FIRST LIGHT
ADVANCED SCHOOL 2019

GALAXY FORMATION

Patricia B. Tissera
Universidad Andrés Bello
Chile

Lecture.I

Galaxy formation: Main observational facts

Lecture.II

Galaxy formation: models and simulations

Lecture.III

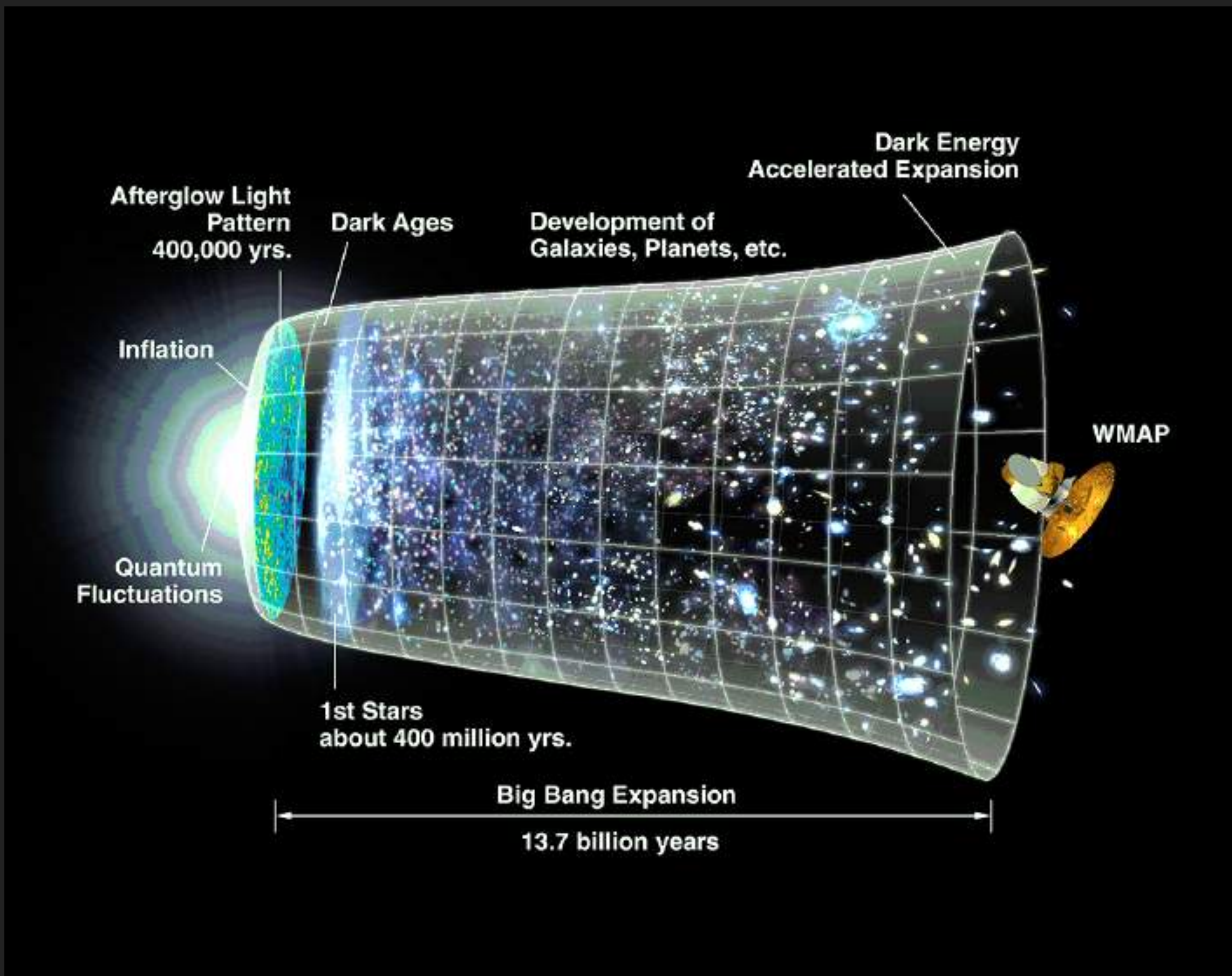
Galaxy formation: chemical evolution

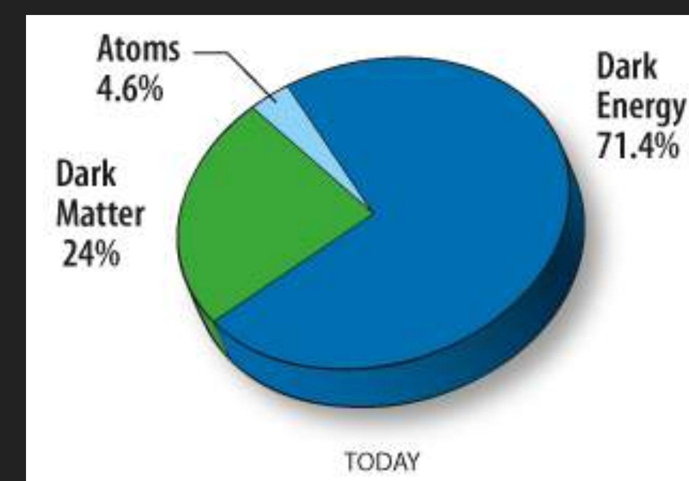
- Madau P. Cosmic Star-formation history ARA&A 2014
- Naab,T & Ostriker, J, Theoretical Challenges in Galaxy Formation ARA&A 2017
- Shapley, A, Physical properties of galaxies between z=2-4,ARA&A,2011
- Maiolino, R. & Mannucci, F., Chemical Evolution of galaxies, ARA&A,2019
- Mo,Van den Bosch &White,Galaxy formation and evolution

Lecture.I

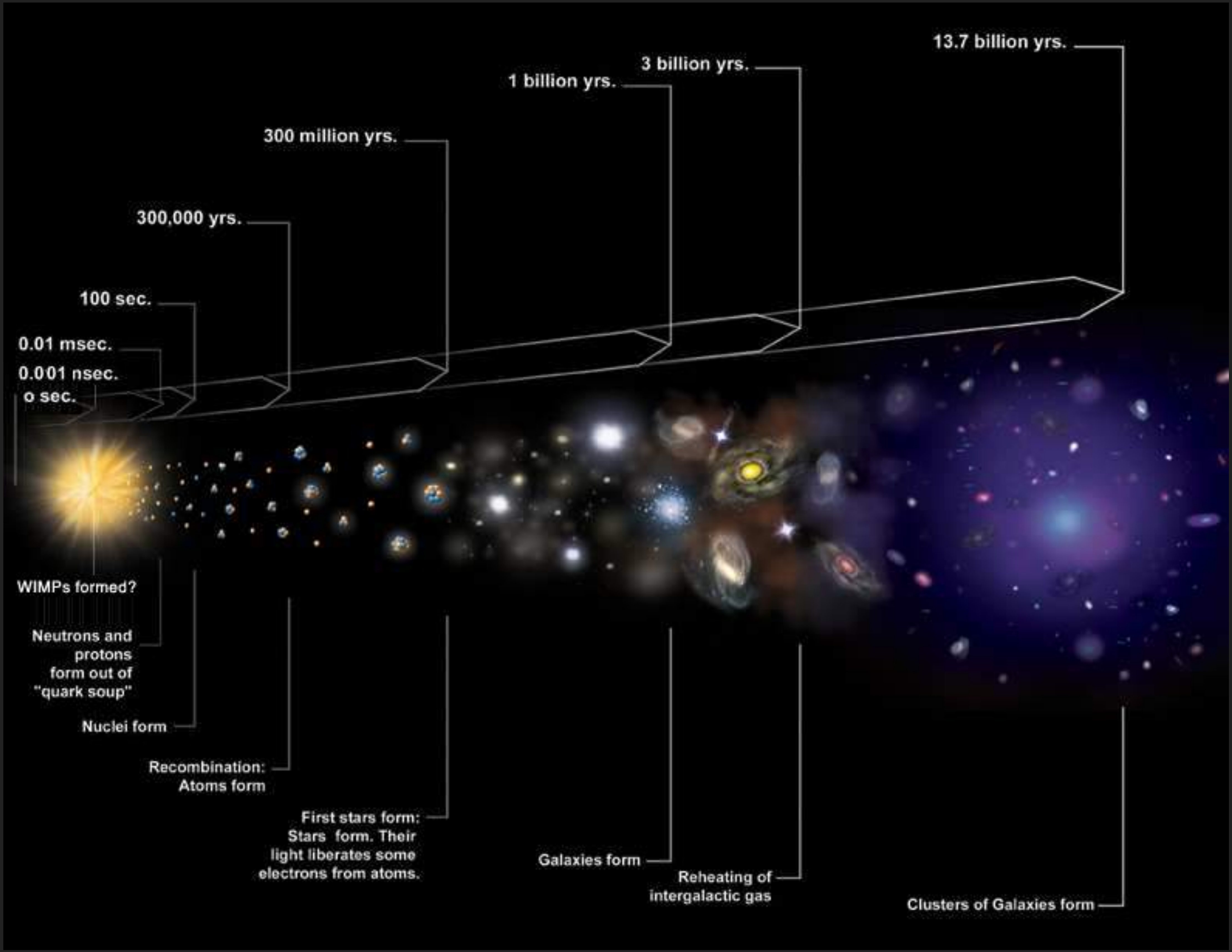
- Cosmological framework
- Galaxies in the Local Universe: main properties
- The cosmic star formation history
- Main galaxies properties around z~2 and at high z.

- Initial Conditions are given by precision cosmology

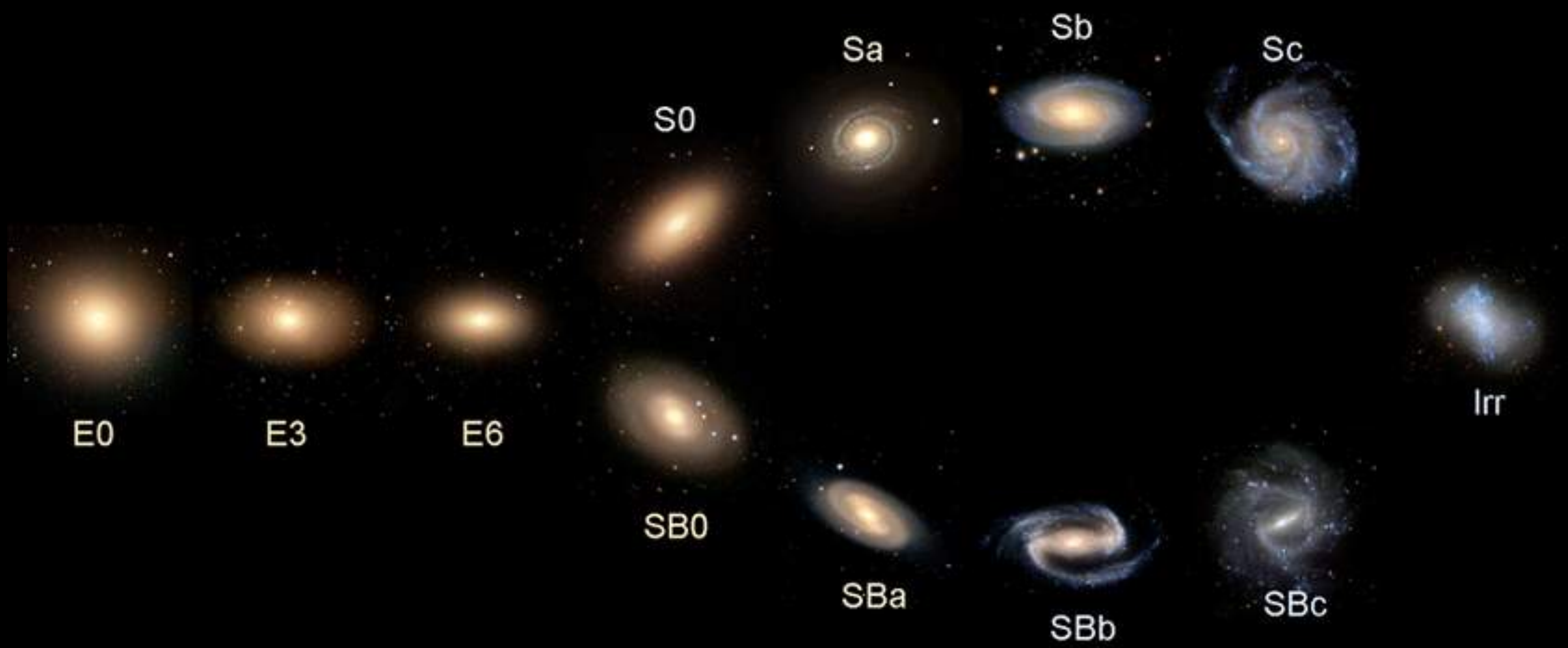




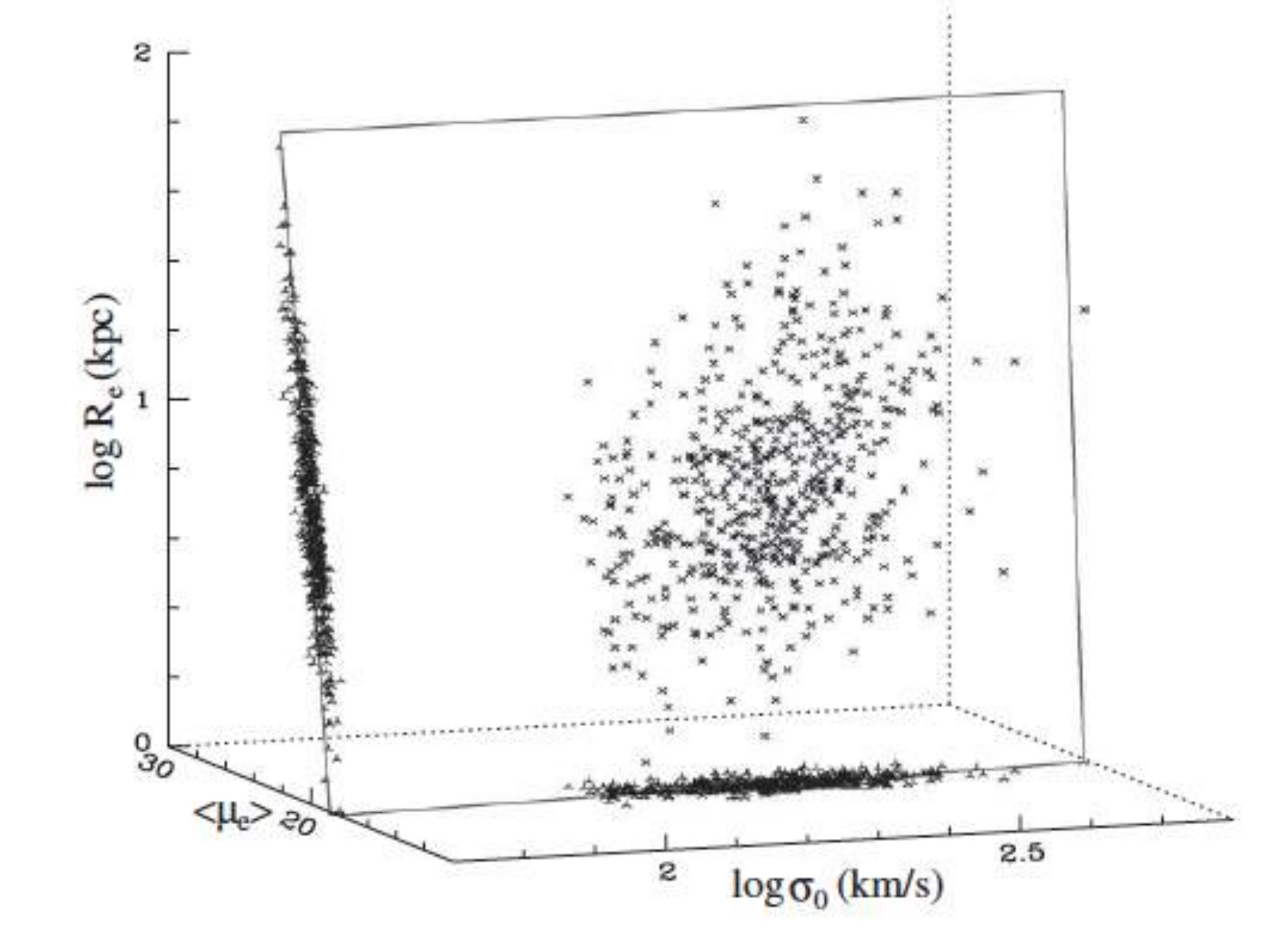
GALAXY FORMATION



How did galaxy form?
What processes regulate star formation?
What processes transform galaxies ?



Hubble 1936



Taken from Mo,Mao & White book

The fundamental plane of early type galaxies (ETGs) galaxies can be used to constrains galaxy formation models and determine distances

$$\log R_e = a \log \sigma_0 + b \log \langle I \rangle_e + \text{constant},$$

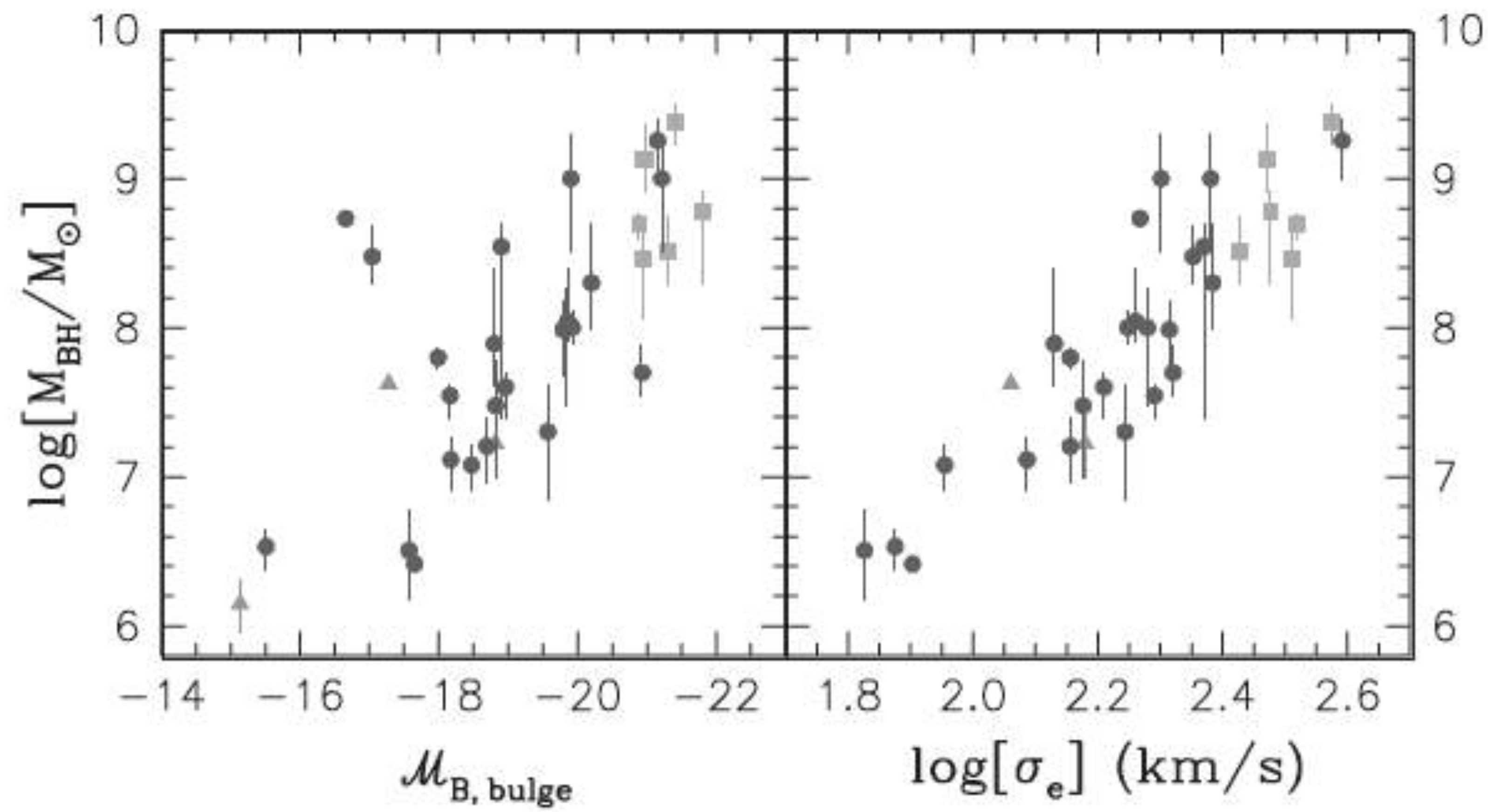
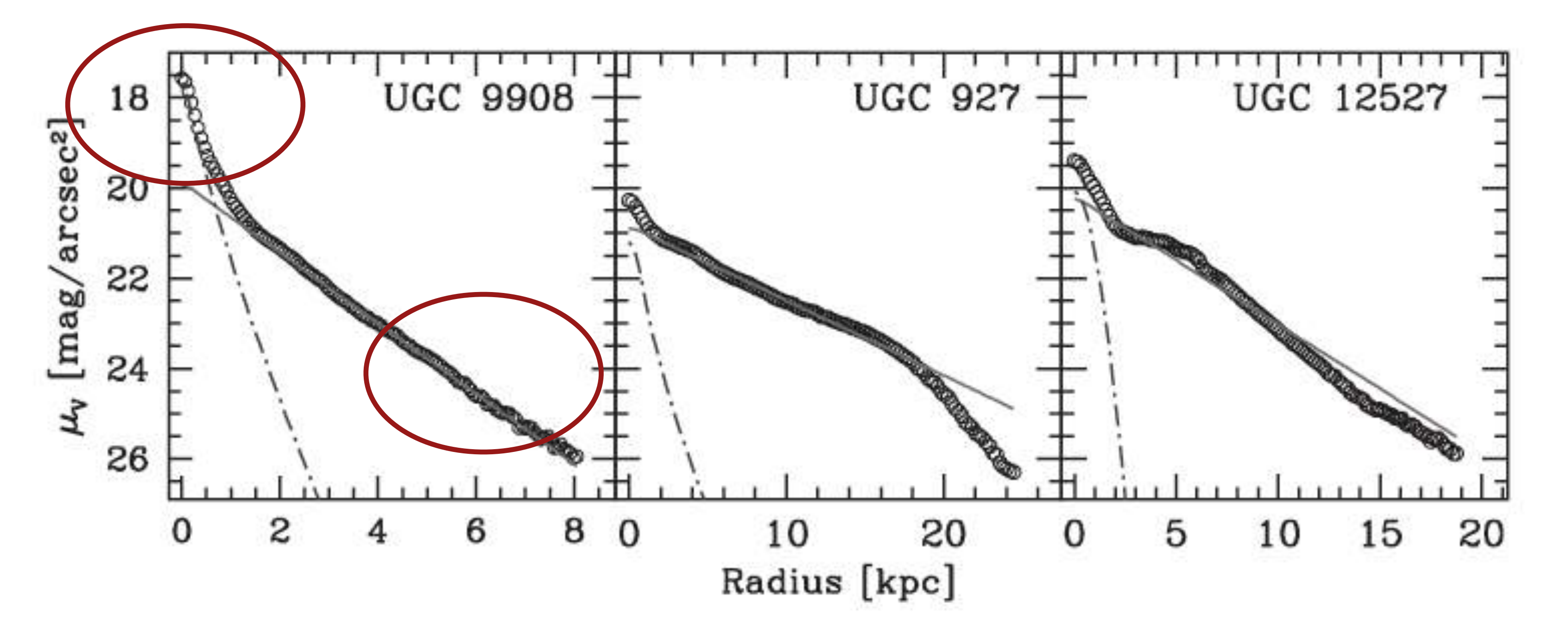


Fig. 2.17. The masses of central black holes in ellipticals and spiral bulges plotted against the absolute magnitude (left) and velocity dispersion (right) of their host spheroids. [Adapted from Kormendy (2001)]

ETGs are dominated by old stellar populations, suggesting the bulk of star formation at $z>2$.
The correlation between the properties of ellipticals (and bulges) with their central black holes suggests a connection between their formation/evolution.

Sèrsic law

$$\mu(R) = \mu_e + 1.086\beta_n \left[\left(\frac{R}{R_e} \right)^{1/n} - 1 \right].$$



Disc galaxies show flat rotational velocity curves: dark matter determines the global potential well but baryons matter

The dark matter distribution depends is affected by the presence of baryons (e.g.Tissera & Dominguez-Tenreiro 1998).

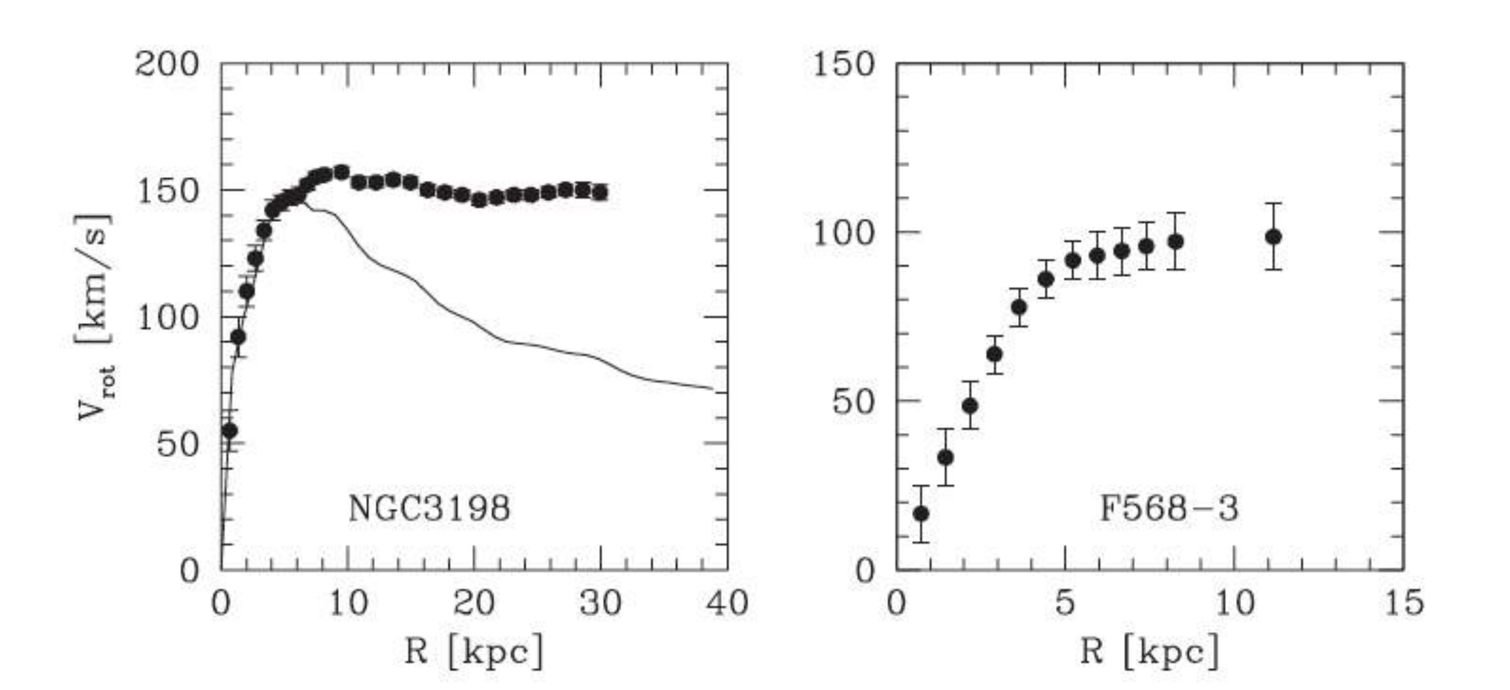
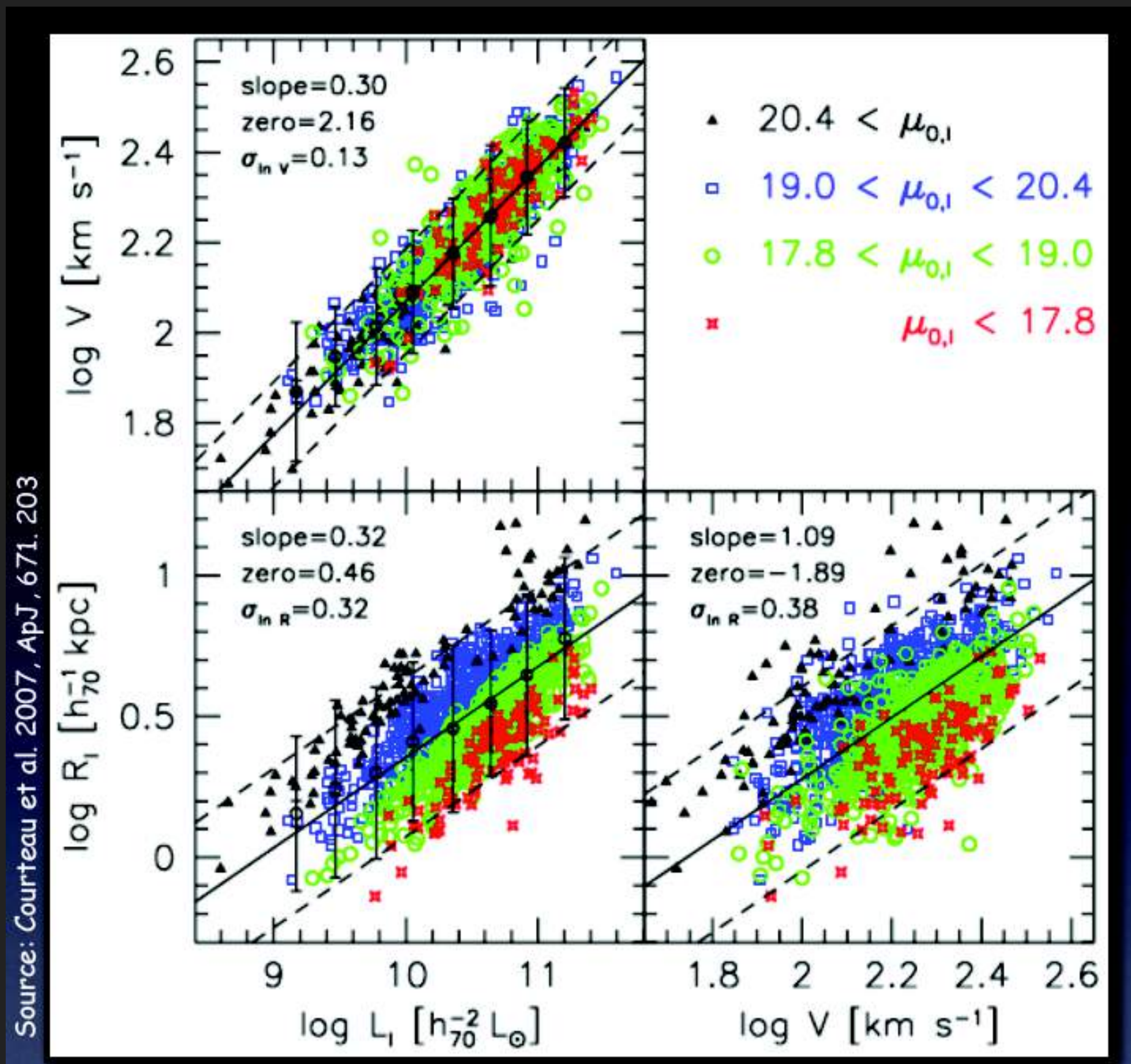
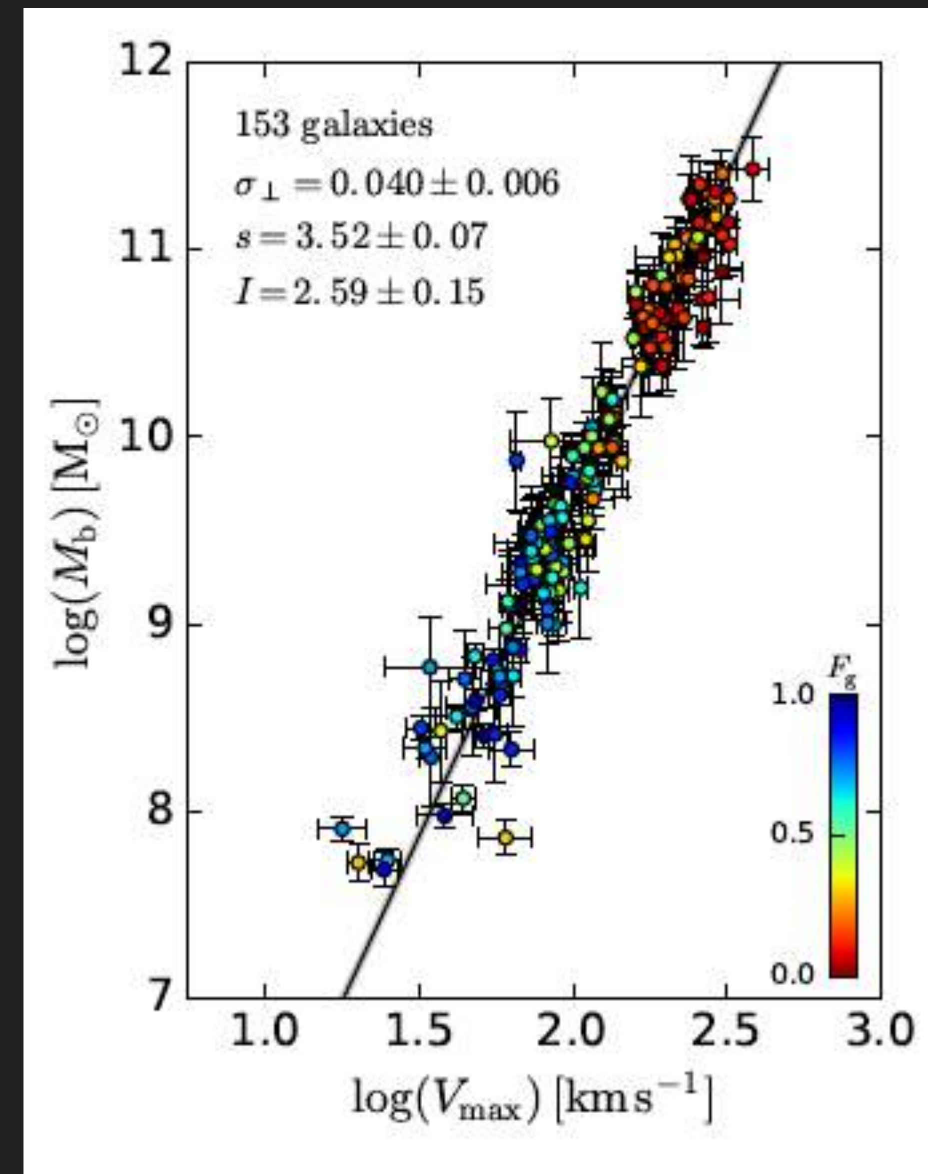


Fig. 2.21. The rotation curves of the Sc galaxy NGC 3198 (left) and the low surface brightness galaxy F568-3 (right). The curve in the left panel shows the contribution from the disk mass assuming a mass-to-light ratio of 3.8$M_\odot/L_\odot$. [Based on data published in Begeman (1989) and Swaters et al. (2000)]



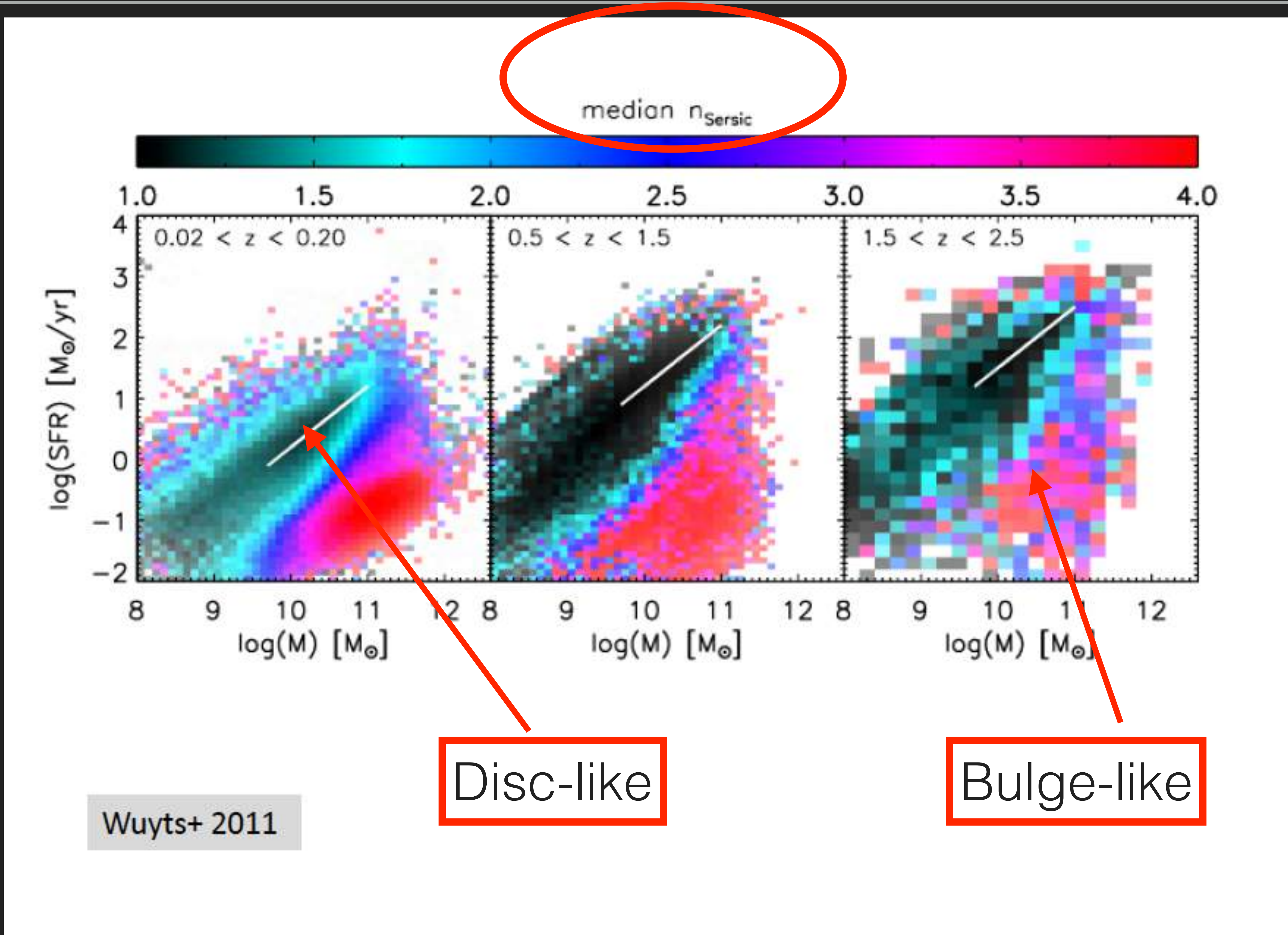


Lelli+2019

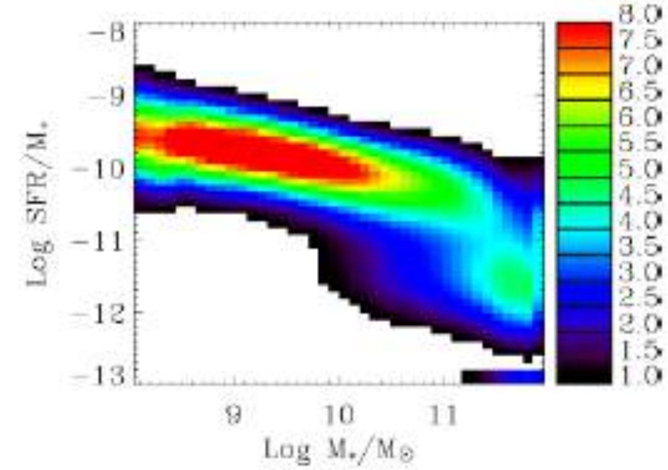
The tight correlation between Mb and V_{max} encodes the combined action of different physical processes.

ETGs follow the 'TFR' is dispersion is taken into account:

$$S_K = \sqrt{K V_{rot}^2 + \sigma_g^2}$$


median n_{Sersic}
1.0 1.5 2.0 2.5 3.0 3.5 4.0
0.02 < z < 0.20
0.5 < z < 1.5
1.5 < z < 2.5
log(SFR) [M☉/yr]
log(M) [M☉]
log(M) [M☉]
log(M) [M☉]
Disc-like
Bulge-like
Wuyts+ 2011

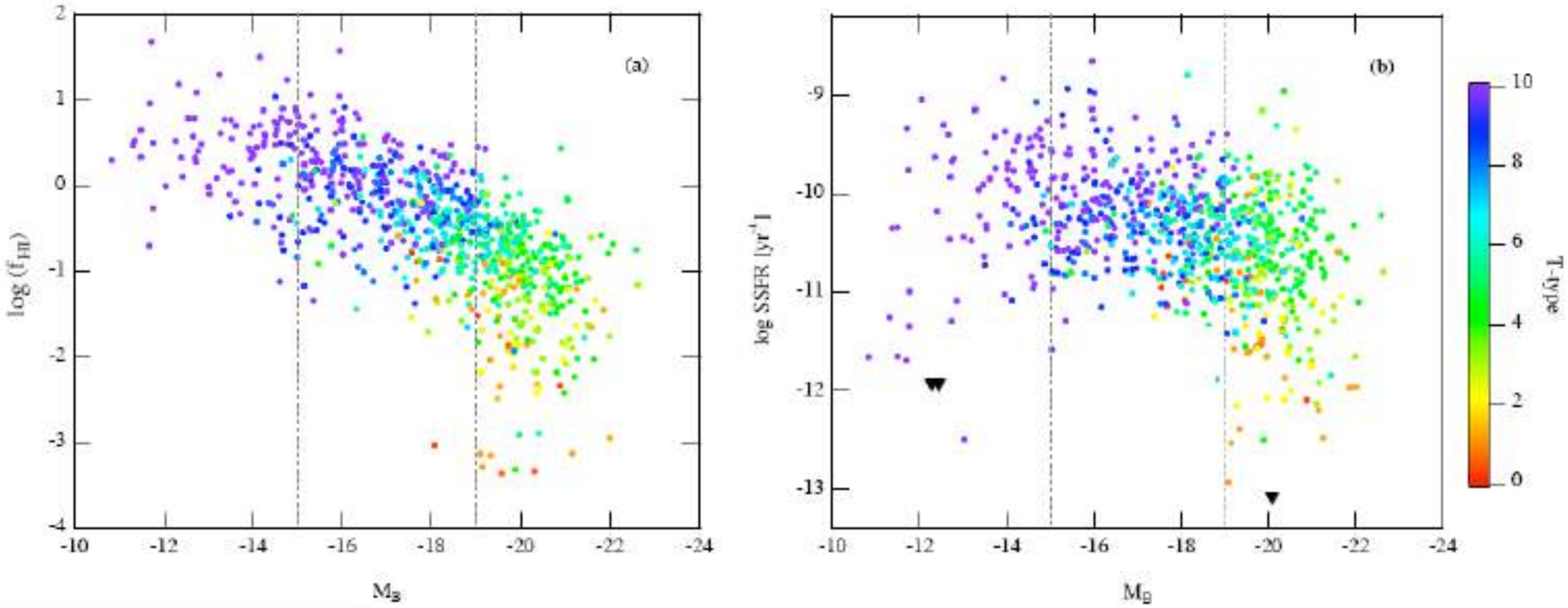
Main driver of SFR trends is the cold gas supply



sSFR=SFR/M_{star}

HI fraction

sSFR



Tacconi+2011

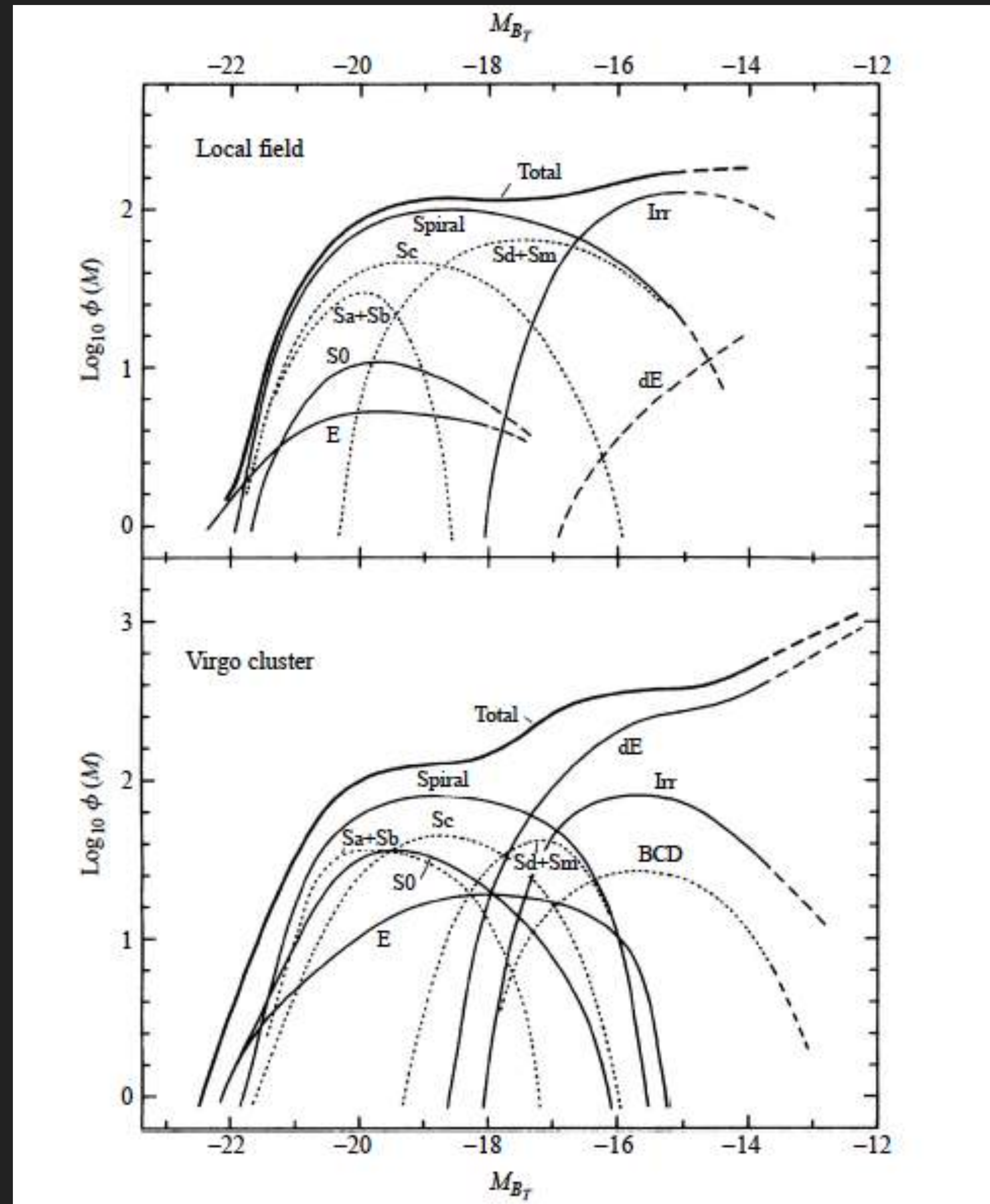
Higher cold fractions can be related to higher SFR: Is it enough to have available HI? Is it necessary to have triggering mechanisms such as mergers? What is the role of environment?

•LUMINOSITY/STELLAR MASS FUNCTIONS IN DIFFERENT ENVIRONMENT

$$\phi(L)\,dL \sim L^{\alpha} e^{-L/L^{*}}\,dL,$$

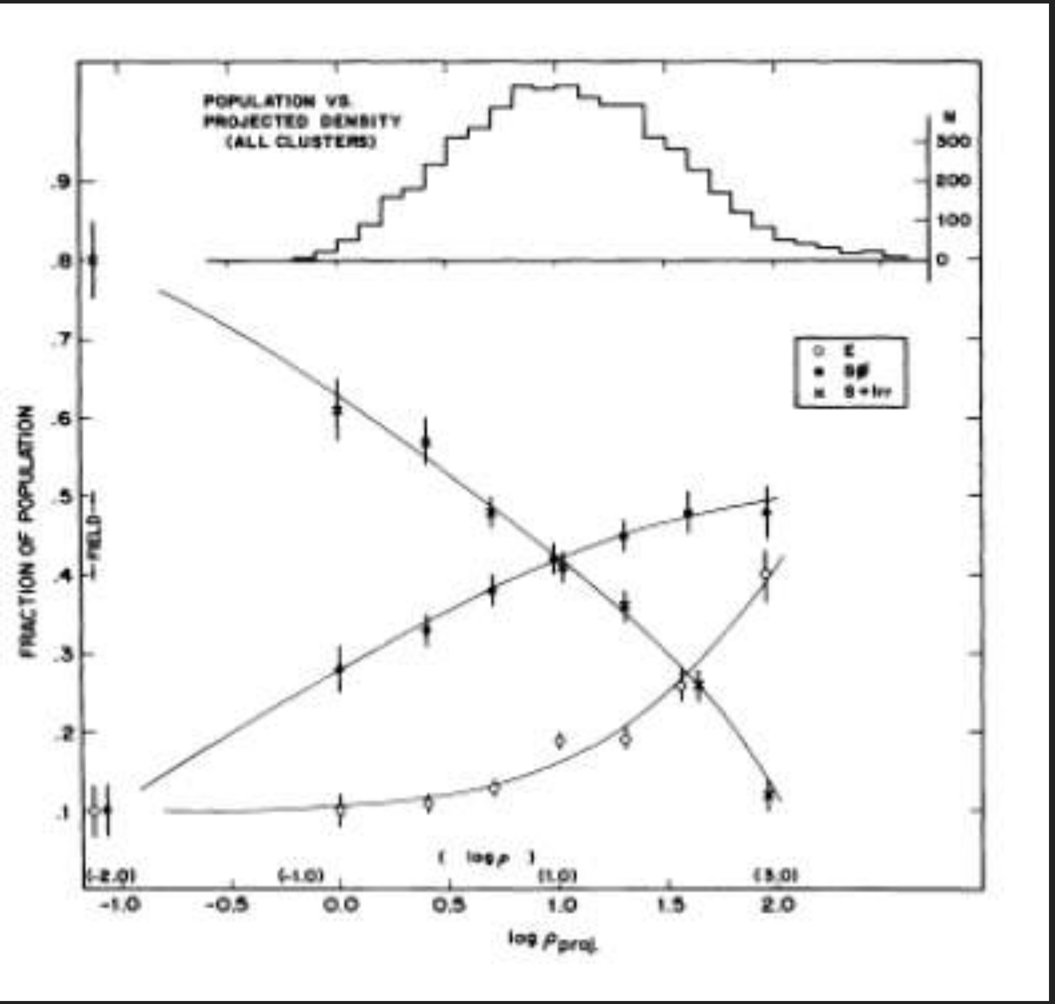
$$\phi(M)\,dM \sim 10^{-0.4(\alpha+1)M} e^{-10^{0.4(M^{*}-M)}}\,dM.$$

Different contributions of morphologies in different environments (e.g.Dressler 1980)



•ENVIRONMENT

Dressler 1980



As the local density increases, the effects of environment are more important. galaxy-galaxy encounters, galaxy stripping, etc.

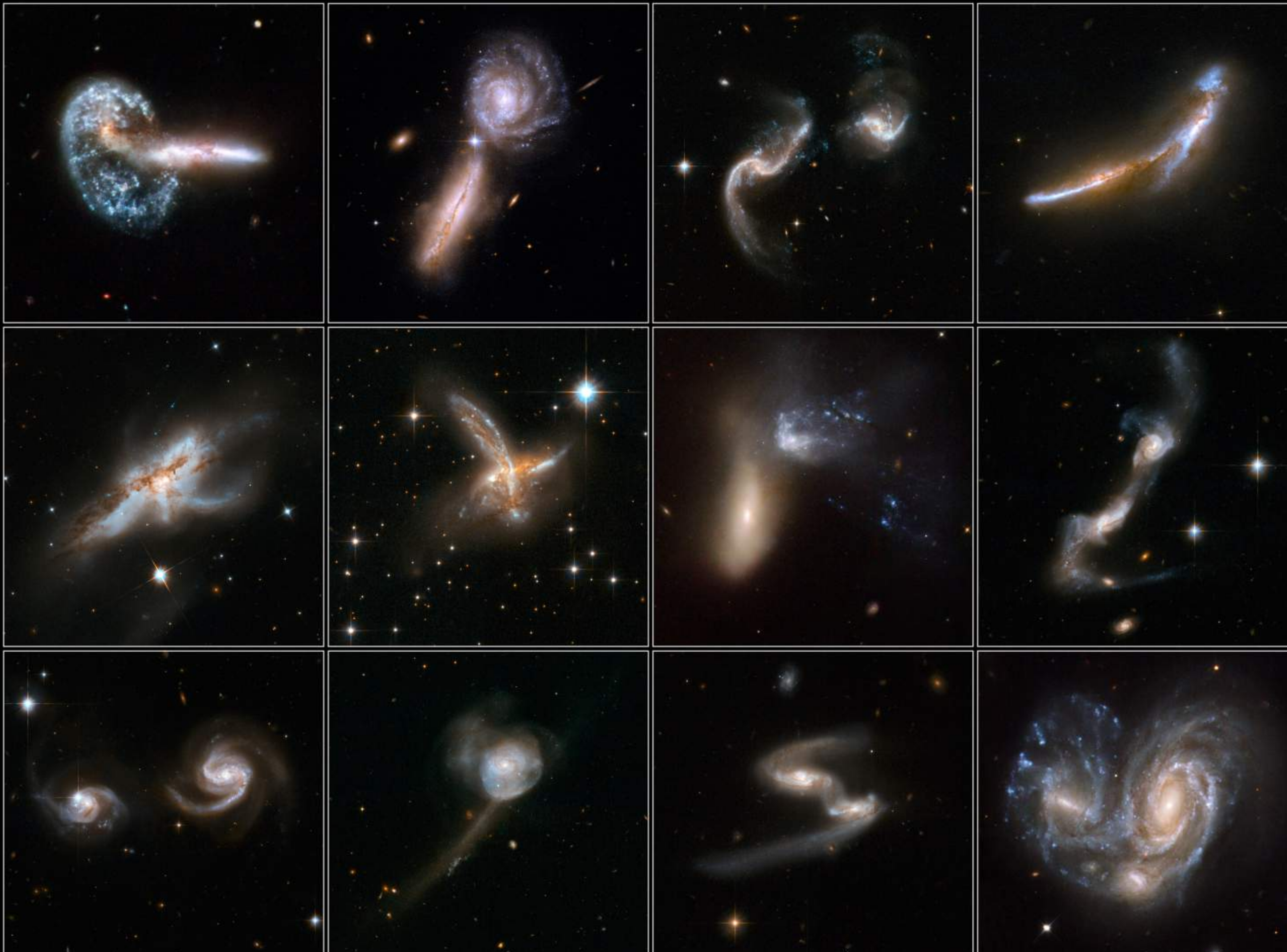
Dynamical friction: galaxies loose orbital angular momentum and sinks galactic (galactic cannibalism)

Ram-pressure: interaction of the galaxy with the IGM that can deprive (cold/hot) gas (strangulation/starvation)

The remotion of gas from galaxies by environmental processes contribute to enrich the IGM and might lead to the quenching of the star formation in galaxies (pre-processing).

Interacting Galaxies

Hubble Space Telescope • ACS/WFC • WFPC2



MERGERS

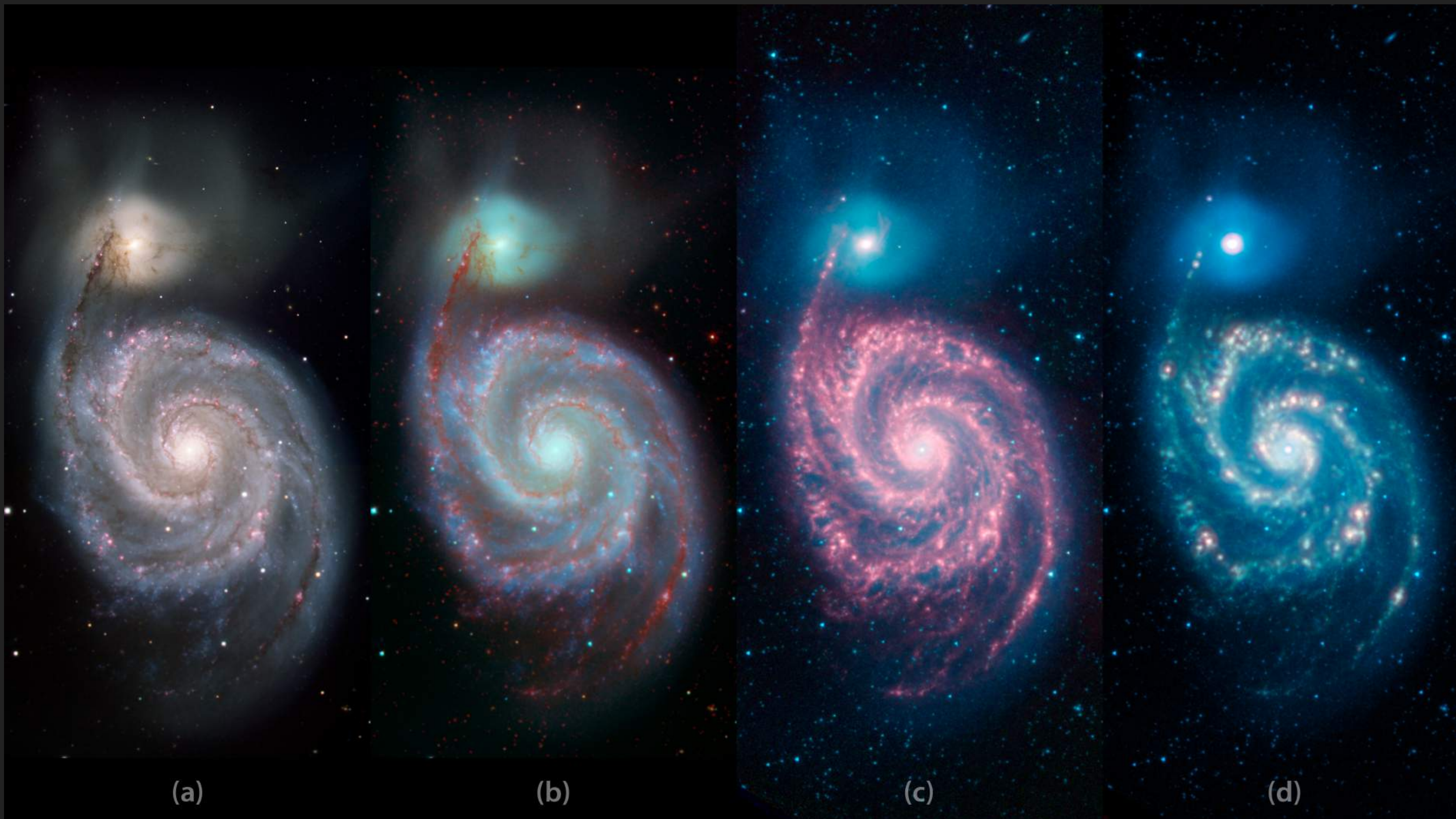
- **mass ratio of the galaxies:**
  major mergers: $M_1/M_2 > 3 - 4$
  minor mergers: otherwise; satellites
  major mergers are more destructive than minor mergers

- **morphologies of the progenitors (disks or spheroids):**
  disks are more fragile; even minor mergers may have a structural impact (e.g. disk thickening, bars, warps)

- **gas mass fraction of the progenitors:**
  wet mergers: between gas-rich galaxies
  dry mergers: with gas-poor progenitors
  gas responds to pressure as well as to gravity and may loose energy by radiation

- **orbital properties:**
  the orbital energy and angular momentum determine the fate of a merger

Taken from L. Sodré's lectures
at UNAB 2016



Optical image + 0.4m (blue) and 0.7 m(green)

Visible light (blue and green) + infrared (red)

Spitzer: 3.5m(blue), 4.5m(green), 7m(red). Red features show dust composed mostly of C

Spitzer includes 24m(red), hot dust. Red/white spots—> new stars heating their surroundings.

•FROM LUMINOSITY TO STAR FORMATION

+ The technique relies on some basic properties of stellar populations and dusty starburst galaxies.

1. The UV -continuum emission is dominated by short-lived massive stars, except for the oldest galaxies. Hence, for a given (Initial Mass Function) IMF and dust content —> it is a measure of the instantaneous star formation rate density (SFRD).

2. The rest-frame NIR light is dominated by near-solar-mass-evolved stars —> they can be used as tracers of the total stellar mass density (SMD).

3. Interstellar dust preferentially absorbs UV light and re-radiates it in the thermal IR —> the FIR emission of dusty galaxies can be a sensitive tracer of young stellar populations and the SFRD.

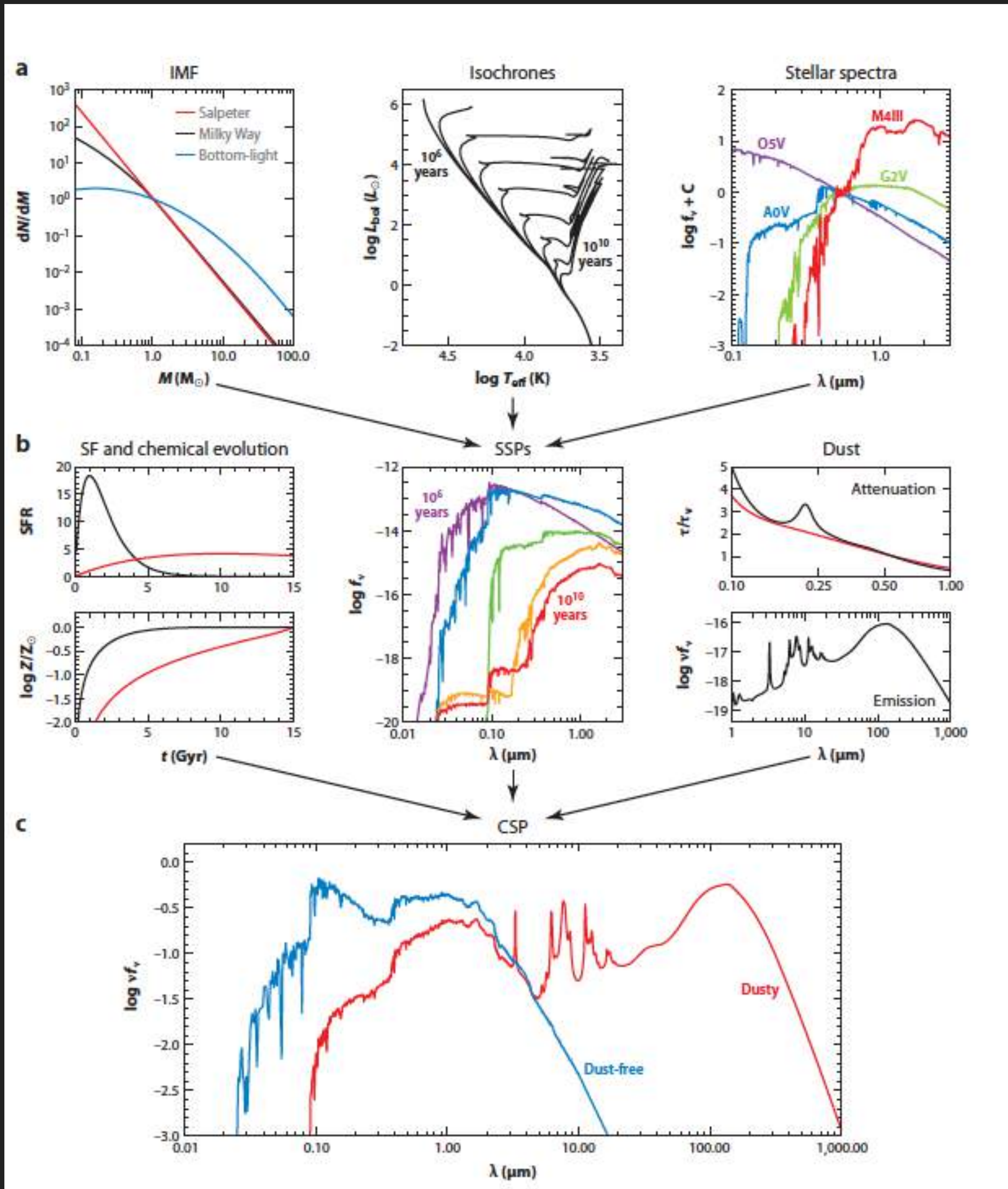
Spectral Energy Distributions (SEDs) models:

Single Stellar Populations (SSPs): stars formed at a given time (same age), with a given a metallicity (Z), assuming an Initial Mass Function (IMF),

$$f_{\mathrm{SSP}}(t, Z) = \int_{m_{\mathrm{lo}}}^{m_{\mathrm{up}}(t)} f_{\mathrm{star}}[T_{\mathrm{eff}}(M), \log g(M)|t, Z]\, \Phi(M)\, \mathrm{d}M\,,$$

Metallicity: the fraction of chemical elements heavier than He in the gas or stars, $Z=M(Z)/M_{gas}$)

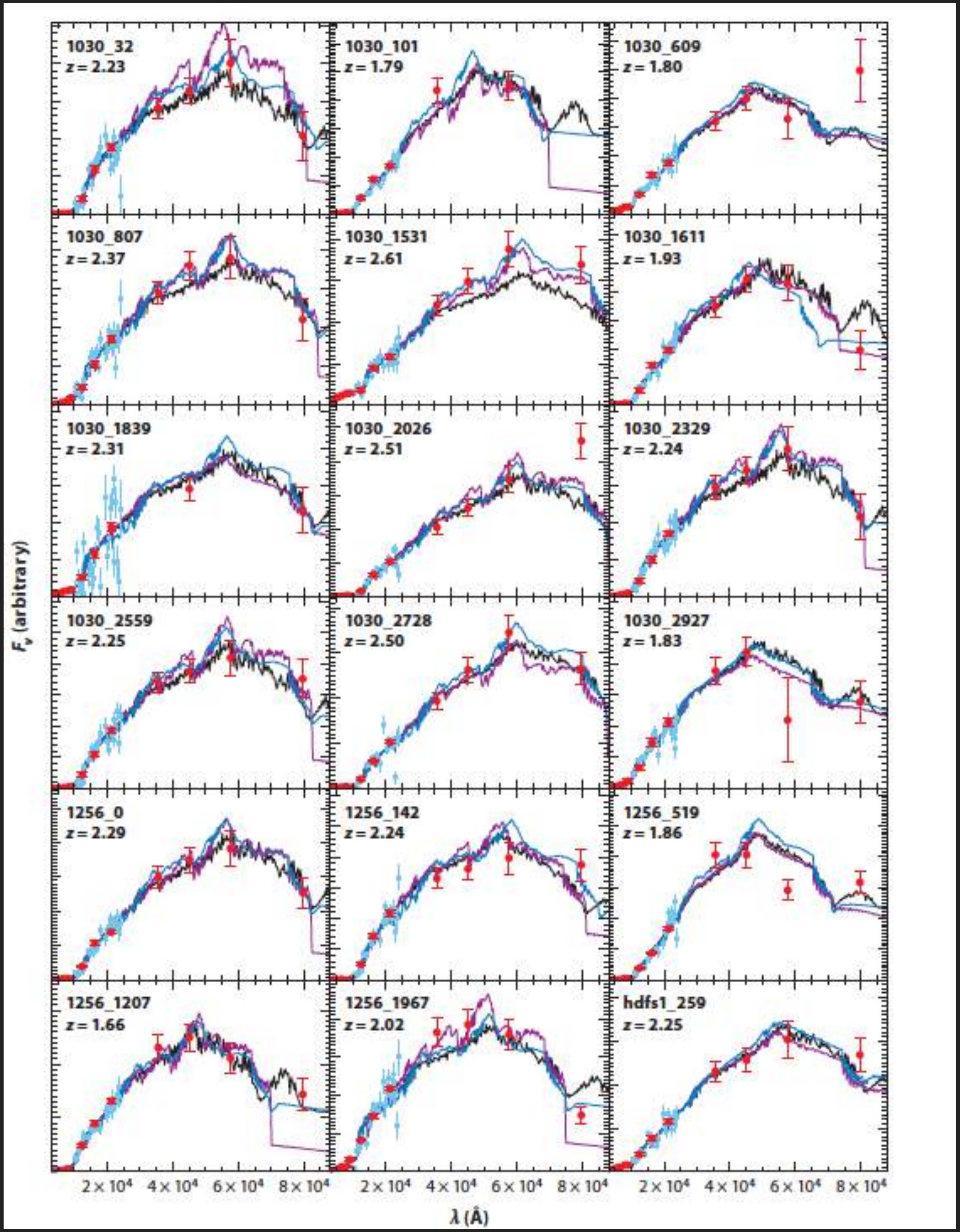
Madau & Dickinson 2013



$$f_{\rm CSP}(t) = \int_{t'=0}^{t'=t} \int_{Z=0}^{Z_{\rm max}} \left({\rm SFR}(t-t') P(Z, t-t') f_{\rm SSP}(t', Z) e^{-\tau_d(t')} + A\, f_{\rm dust}(t', Z) \right) {\rm d}t'\, {\rm d}Z,$$

CSPs provide estimations of:

- **The characteristics of the SPs that are in a galaxy**
- **The fraction of gas.**
- **The stellar mass.**

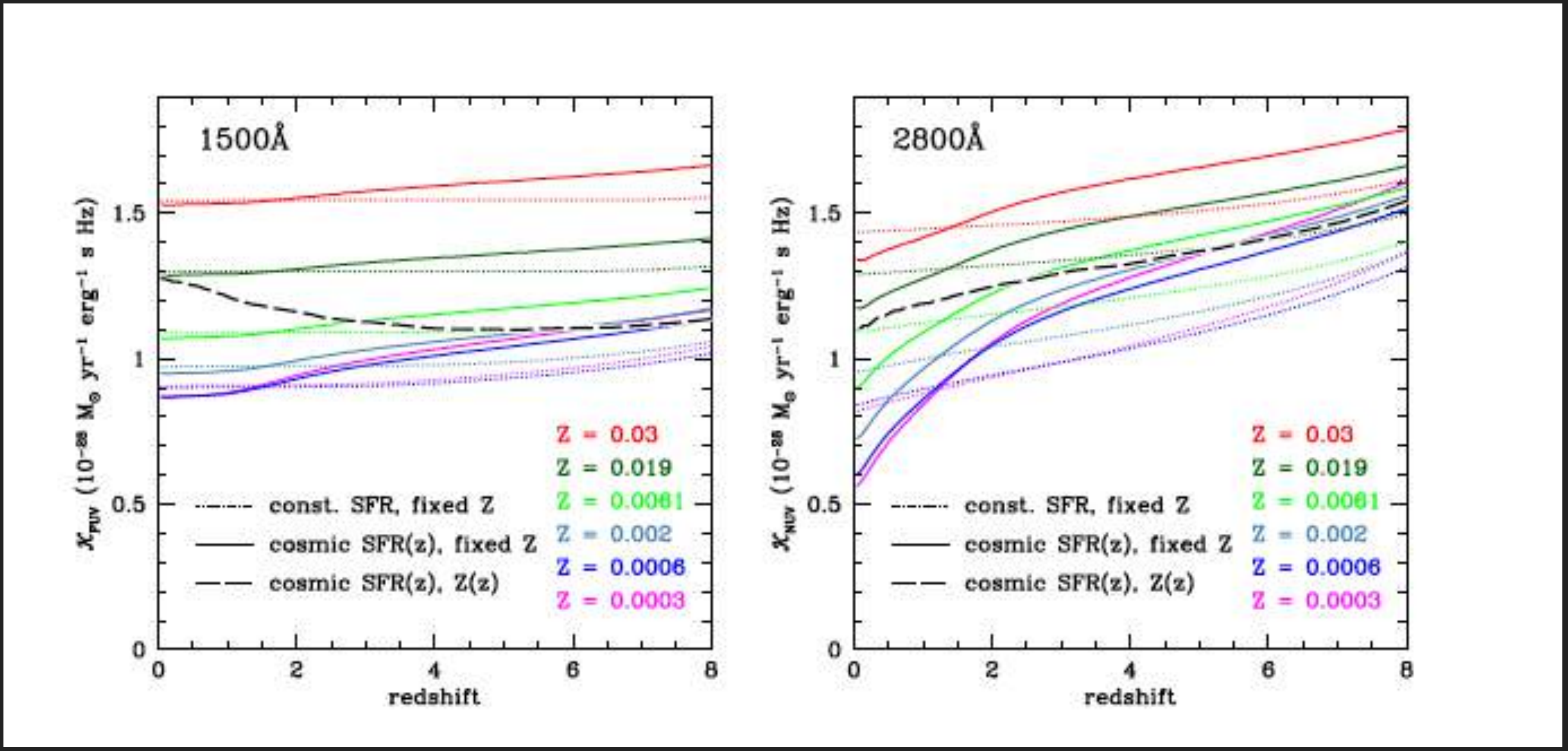


Shapley 2011

$$\mathrm{SFR} = \mathcal{K}_{\mathrm{FUV}} \times L_\nu(\mathrm{FUV}),$$

$$\mathrm{SFR}_{\mathrm{tot}} = \mathcal{K}_{\mathrm{FUV}} L_{\mathrm{FUV}} + \mathcal{K}_{\mathrm{IR}} L_{\mathrm{IR}},$$

Madau & Dickinson 2014

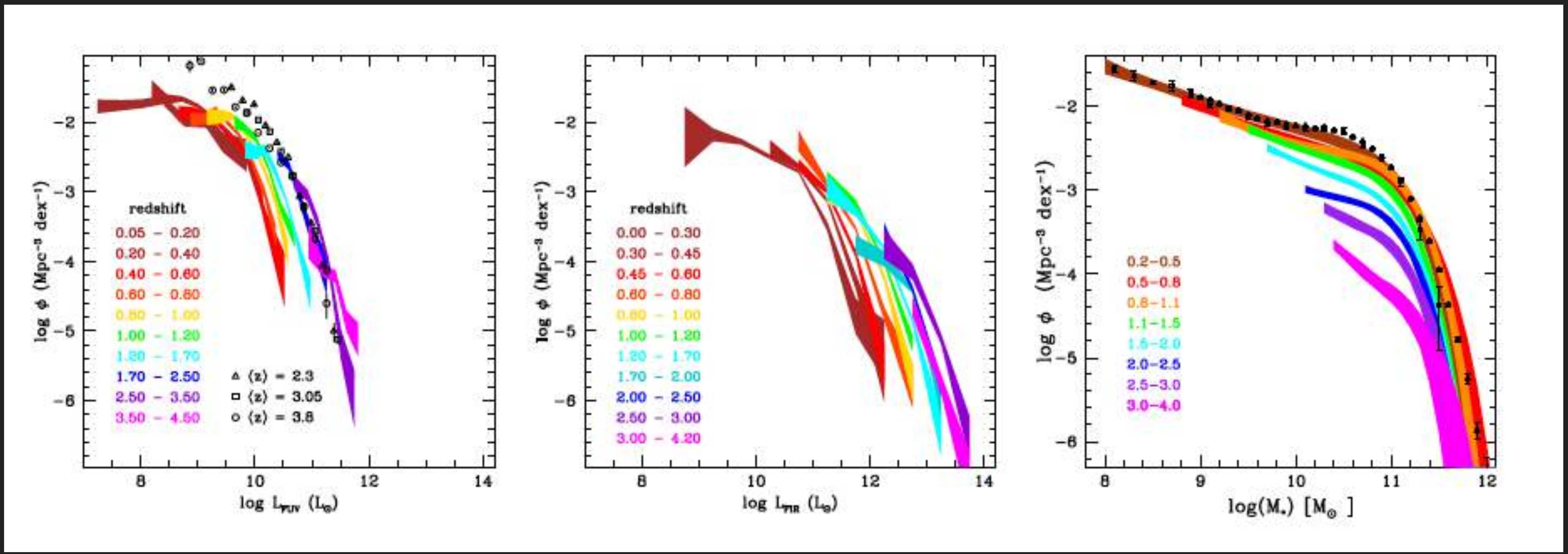


The value of the conversion factor is sensitive to the recent SFH and metal-enrichment history as well as the choice of the IMF.

•EVOLUTION WITH REDSHIFT

Caution: calibration of conversion factors done at z~0

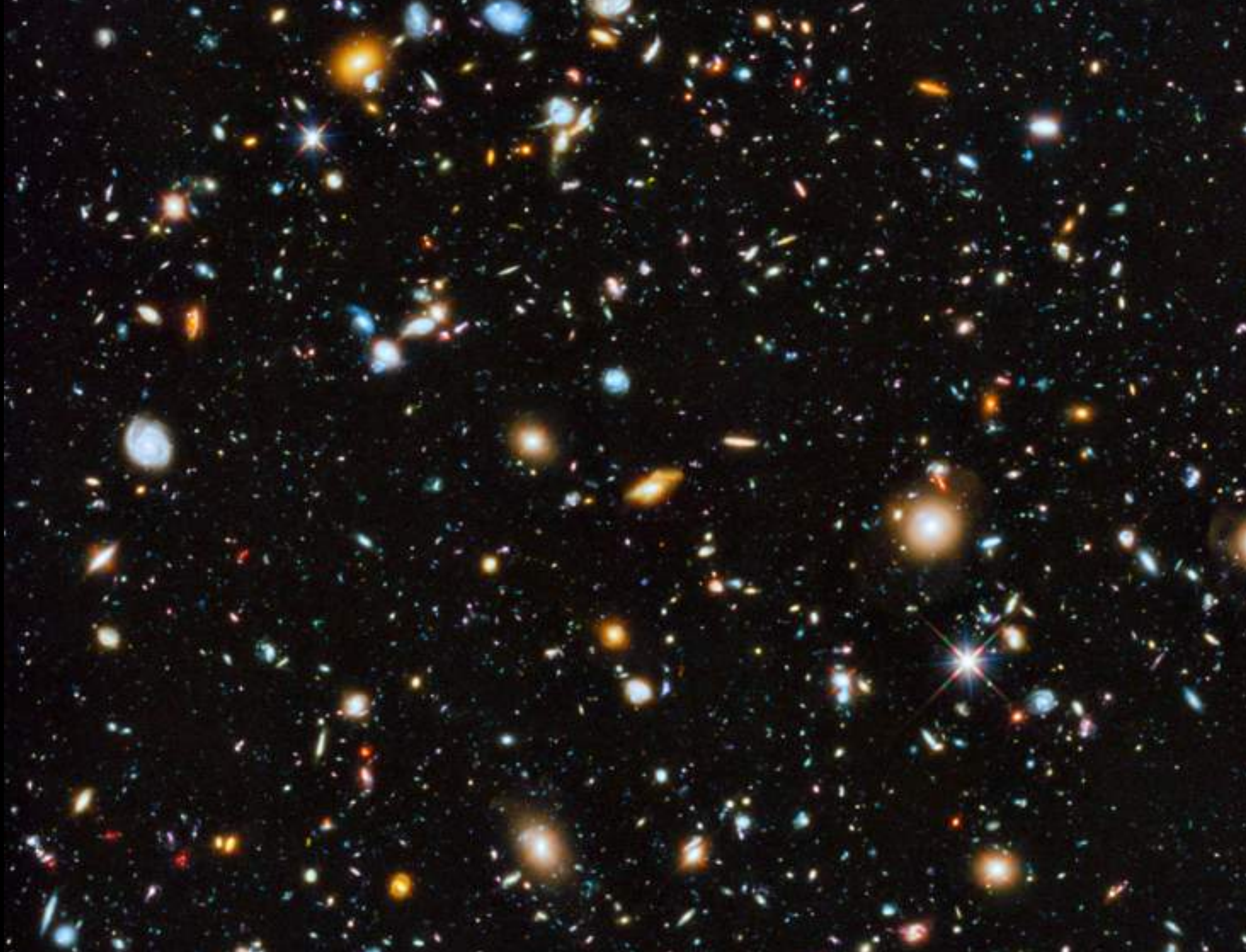
Madau & Dickinson 2014

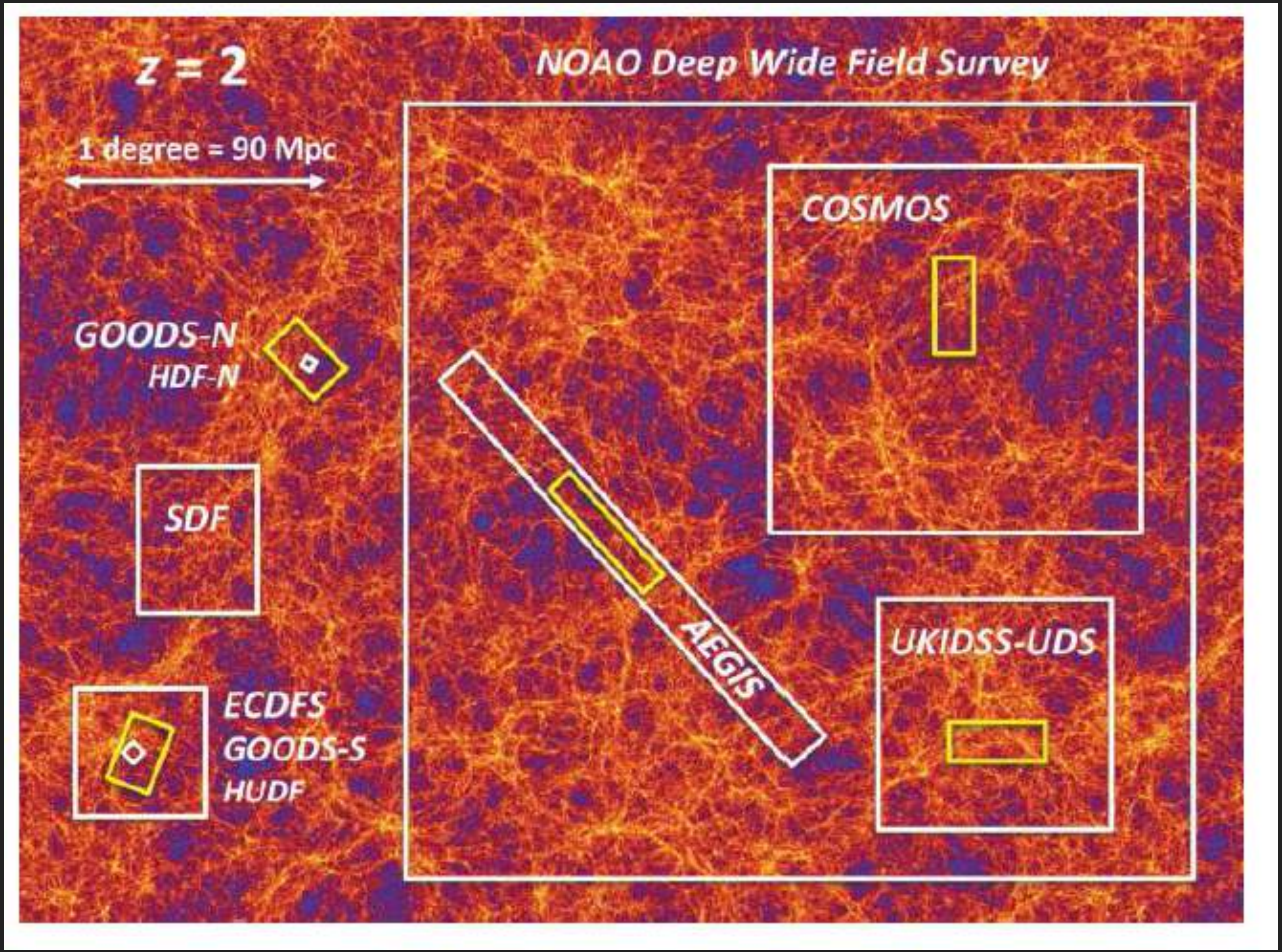


There are higher LUV at higher redshift —> higher star formation activity

LFIR —>extends to higher L Starburst galaxies are obscured in UV.

Stellar masses by SED



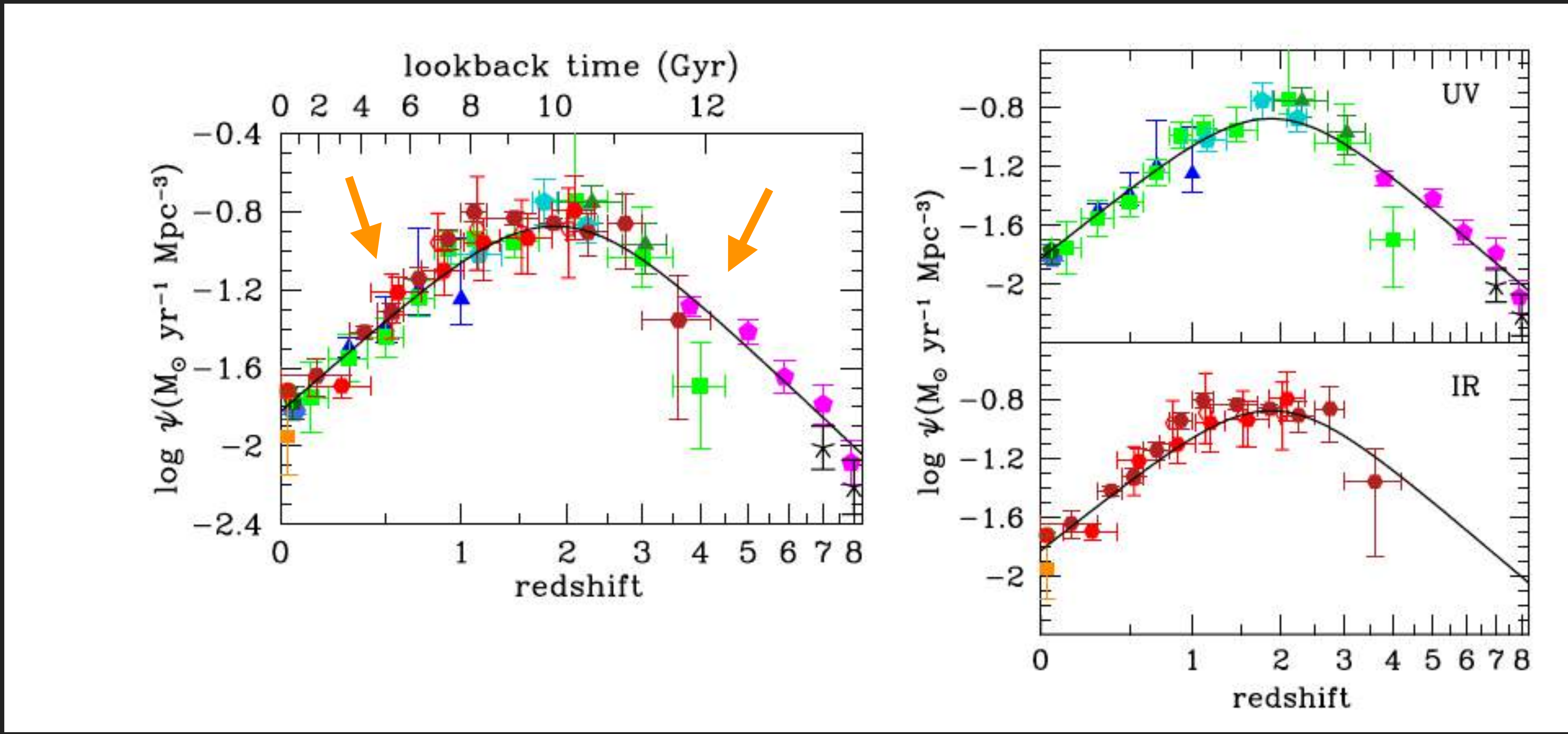

z = 2
1 degree = 90 Mpc
NOAO Deep Wide Field Survey
COSMOS
GOODS-N
HDF-N
SDF
AEGIS
UKIDSS-UDS
ECDFS
GOODS-S
HUDF

•COSMIC STAR FORMATION RATE

Equation 1 was first used by Lanzetta et al. (1995) to study the chemical evolution of the damped Lyα absorption systems, where one infers the comoving rate of star formation from the observed cosmological mass density of H I. Pei & Fall (1995) then generalized it to models with inflows and outflows. Madau et al. (1996, 1998b) and Lilly et al. (1996) developed a different method where data from galaxy surveys were used to infer the SFRD $\psi(t)$ directly. This new approach relies on coupling the equations of chemical evolution to the spectrophotometric properties of the cosmic volume under consideration. The specific luminosity density at time t of a "cosmic stellar population" characterized by an SFRD $\psi(t)$ and a metal-enrichment law $Z_*(t)$ is given by the convolution integral

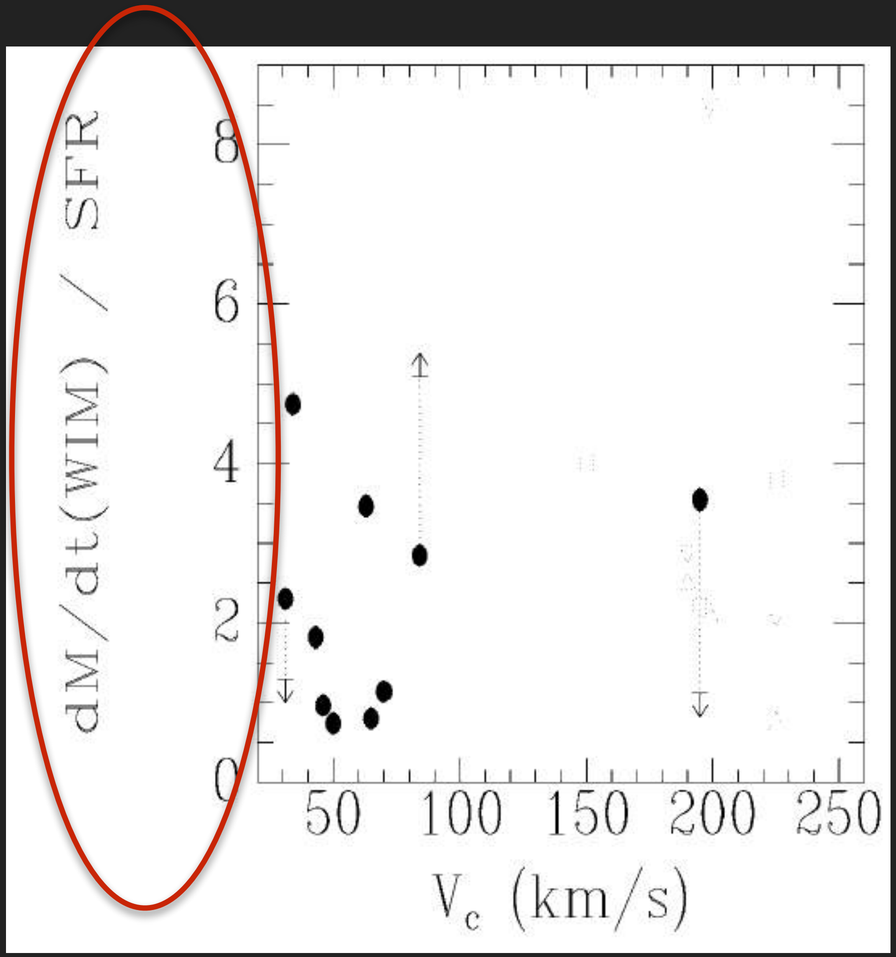
$$\rho_\nu(t) = \int_0^t \psi(t-\tau)\mathcal{L}[\tau, Z_*(t-\tau)]d\tau, \tag{13}$$

where $\mathcal{L}_\nu[\tau, Z_*(t-\tau)]$ is the specific luminosity density radiated per unit initial stellar mass by a SSP of age τ and metallicity $Z_*(t-\tau)$. The theoretical calculation of $\mathcal{L}_\nu$ requires stellar evolutionary tracks, isochrones, and stellar atmosphere libraries. As an illustrative example of this technique, we provide in this section a current determination of the SFH of the Universe and discuss a number of possible implications.

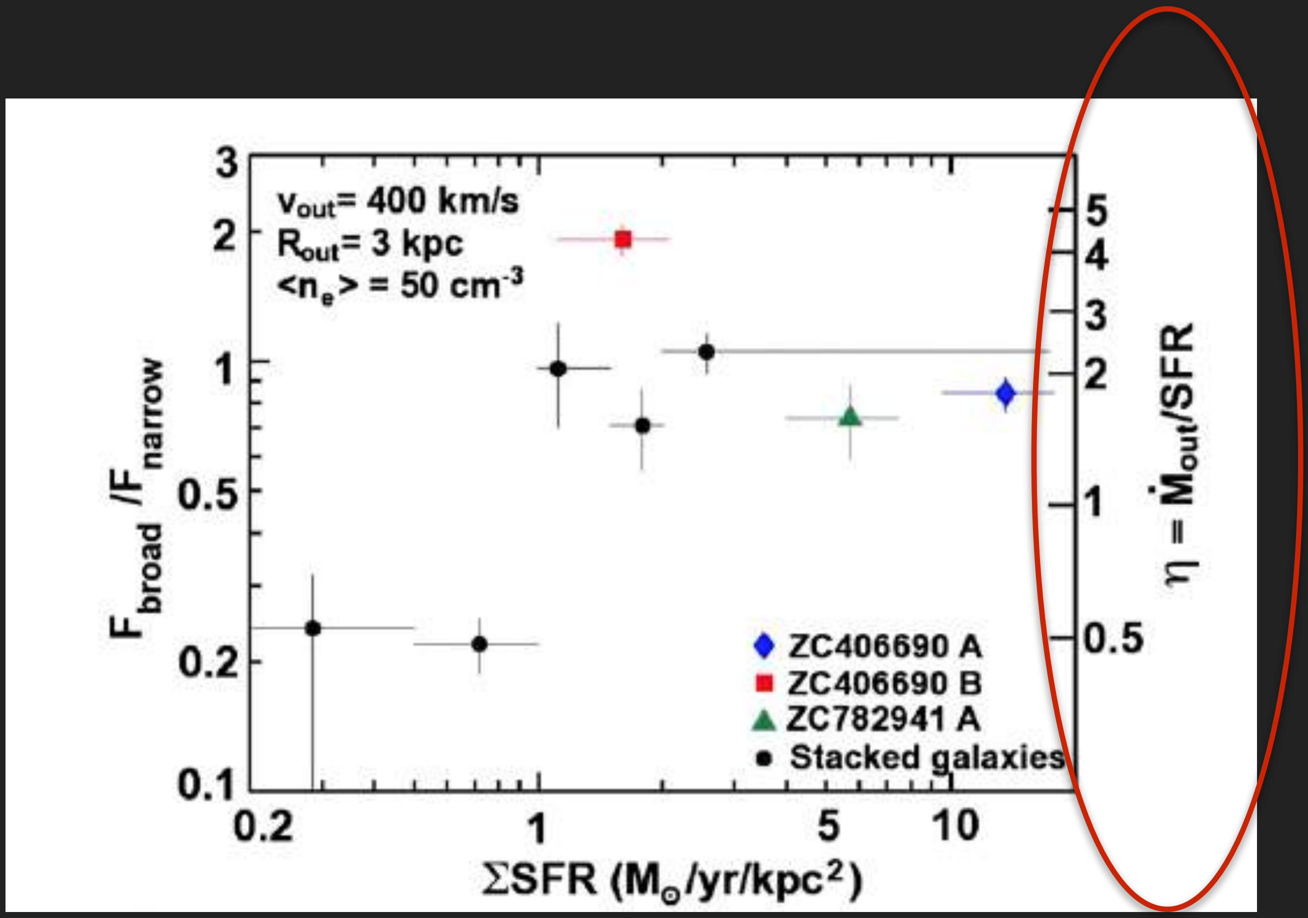


Madau & Dickinson 2014

Mass-loaded galactic winds are detected in star-forming galaxies, carrying up to ~300-500 Mo/yr in Local (Martin1999; Rubin+2014) and high redshift universe (e.g.Martin+2013).

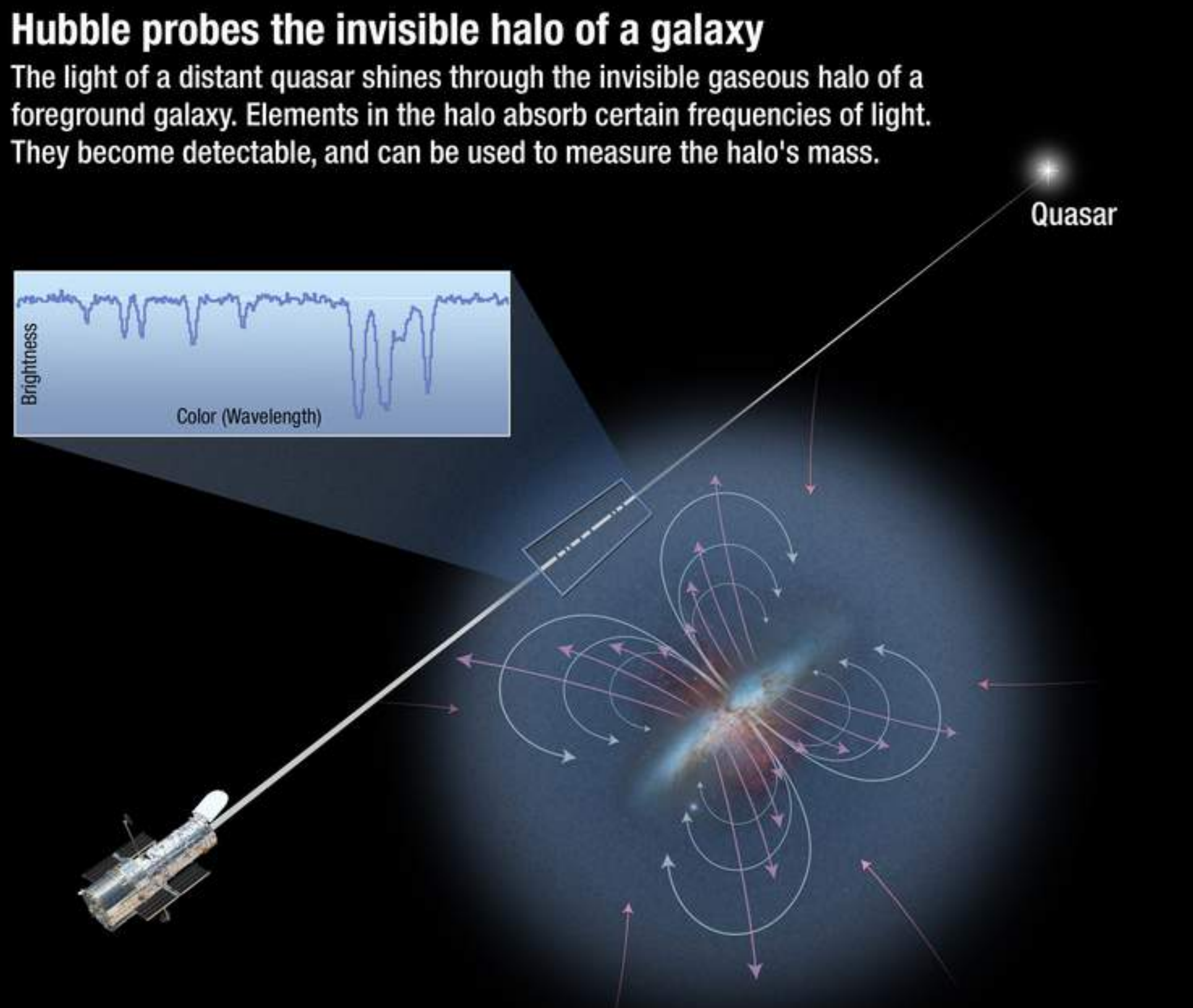


z~0; Martin 1999



z~2; Newman 2012

Galactic wind can be also AGN-driven (e.g. Genzel+2014)



Enriched mass-loaded winds:

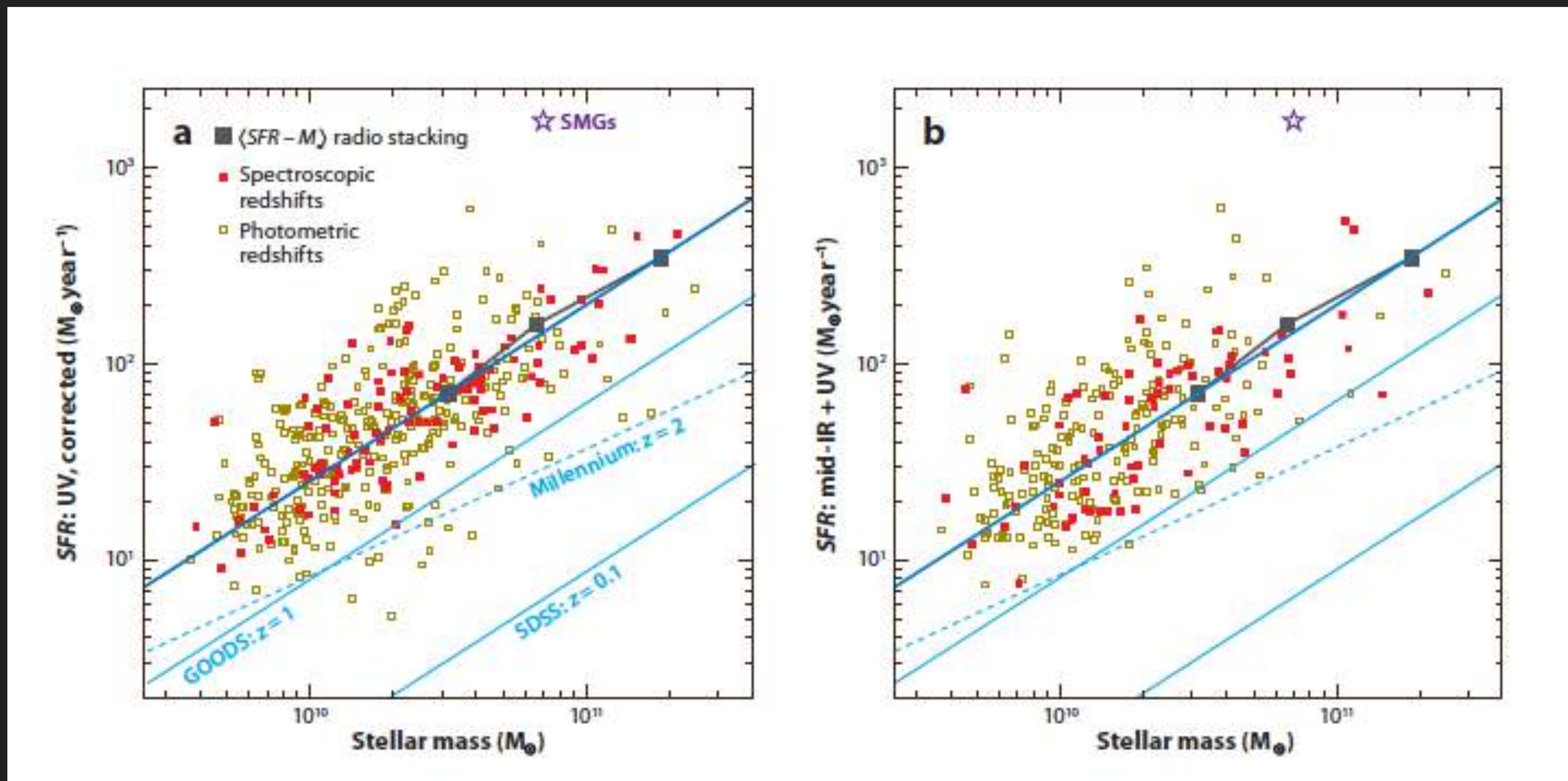
enriching of the CGM/ICM

contribute to galactic fountain

COS-Halo survey
Tumilson+2011
Borthakur-201

EVOLUTION OF THE GAS FRACTION AND SFR

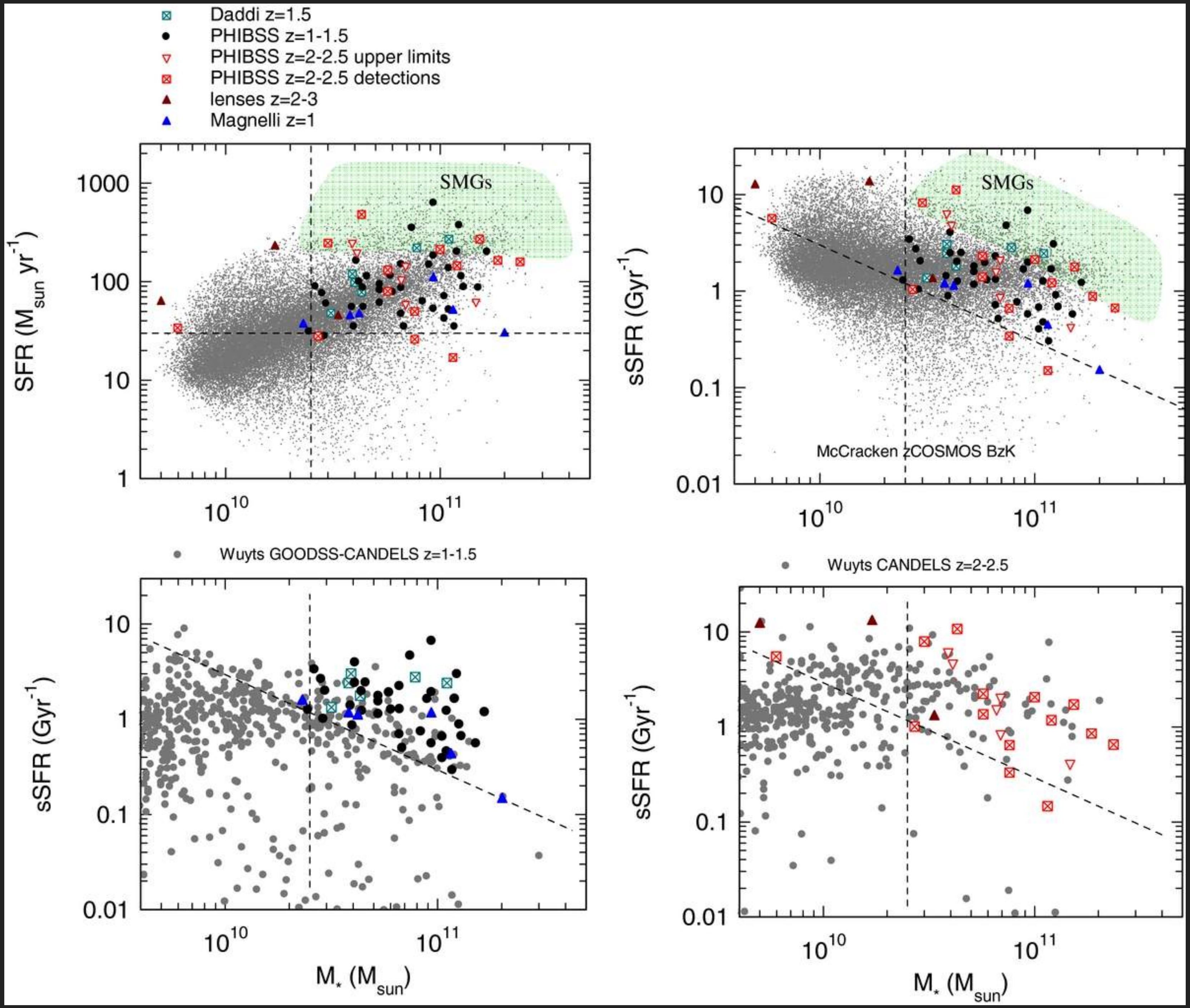
Daddi +2007



Star formation-M_{star} sequence for galaxies at different redshift (blue lines, Elbaz+2007)

At a given stellar mass, galaxies are more actively forming stars and are more gas-rich for higher redshift.

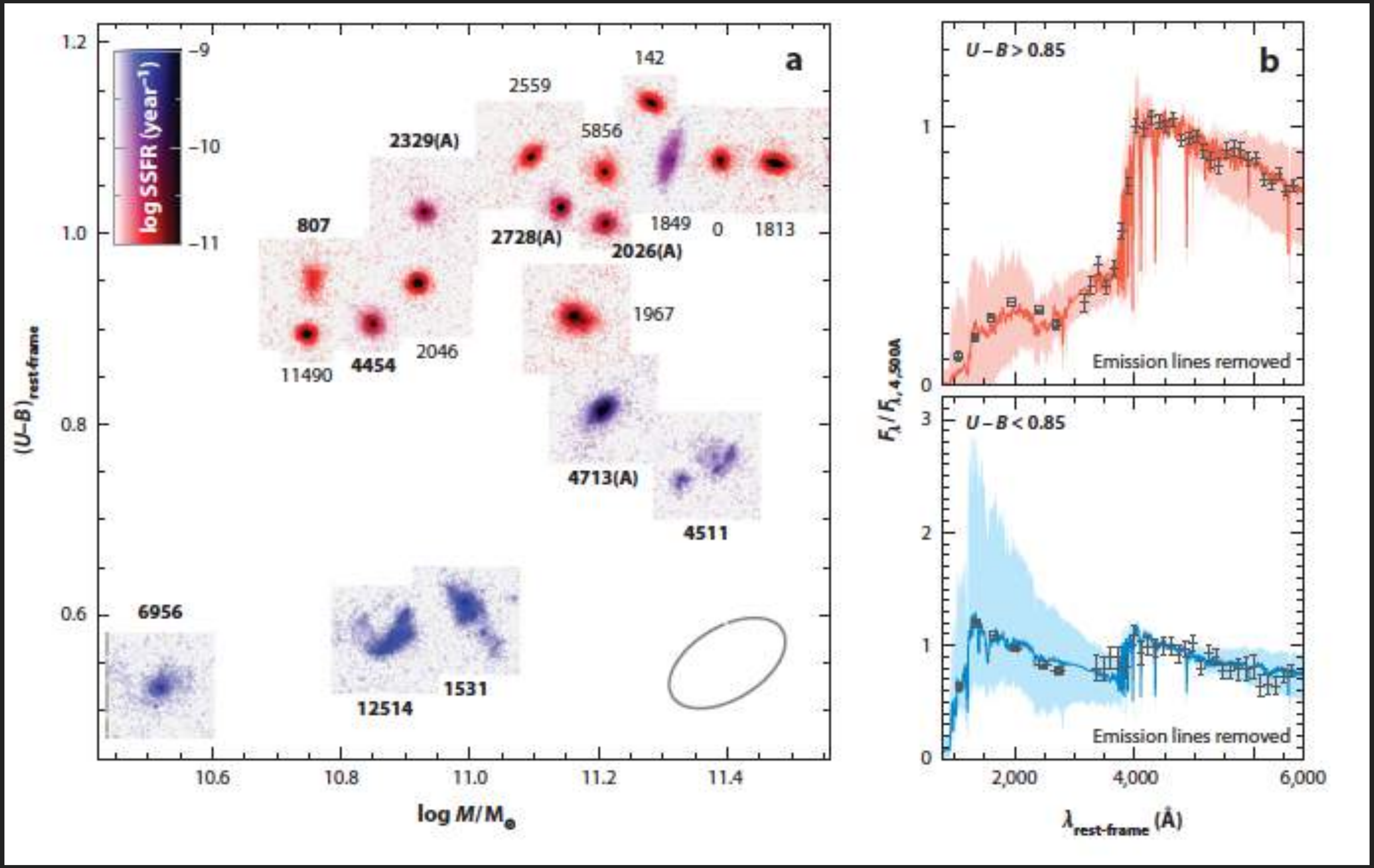
Tacconi+2013



The increase in star formation rate —> increasing gas fraction 50 % at z ~2 (e.g. Daddi+2010).

Submillimiter star forming galaxies (SMGs) at z=1-4

Shapley 2011

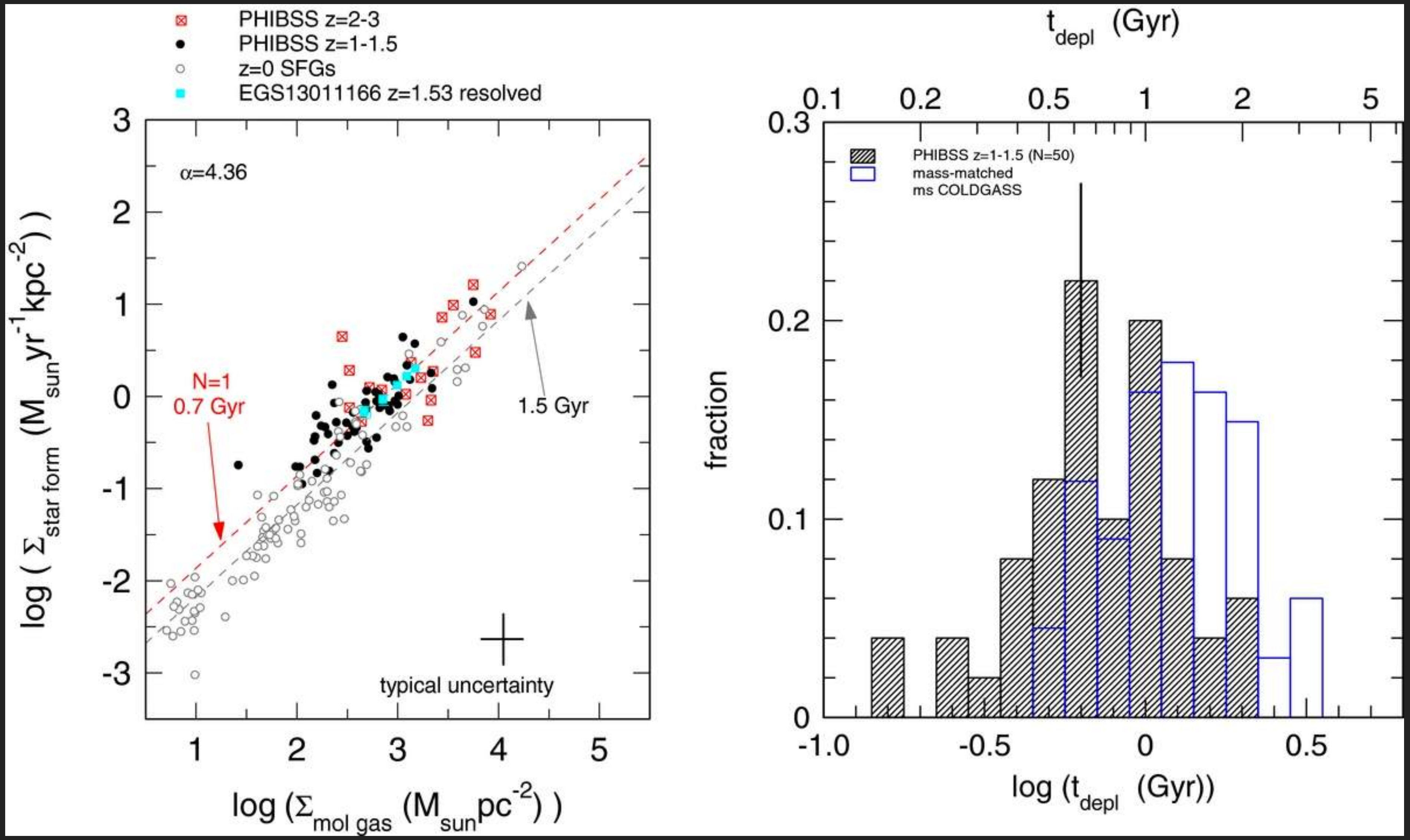


U-B versus M_{star}
A: AGN activity

Large, clumpy irregular galaxies reside mainly in the blue cloud.

Compact, quiescent galaxies lie on a red sequence.

Tacconi+2013



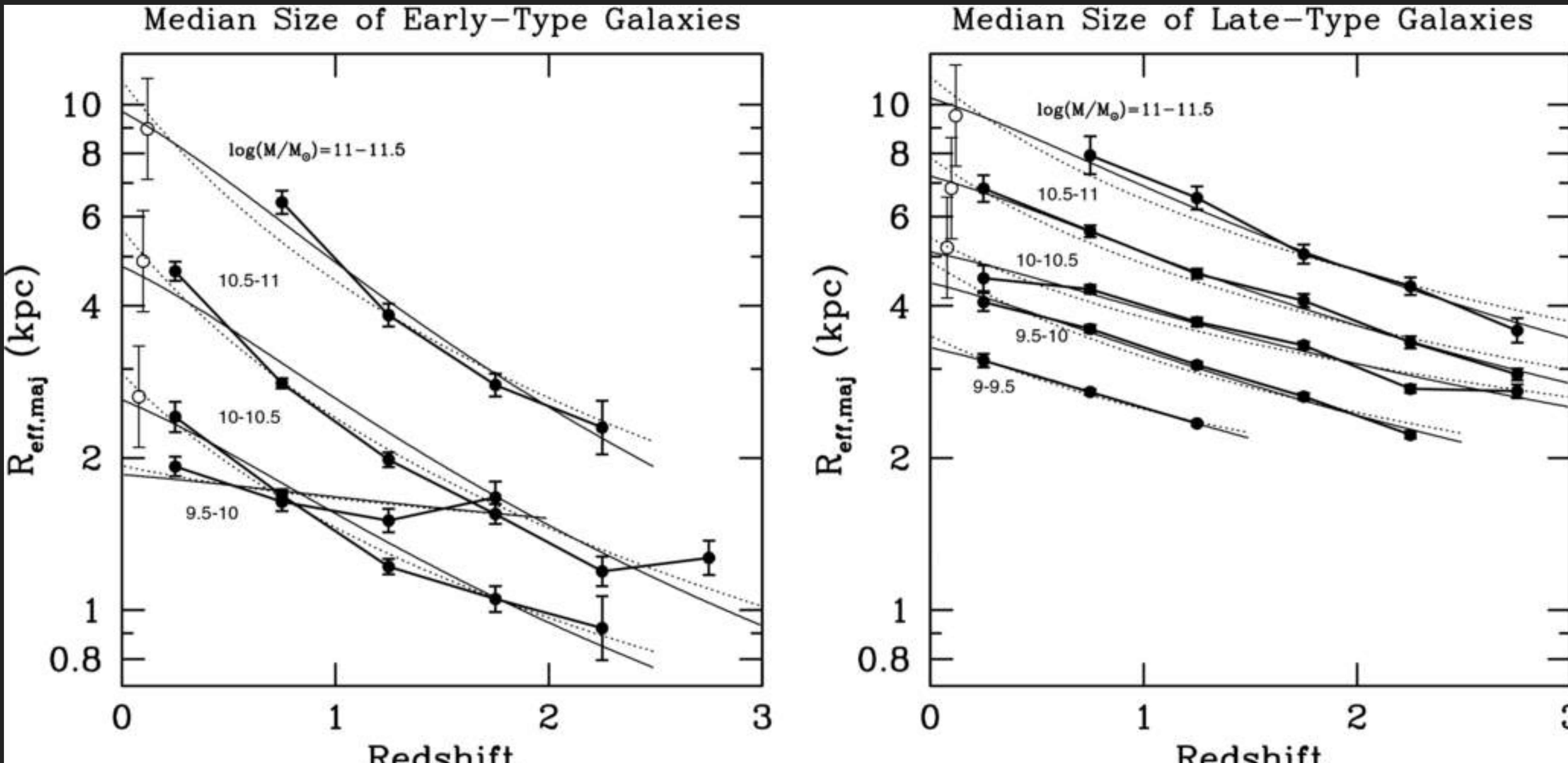
Kennicutt-Schmit (KS) law:

Grey points: KS law at z~0 (Kennicutt 1998; Garcia-Genzel+2010;Armus+2009)

Depletion times:

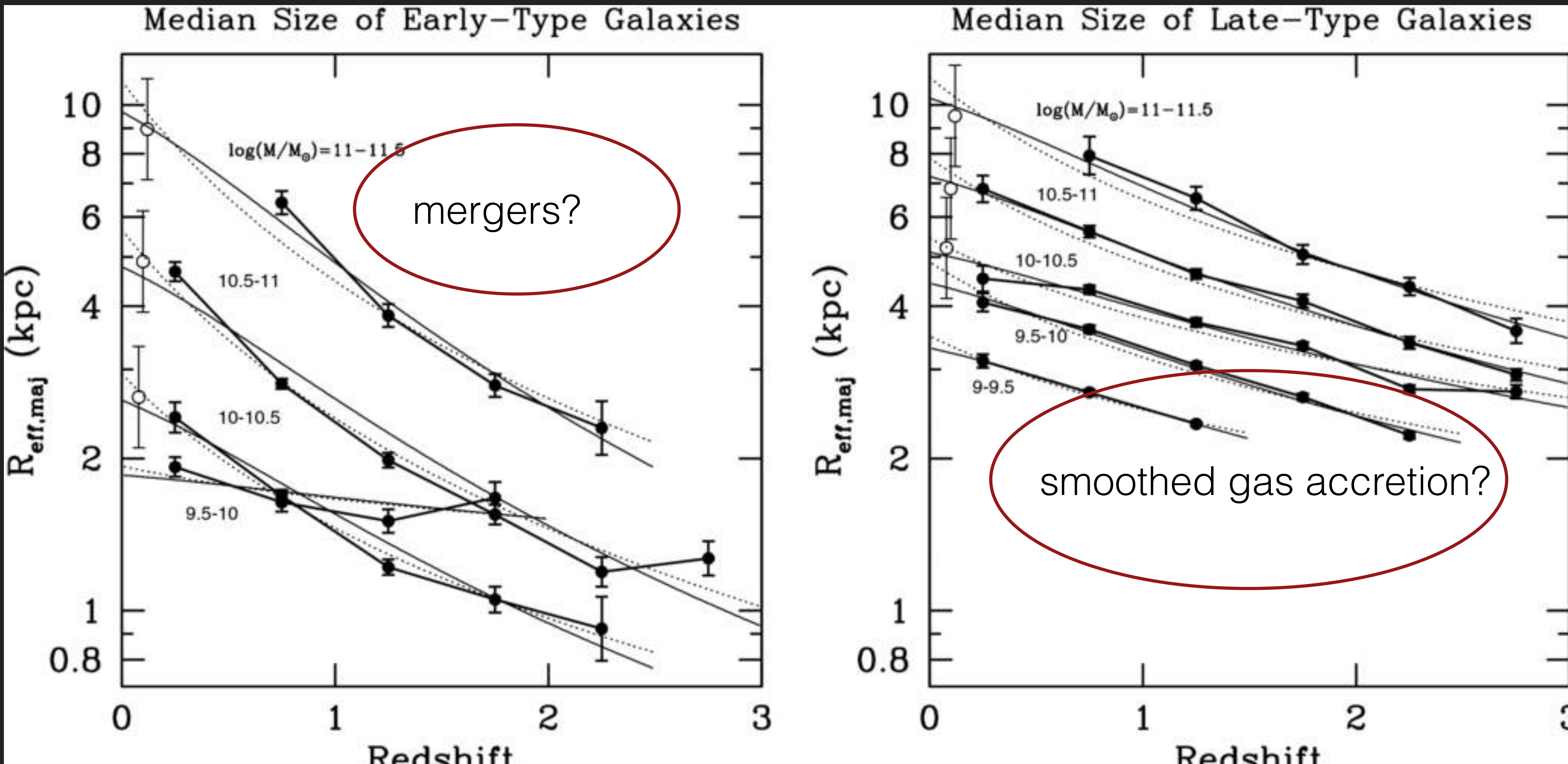
$t_{dep}= M_{molecular}/SFR$

z~1-3 —> t_{dep} =0.70 (0.34) Gyr
z~0 —> t_{dep} =1.24 (0.24) Gyr



Shapley 2011

THE EVOLUTION OF GALAXY SIZE



The evolution of the galaxy sizes from z~3 (van der Wel+2014) using 3D-HST+ CANDELS survey

The evolution of ETGs is stronger than for LTGS —> Different assembly histories.

Disc galaxies are common at high redshift but they are more turbulent and clumpy.

- The cosmic star formation history shows maximum activity at z~1-2 after an increasing rate at higher redshift and a strong decline at lower ones.
- Galaxies at higher redshift are gas-rich and have higher star formation rates. Main star formation sequences are identified: the regulation of the star formation rate is associated to the gas availability.
- At high z, discs are frequent and more disturbed and clumpy. The fraction of irregular galaxies increases as well the signs for mergers and interactions.
- Galaxies sizes evolve: at a given stellar mass, galaxies grow. The rate of grow is more pronounced for ellipticals. The size growth favours dry mergers as a possible formation mechanism after in situ formation phase.
- Supernova feedback and/or AGN feedback are important together with environmental effects. How do they work to establish self-regulated star formation activity?

There are still many aspects to understand in relation to triggering/regulation/quenching of star formation and the connection with morphology.