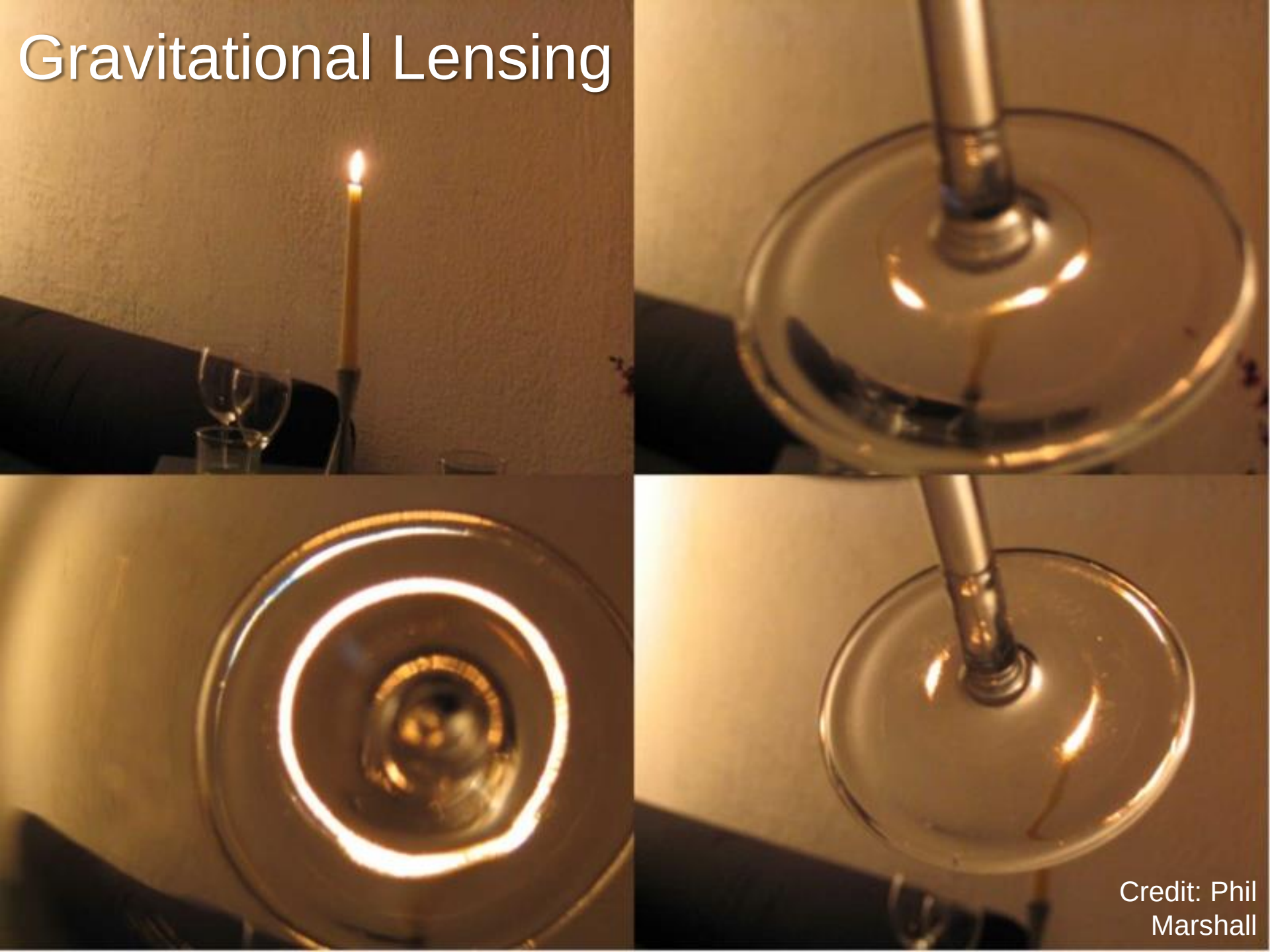
The Problem:



M82 will subtend 0.3” at z=2
(6 pixels of HST)

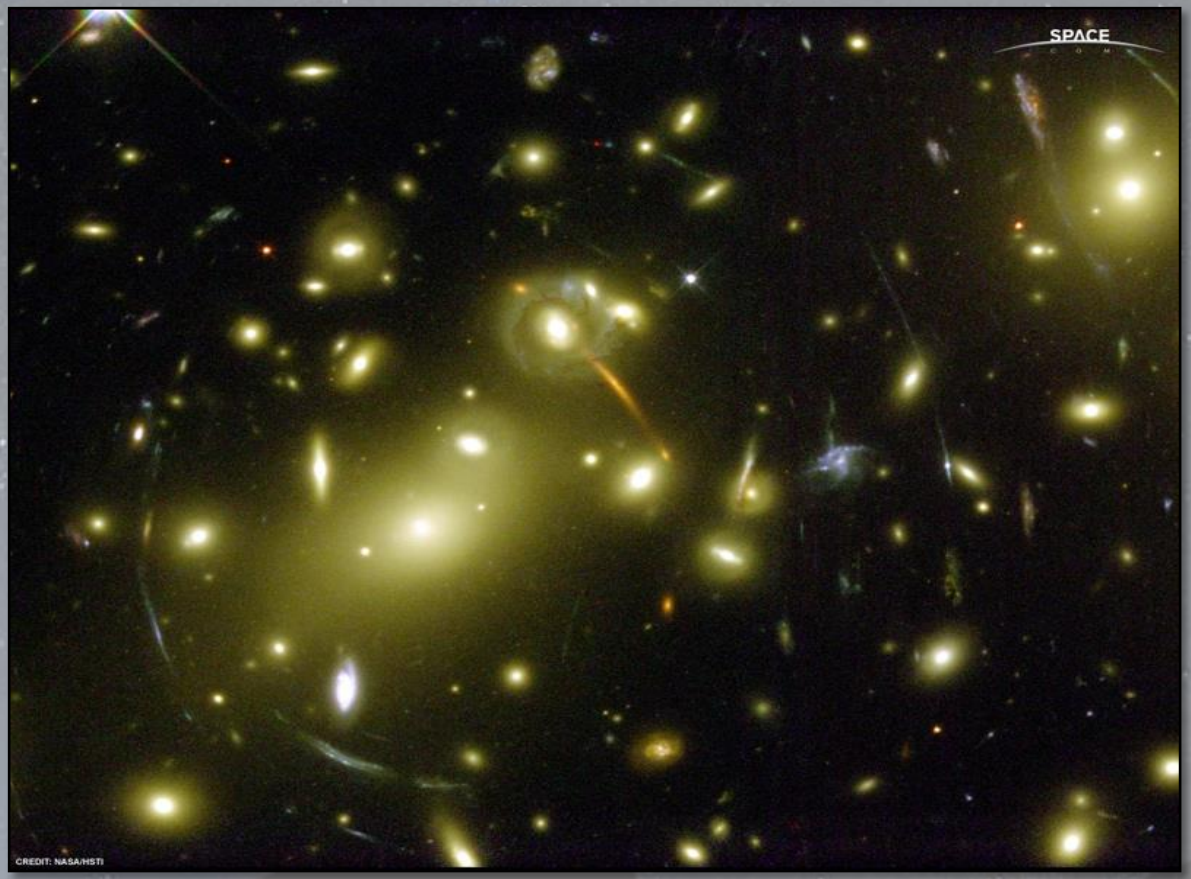
To observe a Milky-Way like progenitor galaxy in detail at z=2, we need a big telescope

Gravitational Lensing



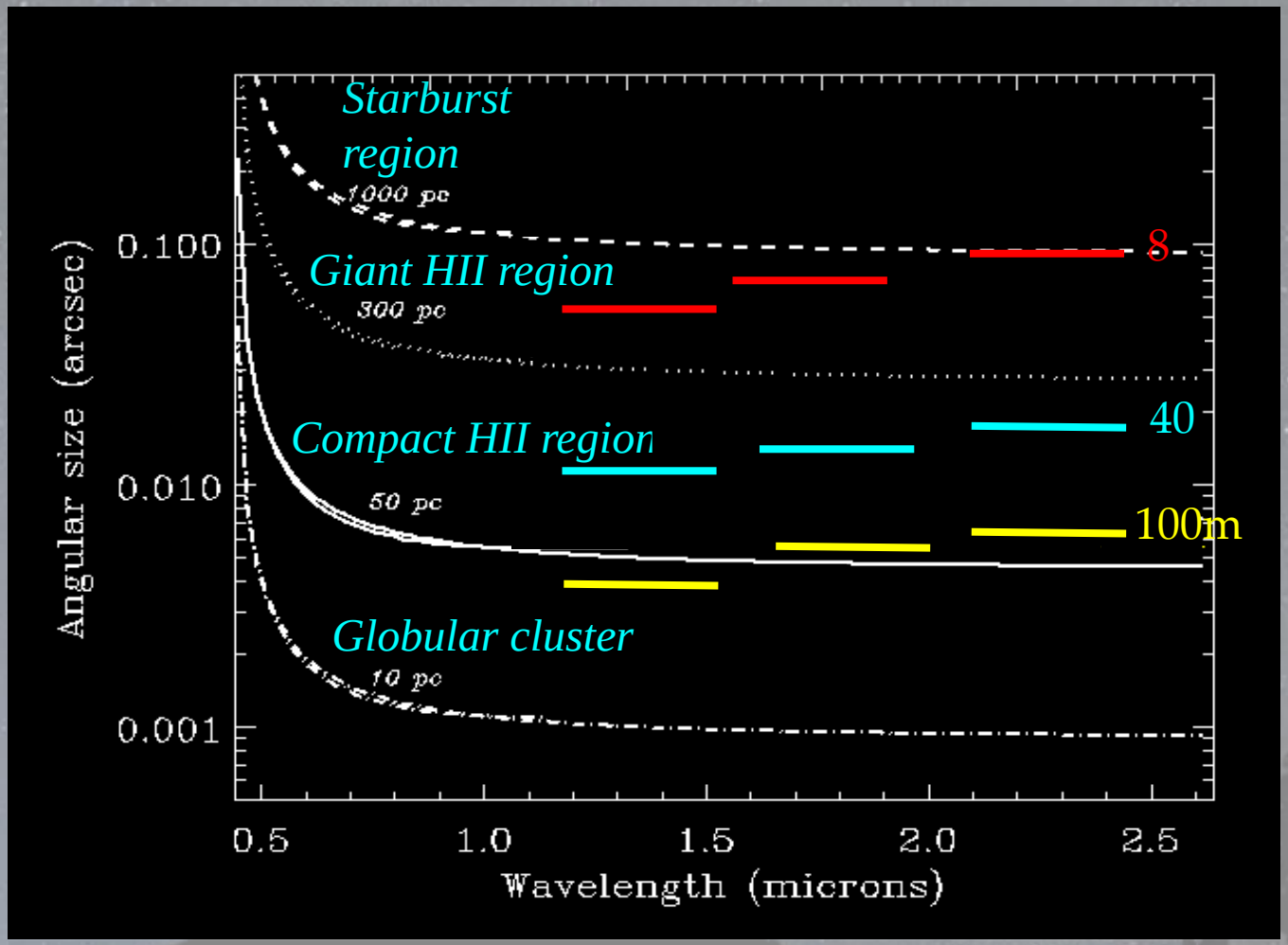
Credit: Phil Marshall

Really, really big telescopes

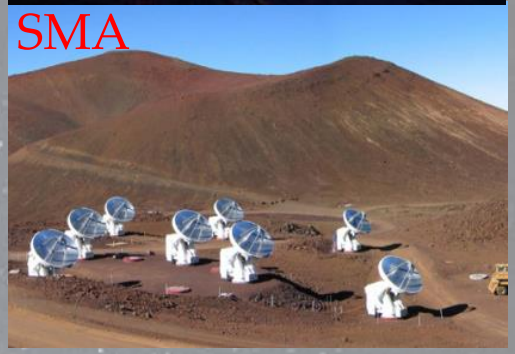


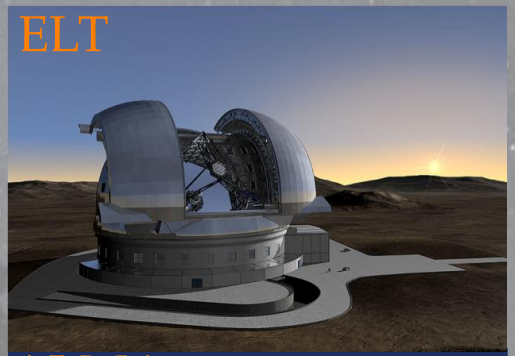
~ 10^{21}m

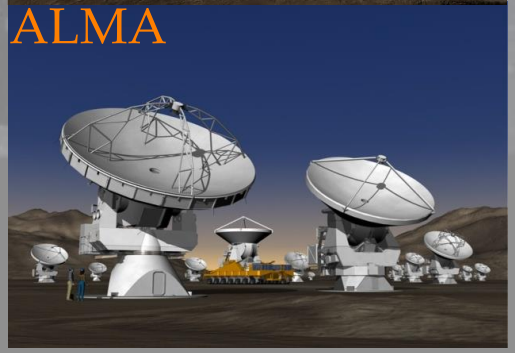
Boosts total flux AND spatial resolution


Starburst region
1000 pc
Giant HII region
300 pc
Compact HII region
50 pc
Globular cluster
10 pc
8
40
100m
0.100
0.010
0.001
Angular size (arcsec)
0.5
1.0
1.5
2.0
2.5
Wavelength (microns)


VLT

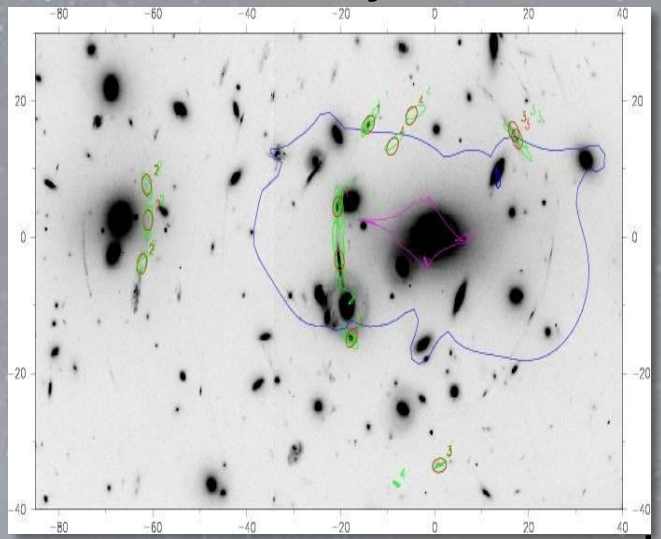

SMA

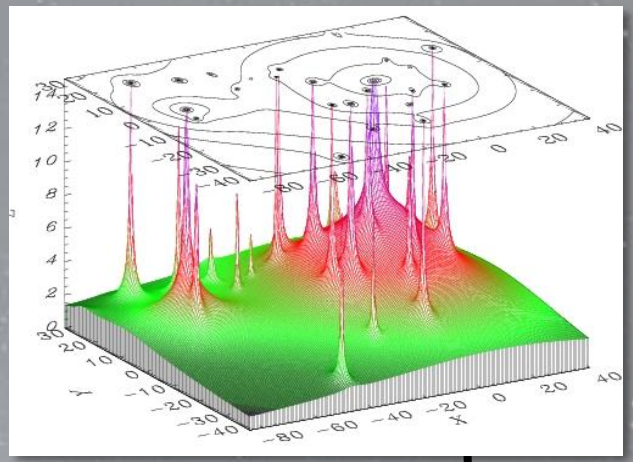

ELT


ALMA

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

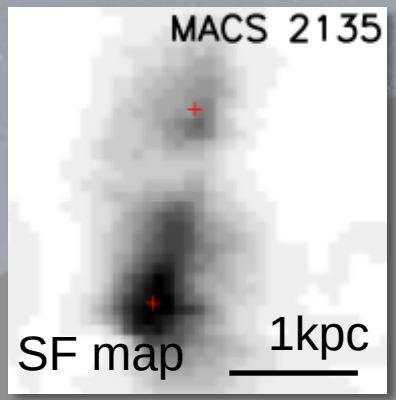
Original image → Galaxy Cluster → Lens model



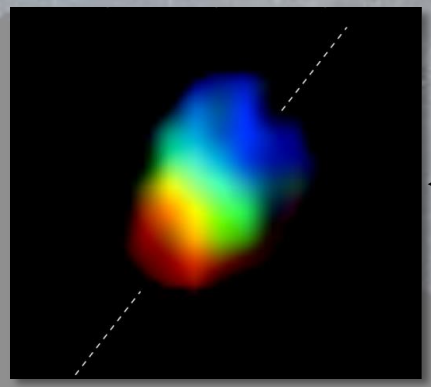


SF and dynamics maps with spatial scale of 100pc!

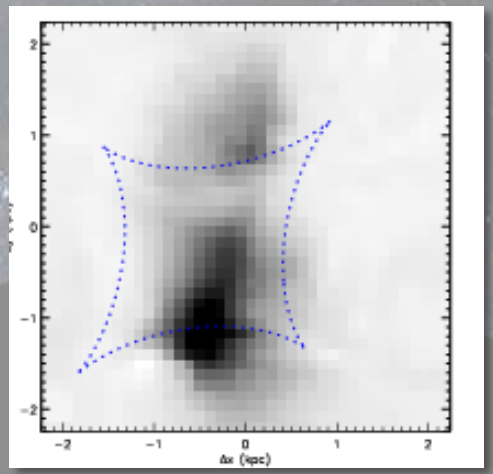
Unlensed Image



+

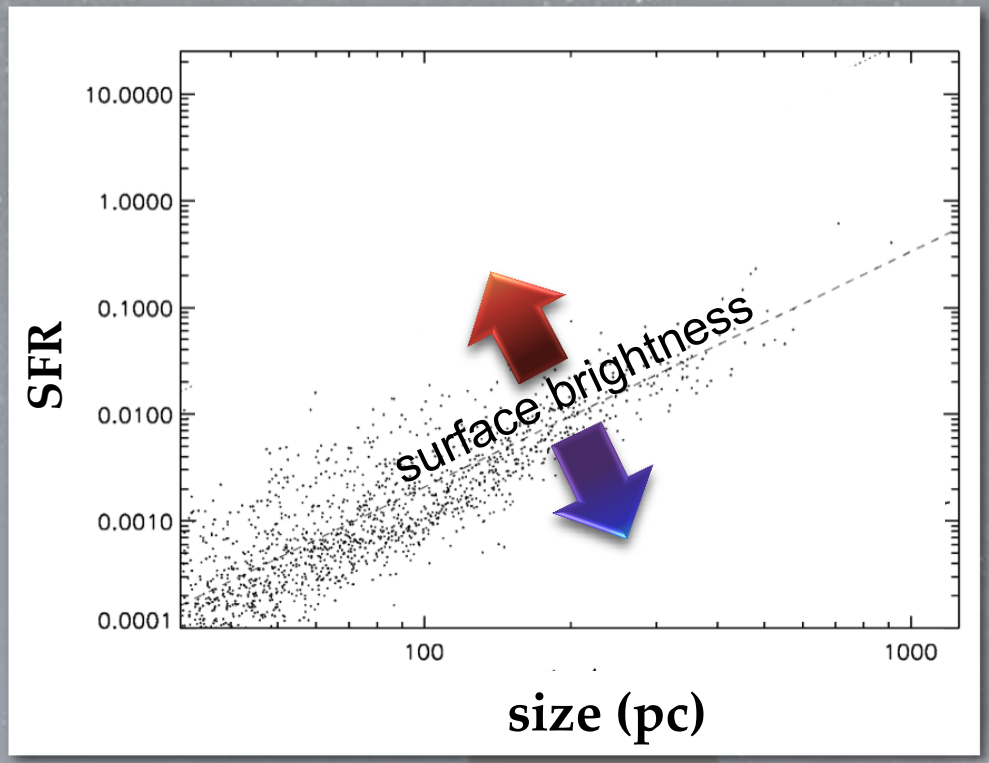


dynamics

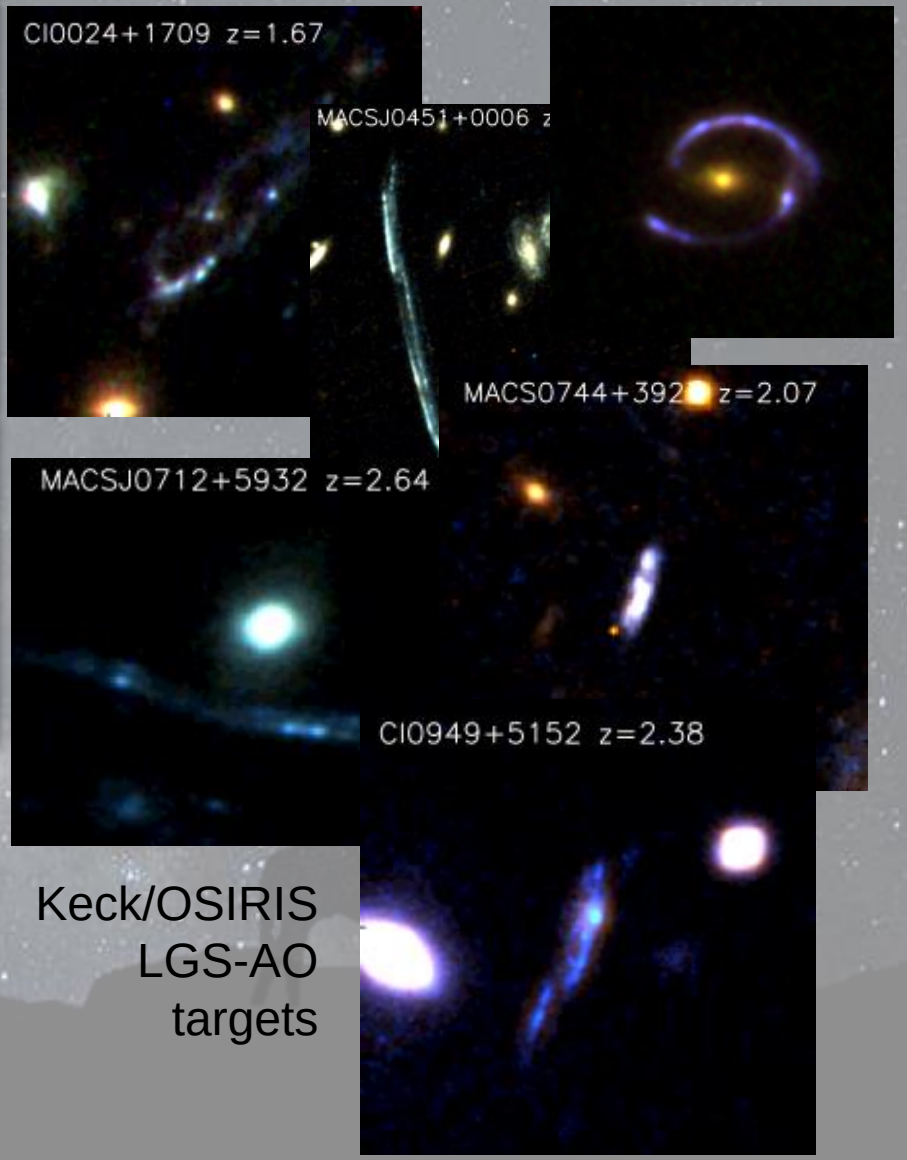


Stark et al. 2008

HII Regions

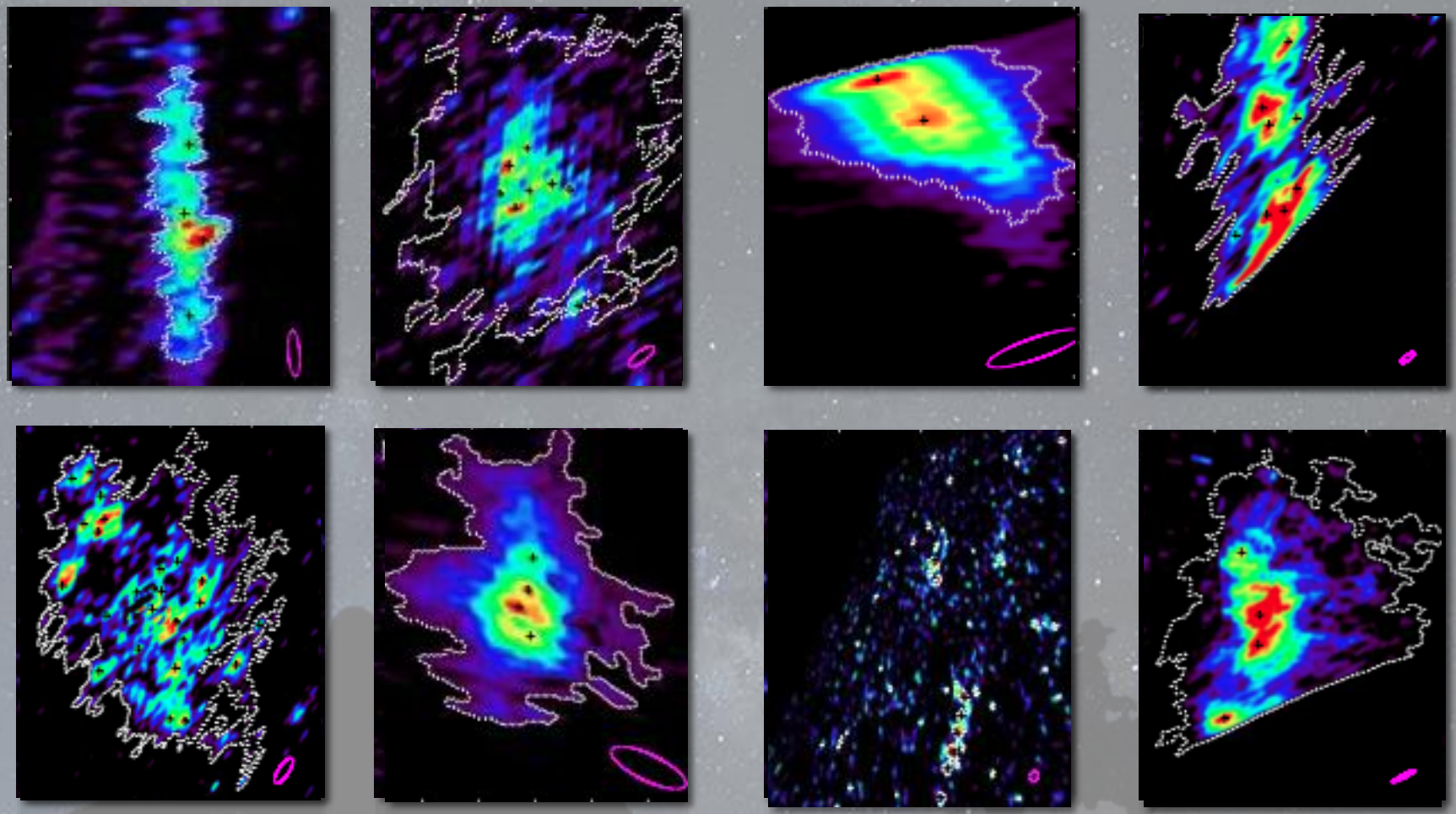


Jones et al. 2010



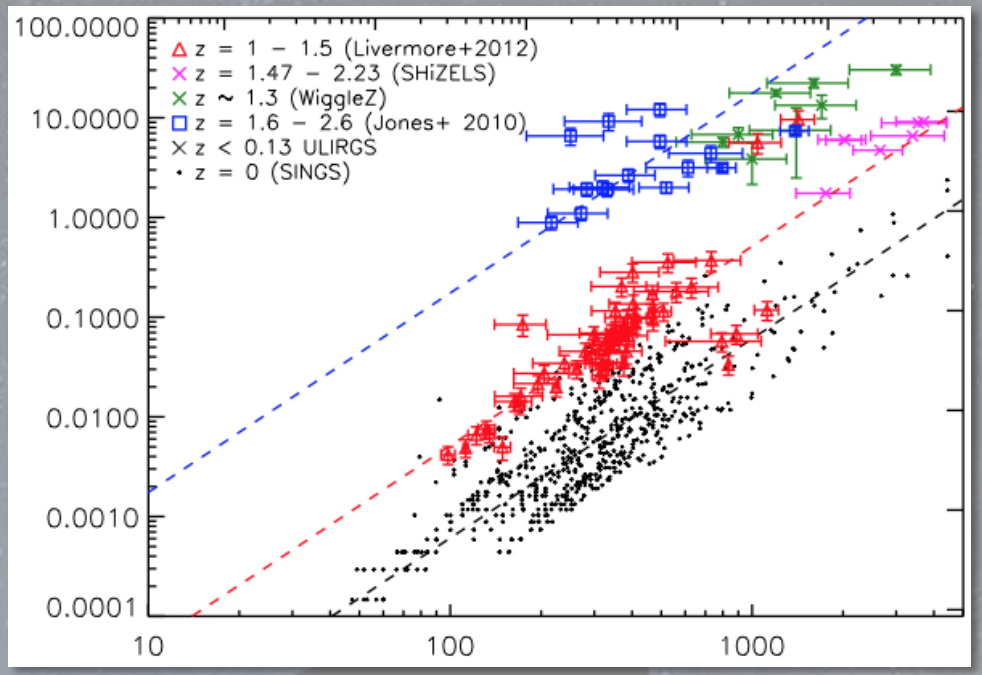
Keck/OSIRIS
LGS-AO
targets

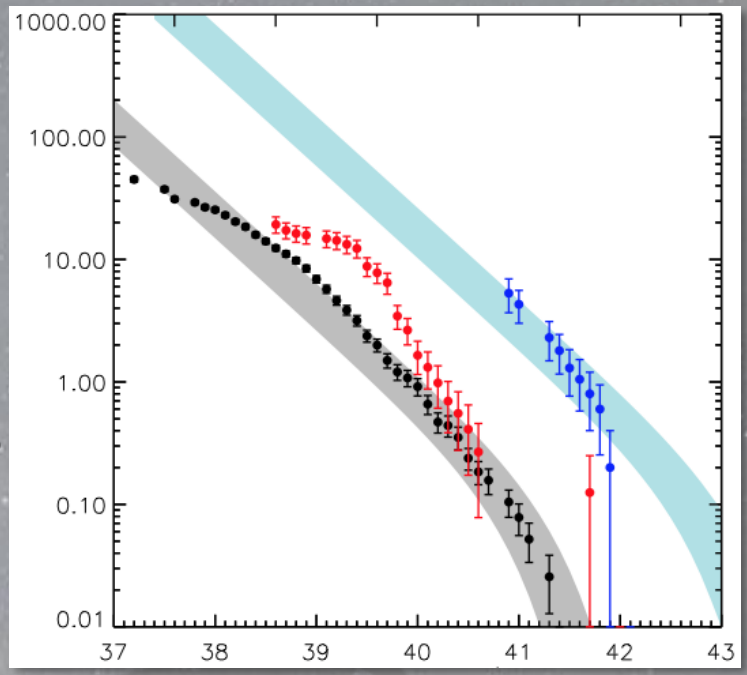
Hα narrowband imaging at 1 < z < 1.5



Livermore et al. 2012a

High-z HII Regions





Livermore et al. 2012a

What drives brighter clumps at high-z?

Toomre stability criterion:

mass surface density

$$Q=\kappa_r\sigma/\pi G\Sigma$$

$1.5V_{max}/R$

Q < 1 ⟶ fragmentation

In a marginally stable disk (Q=1), the Jeans mass is:

$$M_0 \sim \Sigma^3 \kappa^{-4}$$

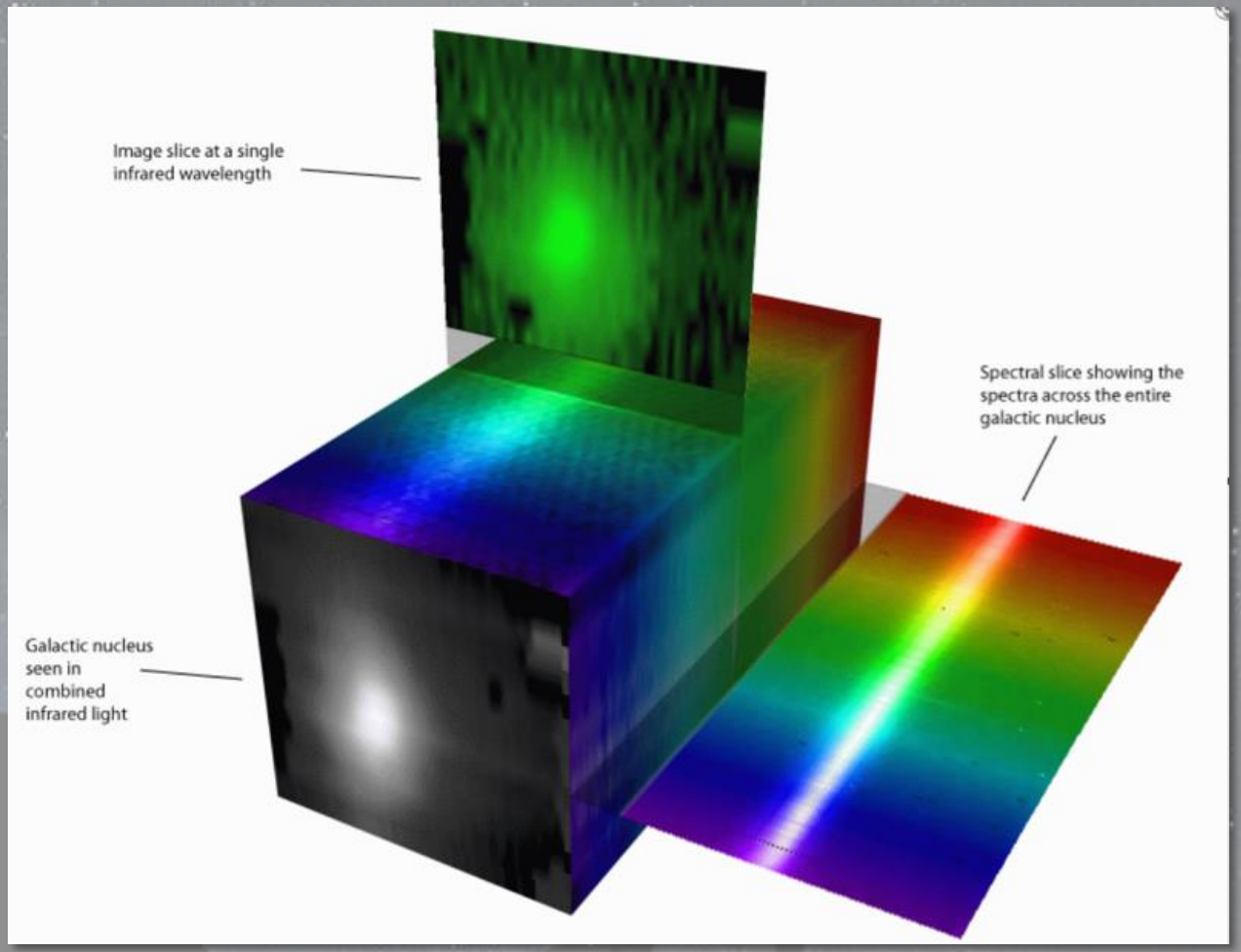
dominated by gas component

→ Drivers of star formation at high-z are gas fraction and dynamics

Integral Field Spectroscopy

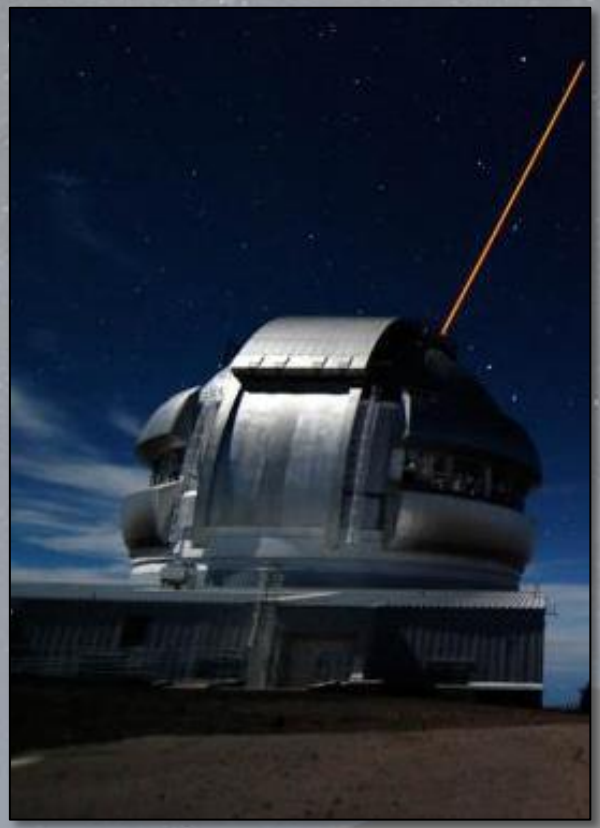
- At every wavelength you get an image

- At every pixel you get a spectrum

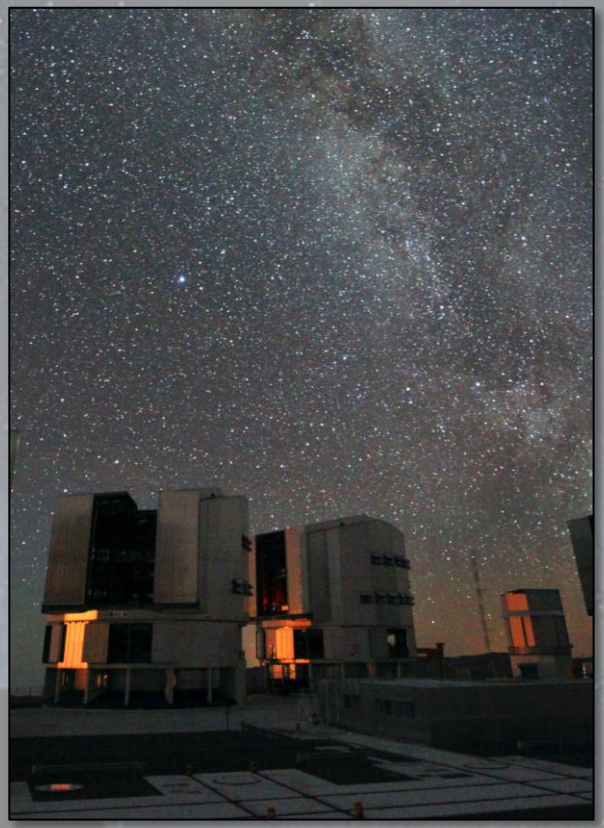


Credit:ESO

Integral Field Units



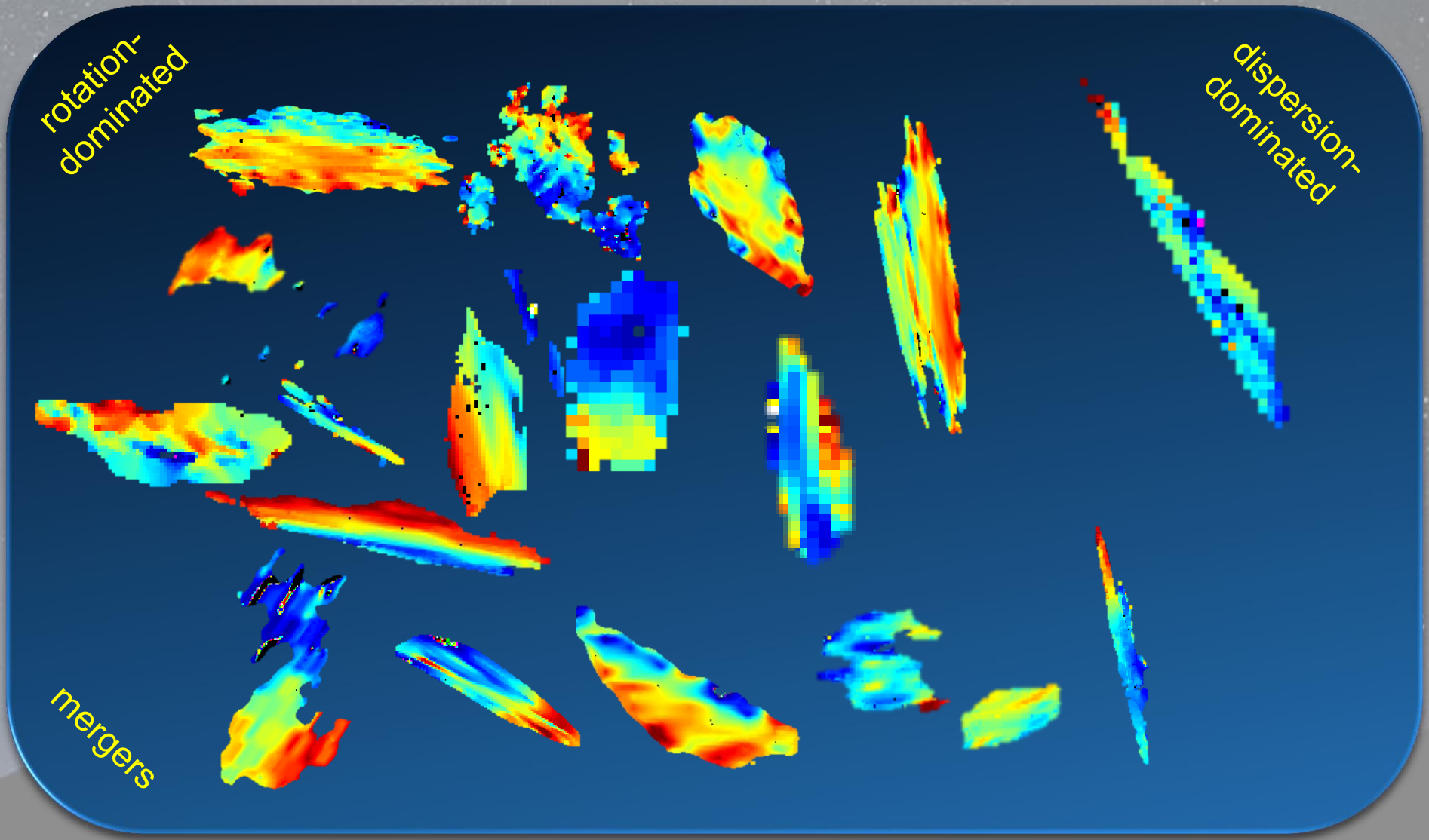
NIFS



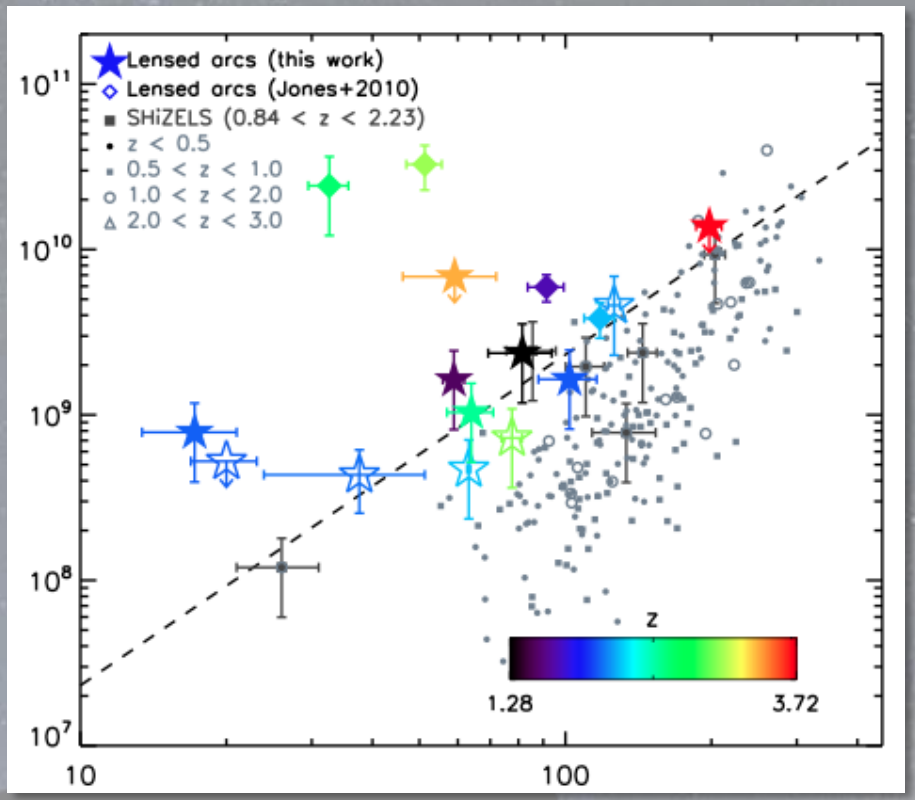
SINFONI

OSIRIS

Galaxy dynamics at z = 1-4



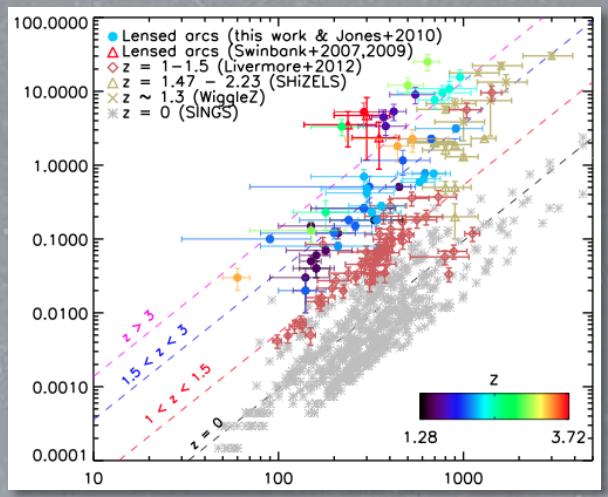
The Tully-Fisher Relation



No (coherent) evidence for evolution with redshift

Dynamics dominated by baryons

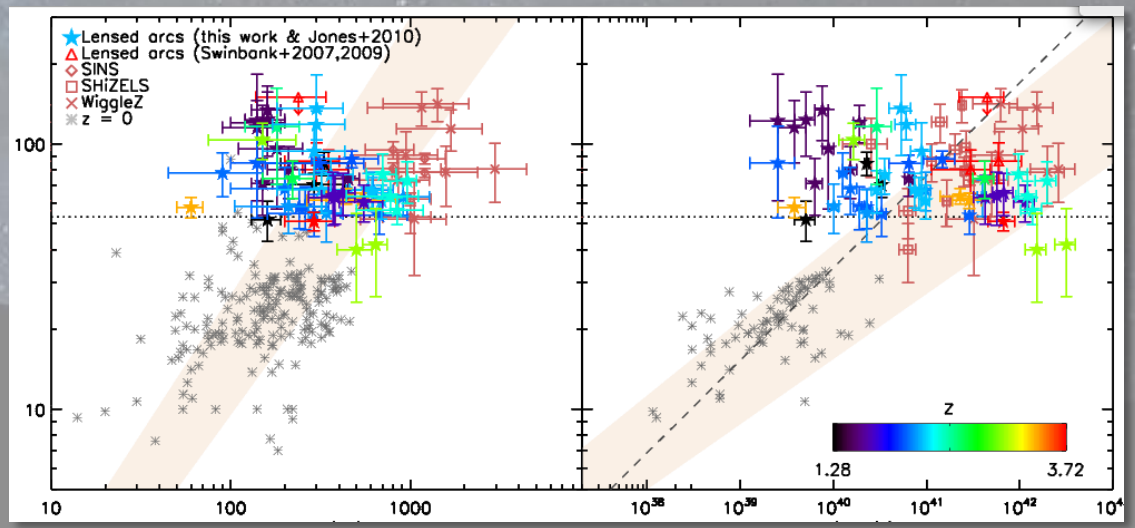
Clumps in the IFU sample



SFR

radius (pc)

Evolution in surface brightness continues to higher-z

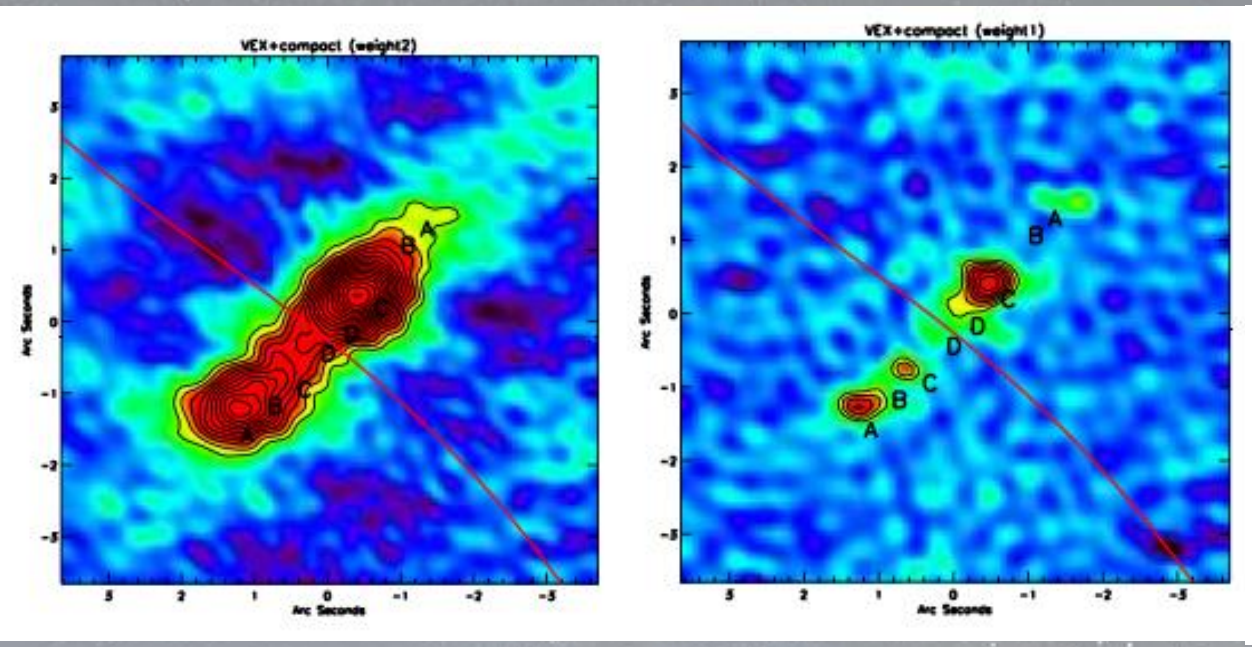


Velocity dispersion (km/s)

radius (pc)

$L_{H\alpha}$ (erg/s)

Clumps in the sub-mm: The Eyelash



3x brighter than any other SMG

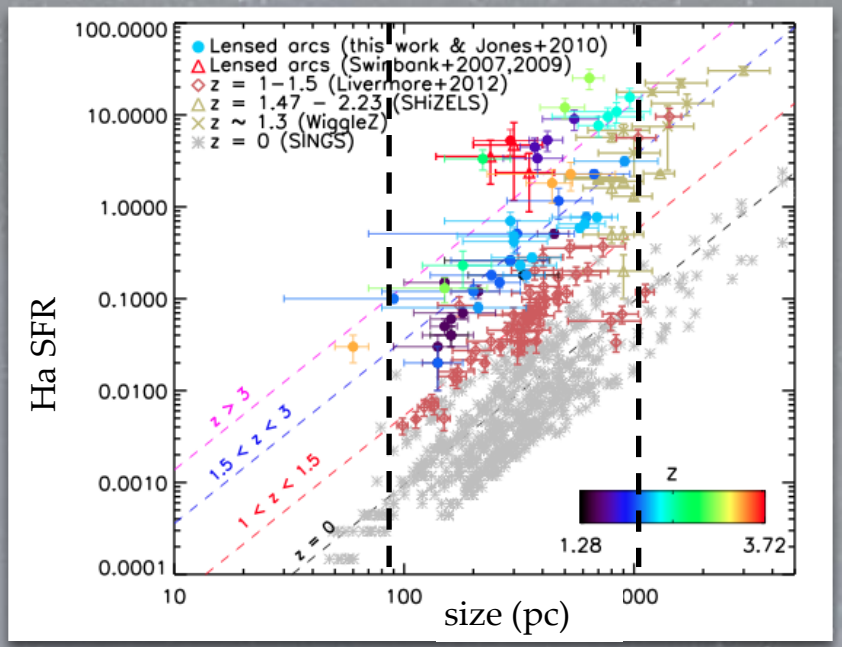
Observed with the Smithsonian Sub-mm Array (SMA) at 3 configurations: compact (1.5″), Extended (0.7″), Very Extended (VEX; 0.2″)

In highest configuration, beam is 0.2″ (90-150pc).

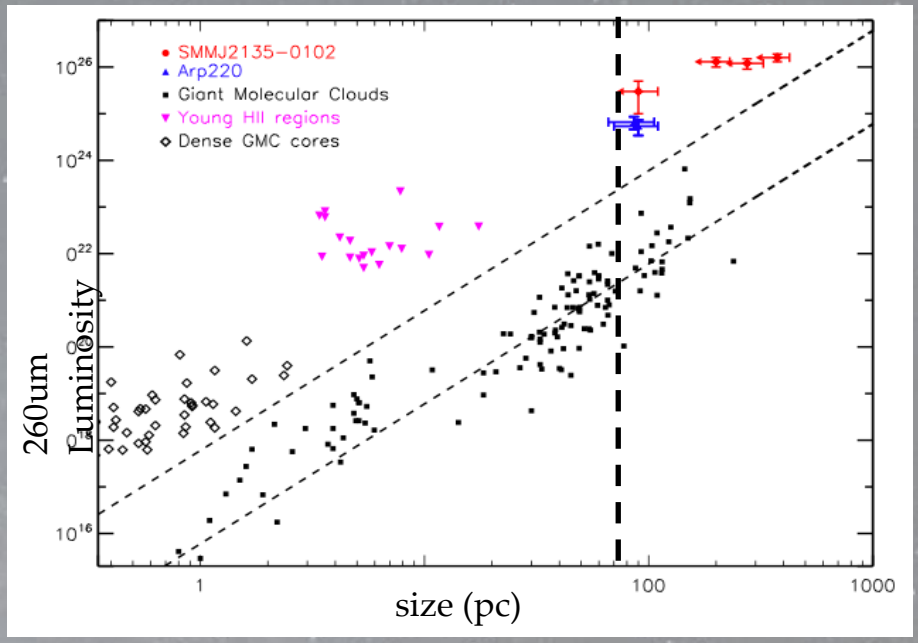
Swinbank et al. 2011

Intense Star-Formation Within Compact Regions at z=2-5

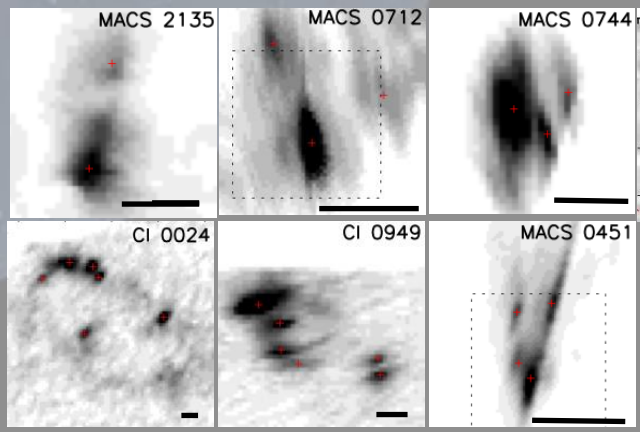
Nebular Emission Lines



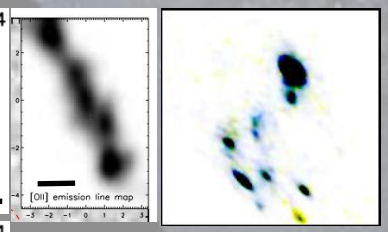
Sub-mm emission



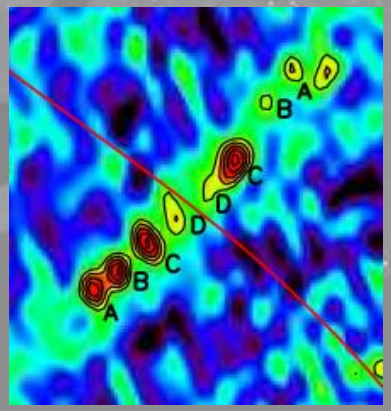
z=2-3 Lensed LBGs



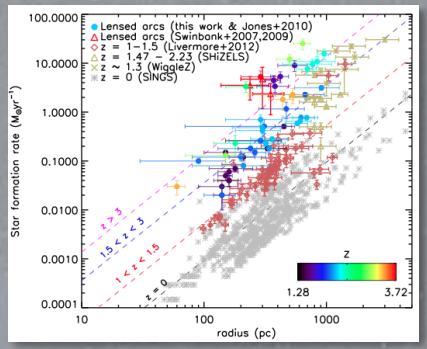
z=5

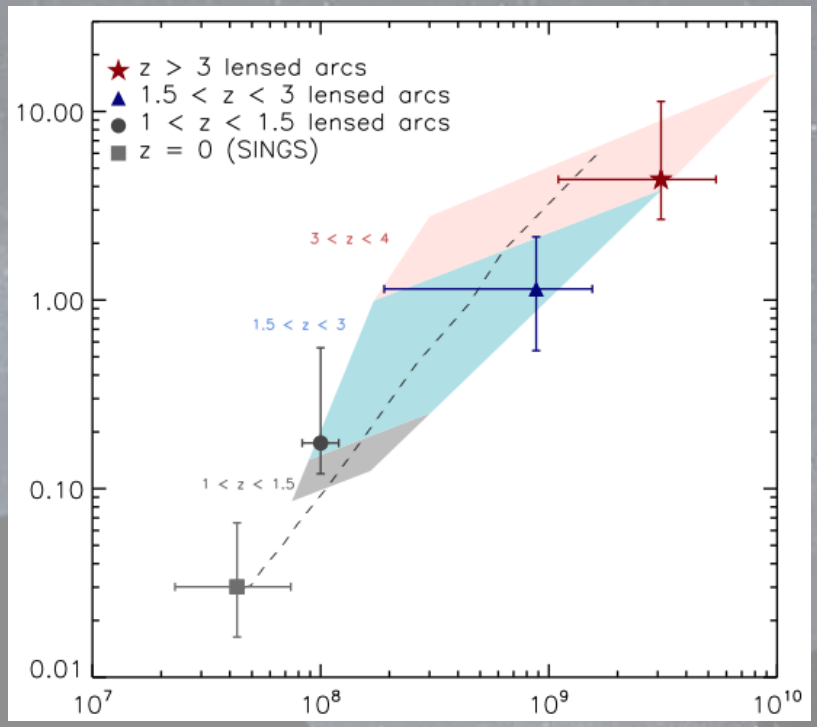


z=2.3 Lensed Sub-mm Galaxy



Clump evolution



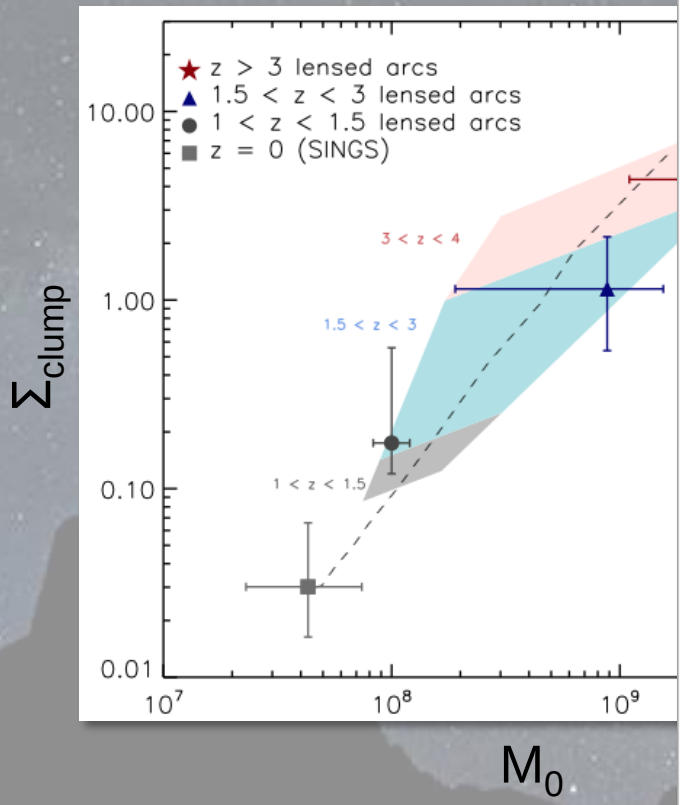


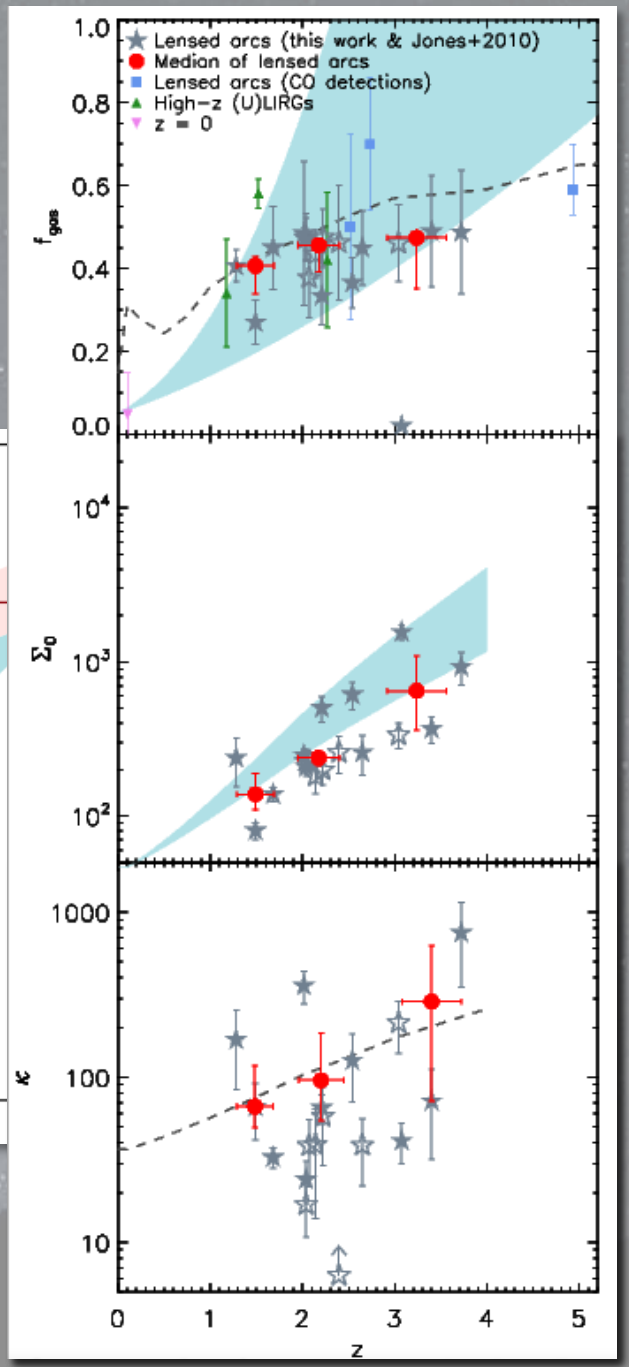
Σ_{clump}

M_0

$$M_0 \sim \Sigma^3 \kappa^{-4}$$

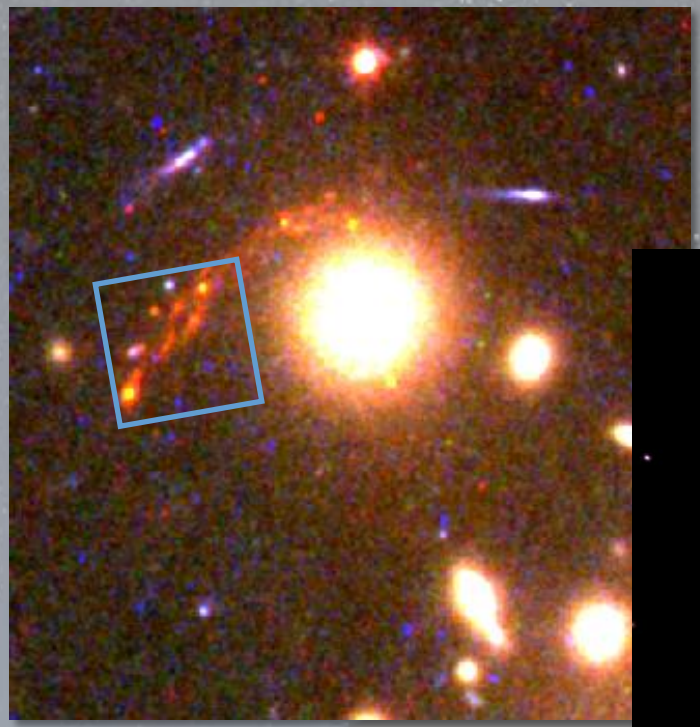
Clump evolution





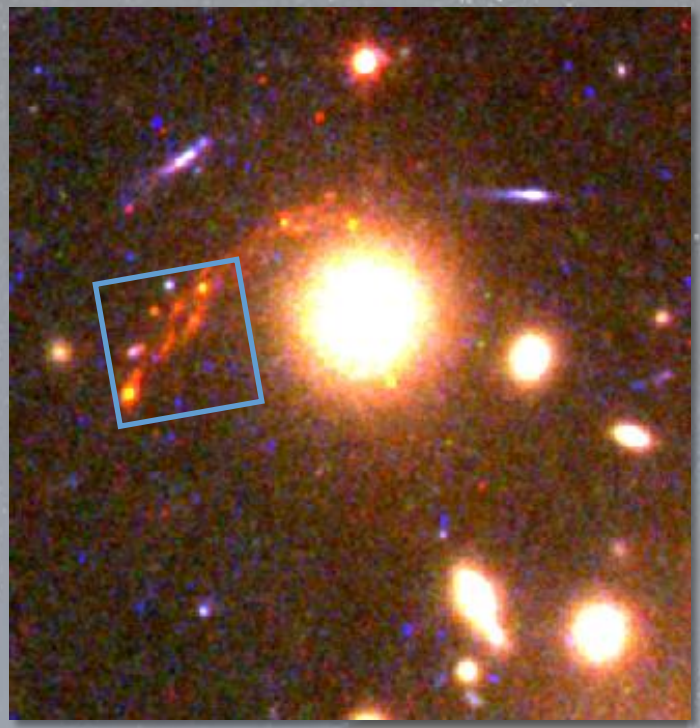
MS1358: a lensed galaxy at z=5

HST ACS BVI composite

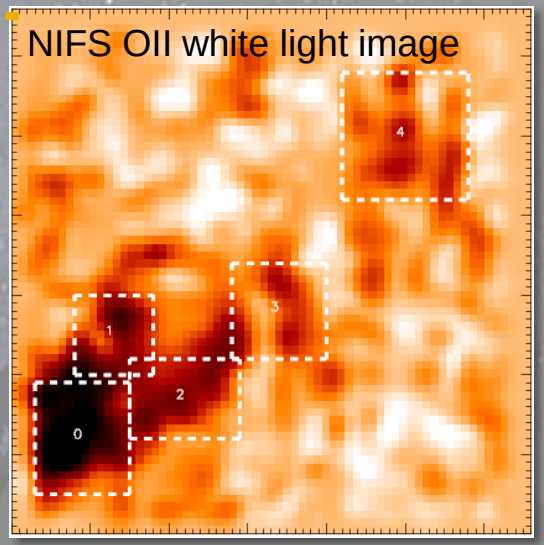


MS1358: a lensed galaxy at z=5

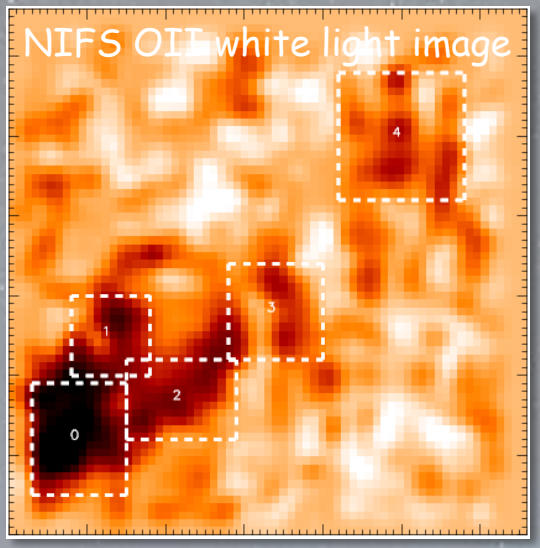
HST ACS BVI composite



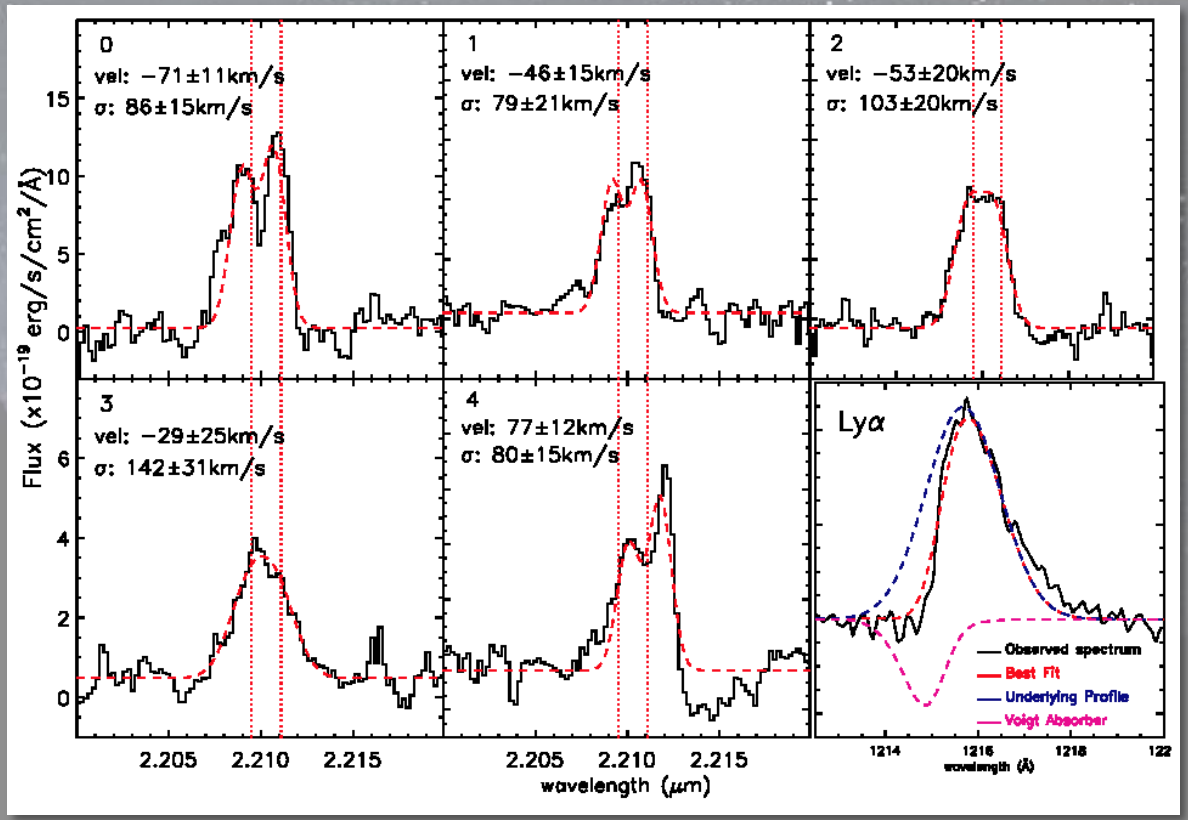
NICMOS JH



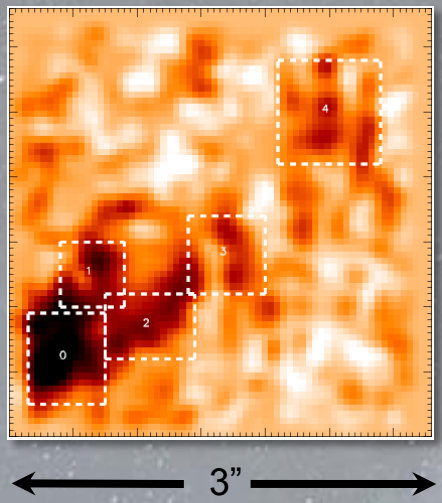
MS1358: a lensed galaxy at z=5

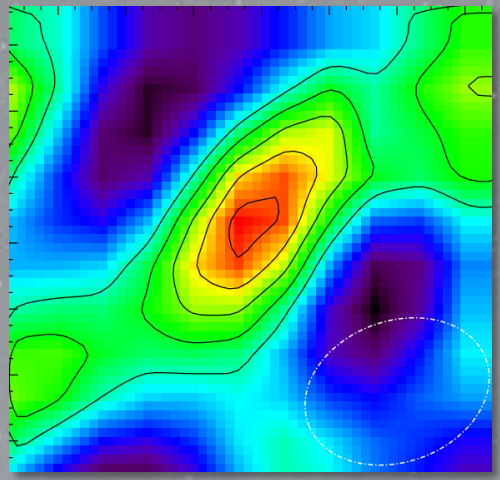


Swinbank et al. (2009)



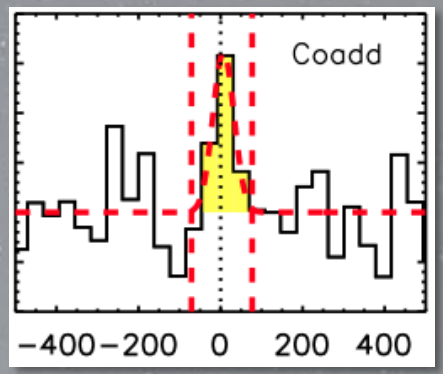
Molecular gas at z=5

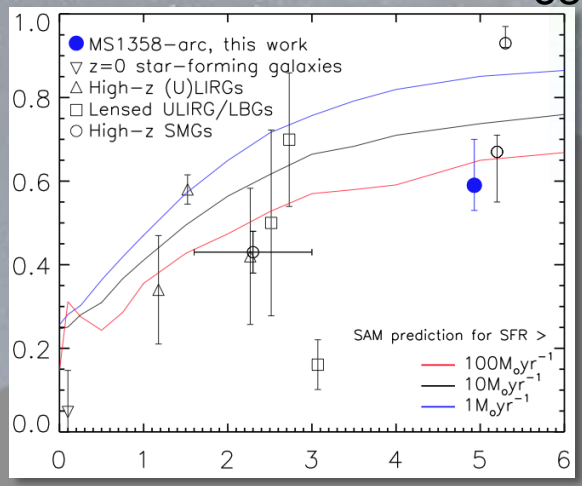


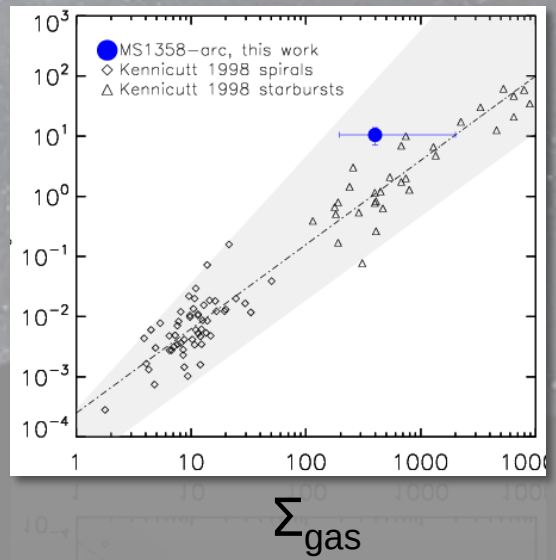


PdBI CO(5-4)
coadded channel map

Livermore et al. 2012b







Conclusions

- Gravitational lensing allows us to probe z > 1 galaxies on 100pc scales and resolve individual HII regions.
- In a sample of 17 lensed z = 1-4 galaxies, all have observable (if small) velocity gradients
- Large, bright clumps are seen in high-z galaxies…
- …possibly due to high gas fractions