Dynamics of Galaxies: Effect of interstellar gas and dark matter halo

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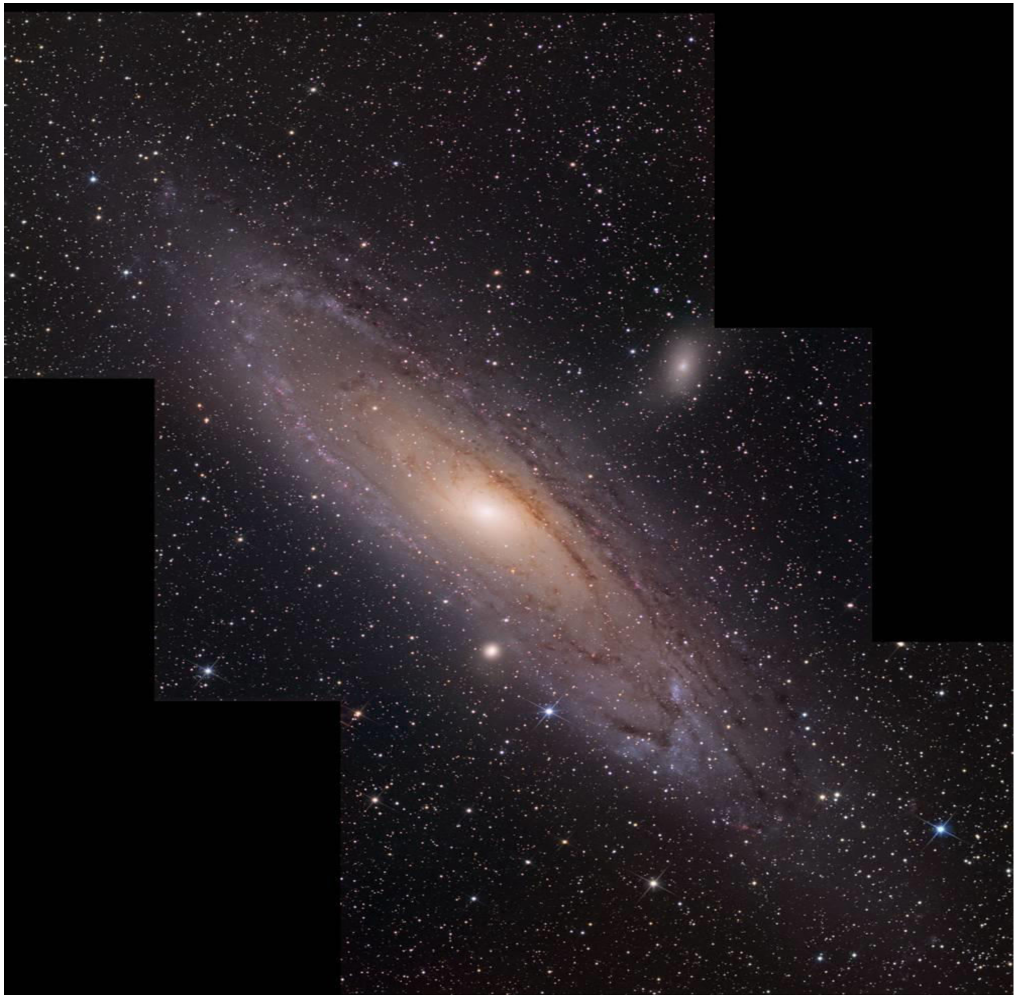
Astrophysics of Galaxies:

- Vast and active field, growth triggered by new observations
- Galaxies : Basic unit of mass distribution in the Universe
- Milky Way Galaxy – a typical disk galaxy
- Complex systems – multi-component, evolving structures

→ Challenge of Galactic Dynamics is to extract well-defined problems that can be modeled theoretically

Nearest neighbour : Andromeda Galaxy (M31)

- comparable in size to our Galaxy



From NOAO, USA

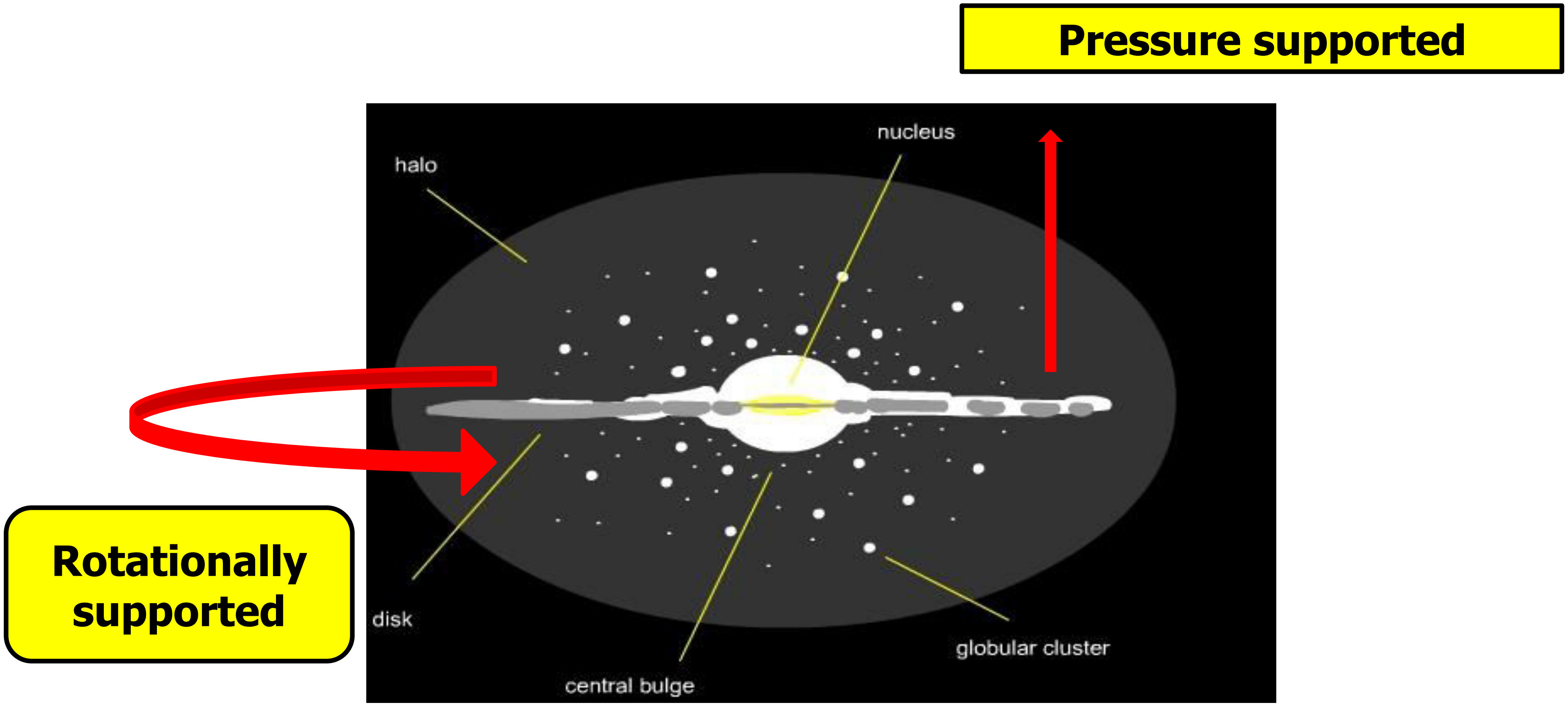
Face-on and Edge-on configurations of two spiral galaxies

NGC 628, a face-on galaxy
Outer rotating disk, spiral arms, central bulge

NGC 891 – an edge-on galaxy
→ thin disk

From NOAO, USA

Schematic structure of a typical galaxy



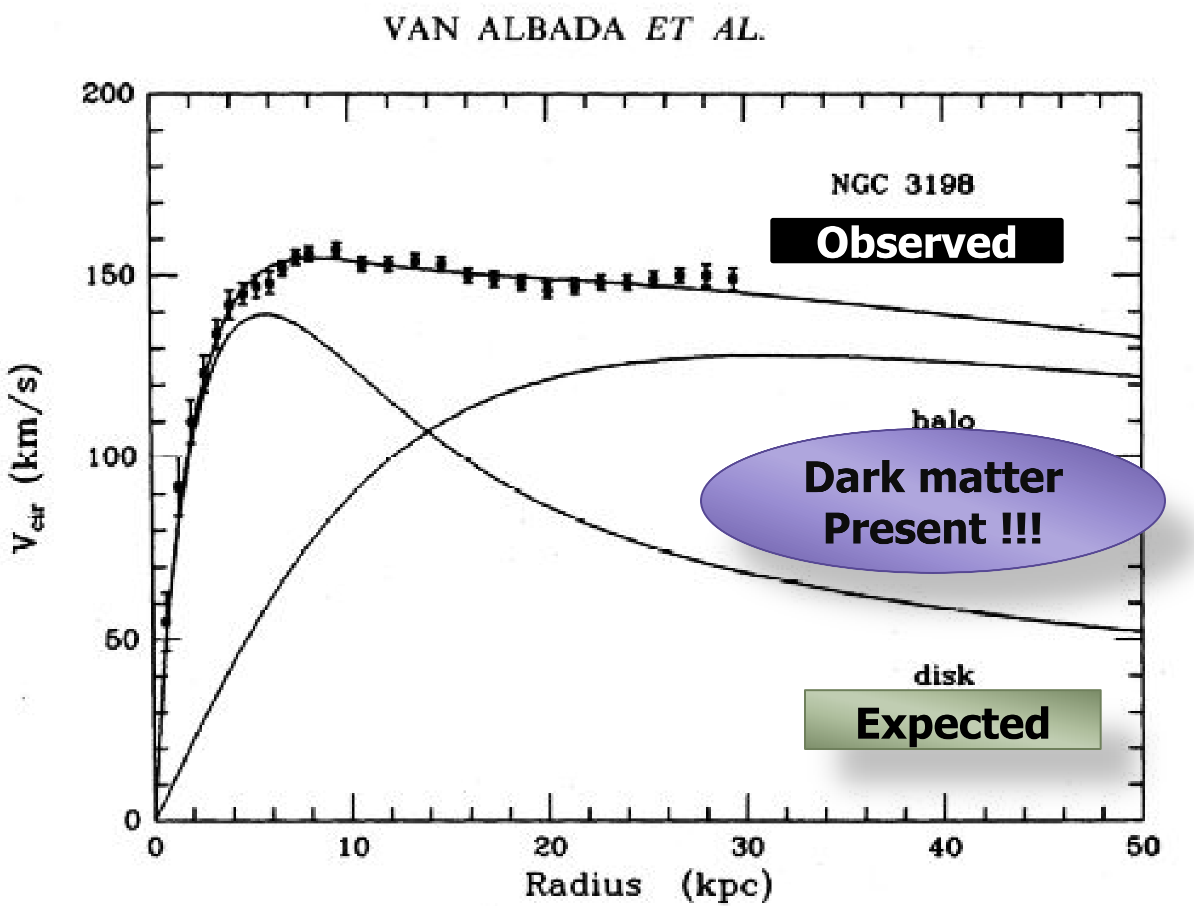
Thin disk consisting of stars and gas + central bulge

Dynamics separated into planar and vertical studies

Courtesy: S. Ghosh

Also, DARK MATTER HALO

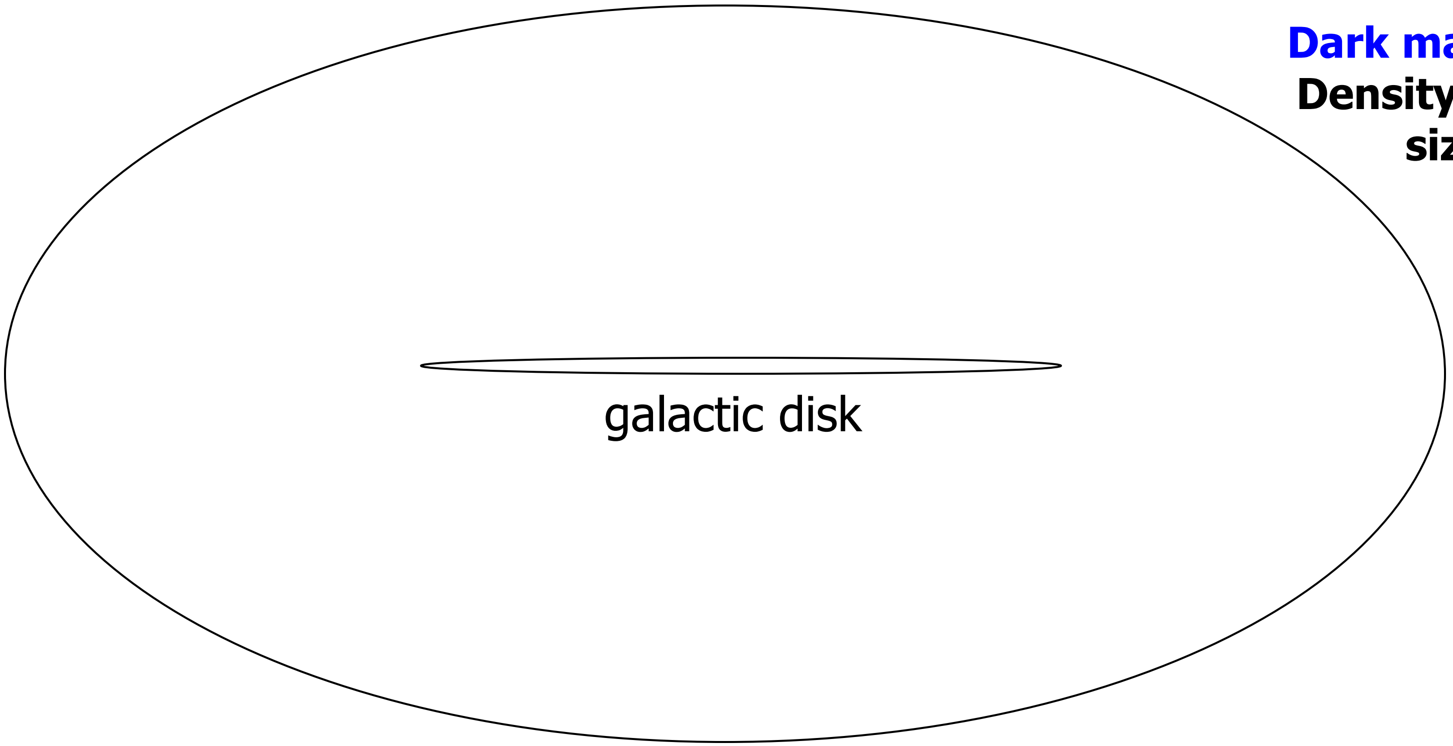
Existence deduced from observed rotation curve



PARADIGM SHIFT (1980's) : Dark matter halo dominates at large radii

Hence crucial for present-day structure & formation of galaxies

Schematic representation of a typical galaxy



Dark matter halo:
Density, shape & size ??

We have used observed Rotation curve and Vertical HI flaring in disk as two independent constraints → to model halo parameters

Physical properties of a spiral galaxy

- Visible matter - Stars (~ 90 % by mass), Interstellar gas (~10%),

& dark matter halo (more important at larger radii)

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

- Self-gravitating systems → hence structure and dynamics correlated

- Treat mean behaviour in terms of gravitational potential
  - different for each structural component - disk, halo

Important feature:

We have treated stars, gas and dark matter halo cohesively under their mutual gravitational interaction – more realistic.

This talk will highlight some of our work on:

Disk stability, spiral structure, vertical disk structure, DM halo profile.

Many thanks to my students (past and present) !

Soumavo Ghosh

Chaitra Narayan

Kanak Saha

Arunima Banerjee

R. Rathulnath

Gravitational Instabilities in a Two-Component Galactic Disk

(Jog & Solomon 1984, ApJ)

New Feature: Included gas on an equal footing with stars

- Stars and Gas treated as two fluids (with $C_g << C_s$) which are gravitationally coupled
- local, axisymmetric perturbations ~ $\exp[\,i\,(w\,t - k\,R)]$,

Dispersion relation:

stars-alone **gas-alone**

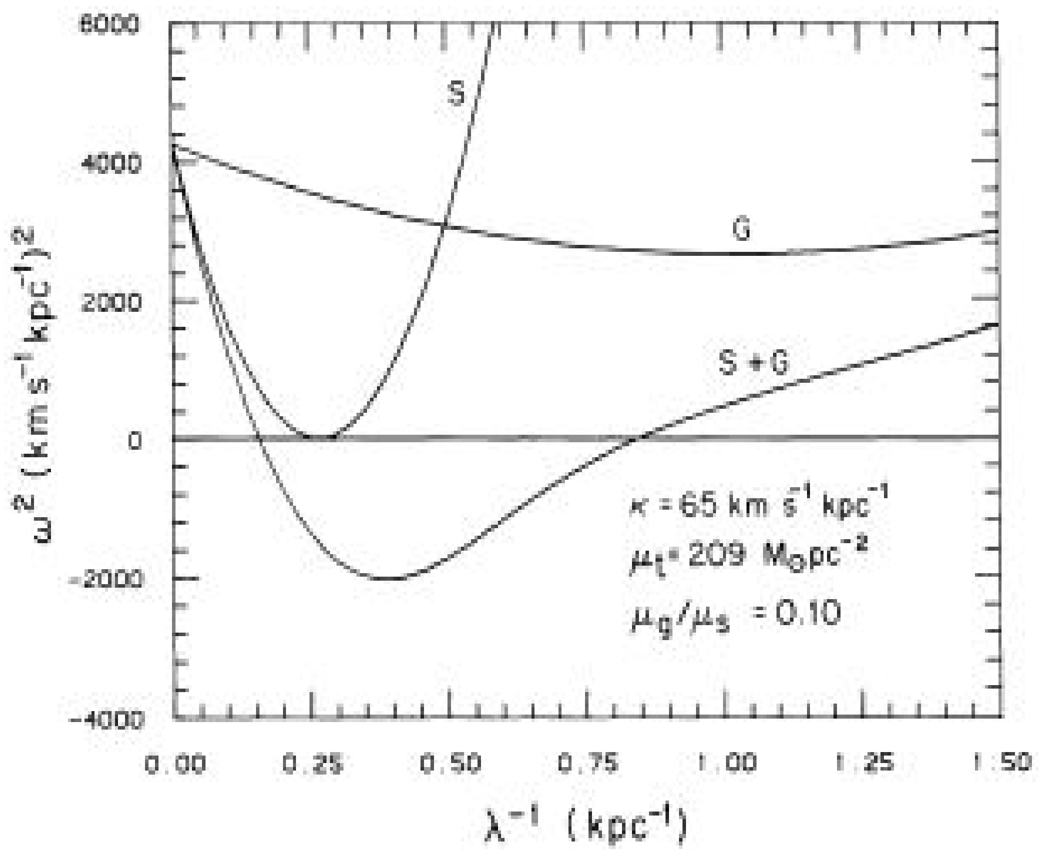
$$(w^2 - \kappa^2 - k^2 C_s^2 + 2\pi G k \mu_s)\,(w^2 - \kappa^2 - k^2 C_g^{\,2} + 2\pi G k \mu_g) - (2\pi G k \mu_s)\,(2\pi G k \mu_g) = 0$$

Results: Dispersion relation is general, displays rich physics.

Due to low Cg , gas contribution comparable, even if gas only ~15% by mass.

Two-Fluid gravitational instabilities in a galactic disk
(Jog & Solomon 1984, ApJ)

Unstable,
$W^2 < 0$



Stars-alone stable, addition of gas makes makes both unstable

Features of same k in both

Strong impact on the field → <u>Must include gas in dynamical studies.</u>

Widely cited, applied to other astrophysical disk systems.

Dynamical effect of gas on spiral pattern speed in galaxies

(Ghosh & Jog 2016, MNRAS)

- Many galaxies show two-armed global spiral structure : Assumed to rotate rigidly with pattern speed Ω_p in standard density wave theory

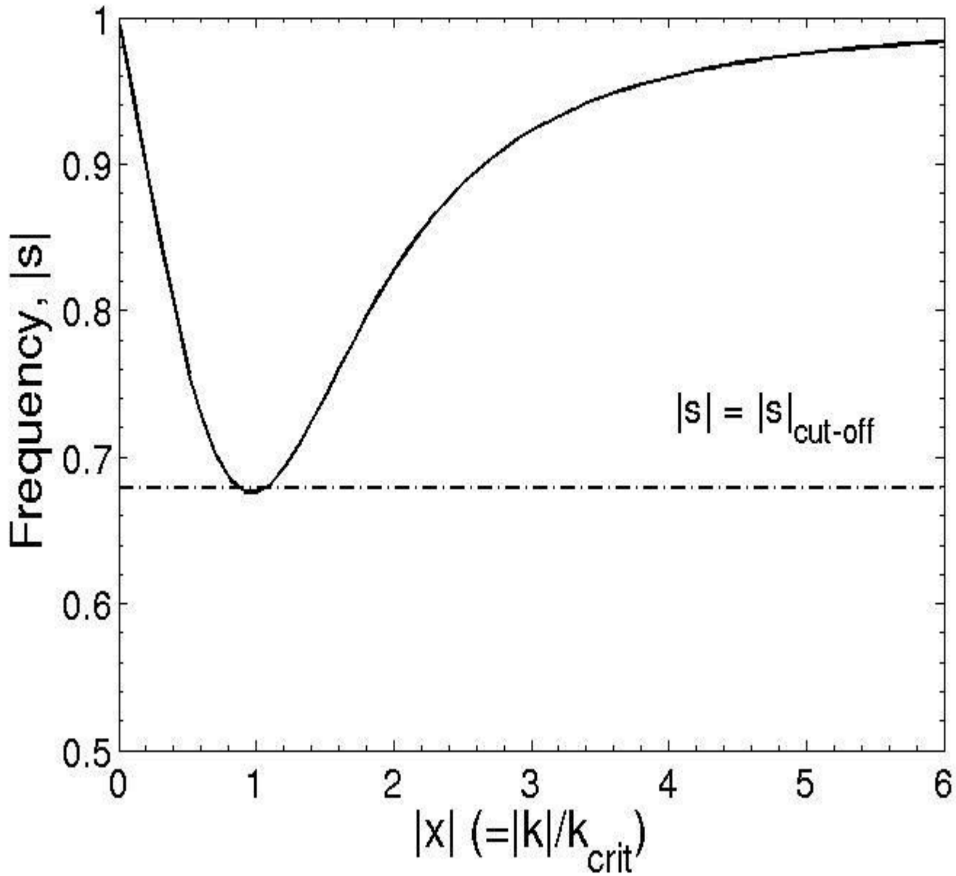
- Ω_p sets resonance points which play important role in disk evolution. Observational value is known for a few galaxies.

- We find that for observed Ω_p value, usual stars-alone case cannot support stationary wave.
- So we include gas, obtain stars-plus-gas dispersion relation in WKB limit

  $|S|$ = dimensionless frequency = $m\,|(\Omega_p - \Omega)|\,/\,\kappa$ vs. $X = k/\,k_{crit}$

  → show that this permits a stationary wave solution.

Dispersion relation for stars-alone galactic disk

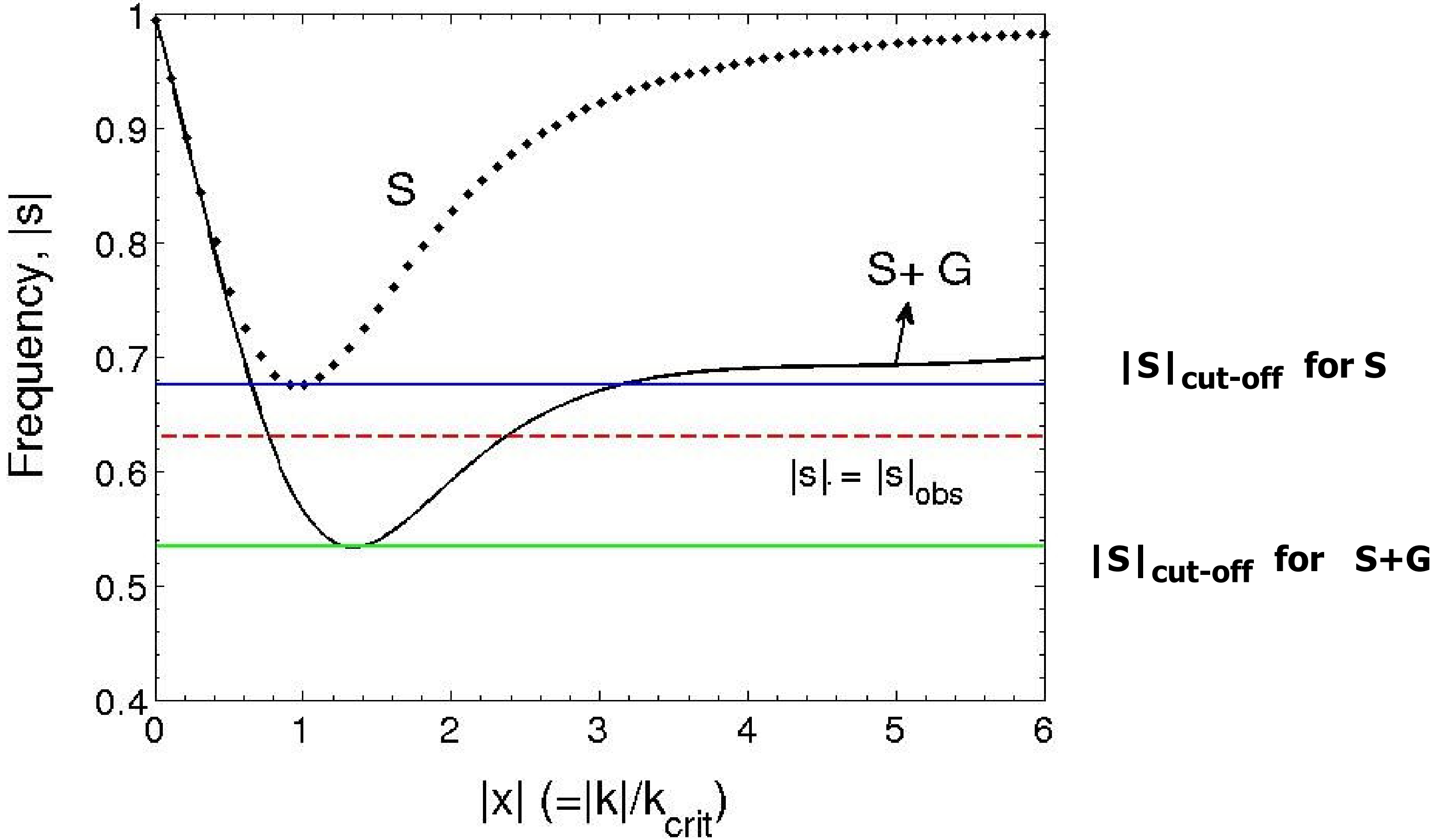


Forbidden region: k imaginary, wave evanescent

Note: A real k solution possible only when |S|$_{\{obs\}}$ > |S|$_{\{cut\text{-}off\}}$

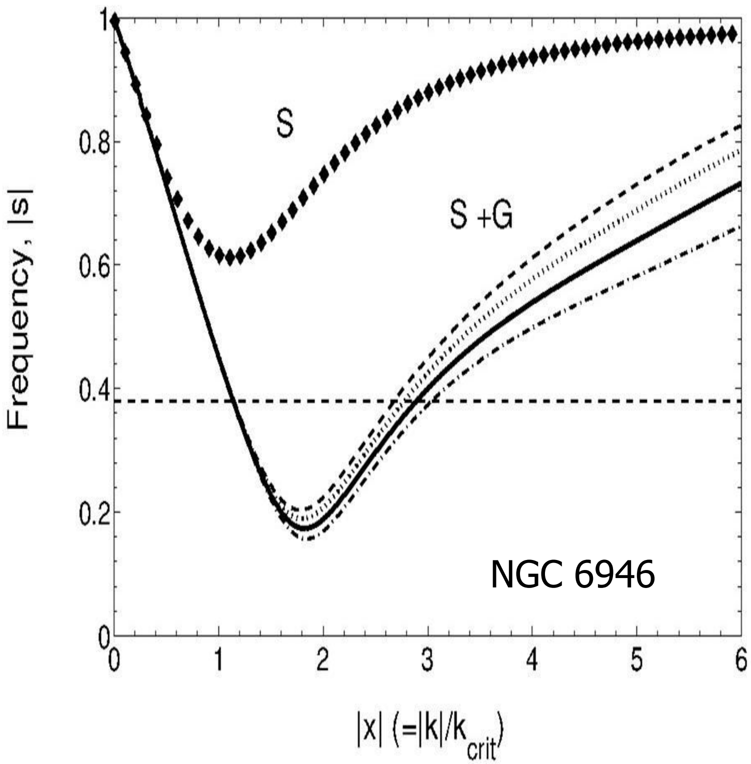
Not satisfied by real galaxies → Stars-alone do not support stationary wave

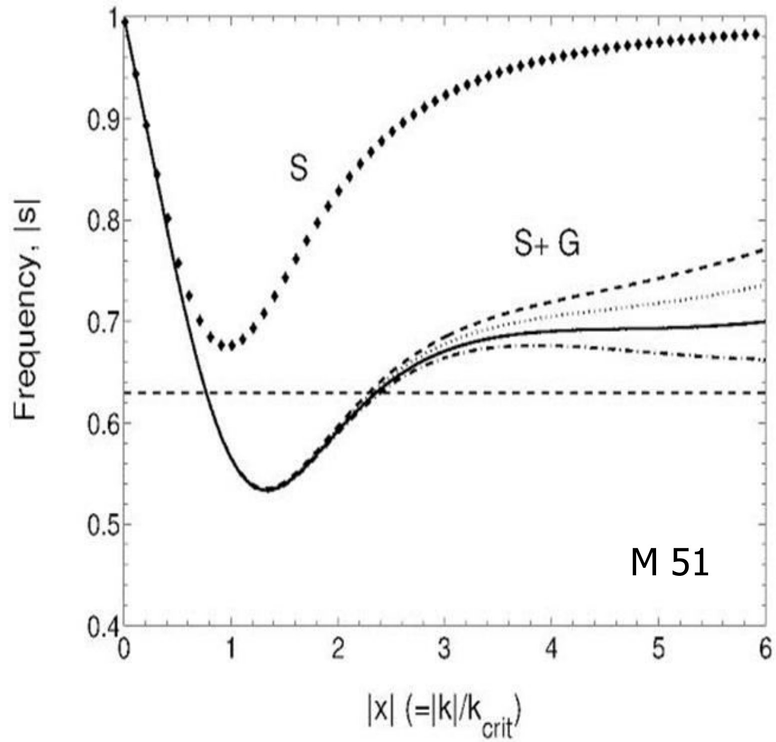
Two-component (Stars +Gas) dispersion relation



Addition of gas lowers $|S|_{\{cut\text{-}off\}}$ so S+G case permits stable density wave for the observed pattern speed, whereas stars-alone does not

Applications to two galaxies NGC 6946 and M 51





|s|$_{obs}$
dashed line

Inclusion of gas allows a stationary density wave → pattern speed not free paramater, but set by disk properties, especially gas content

Generated interest: Future work with D'Onghia (USA) to compare with their simulations; and Dettmar (Germany) to compare with CALIFA survey data

Dynamical effect of dark matter halo: Enhances disk stability

- Local stability of disk supported by rotation and random motion

  $Q = \kappa C / \pi G \mu > 1$ stable ; < 1 unstable

  Toomre Q Criterion (1964) – classic paper – for an isolated disk

- Galactic disk embedded in DM halo, yet surprisingly impact of halo on disk stability not studied correctly.

- We show that for a correct treatment, need to include the external potential due to halo - together set rotational equilibrium.

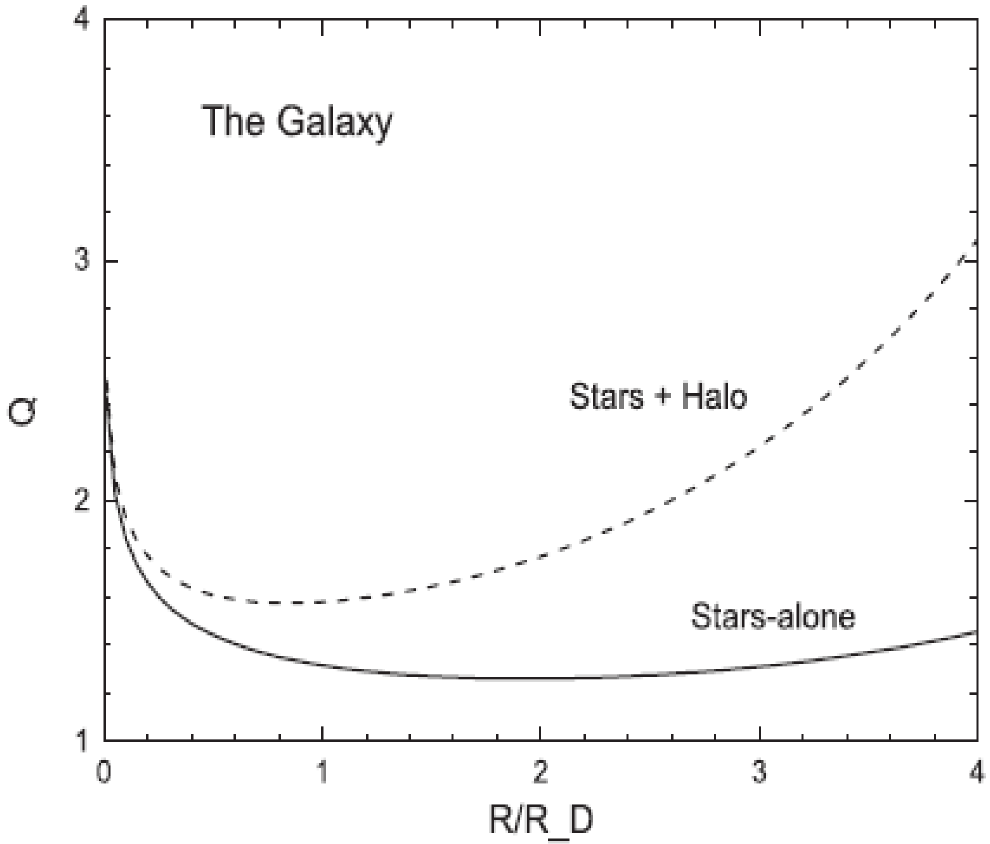
Modified Q criterion (Jog 2014) :

$Q_{net} = \kappa_{net} C / \pi G \mu$ where $\kappa_{net}^2 = \kappa_{disk}^2 + \kappa_{halo}^2$

$> Q_{disk\text{-}alone}$

Results for Q vs. R for disk-alone and disk+halo for the Milky Way Galaxy

(Jog 2014, AJ)

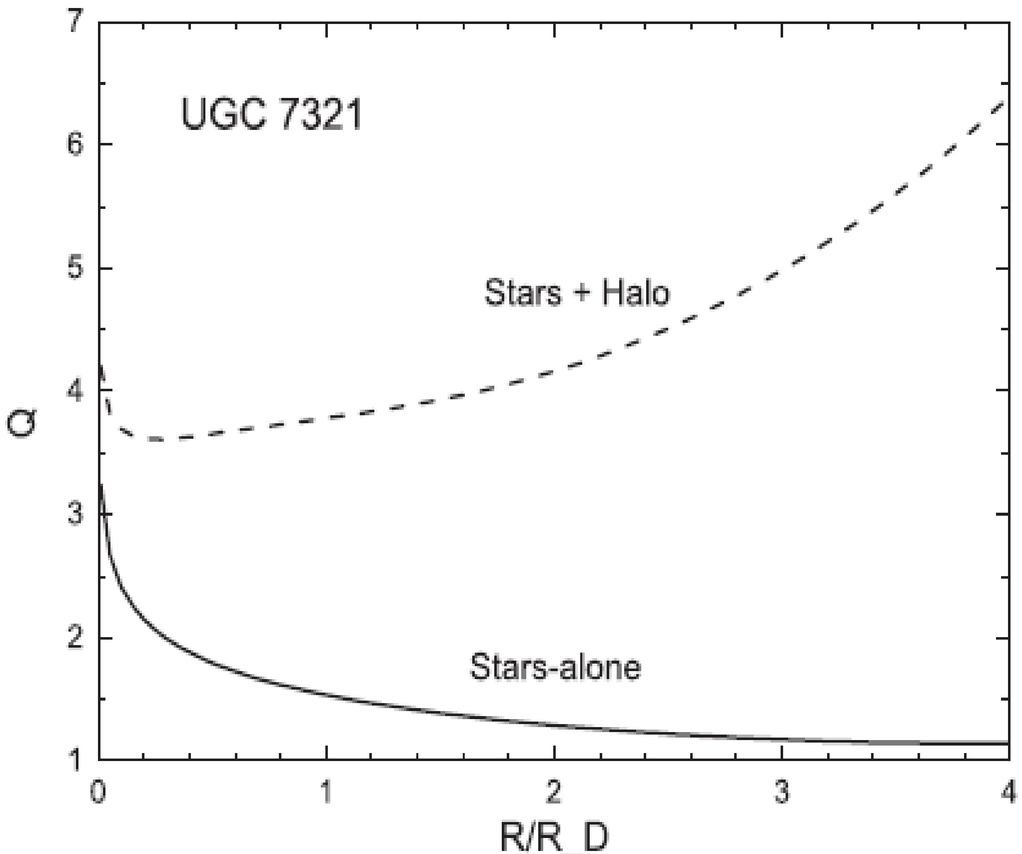


Inclusion of halo ensures Q > 1 → stable disk

Thus, dark matter halo crucially important to prevent local instabilities all over a galactic disk

Stabilizing effect of halo stronger for low surface brightness galaxies

(Jog 2014, AJ)



Here DM halo dominates from innermost regions, and the effective Q values are high > 3 - thus SF and spiral structure is suppressed in LSB galaxies

(Ghosh & Jog 2014 for further details)

Vertical Mass Distribution - normal to the galactic plane

Important as a tracer of galactic potential, and dynamical evolution – but not studied too well.

What decides the disk thickness?

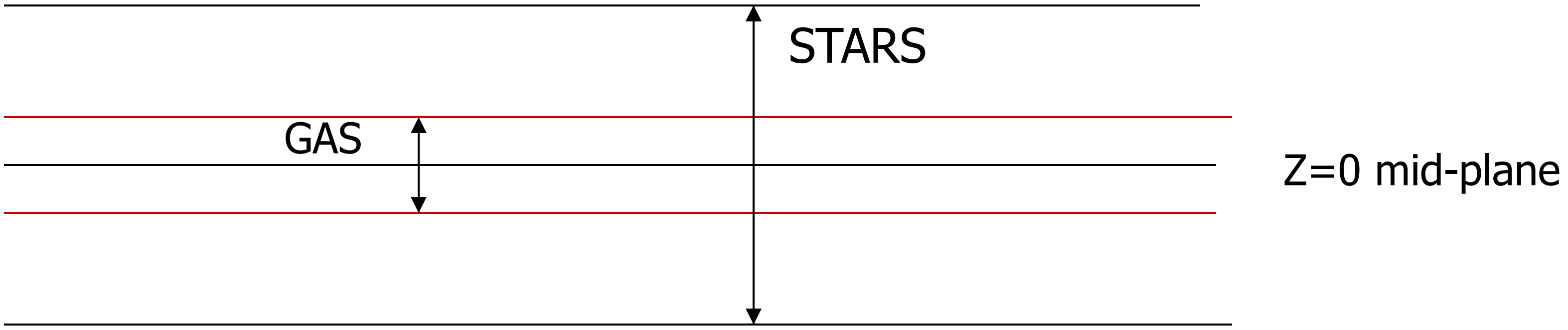
Disk supported vertically by pressure : Balance of self-gravity and pressure → vertical scaleheight

Need to solve Poisson equation and the force equation together for a self-consistent solution.

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

Real galaxy consists of stars and gas, gravitationally coupled

General model for a multi-component disk (Narayan & Jog 2002)



Stars and gas are coplanar, with z-extent much smaller for gas (low dispersion)

We show: Gas is only ~15 % by mass, but it is closer to mid-plane ,
hence it significantly affects dynamics of both stars & gas

Vertical Disk Structure:

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

Each component obeys:

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

where [ ] – force term due to three disk components +halo
-- but different dispersion, hence different ρ_i (z)

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

Simultaneously gives ρ_i (z) and thus thickness (HWHM) for stars and gas -- repeat at different radii & compare with observations.

Result: Explains observed thickness of all three disk components (Stars, HI, and H_2) in the Galaxy (Narayan & Jog 2002)
- Gas gravity crucially important for vertical equilibrium of stars

This approach has been widely adopted by others - because of the self-consistent, rigorous treatment
e.g. applied to SPITZER data on 77 edge-on galaxies
(Comeron et al 2010-2017)

Density Profile of Dark Matter Halo

- In the outer regions, Dark Matter halo dominates

- Apply the above model, use the observed gas scaleheights in outer Galaxy to constrain shape and density profile of Dark Matter Halo.
  (Narayan, Saha & Jog 2005, A & A)

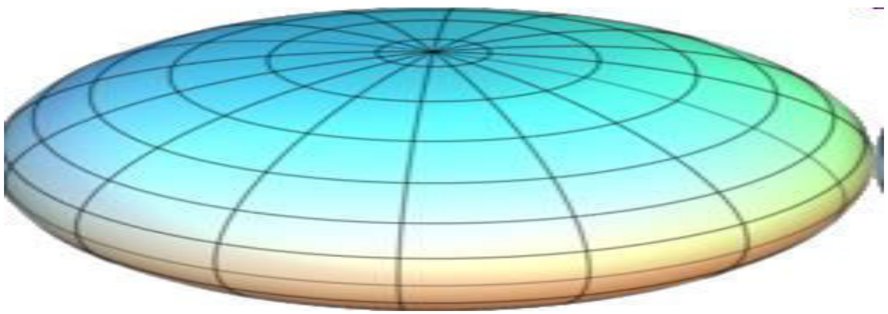
- Two simultaneous constraints:
  Observed rotation curves give M (R) , and
  Vertical structure of disk (new feature) → gives shape of halo

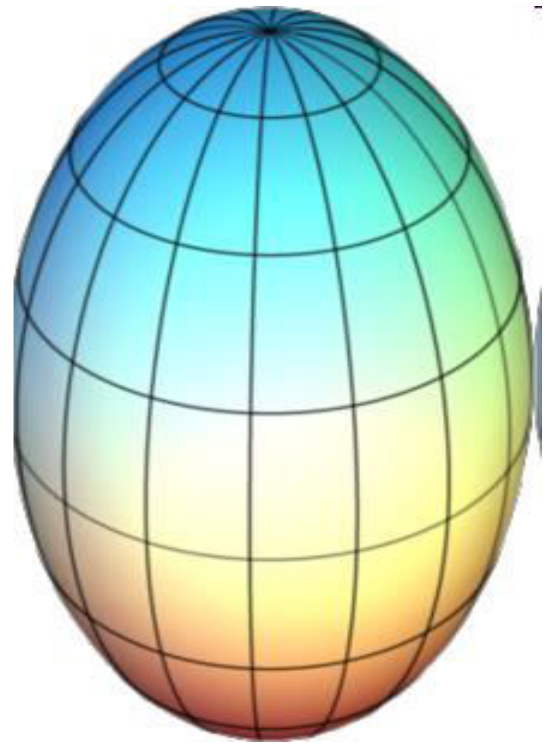
- Scan halo parameters → get best-fit to observed gas scale-height data - tried spherical shape, then other shapes

Different shapes of DM halo tried

Prolate spheroid

Oblate spheroid





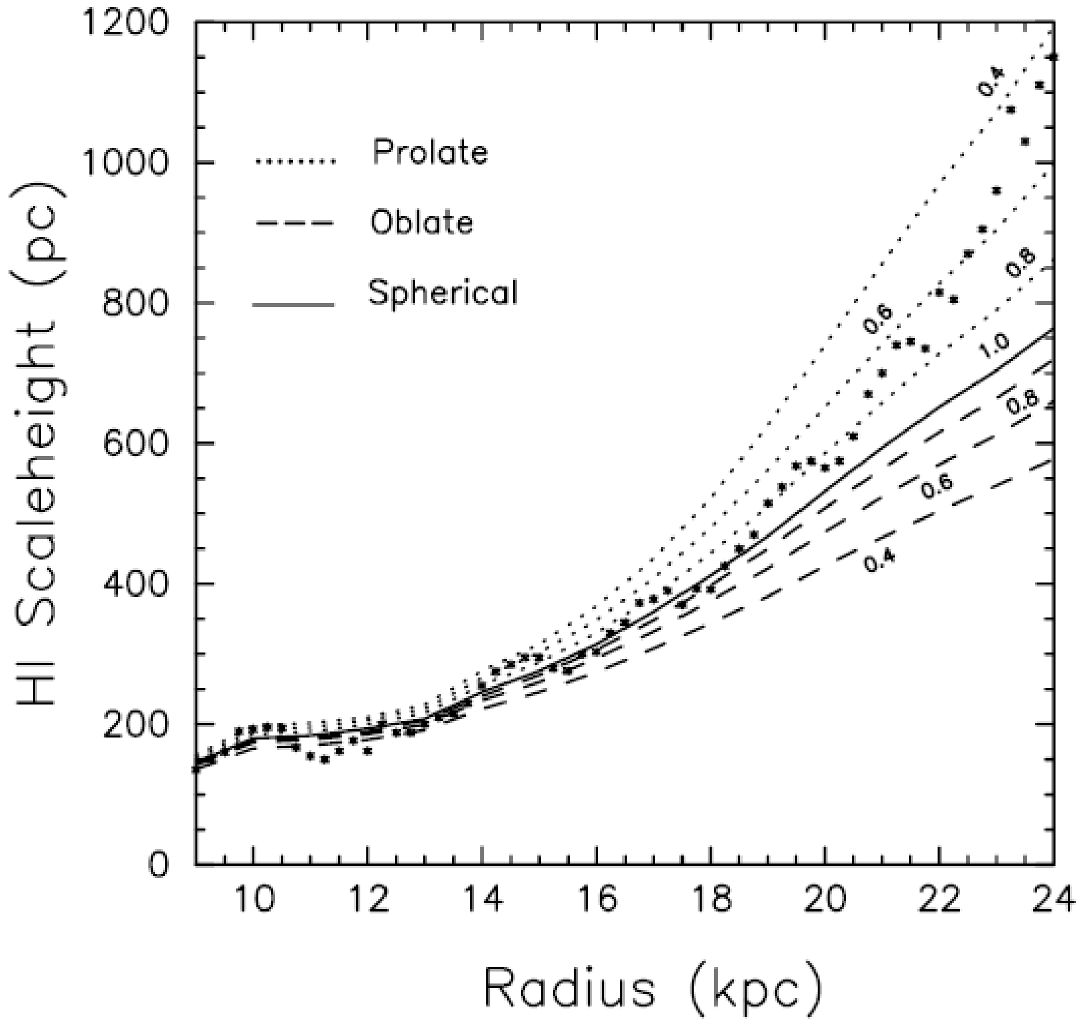
c/a = vertical to planar axis ratio < 1

For same total mass, vertical gravitational force higher
→ lower disk thickness

c/ a > 1

Lower force → Flaring disk

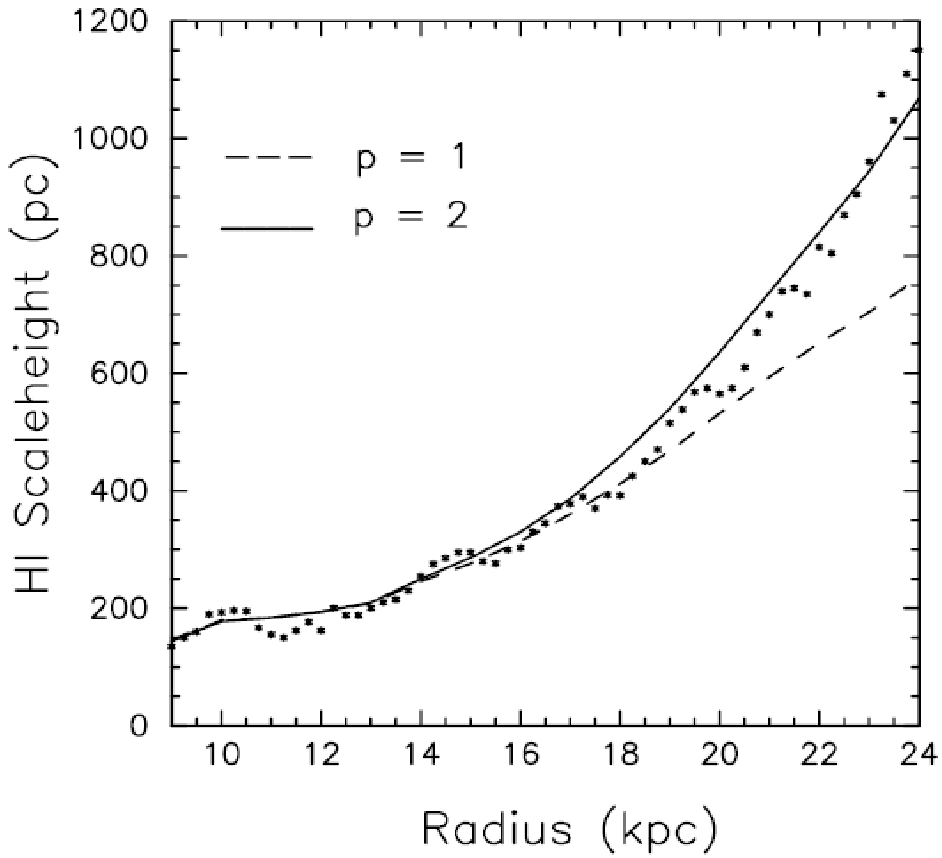
Results (Narayan et al. 2005)



Data (**) : Gas thickness increases by a factor of 6

- **Spherical halo gives a good fit till 18 kpc, beyond that HI flares.**
- **Oblate shaped halos give worse fit as expected.**
- **Better fit to HI data given by prolate halos, but any single shape cannot explain scale heights over the large range 9-24 kpc.**

Next, tried steeper density fall-off & spherical shape – fits data well



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

(Narayan et al. 2005)

Result: halo density as $1/R^4$ → Total halo mass ~ 2.8×10^{11} M_{sun} (<100 kpc).
At lower end of mass range as deduced from other indicators.

Relook at the problem of HI flaring in the outer Galaxy

Banerjee & Jog 2011, ApJ Letters

Novel approach: Halo shape is prolate and taken to vary with radius

Recall, prolate shape is preferred since mid-plane density, hence vertical force, is lower → hence would give higher scale height

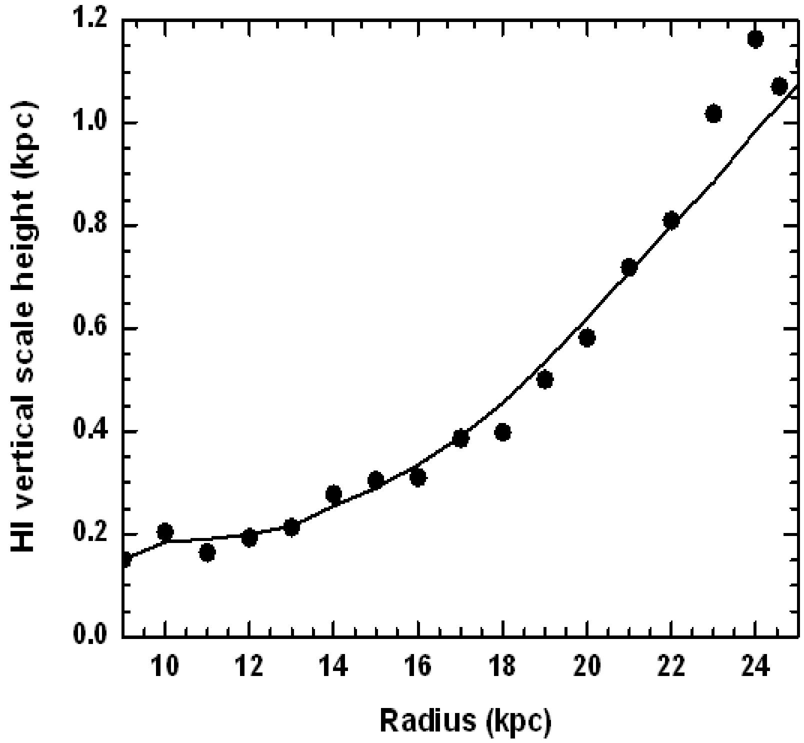
A more prolate halo at larger radii → could explain the observed flaring

Each shell is treated separately:

$q_R = c / a \ (> 1)$ is a local property of each shell

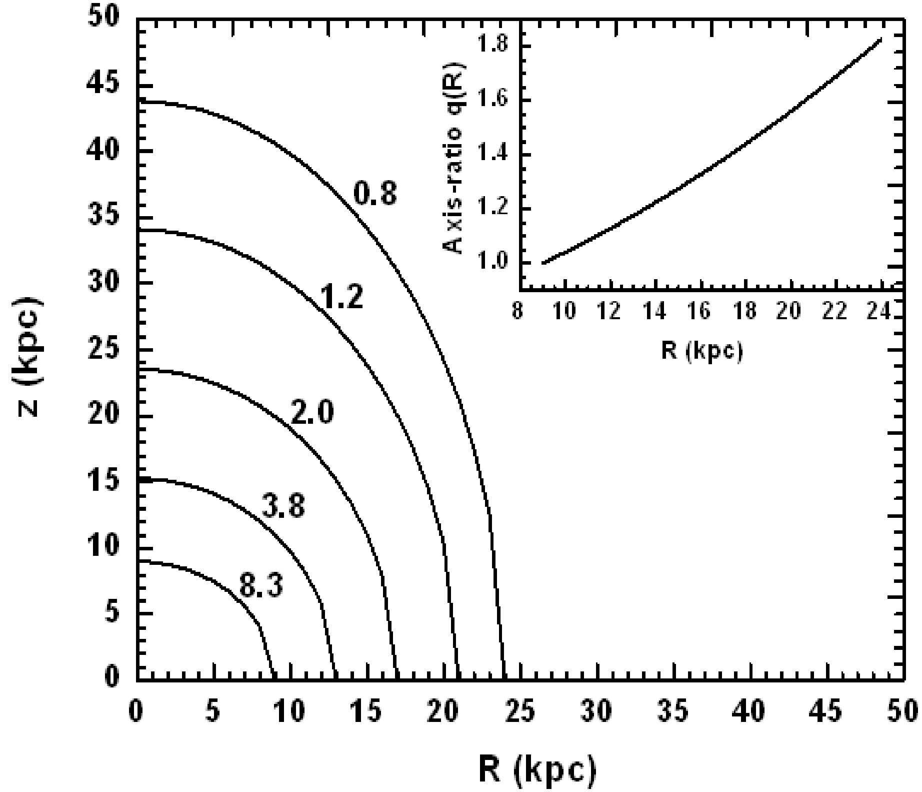
Match results for scale heights to HI data : best-fit prolate halo parameters, with a maximum axis ratio q= 2.0 at R = 24 kpc

Calculated and observed HI Vertical scale height vs. Radius



The plot for the best-fit prolate halo parameters (q=2 at R=24 kpc)

Isodensity contours of the prolate halo on the R-z plane



The inset shows q, axis ratio increasing with radius R

Density contours in units of $10^{-3}\ M_{sun}\ pc^{-3}$

Density contours show halo is progressively more prolate at larger radii. **Confirmed by trends from cosmological simulations where prolate halos are preferred**.

Potential of a prolate spheroid with varying shape: Exact calculation
(Rathulnath & Jog 2013, MNRAS)

Potential of spheroidal mass distribution :

Classic problem → Inversion of Poisson equation

see Chandrasekhar 1969, "Ellipsoidal figures of equilibrium" .

These typically assume constant shape with radius.

- We consider the prolate ellipsoids to be concentric and coplanar
- And where eccentricity varies with radius - much harder problem
- Add the shell-by-shell contribution to get the net potential
- Apply to the Milky Way case with halo + disk – to study warps

An unexpected off-shoot of this work:

Prolate halo with varying shape : Is it stable ?

or do the overlying shells collapse faster?

We calculated this and showed that for the variation in halo shape q(R) implied by HI flaring, the halo is stable for Hubble time

(Rathulnath & Jog 2013)

We are now doing this check for halo parameters obtained from real cosmological simulations

(work in progress with Isha Pahwa, IUCAA)

This sort of stability of halos has not been studied by others

– a new, open field, can help us rule out shapes which will not be stable over long times.

Summary:

In this talk, I have tried to give you a flavour of the work done:

Structure and dynamics of galaxies- keeping track of observations; and treating stars, gas and dark matter halo cohesively

Gas makes the disk unstable, while dark matter halo stabilizes it.

DM halo exerts dynamical effect on disk, and halo is necessary to ensure disk stability.

Study of galaxies: Exciting, vibrant field, with many open problems, fed by comparisons with observations and also N-Body simulations.

Hope to have more results to report in future years!!