# Vertical Structure and Dynamics of Galaxies

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And

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# Outline of talk:

- Introduction :
  Physical properties of a spiral galaxy
- Main problems about the vertical structure
- Details of our work
- Current work in related topics

# Background:

Our Milky Way is a typical spiral galaxy - The Galaxy

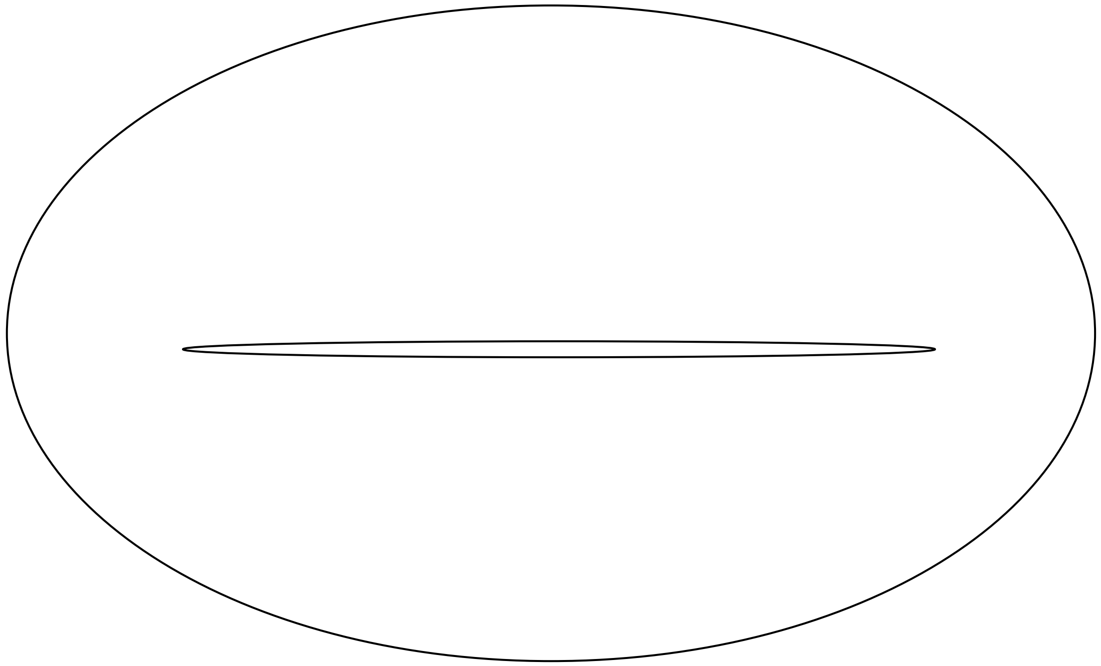
- Most of the visible mass is in the galactic disk --- typical radius of stellar disk ~ 12 kpc (1pc~ 3 light yr)
  - e.g., The Sun is at R=8.5 kpc from centre
- Disk is thin : $z / R \sim 1 / 30$
- stars ~ 90 % by mass
  interstellar gas ~ 10 % - HI, $H_2$ gas
  – But important for disk dynamics
- HI gas extends to ~ 2-3 x stellar disk -- hence HI gas is an excellent tracer of dynamics in outer regions

Disk supported in plane by rotation --- gives M ( R )

Rotational velocity observed ~ constant to farthest radii

➔ existence of a dark matter halo

Dark matter dominates in the outer parts



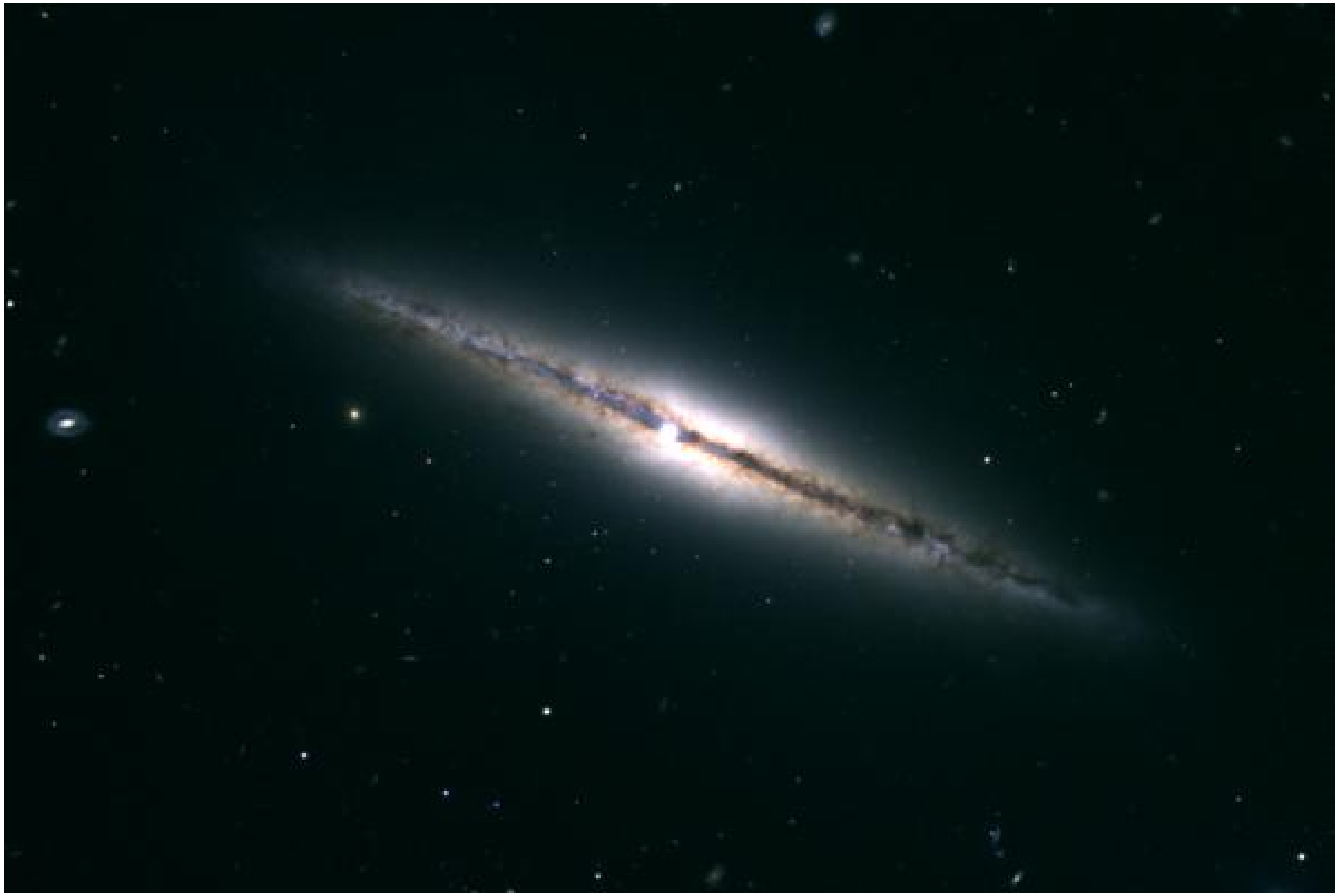
Size and shape of halo??

Outer edge of disk ??

NGC 628 - a typical spiral galaxy, seen face-on

NGC 891 – A spiral galaxy, seen edge-on

NGC 4565, another edge-on spiral galaxy



NGC 4013 – an edge-on spiral galaxy

## Vertical Mass Distribution - normal to the galactic plane

not received much attention theoretically

But, important as a tracer of galactic potential, and dynamical evolution.

A galaxy is a self-gravitating system, hence structure and dynamics are related.

What decides the disk thickness?

Disk supported vertically by pressure : Balance of self-gravity and pressure → vertical scaleheight

Need to solve Poisson equation and the force equation together for a self-consistent solution of $\rho$ (z)

## Vertical Disk Structure:

A one-component gravitating isothermal disk -
classic paper (Spitzer 1941)

Density distribution $\rho\,(z)$ prop. to $\mathrm{sech}^2\ z/\,z_0$
→ Gaussian for low z

HWHM of distribution = scale-height = $h_{1/2}$

However, the physical origin of thickness for stars & gas in a real galactic disk,
esp. their radial variation -- not fully understood.

→ **Motivation for our work.**

- In the past, gas gravity ignored – EVEN when studying the density distribution for gas !

- We show that even though gas is only 10% by mass
  - -- it is closer to the mid-plane (low dispersion)
  - -- hence it significantly affects the dynamics of both gas and stars.

- Thus, star and gas have to be treated jointly for correct vertical distribution --

  Main New Feature of our work.

  Also, we include the dark matter halo – esp. important in studying outer regions

# Problems on vertical structure and dynamics:
## Outstanding puzzles from observations

1. Nearly constant HI scaleheight in the inner Galaxy (Oort 1962, Dickey & Lockman 1990)
2. Stellar disk is claimed to be rigorously constant (van der Kruit & Searle 1981) -- Is this true ? Why ?
3. HI flares in the outer Galaxy – can use this to study the dark matter halo properties
4. $H_2$ gas is condensed into large complexes- can this cause "pinching" of matter around it? Can it be detected?

1. Constant thickness of HI in inner Galaxy –
(Oort 1962, & later observations)

Why is this a puzzle?

Gas scaleheight should increase with radius – when responding to gravitational potential of an exponential stellar disk

Vertical scaleheight is a measure of equilibrium between gravitational force and pressure.

**We propose**: An increase in gravitational force (due to inclusion of gas) can decrease scaleheight

----- studied this quantitatively

**Formulated a general treatment:**

**Narayan & Jog, 2002, A & A, 394, 89**

- Consider stars, HI and $H_2$ gas as three gravitationally coupled disk components, embedded in the dark matter halo
- Obtained a self-consistent vertical distribution and hence scaleheights for all three – at a stroke.
- HI and $H_2$ taken as separate components because they have different dispersions and radial distributions.

The equation of hydrostatic equilibrium along z for each
& The Joint Poisson Equation -- are solved together.

**Each component obeys**:

$$\frac{d^2\rho_i}{dz^2} = (\rho_i / \langle (v_z)_i^{\ 2} \rangle) [ - 4 \pi G (\rho_s + \rho_{HI} + \rho_{H2}) + d(K_z)_{DM} / dz ] + 1/\rho_i (d \rho_i / d z)^2$$

[ ] – force term due to three disk components +halo

- but different response and hence different $\rho_i$ (z)

Solved the above three coupled, second order differential equations, numerically and iteratively ----
Using $d \rho_i (z) /dz = 0$ and $\Sigma_i$ as boundary conditions
(New idea)

First for stars, then add HI, and then the full 3-component system

Simultaneously gives $\rho_i (z)$ for all components
Used HWHM to define the scaleheight in each case

Repeat procedure at different galactic radii →
& compare the scaleheight profiles with observations.

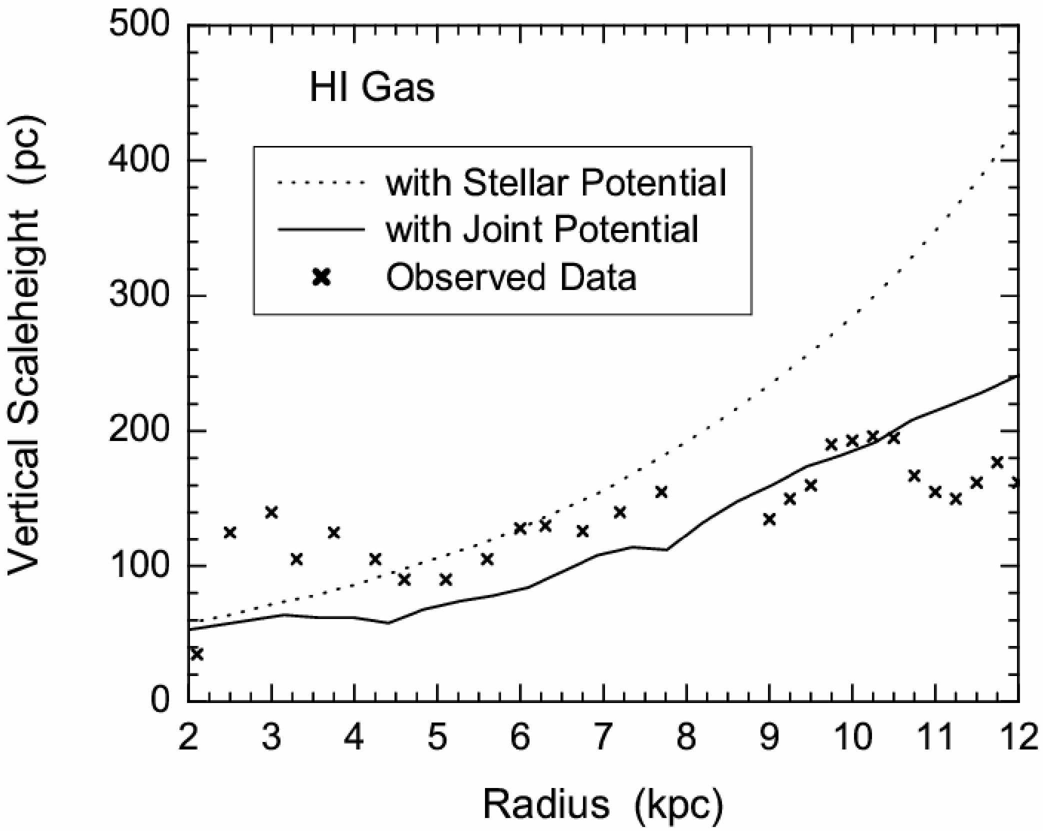
Used realistic input parameters from observations
for dispersion and surface densities of each component

# Results: Vertical scaleheight h1/2 vs. R

**HI Gas :**

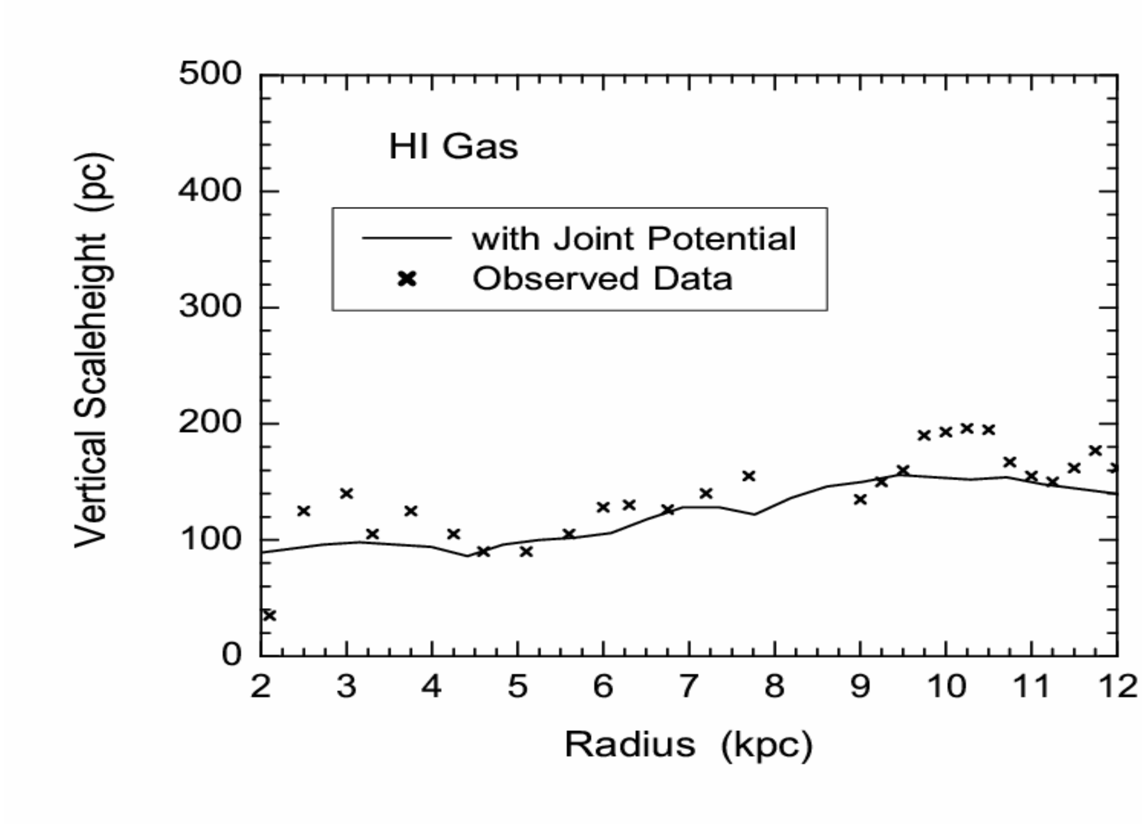
- On using the joint potential, scaleheight decreases, esp. at large R. Results explain the observed ~ constant scaleheight.

- In inner Galaxy combined gravity of HI + $H_2$ leads to decrease in scaleheight, while HI important at large R

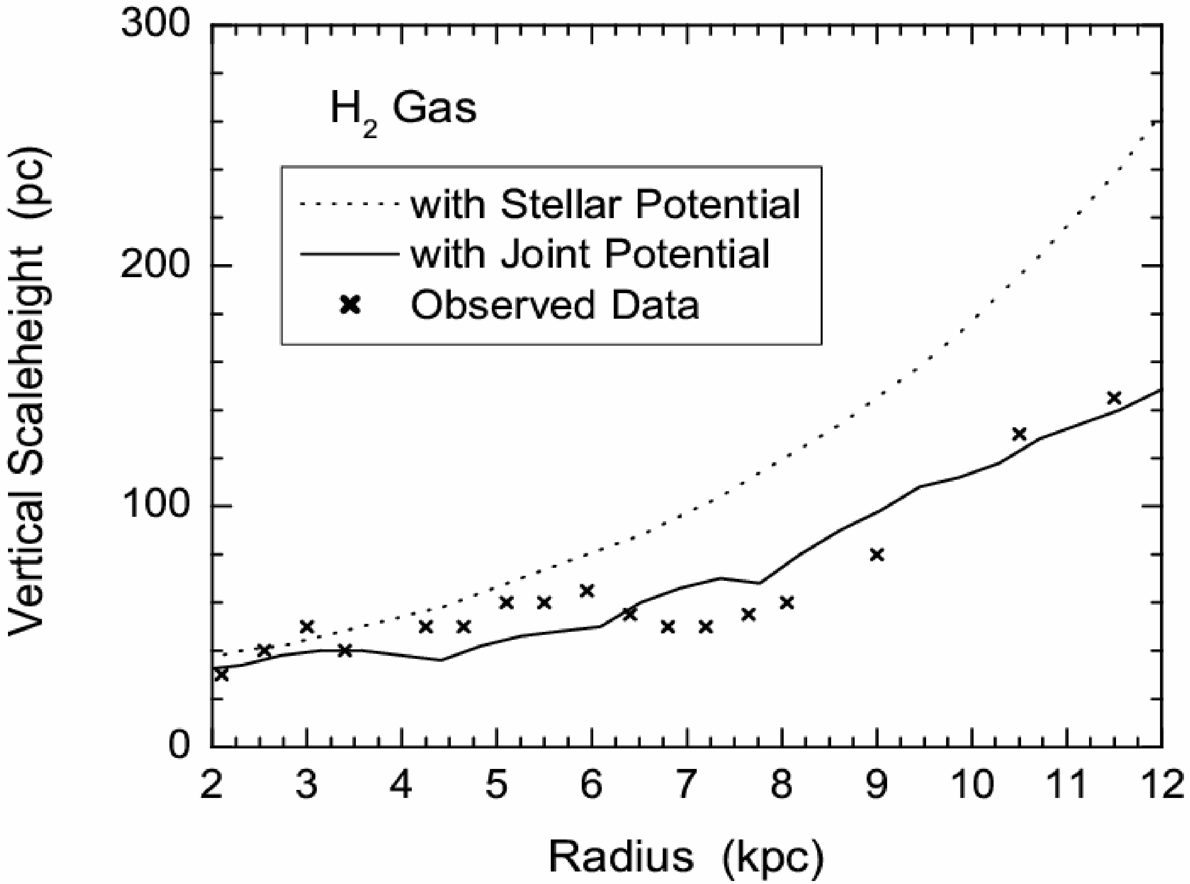


Joint potential gives better agreement with data.

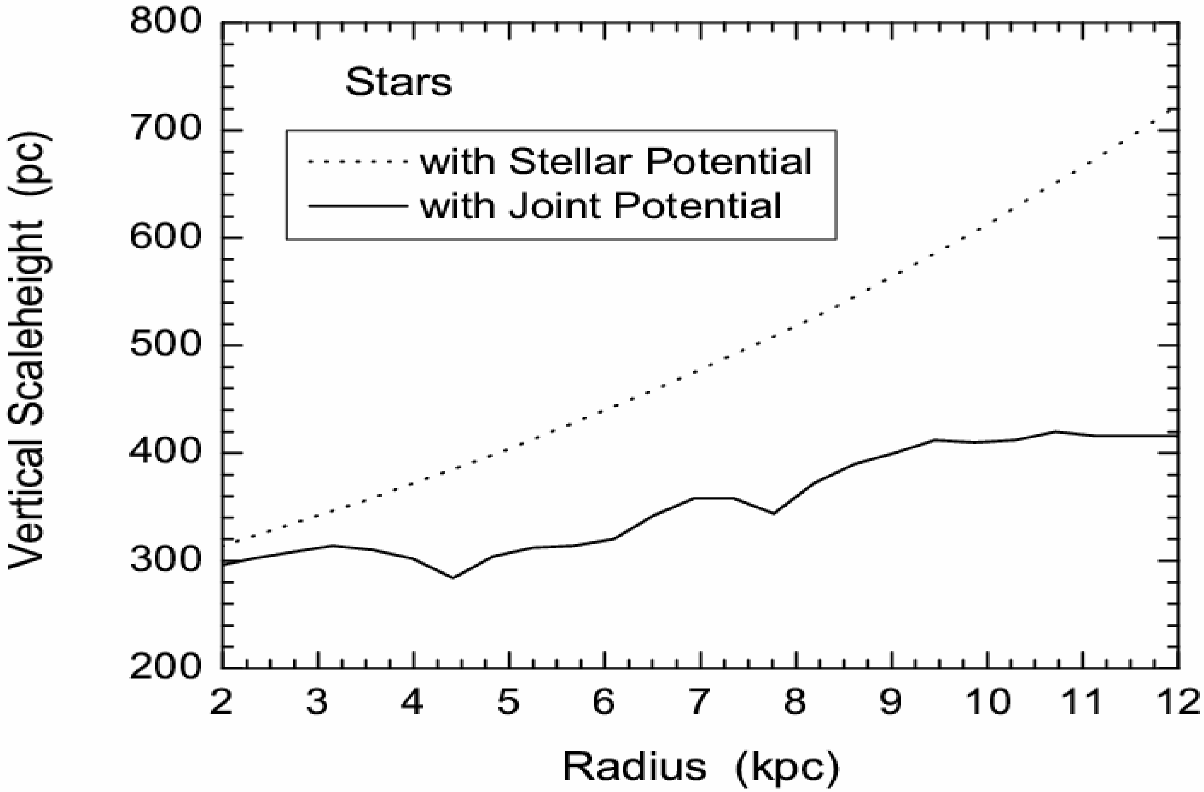
Dents are due to local peaks in $H_2$ distribution



Agreement much better with slight change in $C_{HI}$ (-0.8 km $s^{-1}$ $kpc^{-1}$)
-- higher dispersion in inner Galaxy due to larger SN rate



For $H_2$ , Joint Potential gives good agreement at all R.



Joint potential gives nearly flat curve that slowly rises with R.

- agrees with near-IR observations (Kent et al. 1991, Drimmel & Spergel 2001)

**Thus,**

- Inclusion of HI and $H_2$ gas gravity crucially important even in the vertical equilibrium of stars
- The multi-component approach cohesively explains observed vertical scaleheights of all three disk components (Stars, HI, and $H_2$) in the Galaxy

# 2. Stellar thickness in NGC 891 and NGC 4565

Two prototypical edge-on spiral galaxies,
Ideal for studies of vertical structure.
-- for which gas parameters are now known observationally.

Vertical Luminosity distribution of edge-on galaxies –
pioneering work by van der Kruit & Searle (1981).

From data analysis – in terms of composite $\mu$ – z plots –
concluded that stellar vertical scaleheight is CONSTANT with radius

Paradigm in galactic structure for 25 years
However, there is no physical explanation for this.

Flat scaleheight explained if $R_{vel} = 2R_D$

where $R_{vel}$ is the scalelength with which velocity dispersion falls off exponentially. (ad-hoc assumption)

Unrealistic given the various sources of stellar heating-
internal - scattering off clouds, spiral arms
external - tidal encounters with galaxies

**Relaxing the above constraint:**

$R_{vel} > 2\,R_D$ -- gives flaring of vertical scaleheight
& $R_{vel} < 2\,R_D$ -- gives tapering

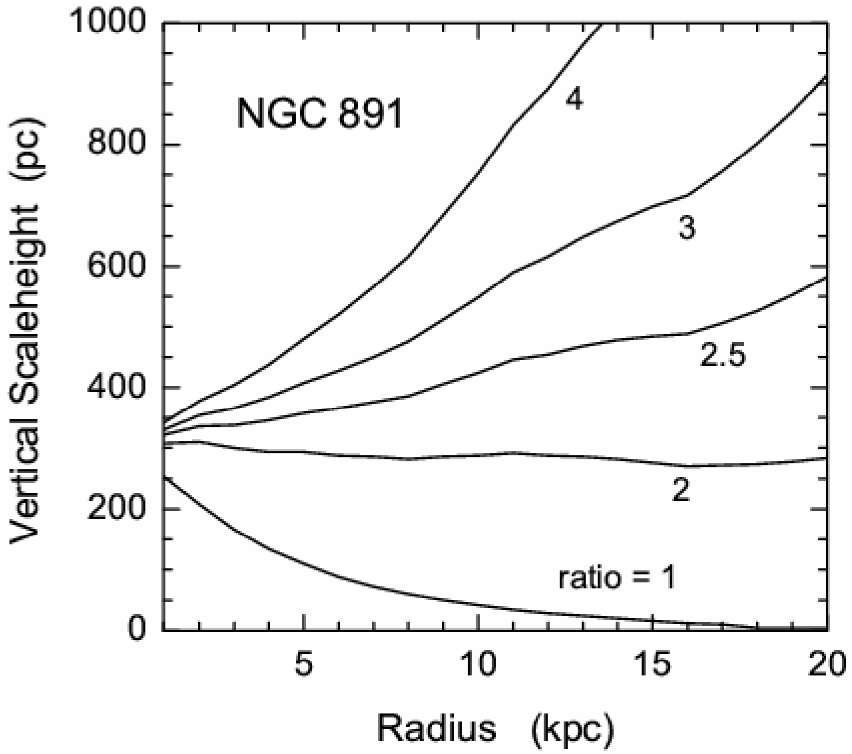
## Narayan & Jog, 2002, A & A Letters, 390, L35

- We obtained stellar scaleheight $h_{1/2}$ vs. R , where $R_{vel}/R_D$ treated as a free parameter - varied from 1 - 4
- Applied our model to NGC 891 and NGC 4565

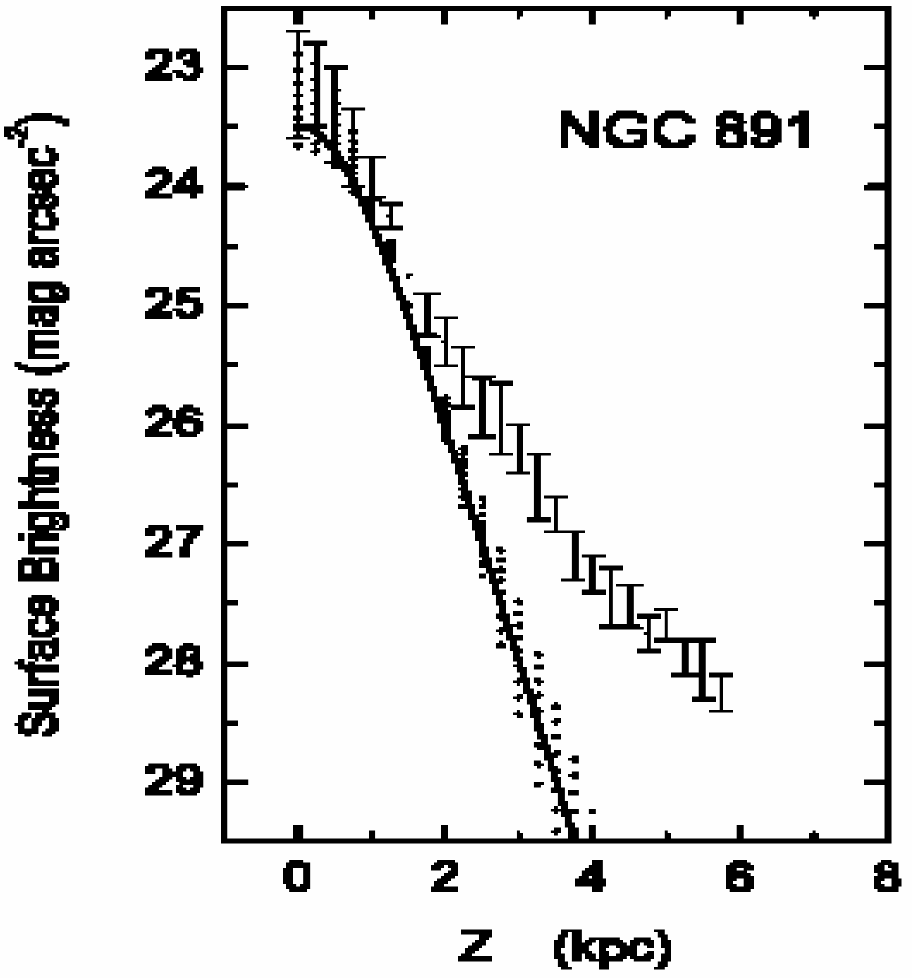
**Result:**

The scaleheight is NOT constant with radius, but shows moderate flaring of a factor 2-3 within optical radius

- agrees well with observations
  de Grijs & Peletier (1998)
  & van der Kruit et al (2005)



The stellar scaleheight shows moderate flaring for a general $R_{vel} / R_D > 2$ (Narayan & Jog 2002)



**Composite μ – z profile**: the spread is explained by a variation in vertical scaleheight with R by factor of 1.7

- Thus the ratio $R_{vel} / R_D$ ~ 2 - 2.5 for NGC 891

  Similarly, ~ 2.5 – 3 for NGC 4565

Interestingly, for our Galaxy can measure $R_{vel}$ and $R_D$
from stellar velocity dispersion vs. radius
(Lewis & Freeman 1988)

This gives: $R_{vel} / R_D \sim 3$ → similar to external galaxies.

Stellar disk flares by a factor of 2-3 :
Important result for galactic structure & formation

1. Rules out various spurious theoretical models for flat disk
2. can affect other studies which implicitly assume a flat disk

Three-component disk plus halo model developed- general
Future work planned (with A. Banerjee & L. Matthews)

To apply to Low Surface Brightness (LSB) galaxies – e.g. Malin 1
~ 30 times fainter but could be more common
So important to understand their structure & dynamics.

# 3. Back to the Galaxy – OUTER GALAXY

- HI scaleheight observed to rapidly flare beyond $R > R_0$
  (Kulkarni et al. 1982, Wouterloot et al. 1990, …etc)
  → Implies a sharp decrease in gravitational force

- Similar flaring in outer regions detected in few external galaxies
  (Olling 1996, Matthews & Wood 2003)

- In the outer Galaxy, the halo dominates

Our New Idea:

Used the observed sharp flaring of HI gas to constrain the shape and the density profile of the Dark Matter Halo.

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

- First possibility: If the stellar disk is truncated – (as claimed by van der Kruit et al. 1980's) → drop in force → gas flaring

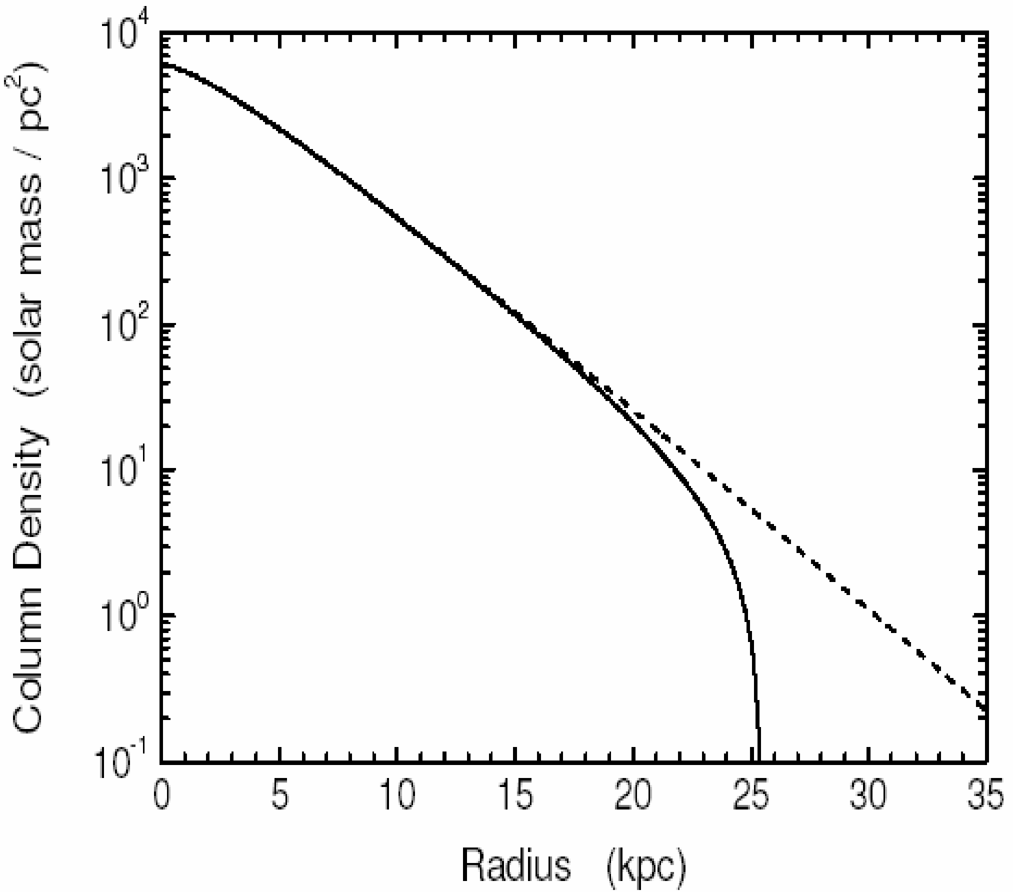
But Literature on Truncation – esp. value of $R_{max}$

NO CLEAR evidence for physical truncation
Narayan & Jog, 2003, A & A Letters , 407, L59

We argued that the "SHARP DROP" denotes a minor change in luminosity in outer disks (exaggerated on a log-normal plot)

This idea directly confirmed (2005) by extended , faint stellar disk observed in Andromeda and NGC 300 to ~ 2 the normal size
(Ibata et al., Bland-Hawthorn et al.)

Lorentz Centre workshop on "Outer disks: Truncated or not??"
Leiden, 2005 --- Invited talk on this work



A slight overestimate (0.5 %) in sky background results in a sharp drop (solid profile) → Spurious Truncation of Stellar disk !

## Narayan, Saha & Jog 2005 , A & A, 440, 523

Consider a three-component disk but THICK
in a dark matter halo (taken to be rigid as before)

Try a variety of halo shapes and density profiles
(de Zeeuw & Pfenniger 1988)

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

where $m^2 = R^2 + z^2 / q^2$ -- the surfaces of concentric ellipsoids
q = spherical, q < 1 oblate, > 1 prolate

p= 1 isothermal case (standard choice) – flat rotation curve

**New choice : p= 2 gives the best fit**
- density falls faster than isothermal → flaring of gas

The parameter space for density profile (p) , shape (q) scanned methodically

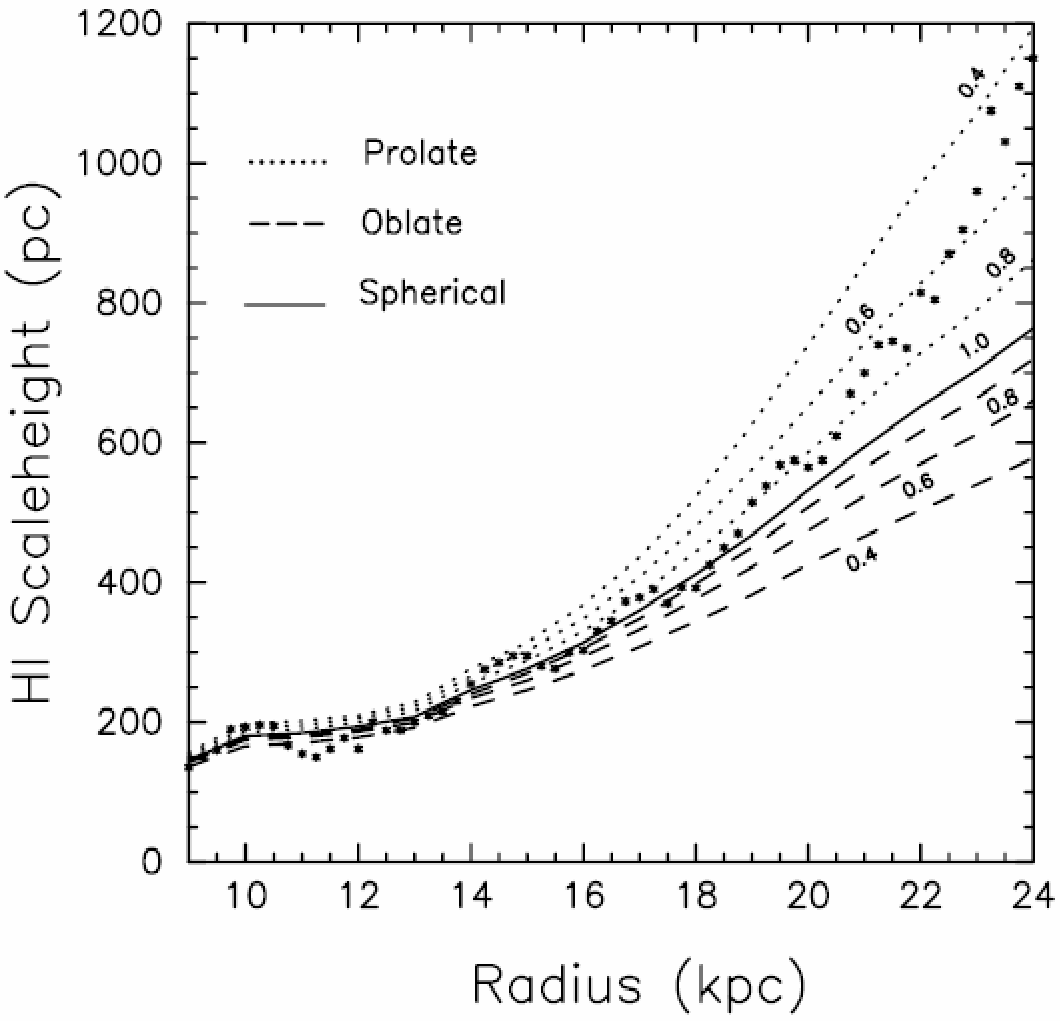
For each p, a realistic range of $\rho_0$ , $R_c$ is chosen (since values not known a priori) ---- 0.001 – 0.1 M_sun $pc^{-3}$ , 4- 15 kpc

A grid of ~ 50 x 100 ~ 5000 points scanned !

Vast range narrowed by the constraints :

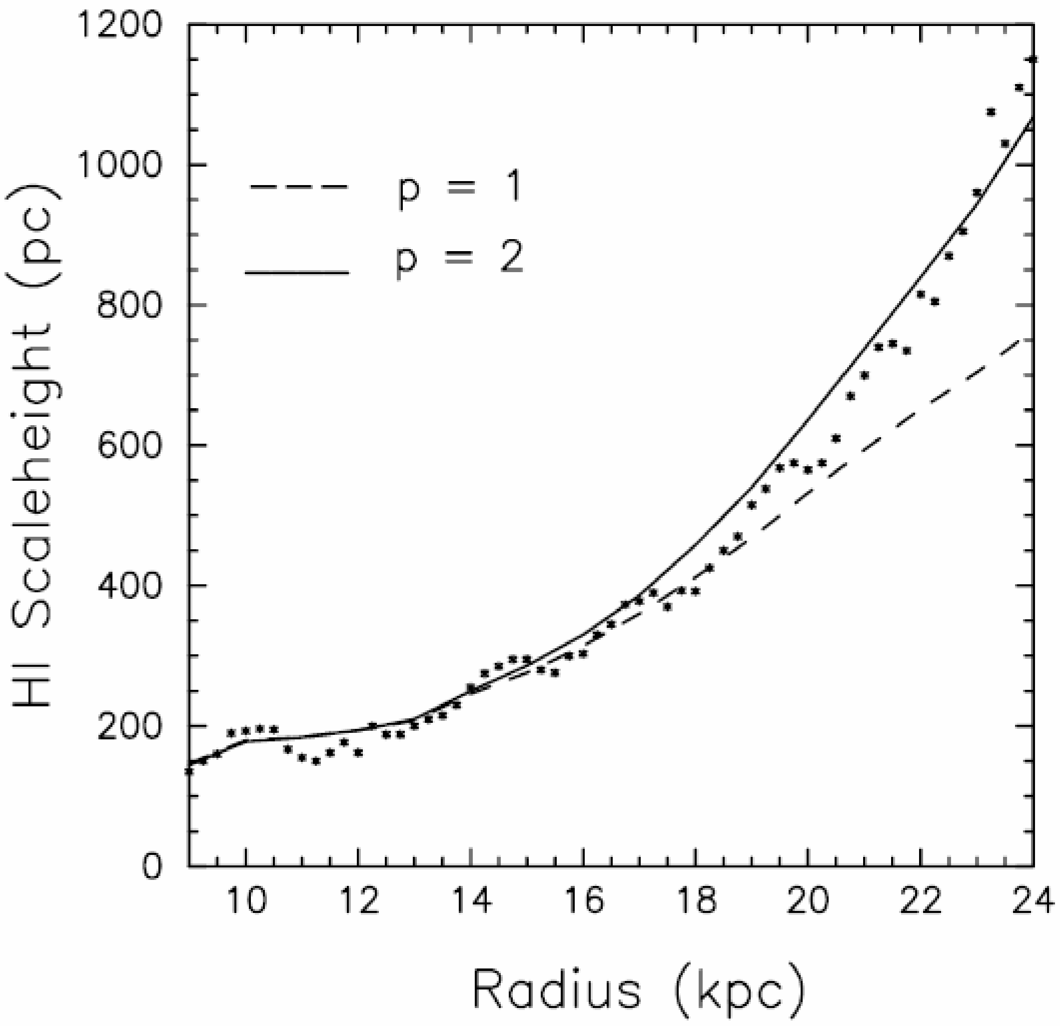
1. Galactic constants: V_rot = (27 +/- 2.5) R_0 (Kerr & L.Bell 1986)
2. Matching with the HI scaleheight vs. R (Wouterloot et al.)
3. Observed features of rotation curve (Honma & Sofue 1997)

Best fit obtained for p=2 (Different from isothermal case)
and $\rho_0$ = 0.035-0.06 M_sun $pc^{-3}$ , $R_c$ = 8 – 9.5 kpc

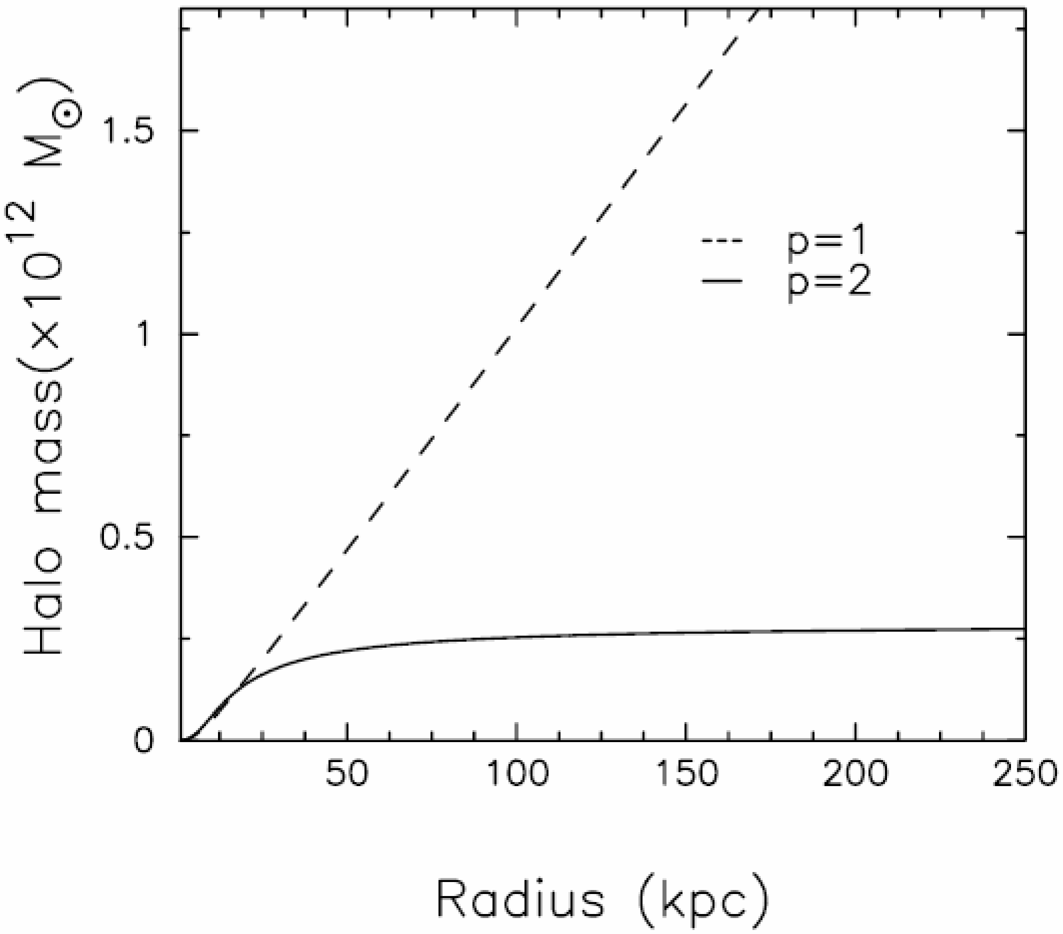


Neither spherical, oblate, or prolate shape of dark matter halo gives a good fit [ for $1/R^2$ density profile]

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



P=2 or Density of halo as $1/R^4$ gives the best fit
(vs. P =1 for isothermal case )



For p=2 , halo mass saturates to ~ 2.8 x $10^{11}$ M_sun
so that 90 % of total mass is within ~ 100 kpc

## Striking feature of Result : $p = 2$

- Density of dark matter halo $\rho$ proportional to $1/R^4$
  → leads to "finite" size halos
  with density falling to $10^{-4}\ \rho_0$ by ~ 100 kpc (90% of mass)
  Dark matter halo mass ~ $2.8 \times 10^{11}\ M_{sun}$
- Our result in agreement with independent recent studies – analysis of SDSS data on satellite motions (Prada et al. 2003)
- Important for galaxy formation and evolution

Thus, the observed flaring of HI gas is used to obtain important new information on the shape, mass and size of the Dark Matter Halo – which cannot be seen directly.

# 4. Vertical constraining around a cloud complex

**(Jog & Narayan 2001, MNRAS,327,1021)**

$H_2$ gas is self-gravitating and is condensed into massive, extended cloud complexes

With typical mass of ~ $10^7$ $M_0$ and size a few 100 pc

- seen in our Galaxy and external galaxies

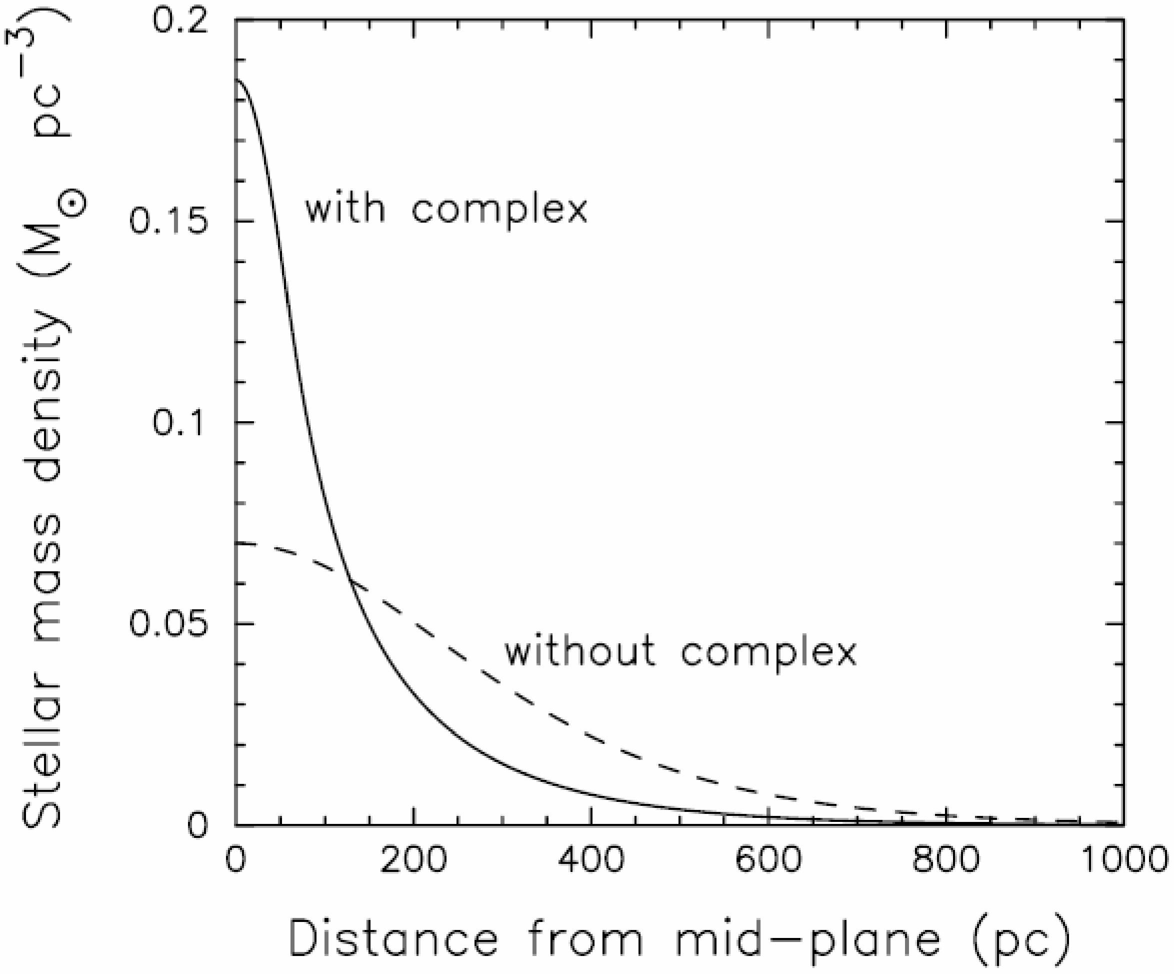
We note:

The average density ~ 6 times the Oort limit (local disk density),

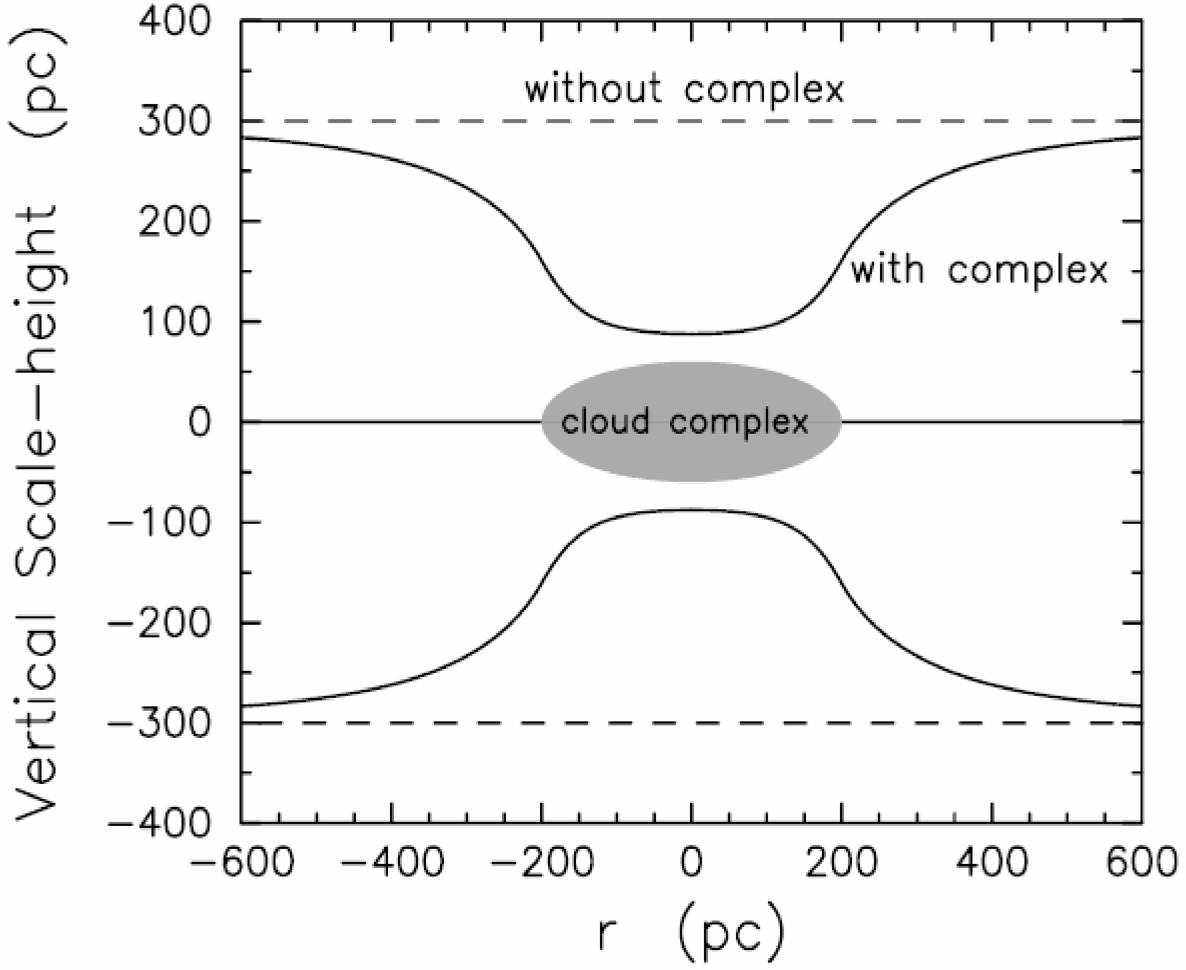
→ complex dominates the gravitational field around itself.

We calculated the redistribution due to field due to complex

→ results in reduction in vertical scaleheights by a factor of 1/3 around it --- effect seen upto a large distance of > 500 pc



In the presence of the complex, mid-plane stellar density increases by a factor of 2.8



Vertical “pinching” of disk around a cloud complex

- effect seen over a large radial distance

The net result of many such complexes is that:

1. The net galactic disk potential is distinctly non-uniform

   Separation between complexes ~ 1 kpc, so that the integrated effect could "cover" the entire disk

   An important new source of heating for stellar dispersion

   --- collaboration with Chris Flynn (Finland), and Arunima Banerjee (IISc)

2. The scaleheights of stars and gas show local corrugations -- as observed (Florido et al., Sicking)

# Current work on Warps in galaxies

The galactic plane is often twisted out of the mid-plane in outer parts

with a cos $\varphi$ (or m=1) vertical distribution

Warps - common, nearly all galaxies show this.

1. Asymmetric warps :

Proposed and studied the origin of these due to dynamical interference between m=1 and m=0 (bowl-shaped) modes

(Saha & Jog 2006, A & A, 446 , 897)

- naturally produces the variety of asymmetric shapes observed

Our results confirmed in N-body simulations on warps

(Revaz & Pfenniger, private communication)

## 2. Radius for onset of warps :

Saha & Jog 2006, MNRAS, 367, 129760)

Studied self-consistent disk response to a perturbation (by inversion of Poisson equation)

-- surprisingly the disk self-gravity resists response in inner regions, hence the net warps only seen beyond a radius of 4-5 disk scalelengths

-- exactly as observed (Briggs, Combes, Reshetnikov et al.)

References:

1. Jog & Narayan 2001, MNRAS,327,1021
2. Narayan & Jog, 2002, A & A, 394, 89
3. Narayan & Jog, 2002, A & A Letters, 390, L35
4. Narayan & Jog, 2003, A & A Letters , 407, L59
5. Narayan, Saha & Jog 2005, A & A, 440, 523
6. Saha & Jog 2006, A & A, 446 , 897
7. Saha & Jog 2006, MNRAS, 367, 1297