Stellar Dynamics and Structure of Galaxies

Gerry Gilmore H47 email: gil@ast.cam.ac.uk

Lectures:

Monday	12:10 - 13:00
Wednesday	11:15 - 12:05
Friday	12:10 - 13:00

Books:

Binney & Tremaine "Galactic Dynamics" Princeton (1987)

.... mainly theoretical, and closest to this course

Binney & Merrifield "Galactic Astronomy" Princeton (1999)

.... more observational, and useful background for all galactic astronomy including dynamics. Particularly for information on observing dynamical properties of galaxies and other stellar systems which we will cover.

STELLAR DYNAMICS AND STRUCTURE OF GALAXIES Lent Term, 24 Lectures

Orbits in a given potential. Particle orbit in Newtonian gravity; energy, angular momentum. Radial force law - general orbit is in a plane; equations of motion in cylindrical polars. Inverse square law; bound and unbound orbits, Kepler's laws; escape velocity; binary stars; reduced mass. General orbit under radial force law; radial and azimuthal periods; precession. [4]

Derivation of potential from density distribution. Poisson's equation. Description of structure of galaxies. Gravitational potential for spherical systems: homogeneous sphere, modified Hubble profile, power law. Circular orbits; rotation law Vc(R); escape velocities Vesc(R). [2]

Nearly circular orbits. Radial perturbations; epicyclic frequency; stability; apsidal precession. Application to pseudo-black hole potential -GM/(r-rs). Vertical perturbations in axisymmetric potential; vertical oscillation frequency; nodal precession. [2]

Axisymmetric density distribution. General axisymmetric solution of Poisson's equation outside matter. Potential due to ring of matter; series solution; 18-year eclipse cycle. Potential due to thin disc; rotation curves of Mestel's disc; exponential disc. Rotation curve of the galaxy; Oort's constants. Rotation curves of spiral galaxies; need for dark matter. [5]

Collisionless systems. Relaxation time. Estimates for stellar and galaxy clusters. Gravitational drag. The stellar distribution function; collisionless Boltzmann equation. The Jeans equations as moments of the Boltzmann equation. Analogy with fluid equations. Application to mass in the solar neighbourhood (Oort limit). [4]

Jeans Theorem. Application to simple systems in which the distribution function depends only on energy. Useful approximate galactic potentials; polytrope, Plummer's model, isothermal sphere. [3]

Globular cluster evolution. Models of globular clusters. King models. *Models with anisotropic velocity distributions.* Observational tests. [3]

Books

Goldstein Classical Mechanics, Addison-Wesley (2nd edition 1980).
† Binney, J. & Tremaine, S.D. Galactic Dynamics, Princeton University Press (1987).
Landau & Lifshitz Mechanics, Pergamon (3rd edition 1976, reprinted 1994).
† Binney, J. & Merrifield, M. Galactic Astronomy, Princeton University Press (1998).

Importance of Stellar Dynamics

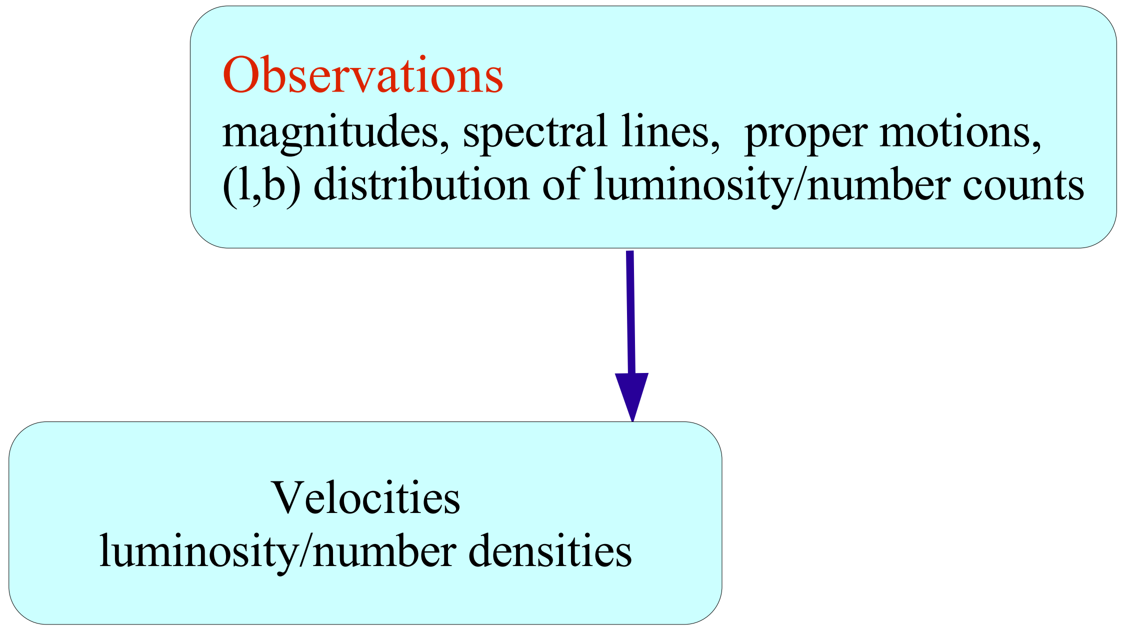
Importance of Stellar Dynamics

Understanding
& interpreting
observations

Observations
magnitudes, spectral lines, proper motions,
(l,b) distribution of luminosity/number counts

Importance of Stellar Dynamics

Understanding & interpreting observations



Importance of Stellar Dynamics

Understanding & interpreting observations

Observations
magnitudes, spectral lines, proper motions, (l,b) distribution of luminosity/number counts

↓

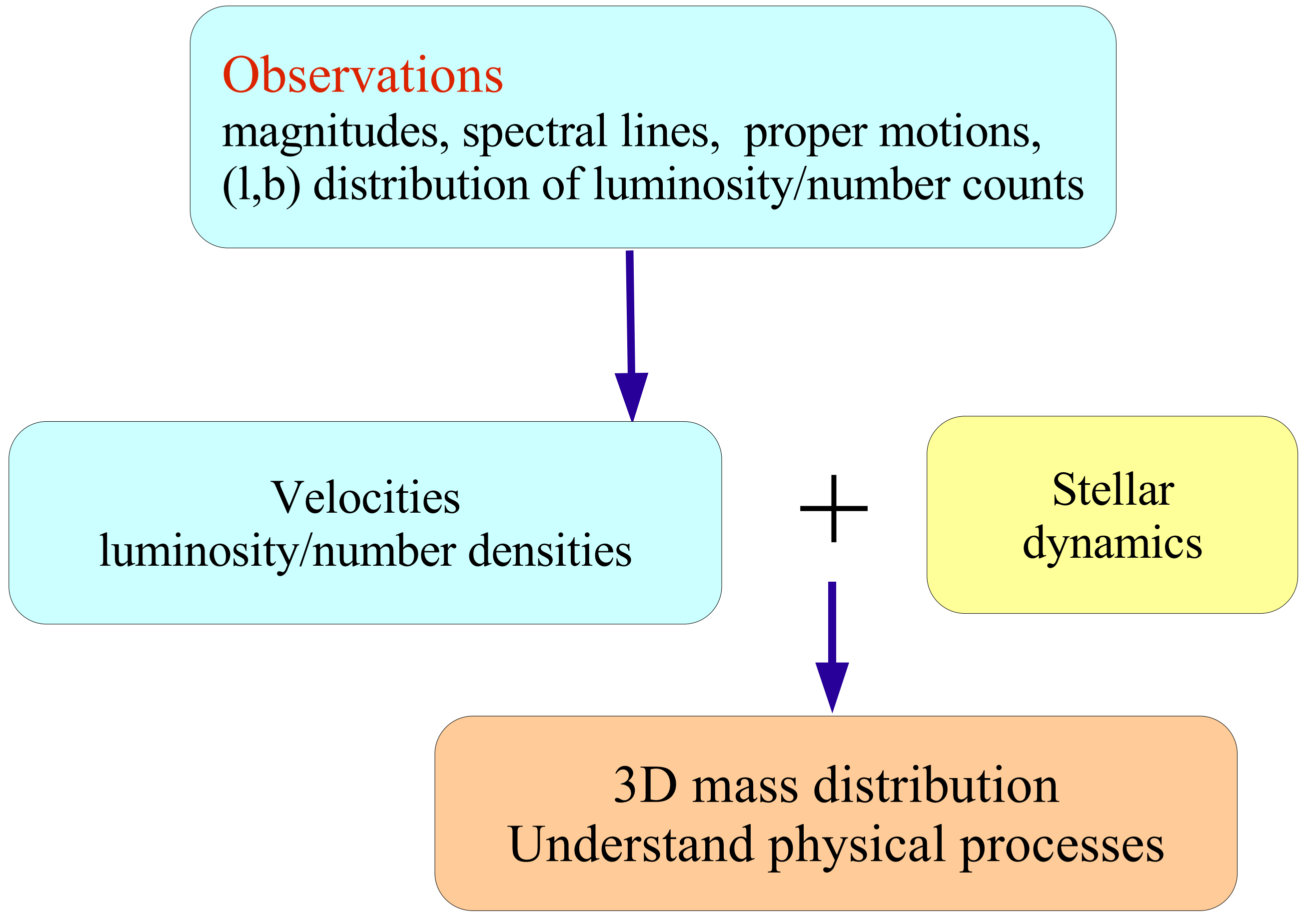
Velocities
luminosity/number densities

+

Stellar dynamics

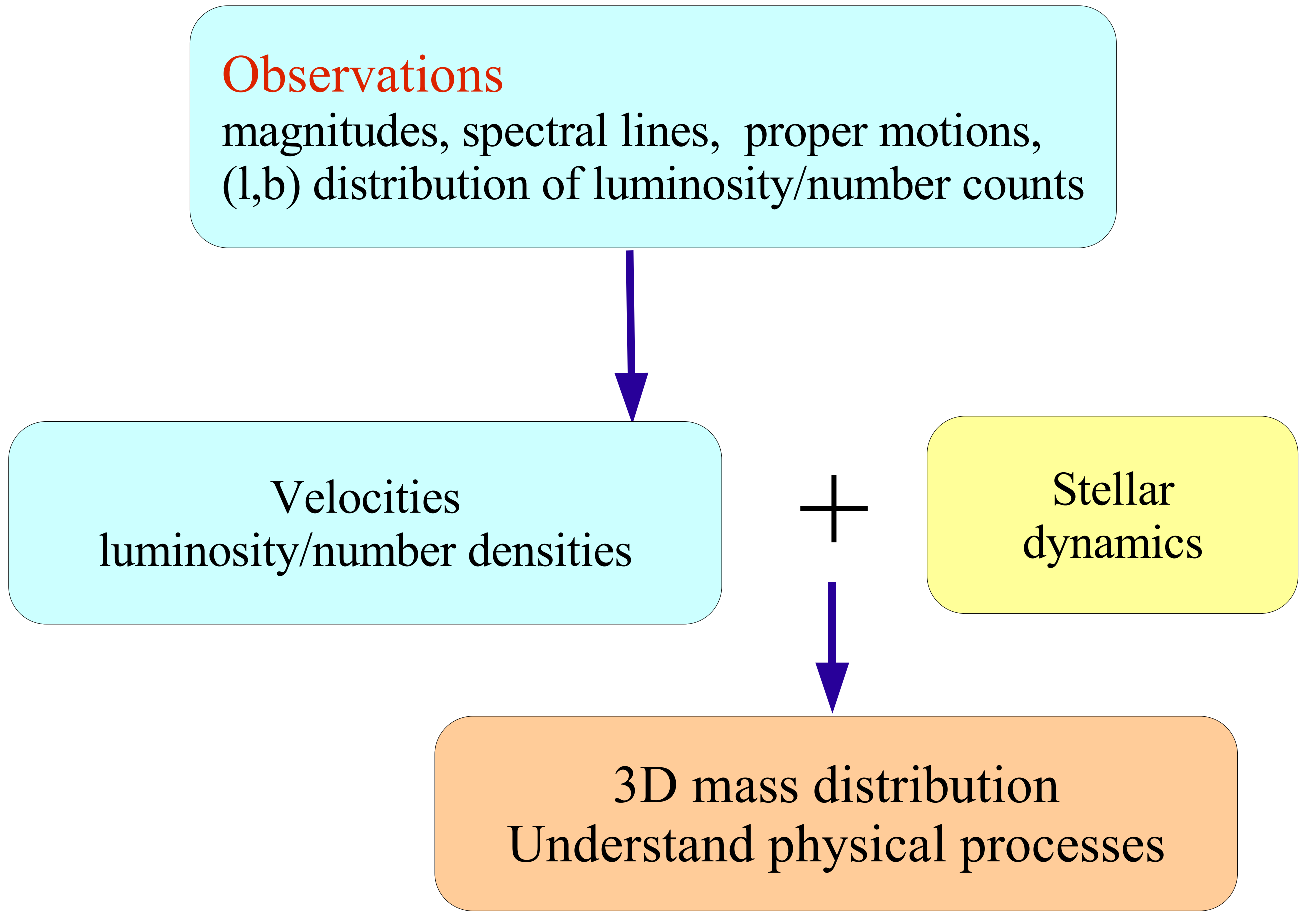
Importance of Stellar Dynamics

Understanding
& interpreting
observations



Importance of Stellar Dynamics

Understanding & interpreting observations



- Dynamics connects kinematics to stellar density distribution *and* underlying mass distribution
- Without understanding of dynamics, cannot distinguish between plausible galactic structure models

Applications of gravitational dynamics

Applications of gravitational dynamics

- Two body systems - binary stars (allow stellar masses to be found)

Applications of gravitational dynamics

- Two body systems - binary stars (allow stellar masses to be found)
- Planetary systems

Applications of gravitational dynamics

- Two body systems - binary stars (allow stellar masses to be found)
- Planetary systems
- Stellar clusters – globular, open

ω Cen

Applications of gravitational dynamics

- Two body systems - binary stars (allow stellar masses to be found)
- Planetary systems
- Stellar clusters – globular, open

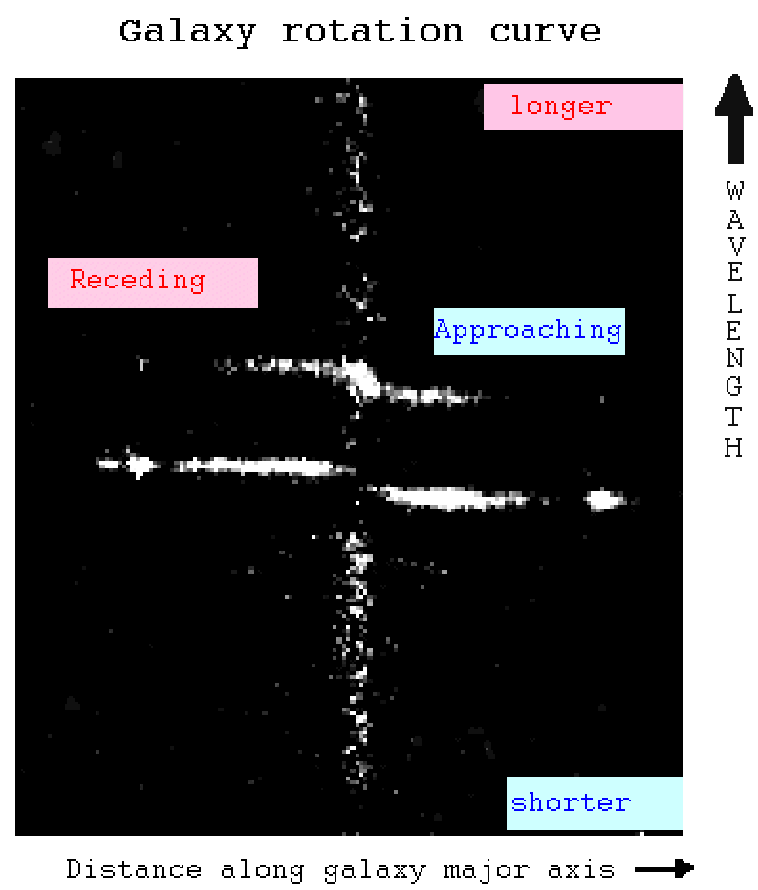
NGC6405 (M6)

Applications of gravitational dynamics

- Two body systems - binary stars (allow stellar masses to be found)
- Planetary systems
- Stellar clusters – globular, open
- Galactic structure – orbits, rotation curves, spiral arms

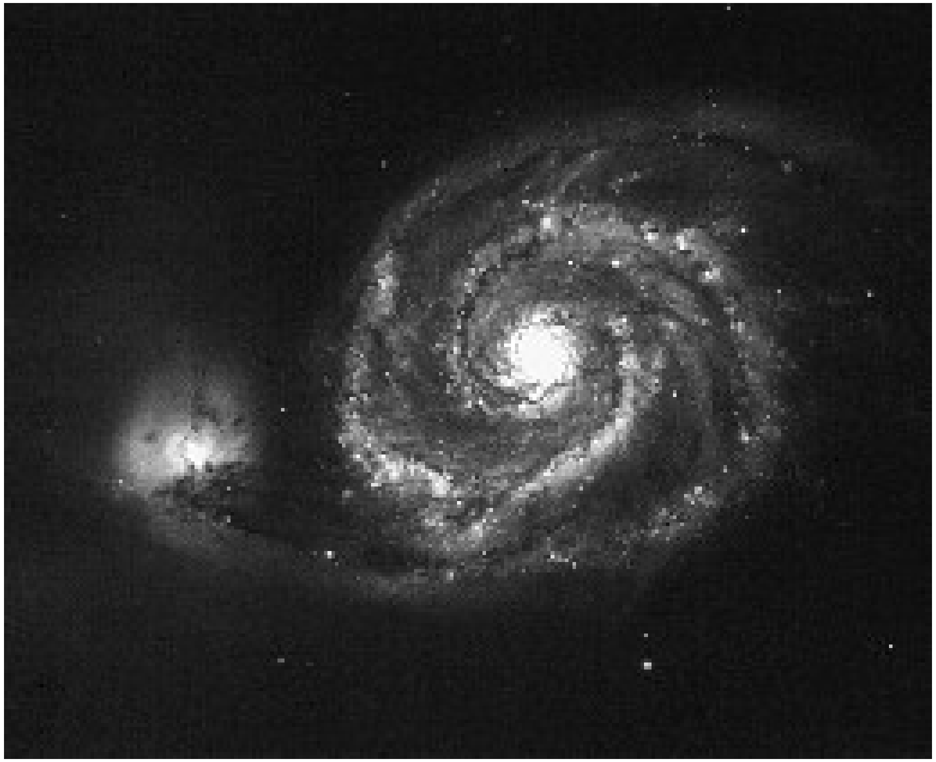
Applications of gravitational dynamics

- Two body systems - binary stars (allow stellar masses to be found)
- Planetary systems
- Stellar clusters – globular, open
- Galactic structure – orbits, <u>rotation curves</u>, spiral arms



Applications of gravitational dynamics

- Two body systems - binary stars (allow stellar masses to be found)
- Planetary systems
- Stellar clusters – globular, open
- Galactic structure – orbits, rotation curves, spiral arms



M51

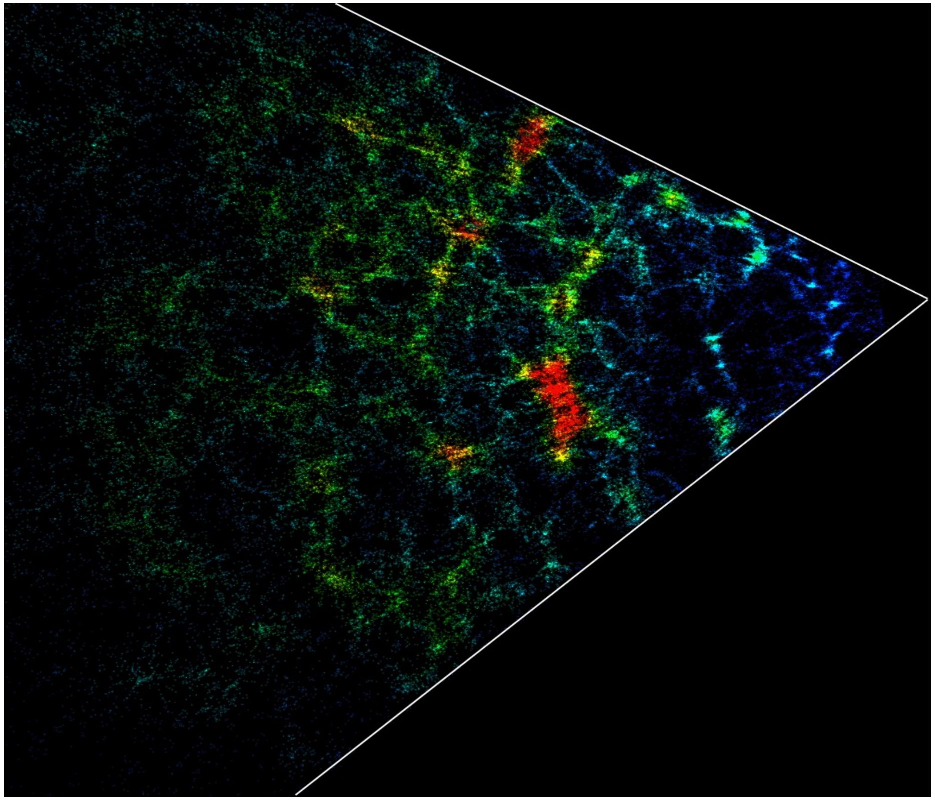
Applications of gravitational dynamics

- Two body systems - binary stars (allow stellar masses to be found)
- Planetary systems
- Stellar clusters – globular, open
- Galactic structure – orbits, rotation curves, spiral arms
- Clusters of galaxies

Coma cluster

Applications of gravitational dynamics

- Two body systems - binary stars (allow stellar masses to be found)
- Planetary systems
- Stellar clusters – globular, open
- Galactic structure – orbits, rotation curves, spiral arms
- Clusters of galaxies
- Large scale structure of the Universe



AAT 2dF galaxy survey

Applications of gravitational dynamics

- Two body systems - binary stars (allow stellar masses to be found)
- Planetary systems
- Stellar clusters – globular, open
- Galactic structure – orbits, rotation curves, spiral arms
- Clusters of galaxies
- Large scale structure of the Universe

All use the same principles,
with different “point” particles.

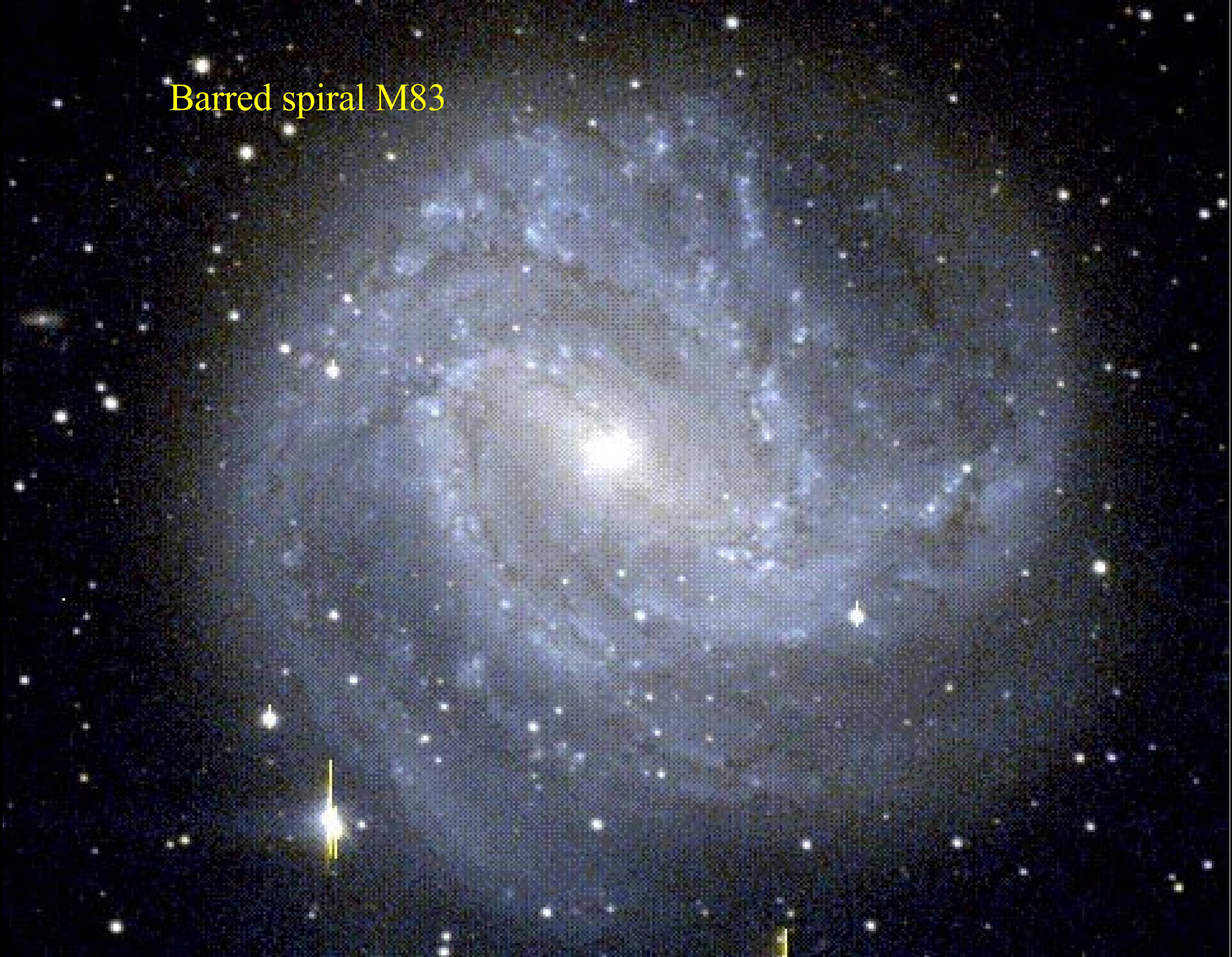
Applications of gravitational dynamics

- Two body systems - binary stars (allow stellar masses to be found)
- Planetary systems
- Stellar clusters – globular, open
- Galactic structure – orbits, rotation curves, spiral arms
- Clusters of galaxies
- Large scale structure of the Universe

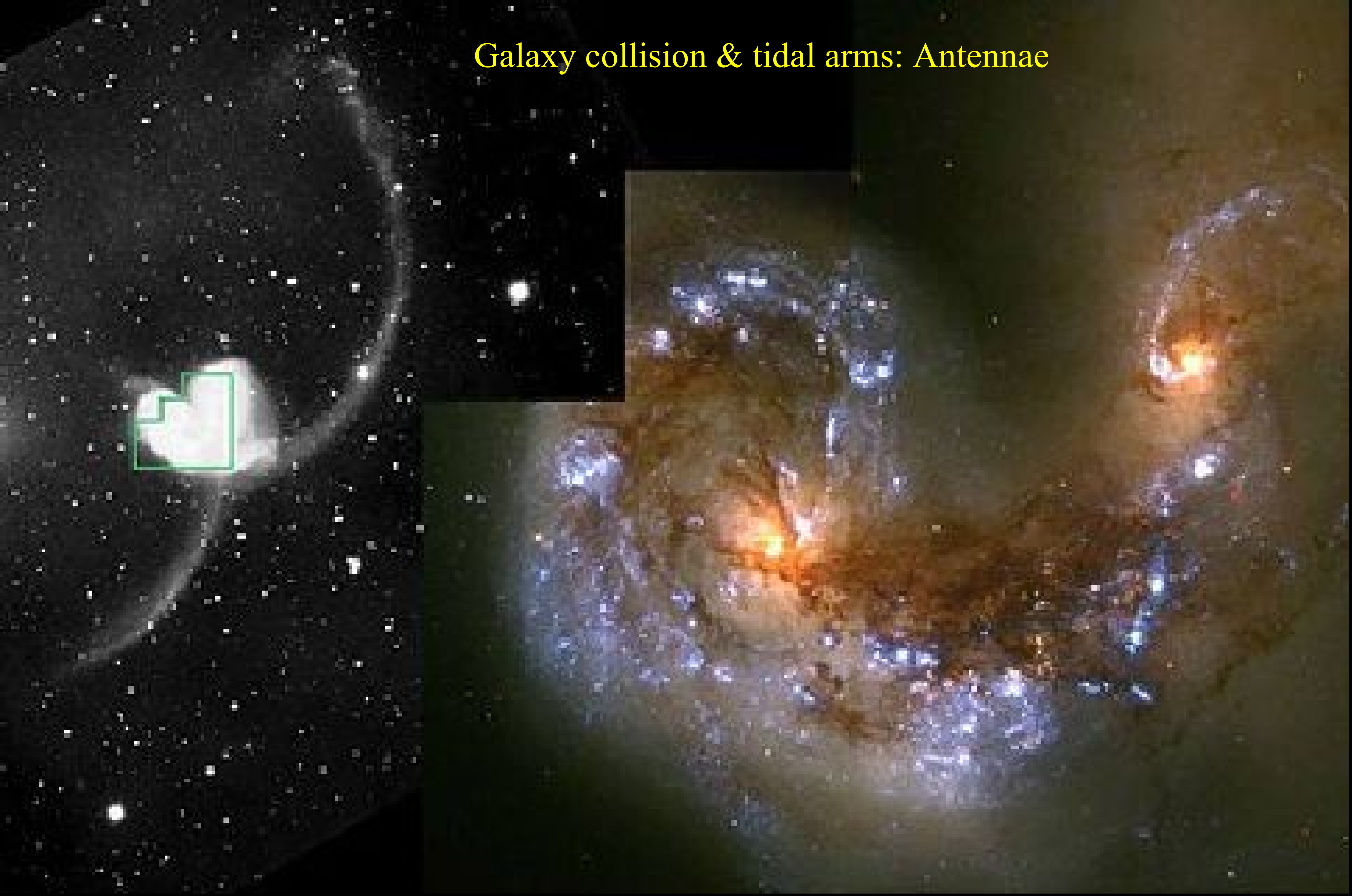
All use the same principles,
with different "point" particles.

Some more examples of structures resulting from stellar dynamics follow ....

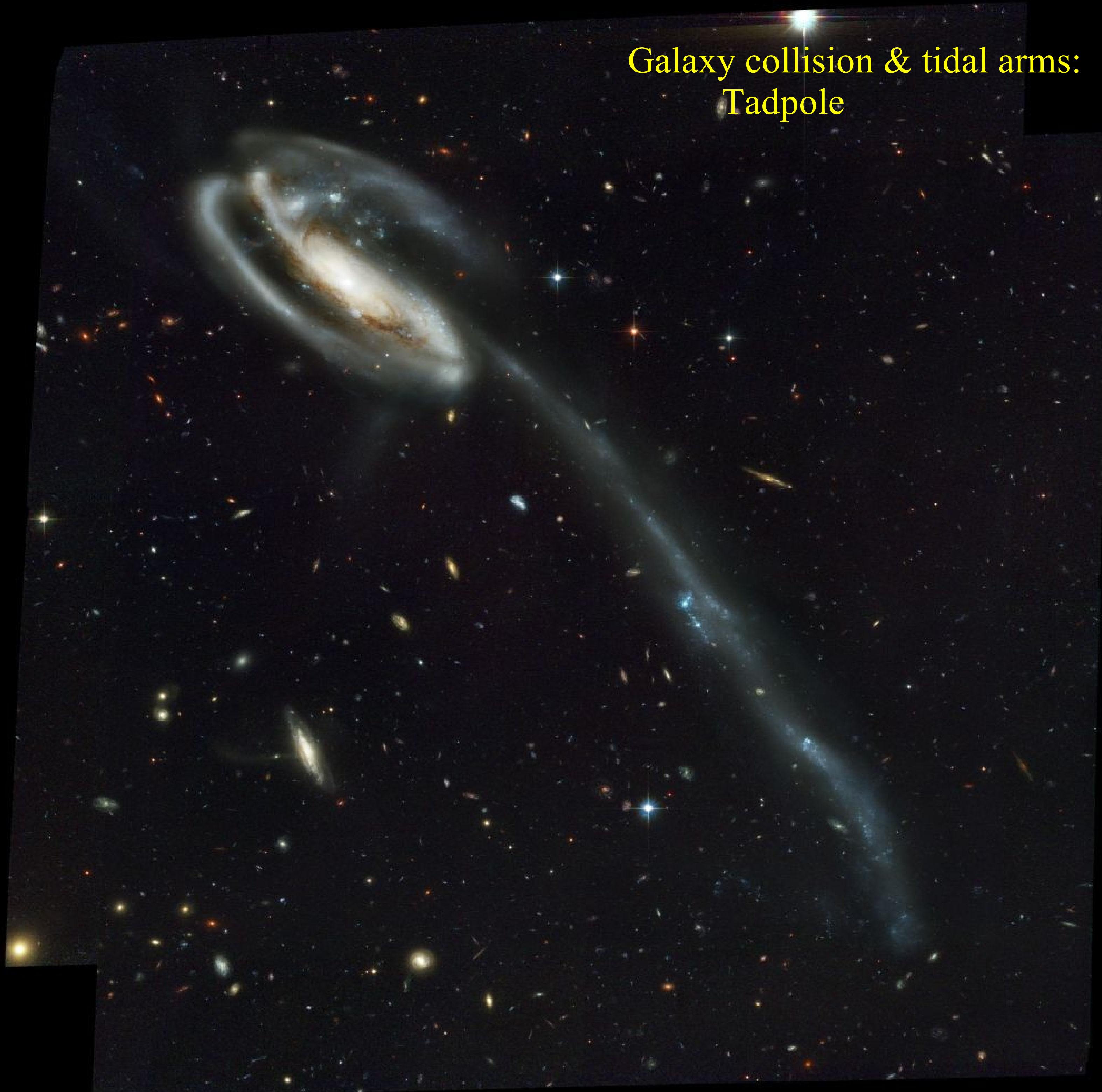
Whirlpool galaxy


Barred spiral M83

Galaxy collision & tidal arms: Antennae

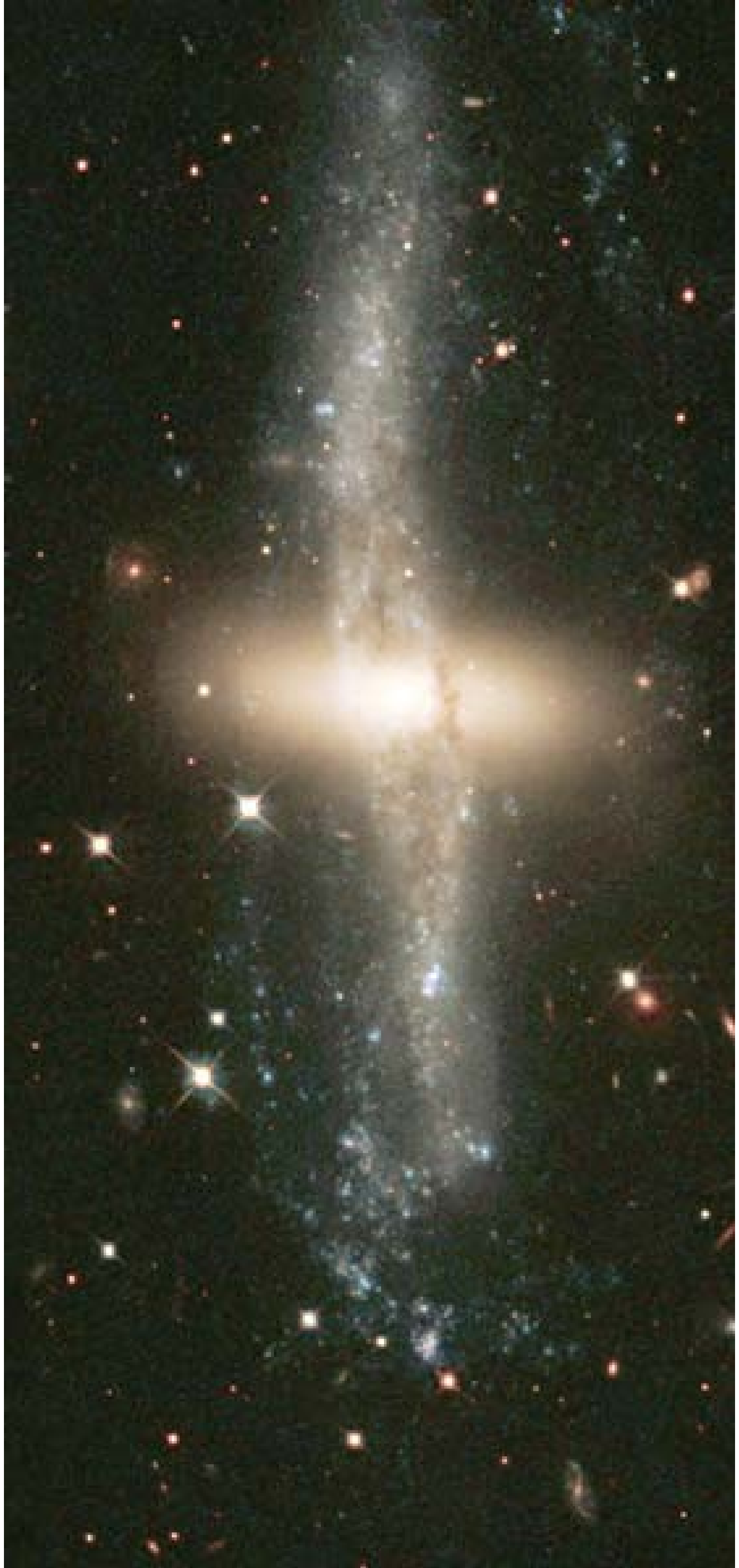


Galaxy collision & tidal arms:
Tadpole



Polar ring galaxy NGC4650A

Ring of young stars around an old central group



Also, feeding of a black hole at the centre of a galaxy requires stellar dynamics to explain the mechanism.

Do all stars fall in? How long does it take?

Aim of course: to provide the grounding to understand all these processes, and in particular the structure of star clusters and galaxies.

The Galaxy (schematic)

The Galaxy (schematic)

Thin Disk:

- young stars (Pop I), $Z > 0.02$ solar, gas (HI, molecular H)
- spiral arms, star formation, open clusters
- more complicated: moving groups, warp, flare
- radius ~15 kpc
- $V_c(R_\odot) = 220$ km/s

The Galaxy (schematic)

Bulge:

- Spheroidal shape, probably contains bar also
- Age: mostly old stars, but also intermediate & young

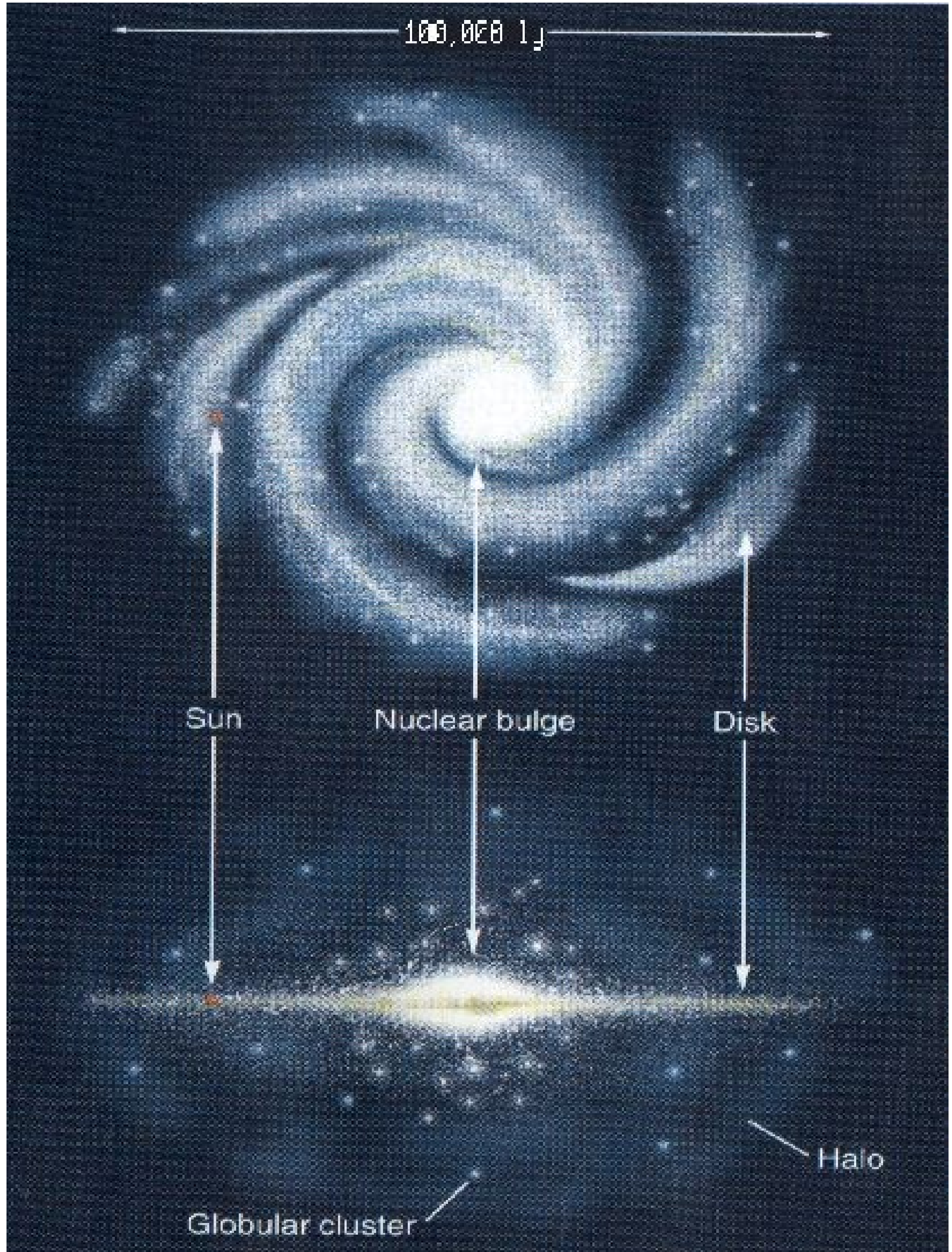

The Galaxy (schematic)
Globular clusters
~8 kpc
3.54"
Sun
Bulge/bar
Thin disk
Thick disk (older)
Thick disk:
• Older stars than disk
• Possibly formed by merger

The Galaxy (schematic)

Halo:
- Old stars, Pop II, Z<0.01 generally
- Globular clusters
  Spheroidal shape

Dark matter halo – provides most of the gravitating mass outside ~20kpc, but not in the bulge/disk region (from microlensing). Probably extends to radii ~ 100 - 200kpc.

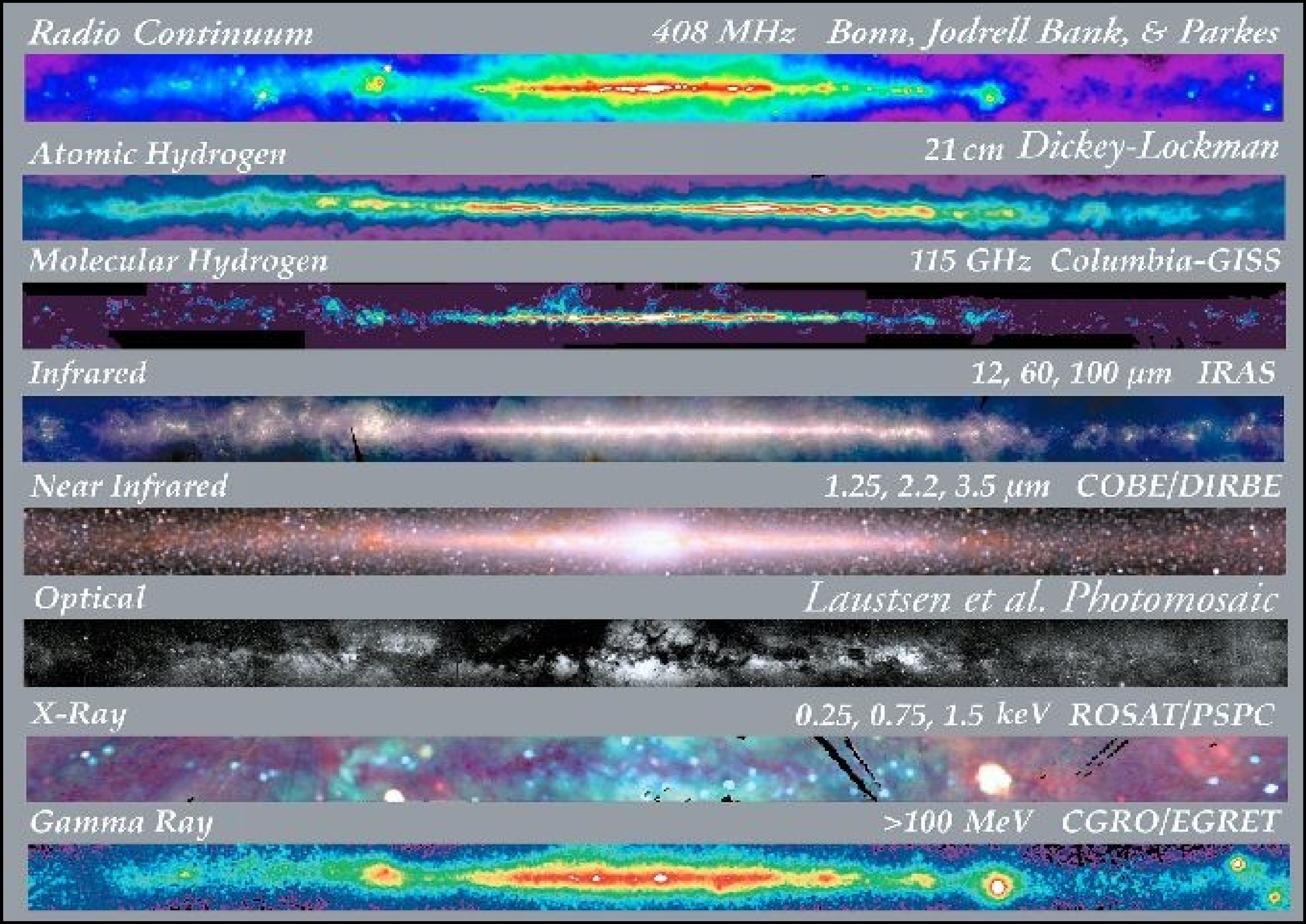
Another schematic



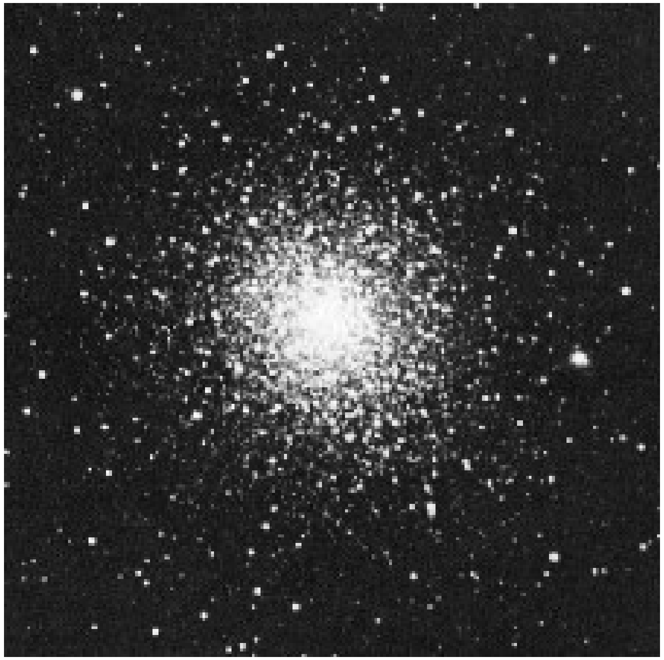
A view from where we (are at optical wavelengths)

Dominated by star emission and dust absorption
- we can see only about 300pc in the plane

Views from here at different wavelengths

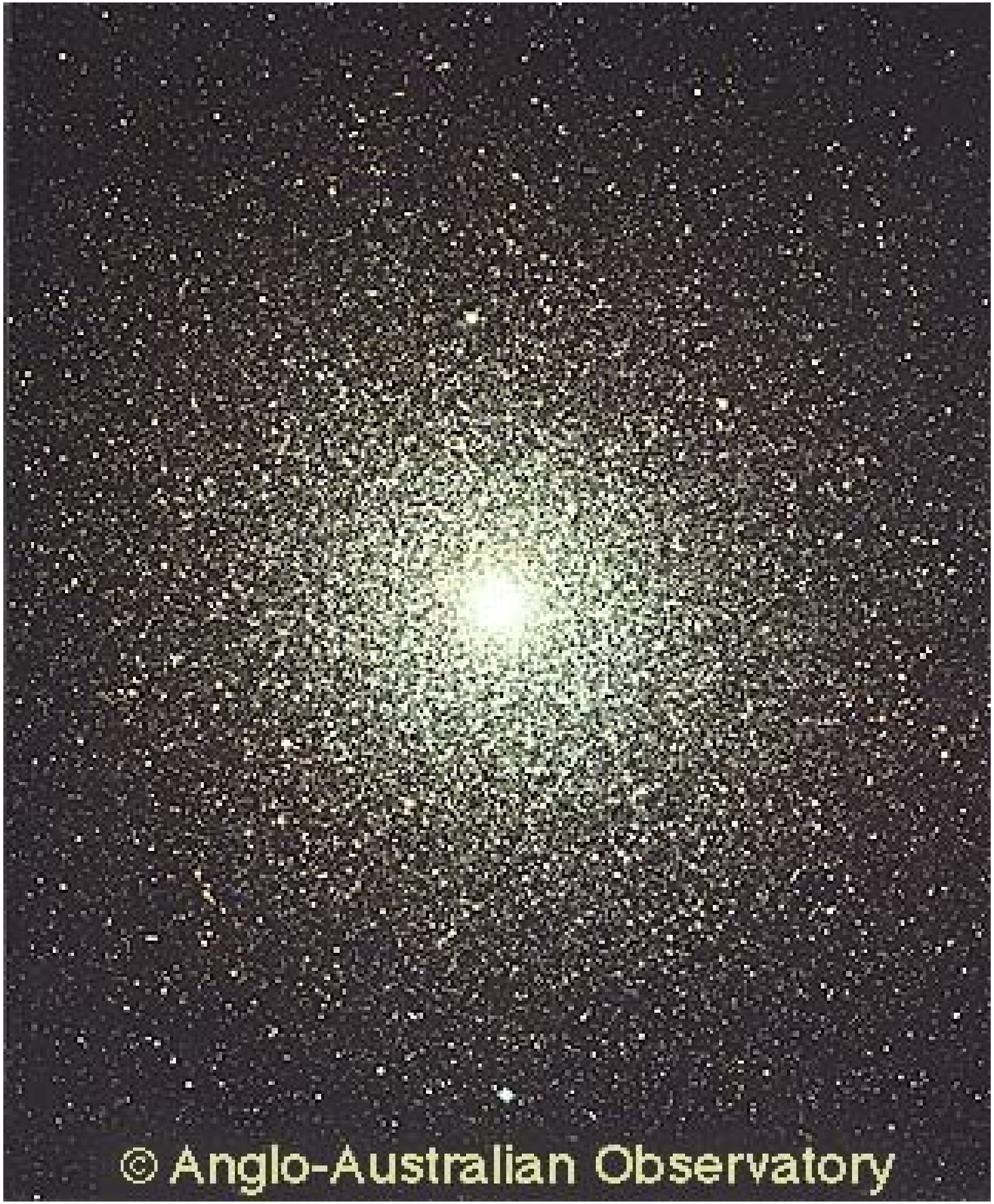


Globular clusters



M92

47 Tuc



Globular Cluster Star Densities

Stars are population (II) *i.e.* old.

$N \sim 10^4$ - 10^6 stars

Number of globular cluster is around the Galaxy $\sim$ 150

Useful since all stars at the same age and distance, so can obtain accurate parameters. Measure metallicity Z, age (from HR diagram and stellar evolution tracks, isochrone fitting), mass (assuming all visible and no gas).

Observations

They all appear to be round (apart from ωCen), so assume they are spherical.

Traditionally measure surface brightness as a function of radius R (in magnitudes per square arcsec) $\mu(R)$ *or* use high resolution images (HST more recently) to count stars.

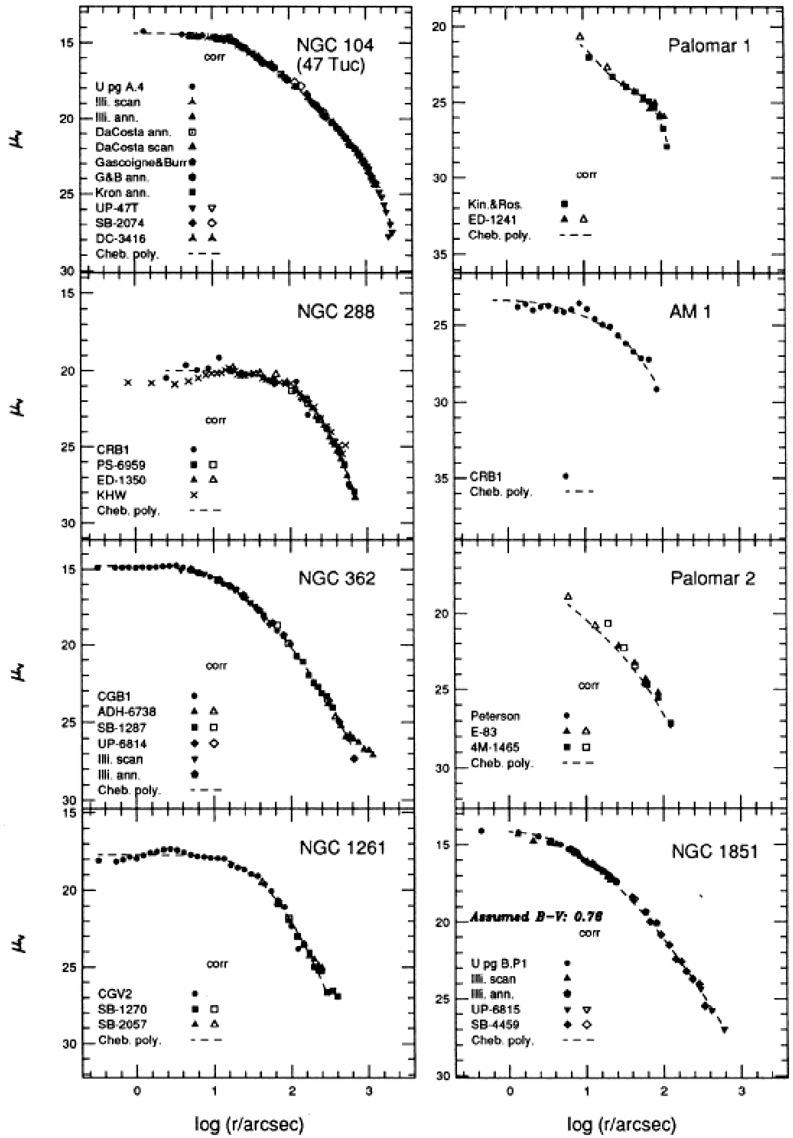


FIG. 2. The SBPs. The CCD data follow a naming convention: "*C*" stands for data taken at CTIO; e.g., "CRB1" stands for the first "*B*" image from the CTIO 1.5 m reflector with the RCA chip. "*L*" stands for the Lick 1 m Nickel reflector: these datasets are labeled as, e.g., "LTR-B," the second frame from the Lick Nickel reflector, taken with the TI chip through the Spinrad "*R*" filter. See Sec. *2.1* for details of chips and filters. "DJB2" stands for the second "*B*" image taken by Djorgovski. For Terzan 5, "*I*" refers to an *I*-band image from CTIO kindly provided to us by Dr. T. Armandroff. "U pg A.4" means the first ("A") ultraviolet ("U") plate used for photographic photometry ("pg") of the cluster in question. "Scan" data are scanning photoelectric photometry. "Ann" data are centered-aperture photoelectric photometry. Photographic star counts are referenced by plate number; see King *et al.* (1986), Peterson [(1976), labeled "C-" and "CF-," as well as a few without alphabetic prefix], and DaCosta [(1982), labeled "DC-"]. "Kin & Ros" are star counts from Kinman & Rosino (1962) (continued on p. xxxx).

Want star density $\rho(r)$

- First use M/L, or star mass M* to convert $\mu(R)$ [or N(R)] to surface mass density $\Sigma(R)$
- Assume spherical symmetry to convert $\Sigma(R)$ to $\rho(r)$

Want star density $\rho(r)$
- First use M/L, or star mass M* to convert $\mu(R)$ [or N(R)] to surface mass density $\Sigma(R)$
- Assume spherical symmetry to convert $\Sigma(R)$ to $\rho(r)$

From the plot of $\mu(R)$ it is clear that the cluster is not homogeneous

For a uniform distribution

$$\mu = \mu_0 + 2.5 \log\left(2/\sqrt{1 - R^2/R_0^2}\right)$$

and this is approximately constant for $\log(R/R_0) < -0.5$

The core radius r_c *is where* $\mu = \frac{1}{2}\mu_0$ *Generally* $r_c \approx 0.5\text{pc}$, $\rho \approx constant$ *for* $r < r_c$

Median radius (“typical” radius, “characteristic” radius) = radius which contains half the light (half-light radius).
Note: This is a two-dimensional definition, based on projected light distribution.

$r_h \approx 10\text{pc}$

Theoreticians use $\boldsymbol{r_h}$= half mass radius in 3 dimensions. Be aware of which definition is being used!

The tidal radius is the radius beyond which the external gravitational field of the galaxy dominates the dynamics. It is effectively the edge of the cluster, where $\mu \to 0$

$r_t \approx 50\text{pc}$

Mass $M \sim 6.10^5 M_\odot$

Stellar mass M^* up to $0.8\, M_\odot$

M/L~ 2 (times that for the sun)

Age ~ 10^{10} years [from stellar evolution models]

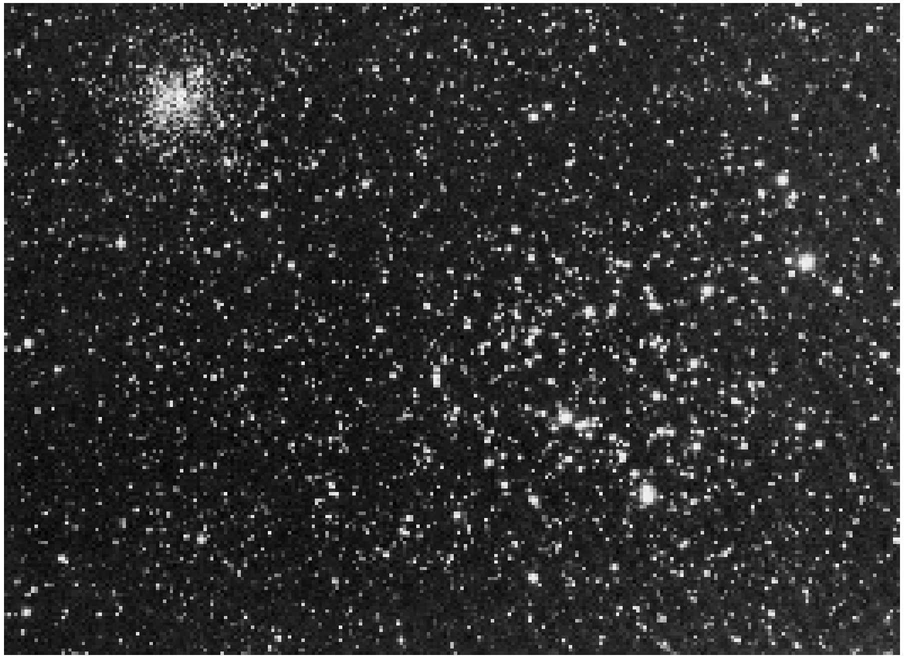
ρ ~ $8.10^3\, M_\odot$ /cubic pc

(One dimensional) central velocity dispersion $\sigma_r = \sqrt{\overline{v_r^2}}$ = 7 km/s

Range is 2 – 15 km/s. (Pal 5, NGC2419 have 2 km/s)

Open Clusters

NGC752



NGC2158 & M35

NGC2158 is the more compact, older cluster upper left

Open clusters

$N \sim 10^2$ - 10^3 stars

Age $\lesssim 10^8$ years $\Rightarrow$ either all formed recently or form and disperse continually.

$R_c \sim 1$ pc

$R_h \sim 2$ pc

$r_t \sim 10$ pc, because of stronger gravity in the disk of the Galaxy, and lower cluster mass.

Mass $\sim 250\ \mathrm{M}_\odot$

$M/L \sim 1$ (solar units)

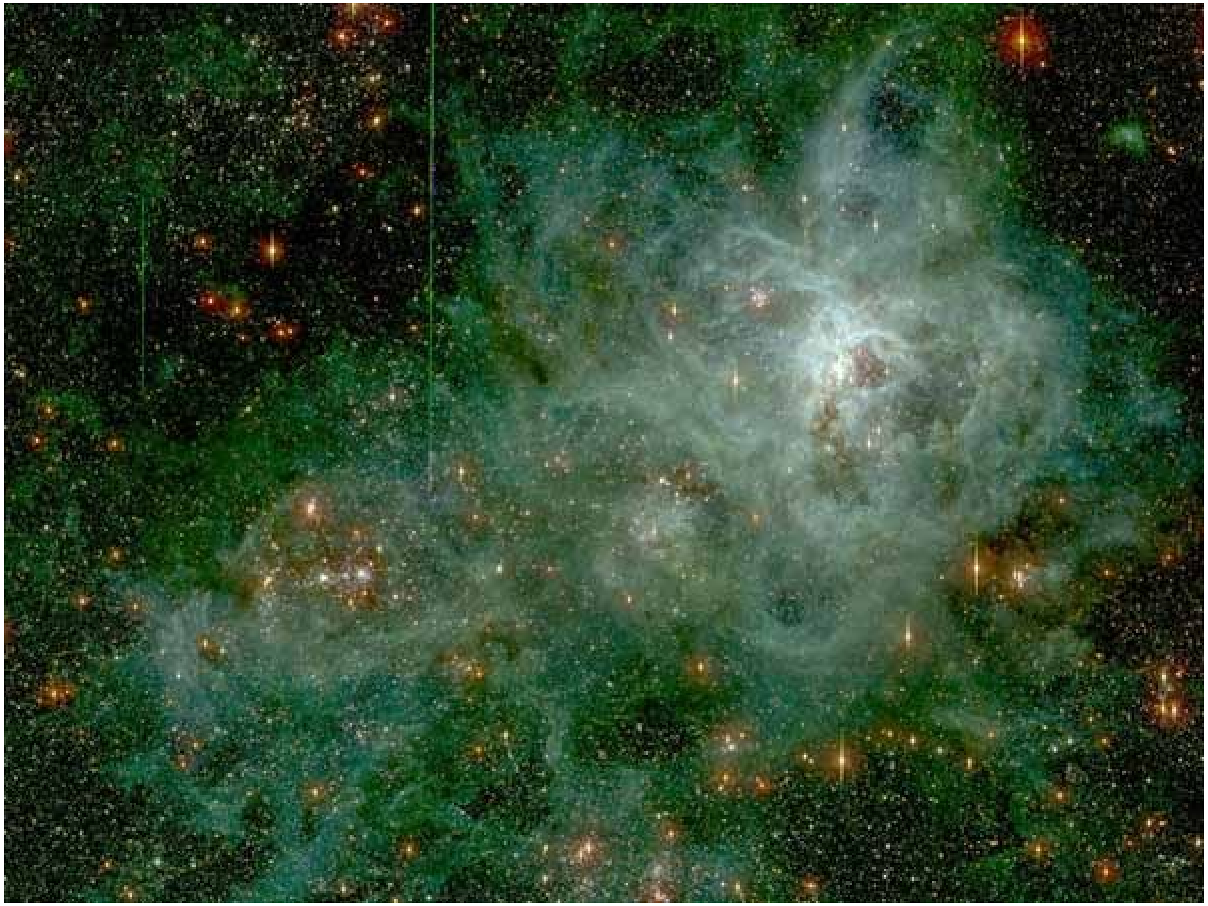
$\rho_c \sim 100\ \mathrm{M}_\odot\ \mathrm{pc}^{-3}$ (cf solar neighbourhood $\bar{\rho} = 0.05\ \mathrm{M}_\odot\ \mathrm{pc}^{-3}$).

$\sigma_r = \sqrt{\bar{v_r^2}} \sim 1\ \mathrm{km\ s}^{-1}$ (system assumed approximately isothermal).

The Galaxy is not now forming globular clusters,
only low-mass open clusters

.. this makes globular cluster evolution hard to study.

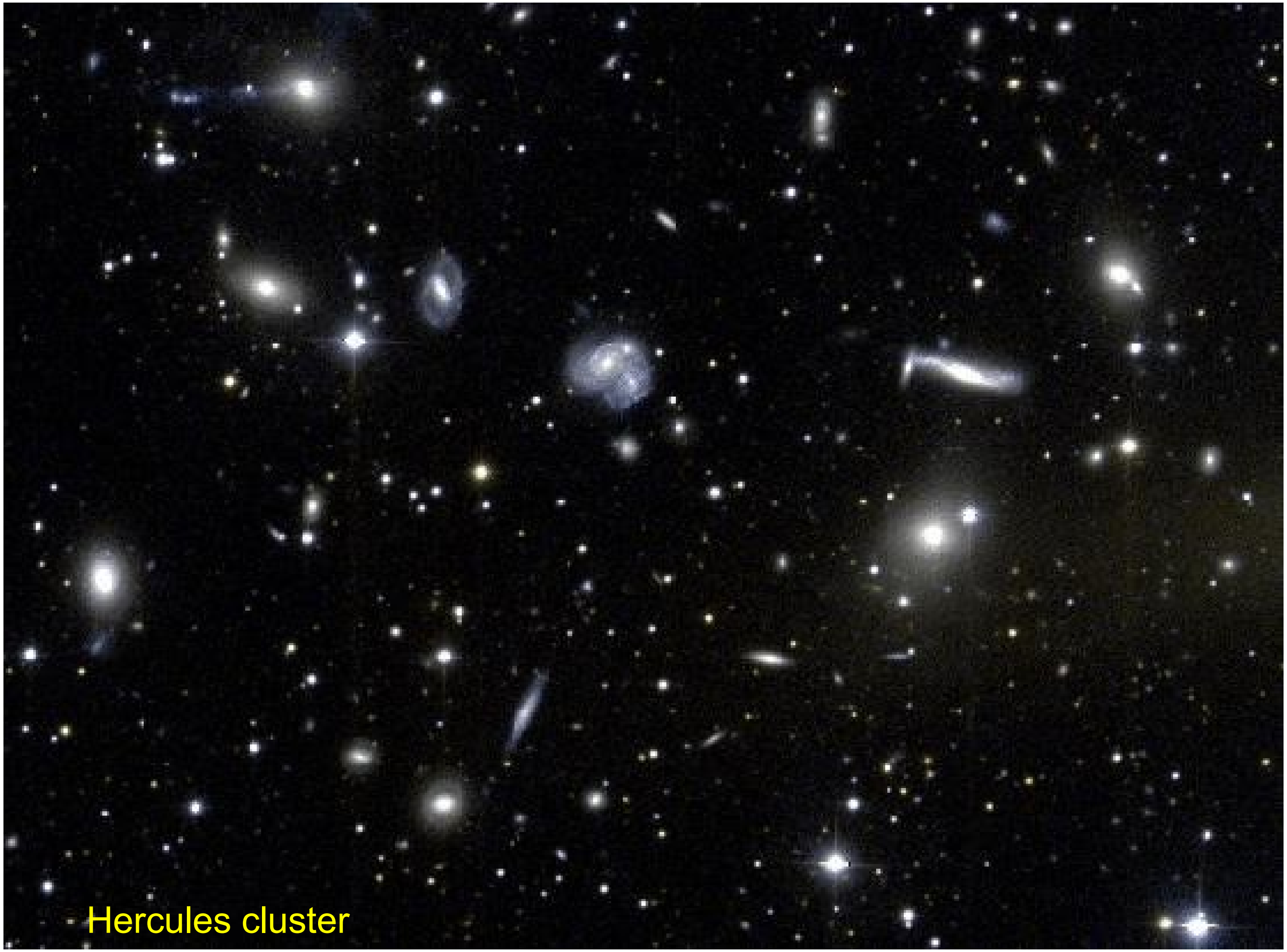
The Large Magellanic Cloud has young, massive clusters which
are near enough to study. These might become globulars...



30 Doradus in the LMC

Clusters of Galaxies

Same physics (gravity), but different particles (galaxies instead of stars)



No. of galaxies in a cluster N~100 -- but a large range of N, and a wide range of cluster masses.

Core radius r_c ~ 250kpc

Typical radius r_h ~ 3Mpc

Mass ~ 10^{15} $M_\odot$ (much not visible)

σ_r ~ 800 km/s

Crossing time $$t_{cross} \sim \frac{r_h}{\sigma_r} \sim 10^9 \left(\frac{r_h}{1\mathrm{Mpc}}\right)\left(\frac{\sigma_r}{10^3\mathrm{km/s}}\right)^{-1} \text{ years}$$

Compare this with the age of the Universe ~ 13.7 10^9 years (see Cosmology course)

⇒ clusters of galaxies are dynamically young, often still forming, collapsing for the first time.