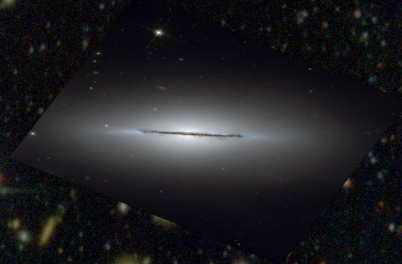
INTRODUCTION TO AMAZING AND DIVERSE WORLD OF GALAXIES (Part 1.)

Mirjana Pović

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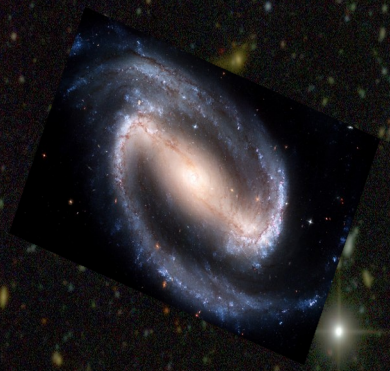
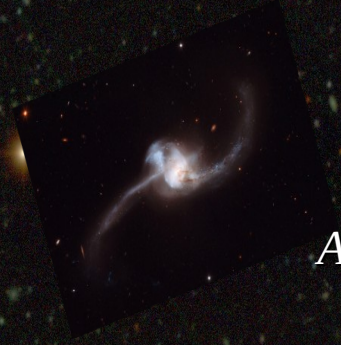
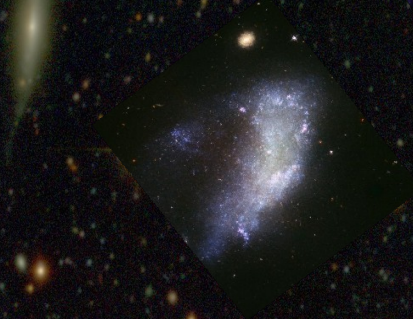





ASP lectures, 17 of Sep, 2020

(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

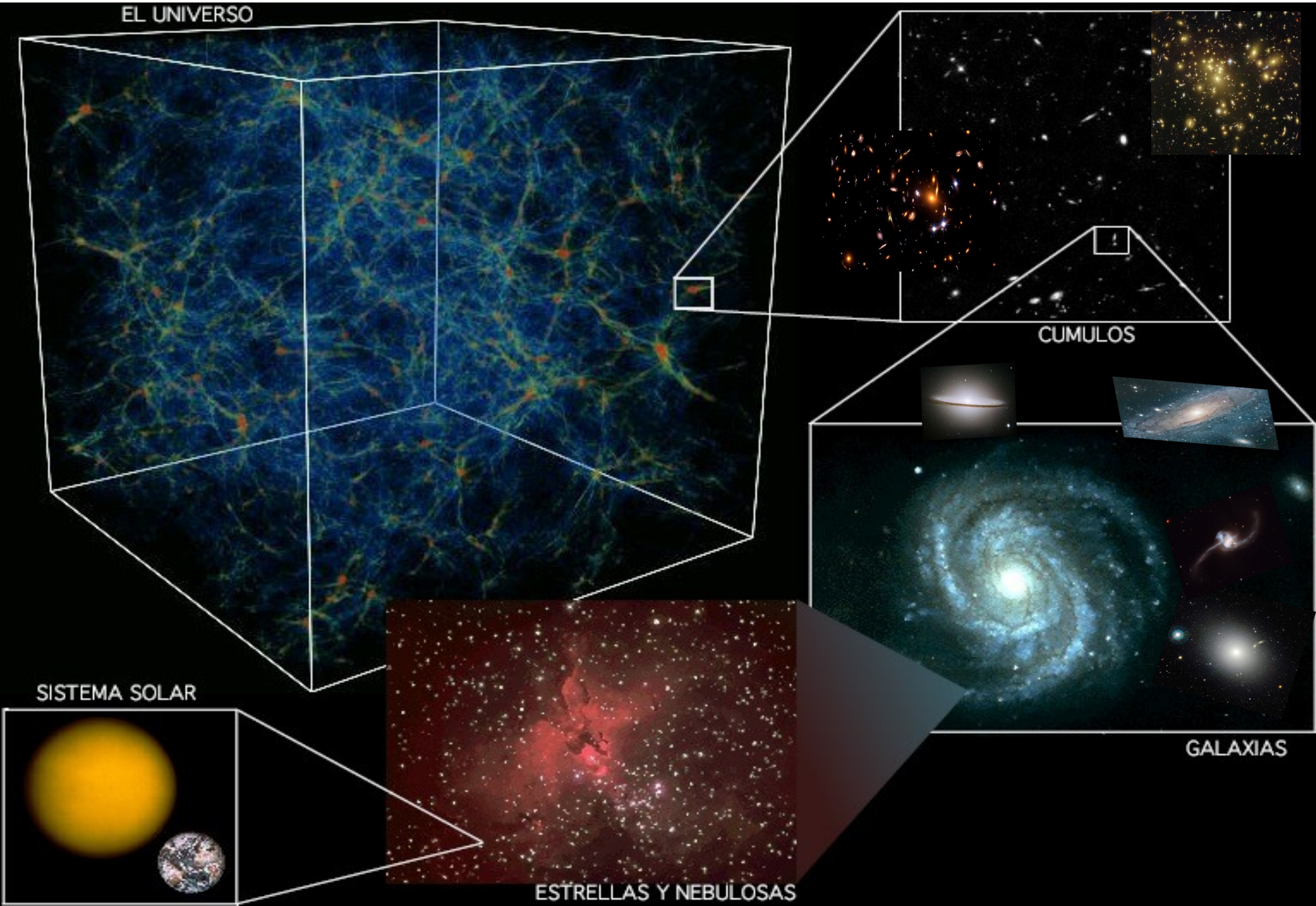
- Galaxy groups and clusters

- Briefly on galaxy formation and evolution

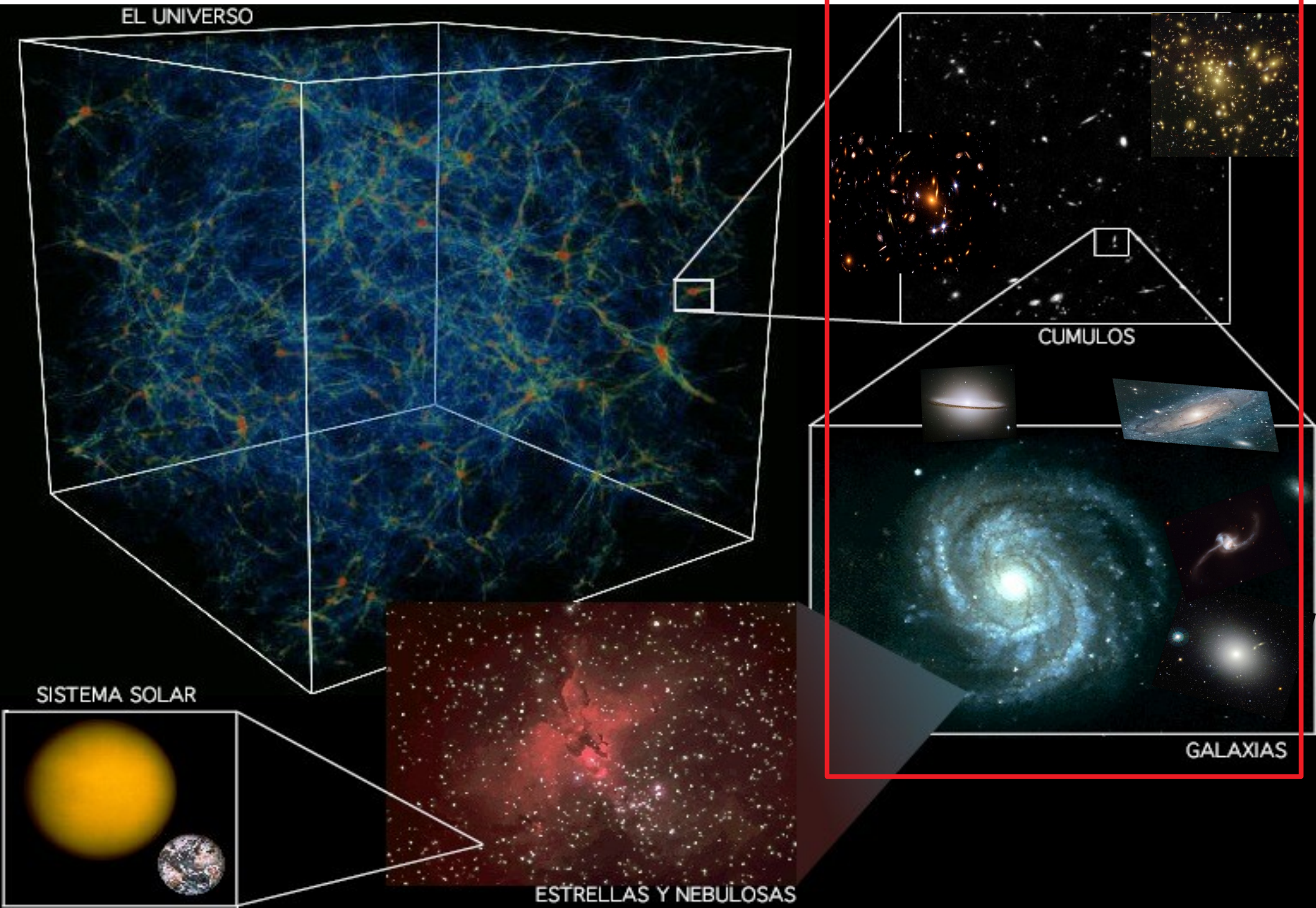
Components and scales in the Universe?

Fields of study in astrophysics?

Components and scales in the Universe



Components and scales in the Universe



Galaxy - massive, gravitationally bound system that consists of stars and stellar remnants, an interstellar medium, and dark matter

(def. International Astronomical Union - IAU)

NGC 4414, Credit: NASA/HST

NGC 3923, Credit: NASA/HST

A bit of history

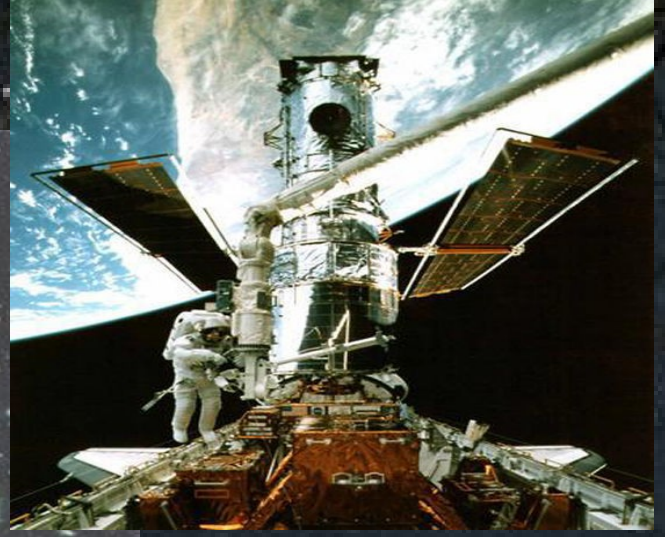
1755 - Immanuel Kant theorized that the galaxy has a planar structure, some nebulae might actually be entire other galaxies or *island universes.*

1774 -1781 - Messier catalog compiled including Andromeda galaxy as M31.

1845 - William Parsons (Lord Rosse), using a 72-inch telescope, classified the nebulae into featureless *elliptical* and whirlpool-like *spiral nebulae.*

In 1922-1924 Edwin Hubble resolved the controversy if some of the observed nebulae are outside of MW, by using the superior 100-inch telescope at Mount Wilson. He observed Cepheid variables in Andromeda and, using the P-M relation (distance method), determined its distance to be 300kpc → well outside of the MW (off by a factor of 2 due to poor Cepheid calibrations).

→ beginning of extragalactic astronomy!!



The Hubble Deep Field: 10-day exposure on an apparently empty field in the sky in Dec 1995
(> 340 exposures)

Even seemingly empty regions of the sky contain thousands of very faint, very distant galaxies.

Large variety of galaxy properties, including morphologies

Credits: NASA, HST

Beginning of the era of deep surveys and of intensive extragalactic astronomy research

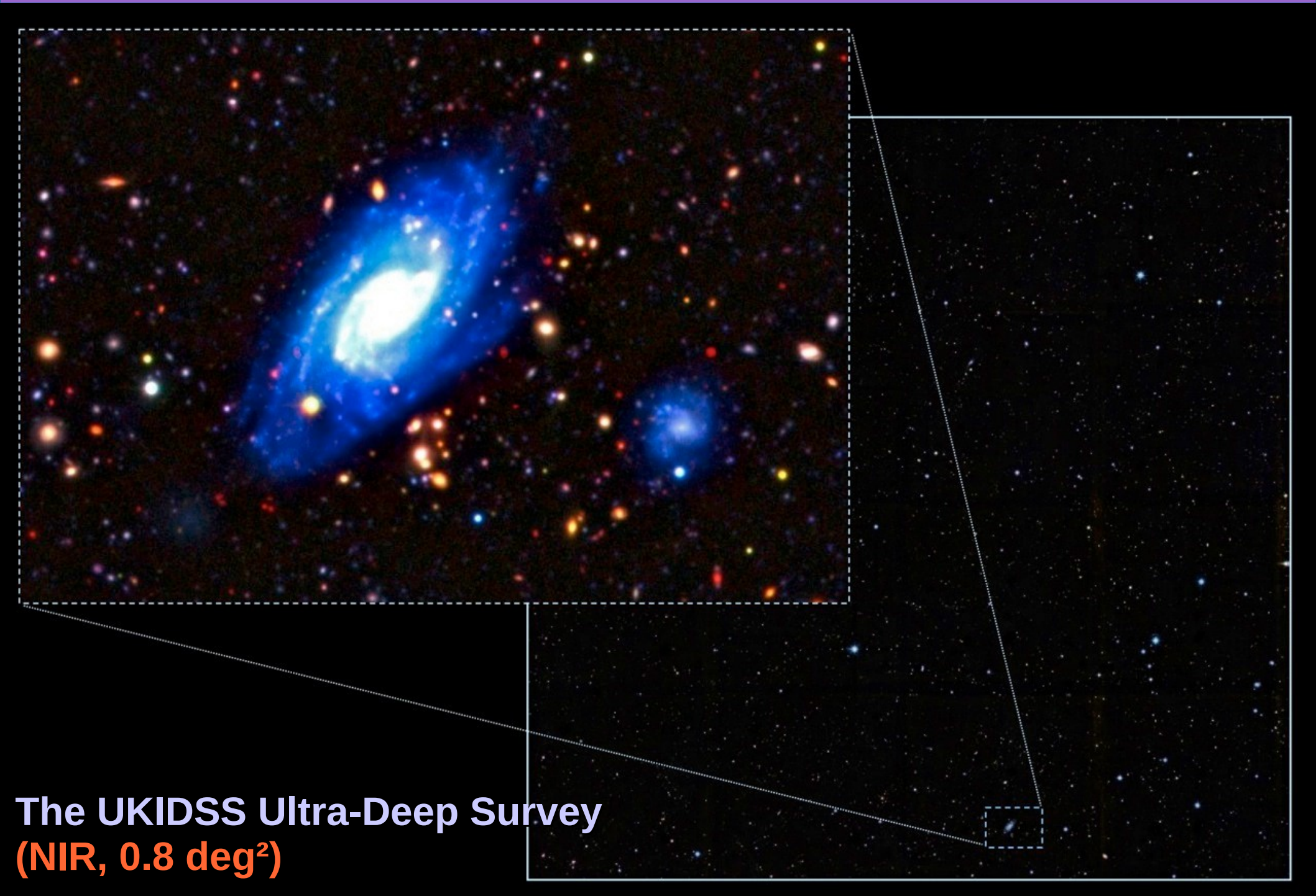
, very distant galaxies.

Large variety of galaxy properties, including morphologies

The Hubble Deep Field: 10-day exposure on an apparently empty field in the sky in Dec 1995
(> 340 exposures)

Credits: NASA, HST

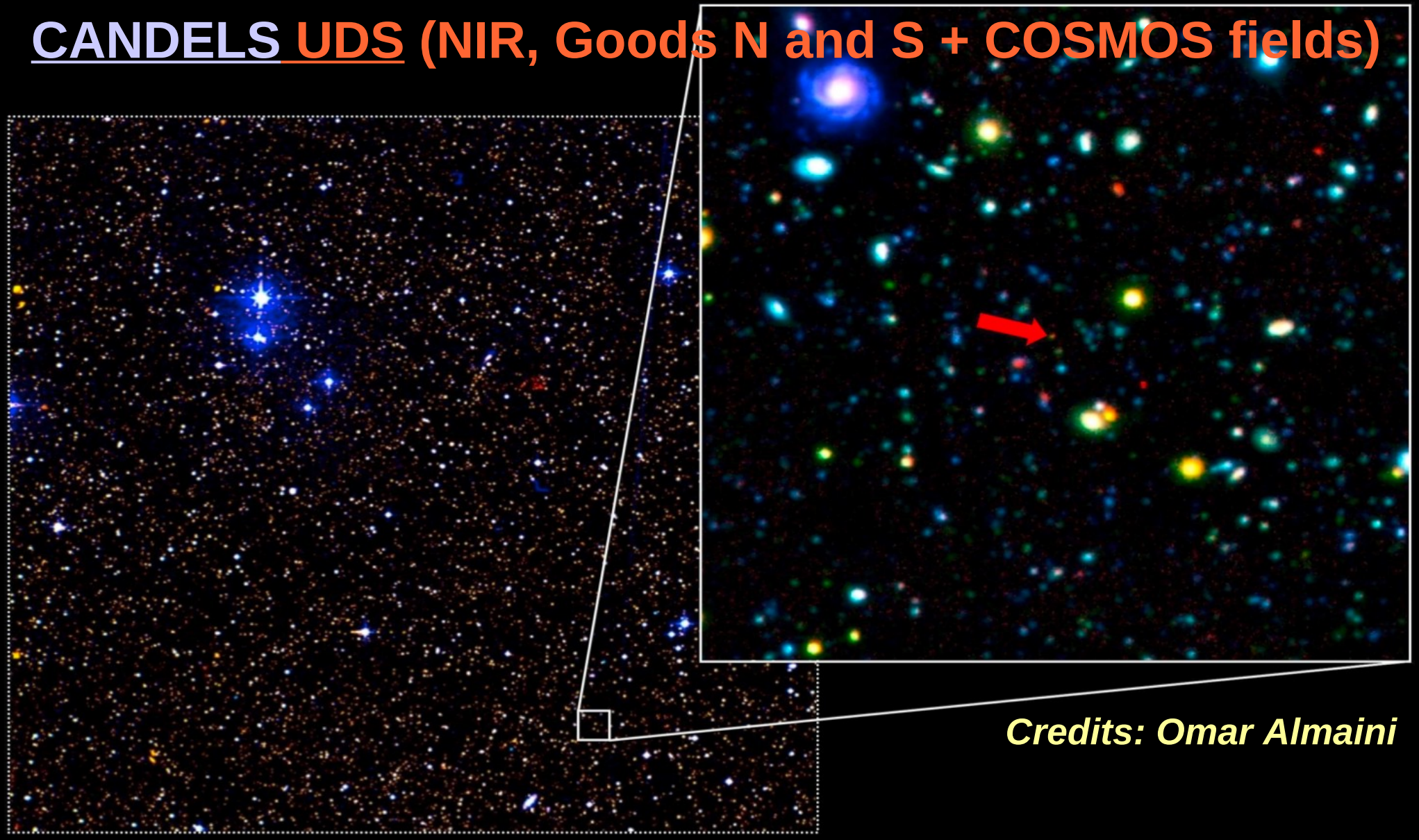
Deep surveys (example)



The UKIDSS Ultra-Deep Survey
(NIR, 0.8 deg²)

Deep surveys (another example)

CANDELS UDS (NIR, Goods N and S + COSMOS fields)



Credits: Omar Almaini

The zoom-in shows the location of a galaxy at redshift z = 6 (red arrow), identified at an epoch when the Universe was only 5% of its present age.

ASTRONOMY is OBSERVATIONAL SCIENCE

The main source of information about celestial objects is the light, and more generally electromagnetic radiation (EMR)

We study the Universe by analysing the EMR.

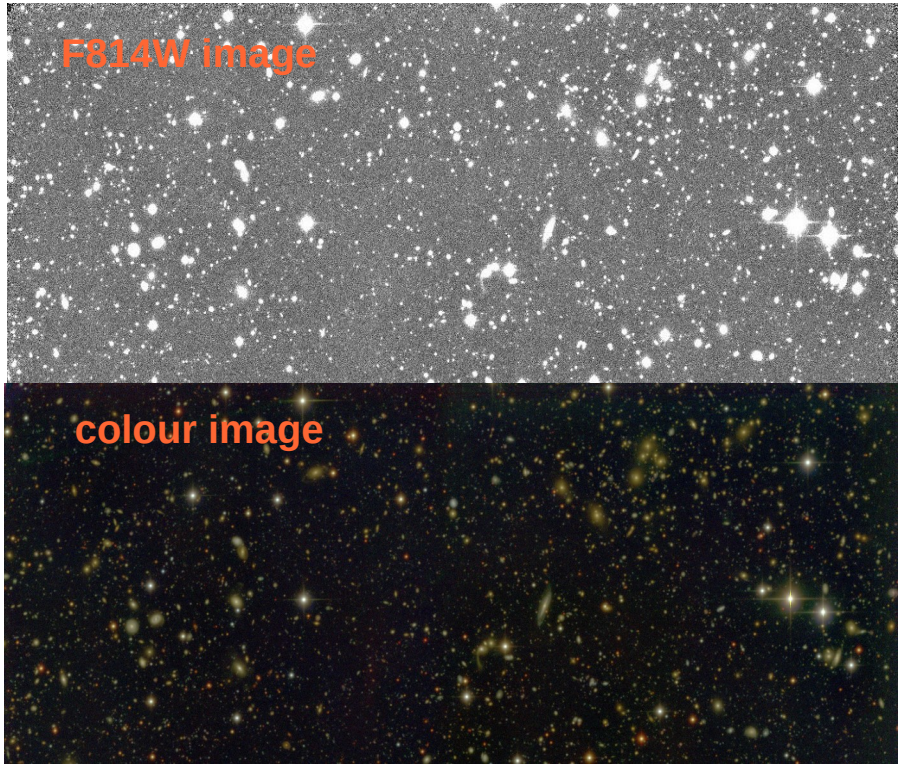
In astronomy, we cannot perform experiments with our objects (stars, galaxies, etc.).

Problems with sizes (distances) and time

Two main techniques to get observational data

PHOTOMETRY

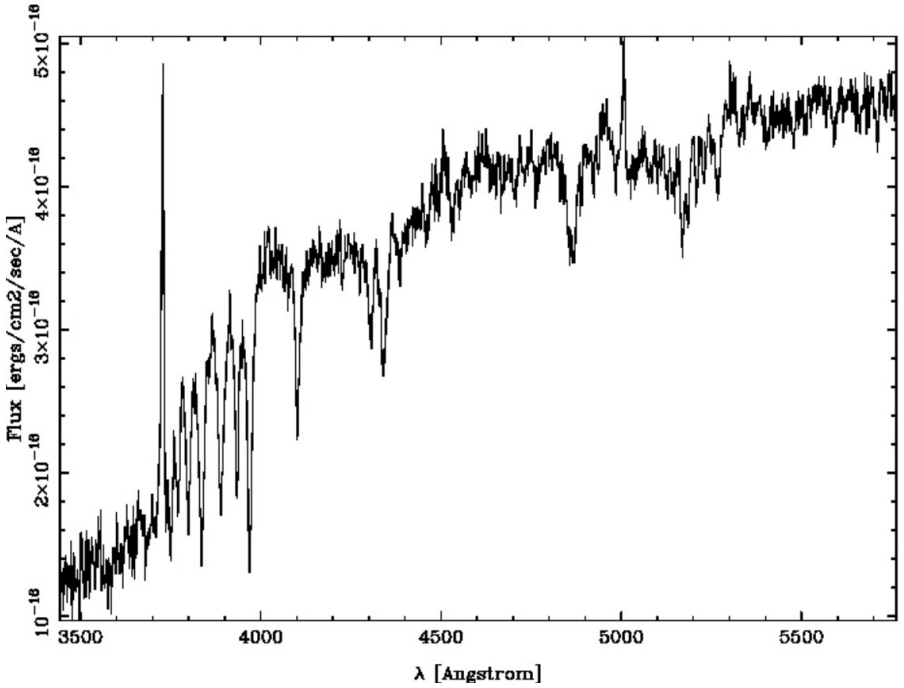
Data products: images



ALHAMBRA survey, Molino et al., 2014, MNRAS, 441, 2891

SPECTROSCOPY

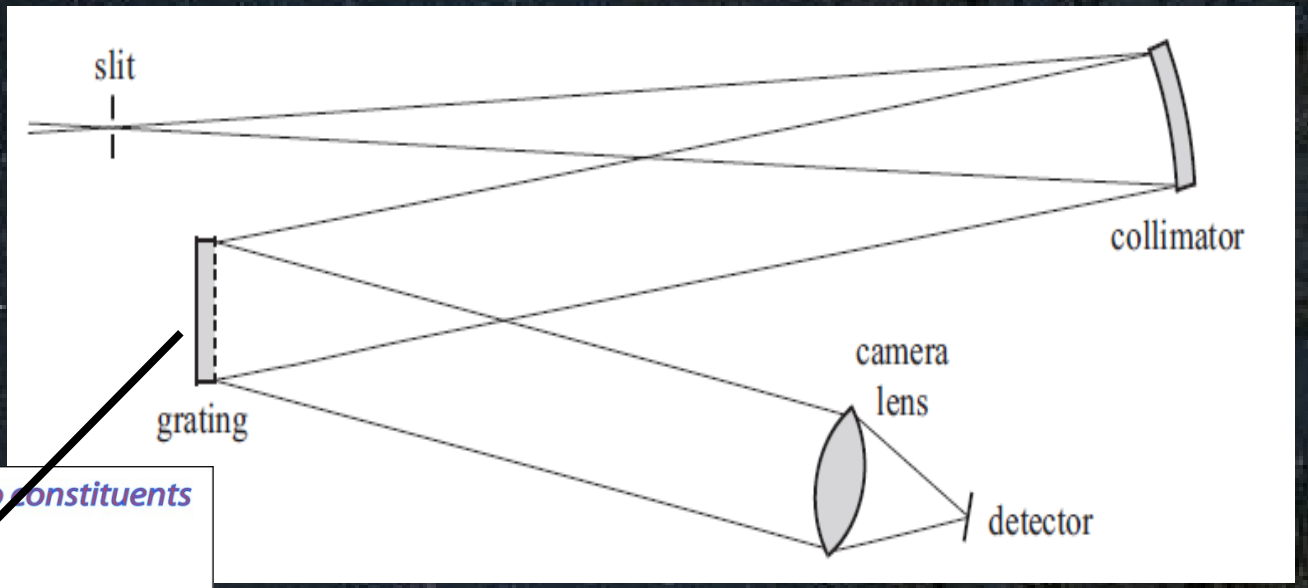
Data products: spectra

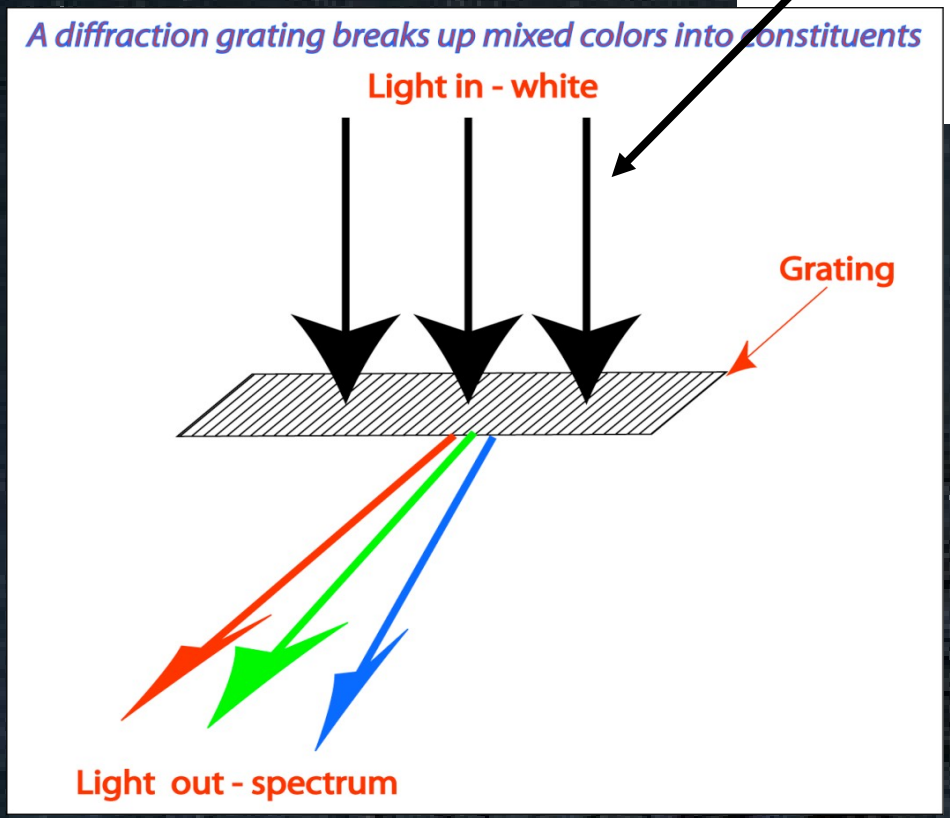


Pović et al., 2016, MNRAS, 462, 2878

Spectroscopy

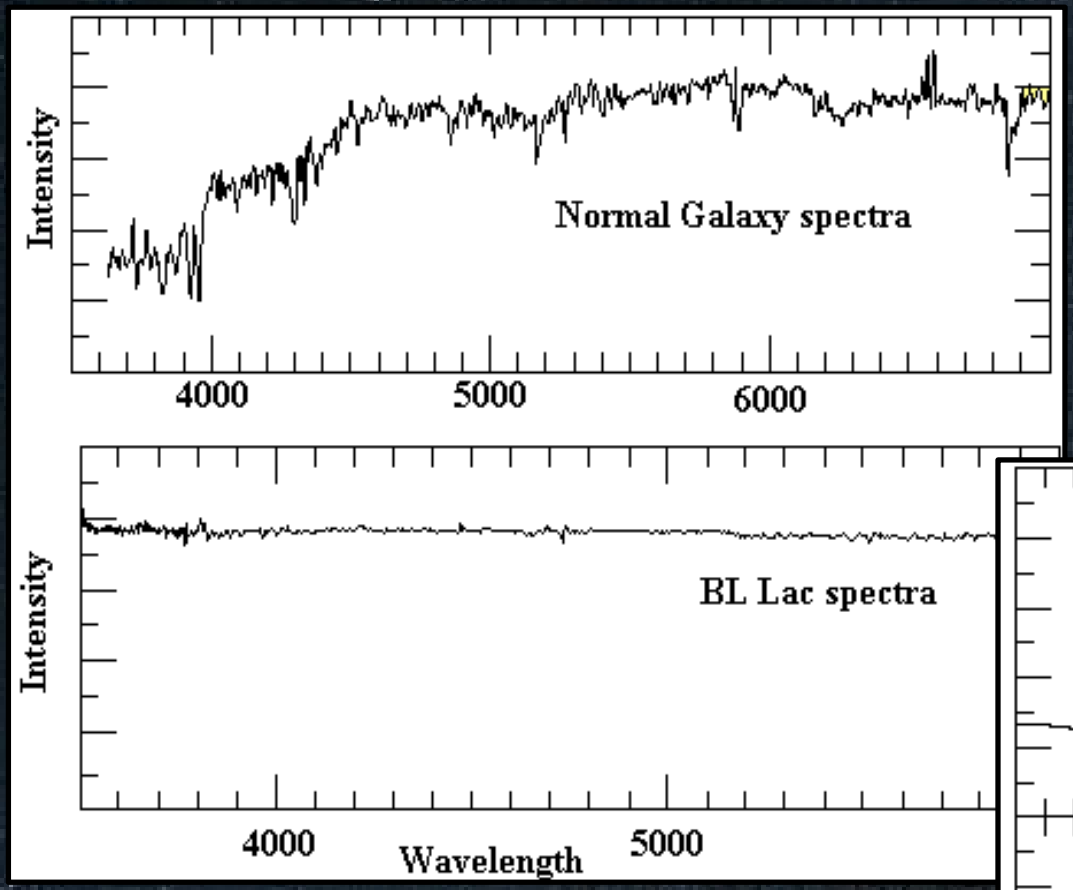
Spectrograph



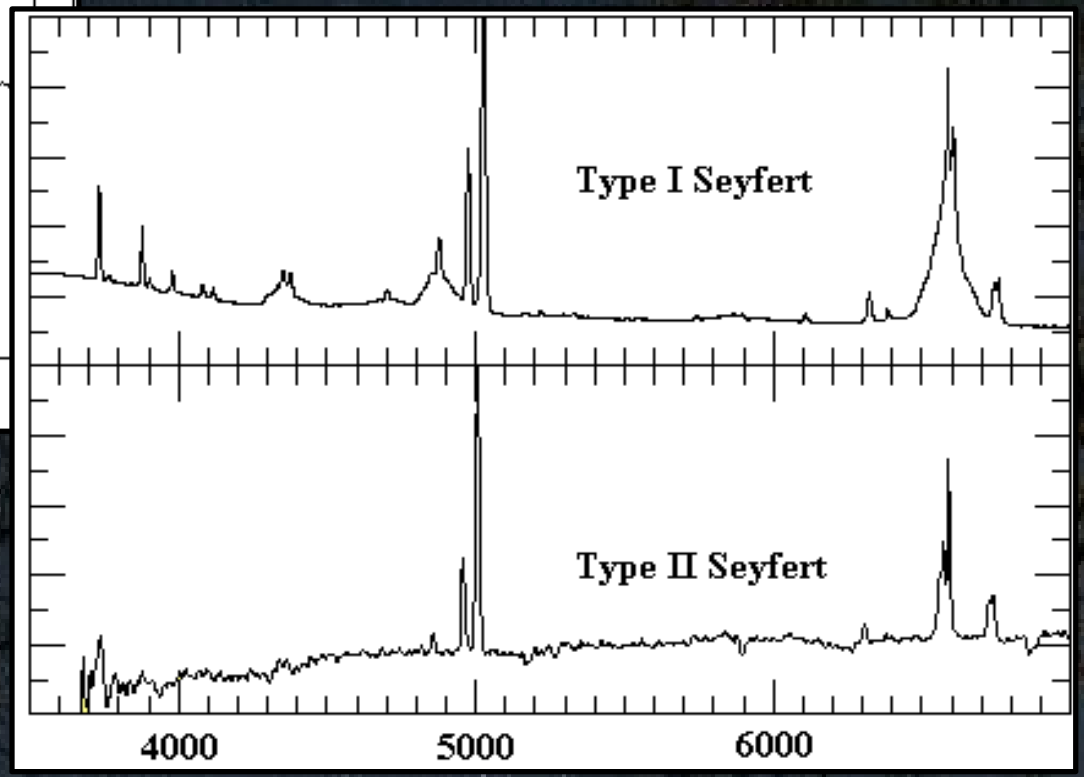


SPECTRA

Spectroscopy

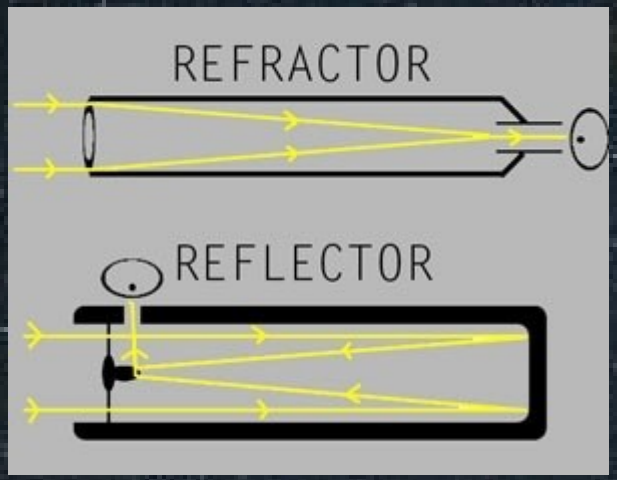


mass, intrinsic extinction, temperature, stellar populations and age,etc.

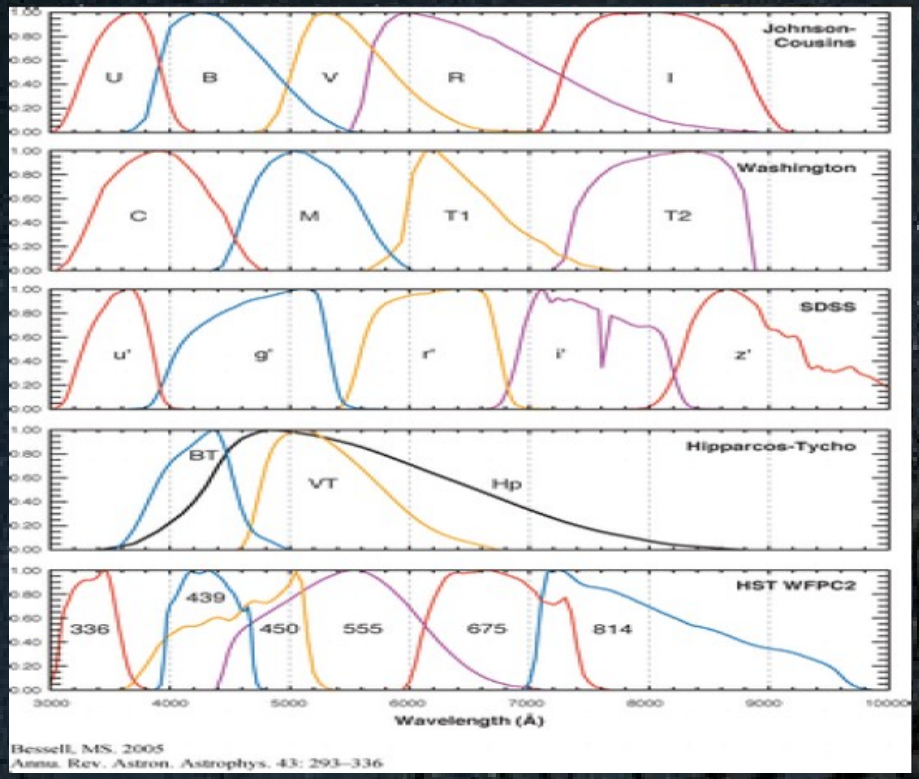


object classification, chemical composition, distance,

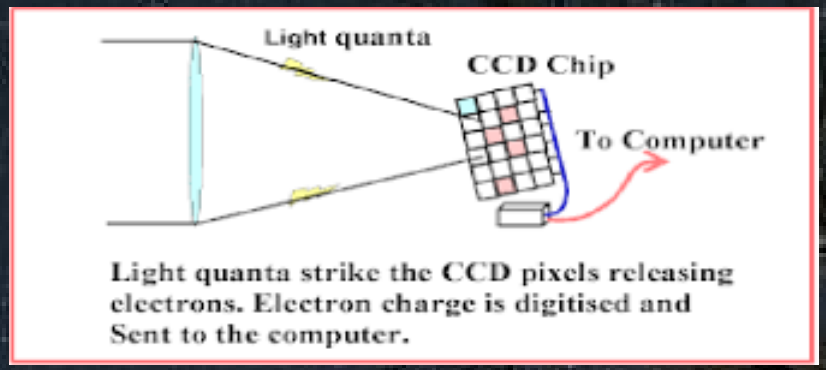
Photometry



Photometric bands/filters

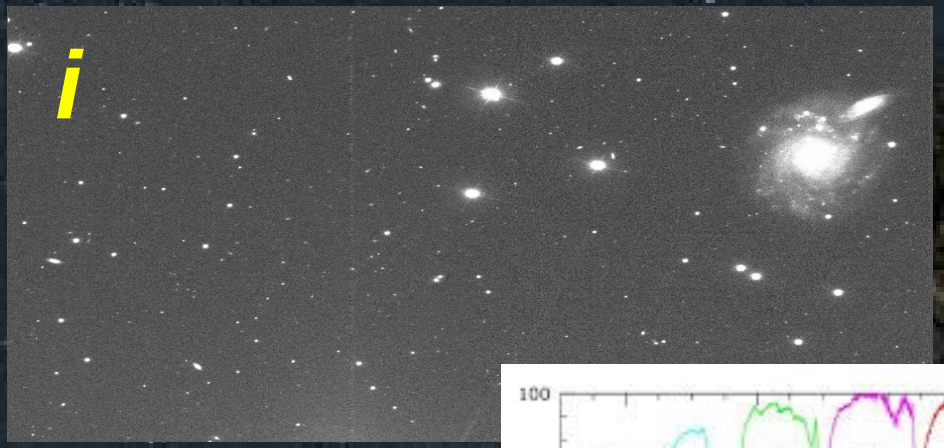


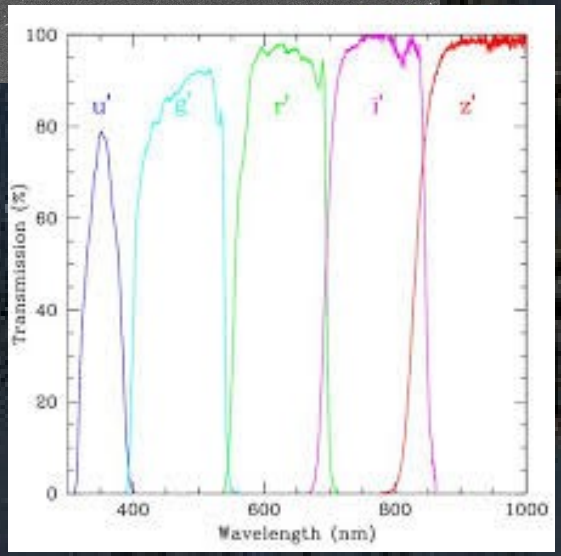
detector



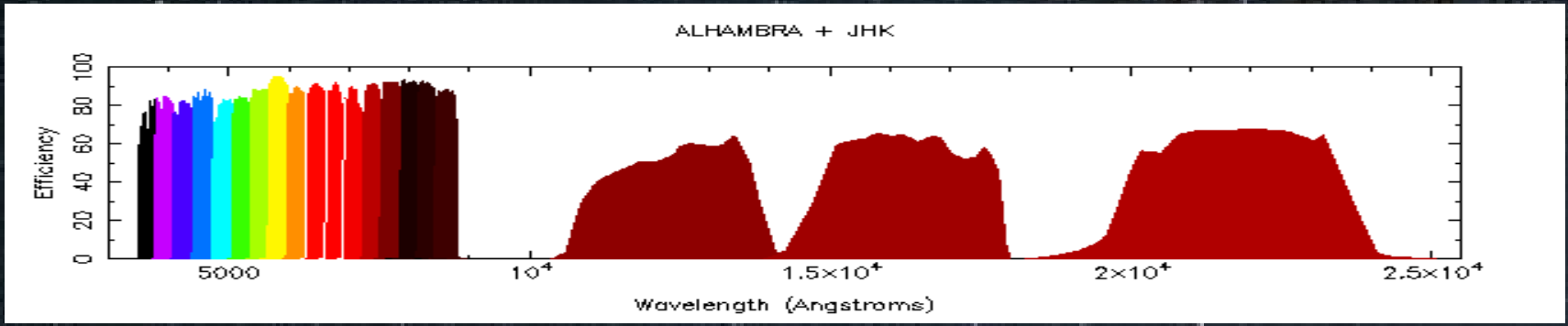
IMAGE

Example: SDSS photometric system

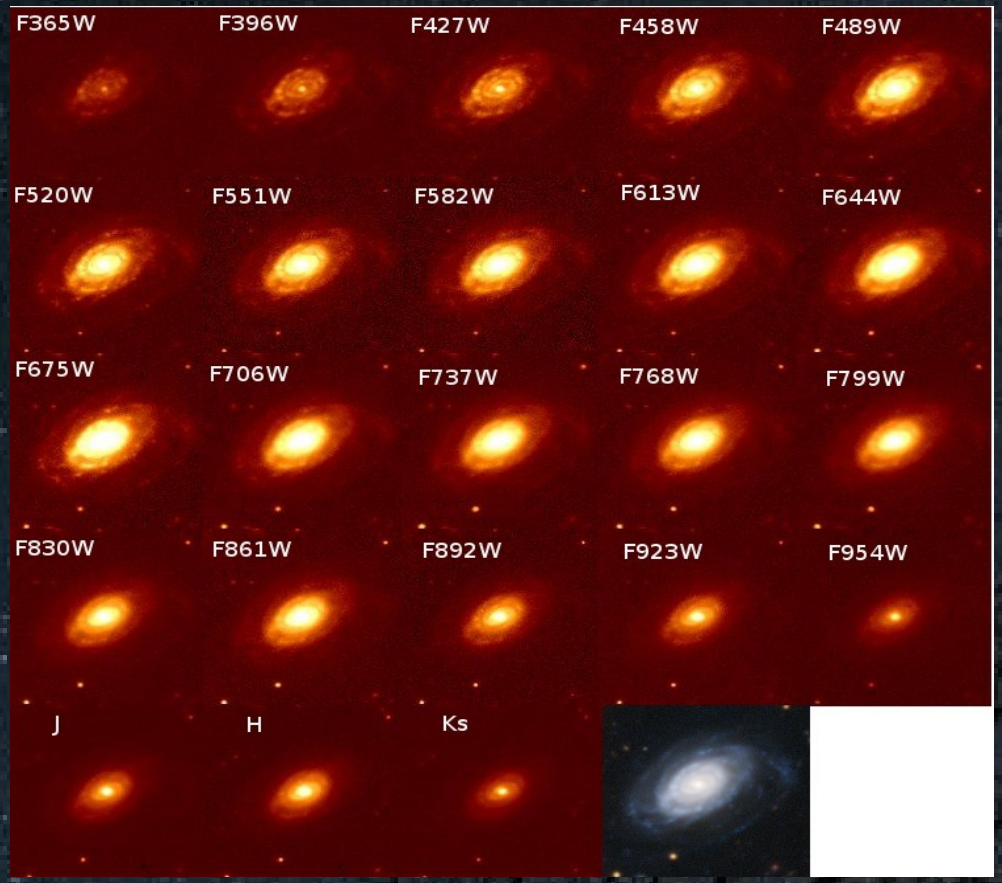




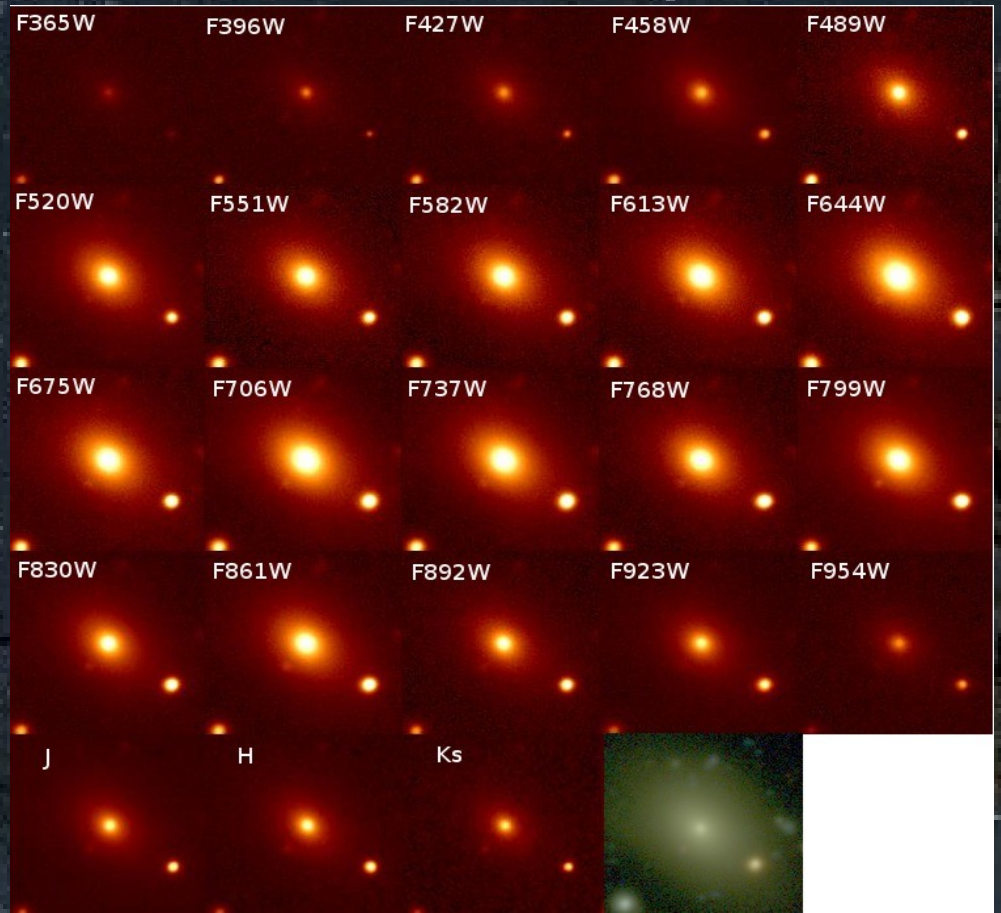
Example: ALHAMBRA photometric system



example of spiral galaxy in all ALHAMBRA bands

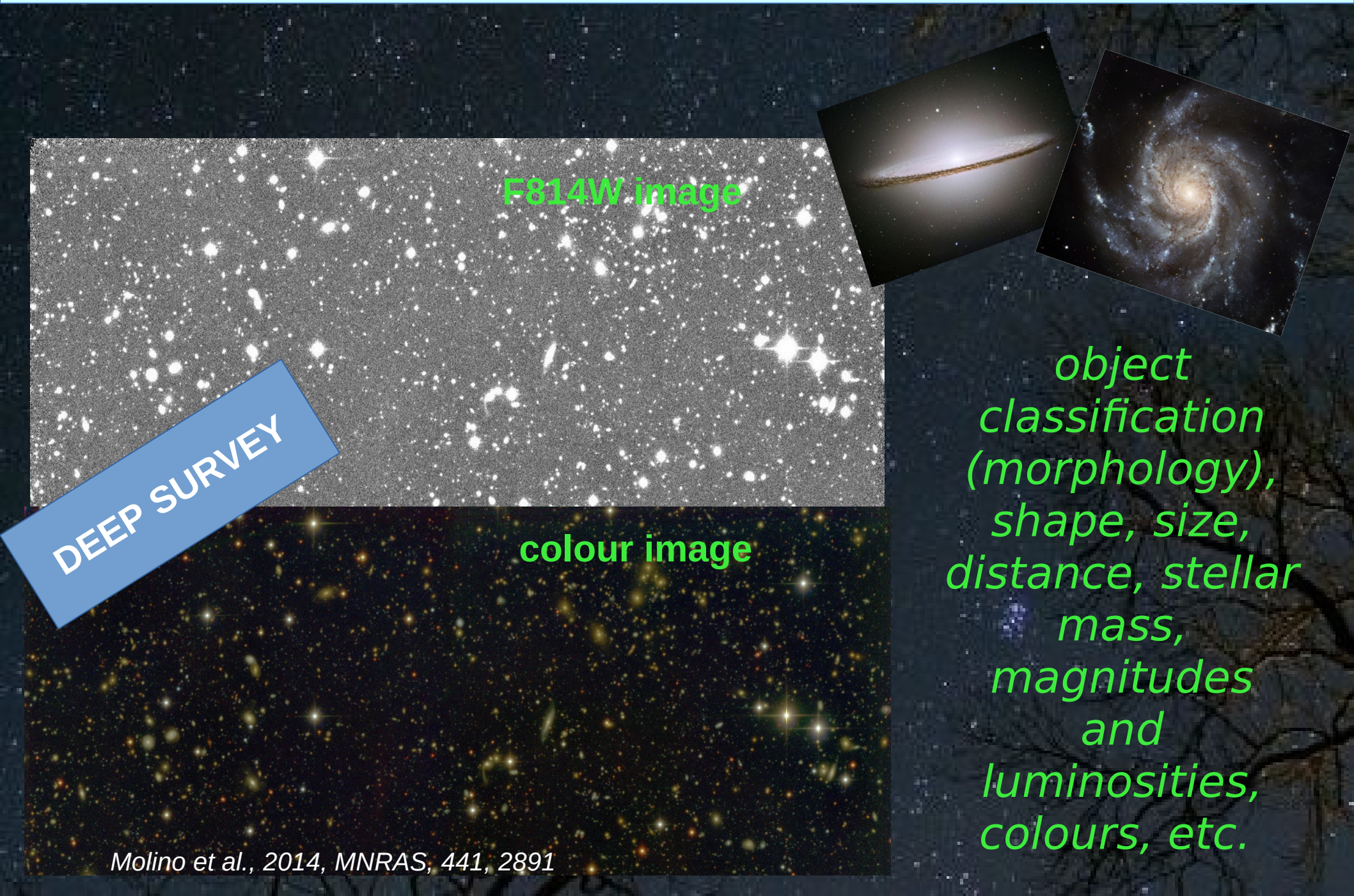


example of elliptical galaxy



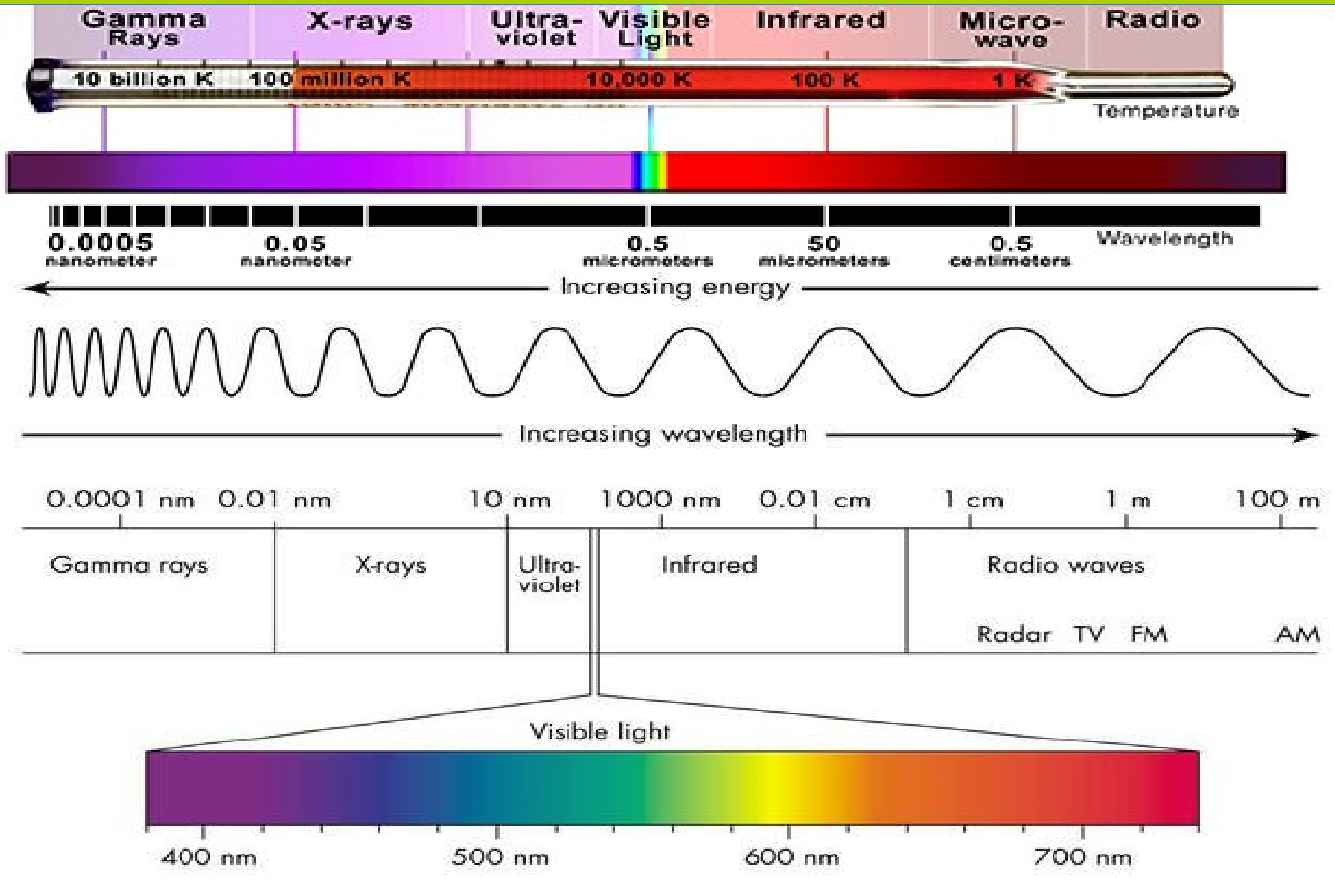
Povic et al. 2013, MNRAS, 435, 3444
Molino et al., 2014, MNRAS, 441, 2891

Photometry



object classification (morphology), shape, size, distance, stellar mass, magnitudes and luminosities, colours, etc.

Electromagnetic radiation (EMR)

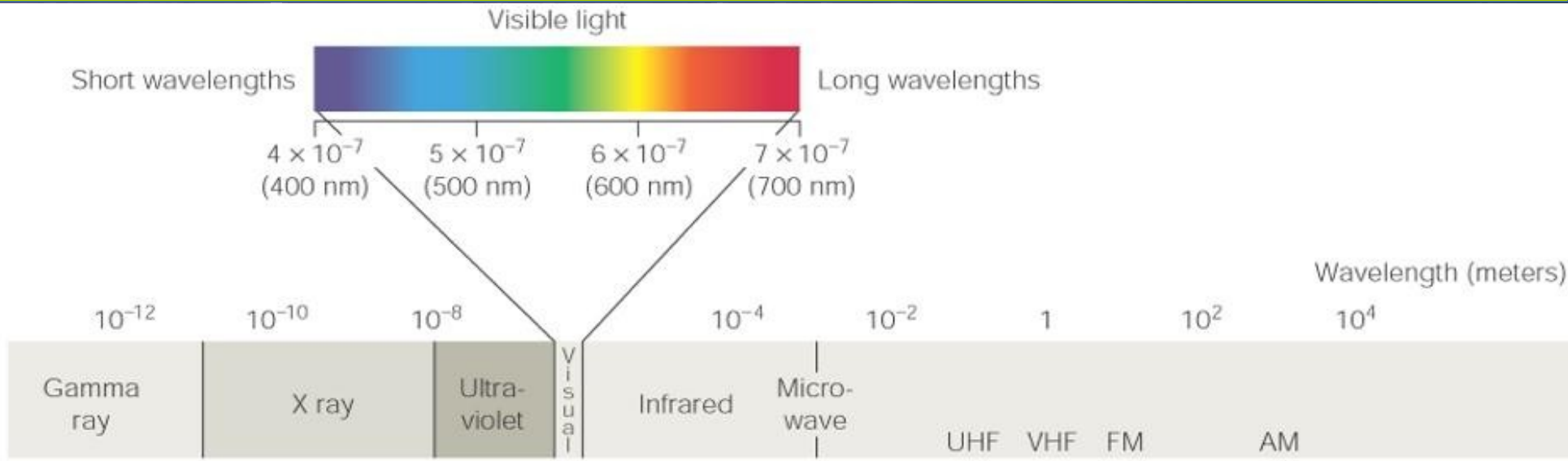


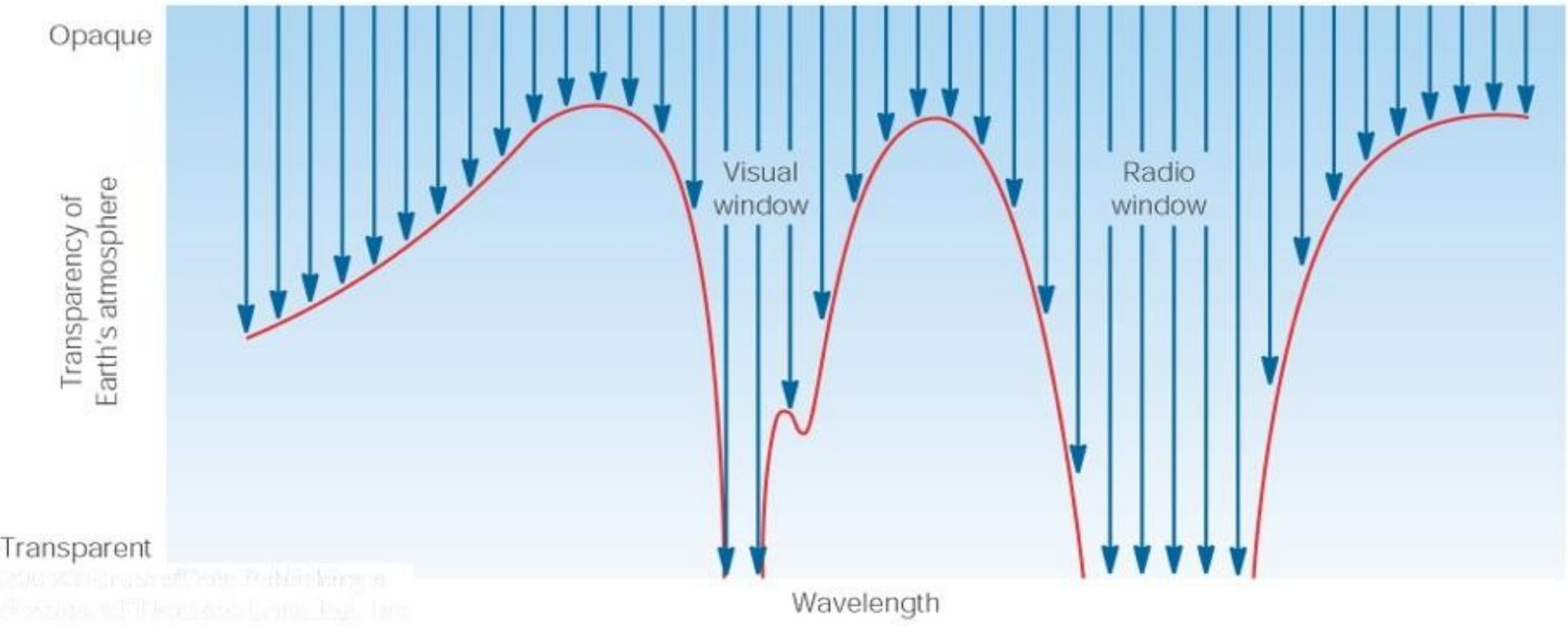
Observational Astronomy

Divided according to the observed region of the EMR:

1. Radio Astronomy (λ ≥ 1 mm)
2. Infrared (IR) Astronomy (λ: 1 - 10^3 μm)
3. Optical Astronomy (λ: 400 - 800 nm)
4. Ultraviolet (UV) Astronomy (λ: 10 - 300 nm)
5. X-ray Astronomy (λ: 10^(-3) - 10 nm)
6. Gamma-ray Astronomy (λ ≤ 10^(-3) nm)

EMR and atmospheric transmittance





EMR and telescopes

SALT, South Africa (optical telescope)

GALEX
(UV telescope)

X-ray telescopes

Chandra, NASA

XMM-Newton,
ESA

Spitzer
(Infrared
telescope)

Radio
telescopes

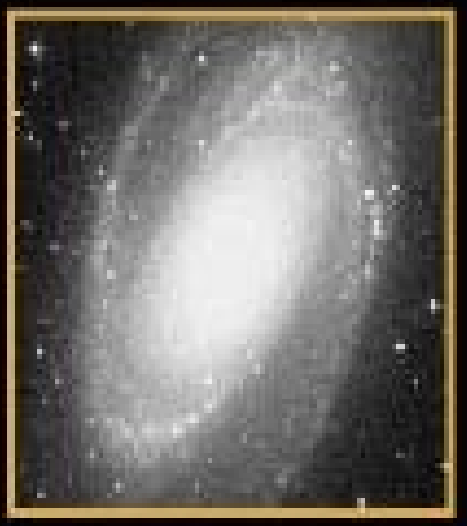
IRAM,
Spain

Kat-7, South
Africa

MAGIC, La Palma, Spain
(gamma-ray telescope)

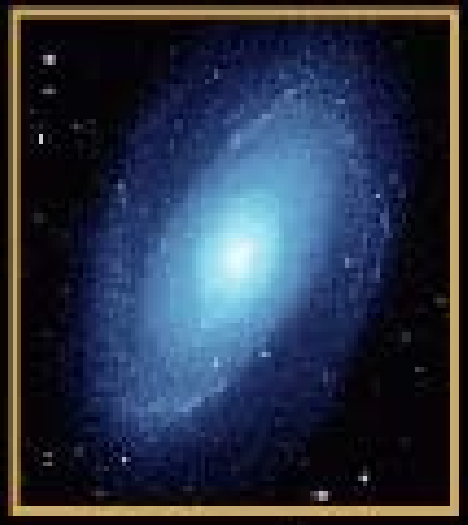
X-Ray: ROSAT

Ultraviolet: ASTRO-1

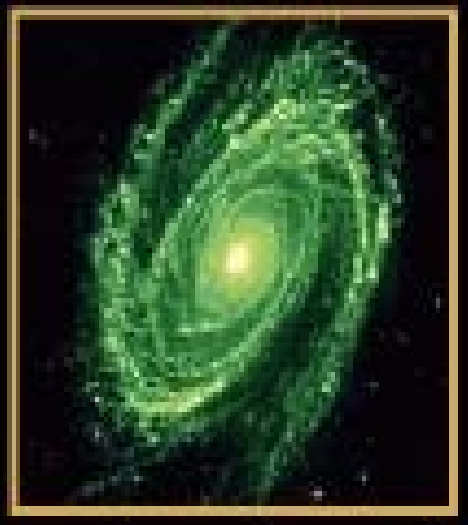


Visible: DSS

Visible: R. Gendler



Near-Infrared: Spitzer

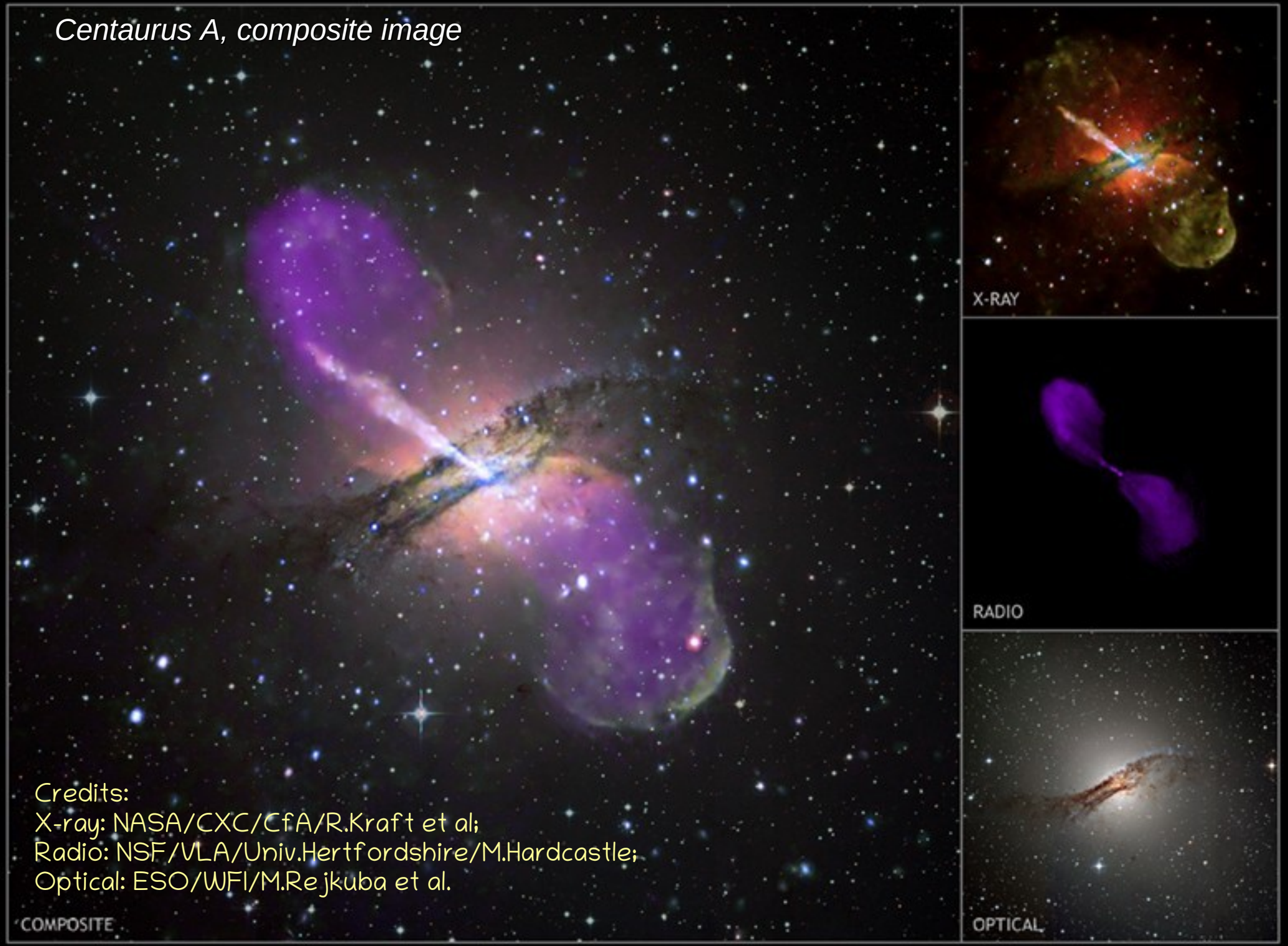


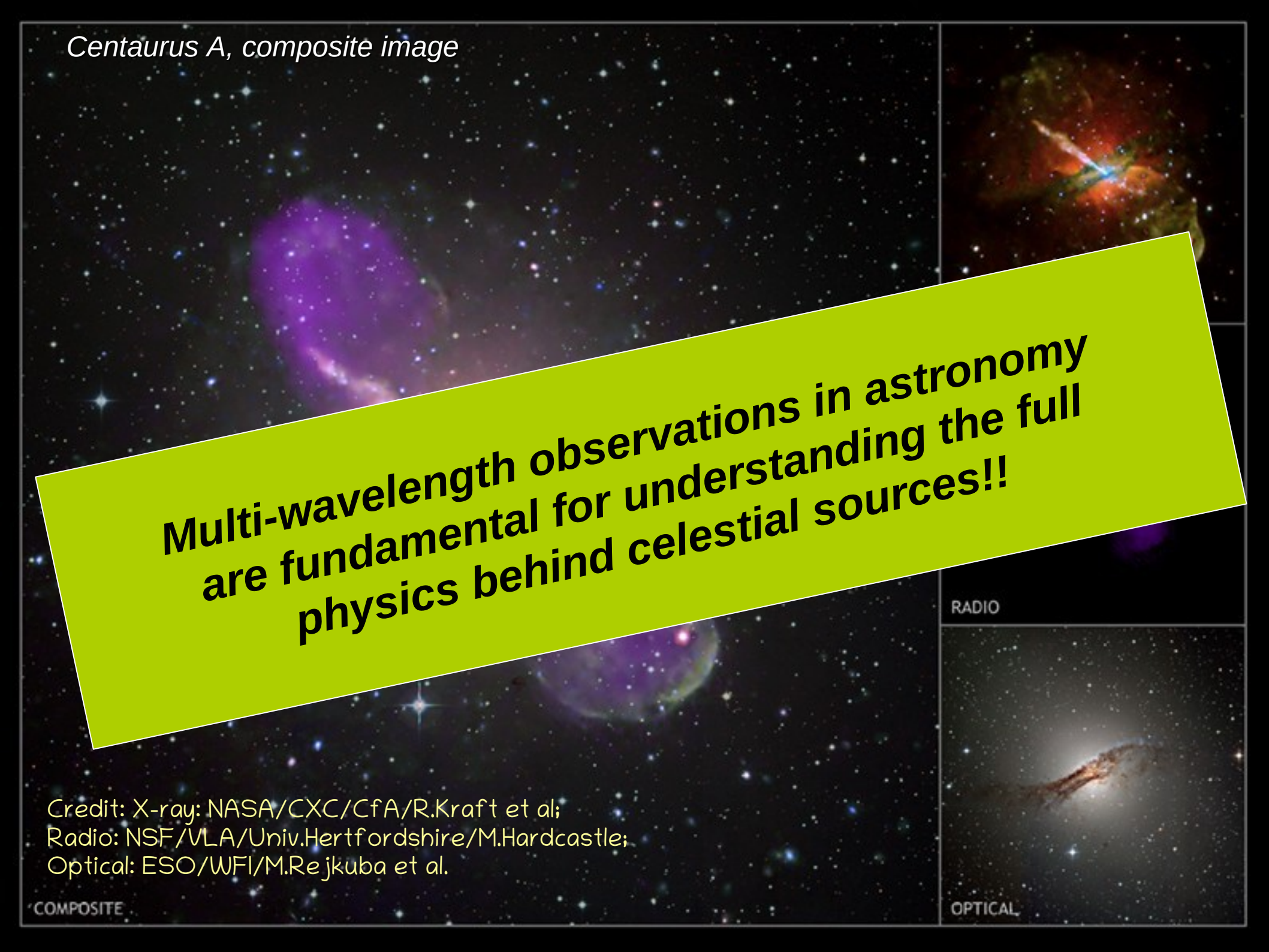
Mid-Infrared: Spitzer

Far-Infrared: Spitzer

Radio: VLA

Credits: NASA, Univ. of Chicago


Centaurus A, composite image
X-RAY
RADIO
OPTICAL
COMPOSITE
Credits:
X-ray: NASA/CXC/CfA/R.Kraft et al;
Radio: NSF/VLA/Univ.Hertfordshire/M.Hardcastle;
Optical: ESO/WFI/M.Rejkuba et al.


Centaurus A, composite image
Multi-wavelength observations in astronomy are fundamental for understanding the full physics behind celestial sources!!
RADIO
OPTICAL
COMPOSITE
Credit: X-ray: NASA/CXC/CfA/R.Kraft et al;
Radio: NSF/VLA/Univ.Hertfordshire/M.Hardcastle;
Optical: ESO/WFI/M.Rejkuba et al.

Summary:

Deep surveys + multi-wavelengh data

brought the revolution to

extragalactic astronomy research

Both are crucial for our understanding of the properties of galaxies,
their formation and evolution across the cosmic time

Types of galaxies - summary

Classification of galaxies can be based on different criteria related with their properties (and measured parameters) and/or type of observations
(e.g., X-ray emitters, radio galaxies, etc.)

Types of galaxies - summary

MAIN CLASSIFICATION is using MORPHOLOGY:

- 4 main types: E, S0, Sp, and Irr
- peculiar galaxies

But there are also others, such as:

Classification using SIZE:
from few tens of kpc up to hundreds of kpc or even Mpc → from dwarf to giant galaxies

Classification using NUCLEAR ACTIVITY:
2 main types depending on absence/presence of active galactic nuclei (AGN): normal (or inactive, non-active) and active galaxies

Classification using STAR FORMATION:

- main types: retired, star-forming, and starburst galaxies

Types of galaxies - summary

Classification using MASS:

- 2 main types: massive and no-massive (usually a limit of 10^{10} solar masses is used)

Classification using REDSHIFT:

- main types: local and/or nearby (for local and very close universe), low-redshift (usually z < 1), intermediate-redshift (usually z between 1 and 2 or 3), and high-redshift (usually z > 2 or 3) galaxies

Classification using IR LUMINOSITY:

- 5 main types: normal, luminous IR galaxies (LIRG, L > 10^{11} Lo in FIR), ULIRG (> 10^{12}), HLIRG (> 10^{13}), ELIRG (> 10^{14})

Types of galaxies - summary

Classification using ENVIRONMENT:

different types:

- interacting and non-interacting galaxies
- isolated galaxies, field galaxies, pair galaxies, group galaxies, and cluster galaxies

Classification using COLOURS:

- red sequence, blue cloud and green valley galaxies

Classification using SPECTROSCOPIC PROPERTIES:

- e.g., emission-line galaxies (ELG) or absorption-line galaxies (ALG)

.... etc (using other galaxy properties)....

However, the morphological classification based on optical observations known as Hubble sequence is still the best-known today, and the most used one.

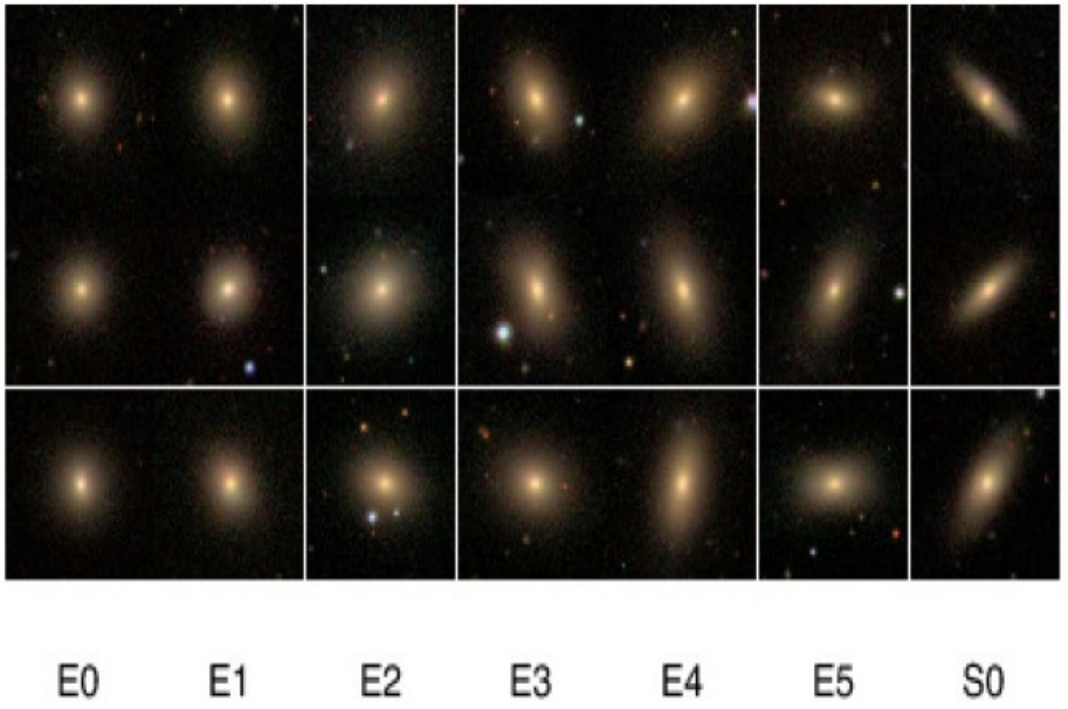
In 1924-26 Edwin Hubble divided galaxies into different "classes" based on their appearance.

*** Hubble classification serves as the basic one in the field.**

*** Morphological sequence reflects a fundamental physical and evolutionary sequence, which offers important clues to galactic structure, formation and evolution.**

Morphological classification of galaxies (Hubble sequence)

Reynolds 1920
Hubble 1926, 1932



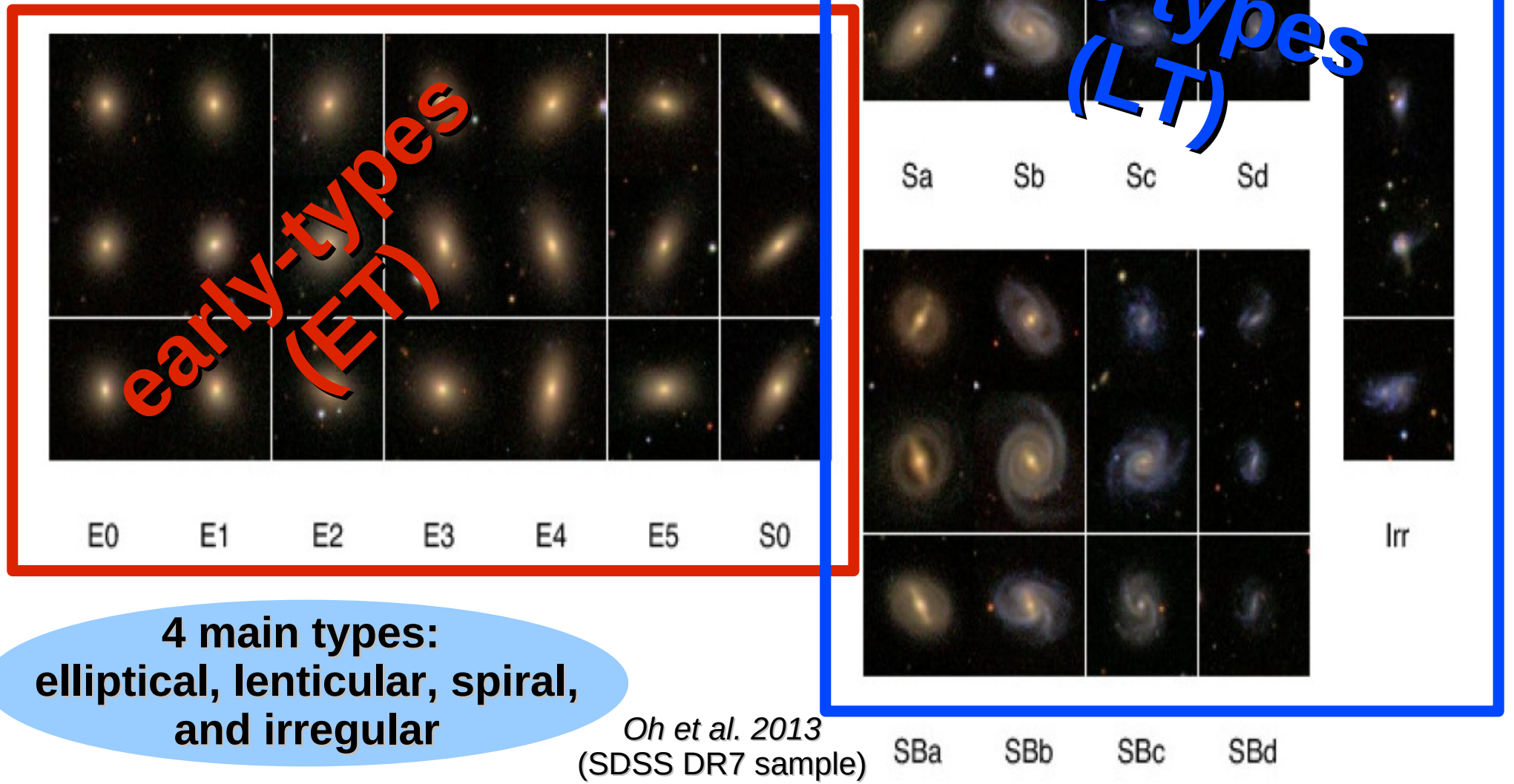
4 main types: elliptical, lenticular, spiral, and irregular

Oh et al. 2013
(SDSS DR7 sample)

Morphological classification of galaxies (Hubble sequence)

→ **more broad classes**

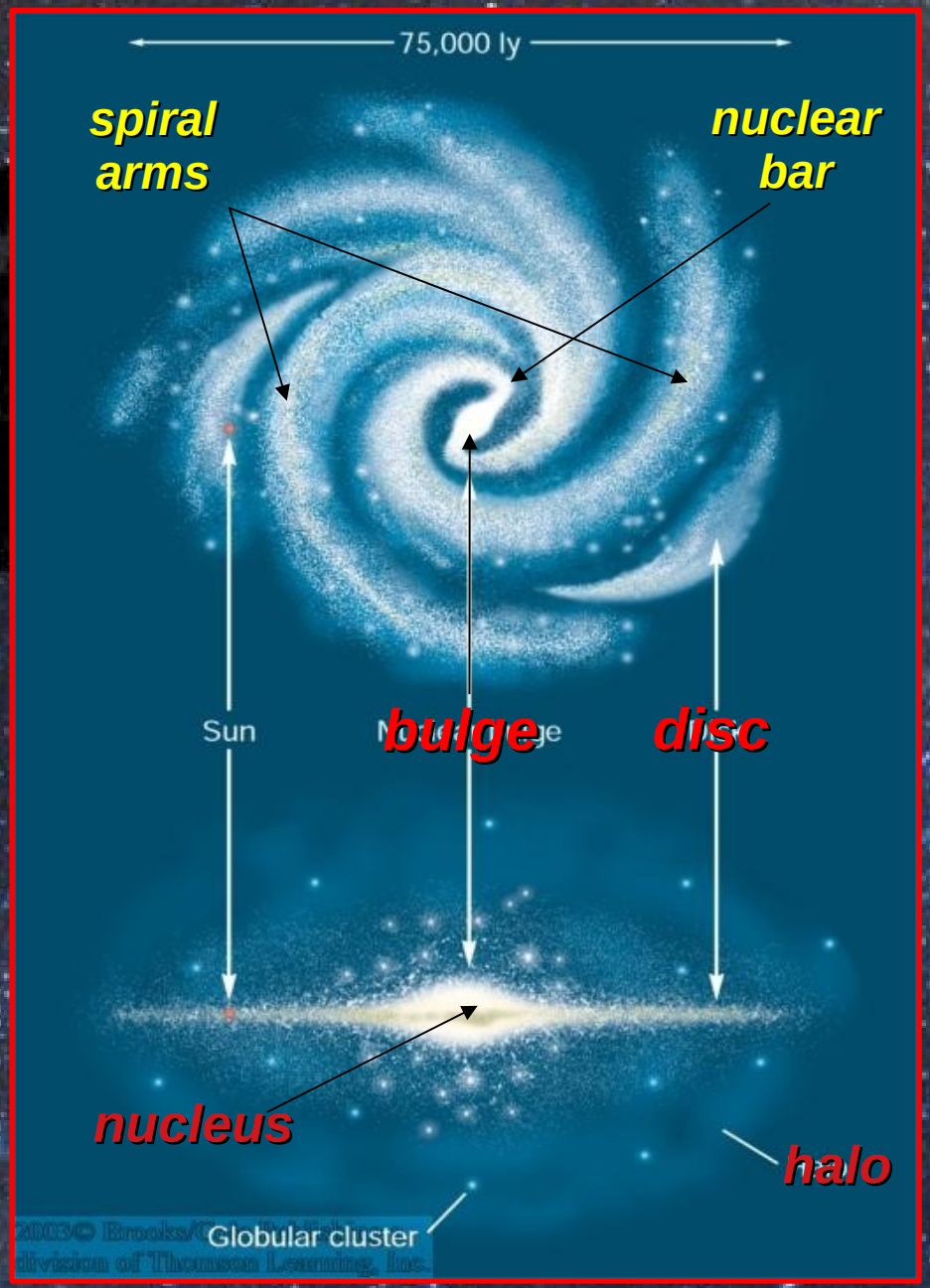
Reynolds 1920
Hubble 1926, 1932



4 main types: elliptical, lenticular, spiral, and irregular

Oh et al. 2013
(SDSS DR7 sample)

Main galaxy components



Other galaxy components

Why should we care about morphology?

Key element in galaxy formation and evolution studies!

Correlation or trends between morphology and other galaxy properties

colour
stellar mass
luminosity / absolute magnitude
(e.g., Strateva et al. 2001; Hogg et al. 2003; Bell et al. 2003; Weiner et al. 2005; Kelm et al. 2005; Melbourne et la. 2007; Cassata eta l. 2007; Deng et al. 2013; Pović et al. 2013; Schawinski et al. 2014; Zewdie et al. 2020)

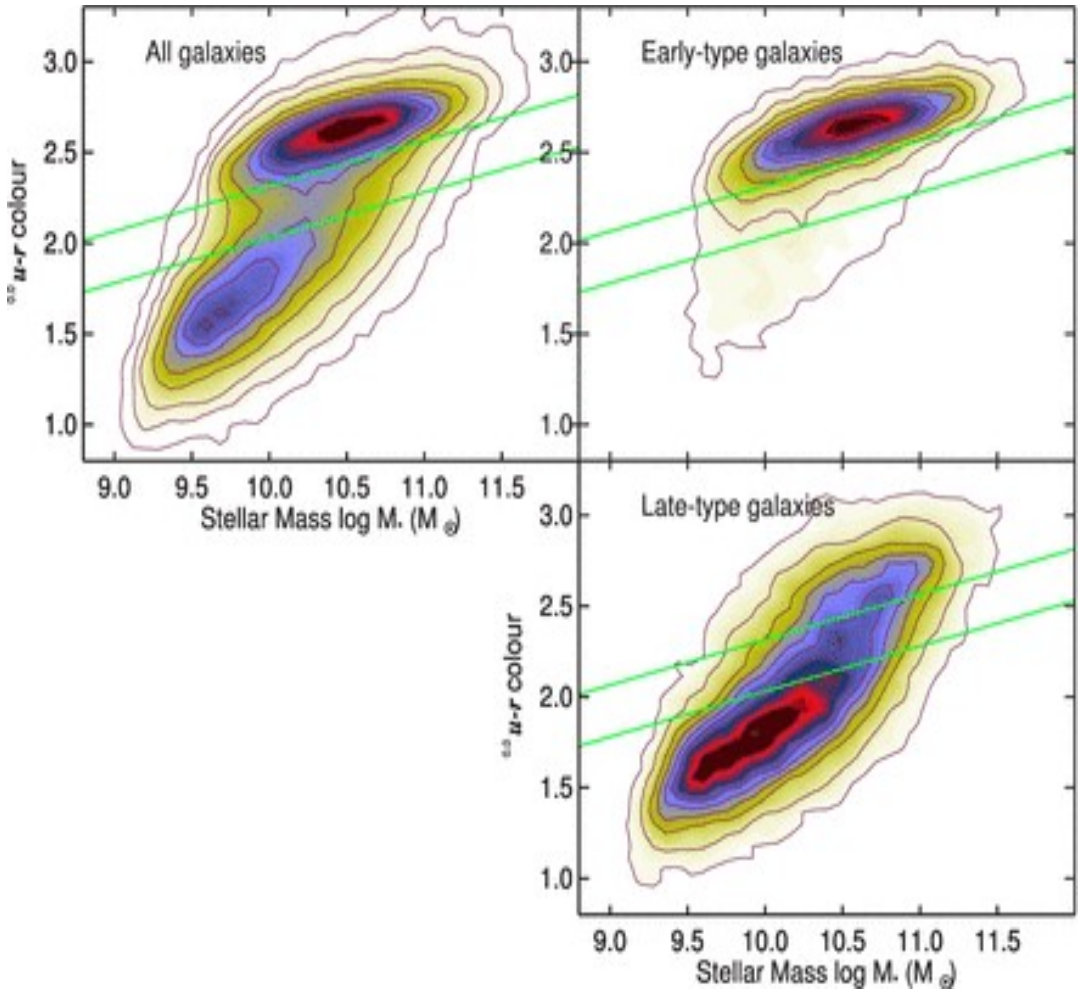
black hole mass
(e.g., Kormendy & Richstone 1995; McLure et al. 2000; Graham et al. 2001; Marconi & Hunt 2003)

nuclear activity
(e.g., Adams 1977; Heckman 1978; Ho, Filippenko, & Sargent 1995; Kauffmann et al. 2003; Choi et al. 2009; Pierce et al. 2007; Gabor et al. 2009; Pović et al. 2012)

environment
(e.g., Cassata et al. 2007, Beyoro-Amado et al. 2019)

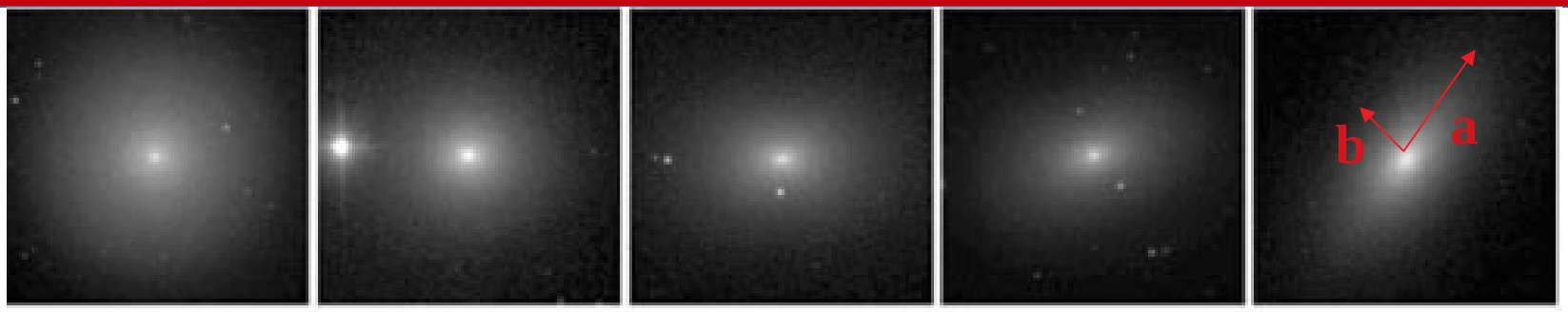
X-ray properties
(e.g., Hickox et al. 2009; Pović et al. 2009a,b)

....



Schawinski et al. 2014
(GalaxyZOO)

Elliptical galaxies - summary



Credits: R. Buta

*** Classification due to their ellipticity: E0 nearly spherical, E7 highly elongated.**
*** En, where n = 10 x (a-b)/a, with a and b being the projected major and minor axes**

*** In general show little structure.**
*** Very strong bulge, very poor or no disc, do not have spiral arms or nuclear bars.**

*** Previously believed that ellipticals contain neither gas nor dust, but these components (e.g., hot gas ~ 10^7 K detected in X-rays, H_α emission lines of warm gas (~ 10^4 K), cold gas (~100 K) in the HI 21-cm, CO molecular lines) have now been found, though at a much lower mass-fraction than in spirals.**

*** Some of the normal ellipticals contain visible amounts of dust, partially manifested as a dust disk.**

Example: dust lane in Cen A

Elliptical galaxies - summary

*** Many (if not all) formed due to galaxy mergers and interactions.**

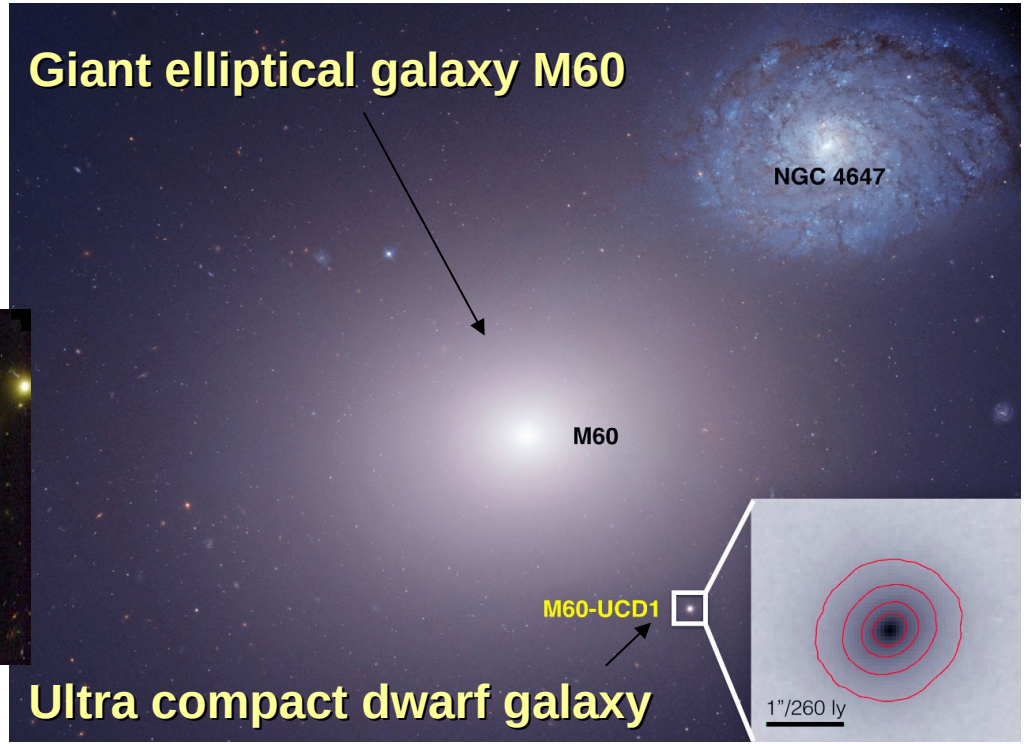
*** Reduced rate of new star formation.**
*** In general, appear red when observed in the optical, which suggests older stellar populations (or higher metallicity?). But can also show bluer colours due to recent star formation and/or AGN activity.**

*** Low number of open stellar clusters, presence of globular clusters both in the halo and in the bulge.**

*** Show large ranges in both mass and size.**
Masses - from 10^7 to 10^{13} Mo.
Sizes: from dwarfs to giant ellipticals
(or from tenth of kpc to few hundreds of kpc).

***Often found near the core of galaxy clusters, also as Brightest Cluster Members (BCM)**

Credits: HST

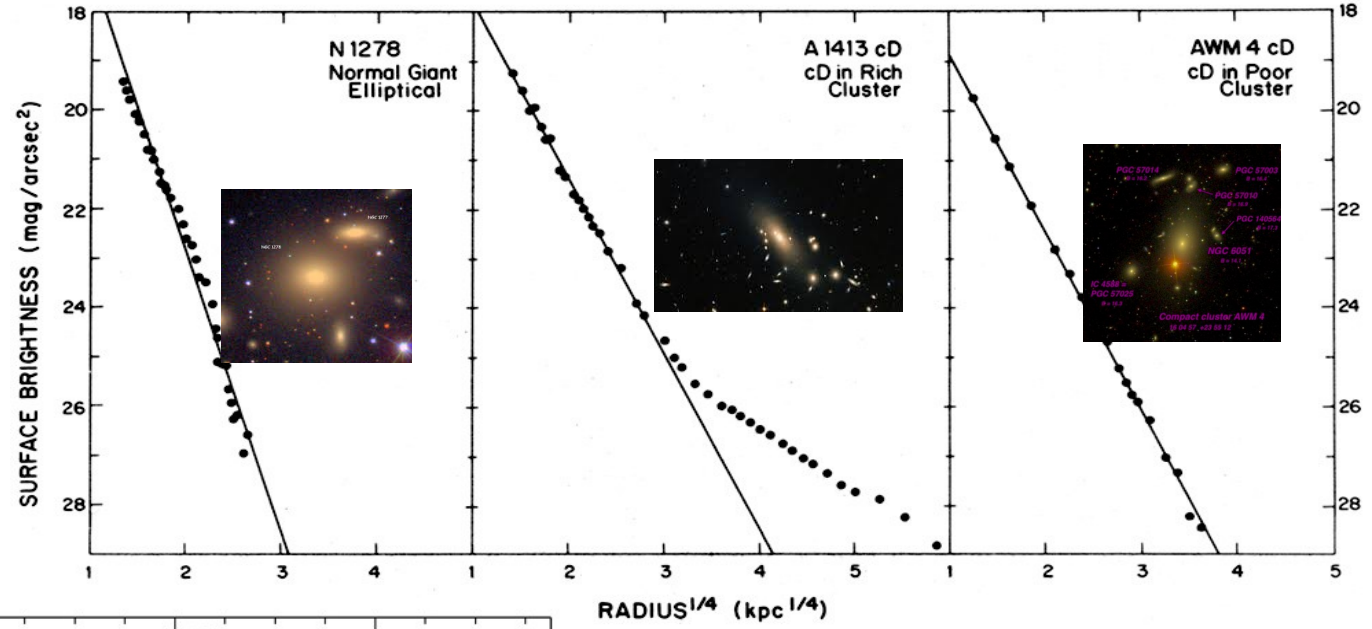


Elliptical galaxies - summary

Sersic profile used in general as an empirical law for describing light profiles in galaxies

$$\mu_b(r) = \mu_e + c_n[(r/r_e)^{1/n} - 1]$$

*** Brightness profiles of elliptical galaxies are best fitted with de Vaucouleurs law with n = 4**



Oemler 1976

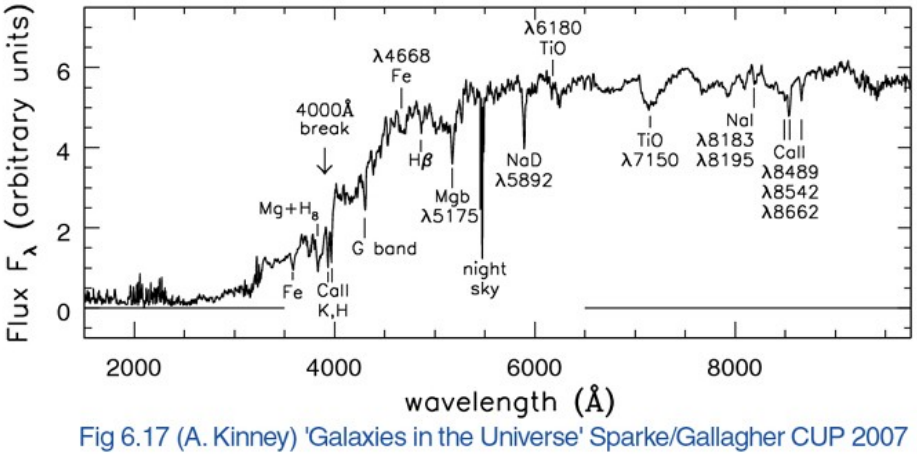


Fig 6.17 (A. Kinney) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

*** Spectral properties: strong absorption lines, due to metals in the stellar mospheres of the low luminosity stellar pulations. In most of cases of normal, ve Ells few to no emission lines.**

Elliptical galaxies - summary

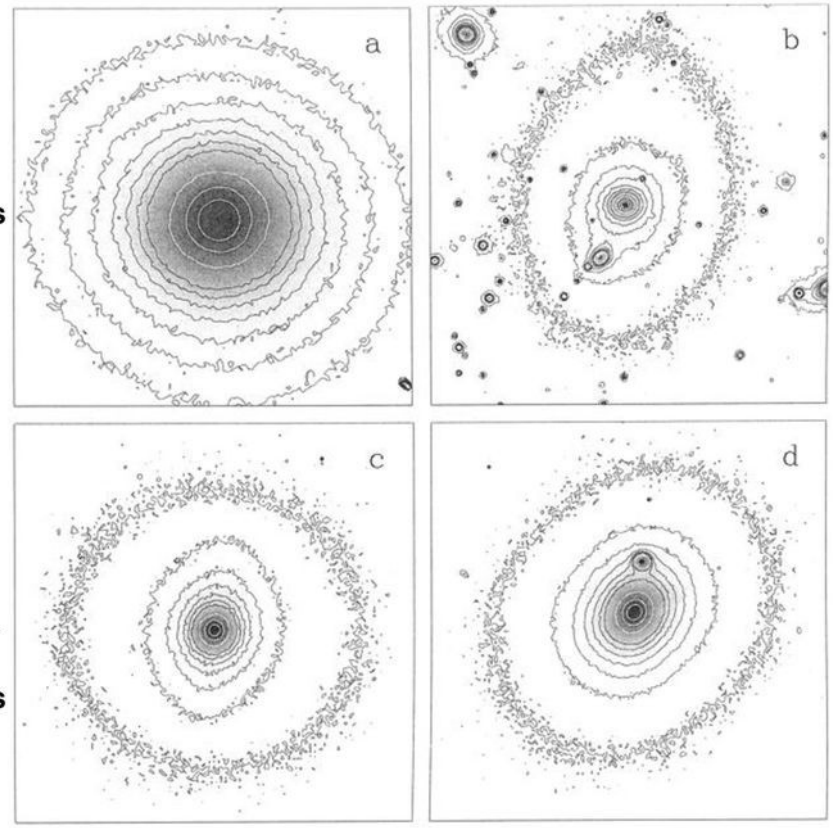
*** Complex dynamics and kinematics.**

The isophotes (curves of constant surface brightness) of many of the normal elliptical galaxies are well approximated by ellipses, concentric to high accuracy, with the deviation of the isophote's center from the center of the galaxy being typically < 1% of its extent.

*** However, in many cases the ellipticity varies with radius. Plus many ellipticals show isophote twisting - the orientation of the semi-major axis of the isophotes changes with radius, indicating that elliptical galaxies are not spheroidal, but triaxial systems**

(or that there is some intrinsic twist of their axes).

*** Dust disks are not necessarily perpendicular to any of the principal axes. They may rotate in a direction opposite to the galactic rotation**

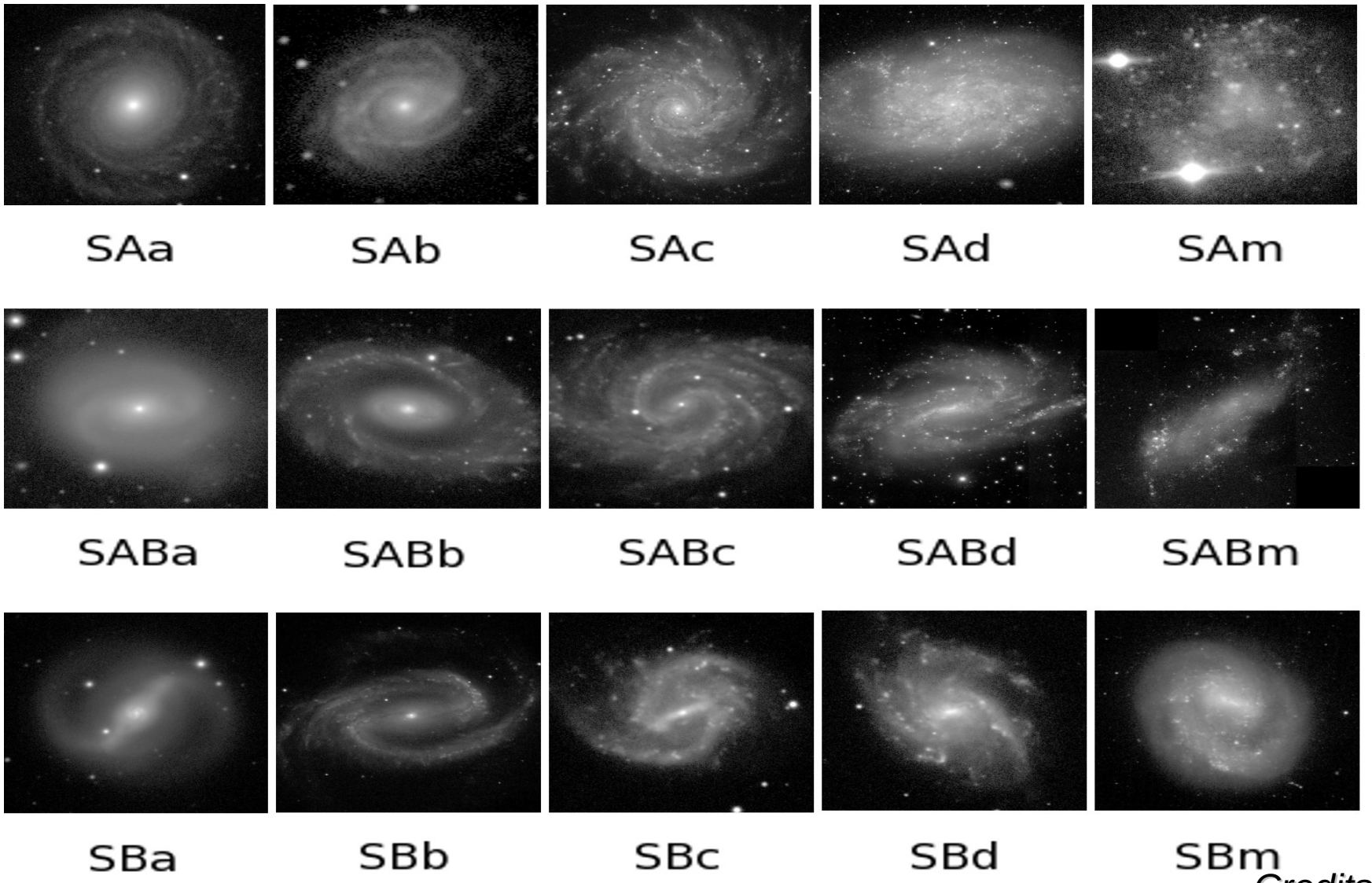


Credits: de Jong, 2007; Laurits Ludvingsen

Spiral galaxies - summary

Classification due to:

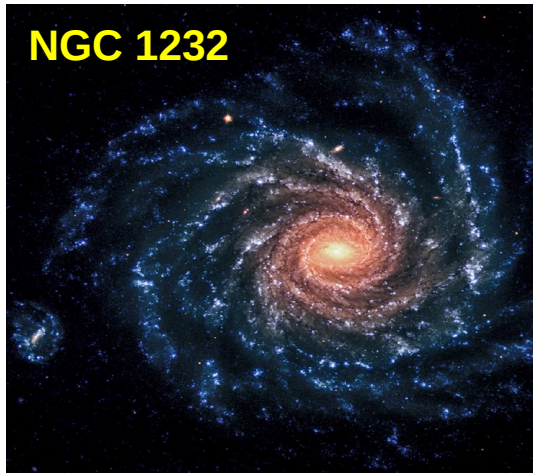
- **the existence of nuclear bar: non- barred and barred spiral galaxies**
- **the size of central bulge and degree of tightness of their spiral arms**



Credits: R. Buta

Spiral galaxies - summary

Components:
*** Disc + bulge (B/D ratio changes for spirals; B/D > 1 for Sa, B/D < 0.2 for Sc).**
*** Have spiral arms and can have a nuclear bar.**



Stellar populations and colours:
*** Older spiral galaxies (Sa, Sb) appear with reddish bulges and bluish discs when observed in the optical, which suggests <u>older stellar populations</u> in the bulge (and/or higher metallicity (Z) and/or internal extinction effects due to dust) and <u>younger stellar populations</u> in the disc.**

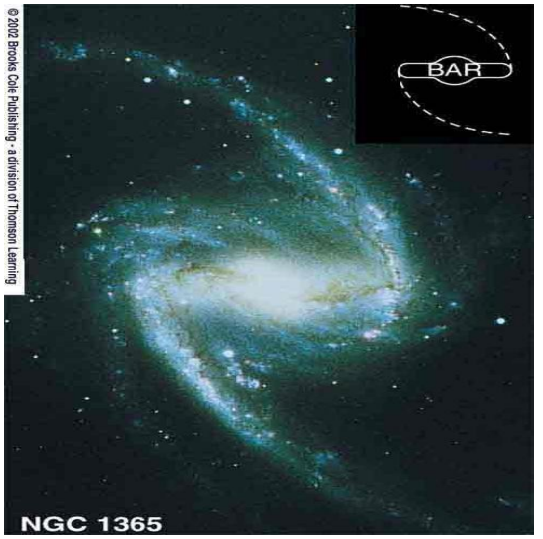
*** Previous scenario can change for later-type spirals (Sc, Sd) that usually contain less evolved bulges with a higher number of young, blue population I stars.**

*** High number of open stellar clusters in the disc; presence of globular clusters both in the halo and in the bulge (as in the case of Ell and S0 galaxies).**

Spiral galaxies - summary

*** Spiral arms: rotate around the centre; areas of high density matter ("density waves"); places where the star formation occurs; harbour many bright and young stars, as hot OB stars; contain high amounts of gas and dust lanes.**

*** Nuclear bars: a bar-like pattern of older stars that crosses the centre; extends outward to either side of the core and mergers into the spiral arm structure - spiral arms break from the ends of this bar. Bars are temporary structures that can occur as a result of a density wave radiating outward from the core, or due to tidal interaction with another galaxy.**

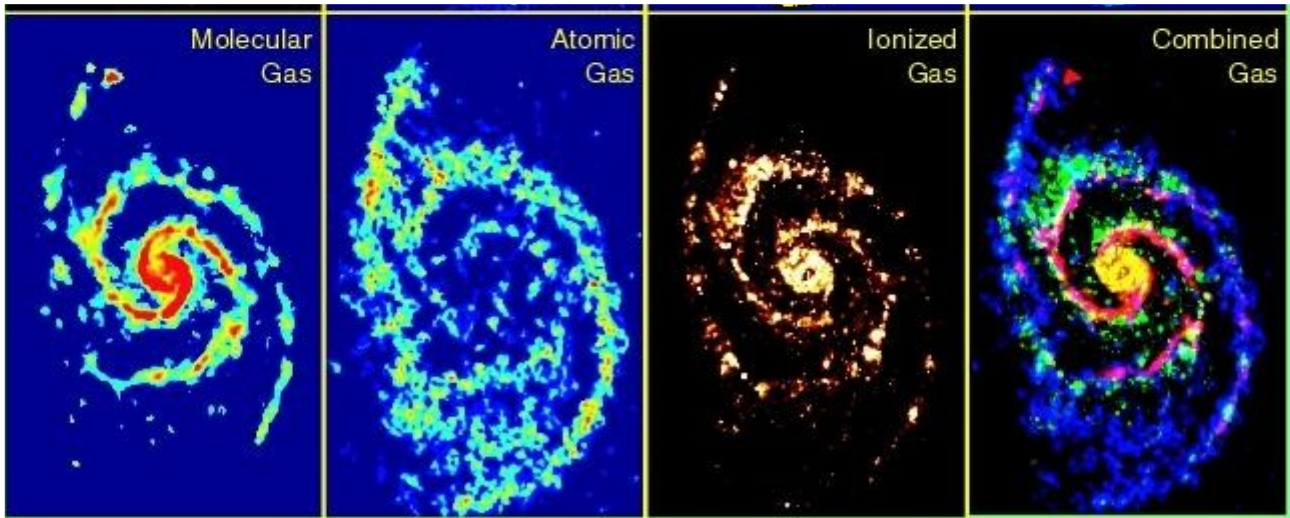


Whirlpool spiral galaxy. Credits: S. Vogel

*** Presence of molecular, atomic, and ionised gas in the disc.**

*** Presence of dust.**

*** Enhanced star formation in the disc.**



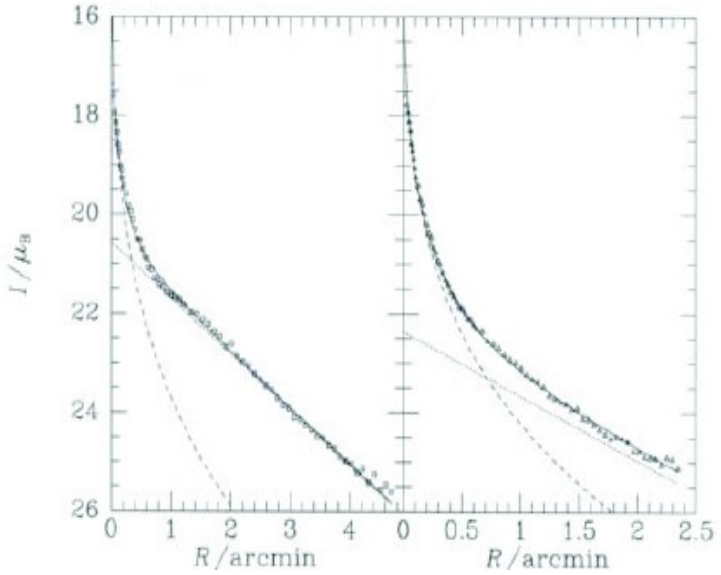
Spiral galaxies - summary

Brightness profiles:

*** normally discs fitted well using exponential law, with n = 1.**

$$\mu_b(r) = \mu_e + c_n[(r/r_e)^{1/n} - 1]$$

*** however, complex profiles due to the number of components (central bulge, disc, spiral arms, bar, rings, etc.) and often due to extinction (large amounts of dust).**



Dotted line: exponential fit to the disk

Dashed curve is an $R^{1/4}$ profile fitted to the central bulge of these galaxies.

The full curve is the "sum" of both components.

*** Inclination matters for studying spiral galaxies and their brightness profiles**

Face-on (I = 0^o), light passes through smaller column densities of ISM

Inclined

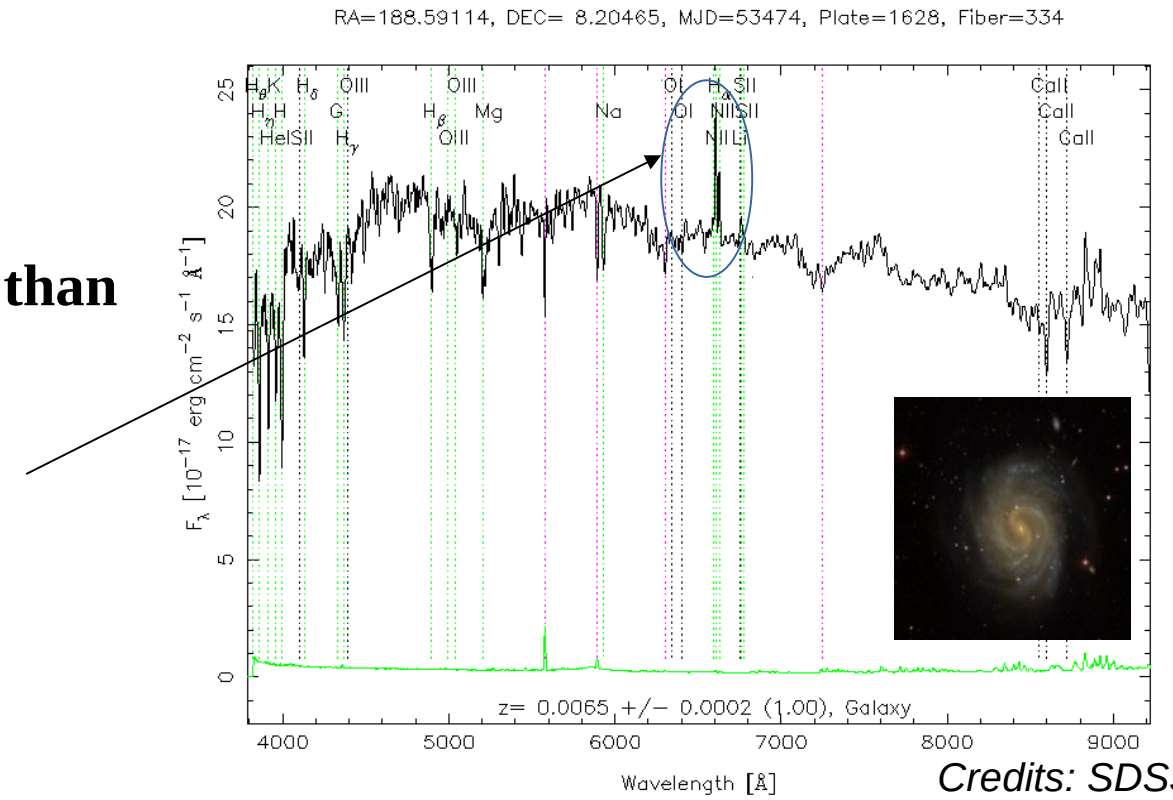
Edge-on (I = 90^o), light passes through larger column densities of ISM

Spiral galaxies - summary

Spectral properties:

*** absorption lines, but less strong than in the case of Ell galaxies**

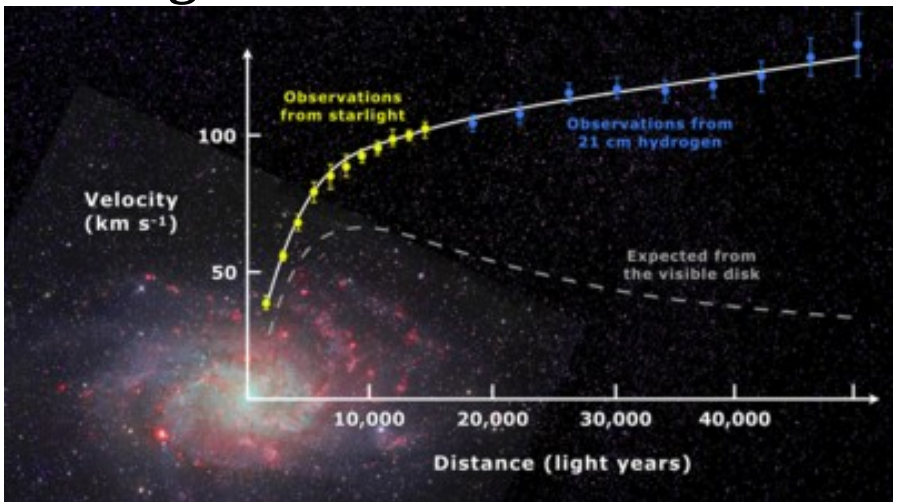
*** Hα emission line due to the star Formation**



Credits: SDSS

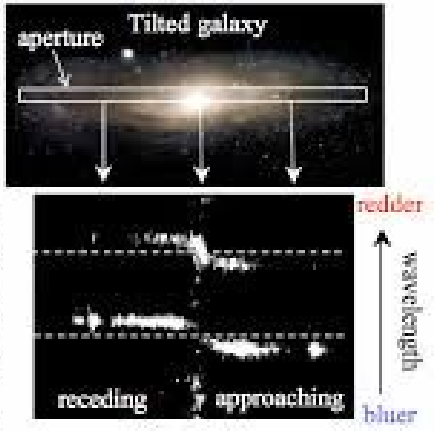
*** Rotationally supported systems**

→ used for measuring the rotational curves and the amount of dark matter



Credits: Corbelli and Salucci, 2000

Vera Rubin measuring galaxy rotation curves (~1970)



Resulting spectrum of light within aperture

Lenticular (S0) galaxies - summary

*** Intermediate form, with properties between ellipticals and spirals.**

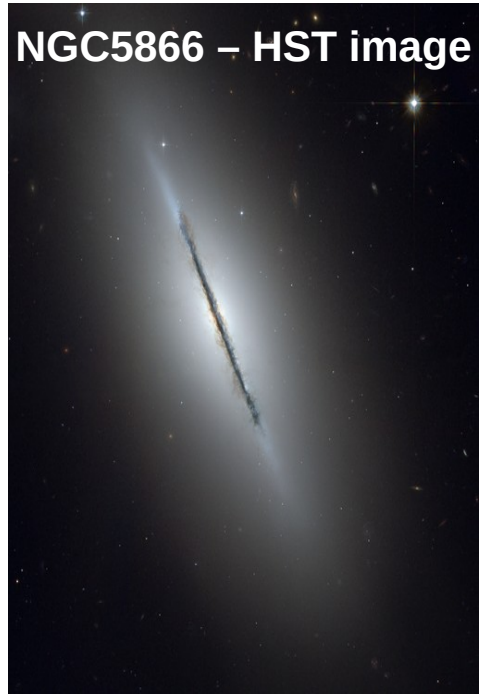
*** Smooth, central brightness concentration (bulge similar to Ell) surrounded by a large region of less steeply declining brightness (similar to a disk).**

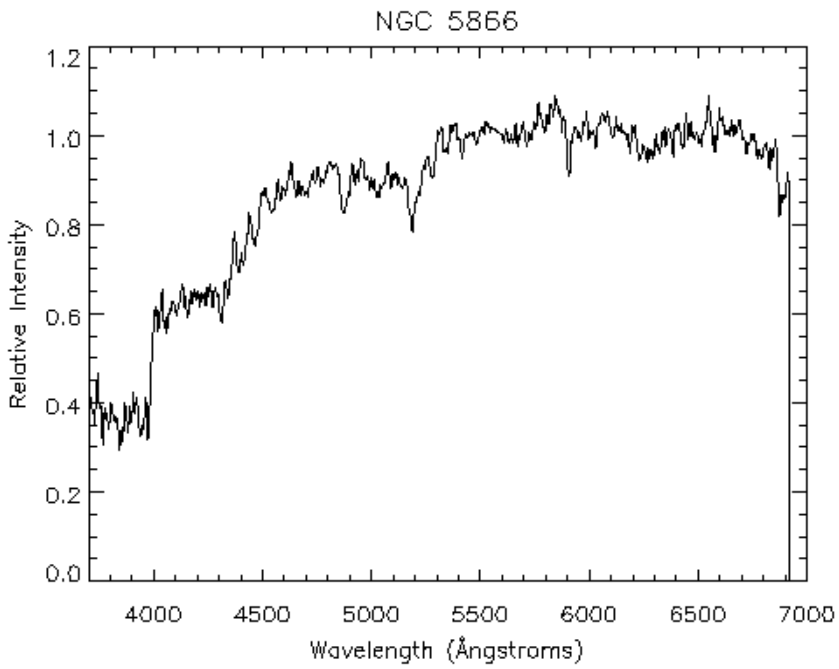
*** Galaxies with small amounts of dust and gas, and therefore have very little ongoing star formation.**

***Consist mainly of older stars (like Ell).**

*** Similar spectral properties like Ell galaxies, and in general considered as early-types.**

***More difficult surface brightness profiles. However, more similar to Ell since the bulge is dominating the galaxy. Very often fitted with multiple Sersic profiles (e.g., if decomposing the galaxy the outermost parts of the disc have n = 1)**





Irregular galaxies - summary

*** Galaxies that can not be classified into an elliptical or spiral morphology → without a particular shape and clear components.**

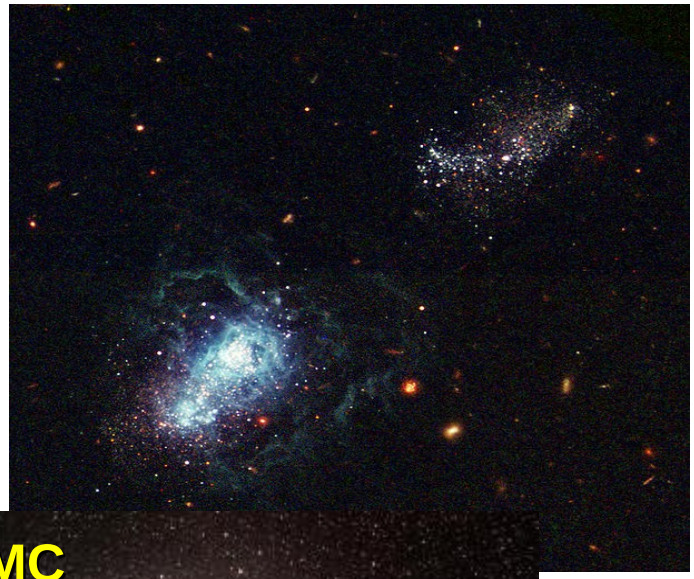
*** Contain large amounts of gas and dust, young stellar populations, and open stellar clusters.**

*** Three types of irregular galaxies:**
Irr-I, Irr-II, and dIrr.

*** Irr-I galaxies have some structure, but do not align clearly with the Hubble classification Scheme.**

*** Irr-II galaxies do not posses any structure and may have been disrupted.**

*** Dwarf Irregular galaxies (dIrr) – similar as previous two types, but with much smaller sizes, masses, brightnesses, and numbers of stars.**



Peculiar galaxies - summary

* Galaxies that develop unusual properties due to tidal interactions with other galaxies.

* Have atypical structures, and large amounts of gas and dust.

* Recent mergers and interactions between the two or more galaxies.

* Have enhanced star formation.

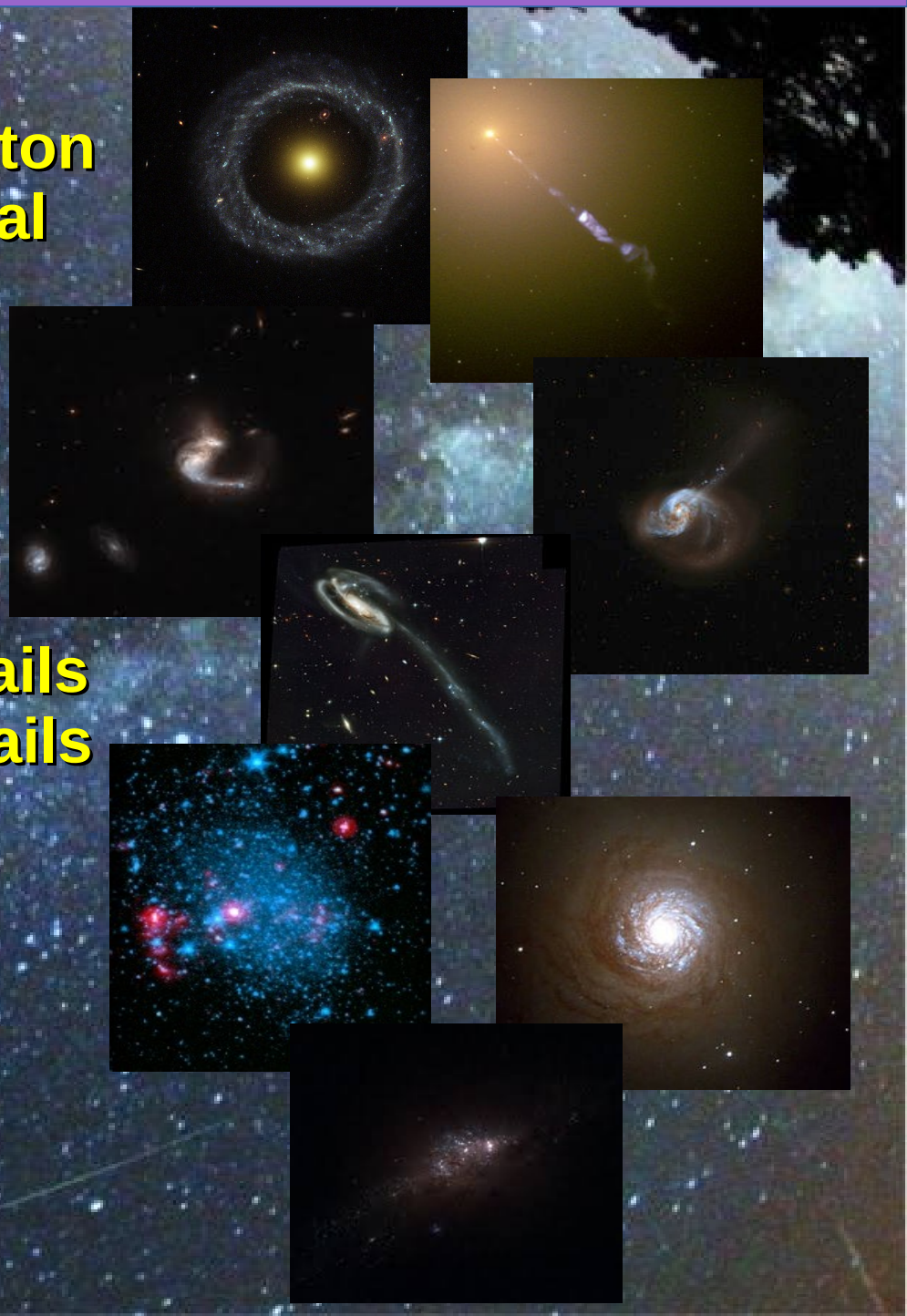
* Very often related with starbursts, LIR galaxies, and active galaxies.

Peculiar galaxies - summary

* Atlas of peculiar Galaxies – Halton Arp → classification of 338 local galaxies as peculiar.

- galaxies with rings
- galaxies with jets
- galaxies with diffuse counter-tails
- galaxies with narrow counter-tails
- galaxies with filaments
- galaxies with irregular clumps
- galaxies with peculiar spirals
- galaxies with diffuse filaments

… etc...



How can we classify galaxies?

Methods of morphological classification

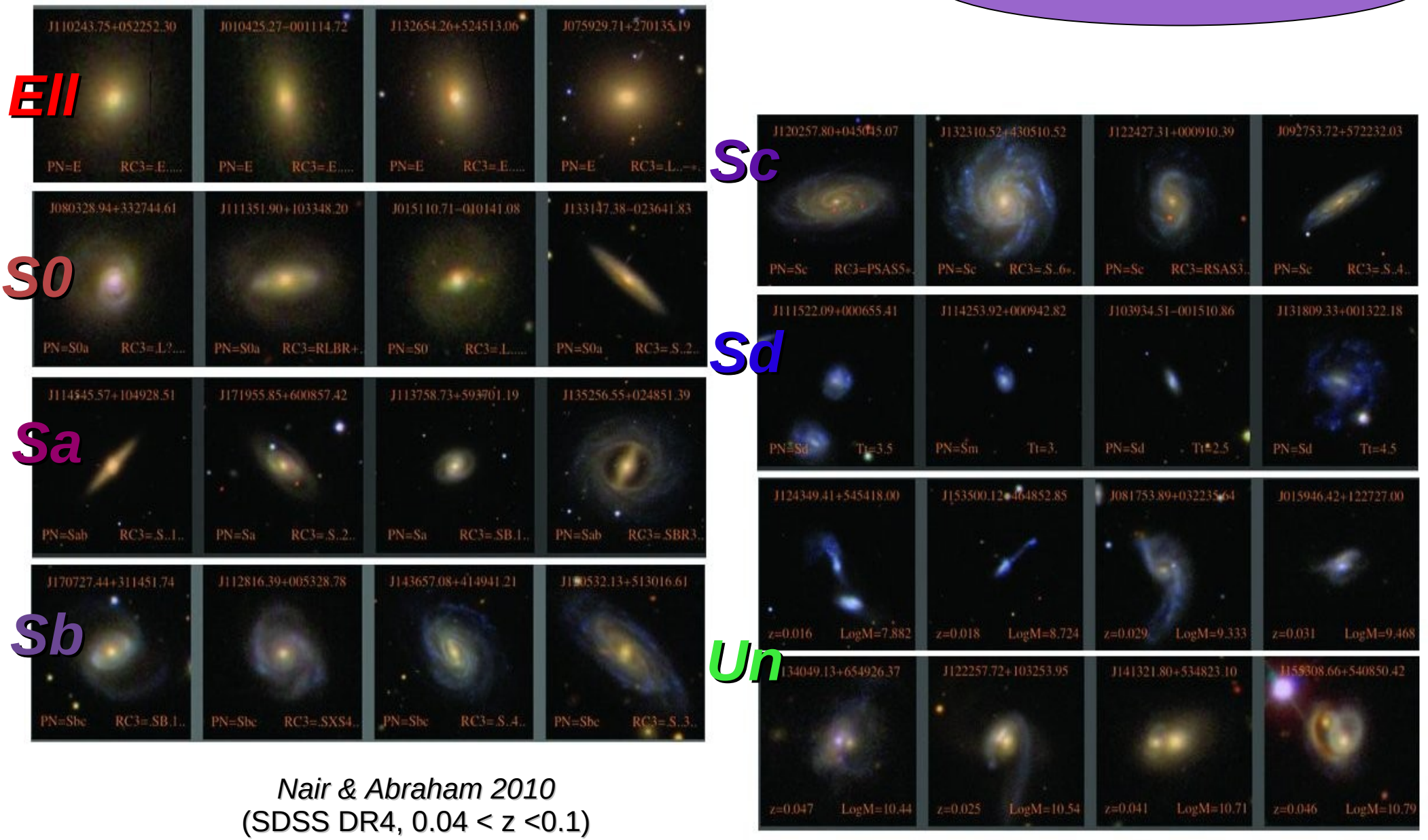
I. Visual classification

II. Parametric methods

III. Non-parametric methods/ machine learning

Methods of morphological classification

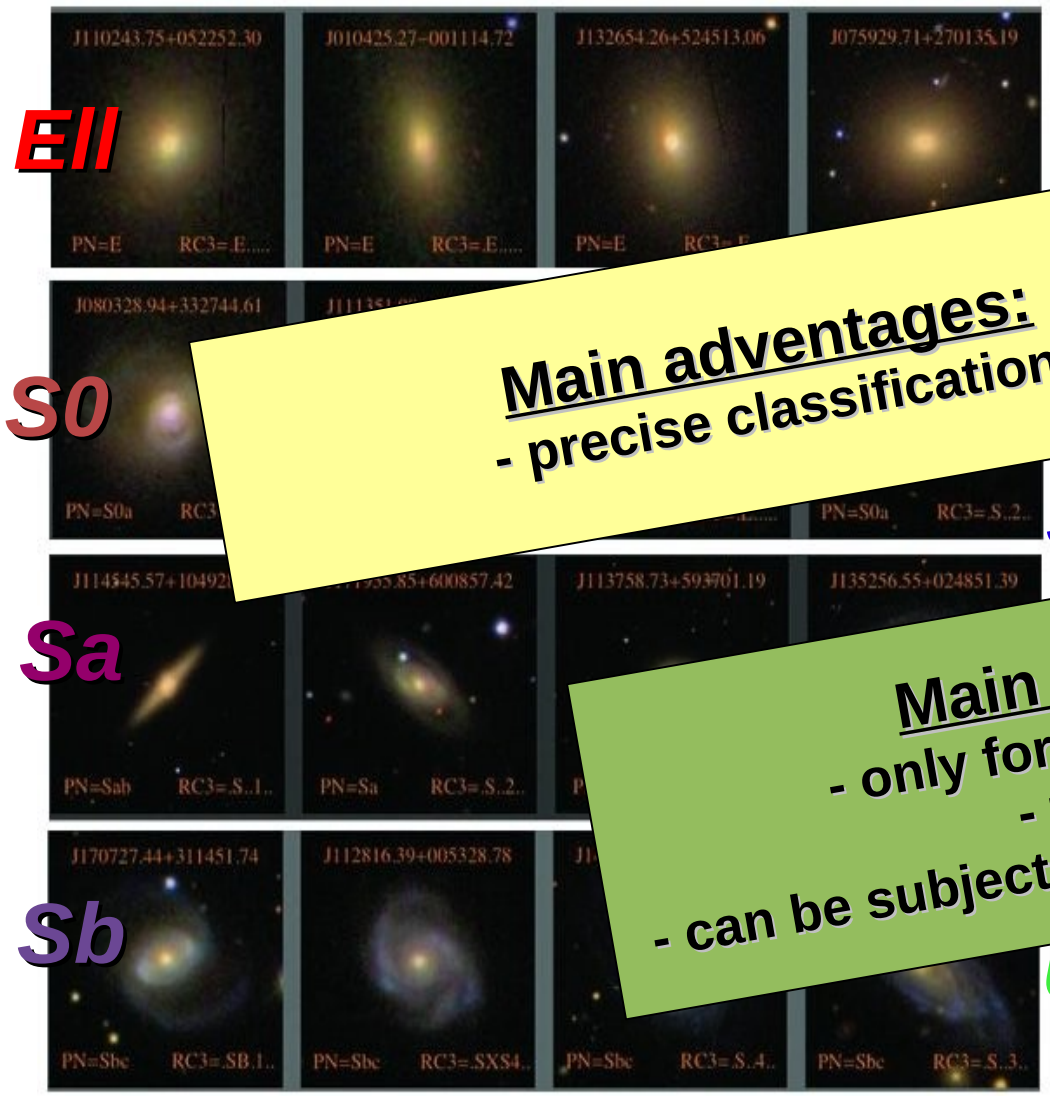
I. Visual



Nair & Abraham 2010
(SDSS DR4, 0.04 < z <0.1)

Methods of morphological classification

I. Visual



Main adventages:
- precise classification

Main disadventages:
- only for well-resolved galaxies
- time consuming
- can be subjective (several classifiers needed)

Nair & Abraham 2010
(SDSS DR4, 0.04 < z <0.1)

Methods of morphological classification

II. Parametric

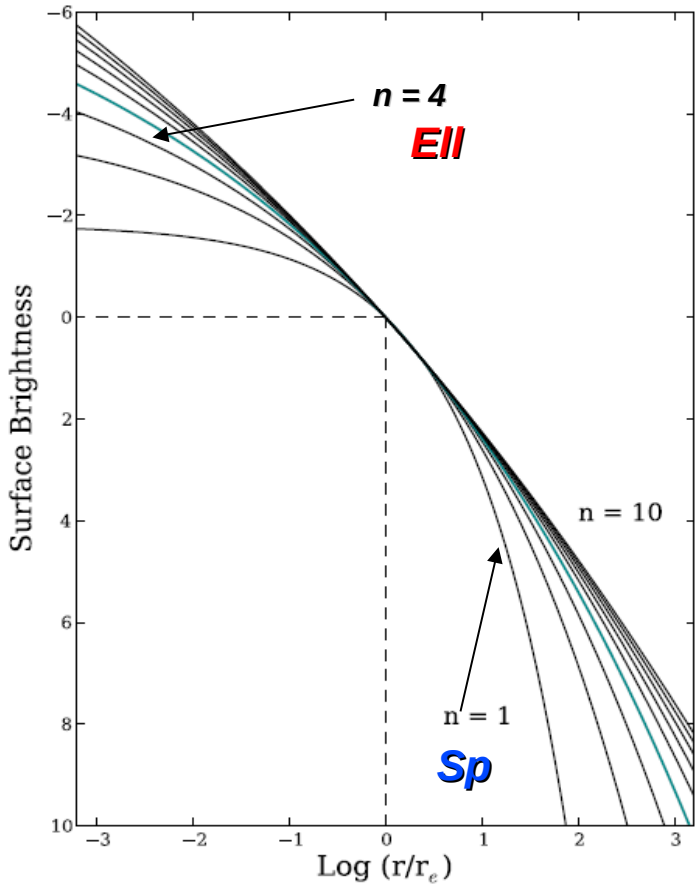
a) based on physical parameters (galaxy decomposition)

- Surface brightness fitting
  (Sersic et al. 1963)

$$\Sigma(r) = \Sigma_e \, e^{-k(n)((r/r_e)^{1/n}-1)}$$

- Codes: e.g., GALFIT (Peng et al. 2002), GIM2D (Simard et al. 2002), BUDDHA (de Souza et al. 2004), etc.

Output => B/T flux ratio (B/D flux ratio)
Sersic index n
Bulge (disk) effective radius
Residual parameter
.....



I. Pintos-Castro, 2014
(PhD thesis)

b) based on mathematical parameters (still in developing phase)

Methods of morphological classification

II. Parametric

a) based on physical parameters (galaxy decomposition)

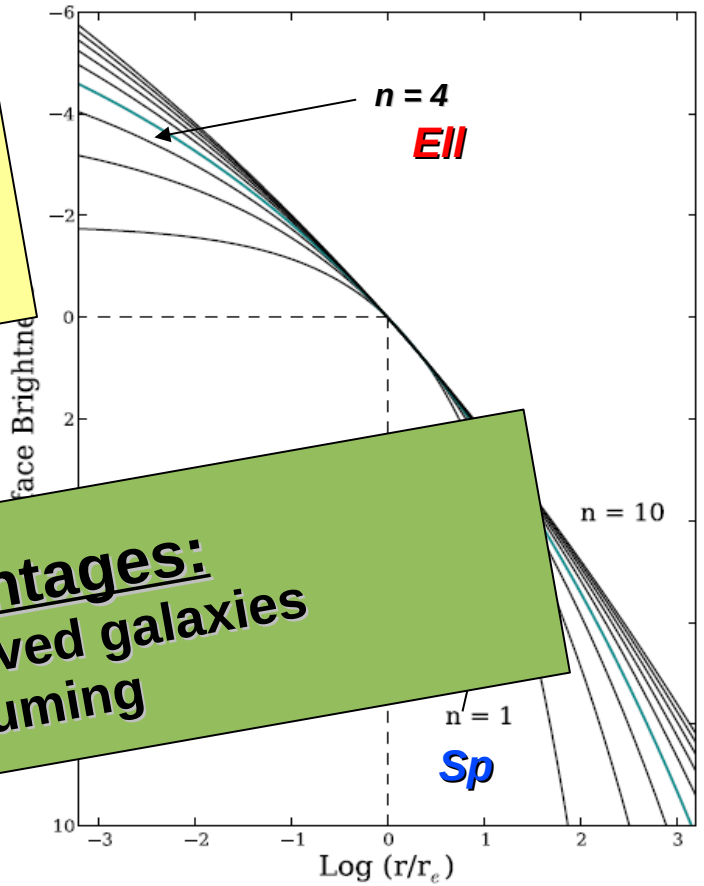
- Surface brightness fitting
  (Sersic et al. 1963)

Main adventages:
- detailed structure analysis

- Codes (Peng et al. 2002), GIM2D (Simard et al. 2002), BUDDHA (de Souza et al. 2004)

Output => B/T flux ratio
Sersic index
Bulge (disk) e
Residual para
.....

Main disadventages:
- only for well-resolved galaxies
- time consuming



I. Pintos-Castro, 2014
(PhD thesis)

b) based on mathematical parameters (still in developing phase)

Methods of morphological classification

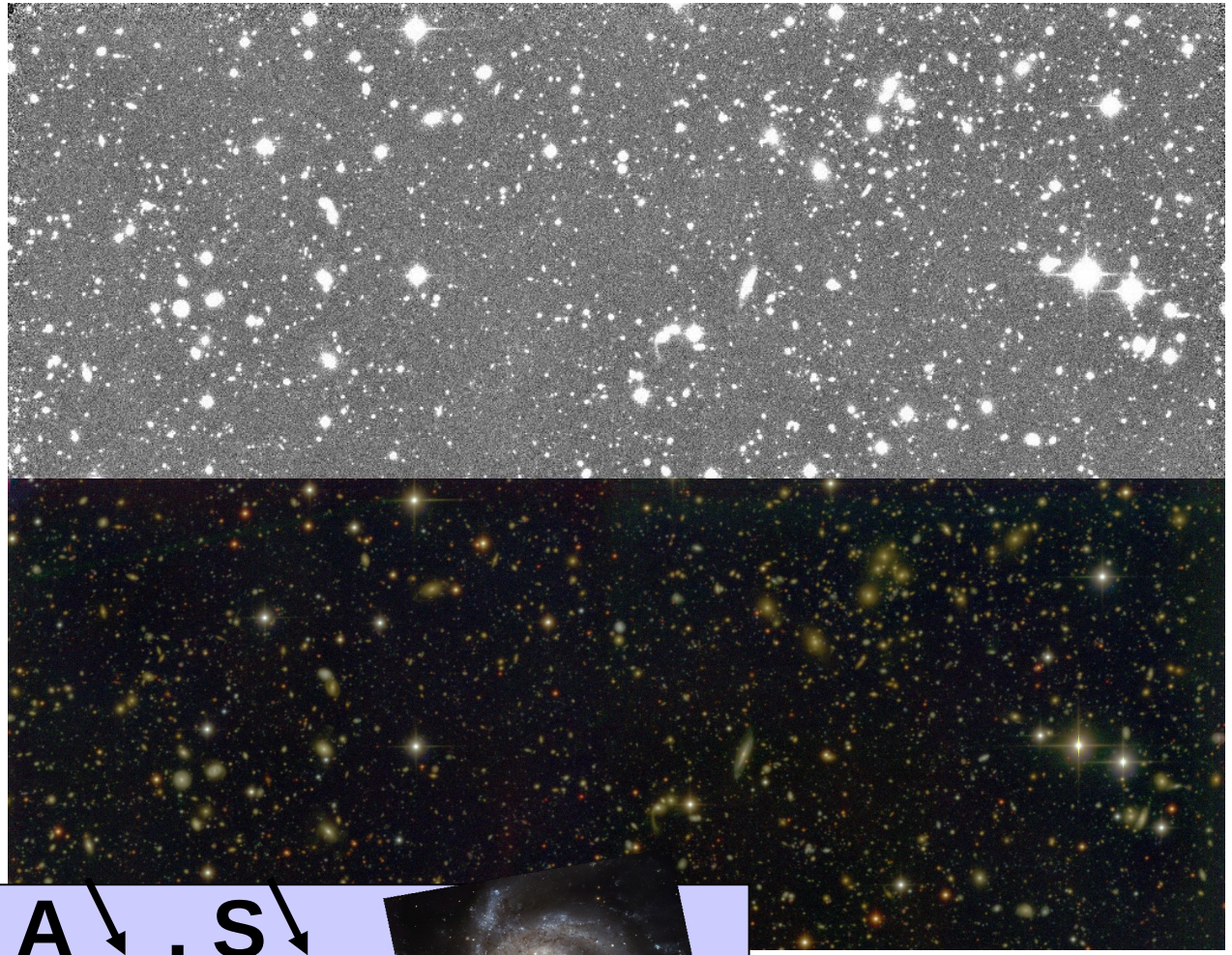
III. Non-parametric

- for low resolution and/or higher-redshift data
- for large surveys

Authomated methods

Based on measuring different galaxy parameters that correlate with morphological types
→ mainly with light distribution and shape

→ e.g., concentration indexes, asymmetry, M20 moment of light, smoothness (clumpiness)



ET: C ↗ , A ↘ , S ↘
LT: C ↘ , A ↗ , S ↗

ALHAMBRA survey
(Moles et al. 2007)

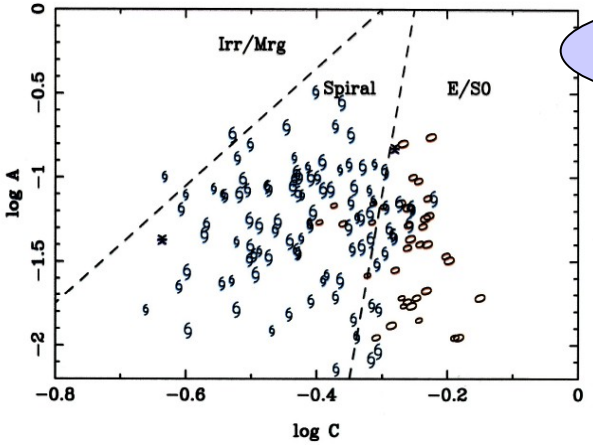
Methods of morphological classification

III. Non-parametric

2-3 parameter diagrams for:

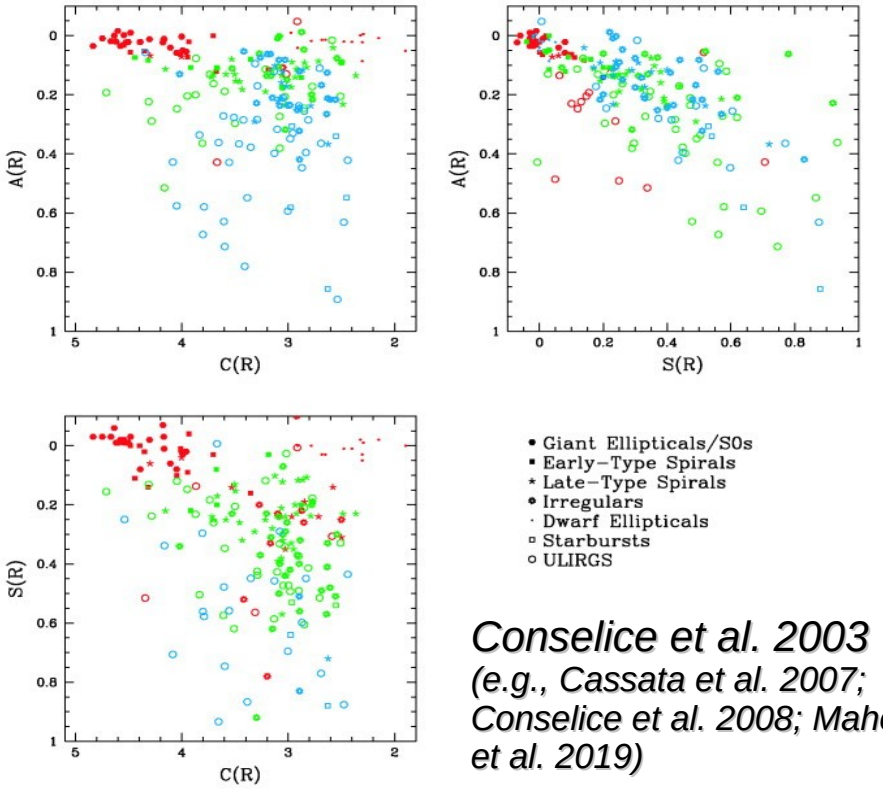
- **ET/LT separation**
- **selection of distrurbed (peculiar) galaxies**
- **selection of merger candidates**

CABR-ASYM



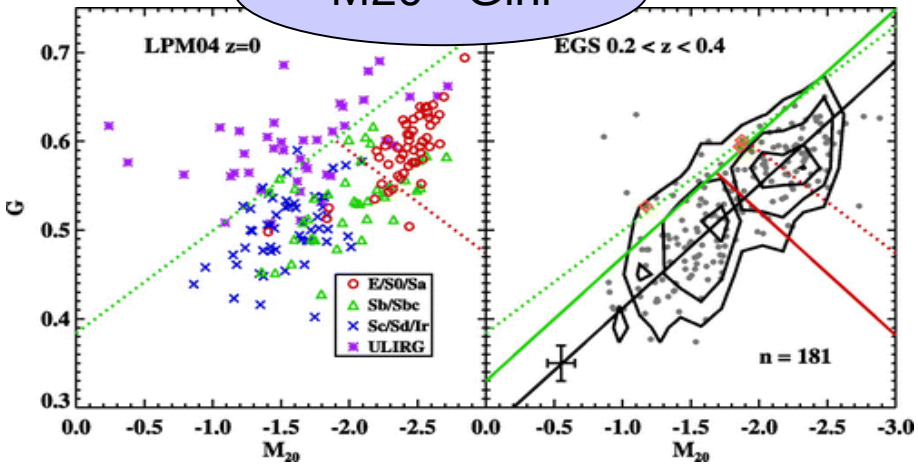
Abraham et al. 1996
(e.g., Conselice et al. 2006; Huertas Company et al. 2007; Pović et al. 2009A, 2015; Mahoro et al. 2019; Beyoro-Amado et al. 2019)

CCON-ASYM-SMOOTH



Conselice et al. 2003
(e.g., Cassata et al. 2007; Conselice et al. 2008; Mahoro et al. 2019)

M20 - Gini



Lotz et al. 2004
(e.g., Pierce et al. 2007; Lotz et al. 2008; Conselice et al. 2008; Mendez et al. 2011; Chen et al. 2009; Scott et al. 2013; Petty ey al. 2014; Hung et al. 2014; Povic et al. 2015)

Methods of morphological classification

III. Non-parametric

2-3 parameter diagrams for:

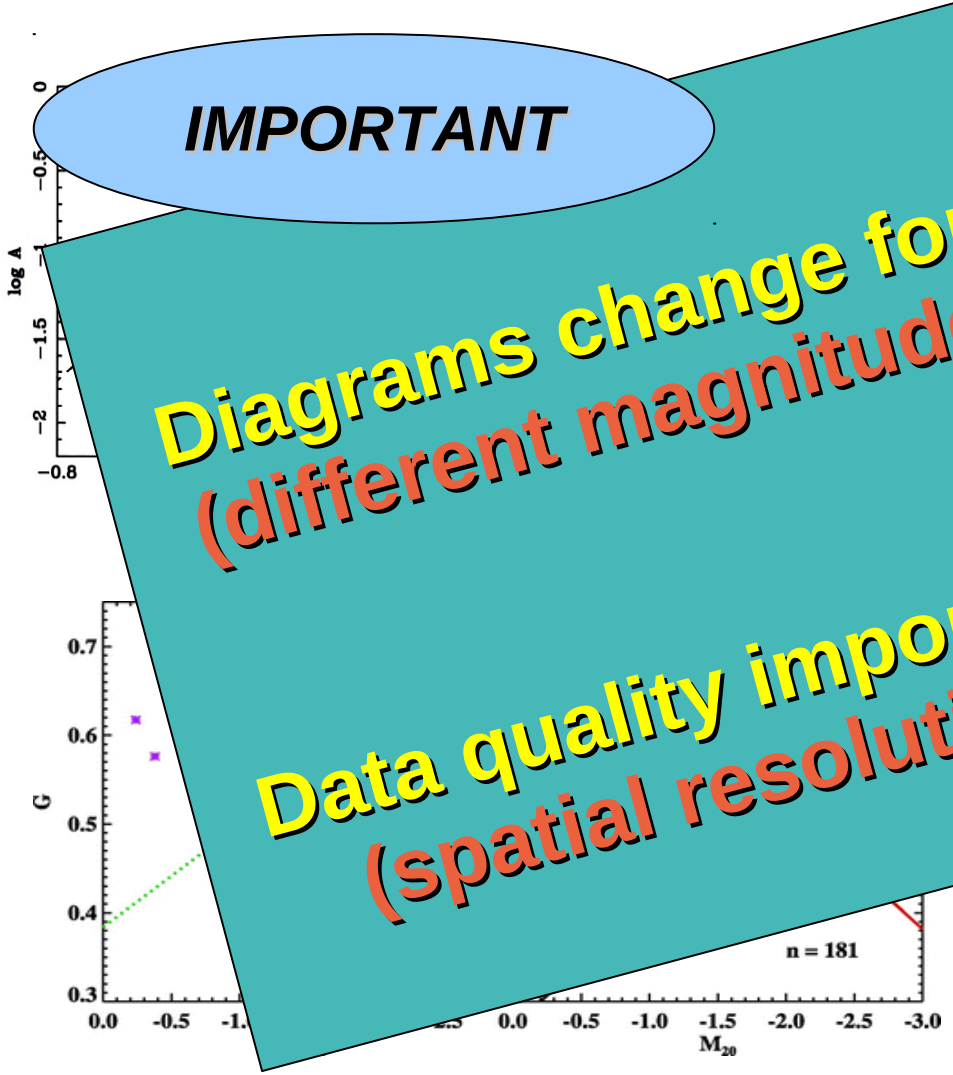
- *ET/LT separation*
- *selection of distrurbed (peculiar) galaxies*
- *selection of merger candidates*

OTH

IMPORTANT

Diagrams change for different data sets!!
(different magnitude and z distributions)

Data quality important for classification!!
(spatial resolution and survey depth)



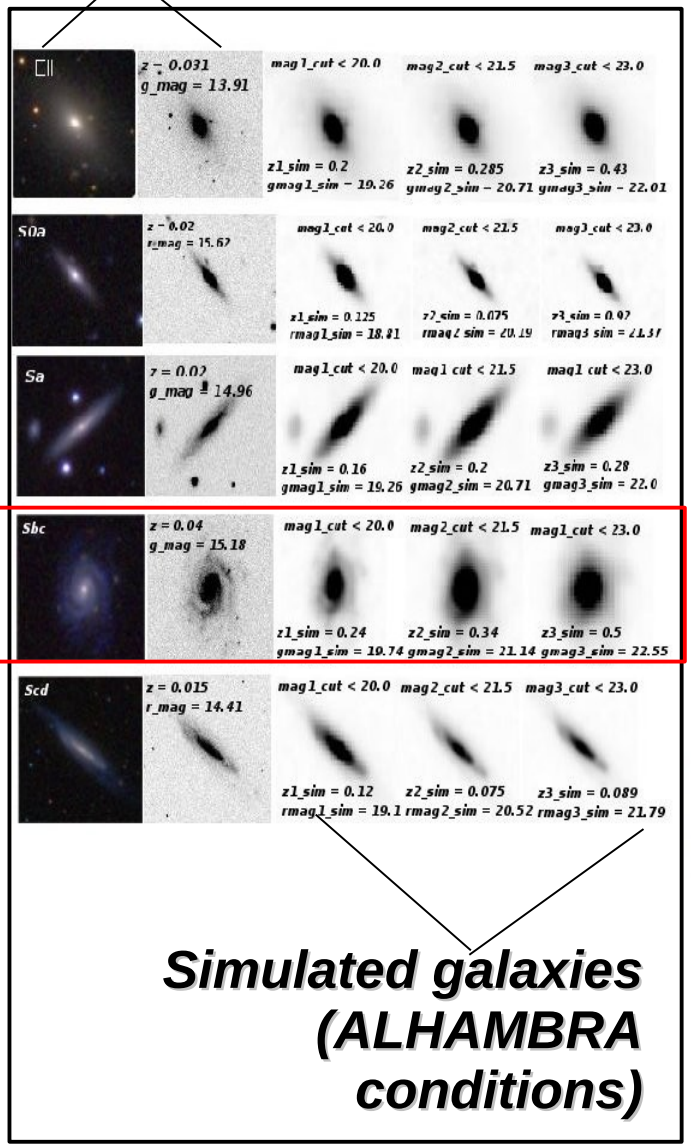
al. 2003
assata et al. 2007;
Conselice et al. 2008)

2004
(e.g., Pierce et al. 2007; Lotz et al. 2008; Conselice et al. 2008; Mendez et al. 2011; Chen et al. 2009; Scott et al. 2013; Petty ey al. 2014; Hung et al. 2014)

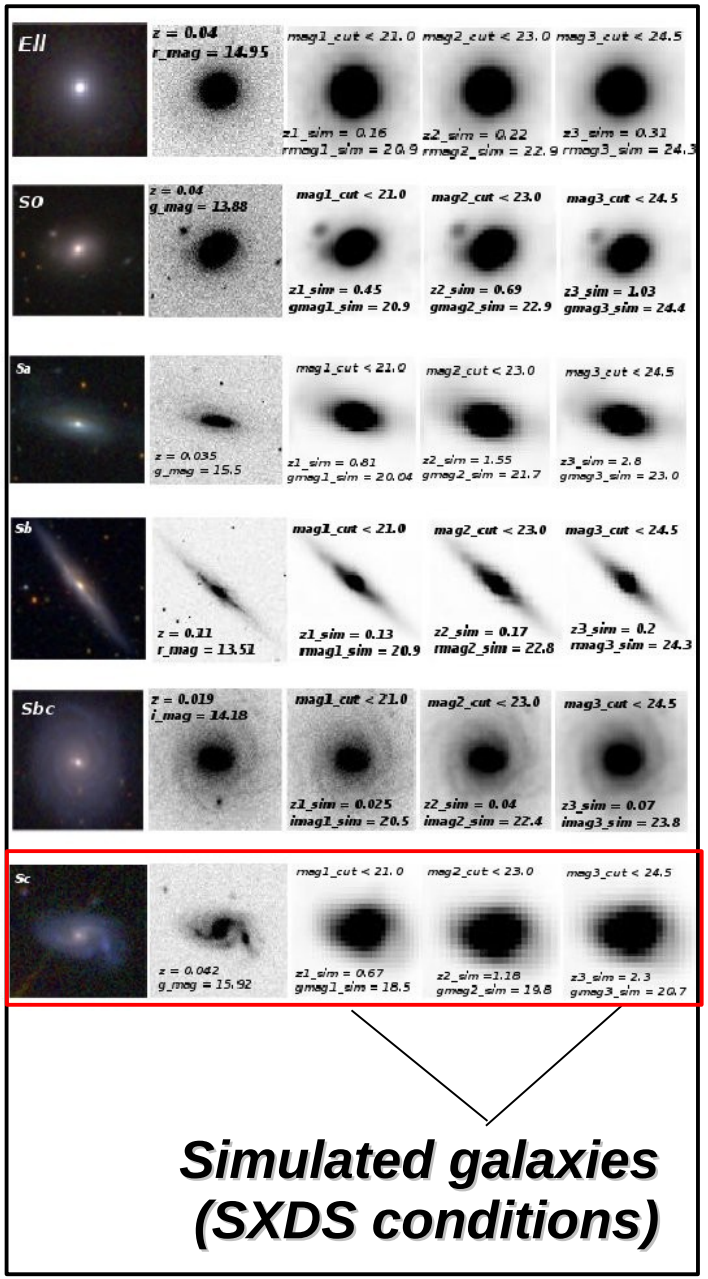
Impact of spatial resolution and data depth on morphological parameters

Pović et al. 2015

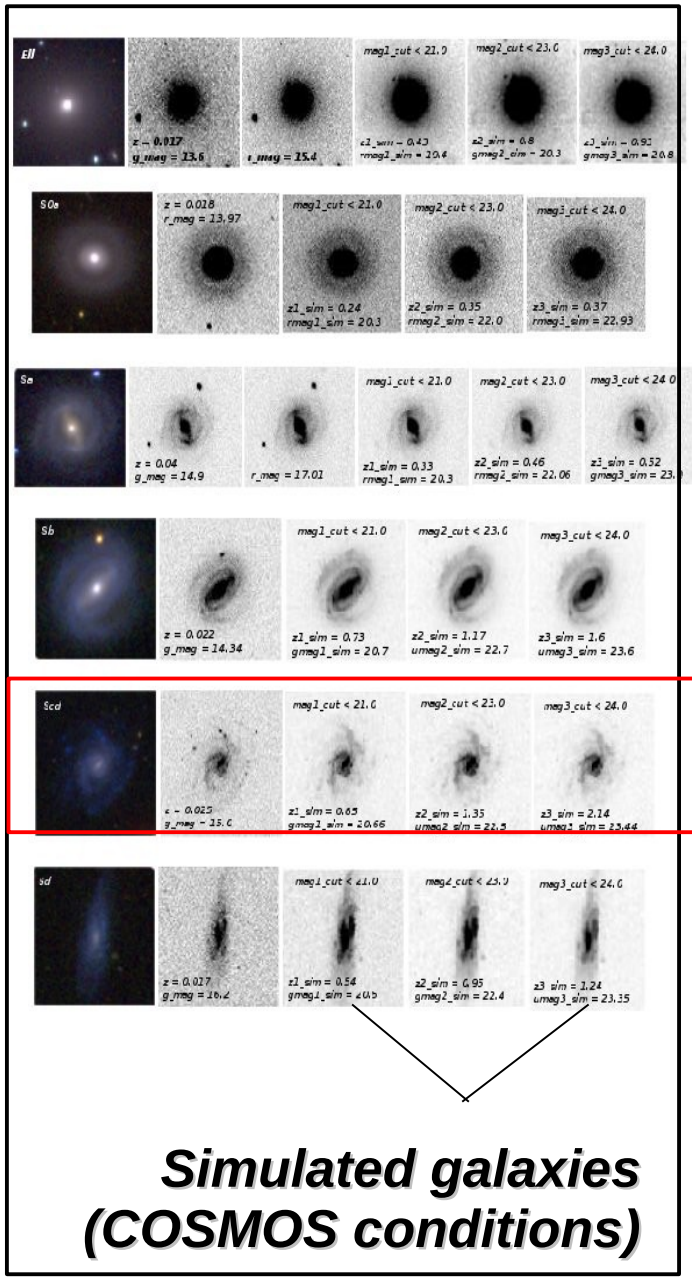
Local galaxies



Simulated galaxies (ALHAMBRA conditions)



Simulated galaxies (SXDS conditions)

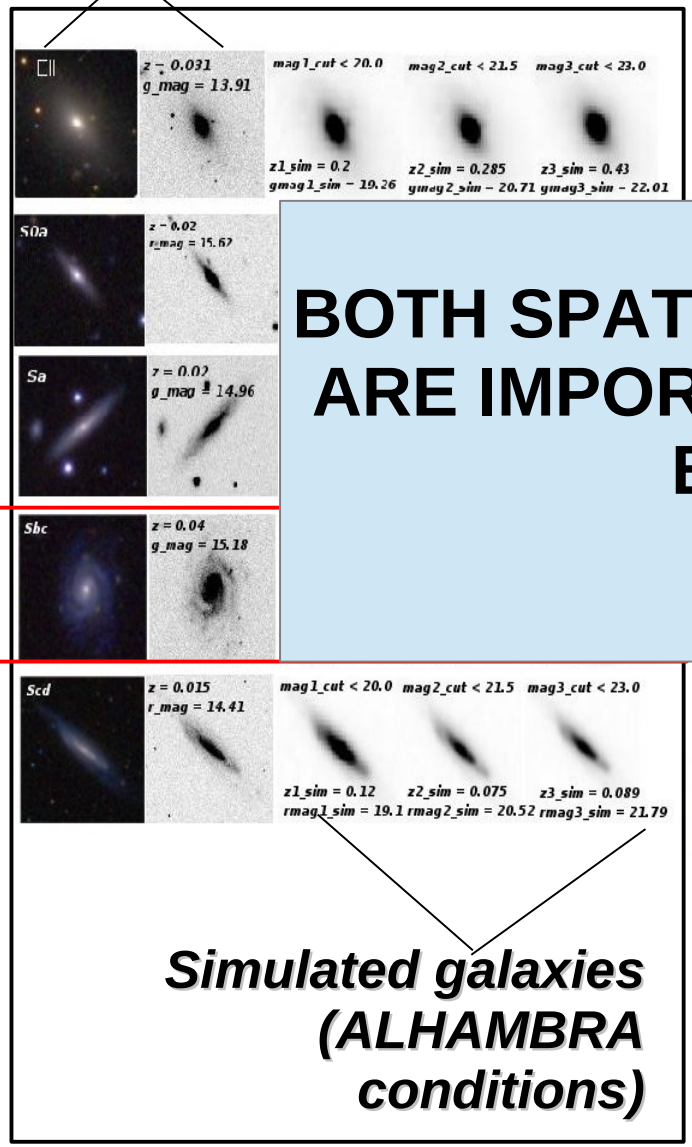


Simulated galaxies (COSMOS conditions)

Impact of spatial resolution and data depth on morphological parameters

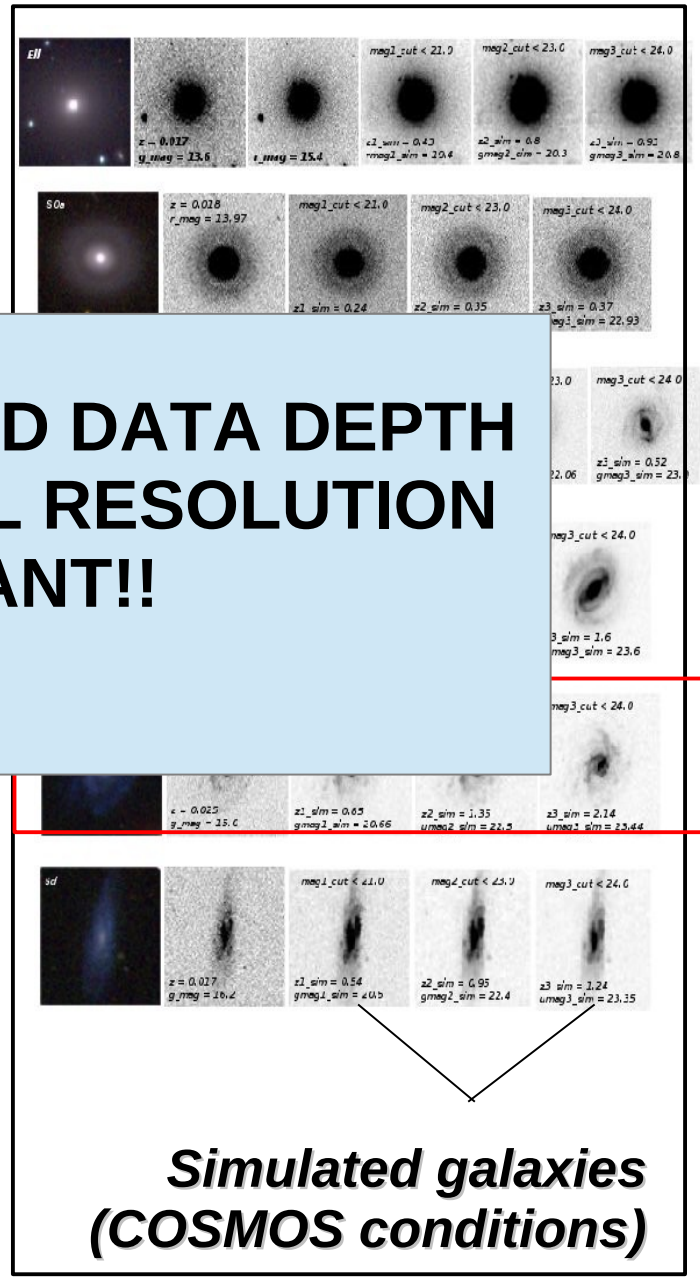
Pović et al. 2015

Local galaxies



Simulated galaxies (ALHAMBRA conditions)

Simulated galaxies (SXDS conditions)



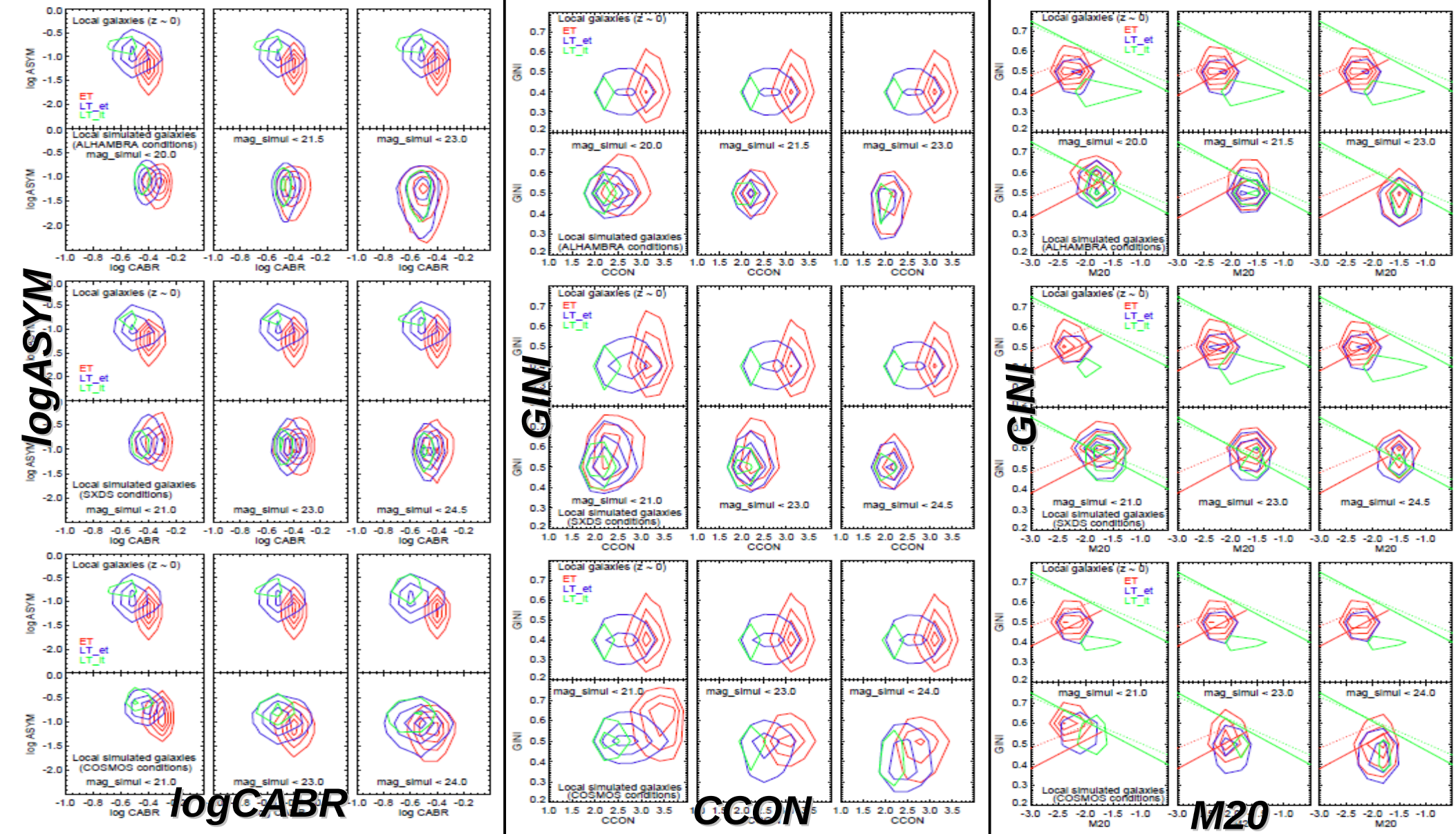
Simulated galaxies (COSMOS conditions)

BOTH SPATIAL RESOLUTION AND DATA DEPTH ARE IMPORTANT, WITH SPATIAL RESOLUTION BEING MORE RELEVANT!!

Impact of spatial resolution and data depth on morphological parameters

Pović et al. 2015

Behaviour of the most used morphological diagnostic diagrams




Thank you very much for your attention!
Have a nice and peaceful day!