Diagnostics of the Galaxy Population in the Early Universe

or

Getting to the physically interesting quantities from observational 'proxies'

Hans-Walter Rix

March 28, 2008

Basic Goals of High-z Galaxy Studies

As a proxy for studying the typical
evolutionary fates of galaxies,
one needs to study the
evolution of the galaxy population
as a function of cosmic epoch.

- At what epoch (redshift) was star-formation most vigorous?
- When did the first 'massive' galaxies appear?

- Need model comparison to go from observable **population evolution → object evolution.**

Questions that can be answered by direct observations

- Frequency of galaxies as function of
  - Epoch (Redshift)
  - Stellar Mass / Luminosity (Halo Mass?)
  - Spectral Energy Distribution (SED, color → age)
  - Structure (size, bulge-to-disk)
  - Gas content (hot, cold)

- What is the incidence of "special phases"?
  - (major) mergers; QSO-phases
- How are these properties related to the larger "environment"?

Part I:
Identifying High-z Galaxies

Or

To compare galaxy samples at different epochs, you need to know how you selected them

Issues in Sampling the high-z Galaxy Population

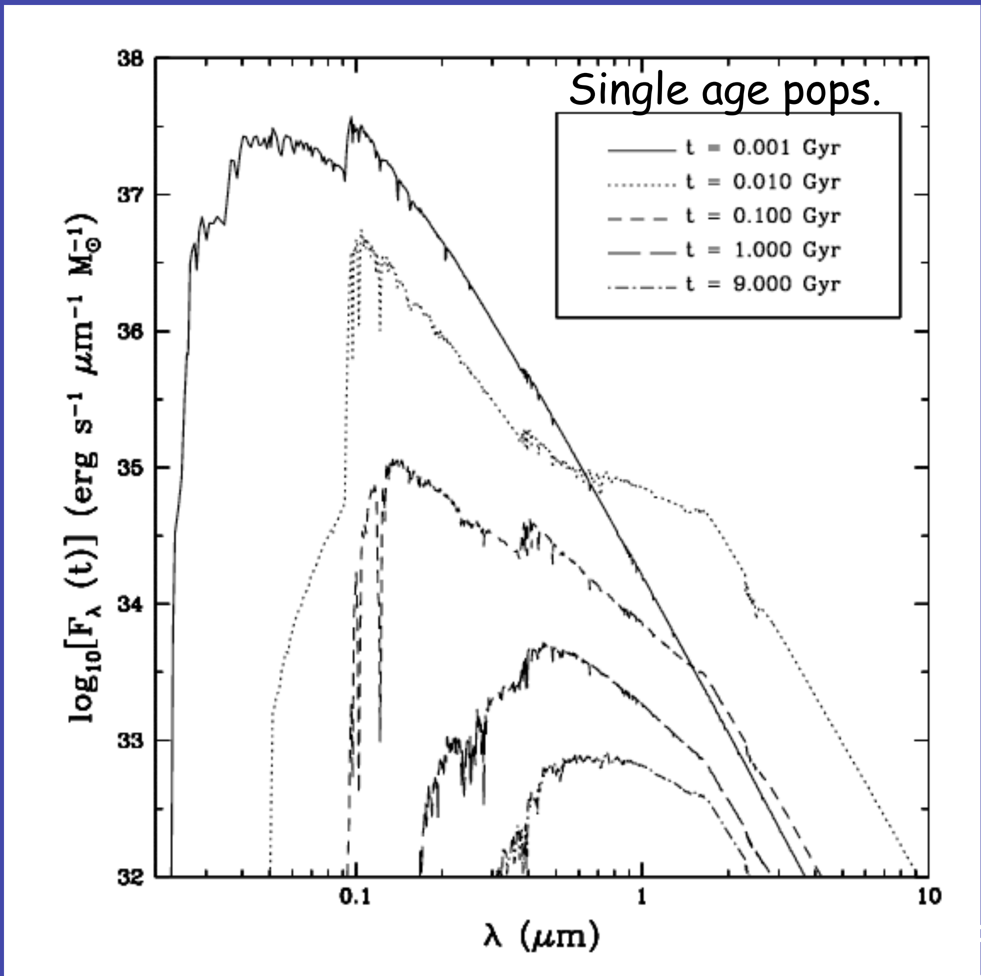
- "Consistent" selection of galaxy samples becomes increasingly difficult as the redshift range expands.
  - K-correction ($F_{\lambda,observed} \leftrightarrow F_{\lambda,emitted}$)
  - $(1+z)^4$ surface brightness dimming
- Multi-variate distribution requires very large samples
- Clustering of objects requires large-ish areas.

Search Strategies for High-z Galaxies

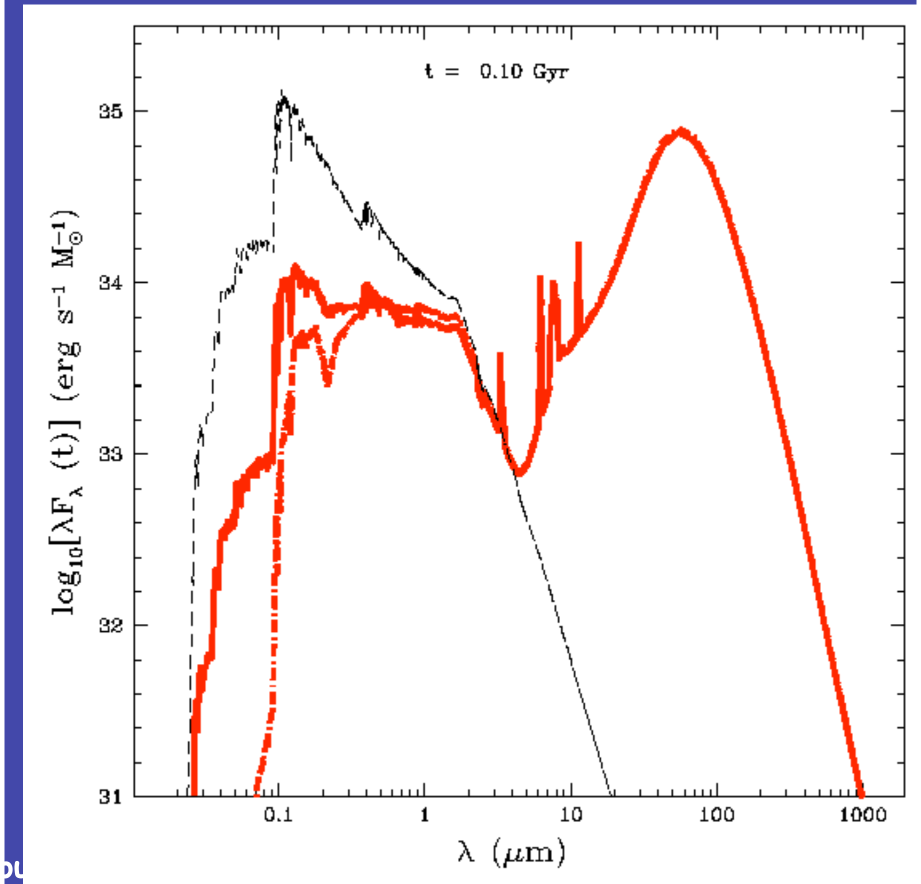
- Size: 0.1" – 1" (almost independent of redshift)
- Proxies for star-formation rate
  - UV, mid-IR and bolometric energy from young, massive stars
- Proxies for stellar/halo mass?
- "Foregrounds", those pesty z~0.7 galaxies
- Atmospheric windows and available technology

For a galaxy of given stellar mass, the SED depends drastically on

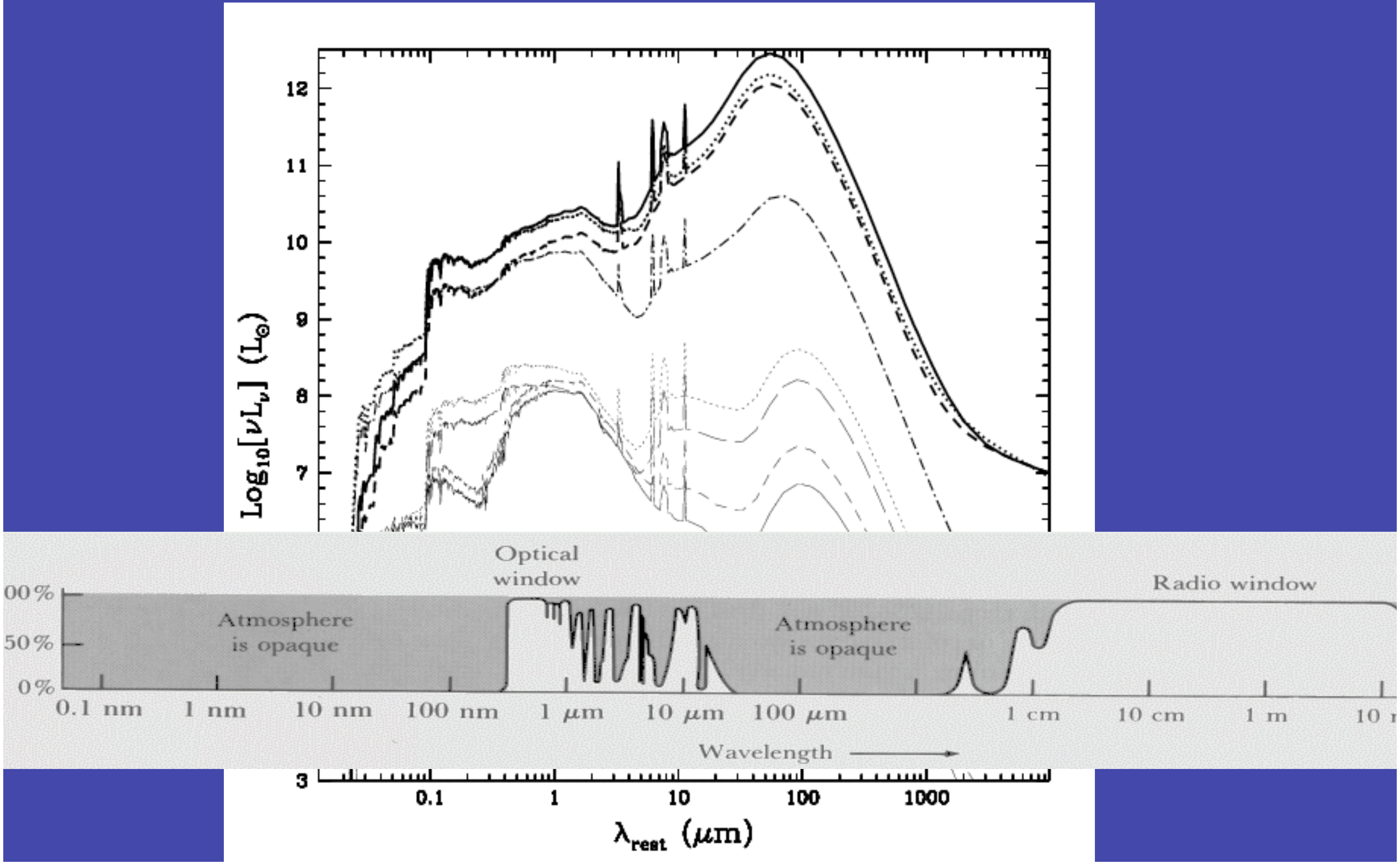
- age of the stars
-fraction of light absorbed by dust



Devriend et al 2000

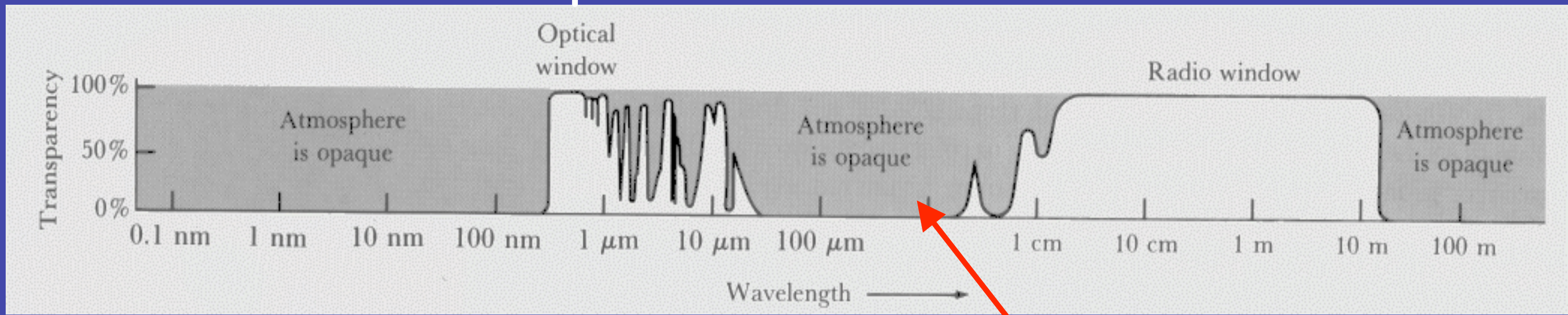


Practicalities of observing (high-redshift) galaxies



Ground-based vs. space-based?

........................opt..NIR................radio window.......

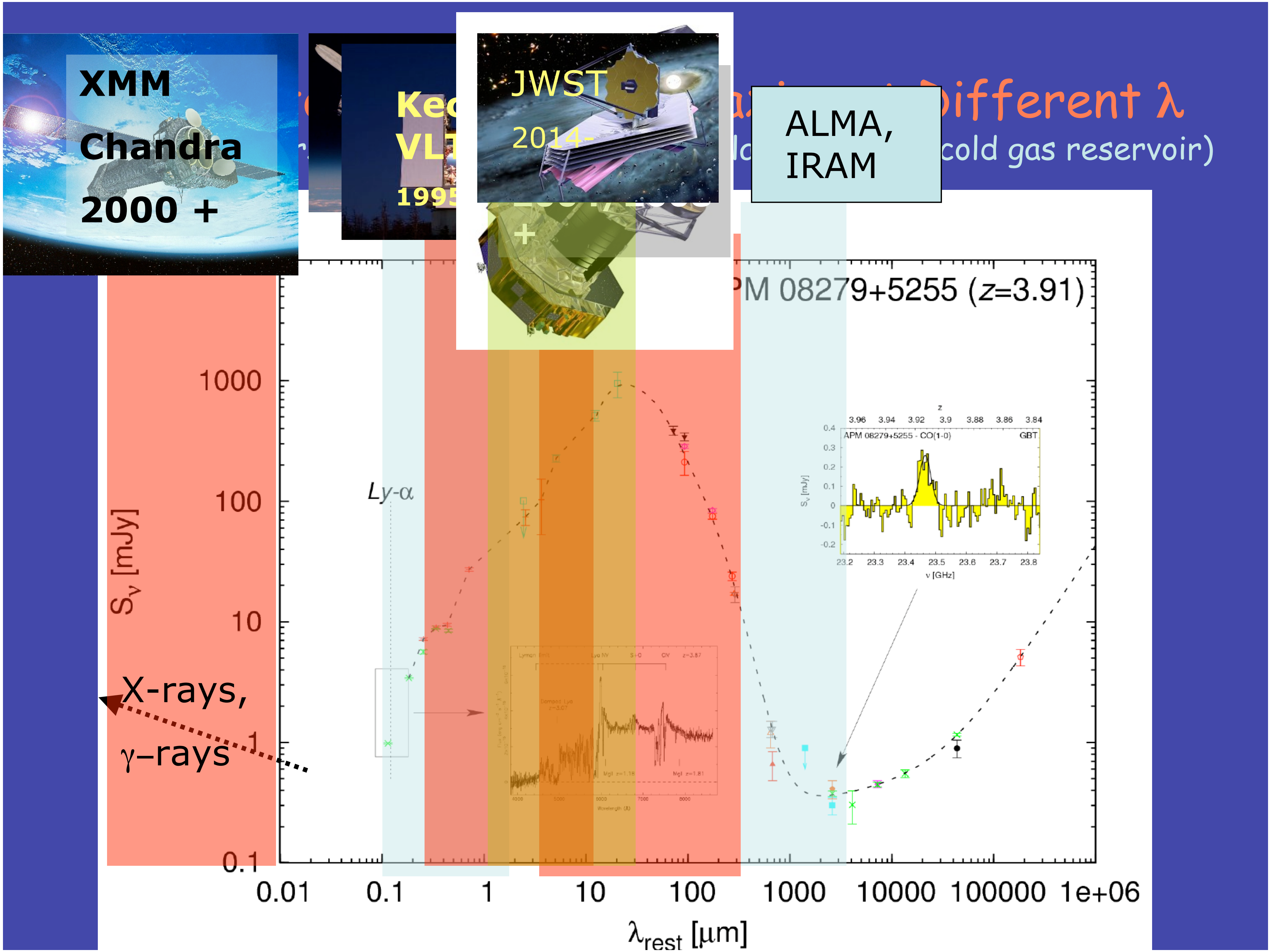


0.1nm 1 10 100 1μm 10 100 1cm 10 1m 10 100m

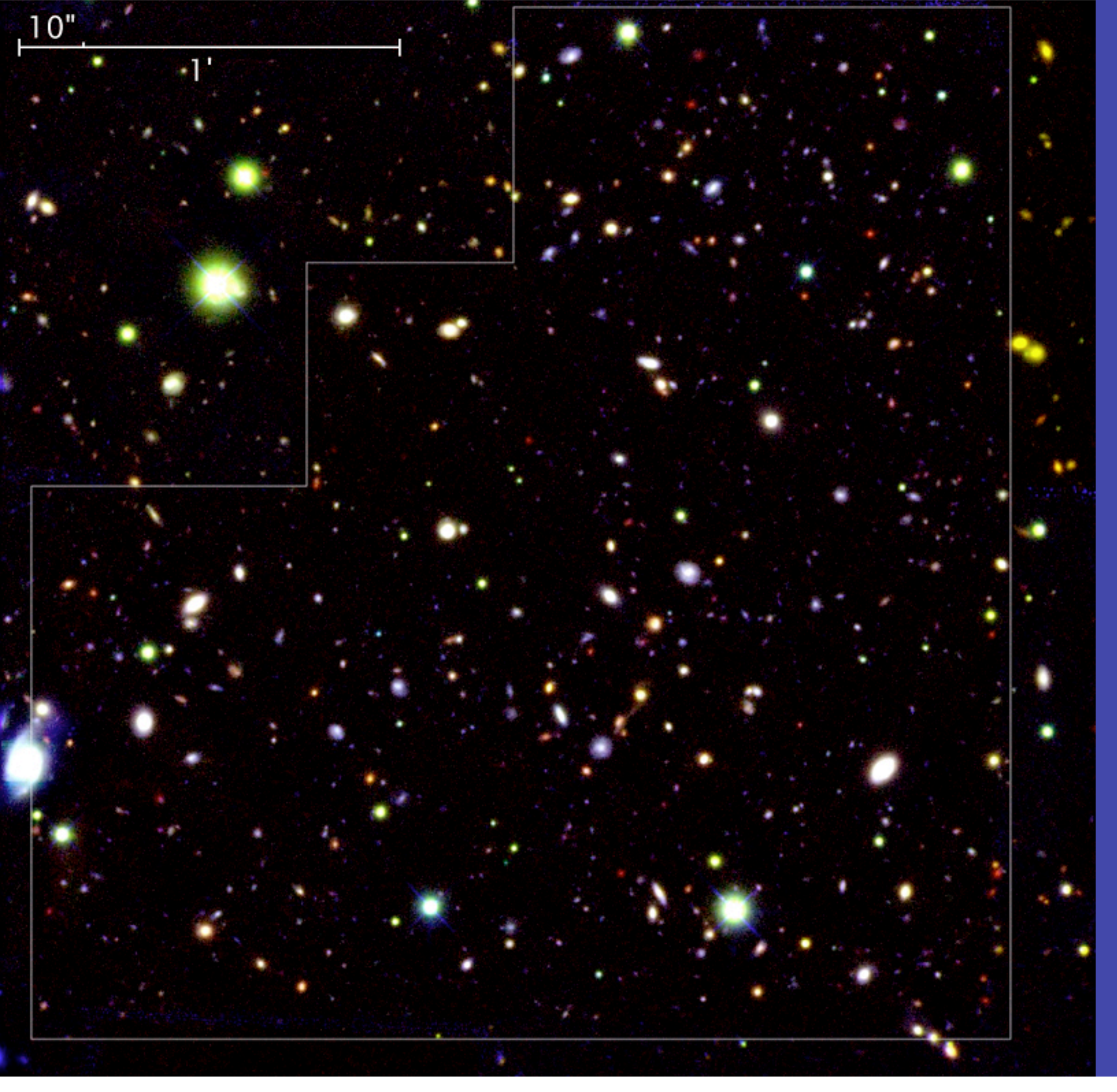
wavelength

Some sub-mm windows from good sites

NB: in addition to transmissivity, the emissivity of the Earth's atmosphere is a big problem: sky at 2μm is 10,000 brighter than at 0.5μm

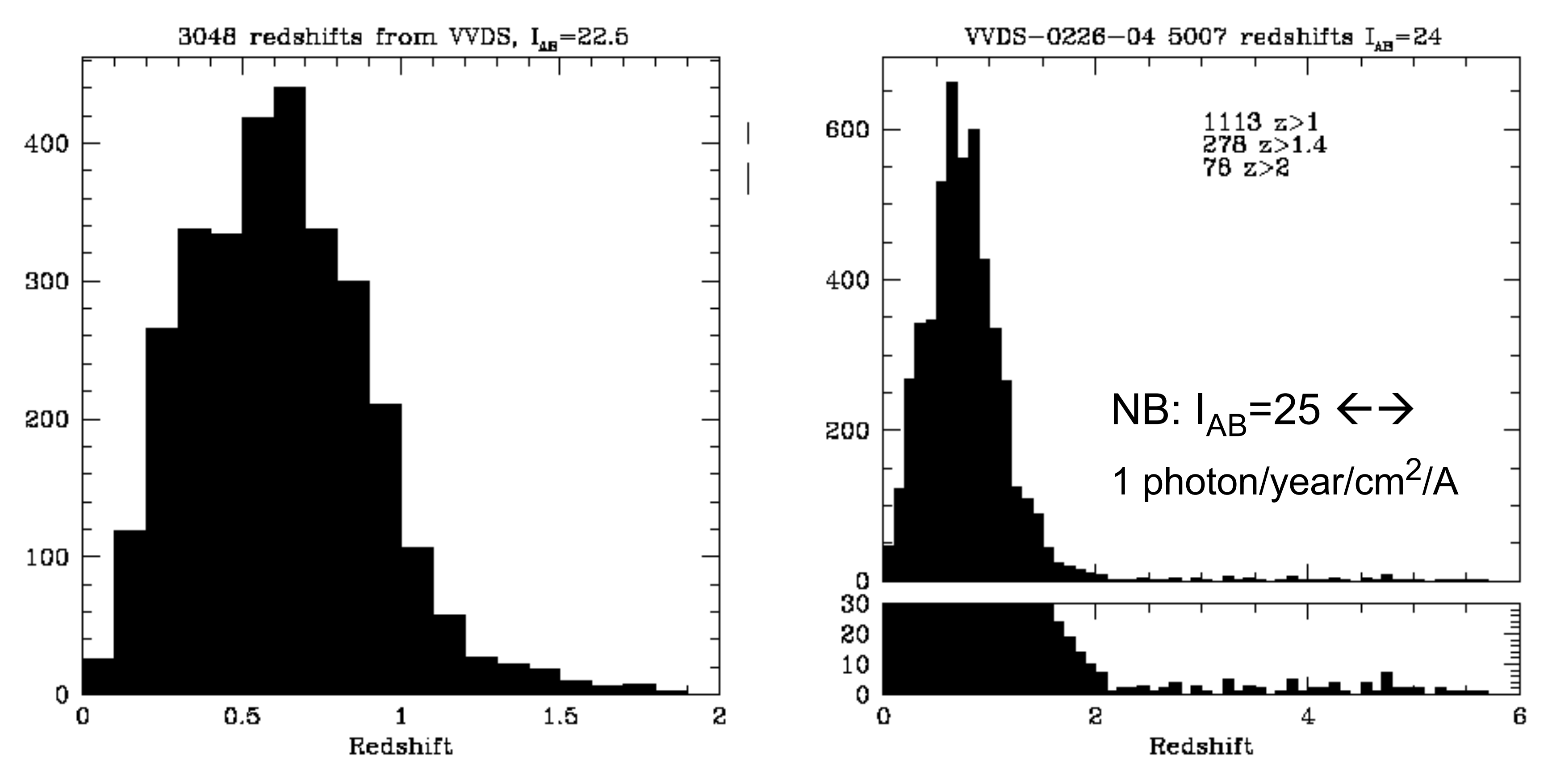

XMM
Chandra
2000 +
JWST
2014-
ALMA,
IRAM
Different λ
cold gas reservoir)
M 08279+5255 (z=3.91)
Ly-α
X-rays,
γ-rays
APM 08279+5255 - CO(1-0)
GBT
S_ν [mJy]
λ_{rest} [μm]
ν [GHz]
0.1
1
10
100
1000
0.01
0.1
1
10
100
1000
10000
100000
1e+06

Identifying Samples of High-Redshift Galaxies



"Foreground (z<2) Galaxies"

when looking at a flux-limited sample



From: LeFevre, Vettolani et al 2003

→ "Brute force" spectroscopy is inefficient for z>2!

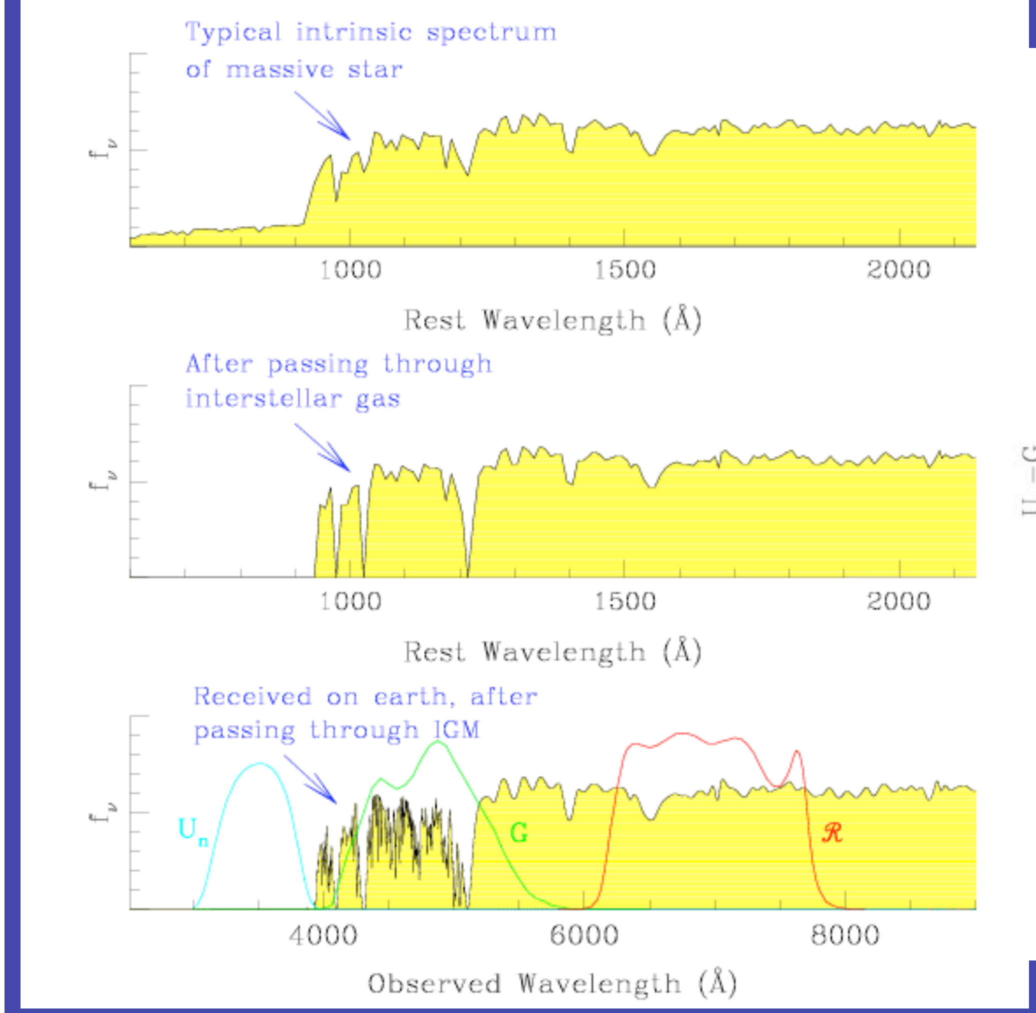
Star-Formation Rate Proxies

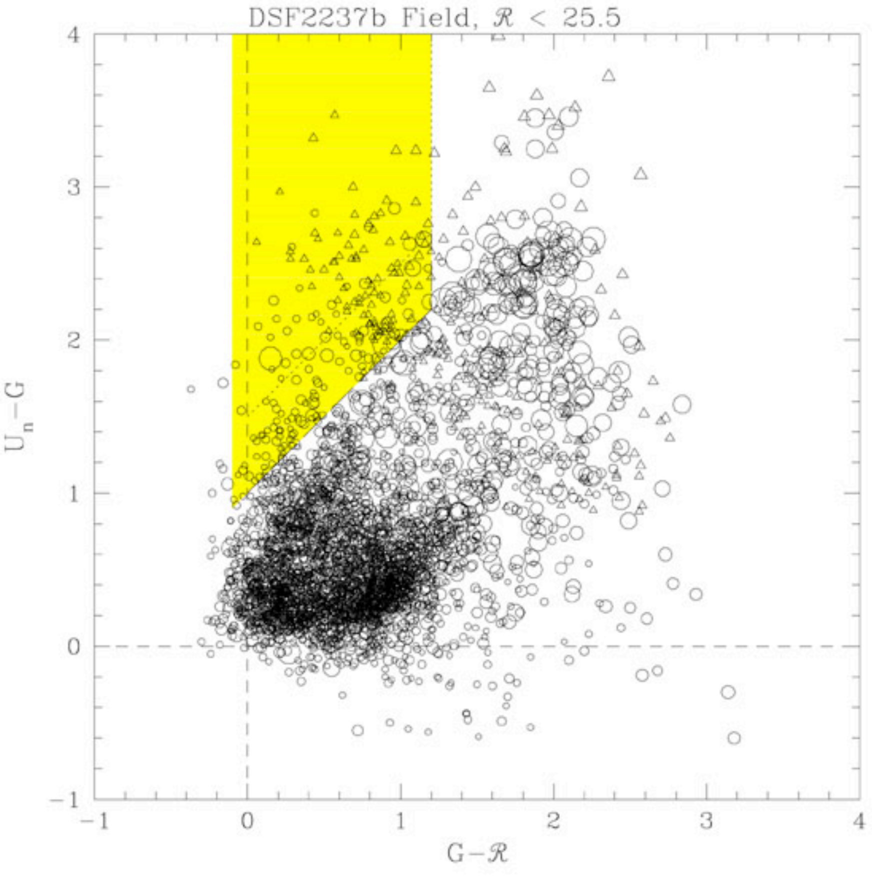
- SFR ←→ Power and ionizing photons from hot, massive, short-lived stars.
- UV flux and thermal-IR are the best and most practical proxies, but are inaccessible from the ground for z<1-2
  - The peak of dust emission 100-300μm are almost inaccessible with current technology

Selecting Galaxies by their Rest-Frame UV Properties

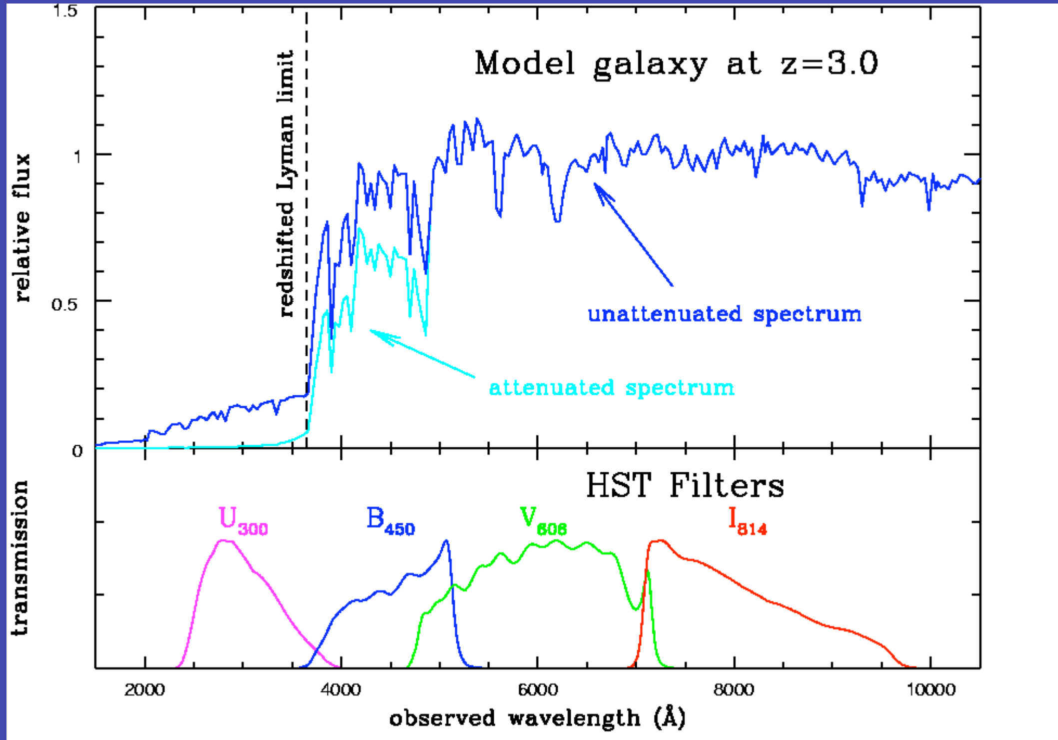
- Until mid-1990s only a handful of high-z galaxies were known (radio galaxies)
- Breakthrough from the combination of color-selection and Keck spectroscopy (C. Steidel and collaborators, 1996 ff.)
- "Break" arises from absorption of λ<912A radiation through the intervening ISM and IGM

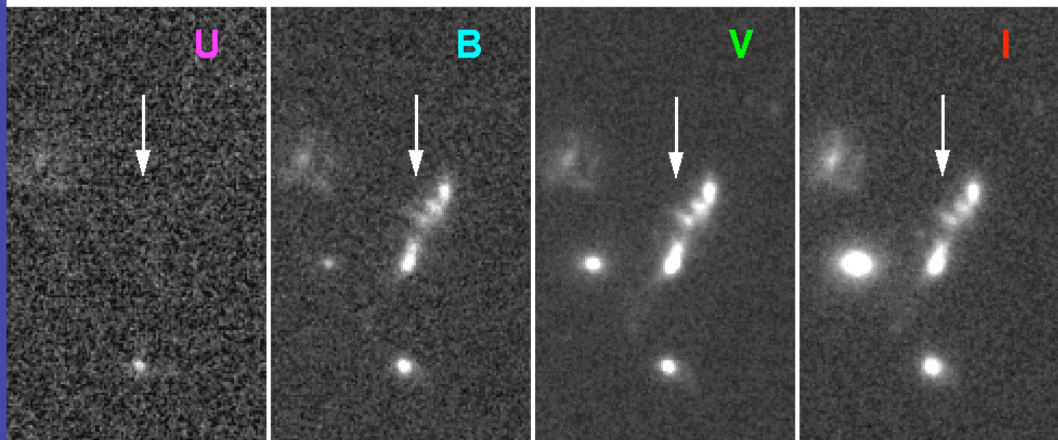
The Lyman Break Technique





- Example: what Ly-brak galaxies look like





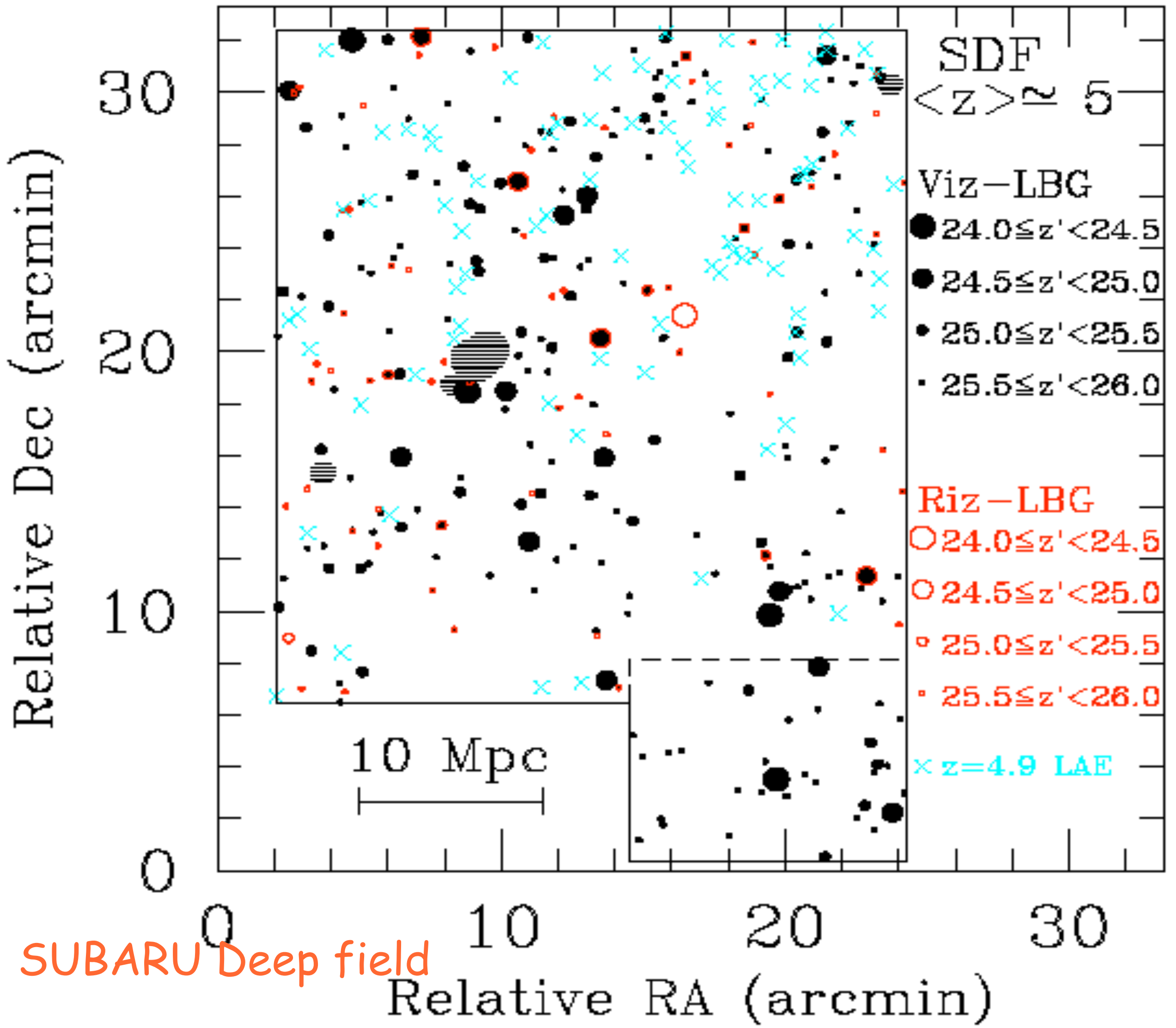
Ly-break Selection

- **Current sensitivity: >5 M_{Sun}/yr at z~3 (as inferred from UV-flux)**
  - Very dusty galaxies or those with low-SFR will not be found.

- **Choice of filters sets redshift range**
  - Z>2.2 from the ground
- **Ly-limit break at z~2 ←→ Lα break at z>4.5**

- **By now: > 2000 spectroscopically confirmed**

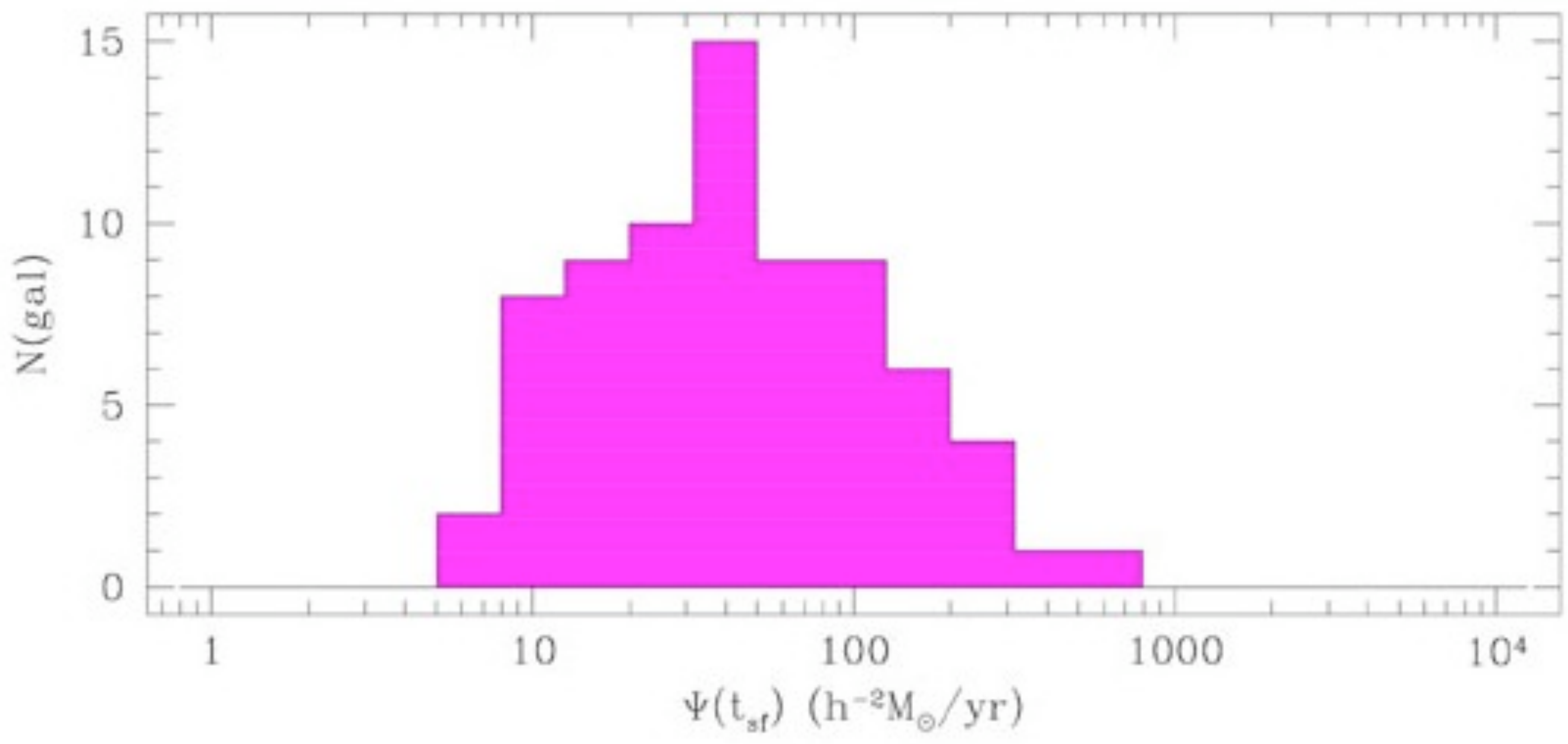
Example of recent deep searches



SUBARU Deep field

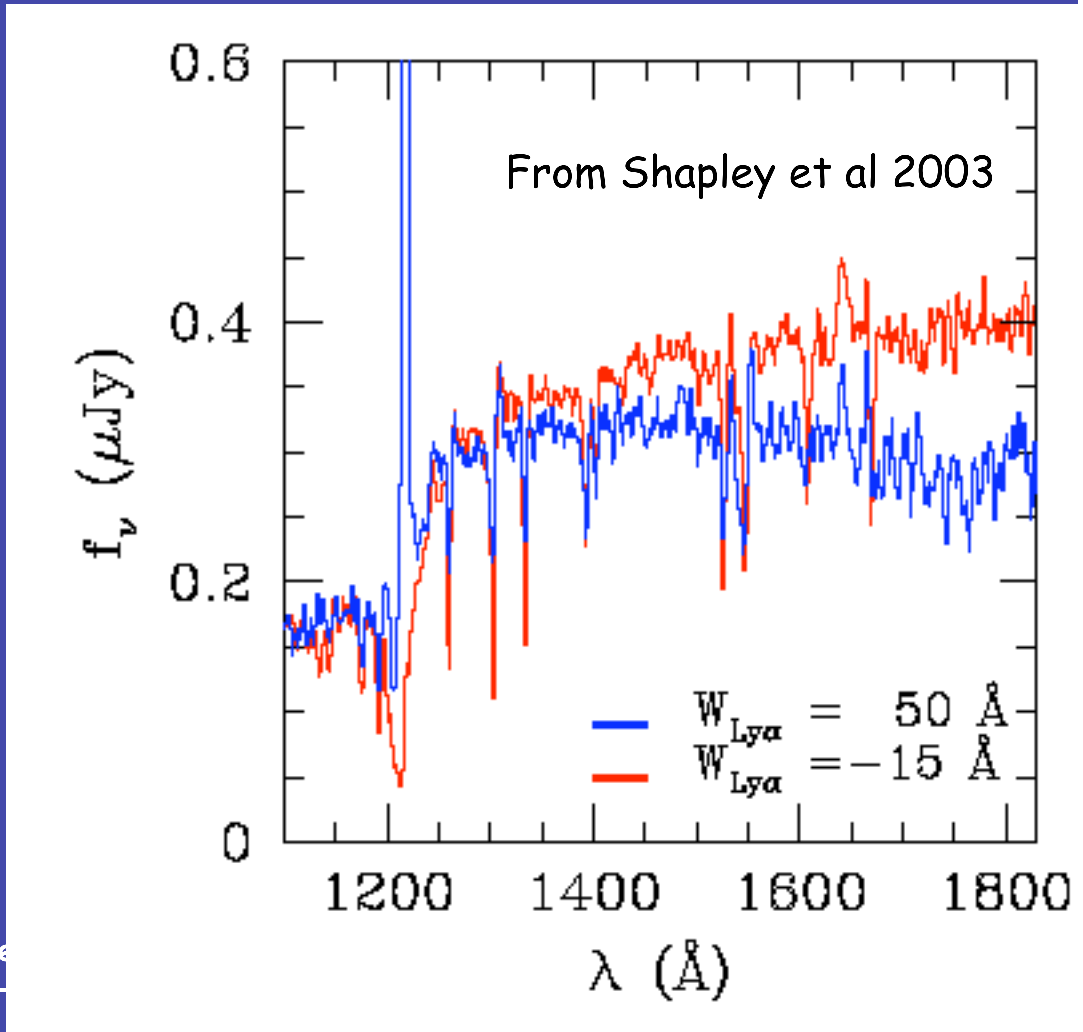
Typical SFRs in Ly-break Galaxies

(from Pettini, Shapley et al 2003)

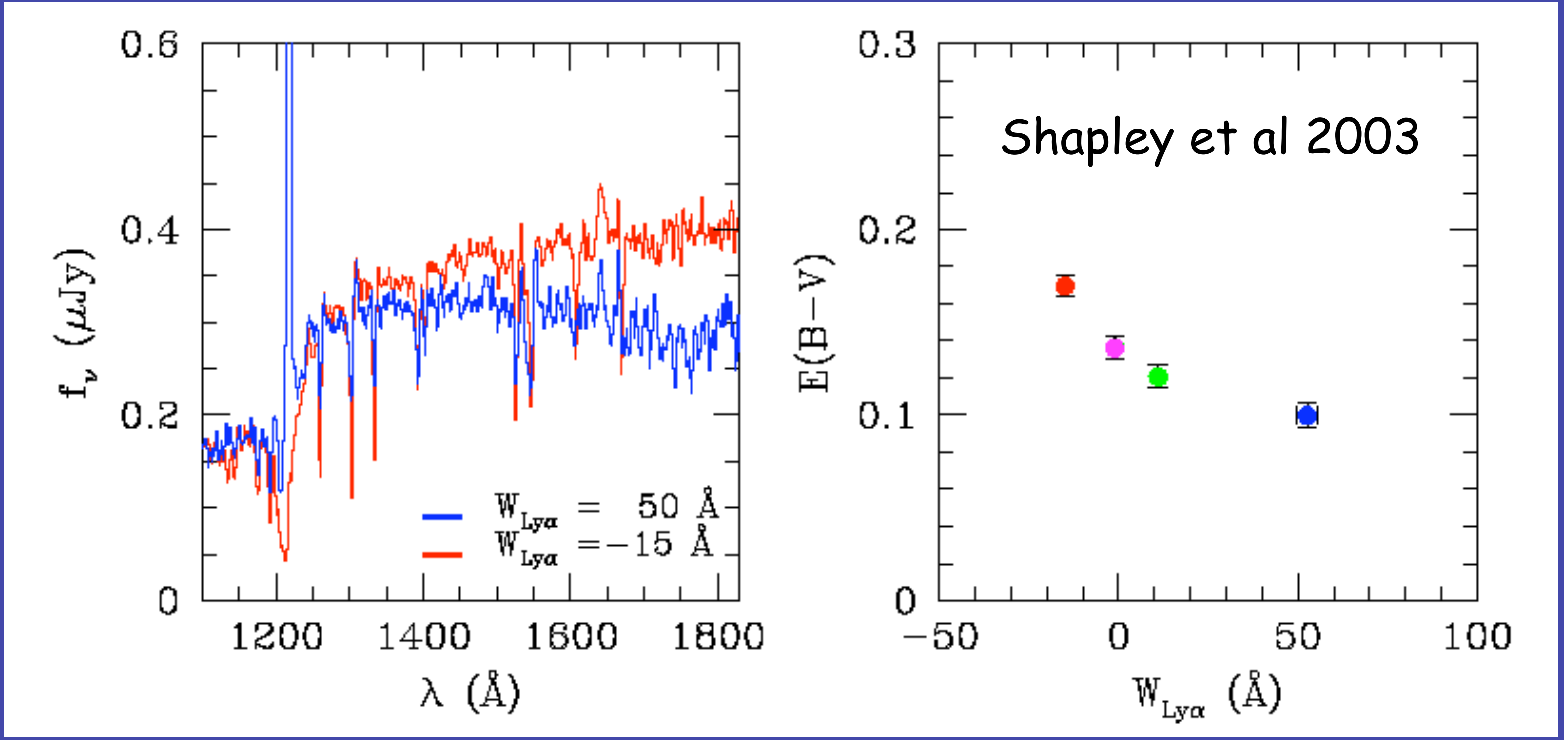


Selecting High-z Galaxies by their Emission Lines

- UV photons in star-forming galaxies will excite Ly-a line
- High contrast → easier detection?



UV Continuum vs Ly-α Line



Strongest Ly a emitters have

- Bluest (=least reddened) stellar continua
- Lowest warm-gas absorption

→ gas/dust covering fraction and outflow structure determine line to continuum ratio

Selecting Galaxies by their Rest-Frame Optical Emission

- **Selection less sensitive to high present star formation rate.**
  - Still: populations fade in the rest-frame optical *and* IR, as populations age!

- **Less sensitive to dust extinction.**

- **More differential comparison to lower-z population.**

- **Note that $\lambda_{selection}$ ~ (1+z) x 0.5μm ~ 2μm at z~3**

  → deep (near-)infrared imaging

Example: Faint Infra-Red-Extragalactic-Survey

HDF-south

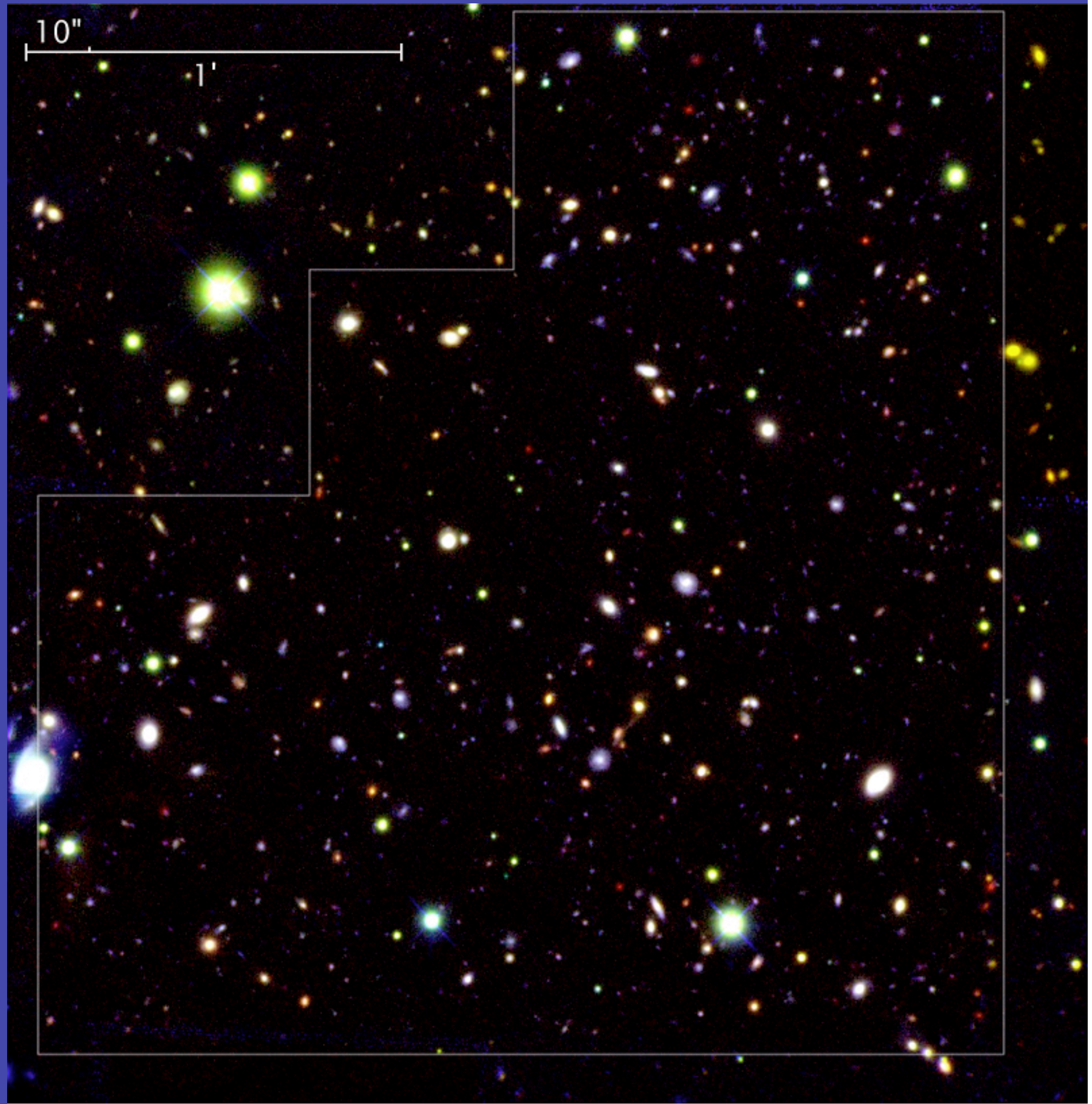
100 hours in JHK

MS1054:

6xlarger area

25 hours in JHK per pointing

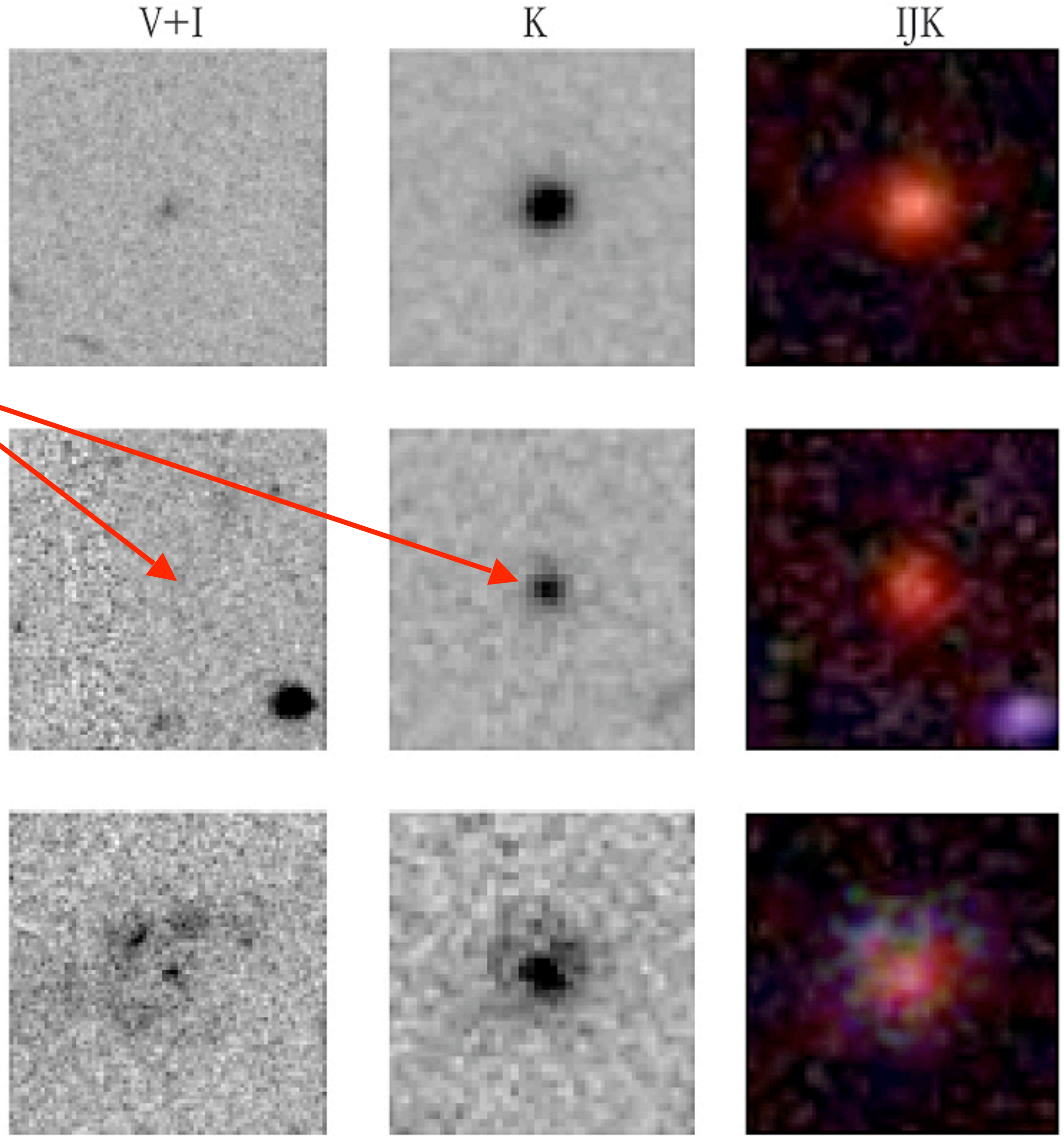
Franx, Rudnick, Labbe, Rix, Trujillo, Moorwood, et al. 2001-2004



Three-Colour Image of the Hubble Deep Field-South

Not a Ly-break!!

Just a red SED



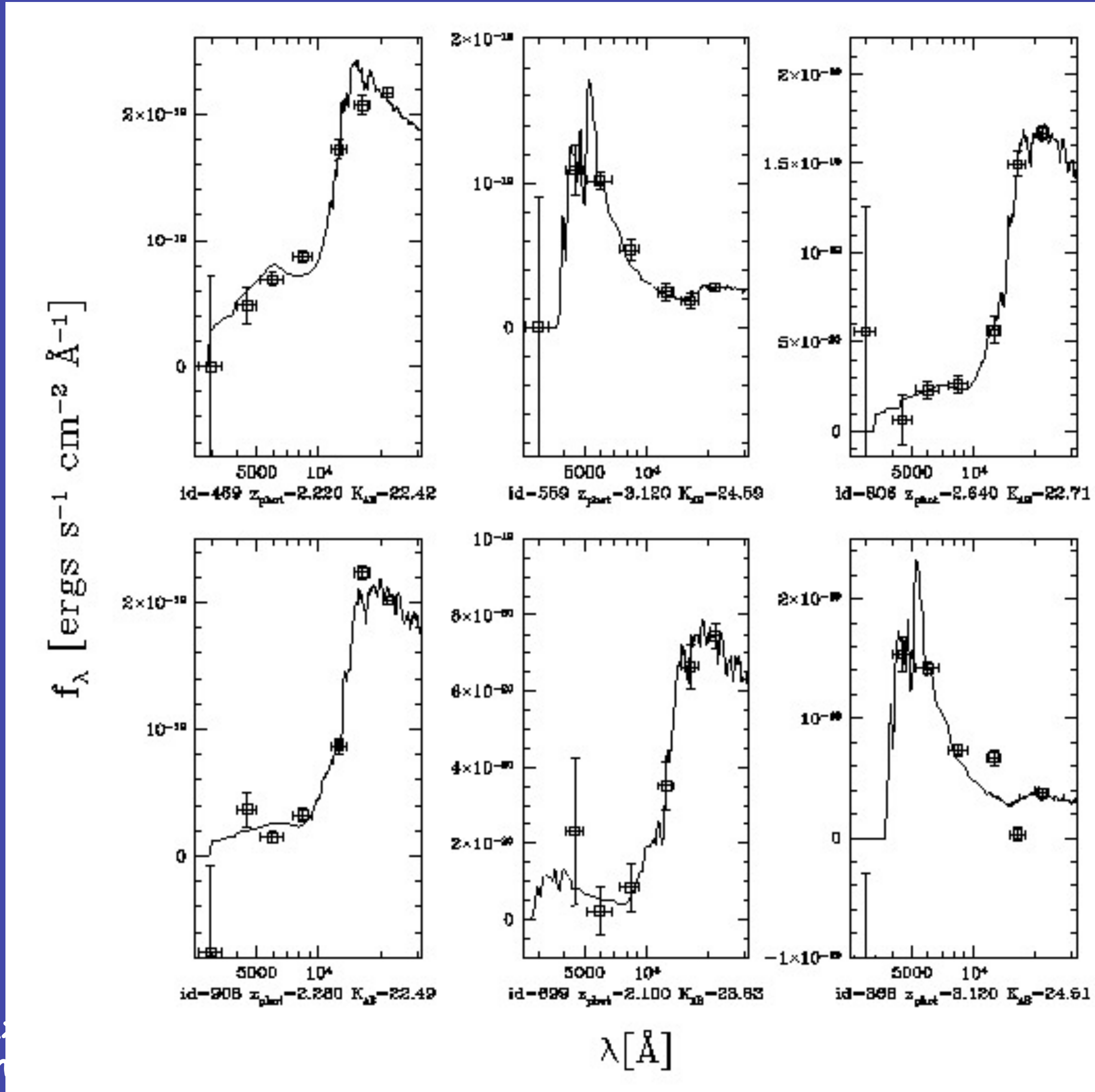
Very Red, Compact Galaxies in HDF-S
(VLT ANTU/ISAAC + HST/WFPC2)

Photometric Redshift Estimation

- Fit sequence of model population spectra to flux data points (=VERY low resolution spectrum)

- Find best combination(s!) of SED and z

- Use spectroscopic redshifts to check sub-samples



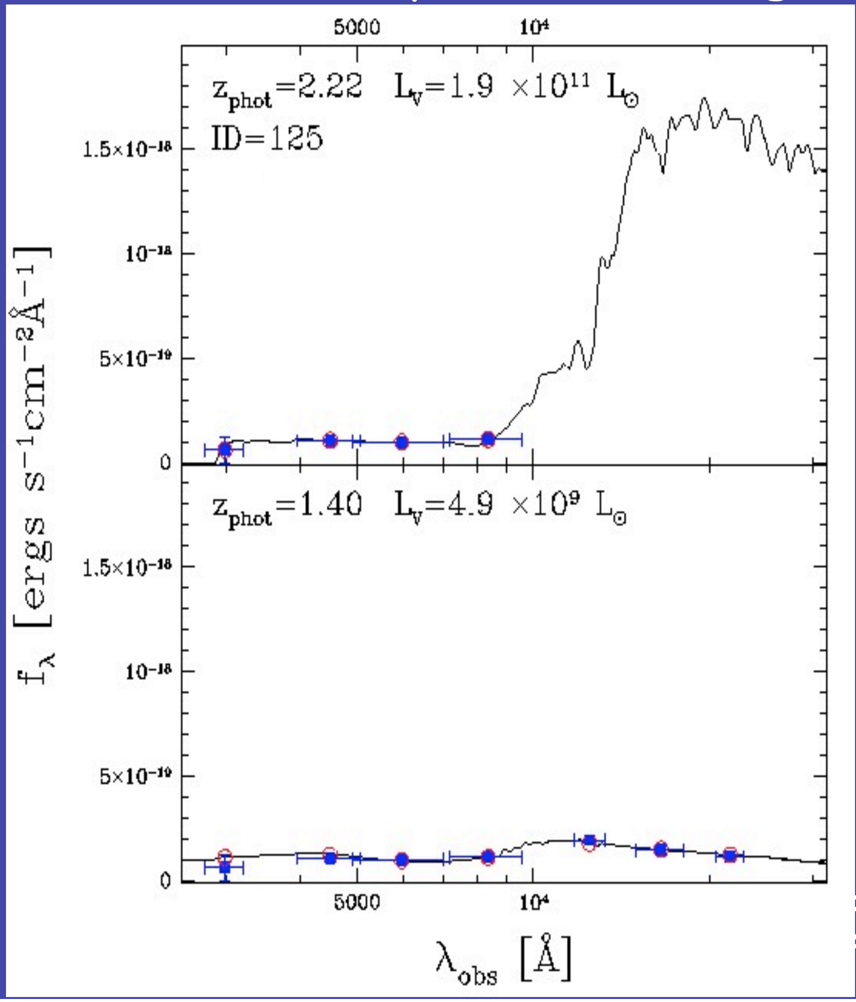
Gala
Har

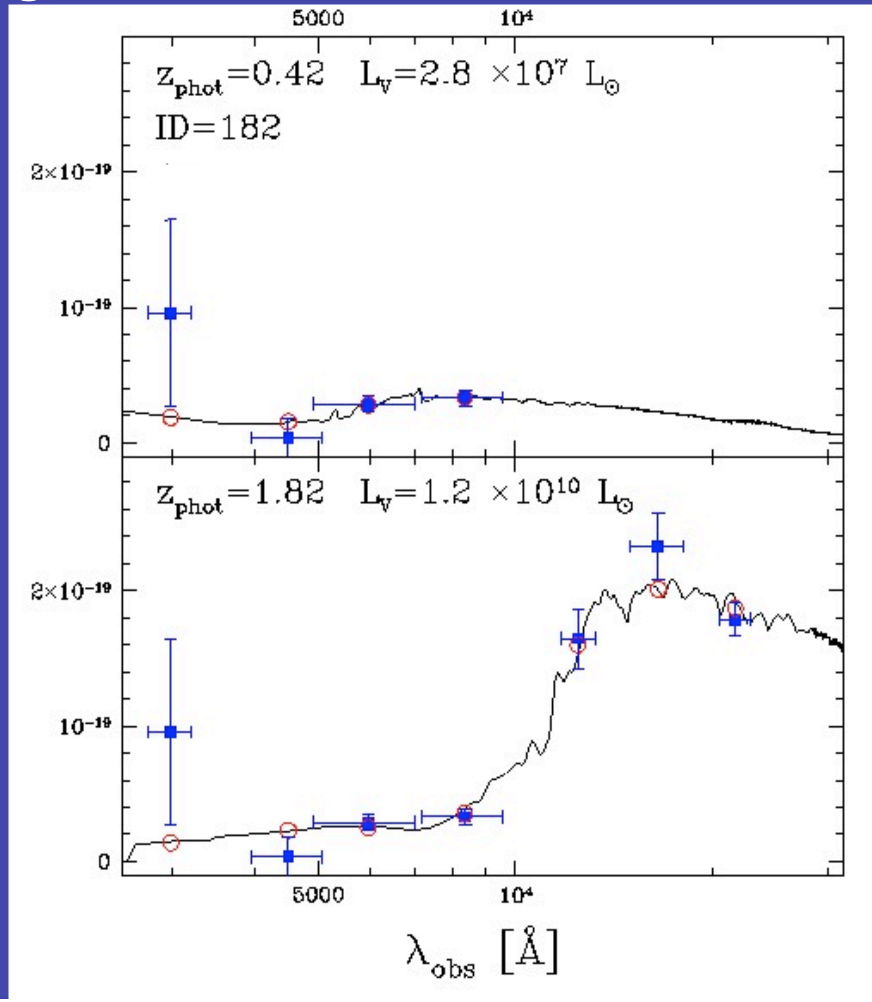
For robust photo-redshifts one needs at least one strong spectral break, either

Ly-break (912A - 1216A) or

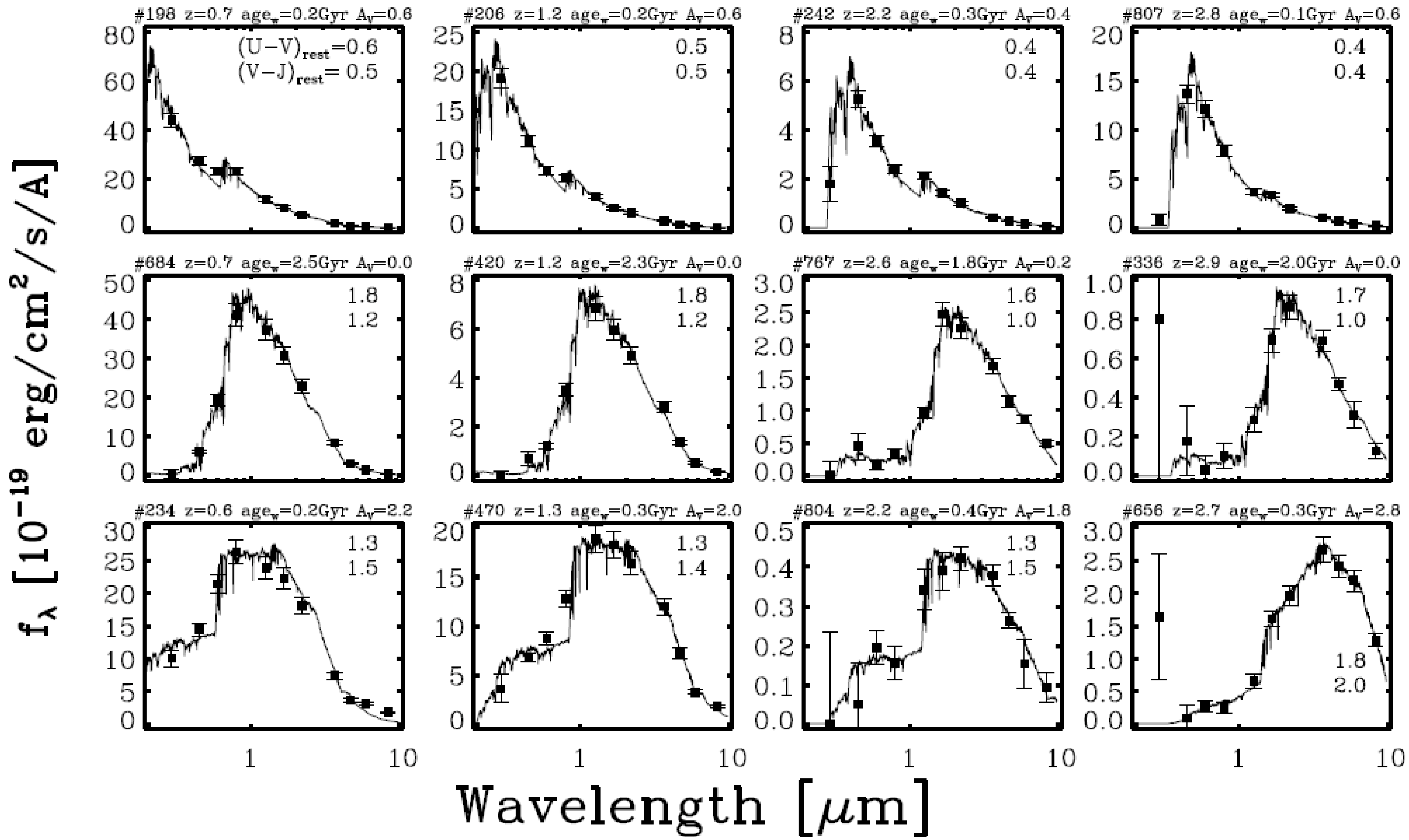
"4000A"-break (Balmer break; H&K break)

→ broad spectral coverage, e.g. 0.3μm to 2.2μm





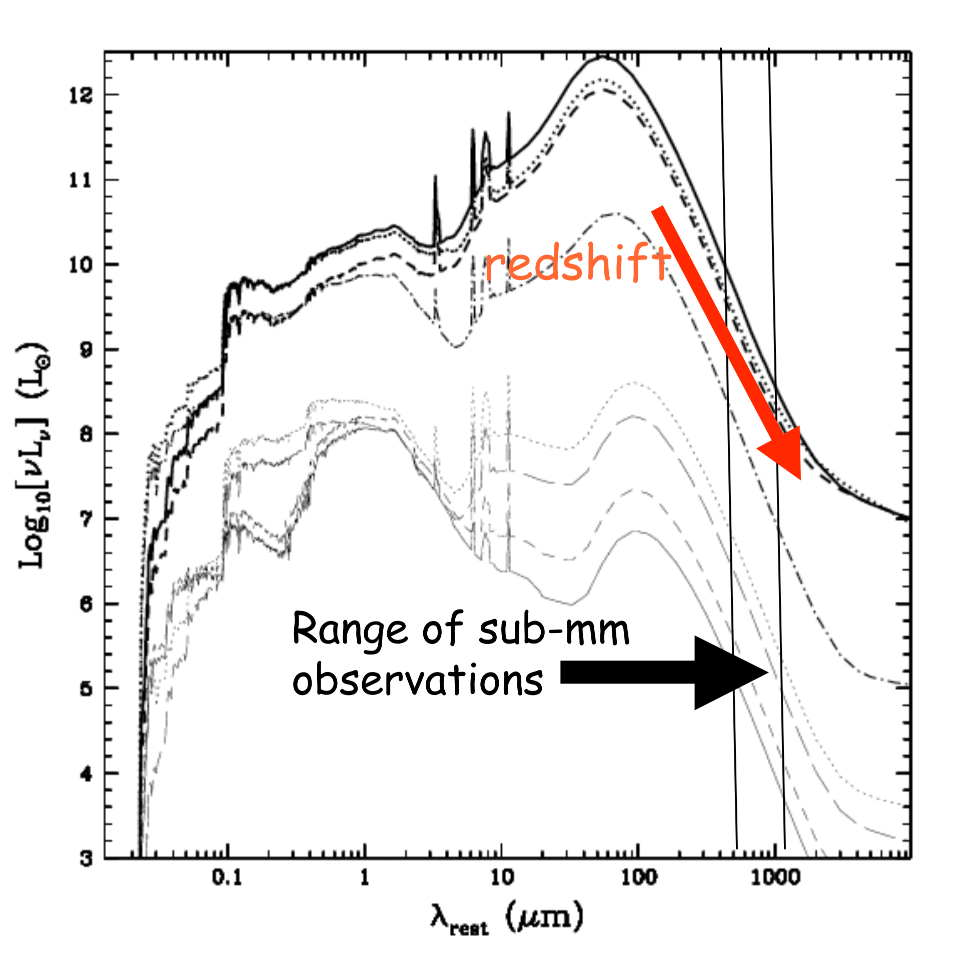
Data from the Spitzer satellite (3.5-8μm) help enormously in determining the SED of galaxies at z>2 → stellar M/L, age etc.. (Wuyts, Franx, Rix et al 07)

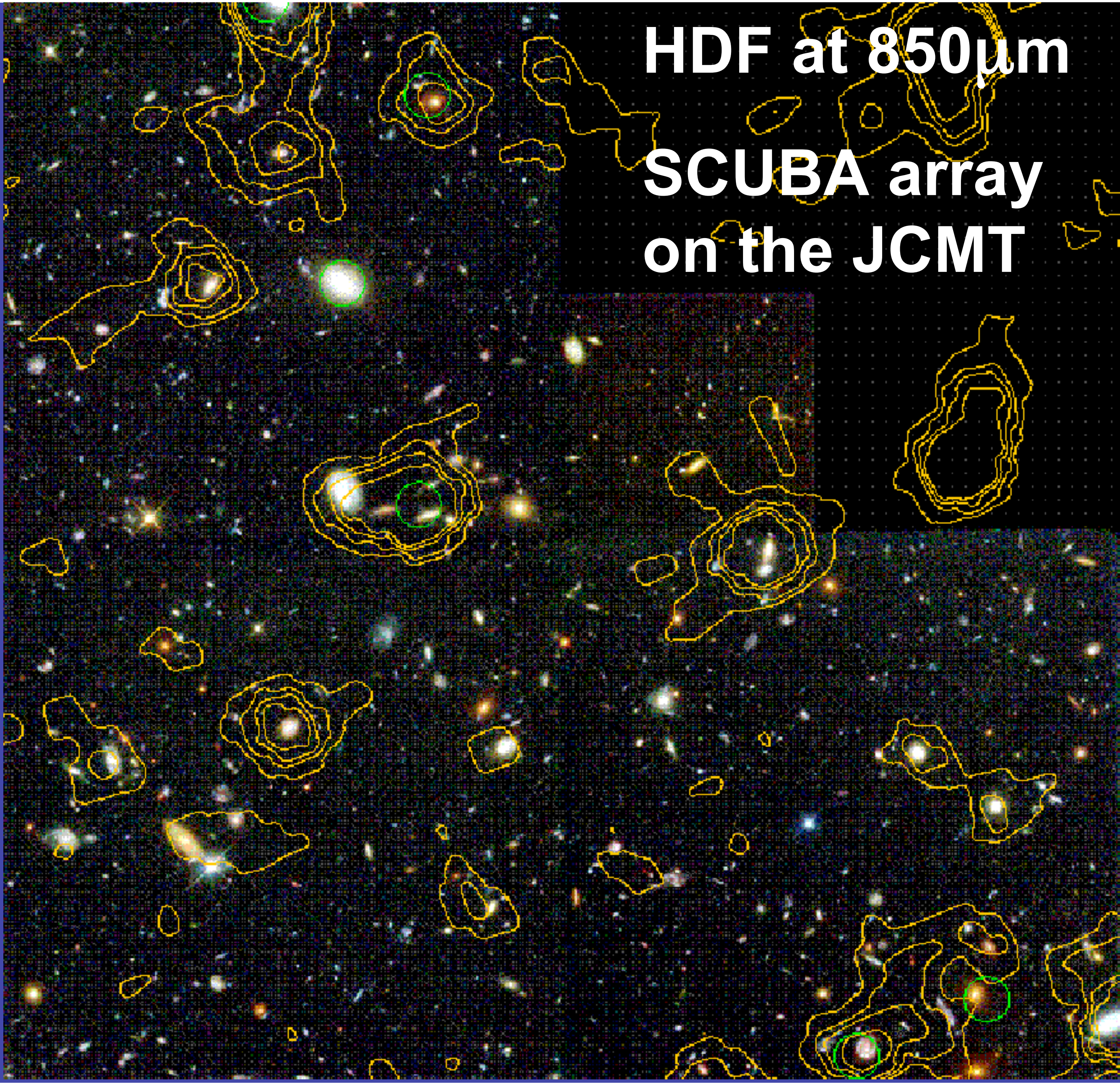


Selecting Galaxies by their Thermal IR (sub-mm) Emission (from the ground)

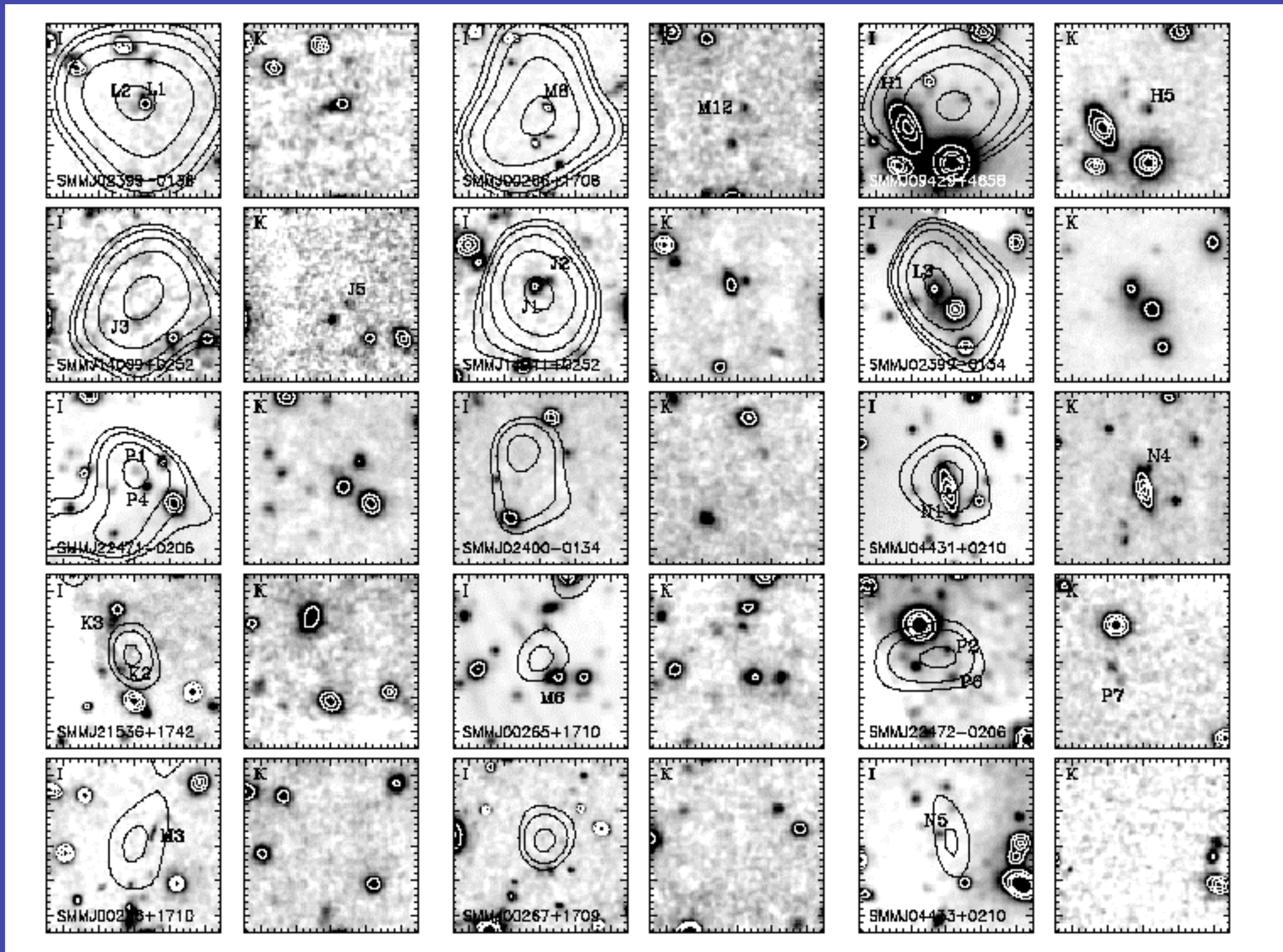
Smail et al, Ivison et al, Barger et al. 1998-2002

- Observations currently feasible only on the long-wavelength tail of the thermal dust emission
- Sub-mm K-correction very favourable!!
- Spatial resolution (single-dish) is low 5"-10"




HDF at 850μm
SCUBA array
on the JCMT

Get a flavor of how easy "optical identification" is



The current generation of ‚machines' to study high-redshift galaxies

Part II:

Studying their Physical Properties

Star Formation Rate

Mass

Gas Content

Chemical Abundances

Galaxies Block Course 2008
Hans-Walter Rix - MPIA

Estimating Star Formation Rates

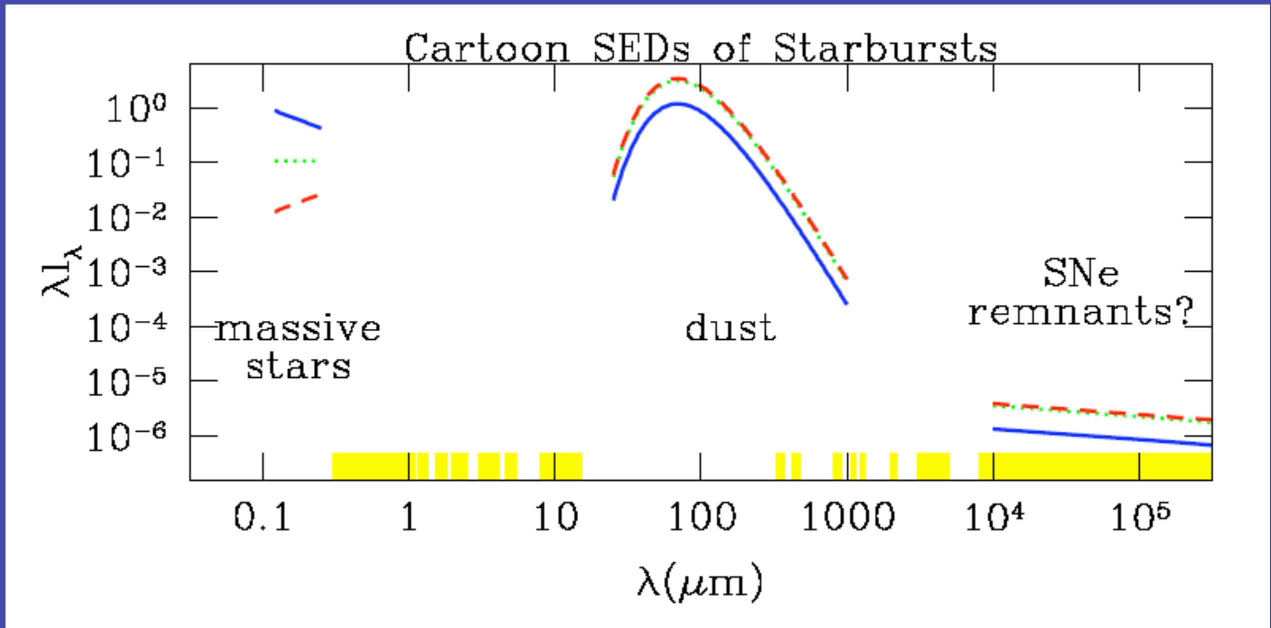
- **Step 1:** Verify that UV continuum is from stars and thermal-IR is powered by such stars (no AGN)
- **Step 2:** assume IMF + SFR → bolometric luminosity
- **Step 3:** bolometric luminosity + dust content → SED
- **Step 4:** Scale SED to observations → SFR (obs!)

Bolometric Luminosities from UV?

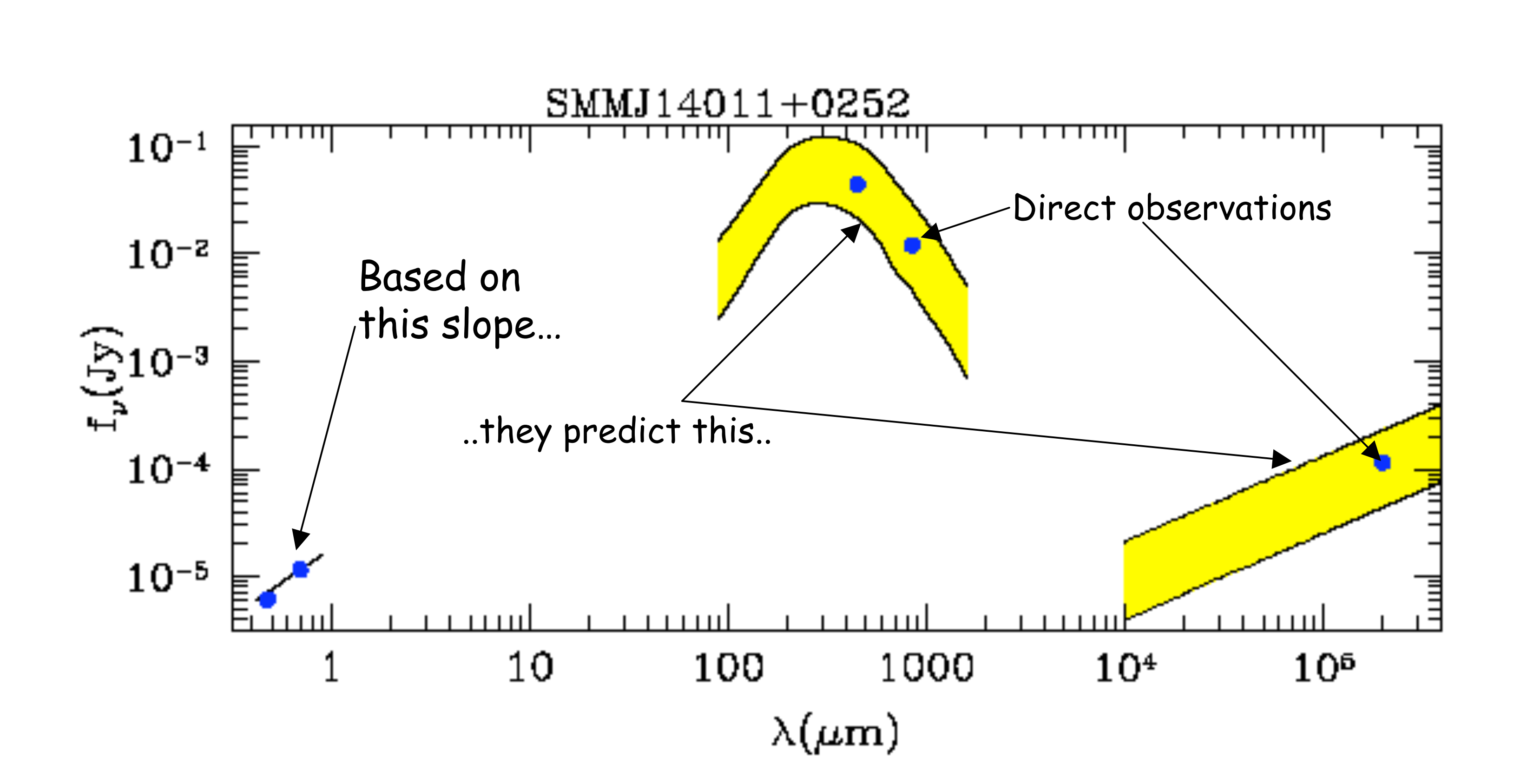
in star-forming galaxies, most UV photons are absorbed by dust
so … how do you use UV radiation to estimate the SFR?

- **Idea:** extinction (=?absorption) is reflected in the UV continuum slope
- $L_{bol,dust} = 1.66\ L_{1600A}\ (10^{0.4(4.4+2\beta)} - 1)$

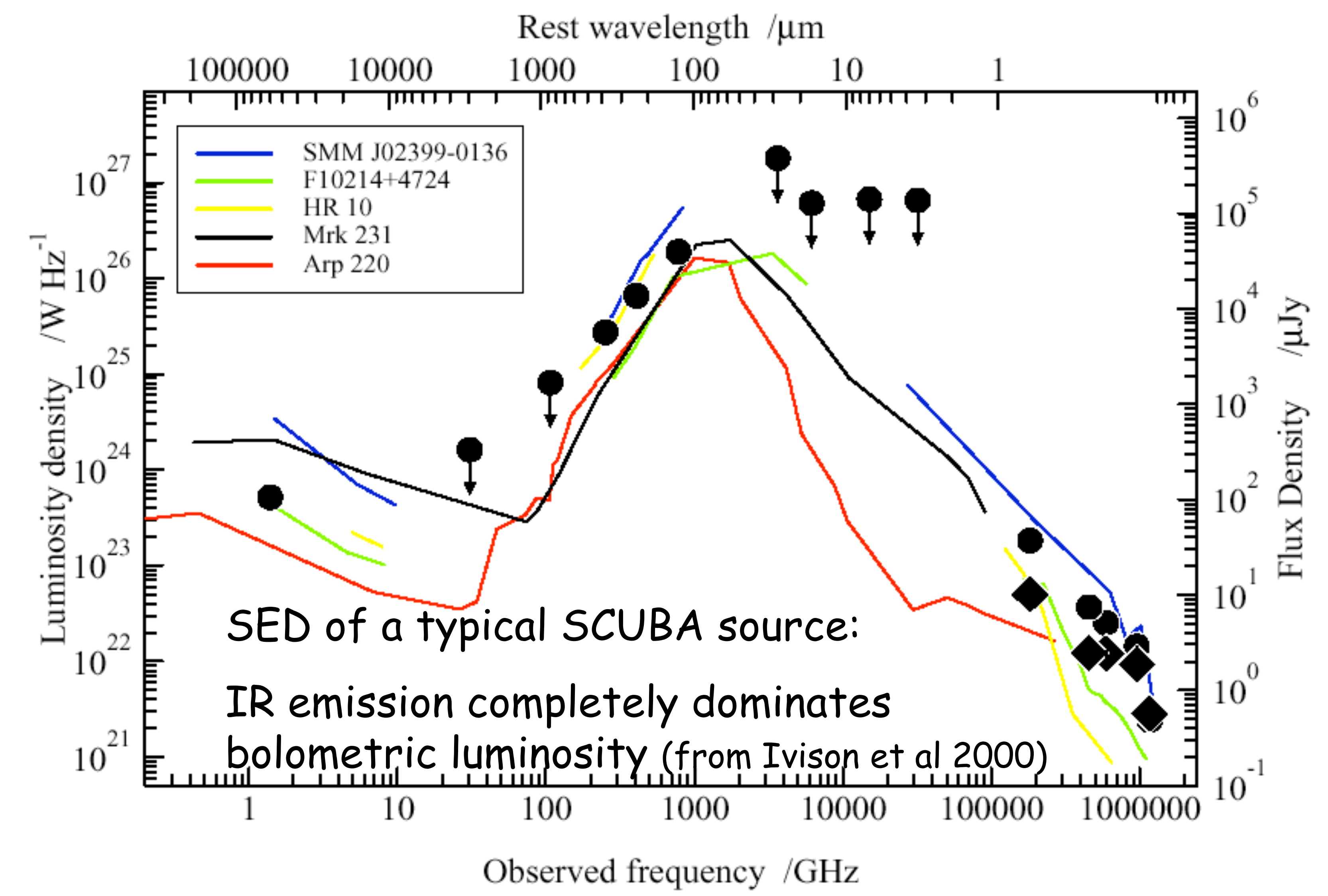
  with $I_\lambda \sim \lambda^\beta$ (Meuer, Heckman and Calzetti 1999)



How well does this work?



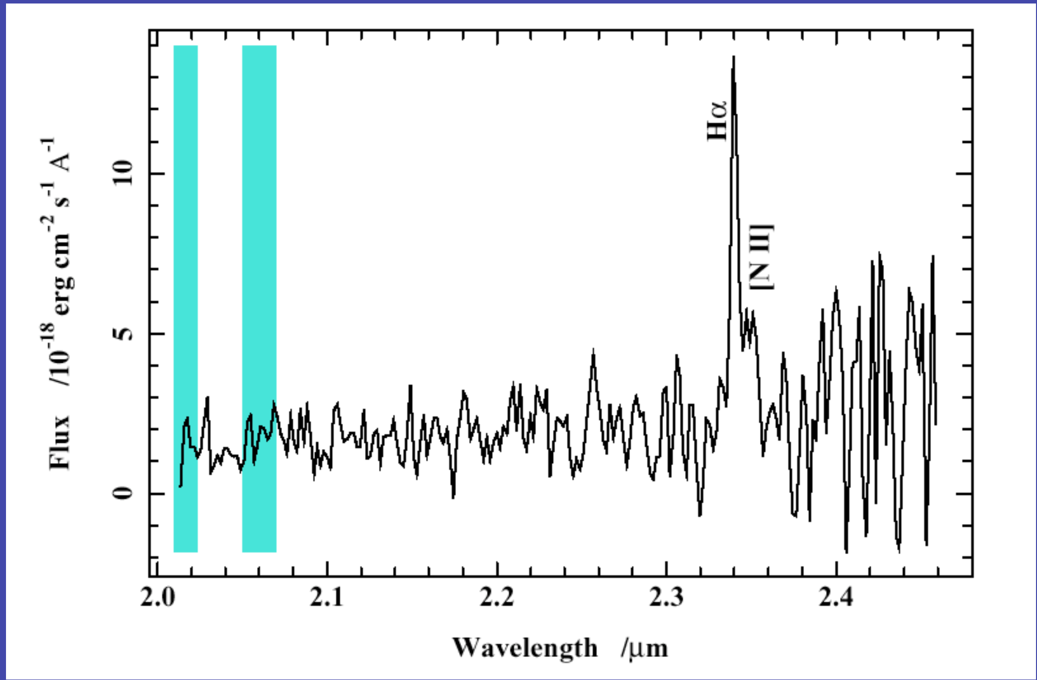
Star-Formation Rates at high-redshift from the heated-dust emission



L_{bol} up to $10^{13} L_{Sun}$ → SFRs to a few 1000 M_{Sun}/yr

Nature of SCUBA Sources: Star-burst or AGN?

- Sub-mm data only demonstrate that dust is heated with enormous power
- Check for AGN signatures:
  - Emission line diagnostics
  - X-ray emission?
- Majority of them are star-bursts

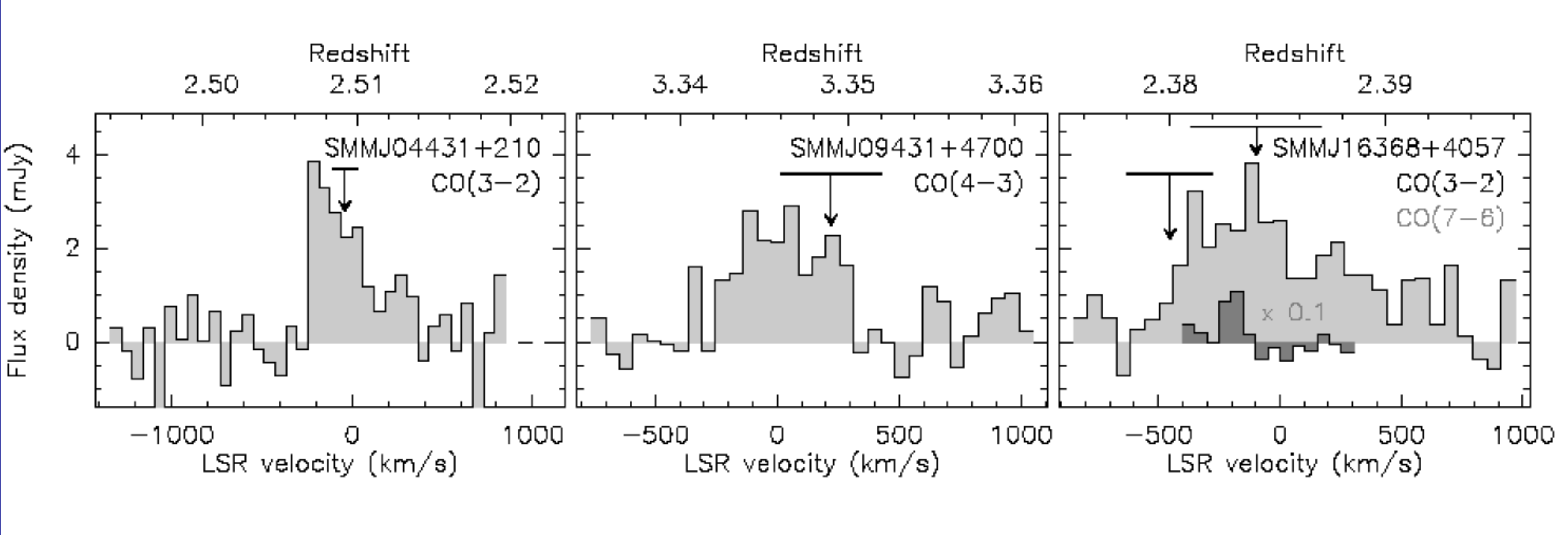


Estimating (Cold) Gas Masses

- True reservoir for star-formation
- HI and H_2 (currently) not detectable
- Thermal dust emission
  →? Dust mass
  →?? Gas Mass
- CO gas now detectable!!
  at mm wavelengths

Examples of extremely gas rich galaxies at z~2-3

Neri et al 2003 (Plateau de Bure)



$M(H2) = \alpha \times L_{CO(1-2)}$

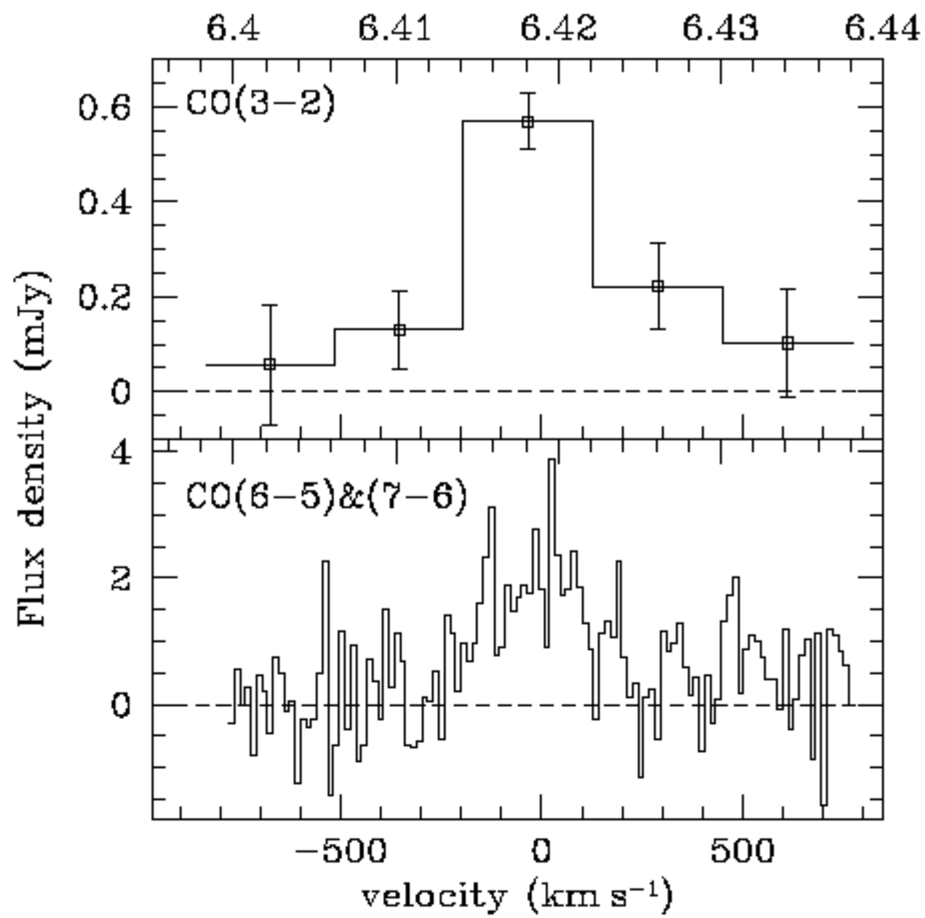
with $\alpha = 0.8 M_{Sun}$ $(K\ km/s\ pc^2)^{-1}$ for local ULIRGS

→ $M(gas) \sim 1\text{-}2 \times 10^{10}\ M_{Sun}$

Rough estimates of M_{dyn} is only twice that!!

CO Gas at z~6.42:

QSO host has vast gas reservoir



Walter et al 2002

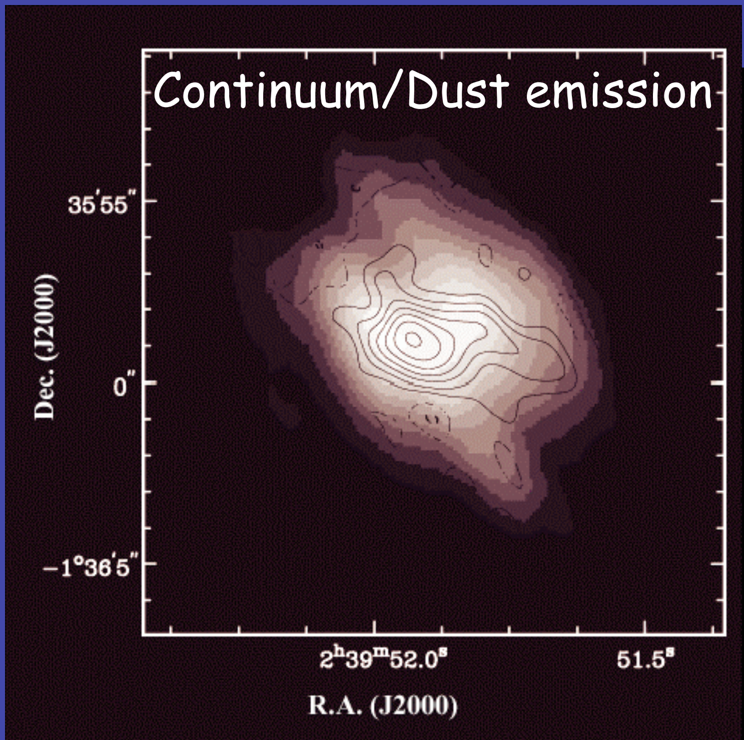
Estimating Stellar Masses

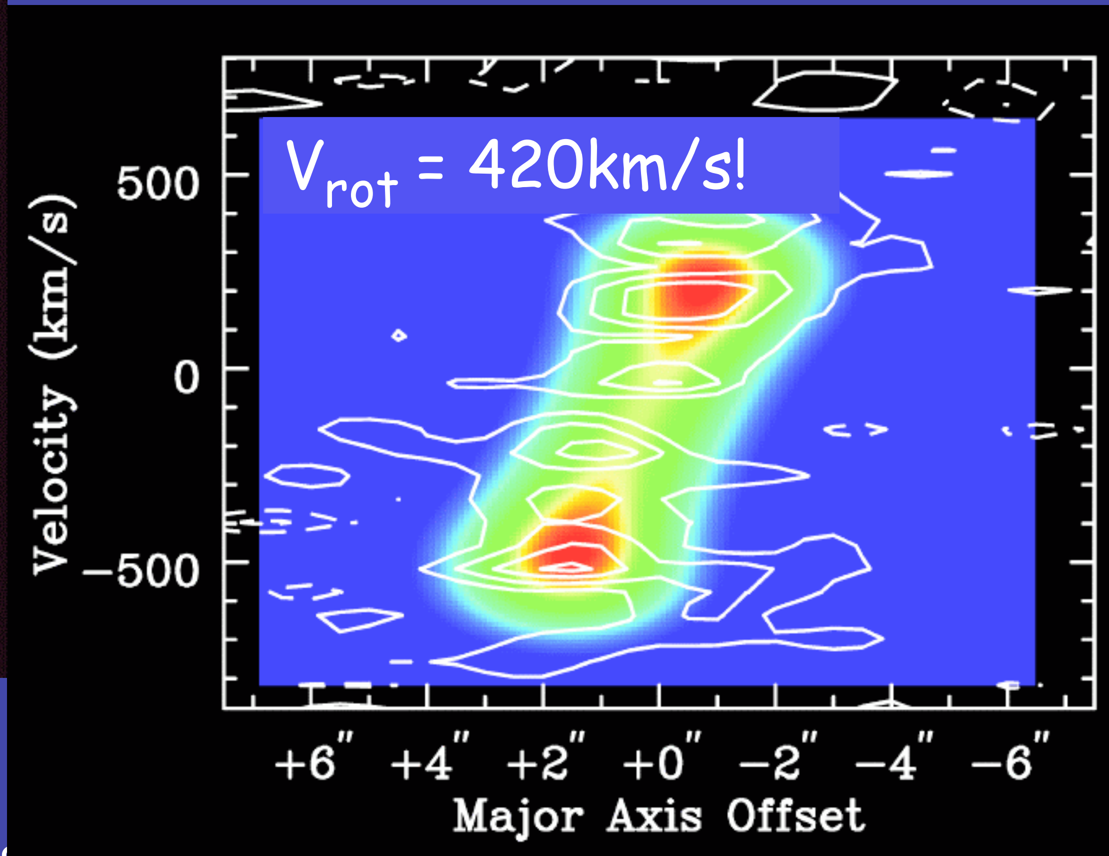
- **Kinematics/dynamics z>2 currently very hard**
  - Spatial resolution
  - Ionized gas not (only) subject to gravity
  - Molecular gas only in very gas rich/rare(?) galaxies
- **Stellar SED to estimate M/L**
  - Need (good) data beyond λ_{rest} ~ 4000
- **Clustering (of galaxies)**
  - vs clustering of halos in simulations

Dynamical Masses from CO

Case Study: SMMJ02399 (z=2.8)

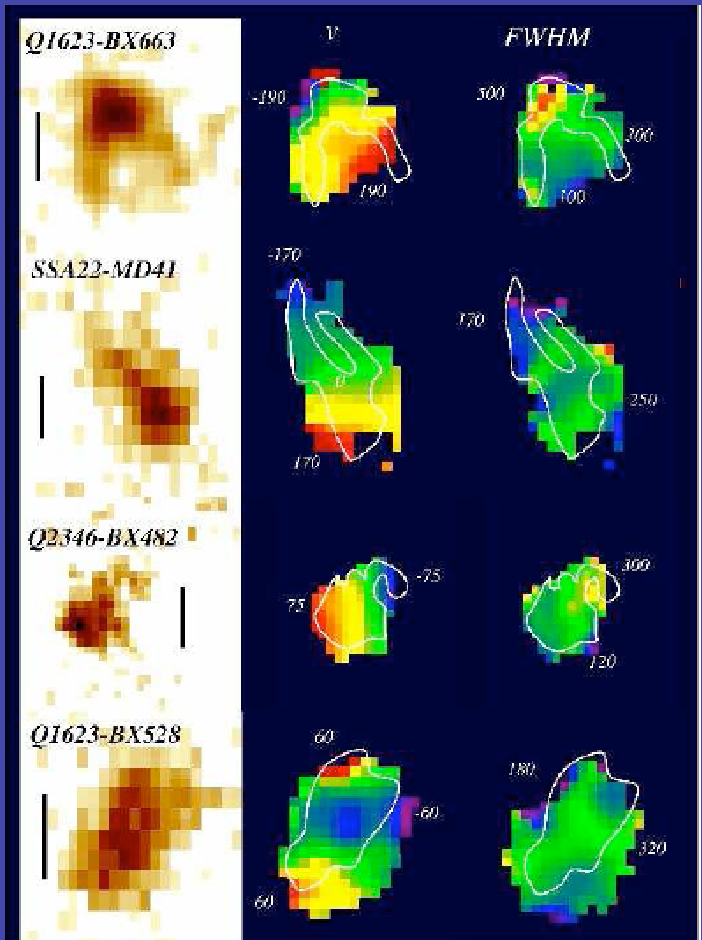
Genzel et al. 2003





$>3\times10^{11} M_{sun}$ within 6kpc

Hα Kinematics of high-redshift galaxies



Flux Velocity Dispersion

Hα at z~2

- N. Foerster Schreiber et al 2006 (SINFONI @ VLT)
- When velocity fields are regular:
  Masses within optical radius comparable to SED-based stellar masses
- Irregular velocity fields common → mergers?

Stellar Masses from SEDs

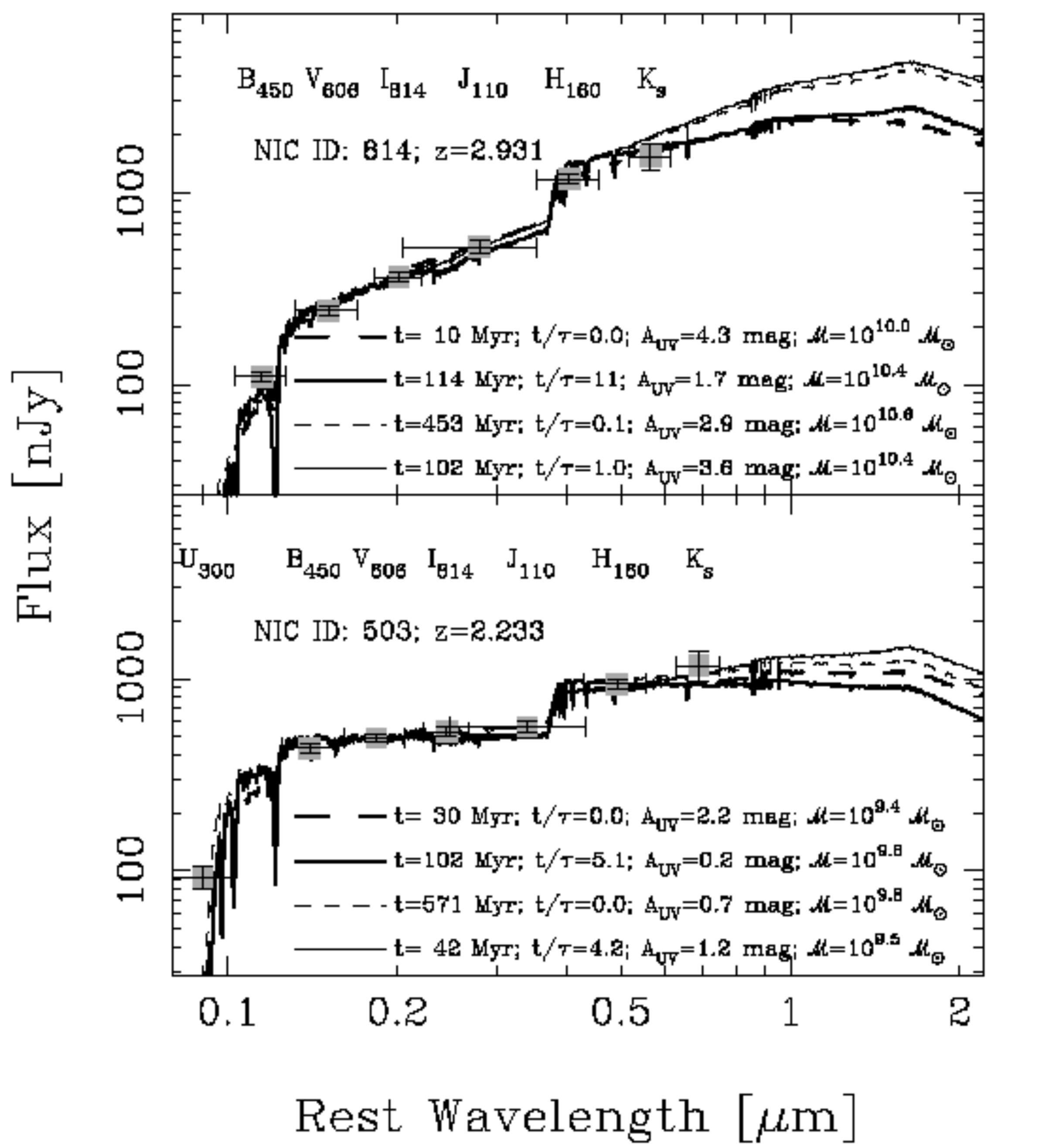
- Age makes populations redder
- Metallicity makes populations redder
- Dust makes populations redder

→ Degeneracies abound!

But: all effects that make redder also increase the M/L in a similar fashion

- → good correlation SED vs M/L !

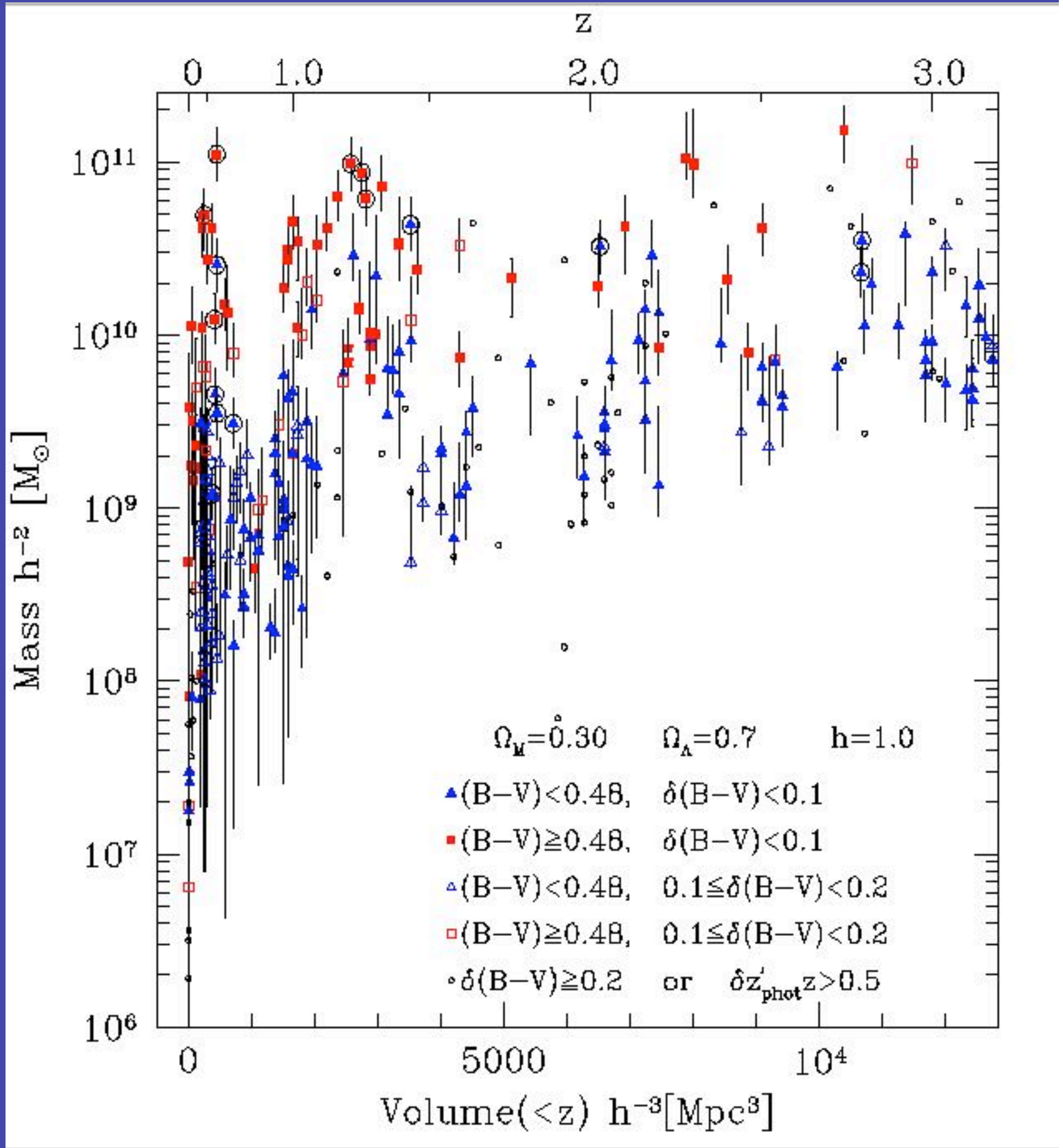
(Bell and de Jong 2001)



Papovich et al 2002

Masses of the Galaxies in the HDF South

Rudnick et al 2003

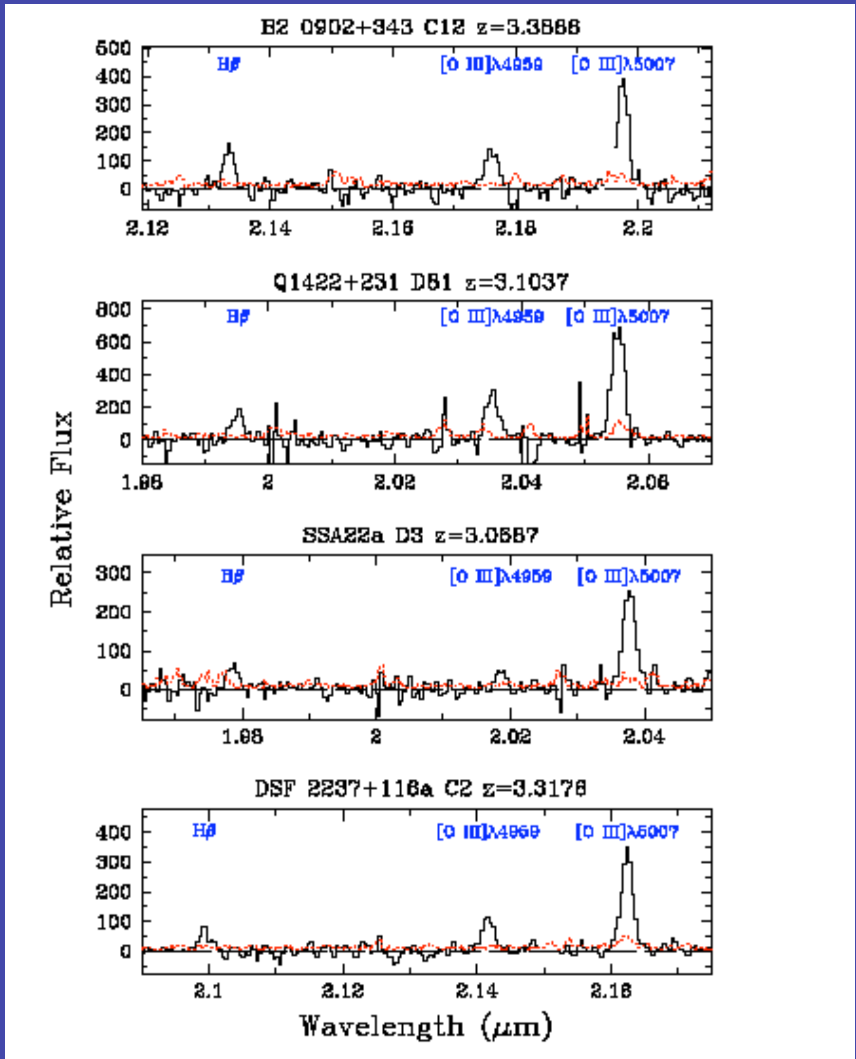


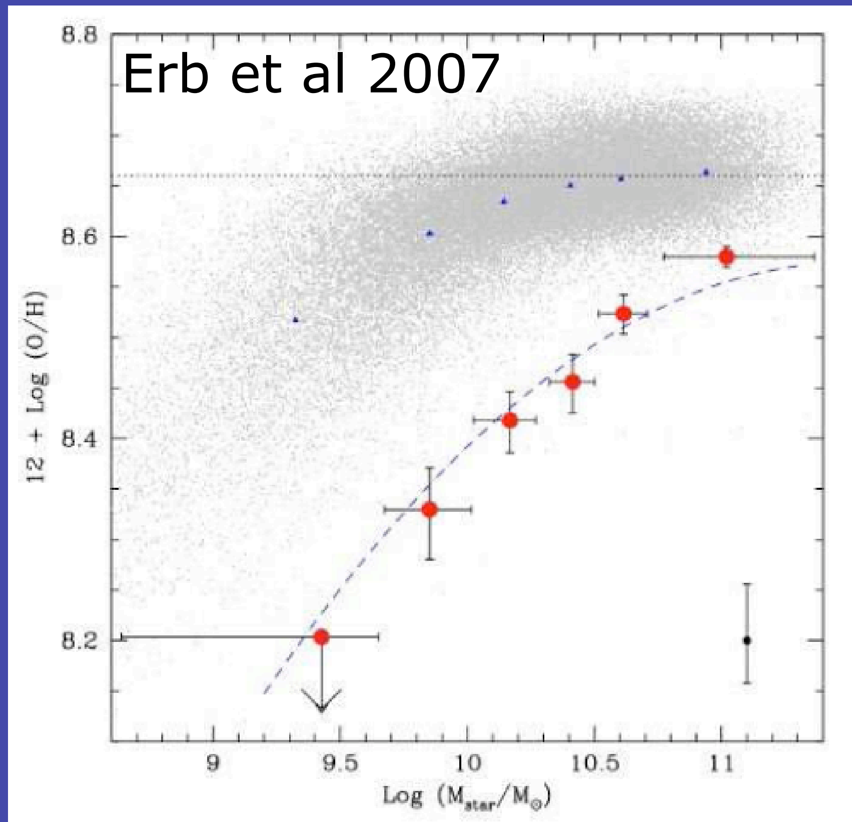
Estimating Chemical Abundances

- Cosmic star-formation history implies progressive enrichment of
  - ISM
  - Stars that form from it

- 'Metals' (=stellar nucleosynthesis products) are the 'garbage' of successive stellar population

Estimating ISM Abundances in Galaxies at z>2



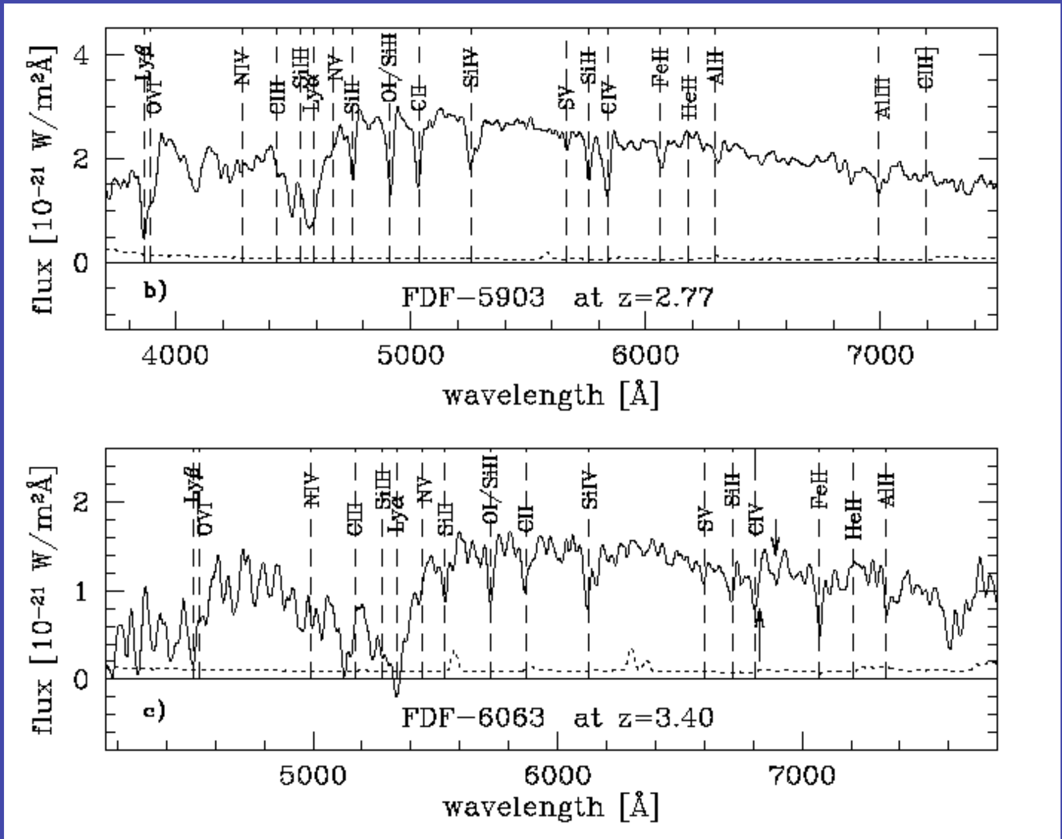


@given M*, Fe/H used to be (at z=2) 2-3x lower

Estimating Stellar Metalicities

(from the photospheres of stars)

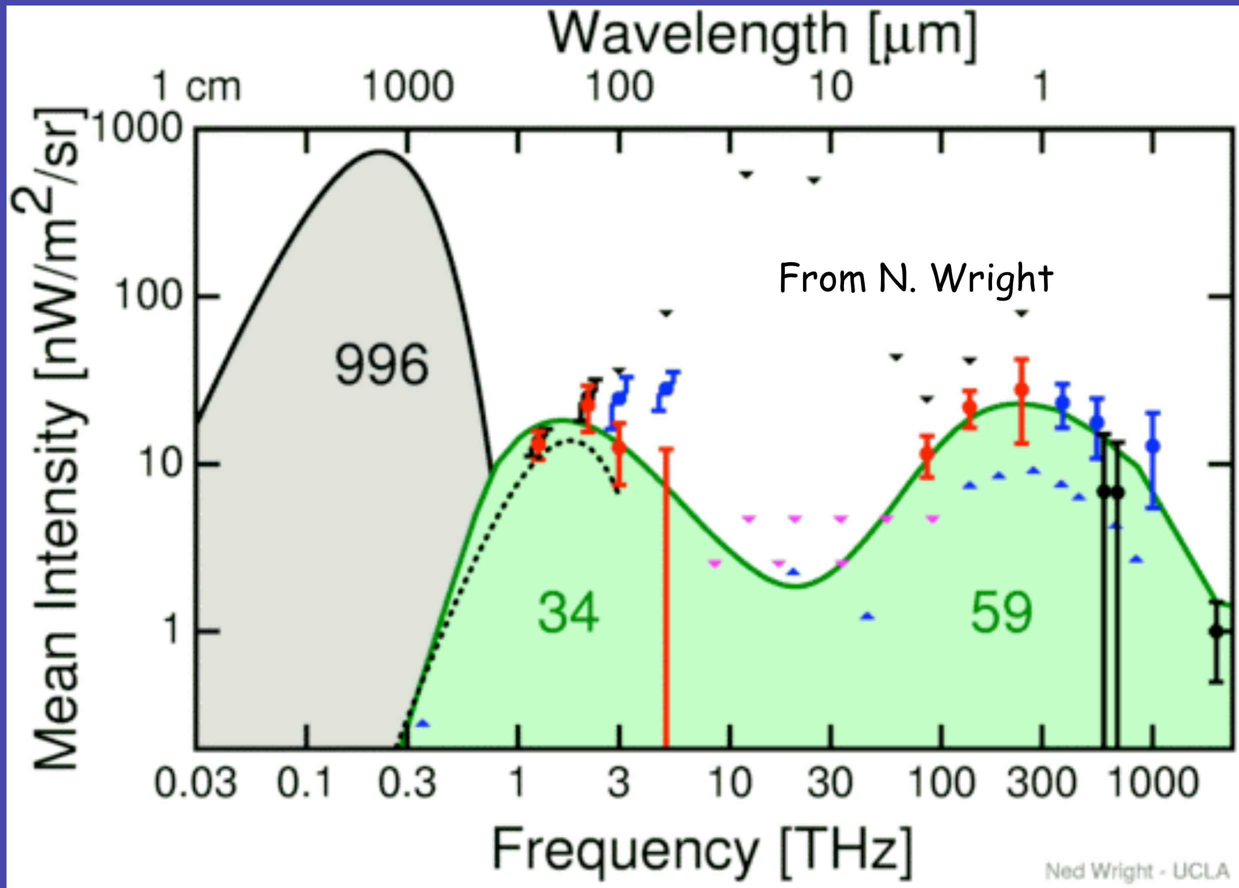
Mehlert et al 2002 FORS Deep Field



- **Typical stellar metallicities at z~2 are 1/3 as high as at z~0**

"Cosmological Backgrounds"

- **Powerful constraint on the epoch-integrated, distance-weighted spectrum emitted by all sources**



Summary

- **Z>2 Galaxies are being sampled by**
  - UV continuum (many 1000)
  - Optical continuum (~1000)
  - Thermal-IR continuum (~100) ← "beasts" only
  - Ly-a emission (~100) →

  strong bias in most techniques towards finding them during high star-formation phases z~6.5 current practical limit for samples
- **SFR estimates**
  - from thermal-IR: robust, but tedious? (Spitzer+Herschel,ALMA)
  - Practical from the UV, but UV is usually strongly extincted!!
- **Mass estimates**
  - CO dynamics: good, but large samples not yet feasible
  - From stellar SEDs: need very good IR data (λ_{rest}>4000A)

Part III:
The Intergalactic Medium
or: Where Galaxies get their fuel

1) Baryon Census: We know from WMAP (and others): Ω_b =

Of those baryons at z ≈ 0 we have identified:

~ 10% in stars in galaxies (Bell 03)

~ 1% in cold HI or CO gas

~ 10% in the hot X-ray emitting gas in galaxy clusters

Where is the rest of the baryons?

-(still) in the intergalactic medium (IGM)

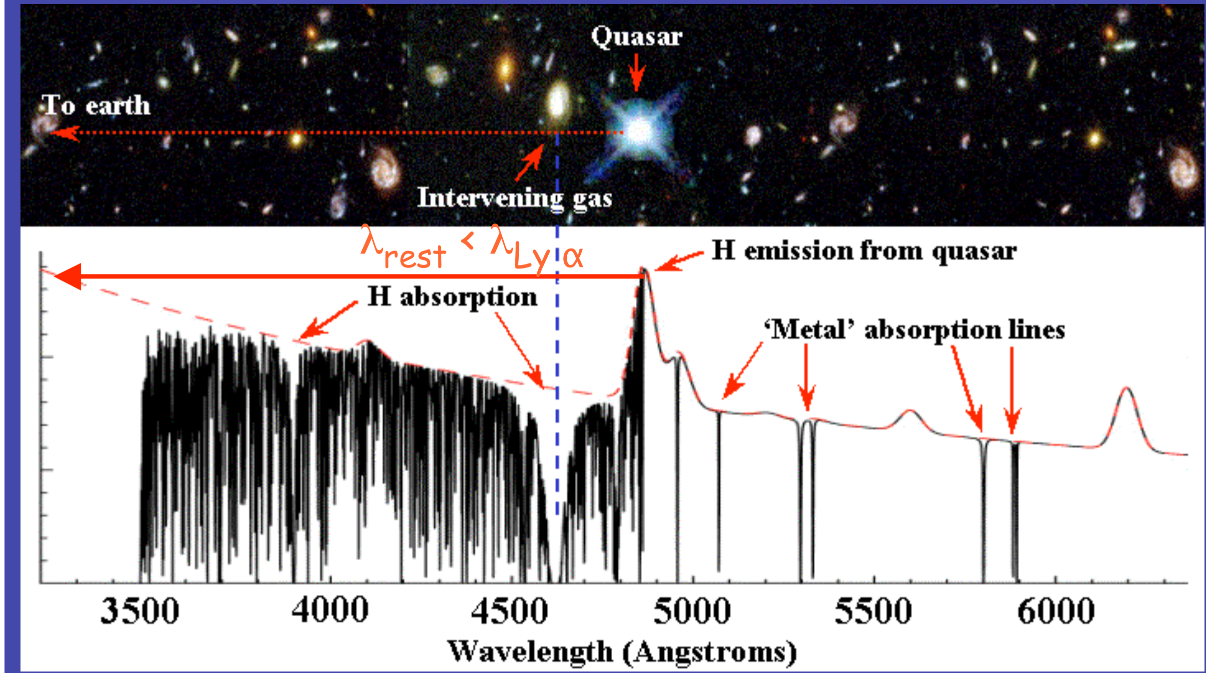
-Presumably in two main phases

a) cool, photo-ionized gas @ T ~ 10^4 K

small neutral fraction visible in absorption

b) warm-hot medium, gas-shocked to $10^{4.5-6}$ K

2) Basic IGM diagnostic (to date): Ly α absorption



- first detected 1960's M. Schmidt
- 1965:

1) Gunn-Peterson: Why is any flux $\lambda_{rest} < \lambda_{Ly\,\alpha}$ transmitted? -> mostly ionized

2) Bahcall and Salpeter "forest" of lines is all Ly α along the line of sight

The "Gunn-Peterson" trough:

$\tau_{Ly\alpha} = 5\times 10^4 \, [(1+Z)/7]^{3/2} \; n_{HI}/n_H$ → if any flux is seen: $n_{HI} \ll n_H$

But even @ Z=6 a neutral fraction of $10^{-3.5}$ would make a spectrum opaque

=> „re-ionization" of the IGM must have occurred

Energy and Ionization Balance of the IGM

Number of ionizations = number of recombinations

$$\int_{\nu_{\rm ion}}^{\infty} \sigma_{\rm bf}(\nu)\frac{F_\nu}{h\nu} n(X^r)\,{\rm d}\nu = \alpha(T) n_{\rm e} n(X^{r+1})$$

Note: where X^r = HI and H^{r+1}= H+ (HII) and we have $n_e \cdot n_{HI} \approx n_H^2$

$\alpha_{H+} = 5\times 10^{-13}\, T_4^{-0.7} / (1+T_6^{0.7})\ \mathrm{cm^3/s}$

At $z \approx 9$: $n_H \sim 10^{-4}$ -> $t_{recomb} \approx 0.5$ Gyrs ~ t_{Hubble}

=> need ongoing photo-ionization

What sets gas temperature (no shocks)?

balance of adiabatic cooling and photo-ionization heating

3) Modelling the IGM

a) *old picture:* discrete neutral 'clouds' (1 cloud/line)

Minimal linewidths observed (thermal) -> 20.000k

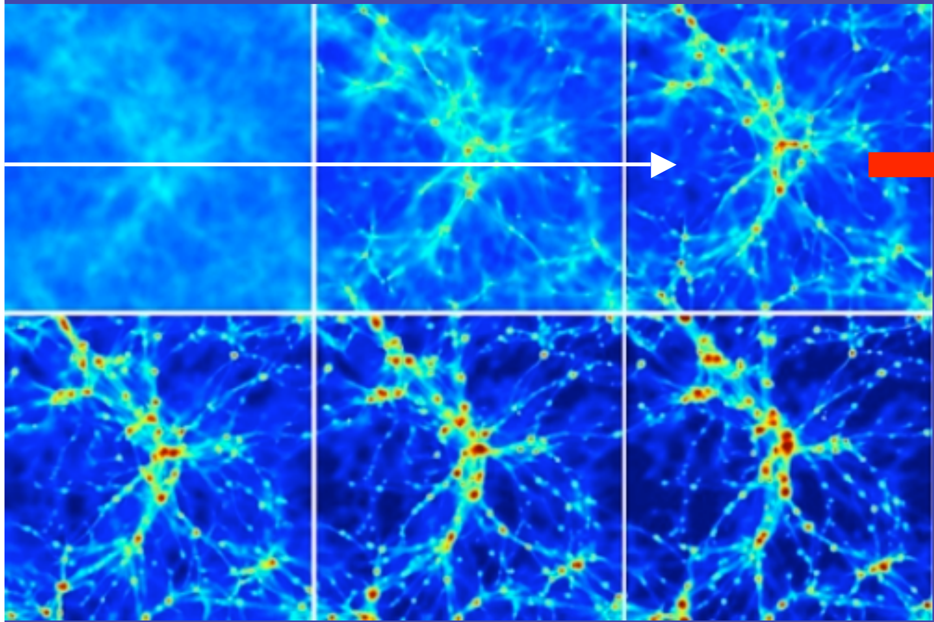
$N_{HI} > 10^{17} cm^{-2}$ **Lyman limit system**

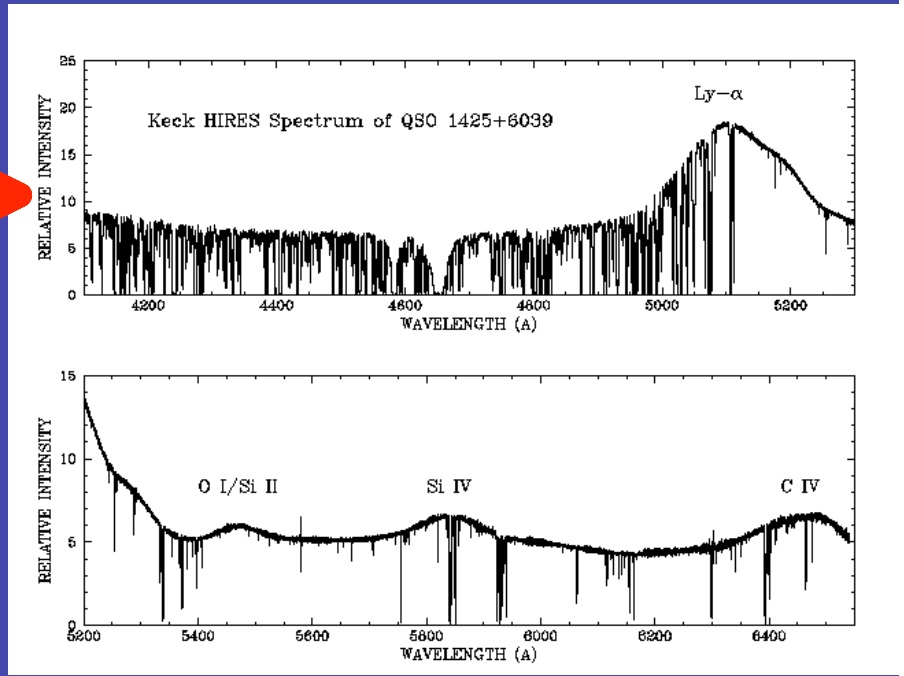
$N_{HI} > 2 \times 10^{20}\ cm^{-2}$ **damped Ly α systems**

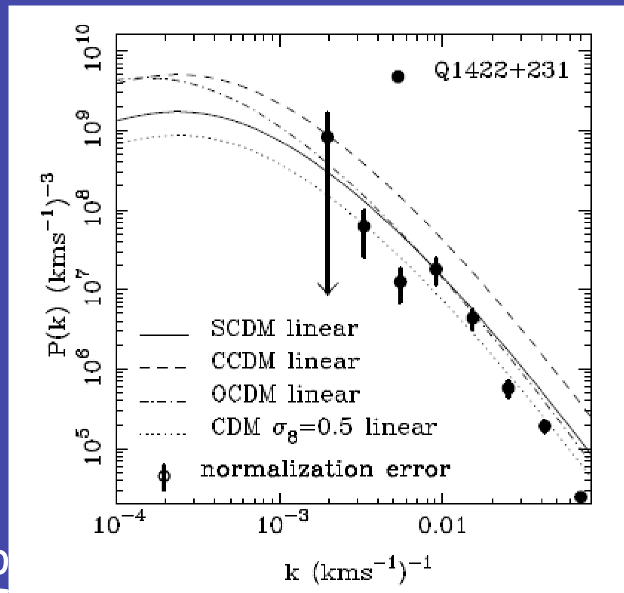
b) *'recent picture* (1990's): Cen, Ostriker, Weinberg, Katz, Hernquist

The dark matter large-scale structure is traced by diffuse (photo-ionized) gas:

fluctuating density, (convergent) streaming motions and the n_H^2-dependence of recombination lead to strongly-fluctuating neutral column density as a function of velocity







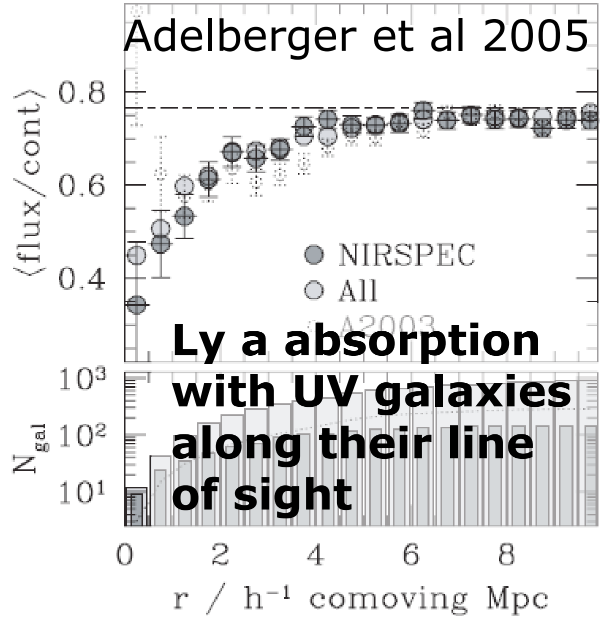
One can define the abs*ortivity correlation* function and compare between data and models

→powerful diagnostic tool

(e.g. Croft et al 2001)

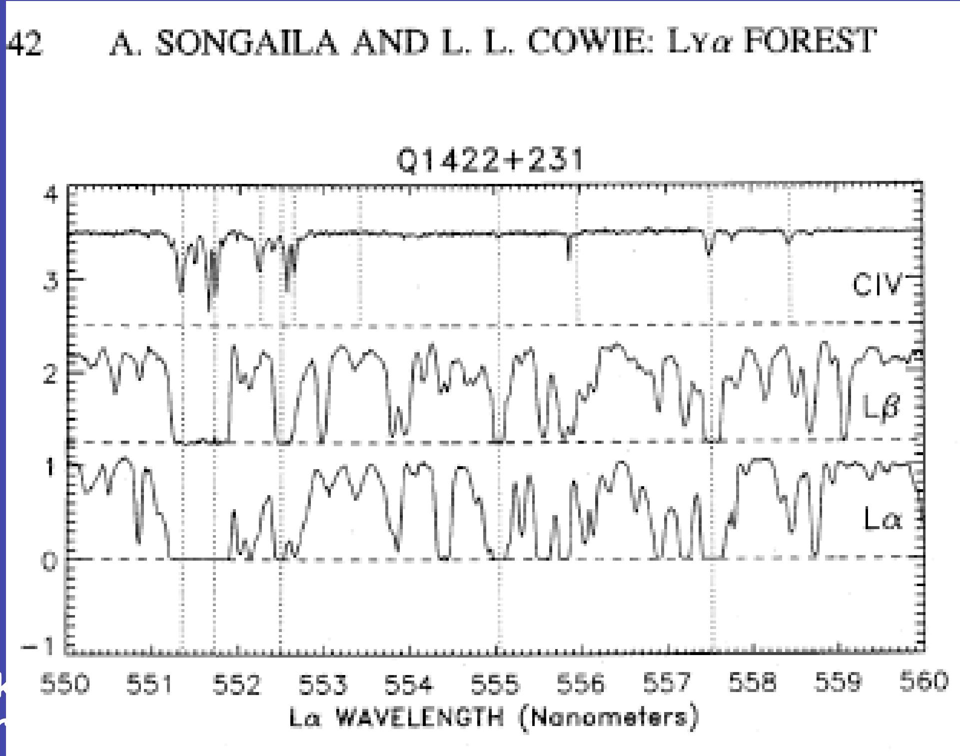
The impact of galaxies on the IGM

- **Star-forming galaxies 'over-ionize' an IGM around them**
  - 'proximity effect'
  - → less Ly a absorption



- **The IGM has some metals in them, even**
  - At high redshift
  - Far away from recognizeable galaxies

→ **Metals produced in galaxies must be 'blown out'**



In this picture the Ly α can be used to

a) Determine the matter power spectrum on small scales

b) Determine the baryon density and/or the photo-ionization rate

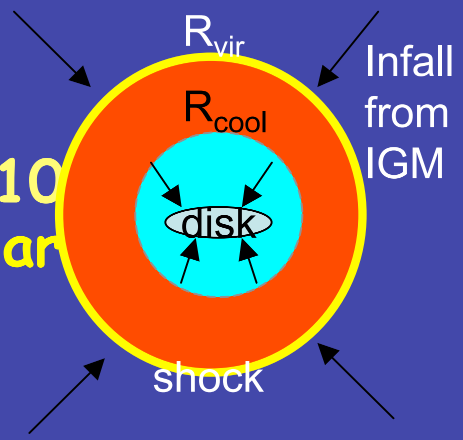
Rauch (1997) $Z \geq 2$ Ω_b (IGM) ≥ 0.02
(at least 50% of the baryons)

Given that we know Ω_b from WMAP, this can constrain the photo-ionization rate (from all galaxies and QSOs)

How Gas Gets Into Galaxies

- **Modes of Gas Accretion (Keres et al 05):**
  - Hot Mode: (White&Rees 78) Gas shock heats at halo's virial radius up to T_{vir}, cools slowly onto disk. Limited by t_{cool}.
  - Cold Mode: (Binney 77) Gas radiates its potential energy away in line emission at $T << T_{vir}$, and never approaches virial temperature. Limited by t_{dyn}.

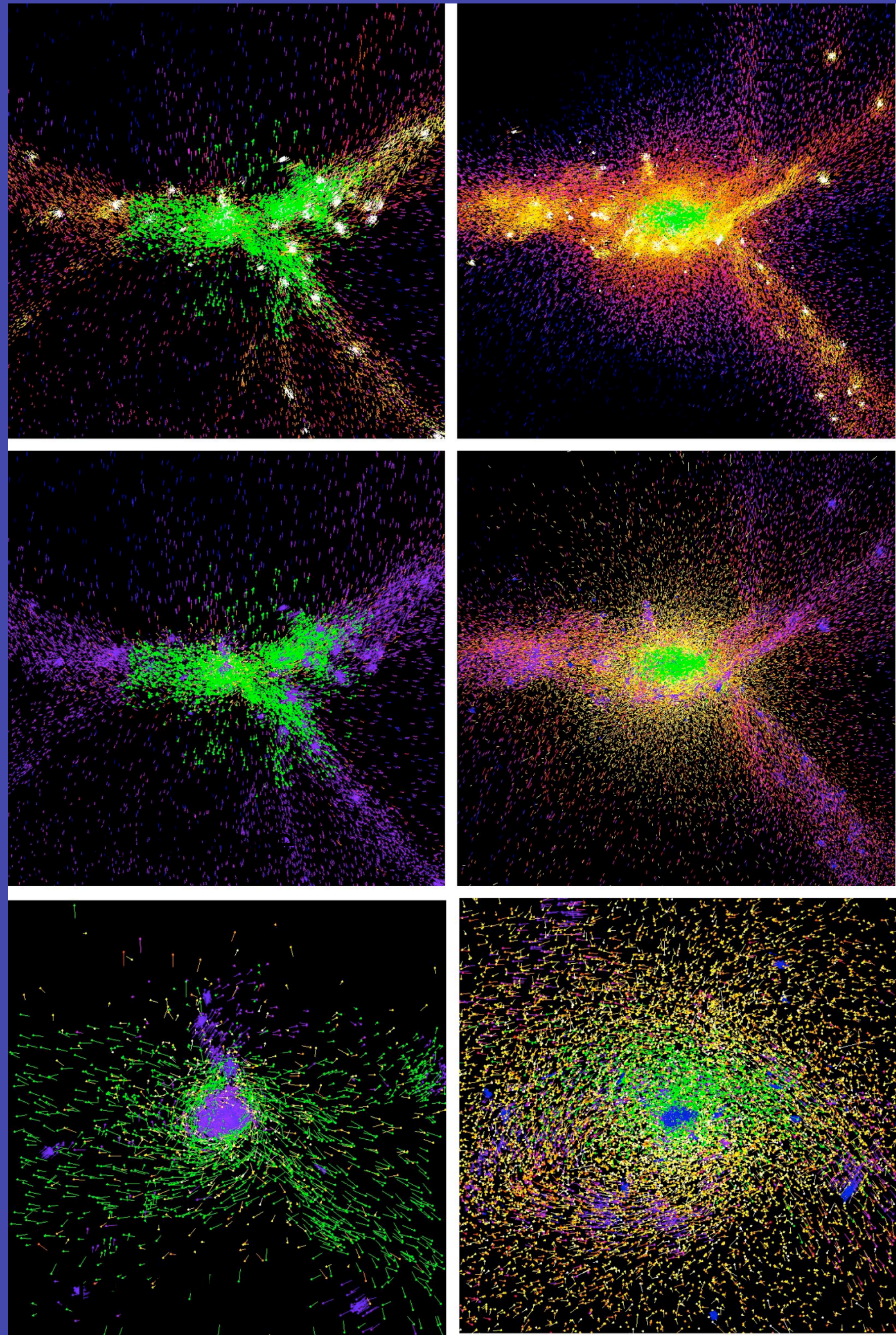
- **Cold mode dominates in small systems ($M_{vir} < 3x10$ $_\odot$), and thus at ear times.**



Accretion in a Growing Halo

(Keres at al 06; from Dave)

- Left panels: z=5.5, right panels: z=3.2.
- Halo grows from $M \sim 10^{11} M_{\odot} \rightarrow 10^{12} M_{\odot}$, changes from cold → hot mode dominated.
- Left shows cold mode gas as green; Right shows hot mode as green.
- Cold mode filamentary, extends beyond R_{vir}; hot mode quasi-spherical within R_{vir}. Filamentarity enhances cooling.



Keres et al 2005

Summary

- **The intergalactic medium (IGM) has been highly (re-)ionized since z>7**
  - Gunn-Peterson effect
  - by UV light from stars and AGN
- **Most of the baryons (at z>2) are seen to be still in the intergalactic medium (IGM)**

Basic Goals of High-z Galaxy Studies

- As a proxy for studying the typical *evolutionary fates of galaxies,* one needs to study the *evolution of the galaxy population* (and its environs) as a function of cosmic epoch.

- Need model comparison to go from observable population evolution to object evolution.

Questions we'd like to see answered

- Is there a (unique) *ab initio* model that matches (most) observations at (nearly) all epochs?
- What is the relative time order of star-formation and dynamical (galaxy)-structure assembly?
- What are the important regulatory processes for star-formation, BH-growth, evolution of galaxy structure?