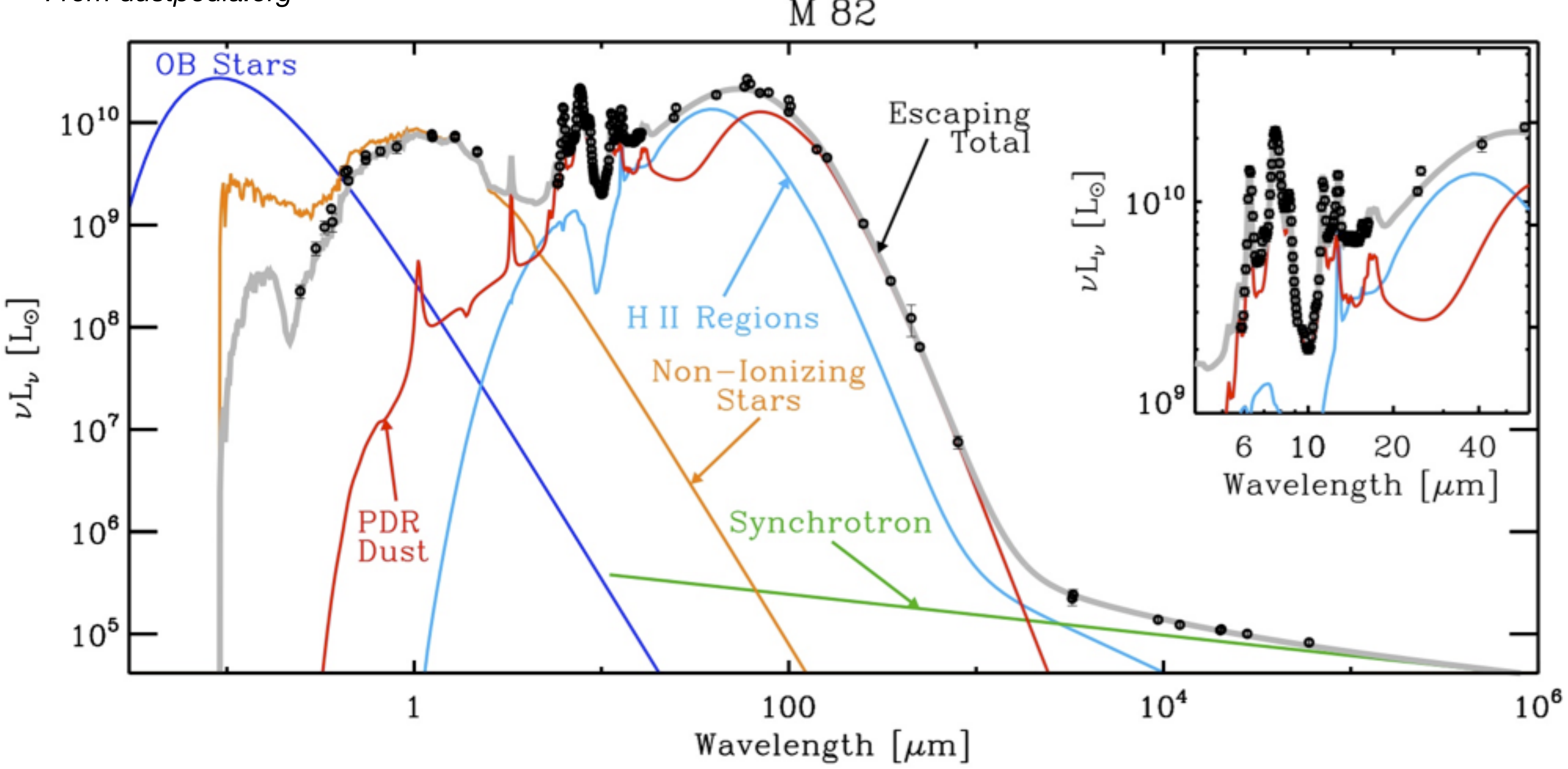
High-z galaxies

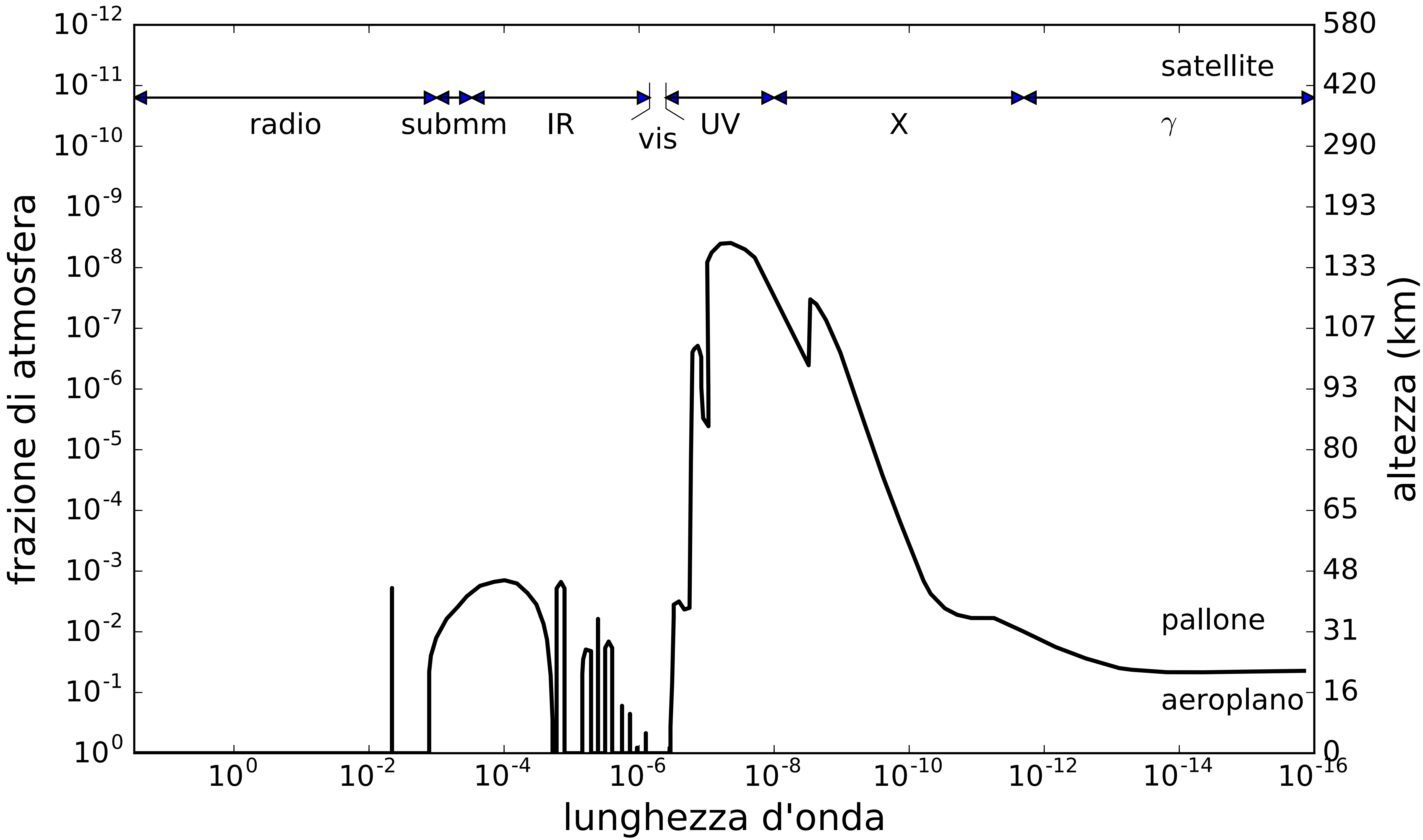
Pierluigi Monaco,
Galaxy Formation
PhD course 2019

From dustpedia.org



Observing the deep sky

Atmospheric absorption



banda	sotto-banda	λ
RADIO	(non oss.) radio microonde	>30m 30m – 3cm 3cm – 1mm
sub-mm		1mm – 300μ
IR	FIR MIR NIR	300μ – 30μ 30μ – 5μ 5μ – 7000Å
ottico (visuale)		7000Å – 4000Å
UV	NUV soft UV EUV	4000Å – 3100Å 3100Å – 912Å 912Å – 100Å
X	soft X hard X	100Å – 10Å 10Å – 0.02Å
γ		<0.02Å

λ	assorbimento	osservazioni
$>$ 300m	plasma interplanetario	opaco
$>$ 30m	ionosfera	(satellite)
30m – 3cm	finestra radio	da terra
3cm – 1mm	H_2O e O_2	alta montagna
1mm – 10μ	H_2O, O_2, CO_2	pallone o satellite
850μ e 450μ	finestre sub-mm	alta montagna
10μ – 7000Å	H_2O, molte finestre	alta montagna
7000Å – 3100Å	finestra ottica	da terra
3100Å – 912Å	O_3	satellite
~912Å	HI galattico	quasi opaco
$\lesssim$ 100Å	ionizzazione di stratosfera	satellite
$\lesssim$ 0.02Å	*scattering* Compton etc.	satellite
$E >$ 100GeV	creazione di sciami	da terra

Angular resolution:

- diffraction limit
- seeing (atmospheric turbulence)
- ability to deflect photons

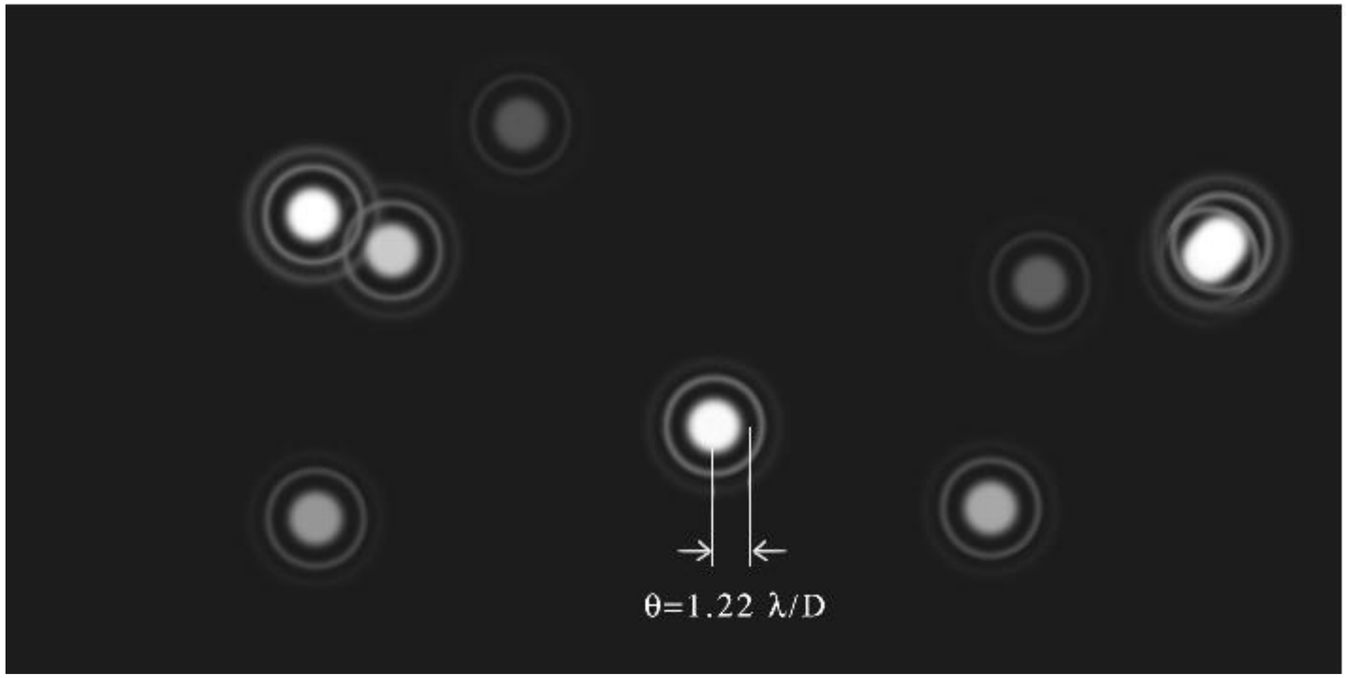
Spectral resolution:

- slitless spectroscopy,
- slits,
- Multi-Objects Spectroscopy (MOS),
- Integral Field Units (IFU)

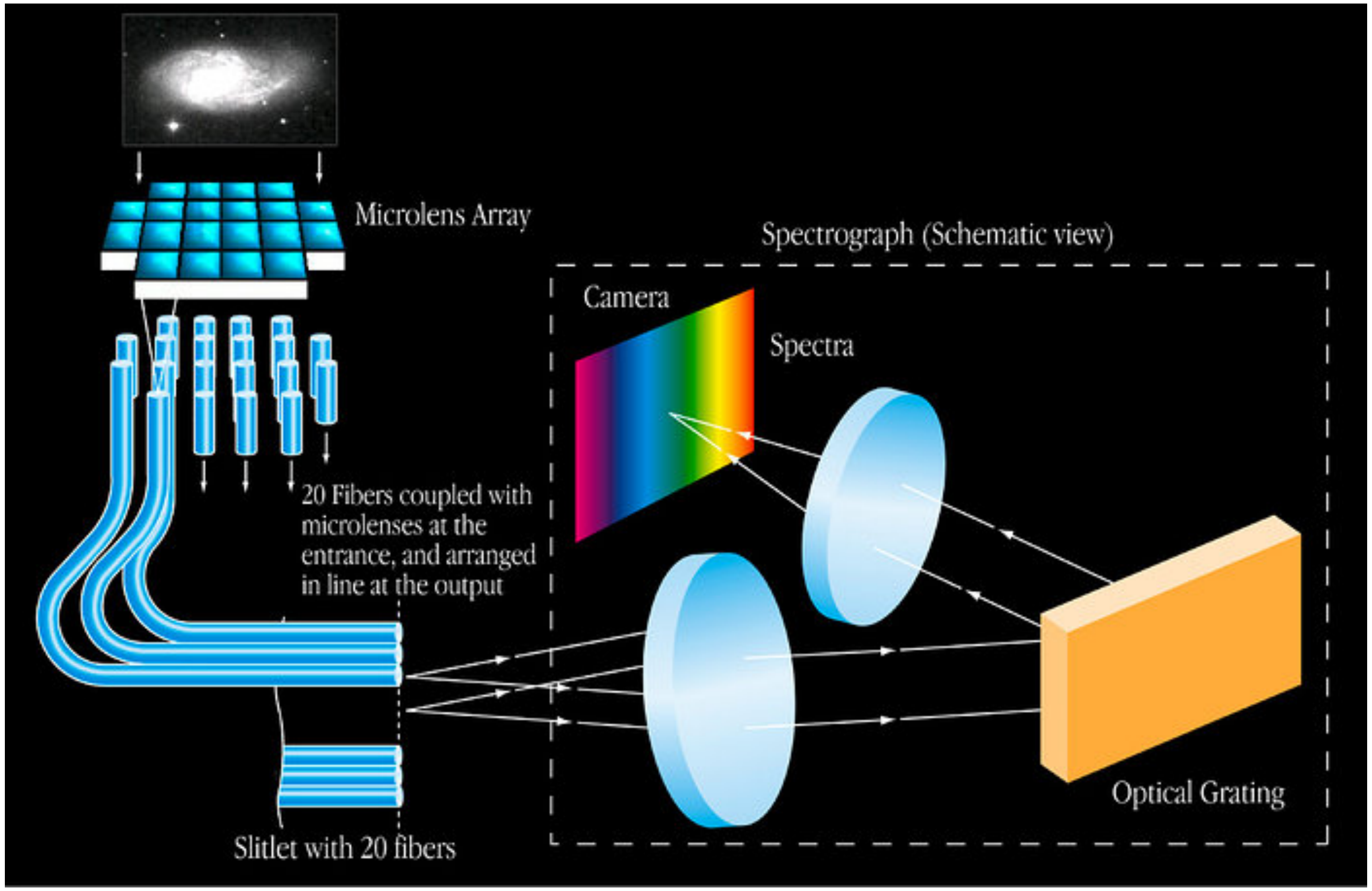
Image depth (given the exposure time!):

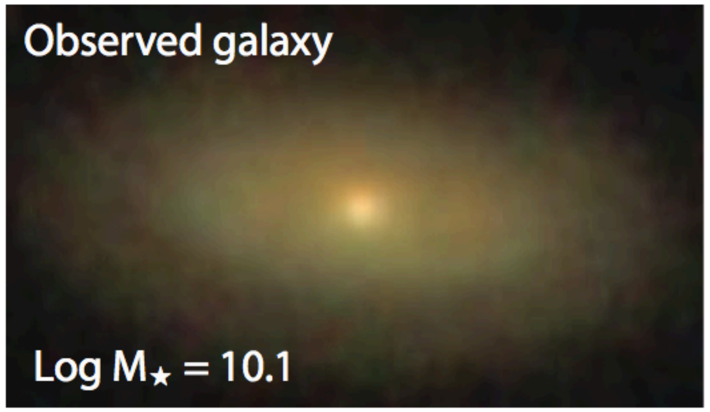
- telescope size
- detector sensitivity
- backgrounds
- angular resolution / confusion limit

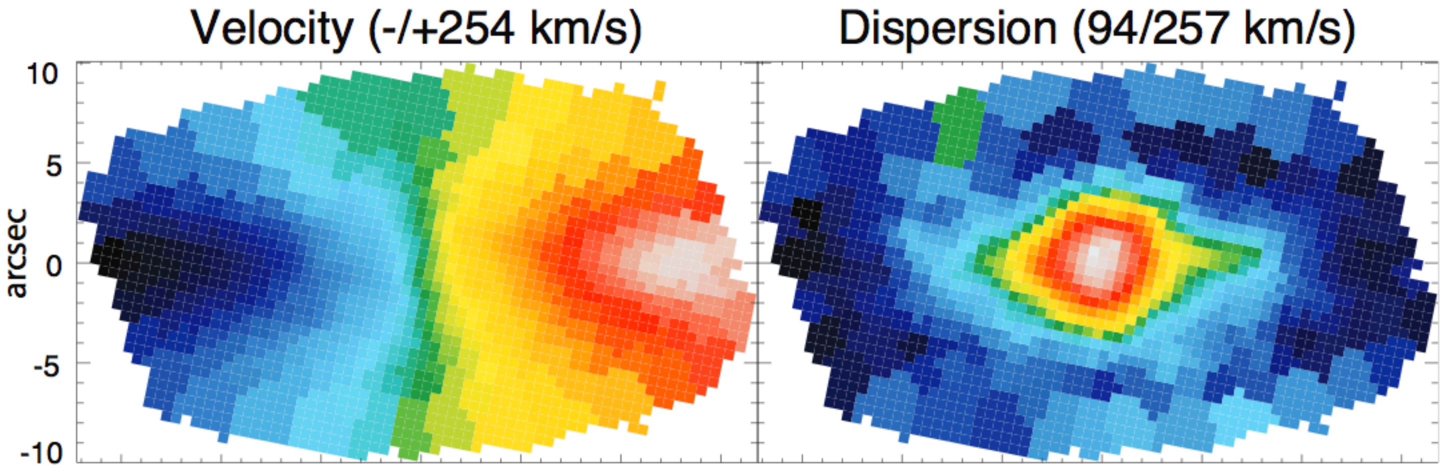
Survey vs pointings!



Integral field units







From stellar spectra to galaxy SEDs

Needed ingredients:

Stellar spectra libraries

Stellar evolution models

Stellar Initial Mass Function (IMF)

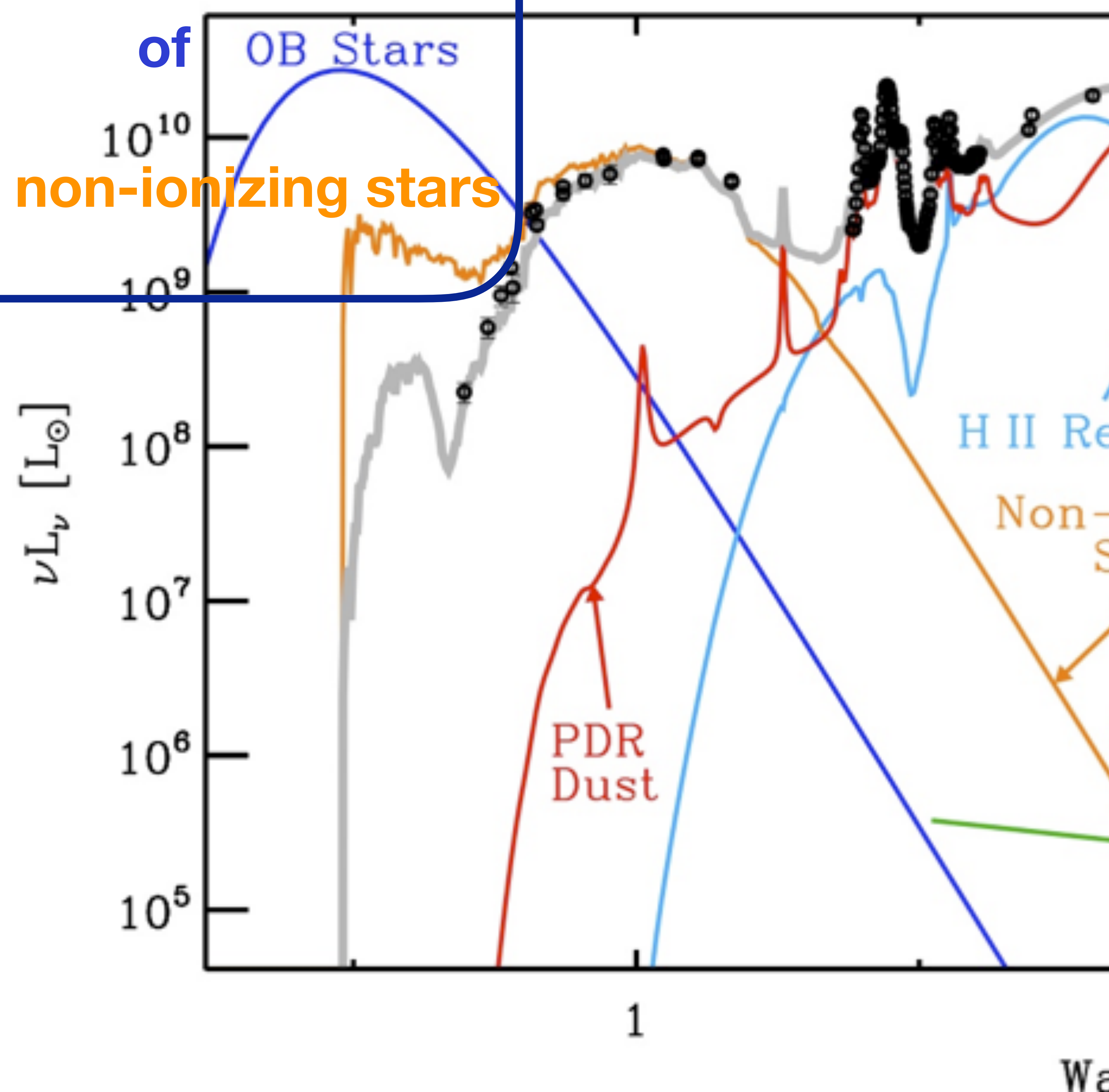
Star Formation Rate - SFR(t)

Gas metallicity Z(t)

un-extincted stellar light

of

and of non-ionizing stars



SED of a Simple Stellar Population (SSP)

An SSP is a population of stars that share the same age and metallicity.

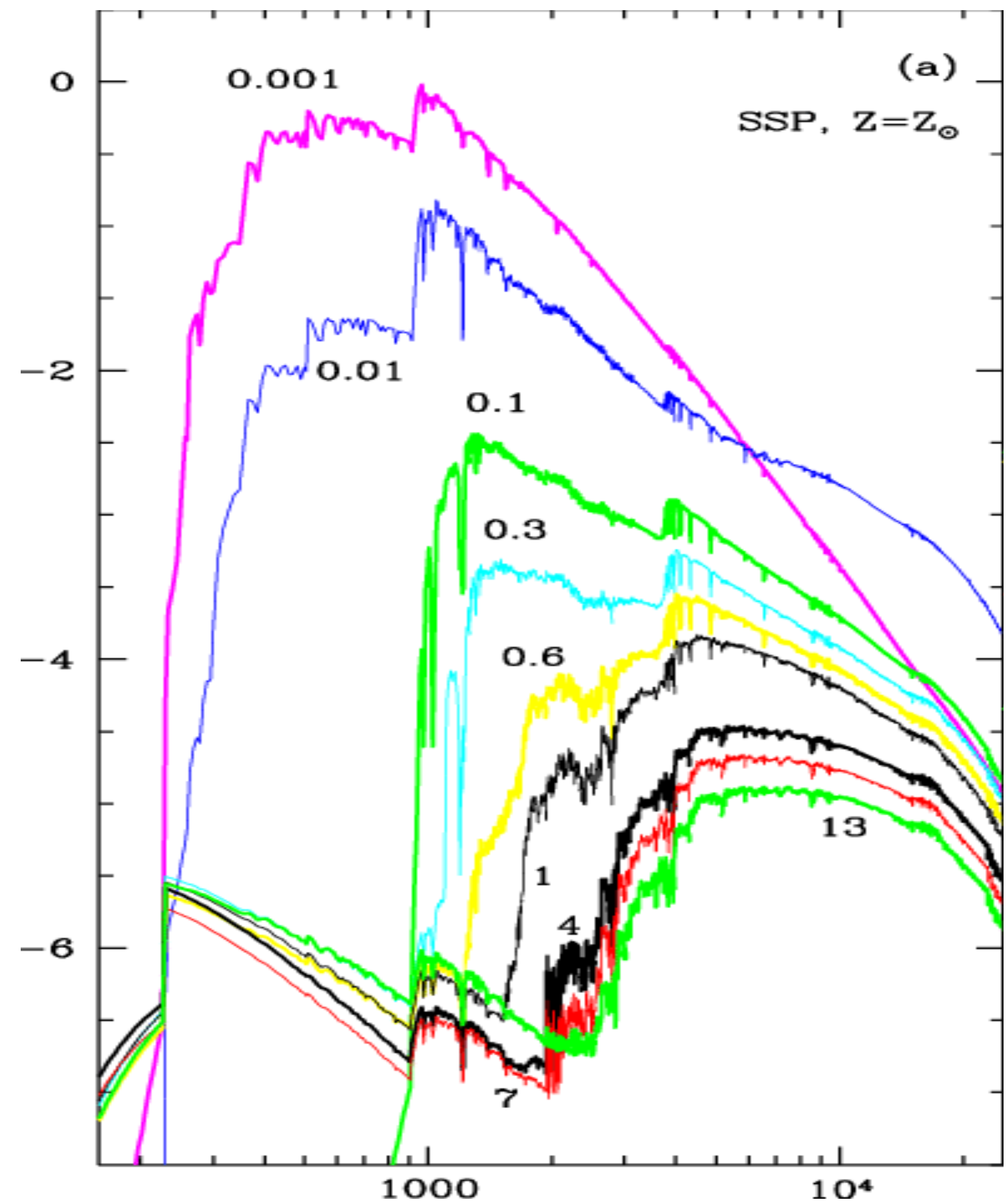
A star cluster may be a good example of SSP - with the exception of the early evolution phases, where the little age differences between stars can be important.

Parameters are:

- (luminosities scale with) mass,
- stellar age,
- stellar metallicity,
- stellar IMF,

plus:

- spectral libraries,
- stellar tracks.



Bruzual 2000, arXiv:astro-ph/0011094

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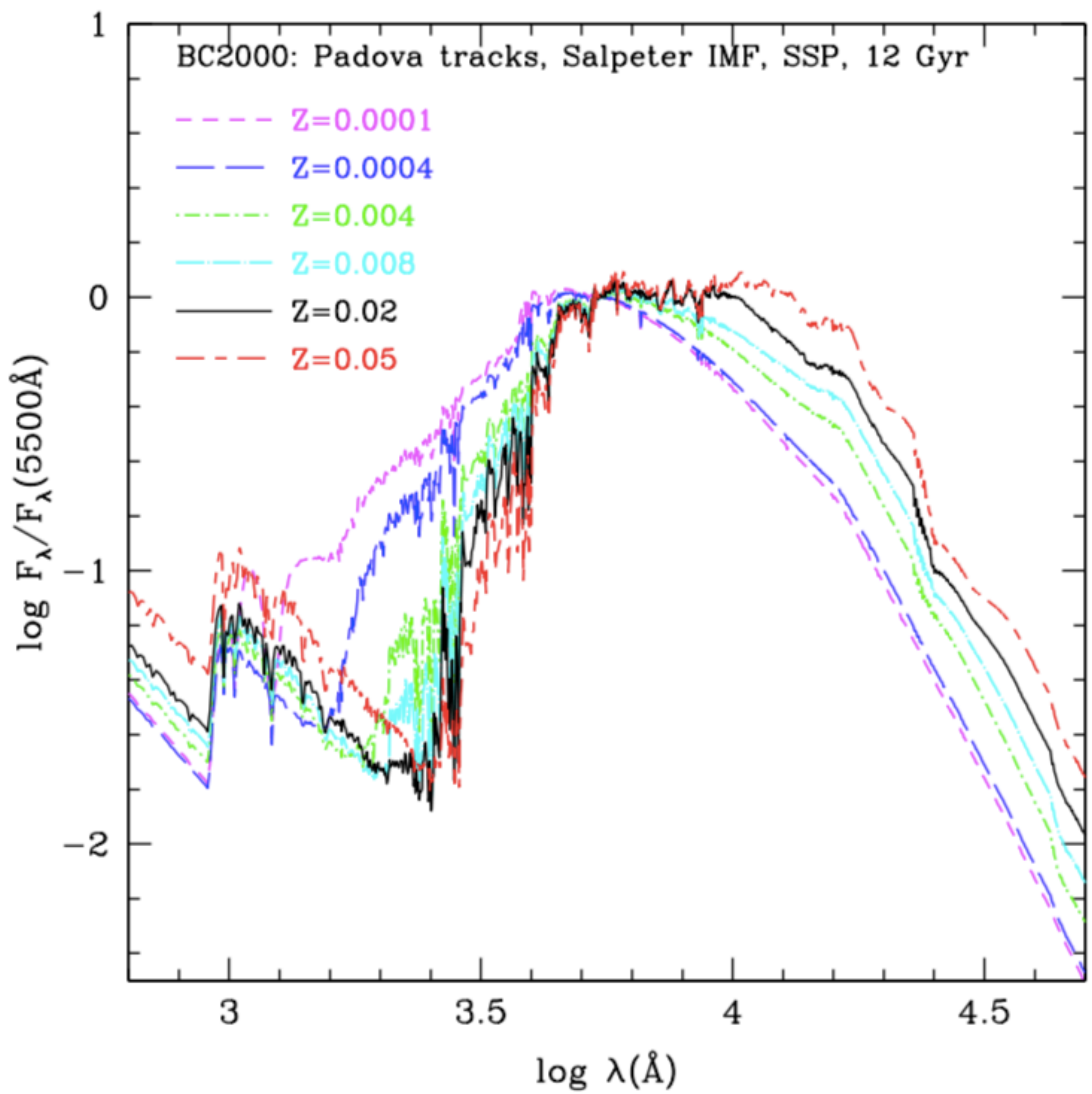
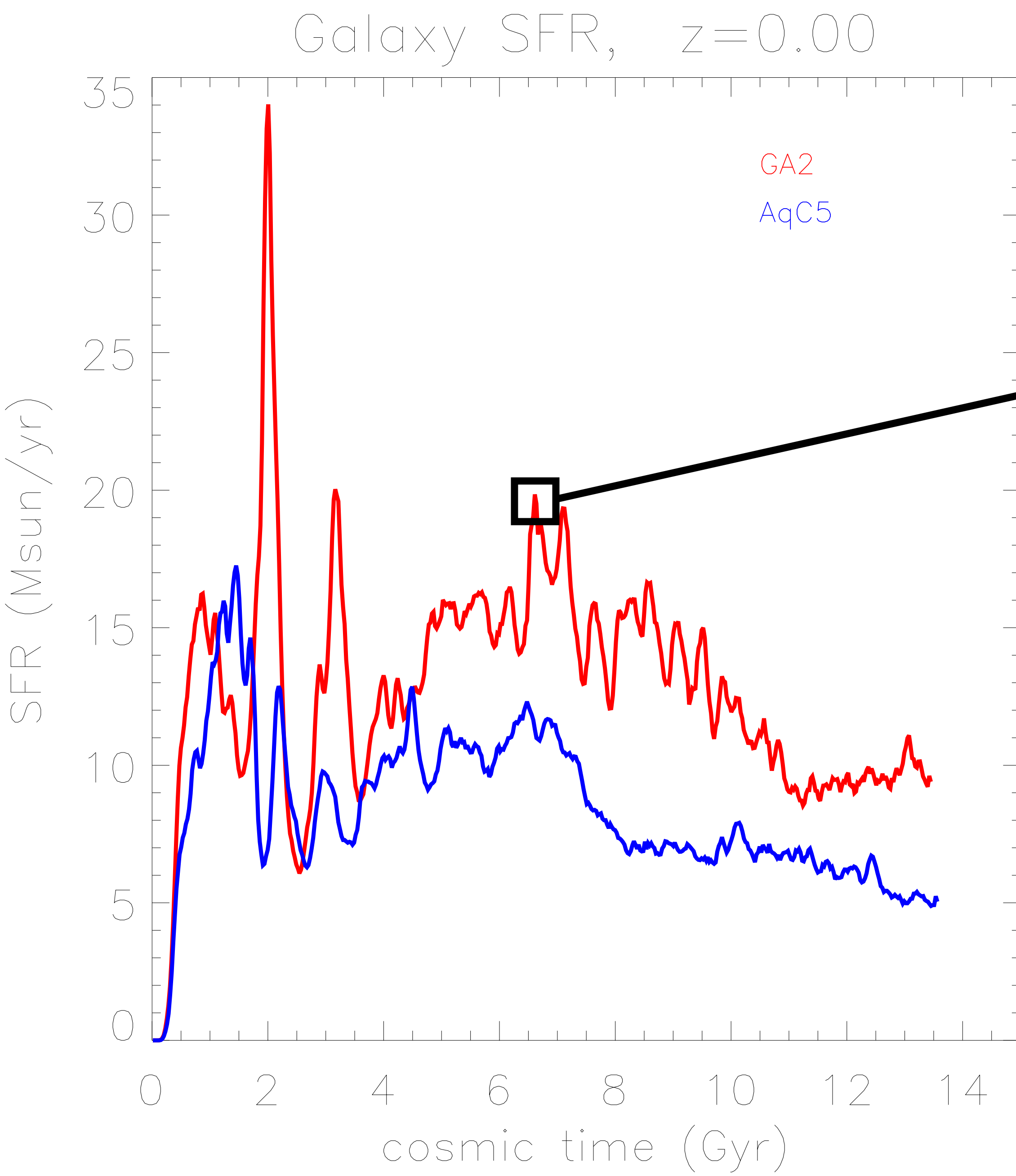


Bruzual 2000, arXiv:astro-ph/0011094

SED of a stellar population with a complex SFR(t)



Stars formed in a time interval are treated like an SSP

as an example,
SFR of a simulated galaxy,
Murante et al. 2015,
MNRAS 447, 178

$$L_\nu = \int_o^{t_0} dt\ SFR(t)\ L_\nu^{(\mathrm{SSP},1\,\mathrm{M}_\odot)}(t_0 - t, Z_{\mathrm{gas}}(t))$$

$$L_\nu^{(\mathrm{SSP},1\,\mathrm{M}_\odot)}(t_0 - t, Z_{\mathrm{gas}}(t)) = \mathrm{const} \times \int_{m_l}^{m_u} dm\ \boxed{\phi(m)}\ L_\nu^{\mathrm{star}}(m, t_0 - t, Z)$$

IMF

Adding dust

Historical evidence for dust: Trumpler, 1930

The apparent size of an open cluster decreases like the inverse of the diameter distance.

The total flux of an open cluster decreases like the inverse square of the luminosity distance.

If open clusters have on average the same size and luminosity, one can get their luminosity ("photometric" in the plot) and diameter distances from observed flux and angular size.

As we are inside the galaxy, luminosity and diameter distances are the same.

Extinction of more distant objects is revealed by a flattening of the relation of luminosity vs diameter distance.

Because it is a continuum absorption, it must be due to dust.

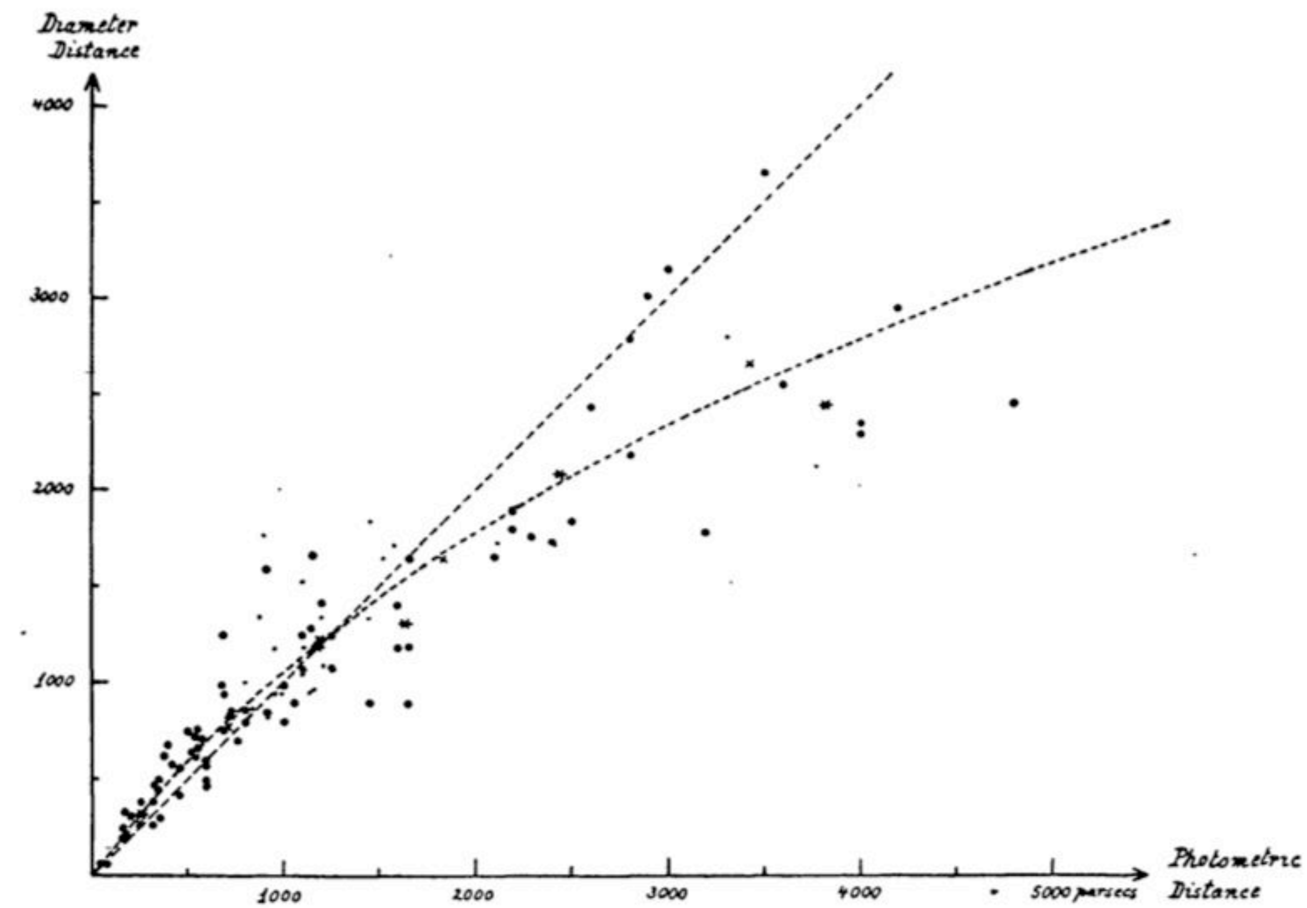


FIG. 1.—Comparison of the distances of 100 open star clusters determined from apparent magnitudes and spectral types (abscissae) with those determined from angular diameters (ordinates). The large dots refer to clusters with well-determined photometric distances, the small dots to clusters with less certain data (half weight). The asterisks and crosses represent group means. If no general space absorption were present, the clusters should fall along the dotted straight line; the dotted curve gives the relation between the two distance measures for a general absorption of $0^{m}.7$ per 1000 parsecs.

Size distribution: from a few Å (PAH molecules) to ~1-10 μm, with max at ~0.5 μm (~the wavelength of visible light).

Composition: C, Si, O, Mg, Fe. two main groups carbonaceous (graphite and/or amorphous C) and silicate (Mg+Fe+Si+0, eg olivine) grains.

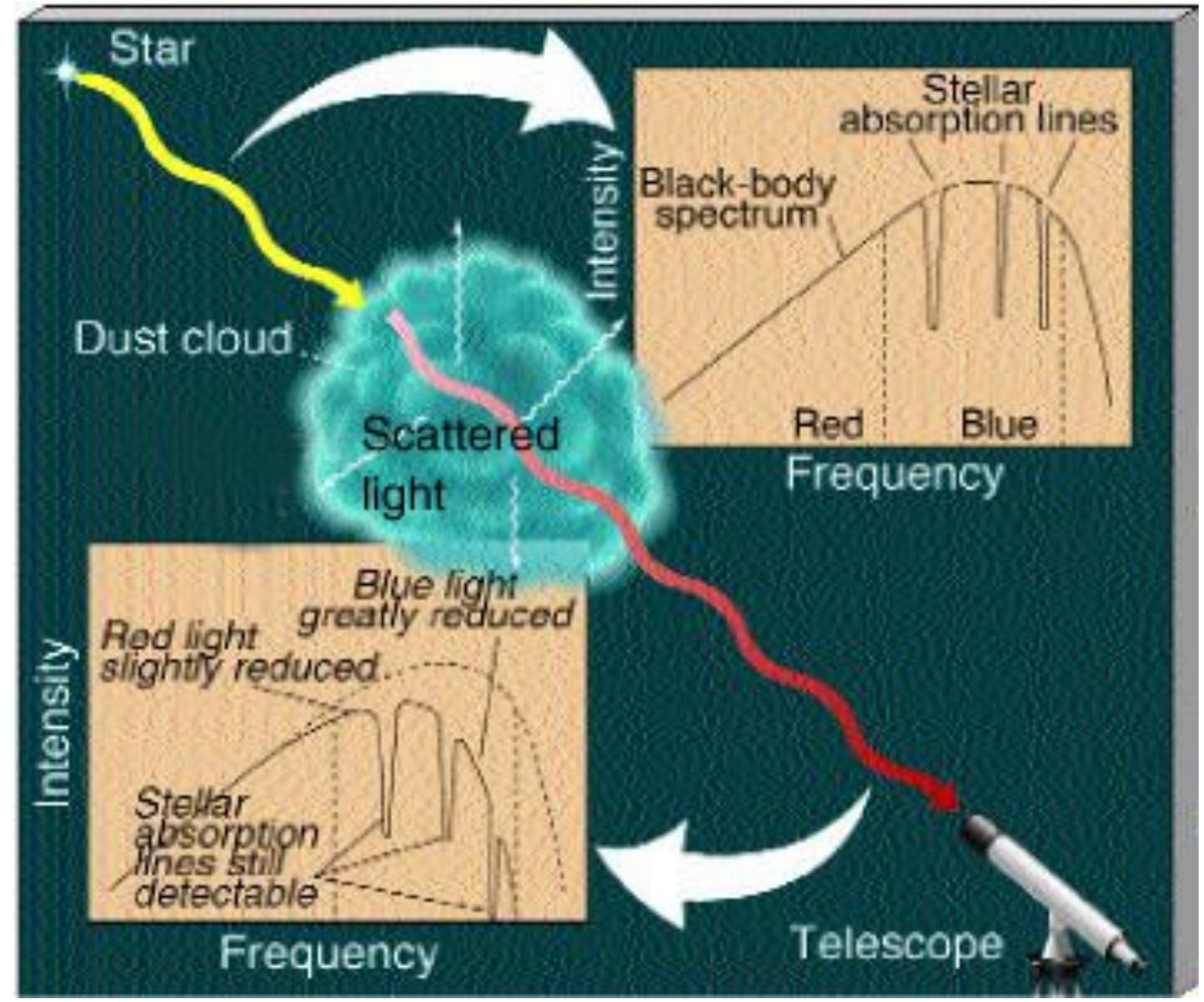
Typically from 0.5 to 1% of ISM mass is in dust at z=0, about 1/2 of heavy elements are *depleted* to dust.

Dust particles interact with photons emitted by astrophysical objects, mostly at optical/UV wavelengths:

- absorption,
- scattering,
- polarization.

Absorbed energy is then thermally re-radiated at λ~ 10-100 μm

The effect of dust



reddening:

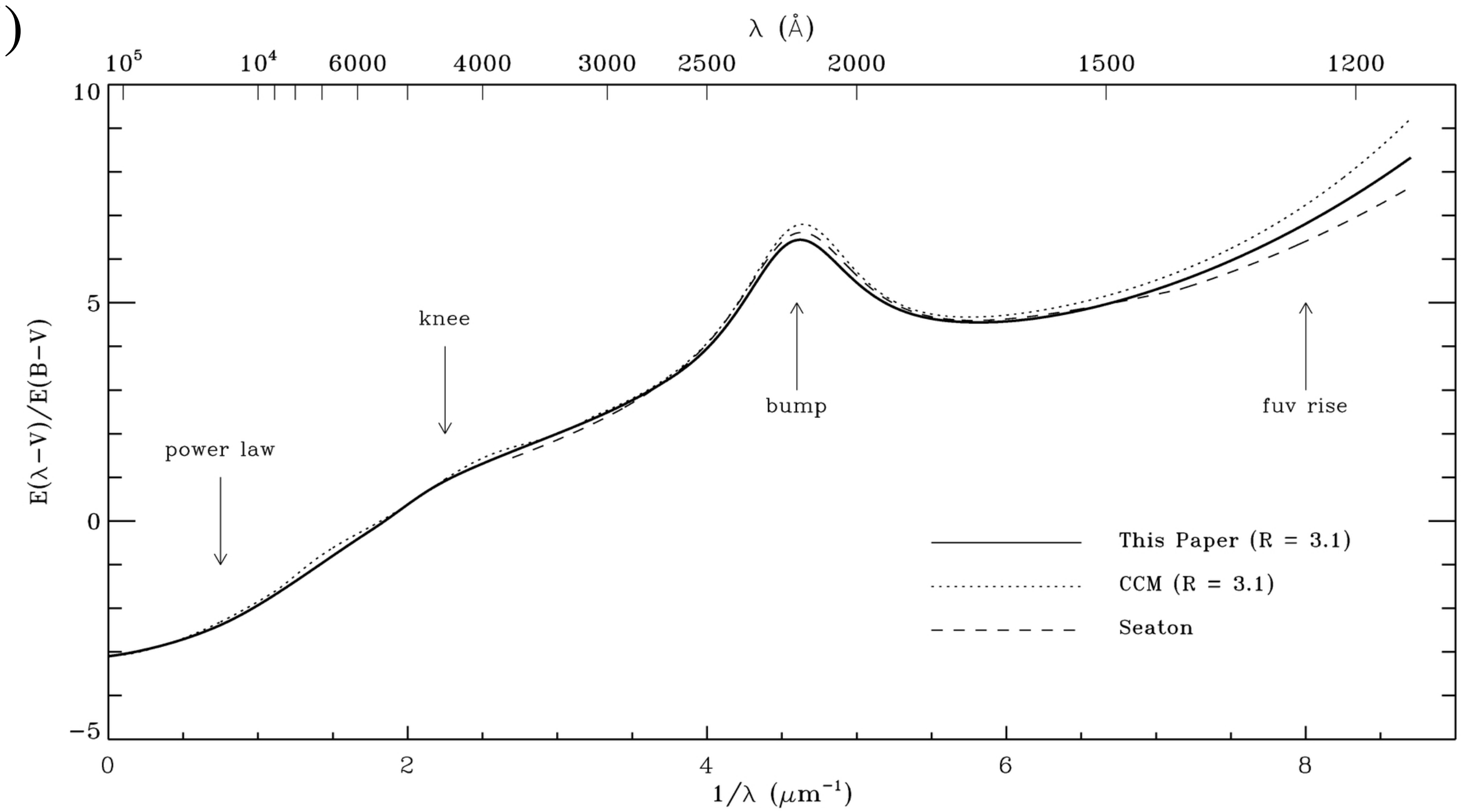
$$E(B-V) := (B-V)_{\rm obs} - (B-V)_{\rm true}$$

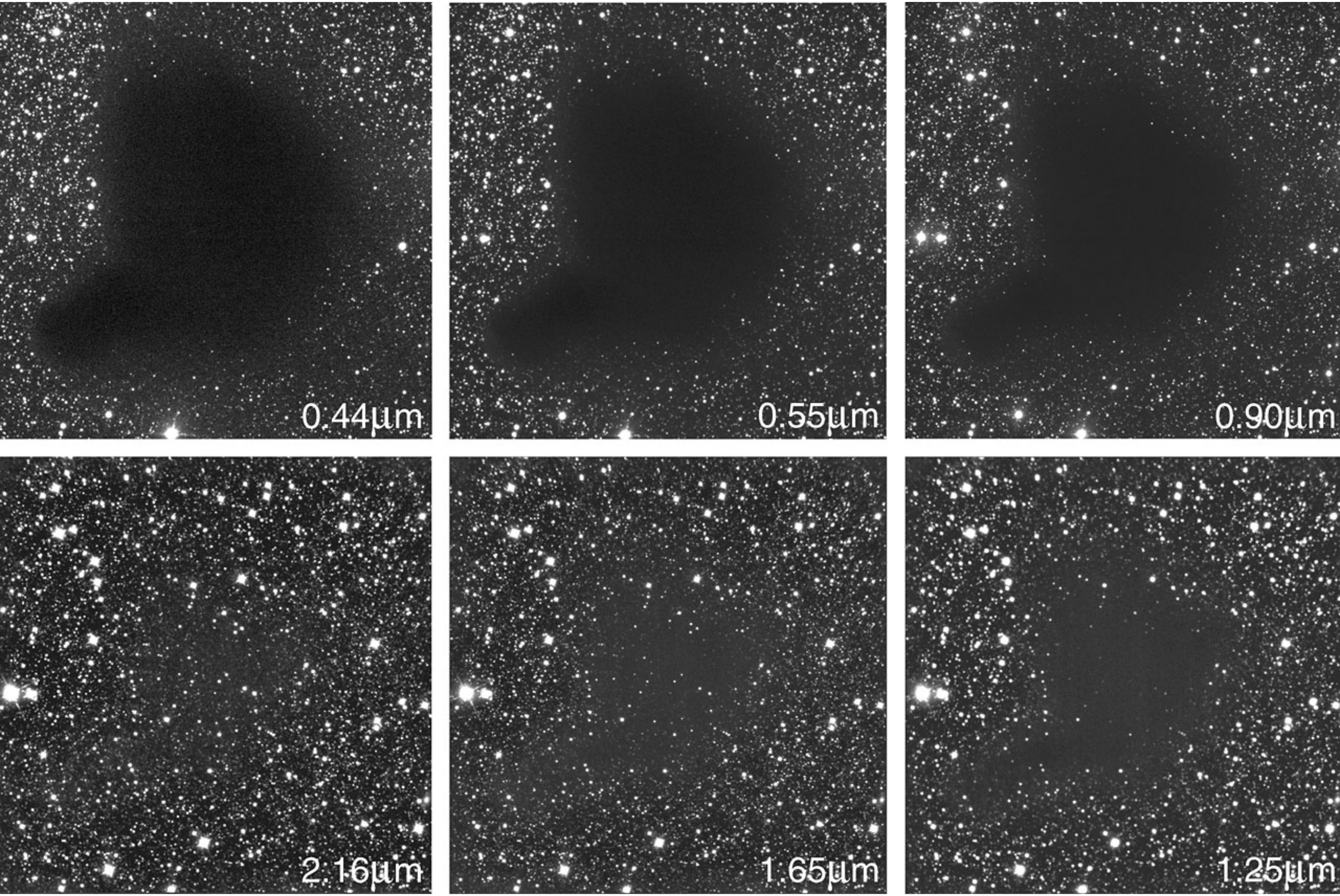
extinction in the V band:

$$A_V = m_V - m_{V,\rm true} = R_V\, E(B-V)$$

extinction at wavelength λ :

$$A_\lambda = R(\lambda)\, E(B-V)$$




0.44µm
0.55µm
0.90µm
2.16µm
1.65µm
1.25µm

Optical:
dust absorbs background Hα light
from hydrogen recombination

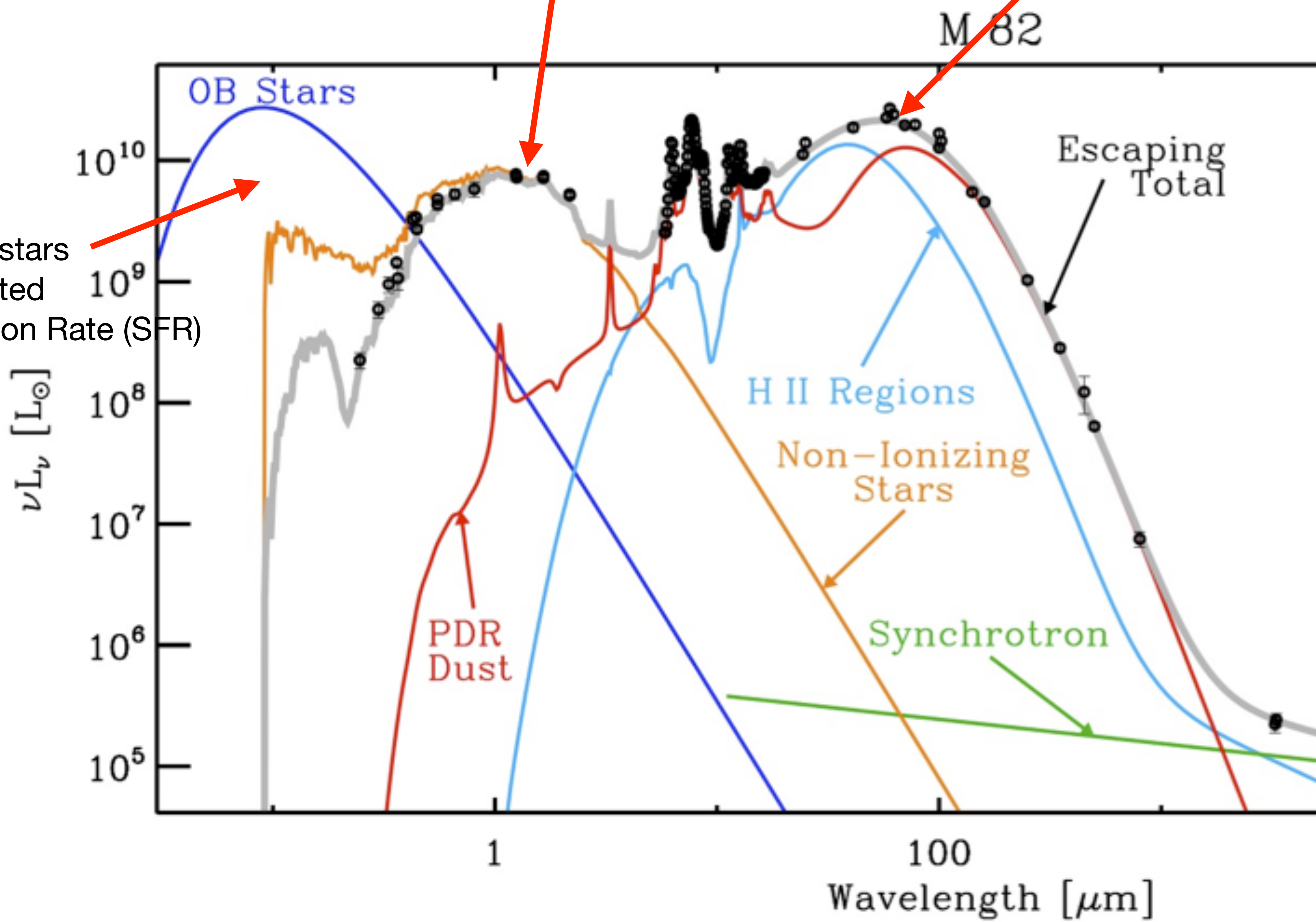
MIR: dust thermal emission + PAH

The effect of dust on SED

NIR: ~1 M_{sun} giant stars
-> stellar mass

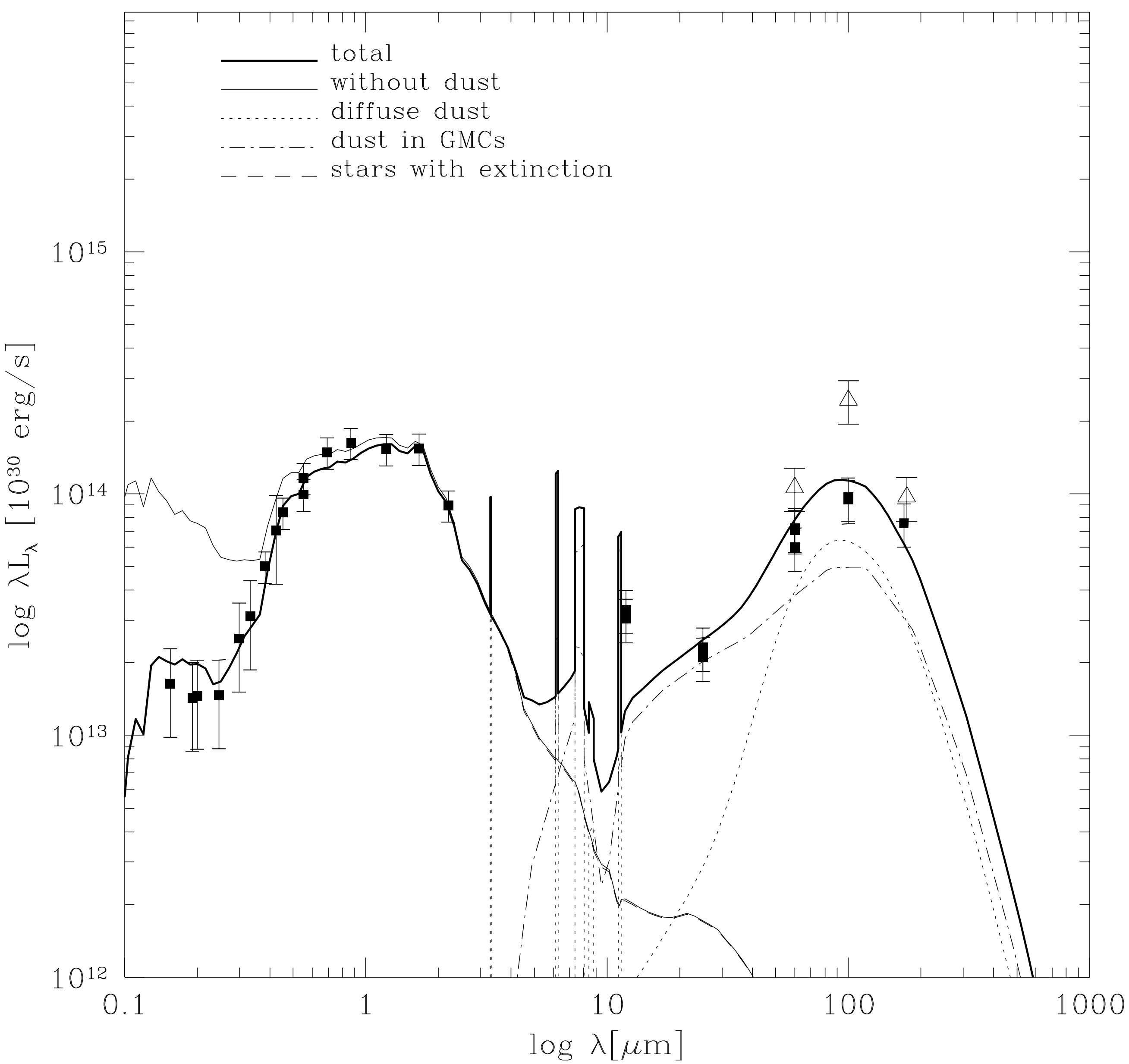
FIR: dust heated by (young) stars
-> extincted SFR

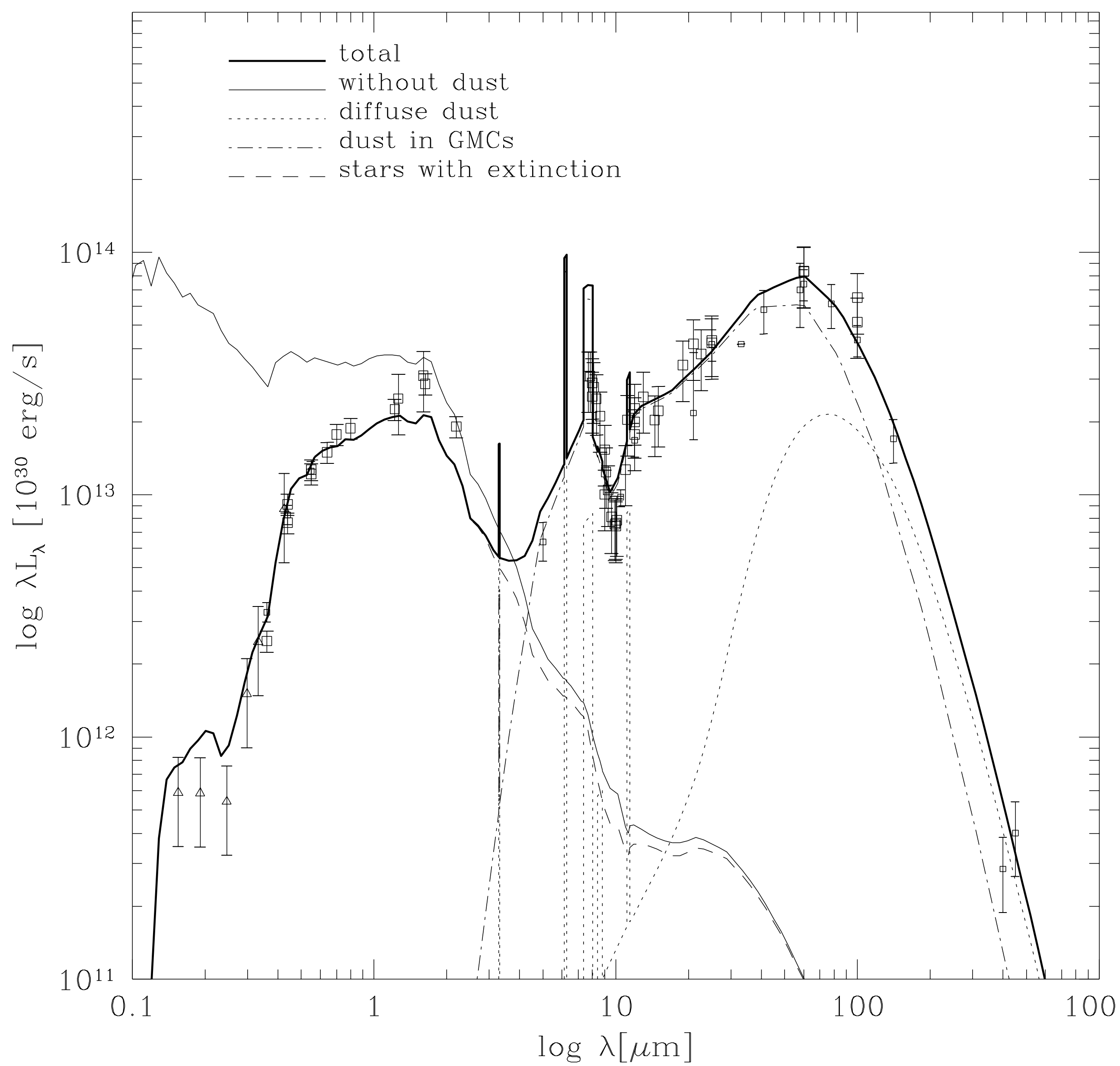
FUV: young stars
-> un-extincted Star Formation Rate (SFR)



M51

M82





Silva et al. 1998, ApJ 509, 103

Full SED of a simulated galaxy

stars

gas

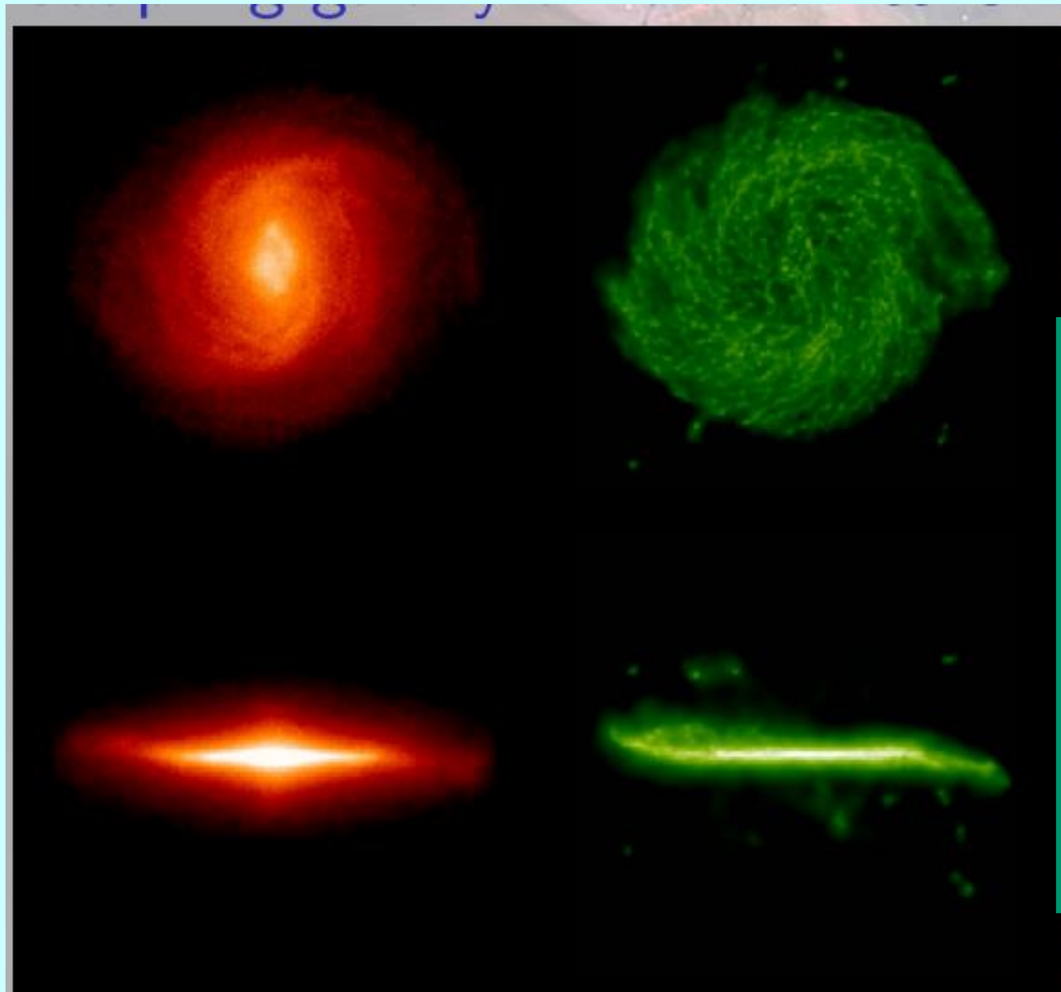


Figure 6 : Simulated galaxy (Murante et al., 2015)

RT predicts SED and optical image

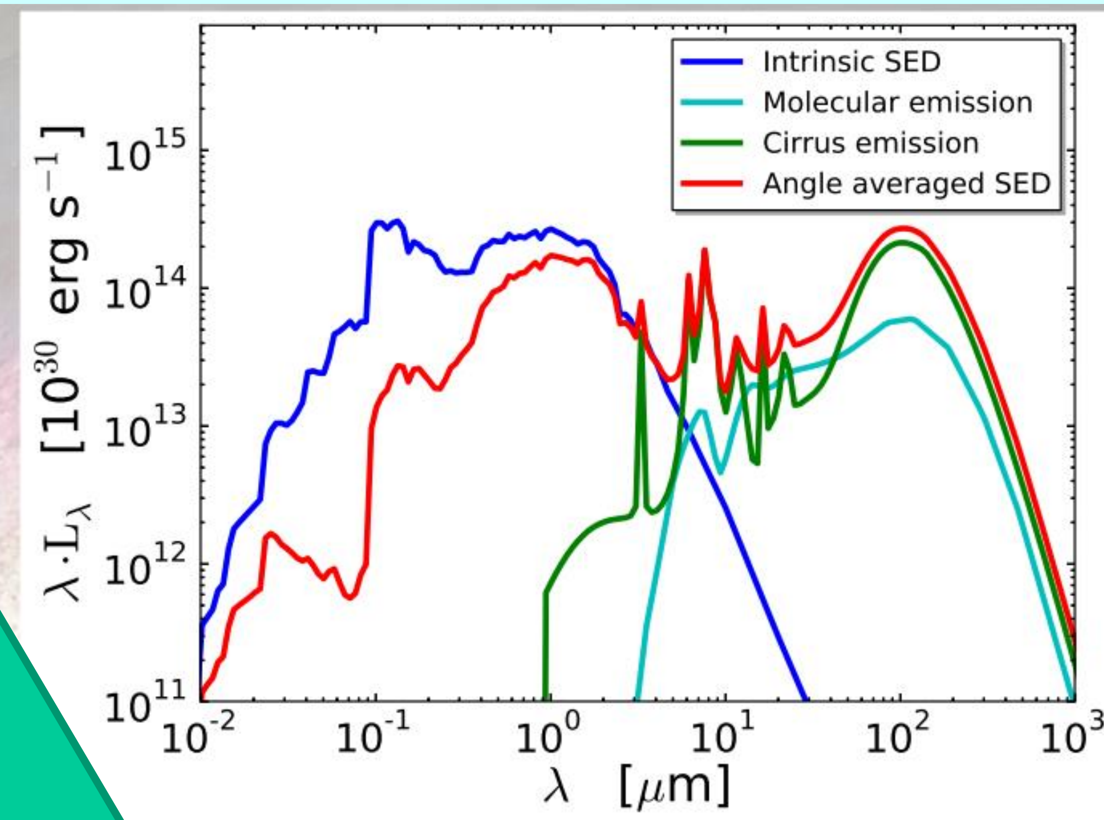
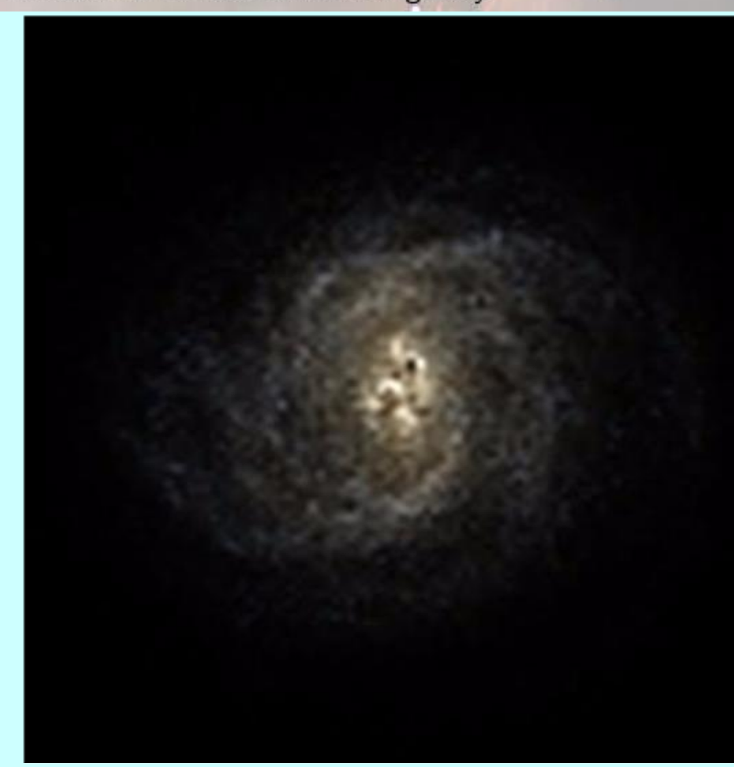
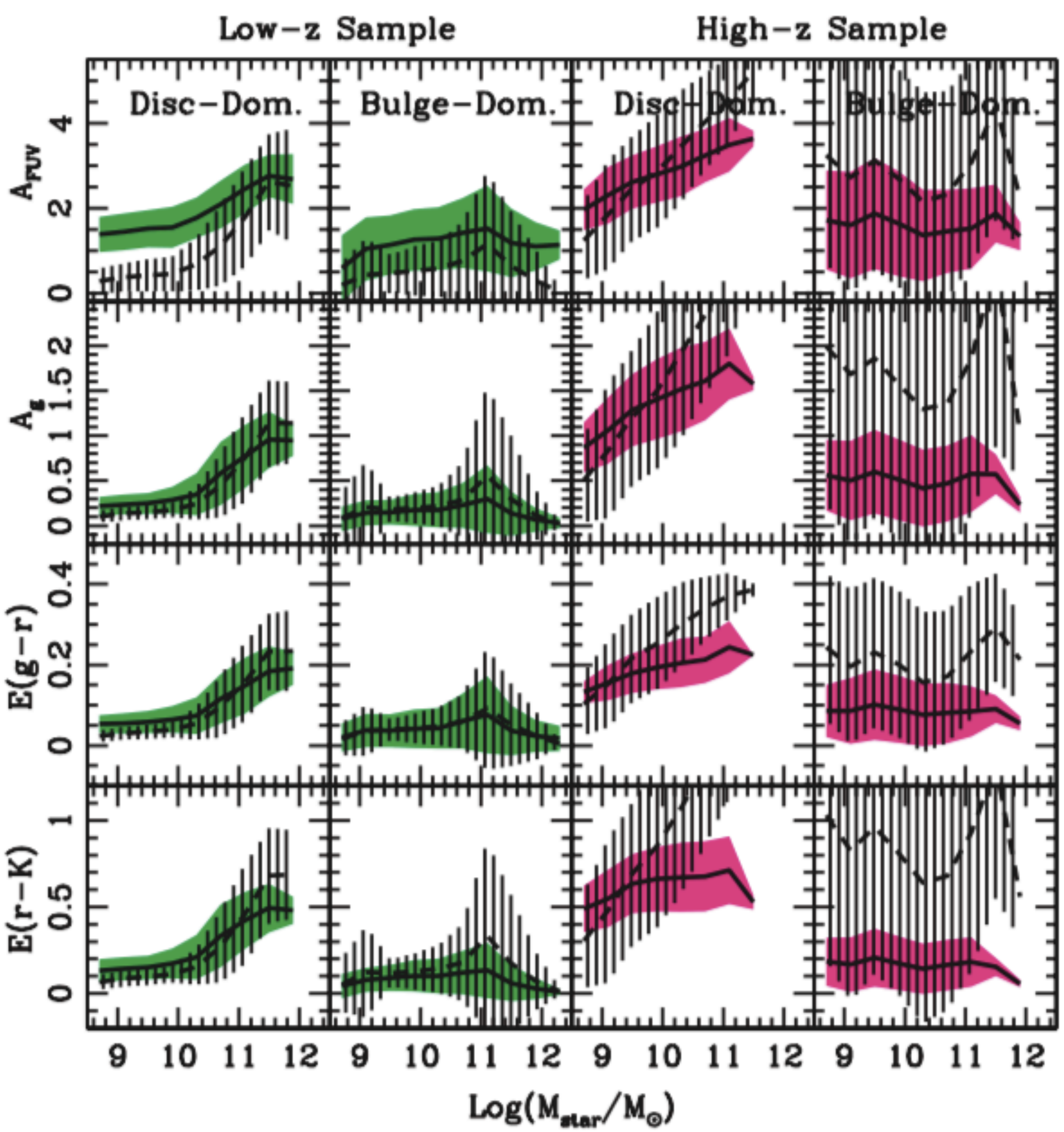
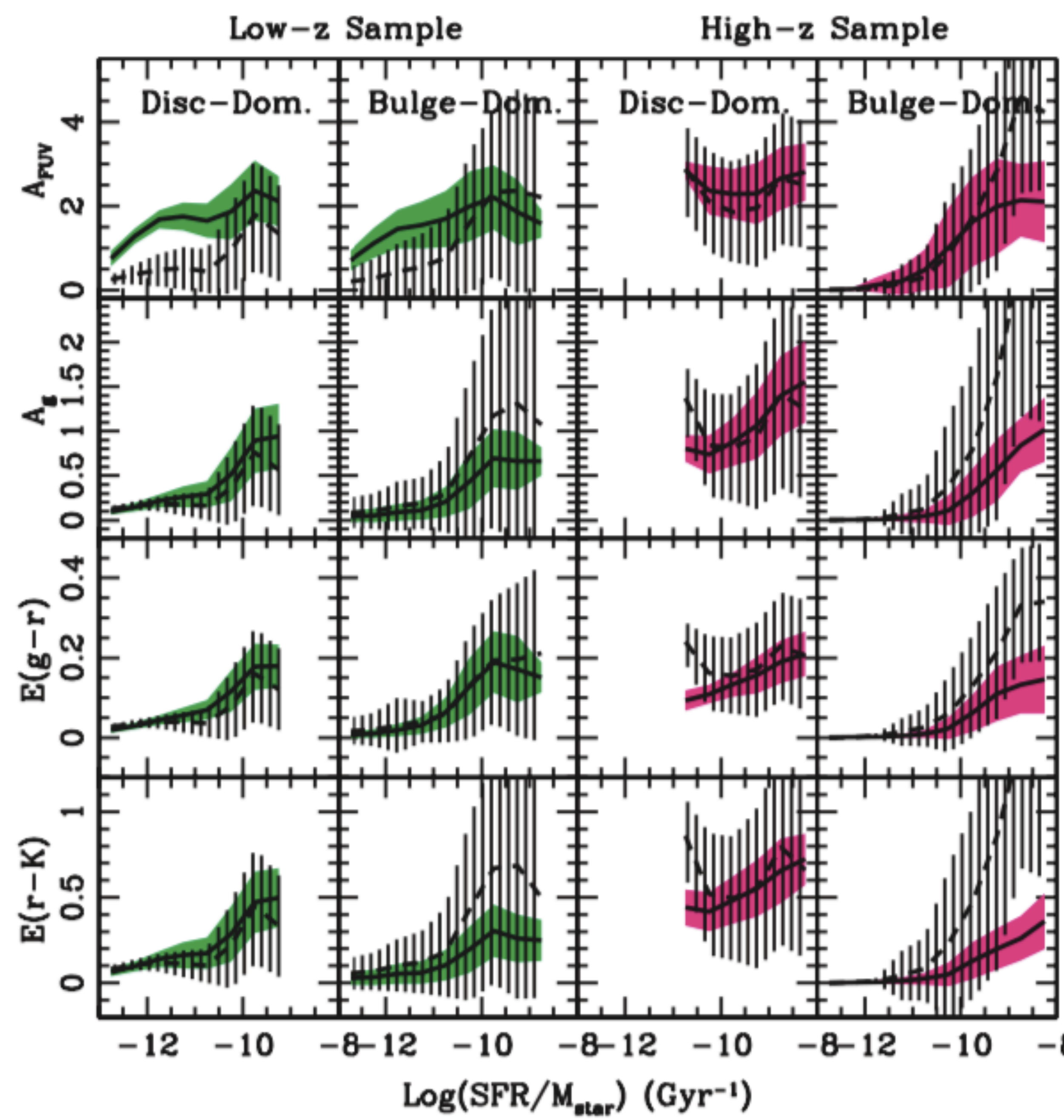


Figure 7 : Broadband SED of simulated galaxy.



Radiative transfer vs simple recipes on a set of model galaxies





Fontanot et al. 2009, MNRAS 392, 553

From galaxy SEDs to physical quantities

Star Formation Rate indicators

SFR is mainly calibrated on local molecular clouds by counting the number of "Young Stellar Objects", that is massive newly born (pre-main sequence) stars. If <*M*> is the total mass of new stars for each YSO and τ the YSO lifetime:

$$SFR = N_{\rm YSO} \frac{\langle M \rangle}{\tau}$$

Then light at a SFR-sensitive wavelength is correlated with this SFR.

The main SFR indicators are:

- UV (1500 A) luminosity,
- 24 μm luminosity,
- total IR luminosity, from 8 to 1000 μm,
- Hα line luminosity, emerging from HII regions,
- Paschen-α line luminosity, if observable,
- other nebular lines,
- radio luminosity,
- X-ray luminosity.

To account for dust extinction:

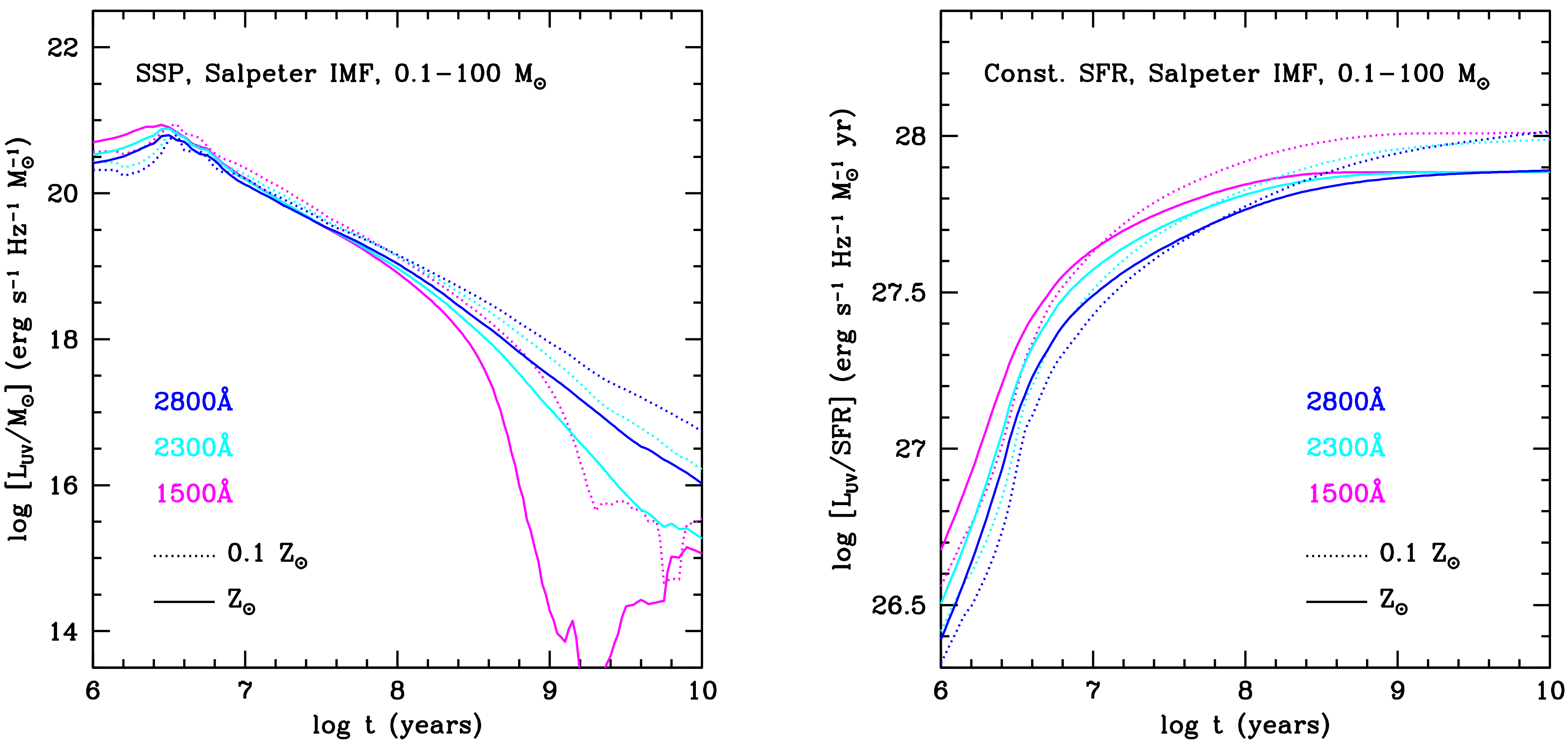
- correct UV data for extinction, using the (reddened) UV slope,
- add UV and FIR SFR indicators.

(Un-extincted) UV light

The 1500 A luminosity of an SSP drops quickly with time, especially after 3 x 10^8 yr.

For a constant SFR, the UV luminosity is constant after ~10^8 yr.

These numbers depend weakly on metallicity.

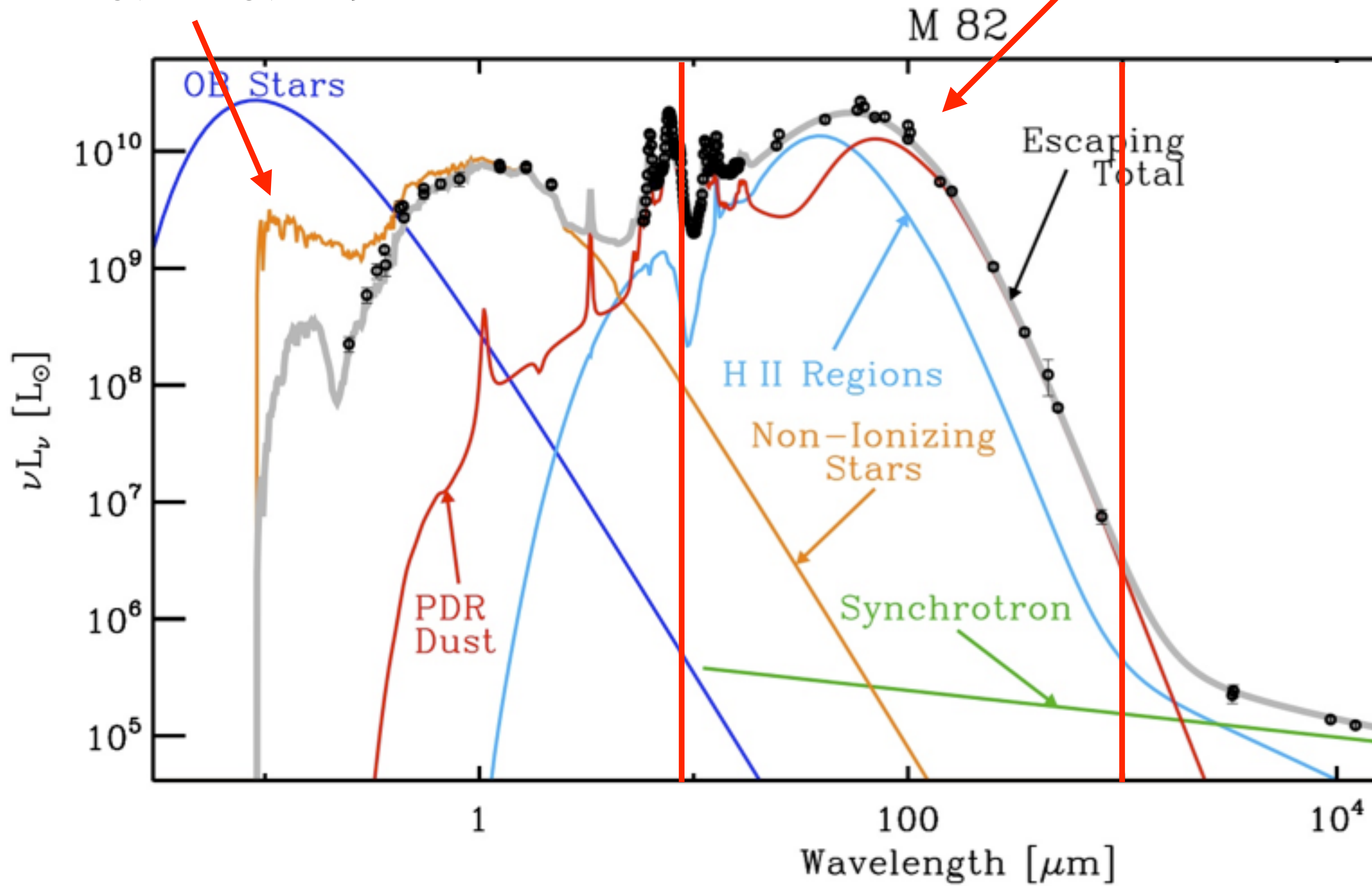


Madau & Dickinson 2014, ARA&A 52, 415

$$SFR = SFR_{\mathrm{UV}} + SFR_{\mathrm{IR}}$$

$$SFR_{\mathrm{UV}} = \kappa_{\mathrm{FUV}} \times L_{\nu}(FUV)$$

$$SFR_{IR} = \kappa_{\mathrm{FIR}} \times L_{\mathrm{IR}}$$

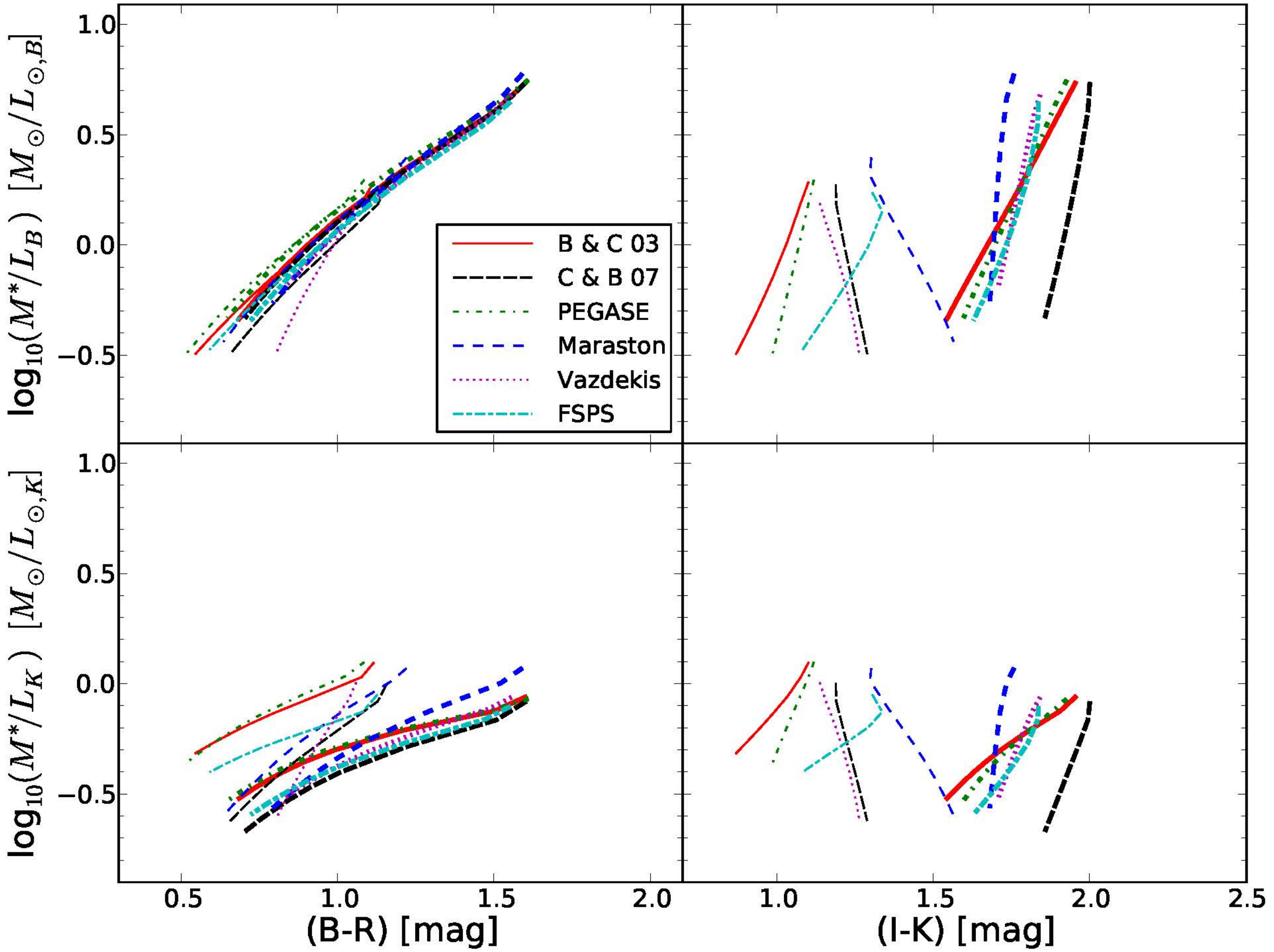


Stellar mass measurements

- Luminosity in some red band (K band at 2 m, or Spitzer NIR bands)
- Average M/L in the K-band
- Correction for (little) extinction

FIGURE: M/L ratio for 12 Gyr SSP and different SSP SED libraries,

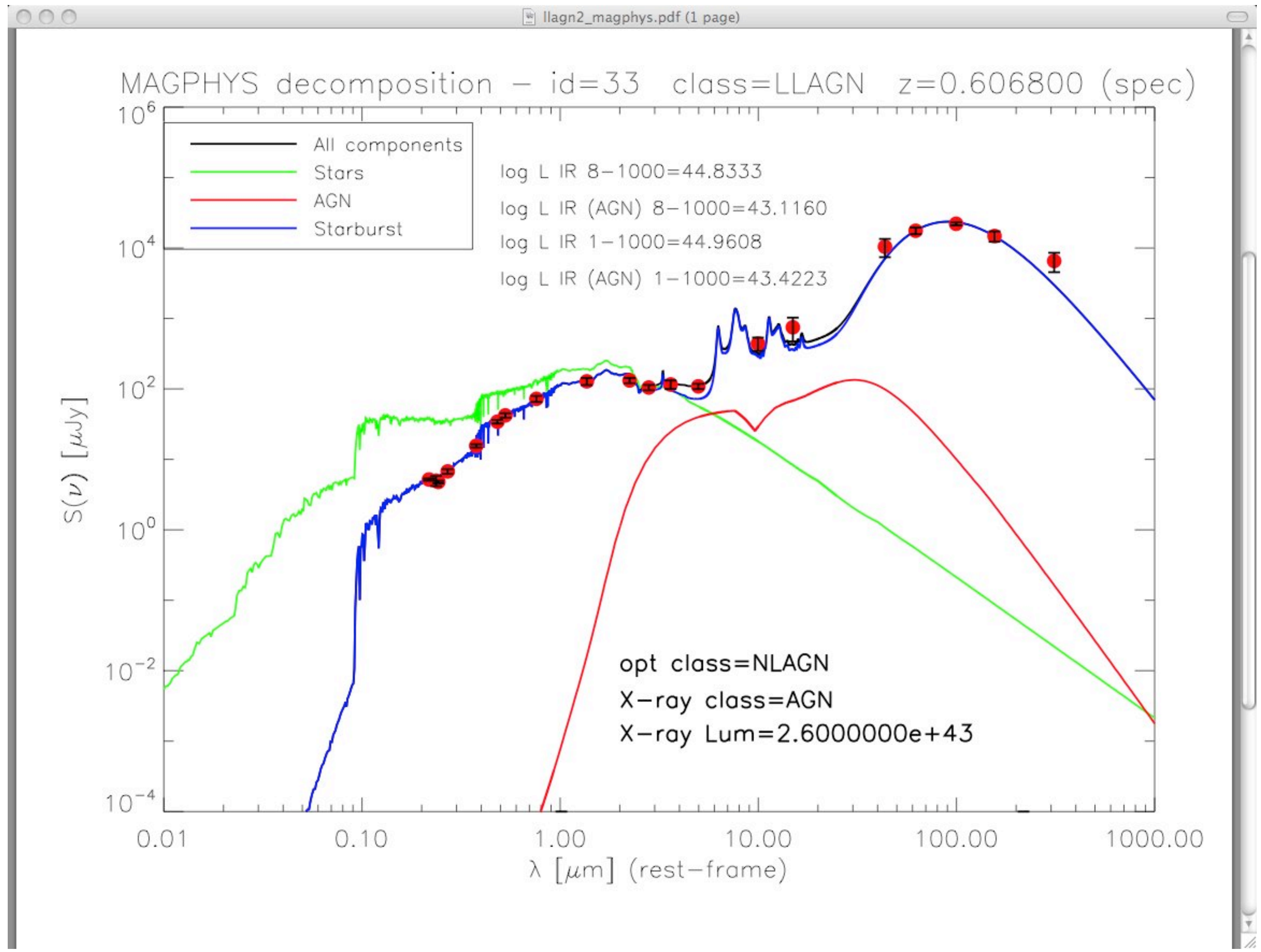
from Courteau et al 2014, Reviews of Modern Physics, 86, 47



SED fitting

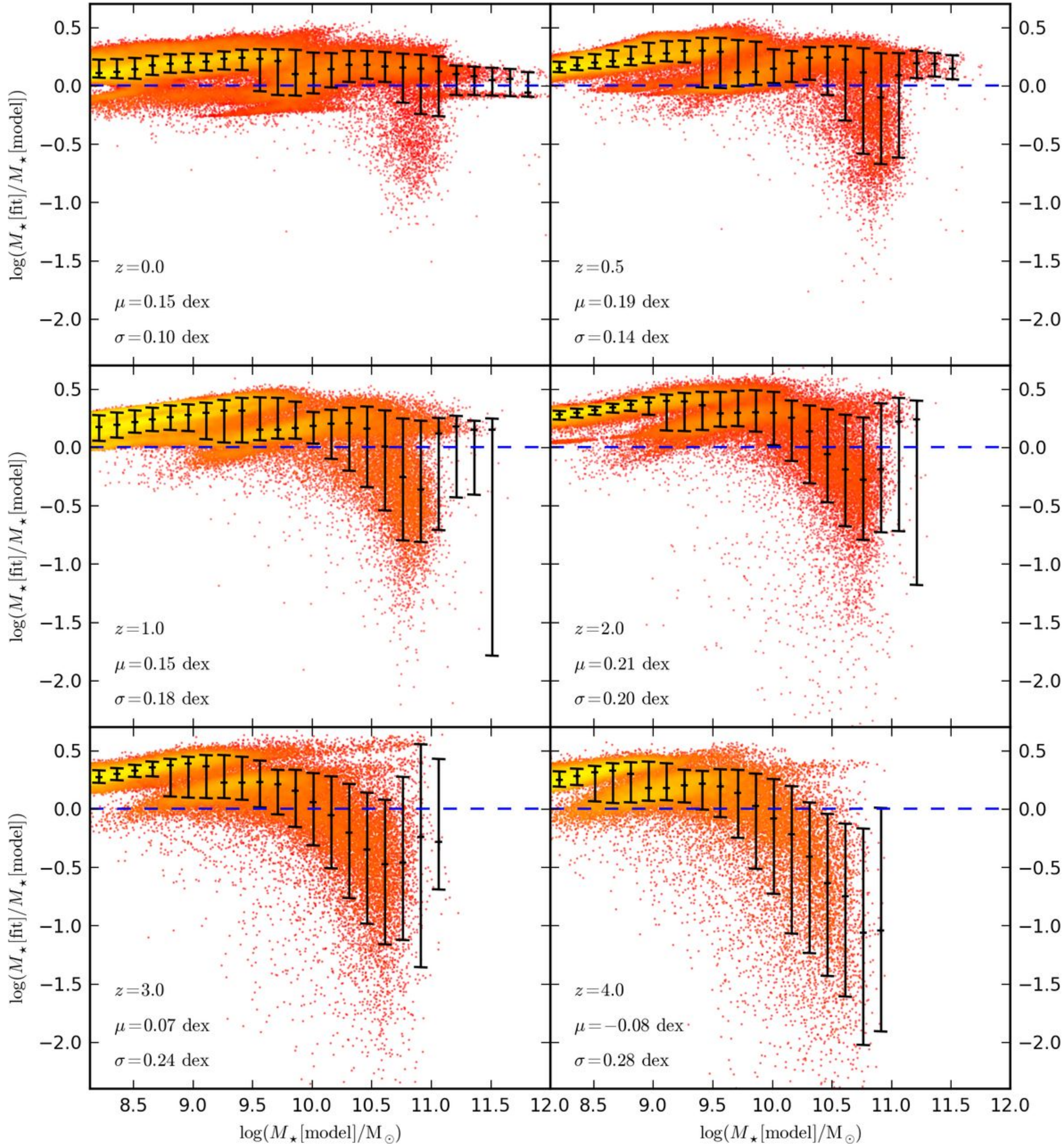
Main parameters:

- REDSHIFT!
- stellar mass
- Star Formation Rate, SFR(t_{obs})
- Star Formation Rate history, SFR(t)
- metallicity, Z(t_{obs})
- metallicity history Z(t)
- IMF
- extinction and reddening (dust mass and geometry)
- library of galaxy SEDs
- **AGN contamination**



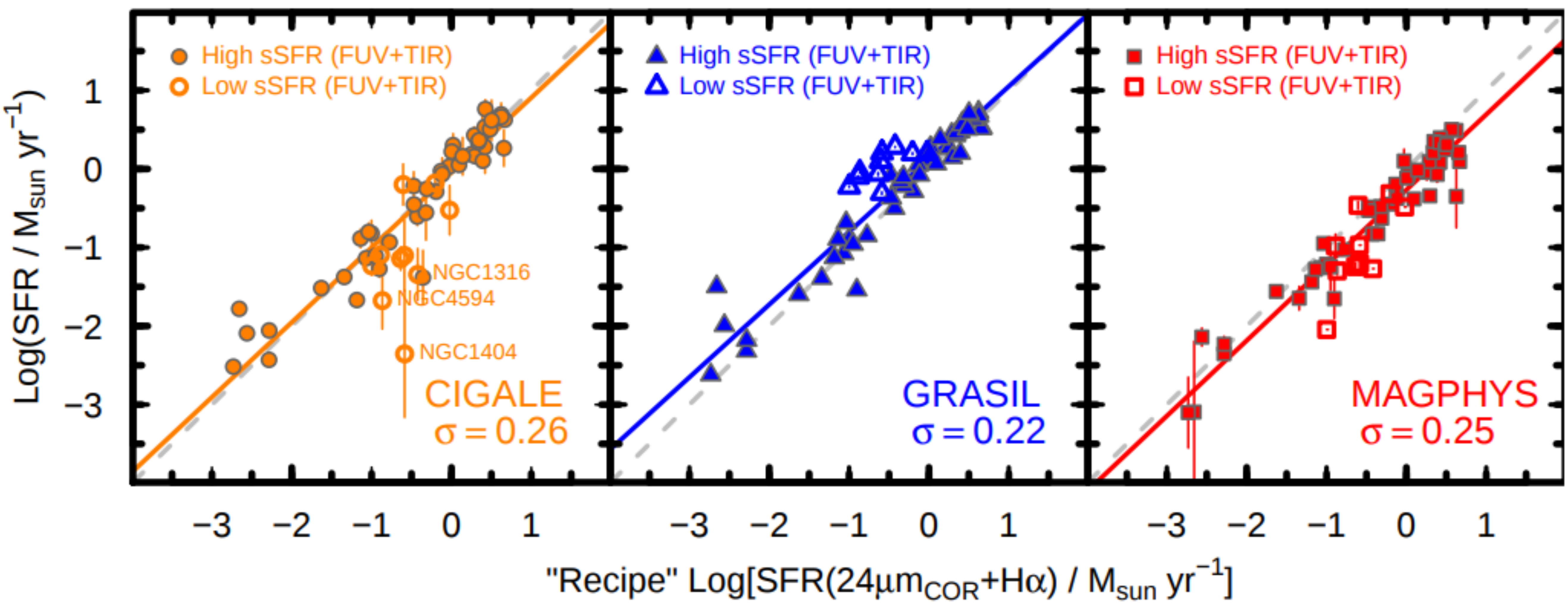
courtesy of C. Gruppioni

SED fitting tested on model galaxies: stellar masses



Mitchell et al. 2013, MNRAS 435, 87

SFR from SED fitting versus 24 μm + Hα



Hunt et al. 2019, A&A 621, A51

The Schmidt-Kennicutt relation

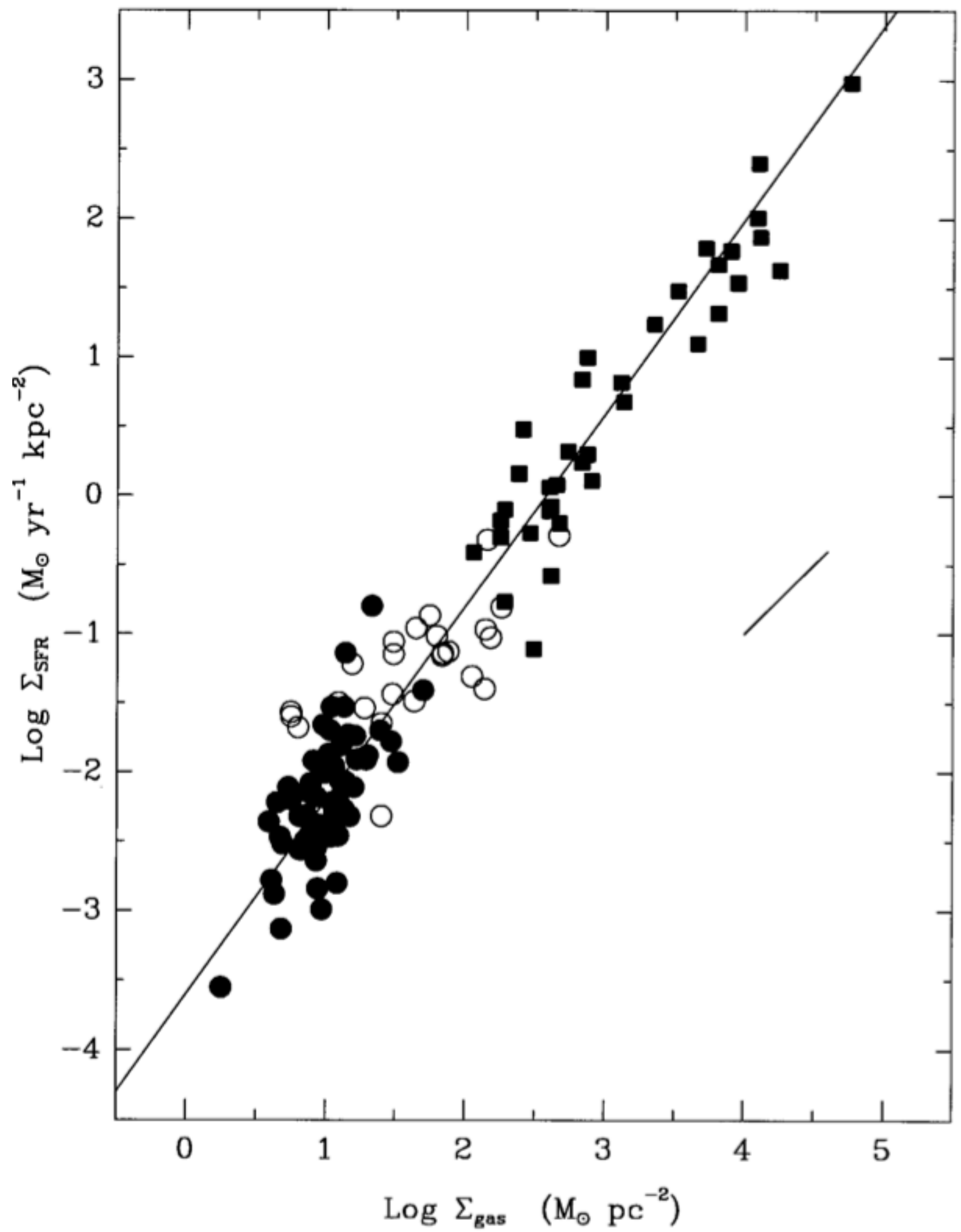
The Schmidt-Kennicutt relation

Estimating the SFR of a galaxy, it is possible to notice a correlation of surface densities of SFR and gas mass.

This was first noticed by Maarten Schmidt in 1959, then confirmed by several authors among which Robert Kennicutt.

With significant uncertainties, the relation has been fit as:

$$\Sigma_{\text{SFR}} \propto \Sigma_{\text{gas}}^{1.4}$$

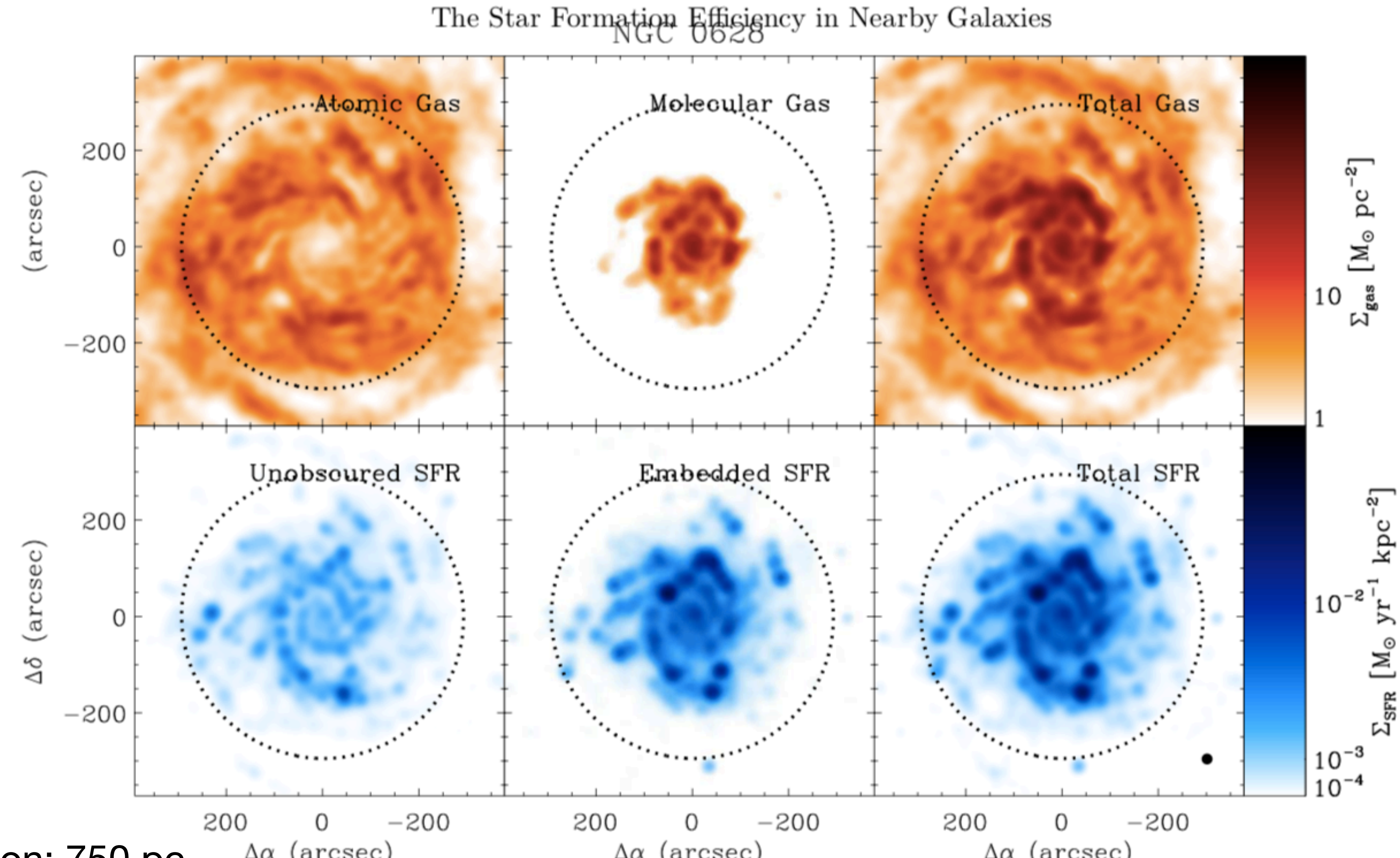


Kennicutt 1998, ApJ 498, 541

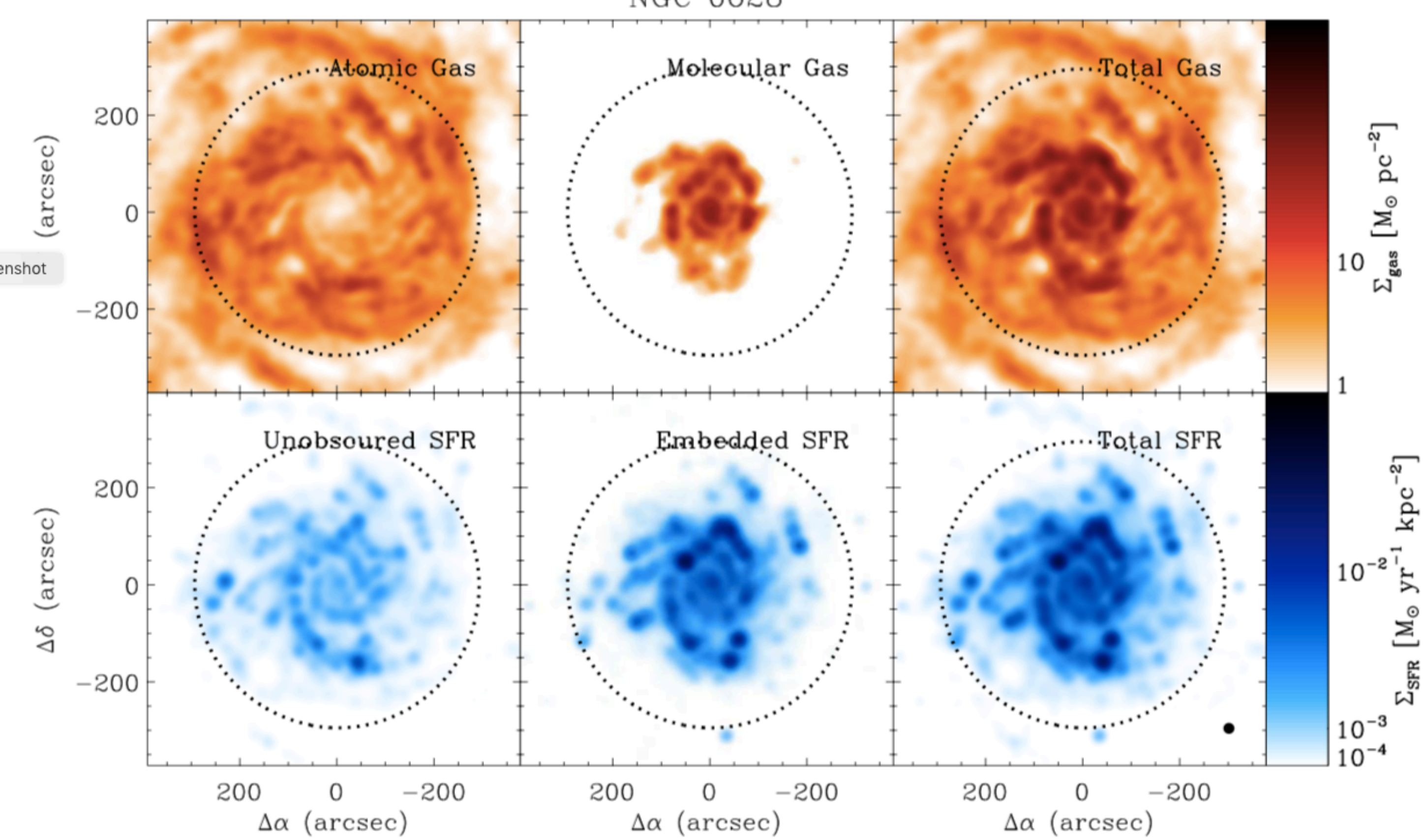
The Schmidt-Kennicutt relation

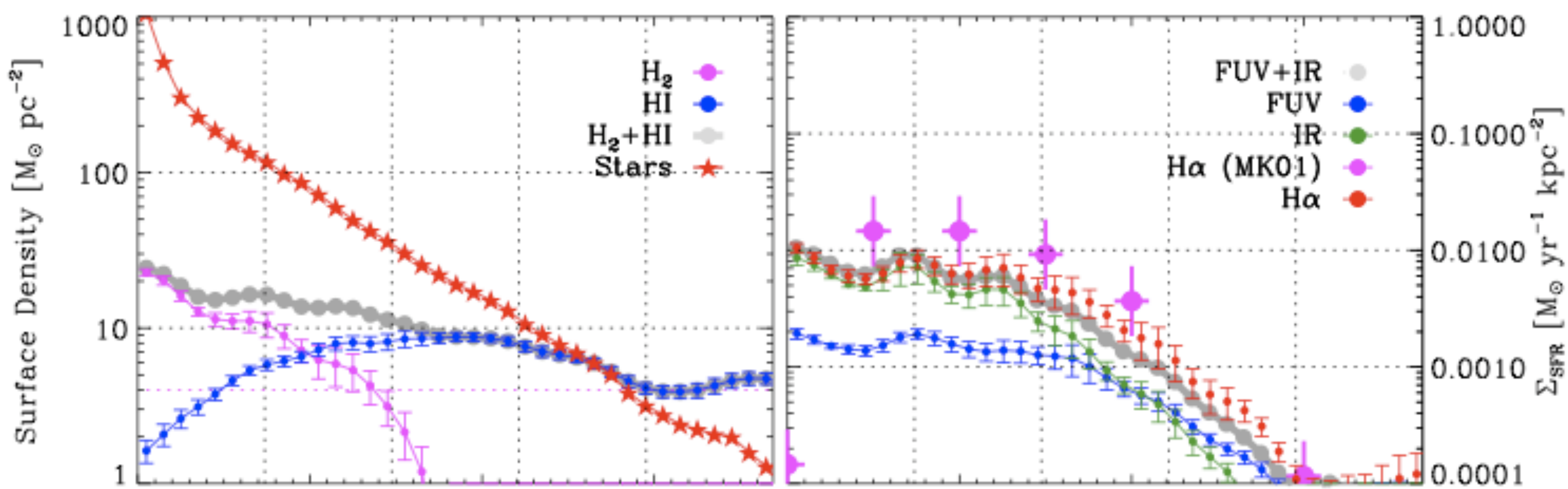
A breakthrough was obtained in 2008 thanks to a suite of multiwavelength surveys of a sample of nearby spirals.
(Leroy et al. 2008, AJ 136 2782; Bigiel et al. 2008, AJ 136, 2846)

VLA: 21 cm -> HI
mm antennas: CO -> H2
Spitzer: 24 µm
GALEX: UV
24 µm + UV -> SFR

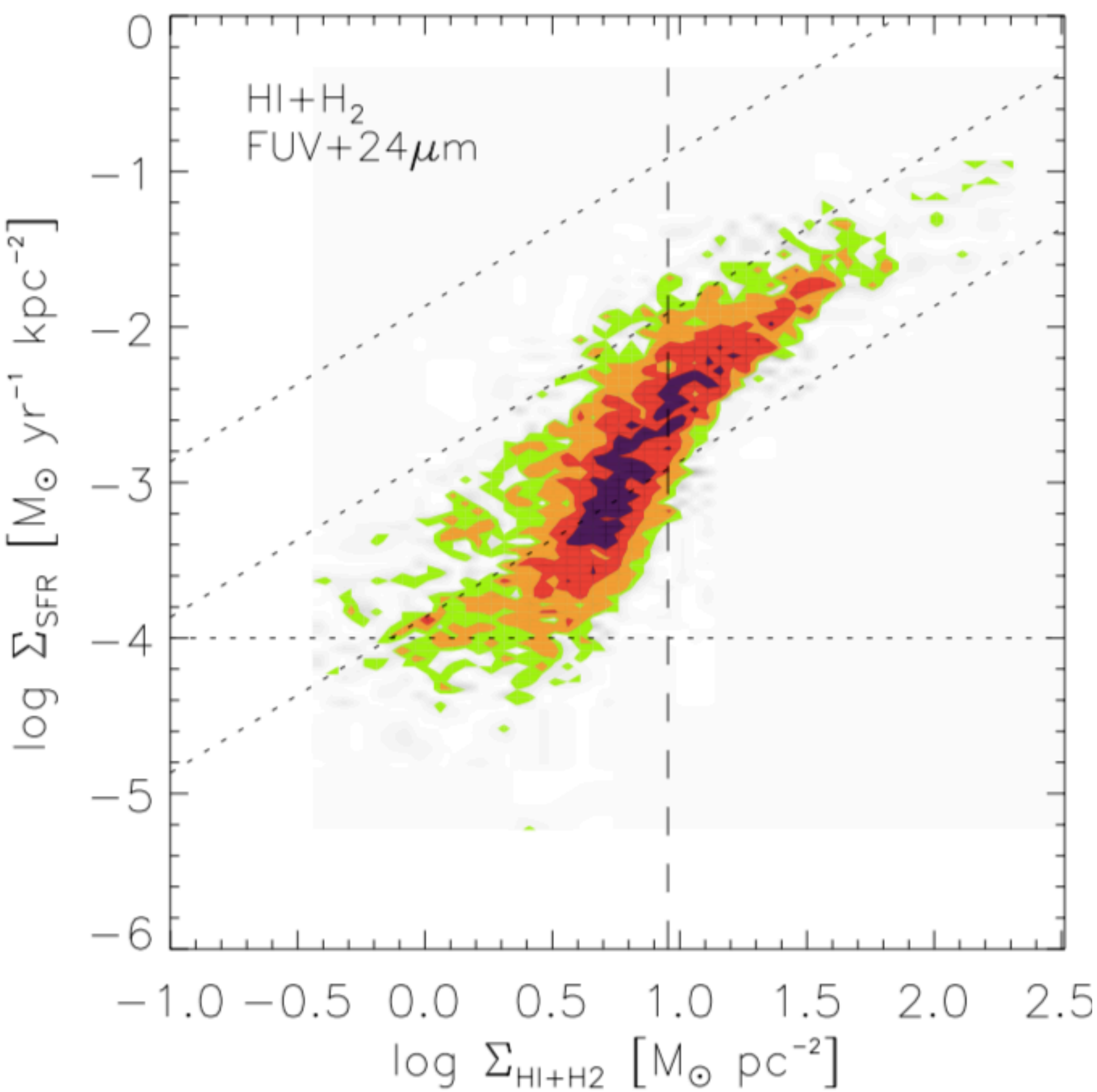


Resolution: 750 pc

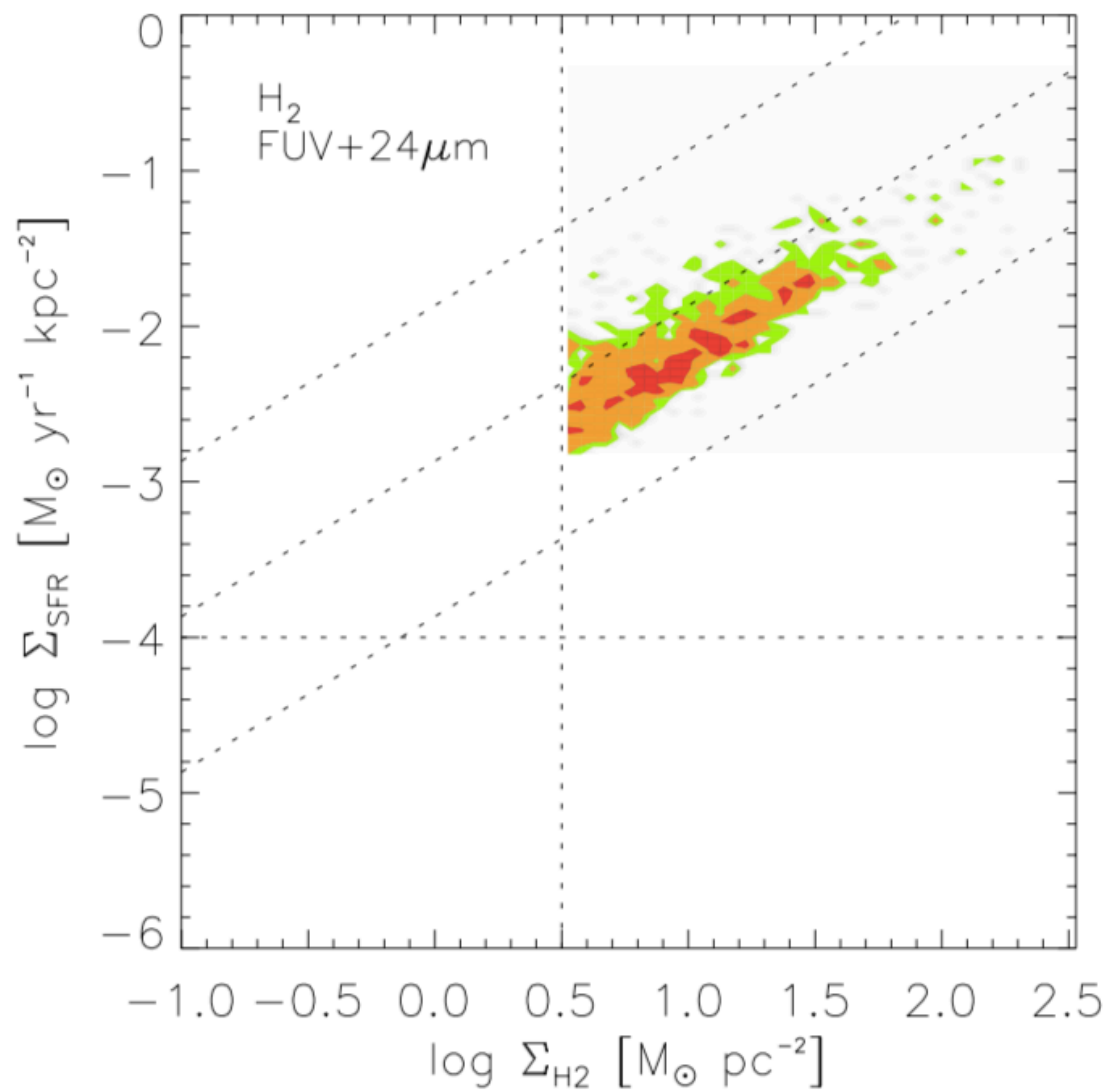

NGC 0628
Atomic Gas
Molecular Gas
Total Gas
Unobsoured SFR
Embedded SFR
Total SFR
Σ_{gas} [$M_\odot$ pc^{-2}]
Σ_{SFR} [$M_\odot$ yr^{-1} kpc^{-2}]
$\Delta\delta$ (arcsec)
$\Delta\alpha$ (arcsec)


Surface Density [$M_\odot$ pc^{-2}]
H_2
HI
H_2+HI
Stars
FUV+IR
FUV
IR
Hα (MK01)
Hα
Σ_{SFR} [$M_\odot$ yr^{-1} kpc^{-2}]

The Schmidt-Kennicutt relation

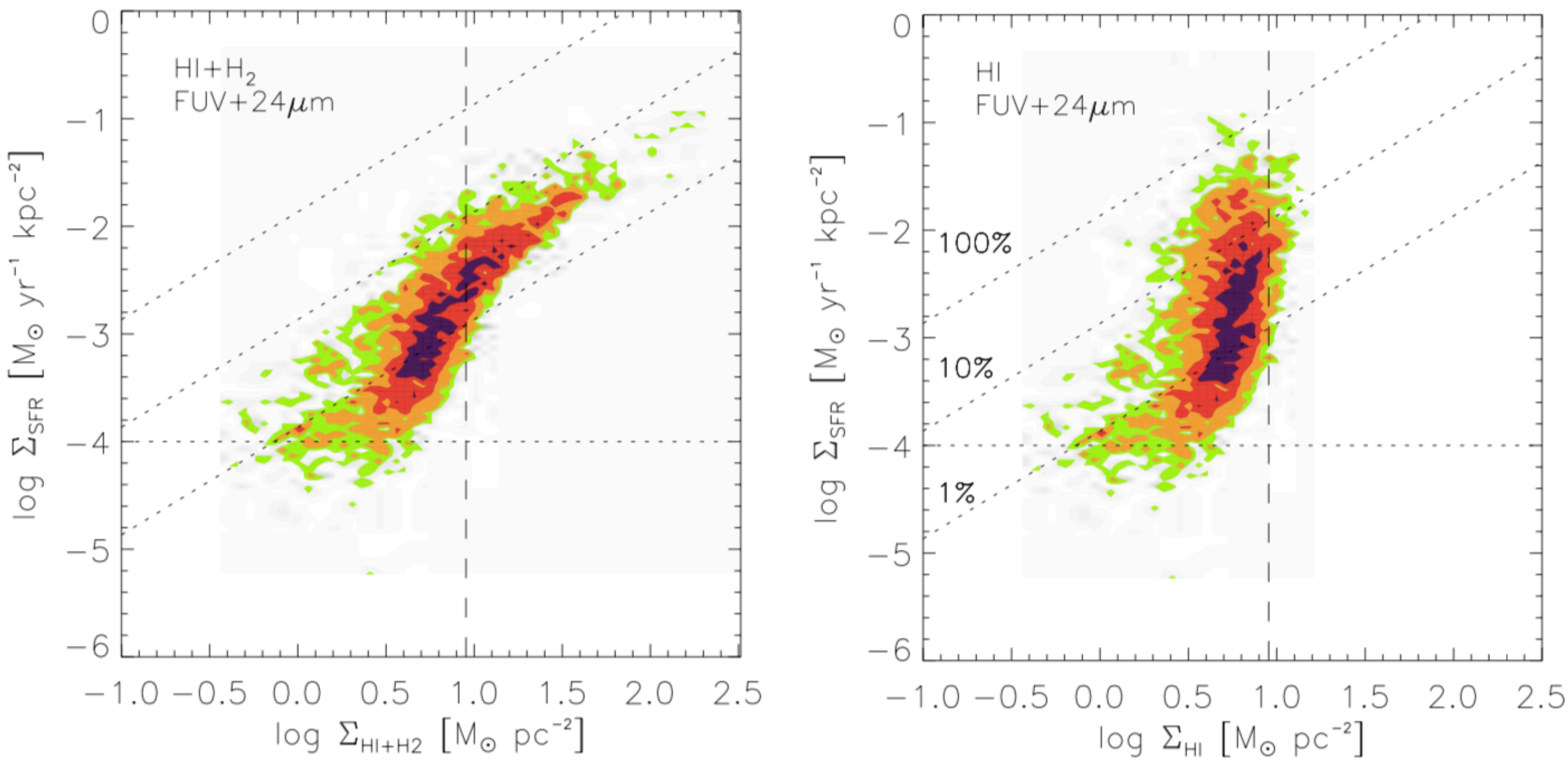


total gas: different regimes



molecular gas: linear relation

The Schmidt-Kennicutt relation



total gas: different regimes

neutral gas: no correlation

Timescales of star formation

Gas consumption timescale:

$$t_{gc} = \Sigma_{mol}/\Sigma_{SFR} \simeq 2 \text{ Gyr}$$

Dynamical time of molecular clouds:

$$t_{dyn} \simeq 20 \text{ Myr}$$

Fraction of stars formed per dynamical time:

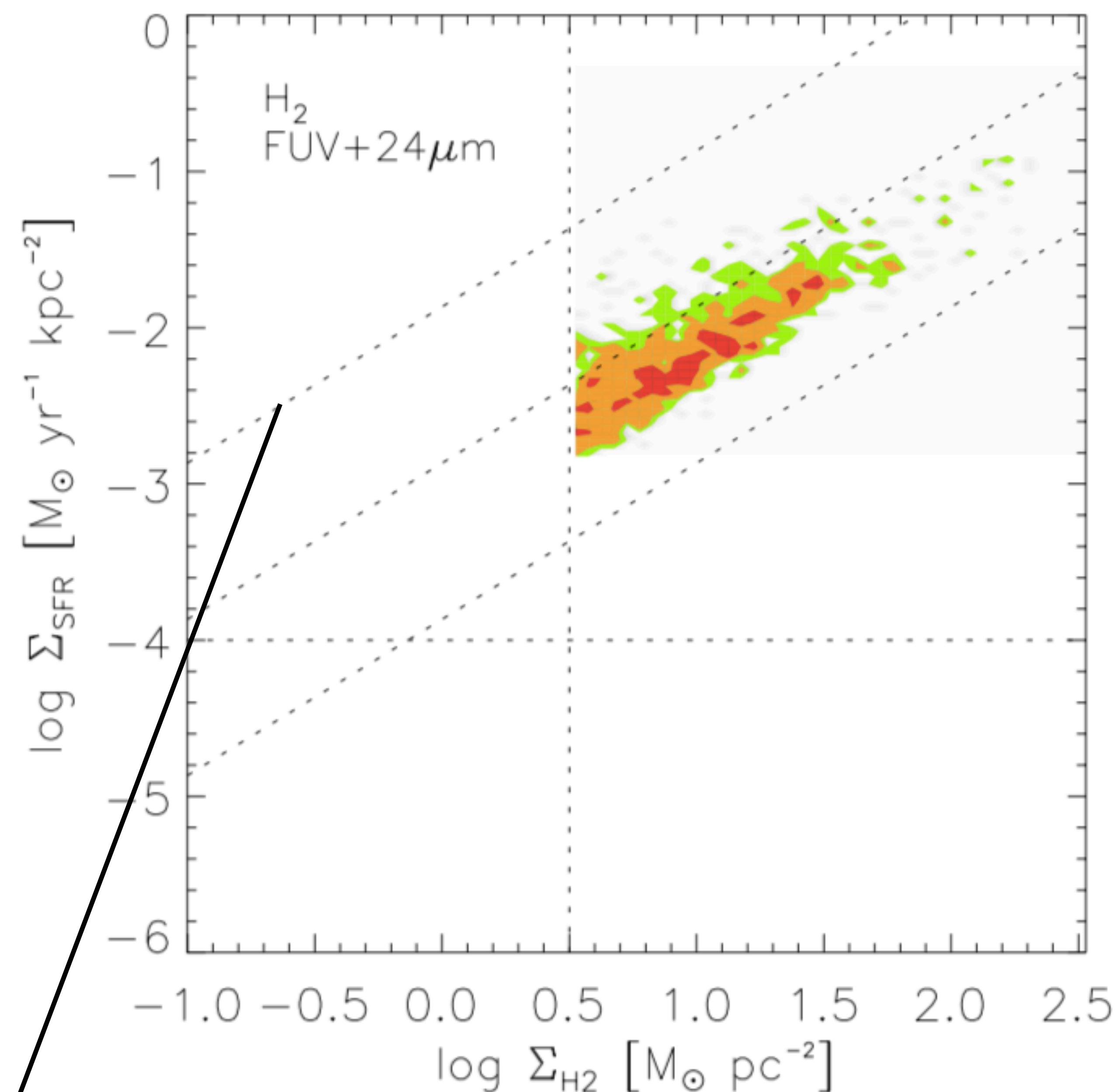
$$f_\star \simeq 1 \ \%$$

Star formation rate:

$$SFR = f_\star M_{mol}/t_{dyn}$$

Then:

$$t_{dyn} \simeq f_\star t_{gc}$$

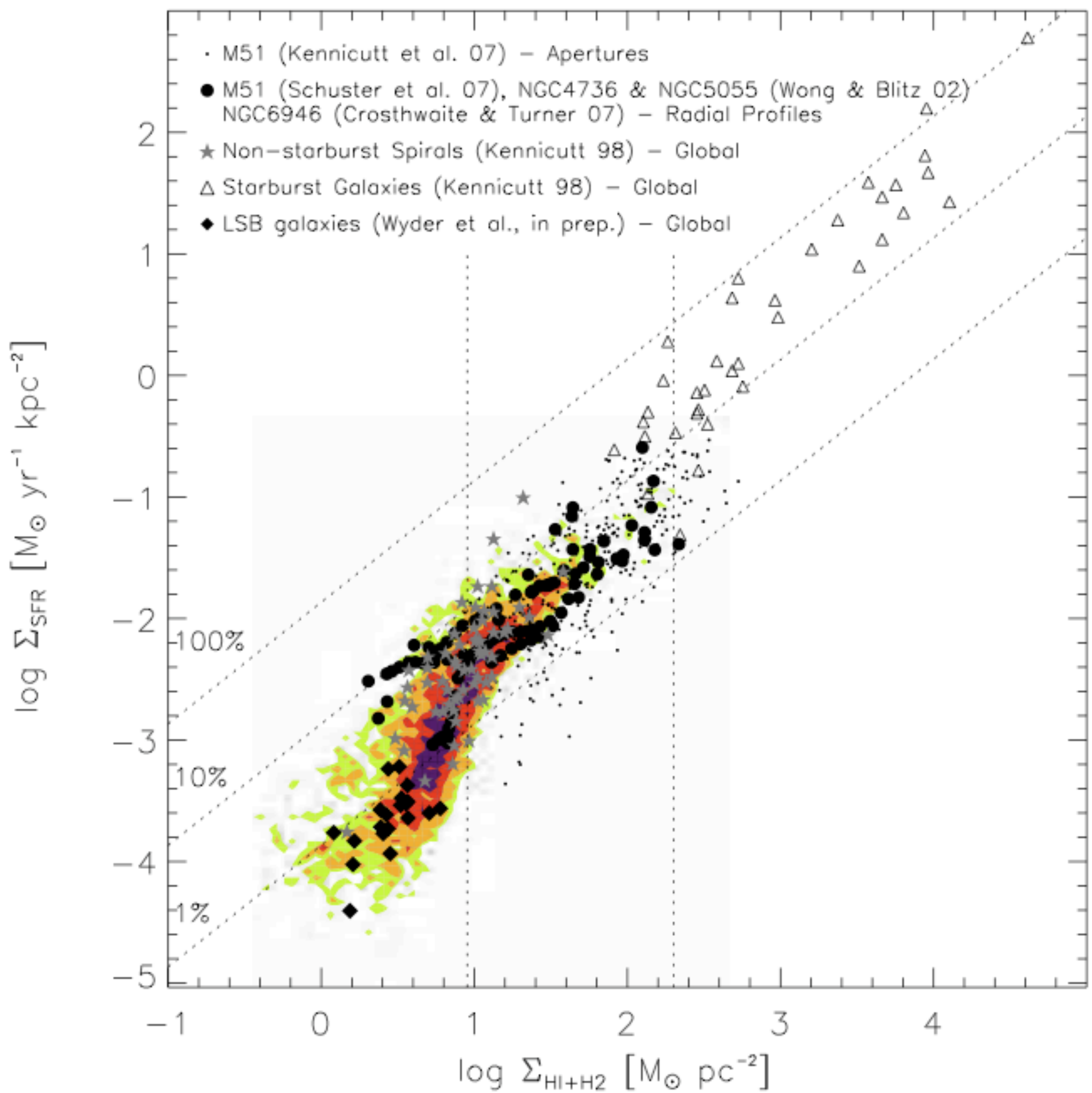


Lines of constant gas consumption timescale

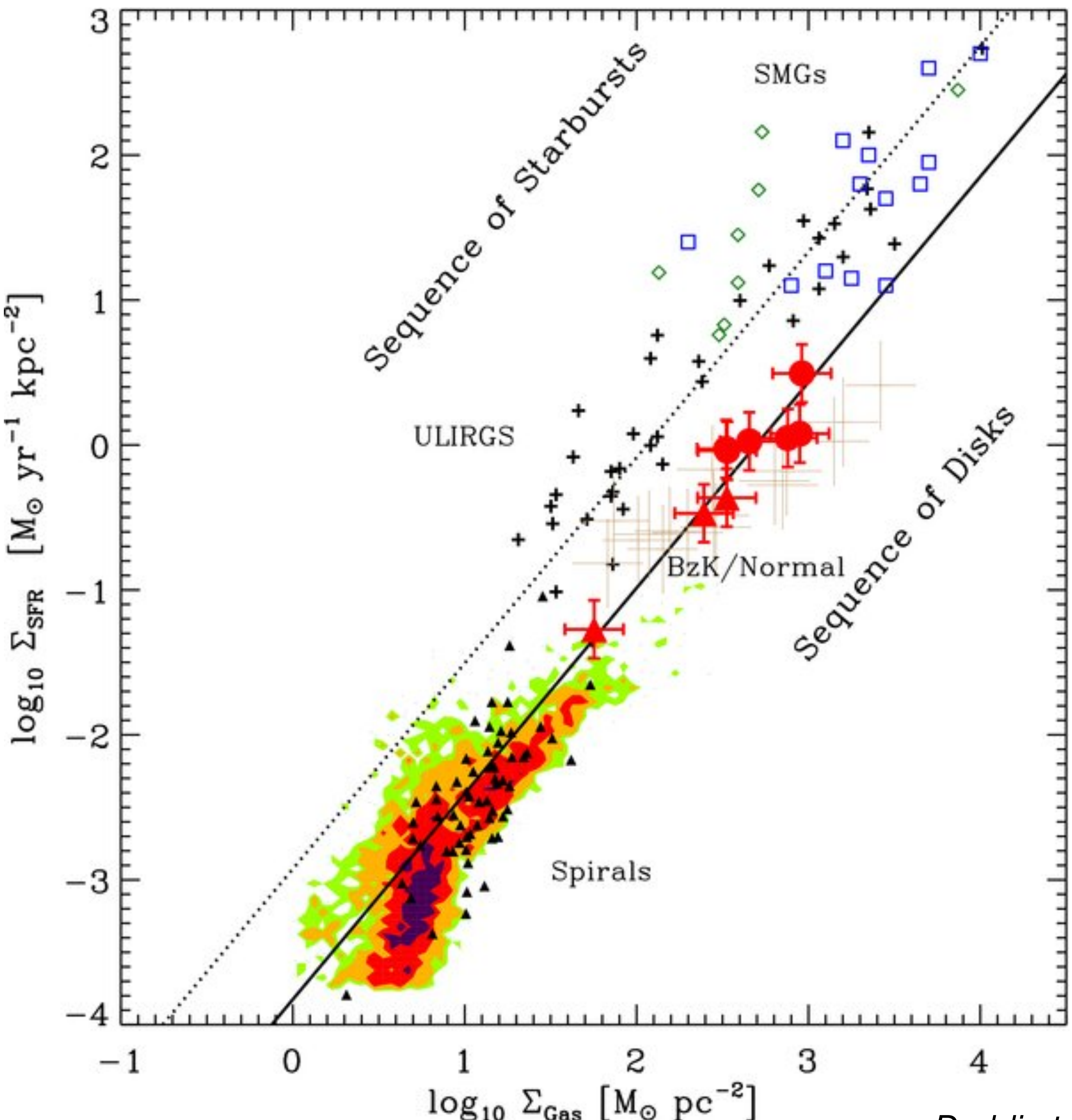
Kennicutt relation with starbursts

Problem: does the ratio of (visible) CO to (wanted) H_2 change in these extreme environments?

$$M_{\rm gas} = \alpha_{CO} L_{CO}$$



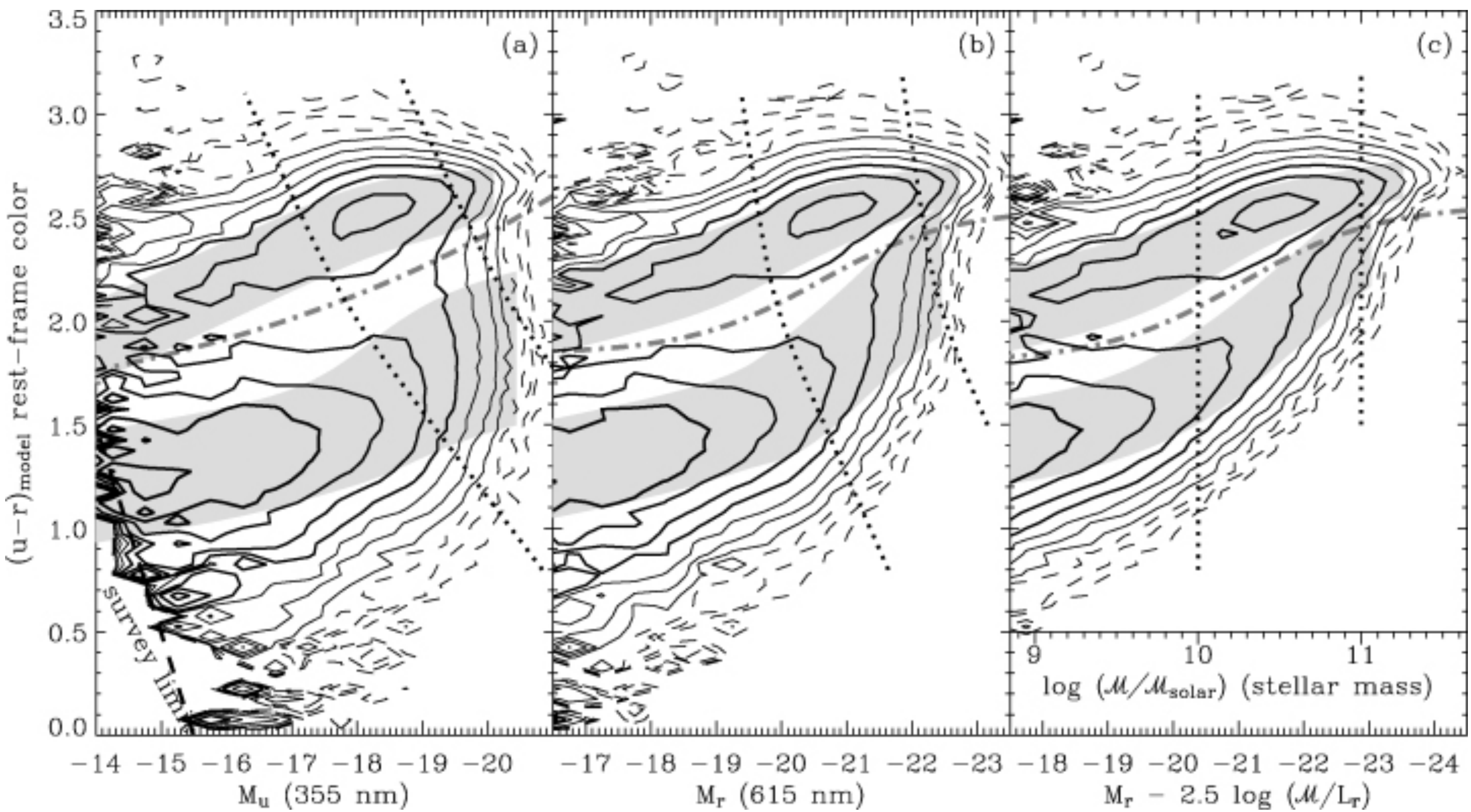
Two relations at high densities?



Daddi et al. 2010, ApJ 714, L118

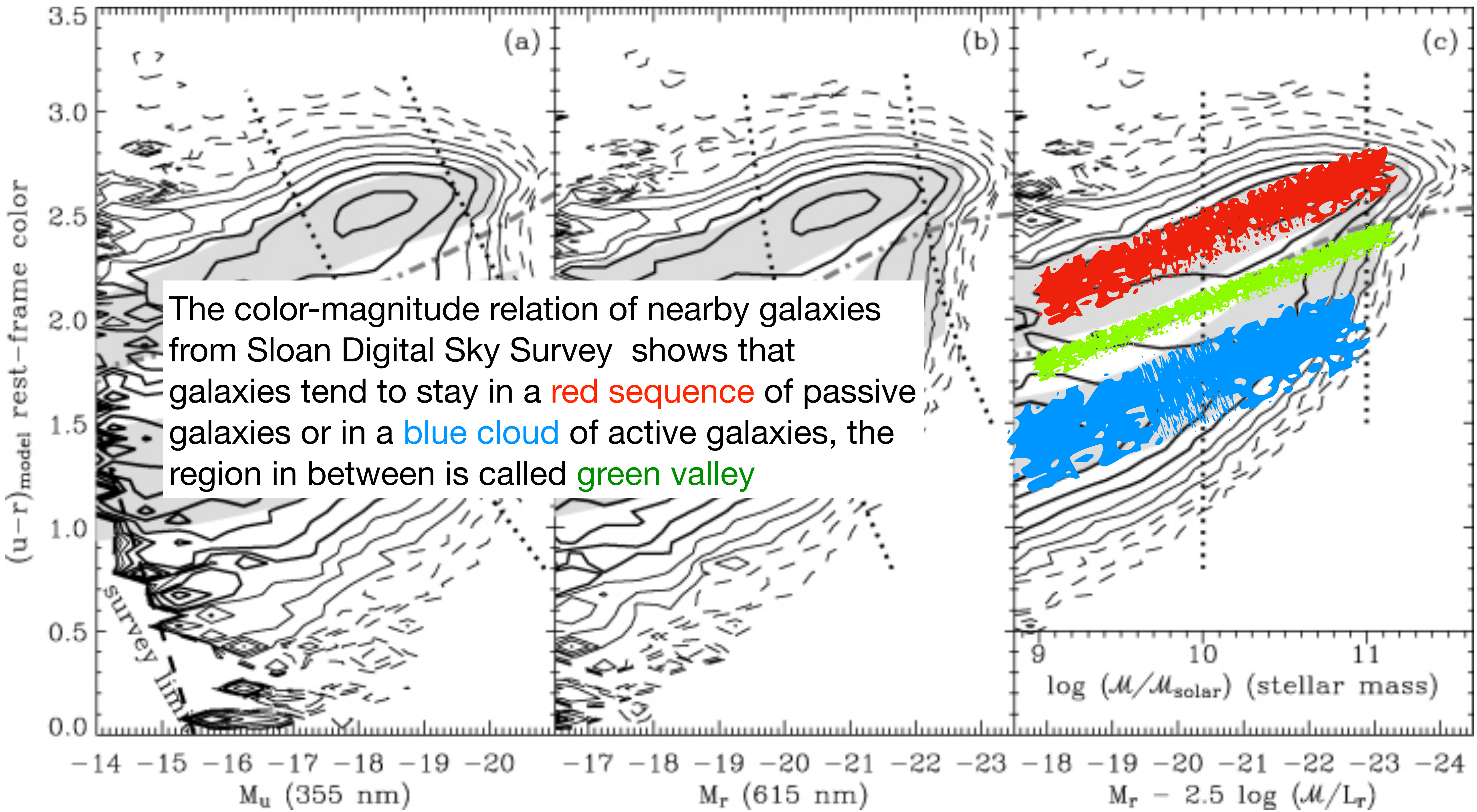
Passive and active galaxies

Bimodality of the color-magnitude relation



Baldry et al. 2006, MNRAS, 373, 469

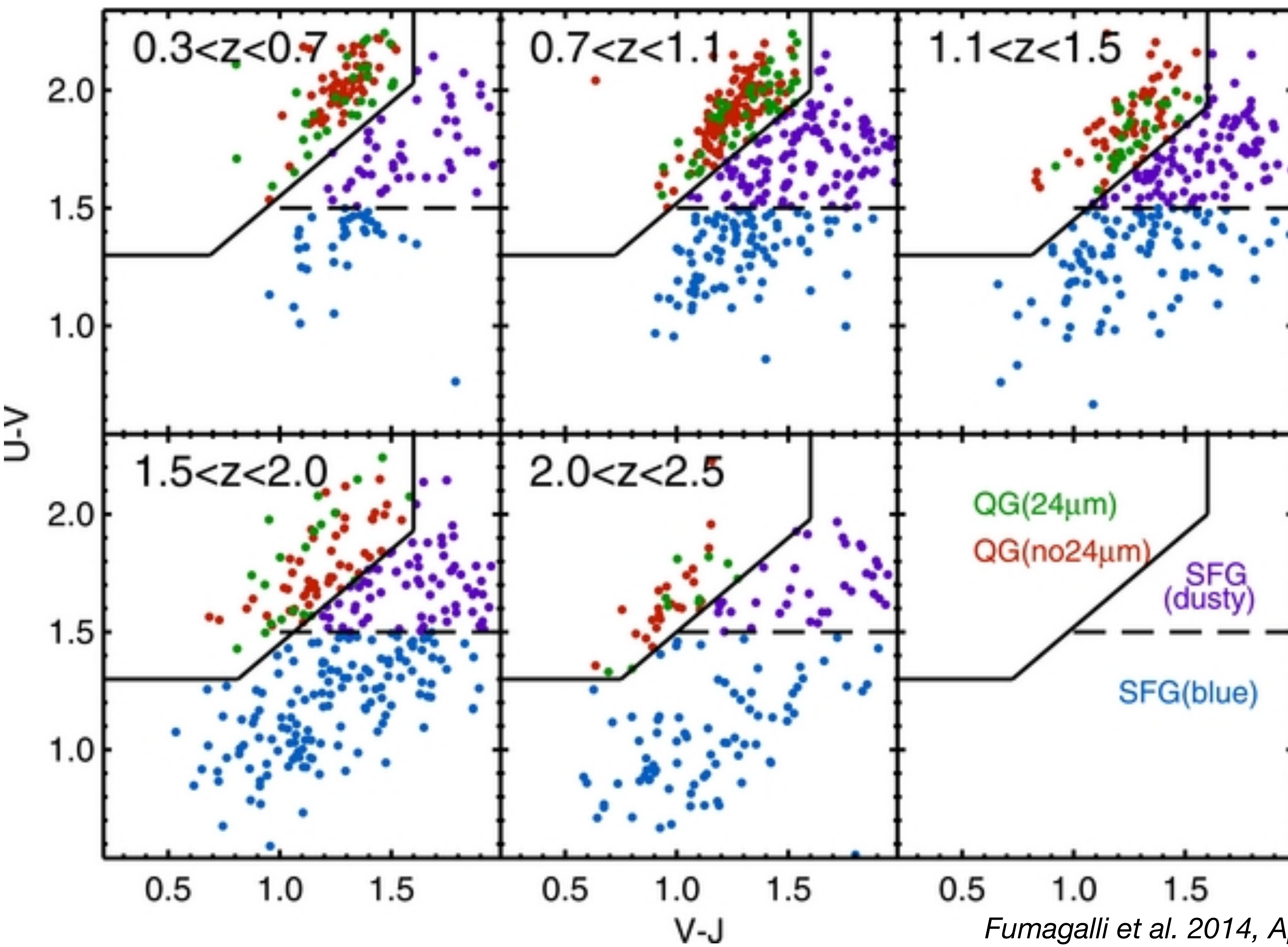
Bimodality of the color-magnitude relation



The color-magnitude relation of nearby galaxies from Sloan Digital Sky Survey shows that galaxies tend to stay in a red sequence of passive galaxies or in a blue cloud of active galaxies, the region in between is called green valley

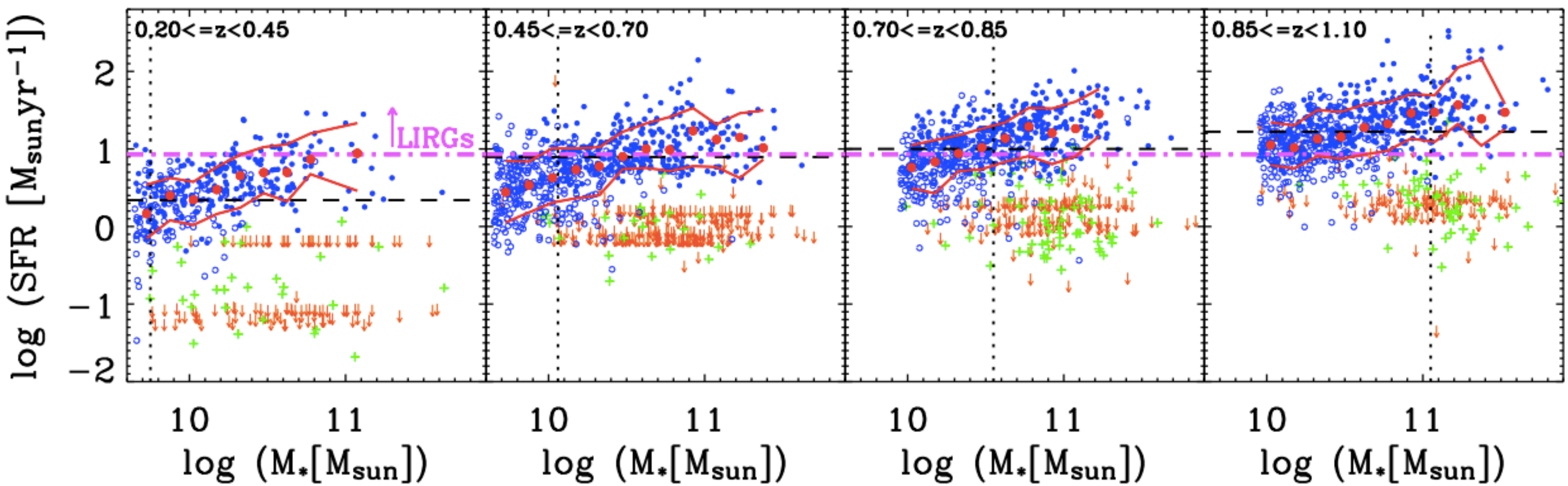
Baldry et al. 2006, MNRAS, 373, 469

Selection of active and passive galaxies from rest-frame colors



Fumagalli et al. 2014, ApJ 796, 35

Main sequence of star-forming galaxies

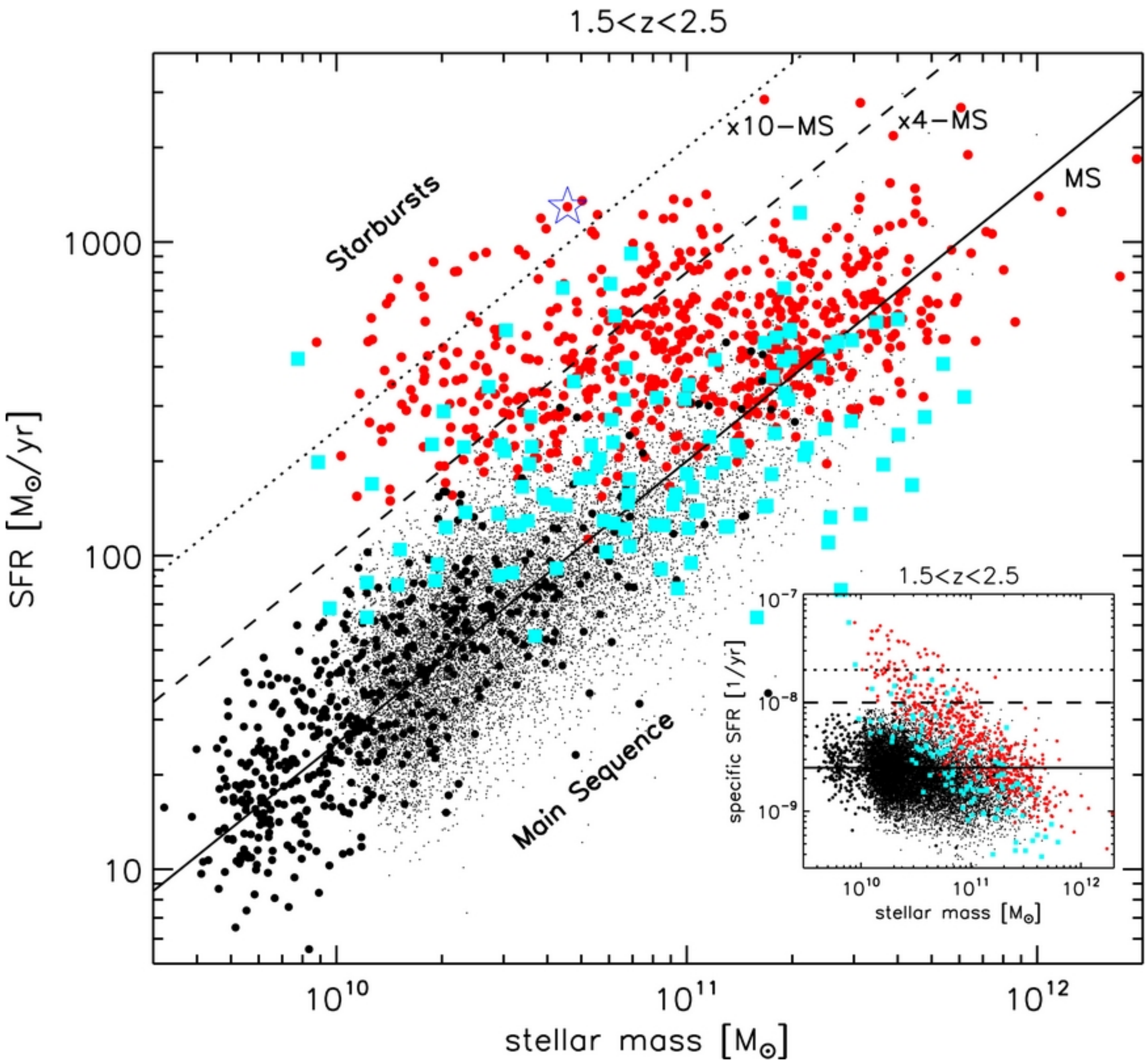


Noeske et al. 2007, ApJ 660, L43

$$SSFR = \frac{SFR}{M_\star}, \quad \mathrm{yr}^{-1}$$

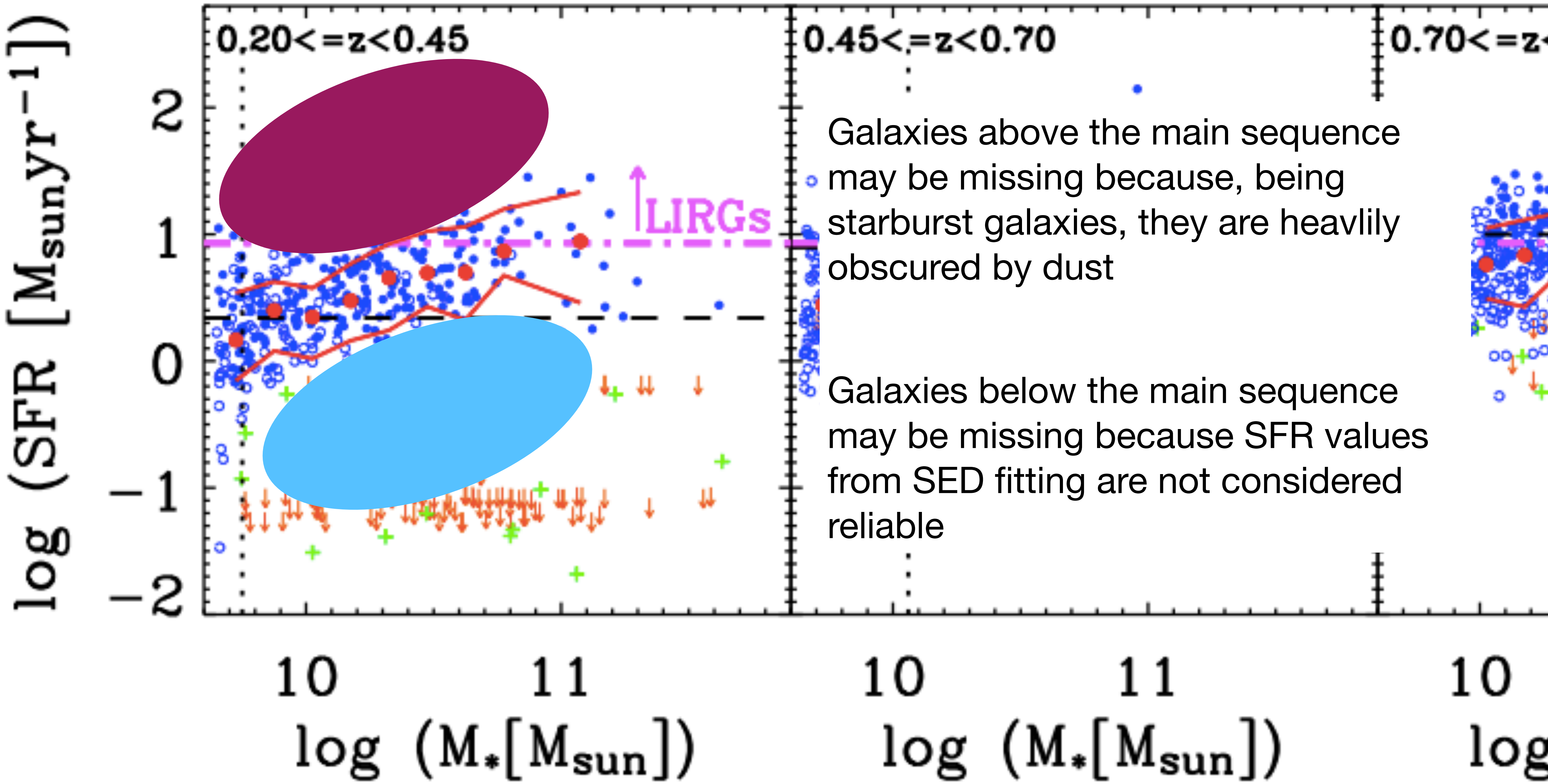
$$\text{Passive galaxies} : SSFR < 10^{-11} \ \mathrm{yr}^{-1}$$

Main sequence of star-forming galaxies?



Rodhighiero et al. 2011, ApJ 739, L40

Potential biases in the main sequence



Galaxies above the main sequence may be missing because, being starburst galaxies, they are heavlily obscured by dust

Galaxies below the main sequence may be missing because SFR values from SED fitting are not considered reliable

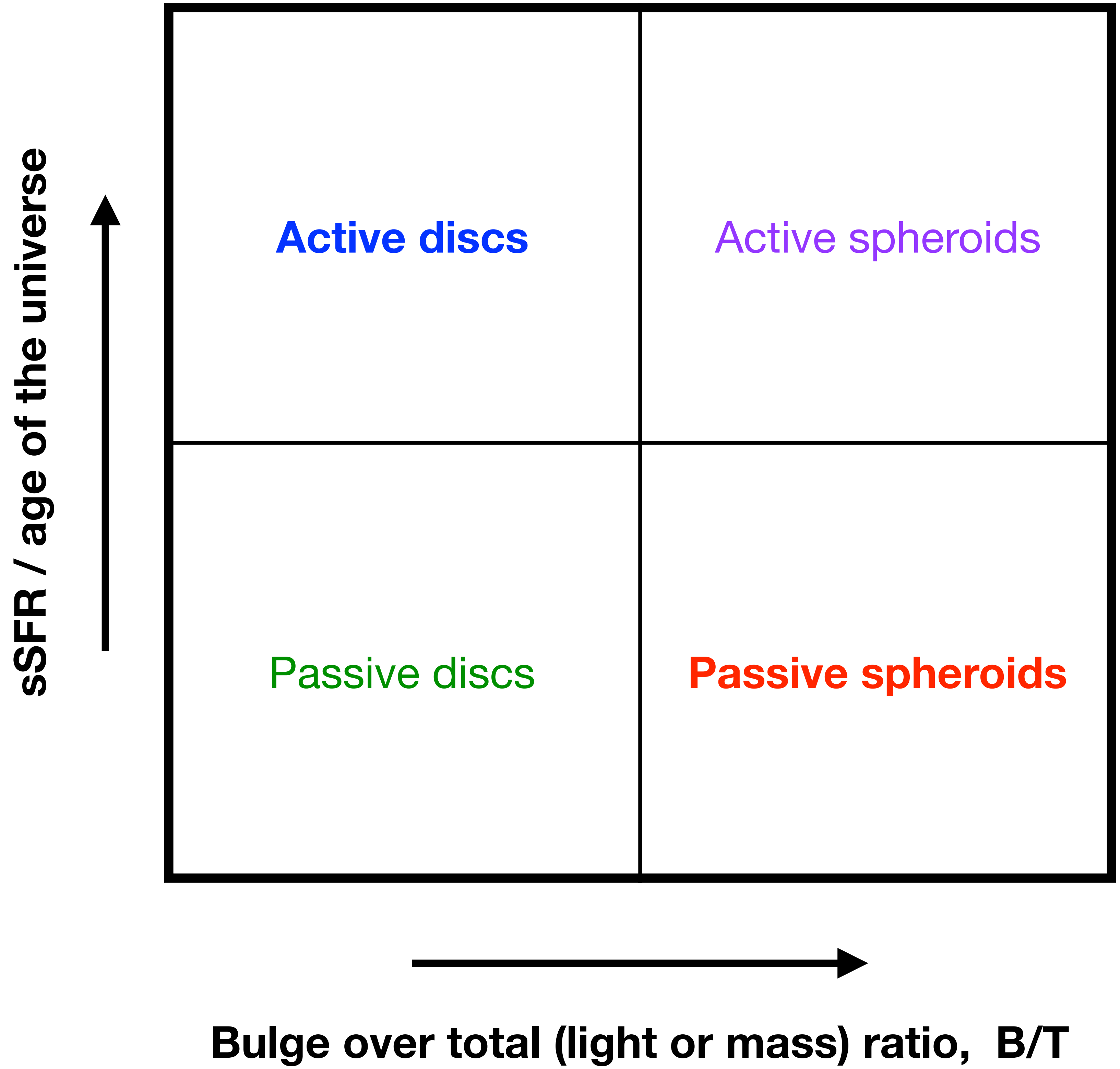
A personal opinion on morphologies

Evaluation by experts

(Gini coefficients etc.)

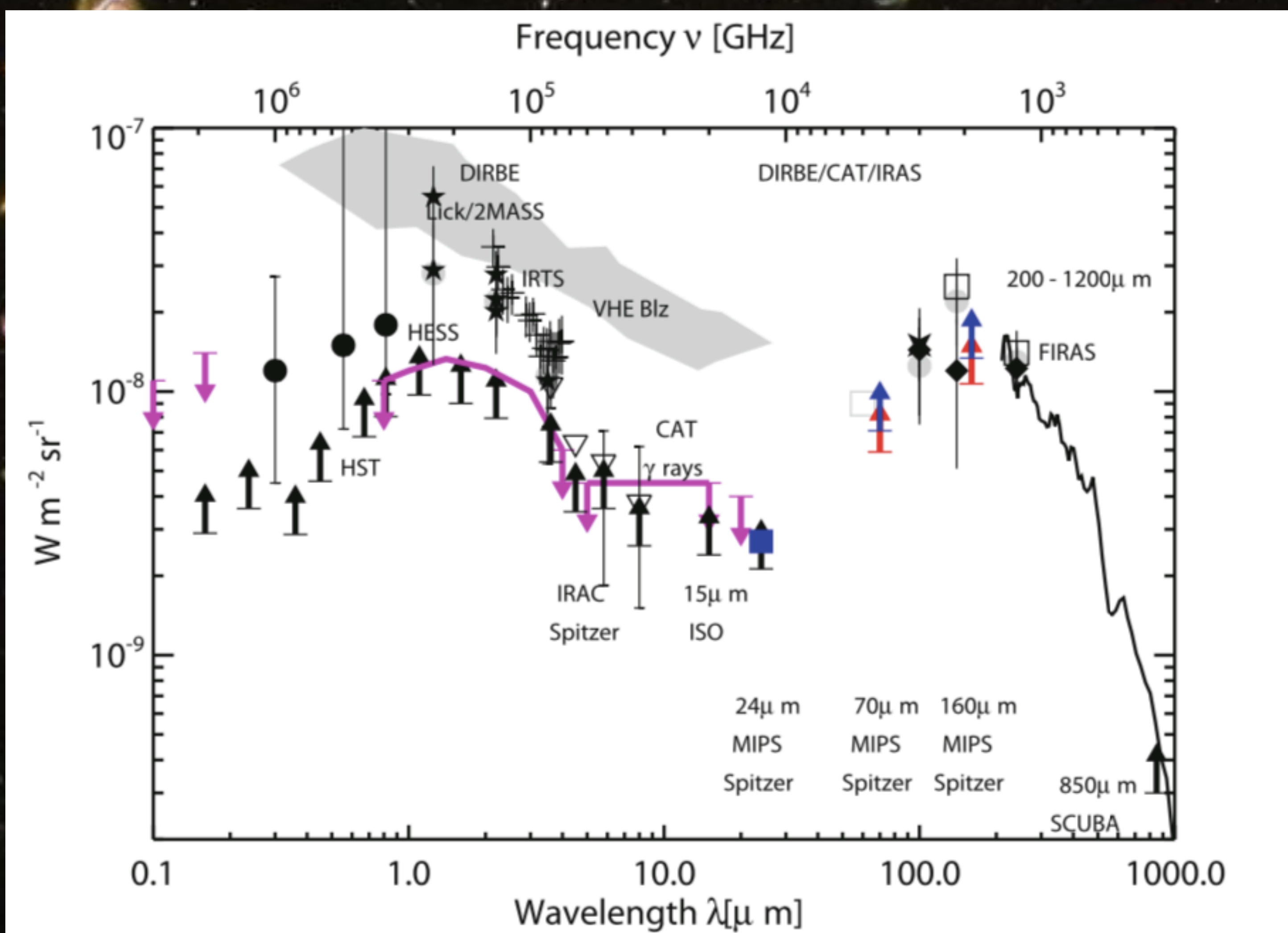
Galaxy zoo: citizen science

Sersic index...

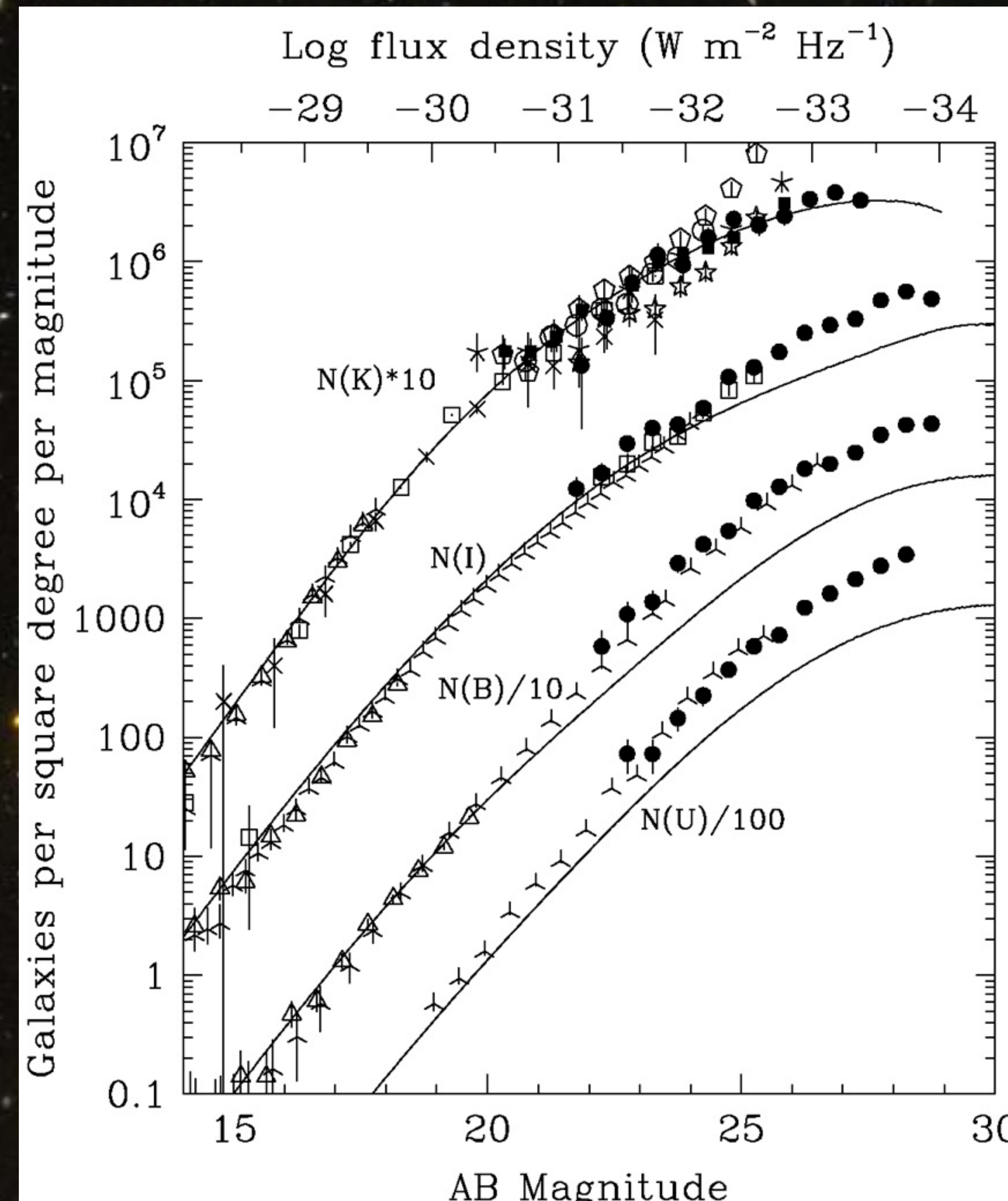


Observing galaxies at high redshift

Number counts -> backgrounds



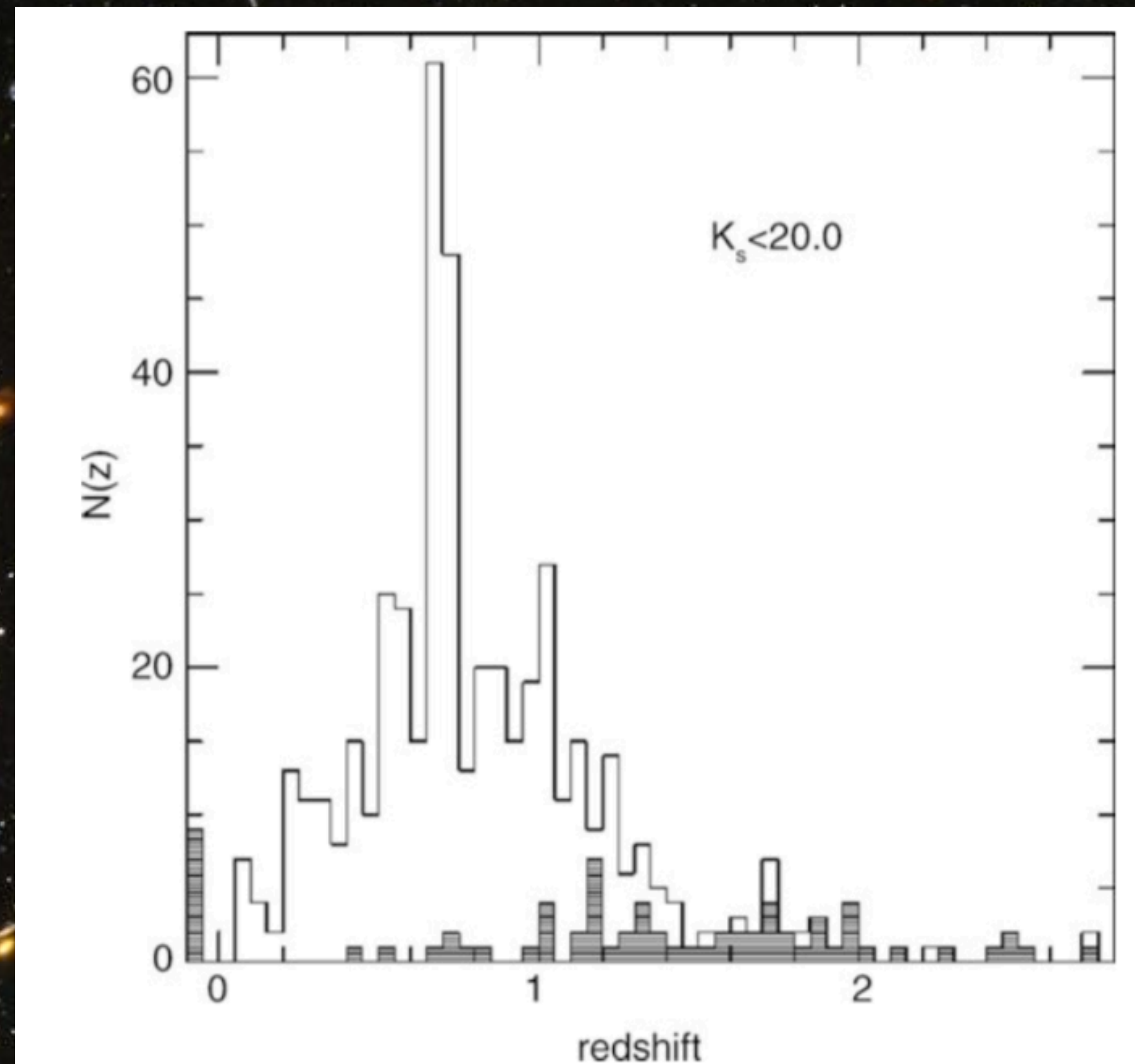
Dole et al. 2006, A&A 451, 417



Ferguson, Dickinson & Williams, 2000
ARA&A 38, 667

Number counts -> backgrounds

Redshift surveys

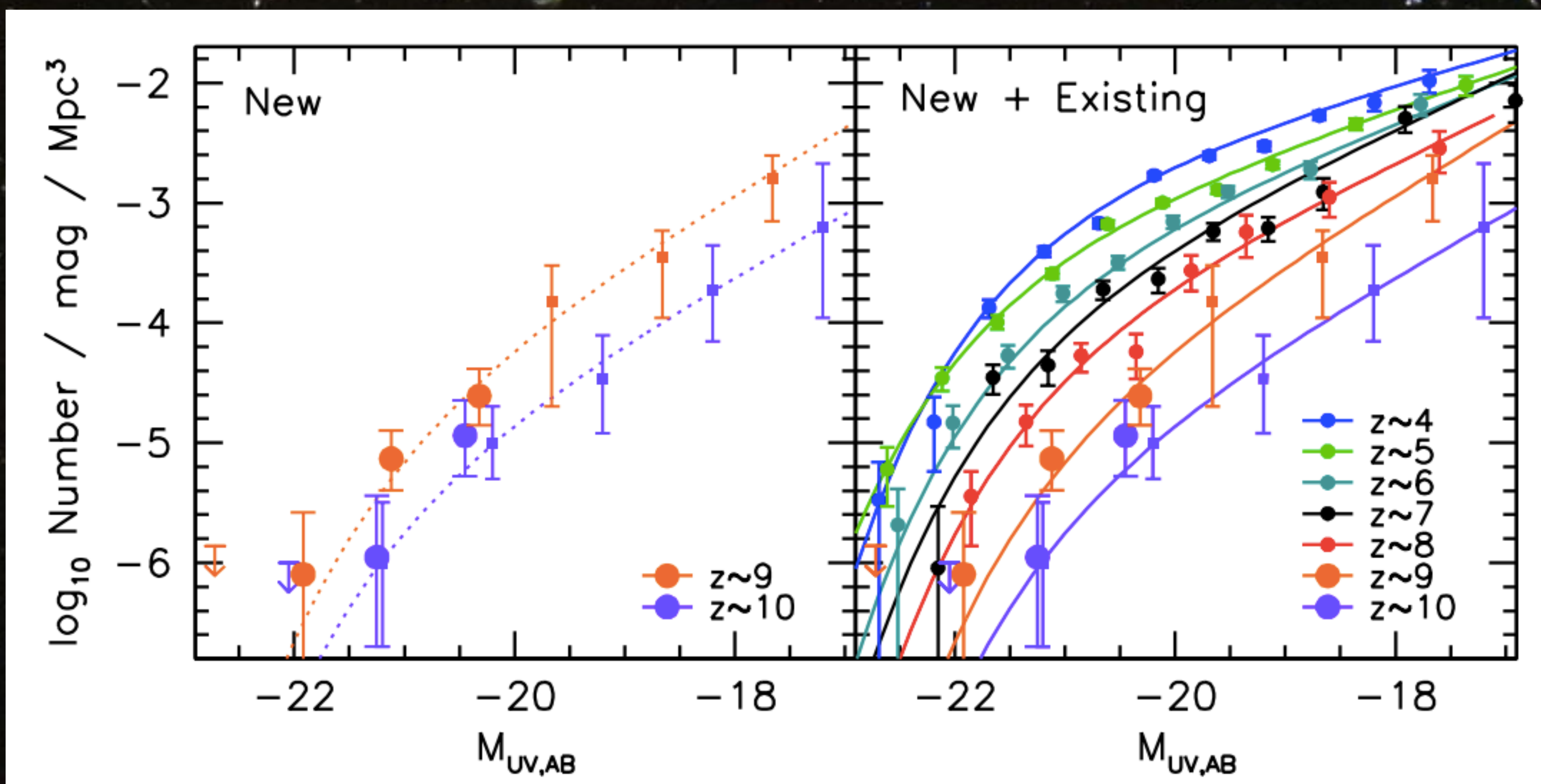


Cimatti et al. 2002, A&A 391, L1

Number counts -> backgrounds

Redshift surveys

Luminosity functions



Bouwens et al. 2019, arXiv:1905.05202

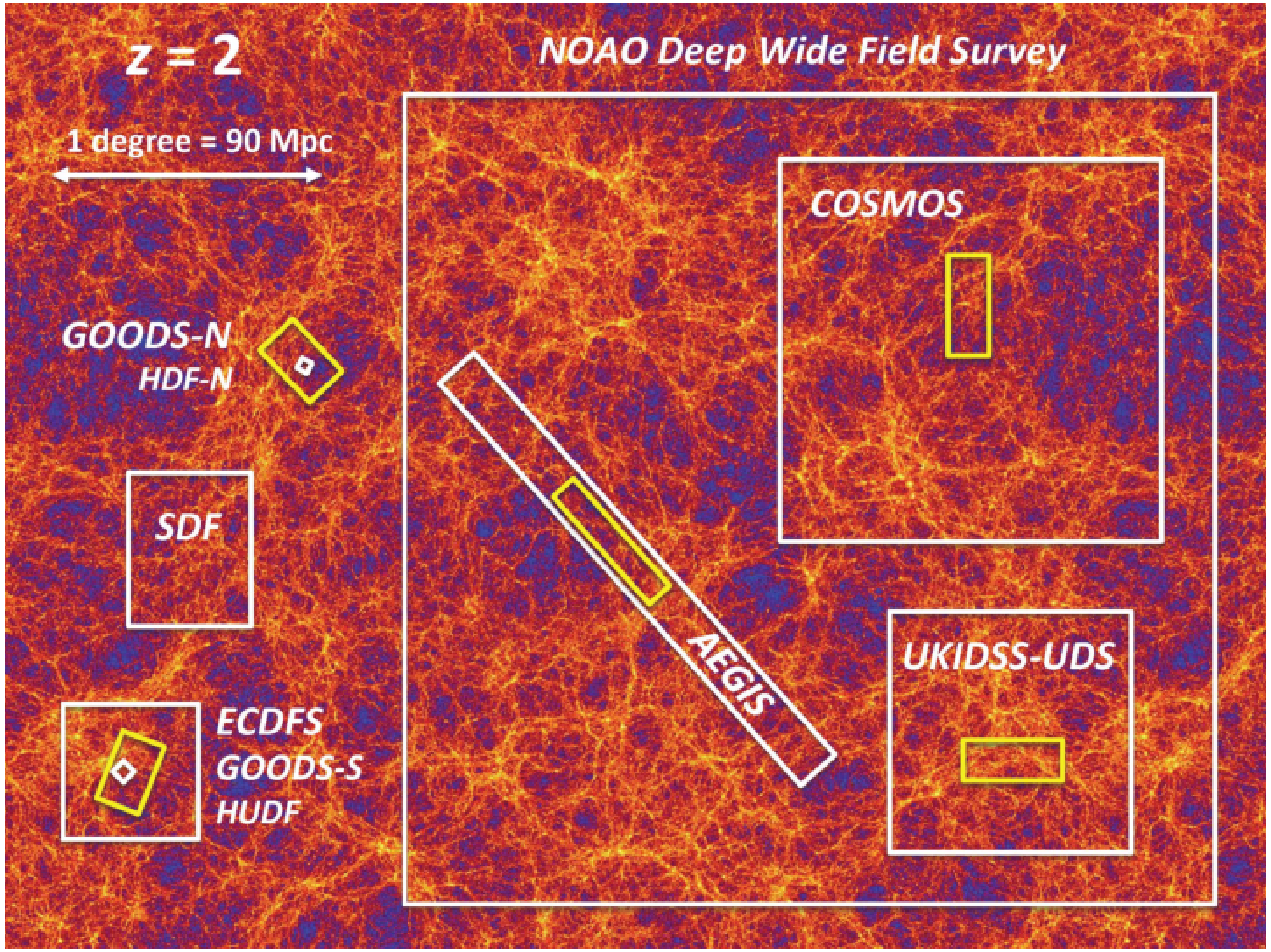
Extragalactic surveys

Main properties:

Surveyed area on the sky
Observed bands
Depth in each band -> confusion limit
Target selection for spectroscopy
Spectroscopic redshifts
Photometric redshifts

To control systematics:

Completeness: fraction of galaxies really observed as a function of magnitude
Purity: fraction of objects that are true galaxies
Angular mask: completeness and purity maps on the sky
Spectroscopic redshift errors
Photometric redshift errors

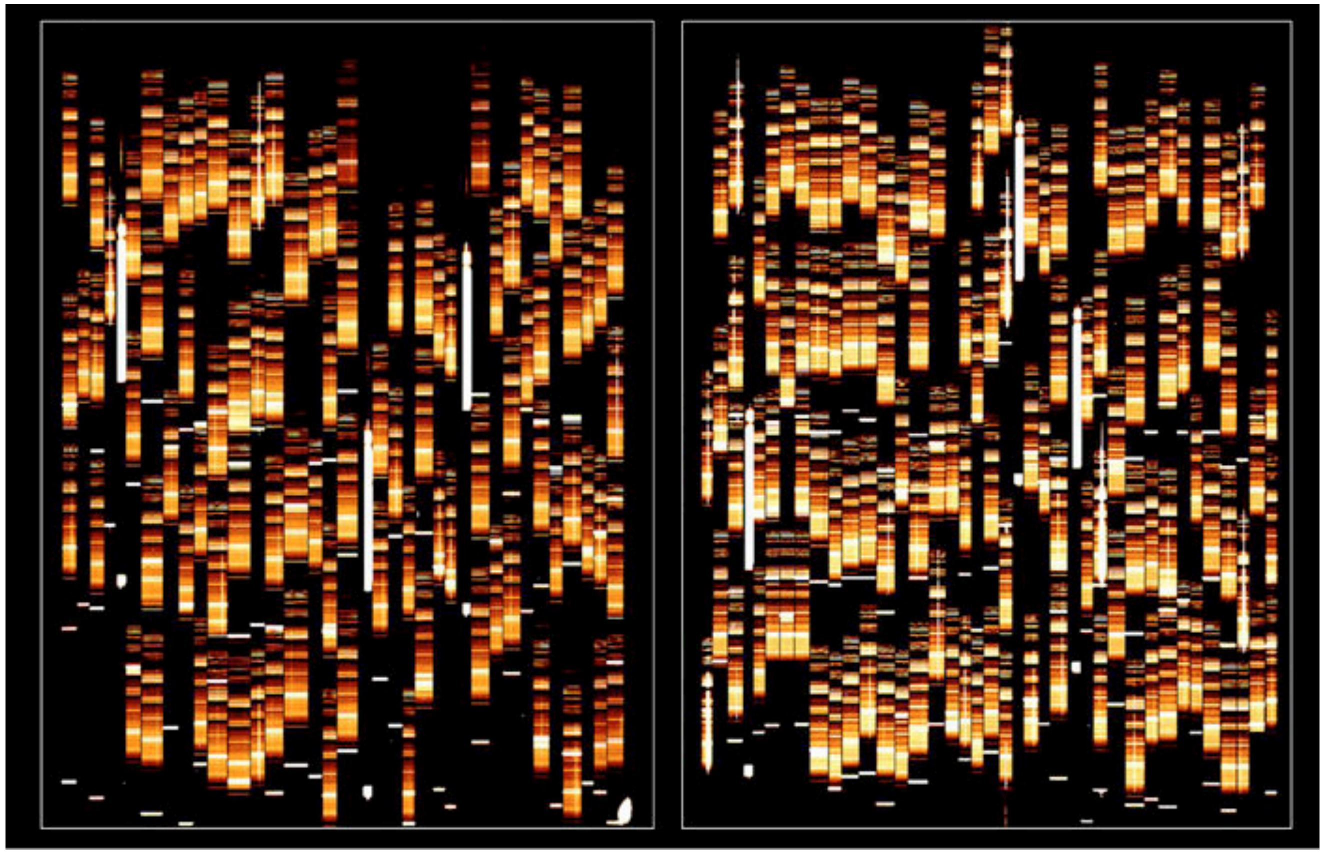


Madau & Dickinson 2014, ARA&A 52, 415

Selection of high-redshift galaxies

Complete spectroscopic surveys of a deep field with Multi-Object Spectrographs:

just observe one small field, like the Hubble deep and ultra-deep fields, and take spectra for all the galaxies that are bright enough

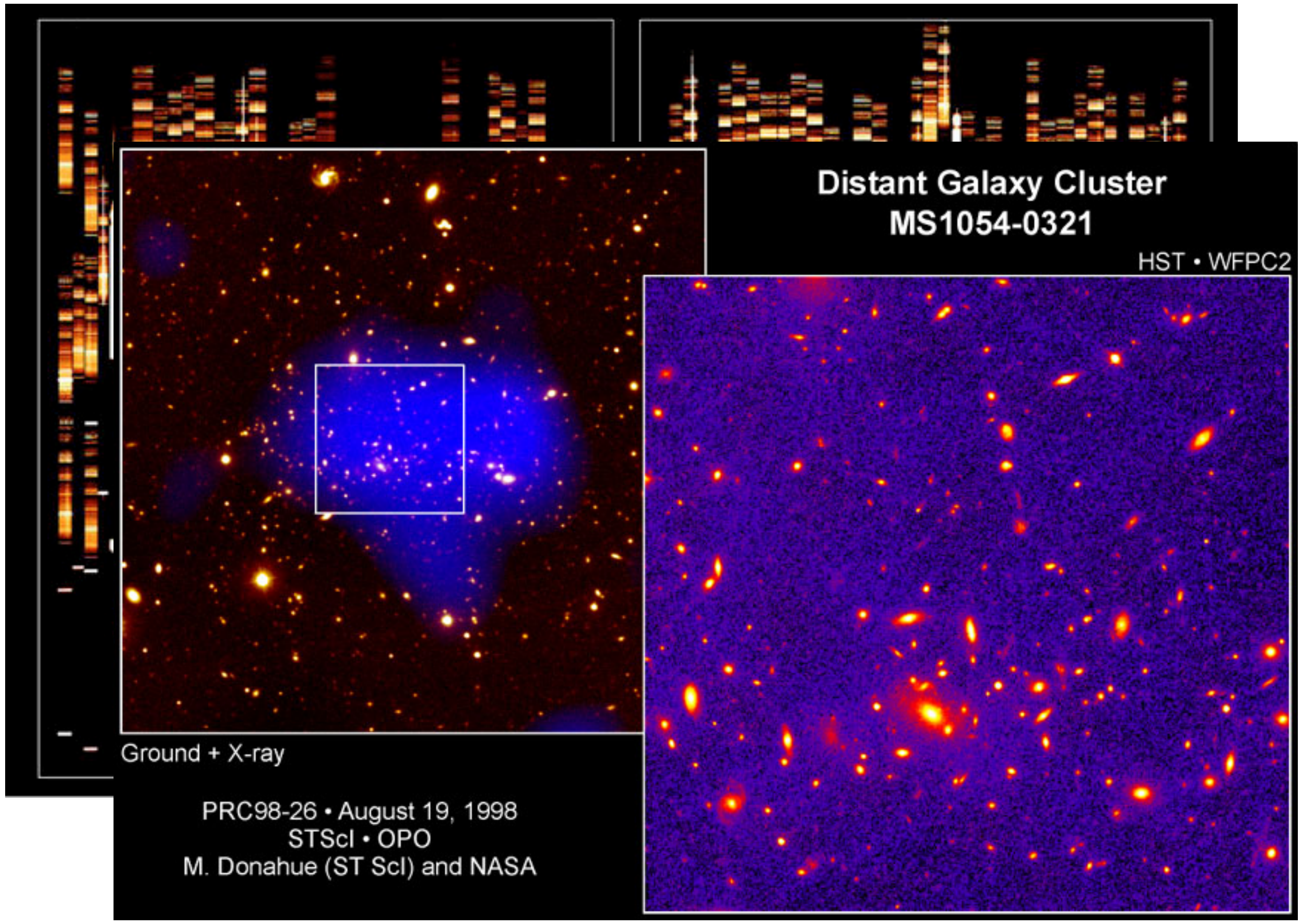


Selection of high-redshift galaxies

Complete spectroscopic surveys of a deep field with Multi-Object Spectrographs;

Galaxies in massive galaxy clusters at z~1:

these systems can be recognized both as galaxy overdensities and as X-ray soures, galaxies in that field have a high probability of belonging to the cluster



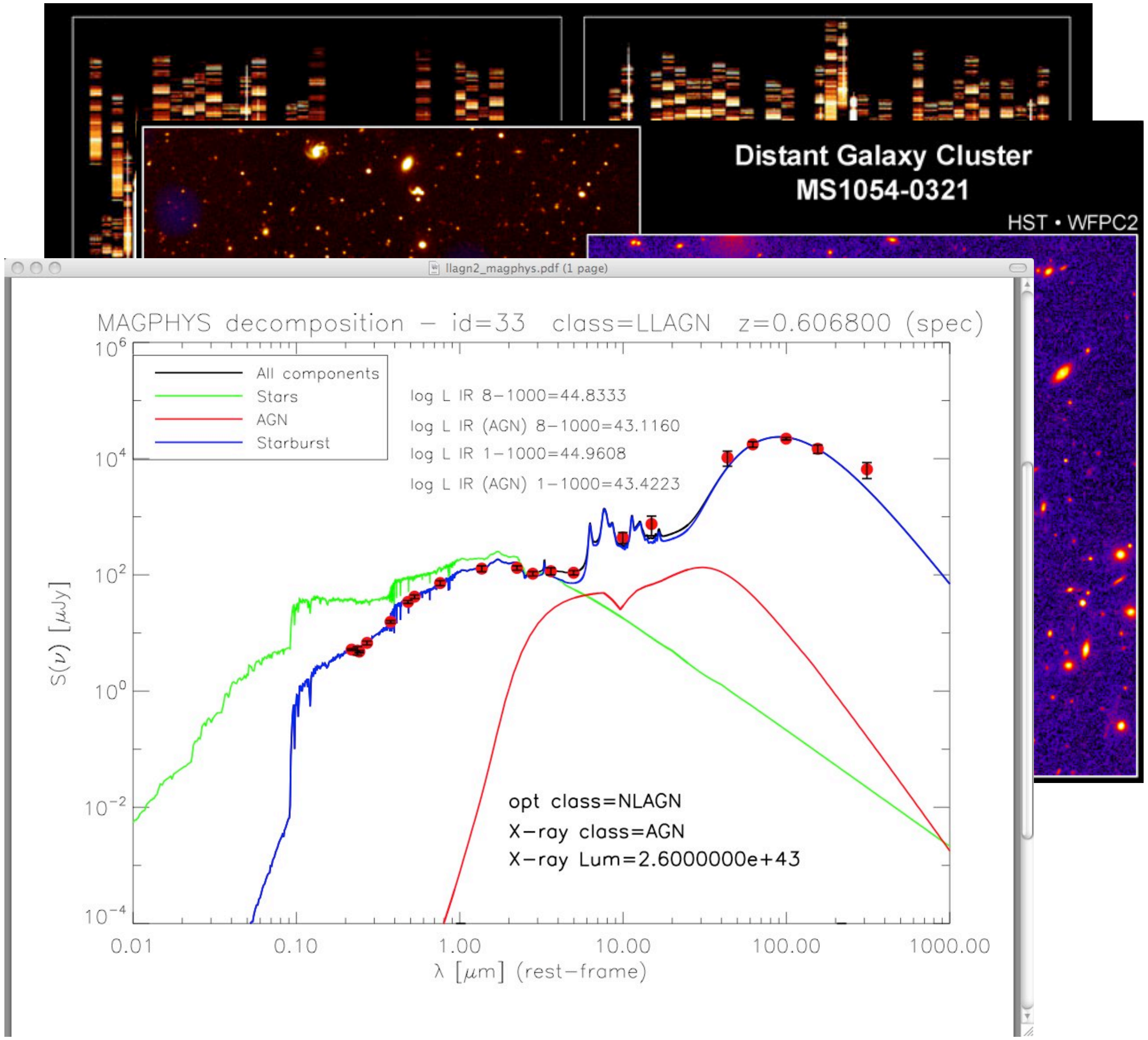
Selection of high-redshift galaxies

Complete spectroscopic surveys of a deep field with Multi-Object Spectrographs;

Galaxies in massive galaxy clusters at z~1;

photometric redshifts from SED fitting:

redshift is one of the crucial parameters for SED fitting, even few bands are sufficient to obtain a redshift determination



Selection of

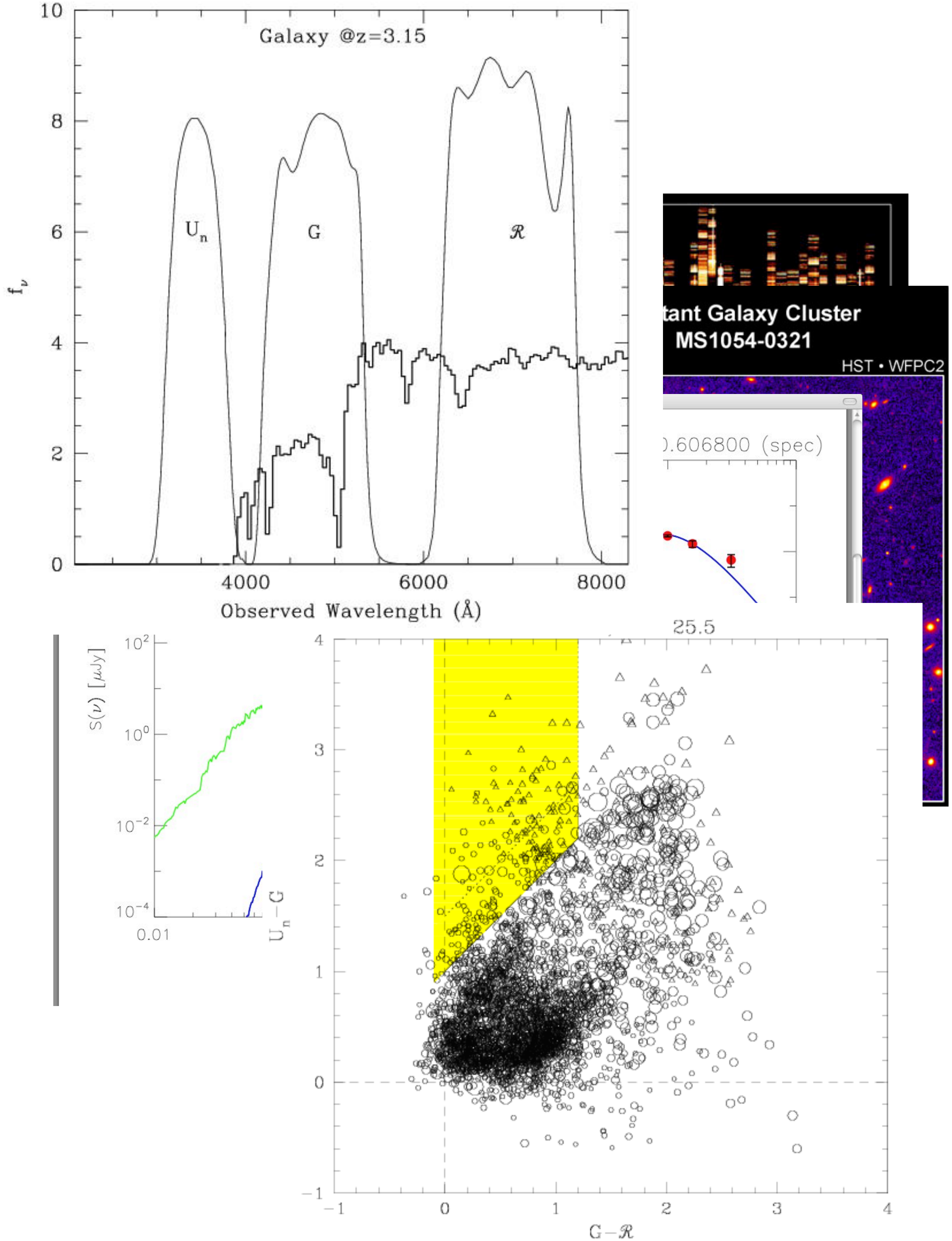
Complete spectroscopic surveys of a deep field with Multi-Object Spectrographs;

Galaxies in massive galaxy clusters at z~1;

photometric redshifts from SED fitting;

Lyman-break galaxies:

at high redshift the Lyman break enters optical or NUV filters, galaxies then "drop out" of blue images and their colors are easily recognisable



Selection of high-redshift galaxies

Complete spectroscopic surveys of a deep field with Multi-Object Spectrographs;

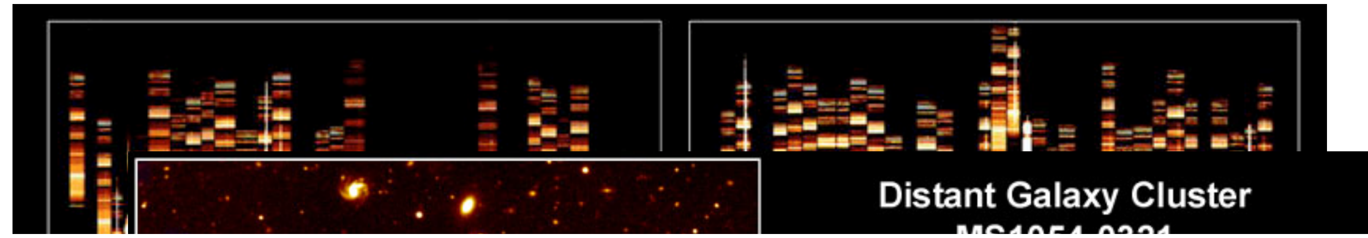
Galaxies in massive galaxy clusters at z~1;

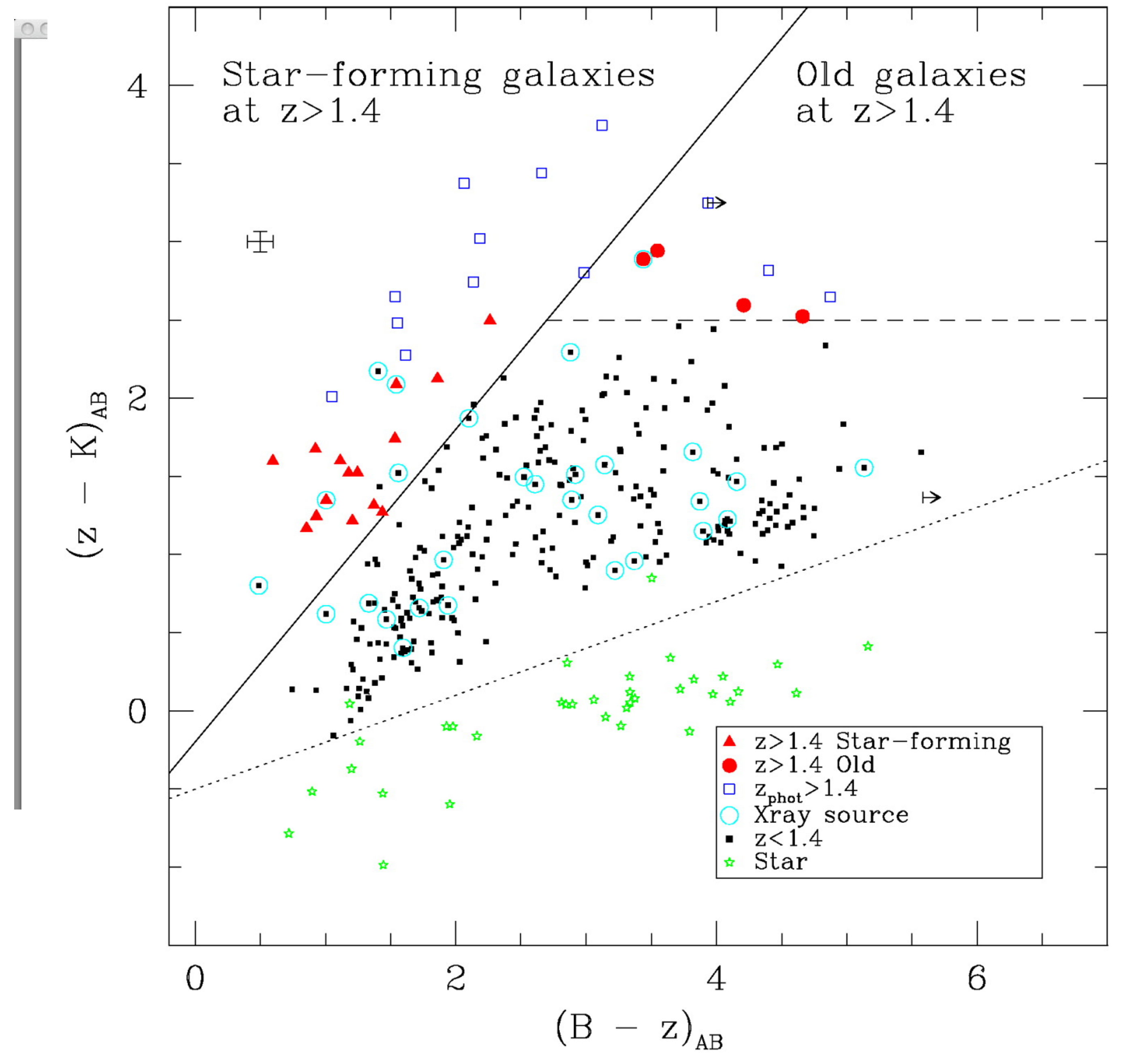
photometric redshifts from SED fitting;

Lyman-break galaxies;

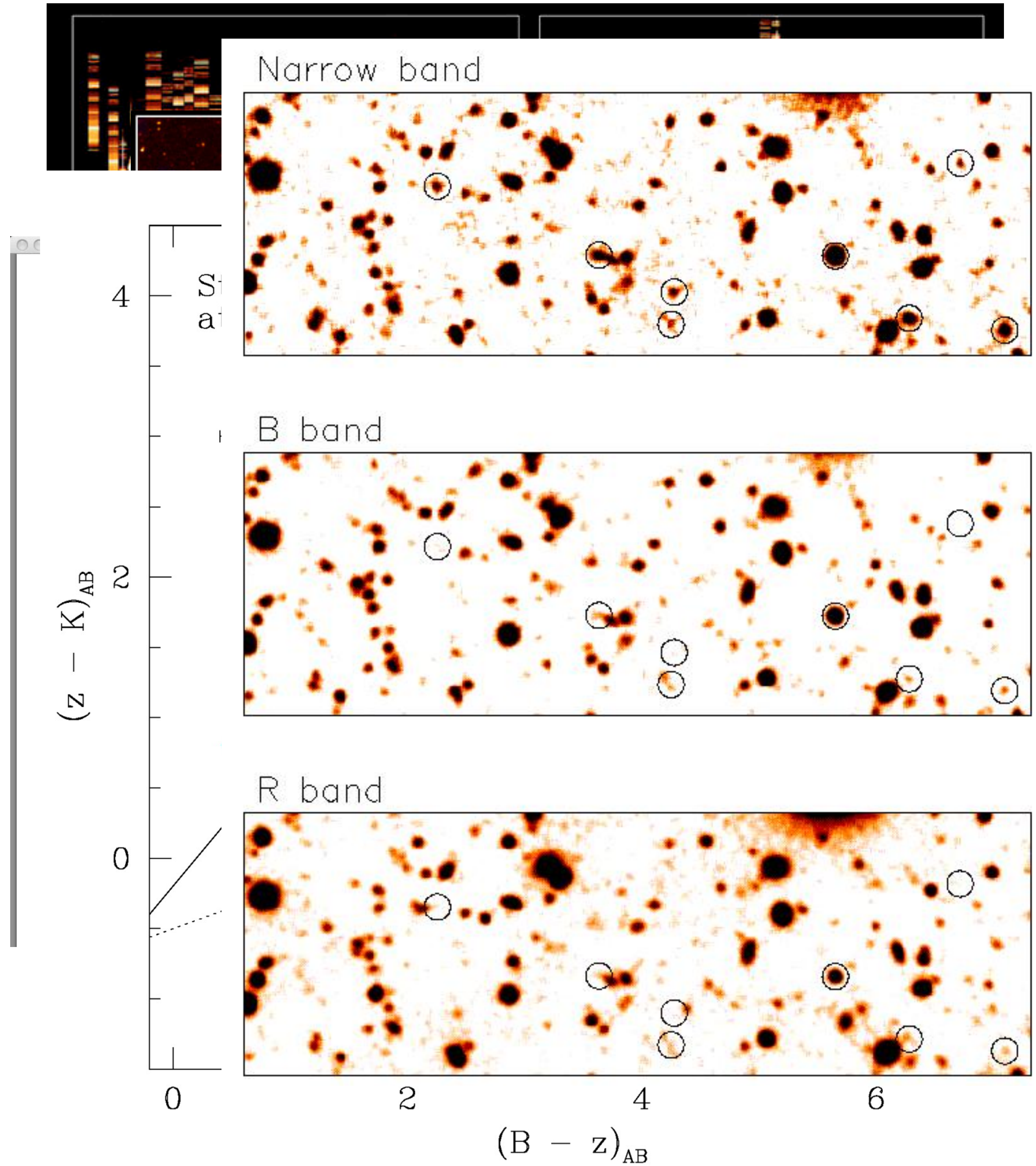
other color-color techniques (BzK):

star-forming or passive galaxies at z~1.5 acquire recognizable colors due to their redshift.





Selection of high-redshift galaxies



Complete spectroscopic surveys of a deep field with Multi-Object Spectrographs;

Galaxies in massive galaxy clusters at z~1;

photometric redshifts from SED fitting;

Lyman-break galaxies;

other color-color techniques (BzK);

Lyman-alpha emitters:

observations with a narrow filter can reveal galaxies that have a strong Lyman alpha emission line.

Selection of high-redshift galaxies

Complete spectroscopic surveys of a deep field with Multi-Object Spectrographs;

Galaxies in massive galaxy clusters a z~1;

photometric redshifts from SED fittin

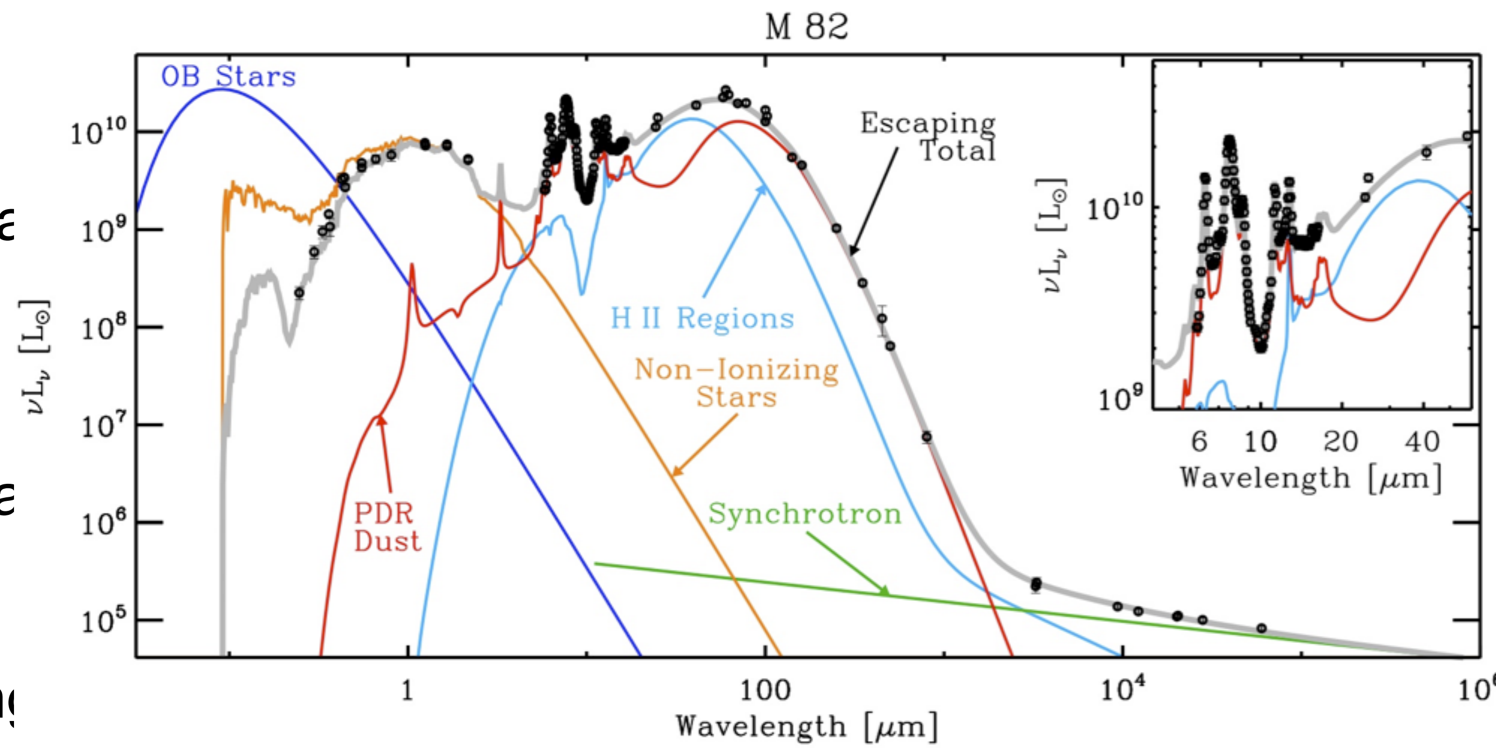
Lyman-break galaxies;

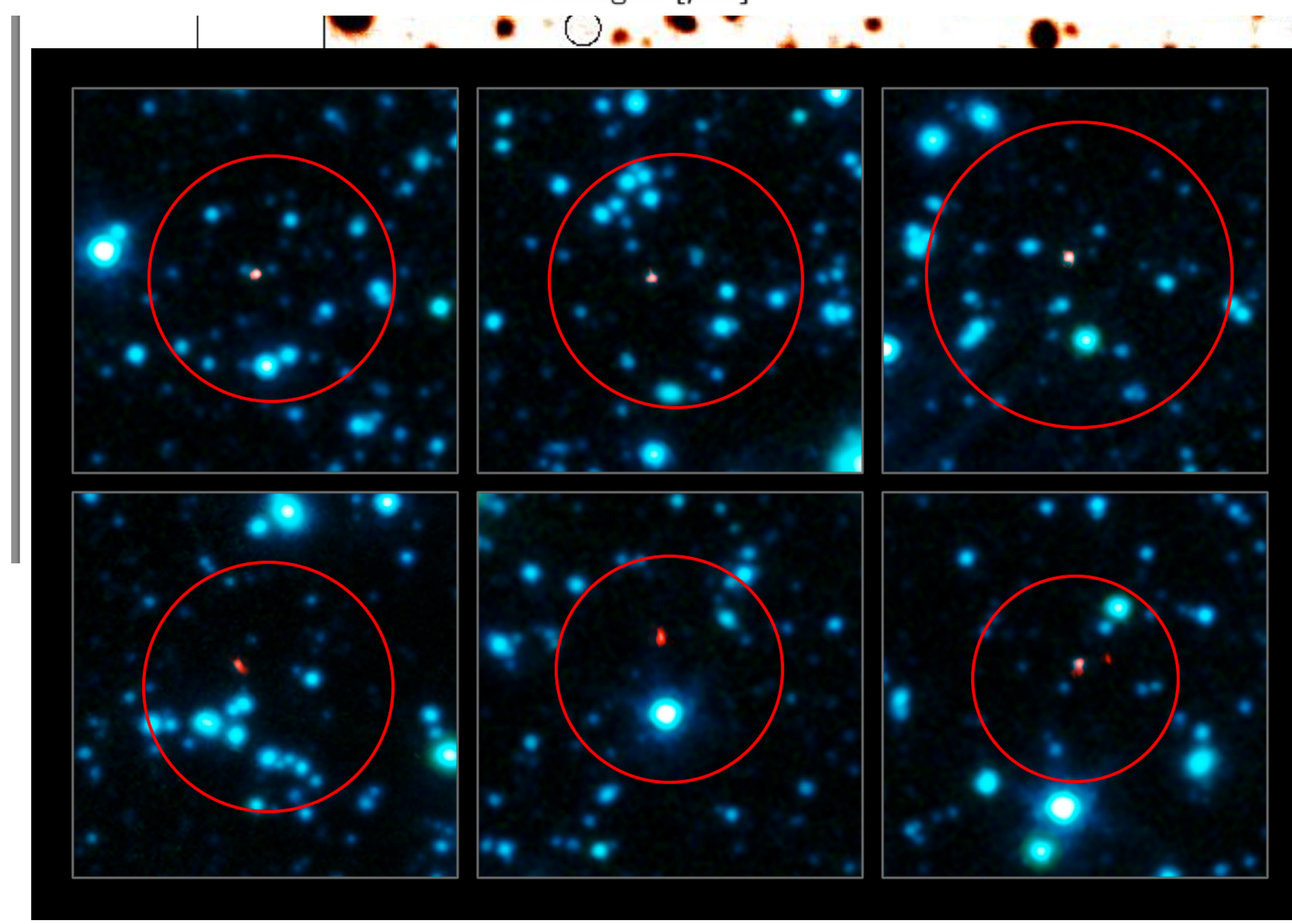
other color-color techniques (BzK);

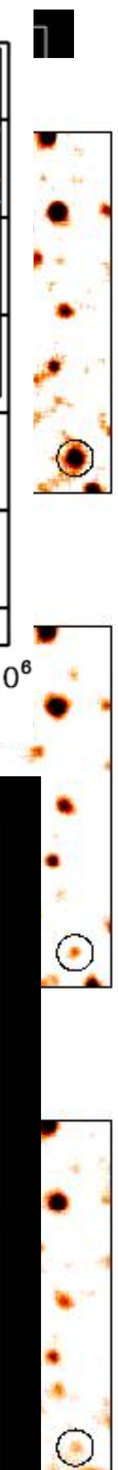
Lyman-alpha emitters;

sub-mm galaxies:

the large positive K-correction at such long wavelenghts allows us to observe dusty star-forming galaxies in the sub-mm to very high redshift.







Selection of high-redshift galaxies

Complete spectroscopic surveys of a deep field with Multi-Object Spectrographs;

Galaxies in massive galaxy clusters at z~1;

photometric redshifts from SED fitting;

Lyman-break galaxies;

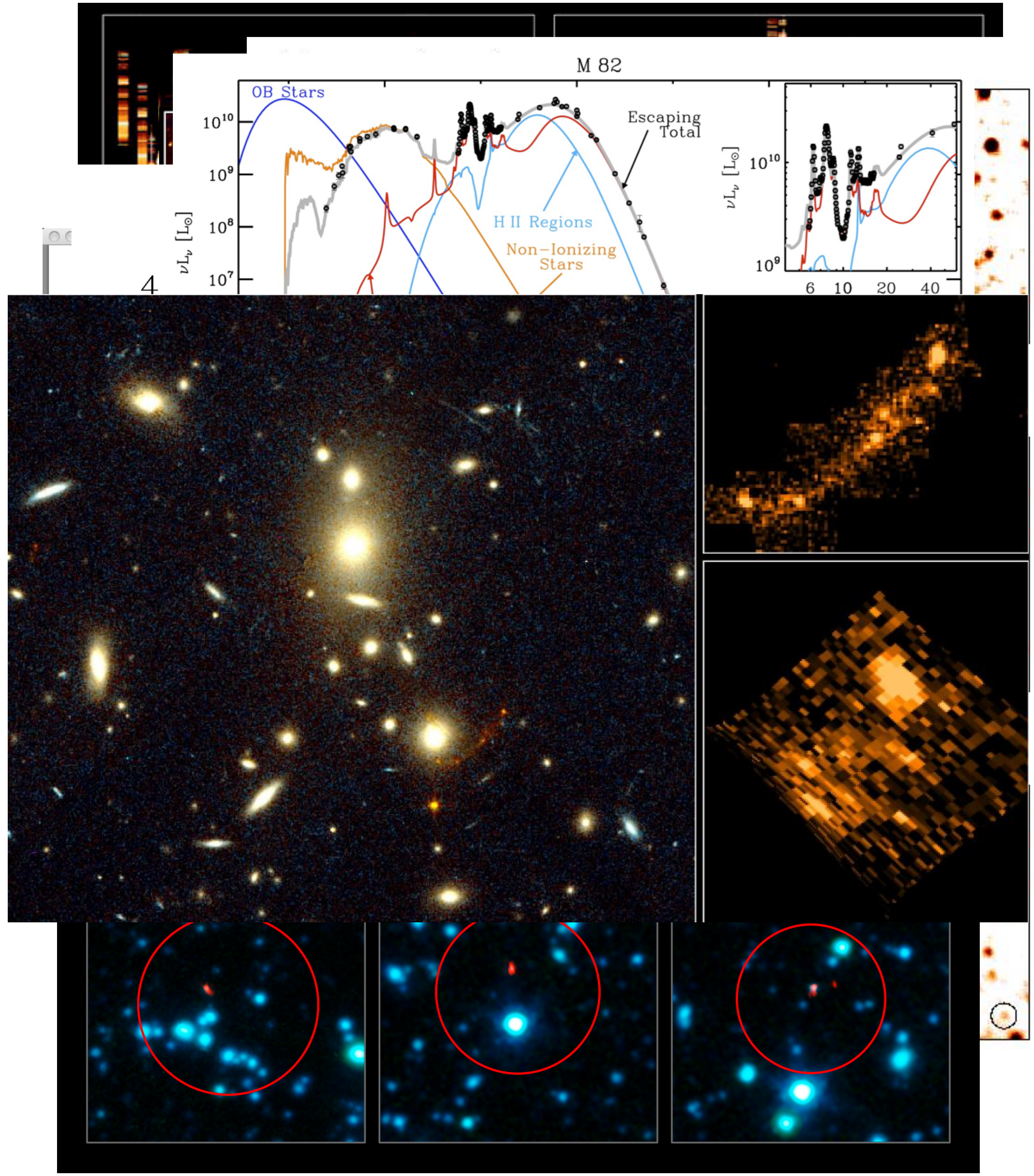
other color-color techniques (BzK)

Lyman-alpha emitters;

sub-mm galaxies;

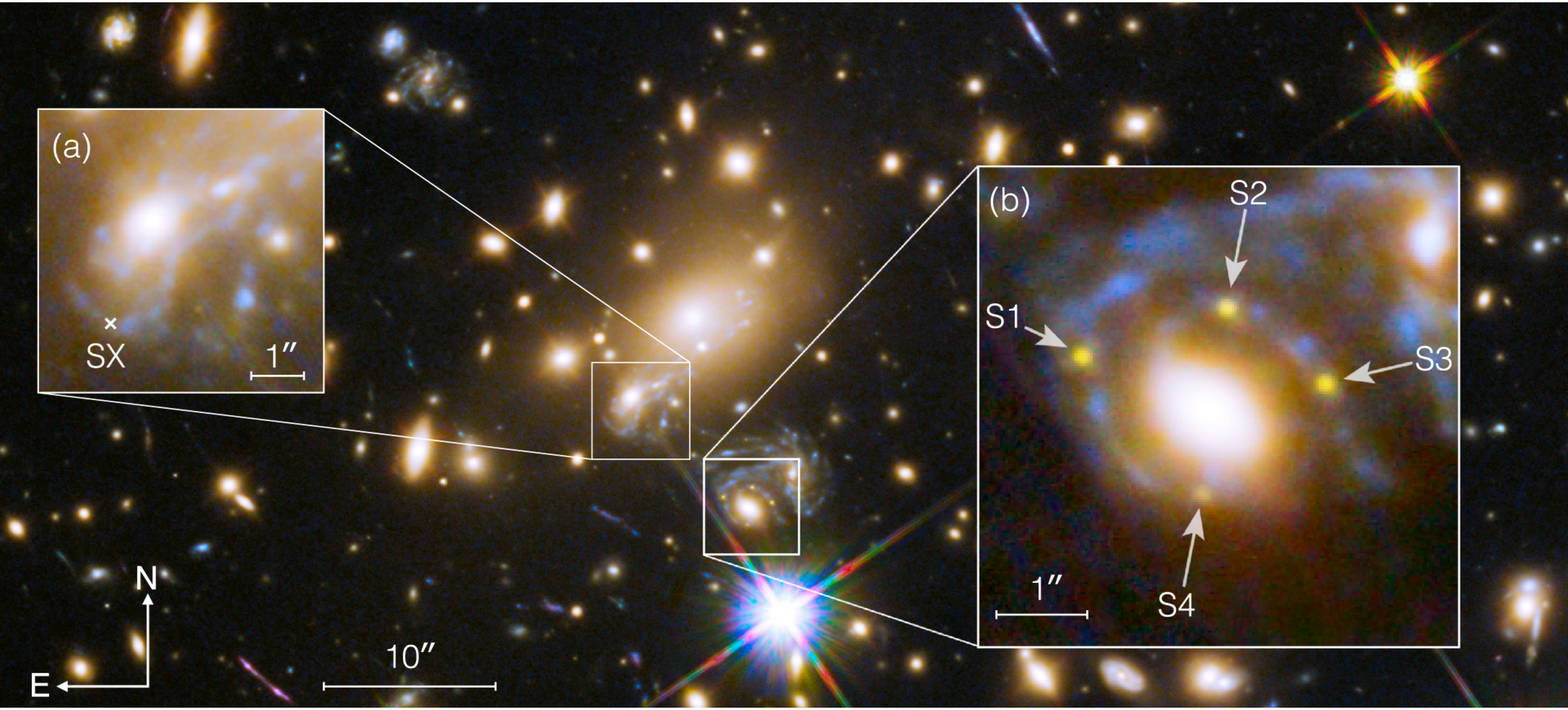
gravitational lenses:

high-redshift galaxies can be observed, highly amplified by lensing, in as background sources of clusters.



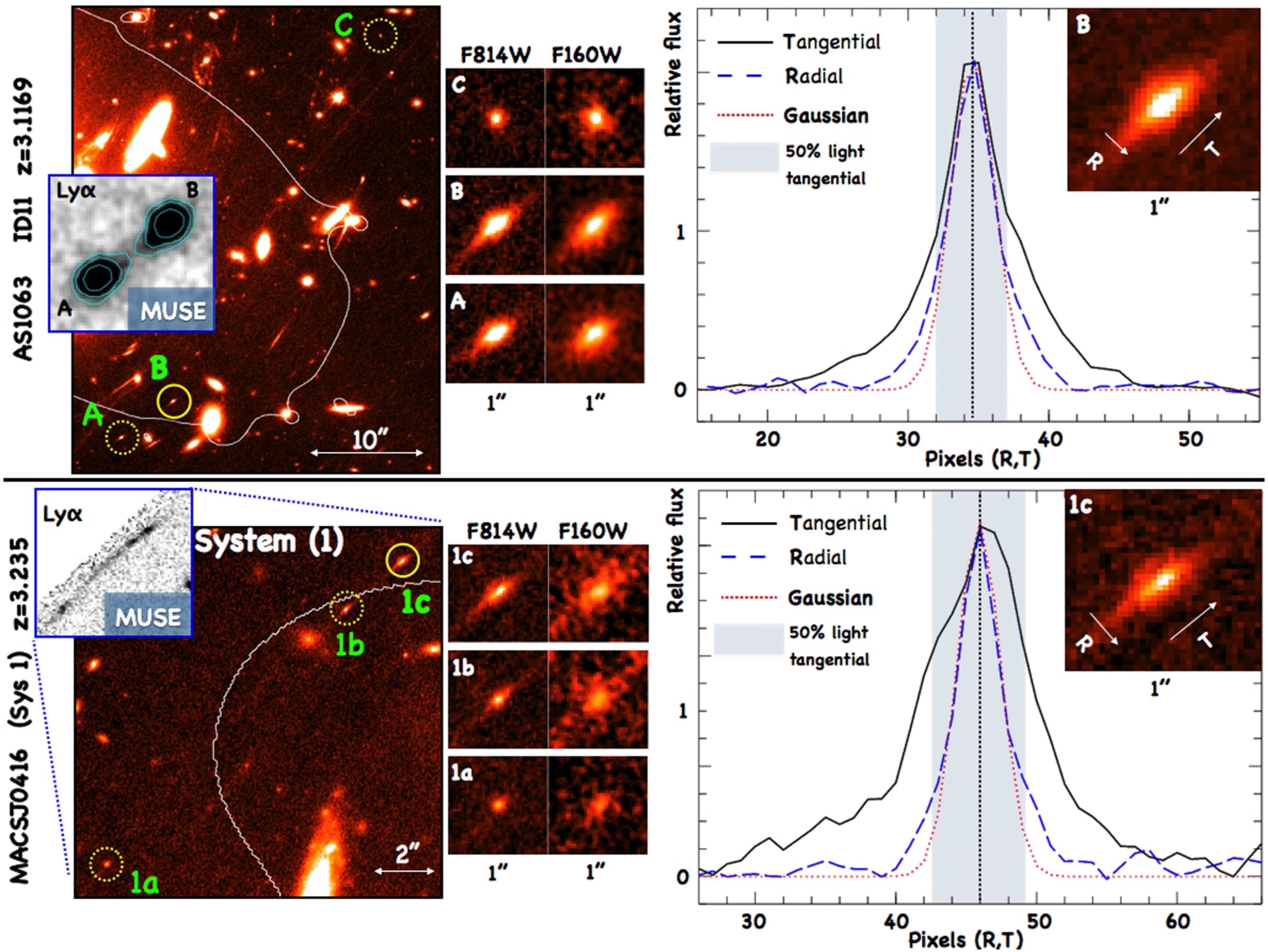
Two cool things related to lensing

On lensing: Refsdal supernova



Grillo et al 2018 ApJ 860 94

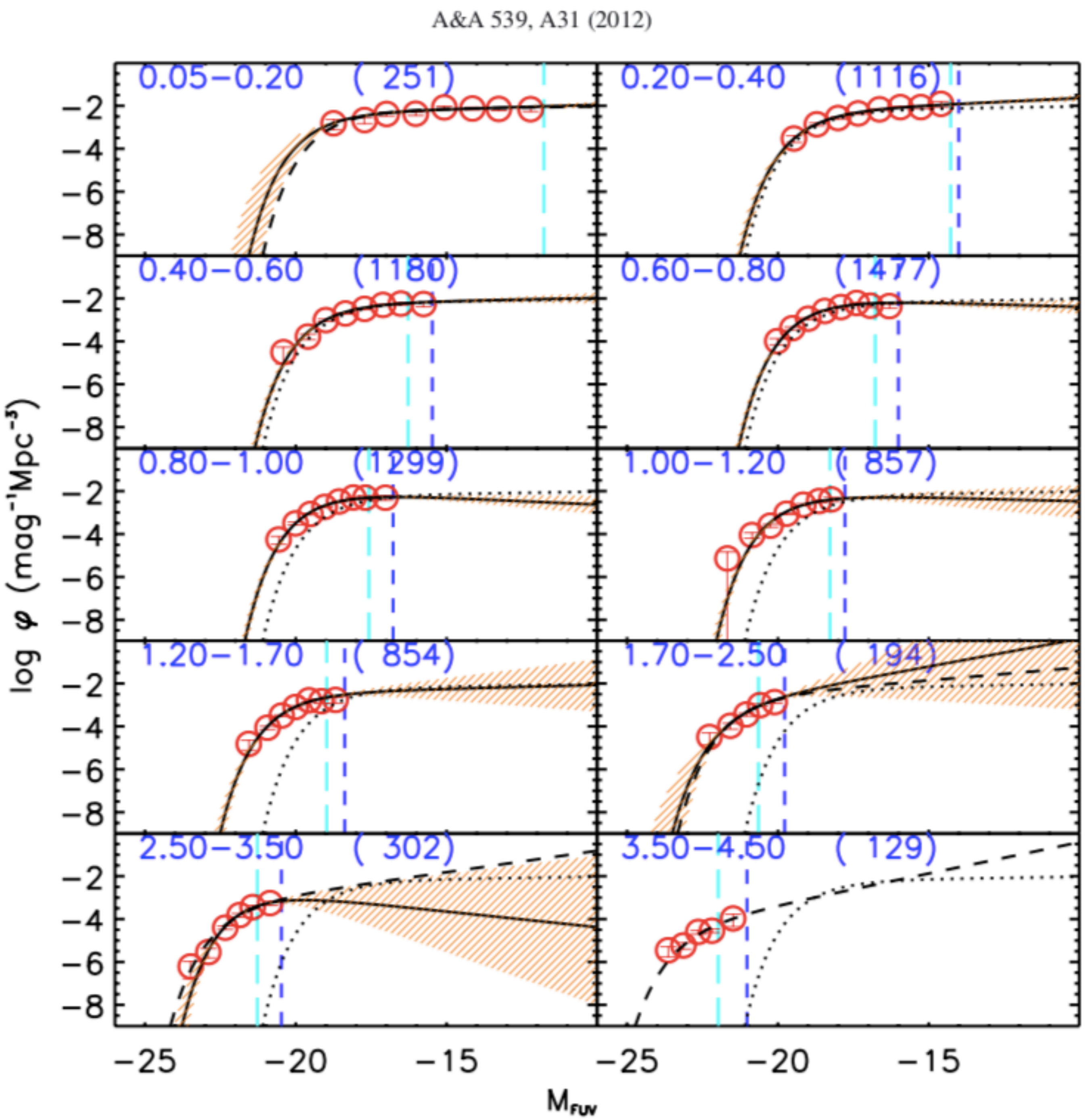
Globular cluster formation caught in act?



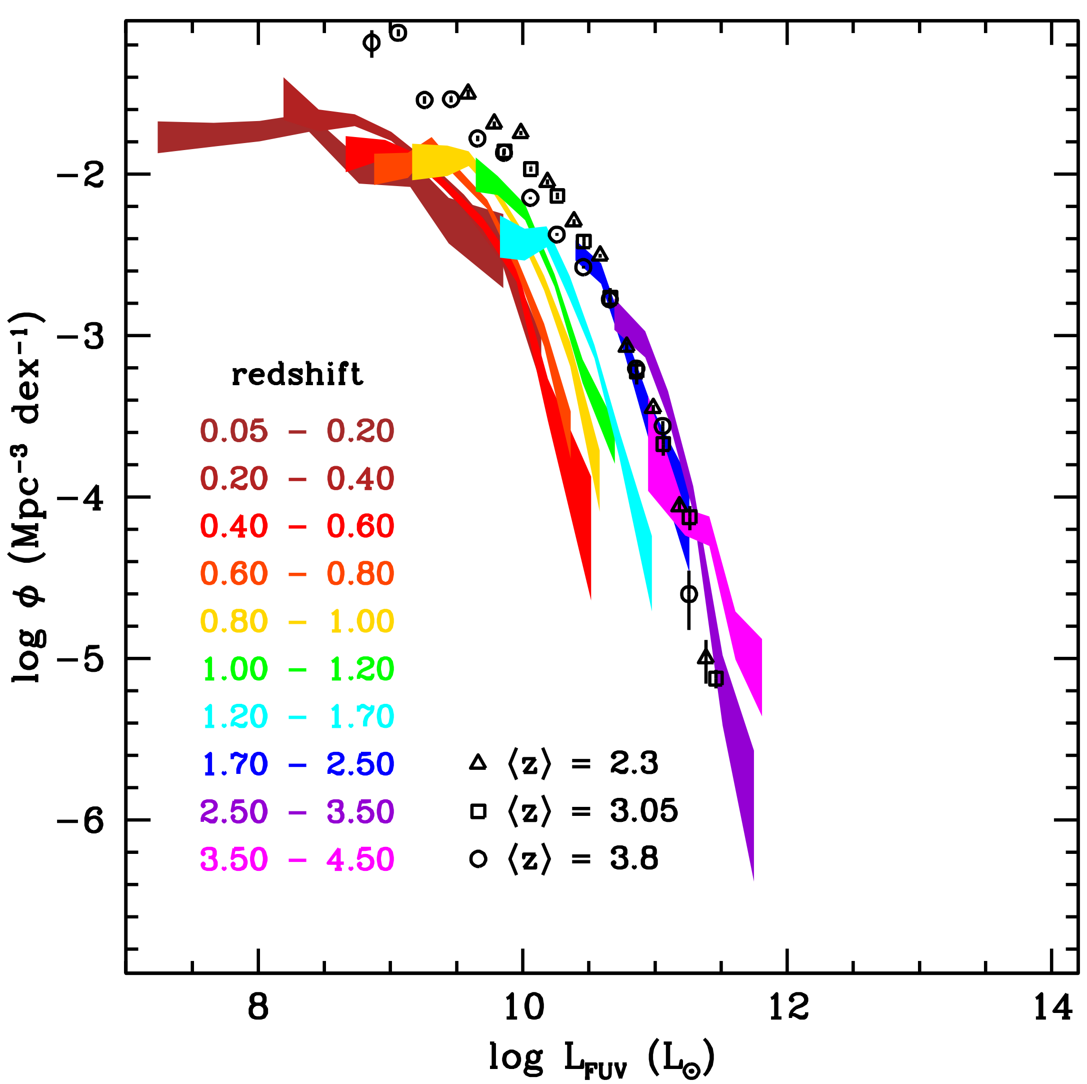
Vanzella et al. 2017, MNRAS 467, 4304

The cosmic star formation history

Evolution of the rest-frame UV luminosity function

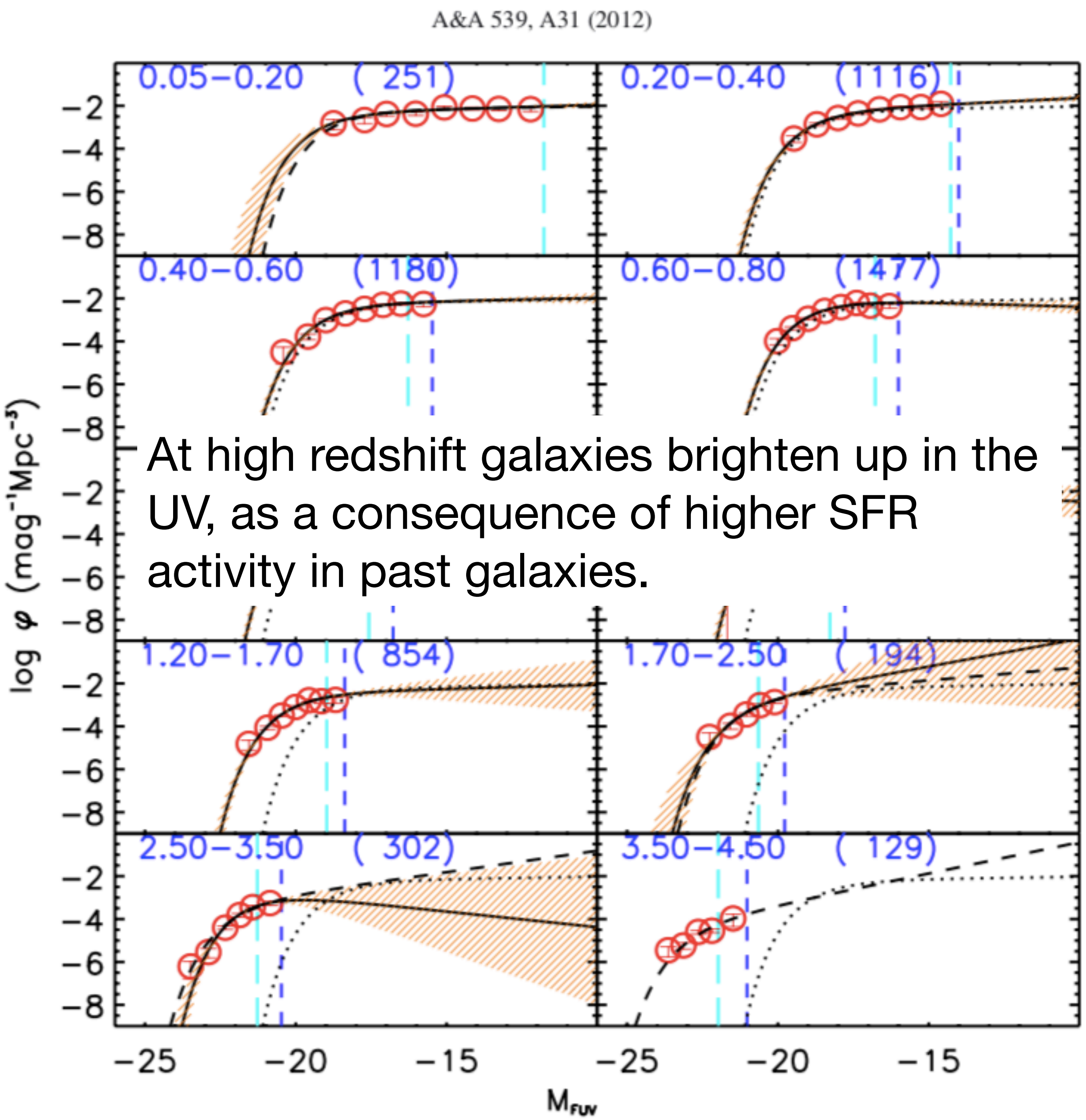


Cucciati et al. 2012, A&A 539, 31

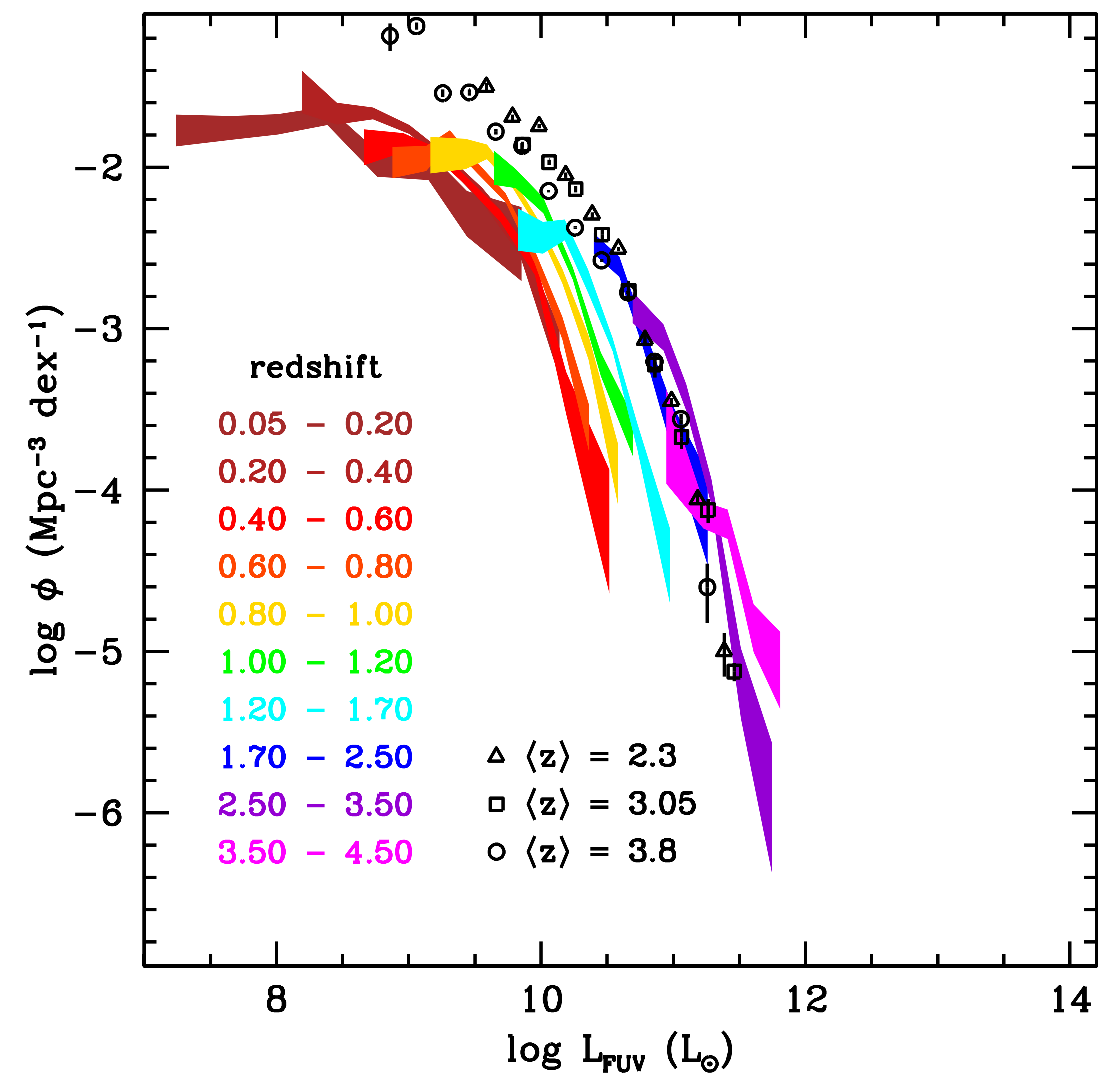


Madau & Dickinson 2014, ARA&A 52, 415

Evolution of the rest-frame UV luminosity function



At high redshift galaxies brighten up in the UV, as a consequence of higher SFR activity in past galaxies.

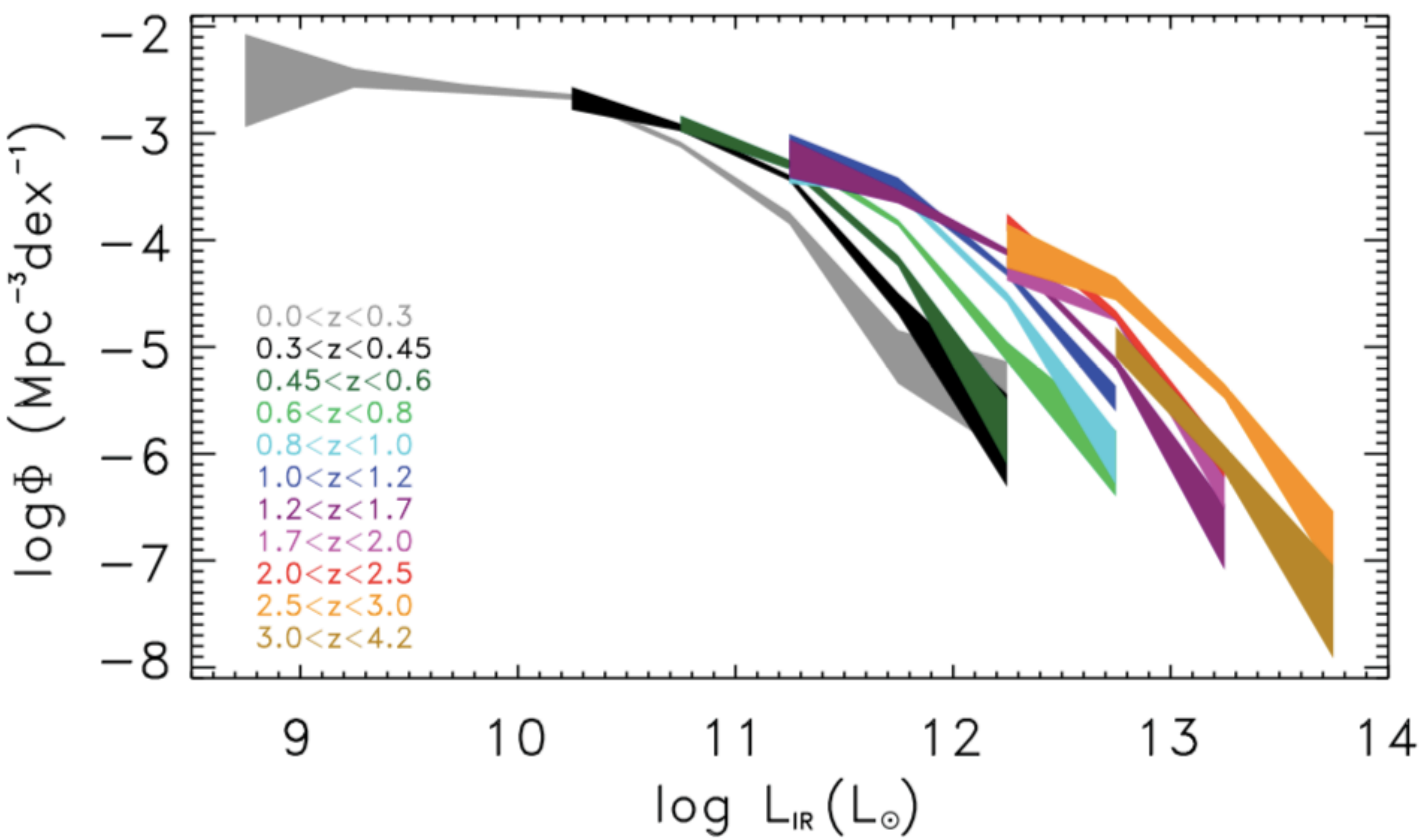


Cucciati et al. 2012, A&A 539, 31

Madau & Dickinson 2014, ARA&A 52, 415

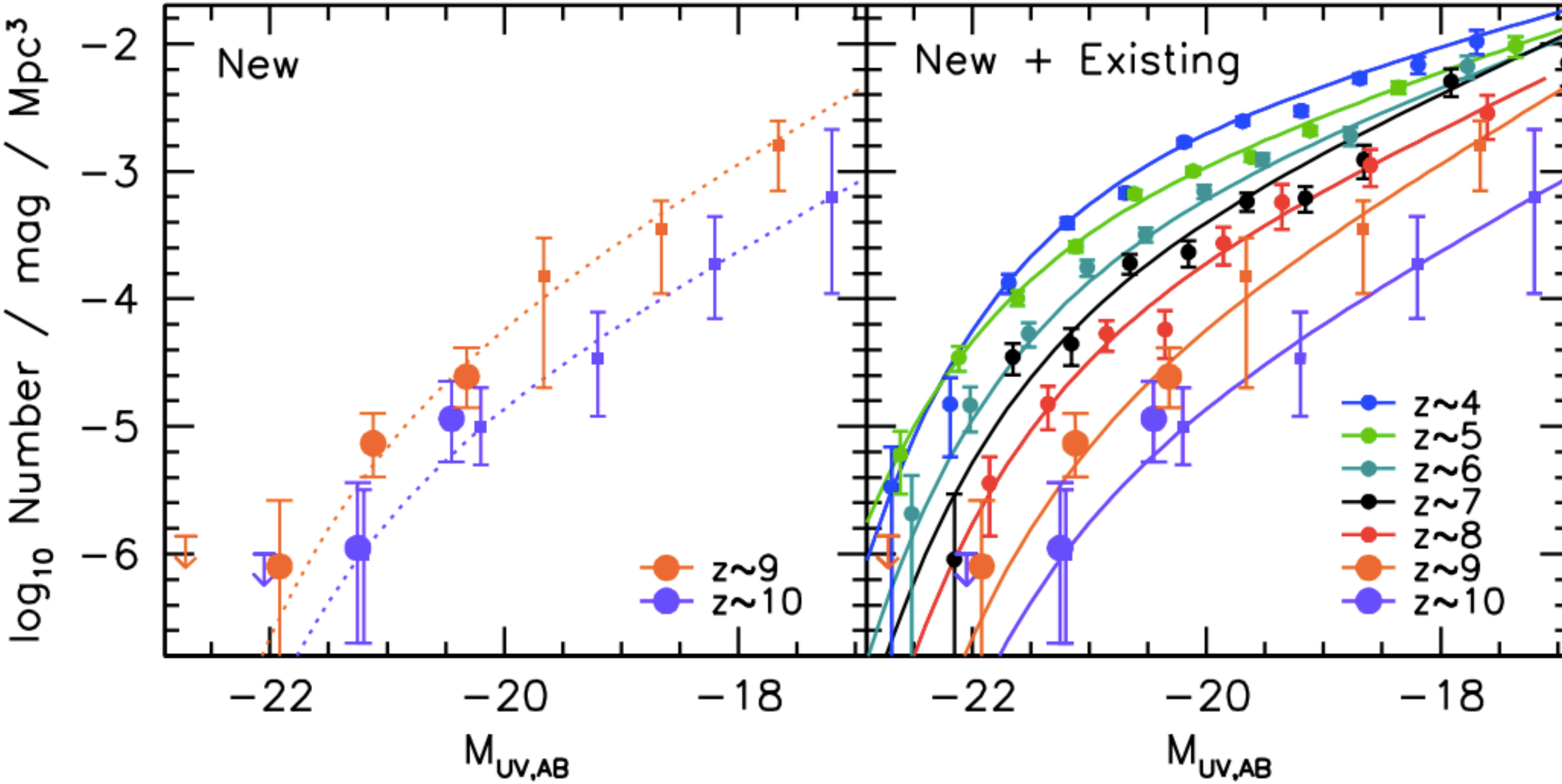
Evolution of the total IR luminosity function

The same is observed in the IR, that however does not go deep enough to see faint galaxies at high redshift



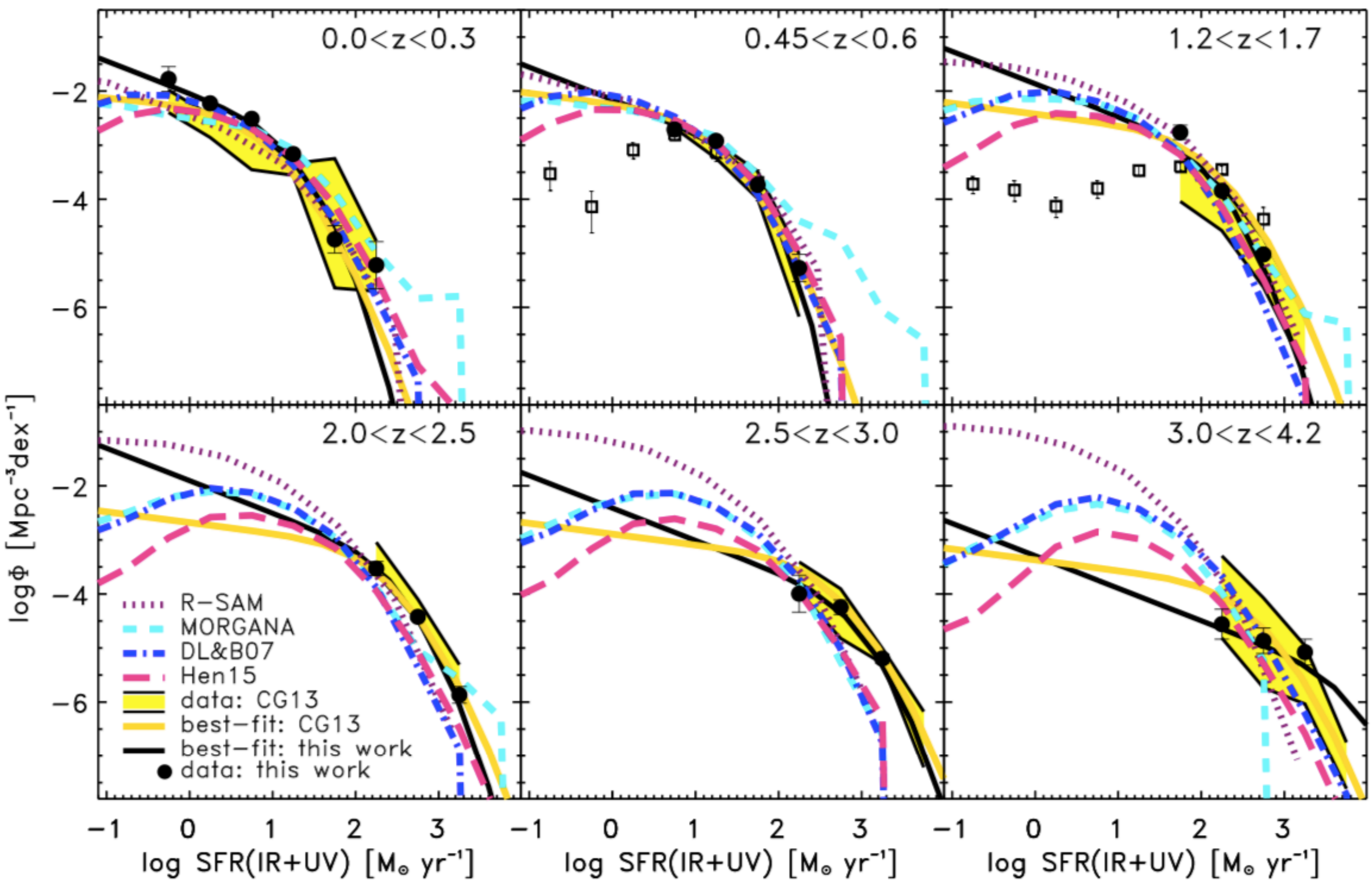
Gruppioni et al. 2013, MNRAS 432, 23

Very high redshift galaxies



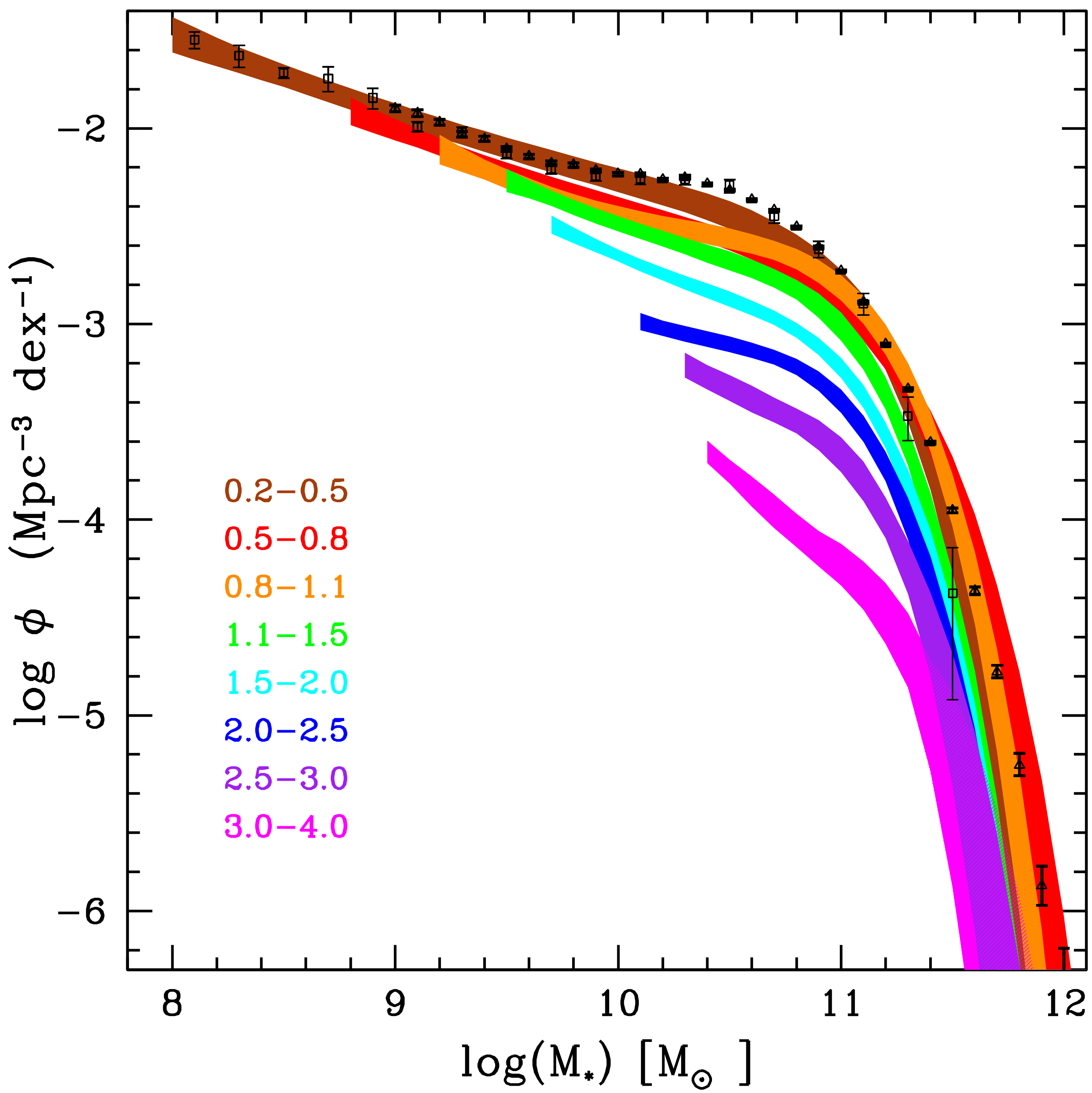
Bouwens et al. 2019, arXiv:1905.05202

Evolution of SFR function



Gruppioni et al. 2015, MNRAS 451, 3419

Evolution of stellar mass function



Madau & Dickinson 2014, ARA&A 52, 415

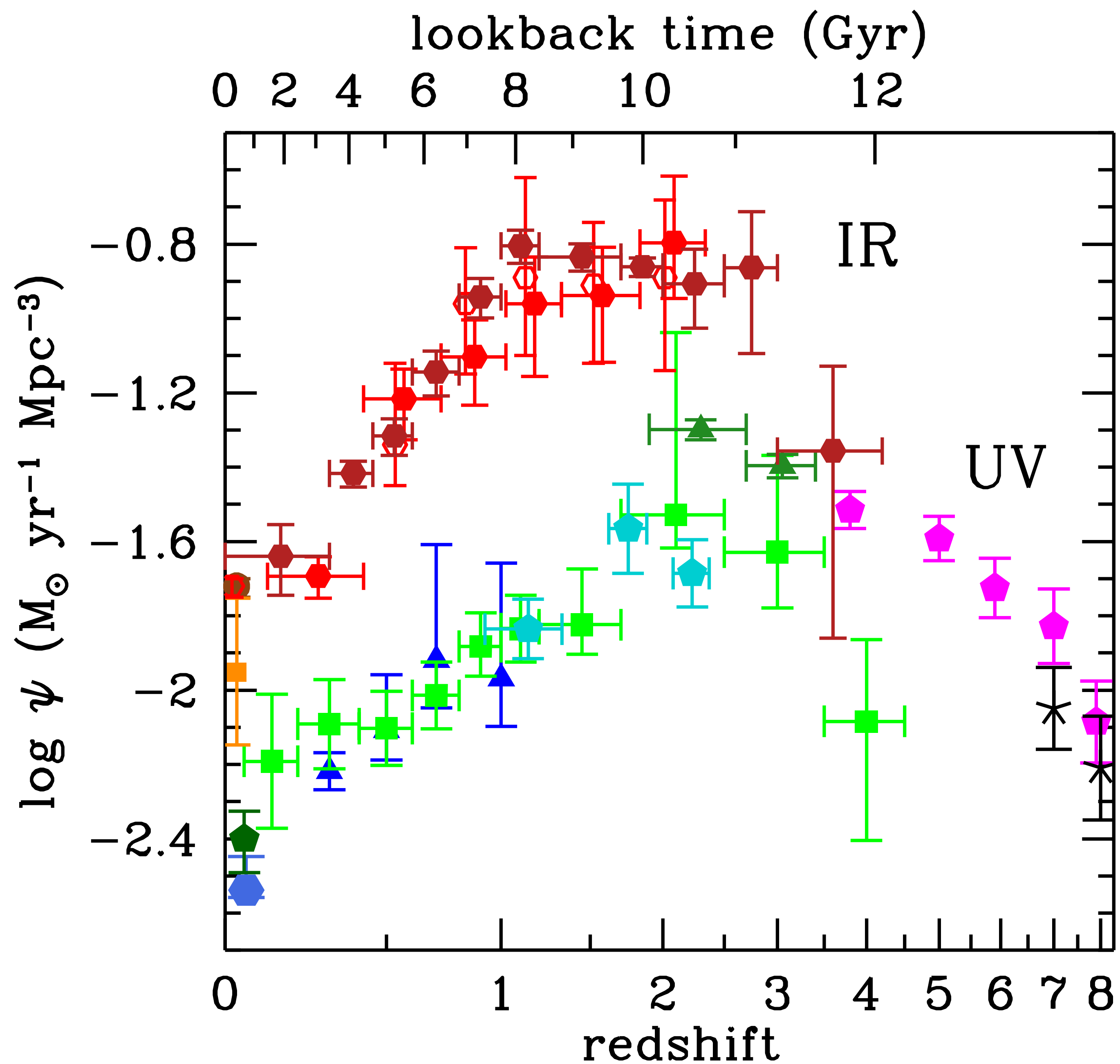
The cosmic star formation history - UV and IR

$$LD(z) = \int_{L_{\min}}^{\infty} L\Phi(L; z)dL$$

$$\psi(z) = \kappa \, LD(z)$$

$$= \kappa_{\rm FUV} \, LD_{\rm FUV}(z)$$

$$+\kappa_{\rm IR} \, LD_{\rm IR}(z)$$



Madau & Dickinson 2014, ARA&A 52, 415

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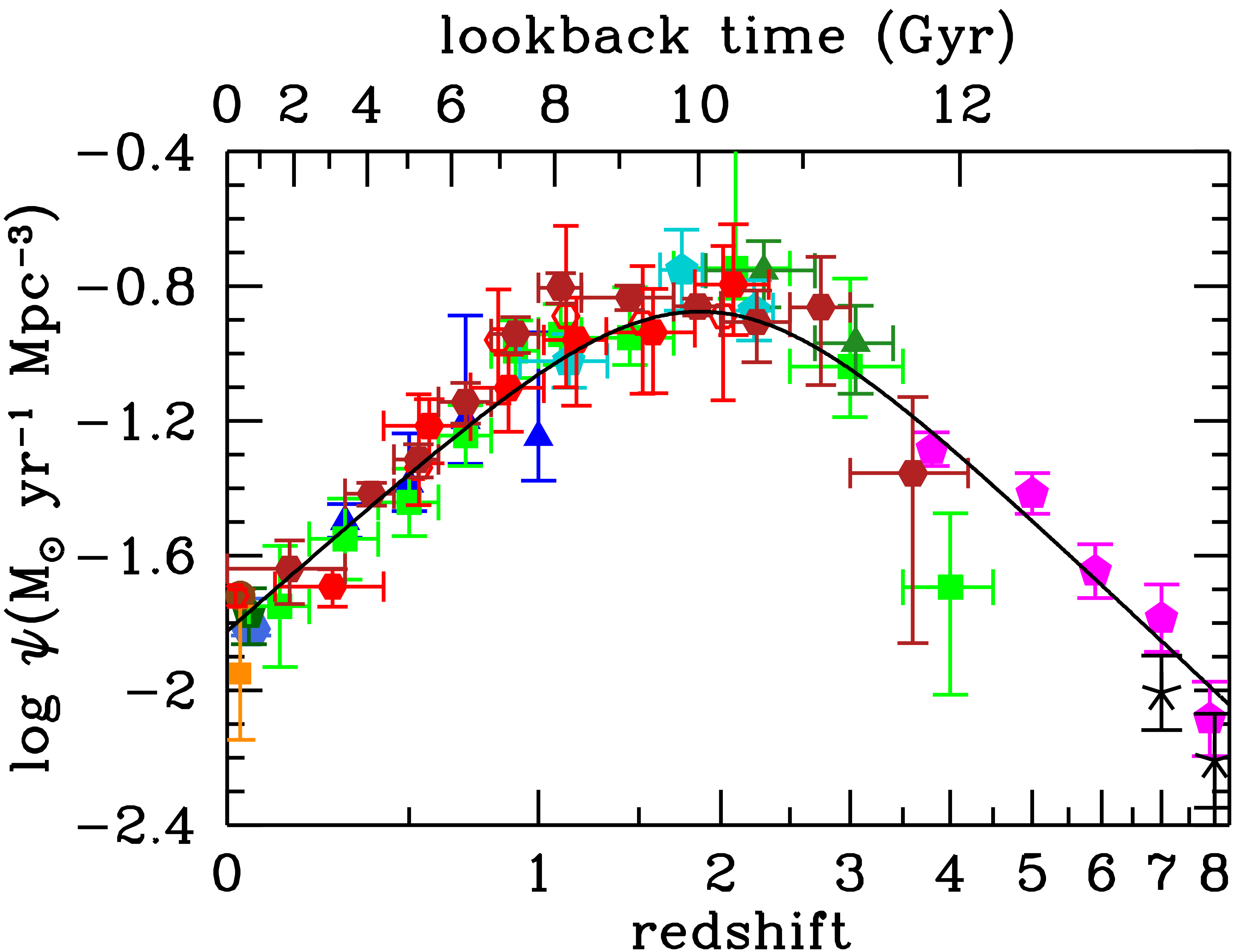
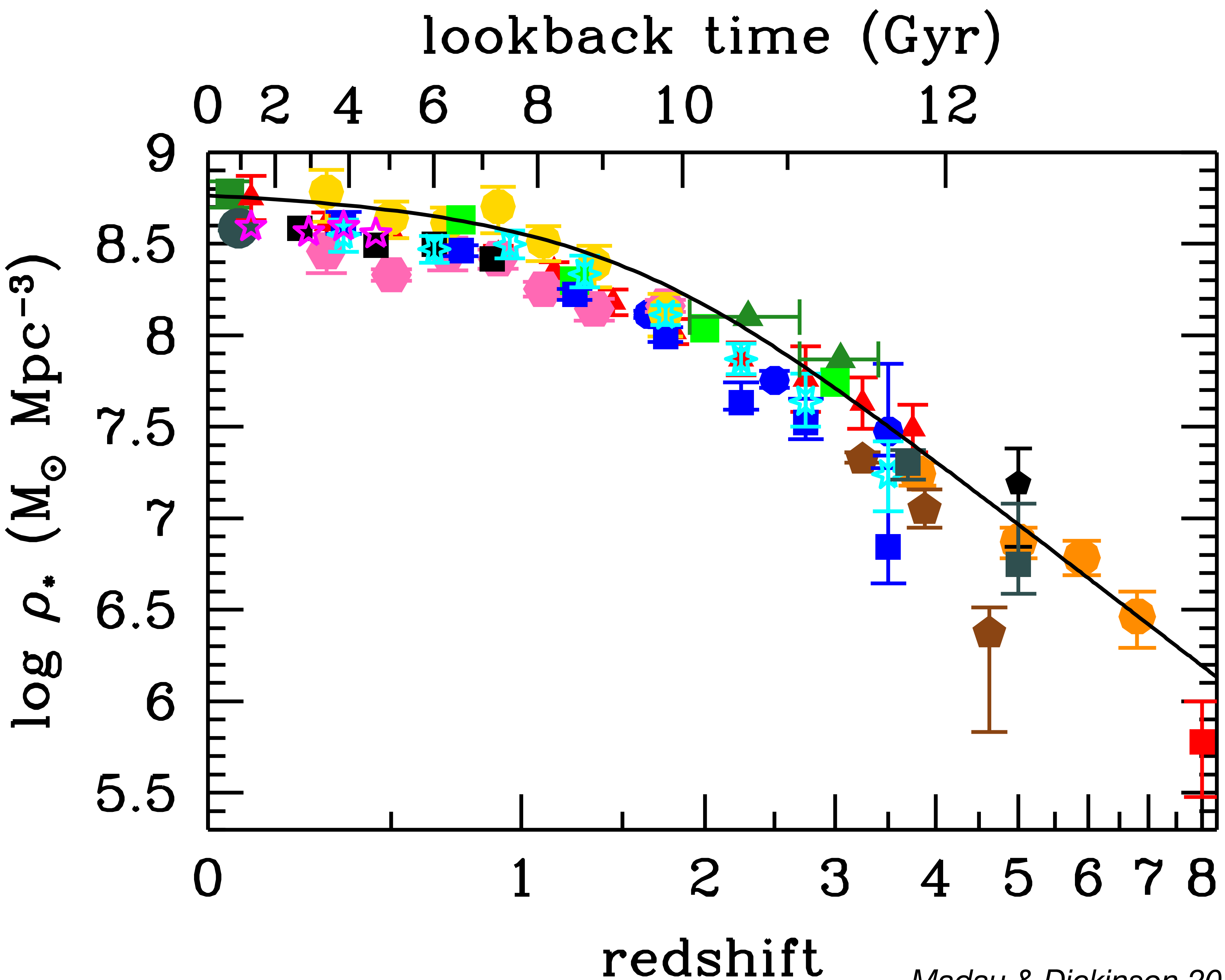


Madau & Dickinson 2014, ARA&A 52, 415

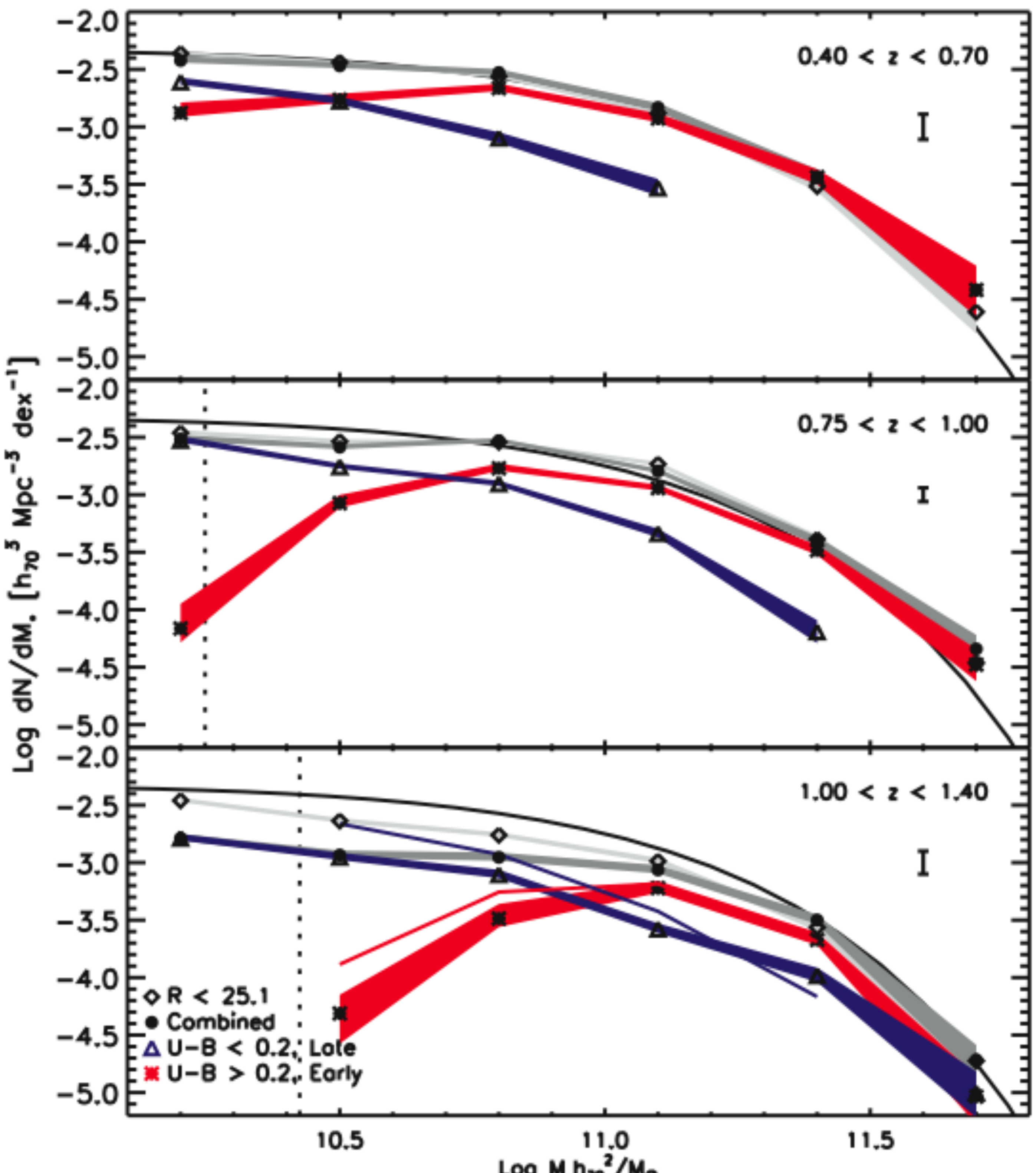
The stellar mass density



Madau & Dickinson 2014, ARA&A 52, 415

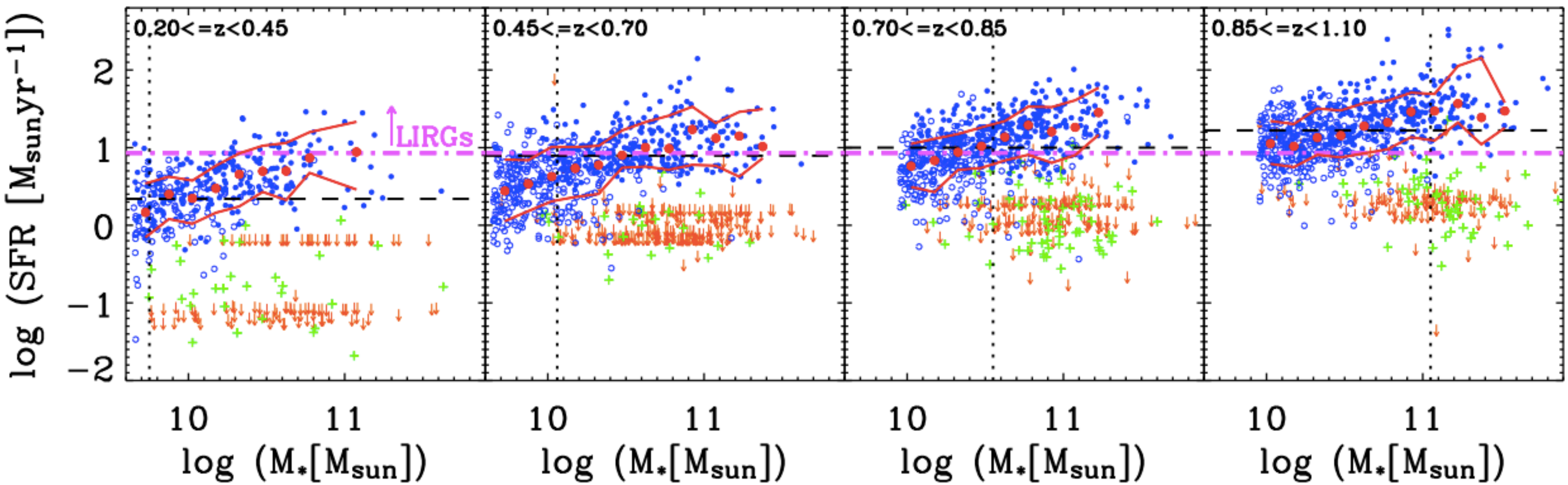
Evolution of galaxy properties with redshift

Stellar mass function for passive and active galaxies



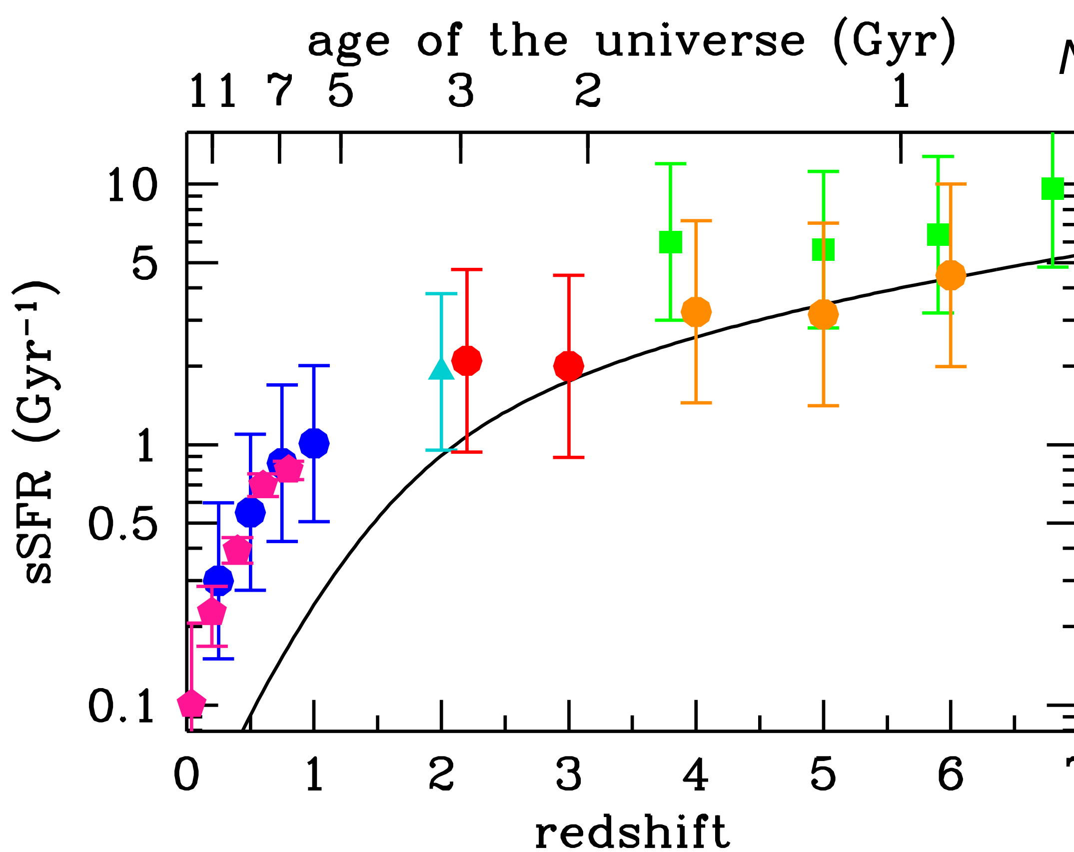
Bundy et al. 2006, ApJ 651, 120

Evolution of the main sequence



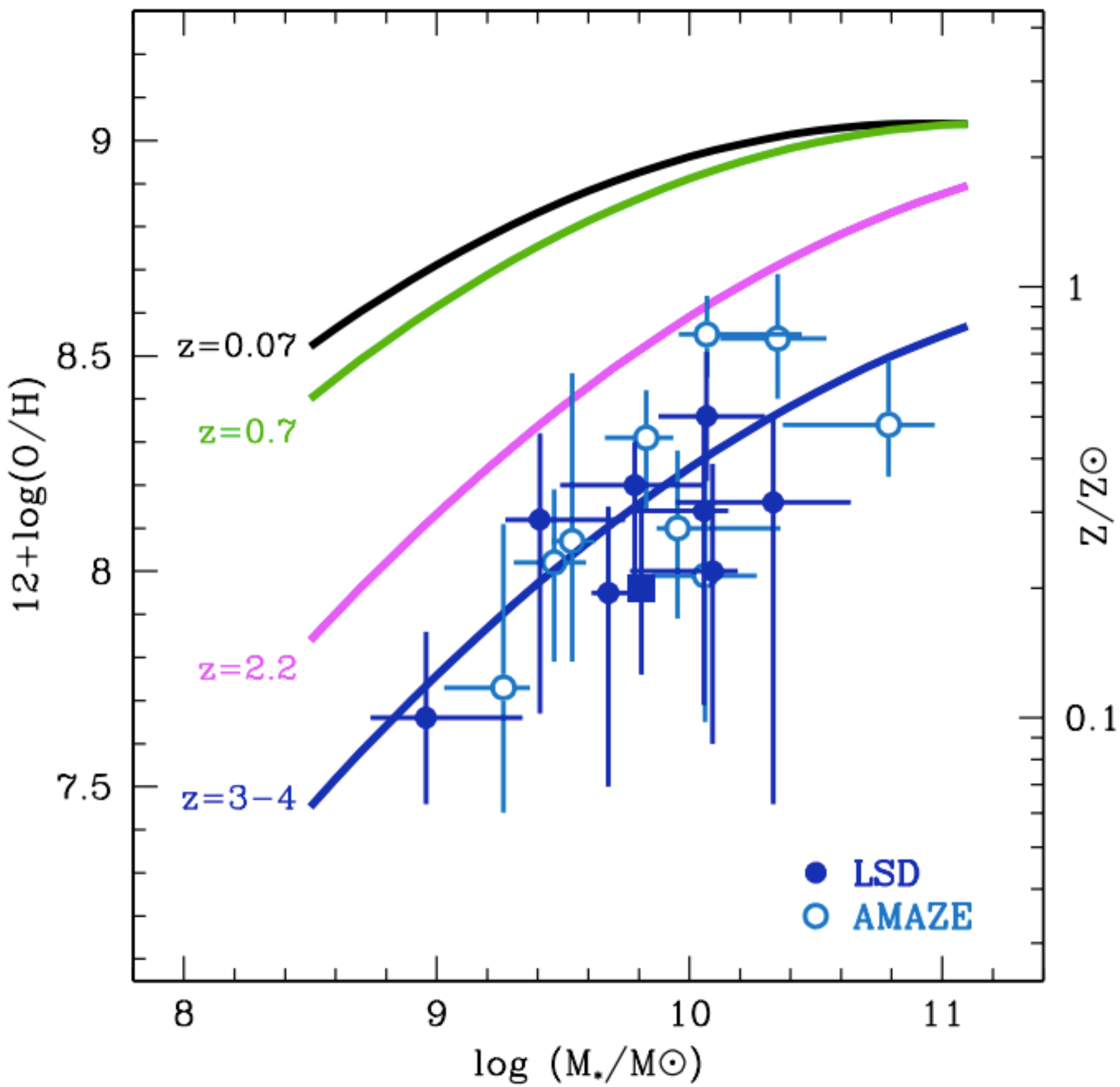
Noeske et al. 2007, ApJ 660, L43

This is the evolution of the average sSFR, i.e. of the height of the main sequence



Madau & Dickinson 2014, ARA&A 52, 415

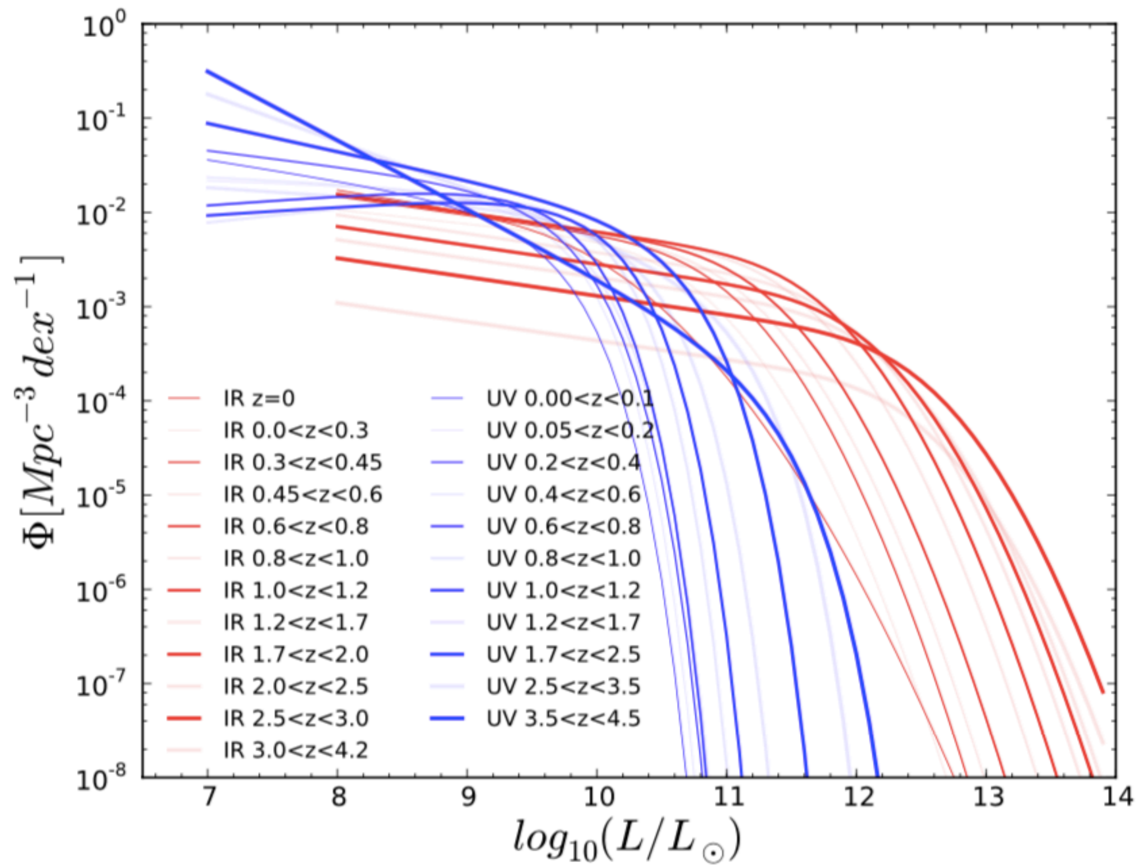
Evolution of galaxy (gas) metallicities

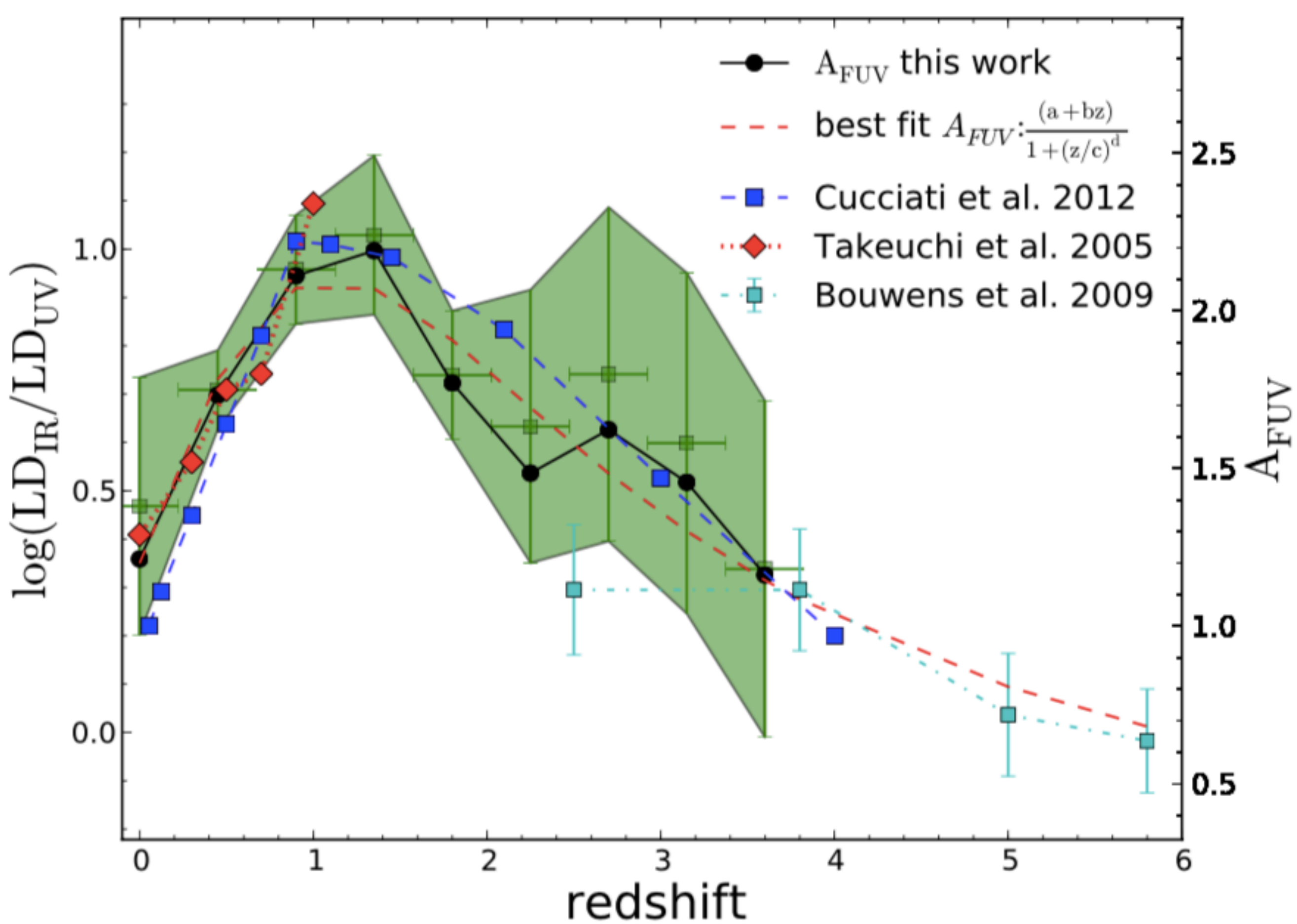


Mannucci & Cresci, arXiv:1011.0264

Ratio of IR and UV luminosity densities

$$LD = \int_{L_{\min}}^{\infty} L\Phi(L)dL$$

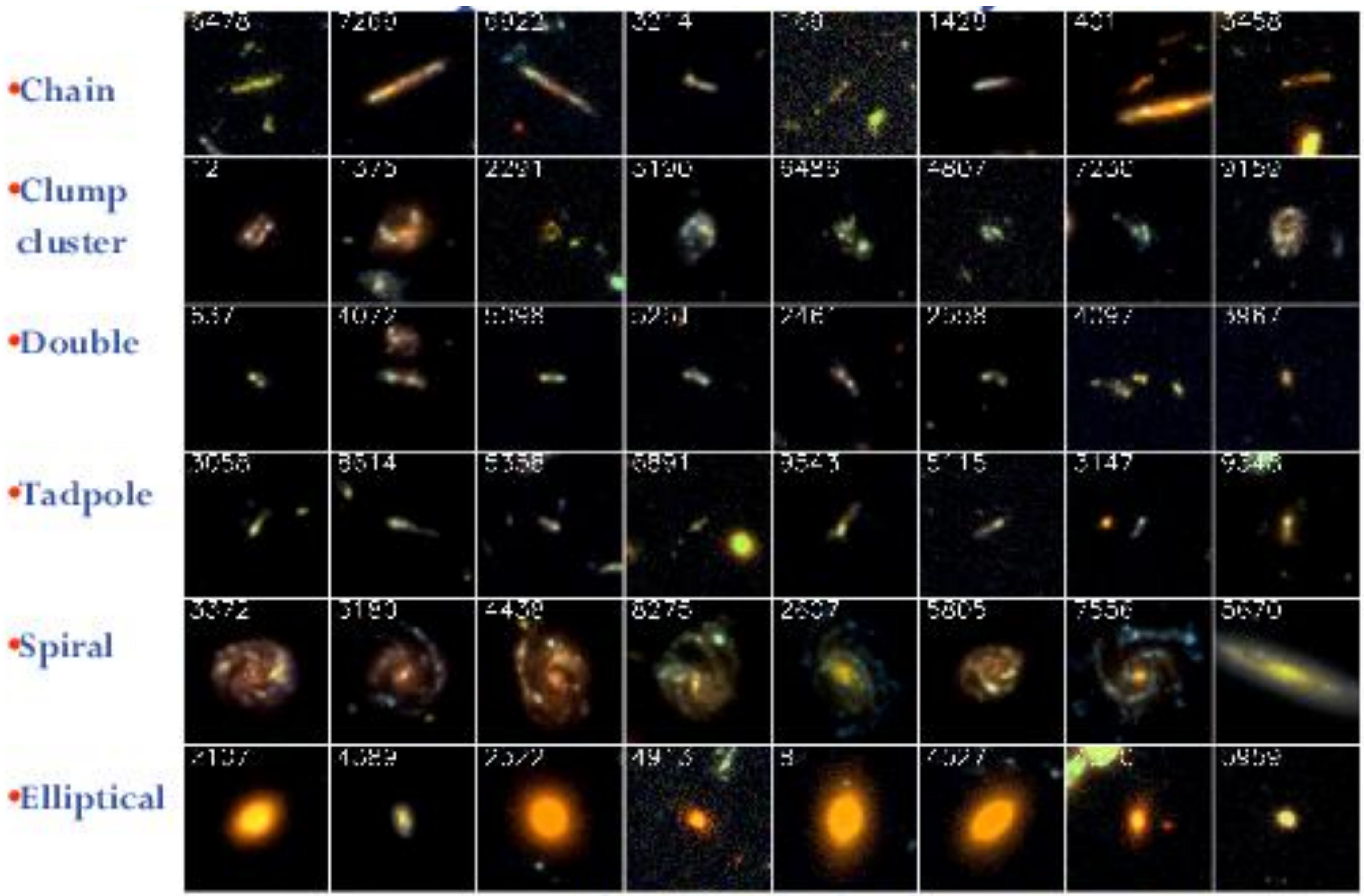




From the luminosity functions, one can compute the luminosity density of observed galaxies in the UV and IR; its ratio is a proxy of how dust extinction evolves with cosmic time.

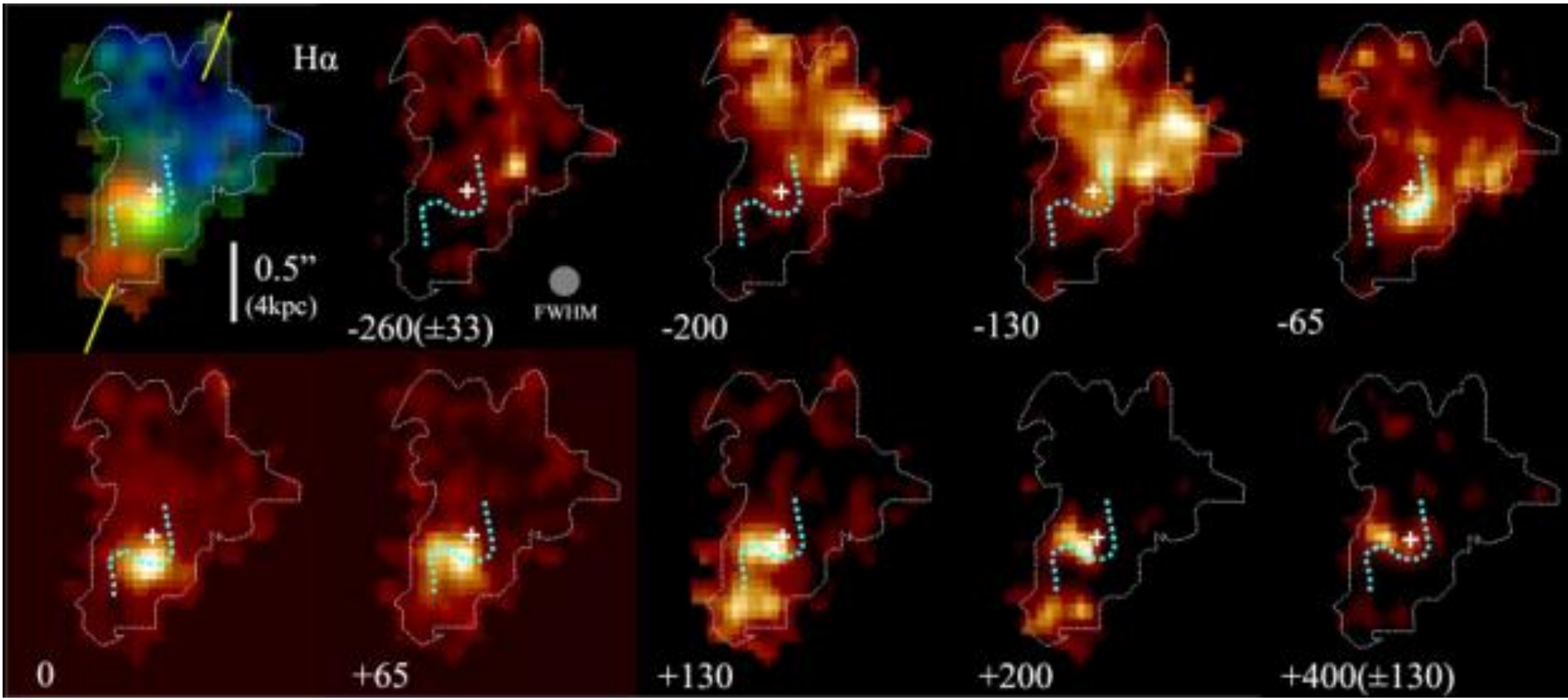
Burgarella et al. 2013, A&A 554, A70

Evolution of morphology



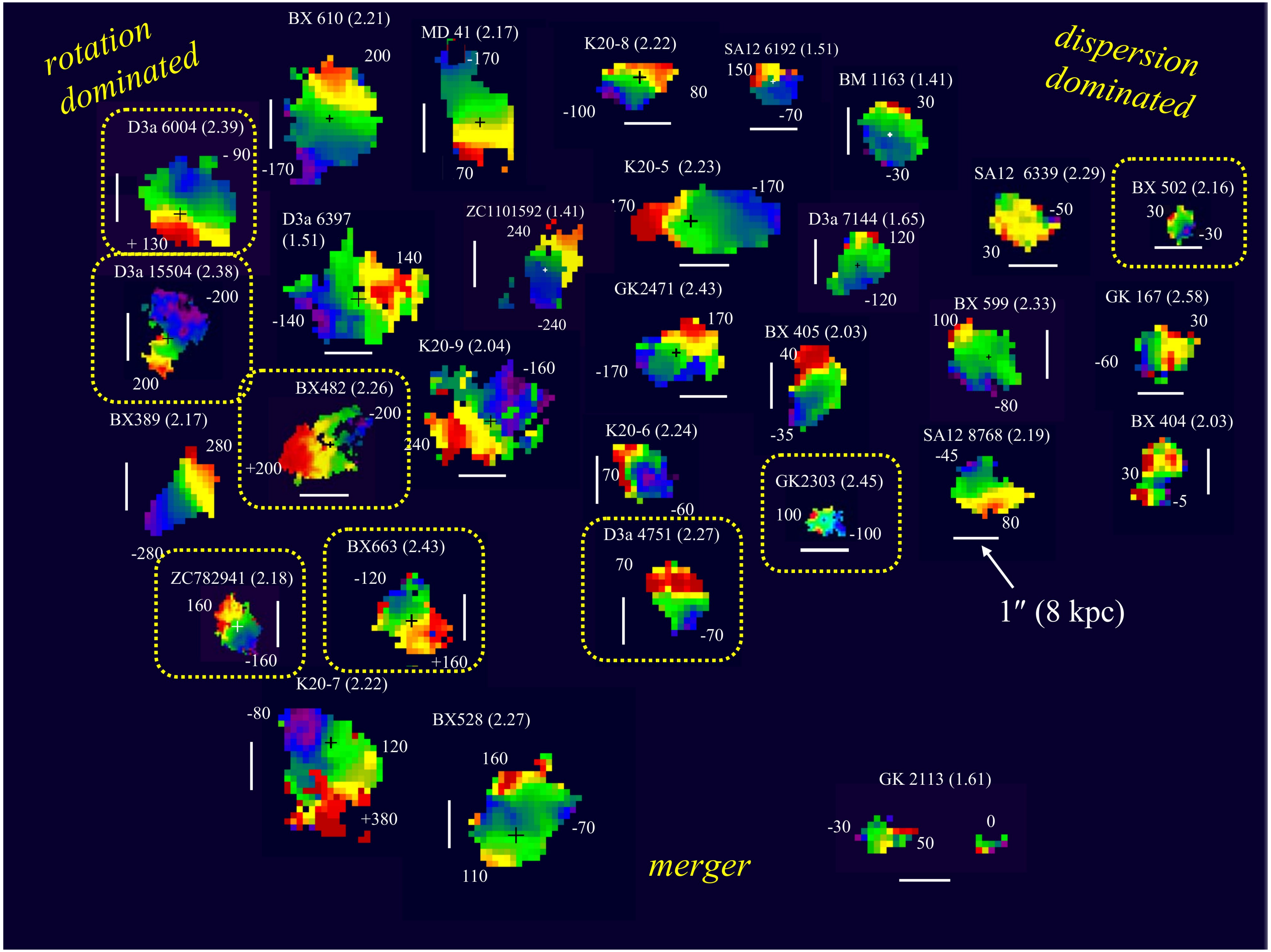
(from Steve Beckwith, private comm.)

Evolution of morphology: clumpy discs at z~2



Genzel et al. 2006, Nature, 442, 786

Galaxy kinematics at z~2



Förster Schreiber, N. M., et al. 2009 ApJ, 706, 1364

Evolution of galaxy sizes

z~0, SDSS

What size?

- scale radius of a disc, R_d
- optical radius (= 3.2 R_d)
- effective - half-light - radius R_e
- Petrosian radius
  (surface brightness (SB) at that radius = a fraction of average SB within that radius
- half-mass radius (not projected)

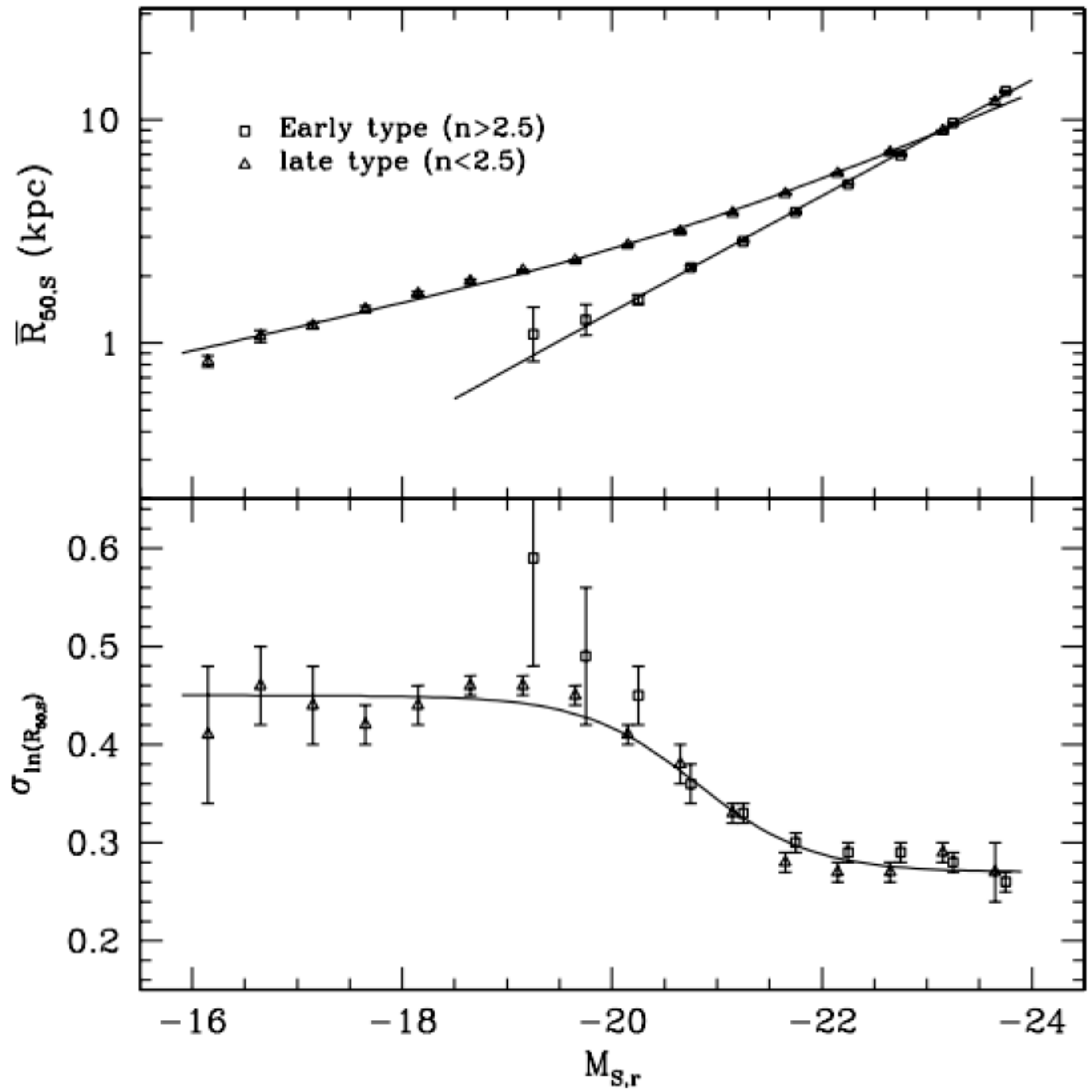
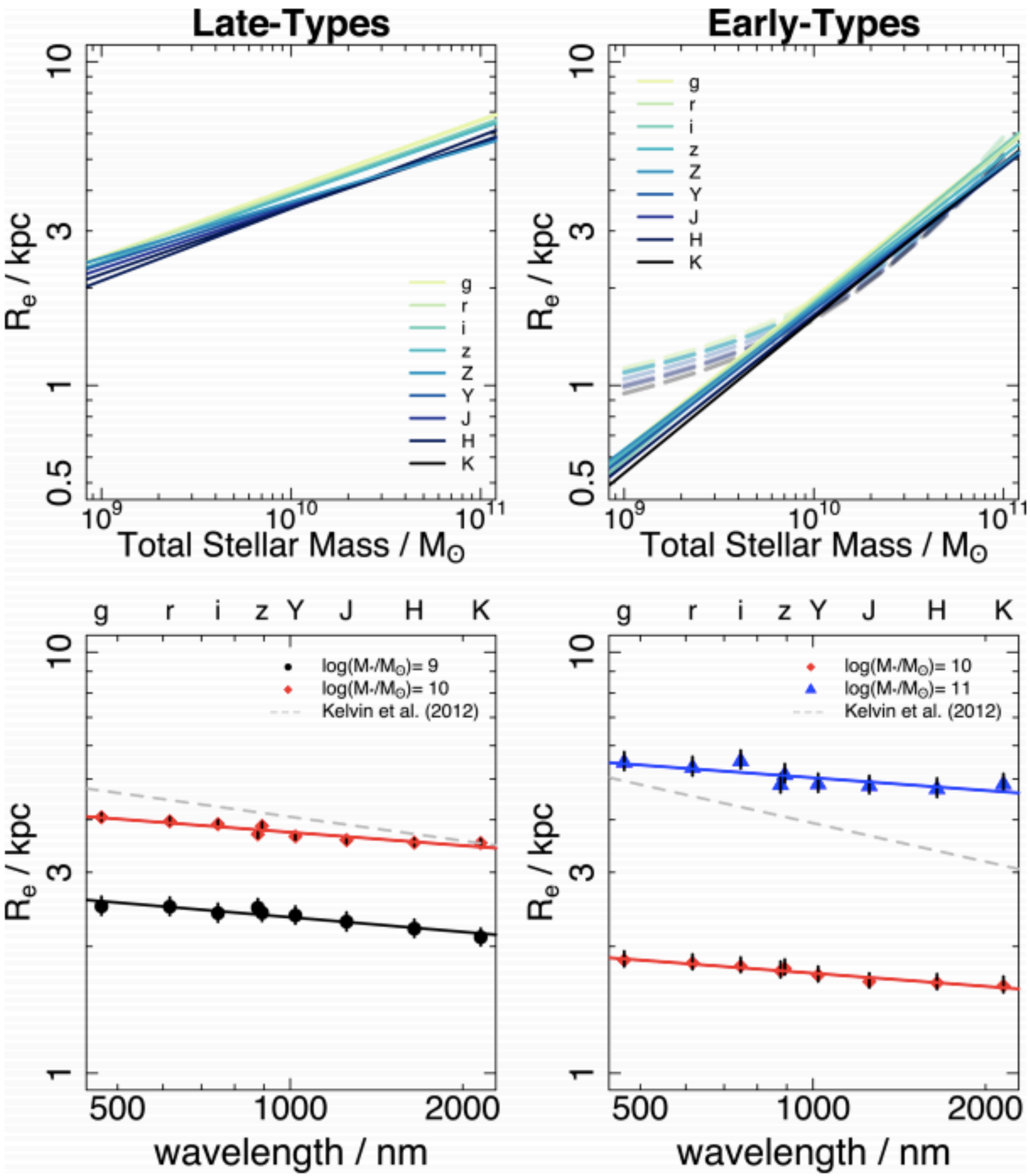


Figure 6. The median and dispersion of the distribution of the Sérsic half-light radius $R_{50,S}$ (in the r band) as functions of r-band absolute Sérsic magnitude. Here a galaxy is separated into early or late type according to whether its Sérsic index n is larger or smaller than 2.5. The error bars represent the scatter among 20 bootstrap samples. The solid curves are the fit of the $\bar{R}$–M and $\sigma_{\ln R}$–M relations by equations (14), (15) and (16).

Shen et al. 2003, MNRAS 343, 978

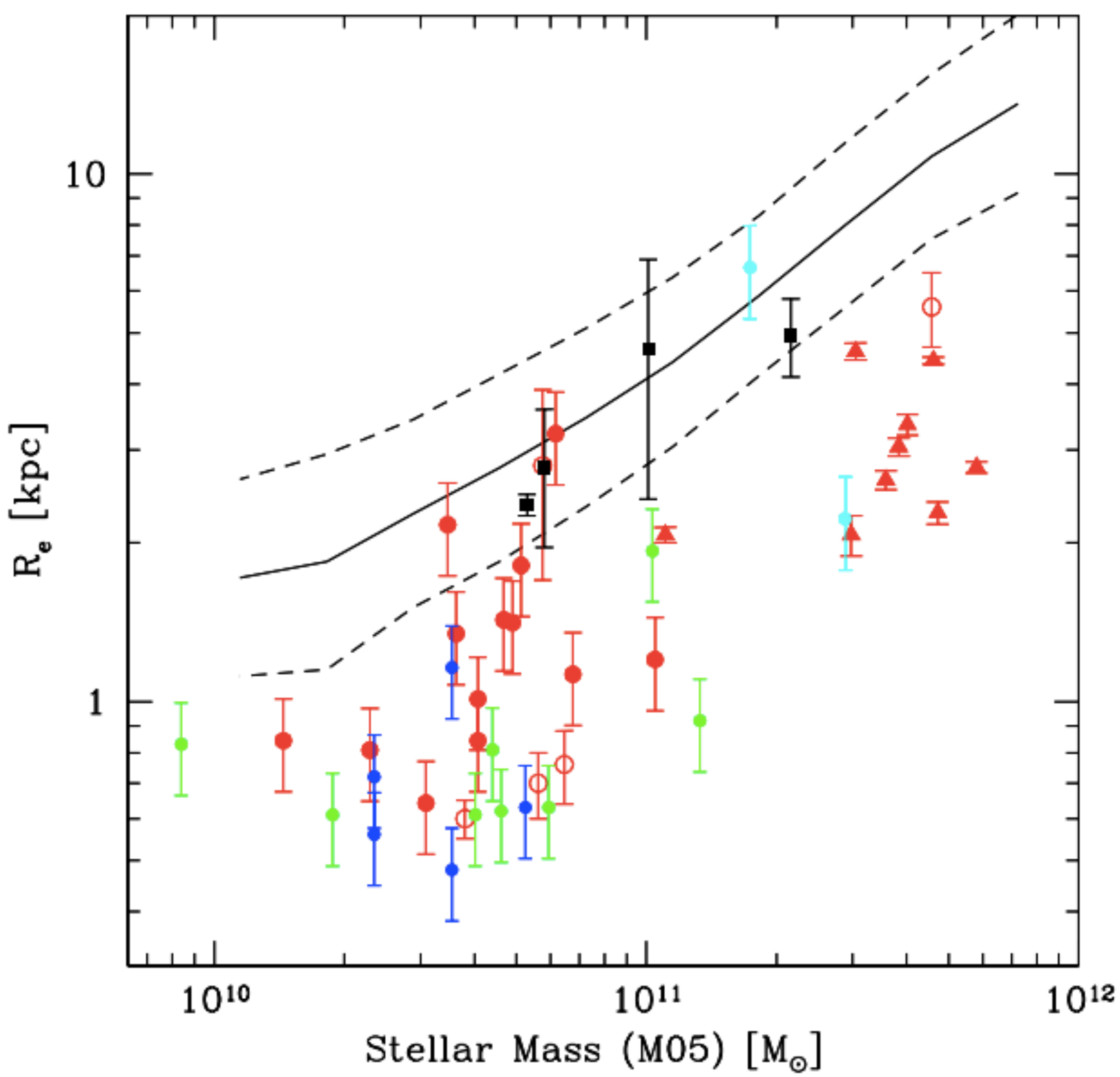


Lange et al. 2015, MNRAS 447, 2603

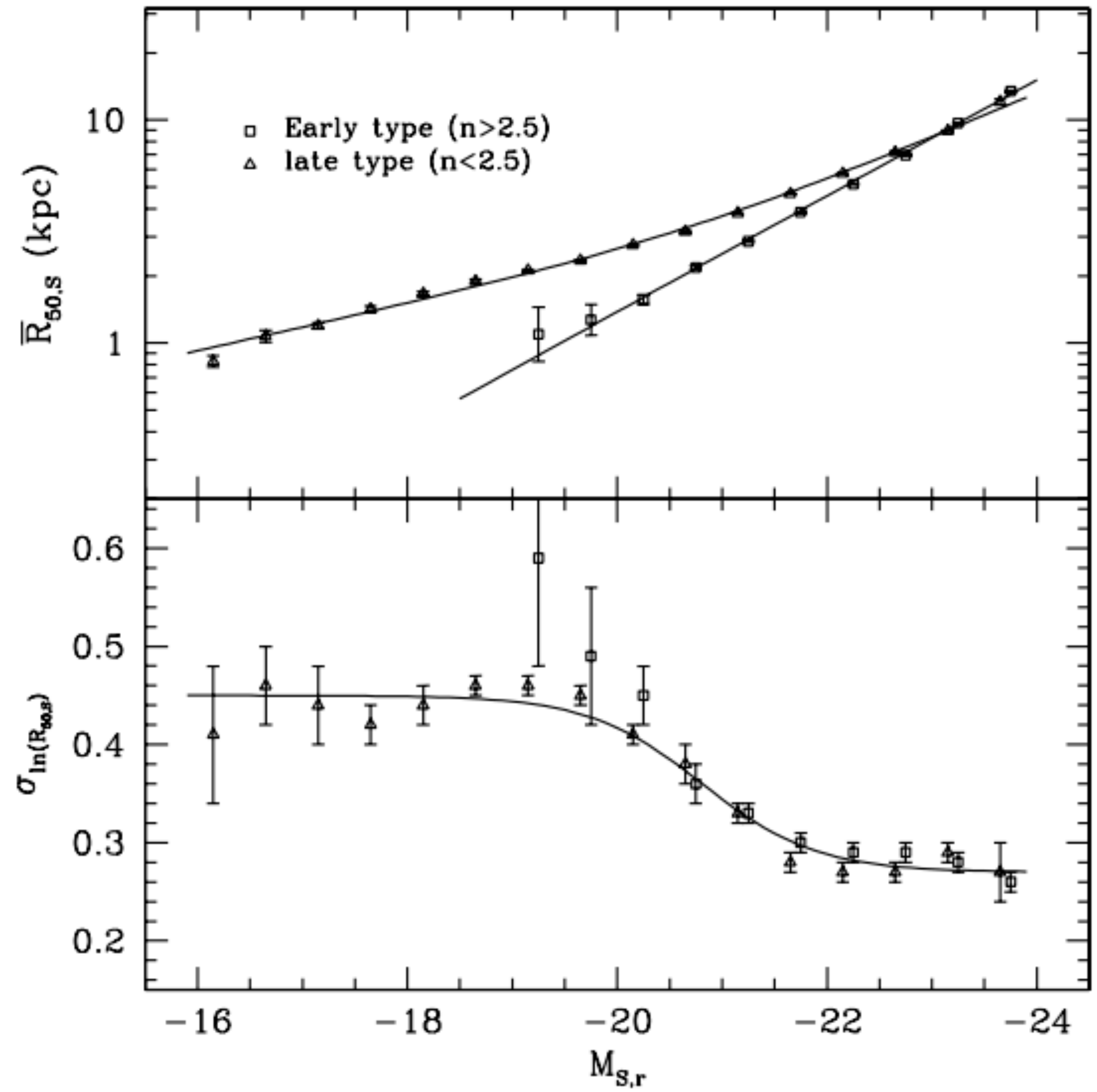
Evolution of galaxy sizes

z~2, GMASS

z=0, SDSS



Cimatti et al. 2008, A&A 482, 21



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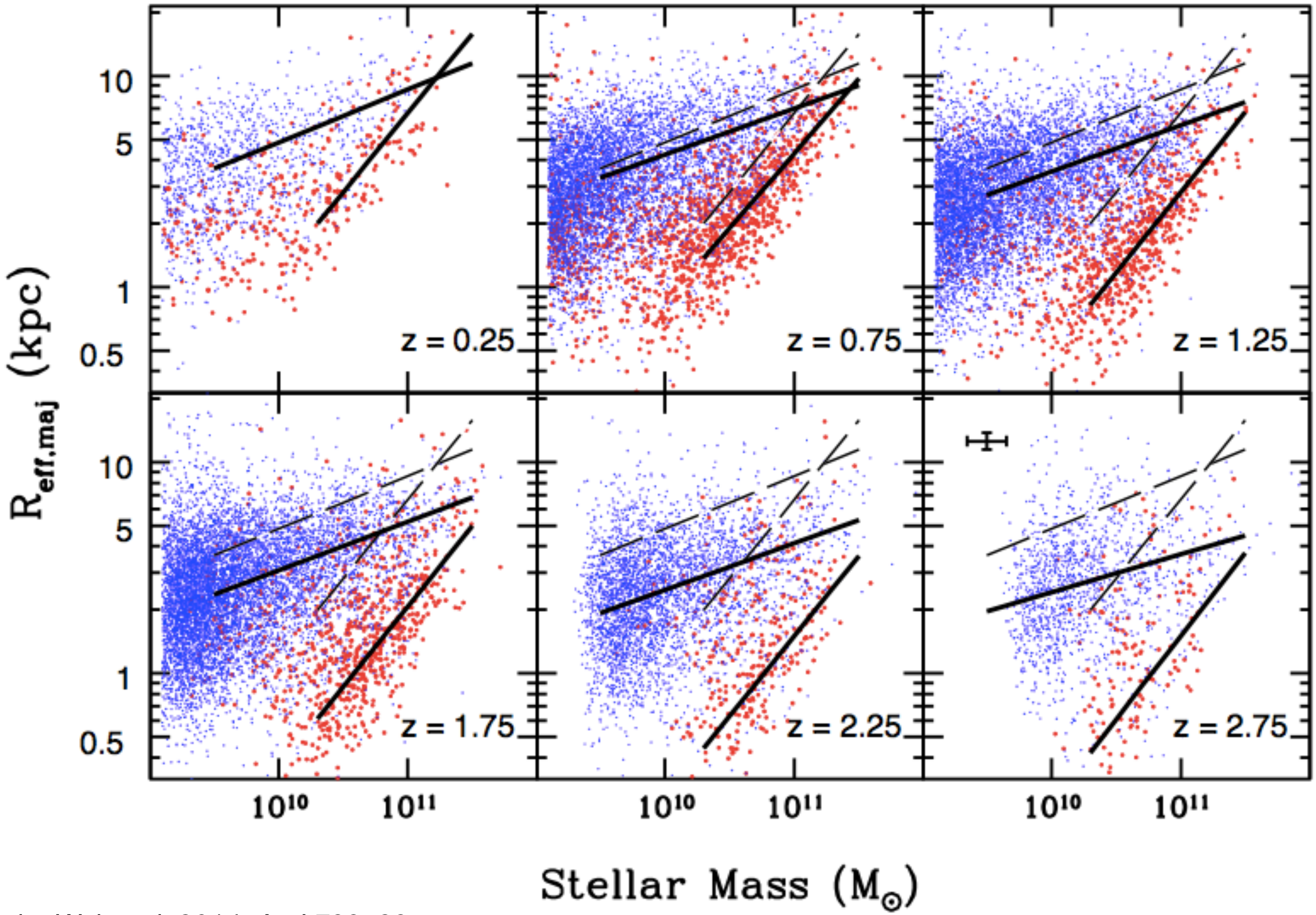
What makes elliptical galaxies larger at z=0?
minor dry mergers?

Shen et al. 2003, MNRAS 343, 978

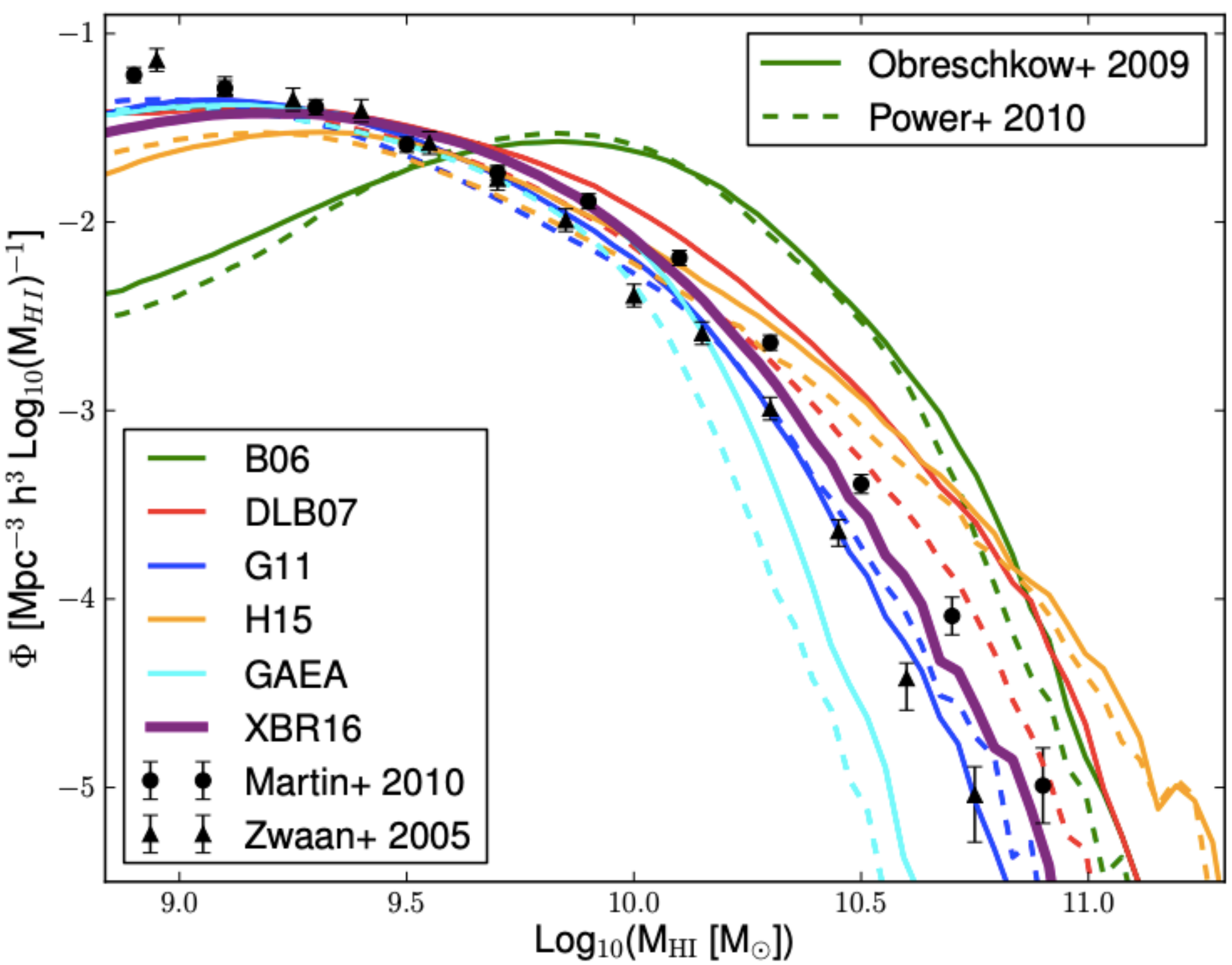
Evolution of galaxy sizes



van der Wel et al. 2014, ApJ 788, 28

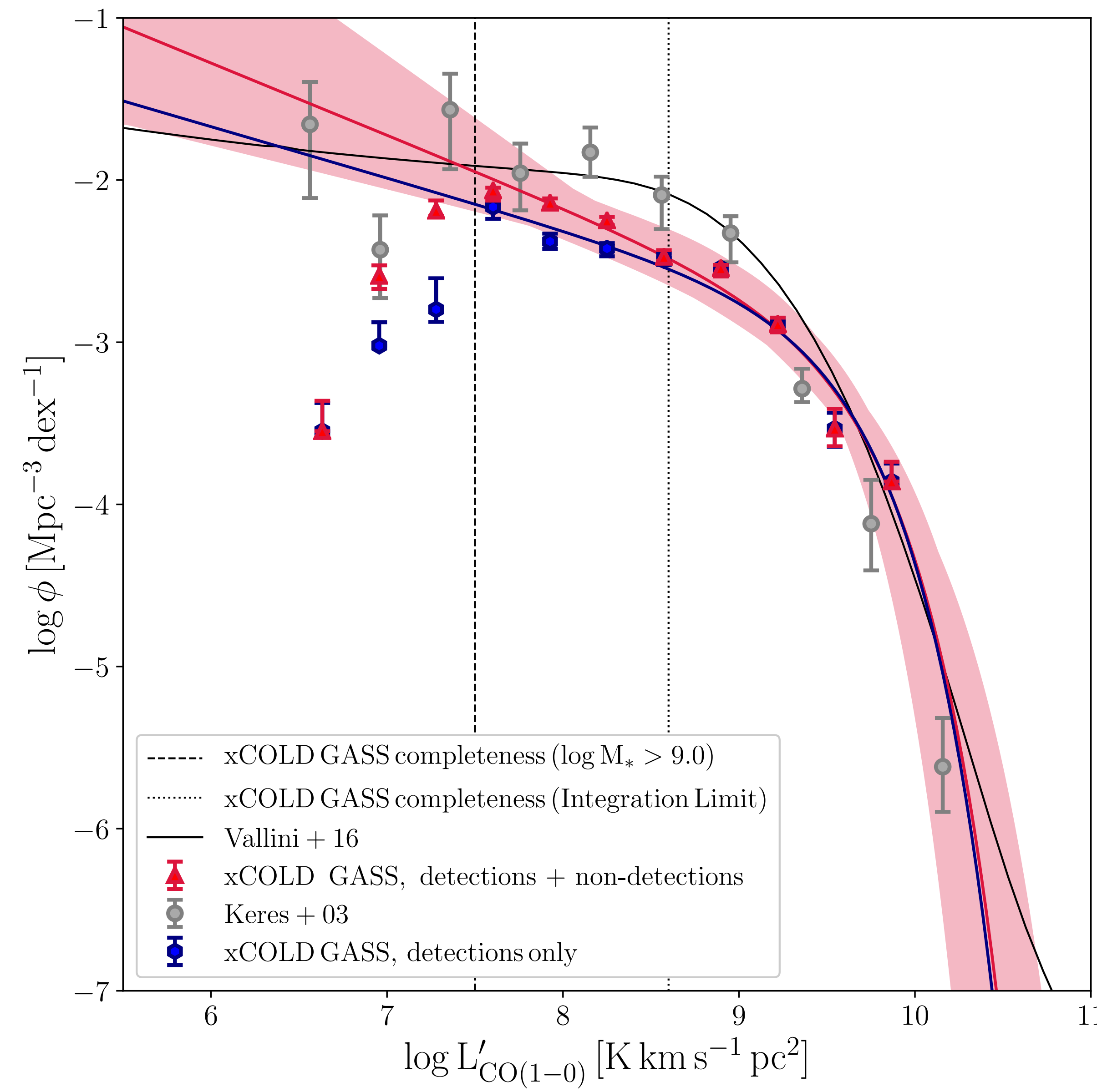
The gas content of local galaxies

neutral hydrogen (21 cm)

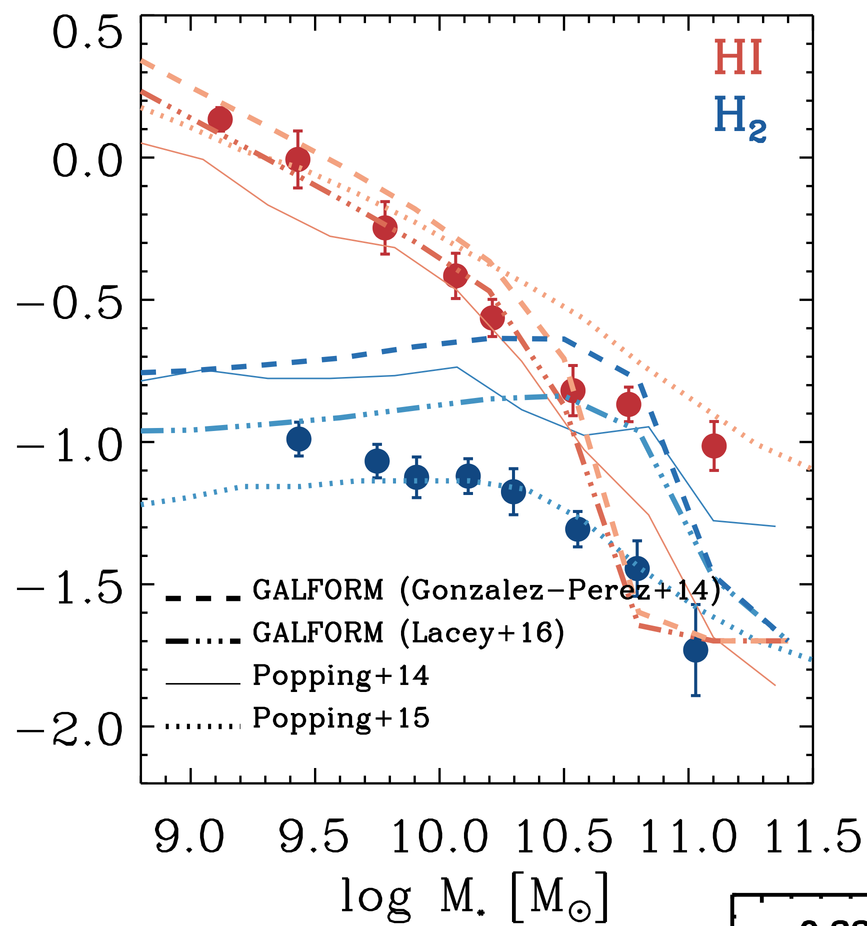


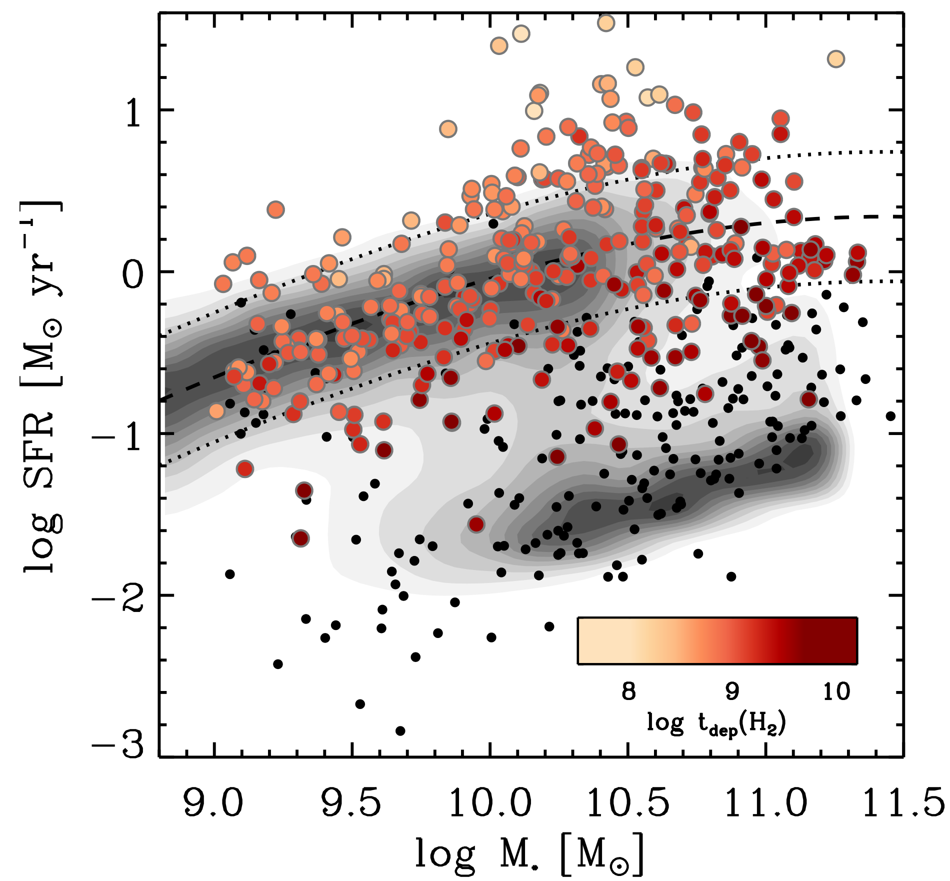
from Zoldan et al. 2015, MNRAS
latest data from Martin et al 2010, ApJ 723, 1359

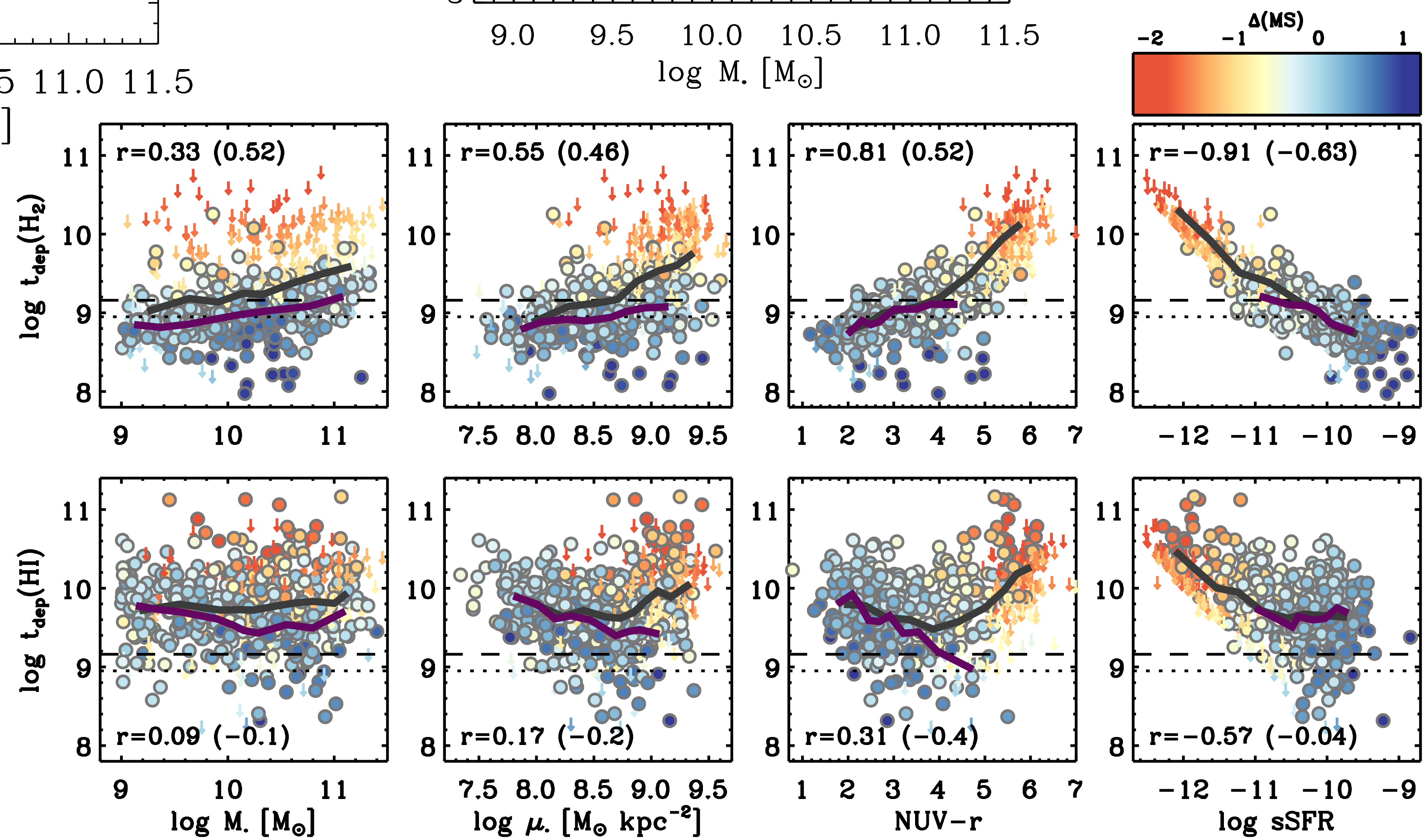
molecular hydrogen (CO + α_{CO})



Saintonge et al. 2017, ApJS 233, 22

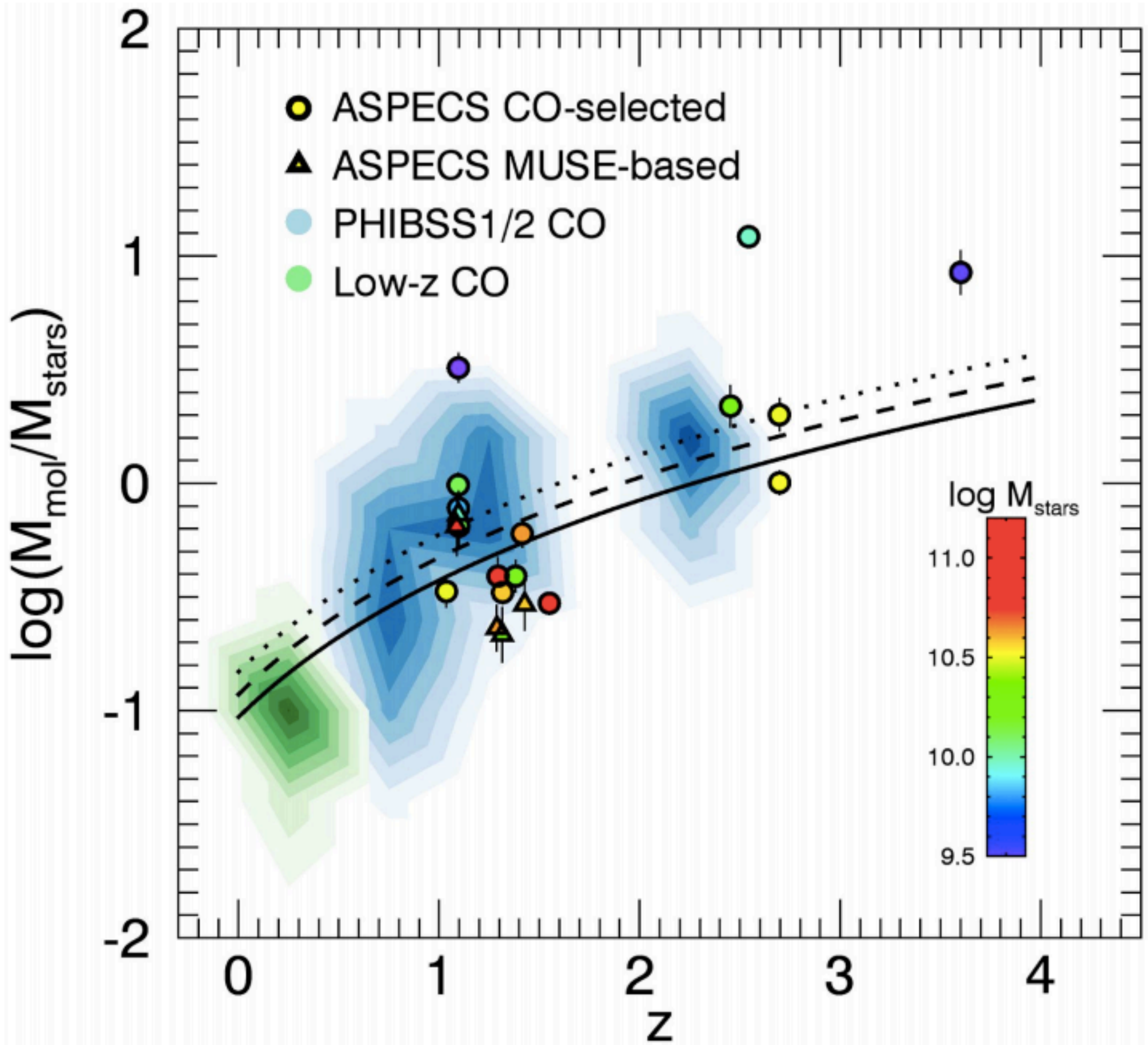


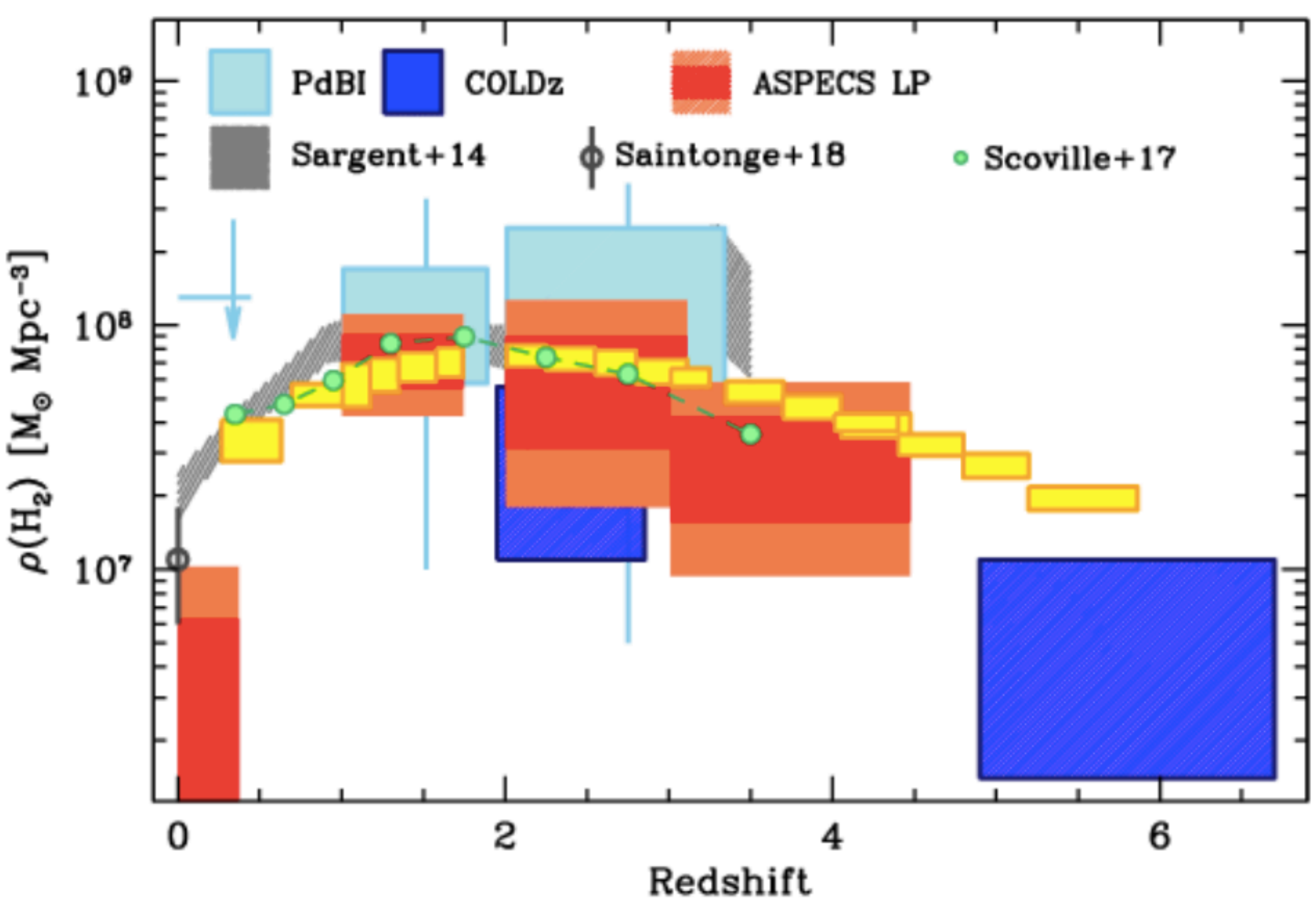




Saintonge et al. 2017, ApJS 233, 22

Evolution of molecular hydrogen





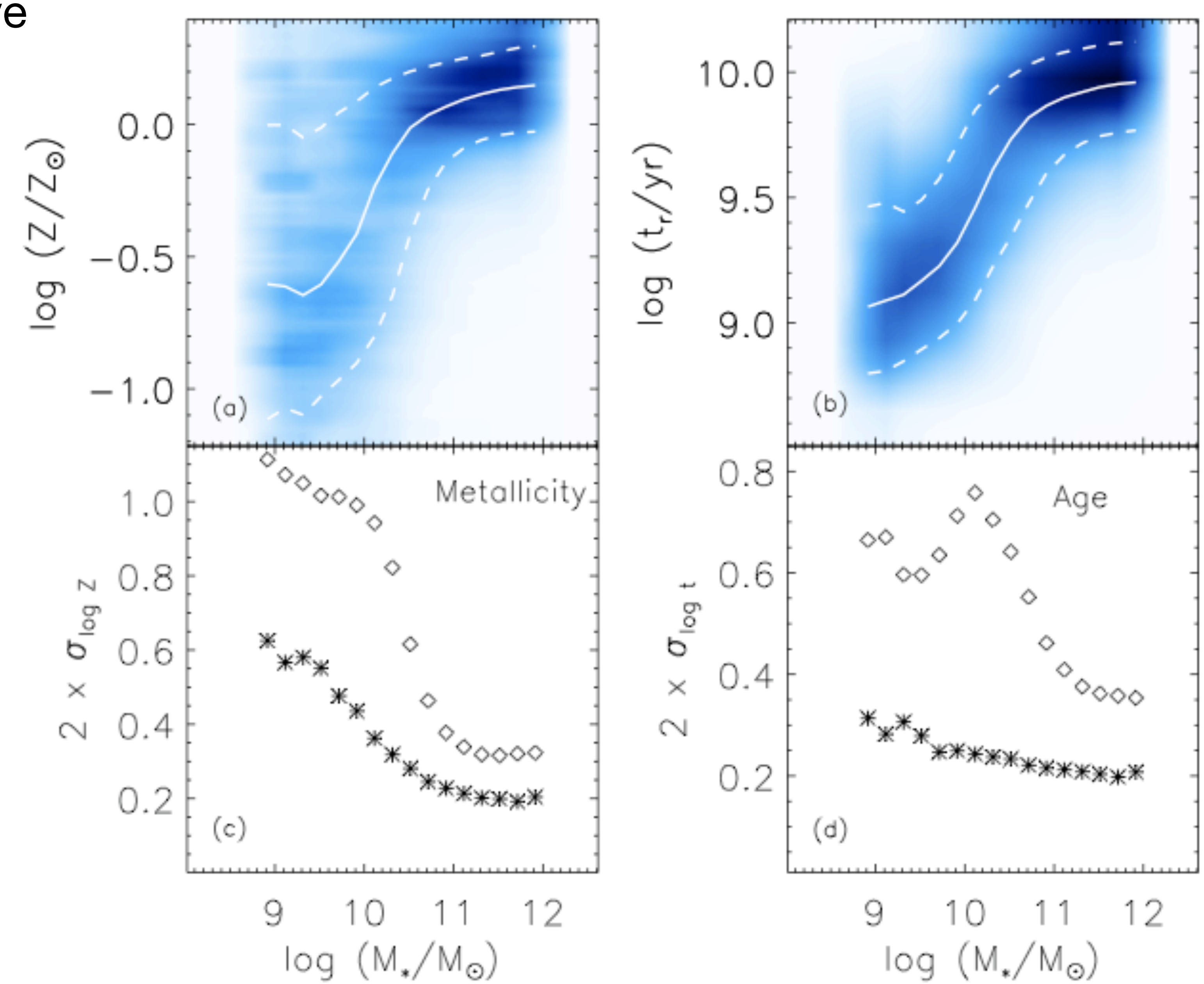
Walter et al. 2019, arXiv:1903.08659

Cosmic downsizing

The many manifestations of downsizing

Fontanot et al. 2009, MNRAS 397, 1776

Archaeological DS: more massive galaxies host older stellar populations.



Gallazzi et al. 2005, MNRAS 362, 41

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Fontanot et al. 2009, MNRAS 397, 1776

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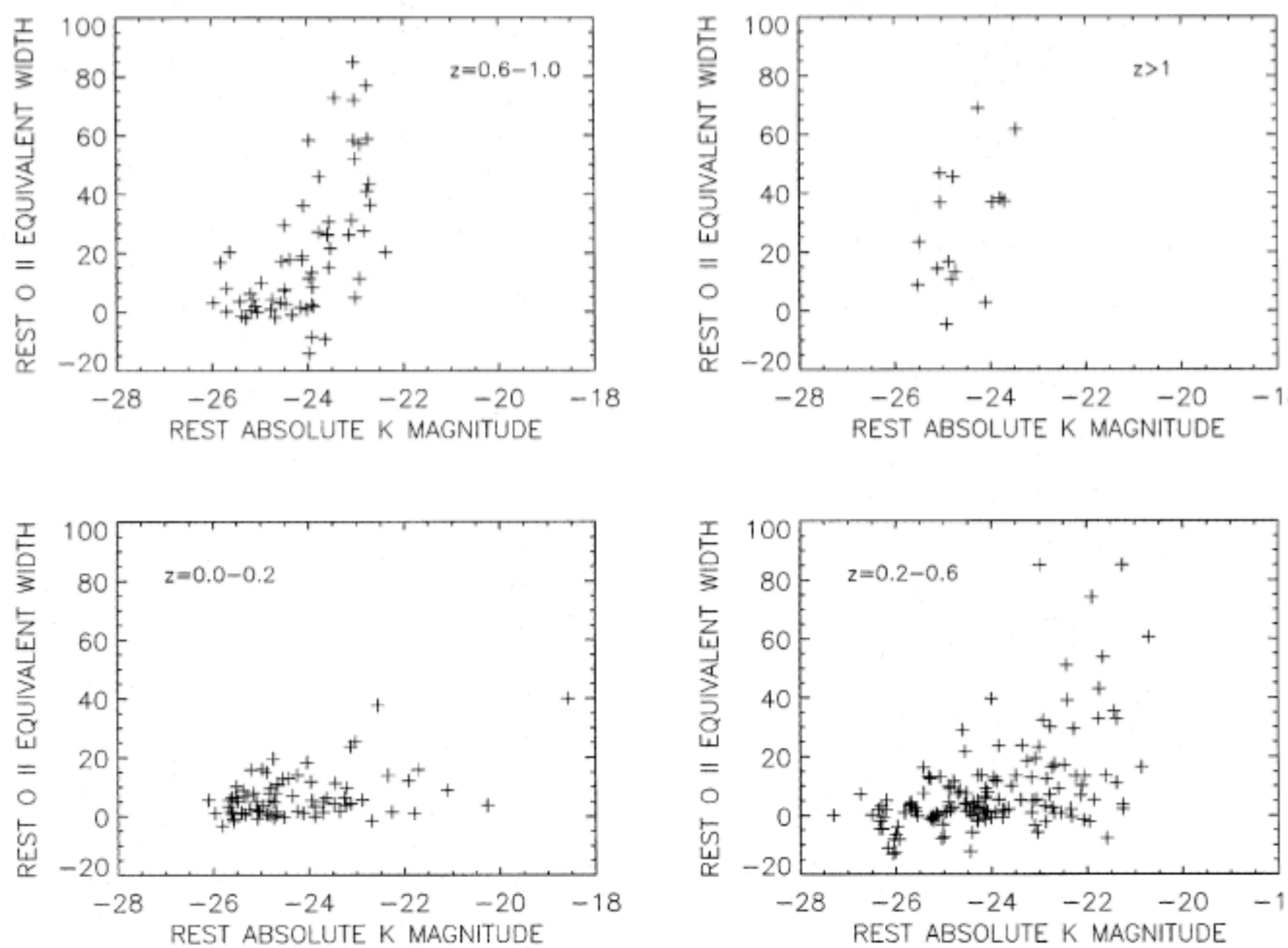
Star formation DS: the mass of the typical star-forming galaxy grows with time.



Cowie et al. 1996, AJ 112, 839

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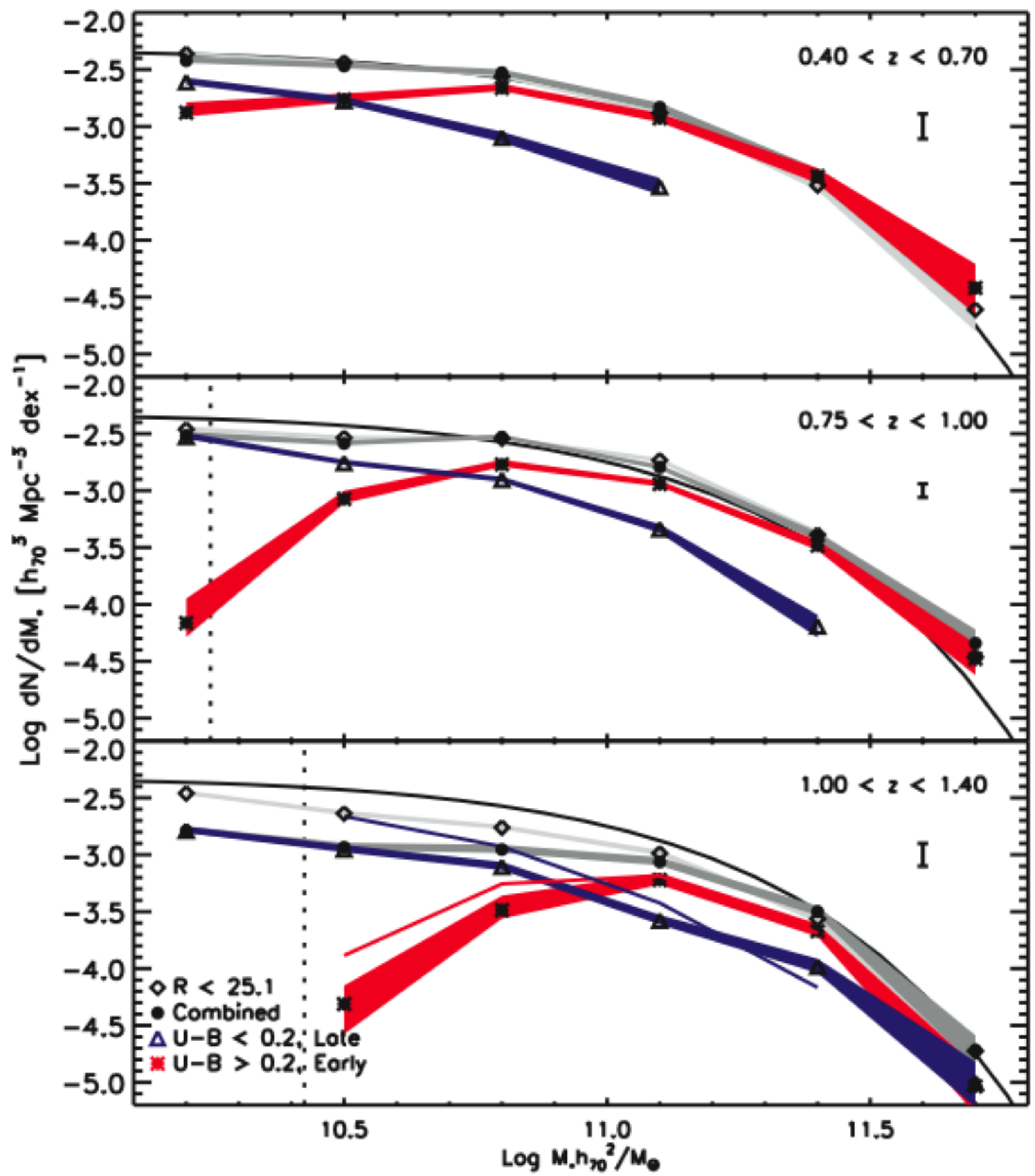


Bundy et al. 2006, ApJ 651, 120

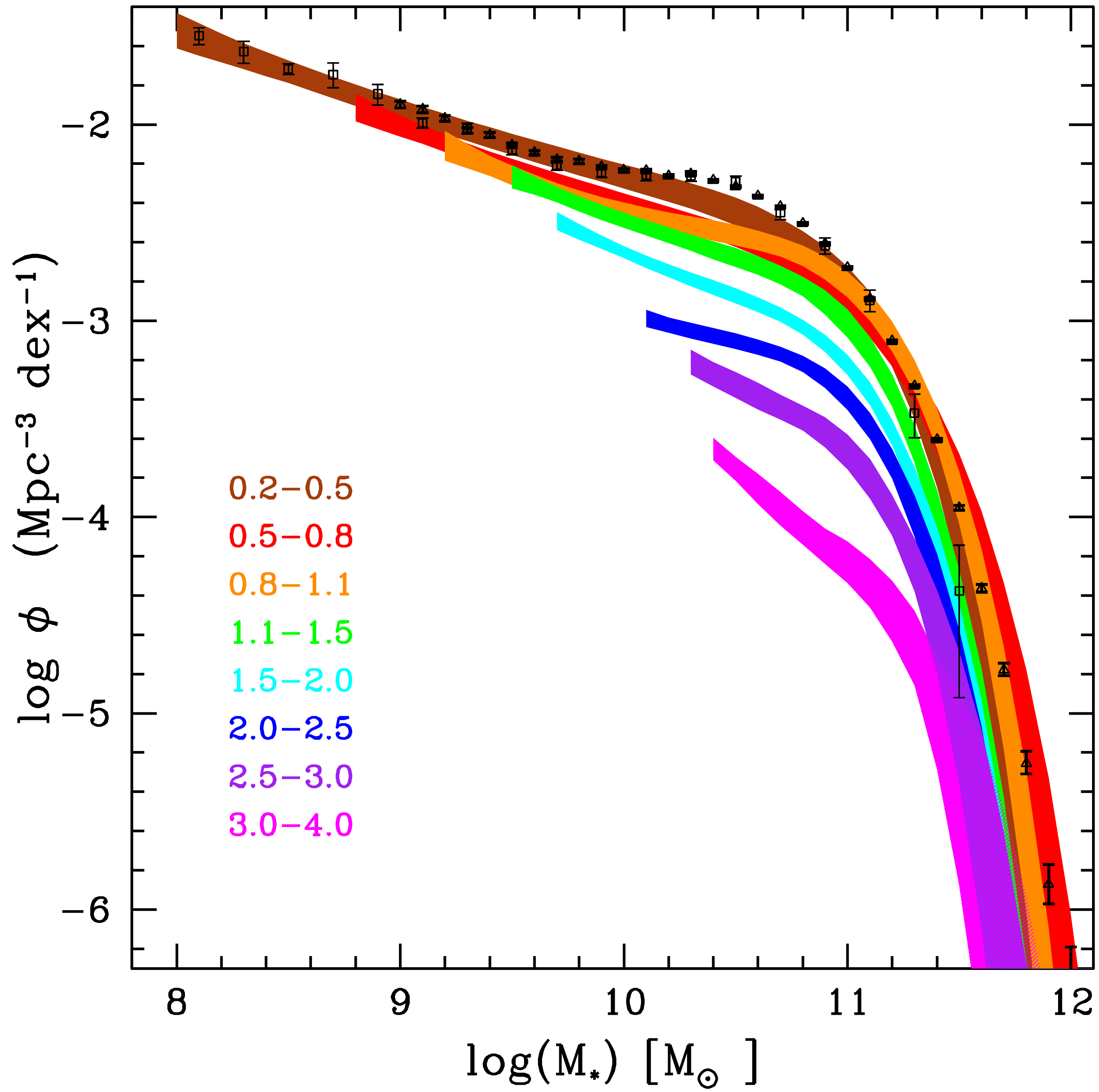
The many manifestations of downsizing

Fontanot et al. 2009, MNRAS 397, 1776

Archaeological DS: more massive galaxies host older stellar populations.

Star formation DS: the mass of the typical star-forming galaxy grows with time.

Stellar mass DS: at z≲1 the number density of smaller galaxies evolves faster



Madau & Dickinson 2014, ARA&A 52, 415

The many manifestations of downsizing

Fontanot et al. 2009, MNRAS 397, 1776

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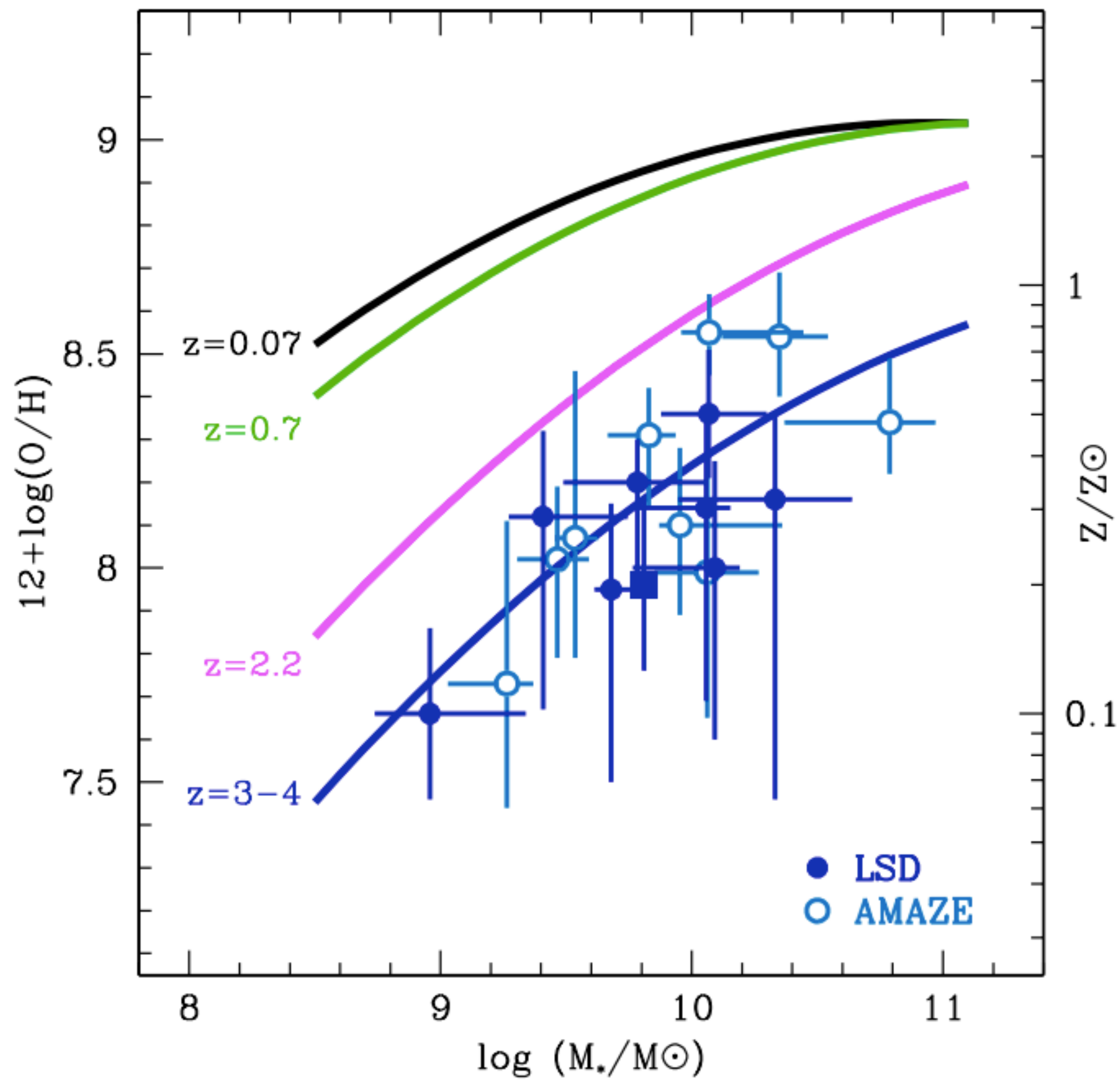

Mannucci & Cresci, arXiv:1011.0264

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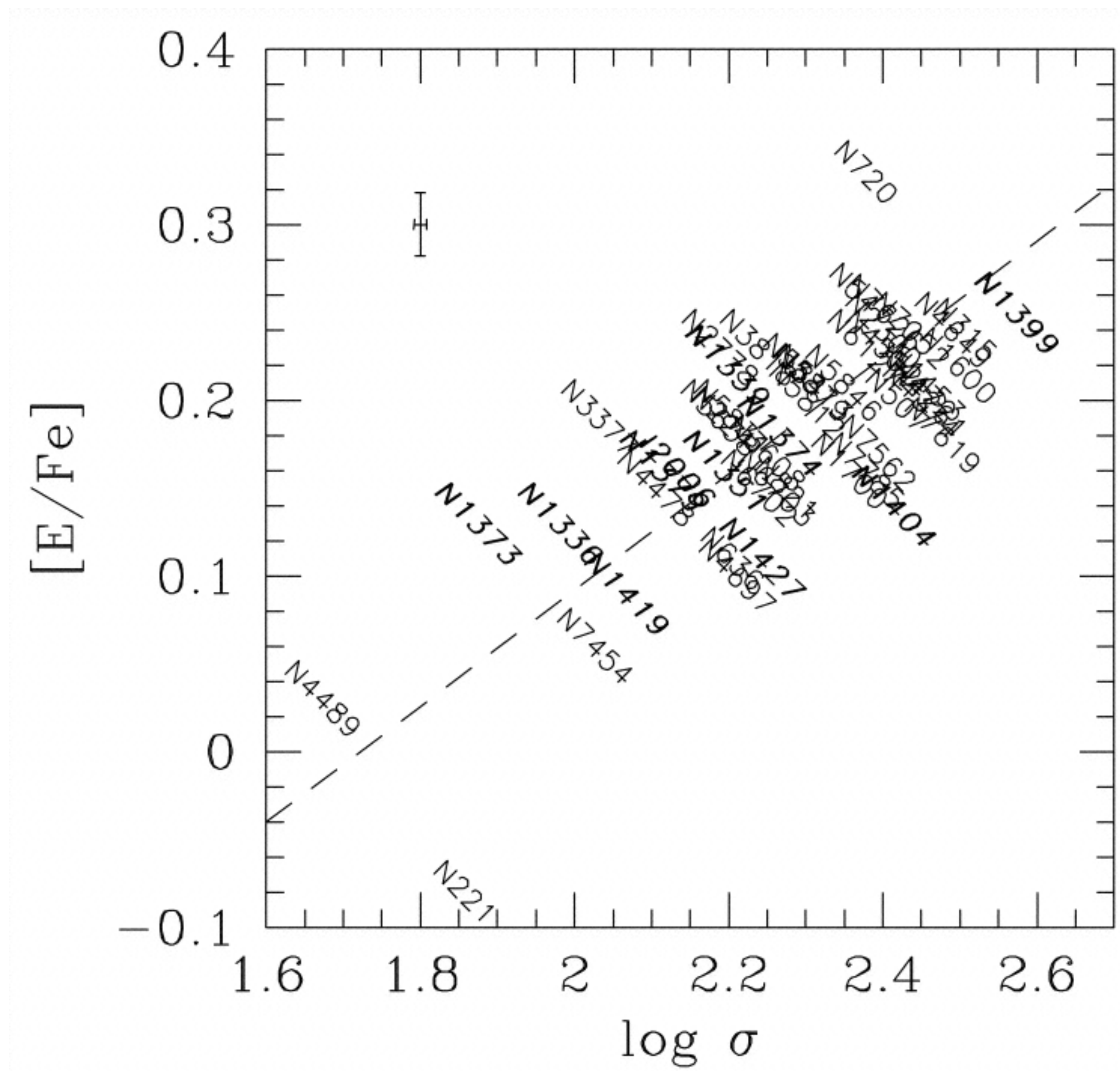

Trager et al. 2000, AJ 120, 165
see also Matteucci 1994, A&A 288, 57

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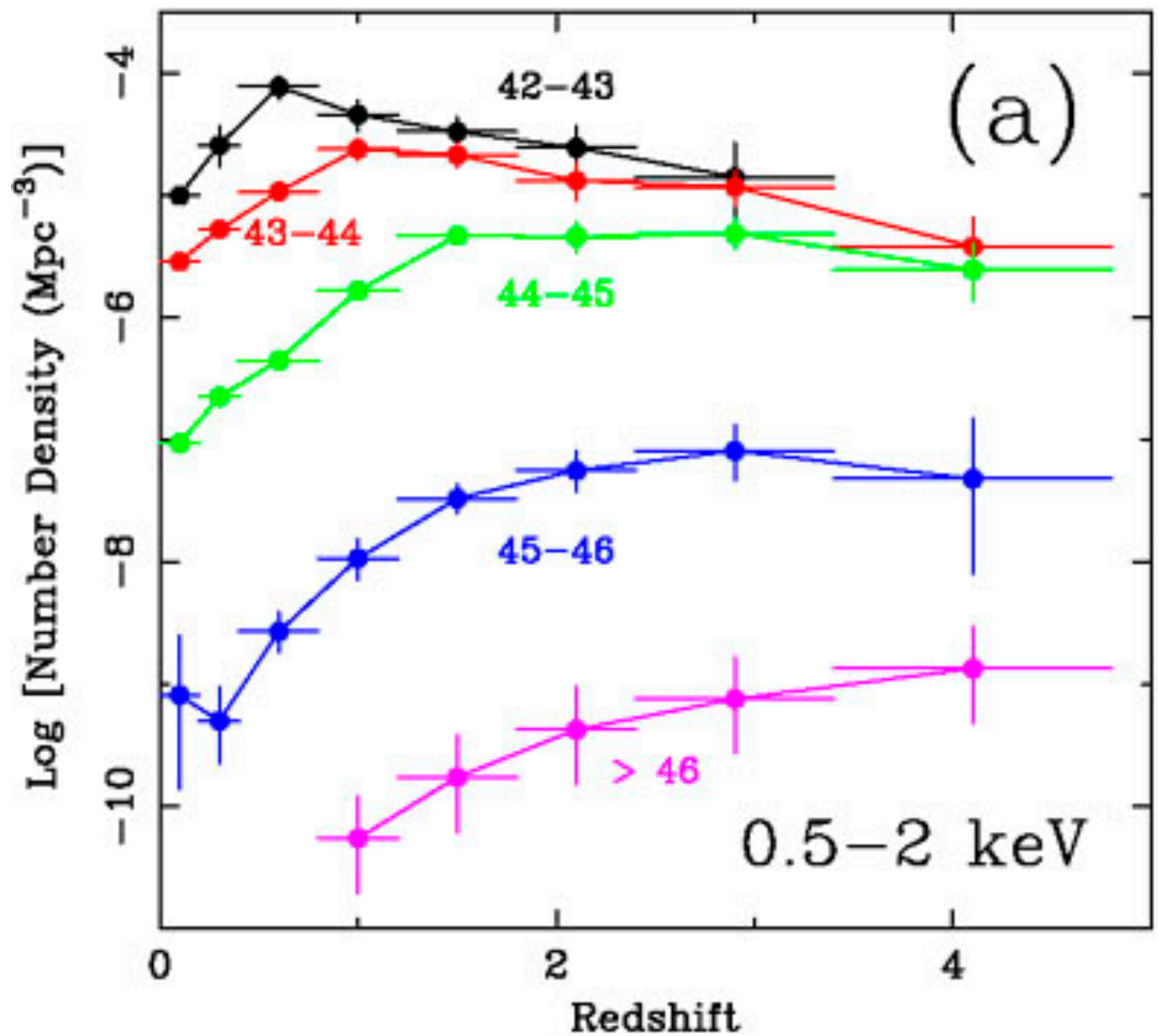
AGN DS: the number density of fainter AGNs peaks at lower z.



Brandt & Hasinger 2005, ARA&A 43, 827