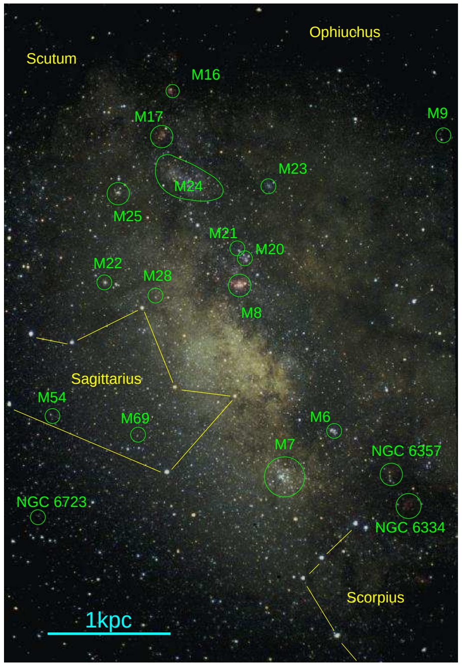
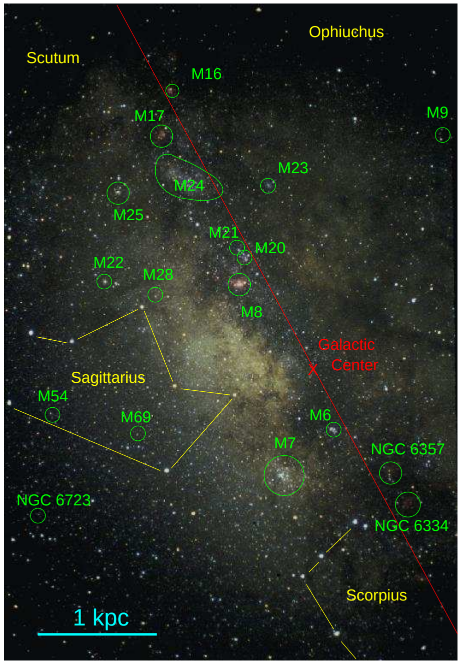


W. Keel (U Alabama)

Milky way in Saggitarius
$27^\circ \times 40^\circ$

Distance: 8 kpc
$\Longrightarrow 1^\circ \sim 140\,\mathrm{pc}$
$\Longrightarrow 1' \sim 2\,\mathrm{pc}$
$\Longrightarrow 1'' \sim 0.03\,\mathrm{pc}$



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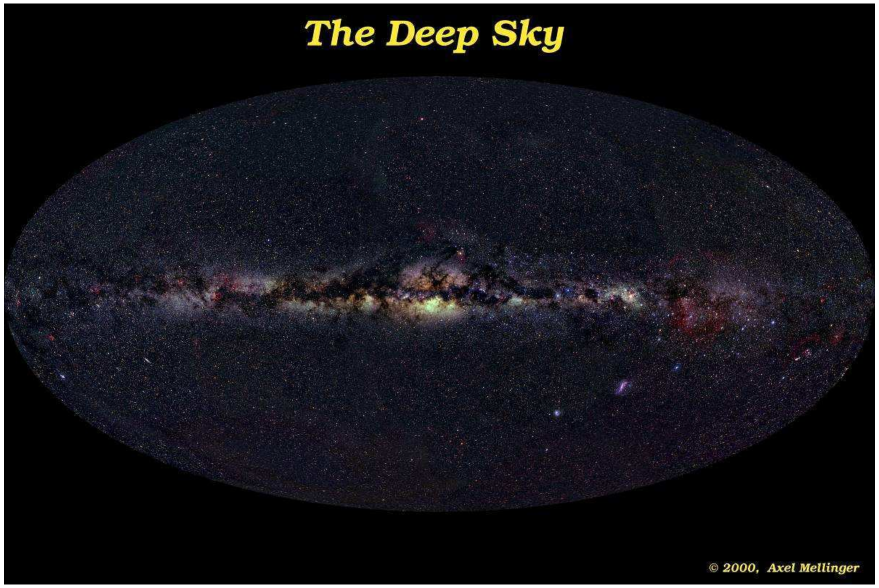
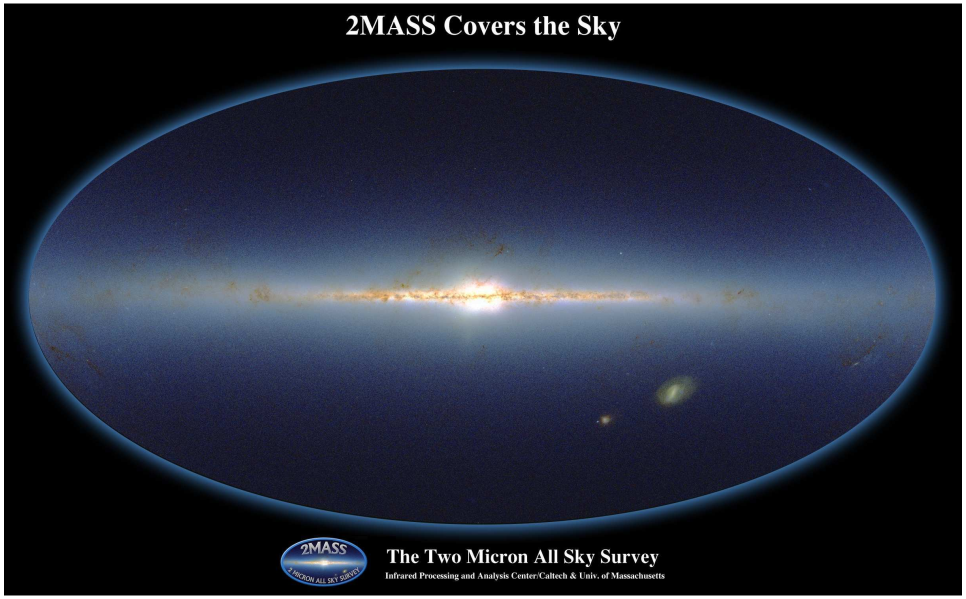
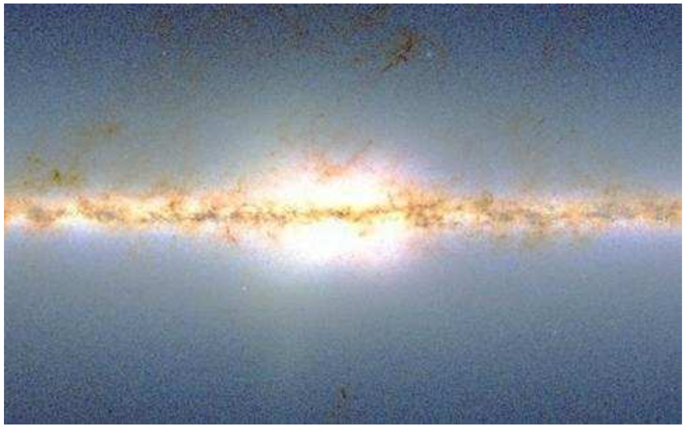


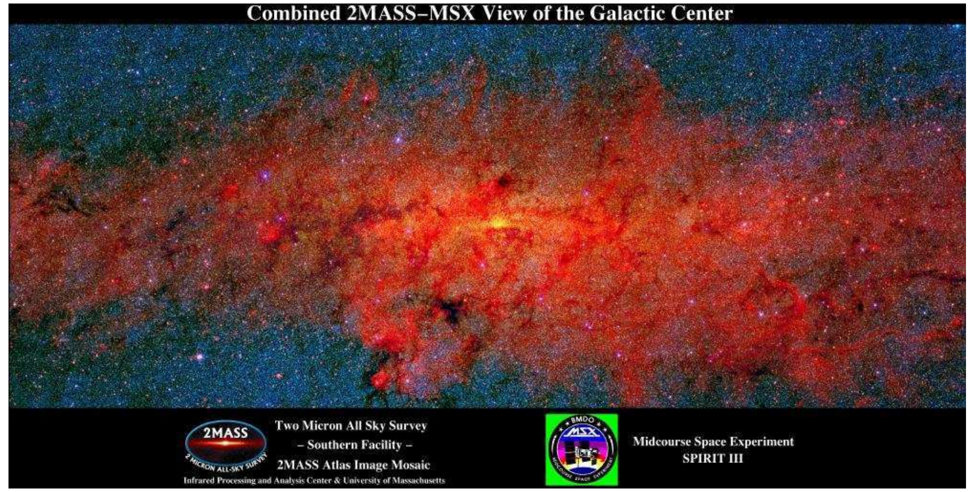
Problem: strong extinction due to dust
($A_\mathrm{V} \sim 30$ mag: 10^{12} times reduction in the optical!)
$\Longrightarrow$ Multiwavelength astronomy!



Infra red: Dust becomes transparent!
2MASS: 3 IR Bands: J (1.25 μm), H (1.65 μm), K_s (2.17μm)



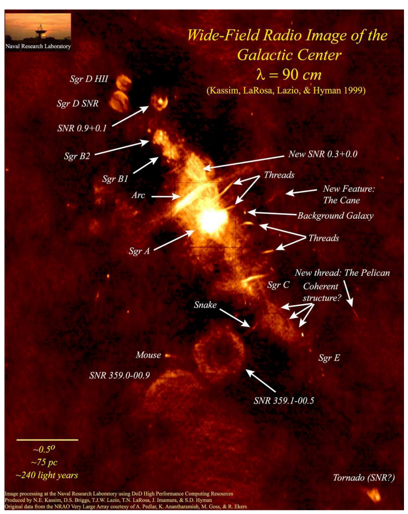
2MASS: inner 60° × 45°



2MASS/MSX: Inner 4° × 2°

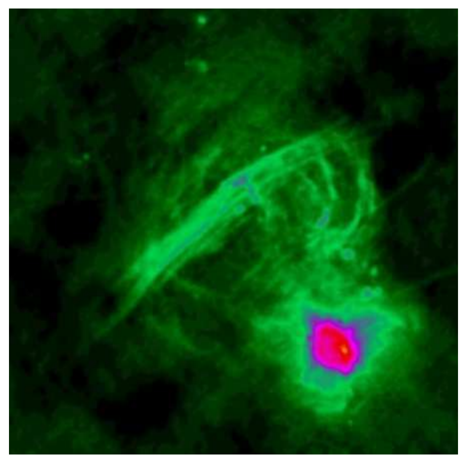
2MASS (J [1.25 μm], red), (K [2.17 μm], green), MSX (A [6–11 μm], blue)

The Galactic nucleus



- the stellar density rises towards a sharp central peak.
- Galactic gas disc has a central hole of 3 kpc radius
- dense nuclear gas disc (R=1.5 kpc) within the central gas hole
  - neutral hydrogen
  - mostly molecular clouds concentrated within central 300pc: 10^8 $M_\odot$ = 5% of the total Galactic molecular mass!
  - embedded in very hot gas (10^8K)
  - supernova remnants
- central 10pc are dominated by radio source Sgr A

The Galactic nucleus



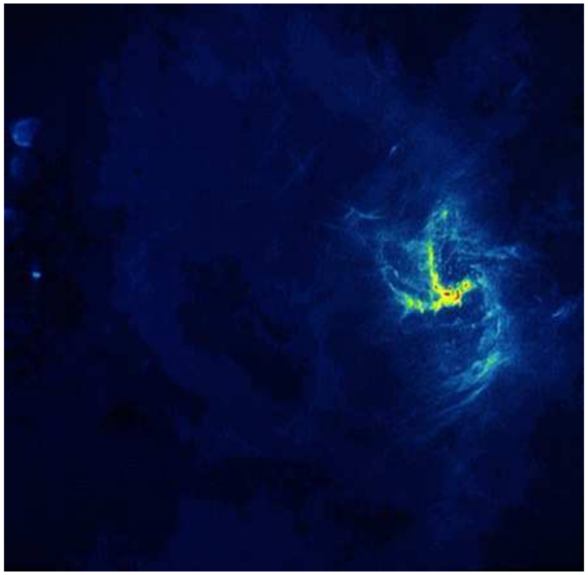
70 pc × 70 pc, VLA (F. Yusef-Zadeh et al., 1982–1984)
©NRAO/AUI

Radio source Sgr A:
Sgr A (West) (Arc): broad radio filaments, part of a much larger Ω-shaped structure $\perp$ galactic plane.

polarized, steep radio spectrum $\Longrightarrow$ synchrotron radiation (nonthermal electrons; $n_\mathrm{e}(E) \propto E^{-p}$)!

caused by shocks from supernovae?

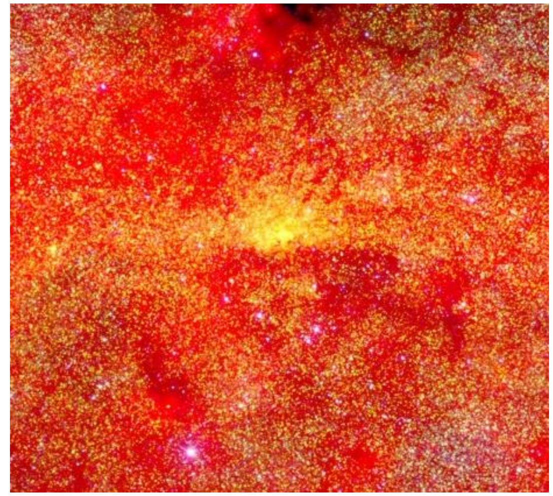
central radio point source, unresolved: Sgr A*



Sgr A (3.6 cm, courtesy K.Y. Lo/NRAO/AUI)

Sgr A West ("spiral"):
2 pc diameter,
$\sim$ 60 $M_\odot$ ionized gas, shaped by tidal forces
northern arm falls on centre, east and south arms rotate.

The Inner Parsec: Central Cluster



Centre of Sgr A contains massive and dense cluster
($> 10^6\,M_\odot\,\mathrm{pc}^{-3}$, compare solar neighborhood: 0.1 $M_\odot\,\mathrm{pc}^{-3}$)
Spectroscopy: Stars are rich in Helium, early type (=massive), strong winds
($v_{\mathrm{Wind}} \sim$ 1000 km s^{-1}).

The Inner Parsec: Central Cluster

Gemini North/AURA

Observations are difficult because of astronomical seeing
($\sim$ 0.7$''$=0.2 pc)

The Inner Parsec: Central Cluster

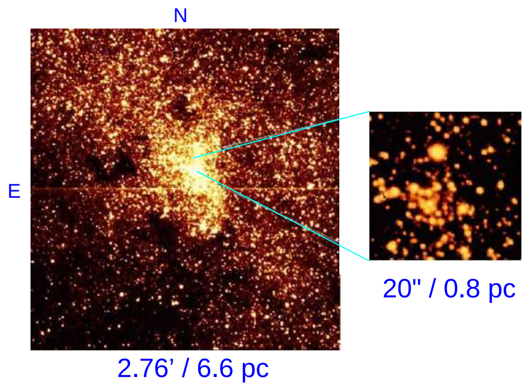
Gemini North/AURA

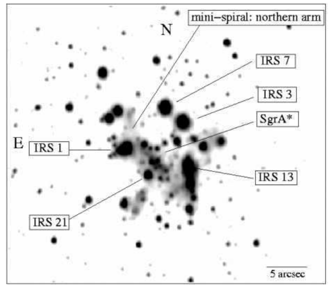
Observations are difficult because of astronomical seeing
($\sim$ 0.7$''$=0.2 pc)
. . . which can be corrected by adaptive optics
$\Longrightarrow$ resolution: diffraction limit!

$$\theta = 1.22\,\mathrm{rad} \cdot \lambda/d \sim 1\,\mathrm{mas}$$

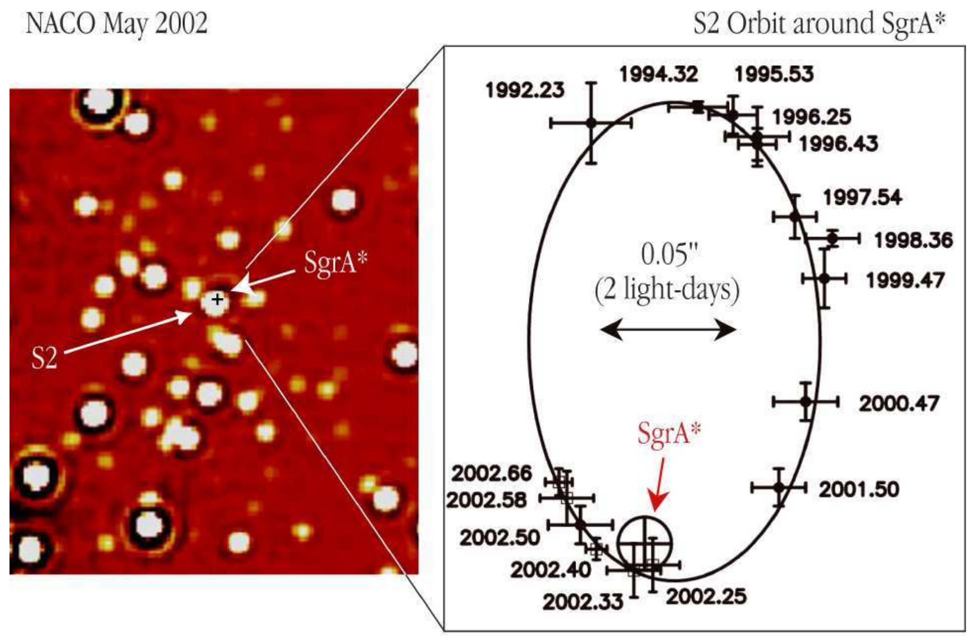
(for $d = 8$ m, $\lambda = 2.2\,\mu$m)
$\Longrightarrow$ 140 AU for gal. centre!

The Inner Parsec: Central Cluster

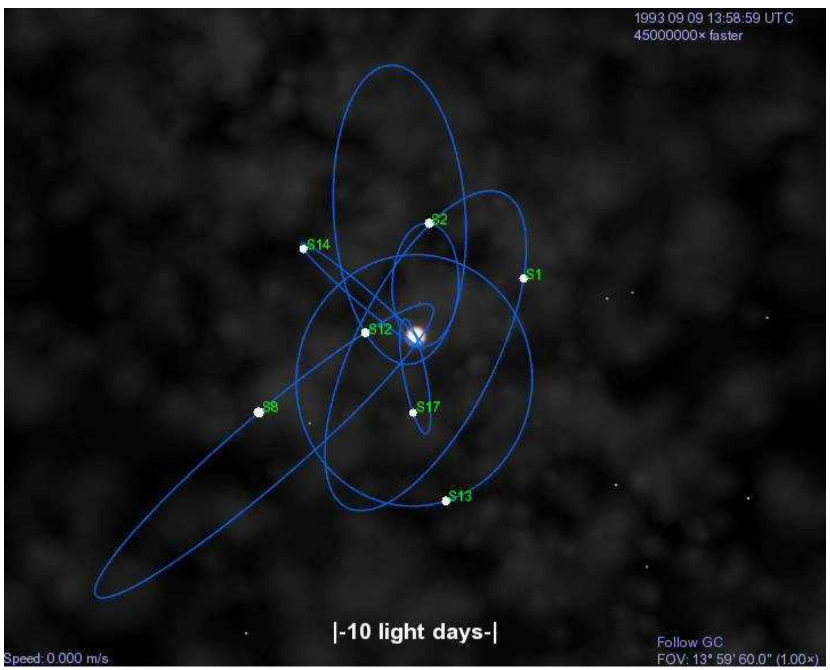




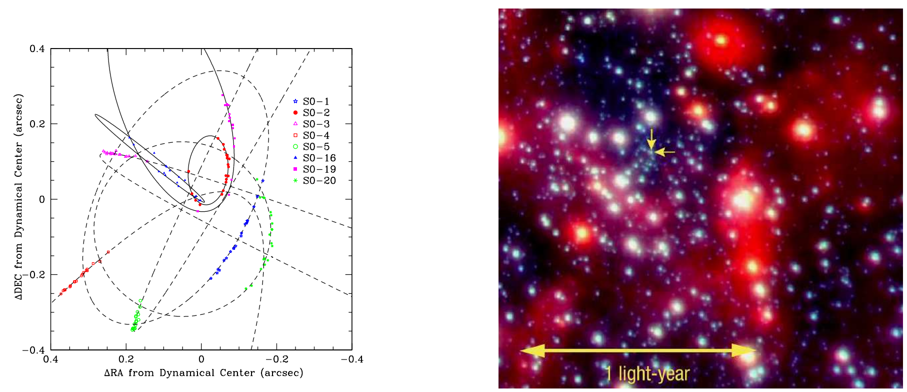
VLT ISAAC K-Band (2.2 μm) (Genzel/Eckart)



ESO, Oct 2002



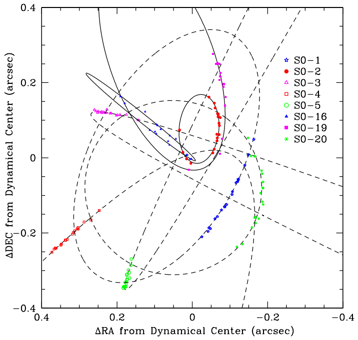
The inner parsec: mass determination

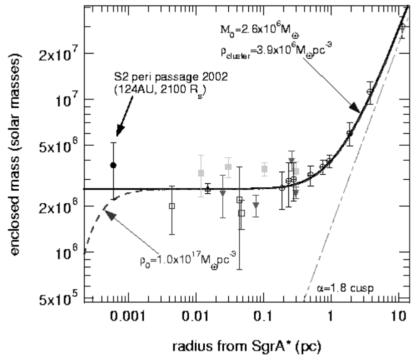


Ghez et al. (2003)

ESO

The inner parsec: mass determination



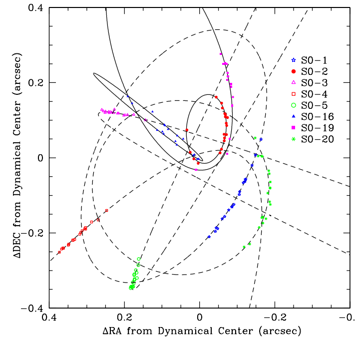


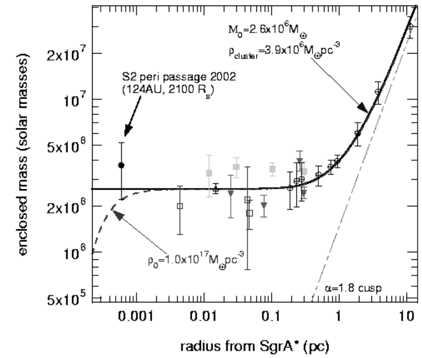
Ghez et al. (2003) Schödel et al. (2002)

Mass determination: 3. Kepler

$$a = 5.5 \text{ light days} \qquad P = 15.2 \text{ years} \quad \Longrightarrow \quad \frac{P^2}{a^3} = \frac{4\pi^2}{G(m_* + M_{\mathrm{BH}})}$$

The inner parsec: mass determination





Ghez et al. (2003) Schödel et al. (2002)

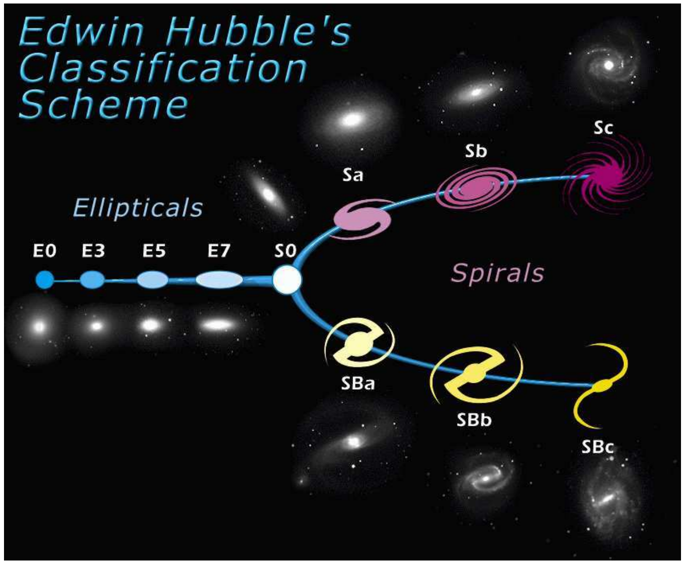
The center of the Galaxy harbors a black hole with $M_{\mathrm{BH}} = (3.7 \pm 1.0) \times 10^6\, M_\odot$

Galaxies: Classification

Galaxy Classification

1920s: Hubble and others: classification of galaxies

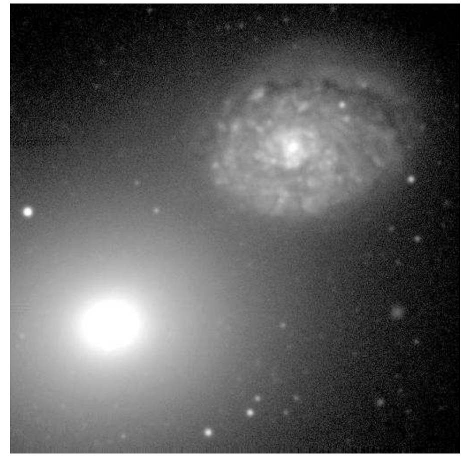
- Morphology: Appearance on photographs, photographic emulsion is blue sensitive
- *Warning:* scheme is in parts not so well defined, incomplete, and not unique
- Note: photometric (colors) and spectroscopic information are not part of the Hubble scheme.



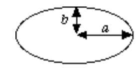
SDSS

Galaxy classification via the Hubble “tuning fork diagram”: “early types”: elliptical galaxies; “late types”: spiral galaxies, Not an evolutionary sequence!

Elliptical Galaxies



M60 (NGC 4649), E1, U. of Alabama

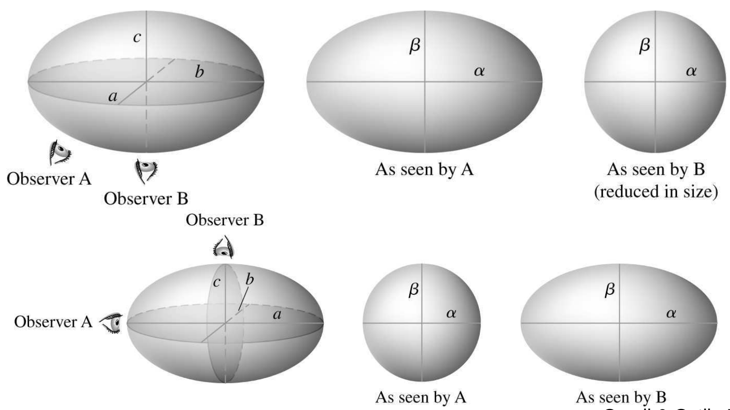


Elliptical galaxies: Classification as Ex where $x = 10(a-b)/a$ (integer part; between 0 and 7)

Ellipticals are low on dust and gas, reddish color (=old stars!), typically low luminosity and low mass ($10^6\,M_\odot$)

Monsters: Also elliptical, from mergers in galaxy clusters (e.g., M87 in Virgo), M up to $10^{12}\,M_\odot$, designated cD.

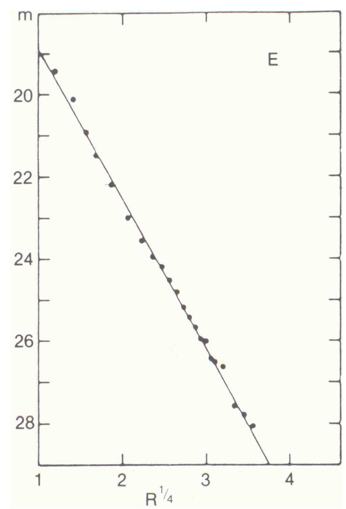
Elliptical Galaxies



Caroll & Ostlie Fig. 25.2/3

Note that the observed shape (=sub-type) of an elliptical galaxy depends on the aspect angle!

Elliptical Galaxies



Radial brightness distribution in ellipticals is given by de Vaucouleurs’ law:

$$\log\left(\frac{I(R)}{I_e}\right) = -3.3307\left[\left(\frac{R}{R_e}\right)^{1/4} - 1\right] \qquad (15.1)$$

where

- $I(R)$: surface brightness, e.g., in $L_\odot\,\mathrm{pc}^{-2}$
- R_e: effective radius, i.e., radius containing in half of the total luminosity

Spiral Galaxies

M51 (NGC 5194 and 5195), Sc and Irr, Kitt Peak 0.9 m

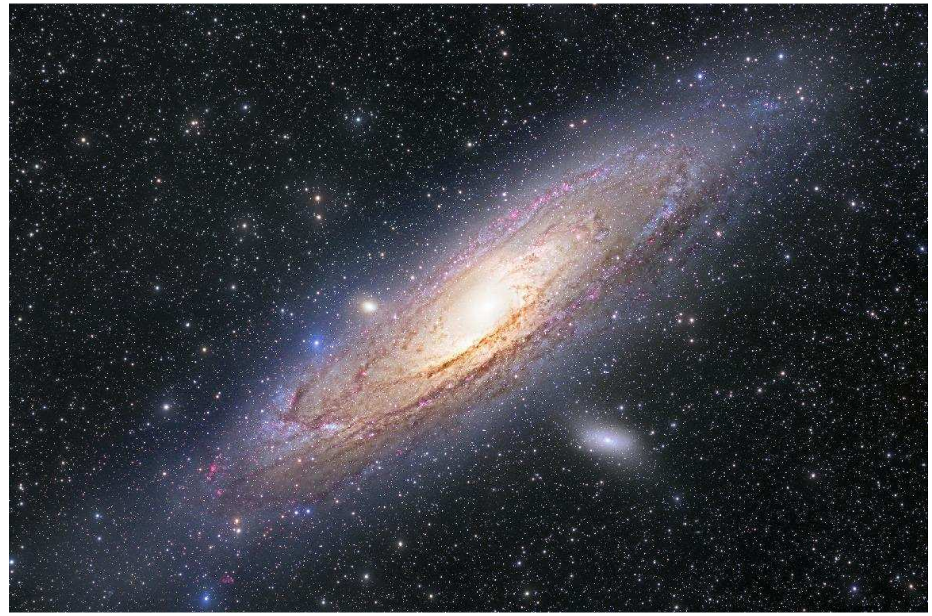
Spiral Galaxies: Elliptical nucleus (“bulge”) plus disk with spiral arms, designated Sa, Sb, Sc depending on opening angle of spiral (Sa: $\sim 10^\circ$, Sc: $\sim 20^\circ$) and dominance of nucleus.

Bluer than ellipticals.

Mass content $\sim 3 \times 10^{11}\,M_\odot$, with $M/L \sim 20$,

Gas content increases from Sa to Sc from 1% to 8%.

Spiral arms probably due to density wave.

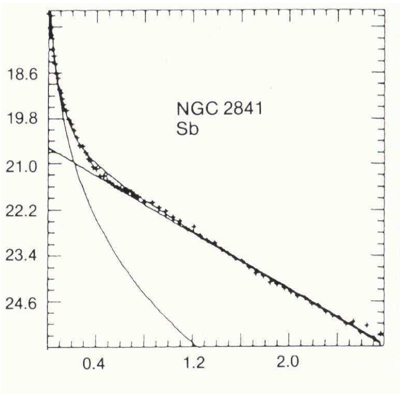


M31 (Sb; “Andromeda galaxy”), `http://www.rosa-obs.com/images/ccd/M31C_karel_full.jpg`

M90 (Sb), NOAO/AURA/NSF

NGC 300 (Sc), M. Schirmer/ESO/2.2 m

Spiral Galaxies



Radial intensity profile:
Bulge: de Vaucouleurs' law (same as ellipticals!):

$$\log\left(\frac{I(R)}{I_e}\right) = -3.3307\left[\left(\frac{R}{R_e}\right)^{1/4} - 1\right] \quad (15.2)$$

where

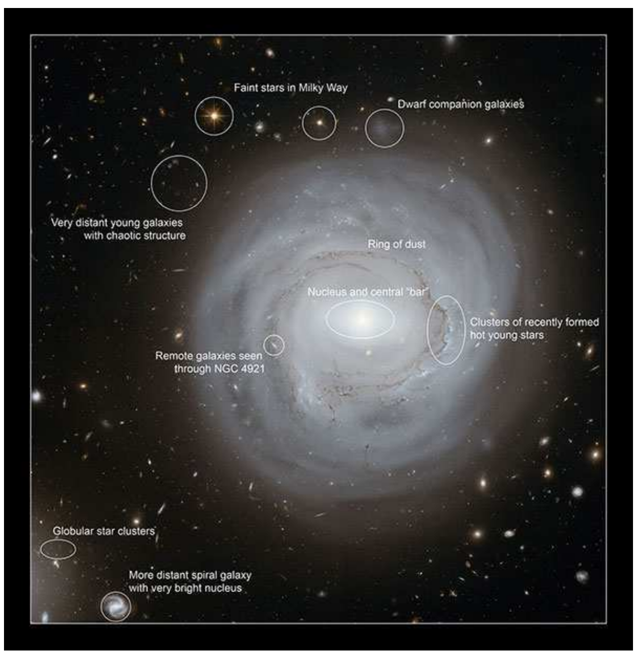
- $I(R)$: surface brightness, e.g., in $L_\odot\,\mathrm{pc}^{-2}$
- R_e: effective radius, i.e., radius containing in half of the total luminosity

Disk: Exponential law:

$$I(R) = I_0 \exp\left(-R/R_0\right) \quad (15.3)$$

where R_0: scale length (typical, e.g., thin disk of Milky Way: 3 kpc)

NGC 4921 (SBab; but note low star formation! HST/STScI)



NGC 4921 (SBab; but note low star formation! HST/STScI)

Barred Galaxies

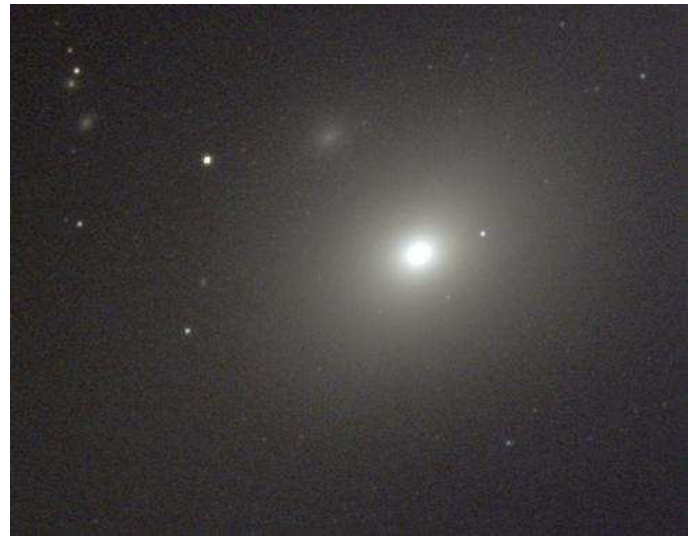
M95 (NGC 3351), SBb, INT

Barred Galaxies: Classification as SBa, SBb, SBc similar to Sx galaxies, but additional presence of a bar (cause of bar production and stability are still debated).

Similar masses and gas content as in normal spirals.

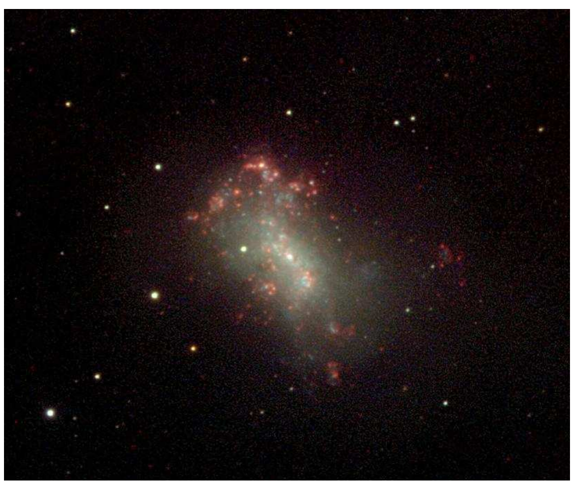
Milky Way is a barred spiral.

NGC 1365 (SBb, VLT/FORS/ANTU): note old “reddish” bar, young spiral arms



M86 (lenticular, S0), NOAO/AURA/NSF
S0 = eliptical galaxy + disk
S0 = spiral galaxy without spirals

Irregular Galaxies: Irr I



NGC 4449, Univ. Bonn

Irr I: no symmetry or spiral arms, bright knots of O- and B-type stars, very blue ($B-V \sim$ 0.5), high dust content ($\sim$ 16%), $M/L \sim$ 3, masses vary appreciably from 10^6 to 10^{10} $M_\odot$.

Examples: SMC, LMC
$\Longrightarrow$ “Magellanic type irregulars”.

Large Magellanic Cloud (LMC; Irr I), Loke Kun Tan

Large Magellanic Cloud (LMC; Irr I), AURA/NOAO/NSF

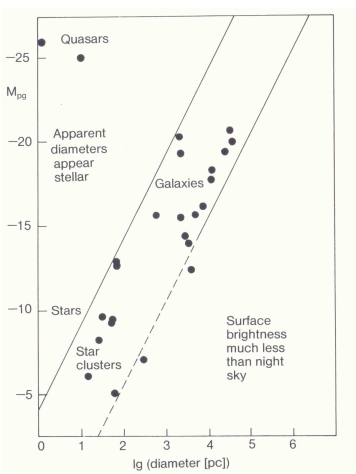
Irregular Galaxies: Irr II

M82, HST-WFPC

Irr II: asymmetrical and "abnormal"

$\Longrightarrow$ All objects that do not fit in the rest of the classification: starburst galaxies, interacting galaxies, Seyfert galaxies,. . .

Caveats: Selection Effects



Karttunen

- diameter: edge of a galaxy is not well defined as intensity decreases strongly from center.

  Wide range of observed radii: 0.1 . . . 10 kpc (dwarf galaxies) to 30 kpc (normal spirals) and 50 kpc (ellipticals)

- Angular diameters depend on sky brightness

  Often used: D_{21} contour (= isophotal contour where galaxy becomes fainter than 21 mag arcsec^{-2})

- Small Galaxies can not be distinguished from stars
- Low surface brightness galaxies can not be seen against sky background.