

Galaxy evolution

An overview

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Major questions

- When and how did the first stars and galaxies form?
- How did their evolution affect their environment?
- How did their environment affect their evolution?
- How did galaxies grow their masses?
- How did they achieve their morphologies?
- Why did they stop forming stars?
- How are giant black holes related to galaxy evolution?

Overview: a timeline

- The Milky Way and nearby galaxies
- The local baseline (SDSS etc.)
- Cosmic octaves ($1+z = 2^N$) :
 - The declining years ($0 < z < 1$)
 - The boom years ($1 < z < 3$)
 - Early growth ($3 < z < 7$)
 - Here lie monsters ($7 < z < 15\text{-ish}$)
- Problems = possibilities

Egregious omissions

- $z \sim 0$ will get regrettably short shrift
- AGN even worse
- No cosmology

Milky Way and nearby galaxies

- Multiband, wide-field imaging surveys:
 - SDSS, 2MASS -> PAN-STARRS, LSST
- High-multiplex spectroscopy:
 - SDSS, SDSS2/SEGUE, RAVE, 6dF, VLT/FLAMES
 - Kinematics
 - Metal abundances
- Substructure and satellites:
 - New dwarf satellites
 - Tidal streams
- Deep imaging & kinematic spectroscopy of nearby galaxies:
 - Wide-field ground-based
 - Ultradeep HST

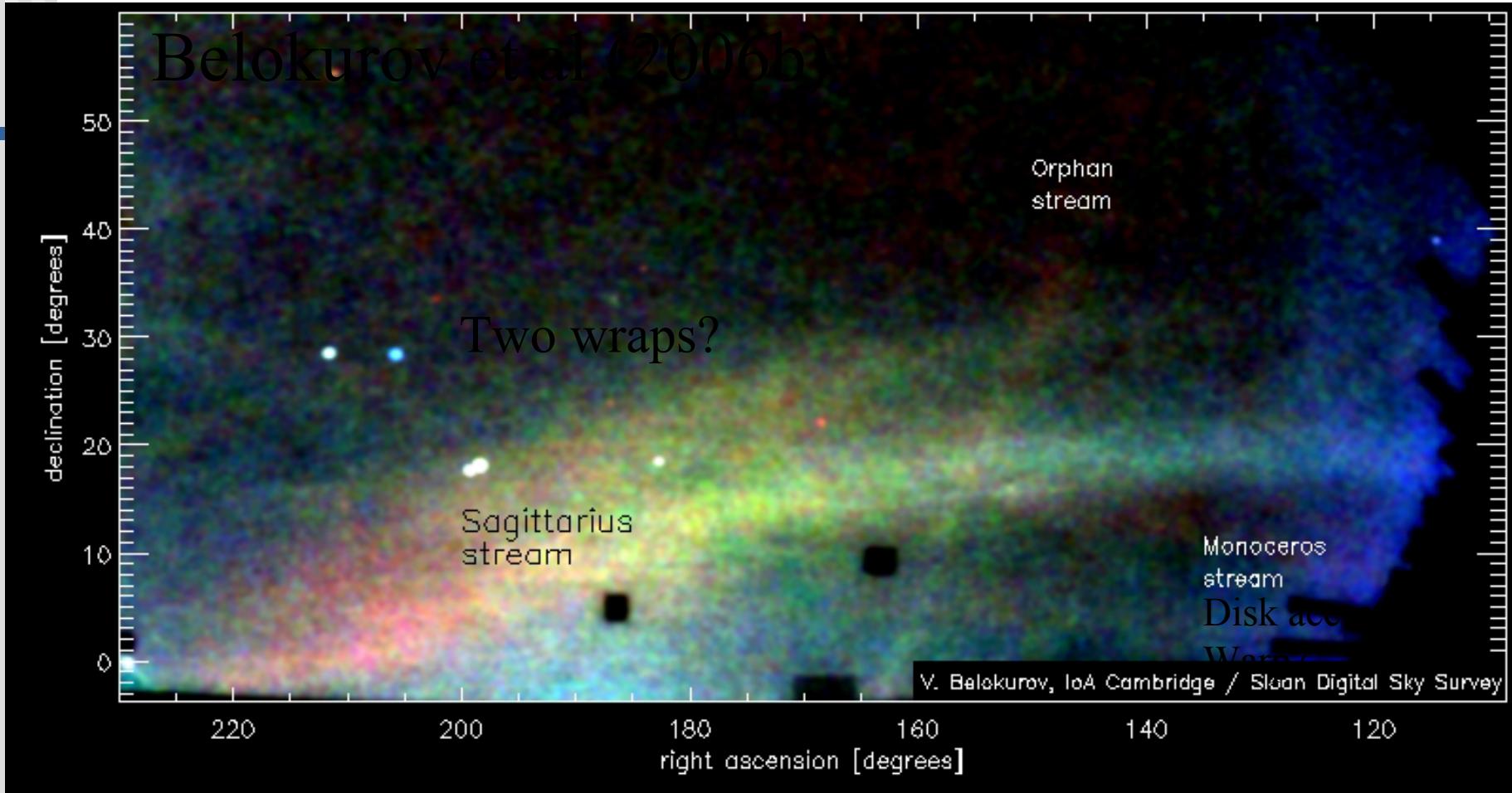
Substructure and accretion: outer Galaxy

Wyse, Gilmore & Franx 1997; Ibata et al 1994; 1996



Sgr dSph as known
in 1996

Field of Streams



SDSS data, $19 < r < 22$, $g-r < 0.4$ colour-coded by mag (distance), blue ($\sim 10\text{kpc}$), green, red ($\sim 30\text{kpc}$)

New Milky Way satellites

Belokurov et al. 2006

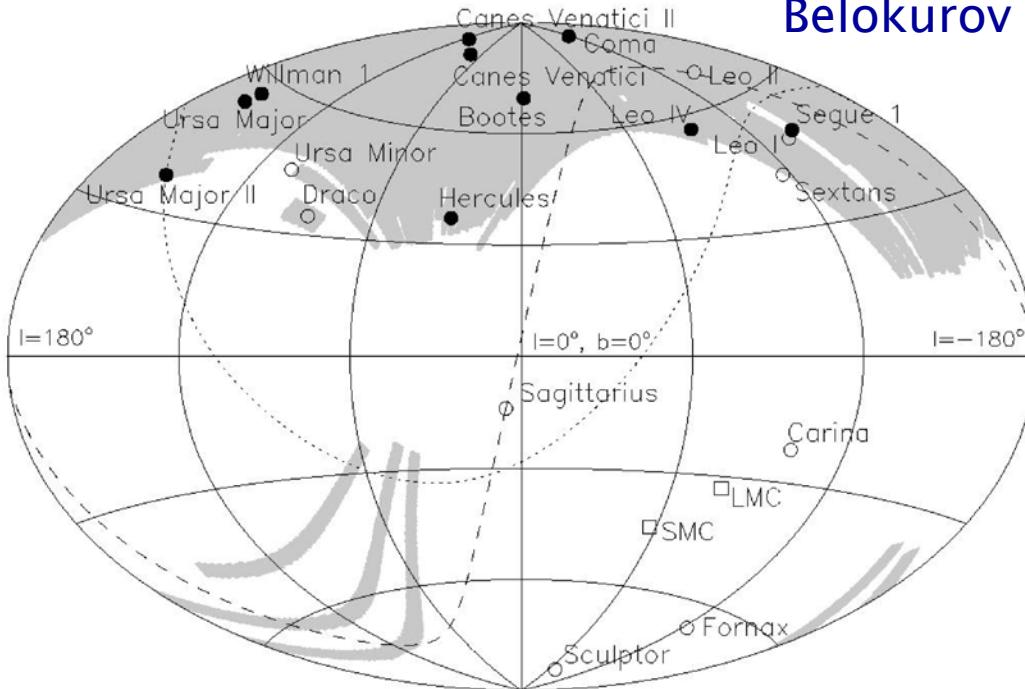
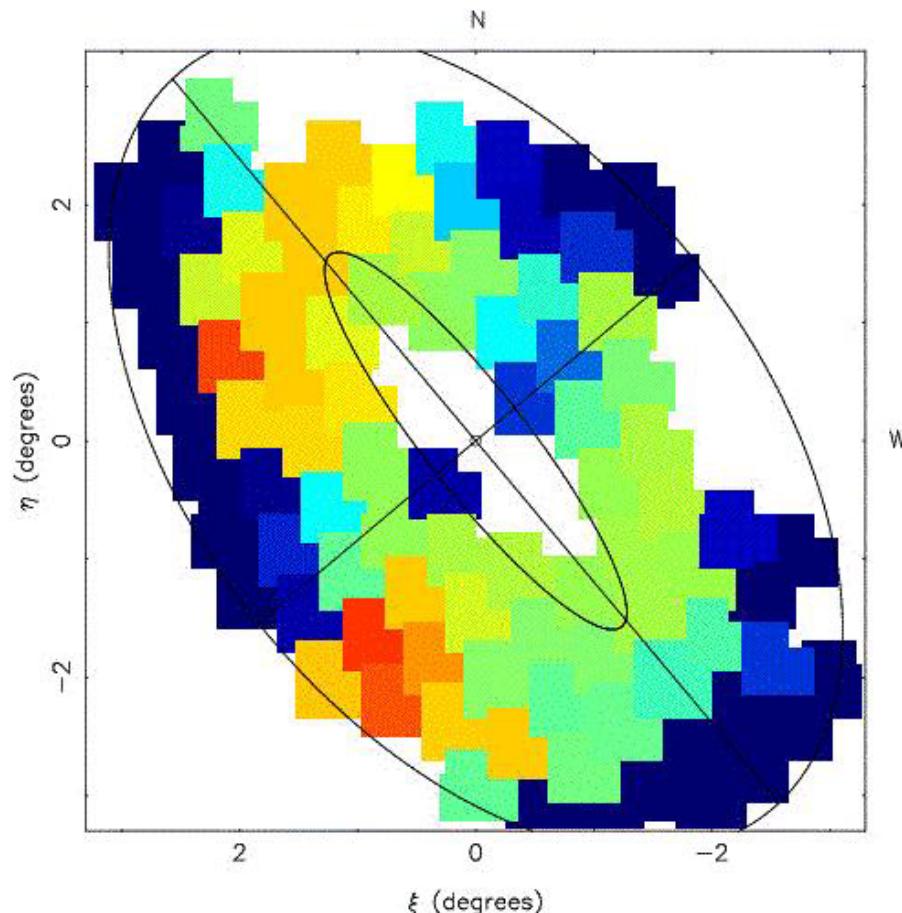
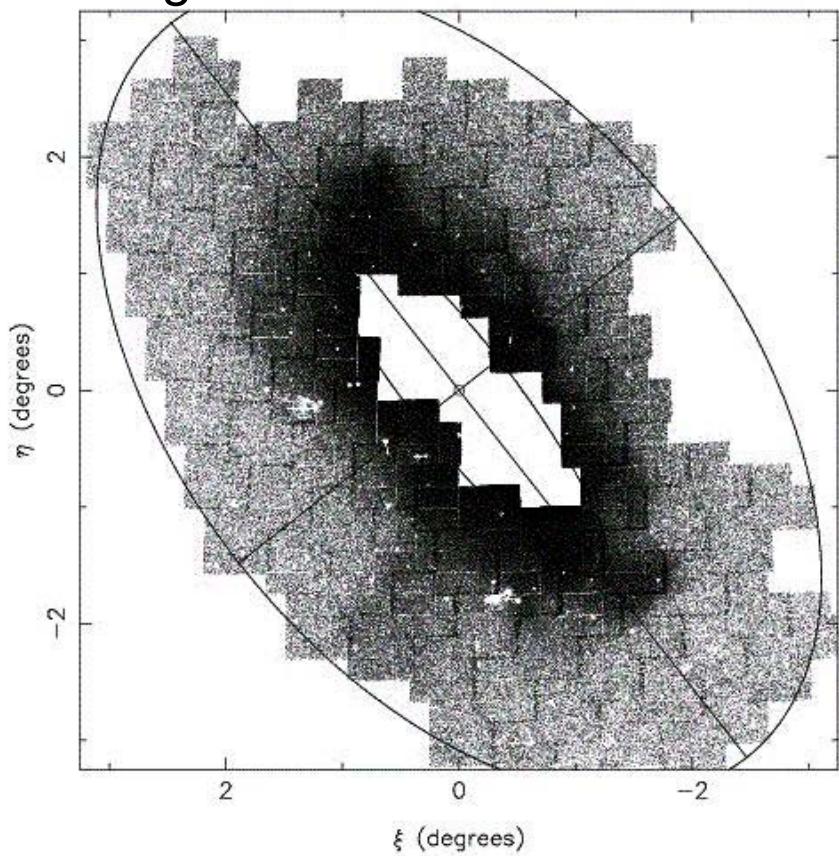


FIG. 7.— The locations of Milky Way satellites in Galactic coordinates. Filled circles are satellites discovered by SDSS, unfilled circles are previously known Milky Way dSphs. The light grey shows the area of sky covered by the Sloan survey and its extensions to date. The dashed and dotted lines show the orbital planes of the Sagittarius and Orphan Streams, respectively, taken from Fellhauer et al. (2006a) and Fellhauer et al. (2006b).

M31 substructure

Ferguson et al 2002

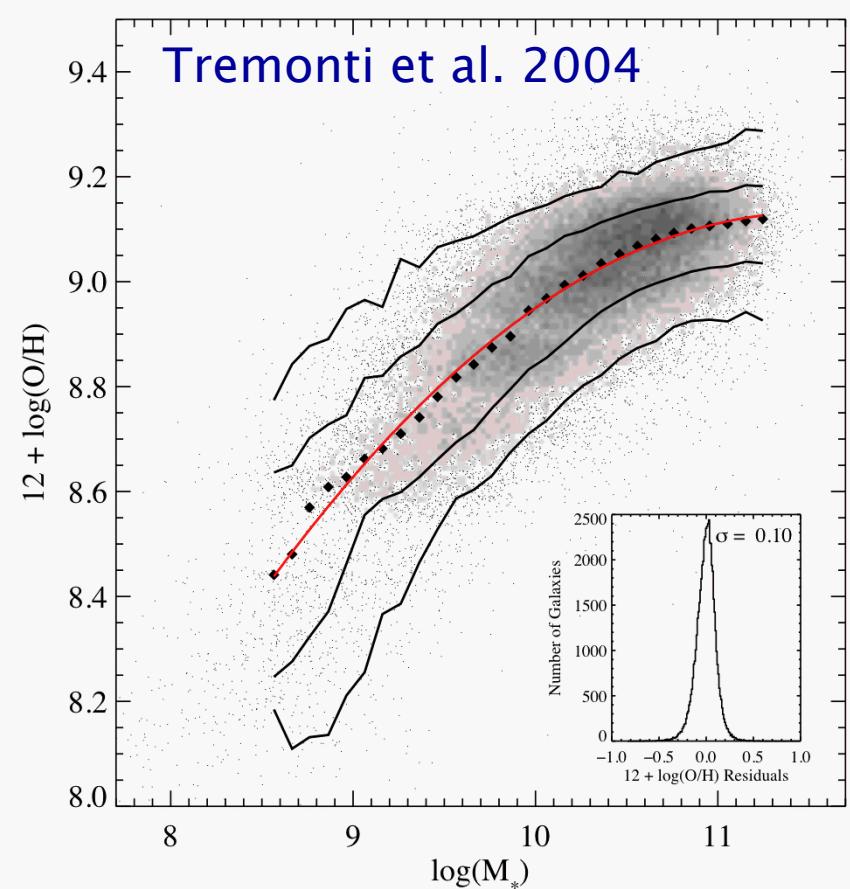
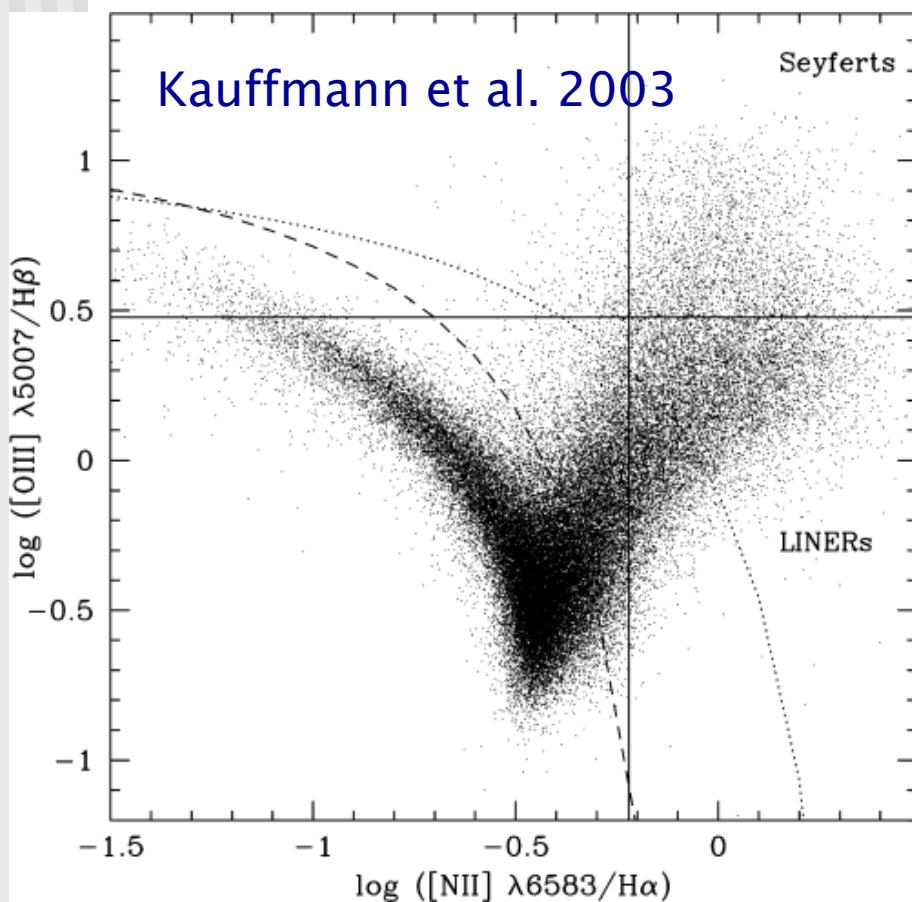


Inhomogeneities in stellar spatial distributions and colors, metallicity – also age ranges and kinematics; Guhathakurta

The local baseline (SDSS etc.)

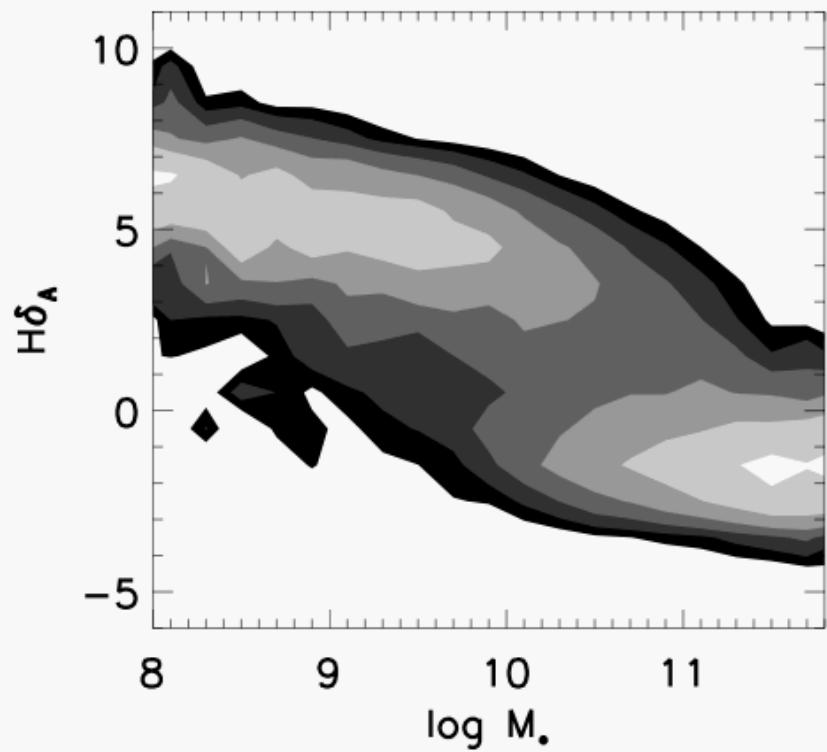
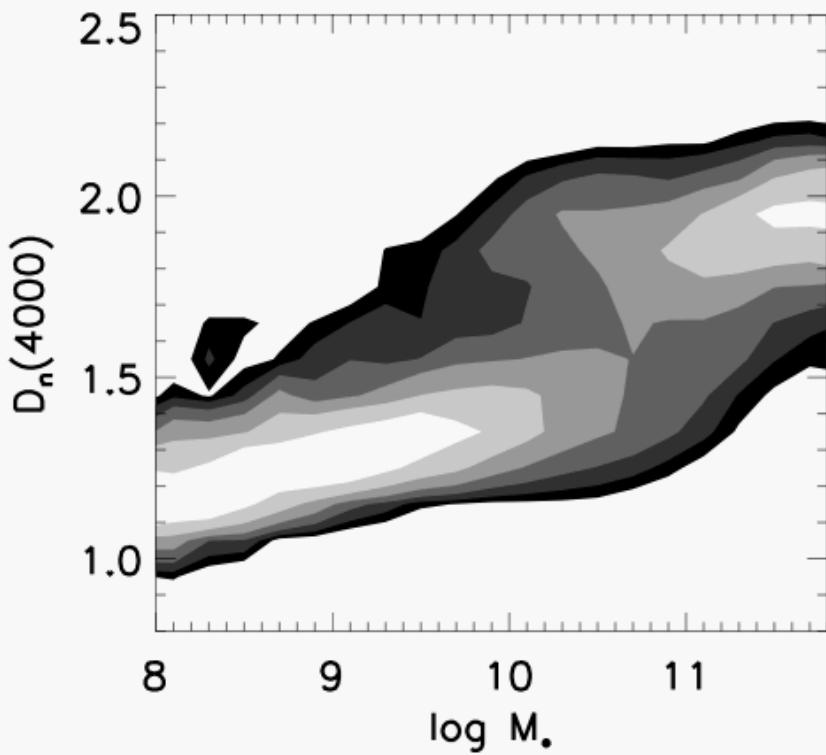
- Detailed characterizations of the interplay between properties for $\sim 10^{5-6}$ galaxies:
 - Stellar masses
 - Stellar populations
 - Chemical abundances
 - AGN activity
 - Galaxy structure & morphology (crude)
 - Environment
- Enhanced by combining SDSS with other data (GALEX, NVSS, ROSAT, Spitzer, etc.)

Emission line diagnostics



Stellar populations

Kauffmann et al. 2003



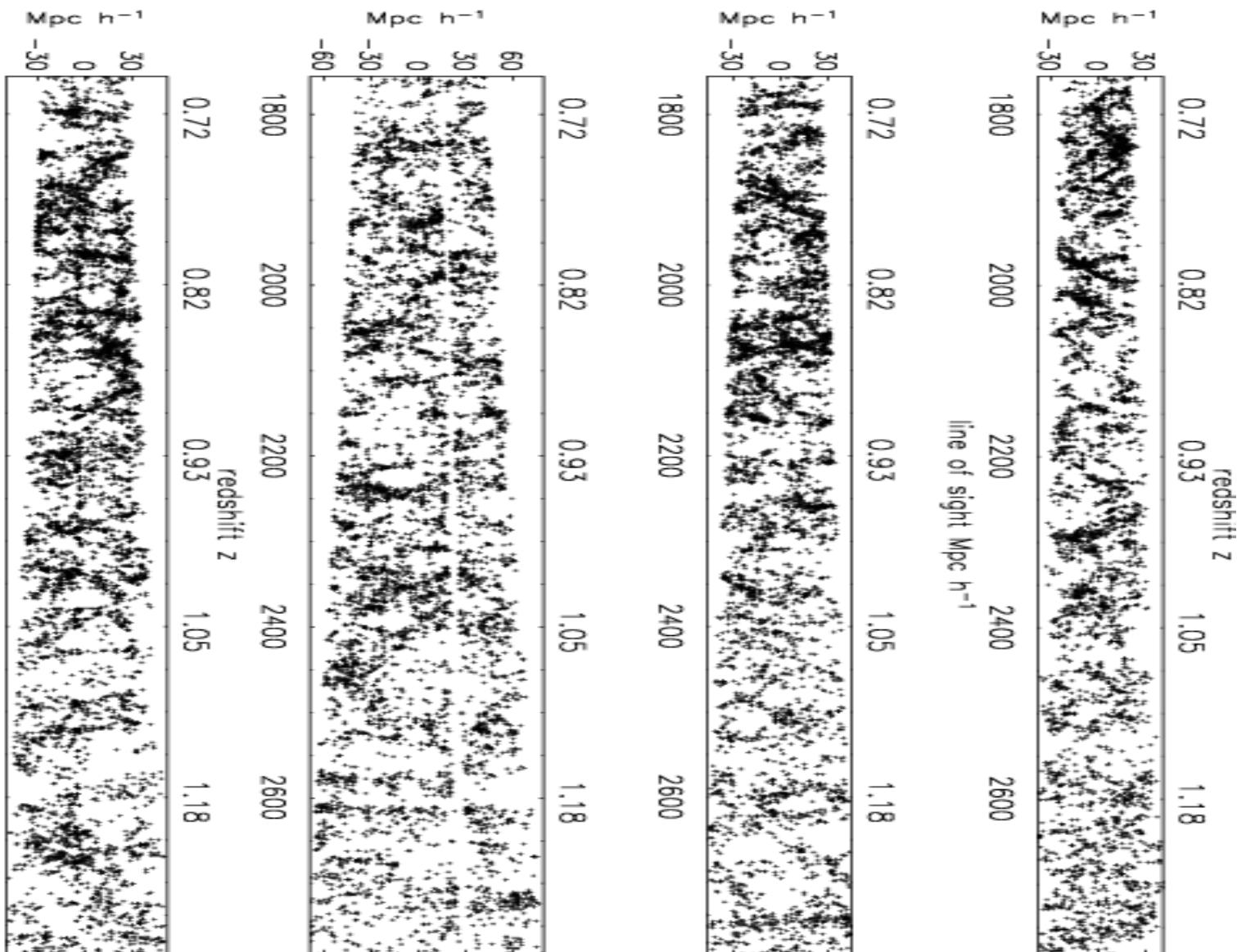
The decline & fall ($z < 1$)

- Modern deep surveys cover a few to $\sim 100 \text{ deg}^2$.
- Multiwavelength data are becoming the norm
 - Spitzer, radio, X-ray, etc. - only in a few cases over the whole survey areas.
 - Near-IR coverage tending to lag behind
- Spectroscopic surveys of $10^4\text{-}10^5$ objects:
 - SDSS LRGs, AGES, DEEP2, VVDS, Z-COSMOS, etc.
 - Some surveys have resolution adequate for additional science, e.g., kinematics or more subtle spectral diagnostics (SDSS, AGES, DEEP2)
- Photometric redshifts can extend to larger samples or greater completeness / denser sampling

The decline & fall ($z < 1$)

- Decline of SFR, $z=1$ to 0
 - Global SF evolution
 - Dusty SF from Spitzer
- Persistence of color bimodality
- Persistence of the Hubble Sequence
- Evolution of the red galaxy population? Still controversial
- Environmental drivers of galaxy evolution

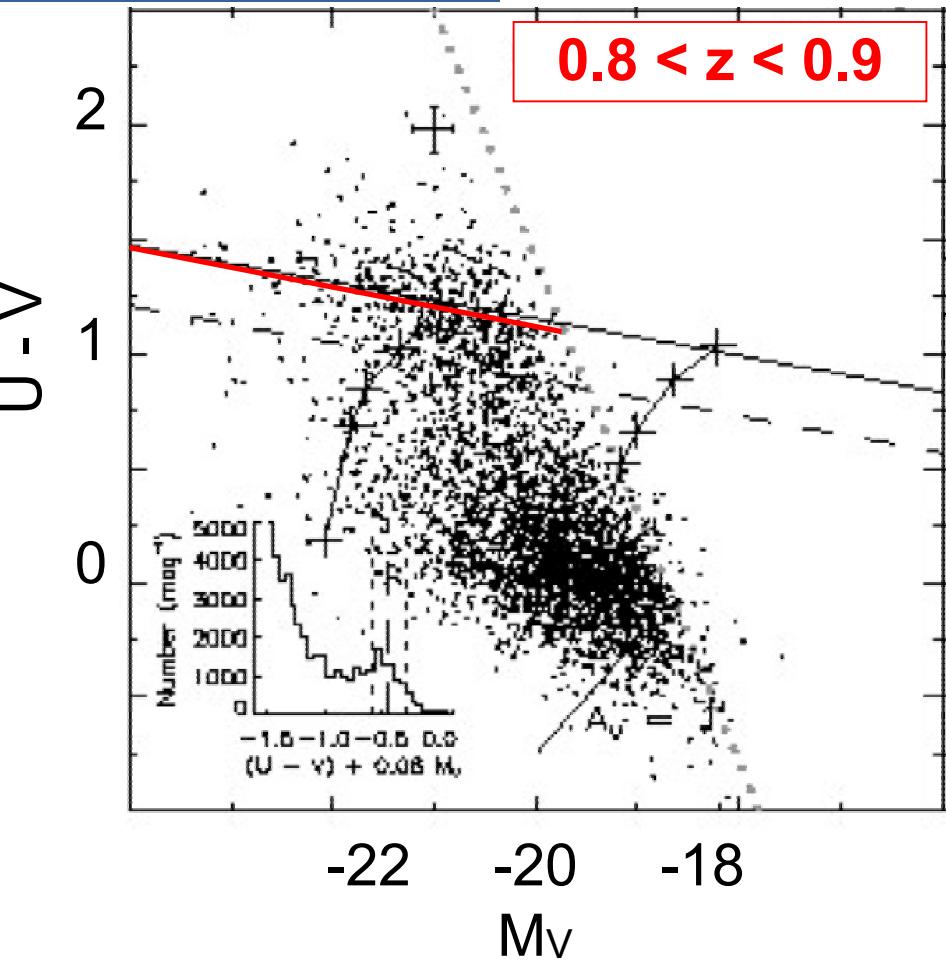
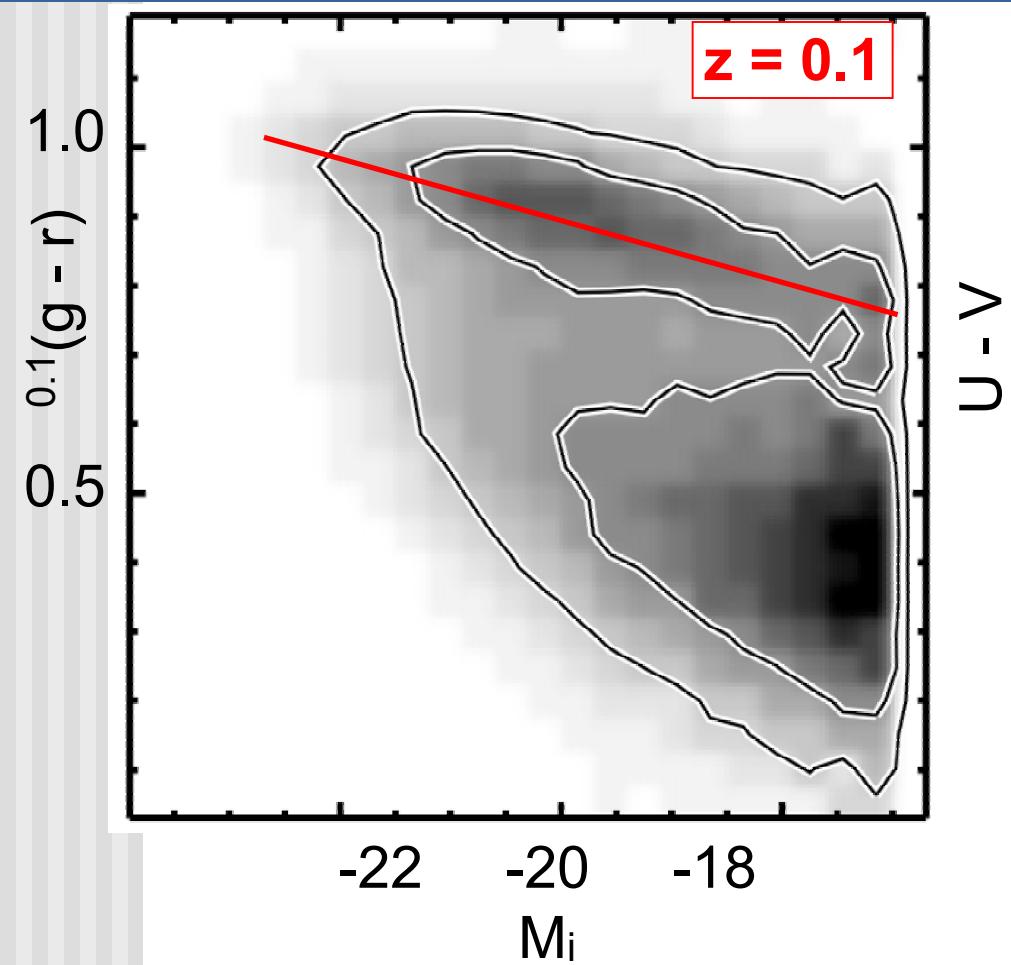
DEEP2: figure courtesy A. Coil



Plus ça change...

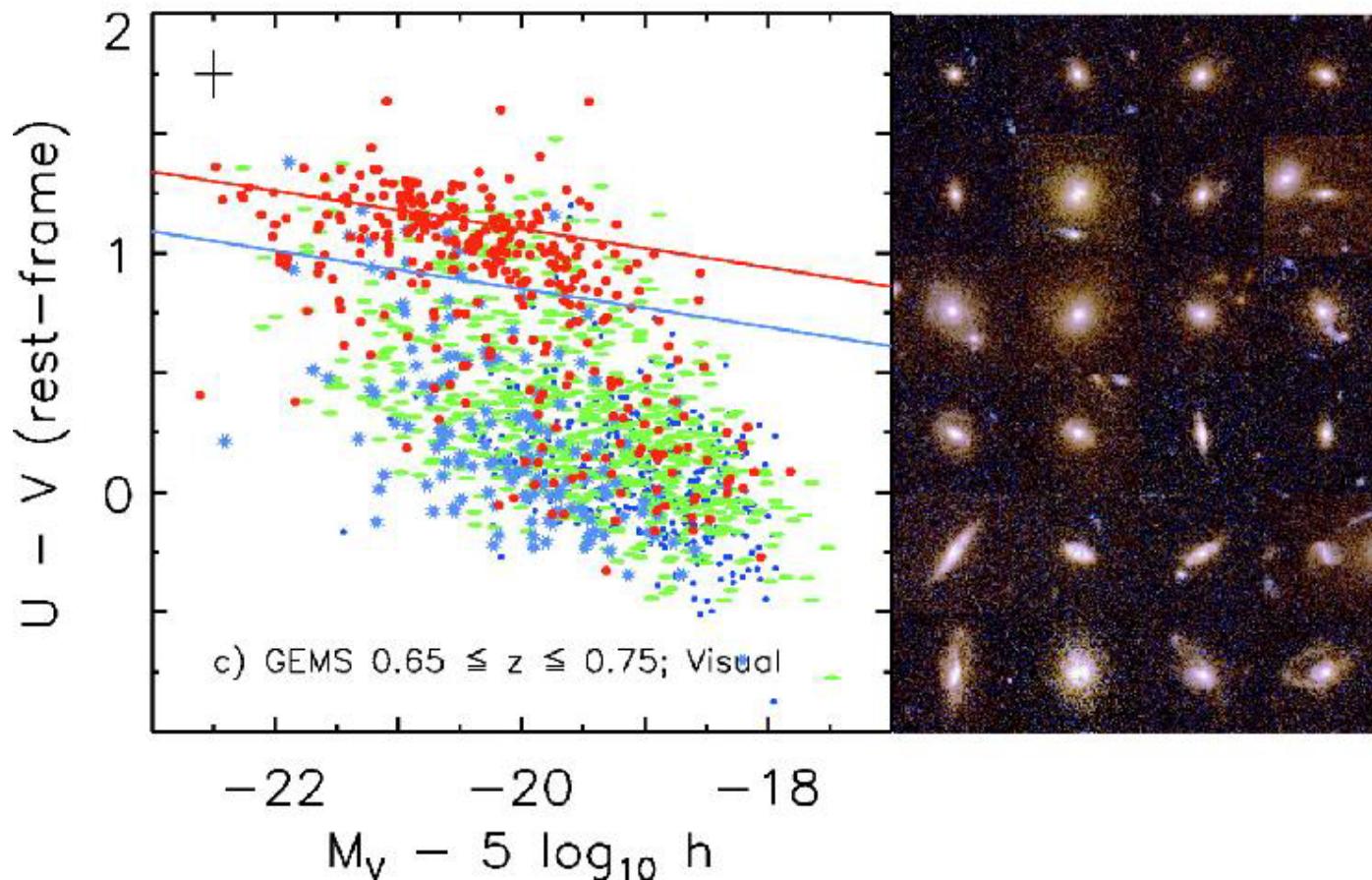
SDSS, Blanton et al. 2002

COMBO-17, Bell et al. 2004



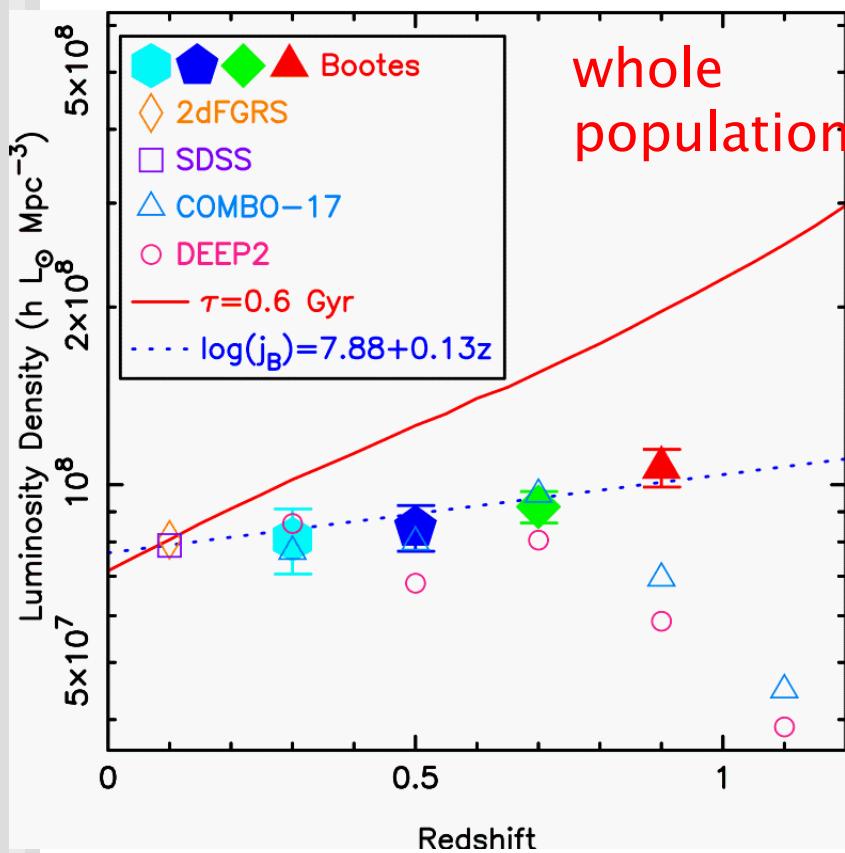
Still familiar galaxies to $z \sim 1$

Bell et al. 2004b

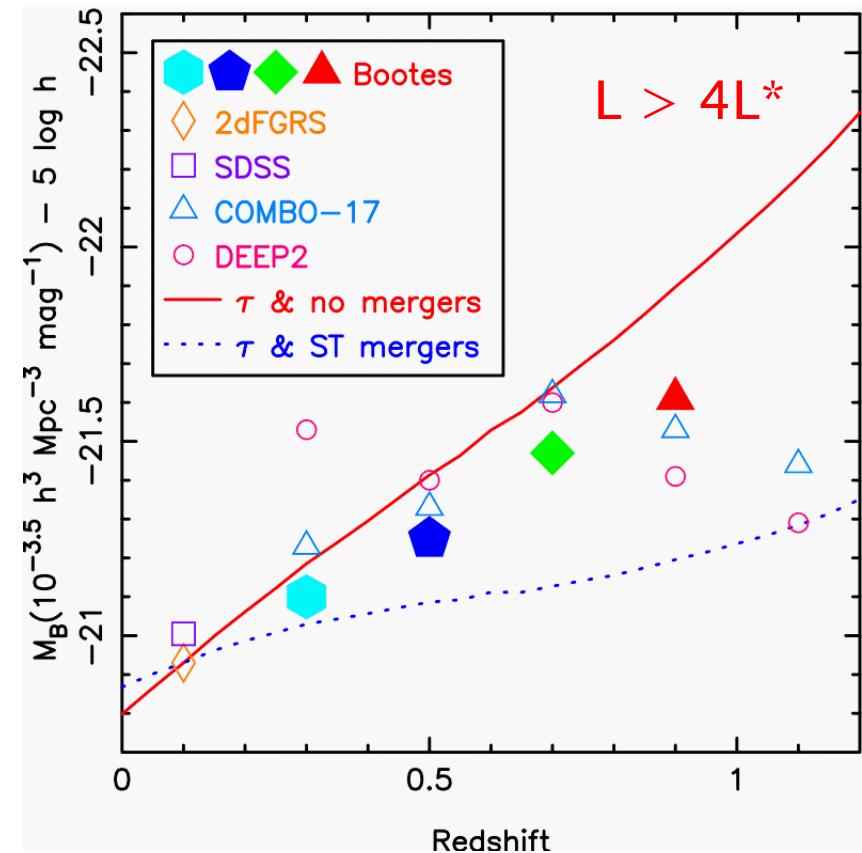


Mild evolution of the red galaxy population

Brown et al. 2006

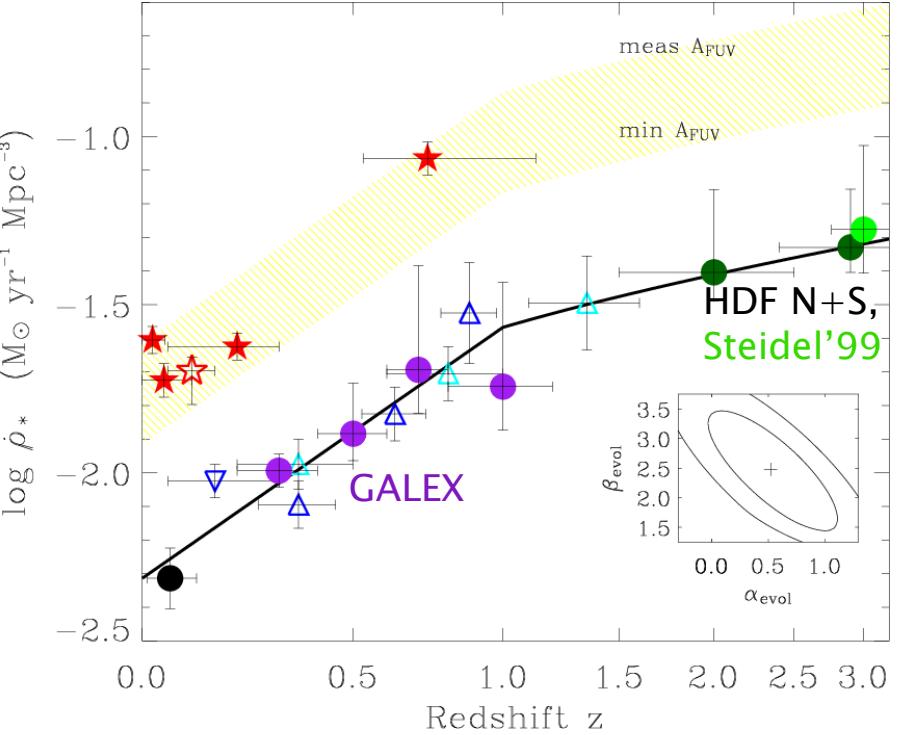
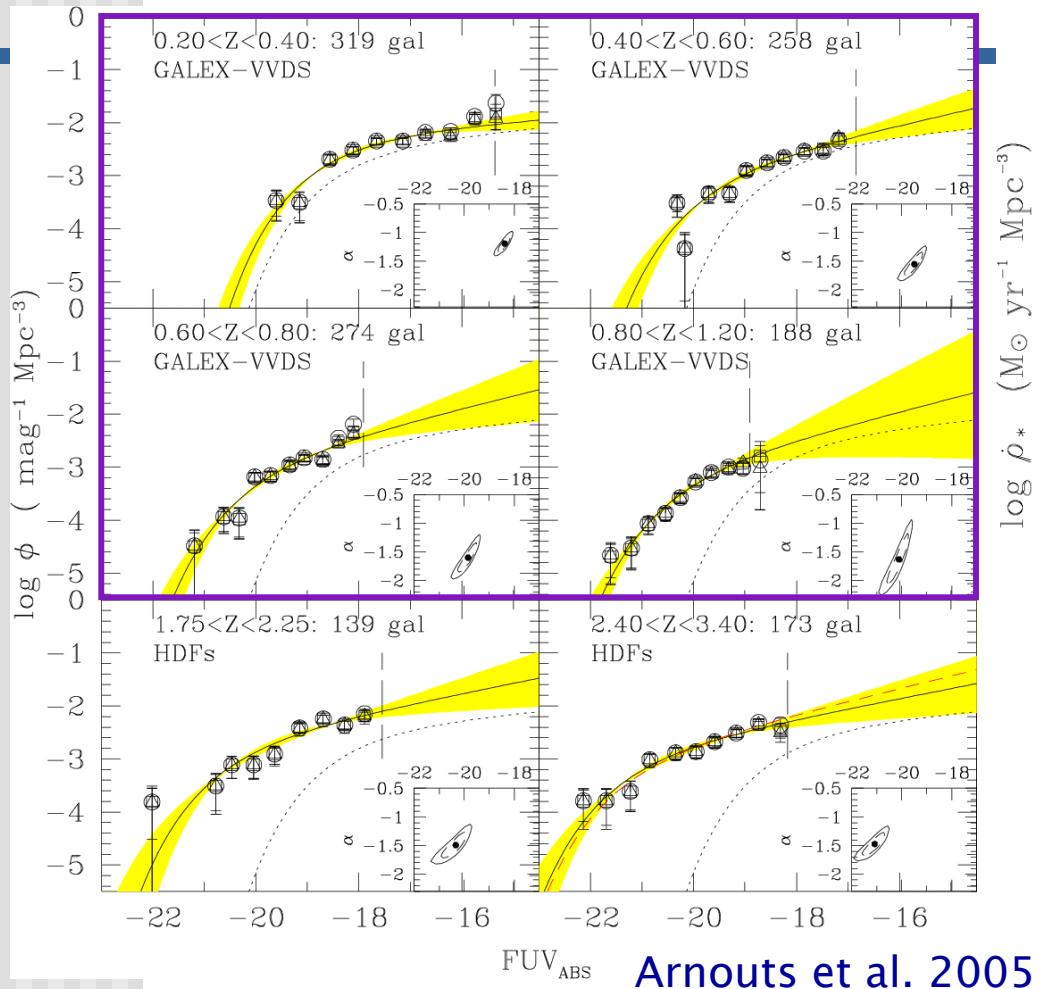


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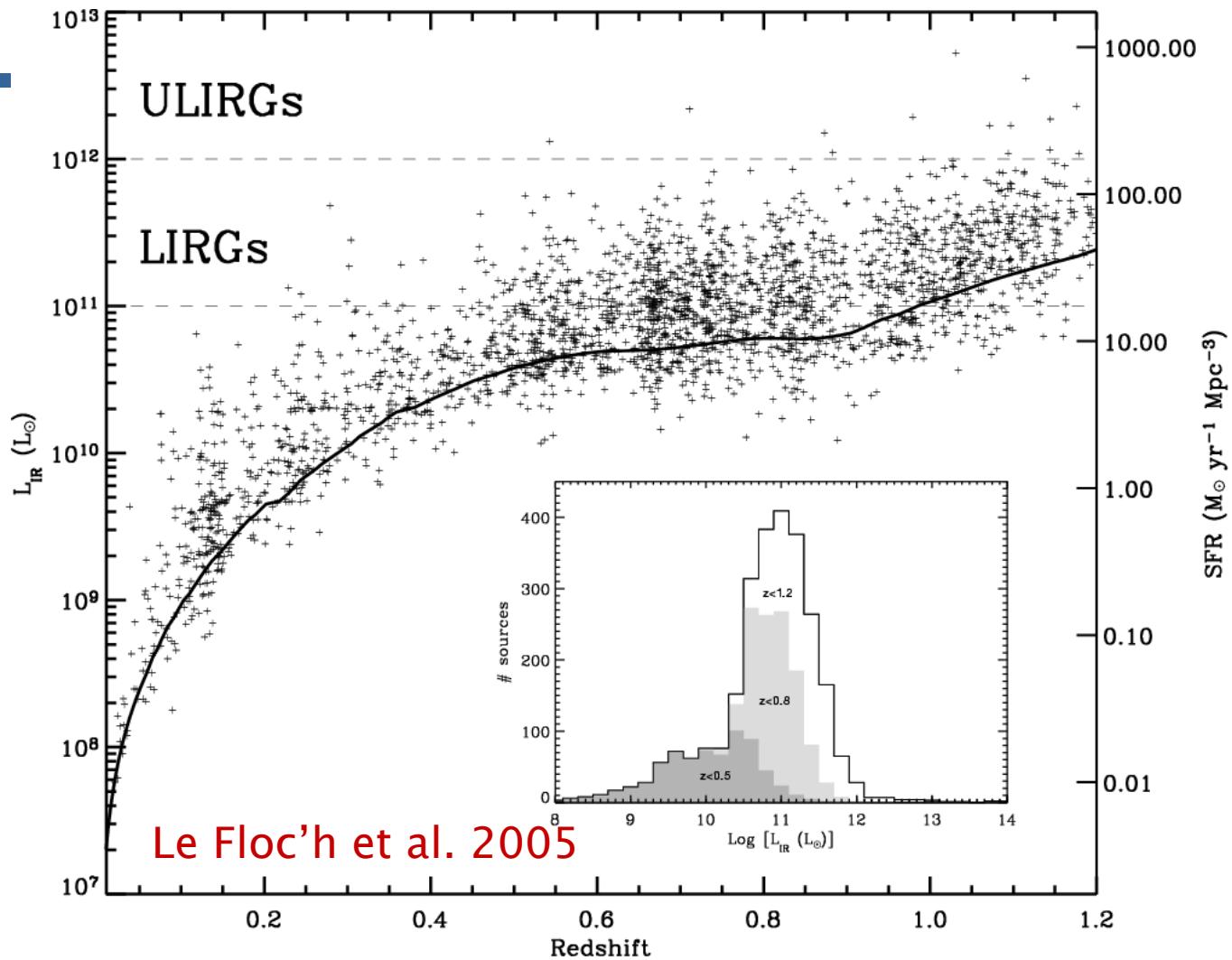
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The decline & fall of star formation: VVDS+GALEX at $z < 1.2$



Schiminovich et al. 2005

Surveying dusty star formation with Spitzer



Evolution of the IR luminosity density, $0 < z < 1$

$0 < z < 1:$

$$\rho_{\text{UV}}(z) \sim (1+z)^{2.5}$$

(Schiminovich et al. 2001)

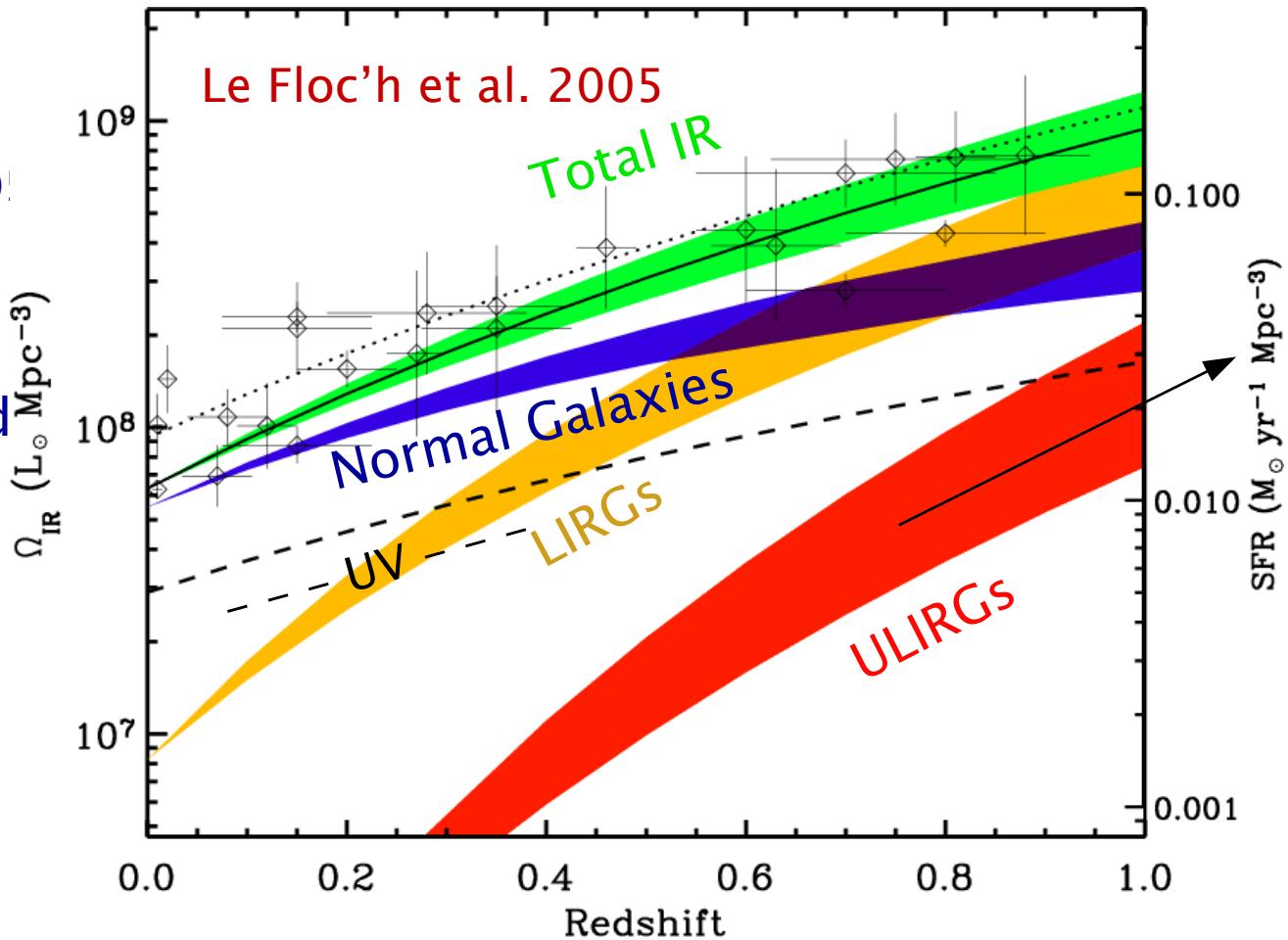
$$\rho_{\text{IR}}(z) \sim (1+z)^{3.9}$$

(Le Floc'h et al. 2005)

Infrared/UV emitted energy from star formation:

$$z=0 \quad \sim 1.5 : 1$$

$$z=1 \quad \sim 4 : 1$$

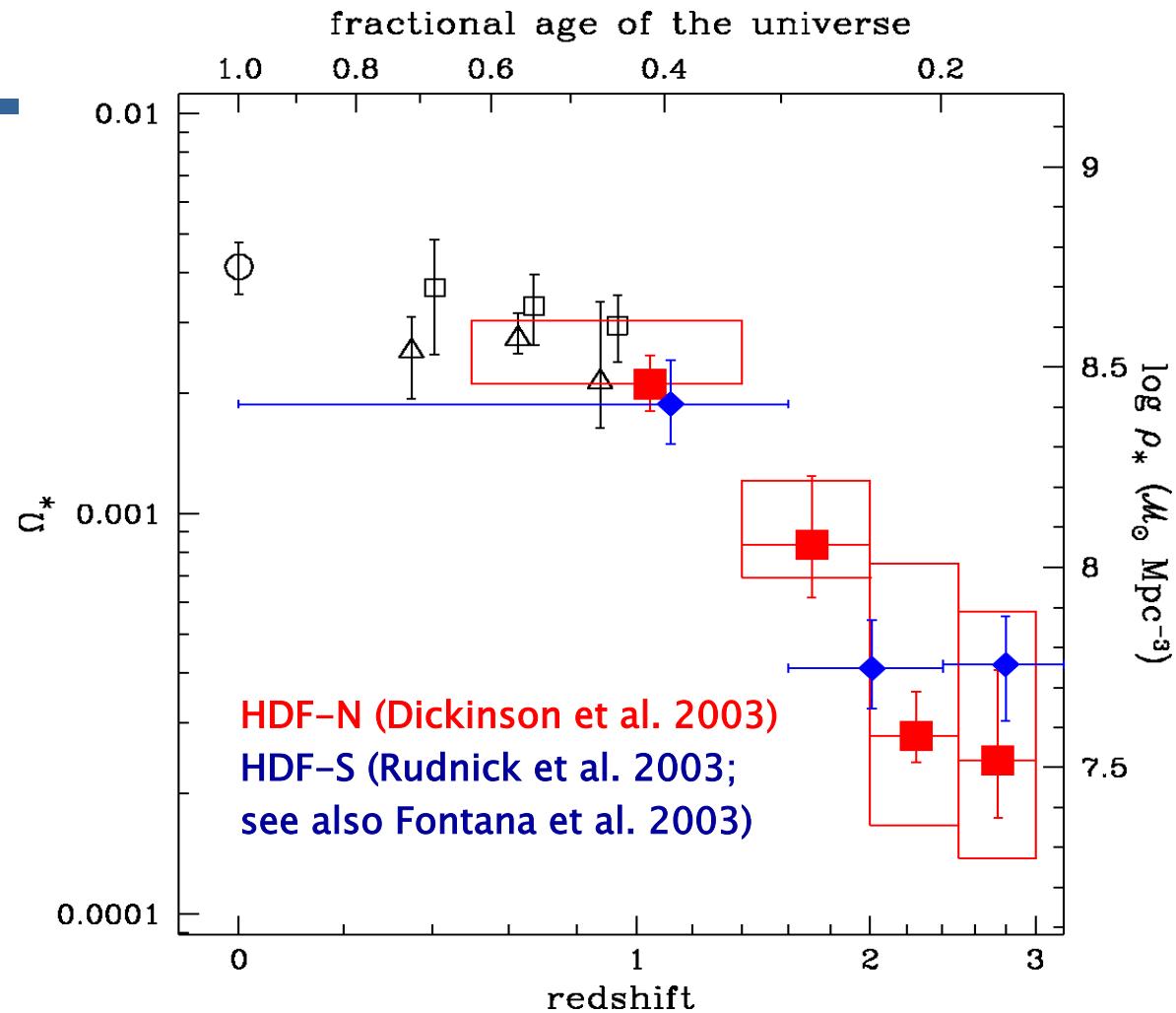


The boom years ($1 < z < 3$)

- An era of rapid galaxy growth & transformation
 - SFR(z)
 - Stellar mass buildup
 - Rapid SF in massive galaxies
 - “Downsizing”
 - Birth of bimodality?
 - Birth of the Hubble Sequence?
 - Clustering and halo mass
 - Kinematics, metallicity, etc.

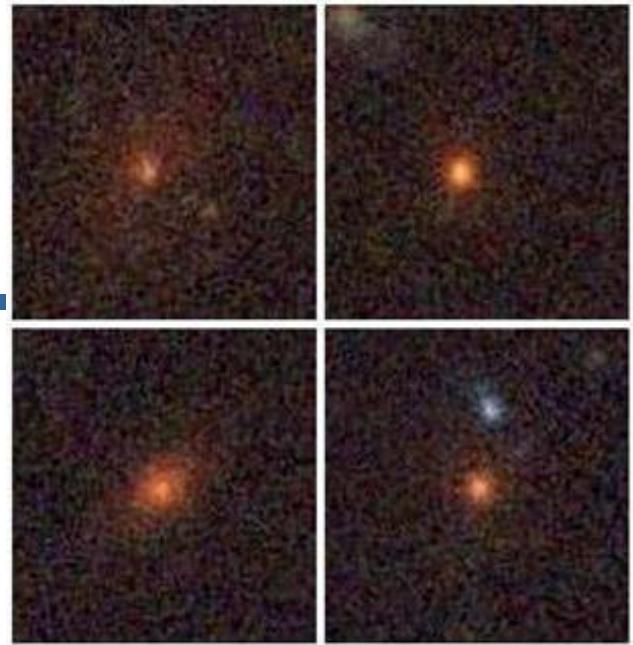
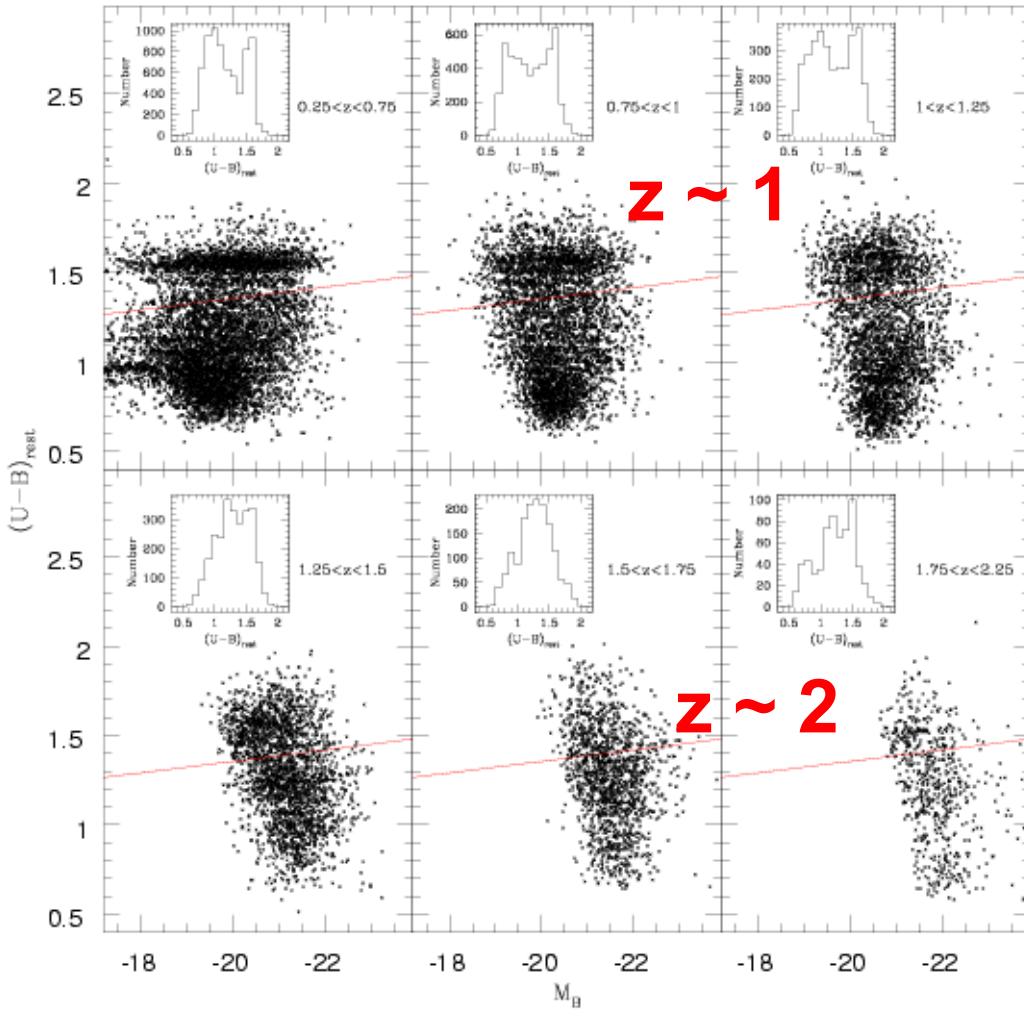
Ω_* vs. redshift

Co-moving
stellar mass
density grew
rapidly from
 $z \sim 3$ to $z \sim 1$

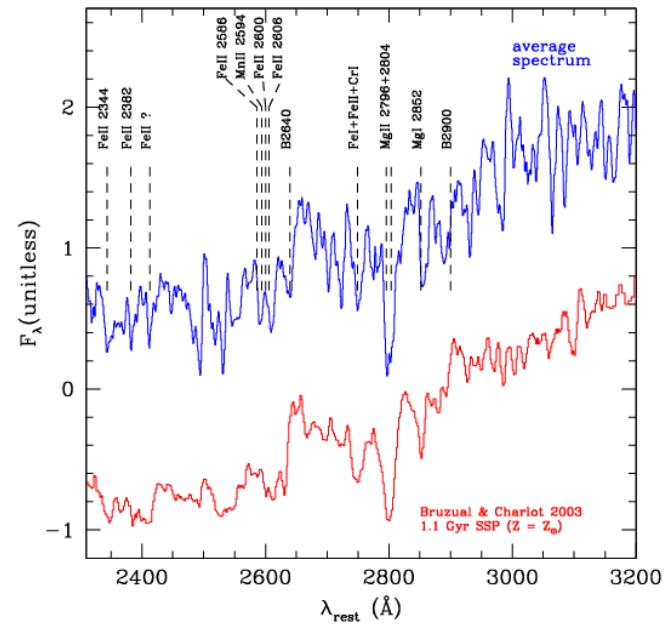


The birth of bimodality?

Cirasuolo et al. 2006 (UKIDSS)

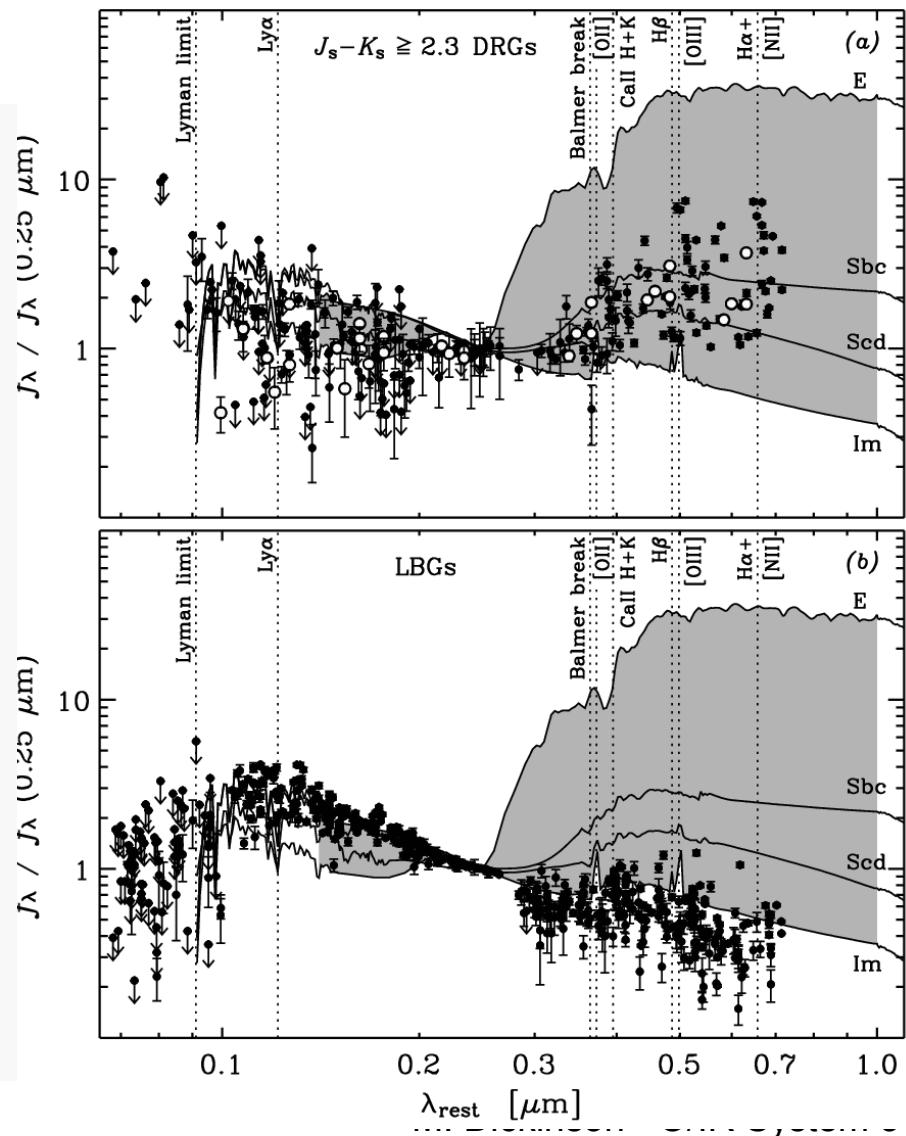
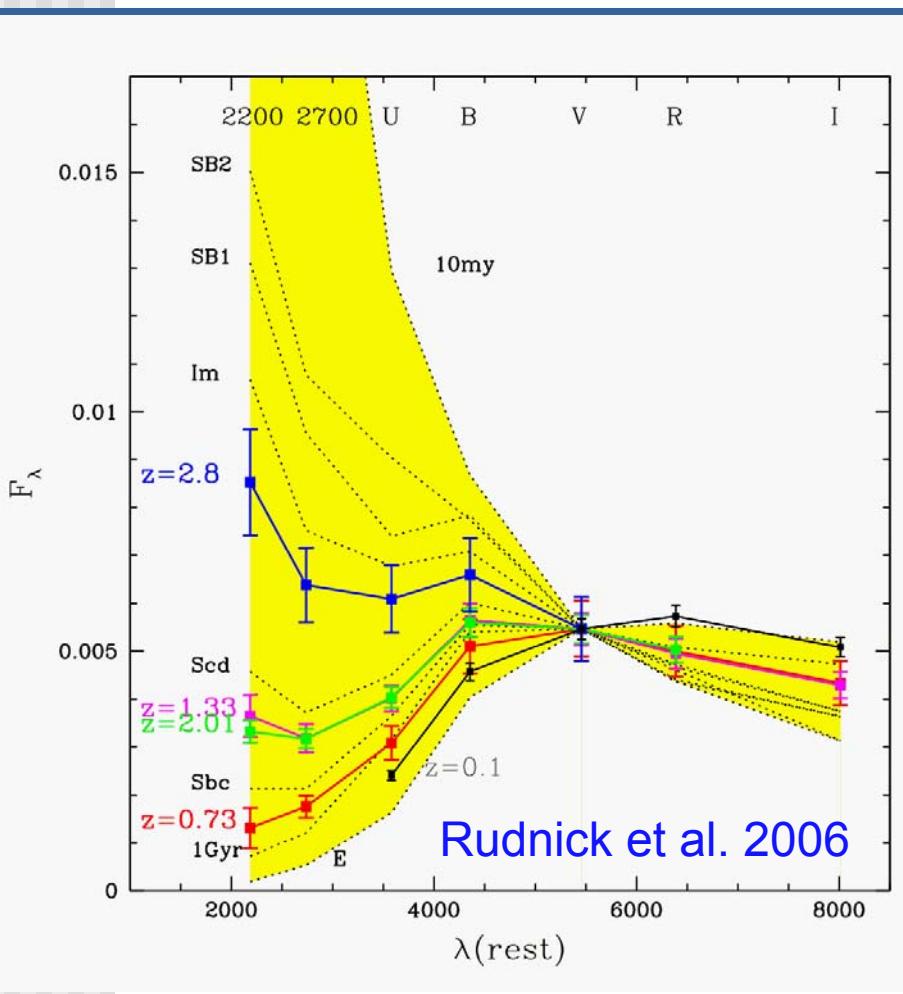


Cimatti et al. 2004



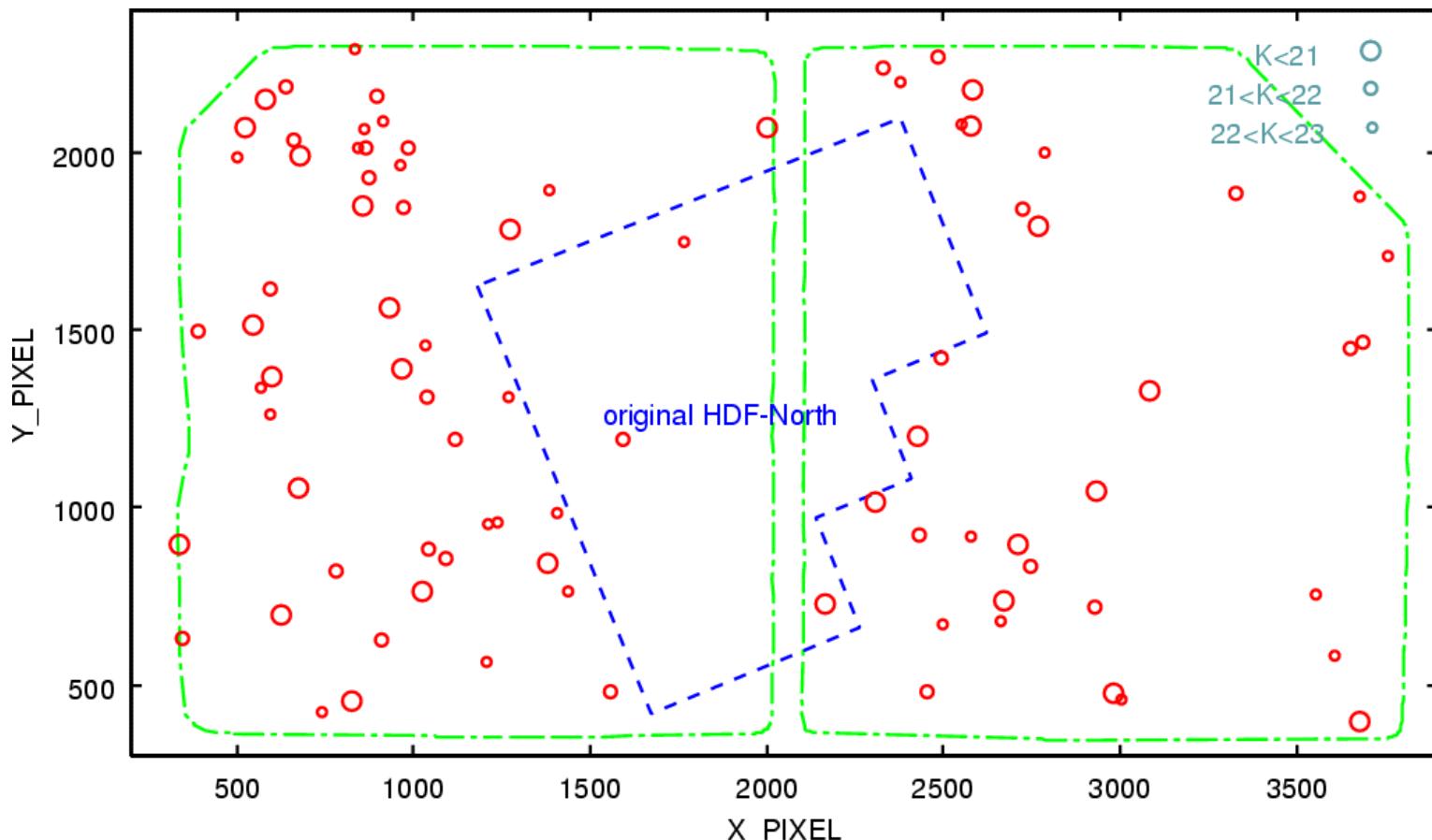
Blue cosmos - but some red galaxies

Förster-Schreiber et al. 2006



HDF-N: Negative serendipity

Kajisawa et al. 2006: Subaru/MOIRCS distant red galaxies in GOODS-N

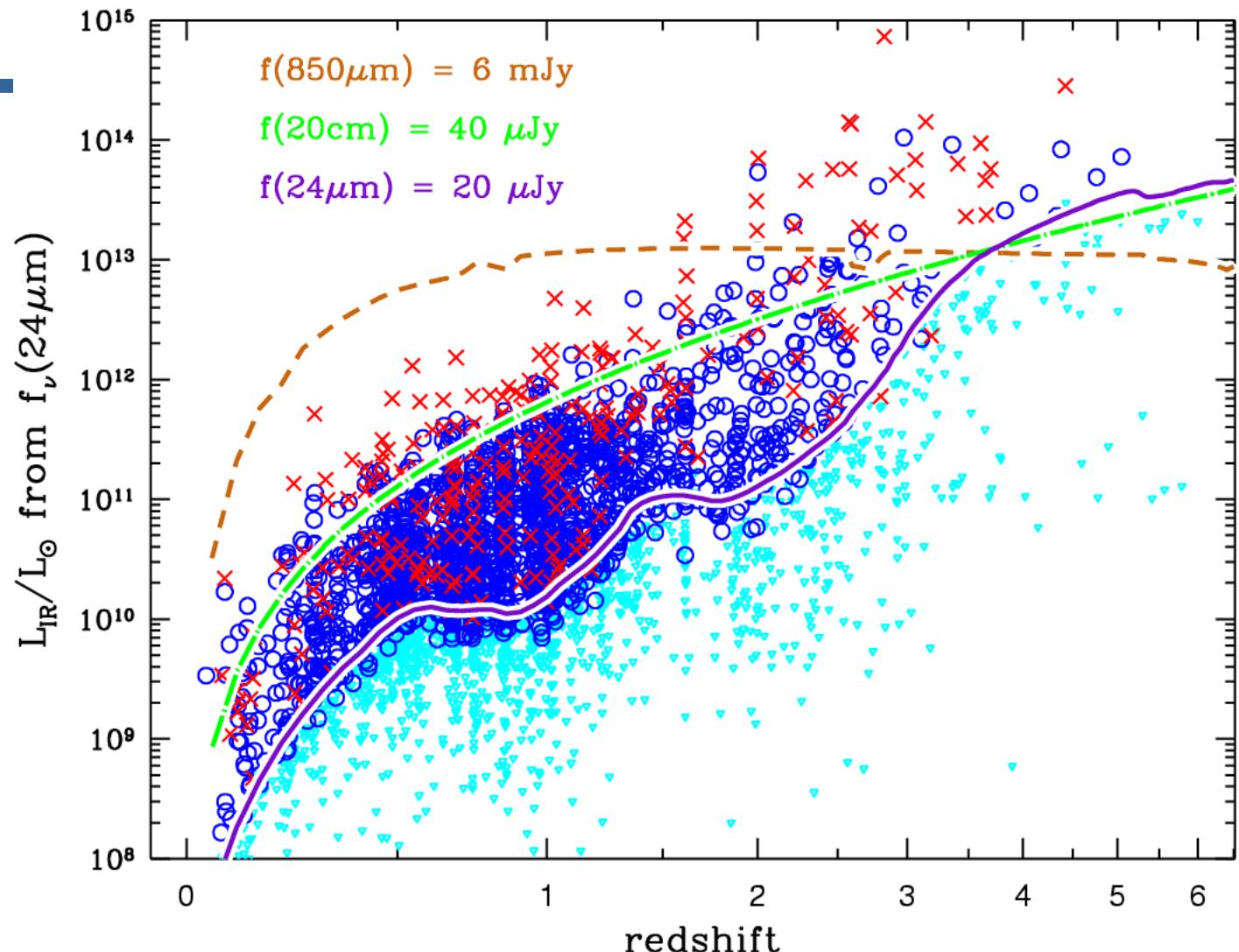


Dusty star formation at z~2

GOODS
Spitzer/MIPS

2000+ galaxies
with
spectroscopic
redshifts

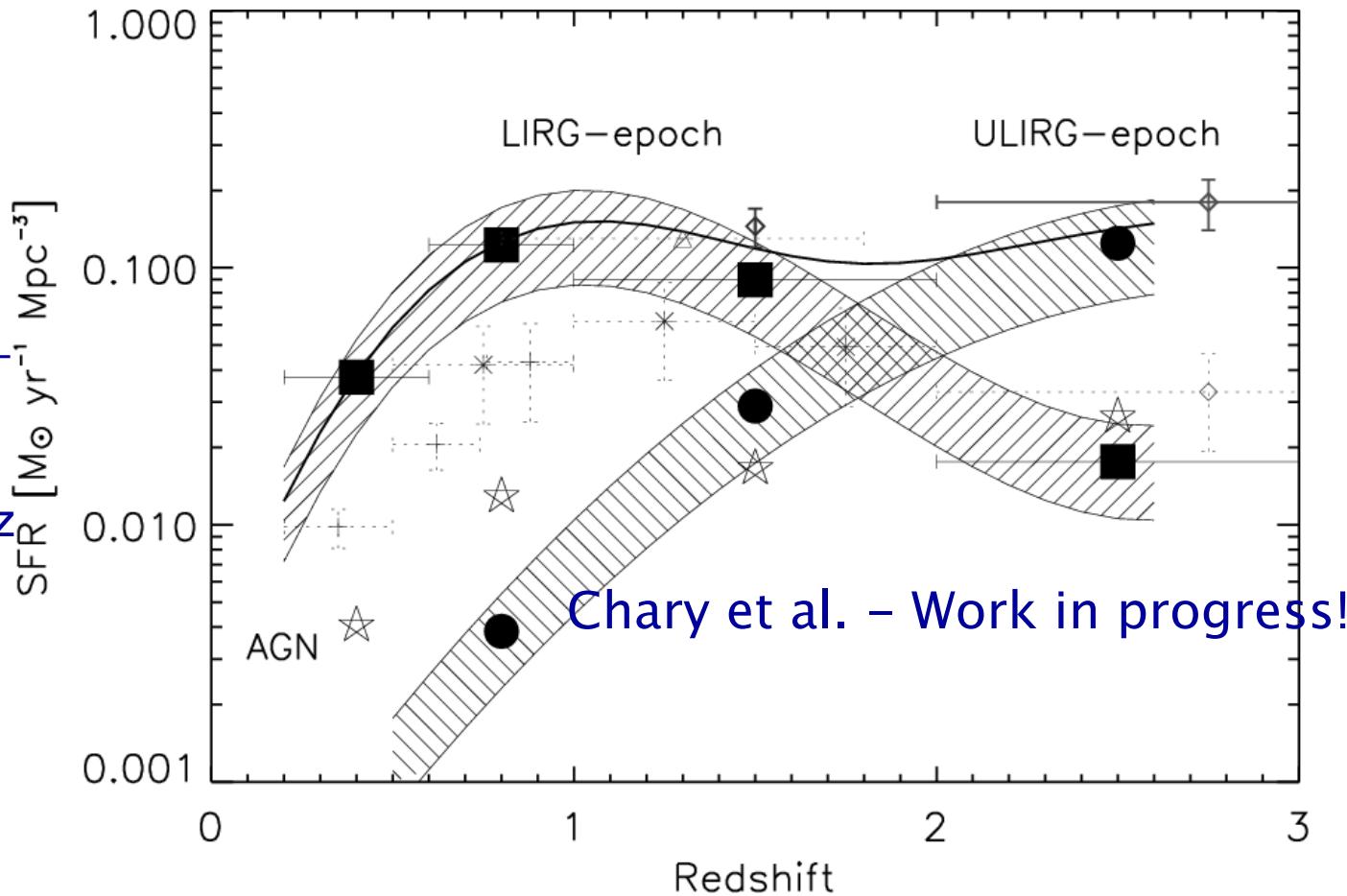
At $1 < z < 2.5$,
MIPS 24 μ m is
 ~ 10 to 1000x
more sensitive to
star formation
than are deep
VLA or SCUBA
surveys.



$z \sim 2-3$: the ULIRG era?

Caveats:

- Spectroscopic (and photo-?) z samples incomplete)
- Templates for MIR-to-SFR conversion uncertain, esp. at higher L and higher z
- AGN identification uncertain
- SF component of AGN IR emission uncertain



Rapid star formation in massive galaxies at z~2

Daddi et al. 2005

Papovich et al. 2006

Caputi et al. 2006

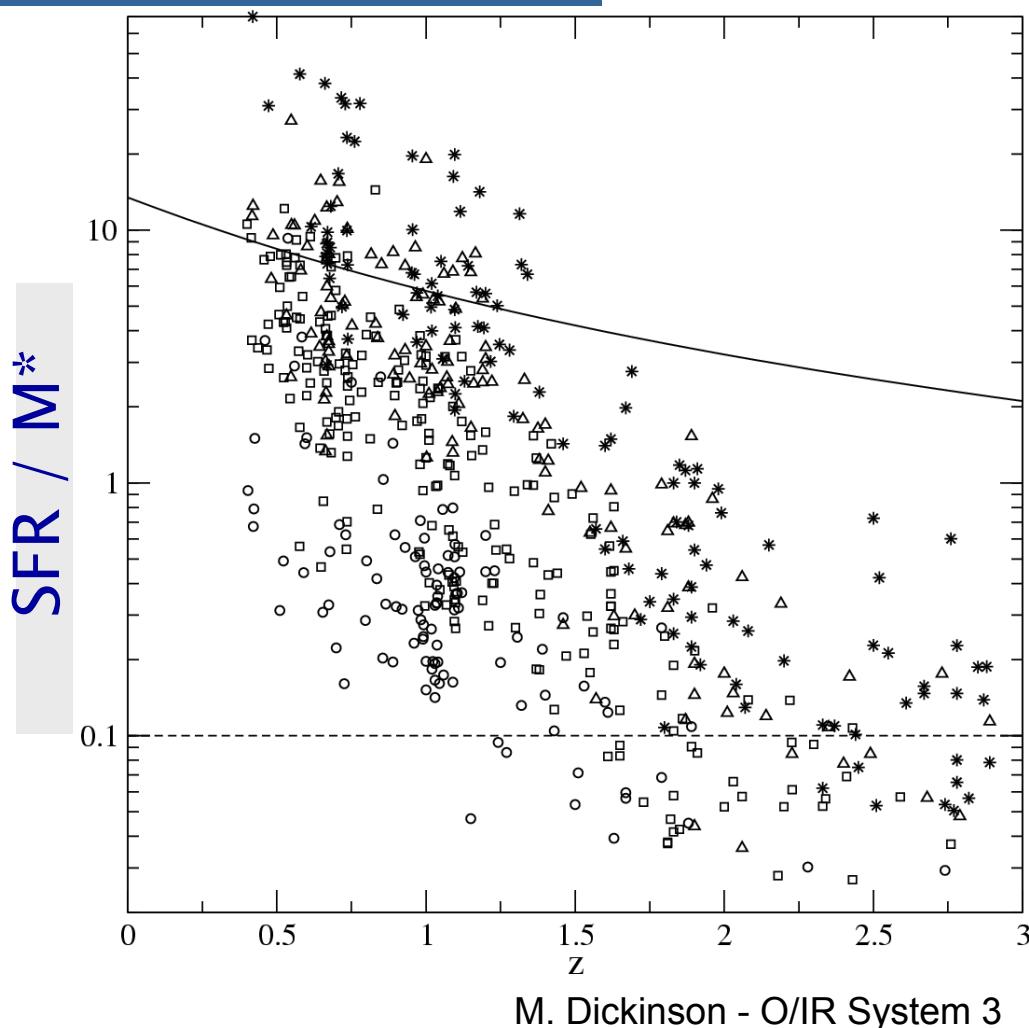
K-selected galaxies at $z \sim 2$ with typical stellar mass $\sim 10^{11} M_\odot$

50–80% have $24 \mu\text{m}$ detections implying $\langle \text{SFR} \rangle \sim 100+ M_\odot/\text{year}$

Sufficient to build most of the stellar mass in these galaxies within the local Hubble time

Daddi et al. 2005, Reddy et al. 2006 show that on average $24 \mu\text{m}$ SFR calibrations appear robust

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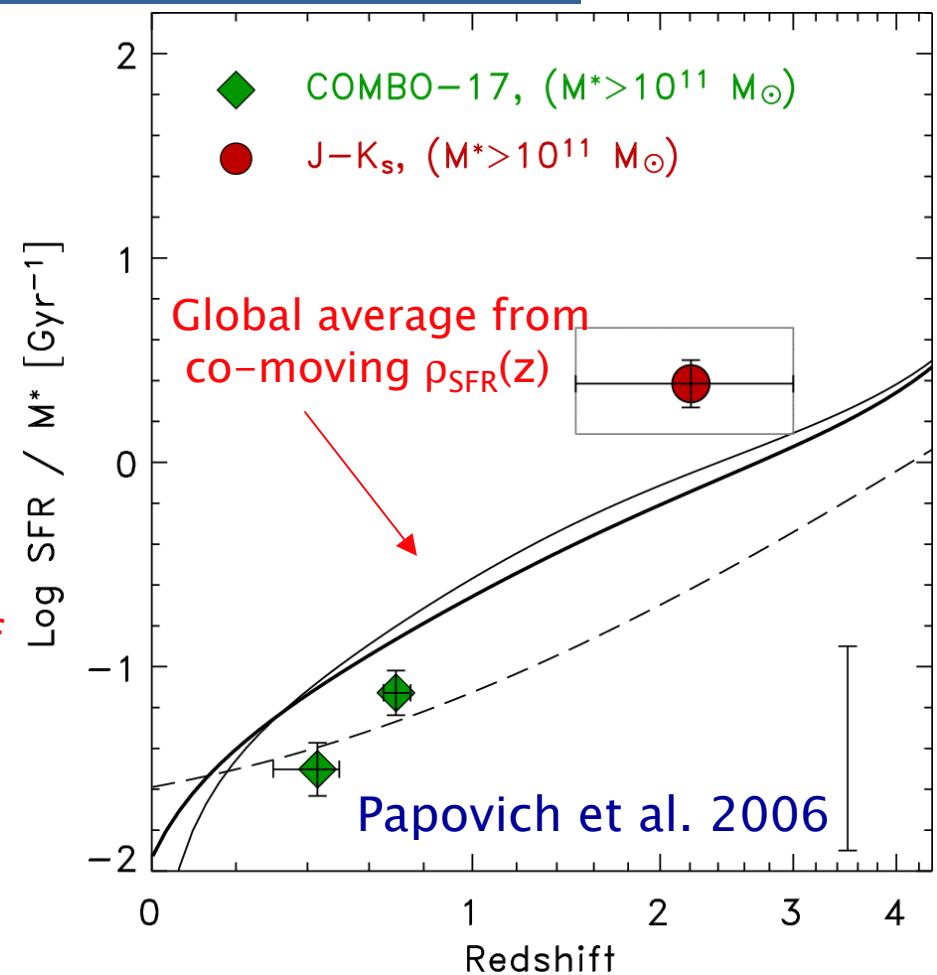
“Downsizing” of star formation in massive galaxies

For galaxies with stellar mass $> 10^{11} M_{\odot}$:

$z \sim 2.3$: forming stars with SSFR $>$ cosmic average

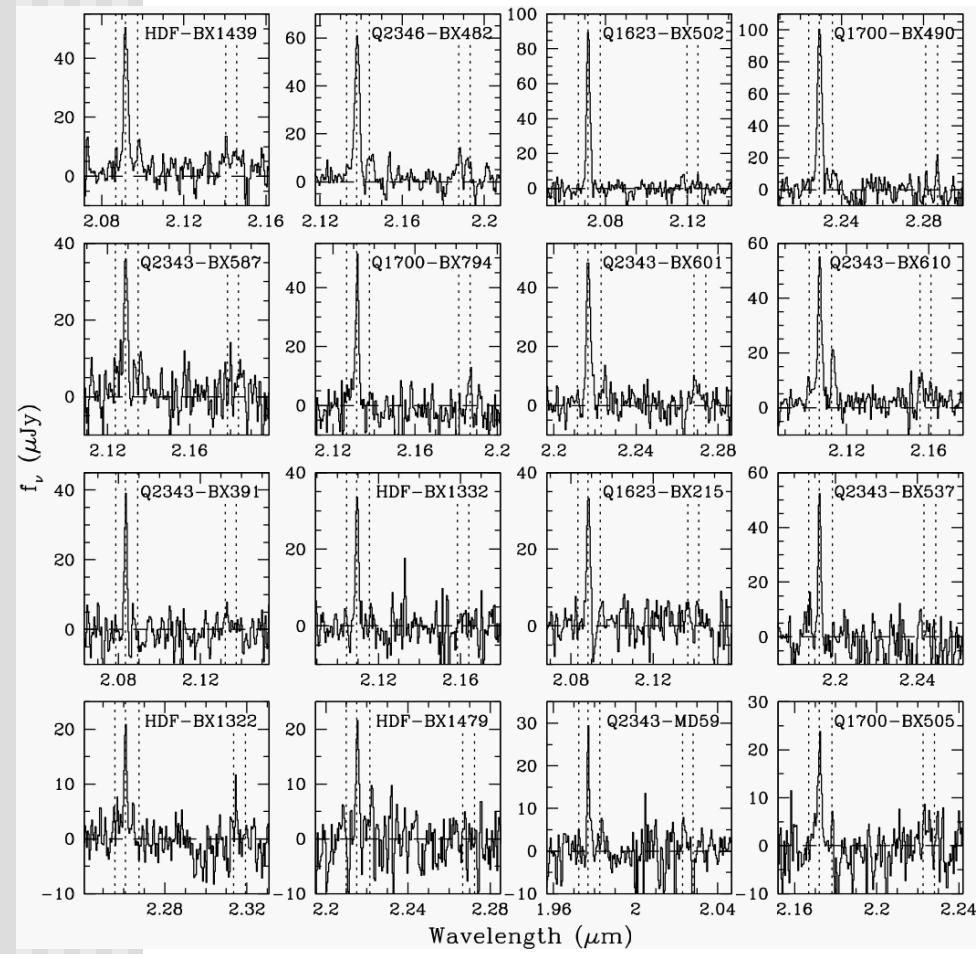
$z < 1$: forming stars more slowly than the global average

Further evidence that $1.5 < z < 3$ was a key era for the rapid growth of stellar mass in the most massive galaxies.

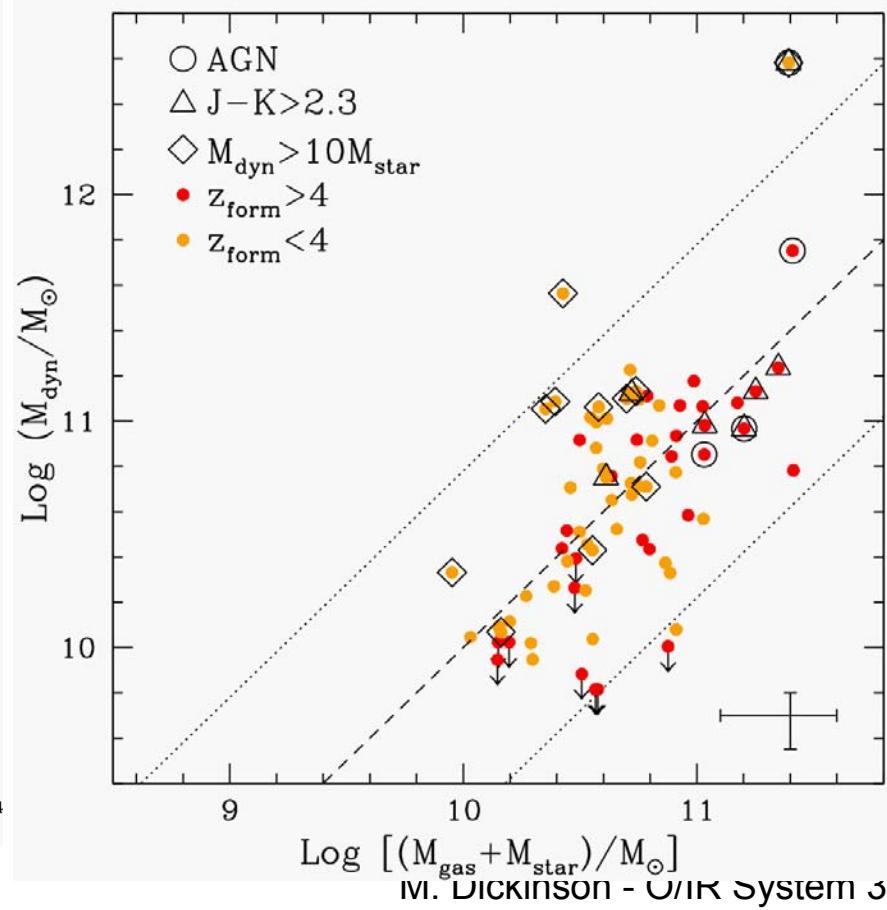


Kinematics and masses at z~2

Erb et al. 2006



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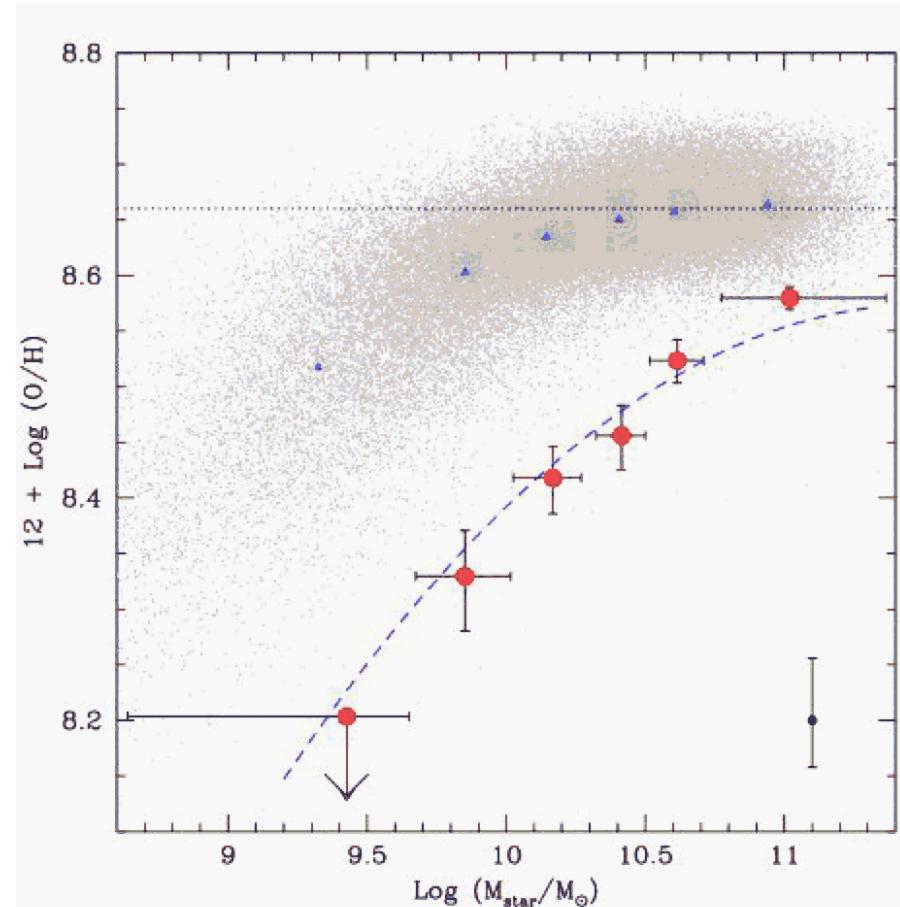
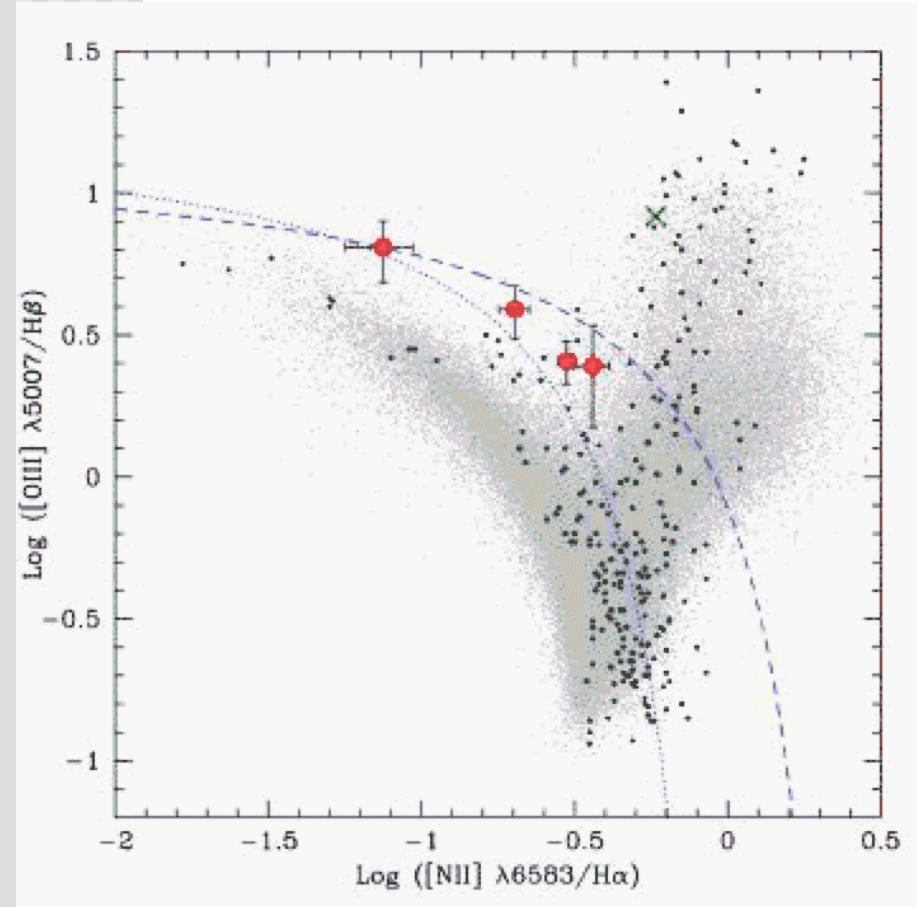


$$\text{Log } [(M_{\text{gas}} + M_{\star}) / M_{\odot}]$$

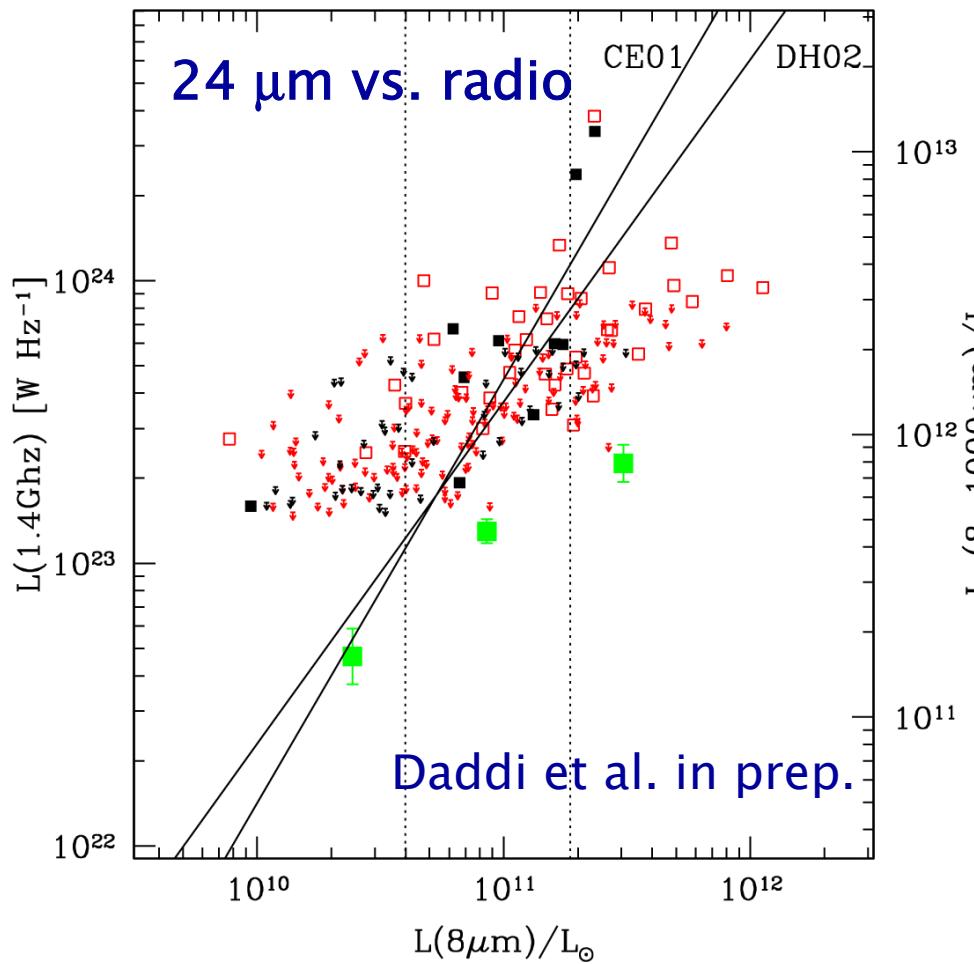
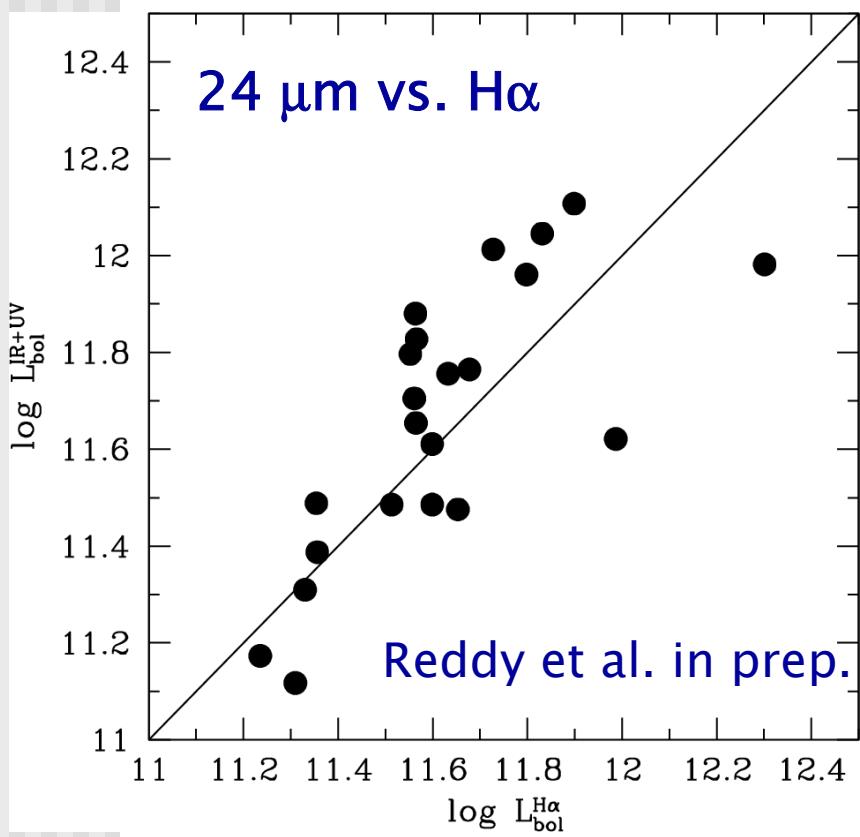
IV. DICKINSON - O/I/R System 3

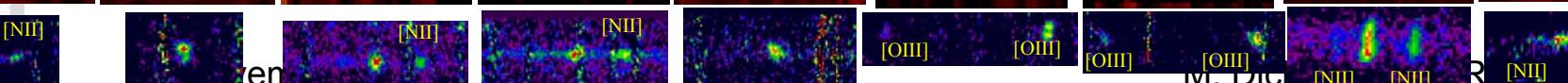
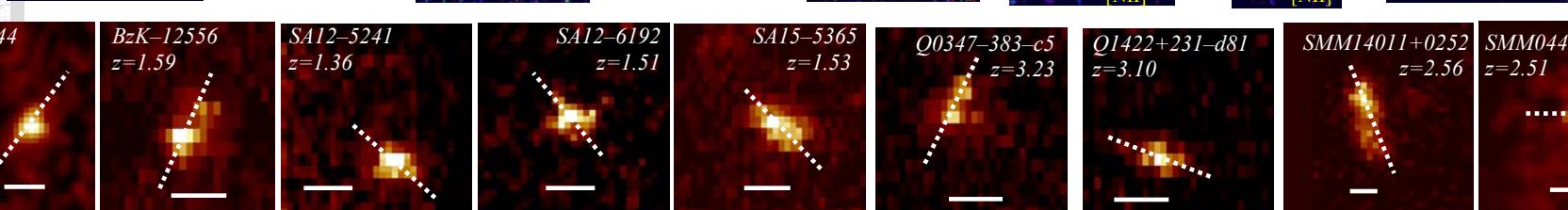
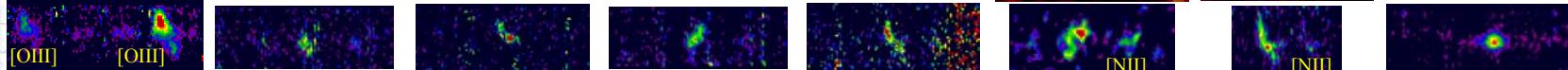
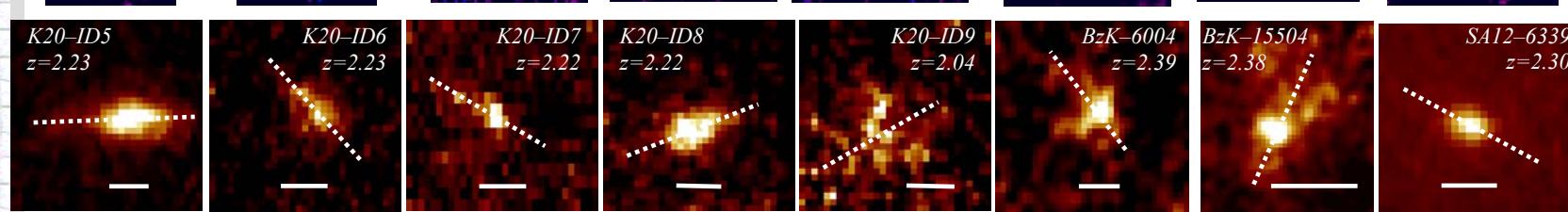
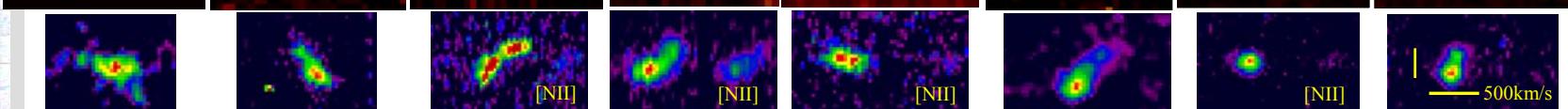
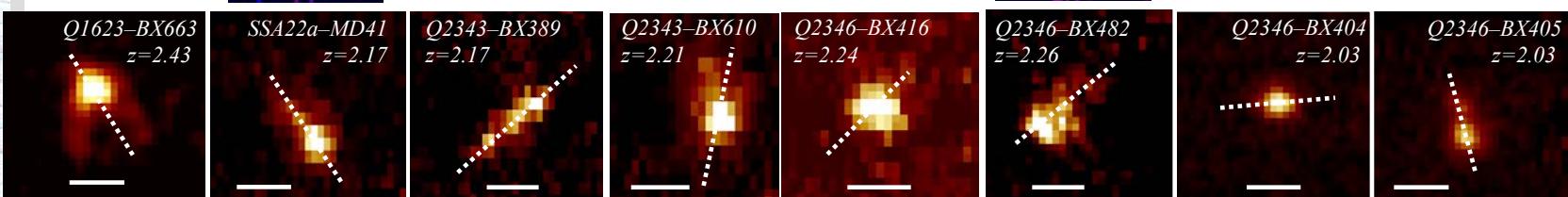
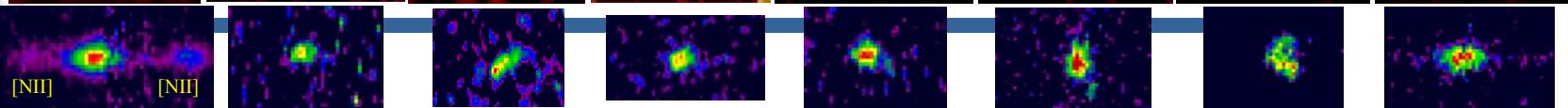
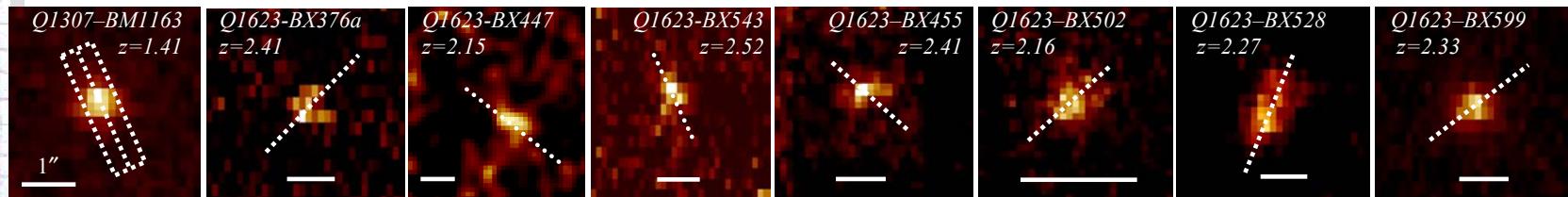
Nebular diagnostics at z~2

Erb et al. 2006ab



Object by object SF comparisons at z~2

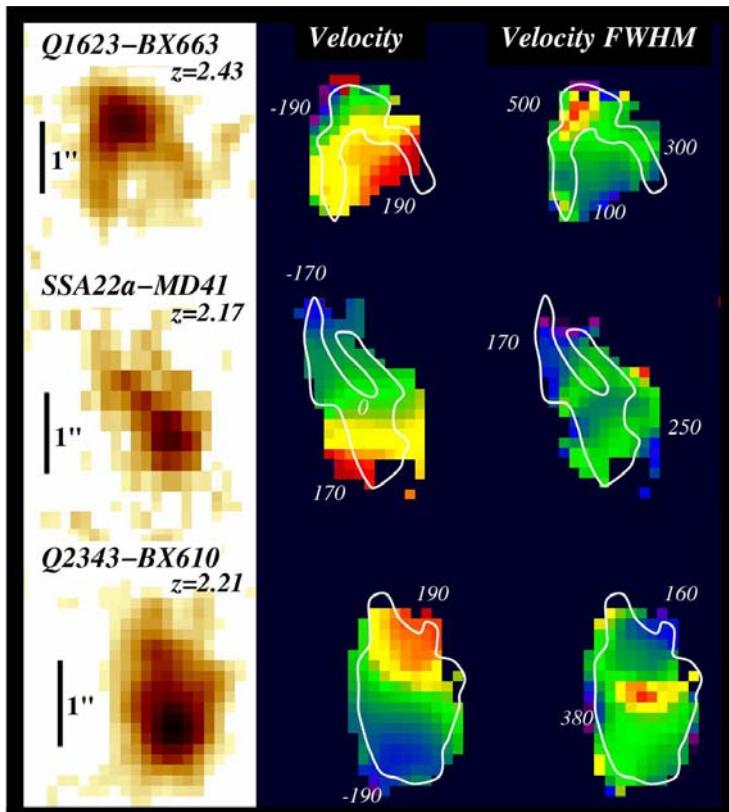




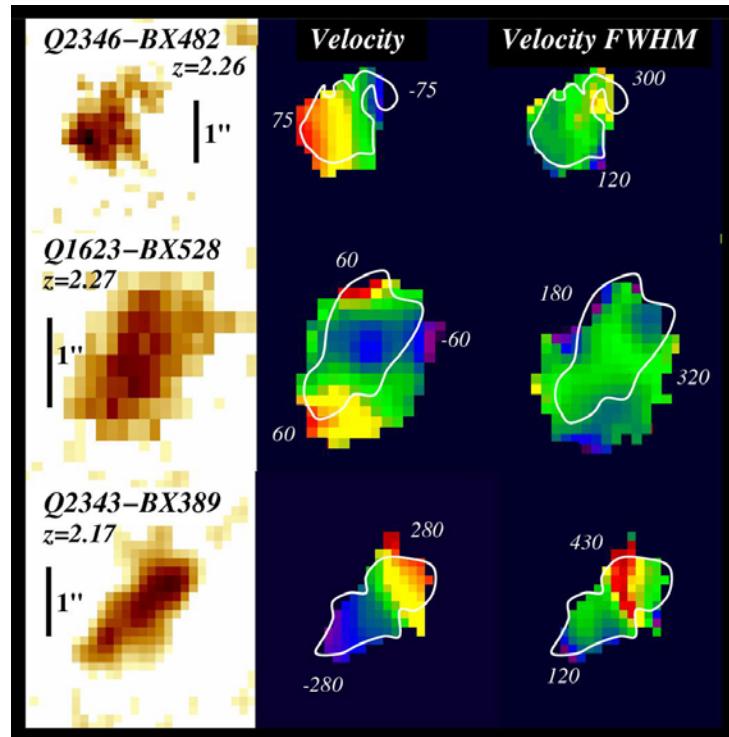
2D kinematics with SINFONI

Orbital motions at $z \sim 2$

BX galaxies



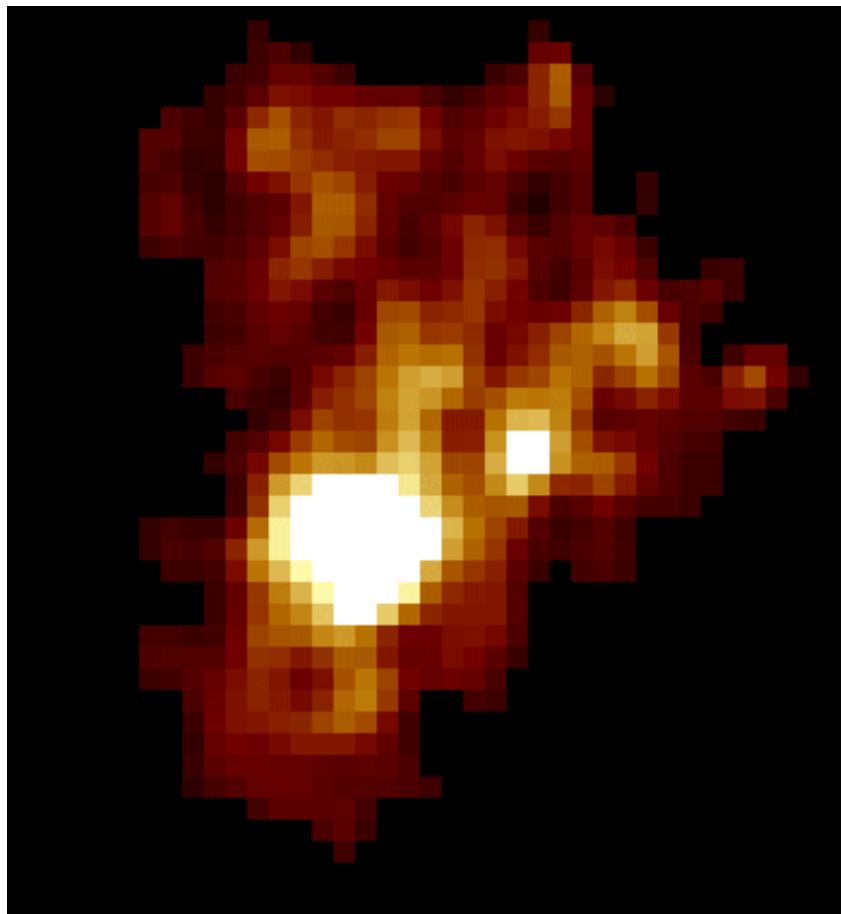
$\text{FWHM} \sim 0.5'' - 0.6'' \rightarrow \sim 4.5 \text{ kpc}$



Förster Schreiber et al. (2006)
(SINFONI sample drawn from Erb et al. 2006)

Dynamics at $z \sim 2$ on AO scales

BzK-15504 at $z = 2.38$



Genzel et al. (2006)

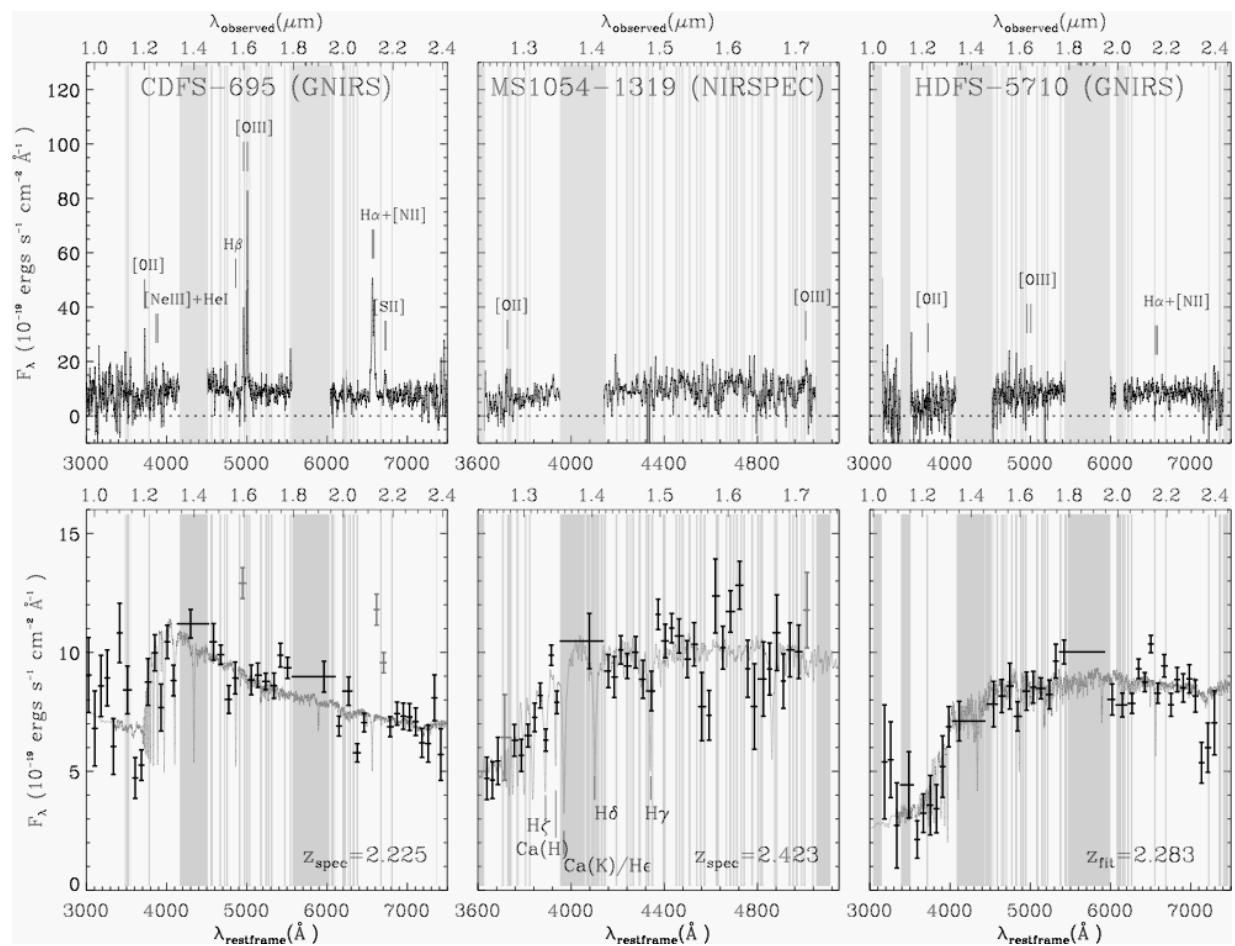
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Near-IR continuum spectroscopy: pain & suffering

Kriek et al. 2006
Gemini/GNIRS,
Keck/NIRSPEC
 $K < 19.8$

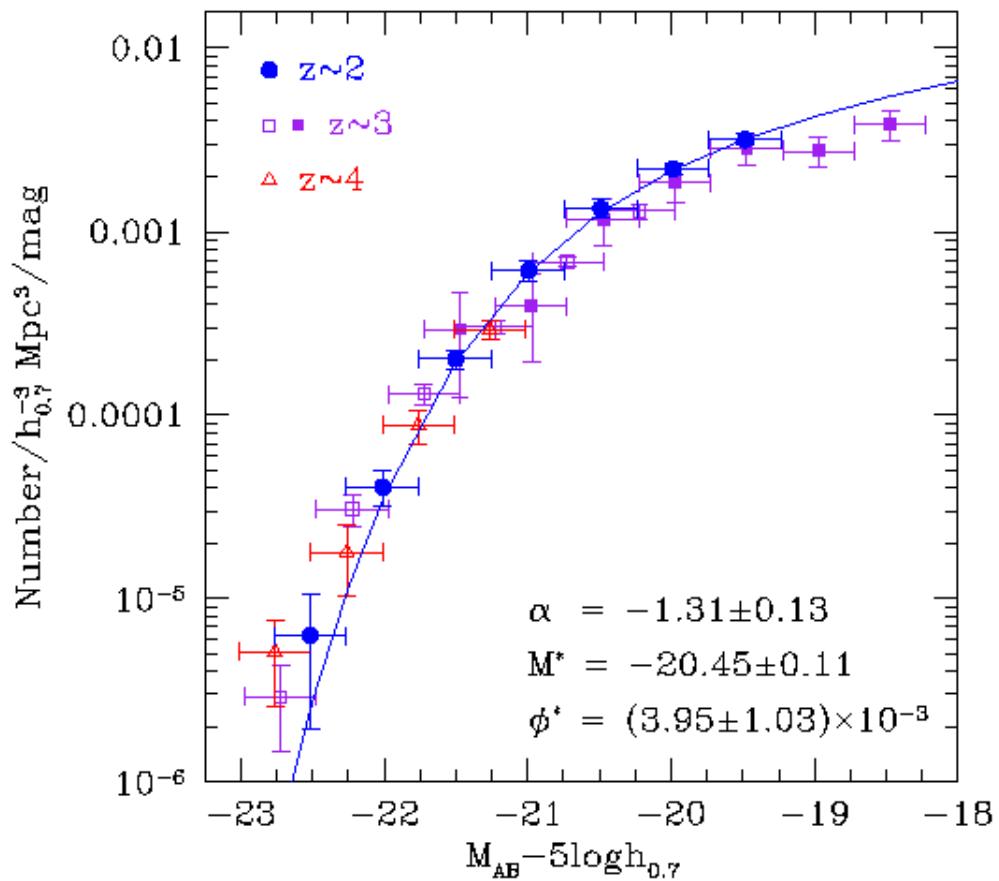
Binned continuum
heavily between sky
lines to measure shape.
Direct absorption line
measurements
impossible.



Early growth ($3 < z < 7$)

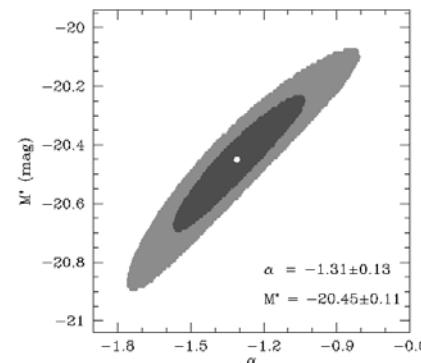
- Almost all knowledge from UV rest-frame surveys:
 - Lyman break continuum selection
 - Lyman α emission selection
- Virtually no information (yet) on dusty star formation for typical objects
- UV-bright end of the LF builds up with time
- Typical stellar masses $<\sim 10^{10} M_\odot$
- Stellar population relics of the reionization epoch?

Rest-Frame UV Luminosity Function at z~2-4

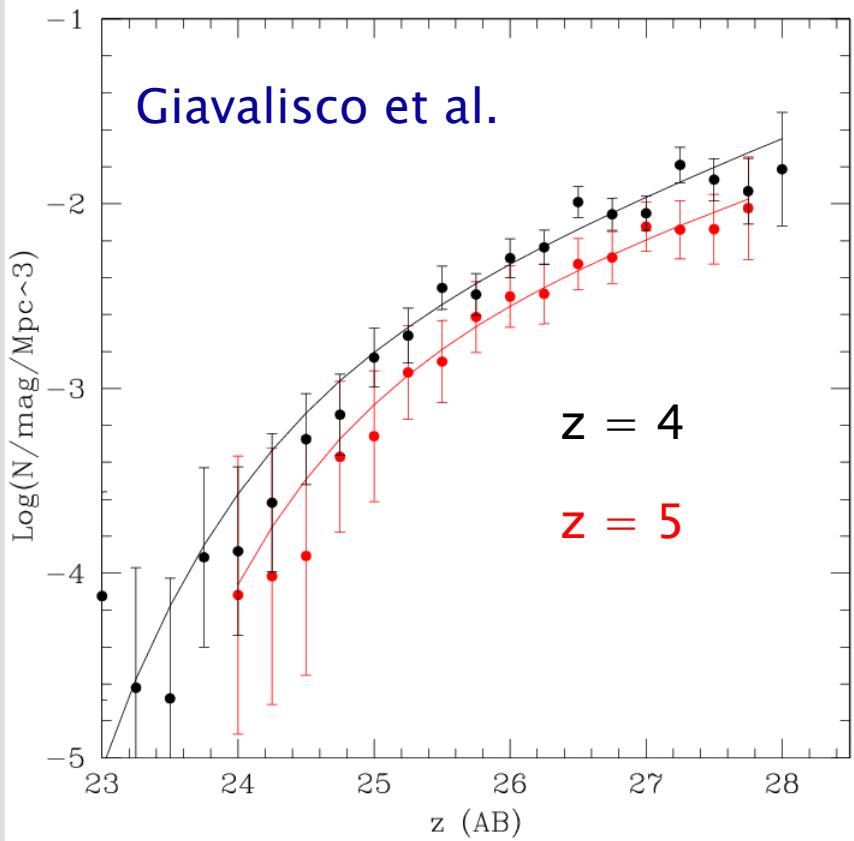


Very little evolution seen

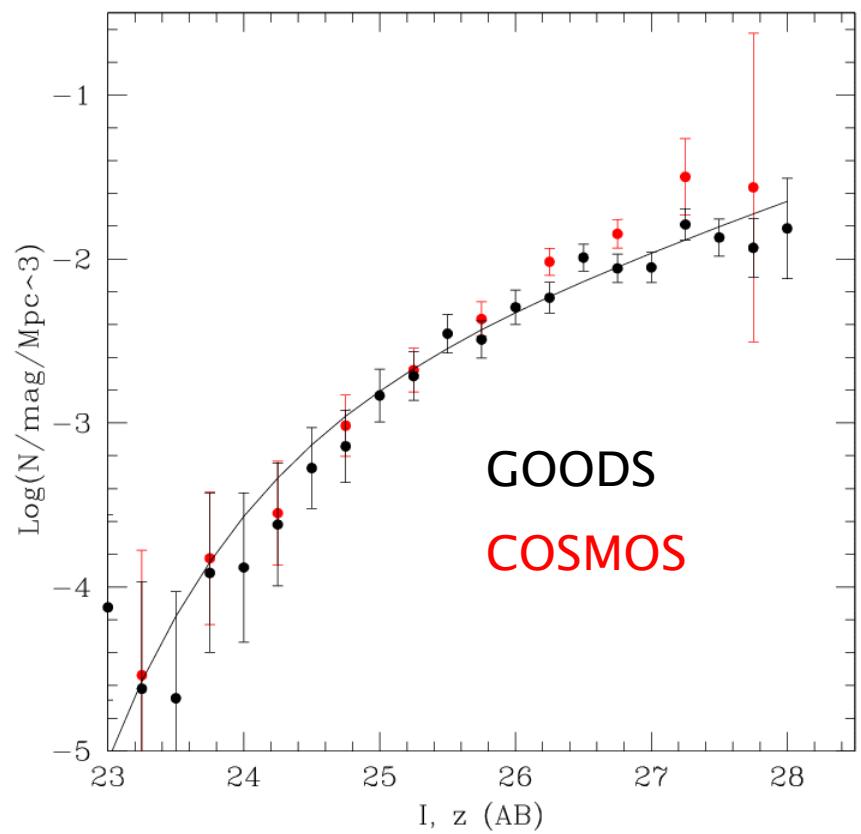
Reddy et al. 2006



Dimming at $z > 4$



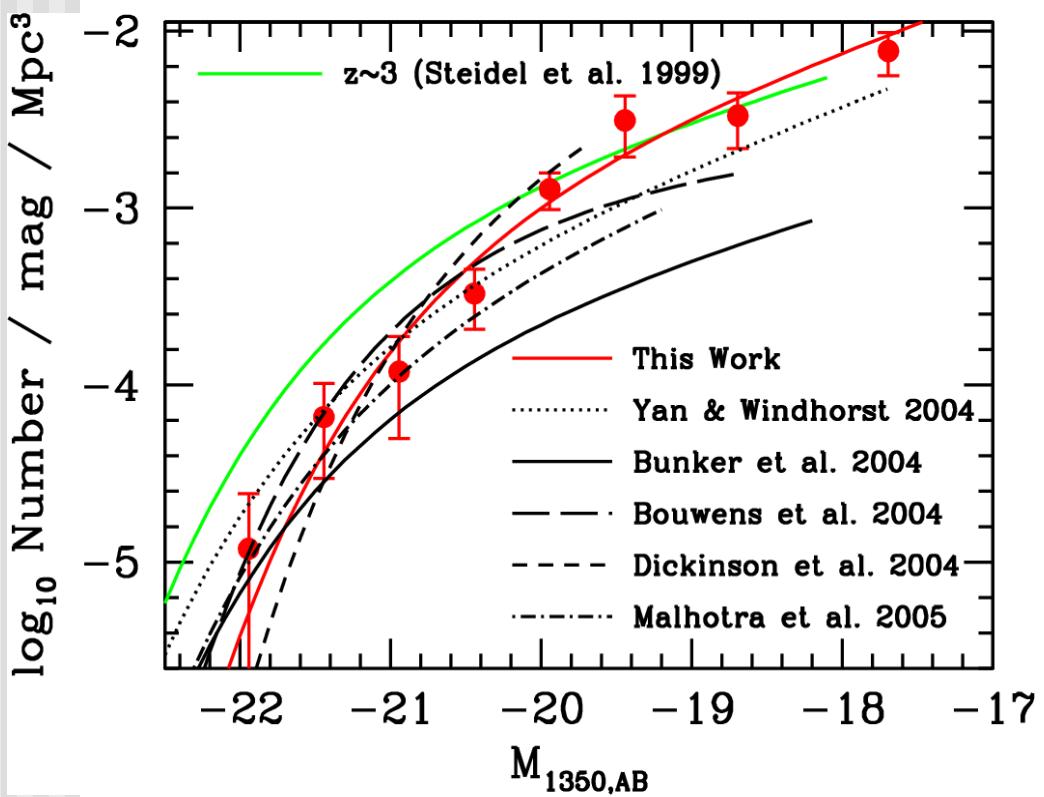
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...and out to $z \sim 6$

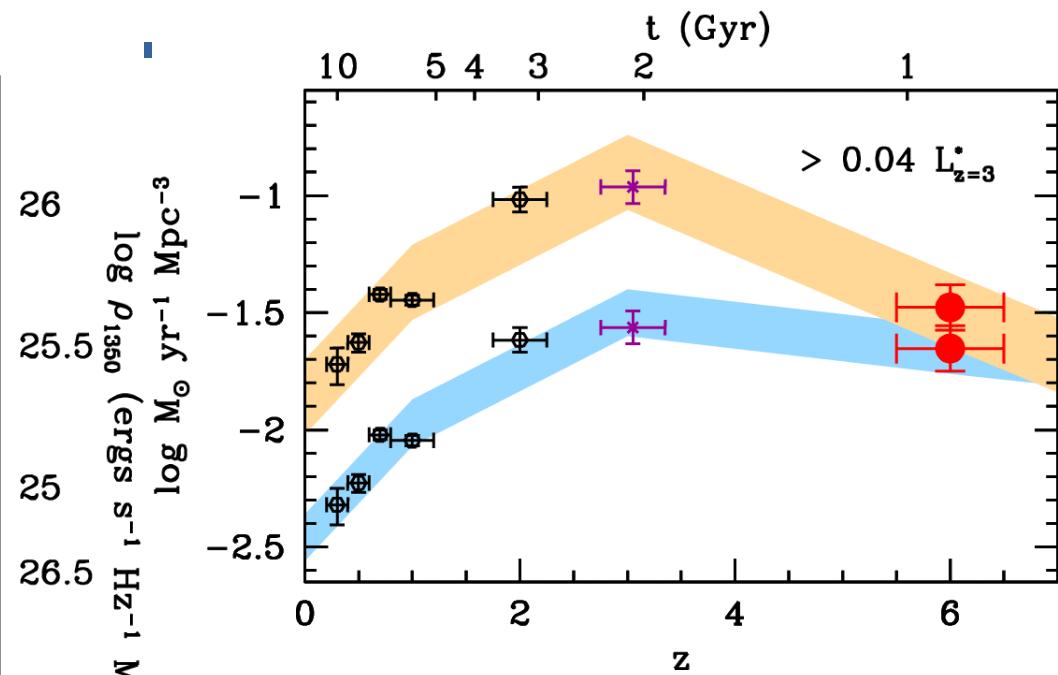
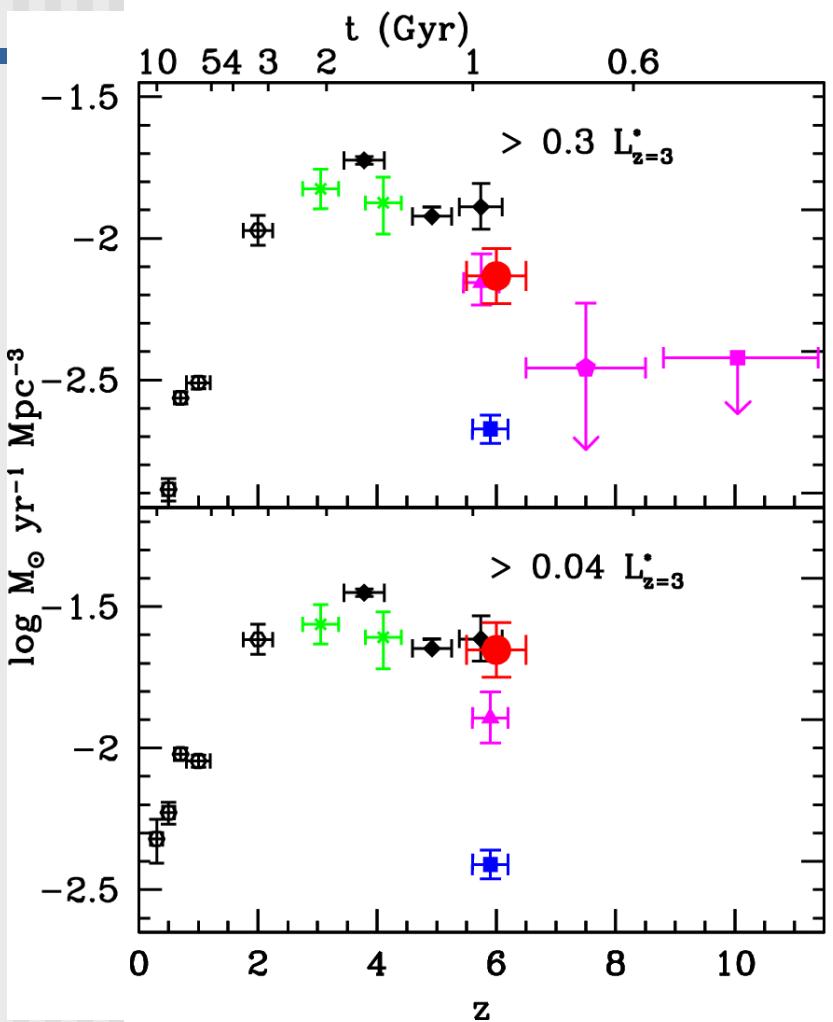
Bouwens et al. 2006



$M^* \sim 0.6$ mag fainter
than at $z=3$

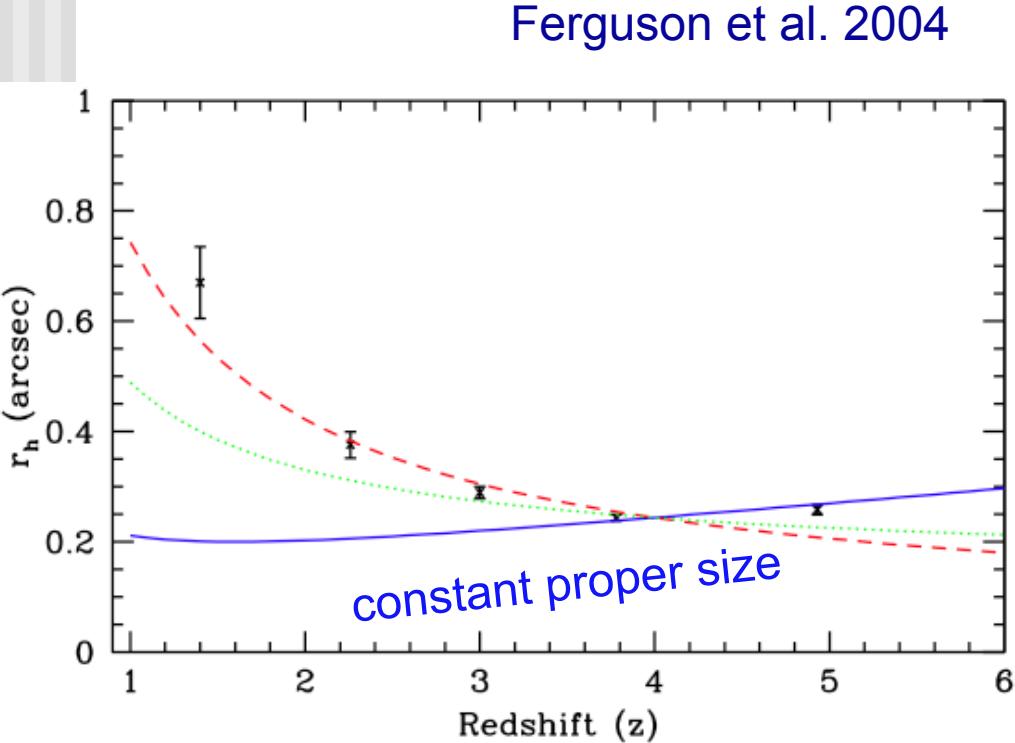
ϕ^* slightly larger
 α slightly steeper

SFR(UV): $3 < z < 6$

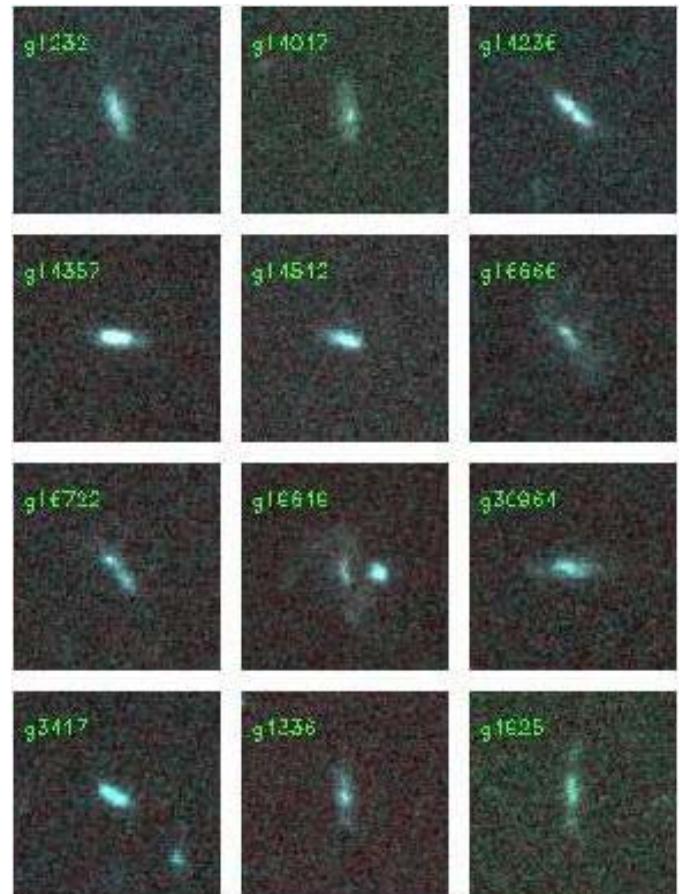


Bouwens et al. 2006

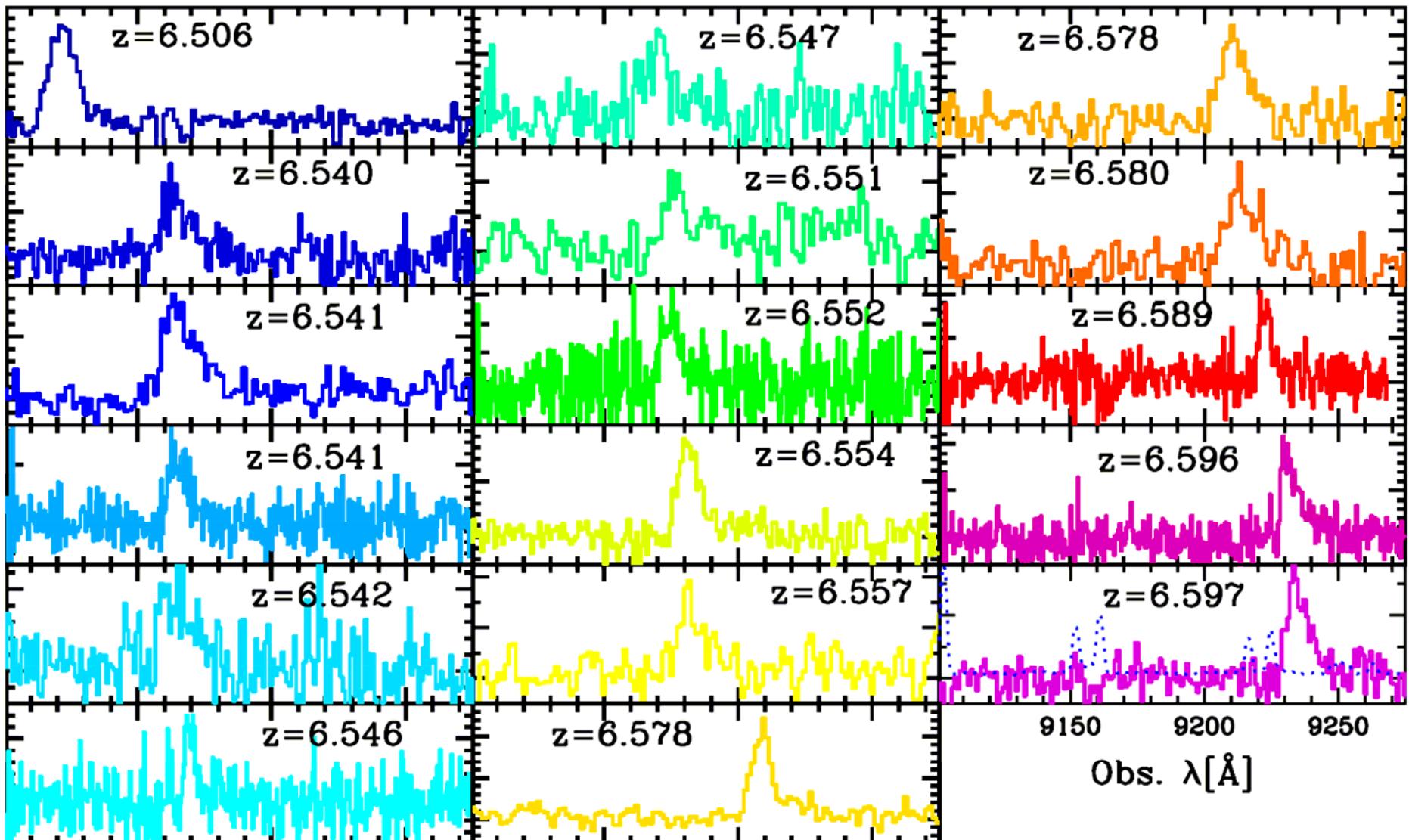
Growth of galaxy sizes



Ravindranath et al. 2006



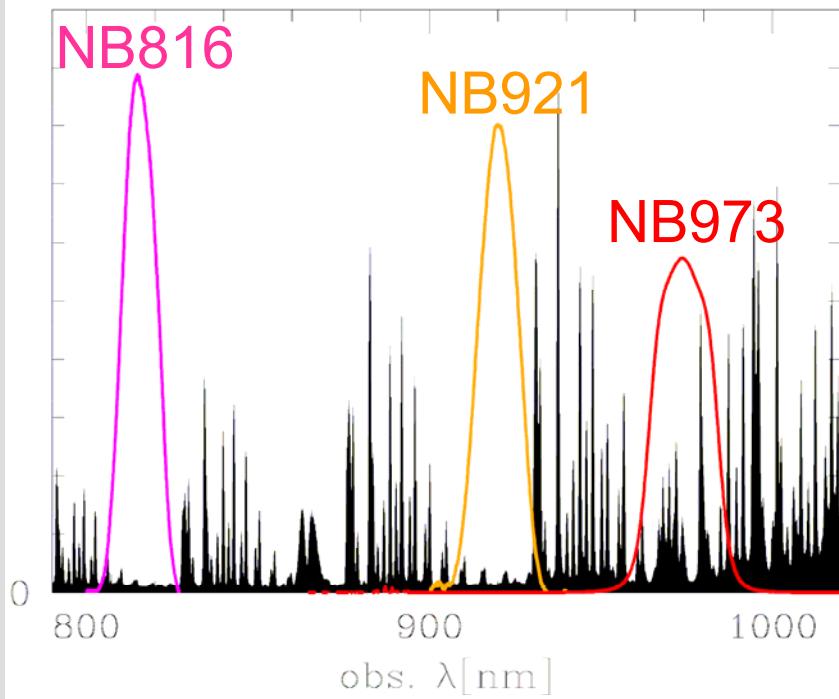
$z > 6.5$ Lyman α emitters (Kajisawa et al.)



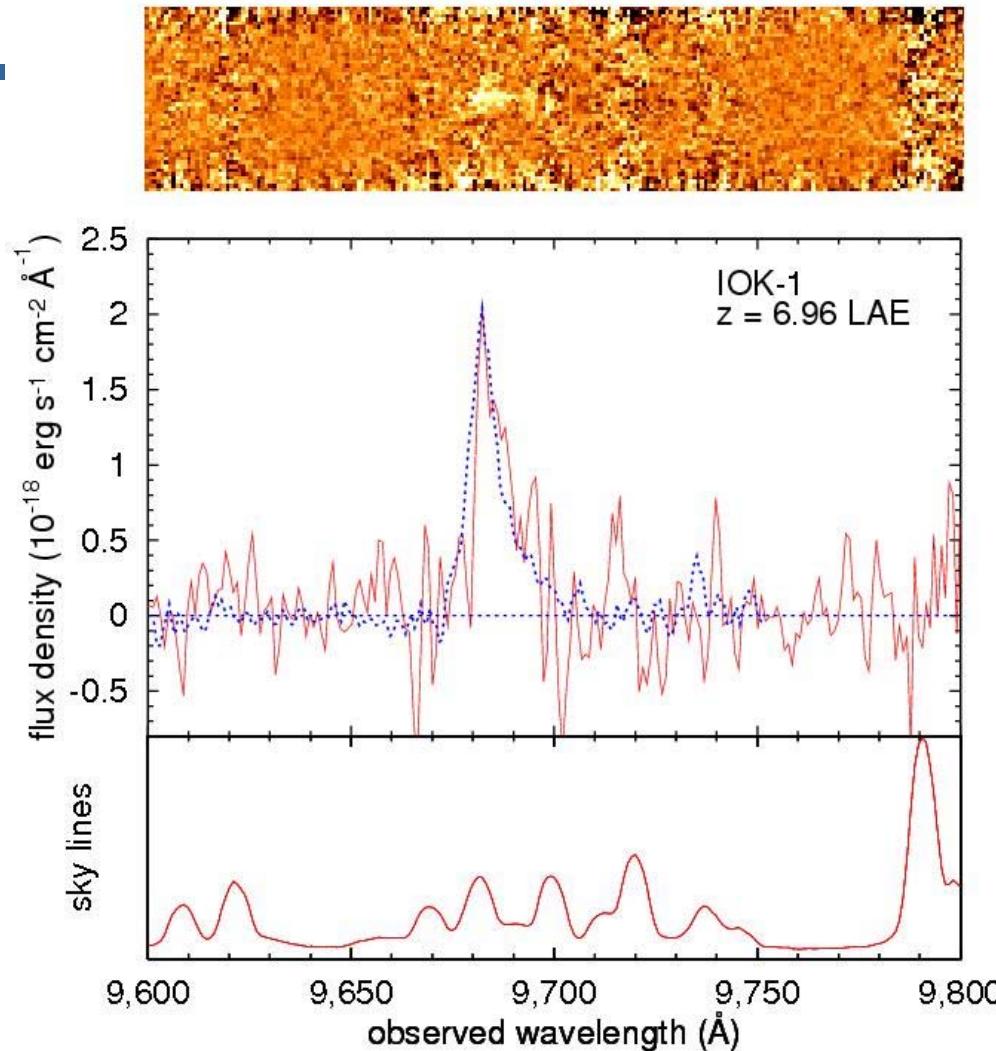
LAE at $z=6.96$ in the SDF

Iye et al. 2006

- NB973-excess object
- 2 candidates
- 1 spec. confirmed



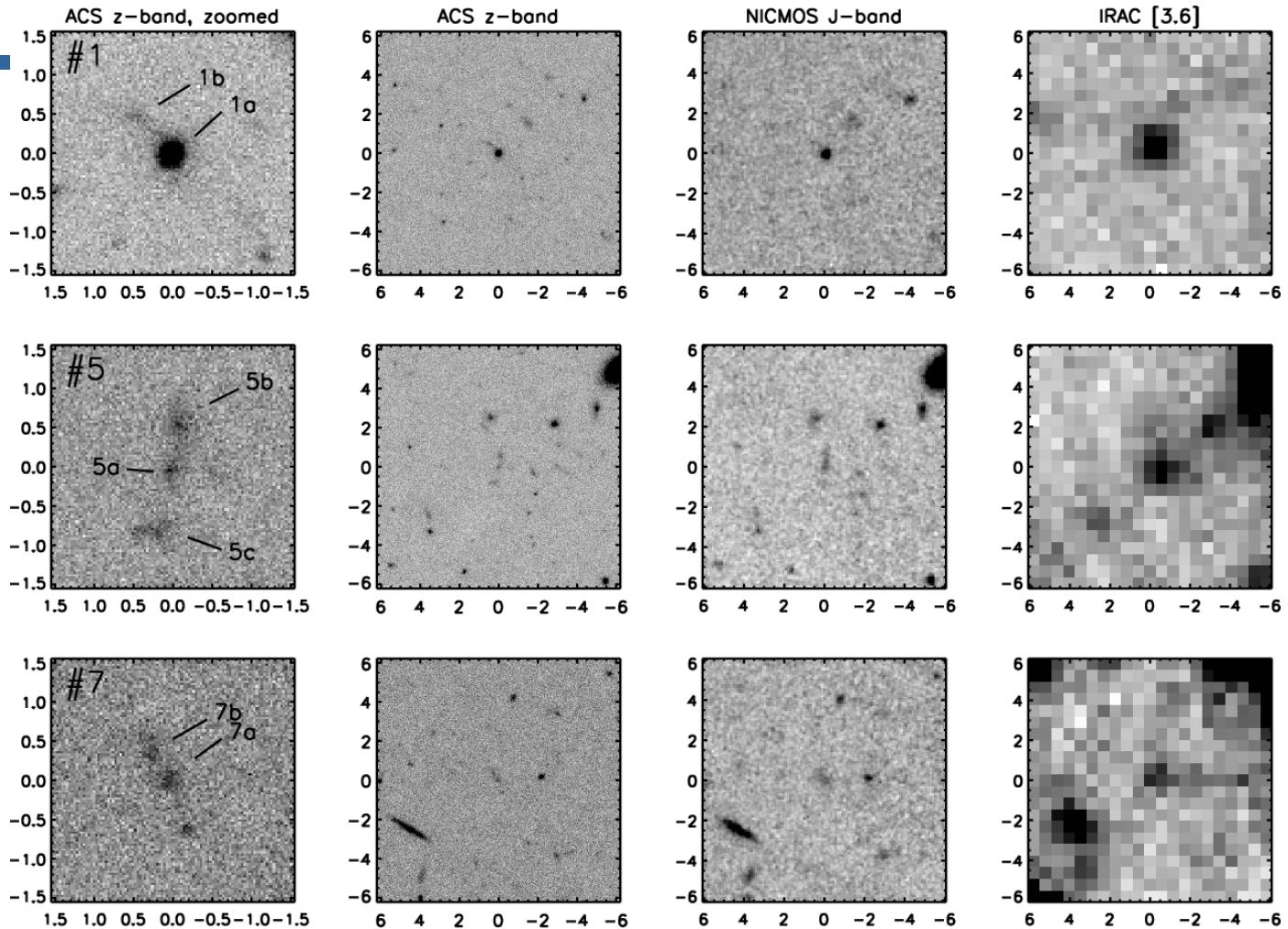
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$z \sim 6$ with an 85cm telescope

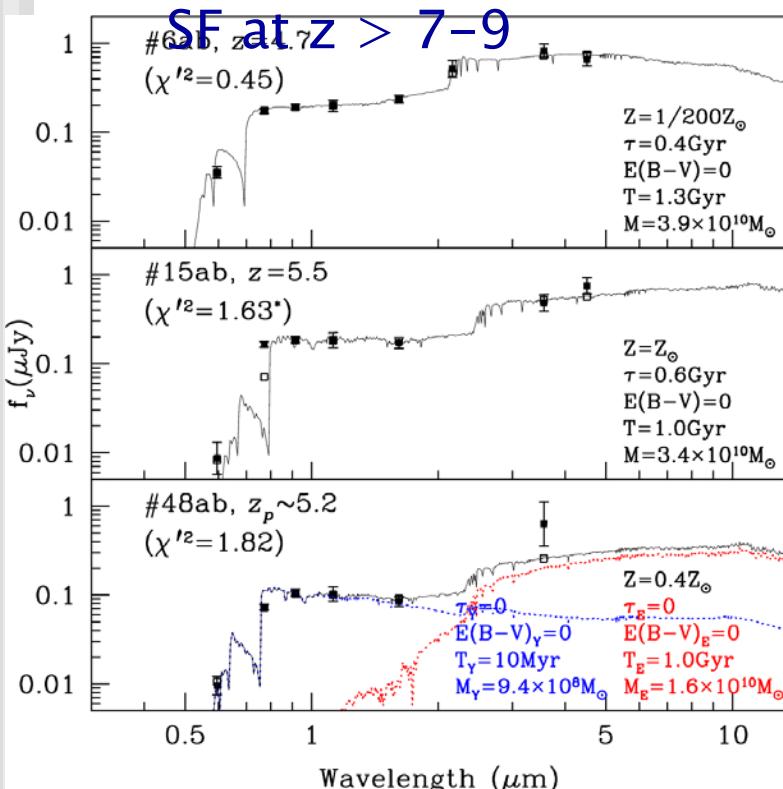
Yan et al. 2005, 2006



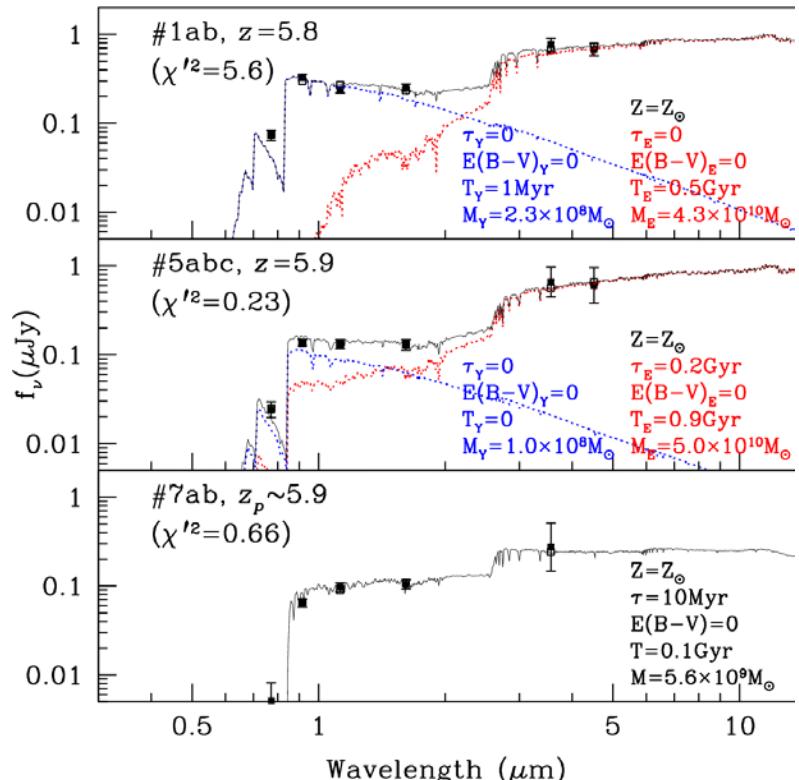
Stellar population modeling for z~5-6 galaxies

(Eyles et al. 2005, 2006; Yan et al. 2005, 2006; Stark et al. 2006)

IRAC-detected $z \sim 5-6$ galaxies in GOODS+HUDF have stellar masses $10^9 < M/M_\odot < 10^{11}$, with Balmer breaks indicating ages \sim few $\times 10^8$ years, and initial



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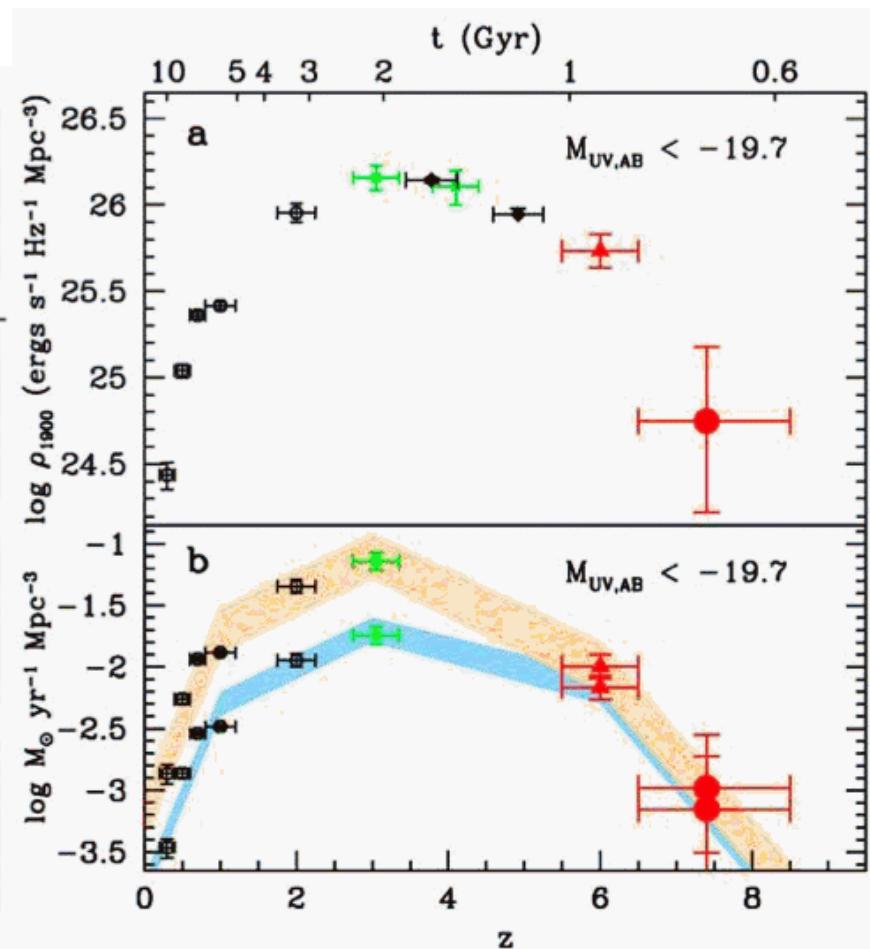
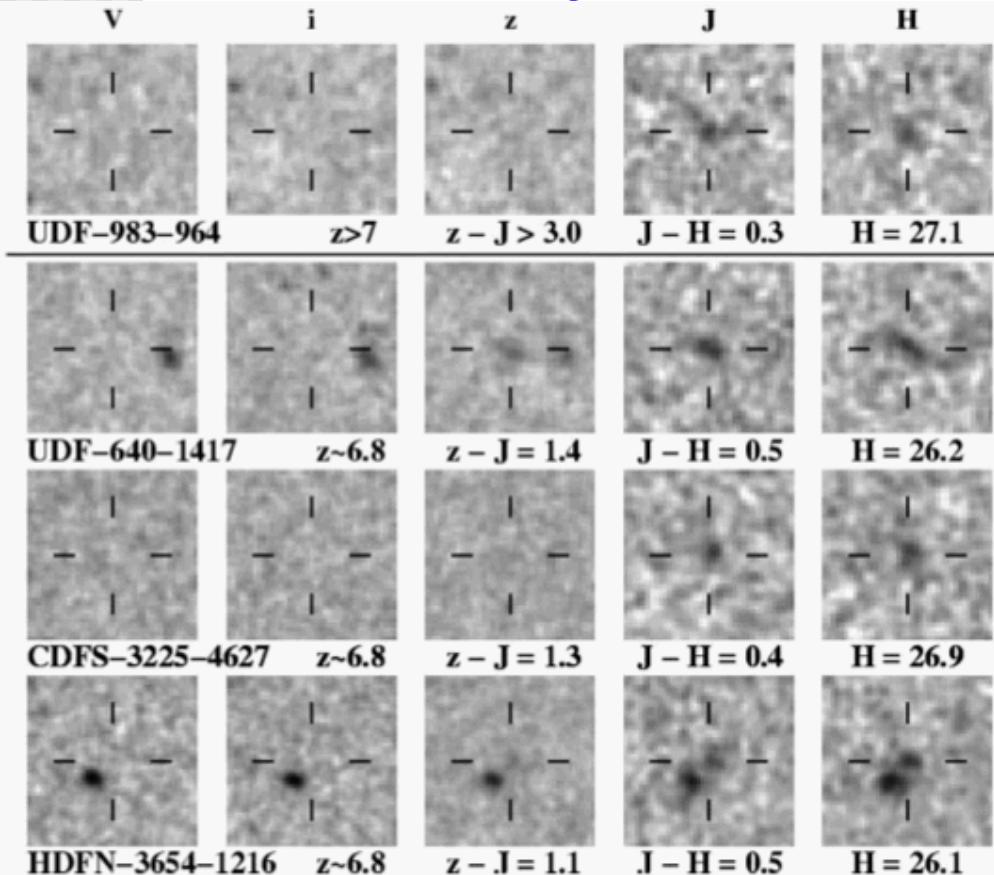
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Here lie monsters ($z > 7$)

- Mainly color selection only so far
 - All plausible candidates at the margins of detection!
(cf. Bouwens & Illingworth 2006)
 - Candidate lensed objects from near-IR spectra (e.g., Pello et al., Ellis et al.)
- Limited evidence points to continuing evolution in the number density of bright objects
- Some monsters?
- The fossils of reionization

Digging into the noise...

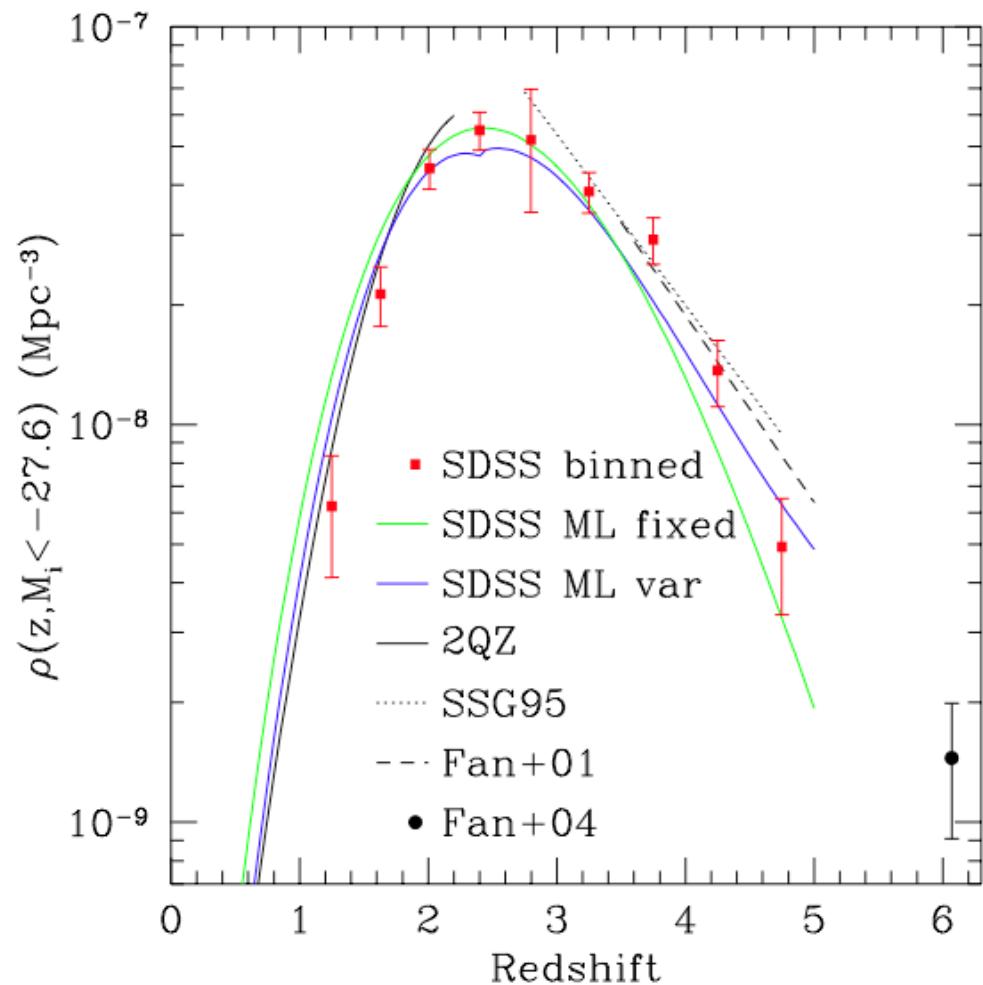
Bouwens & Illingworth 2006

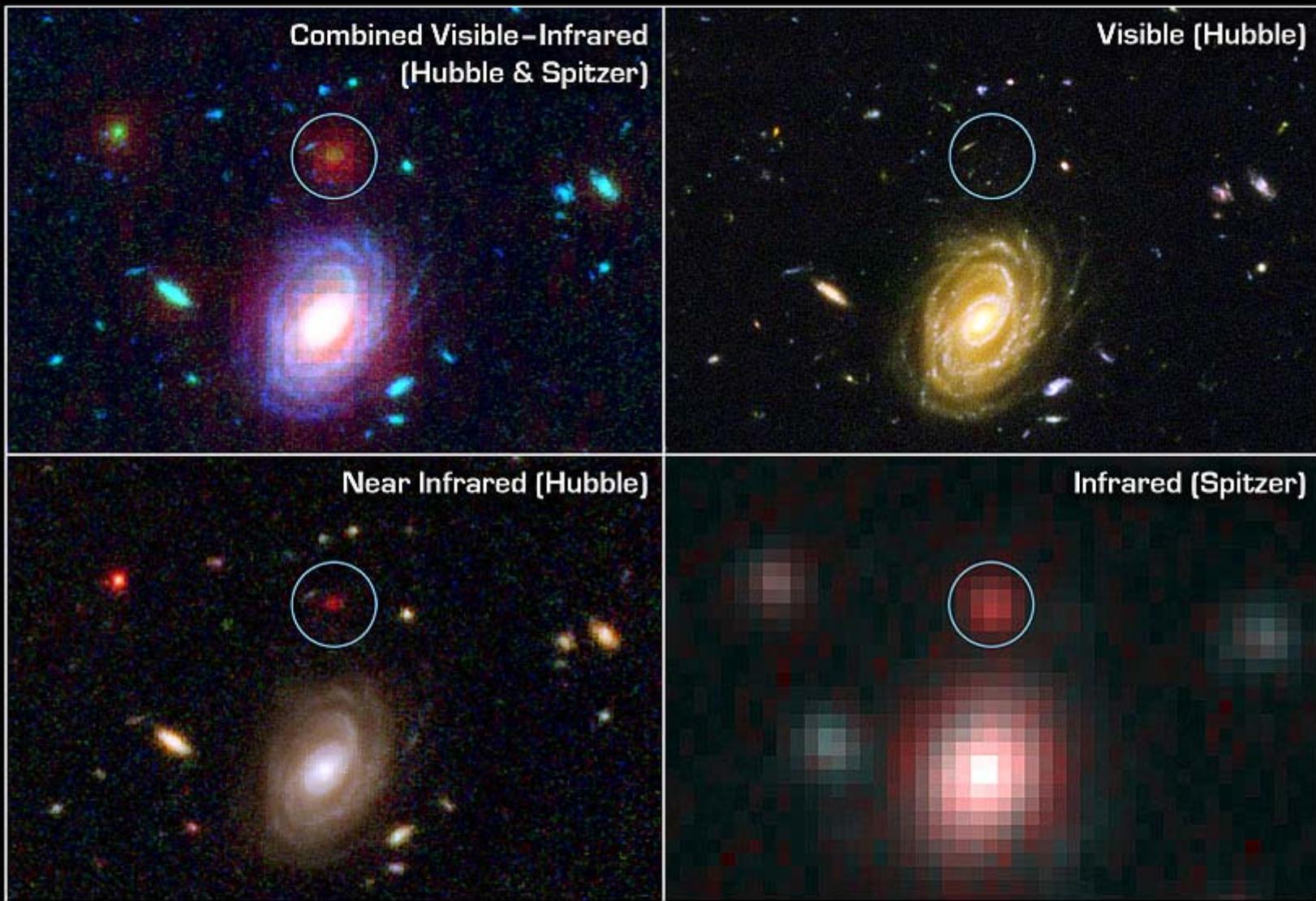


Tough sledding ahead

QSO evolution
from SDSS

Richards et al. 2006
Fan et al. 2004





Distant Galaxy in the Hubble Ultra Deep Field

NASA, ESA / JPL-Caltech / B. Mobasher (STScI/ESA)

Spitzer Space Telescope • IRAC
Hubble Space Telescope • ACS • NICMOS

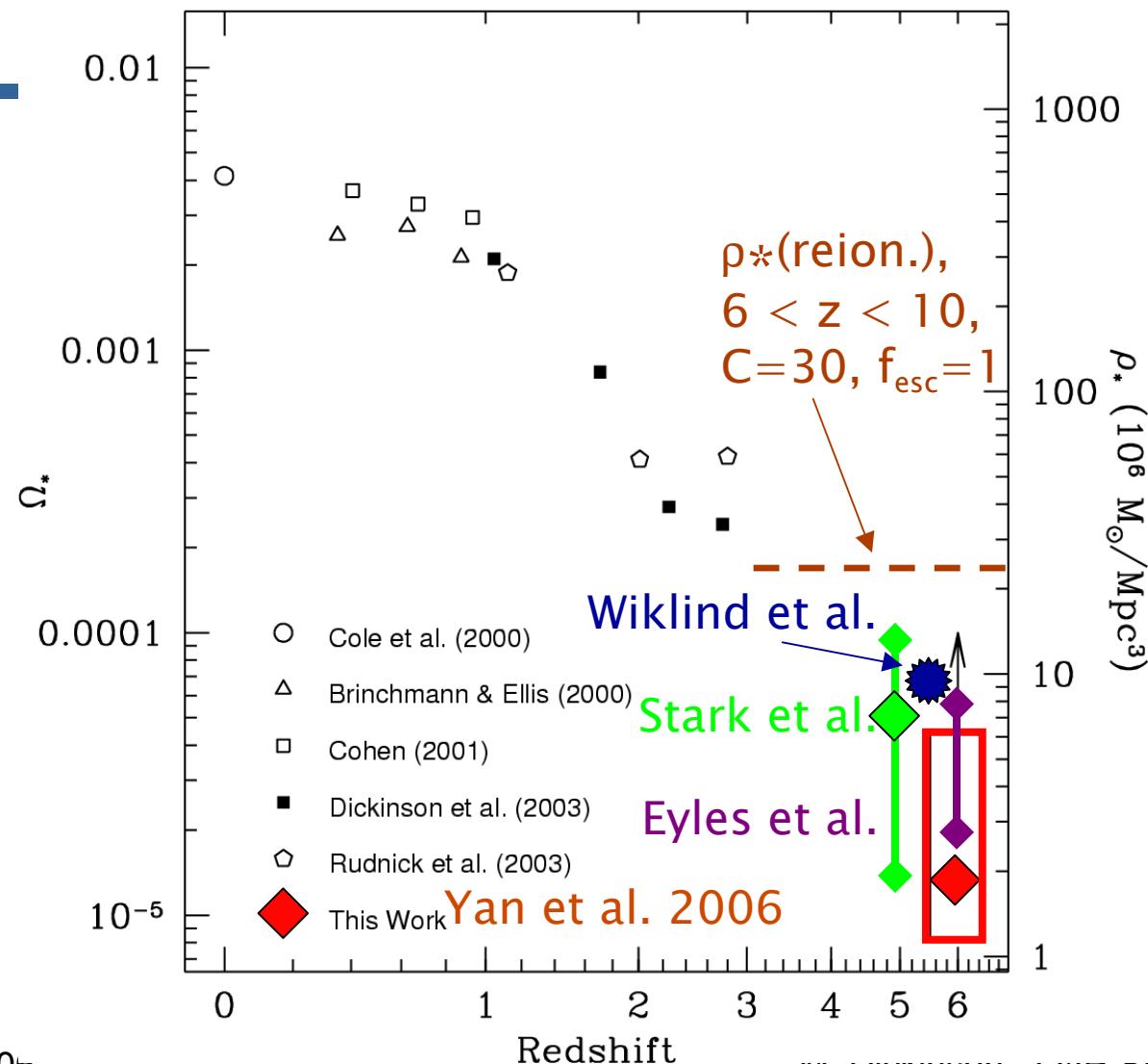
ssc2005-19a

Stellar mass density, $z \sim 5$ to 6

Estimates for ρ^* at
 $z=5-6$ are 5–50x
smaller than at
 $z \sim 2-3$

Stars whose formation
produces sufficient
reionizing photons at
 $6 < z < 10$ for 100% Lyman
contin. escape fraction
(Madau, Haardt & Rees
1999)

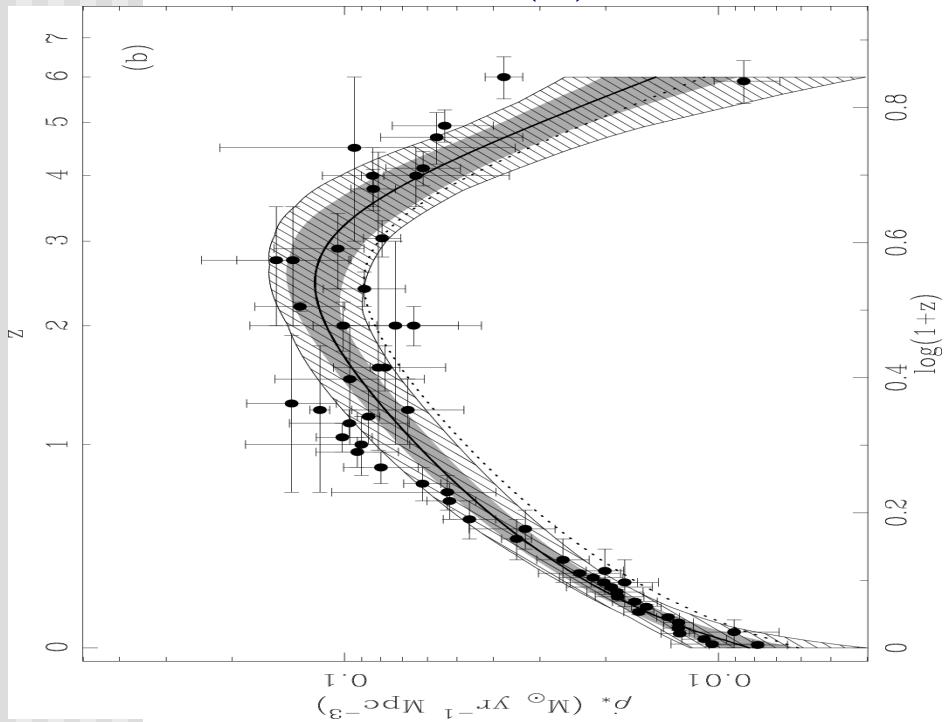
See Ferguson et al. 2004



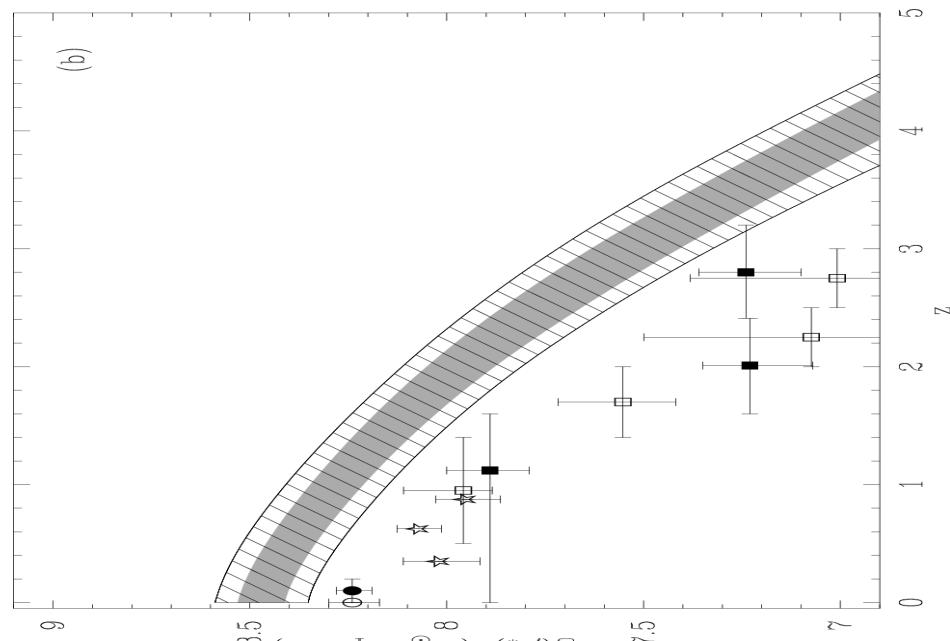
SFR(z) vs. $\Omega^*(z)$: tension at all redshifts?

Derived SFR(z) *may* overproduce derived $\Omega^*(z)$ at most redshifts

SFR(z)



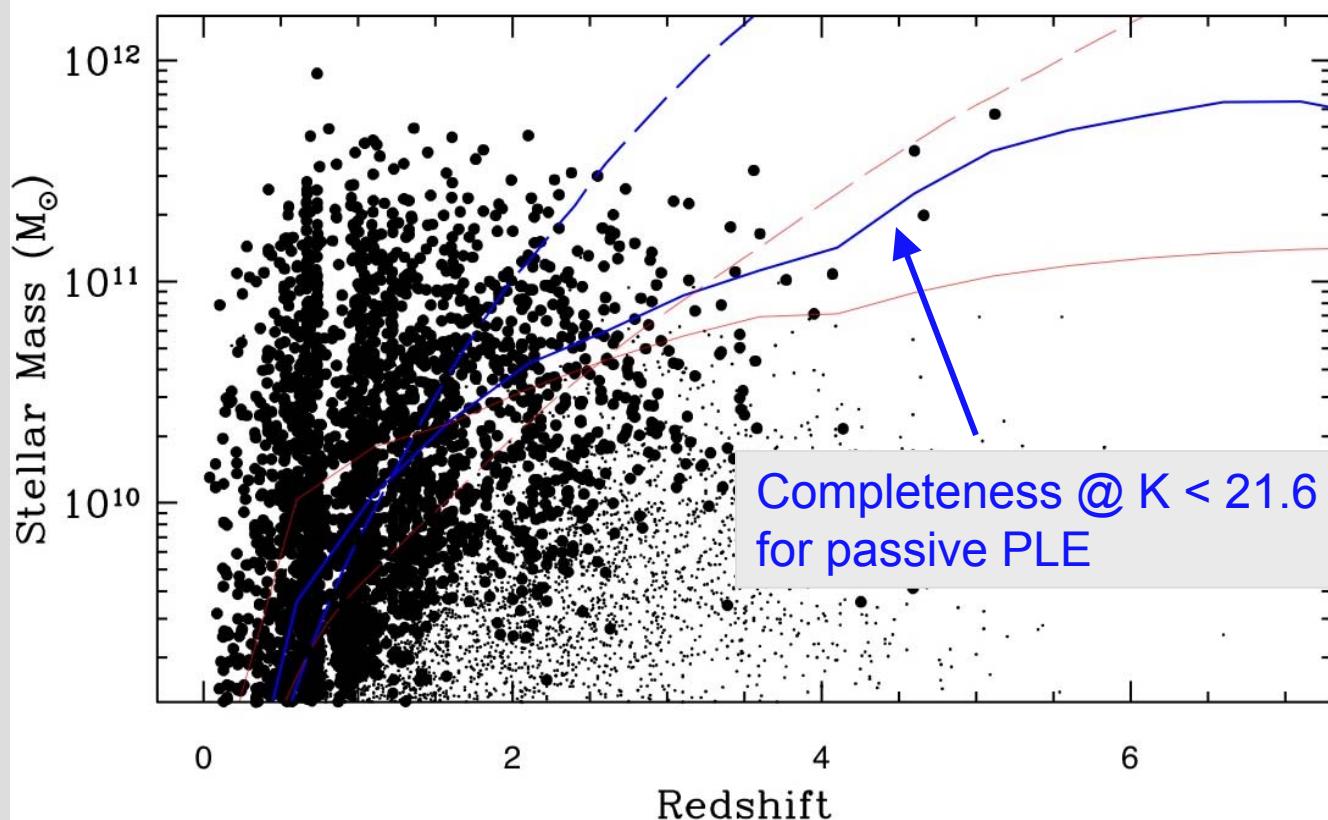
$\Omega_{\text{stars}}(z)$



Hopkins & Beacom 2006; see also Chary & Elbaz 2001; Dickinson et al. 2003; Ferguson et al. 2003

Near-infrared imaging: a vital ingredient

Fontana et al. 2006



Very deep JHK
data utterly vital for:

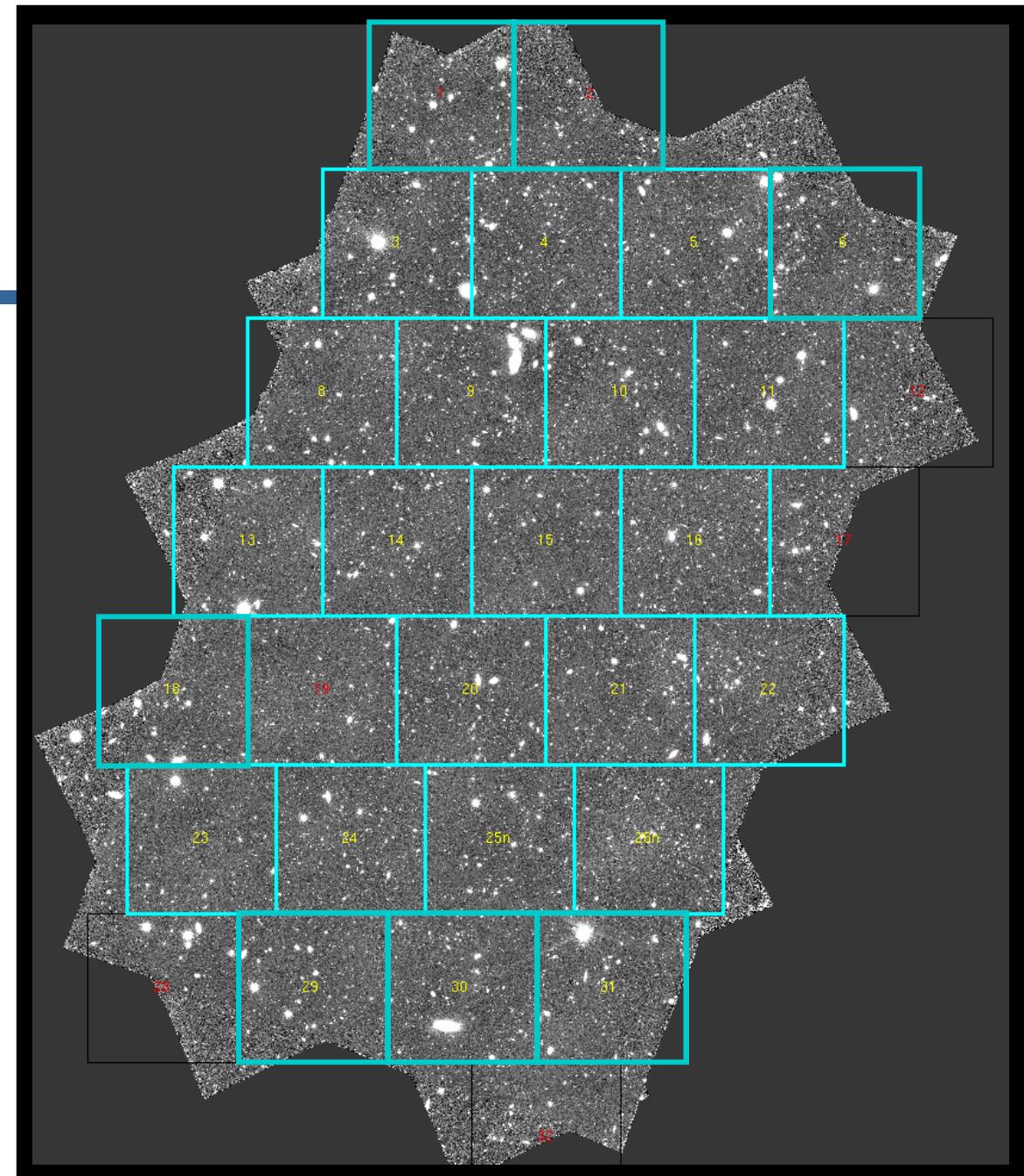
- Detecting high-z galaxies
- Photo-z estimation (unavoidable, alas)
- Stellar population modeling

GOODS-S ISAAC near-IR imaging

500+ hours (~80 nights)
of JHKs imaging covering
160 arcmin²
20h x 26 pointings

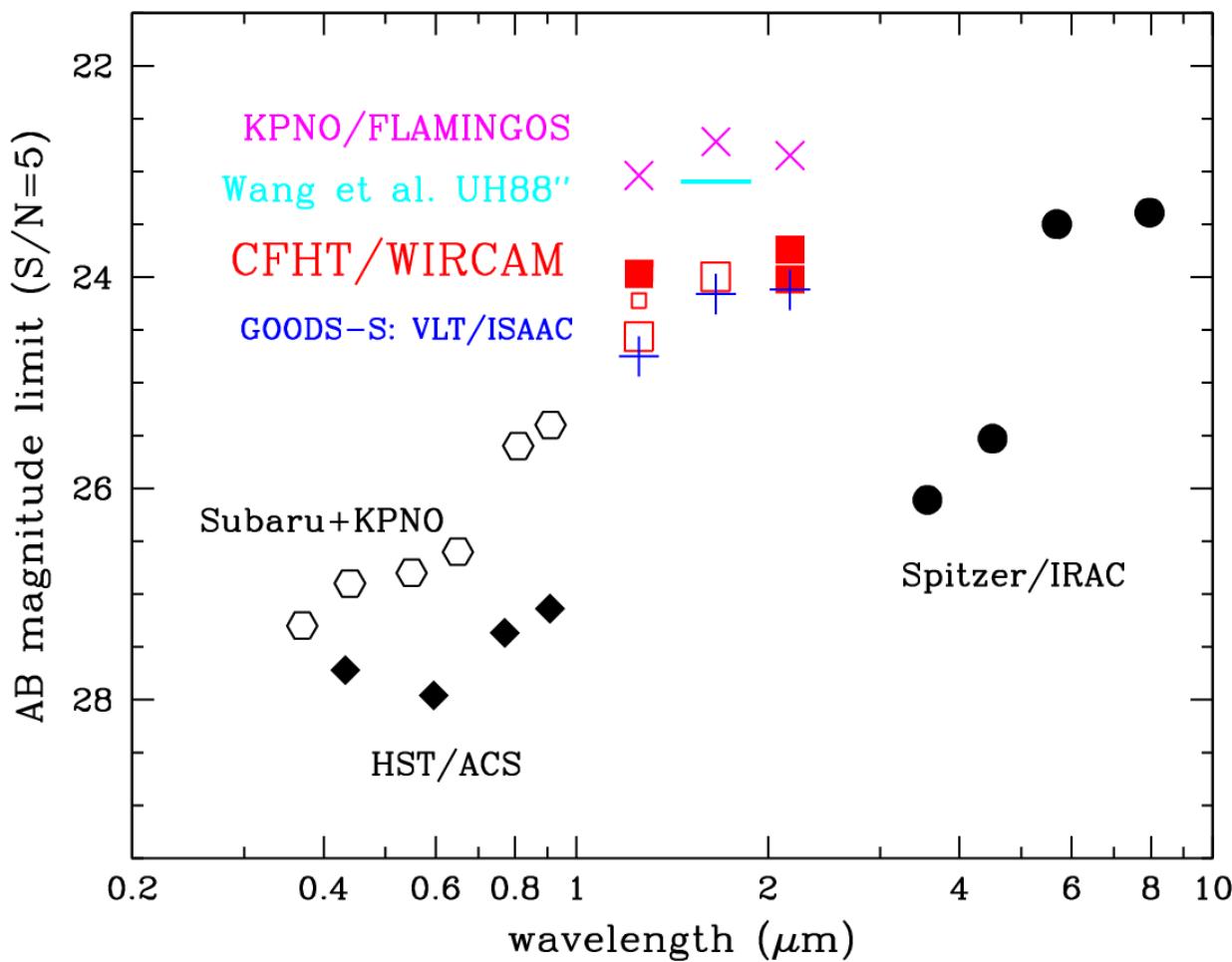
2 incremental data
releases,
3rd (final?) upcoming

Next generation VLT
instrument HAWK-I would
require 9 nights for the
same, or go ~1.2 mag
deeper in ~80 nights:
still shallower than
desired to match ACS +
IRAC



The near-IR data gap

For almost any high-z survey, near-IR data are the weakest photometric link.



New NIR imagers* on 6.5-10m telescopes

- MMT/SWIRC: 5'.1 x 5'.1
- MMT+Magellan/MMIRS*: 7' x 7'
- Magellan/FourStar: 10'.9 x 10'.9
- Subaru/MOIRCS*: 7' x 4'
- Gemini/FLAMINGOS-2*: 6'.2 diameter
- VLT/HAWK-I: 7'.5 x 7'.5
- Keck/MOSFIRE*: 6'.1 x 6'.1
- GTC/EMIR*: 6' x 6'

*also multiobject spectrograph

Redshift samples

- $z \sim 0.1$: $\sim 10^5 - 10^6$ galaxies (e.g. SDSS, 2dF)
- $0.3 < z < 1$: $\sim 10^4 - 10^5$ galaxies (e.g. AGES, DEEP2, VVDS, Z-COSMOS)
- $1 < z < 3$: $\sim 10^3$ galaxies (e.g. GDDS, VVDS, GOODS/K20/GMASS, Steidel et al.)
- $3 < z < 7$: $\sim 10^2$ galaxies (LBGs, Ly α emitters)

Redshift samples

- Even by generous assessment, high-z spectroscopic survey volumes are falling ~1-3 orders of magnitude short compared to SDSS ($\sim 1 \text{ Gpc}^3$).

Is that ok?

- Surveys covering $\sim 100 \text{ deg}^2$ will approach the SDSS volume at high redshifts
 - Initially limited to photometric redshifts
 - ~ 1000 aperture, deg^2 FOV spectrographs
- Very large multiplex strongly driven by:
 - Cosmology (e.g. baryon oscillations)
 - Sophisticated studies of large-scale structure
 - Galactic archaeology

Going beyond redshifts

- Nebular spectral lines are key for deriving chemical abundances, ionization, AGN diagnostics.
 - E.g. see SDSS where “value added” nebular diagnostics have played a huge role
- AGN and abundance diagnostics may help us to understand the role of AGN in shutting down SF
- Adequate resolution enables:
 - Kinematics
 - Gas dynamics (winds/outflows, etc.)

Going beyond redshifts

- Purely optical spectral diagnostics limited for large samples at high z :
 - H α , [NII] only at $z < 0.5$
 - H β , [OIII] only at $z < 1$
- Near-IR MOS will extend the redshift range, but:
 - Much lower multiplex
 - Cross calibration issues between bands, optical/IR

Summary

- Most of the galaxy evolution timeline is within view!
- Statistical richness is yielding scientific richness (redshift surveys; Galactic stars)
- New tools (IFUs, AO) are opening up new horizons
 - Kinematics/dynamics
 - Star formation diagnostics
 - Chemical evolution
 - ISM/IGM interplay
- Near-IR imaging still falls far short of what we need
- Ditto for sensitivity of near-IR spectroscopy
- Colossal spectroscopic multiplex may open new possibilities