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?

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

Ceverino et al. 2011
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
Really, really big telescopes

- Boosts total flux AND spatial resolution

- $\sim 10^{21} \text{m}$
Starburst region

Giant HII region

Compact HII region

Globular cluster

Angular size (arcsec)

Wavelength (microns)
Example: Mass modelling and source plane reconstruction of $z=3$ galaxy

Original image $\rightarrow$ Galaxy Cluster $\rightarrow$ Lens model

SF and dynamics maps with spatial scale of 100pc!

Unlensed Image

SF map $\rightarrow$ 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:

\[ Q = \frac{\kappa r \sigma}{\pi G \Sigma} \]

\[ 1.5 V_{\text{max}}/R \]

\[ Q < 1 \quad \rightarrow \quad \text{fragmentation} \]

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

\[ M_0 \sim \Sigma^3 \kappa^{-4} \]

dominated by gas component

\[ \rightarrow \text{Drivers of star formation at high-z are gas fraction and dynamics} \]
Integral Field Spectroscopy

- At every wavelength you get an image

- At every pixel you get a spectrum
Integral Field Units

NIFS
SINFONI
OSIRIS
Galaxy dynamics at $z = 1-4$
The Tully-Fisher Relation

![Graph showing the Tully-Fisher relation with marked values for different redshift ranges.]

- No (coherent) evidence for evolution with redshift
- Dynamics dominated by baryons
Clumps in the IFU sample

Evolution in surface brightness continues to higher-\( z \)
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

\[ M_0 \sim \Sigma^3 \kappa^{-4} \]
Clump evolution

![Graph showing clump evolution with parameters $M_0$ and $\Sigma_{\text{clump}}$.](image)
MS1358: a lensed galaxy at $z=5$
MS1358: a lensed galaxy at $z=5$
MS1358: a lensed galaxy at z=5

Swinbank et al. (2009)
Molecular gas at z=5

Livermore et al. 2012b

PdBI CO(5-4) coadded channel map

Gas fraction vs. z

ΣSFR vs. Σgas

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 $z = 1\text{-}4$ galaxies, all have observable (if small) velocity gradients.

- Large, bright clumps are seen in high-$z$ galaxies…

- …possibly due to high gas fractions.