Chemical Enrichment & Galaxy Growth

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Chemical Enrichment

Closed-box model

The metallicity evolution as a function of time is given by

$$Z(t) = -p \ln\left[\frac{M_g(t)}{M_g(0)}\right]$$

where *p* is the metal yield and is assumed to be constant.

Closed-box model - derivation

Models of chemical enrichment:

Let's only see the simplest one:

Closed-box model → Talbott & Arnett (1971)

Portion of a galaxy in a period of time in which no material enters or leaves the region.

Initially ($t=0$) → all gas in the region. No heavy elements

At $t>0$ → star formation → H, He & heavy elements returned to the ISM.

Turbulence keeps the gas well stirred. (and therefore homogeneous)
Gas is gradually consumed and the remaining gas becomes steadily more polluted w/ metals.

Assume M_g → gas mass
M_h → mass of heavy elements.

$$Z \equiv \frac{M_h}{M_g}. \qquad (Z_\odot \approx 0.02)$$

Consider { M_s → mass in stars
δM_s → differential of mass being formed in new stars.

We will assume no delay between (new star form. and consequent ISM chemical enrichm. The timescales are typically short for cosmic times, so this approx. is ok.

Consider also δM_s → mass in new stars after the massive stars making δM_s have died.
The mass in heavy elements produced by this stellar generat. is $(p\,\delta M_s)$, where p is the yield of that generat of stars.

Closed-box model - derivation (cont.)

the total change in the heavy element content of the interstellar gas that arises from the new stars is:

$$\delta M_h = p\,\delta M_s - Z\,\delta M_s = (p-Z)\,\delta M_s \qquad (1)$$

(Z: "existing" metallicity.)

The metallicity of the interstellar gas changes by an amount

$$\delta Z = \delta\left(\frac{M_h}{M_g}\right) = \frac{\delta M_h}{M_g} - \frac{M_h}{M_g^2}\,\delta M_g = \frac{1}{M_g}\left(\delta M_h - Z\,\delta M_g\right) \qquad (2)$$

(chain rule)

By conservation of mass we have $\delta M_s = -\delta M_g$, so combining (1) and (2) we have:

$$\delta Z = -p\,\frac{\delta M_g}{M_g} \qquad (3)$$

$$\delta Z = \frac{1}{M_g}\left(\delta M_h + Z\,M_s\right) = \frac{1}{M_g}\left((p-Z)\,\delta M_s + Z\,M_s\right) = \frac{1}{M_g}\,\delta M_s = -p\,\frac{\delta M_g}{M_g}$$

If the yield p is constant for every generation of stars, we can integrate (3) to obtain the metallicity at time t as:

$$Z(t) = -p\,\ln\left[\frac{M_g(t)}{M_g(0)}\right], \qquad (4)$$

where we have assumed that $Z(t=0)=0$.

this relation (4) indicates that the metallicity increases as the gas mass decreases in a galaxy.

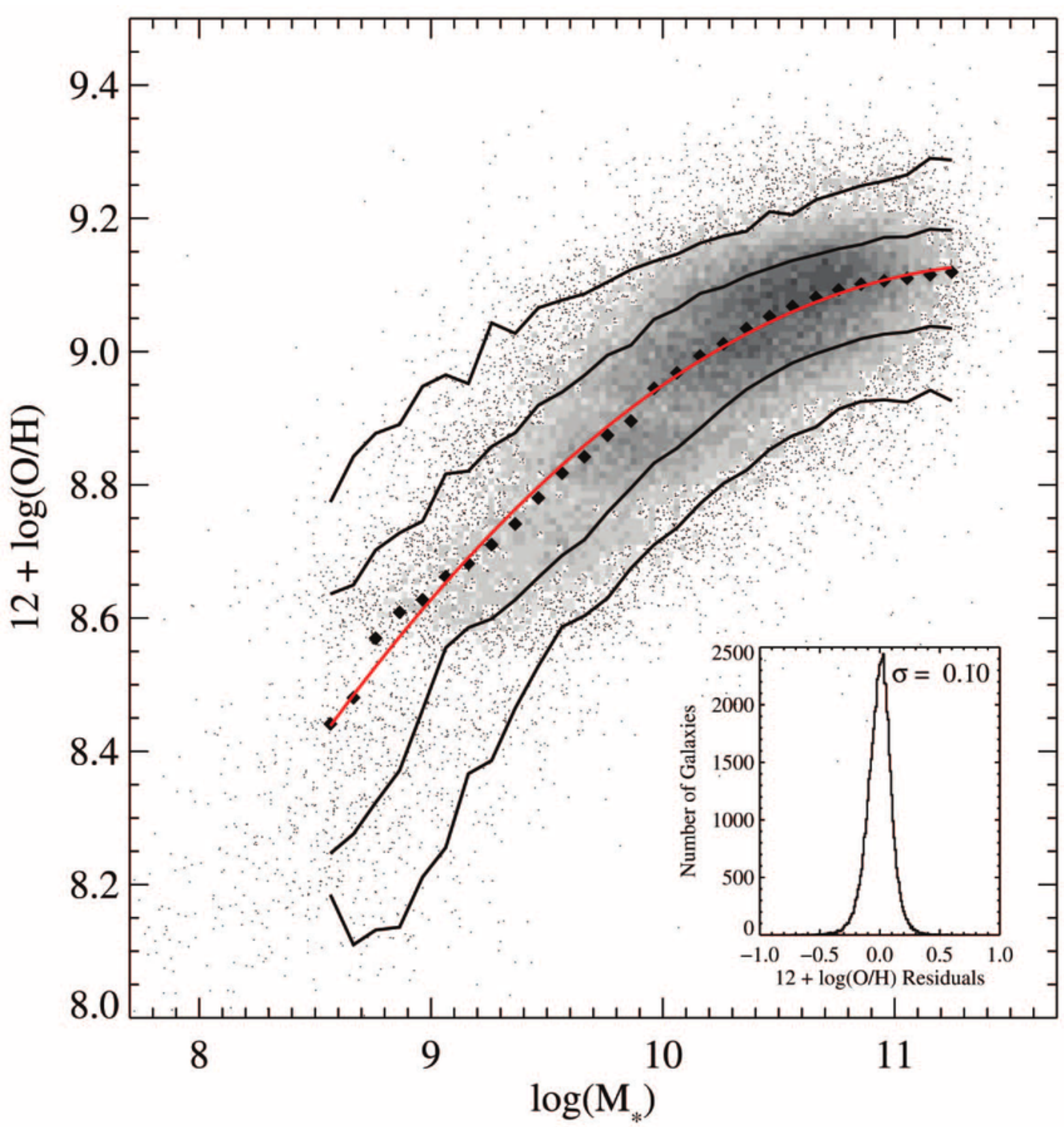
With the closed-box model, we can also predict the metallicity distribution of stars. From eq. (4), the mass of the stars, formed, which have metallicity less than $Z(t)$, is

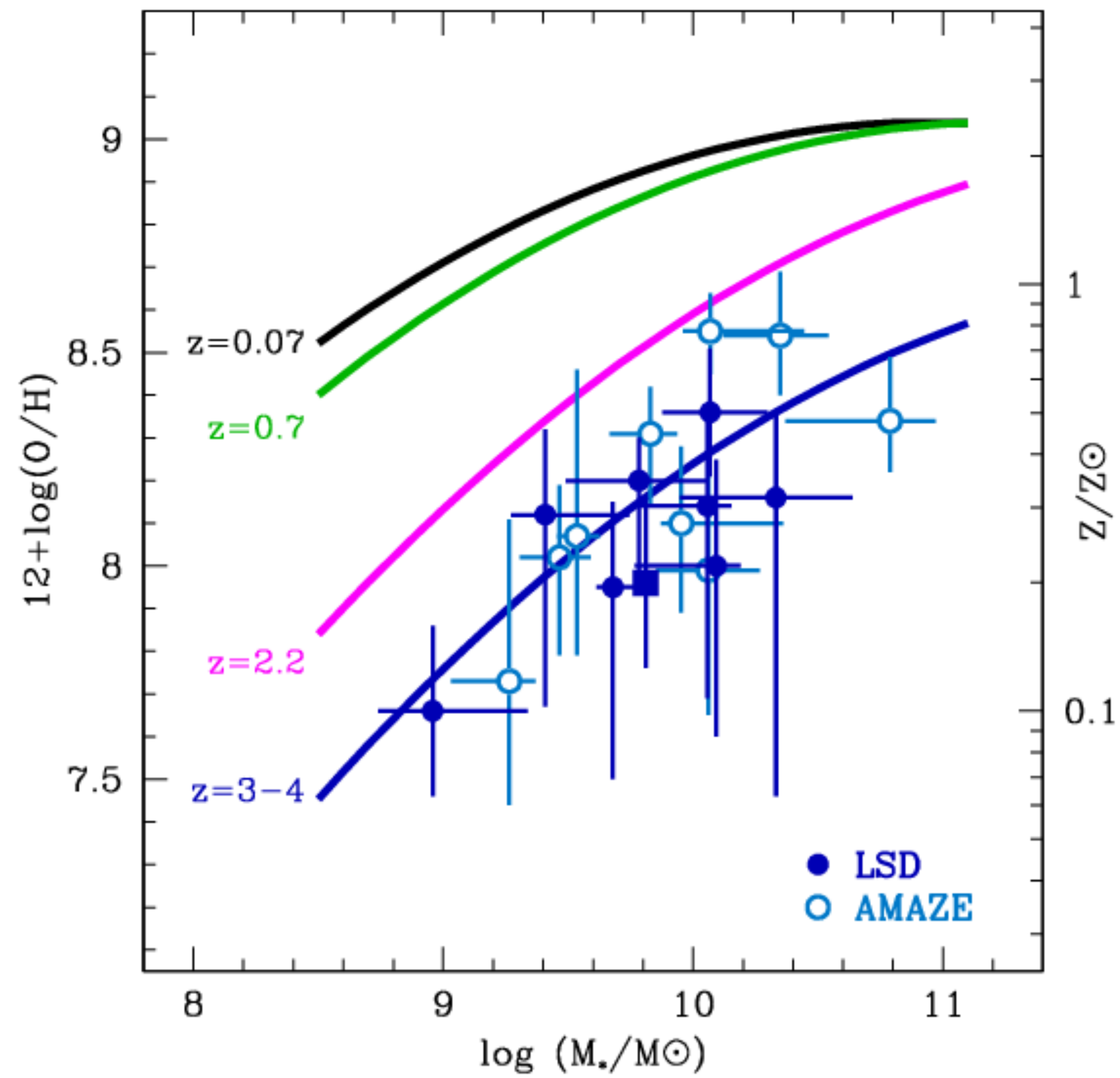
$$M_s[<Z(t)] = M_s(t) = M_g(0) - M_g(t) = M_g(0)\left[1 - e^{-Z(t)/p}\right].$$

This is just obtained integrating eq. (4).

So, the formed stars will have a wide range of metall. $< Z(t)$.

The mass-metallicity relation



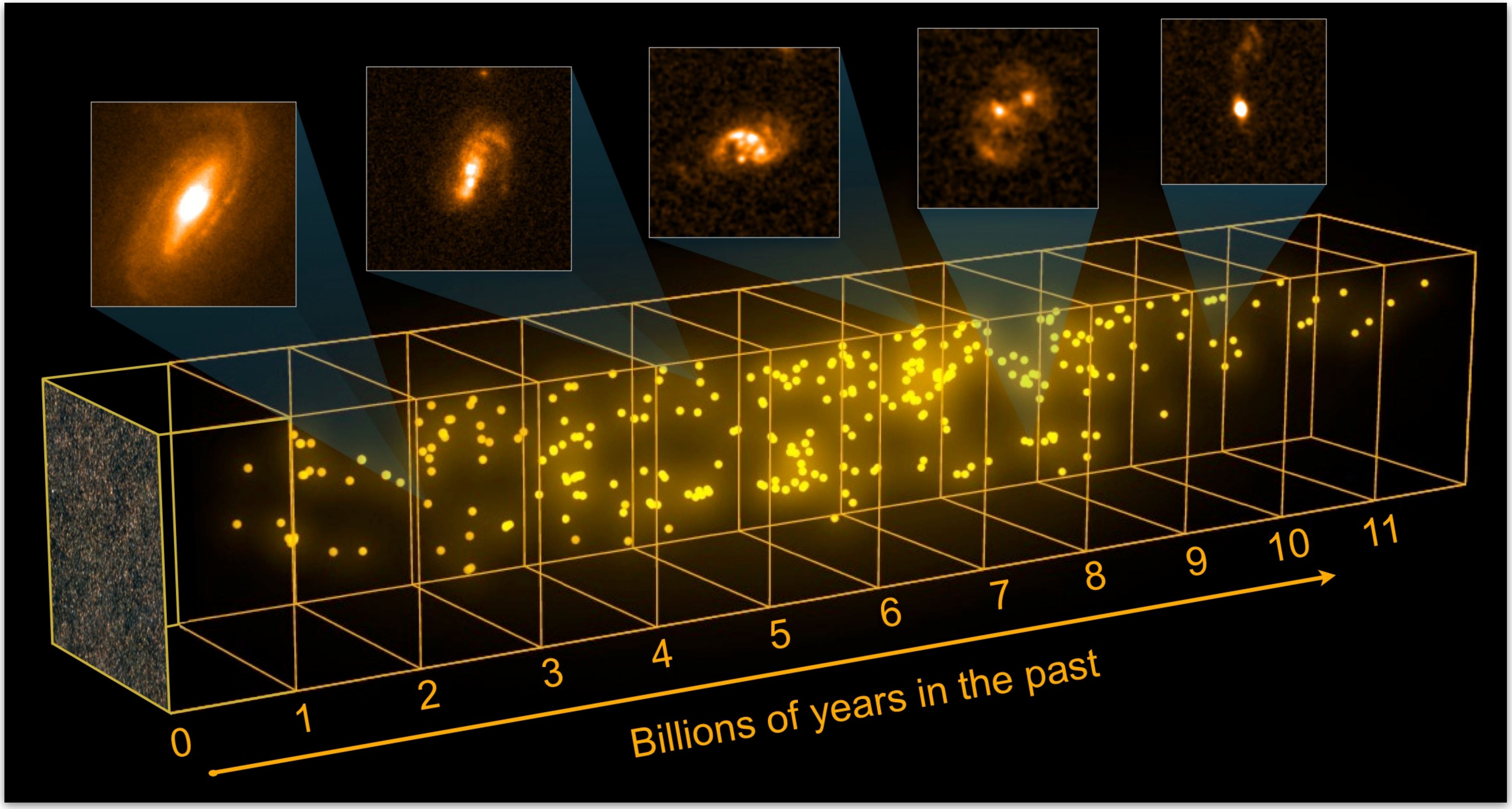


Tremonti et al. (2004)

Mannucci et al. (2009)

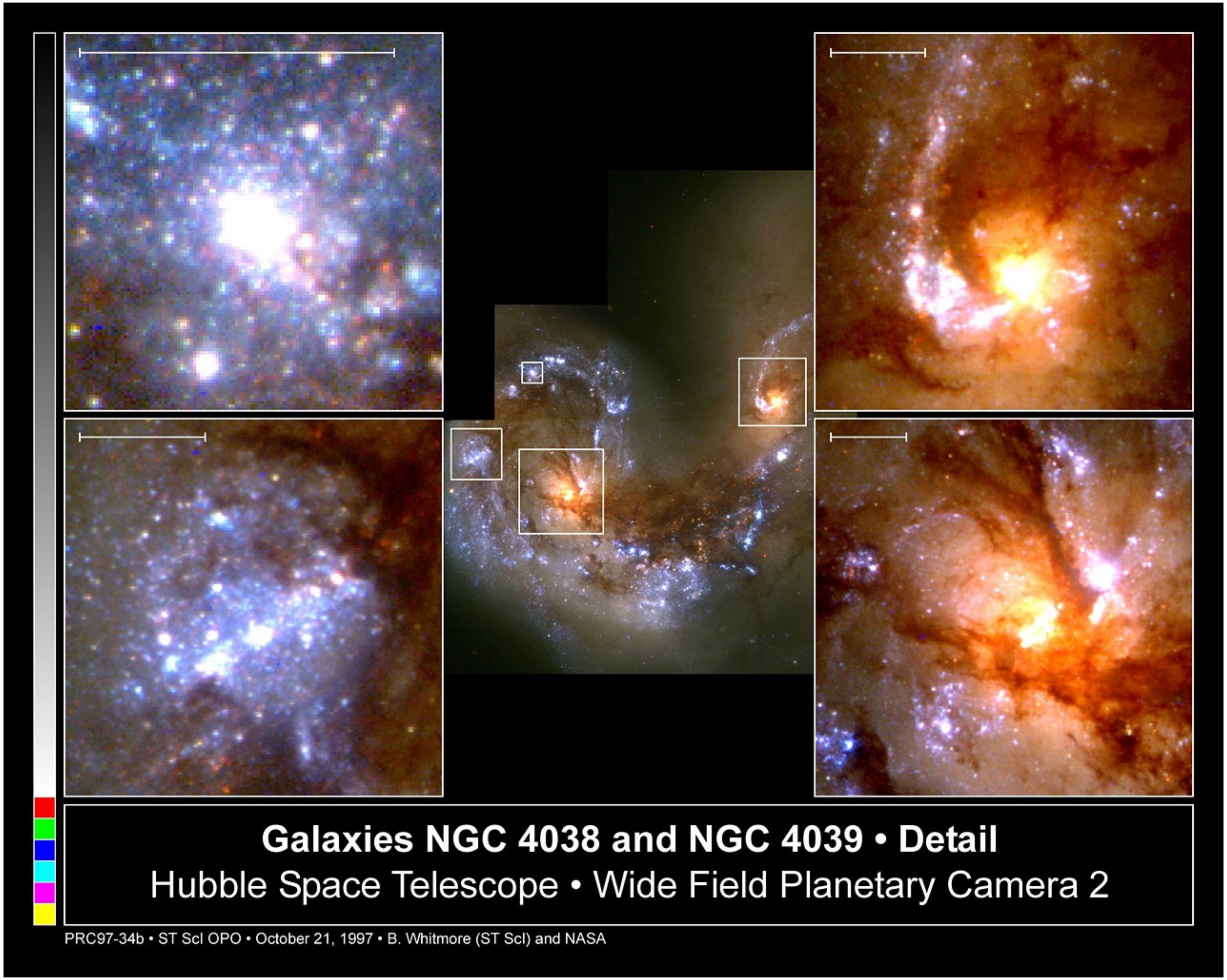
Galaxy Growth

Galaxy formation and growth - big picture



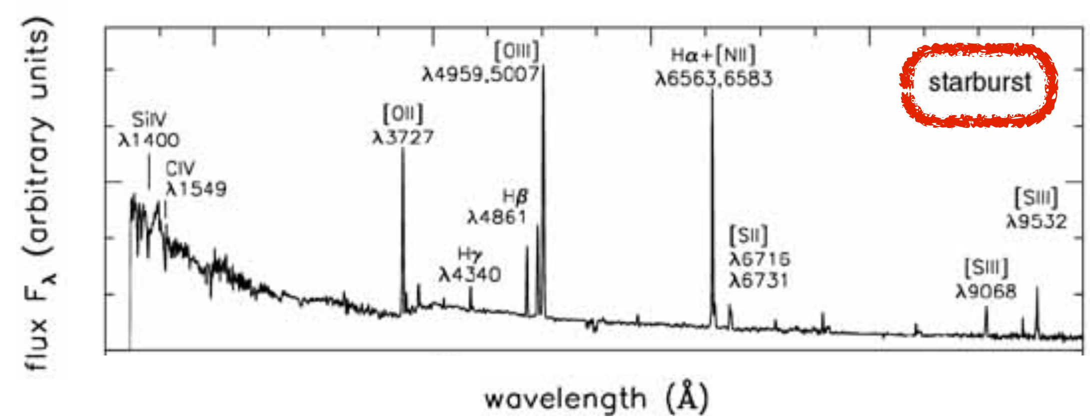
Credit: ESA; C Carreau

Star formation in galaxies

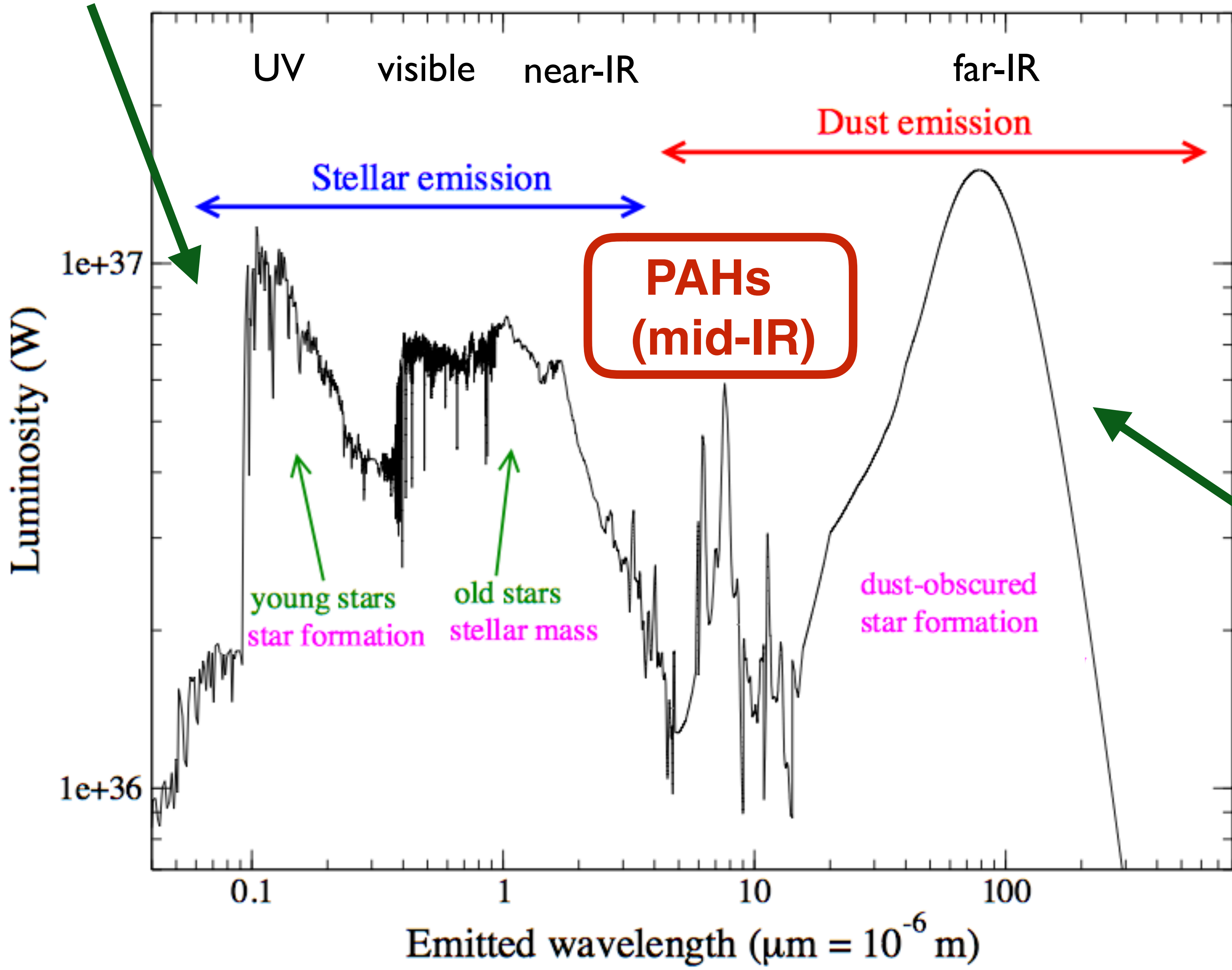


Star formation tracers in a galaxy

Emission lines (particularly Balmer lines)



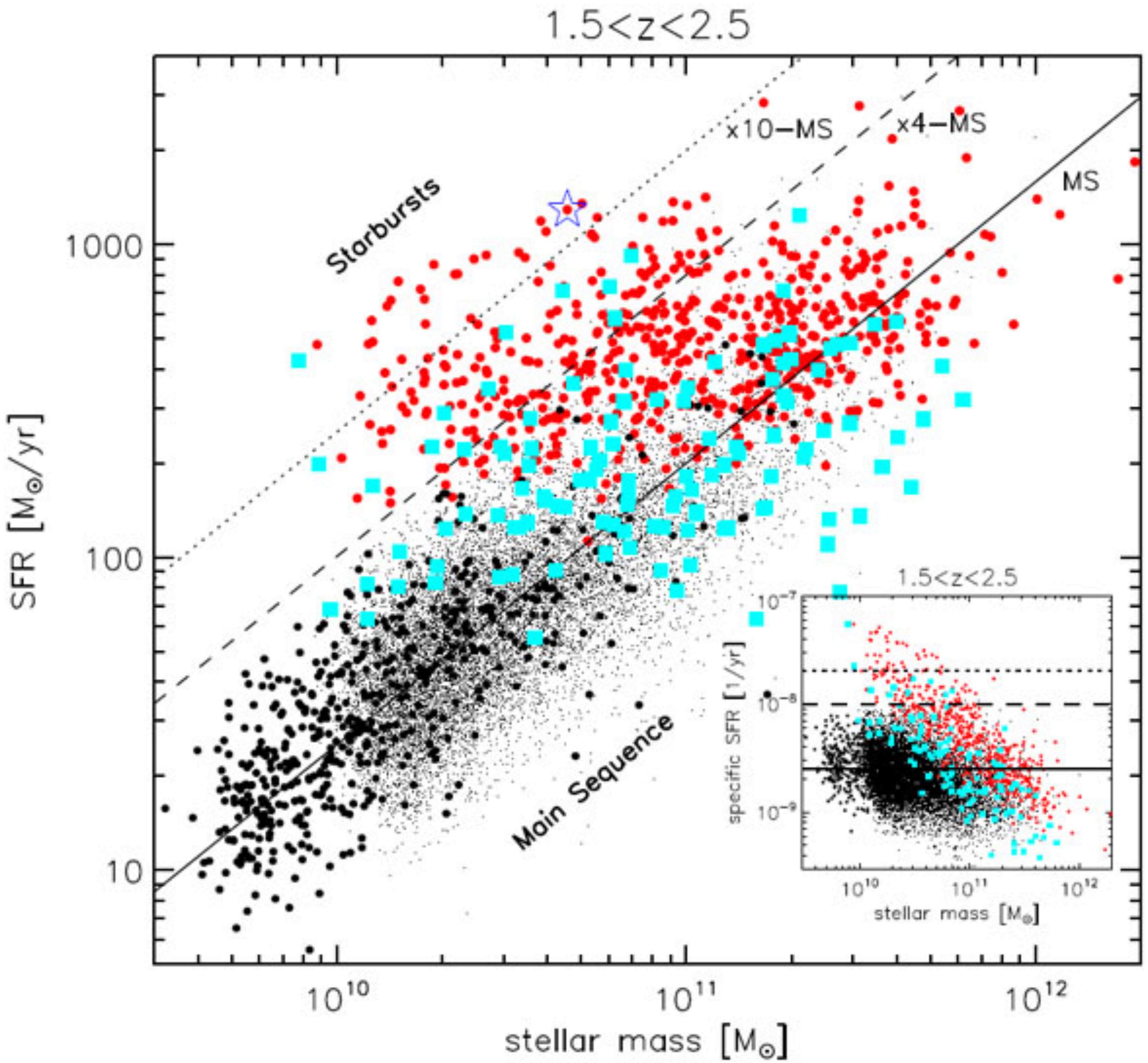
rest UV light



PAHs (mid-IR)

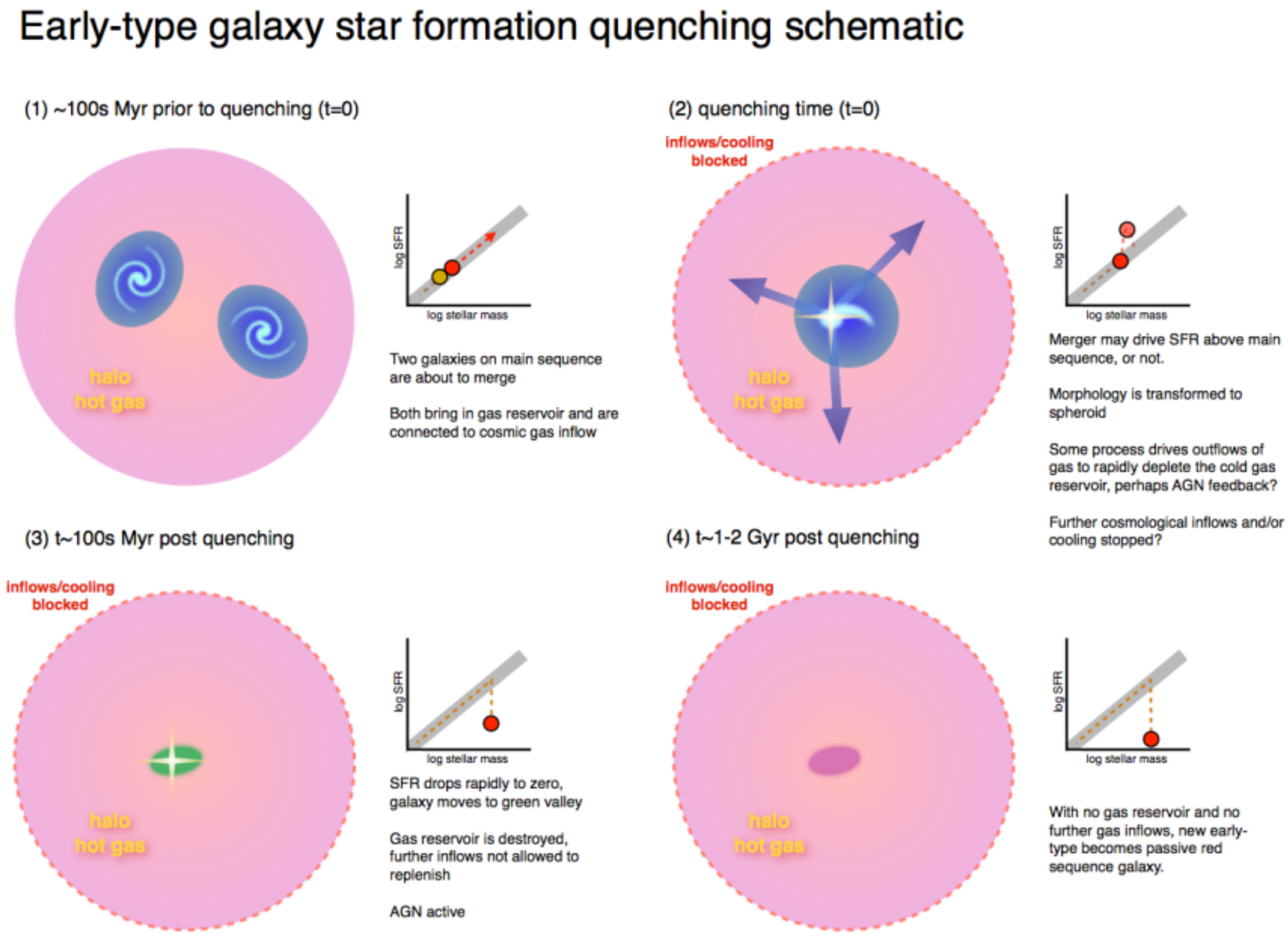
far-IR/(sub)-mm emission

The SFR - M* plane



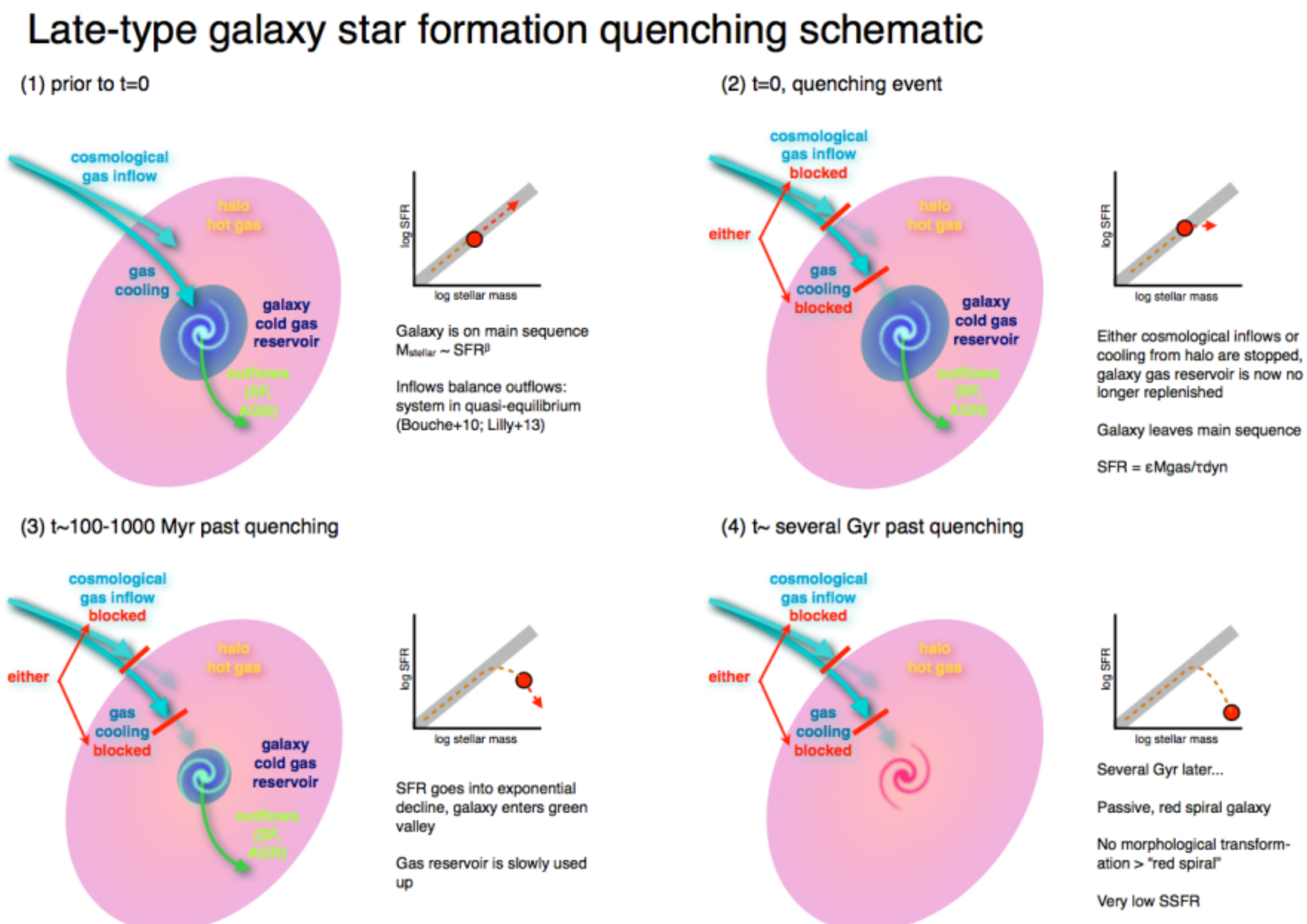
Rodighiero et al.

Star formation quenching I



Credit: K. Schawinski

Star formation quenching II

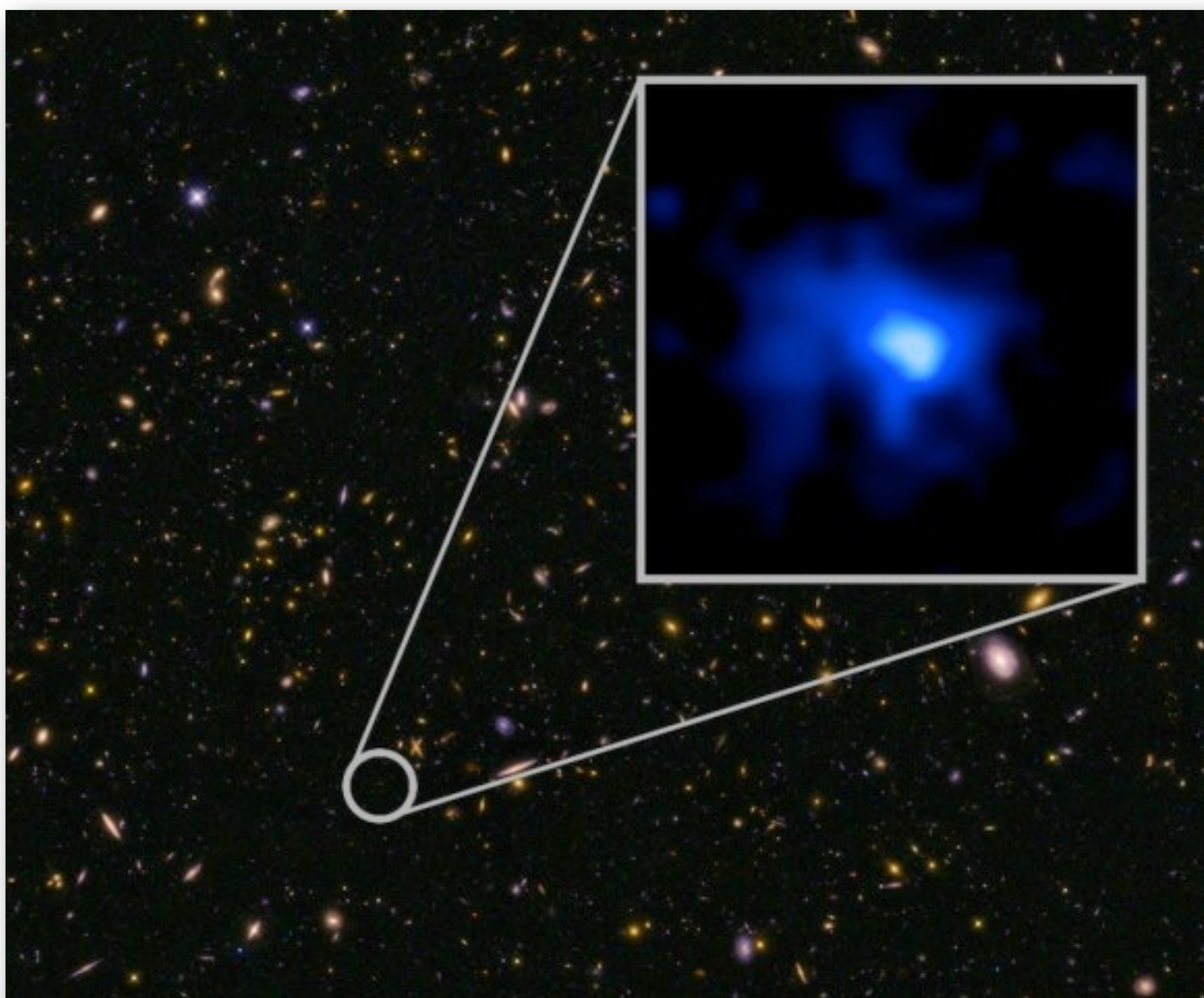


Credit: K. Schawinski

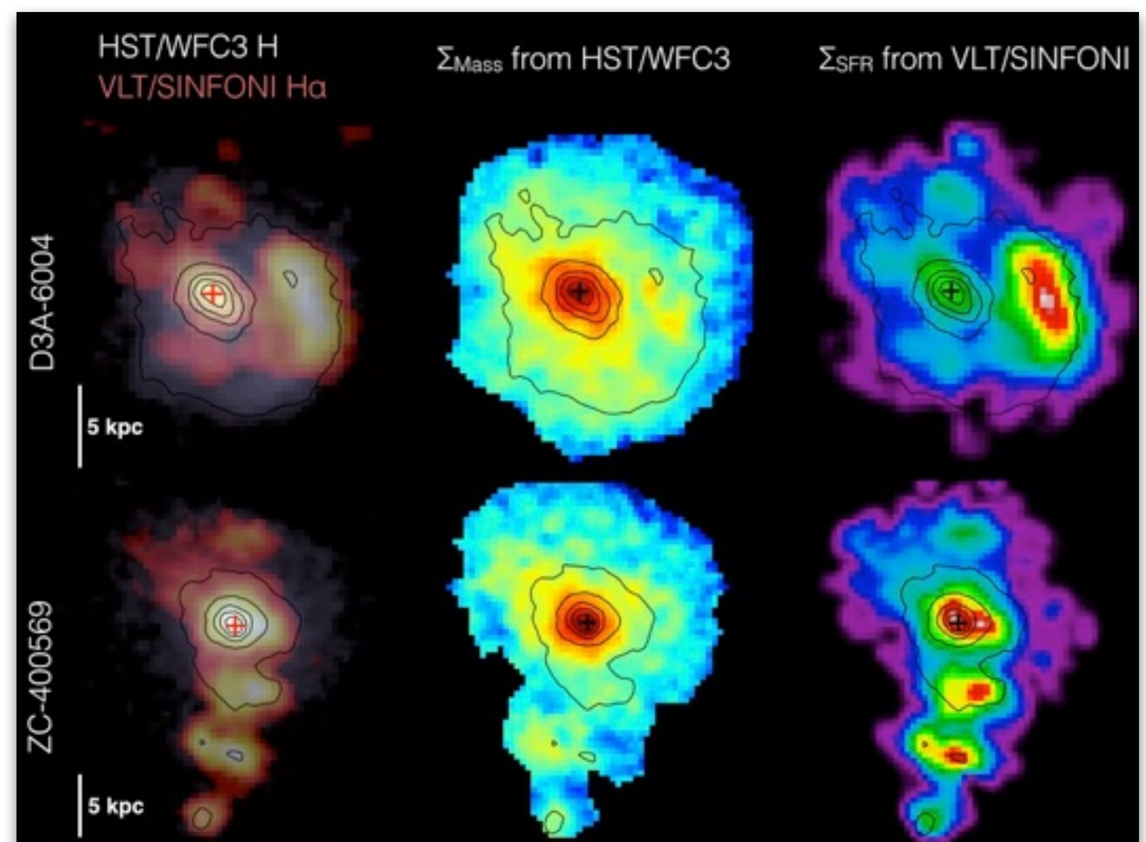
High-z Galaxies

Two types of studies of distant galaxies

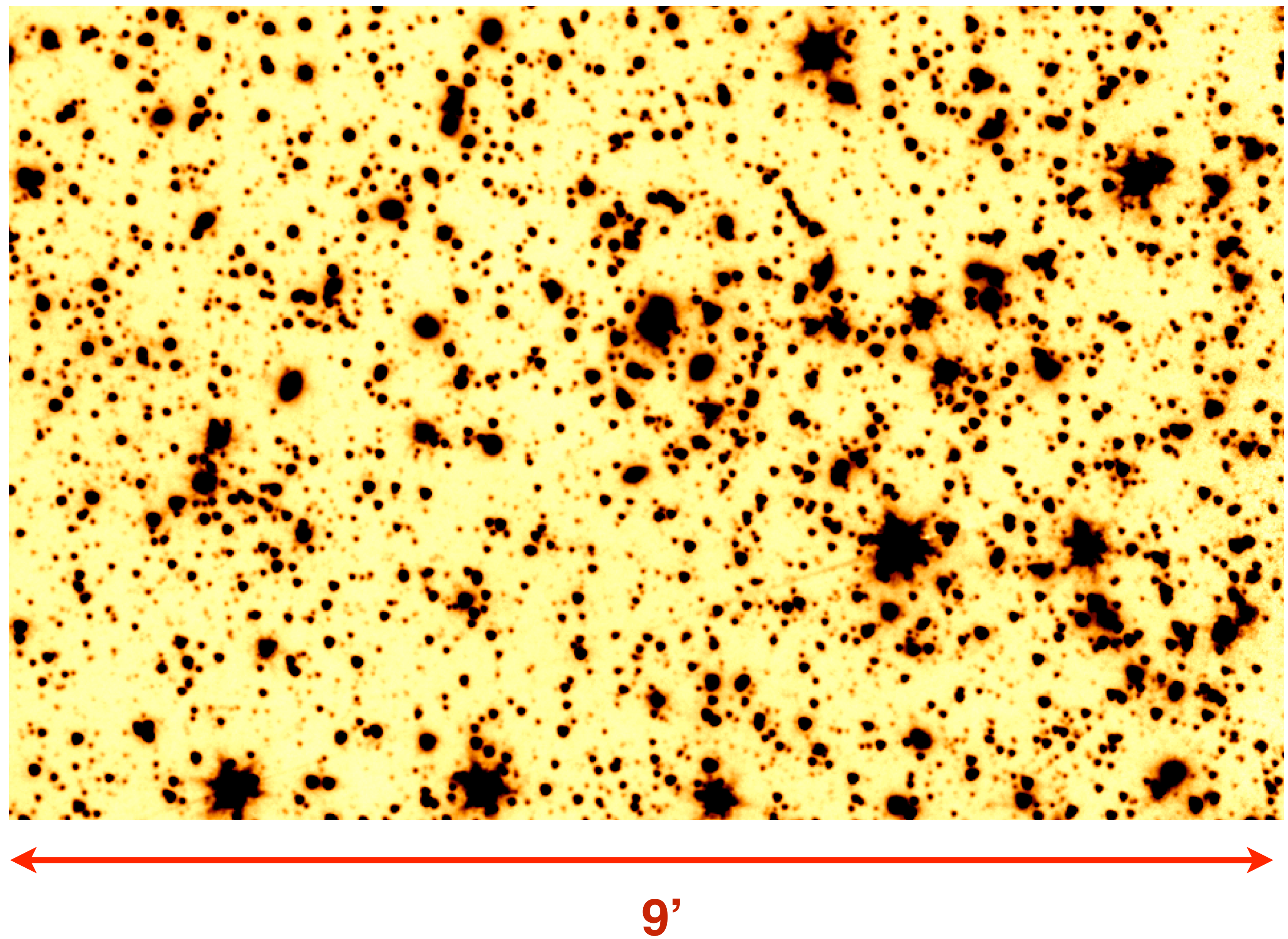
Statistical studies
general properties of hundreds of thousands of galaxies

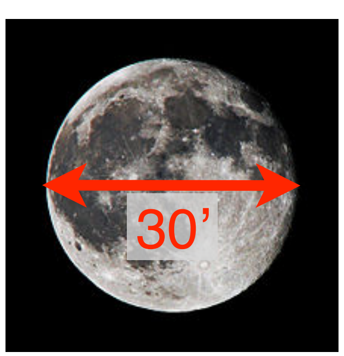


Individual galaxy studies
investigate detailed physical processes



Studying the high-z Universe with blank surveys





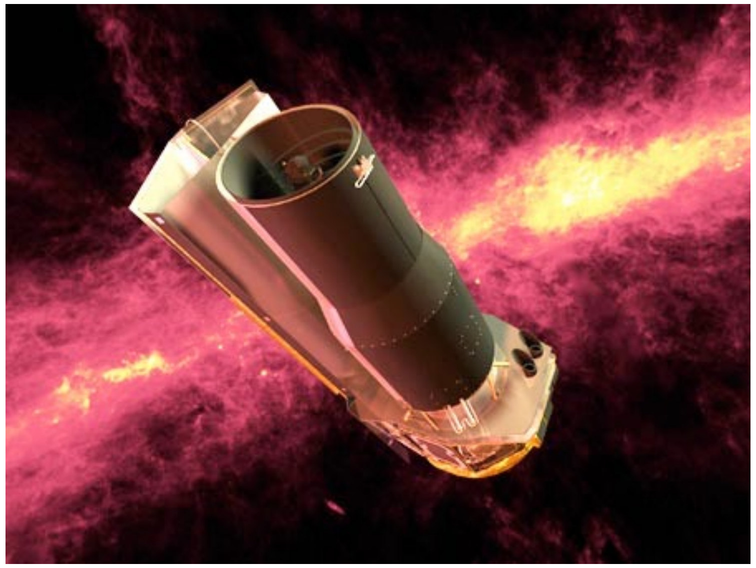
Thousands of galaxies can be observed in a blank patch of sky with the size of the full moon

In perspective...

Until only ~20 years ago, we had quite a sparse knowledge of galaxies at z>1.5

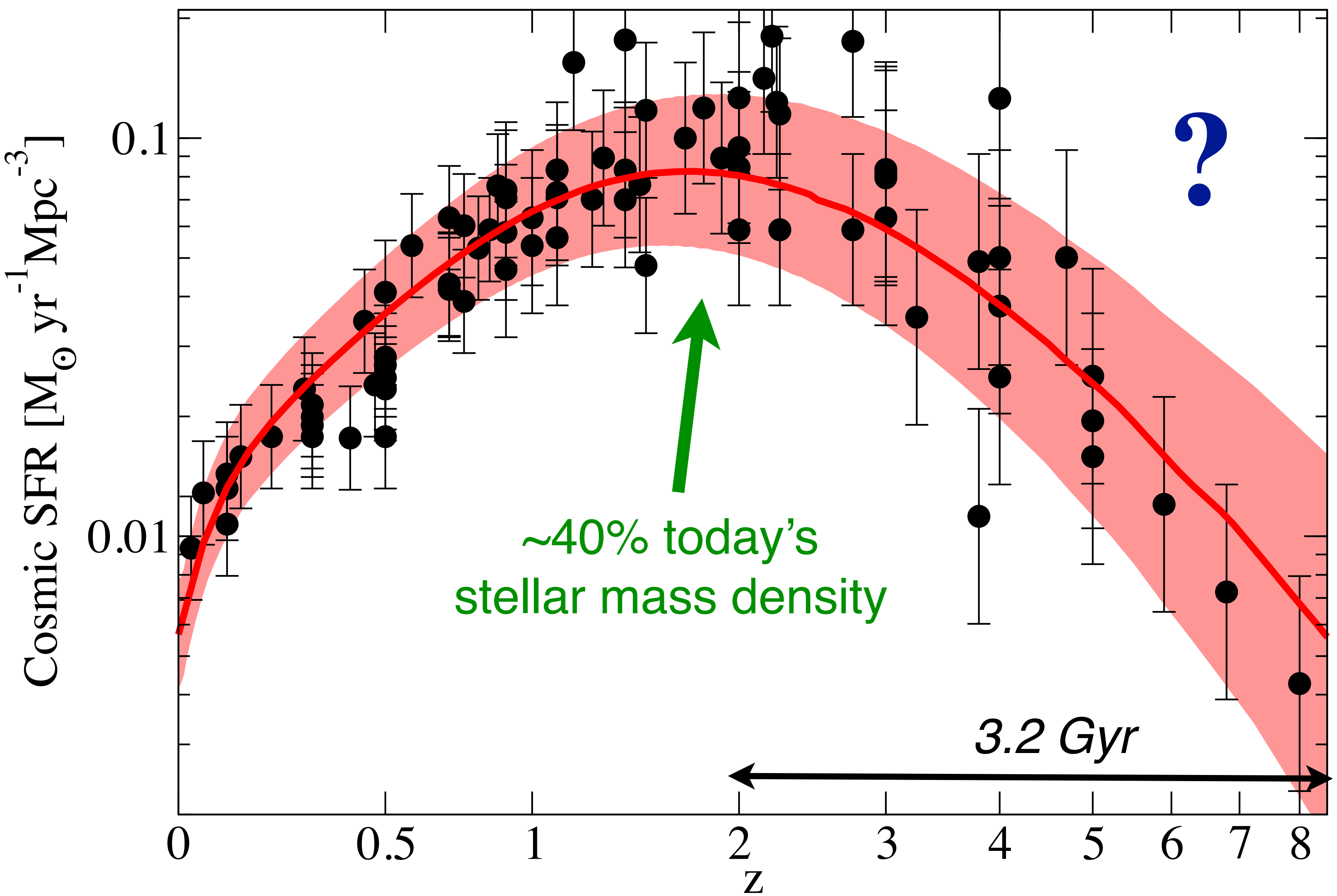
the connection between different galaxy populations was unclear

New facilities (*HST, Spitzer,* ground-based 8m-diam. telescopes) allowed us to create a more complete and clearer picture of the Universe at high z



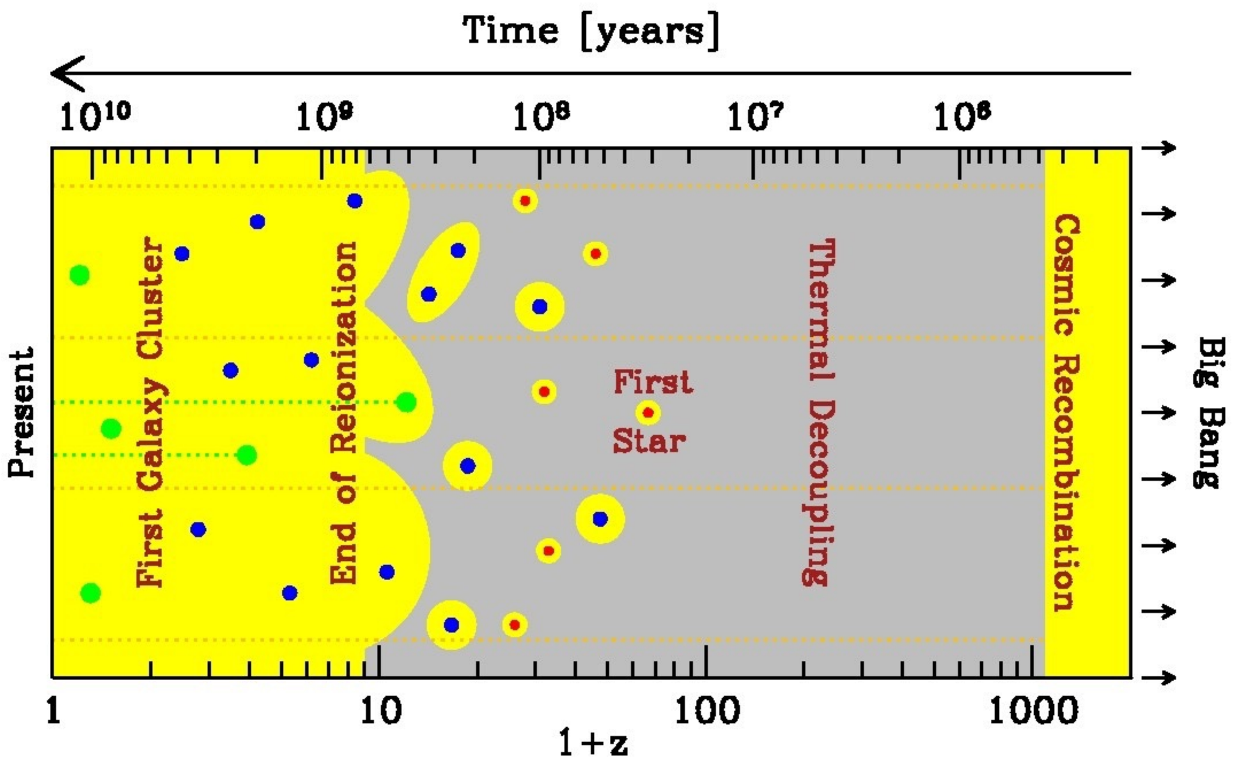
The cosmic SFR density

Galaxy formation and growth was much more efficient in the past

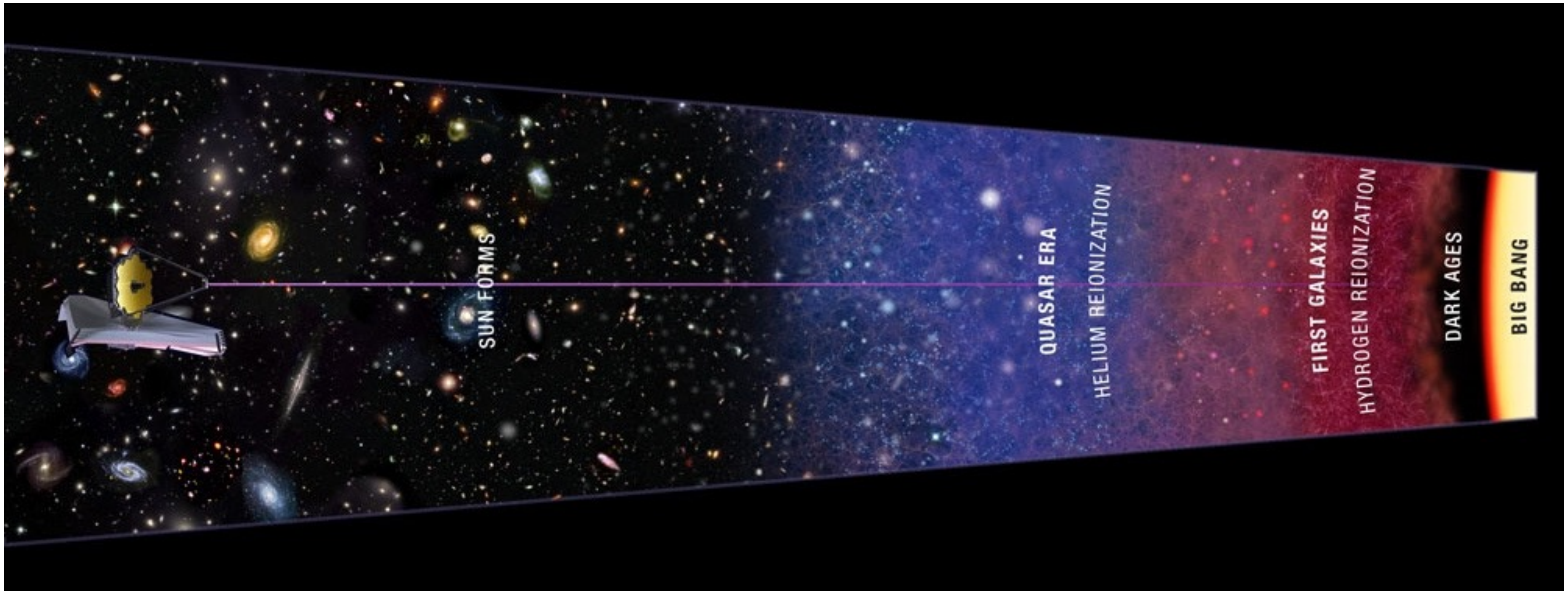


Behroozi et al. (2013); Madau & Dickinson (2014)

The sources of reionization



Understanding when first galaxies formed is one of ultimate goals



Selection of High z Galaxies

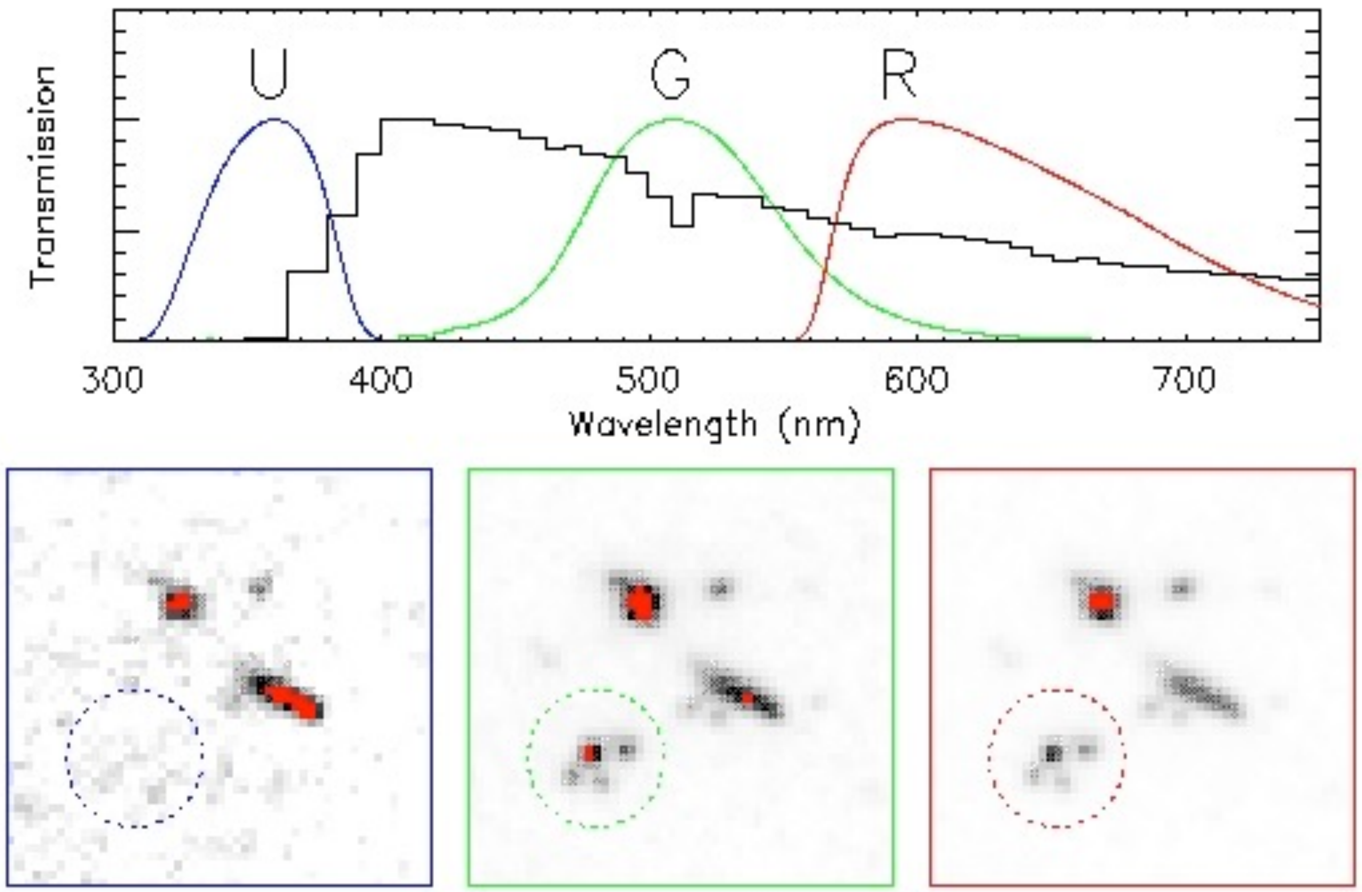
The highest *z* known galaxy over the last decades

Date	Galaxy	z	Search Technique	Reference
1999...	SSA 22-HCM1	5.74	Narrowband imaging	1
1998 Oct...	HDF 4-473.0	5.60	Photometric selection	2
1998 May...	0140+326 RD1	5.34	Serendipity	3
1997...	Cl 1358+62, G1/G2 arcs	4.92	Serendipity/gravitational lensing	4
1996...	BR 1202-0725	4.695	Narrowband imaging	5
1994...	8C 1435+63	4.26	Radio selection	6
1990...	4C 41.17	3.80	Radio selection	7
1988...	B2 0902+34	3.39	Radio selection	8
1985...	PHS 1614+051 companion	3.215	Narrowband imaging	9
1984...	3C 256	1.82	Radio selection	10
1983...	3C 324	1.206	Radio selection	11
1982...	3C 368	1.131	Radio selection	12
1979...	3C 6.1	0.840	Radio selection	13
1976...	3C 318	0.752	Radio selection	14
1975...	3C 411	0.469	Radio selection	15
1960...	3C 295	0.461	Radio selection	16
1956...	Cl 0855+0321	0.20	Cluster selection	17

Credit: http://ned.ipac.caltech.edu/level5/Sept04/Stern/Stern1.html

To date we know a few thousand galaxy candidates at z>5-6 and a few at z~10-11

Selection of SF galaxies at z~2-3



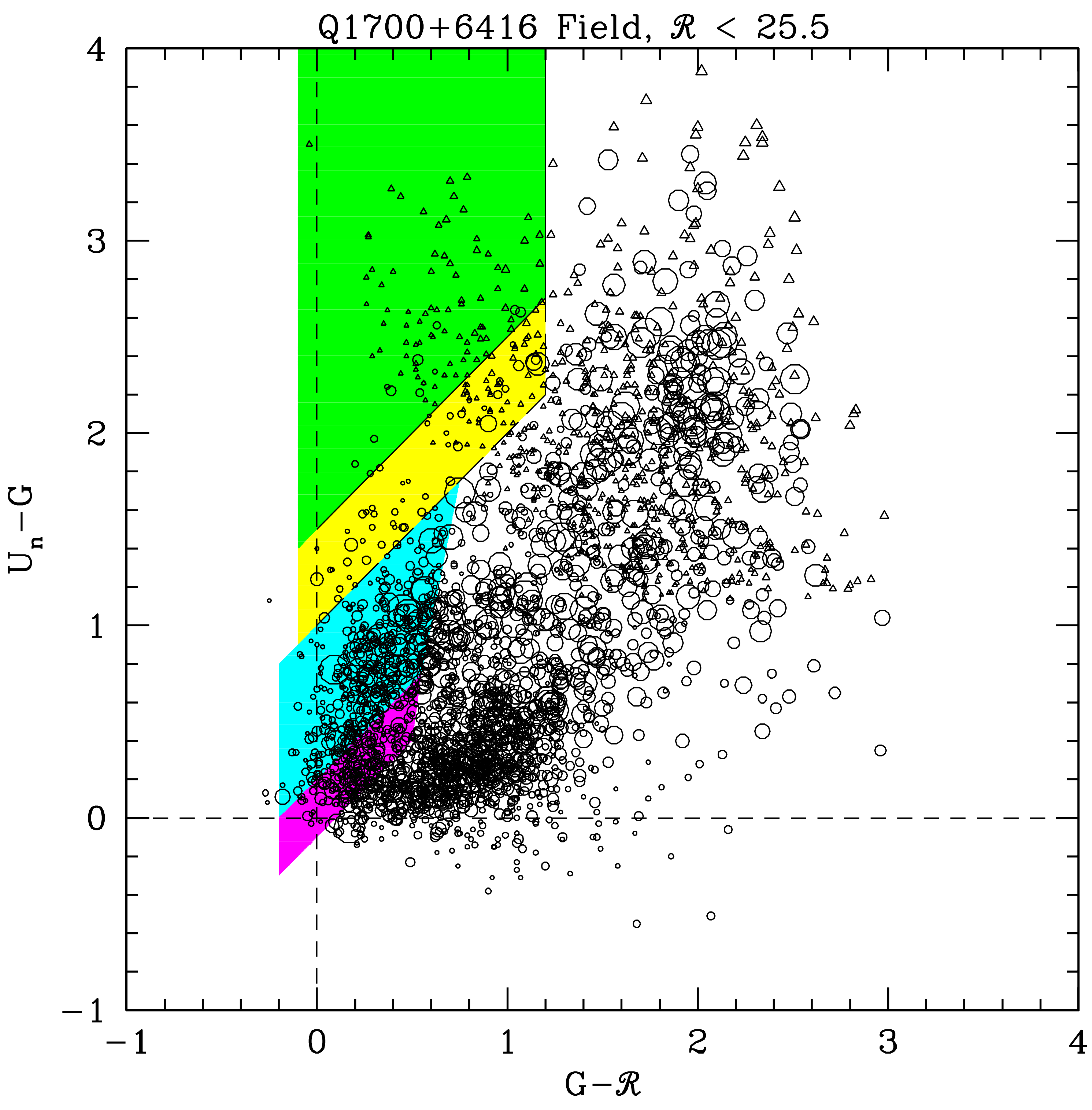
Lyman-break selection technique

Introduced by Steidel et al. (1996) to select star-forming galaxies at z~3

Picture Credit: http://www.astro.ku.dk/~jfynbo/LBG.html

Note: *low-z contaminants can be 20-30% of sample*

Selection of SF galaxies at z~2-3

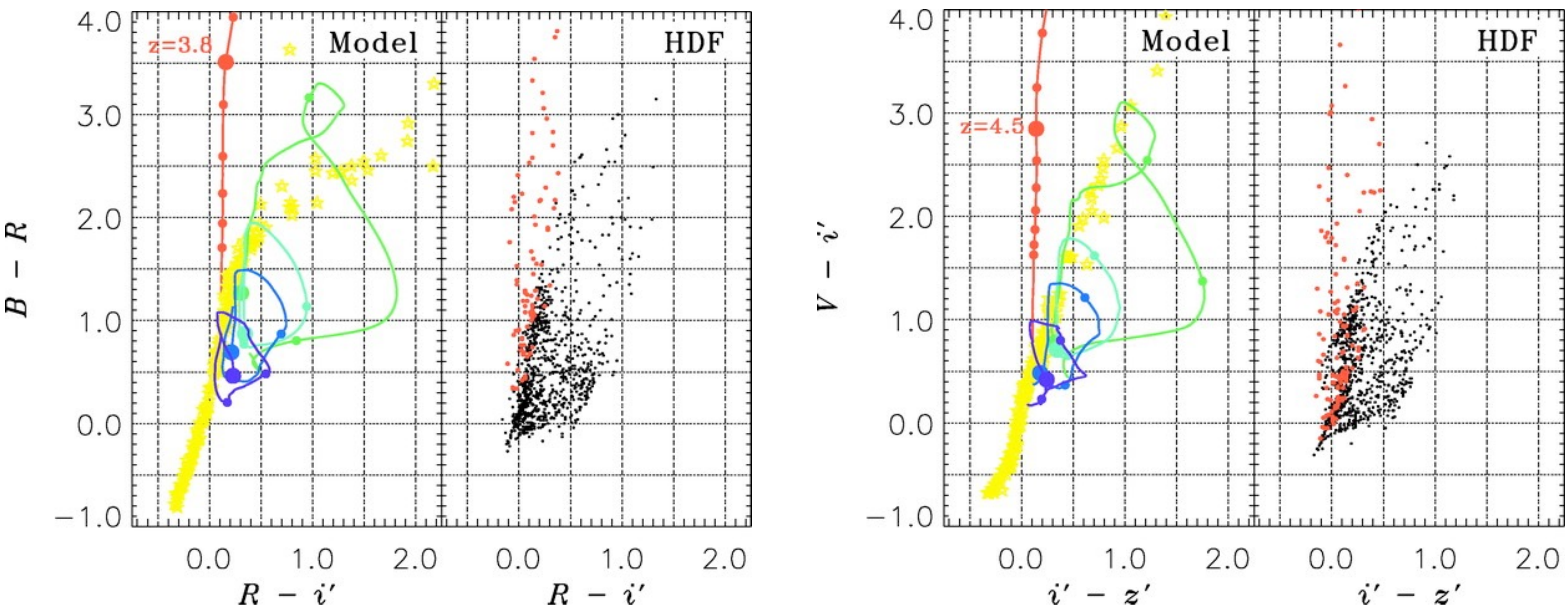


Lyman-break selection technique

Shapley (2011), based on Steidel et al. (2004)

Selection of SF galaxies at z~4-5

changing the set of filters, the technique can be extended to select higher-z galaxies

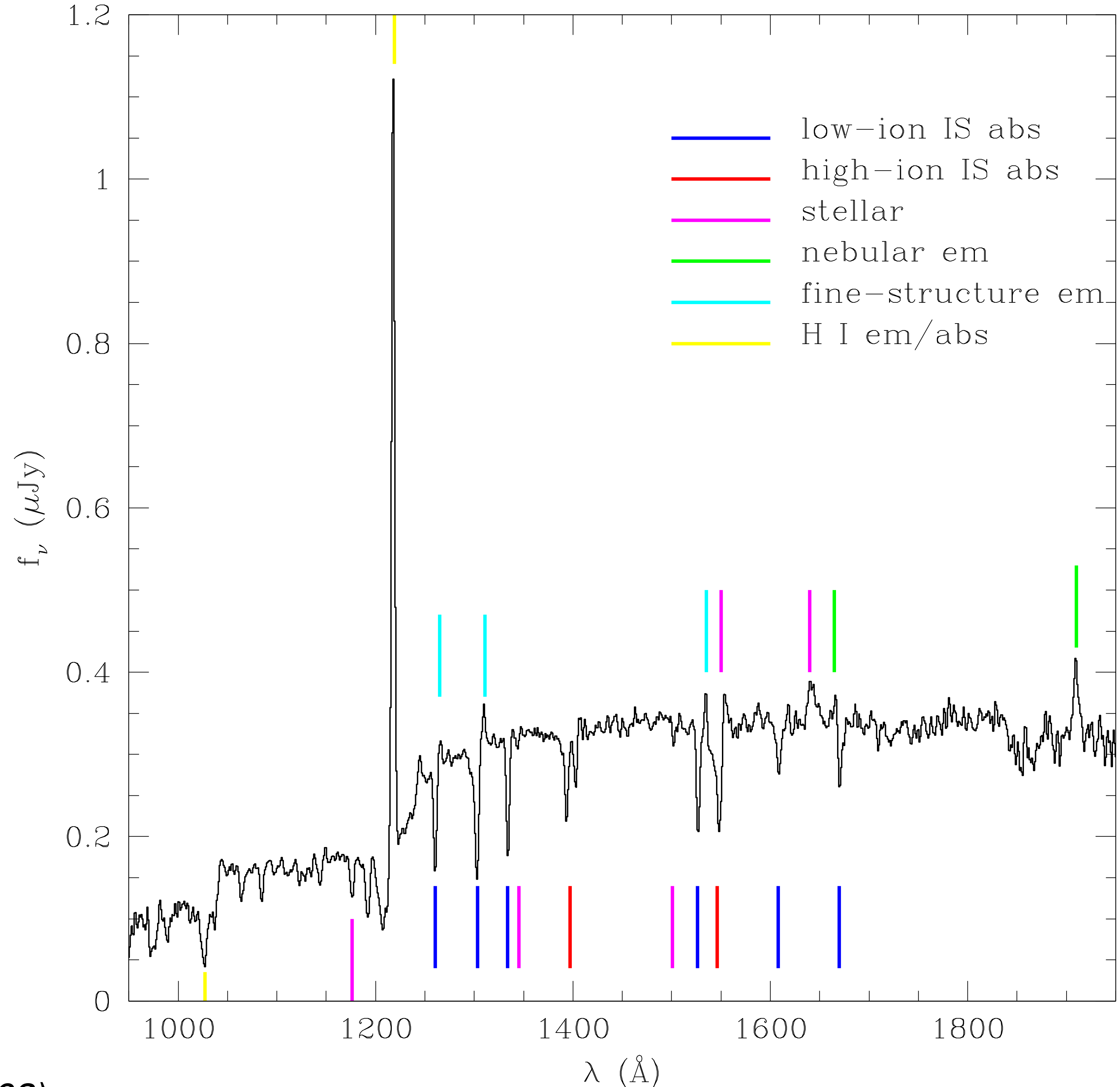


Ouchi et al. (2004)

<u>Caveat of this technique:</u> biased against dusty galaxies!

The spectroscopic confirmation

stacked spectra of ~800 Lyman-break-selected galaxies



Shapley et al. (2003)

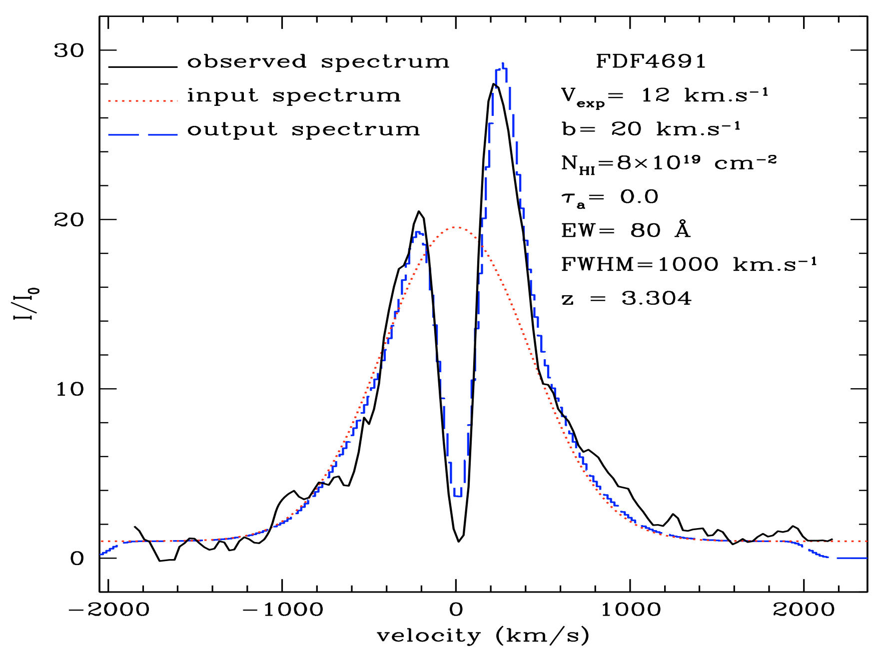
Ly-break galaxies vs. Ly-alpha emitters

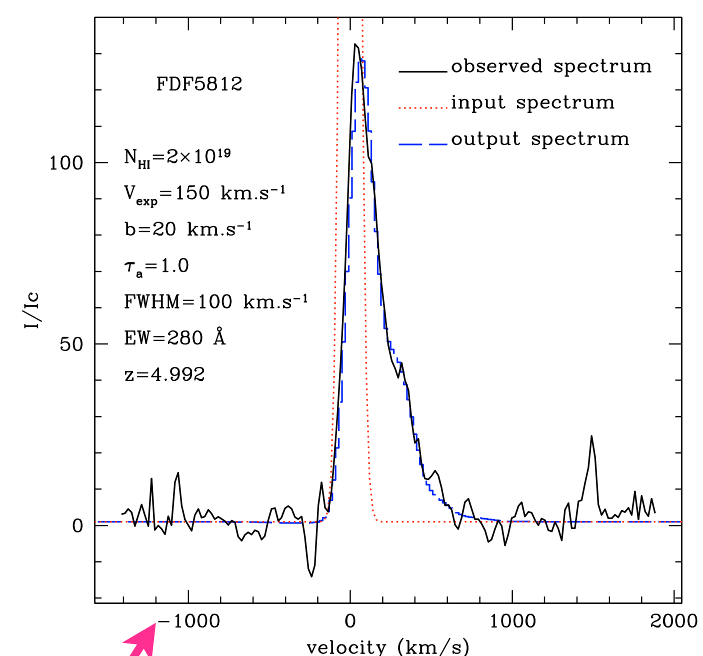
Lyman-break galaxies are not necessarily Lyman-alpha emitters

The Lyman-alpha line profile depends on the ability of Lya photons to escape dusty/clumpy interstellar medium

<u>problem:</u> *resonant scattering of photons with HI*

<u>note:</u> if Lya EW > 100 A, then age < 50 Myr





most common profile in high-z galaxies

Pictures Credit: Verhamme et al. (2008); see also Neufeld (1990)

Optical vs Near-IR Galaxy Surveys

for many years, the search of $z>1.5$ galaxies has been performed on optical images

but the advent of near-IR surveys showed that optical surveys miss a significant fraction of high-z galaxies

Why?

Optical vs Near-IR Galaxy Surveys

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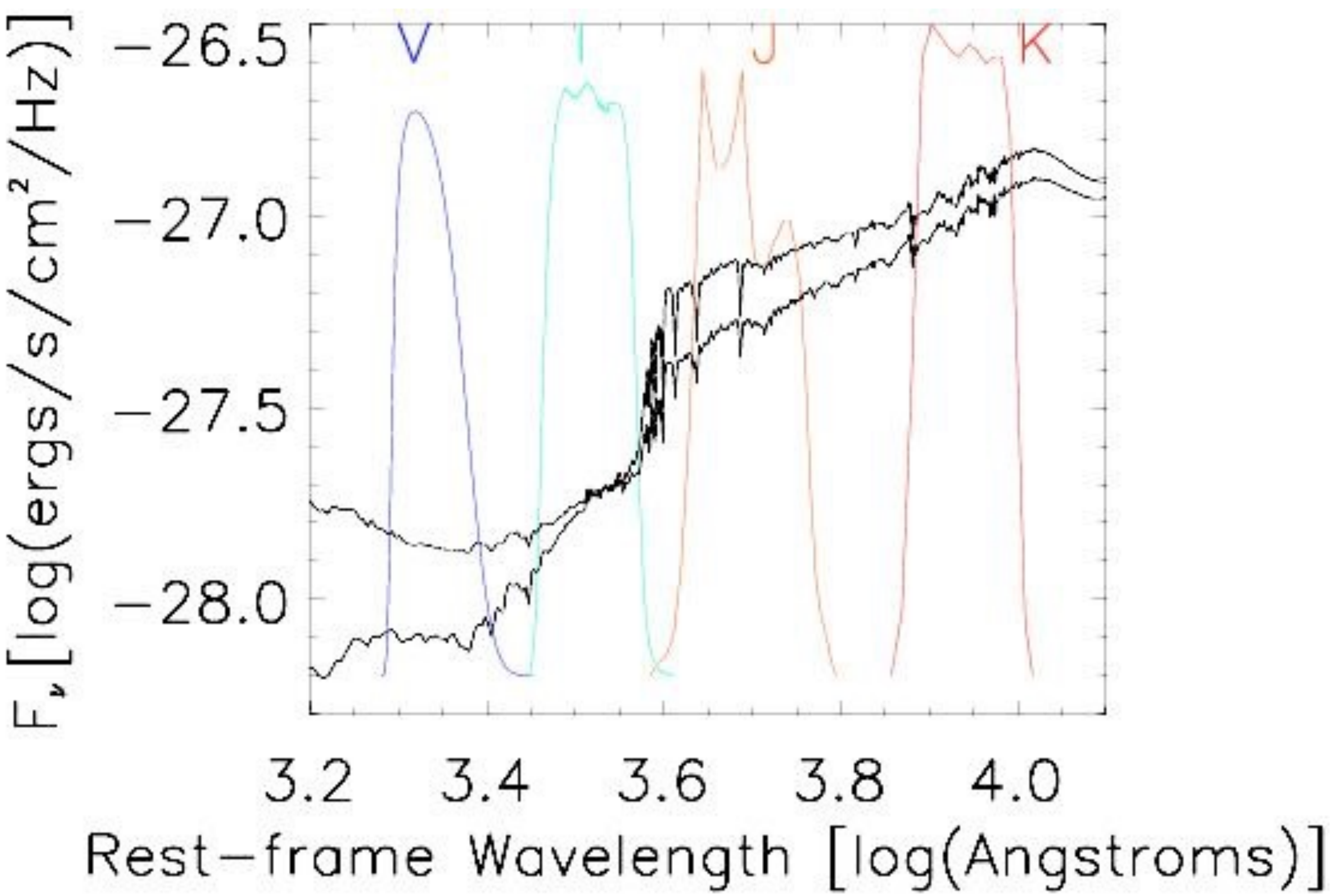
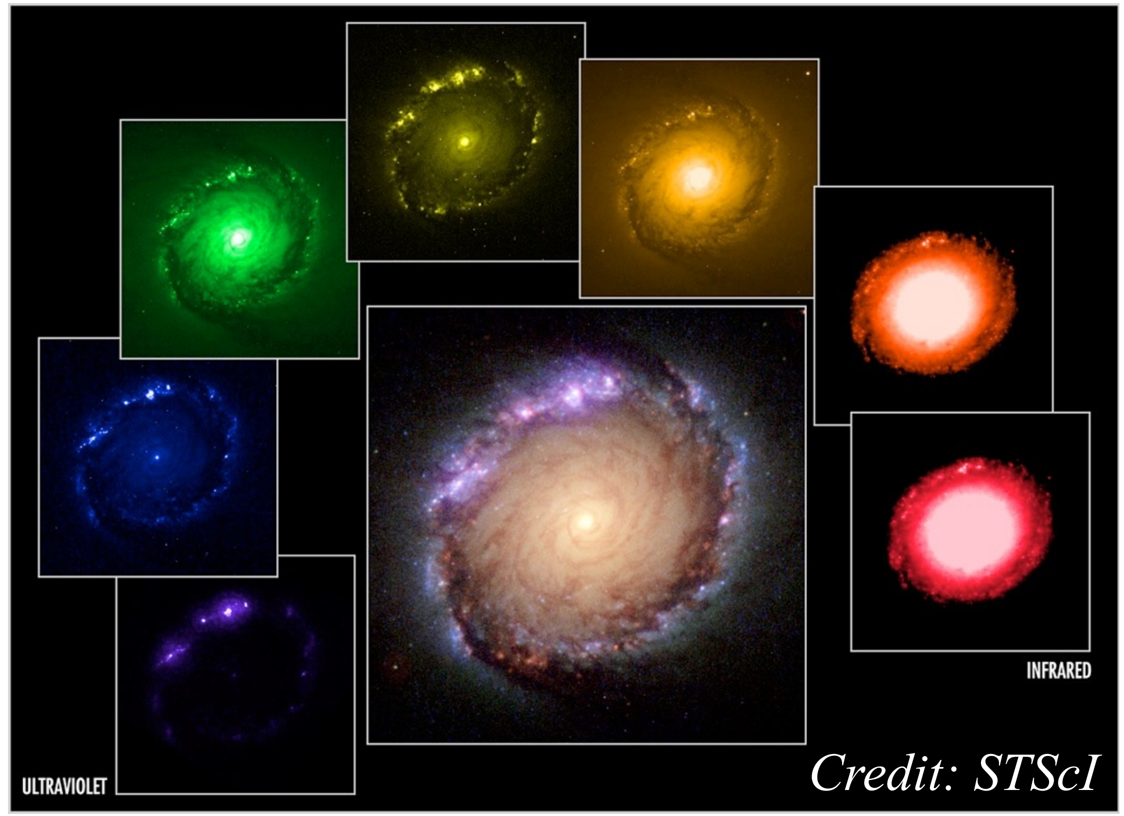
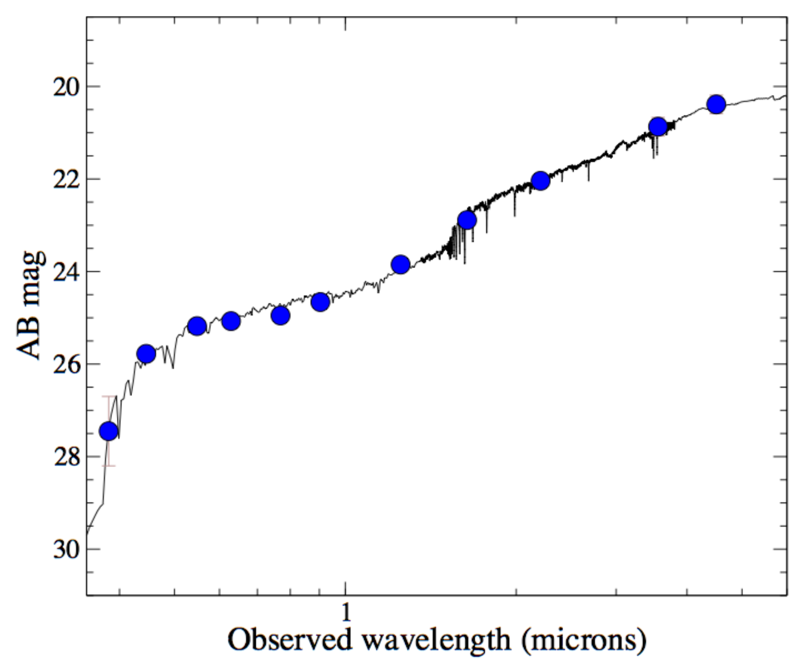
Why?



Picture Credit: http://ned.ipac.caltech.edu/level5/Sept01/Malkan/Malkan2.html

Galaxy selection through photometric redshifts





Photometric redshift → **'cheap' alternative to spectroscopic redshifts**

Age

Dust Extinction

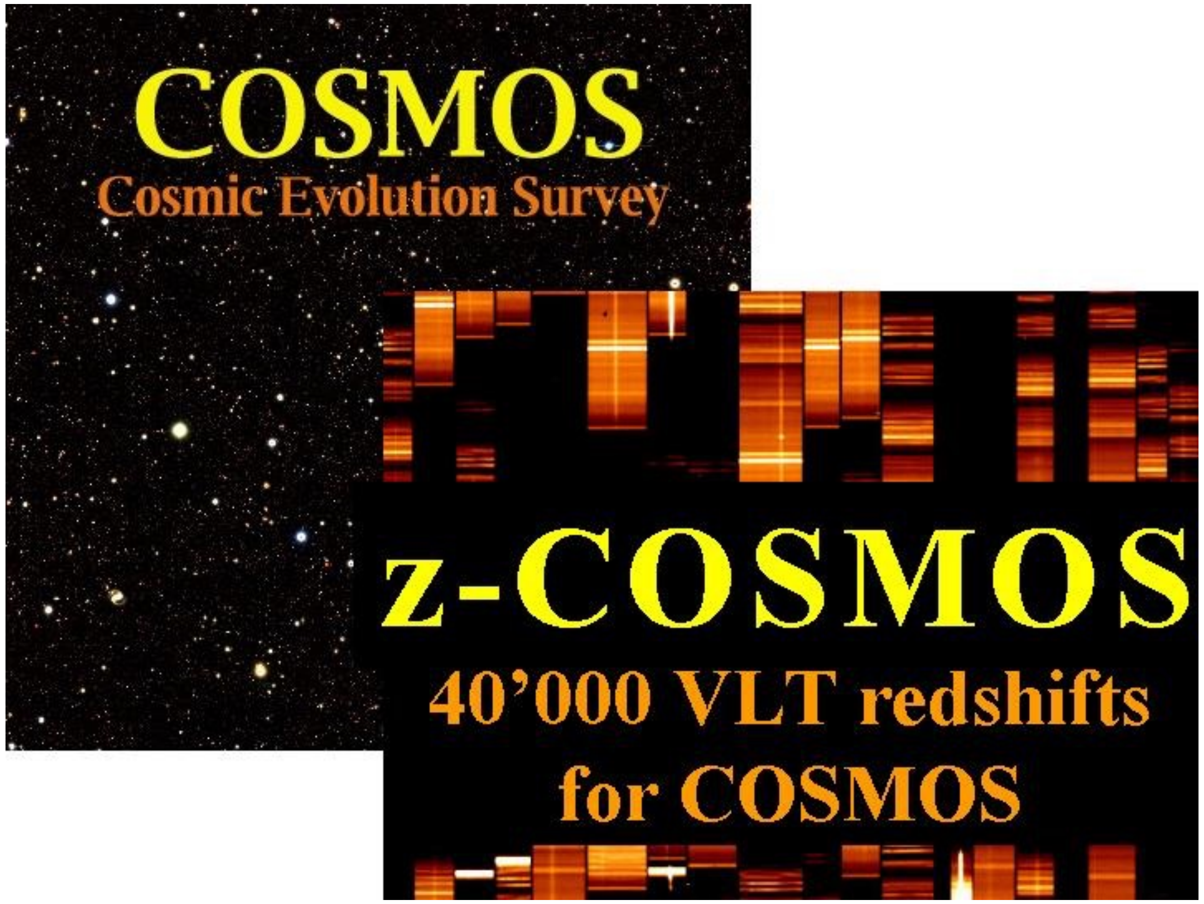
Stellar Mass

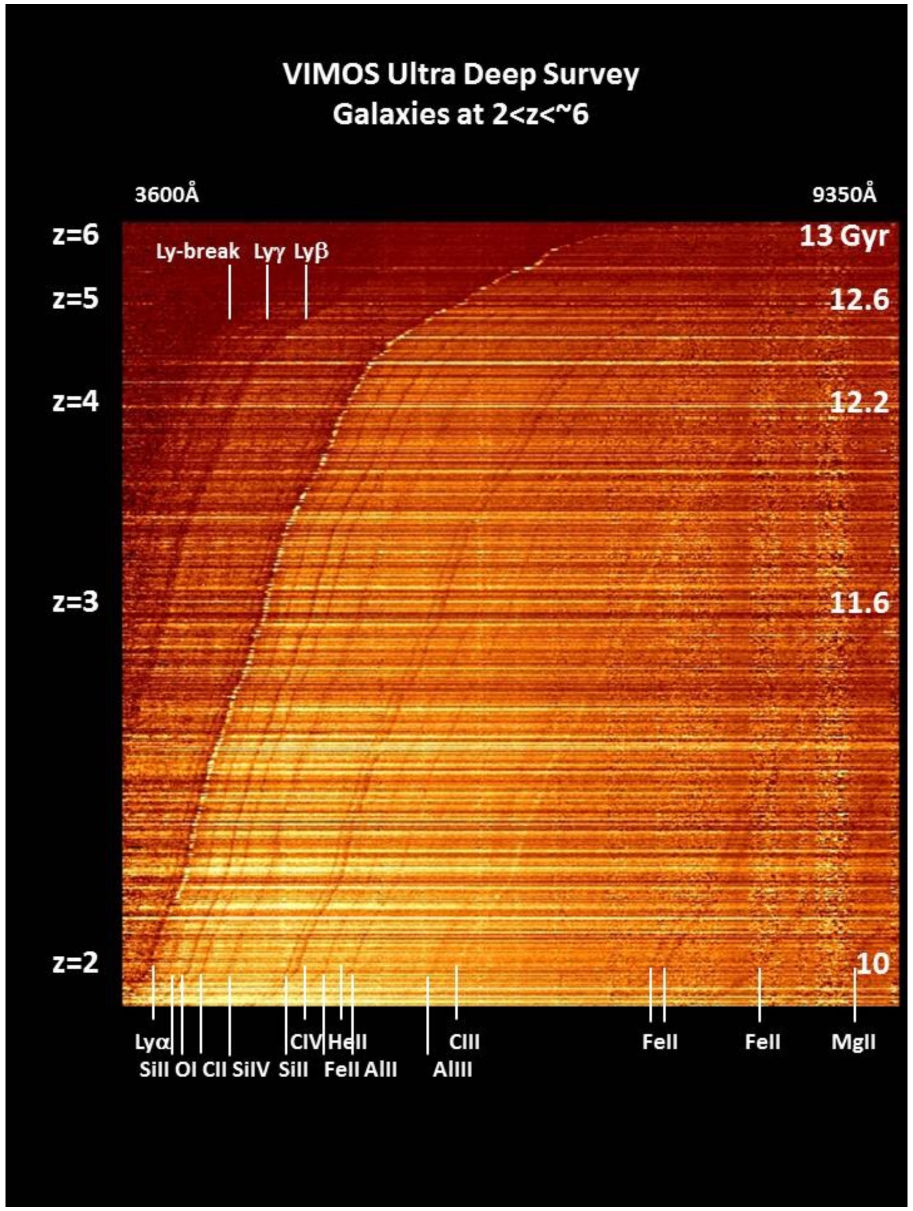
Spectroscopic surveys

Spectroscopic galaxy surveys require big telescope time investments

necessary to confirm photometric techniques and for precision studies

(e.g. study of galaxy pairs)

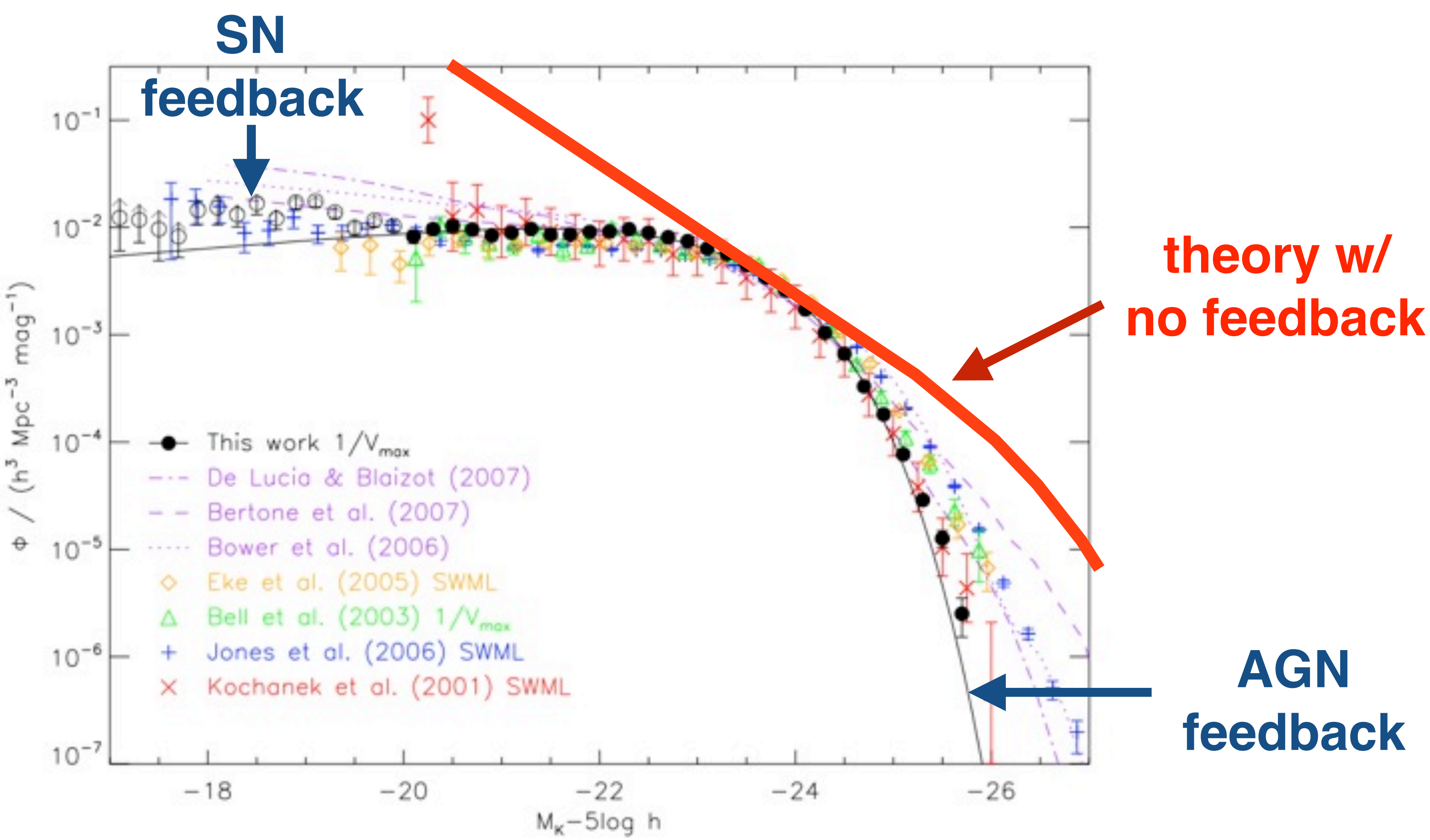




They usually require target pre-selection

Physics of High-z Galaxy Evolution

Galaxy luminosities: theory vs. observations

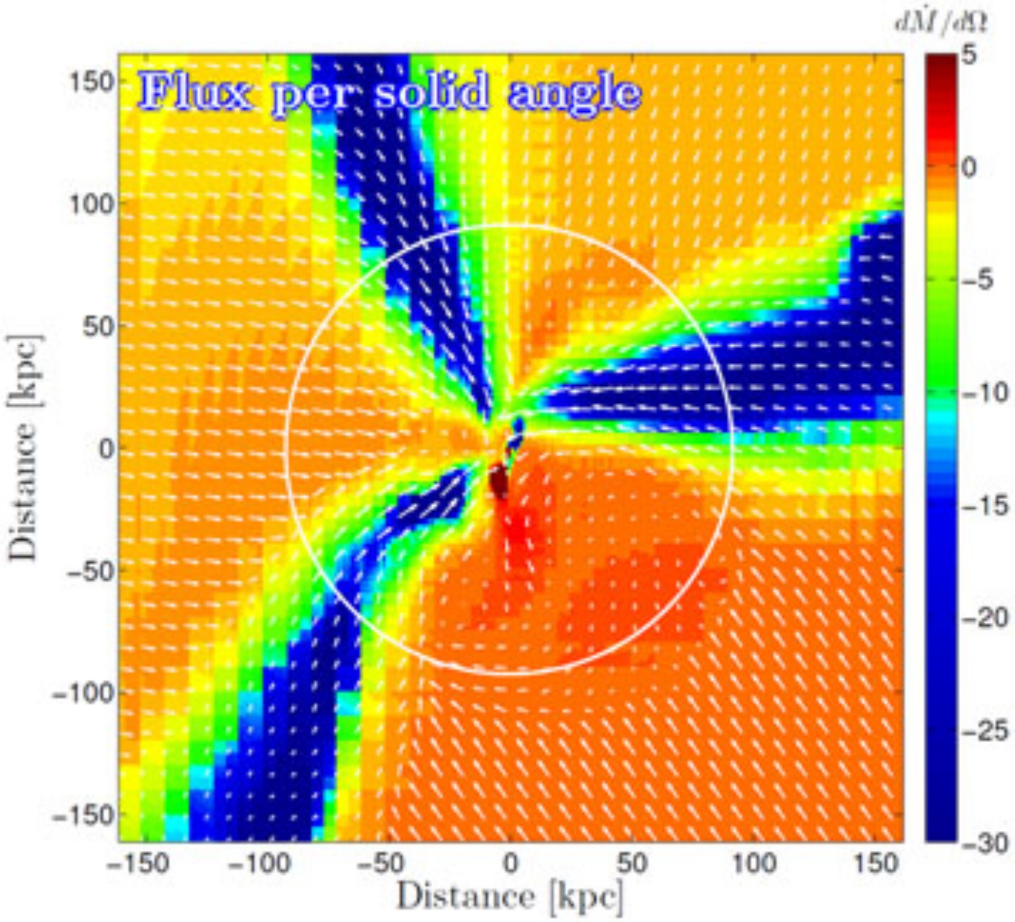


under the assumption that dark matter halos host gas: need to find mechanisms why conversion to stars is less efficient in low and high mass systems

either gas can never cool or gas gets reheated/removed

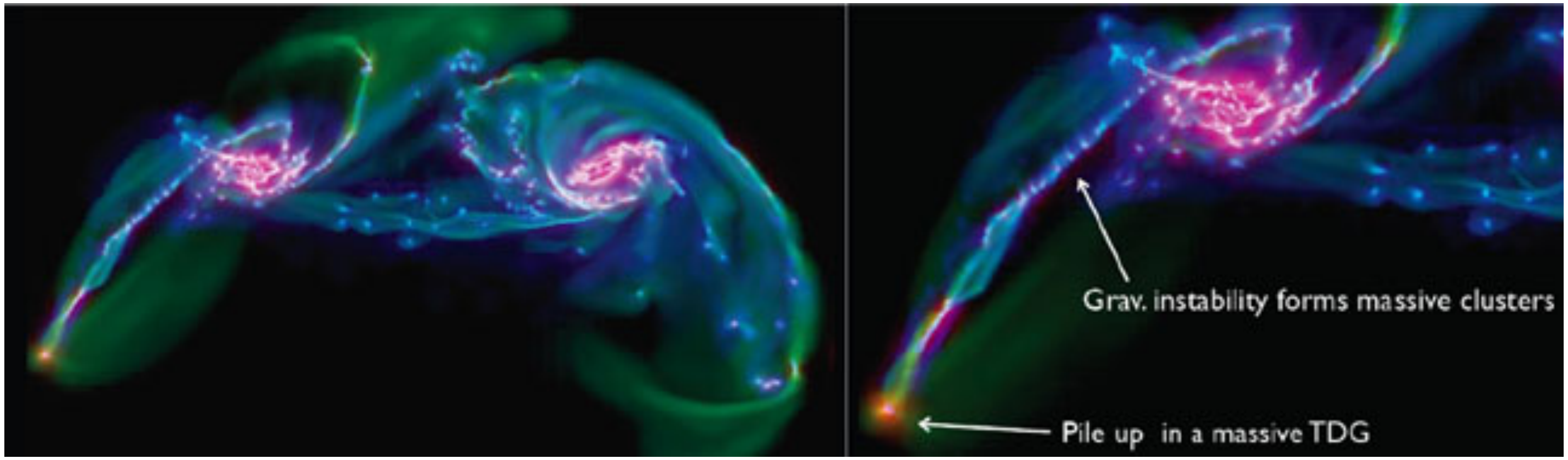
e.g. Springel et al. (2005); Somerville et al. (2008)

Star formation: cold flows versus mergers



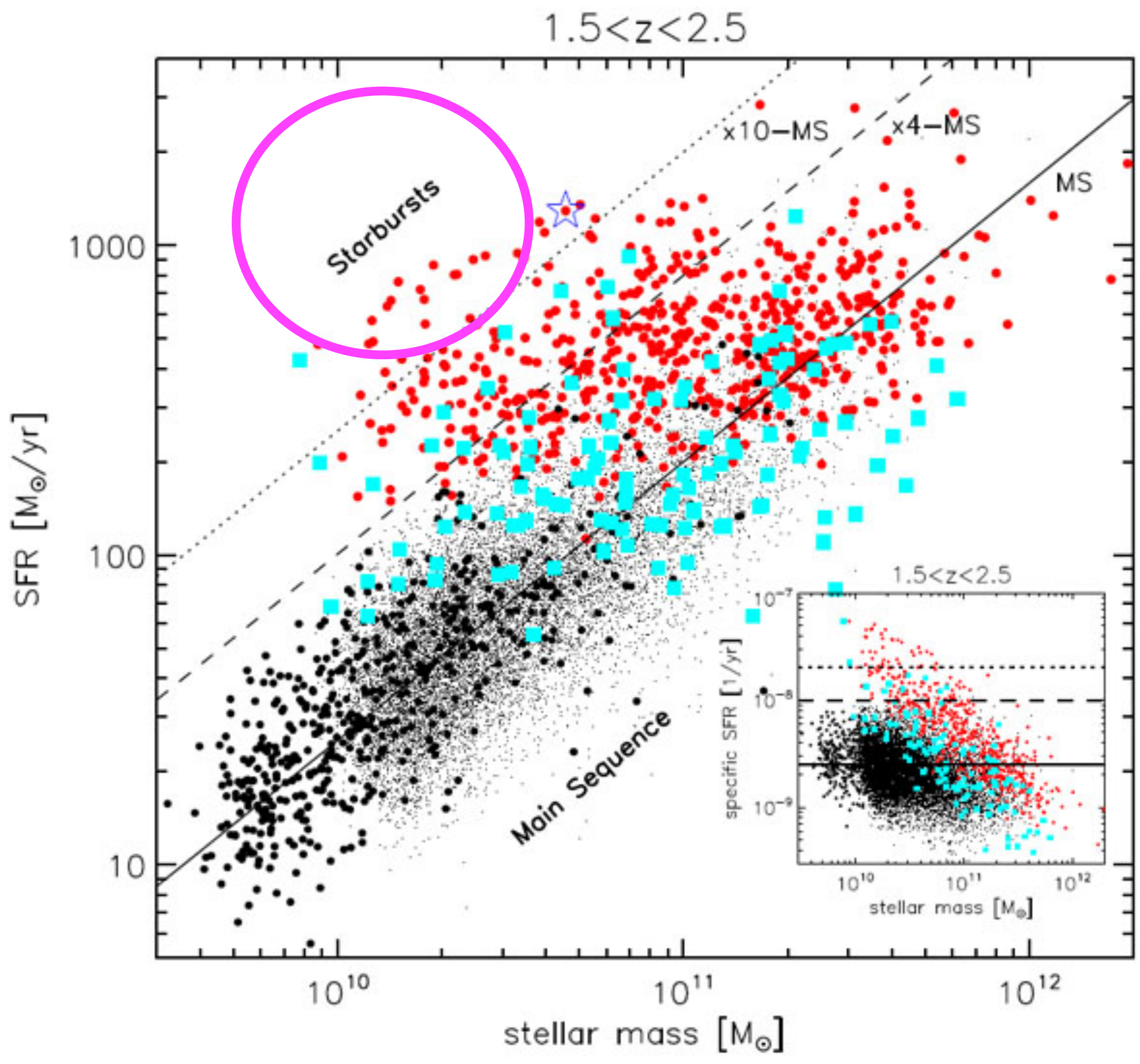
Dekel et al. (2009)

The relative importance of cold flows versus mergers is still under debate



Bournaud et al. (2010)

Observational constraints - the SFR-M* plane



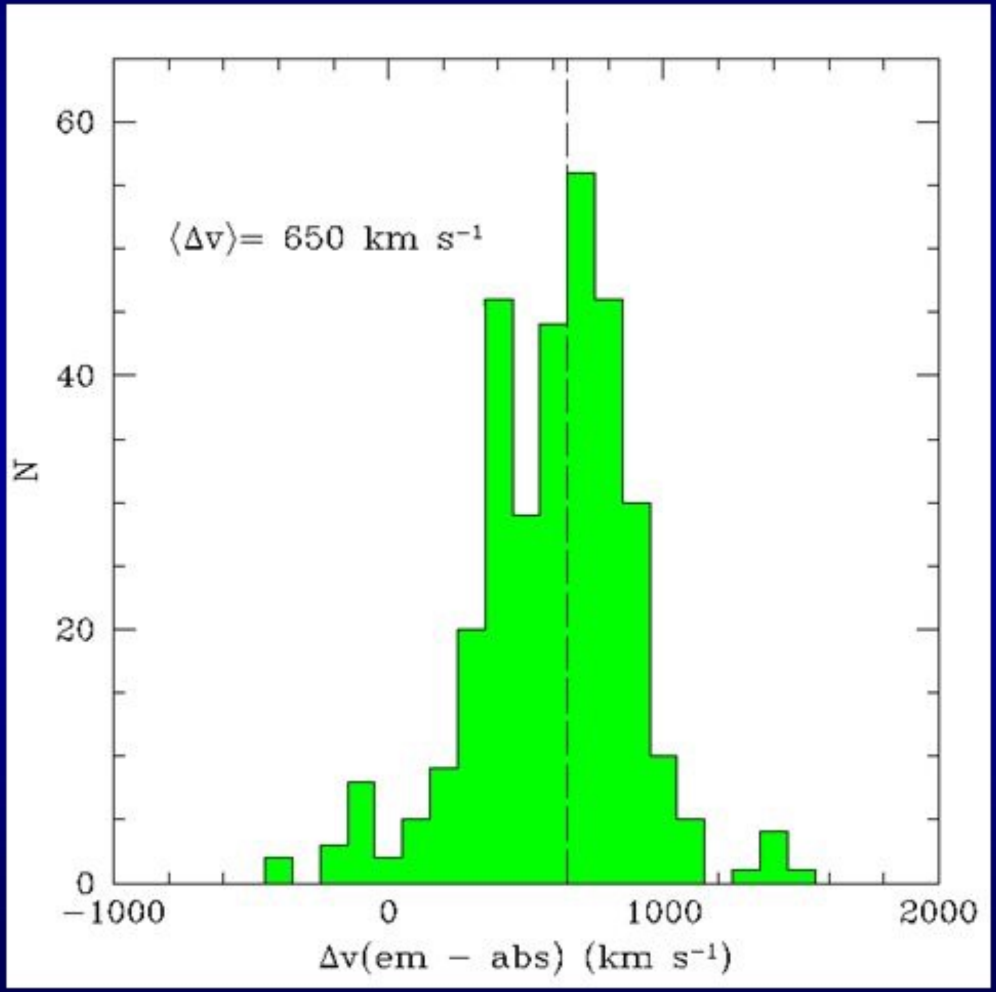
Starbursts may be more important than what it was thought a few years ago

but needs to look for them among galaxies with lower stellar masses

Rodighiero et al. (2011)

Searching for galaxy outflows

Evidence for outflows in spectra

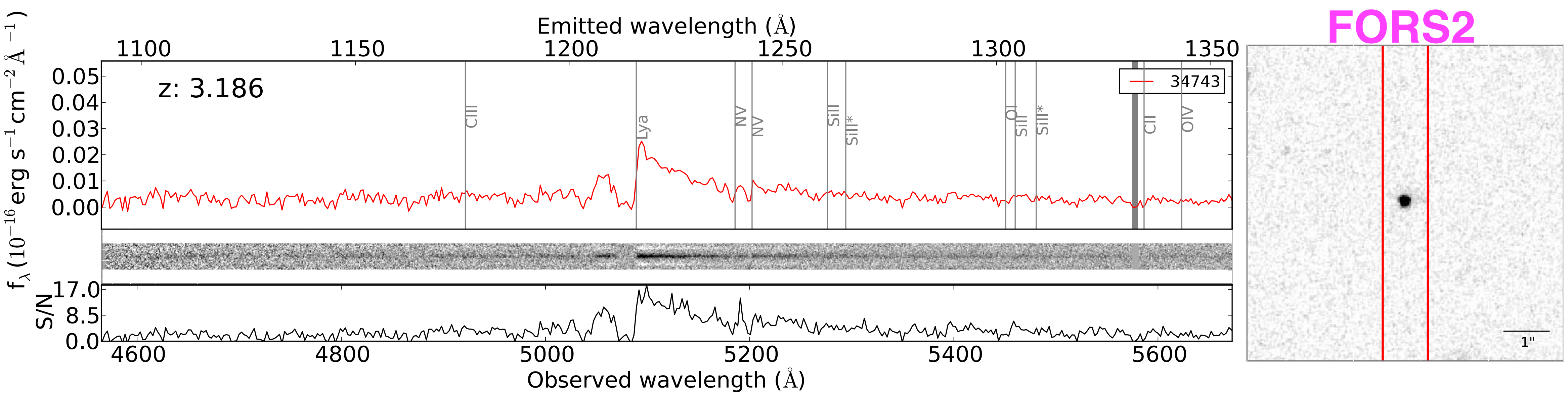


Velocity offsets (em-abs)

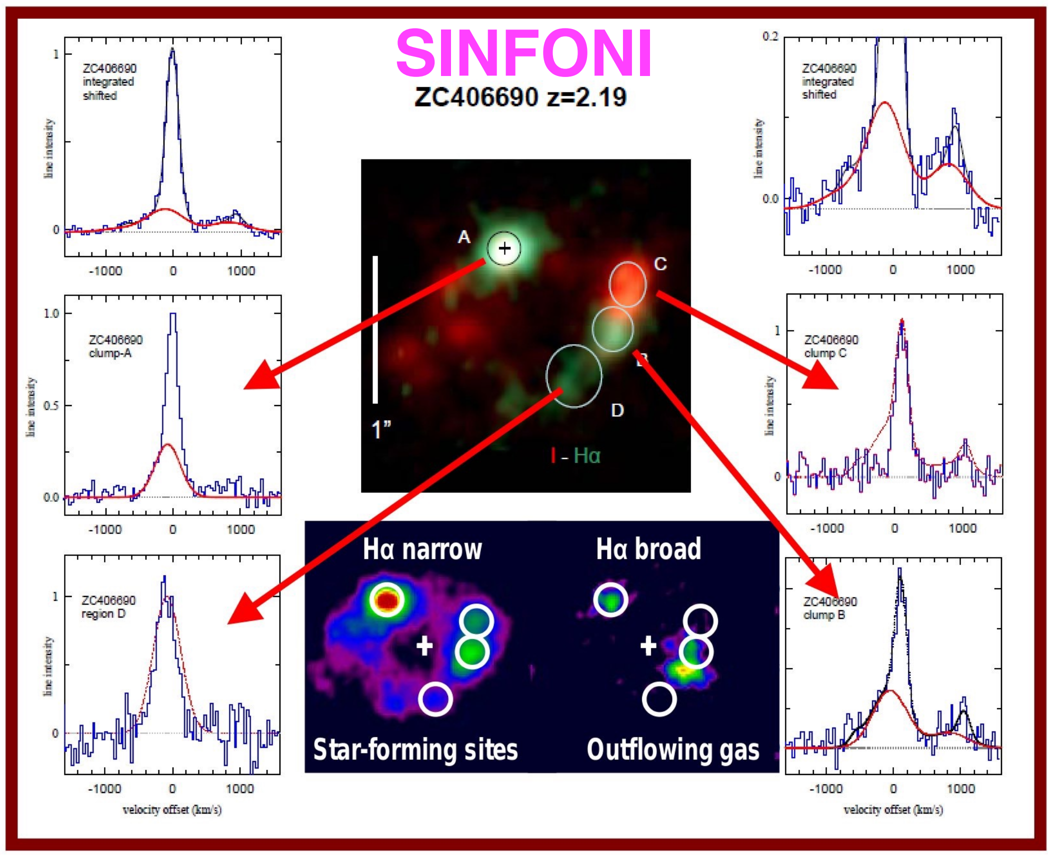
- **Redshifted Lyα**
- **Blueshifted IS abs**
- **Avg offset is 650 km s^{-1} (Δz=0.008) → outflow**
- **Stellar photospheric features are too weak to detect, so we need to guess what the systemic redshift is**

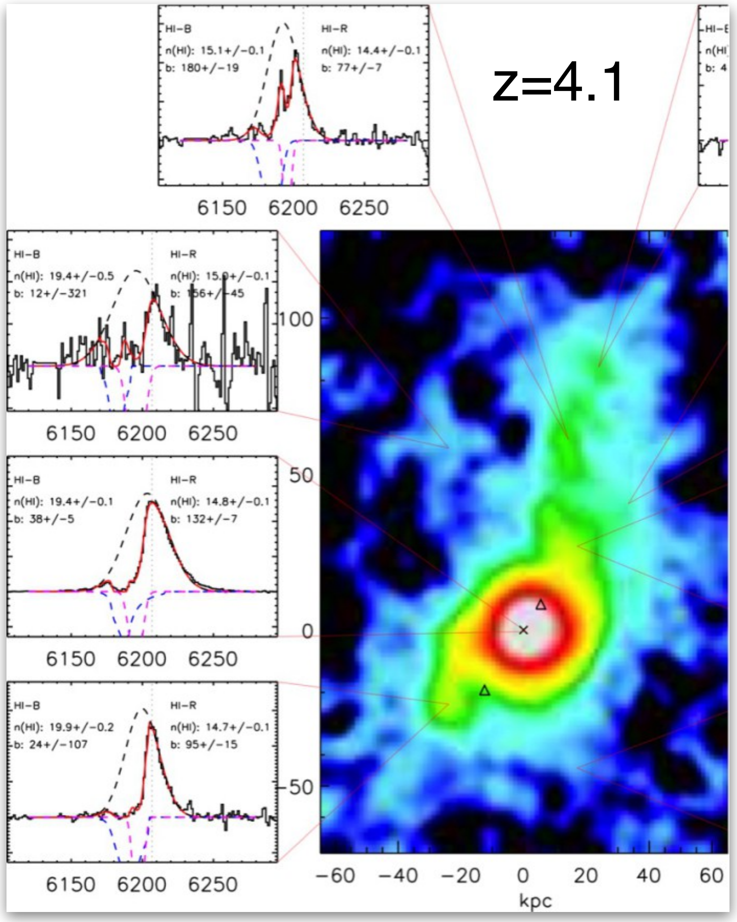
(Shapley et al. 2003)

Physics of star formation - gas outflows



Karman, KC et al. (2014)





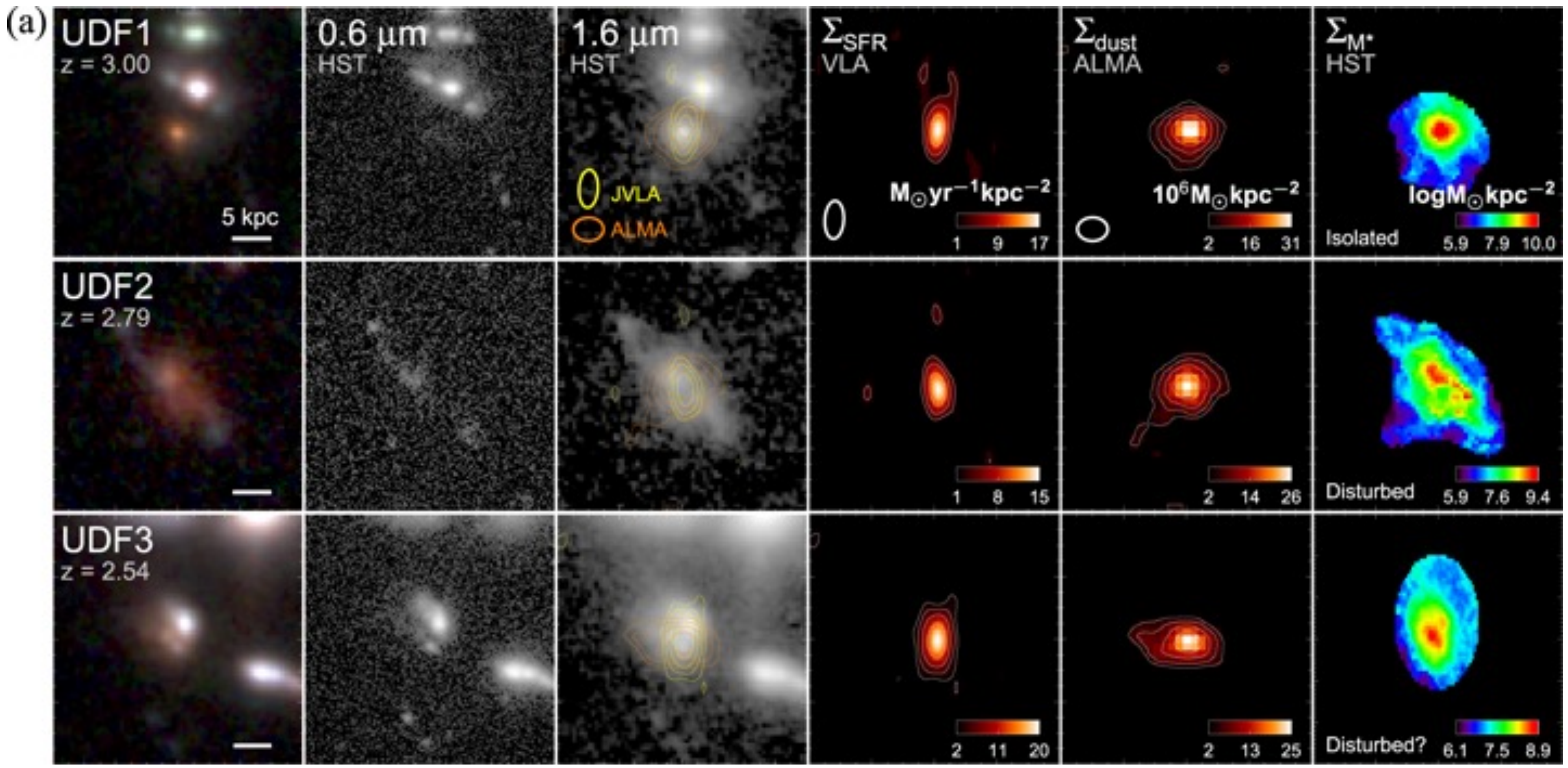
Newman et al. (2012)

Swinbank et al. (2015)

Dusty Galaxies at High z

Dust in the young Universe

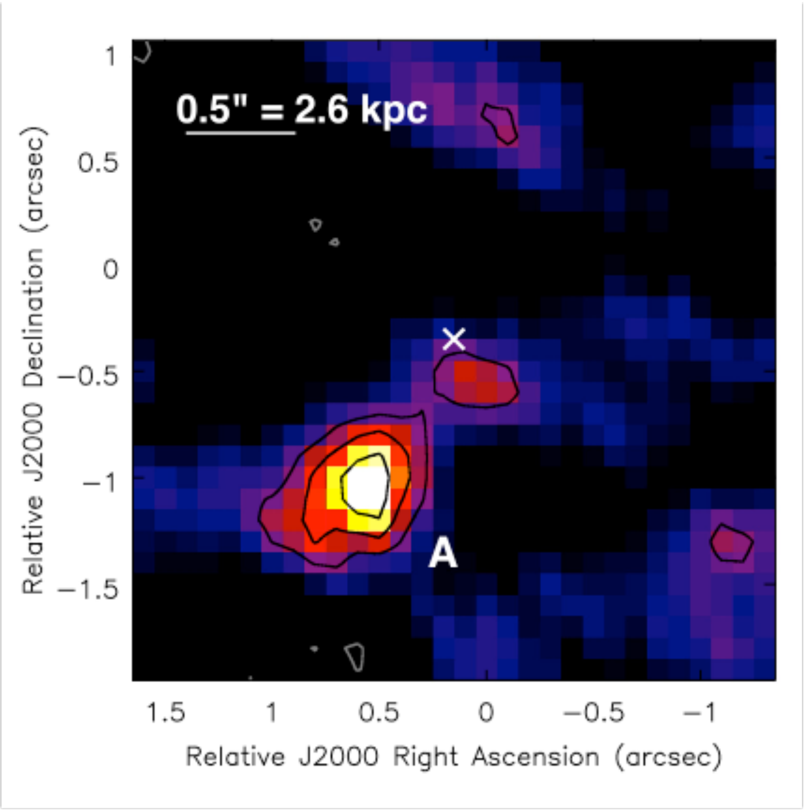
z~2



Rujopakarn et al. (2016)

Dust was very common in galaxies at z~2-4 (Universe was 1.5-3.5 Gyr old)

z~7



Maiolino et al. (2015)

Dust is rare in the first billion years, but evidence of dust has been found in galaxies up to z~7-8.