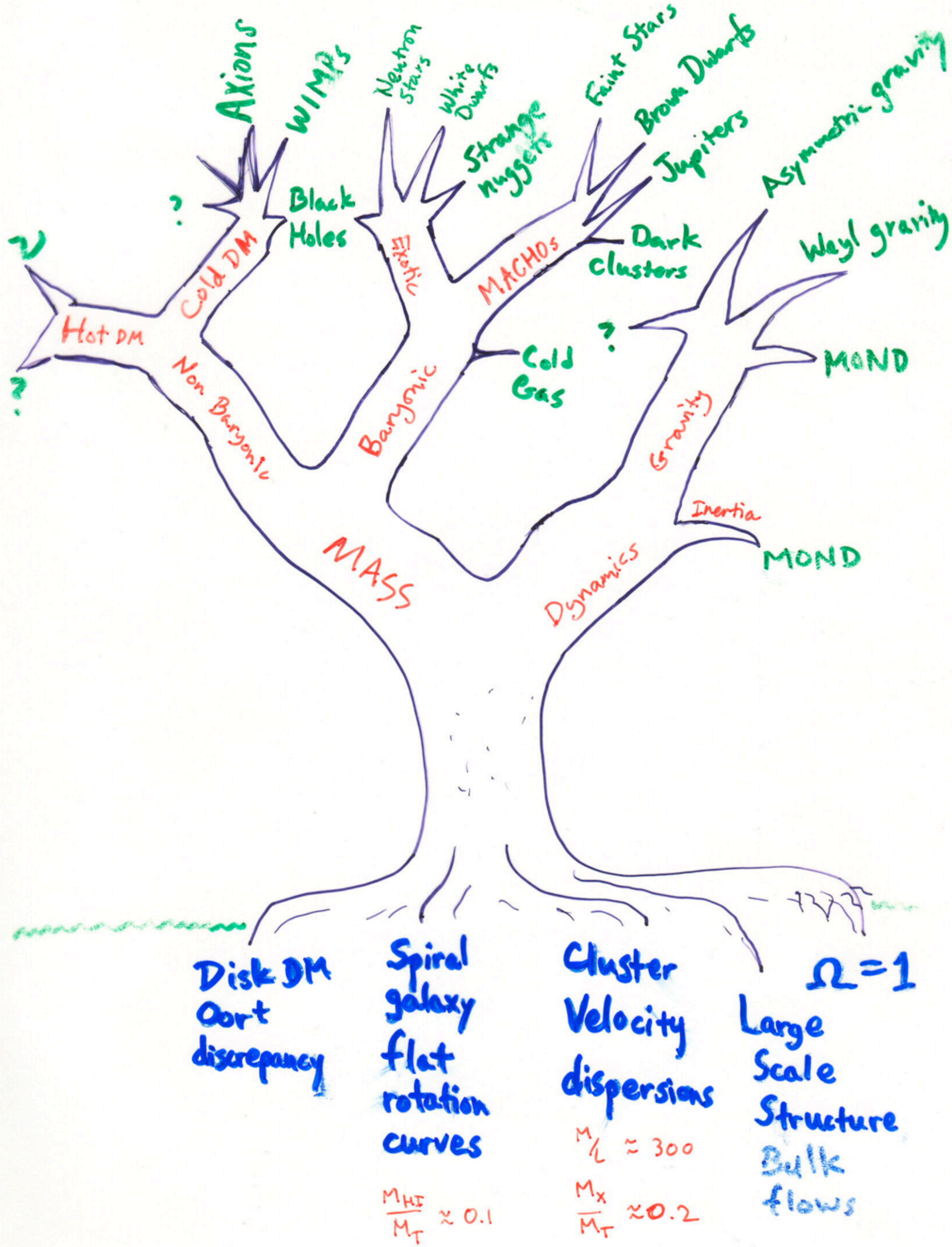
# Dark Matter

## ASTR 333/433

## TODAY

**Stellar Populations**
**Velocity Fields**
**Galactic Kinematics**



# Baryonic Mass of Galaxies

$$M_b = M_* + M_g = \Upsilon_* L + X^{-1}\left(M_{HI} + M_{H_2}\right)$$

$$X^{-1} \approx 1.33 \ - \ 1.42$$

- **Stars** $M_* = \Upsilon_*^i L_i$ $L_i = 4\pi D^2 F_i$
  - $\Upsilon_*^i$ is the stellar mass-to-light ratio in photometric band $i$
- **Gas**
  - *Atomic gas* - H I
    - $M_{HI} = 2.36 \times 10^5 D^2 F_{HI}$
  - *Molecular gas* - $H_2$
    - $M_{H_2} = 1.1 \times 10^4 D^2 F_{CO}$

also scales with stellar mass $M_{H_2} \approx 0.07\, M_*$

# Stellar populations

- Simple Single Population (SSP)
  - stars of all masses born at the same time
  - e.g., a star cluster

- Complex stellar population (CSP)
  - Convolution of many star forming events
  - need to know
    - IMF (initial mass function)
    - Birthrate (star formation rate history)

open cluster

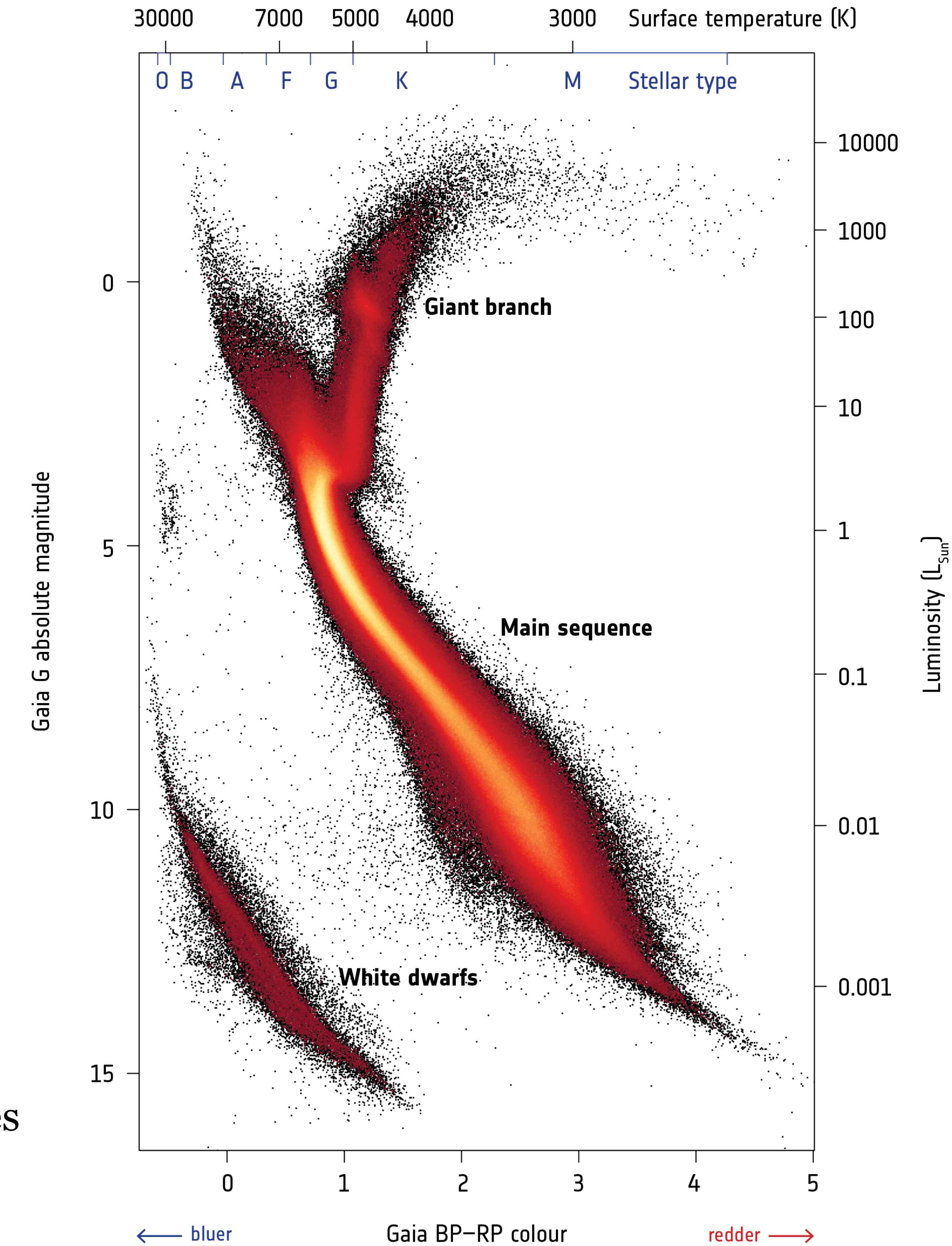
globular cluster

# Stars & Stellar populations

To separate the dark from the lights, gotta understand stars

The Milky Way has a complex stellar population composed of many generations of stars

- Stellar Evolution
  - lives of individual stars
- IMF (Initial Mass Function)
  - mass spectrum of stars formed
- Star Formation History
  - rate at which stars form
- Metallicity
  - distribution of chemical abundances



# Galaxy spectra composed of complex stellar populations

In general, one has only the integrated spectra of distant galaxies, not resolved color-magnitude diagrams.

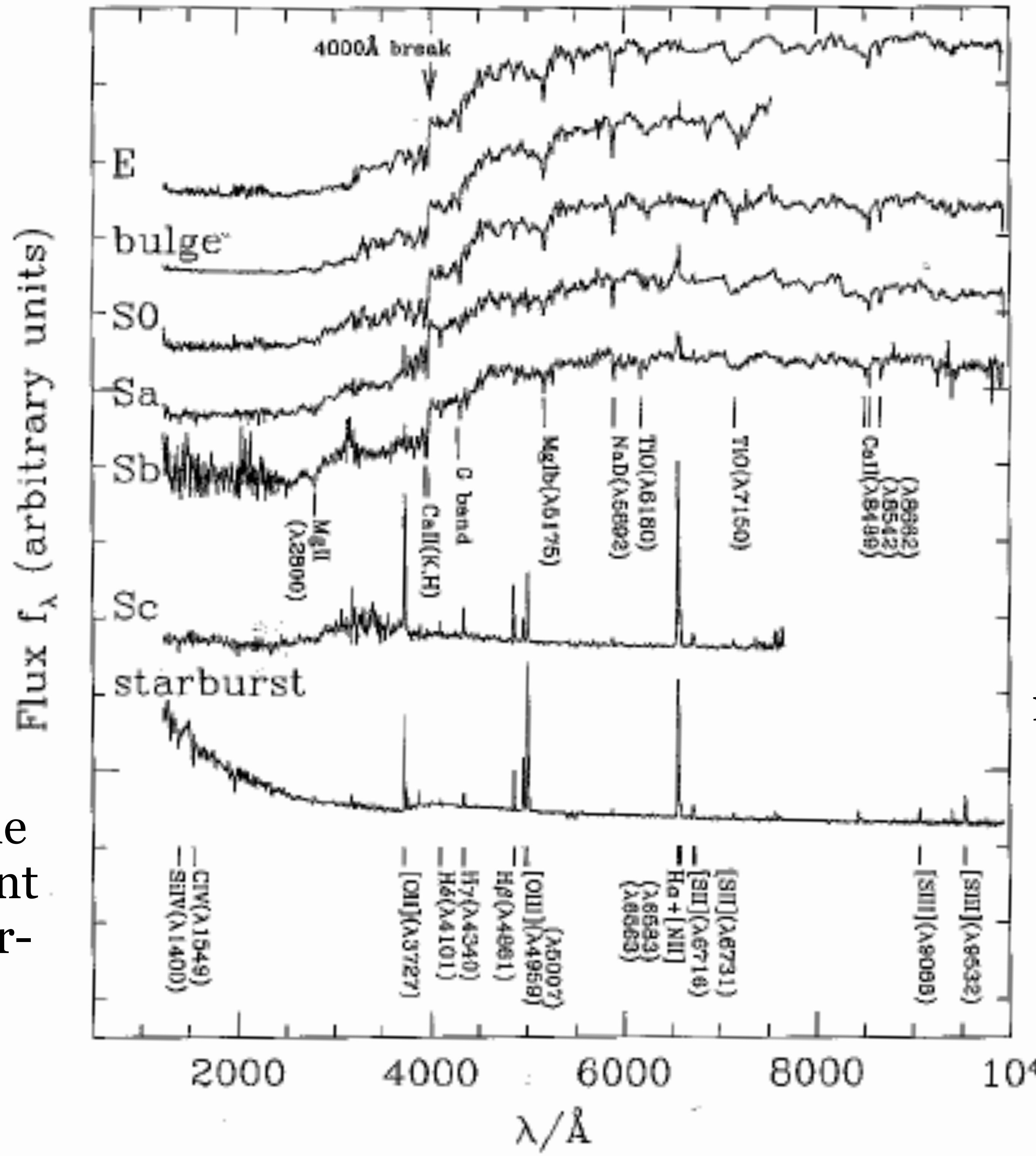


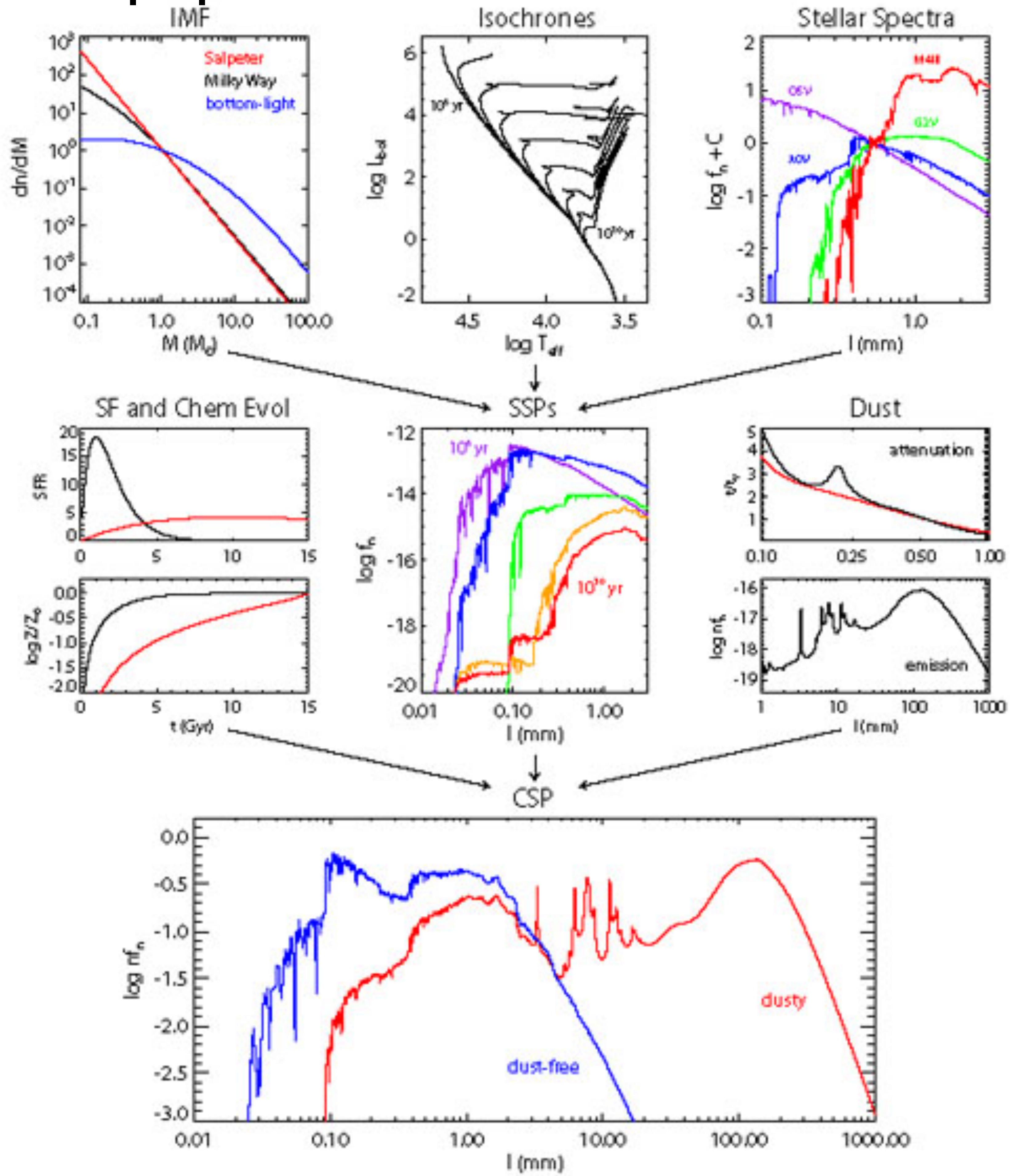

Fig. 2.12. Spectra of different types of galaxies from the ultraviolet to the near-infrared. From ellipticals to late-type spirals, the blue continuum and emission lines become systematically stronger. For early-type galaxies, which lack hot, young stars, most of the light emerges at the longest wavelengths, where one sees absorption lines characteristic of cool K stars. In the blue, the spectrum of early-type galaxies show strong H and K absorption lines of calcium and the G band, characteristic of solar type stars. Such galaxies emit little light at wavelengths shorter than 4000 Å and have no emission lines. In contrast, late-type galaxies and starbursts emit most of their light in the blue and near-ultraviolet. This light is produced by hot young stars, which also heat and ionize the interstellar medium giving rise to strong emission lines. [Based on data kindly provided by S. Charlot]

mostly old stars

mostly young stars

# Stellar population models

## Stellar population synthesis modeling:

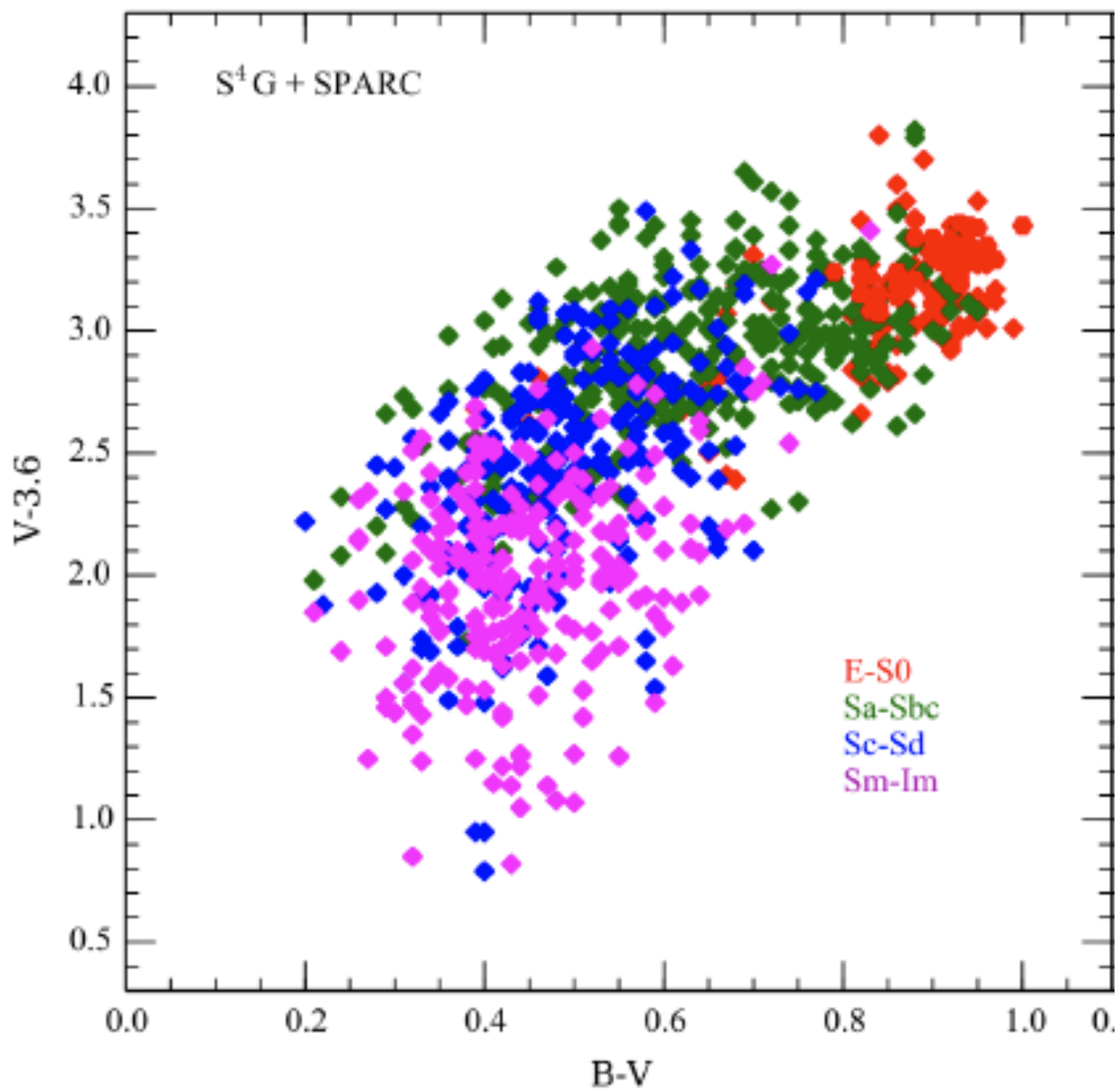



Stellar population synthesis modeling is a common way to estimate the stellar mass-to-light ratio.

# Stellar population models

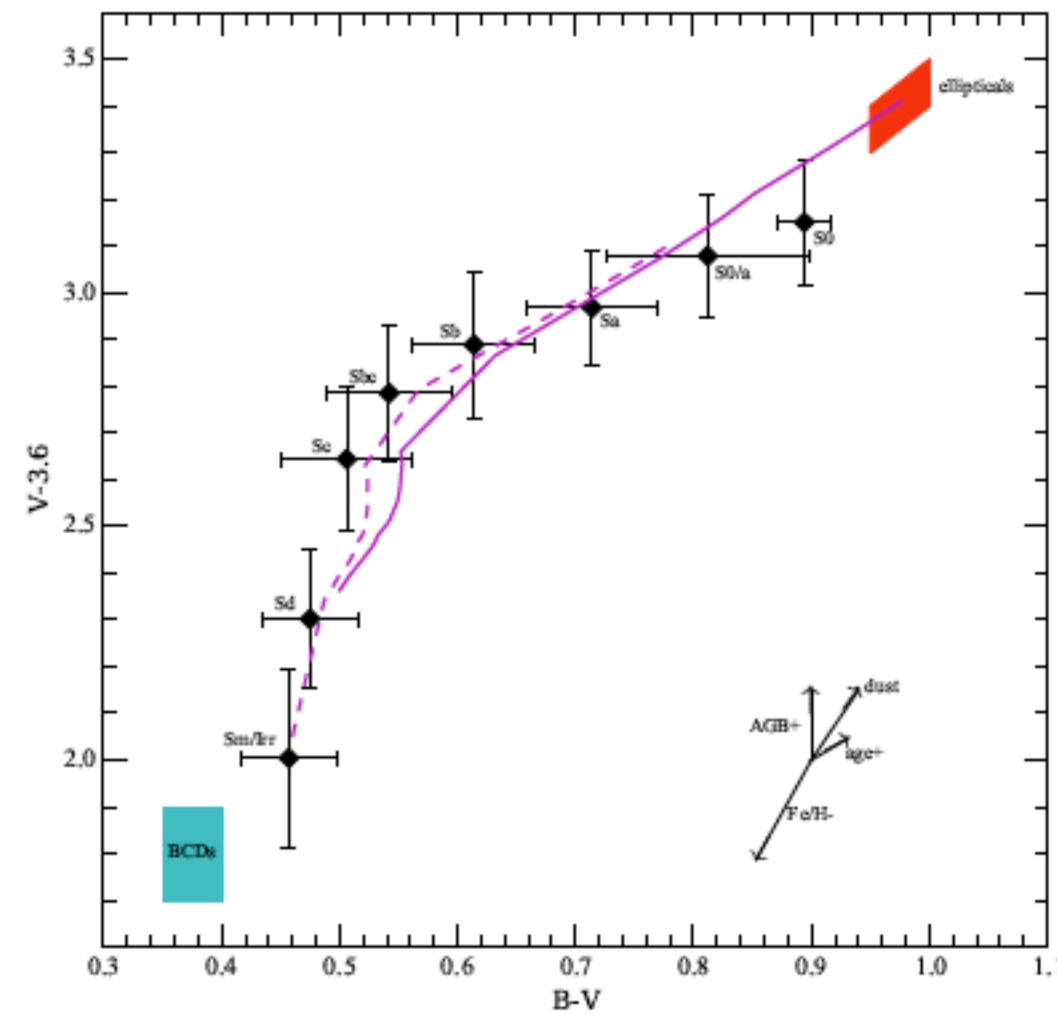
galaxy color-color diagram

$V - [3.6]$




$B - V$

mean galaxy colors with CSP models (lines)



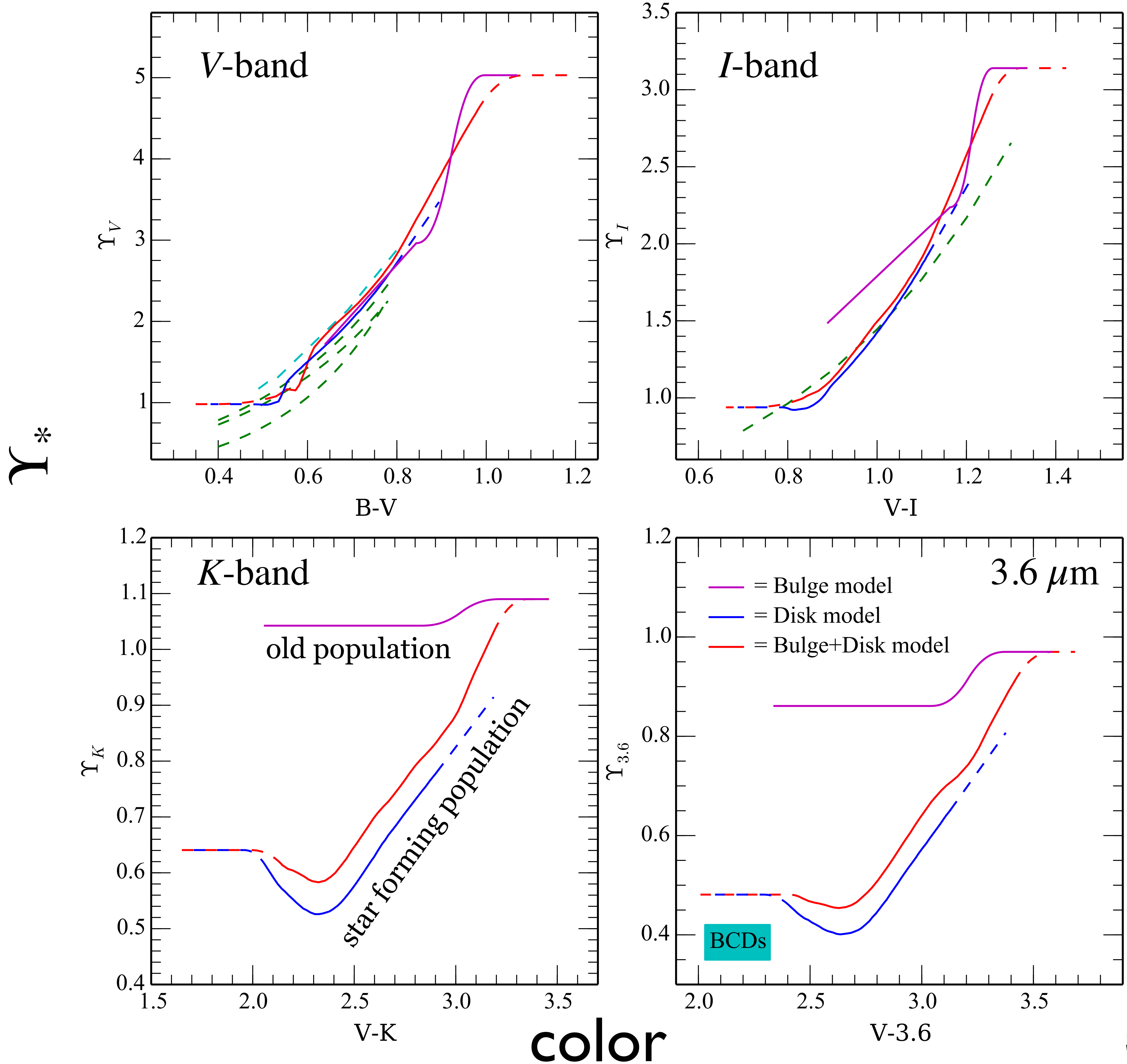

$B - V$

galaxies color coded by Hubble type

Schombert et al (2019, 2021)

# Stellar population models

## Typically, redder colors mean higher mass-to-light ratios




Can use multiple colors, but most of the information is in the first one.

Schombert et al (2021)

# Baryonic Mass of Galaxies

$$M_b = M_* + M_g = \Upsilon_* L + X^{-1}\left(M_{HI} + M_{H_2}\right)$$

$X^{-1} \approx 1.33 \ - \ 1.42$

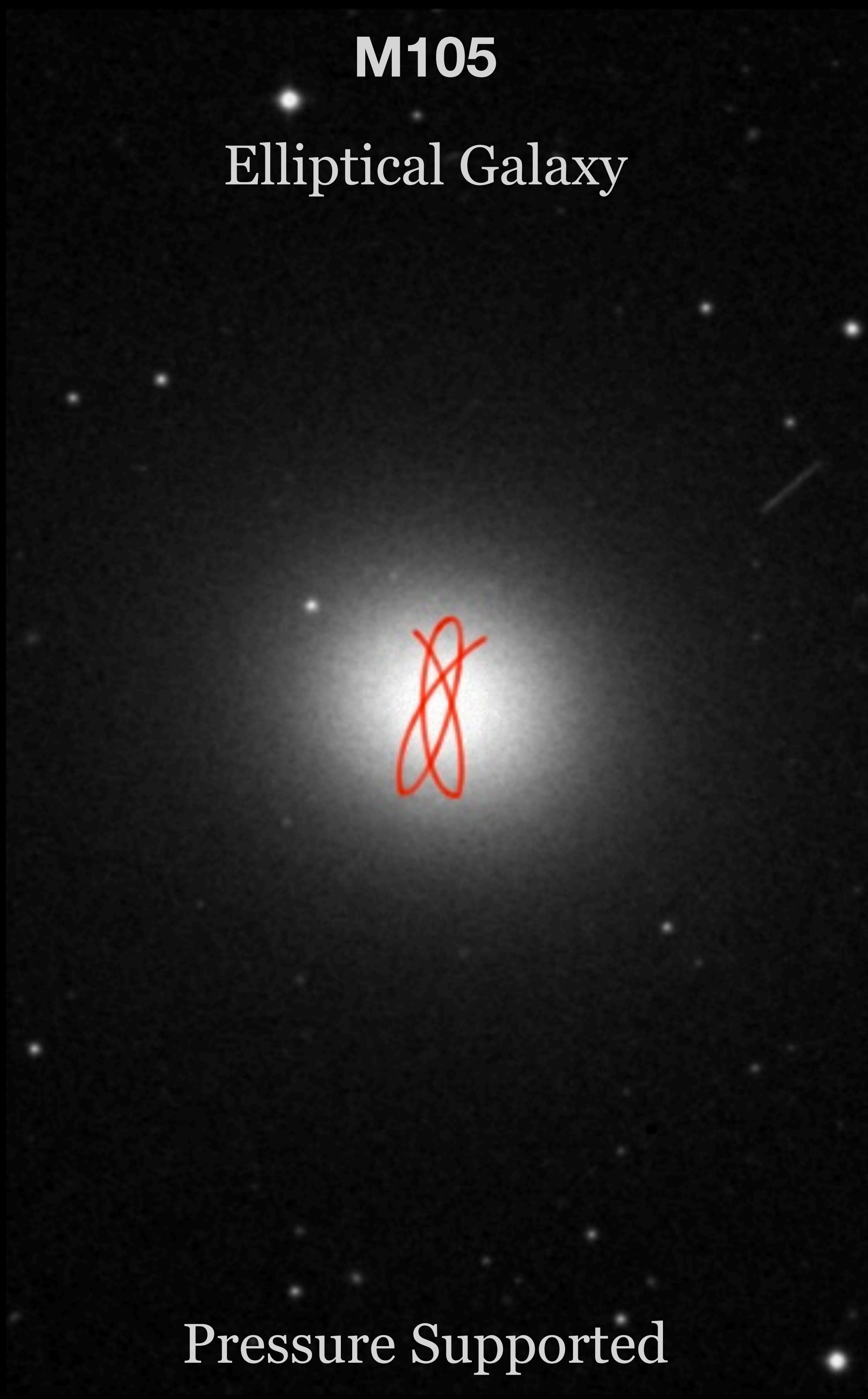
- **Stars** $\quad M_* = \Upsilon_*^i L_i \qquad L_i = 4\pi D^2 F_i$
  - $\Upsilon_*^i$ is the stellar mass-to-light ratio in photometric band $i$

To a surprisingly good approximation,

$$M_* \approx 0.5\, L_{[3.6]} \qquad \approx 0.63\, L_K$$

for star forming (late type) galaxies

# Stellar orbits in galaxies





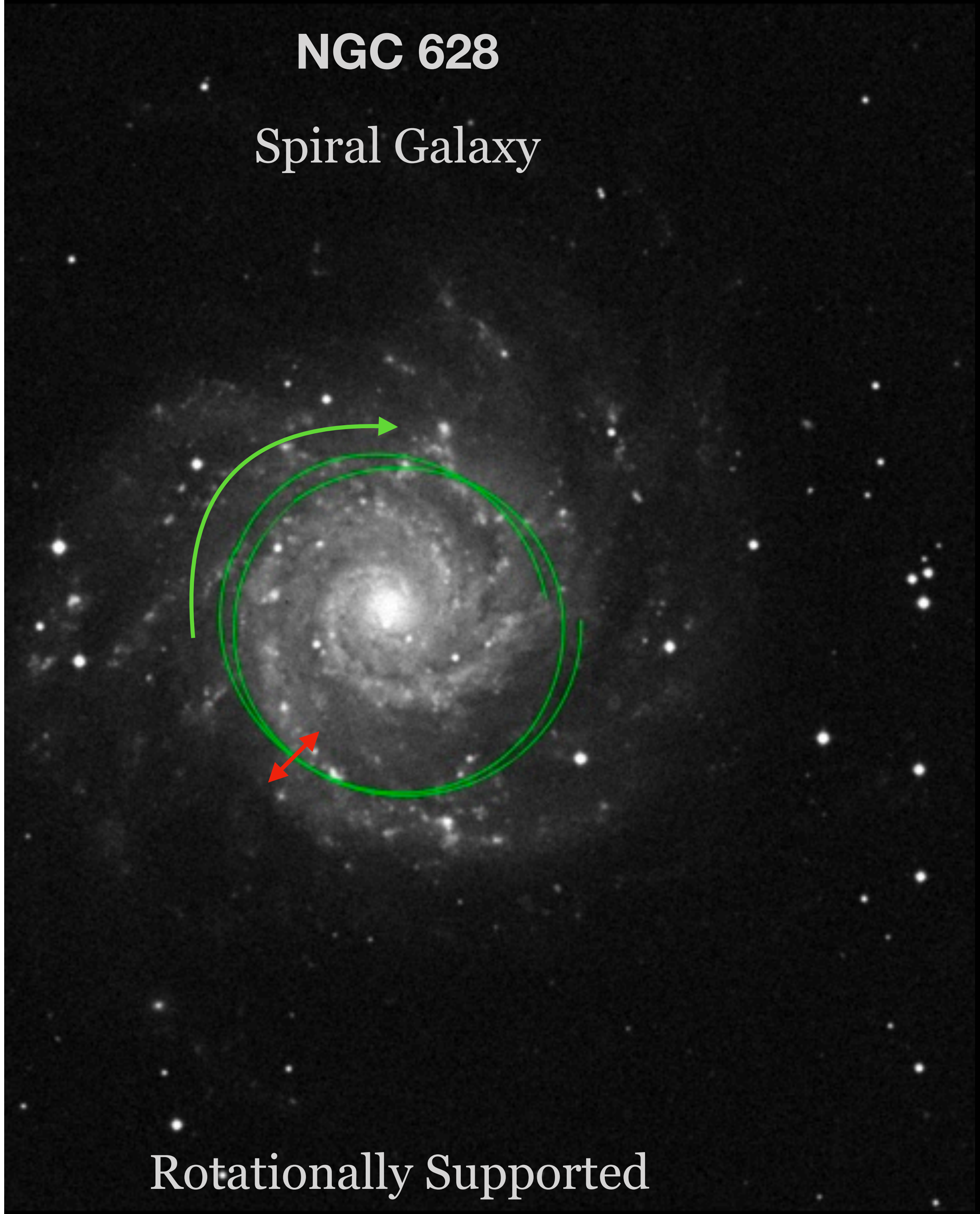
Eccentric radial orbits
Random orientations

Nearly circular orbits
Same direction, same plane

# Stellar orbits in galaxies

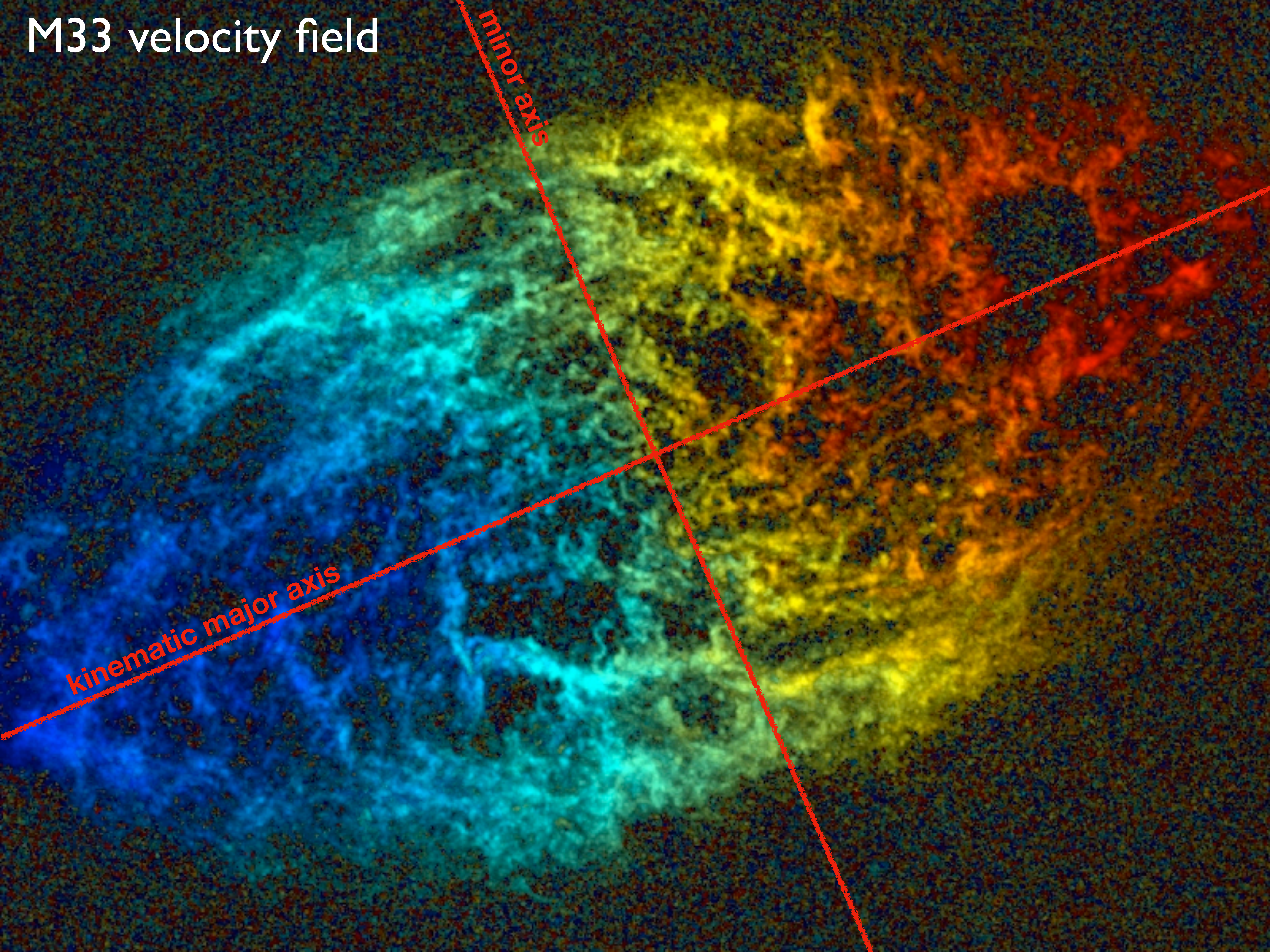
orbital frequency $\Omega$
round & round

epicyclic frequency $\kappa$
in & out




Nearly circular orbits
Same direction, same plane

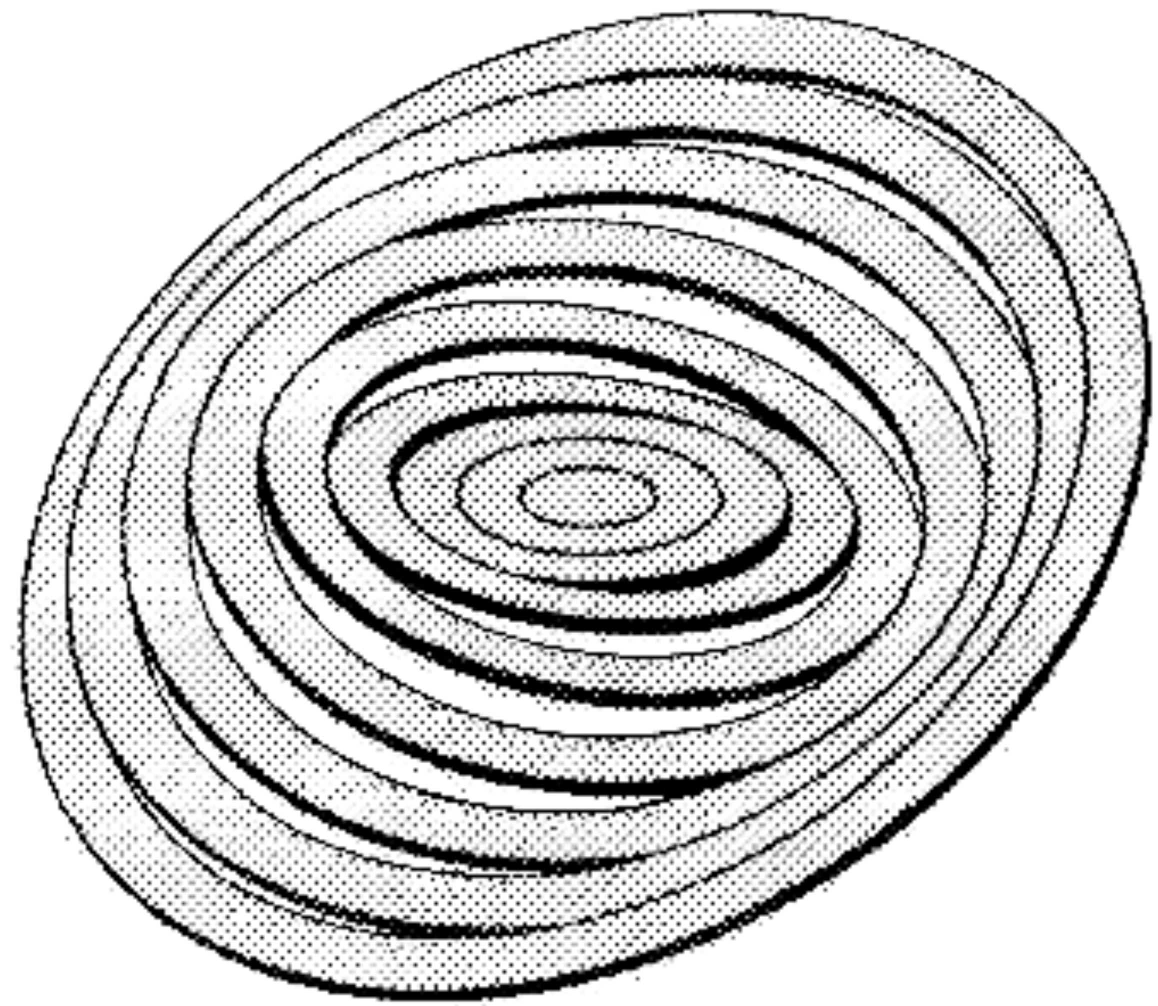
# M33 velocity field

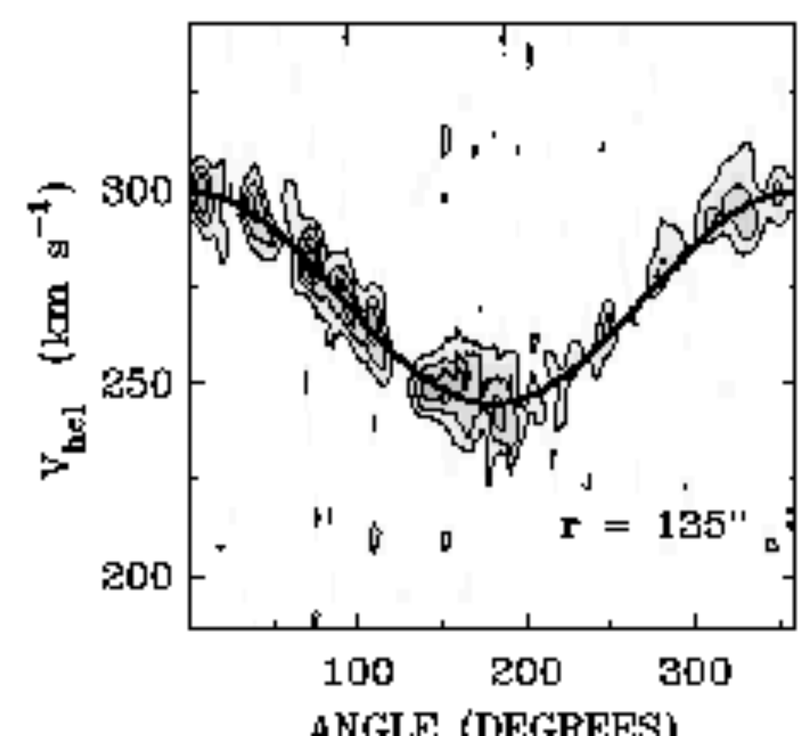


Rotation curves extracted using "tilted ring" fits

Fit ellipses that most closely match the circular velocity at a given radius. In principle, get ellipse center, position angle, axis ratio, inclination, and rotation velocity. In practice, usually have to fix some of these parameters.

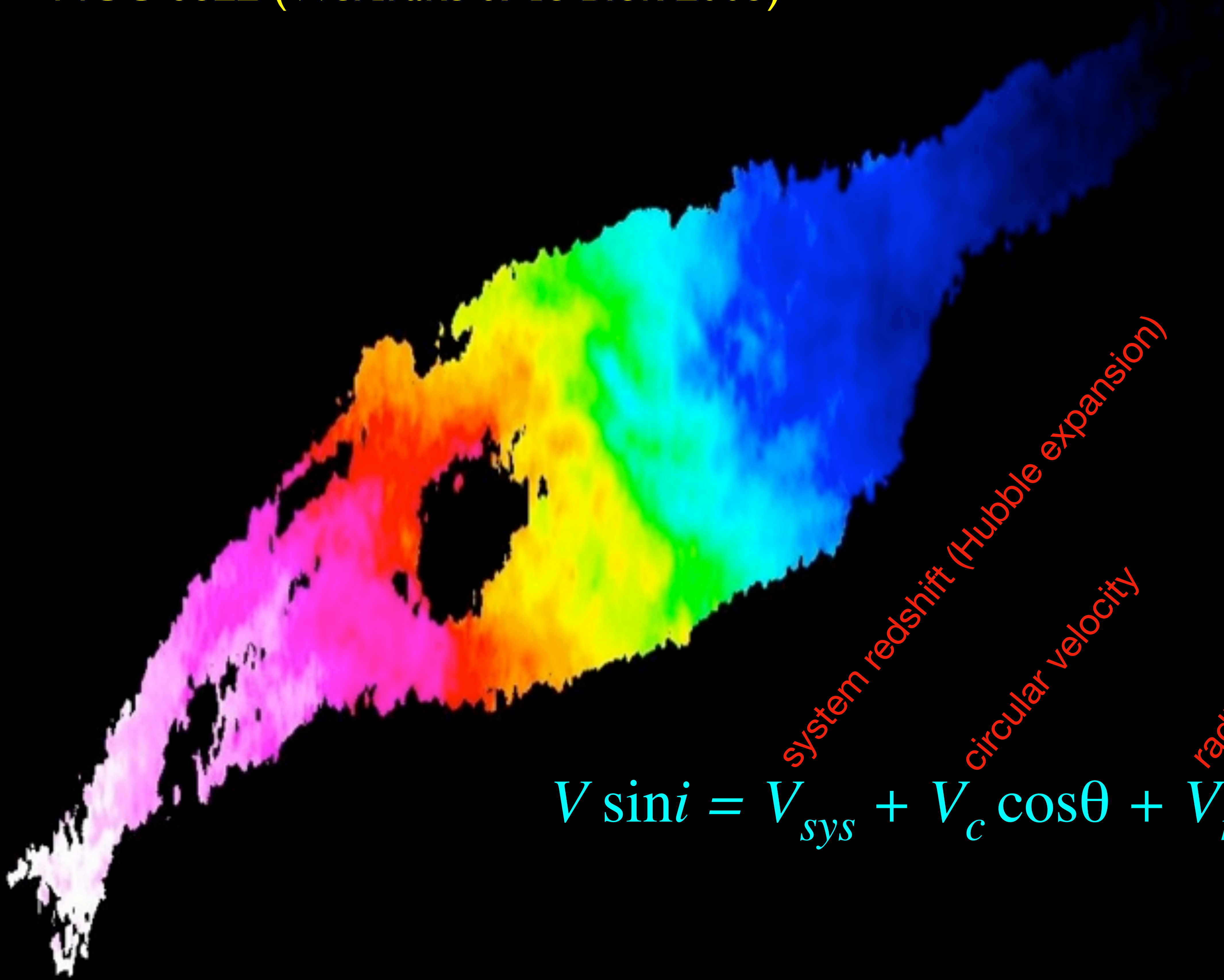
tilted ring model






velocity variation along ring

NGC 6822 (Weldrake & de Blok 2003)

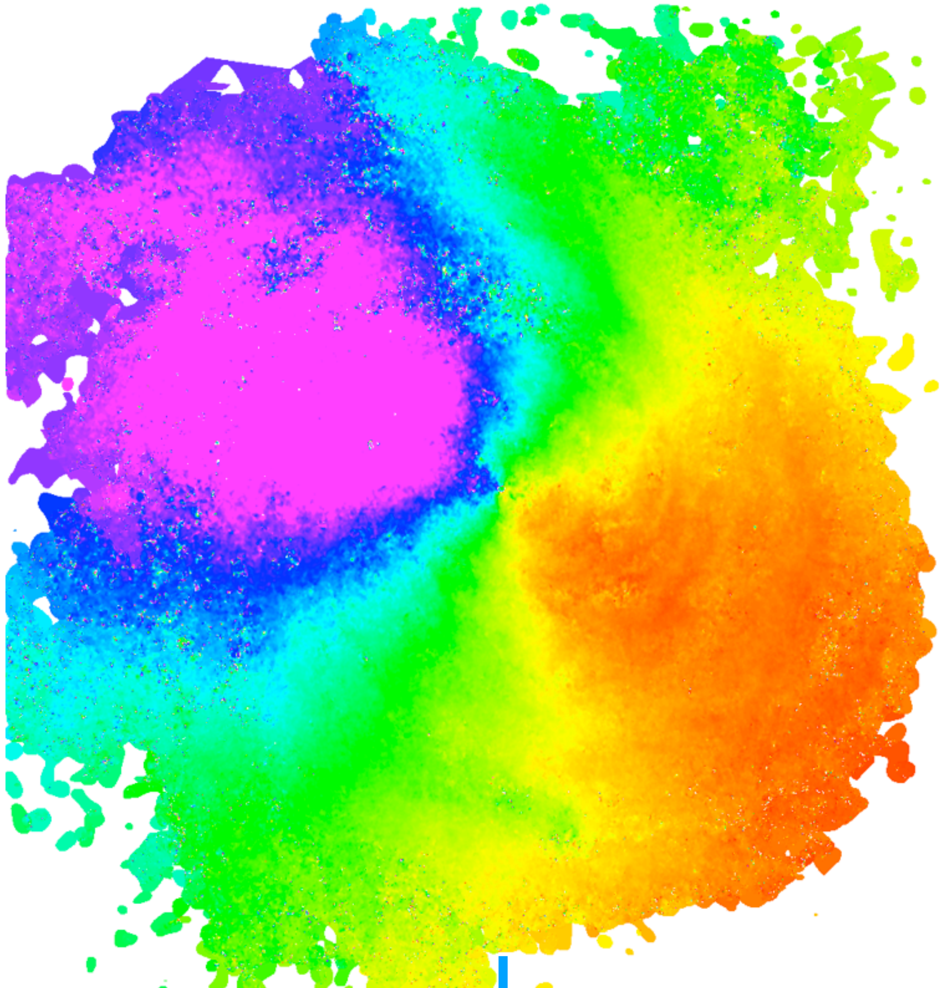


$$V \sin i = V_{sys} + V_c \cos\theta + V_r \sin\theta$$

system redshift (Hubble expansion)
circular velocity
radial velocity

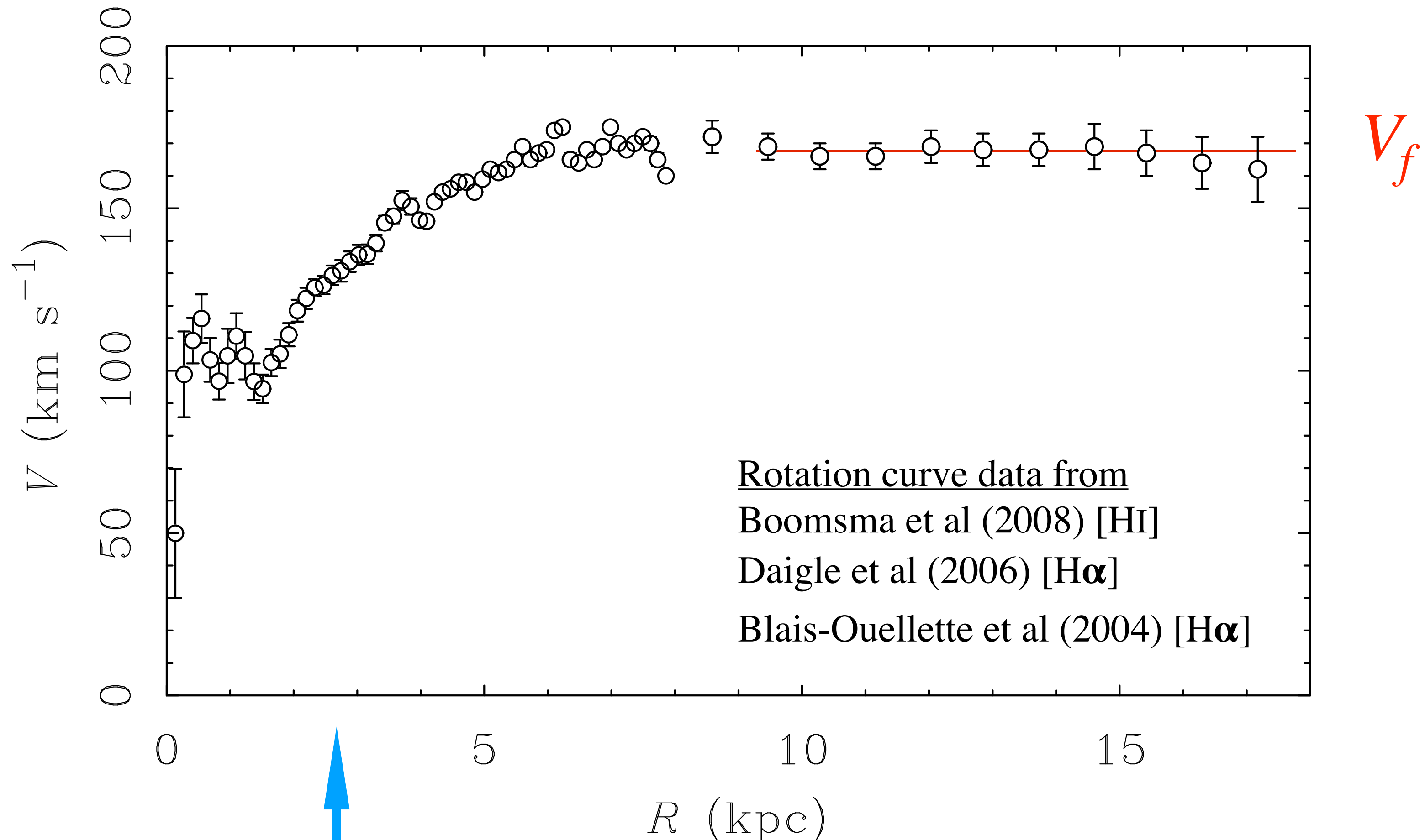
**21cm interferometric observations give atomic gas distributions and velocity fields**

# NGC 6946

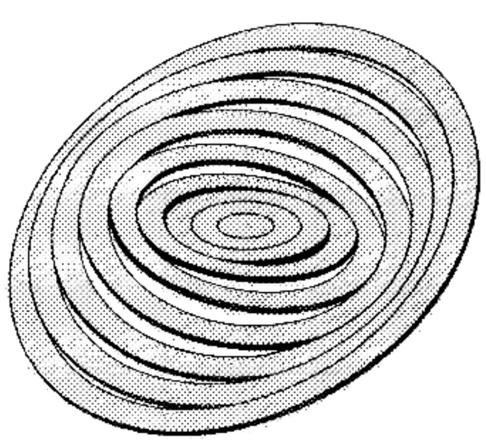


THINGS (Walter et al. 2008; de Blok et al. 2008)

# Rotation curve




tilted ring model



to which we make tilted ring fits

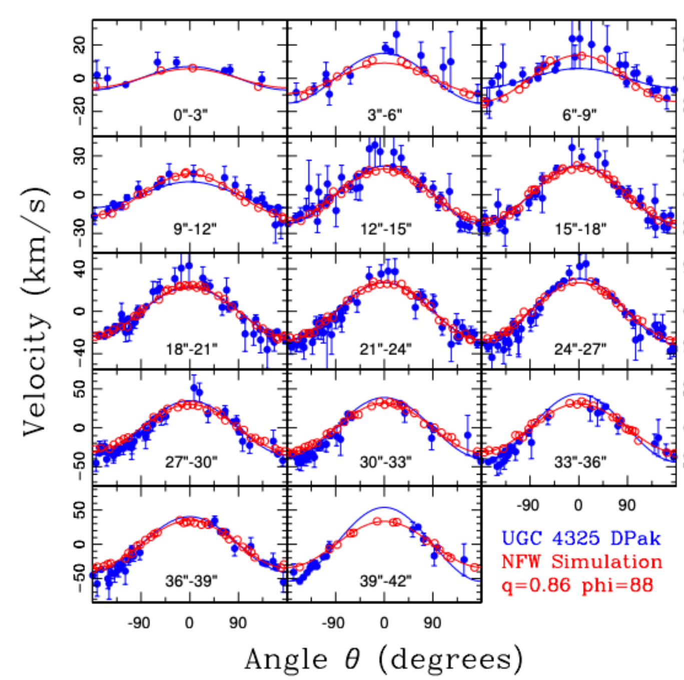



Figure 5.6: – The (0.86, 88°) simulation results (red) over-plotted with the observed UGC 4325 data (blue). The simulation and data match well between ~ 12″ - 30″.

The sinusoidal variation of velocity in each ring measures the position angle, inclination, and rotation curve $V_c(R)$.

$$V \sin i = V_{sys} + V_c \cos\theta + V_r \sin\theta$$

# Galactic Kinematics

Galactic constants

$$R_0 \; \Theta_0 \; A \; B$$

$$\Omega < \kappa < \nu_z$$

Local Standard of Rest

Epicycle approximation

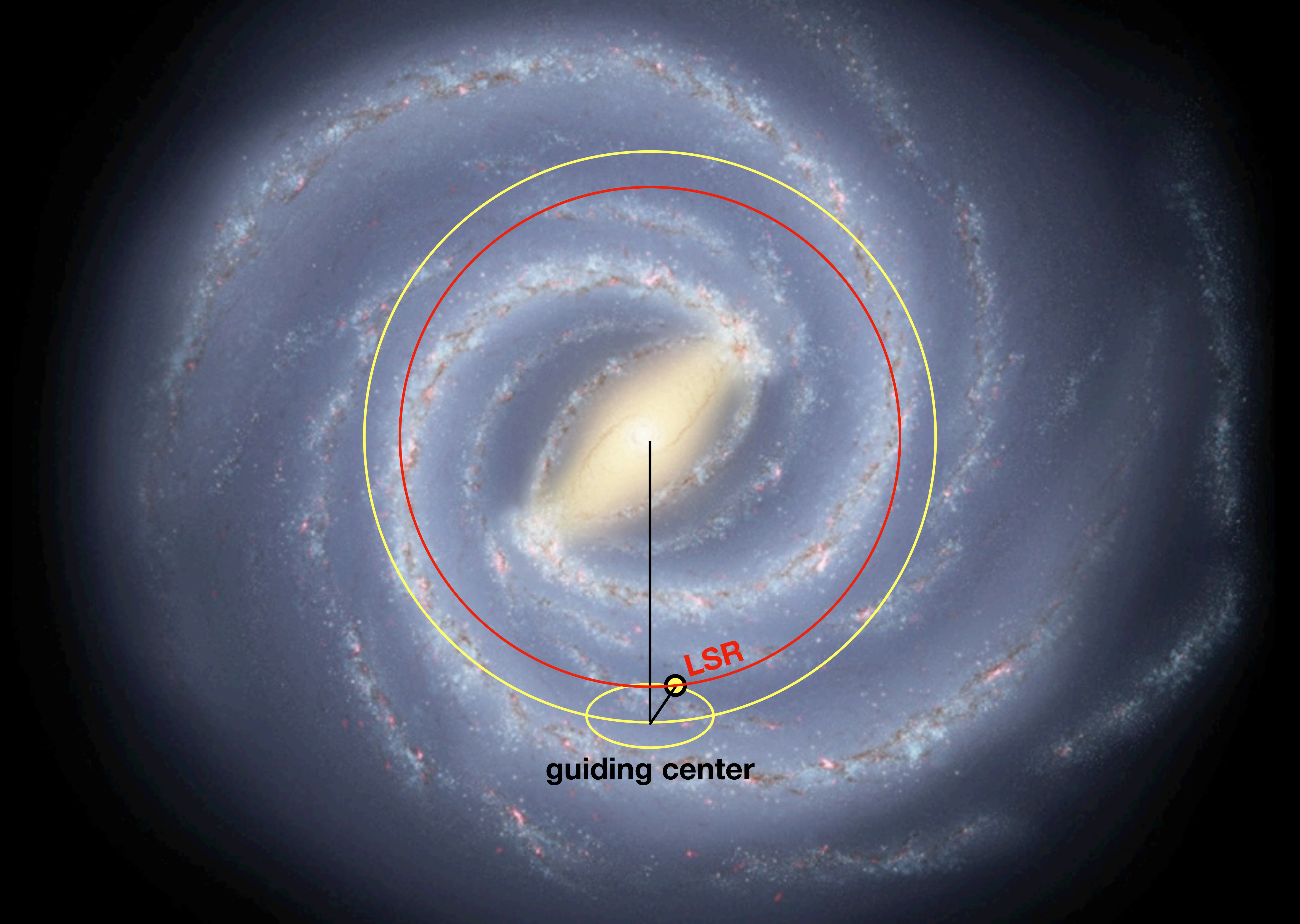
# LSR - local standard of rest

The Local Standard of Rest (LSR) is the point coincident with the sun that is on a perfectly circular orbit.
(The sun itself is not on a circular orbit.)

The net velocity of populations of stars is zero wrt the LSR; this is how we measure it.

More generally, if the Galactic potential is not axis-symmetric (e.g., because of the Galactic bar), then the LSR orbit is oval.

## Orbits of individual stars: the epicycle approximation



# Definitions of Galactic Quantities

$R_0$ distance to Galactic Center 8.12 kpc

$\Theta_0$ orbital velocity of LSR 233 km/s

$\Omega_0$ angular velocity of LSR $\Omega = \frac{V}{R}$ $P = \frac{2\pi R}{V} = \frac{2\pi}{\Omega}$

$A$ Oort constant A $A = \frac{1}{2}\left(\frac{V}{R} - \frac{dV}{dR}\right)_{R_0}$

$B$ Oort constant B $B = -\frac{1}{2}\left(\frac{V}{R} + \frac{dV}{dR}\right)_{R_0}$

$\kappa$ epicyclic frequency $\kappa^2 = -4B(A - B)$

Frequencies often expressed in Galactic units: km/s/kpc

# Solar Motion

The residual solar motion wrt the average of local stars is

radial $U_{\odot} = 10\,\mathrm{km\,s^{-1}}$

azimuthal $V_{\odot} = 12\,\mathrm{km\,s^{-1}}$

vertical $W_{\odot} = 7\,\mathrm{km\,s^{-1}}$

Some say V = 5 km/s, some say 15 km/s!

The Sun is moving

- a bit towards the galactic center
- faster than the LSR
- northward out of the galactic plane

Currently we are near the mid-plane

(Remember this doesn't account for the rotation of the disk!)

# Orbits for 4 individual stars

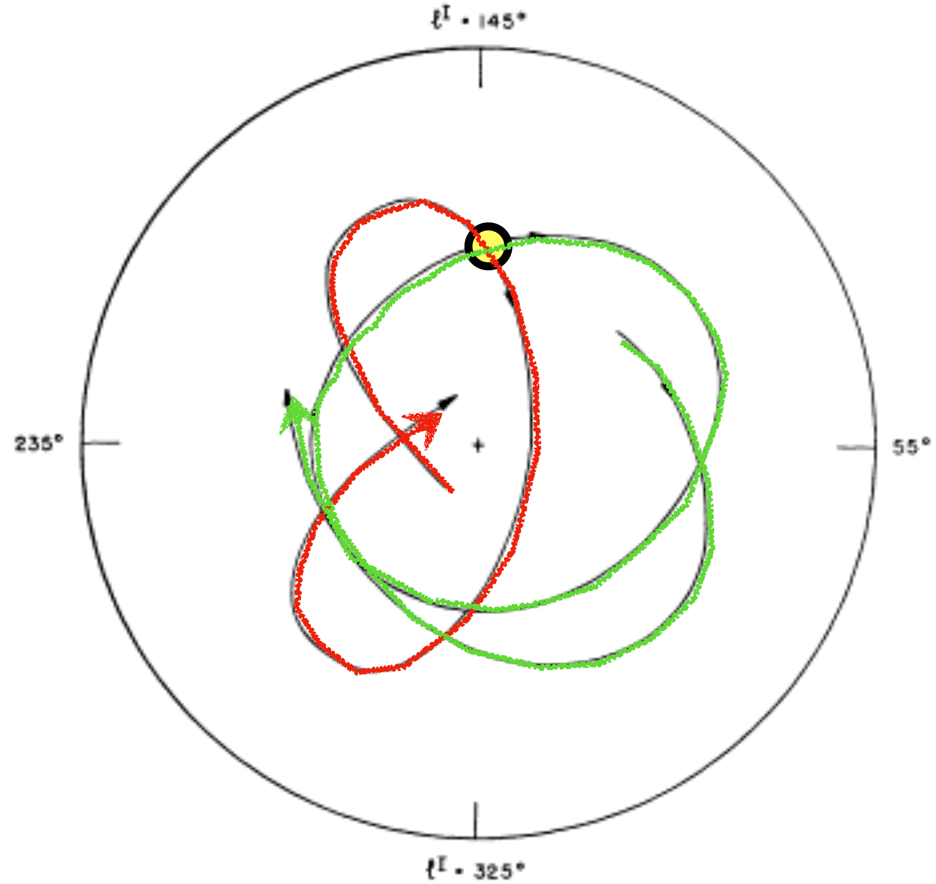



Fig. 2.—Segments of the galactic orbits for two of the program stars. The more circular orbit is for HD 117635 with an ultraviolet excess of $\delta = +0^{m}.05$ The more elliptical orbit is for HD 11980 with $\delta = +0^{m}.17$. Both orbits pass through the solar neighborhood, which is designated by a circle on the $l =$ 145° axis at a distance of 10 kpc from the galactic center The galactic center is shown as a cross The outer circle has a radius of 20 kpc.

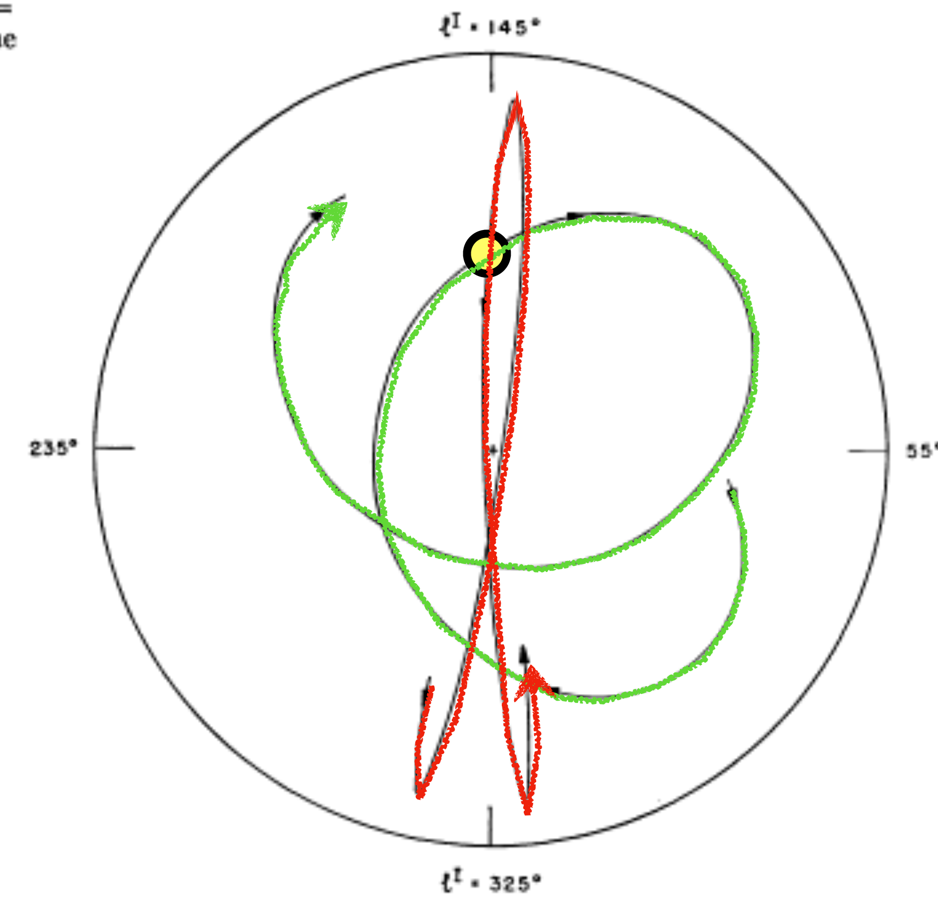



Fig 3.—Same as Fig. 2 The more circular orbit is for HD 29587 with $\delta = +0^{m}.13$. The more elliptical orbit is for Ross 106 with $\delta = +0^{m}.26$. The orbit for Ross 106 is retrograde.

from Eggen, Lynden-Bell, & Sandage (1962)