The Birth and Assembly of Galaxies: the Case for a 30-meter Ground-based Telescope

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Galaxy formation and evolution

How did galaxies like the Milky Way form?

- Learning histories of local galaxies from their stars
- Using the early universe to "see" it happening

M31

(http://zebu.uoregon.edu/images)

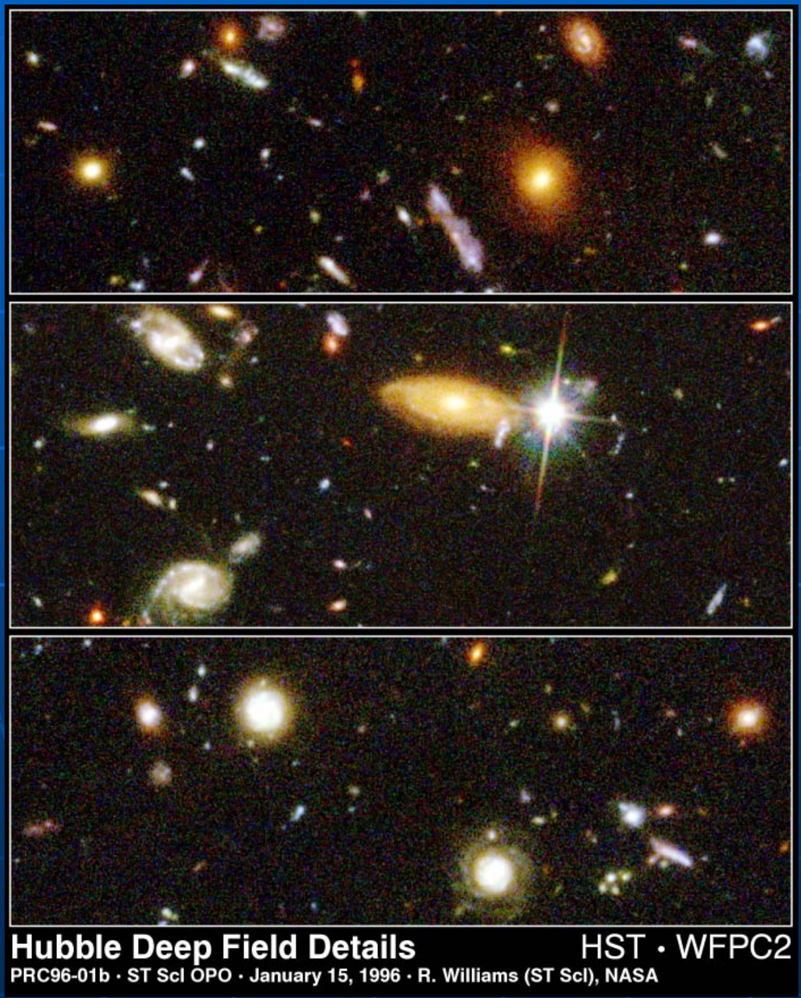
Galaxy evolution

- **Where and when did the first stars form?**
- **When and how did the build-up of galaxies occur?**
- **What determines the size and structure of a galaxy?**

“Nature” vs. “nurture”:

- **What role does environment play?**
- **What roles do dark matter and dark energy play?**

The Current landscape



- **Powerful combination of:**
  - Hubble Space Telescope
  - 2-10-meter ground-based telescopes
  - Very Large Array
  - Chandra satellite
  - Ground-based submillimeter facilities
  - The Space Infrared Telescope Facility…

The Current landscape

When these facilities have been fully exploited, we will know about:

- The composition of the Milky Way and its closest companions
- The broad star formation histories and properties of local galaxies and large-scale structure (LSS)
- The basic properties of typical galaxies and LSS as far back as 7 billion years (to z=1-1.5)
- The basic properties of the most luminous galaxies 12 billion years ago (z=2-5)
- The existence of some galaxies 12.5-14 billion years ago (z=6-8 or 10)
- Possibly the equation of state of the universe

The requirements for progress

- **The relationship between the IGM and galaxy evolution: the tomography of the IGM**
  - Surveys of absorption lines in background sources

- **Measuring morphologies and the merger rate as a function of time to z=6:**
  - Evolution of different morphological types; identification of most strongly evolving populations at different redshifts

- **The star formation and chemical enrichment histories of galaxies as a function of time:**
  - Star formation histories of typical galaxies to z=6
  - Chemical enrichment as a function of position in the galaxy

The requirements for progress

- The intrinsic properties, ultimately the masses, of galaxies at high redshift
  - Mass measures from internal dynamics as far as z=5
- Detecting the first luminous objects in the universe
  - Sizes, luminosity function, IMF, enrichment

What are the true “paradigm” shifts allowed by a 30-meter telescope?

- Some projects represent qualitative difference

- Examples:

  - IGM tomography from abundant sources
  - Spectroscopy of far sub-L* galaxies at z=3-5
  - Internal properties of galaxies at z=3-5
  - Characterization of stars with multiple emission lines and high-resolution spectroscopy at z > 6

Galaxy surveys

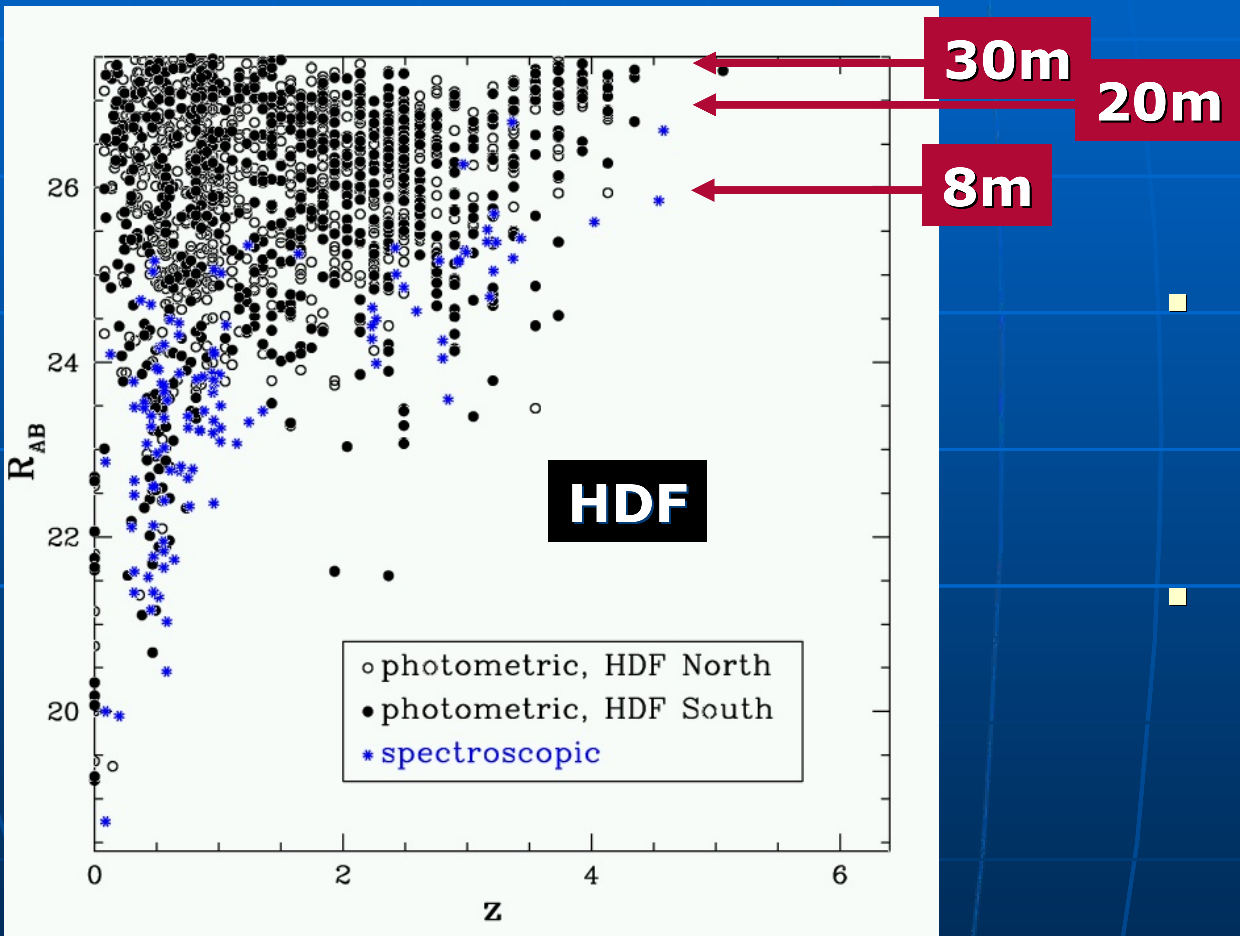
Galaxy evolution and large-scale structure:

- 5°x5° survey at 2.5<z<3.5 gives a volume 600Mpc x 600Mpc x 900 Mpc=3×10^{8} Mpc^{3}
- to R=26.5, 10 $arcmin^{-2}$
- 1 million galaxies, ~ 15 arcmin FOV, with multiplex ~ 2000 in about 100 nights

IGM tomography:

- 10^{4} background sources 25 deg^{2} corresponds to LBGs at R≈24
- high-S/N spectra require whole-night integrations
- FOV ~ 15 arcmin with mulitplex ~ 20, requires 400 nights

Galaxy evolution down the luminosity function

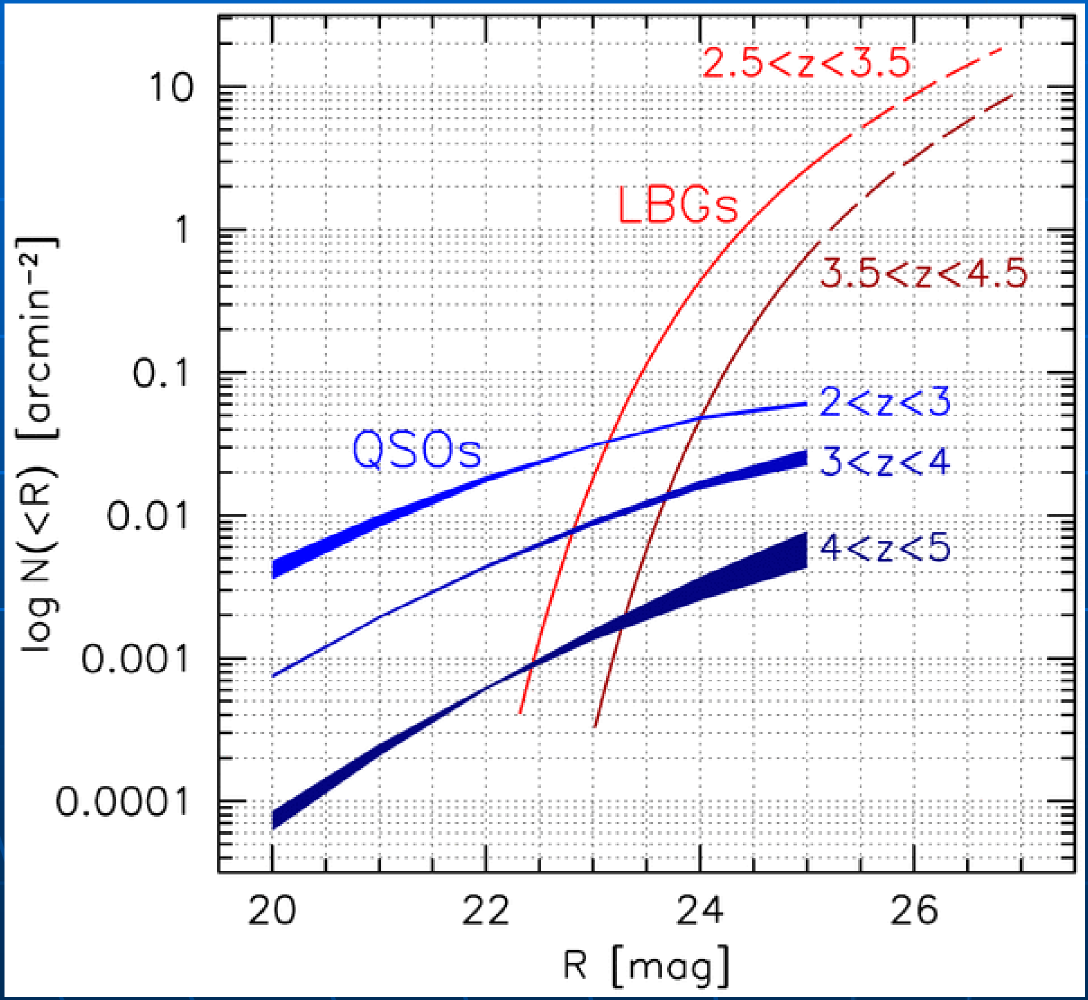


RAB

PHOTOMETRIC REDSHIFT

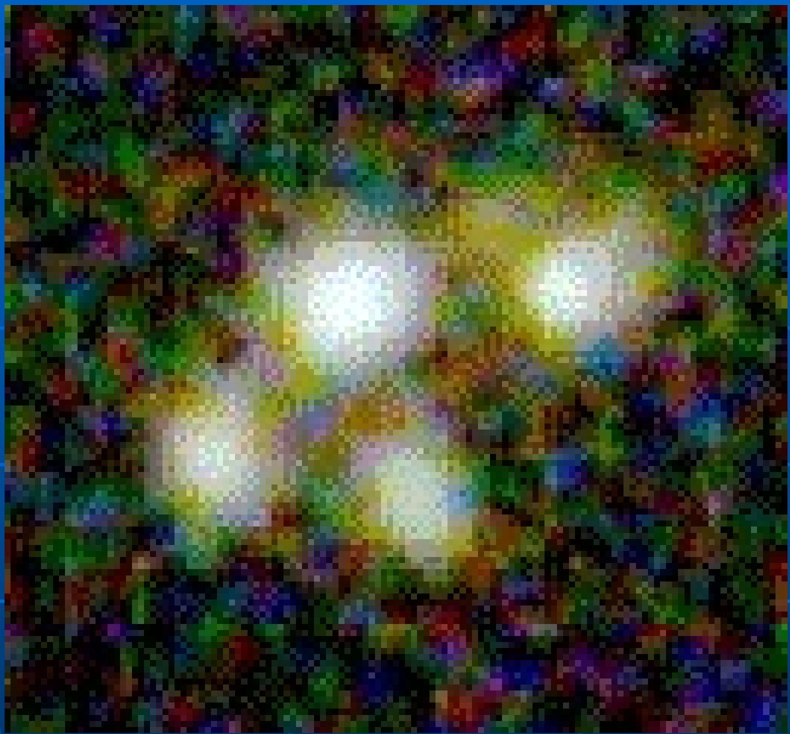
- **Arrows show S/N=10 limits for 10,000 seconds in 0.3-arcsec seeing (6400 Å; R=2000)**
- **100m, R_{AB}=28.6**

Background sources for IGM probes



- **At R=24 Lyman break galaxies become extremely abundant**

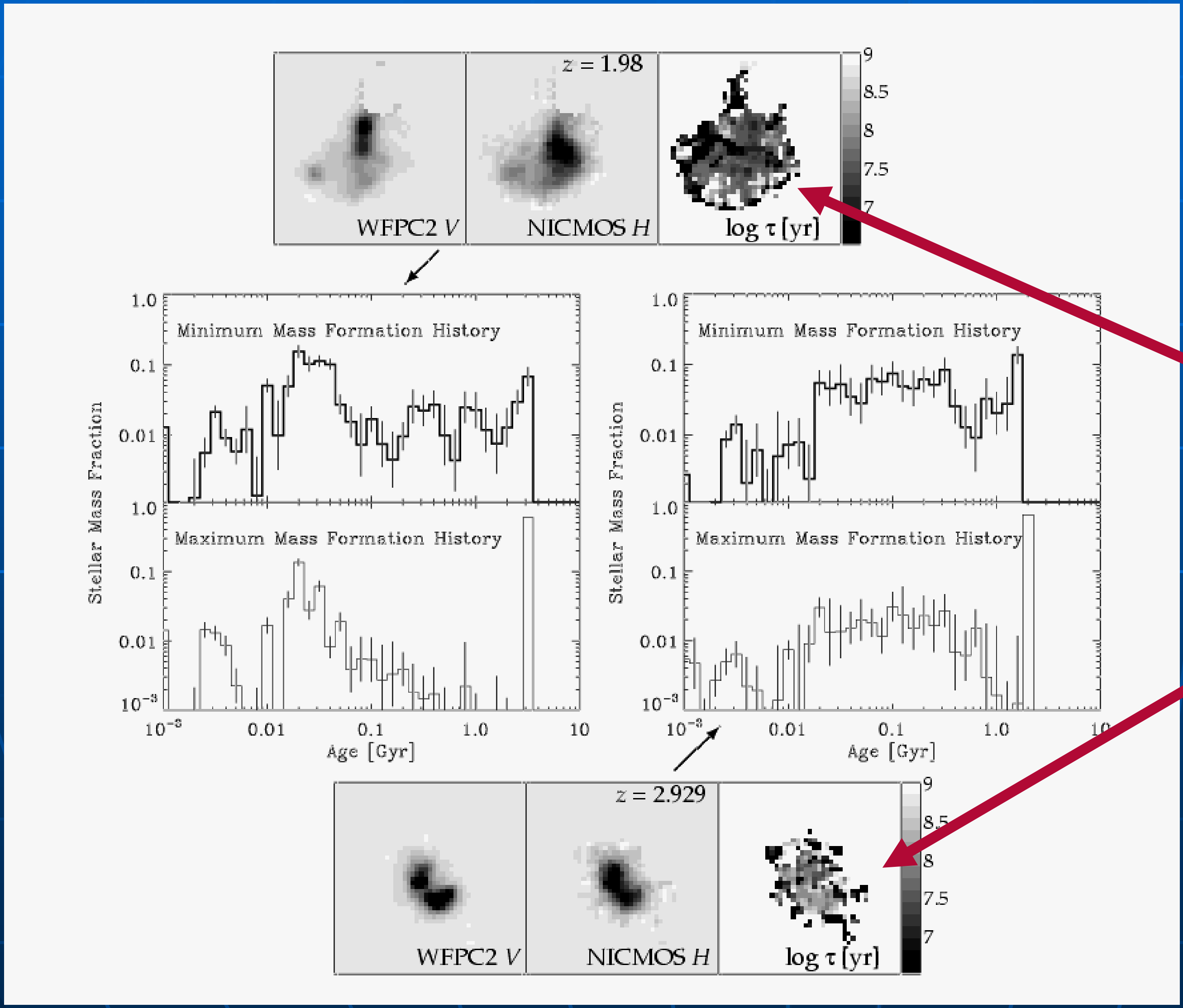
Detailed internal properties of high-redshift galaxies



(z=3 galaxy from Hubble Deep Field; HST psf ~ 0.1" ~ 770 pc)

- **Science goals:**
  - **Dynamical masses**
  - **Enrichment and star formation history as a function of position**
  - **Direct observations of the build-up of mass through merging**

Hints of internal structure at high redshift

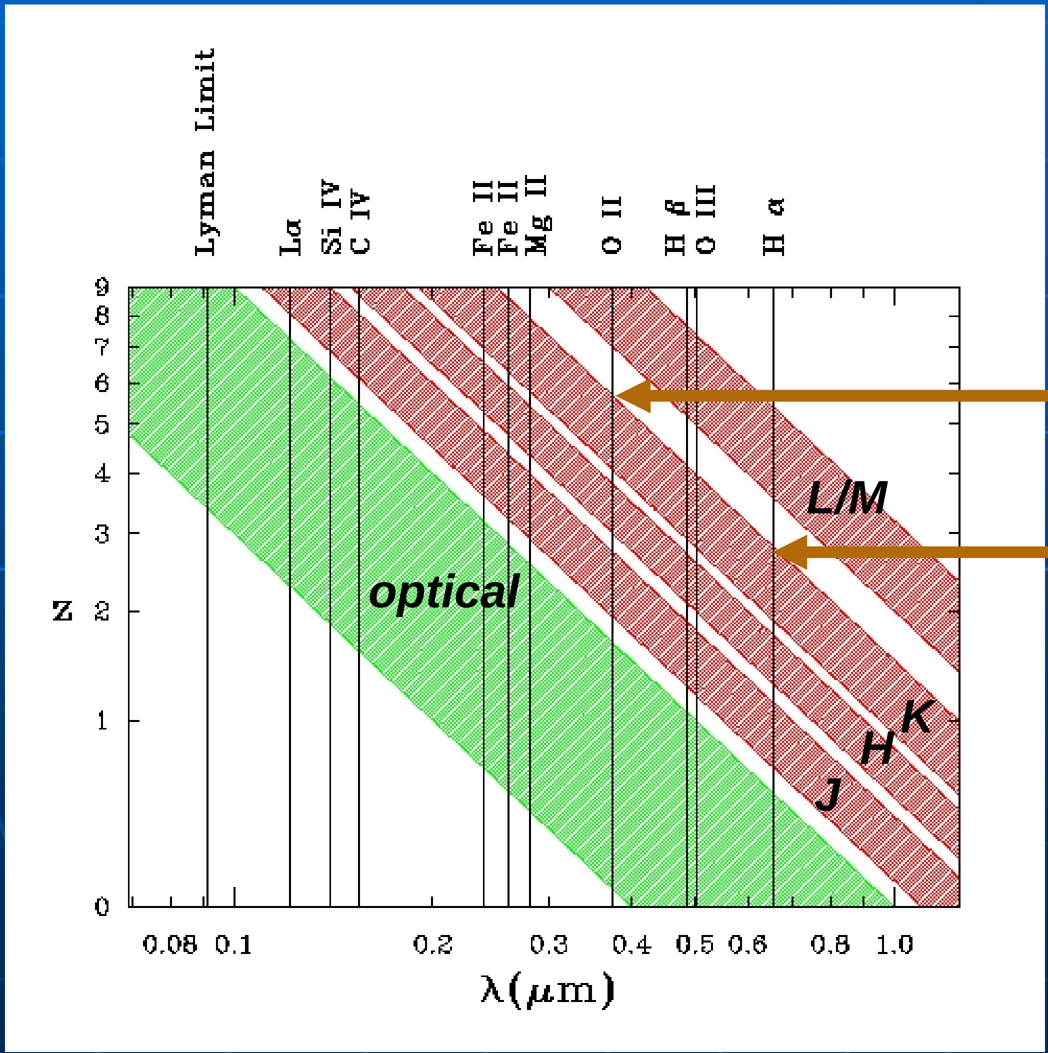


HST/WFPC2
HST/NICMOS
colors

color/age variation inside high-z galaxies

Figure from Casey Papovich

Near-IR case: for chemical abundances, star formation histories



Lines in the optical and near-infrared

[OII] to z = 6

Hα to z = 3

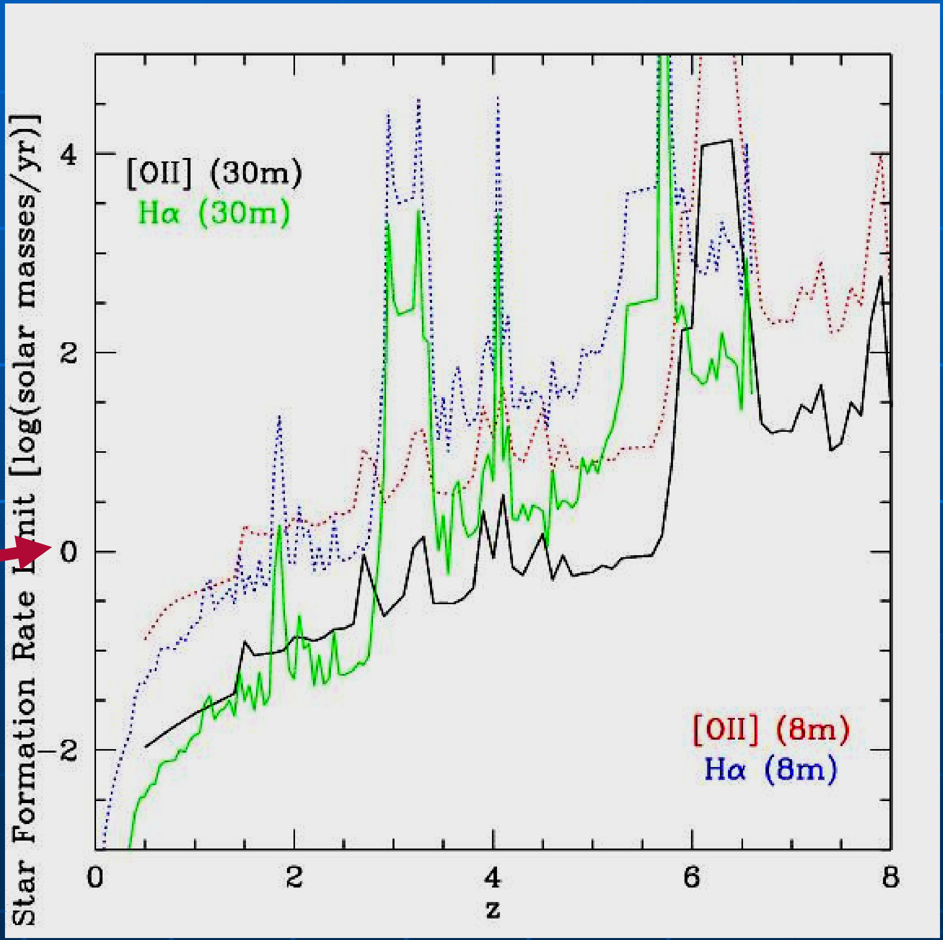
- *Few strong lines in optical between redshifts of about 1 to 3*
- *NEED near-IR*

Plot from Oke & Barton (2000)

Line sensitivity as a function of z in Hα and [OII]

- **At z < 1.5, [OII] in optical and Hα in NIR are comparable even with no dust; no metallicity effects in using Hα star formation rate**
- **Beyond z=1.5, both lines perform well in NIR; for z=2-3, Hα is best**

Globular cluster forming in 1 dynamical timescale

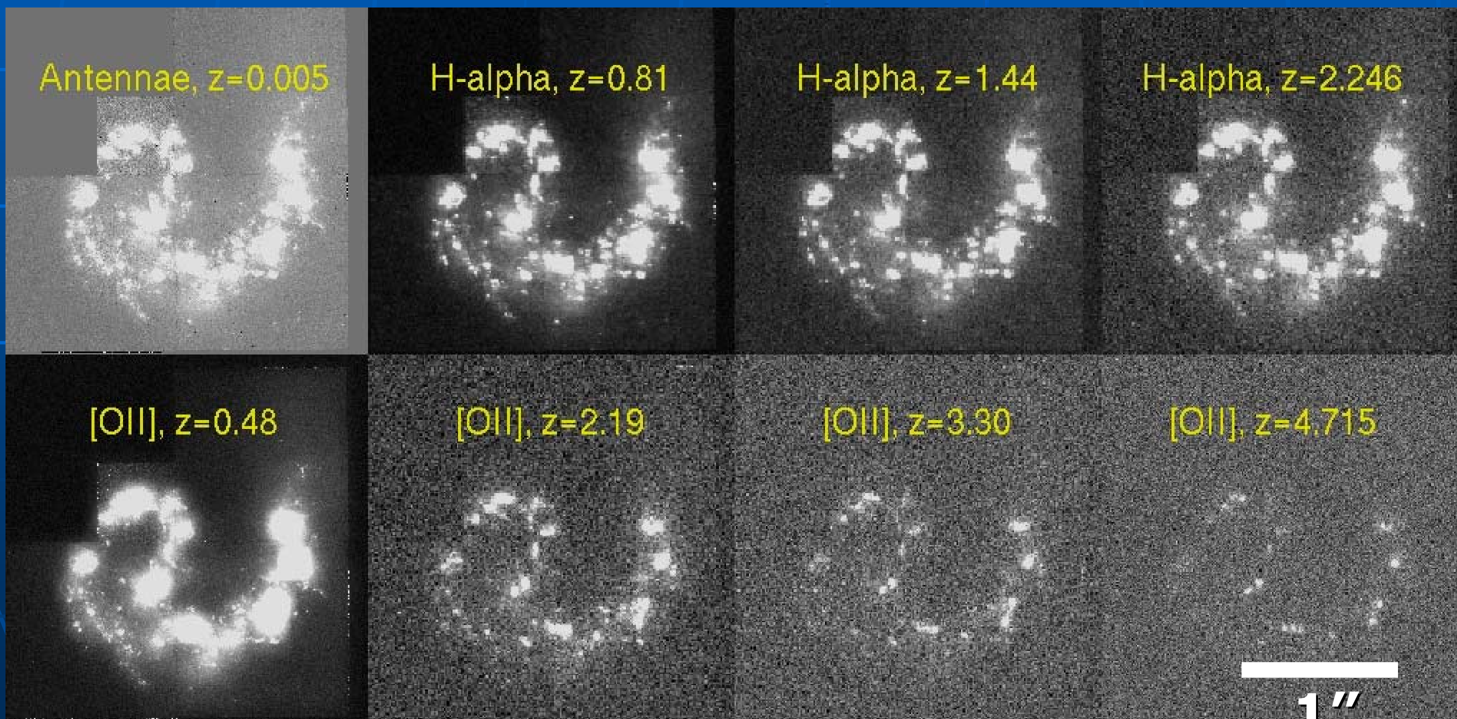


Sensitivity to unresolved emission lines, R=3000, T=10,000 sec, "optimistic" AO

The potential to detect lines from star forming regions

- **The Antennae: a lumpy local starburst**

J **H** **K**

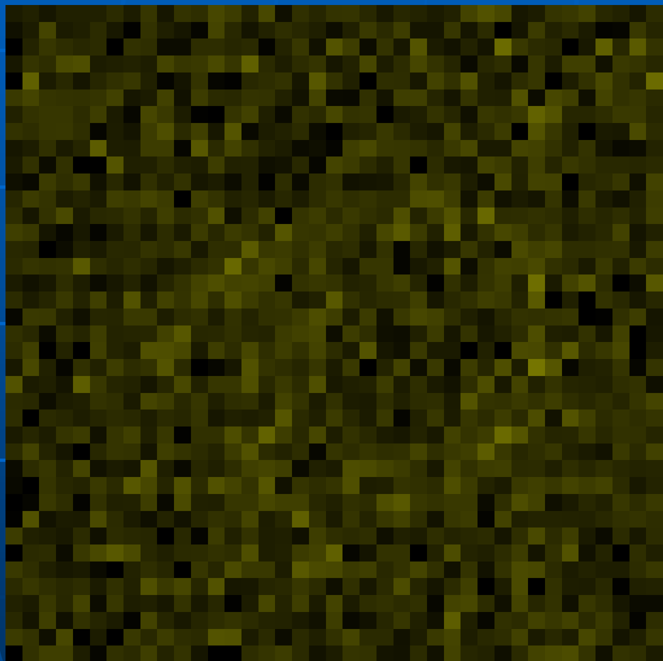


10^5 sec with 30m telescope, good AO, small pixels

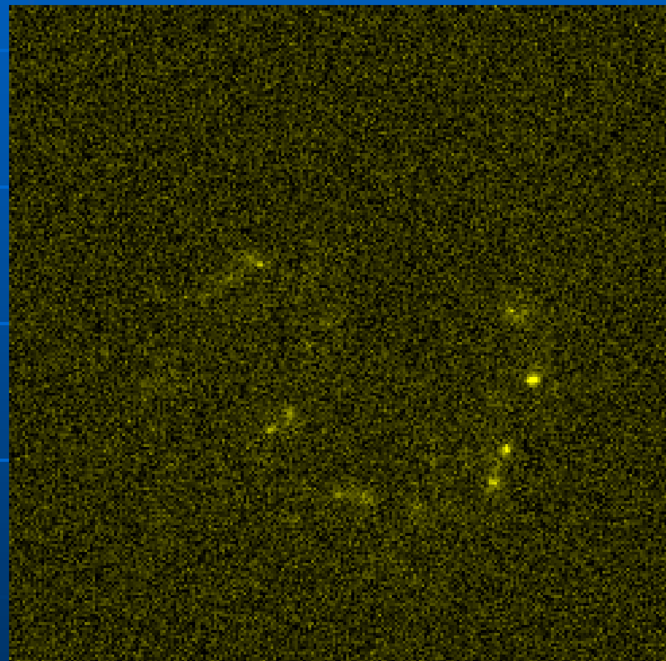
R=3000

(image of Antennae courtesy of B. Whitmore)

The potential to detect lines from star forming regions



8m



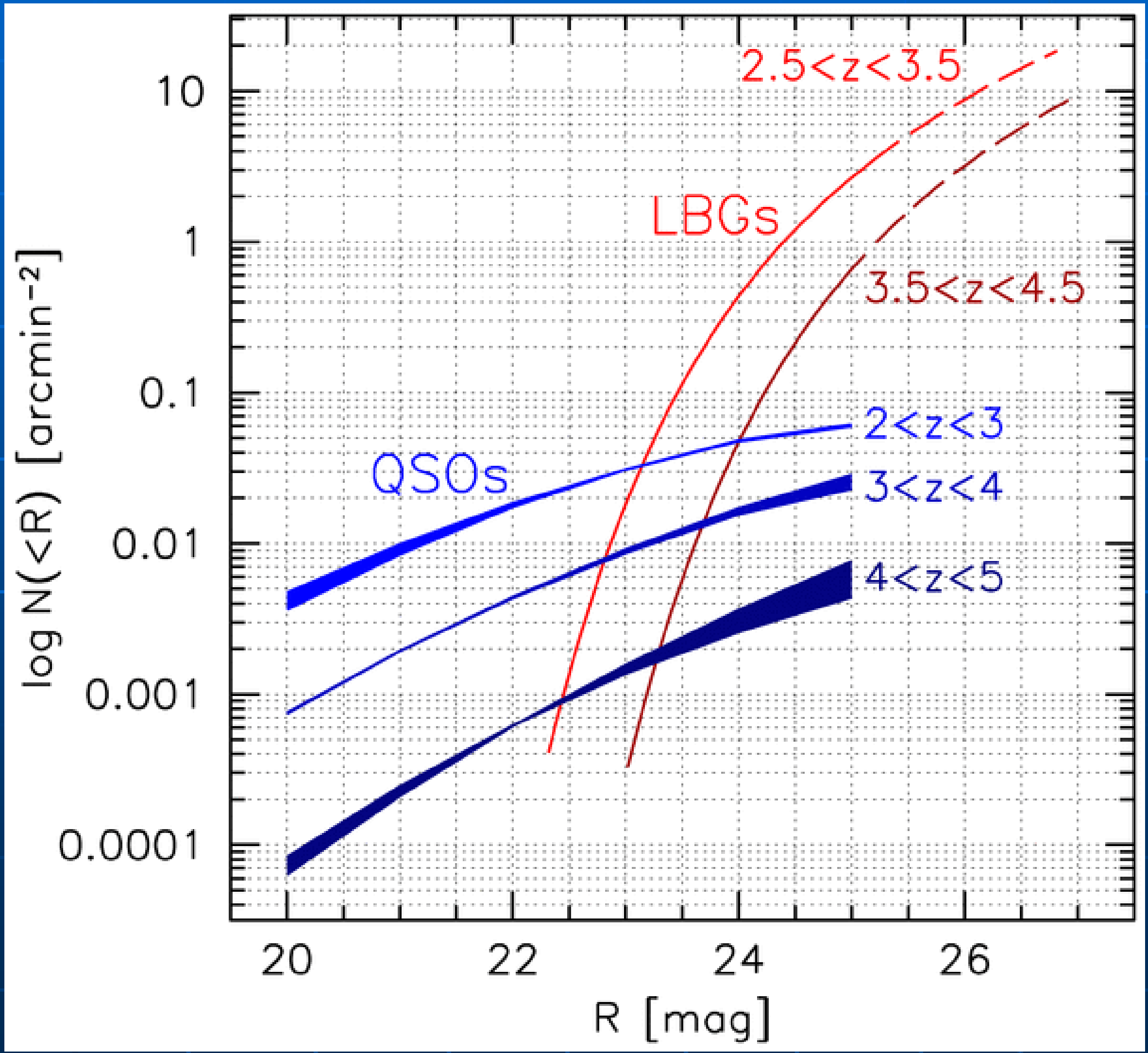
30m

10^5 sec with 30m telescope, good AO, Z=4.715

R=3000

(image of Antennae courtesy of B. Whitmore)

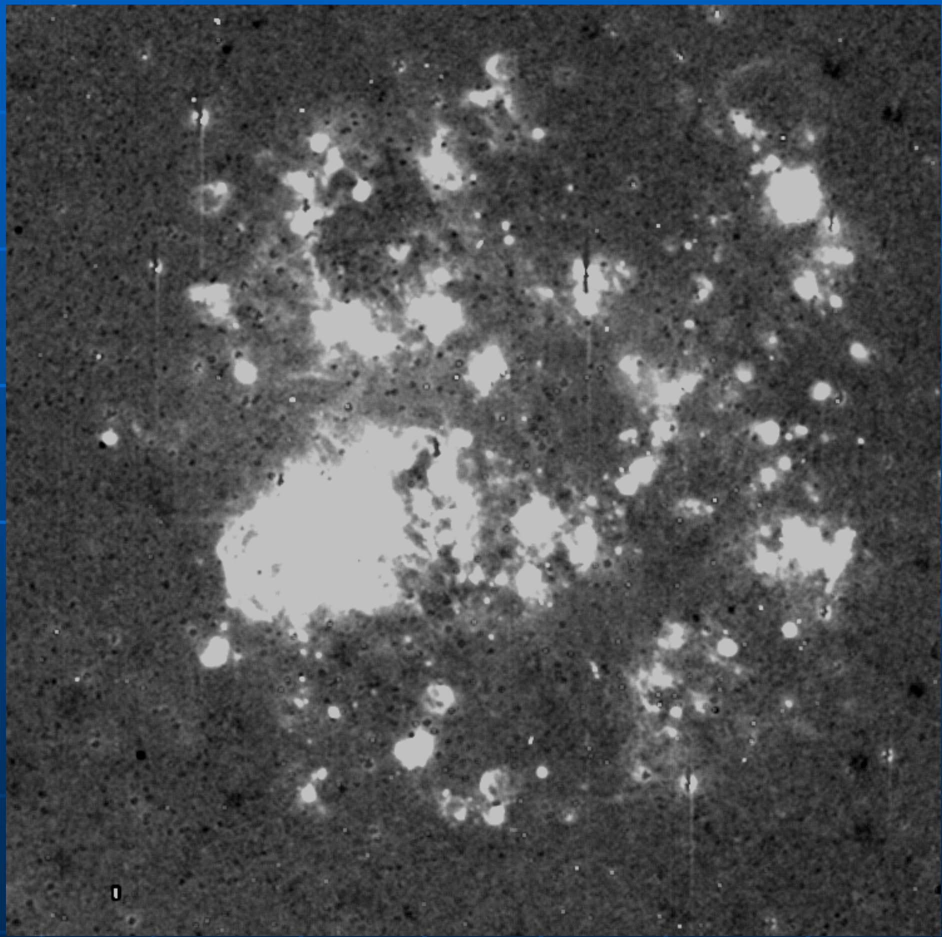
Kinematics of Lyman break galaxies



- **At R < 25, ~3-4 LBGs per square arcminute at 2.5 < z < 3.5; ~1 at z > 3.5**
- **8-hour exposures, multiplex ~ 40 objects with GLAO, FOV~10′x10′ yields 1,000 galaxies in 25 nights**
- **MCAO for ~240 objects (16 per 2′x2′ field) with ~100 pc resolution with 24-hour exposures in another 45 nights**

The potential to detect lines from normal star forming regions

- **Hα image of 30 Dor in the LMC: a local star-forming region**



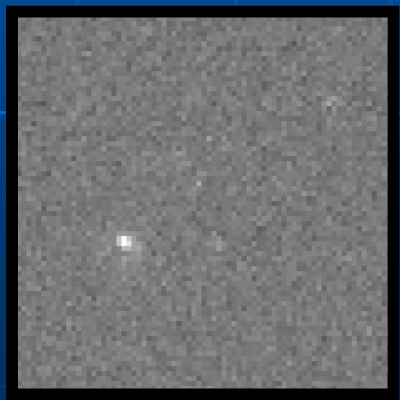
LMC courtesy of R. Kennicutt

(Kennicutt et al. 1995)

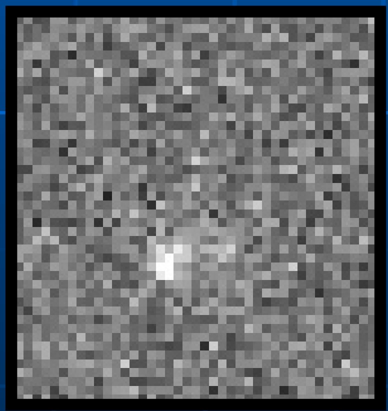
The potential to detect lines from star forming regions

- 30 Dor in [OII](3727)
- 10^5 sec., R=3000, excellent image quality

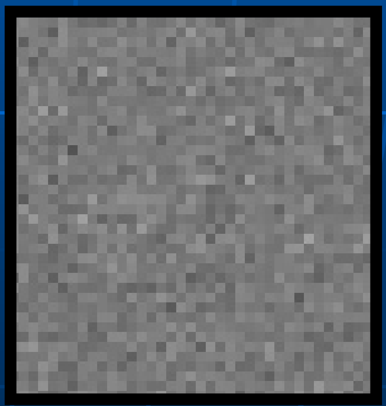
z=0.47 (30m)



z=2.19 (30m)

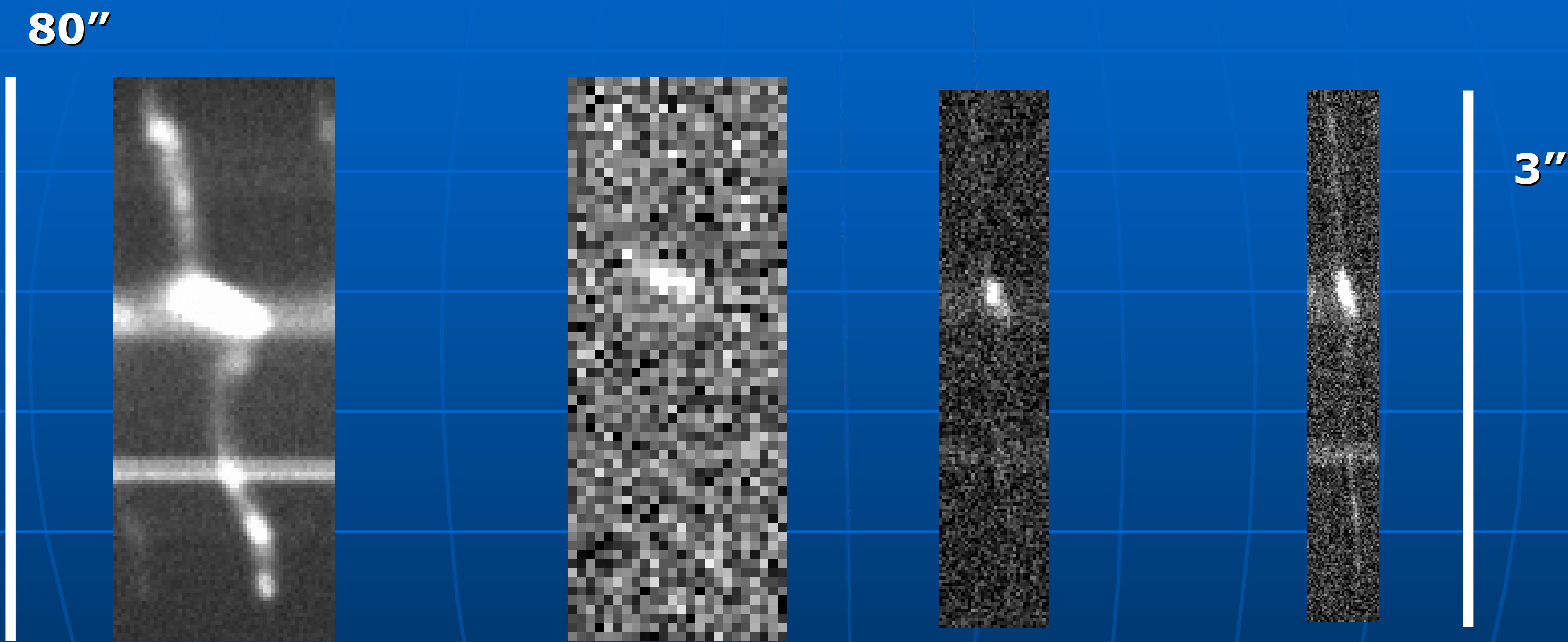


z=3.3 (30m)



z=2.19 (8m)

Emission lines: "Typical galaxies" at z=1.5 in Hα



z=0

z=1.5
8m

z=1.5
20m

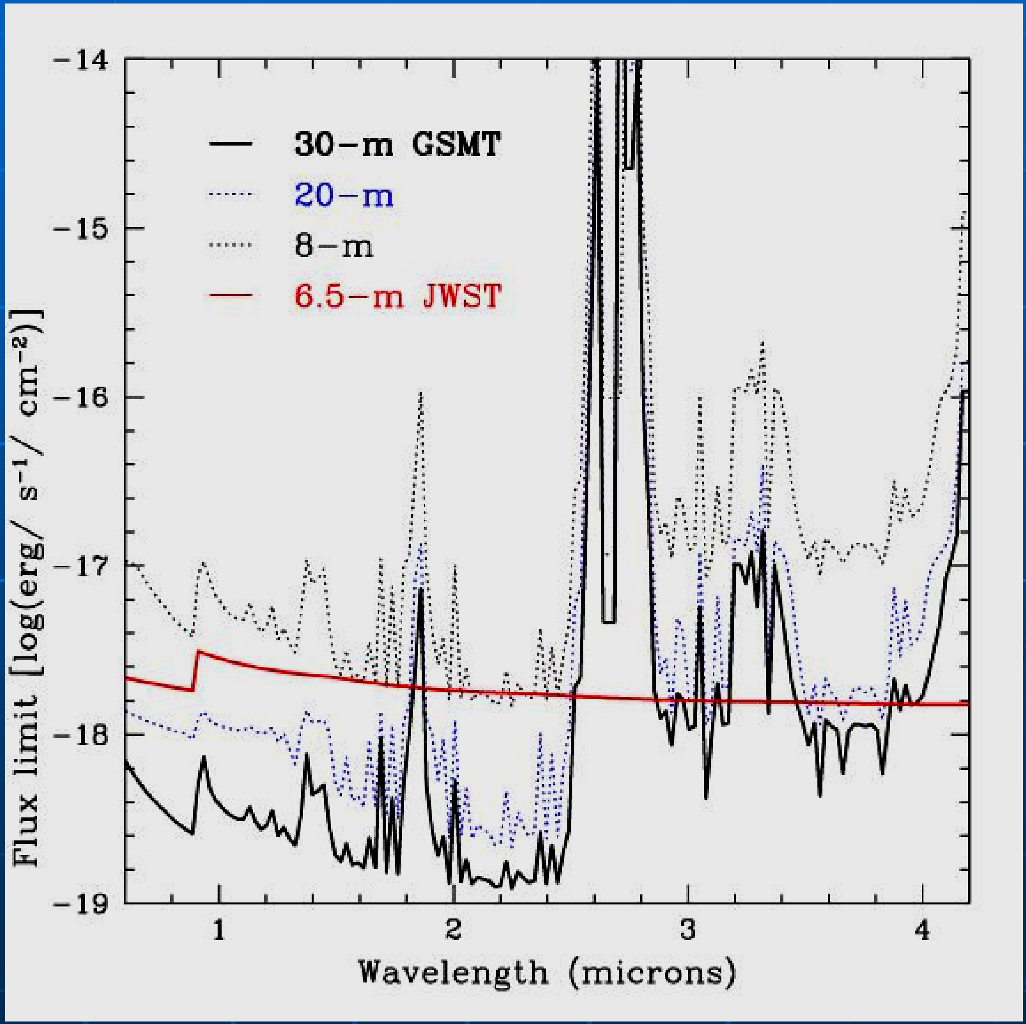
z=1.5
30m

20-hour exposure

8-meter telescopes only detect the center!

Detecting the first objects in the universe

- **At z=6-10, Lyα is at $0.85 < \lambda < 1.4$ μm: regime where a 30-meter is much more sensitive than JWST**

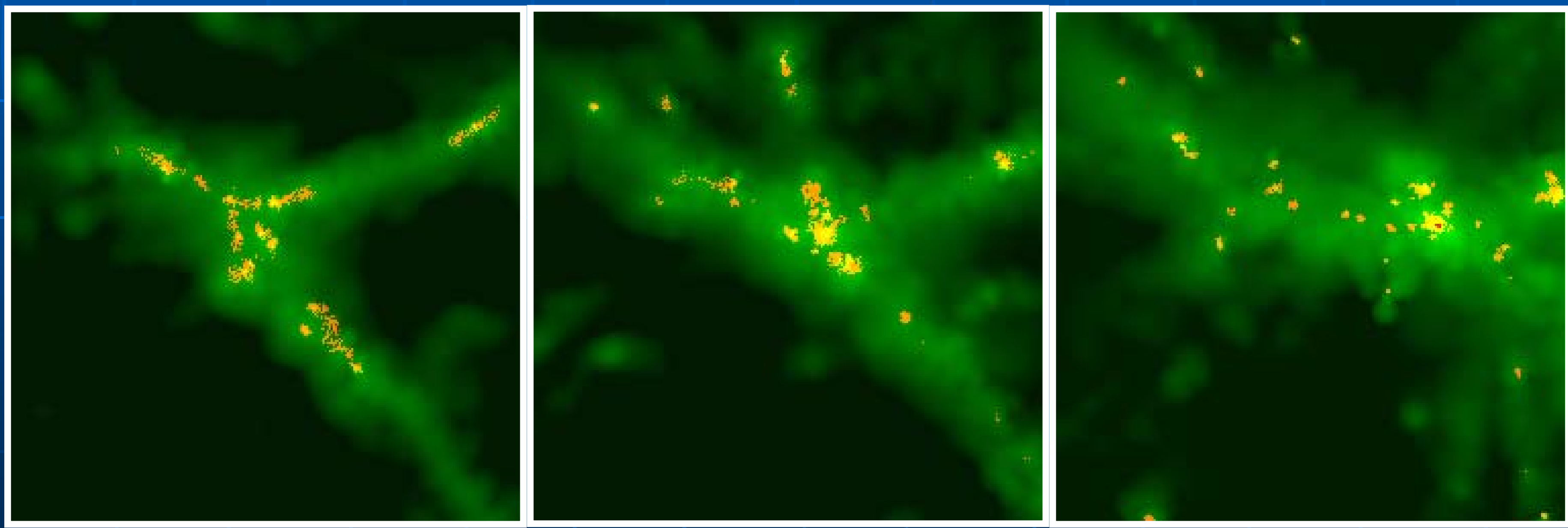


Sensitivity to unresolved emission lines, R=3000, t=10,000 seconds

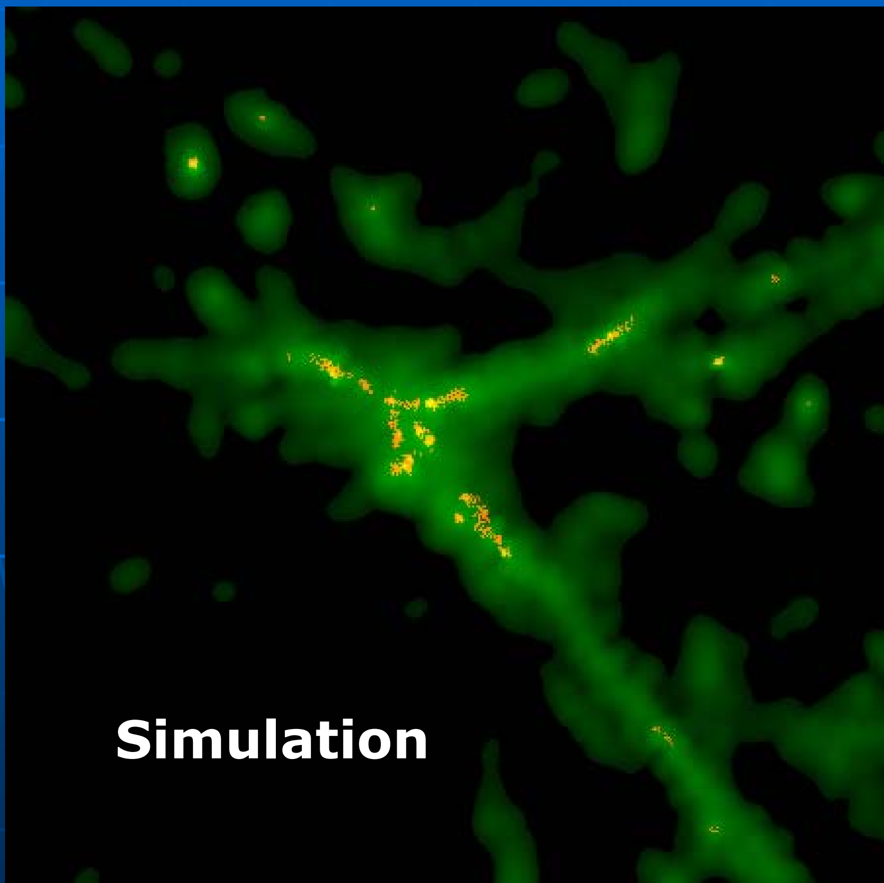
Clues from hydrodynamic simulations

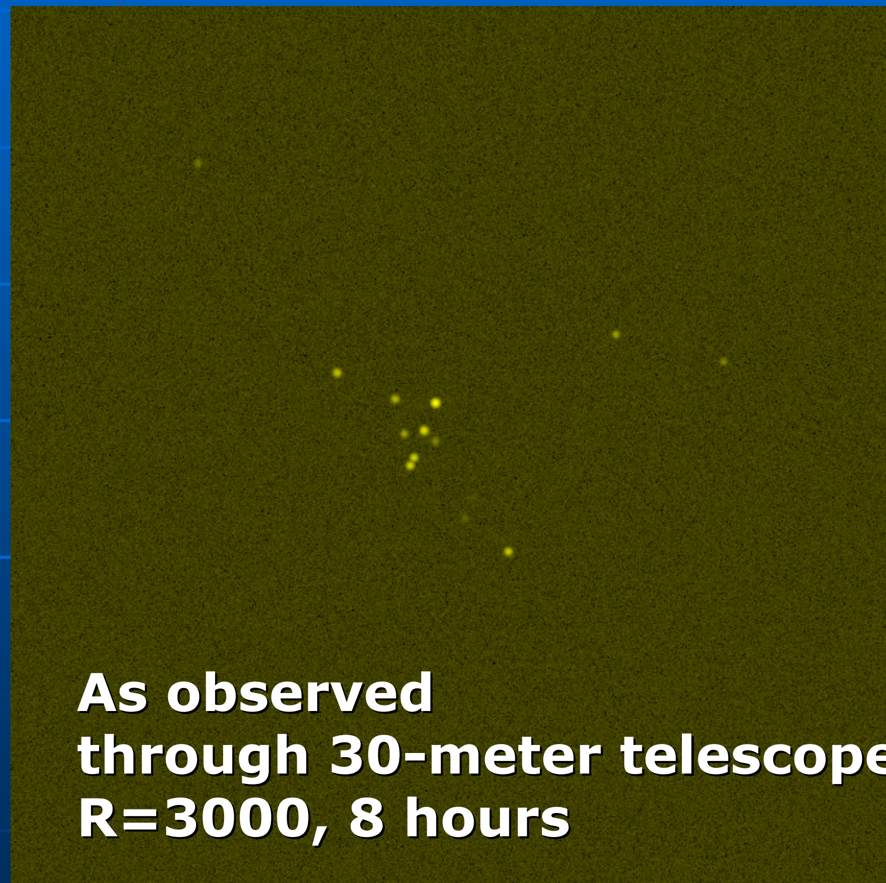
- **Hydrodynamic simulations of Davé, Katz, & Weinberg**
  - **Lyα cooling radiation (green)**
  - **Light in Lyα from forming stars (red, yellow)**

z=10 **z=8** **z=6**



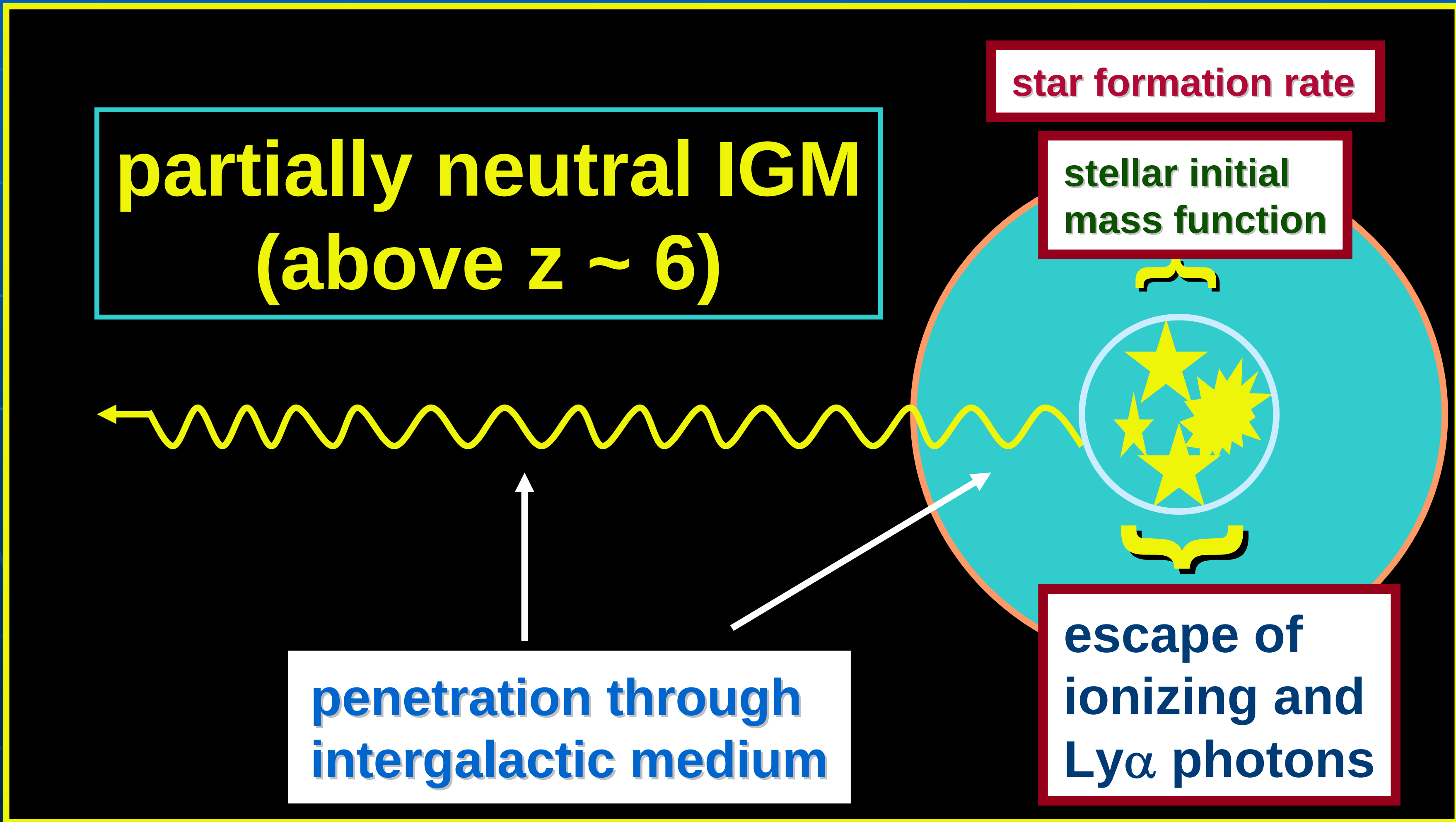
Lyα from Stars forming at z=10



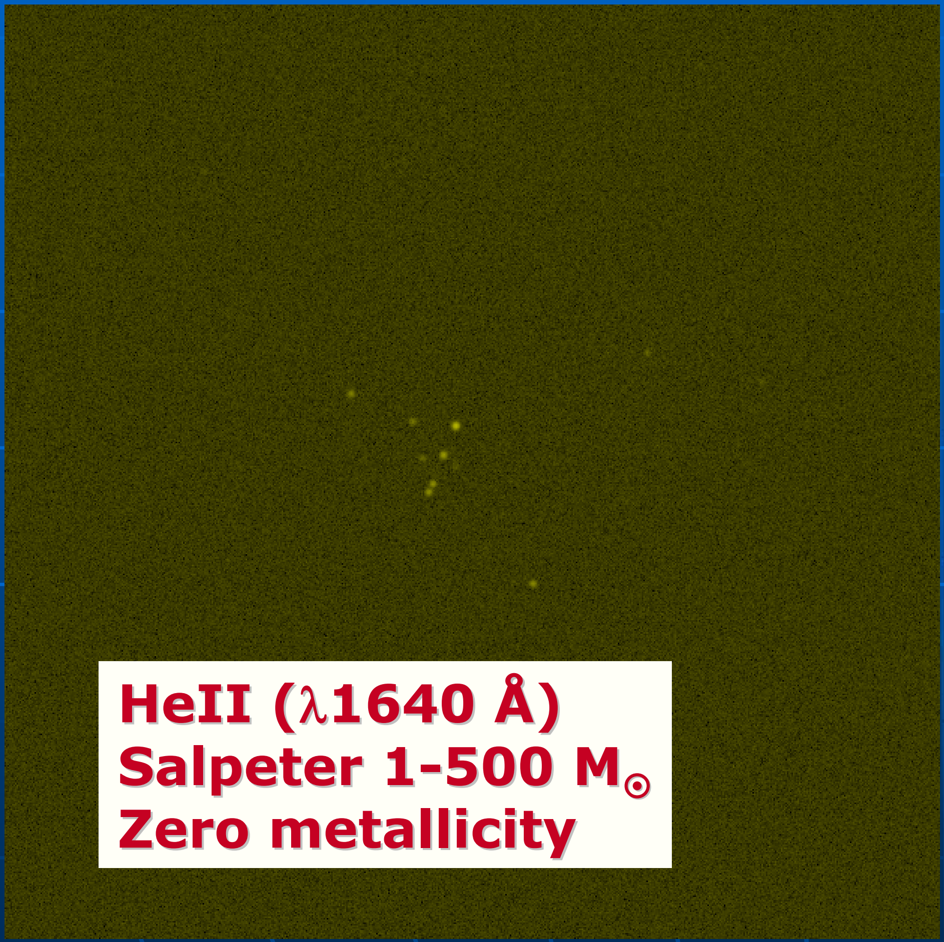


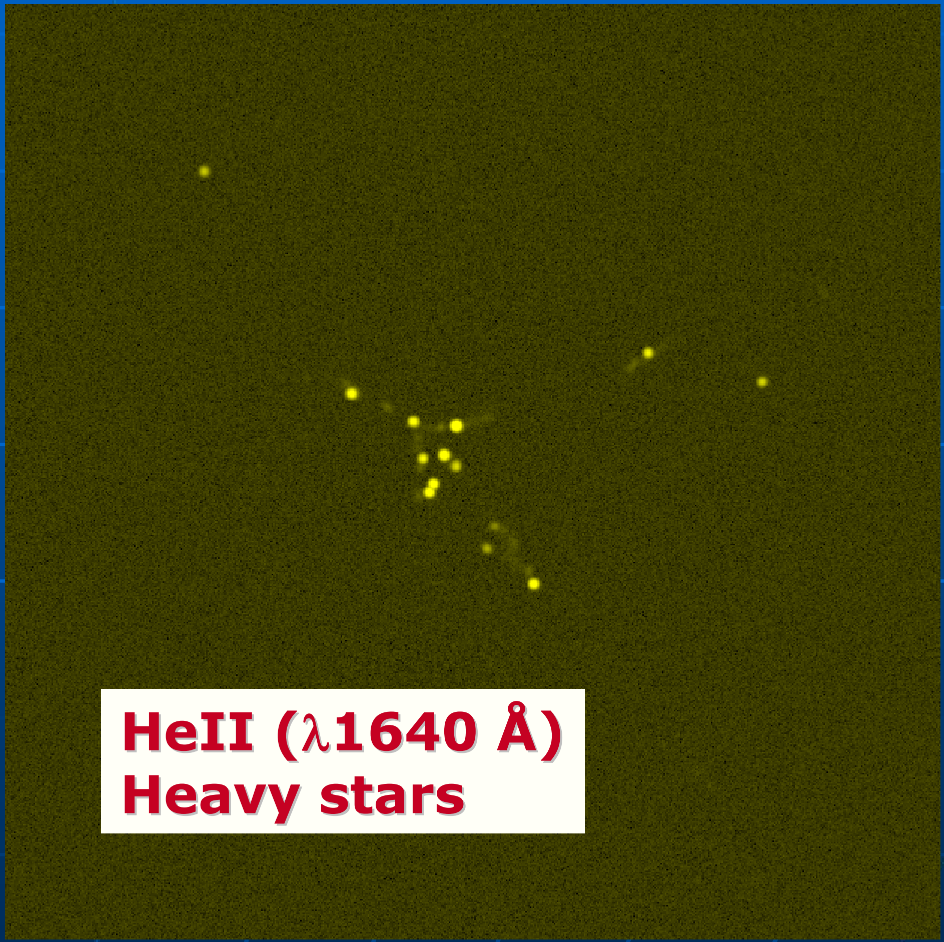
(Many thanks to R. Davé, J.-D. Smith)

Physical elements of star formation beyond reionization



Weighing z=10 stars





Simulation through 30m telescope, 8 hours, R=3000

Summary of major shifts

- **Probing the IGM with high spatial frequency**

- **Building galaxies**
  - Rotation curves of galaxies at z=1-1.5 that are as good as local samples now
  - Kinematics of Lyman break galaxies
  - Understanding sub-L* galaxies at z=2-5

- **Exploring the extremely high-redshift universe**
  - z=6-10 objects may be discovered with 8-m-class telescopes or JWST, but no detailed properties available
    - IMF
    - IGM from the Lyα line profile beyond reionization

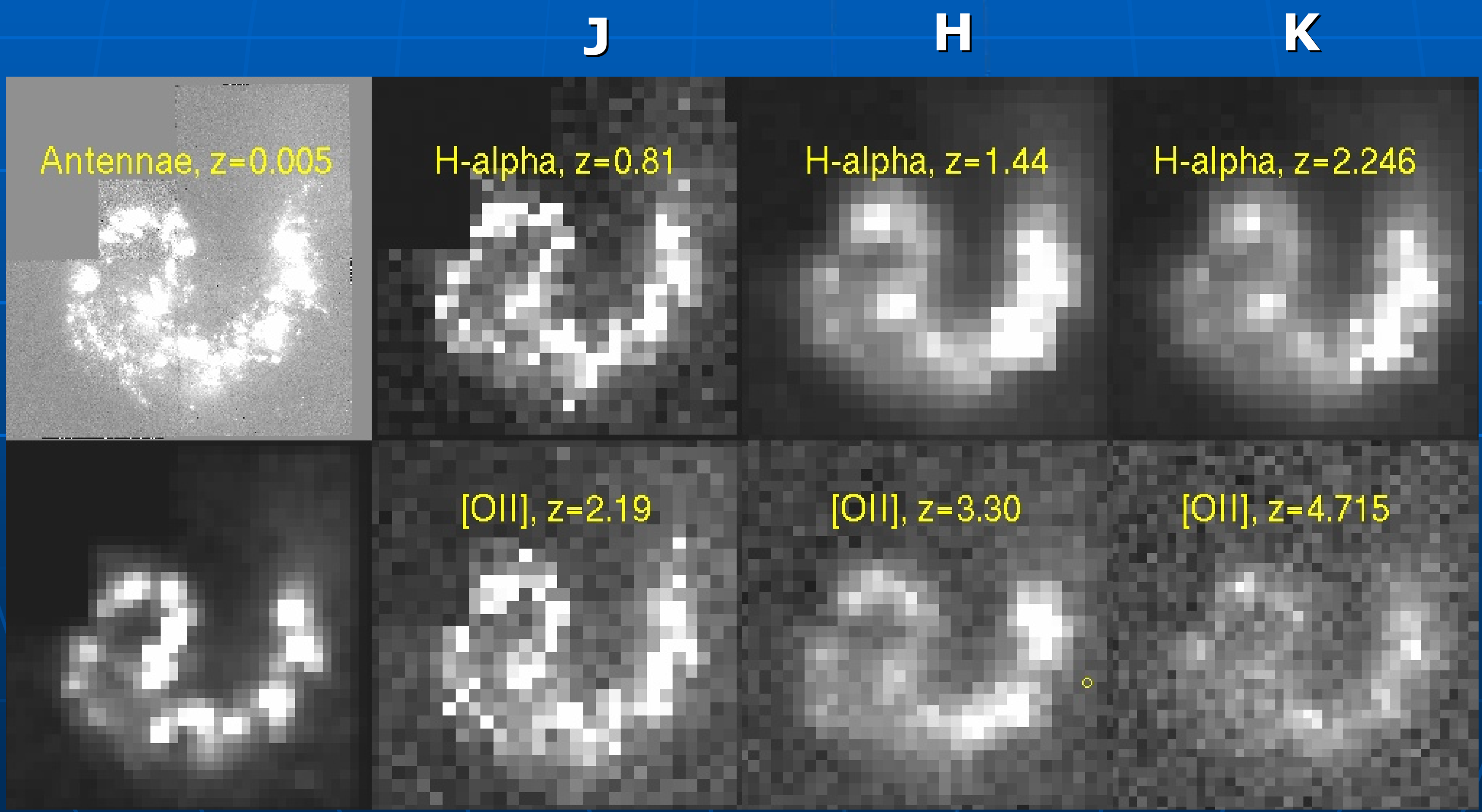
What is beyond a 30-meter telescope?

- **Older or lower-surface-brightness stars and star formation at z > 2; dwarf galaxies at z > 2**

- **Faint emission lines and absorption lines at z > 5-6; lines in the mid-IR**
  - **More detailed metal abundances**
  - **Rest-frame optical lines in “first-light” objects**

The potential to detect lines from star forming regions

- **The Antennae: a luminous, lumpy local starburst**



10^5 sec. with 30m telescope: big pixels

R=3000

(image of Antennae courtesy of B. Whitmore)

Scalings: Magnitude Limits

SENSITIVITIES				
	Sensitivity (Fixed S/N, fixed exposure time, different source)		**Sensitivity over 8–meter** (Fixed S/N, fixed exposure time, fainter source)	
	Object Noise	Sky Noise	Object Noise	Sky Noise
Light Bucket (fixed seeing)	**$F \sim D^{-2}$**	**$F \sim D^{-1}$**	20m: 2 magnitudes 30m: 2.9 magnitudes	20m: 1 magnitude 30m: 1.44 magnitudes
Diffraction Limited	**$F \sim D^{-2}$**	**$F \sim D^{-2}$**	20m: 2 magnitudes 30m: 2.9 magnitudes	20m: 2 magnitudes 30m: 2.9 magnitudes

Scalings: Exposure Times

EXPOSURE TIMES				
	Exposure time scalings (Fixed S/N, fixed source flux)		Time savings over 8–meter (Fixed S/N, fixed source flux, shorter exposure)	
	Object Noise	Sky Noise	Object Noise	Sky Noise
Light Bucket (fixed seeing)	$t \sim D^{-2}$	$t \sim D^{-2}$	20m: factor of 6.25 30m: factor of 14.1	20m: factor of 6.25 30m: factor of 14.1
Diffraction Limited	$t \sim D^{-2}$	$t \sim D^{-4}$	20m: factor of 6.25 30m: factor of 14.1	20m: factor of 39.1 30m: factor of 198

Not just a matter of patience! Many studies require large samples of objects.