Leiden Observatory

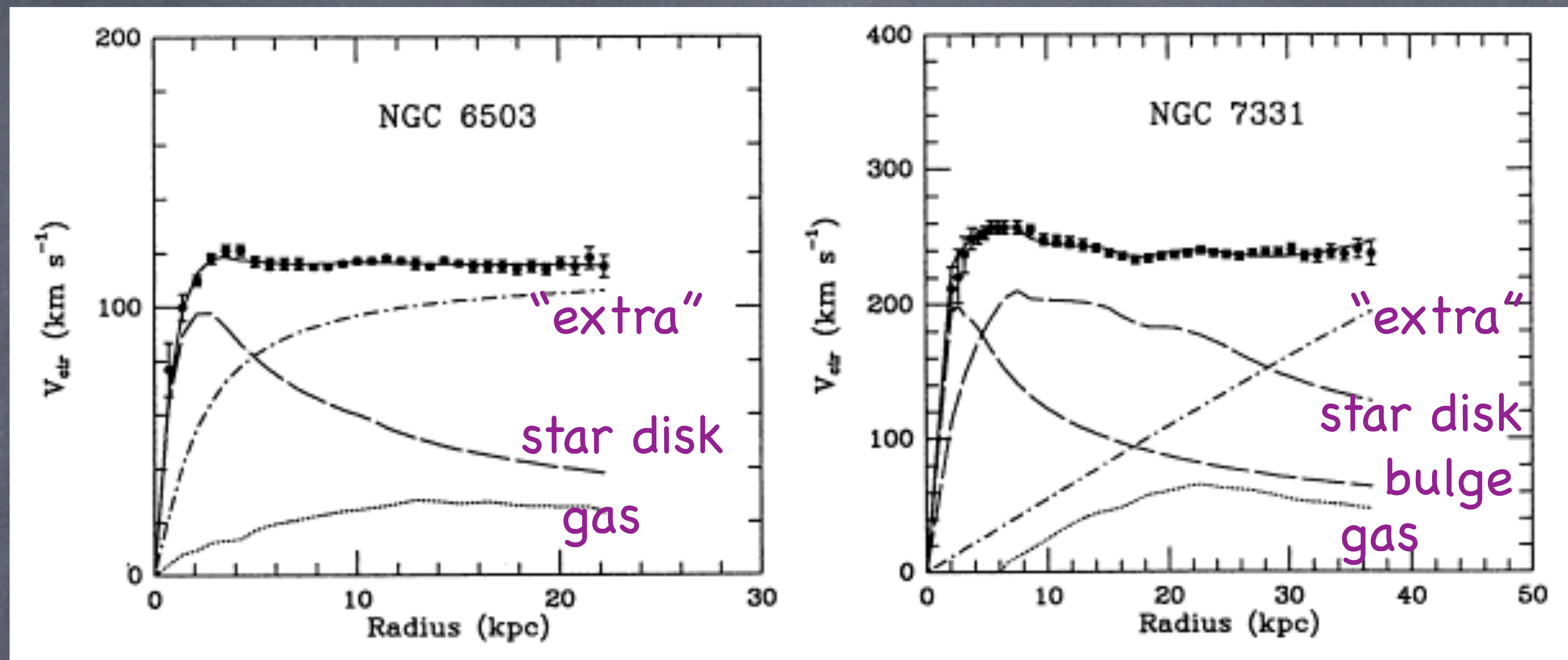
Universiteit Leiden

Local Dark Matter

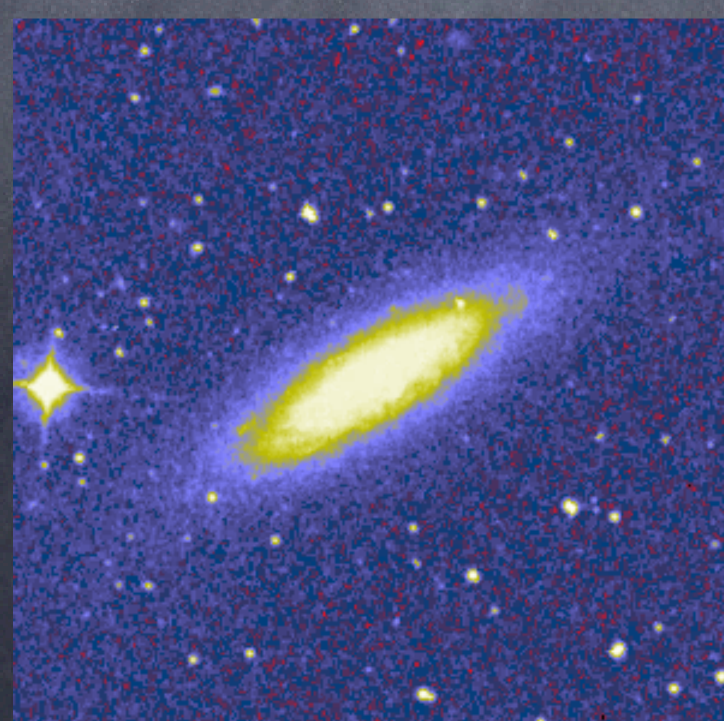
Konrad Kuijken

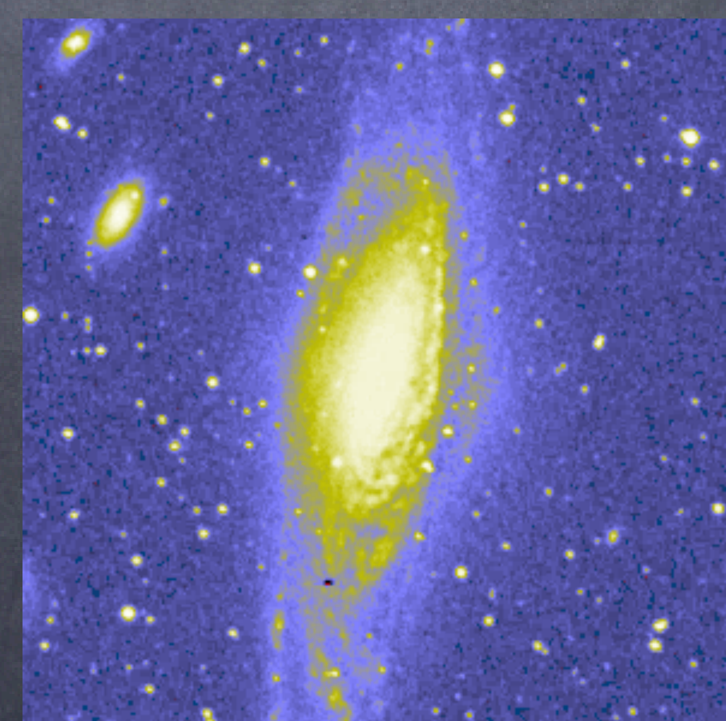
Leiden Observatory, Leiden University

Galaxy haloes



- ~ flat rotation curves: galaxies are not WYSIWYG



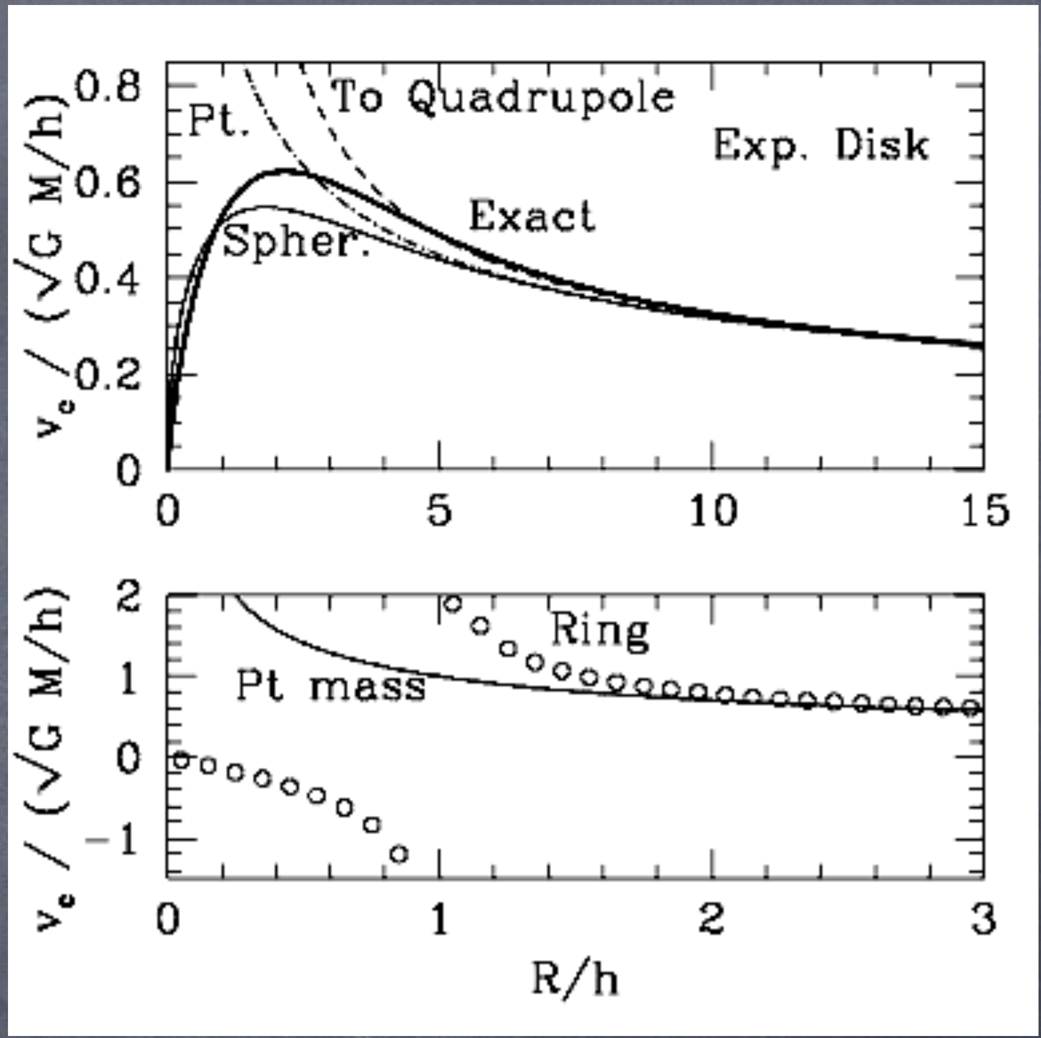


Rotation curves

$$\frac{GM(<r)}{r^2} \simeq \frac{V_{\rm circ}^2}{r}$$

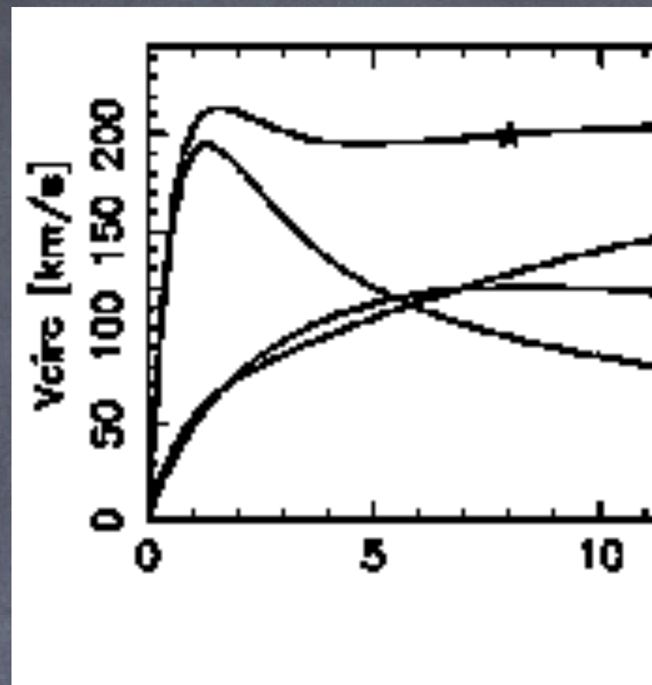
- Even in very flattened systems, the rotation curve mostly probes the enclosed mass (monopole) of the mass distribution
- example: exponential disk

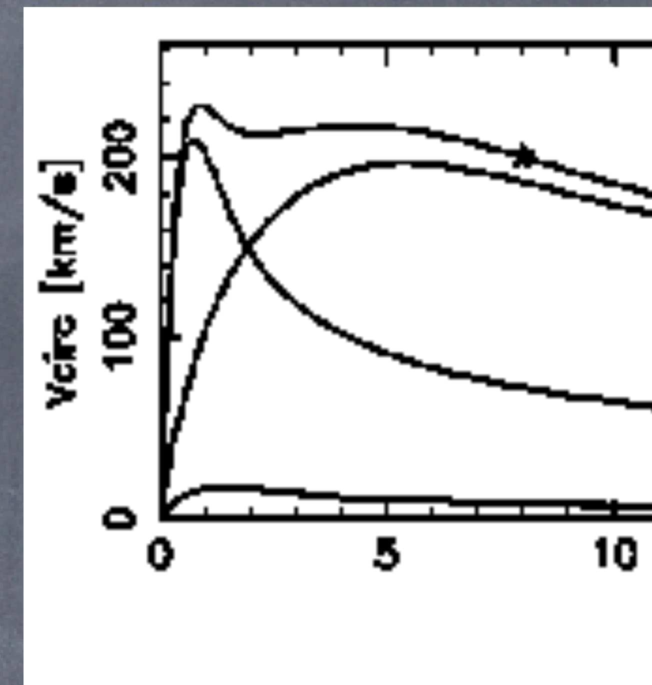
$$\Sigma = \Sigma_0 e^{-r/h}$$



In finite systems, Keplerian falloff $V=r^{-1/2}$ inevitable

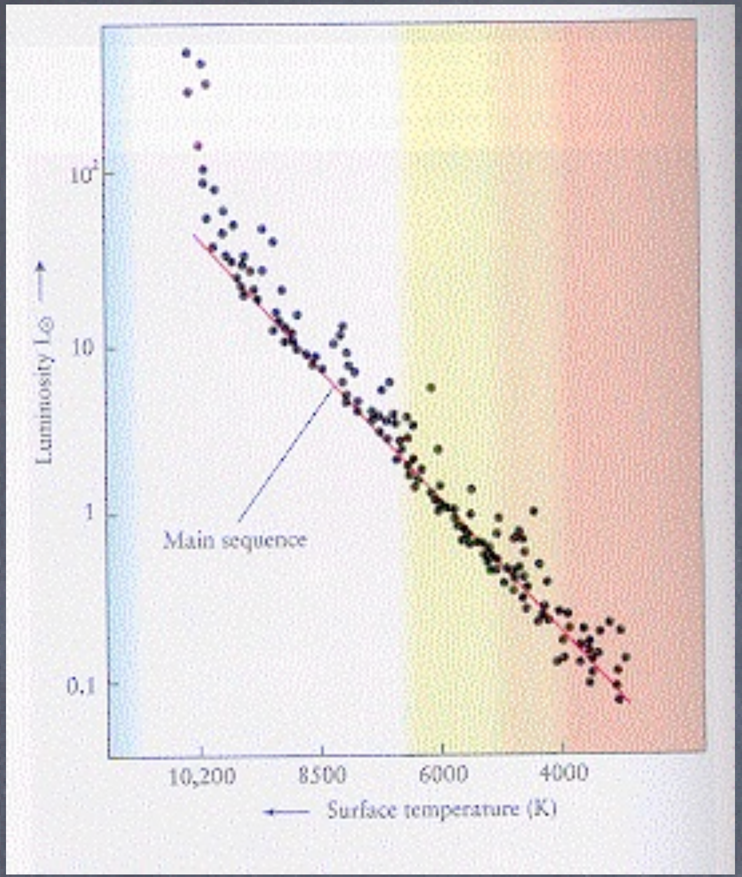
Rotation curve decomposition



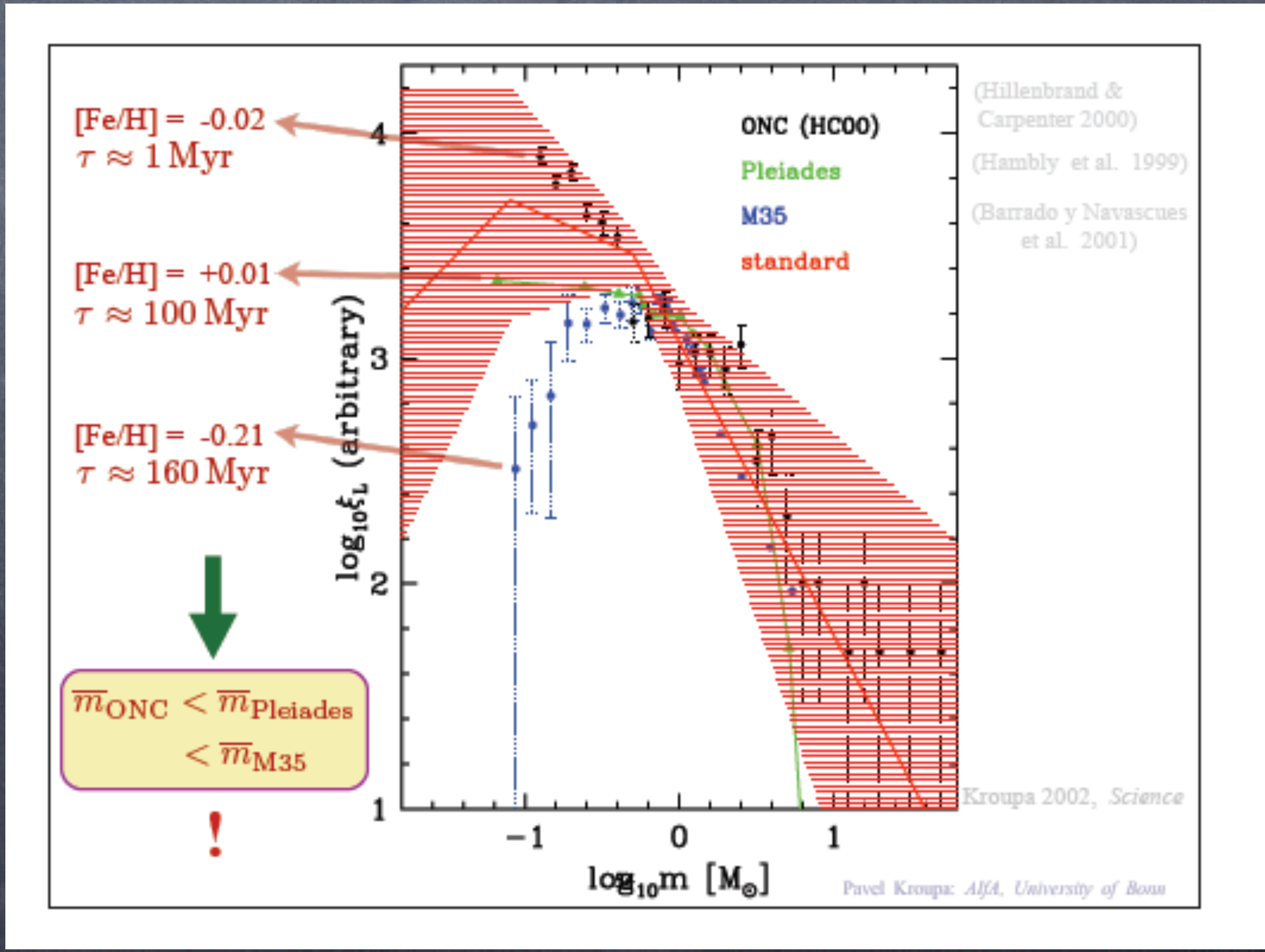


- Assign fraction of potential to ‘visible’ components
  - ‘Maximum disk’ decomposition (‘minimum extra’)
- Requires knowledge of Mass-to-Light ratio
  - WYSIWYG models not feasible in most cases

Stellar Mass Function



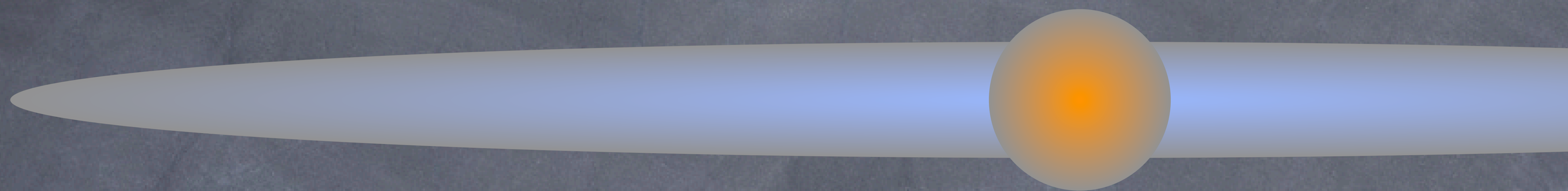
- Starlight is a poor tracer of stellar mass
- Most light emitted by most massive stars
- Most of the mass is 'invisible'



Leiden Observatory

Universiteit Leiden

Direct measurements of M/L in disk galaxies



- Dynamics of self-gravitating thin disks
  - gravity field ~ vertical
  - vertical motions decouple from horizontal ones
- stars move in 1-D vertical potential ψ(z)

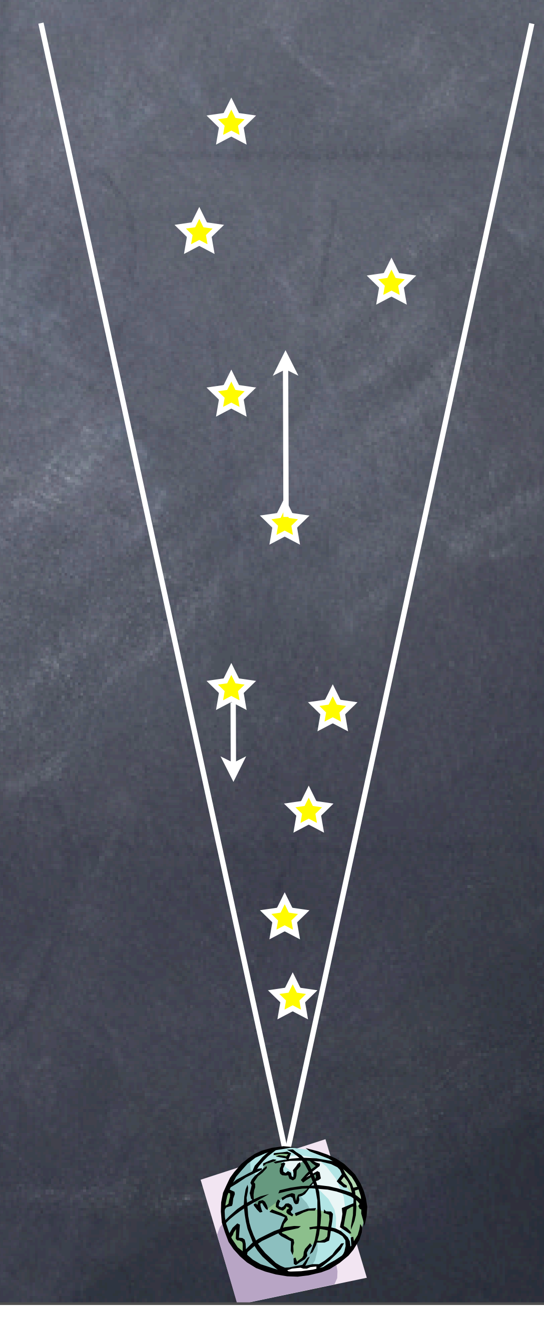
$$\nabla^2\psi = 4\pi G\rho_m \Rightarrow \frac{d^2\psi(z)}{dz^2} = 4\pi G\rho_m \Rightarrow \boxed{\frac{d\psi(z)}{dz} = 2\pi G\Sigma_m(<|z|)}$$

Direct measurements of M/L in disk galaxies

- Essentially compare mean orbital v_z^2 at $z=0$ with mean z reached
- Problem in practice:
  - need disk thickness (edge-on view)
  - velocity dispersion (face-on view)

Solar Neighbourhood

- Can measure 3D structure from star counts
- Can measure dynamics from individual stars
  - Kapteyn (1922) - Oort (1932)



Kapteyn 1922

FIRST ATTEMPT AT A THEORY OF THE ARRANGEMENT AND MOTION OF THE SIDEREAL SYSTEM[1]

BY J. C. KAPTEYN[2]

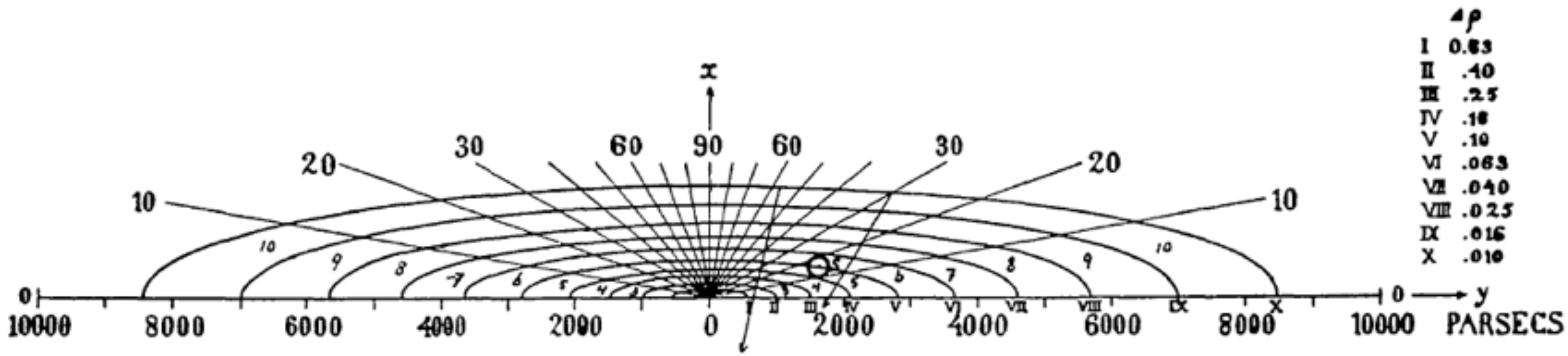


FIG. 1

the relative velocity is also in the plane of the Milky Way and about 40 km/sec. It is incidentally suggested that when the theory is perfected it may be possible to determine *the amount of dark matter* from its gravitational effect. (5) The *chief defects*

Leiden Observatory

Universiteit Leiden

Oort 1932

BULLETIN OF THE ASTRONOMICAL INSTITUTES OF THE NETHERLANDS.

1932 August 17 | Volume VI. | No. 238.

COMMUNICATION FROM THE OBSERVATORY AT LEIDEN.

The force exerted by the stellar system in the direction perpendicular to the galactic plane and some related problems, by *J. H. Oort.*

11. *The amount of dark matter.*

From the results found for the decrease of $K(z)$ with z we may derive an approximate value of the total density of matter, Δ, in the neighbourhood of the sun. Let us suppose that we are situated inside a homogeneous ellipsoid of revolution with semi-axes a and c, and density Δ. For $z = 0$ there will then be the following relation:

$$\partial K(z)/\partial z = -4\pi\gamma x \Delta \quad (14)$$

Case	Δ
I *a*)	·108
I *b*)	·093
II *a*)	·089
II *b*)	·079

total mass density ($M_\odot/pc^3$)

Monday, July 16, 2012

Stellar dynamics

- Describe stars with phase space density $f(x_i, v_j)$

$$\int f d^3v = \rho; \qquad \int v_z^2 f d^3v = \rho\sigma_z^2;$$

- Collisionless Boltzmann equation

$$\frac{Df}{Dt} = \frac{\partial f}{\partial t} + v_i \frac{\partial f}{\partial x_i} - \frac{\partial \psi}{\partial x_i}\frac{\partial f}{\partial v_i} = 0$$

- Ignore all x,y gradients

$$v_z \frac{df}{dz} = -K_z \frac{df}{dv_z}$$

- x v_z, integrate over v_z:

$$\frac{d(\rho\sigma_z^2)}{dz} = K_z \rho$$

Leiden Observatory

Universiteit Leiden

Stellar dynamics

- More generally, for an axisymmetric system in cylindrical polar coordinates (R,ϕ,z)

$$\frac{Df}{Dt} = \frac{\partial f}{\partial t} + v_R \frac{\partial f}{\partial R} + v_z \frac{\partial f}{\partial z} + \left(K_R + \frac{v_\phi^2}{R} \right) \frac{\partial f}{\partial v_R} - \frac{v_R v_\phi}{R} \frac{\partial f}{\partial v_\phi} + K_z \frac{\partial f}{\partial v_z} = 0$$

- x v_i, integrate gives Jeans equations

$$\frac{1}{R} \frac{\partial (R \rho \sigma_R^2)}{\partial R} + \frac{\partial (\rho \sigma_{Rz})}{\partial z} - \frac{\rho (v_\phi^2 + \sigma_\phi^2)}{R} = \rho K_R$$

$$\frac{\partial (\rho \sigma_z^2)}{\partial z} + \frac{\partial (\rho \sigma_{Rz})}{\partial R} = \rho K_z$$

- NB: in a thermalized system velocity dispersion is isotropic: $\sigma_{Rz}=0$; $\sigma_R=\sigma_z=\sigma_\phi$

Stellar dynamics

- More generally, for an axisymmetric system in cylindrical polar coordinates (R,ϕ,z)

$$\frac{Df}{Dt} = \frac{\partial f}{\partial t} + v_R \frac{\partial f}{\partial R} + v_z \frac{\partial f}{\partial z} + \left(K_R + \frac{v_\phi^2}{R} \right) \frac{\partial f}{\partial v_R} - \frac{v_R v_\phi}{R} \frac{\partial f}{\partial v_\phi} + K_z \frac{\partial f}{\partial v_z} = 0$$

- x v_i, integrate gives Jeans equations

$$\frac{1}{R} \frac{\partial (R \rho \sigma_R^2)}{\partial R} + \frac{\partial (\rho \sigma_{Rz})}{\partial z} - \frac{\rho (v_\phi^2 + \sigma_\phi^2)}{R} = \rho K_R$$

$$\frac{\partial (\rho \sigma_z^2)}{\partial z} + \frac{\partial (\rho \sigma_{Rz})}{\partial R} = \rho K_z$$

- NB: in a thermalized system velocity dispersion is isotropic: $\sigma_{Rz}=0$; $\sigma_R=\sigma_z=\sigma_\phi$

Stellar dynamics

- More generally, for an axisymmetric system in cylindrical polar coordinates (R,ϕ,z)

$$\frac{Df}{Dt} = \frac{\partial f}{\partial t} + v_R \frac{\partial f}{\partial R} + v_z \frac{\partial f}{\partial z} + \left(K_R + \frac{v_\phi^2}{R} \right) \frac{\partial f}{\partial v_R} - \frac{v_R v_\phi}{R} \frac{\partial f}{\partial v_\phi} + K_z \frac{\partial f}{\partial v_z} = 0$$

- x v_i, integrate gives Jeans equations

$$\frac{1}{R}\frac{\partial(R\rho\sigma_R^2)}{\partial R} + \frac{\partial(\rho\sigma_{Rz})}{\partial z} - \frac{\rho(v_\phi^2 + \sigma_\phi^2)}{R} = \rho K_R$$

$$\frac{\partial(\rho\sigma_z^2)}{\partial z} + \frac{\partial(\rho\sigma_{Rz})}{\partial R} = \rho K_z$$

- NB: in a thermalized system velocity dispersion is isotropic: $\sigma_{Rz}=0$; $\sigma_R=\sigma_z=\sigma_\phi$

Leiden Observatory

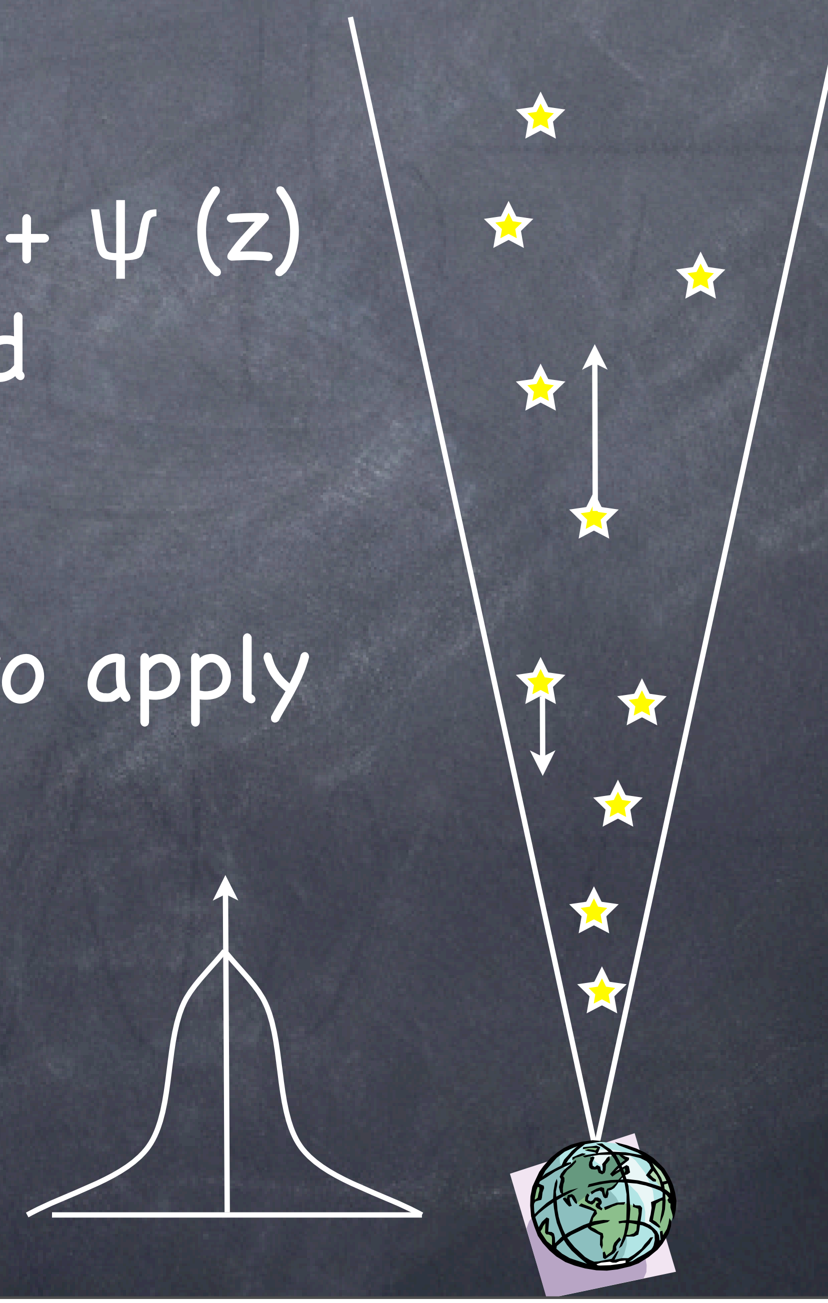
Universiteit Leiden

Vertical kinematics

$$v_z \frac{df}{dz} + \frac{d\psi(z)}{dz}\frac{df}{dv_z} = 0 \quad \Rightarrow \quad f(z, v_z) = f(\psi(z) + v_z^2) = f(E_z)$$

- Velocity distribution at z=0 + ψ (z) ==> velocity distribution (and density) at height z
- (avoids derivatives needed to apply the Jeans equation)

$$\frac{d(\rho\sigma_z^2)}{dz} = K_z \rho$$



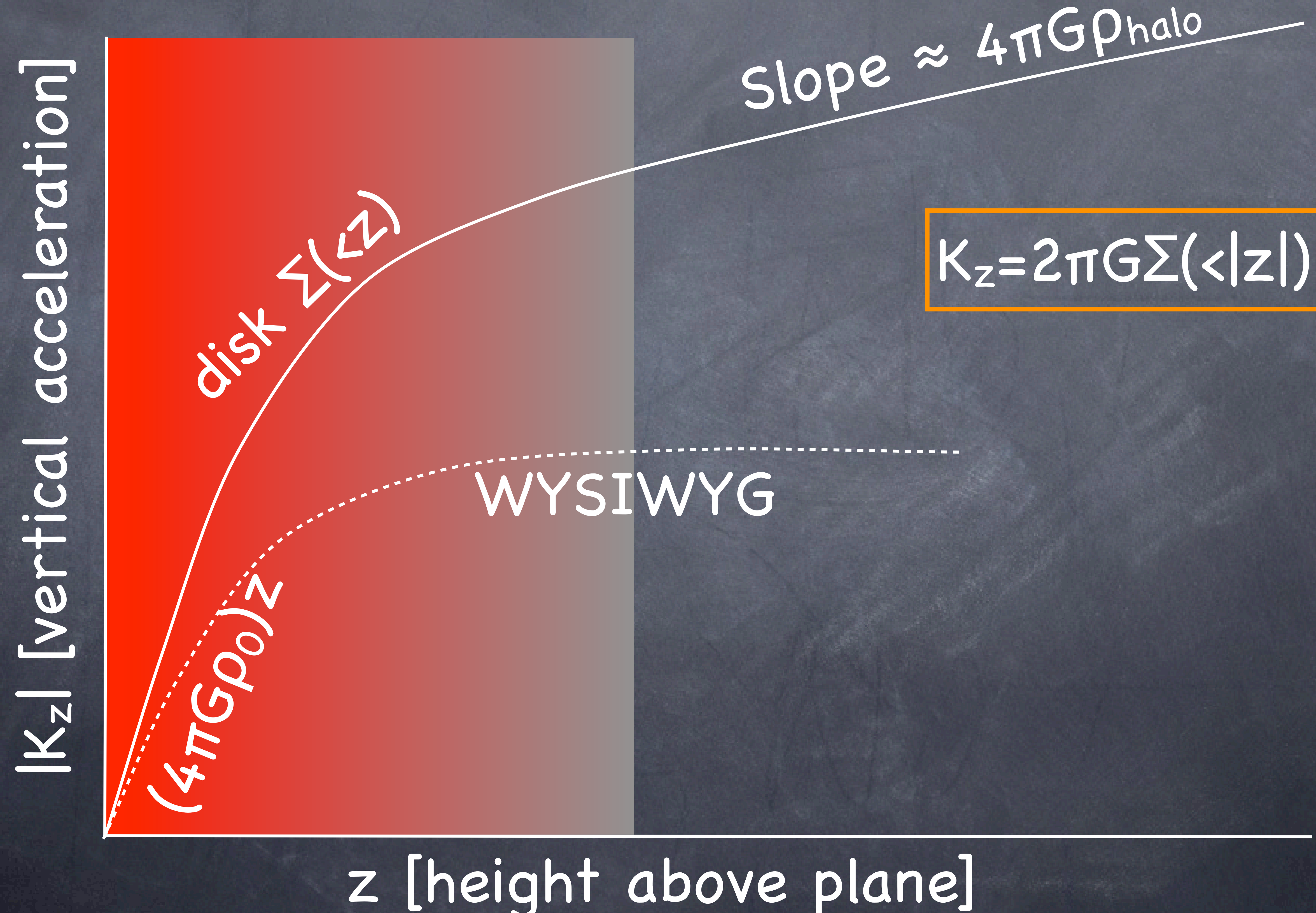
Leiden Observatory

Universiteit Leiden

In practice

- Pick a good tracer population that probes the disk (z<~1kpc)
  - numerous
  - sufficiently old, well-mixed
  - well-calibrated distances
  - good radial velocity measurements
- Lower main sequence stars (G - K dwarfs)
- Parameterize possible potentials
  - Known star populations + gas + dark disk + halo

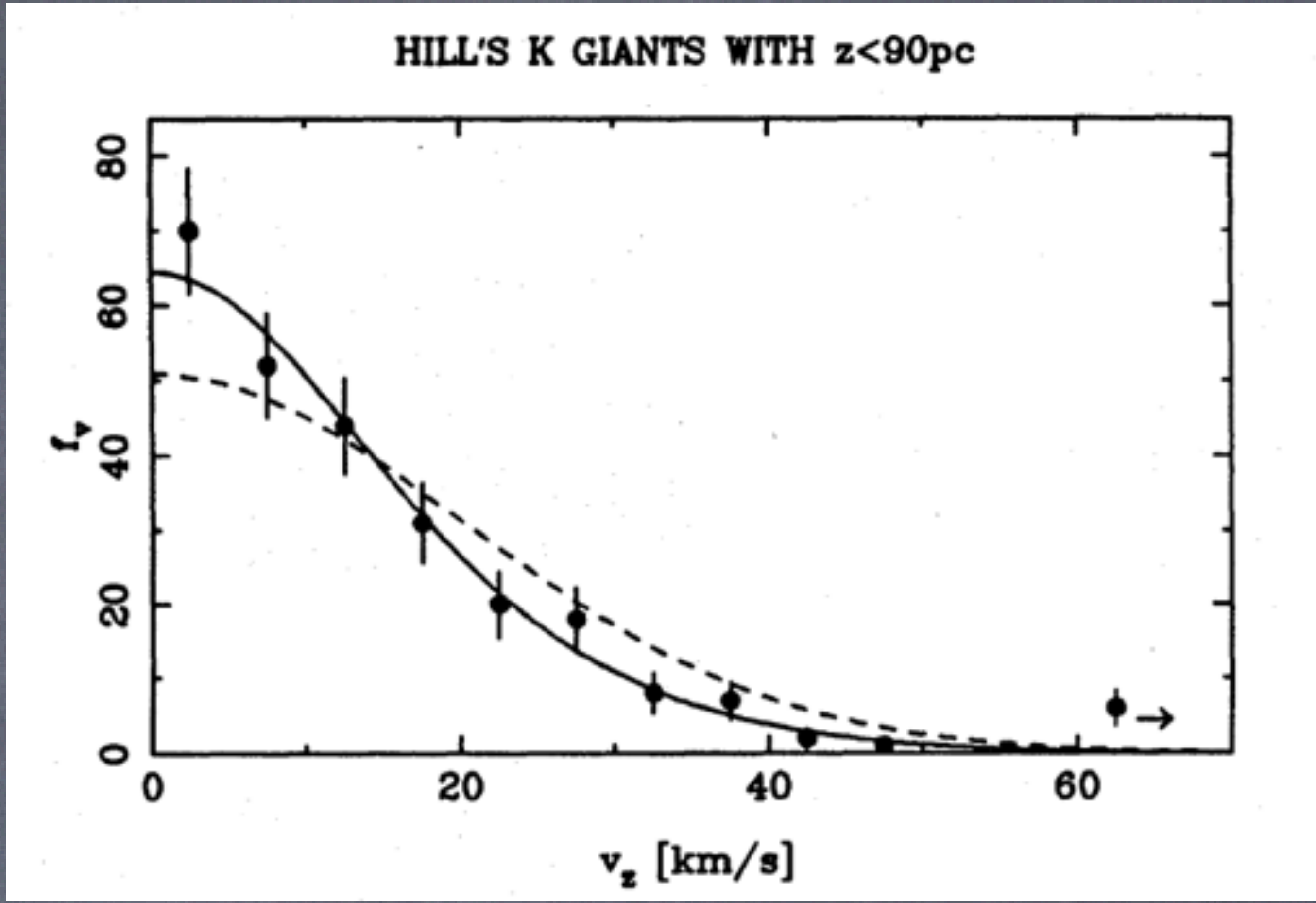
Trial potentials

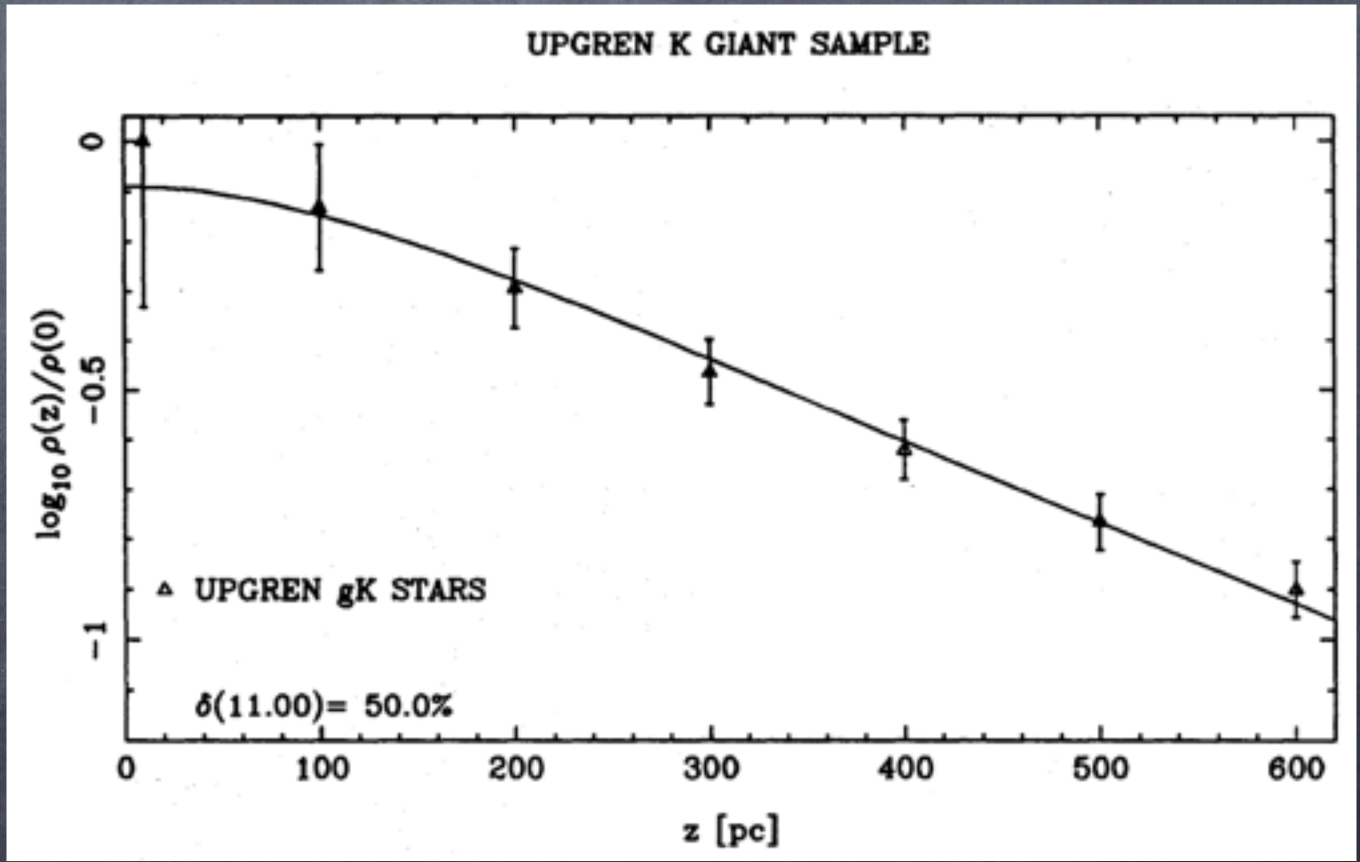


$K_z = 2\pi G \Sigma(<|z|)$

Leiden Observatory

- Example (KK+Gilmore 1989)
- f(v) at z=0
- predicted ρ(z) in a WYSIWYG potential

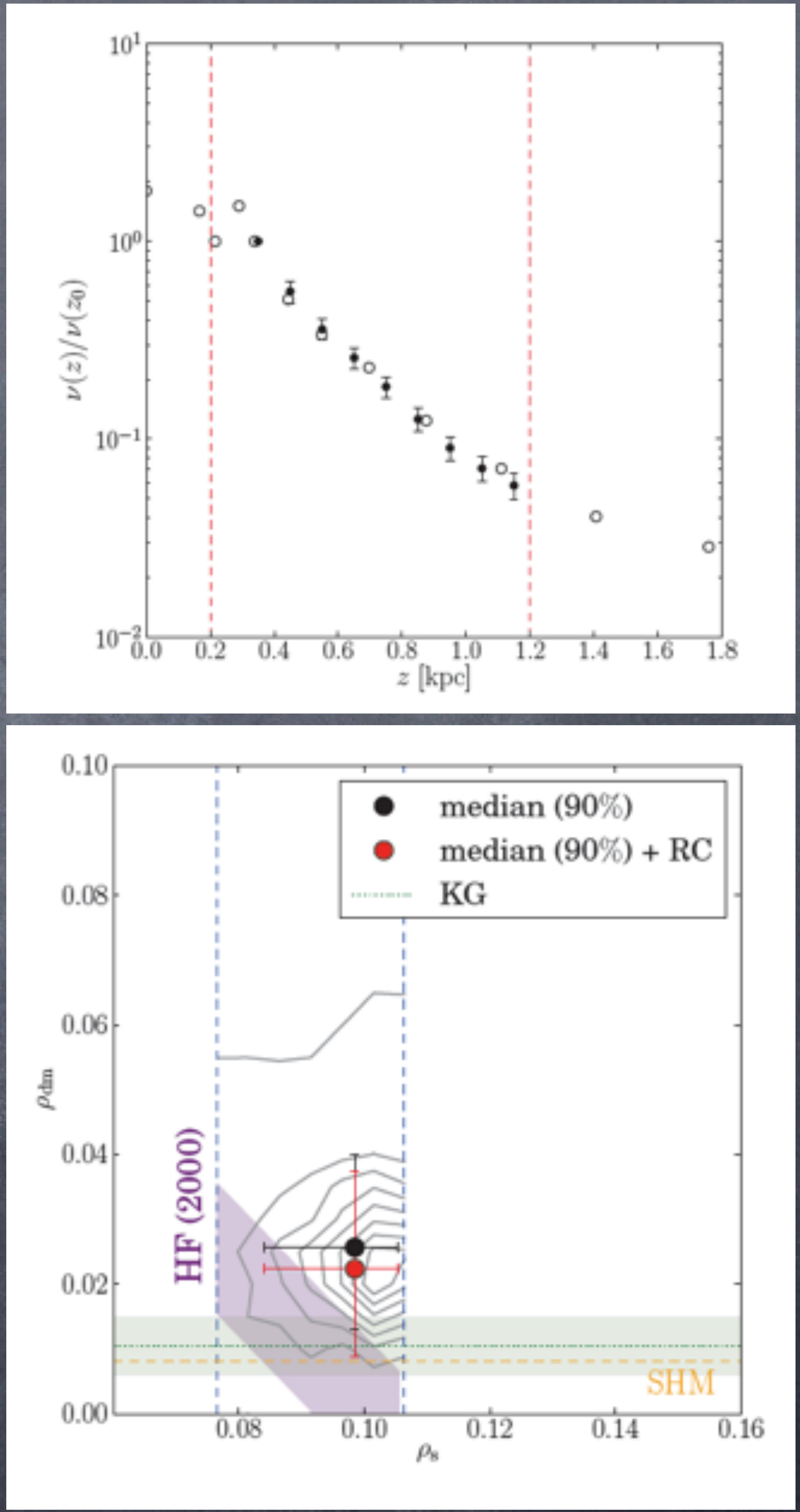




Universiteit Leiden

Disk dark matter?

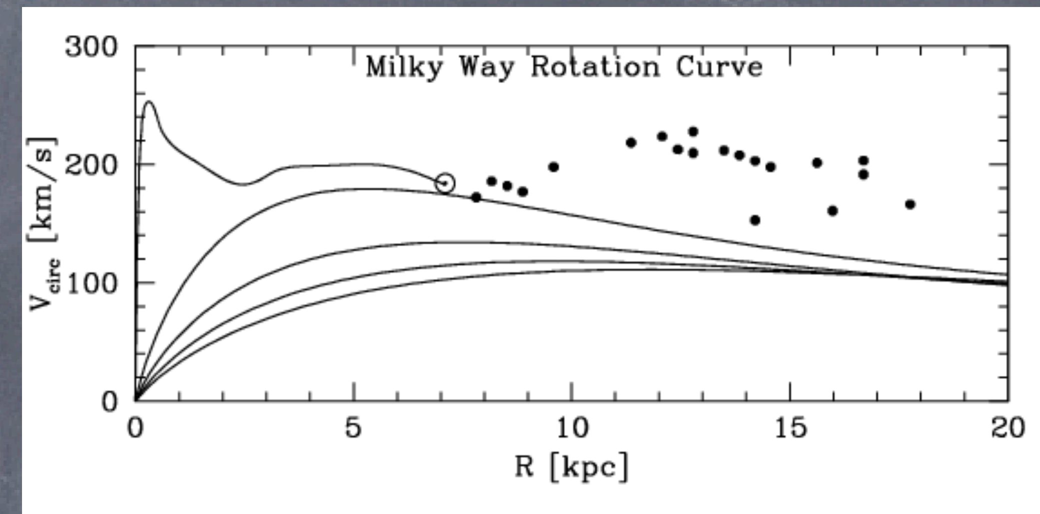
- Since 1990's, most analyses agree:
  - disk kinematics below z=500pc consistent with known populations' gravity
  - disk volume density at z=0 is about $0.1 M_\odot/pc^3$, 50-50 stars and gas
  - disk surf. density $50 M_\odot/pc^2$
- Halo dark matter density?

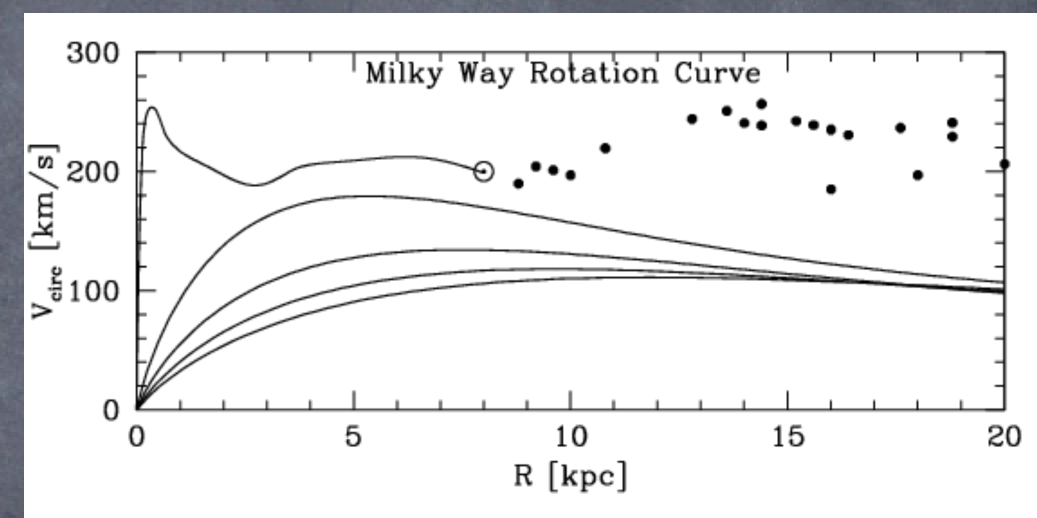


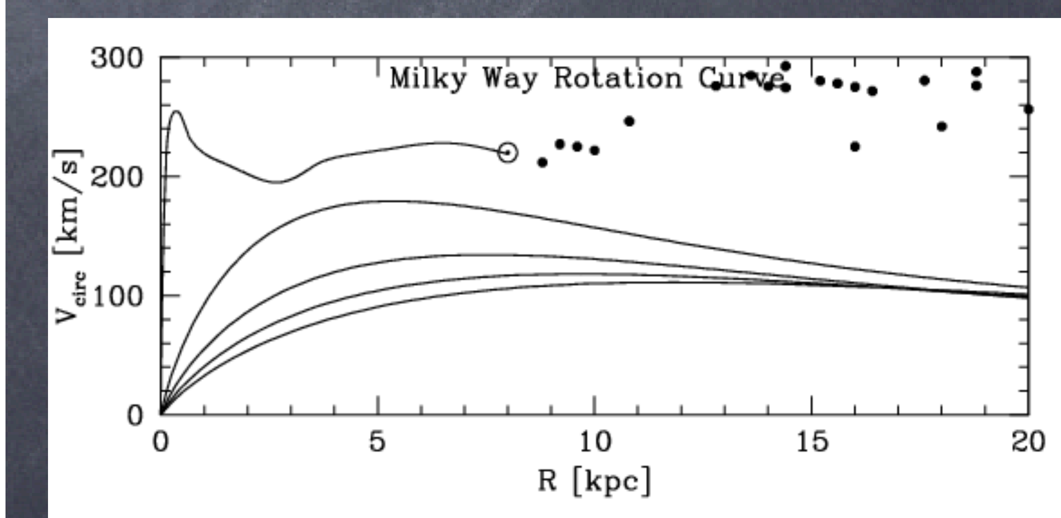
Garbari et al 2012

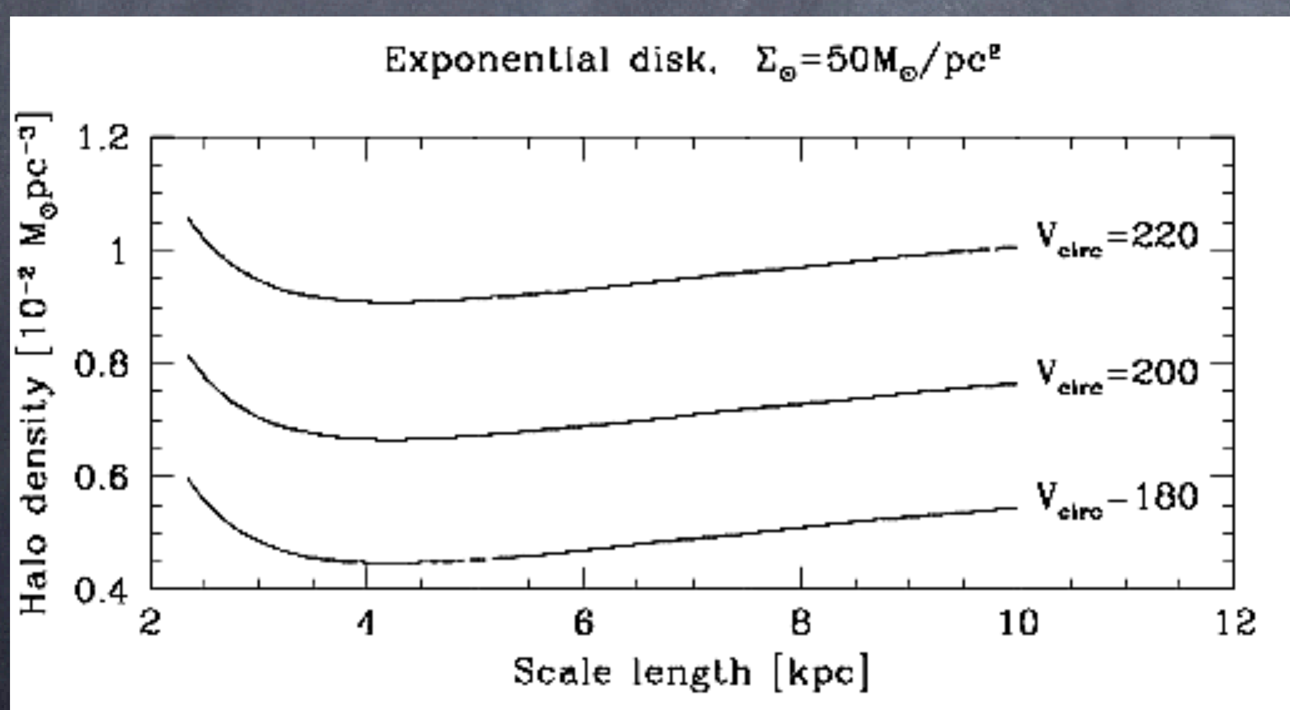
Halo dark matter

- Milky Way rotation is a bit awkward to model
- Fix local disk surf. density
- Vary scale height, solar orbit speed, fit V_{circ} curve









(spherical halo model)

Leiden Observatory

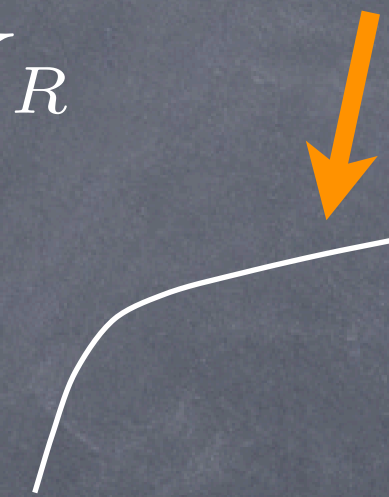
Universiteit Leiden

Using disk stars to probe halo dark matter

$$\frac{1}{R}\frac{\partial(R\rho\sigma_R^2)}{\partial R} + \frac{\partial(\rho\sigma_{Rz})}{\partial z} - \frac{\rho(v_\phi^2 + \sigma_\phi^2)}{R} = \rho K_R$$

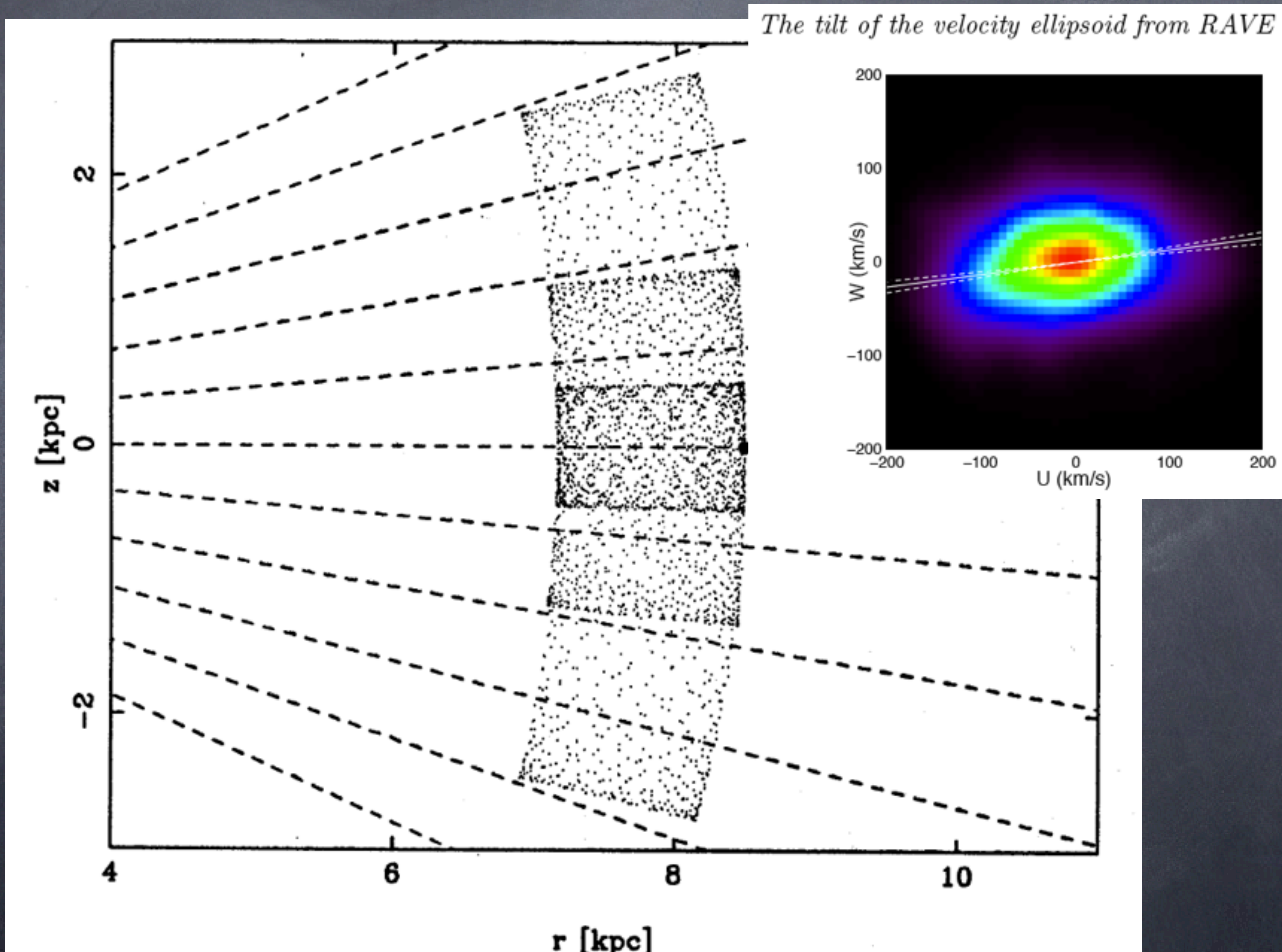
$$\frac{\partial(\rho\sigma_z^2)}{\partial z} + \frac{\partial(\rho\sigma_{Rz})}{\partial R} = \rho K_z$$

$$4\pi G\rho_m = -\frac{\partial K_z}{\partial z} - \frac{1}{R}\frac{\partial(RK_R)}{\partial R}$$



- At high z, no longer vertical-only kinematics
- Velocity ellipsoid tilts, is anisotropic
- Need to measure radial gradient of this tilt
- Also Poisson equation not separable

Orbit tilt



Leiden Observatory

Universiteit Leiden

Orbit tilt

$$\frac{\partial(\rho\sigma_z^2)}{\partial z} + \frac{\partial(\rho\sigma_{Rz})}{\partial R} = \rho K_z$$

- For a 2:1 radial:vertical velocity dispersion ratio

$$\sigma_{Rz} \simeq (\sigma_R^2 - \sigma_z^2)\frac{z}{R}$$

- Radial gradient set by disk scale length H

$$(\rho\sigma_{Rz})_{,R} \simeq (\sigma_R^2 - \sigma_z^2)\frac{2z}{HR}$$

- Vertical force due to halo is

$$F_h \frac{z}{R} K_R \simeq F_h \frac{z}{R^2} V_{\rm circ}^2$$

- Ratio halo K_z : 'fake tilt force'

$\sigma_z \approx 40$km/s
$V_{circ} \approx 200$km/s
$H \approx R/2$

$$F_h \frac{V_{\rm circ}^2}{4\sigma_z^2}\frac{H}{2R} \simeq F_h$$

Leiden Observatory

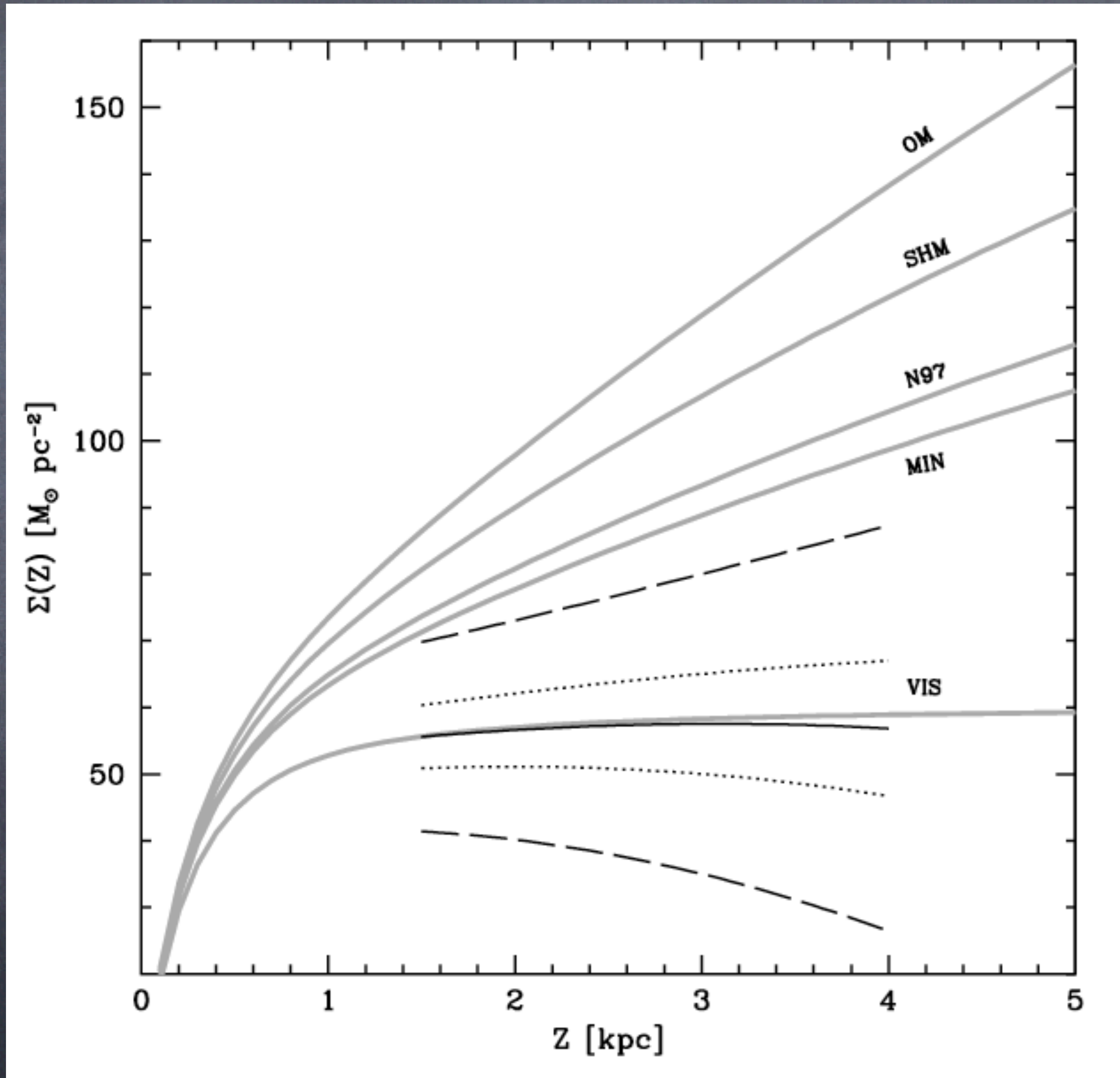
Universiteit Leiden

Moni Bidin et al. 2012

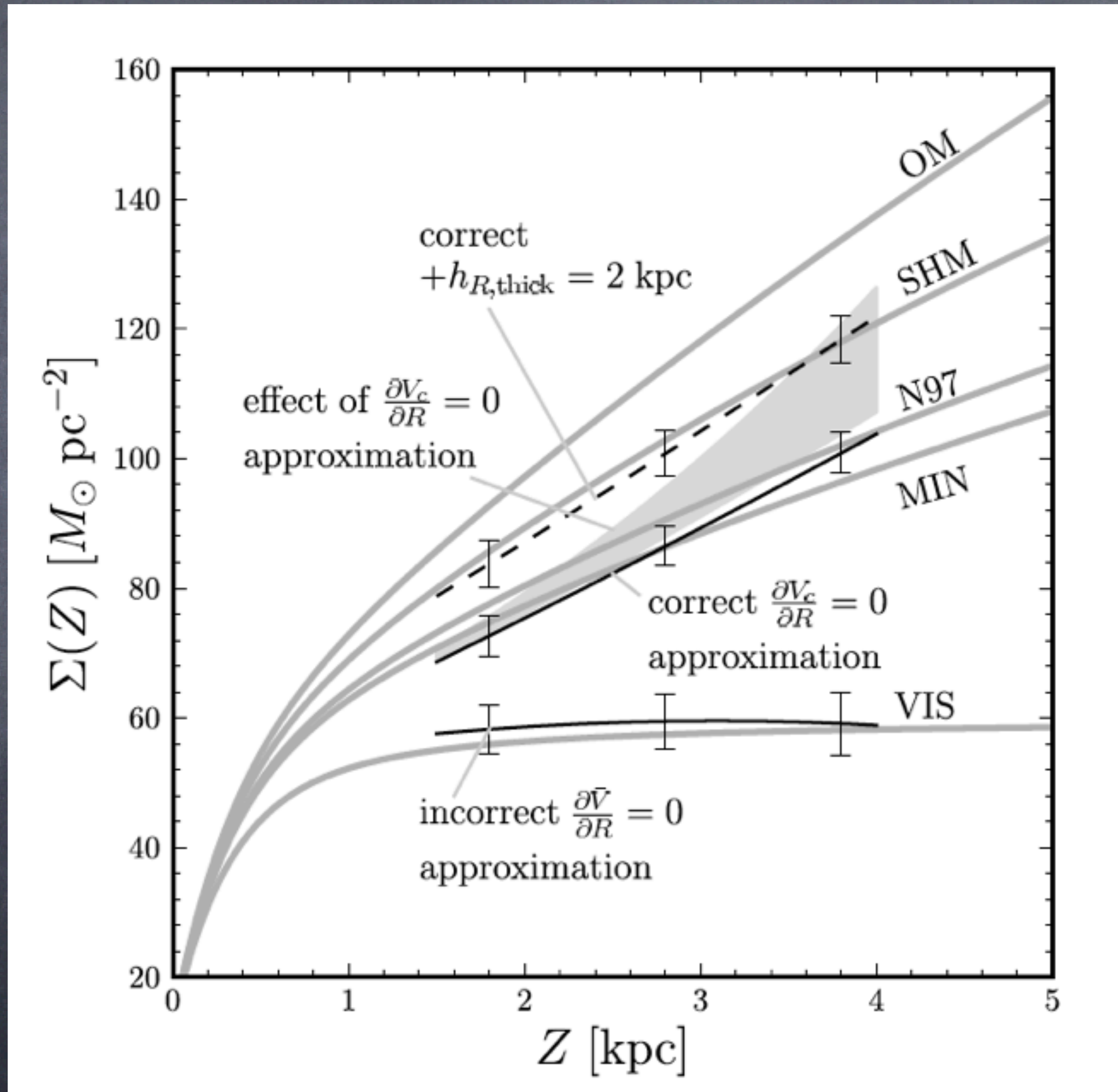
Kinematical and chemical vertical structure of the Galactic thick disk[1,2]
II. A lack of dark matter in the solar neighborhood

- Study of the vertical kinematics using red giant stars up to 4kpc from the disk plane.
- Large number of assumptions on missing terms; reasonable for disk population but uncertain
  - criticised by Bovy & Tremaine (2012)

Bovy & Tremaine 2012

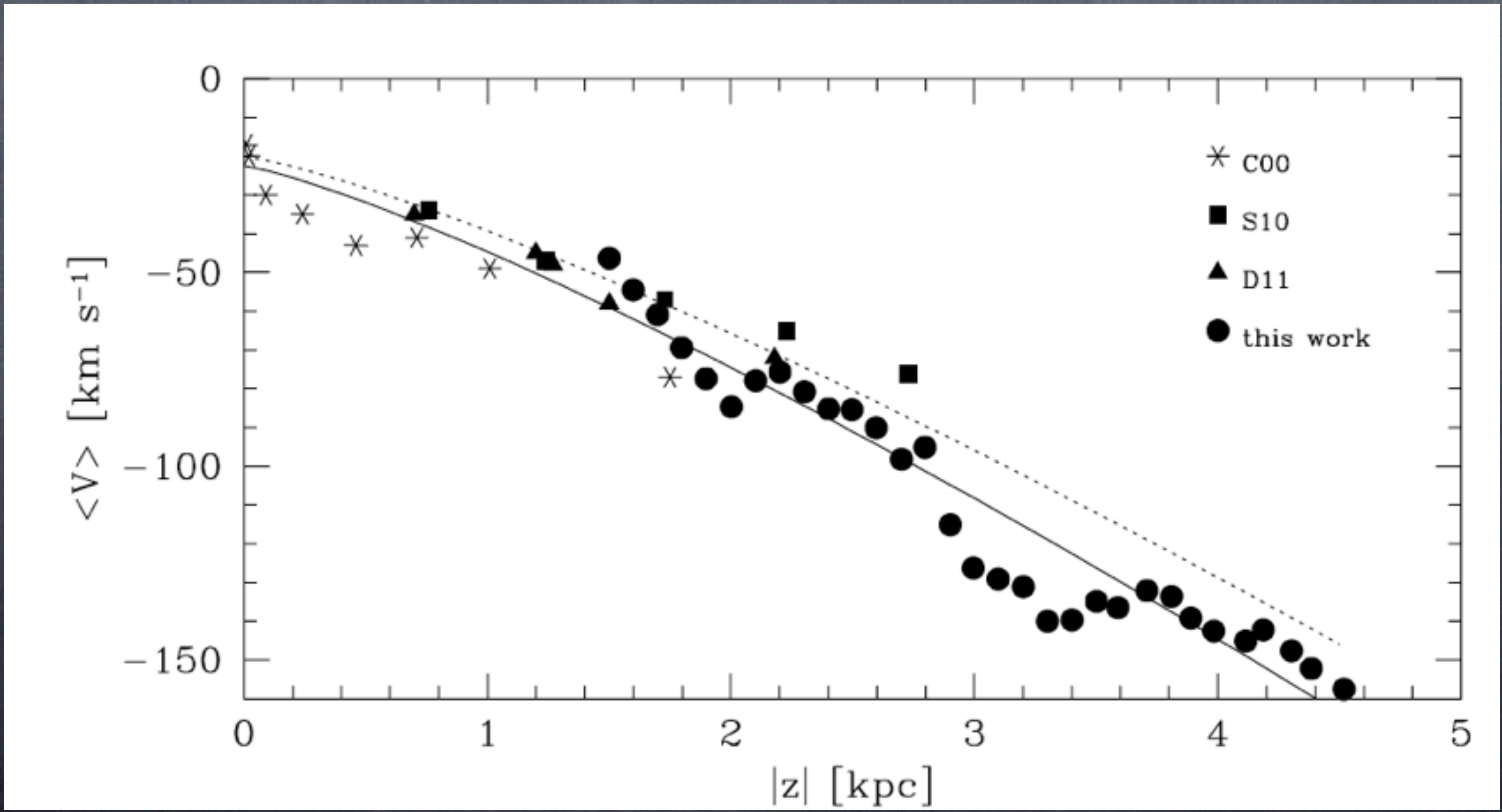


Bovy & Tremaine 2012



Moni Bidin et al. 2012

- Rotational velocity profile from MB & al Paper I
- $v_{rot} < 0.5 v_{circ}$!   Are these disk stars?



Not discussed here

- Halo flattening: barely affects rotation curve, but increases local density
  - prolate halo would lower it
- Local substructure: could lead to higher or lower densities
- Overall dark halo structure (size, extent, shape)

Summary

- Long history of measuring local DM density
- No convincing evidence for 'cold' DM component in the disk (as thin as a few 100 pc)
- Halo density derived from vertical kinematics unreliable:
  - velocity ellipsoids tilt, radial Poisson eq. terms
  - Needs a full picture of 3-D kinematics (Gaia!)
- Rotation curve decompositions lead to estimates of 0.005 - 0.01 $M_{\odot}/pc^3$.

Leiden Observatory

Universiteit Leiden