Baryonic Mass Components of Galaxies

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

$X \approx 0.73$ (hydrogen fraction)

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

dust and hot ionized gas are typically negligible within the optical radius

  - *Atomic gas* - H I
    - $M_{HI} = 2.36 \times 10^5 D^2 F_{HI}$ counting hydrogen atoms
  - *Molecular gas* - H_2
    - $M_{H_2} = 1.1 \times 10^4 D^2 F_{CO}$ using carbon monoxide as a proxy

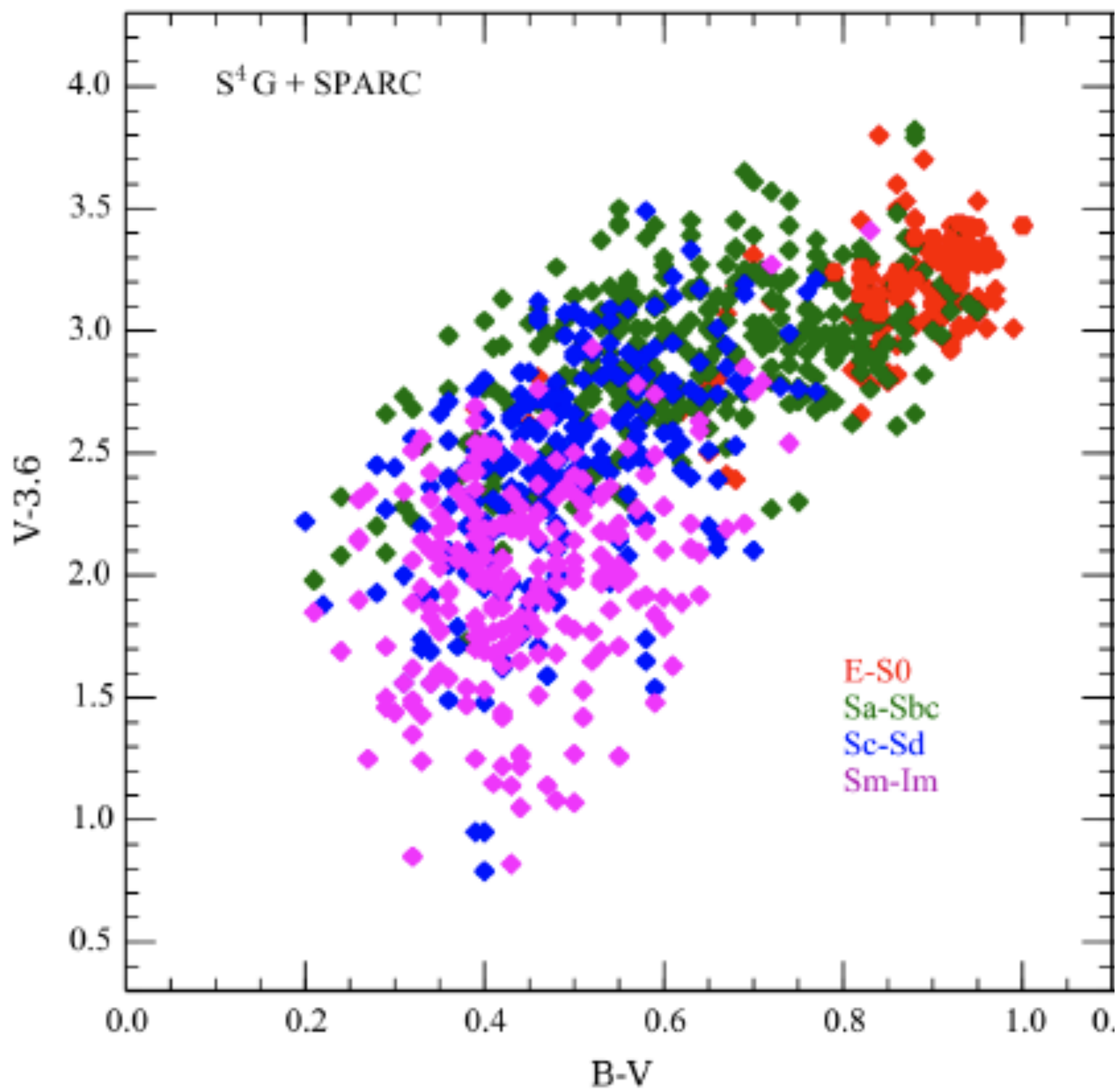
also scales with stellar mass at least for late type galaxies $M_{H_2} \approx 0.07\, M_*$

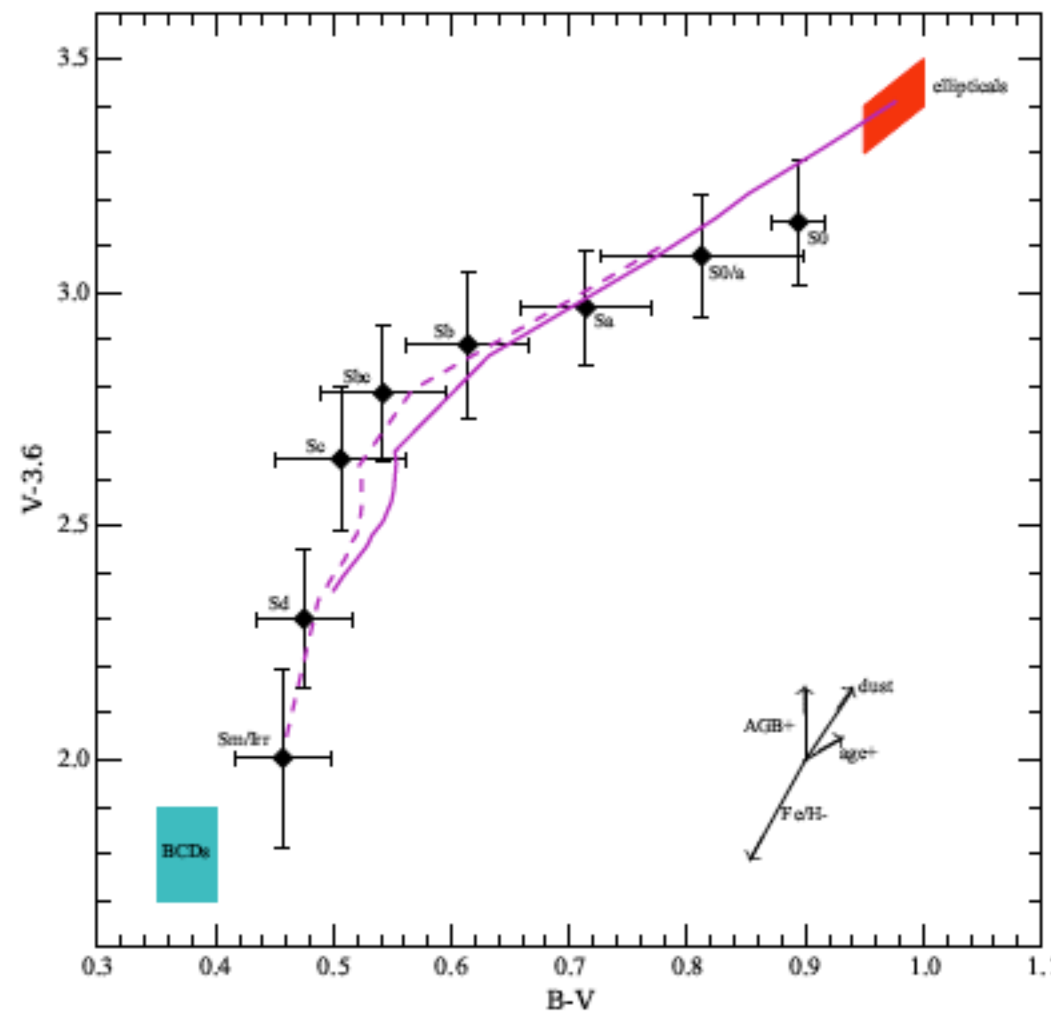
Stellar mass-to-light ratios from stellar population models

galaxy color-color diagram

mean galaxy colors with
CSP models (lines)

$V - [3.6]$





$B - V$

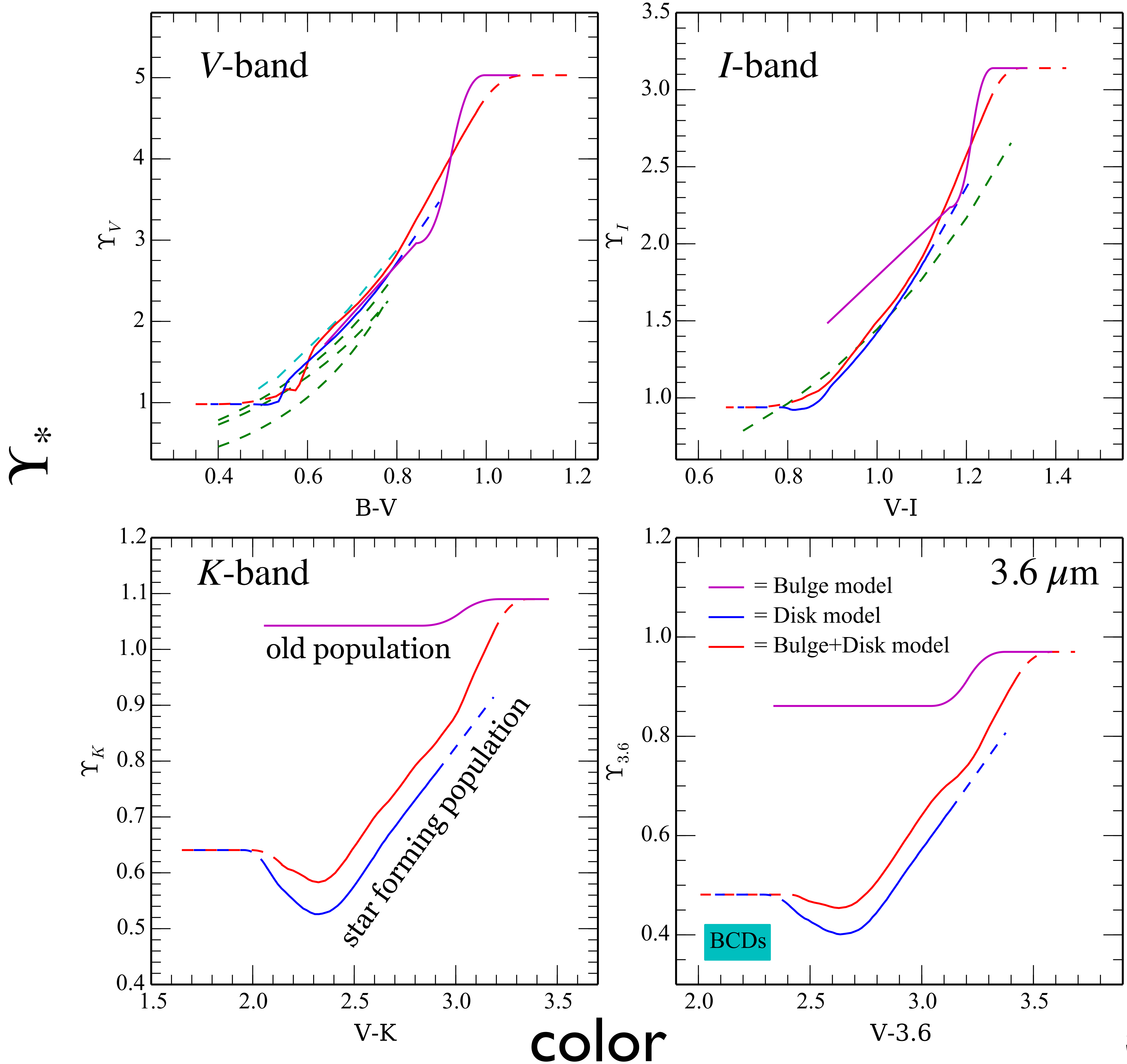
$B - V$

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

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

$X^{-1} \approx 1.33 \;-\; 1.42$
hydrogen fraction

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

To a surprisingly good approximation (~20%), for star forming (late type) galaxies

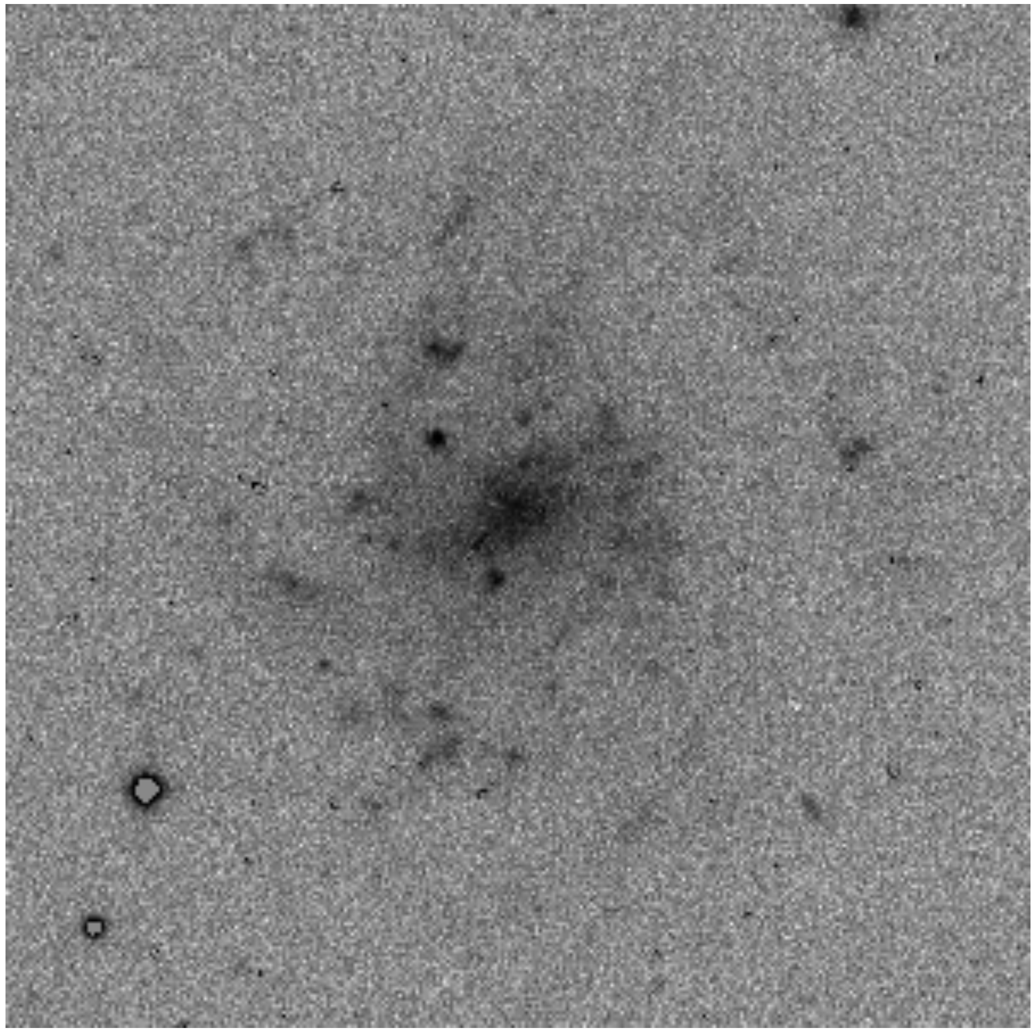
$$M_* \approx 0.5\, L_{[3.6]} \qquad \approx 0.63\, L_K$$

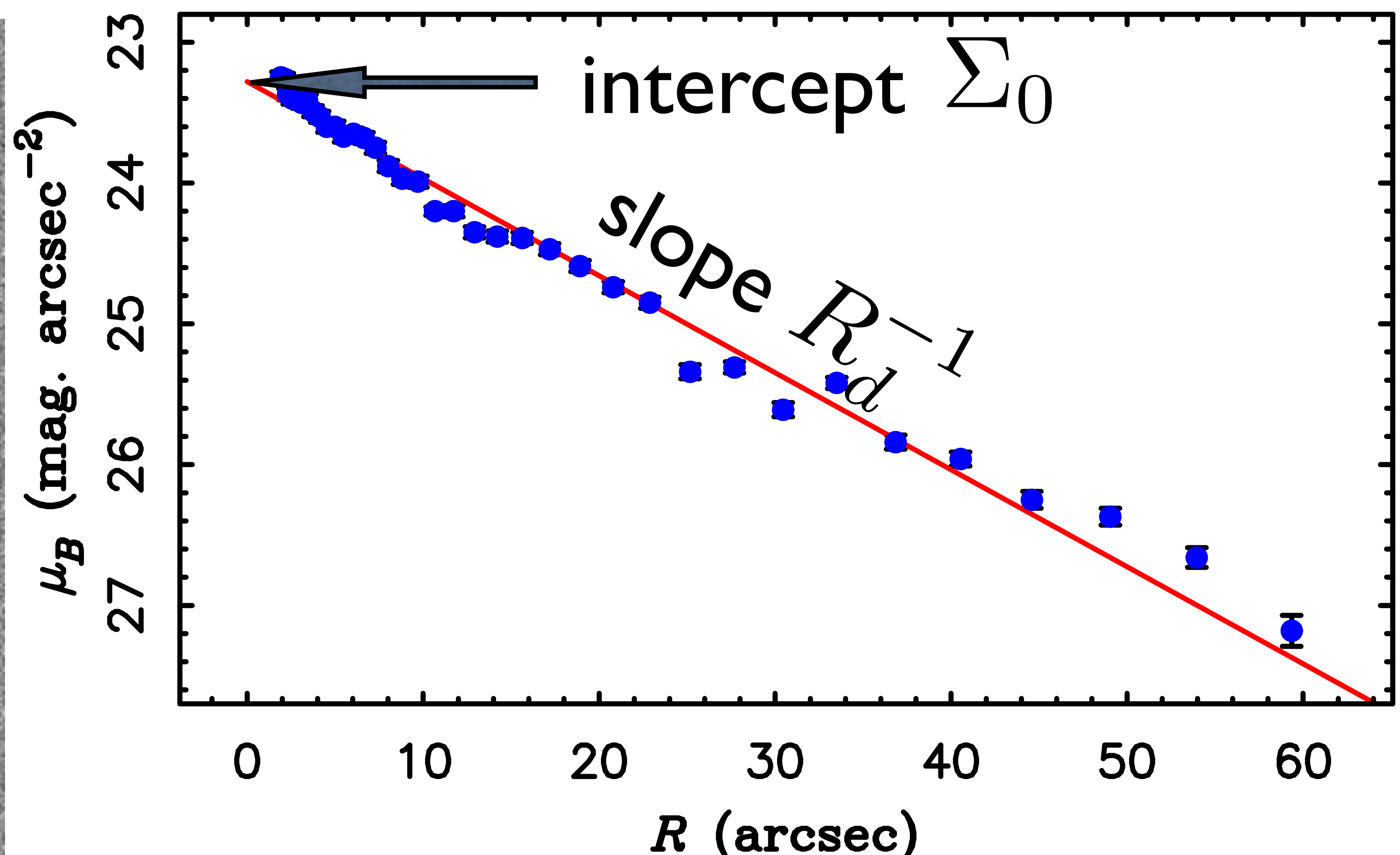
For early type galaxies and the bulge component of spirals

$$M_* \approx 0.9\, L_{[3.6]} \qquad \approx 1.1\, L_K$$

That gets us the total mass. We also need to know its distribution.

Fit ellipses → Get surface brightness profile





For analytic approximation to the mass profile like exponential disk $\Sigma(R) = \Sigma_0 e^{-R/R_d}$

There can be a formula for the corresponding rotation curve

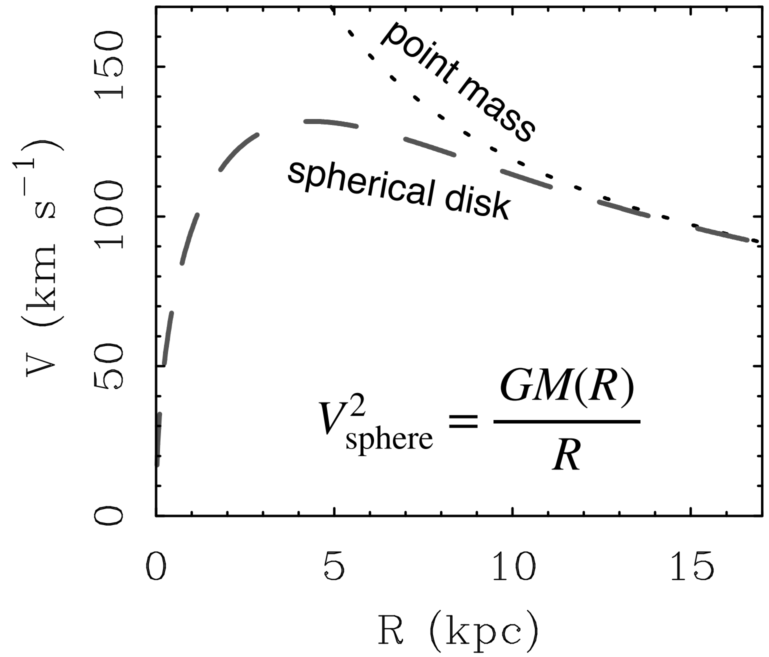
$$M_*(R) = 2\pi \int_0^R \Sigma(R')R'dR'$$

$$V_*^2(R) = \frac{2GM_*}{R_d}\left(\frac{R}{2R_d}\right)^2 \left[I_0\left(\frac{R}{2R_d}\right)K_0\left(\frac{R}{2R_d}\right) - I_1\left(\frac{R}{2R_d}\right)K_1\left(\frac{R}{2R_d}\right)\right]$$

$$M_* = 2\pi R_d^2 \Sigma_0$$

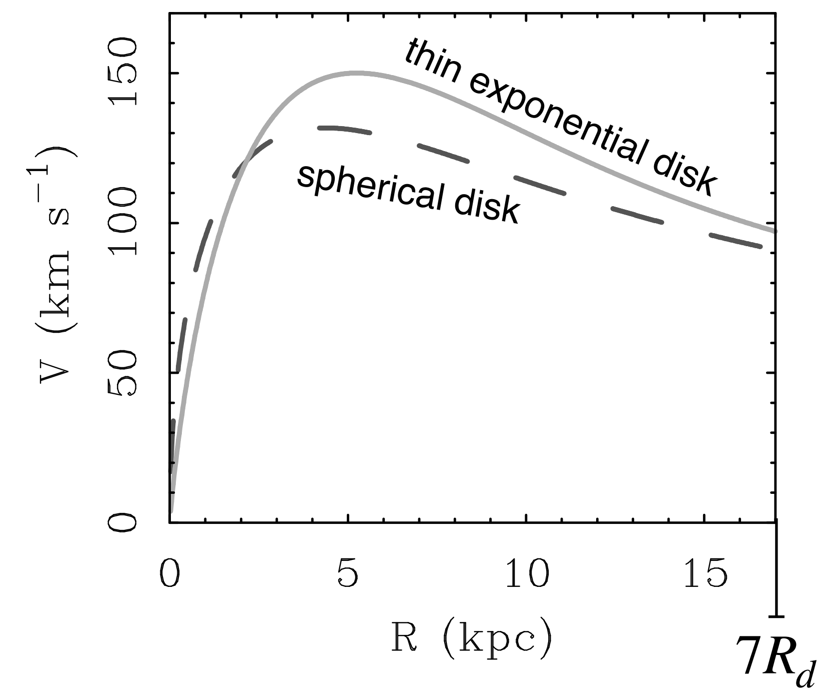
Progressive approximations
in mass modeling

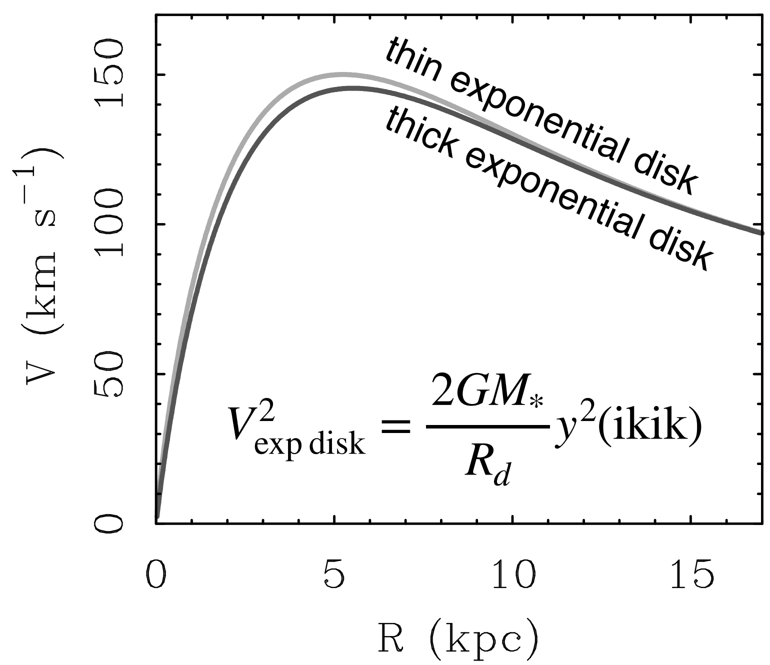
- Point Mass
- “spherical” disk
- thin exponential disk
- thick exponential disk
- surface density $\Sigma(R)$
- 2D $\Sigma(R, \phi)$ [e.g., bars]
- 3D $\rho(R, \phi, z)$
- 3D + non-equilibrium



Examples for the size and mass of NGC 6946

$M_* = 3.3 \times 10^{10}\ M_\odot$
$R_d = 2.44$ kpc

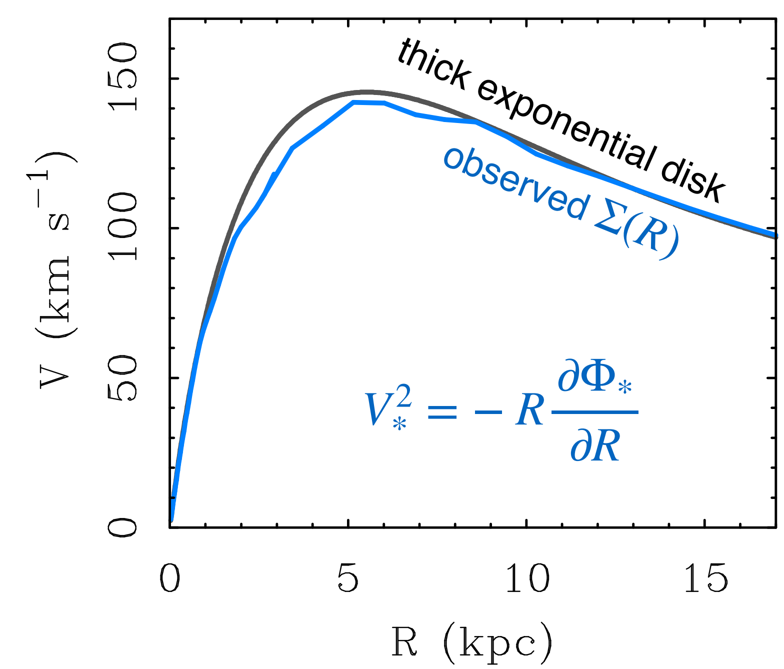




$${\rm ikik} = [I_0(y)K_0(y) - I_1(y)K_1(y)]$$

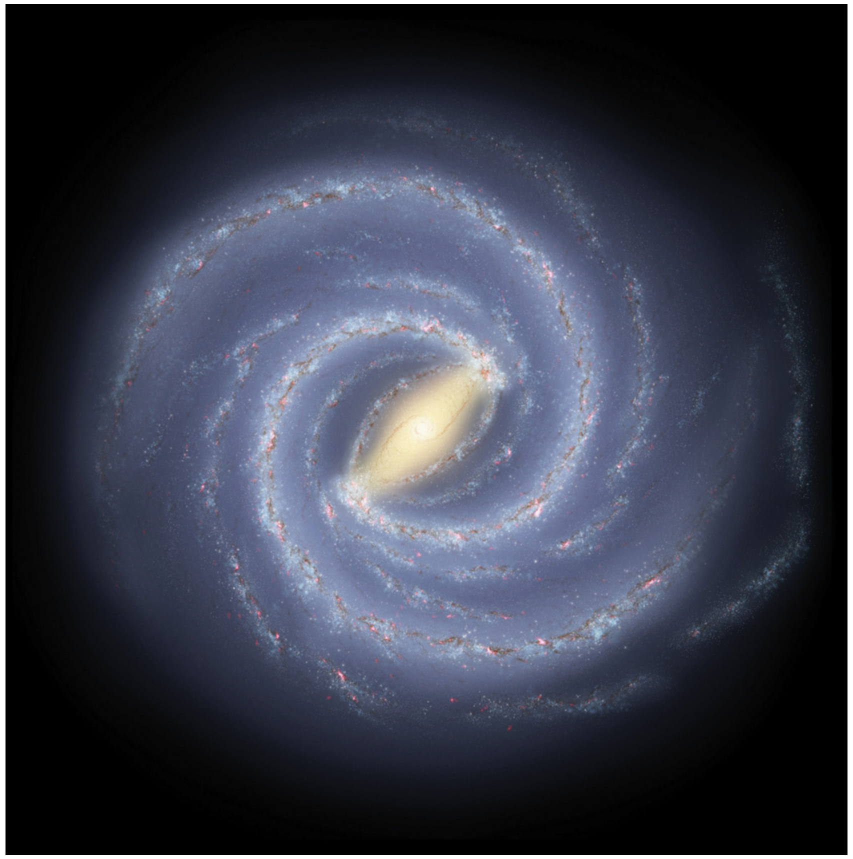
$$y = \frac{R}{2R_d}$$

We numerically solve the Poisson equation to obtain the gravitational potential Φ_* from the observed surface density $\Sigma_*(R)$



I and *K* are modified Bessel functions

Example: model Milky Way



Numerically solve the Poisson equation

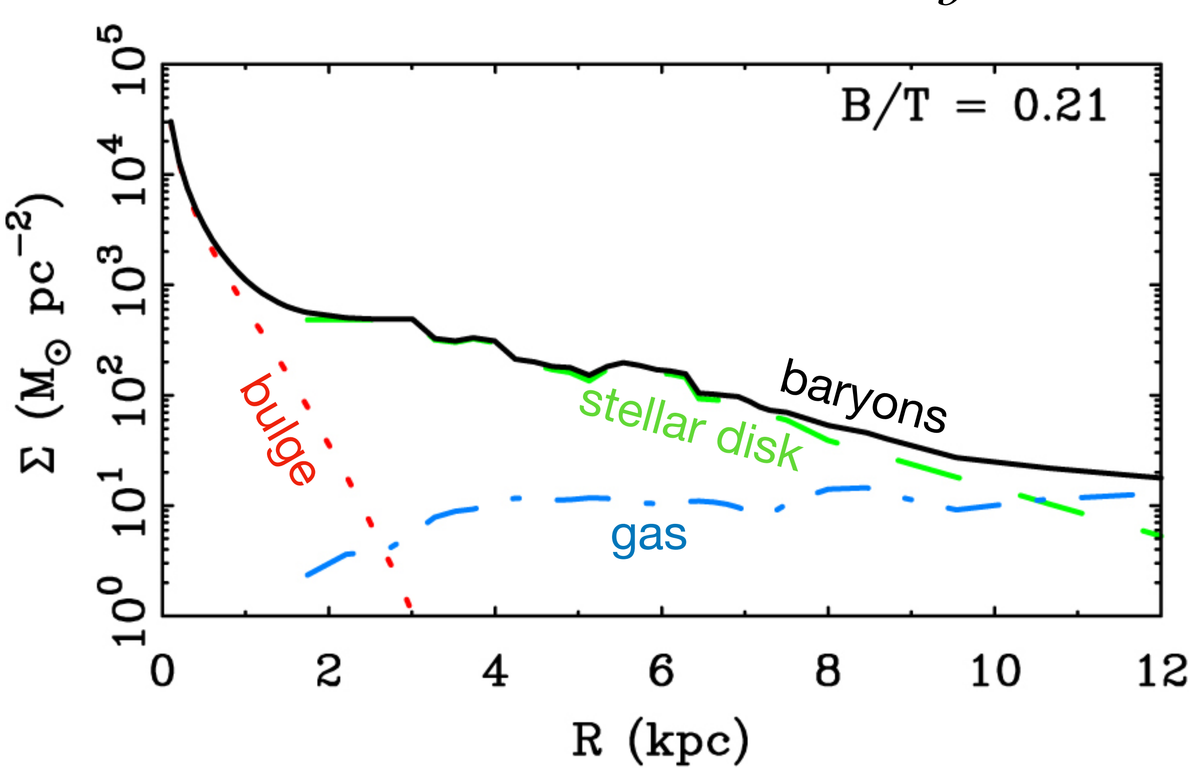
$$\nabla^2 \Phi_* = 4\pi G \rho_*(R, \theta, Z)$$

$$g_*(R) = \frac{V_*^2}{R} = -\frac{\partial \Phi_*}{\partial R} = 2\pi G \Sigma_*(R)$$

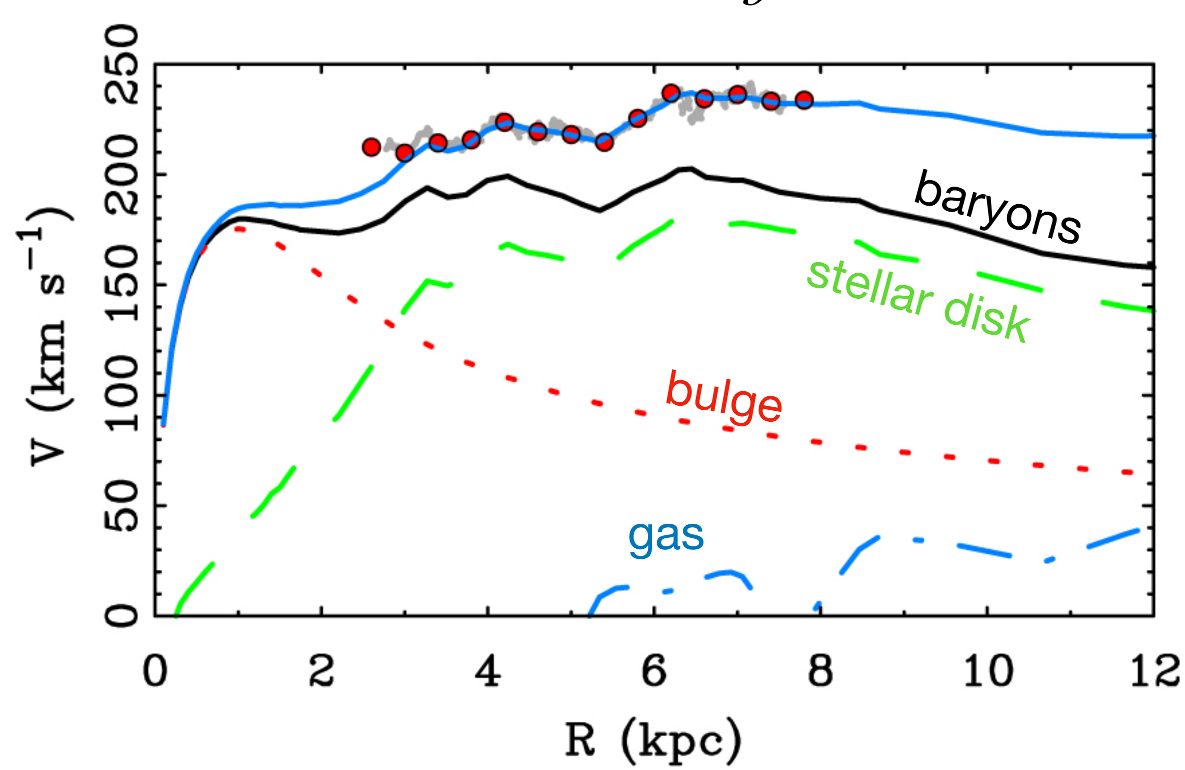
for each observed component.
Velocities add in quadrature:

$$V_b^2(R) = V_*^2(R) + V_g^2(R)$$

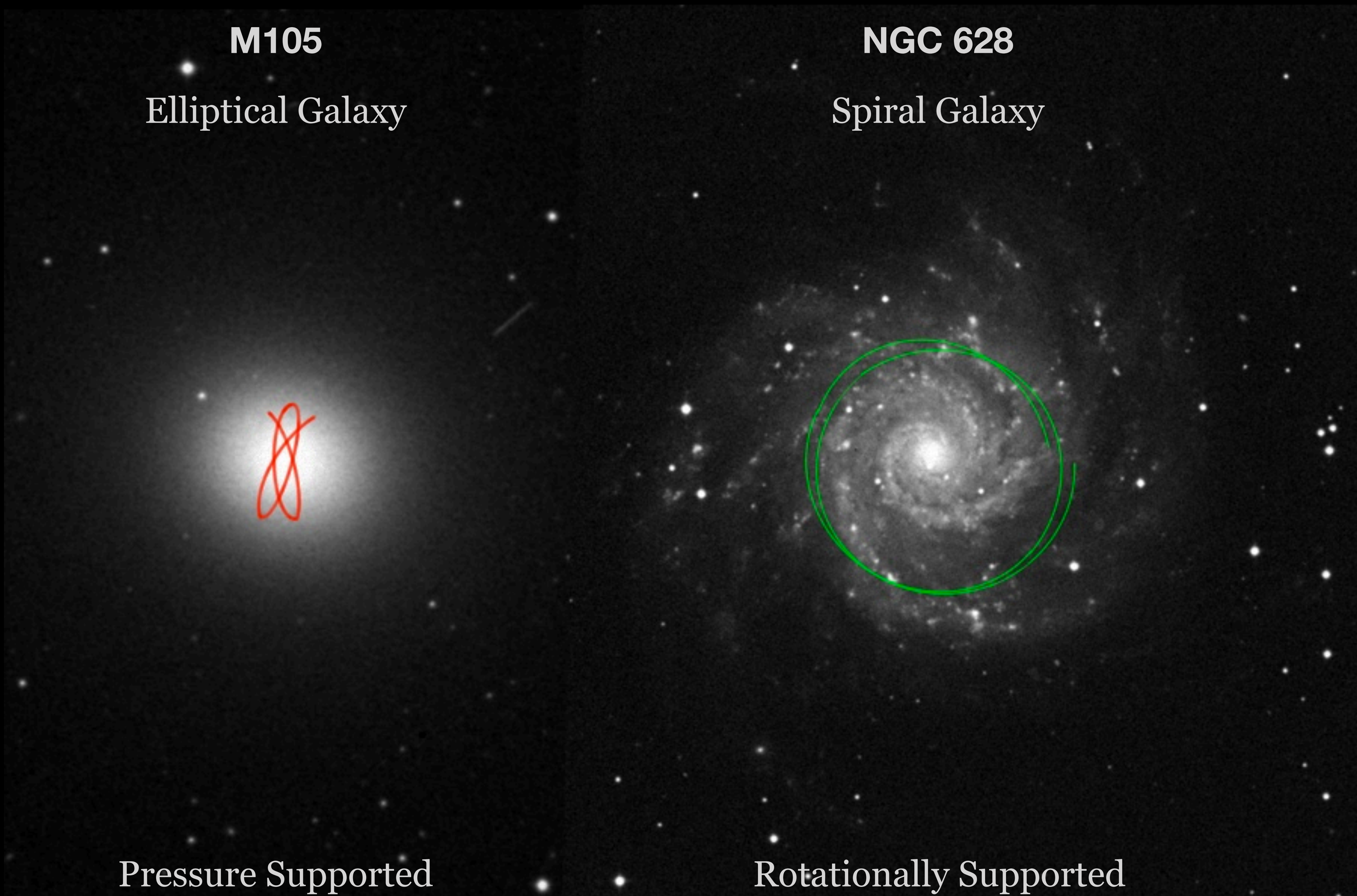
Surface density profile $\Sigma_b(R)$



Rotation curve $V_b(R)$



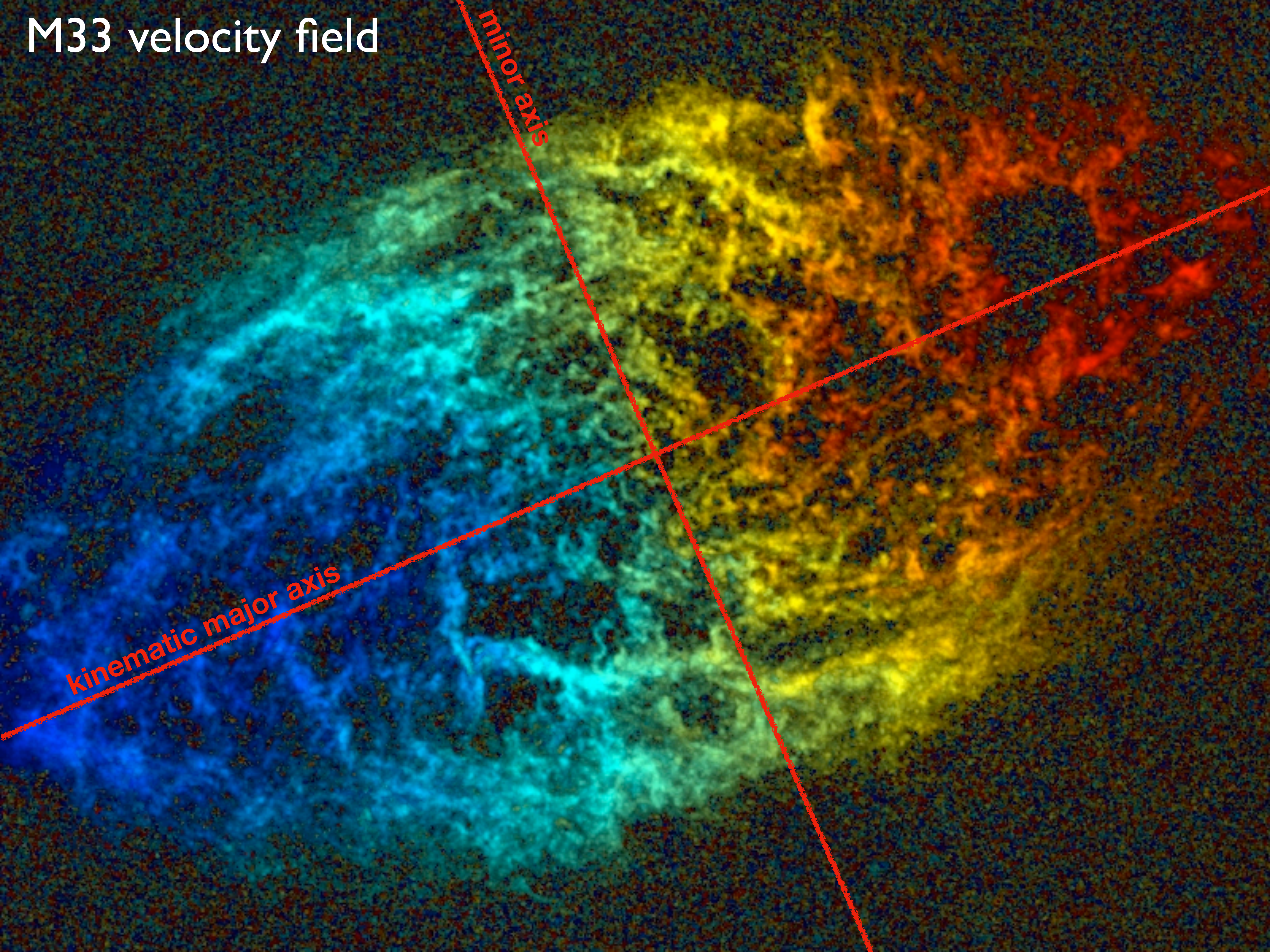
Stellar orbits in galaxies



Eccentric radial orbits
Random orientations

Nearly circular orbits
Same direction, same plane

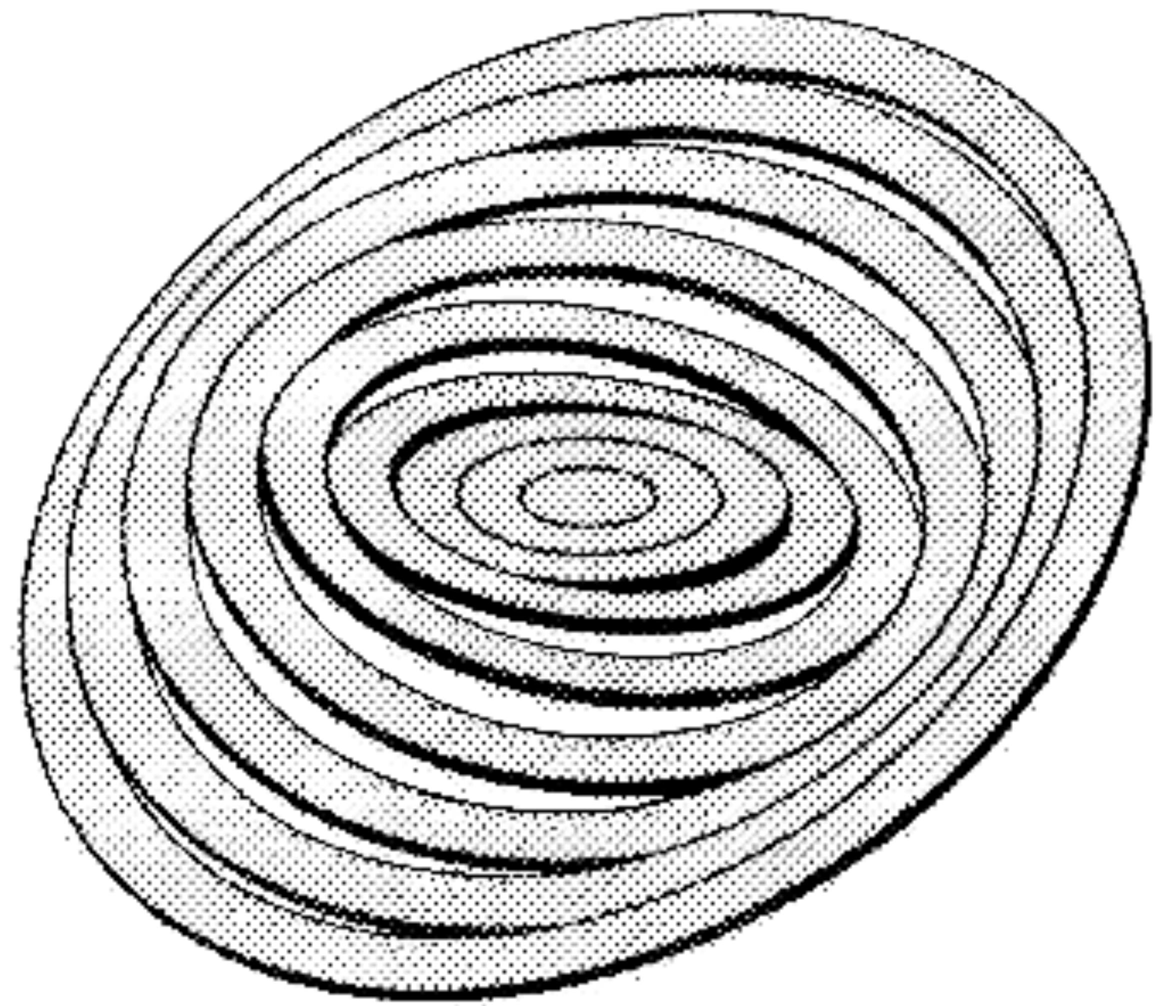
M33 velocity field

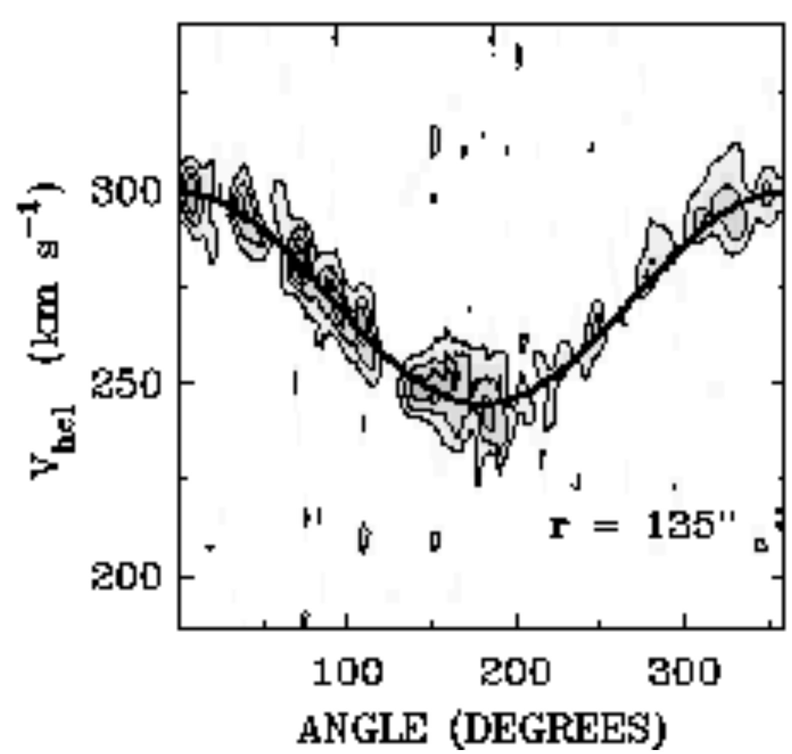


Rotation curves extracted using "tilted ring" fits

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.

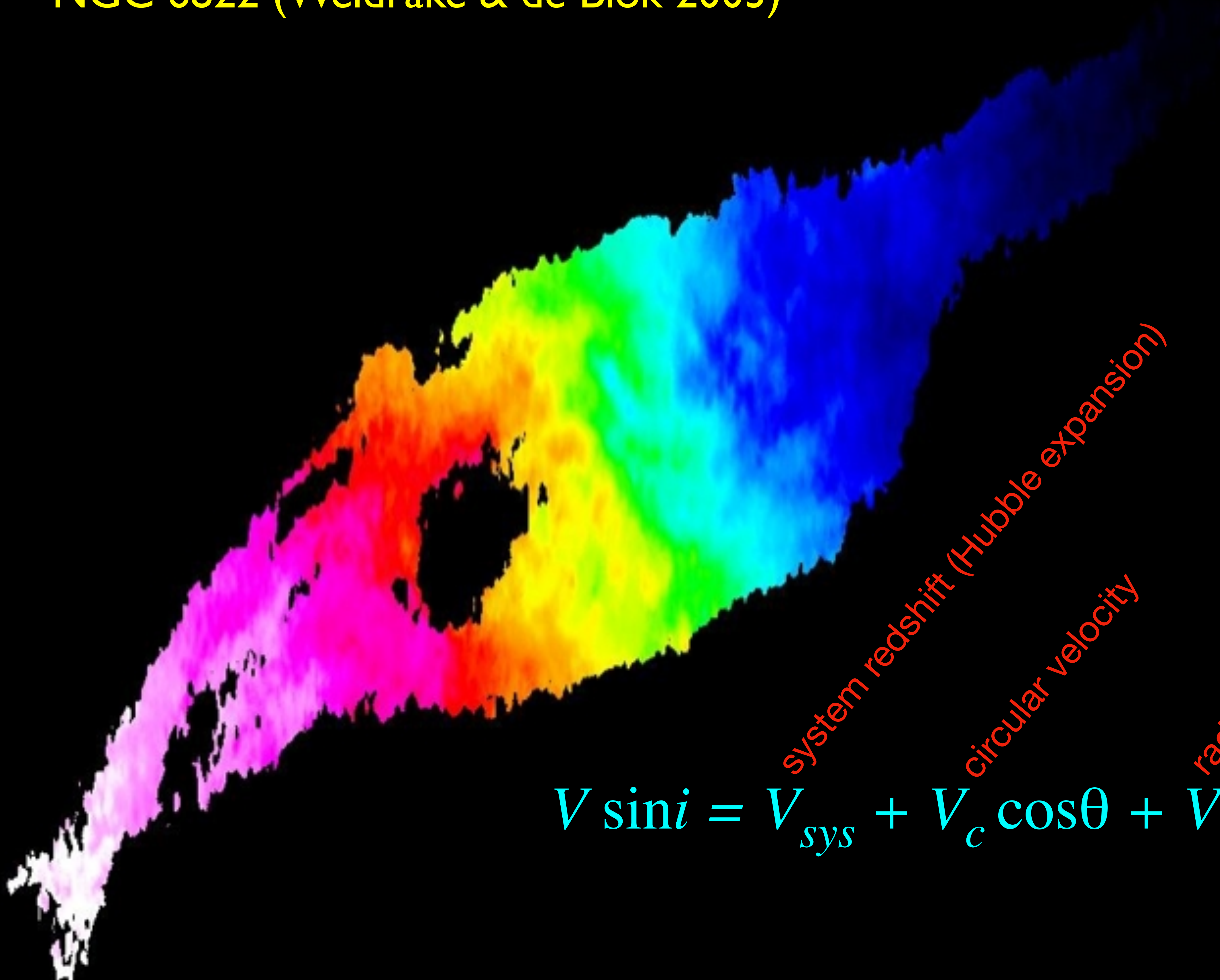
tilted ring model





velocity variation along ring

NGC 6822 (Weldrake & de Blok 2003)



system redshift (Hubble expansion)

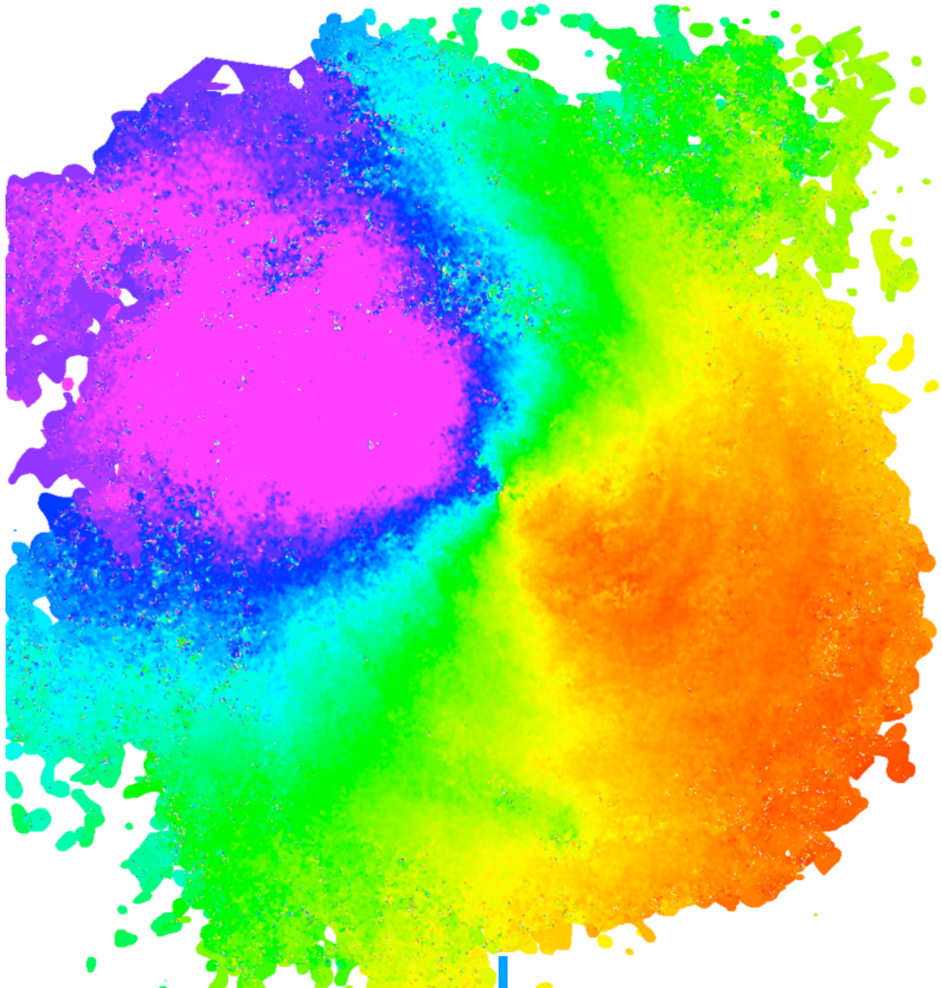
circular velocity

radial velocity

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

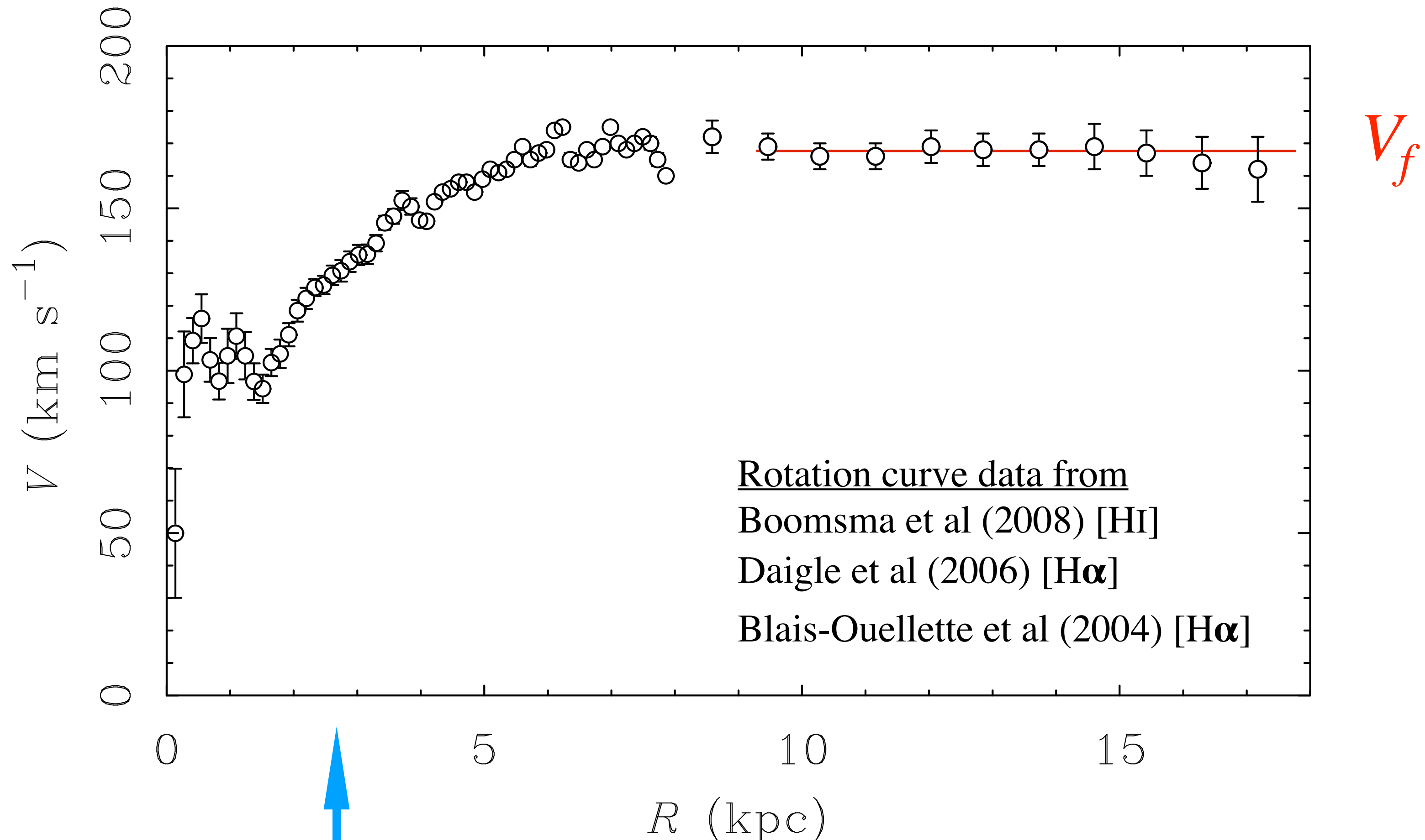
21cm interferometric observations give atomic gas distributions and velocity fields

NGC 6946

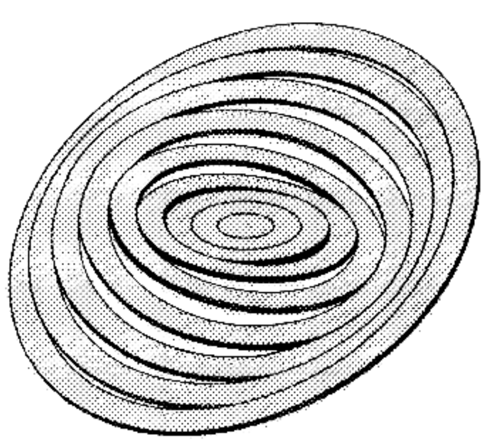


THINGS (Walter et al. 2008; de Blok et al. 2008)

Rotation curve



tilted ring model



to which we make tilted ring fits

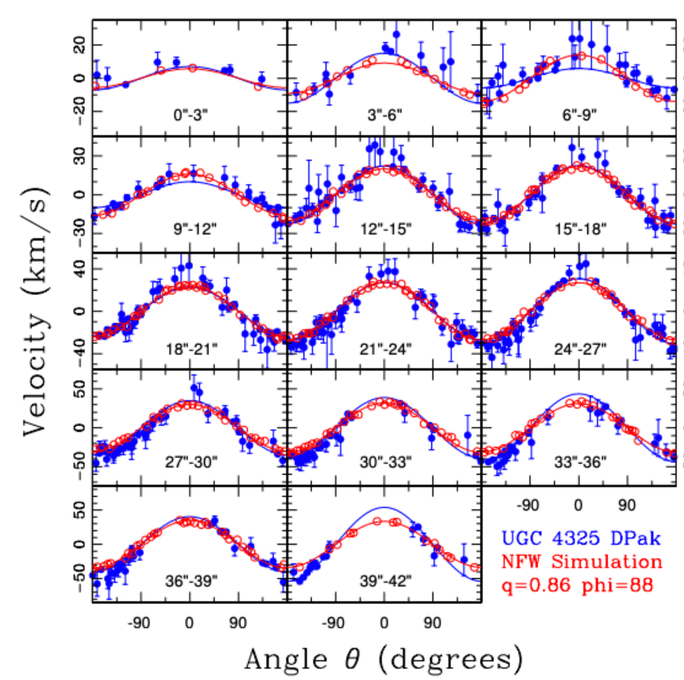
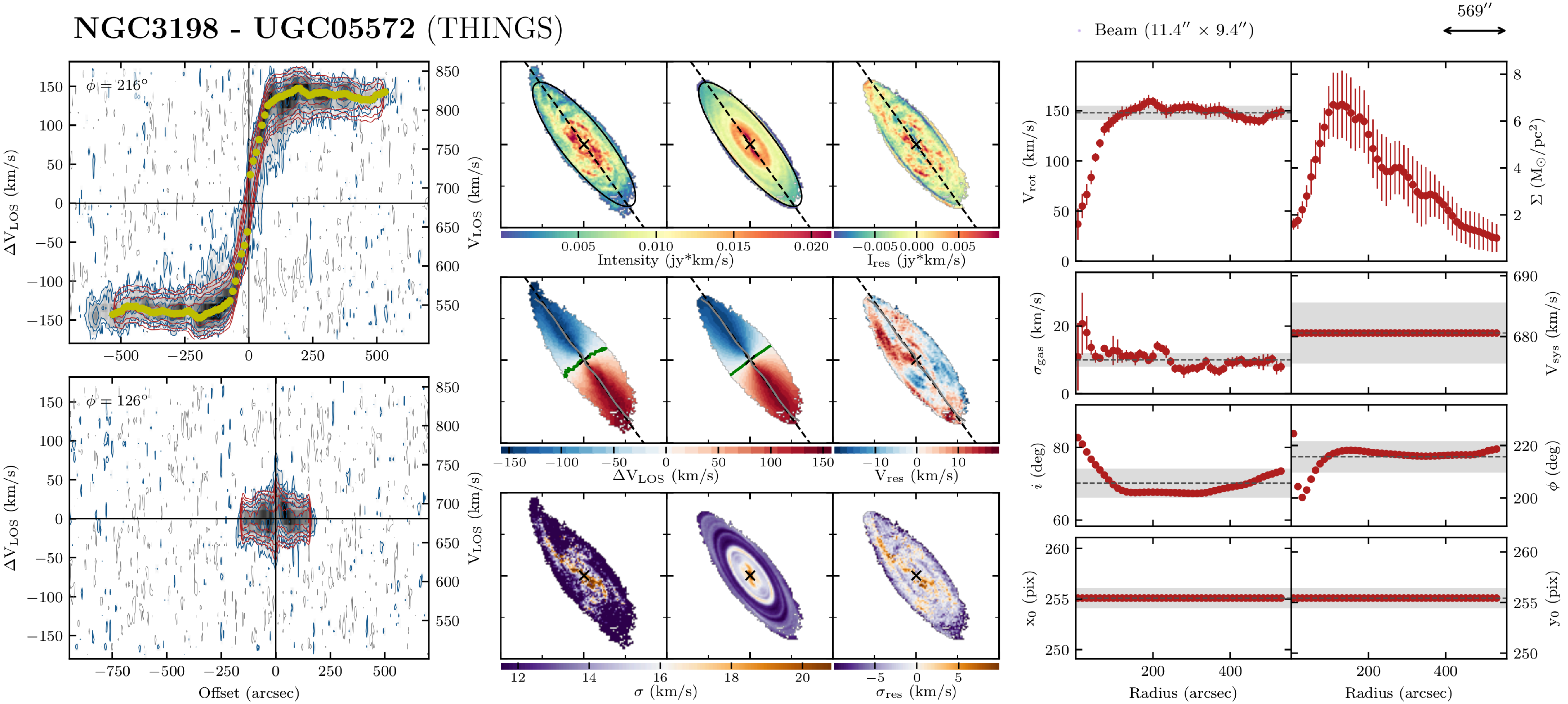


Figure 5.6: – The (0.86, 88°) simulation results (red) over-plotted with the observed UGC 4325 data (blue). The simulation and data match well between ~ 12″ - 30″.

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

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



Example analysis for one galaxy. Left: position–velocity diagrams along the major (top) and minor (bottom) axis. Center: 2D Hi map (top), velocity field (middle), and velocity dispersion (bottom). The left panels show the data, the center panels the fitted model, and the right panels the residuals. Right: derived radial quantities: the rotation curve (top left, with Vf noted in grey), the Hi surface density (top right), followed by the velocity dispersion, system redshift, inclination, position angle, and x and y centroids.