Exploring the dark matter distribution of nearby galaxies using HI velocity dispersion

Mousumi Das
Indian Institute of Astrophysics, Bangalore

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Outline of this talk

- Observational and simulation studies of dark matter halo shapes.
- How does halo oblate/prolate shape affect galaxy disks?
- Using the HI velocity dispersion in the outer disks of galaxies to derive the dynamical mass and dark matter mass.
- Deriving the oblateness q of galaxy halos and its implications.
- Using HI dispersion to determine the 2-d distribution of halo dark matter in the nearby ultra diffuse satellite galaxy Leo-T.

Contributors

- Amrutha S. (IIA)
- Roger Ianjasimanana (Instituto de Astrofísica de Andalucía, Spain)
- Ankit Kumar (UNAB, Chile)
- S. McGaugh (Case Western Reserve University)
- J.Schombert (University of Oregon)
- K.S.Dwarakanath (Raman Research Institute)

Observations of halo 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 oblate (E6 to E7) (Sackett et al. 1994, Arnaboldi et al. 1993a). But later studies on some other galaxies suggest that halo shapes cannot be easily determined (Combes and Arnaboldi 1996). These studies suggest that halos dominate in the outer parts of galaxies.
- The **hydrostatic equilibrium :** of HI gas disks in edge on galaxies (e.g. Olling et al. 2004). 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

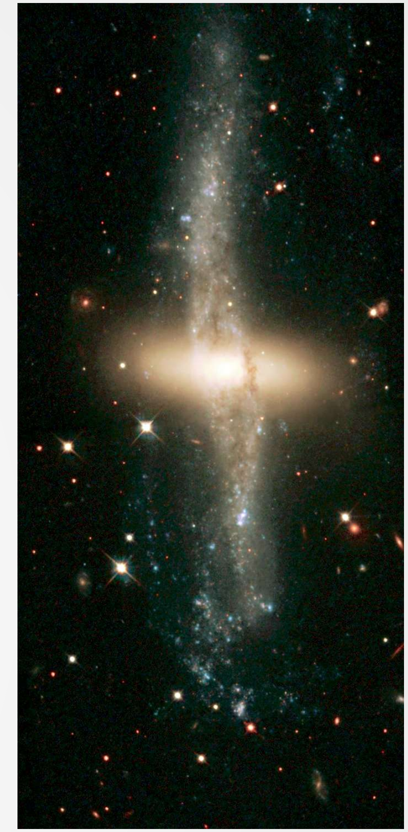


Image credit : The polar ring around the disk galaxy NGC4650A, spacetelescope.org

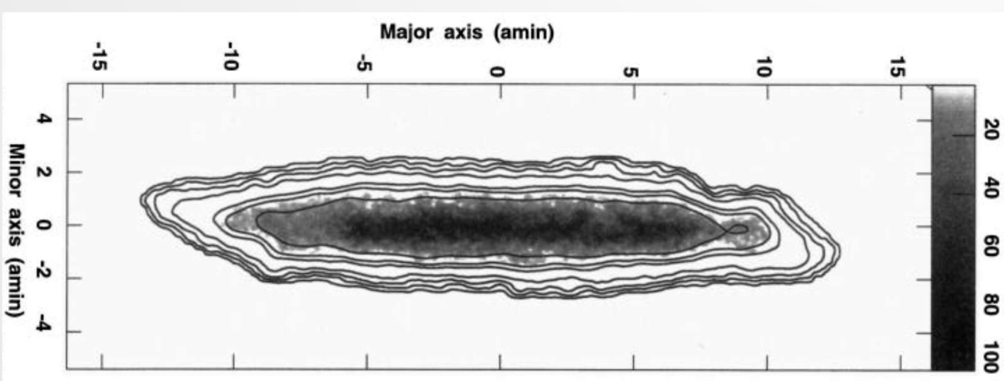


Image credit : NGC4244 (Olling et al. 1996).

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 (e.g. Bannerjee and Jog, 2011).
- Gaia observations of globular clusters also indicate that the Milky Way could be prolate but oblate halos are ruled out (Posti & Helmi 2018).

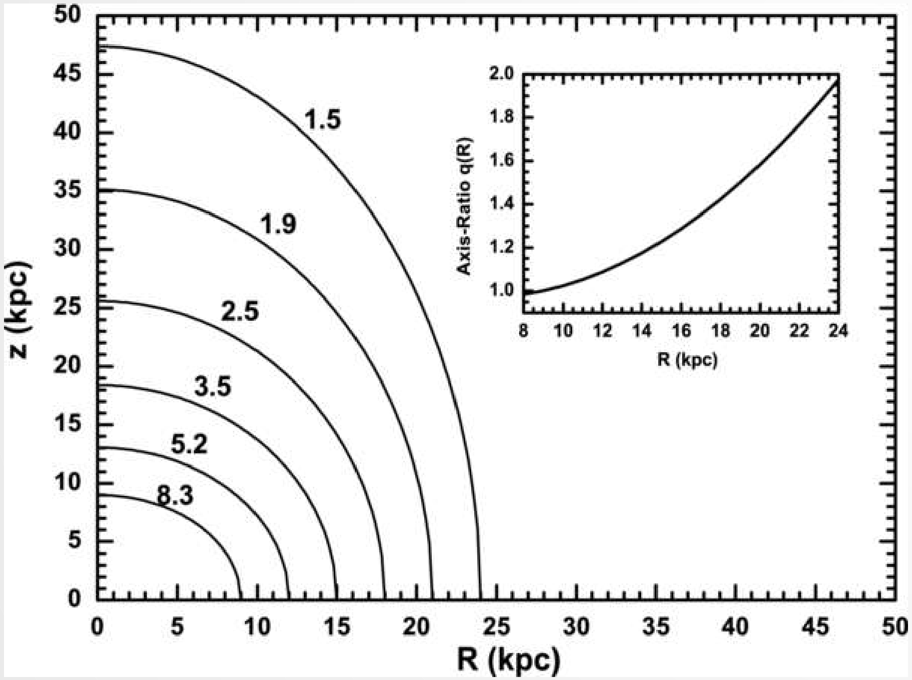


Image shows the prolateness with radius : Banerjee and Jog, 2011

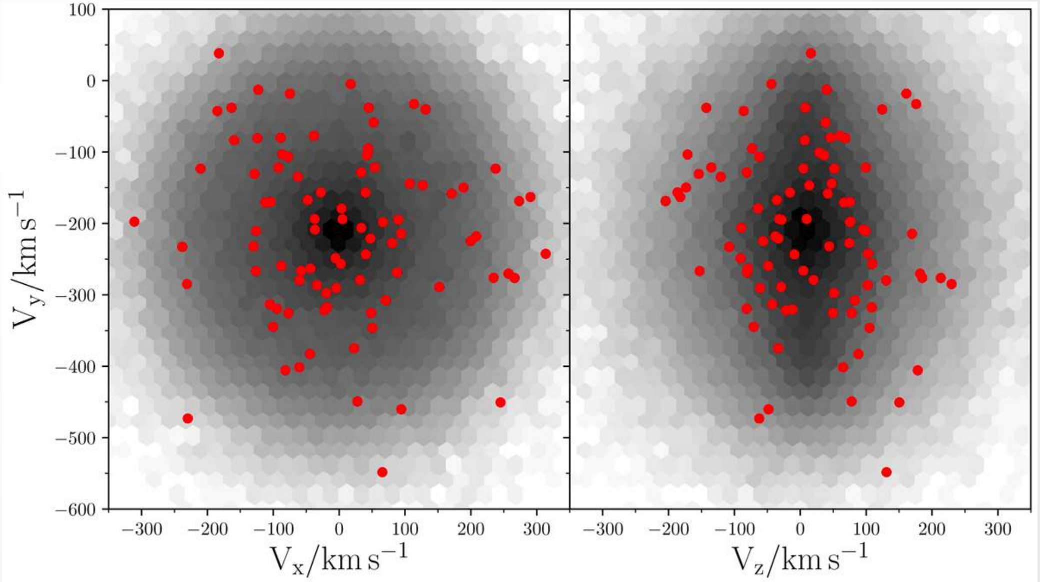


Image shows the distribution of clusters in the x-y plane (left) and x-z plane (right) : Posti and Helmi, 2018

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)

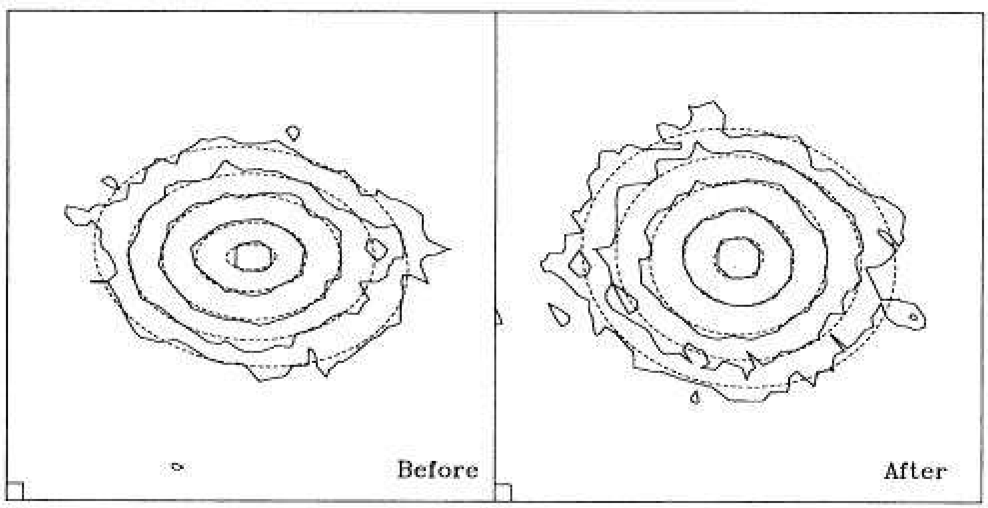


FIG. 5.—The surface density contours ("isophotes") of the dark halo in the plane of intermediate and major axis before and after the growth of the spherical Hernquist potential. The halo becomes considerably rounder in the equatorial plane and therefore more oblate.

Image credit : Dubinski 1994

Cosmological simulations of halo shapes

- Large scale cosmological simulations show that it is not just the stellar disk but dissipation due to baryonic processes such as star formation and feedback associated with strong star formation is also important.
- The AGN activity and feedback associated with SMBH accretion will push out central mass and can affect the halo shape (e.g. Chua et al. 2019).
- Studies 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).

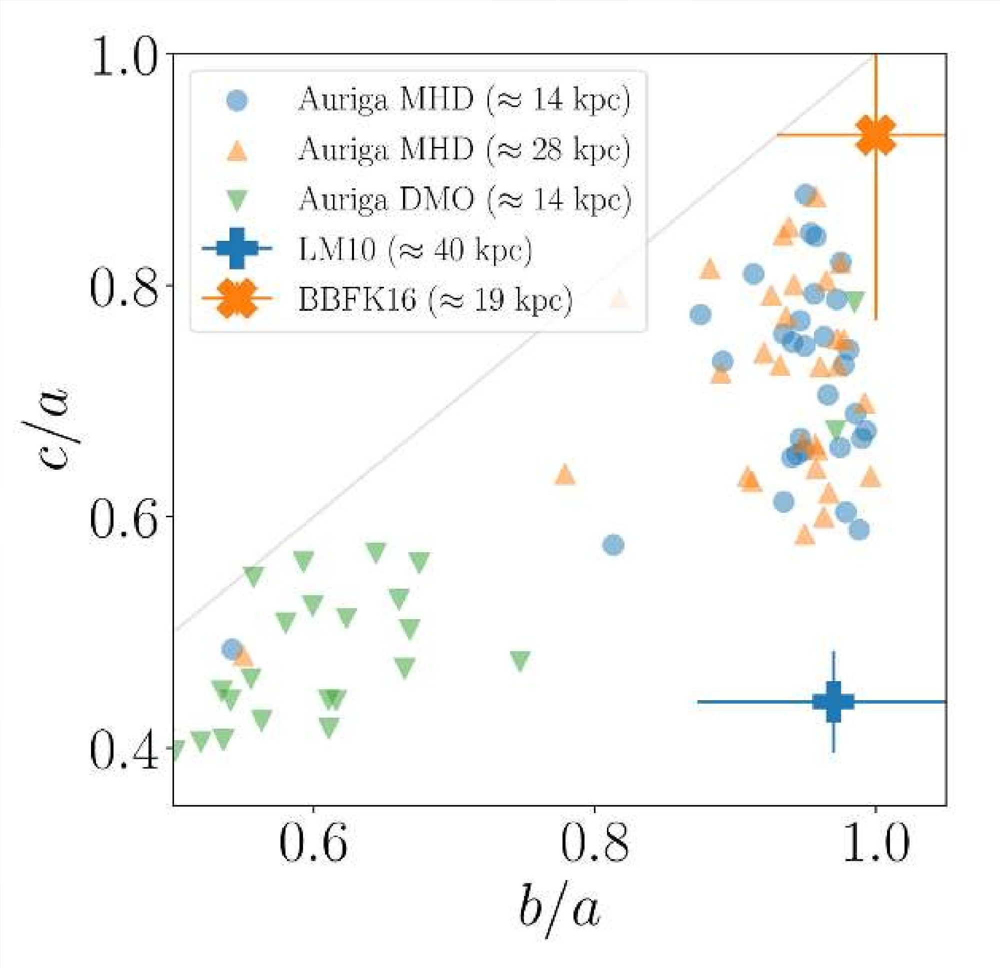
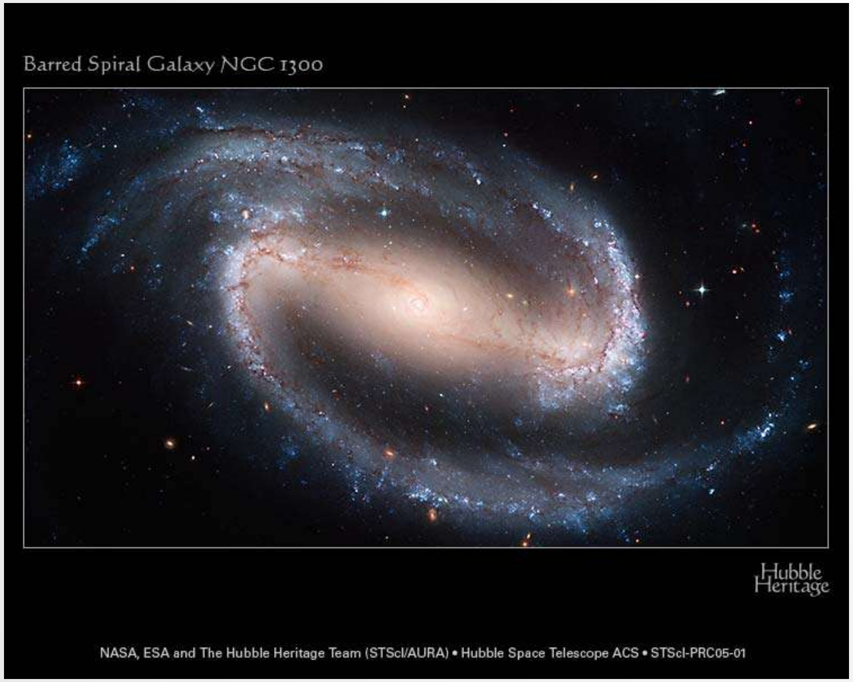


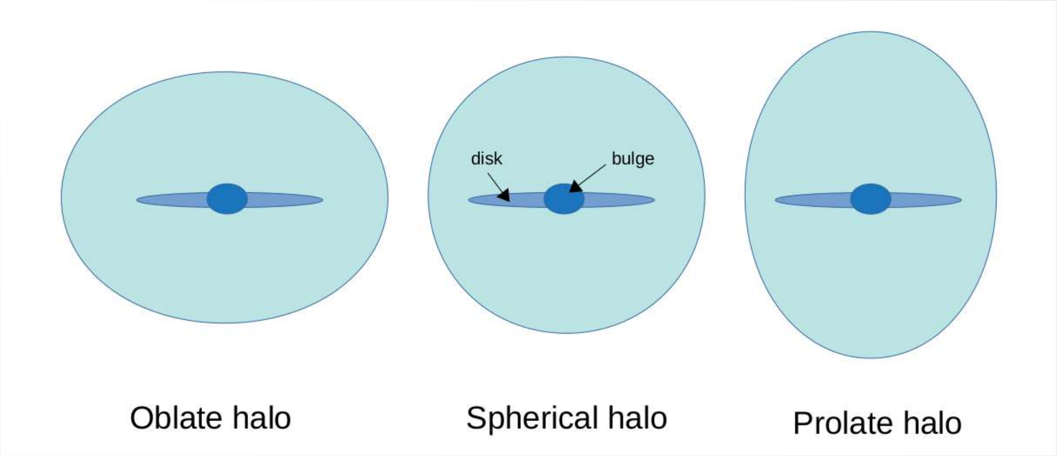
Image credit : Prada et al. 2019, MNRAS

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.
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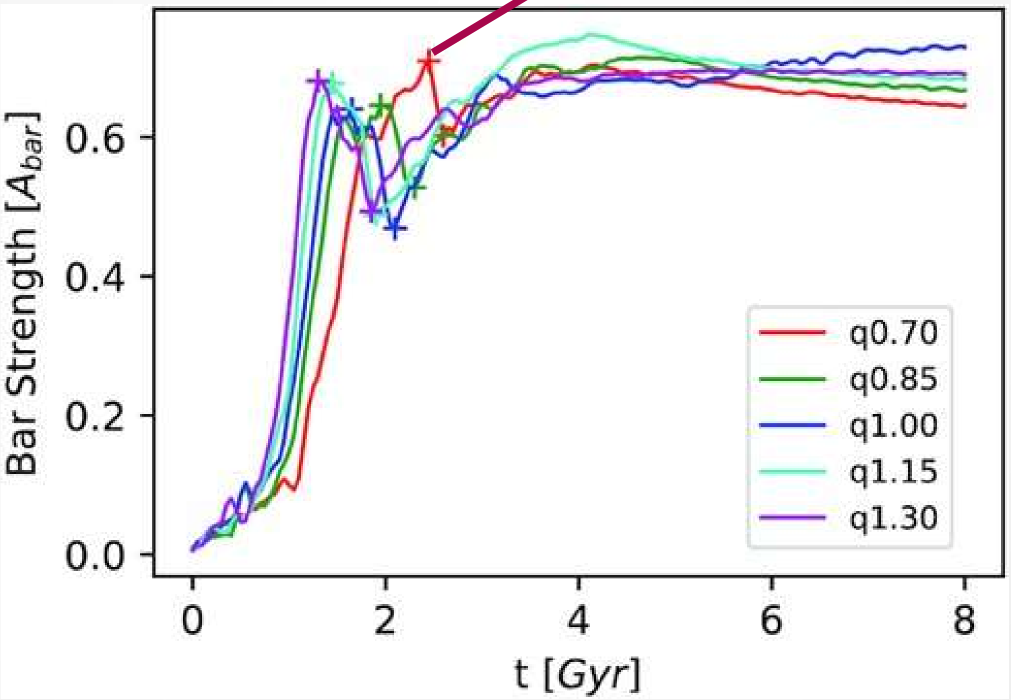
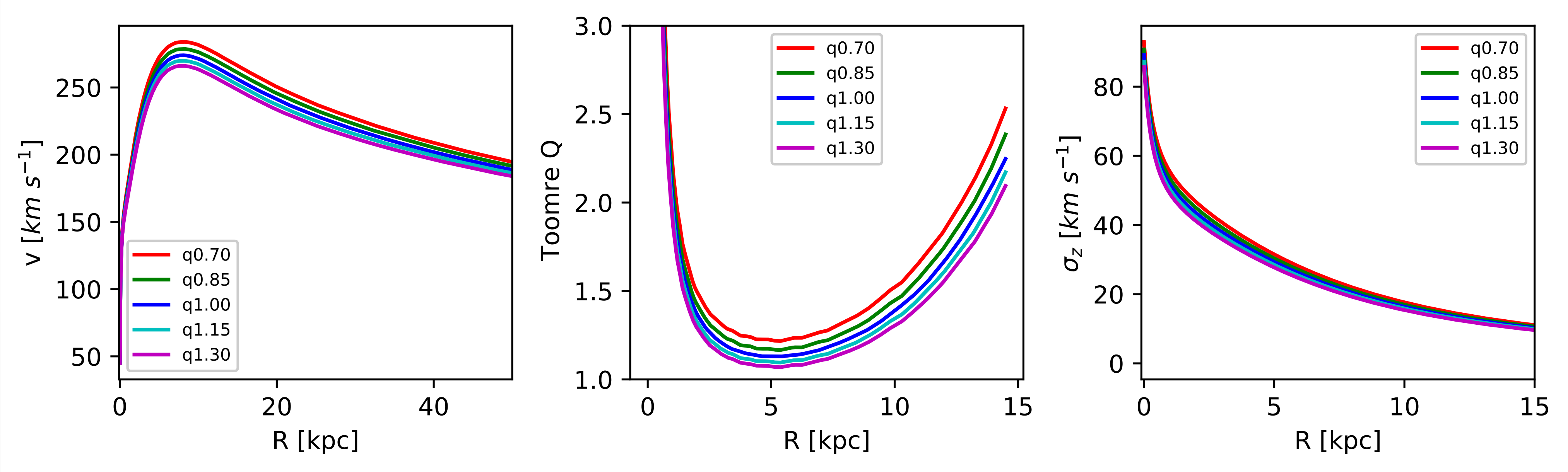
Delayed bar formation



Delayed bar formation due to higher velocity dispersion

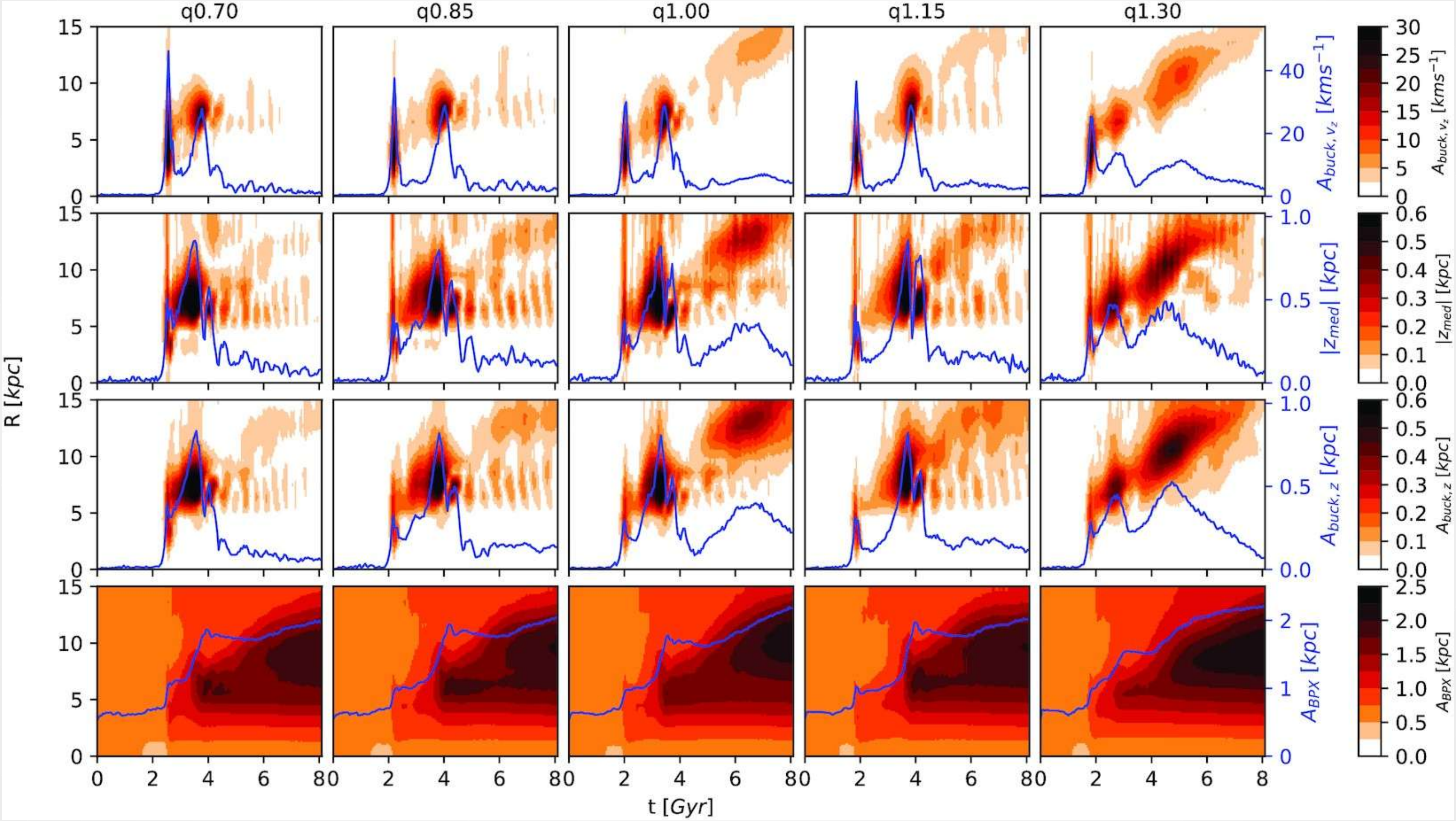
- The stellar velocity dispersion is higher in disks with oblate halos. More mass associated with the disk.
- So the Toomre stability factor is affected suggesting that the disk instabilities (global and local) are more difficult to form.



Kumar+2022, MNRAS.

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

Main questions

- How is the vertical equilibrium maintained in the extended HI disks of galaxies and is disk dark matter important for the vertical equilibrium?
- If it is, then how does it affect the shape of the halo?
- How is the dark matter distributed within halos? The case of **Leo-T.**

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

(Das+2020)

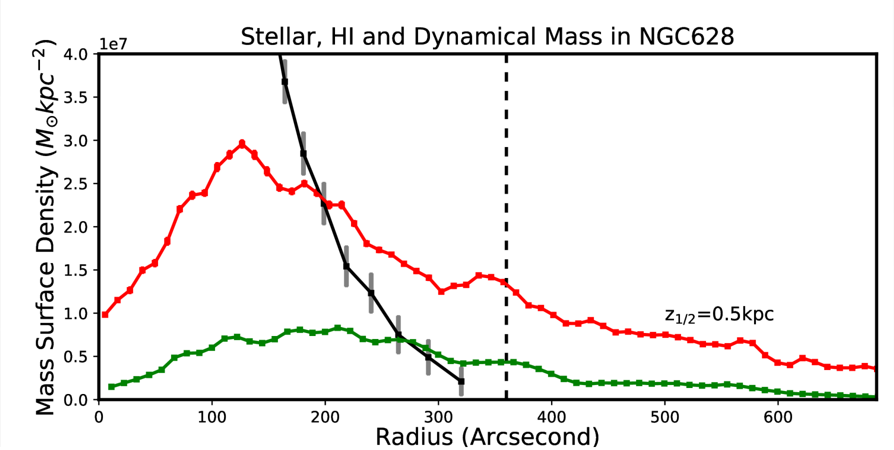
- The HI can be used to trace the potential of the disk using simple vertical equilibrium.

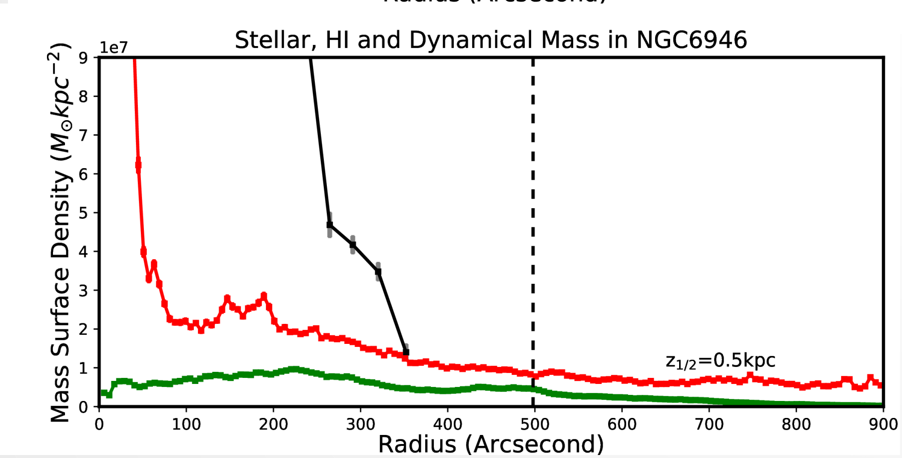
$$1/\rho_{HI}\ d/dz[\rho_{HI}\sigma_{HI}^2] = -d\Phi/dz$$

- 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.
- Σ(dark matter) = Σ_{dyn} - Σ(baryonic)

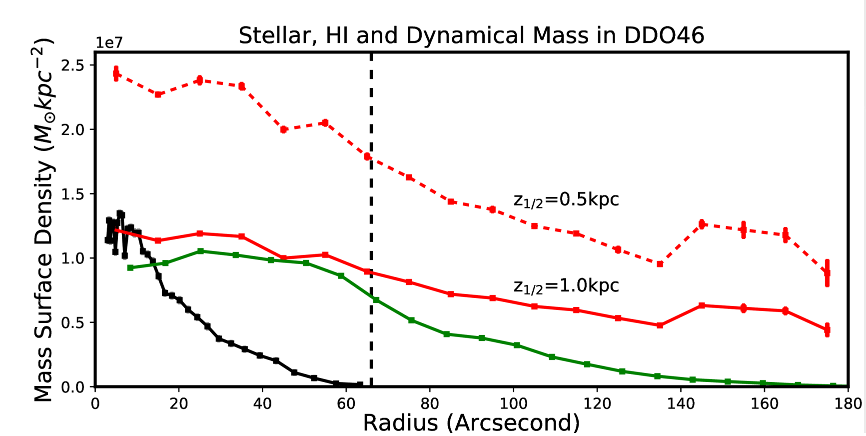
The difference in dynamical and baryonic mass densities in the outer disks of large spirals and dwarfs

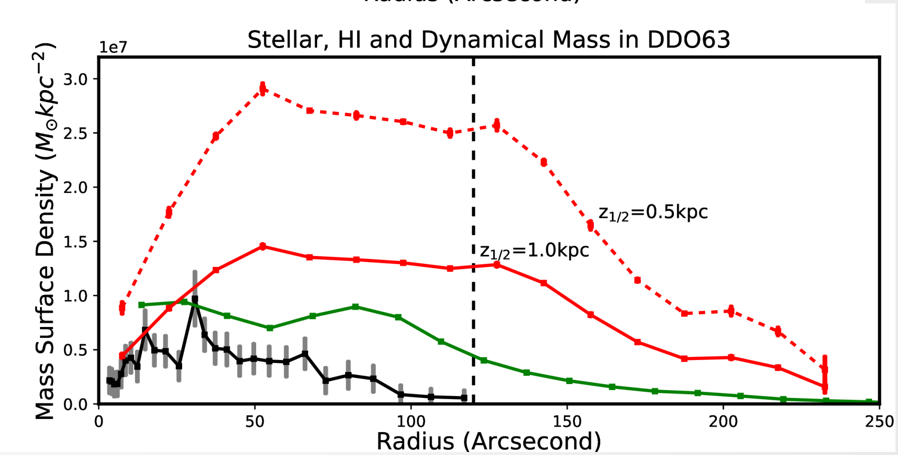
Large disk galaxies





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 $\Phi_{halo} = ½\ v_o^2 \ln(R_c^2 + R^2 + z^2/q^2)$

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

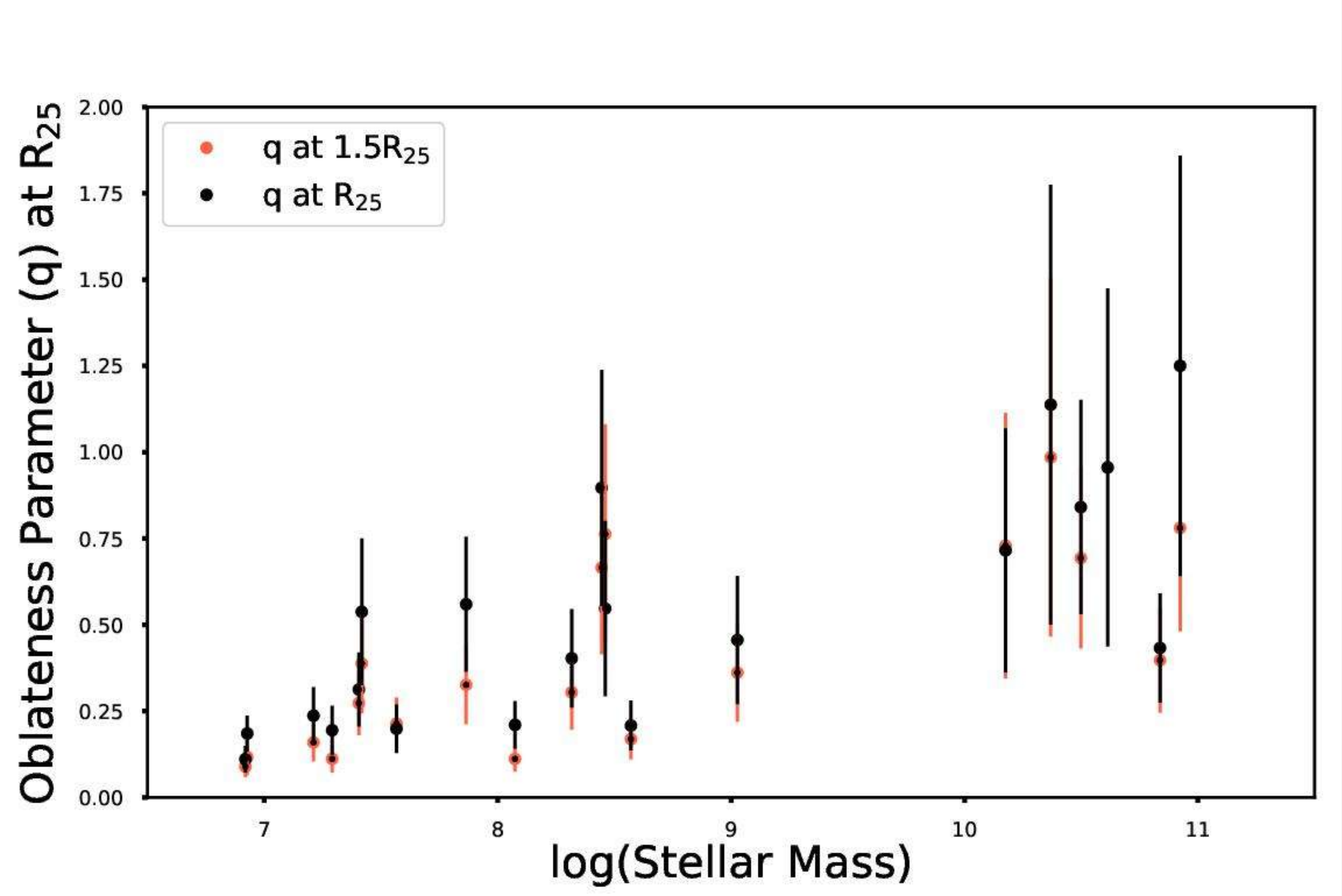
$$\mathbf{q^2 = v_o^2 z_{g0}^2 \times 1/R^2[\sigma^2 - \pi G z_{g0} \Sigma(HI)]}$$

- 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).

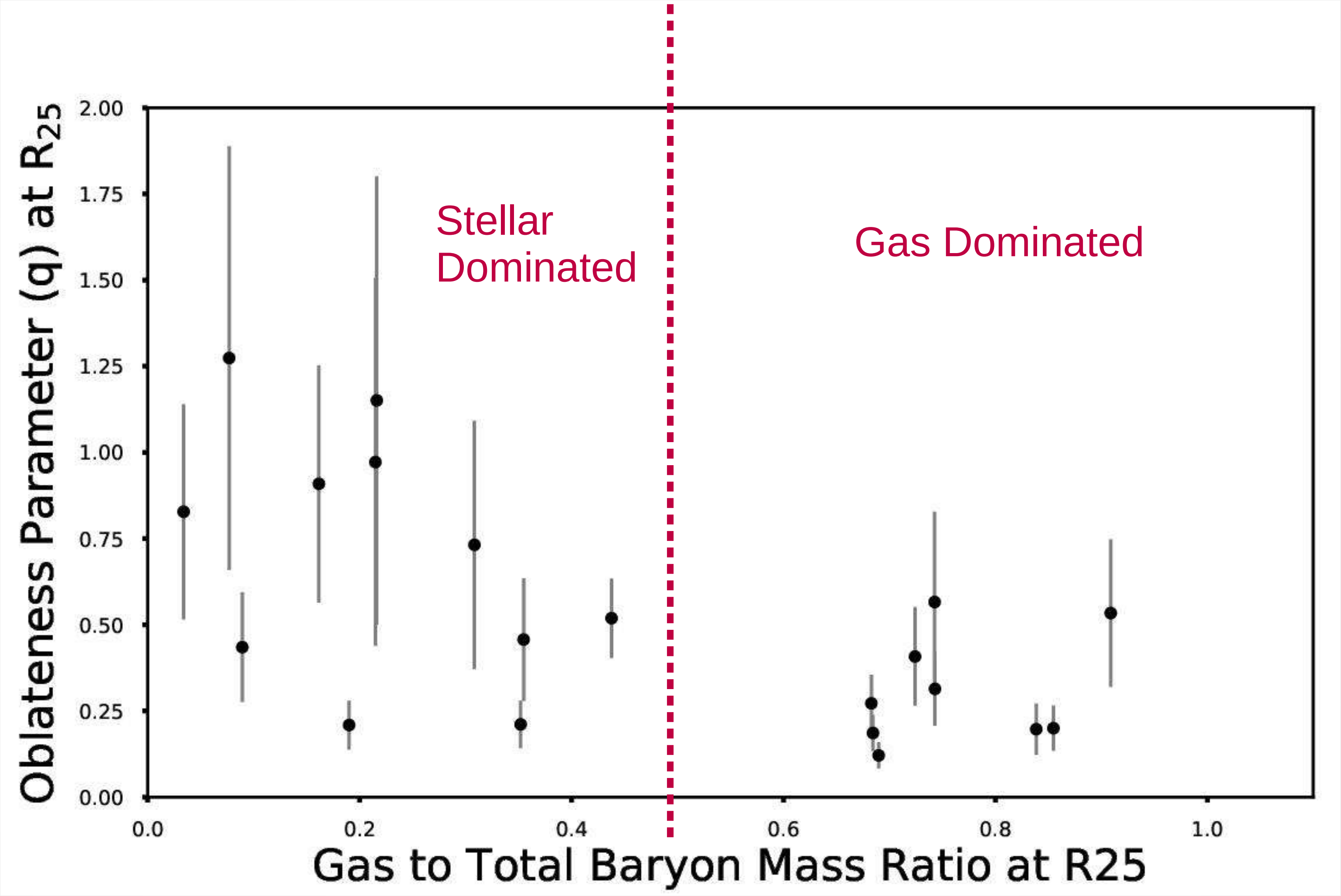
- Totally 20 galaxies : **12 dwarfs** i.e. have very low stellar masses, and **8 high stellar masses.**

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)



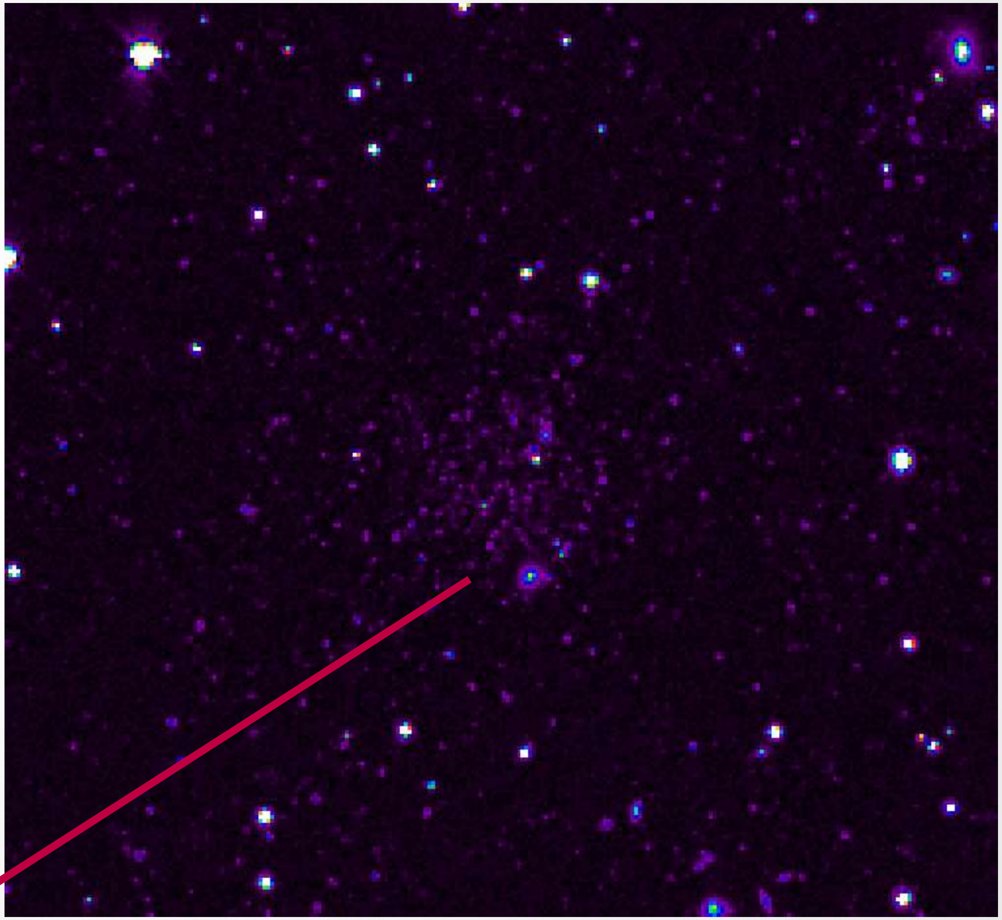
- There is a clear difference in q values for gas dominated galaxies that have M(gas)/M(baryon) > 0.5 where q is calculated at R_{25} radius. Gas dominated galaxies have oblate halos with q<0.55.
- But stellar dominated galaxies can have a range of q values.

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 derived for the dwarf NGC4244 (Olling et al. 1996). For the other low 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 2-D distribution of dark matter in Leo-T

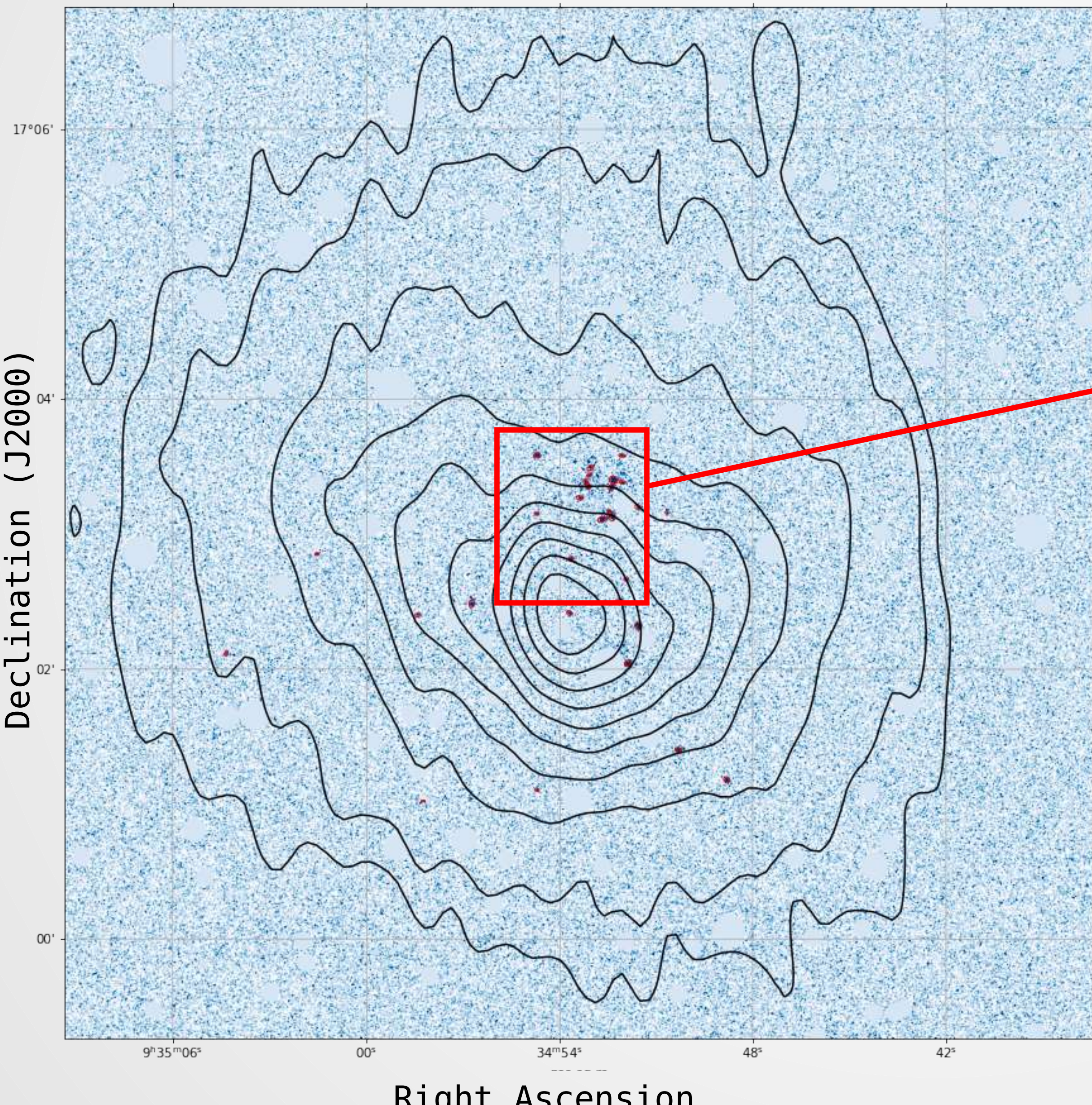
- Leo-T is a close (D=409kpc) ultradiffuse satellite galaxy of the Milky Way.
- Its low luminosity makes it very difficult to detect in optical images and so it was only detected recently in SDSS (Irwin et al. 2006).
- Leo-T is the faintest and least massive galaxy with neutral hydrogen. But it shows signatures of star formation in optical images (Vaz+2023).
- It maybe in transition from Ultra faint dwarf to a dwarf spheroidal.
- Studies broadly agree that 50% of the total stellar mass was formed prior to 7.6 Gyr ago, with the star formation beginning over 10 Gyr ago and continuing until recent times.



Leo-T

Image credit : DECALS g band

The stellar distribution of Leo-T : UVIT, MUSE and HST



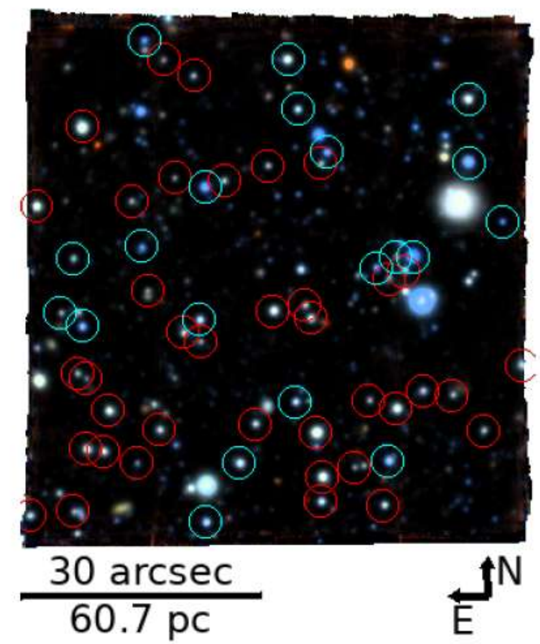
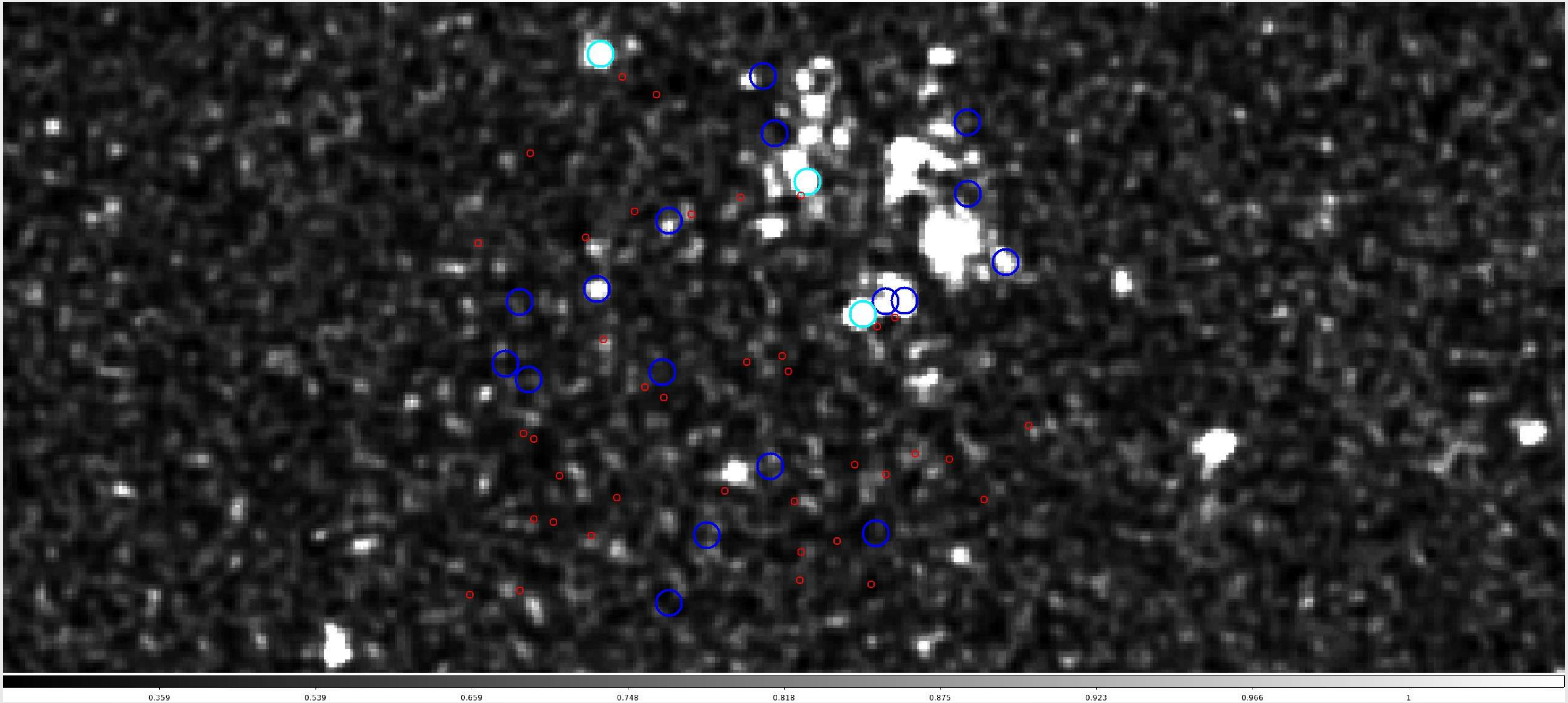


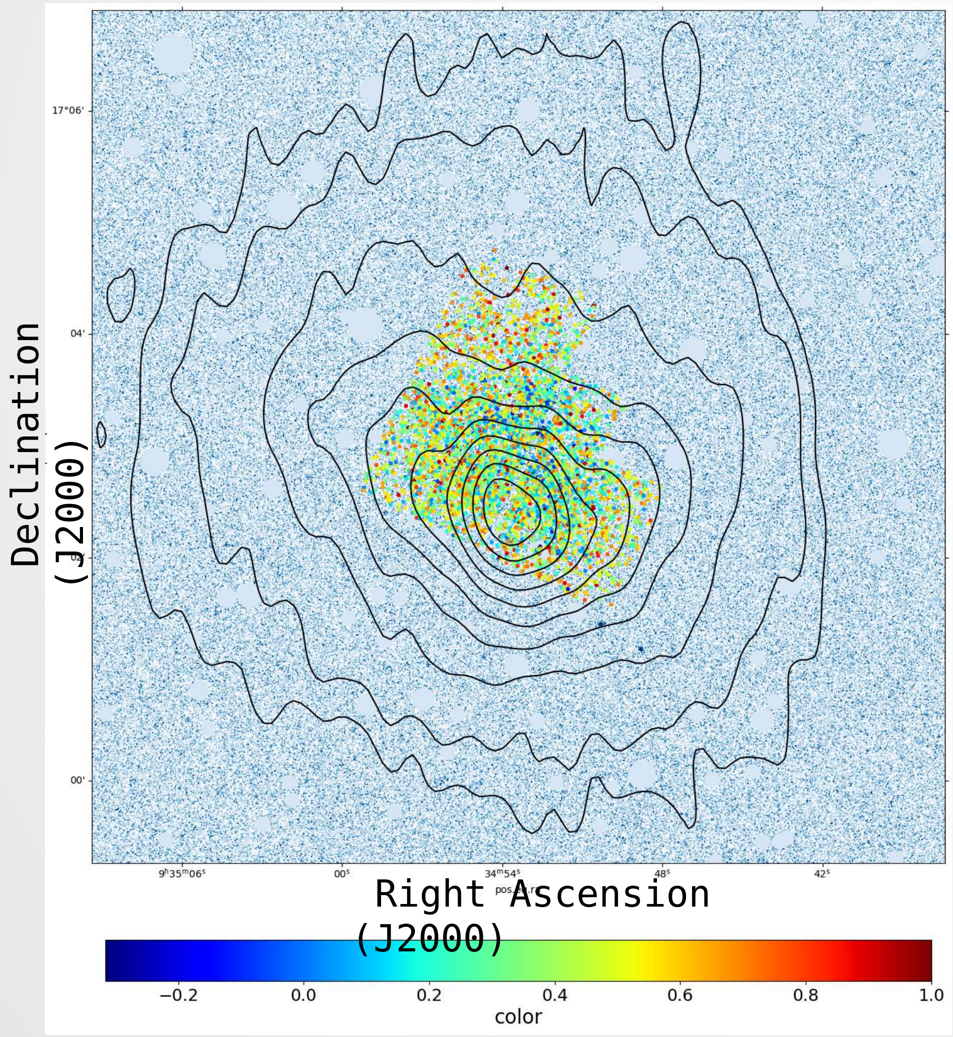
Fig. 2. Composite color image of Leo T based on data from the MUSE-Faint survey, created with fits2comp[2]. We used the Johnson-Cousins filters I, R, and V to create the red, green, and blue channels of the image, respectively. The 58 stars identified in this paper as Leo T members that are located within the bounds of MUSE-Faint observations are identified with circles. As we identify two stellar populations (see Section 4.1), we use blue and red circles for the younger and older population, respectively. The angular and physical scales of the image are indicated in the lower left corner. Directions north and east are indicated in the lower right corner of the image.

MUSE sources overplotted on UVIT FUV Image (Blue sources <1Gyr, Red sources >1 Gyr)



The stellar distribution : no massive stars

Contours – HI (Adams & Oosterloo 2018)
Points with HST colors – HST stars (3970 stars) (Weisz et al. (2012).
FUV emitting stars – UVIT (38 FUV stars or clusters, B stars, evolved HB stars, blue stragglers).



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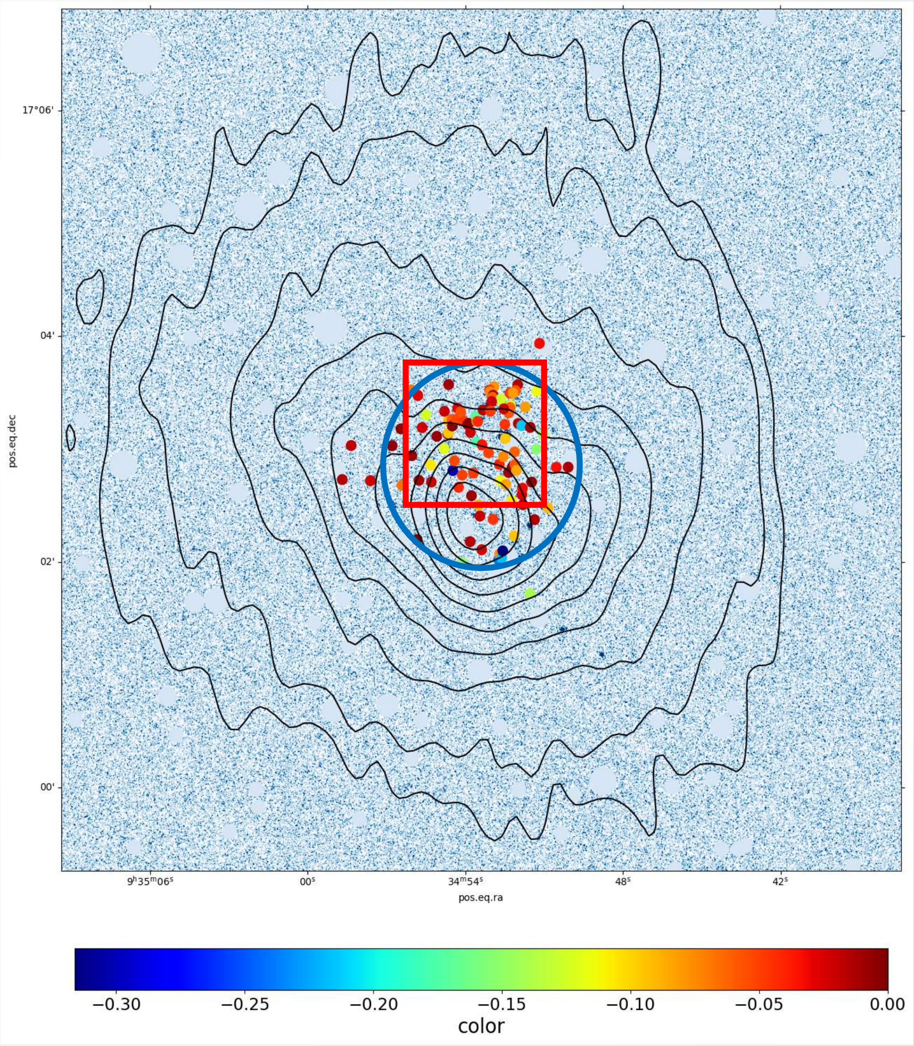


The HI in Leo-T

- Leo-T is one of the few UFDs that is rich in gas. The HI gas mass is M(HI)=$4.1x10^5$ M_sun and cold HI is 10% (CNM).
- It is similar to the stellar mass M(*)=$4.1x10^5$ M_sun.
- The HI mom1 map indicates that the galaxy is approximately face-on, and has a diameter of ~500” or 1 kpc. The mom2 map indicates that the velocity dispersion drops in the center. It has a distribution over the disk (1.5 to 13 km/s).

E. A. K. Adams and T. A. Oosterloo: Deep H I observations of Leo T with WSRT

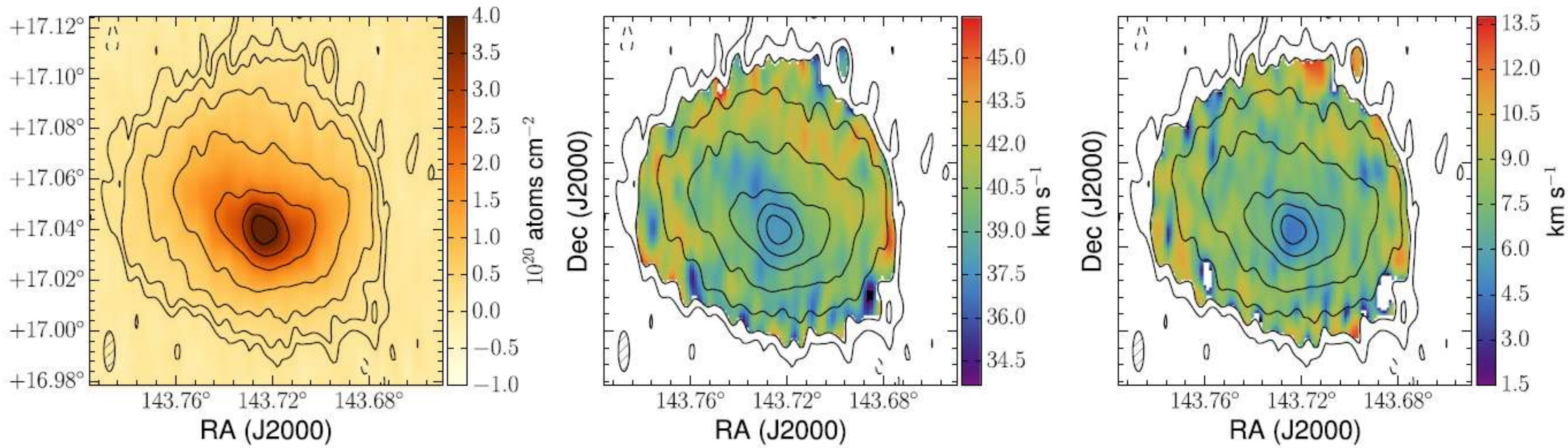
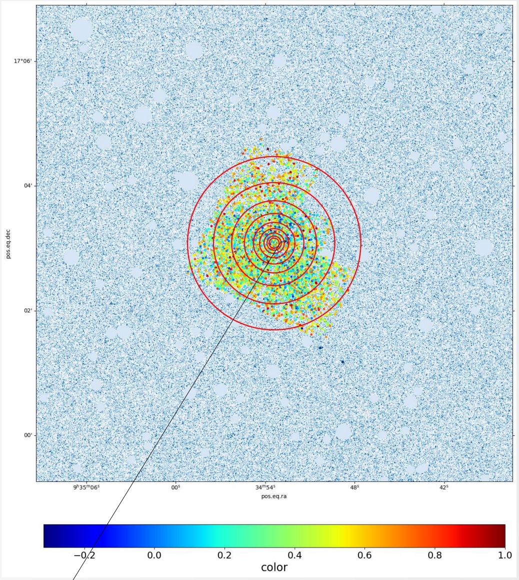
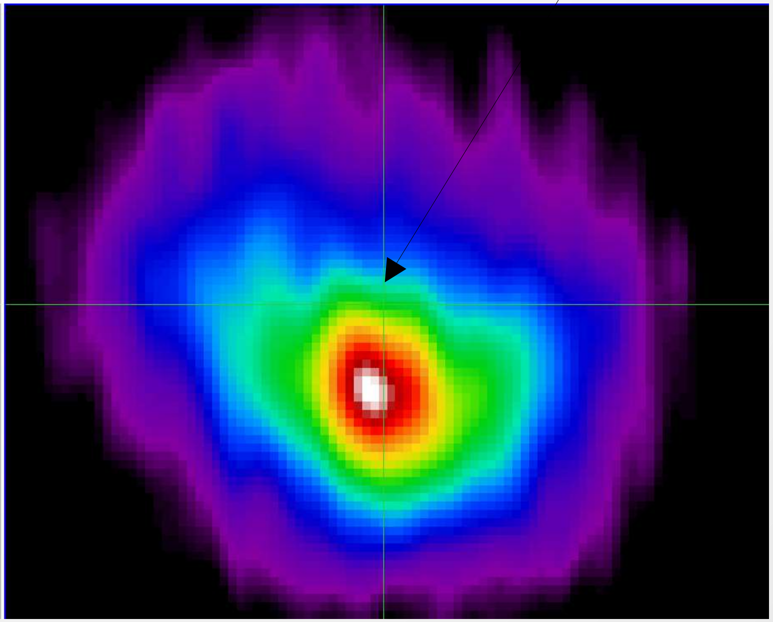


Fig. 2. Total intensity (primary-beam corrected), moment one (velocity field) and moment two (velocity dispersion) maps of Leo T. H I contours shown in each panel are [−1.5, 1.5, 2.5, 5, 10, 20, 30, 40] $\times 10^{19}$ atoms cm^{-2}; the lowest contour level is slightly below the 3-σ level.

The halo masse and separation of HI stellar centers

- Dynamical modelling suggests that the dark matter mass is M(DM)=2.6x10^6 Msun (Nath 2006).
-
- So using the M(HI) and M(*) masses M(DM) is ~ 80%
- The stellar center is separated from the HI center in Leo-T by 80pc. We have checked this by finding the stellar centroid using the HST stellar observations. The center is similar to earlier studies (Irwin+2006).
- The separation maybe due to the tidal field of our Galaxy or the interaction with the CGM. It may also indicate that the gas disk is “sloshing” about the stellar disk center.

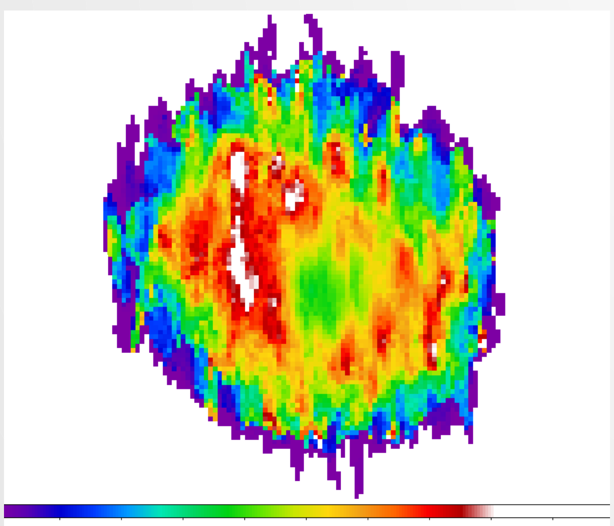




Using the velocity dispersion to derive the disk dynamical mass

- The disk dynamical mass surface density is given by $\Sigma_{dyn}=\sigma_{HI}^{2}/\pi G z_{g0}$ where z_{g0} is the disk vertical scale length. We used the velocity dispersion from the mom2 map to derive the disk dynamical mass.
- The disk dark matter density is given by

$$\Sigma(\text{dark matter}) = \Sigma_{dyn} - \Sigma(\text{HI})$$



2-d distribution of dynamical mass

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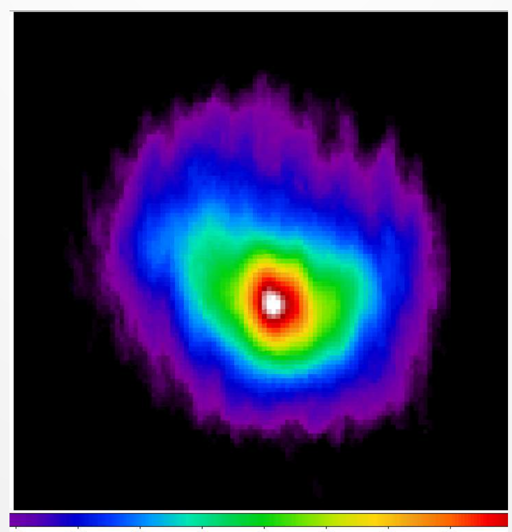

HI mass (mom0 map)

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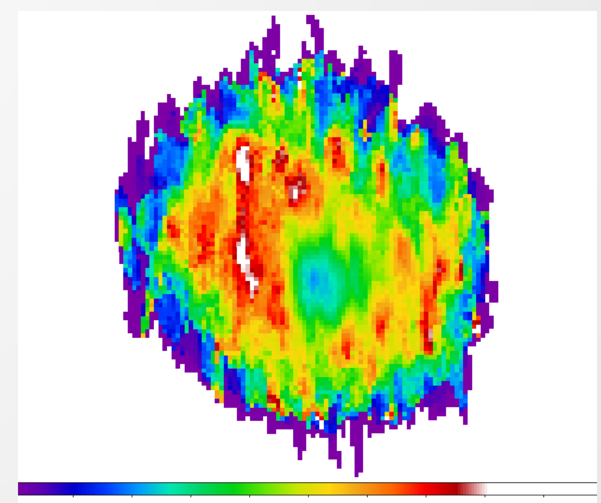


The dark matter distribution in Leo-T

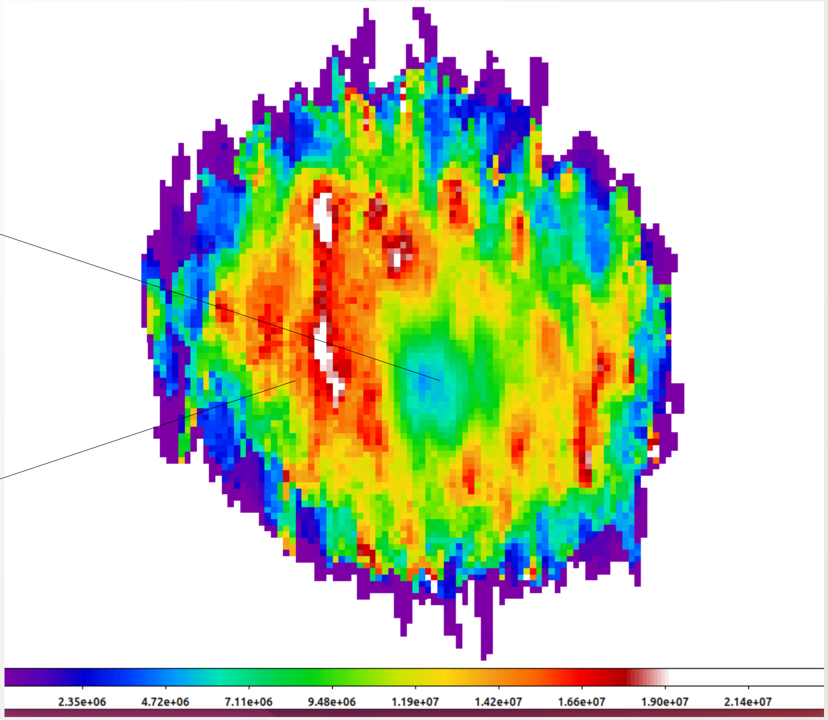
- If we assume that the disk thickness is approximately constant and the stellar mass surface density in the disk is low, then we obtain 2 tentative results.

  (i) The dark matter halo has a low density or flat halo core which maybe pesudo-isothermal as suggested in literature (Patra 2020) ?

  (ii) The disk dark matter is lopsided or basically the dark matter halo is lopsided. This is observed in HI disks for massive galaxies.

Low density core, or evidence for isothermal halo?

Evidence for a lopsided halo.



Summary

- Galaxy halos can have different shapes, as suggested by observations and cosmological simulations. It 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 dynamical mass and hence dark halo masses associated disks. 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. It can also be used to determine the oblateness q or c/a of dark matter halos.
- 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.
- We have studied the stellar distribution of the Milky Way satellite galaxy and UDG Leo-T, using UVIT, MUSE and HST data. We find several FUV emitting stars that could be Be stars.
- Our preliminary modeling of the HI velocity dispersion of Leo-T indicates that (i) the dark matter halo is lopsided and (ii) the galaxy center has less dark matter, suggesting a flat core or isothermal halo profile for this galaxy.