Dark Matter

ASTR 333/433
Spring 2026
TR 11:30am–12:45pm
Sears 552

http://astroweb.case.edu/ssm/ASTR333/

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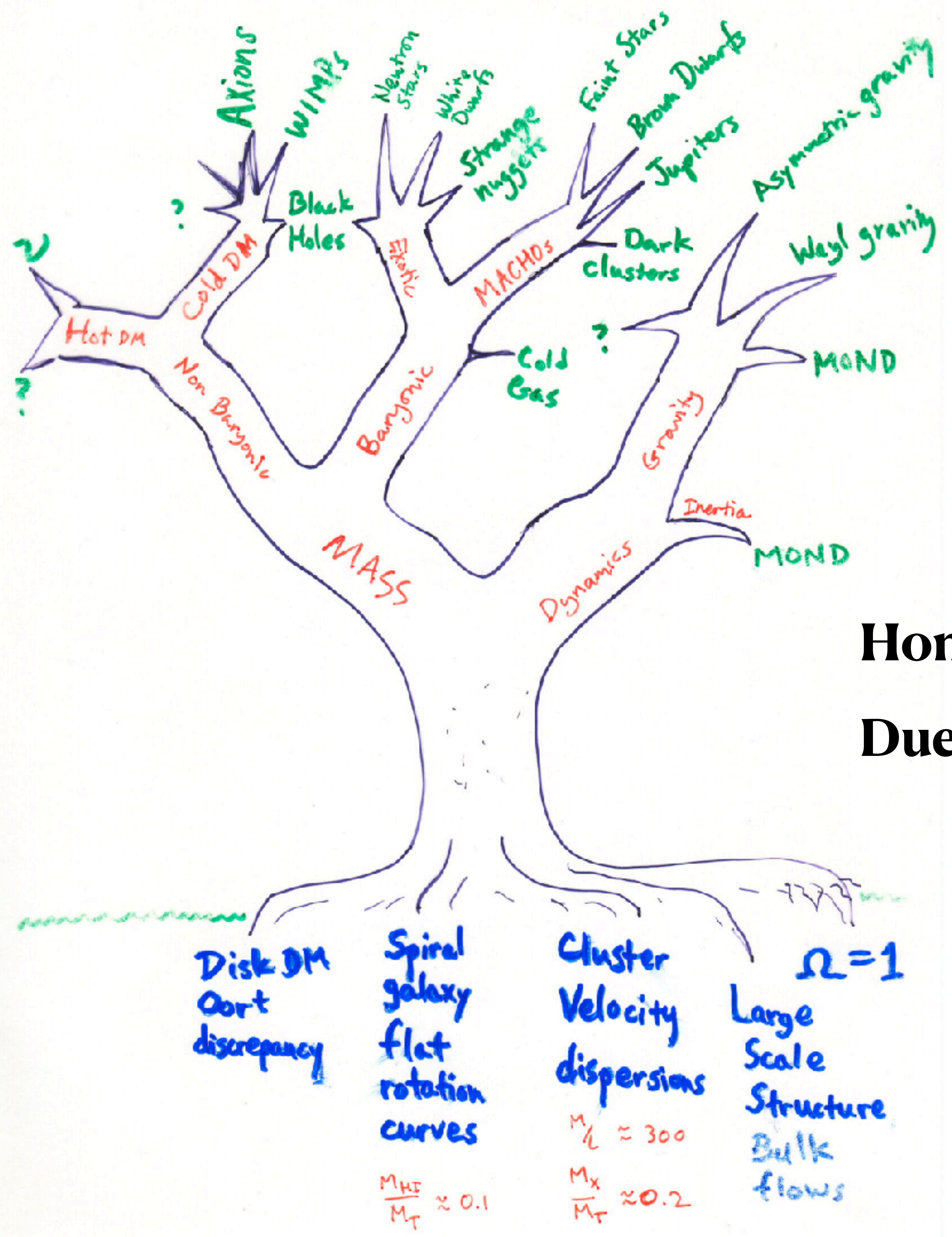
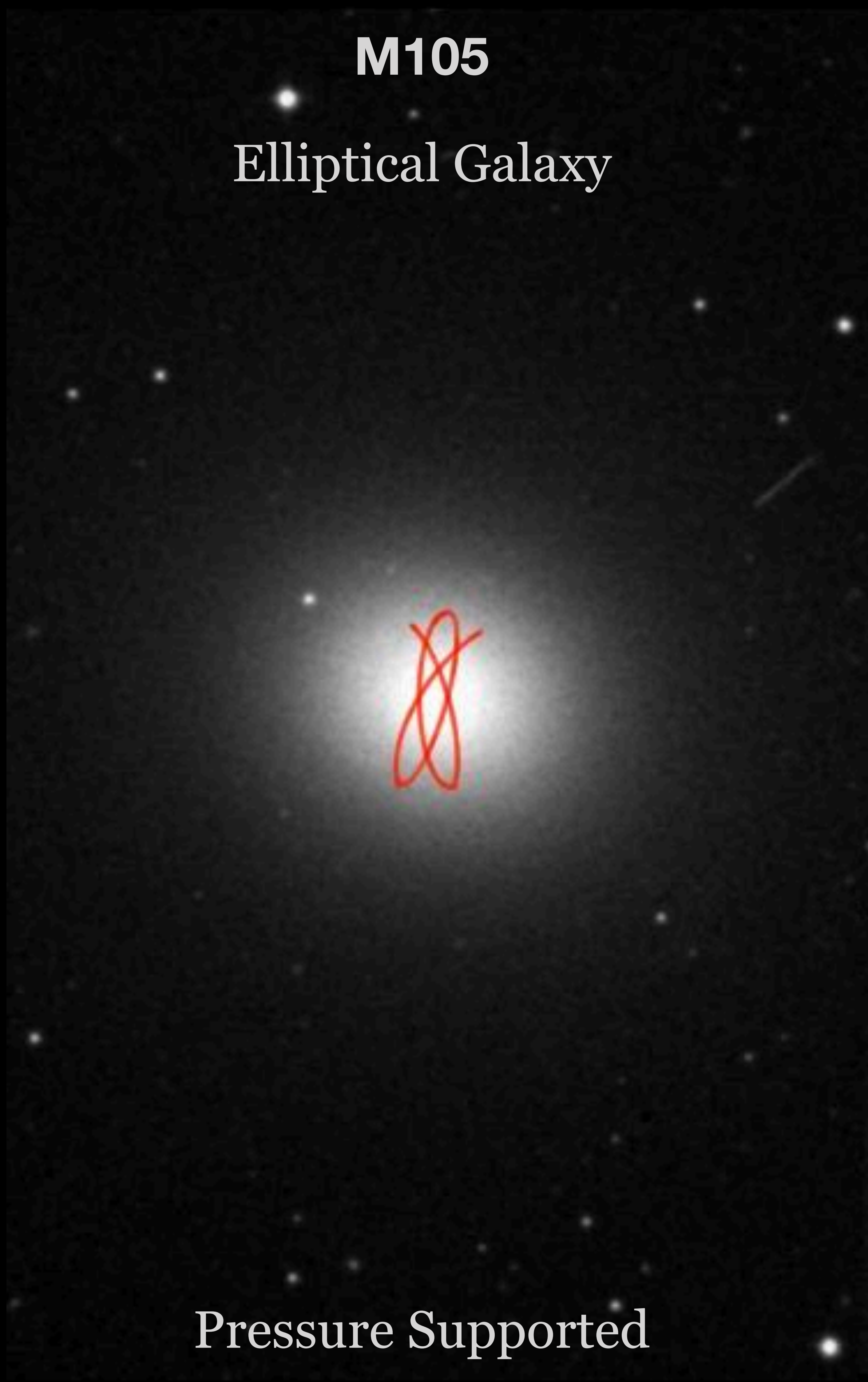


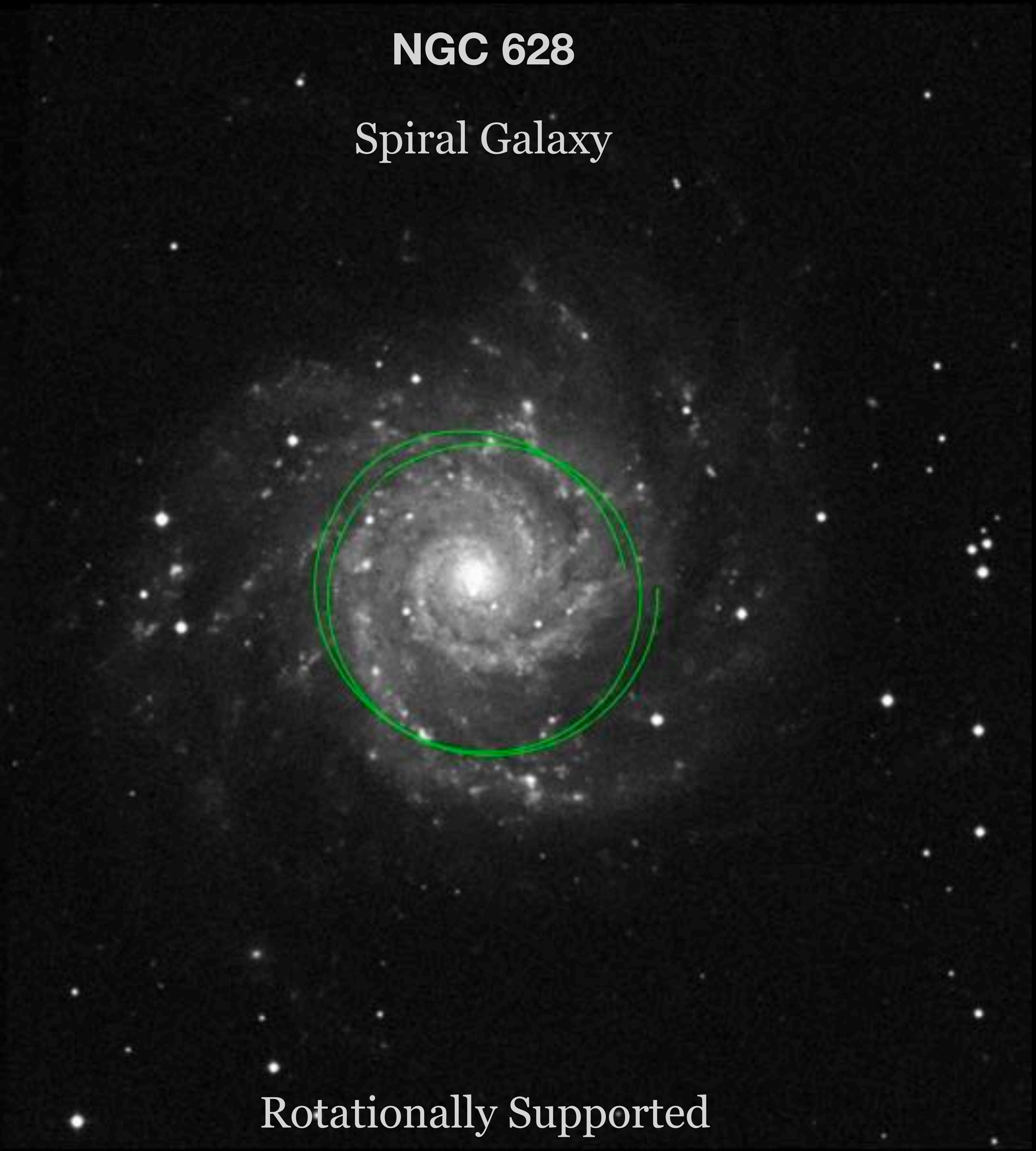
Homework 1

Due Feb. 5

Stellar orbits in galaxies



Eccentric radial orbits
Random orientations

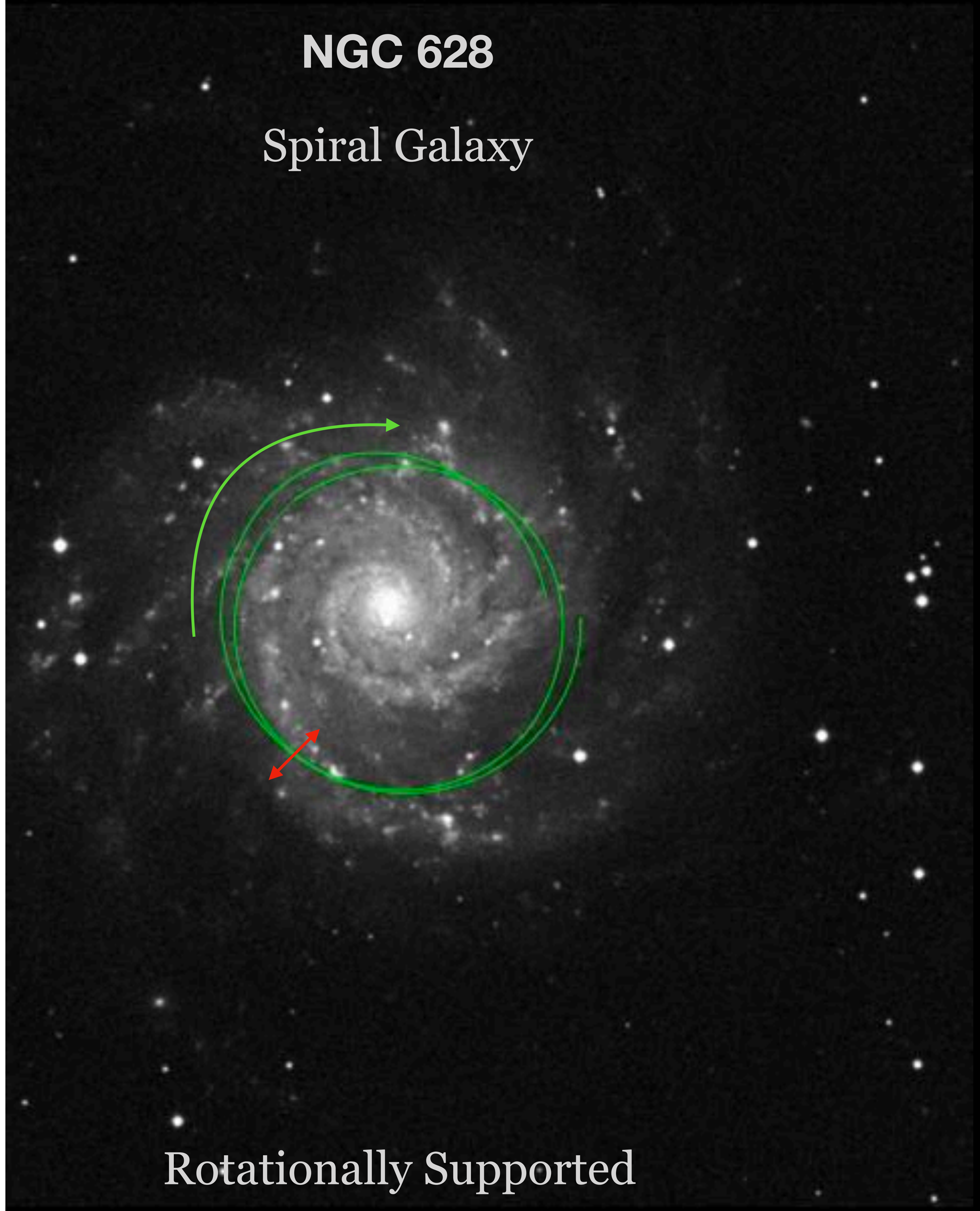


Nearly circular orbits
Same direction, same plane

Stellar orbits in galaxies

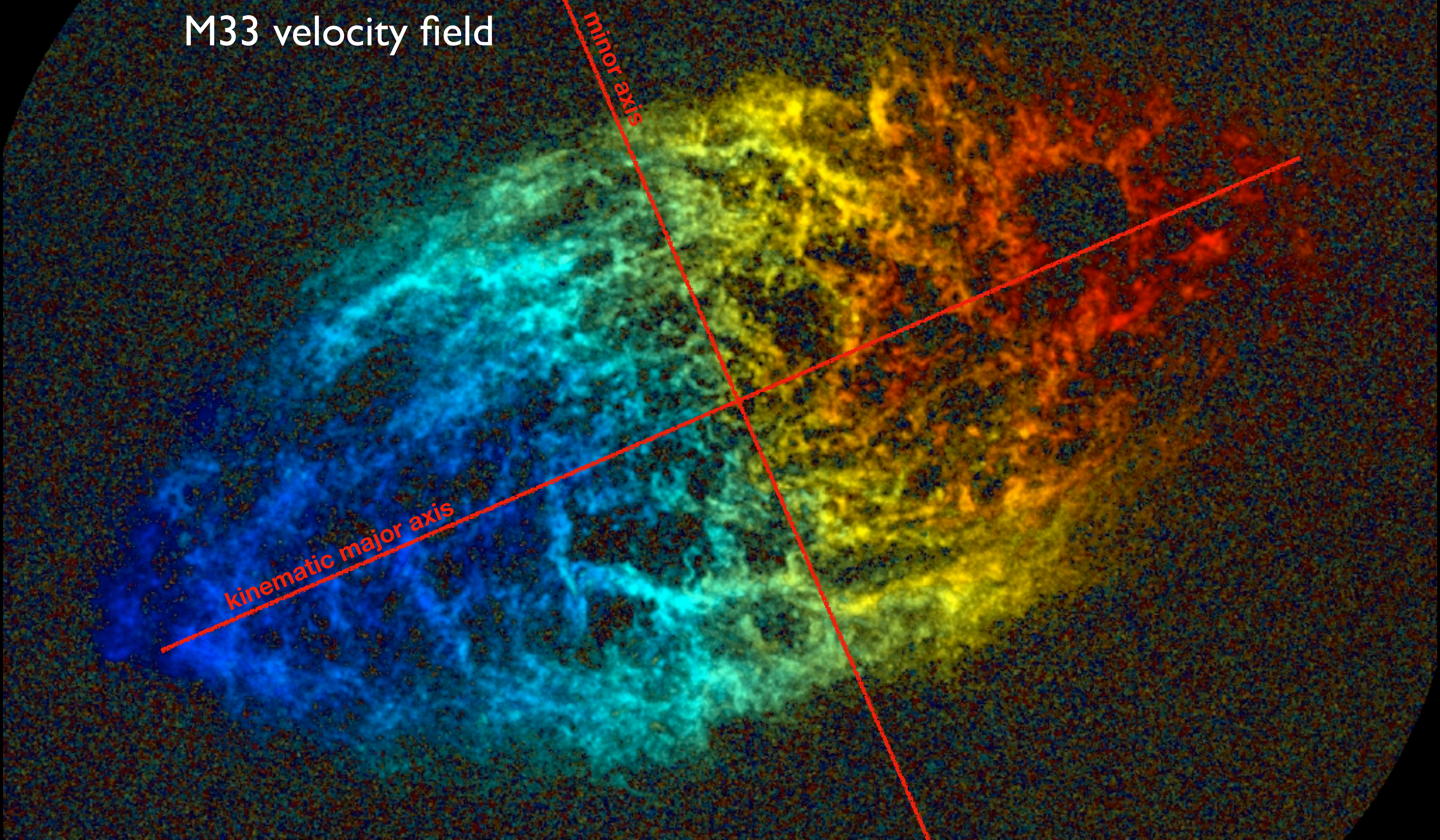
orbital frequency Ω
round & round

epicyclic frequency κ
in & out



Nearly circular orbits
Same direction, same plane

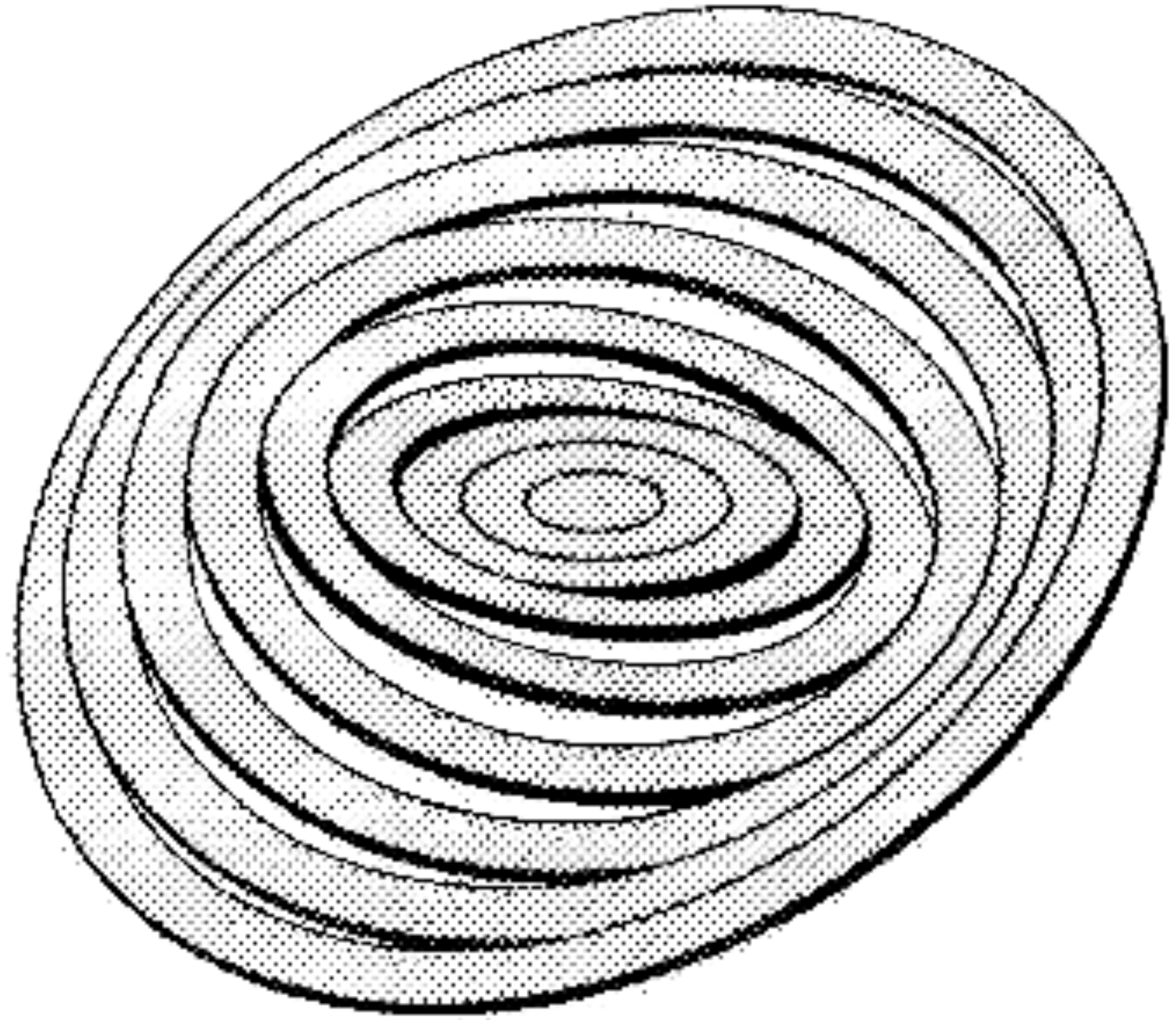
M33 velocity field

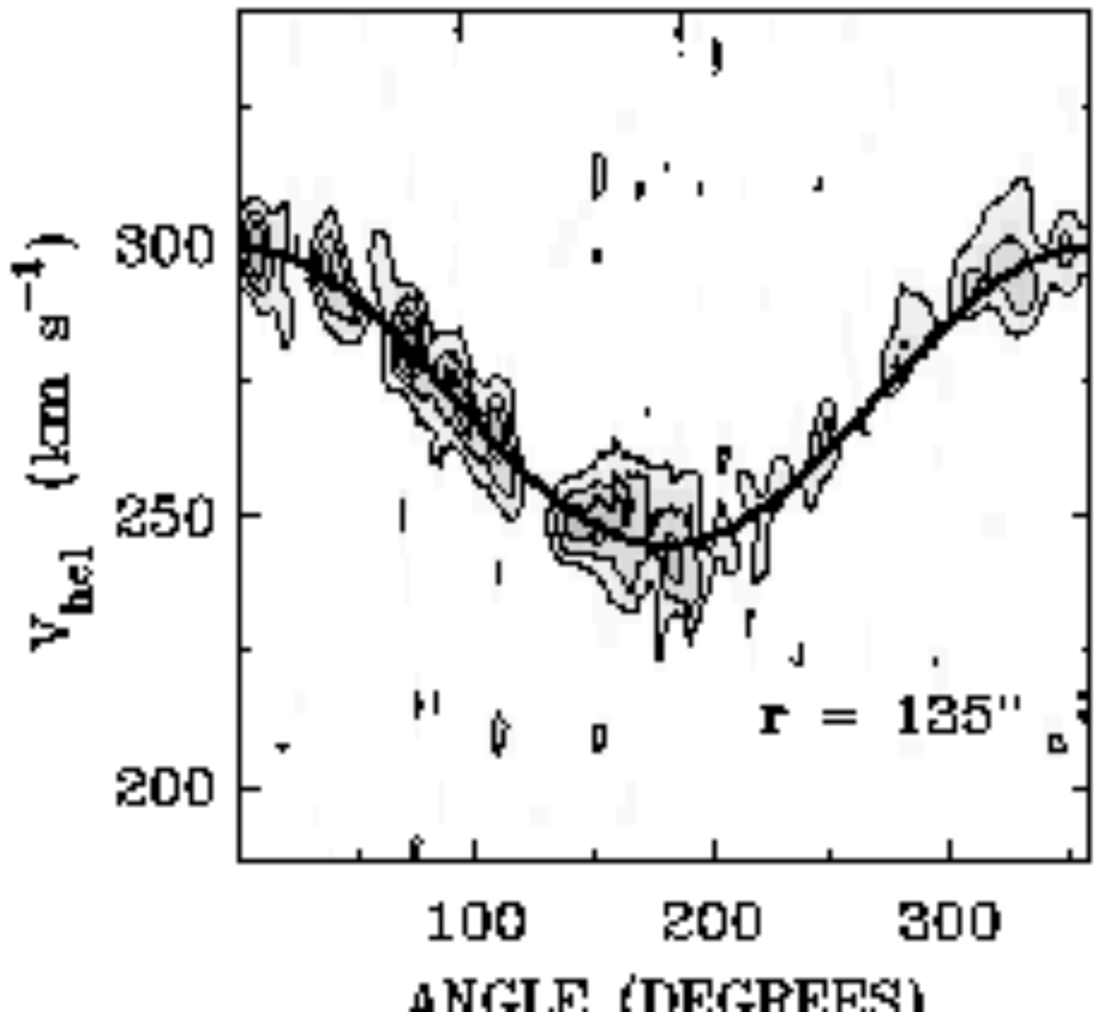


Rotation curves extracted using “tilted ring” fits

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.

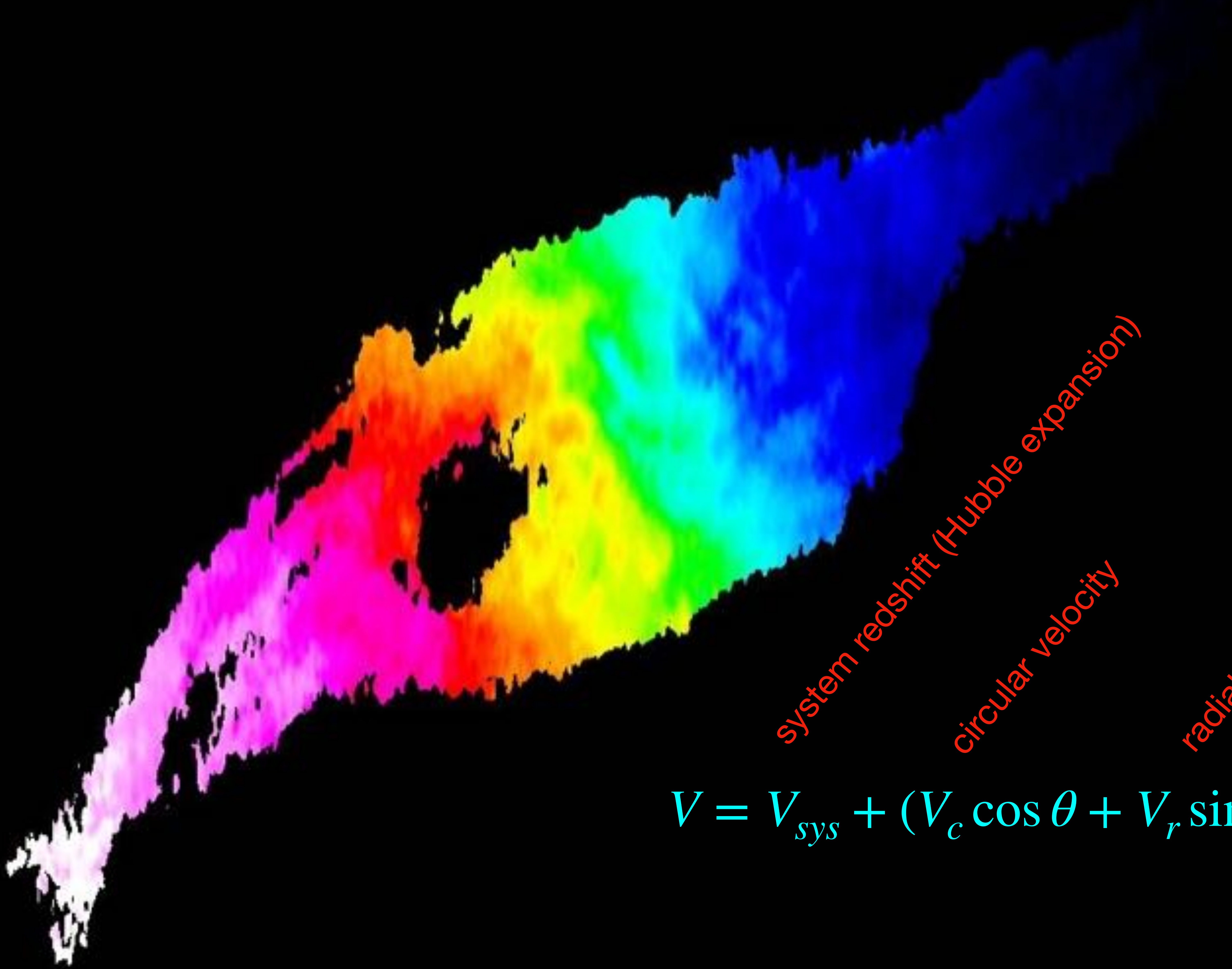
tilted ring model





velocity variation along ring

NGC 6822 (Weldrake & de Blok 2003)



system redshift (Hubble expansion)

circular velocity

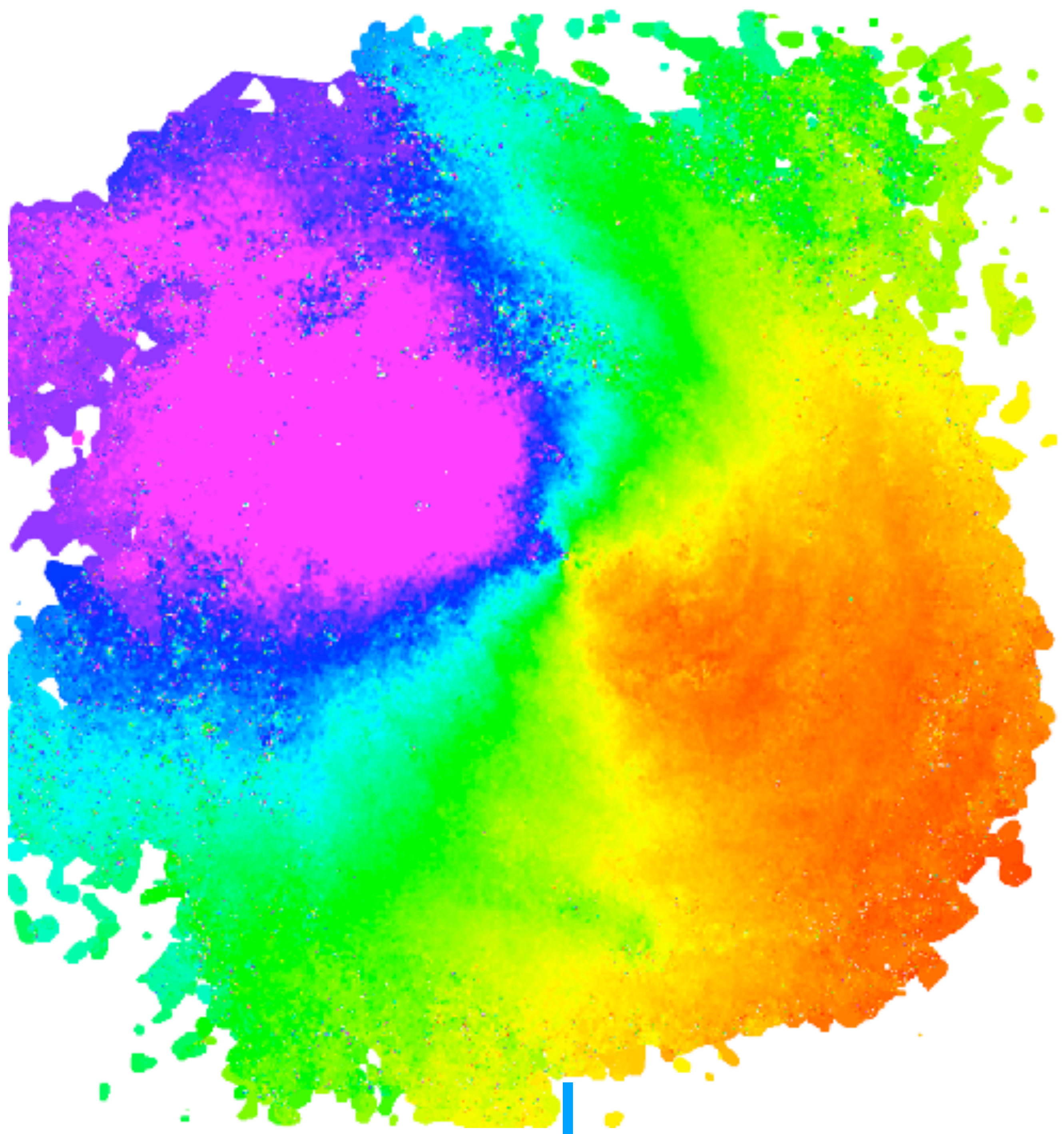
radial velocity

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

inclination

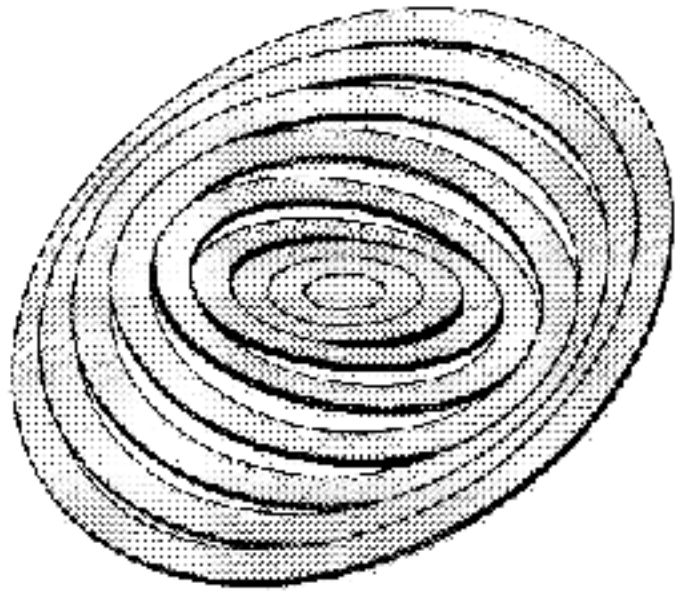
21cm interferometric observations give atomic gas distributions and velocity fields

NGC 6946



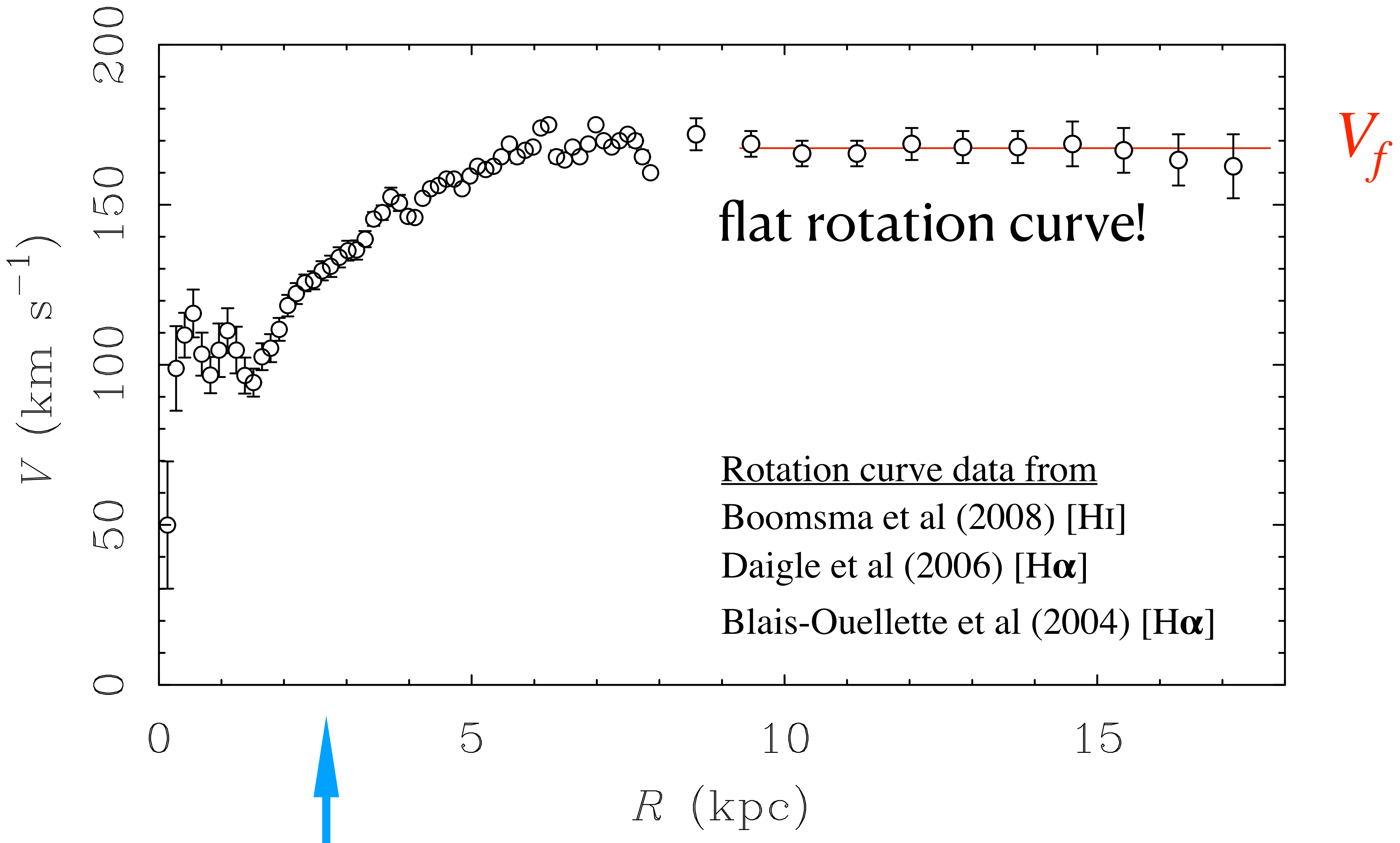
THINGS (Walter et al. 2008; de Blok et al. 2008)

tilted ring model



to which we make tilted ring fits

Rotation curve



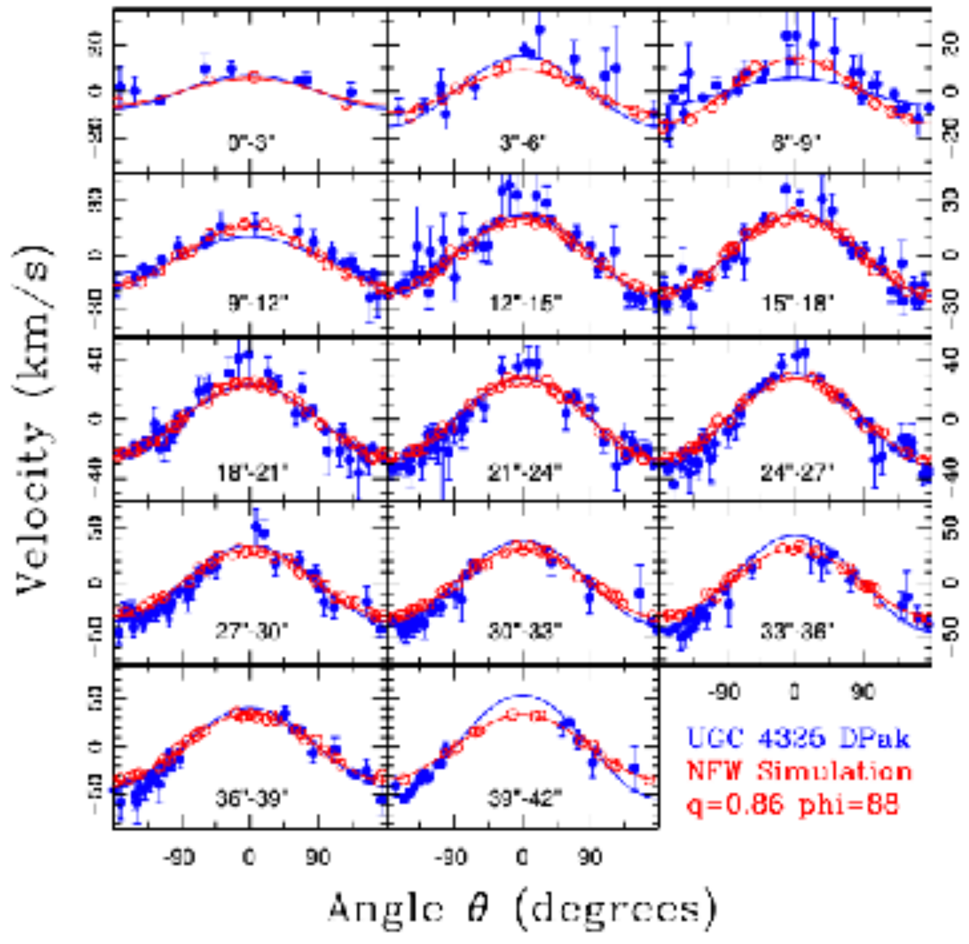


Figure 5.6: The (0.86, 88°) simulation results (red) over-plotted with the observed UGC 4325 data (blue). The simulation and data match well between ~ 12″ - 30″.

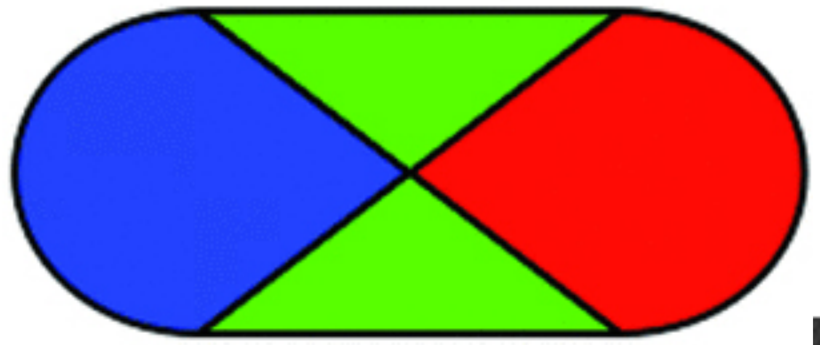
The sinusoidal variation of velocity in each ring measures the position angle, inclination, and rotation curve $V_c(R)$.

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

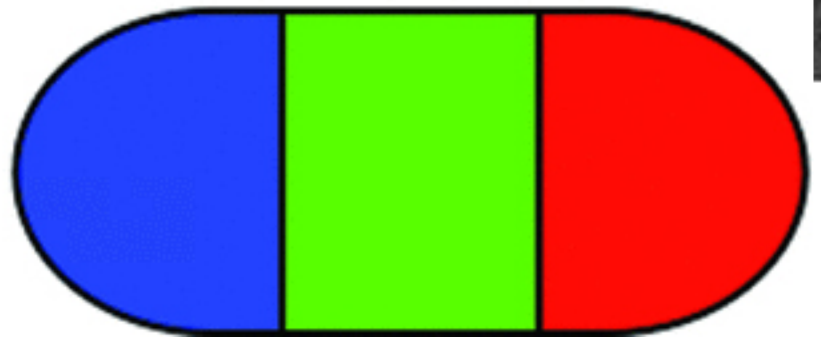
NGC 247

Triaxial

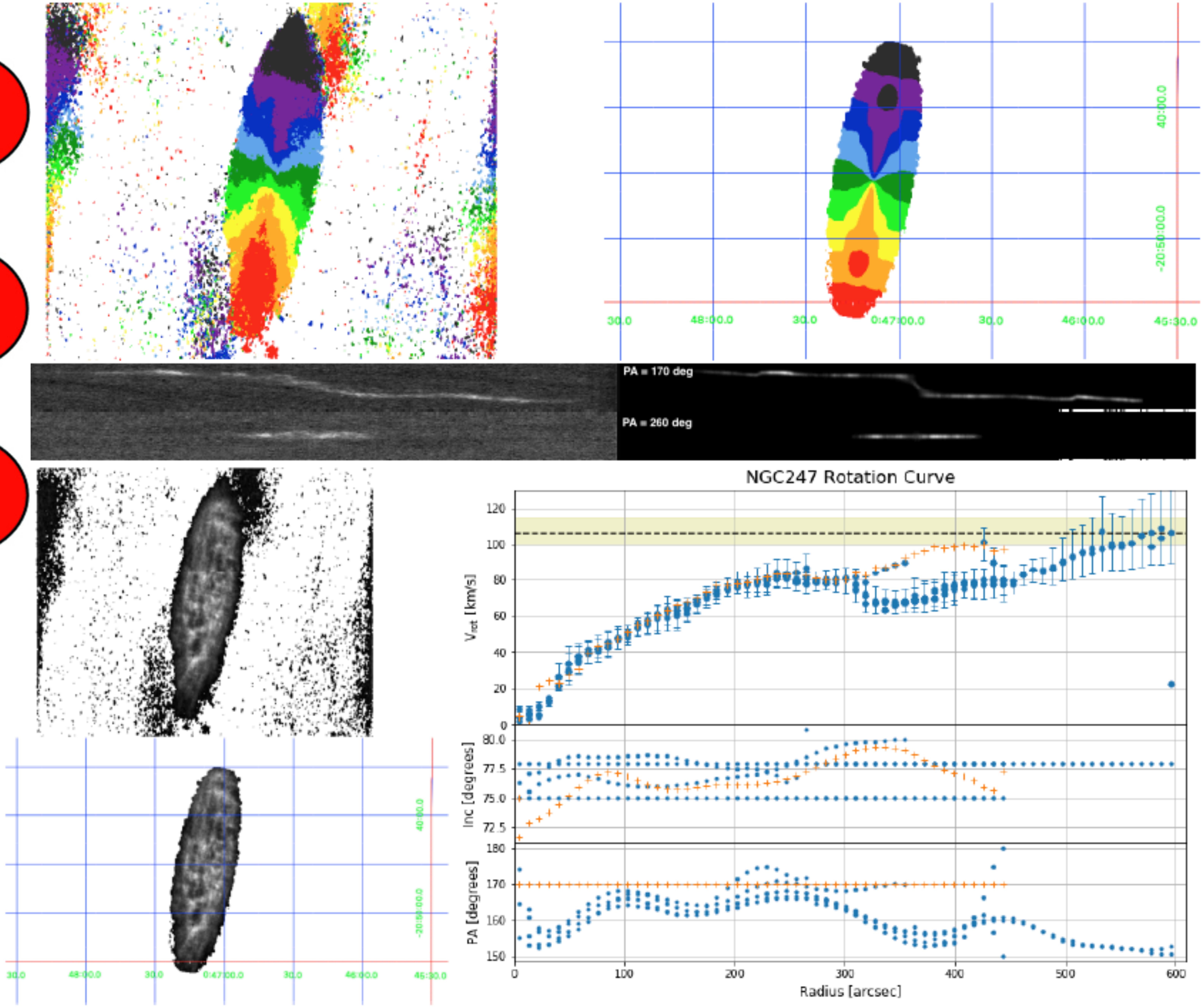
Spherical Cuspy



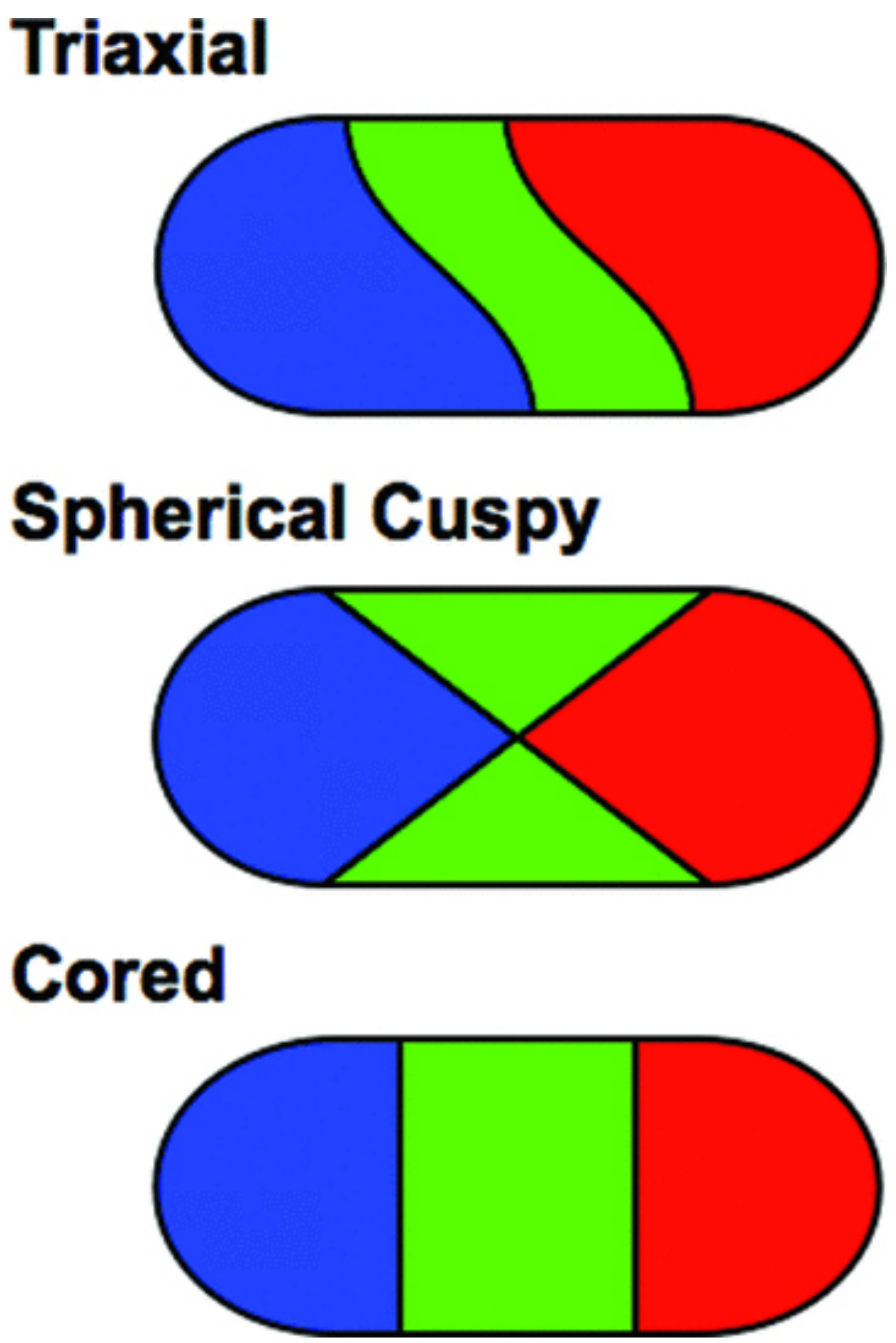
Cored

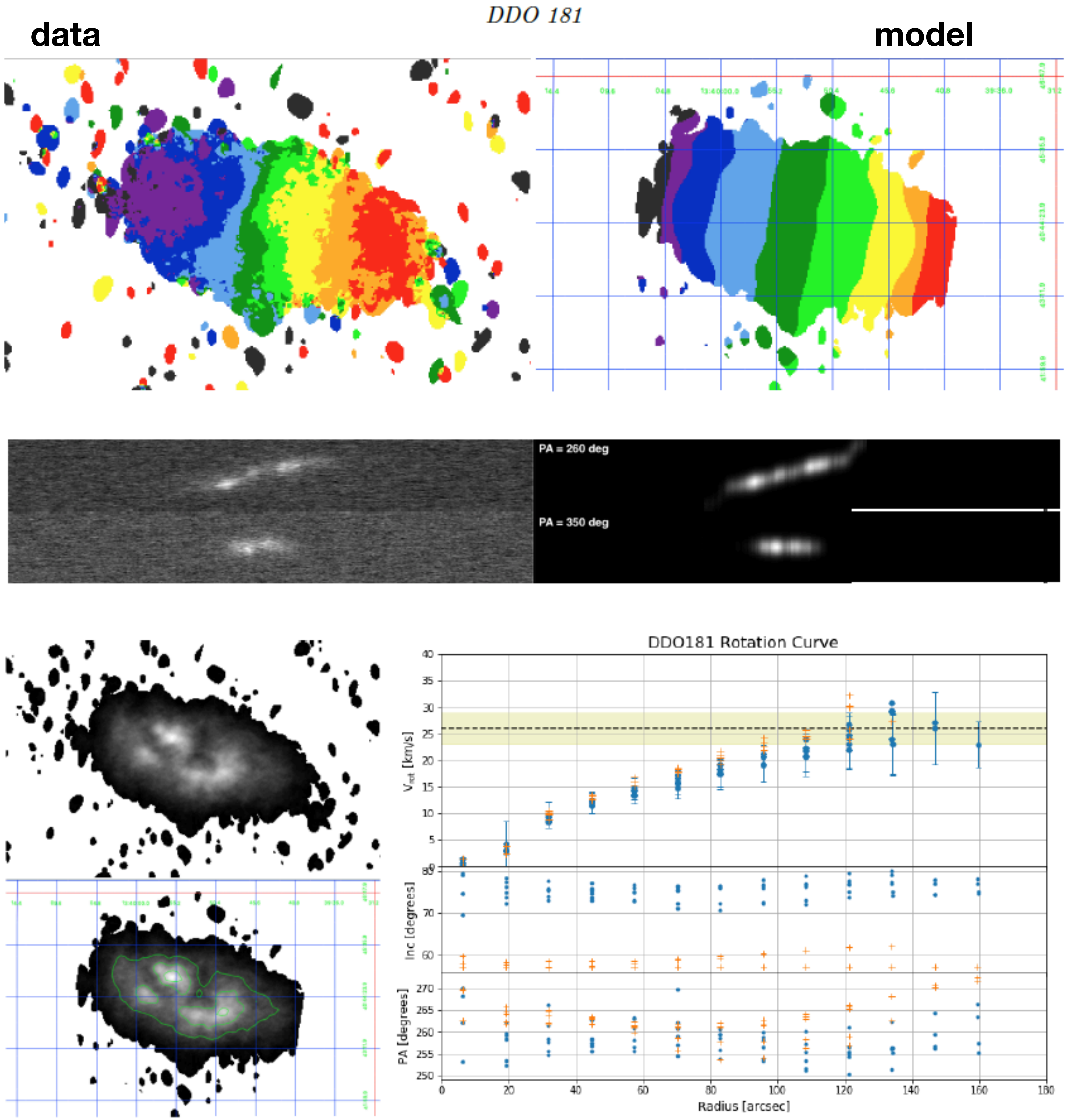


data **model**



Fit made with 3DBarolo by K. Parker





Fit made with 3DBarolo by K. Parker

Galactic Kinematics

Galactic constants

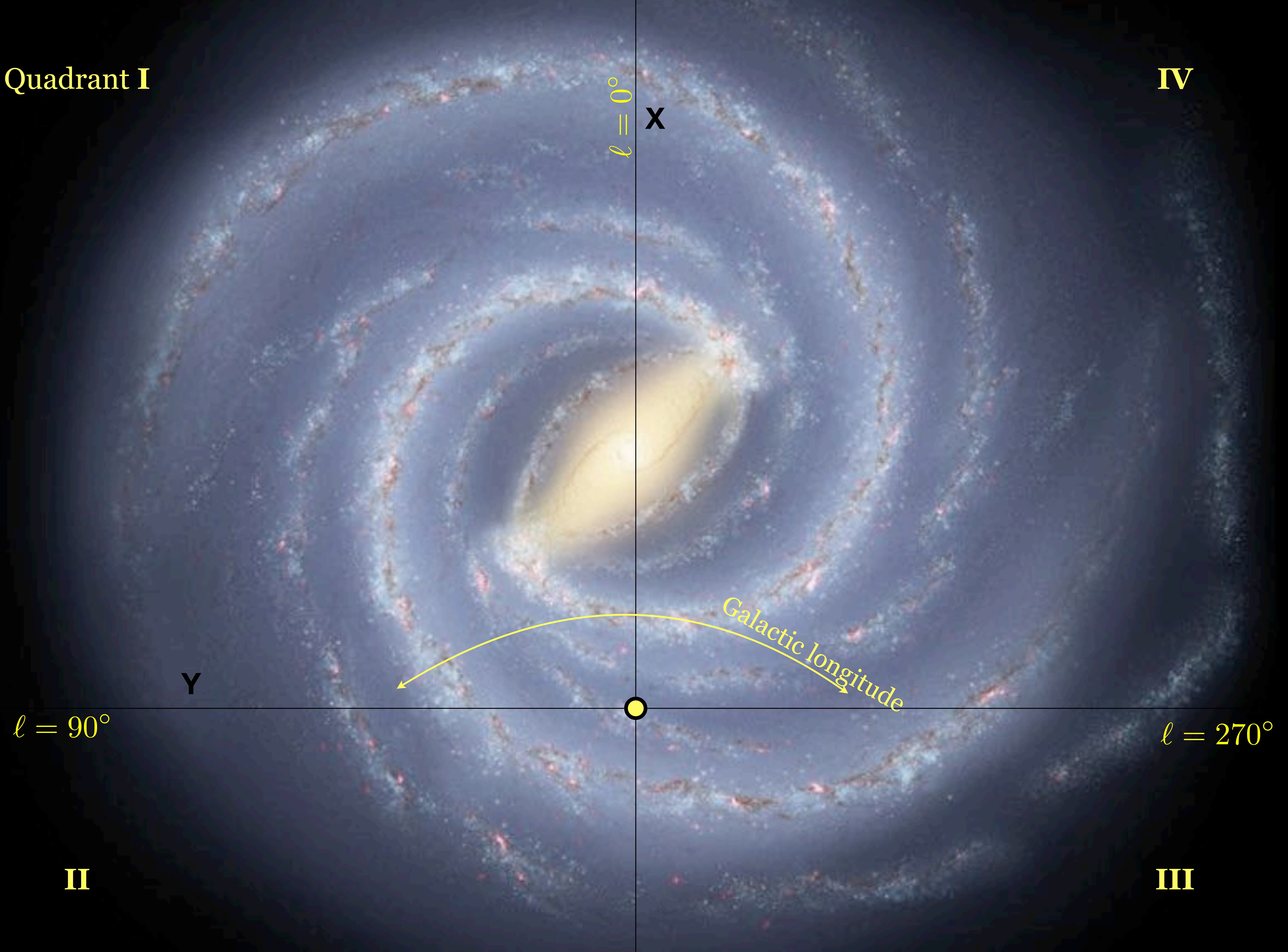
$$R_0 \; \Theta_0 \; A \; B$$

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

Local Standard of Rest

Epicycle approximation

Galactic mass distribution: bulge/bar, stellar disk, gas disk, dark matter

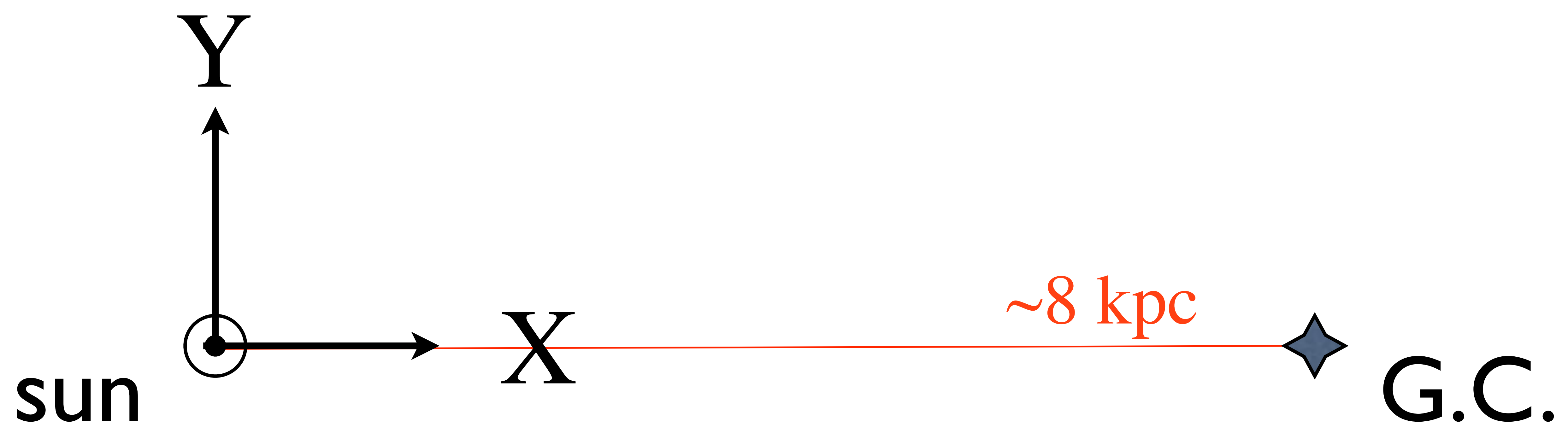


Orbits of individual stars: the epicycle approximation

Local Galactic Coordinates

Cartesian coordinates centered on solar system

As opposed to Galactic Center. Beware sign conventions



X, Y, Z:

X points towards the Galactic Center

Y points in direction of the sun's orbital motion

Z is perpendicular to the Galactic Plane

U, V, W are velocities in these directions

Definitions of Galactic Quantities

R_0	distance to Galactic Center		8.12 kpc
Θ_0	orbital velocity of LSR		233 km/s
Ω_0	angular velocity of LSR	$\Omega = \frac{V}{R}$	$P = \frac{2\pi R}{V} = \frac{2\pi}{\Omega}$
A	Oort constant A	$A = \frac{1}{2}\left(\frac{V}{R} - \frac{dV}{dR}\right)_{R_0}$	shear
B	Oort constant B	$B = -\frac{1}{2}\left(\frac{V}{R} + \frac{dV}{dR}\right)_{R_0}$	vorticity
κ	epicyclic frequency	$\kappa^2 = -4B(A - B)$	

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

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, nor is its mean distance from the galactic center equal to our current location.

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

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

Solar Motion

The residual solar motion wrt the average of local stars is

radial	$U_\odot = 10\,\mathrm{km\,s^{-1}}$	V_r in $V_c \cos\theta + V_r \sin\theta$
azimuthal	$V_\odot = 12\,\mathrm{km\,s^{-1}}$	Some say $V_\odot$ = 5 km/s, some say 15 km/s!
vertical	$W_\odot = 7\,\mathrm{km\,s^{-1}}$	

The Sun is moving

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

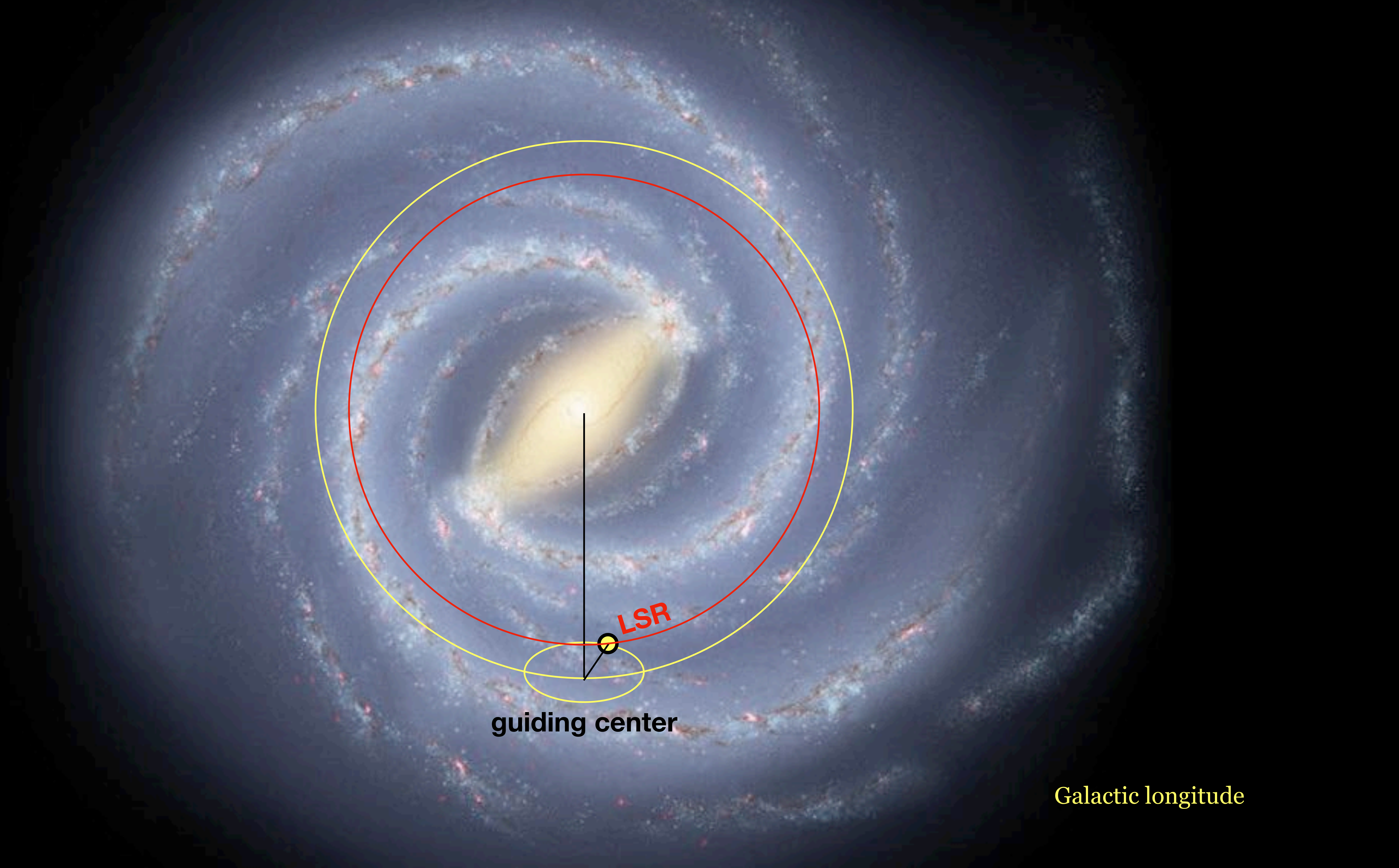
Currently we are near the mid-plane

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

↓

$$V_{tot} = V_c + V_\odot \approx 245\,\mathrm{km\,s^{-1}}$$

Orbits of individual stars: the epicycle approximation



Orbits for 4 individual stars

orbital eccentricity correlates with age

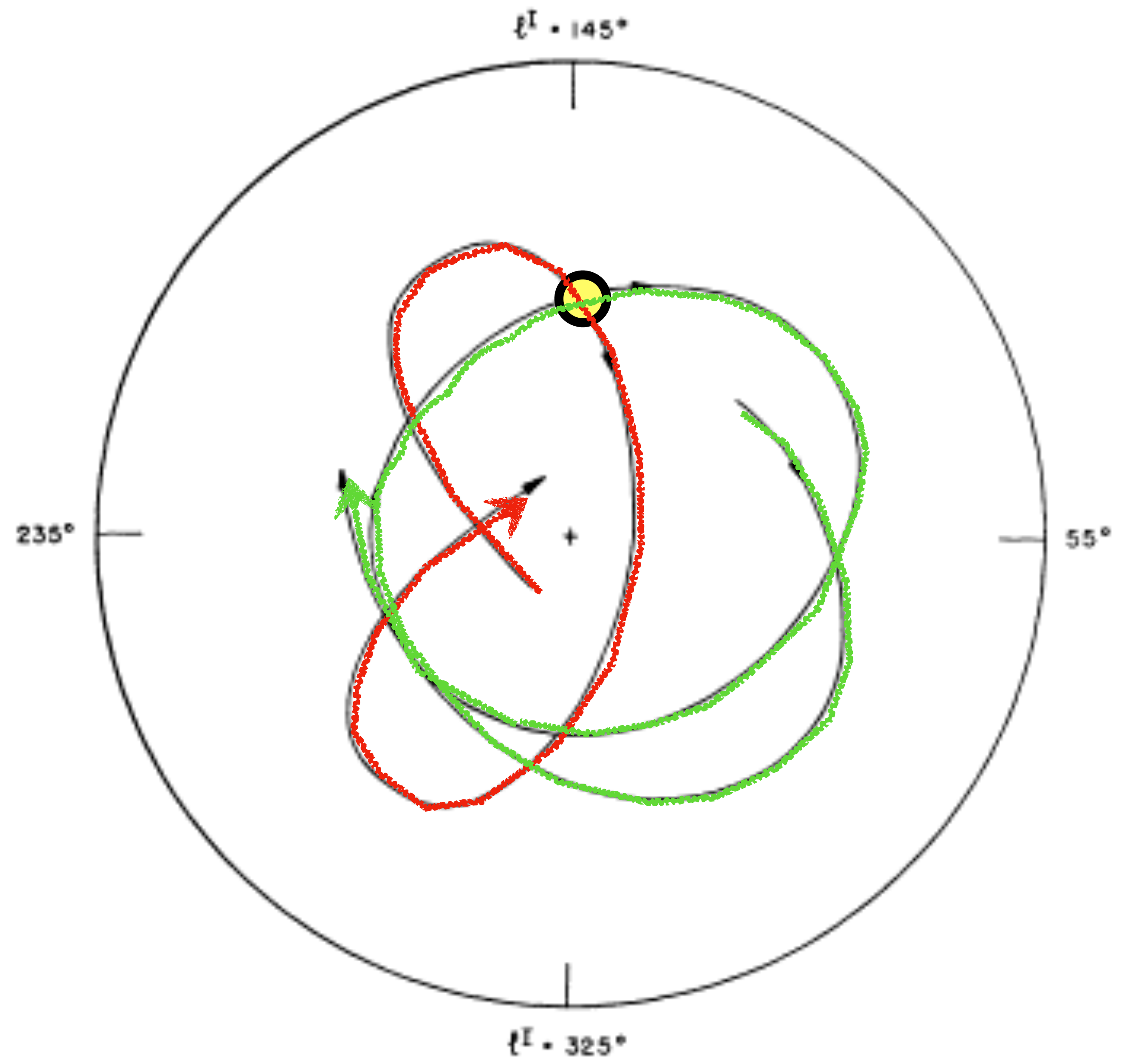


FIG. 2.—Segments of the galactic orbits for two of the program stars. The more circular orbit is for HD 117635 with an ultraviolet excess of $\delta = +0^m.05$ The more elliptical orbit is for HD 11980 with $\delta = +0^m.17$. Both orbits pass through the solar neighborhood, which is designated by a 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.

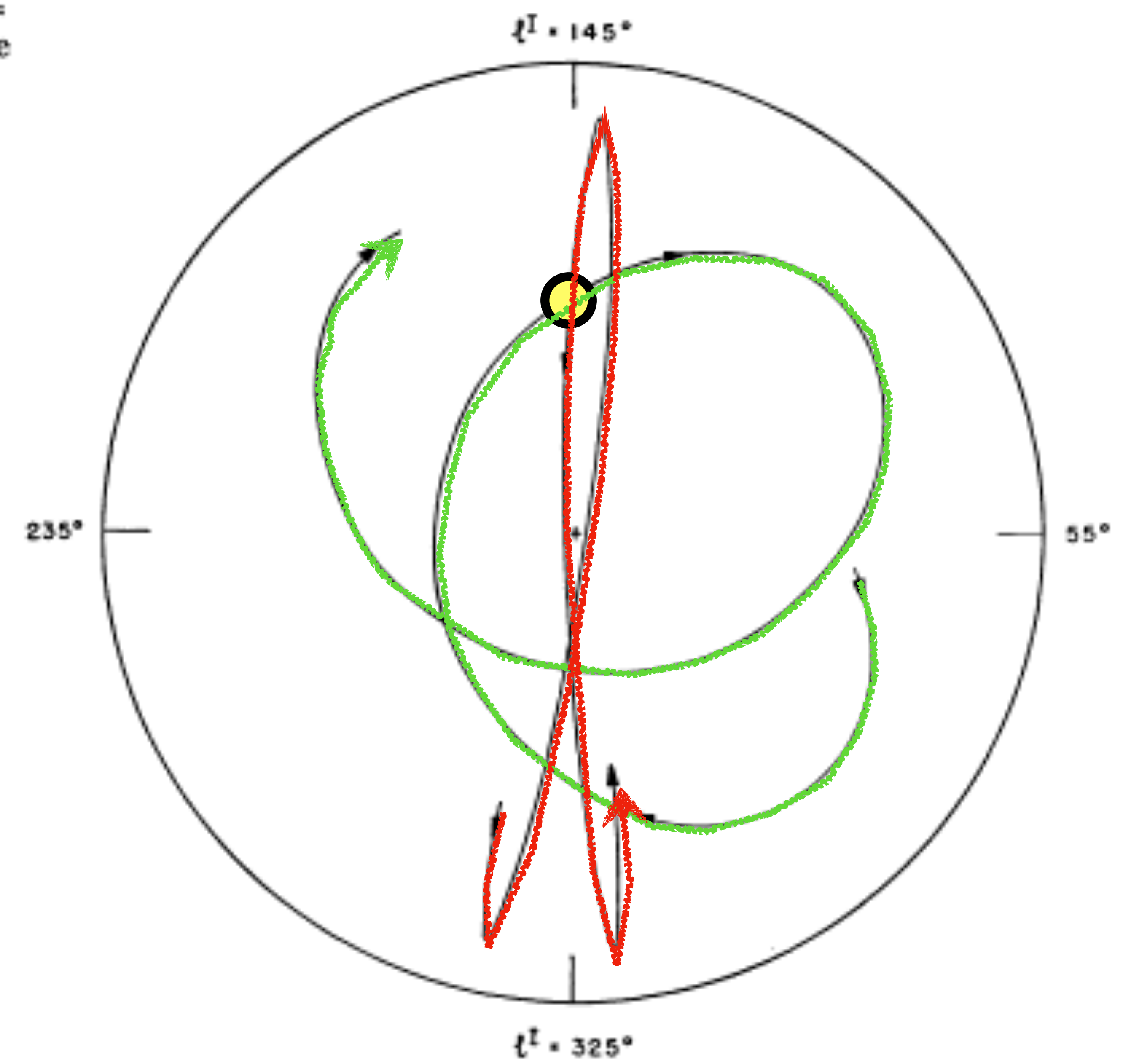


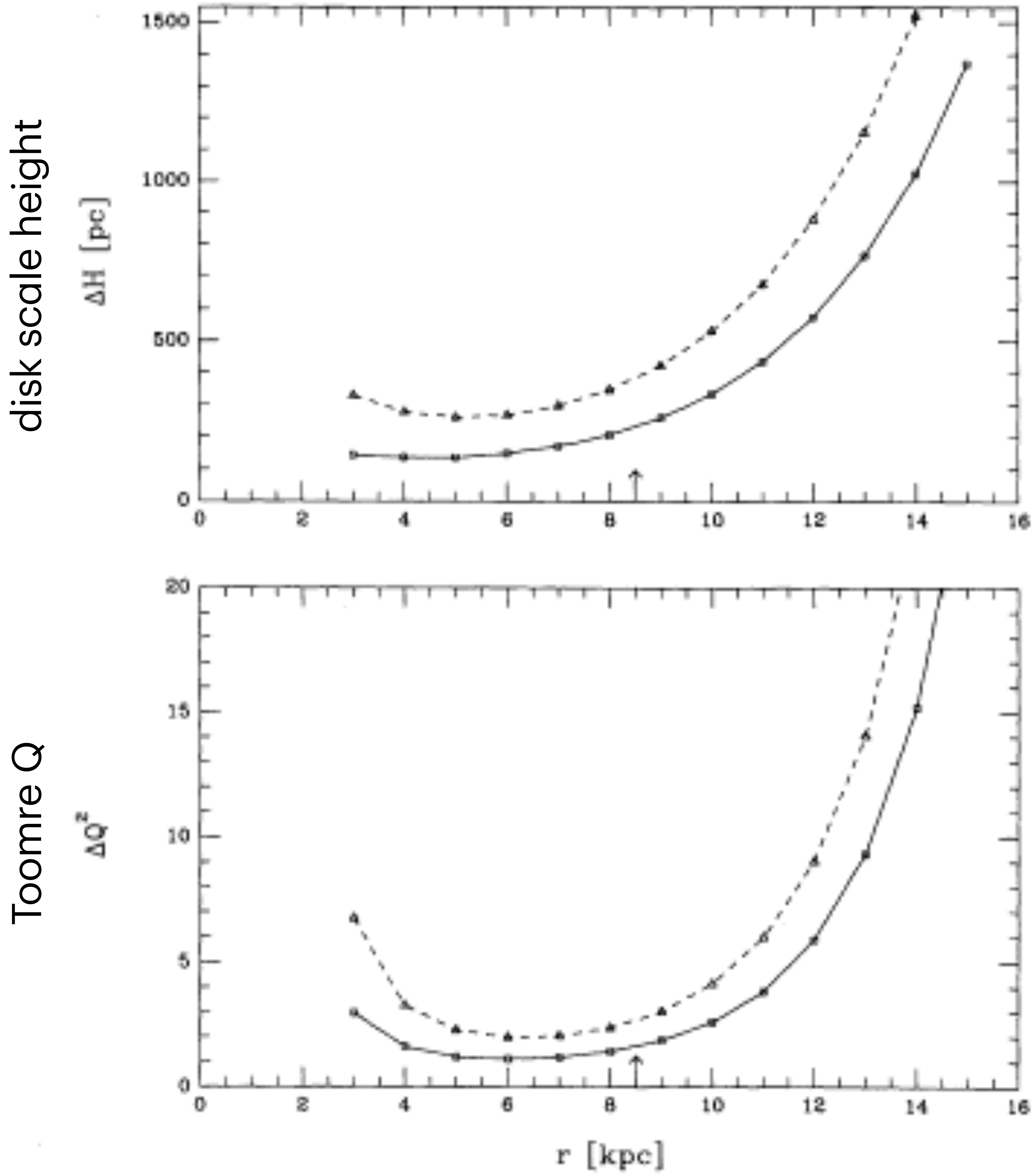
FIG 3.—Same as Fig. 2 The more circular orbit is for HD 29587 with $\delta = +0^m.13$. The more elliptical orbit is for Ross 106 with $\delta = +0^m.26$. The orbit for Ross 106 is retrograde.

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

Disk Heating

Limits on mergers & such

- Spiral disks are dynamically cold
- Mergers heat and thicken disks
  - like dropping stones in a pond
- Places limit on mergers
- Milky Way has not experienced a substantial merger (mass ratio > 1:10) for a long time
  - Thick disk ~8 Gyr old

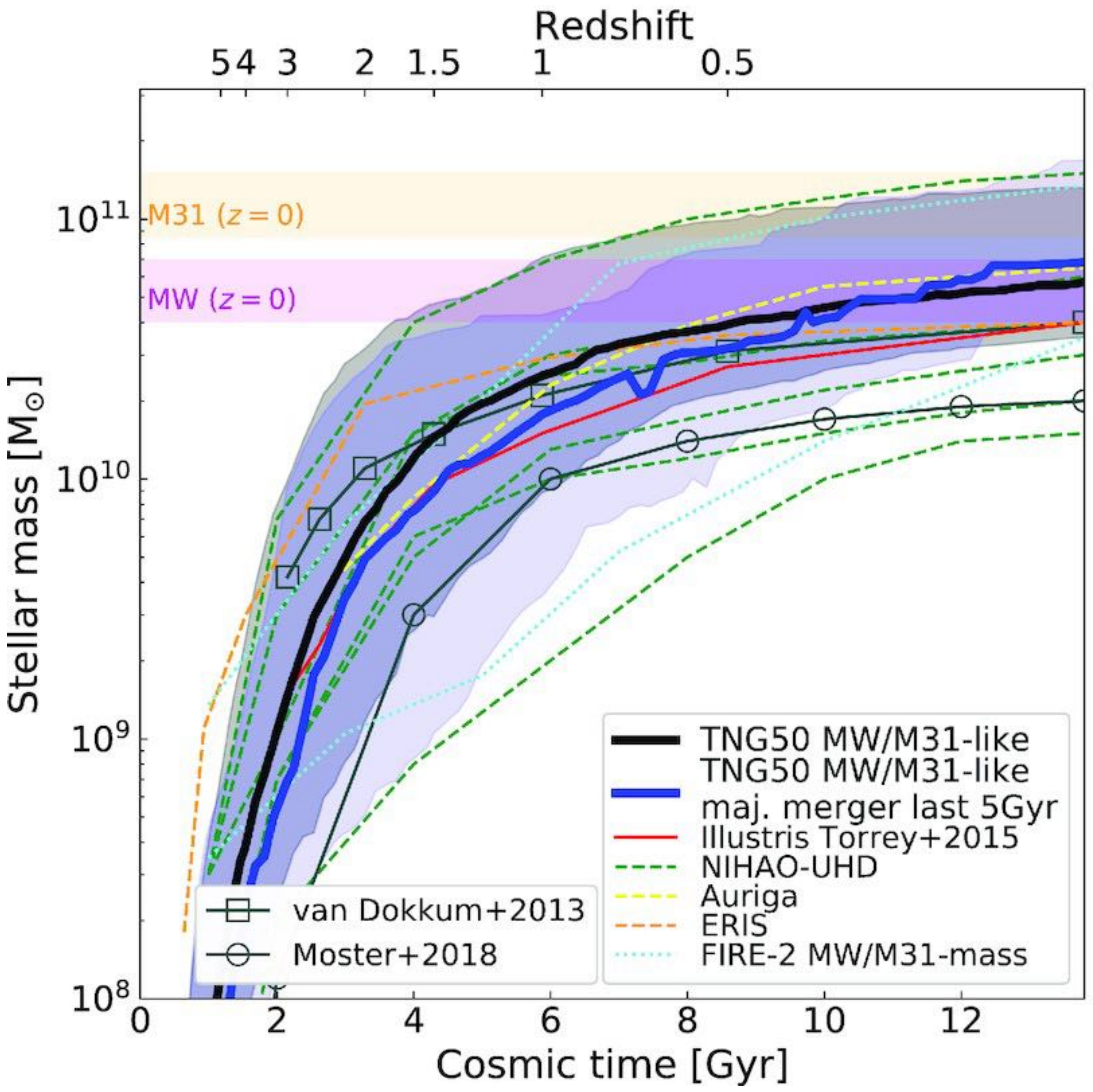


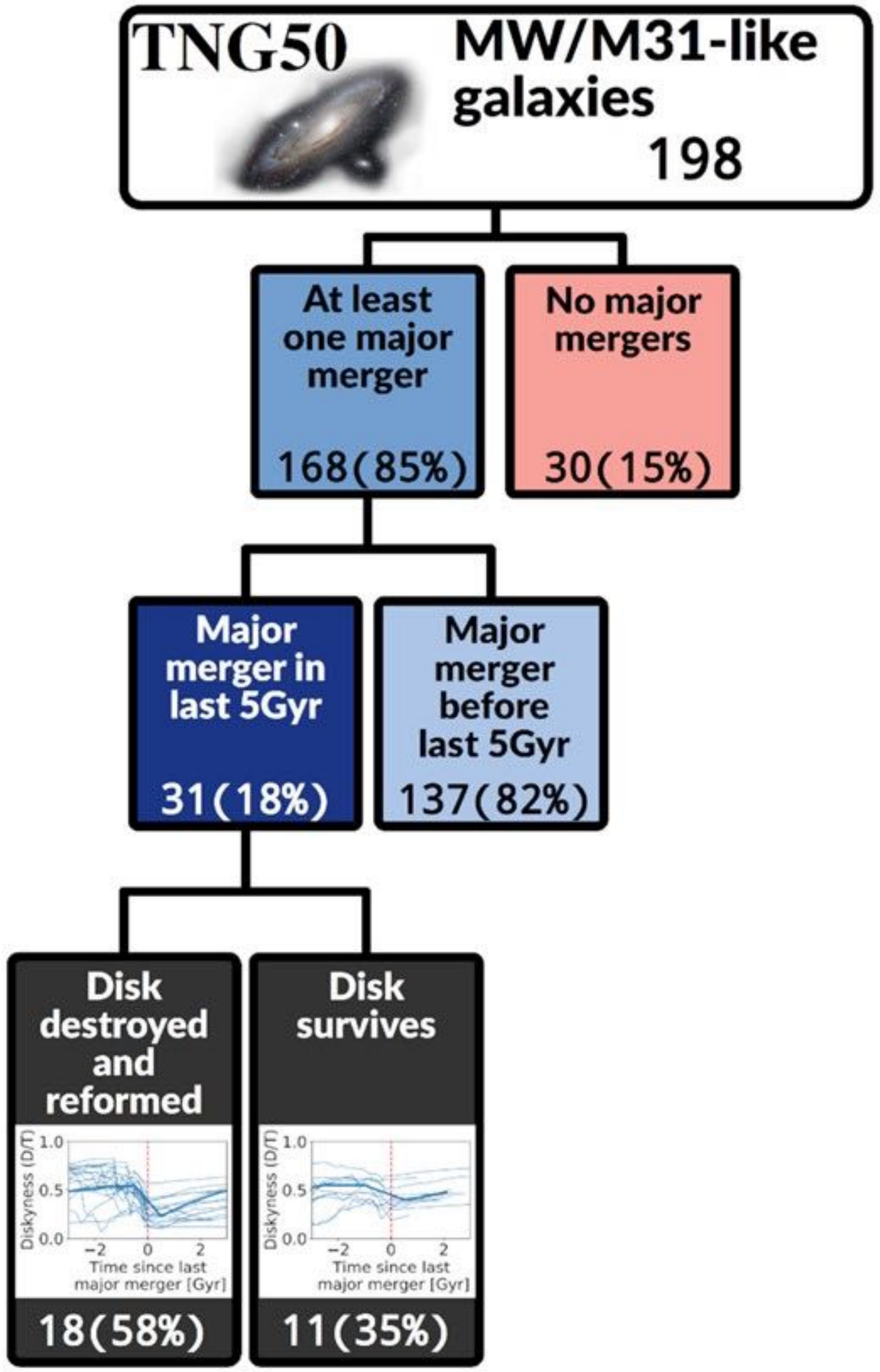
Disk thickening (top) and heating (bottom) due to 1:10 mass ratio merger. Also depends on the concentration of the merging object (solid line fluffy, dashed line dense).

Also constrains nature of dark matter. A DM halo made of million solar mass black holes would stir up the disk too much.

Sotillo-Ramos+ (2022)

What do we expect in LCDM?





Makes a prediction for the ages and orbits of stars -
Disks lacking stars older than 5 Gyr should be common