Ciências ULisboa

Complementary Astrophysics

L5 - Scaling Relations

Evaluation Criteria

0.6 - Laboratory

0.4 - Exam

Laboratory Evaluation

Based on the work you do week after week:

0.35 = Practical Assignments: Laboratory

0.15 = Written Assignments: Resolution of exercise (the procedure that is chosen to solve them)

0.1 = Participation in the class

Exam

The final exam is done at the end and consists of:

0.4 = a short test about topics of the course

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Assignments - General concepts

1. The absolute magnitude of the Sun through a B filter is $\mathrm{M}_B = 5.48$.
   Estimate the apparent magnitude from Earth.
2. The flux density for an object with $m_B = 0$ is $f_B = 4000 \times 10^{-26}$ W m^{-2} Hz^{-1}.
   Estimate the flux density of the Sun through a B filter.

1.1 Solution Assignments

1. The formula for the absolute magnitude is:

$$M = m - 5 \cdot log_{10}(D_{pc}) + 5 \tag{1}$$

where m is the apparent magnitude and D_{pc} is the object distance in parsec. From this we derive the formula for the apparent magnitude at the Sun-Earth distance d_{SH} (NB - d_{SH} must be expressed in parsec to be consistent with the definition of absolute magnitude):

$$m = M + 5 \cdot log_{10}(d_{SH}) - 5 \tag{2}$$

The parameter d_{SH} is derived assuming a distance between the Sun and the Earth of 150 millions of km, c = 3 $\times 10^5$ km/s and the conversion factor parsec-light year 1 pc = 3.26 ly.

To travel 150$\times 10^6$ km light takes 1.5e8 [km]/3e5 [km/s] $\approx$ 500 s $\sim$ 8.3 minutes $\sim 8.3/(60 \times 24 \times 365) \sim 1.58 \times 10^{-5}$ year.

To convert in parsec we divide for 3.26: $1.58 \times 10^{-5}/3.26 = 4.84 \times 10^{-6}$ pc

From this:

$$m = 5.48 + 5 \cdot log_{10}(4.84 \times 10^{-6}) - 5 = -26.09 \sim -26 \;\; in\ B\ filter \tag{3}$$

which is bright (remember that the logarithmic scale of magnitudes are negative). Maybe it is the brightest object in the sky?

2. the solution follows directly from the definition of magnitude and the previous calculation of the apparent magnitude of the Sun ($m_\odot$ = -26):

$$m_\odot - m_B = -2.5 \cdot log_{10}\left(\frac{F_\odot}{F_B}\right) \tag{4}$$

In particular, $m_B = 0$ corresponds to the so-called 'Vega' system where Vega is the reference star for the zero point, having by definition $m_B = m_V = 0$. Nowadays there is a more stable system (AB) which consider as zero point the flux measured along all the pass band when a source of constant flux of 3631 Jy is observed (1 Jy = 10^{-26} W m^{-2} Hz^{-1}).

From Eq. 4 follows:

$$F_\odot = F_B \cdot 10^{-0.4 \cdot (m_\odot - m_B)} = 4 \times 10^{-23} \cdot 10^{-0.4 \cdot (-26)} = 10^{-12} \quad \mathrm{W/m^2/Hz} \tag{5}$$

What did we learn?

What did we learn?

1. What is galaxy kinematics
2. How DM was discovered
3. Galaxy Formation theory
4. Physical parameters from spectral analysis

Highlights

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Highlights

JWST/NIRSpec Measurements of the Relationships Between Nebular Emission-line Ratios and Stellar Mass at $z \sim 3-6$

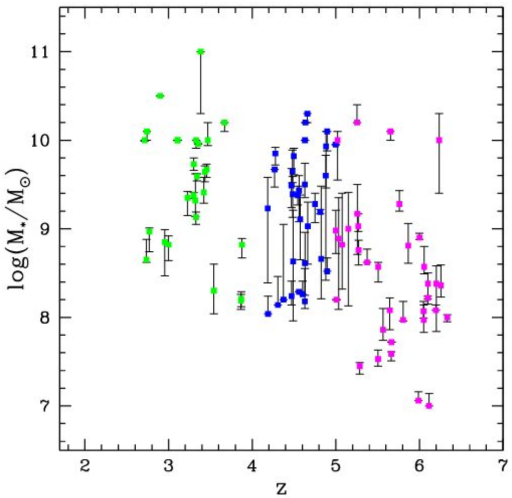
Alice E. Shapley,[1] Naveen A. Reddy,[2] Ryan L. Sanders,[3,*] Michael W. Topping,[4] and Gabriel B. Brammer[5,6]

[1]*Department of Physics & Astronomy, University of California, Los Angeles, 430 Portola Plaza, Los Angeles, CA 90095, USA*
[2]*Department of Physics & Astronomy, University of California, Riverside, 900 University Avenue, Riverside, CA 92521, USA*
[3]*Department of Physics and Astronomy, University of California, Davis, One Shields Ave, Davis, CA 95616, USA*
[4]*Steward Observatory, University of Arizona, 933 N Cherry Avenue, Tucson, AZ 85721, USA*
[5]*Cosmic Dawn Center (DAWN), Denmark*
[6]*Niels Bohr Institute, University of Copenhagen, Lyngbyvej 2, DK2100 Copenhagen Ø, Denmark*

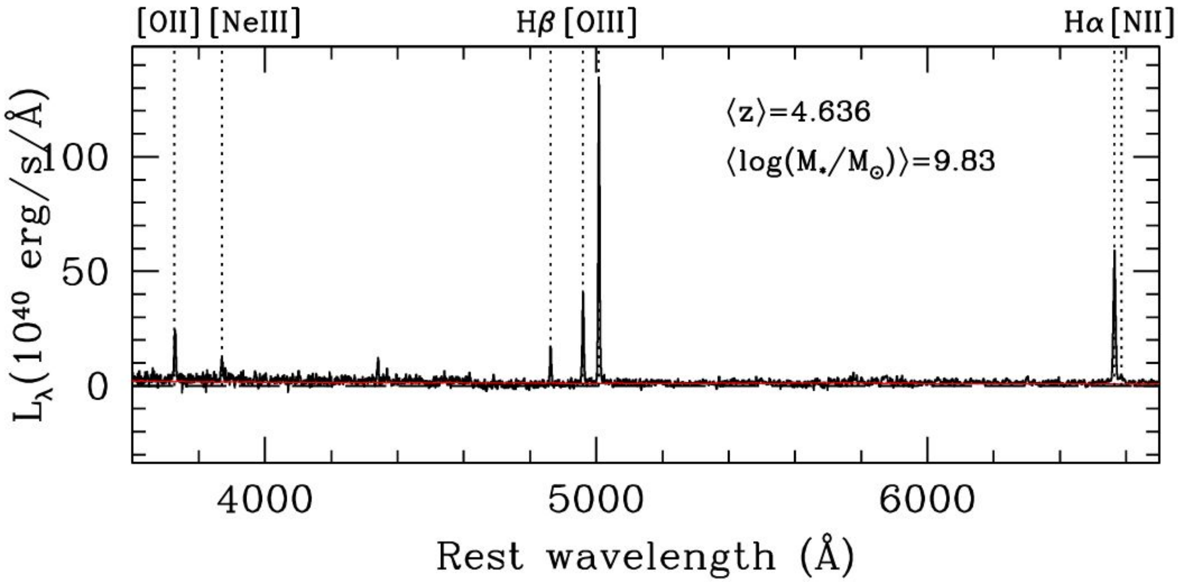
ABSTRACT

We analyze the rest-optical emission-line ratios of star-forming galaxies at $2.7 \leq z < 6.5$ drawn from the Cosmic Evolution Early Release Science (CEERS) Survey, and their relationships with stellar mass (M_*). Our analysis includes both line ratios based on the [NII]λ6583 feature – [NII]λ6583/Hα, ([OIII]λ5007/Hβ)/([NII]λ6583/Hα) (O3N2), and [NII]λ6583/[OII]λ3727 – and those those featuring α elements – [OIII]λ5007/Hβ, [OIII]λ5007/[OII]λ3727 (O_{32}), ([OIII]$\lambda\lambda$4959,5007+[OII]λ3727)/Hβ (R_{23}), and [NeIII]λ3869/[OII]λ3727. Given the typical flux levels of [NII]λ6583 and [NeIII]λ3869, which are undetected in the majority of individual CEERS galaxies at $2.7 \leq z < 6.5$, we construct composite spectra in bins of M_* and redshift. Using these composite spectra, we compare the relationships between emission-line ratios and M_* at $2.7 \leq z < 6.5$ with those observed at lower redshift. While there is significant evolution towards higher excitation (e.g., higher [OIII]λ5007/Hβ, O_{32}, O3N2), and weaker nitrogen emission (e.g., lower [NII]λ6583/Hα and [NII]λ6583/[OII]λ3727) between $z \sim 0$ and $z \sim 3$, we find in most cases that there is no significant evolution in the relationship between line ratio and M_* *beyond* $z \sim 3$. The [NeIII]λ3869/[OII]λ3727 ratio is anomalous in showing significant elevation at $4.0 \leq z < 6.5$ at fixed mass, relative to $z \sim 3.3$. Collectively, however, our empirical results suggest that there is no significant evolution in the mass-metallicity relationship at $2.7 \leq z < 6.5$. Metallicity calibrations based on existing and upcoming *JWST*/NIRSpec observations will be required to translate these empirical scaling relations into ones tracing chemical enrichment and gas cycling, and distinguish among the descriptions of star-formation feedback in simulations of galaxy formation at $z > 3$.

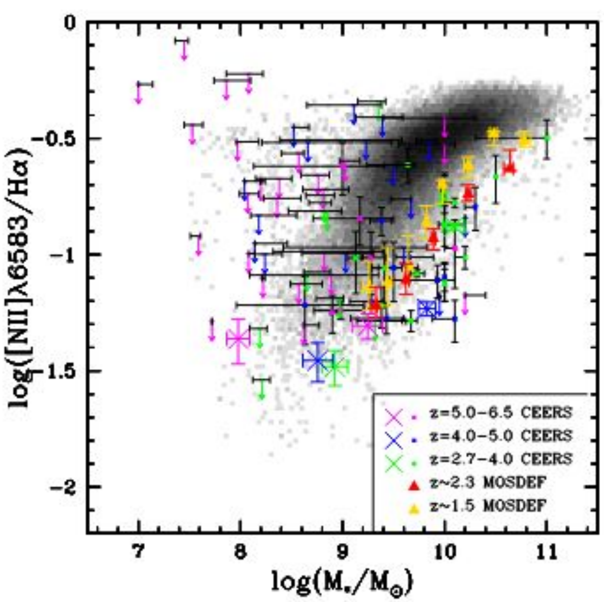
Highlights



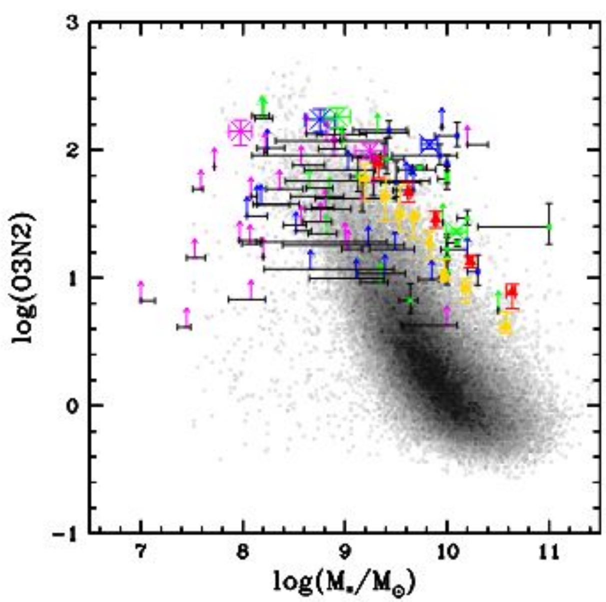
log(M*/M⊙)
z



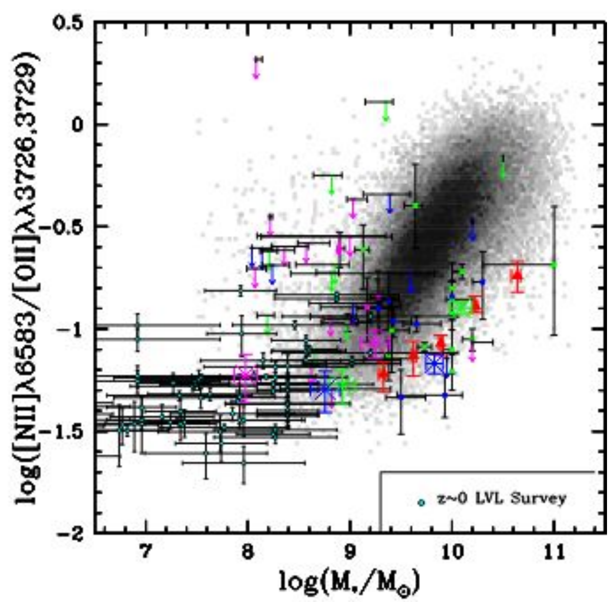
[OII] [NeIII]
Hβ [OIII]
Hα [NII]
⟨z⟩=4.636
⟨log(M*/M⊙)⟩=9.83
Lλ(10^40 erg/s/Å)
Rest wavelength (Å)



log([NII]λ6583/Hα)
log(M*/M⊙)
z=5.0−6.5 CEERS
z=4.0−5.0 CEERS
z=2.7−4.0 CEERS
z~2.3 MOSDEF
z~1.5 MOSDEF



log(O3N2)
log(M*/M⊙)



log([NII]λ6583/[OII]λλ3726,3729)
log(M*/M⊙)
z~0 LVL Survey

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Outline of the course

1. History
2. Review of the general concepts
3. Galaxies in our local Universe
4. Galaxies kinematics
5. **Scaling relations**

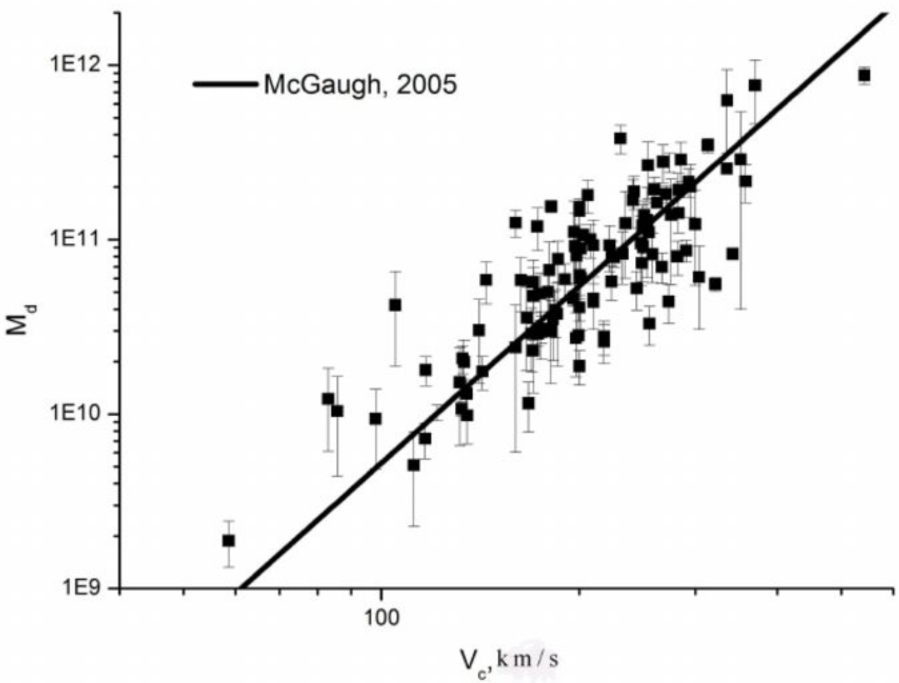
Scaling relations

Spirals: Tully Fisher

It is an empirical relationship between the luminosity (or absolute magnitude) and the rotation velocity of spiral galaxies.

The intrinsic luminosity of a spiral galaxy is directly proportional to its maximum rotation velocity. This means that the more massive a galaxy is, the faster it rotates and the brighter it appears.

It provides a way to estimate the distances to galaxies based on their rotation velocities.



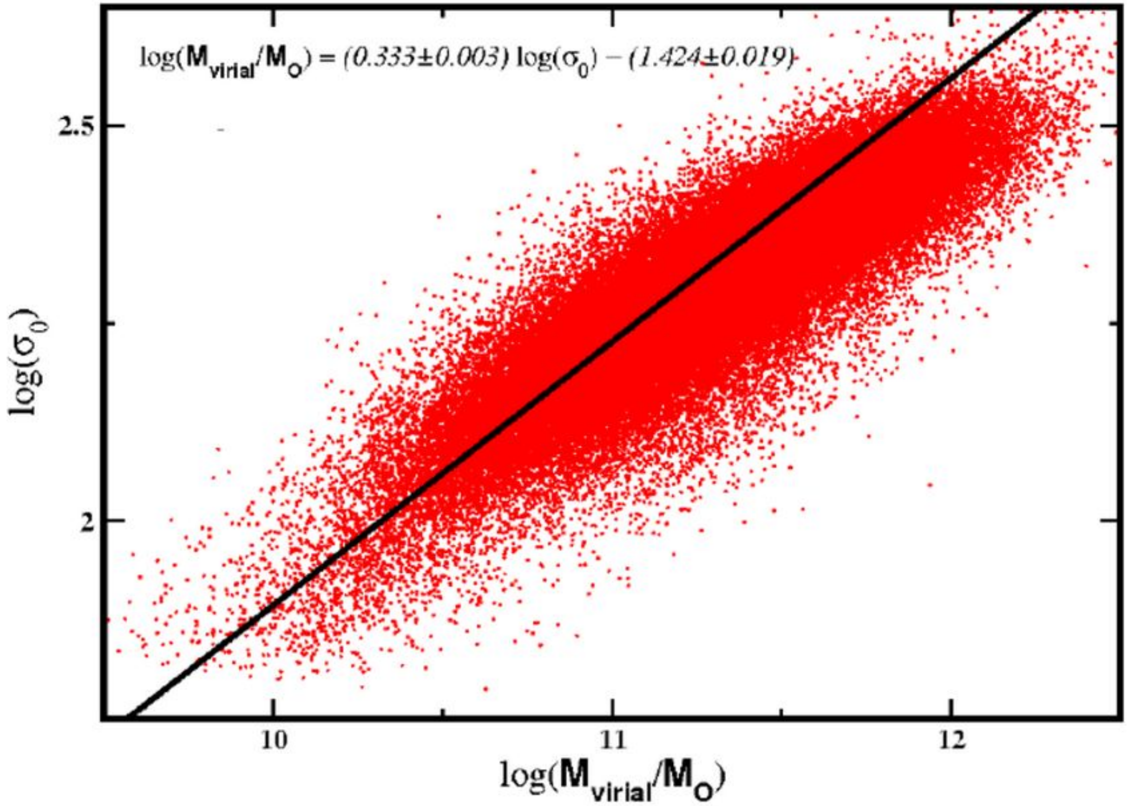
Scaling relations

Ellipticals: Faber & Jackson (FJR)

Correlation between the luminosity L and the central stellar velocity dispersion σ of elliptical galaxies.

- $L \propto \sigma^{\gamma}$: → with $\gamma = 4$

Connect a galaxy's mass, luminosity, and its internal dynamics → these properties are coupled during galaxy formation and evolution.



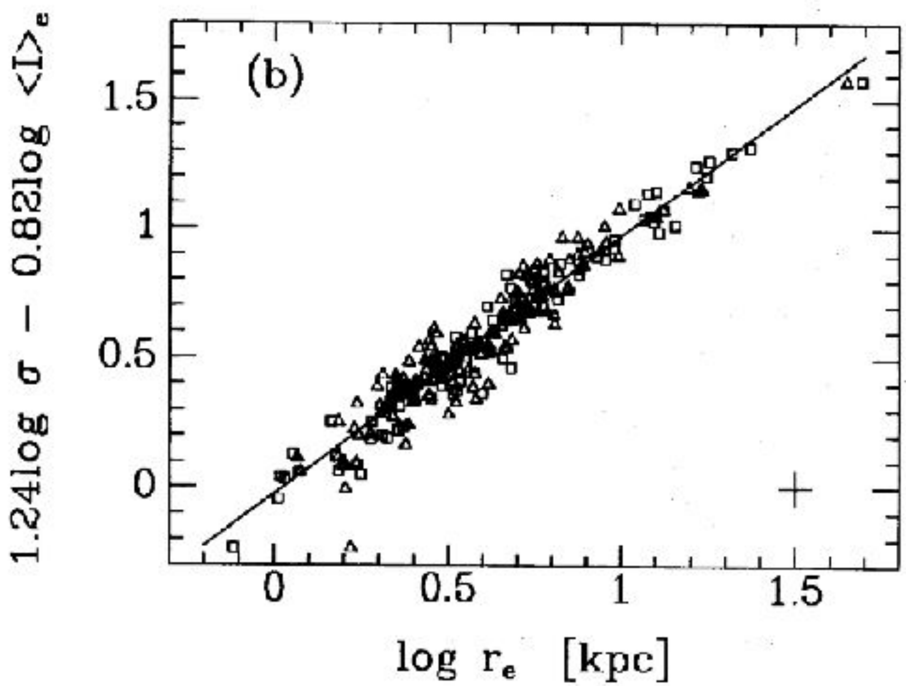
Scaling relations

Ellipticals: Fundamental Plane (FP)

The FJR has a significant correlation of its residuals with galaxy size, with smaller galaxies having lower velocity dispersion. In other words, there is a further correlation, that can be combined with the FJR to reduce the scatter: this is called **Fundamental Plane**

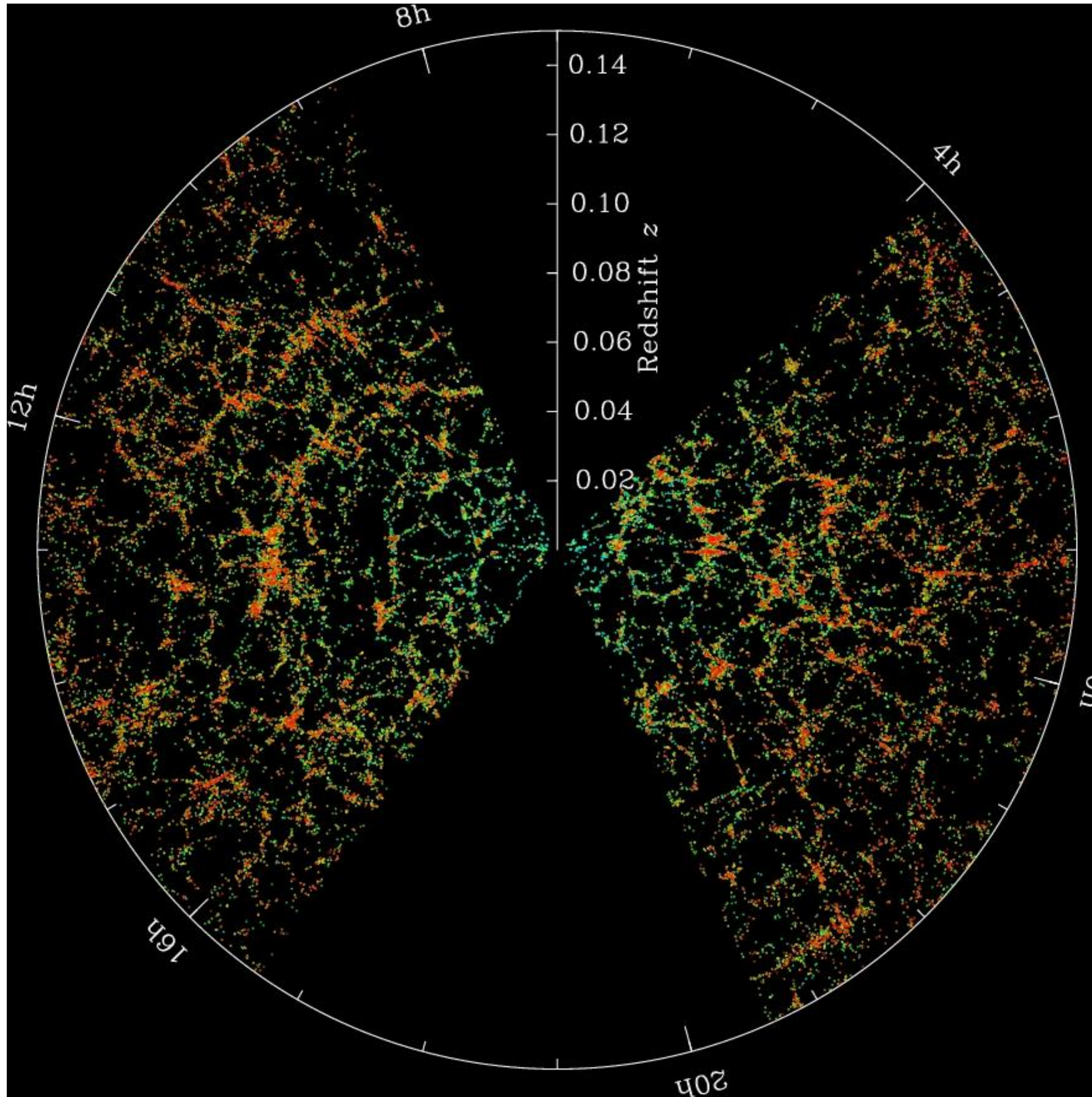
The internal motion of a galaxy depends strongly on the shape and size of its dark matter halo -> the FP gives key insight on the connection between galaxies and their host haloes.

The fundamental plane reflects the balance between a galaxy's gravitational forces and its stellar motions, as described by the virial theorem, which relates kinetic and potential energy in gravitationally bound systems.



SDSS

The Sloan Digital Sky Survey or SDSS is a photometric and spectroscopic survey using a dedicated 2.5-m wide-angle optical telescope at Apache Point Observatory in New Mexico. The project observed more than 1 millions of galaxies: the main galaxy sample has a median redshift of z = 0.1; there are redshifts for luminous red galaxies as far as z = 0.7, and for quasars as far as z = 5; and the imaging survey has been involved in the detection of quasars beyond a redshift z = 6.

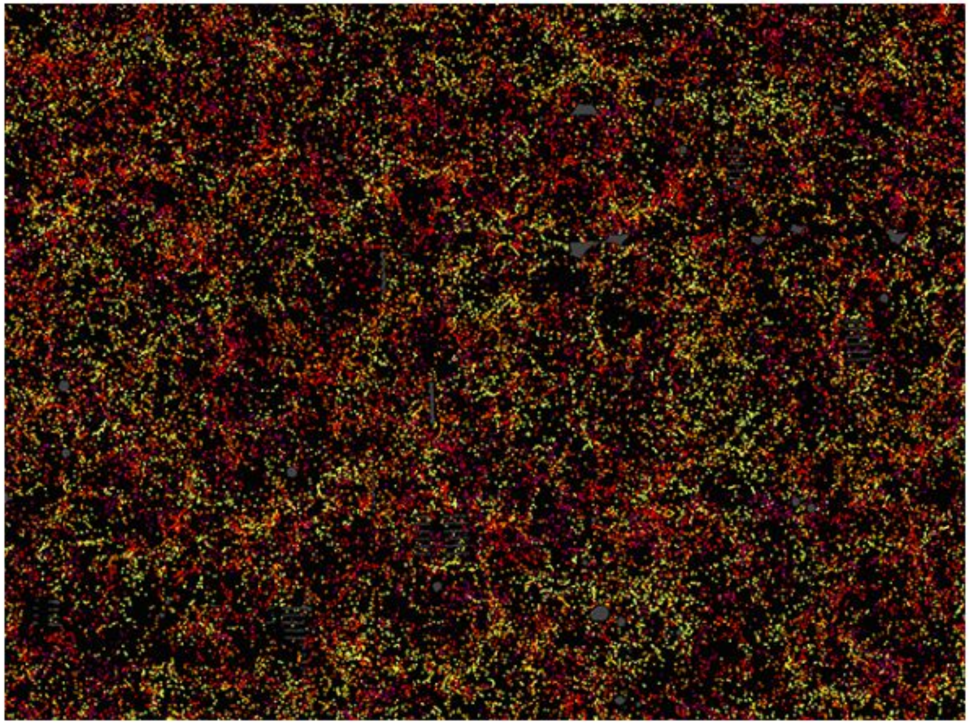


SDSS

Astronomers map a record-breaking 1.2 million galaxies to study the properties of dark energy

July 14, 2016

Astronomers announced this week the sharpest results yet on the properties of dark energy.



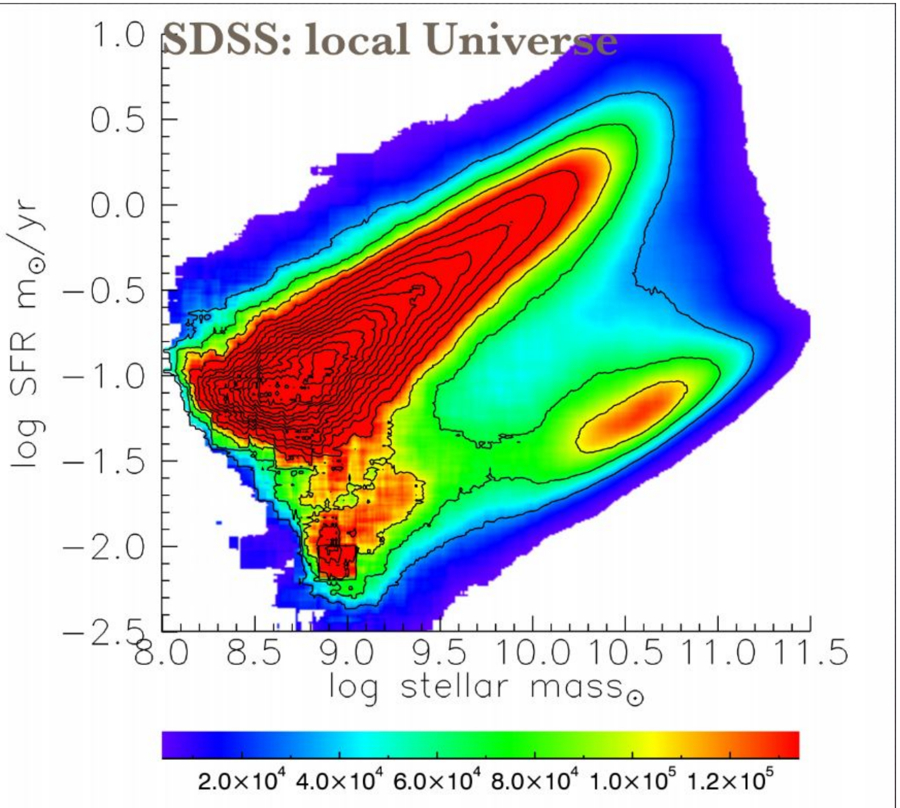
Hundreds of scientists from the Sloan Digital Sky Survey III (SDSS-III) collaborated to make the largest-ever, three-dimensional map of distant galaxies. The scientists then used this map to make one of the most precise measurements yet of the dark energy currently driving the accelerated expansion of the Universe.

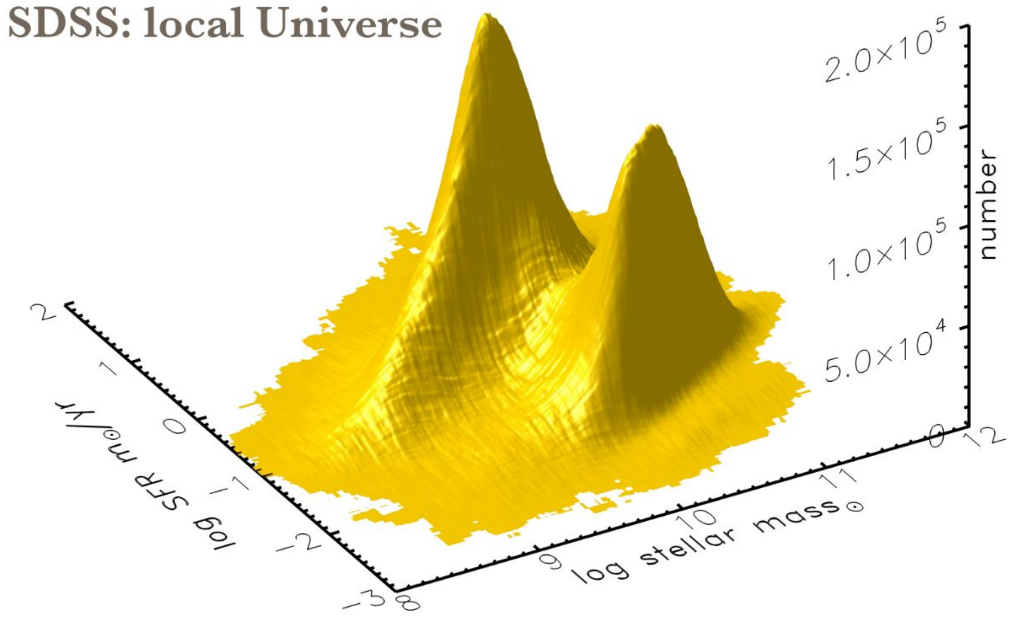
“We have spent a decade collecting measurements of 1.2 million galaxies over one quarter of the sky to map out the structure of the Universe over a volume

Main Sequence

Relationship between a galaxy's star formation (SFR) and its stellar mass (M_*).
- Main sequence galaxy fits the relationship
- Starburst galaxies have higher SFR but still correlate with stellar mass.
- Some gas-poor galaxies (quenched galaxies) form the red sequence
- Between the main sequence galaxies and the quenched galaxies there is the green valley, populated by a mixed population.

Galaxies in the (star forming) main sequence are bluer and the quenched galaxies are redder (blue galaxies and red galaxies).





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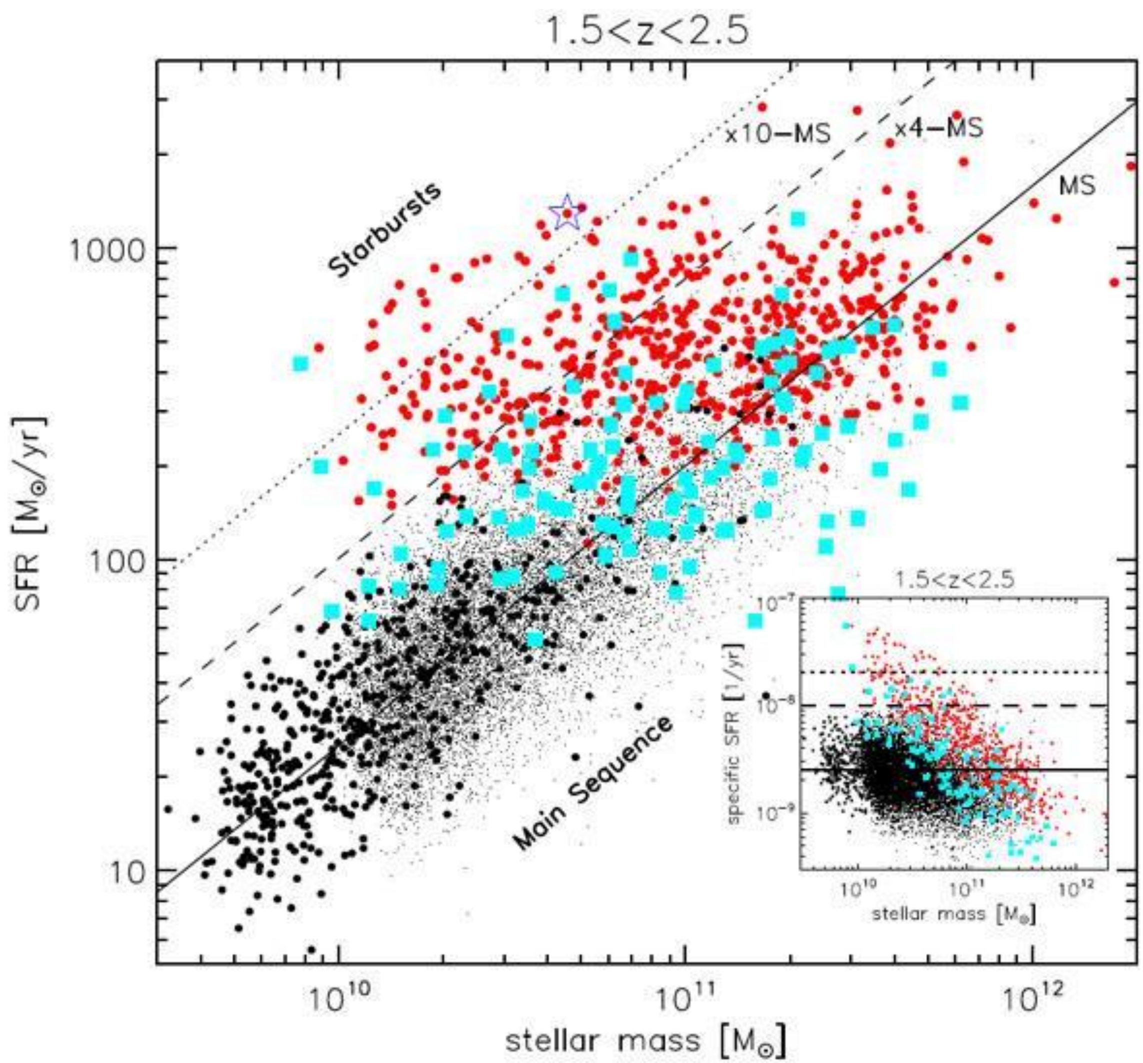
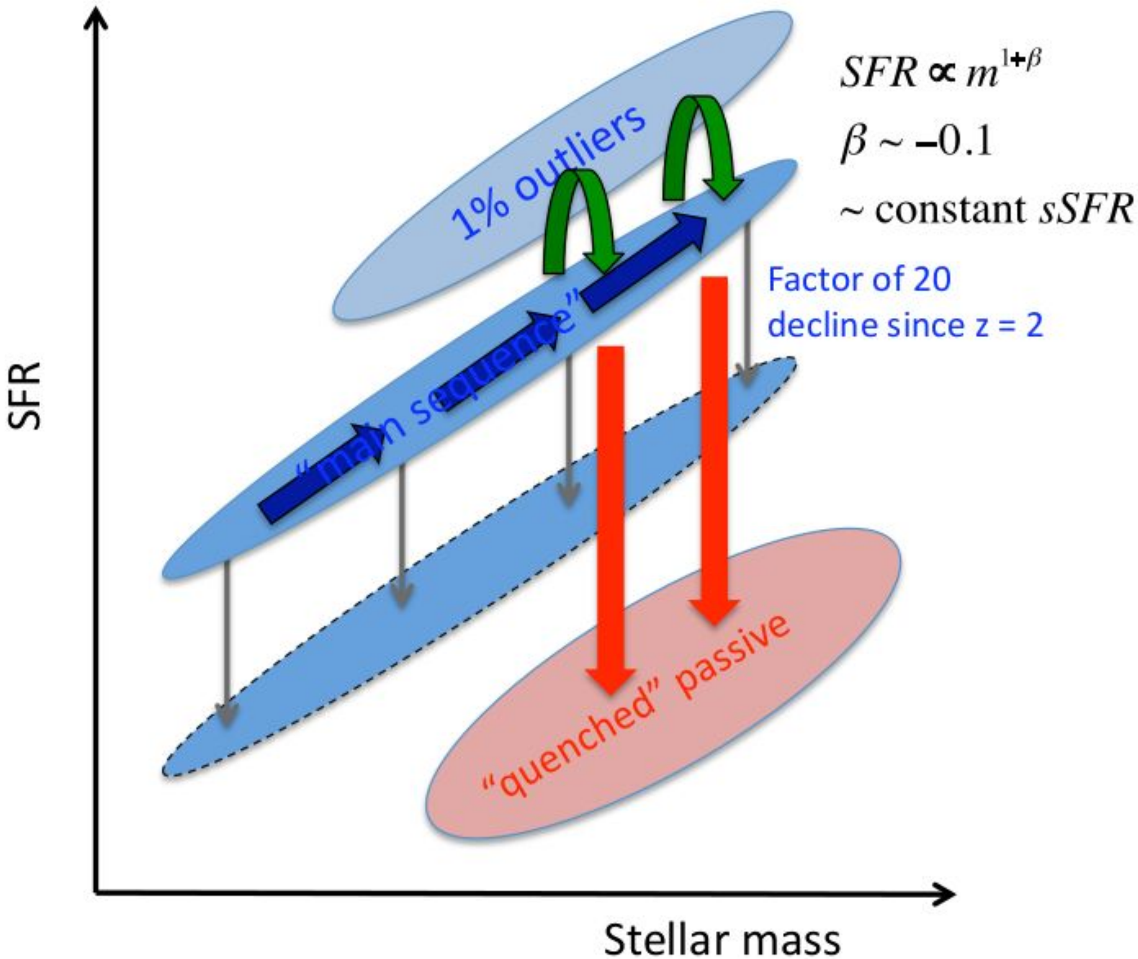


Main Sequence



Some key questions in galaxy evolution:

- What quenches star-formation in some galaxies?
- What controls the evolution of $sSFR_{MS}$?
- What is relative contribution of mass increase due to mergers? i.e. sMMR vs sSFR
- What is the link with central black holes?
- What is the link to structure and morphology

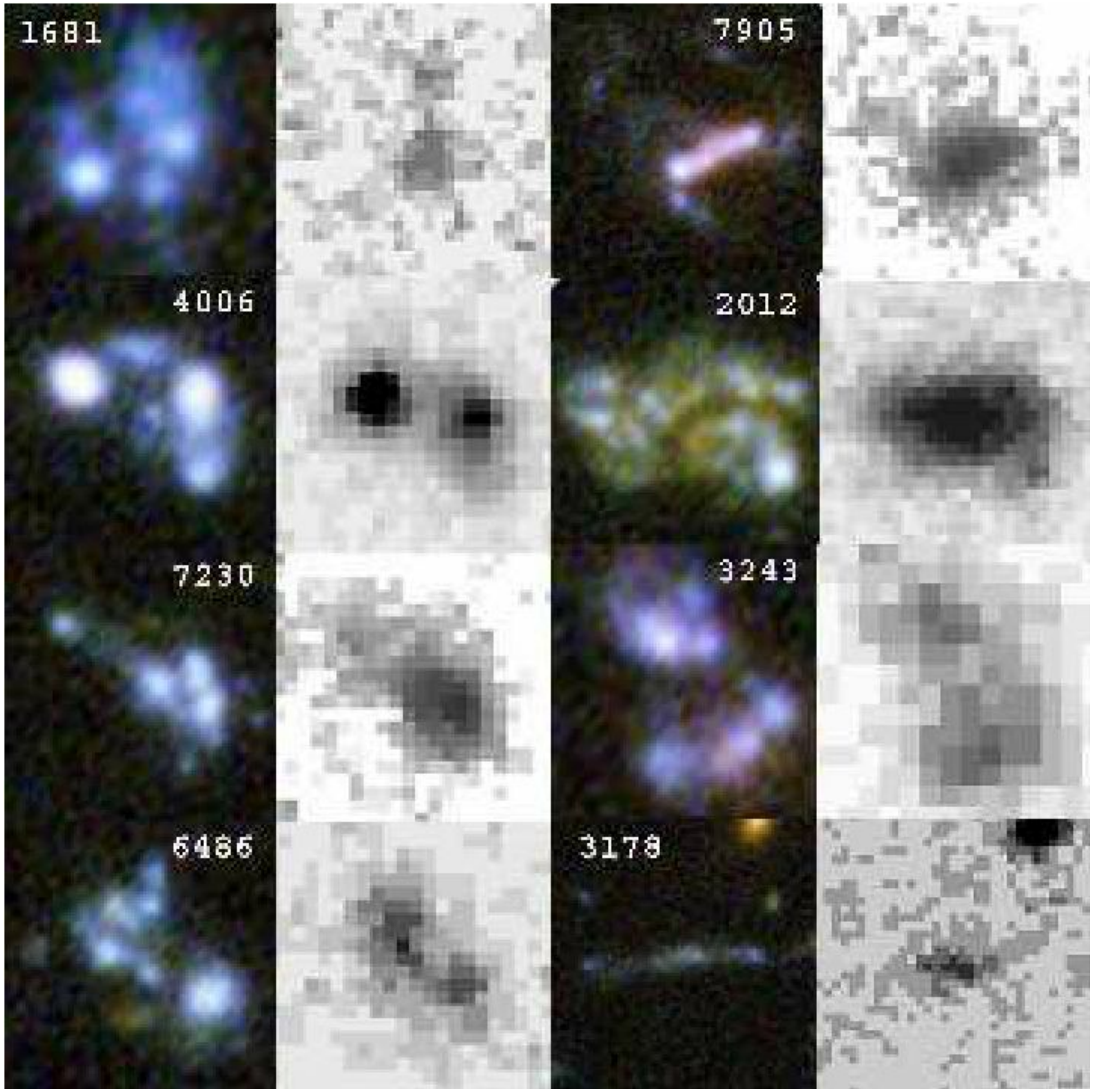
Main Sequence

- Up to the z~2 main sequence SFGs have disky, exponential profiles. This despite the often clumpy and irregular appearance of z>1 SFGs in the rest-frame UV.

- The majority of massive ($\log M^*/M_o$)>10)SFG sare rotationally supported disks.

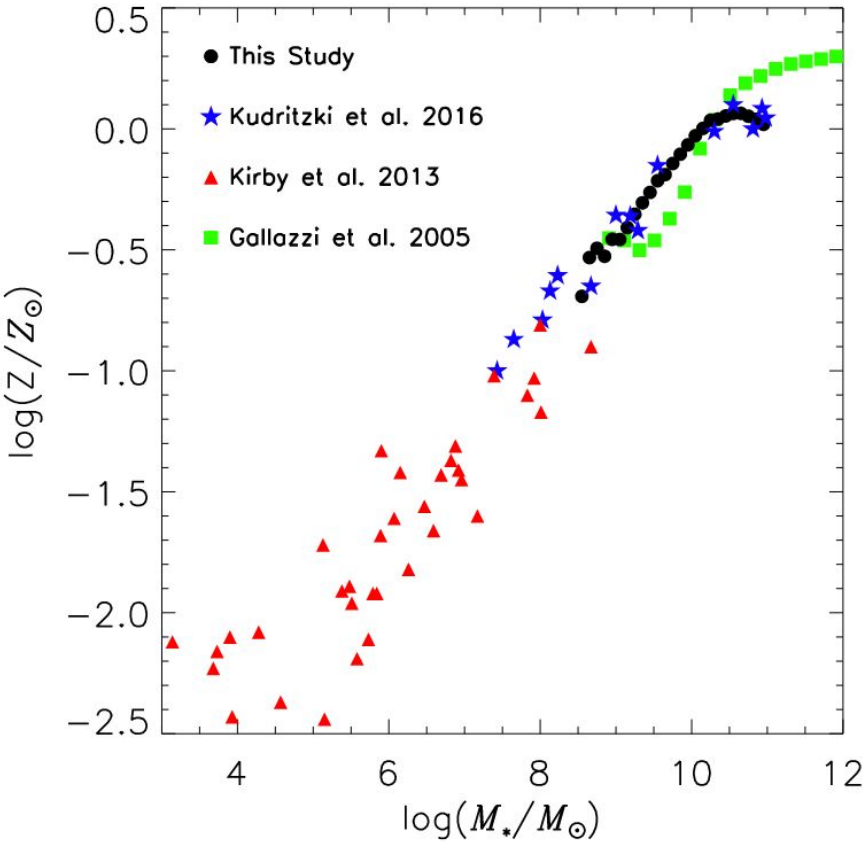
- At higher z low mass galaxies still don't have reached the dynamical equilibrium, and for this reason the fraction of low mass SFGs with 'dispersion' dominated kinematics increases.

- The tightness and constant shape of the MS sugges that star forming galaxies grow along the sequence in an equilibrium of gas accretion,star formation and gas outflows.



Mass-Metallicity (Stars)

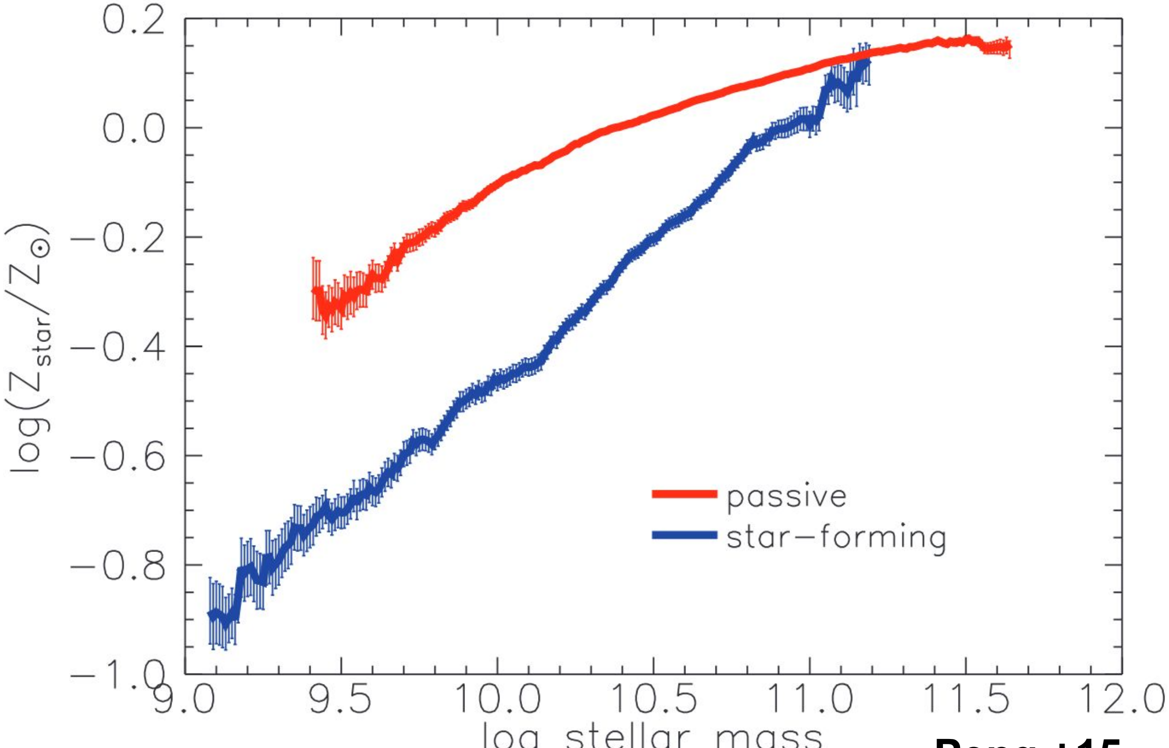
- Discovered in local ellipticals by studying color-magnitude diagrams and stellar spectroscopy (McClure & van den Bergh, 1968)
- Interpreted as the result of chemically-enriched SN winds preferentially ejecting metals from low mass galaxies, due to their shallower gravitational potential well (Tinsley, 1974, 1978; Mould, 1984).
- Extensive SDSS spectroscopic investigation derived stellar MZR of local galaxies, both quiescent and star forming. A clear MZR is seen, with metallicity increasing with mass



Zahid+17

Mass-Metallicity (Stars)

- The stellar metallicity properties of quiescent and star-forming galaxies depend strongly on the so-called "strangulation" or, more generally,"starvation".
- Strangulation Is the suppression of gas accretion due to dynamical or physical processes. Once halted the infall, the galaxies evolve as closed system reducing gas fraction, as an effect of the residual star formation, and producing stars with higher metallicities, as a consequence of the lack of inflowing gas that dilutes the metallicity.
- In such a scenario higher metallicities are expected in quiescent (starved) galaxies with respect to star forming galaxies which are still experiencing infall (hence dilution) of metal-poor gas.

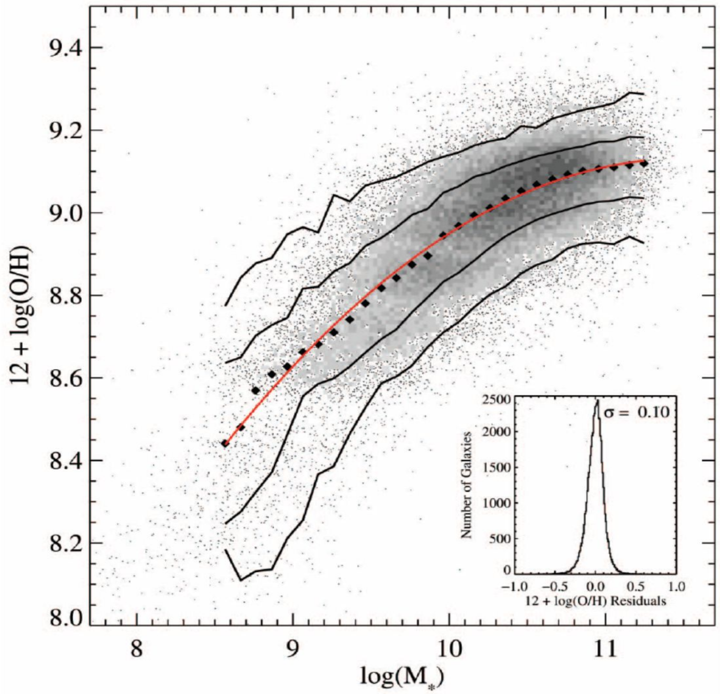


Peng +15

Mass-Metallicity (Gas)

- It is a tight correlation between stellar mass and metallicity spanning over 3 orders of magnitude in stellar mass and a factor of 10 in metallicity, obtained from the analysis of ~53,000 SDSS star-forming galaxies at z~0.1.

- The relation is steep from $10^{8.5}$ to $10^{10.5}$ M_* and flattens above $10^{10.5}$ Msolar.
- The flattens is assumed to be due to the galactic winds, effective in removing metals from the galaxy potential well, but the origin is still debated.
- The MZR constrain the role of outflows of pristine gas and enriched gas driven by feedback processes (SNe and AGN).

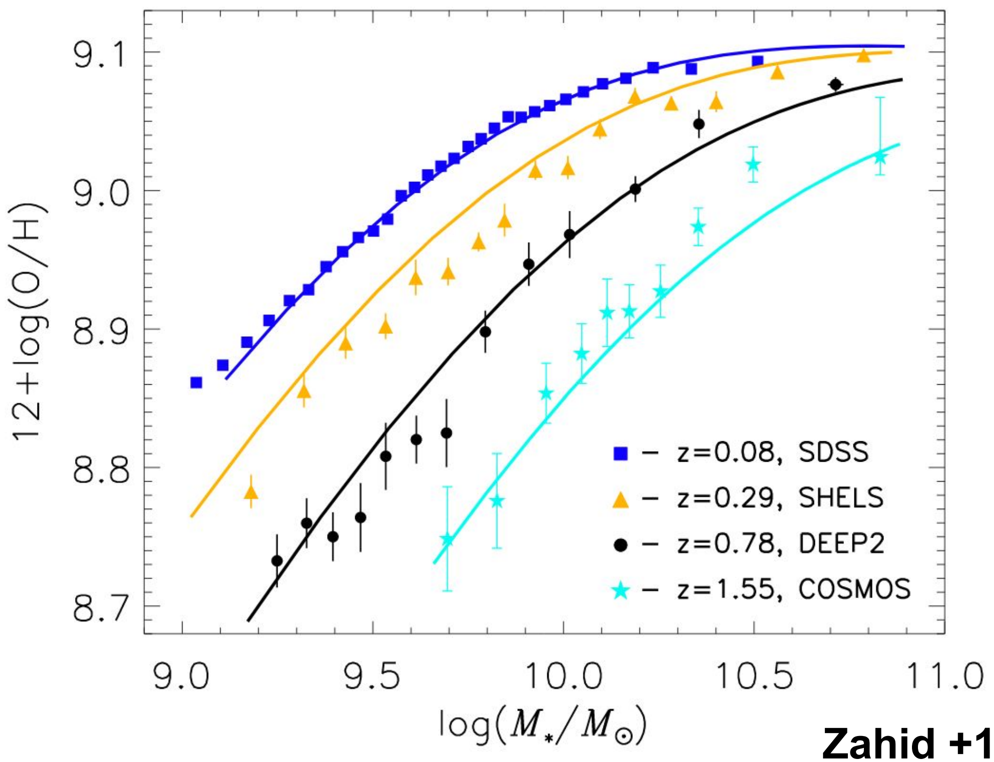


M*-Z relation for local galaxies

(Tremonti et al 2004)

Mass-Metallicity (Gas)

- The MZR evolves monotonically with z: metallicity declines with z at a given mass.
- At low z the evolution is faster at lower mass, while high mass galaxies have already reached their current metallicity by z~1.
- The steady decrease of Z with redshift is probably due to a higher efficiency in ejecting gas and reduced stellar yields.
- Simulation proposes different scenario: increasing gas fraction with redshift, higher infalls and outflows at high redshifts etc.



Zahid +14

Mass-Metallicity

- Metallicity scales with galaxy stellar mass.
- The MZR exists for both gas-phase and stellar metallicities.
- These relations are present in star-forming and quiescent galaxies

Mass-Metallicity (Gas)

Interpretation:

1) MZR is shaped by outflows produced by feedback. Outflows due to SNe common in starburst galaxies, both in the local universe and at high redshift. Outflows have higher metallicities than the ISM of the parent galaxies → more effective in small galaxies, where the potential well is shallower, hence removing a larger fraction of metal-enriched gas from low-mass systems towards the CGM and the IGM

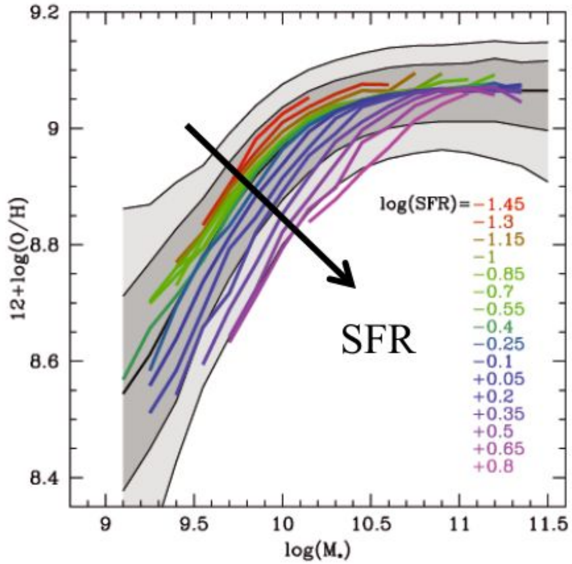
2) High-mass galaxies evolve more rapidly and at higher redshifts than low-mass ones, the so-called “downsizing”. At present they have converted a larger fraction of their gas into stars and metals, reaching a higher metallicity → MZR is a sequence of evolutionary stages

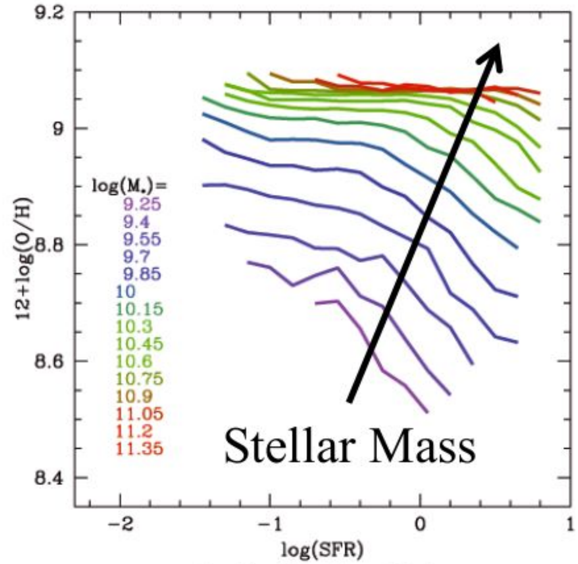
3) The earlier evolutionary stage of smaller galaxies and their larger gas fraction is linked to the
on-going infall of metal-poor gas, which, once mixed with the existing ISM, contributes to reduce metallicity and to the build up of the stellar population through star formation

4) The shape of the high-mass end of the IMF could depend on galaxy mass, introducing a systematic change in the average stellar yields and in the rate of metal enrichment

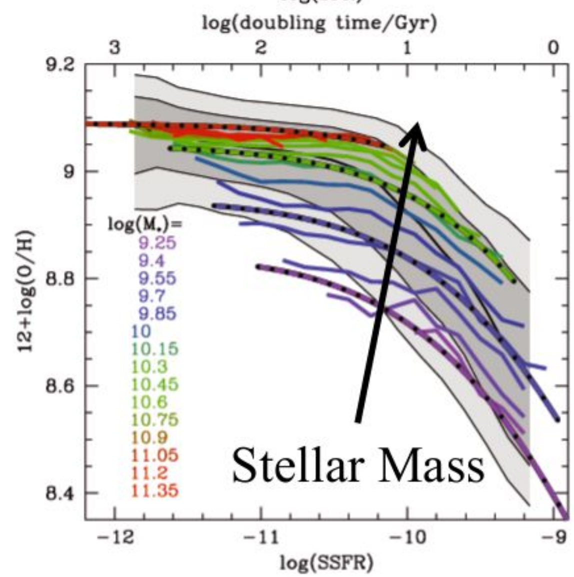
5) The metallicity of the accreted gas, recycled from previous episodes of star formation,

FMR





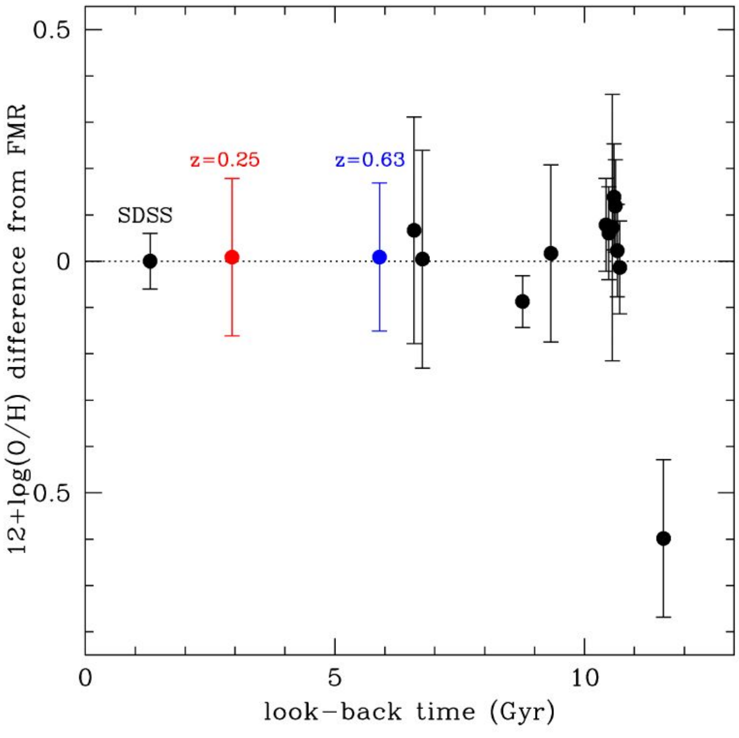
- The fundamental parameters that seem to determine observed metallicity are mass and SFR.
- This forms the fundamental metallicity relation (FMR).
- Despite extremely complex underlying physics, the relation exists out to z=2.5 and in a huge range of galaxies/ environments.



Mannucci +10

FMR

At fixed mass, metallicity decreases with SFR and sSFR, i.e., more actively star-forming galaxies have lower metallicities than more quiescent galaxies.
The FMR does not evolve with redshift up to z=2.5
The origin of this dependence could be the interplay of infall of metal poor gas and star formation :
a) infall provides chemically poor gas, lowering metallicity;
b) gas accretion delivers additional fuel for star formation, enhancing the SFR.
The FMR underline again the importance of cold gas accretion as a dominant driver of galaxy evolution.



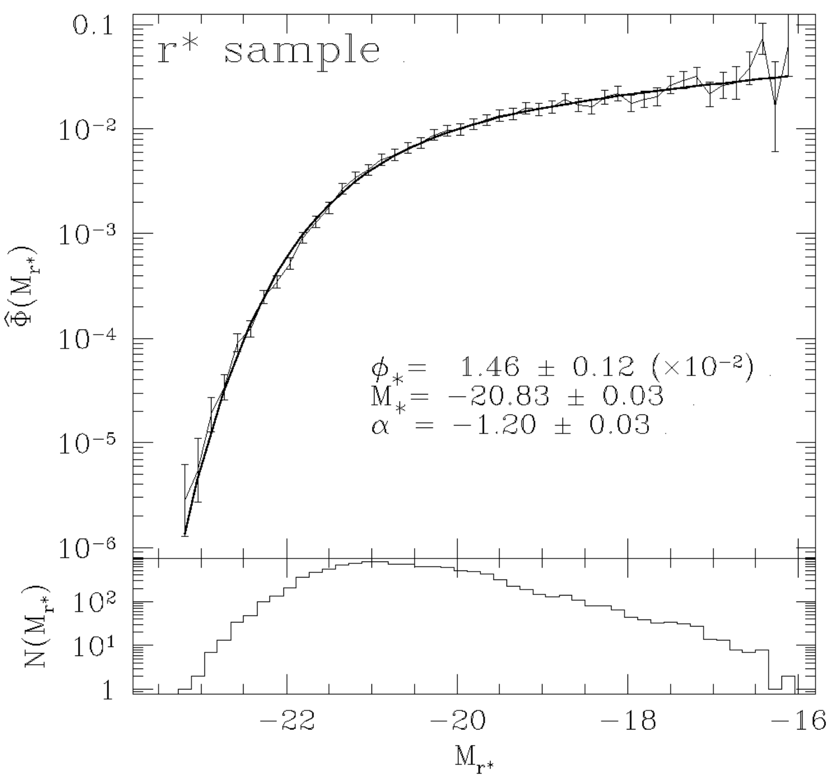
Cresci +15

Luminosity function

The The luminosity function gives the number of galaxies per luminosity interval.

Usually is parametrized with a Schechter luminosity function, with gives space density of galaxies as a function of their luminosity. The form of the function is:

$$n(L)\,\mathrm{d}L = \phi^* \left(\frac{L}{L^*}\right)^{\alpha} \mathrm{e}^{-L/L^*}\,\frac{\mathrm{d}L}{L^*},$$



SDSS data (Blanton +2001)

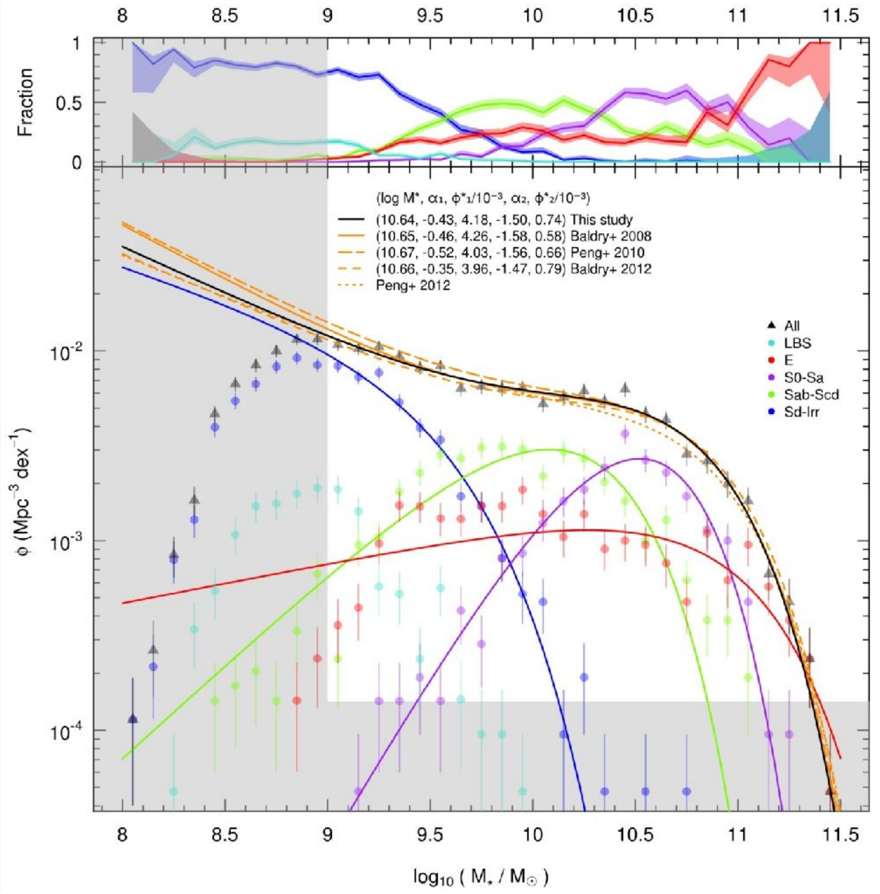
Galaxy Mass Function

Luminosity function can be converted into mass function selecting an appropriate mass-to-light ratio, which depends on galaxy type, age, and metallicity.

Figure below: Estimation of the galaxy stellar mass function divided for morphological type in the local (0.025 < z < 0.06) Universe.

- 71+3−4% of the stellar mass is in spheroid-dominated galaxies, ellipticals and S0-Sas.
- 29+4−3% is Sab-Scds and Sd-Irrs.

This implies that ~50% of the stellar mass today is in spheroidal structures and 50% in disc structures.



Kelvin +14, GAMA data

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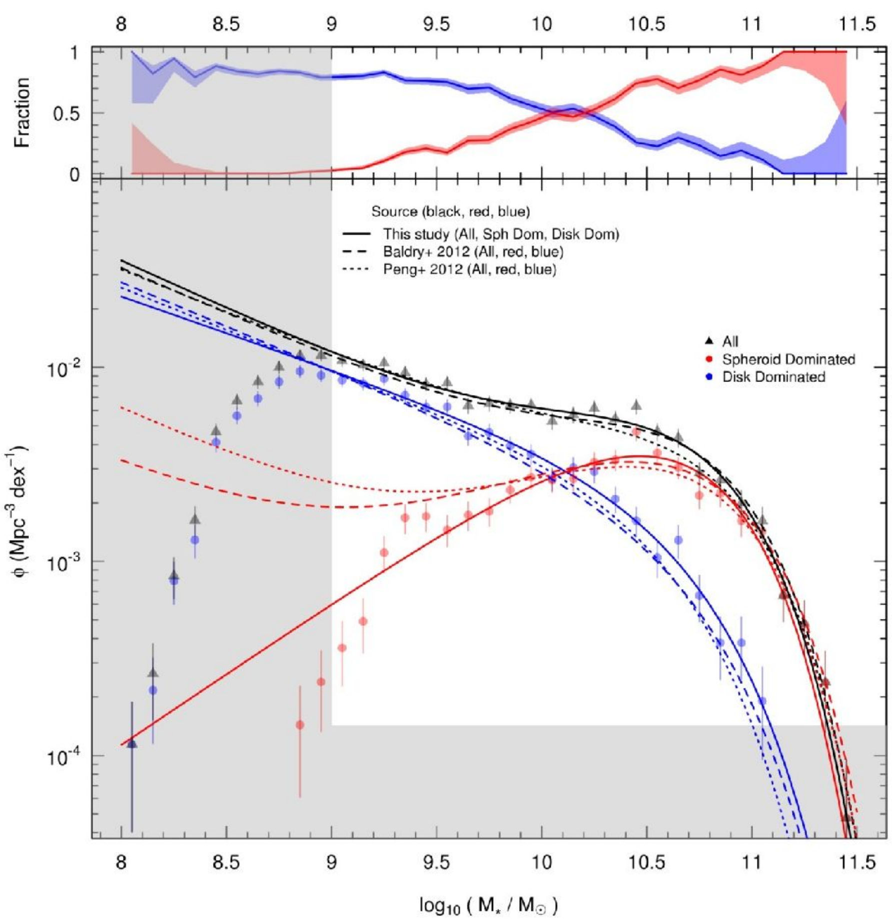
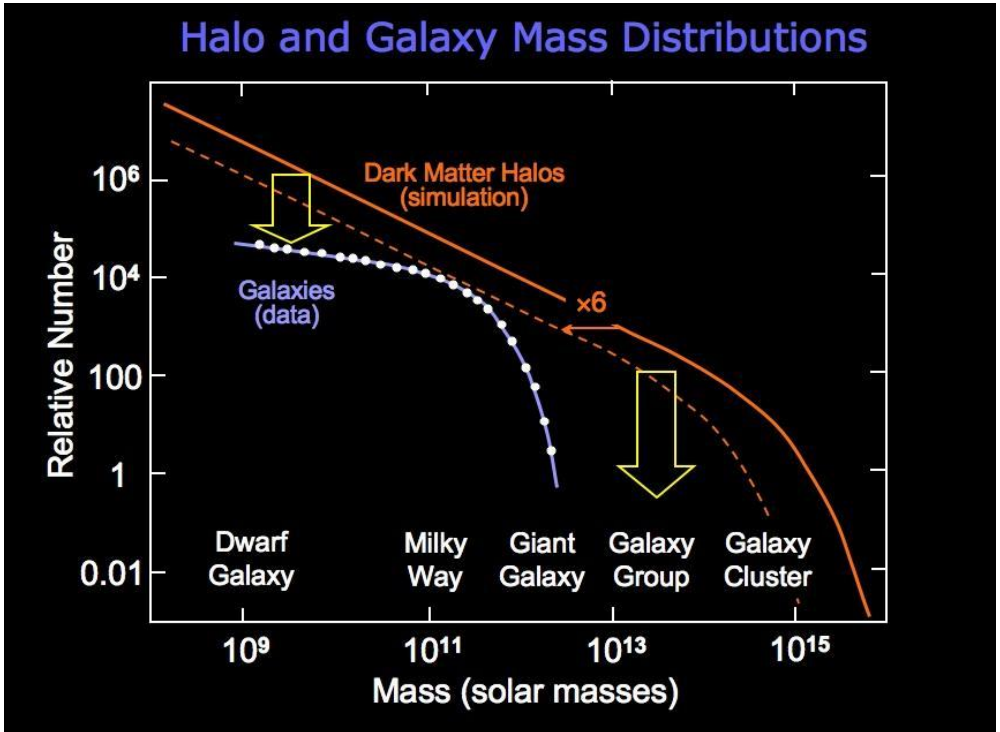


Kelvin +14, GAMA data

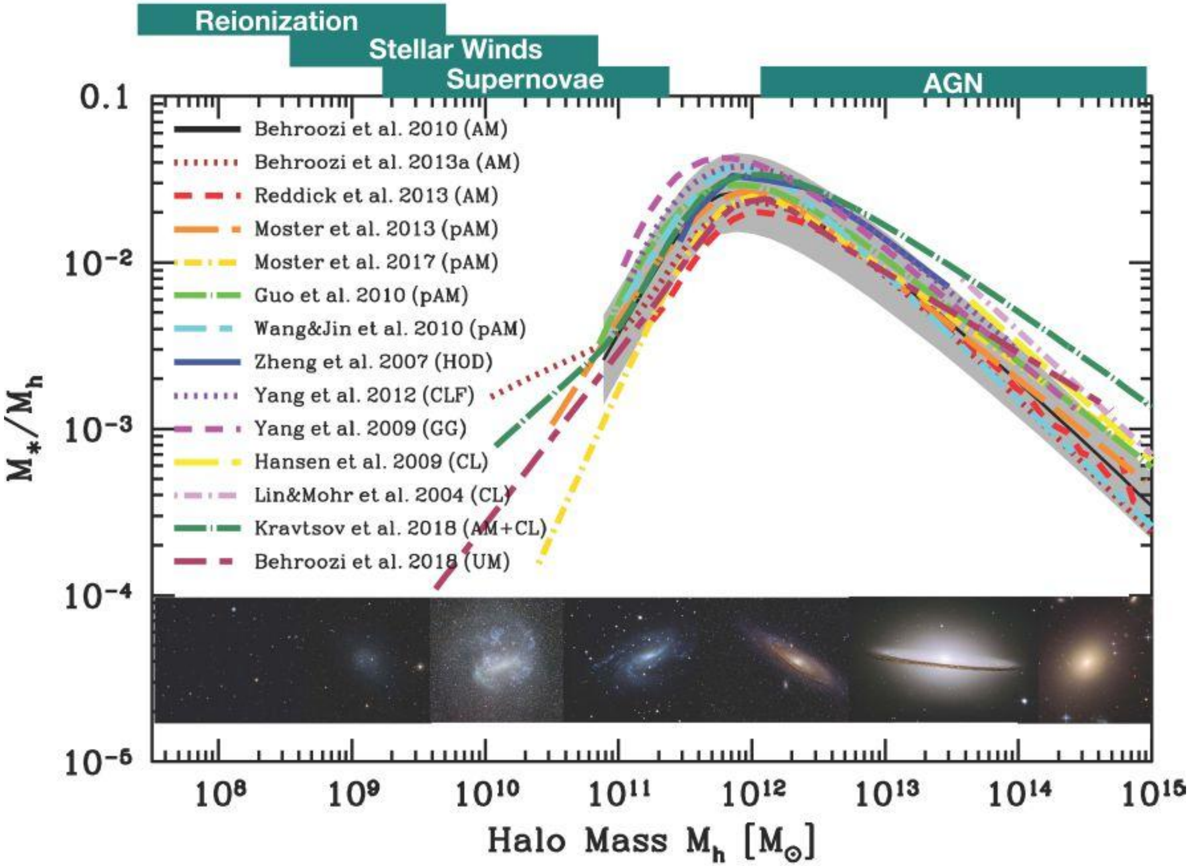
Halo Mass function

The halo mass function is a power law: dashed line shows the mass function if the baryonic matter would follow dark matter perfectly.
In reality star formation most efficient where curves are closes to L*. Near L*, star formation is efficient and LF matches expectations.
Star formation is suppressed at higher masses:
- virial heating in cluster-sized halos
- AGN feedback in most massive galaxies.
Star formation is suppressed at lower masses (missing satellite problem):
- gas ejected from small halos by supernova winds
- gas pressure suppresses collapse in small halos.



Halo function

A method to investigate the relevant mechanisms in galaxies evolution is to constrain the redshift-dependent relation between physical characteristics of galaxies, such as stellar mass, and the mass of their dark matter halos. Many of these physical processes depend primarily on the mass of a galaxy's dark matter halo and investigating their connections one is able to identify and constrain the physical processes responsible for galaxy growth.



Behroozi + 2013

What did we learn?

1. Scaling relations
2. Main sequence
3. MMR
4. FMR
5. Luminosity function
6. Mass function
7. Halo mass function