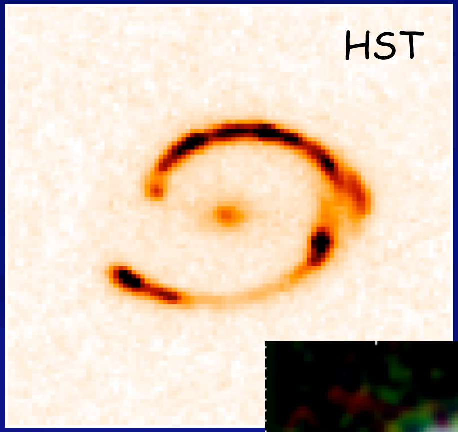
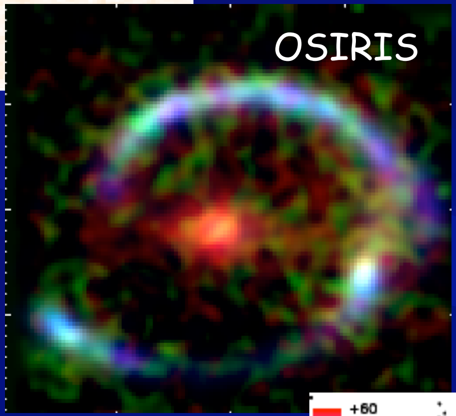
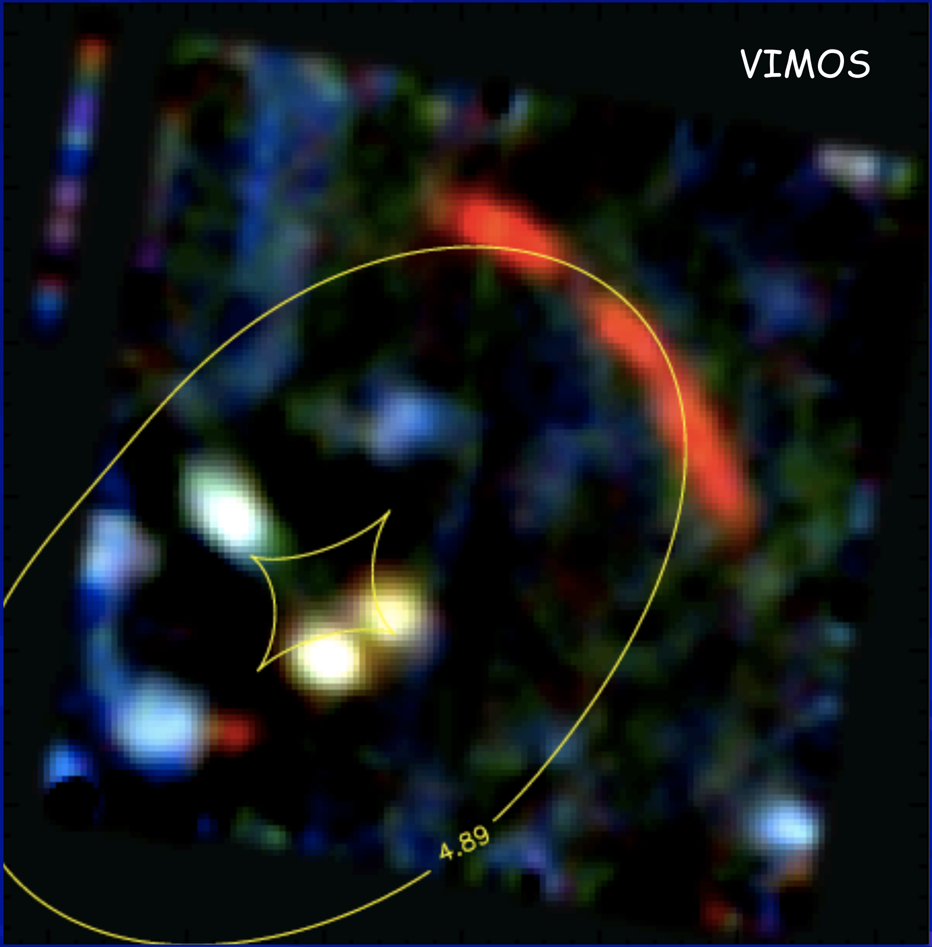
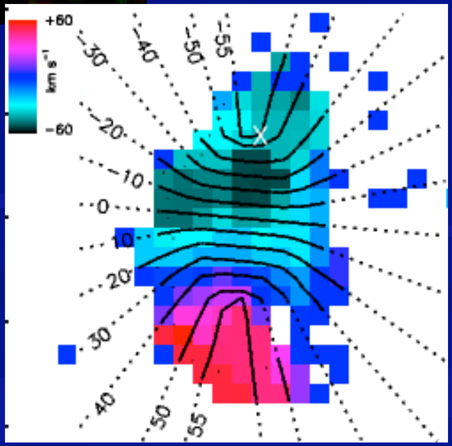
Galaxies Under the Cosmic Microscope: A Preview to ELT and ALMA science









Mark Swinbank

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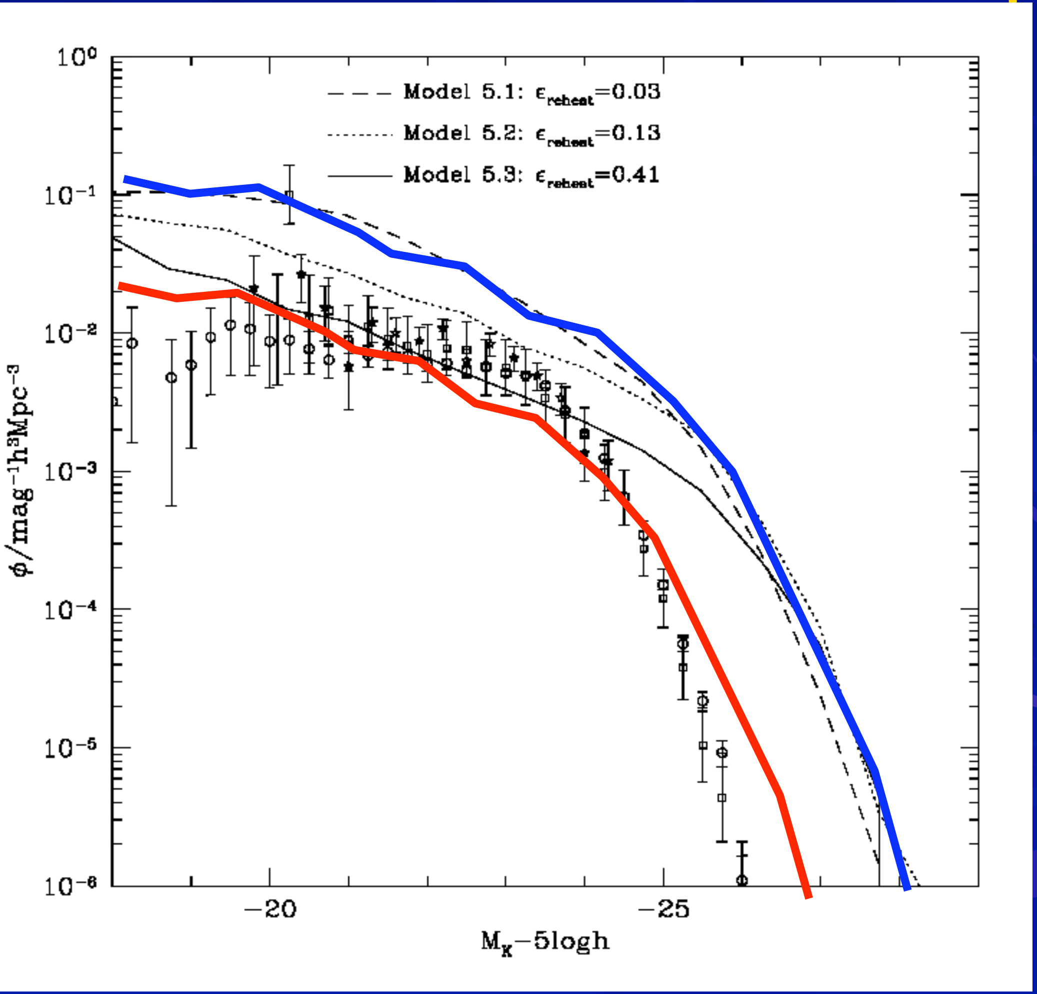
Understanding Galaxy Evolution

How did the galaxies in the local Universe form and evolve?

Galaxy formation is a complex process:

- cold diffuse gas inside dark matter halo
- gas heated by gravitational collapse
- cooling via X-ray emission
- condensing of gas into stars forming a disk which is supported by angular momentum
- feedback by stellar winds and supernova
- merging of galaxies to build up halo and stellar mass

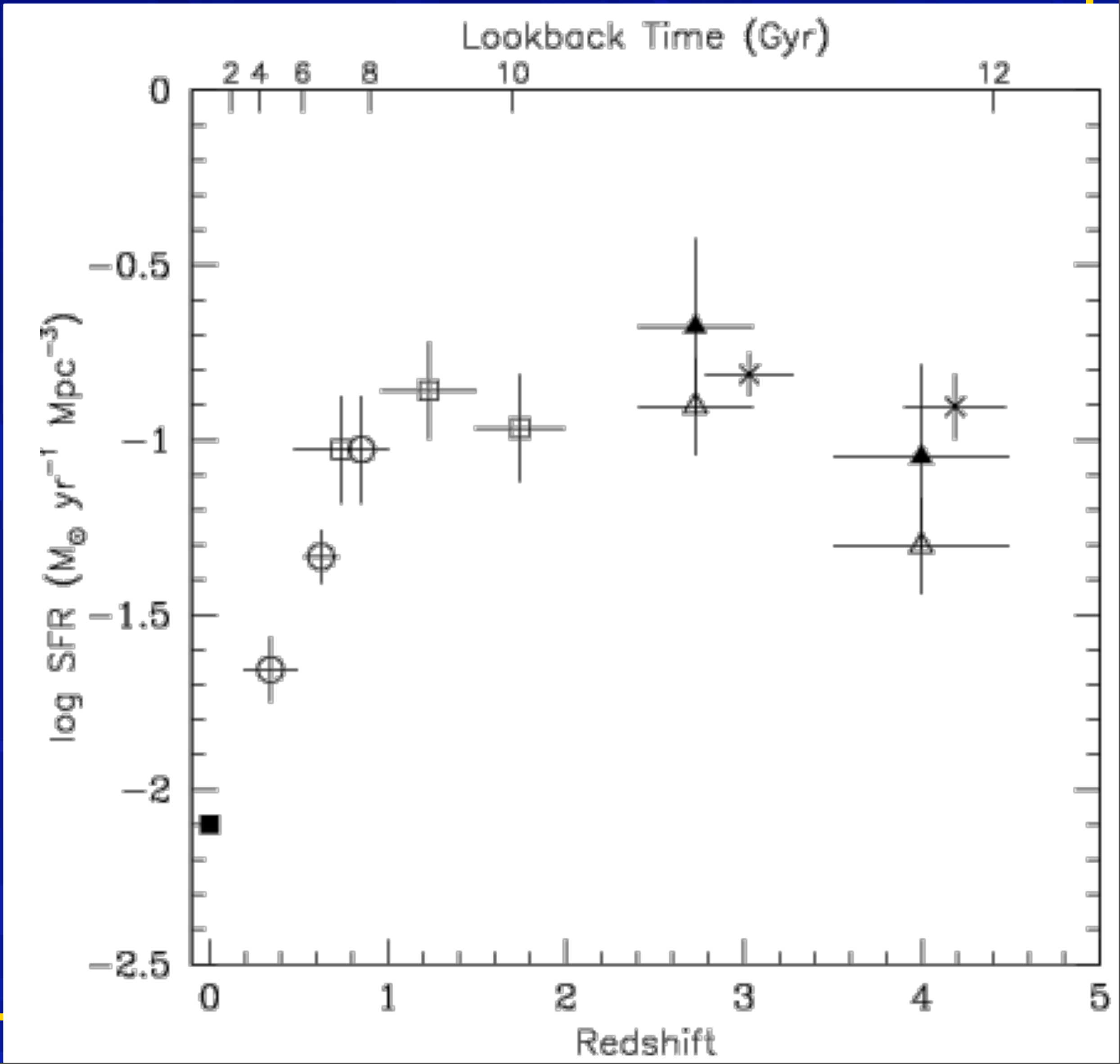


Epoch of galaxy formation

- Redshift surveys have shown that galaxy formation was much more efficient at high-z

- Most of todays "normal" galaxies were being assembled at z=1-5

- What are the properties of galaxies at these early times:
- Dynamical states?
- Distribution of SF? (clump sizes, bars, instabilities)
- Gas Masses, SFEs?
- Gas dynamics?
- Interaction between SF and gas dynamics?
- Chemical Abundances?



What we need is a way to spatially resolve distant galaxies.

…then we could figure out the dynamics, distribution of SF, scale, energy and mass involved in outflows

Key Questions:

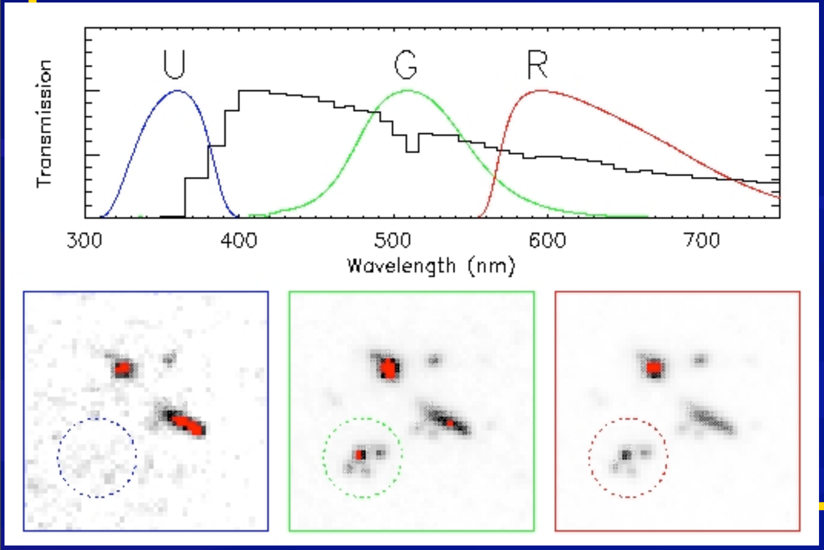
- What are dynamics? v_{rot}, σ, M/L ratio?
- Do galaxies form inside out or outside in?
- How much energy & mass do the super-winds have?
- Will outflows escape the galaxy? How far do they travel?

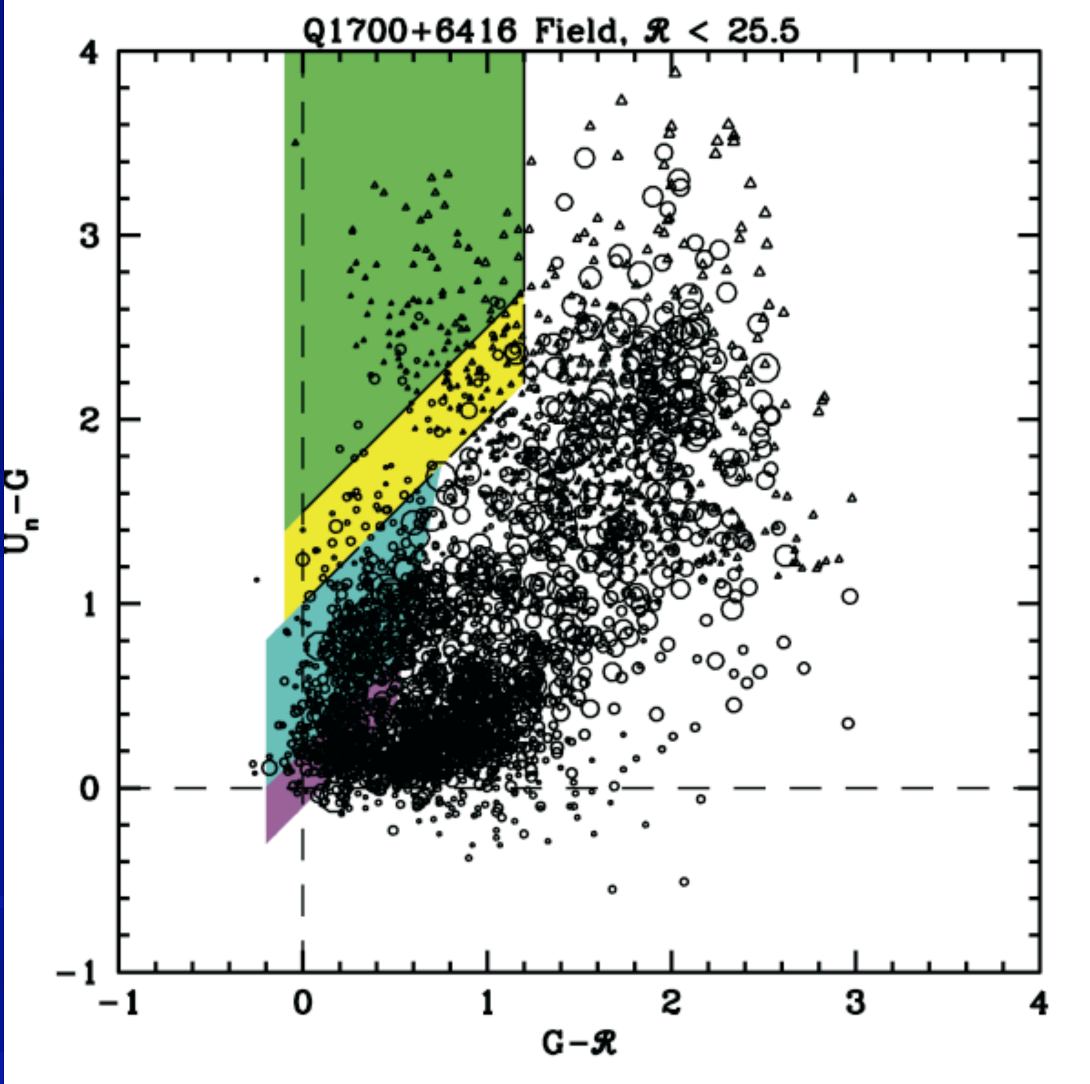
But, the sizes and flux scales involved make it incredibly difficult to spatially resolve the dynamics and SF properties of star-forming galaxies at high-z.

Identifying high-redshift galaxy populations

- Significant population of “normal” galaxies at z~3 identified are LBGs.

- Actively SF, low dust, dynamical/stellar masses and chemical properties expected for local spirals/spheroidals



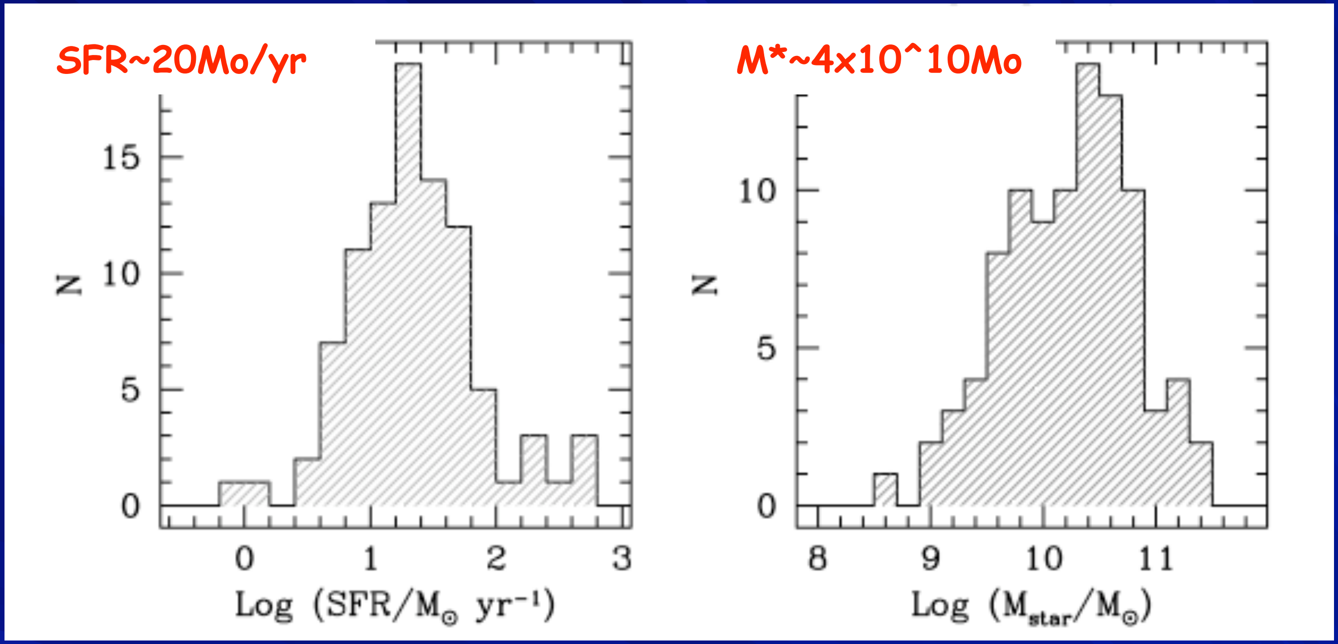


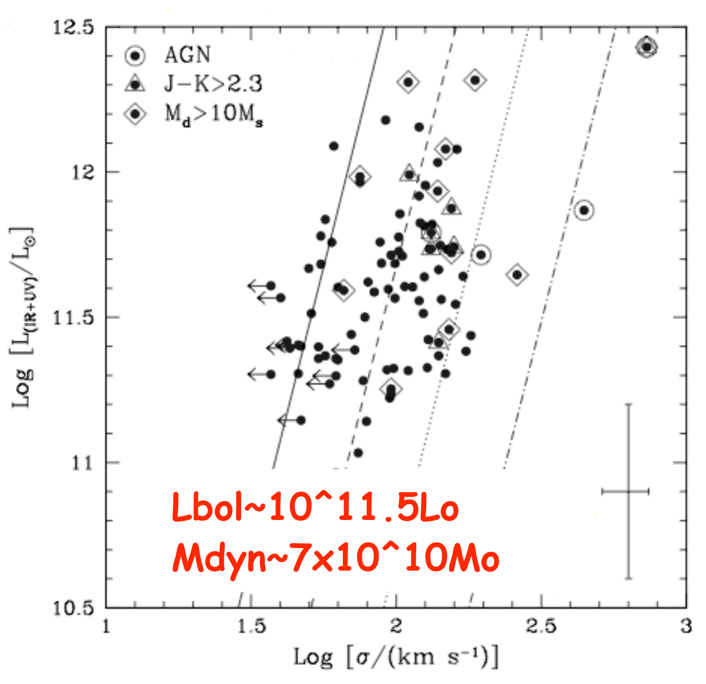
Identifying high-redshift galaxy populations

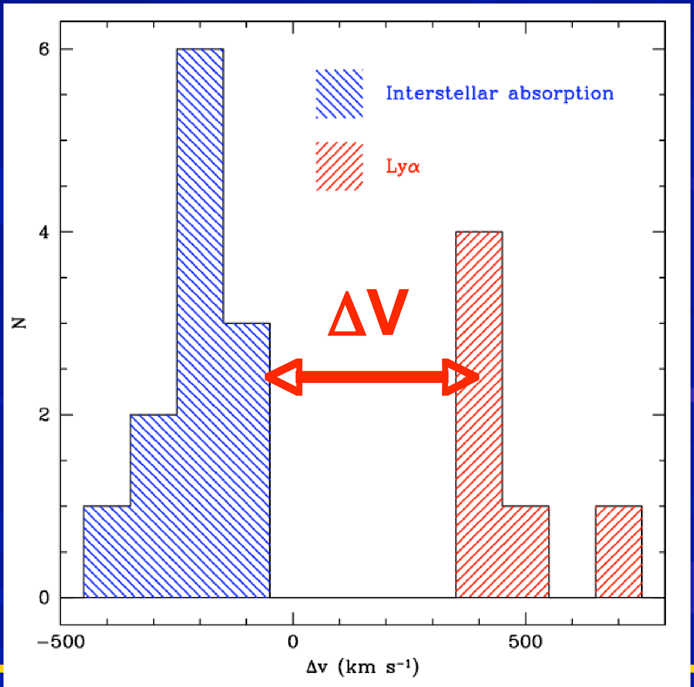
- Actively SF, low dust, dynamical/ stellar masses, chemical properties and space densities expected for local spirals/spheroidals

- Responsible for ~30-40% of the cosmic SF history between z=2-3

e.g. Shapley et al. 2003, 2006, Erb et al. 2004

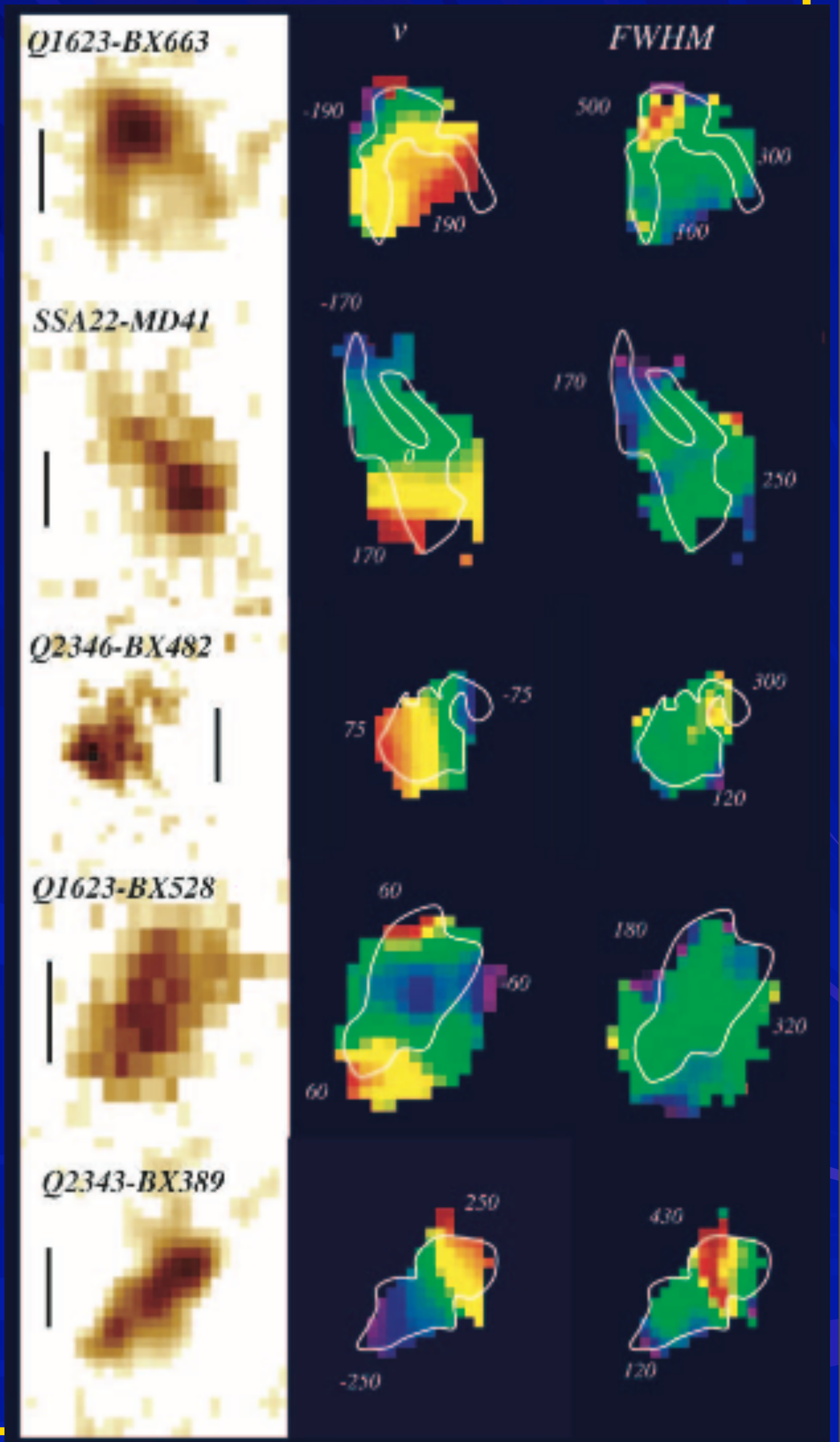


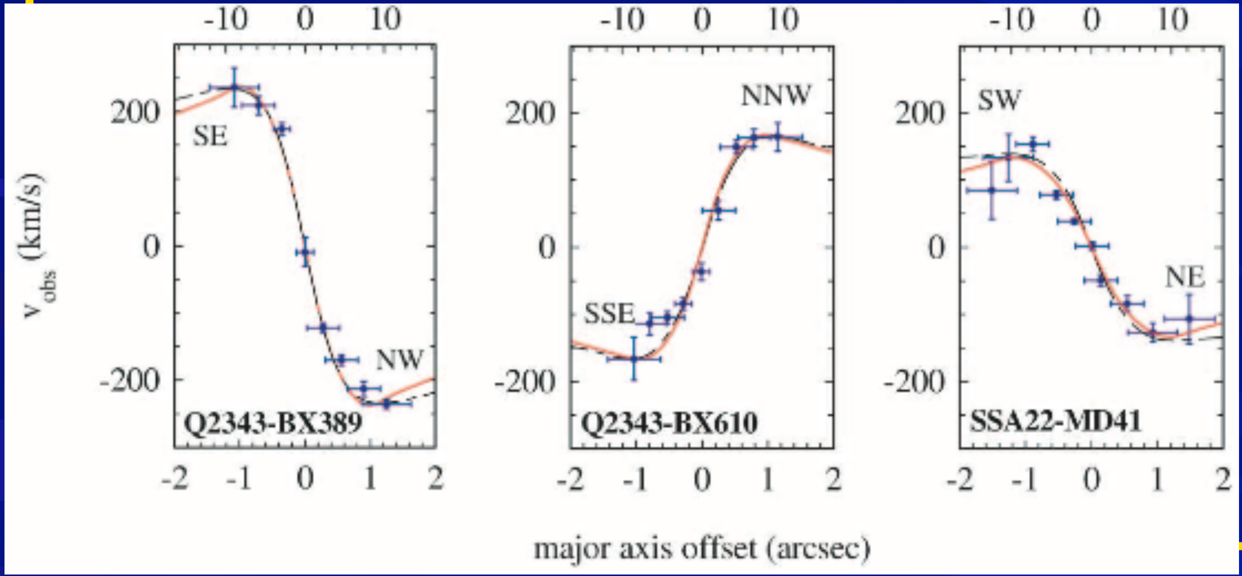




Detailed Studies of high-z galaxies

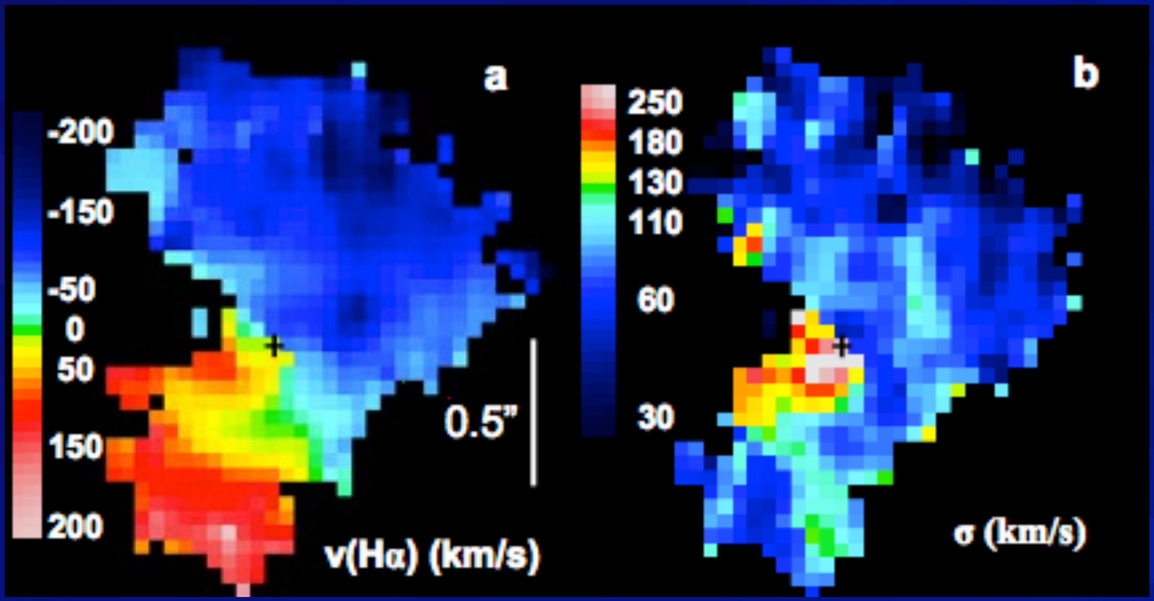
Forster-Schreiber et al. (2006) studied 14 LBGs with SINFONI and found rotation on ~4kpc scales in 3 galaxies and velocity shears in 9/14

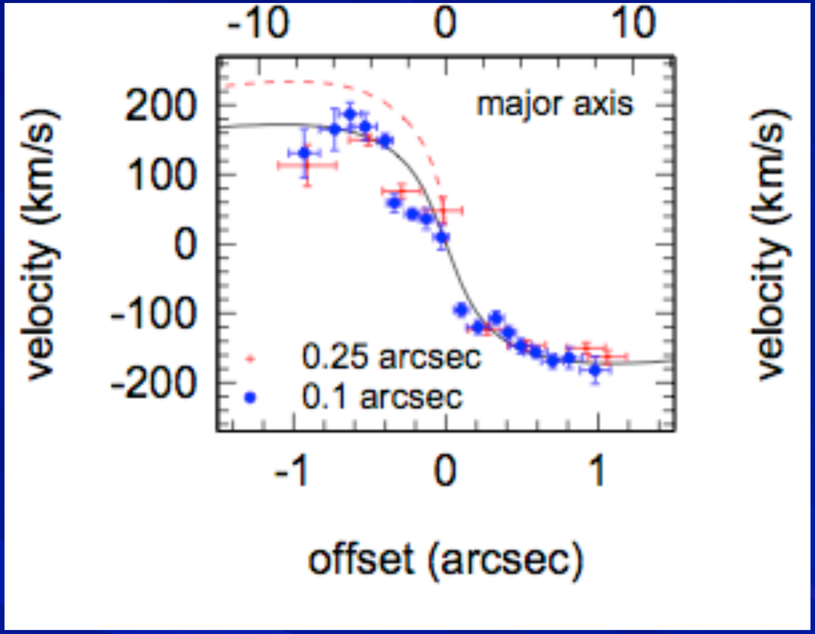




Very Detailed Studies

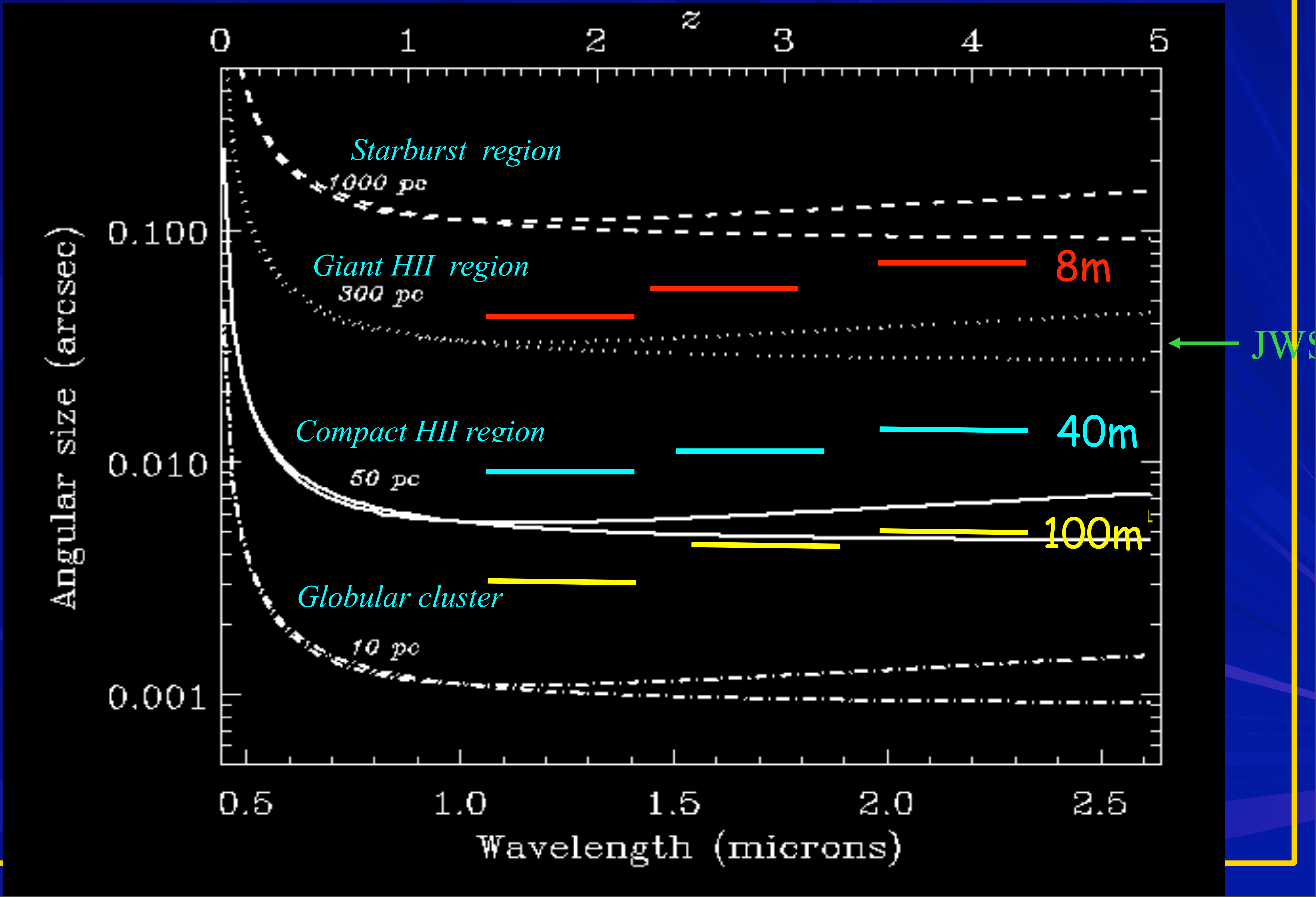
Most studies have mapped the demographics of the population as a whole. What is needed is detailed studies of indivual galaxies





Genzel et al. 2006 studied unusually large object at z=3 on ~1kpc (0.1") scales and found evidence for rotation.

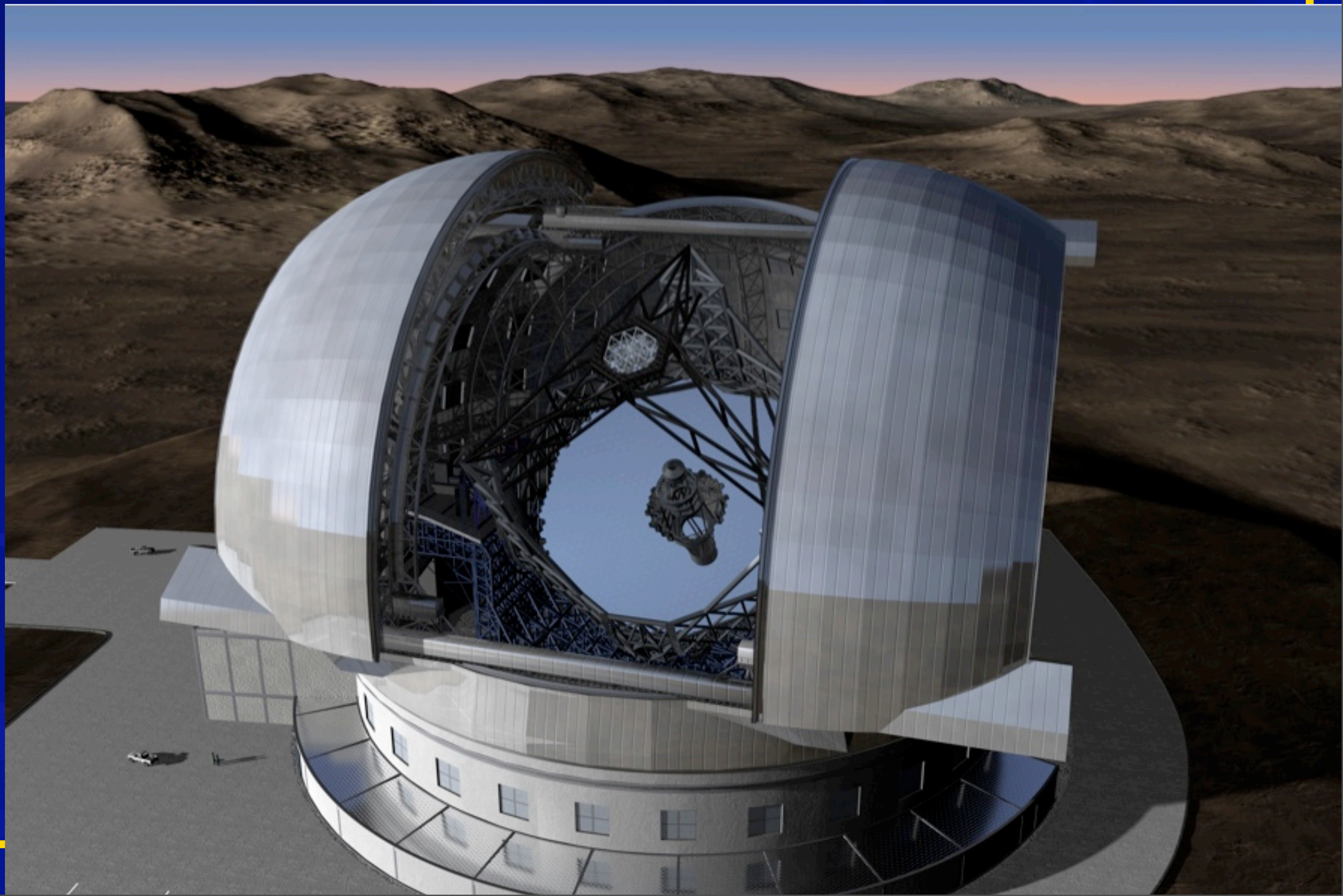
Near-IR Diffraction limits



Observing Galaxies in the Distant Universe

The Problem:

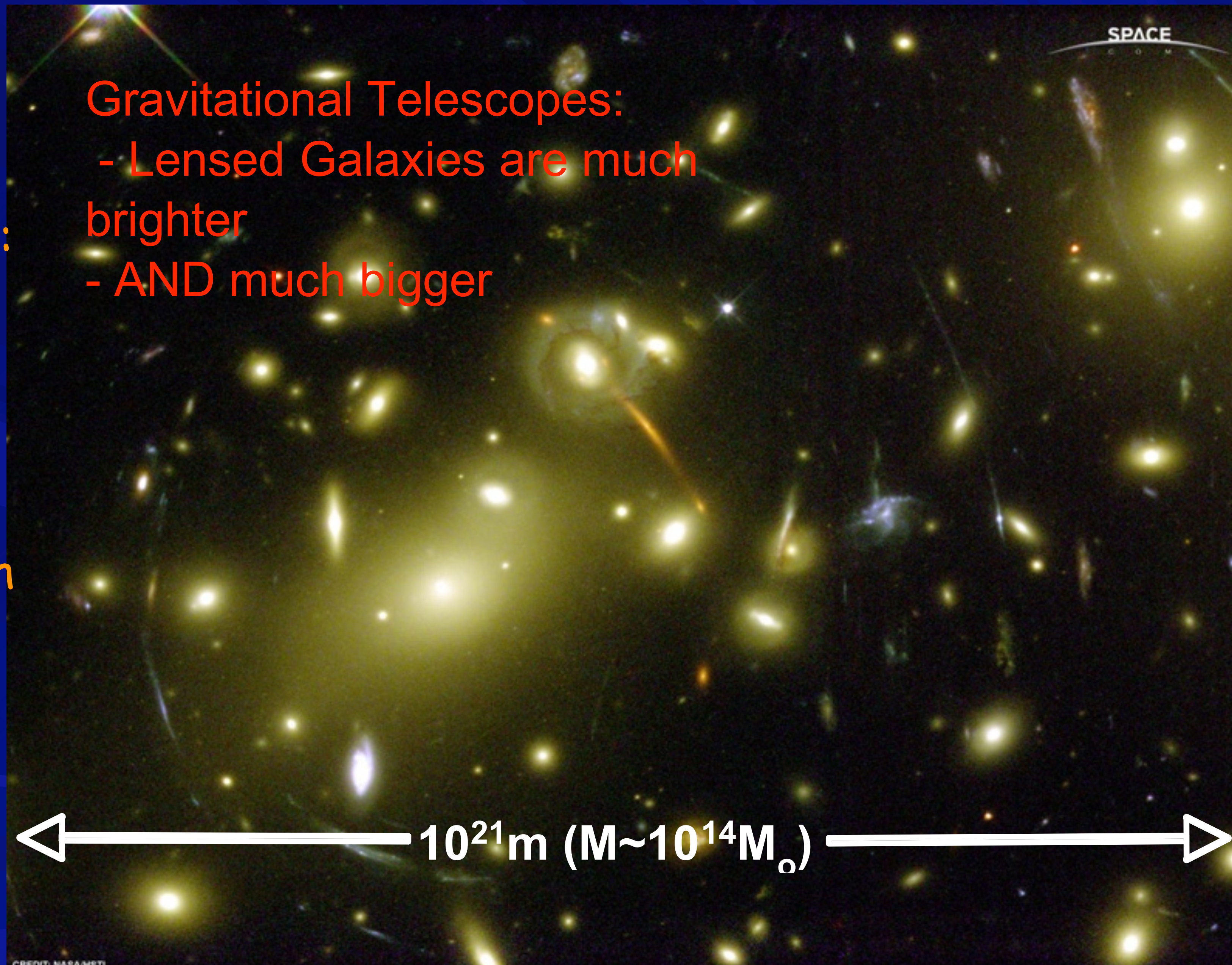
- HII regions have charachteristic sizes of ~50pc
- distant galaxies are faint!
- dispersed light loses contrast (sky noise, flat field errors), read-noise, dark current (in near-IR)
- distant galaxies are small
  (AO correction is not magic!)



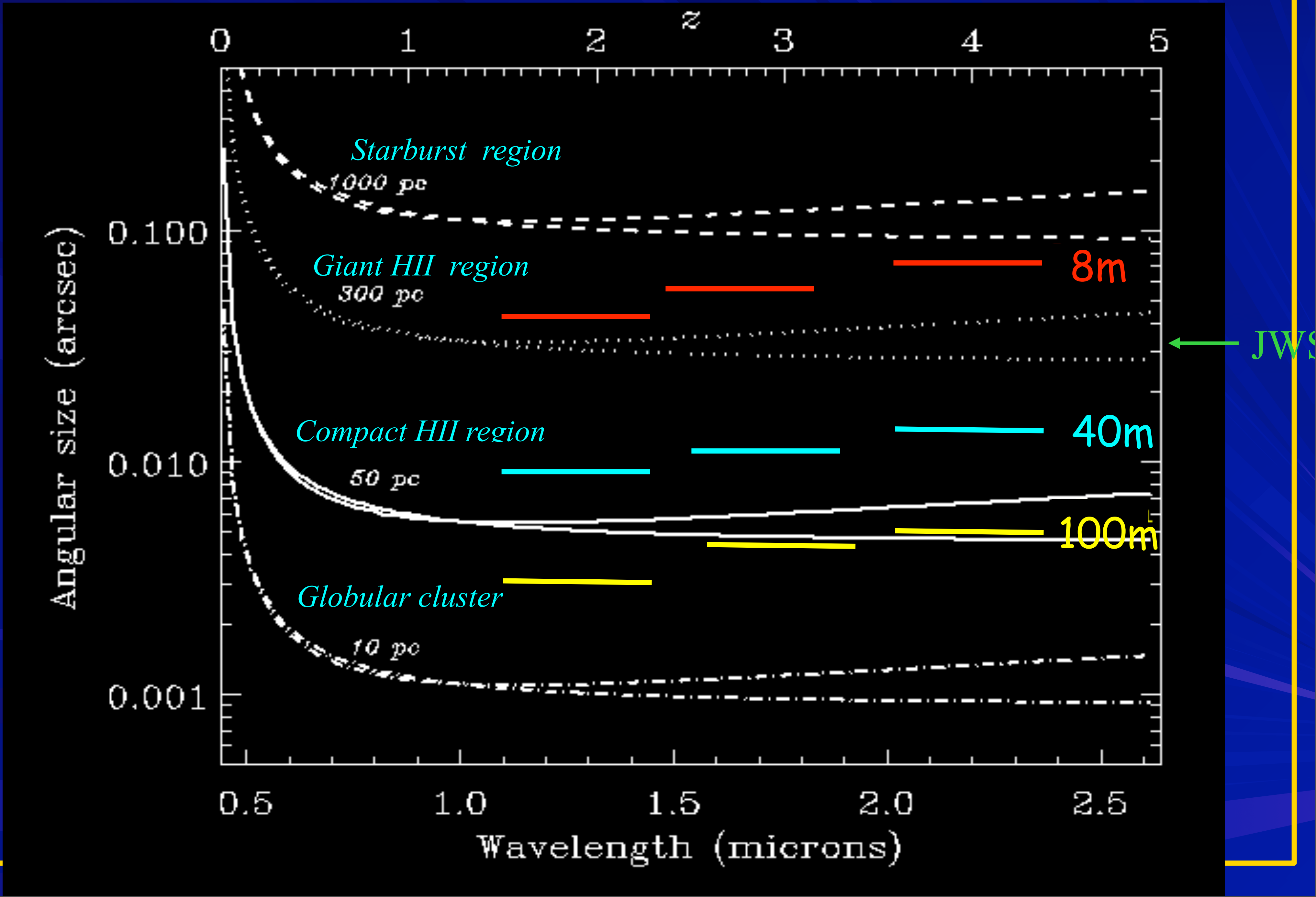
"Galaxies Under the Cosmic Microscope"

The Answer:
Use a BIG telescope!

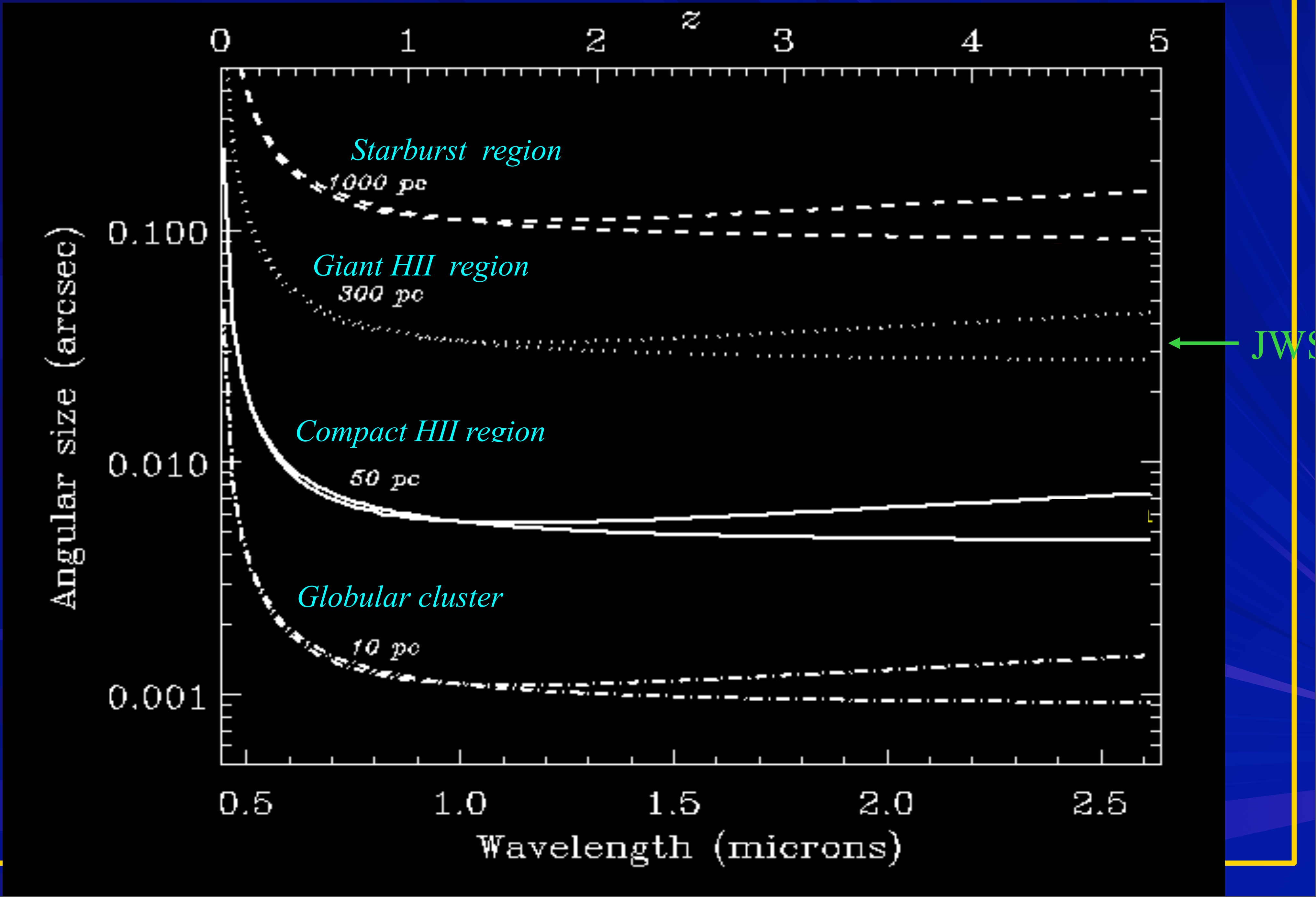
10^{21}m primary with an 8m secondary



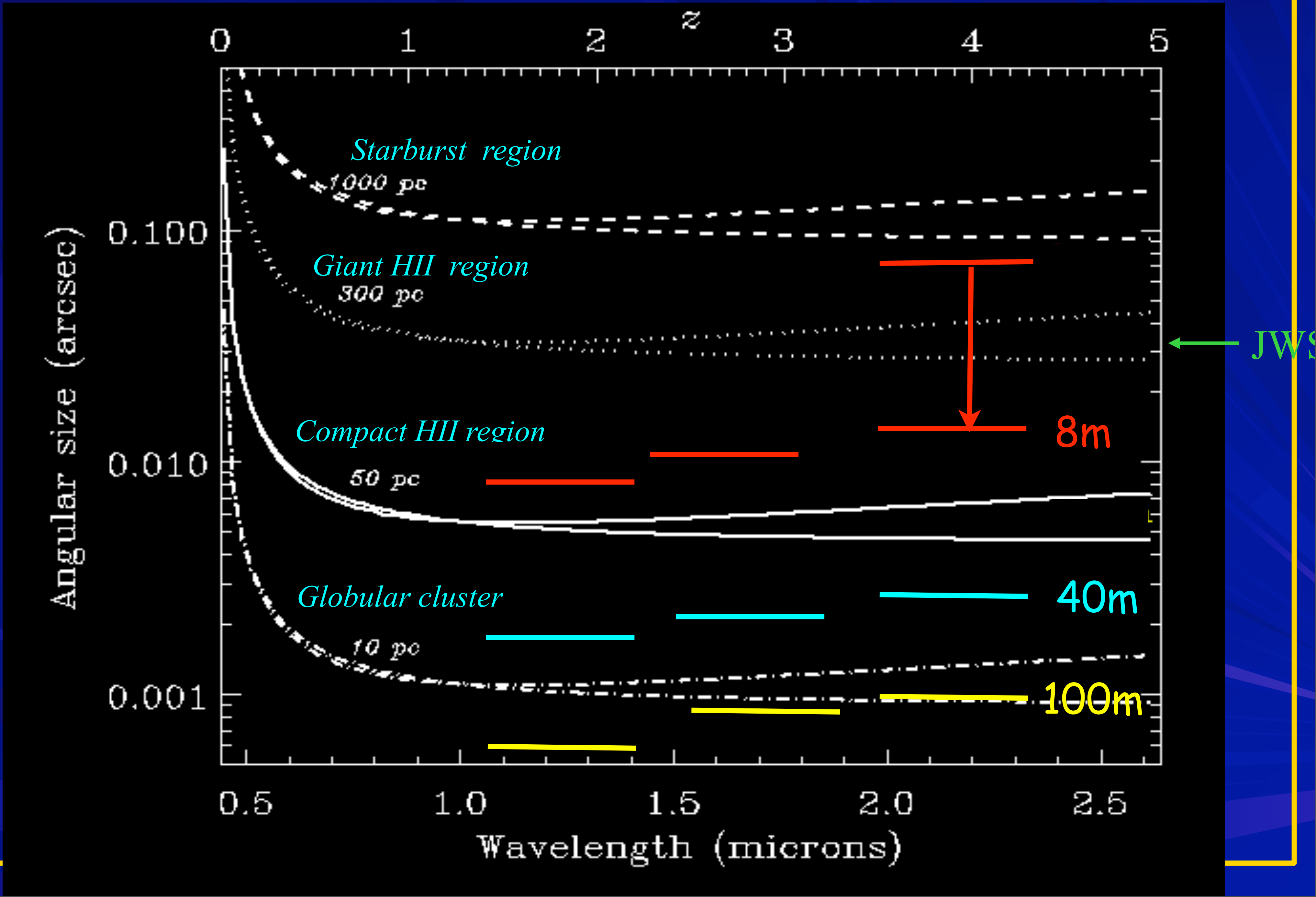
Near-IR Diffraction limits



Near-IR Diffraction limits



Near-IR Diffraction limits



Mass modelling and source plane reconstruction
Example: Abell 2218 arc#289

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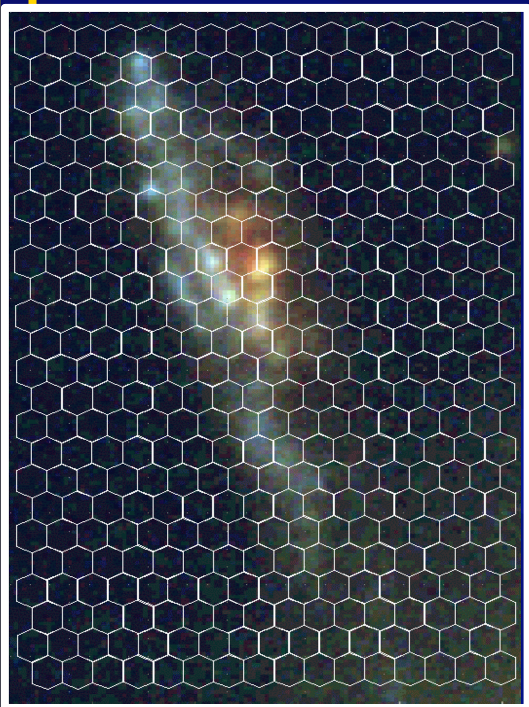
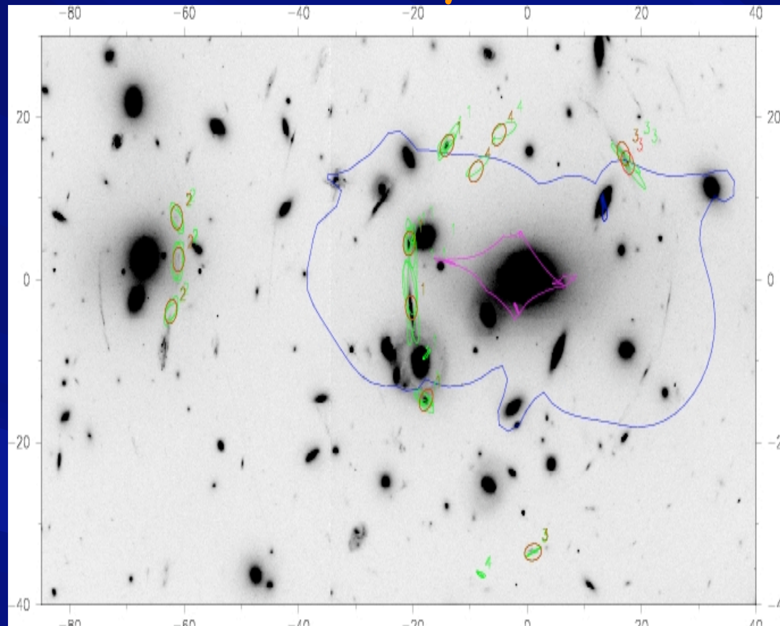
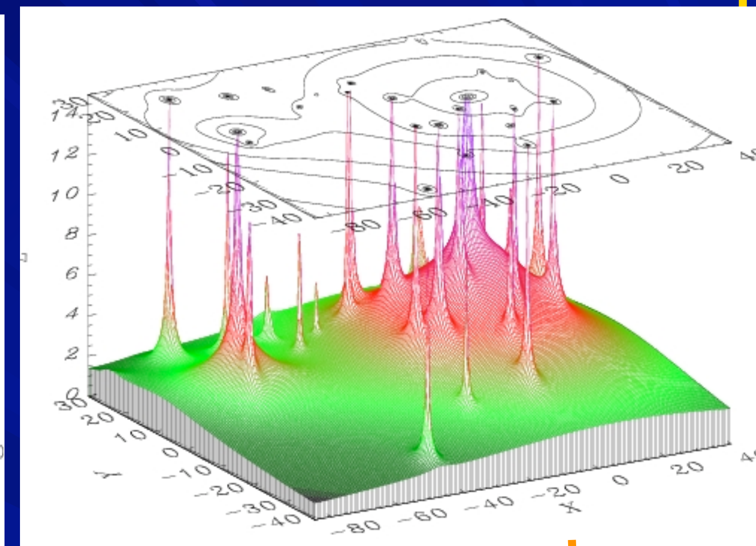
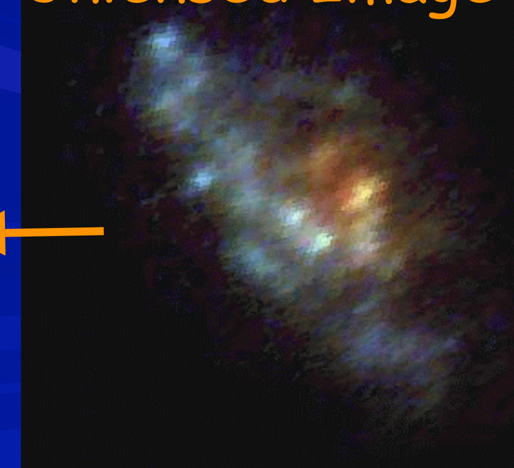
Original image → Galaxy Cluster → Lens model



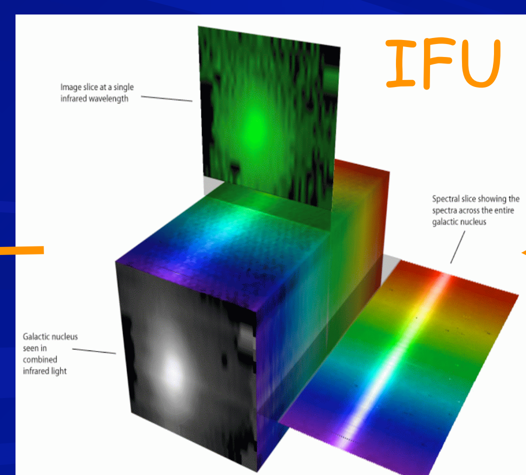




Unlensed Image

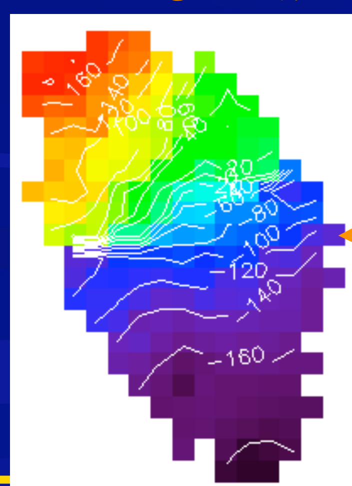


IFU



The 3D view:

+200km/s



-200km/s

Swinbank et al. 2003, 2006

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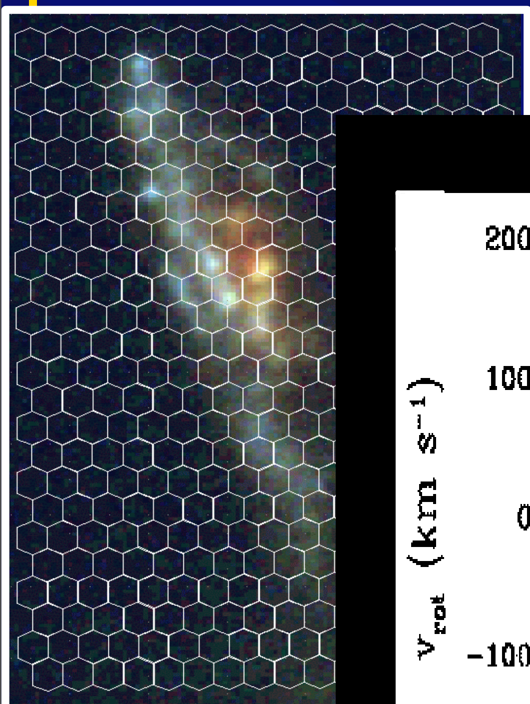
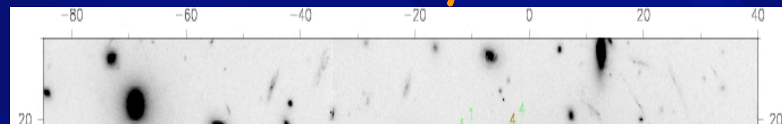
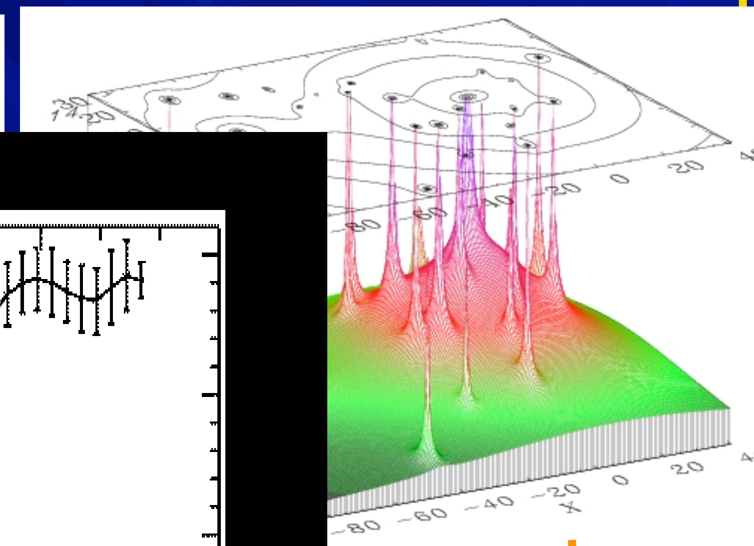
Mass modelling and source plane reconstruction

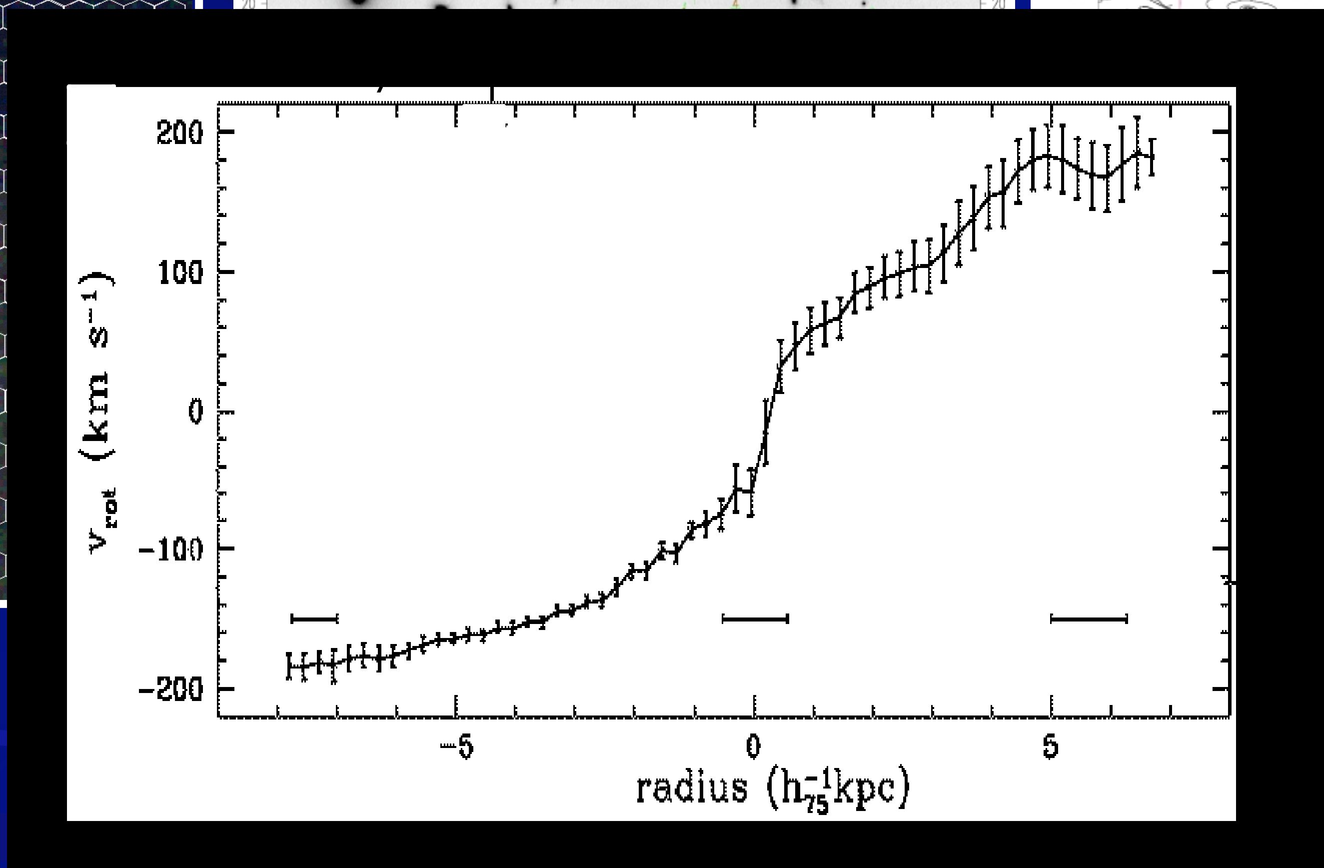
Example: Abell 2218 arc#289

Original image → Galaxy Cluster → Lens model

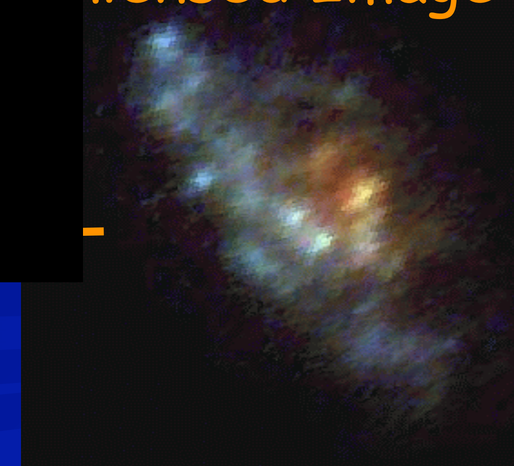


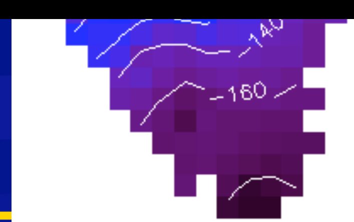


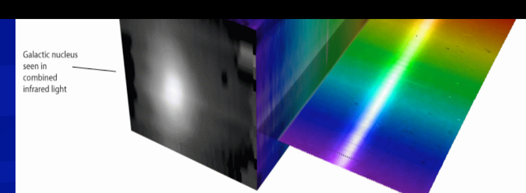




nlensed Image



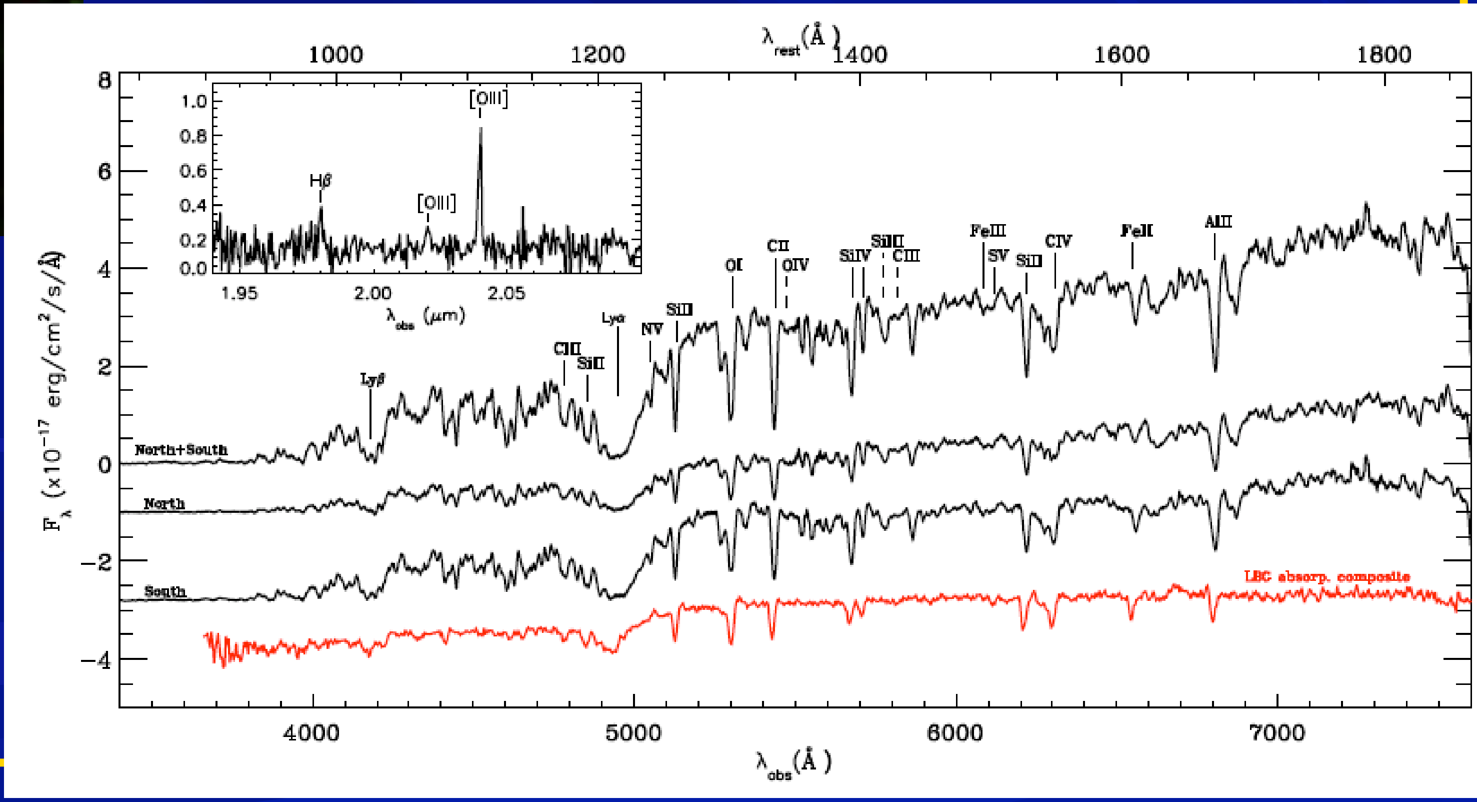




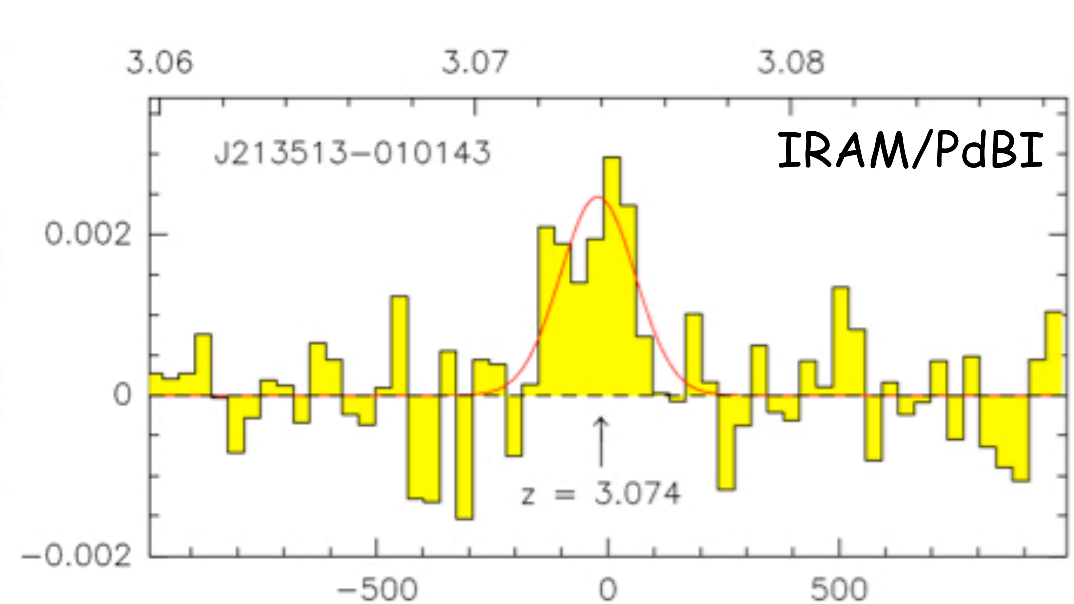
-200km/s

Swinbank et al. 2003, 2006

Extremely Detailed Studies: example of detailed study of lensed L* LBG at z=3



Smail, Swinbank, Richard, Ellis, Coppin et al. 2007



L_K = 22.6 ± 0.2 (AB), M_K=-22.2+/-0.2 (~L_K*)

SFR ~ 100 $M_o yr^{-1}$

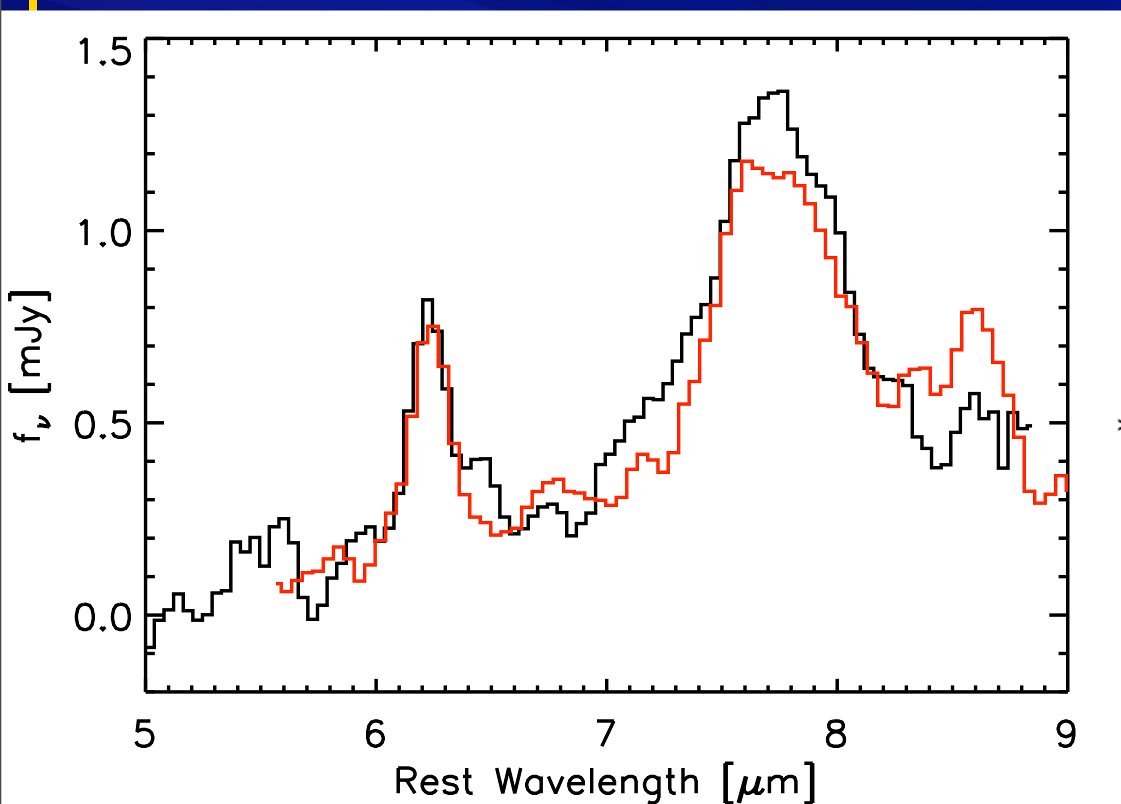
Masses: $1x10^{10} M_o$ (dynamics)

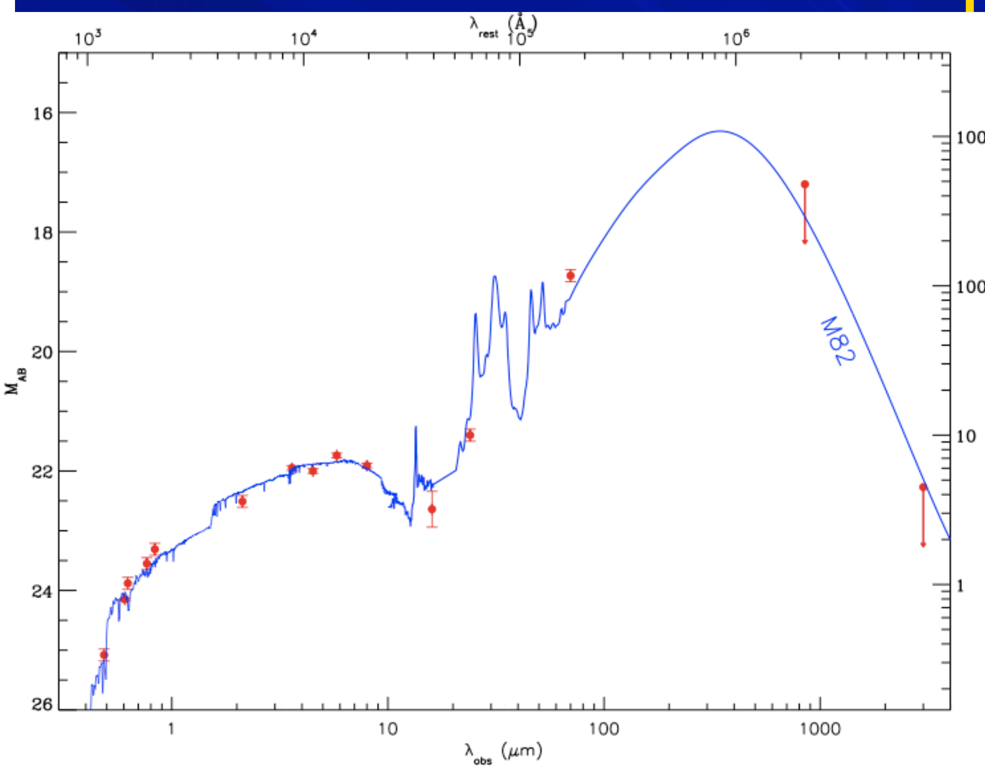
$7x10^9 M_o$ (stellar)

$5x10^8 M_o$ (gas)

Timescale = Gas mass/SFR = 40Myr!

(Coppin, Swinbank, Neri, Cox, Smail et al. 2007)



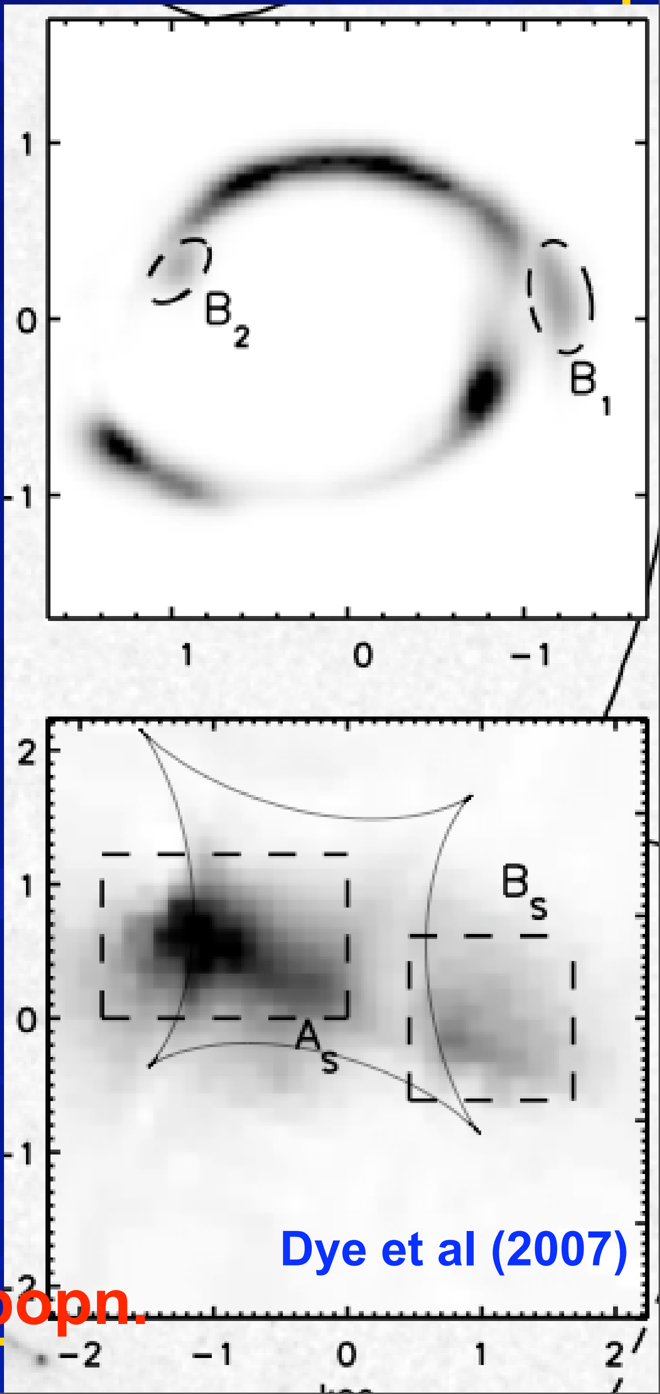


`Cosmic Eye' - Preview of ALMA science

What is gas content of early galaxies?

z~3.07 LGB pair lensed by
L^*_K z=0.73 galaxy + z=0.33 cluster
Cluster provides ~30% boost & induces
non-concentricity of arcs
Magnification = × 28 ± 3
Sources 1.5 kpc apart (< 1kpc in size)

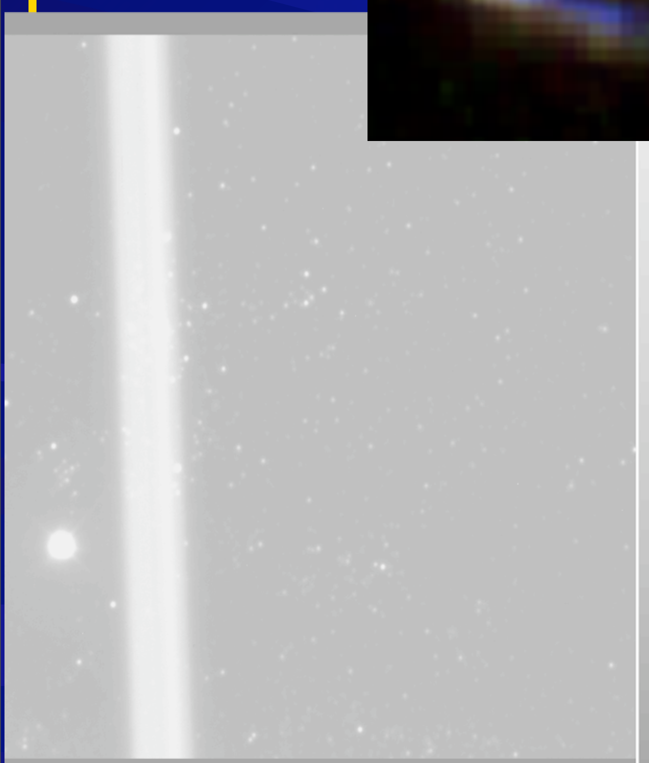
<u>Intrinsic properties:</u>
L_K = 22.6 ± 0.2 (AB), M_K=-22.2+/-0.2 (~L_K*)
SFR ~ 100 $M_{\odot} yr^{-1}$
Masses: $1 \times 10^{10} M_{\odot}$ (dynamics)
$7 \times 10^{9} M_{\odot}$ (stellar)
$5 \times 10^{8} M_{\odot}$ (gas)
Timescale = Gas mass/SFR = 40Myr!

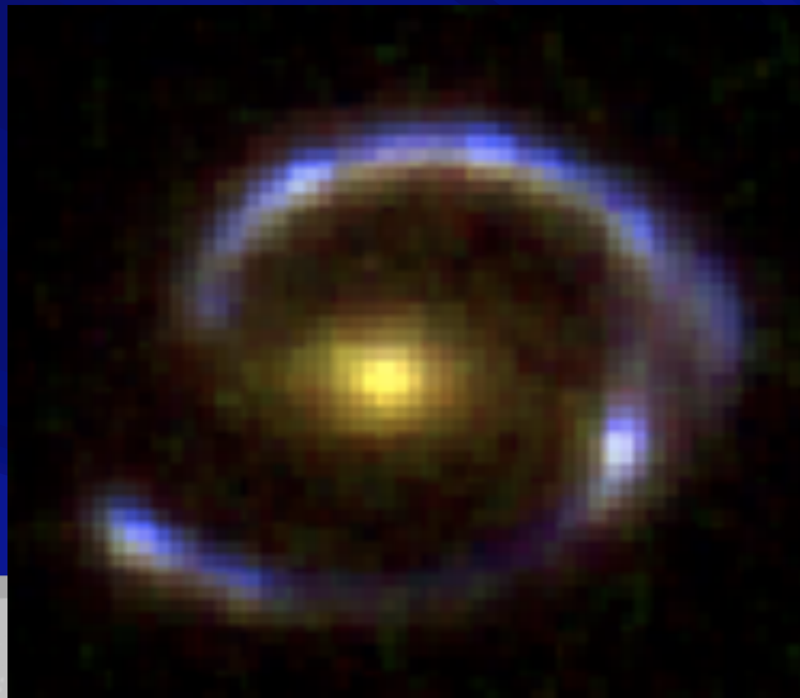


Dye et al (2007)

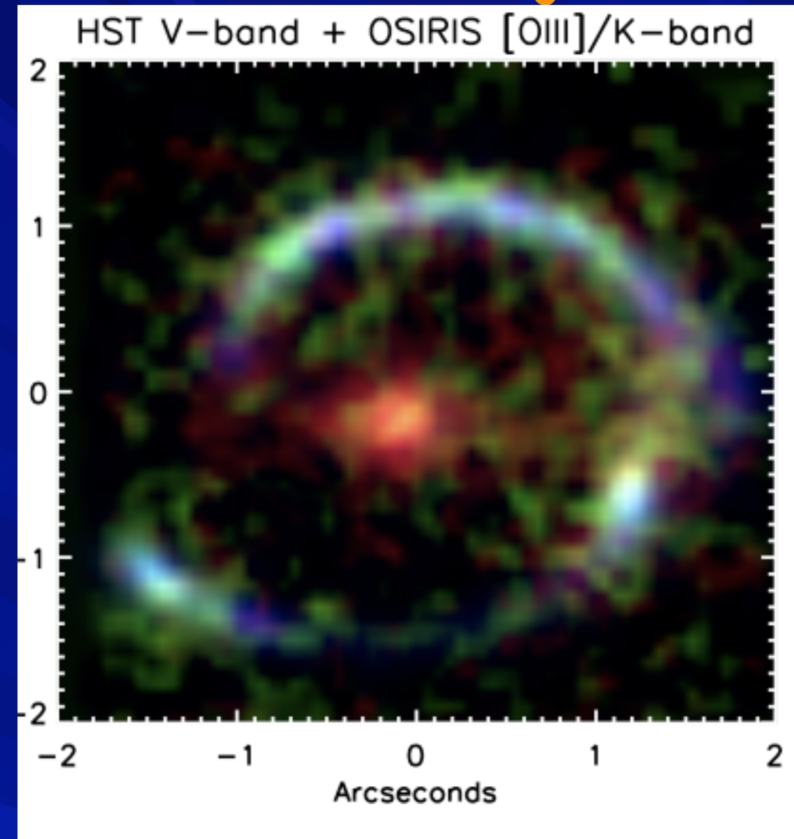
Gas-rich & similar (less vigorous) to sub-mm popn.

HST/ACS images



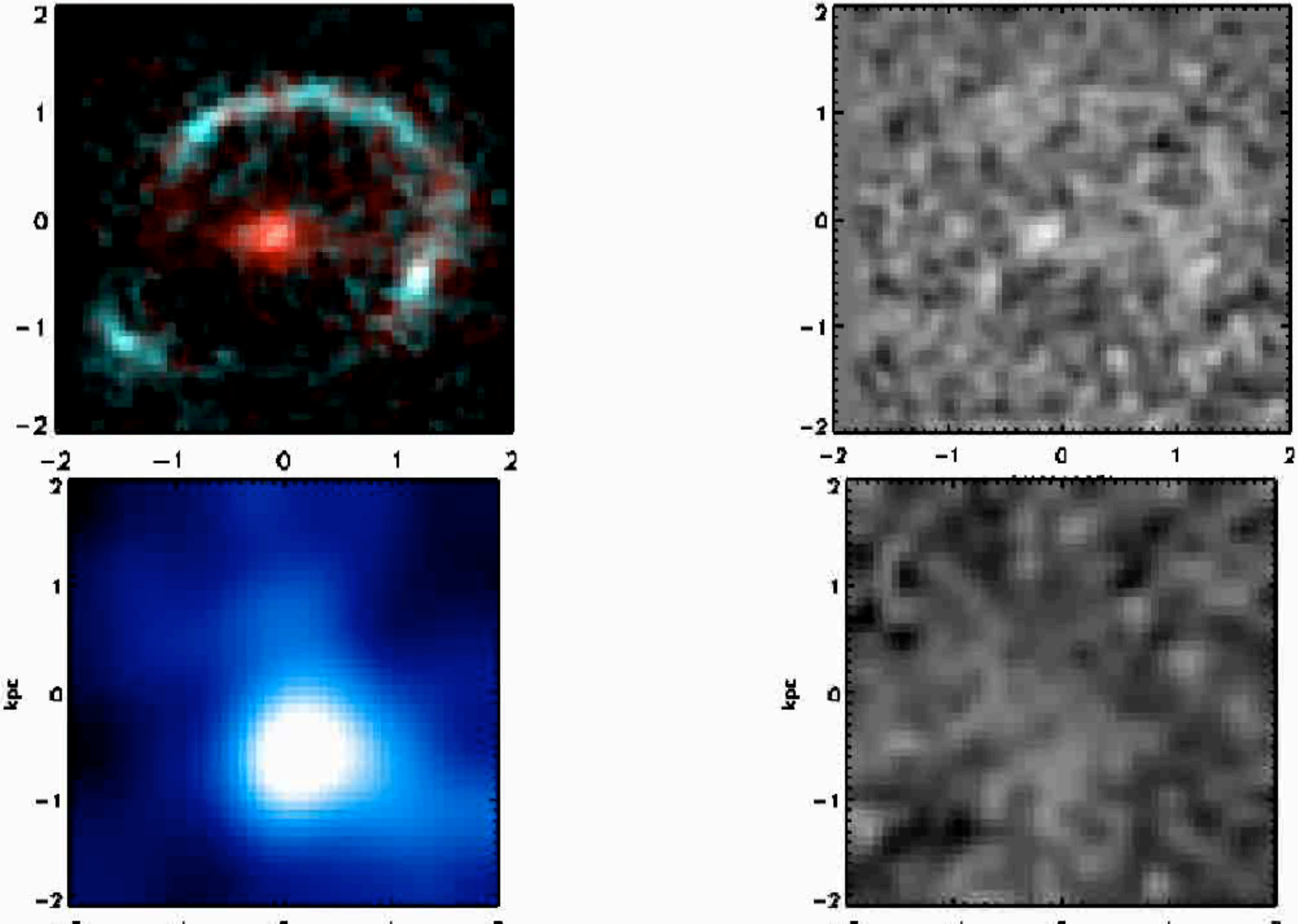


Datacube Projection

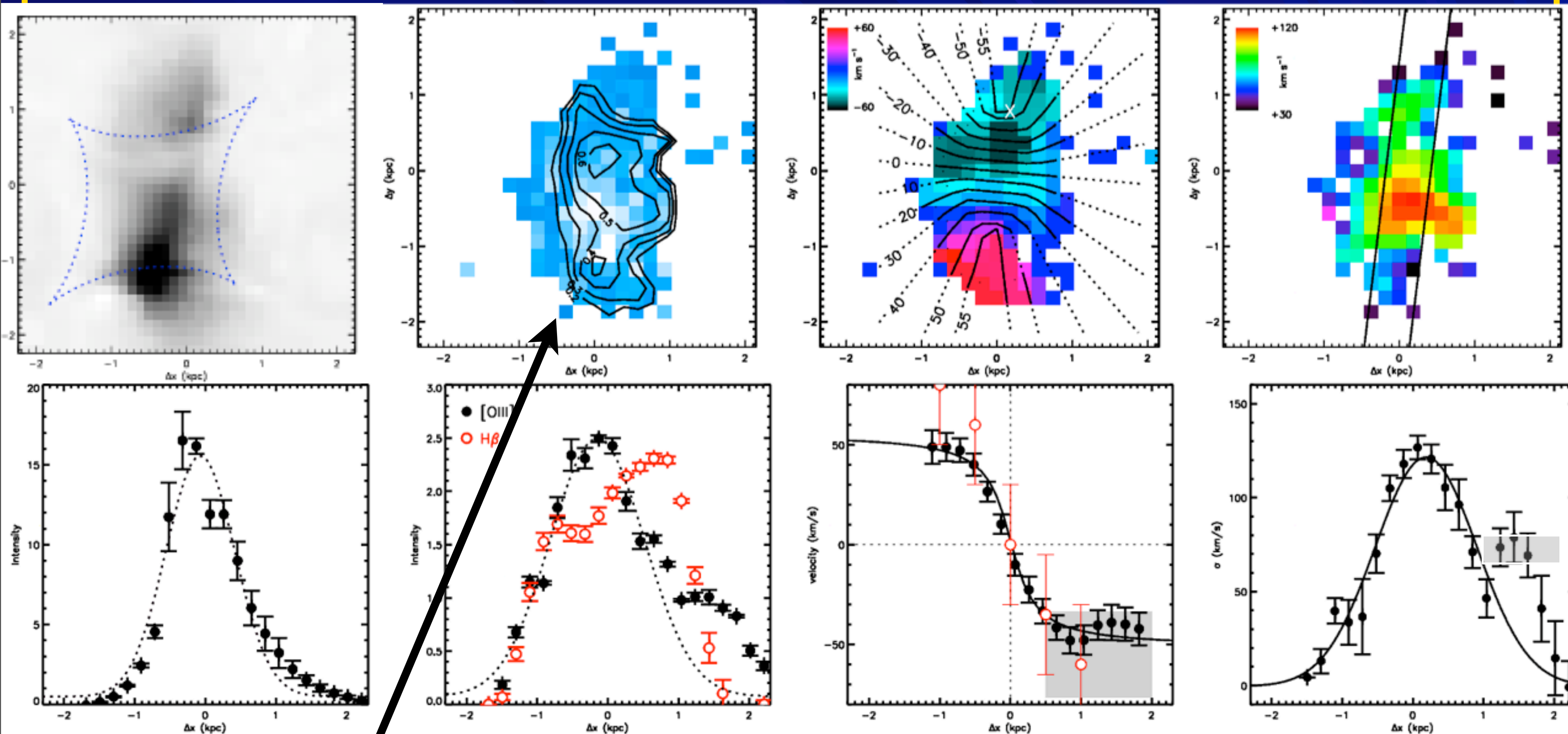


Keck/OSIRIS LGS (Sept 2007). LGS delivers 0.075" resolution (100pc in source plane!)

see also Nesvadba et al. 2007


2
1
0
−1
−2
−2 −1 0 1 2
kpc

V-band | [OIII]+Hβ | velocity field | σ-map



Each pixel in 100pc and independant:
Resolution is 10mas in non-lensed case!

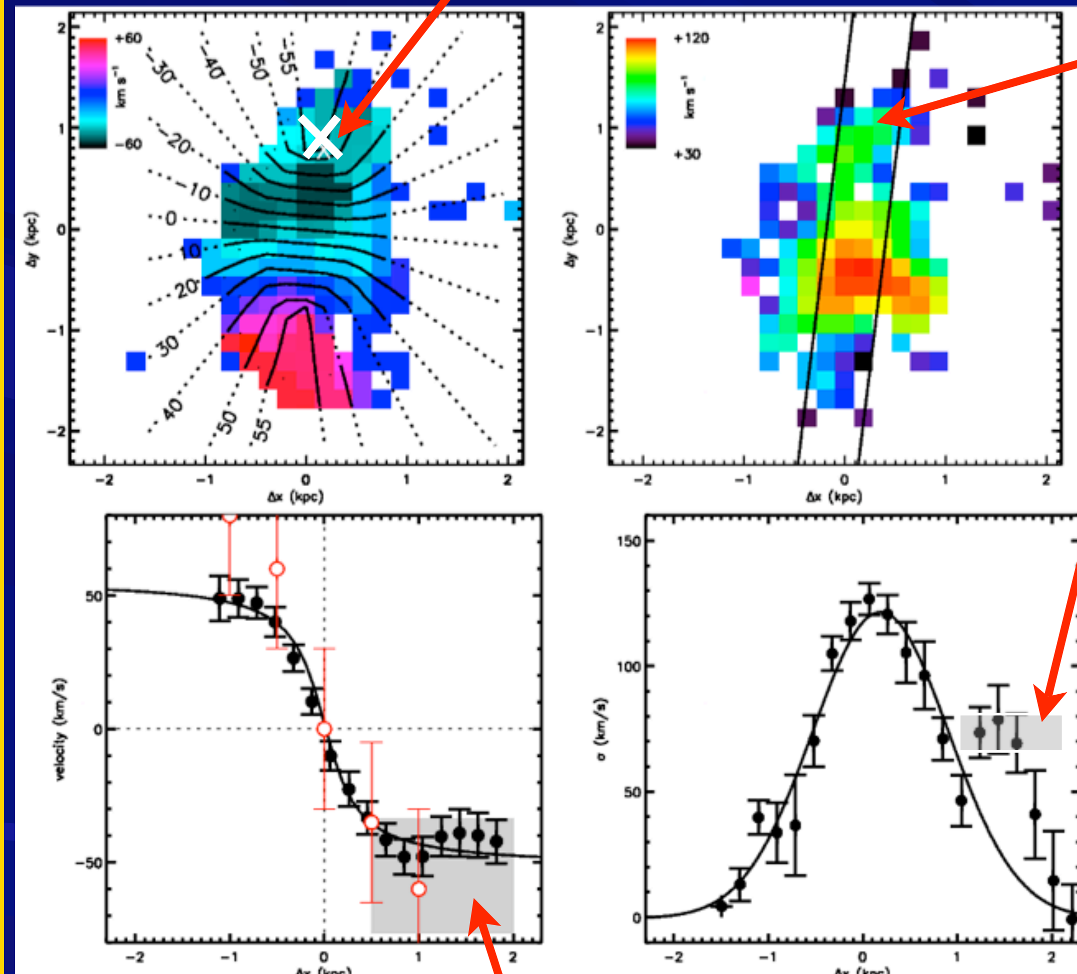
M_{dyn}~$6\times10^9 M_\odot$ (R<1.8kpc)
Σ_{SFR}=4.4$M_\odot$/yr/kpc^2
v/σ=1 (thick disk)

Stark, Swinbank, Ellis et al 2008 Nature

Synergies with other facilities: eg. ALMA

Predicted location of CO

Predicted FWHM of CO

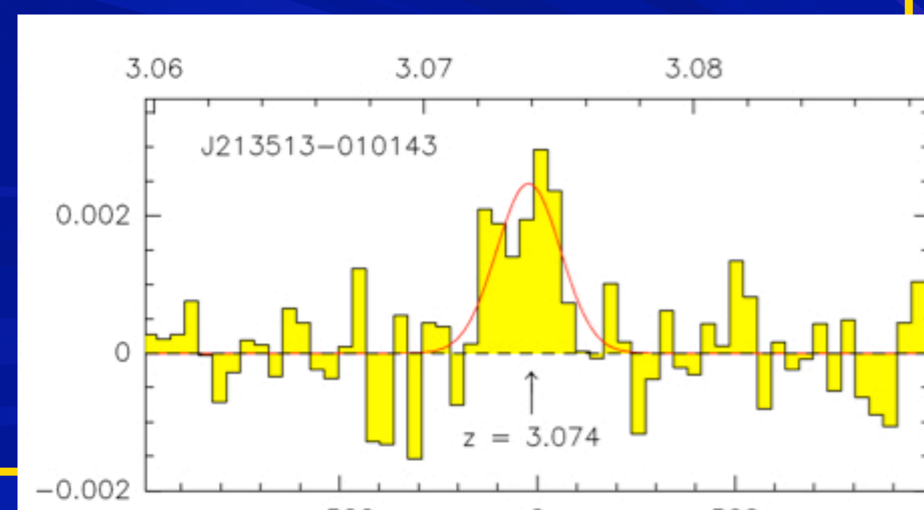


Predicted velocity of CO

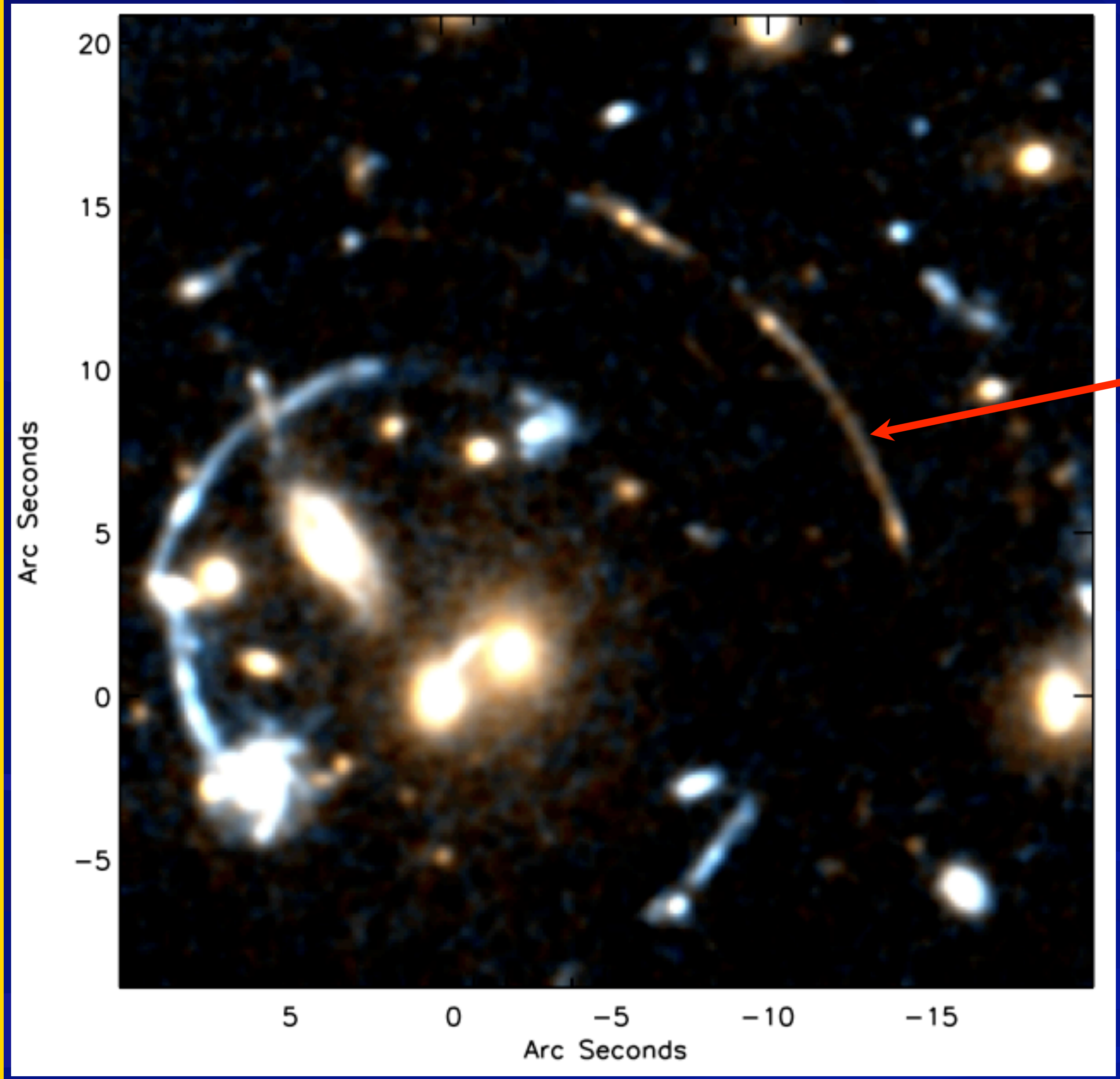
Constraints on α at high-z:

$M(H_2) = \alpha\, L'_{CO}$

Since gas mass MUST to be less than dynamical mass suggests α<0.8 (see also Tacconi et al. 2008)



Push to higher-z:
Quick example: RCS0224-002 z_{cl}=0.78



z=4.88 arc

I=25.2 (source plane) … an L* galaxy at z=5

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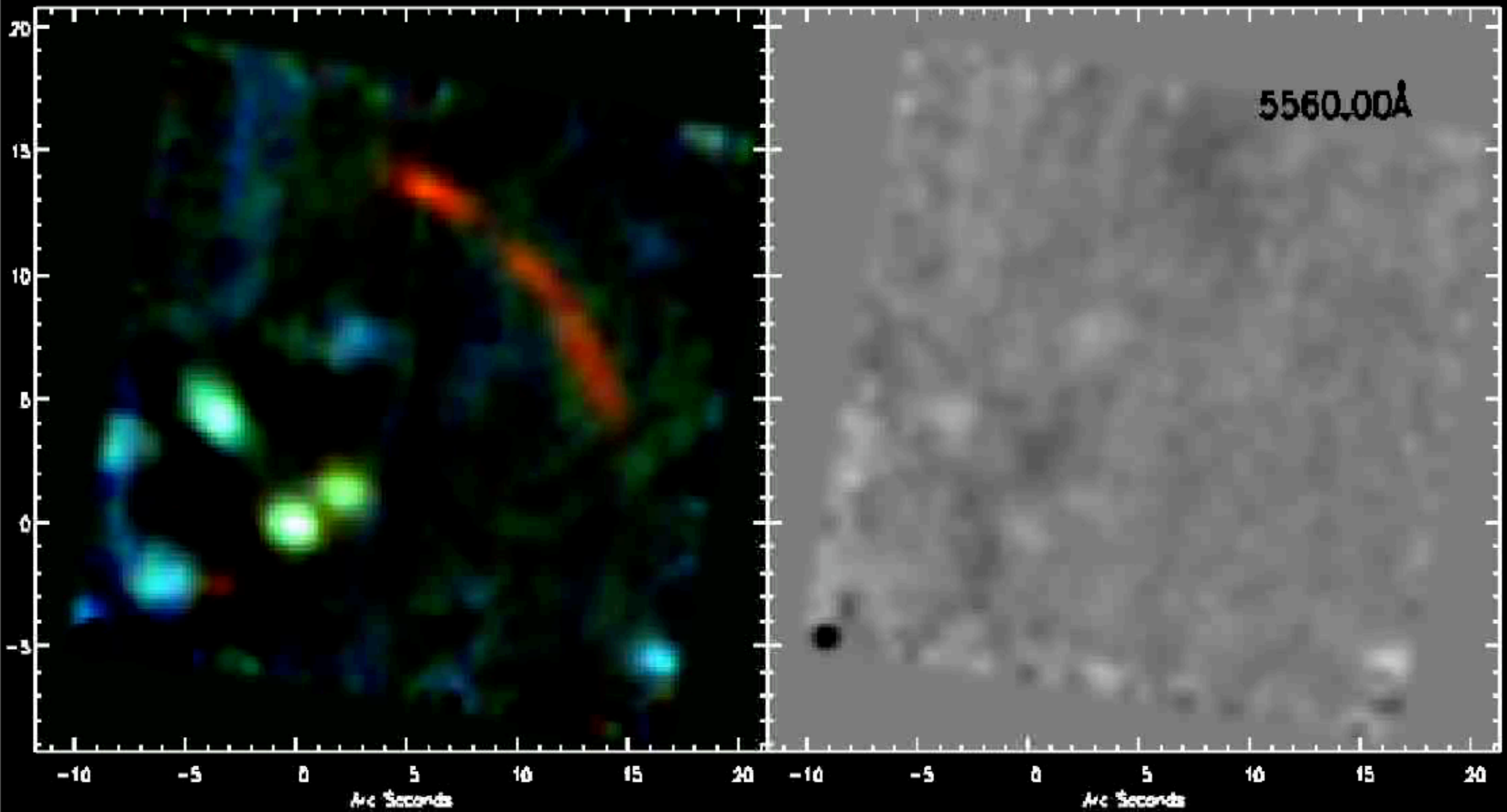
The VIMOS IFU movie



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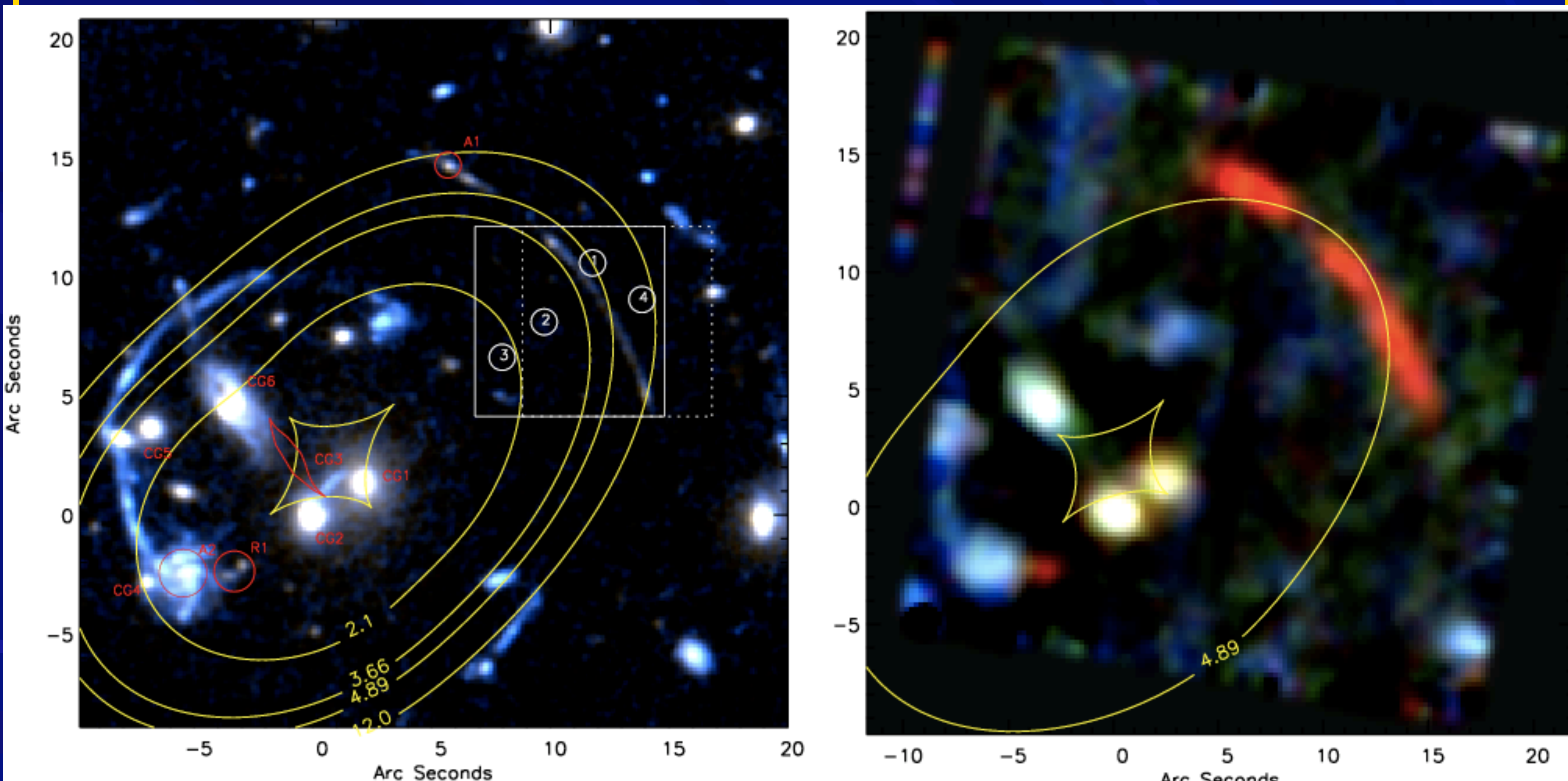

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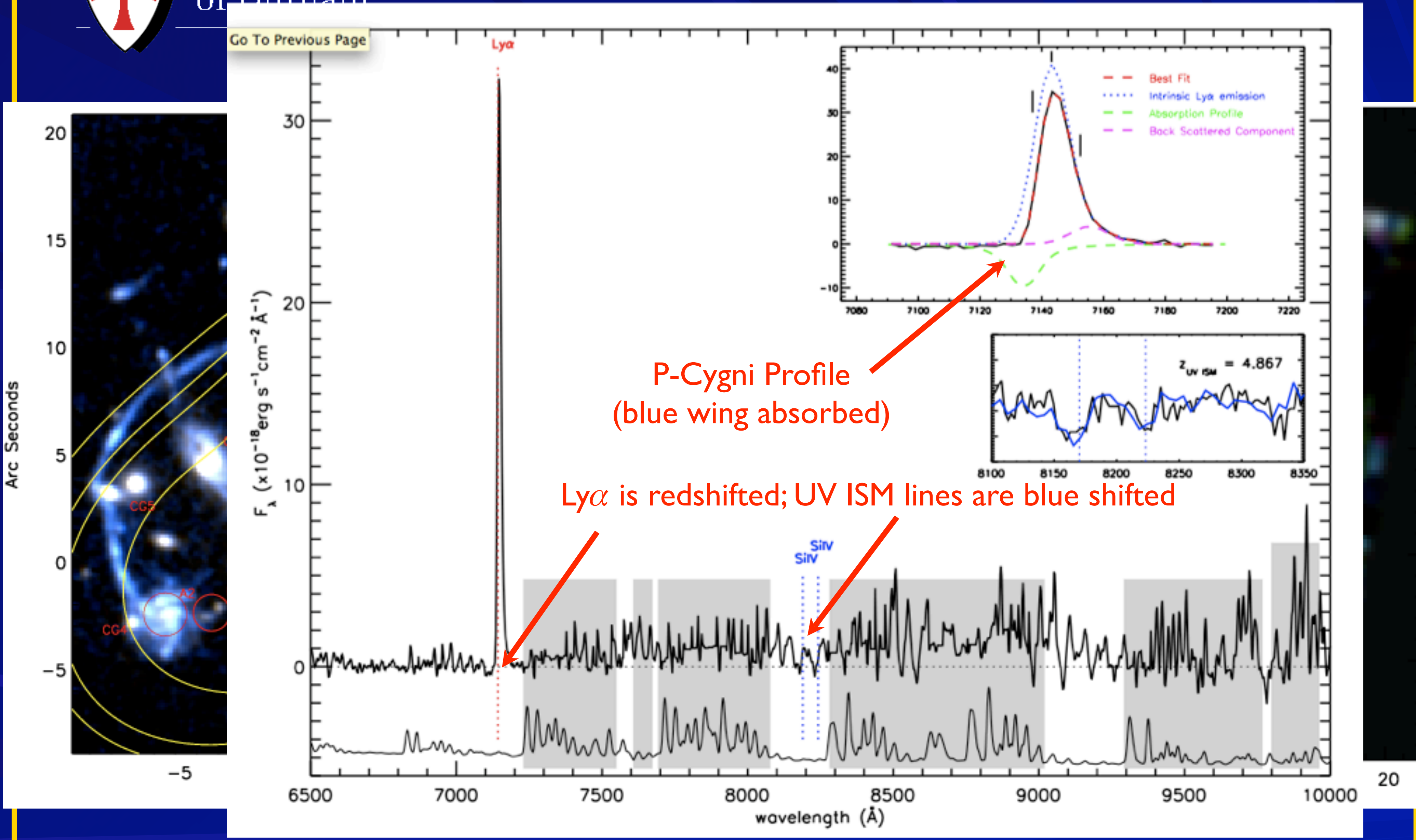

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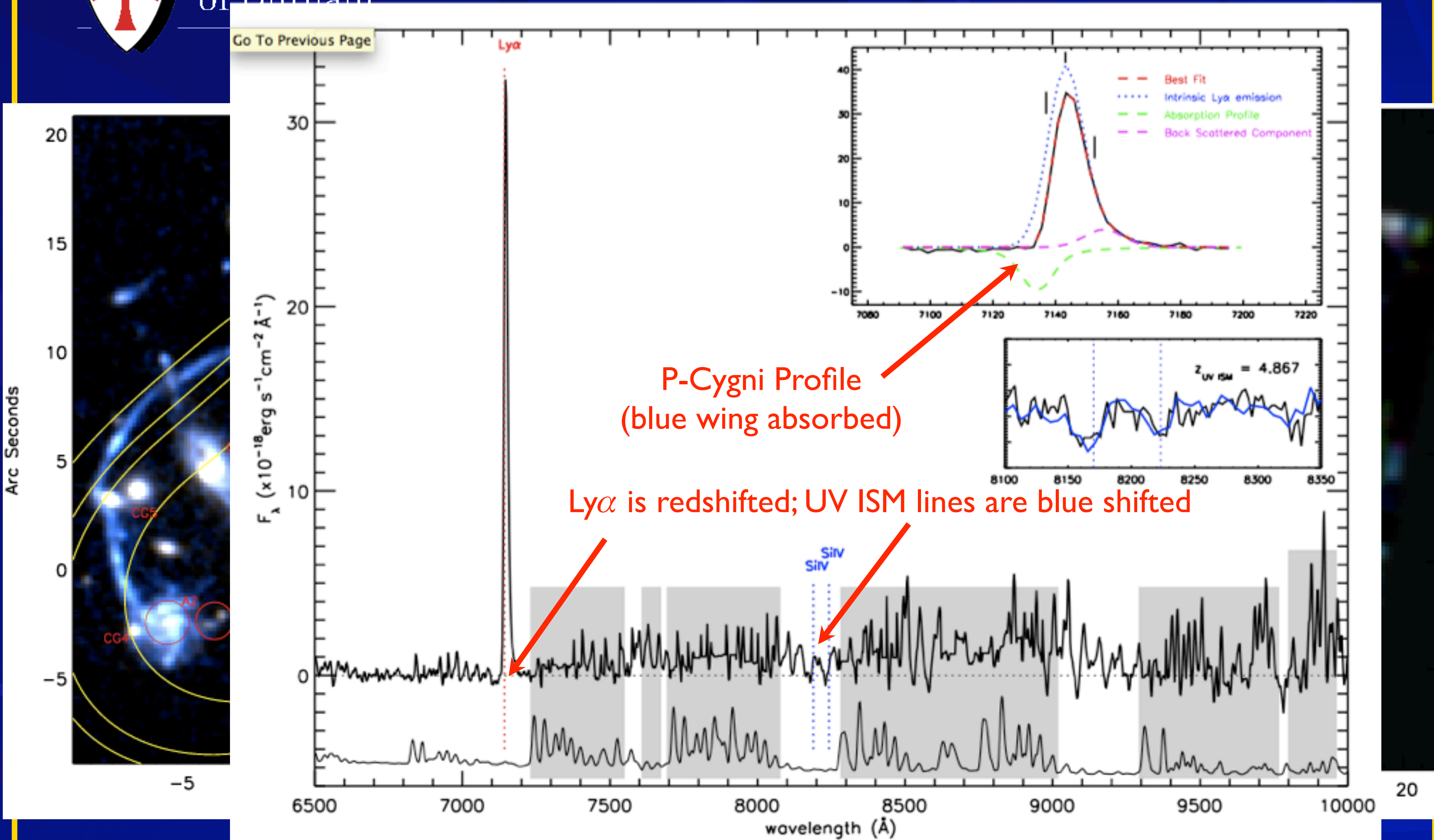

But, Lyα is a pain to interpret on it's own. We really need the nebular emission to interpret the velocity offsets correctly

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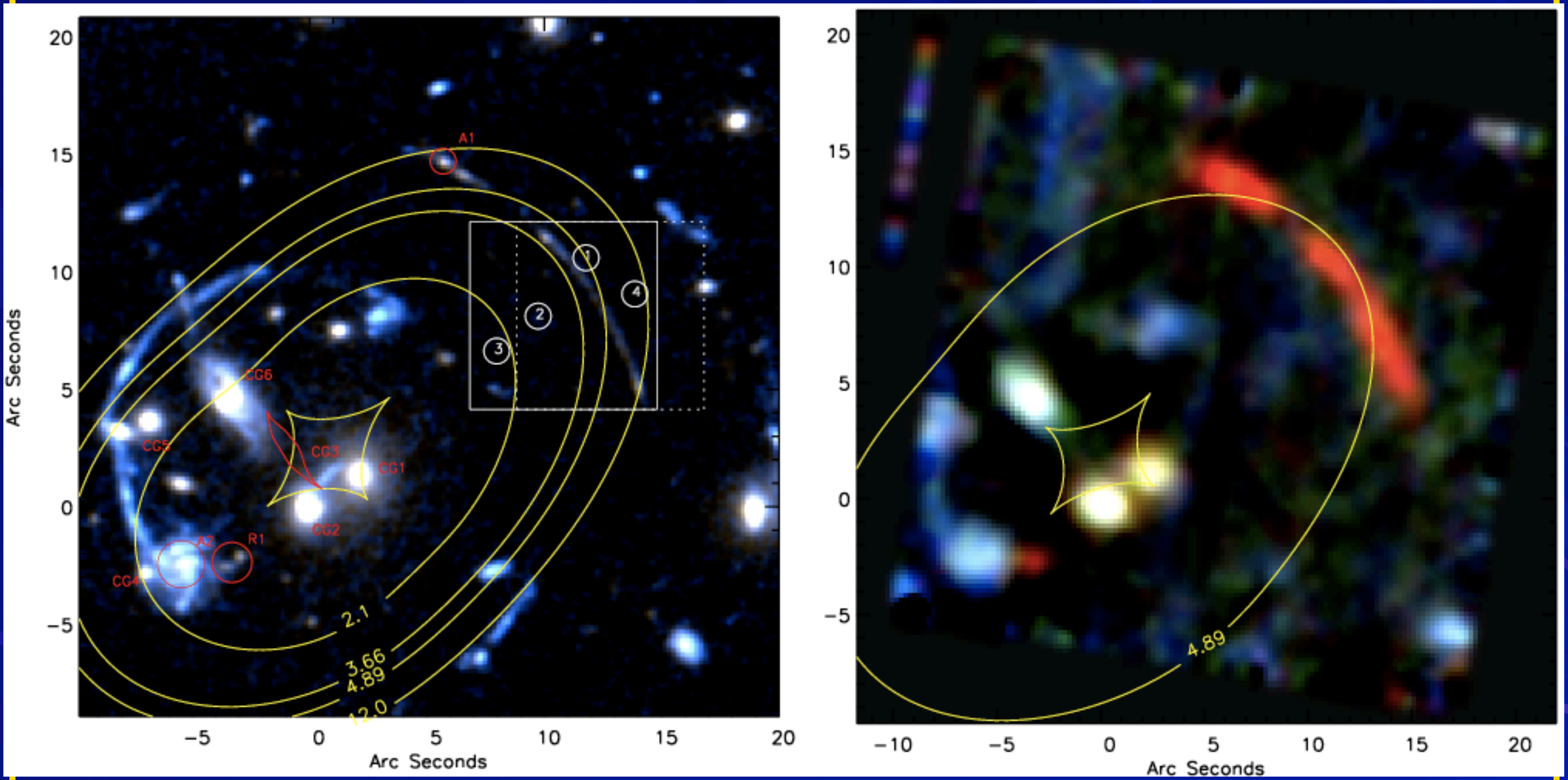
SINFONI IFU observations map the OII emission at 2.2um



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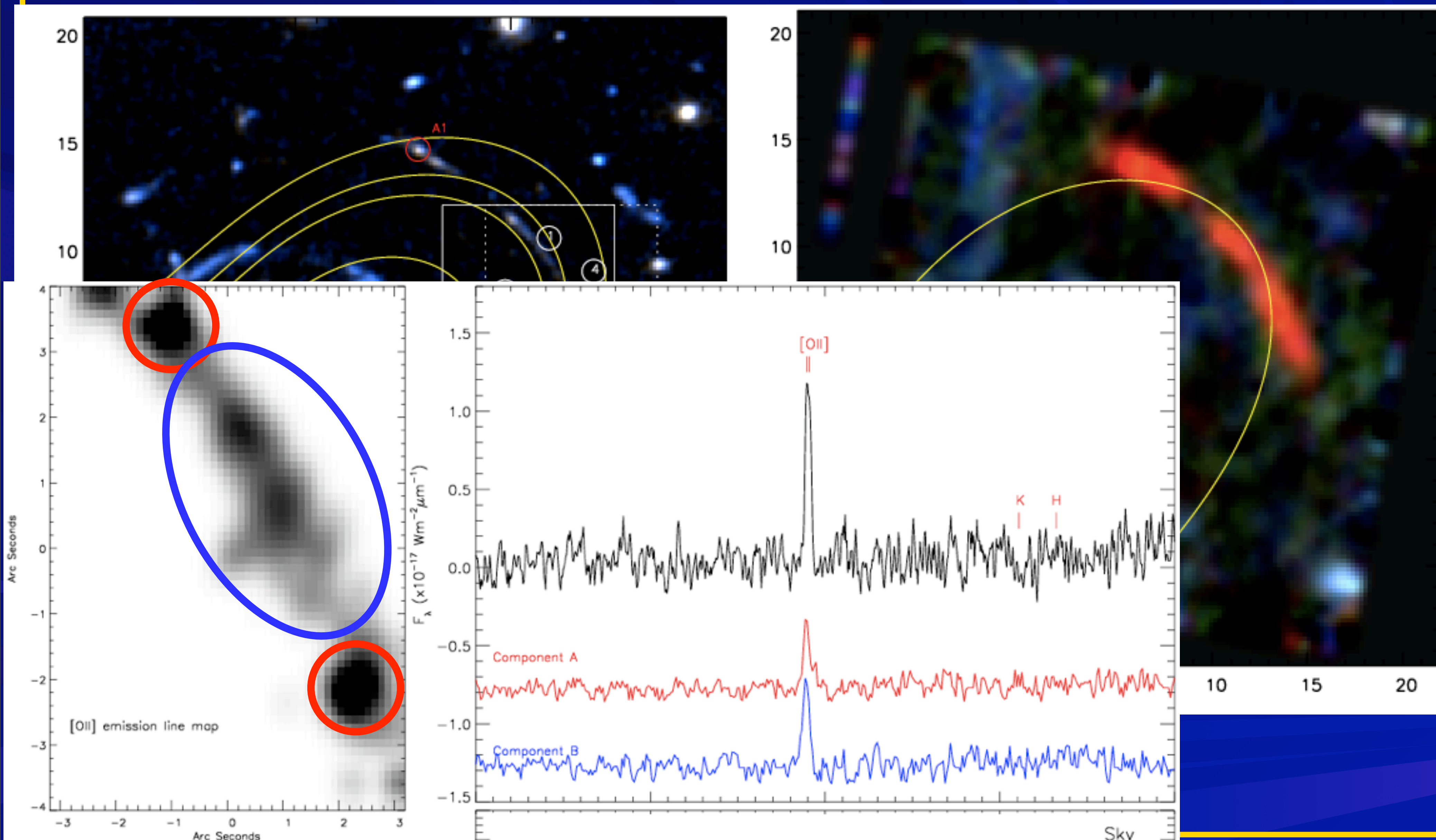
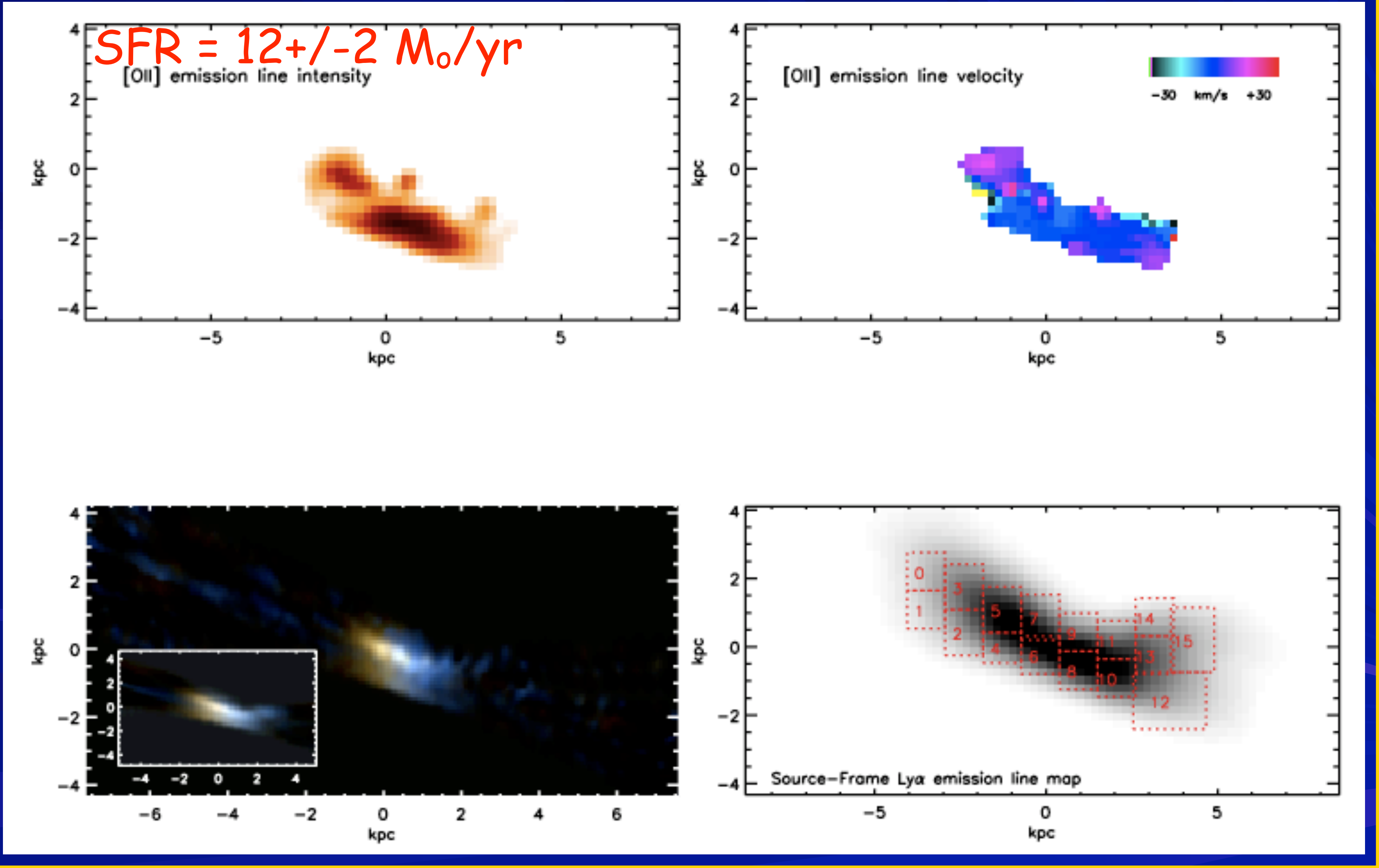


Reconstructed images of the z=4.88 arc

Reconstructed image (HST VI-band)

Amplification = 16 (Δm = 3.0 mags)

SFR = 12+/-2 M_o/yr



Putting the OII, Lyα and UV-ISM diagnostics together

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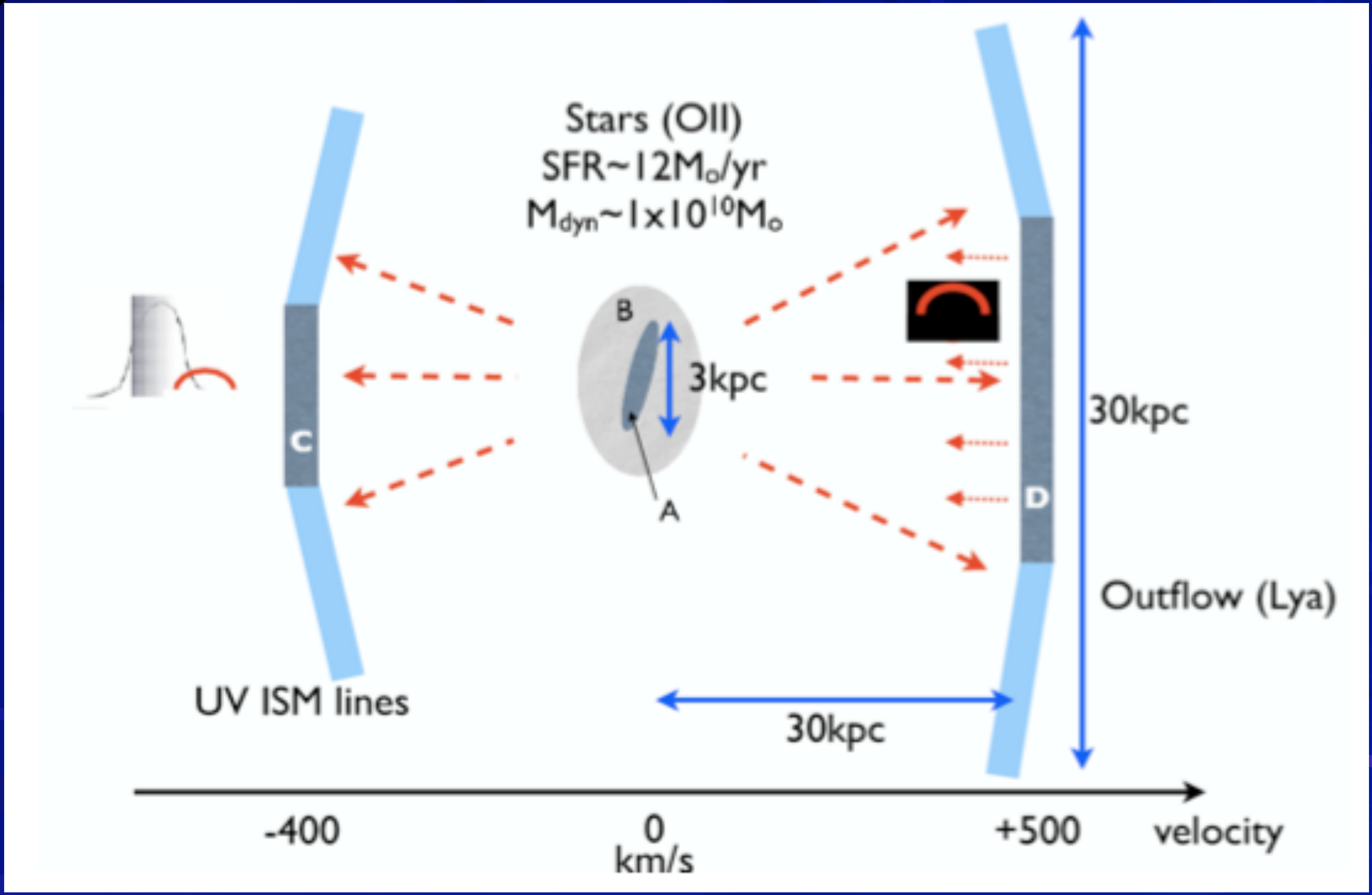

Based on Tenorio-Tagle et al

Implications from RCS0224-002 z=4.88arc

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- Highly magnified galaxy
  - magnification factor ~16
  - Source-frame morphology only ~3kpc in size
  - 200 pc resolution with HST
- OII has small velocity shear (line widths estimate M ~ few x10^{10}Mo)
  - ~6x smaller than median LBG mass at z=3
- SFR~12+/-2 Mo/yr
  - thats small for a z=5 galaxy!
- Lyα redshifted, UV ISM lines blueshifted
  - starburst driven wind
- Emission-line morphology
  - bi-conical outflow with extent >>10 kpc.

- Energetics:
  - *Age of outflow ~60Myr*
  - Mass swept up 2x10^8Mo
  - Outflow rate ~ 3/x M/yr
  - KE ~ 5 x 10^{56} /x erg
  - Energy from SNe ~ 5 x 10^{57} erg
  - Outflow will reach several ~1Mpc (comoving) before it stalls.

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Key Advantages of lensing studies:

- Galaxies are much bigger AND brighter than the non-lensed case
- For a flux gain of factor ~30x, gain in spatial size is factor ~6x
- Begin to resolve the largest HII regions in galaxies at z=1-5

Key disadvantages:

- Need a good lens model (requires at least 3 spectroscopically confirmed multiple images (expensive)
- Even with lens model, there are still uncertainties in the lens plane reconstruction due to degeneracies
- Not that many targets are suitable (highly magnified, correct redshift, etc)

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- IFU are a powerful probe of physics in high-z galaxies.
- In particular, the relation between star-formation and gas dynamics critical for understanding role of feedback

- Coupled with Gravitational Lensing makes IFU studies very appealing:
- Provides complementary view of high-z star-forming galaxies at lower spatial resolution (although limited number of galaxies currently available)

- Provided valuable early glimpse of ELT and ALMA science
- Future Prospects:
- More concerted efforts at finding z>2 lensed sources
- Resolved dynamics (especially with LGS AO)