Galaxies -- Introduction

- Classification -- Feb 13, 2014

Why Begin with Classification?

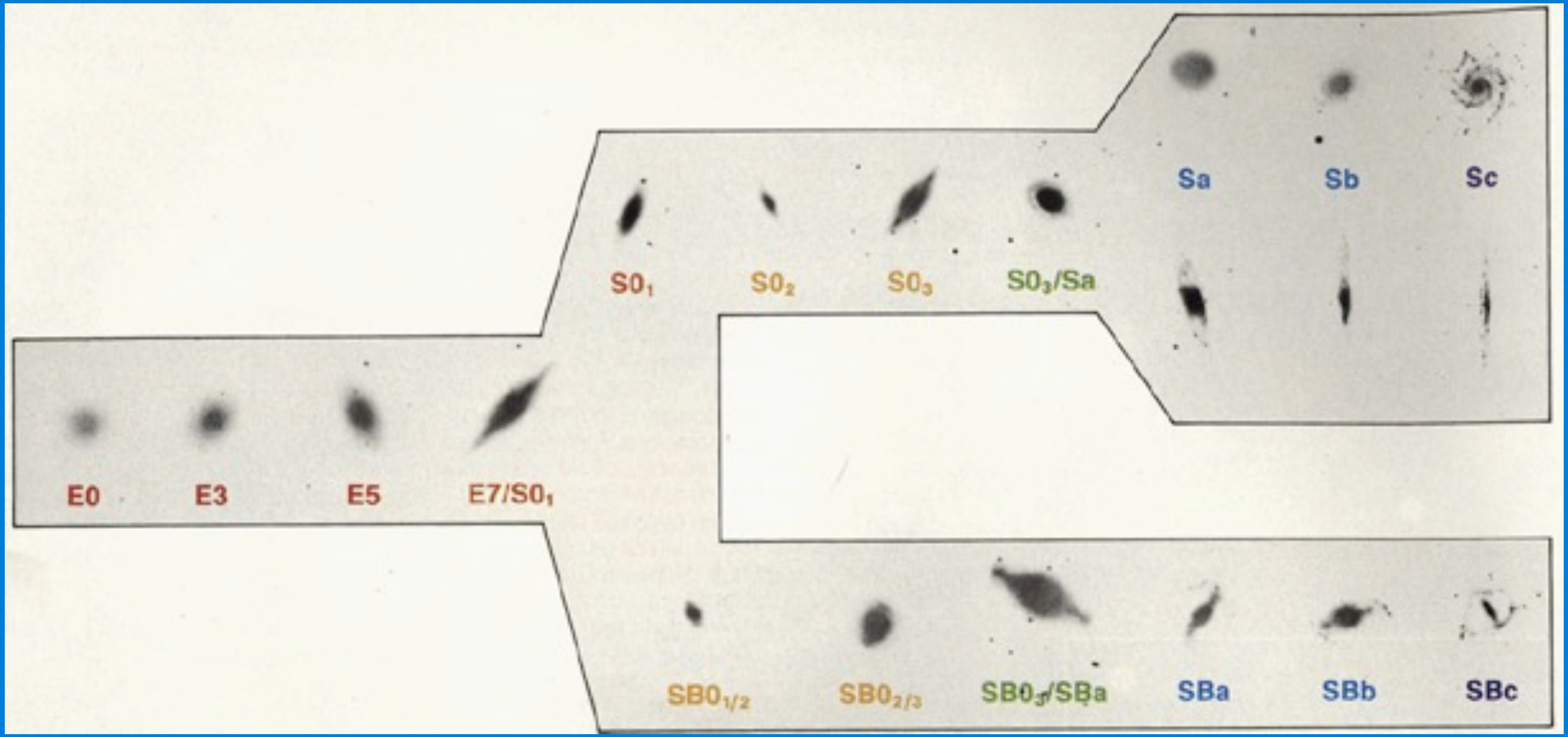
- The Hubble system forms the basic vocabulary of the subject.
- The sequence of galaxy types reflects an underlying physical and evolutionary sequence.
  - provides an overview of integrated properties
  - reproducing the variation in these properties along the Hubble sequence is a major (unsolved) challenge for galaxy formation/evolution theory

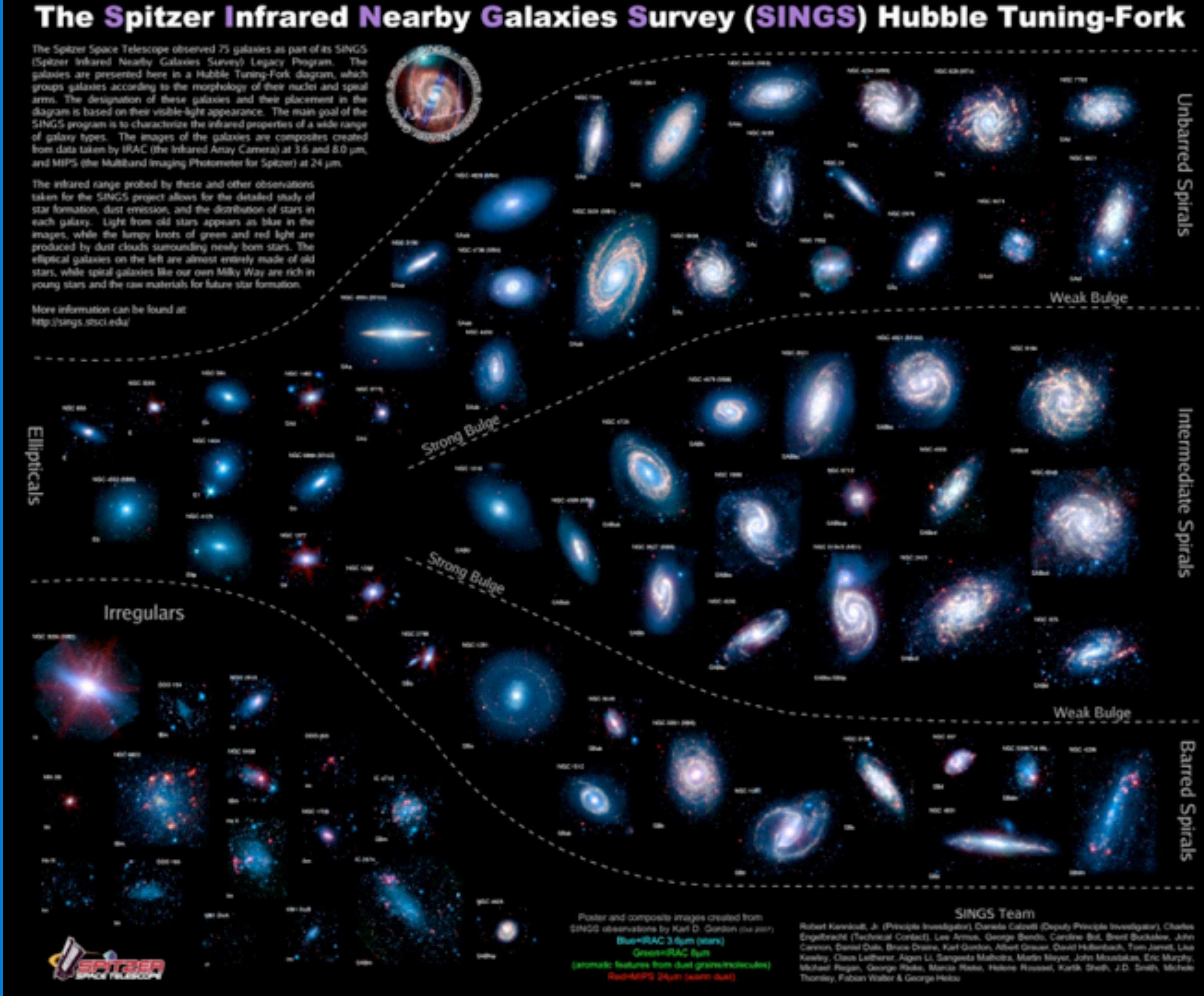
An ideal system

- Classes bring order to diversity of galaxy forms
- Span/include majority of galaxies
- Unambiguous and easily identified criteria
- Relate to important physical properties and provide insight into internal processes, formation and evolution of galaxies

Hubble Classification System

Hubble 1926, ApJ, 64, 321




The Spitzer Infrared Nearby Galaxies Survey (SINGS) Hubble Tuning-Fork
The Spitzer Space Telescope observed 75 galaxies as part of its SINGS (Spitzer Infrared Nearby Galaxies Survey) Legacy Program. The galaxies are presented here in a Hubble Tuning-Fork diagram, which groups galaxies according to the morphology of their nuclei and spiral arms. The designation of these galaxies and their placement in the diagram is based on their visible-light appearance. The main goal of the SINGS program is to characterize the infrared properties of a wide range of galaxy types. The images of the galaxies are composites created from data taken by IRAC (the Infrared Array Camera) at 3.6 and 8.0 µm, and MIPS (the Multiband Imaging Photometer for Spitzer) at 24 µm.
The infrared range probed by these and other observations taken for the SINGS project allows for the detailed study of star formation, dust emission, and the distribution of stars in each galaxy. Light from old stars appears as blue in the images, while the lumpy knots of green and red light are produced by dust clouds surrounding newly born stars. The elliptical galaxies on the left are almost entirely made of old stars, while spiral galaxies like our own Milky Way are rich in young stars and the raw materials for future star formation.
More information can be found at:
http://sings.stsci.edu/
Unbarred Spirals
Weak Bulge
Strong Bulge
Intermediate Spirals
Ellipticals
Strong Bulge
Irregulars
Weak Bulge
Barred Spirals
Poster and composite images created from
SINGS observations by Karl D. Gordon
Blue=IRAC 3.6µm (stars)
Green=IRAC 8µm
(aromatic features from dust grains/molecules)
Red=MIPS 24µm (warm dust)
SINGS Team
Robert Kennicutt, Jr. (Principle Investigator), Daniela Calzetti (Deputy Principle Investigator), Charles Engelbracht (Technical Contact), Lee Armus, George Bendo, Caroline Bot, Brent Buckalew, John Cannon, Daniel Dale, Bruce Draine, Karl Gordon, Albert Grauer, David Hollenbach, Tom Jarrett, Lisa Kewley, Claus Leitherer, Aigen Li, Sangeeta Malhotra, Martin Meyer, John Moustakas, Eric Murphy, Michael Regan, George Rieke, Marcia Rieke, Helene Roussel, Kartik Sheth, J.D. Smith, Michele Thornley, Fabian Walter & George Helou
SPITZER SPACE TELESCOPE

Basic ideas

- Hubble was impressive by Jean's theory of galaxy formation, and his tuning folk was thought to be an evolutionary sequence: Es are early type, and S and Irr are late type
- 4 basic components used in the classification:
  - Spheroid, disk, bar and arms
  - Presence and absence and relative strength of these components define classes
- Principle criteria for spiral stage:
  - Openness of spiral arms
  - Bulge/disk ratio
  - Degree of resolution of arms into HII regions

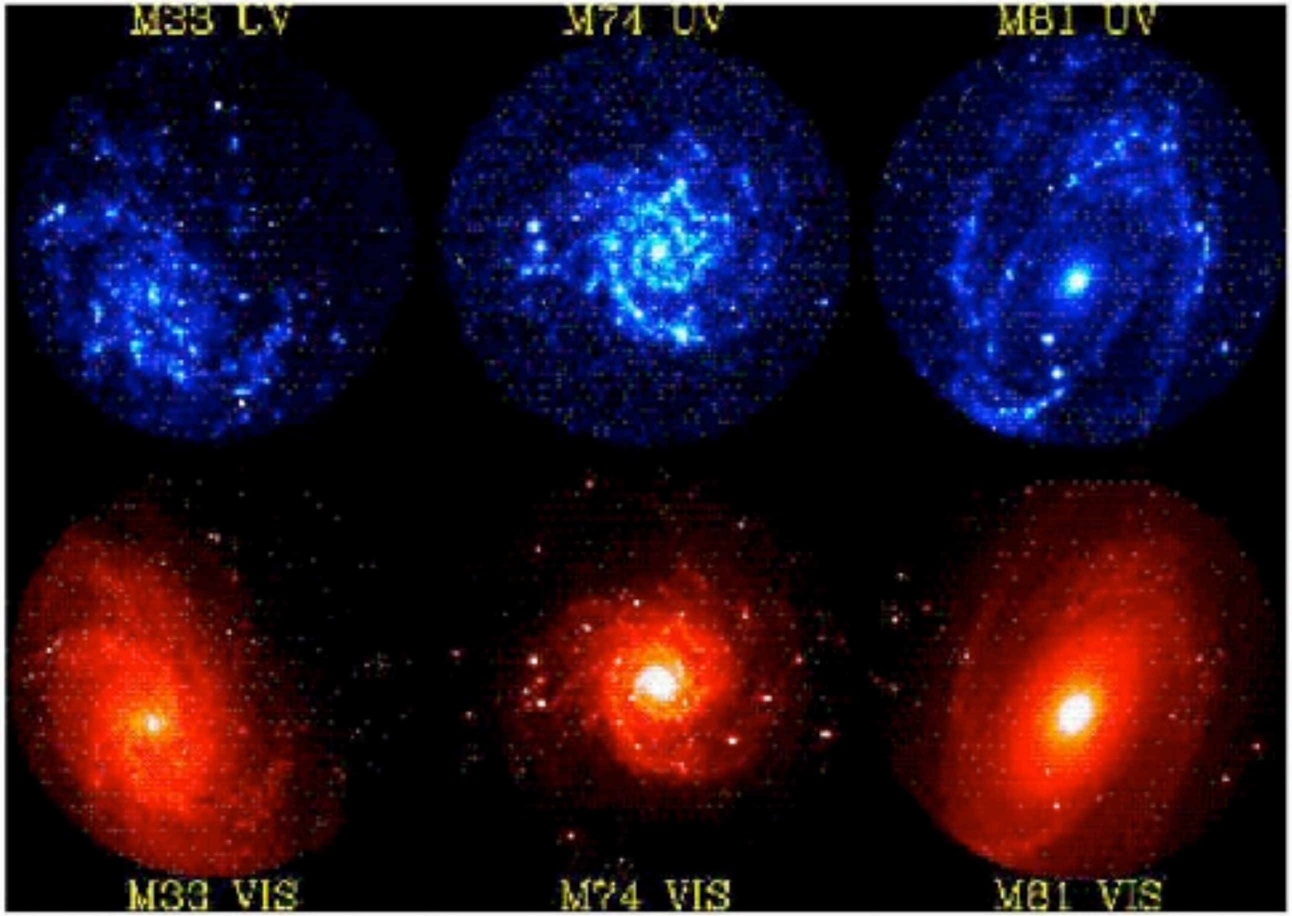
Brief History of the Hubble Sequence

- 1926: Hubble's simple tuning folk
- 1936: Hubble adds S0 & SB0: the tuning folk you see in textbooks
- Revision by Sandage:
  - 1961: Hubble atlas
  - 1992: Carnegie atlas
- Revision by de Vaucouleurs
  - A 3-D system:
  - Stage (E-S-Irr)
  - Family (bar)
  - Varity (inner and outer rings)
  - Used in his RC catalogs – Reference Catalogs of Bright Galaxies

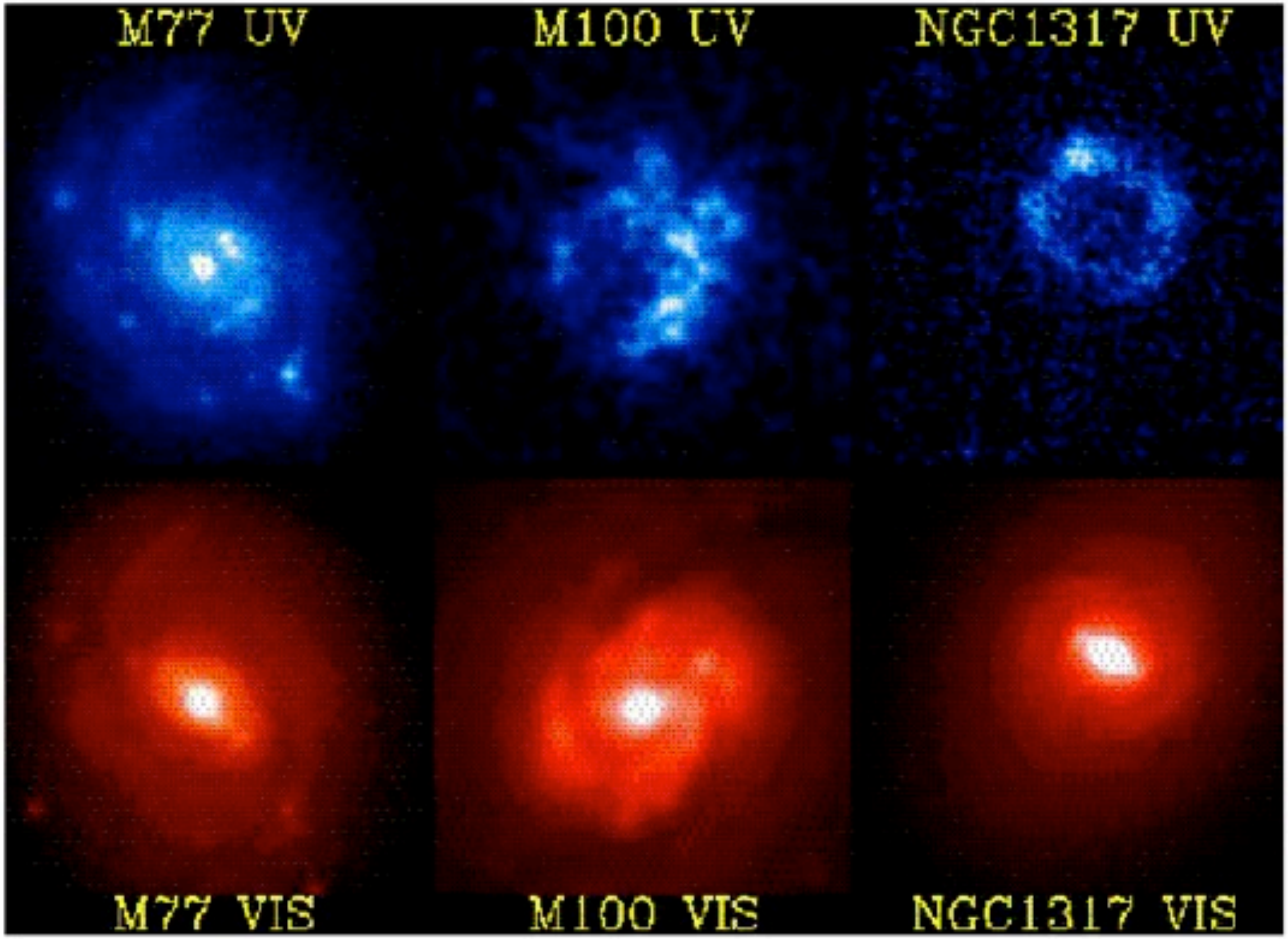
Caveats of current system

- Based on limited number of nearby galaxies, in particular, high surface brightness galaxies, because they are easier to find
- Most criteria are descriptive, I.e., very difficult to quantify and develop automatic procedures
- Does not contain information about the size, luminosity or kinematic information of the galaxy
- Based mostly on photographic images taken in the BLUE
  - Emphasizes star formation rather than mass distribution
  - Appearance can vary greatly with wave-band
- Difficult to compare with high-redshift galaxies, which are mostly observed in the rest-frame UV
- Requires reasonably good spatial resolution, difficult for galaxies at $z>0.1$ from the ground

Galaxies at Non-optical Wavelengths:

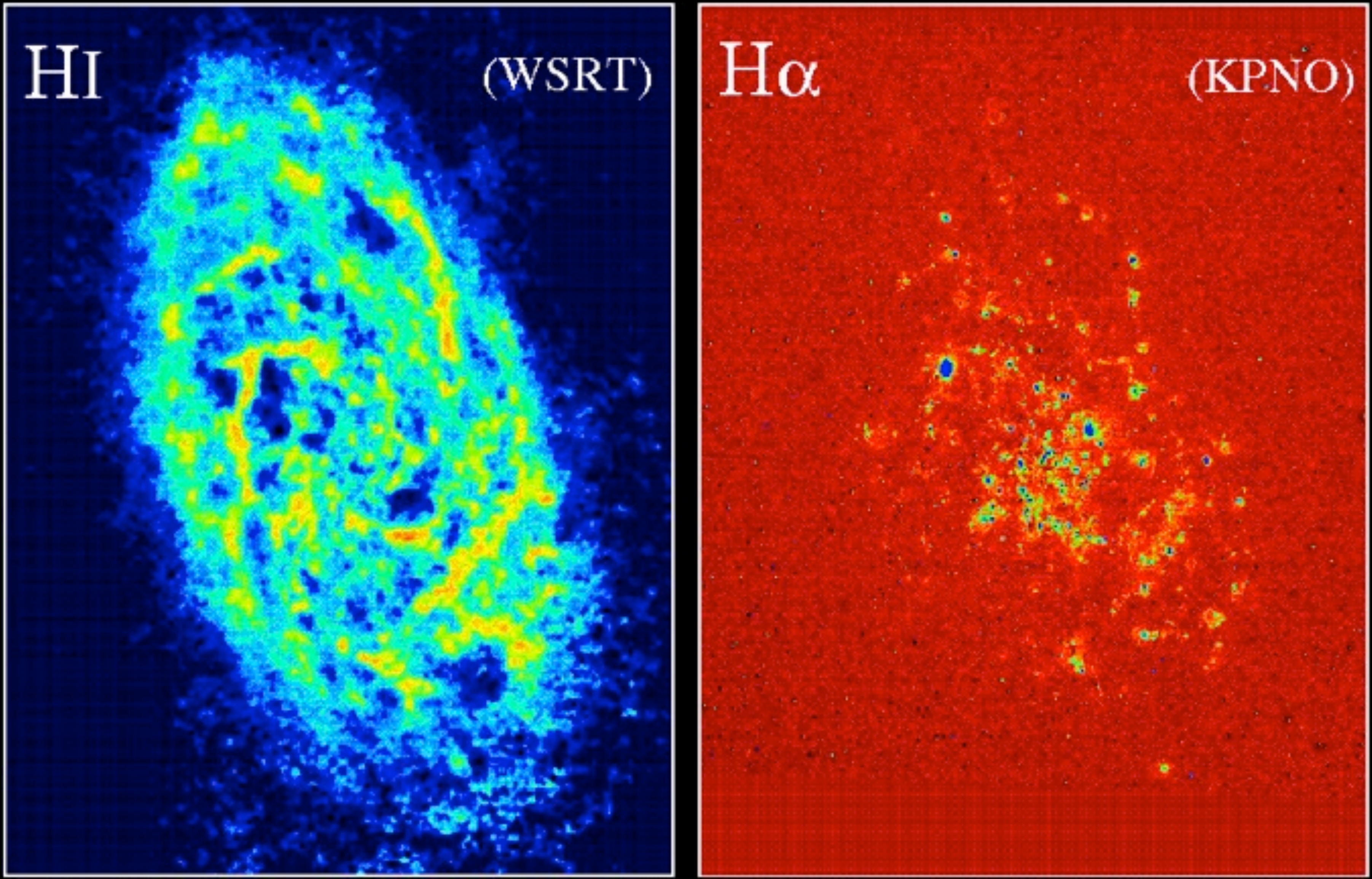


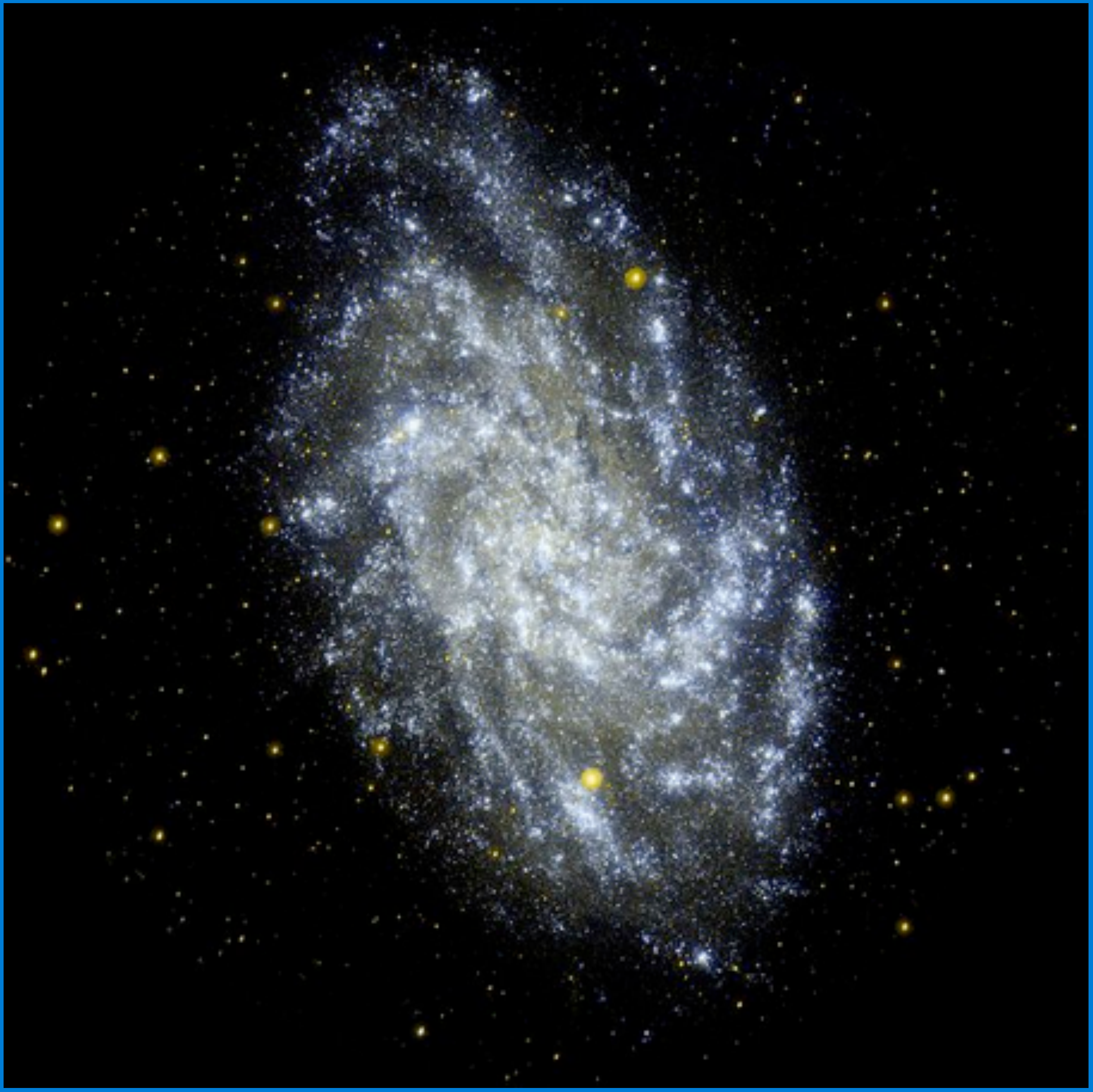
Spirals in ultraviolet (dominated by massive stars) and visual (average population), Ultraviolet Imaging Telescope, Astro mission.

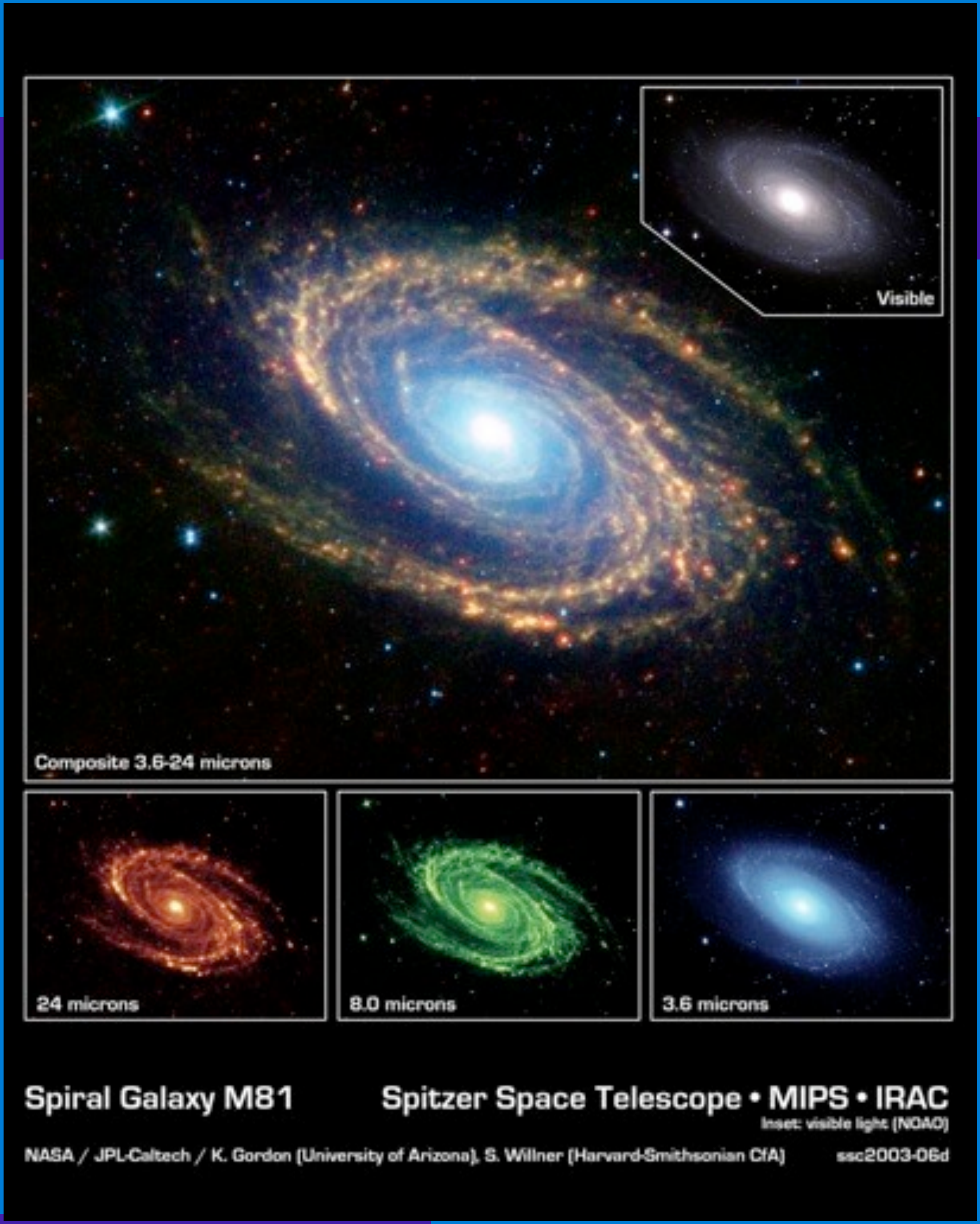


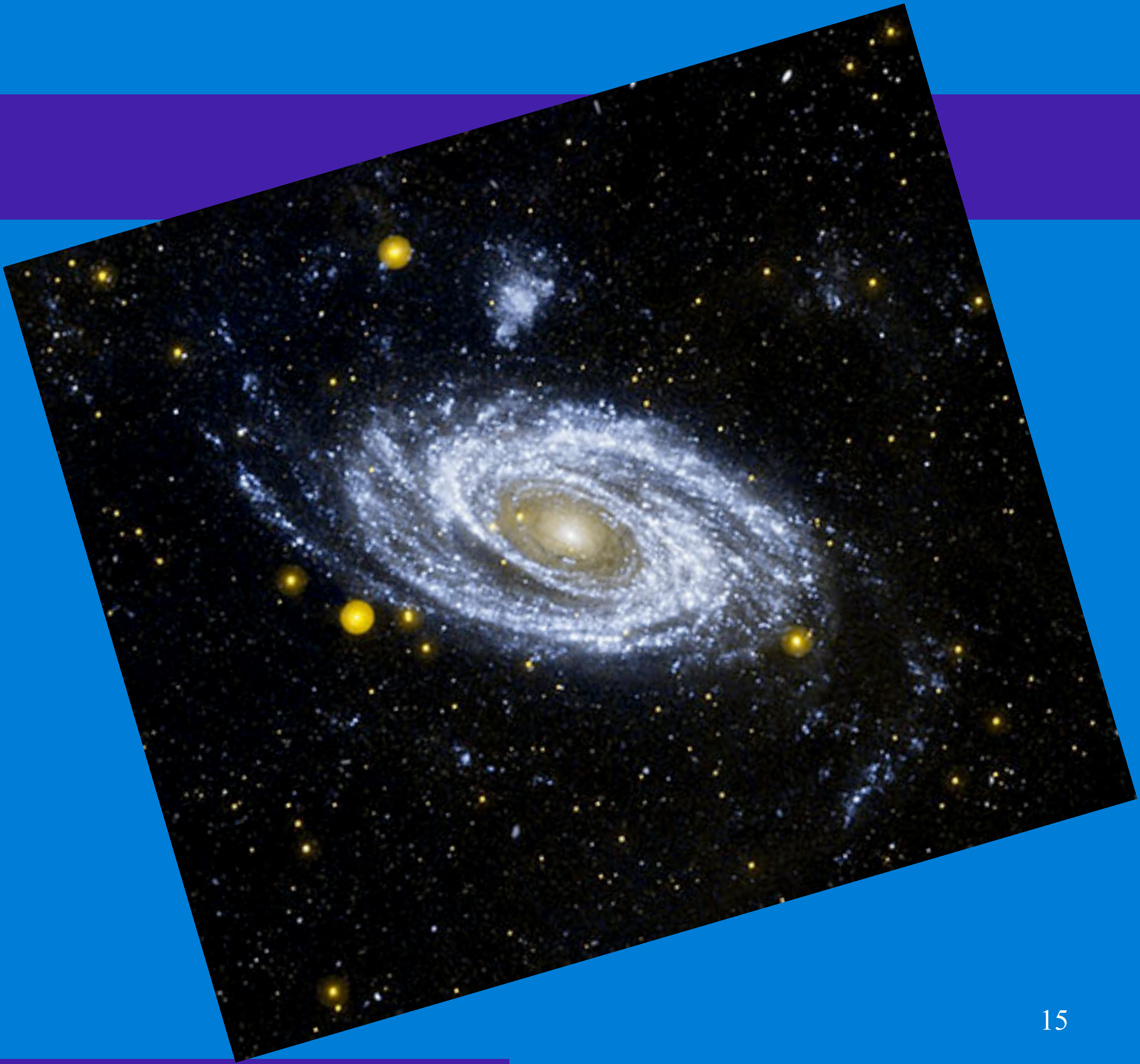
Spirals in ultraviolet (dominated by massive stars) and visual (average population), Ultraviolet Imaging Telescope, Astro mission.

M 33

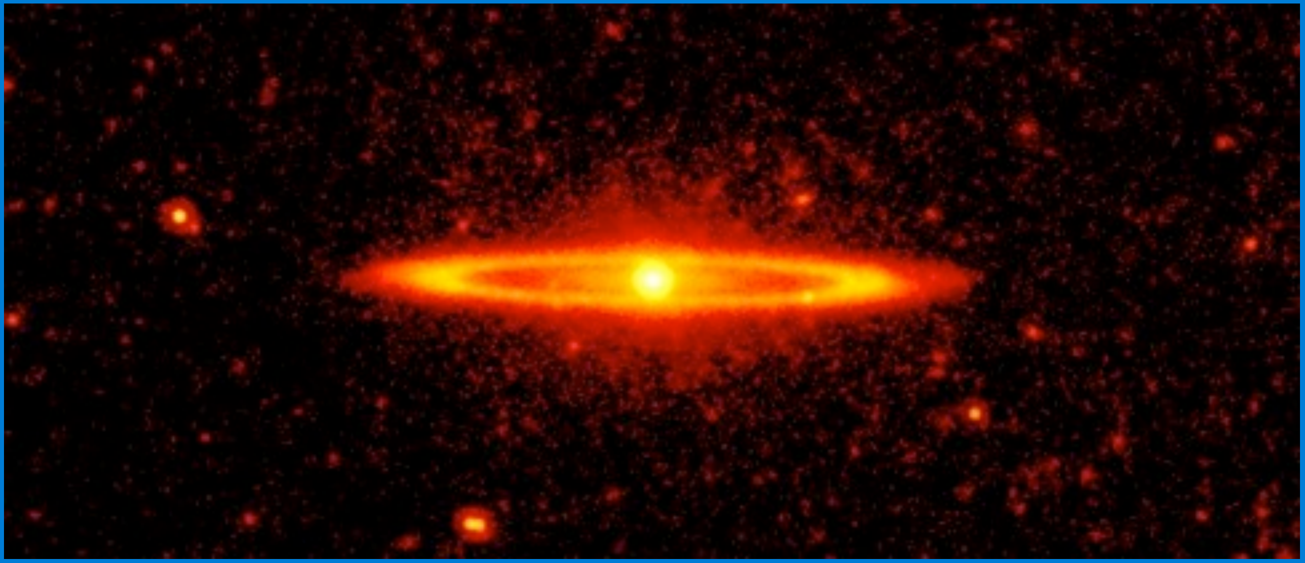





Visible
Composite 3.6-24 microns
24 microns
8.0 microns
3.6 microns
Spiral Galaxy M81
Spitzer Space Telescope • MIPS • IRAC
Inset: visible light (NOAO)
NASA / JPL-Caltech / K. Gordon (University of Arizona), S. Willner (Harvard-Smithsonian CfA)
ssc2003-06d



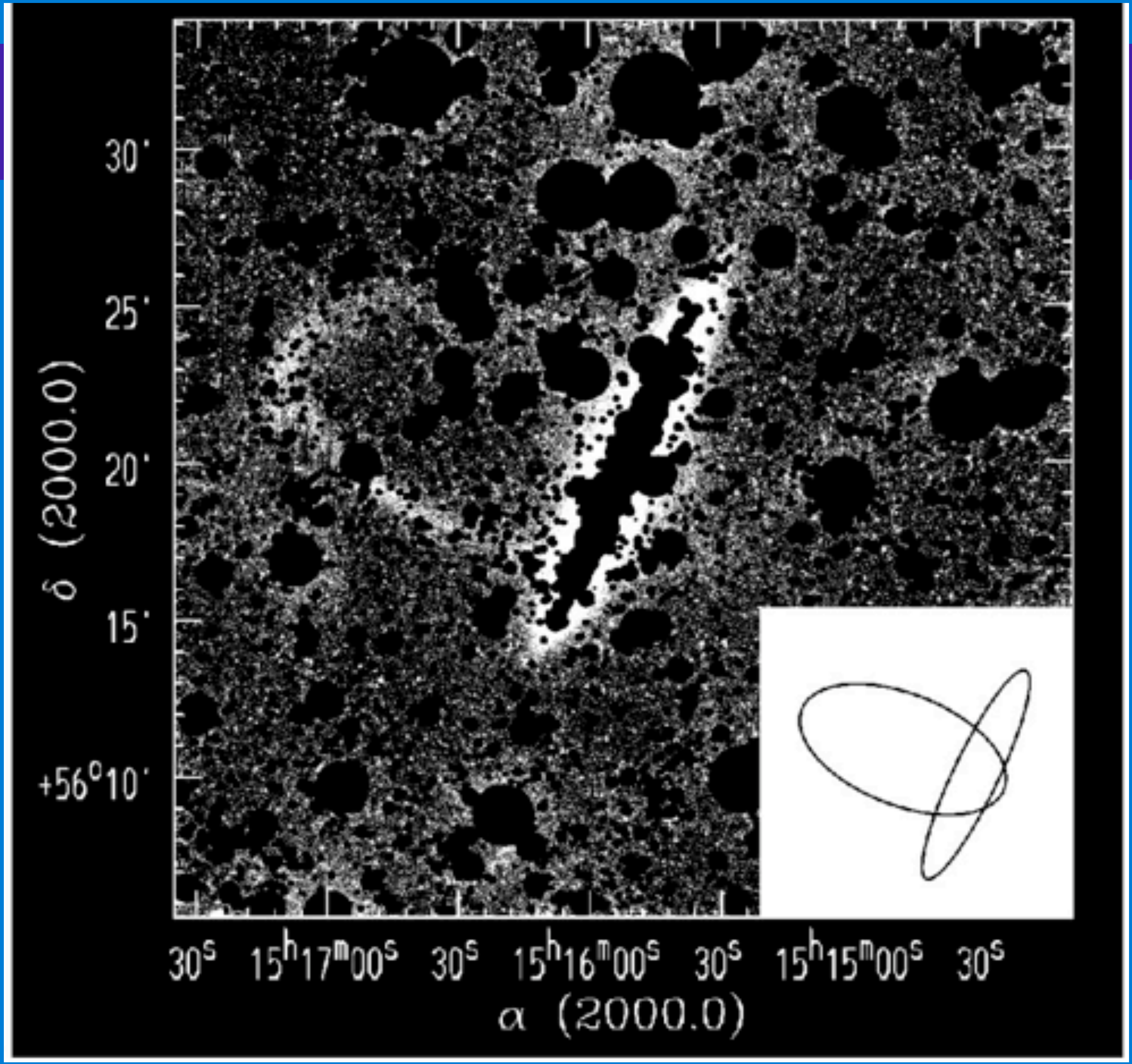
visible



24 μm

NGC 5907

NGC 5907



30'
25'
20'
15'
+56°10'
δ (2000.0)
30s 15h17m00s 30s 15h16m00s 30s 15h15m00s 30s
α (2000.0)

NGC 5907

- Elliptical galaxies
  - smooth structure, elliptical light distribution
  - relatively little evidence of gas, dust
  - subtypes defined by projected flattening

    E0 - E7 where $n = 10(a-b)/a$
  - n is not fully intrinsic: projection
  - Few have n>6, basically stops
  - Deviations from pure ellipse small → concepts of disky and boxy Es (will discuss in E lectures)

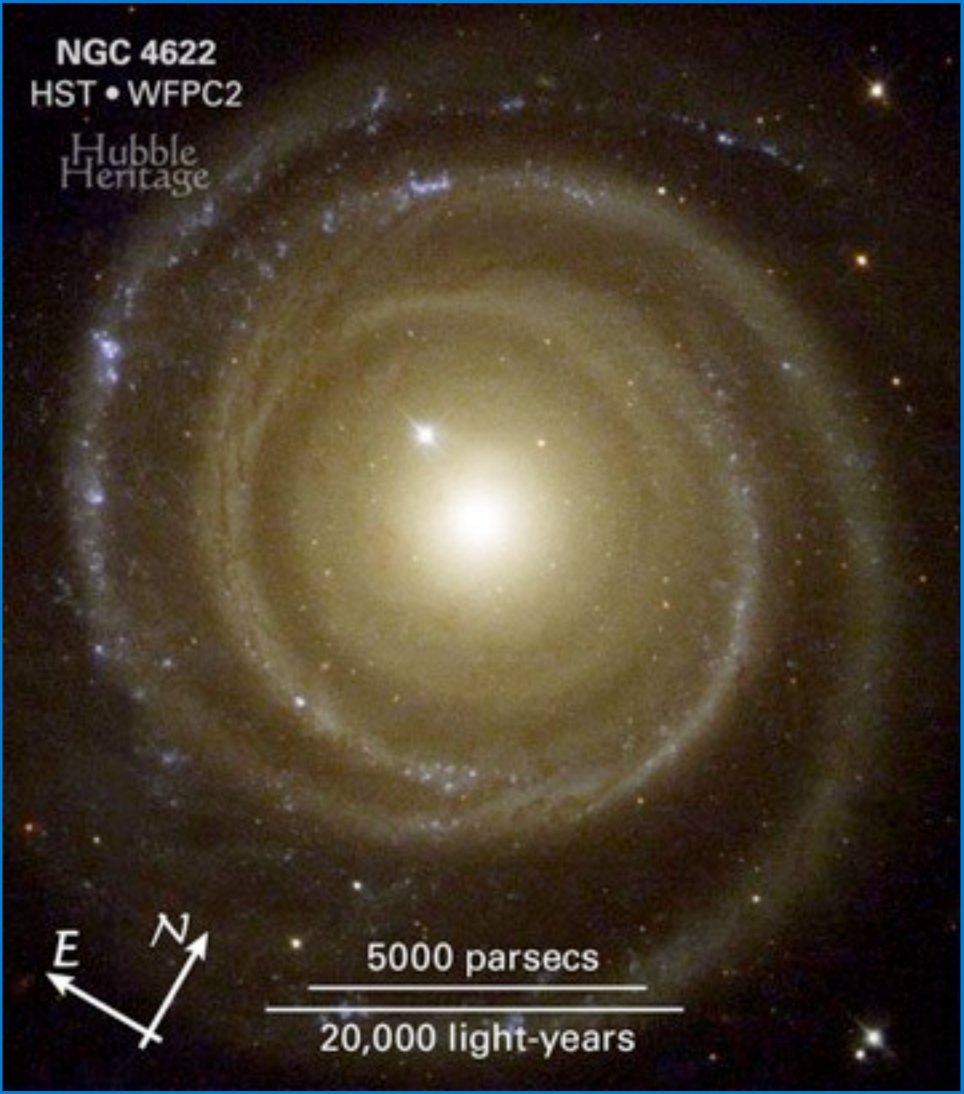
- S0 (lenticular) galaxies
  - introduced in 1936 revision of system
  - Structureless
  - Not elliptical, with disk/bulge structure
  - No spiral structure
  - Difficult to classify
  - In many cases, we just say E/S0 for early type galaxies as a whole

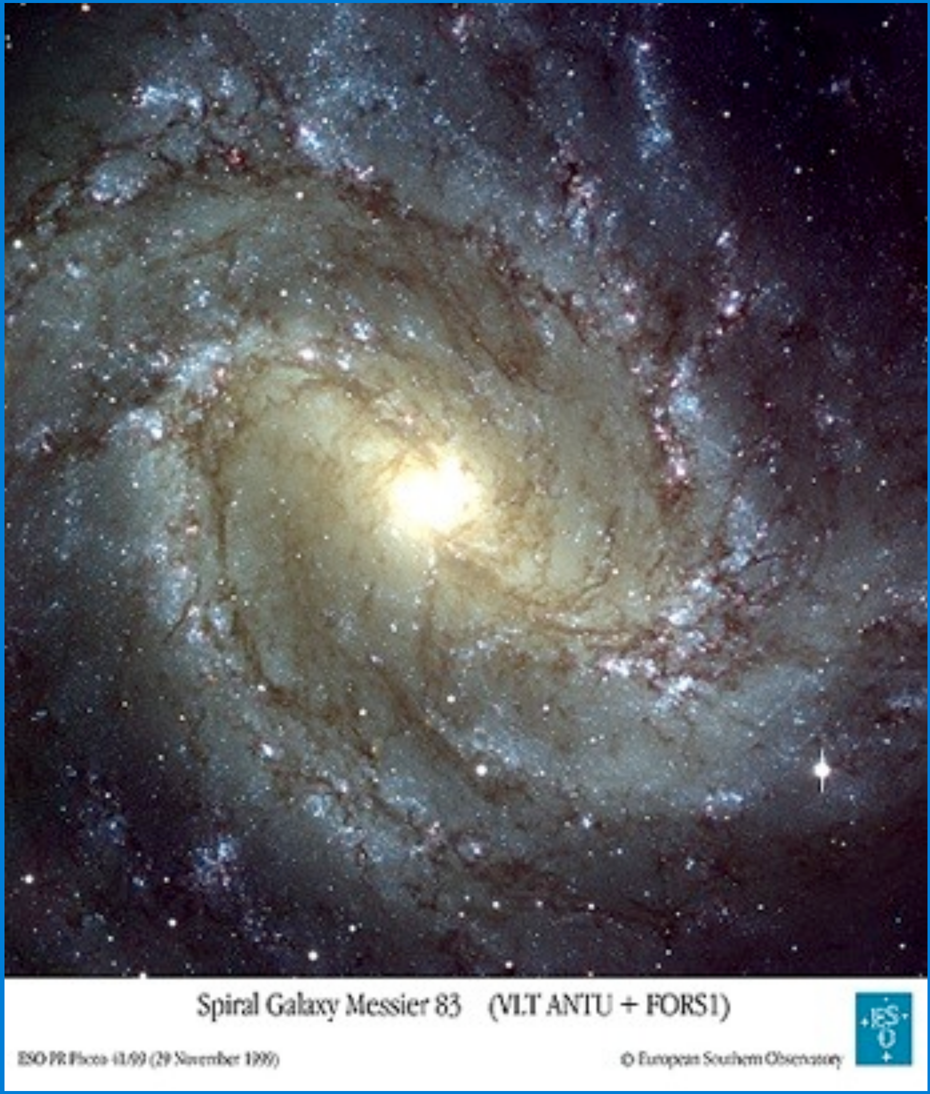
Giant Elliptical Galaxy NGC 1316 in Fornax Cluster (VLT/ANTU + FORS1)

ESO PR Photo 18a/00 (28 July 2000)

- Spiral galaxies
  - flattened disk + central bulge (usually)
  - two major subclasses: normal and barred
  - subtypes Sa, Sb, Sc distinguished by 3 criteria
    - bulge/disk luminosity ratio
      - B/D ranges from >1 (Sa) to <0.2 (Sc)
    - spiral arm pitch angle
      - ranges from 1-7° (Sa) to 10-35° (Sc)
    - "resolution" of disk into knots, HII regions, stars
  - these three criteria are not necessarily consistent!
  - each reflects an underlying physical variable
    - B/D ratio ---> spheroid/disk mass fractions
    - pitch angle ---> rotation curve of disk, mass concentration
    - resolution ---> star formation

Grand Design vs. Patchy Spirals





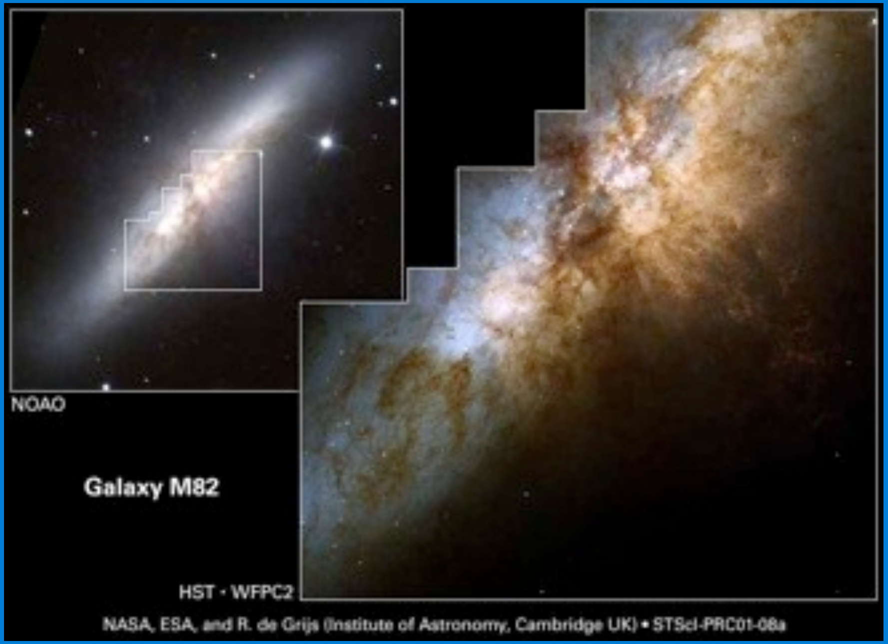
Irregulars: I

- Magellenic Clouds type
- Very late, no nucleus, low luminosity, often dwarfs
- Labelled Irr I by Hubble
- Labelled Sm, SBm, Im, Ibm by de Vaucouleurs and by Sandage later

Irregular II

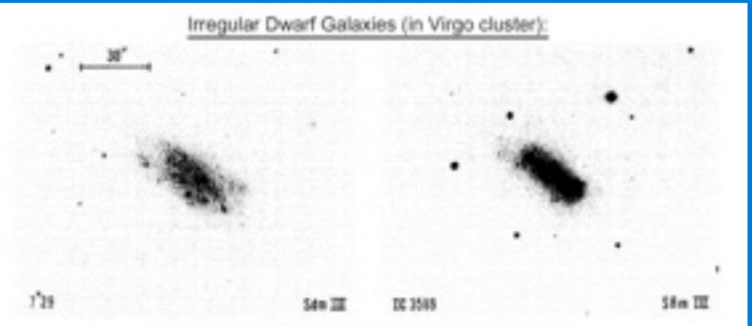
- M82 type; starburst
- probably mergers, amorphous appearance
- Labelled Irr II by Holmberg, Hubble
- Labelled I0 by de Vaucouleoys
- Labelled Am by Sandage

M 82, a starburst galaxy, white/brown: stellar light and dust, red: hot expanding gas in Hα (Subaru telescope)

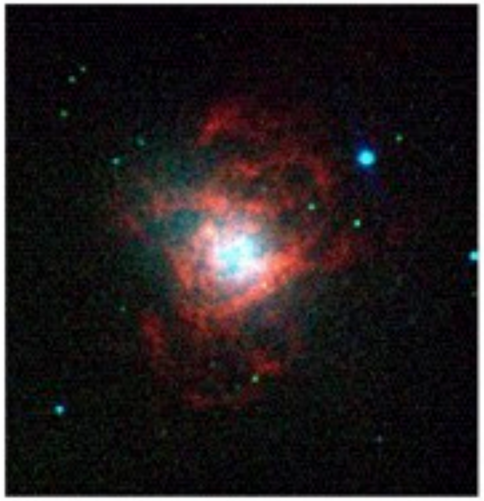


Dwarf Irregulars (dIrr)

- No clear disk or spirals or nucleus
- Patchy star formation on fainter old population
- Often HI rich
- Extreme examples are BCD, blue compact dwarfs with very strong star formation



see: Sandage A., Binggeli B. (1984) *AJ*, **89**, 919



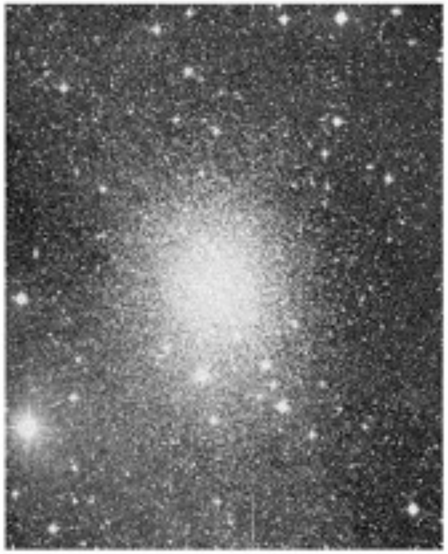
Blue Compact Dwarf (BCD) NGC 1705, blue: blue continuum, green: red continuum, red: Hα (G. Meurer)

Dwarf Elliptials (dE) and Dwarf Spheroidals (dSph)

- Very small, 0.1-1 kpc
- Higher/lower surface brightness corresponds to dE/dSph
- Morphology similar to Es
- Light profile similar to Ss
- Do not follow fundamental law for Es → different origin
- Most common kind of galaxy in the Universe

Dwarf Galaxies:

Leo 1, dwarf elliptical (dwarf spheroidal) companion of Milky Way



Sculptor dwarf, dwarf elliptical companion of Milky Way

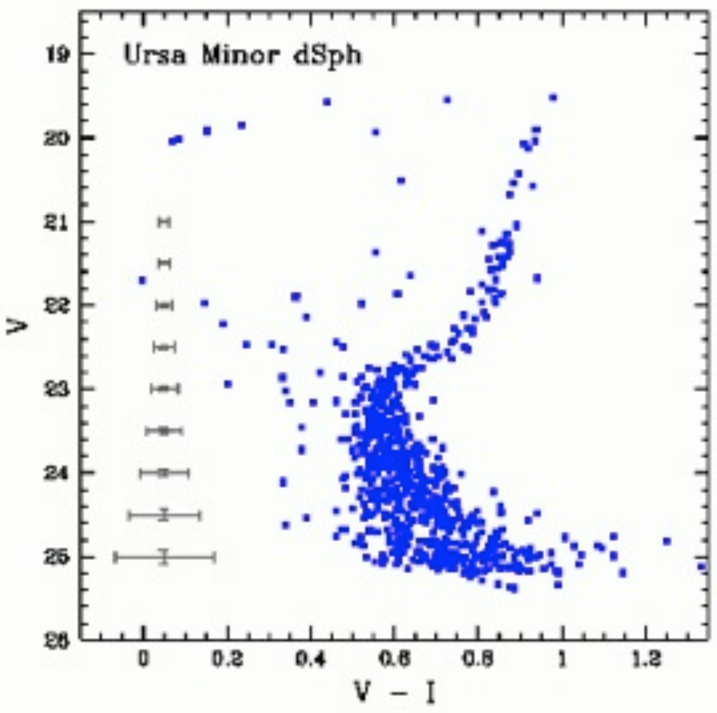
from: Anglo Australian Observatory

Compact Ellipticals (cE)

- M32 (companion of M31)
- Seem to follow the basic laws of Es, just smaller
- Quite rare

Dwarf Spheroidal Galaxies

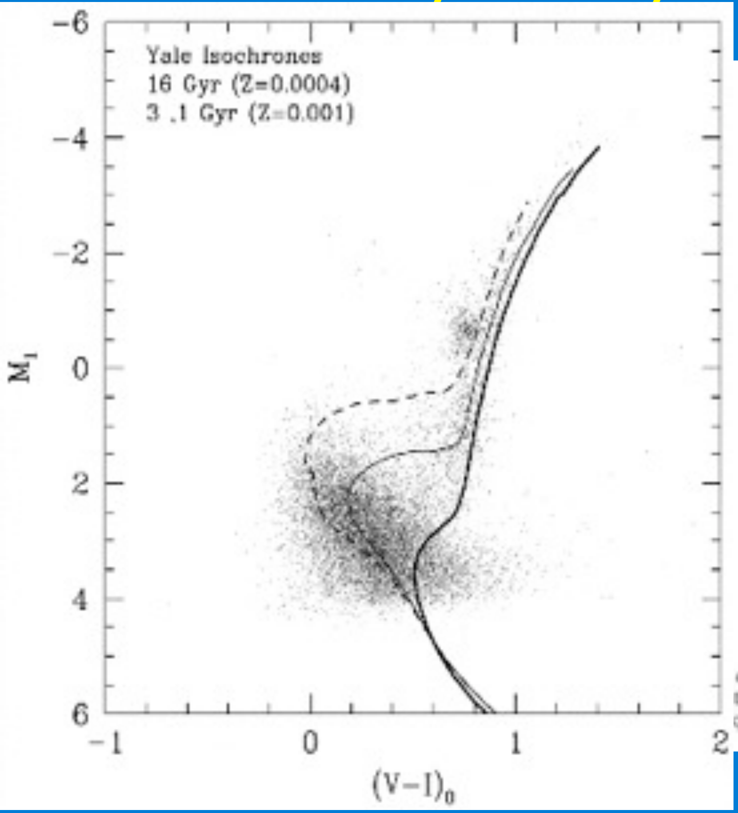
- SF history from HST CMDs
- young population is absent (by definition)
- old population ubiquitous
  - at least one purely old galaxy (Ursa Minor) -------->
- intermediate-age population varies from 0% --> >90%

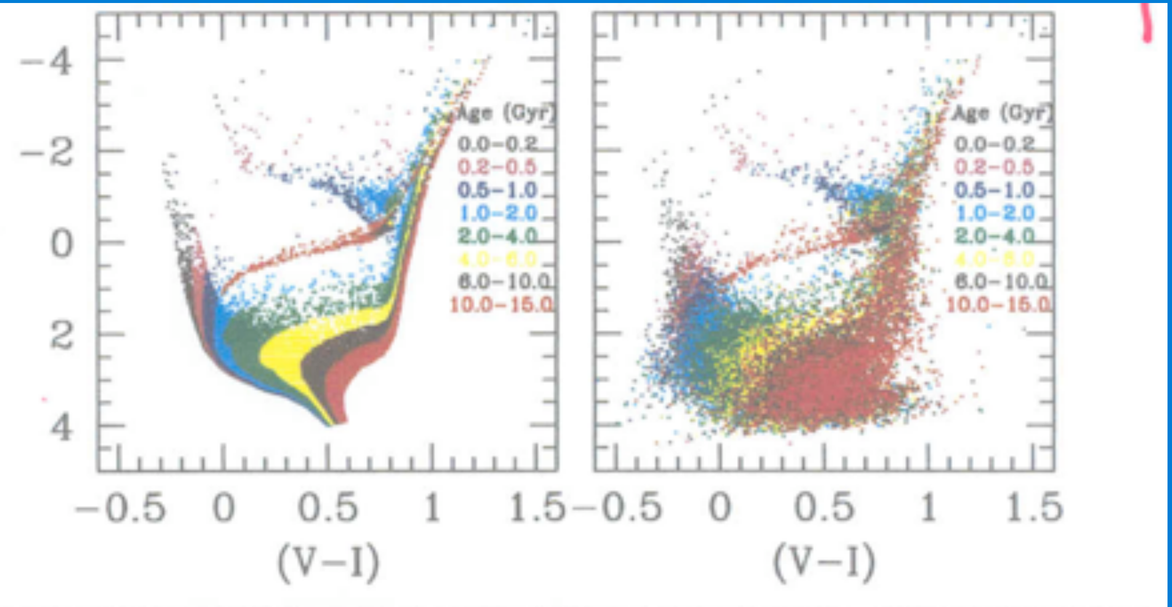


Mighell, Burke 1999, AJ, 118, 366

Leo I

- Relatively steady SF from 10-13 Gyr to 1 Gyr ago

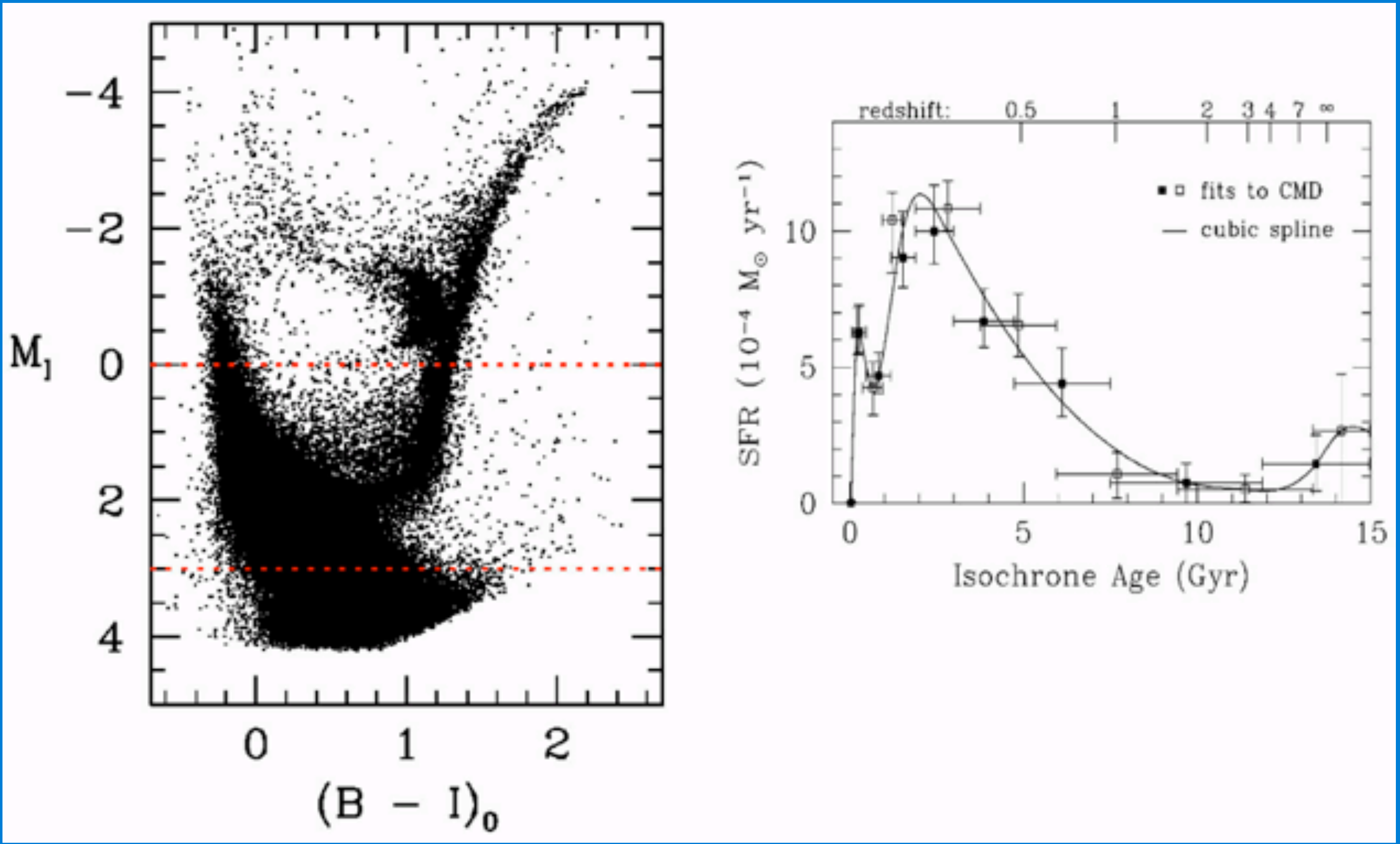




of partial models for a synthetic CMD computed with constant SFR(t) from 15 Gyr ago to the present, Z = 0.0004, Kroupa et al. (1993) IMF, tars. The left panel shows the theoretical synthetic CMD, while in the CMD of the right panel observational errors have been simulated (see quence of ages in both the MS and the subgiant branch and, although less definite, also in the RC and HB.

Gallart et al. 1999, ApJ, 514, 665

Gallart et al. 1999, AJ, 118, 2245



−4
−2
M_I
0
2
4
0
1
2
$(B - I)_0$
redshift:
0.5
1
2
3
4
7
∞
fits to CMD
cubic spline
SFR (10^{-4} $M_\odot$ yr^{-1})
10
5
0
0
5
10
15
Isochrone Age (Gyr)

- Unclassifiable galaxies?
  - ~2% of galaxies cannot be classified as E, S, Irr
  - predominantly disturbed or interacting systems
  - At high-redshift, ~30% galaxies are peculiar

NGC 5128 = Cen A

NGC 4038/9 = "Antennae"

Correlation with Hubble type

THE HUBBLE SEQUENCE 123

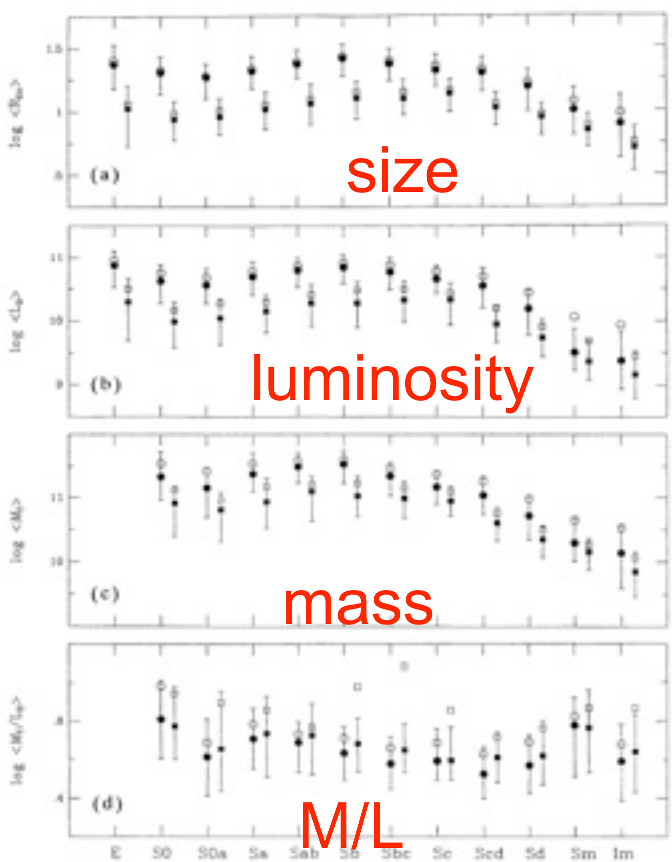


Figure 2 Global galaxy parameters vs morphological type. Circles represent the RC3-UGC sample; squares the RC3-LSc sample. Filled symbols are medians; open ones are mean values. The lower bar is the 25th percentile; the upper the 75th percentile. Their range measures half the sample. The sample size is given in Table 1. (*a*) log linear radius R_{lin}(kpc) to an isophote of 25 B mag/arcsec^2, (*b*) log blue luminosity L_B in solar units, (*c*) log total mass M_T in solar units, (*d*) log total mass-to-luminosity ratio M_T/L_B.

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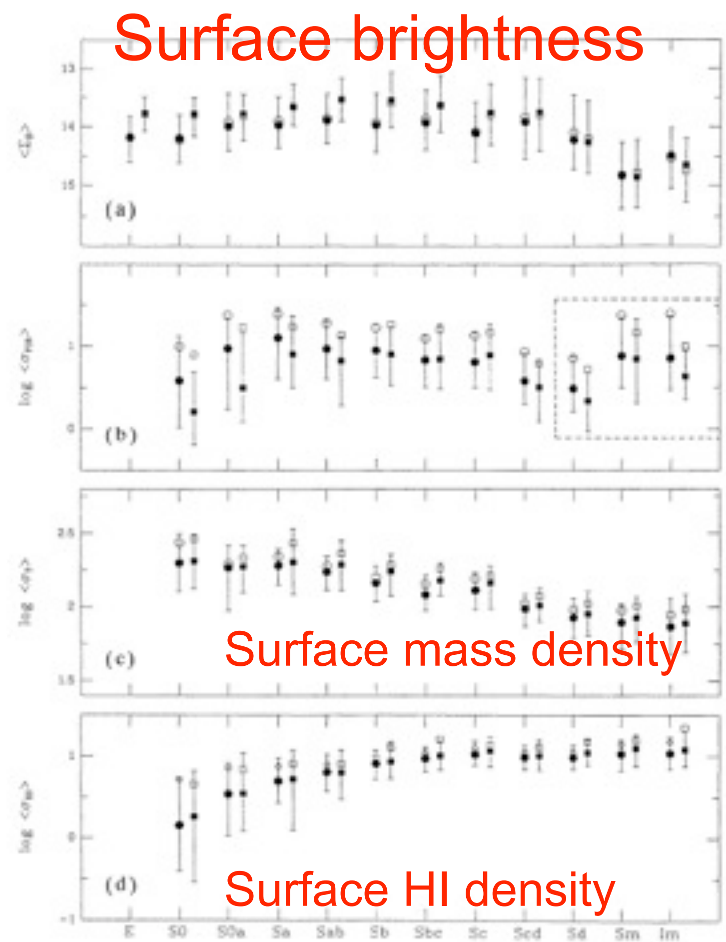


Figure 3 Same as Figure 2, for (*a*) optical (blue) surface brightness Σ_B, (*b*) log FIR surface density σ_{FIR}, (*c*) log total mass surface density Σ_T, (*d*) log HI surface density σ_{HI}. Dashed lines delineate the types with significantly fewer data.

Correlation with Hubble type

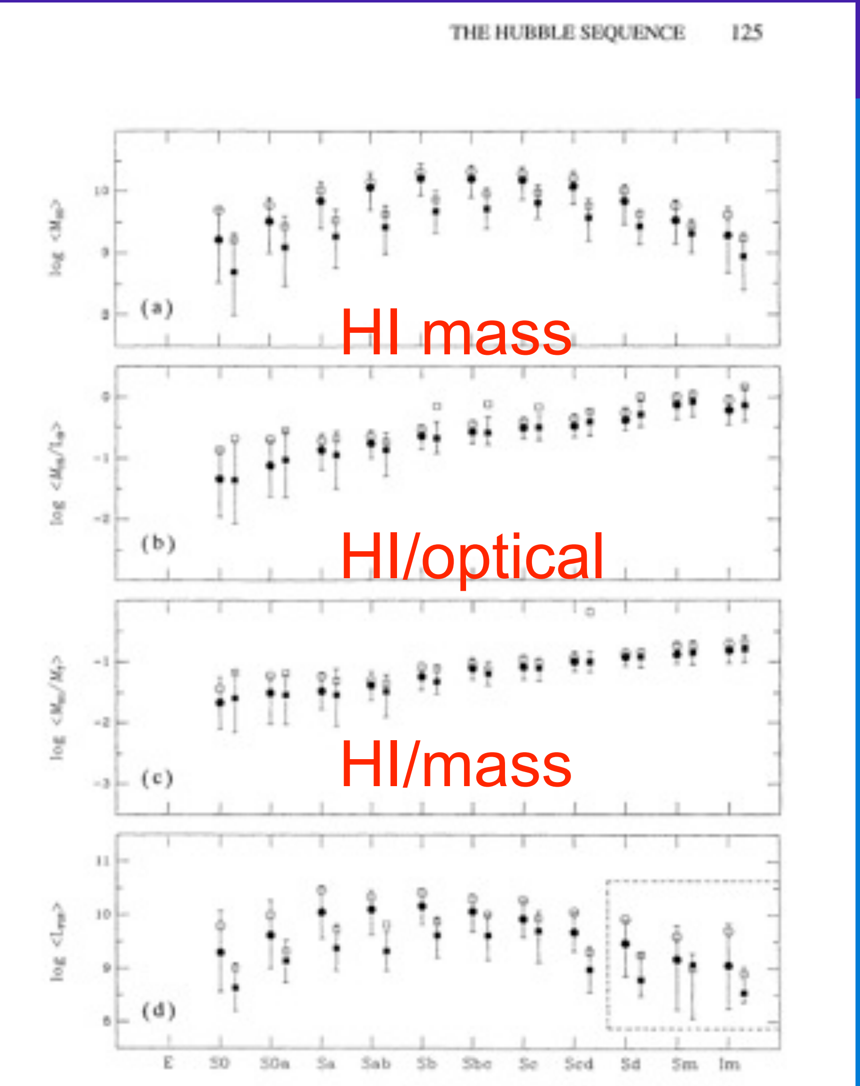


Figure 4 Same as Figure 2, for (*a*) log total HI mass M_{HI}, (*b*) log HI mass-to-blue luminosity ratio M_{HI}/L_B, (*c*) log HI mass fraction M_{HI}/M_T, (*d*) log FIR luminosity L_{FIR}. The dashed lines indicate significantly fewer data for these types.

Other Classification Systems

- Revised Hubble system

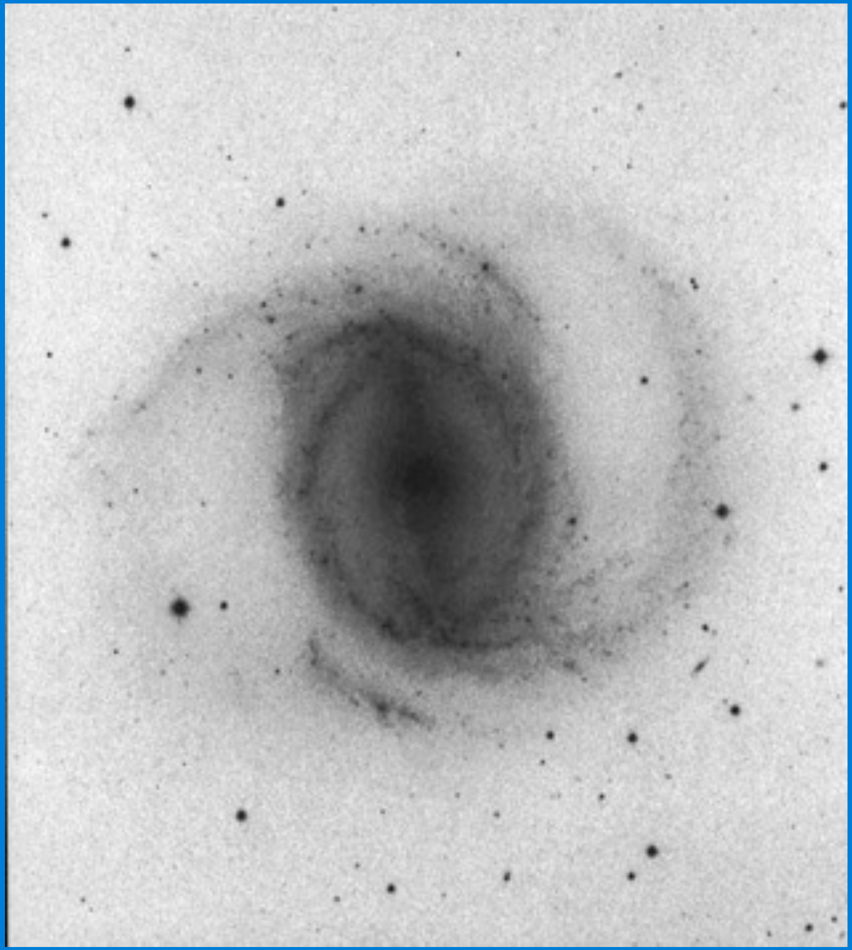
    de Vaucouleurs 1958, Handbuch der Phys, 53, 275

    de Vaucouleurs 1964, Reference Catalog of Bright Galaxies (RC1)

  - goal: retain basic system, add more information
    - mixed types: E/S0, Sab, Sbc, etc
    - intermediate barred: SA, SAB, SB
    - extended types: Sd, Sm, Sdm
    - inner rings: S(r) , S(s)
    - outer rings: (R) S
    - Magellanic spirals, irregulars: Sm, Im
    - t-type numerical scale: E0 -- S0 -- Sa -- Sb -- Sc -- Im
    - -5 -- -1 --- 1 --- 3 --- 5 --- 9

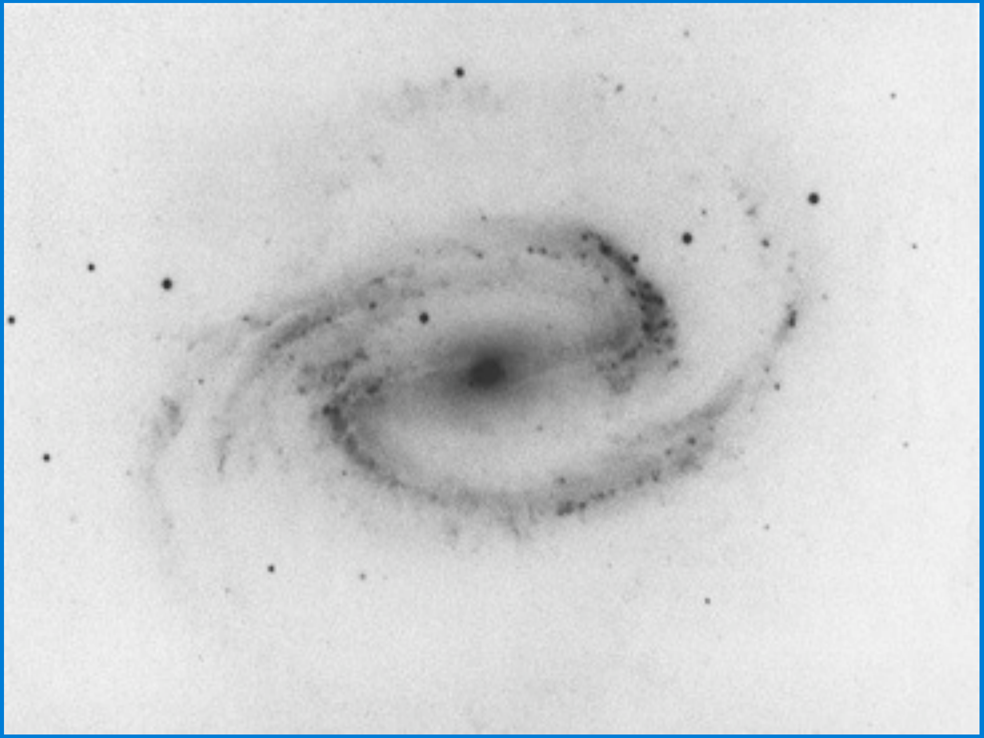
NGC 1433

(R)SB(r)ab



NGC 1300

SB(rs)bc



Quantitative Classification

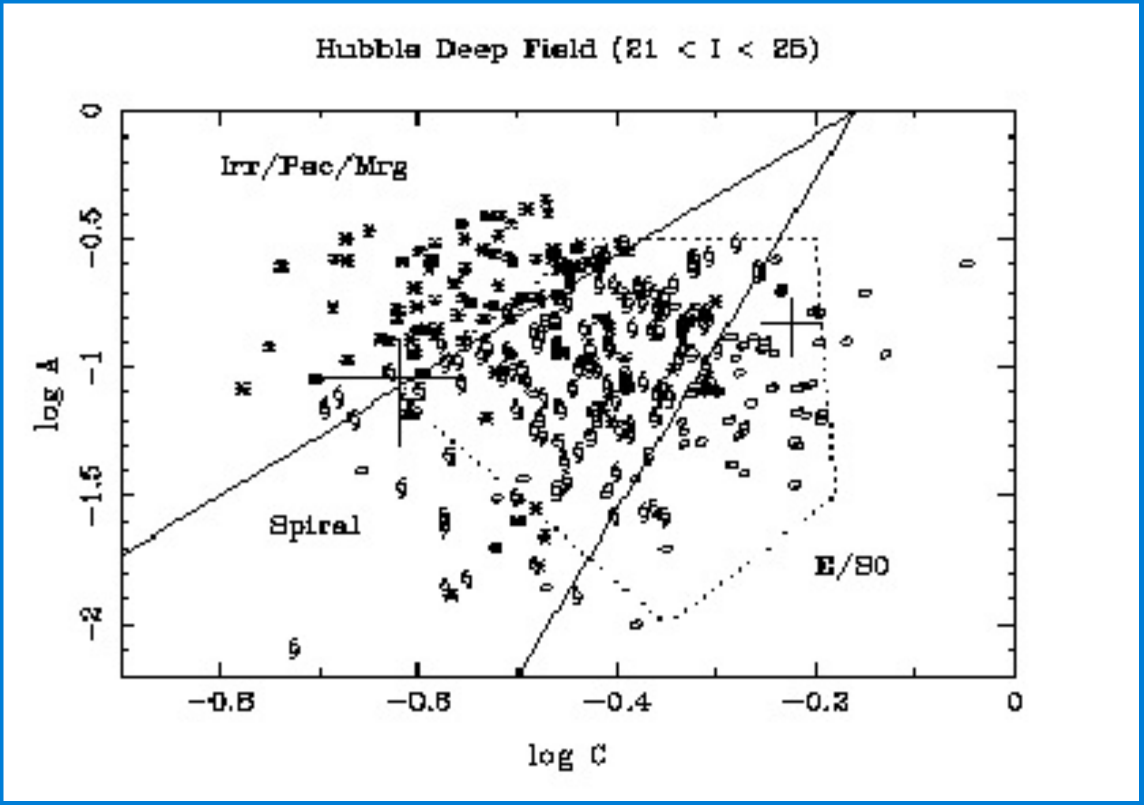
- Motivation
  - automated classification is needed for very large imaging or spectroscopic surveys (e.g., Sloan Digital Sky Survey = SDSS)
  - can obtain objective measures, that are less susceptible to systematic or subjective effects
  - the current morphological sequence may not be representative of galaxies at earlier cosmic epochs
  - since many physical and spectral properties of galaxies correlate with type, a physical classification system can be created
  - parametric classifications provide information on the dimensionality of the galaxy parameter space

- Example 1: Quantitative image classification

  Abraham et al. 1994, ApJ, 432, 75

  Abraham et al. 1996, MNRAS, 279, L49

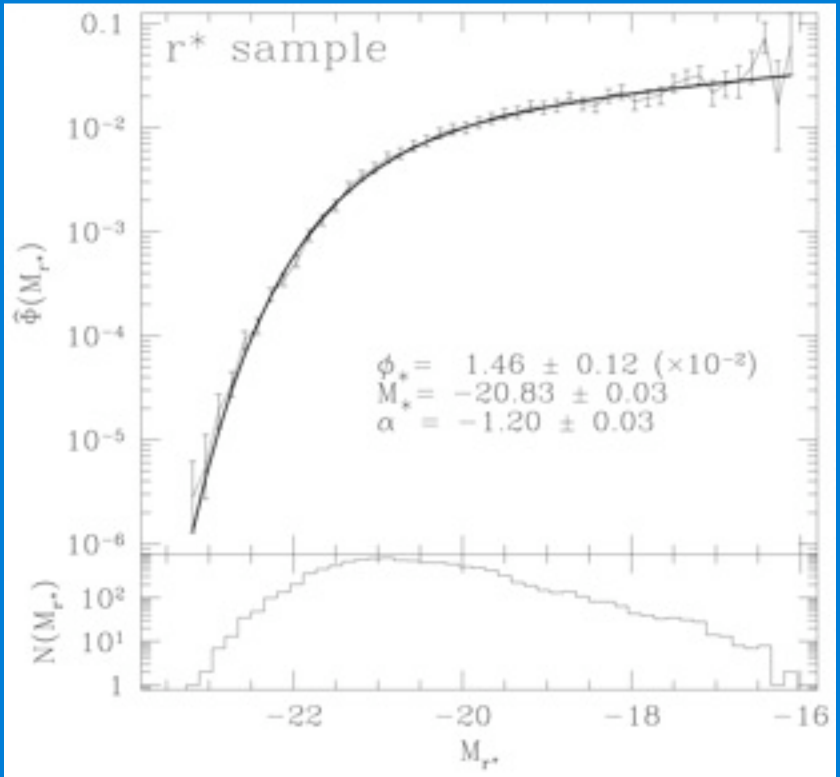
  - simple 2-parameter system



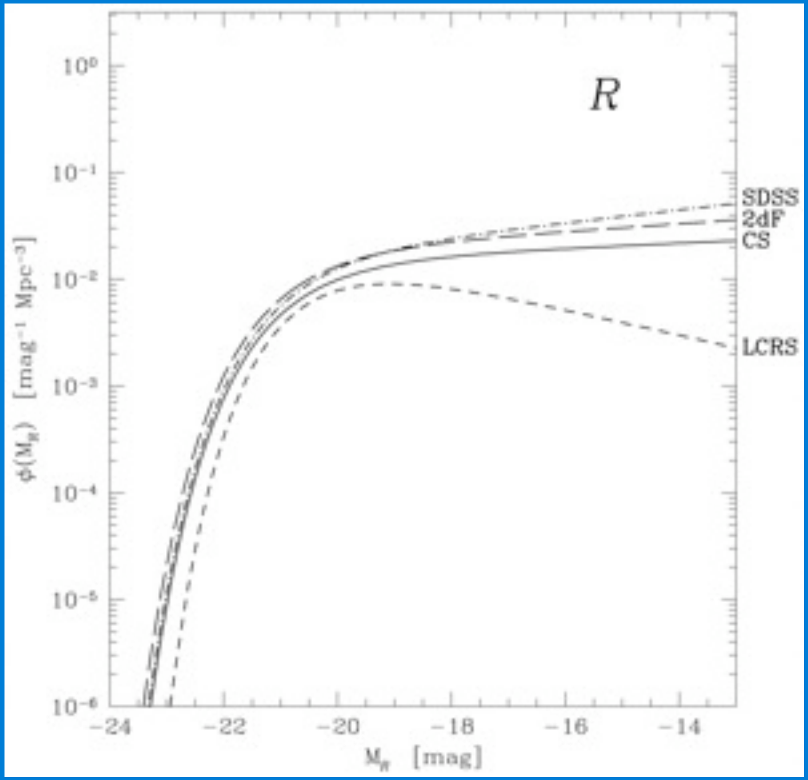
Luminosity Function

- galaxies span enormous luminosity range: M_B = -24 to -10
  - luminosity distribution well constrained for $M_B < -15$
- parametrization: Schechter 1976, ApJ, 203, 297

$$\Phi(L) = \Phi(L^*)\ (L/L^*)^{\alpha}\ e^{-L/L^*}$$

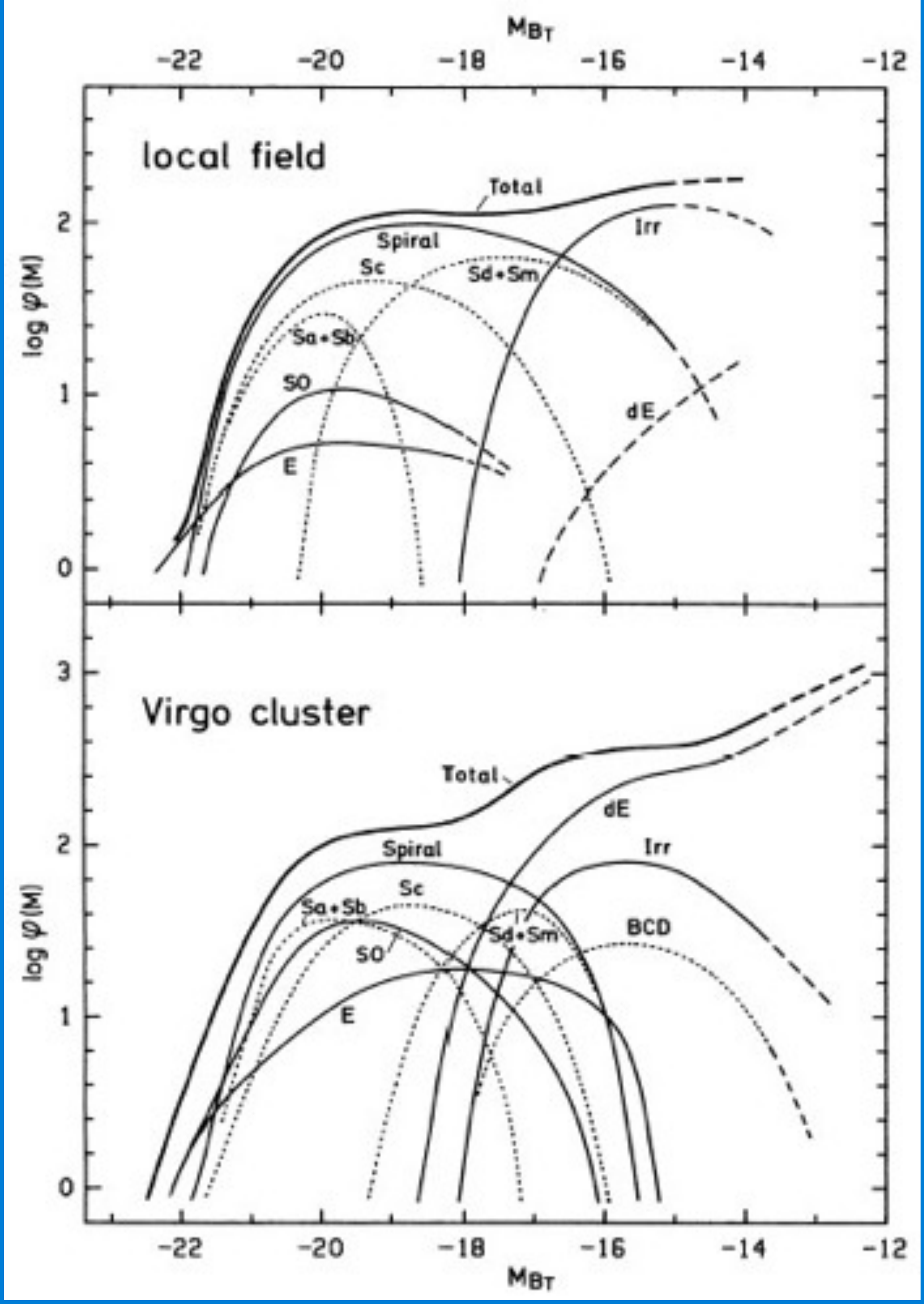


Blanton et al 2001, AJ, 121, 2358 (SDSS)

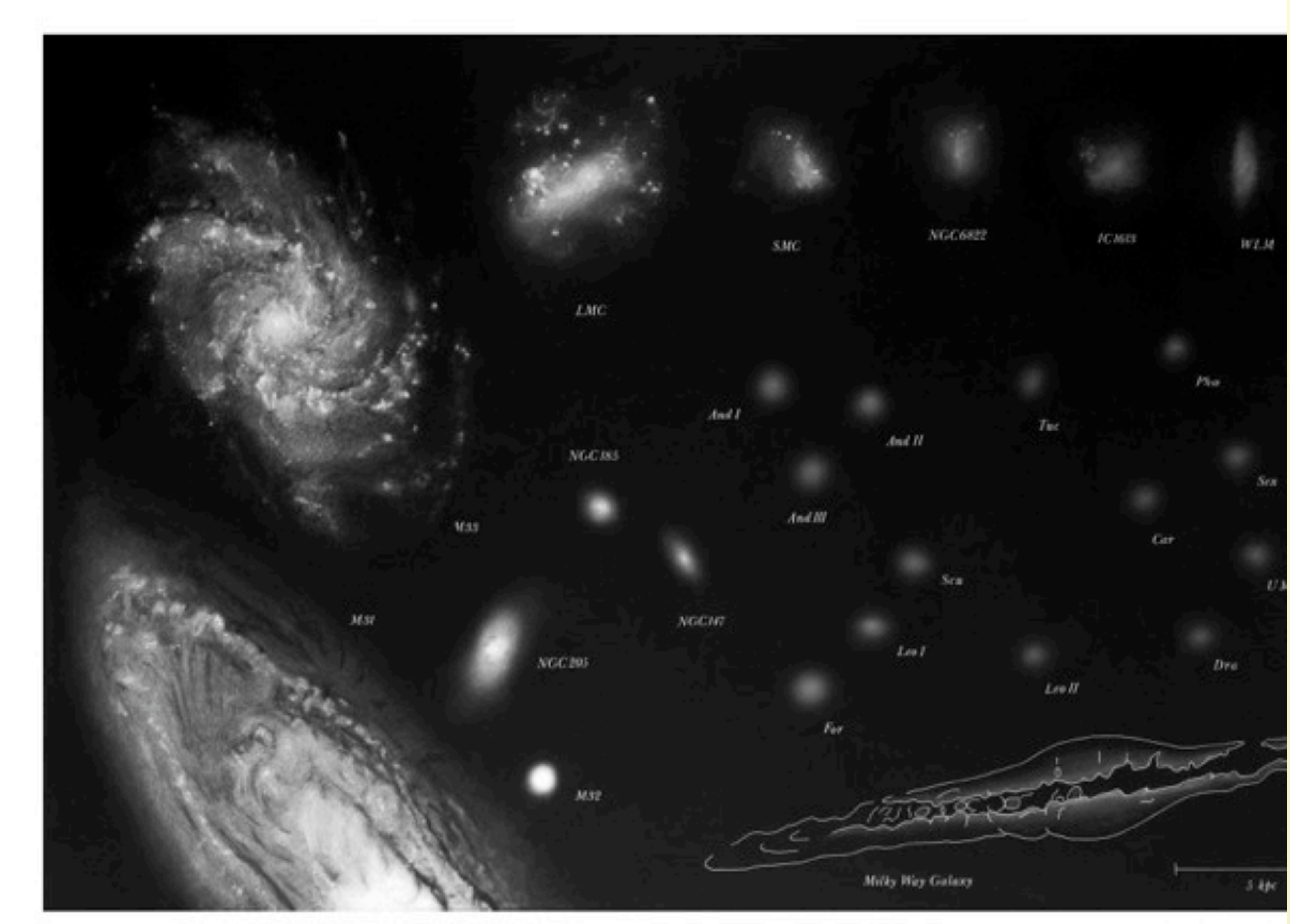


Brown et al 2001, AJ, 122, 297 (CfA)

- Form of LF at faint luminosities still uncertain, controversial
- LF is strong function of galaxy type
- LF probably is dependent on galaxy environment



Binggeli, Sandage, Tammann 1988, ARAA, 26, 509



LMC
SMC
NGC 6822
IC 1613
WLM
M33
M31
M32
NGC 185
NGC 147
NGC 205
And I
And II
And III
Tuc
Phe
Sex
Car
Scu
Leo I
Leo II
Dra
For
Milky Way Galaxy
5 kpc

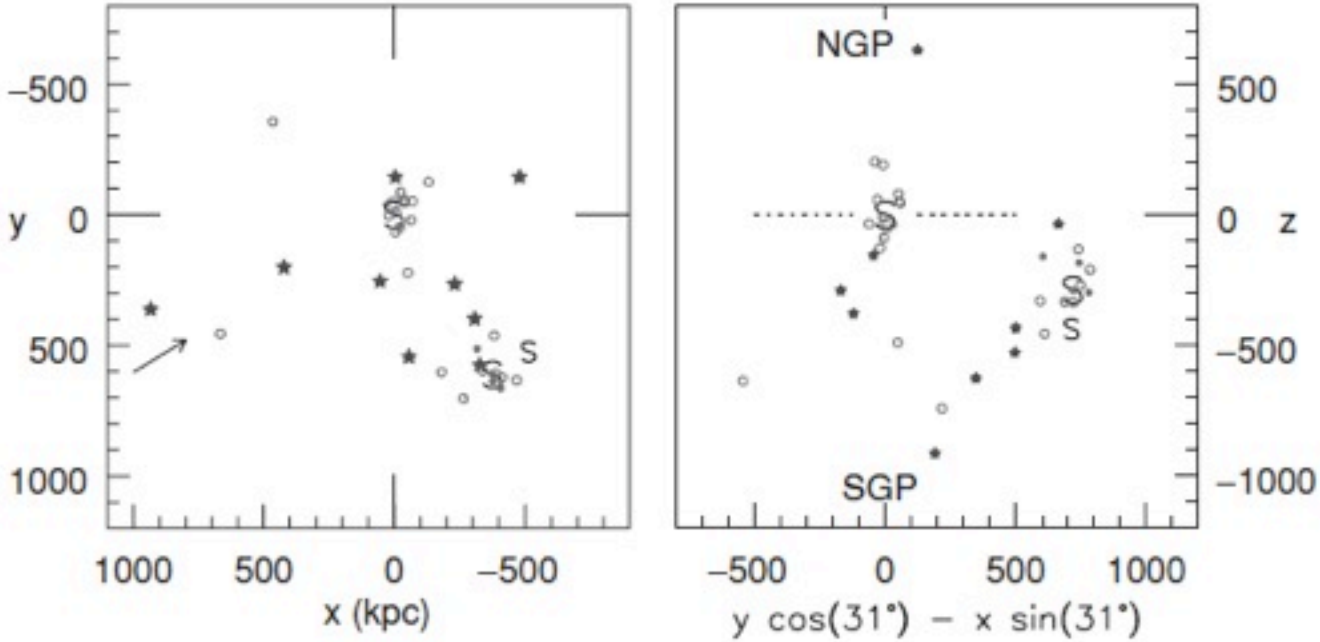


Fig. 4.2. The Local Group: our Milky Way is at the origin. Spirals are designated S; asterisks show the Magellanic Clouds; filled stars mark irregular galaxies; circles are ellipticals or dwarf ellipticals (filled) and dwarf spheroidals (open). Left, positions projected onto the Galactic plane; axis *x* points to the Galactic center, *y* in the direction of the Sun's orbital motion. The arrow shows the direction of view in the right panel. Right, view perpendicular to the plane containing M31 and axis *z* toward the north Galactic pole; the dotted line marks the Galactic midplane. Many of the Milky Way's satellites, including the Magellanic Clouds, lie near a single plane.

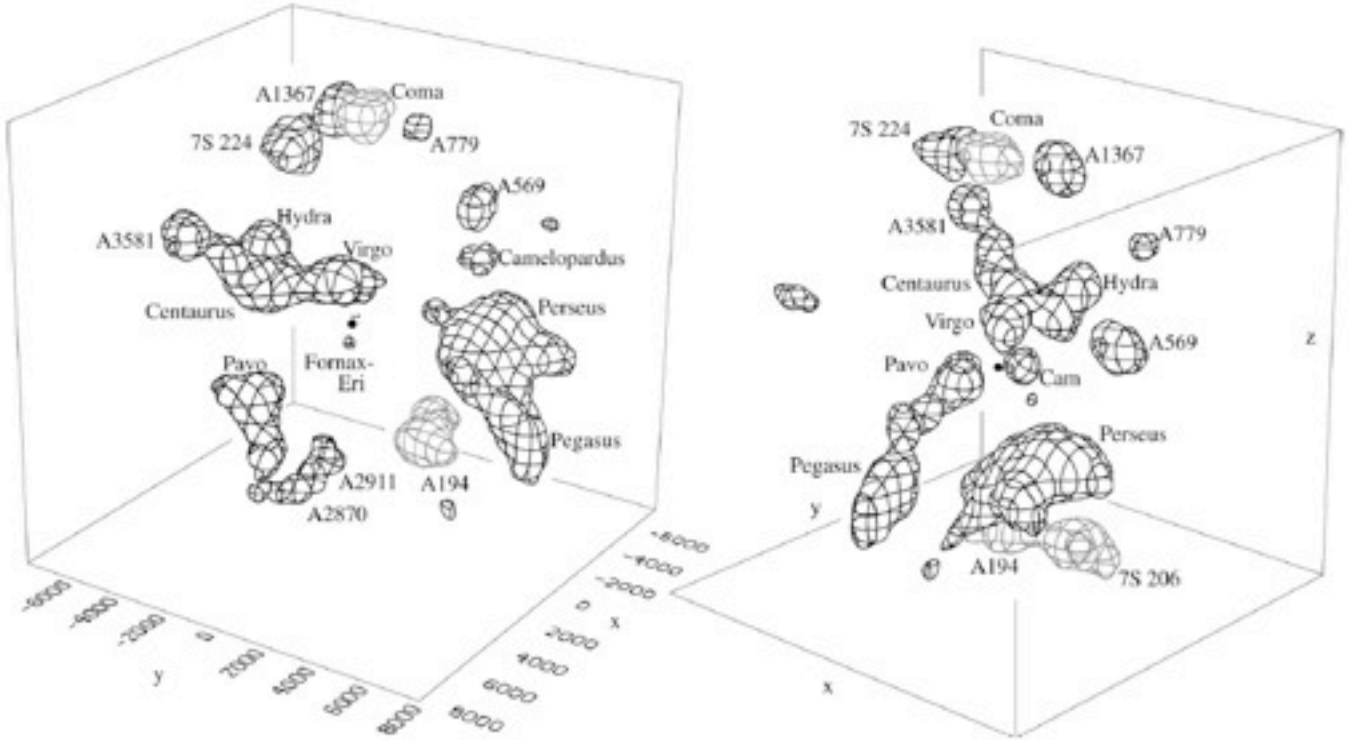
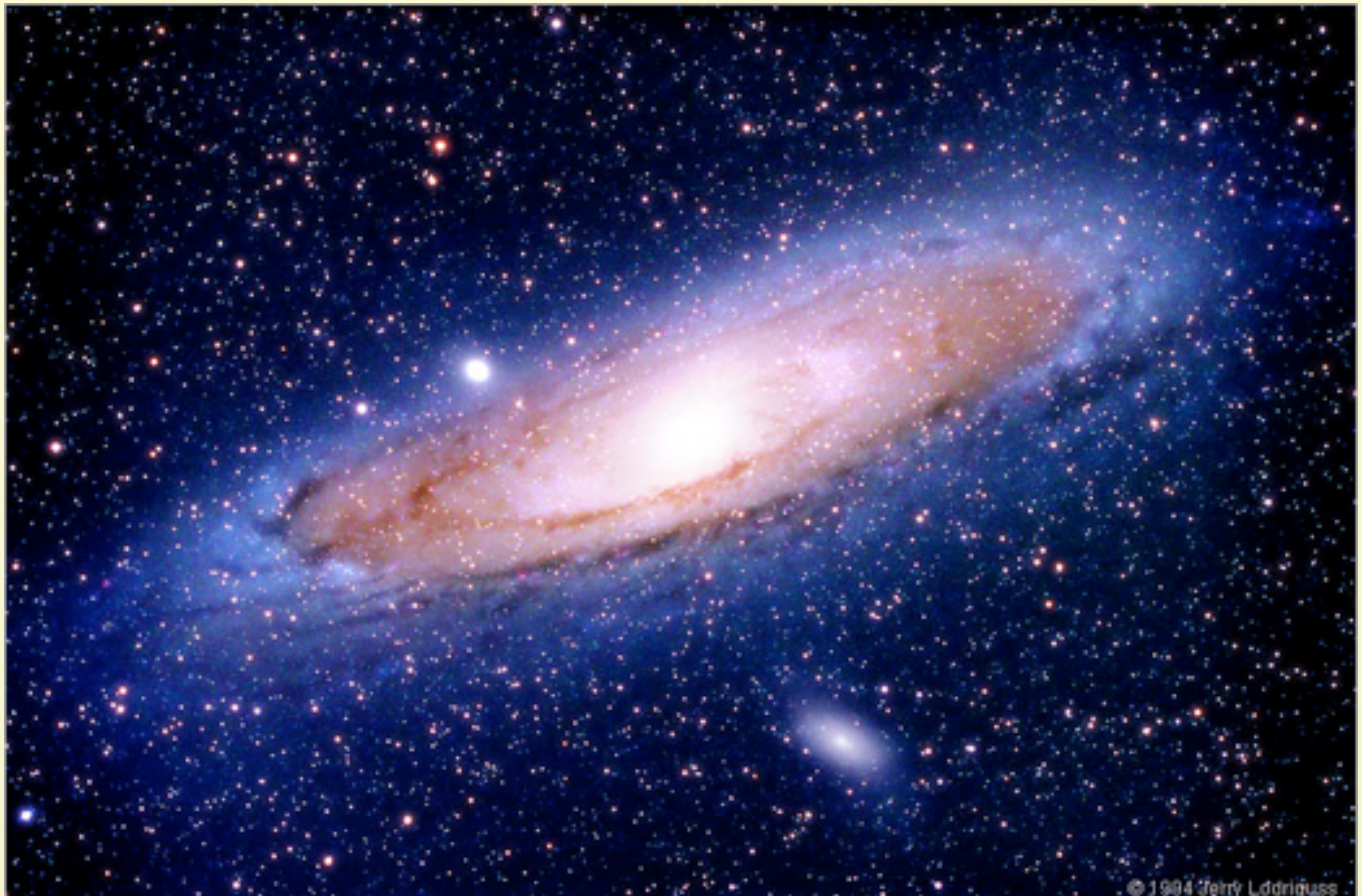
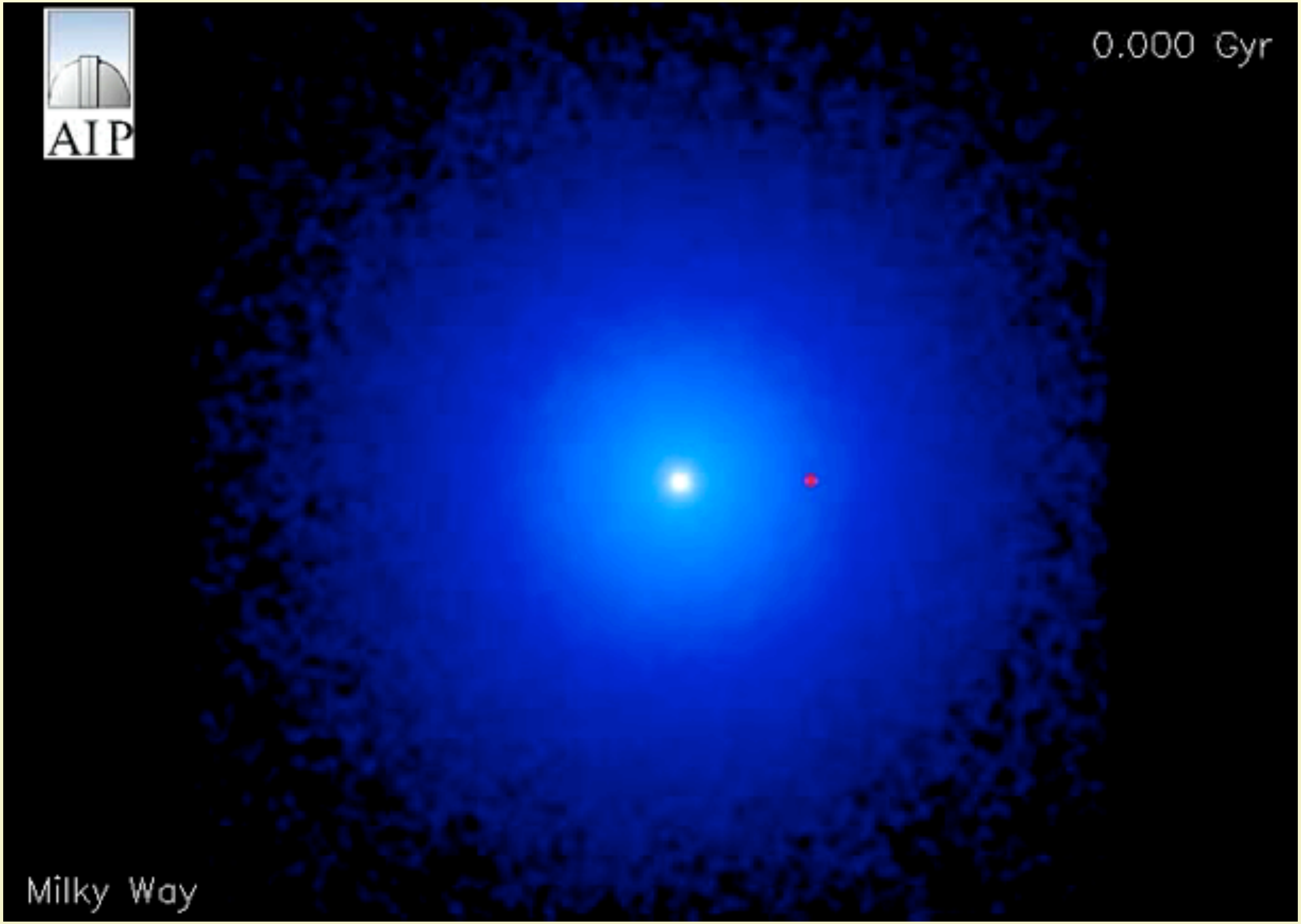


Fig. 4.3. Galaxy concentrations within $80h^{-1}$ Mpc of the Local Group: the 'mesh' encloses regions where the density is $\gtrsim 50\%$ above average. The filled dot gives our position at the origin, and axes x, y, z are as in Figure 4.2. Distance d to each galaxy is calculated from Hubble's law: axes show H_0d in $\mathrm{km\,s^{-1}}$. Objects from Abell's catalogue of galaxy clusters are denoted A. Left, view from $(l, b) = 35°, 25°$, perpendicular to the supergalactic X–Y plane; right, view from $(l, b) = 125°, 25°$, looking nearly along that plane – M. Hudson 1993 *MNRAS* **265**, 43.

M31




AIP
0.000 Gyr
Milky Way

Fate of M31

- Movie

Fate of Local Group

- Night Time View

M33

LMC and SMC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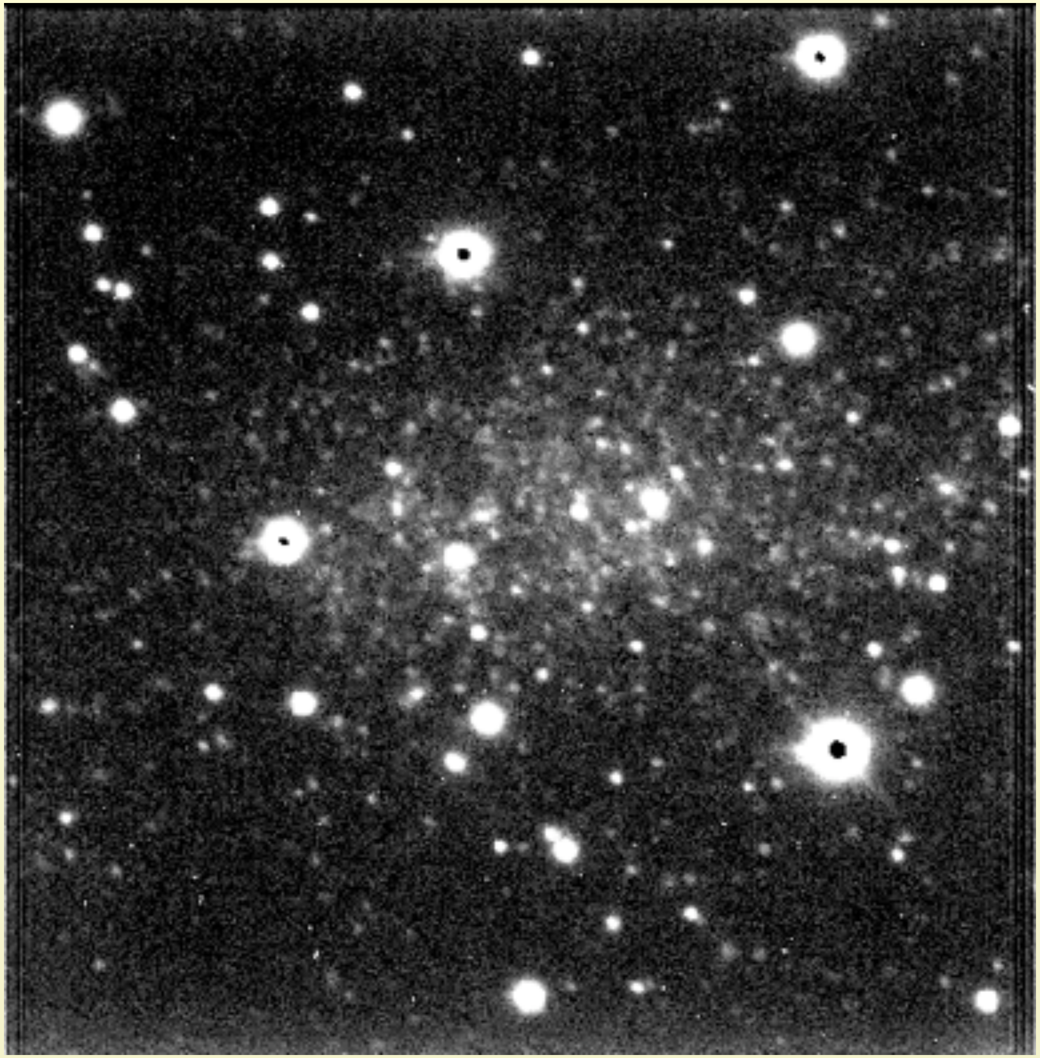
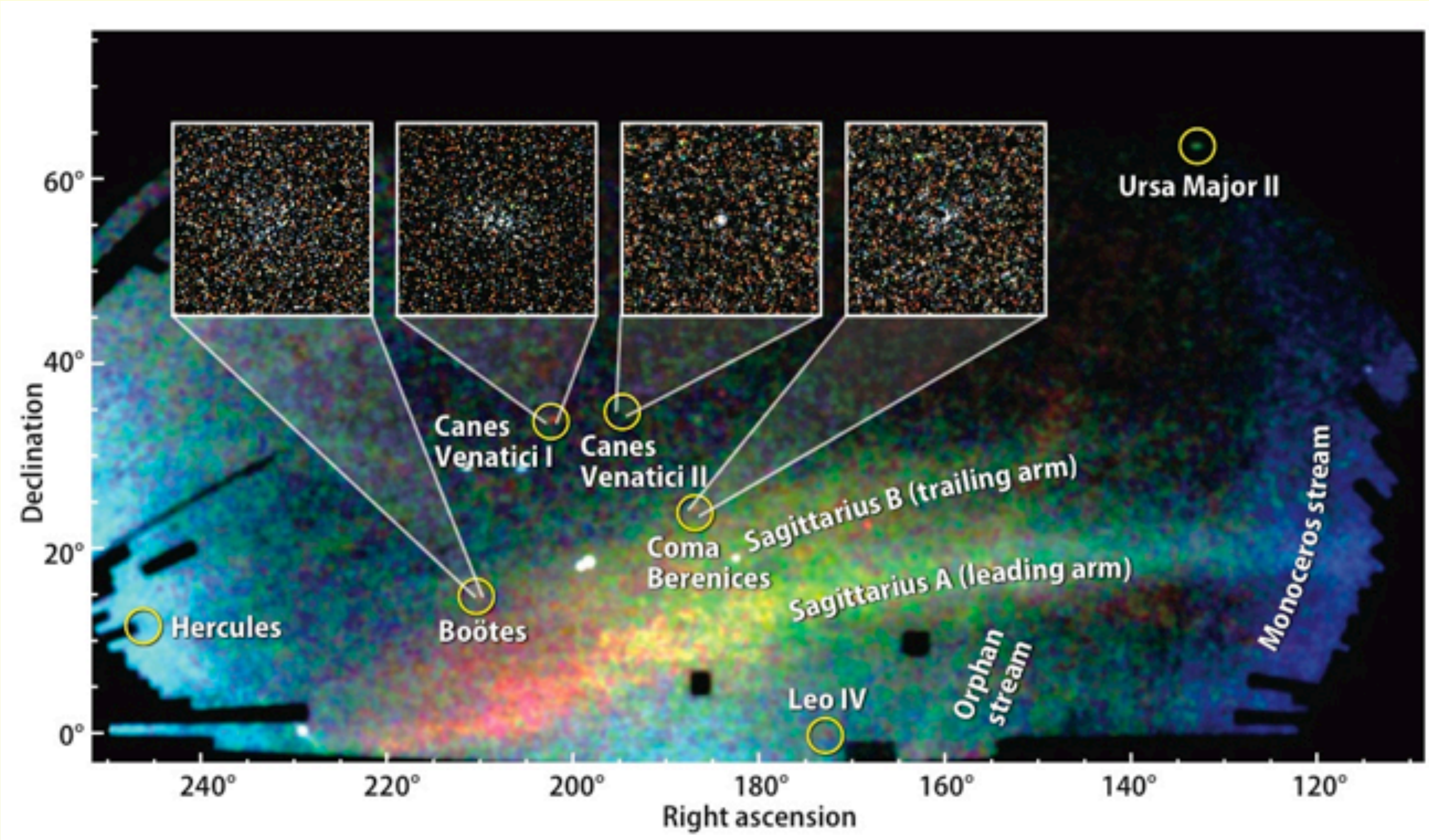
© Anglo-Australian Observatory/Royal Observatory, Edinburgh

Sagittarius Dwarf





Ursa Major II
60°
40°
20°
0°
Declination
Canes
Venatici I
Canes
Venatici II
Coma
Berenices
Sagittarius B (trailing arm)
Sagittarius A (leading arm)
Monoceros stream
Hercules
Boötes
Leo IV
Orphan
stream
240°
220°
200°
180°
160°
140°
120°
Right ascension

Leo T

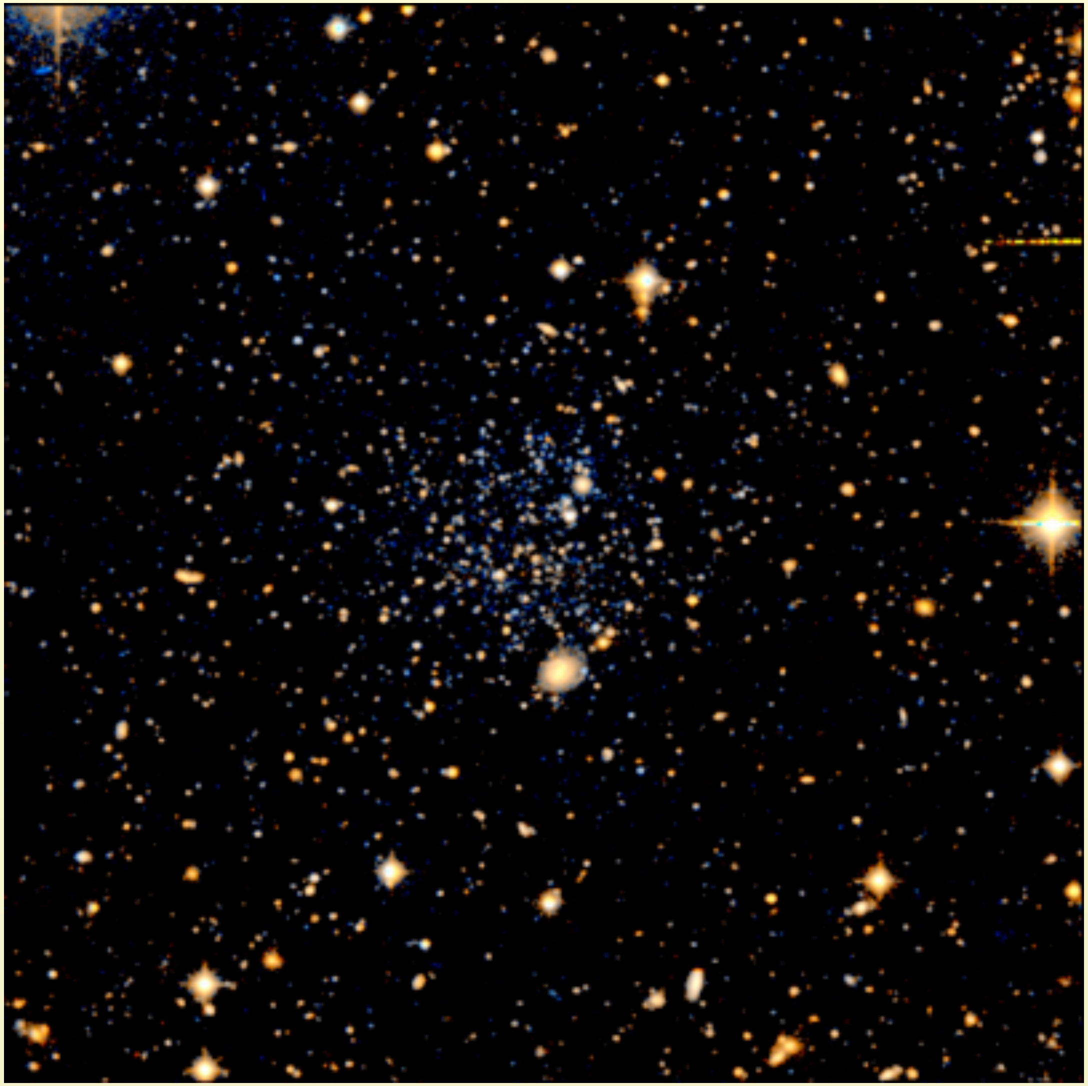
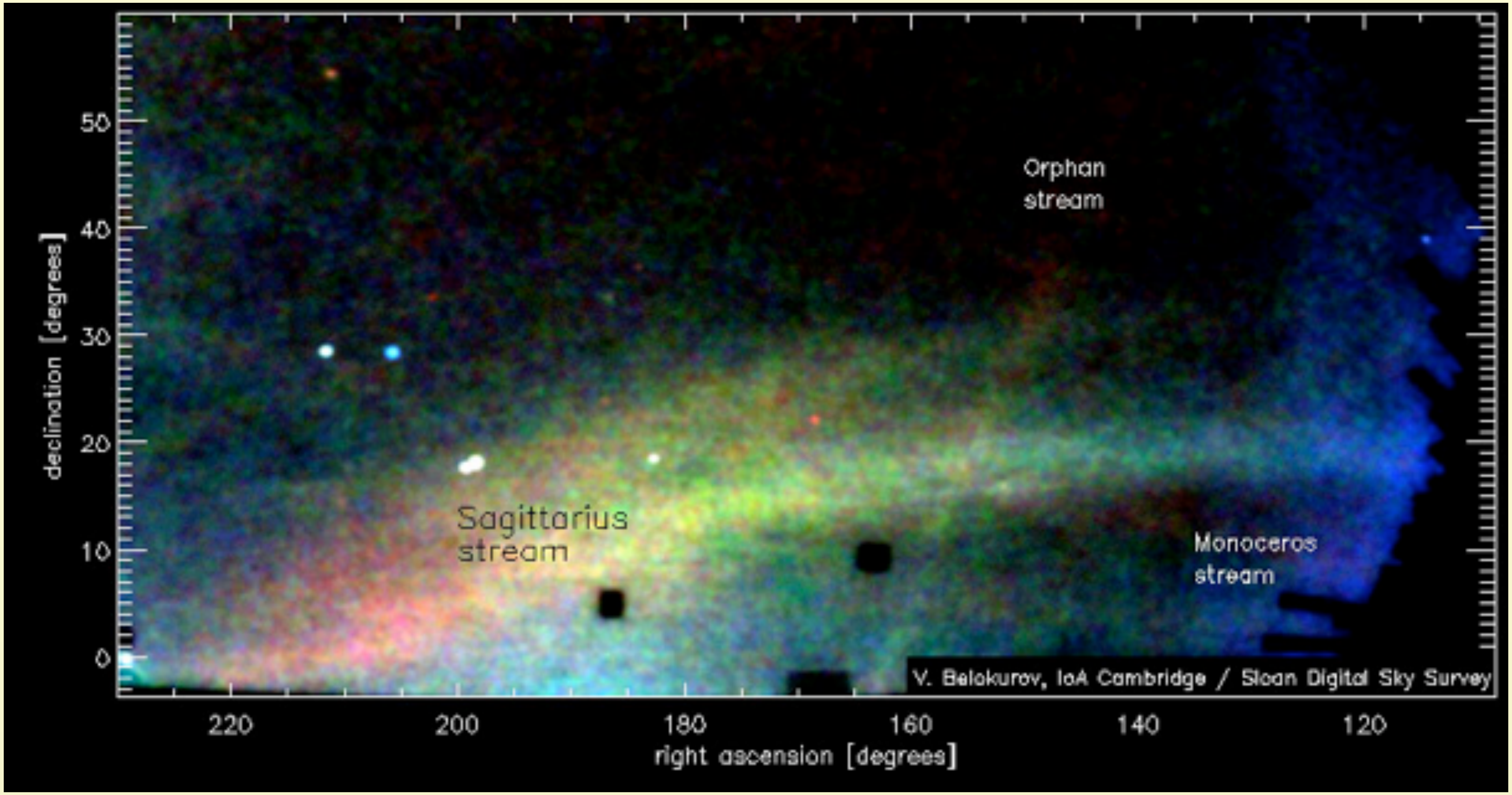


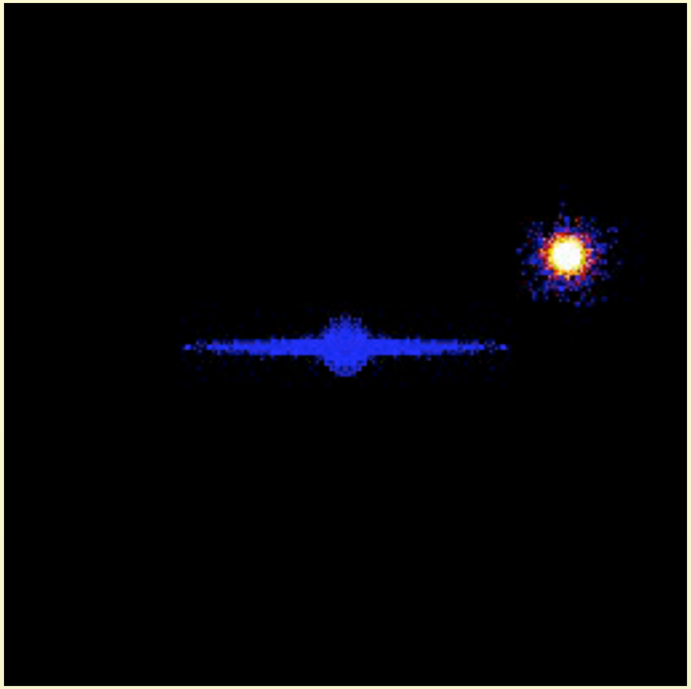
Table 4.2 Dwarf galaxies, compared with the nuclear star cluster of M33, and three Milky Way globular clusters

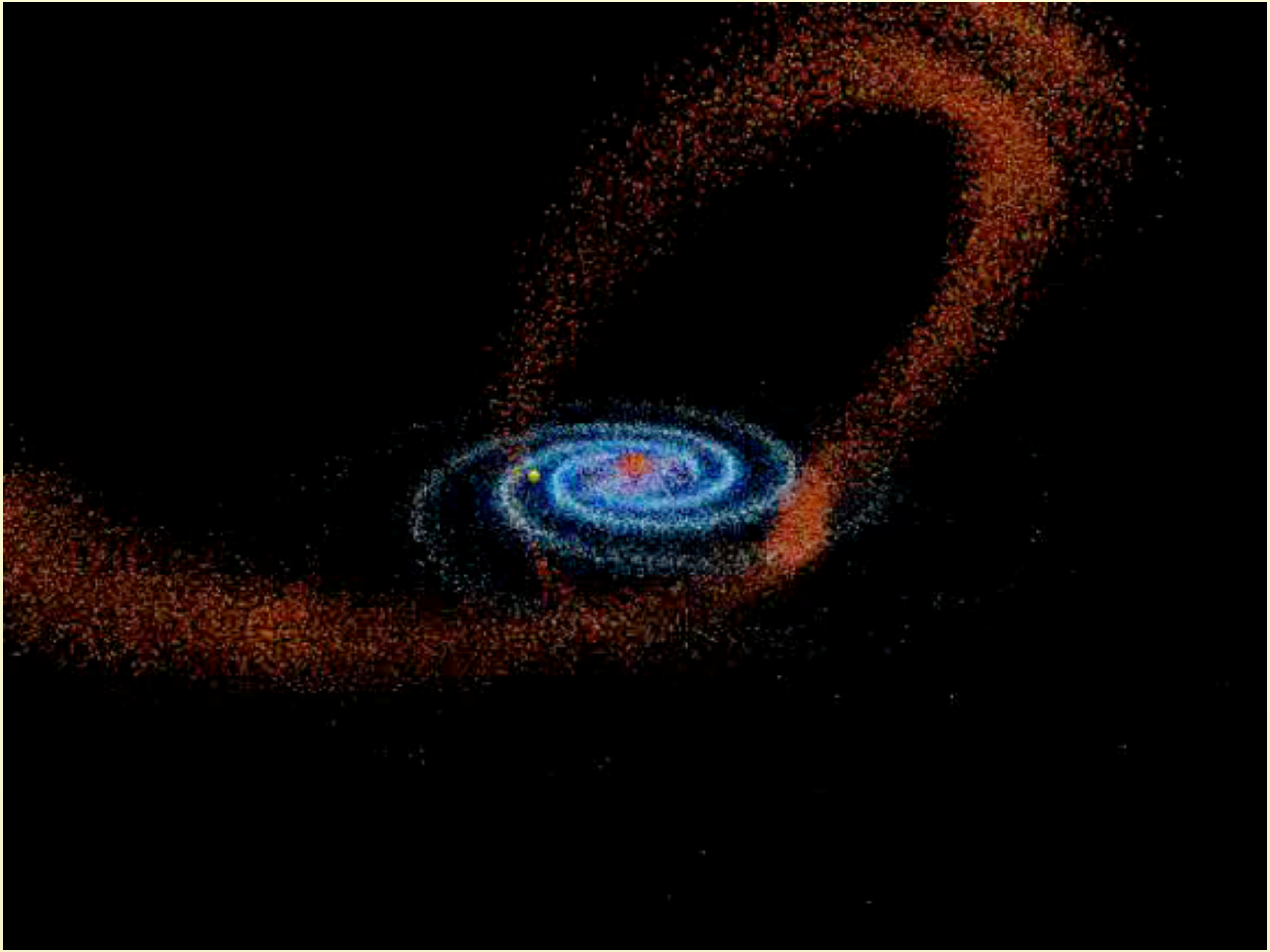
System	L_V ($10^7 L_\odot$)	σ_r (km s^{-1})	r_c (pc)	r_t (pc)	t_{sf} (Gyr)	$\mathcal{M}/L_V$ ($\mathcal{M}_\odot/L_\odot$)	$\log_{10}(Z/Z_\odot)$ range
NGC 147 dE	12	20–30	260	1000	3–5	7 ± 3	-1.5 to -0.7
NGC 185 dE	13	20	170	2000	<0.5	5 ± 2	-1.2 to -0.8
Pegasus dIrr	1	9(HI)		500(HI)	<0.1	2–4	-2.3 to -1.7
Fornax dSph	1.5	13	400	5000	<2	~15	-2 to -0.4
M33 nucleus	0.25	24	<0.4		<1:	~1	-1.9 to -0.7
Sculptor dSph	0.2	9	200	2000	>10	~10	-2.6 to -0.8
ω Cen gc	0.1	20	4	70	>10	2.5	-1.6 to -1.2
M15 gc	0.04	12	<0.01	85	>10	2	-2.15
Carina dSph	0.04	7	200	900	2–10	~40	-2.7 to -0.3
M92 gc	0.02	5	0.5	50	>10	1.5	-2.15

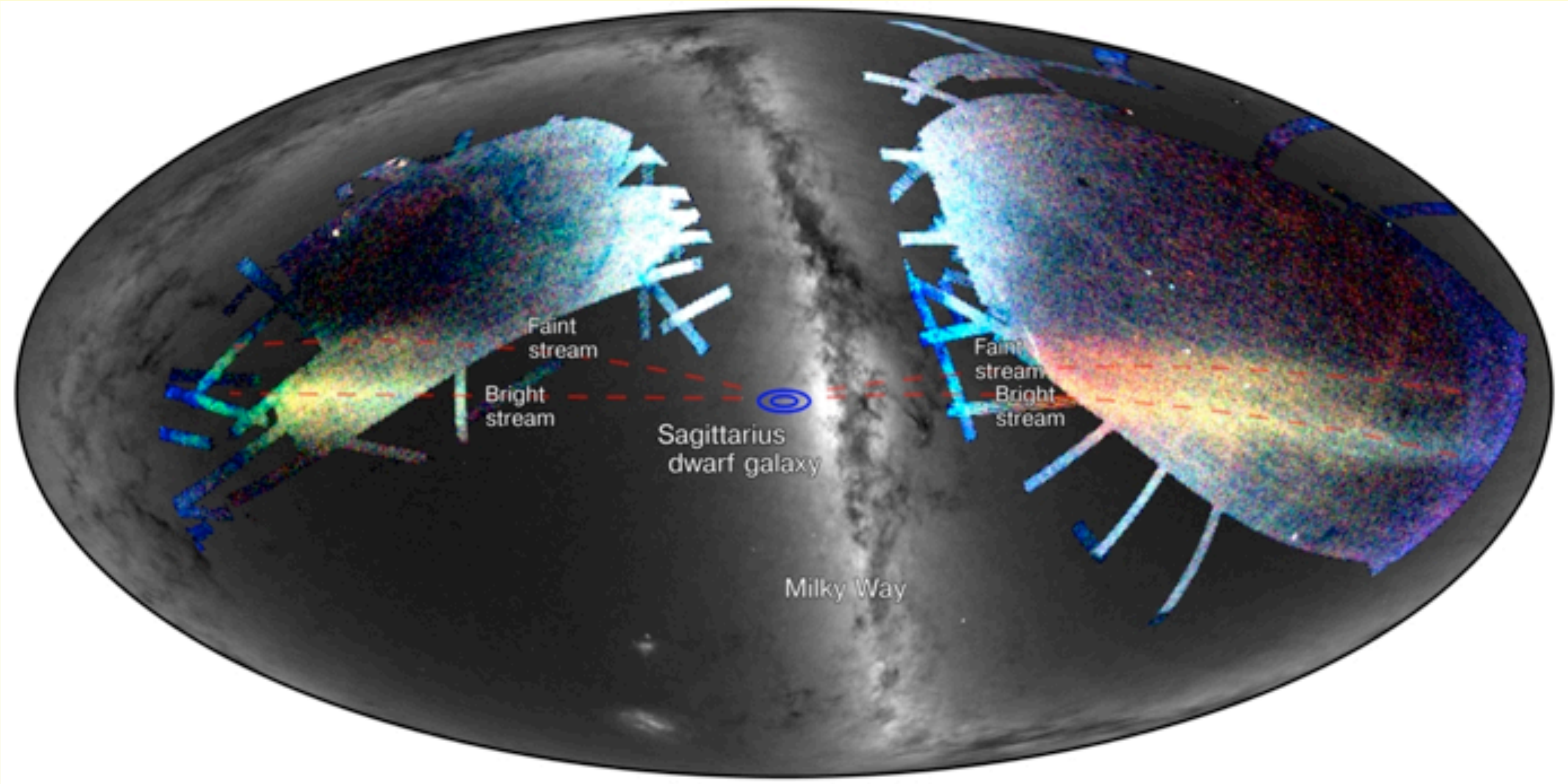
Note: The velocity dispersion σ_r is highest at the center; at the core radius r_c, the surface brightness falls to half its central value, dropping to near zero at truncation radius r_t; t_{sf} the time since last significant star formation, with : indicating an uncertain value; $Z/Z_\odot$ is metal abundance compared with that of the Sun. HI denotes a measurement from HI gas, not stars; globular clusters are labelled gc.



Orphan stream
Sagittarius stream
Monoceros stream
V. Belokurov, IoA Cambridge / Sloan Digital Sky Survey
declination [degrees]
right ascension [degrees]
50
40
30
20
10
0
220
200
180
160
140
120

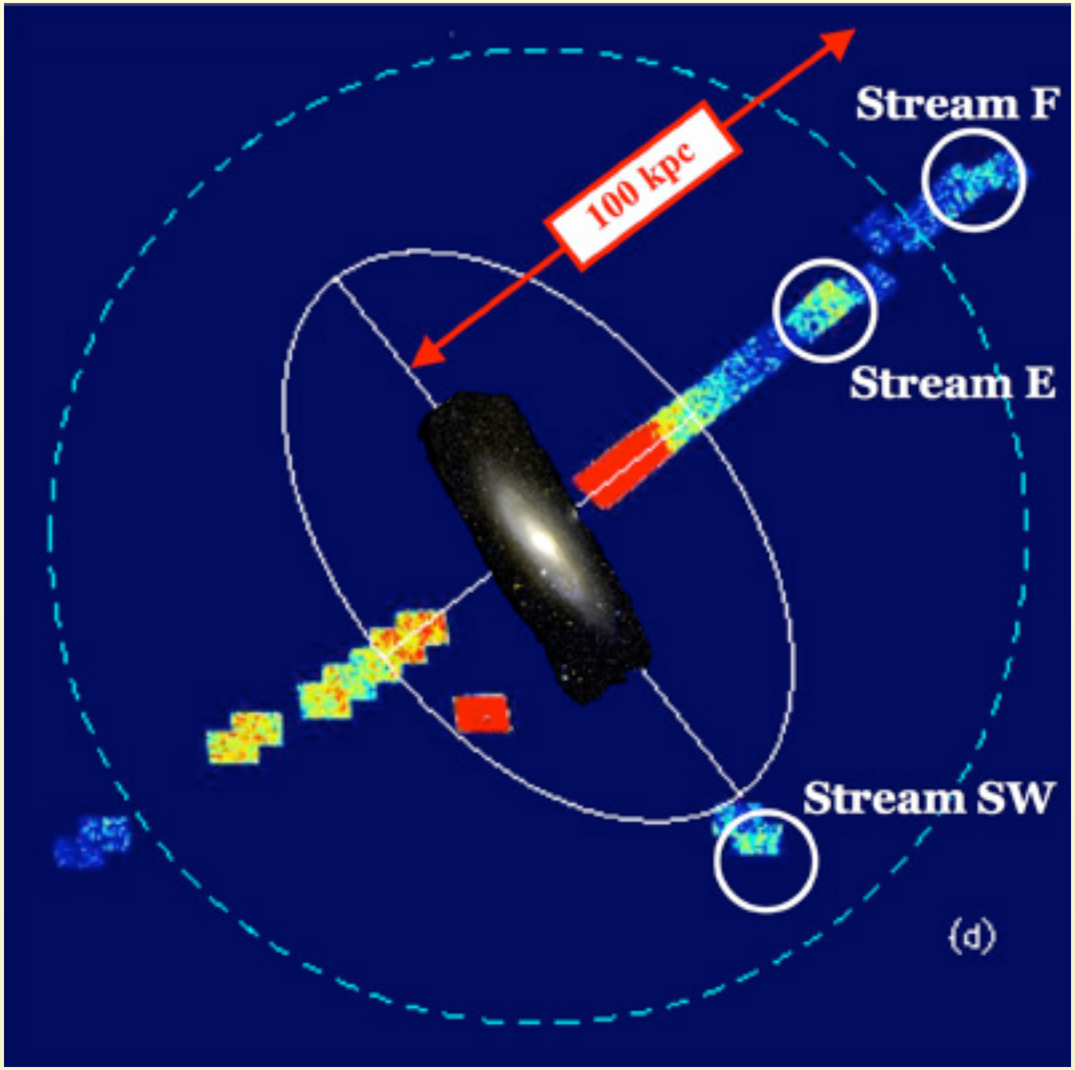


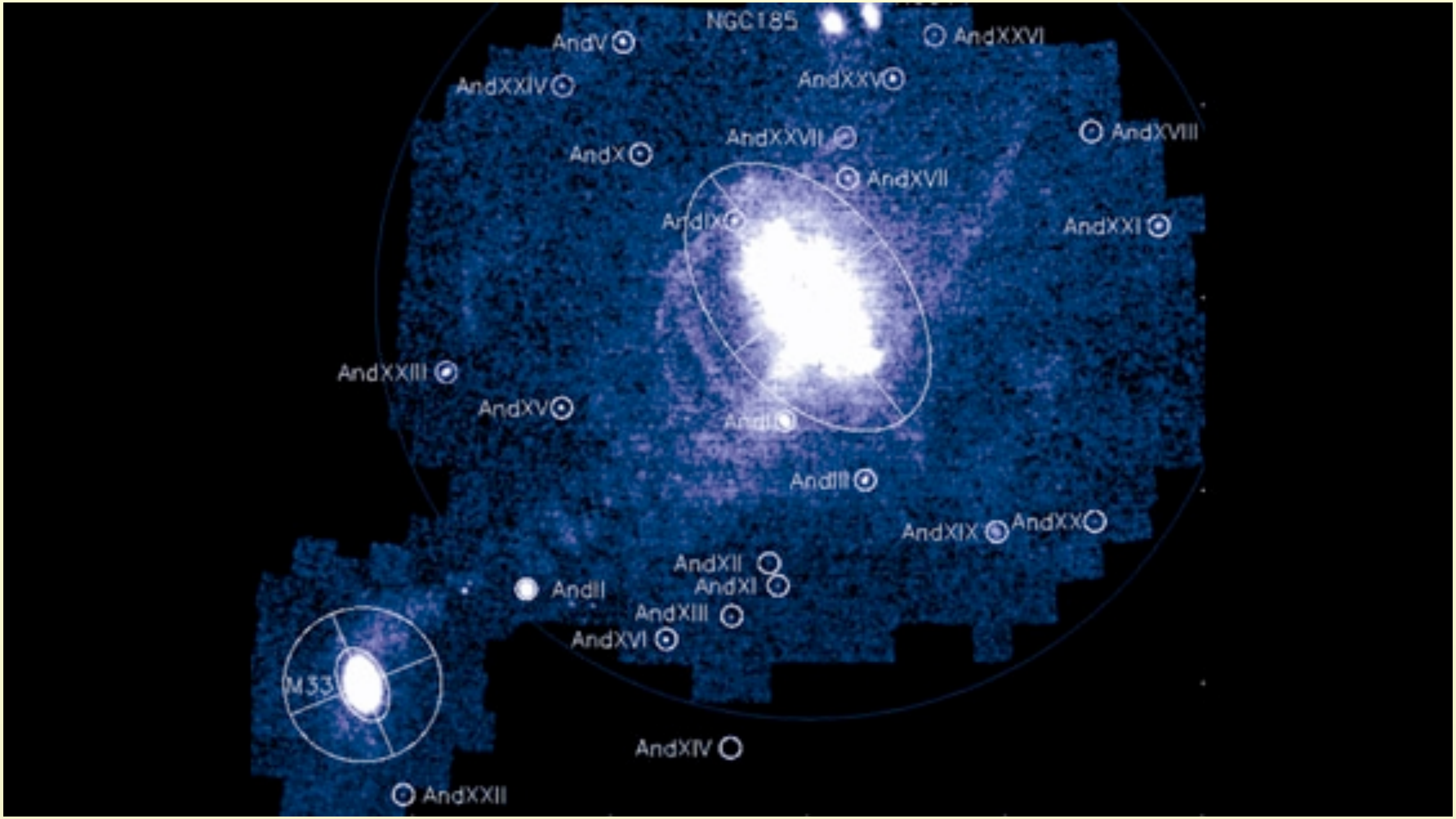



Faint
stream
Bright
stream
Sagittarius
dwarf galaxy
Faint
stream
Bright
stream
Milky Way

- Sagittarius movie

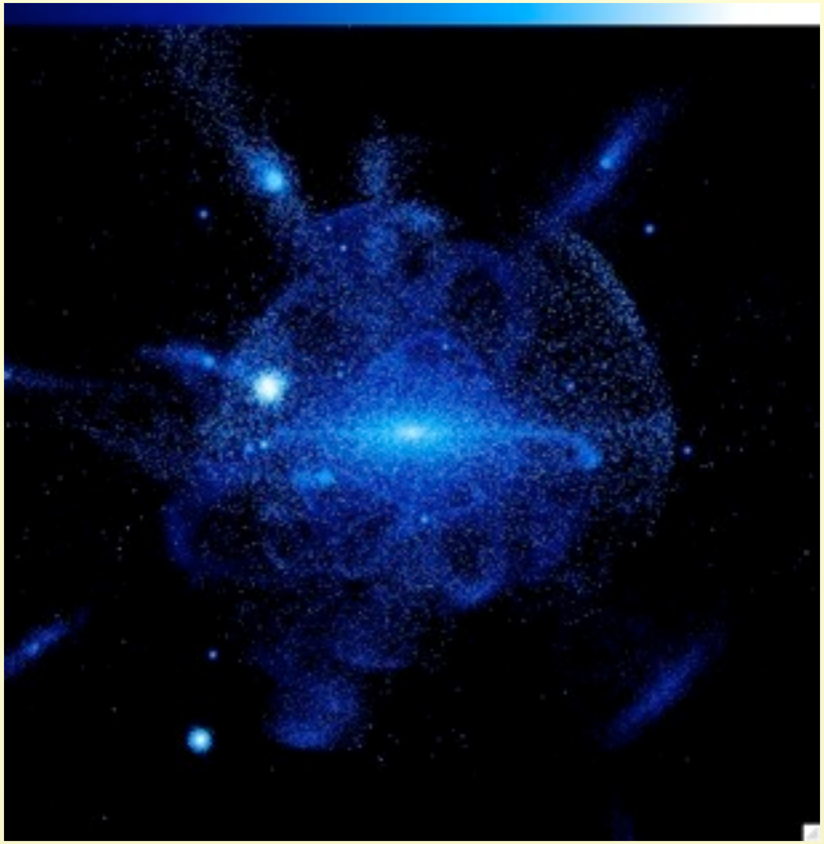
M31 tidal streams




NGC185
AndV
AndXXVI
AndXXIV
AndXXV
AndXXVII
AndXVIII
AndX
AndXVII
AndIX
AndXXI
AndXXIII
AndXV
AndI
AndIII
AndXIX
AndXX
AndXII
AndXI
AndII
AndXIII
AndXVI
M33
AndXIV
AndXXII

NGC 5907

Question: Assembly of Milky Way



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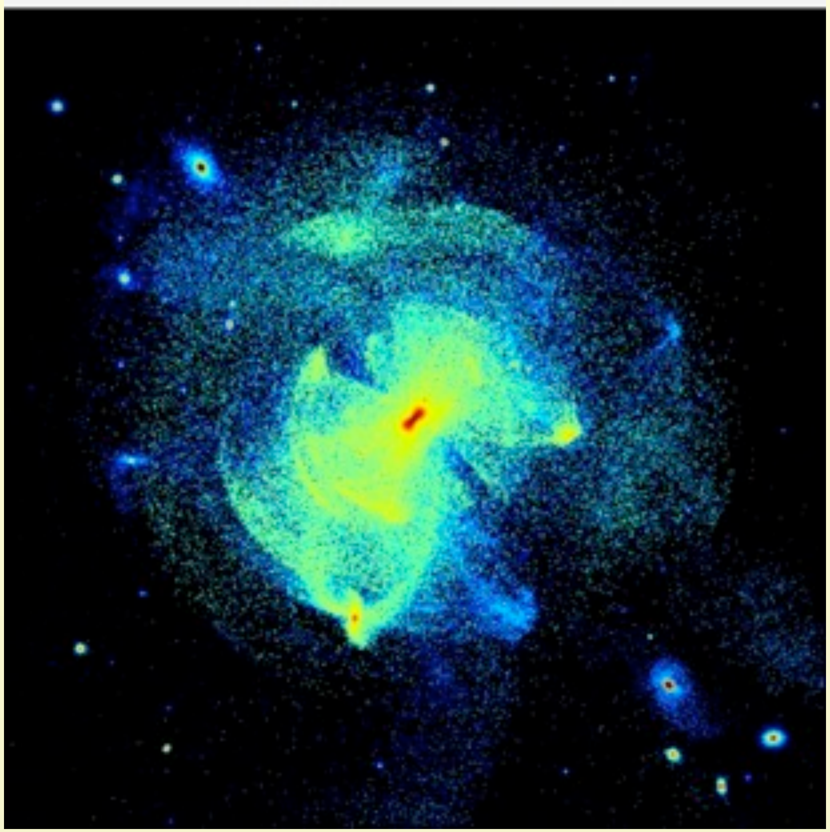
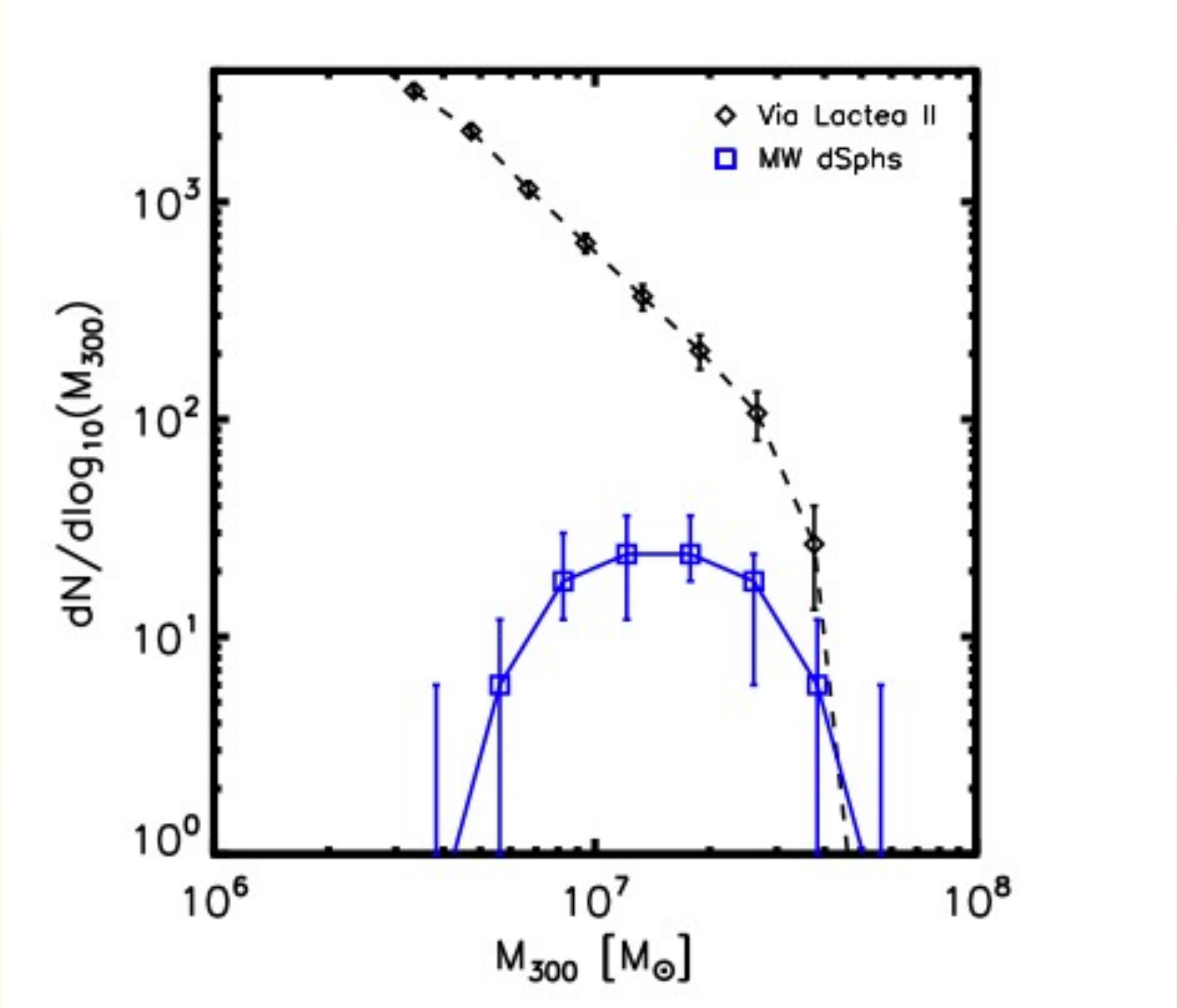
Galactic Archaeology



- Stellar halo largely built up as stellar streams with different degrees of phase-mixing
- Stars – collisionless: encode halo formation history
- Test of hierarchical structure formation
- Near-field cosmology

missing satellite problem



Astro-News: Oldest Star in the Universe

- what NPR has to say?

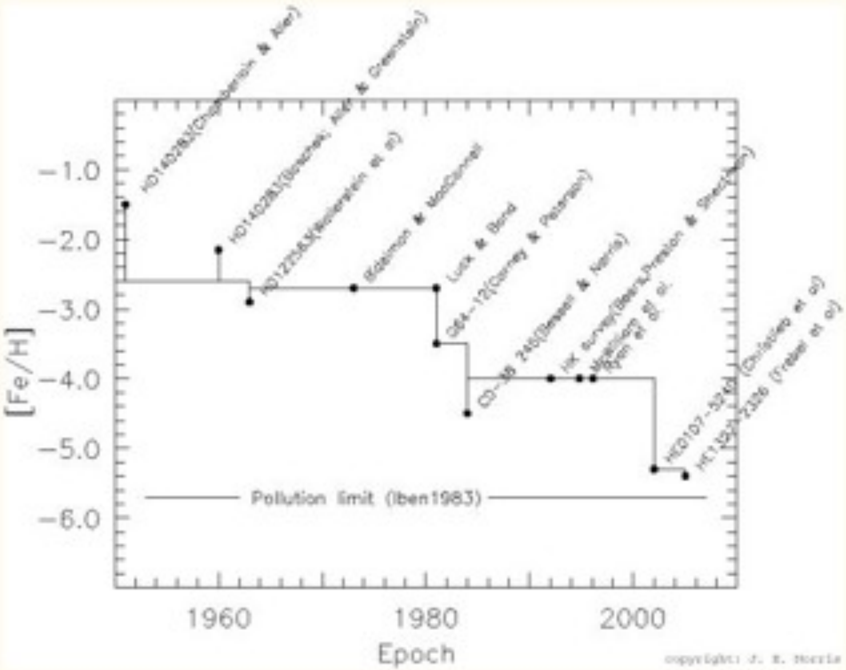
A single low-energy, iron-poor supernova as the source of metals in the star SMSS J031300.36-670839.3

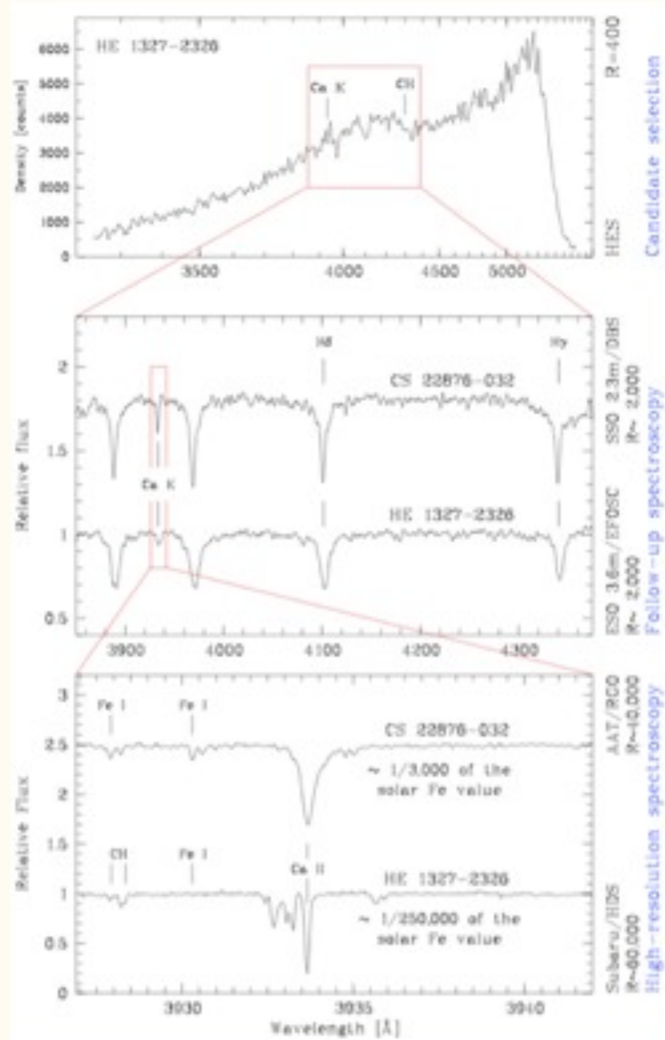
S. C. Keller[\], M. S. Bessell[\], A. Frebel[*], A. R. Casey[\], M. Asplund[\], H. R. Jacobson[*], K. Lind[*], J. E. Norris[\], D. Yong[\], A. Heger[+], Z. Magic[△\], G. S. Da Costa[\], B. P. Schmidt[\], & P. Tisserand[\]

The quest for the most metal poor stars

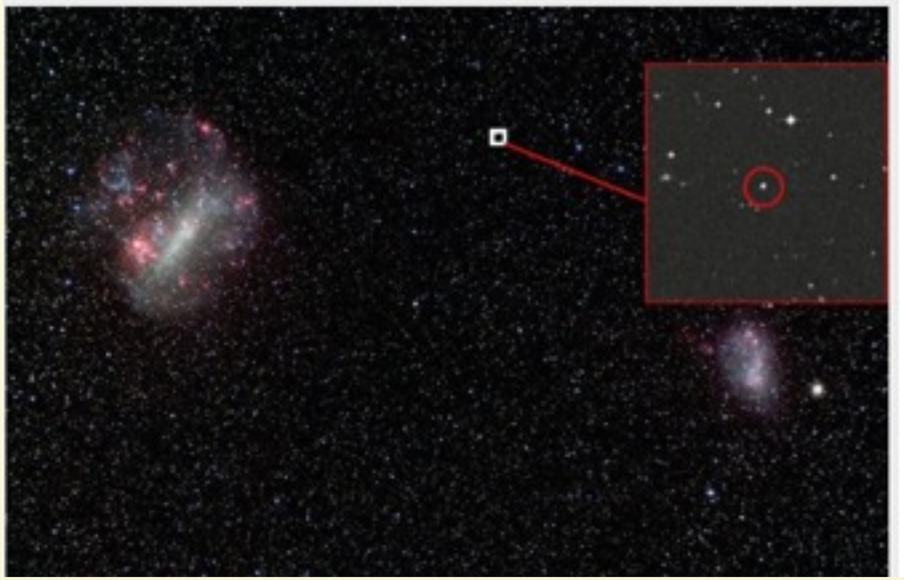
- PopIII star: zero metallicty
  - first generation stars are supposed to be massive
  - no elements other than H and He
  - never found, maybe aren't any around today
- Second generation star: extremely metal poor
  - can be <solar mass
  - chemical abundance pattern consistent with one supernova pollution

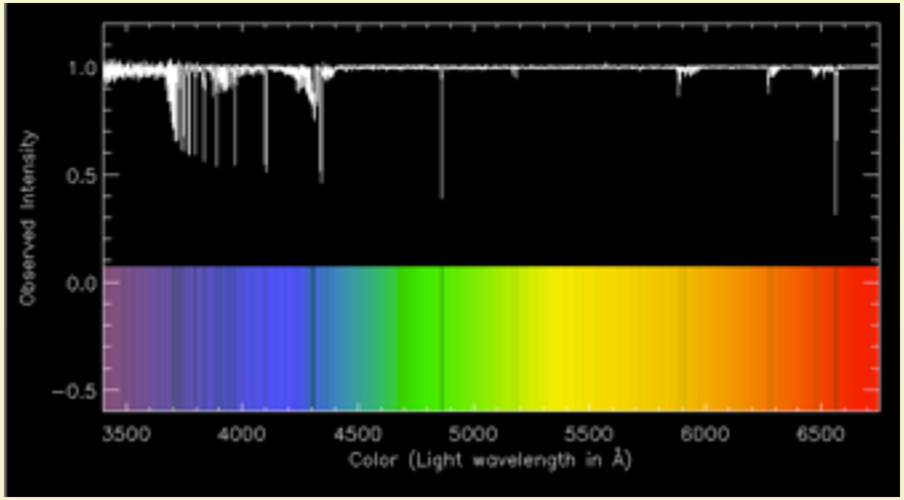
How to Find Metal Poor Stars?

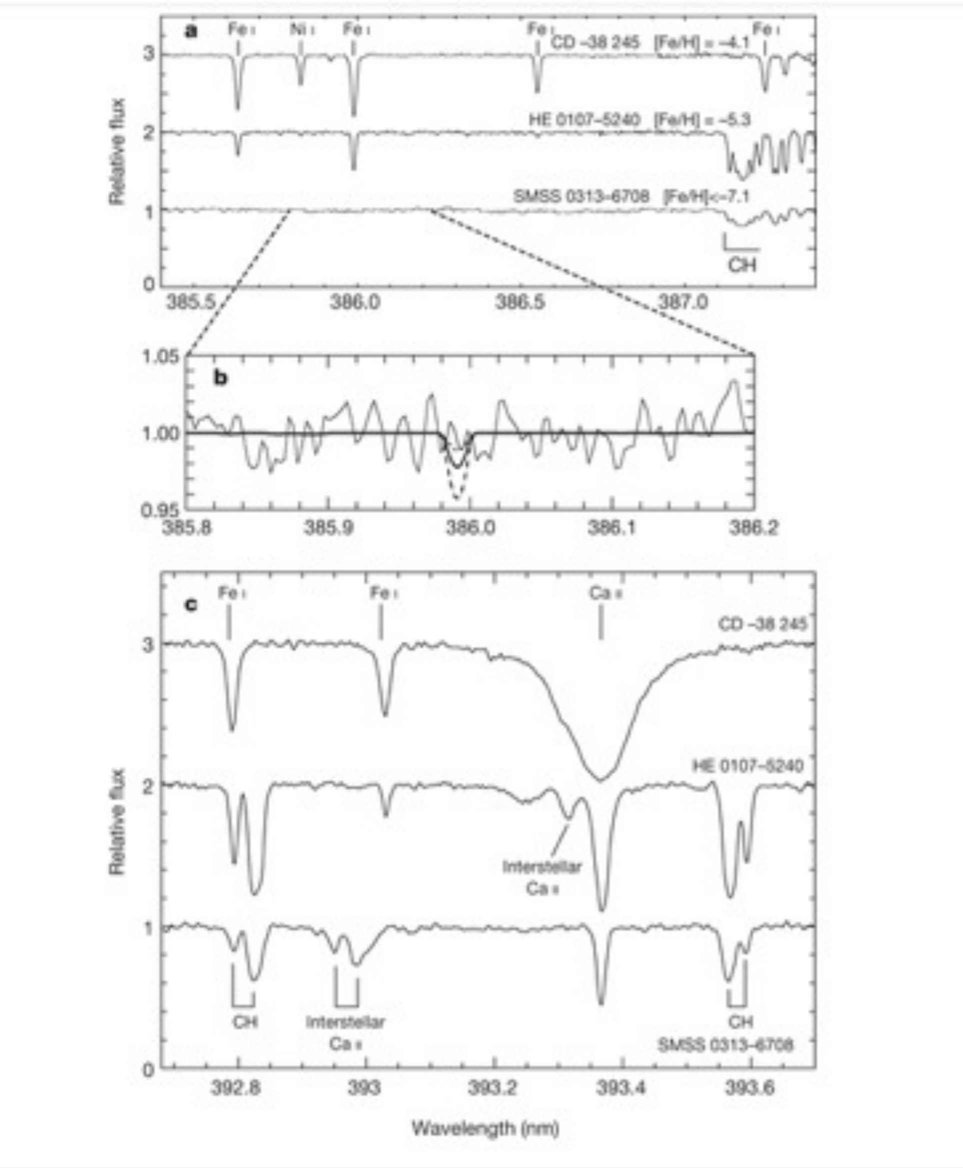




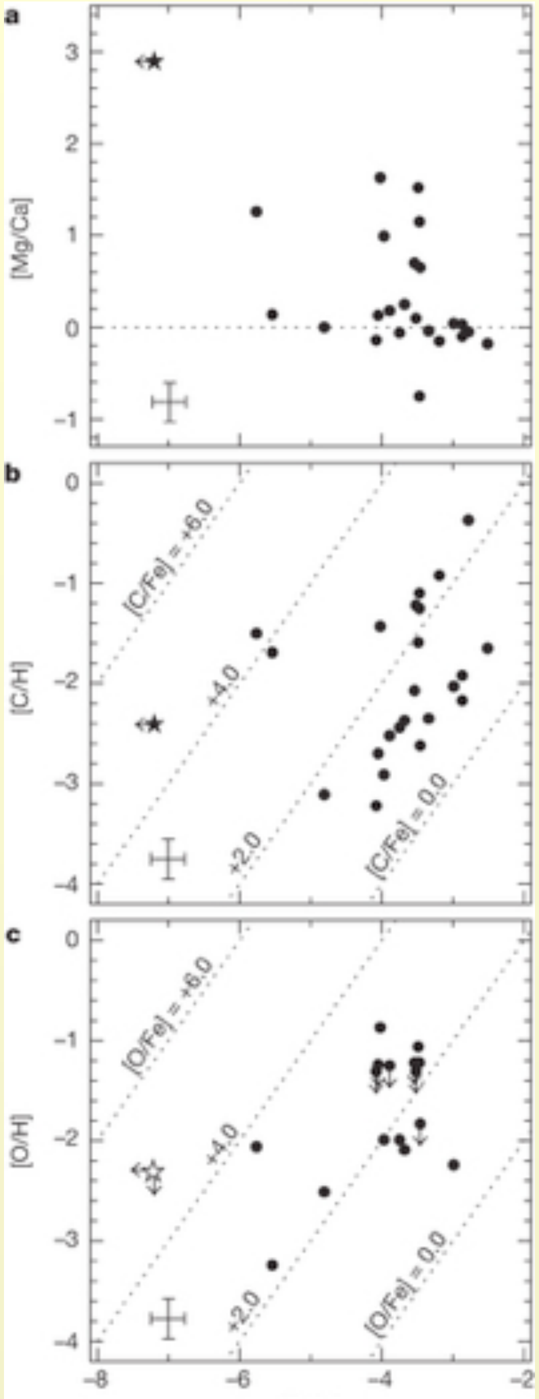
The new most metal poor star: [Fe/H] <-7

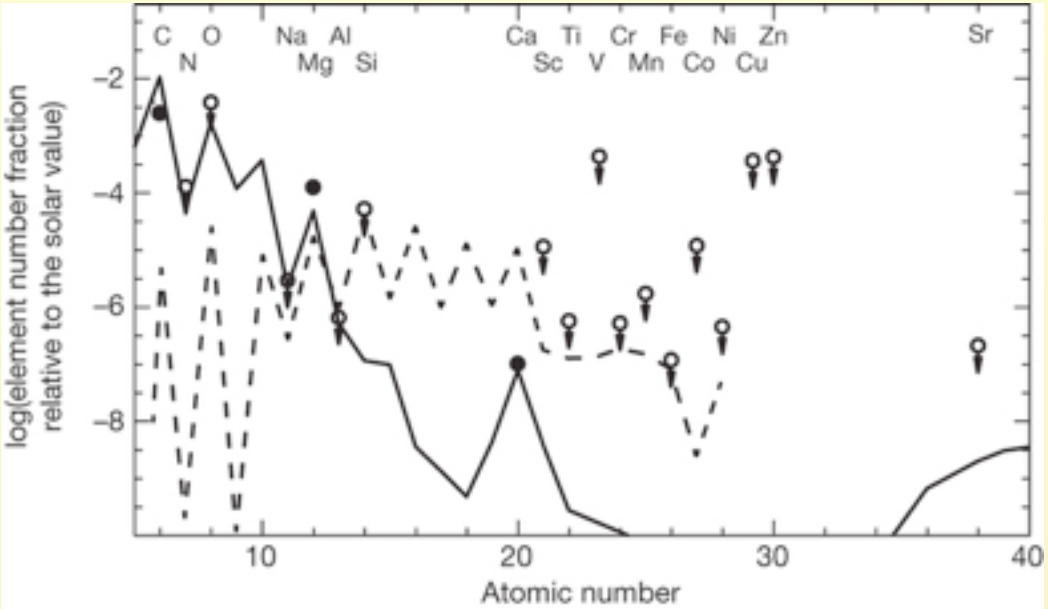






A second generation star: progenitor is a low-energy SN





Homework 3

- Chap 3: 3.2, 3.5, 3.19, 3.20
- Chap 4: 4.5, 4.6
- due Feb 27