INAF
ISTITUTO NAZIONALE DI ASTROFISICA
OSSERVATORIO ASTROFISICO DI ARCETRI

UNIVERSITÀ
DEGLI STUDI
FIRENZE

Introduction and Programme
Visual Morphology

Astrophysics of Galaxies
2019-2020

Stefano Zibetti - INAF Osservatorio Astrofisico di Arcetri

Lecture I

Goals of the course

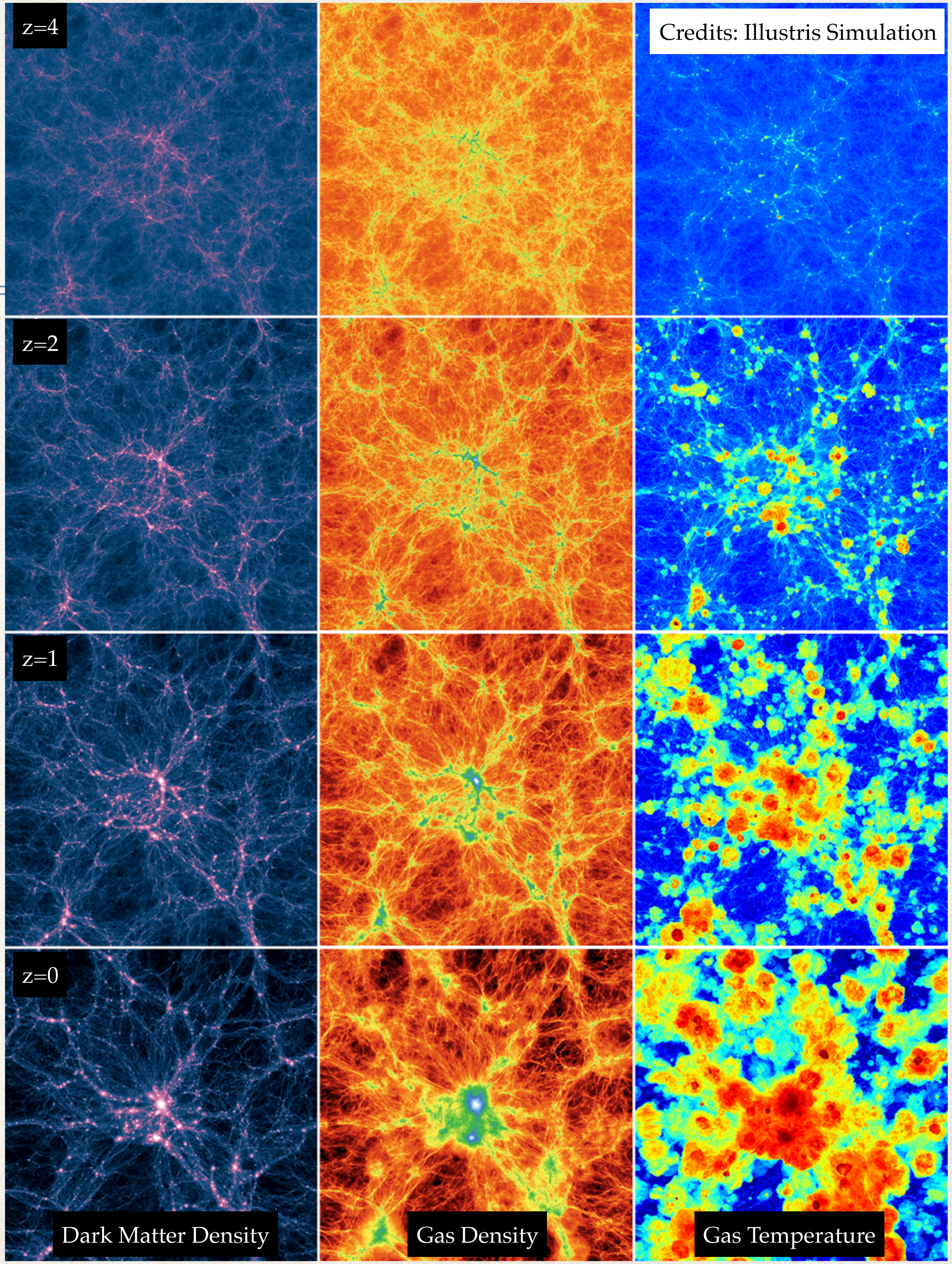
- Provide a physical characterisation of galaxies
- Describe the main physical processes that shape galaxies
- Provide methods and tools to investigate galaxies

What is a galaxy?

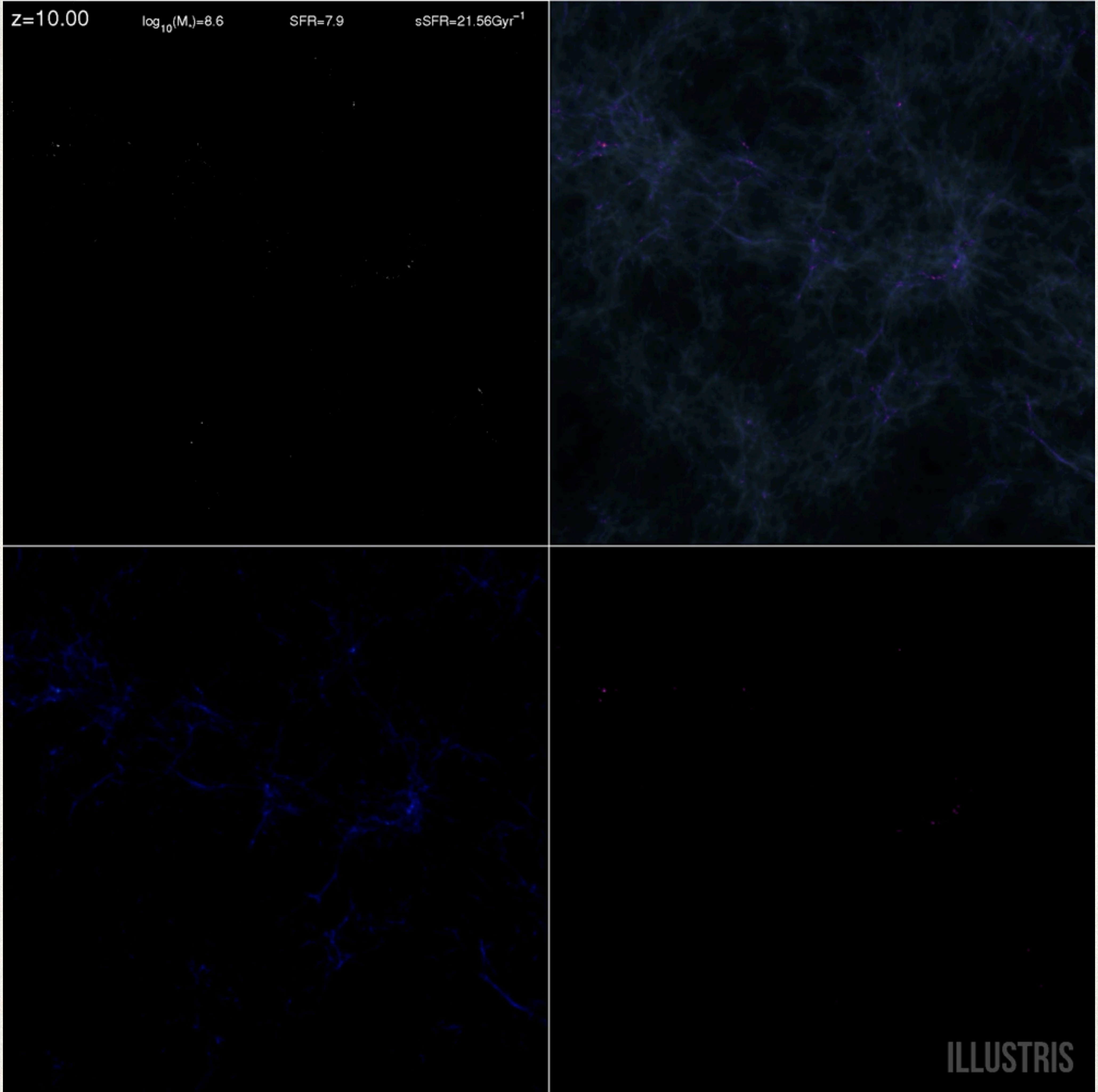
- Not a trivial question until ~90 years ago
  - The great Curtis-Shapley debate (1920)
  - Edwin Hubble (mid 1920's)
- A galaxy is a self-gravitating object made of:
  - stars (unless "dark galaxy"...)
  - gas+dust (InterStellar Medium, ISM)
  - Dark Matter (DM)
    - DM is crucial to define a galaxy at low mass (~10^6 M_{Sun}), e.g. to distinguish a dwarf galaxy from a globular cluster
  - Central supermassive Black Hole (SMBH)

Why study galaxies?

- Galaxies trace the cosmic evolution, from the Big Bang to present day's complexity
- Galaxies are mid-way between the big cosmological "misteries" (the dark sectors) and the "ordinary" physics
- Galaxies are hosts to stellar and planetary systems
- Galaxies are a key tile of the puzzle to answer the question: where do we come from?
- Last but not least… galaxies are beautiful and fascinating objects!



Credits: Illustris Simulation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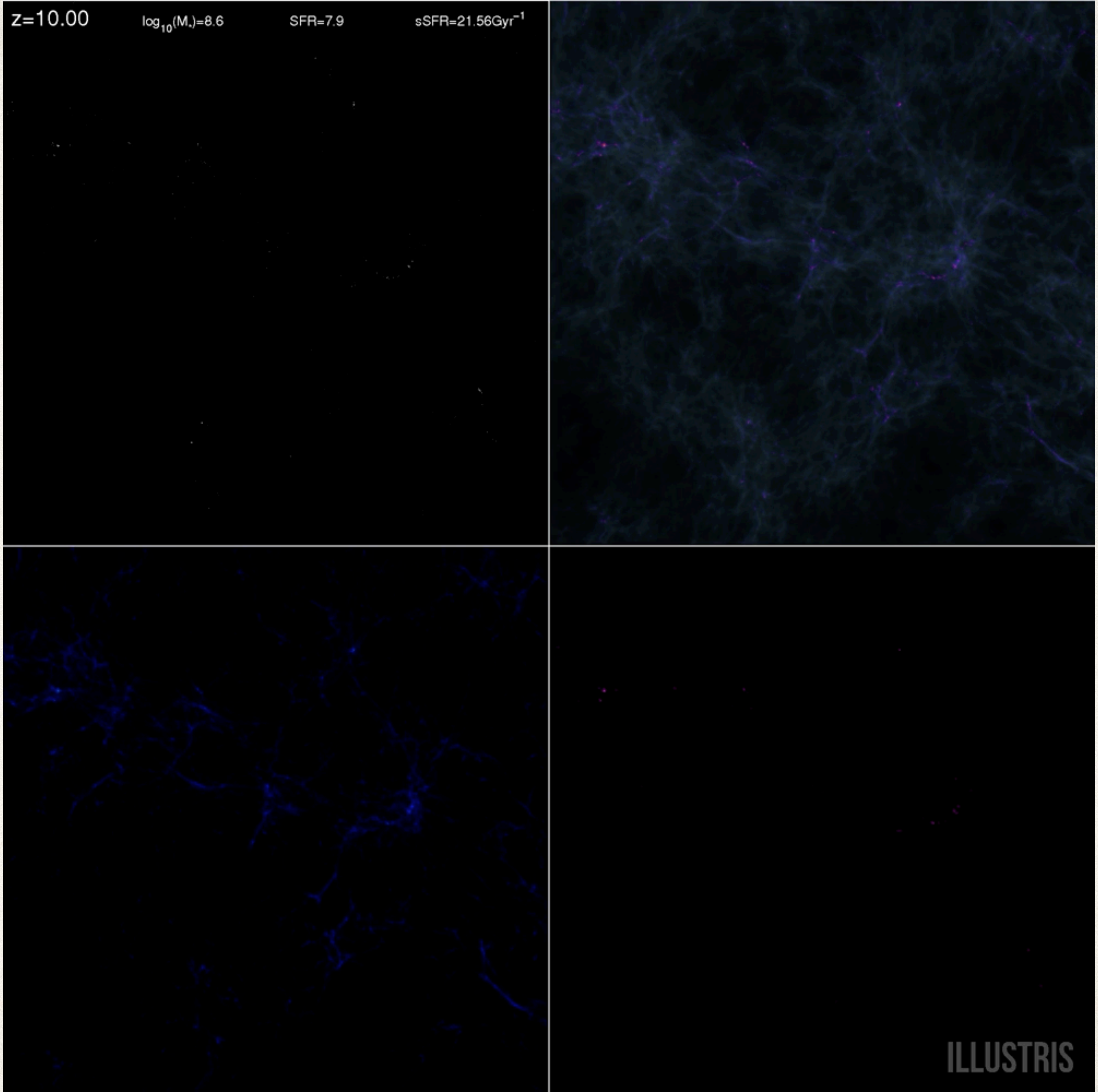
SFR=7.9
sSFR=21.56Gyr^{-1}
ILLUSTRIS


z=10.00
$\log_{10}(M_*)=8.6$
SFR=7.9
sSFR=21.56Gyr^{-1}
ILLUSTRIS

Some units/definitions to get familiar with

- Size and distance:
  - pc=3.086e+18 cm ; kpc, Mpc
  - [lyr = 0.31 pc = c×3.154e+7sec= 9.461e+17 cm — 1 pc = 3.26156 lyr — “deprecated”]
- Distance modulus $DM \equiv m(d) - M_{abs} = m(d) - m(10pc) = 2.5 \log(d^2/(10pc)^2) = 5 \log(d/10pc)$
- Mass: Solar unit: $M_\odot$=1.989e33 g
- Luminosity:
  - Solar unit: $L_\odot$=3.84e+26 W=3.84e+33 erg s^{-1}

— Note that astronomers often talk of “solar luminosity” and omit “per unit frequency or wavelength”

- Flux density (per unit frequency or wavelength)
  - Magnitudes
  - cgs: erg sec^{-1} cm^{-2} Hz^{-1} or erg cm^{-2} sec^{-1} $Å^{-1}$
  - Jansky: 1 Jy=10^{-26} Watt m^{-2} Hz^{-1}
- Surface brightness:
  - mag $arcsec^{-2}$ [this notation is math nonsense!!!]
  - $L_\odot$ pc^{-2}
- Speed:
  - km/s
  - c (speed of light); z=v/c

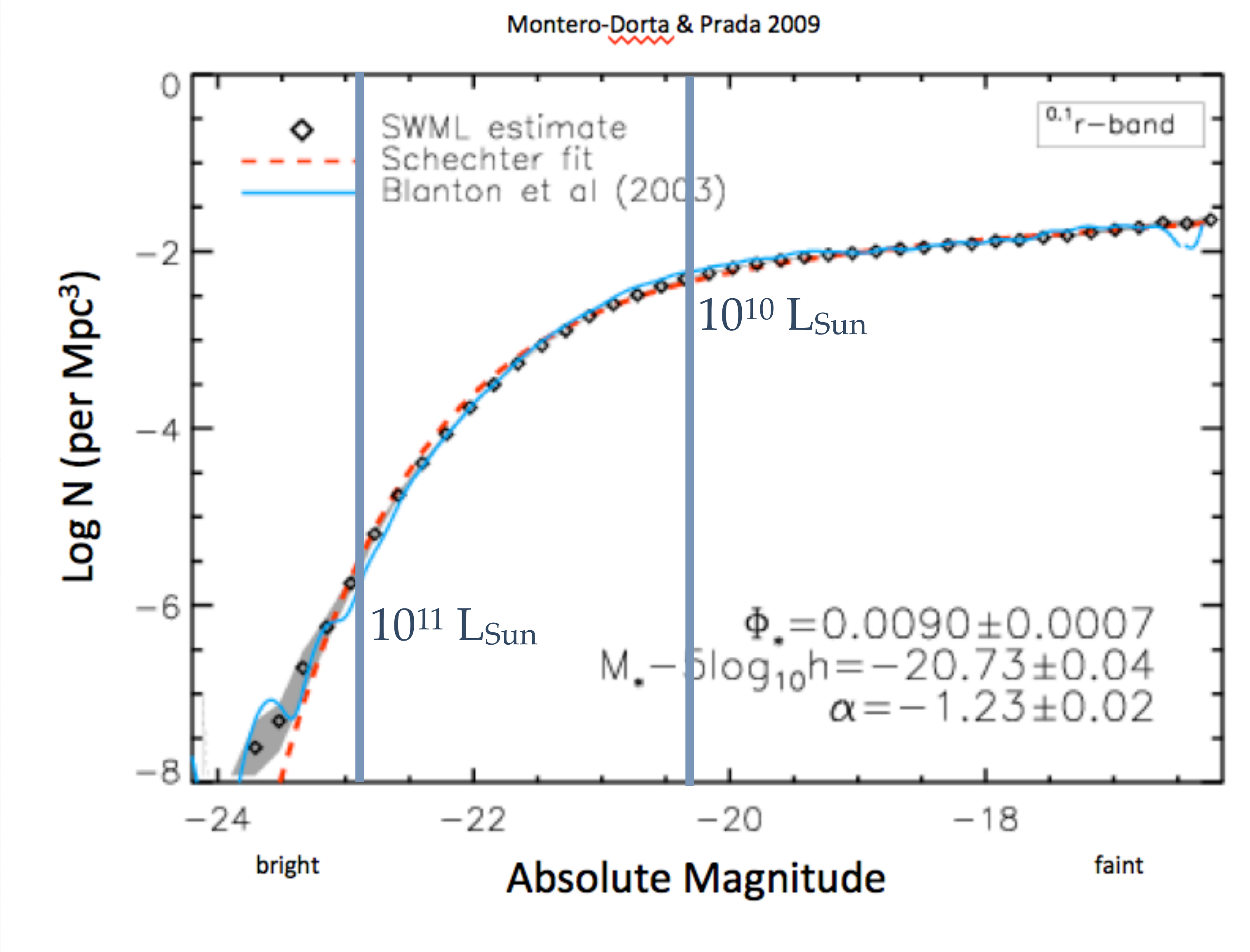
$$m \equiv -2.5 \log \frac{\int_{-\infty}^{+\infty} \frac{d\nu}{\nu} f_\nu(\nu) R(\nu)}{\int_{-\infty}^{+\infty} \frac{d\nu}{\nu} C_\nu(\nu) R(\nu)}$$

$$m_{AB}: C_\nu(\nu) = 3631\,Jy \Rightarrow m_{AB} \equiv -2.5 \log \frac{\int_{-\infty}^{+\infty} \frac{d\nu}{\nu} f_\nu(\nu) R(\nu)}{\int_{-\infty}^{+\infty} \frac{d\nu}{\nu} R(\nu)} - 48.60$$

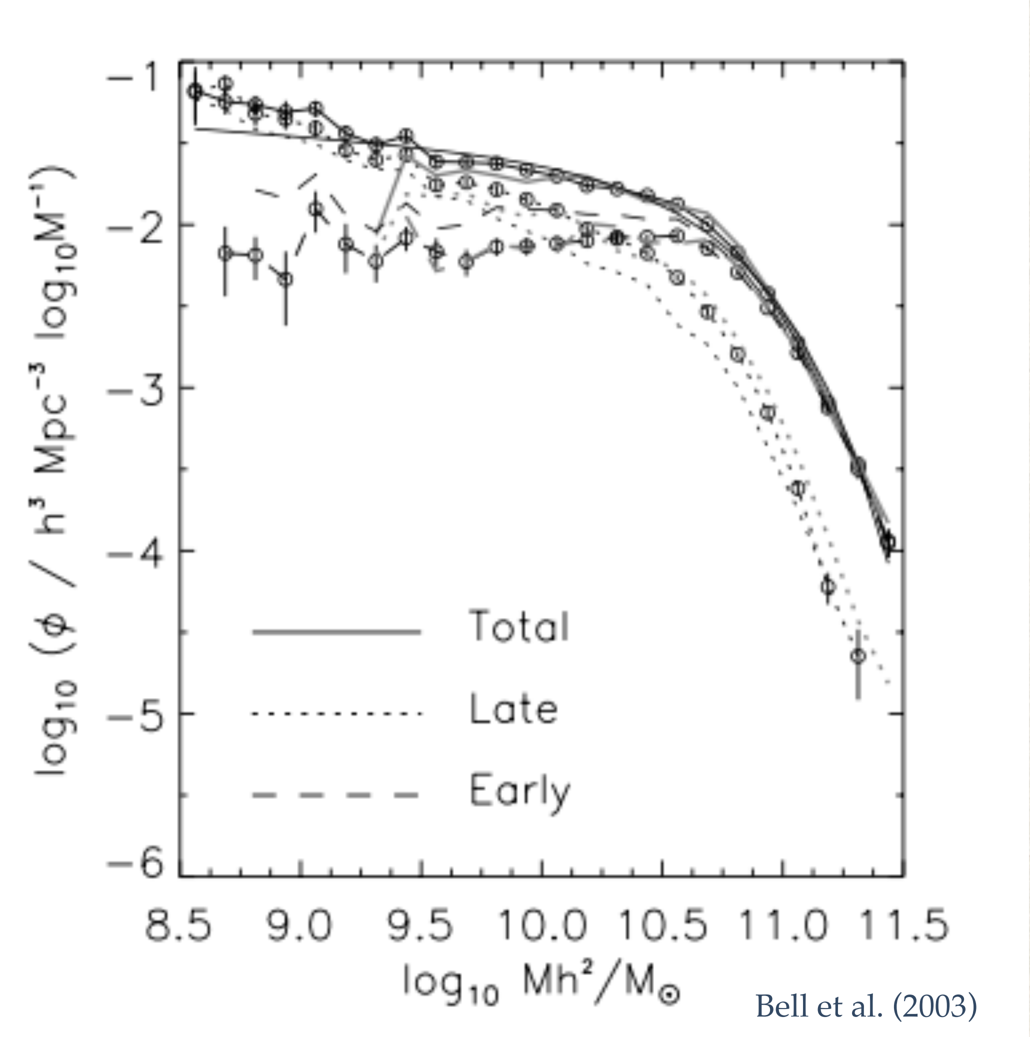
Some order-of-magnitude “facts” about galaxies

Luminosity and Mass

Luminosity



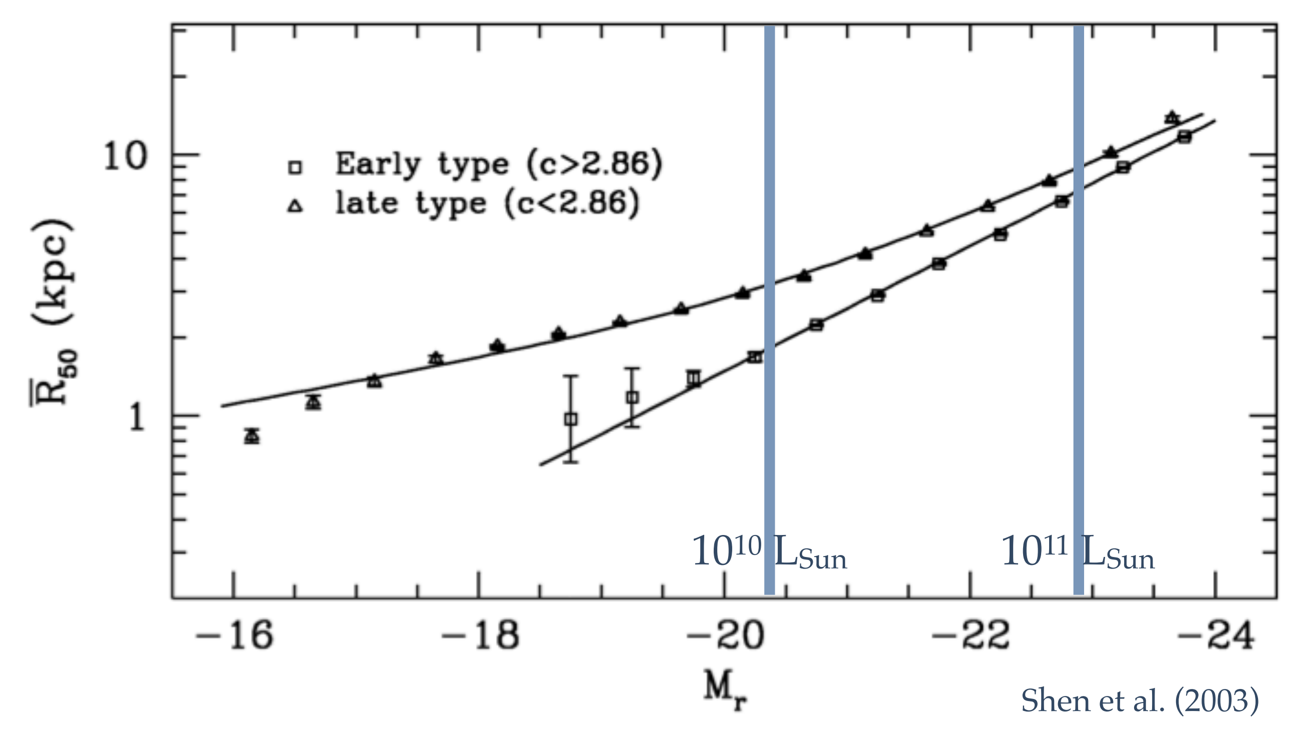
Stellar Mass



Bell et al. (2003)

Size

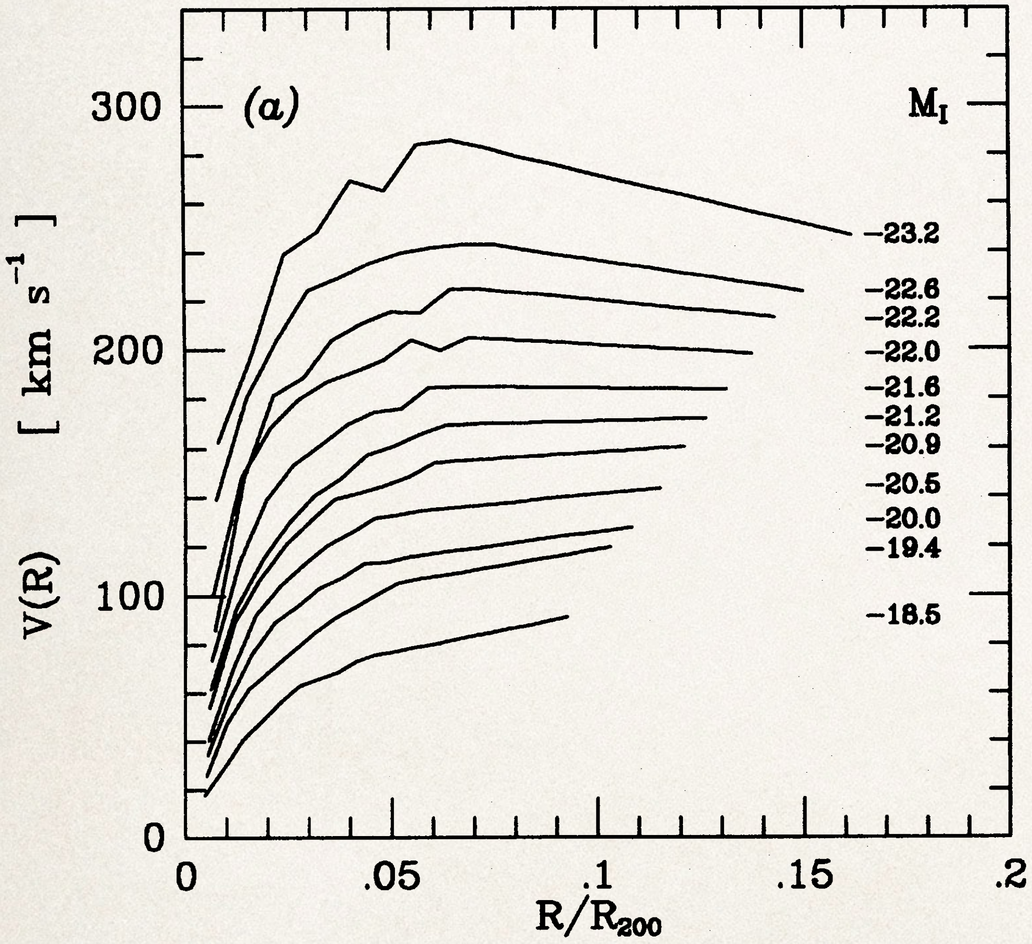
- A galaxy's size is not an obvious parameter: always watch out for the exact definition
- Order of magnitude is kpc, but a range of a factor 10 or even 100 is allowed by the Nature



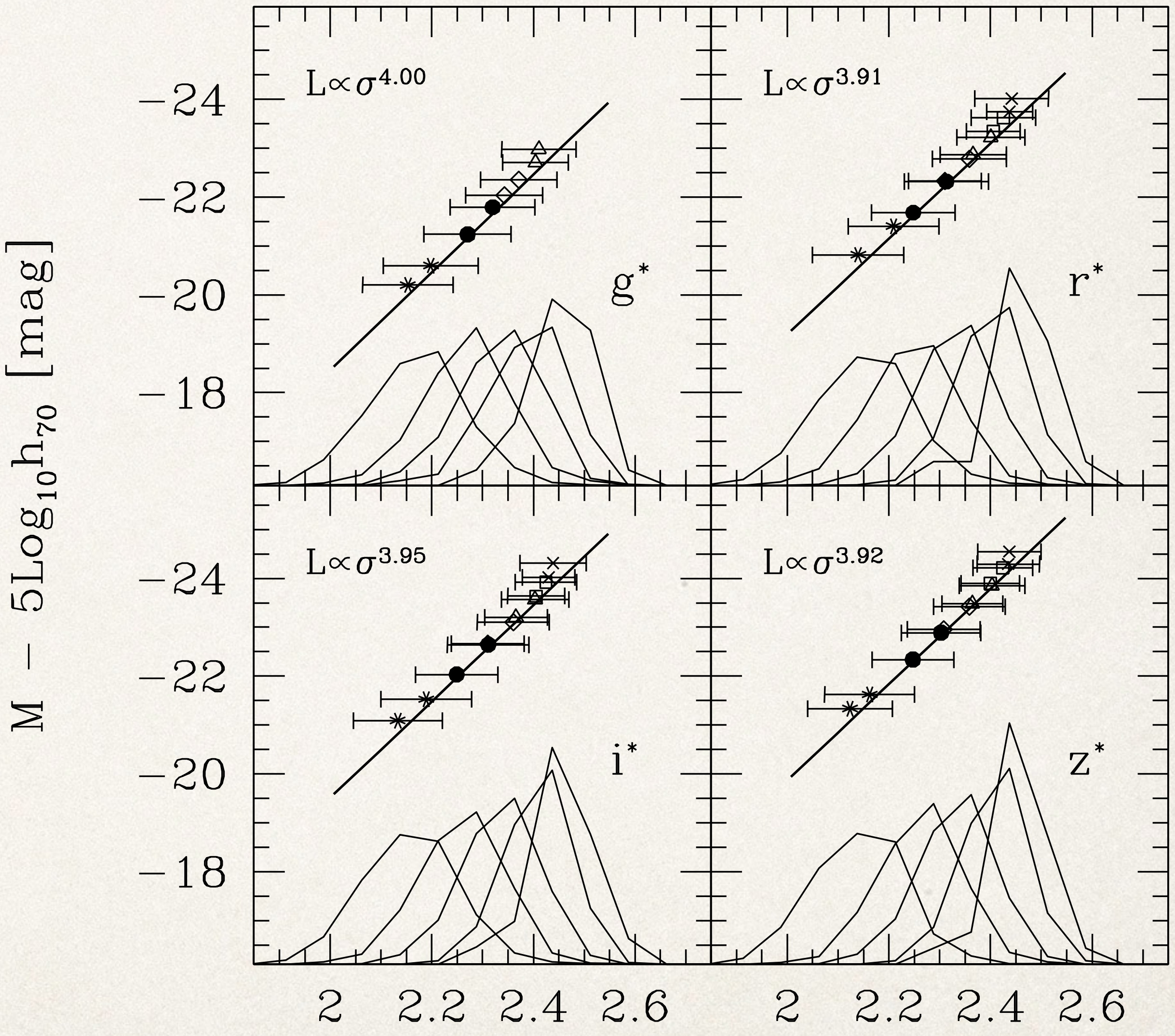
Shen et al. (2003)

Kinematic quantities

- Rotation and velocity dispersion



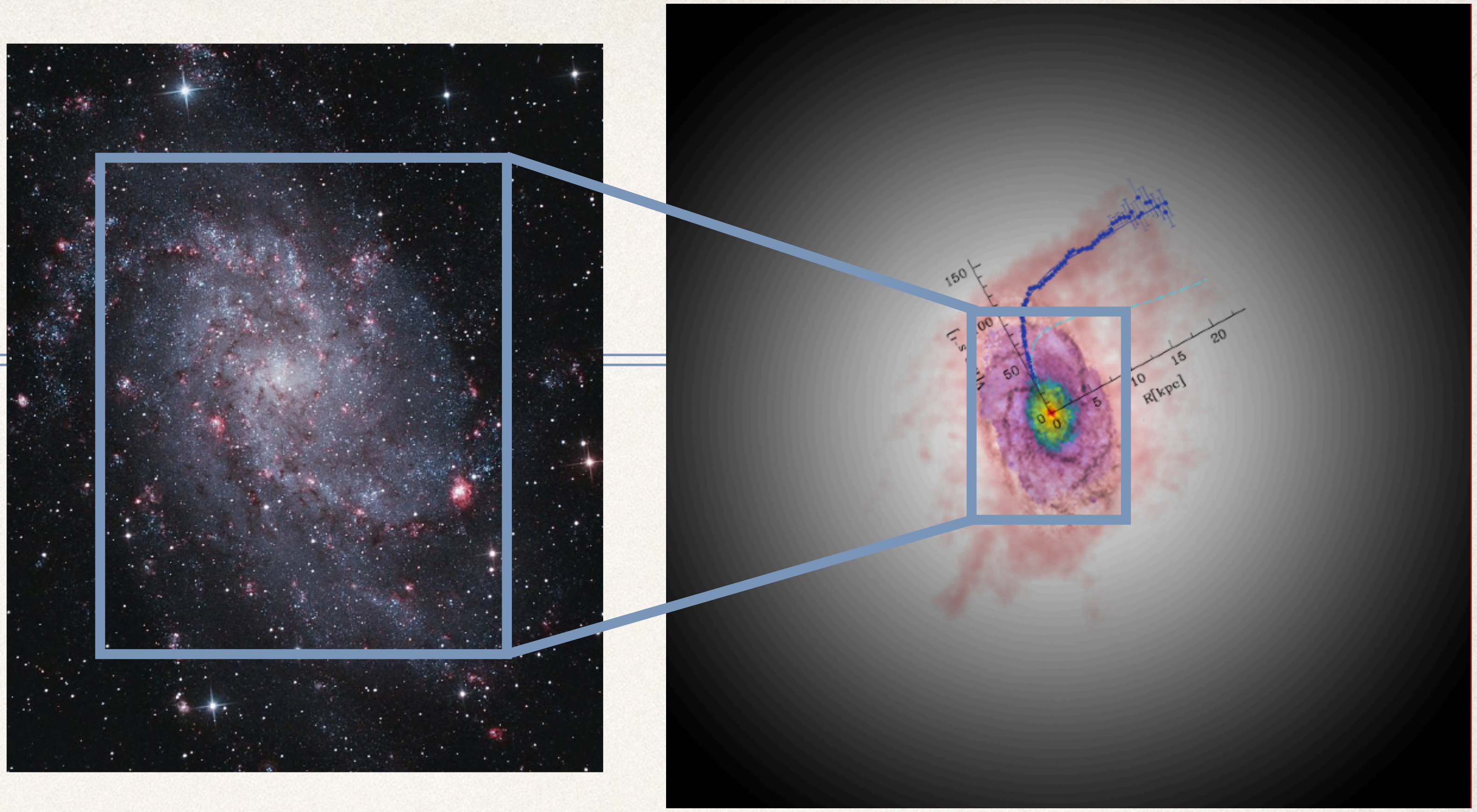
Persic, Salucci & Stel (1996)



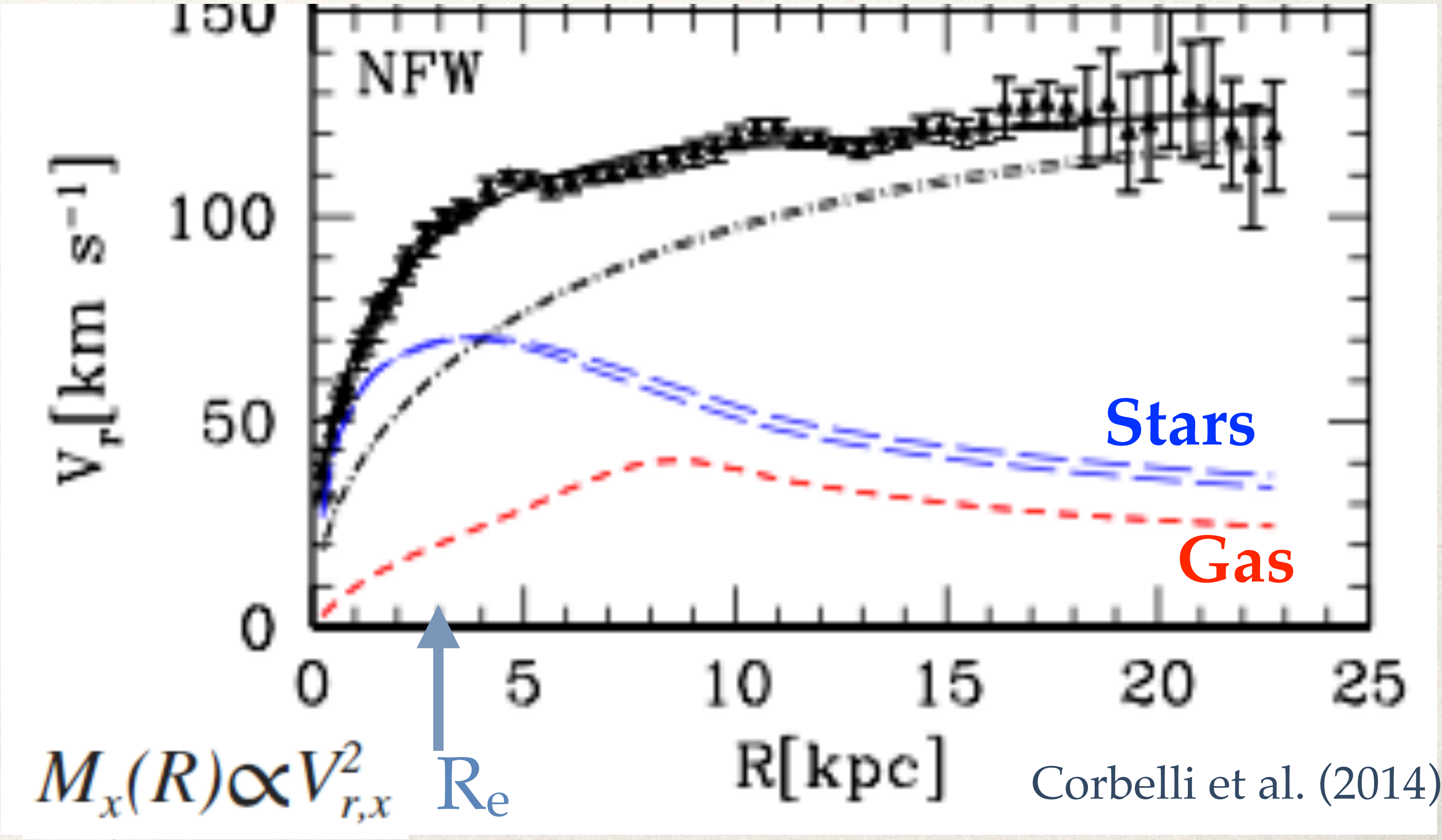
Bernardi et al. (2003)

Mass Budget

- “Baryons” vs Dark Matter
  - Cosmic fraction of baryons: 16%
  - In galaxies: baryons are just a few % (e.g. in M33: ~2%)
- Gas vs stars
  - Cold gas fraction can range from ~0 to ~1
  - In the Local Universe a typical star-forming spiral has 10-30% of baryonic mass in form of neutral hydrogen (HI)
  - Dust is typically <1%



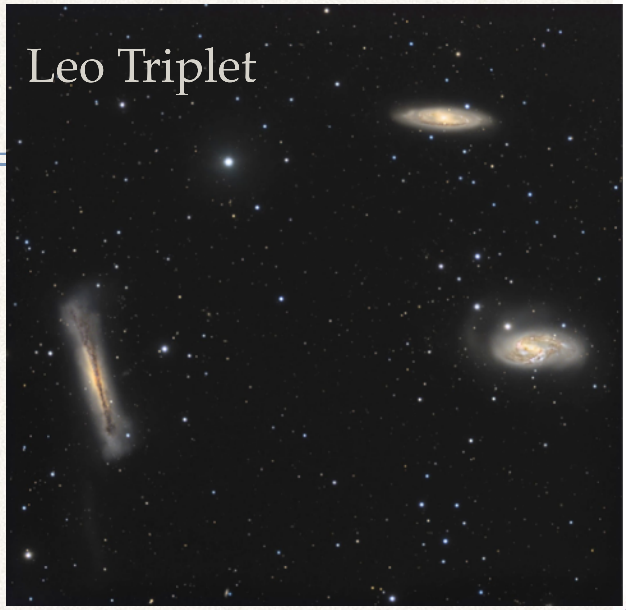
M33

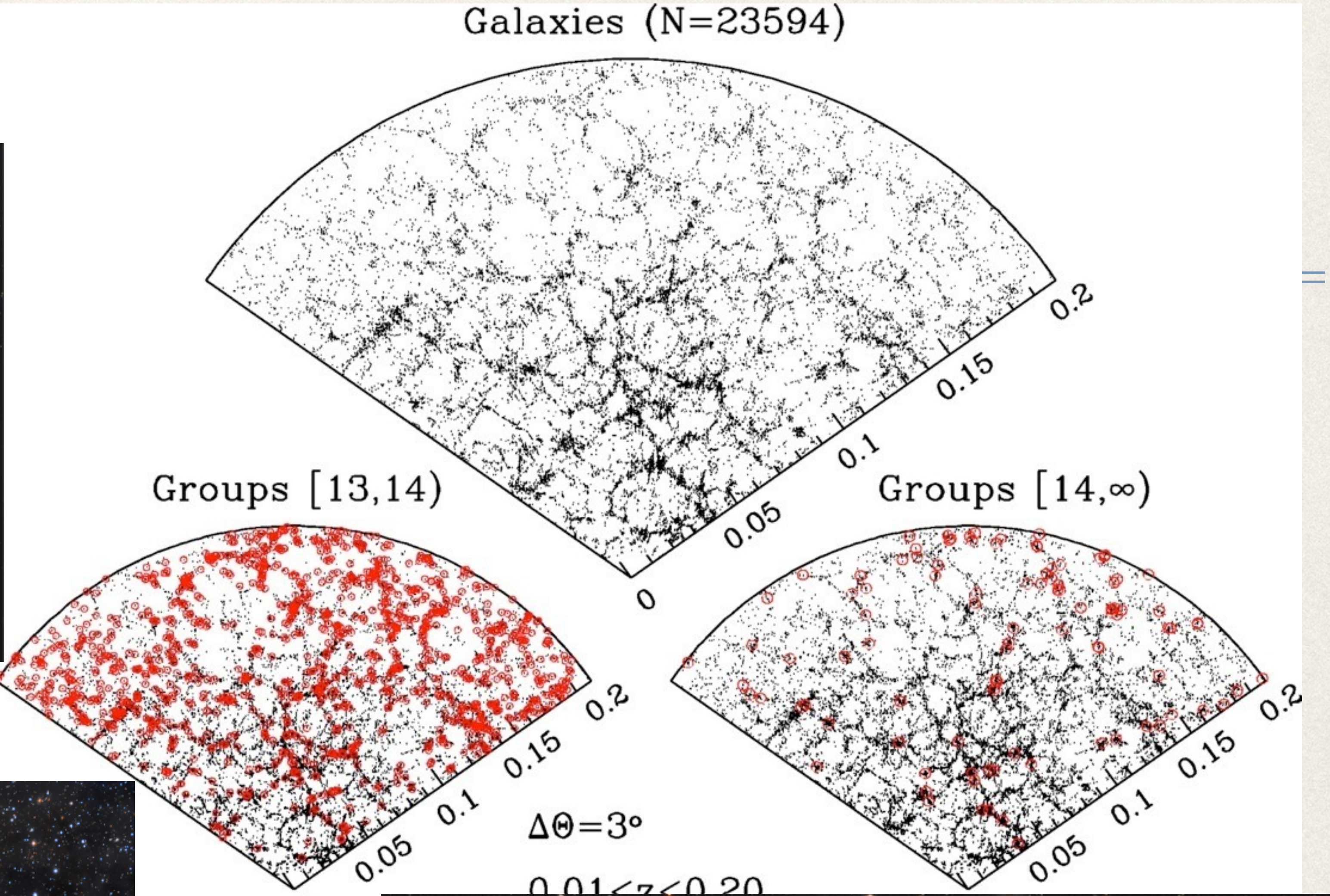


$M_x(R) \propto V^2_{r,x}$ Re

Corbelli et al. (2014)

Environment





Programme

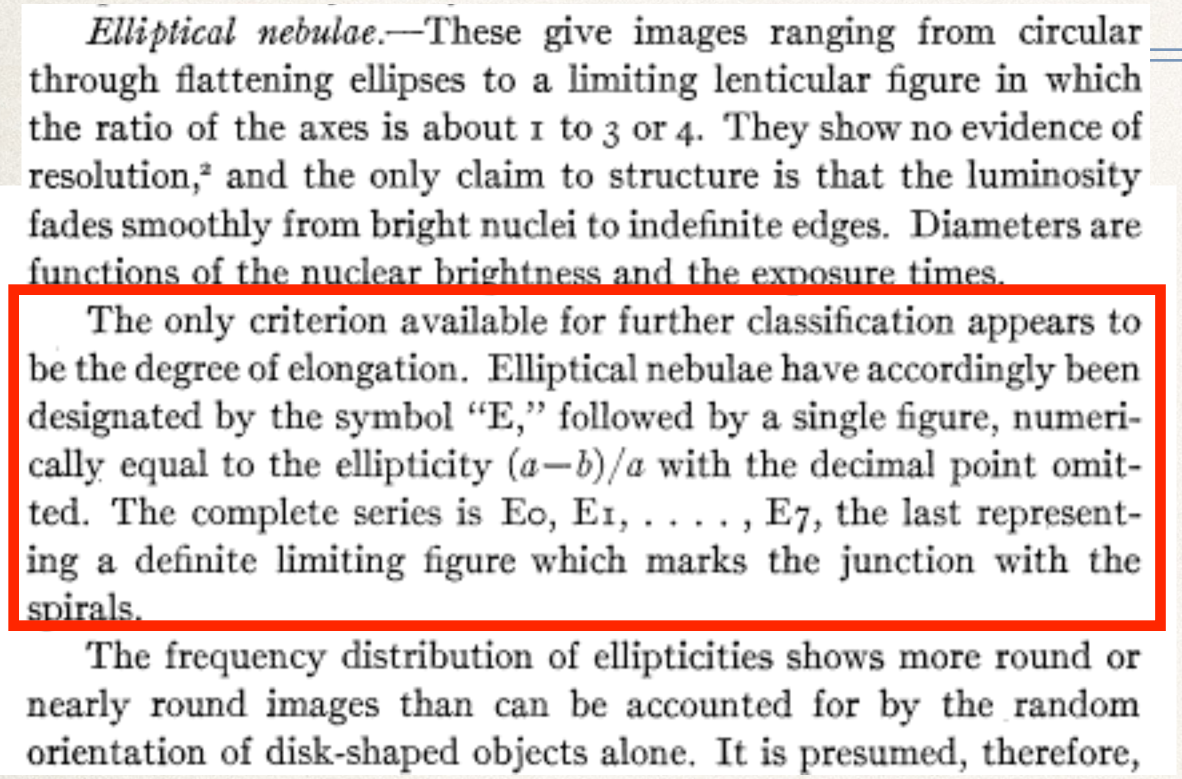
1. Introduction about galaxies and their basic morphological properties
2. Morphology and structure of (spiral) galaxies
3. SED interpretation I: introduction and basic notions of stellar populations
    - SED from UV to FIR and Radio
    - The optical continuum as the sum of stellar spectra
        - Stellar spectra and their dependence on mass, age, chemical composition
        - Stellar Population Synthesis
        - Attenuation by dust
4. SED interpretation II: stellar population properties from optical/NIR spectrophotometry
5. SED interpretation III: star formation and interstellar medium
6. Scaling relations of stellar populations and ISM
    - Global & local
    - Chemical enrichment processes
    - Stellar and AGN feedback
7. Kinematics and dynamics of spiral galaxies
8. Kinematics and dynamics of elliptical galaxies
9. Processes of dynamical evolution of galaxies
10. Galaxies and their Environment
11. Active Galactic Nuclei (AGNs) and SuperMassive Black Holes (SMBHs)
    - Impact on SEDs - diagnostic diagrams
    - Measuring SMBHs and their scaling relations
12. Overview of the redshift evolution of galaxy properties

Morphology

- A morphological classification is the first approach to try and organize our knowledge about galaxies (as about anything else…)
- Obvious visual distinction between spiral and elliptical morphology (first hint at ***bimodality***)
- What kind of structure (and physical property) is relevant for a morphological classification?
    - observationally driven vs physically driven classification: what is relevant depends (also) on our questions

Morphology: brief historical review

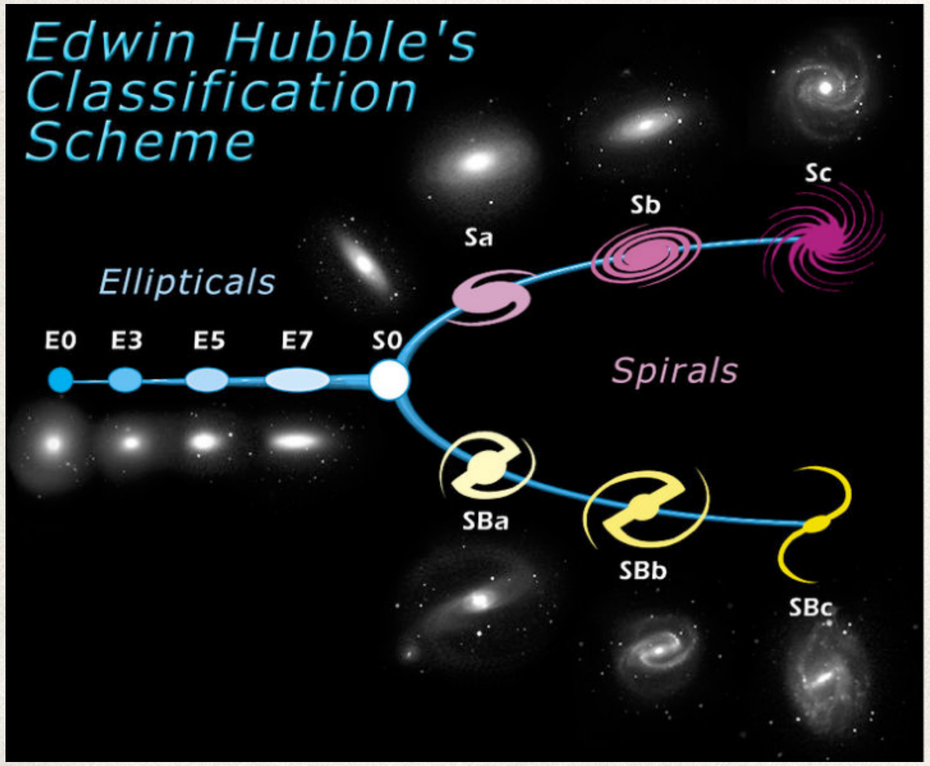
- The Hubble's tuning fork

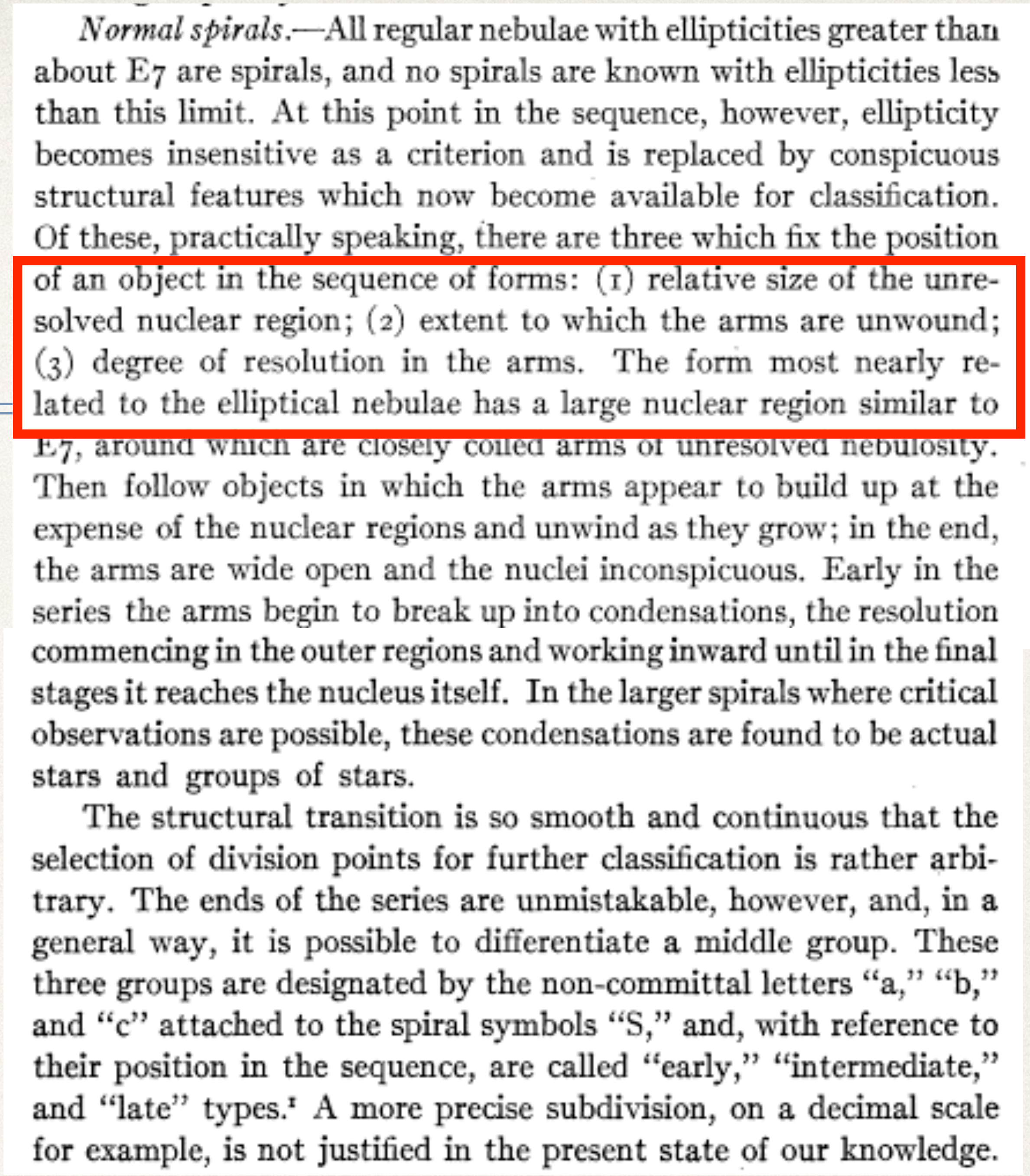


Elliptical nebulae.—These give images ranging from circular through flattening ellipses to a limiting lenticular figure in which the ratio of the axes is about 1 to 3 or 4. They show no evidence of resolution,[2] and the only claim to structure is that the luminosity fades smoothly from bright nuclei to indefinite edges. Diameters are functions of the nuclear brightness and the exposure times.

The only criterion available for further classification appears to be the degree of elongation. Elliptical nebulae have accordingly been designated by the symbol "E," followed by a single figure, numerically equal to the ellipticity $(a-b)/a$ with the decimal point omitted. The complete series is E0, E1, ... , E7, the last representing a definite limiting figure which marks the junction with the spirals.

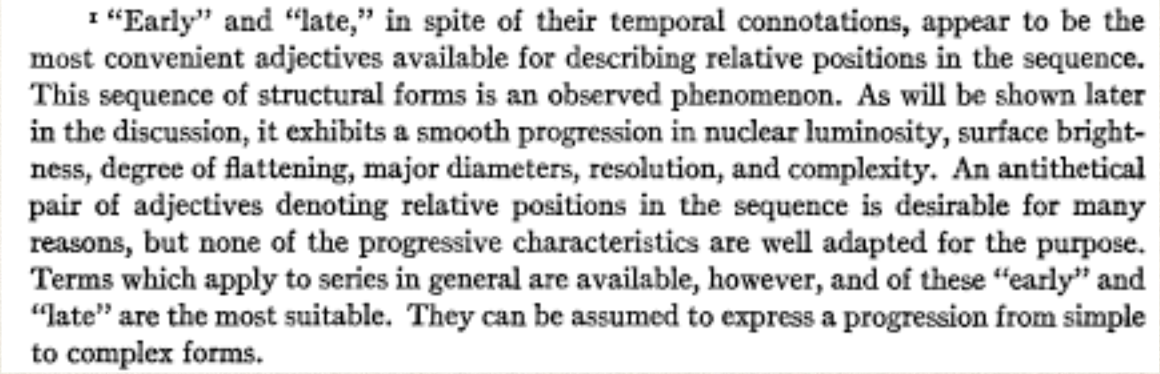
The frequency distribution of ellipticities shows more round or nearly round images than can be accounted for by the random orientation of disk-shaped objects alone. It is presumed, therefore,





Normal spirals.—All regular nebulae with ellipticities greater than about E7 are spirals, and no spirals are known with ellipticities less than this limit. At this point in the sequence, however, ellipticity becomes insensitive as a criterion and is replaced by conspicuous structural features which now become available for classification. Of these, practically speaking, there are three which fix the position of an object in the sequence of forms: (1) relative size of the unresolved nuclear region; (2) extent to which the arms are unwound; (3) degree of resolution in the arms. The form most nearly related to the elliptical nebulae has a large nuclear region similar to E7, around which are closely coiled arms of unresolved nebulosity. Then follow objects in which the arms appear to build up at the expense of the nuclear regions and unwind as they grow; in the end, the arms are wide open and the nuclei inconspicuous. Early in the series the arms begin to break up into condensations, the resolution commencing in the outer regions and working inward until in the final stages it reaches the nucleus itself. In the larger spirals where critical observations are possible, these condensations are found to be actual stars and groups of stars.

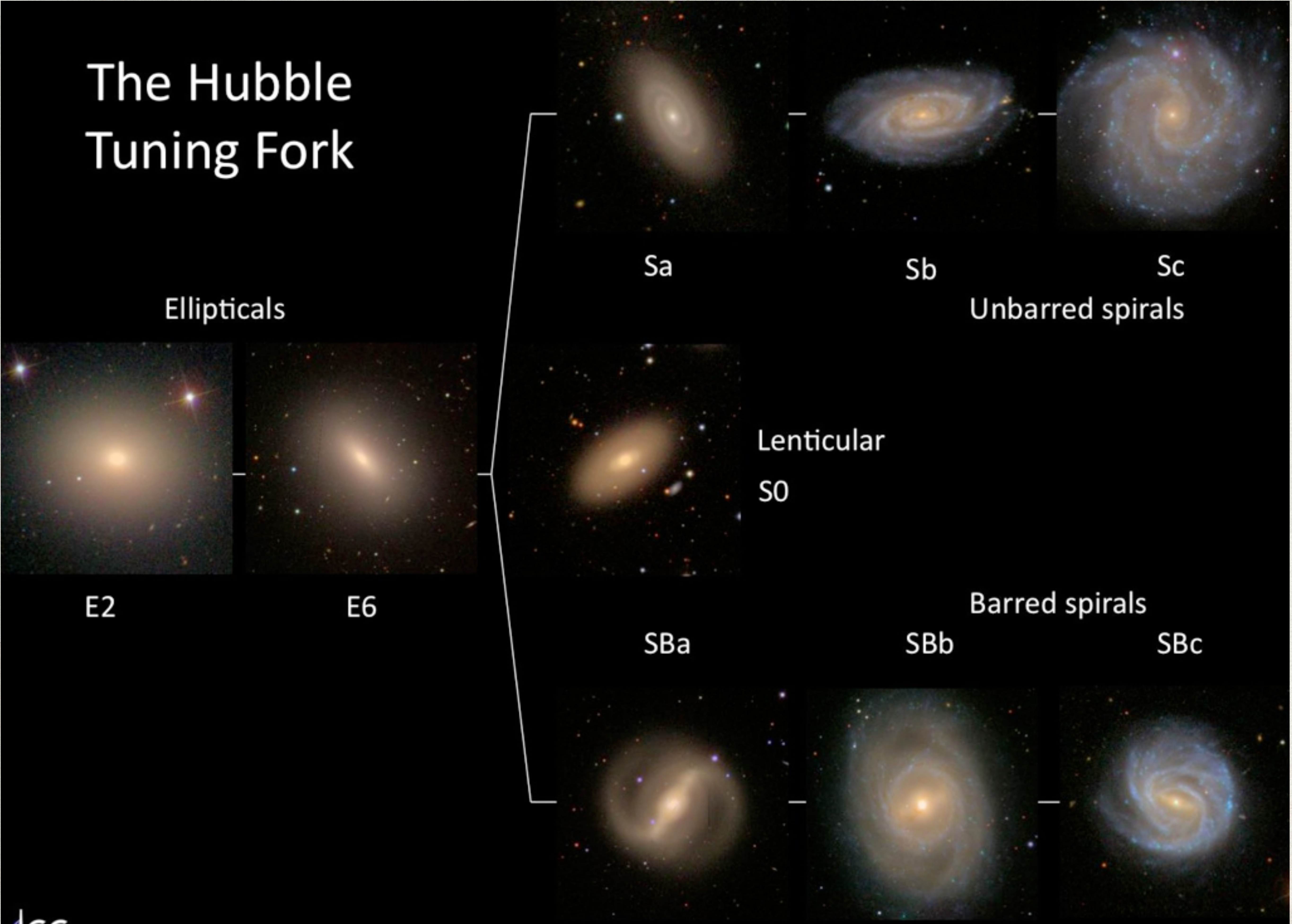
The structural transition is so smooth and continuous that the selection of division points for further classification is rather arbitrary. The ends of the series are unmistakable, however, and, in a general way, it is possible to differentiate a middle group. These three groups are designated by the non-committal letters "a," "b," and "c" attached to the spiral symbols "S," and, with reference to their position in the sequence, are called "early," "intermediate," and "late" types.[1] A more precise subdivision, on a decimal scale for example, is not justified in the present state of our knowledge.



[1] "Early" and "late," in spite of their temporal connotations, appear to be the most convenient adjectives available for describing relative positions in the sequence. This sequence of structural forms is an observed phenomenon. As will be shown later in the discussion, it exhibits a smooth progression in nuclear luminosity, surface brightness, degree of flattening, major diameters, resolution, and complexity. An antithetical pair of adjectives denoting relative positions in the sequence is desirable for many reasons, but none of the progressive characteristics are well adapted for the purpose. Terms which apply to series in general are available, however, and of these "early" and "late" are the most suitable. They can be assumed to express a progression from simple to complex forms.

Hubble, 1926, ApJ, 64, 321

The Hubble Tuning Fork



Ellipticals

E2

E6

Lenticular

S0

Sa

Sb

Sc

Unbarred spirals

Barred spirals

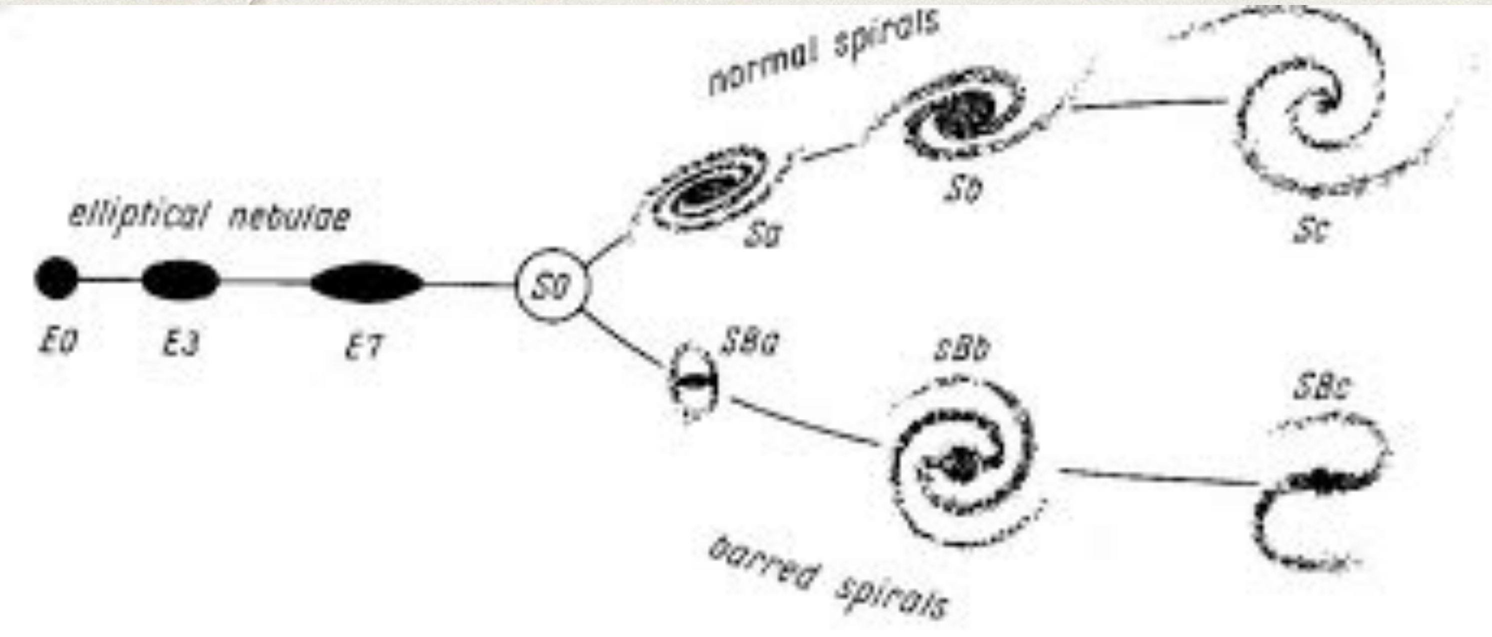
SBa

SBb

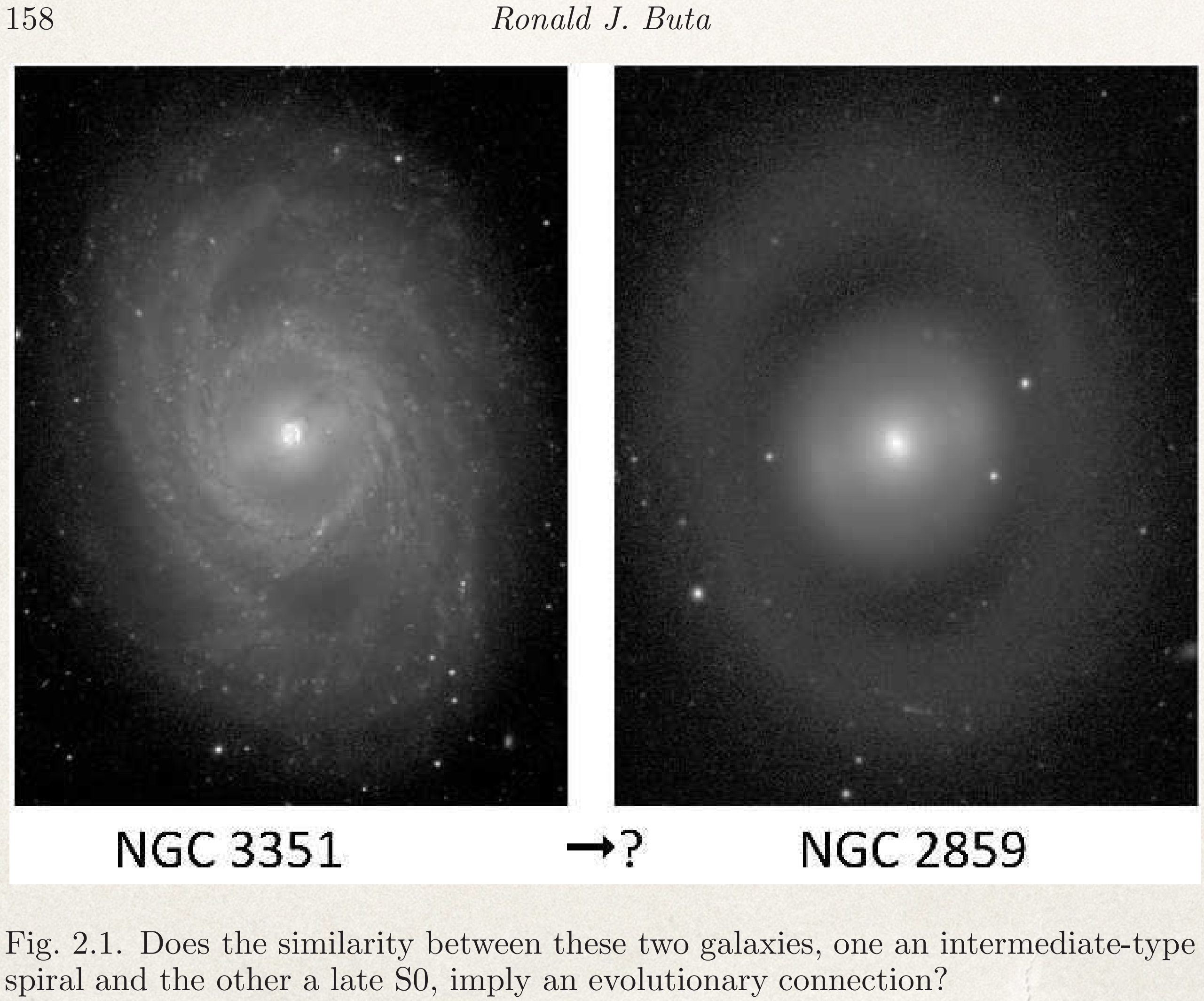
SBc

Credit: Karen L. Masters (ICG Portsmouth). Galaxies: SDSS gri colour images as used in Galaxy Zoo.

S0 galaxies

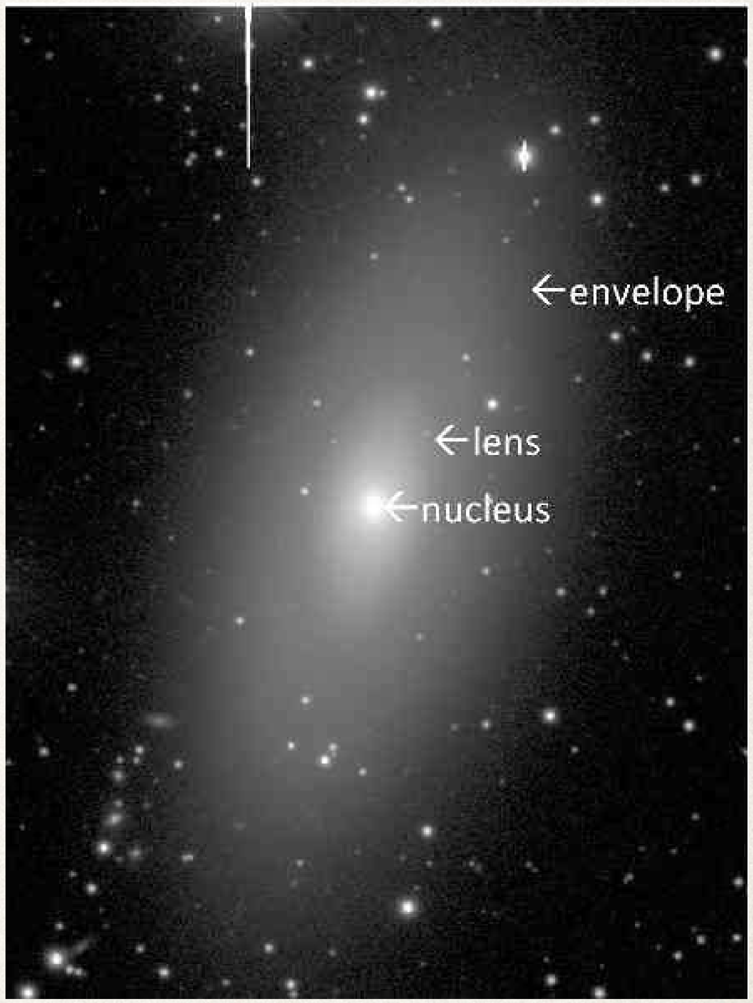


- Sandage (1961): nucleus, lens, envelope
- Evolution across the Hubble sequence?


158 *Ronald J. Buta*

NGC 3351 →? NGC 2859

Fig. 2.1. Does the similarity between these two galaxies, one an intermediate-type spiral and the other a late S0, imply an evolutionary connection?



Buta, arXiv:1304.3529v1

More complexity...

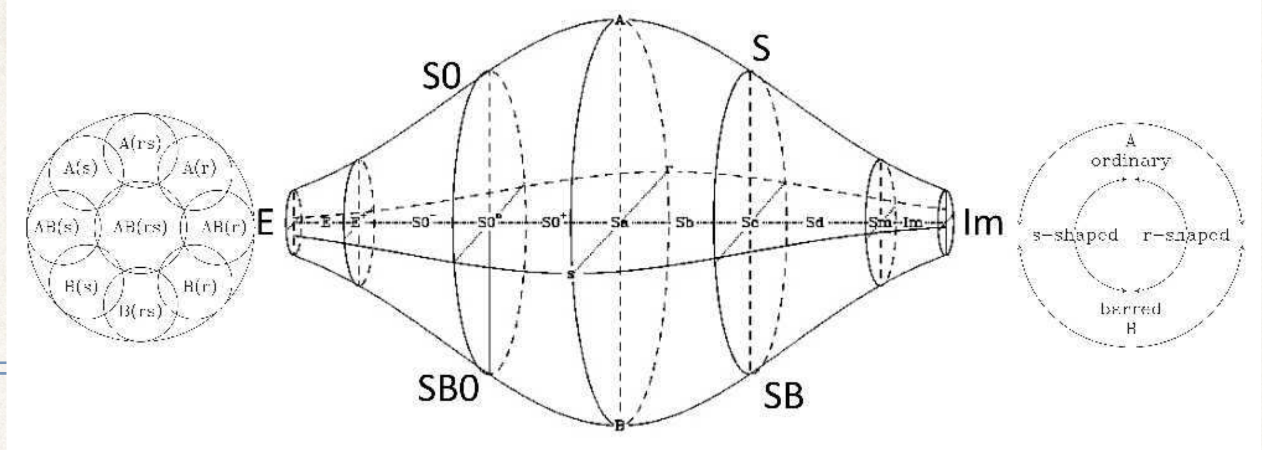


Fig. 2.11. The de Vaucouleurs (1959) revised Hubble-Sandage classification system.

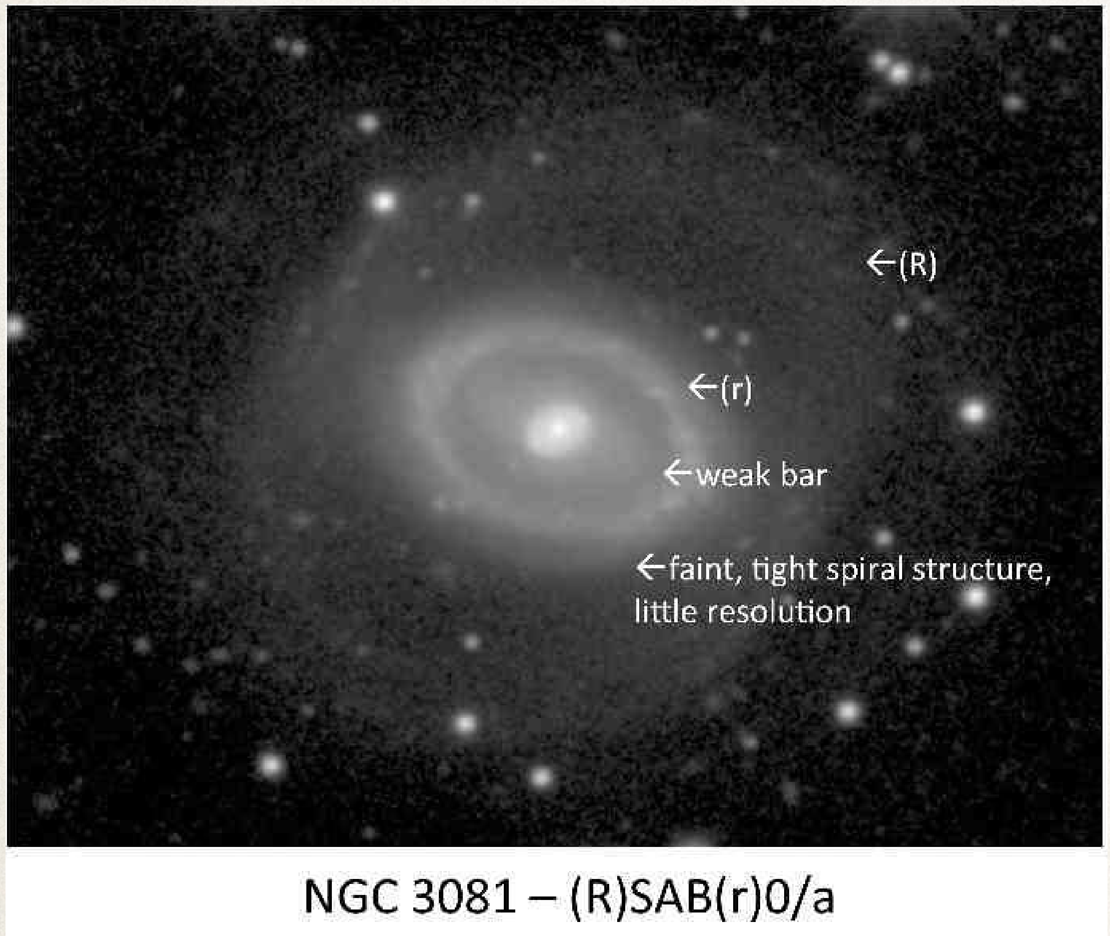


Fig. 2.16. Classification of NGC 3081.

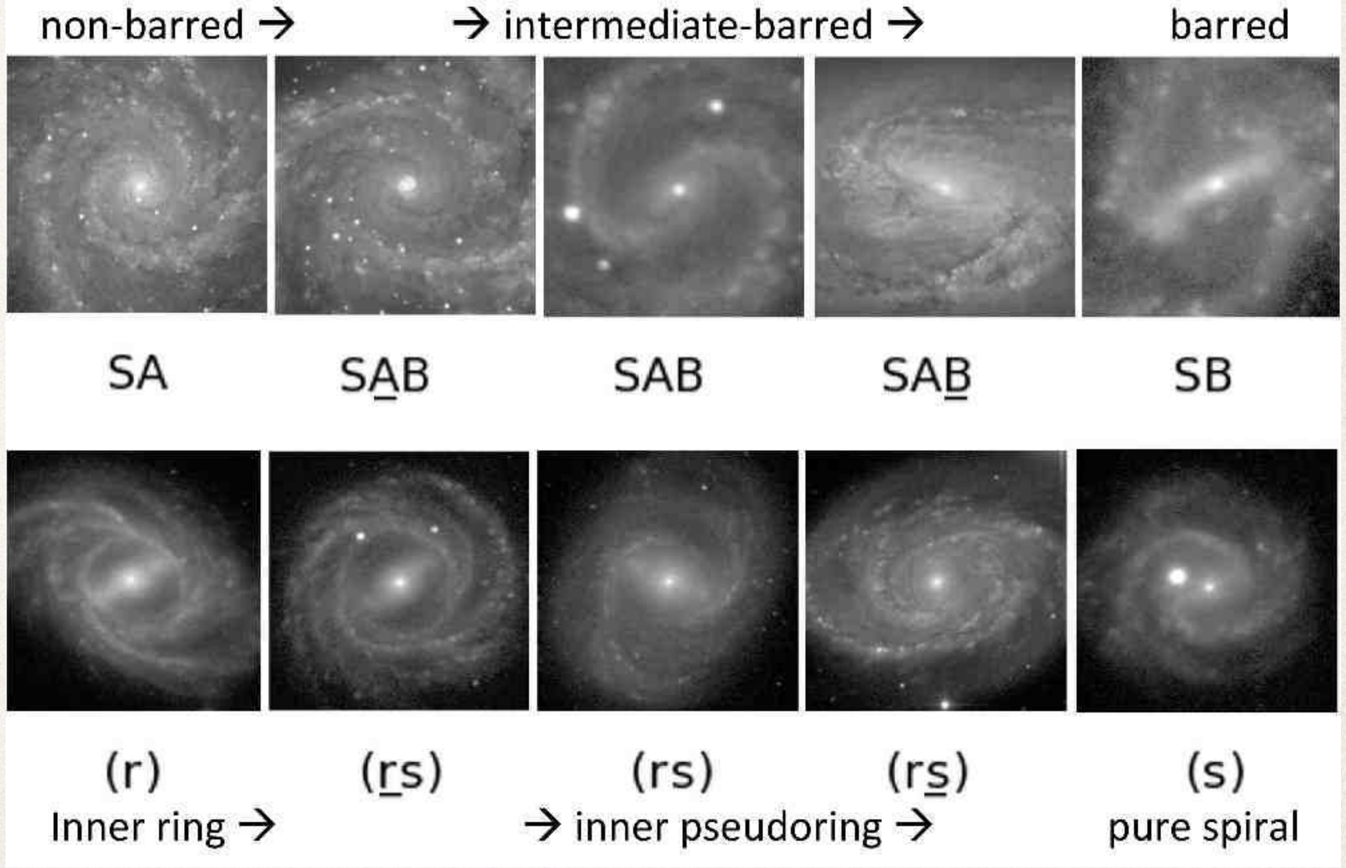
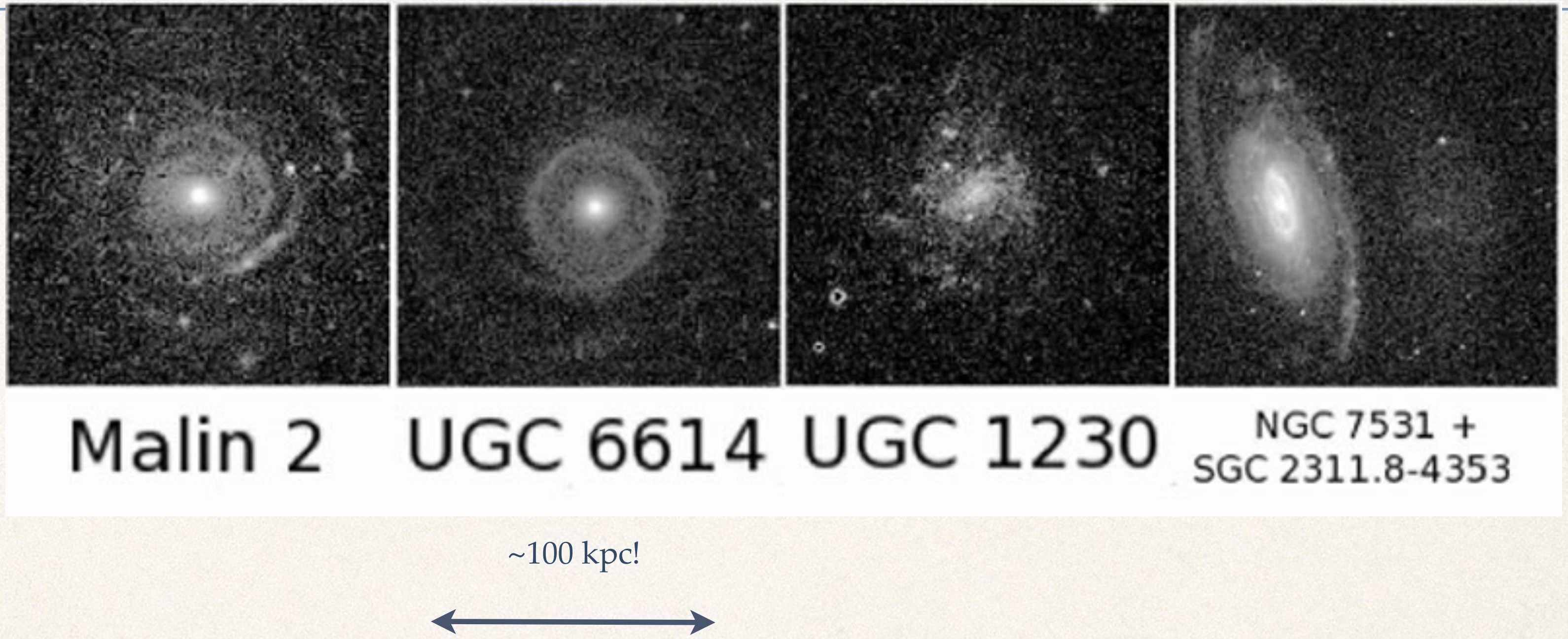


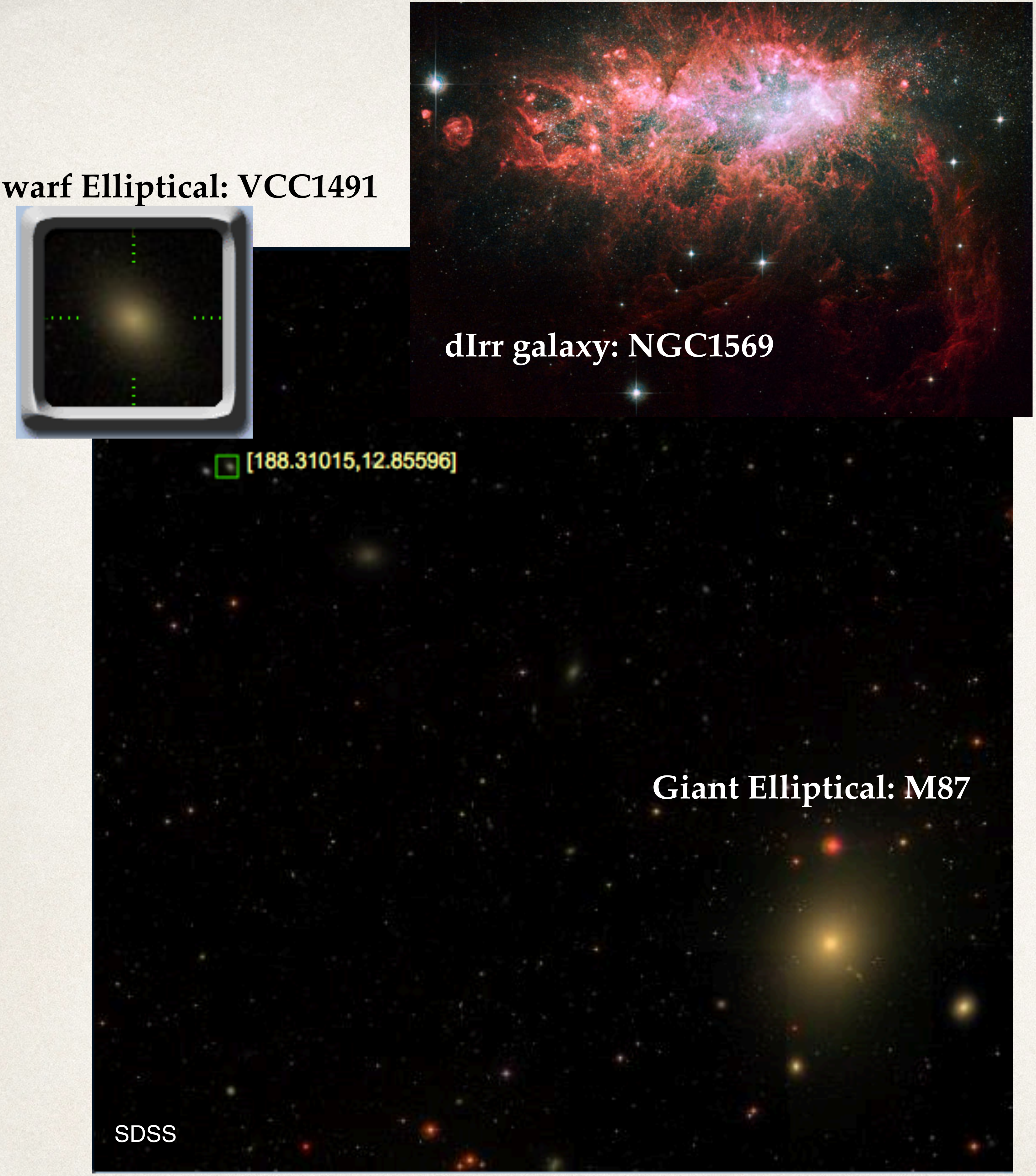
Fig. 2.12. Family and variety in the VRHS as continuous characteristics (from B13).

“Special” classes

- LSB giant galaxies



- dwarf galaxies:
  - dE, dS0, (d)Sph (see Kormendy & Bender 2012)
  - dIrr, dIm



Dwarf Elliptical: VCC1491

dIrr galaxy: NGC1569

Giant Elliptical: M87

SDSS

Fornax dSph (Local Group)

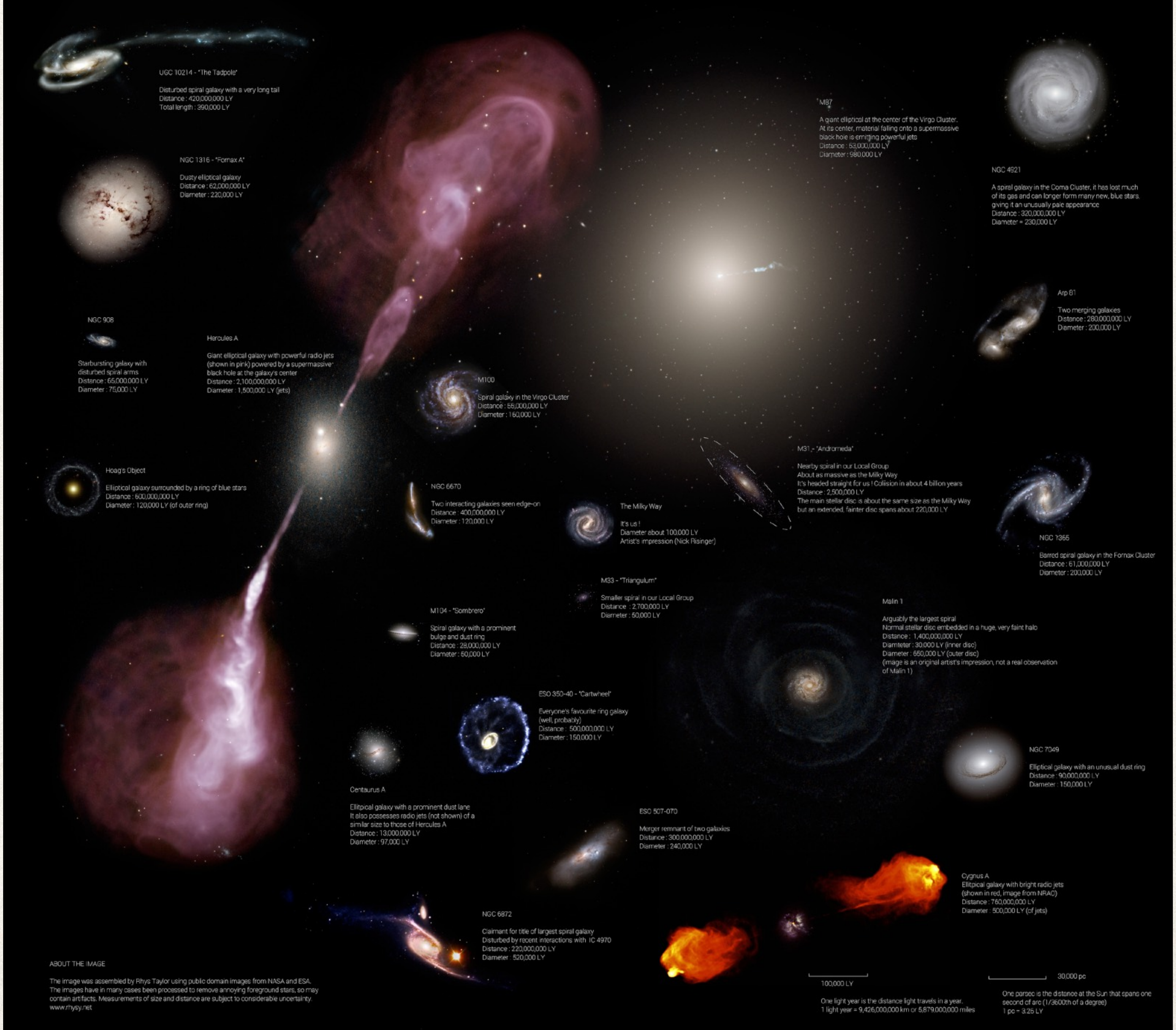
from Wikipedia

dIm: Large Magellanic Cloud

©Eckhard Slawik. Image via ESA

Galaxy Size Comparison Chart

A selection of galaxies shown to the same scale



UGC 10214 - "The Tadpole"

Disturbed spiral galaxy with a very long tail
Distance : 420,000,000 LY
Total length : 390,000 LY

NGC 1316 - "Fornax A"

Dusty elliptical galaxy
Distance : 62,000,000 LY
Diameter : 220,000 LY

M87

A giant elliptical at the center of the Virgo Cluster.
At its center, material falling onto a supermassive black hole is emitting powerful jets
Distance : 53,000,000 LY
Diameter : 980,000 LY

NGC 4921

A spiral galaxy in the Coma Cluster, it has lost much of its gas and can longer form many new, blue stars, giving it an unusually pale appearance
Distance : 320,000,000 LY
Diameter = 230,000 LY

Arp 81

Two merging galaxies
Distance : 280,000,000 LY
Diameter : 200,000 LY

NGC 908

Starbursting galaxy with disturbed spiral arms
Distance : 65,000,000 LY
Diameter : 75,000 LY

Hercules A

Giant elliptical galaxy with powerful radio jets (shown in pink) powered by a supermassive black hole at the galaxy's center
Distance : 2,100,000,000 LY
Diameter : 1,500,000 LY (jets)

M100

Spiral galaxy in the Virgo Cluster
Distance : 55,000,000 LY
Diameter : 160,000 LY

Hoag's Object

Elliptical galaxy surrounded by a ring of blue stars
Distance : 600,000,000 LY
Diameter : 120,000 LY (of outer ring)

NGC 6670

Two interacting galaxies seen edge-on
Distance : 400,000,000 LY
Diameter : 120,000 LY

The Milky Way

It's us !
Diameter about 100,000 LY
Artist's impression (Nick Risinger)

M31 - "Andromeda"

Nearby spiral in our Local Group
About as massive as the Milky Way
It's headed straight for us ! Collision in about 4 billion years
Distance : 2,500,000 LY
The main stellar disc is about the same size as the Milky Way but an extended, fainter disc spans about 220,000 LY

NGC 1365

Barred spiral galaxy in the Fornax Cluster
Distance : 61,000,000 LY
Diameter : 200,000 LY

M33 - "Triangulum"

Smaller spiral in our Local Group
Distance : 2,700,000 LY
Diameter : 50,000 LY

M104 - "Sombrero"

Spiral galaxy with a prominent bulge and dust ring
Distance : 28,000,000 LY
Diameter : 50,000 LY

Malin 1

Arguably the largest spiral
Normal stellar disc embedded in a huge, very faint halo
Distance : 1,400,000,000 LY
Diamteter : 30,000 LY (inner disc)
Diameter : 650,000 LY (outer disc)
(image is an original artist's impression, not a real observation of Malin 1)

ESO 350-40 - "Cartwheel"

Everyone's favourite ring galaxy (well, probably)
Distance : 500,000,000 LY
Diameter : 150,000 LY

NGC 7049

Elliptical galaxy with an unusual dust ring
Distance : 90,000,000 LY
Diameter : 150,000 LY

Centaurus A

Elitpical galaxy with a prominent dust lane
It also possesses radio jets (not shown) of a similar size to those of Hercules A
Distance : 13,000,000 LY
Diameter : 97,000 LY

ESO 507-070

Merger remnant of two galaxies
Distance : 300,000,000 LY
Diameter : 240,000 LY

Cygnus A
Elitpical galaxy with bright radio jets (shown in red, image from NRAO)
Distance : 760,000,000 LY
Diameter : 500,000 LY (of jets)

NGC 6872

Claimant for title of largest spiral galaxy
Disturbed by recent interactions with IC 4970
Distance : 220,000,000 LY
Diameter : 520,000 LY

ABOUT THE IMAGE

The image was assembled by Rhys Taylor using public domain images from NASA and ESA. The images have in many cases been processed to remove annoying foreground stars, so may contain artifacts. Measurements of size and distance are subject to considerable uncertainty.
www.rhysy.net

100,000 LY

One light year is the distance light travels in a year.
1 light year = 9,426,000,000 km or 5,879,000,000 miles

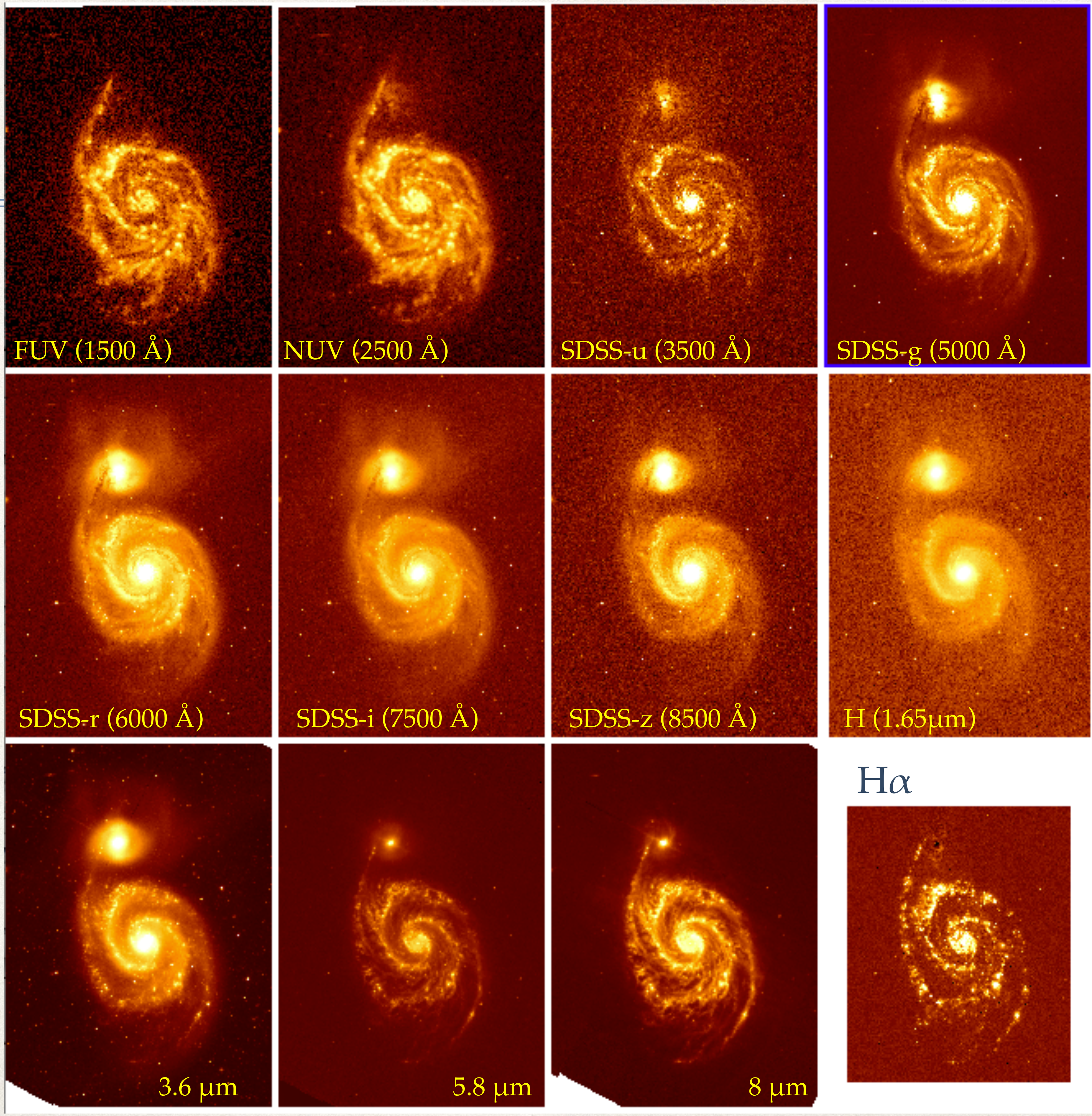
30,000 pc

One parsec is the distance at the Sun that spans one second of arc (1/3600th of a degree)
1 pc = 3.26 LY

Dependence on observing "conditions"

- Wavelength
  - for historical reasons morphological classes are defined on blue/visible light images, i.e. sensitive to starlight and to ~young stars in particular, but also to dust attenuation
  - longer wavelengths up to 2.5μm are sensitive to older stars (~bulk of stellar mass) and less sensitive to dust
  - at λ>3μm ISM/dust emission kicks in
  - at shorter λ (UV) more and more sensitive to the youngest stars and to dust absorption
- Resolution
  - especially *fine* morphology becomes harder and harder when you loose resolution, impossible to spot small bars, rings, lenses etc.

A panchromatic view of M51

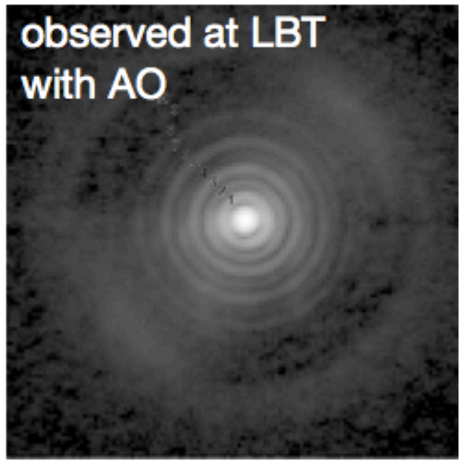


Observing conditions: telescope and seeing

1- Ideal case: limited by the the aperture of the telescope

"Diffraction limited" case:

PSF = airy disk



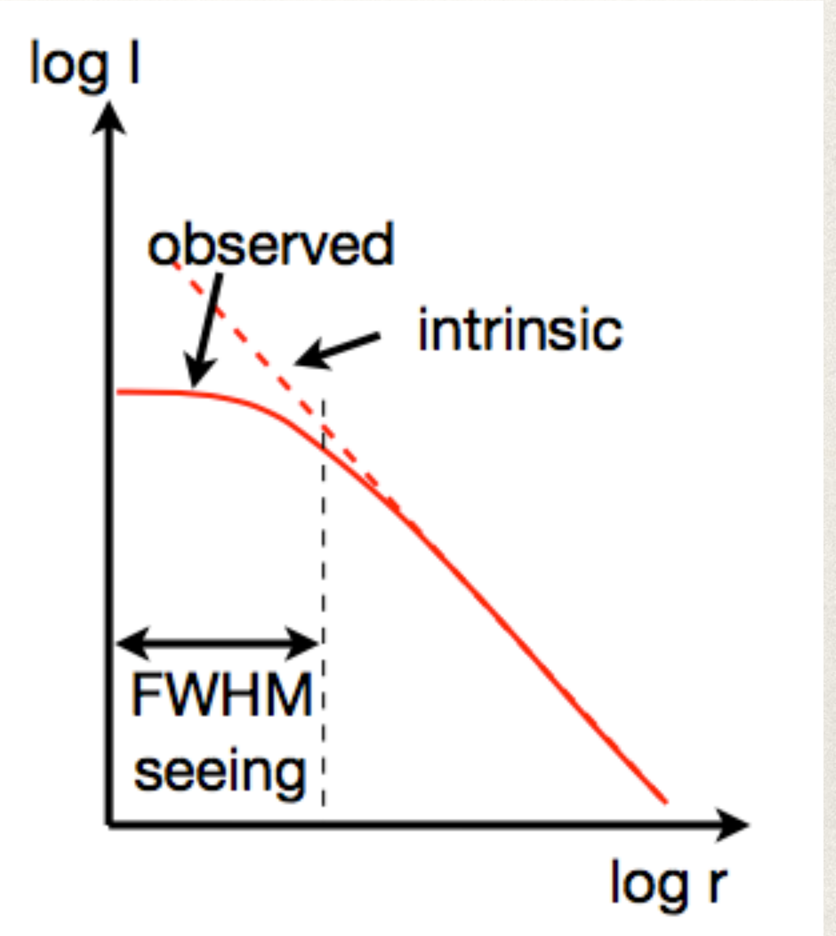
$$\Delta\theta \simeq \left(\frac{\lambda}{d}\right) rad = 0.013'' \left(\frac{\lambda}{5000\text{Å}}\right)\left(\frac{d}{8\text{m}}\right)^{-1}$$

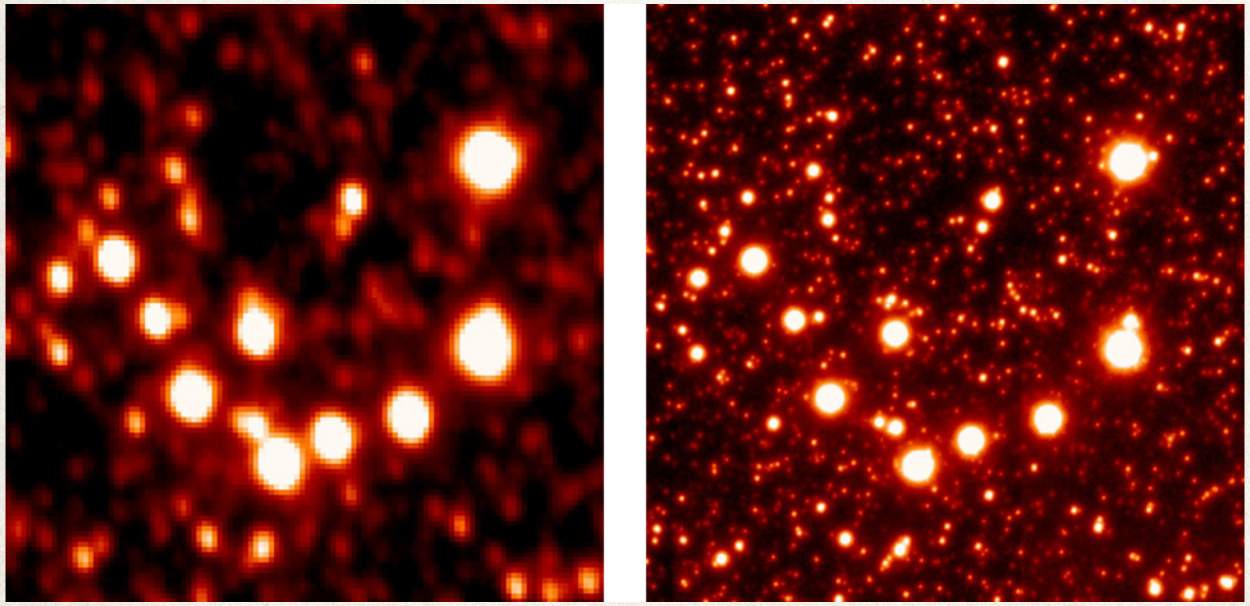
2- limited by the atmospheric turbulence: **"seeing limited" case**

PSF~ gaussian with typical FWHM ~1"

(diffraction limit per d=10 cm a 5000Å)

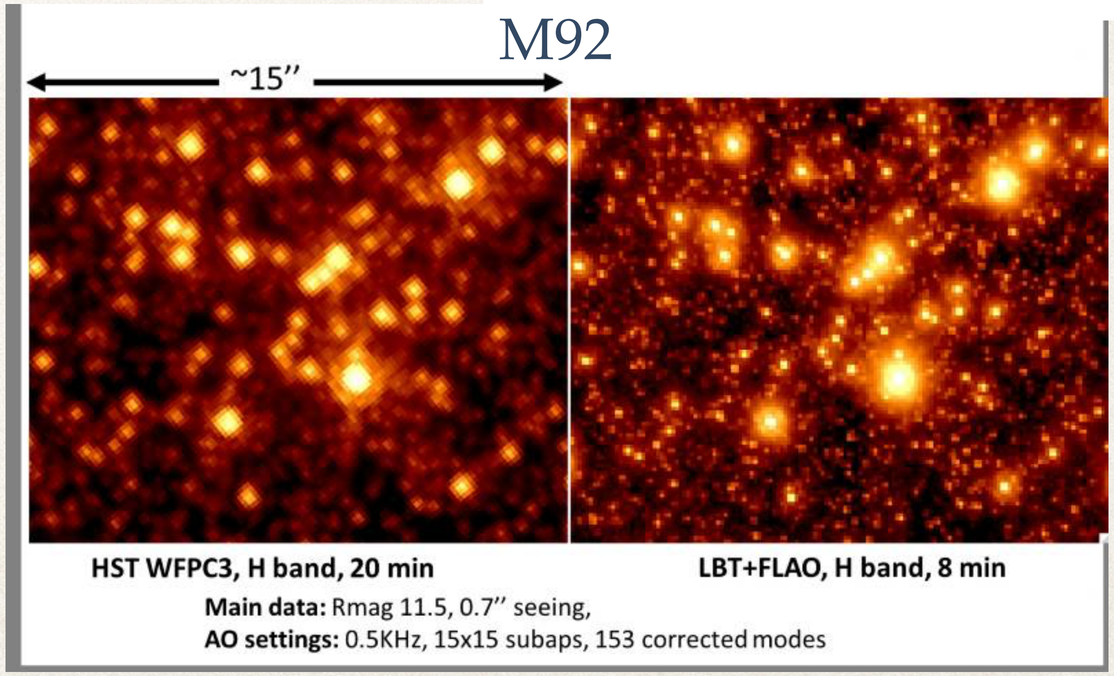
Courtesy F. Mannucci





Omega Centauri without and with AO

— ESO-MAD, from Marchetti et al. (2008)



Main data: Rmag 11.5, 0.7" seeing,

AO settings: 0.5KHz, 15x15 subaps, 153 corrected modes

Effects of seeing

- Seeing degrades resolution

- Loss of details in the structure
- Sharp peaks are smoothed, cuspy profiles are flattened

SDSS

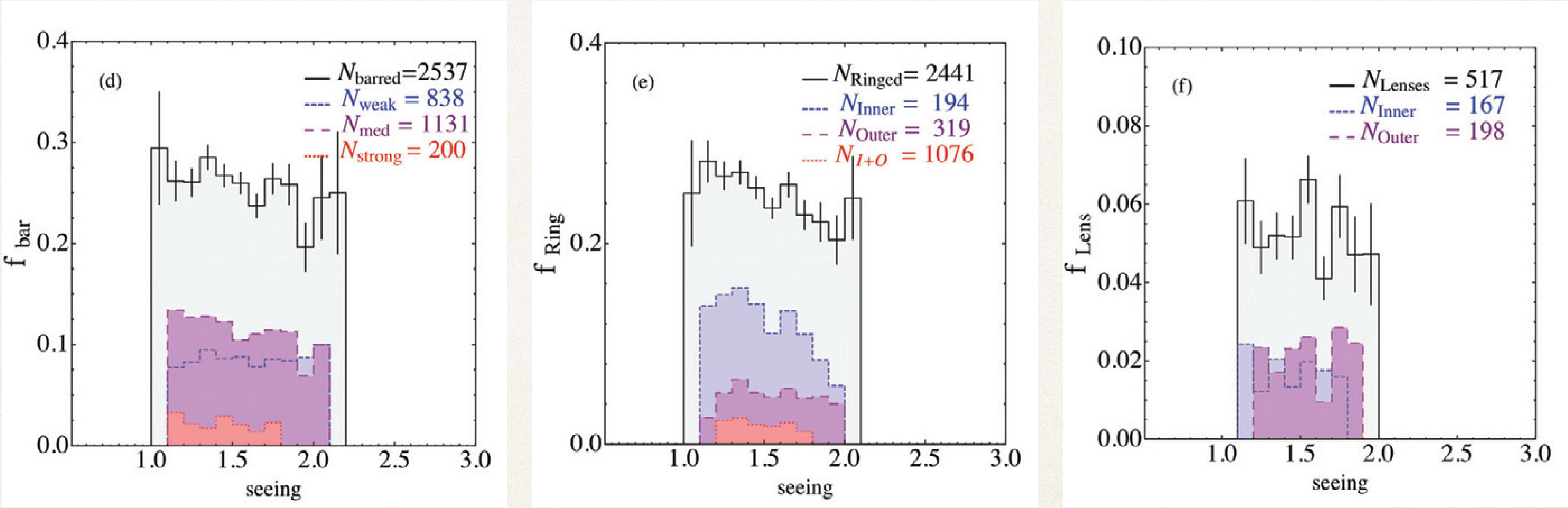


Figure 22. Dependence of fine fraction on seeing. Top: histogram distribution of seeing (PSF FWHM in arcsec) for (a) bars, (b) rings, and (c) lenses. The histograms have not been corrected for volume effects. Bottom: fractional histogram for (d) bars, (e) rings, and (f)lenses as a function of seeing. For barred galaxies, the distribution of strong (red, dotted line), intermediate (purple, long dashed line), and weak (blue, short dashed line) bars are shown. For ringed galaxies, inner (blue, short dashed line), outer (purple, long dashed line), and combination (red, dotted line) ring distributions are shown. In galaxies with lenses, inner (blue, short dashed line) and outer (purple, long dashed line) lens distributions are shown. The solid black line shows the total distribution.

Nair & Abraham (2010)