Studying the shapes of dark matter halos of galaxies and effect on galaxy disks



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Outline of this talk

- Observational studies of dark matter halo shapes.
- How does halo oblate/prolate shape affect galaxy disks?
- Our study using the HI velocity dispersion in the outer disks of galaxies to derive the oblateness q of galaxy halos.
- Apply our method to a sample of galaxies and the implications of our results.
- Using HI disk flaring to study how halo shapes vary with radius.
- Are prolate halos stable in dwarf galaxies? So are oblate halos more common?

Contributors

Derivation of disk dynamical masses and halo shapes

Oblate halos and bar buckling

- Ankit Kumar (UNAB, Chile)
- Sioree Ansar (Durham University)
- S. McGaugh (Case Western Reserve University)
- Prerana Biswas (IIA)
- R. Ianjasimanana (Rhodes University, S.A.)
- J.Schombert (University of Oregon)
- K.S.Dwarakanath (Raman Research Institute)

Observations of halo shapes

Early observations indicate that dark matter halos can have different shapes.

- **Polar rings in galaxies** :This is one of the earliest methods to measure the shape of galaxy halos. Polar rings are rings of gas and stars that wrap around a disk galaxy.
- The structure can be modeled to determine the dark matter content. Some studies suggested that the halos are quite flat (E6 to E7) (Sackett et al. 1994, Arnaboldi et al. 1993a). But later studies on some other galaxies suggest that halos the shape cannot be easily determined (Combes and Arnaboldi 1996).
- However, these studies suggest that halos dominate in the outer parts of galaxies.

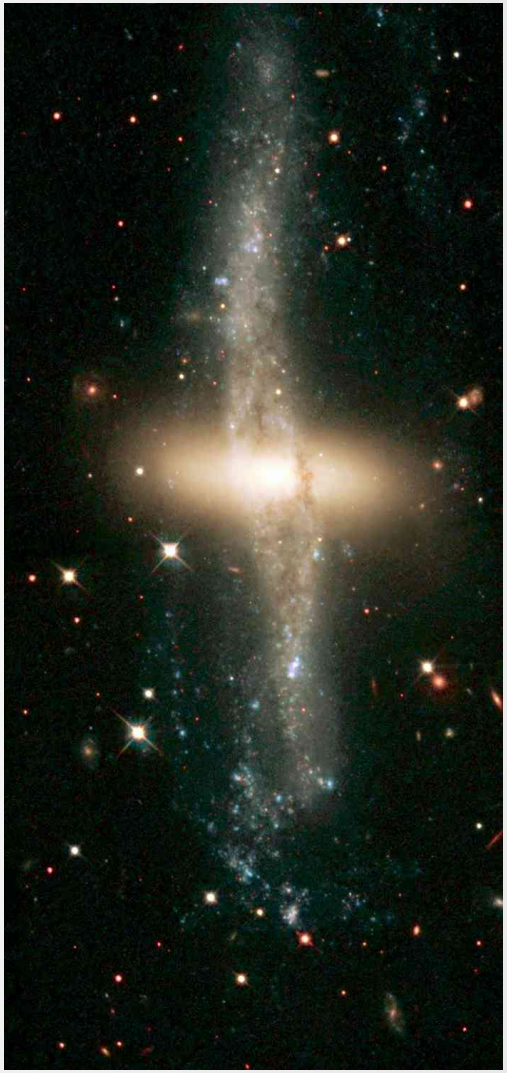
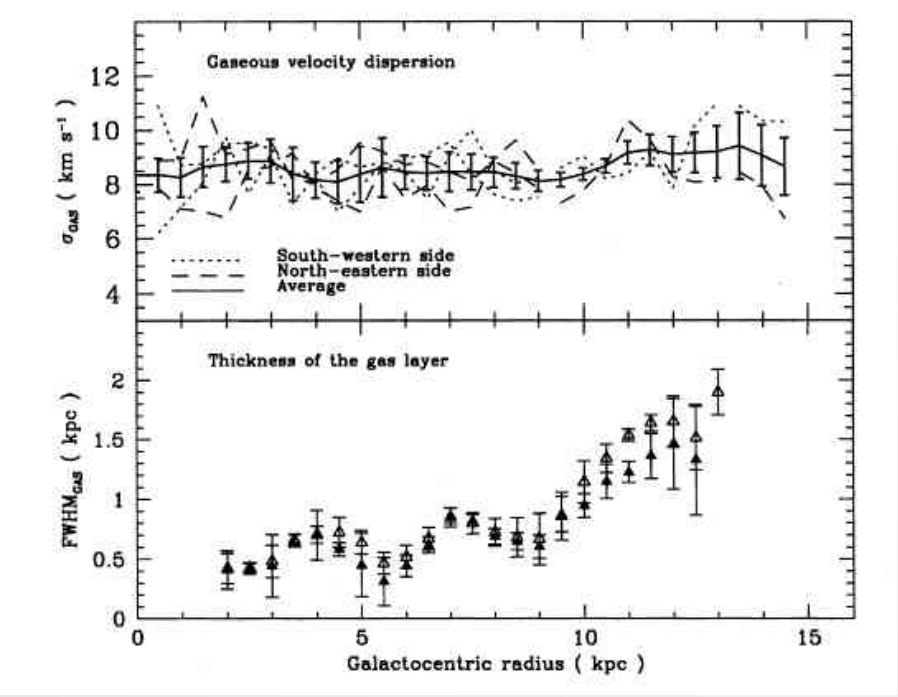


Image credit : The polar ring around the disk galaxy NGC4650A, spacetelescope.org

Observations of halo shapes : flaring of HI in edge on galaxies

- The flaring of HI gas disks in edge on galaxies can be used to estimate the halo shape (e.g. Olling et al. 2004).
- The method uses the hydrostatic equilibrium of the HI gas disk in a disk-halo potential. Some assumptions have to be made about the velocity dispersion as it is difficult to separate from rotation in edge on systems.
- The method was applied to the dwarf NGC4244 and it was found to be very oblate with q=c/a=0.2



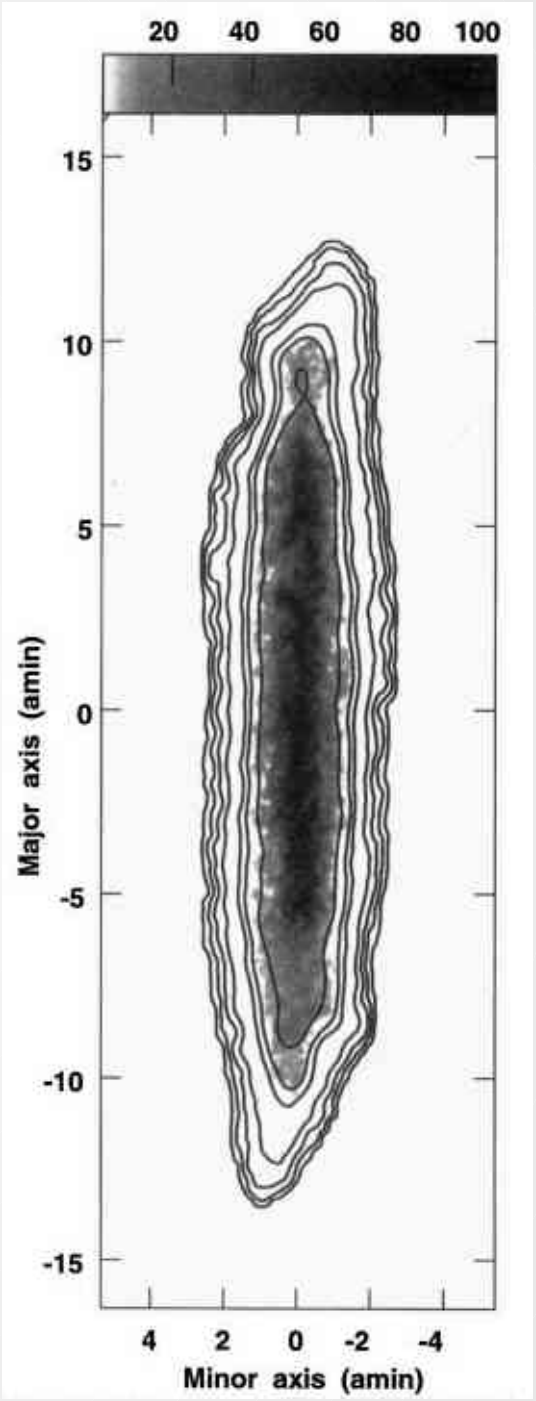


Image credit : Olling, R. 1996, AJ

Observations of the Milky Way halo shape from HI observations and globular clusters

- The HI distribution in the outer parts of our Galaxy have been modeled. The results indicate that the Milky Way may have a prolate halo (Bannerjee and Jog, 2011).
- Recent Gaia results from observations of globular clusters also indicate that the Milky Way could be prolate but oblate halos are ruled out (Posti & Helmi 2018).

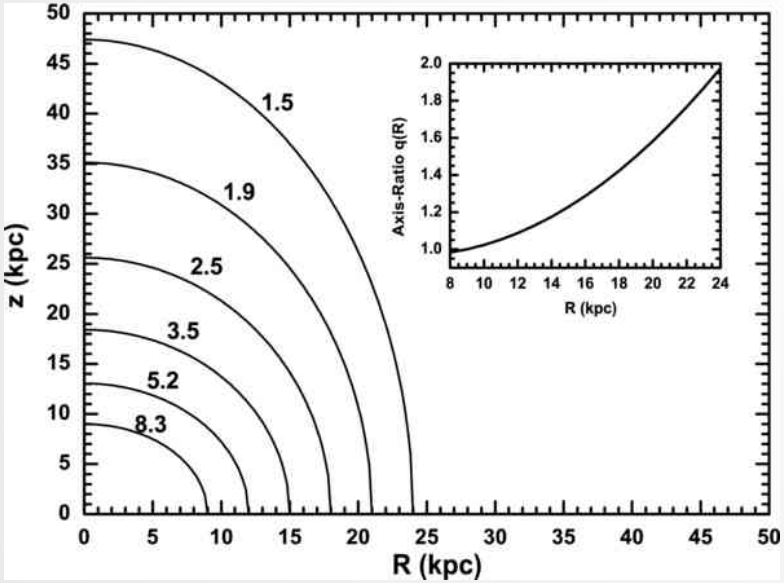


Image shows the prolateness with radius : Banerjee and Jog, 2011

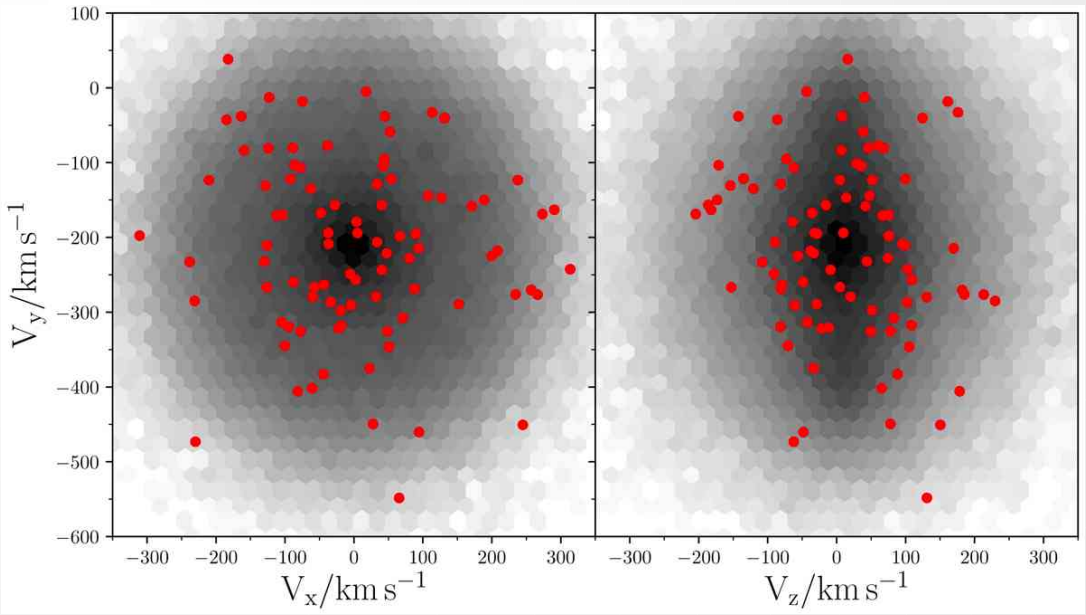


Image shows the distribution of clusters in the x-y plane (left) and x-z plane (right) : Posti and Helmi, 2018

Determining halo shapes from tidal streams

- Tidal streams are detected near the Milky Way and around other nearby galaxies (Bmartinez-Delgado et al. 2009, Chonis et al. 2011).
- Recent Gaia results from observations of tidal streams suggest our Milky Way halo is close to spherical rather than oblate (e.g. Helmi 2020).

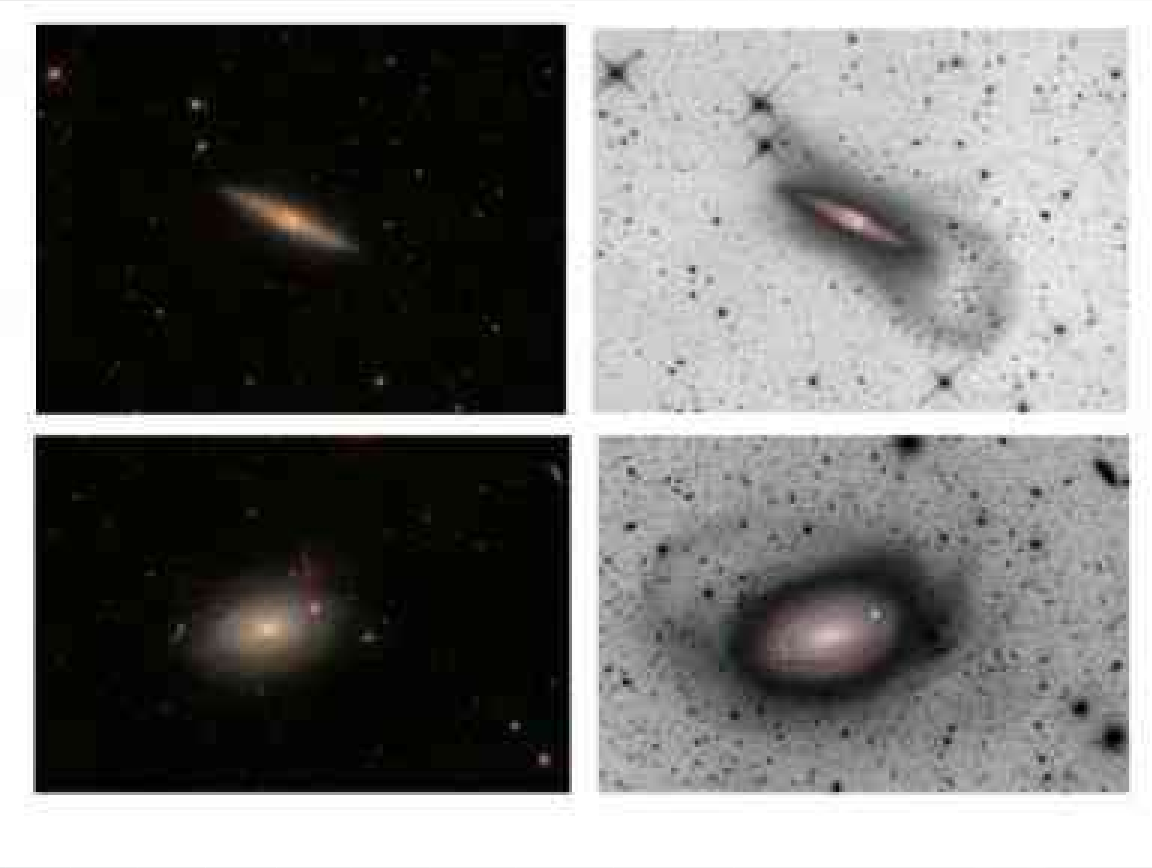


Image shows the distribution of tidal streams around NGC4013 and M63 (Carlin et al. 2016)

Early theoretical studies of dark matter halo shapes

- Early theoretical studies of dark matter halos showed that triaxial halos form in CDM theories of galaxy formation.
- However, several studies showed that the gas infall into the halos modifies the density profiles and the halo shapes. The mass infall and dissipation can alter the halo orbits near the galaxy plane, especially if the stellar disks are heavy (e.g. Dubinski 1994).
- The halo becomes more oblate as the orbit in the plane of the galaxy become rounder
- Later simulations demonstrated that gas infall causes adiabatic contraction of the halo (e.g. Gnedin+2004, Cataldi+2023)

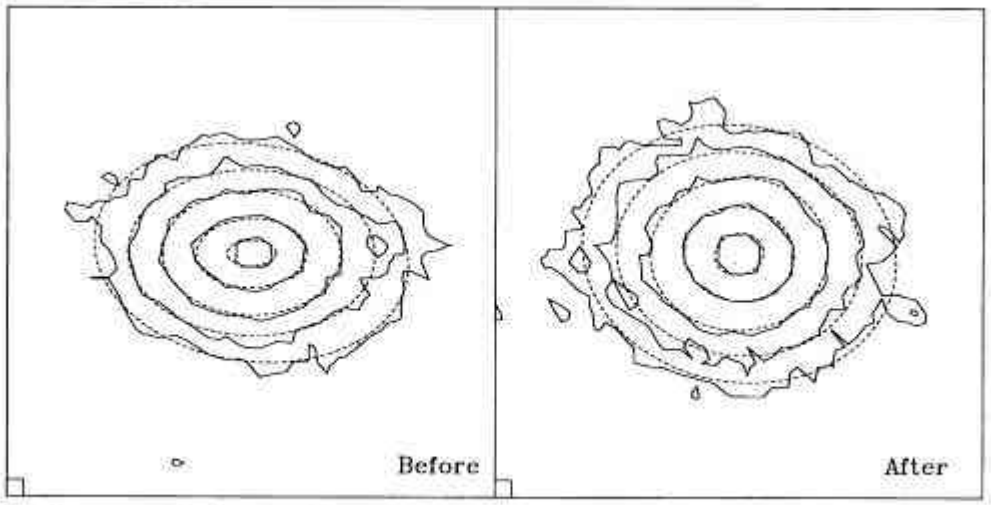


FIG. 5.—The surface density contours ("isophotes") of the dark halo in the plane of intermediate and major axis before and after the growth of the spherical Hernquist potential. The halo becomes considerably rounder in the equatorial plane and therefore more oblate.

Image credit : Dubinski 1994

The Effect of stellar and gas on dark matter halo shapes

- Simulations show that it is not just the stellar disk but dissipation due to baryonic processes such as star formation are important. Feedback associated with strong star formation is also important.
- The SMBH at the galaxy center is not just important for deepening the potential ==> if there is AGN activity associated with SMBH accretion there will be AGN feedback. The feedback will push out central mass and can affect the halo shape (e.g. Chua et al. 2019).
- The distinct difference between dark matter only and hydrodynamic simulations (e.g. Illustris) clearly show the important of the stellar disk and baryonic processes.

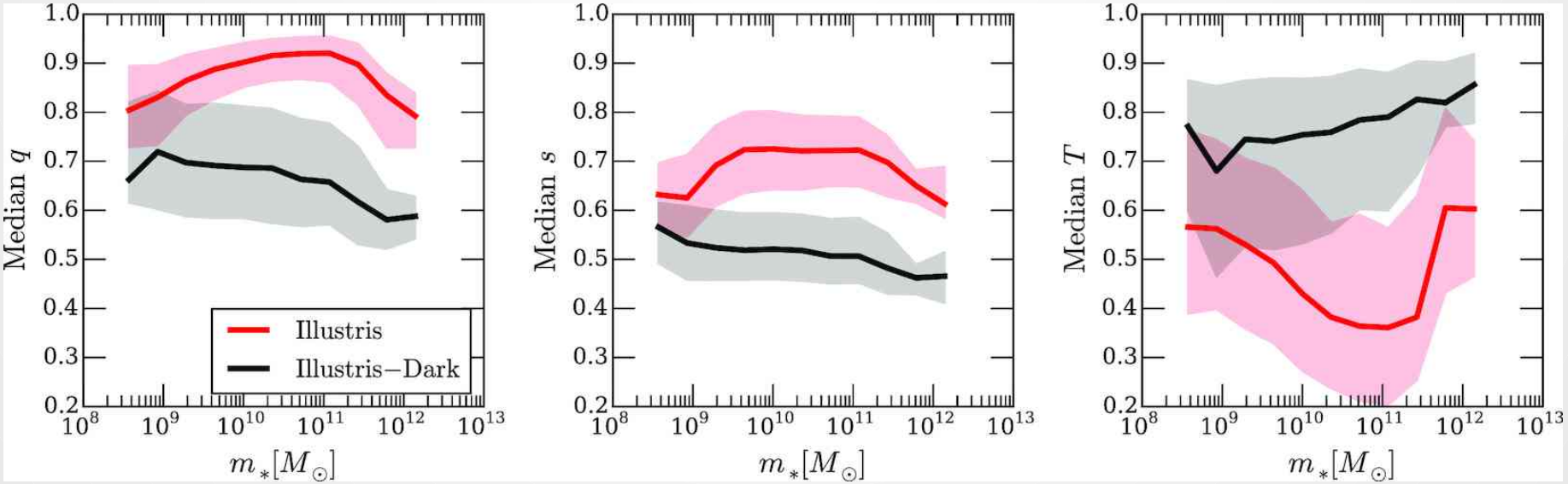


Image credit : Chua et al. MNRAS, 2019

Simulation results of halo shapes

- Large scale cosmological simulations indicate that baryons and feedback play an important role in halo shapes.
- The Auriga zoom in simulations include hydrodynamics and star formation.
- They show that Milky Way mass halos appear to have rounder halos and do not prefer triaxial halos. The b/a ratio has preferred value close to 1 but the vertical axes can extend from c/a~0.6 to 1 (Prada et al. 2019, Auriga simulations).

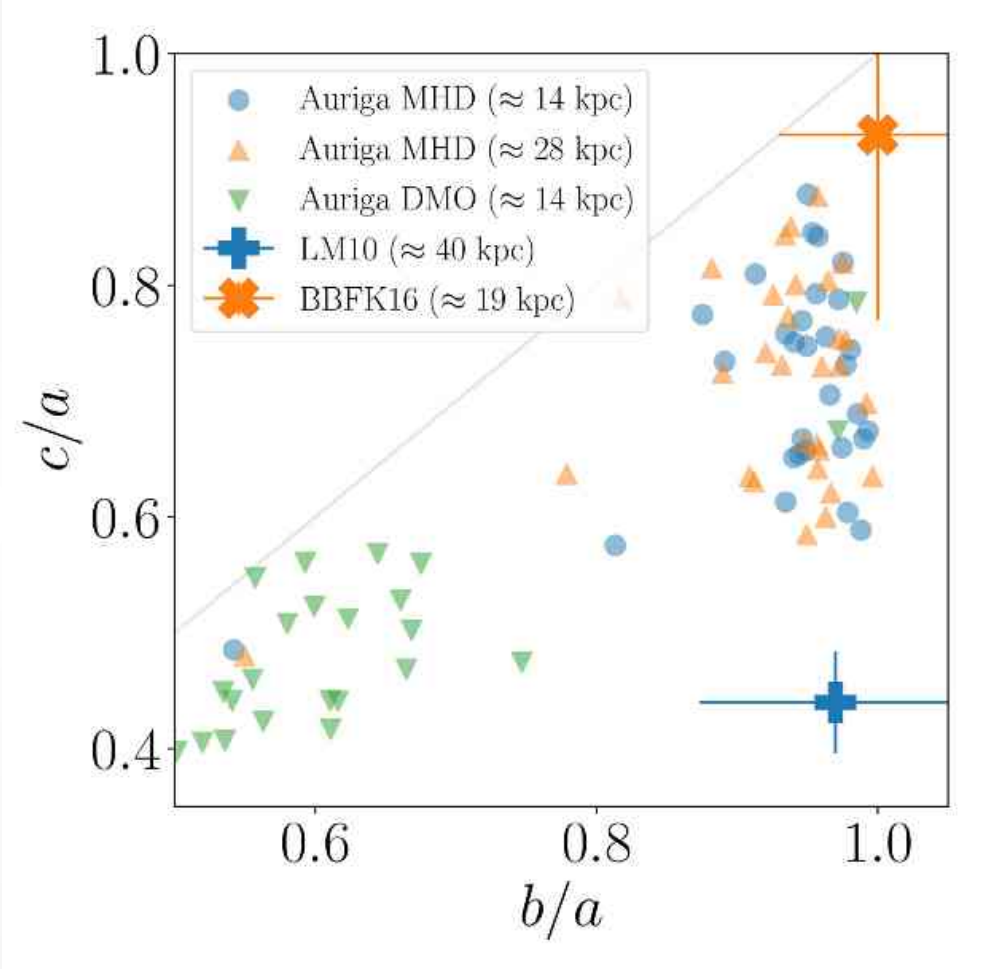


Image credit : Prada et al. 2019, MNRAS

Recent simulation results of halo shapes

- The Milky Way mass galaxies appear to be close to axisymmetric in the plane of the galaxy. The halos appear flatter in the z direction with c/a~ 0.6 to 0.8 (Prada et al. 2019, Auriga simulations).
- At least 20% of the halos have close to spherical shapes.
- This matches recent results that model the tidal streams in our Galaxy which indicate that the Galaxy halo is close to spherical.

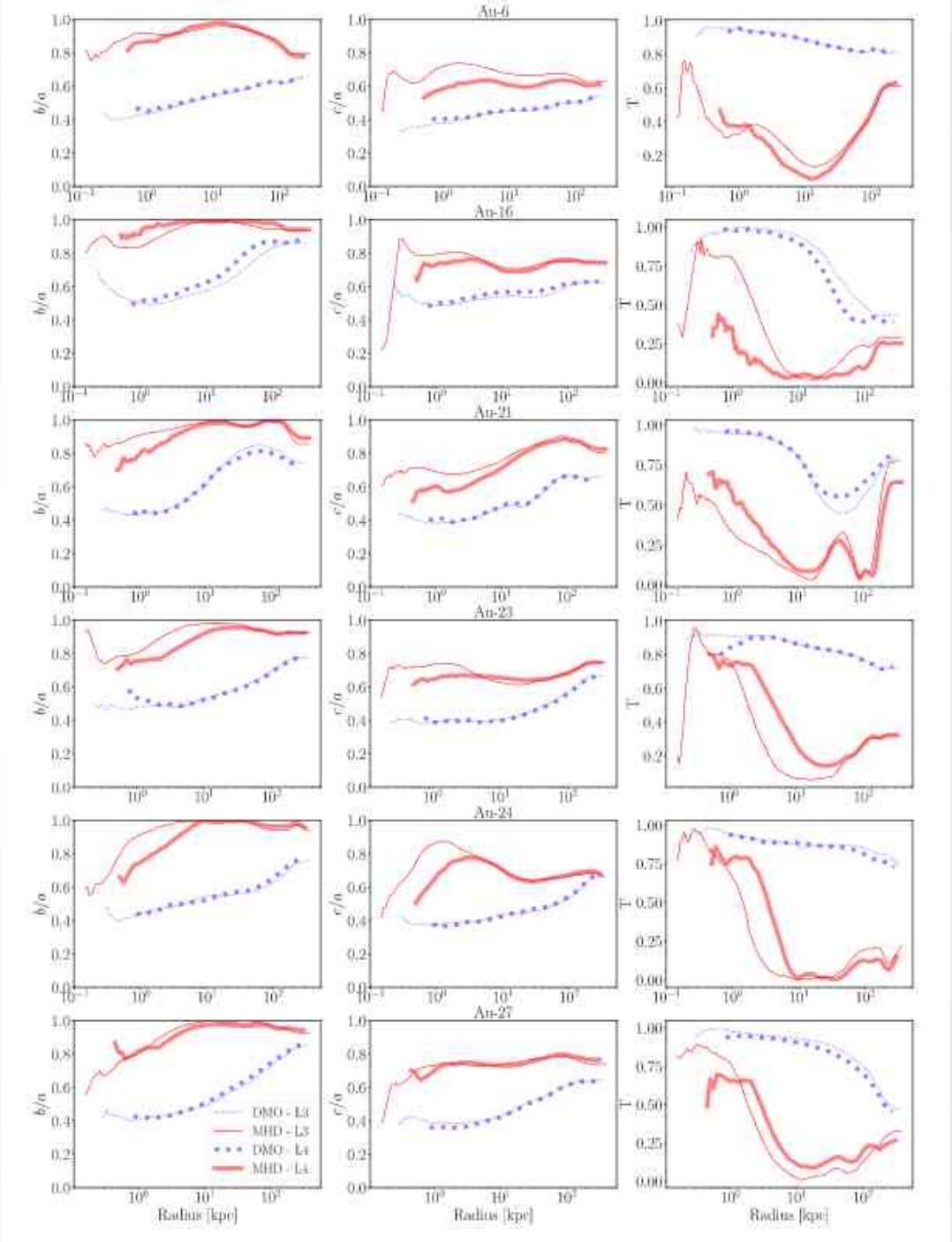


Image credit : Prada et al. 2019, MNRAS

The effect of halo shapes on disk dynamics

- A more oblate halo shape means that there is more dark matter associated with the disk. This can affect the formation of disk instabilities.
- The rotation curve flat velocities will be different from the spherical halos (Binney & Tremaine, 2008).

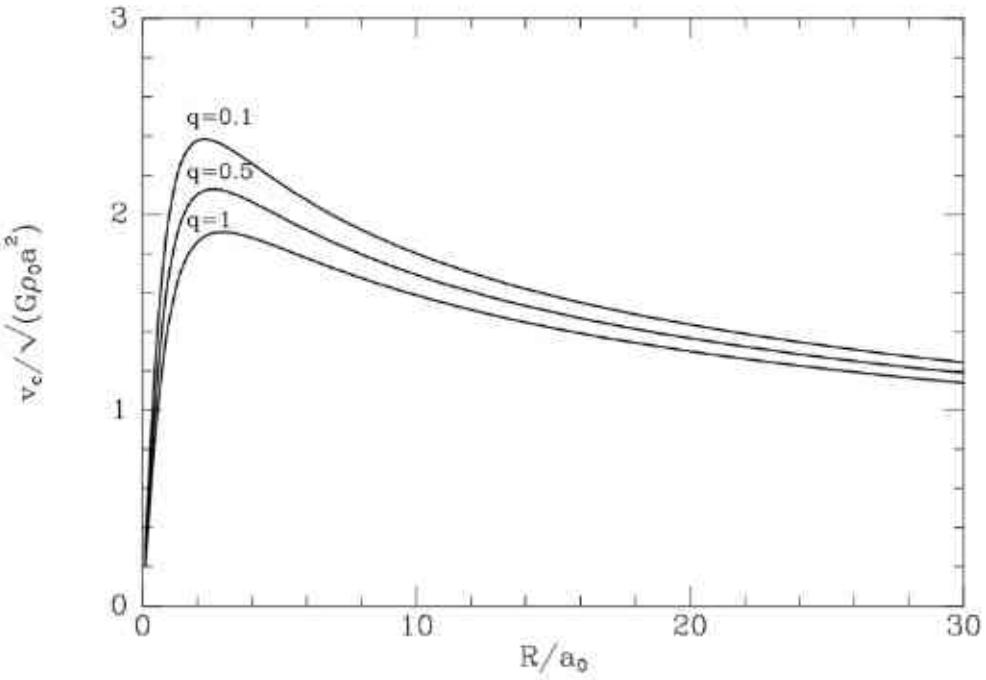
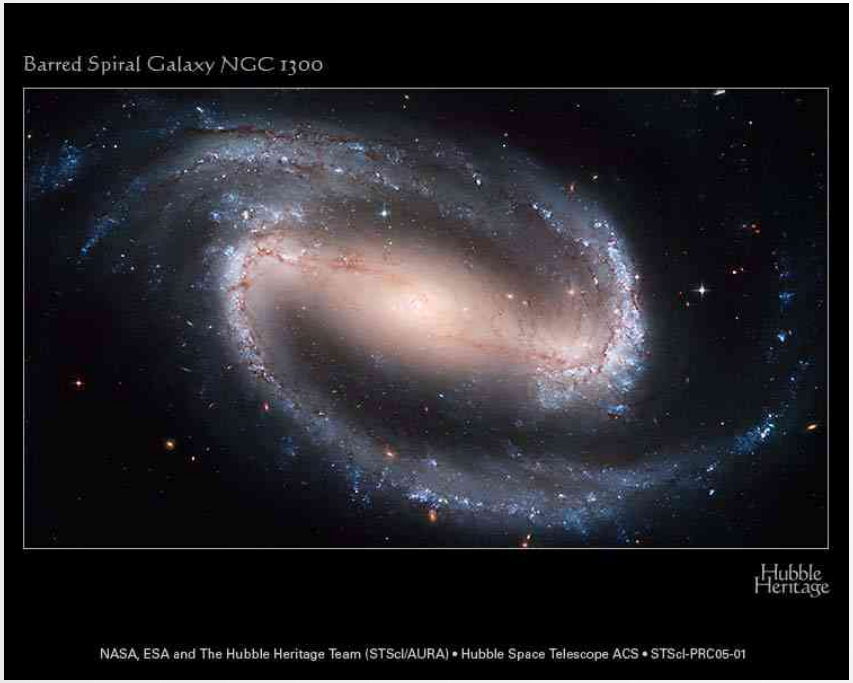


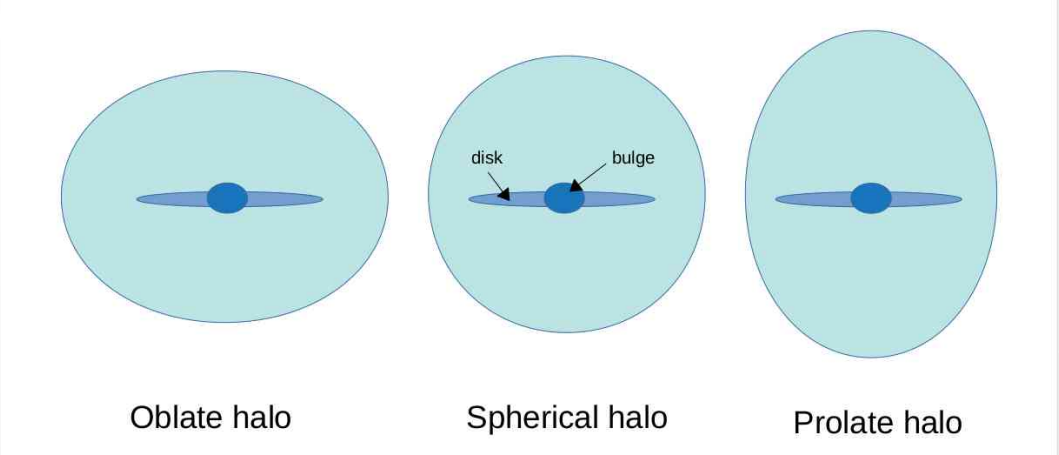
Figure 2.13 Circular speed versus radius for three bodies with the same face-on projected density profile (the modified Hubble model, eq. 2.133) but different axis ratios $q = c/a$. Though all three bodies have the same mass inside a spheroid of given semi-major axis, v_c increases with flattening $1 - q$.

The effect of halo shape on bar formation and bar buckling

Kumar+2022, MNRAS.

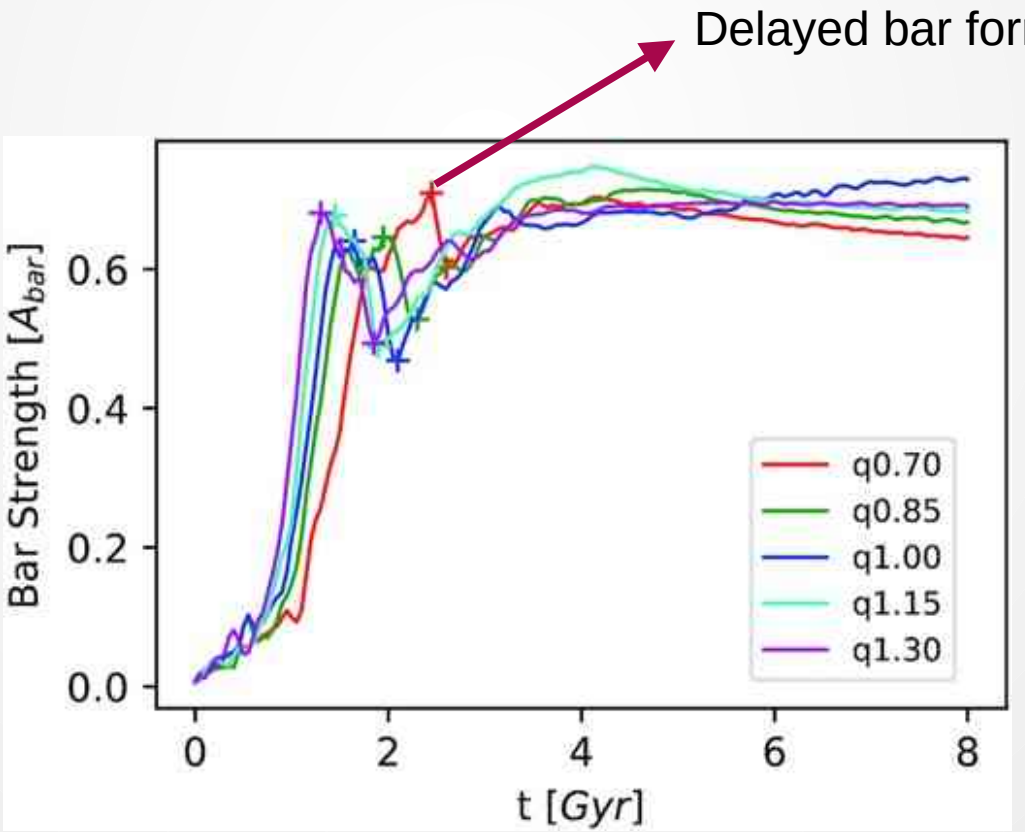
- We have investigated how oblate halos affect bar formation and bar buckling using N-body simulations, where the halo axes ratio c/a in z-direction is changed.
- The evolution of bars is affected. Bars form later in galaxies with oblate halos





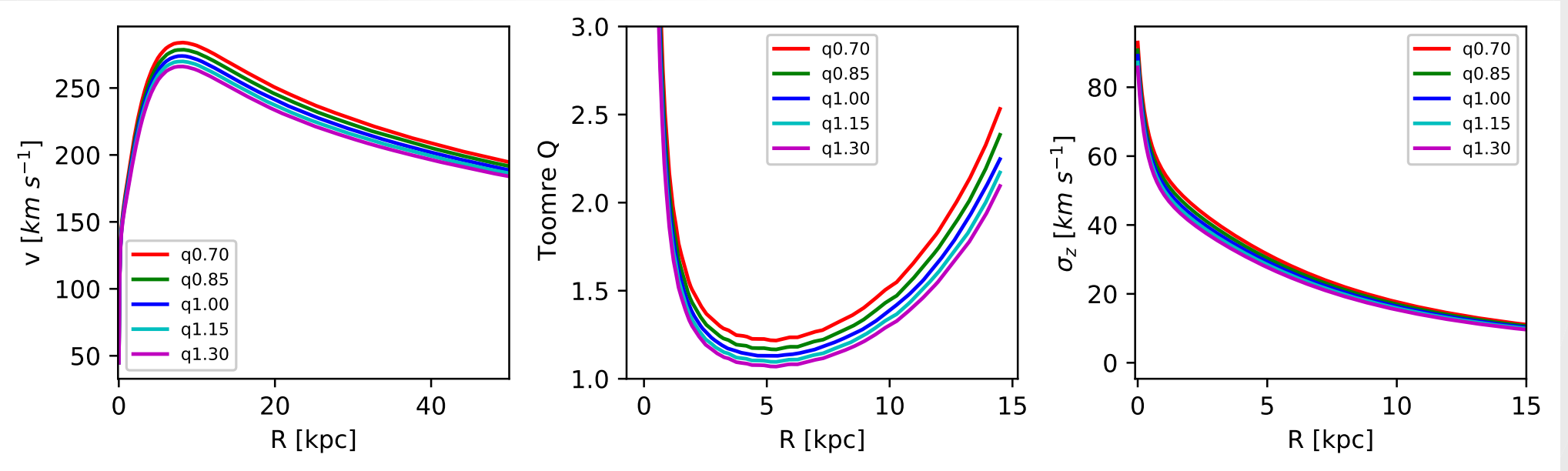
Bar formation delayed in oblate halos

- We have investigated how oblate halos affect bar formation and bar buckling using N-body simulations, where the halo axes ratio c/a in z-direction is changed.
- The evolution of bars is affected. Bars form later in galaxies with oblate halos



Delayed bar formation due to higher velocity dispersion

- The stellar velocity dispersion is higher in disks with oblate halos. More mass associated with the disk.
- So the Toomre stability factor is affected suggesting that the disk instabilities (global and local) are more difficult to form.

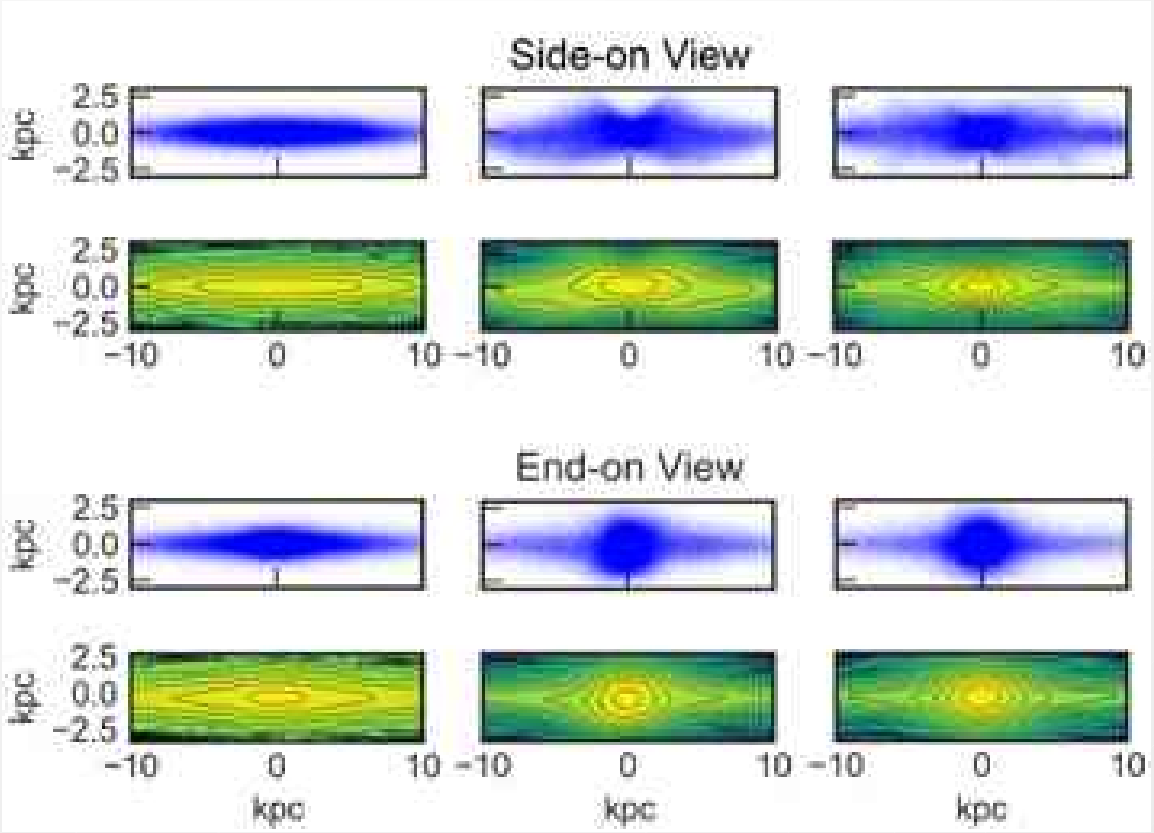


Kumar+2022, MNRAS.

How Halo shape affects bar buckling

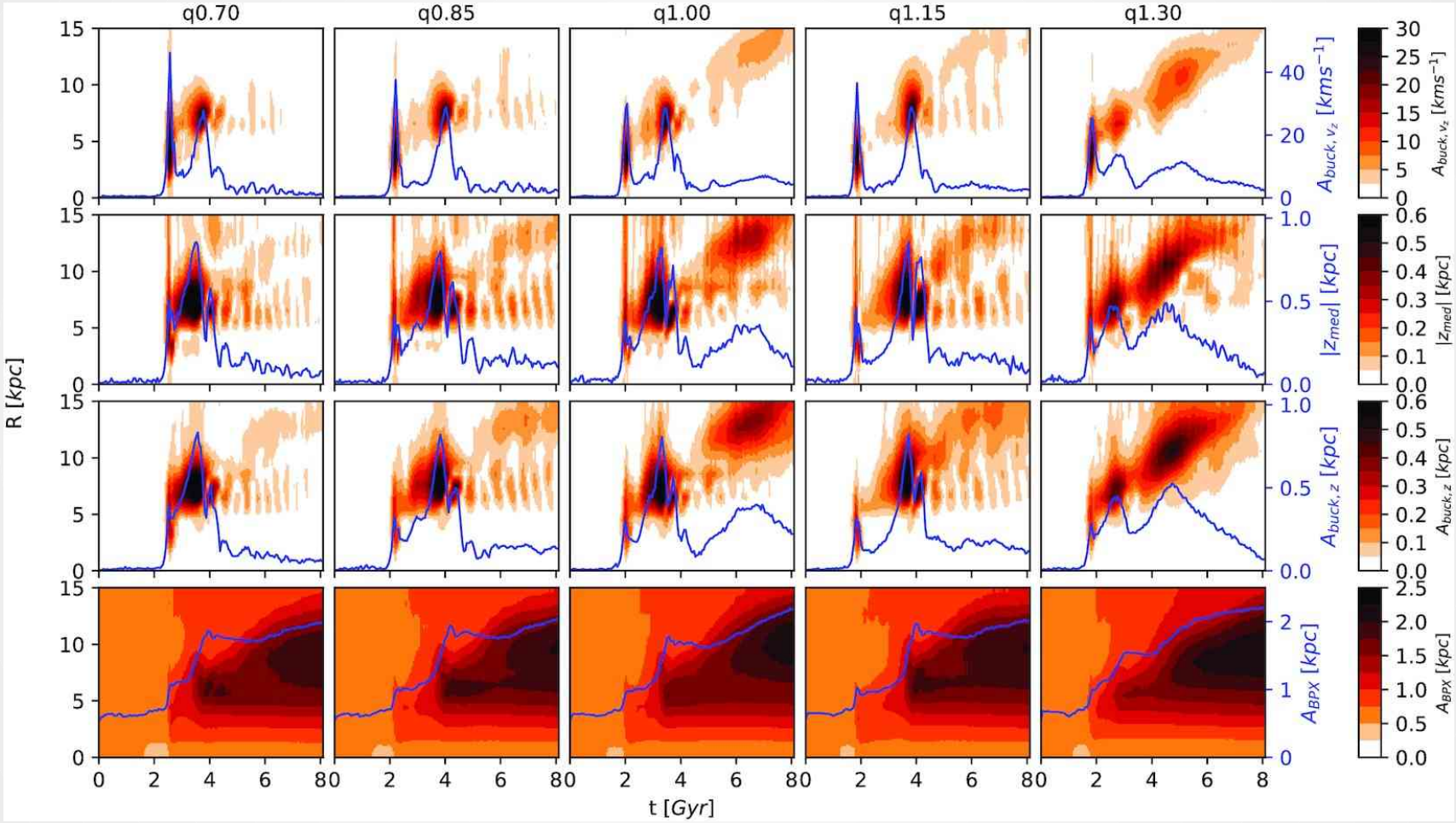
- Bars in galaxies can thicken in the direction vertical to the disk due to instability or secular evolution. This is called bar buckling and maybe affected by the halo shape.
- Buckling results in boxy, peanut or X-shaped bulged or BPX features
- Do bars buckle later in galaxies with oblate halos?

Xiang+2021,



Bars buckle more in prolate halos

Kumar et al. 2022, MNRAS.



In general disk instabilities (bars, spiral arms, local instabilities) maybe less in oblate halos compared to prolate ones.

Disk Dark matter derived from HI velocity dispersion observations

The velocity dispersion σ in a face-on galaxy represents the motion normal to the galaxy plane. So for neutral hydrogen (HI) gas distributions σ_{HI} represents the vertical velocity dispersion. We can use it as a tracer to study disk equilibrium in face on galaxies.

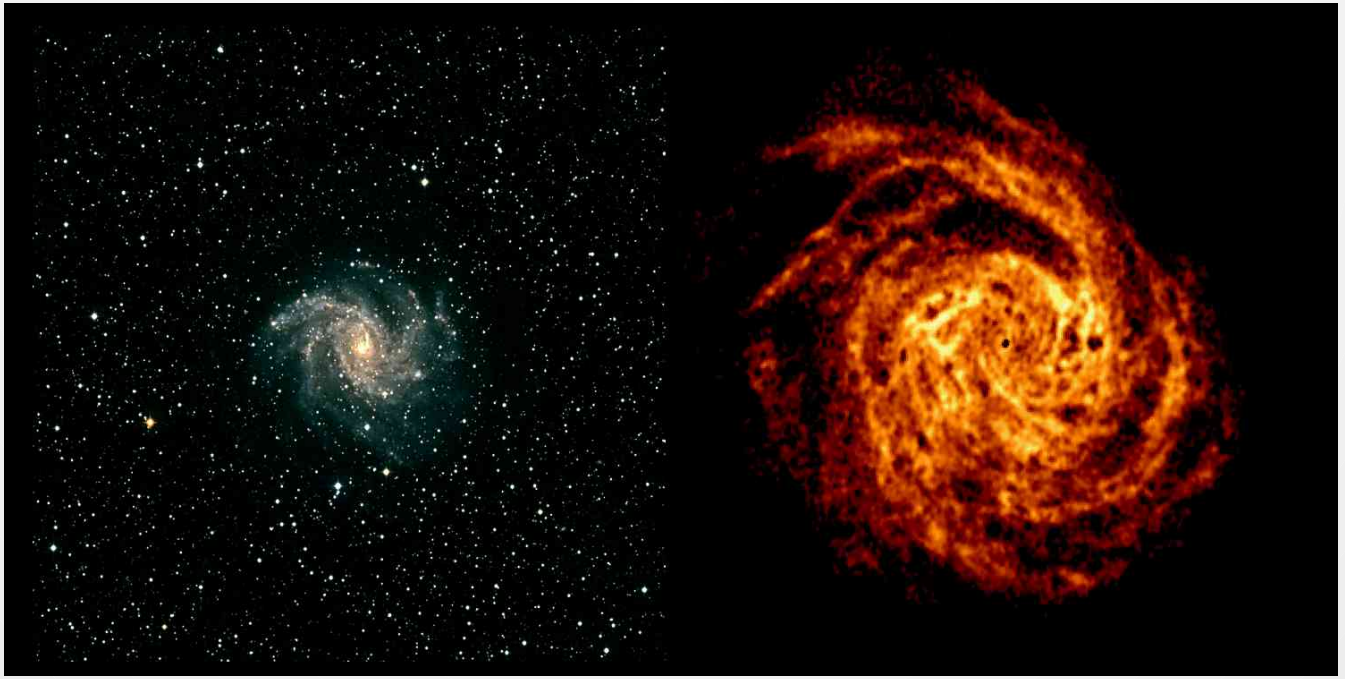
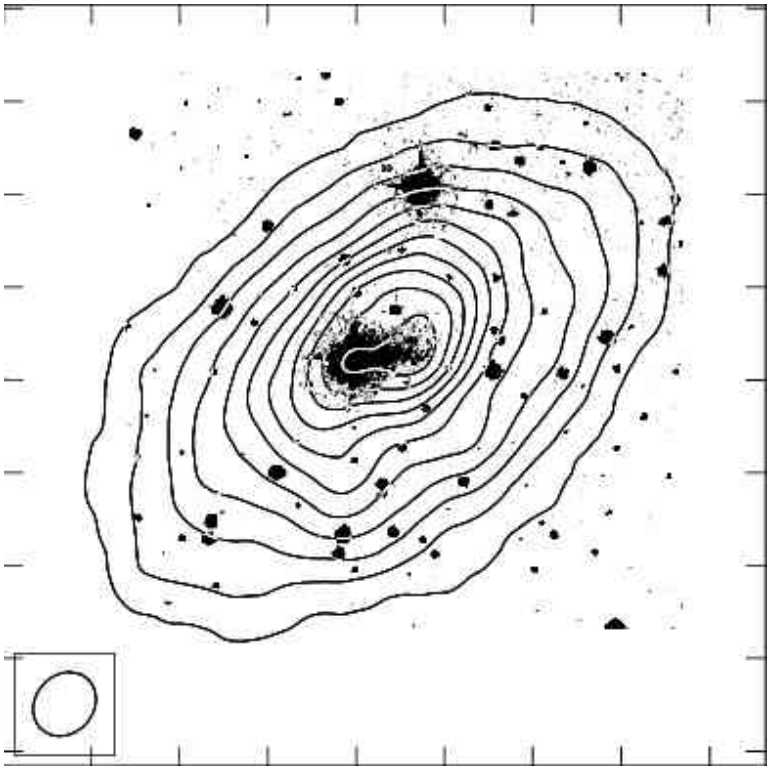


Image credit : van der Hulst, NGC6946 in optical and HI

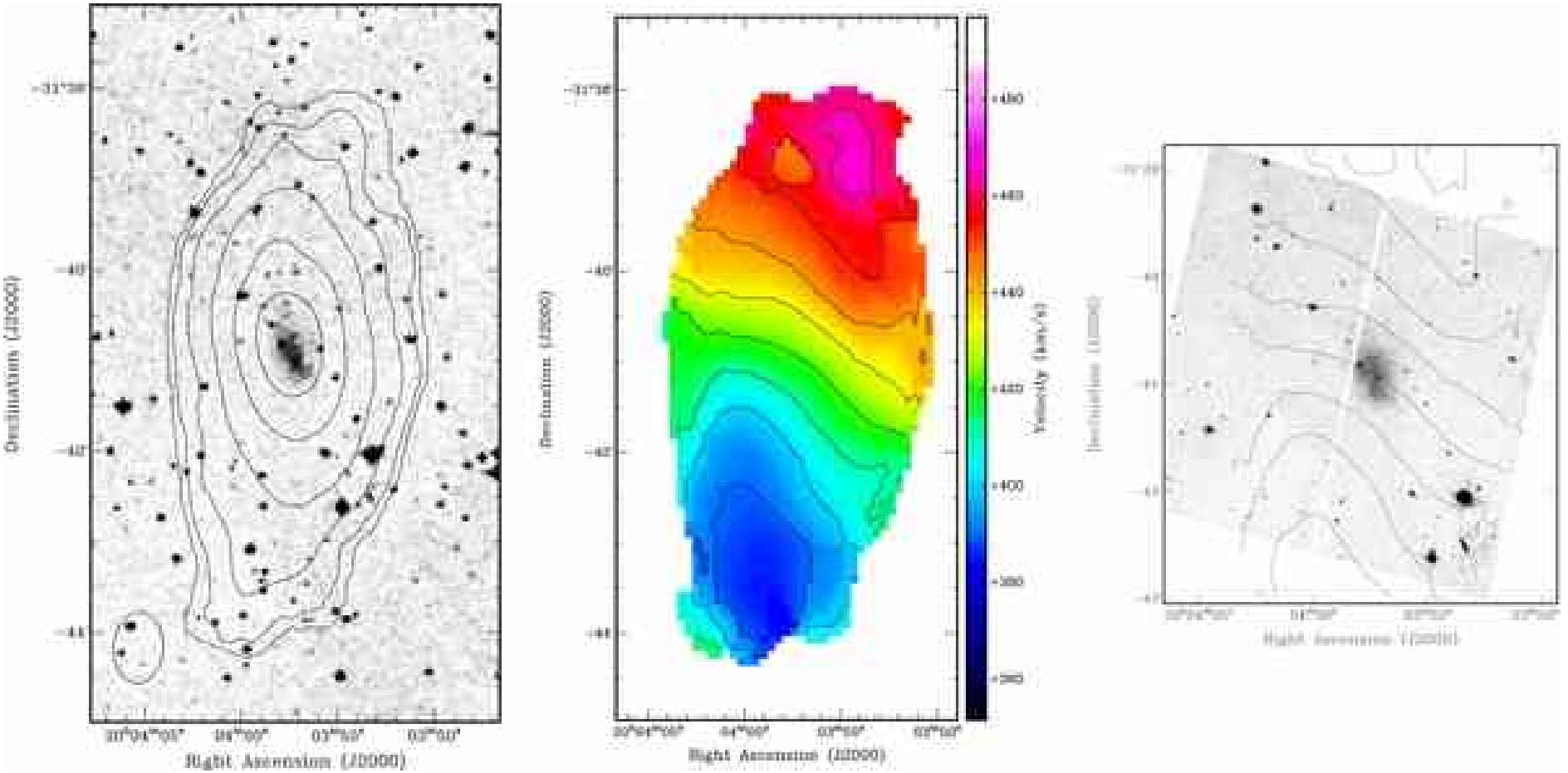
The Gravitational Support of Disks

- **Rotational support** : $GM(dyn)/r^2=v^2/r$
- **Vertical Support :** is due to the self gravity of the stellar disk
- But what happens in regions where there is very little stellar disk mass?
- There are many examples of large extended HI gas disks that are associated with very little stellar mass.
- How can an HI disk support itself without the self gravity of stars?



A gas rich dwarf galaxy from FIGGS survey (Chengalur+2007)

A good example of extended gas disks are the gas rich dwarfs



A gas rich dwarf galaxy KK246 (Kreckel+2012)

Main questions

- How is the vertical equilibrium maintained in the extended HI disks of galaxies?
- How can we estimate the disk dark matter? Can we estimate it from neutral hydrogen (HI) velocity dispersion?
- Is disk dark matter important for the vertical equilibrium? If it is, then how does it affect the shape of the halo?

Using HI velocity dispersion in face-on galaxies to determine dark matter associated with the disk

- The HI can be used to trace the potential of the disk using simple vertical equilibrium.

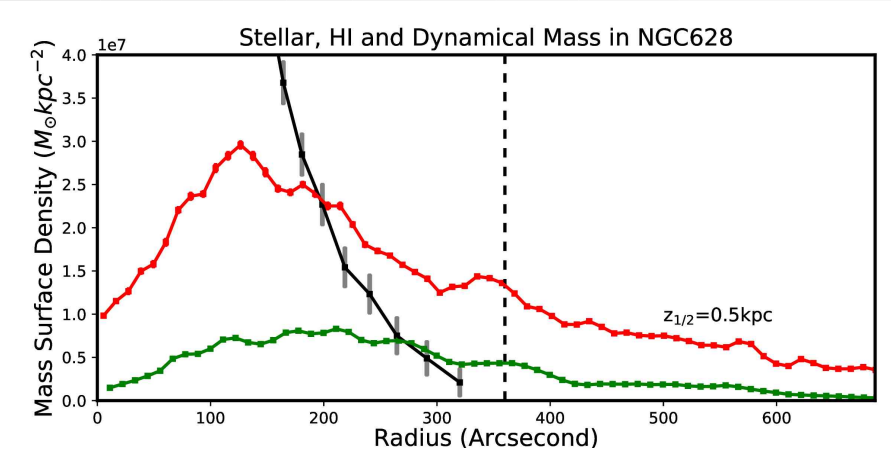
$$1/\rho_{HI}\ d/dz[\rho_{HI}\sigma_{HI}^2] = -d\Phi/dz$$

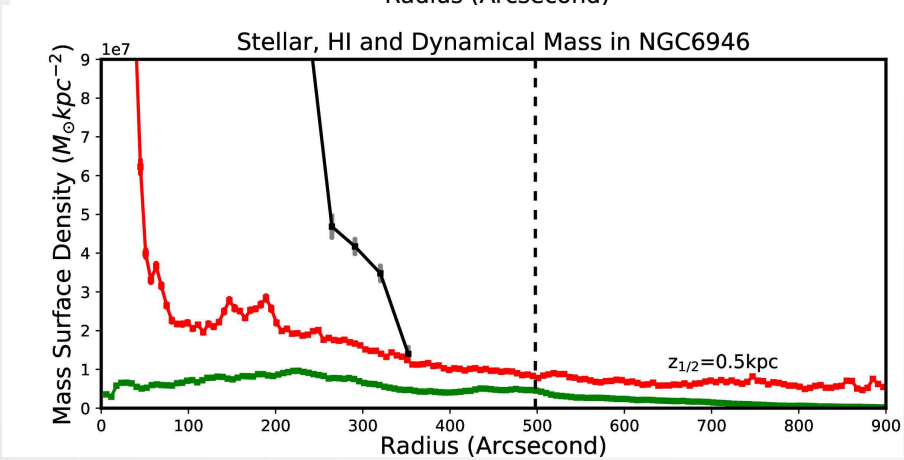
- We can then determine an expression for the disk dynamical mass surface density which is given by $\Sigma_{dyn}=\sigma_{HI}^2/\pi G z_{g0}$ where z_{g0} is the disk vertical scale length.
- If $\Sigma_{dyn} > \Sigma$(baryonic), it means that the disk dark matter is significant. In these regions the dark matter associated with the galaxy disk helps gravitationally bind the HI to the disk.

(Das+2020)

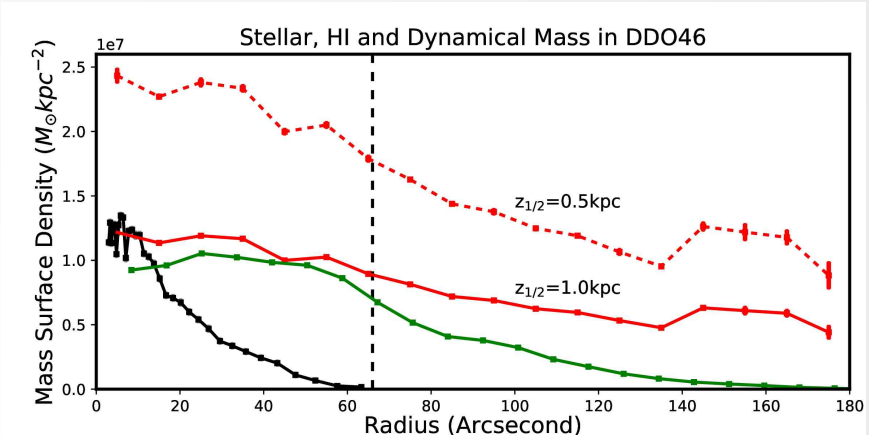
The difference in dynamical and baryonic mass densities in the outer disks of large spirals and dwarfs

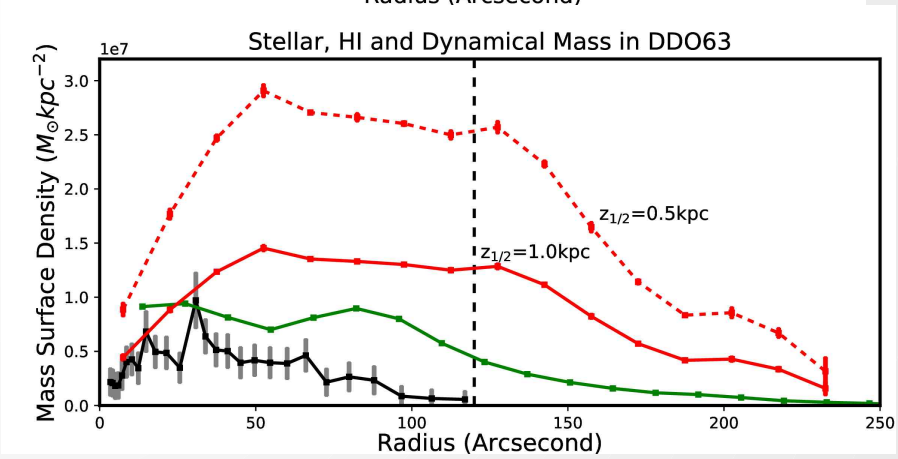
Large disk galaxies





Gas rich dwarf galaxies





- For the outer disks of gas rich dwarfs we clearly have : $\Sigma_{dyn} > \Sigma_{HI}$, which means that the disk dark matter is significant.

Modeling the halo oblateness factor q (c/a)

(Das+2023)

- We assume a logarithmic form for the halo potential and an exponential form for the vertical gas and stellar distributions.

$$1/\rho_{HI}\ d/dz[\rho_{HI}\sigma_{HI}^2] = -d\Phi/dz$$

Where $\Phi_{halo} = \frac{1}{2}\ v_o^2 \ln(R_c^2 + R^2 + z^2/q^2)$

- For regions where there is no stellar disk and only HI gas we obtain

$$\mathbf{q^2 = v_o^2 z_{g0}^2 \times 1/R^2[\sigma^2 - \pi G z_{g0} \Sigma(HI)]}$$

- So if we have HI velocity dispersion and surface density in the outer parts of the disks we can determine the halo oblateness parameter q.
- The sample galaxies were selected based on their inclination angles (nearly face-on). The HI velocity dispersion σ and Σ(HI) were obtained from THINGS survey data products (Walter et al. 2008) and the LITTLE THINGS (Hunter et al. 2012) survey. The velocity decomposition of the moment2 maps were obtained (e.g. Ianjasimanana et al. 2015, Mogotsi et al. 2016). The rotation velocities were obtained from an empirical relation that depends on stellar mass (Lelli et al. 2016).
- Totally 20 galaxies : 12 have very low stellar masses, and 8 have higher stellar masses.

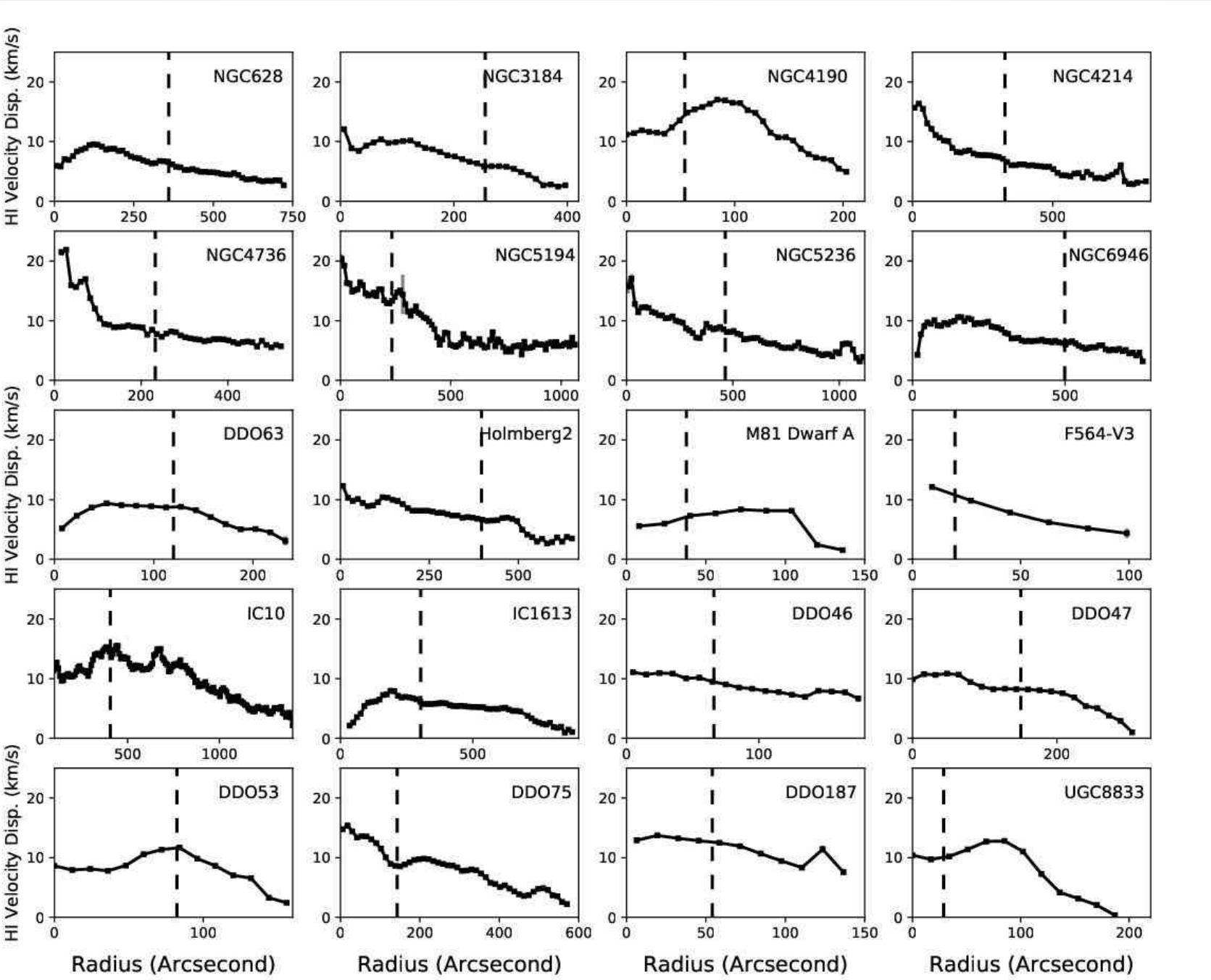
Sample galaxies : table

Table 1
Properties of the Galaxies

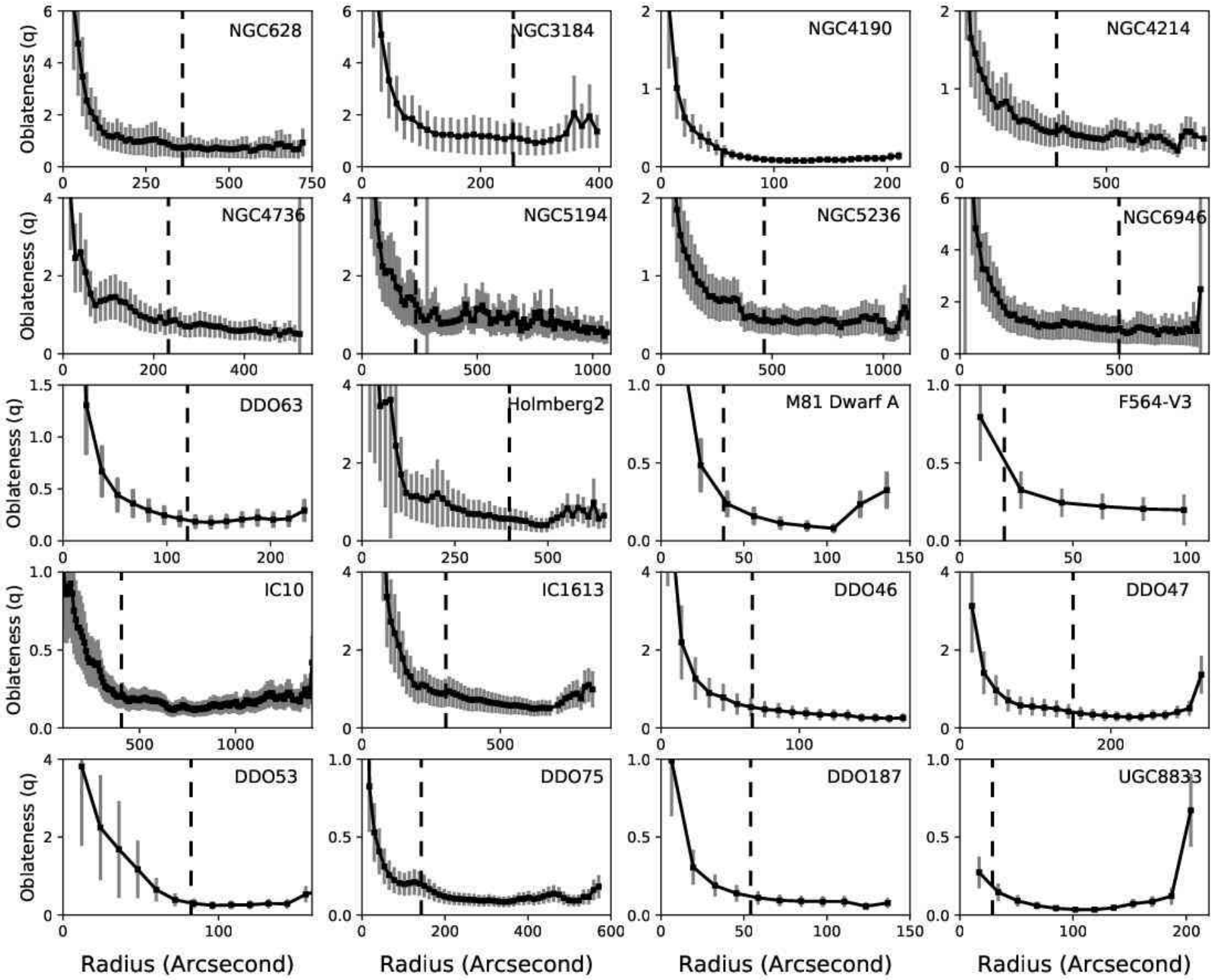
Galaxy	Other Name	Type	Distance (Mpc)	Spatial Scale (pc arcsec^{-1})	Incl. (deg)	R_{25B} (arcsec)	R_d (arcsec)	R_d (kpc)	v_0 (km s^{-1})	Reference for R_d
NGC 0628	UGC 01149	SA(s)c, H II	7.3	35.4	7.0	360.0	70.7	2.5	146.3	Ganda et al. (2009)
NGC 3184	UGC 05557	SAB(rs)cd	11.1	53.8	16.0	255.0	56.4	0.92	158.6	Tamburro et al. (2008)
NGC 4190	UGC 07232	Im pec	2.83	13.7	29.0	54.0	21.1	0.29	44.3	Lelli et al. 2016
NGC 4214	UGC 07278	IAB(s)m	2.9	14.1	44.0	330.0	62.1	0.87	76.8	Hermelo et al. (2013)
NGC 4736	UGC 07996	(R)SA(r)ab	4.7	22.8	41.0	232.9	49.8	1.1	162.2	Casasola et al. (2017)
NGC 5194	UGC 08493;	SA(s)bc pec	8.0	38.8	41.0	232.9	78.0	3.03	209.6	Casasola et al. (2017)
NGC 5236	UGCA 366	SAB(s)c	4.5	21.8	24.0	465.7	54.0	1.18	200.2	Bicay et al. 1989
NGC 6946	UGC 11597	SAB(rs)cd	5.9	28.6	33.0	497.9	68.0	5.31	182.5	Prieto et al. (2001)
Holmberg1	DDO 63	IAB(s)m	3.9	18.9	0.0	120.0	36.0	0.68	47.9	Hunter et al. (2019)
Holmberg2	DDO50	Im	3.4	16.5	41.0	396.4	89.8	1.10	69.5	Hunter et al. (2019)
M81 dwfA	PGC 23521	Irr?	3.6	17.5	23.0	37.8	14.9	0.26	32.2	Hunter et al. (2019)
F564-V3	LSBC D564-08	.....	8.7	42.2	35.0	19.6	12.6	0.53	40.7	Hunter et al. (2012)
IC 10	UGC 192	IBm	0.7	3.4	41.0	405.0	117.8	0.40	55.8	Hunter et al. (2012)
IC 1613	UGC 00668	IB(s)m	0.7	3.4	37.9	303.5	170.9	0.58	51.5	Hunter et al. (2012)
DDO 46	UGC 3966	Im	6.1	29.6	28.6	66.0	38.5	1.14	49.4	Hunter et al. (2012)
DDO 47	UGC 3974	IB(s)m	5.2	25.2	17.0	150.0	54.4	1.37	62.9	Hunter et al. (2012)
DDO 53	UGC 04459	Im	3.6	17.5	39.5	54	41.3	0.72	37.9	Hunter et al. (2012)
DDO 75	Sextans A	IBm	1.3	6.3	33.5	142.8	34.9	0.22	39.8	Hunter et al. (2012)
DDO 187	UGC 9128	Im	2.2	10.7	39.0	54.0	16.9	0.18	27.3	Hunter et al. (2012)
UGC 8833	PGC 049452	Im	3.1	14.9	28.0	28.8	11.3	0.17	27.3	Bremnes et al. 1999

Note. The disk flat rotation velocity v_0 is derived from the baryonic Tully–Fsher relation, as described in Section 2. The last column gives the reference for the disk scale length R_d.

The HI velocity dispersion



Oblateness

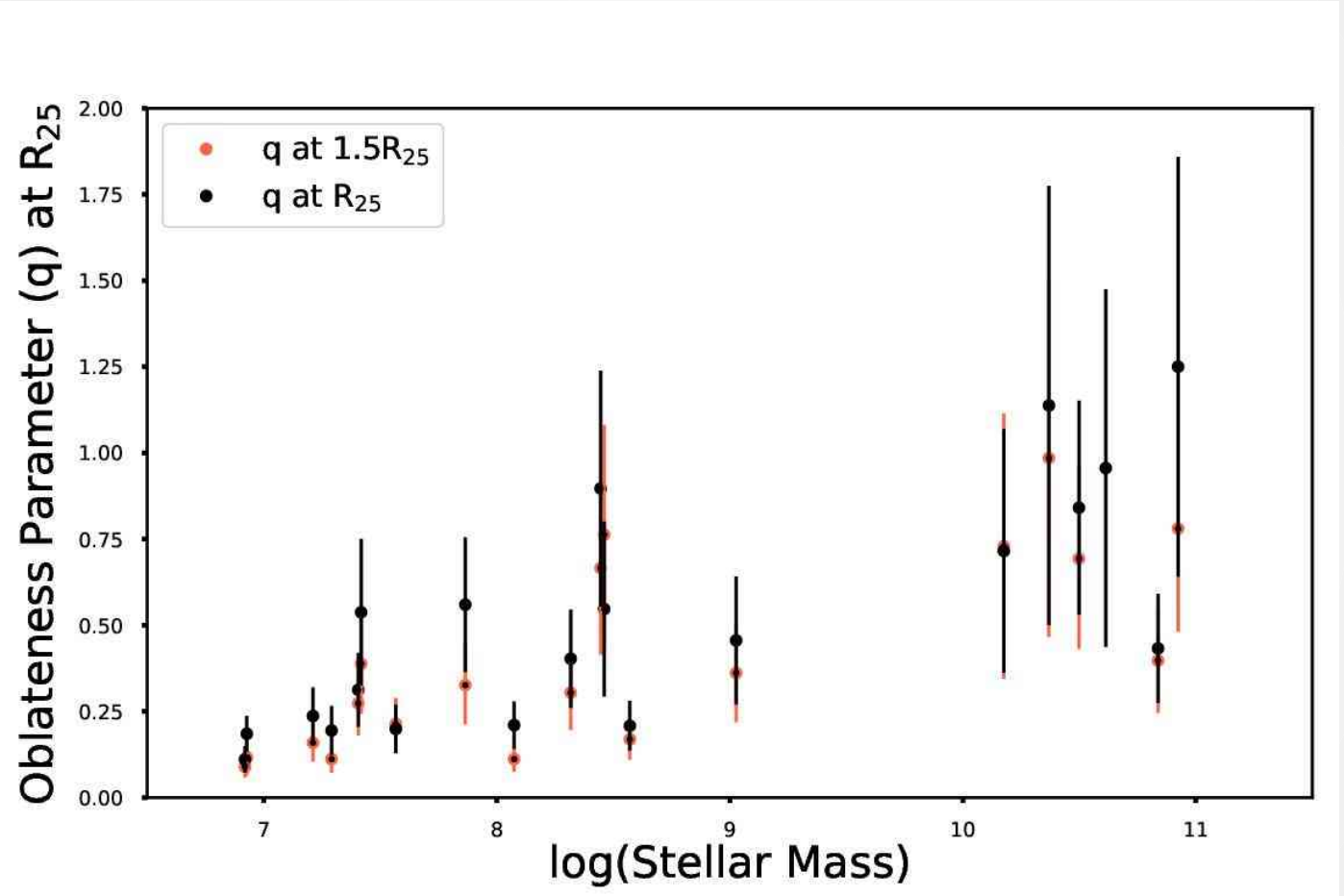

NGC628
NGC3184
NGC4190
NGC4214
NGC4736
NGC5194
NGC5236
NGC6946
DDO63
Holmberg2
M81 Dwarf A
F564-V3
IC10
IC1613
DDO46
DDO47
DDO53
DDO75
DDO187
UGC8833
Oblateness (q)
Radius (Arcsecond)

Oblateness of the galaxies

Table 2
Stellar and Gas Masses, and the Halo Oblateness

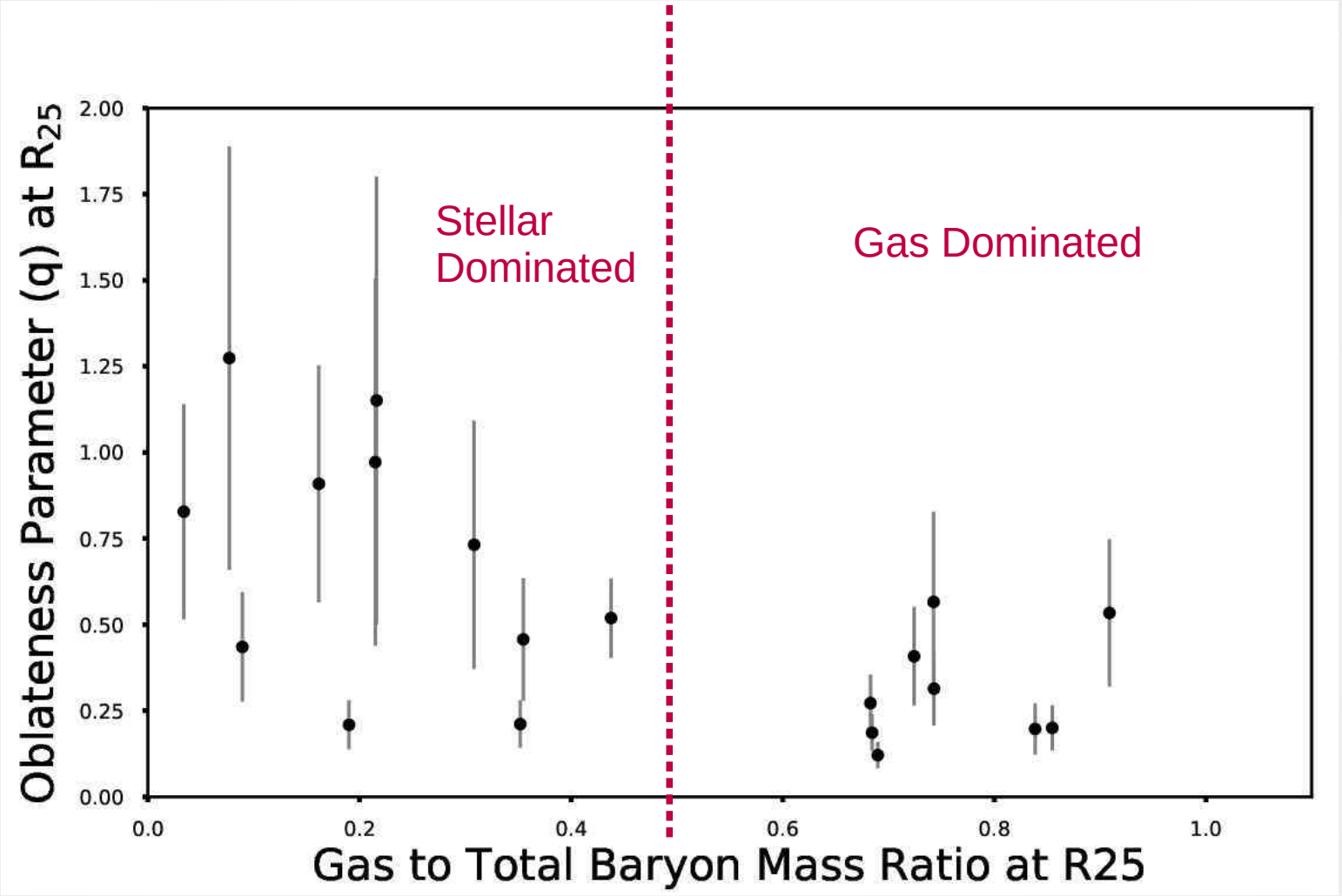
Galaxy	$M(*)$ ($10^8\ M_\odot$)	M(H I) ($10^8\ M_\odot$)	$M(H_2)$ ($10^8\ M_\odot$)	M(gas)/M(total)	q (R_{25})	q ($1.5R_{25}$)
NGC 0628	1.50×10^2	3.80×10^1	10	0.31	0.73 ± 0.36	0.74 ± 0.39
NGC 3184	2.34×10^2	3.07×10^1	15.85×10^2	0.22	1.15 ± 0.65	1.91 ± 1.20
NGC 4190	1.19	0.46	<0.001	0.35	0.21 ± 0.07	0.11 ± 0.04
NGC 4214	1.06×10^1	4.08	10^7	0.35	0.46 ± 0.18	0.36 ± 0.14
NGC 4736	3.15×10^2	4.0	$10^{8.6}$	0.03	0.83 ± 0.31	0.69 ± 0.26
NGC 5194	8.38×10^2	2.54×10^1	$10^{9.4}$	0.08	1.27 ± 0.61	0.79 ± 0.30
NGC 5236	6.88×10^2	1.70×10^1	3.2×10^1	0.09	0.44 ± 0.16	0.40 ± 0.15
NGC 6946	4.10×10^2	4.15×10^1	$10^{9.6}$	0.21	0.97 ± 0.53	1.50 ± 0.58
Holmberg1	0.37	1.55	<0.17	0.85	0.20 ± 0.07	0.21 ± 0.07
Holmberg2	2.89	5.95	<0.40	0.74	0.57 ± 0.26	0.79 ± 0.32
M81 dwfA	0.16	0.25	0	0.68	0.27 ± 0.08	0.16 ± 0.06
F564-V3	0.73	0.41	<0.01	0.44	0.52 ± 0.11	0.32 ± 0.11
IC 10	3.72	0.60	0.02	0.19	0.21 ± 0.07	0.17 ± 0.06
IC 1613	2.79	0.34	0.05	0.16	0.91 ± 0.34	0.67 ± 0.25
DDO 46	0.26	1.86	<0.06	0.91	0.53 ± 0.21	0.39 ± 0.15
DDO 47	2.07	3.89	....	0.72	0.41 ± 0.14	0.28 ± 0.10
DDO 53	0.25	0.52	...	0.74	0.31 ± 0.11	0.27 ± 0.09
DDO 75	0.20	0.57	<0.02	0.84	0.20 ± 0.07	0.11 ± 0.04
DDO 187	0.08	0.13	<0.004	0.69	0.12 ± 0.04	0.09 ± 0.03
UGC 8833	0.08	0.13	...	0.68	0.19 ± 0.05	0.12 ± 0.03

Correlation of halo q with stellar mass logM(*)



- The q calculated at R_{25} radius and at 1.5xR_{25} radius shows an increasing trend of q with logM(*). The correlation with stellar mass is strong and has a correlation coefficient of 0.78

Correlation of halo q with M(gas)/M(baryon)



- There is a clear difference in q values for gas dominated galaxies that have M(gas)/M(baryon) > 0.5 where q is calculated at R_{25} radius. Gas dominated galaxies have oblate halos with q<0.55.
- But stellar dominated galaxies can have a range of q values.

Results of our study of oblateness q of halos

- Gas rich galaxies have oblate halos with q<0.55.
- The q is really small for the gas rich dwarfs (e.g. DDO46, DDO63, DDO75, DDO187). It is < 0.2. Such low q has been observed in NGC4244 (Olling et al. 1996). For the other low stellar mass galaxies q varies from 0.2 to 0.55.
- The main result that q appears to decrease with increasing gas mass in dwarf galaxies may see surprising. With baryonic contraction we would expect massive galaxies to be more oblate.
- Maybe explained by : (i) halo spin- dwarfs have higher halo angular momentum. Maybe due to tidal torques in early epochs. (ii) more massive stellar disks affect halo orbits resulting in rounder halos.

The HI disk flaring and effect on q of halos

(Biswas in prep.)

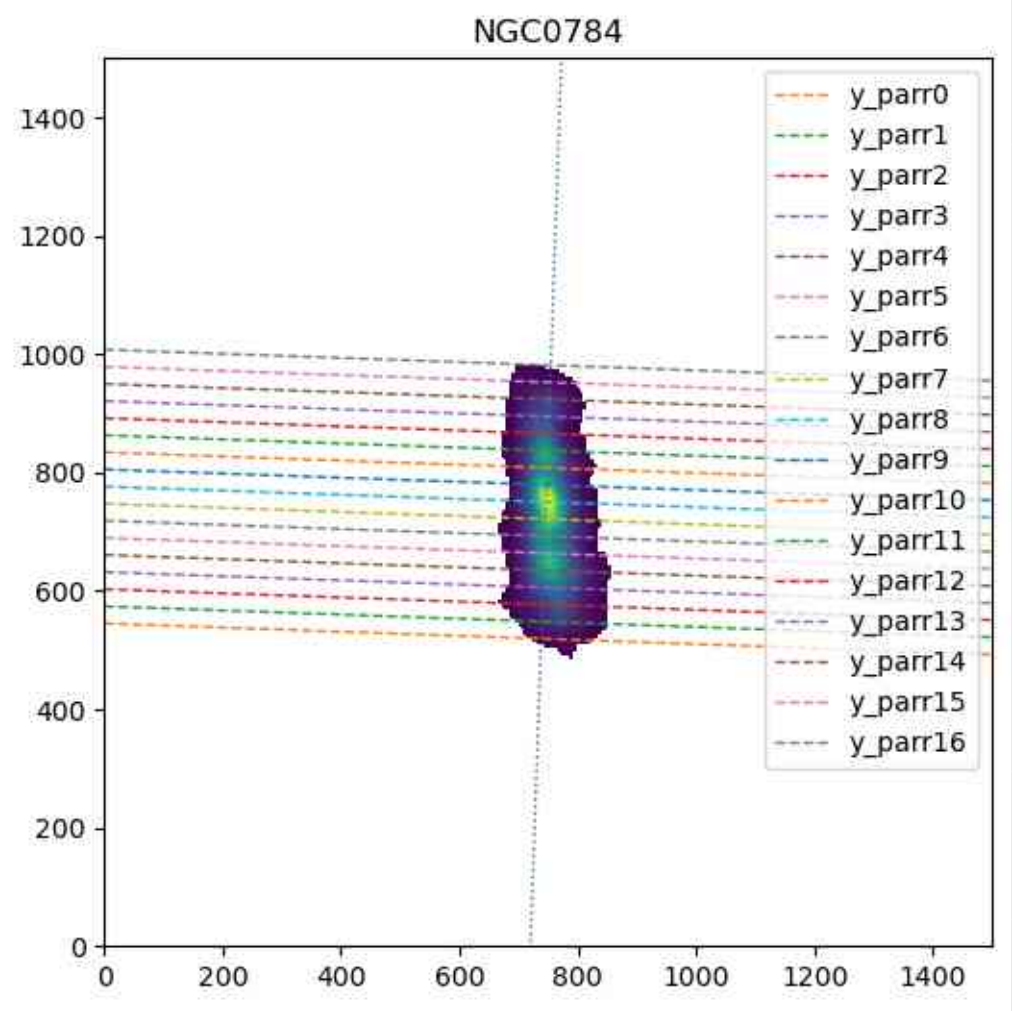
- The extended HI disks of gas rich galaxies are well known to have flared morphology and sometimes warped.
- The flaring will affect the halo q value. If z scale height increases then the q will reduce.

$$q^2 = v_o^2 z_{g0}^2 \times 1/R^2[\sigma^2 - \pi G z_{g0} \Sigma(HI)]$$

- **This can only be determined by calculating the flaring of HI disks with radius.**

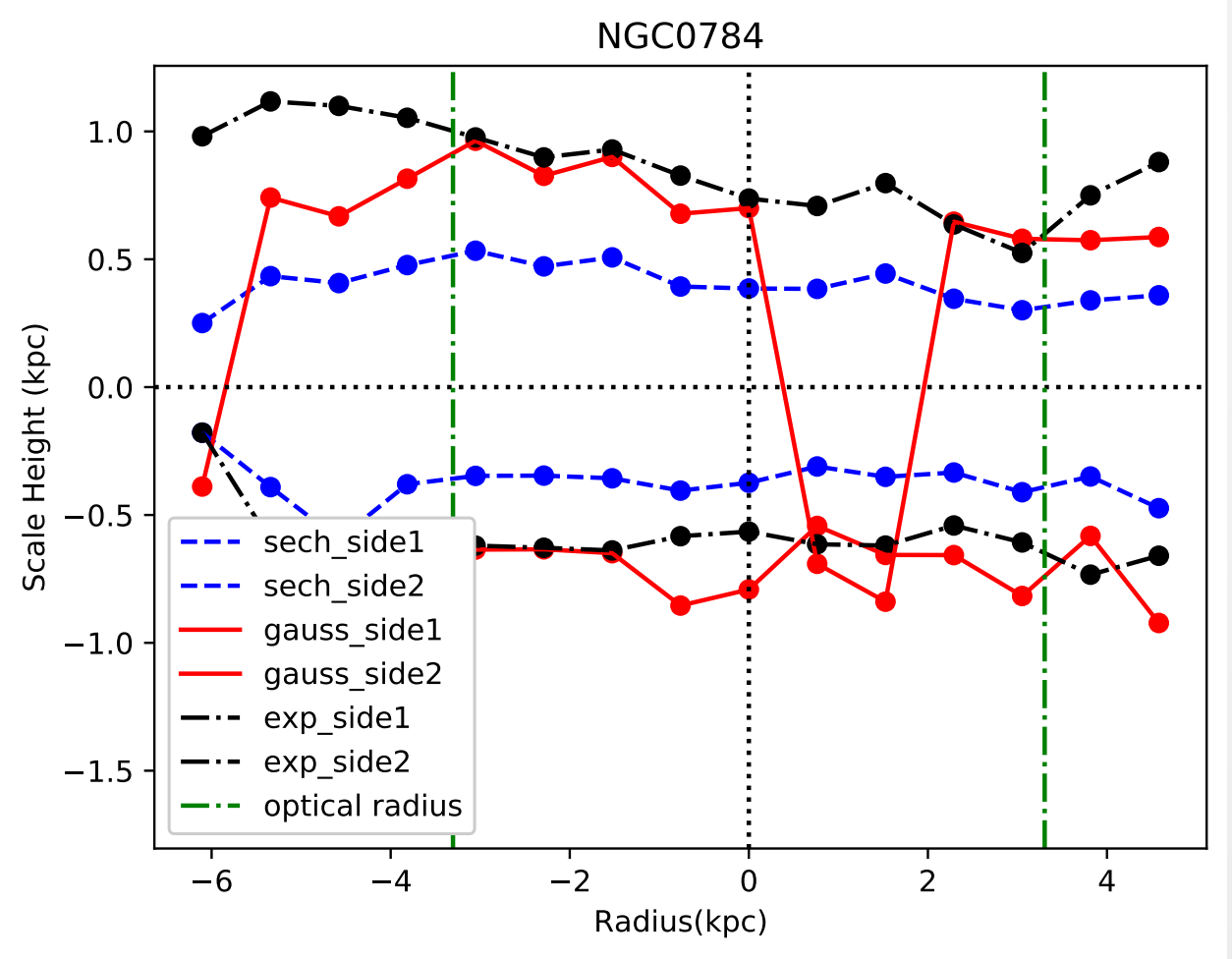
Determining Disk Flaring in NGC0784

- HI disk flaring has been studied earlier but the data is not available for fitting a function or comparing with stellar disk data.
- We have done test studies on the edge on galaxy NGC 0784 using VLA HI observations (GARCIA survey; Biswas+2023).
- Cuts normal to the disk at one beam width apart have been made.



Fitting the Disk Flaring

- Preliminary results suggests that Sech2 function fits the profile the best.
- The flaring within the optical disk is not very large.

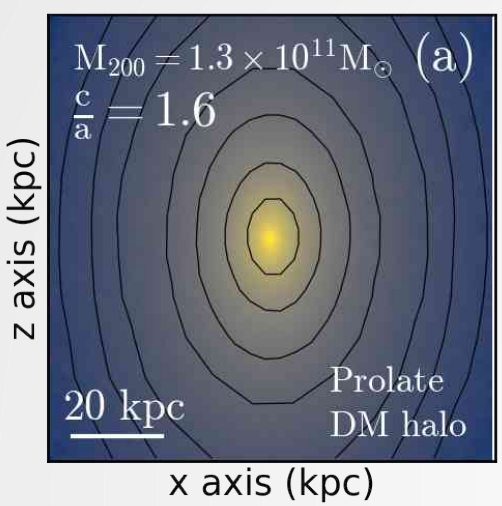


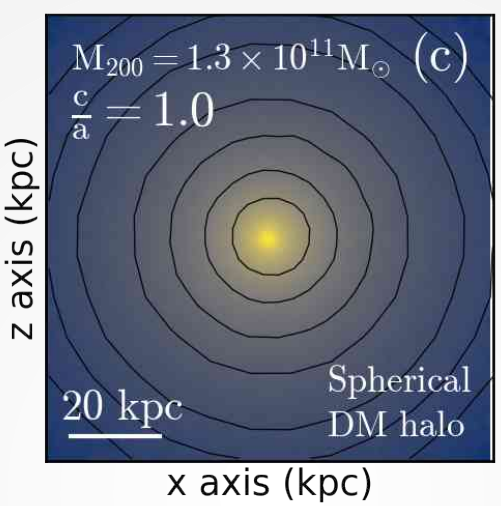
Can dwarf galaxies support prolate halos?

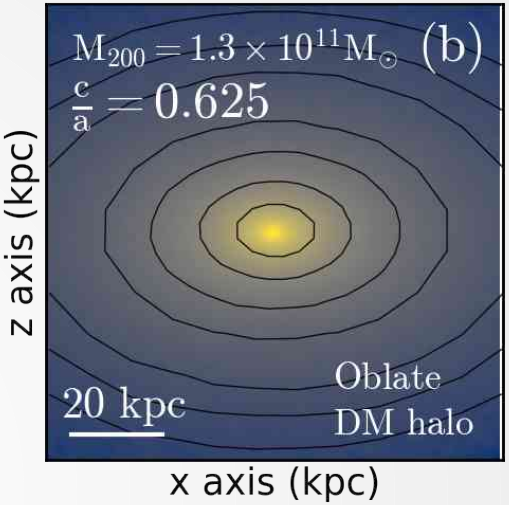
(Ansar & Das in prep.)

- We have found that dwarf galaxies have oblate halos. Is this due to stability?
- Using N-body simulations, with stars and gas particles we explore whether prolate halos are stable in dwarf galaxies?
- We define dwarfs as galaxies with $M(*) < 10^9$ Msun

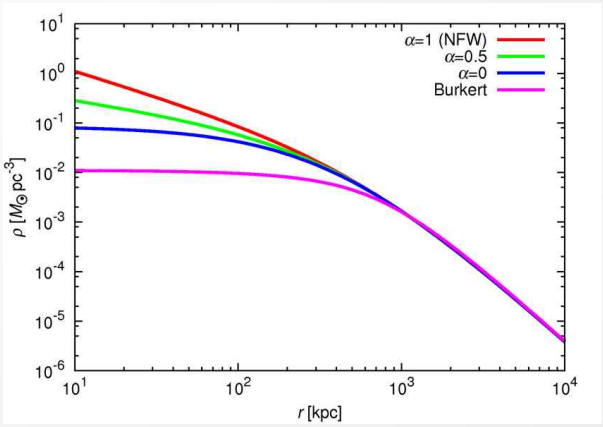
Halos shapes and profiles







- We have done the simulations for both pseudo-isothermal (piso) and cuspy (Hernquist) halos.
- Initial configuration done using GalIc
- We define dwarfs as galaxies with Msun(Yurin & Springel 2016) and evolved with GADGET3.



Ogiya & Burkert 2014

Galaxy Parameters : example

- No. of stellar particles = 10^6
- No. of halo particles = $5x10^6$ to 10^7
- Disk particle mass 41 to 2000 Msun

Table 1. The properties of galaxy disks and PISO halos

Galaxy Model No.	$M_\star$ $M_\odot$	M_{gas} $M_\odot$	M_{disk} $M_\odot$	m_g	V_{200} (kms^{-1})	M_{200} $M_\odot$	m_d	r_{200} (kpc)	R_d (kpc)	R_c (kpc)	$\log \rho_c$ $(M_\odot pc^{-3})$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
1	10^7	4.89×10^7	5.89×10^7	0.83	33.2	1.2×10^{10}	0.0049	47.4	0.197	0.63	-1.27
2	$10^{7.5}$	1.2×10^8	1.51×10^8	0.79	42.1	2.5×10^{10}	0.0061	60.1	0.344	0.77	-1.24
3	10^8	3.02×10^8	4.02×10^8	0.75	53.7	5.1×10^{10}	0.0078	76.6	0.611	1.53	-1.58
4	$10^{8.5}$	7.5×10^8	1.06×10^9	0.71	68.5	1.1×10^{11}	0.0099	97.8	1.07	1.35	-1.29
5	10^9	1.86×10^9	2.86×10^9	0.65	87.6	2.2×10^{11}	0.0128	125.2	1.89	1.99	-1.42

Results

- We find that in the inner galaxy disks (R=5kpc) the prolate halo are not stable and change from q=1.6 to 1.2 in 5 Gyrs. But it changes more slowly in the outer parts (R=40kpc).
- Similar results for Hernquist profiles, but the change takes slightly longer

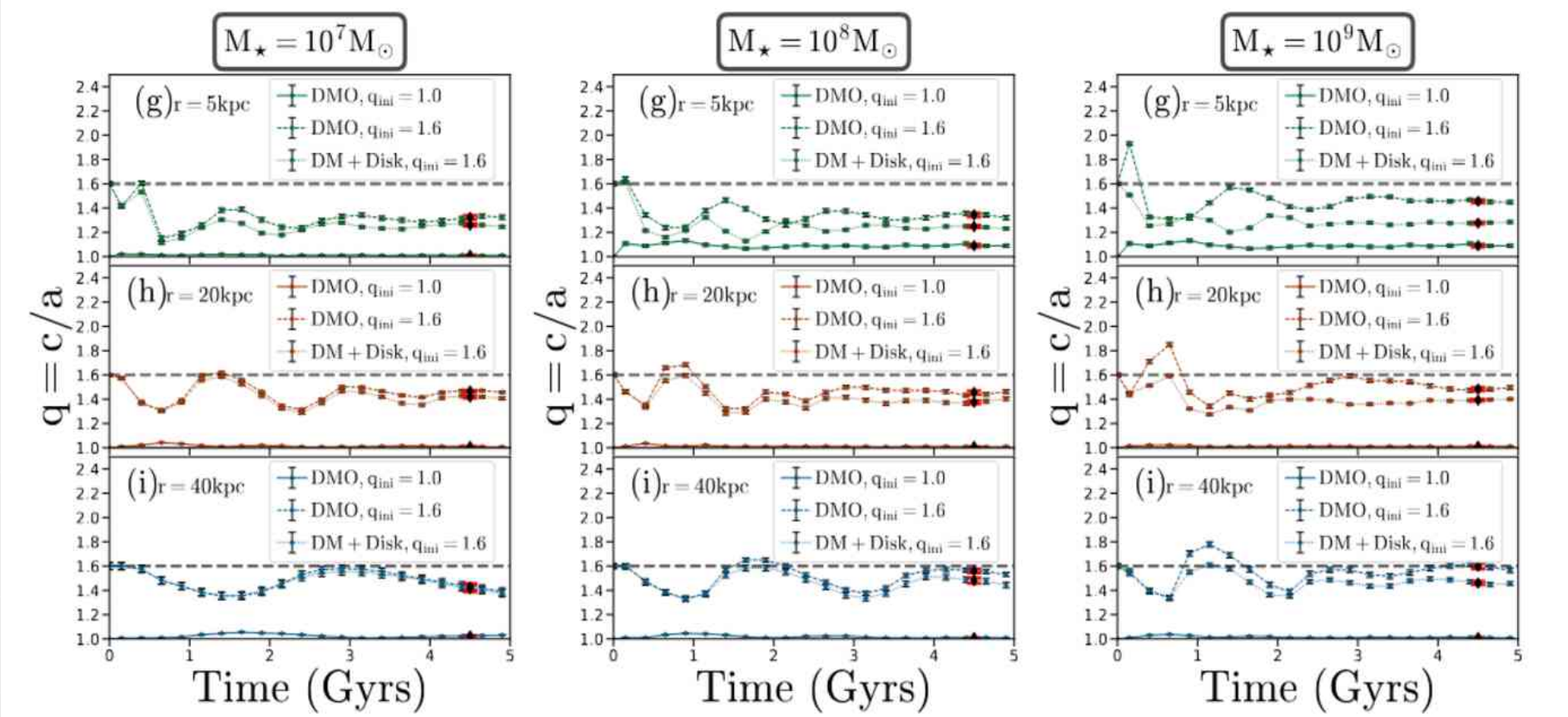
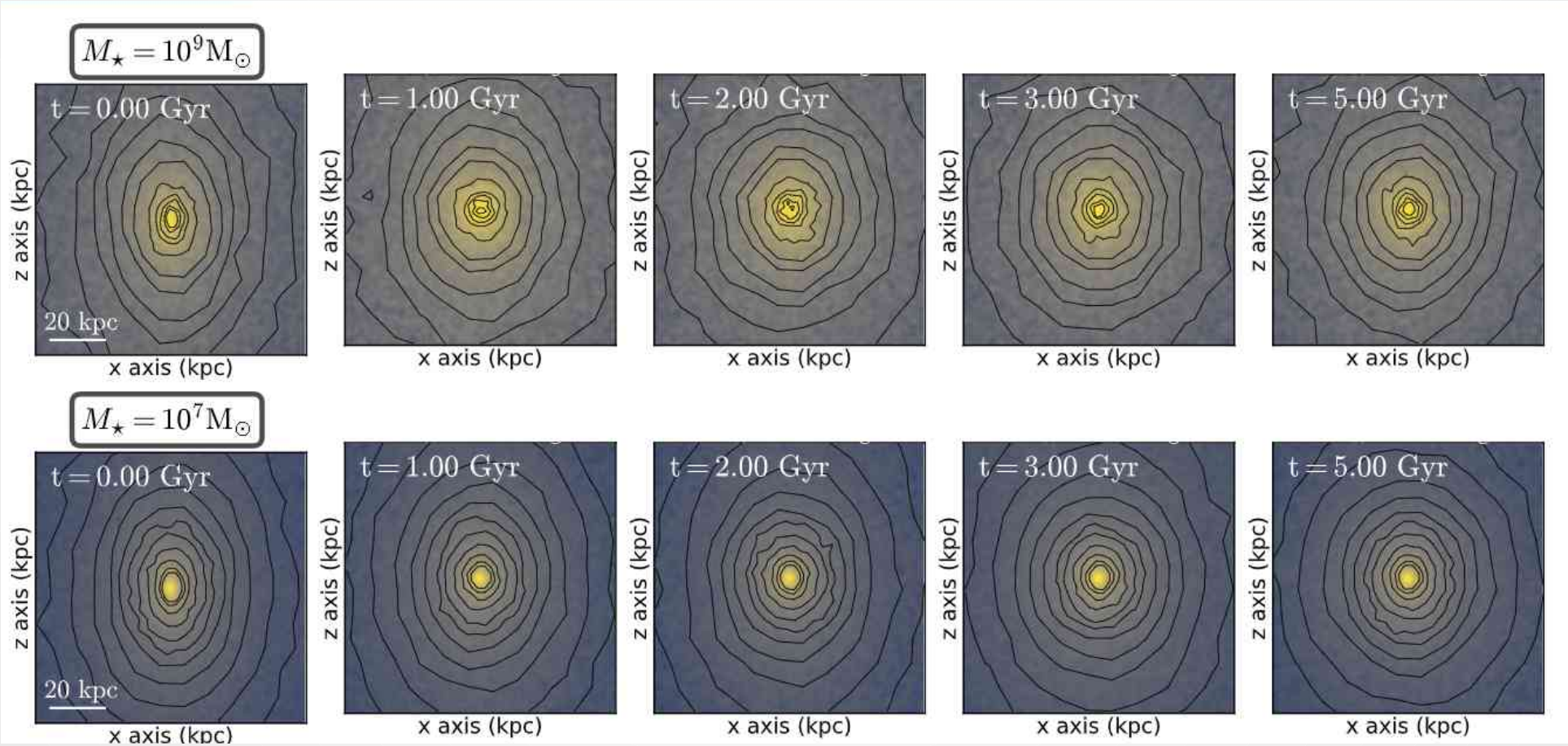


Figure 7. Effect of a cuspy DM halo profile on the evolution of q. Evolution of oblateness q of dwarf galaxy models with Hernquist dark matter halo profiles, for three different masses: $M_\star = 10^7$ (panel (a-c)), 10^8 (panel (d-f)) and $10^9 M_\odot$ (panel (g-i)) and at three radii $r = 5$ (green), 20 (orange) and 40 (blue) kpcs, initial oblateness parameter $q = 1.6$ and for simulations

Change in halo shape with time



Summary

- Galaxy halos can have different shapes, as suggested by observations and cosmological simulations.
- The halo shape can affect disk dynamics and hence galaxy evolution. Oblate halos delay bar formation and possibly disk instabilities. Prolate halos can have more bar buckling.
- The HI dispersion in face-on galaxies can be used to determine the oblateness q or c/a of dark matter halos. The method can be applied to the outer HI disks of face-on galaxies where there is no star formation and the stellar disk is not detected.
- The outer HI disks have significant dark matter. We find that the galaxies with massive stellar disks have larger q, generally between q = 0.5 to 1.0, whereas the gas rich dwarfs have very oblate halos q~0.2. So disk galaxies with large stellar masses have rounder halos.
- Our preliminary simulations show that prolate halos in dwarf galaxies are not stable and tend to become less prolate in a few Gyrs.