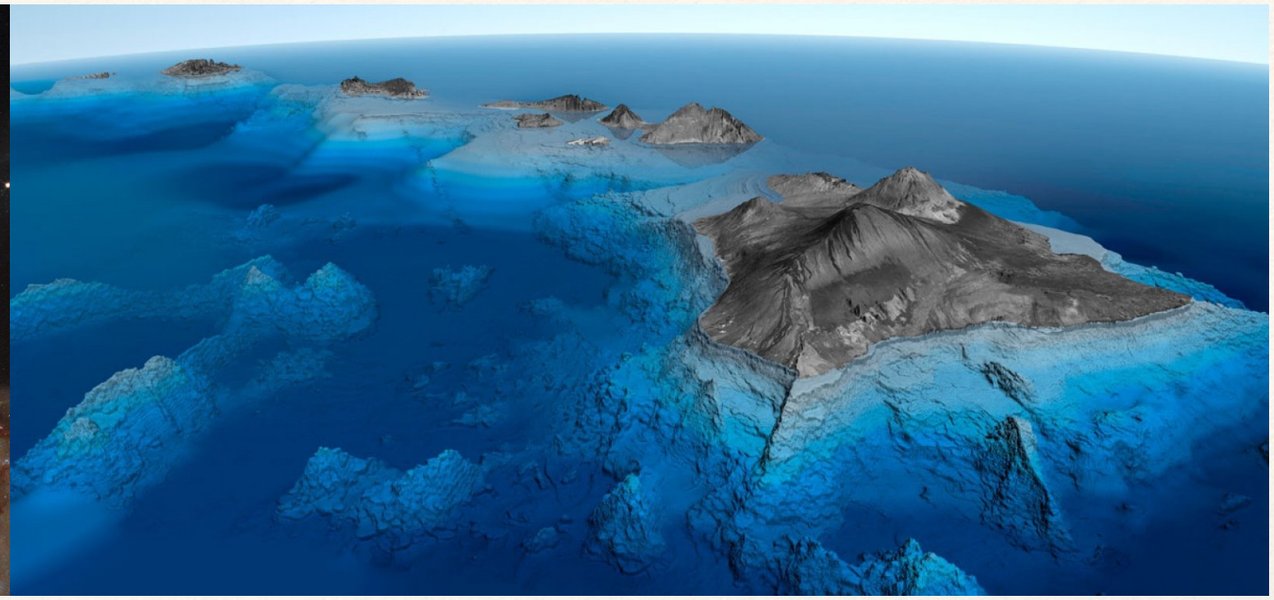


Getting to know the "island universes" out there.

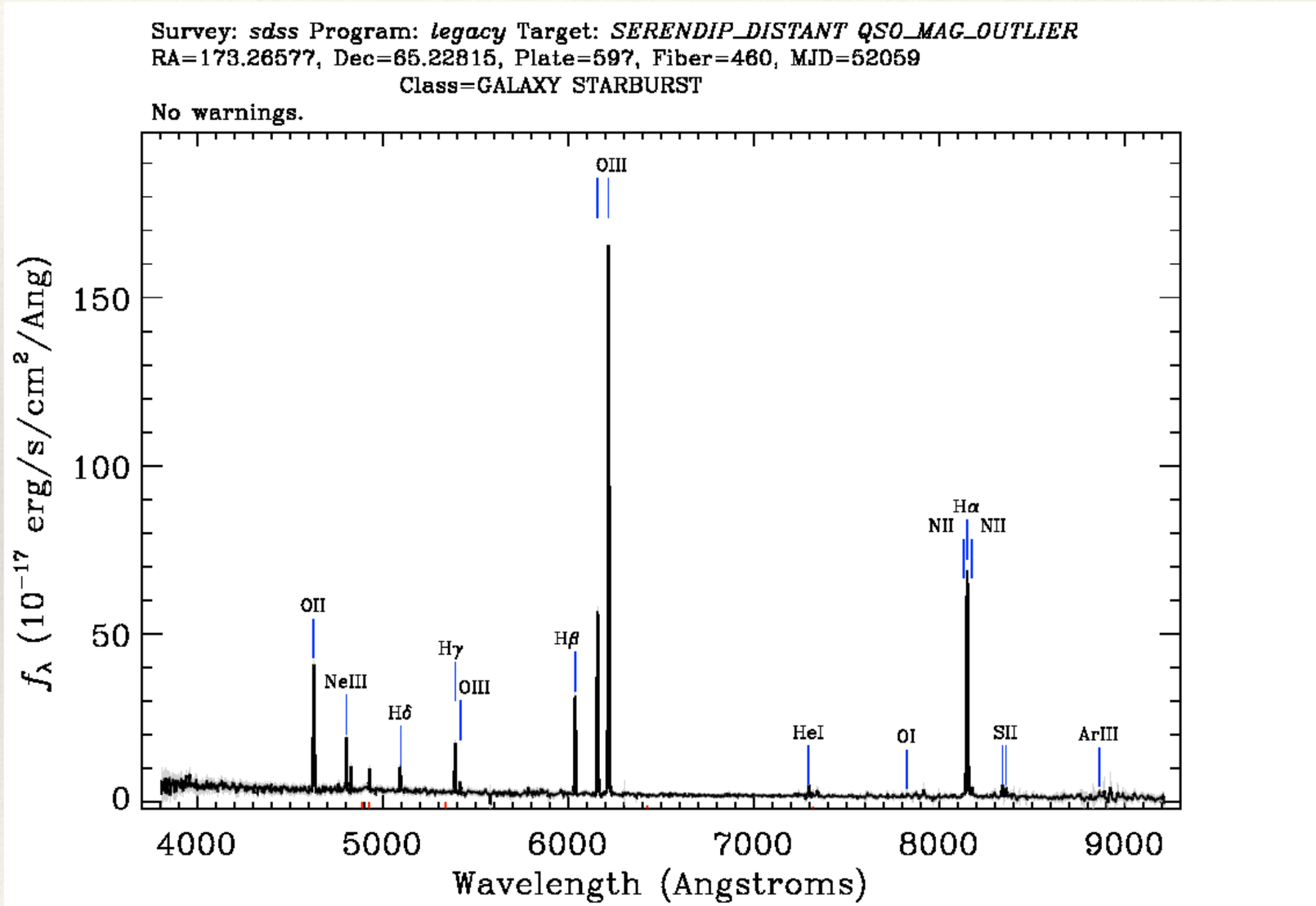
Galaxies I

ASTR 555

Dr. Jon Holtzman

Warm-up

- How would you compute the redshift of this galaxy? What is the redshift of this galaxy?
- What specific steps would you use to calculate the **intrinsic Hα luminosity** of this galaxy? What corrections would or wouldn't you need to worry about?



Warm-up

- **Rest wavelength of Hα — 6563 Å**

$$1+z = \frac{\lambda_o}{\lambda_e} \qquad \lambda_e = 6563\,\text{Å} \qquad \lambda_o = 8150\,\text{Å}$$

$$1+z = \frac{8150\,\text{Å}}{6563\,\text{Å}} = 1.241$$

$$\boxed{z = 0.241}$$

Outline for Today

- Observing Galaxies - Morphology:
  - Visual (by eye)
  - Quantitative
    - Parametric
    - Non-parametric

NGC1232 (ESO)

Observing Galaxies - Morphology

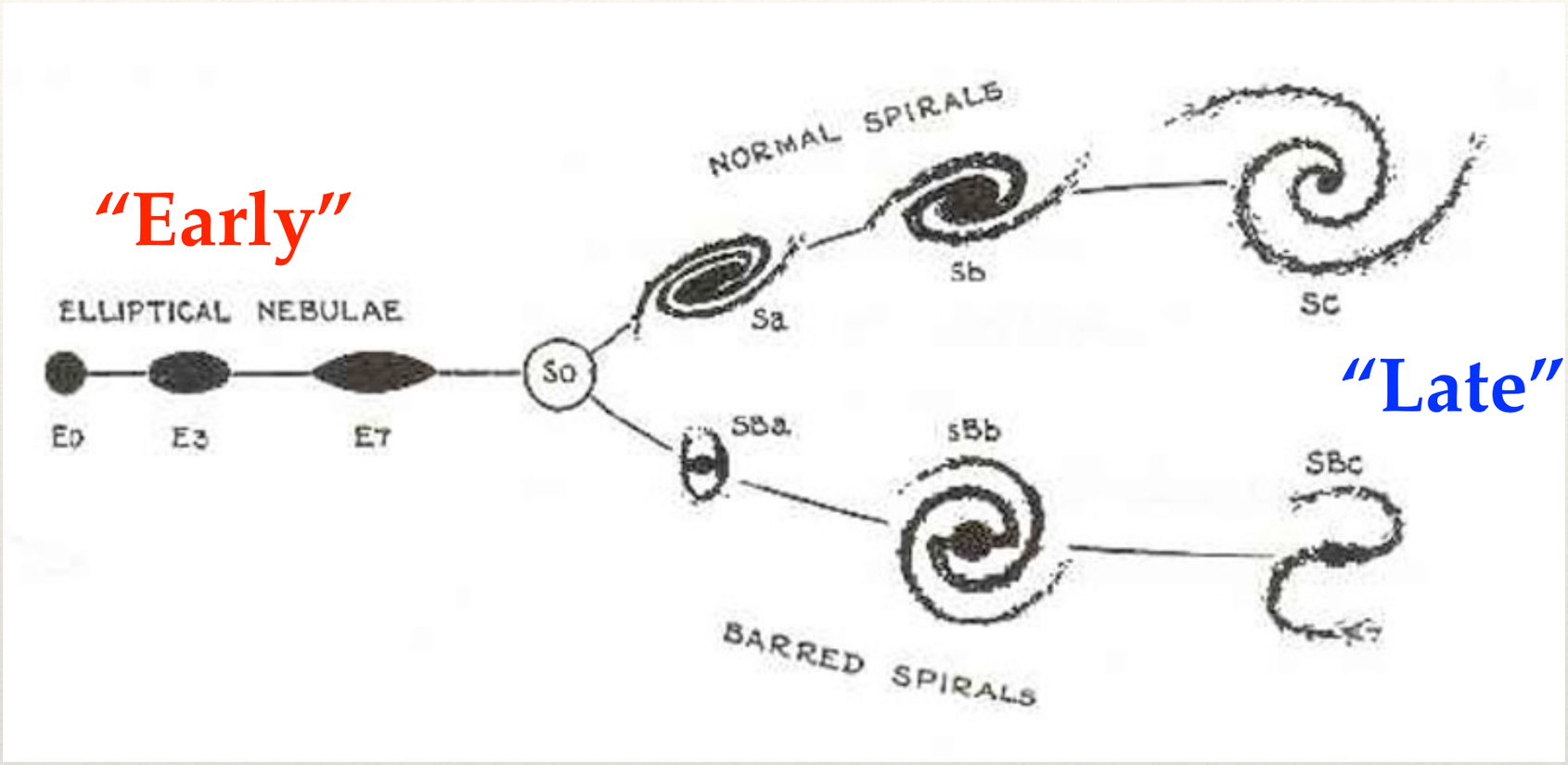
- Historically, people started studying galaxies in terms of morphology

- Basic Components: spheroid, disk, bar, arms, (rings)

  - Presence/absence and relative strength of these components defines **morphological class**

Image: William Parsons, Third Earl of Rosse, using 72-inch meridian-based telescope on the grounds of Birr Castle in Ireland (1845)

Observing Galaxies - Morphology: Hubble Tuning Fork

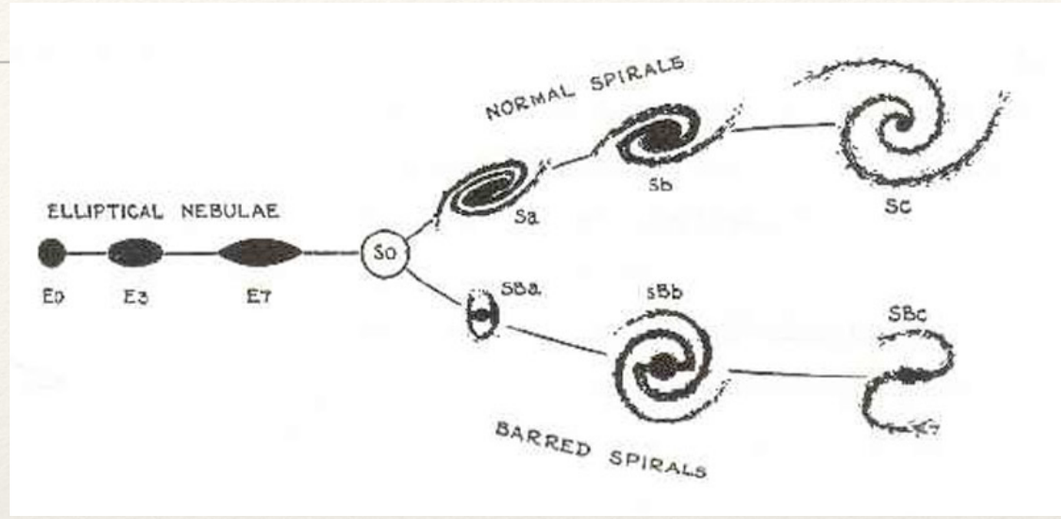


Hubble's (1936) "tuning fork" of galaxy morphologies.

- Several early attempts at a classification system (e.g., Wolf 1908, Reynolds 1920, Lundmark 1926, Shapley 1927)
- Hubble Tuning Fork (1922, 1926, 1936), extended by Sandage (Hubble Atlas, 1961) and de Vaucouleurs (1959; Third Reference Catalogue of Bright Galaxies, RC3 — 1991)
  - Prevailed perhaps because it did not try and account for every detail, and used classes broad enough to encompass the vast majority of galaxies

Observing Galaxies - Morphology: Hubble Tuning Fork

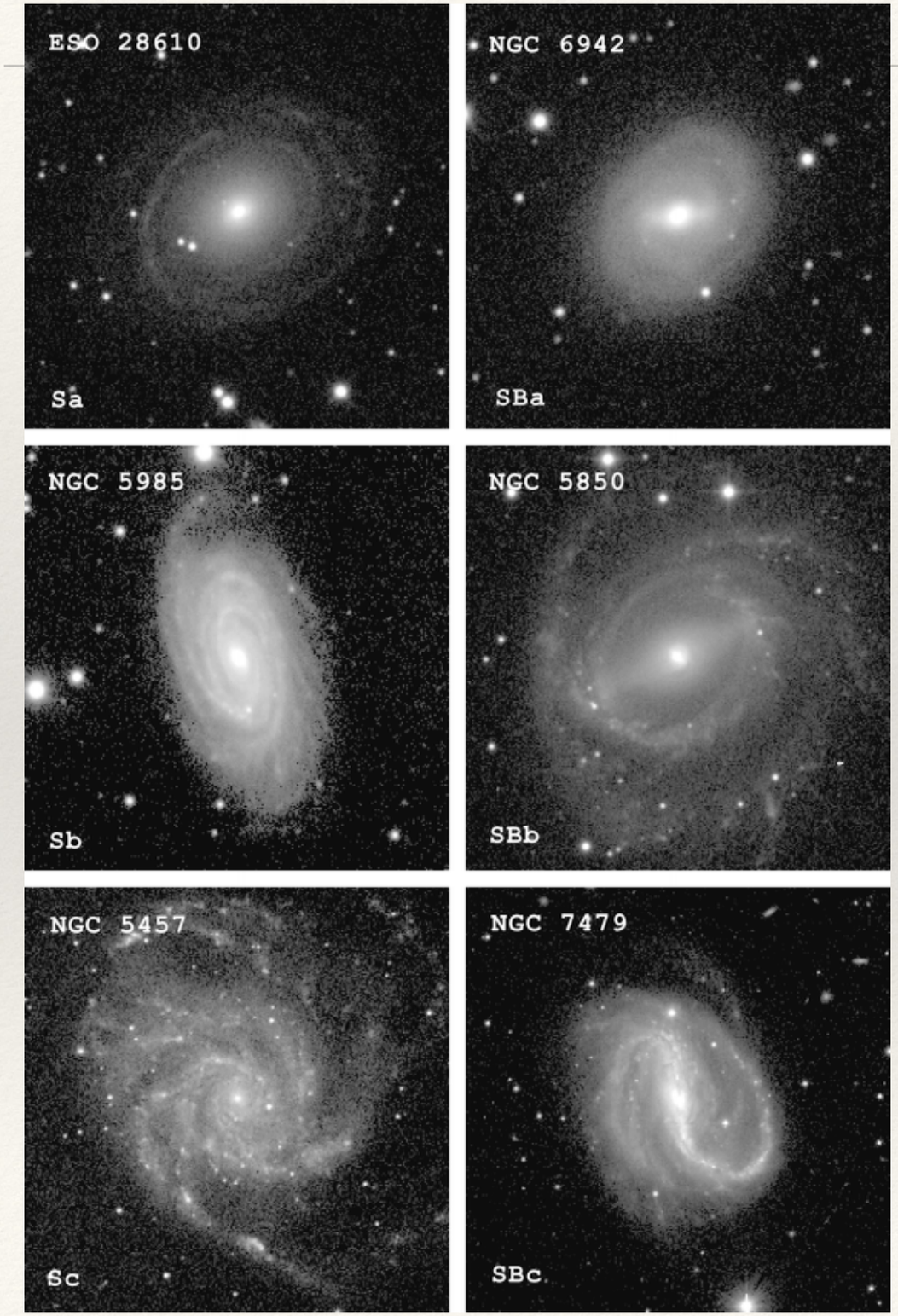
- **Ellipticals:**
  - dominated by spheroidal component
  - smooth, structureless profiles
  - classified by apparent ellipticity E_n
  - $n = 10\,(1 - b/a)$
  - b/a = minor/major axis, i.e., apparent flattening

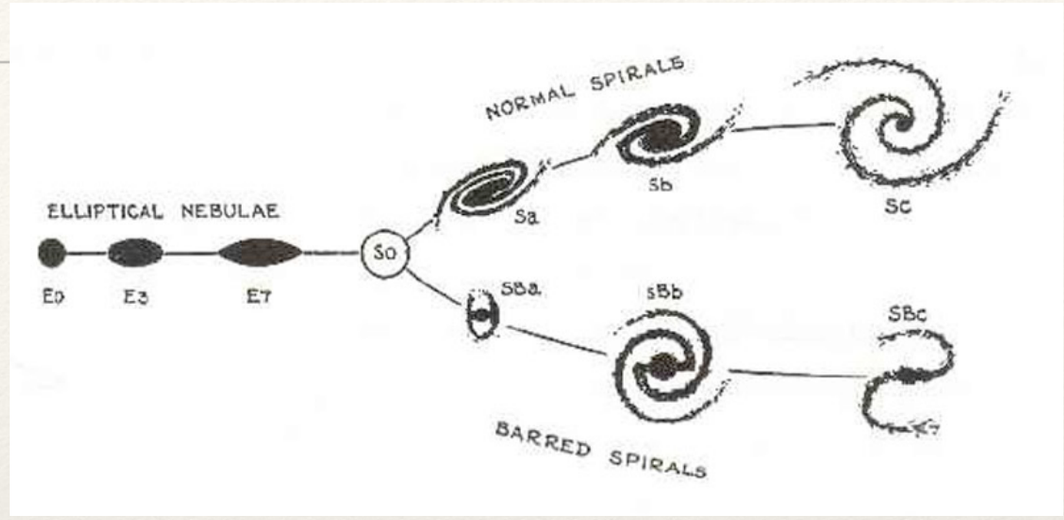


Hubble's (1936) "tuning fork" of galaxy morphologies.

https://ned.ipac.caltech.edu/level5/Sept11/Buta/frames.html

Observing Galaxies - Morphology: Hubble Tuning Fork

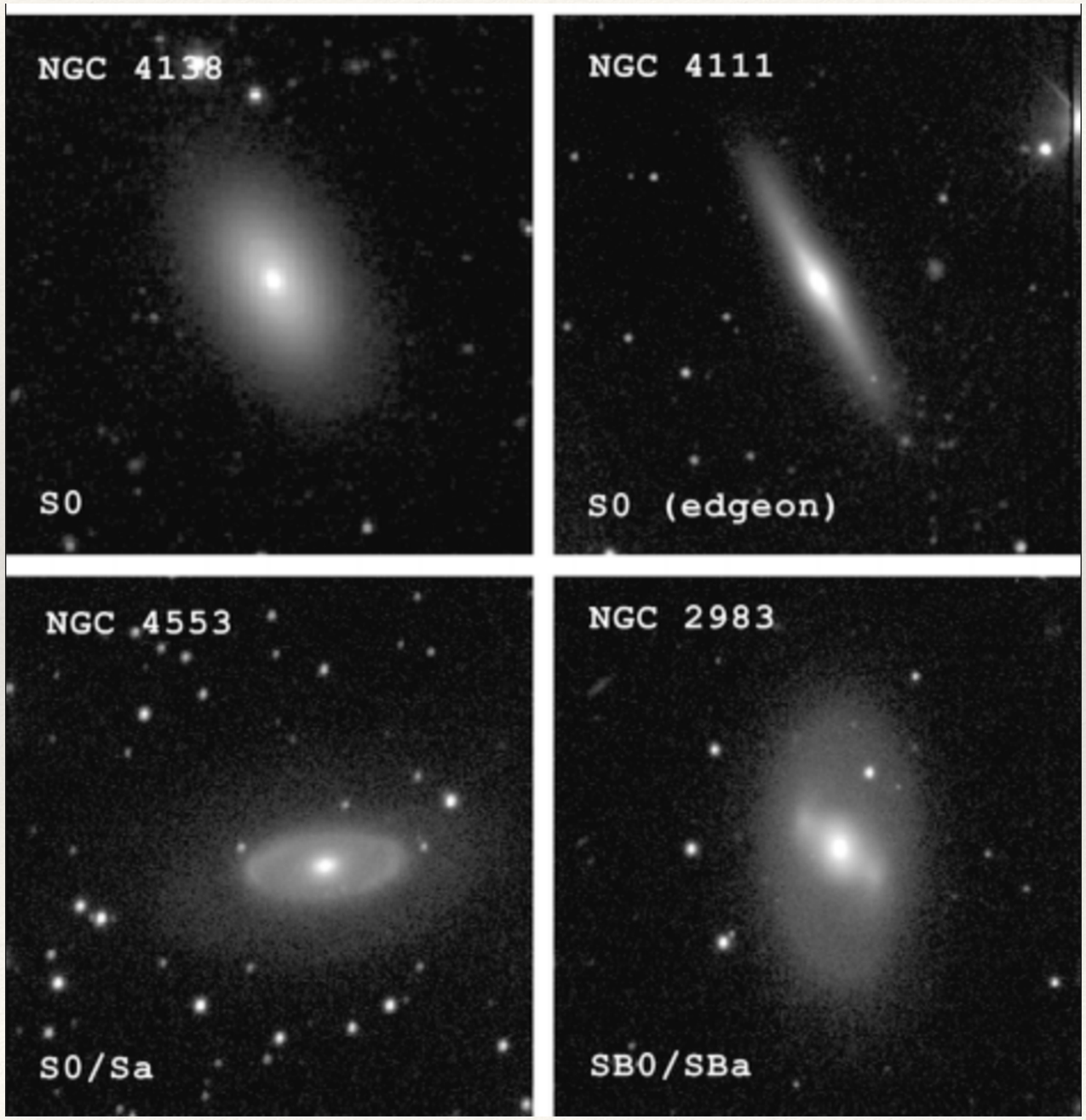


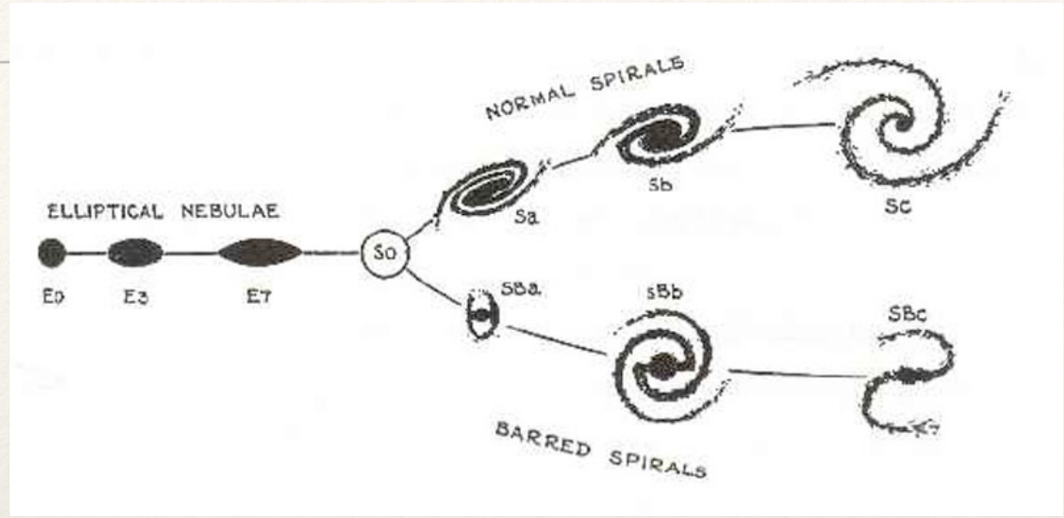


Hubble's (1936) "tuning fork" of galaxy morphologies.

- **Spirals**:
  - bulge + (bar) + disk + arms
  - unbarred or barred (S / SB)
  - classified a/b/c depending on bulge/disk, tightness of arms, degree to which arms resolved into individual knots (HII regions)

Observing Galaxies - Morphology: Hubble Tuning Fork



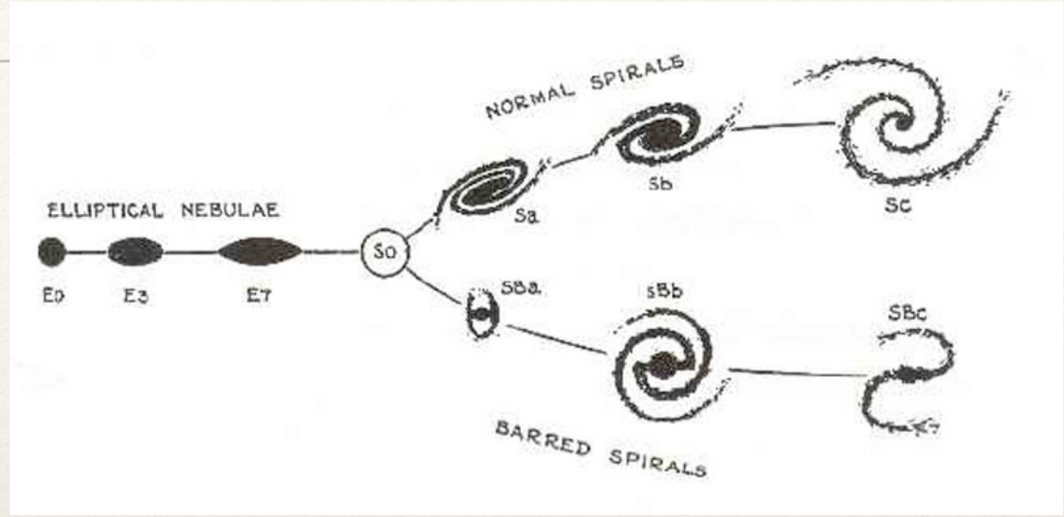


Hubble's (1936) "tuning fork" of galaxy morphologies.

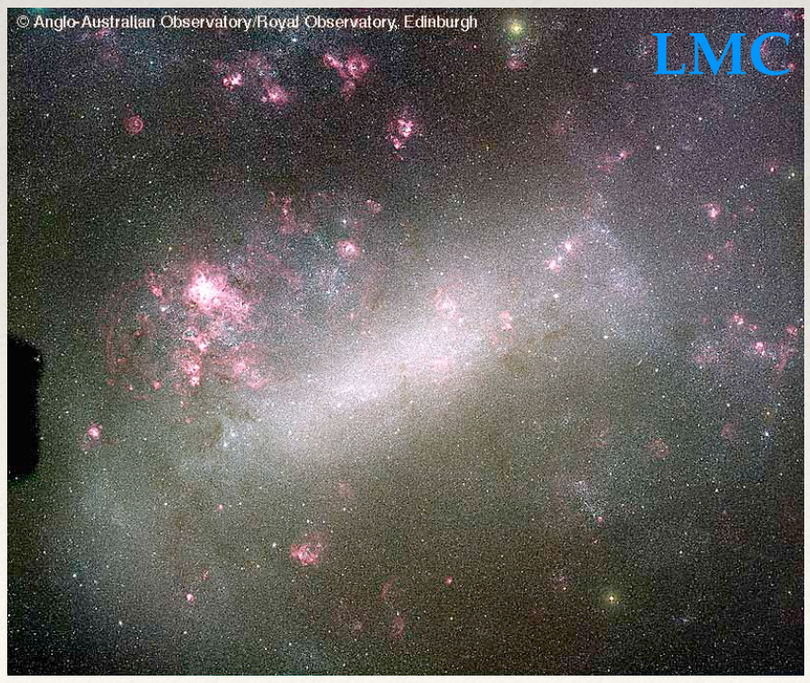
- **S0/Lenticulars:**
  - smooth structureless light profile
  - central concentration (bulge) + envelope (disk)
  - no spiral structure
  - sometimes have a bar

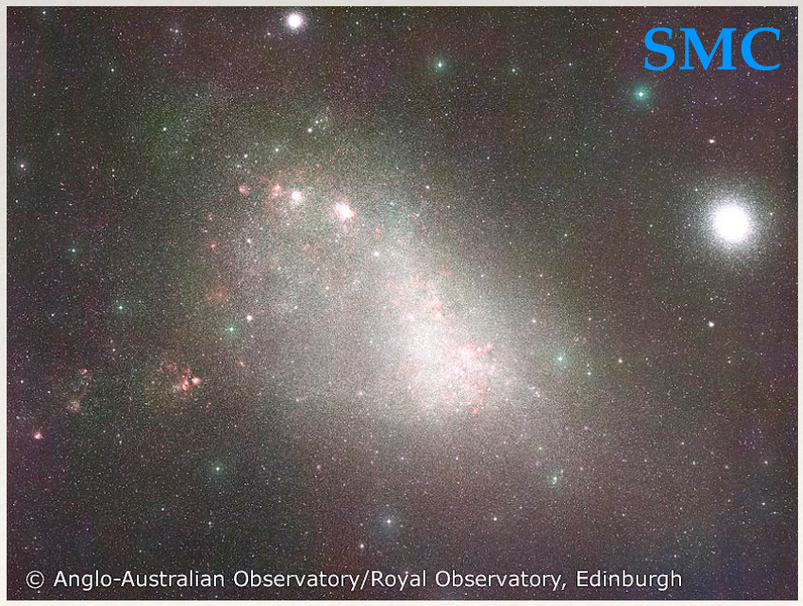
Observing Galaxies - Morphology: Hubble Tuning Fork

- **Irregulars:**
  - IrrI — Magellanic irregulars with lots of distinct knots (HII regions)
  - IrrII — lack distinct knots (HII regions)



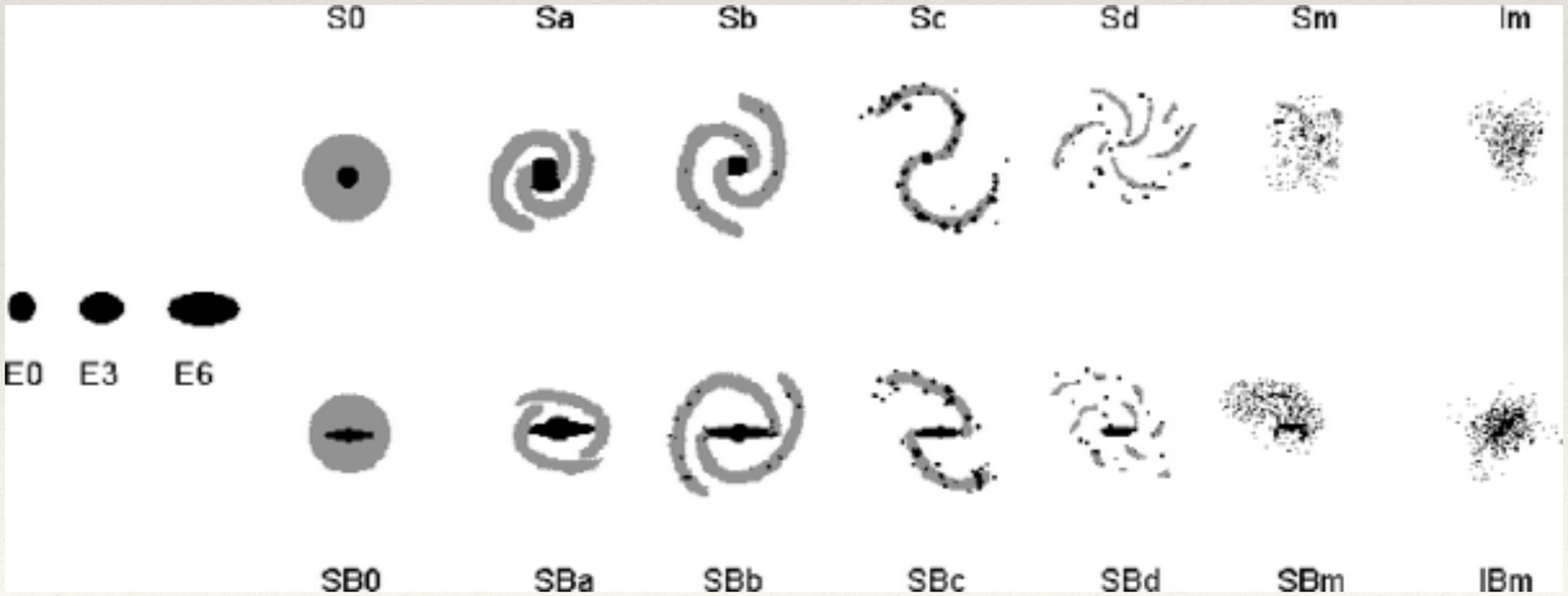
Hubble's (1936) "tuning fork" of galaxy morphologies.





Observing Galaxies - Morphology: deVaucouleurs/RC3

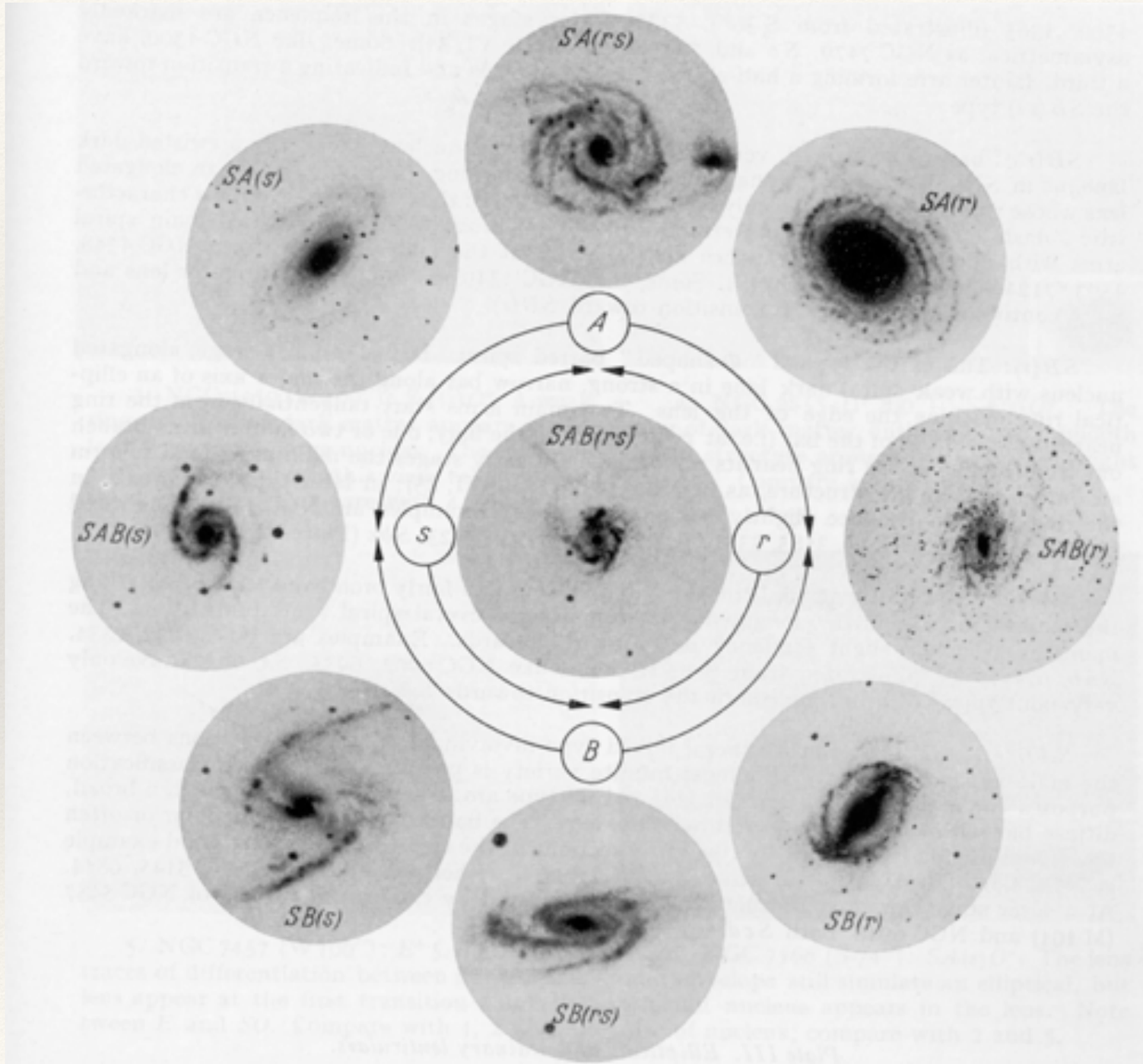
- de Vaucouleurs extended Hubble classification:
  - Added “later” spiral types Sd, Sm, finally Im
  - Added extra S0 classes: $S0^{-}$, $S0^{0}$, $S0^{+}$



https://ned.ipac.caltech.edu/level5/Sept11/Buta/frames.html

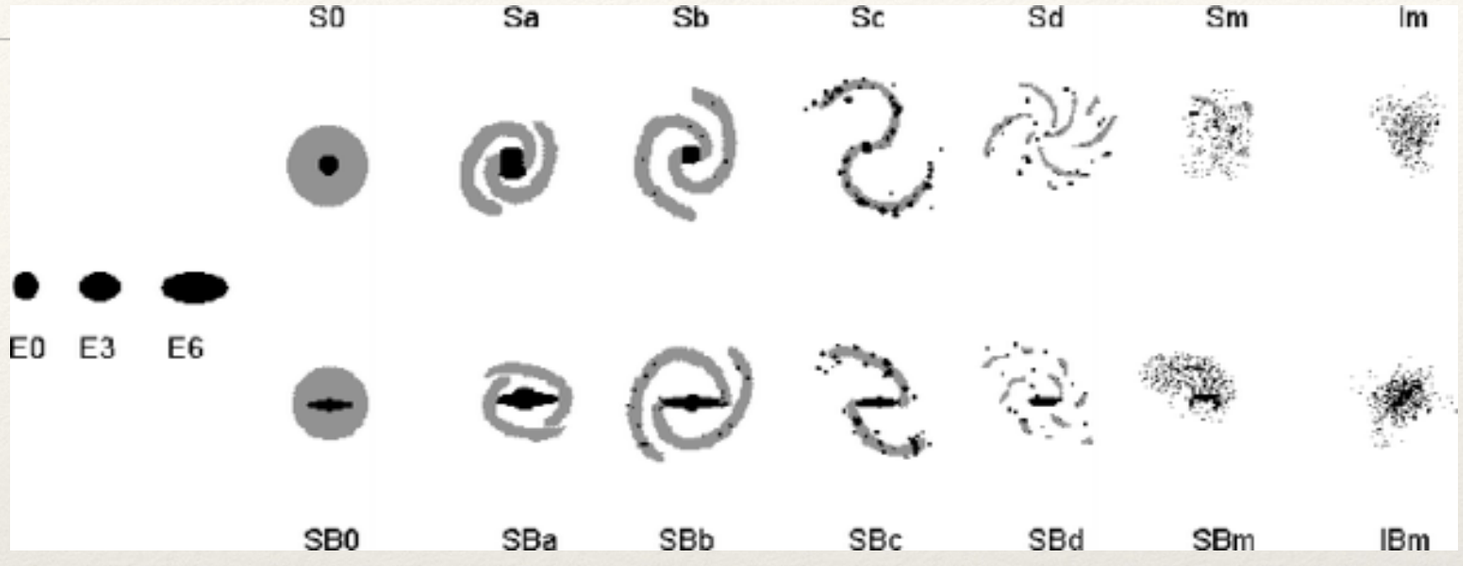
Observing Galaxies - Morphology: deVaucouleurs/RC3

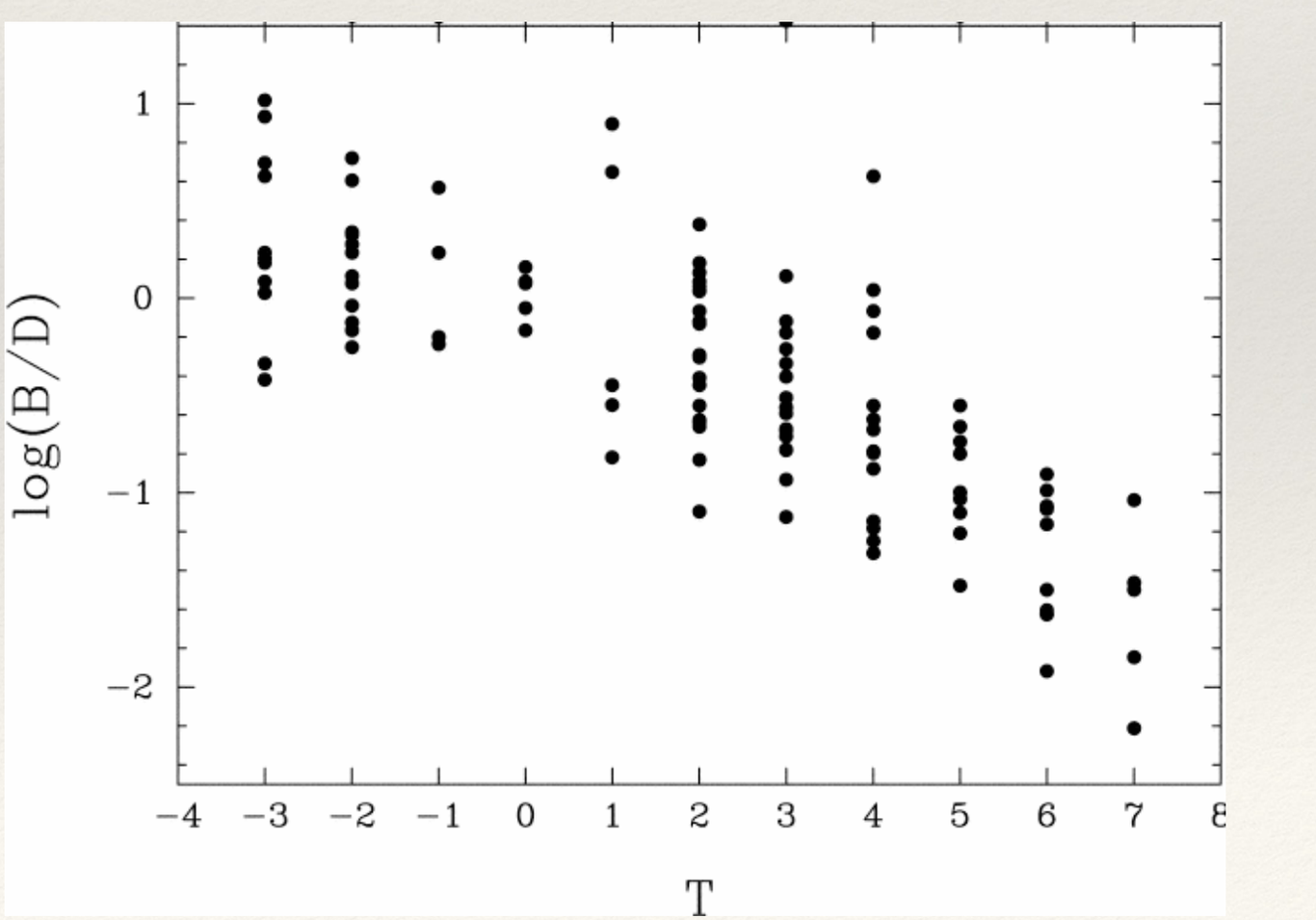
- Allowed for intermediate class between barred and unbarred.
  - Normal spirals SA, barred SB, and transition SAB.
- Added extra distinction for ringed “r” vs. “s” shaped.



Observing Galaxies - Morphology: deVaucouleurs/RC3

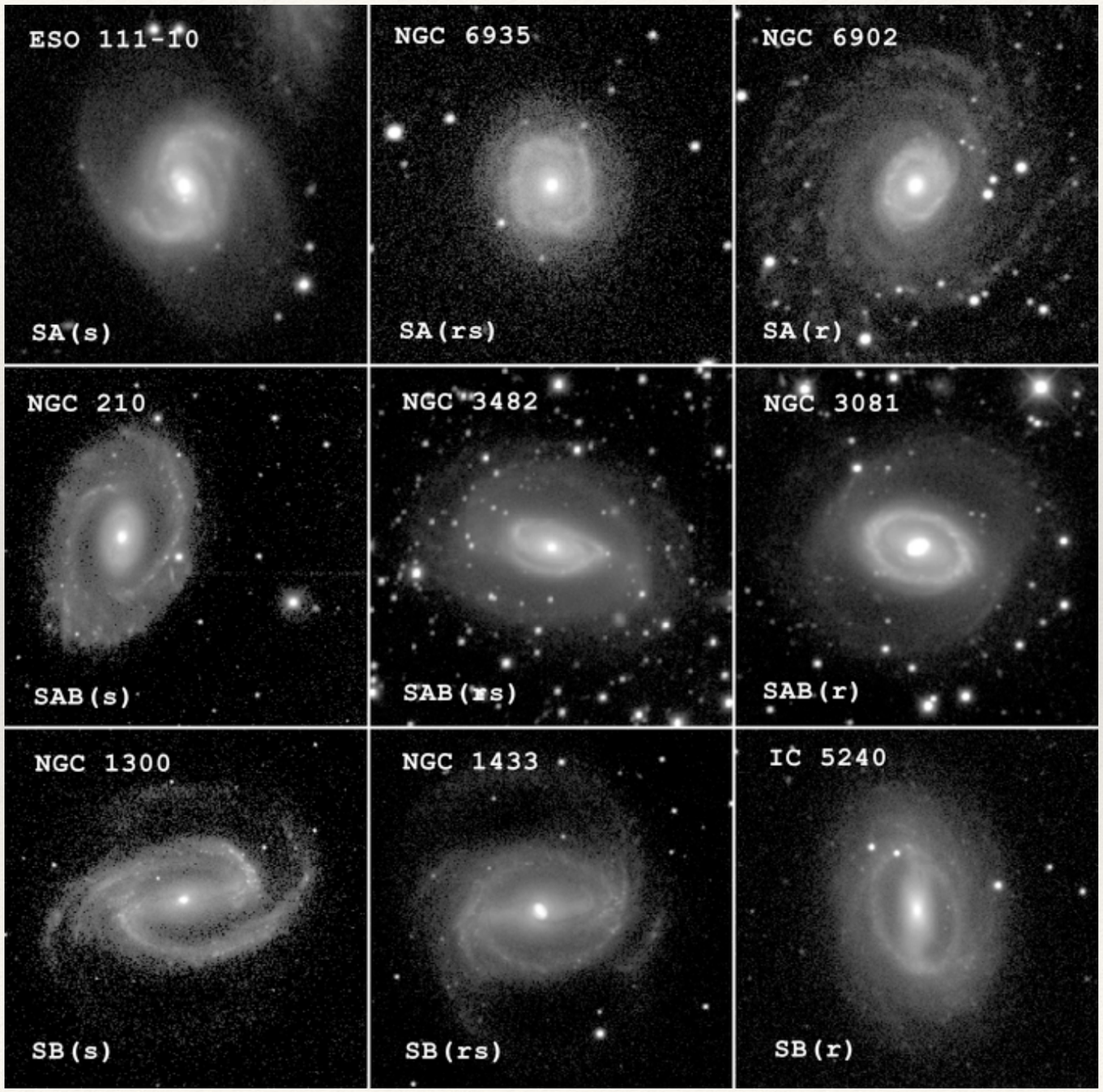
- Introduced numerical galaxy types (T-type):
  - T integer (-5 to +10) tracks Hubble type (E to Im)
- de Vaucouleurs classification is the most familiar due to continuing use of the RC3 (de Vaucouleurs et al. 1991)





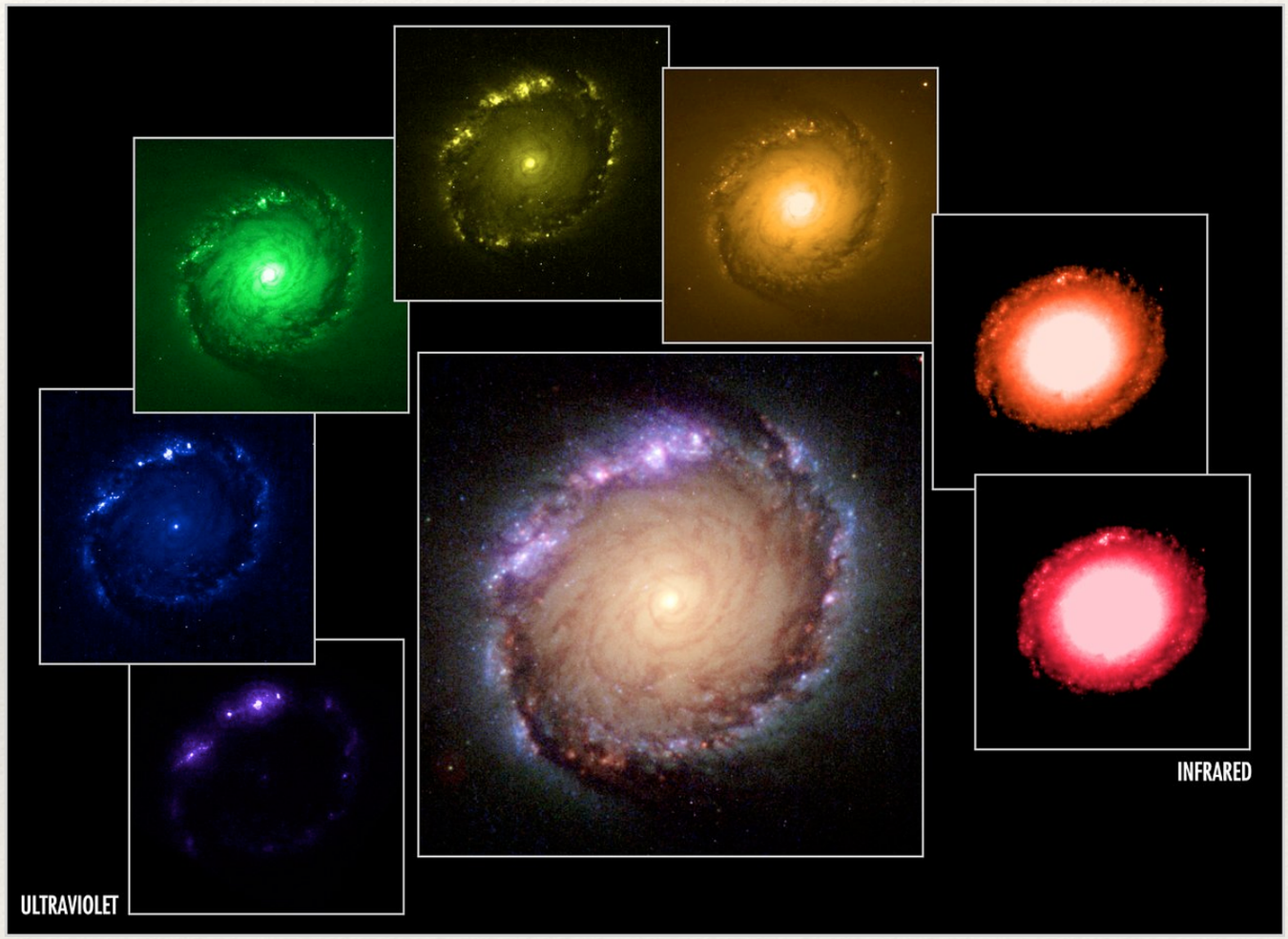
Thought Questions

- What are some advantages of classifying galaxies using the Hubble/de Vaucouleurs morphological system?
- What are some disadvantages?
- What are some alternatives?



Observing Galaxies - Morphology: Morphology Problems

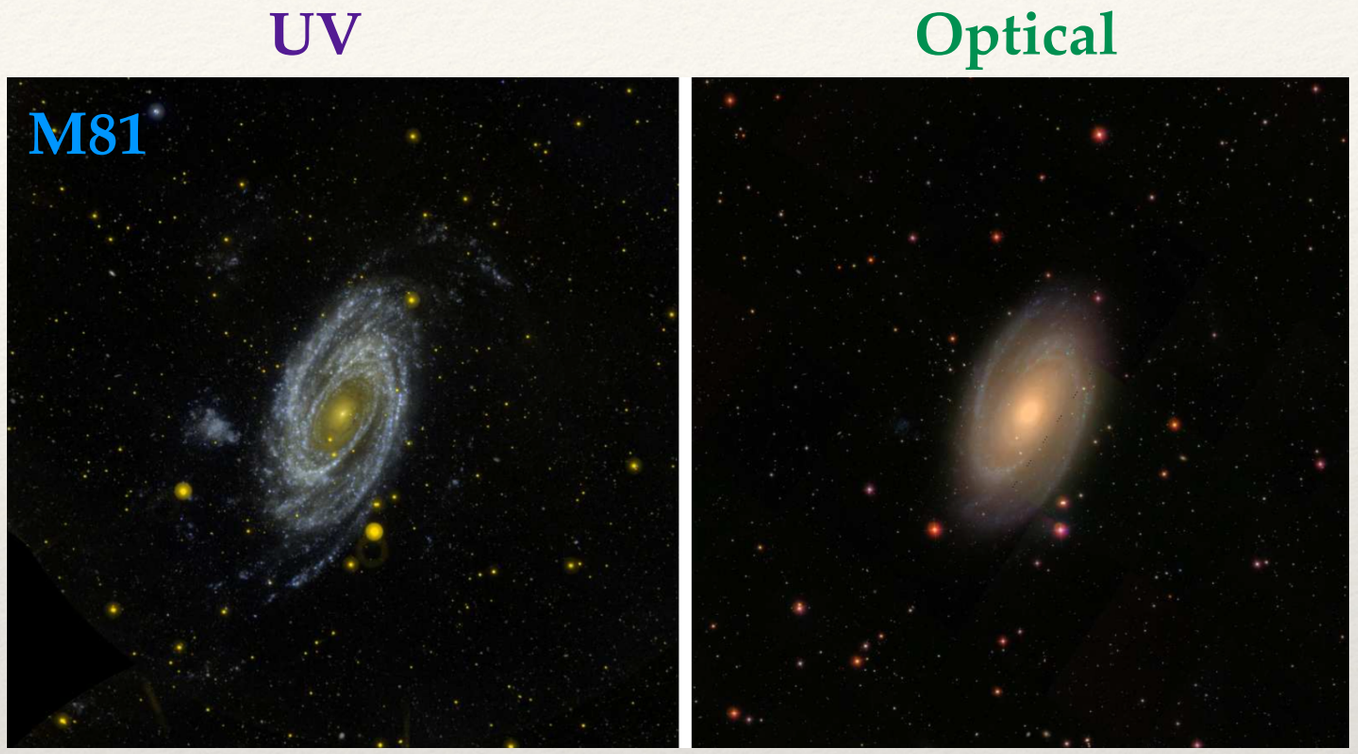
- **Morphology depends on wavelength!**:
  - Need to compare morphologies derived in the same band
- Careful when comparing galaxies at different redshifts (“**morphological K-correction**”)



NASA, ESA, Dan Maoz

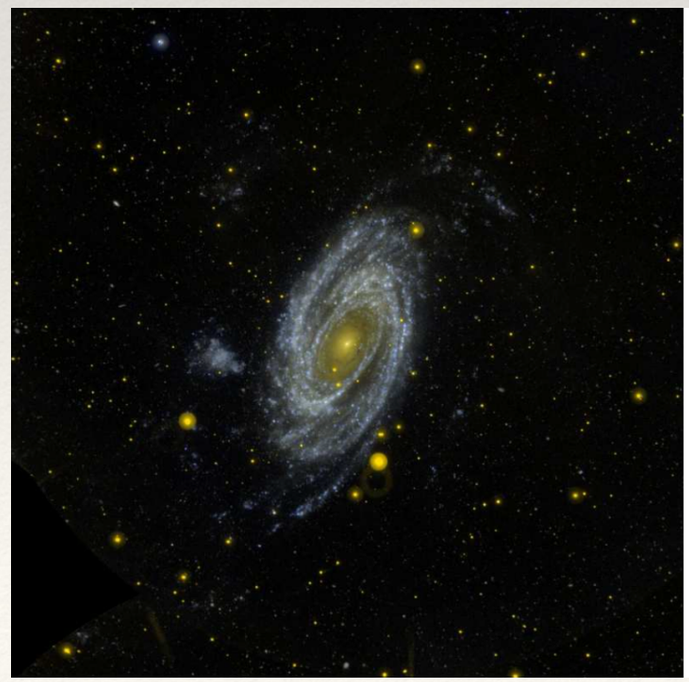
Observing Galaxies - Morphology: Morphology Problems

- **Morphology depends on wavelength!**:
  - Need to compare morphologies derived in the same band
- Careful when comparing galaxies at different redshifts (“**morphological K-correction**”)



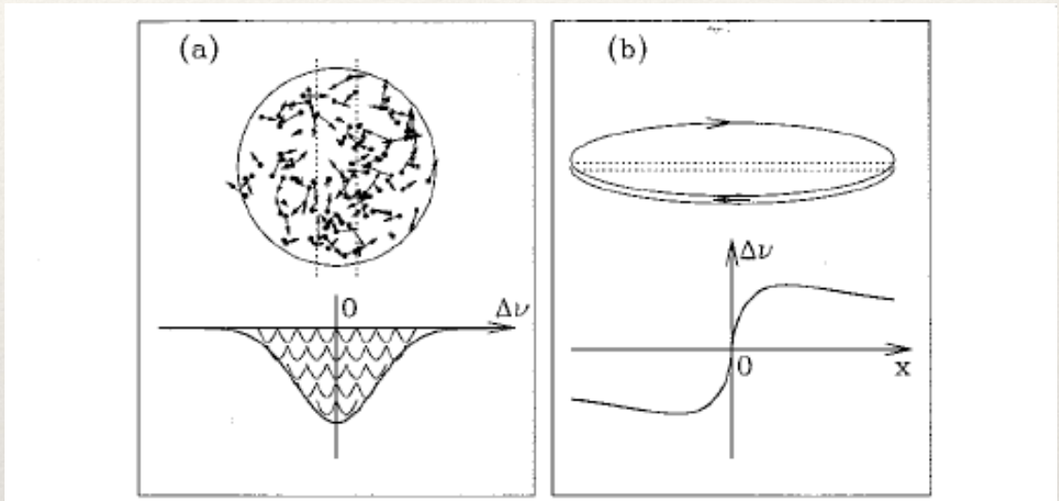
Bianchi et al. 2011, 2017

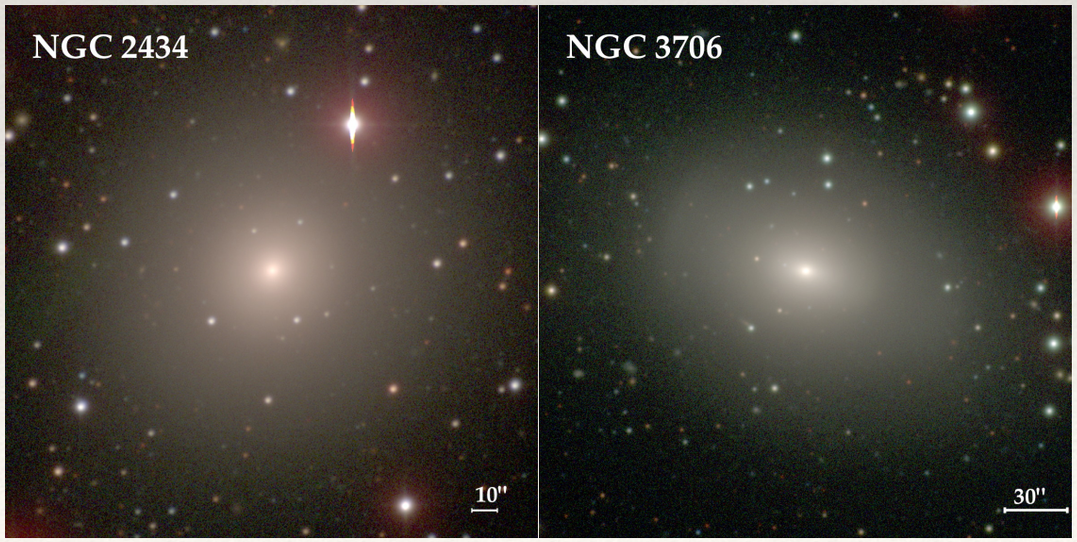
Higher redshift →



Observing Galaxies - Morphology: Morphology Problems

- **How do morphological measures connect to underlying properties?**
- ***Ellipticals:***
  - Hubble morphological classification isn't fundamental
  - *n* value simply the ***projected*** ellipticity, not true flattening
  - virtually no physical characteristics of ellipticals correlate with *n* (Kormendy & Djorgovski 1989)
  - Perhaps more meaningful to classify by **isophotal shape** (e.g., boxy vs. disky; Kormendy & Bender 1996) or kinematically by **V/σ**





Observing Galaxies - Morphology: Morphology Problems

- **How do morphological measures connect to underlying properties?**
- *Spirals:*
  - Physical properties (luminosity, surface brightness, rotational velocity, gas fraction) **do correlate** with Hubble type
  - However, categories have broad range of global observables and overlap significantly (review by Roberts & Haynes 1994)
  - Low surface brightness galaxies are excluded —> possible bias
  - Spiral arms show higher contrast in surface brightness than in mass —> misleading picture?
  - Origin of spiral arms may not be fundamentally related to global galaxy properties

Observing Galaxies - Morphology: Morphology Problems

- **Other problems with visual morphological schemes:**
  - often depend on multiple characteristics —> how to weigh them consistently?
  - are subjective at some level —> check for consistency among multiple expert classifiers?
  - are difficult to expand to larger scale samples, e.g. with millions of galaxies

Observing Galaxies - Morphology: Quantitative Morphology

- Quantitative morphological schemes attempt to address problems with visual classification

- **Parametric** — assume galaxy is smooth and symmetric, and model distribution of light with a prescribed analytic function

  - ***Bulge-disk ratio*** — Bulge-Disk decomposition

  - ***Global profile fit*** — e.g., Sersic index *n*

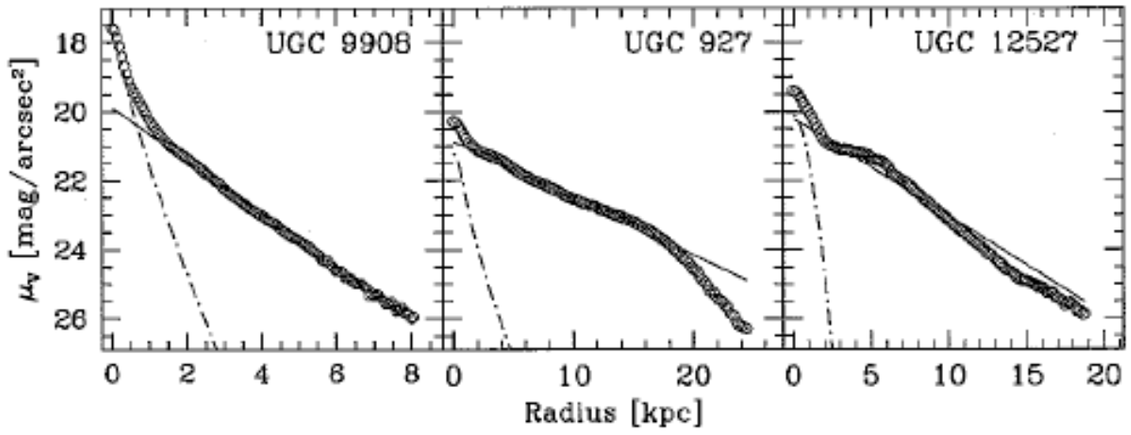
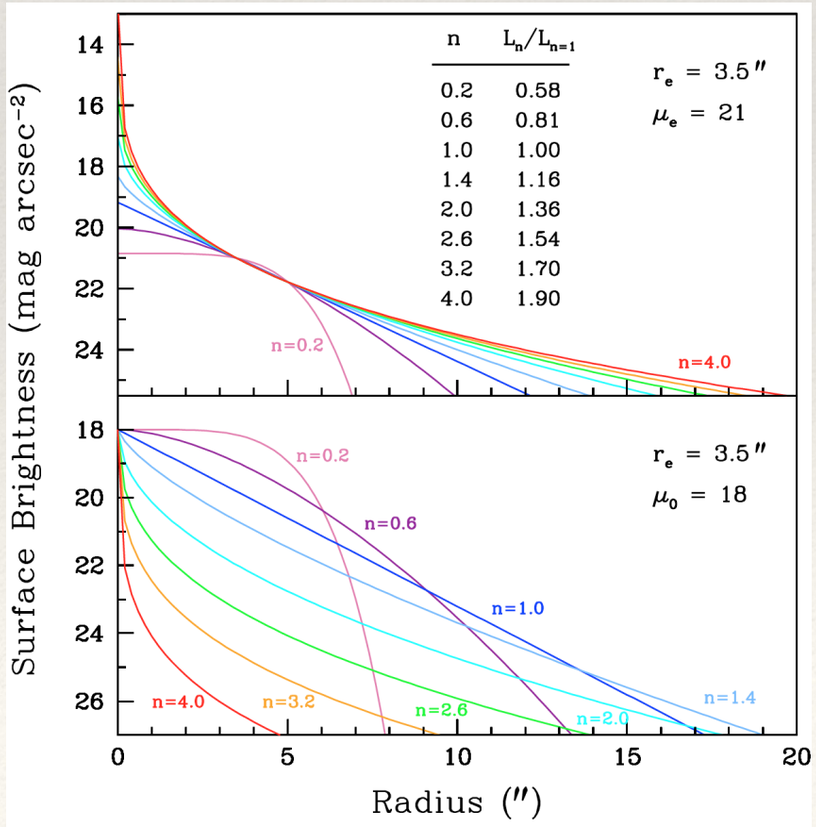


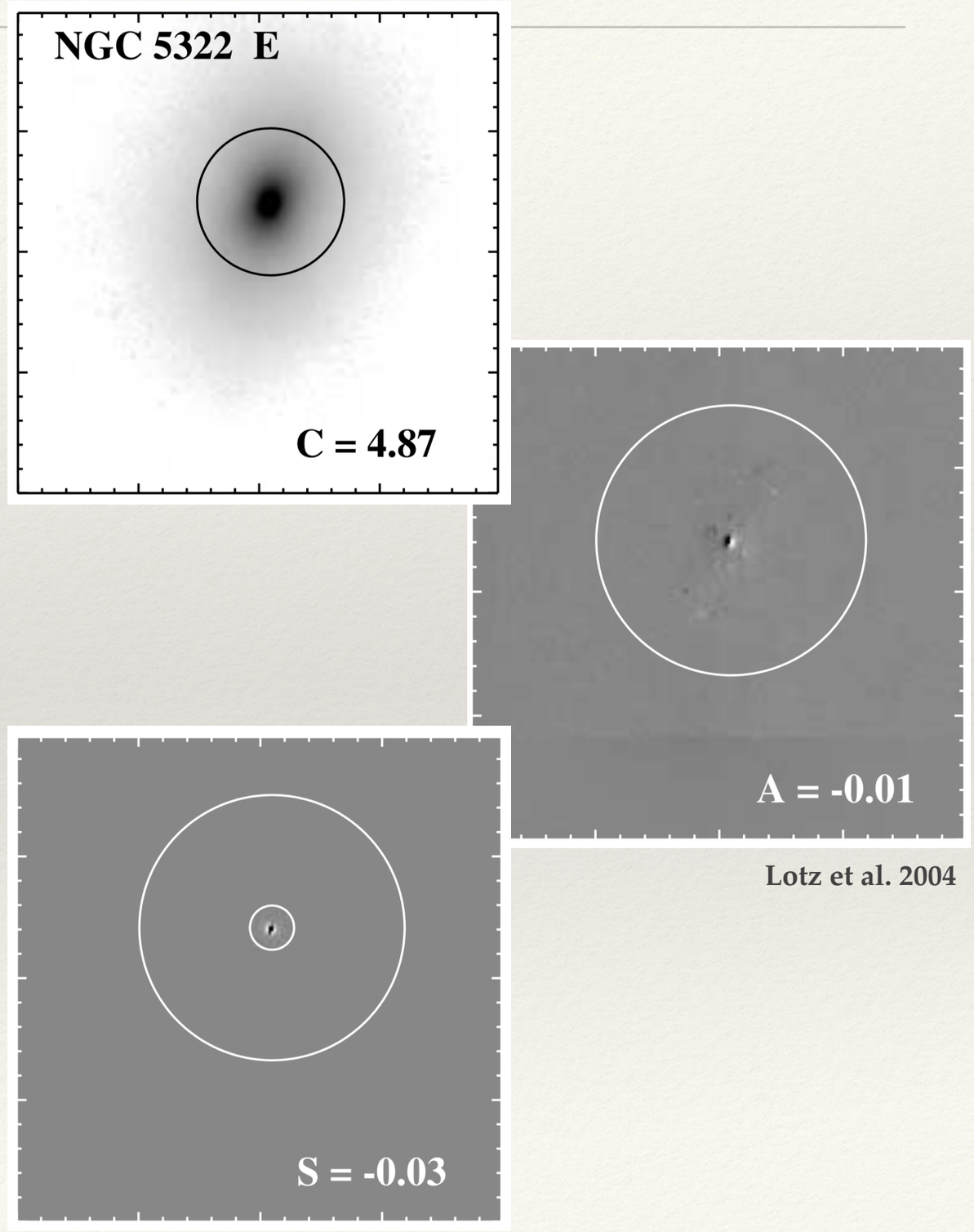
Fig. 2.19. The surface brightness profiles of three disk galaxies plus their decomposition in an exponential disk (solid line) and a Sérsic bulge (dot-dashed line). [Based on data published in MacArthur et al. (2003) and kindly made available by L. MacArthur]

MacArthur, Courteau, & Holtzman 2003



Observing Galaxies - Morphology: Quantitative Morphology

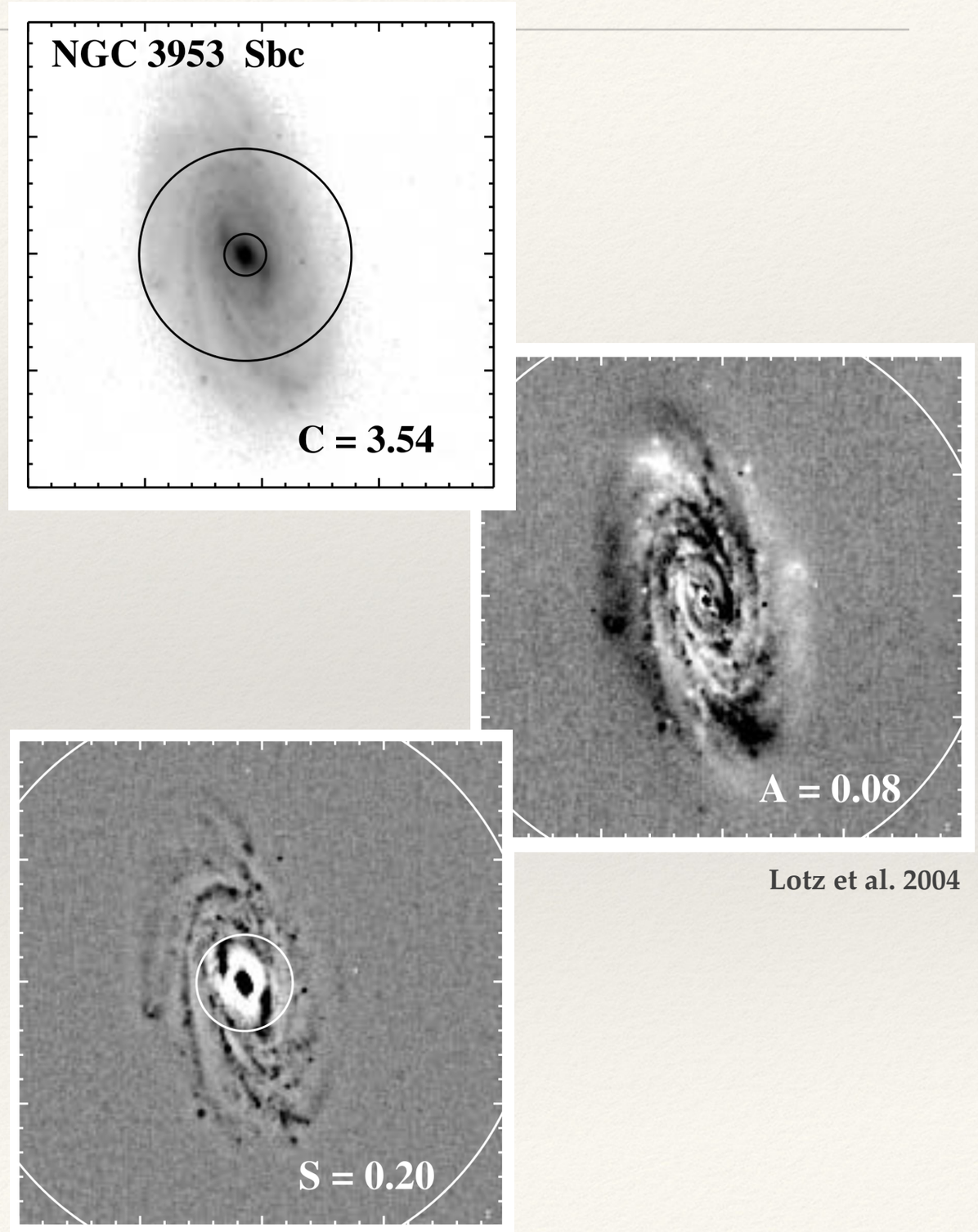
- **Non-parametric** — do <u>not</u> assume symmetry or a particular analytic function for the galaxy's light distribution:
  - ***Concentration (C)*** — r_{90}/r_{50} or r_{80}/r_{20} using circular or elliptical apertures (e.g. SDSS)
  - ***Asymmetry (A)*** — rotate about center, self-subtract (e.g. Abraham et al. 1996)
  - ***Clumpiness (S)*** — subtract smoothed version of image from original image, ratio of flux in subtracted image to flux in original image (e.g. Conselice 2003)



Lotz et al. 2004

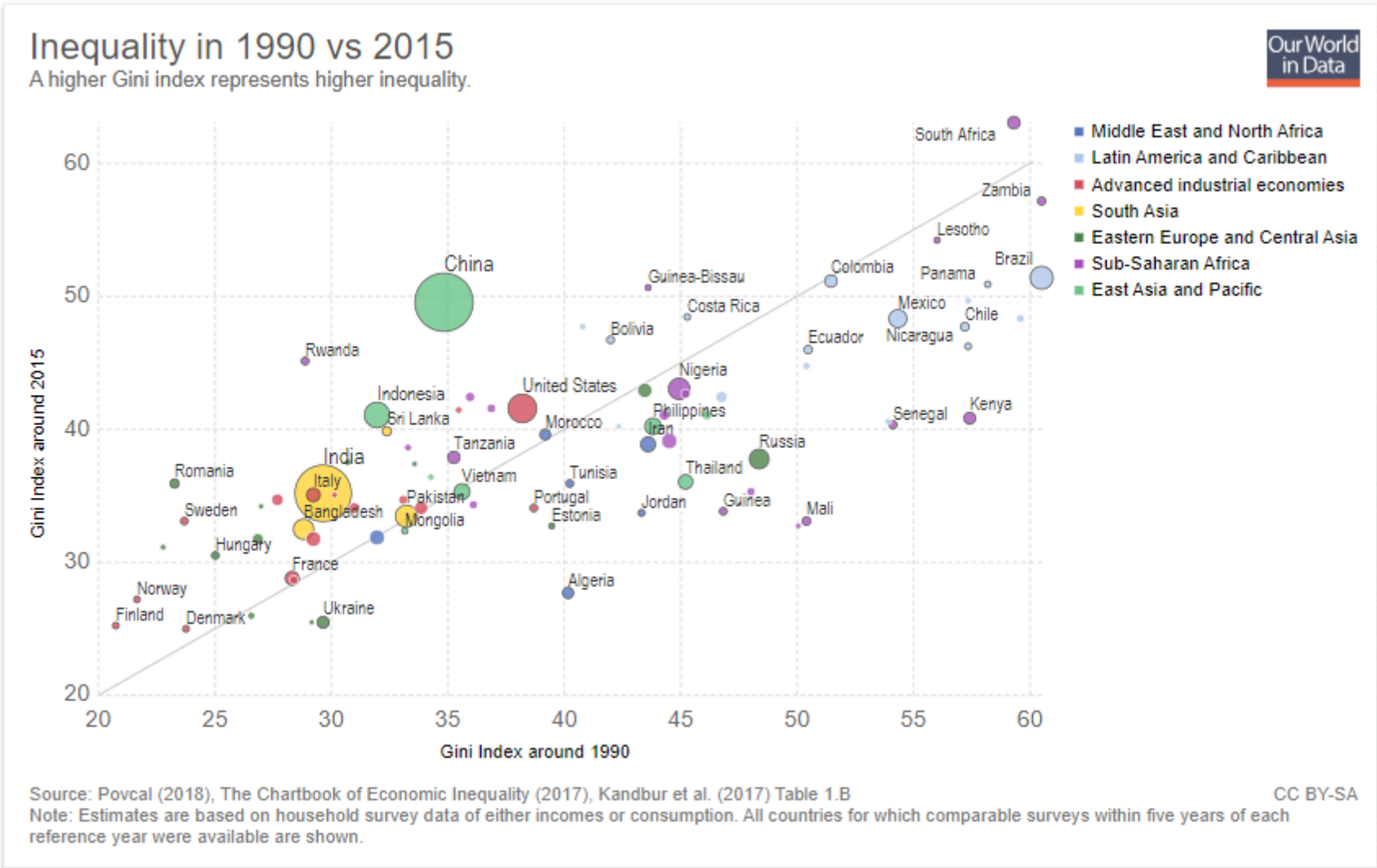
Observing Galaxies - Morphology: Quantitative Morphology

- **Non-parametric** — do not assume symmetry or a particular analytic function for the galaxy's light distribution:
  - ***Concentration (C)*** — r_{90}/r_{50} or r_{80}/r_{20} using circular or elliptical apertures (e.g. SDSS)
  - ***Asymmetry (A)*** — rotate about center, self-subtract (e.g. Abraham et al. 1996)
  - ***Clumpiness (S)*** — subtract smoothed version of image from original image, ratio of flux in subtracted image to flux in original image (e.g. Conselice 2003)



Lotz et al. 2004

Observing Galaxies - Morphology: Quantitative Morphology



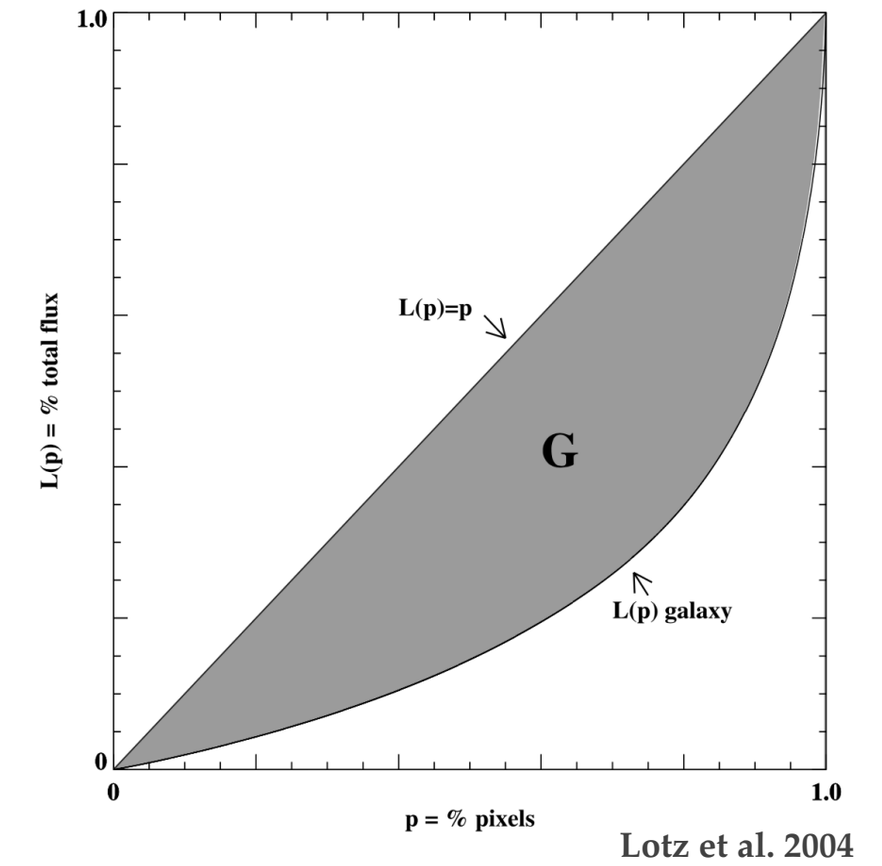


FIG. 1.—Lorenz curve: the Gini coefficient is the area between the Lorenz curve of the galaxy's pixels and that of equitable distribution (*shaded region*). The given curve is for S0 NGC 4526, $G = 0.59$.

- Gini coefficient developed by economists to study income inequality

Observing Galaxies - Morphology: Quantitative Morphology

- ***Gini coefficient*** — sort pixel flux values into increasing order, compute difference from equal distribution (Abraham et al. 2003, Lotz et al. 2004)

$$G = \frac{1}{\bar{X} n(n-1)} \sum_{i}^{n} (2i - n - 1) X_i$$

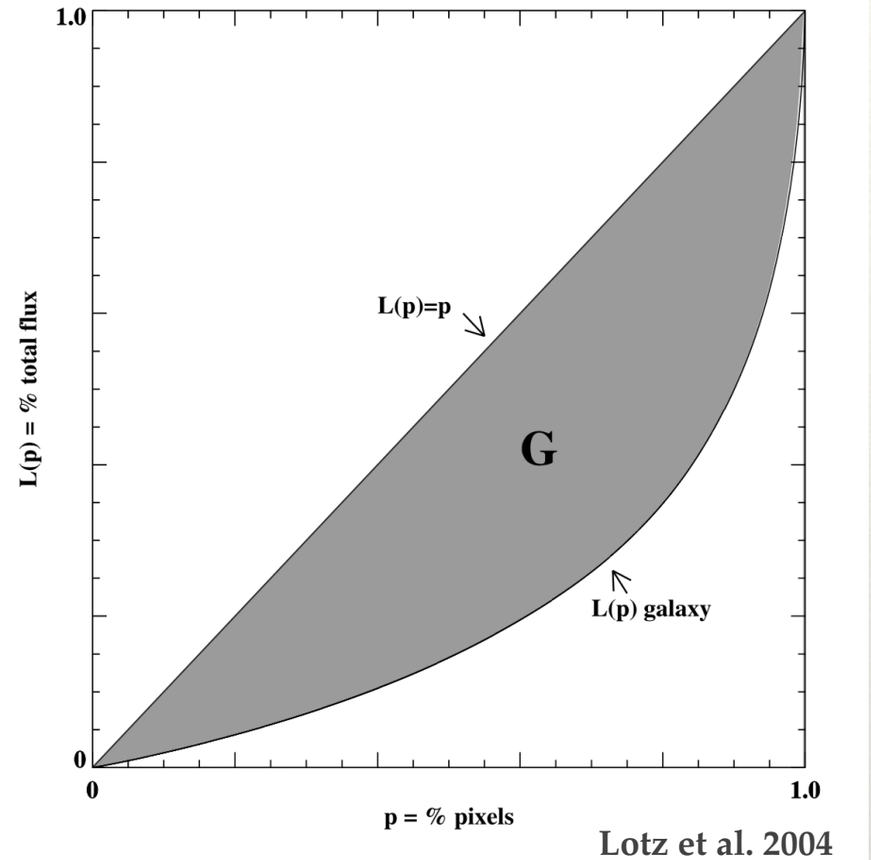
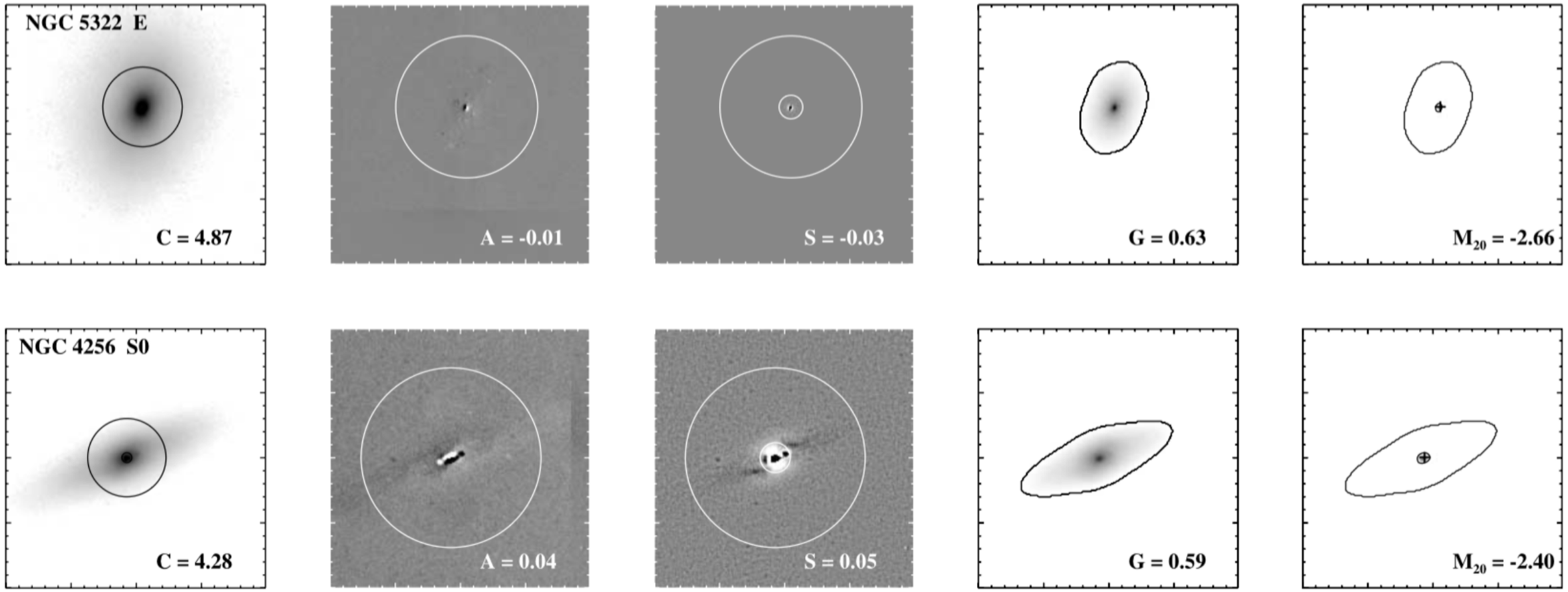


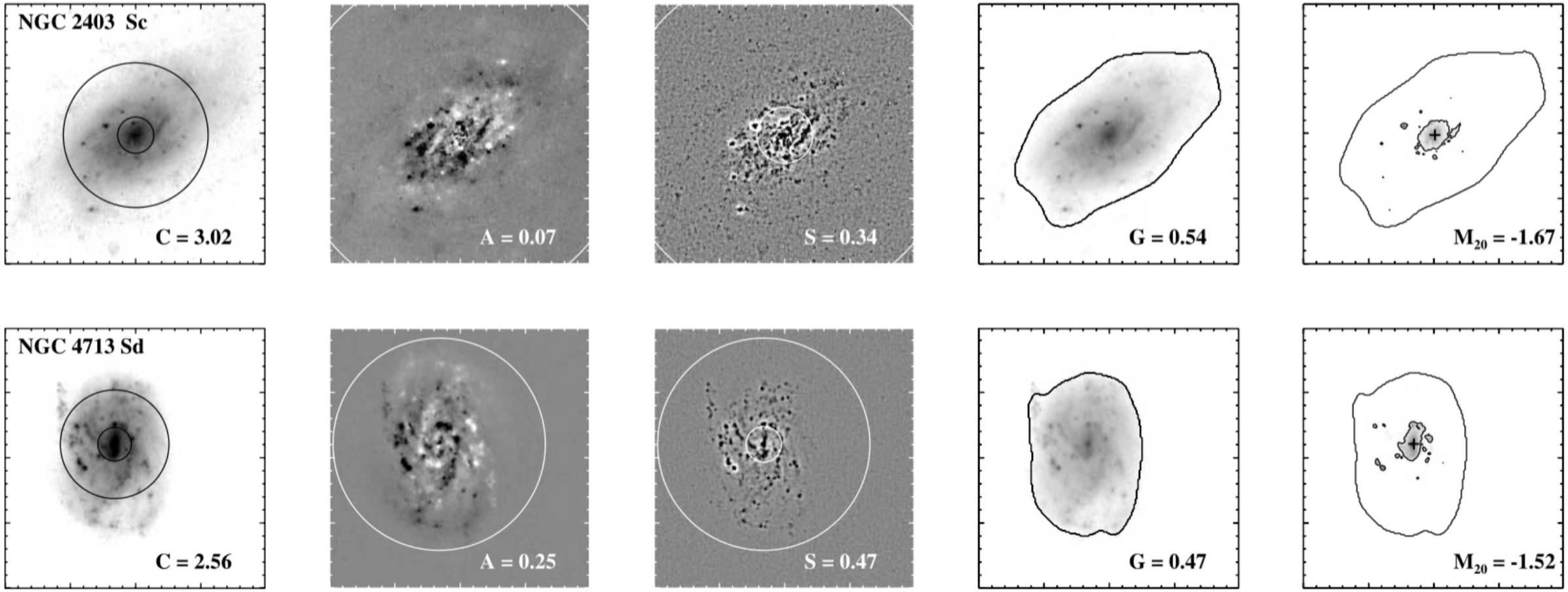
FIG. 1.—Lorenz curve: the Gini coefficient is the area between the Lorenz curve of the galaxy's pixels and that of equitable distribution (*shaded region*). The given curve is for S0 NGC 4526, $G = 0.59$.

- ***M20*** — second order moment of brightest 20% of galaxy light (Lotz et al. 2004)

$$M_{\rm tot} = \sum_{i}^{n} M_i = \sum_{i}^{n} f_i \left[(x_i - x_c)^2 + (y_i - y_c)^2 \right]$$

$$M_{20} \equiv \log10 \left(\frac{\sum_i M_i}{M_{\rm tot}} \right), \text{ while } \sum_i f_i < 0.2 f_{\rm tot}$$


NGC 5322 E
C = 4.87
A = -0.01
S = -0.03
G = 0.63
M20 = -2.66
NGC 4256 S0
C = 4.28
A = 0.04
S = 0.05
G = 0.59
M20 = -2.40
NGC 3368 Sab
C = 3.98
A = 0.06
S = 0.06
G = 0.54
M20 = -2.28
NGC 3953 Sbc
C = 3.54
A = 0.08
S = 0.20
G = 0.51
M20 = -2.19


NGC 2403 Sc
C = 3.02
A = 0.07
S = 0.34
G = 0.54
M20 = -1.67
NGC 4713 Sd
C = 2.56
A = 0.25
S = 0.47
G = 0.47
M20 = -1.52
Arp 220
C = 3.04
A = 0.30
S = ?
G = 0.55
M20 = -1.78
Super Antenae
C = 2.06
A = 0.37
S = 1.04
G = 0.56
M20 = -1.13

Observing Galaxies - Morphology: Quantitative Morphology

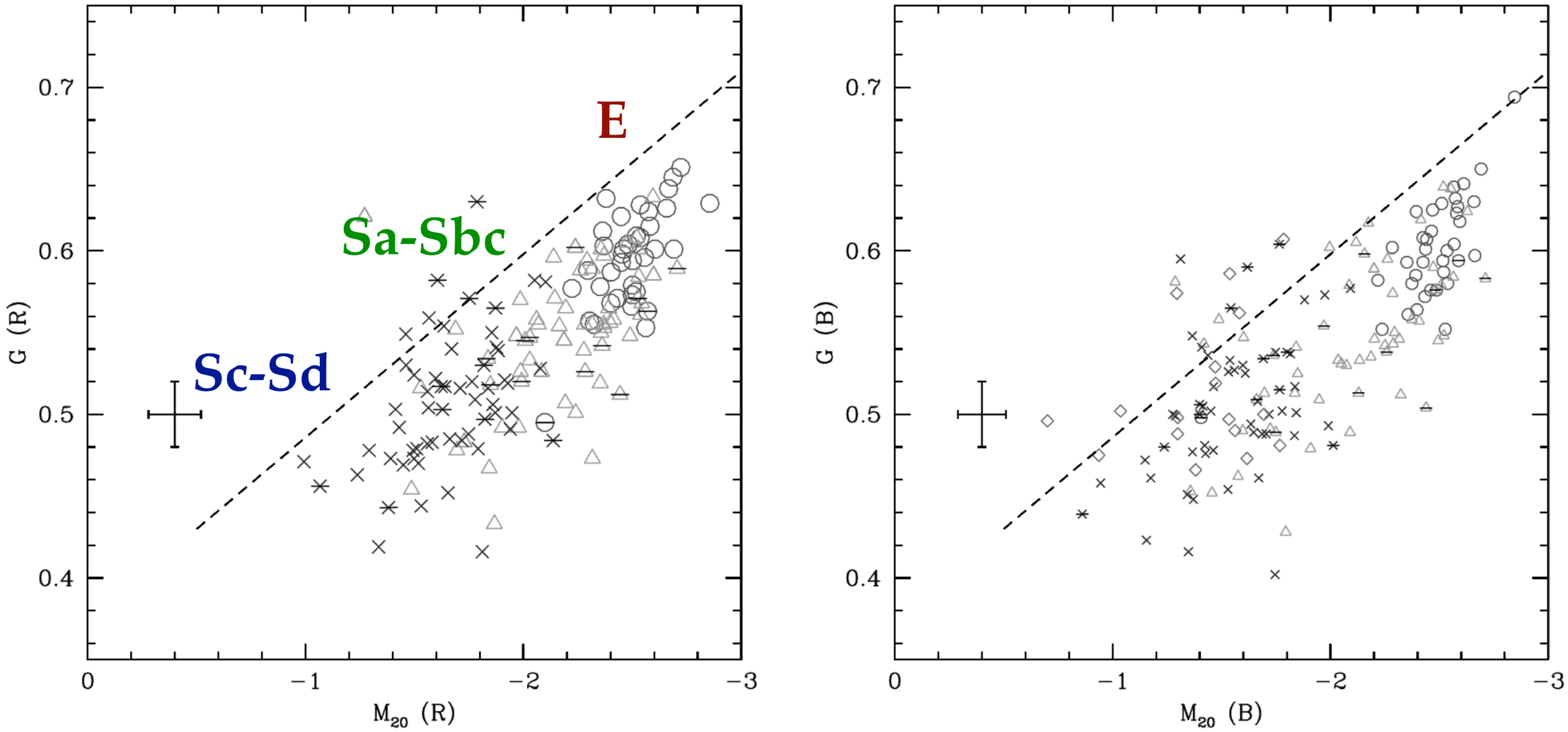


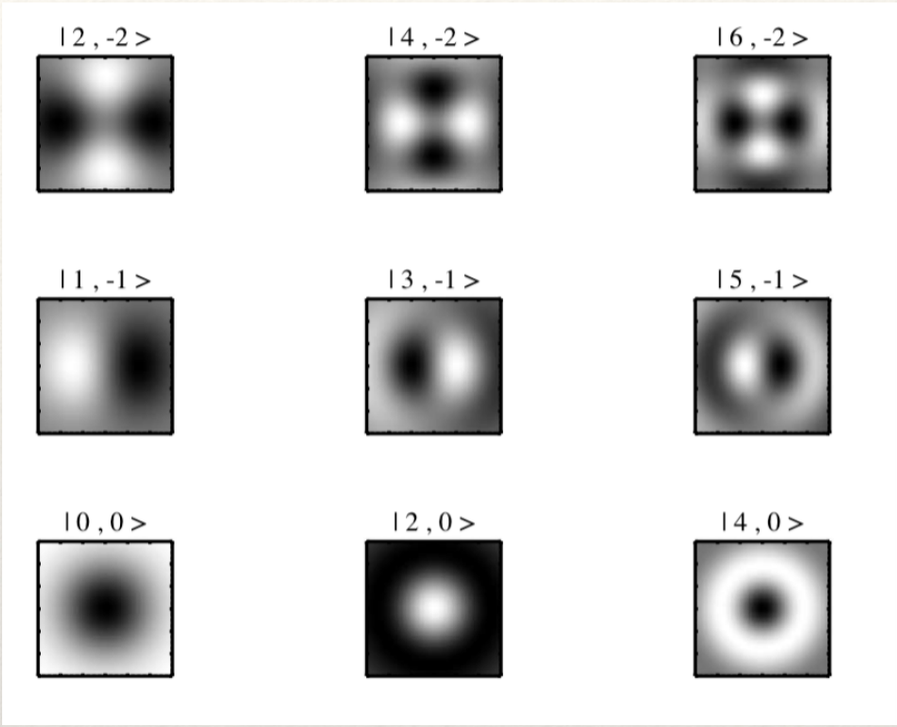
FIG. 9.—M_{20} vs. G for rest-frame ~6500 Å (*left*) and 4400 Å (*right*) observations of local galaxies (*circles*: E/S0; *triangles*: Sa–Sbc; *crosses*: Sc–Sd; *diamonds*: dI; *bars*: edge-on spirals). The error bars are mean difference in G and M_{20} between SDSS r-band and Frei R/r observations of the same objects. Almost all the "normal" galaxies lie below the dashed line in the R-band plot. The outlying Sb galaxy NGC 5850 has a strong star-forming ring and is in a close pair with NGC 5846. Three of the outlying dI's in the B-band plot are starbursting.

Lotz et al. 2004

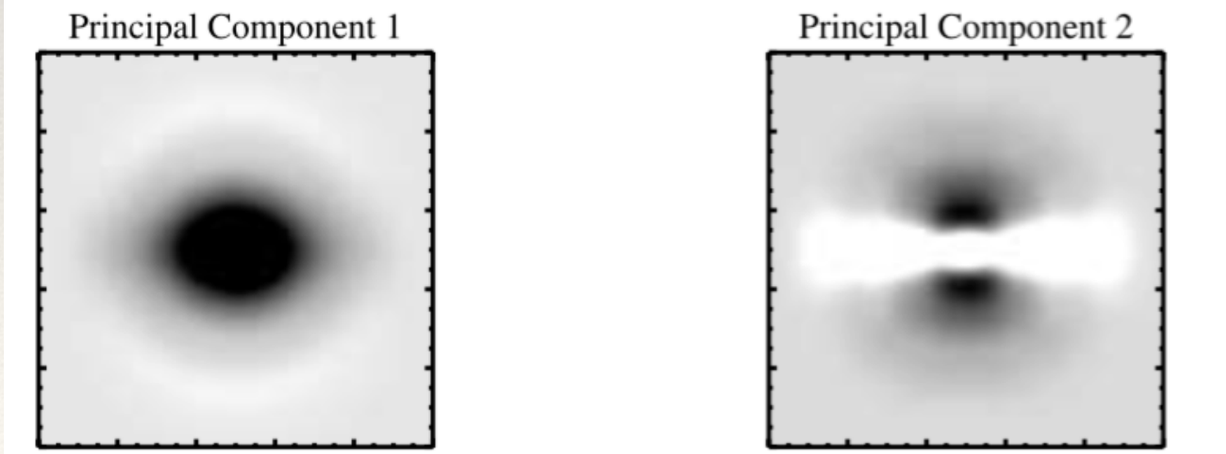
Observing Galaxies - Morphology: Quantitative Morphology

- ***Artificial neural networks*** — trained by astronomer on a set of galaxies with known morphological type (Odewahn et al. 1996, Naim et al. 1997)

- ***Shaplets or Principal Components***— deconstruct galaxy image into a linear combination of polynomials (Refregier 2003, Kelly & McKay 2004) or basis images (Uzeirbegovic et al. 2020)



Real part of sample polar shaplets, |n,m>



Kelly & McKay 2004

Thought Questions

- What are some advantages of classifying galaxies using quantitative morphological schemes?
- What are some disadvantages?
- What are some alternatives?

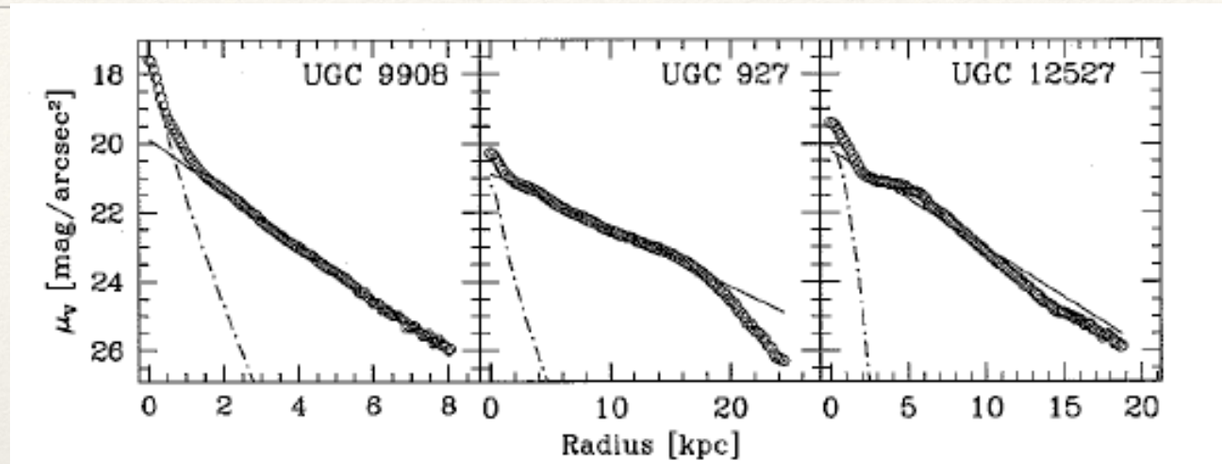


Fig. 2.19. The surface brightness profiles of three disk galaxies plus their decomposition in an exponential disk (solid line) and a Sérsic bulge (dot-dashed line). [Based on data published in MacArthur et al. (2003) and kindly made available by L. MacArthur]

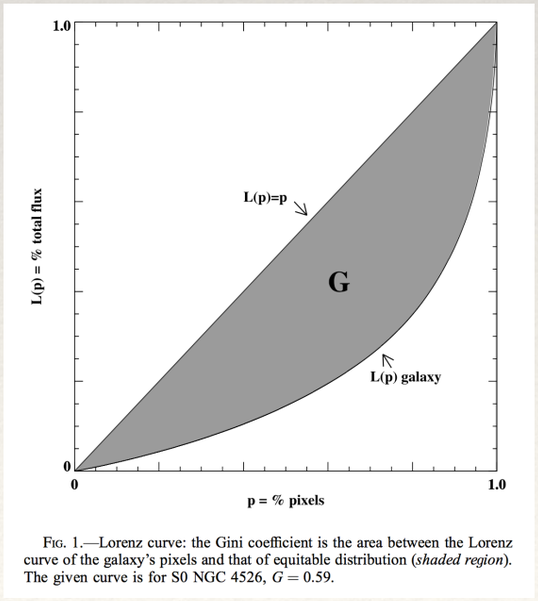
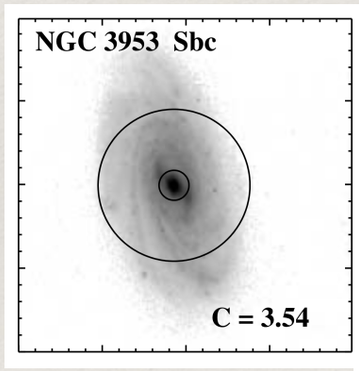
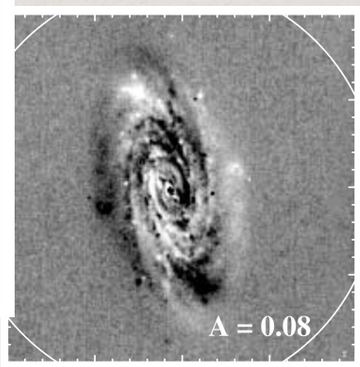
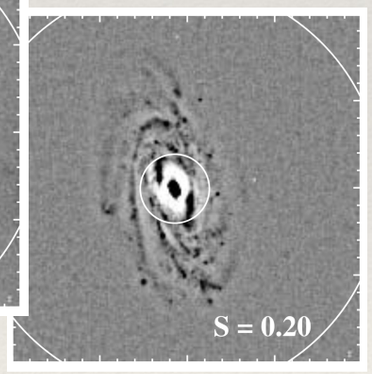
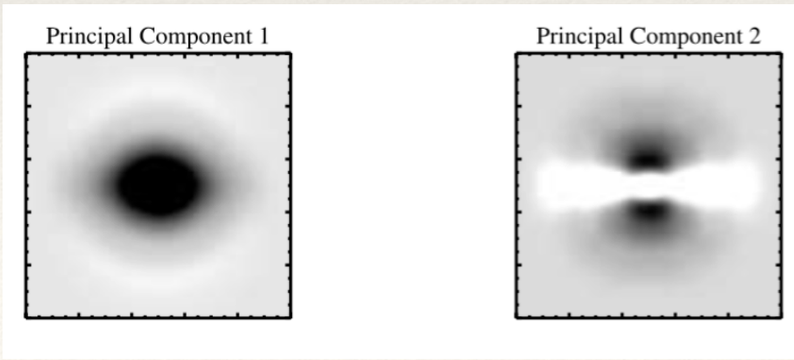


FIG. 1.—Lorenz curve: the Gini coefficient is the area between the Lorenz curve of the galaxy's pixels and that of equitable distribution (*shaded region*). The given curve is for S0 NGC 4526, $G = 0.59$.



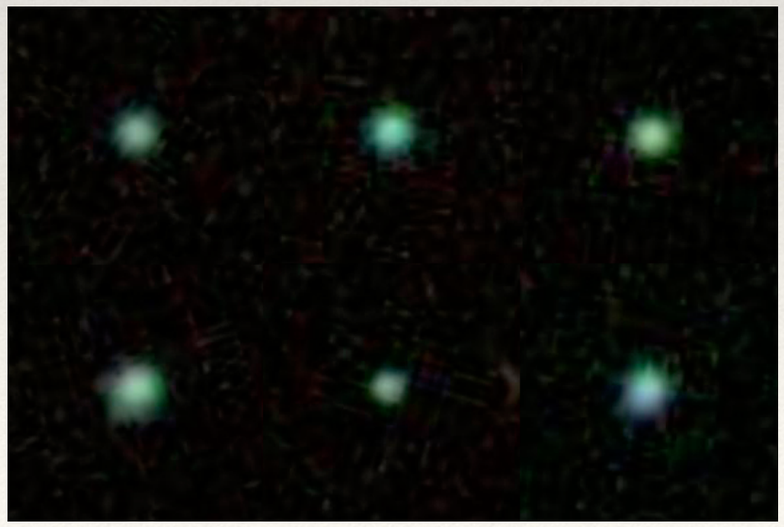






Galaxy Zoo

- Recently, come back full circle with **Galaxy Zoo**:
  - Members of the public learn simple visual classification and classify galaxy images.
  - In first year: 150,000 people made 50 million classifications!
  - Cross-comparisons self-calibrate and reduce "noise".
  - https://www.zooniverse.org/projects/zookeeper/galaxy-zoo/classify



EAGLE galaxies have landed! Read the blog to find out more about them and what to do if some of them appear clumpy.

We've recently had a significant increase in traffic. Welcome to all new classifiers! You can read more information about how to navigate the site and make the most of your time here on the Announcements Board. Thanks for your patience!

You should sign in!

FIELD GUIDE

TASK TUTORIAL

Is the galaxy simply smooth and rounded, with no sign of a disk?

Smooth

Features or Disk

Star or Artifact

NEED SOME HELP WITH THIS TASK?

Done & Talk Done

Homework

- Spectra, velocities, distance methods
- Paper summary 2 - read/synthesize paper - **due September 15, 2020**
  - Danieli et al. 2020 — *"A Tip of the Red Giant Branch Distance to the Dark Matter Deficient Galaxy NGC 1052-DF4 from Deep Hubble Space Telescope Data"*
- Problems 2, coming

Dr. Shany Danieli, Institute for Advanced Study