Galaxies & Dark Matter

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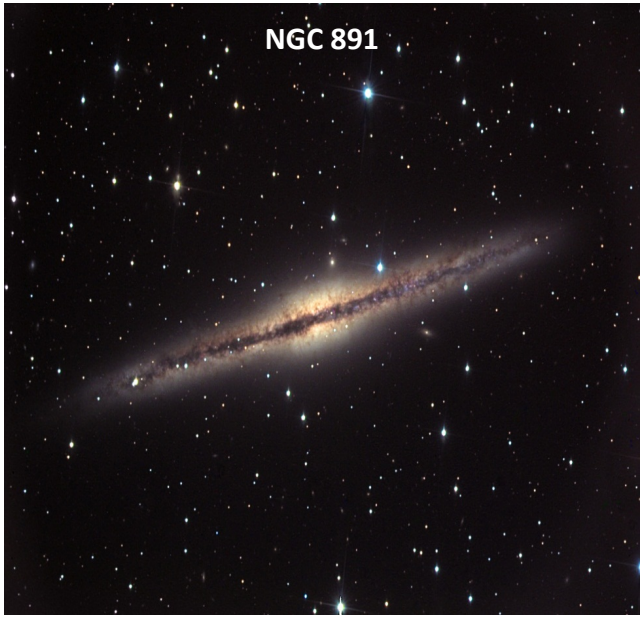
IISER Tirupati

1. Galaxies

Our Milky Way (Akash Ganga)

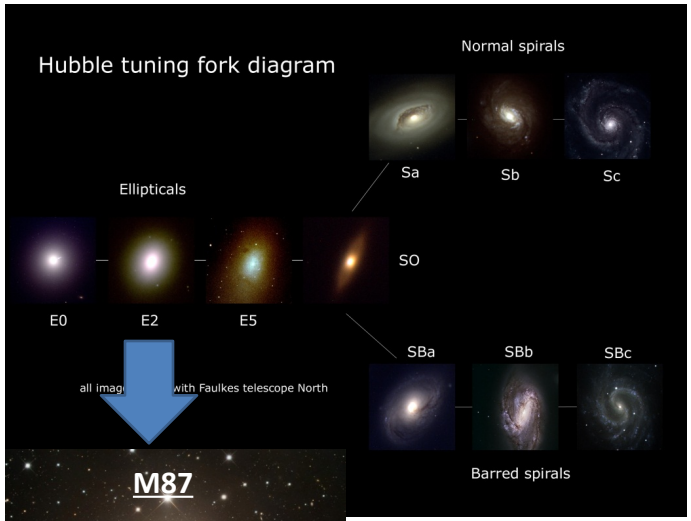
Disk galaxies: Orientations



Edge-on View

Face-on View

Disk Galaxies: Hubble's Tuning Fork Diagram

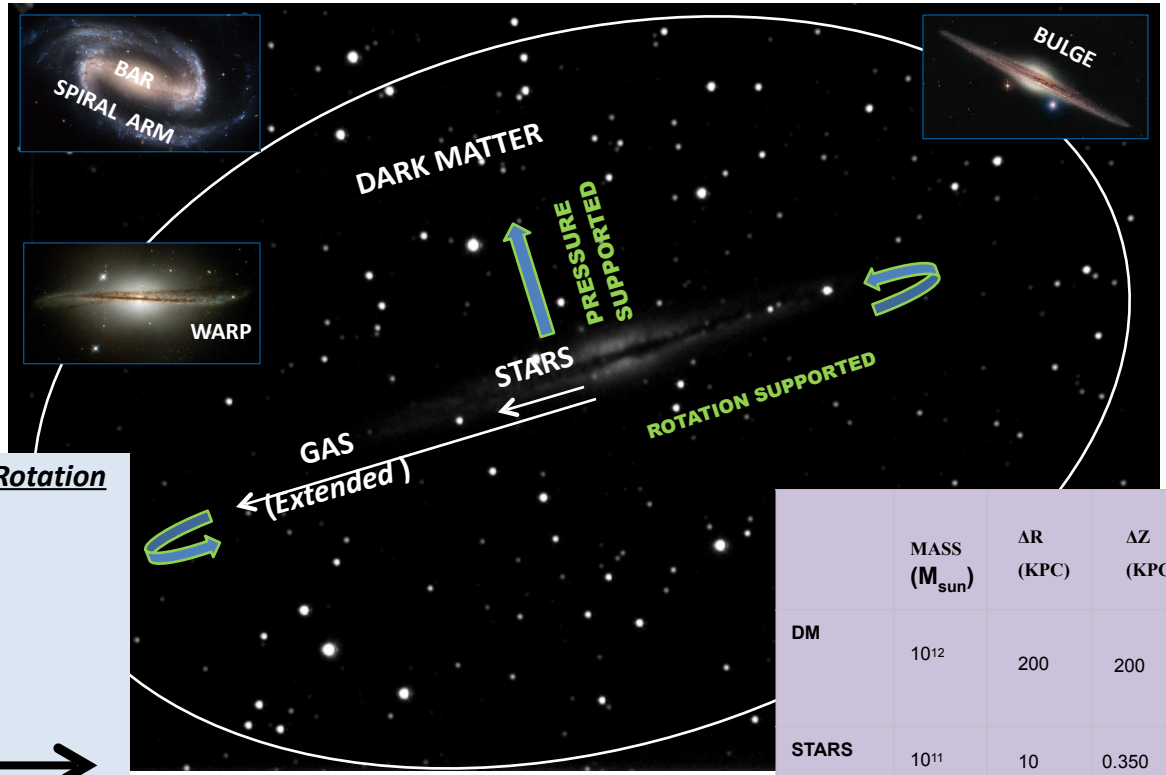


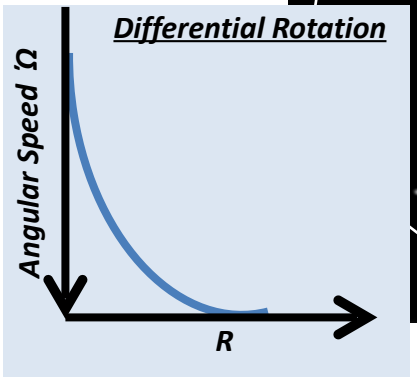
ELLIPTICAL GALAXY

WHIRLPOOL GALAXY:
AN UNBARRED SPIRAL GALAXY

Figure Courtesy: Wikipedia

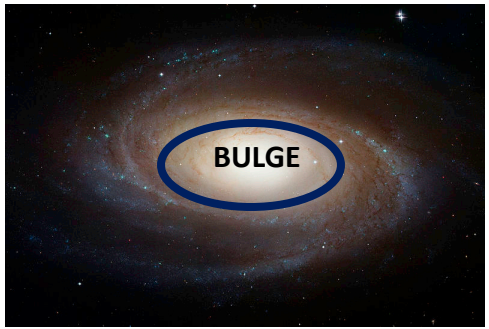
Disk galaxies: A Schematic





	MASS (M_{sun})	ΔR (KPC)	ΔZ (KPC)	σ (km/s)
DM	10^{12}	200	200	
STARS	10^{11}	10	0.350	18
GAS(HI)	10^{10}	30	0.15 - 1	7-9

Spiral Galaxies: Other Disk Features



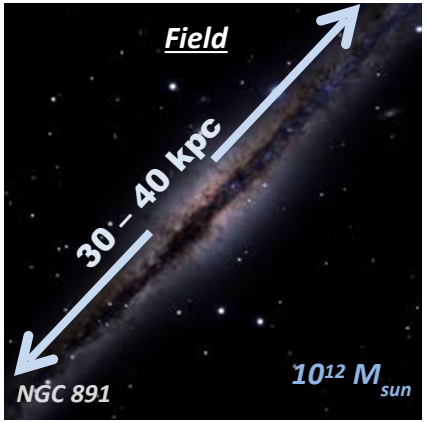
DISK ASSYMETRIC FEATURES

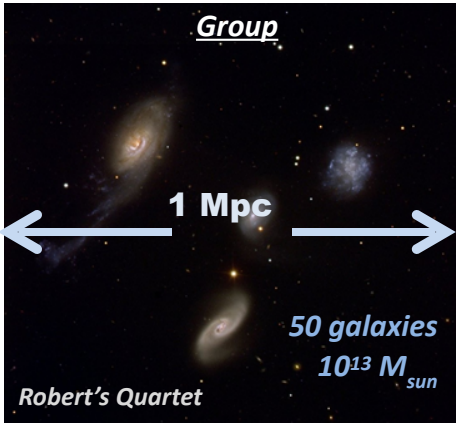
BAR

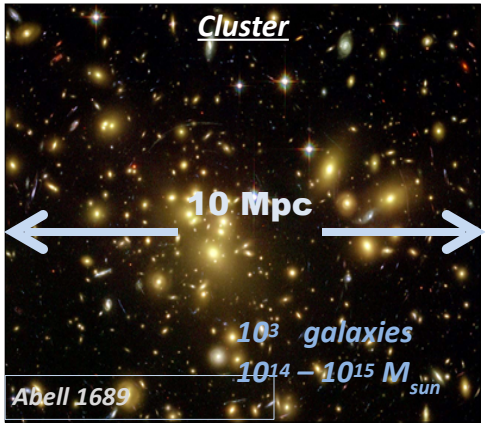
SPIRAL ARMS

WARP

Galaxy Environment



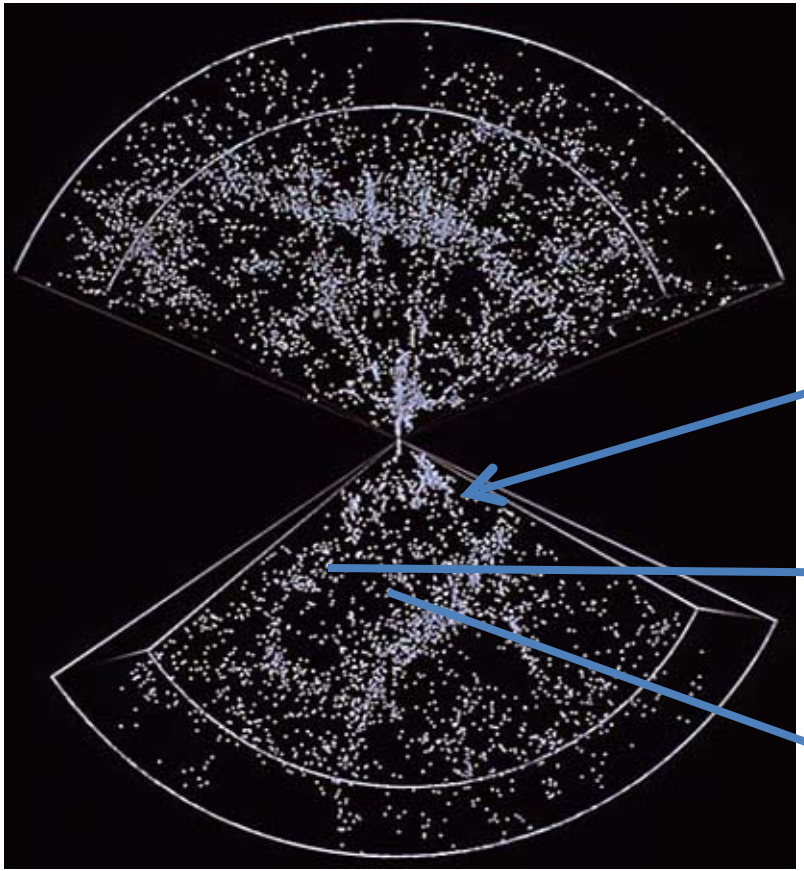




Largest gravitationally-bound objects in the universe!

The idea that dark matter exists starts at this scale of structure

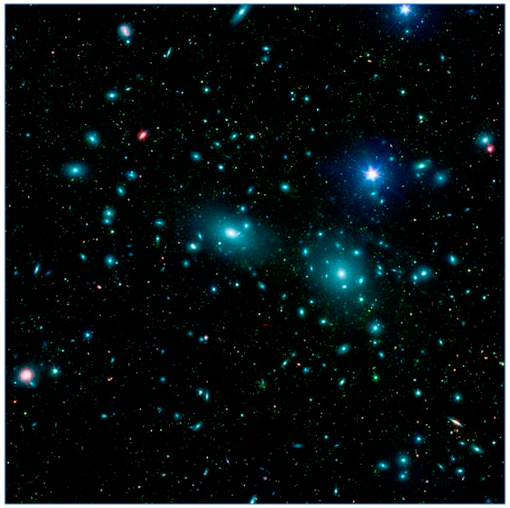
Large Scale Structure in the Universe



Large scale structure in the universe as seen by the Sloan Digital Sky Survey (SDSS)

2. Dark Matter

Dark Matter: Cluster Kinematics (1933)



Coma Cluster (Abell 1669)

Fritz Zwicky

From Virial Theorem,

T + V = 0

i.e. V = -T

Estimable from the Doppler Shifts of the galaxy spectra

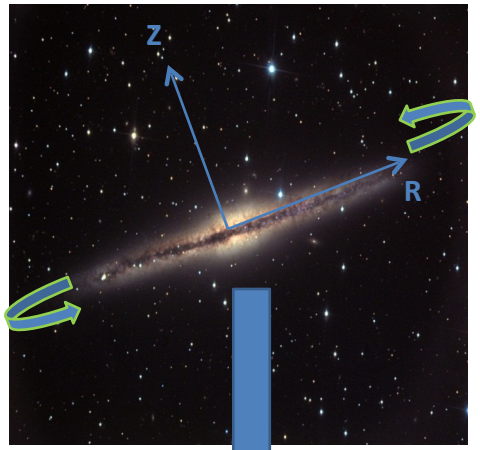
But

V >> V_{obs} !!

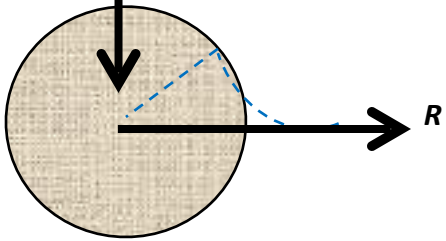
Estimable from the lumininosities of the galaxies

Hints at the existence of Dark Matter!

Dark Matter: Rotation Curve (1980)

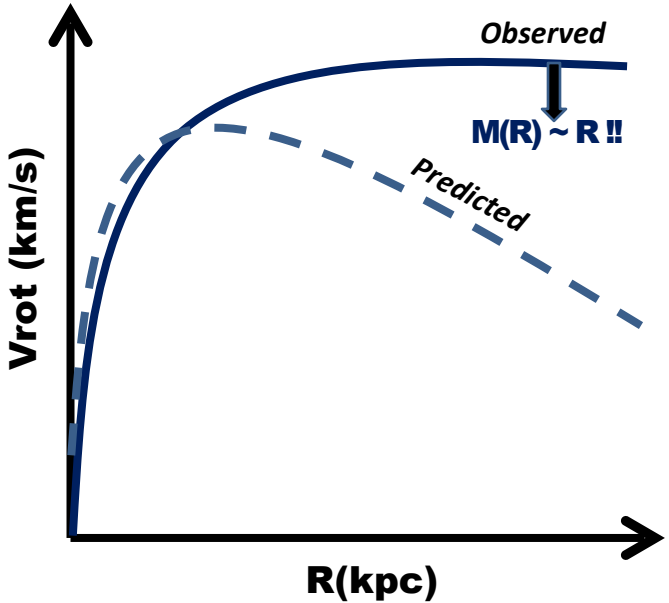


$V_{ROT} = (GM/R)^{½}$

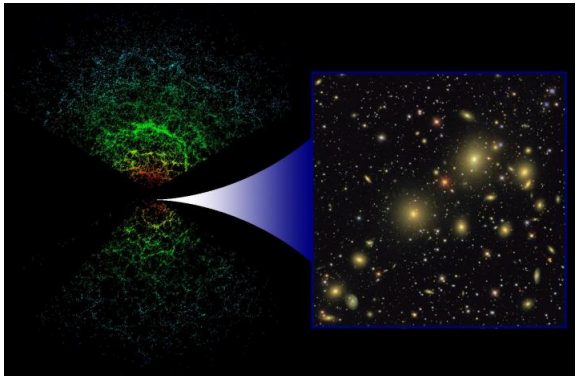


Predicting the rotation curve of the observed light distribution

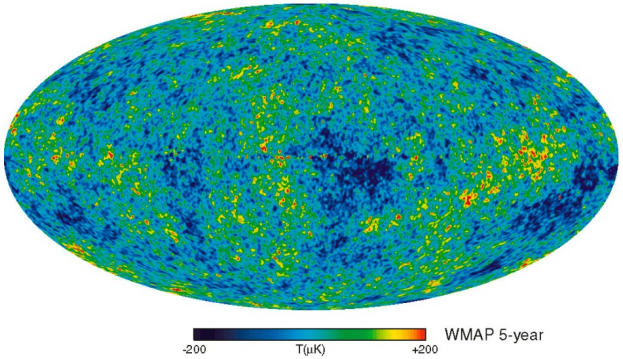
Vera Rubin



Dark Matter: Large Scale Structures



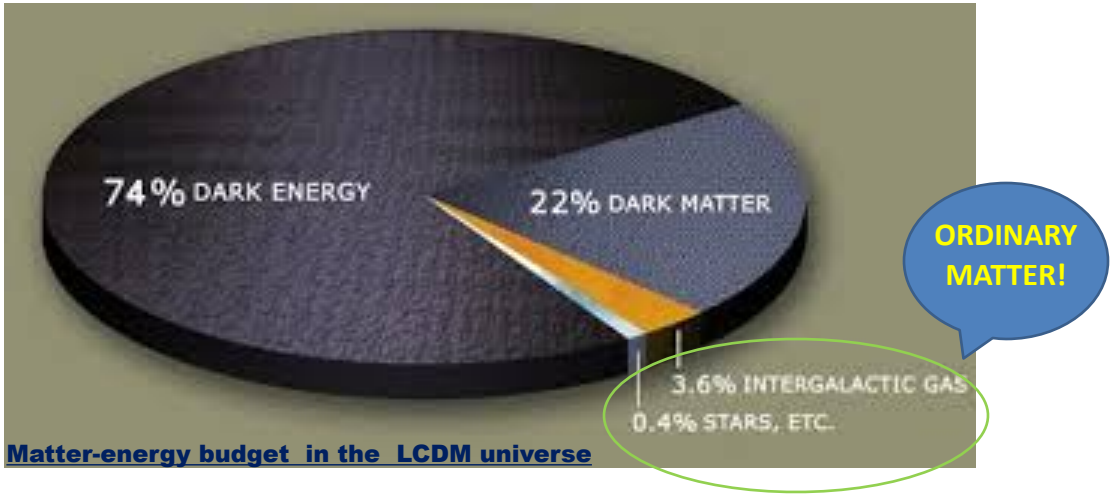
Observed Large Scale Structure (SDSS)



Cosmic Microwave Background Radiation

Observed Abundance of the light elements: Hydrogen, Helium and Lithium

LCDM: Standard Model of Cosmology



Matter-energy budget in the LCDM universe

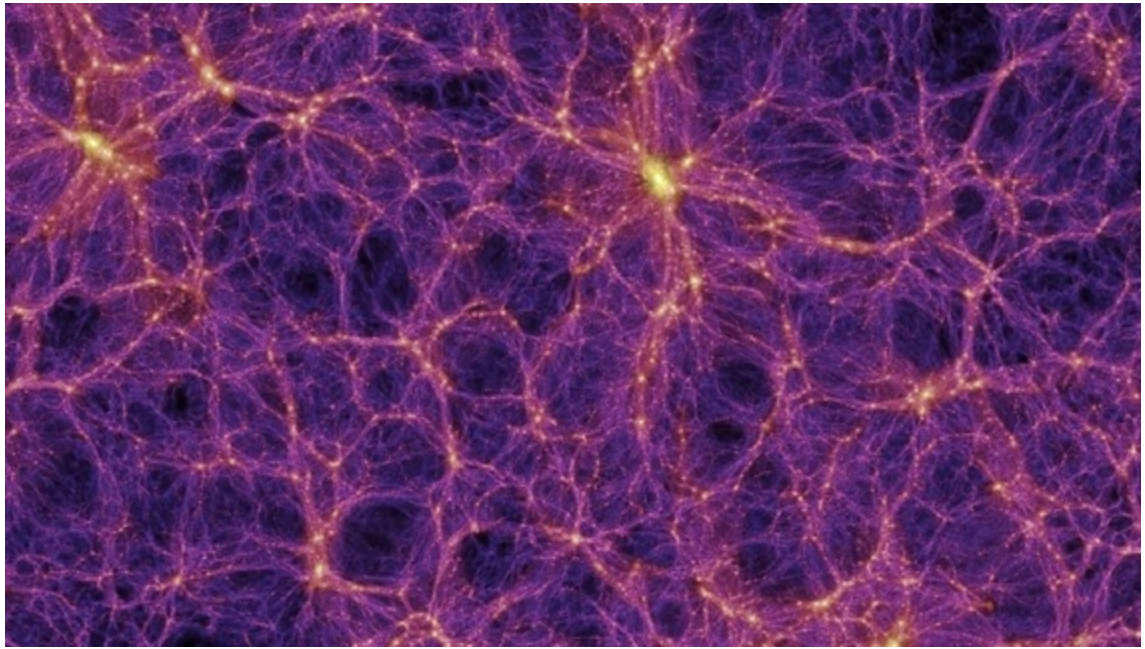
LCDM model constitutes a flat universe

- **dark energy**
- **cold, dissipationless and collisionless dark matter**

and complies with the observed

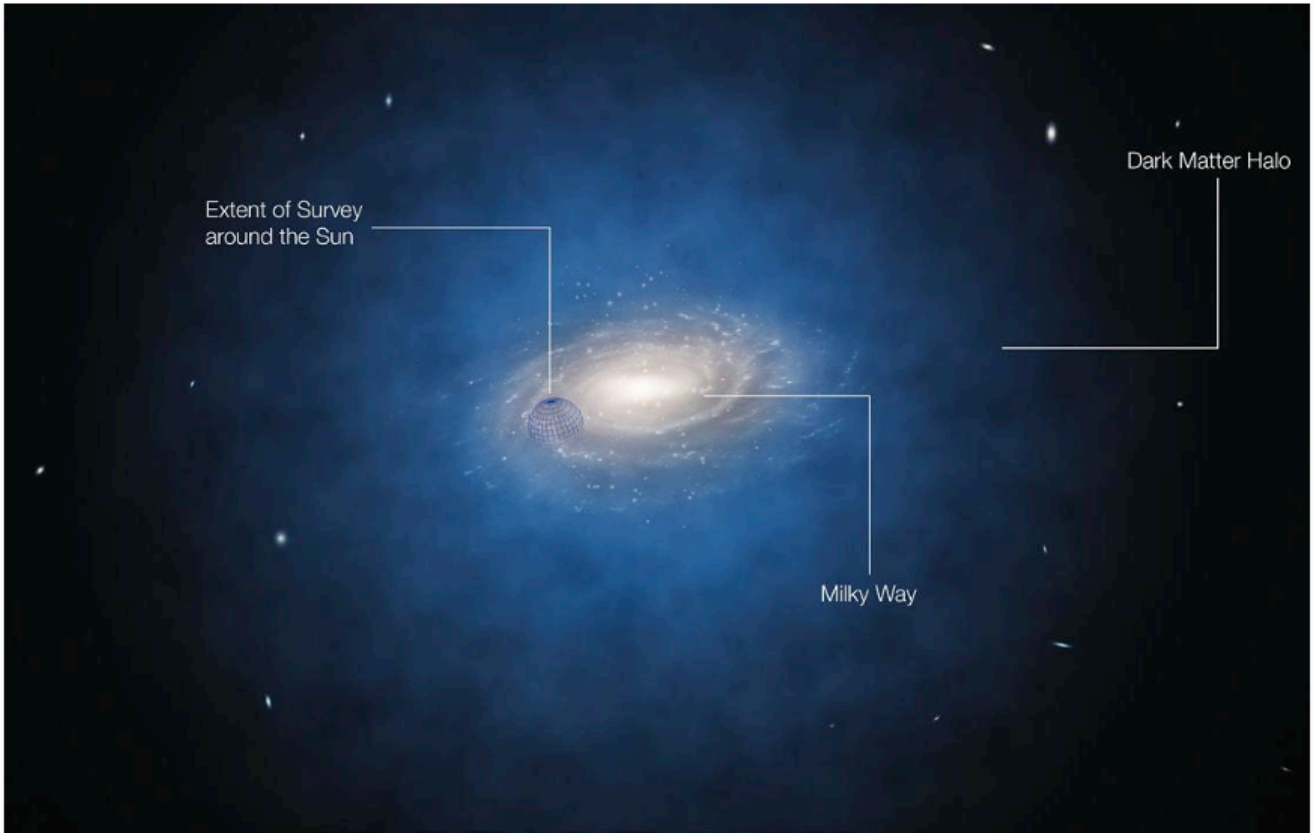
- **acceleration of the universe**
- **its large scale structure**

Large Scale Structure in the LCDM universe



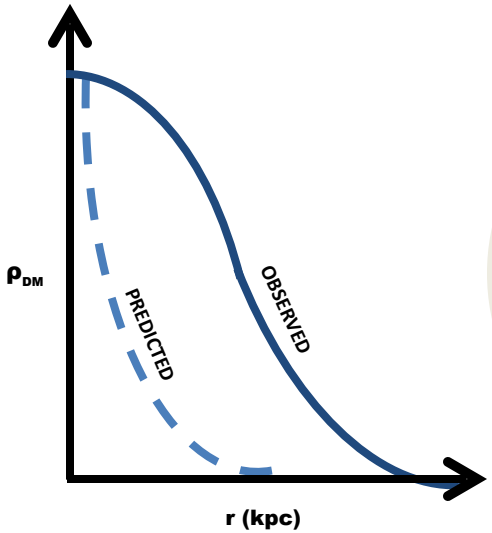
Millenium Simulation

Galaxy Formation in a Dark Matter Halo

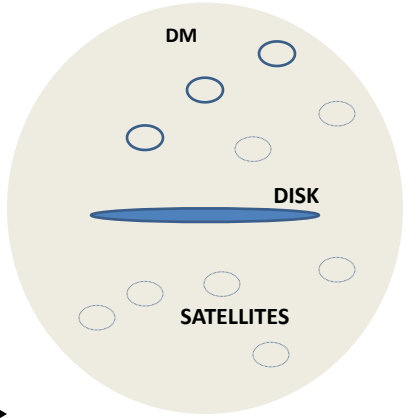


Λ-CDM Universe: Catastrophes

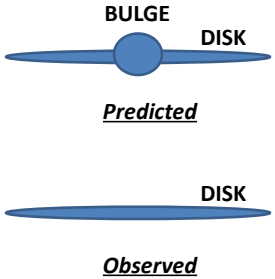
Core/Cusp Issue



Missing Satellite Problem



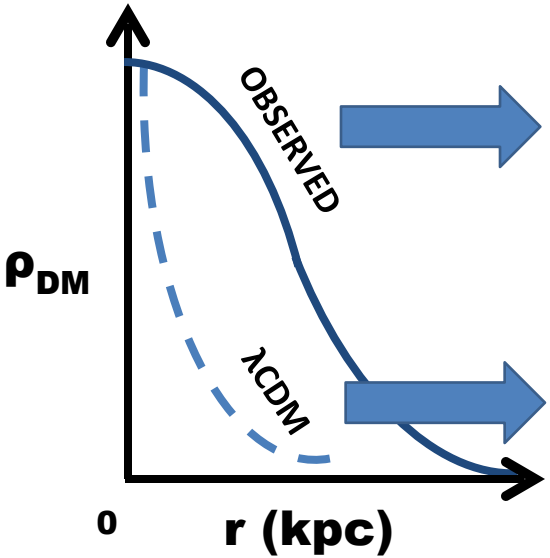
Angular Momentum Catastrophe



Motivation to study Dark Matter on galactic scales!

Λ-CDM Universe: Galactic Scale Catastrophes (1)

Core/Cusp Issue



Pseudo-Isothermal

$$\rho_{DM}(R,z) = \frac{\rho_0}{1 + \frac{R^2 + \frac{z^2}{q^2}}{R_c^2}}$$

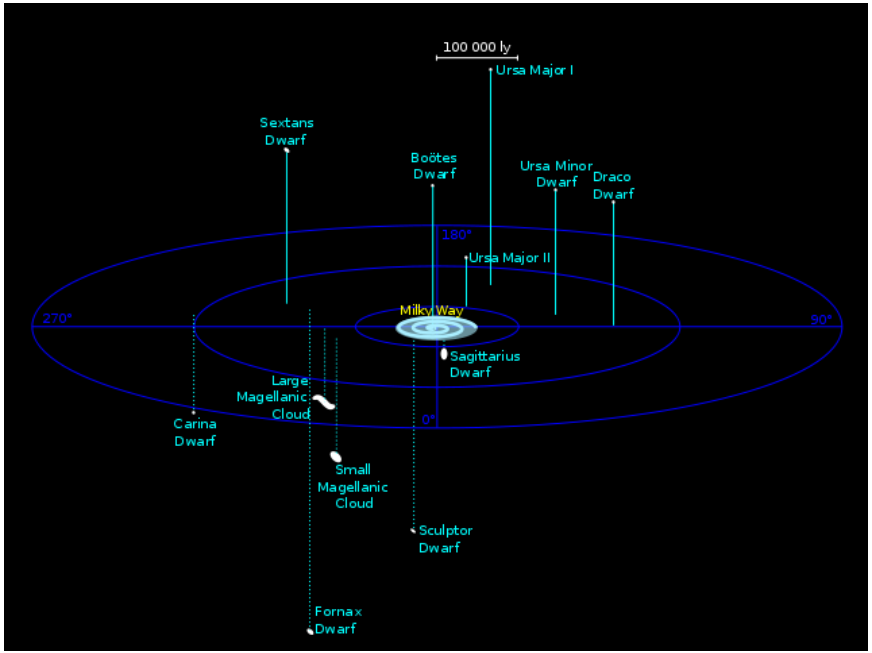
Navarro-Frenk-White (NFW)

$$\rho_{DM}(R,z) = \frac{\rho_0}{\frac{R}{R_S}\left(1 + \left(\frac{R}{R_s}\right)^2\right)}$$

Dark Matter Density: Cuspy (Predicted), Cored (Observed)!

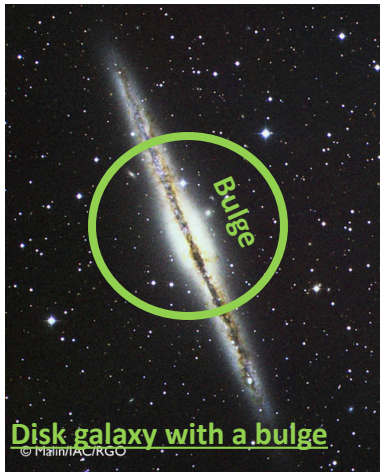
Λ-CDM Universe: Galactic Scale Catastrophes (2)

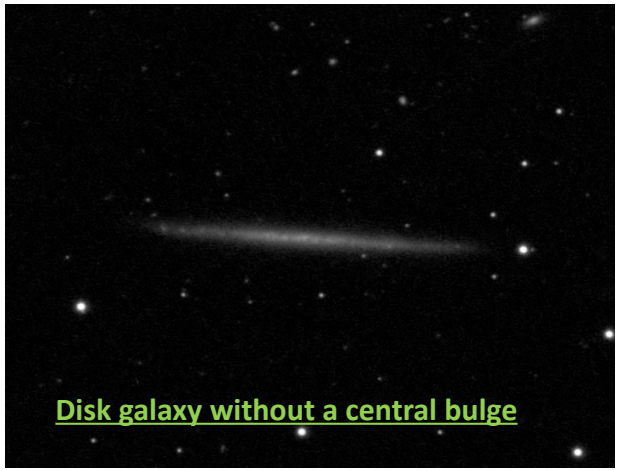
Missing Satellite Problem



Number of Satellite Galaxies: 300 (Predicted), 7-8 (Observed)!

Λ-CDM Universe: Galactic Scale Catastrophes (3)



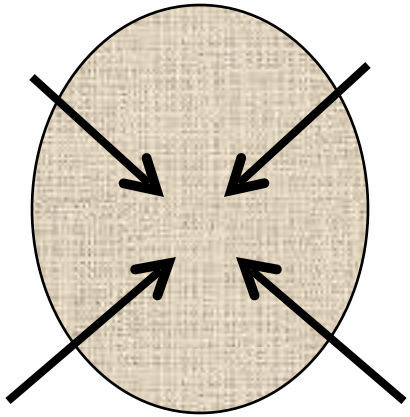


Number of Bulgeless Galaxies: 0 (Predicted), Many (Observed)!

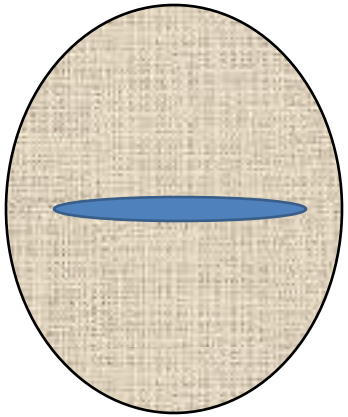
Possible Remedies

- **Inclusion of Feedback:**

  Gas accretion, cooling, Star Formation and Feedback (supernovae/AGN)



Gas Accretion into DM halo



- *Gas Cooling*
- *Disk Formation*

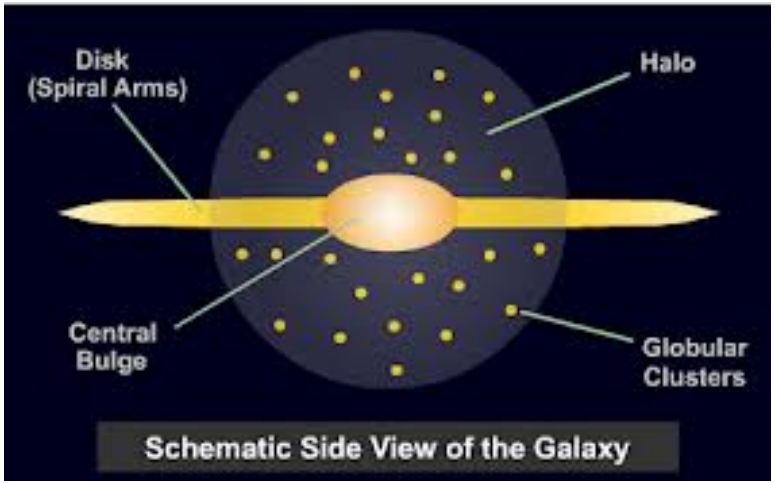
- *Star Formation*
- *Supernovae*
- *Feedback*

Possible Alternatives

- Modified Newtonian Dynamics (MOND)
- Alternative Theories of Gravity

NO CONSENSUS REACHED!

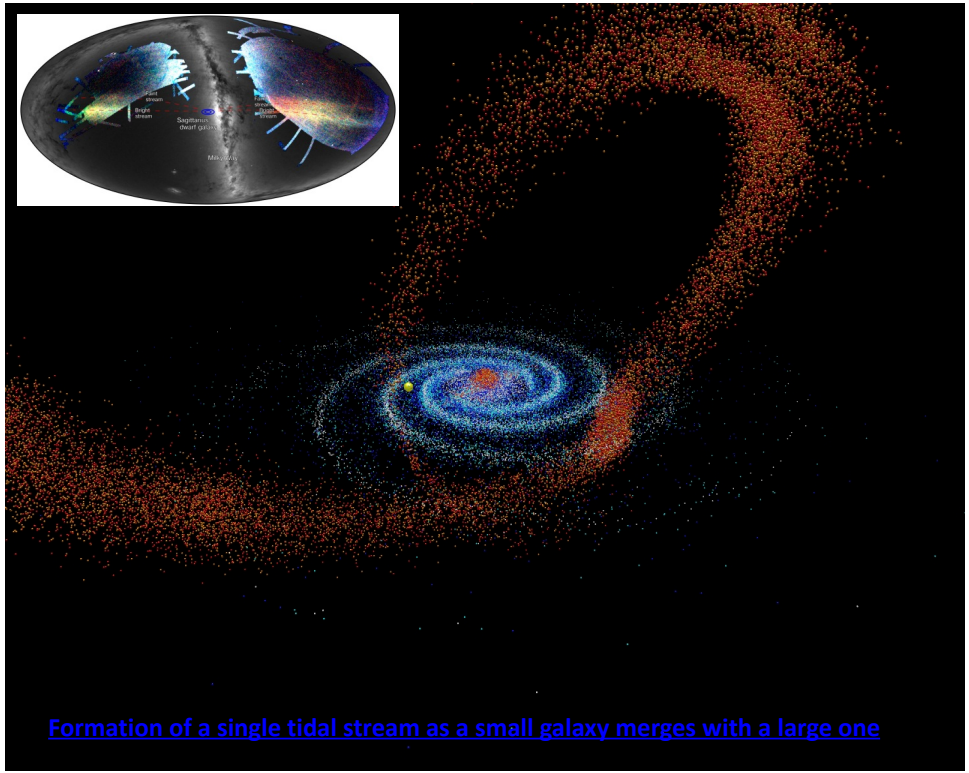
Dark Matter Halos Tracers: Stellar Kinematics



Loebman et al. 2012

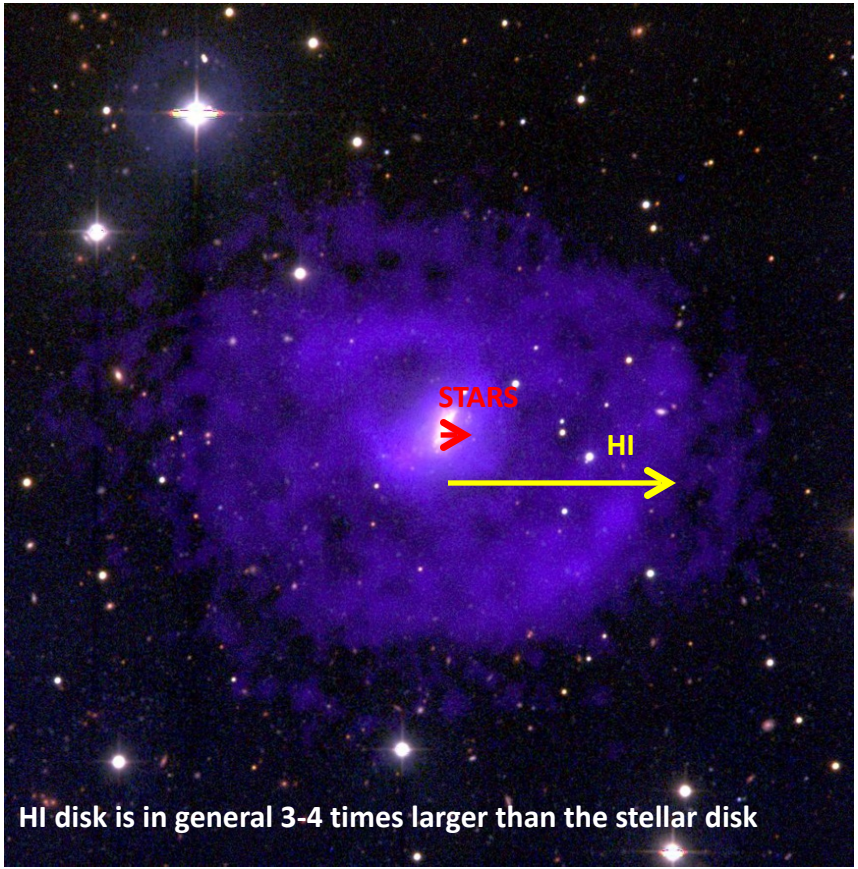
**Galaxy and its immediate neighbours*

Dark Matter Halos Tracers: Stellar Streams



**Galaxy and its immediate neighbours*

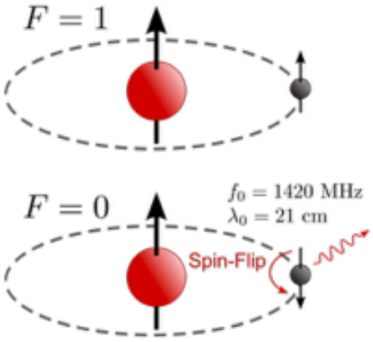
Dark Matter Halos Tracers: HI



**Edge-on galaxies in the nearby universe*

HI 21cm radio-synthesis observations

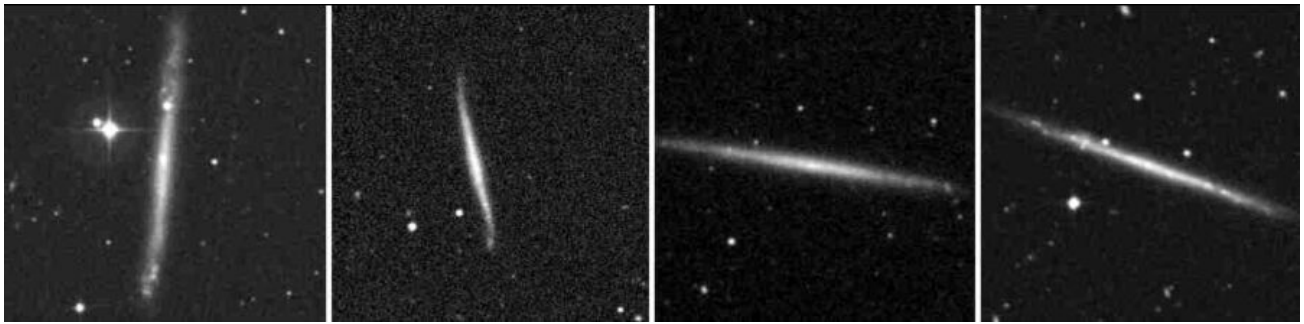
Spin-Flip Transition



Giant Meterwave Radio Telescope (GMRT), near Pune

3. Dark Matter
&
Disc Dynamics

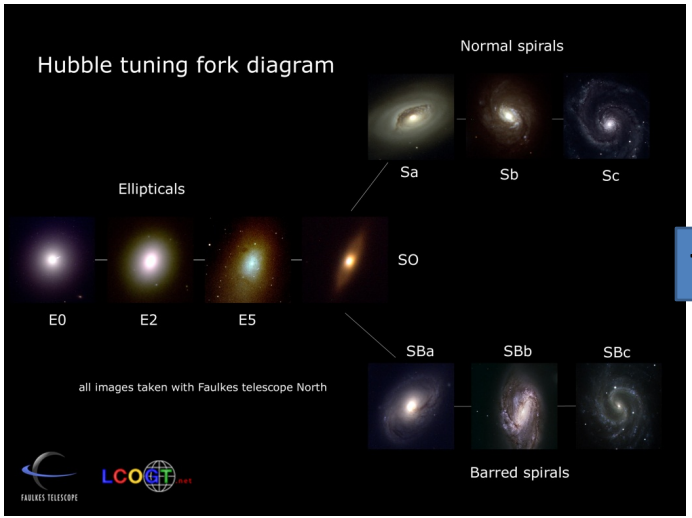
1. Why are some galaxies extremely thin?



The superthin low surface brightness galaxies

Banerjee & Jog 2013, MNRAS, 431, 582

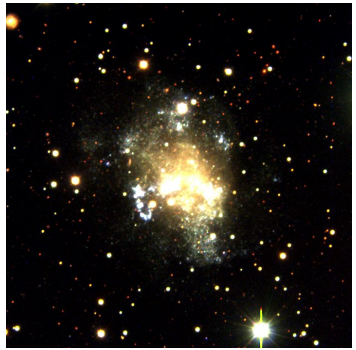
Effect of DM Halo on Disk Structure & Dynamics



Superthin LSBs

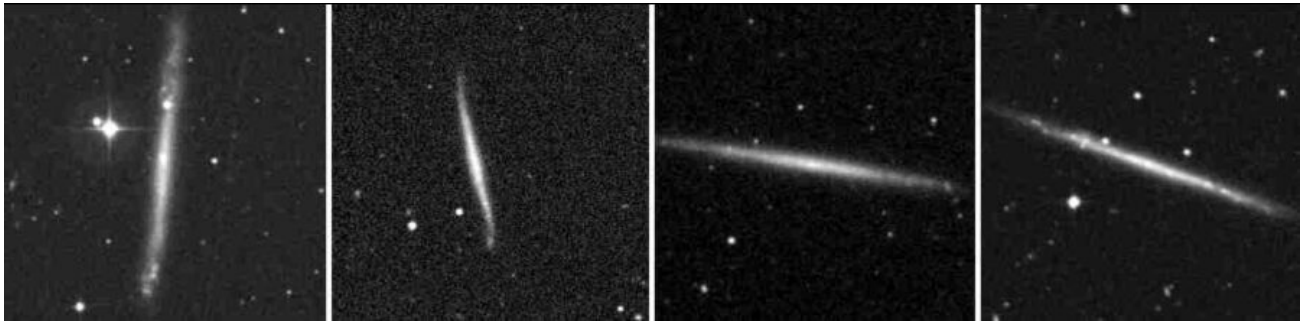
The farthest end of the tuning fork…

Dwarf Irregulars

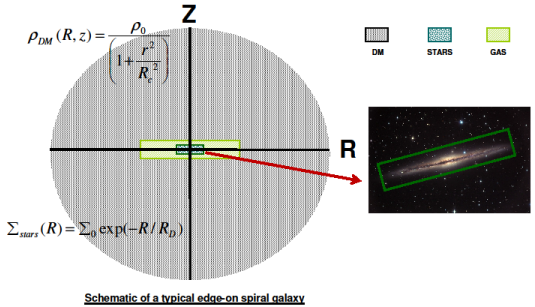


1. Why are some galaxies extremely thin?

The superthin low surface brightness galaxies

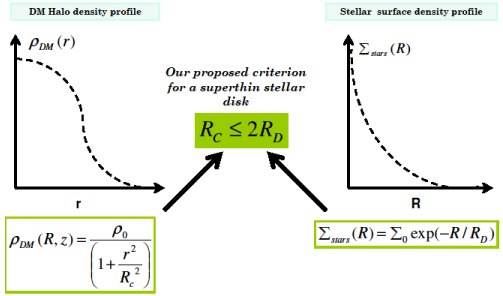


Basic building blocks of a disk galaxy



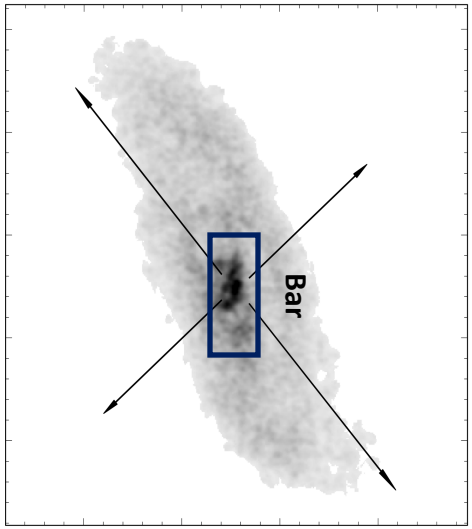
Schematic of a typical edge-on spiral galaxy

Our recipe for a superthin stellar disk



Banerjee & Jog 2013, MNRAS, 431, 582

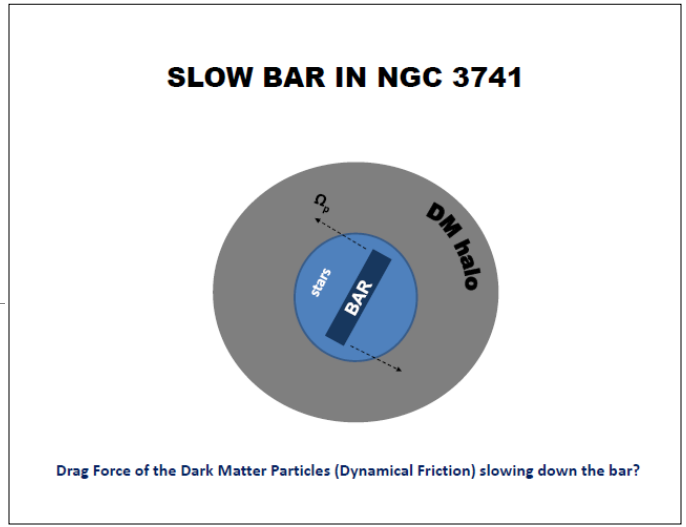
2. The slowly rotating bar in NGC 3741



NGC 3741 (HI 21 cm): ***Dwarf Irregular, Dark Matter Dominated***

Tremaine-Weinberg Method

Bar Pattern Speed from the observed surface density and velocity field of a face-on galaxy assuming **Equation of Continuity.**

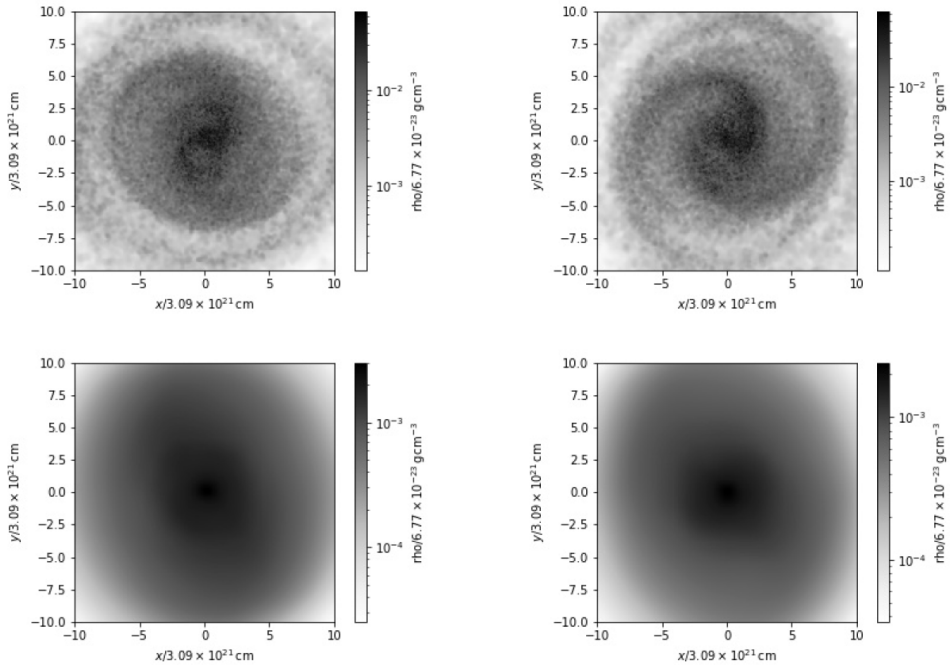


Banerjee, Patra & Chengalur 2013

3. How does a low surface brightness galaxy form spiral arms?

LSB F568-VI in an oblate DM Halo

Dark Matter axis ratio: 0.7
Spin: 0.02
Stellar Toomre Q: 1.5

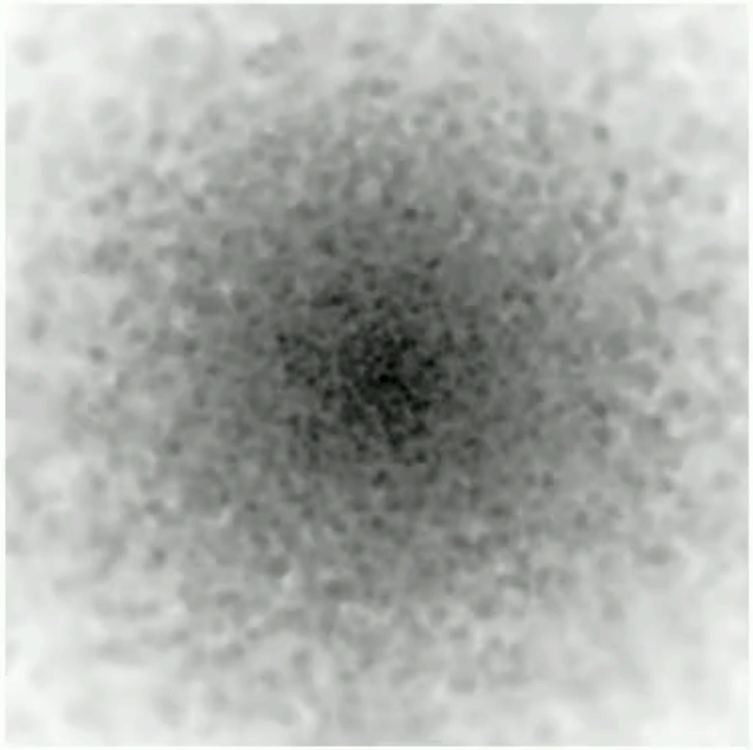


Narayanan, Anagha & Banerjee 2024

A oblate DM halo (q=0.7) sustains a spiral arm in the stellar disc surviving for more than 28 dynamical times

Results: N-body+hydrodynamical simulation

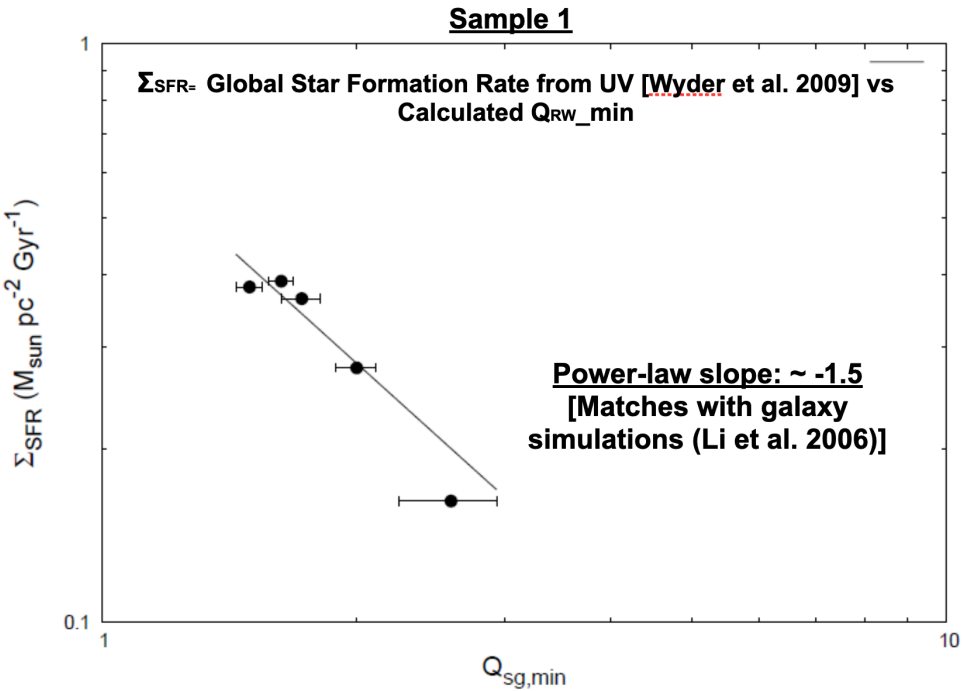
LSB F568-VI in an oblate DM Halo



Narayanan, Anagha & Banerjee 2024

4. Origin of low surface brightness galaxies

Q_{RW} vs observed SFR



Star formation rate surface density falls off with disc stability

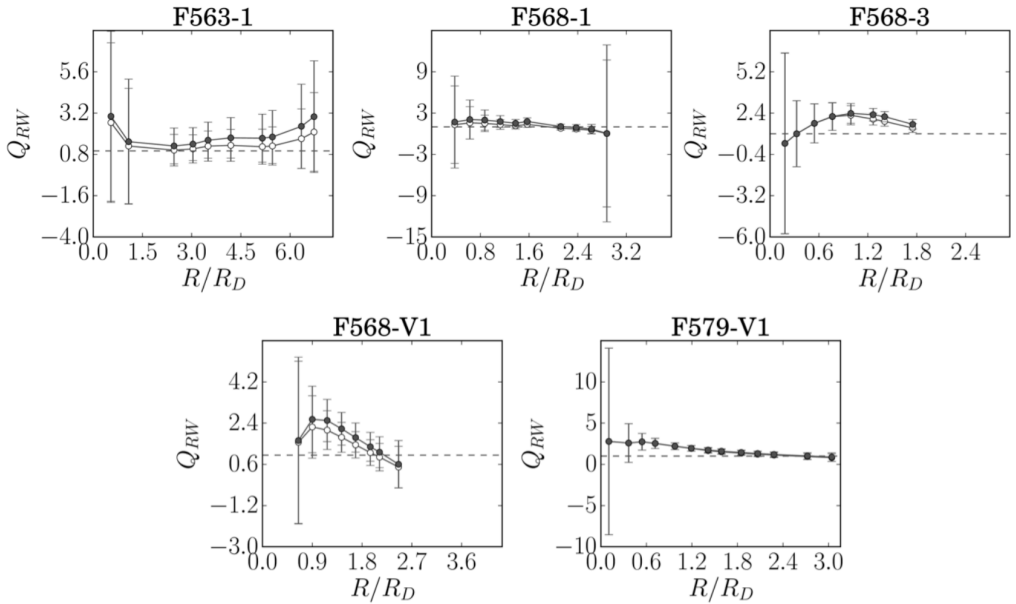
Garg & Banerjee 2017, MNRAS, 472, 166

4. Origin of low surface brightness galaxies

Q_{RW} (Disk Only) vs R

Q_{RW} (σ_{HI} = 7 km/s): ○ Q_{RW} (σ_{HI} = 11 km/s): ●

Sample 1



Disk can not be stable in the presence of only the disk potential

Garg & Banerjee 2017, MNRAS, 472, 166

Summary

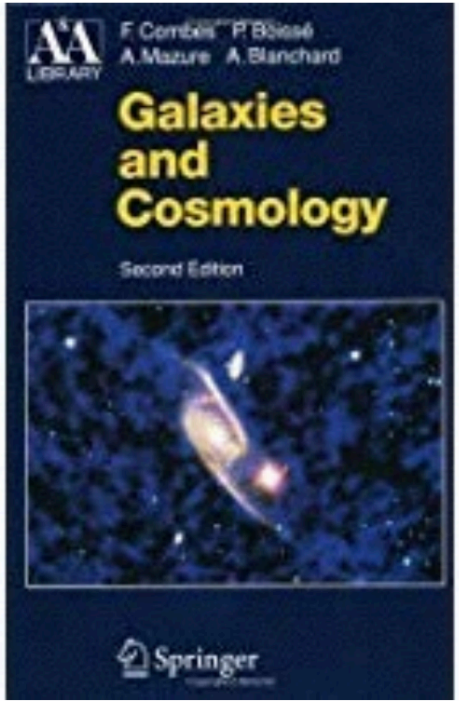
- The basic building blocks of a galaxy are stars, gas and dark matter halo
- The non-axisymmetric structures in galaxies like bars and spiral arms drive galactic secular evolution
- Galaxies lie in groups, groups in clusters and clusters in the large scale structure of the universe

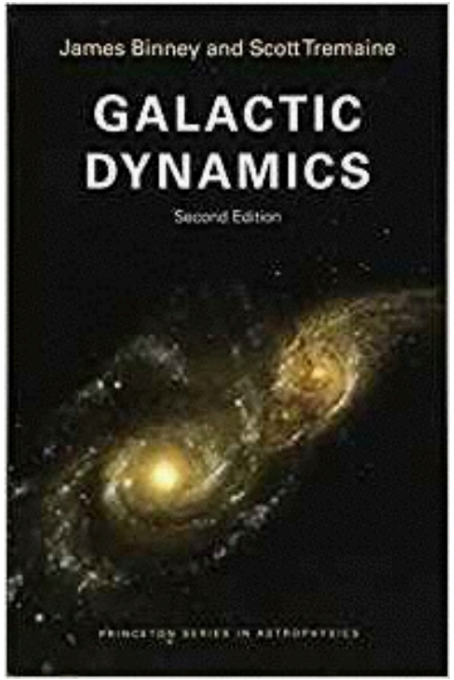
- Galaxies form via the cooling and condensation of baryons in the potential well of the dark matter halos
- There is evidence of dark matter on the scales of the galaxy, the cluster and the large scale structure of the universe
- Alternatives to Dark Matter: Modified Newtonian Dynamics and Alternative Theories of Gravity

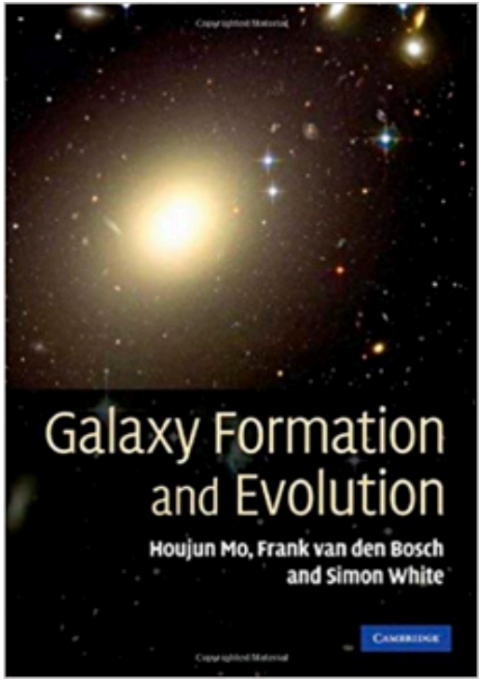
- The Dark Matter regulate disc structure and dynamics including the vertical thickness, pattern speed of the bar, formation of spiral arms and star formation

Figure Courtesy: Wikipedia/Internet

Text Books







Thank You!