TRUNCATIONS AND WARPS IN DISKS OF GALAXIES

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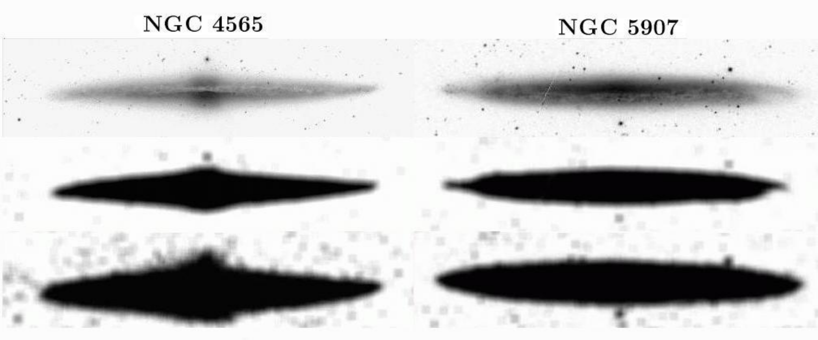
- In their periphesies exponential disks do not continue to infinity, but show truncations. These are seen only in edge-on galaxies.
- I will discuss the relation of the truncations to HI warps and efforts to find truncations in face-on galaxies.
- Conclusions:
  - **The spin vector of the inner disk is extremely constant for increasingly larger annuli, but changes abruptly just beyond the truncations, when warps in the HI set in.**
  - **This abrupt change indicates that differences in the formation history in the inner and outer parts of disk galaxies are discrete rather than gradual.**
  - **In inclined/face-on systems the truncations can sometimes be seen in very deep surface photometry, but are often hidden by faint, extended light from a faint stellar halo and/or from the inner disk scattered by the PSF.**

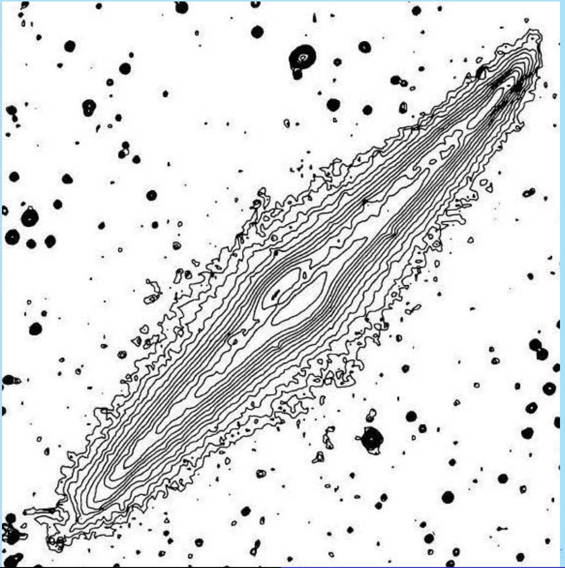
Truncations in edge-on stellar disks

Truncations

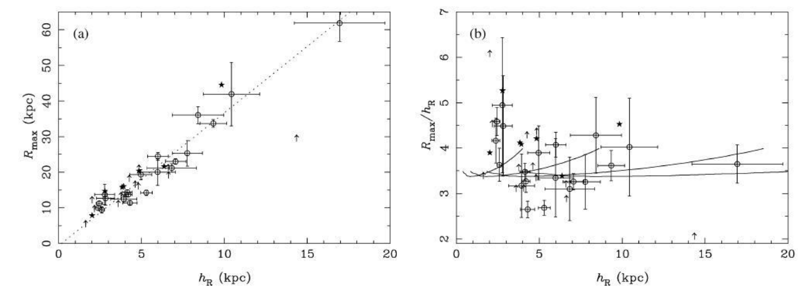
- In edge-on spiral galaxies it was noted[1] that the radial extent did not grow with deeper and deeper photographic exposures.
- Especially when a bulge was present the minor axis did grow with deeper images.
- Prime examples of this phenomenon of so-called disk truncations were the galaxies NGC 4565 and NGC5907.

[1] P.C.van der Kruit, A.&A.Suppl. 38, 15 (1979)


NGC 4565
NGC 5907



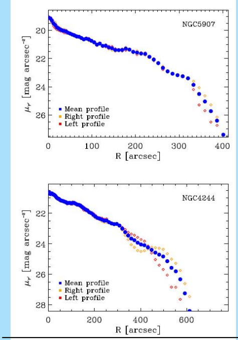
- An analysis[2] of a sample of 34 southern spiral galaxies shows that
  - At least 60% have radial truncations at radius $R_{\max}$.
  - They occur on average at about 4 radial scalelengths h and the ratio $R_{\max}/h$ decreases towards larger scalelengths.

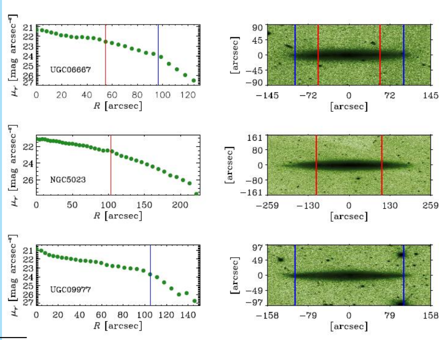


[2] M. Kregel, P.C. van der Kruit & R. de Grijs, MNRAS 334, 646 (2002); M. Kregel & P.C. van der Kruit, MNRAS 355, 143 (2004)

Breaks and truncations

A unified picture of breaks and truncations in spiral galaxies has been proposed using SDSS and S^4G imaging.[3]





[3] I. Martín-Navarro, J. Bakos, I. Trujillo, J.H. Knapen *et al.*(20), MNRAS 427, 1102 (2012).

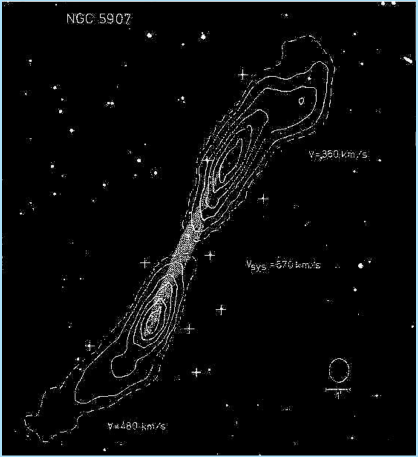
Their conclusions are:

- Breaks occur at $\sim 8 \pm 1$ kpc $[0.77 \pm 0.06\ R_{25}]$.
- Truncations occur close to the outermost optical extent at $\sim 14 \pm 2$ kpc $[1.09 \pm 0.05\ R_{25}]$.
- Breaks are related to a threshold in the star formation [or bars, etc., I would say],
- Truncations represent real drops in the stellar mass density; related to the maximum specific angular momentum in the stellar disks.

Warps in HI-disks

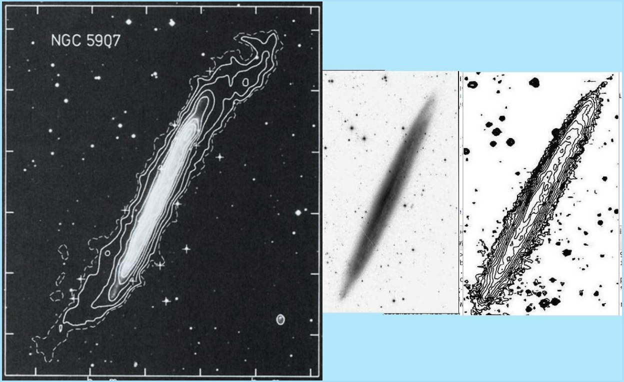
HI warps in edge-on galaxies[4]

- Warps in the HI in external galaxies are most readily observed in edge-on systems as NGC 5907.
- The picture shows the 'extreme channels' of the WSRT observations.
- So we see here the 'line of nodes'.



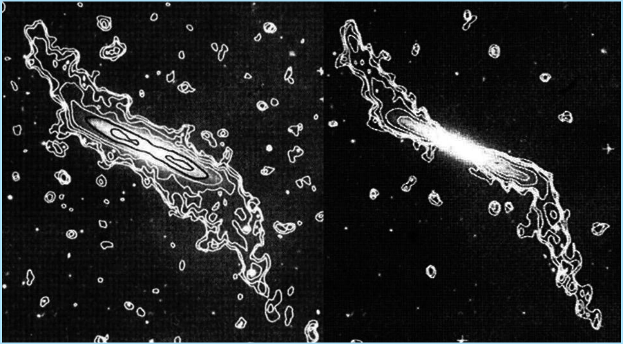
[4] R. Sancisi, A.&A. 74, 73 (1976)

- NGC 5907 has a clear and sharp truncation[5] in its stellar disk, where also the warp sets in.



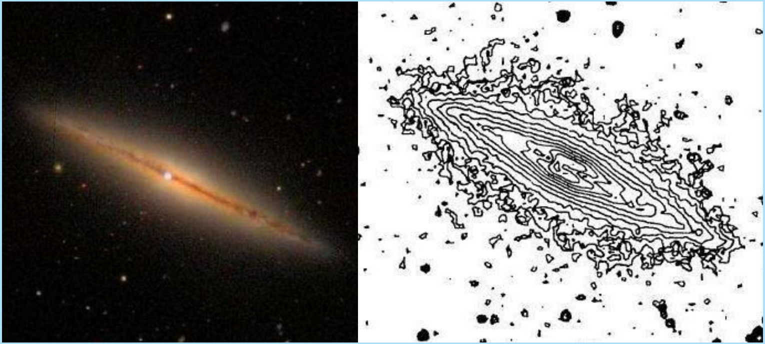
[5]P. C. van der Kruit & L. Searle, *op. cit.*

- An extreme example is "prodigious warp" in NGC 4013[6].
- The warp is very symmetric and starts suddenly near the end of the optical disk (see the extreme channel maps on the left).



[6] R. Bottema, G.S.Shostak & P.C. van der Kruit, Nature 328, 401 (1987); R. Bottema, A.&A. 295, 605 (1995) and 306, 345 (1996)

- NGC 4013 also has a clear truncation[7] in its stellar disk. The three-dimensional analysis[8] does confirm that in de-projection the warp starts very close to the truncation radius.



[7] P. C. van der Kruit & L. Searle, *op. cit.*
[8] R. Bottema, *op. cit.*

The García-Ruiz et al. sample

- Inigo García-Ruiz[9] presented HI observations of a sample of edge-on galaxies ("Hunting for warps").
- His sample consisted of 26 edge-on galaxies in WHISP[10].
- At least 20 have extended HI and all show evidence for an HI warp.
- Sloan Digital Sky Survey (SDSS) images show that at faint levels there is evidence for truncations in 12 there are truncations.

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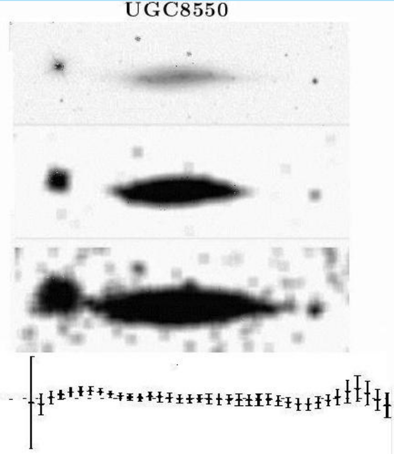
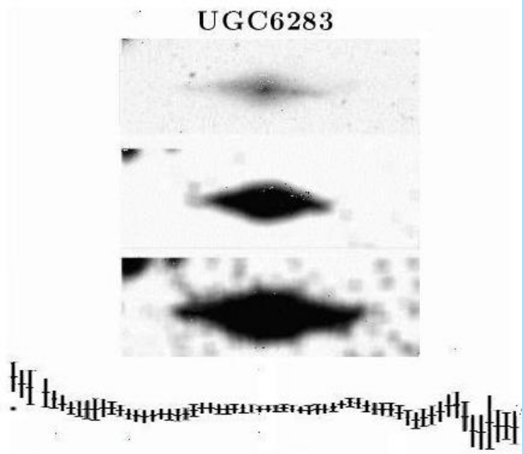
[9] Ph.D. Thesis, University of Groningen (2001); see also I. García-Ruiz, R. Sancisi & K.H. Kuijken, A.&A. 394, 796 (2002)

[10] Westerbork observations of neutral Hydrogen in Irregular and SPiral galaxies; www.astro.rug.nl/whisp/.

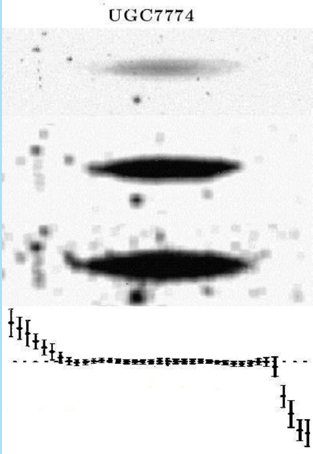
UGC 8550:
No truncation and no warp

UGC 6283:
No truncation, warp at larger radius.

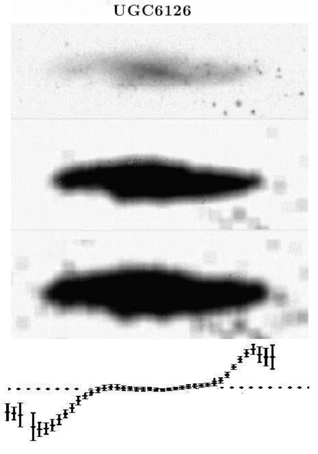




UGC 7774:
Truncation, warp starting at R_{max}.



UGC 6126:
Truncation, warp starting at $< R_{max}$.



The distribution of $R_{\rm warp}/R_{\rm max}$ is consistent with all warps starting at about 1.1 R_{max} for a random viewing angle.[11]

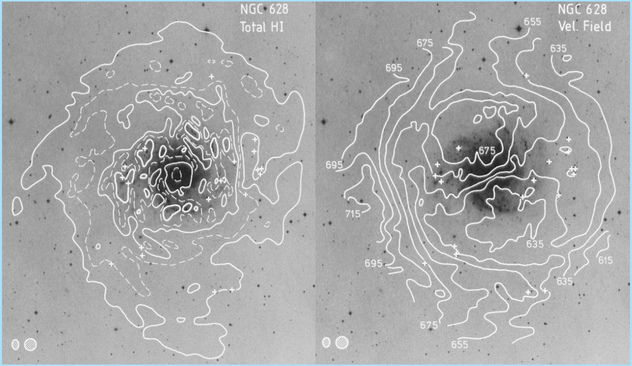
HI warps start abruptly just beyond the truncations in the stellar disks.

This shows that the formation process of the inner disk is discretely different from that of the outer parts.

[11] P.C. van der Kruit, A.&A. 466, 883, 2007.

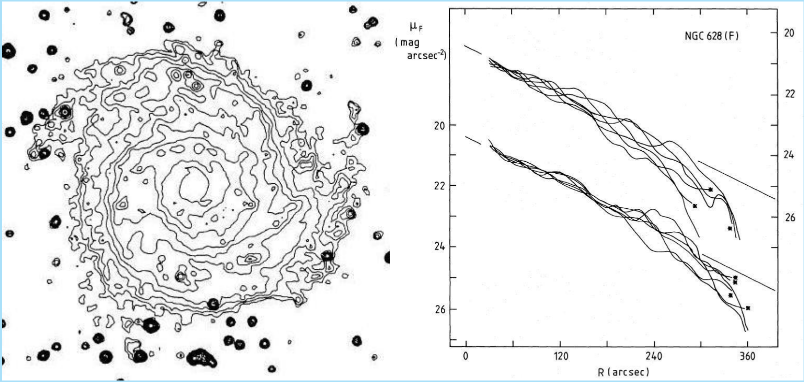
HI warps in inclined/face-on galaxies

- NGC 628 is almost completely face-on.
- The HI-velocity field shows a complicated pattern, that shows that in the HI layer goes through the plane of the sky[12].



[12] G.S. Shostak & P.C. van der Kruit, A&A 132, 20 (1984)

- The radial luminosity profiles[13] show evidence for a truncation.
- This truncation coincides with the onset of the warp.



[13] G.S. Shostak & P.C. van der Kruit, *op. cit.*; P.C. van der Kruit, A.&A. 192, 117 (1988)

Flatness of disks

Disks are very flat.

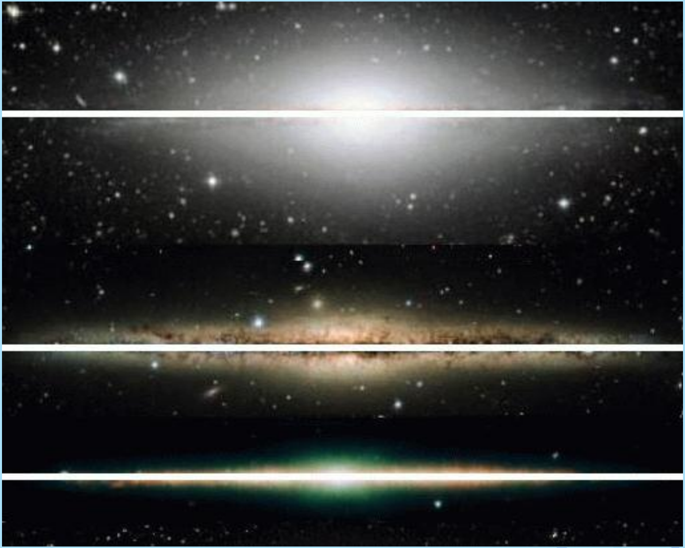
First we look at stellar disks.

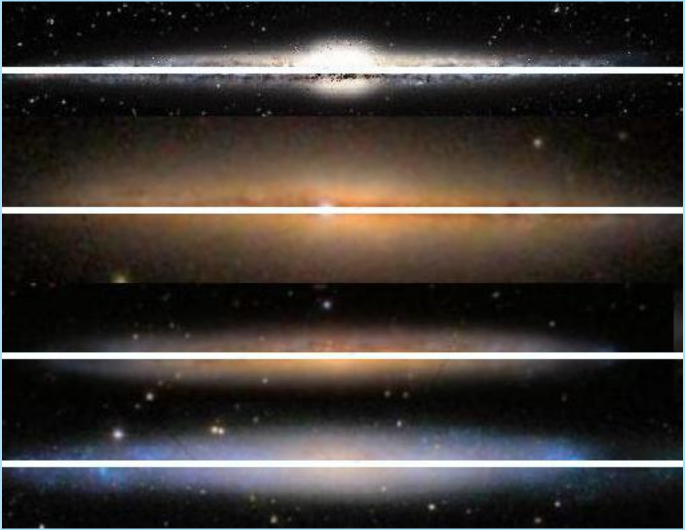
Here are a few edge-on galaxies.

Note from the dust lanes that the disks are **very** straight.

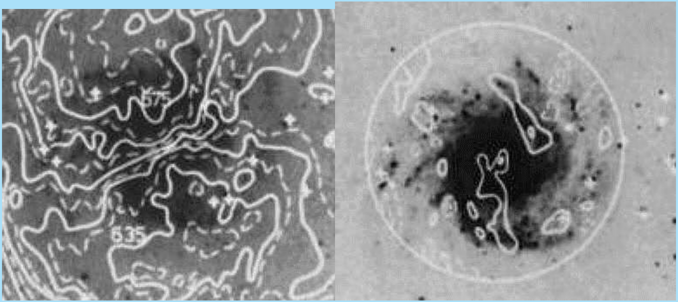
More details elsewhere[14].

[14] P.C. van der Kruit & K.C. Freeman, Ann. Rev. A.&A. 301 (2011).





The residual velocity field in the inner parts of NGC628 after subtraction of the rotation field, has an r.m.s. velocity of only (3-4) km/s, compared to a velocity dispersion of (8-10) km/s.

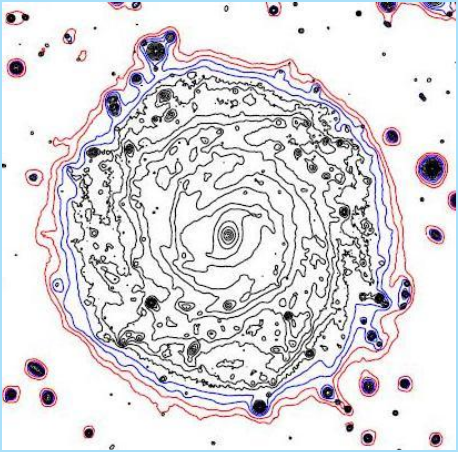


A vertical velocity of 4 km/s corresponds in the Solar Neighborhood to an amplitude of 45 pc, so this shows also that disks are very flat.

Truncations in inclined/face-on stellar disks

Surface photometry of NGC 5923.[15]

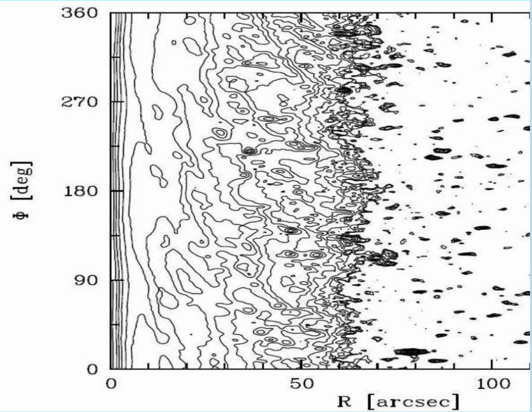
- We expect truncation fainter than the usual limit of surface photometry.
- Disks are not perfectly circularly symmetric.
- But we often see the faintest isophotes to have a smaller spacings.
- Look e.g. at the red and blue contours.



[15] Pohlen, Dettmar, Lütticke & Aronica, A.&A. 392, 807 (2002)

Here is the same data in polar coordinates.

The irregular outline shows that truncations will be smoothed out in most analyses contrary to observations in edge-on systems.



- Spiral galaxies are expected to have faint extended halos.
- This has been modeled in detail[16].
- Conclusion was that '*Stellar haloes outshine disc truncations in low-inclined spirals*'.
- On the other hand, it has been argued that at least part of this may result from scattering of light by the point spread function (PSF) tails, especially around edge-on disc galaxies[17].

New approach in very recent PhD thesis of Stephan Peters to try and overcome these problems.

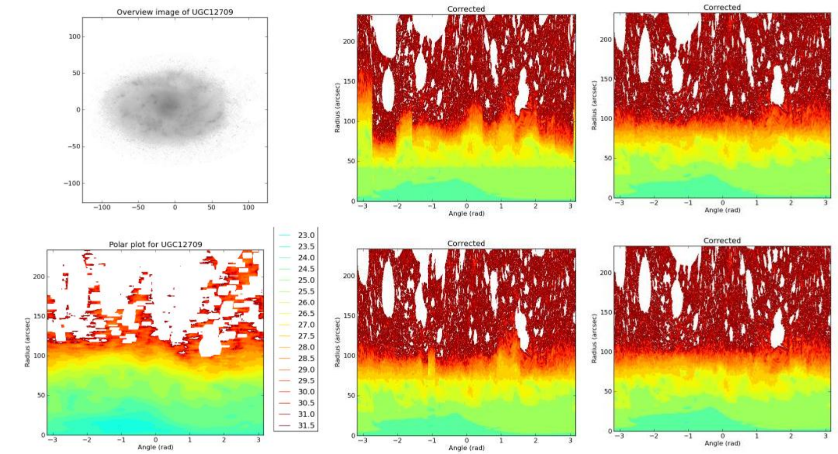
[16] I. Martín-Navarro, I. Trujillo, J. Knapen, J. Bakos & J. Fliri, MNRAS 441, 2809 (2014).

[17] R. de Jong, MNRAS 388, 1521 (2008).

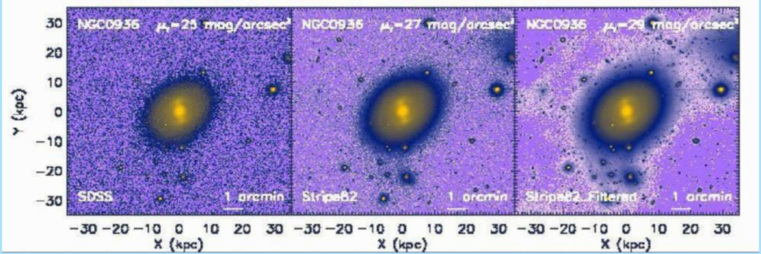
Stripe-82 photometry[18]

- There are four ways in which we analyzed the inclined/face-on brightness distributions.
  - Ellipse Fitting.
    - Too sensitive to departures from circular symmetry.
  - Principle Axis Summation.
    - Too sensitive to background noise and faint stars.
  - Equivalent Profiles.
    - Too difficult to apply at faint levels.
  - Rectified Polar Plots.
    - Probably best method.
- We need very deep data, and for that we use The IAC Stripe 82 Legacy Project of Nacho Trujillo & Jürgen Fliri.

[18] S. Peters, P. van der Kruit & R. de Jong, *in prep.*, S. Peters, P. van der Kruit, J. Knapen, I. Trujillo, J. Fliri & M. Cisternas *in prep.*.

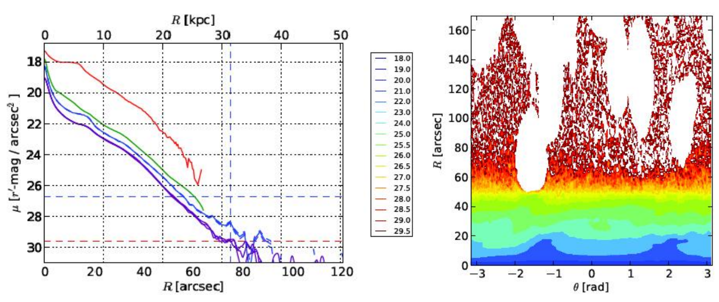

Overview image of UGC12709
Polar plot for UGC12709
Corrected
Corrected
Corrected
Corrected
Radius (arcsec)
Angle (rad)
23.0
23.5
24.0
24.5
25.0
25.5
26.0
26.5
27.0
27.5
28.0
28.5
29.0
29.5
30.0
30.5
31.0
31.5

- The IAC Stripe 82 Legacy Project[19] uses the SDSS Stripe82 dataset.
  - This covers 270 degrees^2 near the equator that has been observed up to $\sim$ 80 times in all 5 filters.
  - Select only the best frames.
  - That gets you deeper by 1.7 mag on average than SDSS DR7 (adding g, r' and i gives a further 0.5 mag).

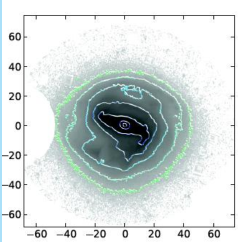


[19] Fliri & Trujillo: www.iac.es/proyecto/stripe82/

- In IAC Stripe82 we found 177 galaxies over 1 arcmin diameter.
- We selected all moderately inclined S0 to Sm galaxies, that looked undistorted and had no bright stars nearby.
- This left uw with 54 galaxies.
- We then rejected all systems with poor sky backgrounds.
- The final sample was 22 galaxies that were suitable for further analysis.

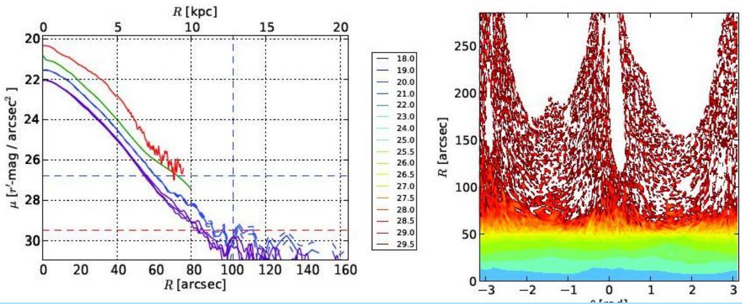


Top to bottom: PAS, Equiv, Ellipse, Polar



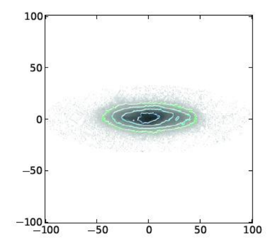
IC 1515:

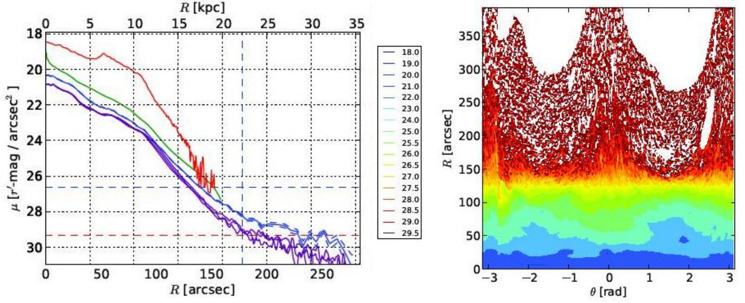
Faint halo beyond ∼ 65 arcsec.



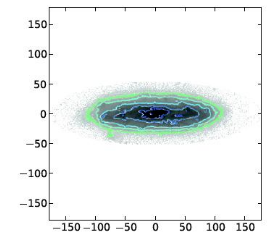
Top to bottom: PAS, Equiv, Ellipse, Polar

UGC 866:
Faint halo beyond ∼ 70 arcsec.
More prominent along minor axis.

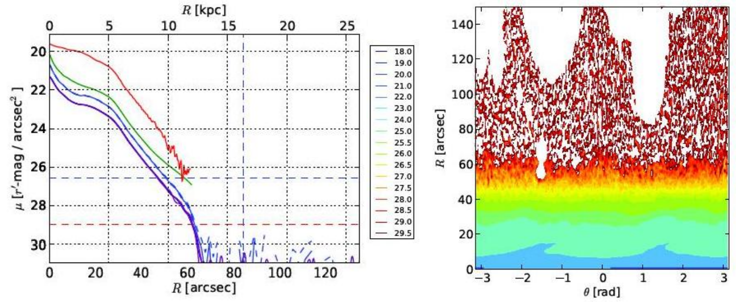




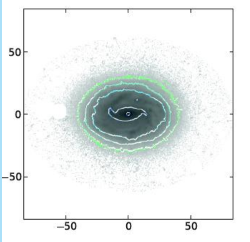
Top to bottom: PAS, Equiv, Ellipse, Polar



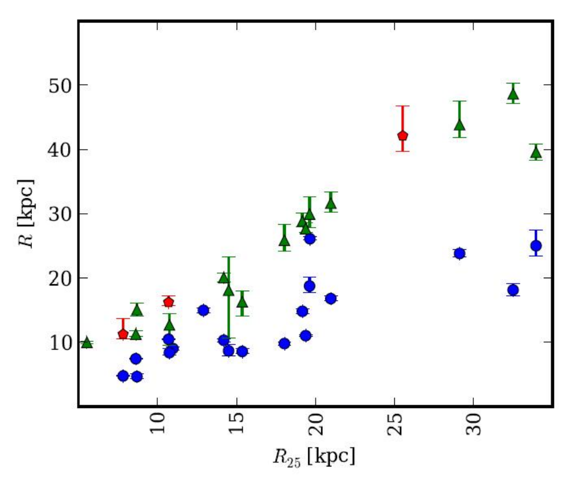
NGC 493:
Faint halo beyond ∼ 150 arcsec.
More prominent along minor axis.



Top to bottom: PAS, Equiv, Ellipse, Polar



UGC 12208:
Truncation at ∼ 60 arcsec.

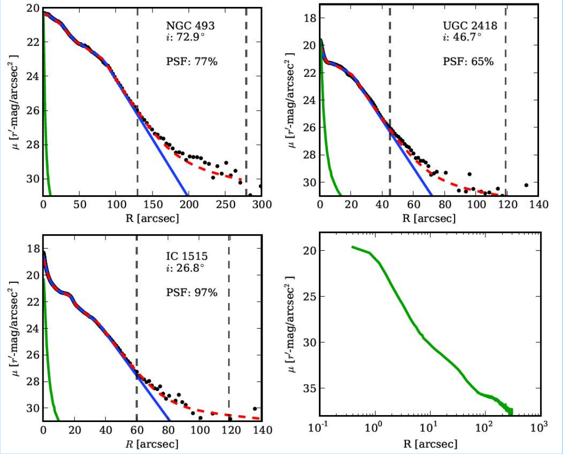


22 galaxies

19 breaks $\mu \sim 23$
15 'halos' $\mu \sim 27.5$
3 truncations $\mu \sim 27$

Truncations only when there is no 'halo'!

- But are these really stellar halos?
- Could for a significant part be scattered light due to PSF.
- At least in part, but if scattered light:
  - Why do we see truncations at all?
  - Where are the expected stellar halos (faint light from Pop. II)?



- Conclusions:
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  - **This abrupt change indicates that differences in the formation history in the inner and outer parts of disk galaxies are discrete rather than gradual.**
  - **In inclined/face-on systems the truncations can sometimes be seen in very deep surface photometry, but are often hidden by faint, extended light from a faint stellar halo and/or from the inner disk scattered by the PSF.**