FRONTIERS OF ASTRONOMY

Alexandria, March 2006

Richard Ellis, Caltech

1. Role of Observations in Cosmology & Galaxy Formation

    Key Results and the Standard Model (ΛCDM)

    Observational Probes of the Dark Matter Distribution

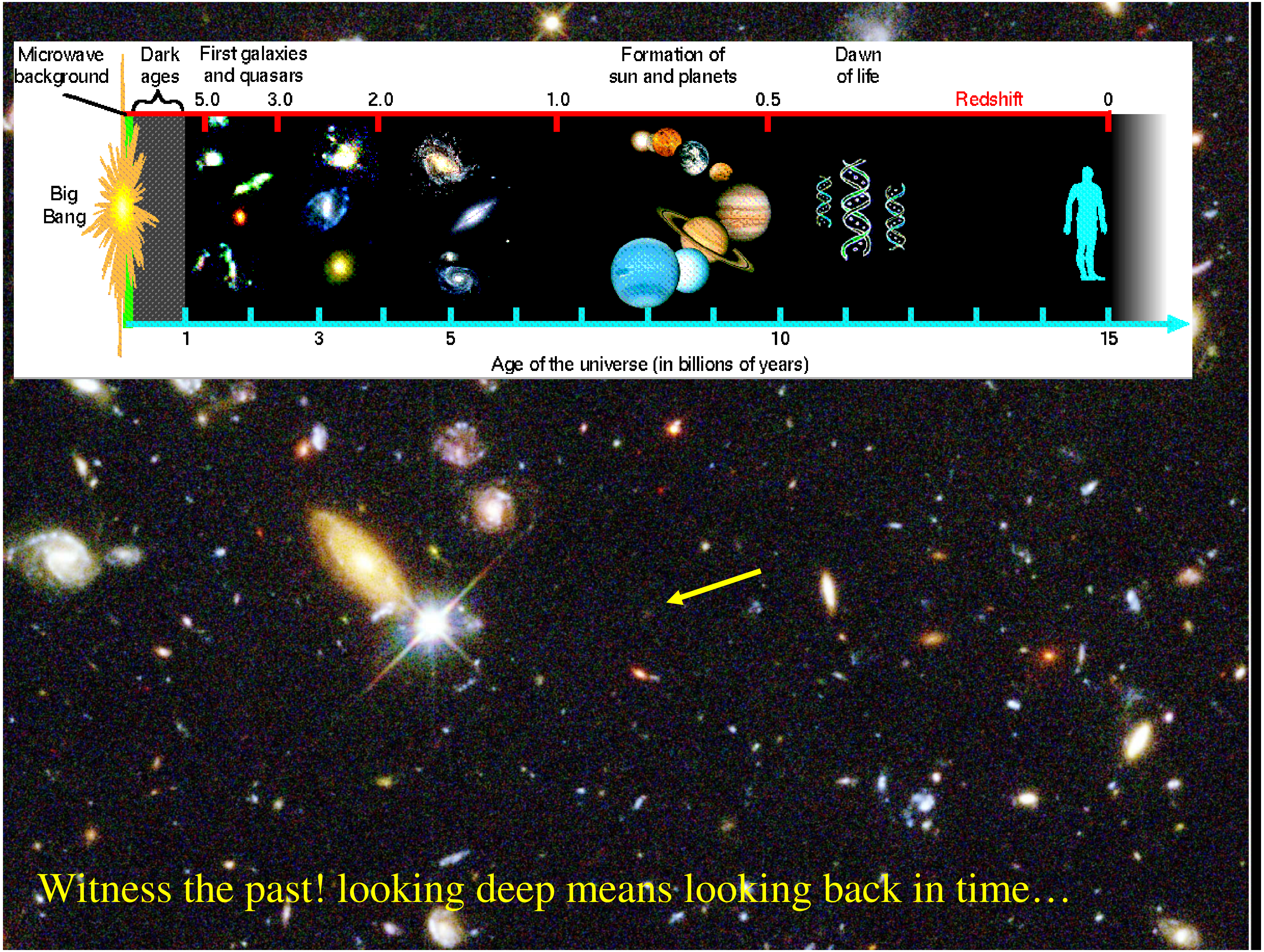
2. High Redshift Galaxies:

    Cosmic Star Formation History and Mass Assembly

    Cosmic Dawn: Searching for the Earliest Sources

3. Observational Probes of Dark Energy

    Supernovae, weak gravitational lensing and studies of large scale structure


Microwave background
Dark ages
First galaxies and quasars
Formation of sun and planets
Dawn of life
Redshift
5.0
3.0
2.0
1.0
0.5
0
Big Bang
1
3
5
10
15
Age of the universe (in billions of years)
Witness the past! looking deep means looking back in time…

Importance of High z Data

Motivation:

- High redshift programs complement more detailed local studies and offer a direct test of theories of galaxy assembly
- Focus here on epochs corresponding to redshifts z > 2 where there is great progress using ground-based and space-based telescopes
- Exciting frontier is the search for the earliest systems which may have reionized the Universe at z~10

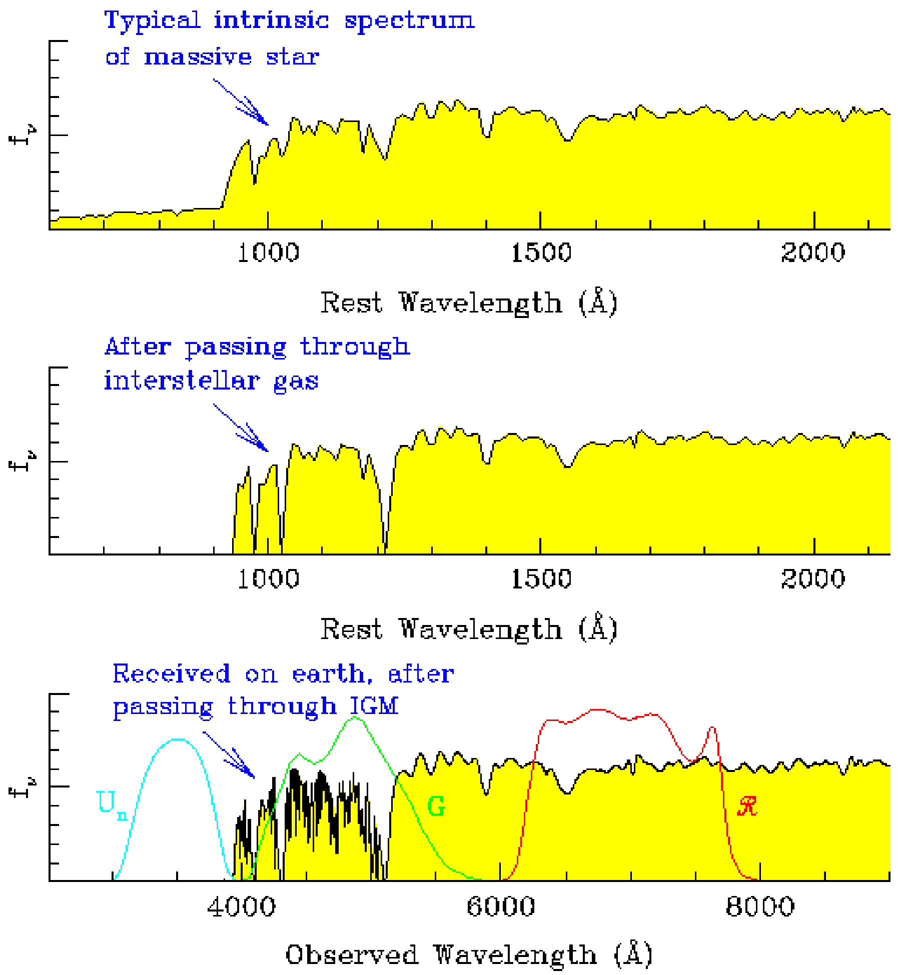
First need to introduce the various populations

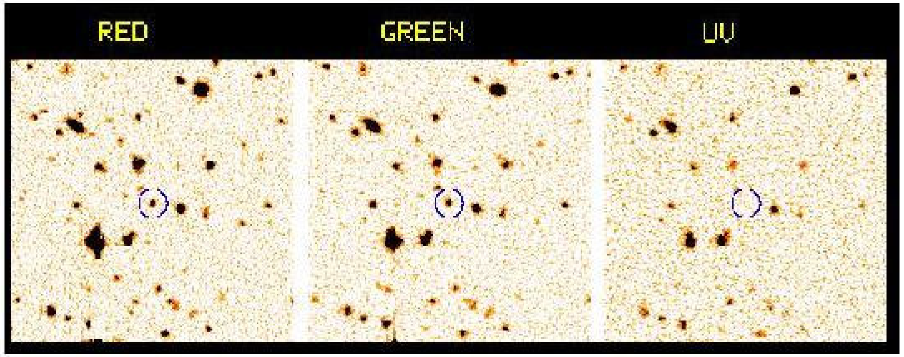
I: Lyman break galaxies: color-selected luminous star forming galaxies z > 2

II: Various categories of passively-evolving sources whose selection has been enabled via deep IR data

III: Sub-mm galaxies located via redshifted dust emission

Finding star-forming galaxies at high z



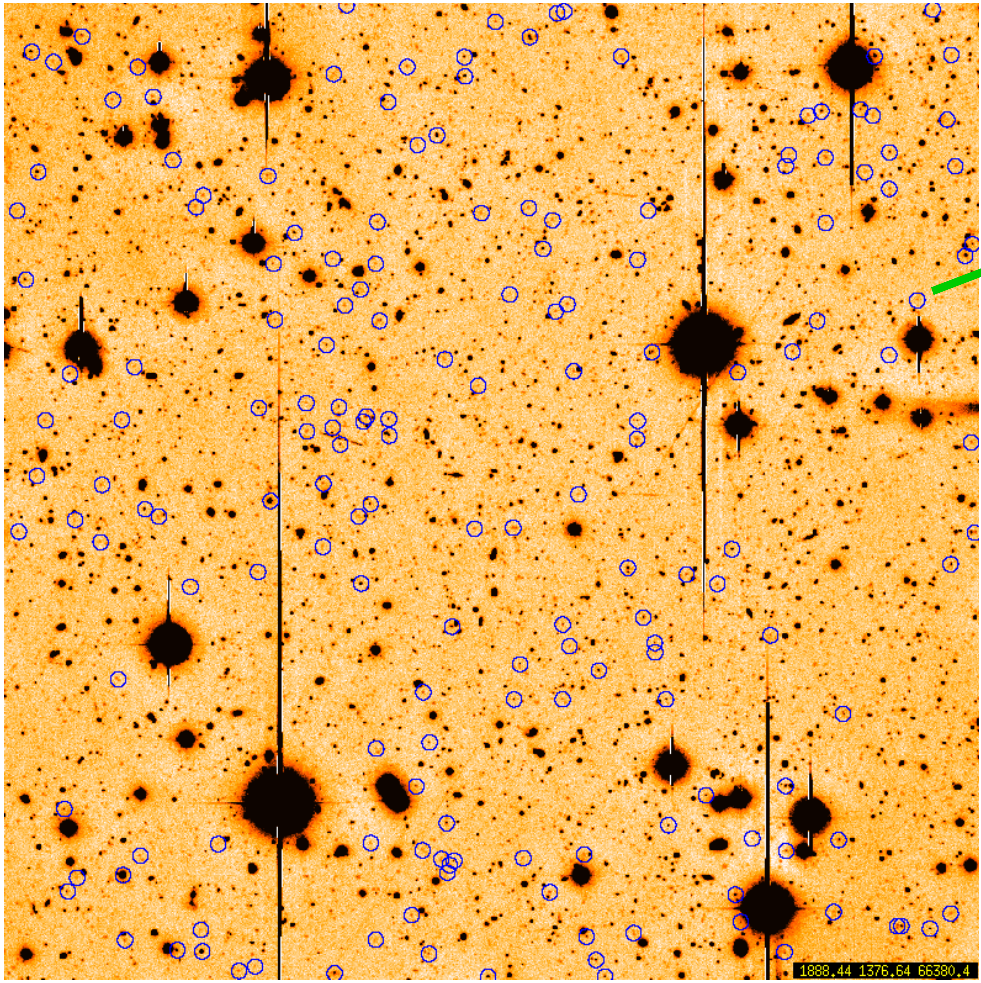


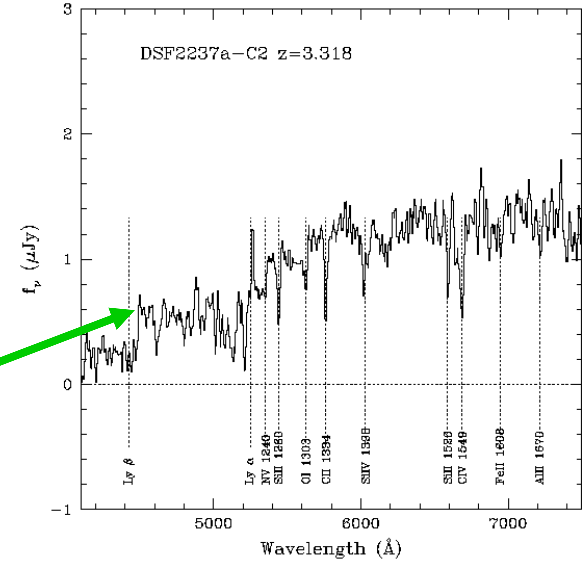
The Lyman continuum discontinuity is particularly powerful for isolating star-forming high redshift galaxies.

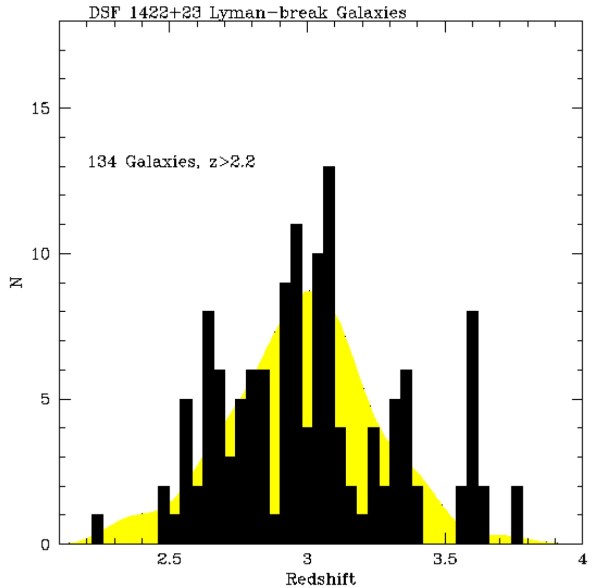
From the ground, we have access to the redshift range z=2.5-6 in the 0.3-1 micron range.

Steidel et al 1999 Ap J 462, L17
Steidel et al 1999 Ap J 519, 1
Steidel et al 2003 Ap J 592 728

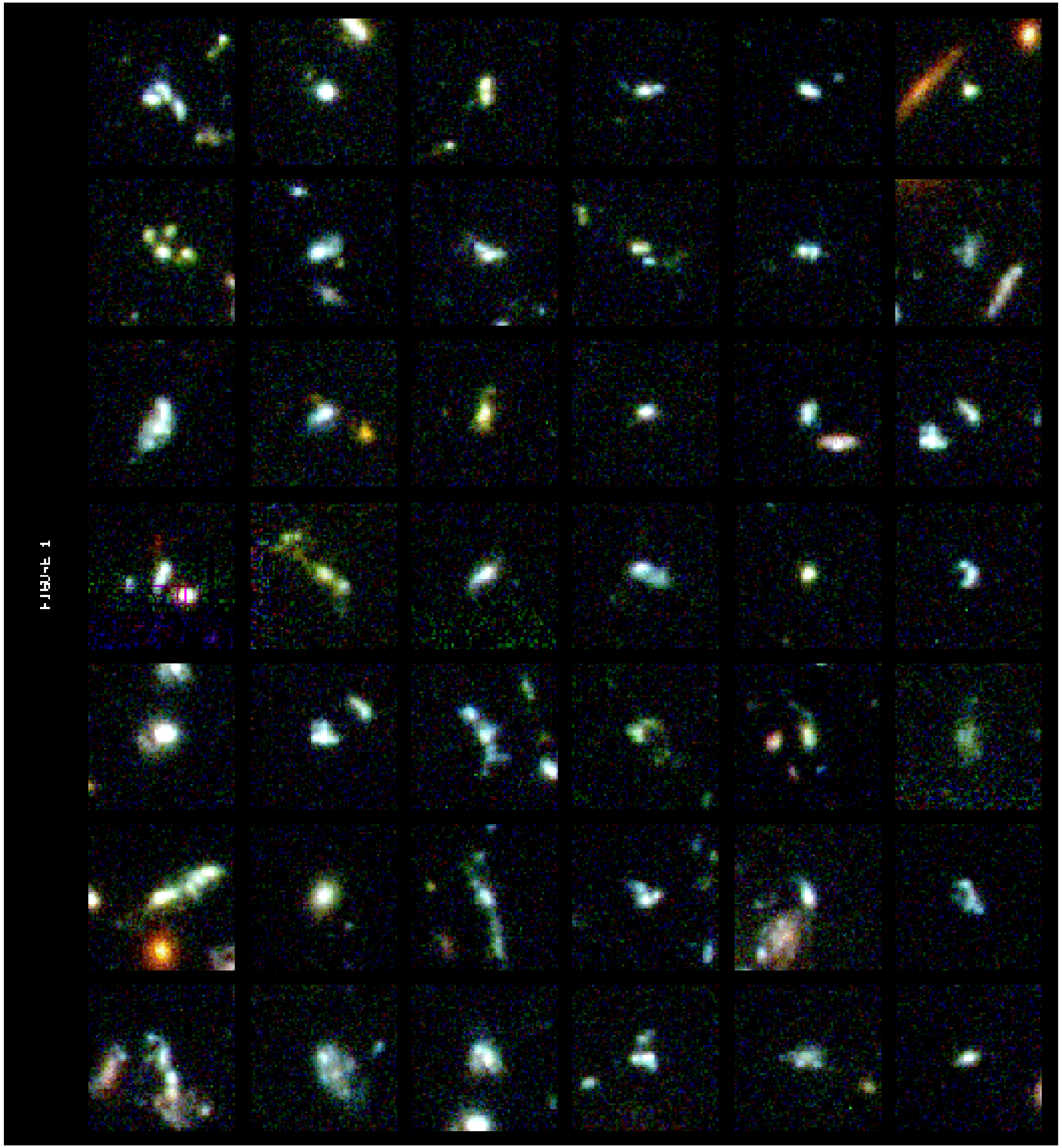
Spectroscopic Confirmation at Keck





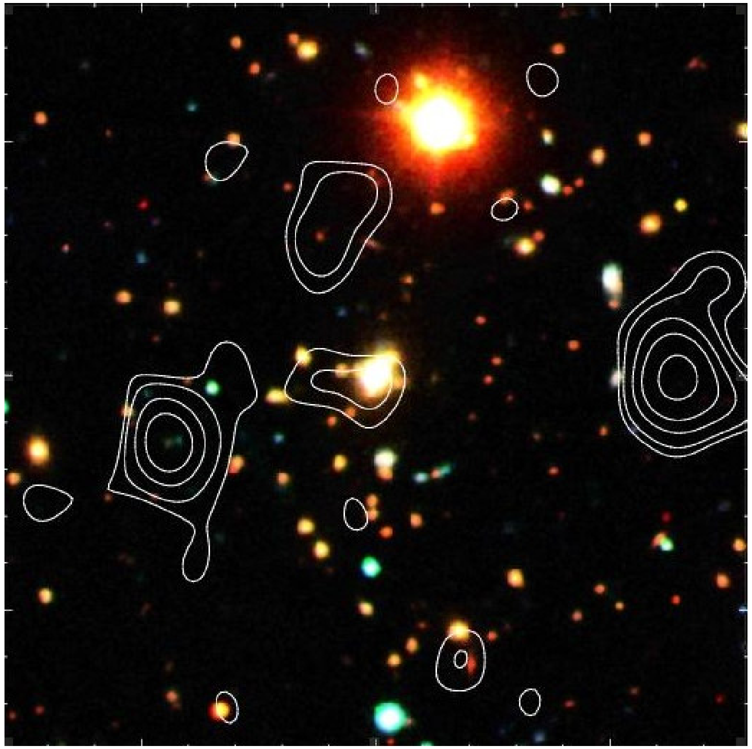


HST images of spectroscopically -confirmed "Lyman break" galaxies with z>2 in Hubble Deep Field North revealing small physical scale-lengths and irregular morphologies

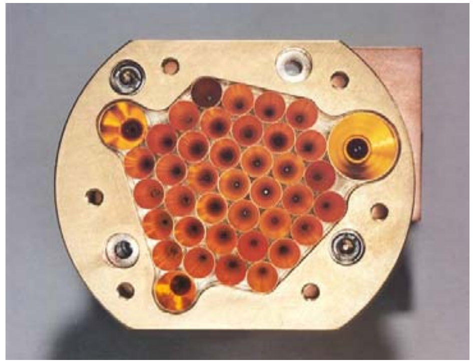


Giavalisco et al 1996
Ap J 470, 189

Sub-mm Star Forming Sources



15m JCMT



SCUBA array

Sub-mm astronomers

SCUBA: 850μm array detects dusty star forming sources:
- behind lensing clusters (Smail et al Ap J 490, L5, 1997)
- in blind surveys (Hughes et al Nature 394, 211, 1998)

Source density implies 3 dex excess over no evolution model based on density of local IRAS sources:

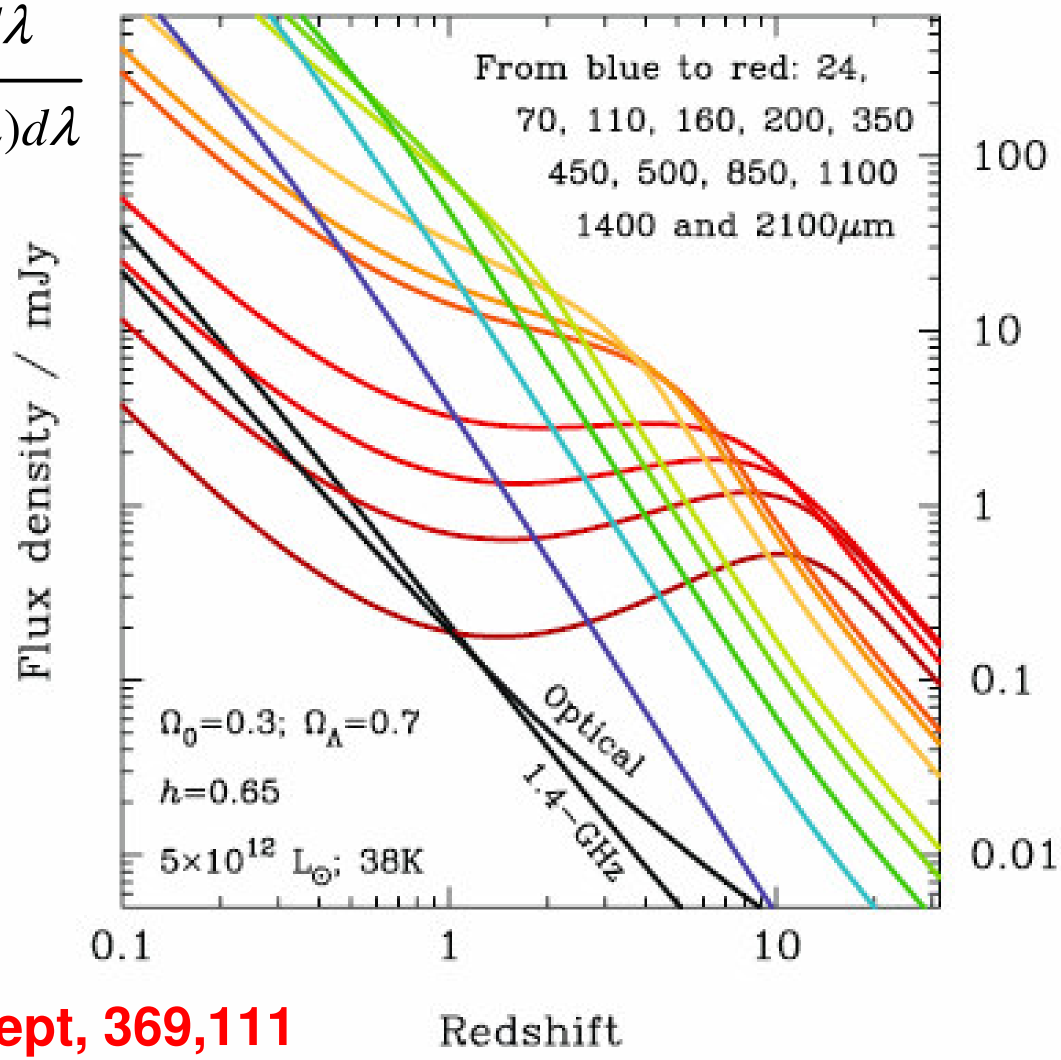
Key question is what is the typical redshift, luminosity and SF rate?

Negative k-correction for sub-mm sources

$$k(z) = (1+z)\frac{\int F(\lambda)S(\lambda)d\lambda}{\int F(\lambda/1+z)S(\lambda)d\lambda}$$

K-correction is the dimming due to the (1+z) shifting of the wavelength band (and its width) for a filter with response S(λ)

In the Rayleigh-Jeans tail of the dust blackbody spectrum, galaxies get ***brighter*** as they are redshifted to greater distance!



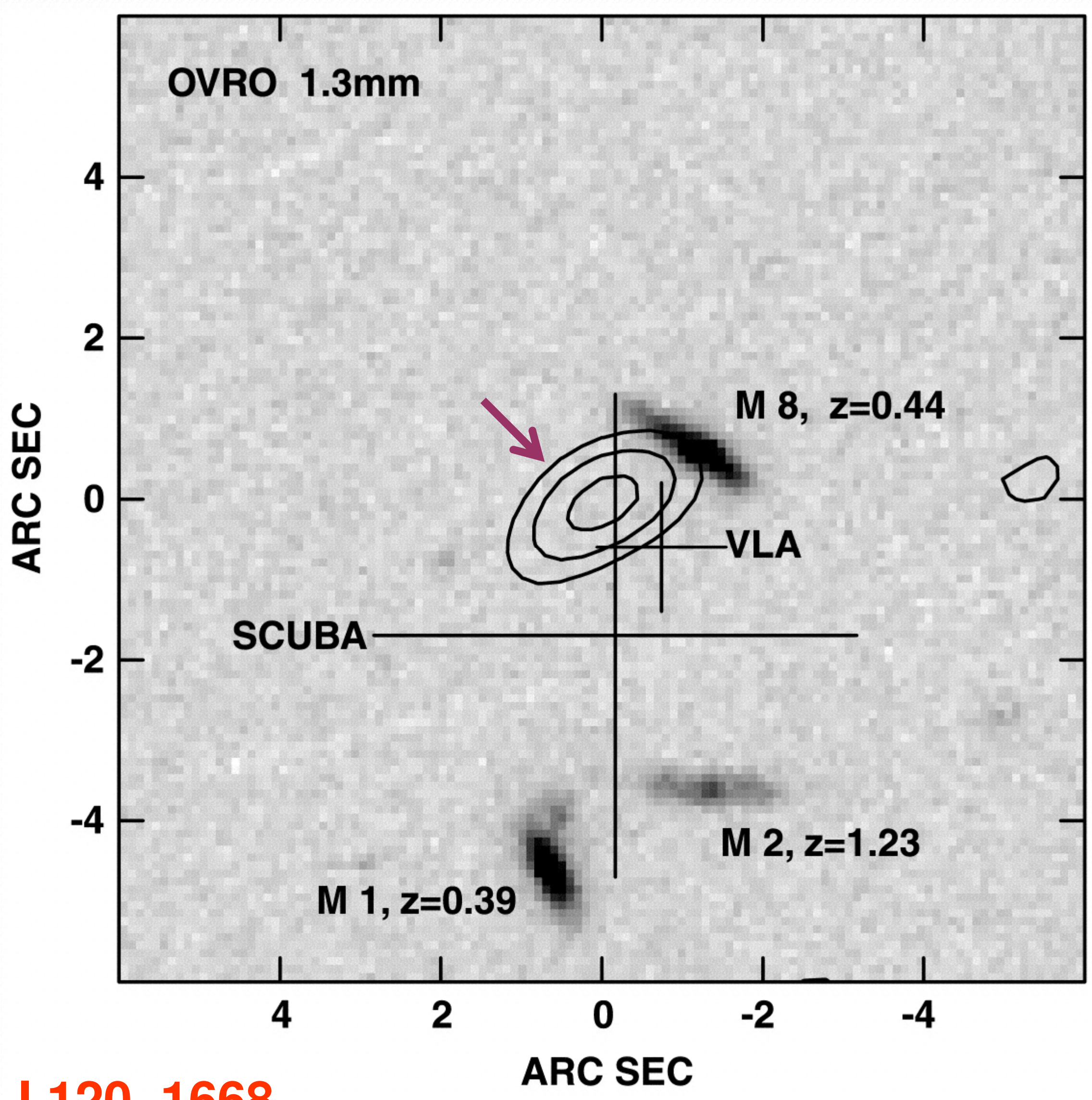
Blain et al (2002) Phys. Rept, 369,111

Radio Identification of Sub-mm Sources

SCUBA sources often have no clear optical counterpart, so we search with radio interferometers

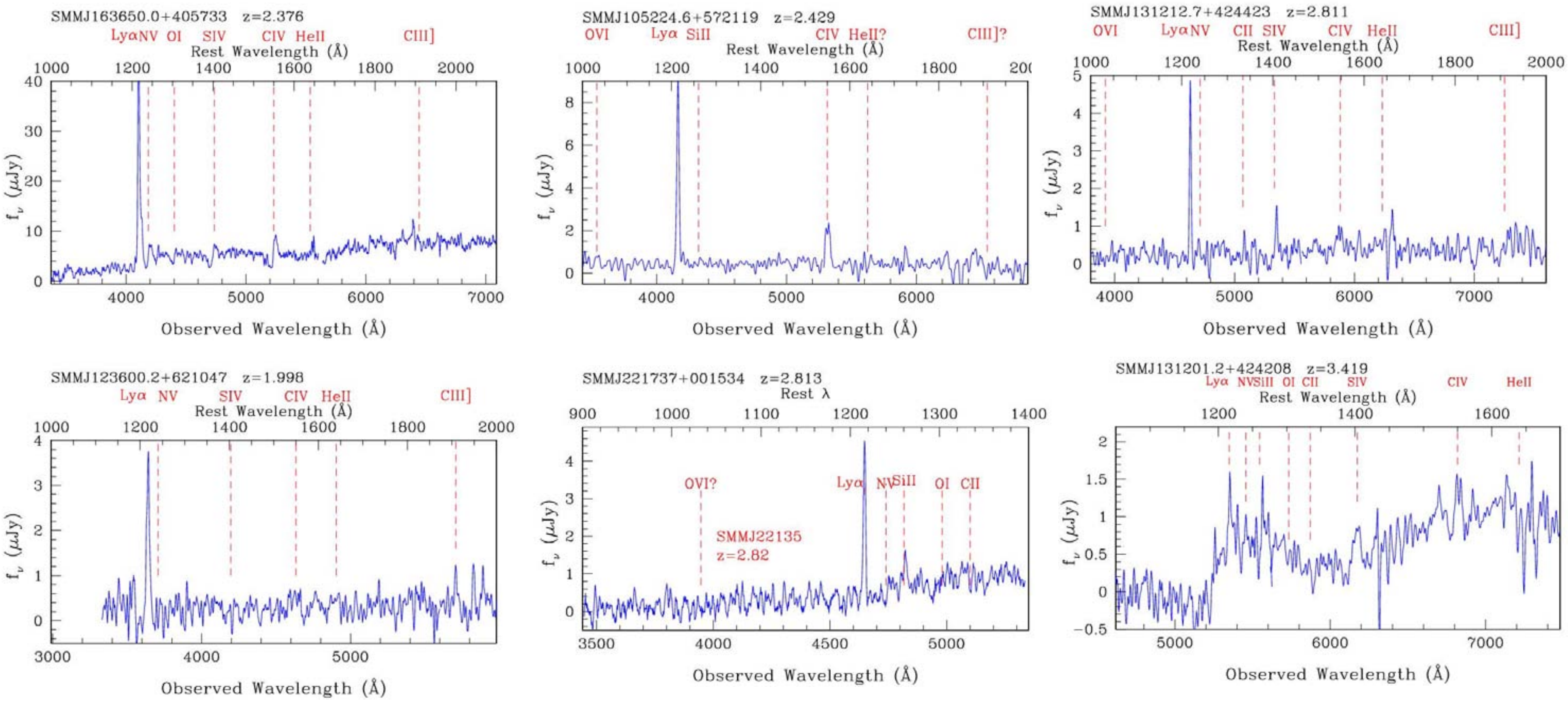
$L \sim 10^{13} L_{\odot}$ if z~2

Could be as important as the UV Lyman break population!



Frayer et al (2000) AJ 120, 1668

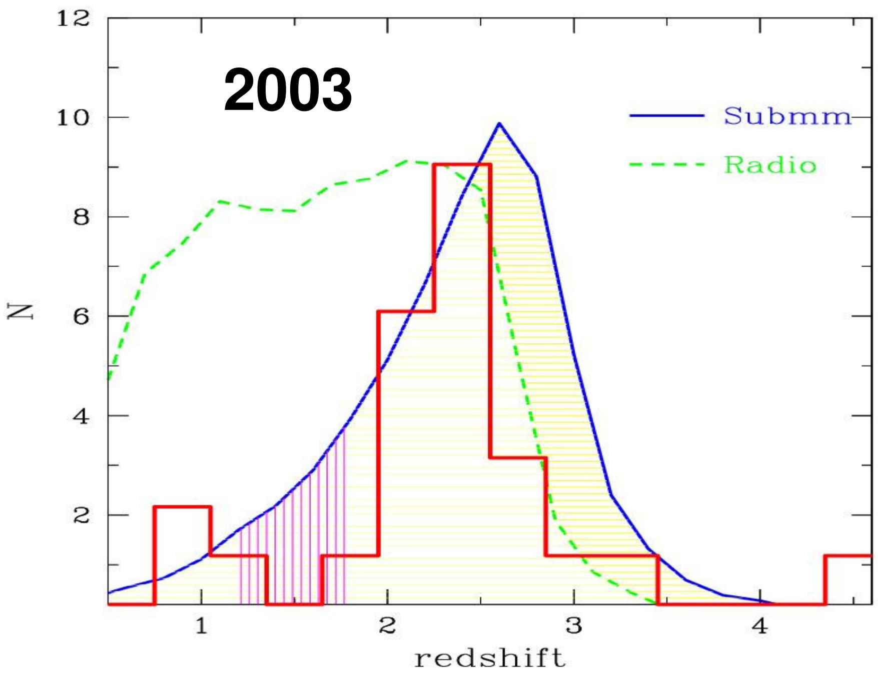
Redshifts for radio-selected SCUBA sources

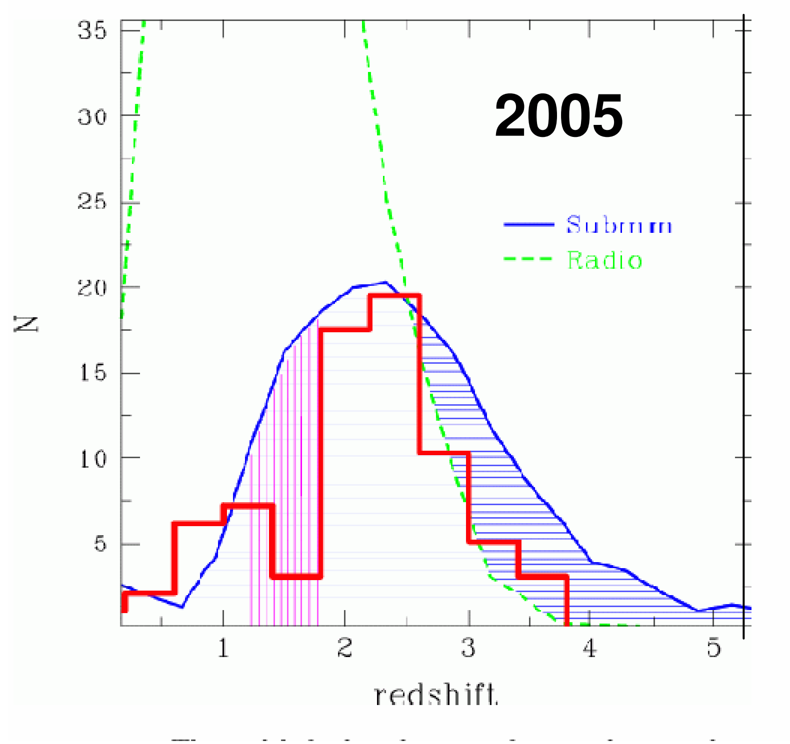


- Radio positions for 70% of f(850μm) > 5 mJy sources
- Slits placed on radio positions (22 < I < 26.5) with Keck
- 10-fold increase in number of SCUBA redshifts (LRIS-B)!

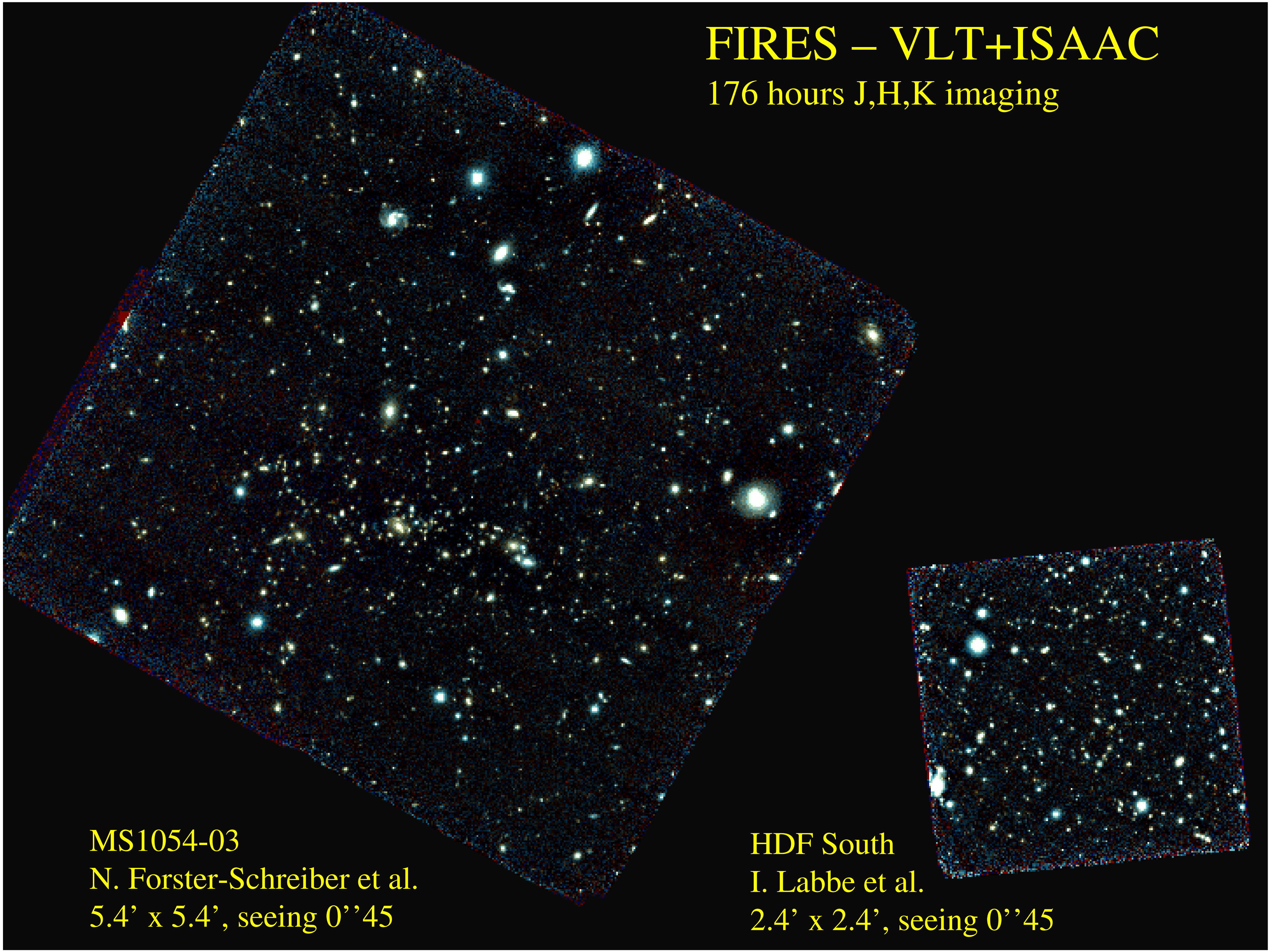
Chapman et al (2003) Nature 422, 695
Chapman et al (2005) Ap J 622, 722

Sub-mm and Lyman break galaxies coeval





- 50% completeness with LRIS-B and radio selection limits
- Radio-selected sub-mm sources » 20% of background
- Most sub-mm sources have z < 4
- Peak z = 2.4 – comparable to that for quasars
- Although ρ(LBG) ~ 10 ρ(SCUBA), luminosity/SF densities comparable


FIRES – VLT+ISAAC
176 hours J,H,K imaging
MS1054-03
N. Forster-Schreiber et al.
5.4’ x 5.4’, seeing 0’’45
HDF South
I. Labbe et al.
2.4’ x 2.4’, seeing 0’’45

Passively-Evolving Sources

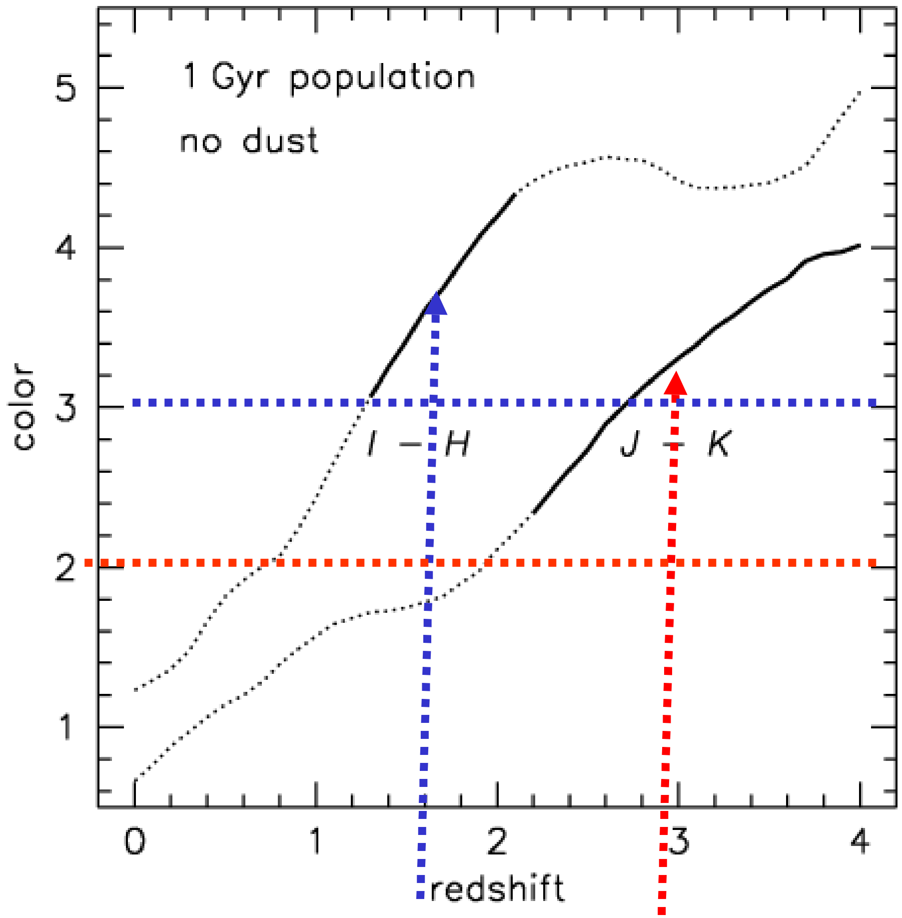
Lyman break and sub-mm galaxies are both hi-z star forming sources

Arrival of panoramic infrared cameras opened possibility of locating other passive galaxies at high z

Termed variously:

- Extremely Red Objects
- Distant Red Galaxies

depending on selection criterion

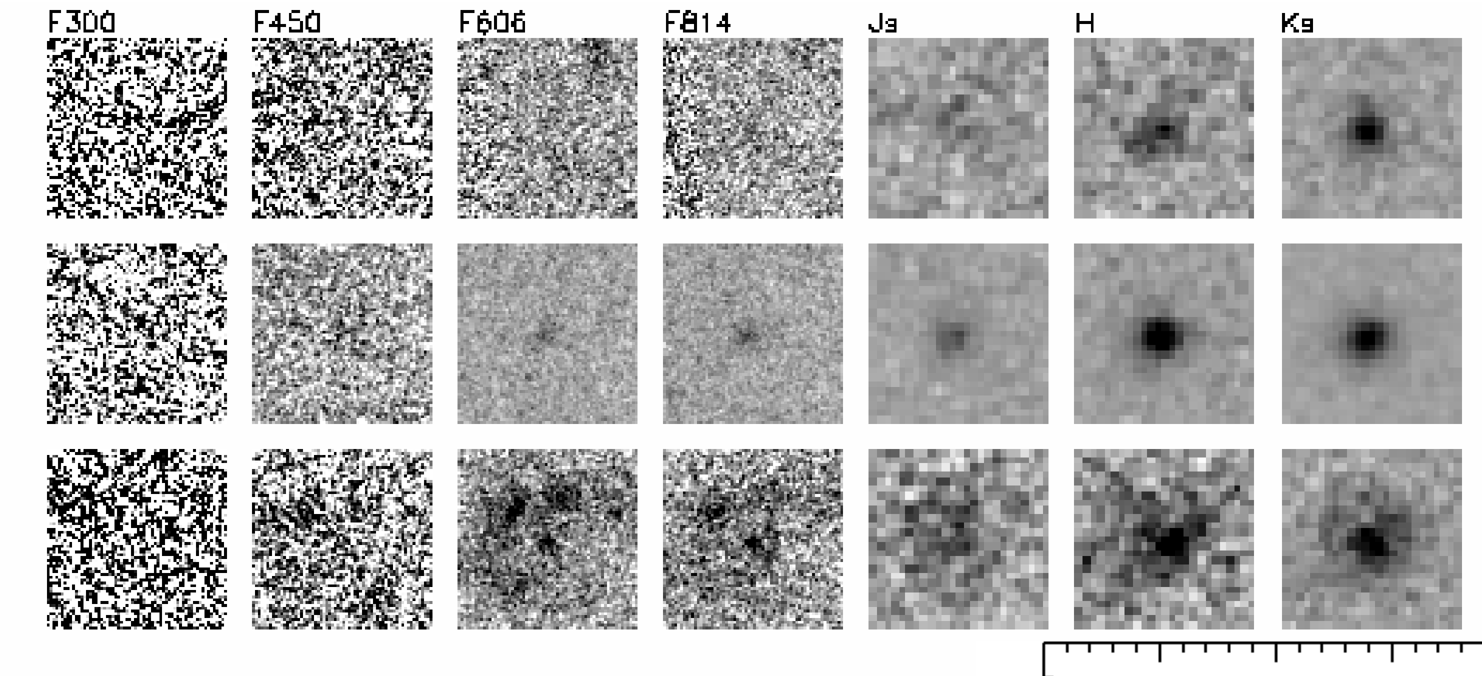


for z ~ 1-2: select on I-H colour

for z > 2: select on J-K colour

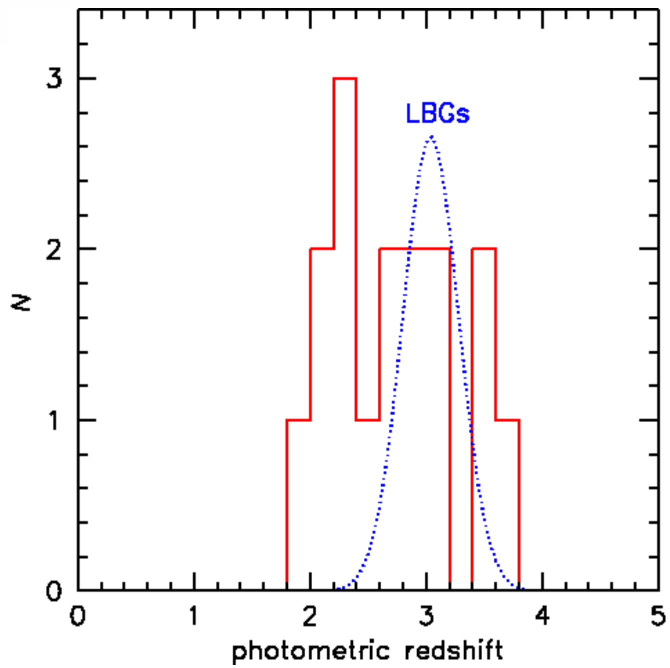
Such objects would not be seen in the Lyman break samples

Objects with *J-K* > 2.3



Surprisingly high surface density:

- ~0.8/arcmin^2 to K=21 (two fields)
- ~2/arcmin^2 to K=22 (HDF-S)
- ~3/arcmin^2 to K=23 (HDF-S)



van Dokkum,Franx, Rix et al

Keck Spectroscopy of Distant Red Galaxies

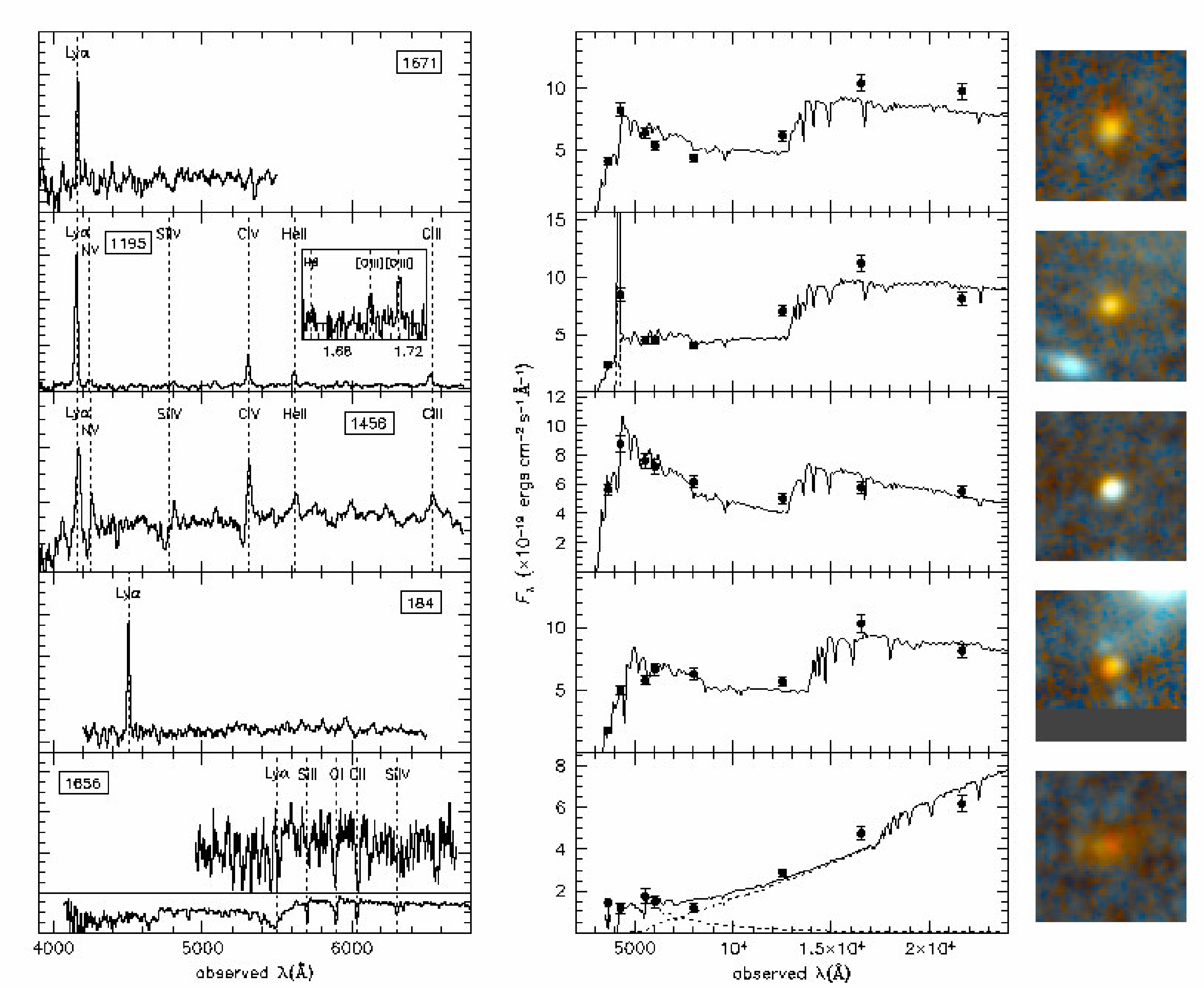
Z=2.43

Z=2.43

Z=2.43

Z=2.71

Z=3.52



Cosmic Star Formation History

Various probes of the global SF rate: ρ_* (z) M yr^{-1} comoving Mpc^{-3}

- UV continuum (GALEX, LBGs)
- Hα and [O II] emission in spectroscopic surveys
- mid-IR dust emission
- 1.4GHz radio emission

No simple `best method': each has pros and cons (dust extinction, sample depth, z range and physical calibration uncertainties)

Each has different time-sensitivity to main sequence activity so if SFR not uniform do not expect same answers for the same sources

Would expect the integral of the past activity to agree with locally-determined stellar density (Fukugita & Peebles 2004)

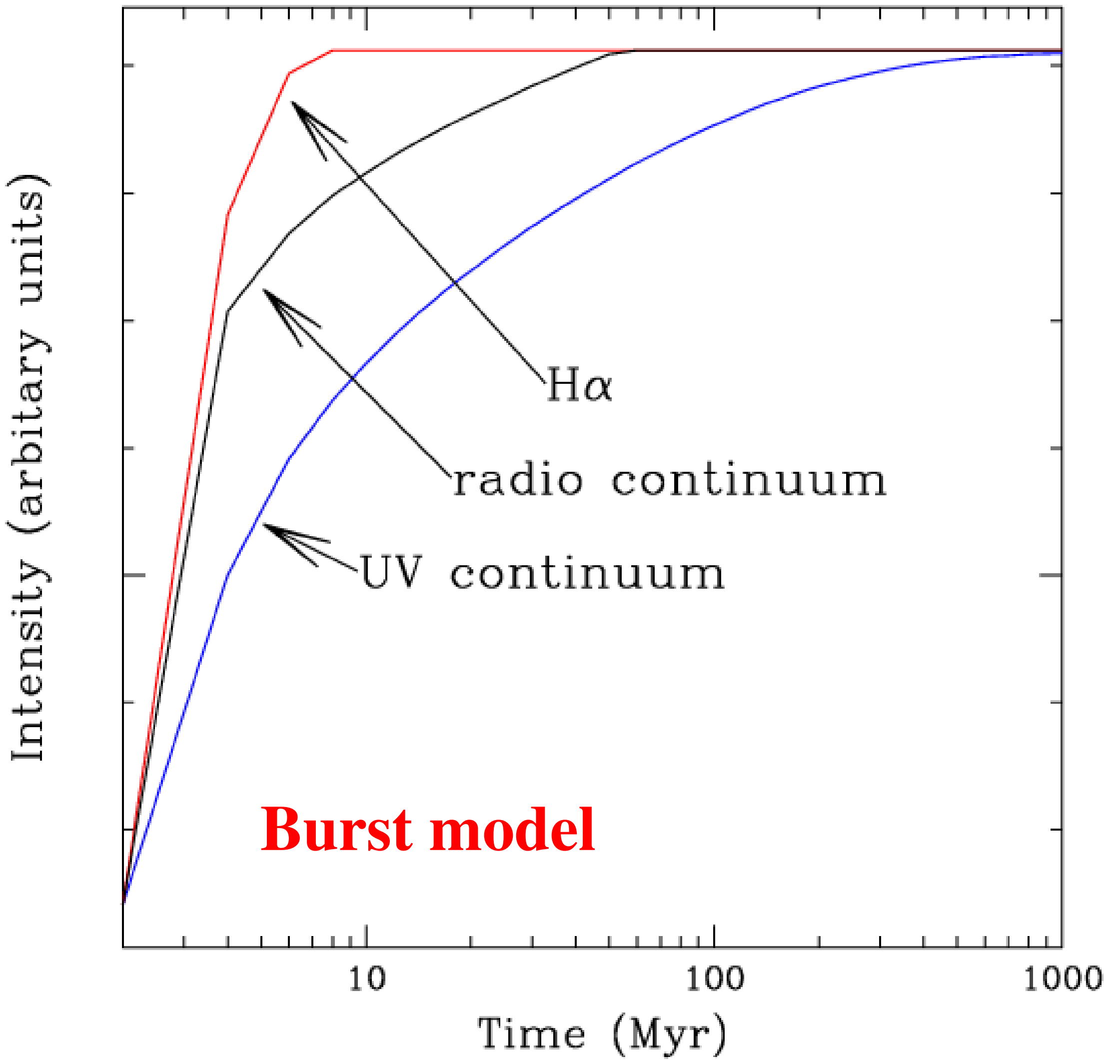
Can also determine the stellar growth rate for comparison with the stellar mass assembly history

Recent review: Hopkins 2004 Ap J 615, 209

Time-Dependence of Various SF Diagnostics

- Each SF diagnostic (UV, Hα..) arises from a component of the stellar population whose lifetime is different, so determining rate of SF is sensitive to whether SF is erratic

- Radio continuum is thought to arise from supernova remnants and offers the potential of a dust-free diagnostic



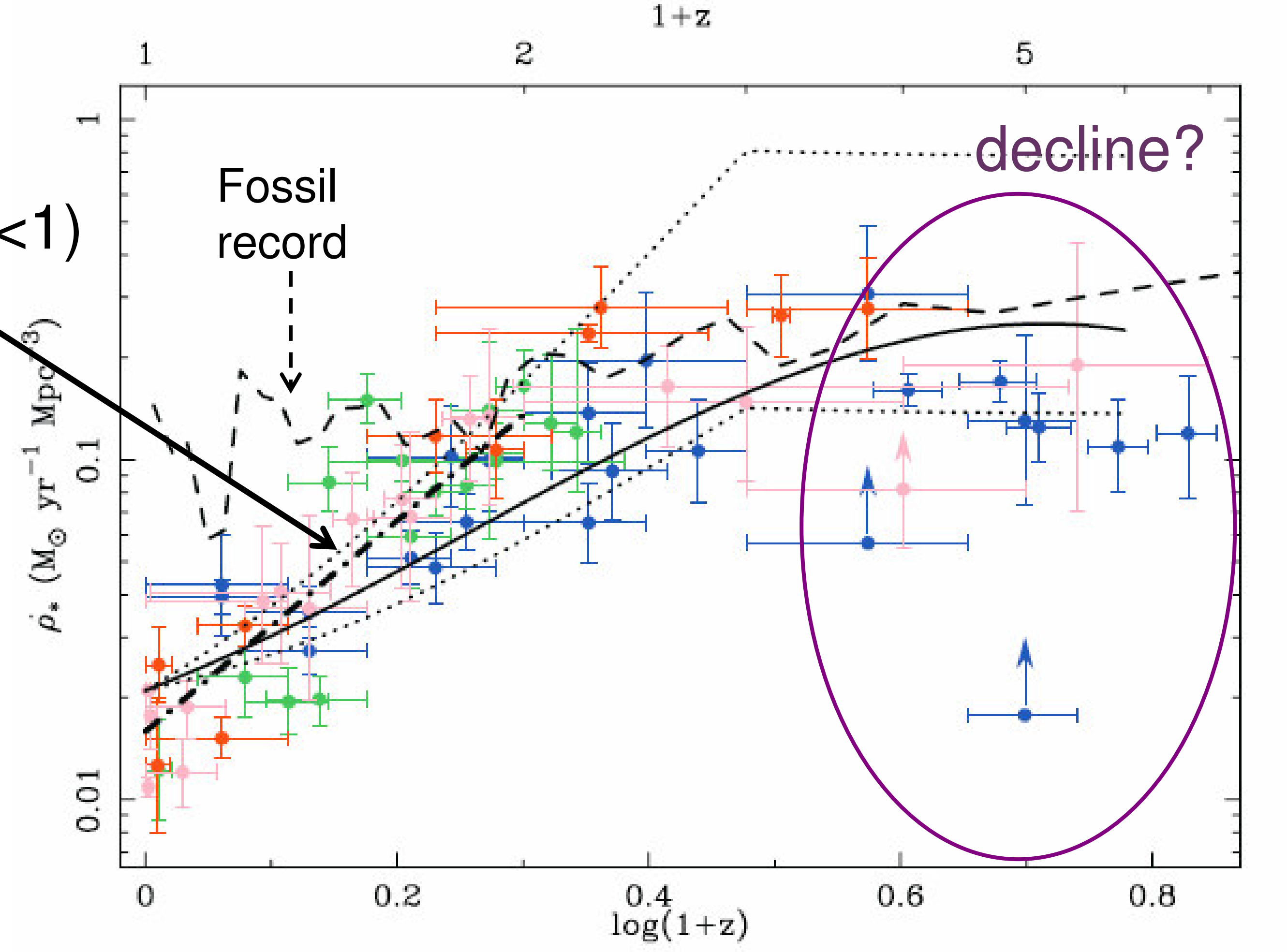
Cosmic SFH: Recent Compilation

Hopkins 2004 Ap J 615, 209 (see also Hogg astro-ph/0105280):

- standardized all measures to same IMF, cosmology, extinction law
- integrated LF over standardized range for each diagnostic (except at v high z)

$\rho_* \propto (1+z)^{3.1}$ (z<1)

Star formation rate per unit comoving volume



Local Inventory of Stars

Relevant papers: Fukugita et al 1998 Ap J 503, 518
Fukugita & Peebles 2004 Ap J 616, 643

Survey data: Kauffmann et al 2003 MNRAS 341, 33 (SDSS)
Cole et al 2003 MNRAS 326, 255 (2dF+2MASS)

Stellar density: derives from local infrared LF, Φ (L_K) scaled by a mean mass/light ratio (M/L_K) which depends on initial mass function

Useful stellar density is that corrected for fractional loss R of stellar material due to winds & SNe: this should be integral of past SF history (R depends on IMF also)

Cole et al find Ω_{stars} h = 0.0014 ± 0.00013; M/L_K = 0.73 (Kennicutt)

Ω_{stars} h = 0.0027 ± 0.00027; M/L_K = 1.32 (Salpeter)

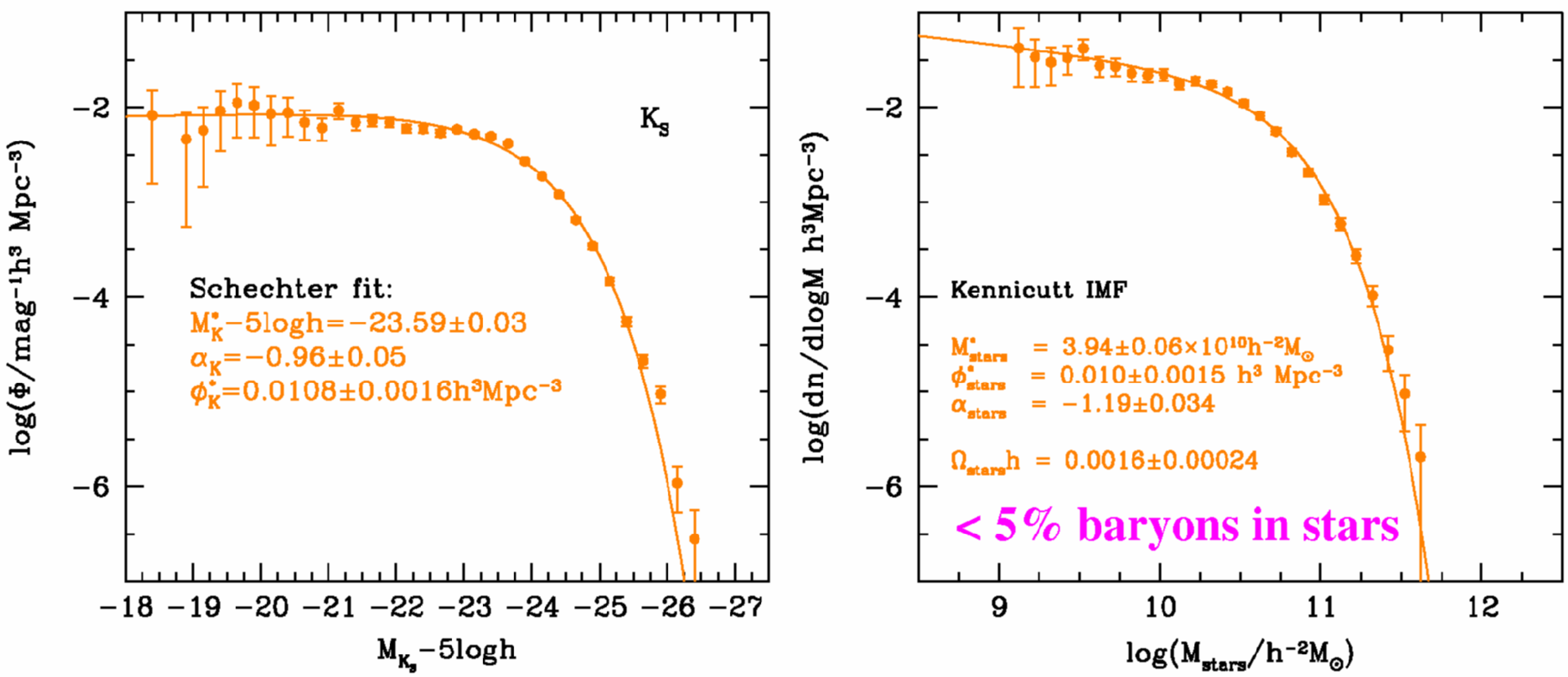
Fukugita & Peebles: Ω_{stars} h = 0.0027 ± 0.0005 (5% in brown dwarfs)

Ω_{gas} = 0.00078 ± 0.00016 (H I, He I, H_2)

NB: only 6% of baryons are in stars!

Stellar Mass Function at z=0

17,000 K-band selected galaxies with K<13.0
2dFGRS redshifts & 2MASS photometry



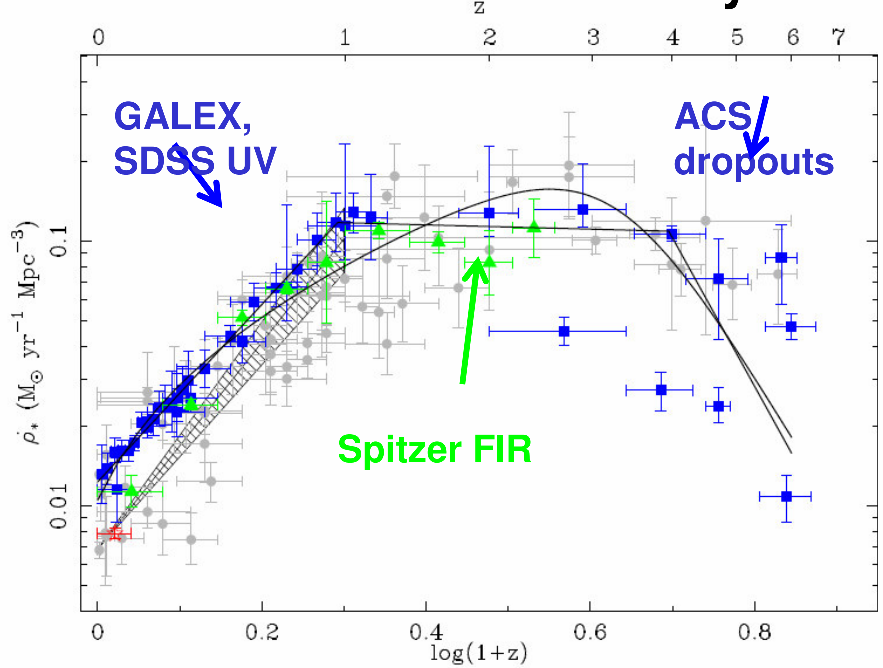
Cole et al. , 2001, MNRAS, 326, 255

Implications of Cosmic SFH

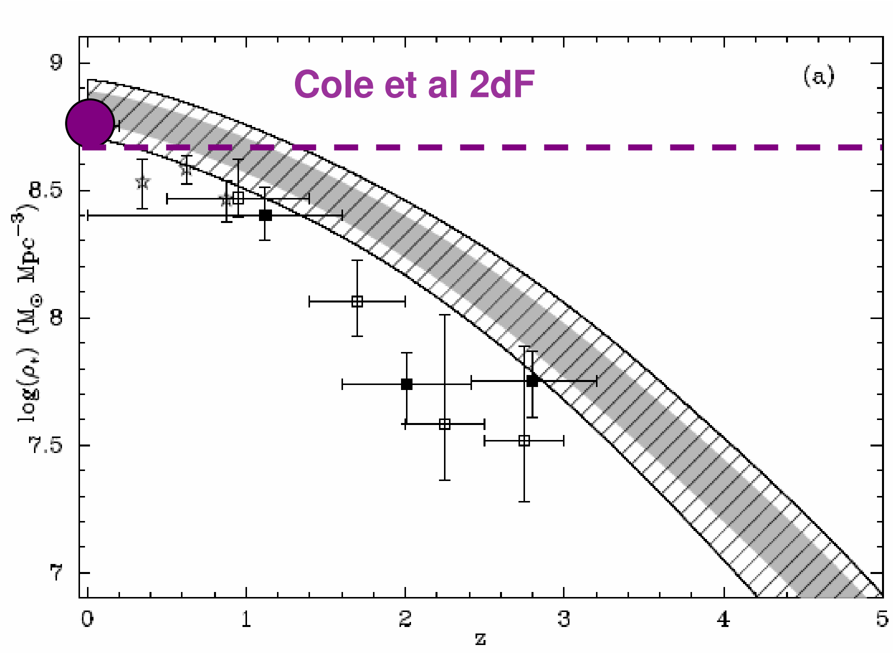
Hopkins & Beacom (astro-ph/0601463)

Fitting parametric SFH can predict ρ_* (z) in absolute units

Star formation history



Mass assembly history



- Satisfactory agreement with local 2dF/2MASS mass density
- Data suggests half the local mass in stars is in place at z~2 ± 0.2
- Major uncertainties are IMF and luminosity-dependent extinction

Unified View of the Various High z Populations

Integrating to produce a comoving cosmic SFH dodges the important question of the physical relevance of the seemingly diverse categories of high z galaxies (e.g. LBGs, sub-mm, DRGs).

Given they co-exist at $1<z<3$ what is the relationship between these objects?

Key variables:

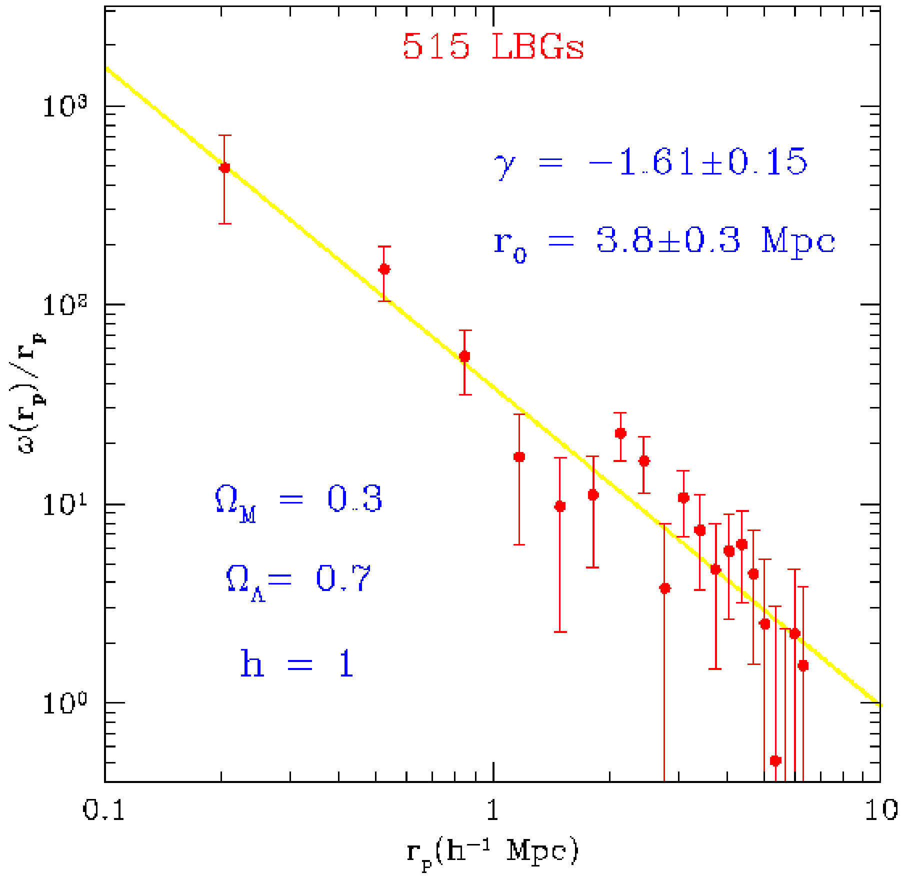
- basic physical properties (masses, SFRs, ages etc)
- relative contributions to SF rate at a given redshift
- degree of overlap (e.g. how many sub-mm sources are LBGs etc)
- spatial clustering (relevant to bias)

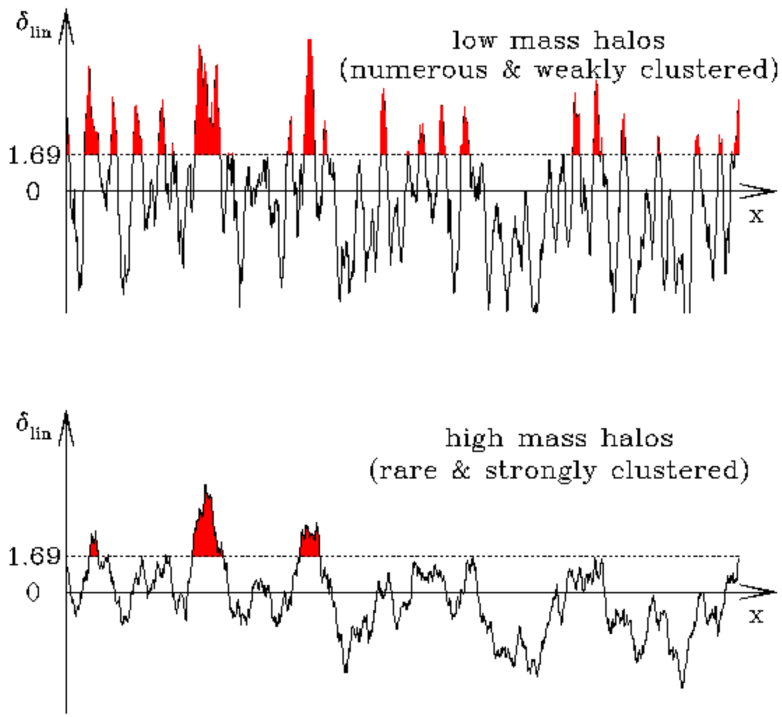
Some recent articles:

Papovich et al (astro-ph/0511289)

Reddy et al (astro-ph/0602596)

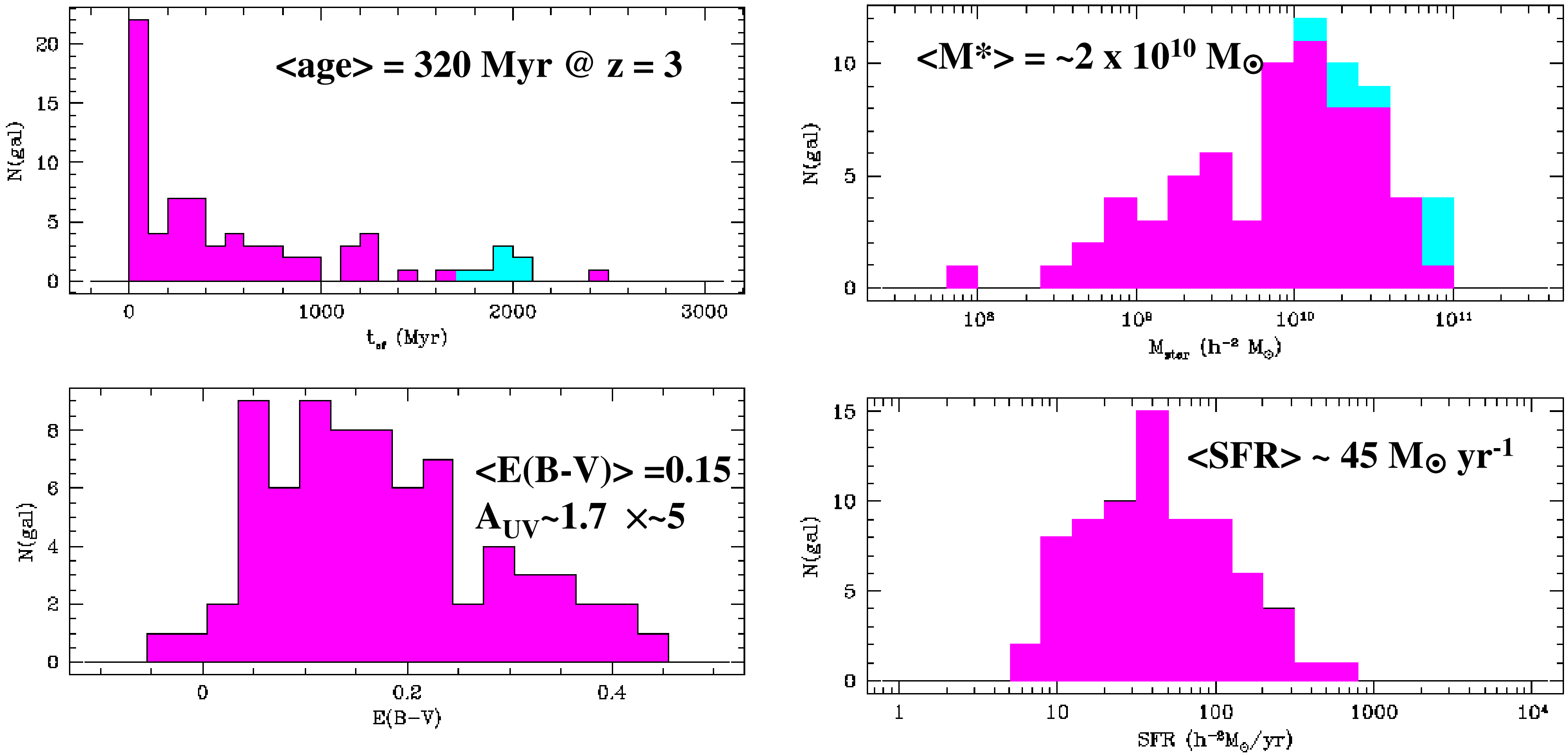
Lyman Break Galaxies - Clustering





Adelberger et al (1998) demonstrated strong clustering of LBGs consistent with their hosting massive DM halos perhaps as progenitors of massive ellipticals (Baugh et al 1998)

Lyman Break Galaxy Properties (z~3)



Extinction correlates with age– young galaxies are *much dustier*

SFR for youngest galaxies average 275 $M_\odot$ yr^{-1} ; oldest average 30 $M_\odot$ yr^{-1}

Objects with the highest SFRs are the dustiest objects

Shapley et al 2001 Ap J 562, 95

Lyman Break Galaxies: Where do they fit in?

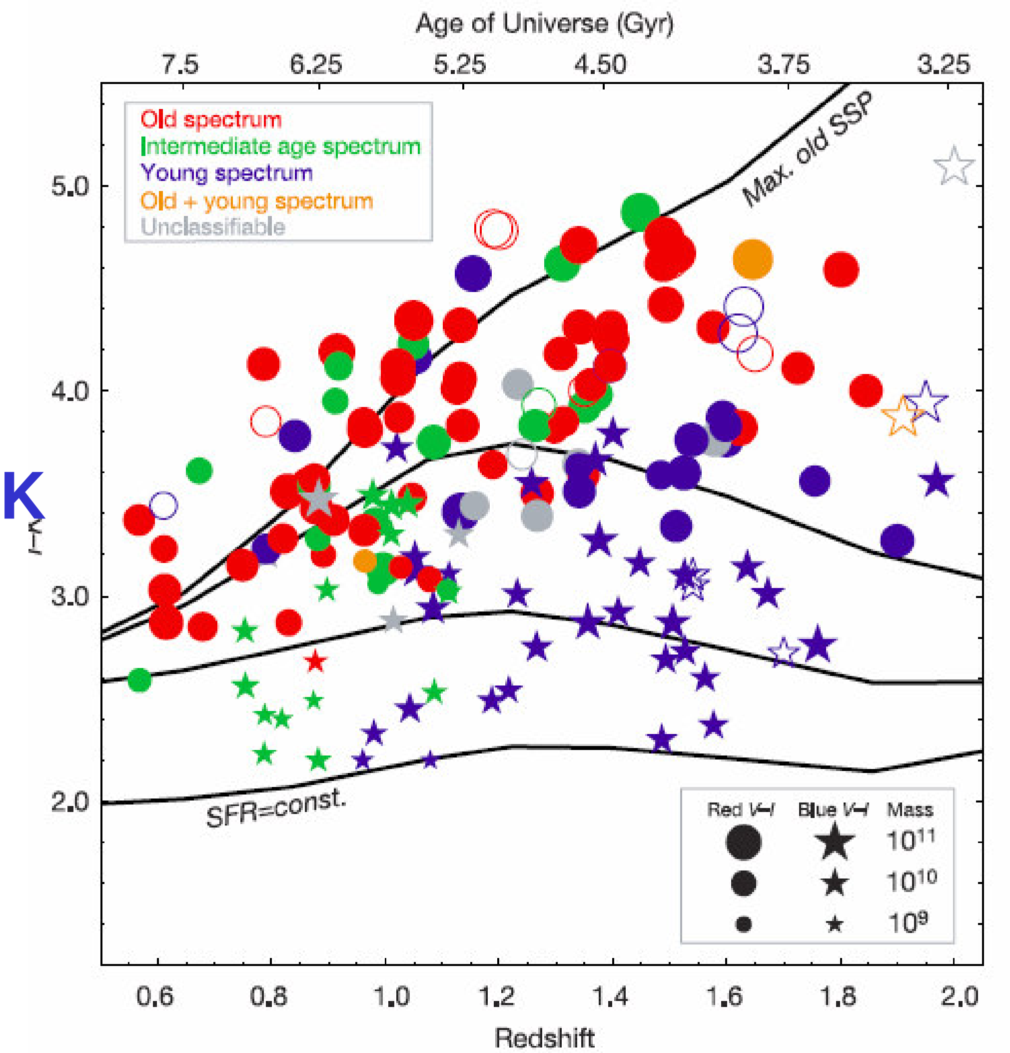
- Period of elevated star formation (~100's $M_{\odot}$ yr^{-1}) for ~50 Myr with large dust opacity (SCUBA overlap?)
- Superwinds drive out both gas and dust, resulting in more quiescent star formation (10's $M_{\odot}$ yr^{-1}) and smaller UV extinction
- Quiescent star formation phase lasts for at least a few hundred Myr; by end at least a few 10^{10} $M_{\odot}$ of stars have formed
- All phases are observable because of near-constant far-UV luminosity

Passive Galaxies: Gemini Deep Deep Survey

Gemini telescope used to secure optical spectra of red galaxies at z>1.5

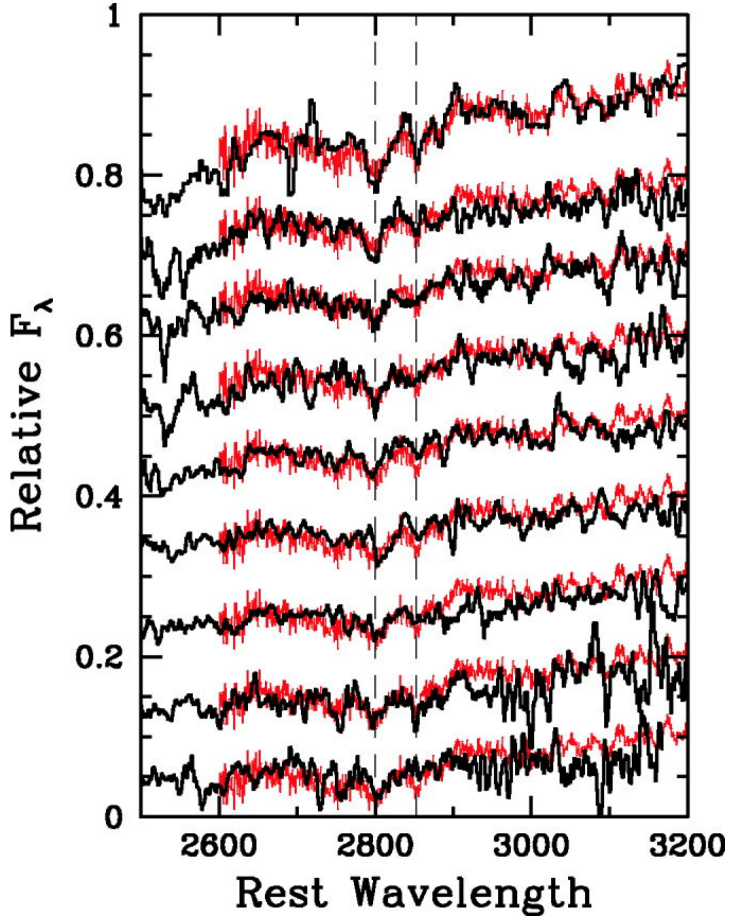
Many examples found of old, passive systems of high stellar mass

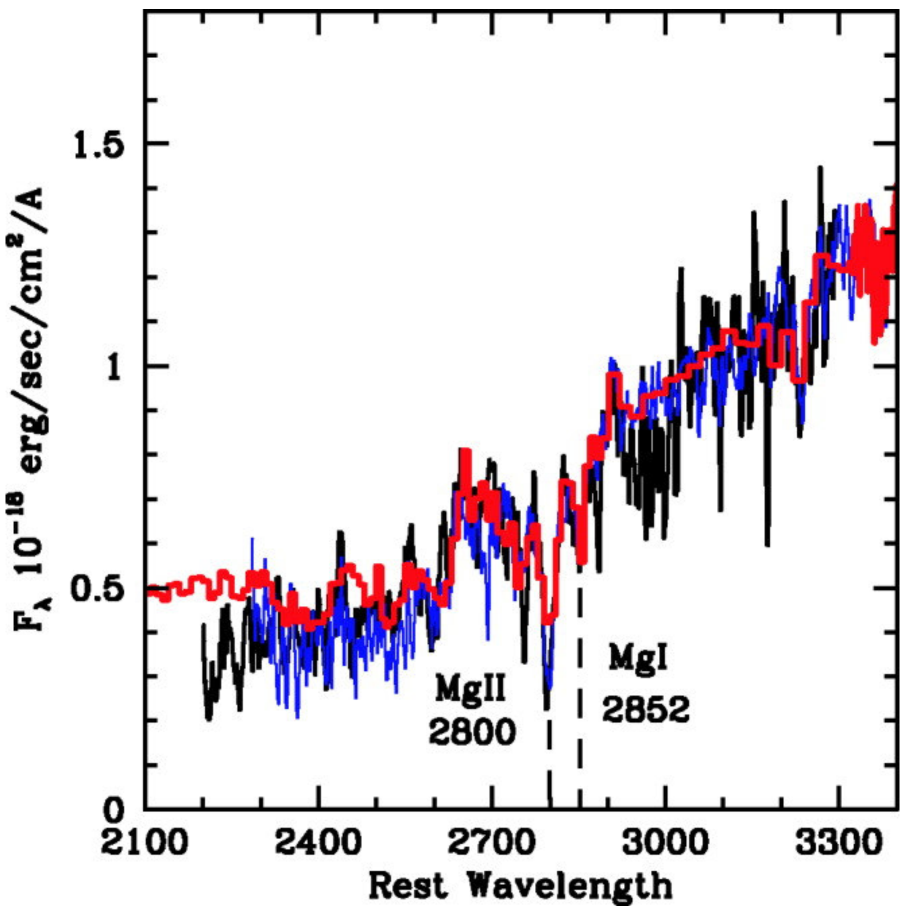
V-K



Glazebrook et al Nature 430, 181 (2004)

Gemini Deep² Survey: Spectroscopic Age-dating





- 20 red galaxies z~1.5, age 1.2 - 2.3 Gyr, z_F=2.4 - 3.3
- Implies progenitors have SFRs ~ 300-500 $M_\odot$ yr^{-1}

McCarthy et al Ap J 614, L9 (2004)

Stellar Masses and Assembly History

Great progress in tracking comoving star formation history but:

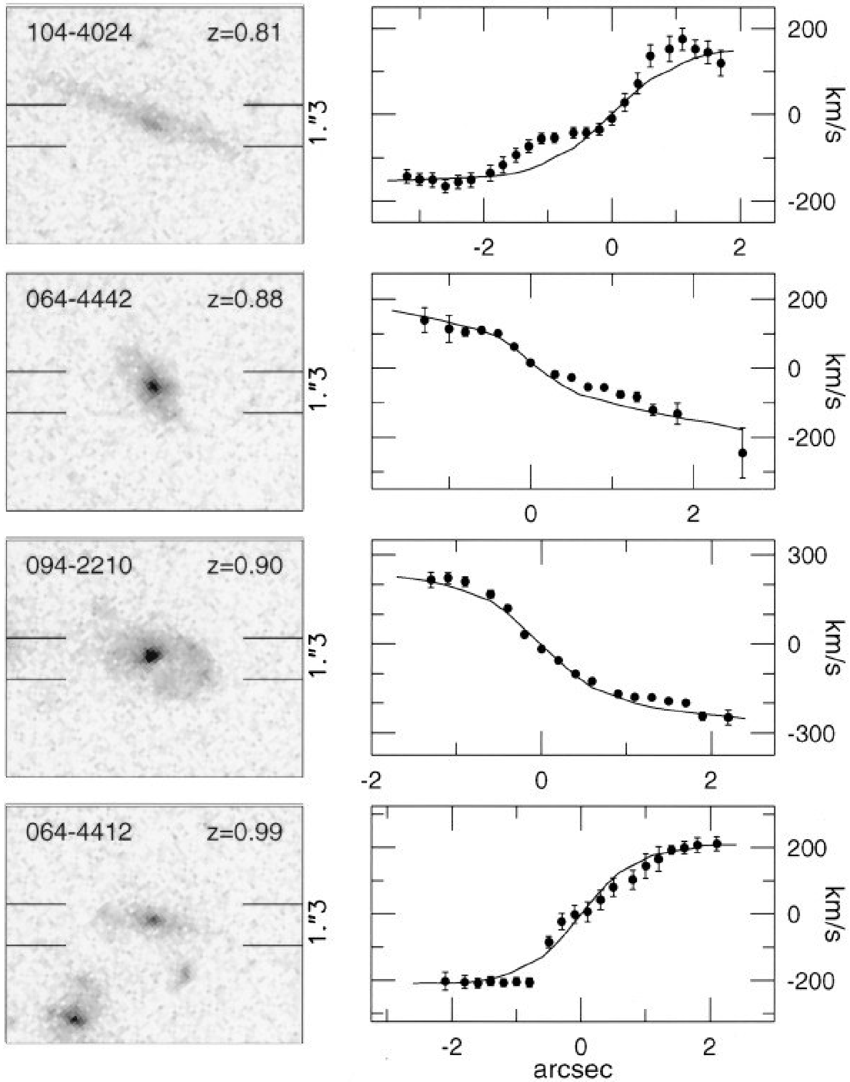
- SF density averages over different physical situations (e.g. bursts, quiescent phases)
- reliability of measures remains a big concern; no ideal method
- hard to link with theory (conversely: theory always seems to be able to explain the SF data!)
- stellar mass assembly is a more profound measurement but observationally challenging

Importance of developing mass diagnostics was stressed in several early papers: Broadhurst et al (1992), Kauffmann & Charlot (1998), Brinchmann & Ellis (2000)

Distant galaxy masses: what are the options?

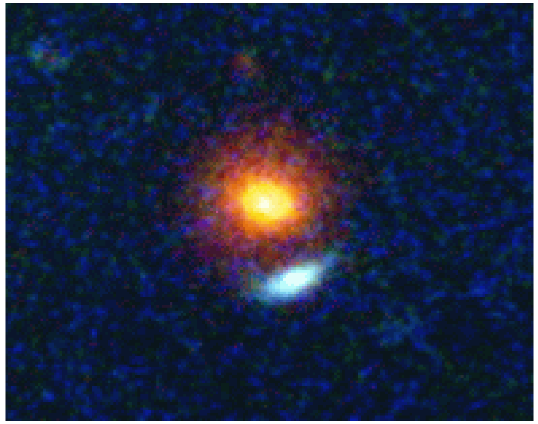
Dynamics: rotation & dispersions

(only for restricted populations)



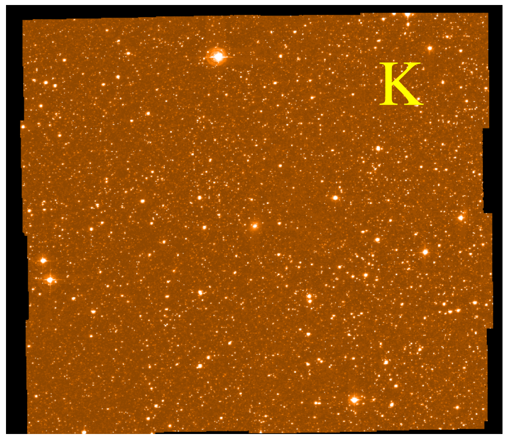
Gravitational lensing

(limited z ranges)

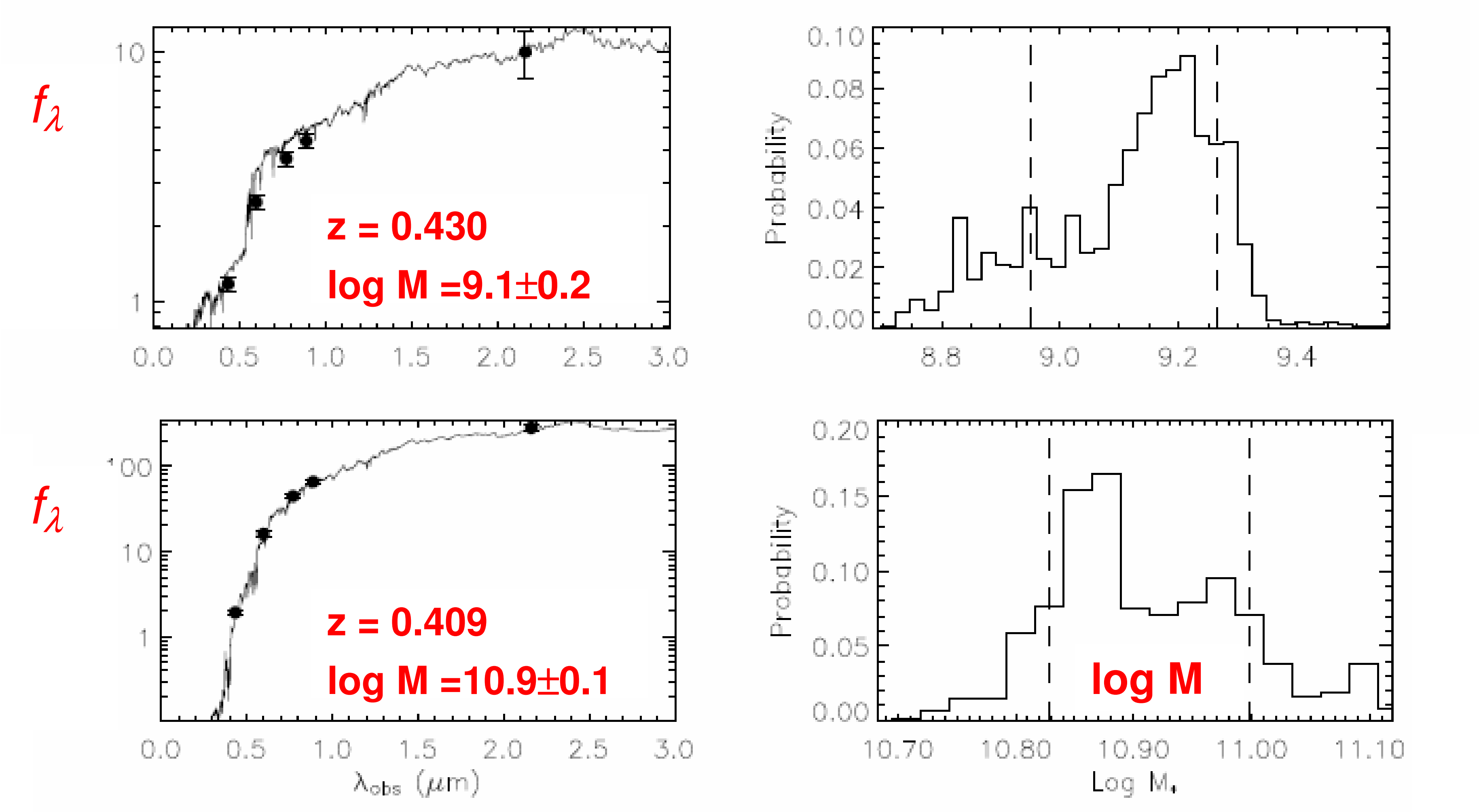


IR-based stellar masses

(universally effective 0<z<6)



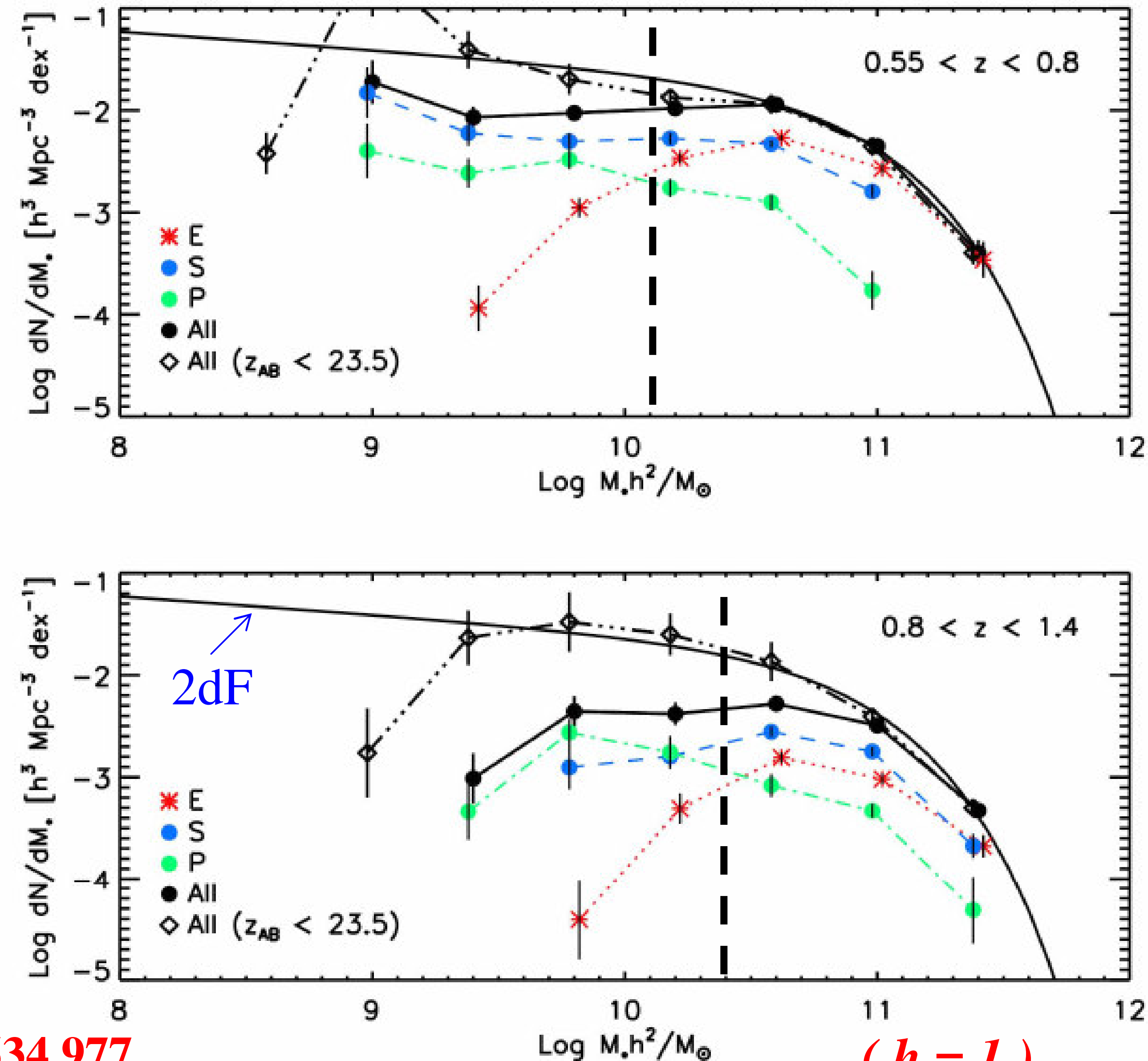
Stellar Masses from Multicolor Photometry



For a galaxy of known redshift, the *spectral energy distribution* f_λ is a good measure of the stellar population and the stellar *mass/light ratio* (M_*/L_K). Combined with the K-band luminosity L_K, this yields the stellar mass M_*

Stellar Mass Assembly by Type in GOODS fields

- No significant evolution in massive galaxies since z~1
- Modest decline with z in abundance of massive spheroidals, most change at lower mass
- Bulk of associated evolution is in massive Irregulars



Bundy et al (2005) Ap J 634,977

(h = 1)

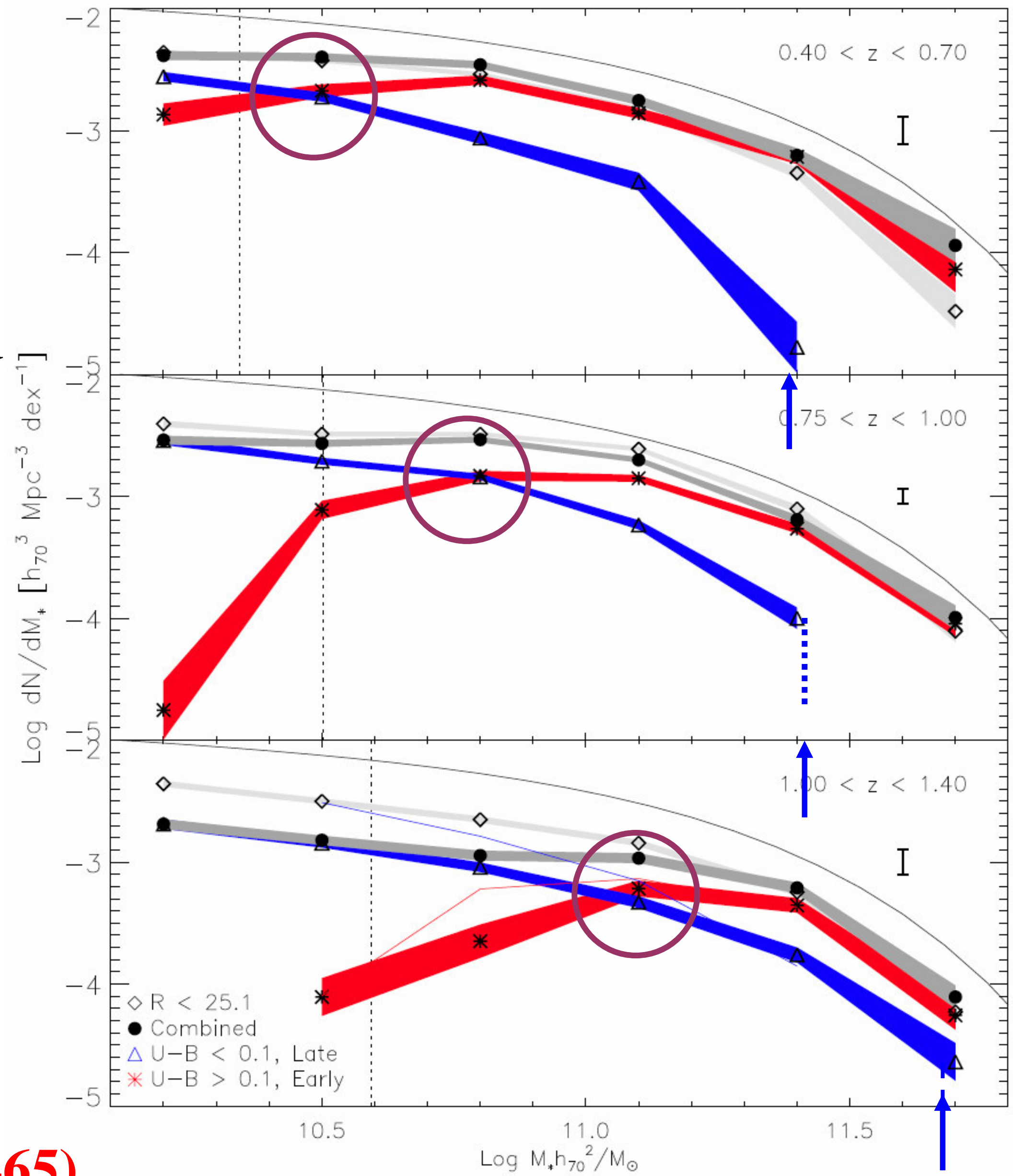
`Downsizing' & Star Formation

- Find a *threshold* stellar mass above which there is no star formation

- Remarkably this threshold *decreases* as the Universe expands - `downsizing'!

- *Cross-over mass* (red=blue) also increases with z

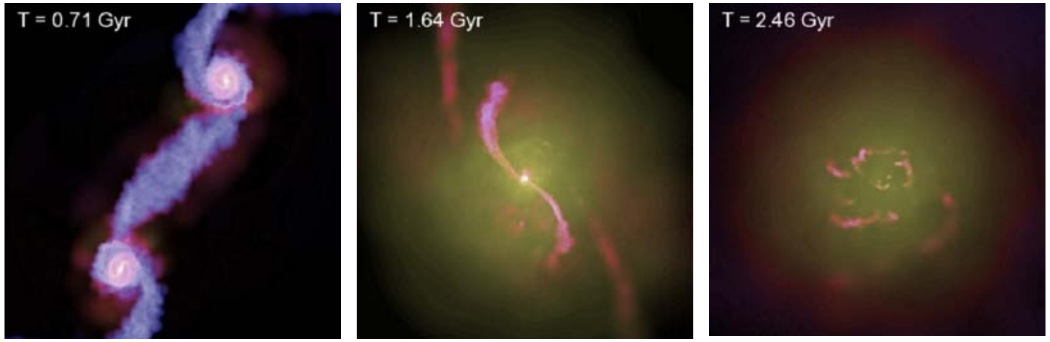
This signature is called downsizing



Bundy et al (astro-ph/0512465)

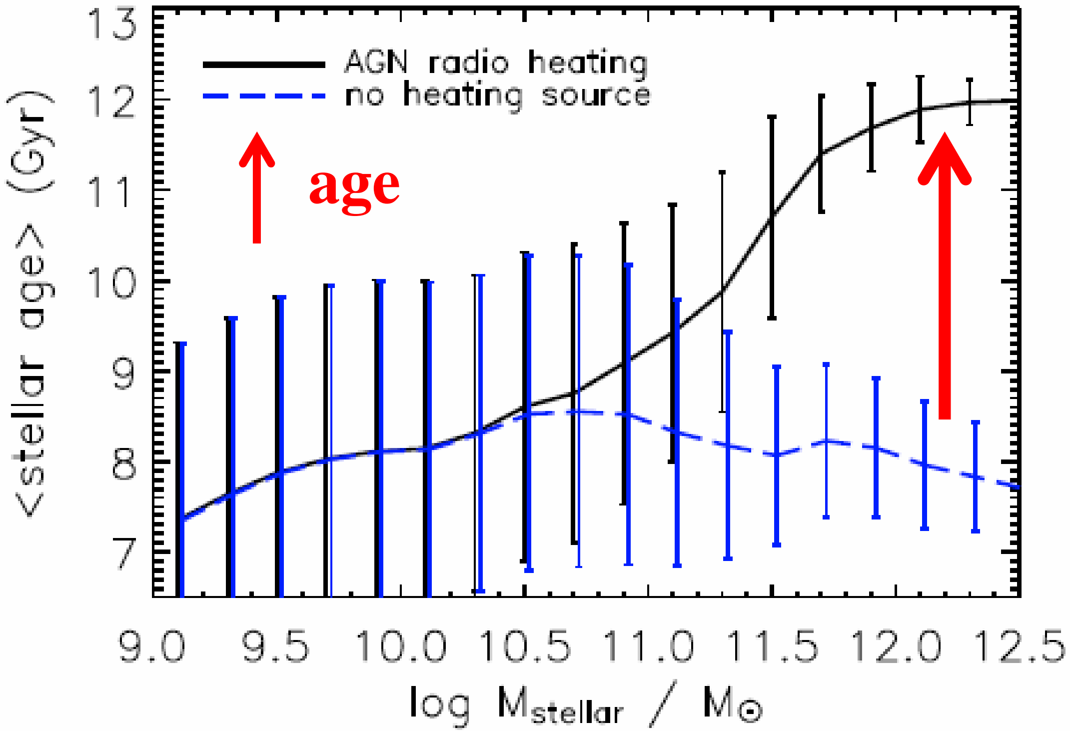
Possible Explanation for Downsizing

Simulated Disk Merger with AGN Feedback



Mergers fuel active galactic nuclei which expel gas and prevent further star formation (Springel et al 2004).

`Radio mode' active galactic nuclei feedback arising from hot gaseous halo leads to early suppression of cooling SF in massive stellar systems (Croton et al 2005)



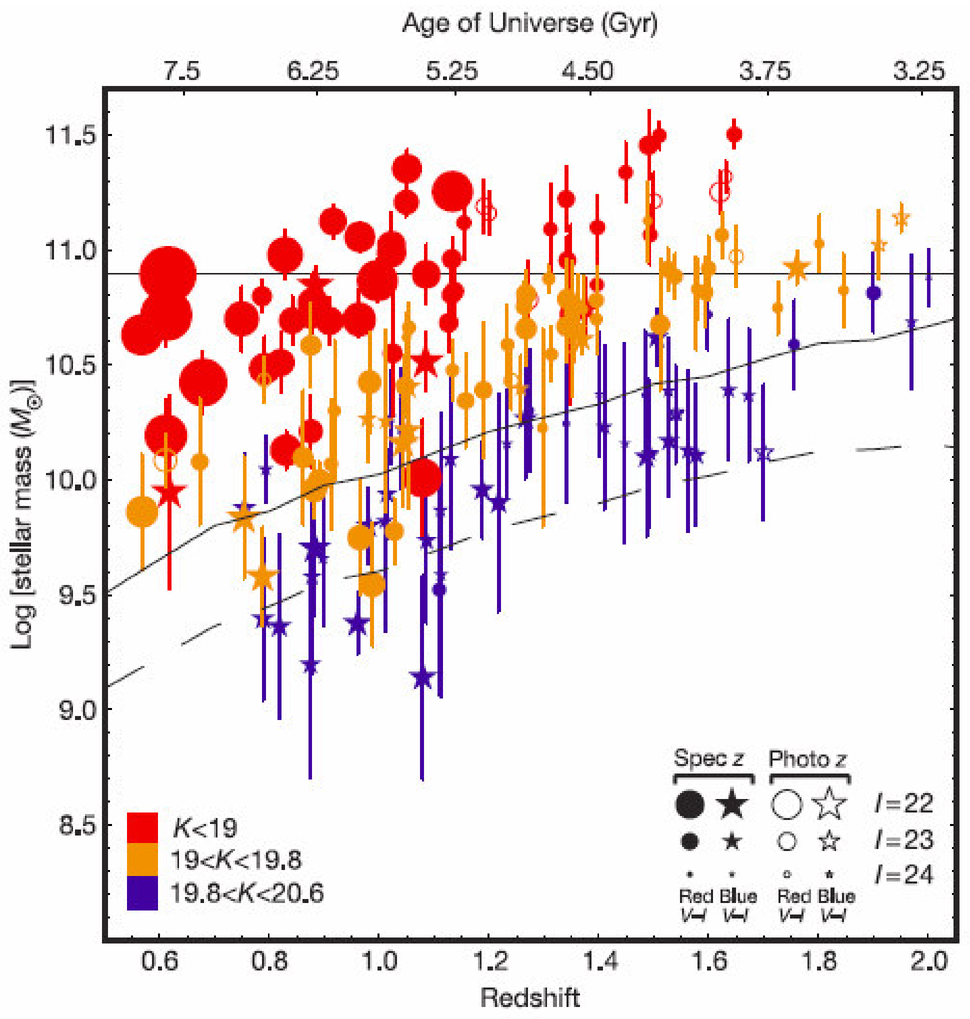
Gemini Deep Deep Survey: Stellar Masses

Color pre-selected Gemini spectroscopic sample
K<20.6, I<24.5

240 galaxies in 4×30 arcmin^2 fields 0.5<z<2

Surprising abundance of massive galaxies at z>1.5

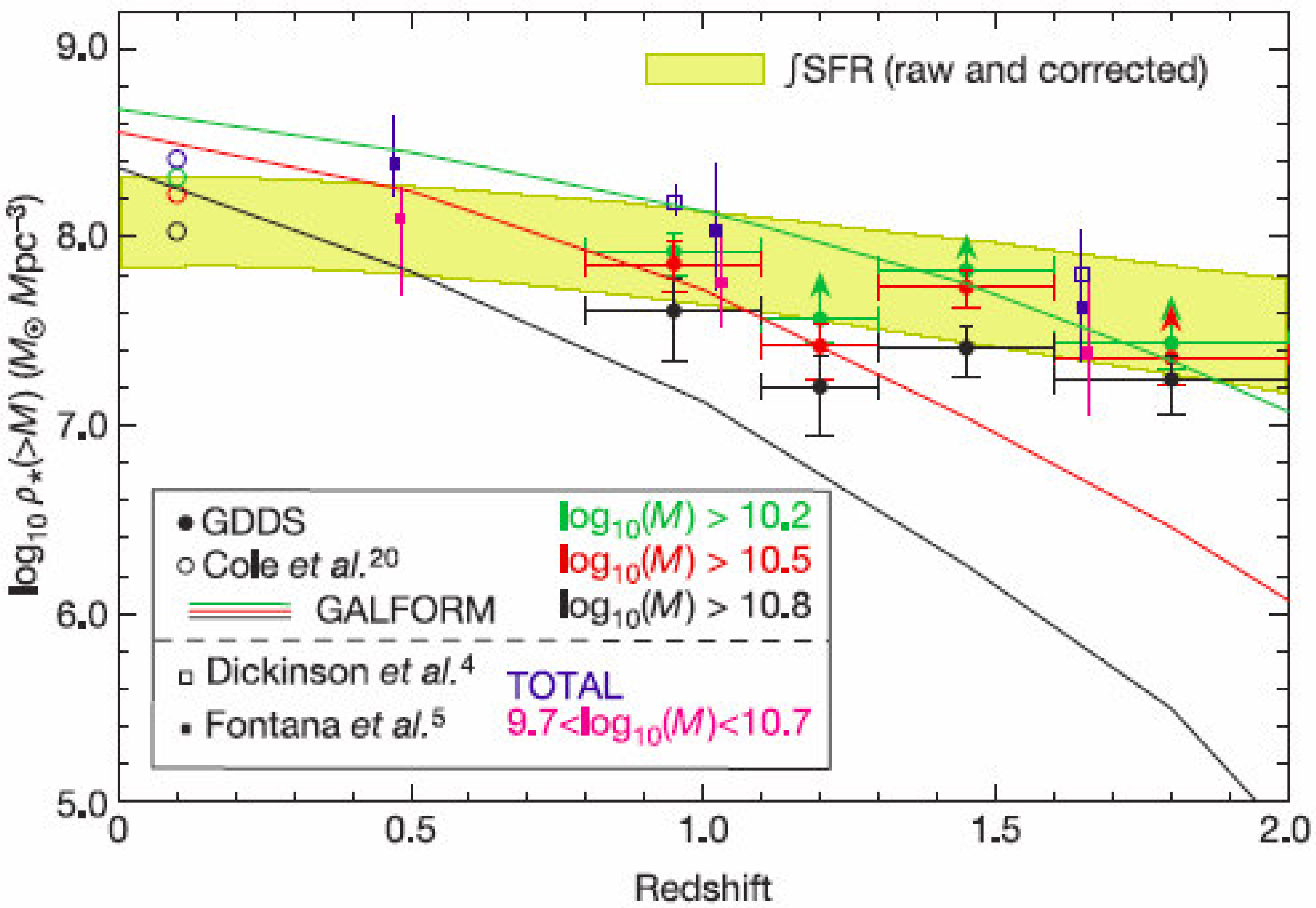
Many are `red and dead'



Glazebrook et al Nature 430, 181 (2004)

Gemini Deep Deep Survey: Slow Mass Assembly

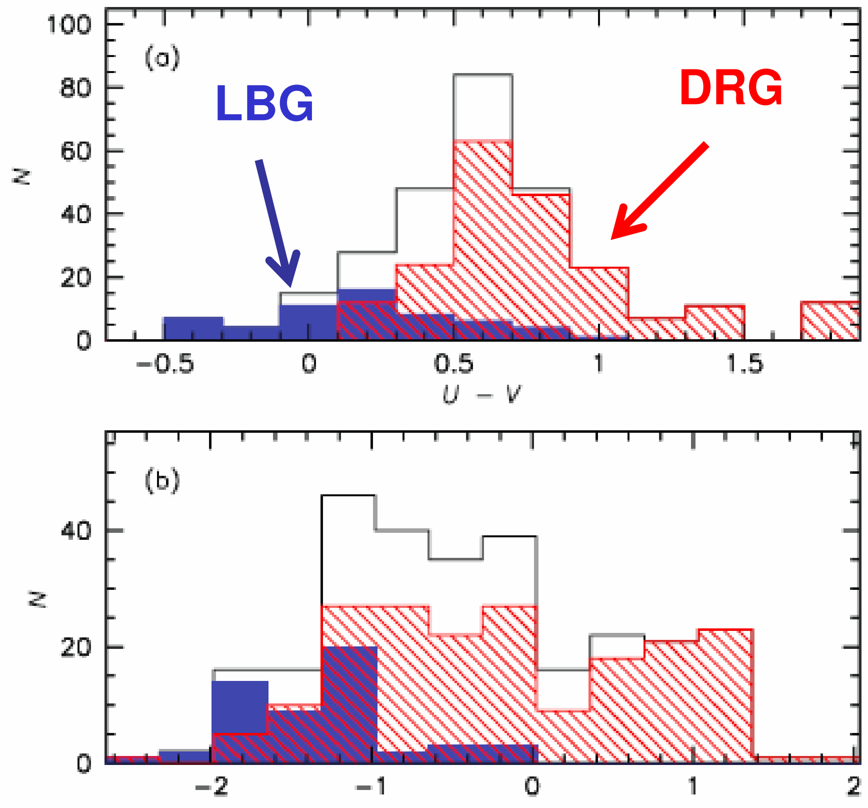
Stellar mass density



Growth rate slower than theoretical models (without AGN feedback)

Glazebrook et al Nature 430, 181 (2004)

Census of Stellar Mass 2<z<3



Which sources contribute most: star-forming Lyman Break Galaxies or passive Distant Red Galaxies?

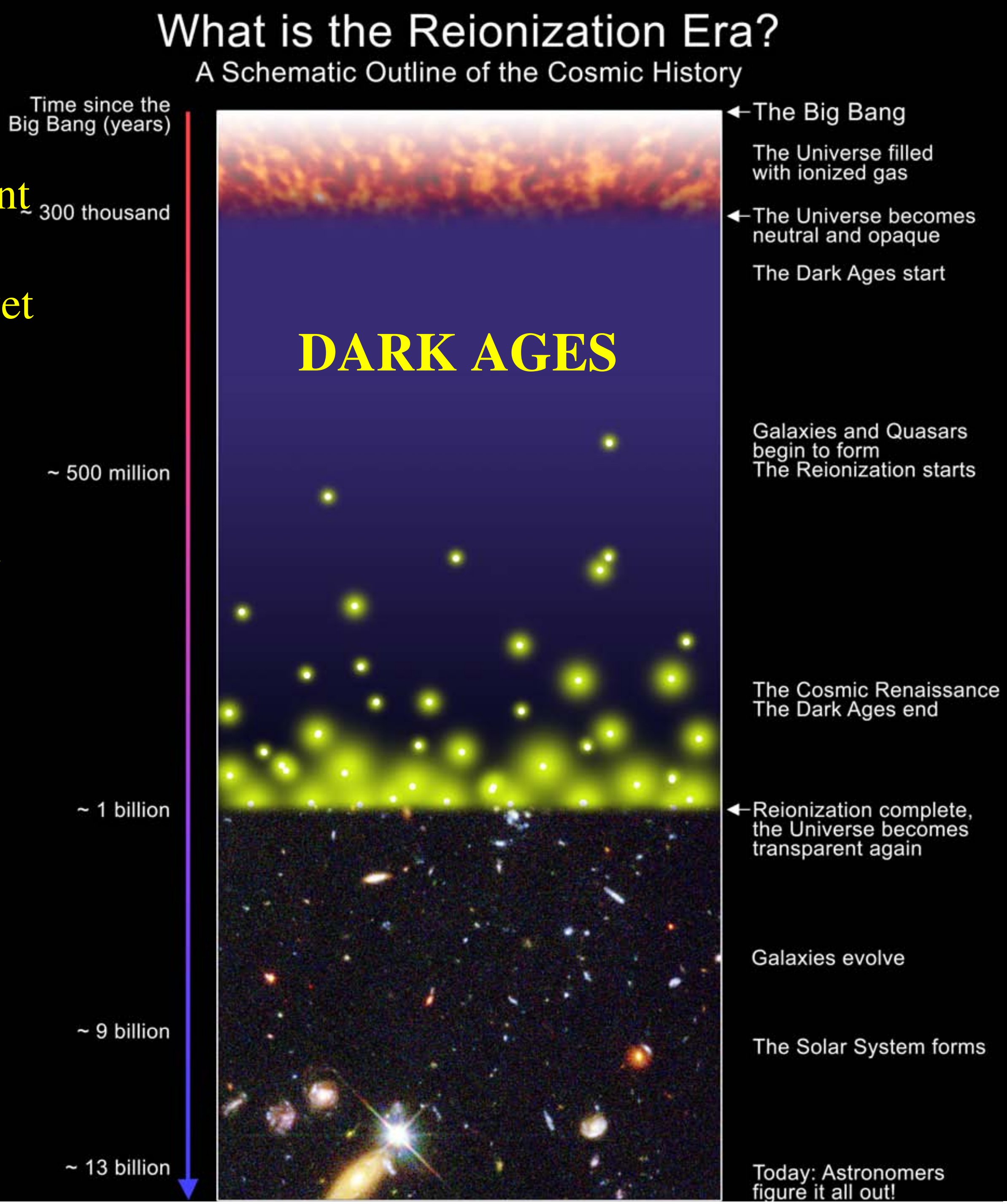
Deep infrared survey of N~300g, $2 < z_{photo} < 3$, 400 arcmin^2

Most $M > 10^{11} M_\odot$ galaxies are DRGs(77%) - LBGs constitute only 17%

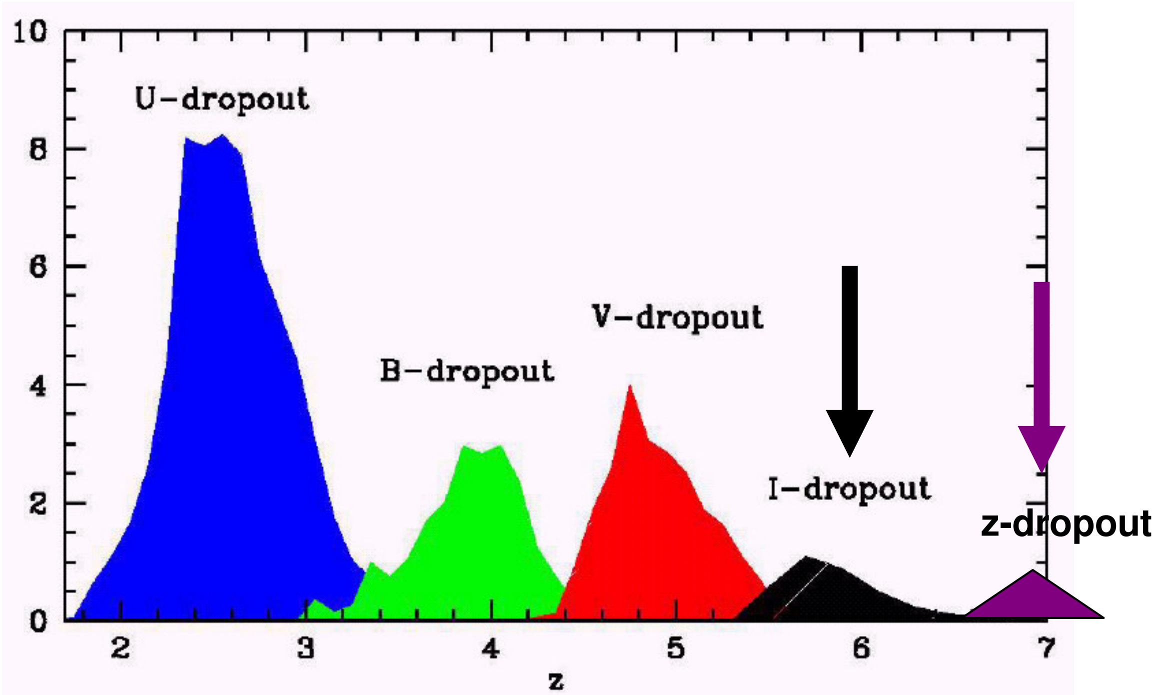
This suggest a lot of earlier SF activity

van Dokkum et al astro-ph/0601113

- Landmark event in history of cosmos, but as yet unobserved
- Physics should be simple: photo-ionization from stars, galaxies and/or QSOs
- Complex in practice: feedback, inhomogeneous IGM etc
- Need data!

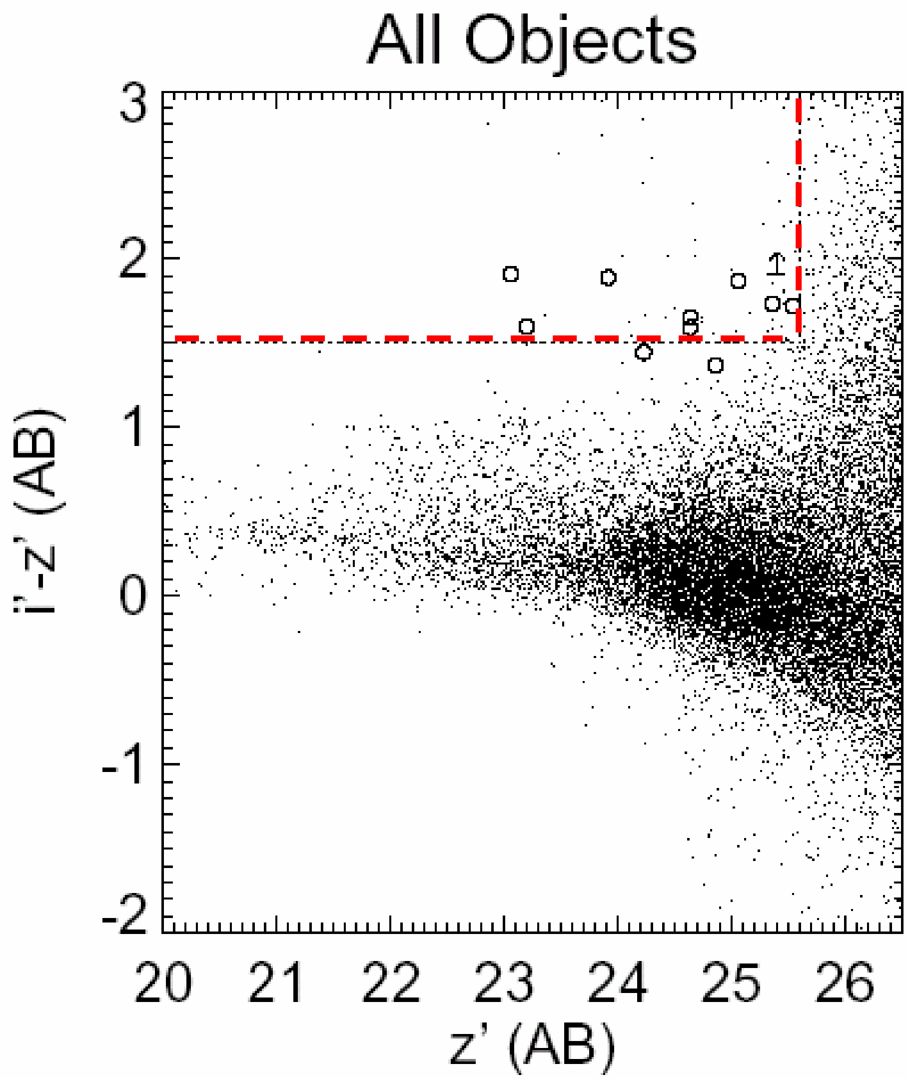


Continuum sources probed via Lyman break technique



Hubble Space Telescope and panoramic ground-based imagers (Subaru) are used to find populations of SF galaxies with z>5 using an extension of the Lyman break technique - shifting to longer wavelength filters

Searching for z~6 galaxies with HST - example



Contamination from foreground sources (cool stars, z~2 ellipticals) an important issue

GOODS-N catalog within reach of Keck

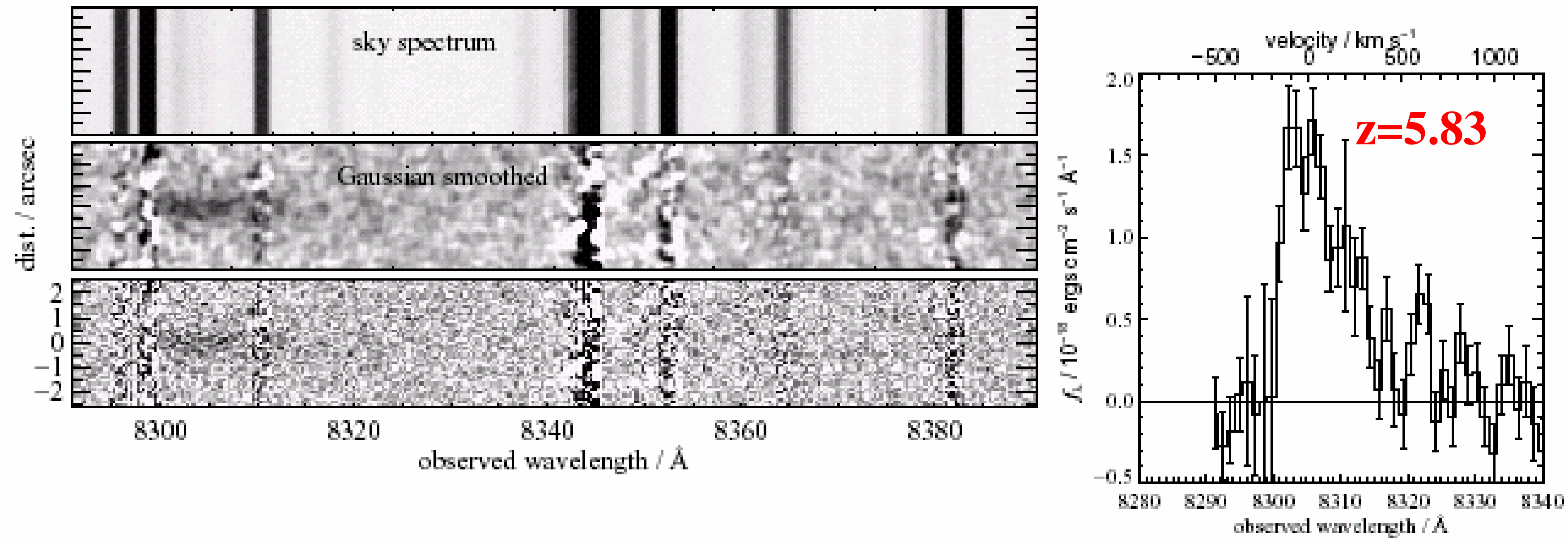
Selection based on v,i,z, HK

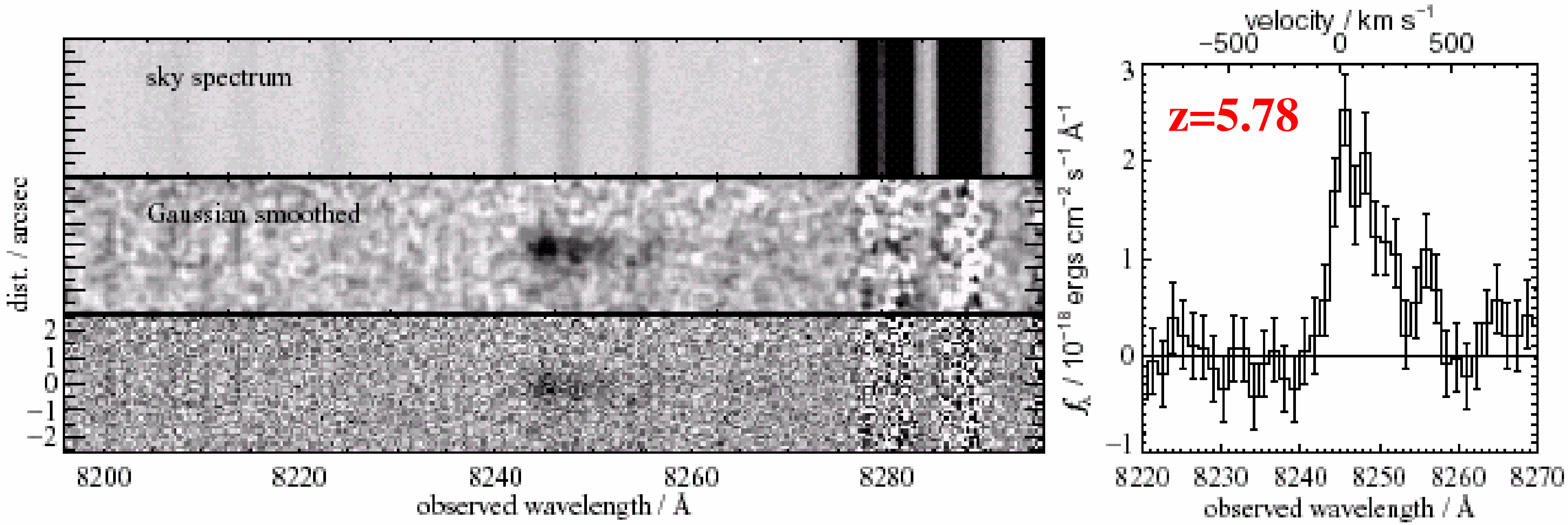
z(AB) < 25.6 i-z > 1.5

11 candidates for spectroscopy

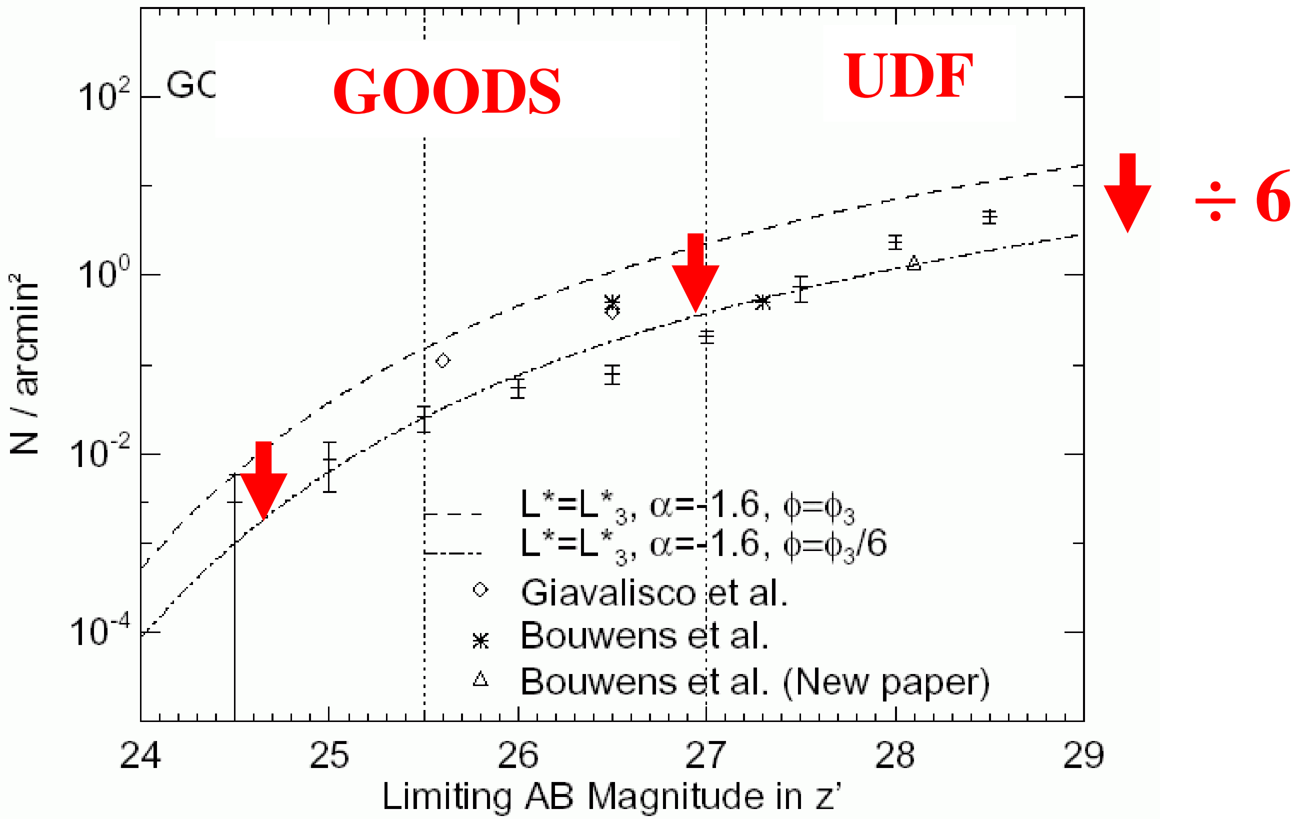
Stanway et al (2004) Ap J 607, 704

Keck spectroscopy revealing Lα emission





Counts for i-band dropouts (GOODS+UDF)



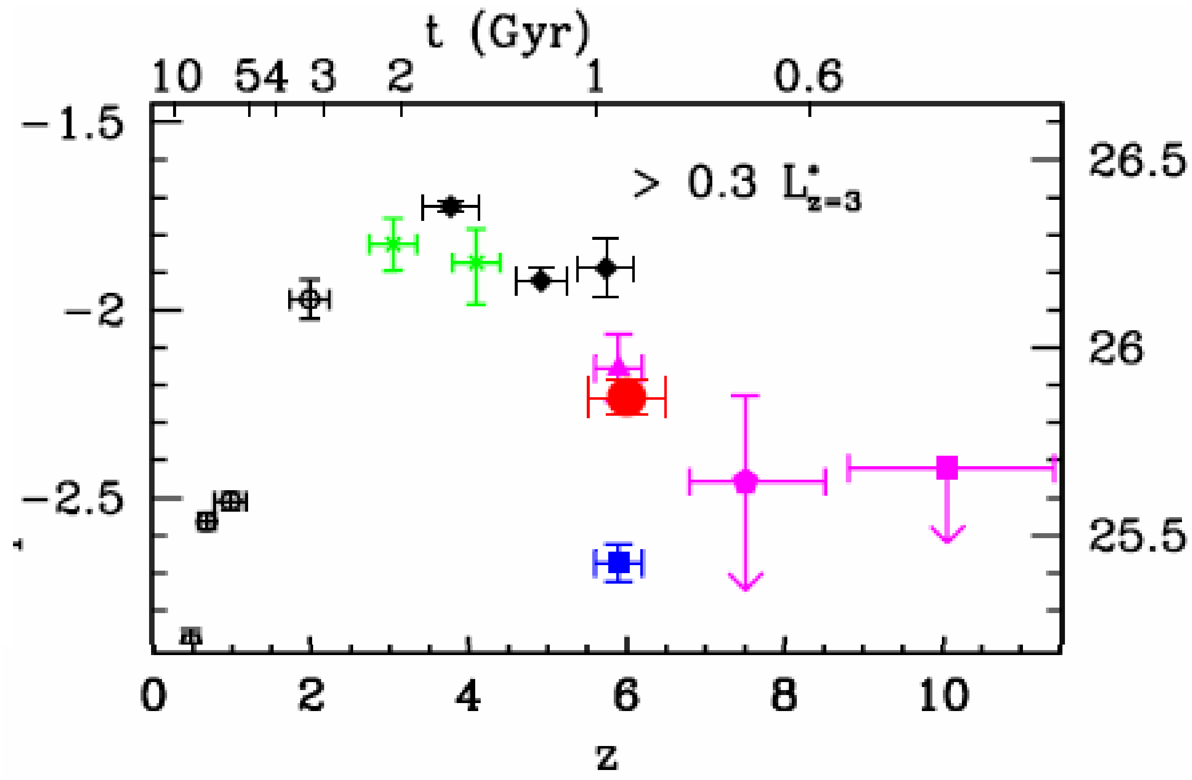
- Combining wide field GOODS survey with narrower Ultra Deep Field reveals z~6 luminosity function for the first time

- Counts of star forming galaxies at z~6 are consistent with those at z=3 with a decline in abundance of ×6 (decline is possibly luminosity-dependent)

Bunker et al MNRAS 355, 374 (2004)

Extending Technique using infrared NICMOS

Density of star formation Mpc^{-3}



Bouwens et al (2005) extend search into infrared to find z- and J-drops

Candidates only - no spectroscopic verification

Suggests a continued decline in star formation rate density to z~10

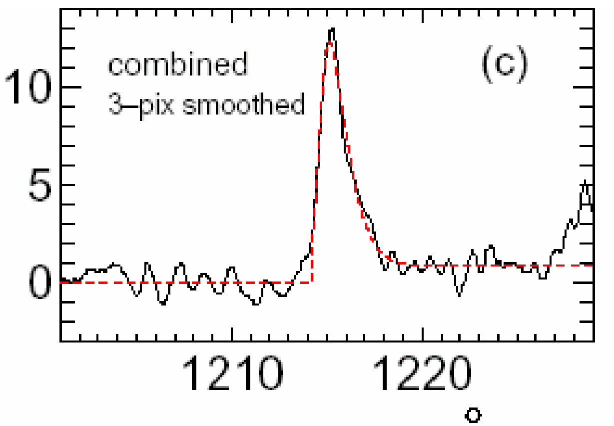
z > 5 Lyman α Surveys

Origin: ionizing flux absorbed by H gas → Lyα photons

Efficient: < 6-7% of young galaxy light may emerge in Lα
depending on IMF, metallicity etc.

Sensitive to reionization: damping by neutral H weakens line

Various techniques:

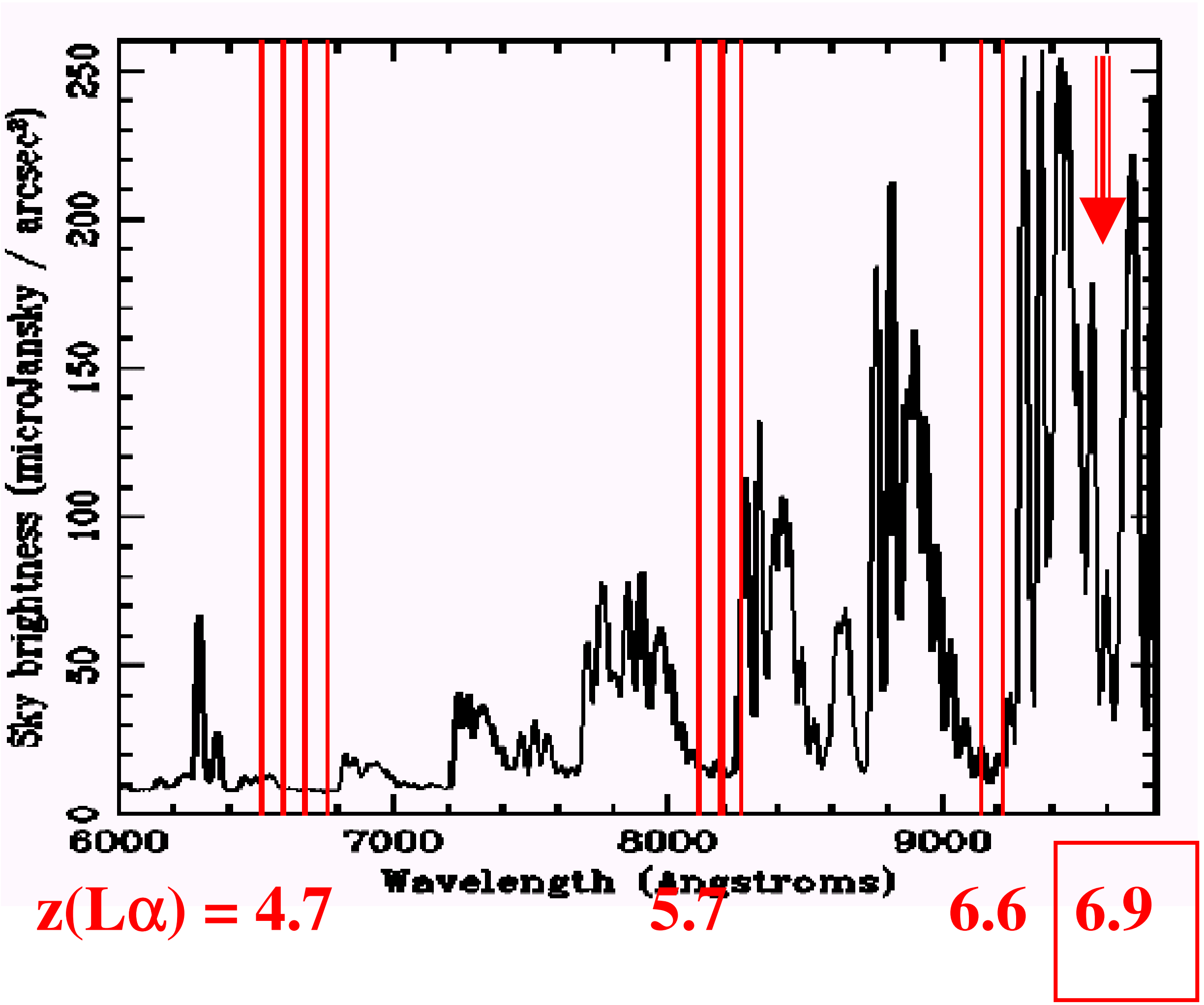


Narrow band imaging (Subaru wide field camera)

Gravitational lensing searches (Keck spectroscopy

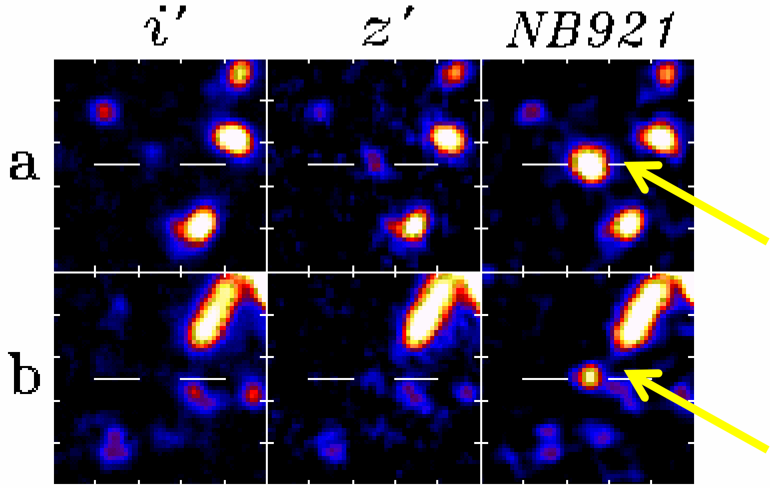
Narrow band filters

Searching is conducted where night sky emission is low

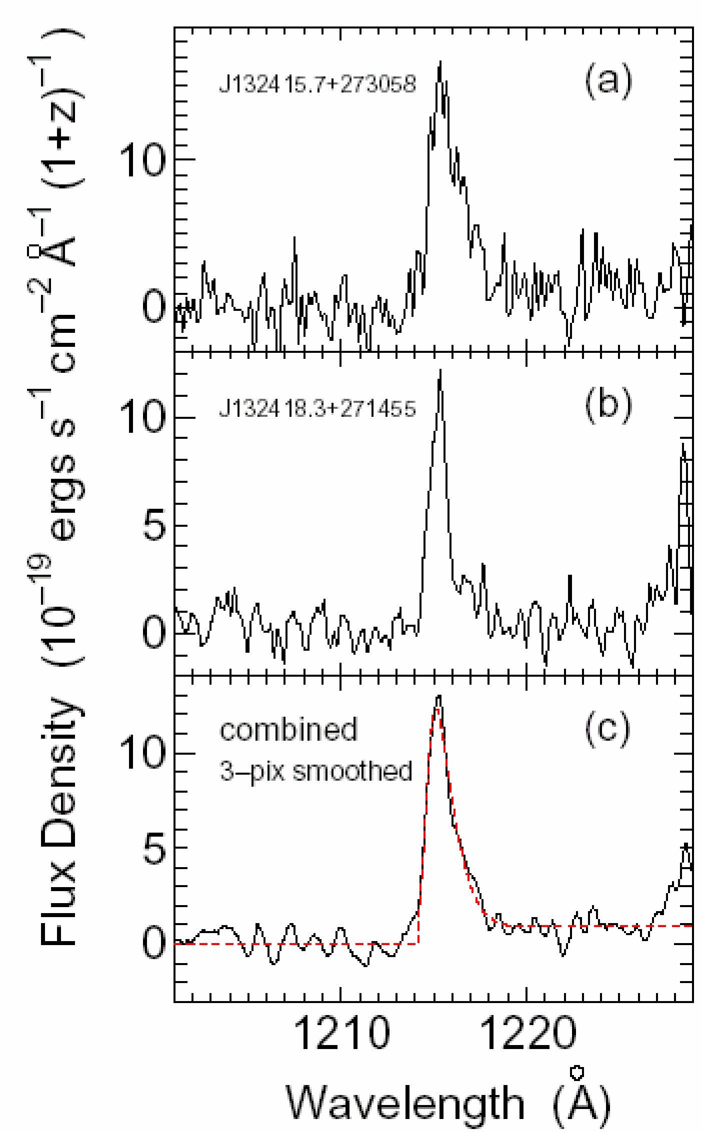


Requires panoramic imaging as Δz range is small: restricted to z<7

Example: Lyα Emitters at z=6.5



spectra



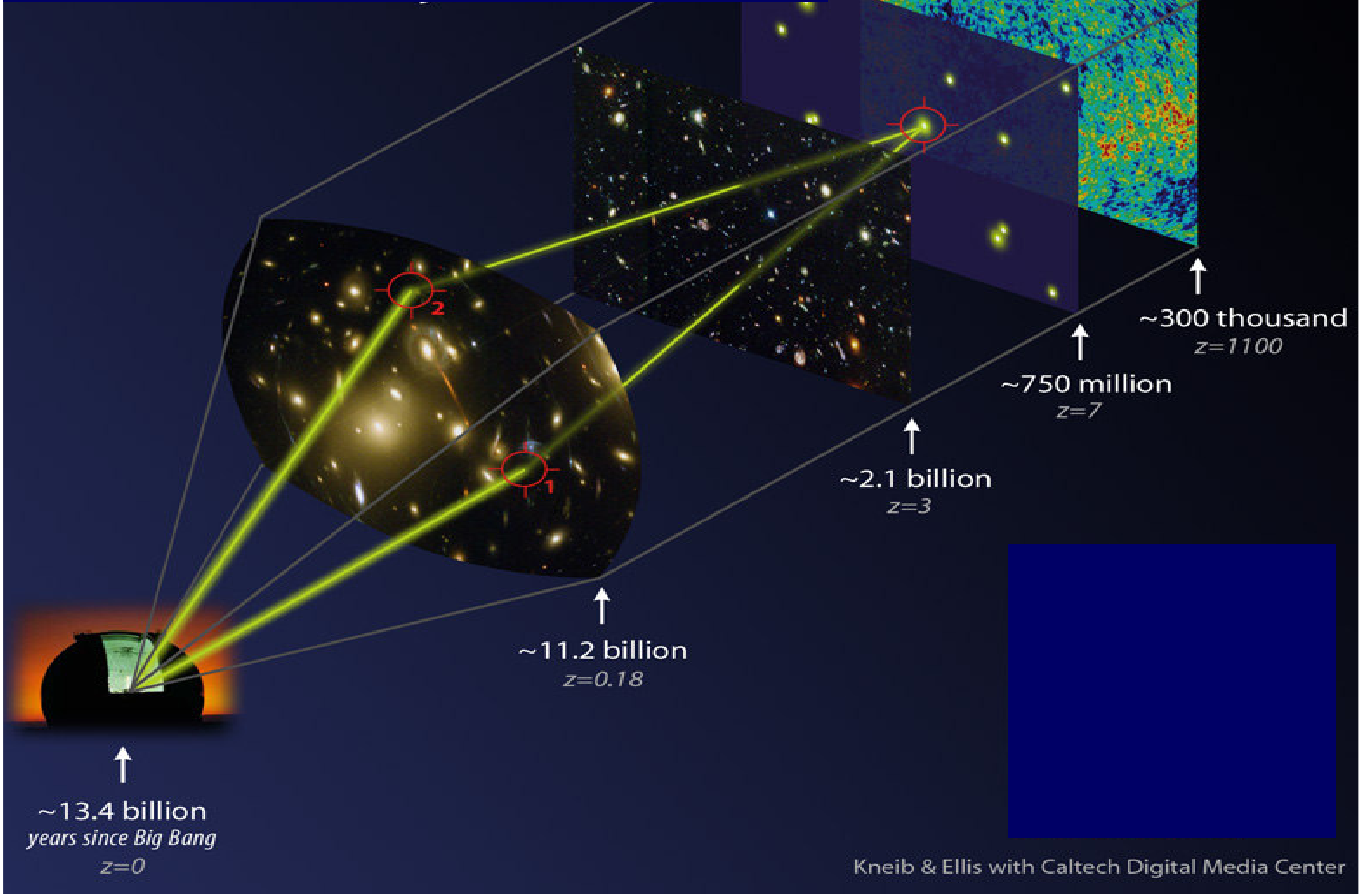
Very distant Subaru Lyα emitters:

(a) $z=6.541$, $W_{\lambda} = 130$, SFR=9

(b) $z=6.578$, $W_{\lambda} = 330$, SFR=5

Kodaira et al (2003)

Strong lensing = high magnification



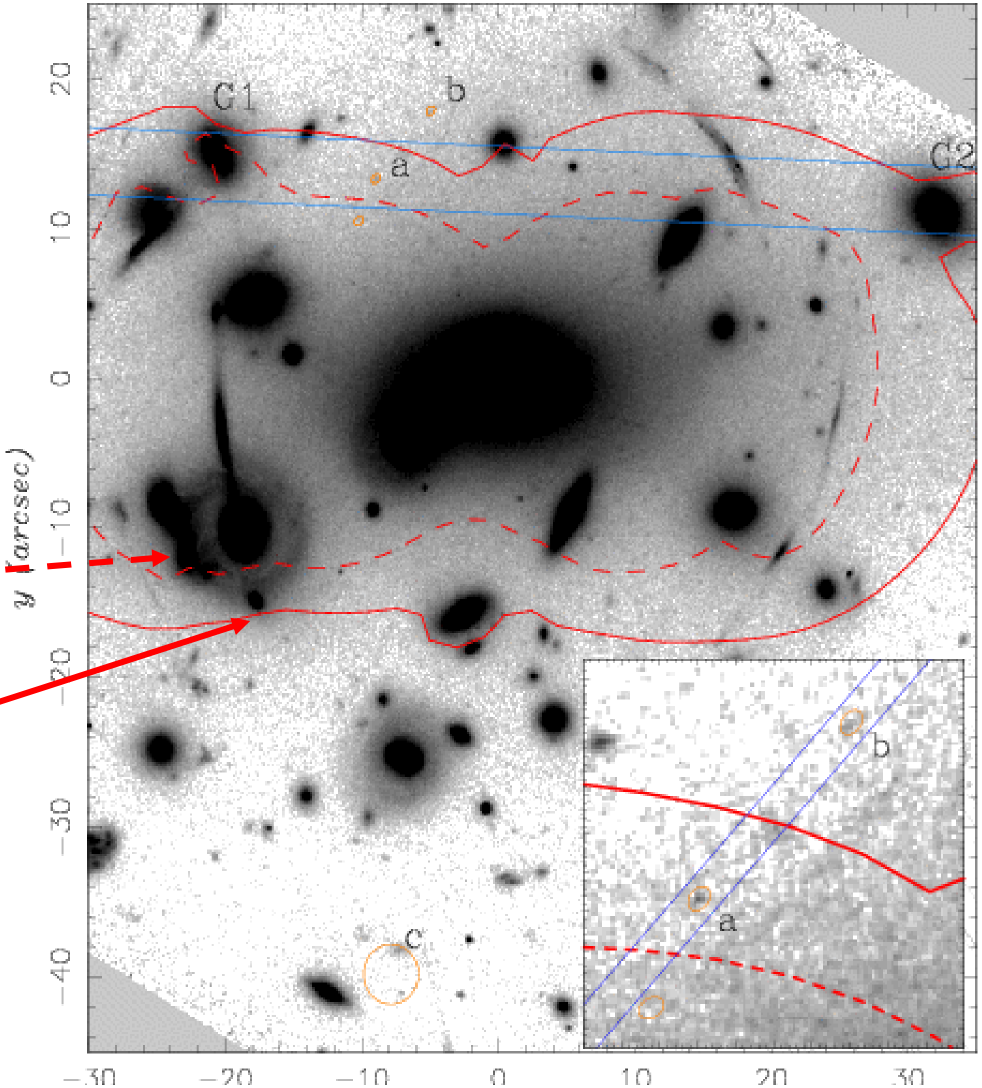
Critical Line Mapping with Keck

From arclet spectroscopy the location of the “critical lines” is known precisely for

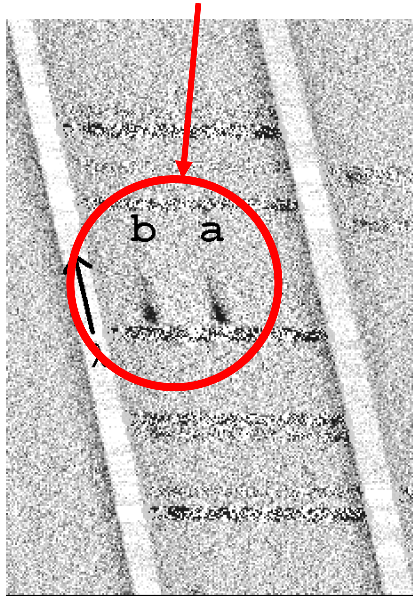
z=1

and for

z=5

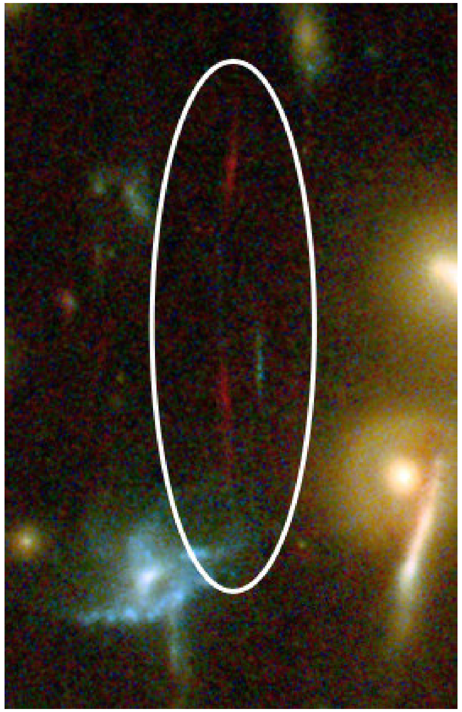


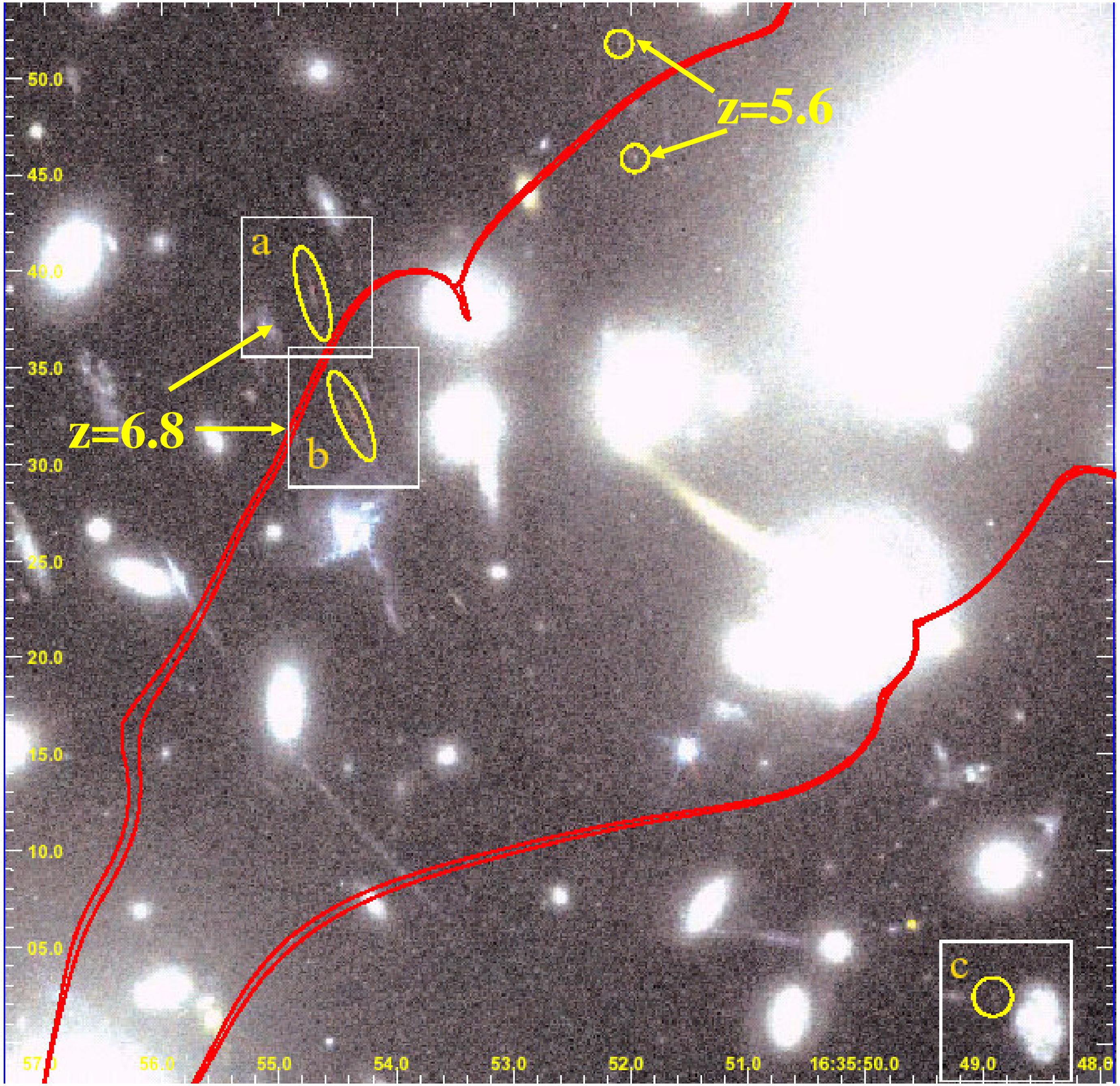
Blind Lyα search with LRIS: hi-res follow-up with ESI

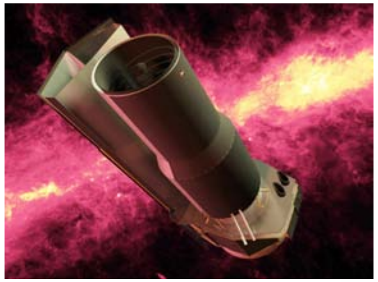


Utilizing strong magnification (×10-30) of clusters, probe much fainter than other methods in small areas (<0.1 arcmin^2 cluster^{-1})

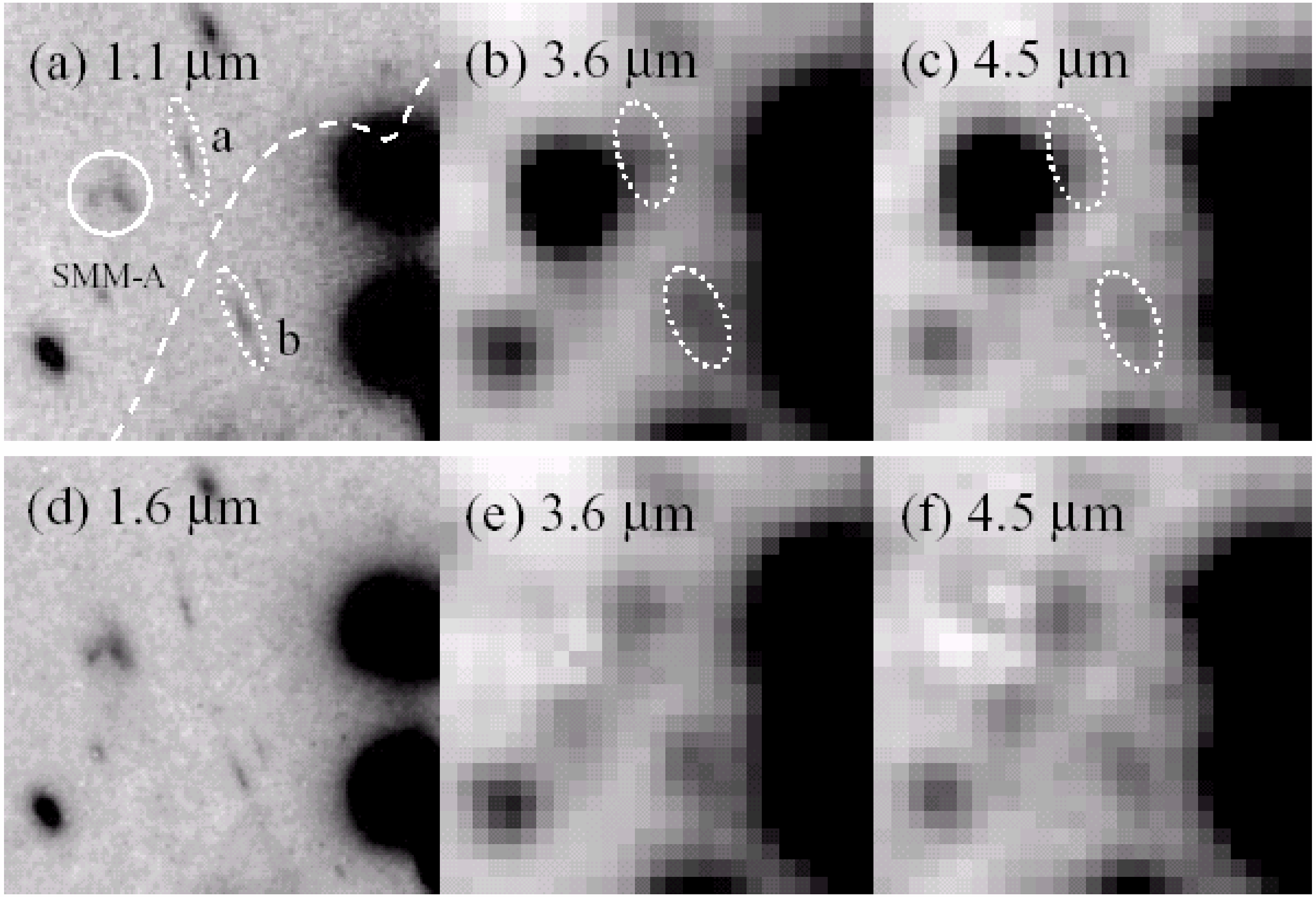
Lensing has found some of the most distant galaxies







Spitzer Detection of Lensed z~6.8 Pair



Spitzer is a mid-infrared space telescope sensitive to rest-frame optical light (and hence older stars) at z~6

Established Stellar Population at z~7

Some parameters:

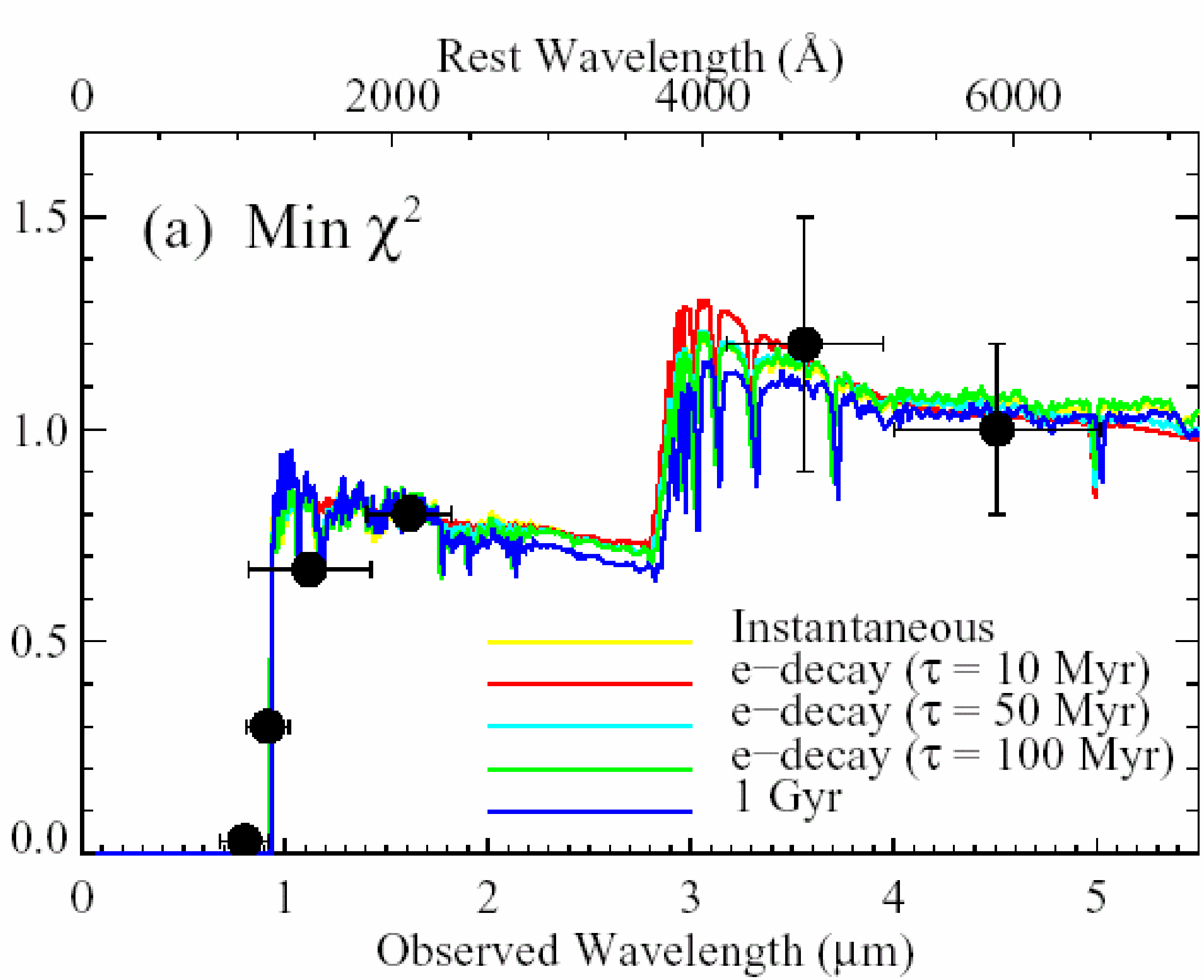
SFR = 2.6 $M_\odot$ yr^{-1}

M_{star} ~ 5-10 10^8 $M_\odot$

z ~ 6.8 ± 0.1

age 40 – 450 Myr
(7 < z_F < 12)

(Egami et al 2005, Ap J 618, L5)



Given small search area, such sources may be very common

Mass Density at Redshift 5

- **Assembled Stellar Mass at High Redshift:**

Integrated stellar mass at z=5: $M_*(z) = \int_5^{10} \rho_* (z)\, dV(z)$

Undertake at highest redshift where sample is well-controlled

Is accumulated stellar mass consistent with observed SFH?

If density at, say, z~5-6 is ***greater*** than can be accounted for by $\int \rho_* (z)\, dV(z)$, options include: extinction, intrinsically faint contributors or upturn in SFH before z~10

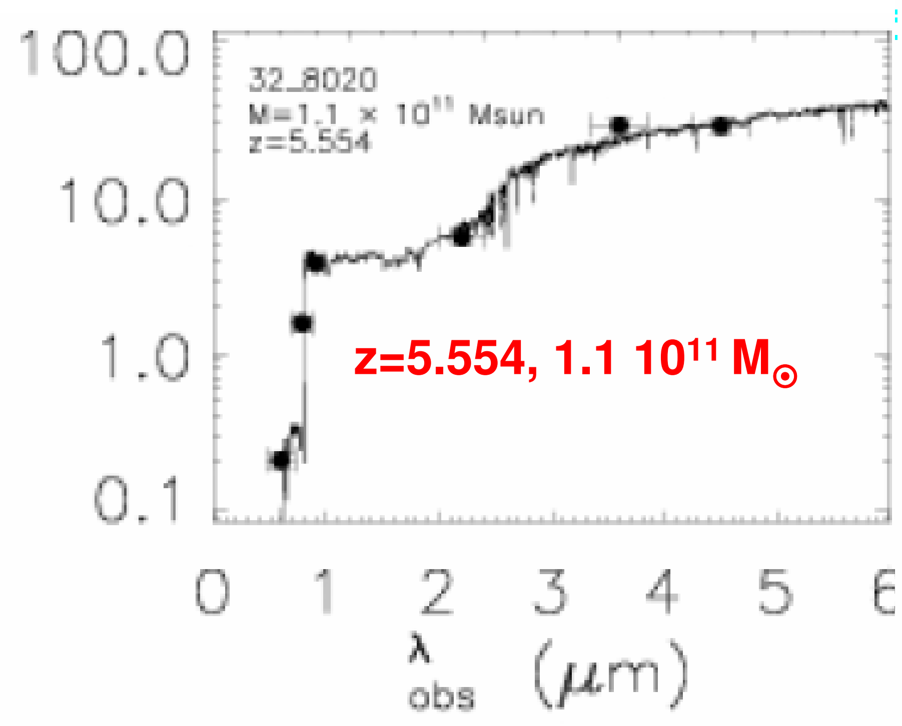
A New Estimate of the Stellar Mass Density at z~5

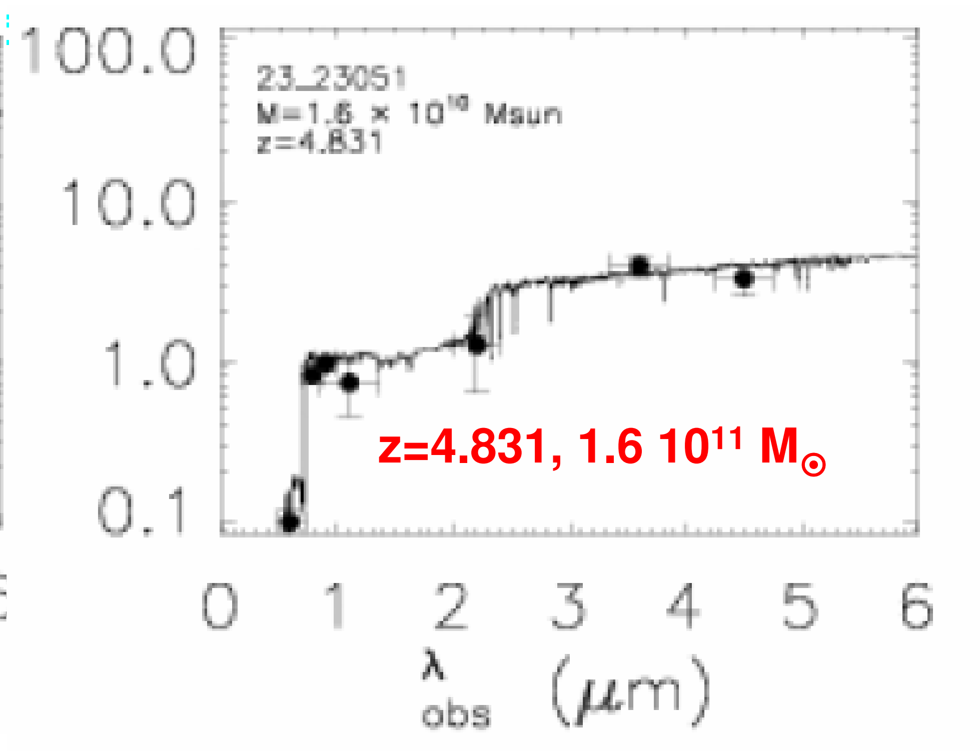
GOODS v-drops is basic sample, with Spitzer and Keck follow-up

Cosmic age at z~5: τ ~ 1.2 Gyr

Spectroscopic confirmation (N~30 so far), Keck campaign underway

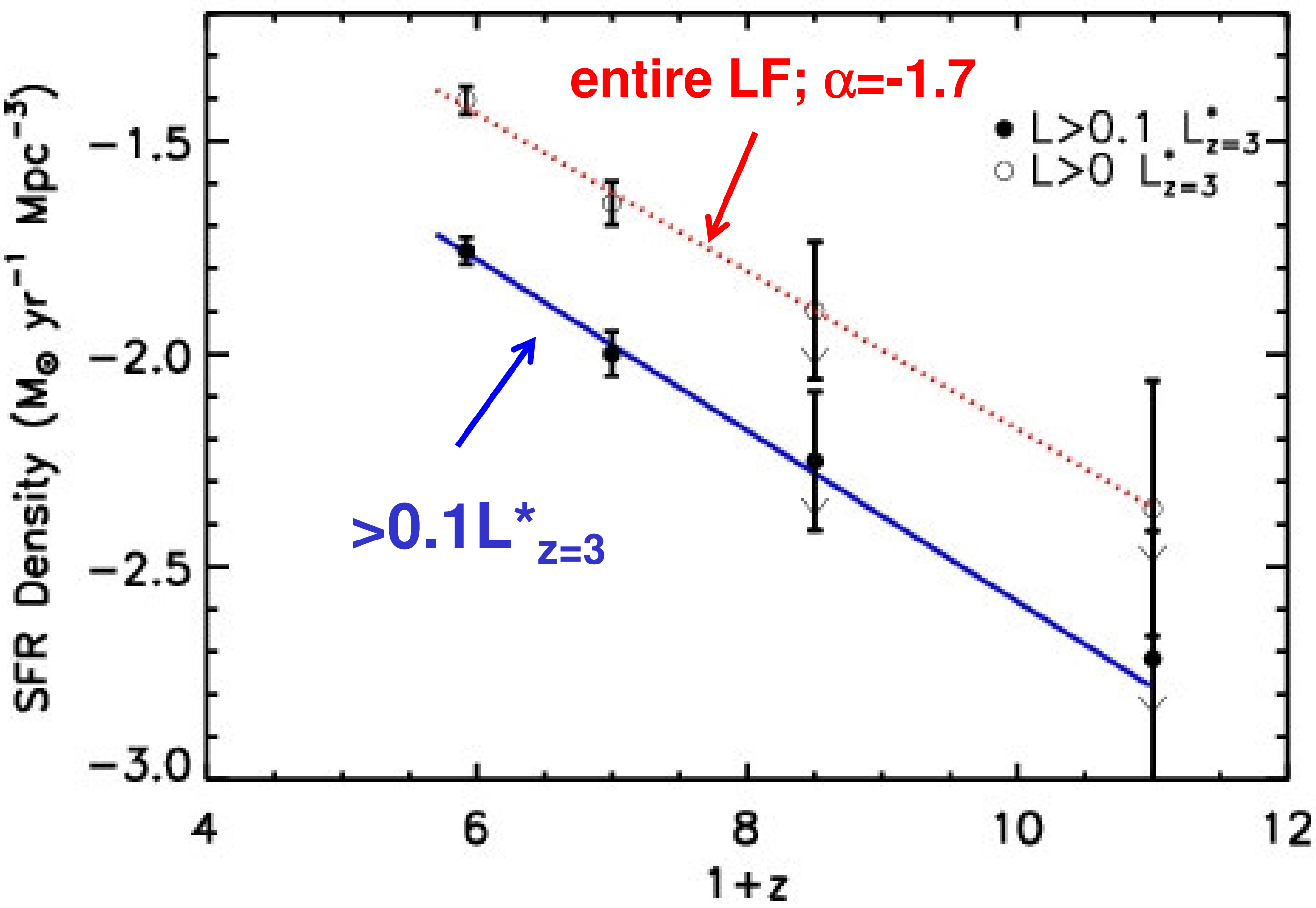
Total sample: 212 z' < 26.5, 108/137 with IRAC in clean fields, 15 spec z's





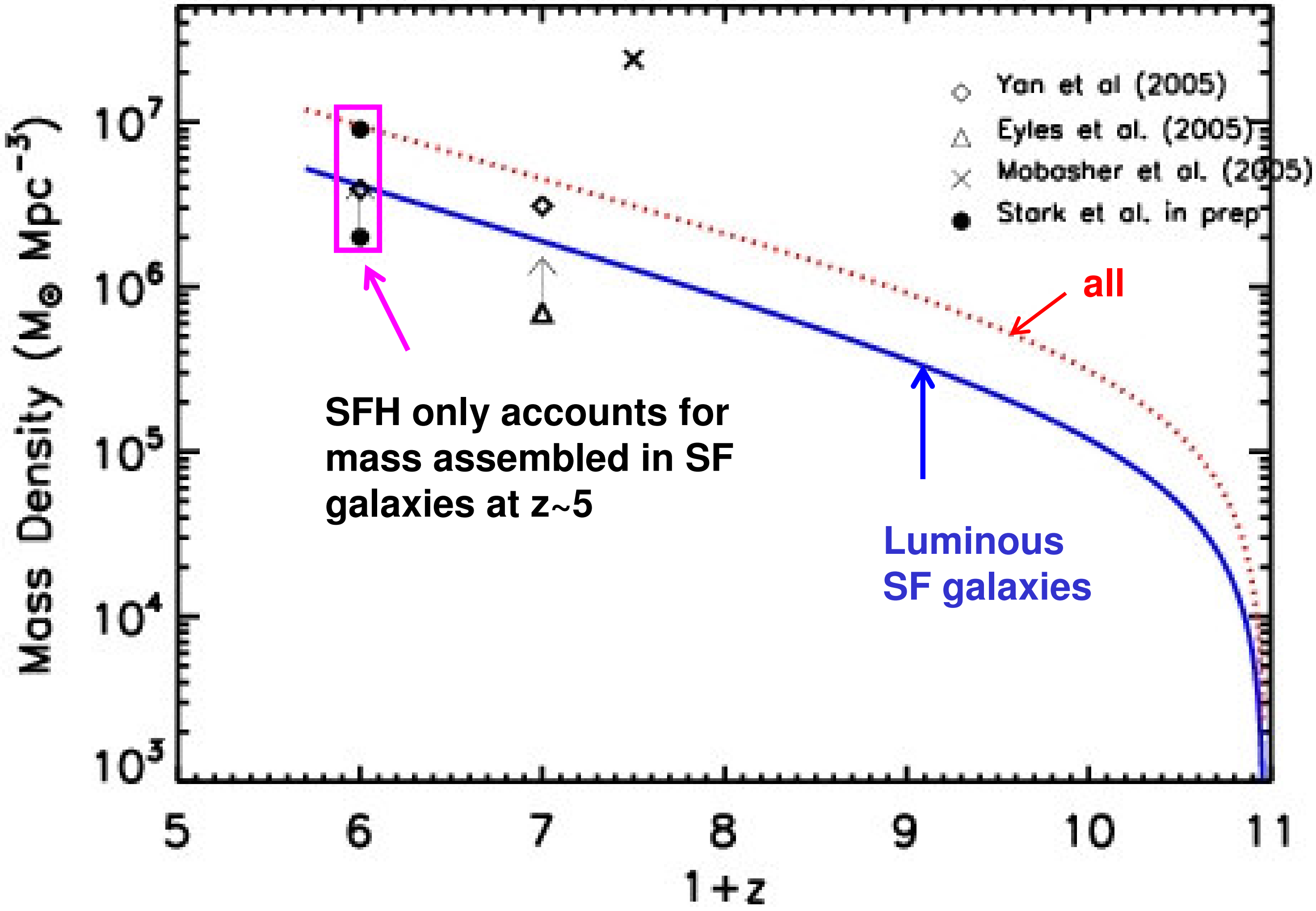
Stark, Bunker, Eyles, Ellis & Lacy, in prep

Parameterized Star Formation History



Based on recent compilations by Bouwens, Bunker et al

Implications of the Measured z~5 Mass Density



Stark, Bunker, Eyles, Ellis & Lacy, in prep

Summary of Lecture #2

• Several complementary observational techniques have been developed to locate samples of galaxies at redshifts $2<z<10$

• Different techniques (optical, infrared, sub-mm) uncover different cross-sections of the evolving population

• We can piece together the bigger picture of cosmic history using the integrated *star formation*, the *mass assembly* and by comparing the *clustering* of each population

• Most exciting perhaps, we are locating examples of the earliest sources at $z>6$ which may have ended the Dark Ages when intergalactic hydrogen was neutral