Tracing the dark matter haloes of galaxies by modeling the observed HI distribution

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Dark Matter in the Universe

Collaborators:

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- Kanak Saha (IISc, now at MPIE)

and,

- Lynn Matthews (MIT-Haystack, U.S.A.)
- Leo Blitz, and E. Levine (UC Berkeley, U.S.A.)

Outline of talk:

- The vertical structure of galactic disk
- Our model : stars+gas+in the field of dark matter halo

Results:

- Radial density profile & vertical shape of dark matter haloes

  M31 , UGC 7321, the Galaxy – haloes show large variation

- Shape of halo in disk plane

  → The Galaxy halo is lopsided & elliptical

Background:

In a typical spiral galaxy, like our Galaxy

- stars ~ 90 % of visible mass,
  interstellar gas ~ 10 % - HI, H_2 gas
  -- due to its lower dispersion, gas important for dynamics

- HI gas extends to ~ 2-3 x stellar disk -- hence HI is an
  excellent tracer of dynamics in outer regions

- Disk supported in plane by rotation --- gives M_{total} (R) → applied to many galaxies
  e.g., NGC 3741 (to 40 R_D), Gentile et al. 2007

- Rotation velocity observed ~ constant to farthest radii

  → Existence of a dark matter halo

- Dark matter dominates in the outer parts :

  Density and shape of halo?? Not well-known

- Important clue provided by vertical structure of disk

  -- underutilized so far

  -- we use this → get shape of halo

Tracing the dark matter haloes of galaxies: by modeling the HI gas data

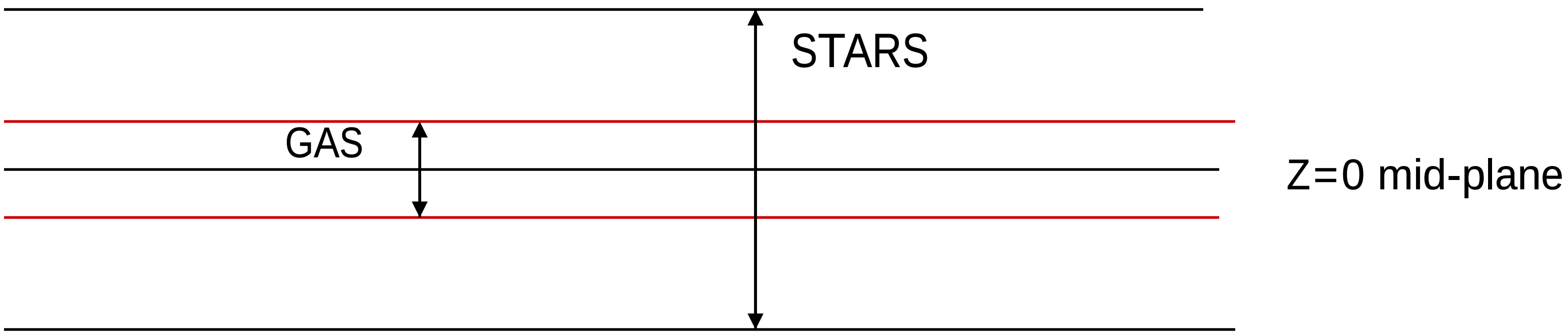
- Disk supported vertically by pressure
  Balance of self-gravity and pressure → thickness

- Solve Poisson equation and the force equation
  together for a self-consistent solution.

- A one-component gravitating isothermal disk –
  classic paper (Spitzer 1942) : $\rho(z) \sim \text{sech}^2 \, z/z_0$

- Real galaxy consists of stars and gas: our model
  -- gravitationally coupled, embedded in the DM halo
  (Narayan & Jog 2002, A & A, 394, 89)

Vertical Structure of A Real Galactic Disk:



-- Stars and gas are coplanar, with z-extent much larger for stars

-- Gas has low dispersion: contributes more to vertical force near z=0

Vertical Disk Structure:

The equation of hydrostatic equilibrium along z for stars and gas & The Joint Poisson Equation -- are solved together. (+ Rigid halo)

Each component obeys:

$$d^2\rho_i / dz^2 = (\rho_i / \langle (v_z)_i^{\,2} \rangle) [- 4 \pi G (\rho_s + \rho_{HI} + \rho_{bulge} + \rho_{DM\_halo})]$$

$$+ 1/ \rho_i \, (d \rho_i / d z)^2$$

where [ ] – force term due to two disk components +bulge+halo

-- but different dispersion, hence different ρ_i (z)

- Solved the two coupled, second-order differential equations, numerically and iteratively ----
  Using $d\,\rho_i\,(z)\,/dz = 0$ and observed Σ_i as boundary conditions

- Simultaneously gives $\rho_i\,(z)$ for both stars and gas
  HWHM defines the scaleheight in each case

- Repeat procedure at different galactic radii to get results for vertical scaleheight vs. R , & compare with observations.

- The halo dominates in the outer galaxy, hence use observed HI scaleheights as constraint to probe the DM halo properties

Density Profile of Dark Matter halo in M31 (Andromeda)

(Banerjee & Jog 2008, ApJ, 685, 254)

Nearest large spiral galaxy, & gas scaleheights have been measured.

(only one of ~ 5 such cases)

Numerical scheme:

- Spiral Galaxy : central bulge, disk, dark matter halo (unknown)
- For different trial halo parameters, obtain rotation curve and scaleheights (R) from our model
- Compare with observations : to get best-fit halo parameters

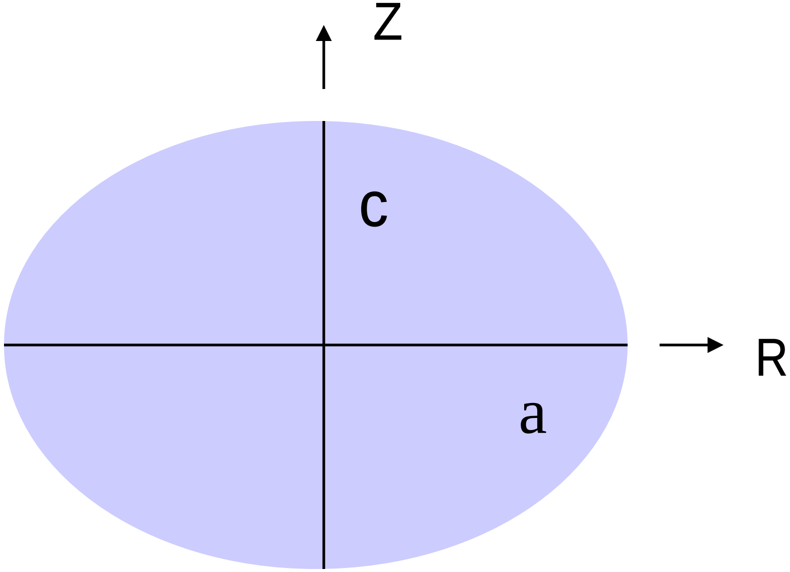
Two simultaneous constraints: Rotation curve → M (R), while scaleheight → ρ (z) – shape of halo

General four- parameter halo profile (de Zeeuw & Pfenniger 1988)

$$\rho\ (R, z) = \rho_0\ /\ [1 + m^2 / R_c^{\ 2}]^p$$

where $m^2 = R^2 + z^2 / q^2$ -- the surfaces of concentric ellipsoids

Four parameters: ρ_0 = central density, R_c = core radius,
q = axis ratio = c/a , p =density index



<u>Our aim is to find the best-fit values of these four parameters</u>

Scanned the 4-D parameter grid for the DM halo
to cover all realistic values:

Parameters	Range	Step-size
ρ_0 (M_{sun} pc^{-3})	0.001 – 0.15	0.001
Rc (kpc)	1 - 35	0.5
p	1 - 2	0.5
q	0.1 - 1	0.1

For each p,q pair, a grid of ~ 150 x 70 ~ 10000 points scanned

(Banerjee & Jog 2008)

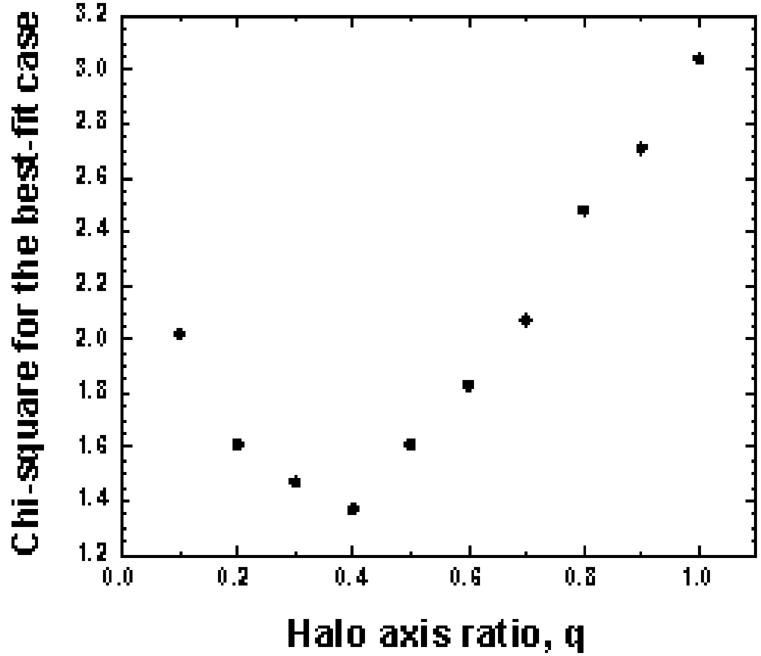
Match the results with constraints :

1. For each grid point, calculate rotation curve & match with the observed curve

2. Locate grid-points showing reduced $\chi^2 < 1$ (~ few 100 points)
--- for each of these, calculate the vertical scaleheights for HI gas in (from our model) and match with observed gas data

The minimum of the chi-square determines the best-fit DM halo parameters.

χ^2 for best-fit (for each q) vs. q, vertical-to-planar halo axes ratio



Lowest χ^2 for q=0.4 → oblate halo - distinct from spherical case.

P=1 (isothermal), ρ_0 = 0. 011 $M_{sun}\,pc^{-3}$, R_c = 21 kpc (~ 4 R_D)

(Ratio agrees with rotation curve studies)

M31 : Surprisingly flattened oblate halo, q=0.4

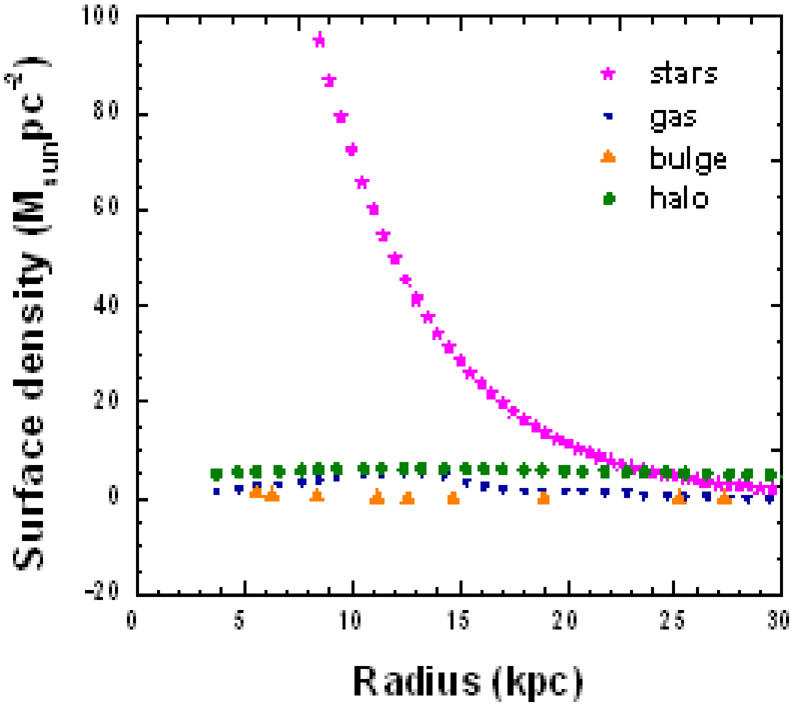
- Cosmological simulations (Bailin & Steinmetz 2005, Bett et al. 2007) give a range 0.4-0.8, & 0.4 is at the most oblate end (not typical !)

  → either M31 is an unusual galaxy
  → or more likely, simulations need additional physics such as effect of baryons – as confirmed by Read et al. (2008)

- Flat halo for M31 also from kinematics of giant stellar stream
  - Ibata (2008, personal communication)

Discussion:

1. Vertical structure set by surface density in disk and halo (within same height)



Halo dominates vertical structure beyond ~ 25 kpc (5 R_D)

Hence, DM halo constrained better if gas data available at R > 25 kpc.

2. HI gas dispersion plays a crucial role, need accurate values

Application to UGC 7321

Banerjee, Matthews & Jog, 2010, New Astronomy, 15, 89

- Applied this approach to UGC 7321 (LSB, superthin galaxy)
- LSB galaxies ~ 30 times less bright, but could be more numerous.

  Dark matter is more important (low-mass disk) .

- This technique ideal for studying such a galaxy.

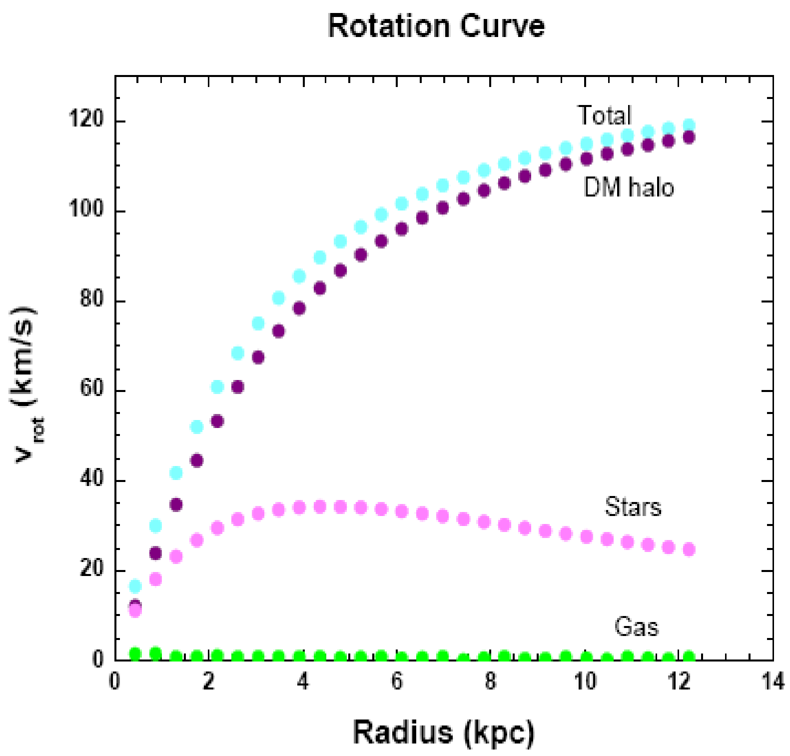
  Again, scanned 4-D grid.

Best-fit halo: Isothermal, spherical, higher density (ρ_0 = 0. 043 $M_{sun}\ pc^{-3}$)

Small R_c ~ R_d -- Different from HSB galaxies

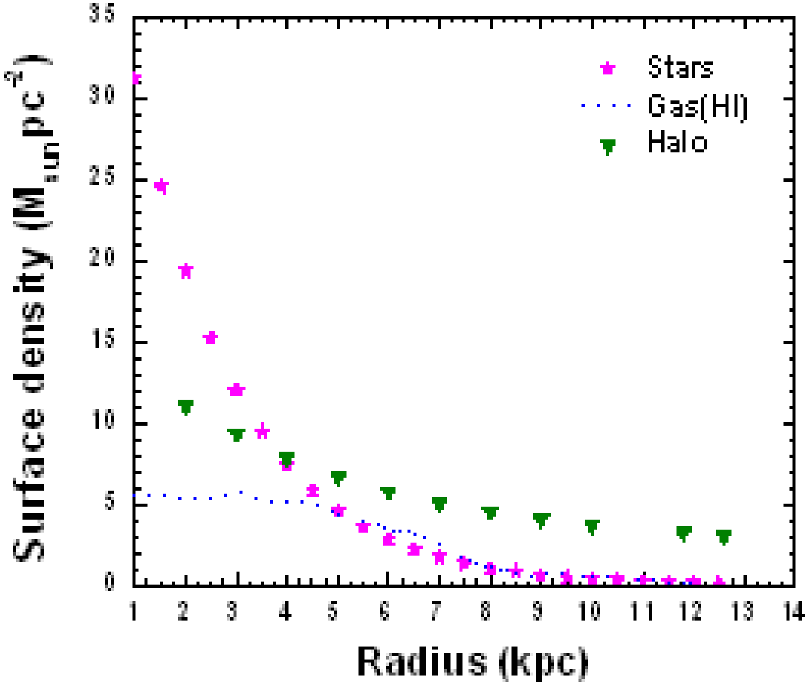
→ Dark Matter halo dominates at all radii

Rotation curve for UGC 7321: Contribution from DM halo, stars, and gas



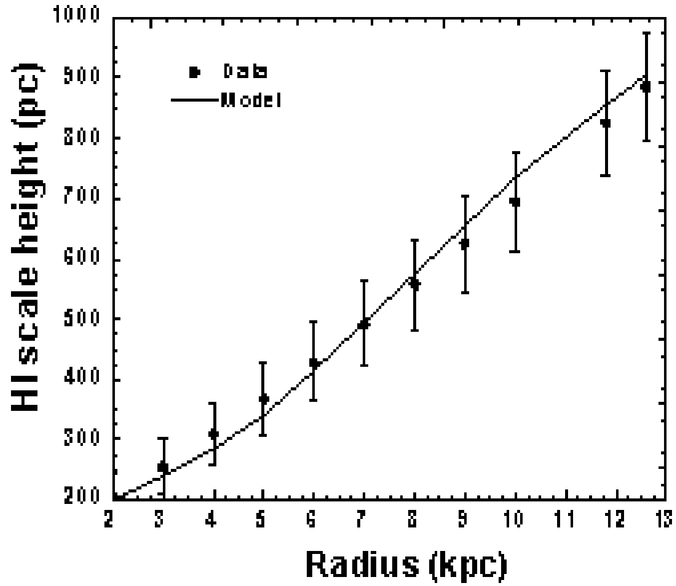
DM halo dominates dynamics at all radii in a LSB galaxy

UGC 7321 : surface density of stars, HI and DM halo vs. Radius



Interestingly, the DM dominates vertical dynamics already by 4 kpc (2 R_D) -- vs. 5 R_D in case of M31

UGC 7321: HI gas scaleheights vs. radius



P=1, q= 1

(Isothermal, spherical)

The best-fit requires high gas dispersion : can in turn explain why there is little star formation in these galaxies (hence LSB).

Unexpected result: origin of high gas dispersion in a LSB is a puzzle

Our work underlines the potential of this approach for further systematic study of the dark matter halo parameters

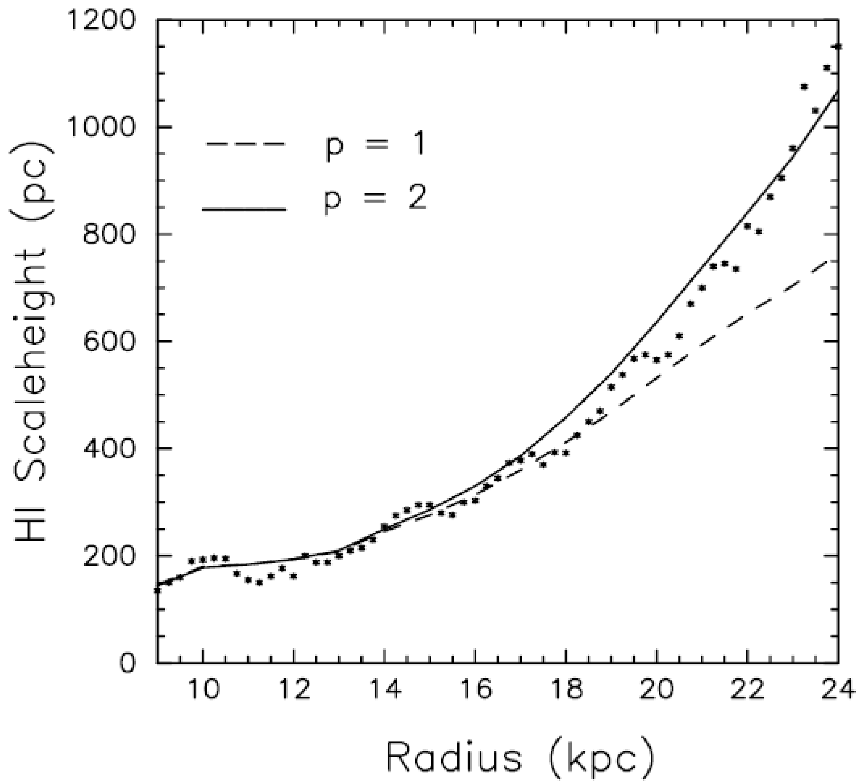
-- in different galaxy types

- M_{disk}/M_{halo} (R) , gas dispersion, vertical shape of halo
  → crucial for vertical HI thickness

- Need outer-galactic HI scale height data & gas dispersion
  -- remains challenging task (Sancisi & Allen 1979)

Earlier applied to the Milky Way Galaxy

(Narayan, Saha & Jog 2005, A & A, 440, 523)



Best-fit p=2 : to explain the gas flaring

Striking Result: **halo density as 1/R^4** → Total halo mass ~ 3.2 x 10^{11} M$_{sun}$ (<100 kpc)
~ Agrees with studies on satellite motions etc → (4– 8 x10^{11} M$_{sun}$) but at lower end of range

New HI data (Kalberla et al. 2008) gives less average flaring, needs to be modeled

Shape of the halo in the galactic disk plane (b/a): Less-explored topic

- Axisymmetry (a=b) is generally assumed for simplicity
- While cosmological simulations give tri-axial shapes ($a \neq b \neq c$)
- Measurement of halo potential in disk plane give low ellipticity ~0.045, from near-IR Fourier analysis for disk asymmetry (Rix & Zaritsky 1995)

We have studied this for the Milky Way Galaxy:

Recent detailed LAB (Leiden-Argentine-Bonn) HI survey of the Galaxy shows huge asymmetry in scaleheights in the N and S (thicker in the north)

→ We explain this as arising due to effect of a distorted halo

Distorted dark matter halo → affects the vertical disk distribution

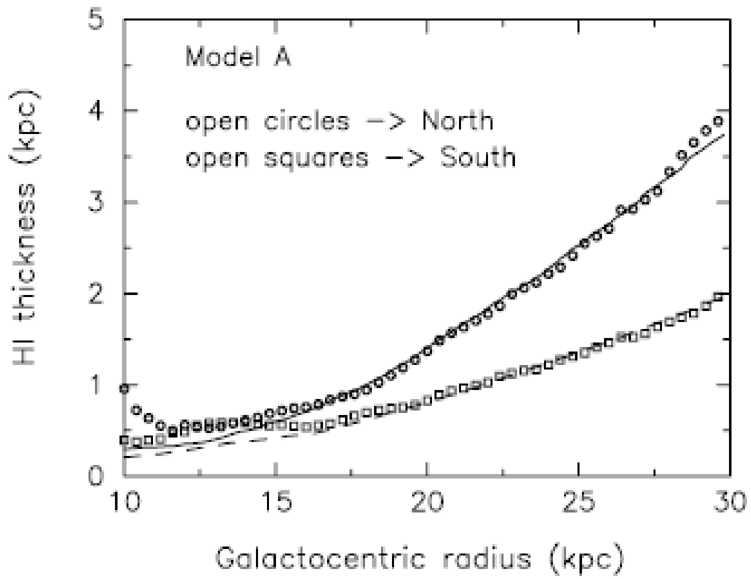
(Saha, Levine, Jog & Blitz 2009, ApJ, 697, 2015)

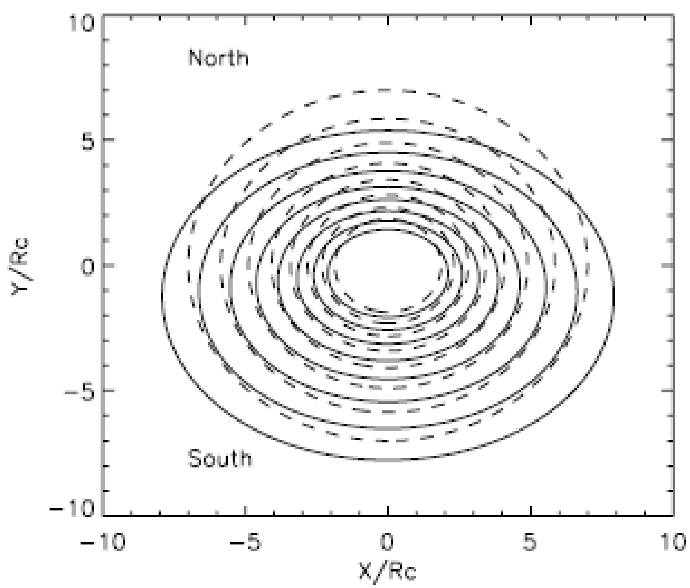
- Start with the DM halo (Narayan et al. 2005)
- consider distortion of type m=1, m=2
- calculate scaleheight (R,Φ) by solving Poisson equation plus equation of hydrostatic equilibrium at each point in 2-D plane & match with data

→ Gives a lopsided, and an ellipsoidal DM halo for the Galaxy

lopsided : m=1, ellipsoidal : m=2

(e.g., Jog & Combes 2009, Physics Reports)





Result:

Lopsided DM halo (with 20% density amplitude)

which is also Ellipsoidal (18%)

Two are out of phase

Origin? Needs modeling.

Saha et al. 2009

Results for Dark Matter halo properties:

We modeled disk plus halo, and compared with rotation curve and HI gas thickness data: thus determine both density and shape of elusive dark matter halo

- M 31 : flattened (q=0.4), isothermal halo
- UGC 7321 : spherical, isothermal, compact & dense halo
- The Galaxy : spherical halo with density falling as $1/R^4$

➢ Thus, DM halo profile in outer galaxy is not universal.

Contrary to cosmological simulations (Navarro et al. 1997):
--in addition to cusp/core problem with NFW profile at low radii

Promising approach :

- Can model HI gas in different types of galaxies
  to obtain DM halo properties (need HI data in outer disks)

- Useful probe for DM halo parameters, which provide important
  constraints on galaxy formation and evolution