Galaxies II
A Fork, a Trident, and a Comb

The Hubble sequence of galaxies

Davor Krajnović

A Fork, a Trident, and a Comb?

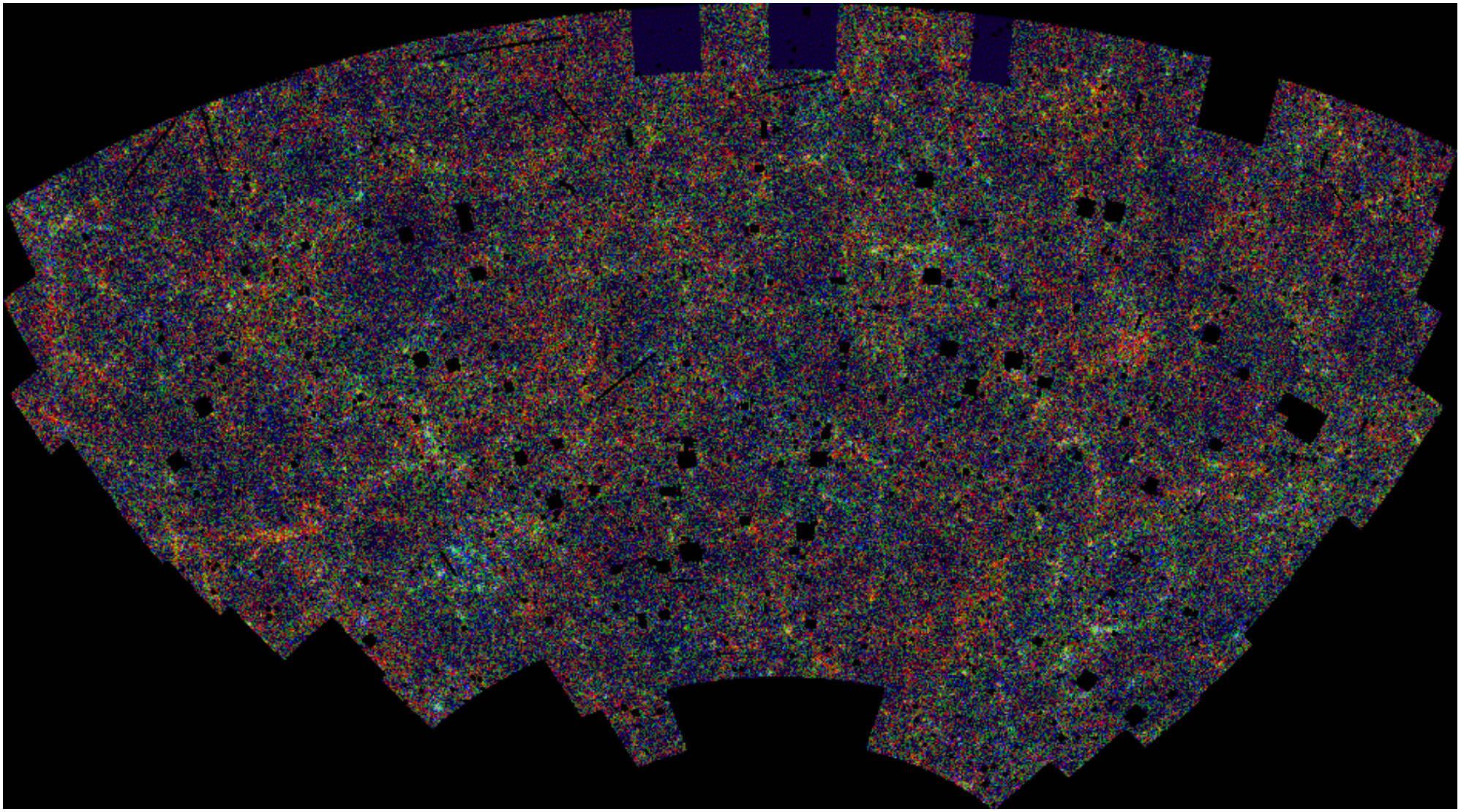
Where are these galaxies ??

The Andromeda galaxy
(Chris Cook)

The Andromeda
constellation
(Janet Slivoski
www.slivoski.com)

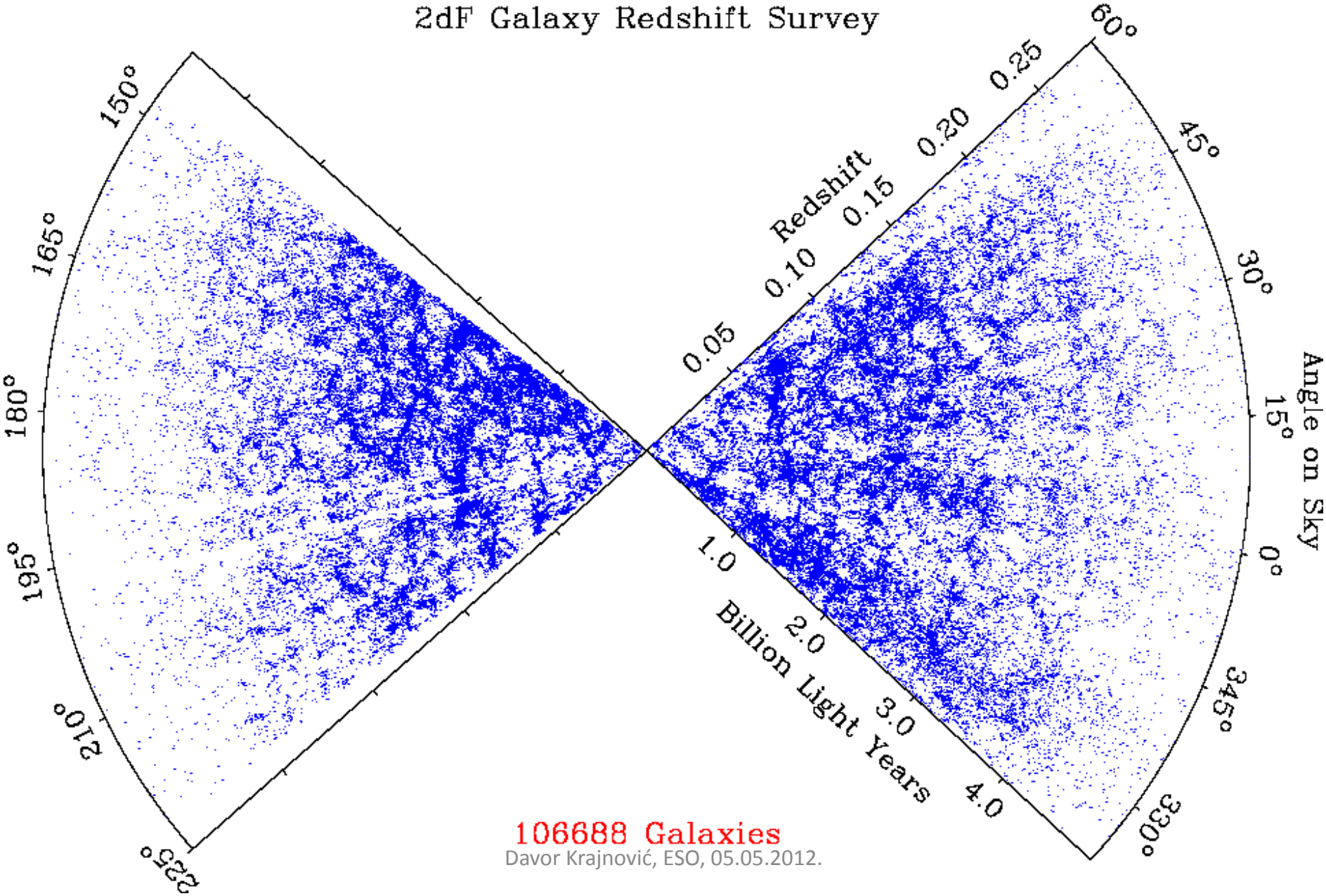
The Andromeda Galaxy
(Sven Kohle &
Till Credner)

Galaxies in the Universe



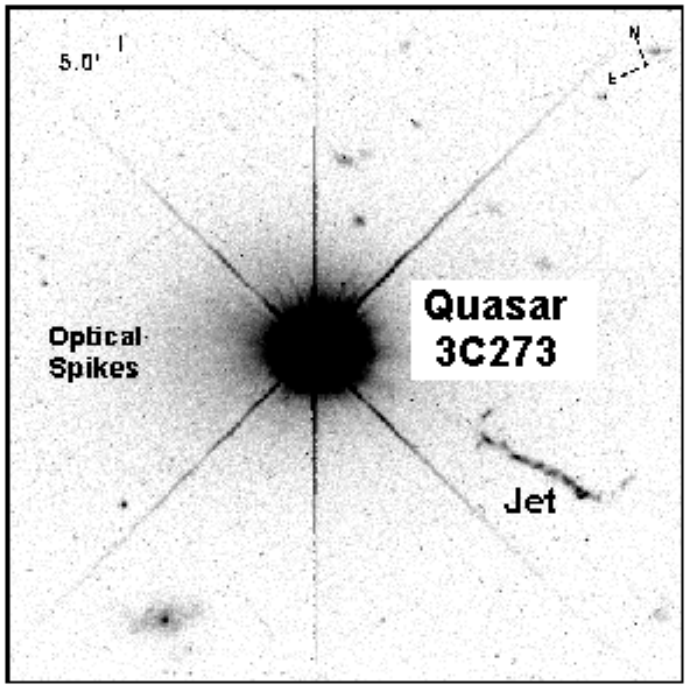
Distribution of observed galaxies in a portion of the sky (Southern Hemisphere; APM galaxy survey).

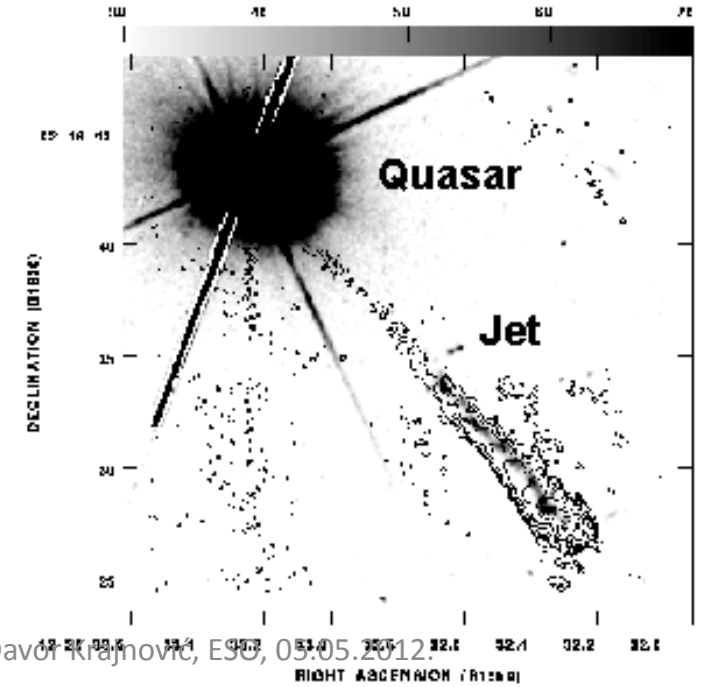
Galaxies in the Universe



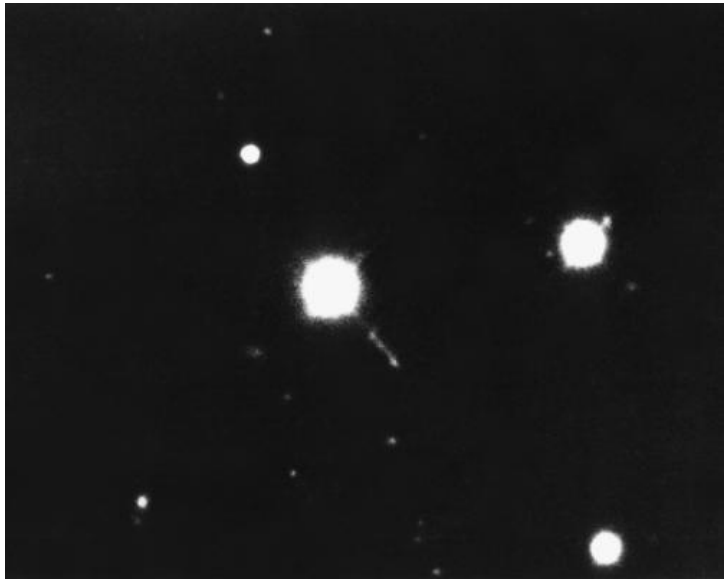
Strange Stars?

- 1960s: certain objects emitting radio waves, but thought to be stars, had very unusual optical spectra
- Central light bulbs: massive black holes





3C 273
A Star-Like Object, far far away



Kitt Peak National Observatory

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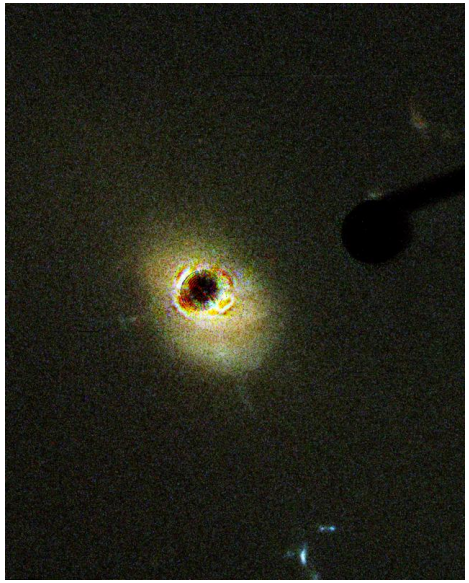
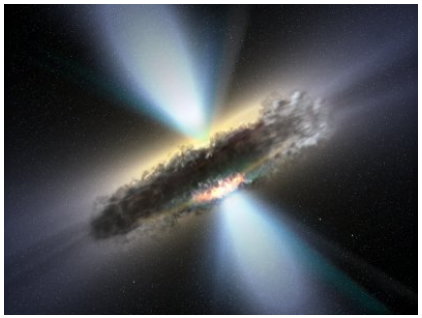
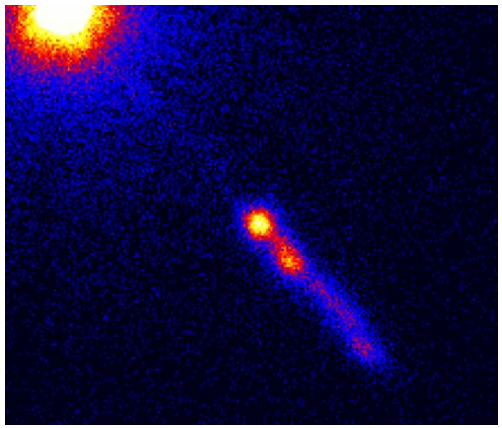


HST

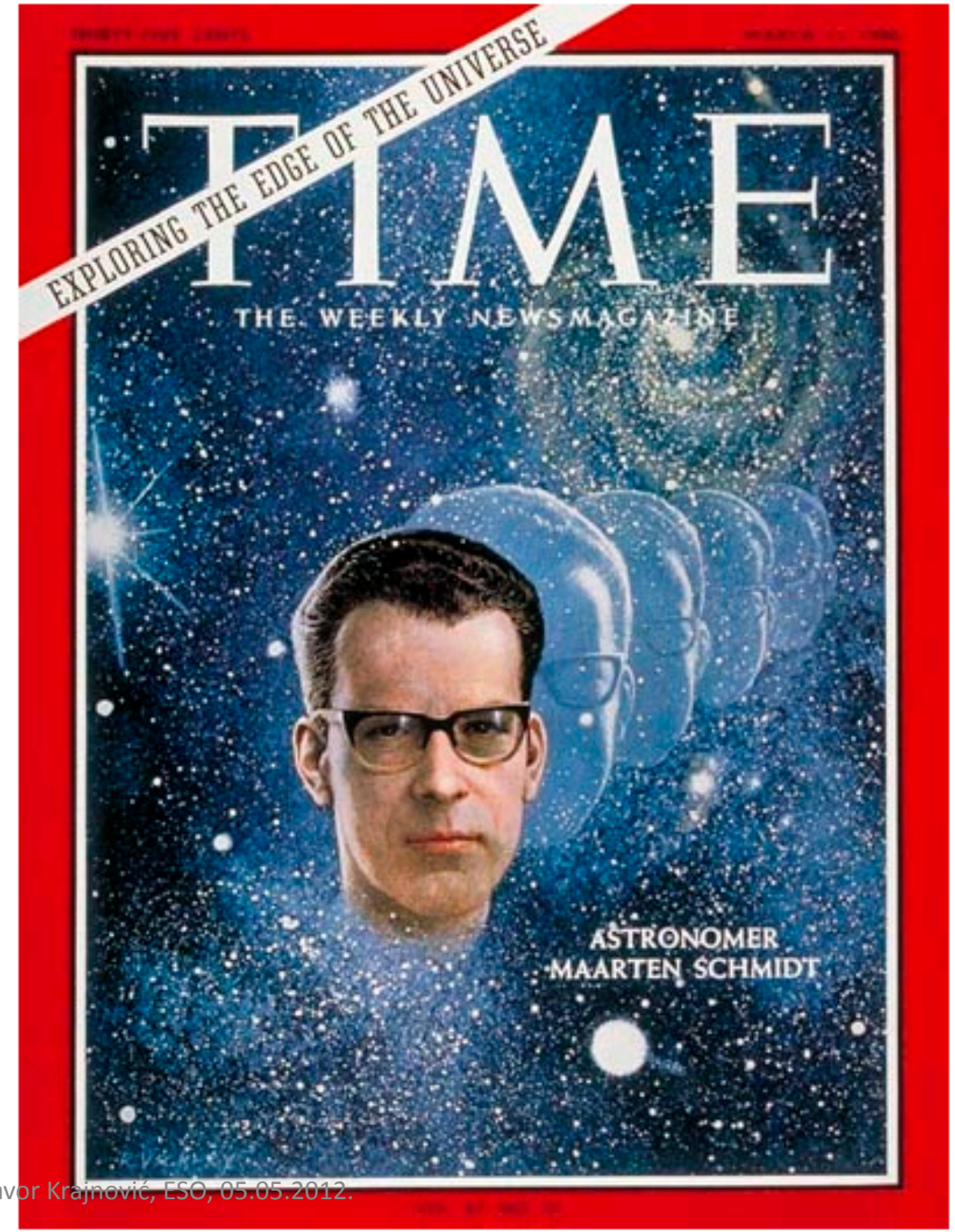
+



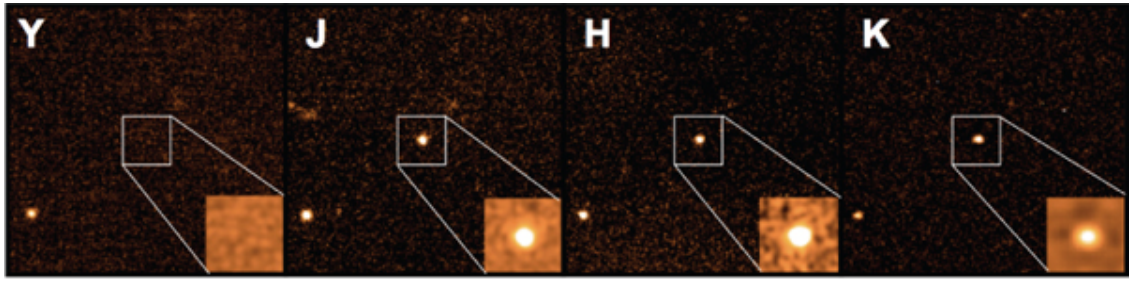
Astro-stars!



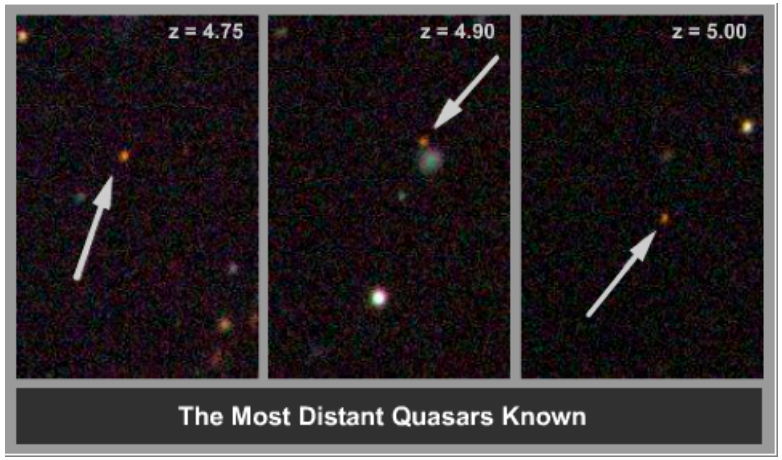
3C 273 (Schmidt 1963)
D=700 Mpc (2 Gly)
t=11.5 Gyr after Big Bang
(Universe age: 13.66 Gyr)



On the edge of the Universe

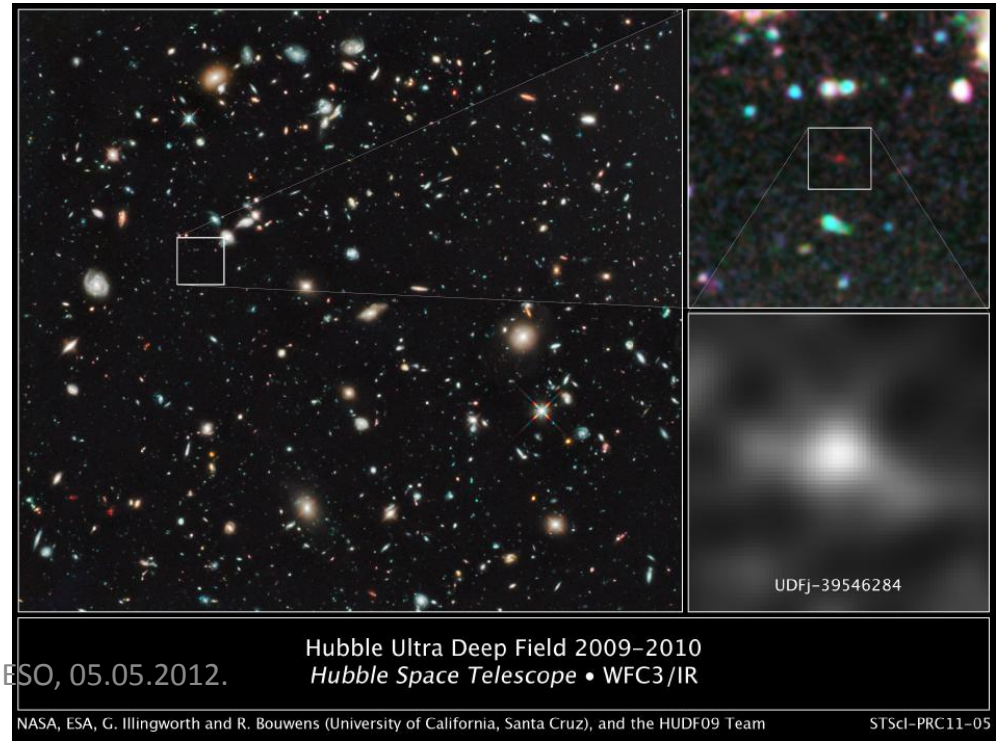


Tanvir et al. (2009)

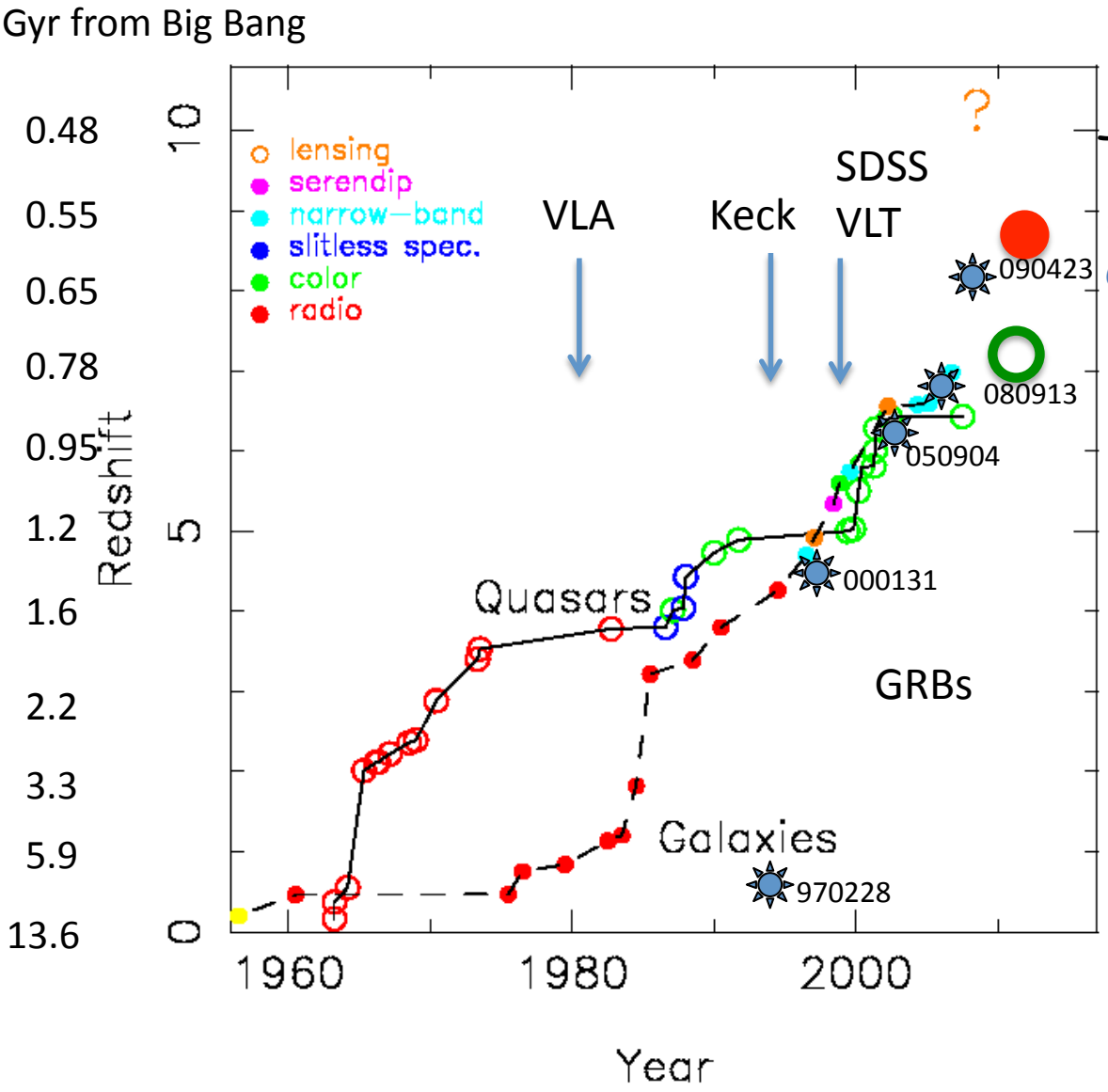


- 6000 galaxies at 900 – 2000 Myr after Big Bang
- Quasars (around 1000 Myr after BB)
- Gama Ray bursts 630 Myr after BB
- New (not confirmed!) Record holder (27.01.2011): a galaxy at 500 Myr after BB

Bouwens et al. (2011)



Quest to the Highest Redshift



The record holders:

Galaxies: 8.7 (Lehnert et al. 2010)

GRBs: 8.2 (Tanvir et al. 2009)

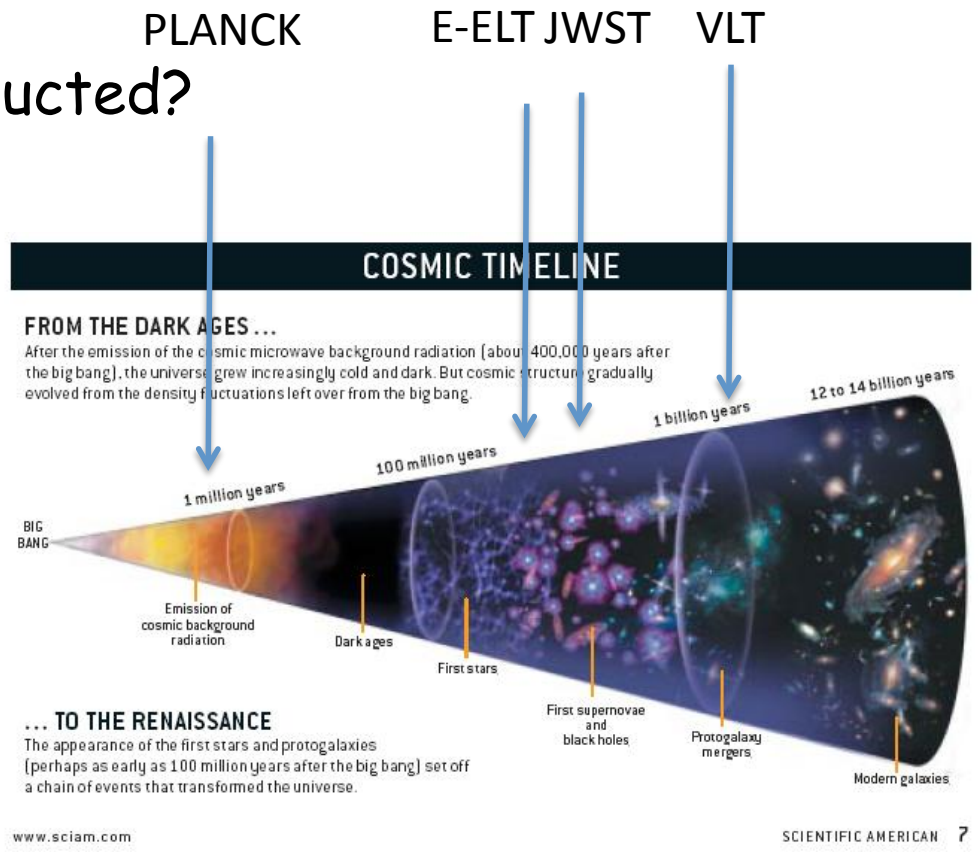
Quasars: 7.1 (Mortlock et al. 2011)

A combination of new ideas, methods and technology

Adapted from presentation of Xiaohui Fan

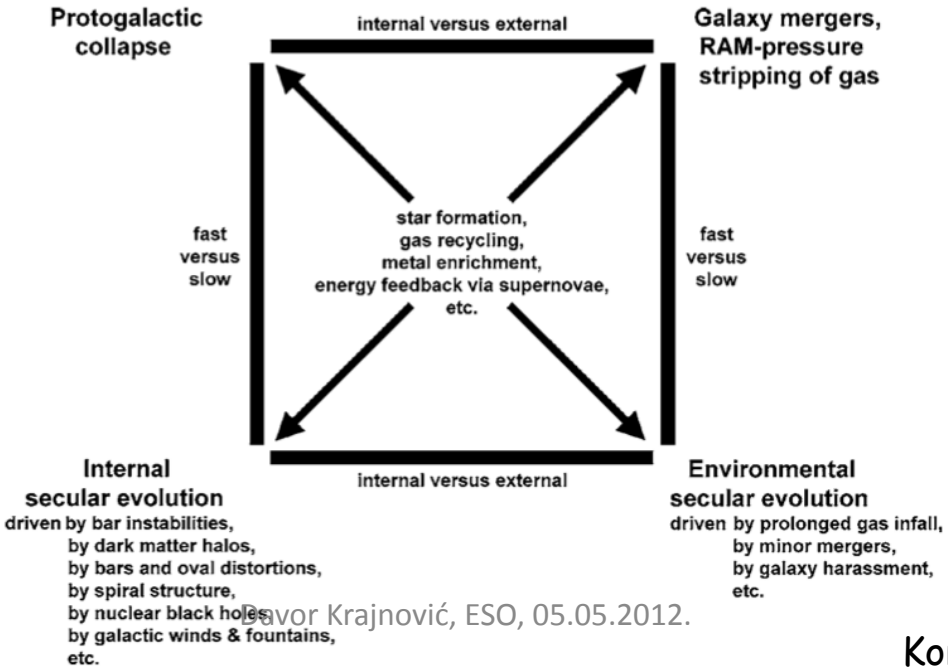
Probing the structure of the Universe

- Galaxies: building blocks of the Universe
- How is the Universe constructed?
  - mass (baryonic, total)
  - shape, size, age
  - expansion
  - end of the Universe
  - constituents
  - structure formation
- Exotic physics (beyond lab
  - black holes
  - dark mater
  - dark energy
- Observational cosmology
- Knowing galaxies ≈ understanding the Universe



Knowing Galaxies ≈ understanding the Universe

- What are the processes of galaxy formation and evolution
- First step: what kind of galaxies are there → Galaxy classification



Kormendy & Kennicutt (2004)

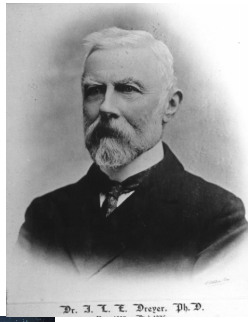
What can we learn by classifying?

- Systematic arrangements of objects to suggests explanation external to classification
- e.g. Biological classification of vertebrates
  - not made with(out) evolution in mind, but supports it
- "A classification of nebulae, it is generally admitted, should be descriptive of appearance, and as independent as possible of interpretative speculations." Shapley (1927)
- An ideal classification system should have the following:
  - Classes which bring order to diversity of galaxy forms, and
  - Span/include majority of galaxies.
  - Unambiguous & easily identified criteria.
  - Relate to important physical properties.
  - Provide insight into internal processes, formation & evolution.

Early attempts

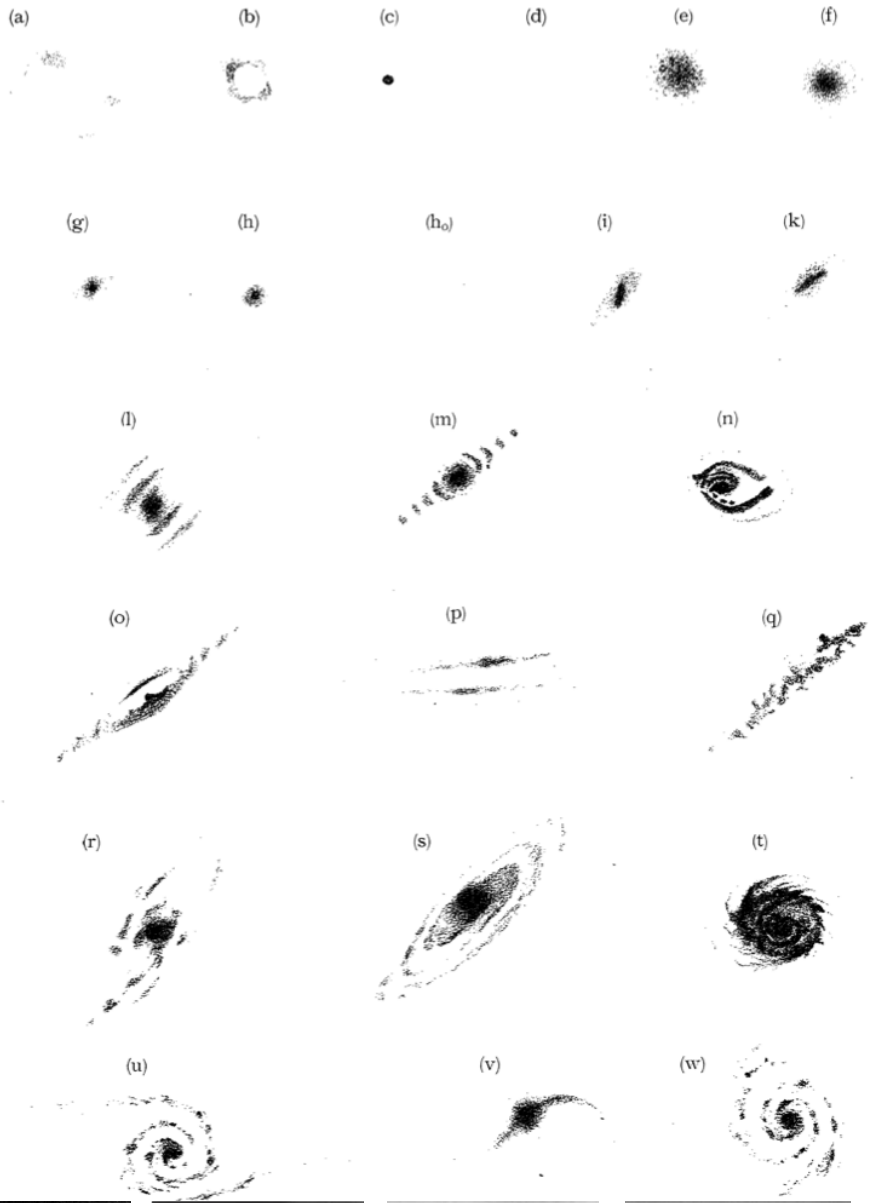
- Observers view: Herschel (William and John), Dreyer (catalogue makers!)
- Very descriptive
- M31: !!!eeB,eL,vmE = "most extremely bright," "extremely large," "very much extended,"
- M33: !eB,eL,R,vgbM,N = "extremely bright," "extremely large," "round," "very gradually brighter in the middle," "nucleus."






Early attempts

- Max Wolf 1908 (Heidelberg): *"Es gibt keine zwei Nebelflecken am Himmel, die sich gleichen. Trotzdem geht das Besterben der Beobachter seit Herschel dahin, die kleinen Nebelflecken zu klassifizieren."*
- Descriptive, but reduced number of classes + spiral pattern, shape, dust
- John Reynolds (1920) ratio of disk to bulge light: I-VII continuous classes (identical to part of latter Hubble's classes)
- Boris Vorontsov-Velyaminov (extended Wolf in 1970s)
- Harlow Shapley (1927) concentration of light towards the centre



Galaxy Portraits

A spiral galaxy
NGC 1232

ESO

Very Large Telescope

Galaxy Portraits

A barred spiral galaxy
NGC 1365

ESO

Very Large Telescope

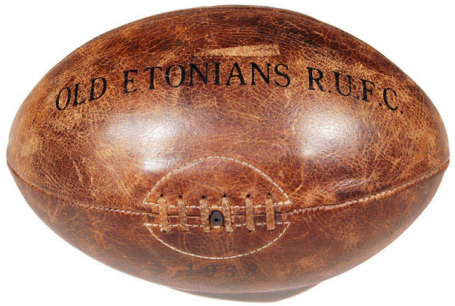
Davor Krajnović, ESO, 05.05.2012.

Barred Galaxy NGC 1365
(VLT UT1 + FORS1)

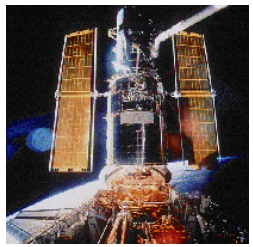
ESO PR Photo 08a/99 (27 February 1999)

Galaxy Portraits

An elliptical galaxy
NGC1132



NASA & ESA

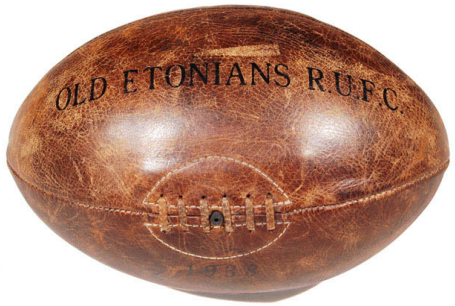


Hubble Space Telescope

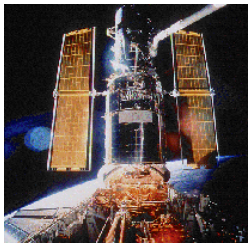
Davor Krajnović, ESO, 05.05.2012.

Galaxy Portraits

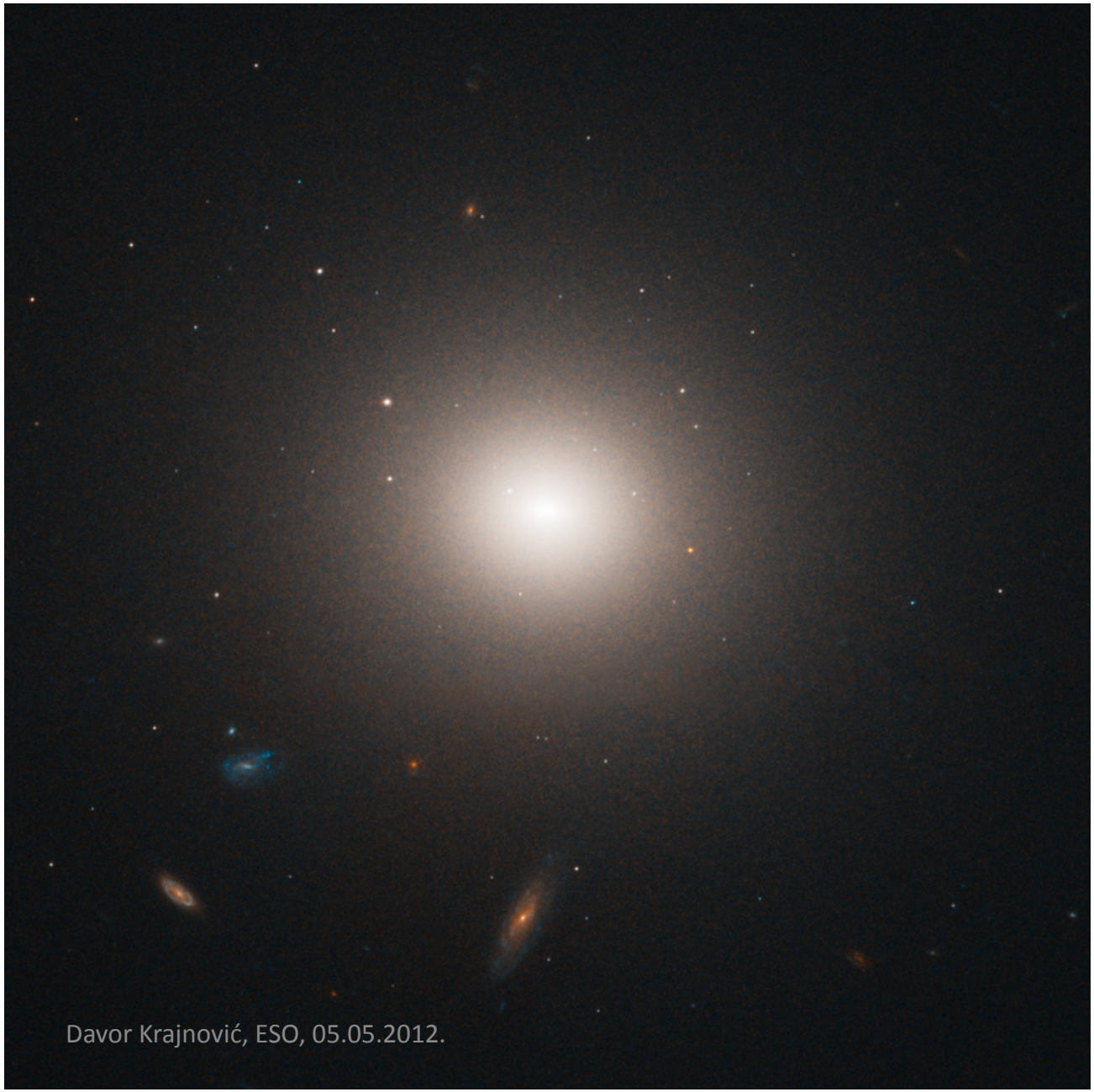
An elliptical galaxy
NGC4458



NASA & ESA

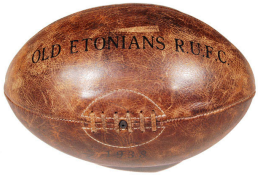


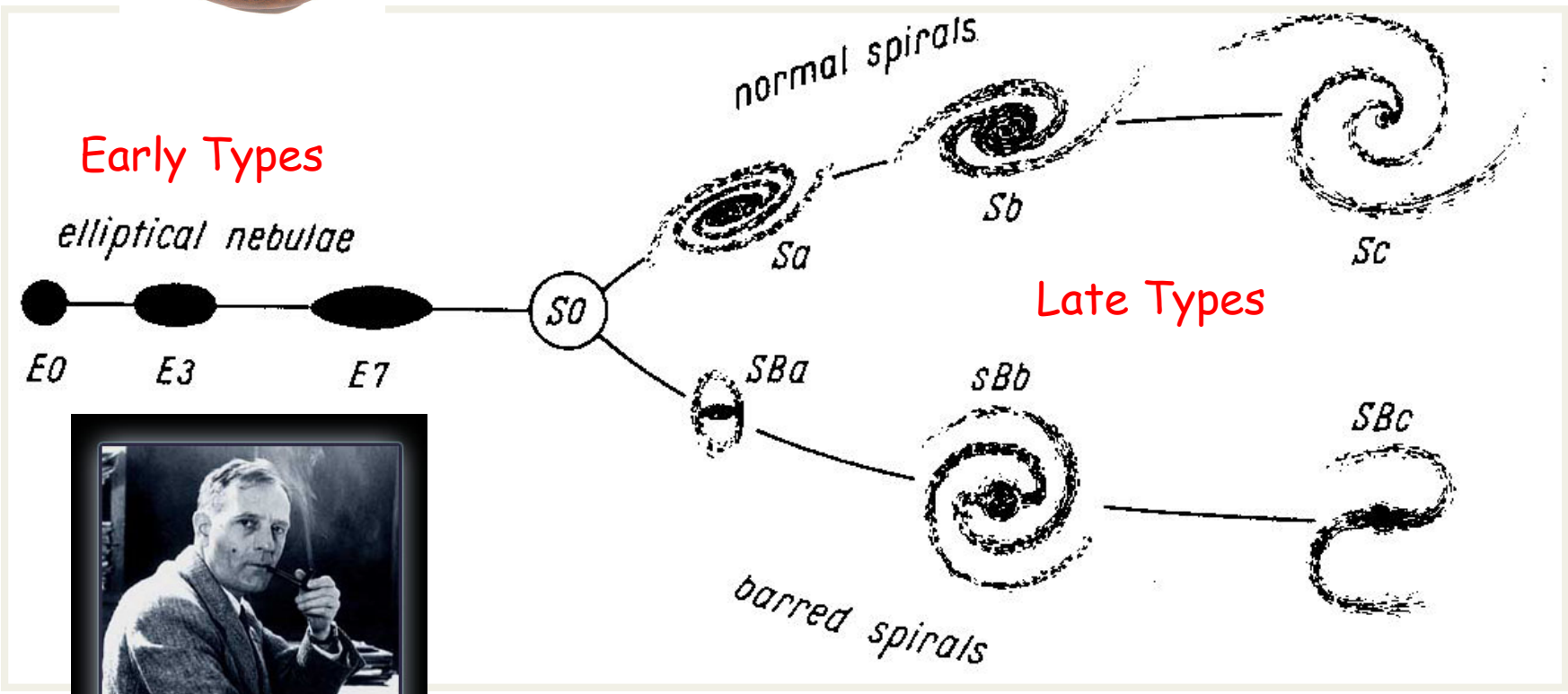
Hubble Space Telescope



Galaxy Classification: 1926/1936

the fork



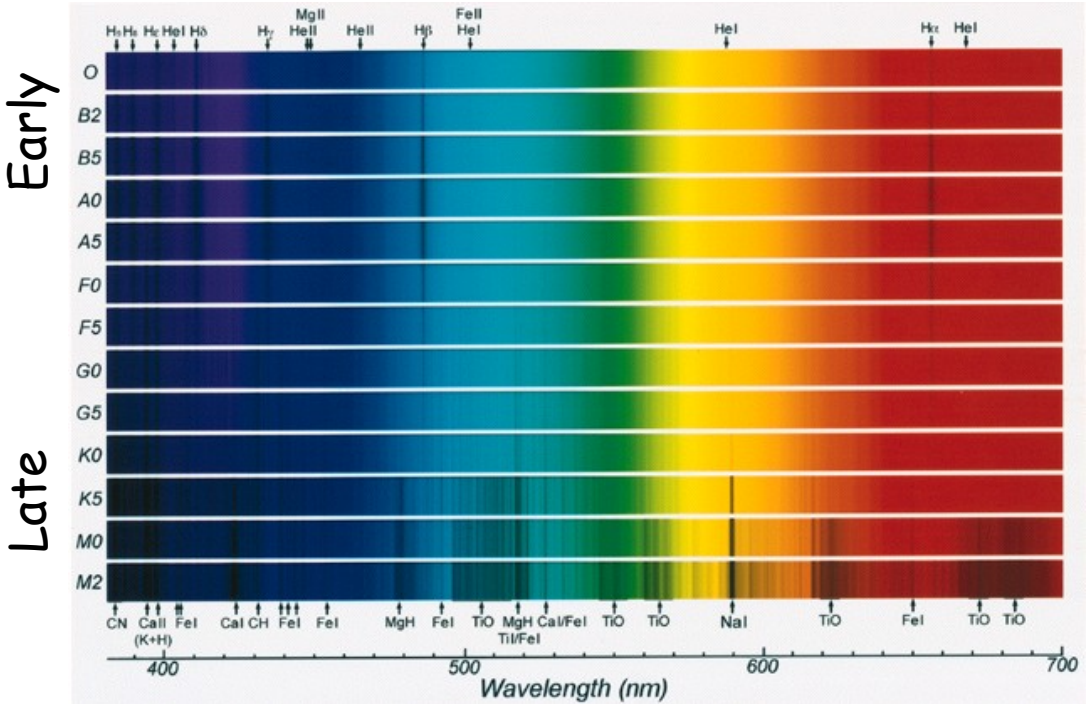


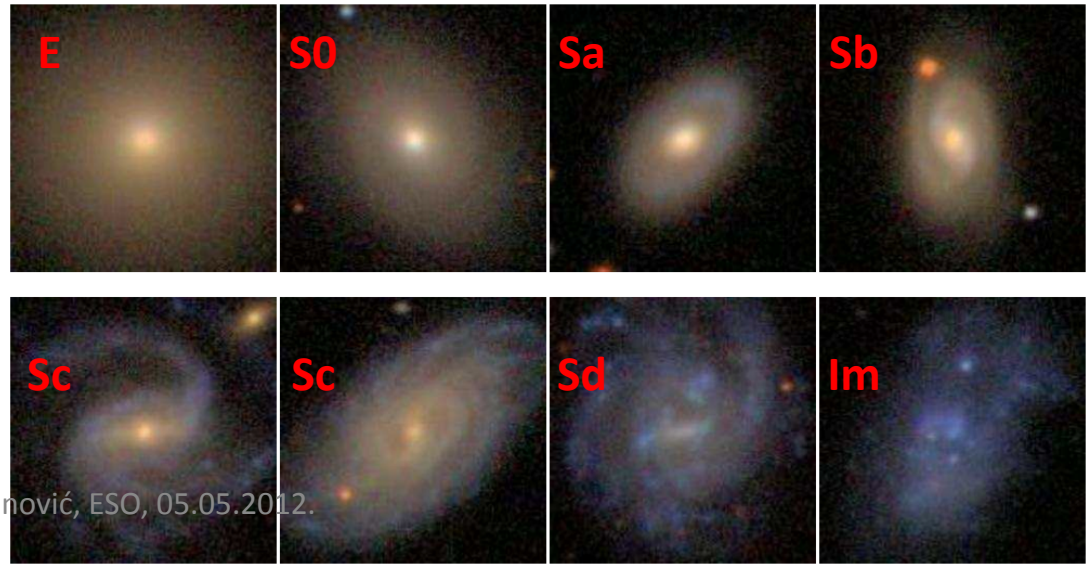
Edwin Hubble (1889-1953)

'Regret cannot accept your invitation. Am of to the war.'

What does it mean?

- Analogy with stars
  - Early→ simple
  - Late → complex
- No implication on time sequence

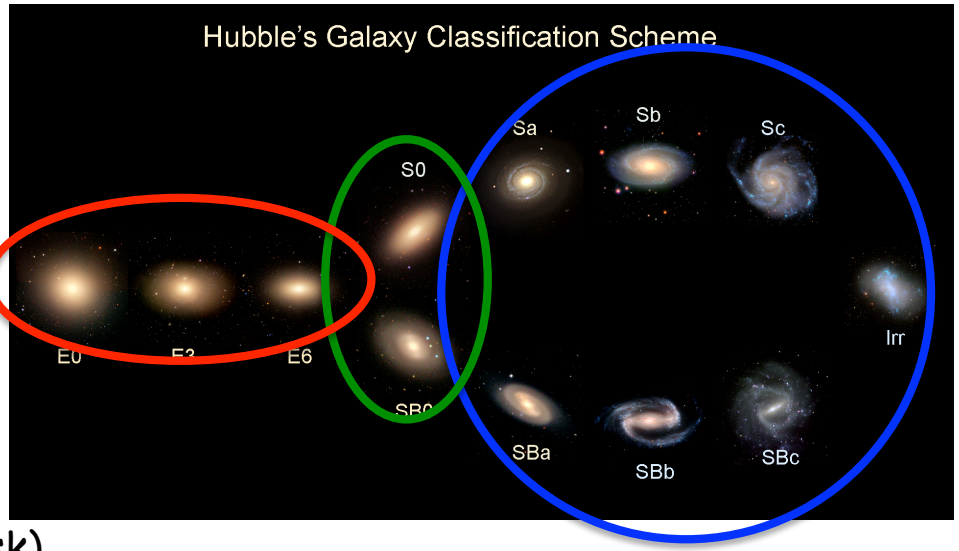




"The nomenclature, it is emphasized refers to position in the sequence, and temporal connotations are made at one's peril. The entire classification is purely empirical and without prejudice to theories of evolution …" (Hubble 1927)

Baldry 2008

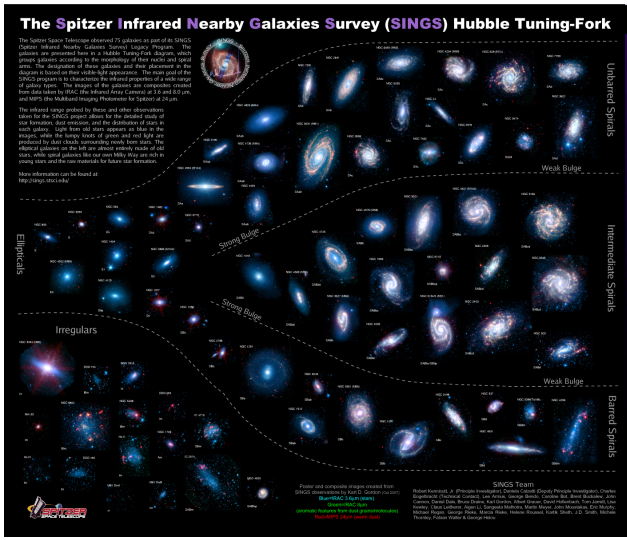
Hubble classification

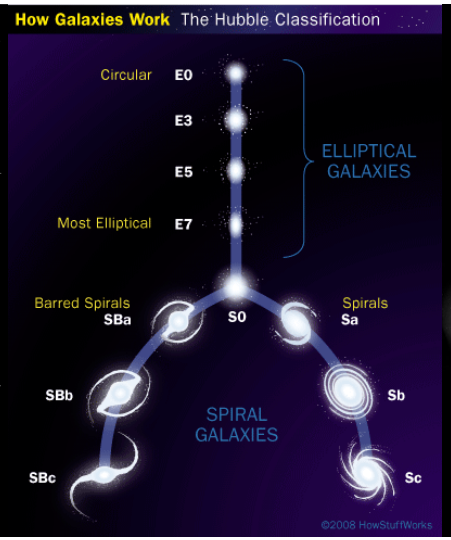


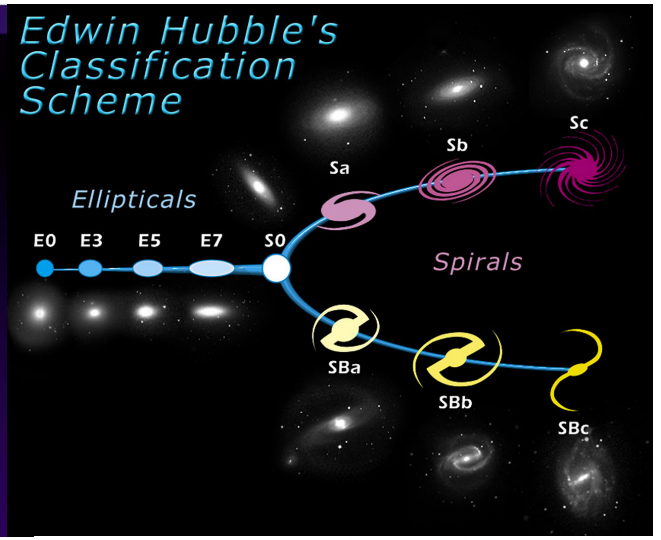
- 90% of massive nearby galaxies included
- Ellipticals
  - Smooth & structurless (a bit of dust)
  - Steep fall-off light
  - Shape: E0-E7 (1-axis ratio)
  - Isophotes: ellipses
- Lenticulars (S0)
  - (almost) structureless
  - Central concentration (bulge) + envelope (disk)
  - Like a lens
  - Sometimes with a bar
- Spirals
  - Bulge + [bar] + [ring] + disk + (spiral) arms
  - Different stages (a,b,c,d): bulge/disk ratio, winding arms, HII regions (star formation)
- Doesn't include:
  - Dwarf galaxies (most common in the Universe)
  - Disturbed galaxies
  - Low- surface brightness galaxies (Dark Matter dominated objects)
  - Galaxies in early Universe (at large distances)

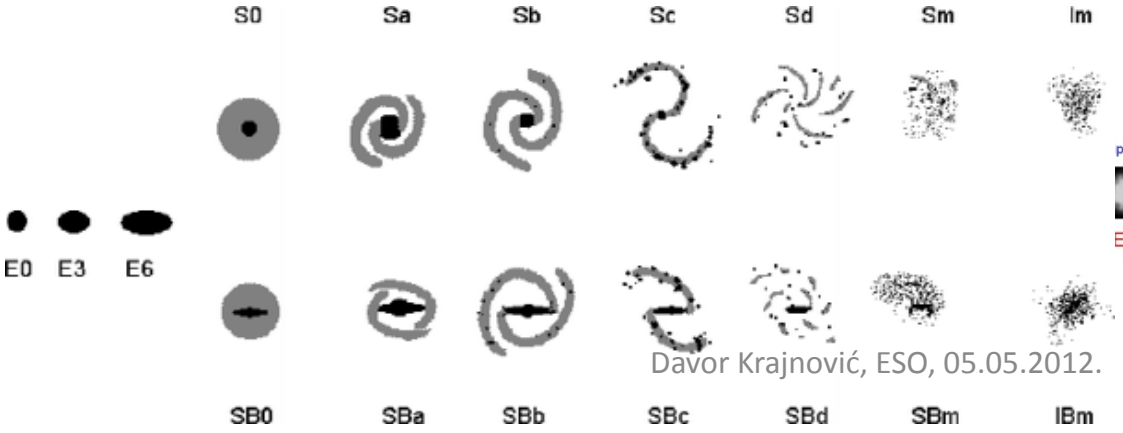
Variations on the theme

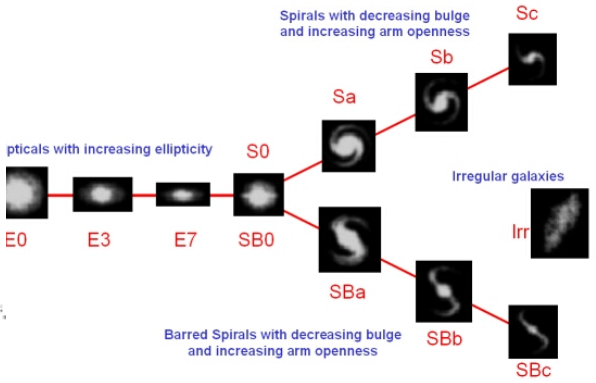
- Very popular: *google it*





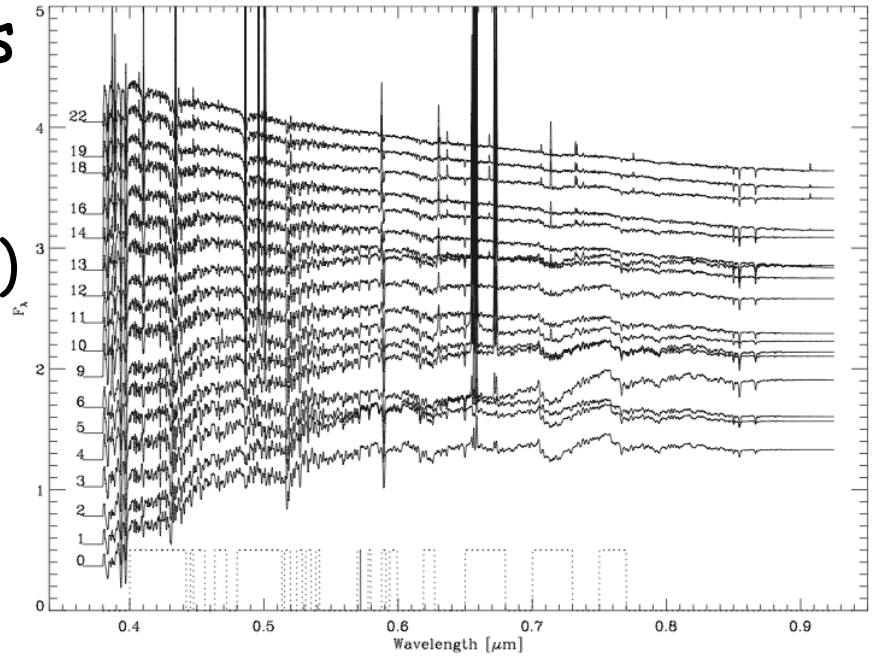


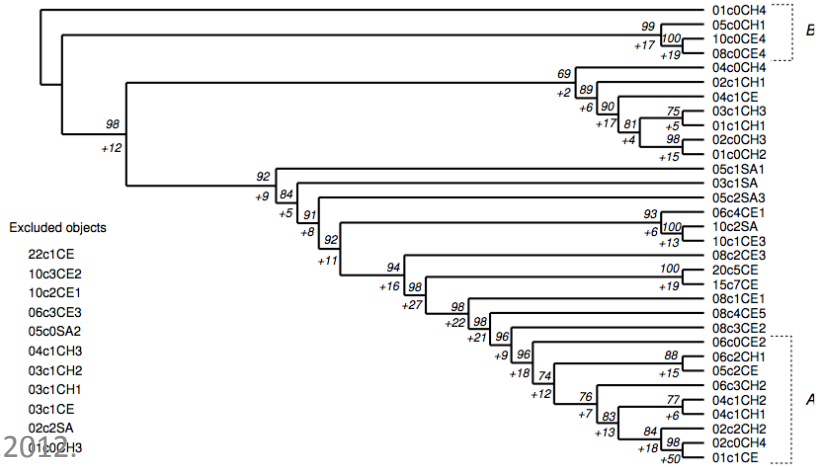




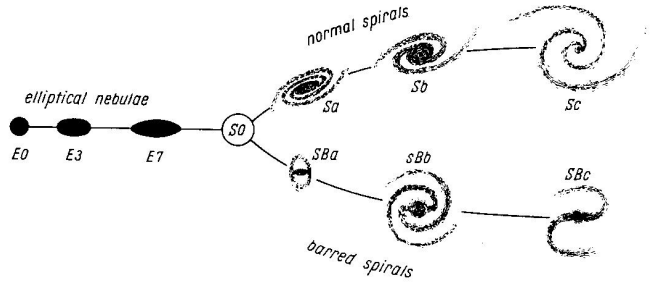
Other attempts:

- Automated classifying schemes – motivated by large datasets
- Light concentration
  - Gini index (Abraham et al. 2003)
- Spectral classification
  - ASK - Automatic Spectroscopic K-means based classification (Sanchez-Almeida et al. 2010)
  - PCA - Principal component analysis (Yip et al. 2004)
- More parameter classifications:
  - "astrocladistics"- biology in astronomy (Fraix-Burnet et al. 2006

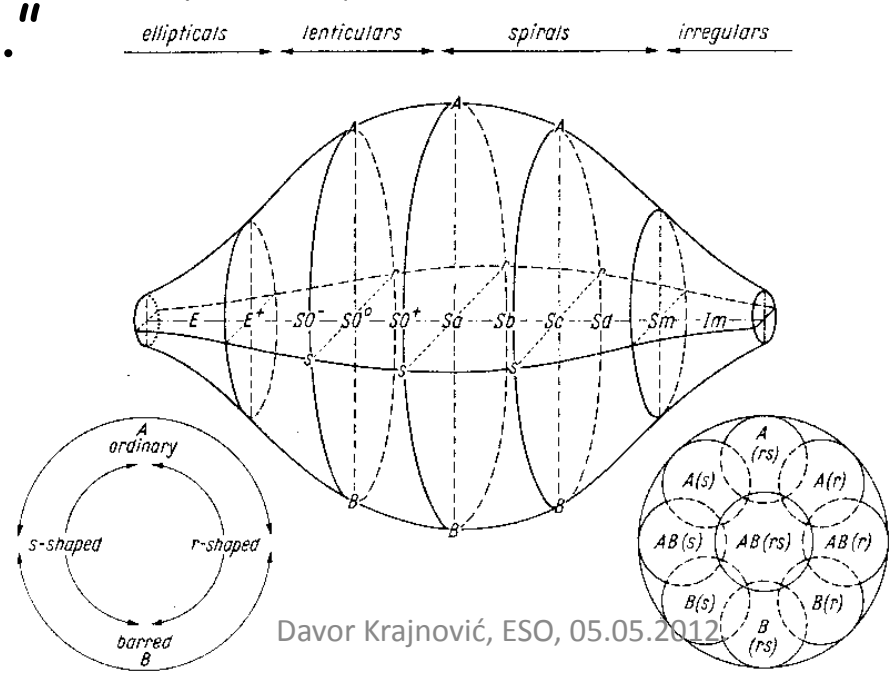


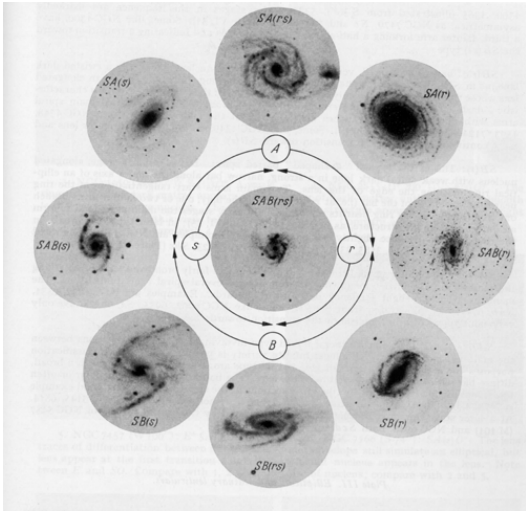


Criticism to:



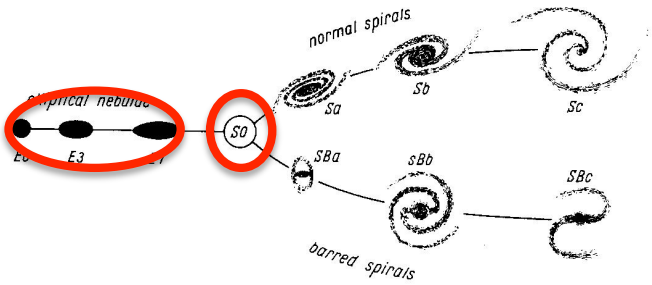
- Too simple (spirals):
  - Reynolds (1920) has 7 classes for Hubble's 3 (4)
  - de Vaucouleurs (1959): 3D diagram
  - Elmegreen & Elmegreen (1982) ask for 12 classes
  - Virtue in simplicity: "Look at images if you want details."





De Vaucouleurs (1959)

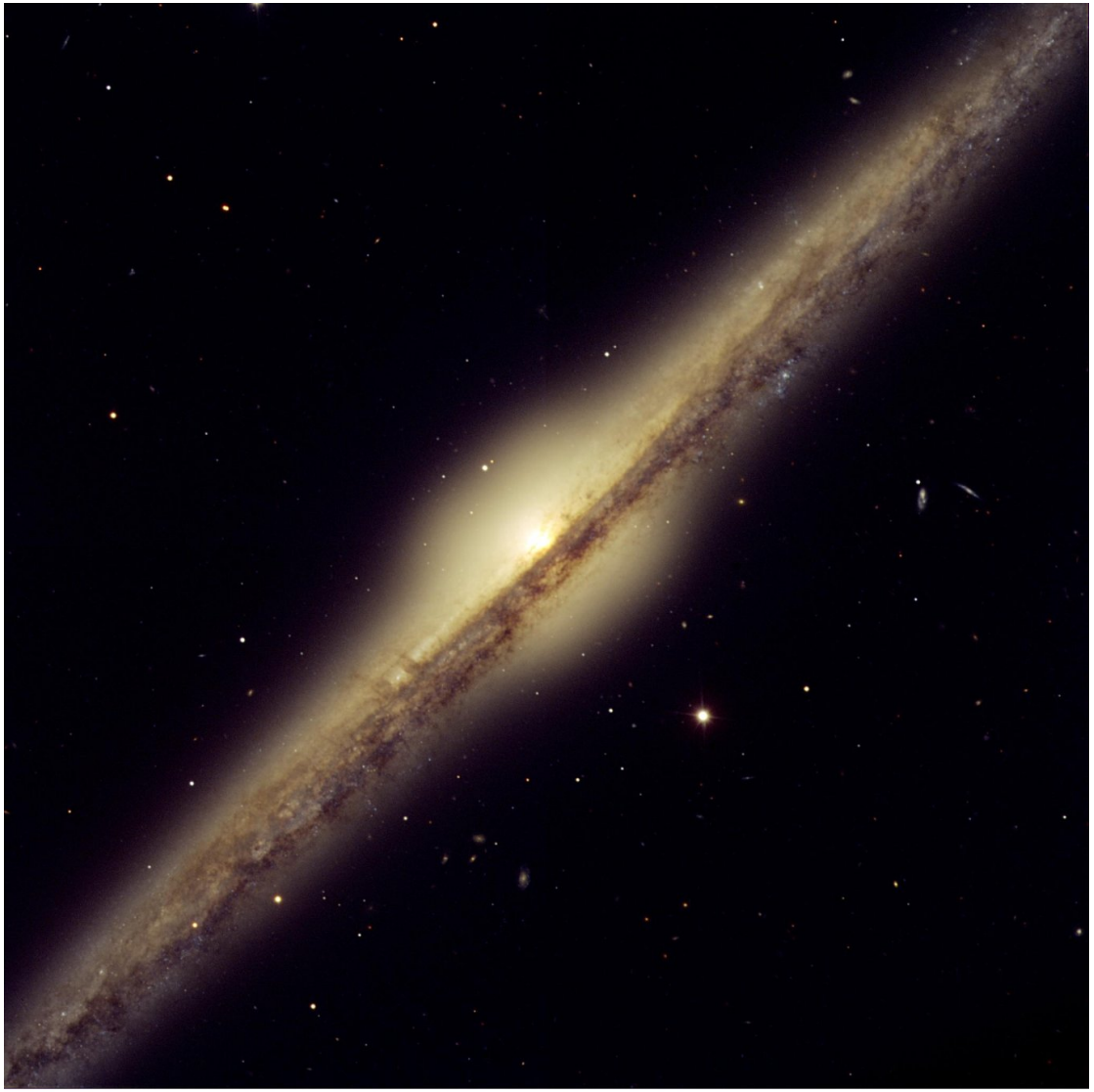
Criticism to



- 1) What are S0 galaxies (lenticulars)?
- 2) Sequence not physical (ellipticals)
  - Spirals: sequence of disk to bulge light (physical parameter)
  - Ellipticals: shape on the sky (depends on chance orientation!)

Galaxy Portraits

An edge on spiral galaxy
NGC4565



Spiral Galaxy NGC 4565
(FORS / VLT)

ESO

Very Large Telescope

ESO PR Photo 24a/05 (August 10, 2005)

Galaxy Portraits

A lenticular galaxy
NGC4594, M104, Sombrero

ESO

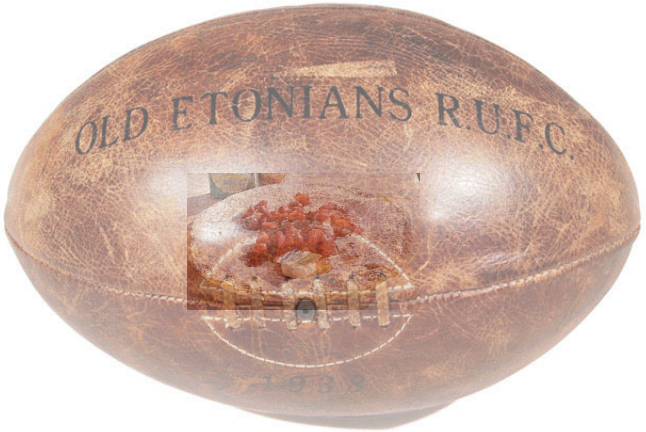
Very Large Telescope

The Sombrero Galaxy (VLT ANTU + FORS1)

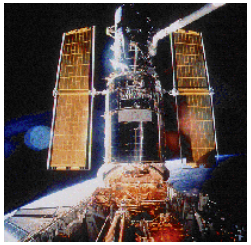
ESO PR Photo 07a/00 (22 February 2000)

Galaxy Portraits

A lenticular galaxy
NGC5866



NASA & ESA

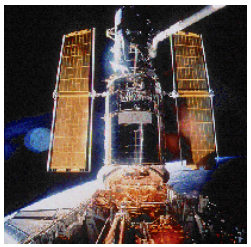


Hubble Space Telescope

Galaxy Portraits

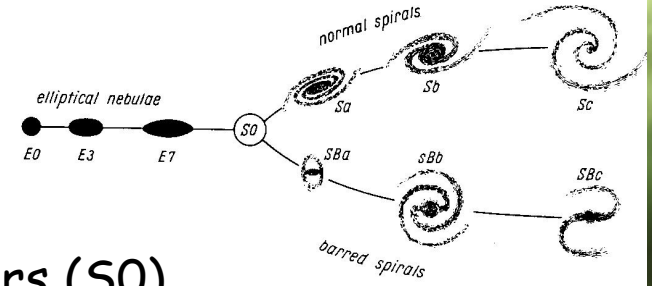
An edge lenticular galaxy
NGC4452

NASA & ESA



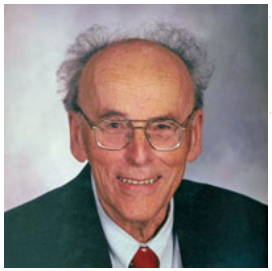
Hubble Space Telescope

An update of

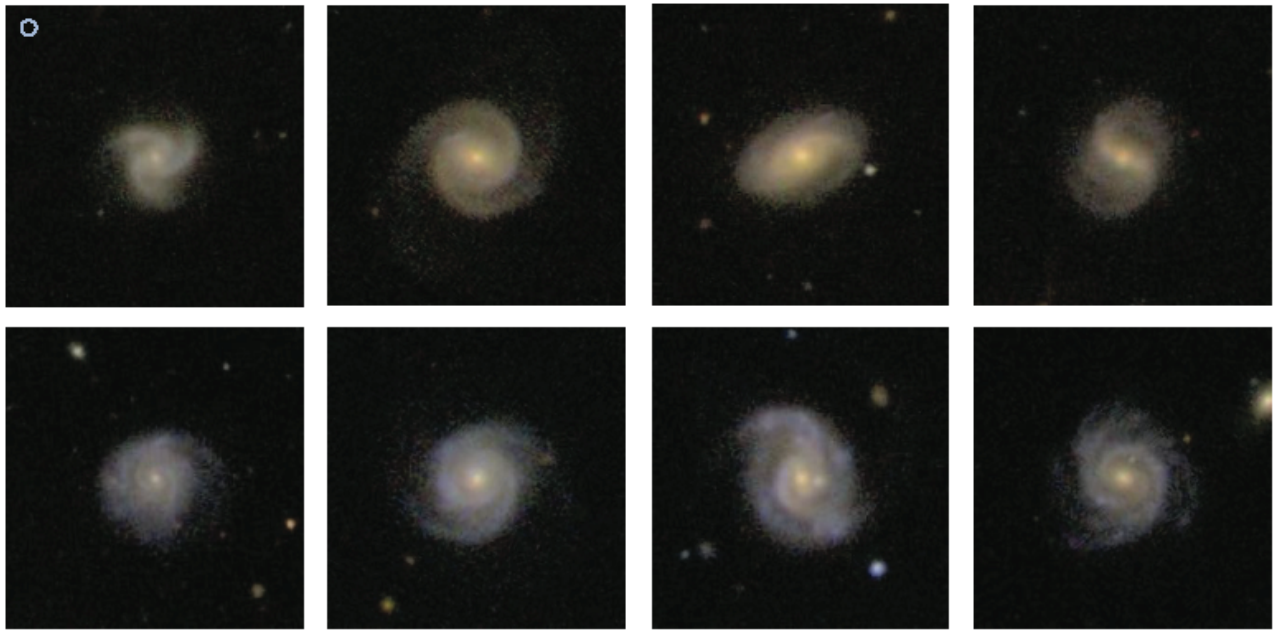


Finding the right position for lenticulars (S0)
- similar to spirals, but no (spiral) arms
- parallel sequence

Lenticulars



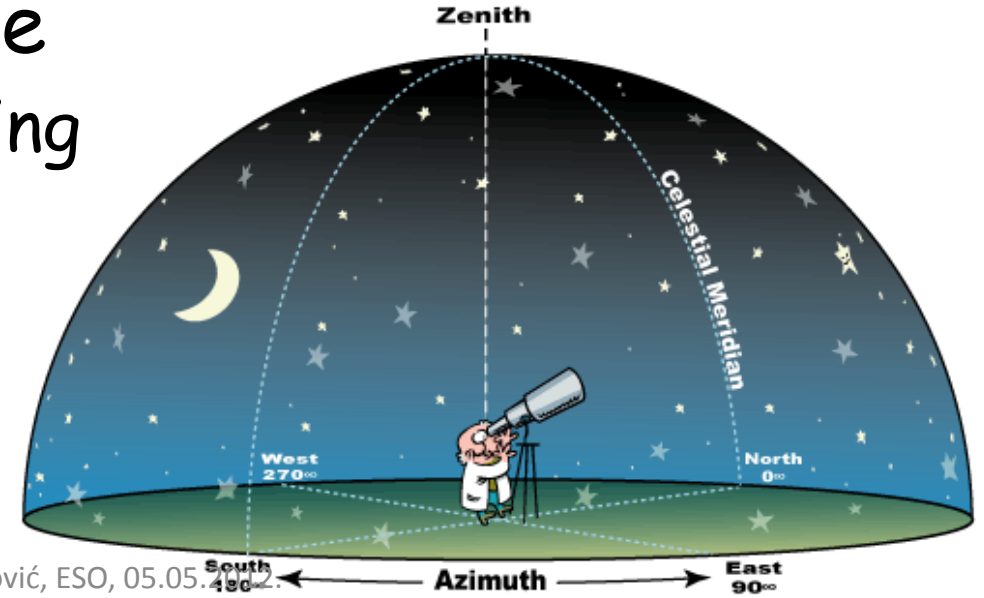
Sidney van den Bergh (1976)



Masters et al. (2010)

Two problems in Astronomy

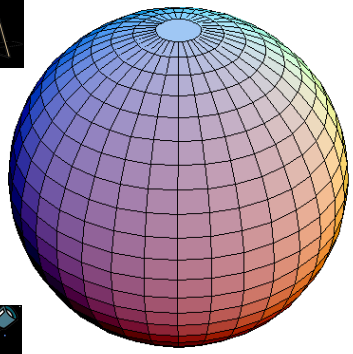
- 1) Distances: how far are the objects (are spiral nebulae within of our galaxy or extra-galactic (Shapley – Curtis Great Debate 1920; Galaxies I)
- 2) Two dimensions: objects are projected on a celestial sphere
  - Shapes are misleading

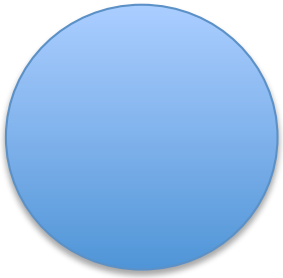


From Herong Yang's web site

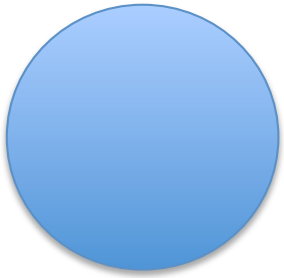
Misleading shapes

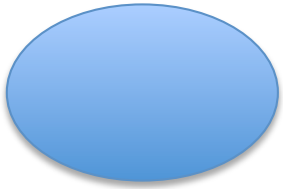
Sphere



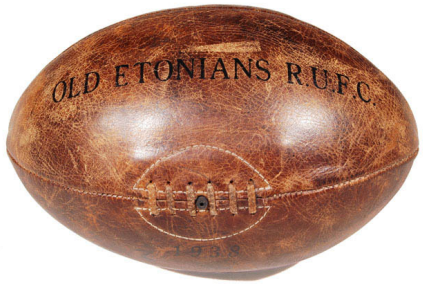


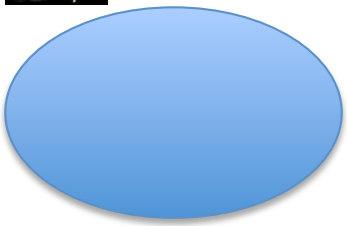
Disk

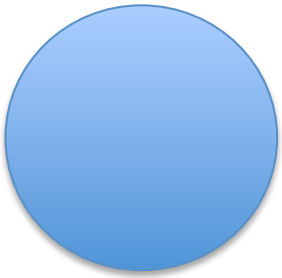




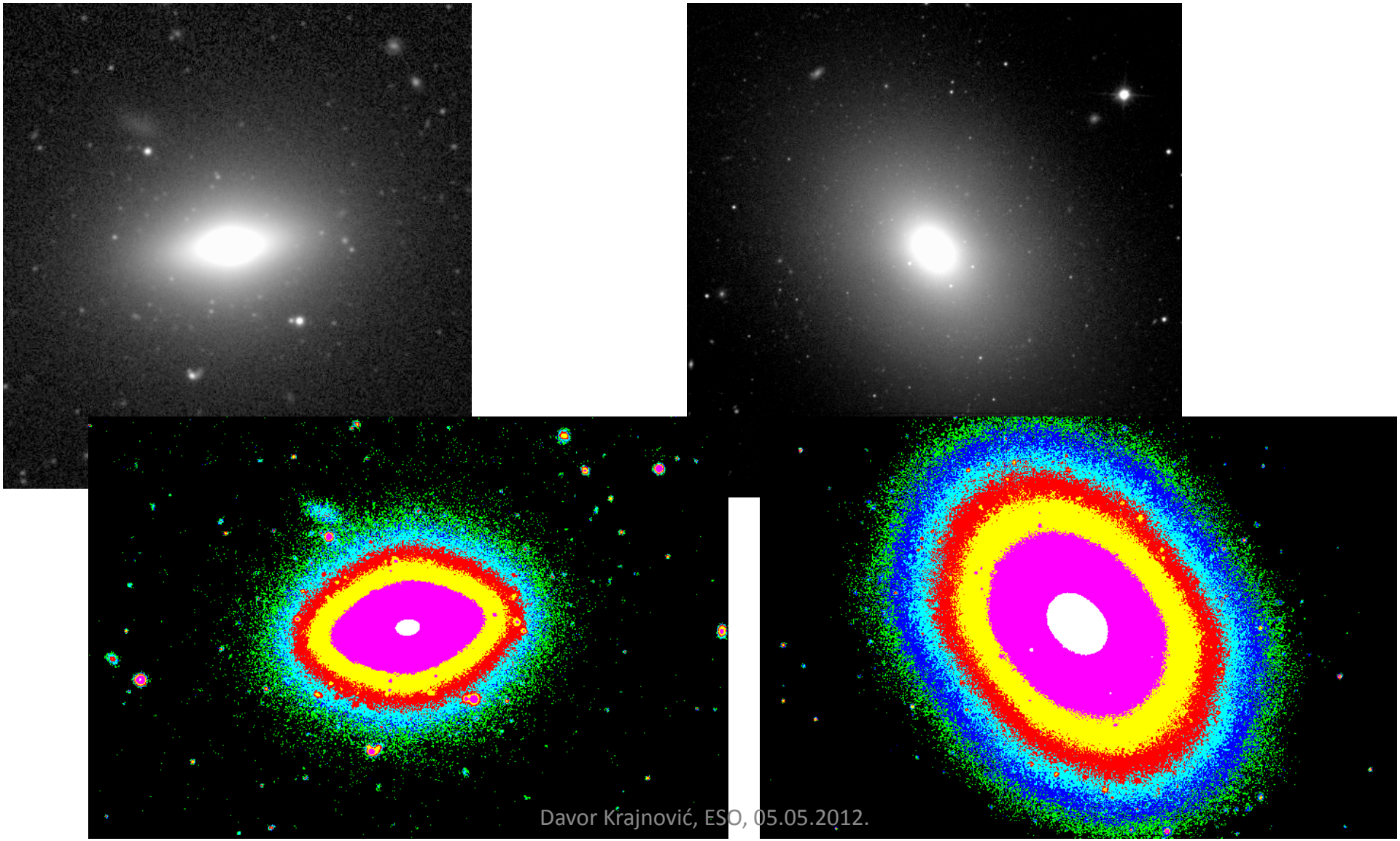
Ellipsoid





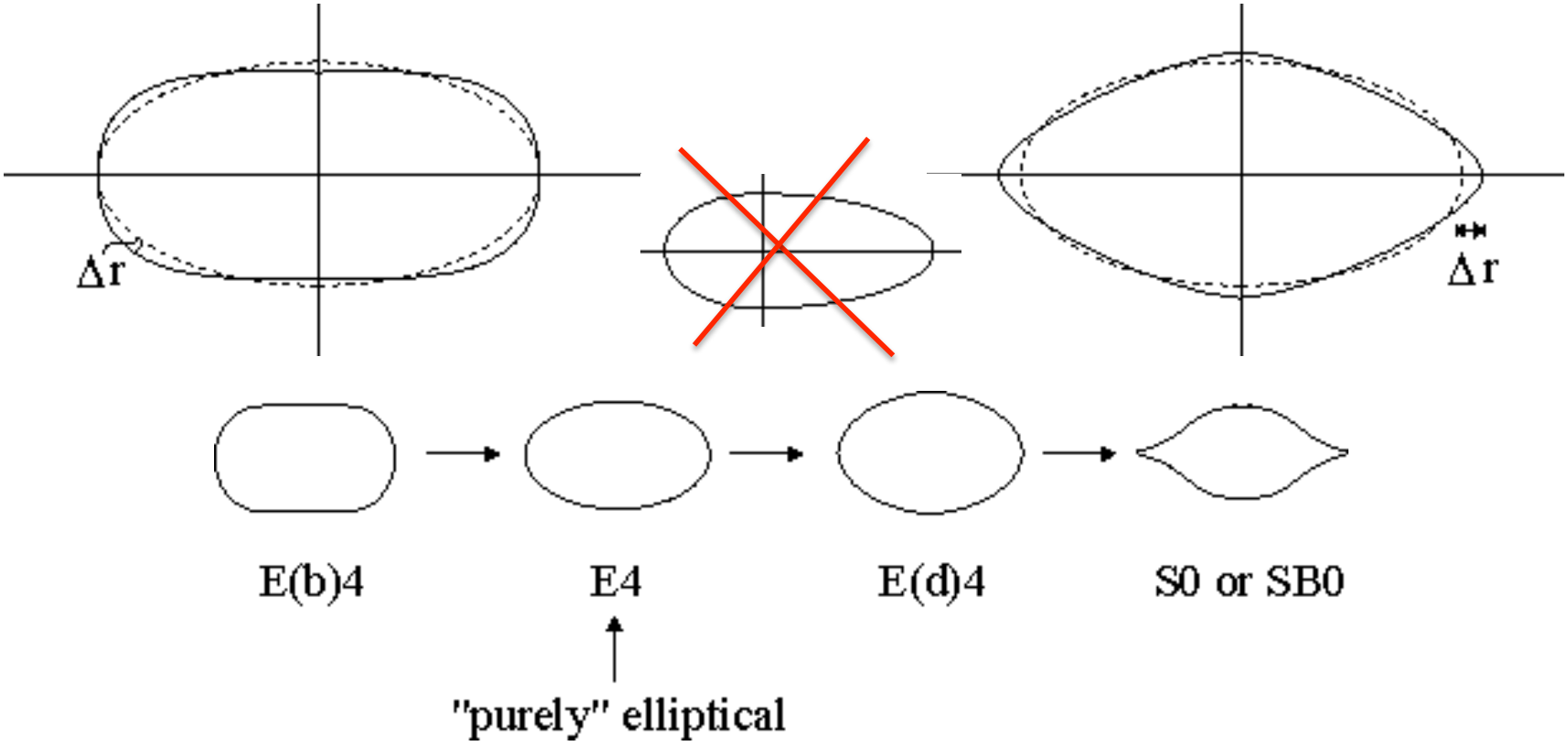


Difference in isophote shape?



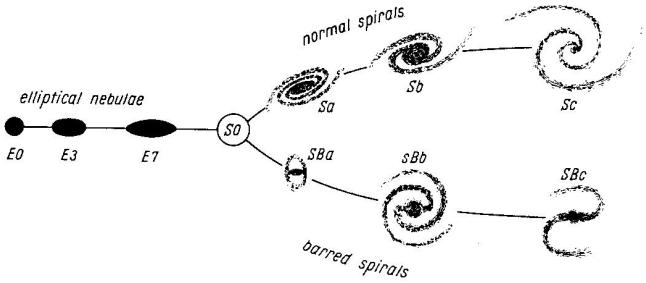
A solution: Disky – boxy

Isophote – contour of constant intensity – elliptical + a few % deviations
→ Disky (positive), Boxy (negative)

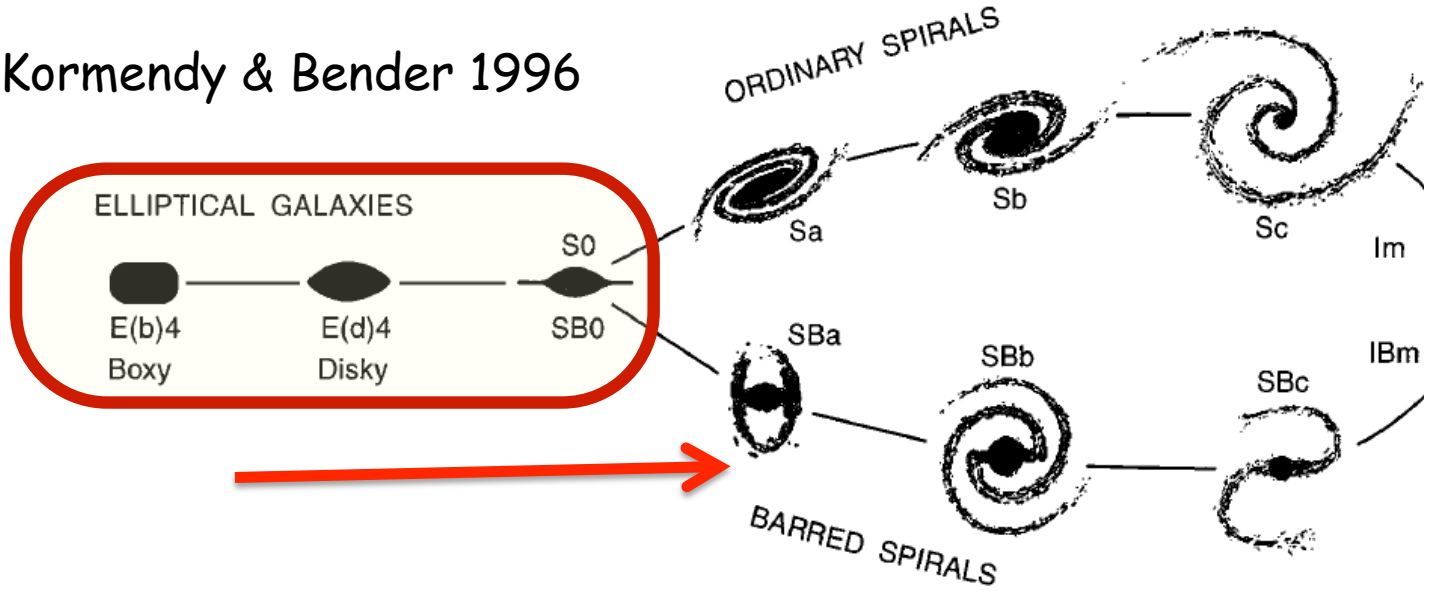


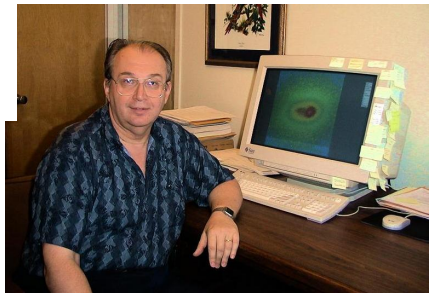
From S. Courteau web site

An update of



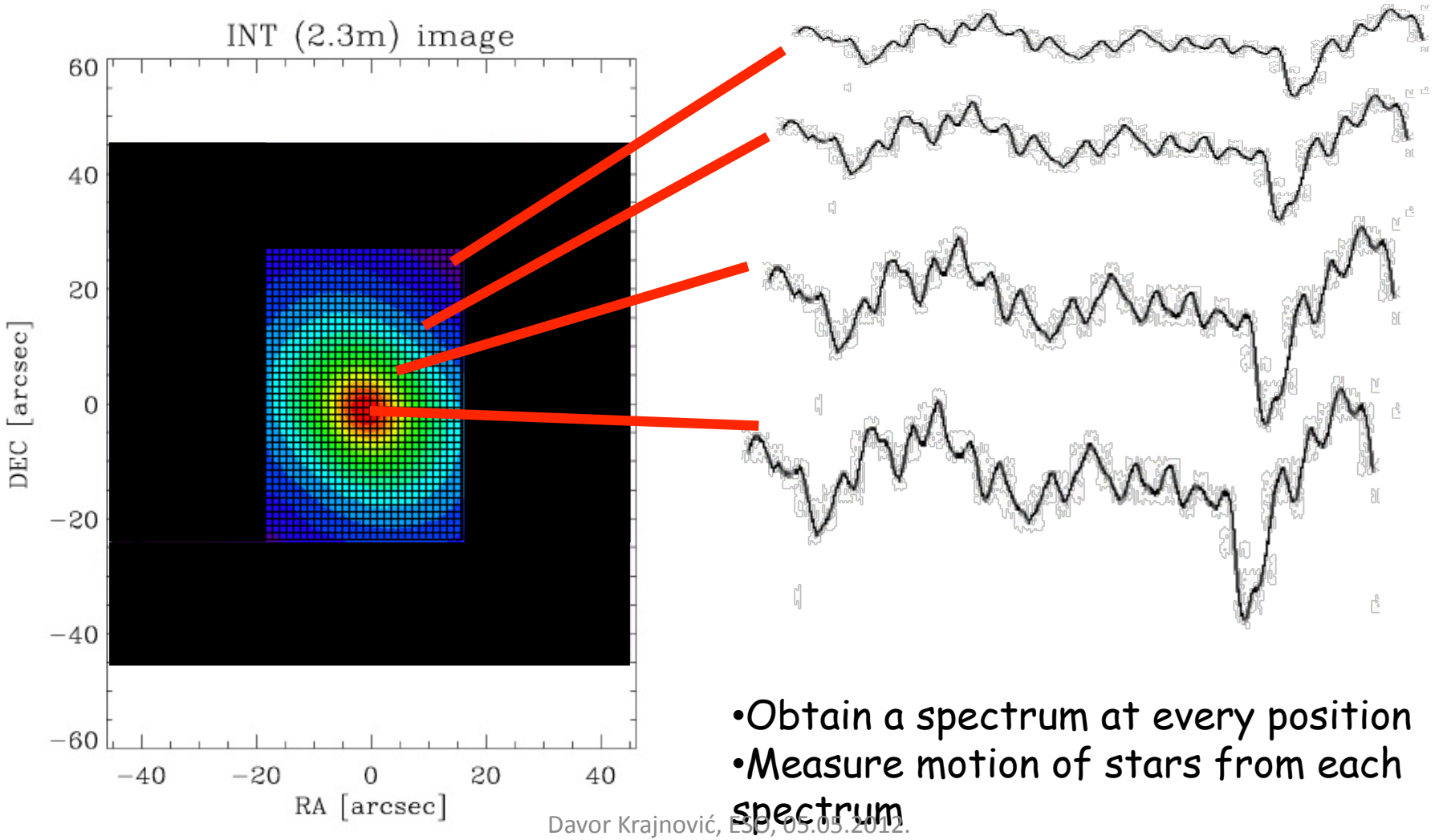
Kormendy & Bender 1996





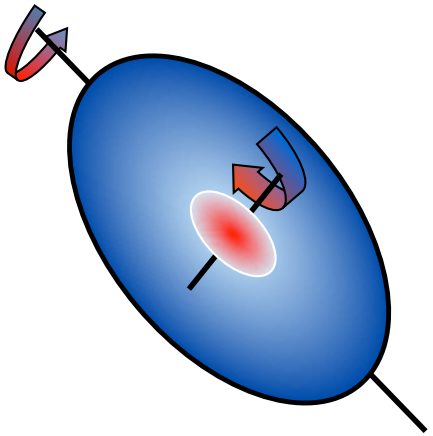
- A revised sequence:
  - Increasing disk contribution
  - E(boxy) – E (disky) – S0 – Spirals
- But E/S0 still problematic: S0 clear only edge-on
- Can we resolve it?
- Pancakes (disks) – rotate; Rugbyballs (ellipsoids) – do not rotate

Integral-field Spectroscopy

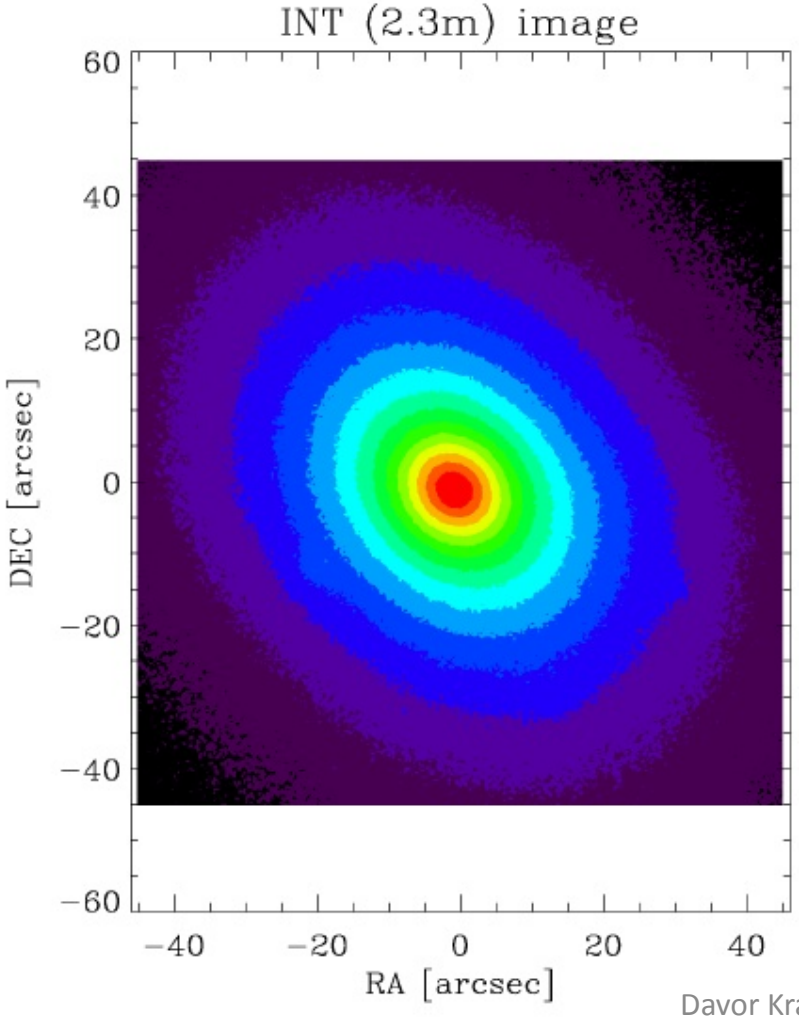


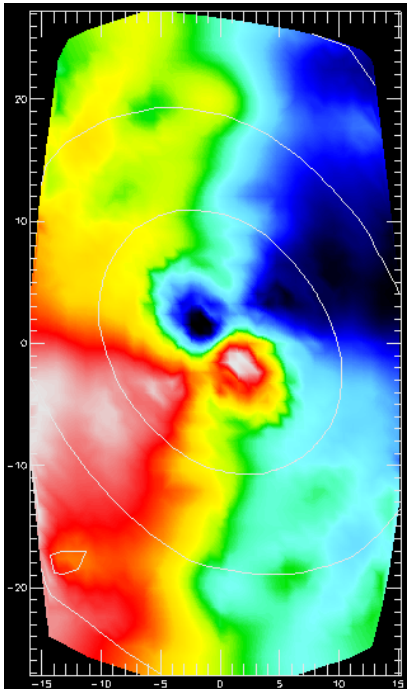
- Obtain a spectrum at every position
- Measure motion of stars from each spectrum

Spectroscopy

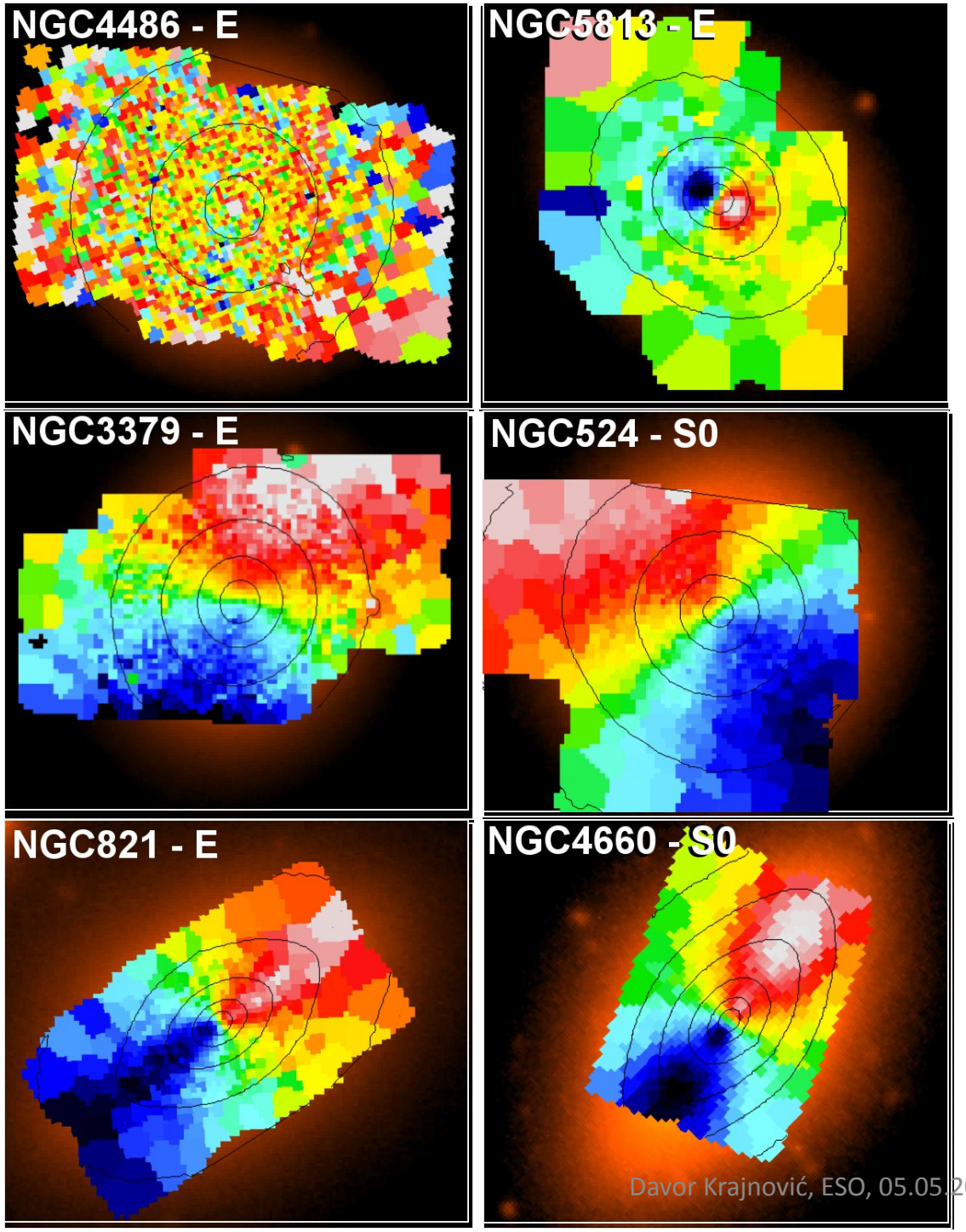


Velocity map





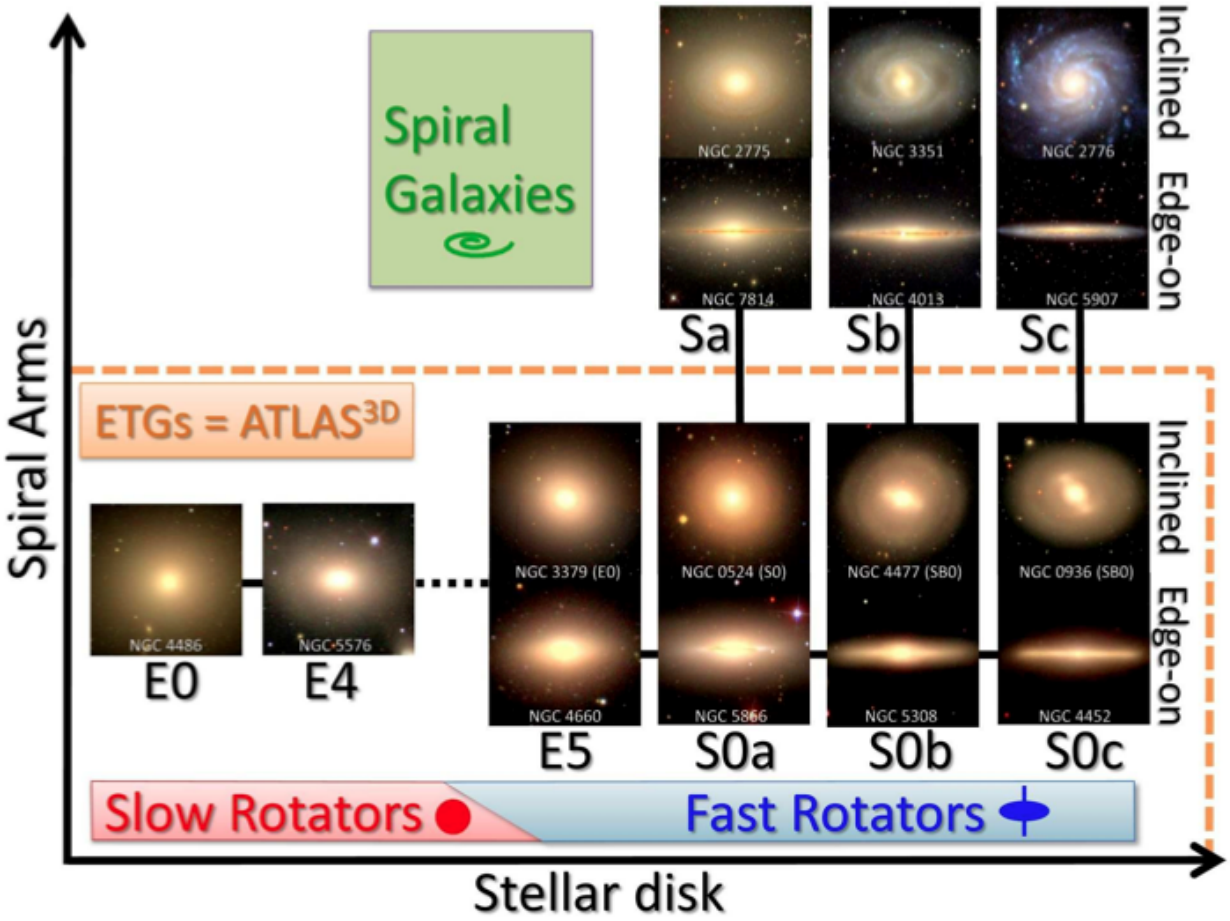
Red: away from you
Blue: towards you



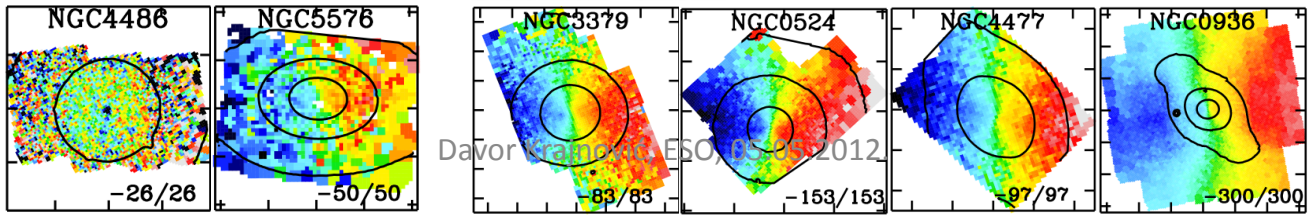
Kinematic Classification

- Kinematics offers a physical classification
- PANCAKES (even if inside RUGBY balls) will show ordered rotation
- True RUGBY balls will show no or complex rotation
- Many Es are actually S0s

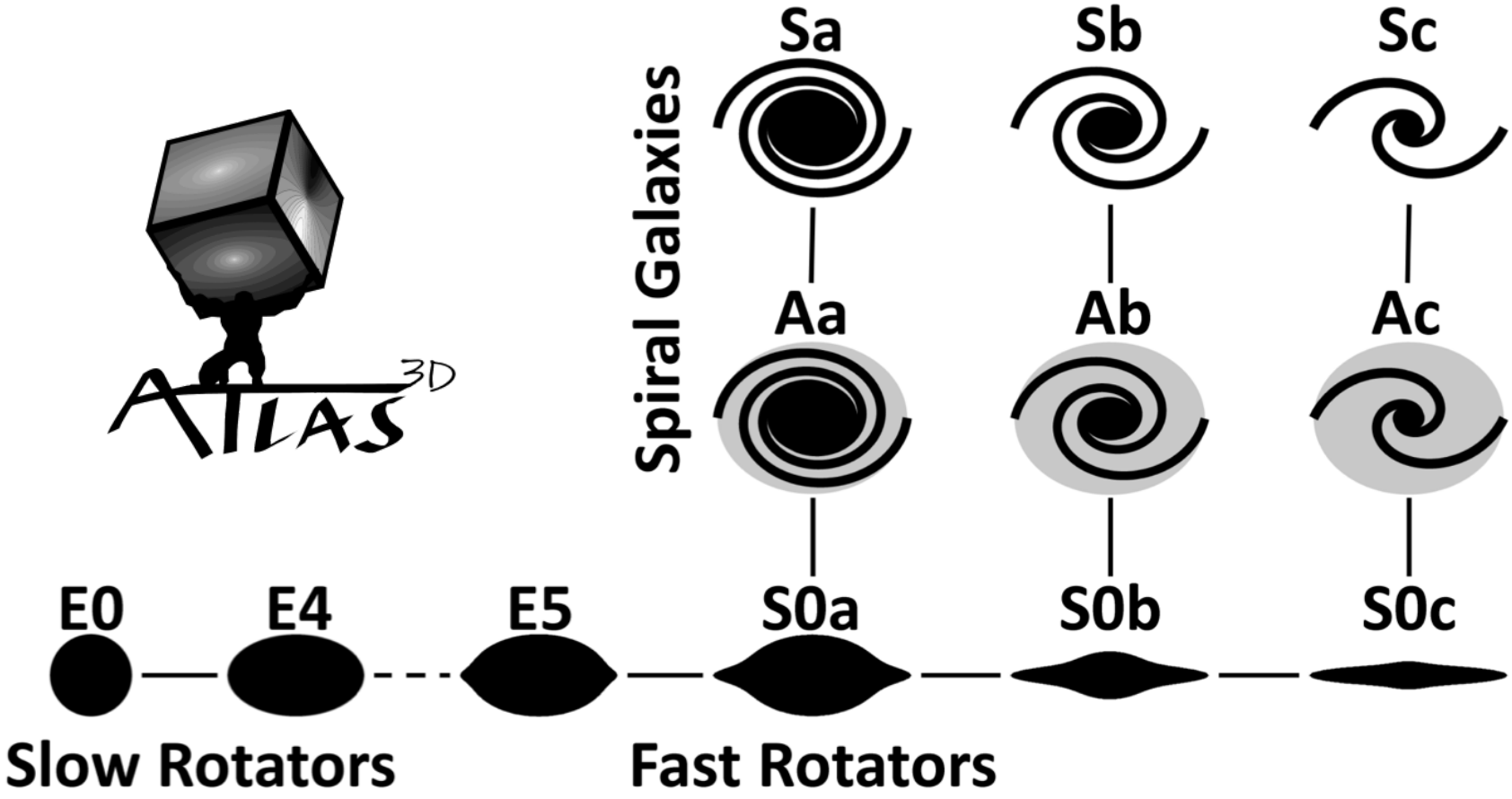
Introducing kinematics



Cappellari et al. (2011)



"Hubble comb"



Cappellari et al. (2011)

History of updates

- **1926:** original Hubble classification
- **1936:** Hubble introduces S0 and SB0
- **1959:** de Vaucouleurs 3D diagram:
  - stage (early, late type) - family (bar) - variety (ring)
- **1975-1992:** Sandage (standard Hubble classification)
- **1976:** Van den Bergh (trident – S0 branch)
- **1996:** Kormendy & Bender (disky-boxy)
- **2011:** kinematics instead of shape for early-types

Do it yourself: Galaxy Zoo

- www.galaxyzoo.org
- Citizen science
- Start 2007:
  - within 24h 70000 classifications per h
  - 50 000 000 classifications from 150 000 people
- Continues beyond astronomy