Dark Matter Cusps in Galaxies from Rotation Curves

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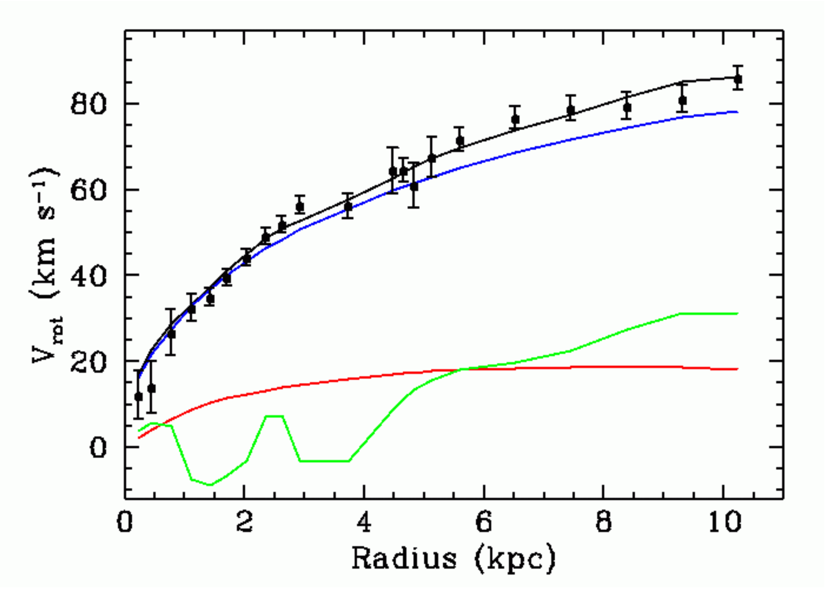
Focus is on dwarf and LSB galaxies

- Dominated by dark matter for reasonable M/L
- Ideal laboratories to study the properties of dark matter and test models of galaxy formation
- Specifically: are rotation curves of dwarf and LSB galaxies consistent with CDM?

DDO 39



Fit with M/L_R=1
and NFW halo
Swaters et al. 2003

HI Observations

- A large range of models is consistent with observations, e.g., inner slopes ($0<\alpha<1.5$) (van den Bosch et al. 2000; van den Bosch & Swaters 2001)
- Beam smearing is not the problem
  - can be corrected for (Swaters 1999; Swaters et al. 2006)
  - can be incorporated in the modeling (e.g., van den Bosch et al. 2000)
- The low resolution of 15" to 30" is insufficient to resolve inner slope

Hα long-slit observations

Long-slit observations yield arcsec resolution for inner regions

Swaters et al. 2000, Borriello & Salucci 2001, de Blok et al. 2001, McGaugh et al. 2001, de Blok & Bosma 2002, Marchesini et al. 2002, Swaters et al. 2003, Spekkens & Giovanelli 2005

Focus on testing CDM, through mass modeling and direct measurement of the inner slopes ... but disagree, especially on whether cusps are consistent with the observations or not...

Measuring the inner slope

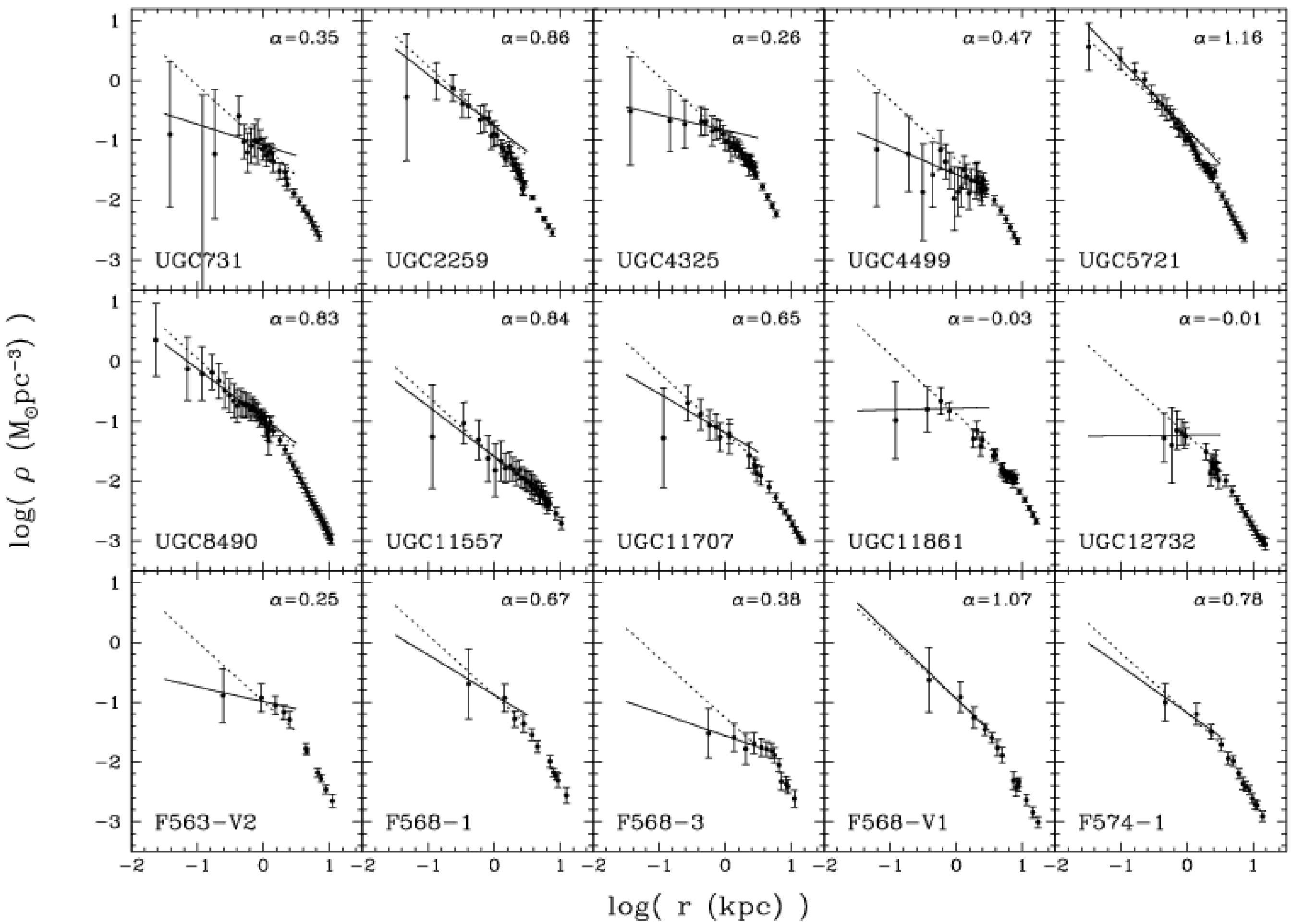
Derive the mass density profile from observations
(e.g. de Blok et al 2001)

Assumptions:

- Dwarf and LSB galaxies are dominated by dark matter
- The mass distribution is spherical
- Observed velocities reflect the gravitational potential (i.e., noncircular motions are not important)

$$\left.\begin{aligned} M(R) &= \int_0^R 4\pi G r^2 \rho(r)\, dr \\ v(R)^2 &= \frac{M(R)G}{r} \end{aligned}\right\} \quad \rho(R) = \frac{1}{4\pi G}\left(\frac{v^2}{r^2} + 2\frac{v}{r}\frac{\partial v}{\partial r}\right)$$

Derived mass profiles



Swaters et al. 2003, see also de Blok et al. 2001

Observed α spans a range from 0 to 1 ... how about the *intrinsic* α?

Systematic effects on Hα long-slit observations

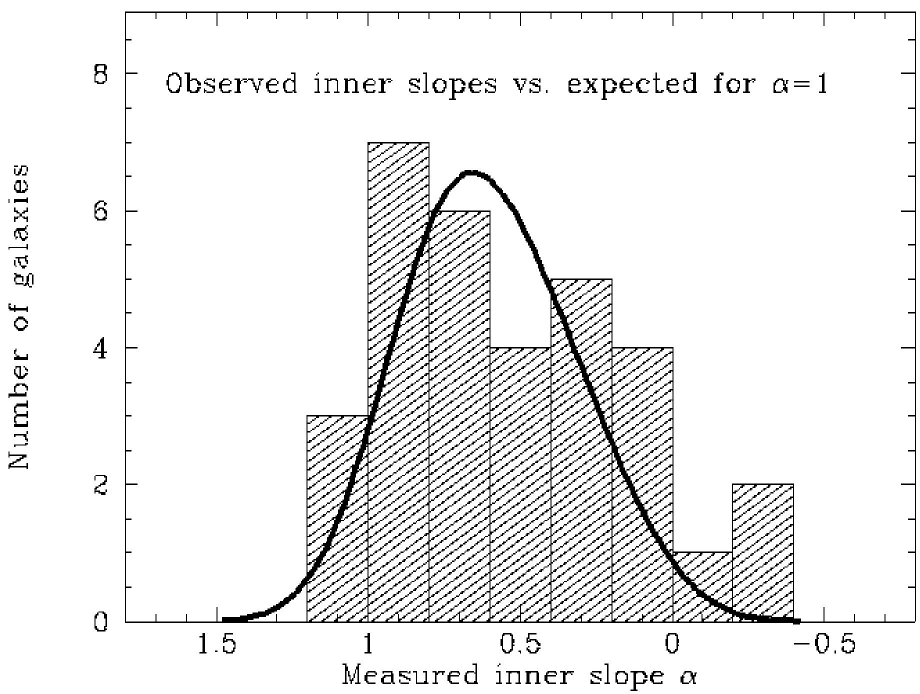
- Seeing and slit width dilute the inner slope, leading to an underestimate
- Slit offsets miss the steepest part, leading to an underestimate
- Edge-on galaxies traditional analysis leads to an underestimate
- Hα distribution if there is no emission on the major axis, this will lead to an underestimate. May be important in the center
- Noncircular motions could go both ways

Strong observational bias towards shallower slopes

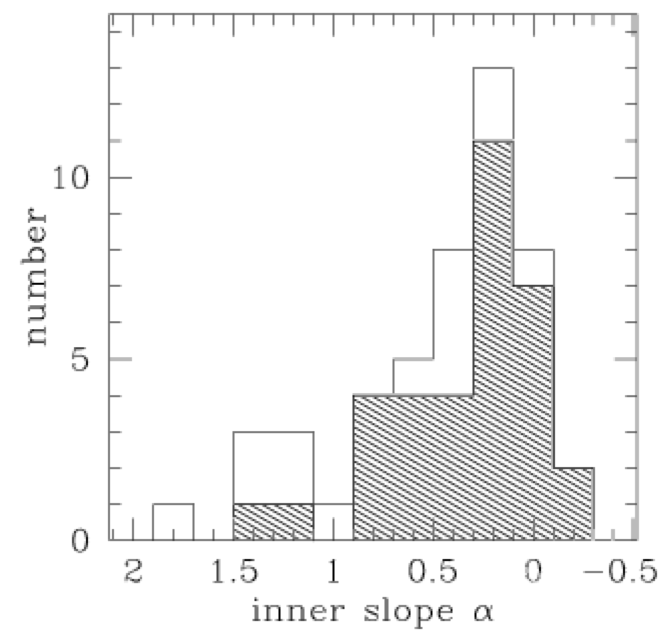
Taking systematic effects into account

Taking systematic effects into account, 0<α<~1 consistent with observations, α=1.5 is ruled out (Swaters et al. 2003)

Revisit results by de Blok et al. (2001)



Data from de Blok et al. 2001, de Blok & Bosma 2002, Swaters et al. 2003 (34 galaxies with suitable inclinations, barred galaxies excluded)



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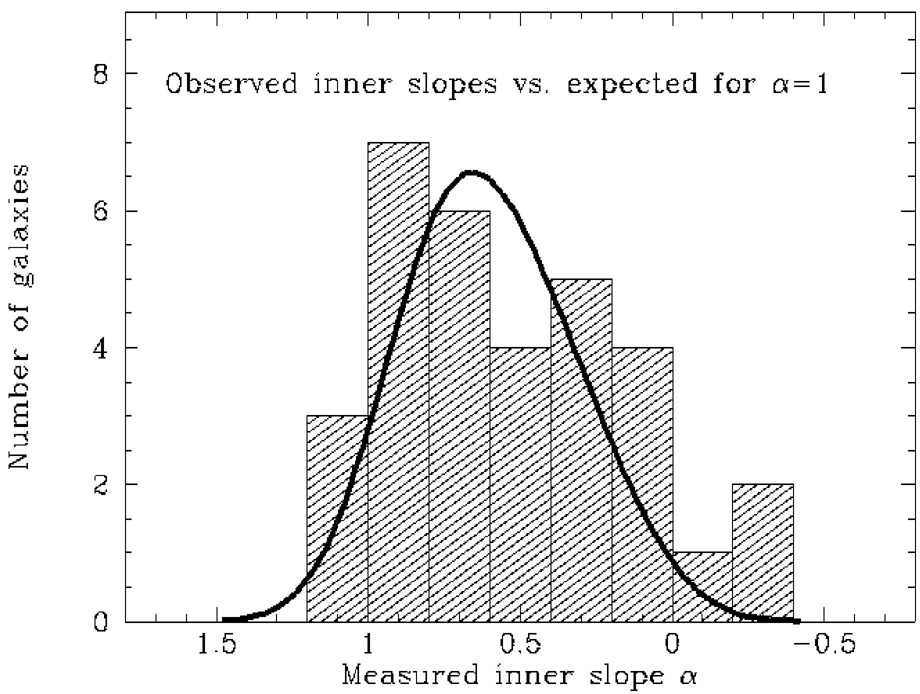

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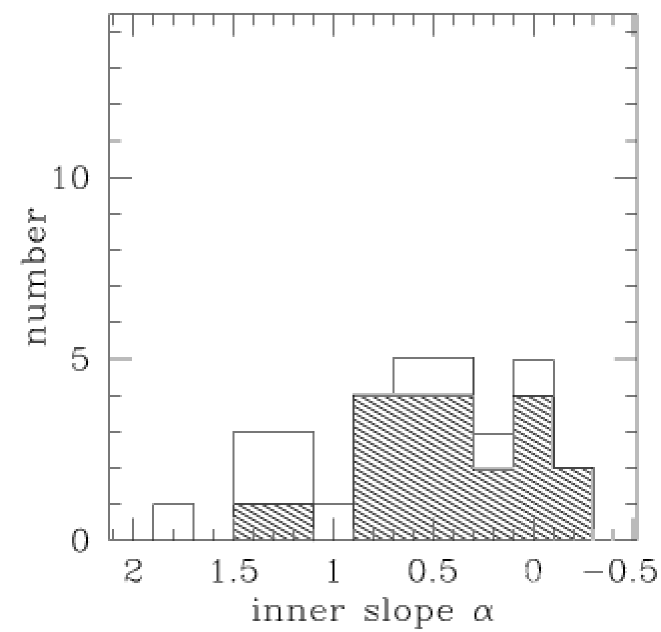

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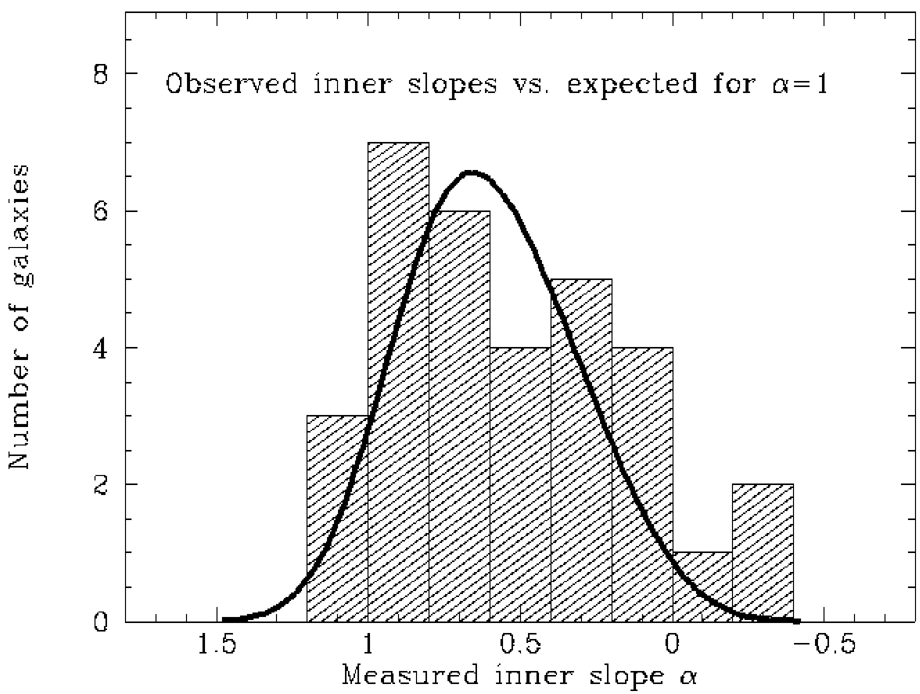

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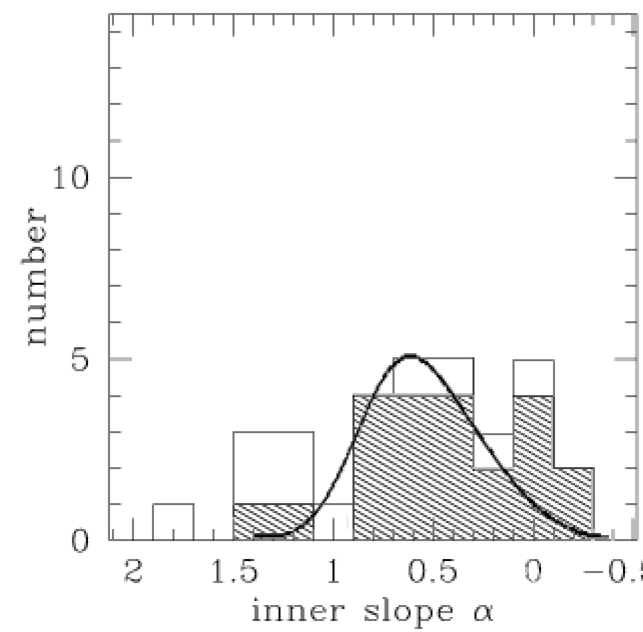
Revisit results by de Blok et al. (2001). After taking out highly inclined galaxies their observed distribution of α is compatible with α=1



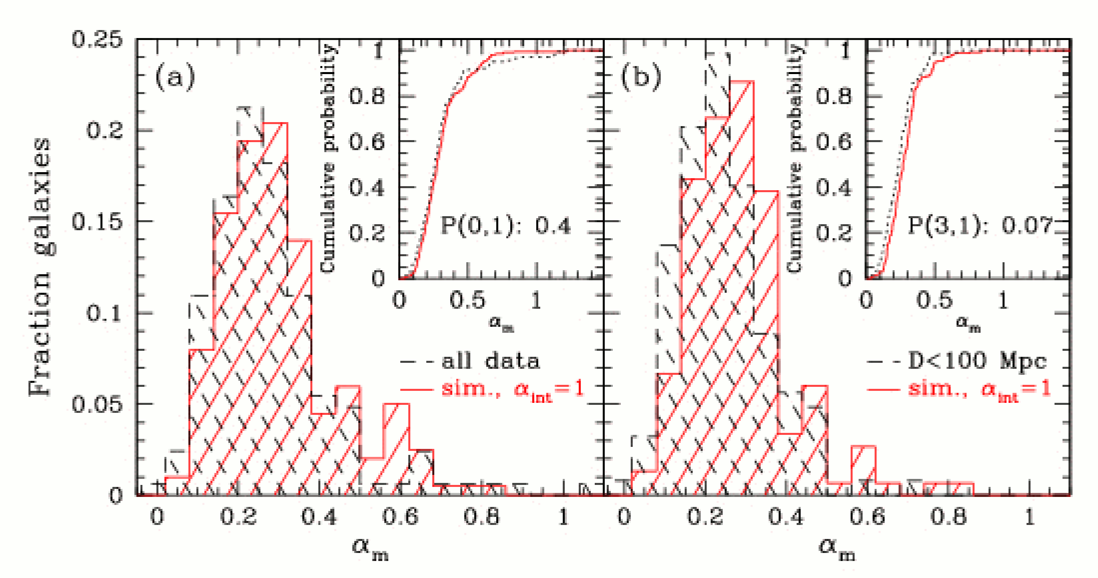
de Blok et al. 2001

Taking systematic effects into account

Previous studies were limited in sample size and selection...

Spekkens & Giovanelli (2005) used the Cornell SFI++ database, selecting galaxies with vrot<130 km/s, no distorted morphologies, no bulges, and well determined inner rotation curves, resulting in a sample of 163 galaxies.

They constructed and "observed" model galaxies with different halos, and found that $0<\alpha<1$-1.25 are consistent with the data, $\alpha=1.5$ is ruled out.

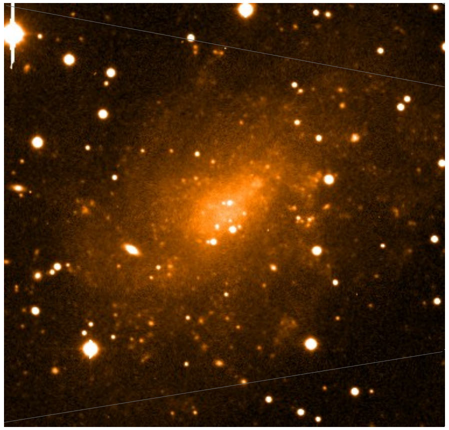


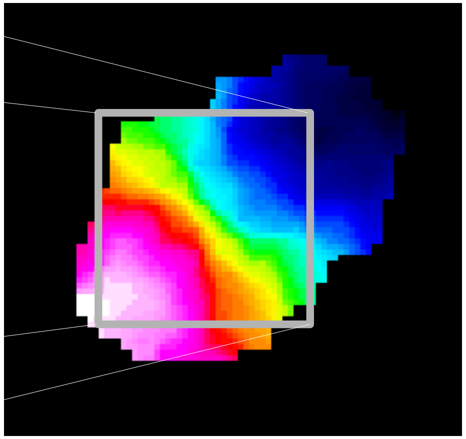
Conclusion based on long-slit data: intrinsic inner slopes in the range $0<\alpha<1\text{-}1.2$ are consistent with the data

Needed: 2D velocity fields

No uncertainty in slit position, Hα distribution and noncircular motions are mapped – fiber size may still affect results

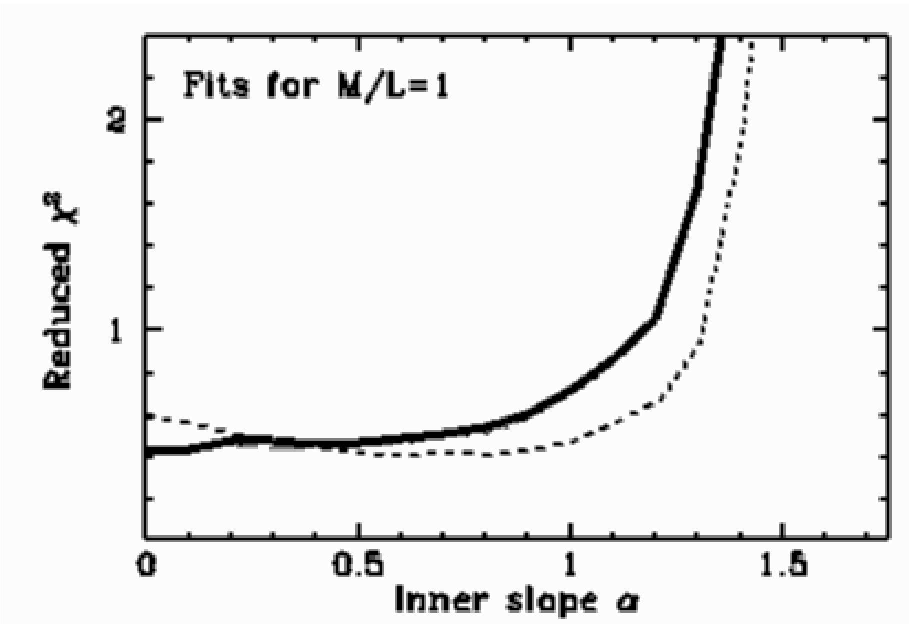
One example is DDO 39, observed with SparsePak, is well suited: i~49° low surface brightness μ_B=24.4 mag arcsec^{-2}, dominated by exponential disk with h=3.5 kpc, regular morphology and HI kinematics.





Swaters, Verheijen, Bershady, Andersen 2003

Limits on *c* and α for DDO 39

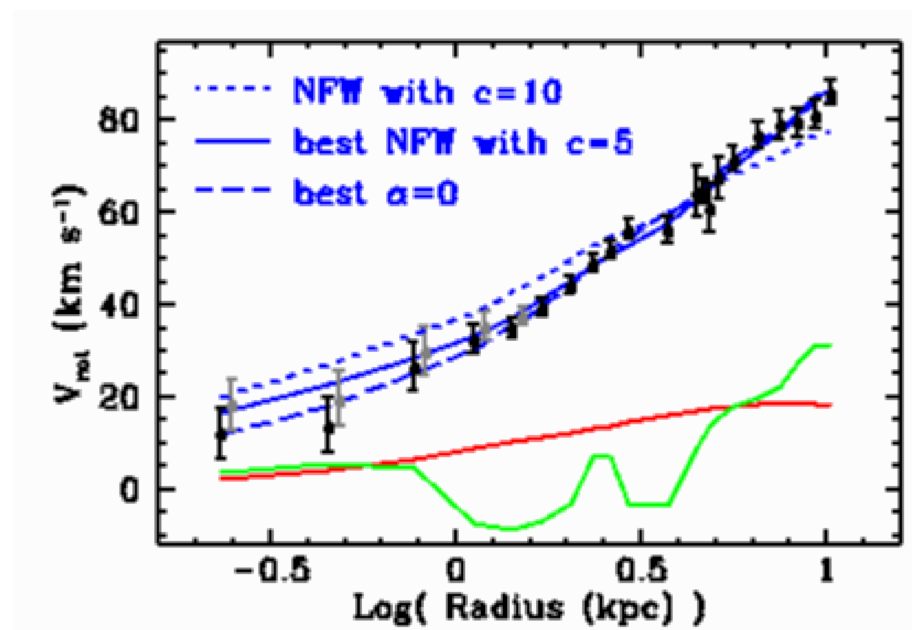


Fits for range in α a with M/L=1 (e.g. van den Bosch et al 2001)

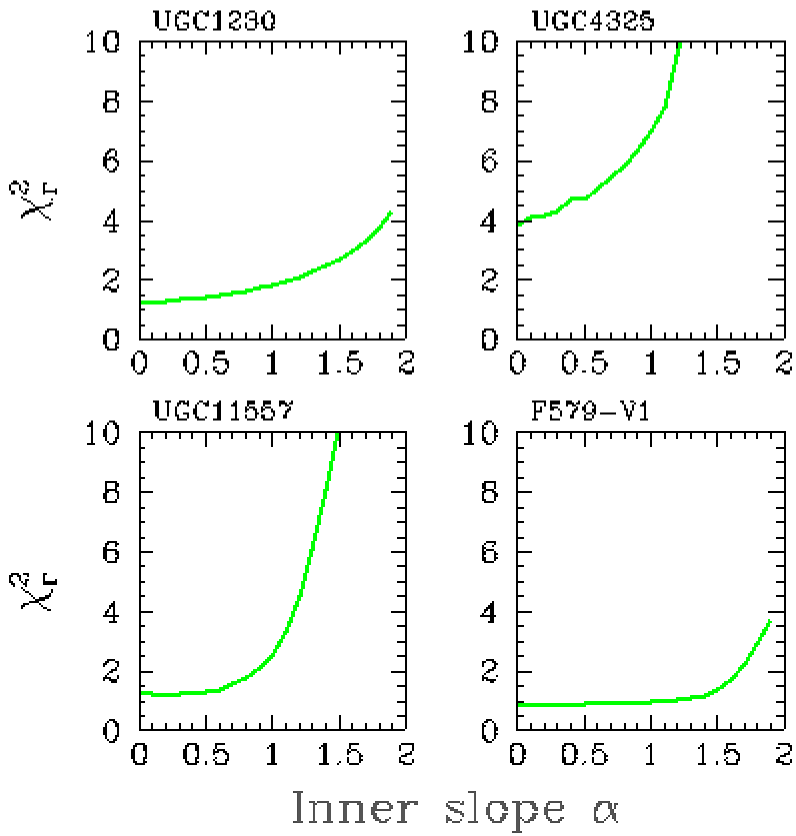
Inner slopes in the range 0 < α < 1 appear consistent with the data.

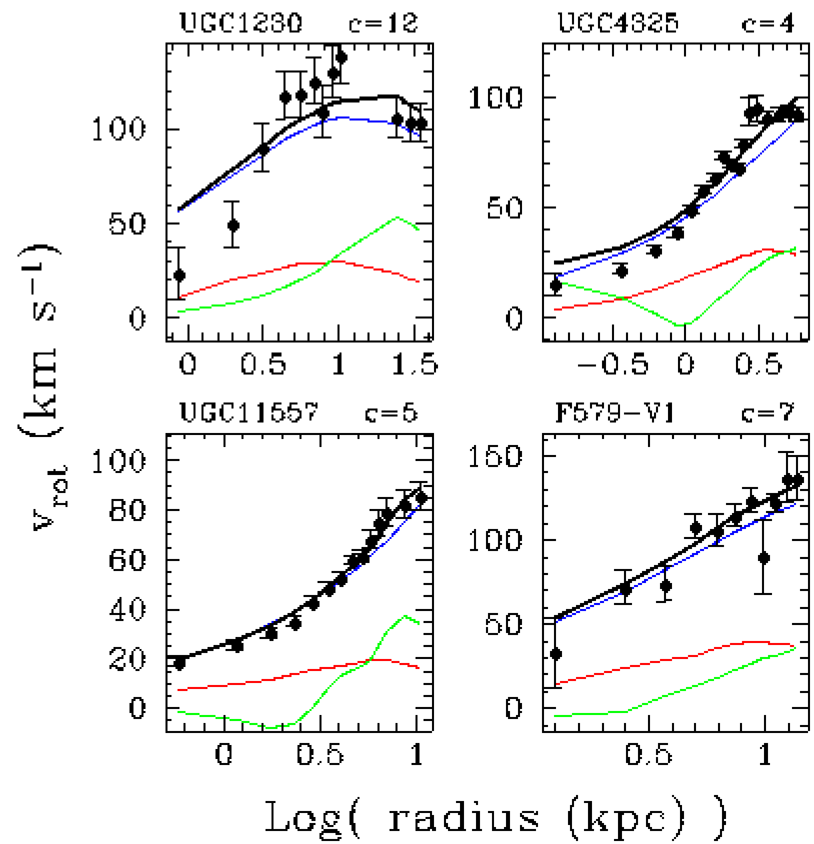
Best fit *c*=5 is on low end for ΛCDM,

***c*=10 is inconsistent with rotation curve**



Limits on c and α



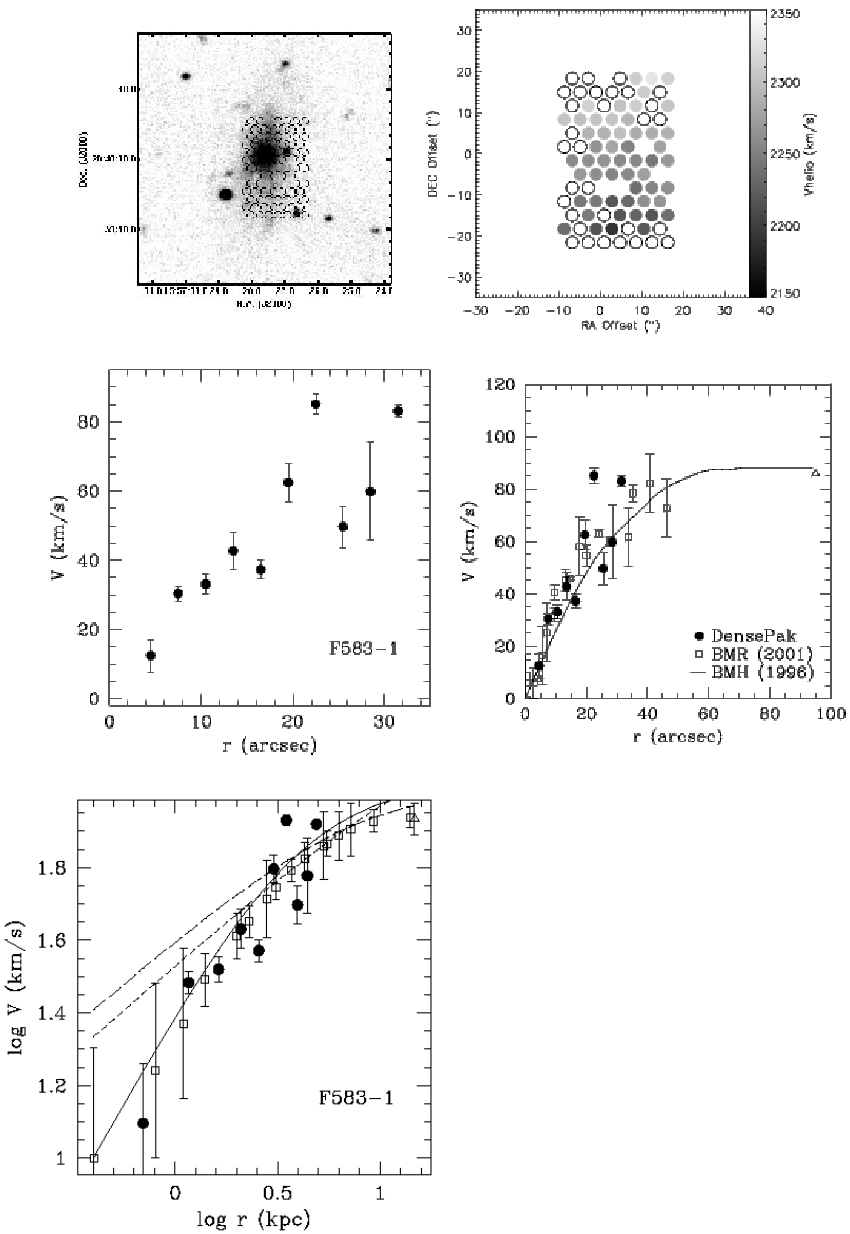


Swaters, Verheijen, Bershady, Andersen, in preparation

Inner slopes in the range $0<\alpha<1$ appear consistent with the data; lower α give better fits

Poor NFW fits for some galaxies, best fit c are on low end for ΛCDM

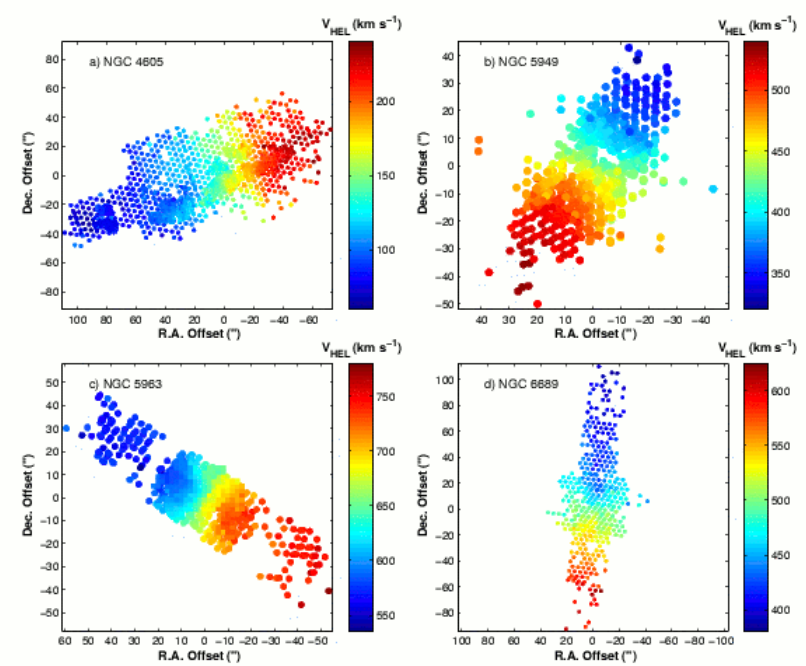
Limits on *c* and α



Kuzio de Naray et al. 2006

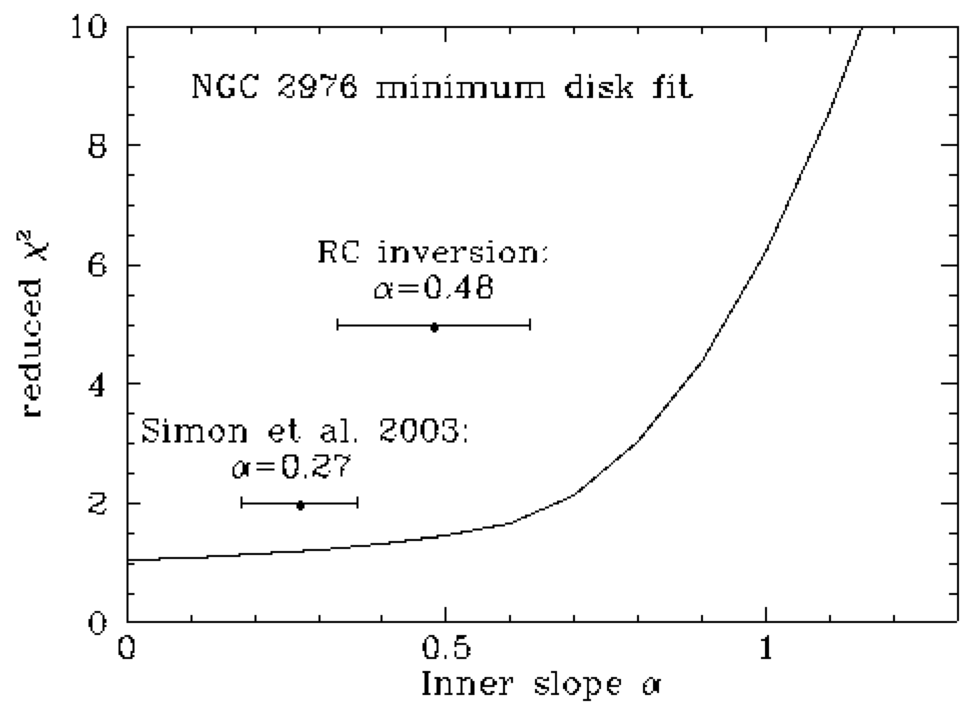
Kuzio de Naray et al. (2006) observed 11 LSB galaxies with DensePak, 4 no fits, other have low c, ranging from 5 to 10, NFW fits poorer than ISO

Limits on c and α



Simon et al. (2003, 2005) observed 5 low mass spiral galaxies with denspak.

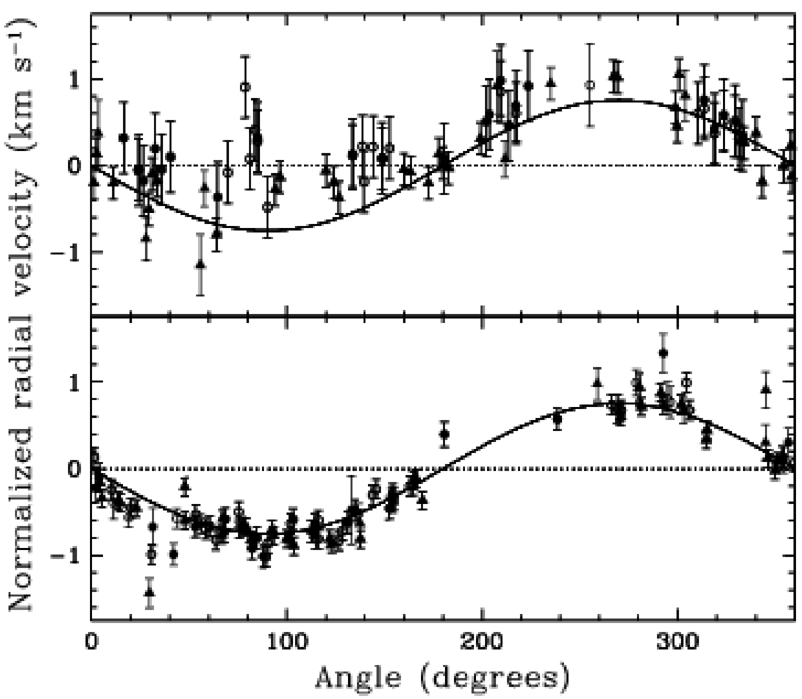
Fit power law slope to entire rotation curve, and find α ranging from 0 to 1.2, with average α=0.73



Conclusion based on 2D data: α still poorly constrained, fits prefer halos with constant density cores over NFW, concentration parameter c tends to low values (also for long-slit data)

Noncircular motions

Strong noncircular motions exist even in galaxies that seem as regular as DDO 39:



Swaters et al. 2003

Noncircular motions are common:

- 4 out of 5 galaxies studied by Simon et al. (2003, 2005) have detectable nonradial motions
- 4 out of 6 in Swaters et al. (in prep) show noncircular motions
- Majority of galaxies in GHASP survey (Garrido et al. 2003)

Origin of noncircular motions

- On small scales:
  - Star formation activity
  - Structure in the disk
  - Small scale structure in the halo
  - Vertical motions?
  - Stochastic in nature, need large sample
- On larger scales:
  - Triaxial halos
  - Bars, spiral structure
  - Lopsidedness
  - Should to be included in the modeling

Conclusions

- The observed inner slopes in dwarf and LSB galaxies show a large spread and are uncertain (inherently, due to systematic effects, and noncircular motions). *Intrinsic* inner slopes $0<\alpha<\sim 1$ are consistent with observations. The inner slope α cannot be reliably measured for individual galaxies.
- The halo concentration parameters c can be measured more robustly and thus these provide a stronger test for CDM. Looking at the best available data, c tend towards low values.
- Noncircular motions are common and should be taken into account, statistically and/or through modeling