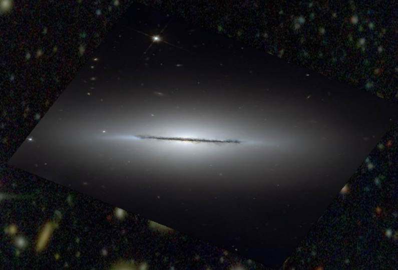
INTRODUCTION TO AMAZING AND DIVERSE WORLD OF GALAXIES
(Part 2.)



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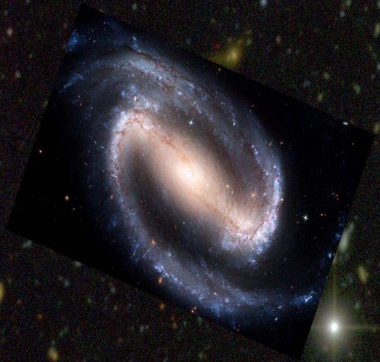
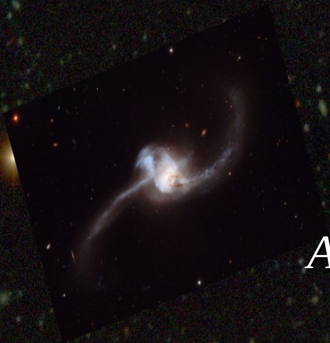
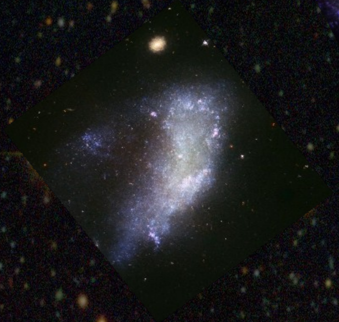






ASP lectures, 18 of Sep, 2020
(virtual)

Brief introduction to extragalactic astronomy and world of galaxies, content:

- Concept of galaxies, deep surveys and multiwavelength data

- Types of galaxies

- Hubble sequence, properties of different morphological types, and morphological classification of galaxies

PART 1

PART 2

- Main relations

- Galaxy mergers and interactions

- Star-forming, starburst, and IR galaxies

- AGN

- Galaxy groups and clusters

- Briefly on galaxy formation and evolution

Main Relations Between Galaxies

'Standard' relations that have been found between different types of galaxies, normally at both low- and higher- redshifts

Main Relations Between Galaxies

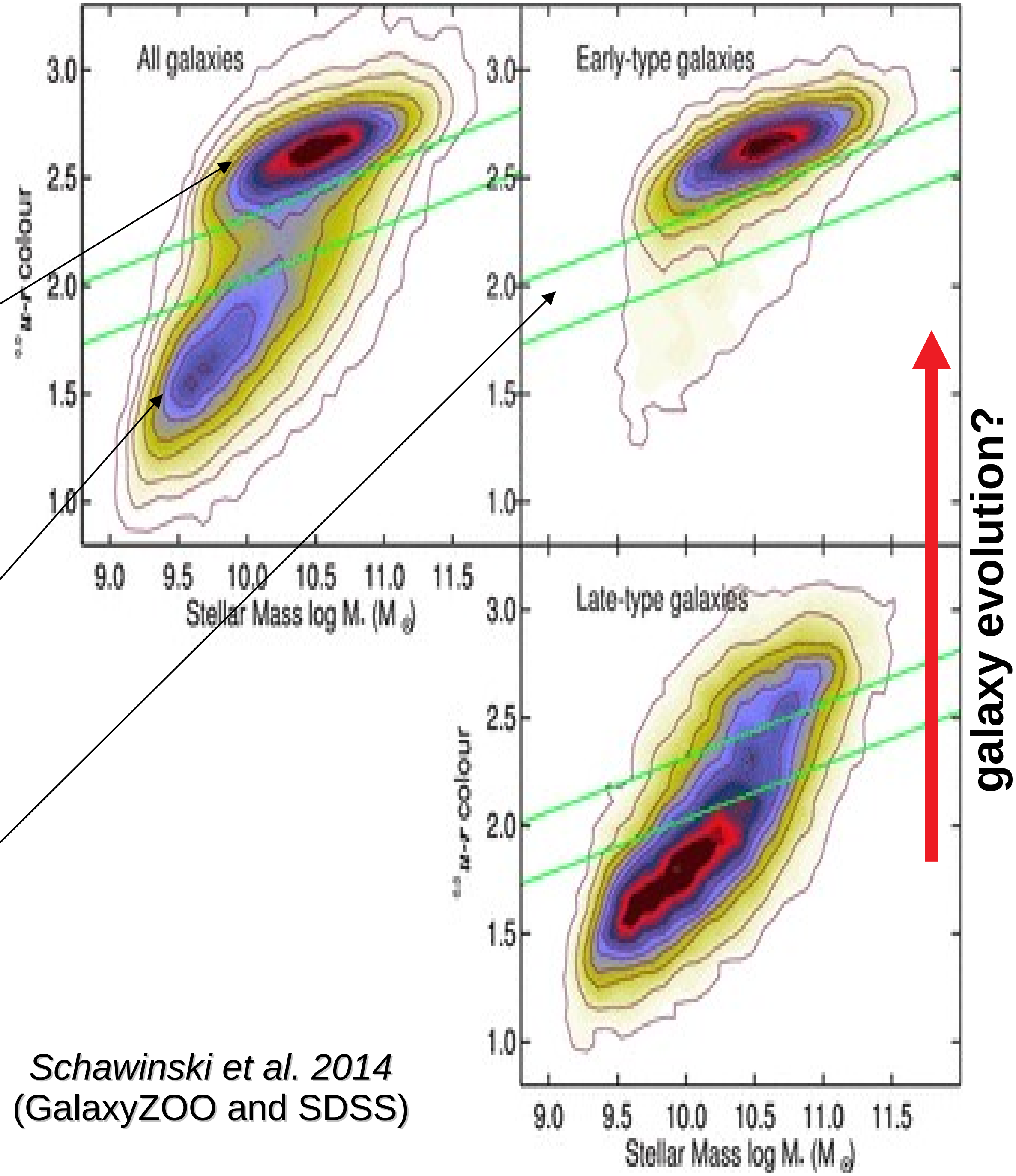
Colour – stellar mass (or magnitude) diagram:

- Bi-polar distribution of galaxies

- **Red Sequence** – mainly populated by early-type galaxies (also some population of late-type galaxies with large amounts of dust)

- **Blue Cloud** – mainly populated by late-type galaxies (also contain the ET galaxies with recent SF)

- **Green Valley** – transition area (?)



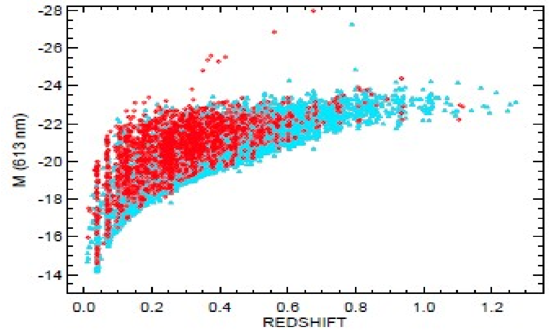
Schawinski et al. 2014
(GalaxyZOO and SDSS)

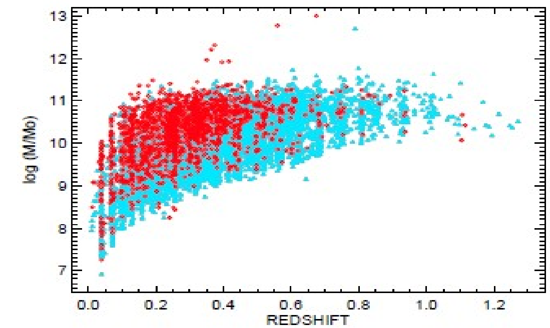
AT LOW REDSHIFT

Main Relations Between Galaxies

Colour – stellar mass (or magnitude) diagram

AT HIGHER REDSHIFT





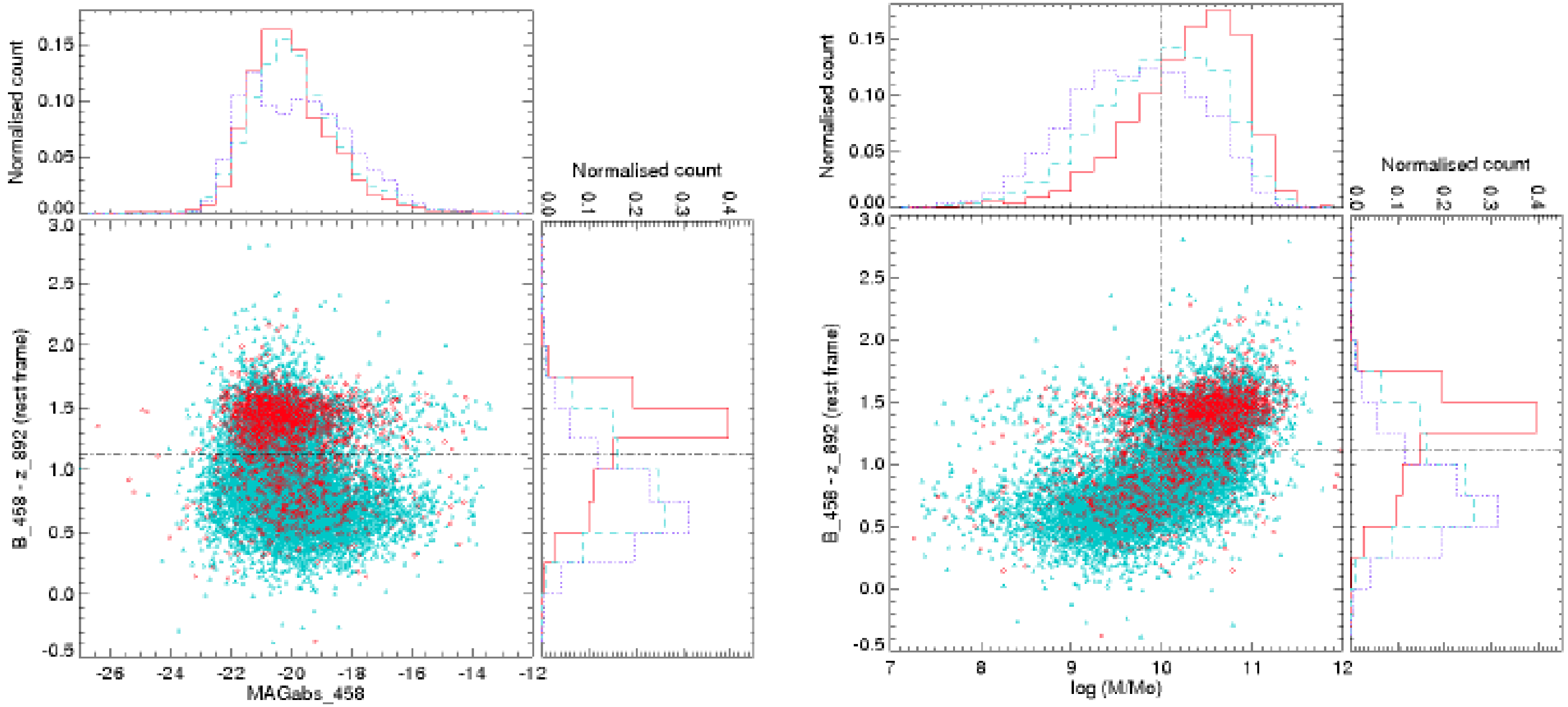


Figure 14. *(Left:)* Relation between the rest-frame $B - z$ colour and absolute magnitude in F458W band (central diagram) of ET (red diamonds) and LT (blue triangles) galaxies down to magnitudes F613W $\leqslant$ 22.0.. To estimate the colour we used the information from the F458W and F892W ALH bands. Histograms present the normalised distributions of compared parameters: absolute magnitude (above the central plot) and colour (to the right of the central diagram) for ET (red solid lines) and LT (blue dashed lines) sources. Dotted violet histograms show the distributions of LT galaxies with magnitudes 22.0 $<$ F613W $\leqslant$ 23.0. *(Right:)* Relation between the rest-frame $B - z$ colour and stellar mass (central diagram). Histograms show the normalised distributions of analysed parameters, as in previous case. All symbols and lines have the same significance as in left diagram.

Pović et al. 2013
(ALHAMBRA Survey)

Main Relations Between Galaxies

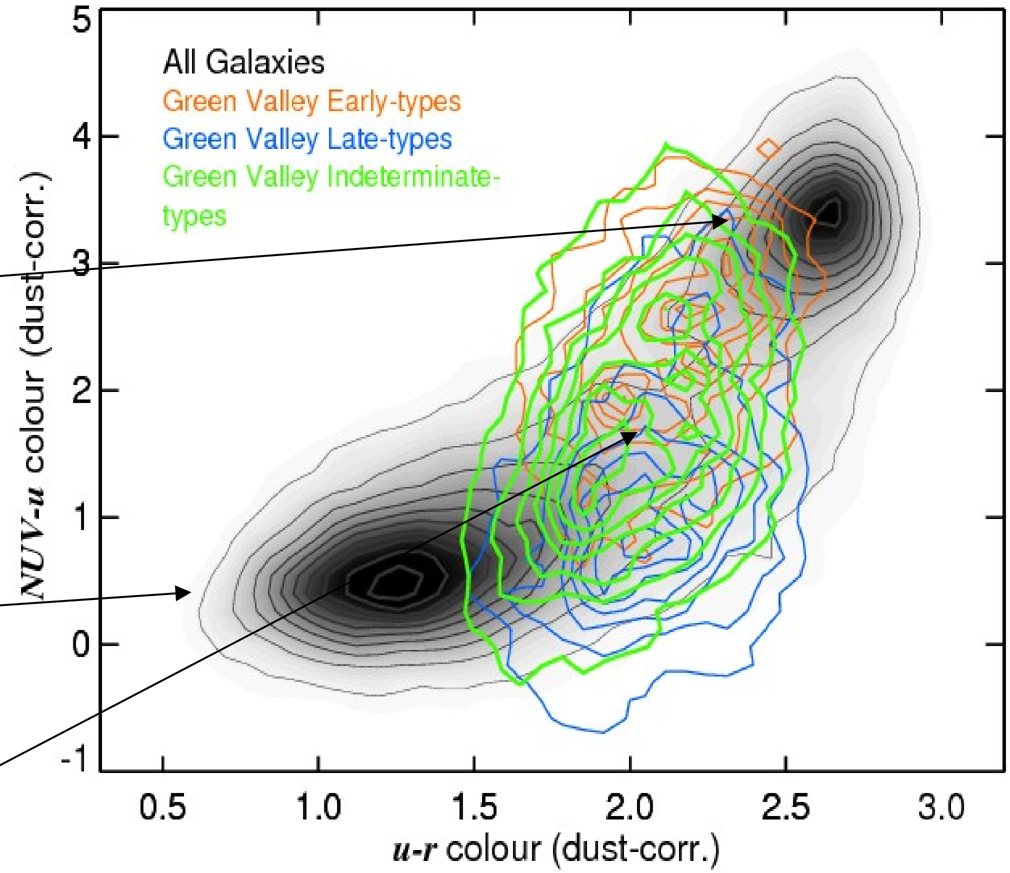
Colour – Colour diagrams

- Again bi-polar distribution of galaxies

- **Red Sequence** – mainly populated by early-type galaxies (also some population of late-type galaxies with large amounts of dust)

- **Blue Cloud** – mainly populated by late-type galaxies (also contain the ET galaxies with recent SF)

- **Green Valley** – transition area(??)

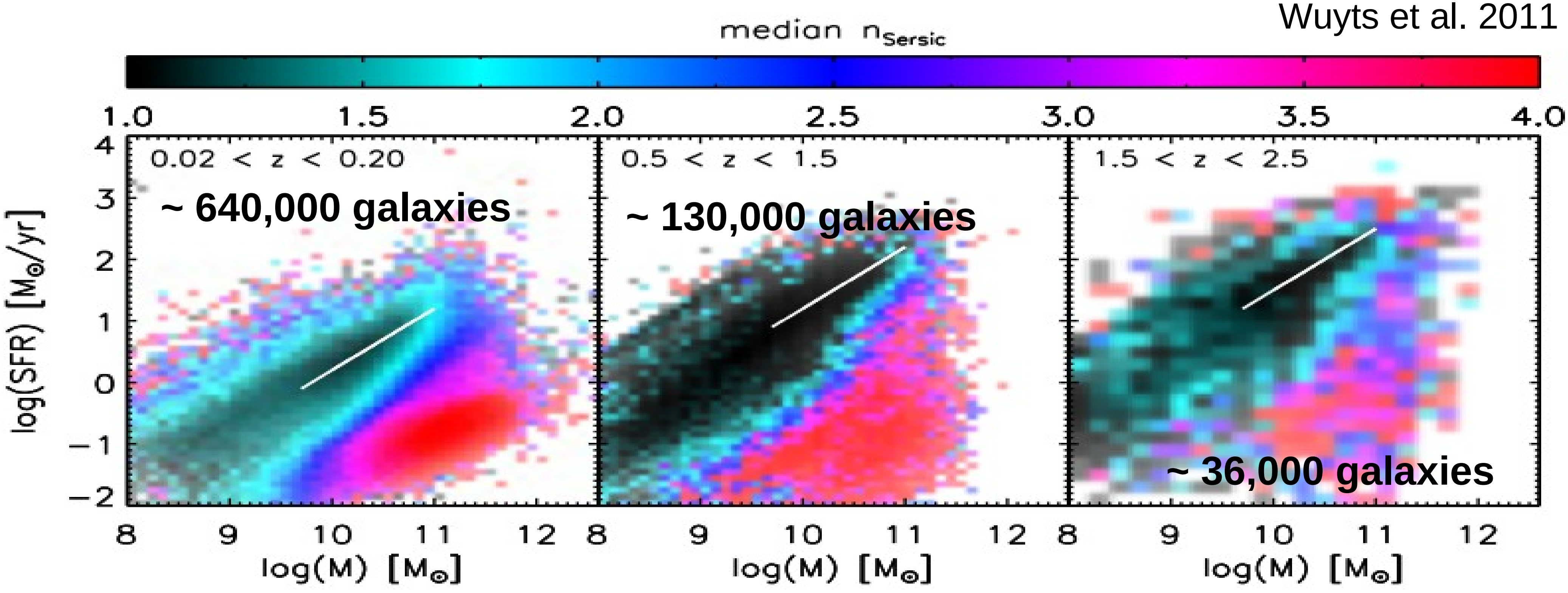


Schawinski et al. 2014
(GalaxyZOO and SDSS)

Main Relations Between Galaxies

SFR vs. M* → Main Sequence (MS) of star-forming (SF) galaxies:

Wuyts et al. 2011



- MS galaxies have disk-like structure (mainly later spiral galaxies).
- Early-type galaxies are located below the MS.

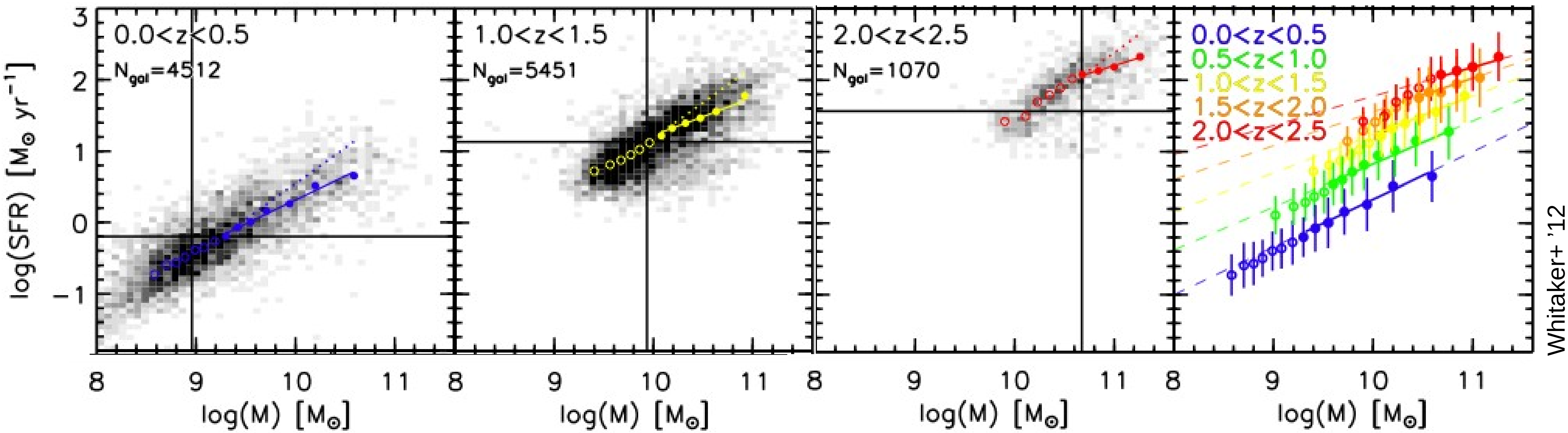
- Evolution of MS of SF with redshift (with cosmic time).

Main Relations Between Galaxies

SFR vs. M → Main Sequence (MS) of SF galaxies:

Whitaker et al. 2012

Presence of MS points to a homogeneity of SF histories.



- Main-sequence of SF evolves with redshift.

Main Relations Between Galaxies

SFR vs. M → Main Sequence (MS) of SF galaxies:

Leslie et al. 2016

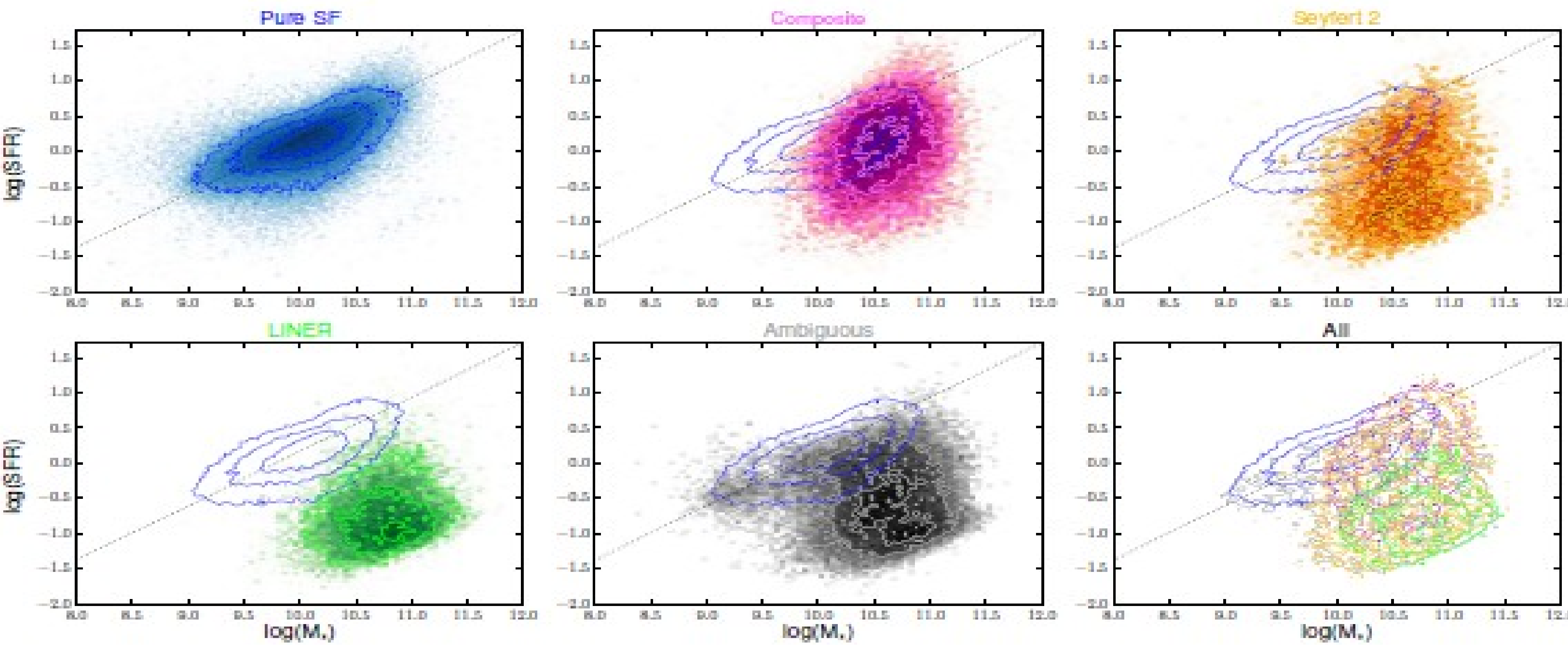
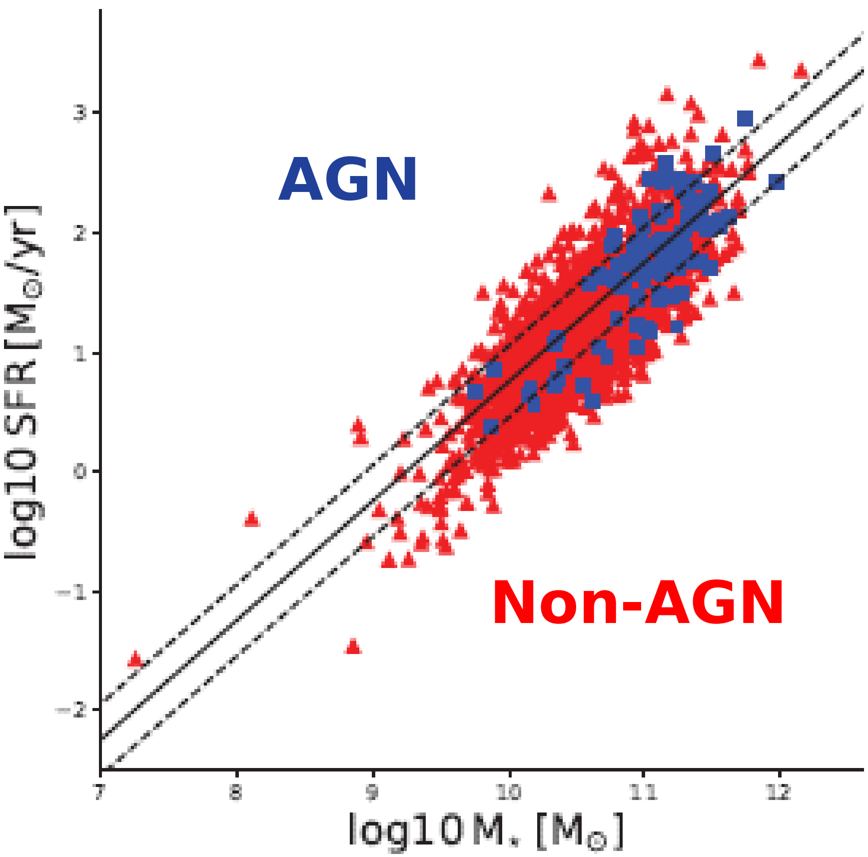


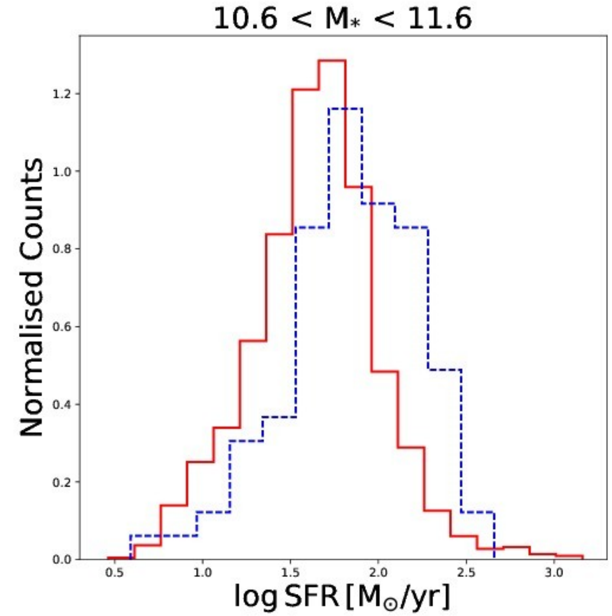
Figure 1. SFR as a function of stellar mass for each class of galaxies. Stellar mass and SFRs are in units of $M_\odot$ and $M_\odot yr^{-1}$ respectively throughout this work. The top-left to bottom-right panels include galaxies classified as purely star-forming, composite, Seyfert 2, LINER, or Ambiguous, and the final panel contains all classes together. A black dashed line in each panel represents the local MS relation for blue SDSS galaxies determined by Elbaz et al. (2007). Contours and colours represent the number density of galaxies in a single class only. Dividing the SFR-M_* space into 150x150 bins, contours are drawn at 10, 30, and 60% of the maximum number density. The blue contours of the star-forming galaxies are included in all panels to indicate the location of the star-forming MS. Contours from previous panels are also shown in the final panel, which displays the MS of all galaxies.

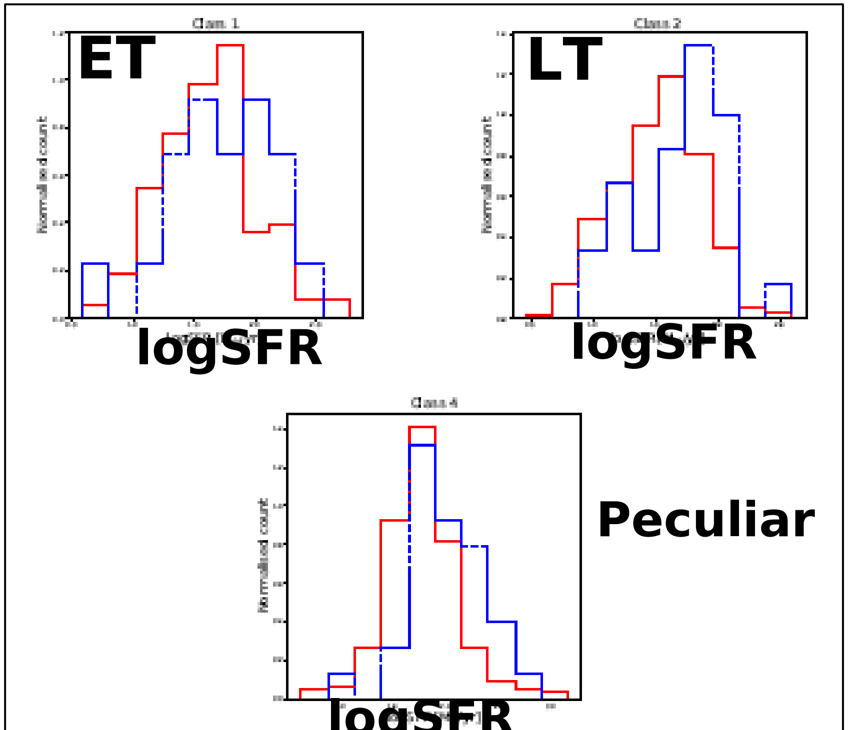
→ AGN responsible for quenching of star formation in galaxies?

Main Relations Between Galaxies

Different results found recently when active and non-active galaxies in the green valley are studied in FIR







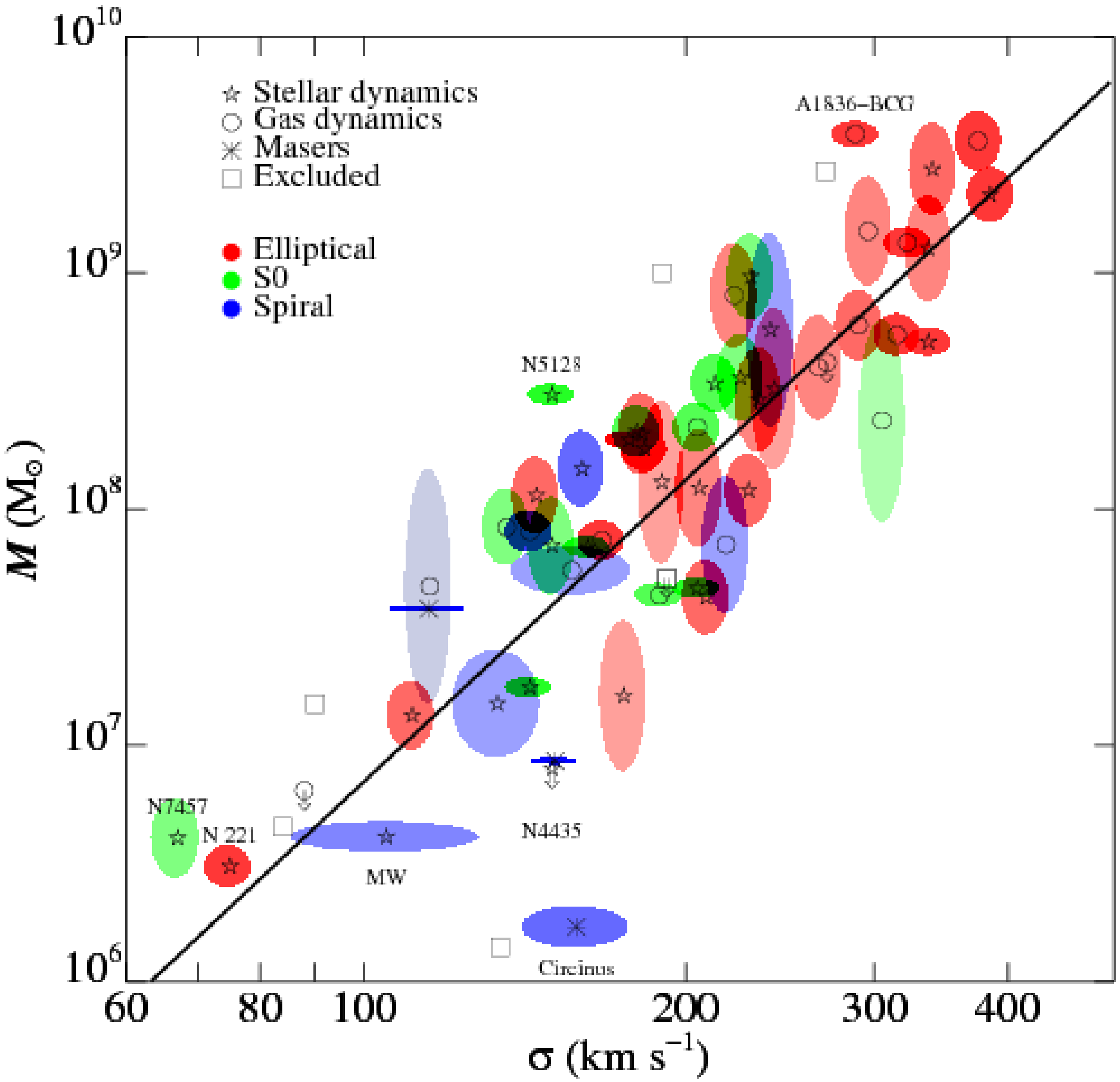
→ no signs of AGN quenching SF in these galaxies, but rather enhancing it

Mahoro, Pović, Nkundabakura et al. 2017
Mahoro, Pović, Nkundabakura et al. 2019

Main Relations Between Galaxies

Co-evolution between SMBH and galaxy/bulge

Mbh – sigma (σ) relation
(black hole mass vs. velocity dispersion of the bulge)



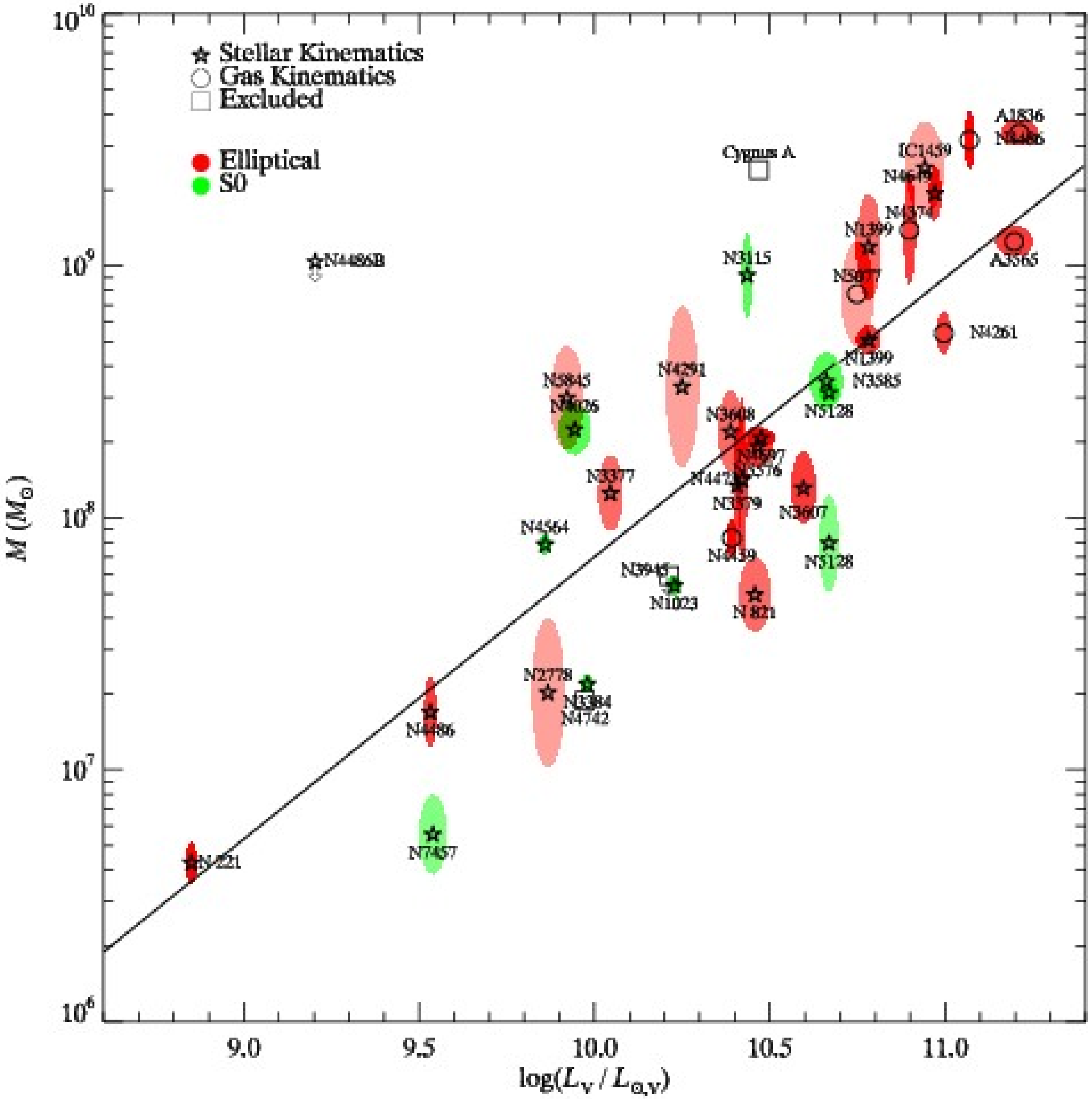
Gultekin 2009

The M-sigma relation for galaxies with dynamical measurements. The symbol indicates the method of BH mass measurement: stellar dynamical (pentagrams), gas dynamical (circles), masers (asterisks). Arrows indicate 3sigma conf upper limits to BH mass. The shade of the error ellipse indicates the Hubble type of the host. The saturation of the shades in the error ellipses is inversely proportional to the area of the ellipse. The line is the best fit relation to the full sample.

Main Relations Between Galaxies

Co-evolution between SMBH and galaxy/bulge

Mbh – L relation
(black hole mass vs. the bulge luminosity or bulge mass)



Gultekin 2009

The M-L relation for galaxies with dynamical measurements. The symbol indicates the method of BH mass measurement: stellar dynamical (pentagrams) and gas dynamical (circles). Arrows indicate upper limits for BH mass. The shade of the error ellipse indicates the Hubble type of the host galaxy, and the saturation of the shade is inversely proportional to the area of the ellipse. The line is the best-fit relation for the sample without upper limits.

Also known as Faber-Jackson relation for Ell galaxies (total luminosity in this case)

Main Relations Between Galaxies

Mbh – σ relation

→ **works also in case of galaxies in clusters**

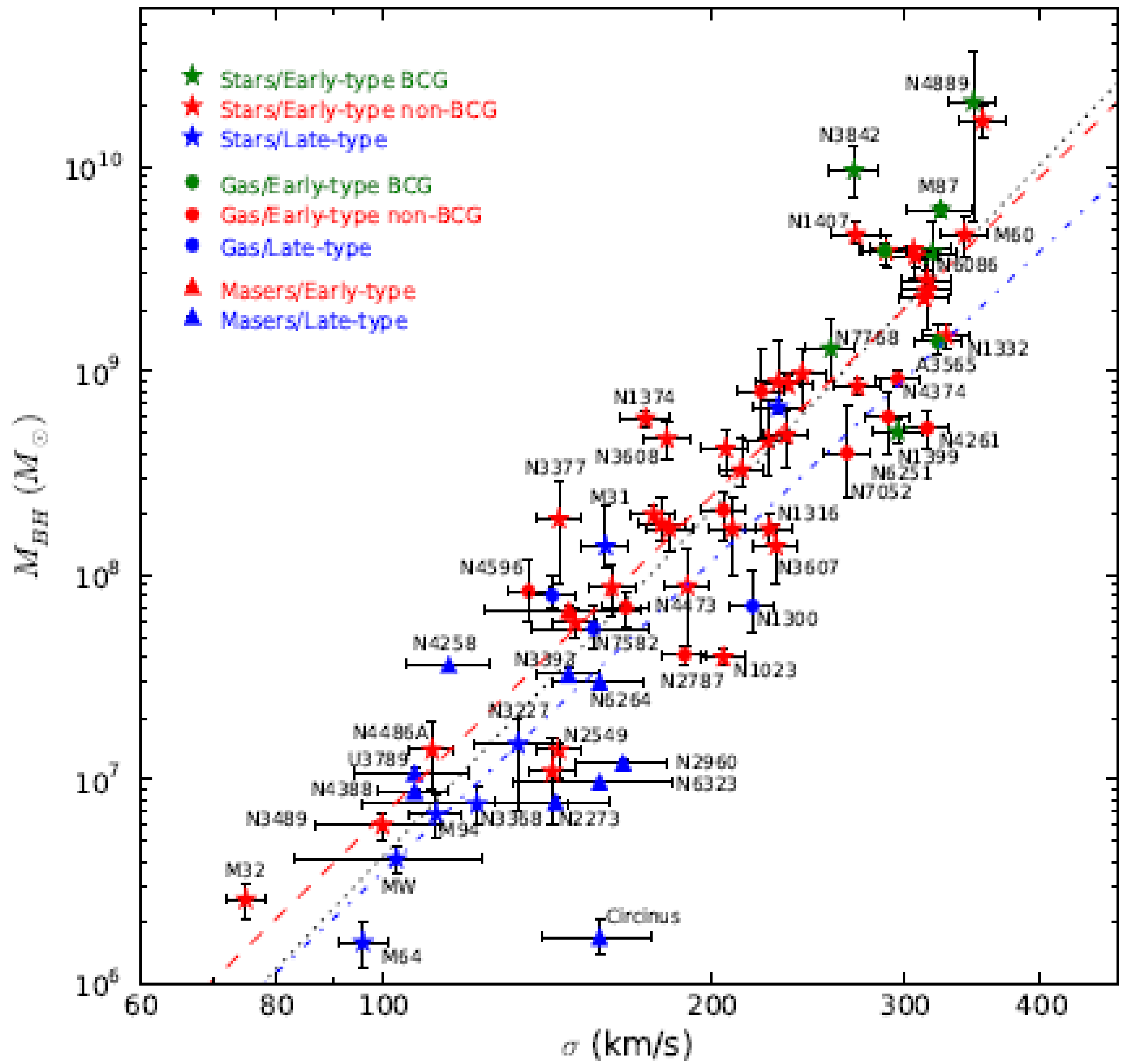


FIG. 1.— The $M_\bullet - \sigma$ relation for our full sample of 72 galaxies listed in Table A1 and at `http://blackhole.berkeley.edu`. Brightest cluster galaxies (BCGs) that are also the central galaxies of their clusters are plotted in green, other elliptical and S0 galaxies are plotted in red, and late-type spiral galaxies are plotted in blue. NGC 1316 is the most luminous galaxy in the Fornax cluster, but it lies at the cluster outskirts; the green symbol here labels the central galaxy NGC 1399. M87 lies near the center of the Virgo cluster, whereas NGC 4472 (M49) lies ~ 1 Mpc to the south. The black-hole masses are measured using the dynamics of masers (triangles), stars (stars) or gas (circles). Error bars indicate 68% confidence intervals. For most of the maser galaxies, the error bars in $M_\bullet$ are smaller than the plotted symbol. The black dotted line shows the best-fitting power law for the entire sample: $\log_{10}(M_\bullet/M_\odot) = 8.32 + 5.64\log_{10}(\sigma/200\,\mathrm{km\,s^{-1}})$. When early-type and late-type galaxies are fit separately, the resulting power laws are $\log_{10}(M_\bullet/M_\odot) = 8.39 + 5.20\log_{10}(\sigma/200\,\mathrm{km\,s^{-1}})$ for the early-type (red dashed line), and $\log_{10}(M_\bullet/M_\odot) = 8.07 + 5.06\log_{10}(\sigma/200\,\mathrm{km\,s^{-1}})$ for the late-type (blue dot-dashed line). The plotted values of σ are derived using kinematic data over the radii $r_{\rm inf} < r < r_{\rm eff}$.

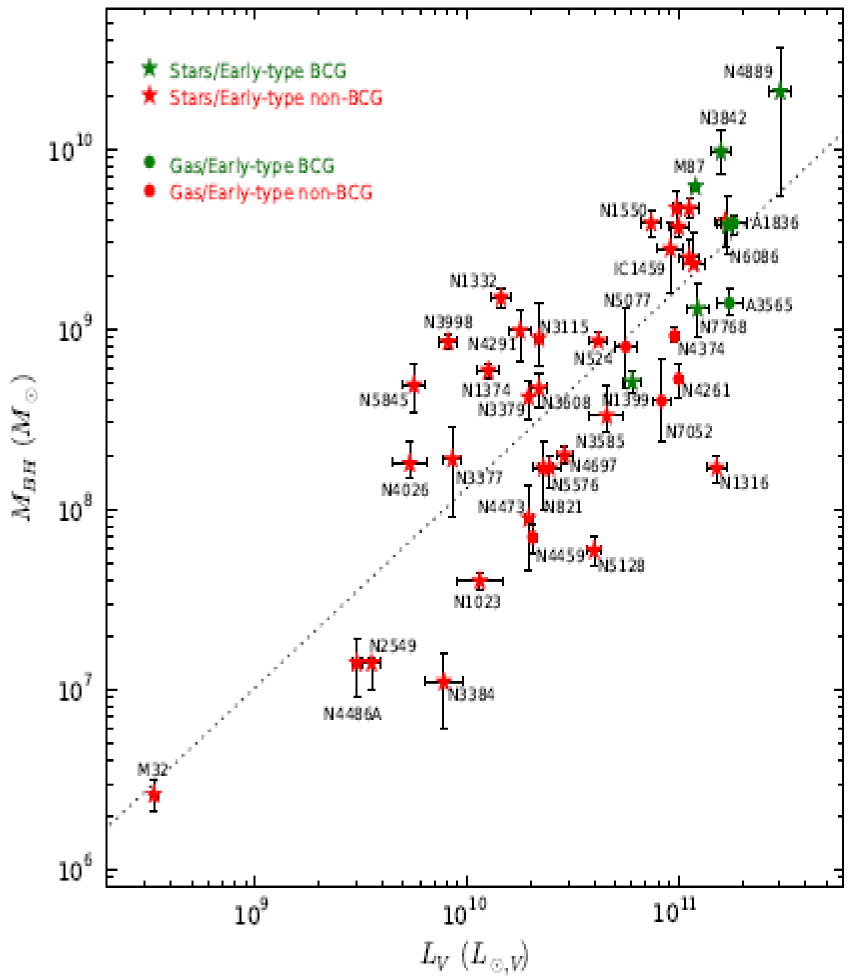
McConnell et al. 2013

Main Relations Between Galaxies

<u>Mbh – L relation</u>
(black hole mass vs. the bulge luminosity or bulge mass):

→ **works also in case of galaxies in clusters**

McConnell et al. 2013



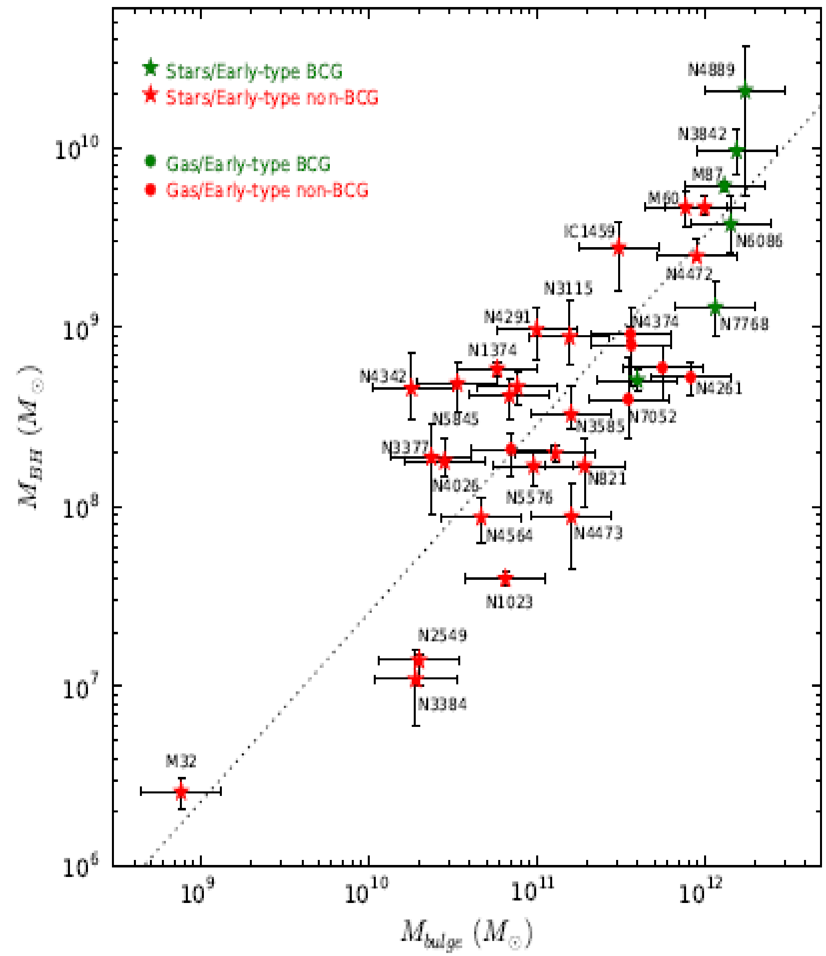


FIG. 2.— The $M_\bullet - L$ relation for the 44 early-type galaxies with reliable measurements of the V-band bulge luminosity in our sam symbols are the same as in Figure 1. The black line represents the best-fitting power-law $\log_{10}(M_\bullet/M_\odot) = 9.23 + 1.11 \log_{10}(L_v/1$

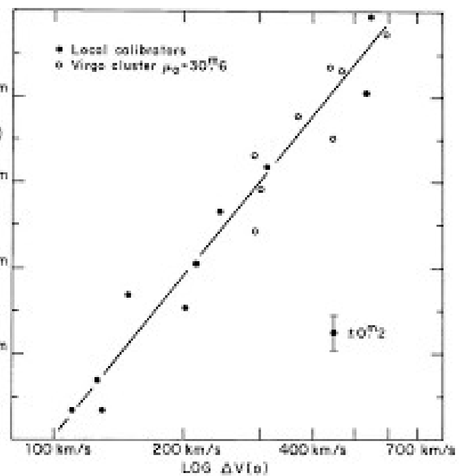
FIG. 3.— The $M_\bullet - M_{\rm bulge}$ relation for the 35 early-type galaxies with dynamical measurements of the bulge stellar mass in our sample. The symbols are the same as in Figure 1. The black line represents the best-fitting power-law $\log_{10}(M_\bullet/M_\odot) = 8.46 + 1.05 \log_{10}(M_{\rm bulge}/10^{11} M_\odot)$.

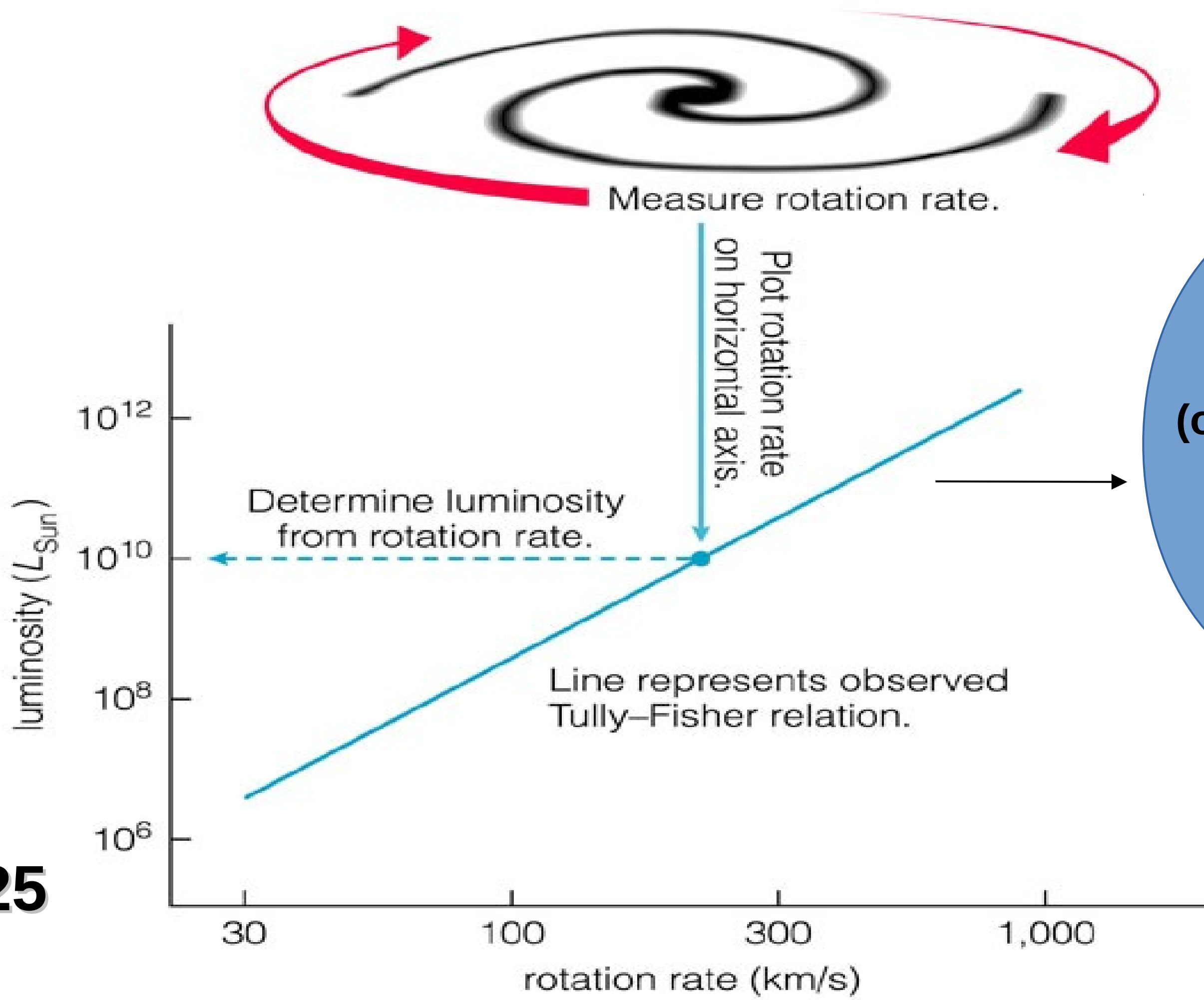
Main Relations Between Galaxies

Tully-Fisher relation

INCLINATION MATTERS!!!

(Tully and Fisher, 1977)





WITH LUMINOSITY (or ABS. MAG) DISTANCE CAN BE MEASURED

Distance ladder

$$M = m - 5\log D - 25$$

Main Relations Between Galaxies

Tully-Fisher relation in optical with redshift

Fernandez-Lorenzo et al. 2009
Fernandez-Lorenzo et al. 2010, in NIR

Can be used for studying dynamical properties of galaxies and galaxy evolution.

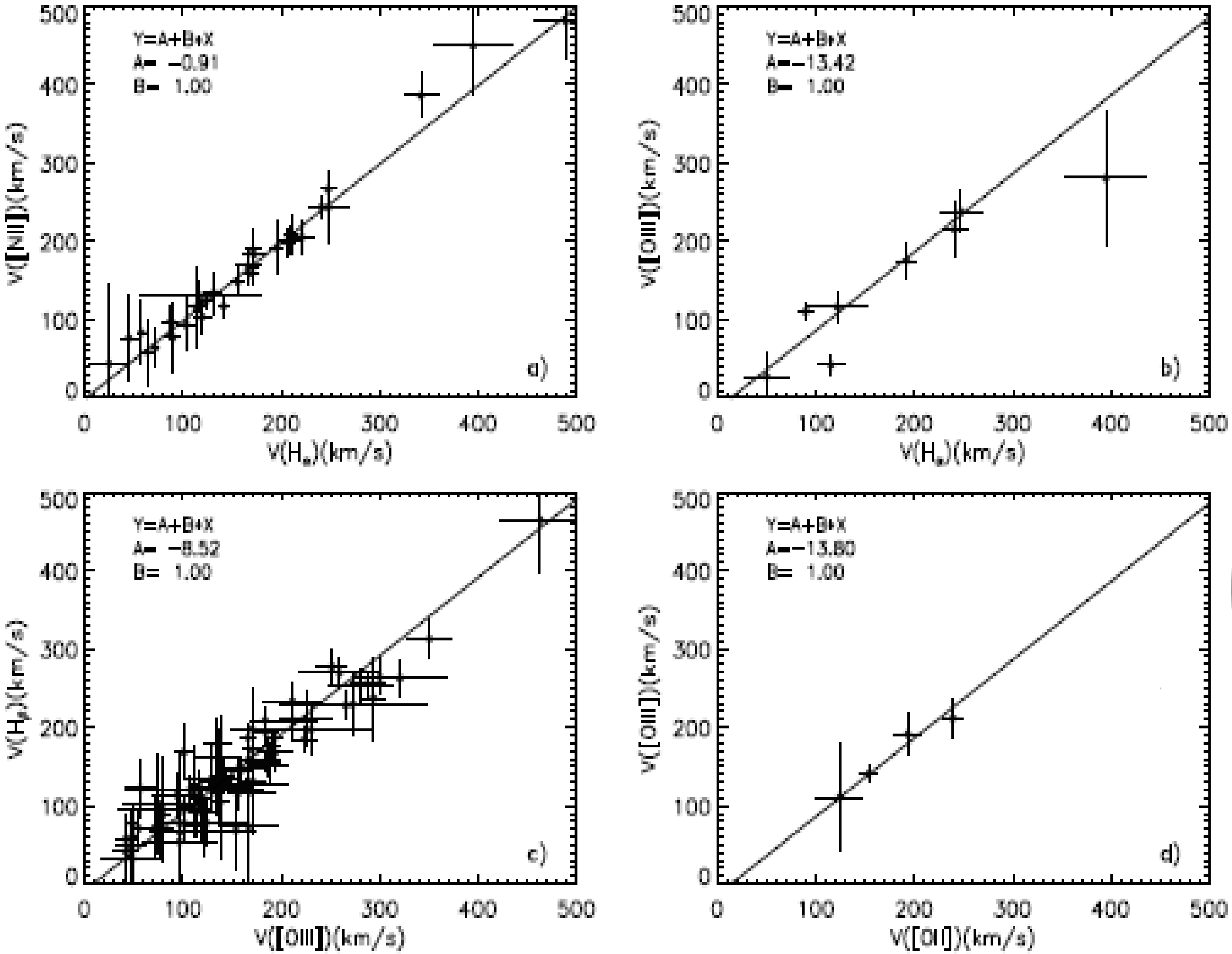
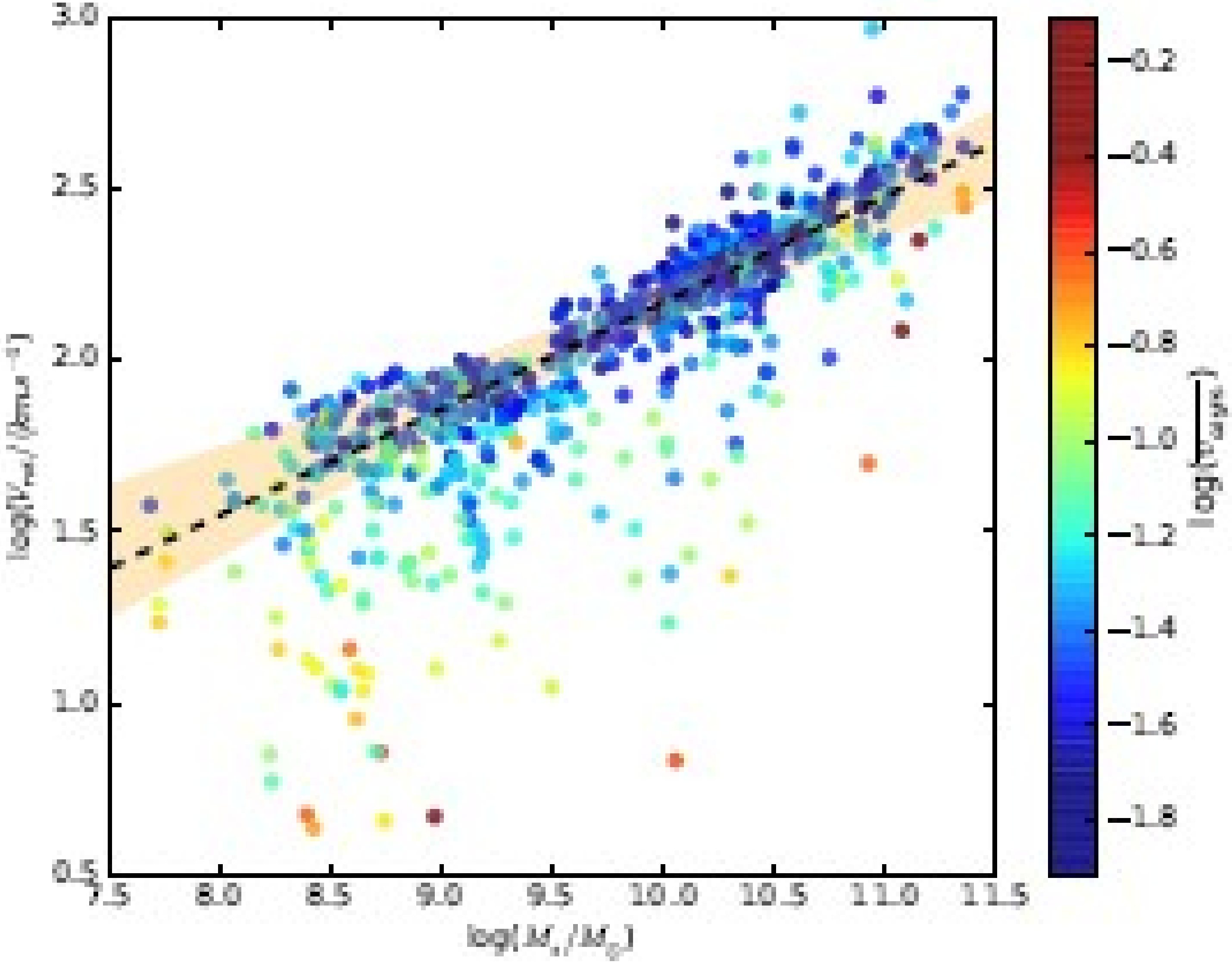


Fig. 3. Comparison of the velocity widths from five optical lines. In each panel, the solid line shows the least-square fits with slope 1. All zero-points are within the errors. a) Velocity obtained from [NII]λ6583 Å and H_α, b) comparison between [OIII]λ5007 Å and H_α, c) velocity from H_β versus [OIII]λ5007 Å, d) comparison between [OIII]λ5007 Å and [OII]$\lambda\lambda$3727 Å velocities.

INCLINATIONS UP TO 75º - 80º

Main Relations Between Galaxies

Stellar mass Tully-Fisher relation

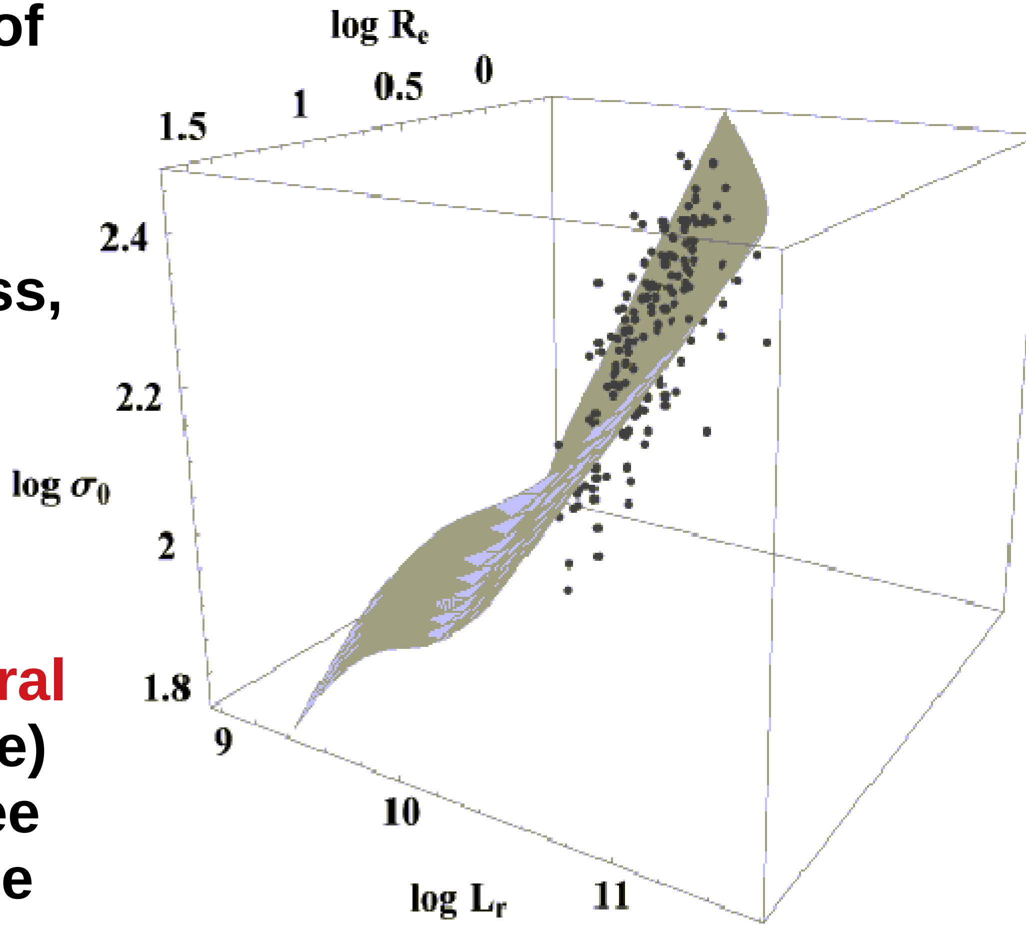


Bloom et al. 2017 (SAMI sample, IFS)

Main Relations Between Galaxies

Fundamental plane of elliptical galaxies

Set of correlations connecting some of the properties of normal (inactive) elliptical galaxies (e.g, radius, mass, luminosity, velocity dispersion, colours, metallicity, surface brightness, etc.) and the shape of their radial surface brightness profiles.



Usually expressed as a relationship between the effective radius (R50), average surface brightness, and central velocity dispersion of normal (inactive) elliptical galaxies. Any one of the three parameters may be estimated from the other two, as together they describe a plane in 3D space.

Main Relations Between Galaxies

Fundamental plane of elliptical galaxies

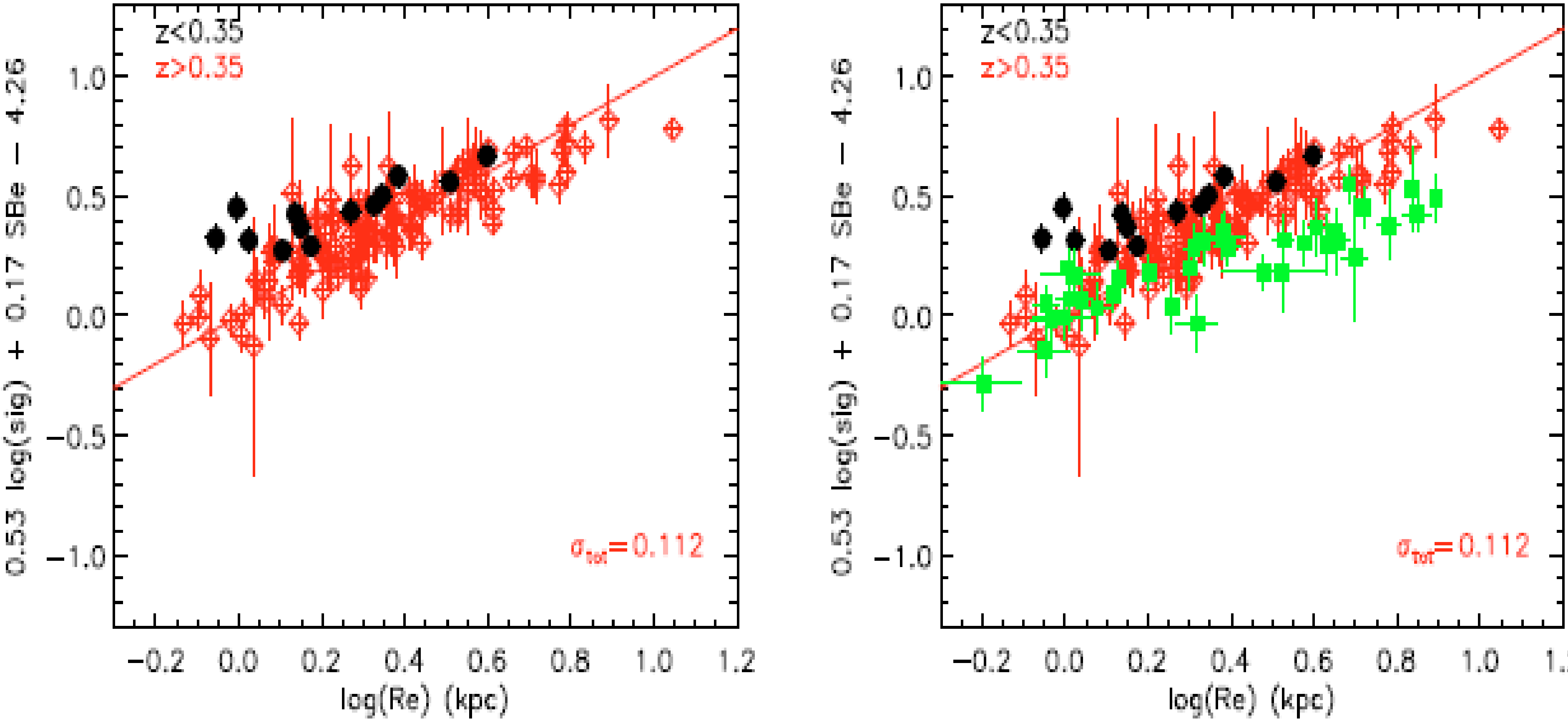


Fig. 4. Edge-on projection of the FP in the *B*-band. The black points represent the galaxies with $z < 0.35$, and the open red diamonds are the objects with $z > 0.35$. The parameters a, b, and the zero-point were obtained by fitting the galaxies at $z > 0.35$, through a non-linear weighted least-squares fit. The green squares added in the right panel are the early-type galaxies of Gebhardt et al. (2003) with redshifts in the range $0.3 < z < 1.0$.

Fernandez-Lorenzo et al. 2011

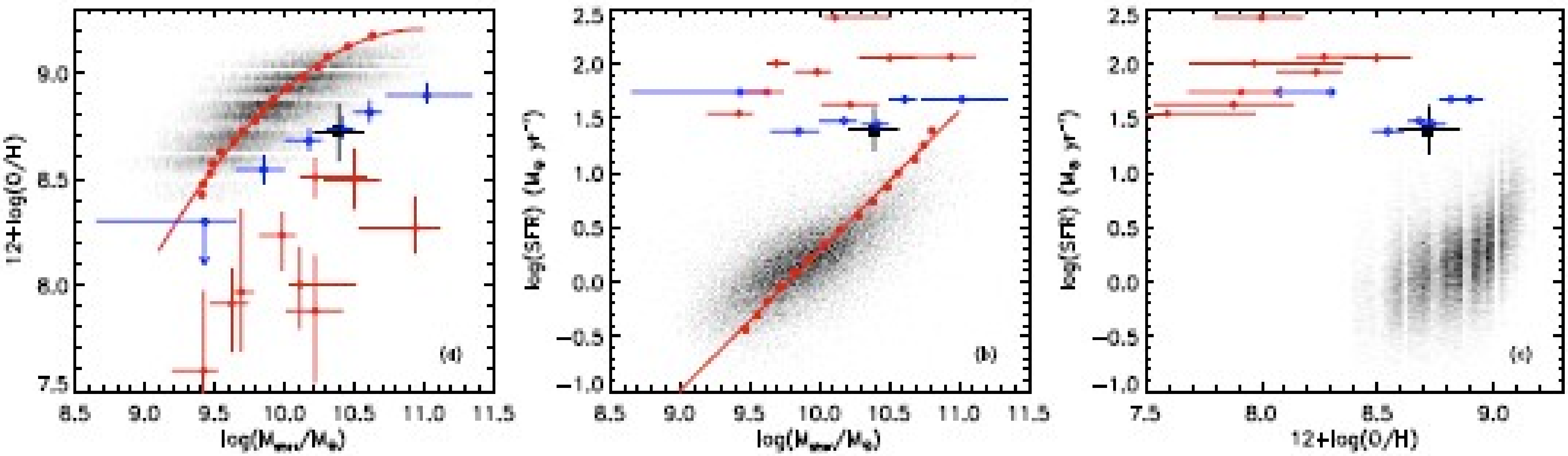
Main Relations Between Galaxies

Fundamental plane of star-forming field galaxies

- Previously well known relation between the:
  mass-metallicity, mass-SFR, and metallicity-SFR

- From recently – existence of a plane in a 3D space of between these three parameters → have been seen in the local universe ($z < 0.1$)

(Lara-Lopez et al. 2010, Mannucci et al. 2010)



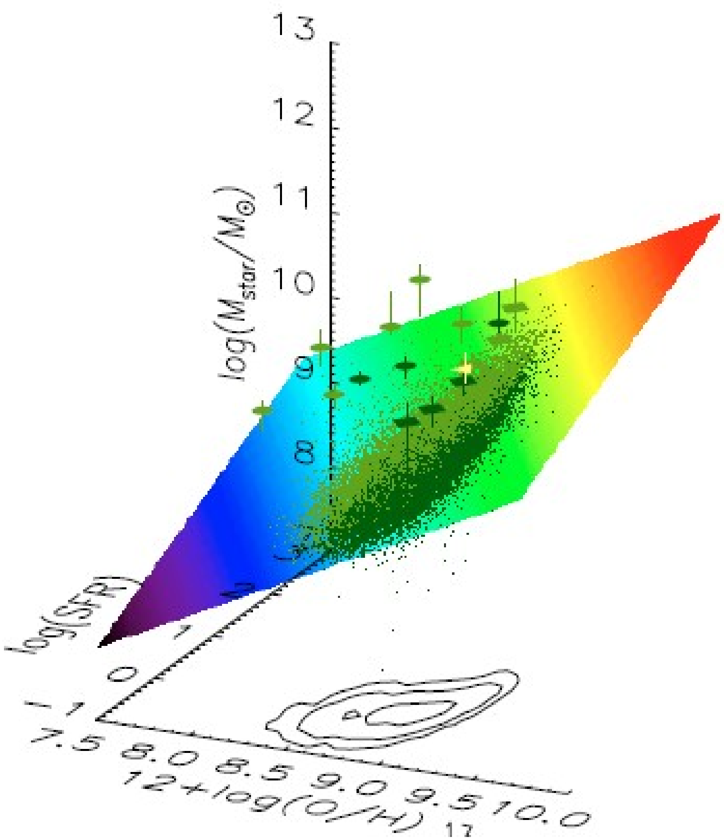
Lara-Lopez et al. 2010

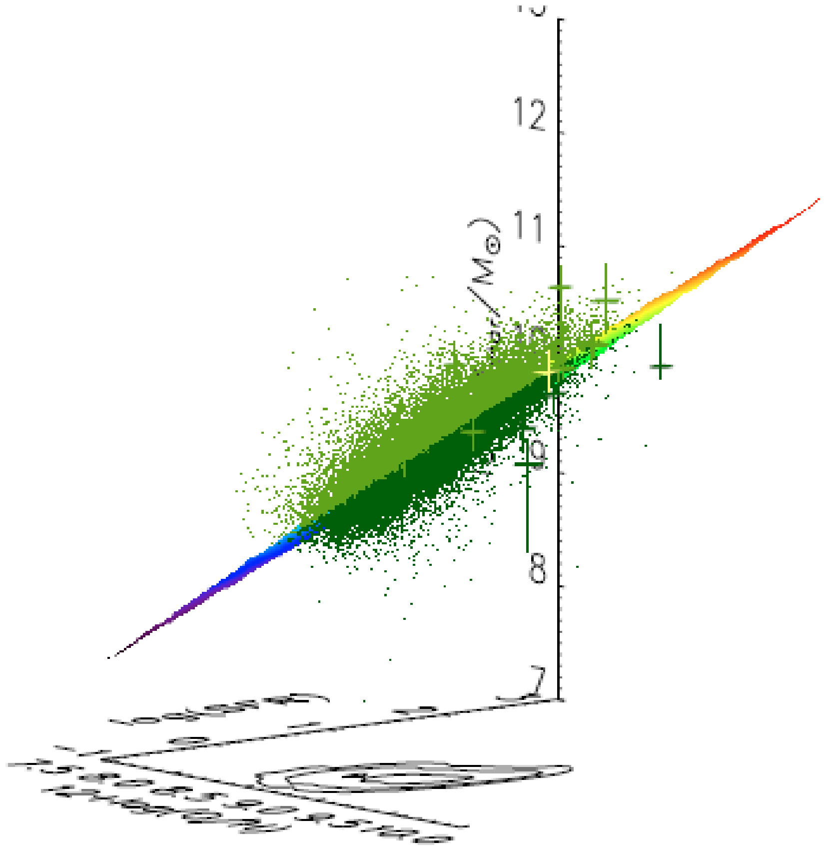
Main Relations Between Galaxies

Fundamental plane of star-forming field galaxies:

$$\log(M_{star}/M_{\odot}) = \alpha\,[12 + \log(O/H)] + \beta\,[\log(SFR)\,(M_{\odot}\,yr^{-1})] + \gamma$$

Where α=1.122 (±0.008), β=0.474 (±0.004),and γ=−0.097 (±0.077)





Lara-Lopez et al. 2010

Interactions and mergers

Result of one galaxy's gravity disturbing another galaxy







Credits: HST

Interactions and mergers

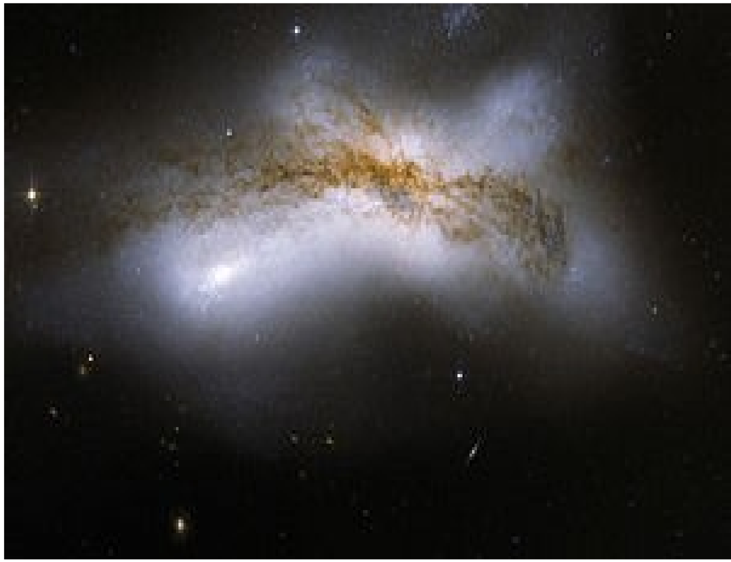
Types of interactions:

Satellite interaction – giant galaxy interacting with its satellite/s
(attraction of spiral arms, triggering of star formation)

Interactions and mergers

Types of interactions:

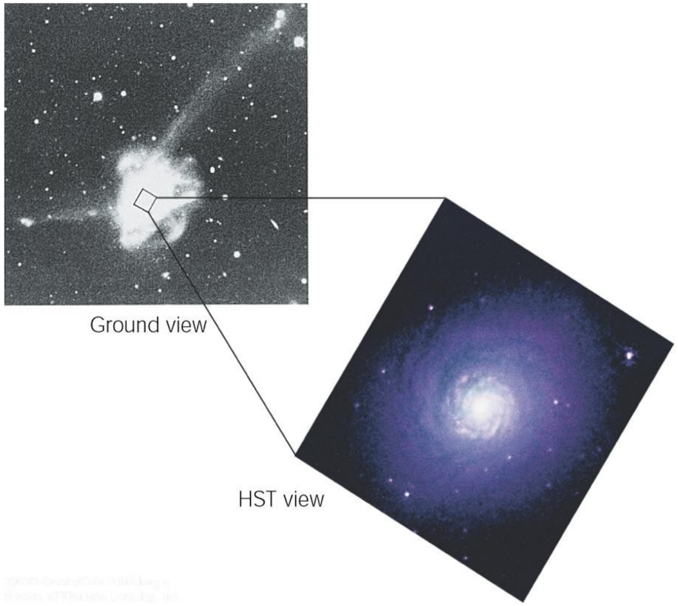
Galaxy collision – two galaxies collide, but do not have enough momentum to continue travelling after the collision; they fall back into each other and merge after many passes through each other, forming one galaxy



Interactions and mergers

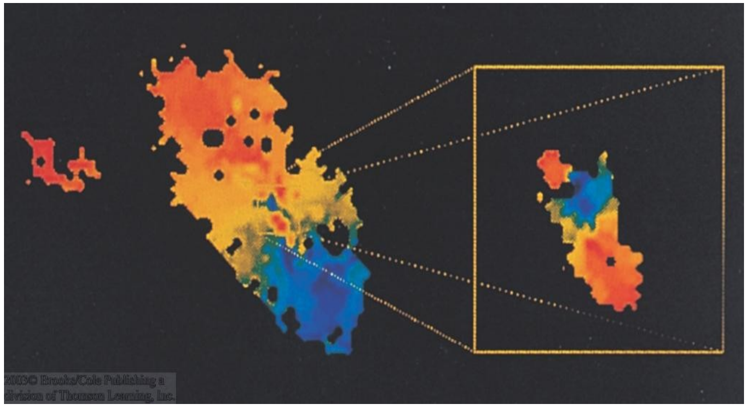
Types of interactions:

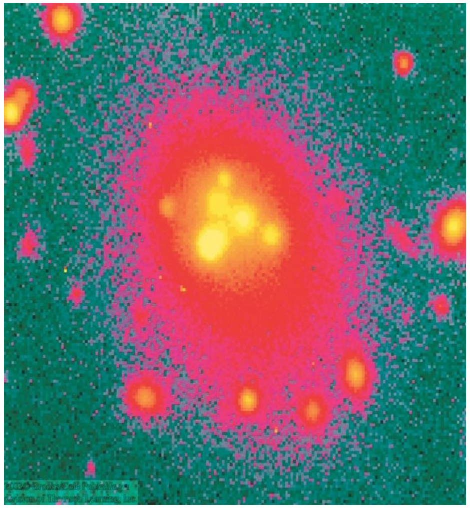
Galaxy mergers – relative momentum of the two galaxies is insufficient to allow the galaxies to pass through each other →they merge together and form a single galaxy. When one of the galaxies is much more massive: cannibalism (larger galaxy relatively undisturbed, but smaller galaxy is torn apart)



NGC 7252: Probably result of a merger of two galaxies, ~ a billion years ago: small galaxy remnant in the centre is rotating backward

Radio image of M64: Central regions rotating backward!





Multiple nuclei in giant elliptical galaxies

Interactions and mergers

Types of mergers:

* **by number:** binary or multiple mergers

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* **by size/mass:** minor (one dominant component in comparison with other/s) or major mergers (for two spiral galaxies of similar sizes)

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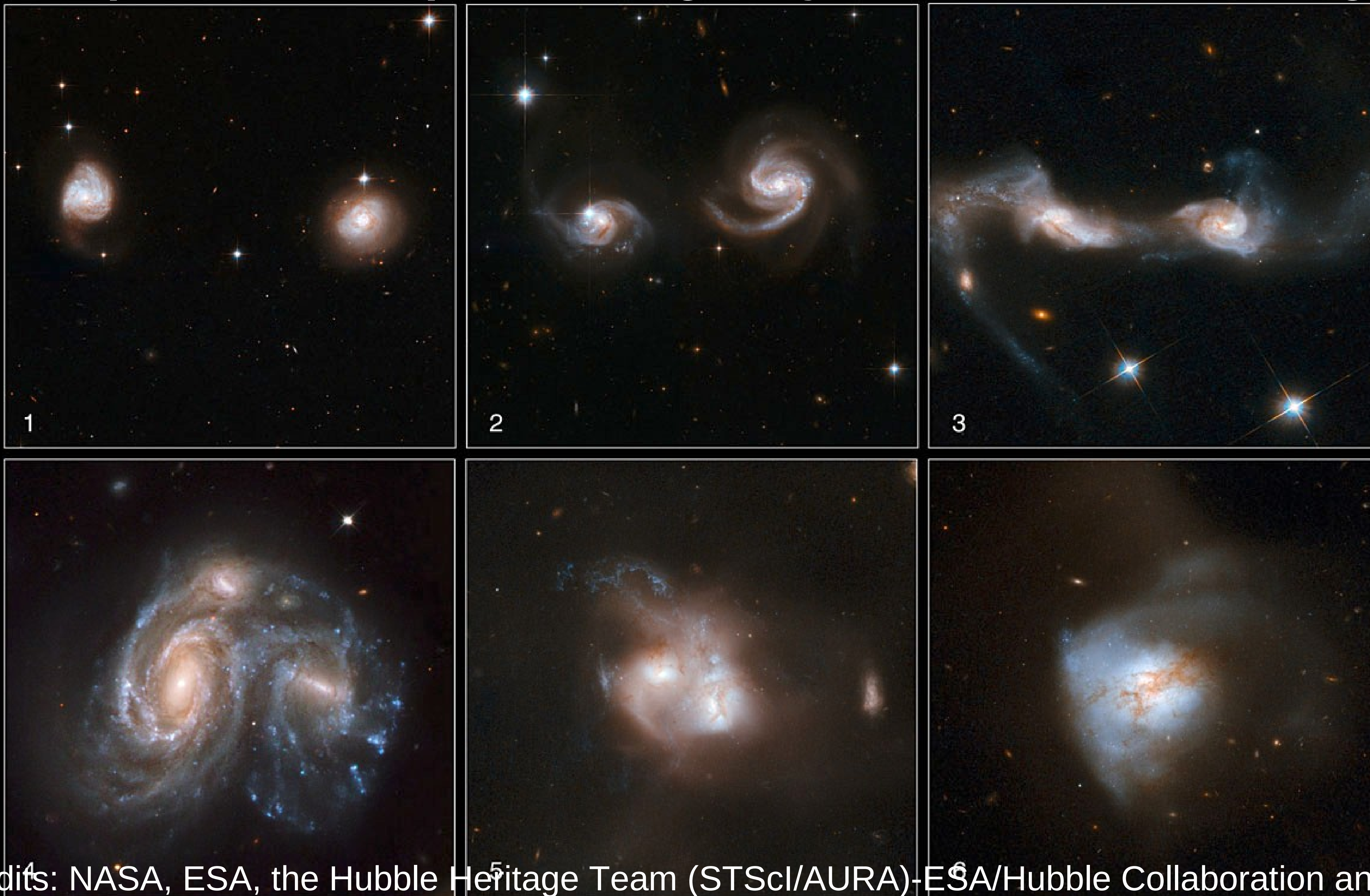
* **by gas richness:**

- wet mergers (between blue gas-rich galaxies; enhanced star formation as a result)
- dry mergers (between red and gas-poor galaxies, stellar-mass growth as a result)
- mixed merger (between blue/gas-rich and red/gas-poor galaxies)

Interactions and mergers

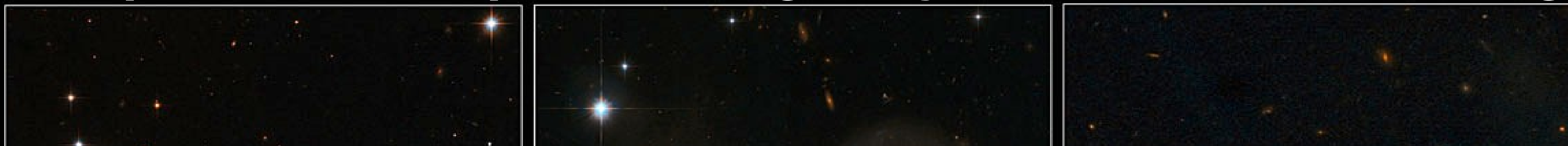
Example: different phases of galaxy interactions and merger



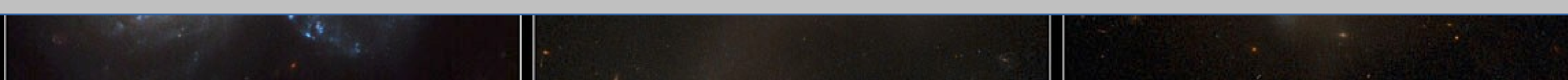
Credits: NASA, ESA, the Hubble Heritage Team (STScI/AURA)-ESA/Hubble Collaboration and A. Evans (University of Virginia, Charlottesville/NRAO/Stony Brook University), K. Noll (STScI), and J. Westphal (Caltech).

Interactions and mergers

Example: different phases of galaxy interactions and merger



THE EFFECT OF MERGER DEPENDS
ON DIFFERENT PARAMETERS:
e.g., SIZE and MASS OF COMPONENTS, COMPOSITION,
NUMBER OF INTERACTING COMPONENTS,
THEIR SPEEDS, COLLISION ANGLES, ETC.



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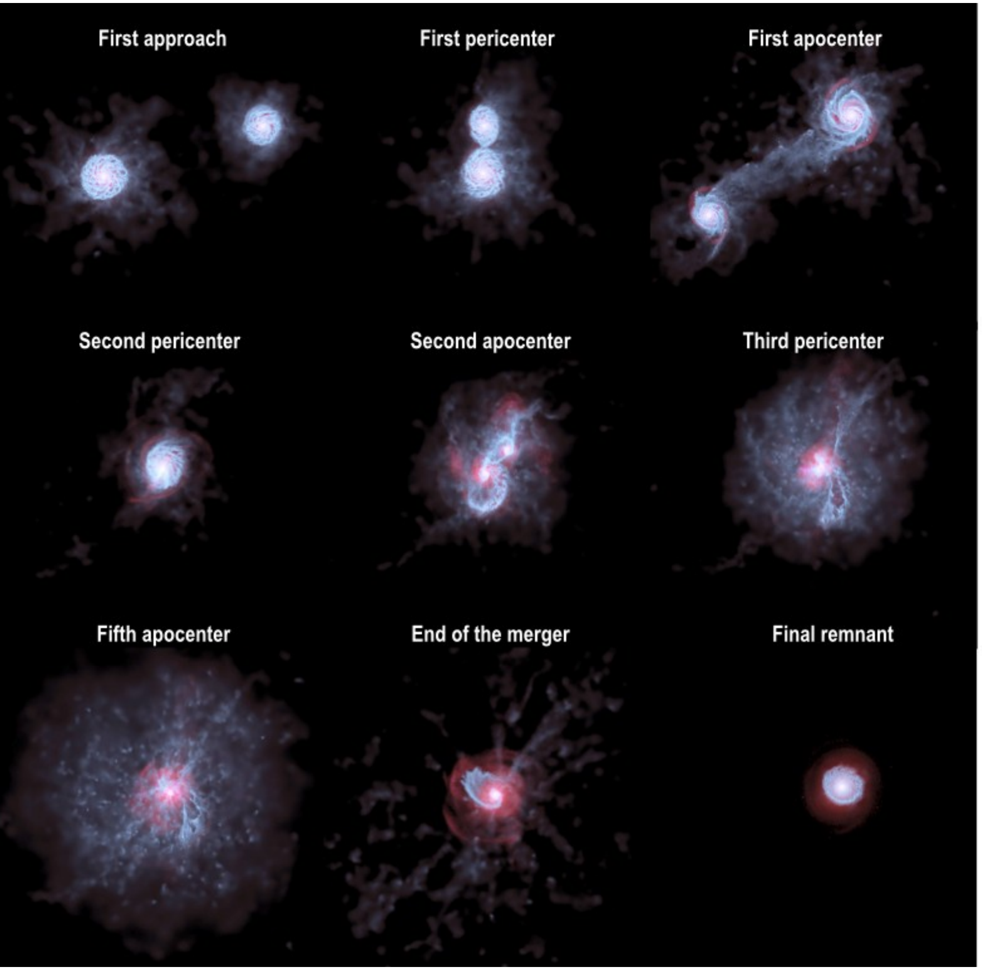
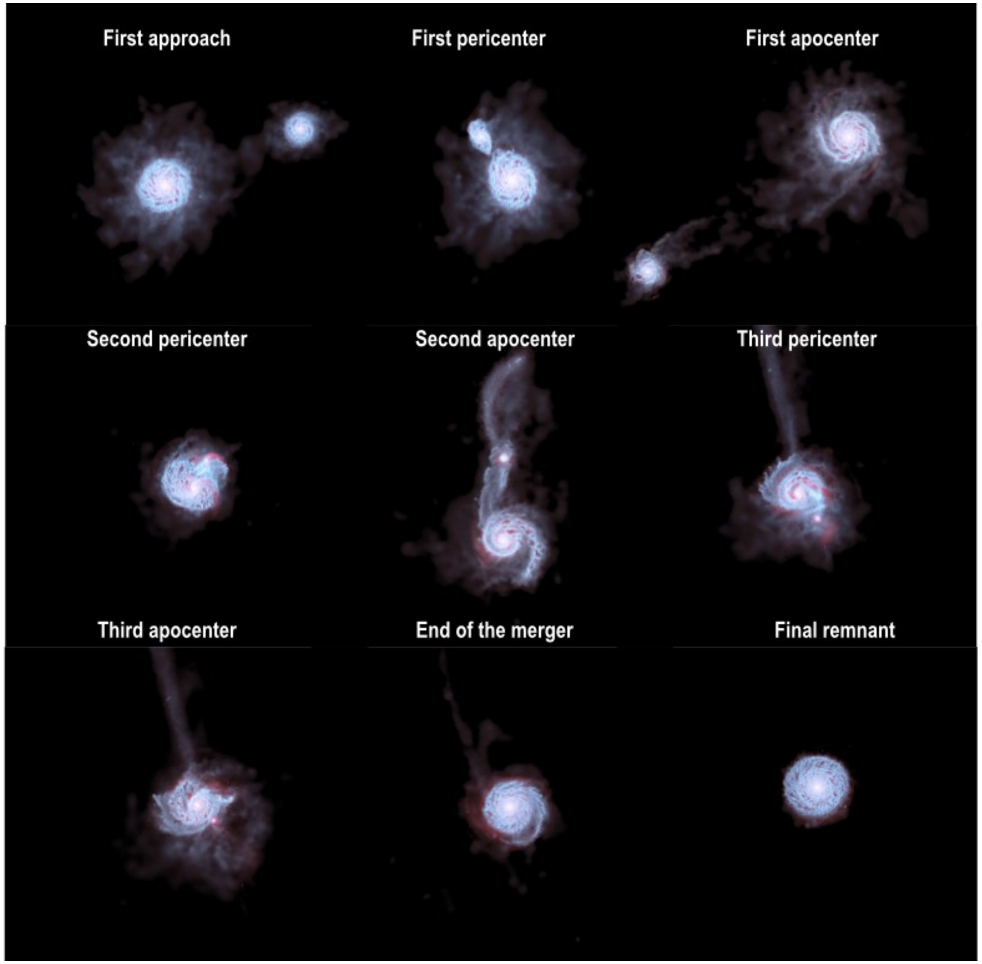
Interactions and mergers

Galaxy merger simulations
(with different initial mass ratios between the two galaxies)



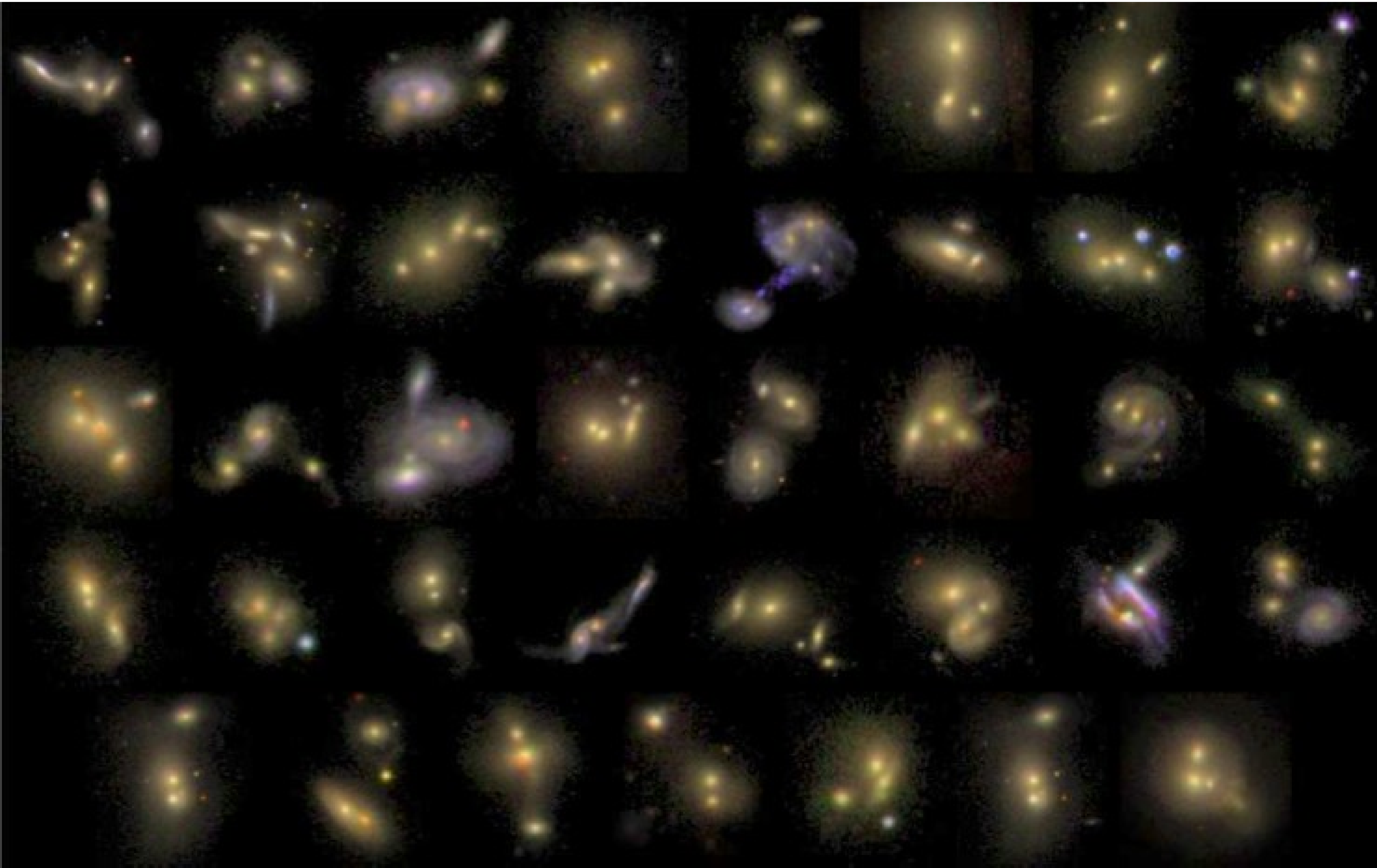


1:2 merger *Credits: Marta Volonteri* **1:6 merger**

Numerical simulations are fundamental for understanding galaxy mergers

Interactions and mergers

Multi mergers, Galaxy Zoo survey



Interactions and mergers

Some important aspects related with mergers:

- violent relaxation
(quick change of galaxy shape and star orbits with the merger)

Example: the collision of two spiral galaxies, with orderly rotation in the plane of the disc, after a collision form an object with random and complex stellar orbits (as in ET galaxies)

- violent star-formation
(starburst phase, up to 100 of stars/yr)

- usually quenched star-formation after a merger

Interactions and mergers

- related phenomenons and terminologies,
(also with galaxy formation and evolution in general):
inflows and outflows,
AGN feedback, SF feedback,
winds,
gas cooling and gas heating

(also related with poor environments,
but on smaller scales)

Interactions and mergers

Their importance:

- To understand the formation and evolution of galaxies and universe across the cosmic time. Merger rate directly related with galaxy evolution (more mergers in the past).

- To understand when and how the galaxies are assembled.

- To understand the formation of different types of galaxies observed in the universe (e.g. active galaxies, starbursts, etc.) and their role in galaxy evolution.

- To provide knowledge (put constraints) for models of galaxy formation and evolution (e.g, hydrodynamical cosmological simulations (HYD) and semi-analitic models (SAM)).

3. Starbursts

Galaxies very rich in gas and dust with an exceptionally high rate of star formation (~ 100 Mo/yr), compared to the usual star formation rate seen in most of galaxies

Usually last for only ~ 10 million years → short period in the lifetime of galaxy

Were more common during the early history of the universe

3. Starbursts

Triggering mechanism

Star formation needs: molecular clouds + shock waves

Necessary to concentrate a large amount of cold molecular gas (needed for star formation) in a small volume → such concentrations + perturbations may cause starburst activity → galaxy mergers and interactions good candidates for triggering

3. Starbursts

Types:

Blue Compact Galaxies (BCGs)

* low mass, low metallicity, dust-free objects

* large number of hot, young stars

* most of them contain also older stellar populations

* most of them show signs of recent mergers and interactions

Small compact galaxies – Blue Compact Dwarf Galaxies

3. Starbursts

Types:

Luminous Infrared Galaxies (LIRGs)

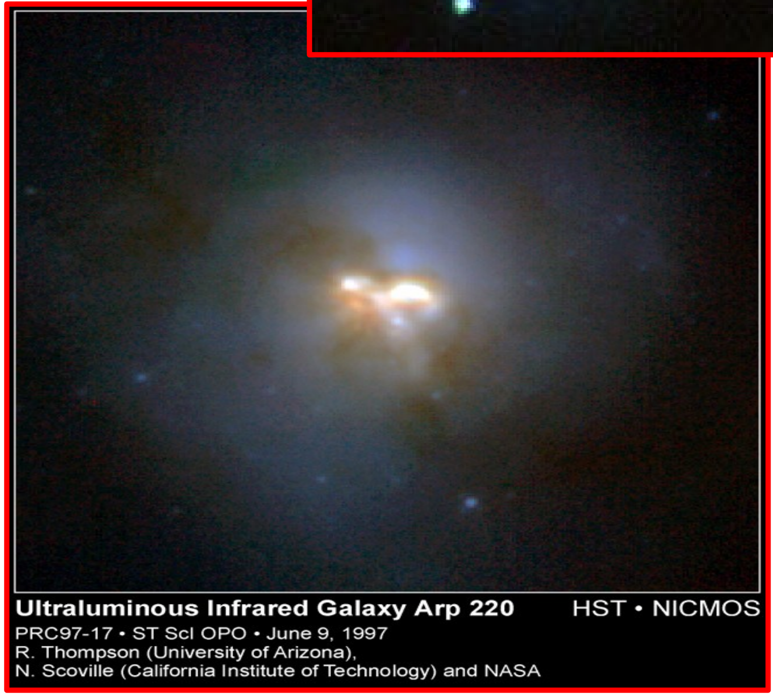
* emit more than 10^{11} solar luminosities in FIR; extremely dusty objects

* often contain AGN

* emit > 90% of light in IR

* most of them show signs of recent interactions and disruptions

* if emit > 10^{12}, 10^{13}, or 10^{14} solar luminosities known as ULIRGs, HLIRGs, ELIRGS, respectively



* High number of young, hot stars, HII regions, OB associations, SN explosions

3. Starbursts

Their importance:

- Large number of very distant galaxies are starbursts → difficult for detailed study, but important for understanding the properties of galaxies when the universe was younger.

- Local starbursts can serve to explore the characteristics of these galaxies at high redshifts.

- However, starbursts rare in the local universe → more frequent mergers and more of them billions of years ago when the universe was younger.

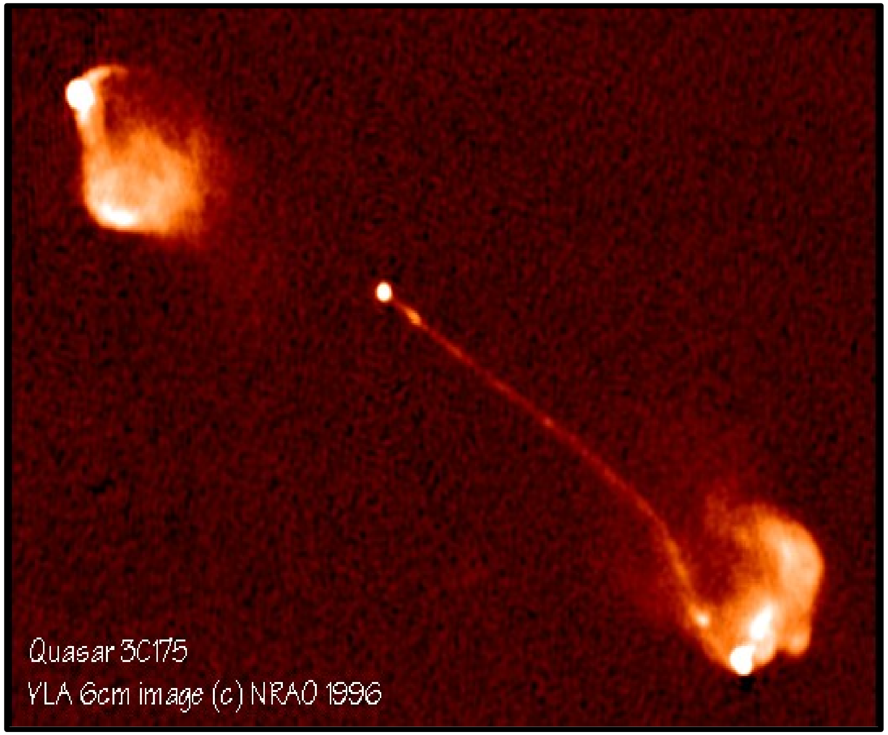
- Important for measuring the rate of mergers across the cosmic time.

- They place constrains on models of galaxy formation and evolution.

Active galaxies, AGN

Active galaxies = galaxies that have an
Active Galactic Nuclei (AGN)
in their centre

AGN = Compact region in the centre of galaxies with extremely violent energy release in most (if not all) parts of EM spectrum



Active galaxies, AGN

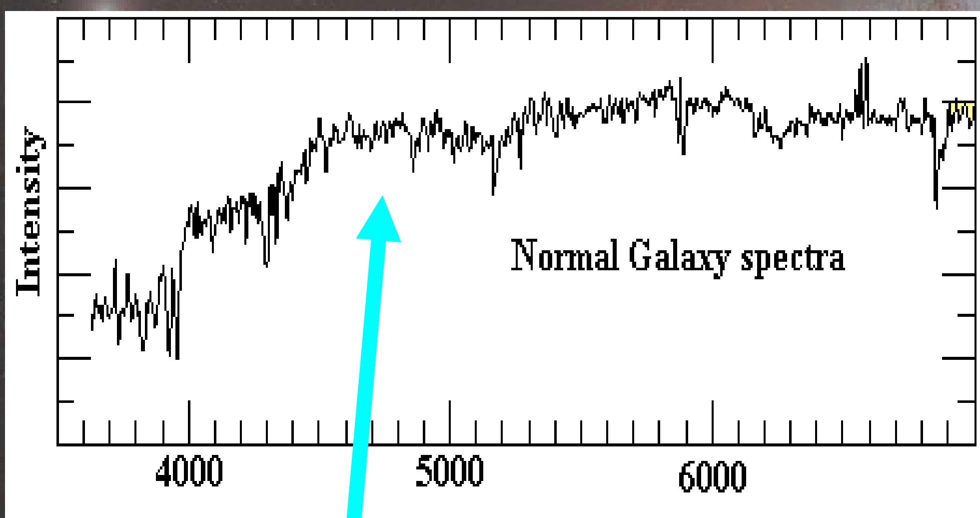
Some of the most luminous sources in the universe!

The most distant objects that we can see in the universe are the most luminous ones
→ by studying active galaxies we observe the edge of the visible universe, and we look back in time to the earliest stages of galaxy formation
→ this makes possible to place important constraints on models of galaxy formation and evolution.

Active galaxies, AGN

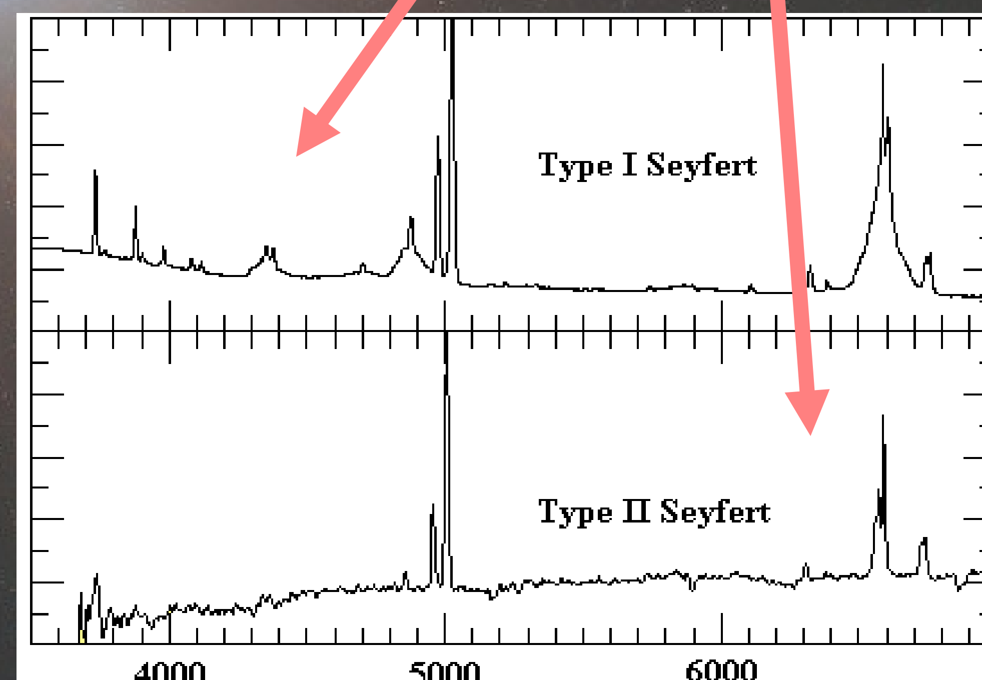
How we discovered them?

Spectra from normal and active galaxies are <u>very</u> <u>different!</u>

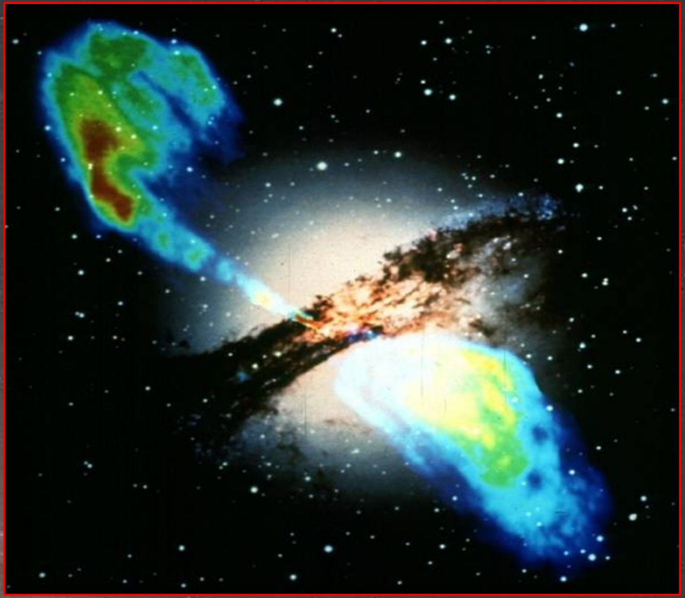


SPECTRUM OF NORMAL GALAXY
(lack of strong emission lines)

SPECTRA OF ACTIVE GALAXIES
(strong emission lines)



Normal vs. active galaxies?



Total luminosities

Normal:
$L \le 10^{11}$ Lo

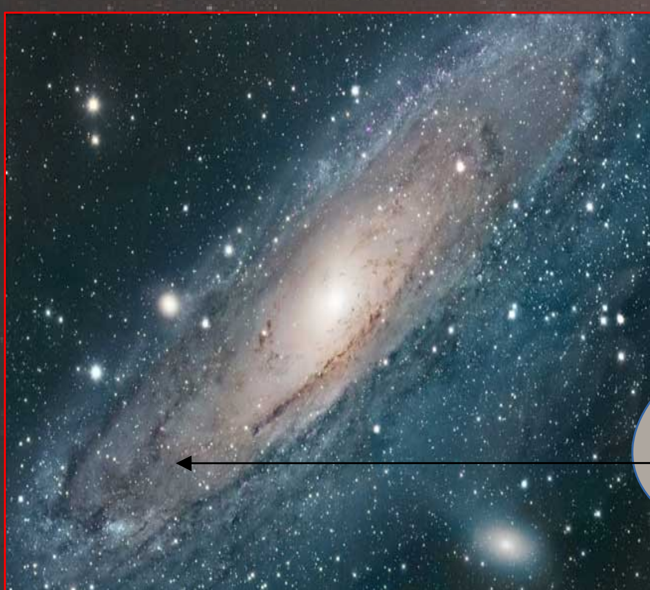
Active:
$L = 10^{11} - 10^{15}$ Lo

Active galaxies can be up to 10.000 times or even more brighter than non-active galaxies

Normal vs. active galaxies?

Nuclei

Normal galaxies much less luminous



Active galaxies many thousands times more luminous than the entire Milky Way

Energy released within the region approximately the size of our Solar System (0.0032% of MW size)

Normal vs. active galaxies?

Variability in luminosity

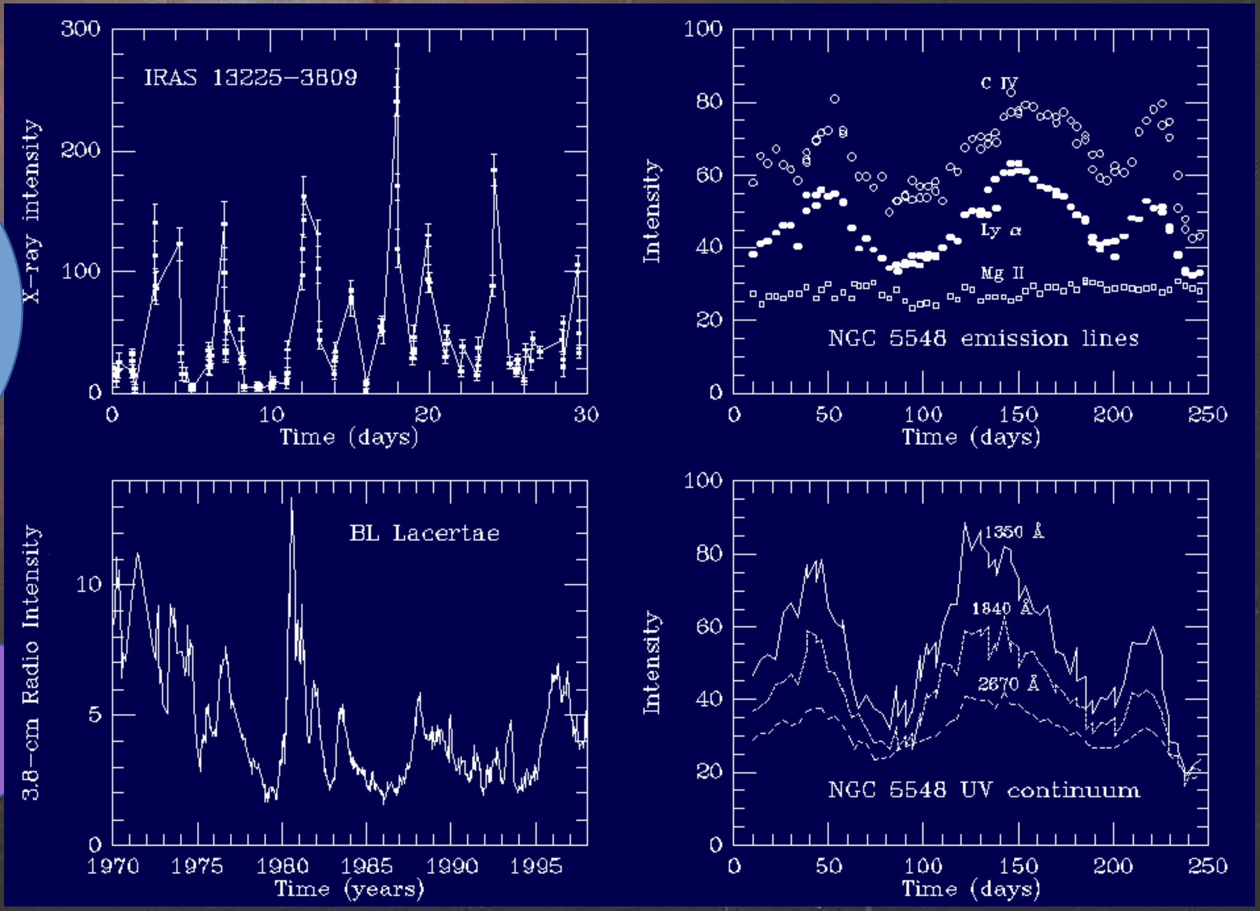
Luminosity in normal galaxies does not change much in short periods of time

In active galaxies L can change even with a factor of 2 in a short period of time (e.g., in few days).

Can be variable also in terms of min, hours.

To change in one hour, the source needs to have a size less than speed of light x 1hr ~ 7AU.

AGN are very compact sources!!



Normal vs. active galaxies?

Relativistic jets and lobes

Non-active galaxies don't have them

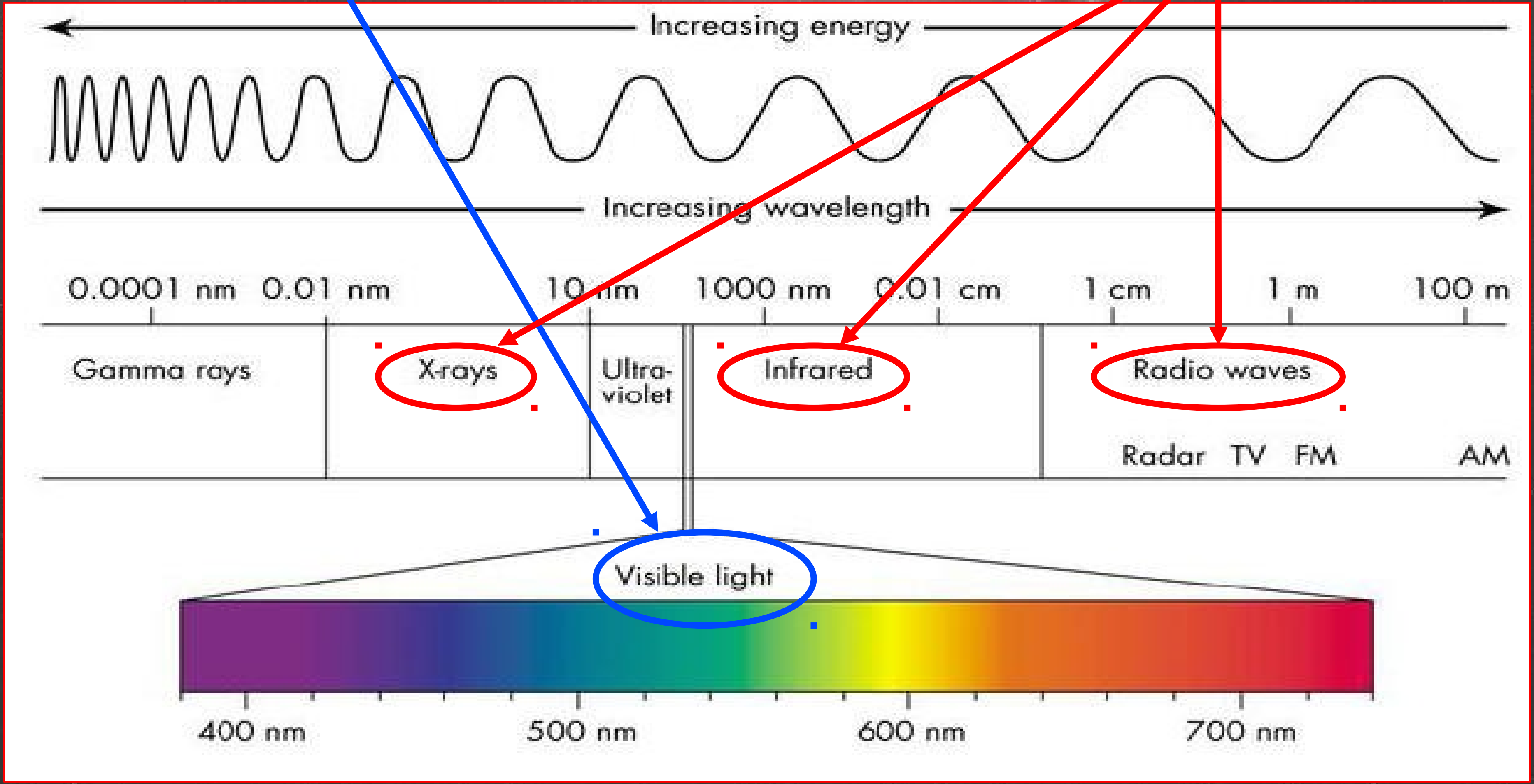
Active galaxies can have them frequently

Normal vs. active galaxies?

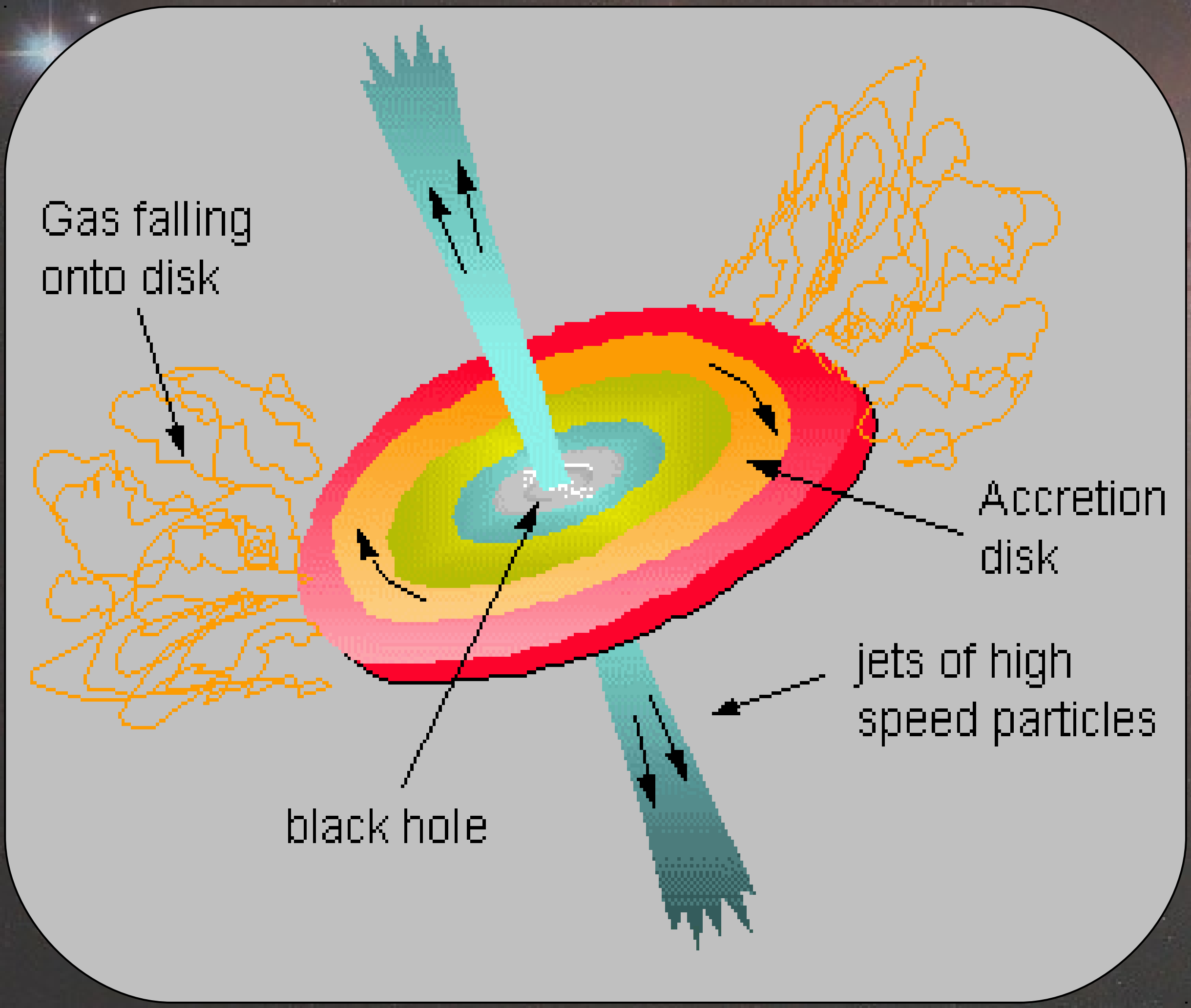
Electromagnetic radiation (the main emission)

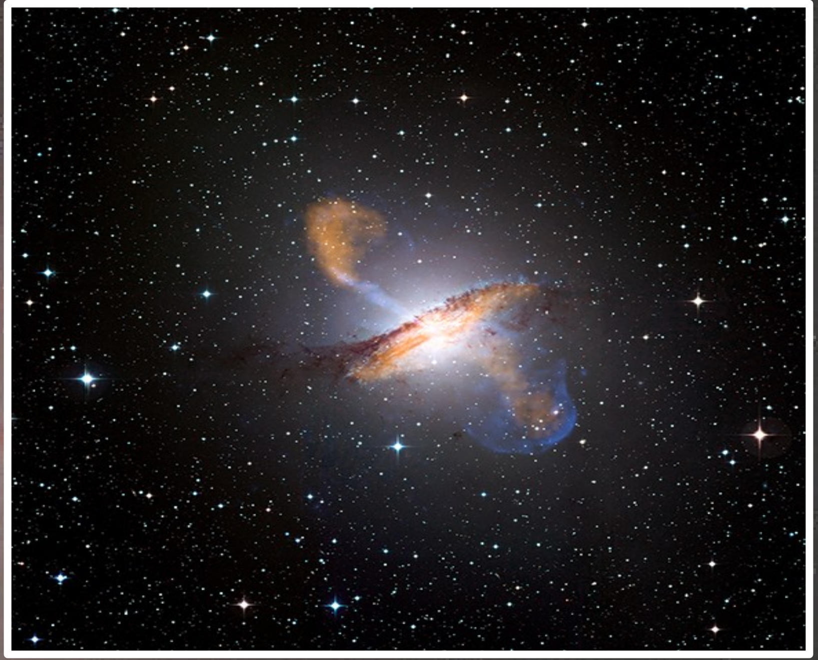
NORMAL GALAXIES

ACTIVE GALAXIES



What is the energy source of AGN?





The release of gravitational energy through the accretion of matter onto a supermassive black hole (thousands of millions of times more massive than our Sun)

Evidences for SMBHs

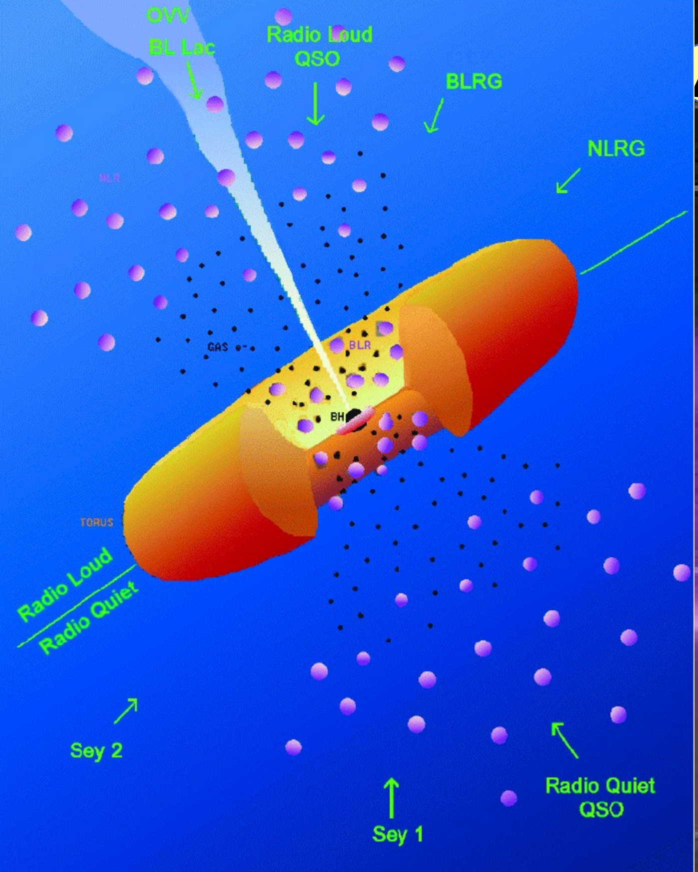
1. Large velocity widths of emission lines
→ typically 2000-15000 km/s, sometimes up to 30000 km/s; typical stellar velocities ~200 km/s)

2. Strongly variable emission
-> relationship with the compact active regions

3. Collimated and straight AGN jets
-> single rotating body

4. Steep rises of the velocity dispersion of stars towards the centres of galaxies
-> massive, non-stellar object in the centre

AGN components and main types



Seyfert 1 QSOs

Radio loud

Seyfert 1.8

LINERs

Compton thin

Type-2 AGN

Type-1 AGN

BL Lac sources

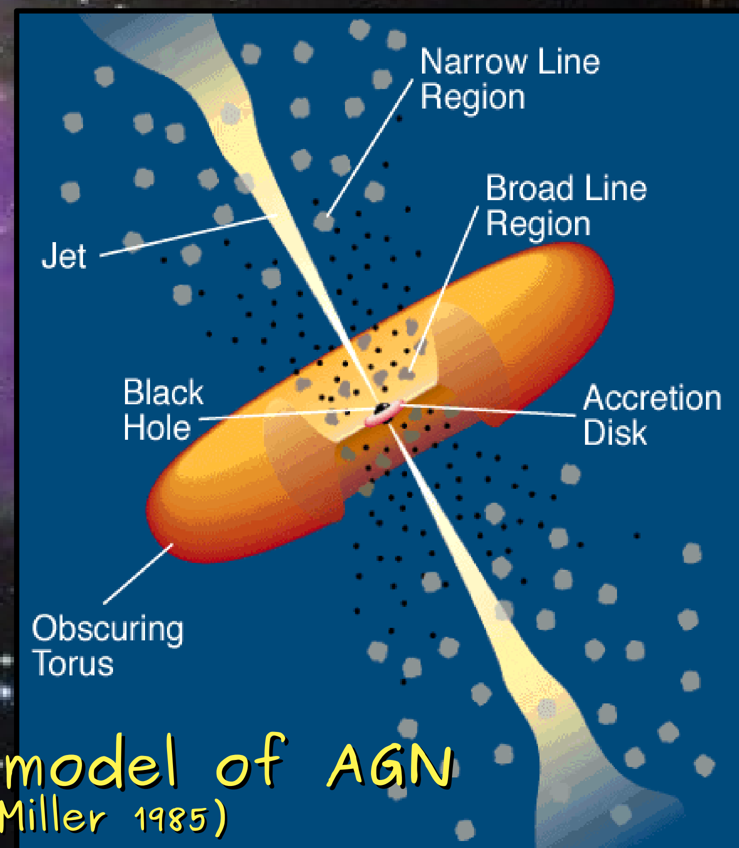
Compton thick

Seyfert 2

Radio quite

Blazars

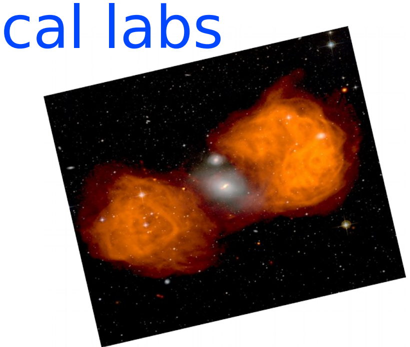
OVV



Standard model of AGN
(Antonucci & Miller 1985)

Why should we care about AGN?

- Have very peculiar and complex physics → challenge, brings important scientific and technological developments and innovation
- High-energetic sources → development of X- and gamma-ray physics and instrumentation
- Possible origin of cosmic rays → important for space weather, satellite technologies, etc.
- Play a key role in galaxy formation and evolution → modeling constraints
- Most luminous and distant visible sources → cosmological labs
- Key element in understanding formation and evolution of the Universe



Still open questions

- Properties of active galaxies at different cosmic times?
- Reliability of unification model and AGN types?
- Origin of relativistic jets?
- Connection between AGN and their host-galaxies?
- Reliability of the standard model of AGN?
- AGN feedback?
- Fraction of AGN at different cosmic times?
- AGN variability?
- Activation of AGN in galaxies?
- Role of AGN in galaxy formation and evolution?
- AGN formation and evolution?
- AGN as cosmological probe?

etc.....

Some of our AGN studies

- **Morphologies of AGN and AGN in deep surveys** – Povic (PhD thesis); Povic et al. 2009a, b; Povic et al. 2013; Getachew (PhD thesis); Getachew et al. 2020a,b (in prep); Bilata (MSc thesis); Bilata et al. 2020 (in prep); different publications under the ALHAMBRA survey

- **Connection between AGN and their host galaxies** – Povic et al. 2012; Povic et al. 2013; Gaulle (MSc thesis); Gaulle et al. 2020 (in prep)

- **Role of AGN in morphological transformation of galaxies** – Povic et al. 2012; Mahoro (MSc and PhD thesis); Mahoro et al. 2017, 2019, 2020a, 2020b (in prep), 2021 (in prep, using our SALT data); Nyirasengiyumva (MS and PhD thesis); Nyirasengiyumva et al. 2020 (in prep)

- **AGN in IR focused on torus properties** – different publications under SAFIR

- **QSOs** – Matute et al. 2015; Terefe (PhD thesis); Terefe et al. 2020, Terefe et al. 2021 (in prep),
and LINERs – Povic et al. 2016; Marquez et al. 2017; Cazolli et al. 2018, 2020; Mazengo (MSc thesis); Mazengo et al. 2020

- **Stellar populations in active galaxies** – Povic et al. 2016; Hernandez-Garcia et al.2018, 2019; Povic et al. 2020 (in prep.)

- **AGN in clusters** – Bekabil (MSc thesis); Beyoro-Amado (PhD thesis); Beyoro Amado et al.2019, 2020 (submitted)

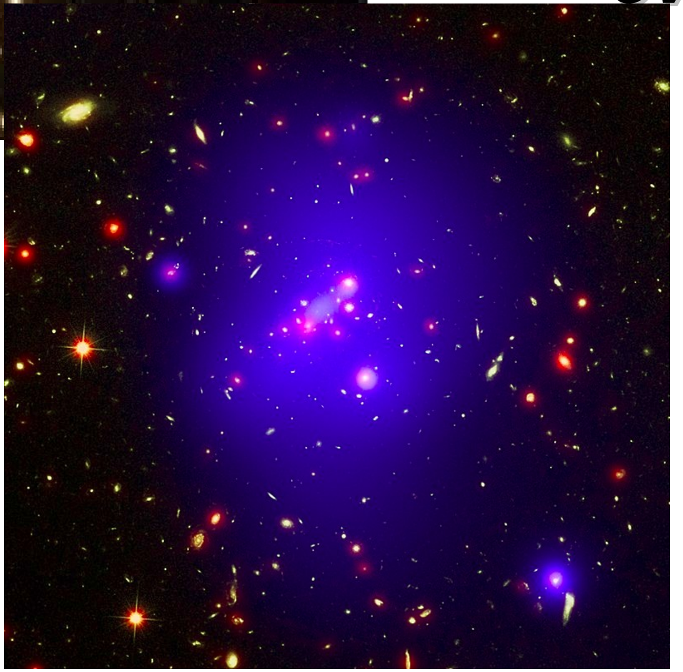
Galaxy groups, clusters, and LSS

Systems of galaxies and inter-galactic matter bounded together by their gravitation

Credits: HST

Probably smallest structures collapsed first in and eventually build the largest structures

→ ***clusters formed possibly over the past 10 billion years (?)***



Credits: NASA/ESA

On-going merger processes heated the inter-galactic gas to very high temperatures!

Evidences of hot inter-galactic gas observed in X-rays

Galaxy groups, clusters, and LSS

Systems of galaxies may contain:

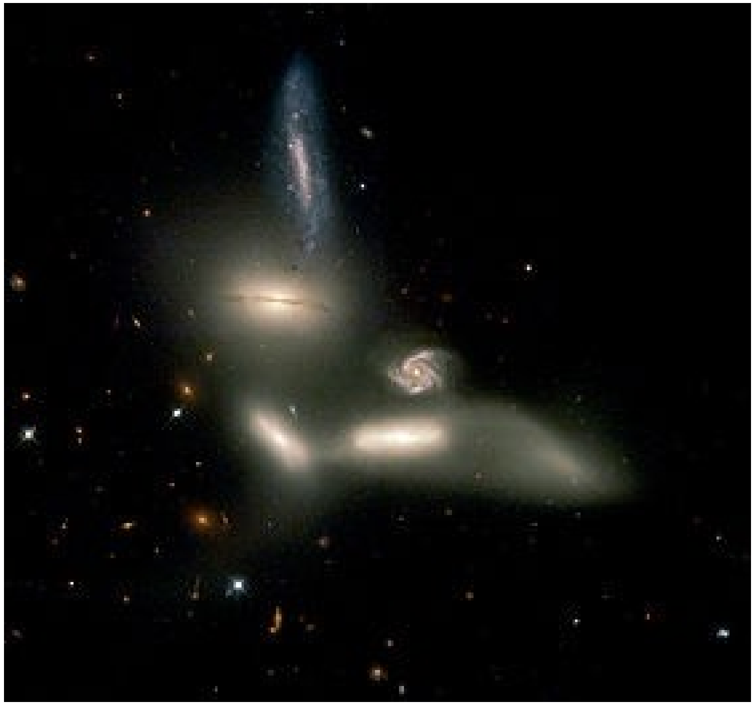
from <u>tens to thousands</u> of galaxies

→ groups and clusters of galaxies, respectively

Usually associated with even larger structures → superclusters

→ associated with filaments and voids, and large scale structure (LSS)

Galaxy groups, clusters, and LSS



Groups of galaxies:

* smallest associations of galaxies

* typically around 50 galaxies
(or few-tens)

* Diameters: ~ 1-2 Mpc,

Masses: ~ 10^{13} solar masses,

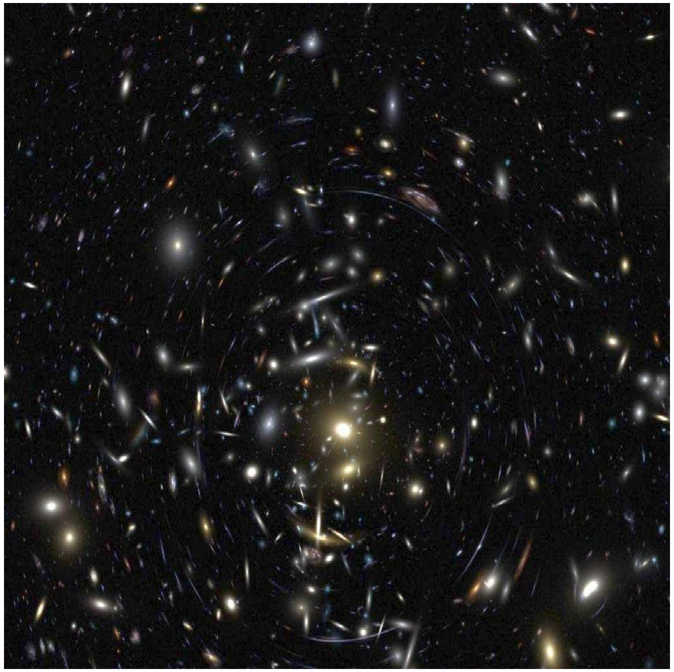
Velocities: ~ 150 km/s.

* Milky Way belongs to the Local Group of galaxies
(~ 50 - 60 galaxies, including Andromeda)

Galaxy groups, clusters, and LSS

Clusters of galaxies:

*** Larger systems than groups, usually contain from few hundreds to few thousands of galaxies, hot X-ray emitting gas, and large amounts of dark matter.**



*** Diameters: ~ 2 - 10 Mpc,**

Masses: ~ 10^{14} – 10^{15} solar masses

Velocities: ~ 800 – 1,000 km/s

*** Environment is important for defining the properties of galaxies. Galaxies in clusters shown to be different then field ones.**

Galaxy groups, clusters, and LSS

Galaxies in clusters have too large velocities to remain gravitationally bound by their mutual attractions

→ presence of additional attractive force besides gravity or additional invisible mass component

Intracluster medium (ICM) **– large amounts of inter-galactic, very hot gas**

Total mass of ICM ~ 2 times greater of that of galaxies → still not enough to keep the galaxies in the cluster

Indications for presence of large amounts of *dark matter (?)*

Galaxy groups, clusters, and LSS

Observational Methods (some of them):

*** Optical or IR imaging and spectroscopy – over-densities at the same redshifts**

*** X-ray imaging and spectroscopy – emission of the hot ICM**

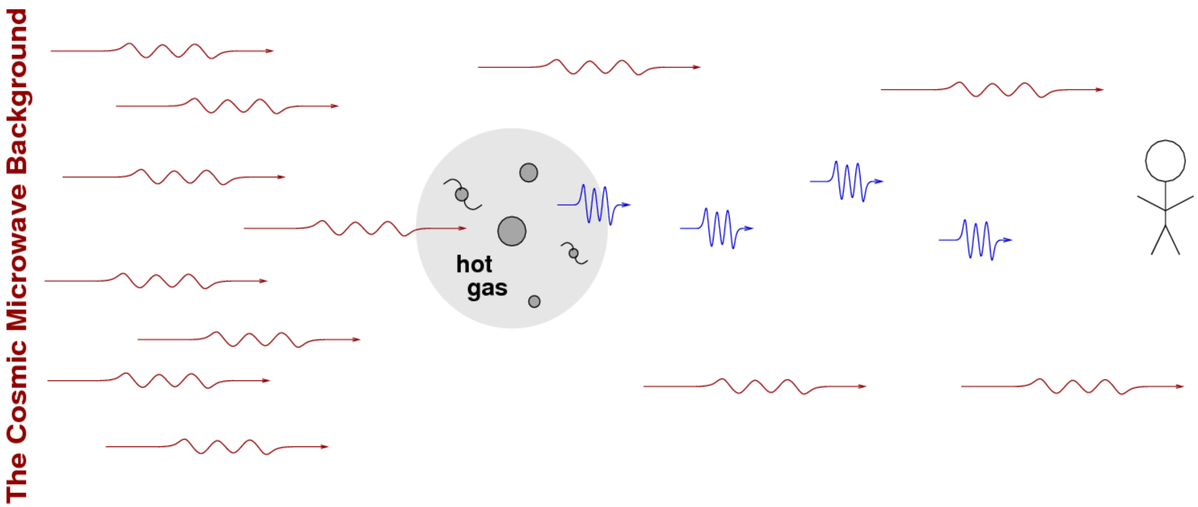
*** Radio emission – number of diffuse structures emitting in radio**

*** Sunyaev-Zel'dovich (SZ) effect – hot, high-energy electrons in the ICM scatter radiation from cosmic microwave background (CMB) -> 'shadow' in the observed CMB at radio wavelengths**

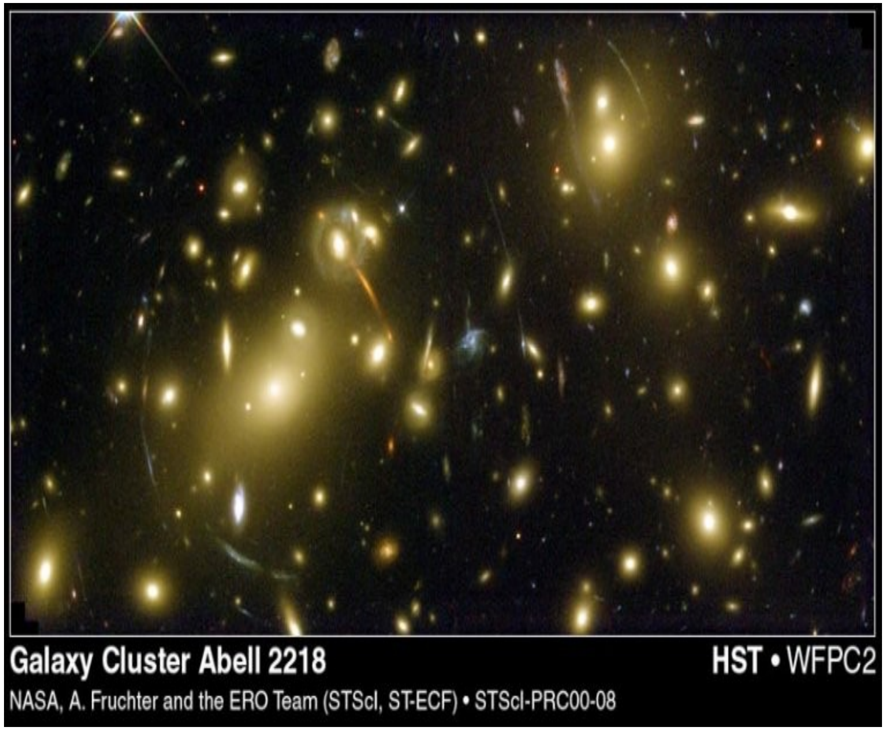
*** Gravitational lensing – distortion of observed light of galaxies behind clusters**

Galaxy groups, clusters, and LSS

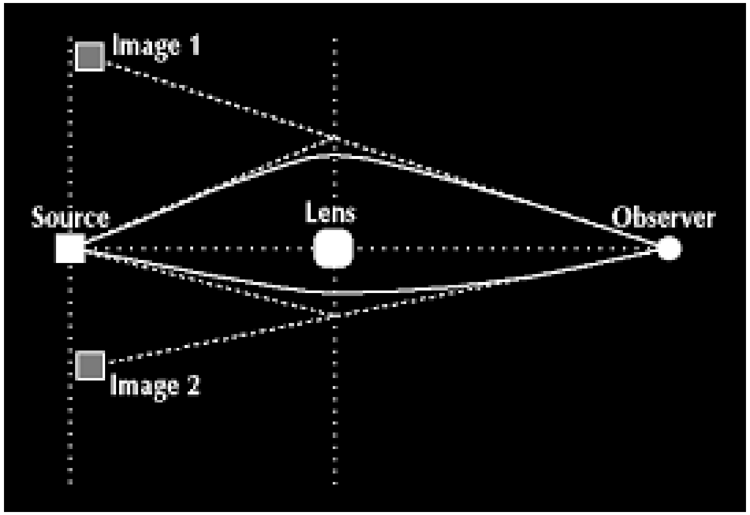
Sunyaev-Zeldovich effect



Observed distortions in the CMB radiation can be used to trace the density perturbations of the universe and LSS. Dense density clusters have been observed using this technique.



Gravitational lensing

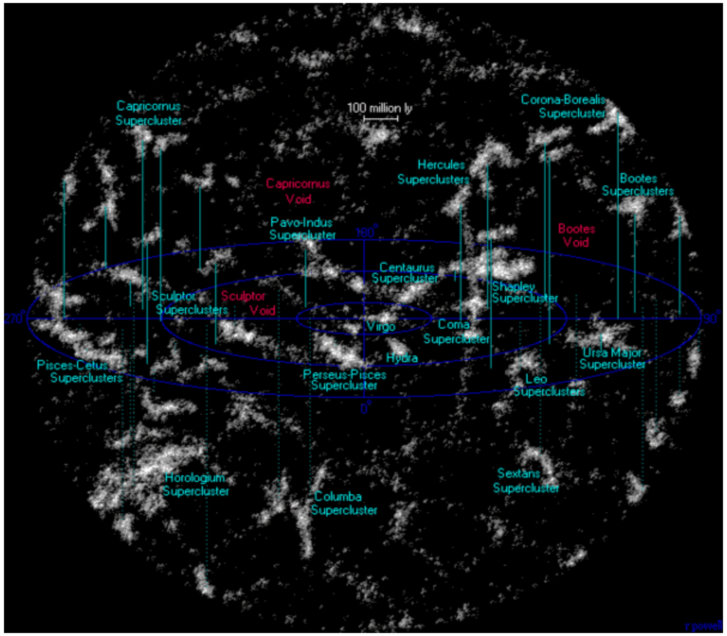


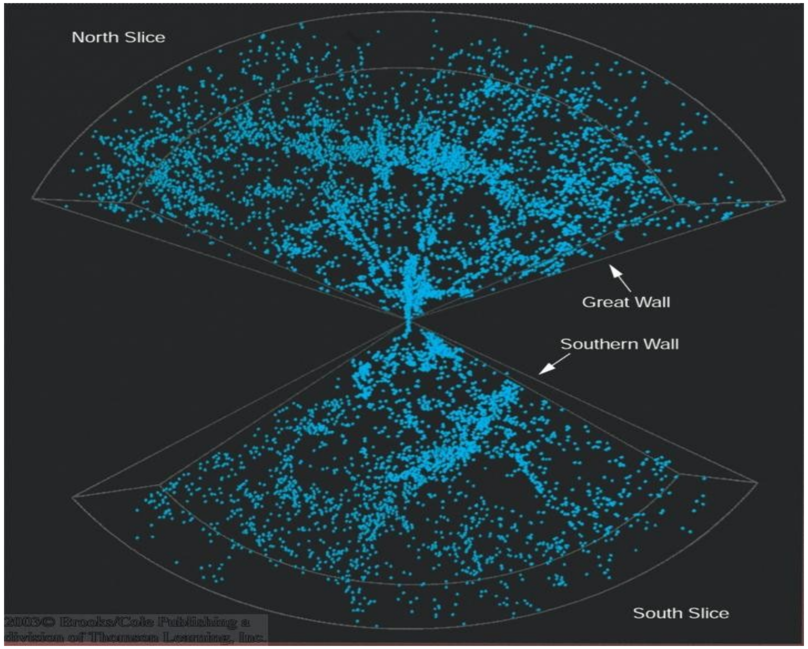
Used to model the distribution of dark matter in clusters

Galaxy groups, clusters, and LSS

Superclusters - contain groups and clusters of galaxies

(Local group inside the Virgo supercluster)

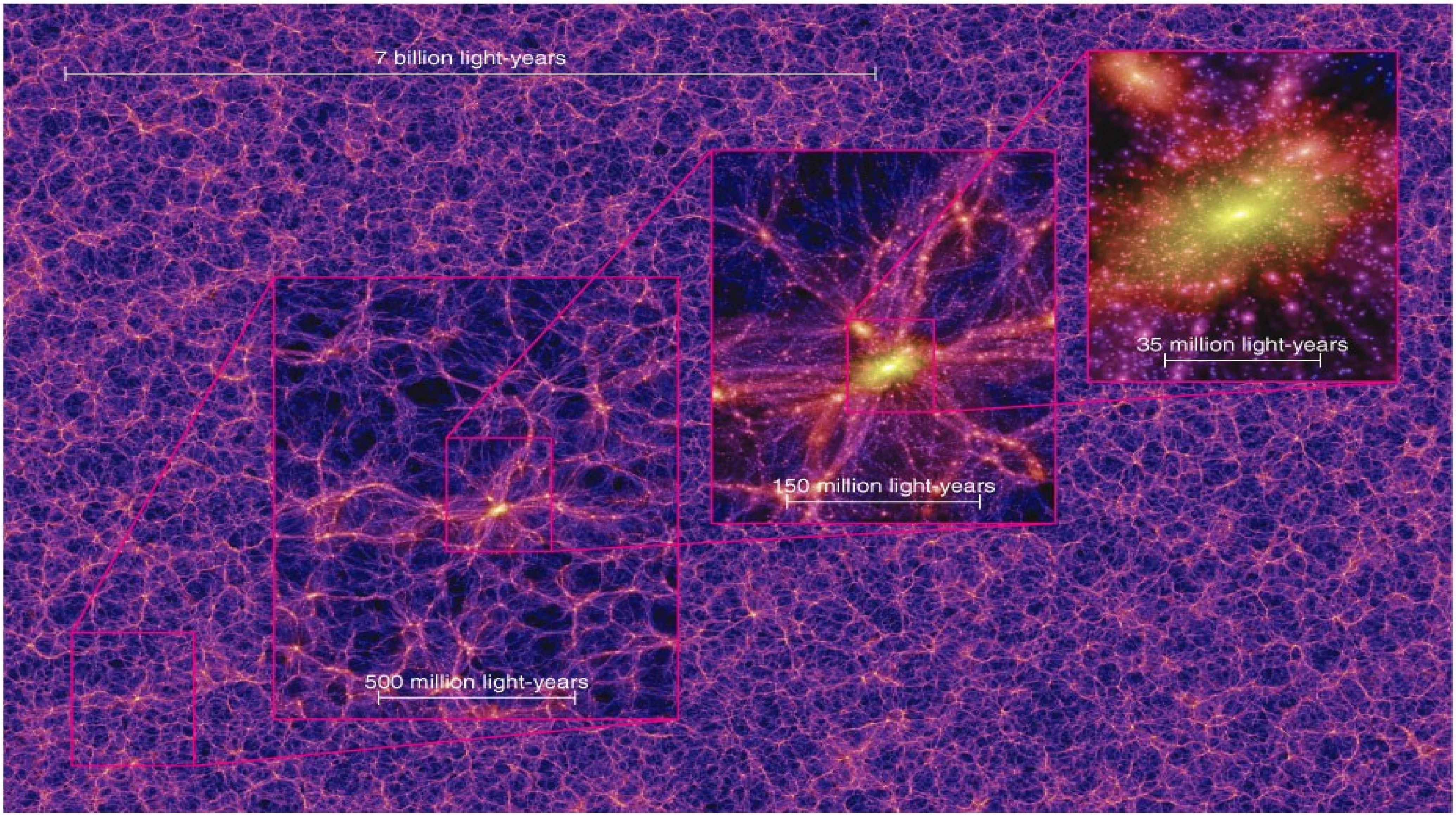




At the supercluster scale galaxies are arranged into sheets and filaments surrounding vast empty voids

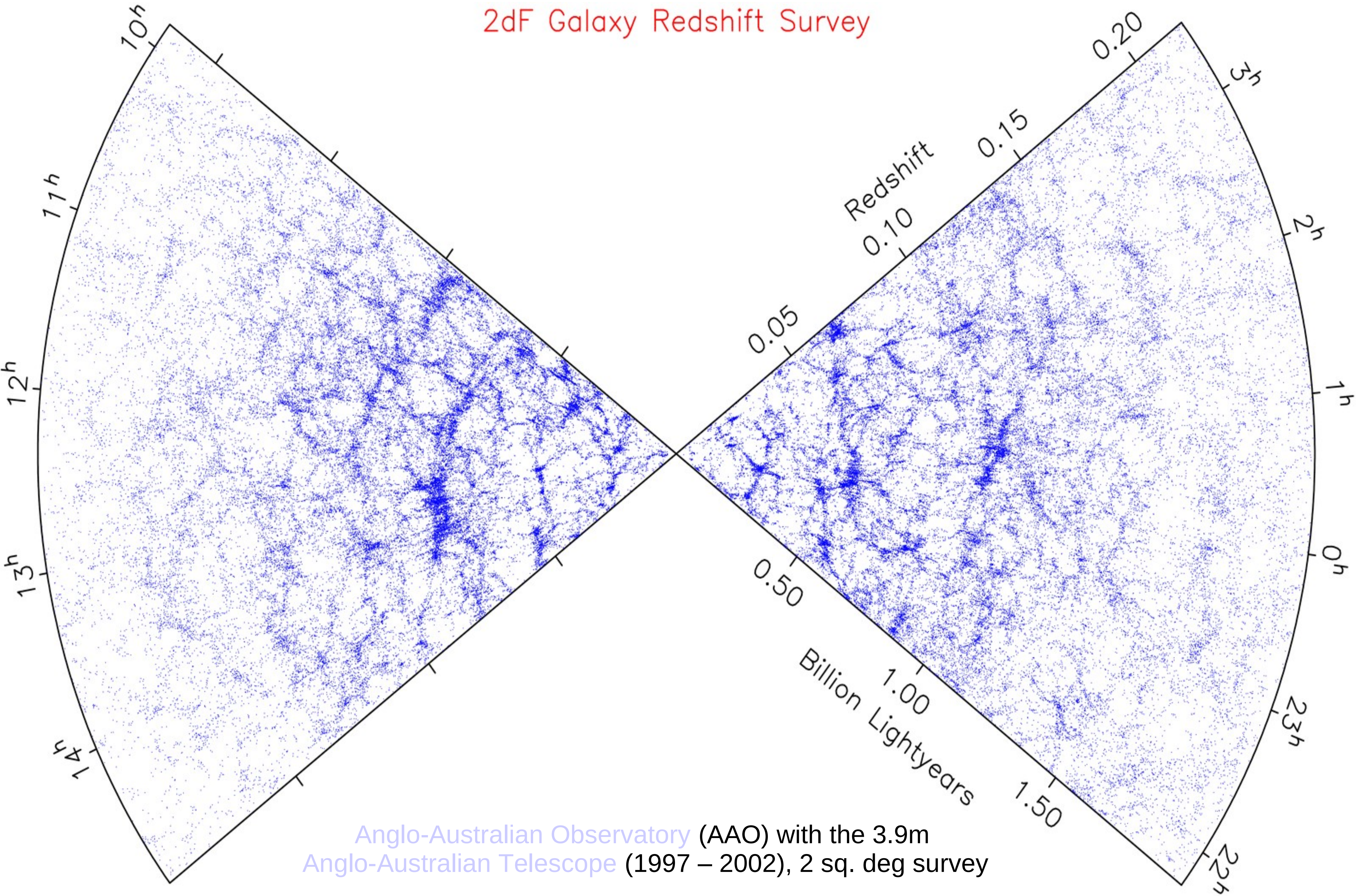
Cosmological Horizon – maximum distance from which particles could have travelled to the observer in the age of the universe

Large Scale Structure in simulations



The Millennium Simulation Project
(http://wwwmpa.mpa-garching.mpg.de/galform/virgo/millennium/)

Large Scale Structure in observations



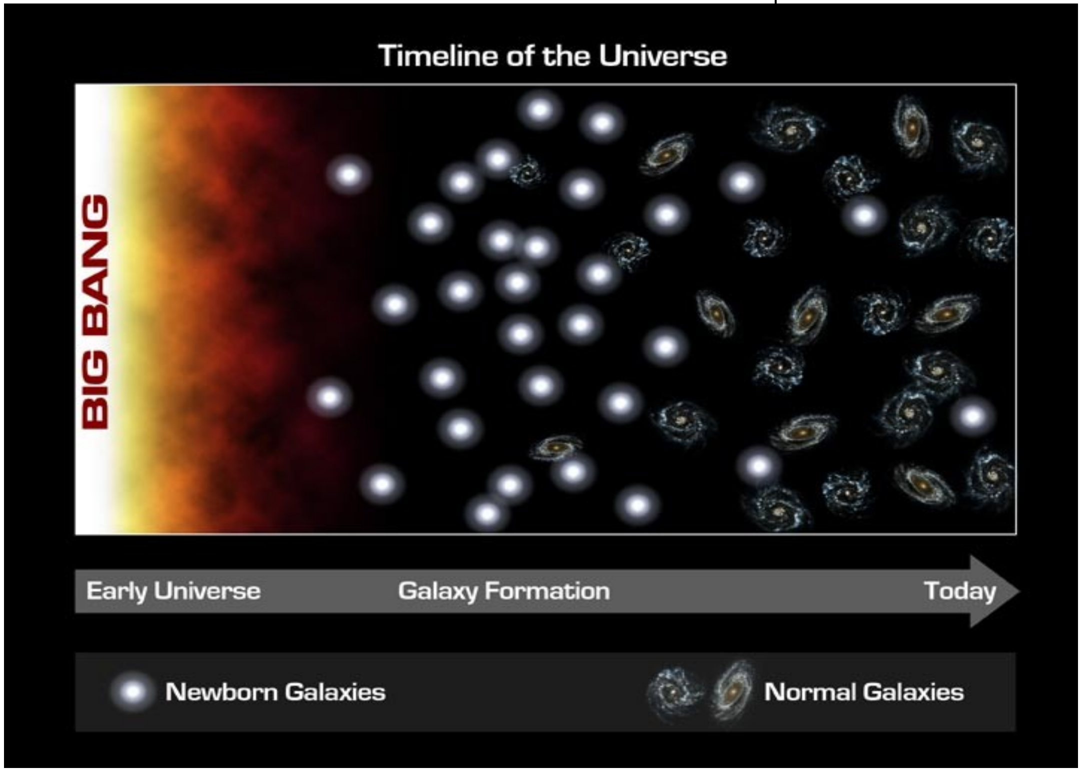
Anglo-Australian Observatory (AAO) with the 3.9m
Anglo-Australian Telescope (1997 – 2002), 2 sq. deg survey

Galaxy formation and evolution

Still one of the main open questions in astronomy

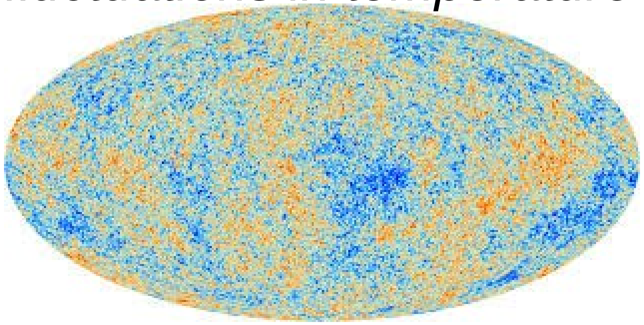
One possibility, larger clouds of gas formed first, making after stars and galaxies

Another possibility, smaller clumps of matter formed first and through collisions and mergers first stars and galaxies have been formed.

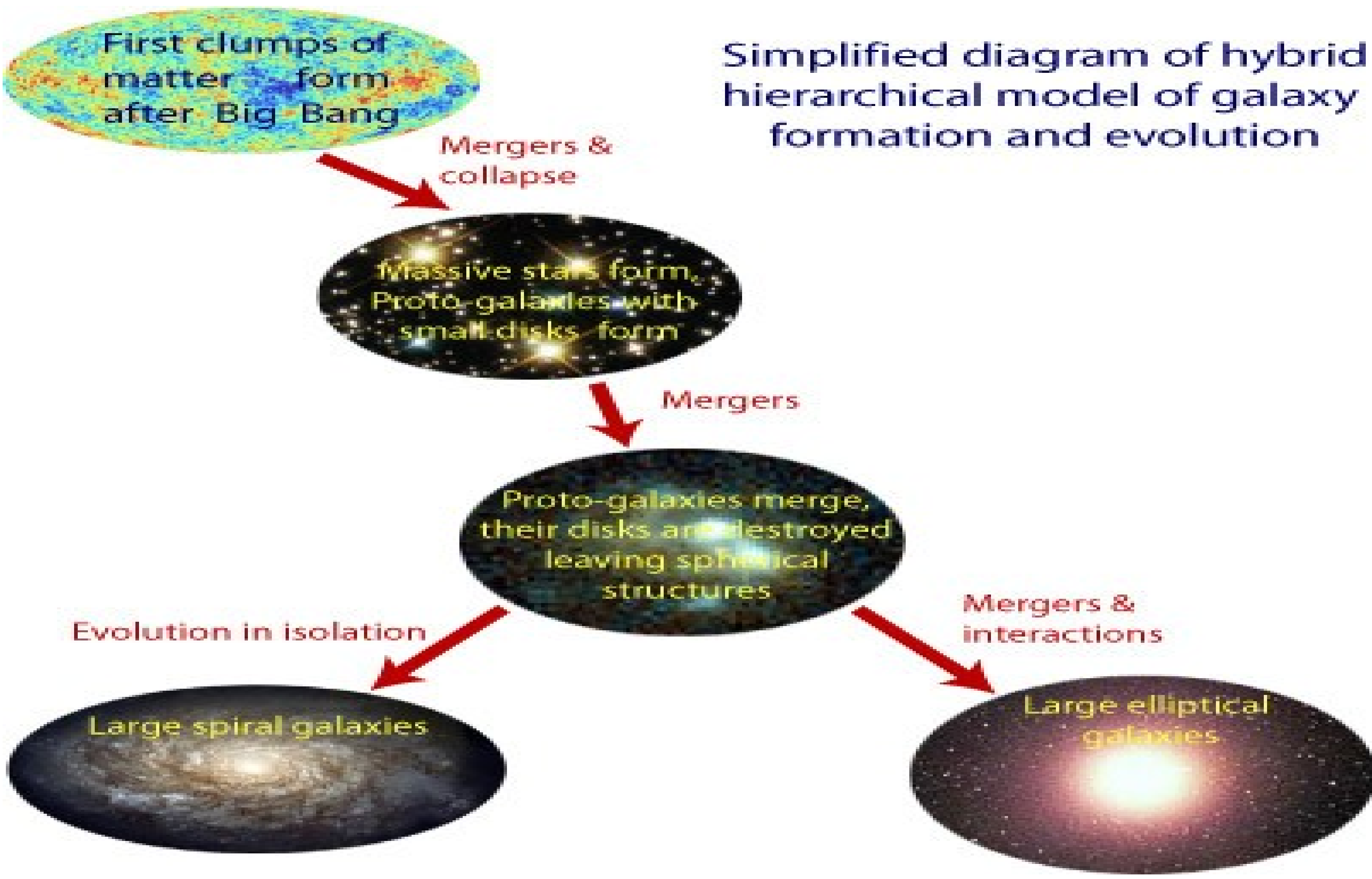


This theory is more supported observationally.

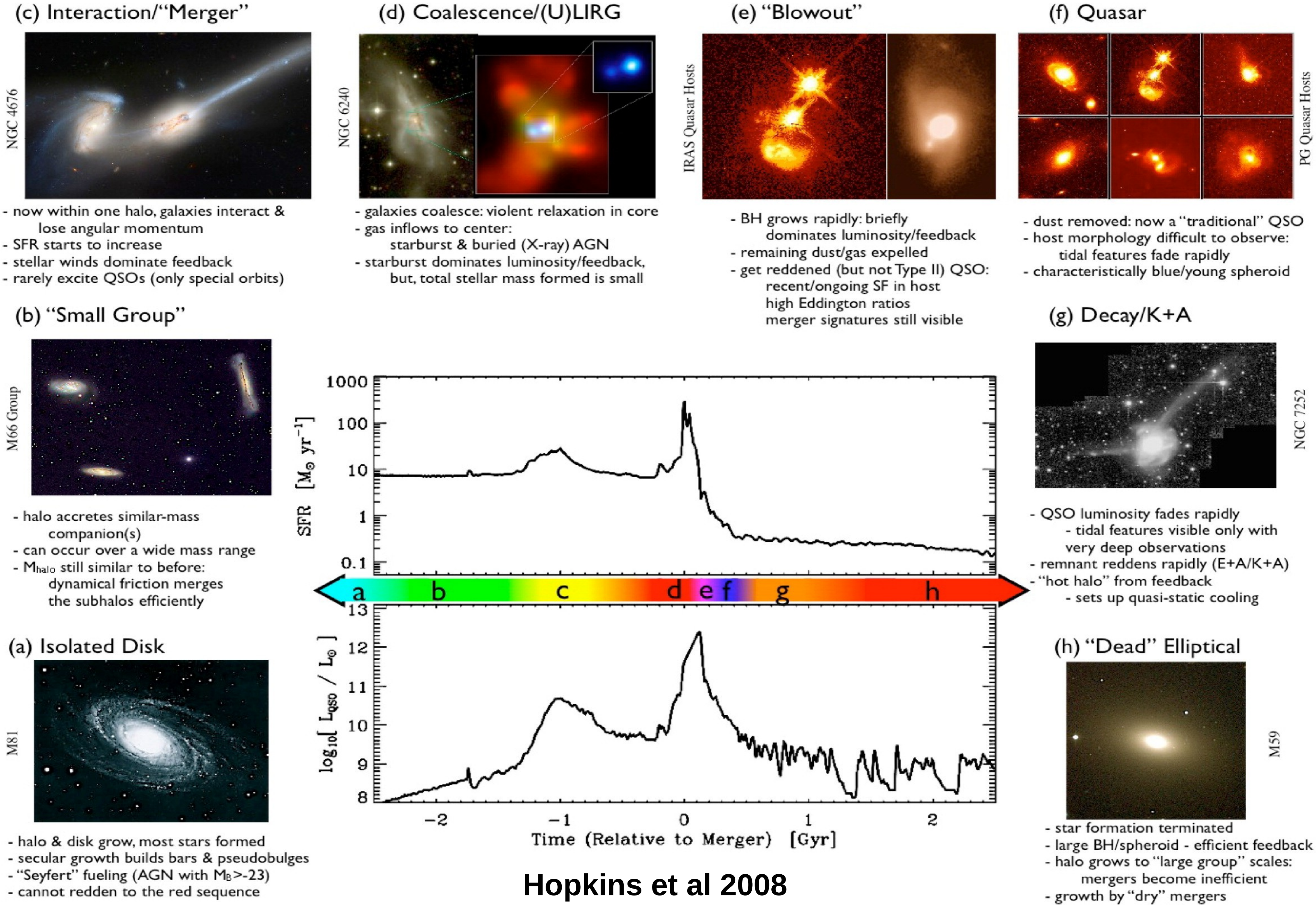
Planck CMB map: small fluctuations in temperature



Galaxy formation and evolution

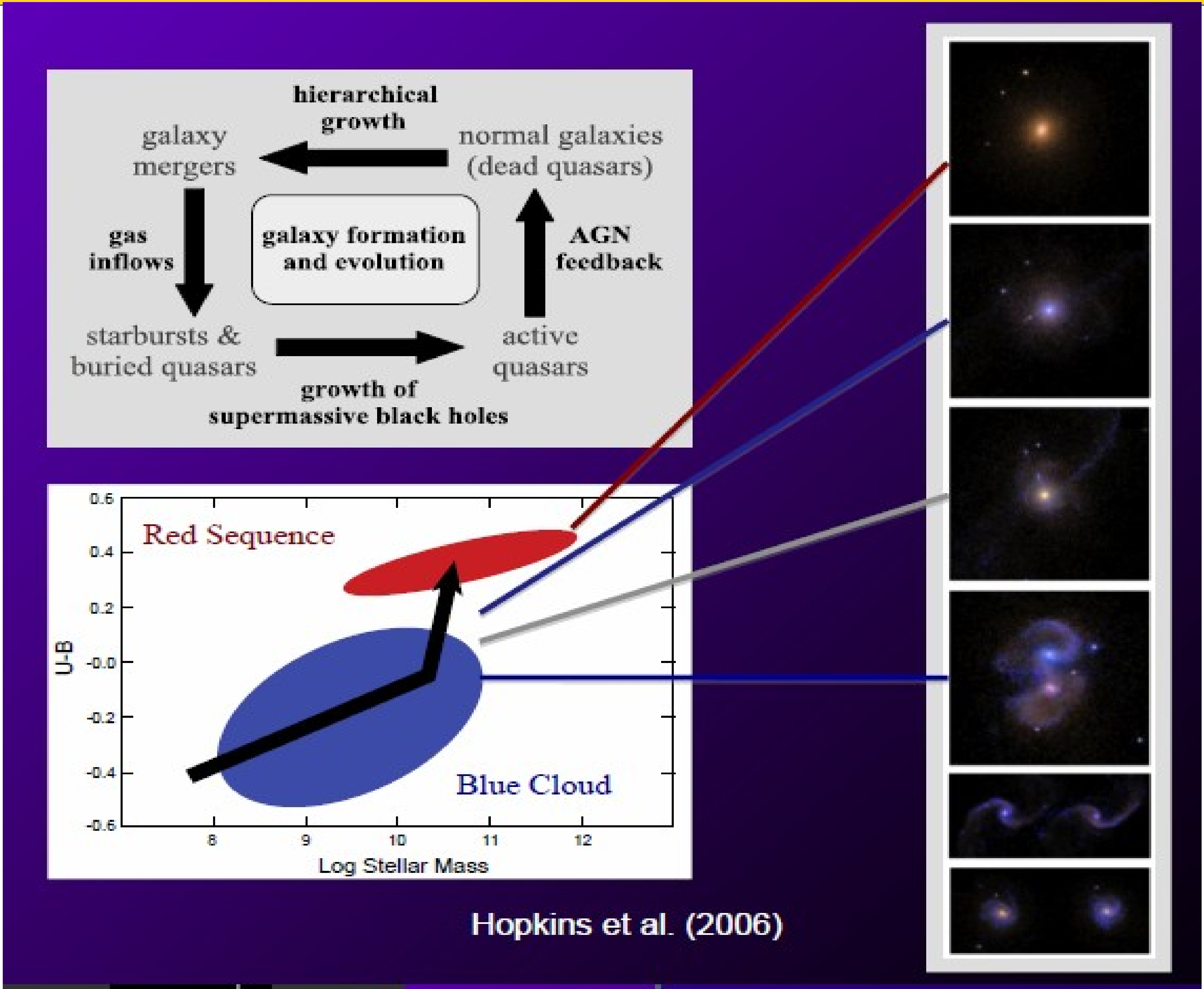


Galaxy evolution model through mergers



Hopkins et al 2008

Galaxy evolution model through mergers



Thank you very much for your attention!

Have a nice and peaceful day!