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Non-circular motions and the cusp/core discrepancy in dwarf galaxies

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Outline

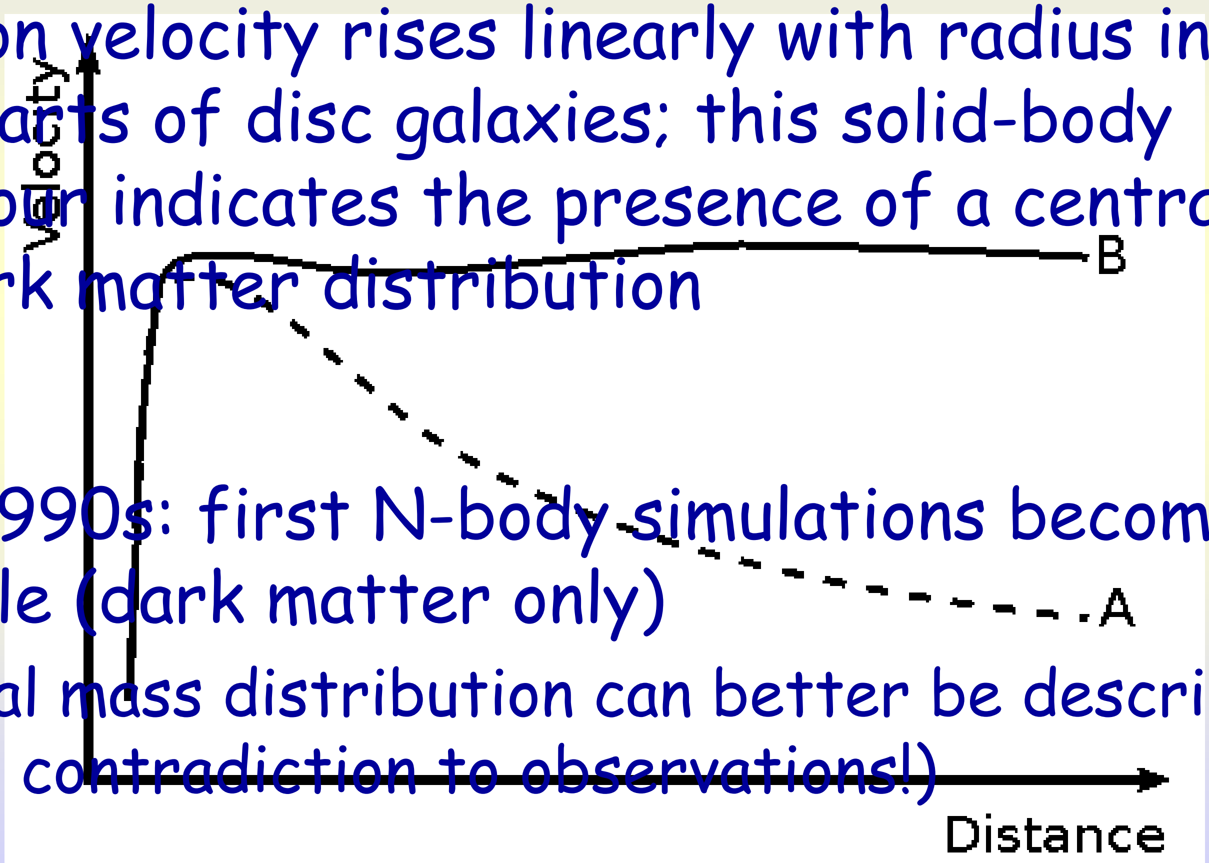
- Introduction
- Presentation of the sample
- Non-circular motions
- Mass decomposition → density slopes
- Summary

Based on van Eymeren et al. 2009, *A&A*, **505**, 1

A little bit of history…

- Rotation curves of disc galaxies are flat in the outer parts (Bosma 1978, Rubin et al. 1978)

- Rotation velocity rises linearly with radius in the inner parts of disc galaxies; this solid-body behaviour indicates the presence of a central core in the dark matter distribution

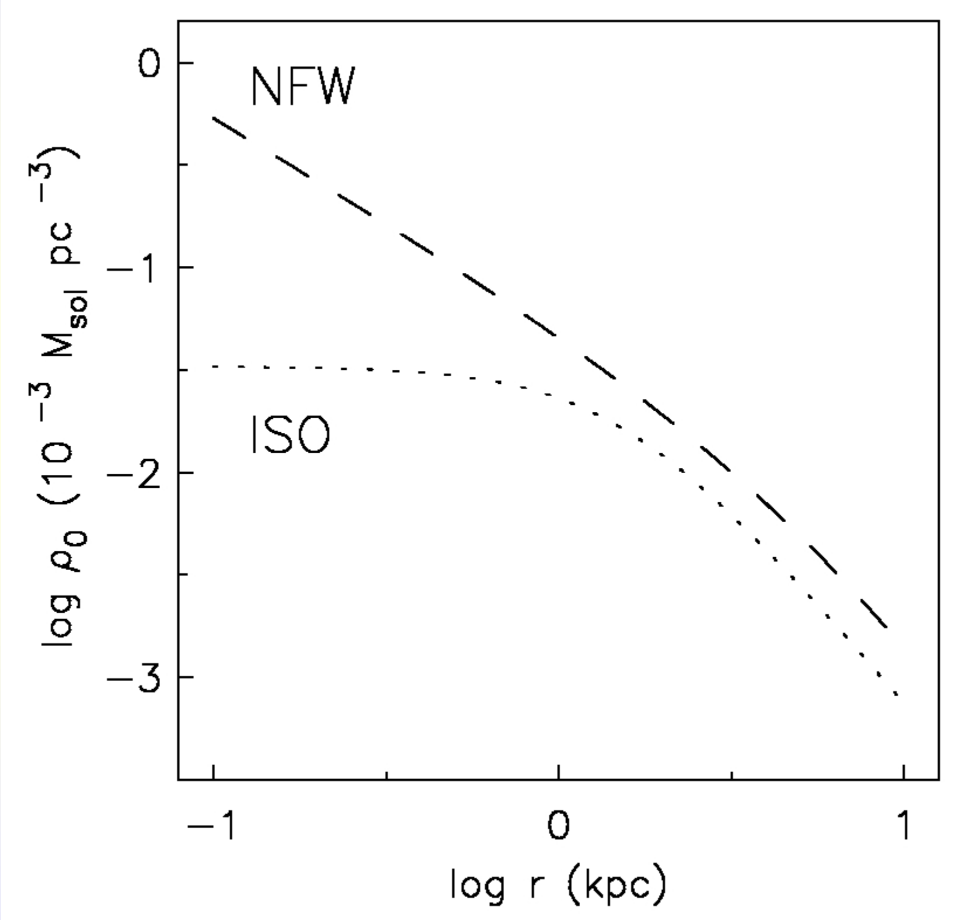


- Early 1990s: first N-body simulations become available (dark matter only)

  - Central mass distribution can better be described as a cusp (in contradiction to observations!)

Cusp-core discrepancy

- The density distribution can be described by a power law $\rho(r) \sim r^{\alpha}$

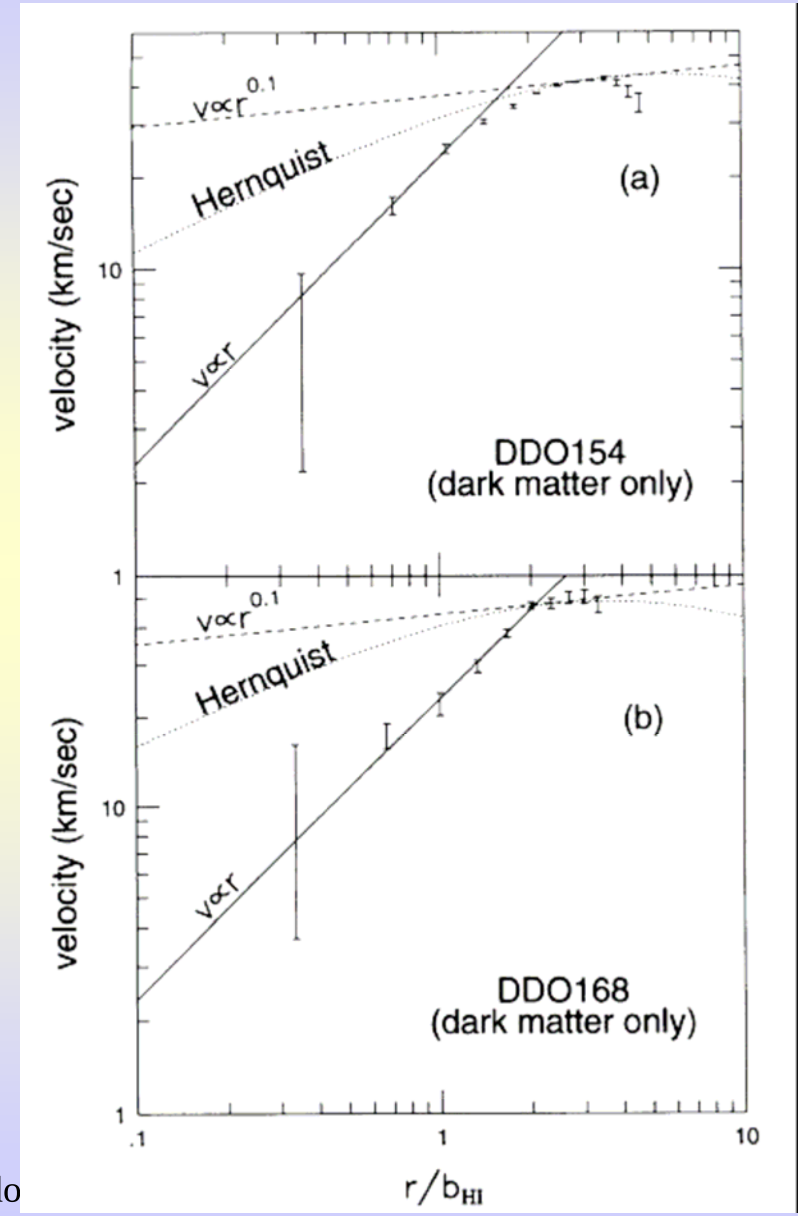


Cusp-core discrepancy
- Simulations -

- Cuspy NFW profile: α=-1 (Dubinski & Carlberg 1991, Navarro et al. 1996) to α=-1.5 (Moore et al. 1999)
- Many studies assumed that the central cusp shows a constant slope in the mass density distribution; however, more recent simulations reveal that the slope keeps getting shallower towards small radii (< 1 kpc): Navarro et al. (2004), Hayashi et al. (2004)

Cusp-core discrepancy
- Observations (1) -

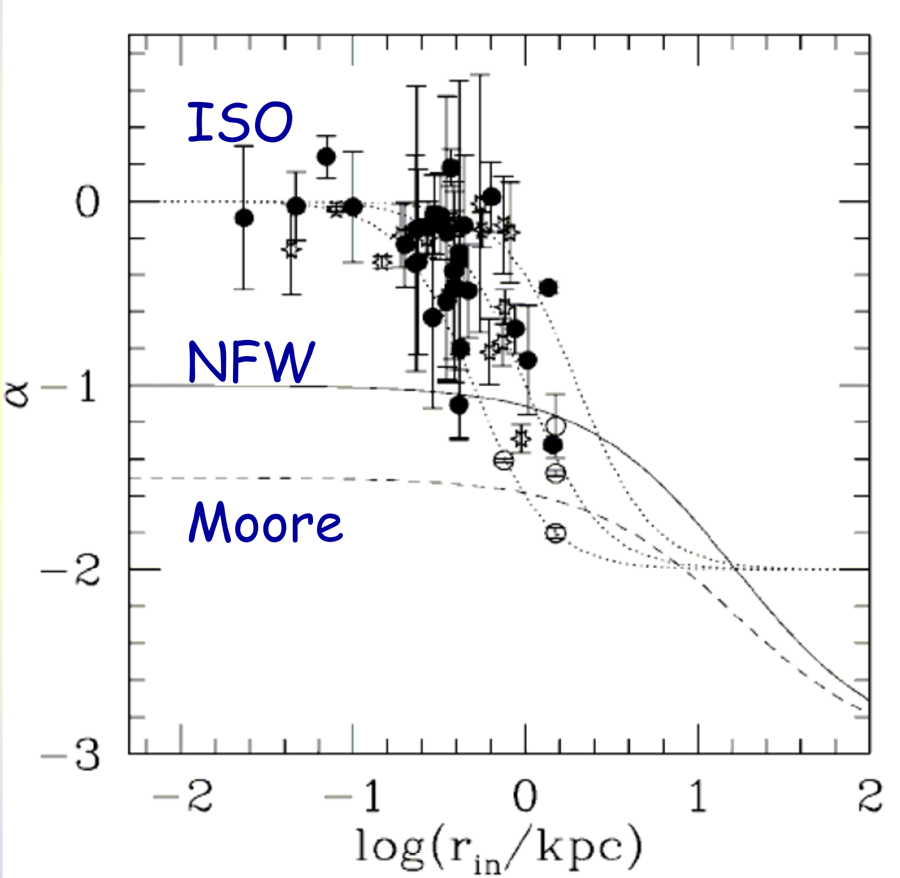
- HI observations of gas-rich dwarf galaxies show large discrepancy between observed rotation curves and those predicted (Moore 1994, Flores & Primack 1994)



Flores & Primack (1994)

Cusp-core discrepancy
- Observations (2) -

- cored pseudo-isothermal halo (ISO), α=-0.2±0.2 (de Blok et al. 2001)



de Blok et al. (2001)

From the perspective of a theorist: issues with observations

- HI observations - **beam smearing**: limited spatial resolution (few tens of arcsec) decreases the observed velocities (steeply rising into solid body)

  - high spatial resolution (< 1 kpc, de Blok et al. 2008)

- Hα observations - **slit misplacement**: missing the dynamic centre of the galaxy

  - repeated 1d long-slit spectra observed by independent observers at different telescopes

  - optical 3d spectroscopy (Kuzio de Naray et al. 2006, 2008; Spano et al. 2008)

- **Non-circular motions**: it is assumed that the gas moves on circular orbits, any deviation will lead to an underestimate of the slope

  - only of the order of a few km s^{-1} (Gentile et al. 2005, Trachternach et al. 2008)

- First attempt of modeling the observational systematic effects (de Blok et al. 2003): to hide a cusp in a core, one needs

  - systematic non-circular motions of 20 km s^{-1} over large parts of the disc

  - systematic telescope pointing offsets of 3-4"

  - dynamic and photometric centres systematically offset by 0.5 - 1 kpc

Physical processes that might turn a cusp into a core

- **Feedback and merging**:

  - Baryonic blow-outs (Navarro et al. 1996, Burkert 1995, Gelato & Sommer-Larsen 1999)

  - Effects of bars (Weinberg & Katz 2002, see, however, Dubinski et al. 2009)

  - Interactions between or merging of dark matter haloes: only mergers between cored haloes give a cored merger product (Boylan-Kolchin & Ma 2004, Dehnen 2005)

- **Adiabatic contraction:**

  - during galaxy formation process gas settling in the halo contract the inner dark matter distribution, makes profile even cuspier

- **Dynamical friction, creation of cores at high red-shift:**

  - initially very steep cusp (α=-2), heated by sub-haloes, becomes shallower from the inside out (Romano-Díaz et al. 2008)

  - see, however, Jardel & Sellwood (2009) who claim that baryonic clumps are not massive enough

  - cannot explain gravitational lensing results (Chen & McGaugh 2008), which demand α=-2 for elliptical galaxies

- **Triaxiality** (Hayashi et al. 2004, 2006):

  - CDM haloes are triaxial objects with a globally elongated potential, this might induce systematic non-circular motions

From the perspective of an observer: issues with simulations

- Spatial resolution
- Based on DM only (baryons and the associated physics – star formation activity, supernova feedback – are completely neglected), this is now changing (Pedrosa, Tissera & Scannapieco 2009, Navarro et al. 2010)

Our project - Strategy

(1) Look at a sample of dwarf galaxies (dark matter dominated throughout the disc)

(2) Obtain HI synthesis observations with sufficiently high spatial resolution

(3) Derive kinematic parameters by performing a tilted-ring analysis of the velocity fields

(4) Quantify non-circular motions by performing a harmonic decomposition

(5) Decompose the rotation curves into contributions from baryons (gas, stars) and dark matter

- use NFW halo and empirically derived pseudo-isothermal (ISO) halo

(1)+(2) Sample

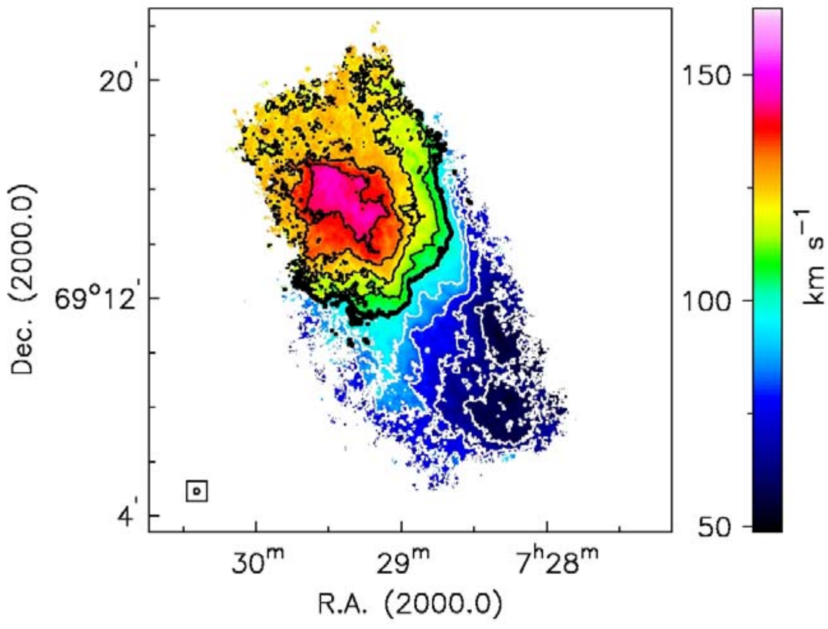
- VLA
  - NGC 2366 (THINGS, PI: F. Walter)
  - NGC 4861

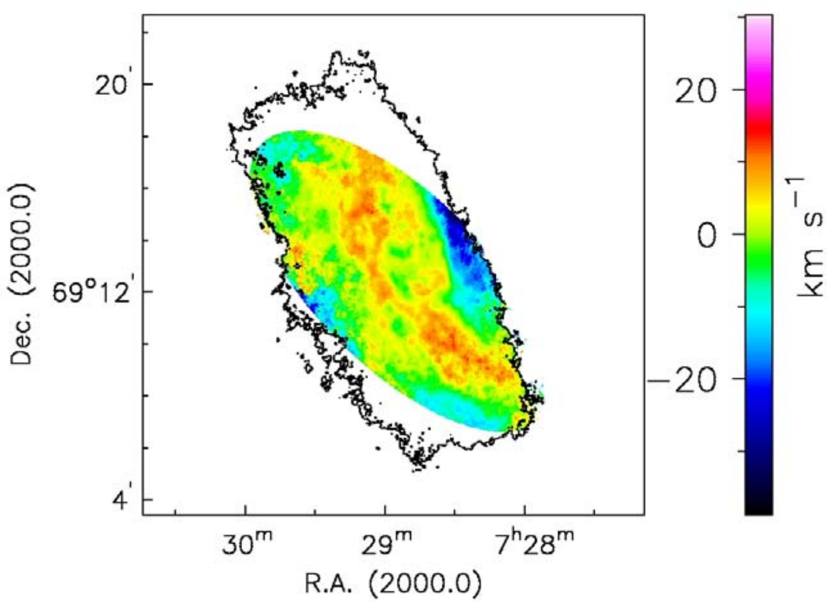
http://www.physast.uga.edu/

- ATCA (LVHIS, PI: B. Koribalski)
  - ESO 059-G001
  - ESO 215-G?009
  - NGC 5408
  - IC 5152

Spectral res.: 3-5 km s^{-1}

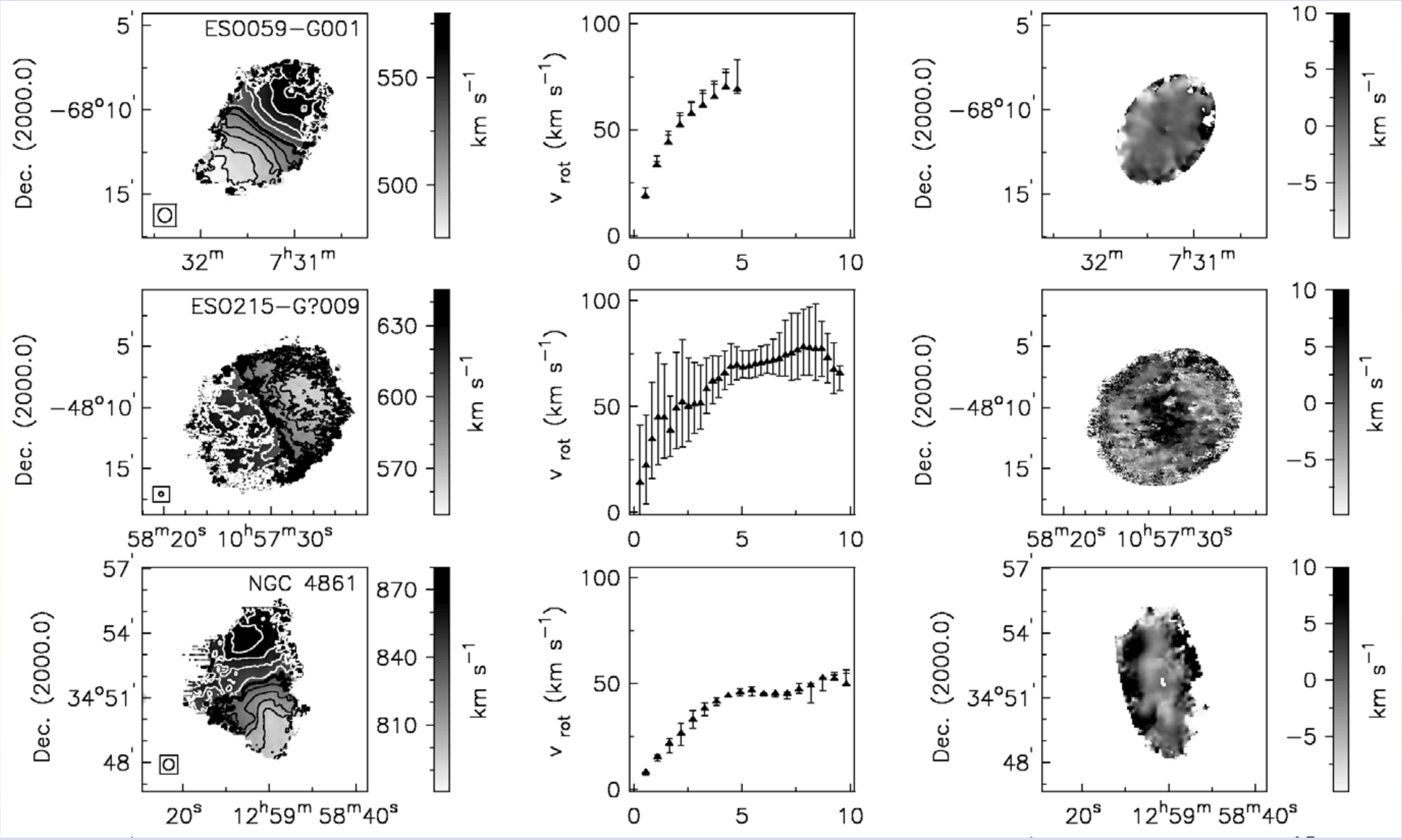
Beam size: 200-1200 pc

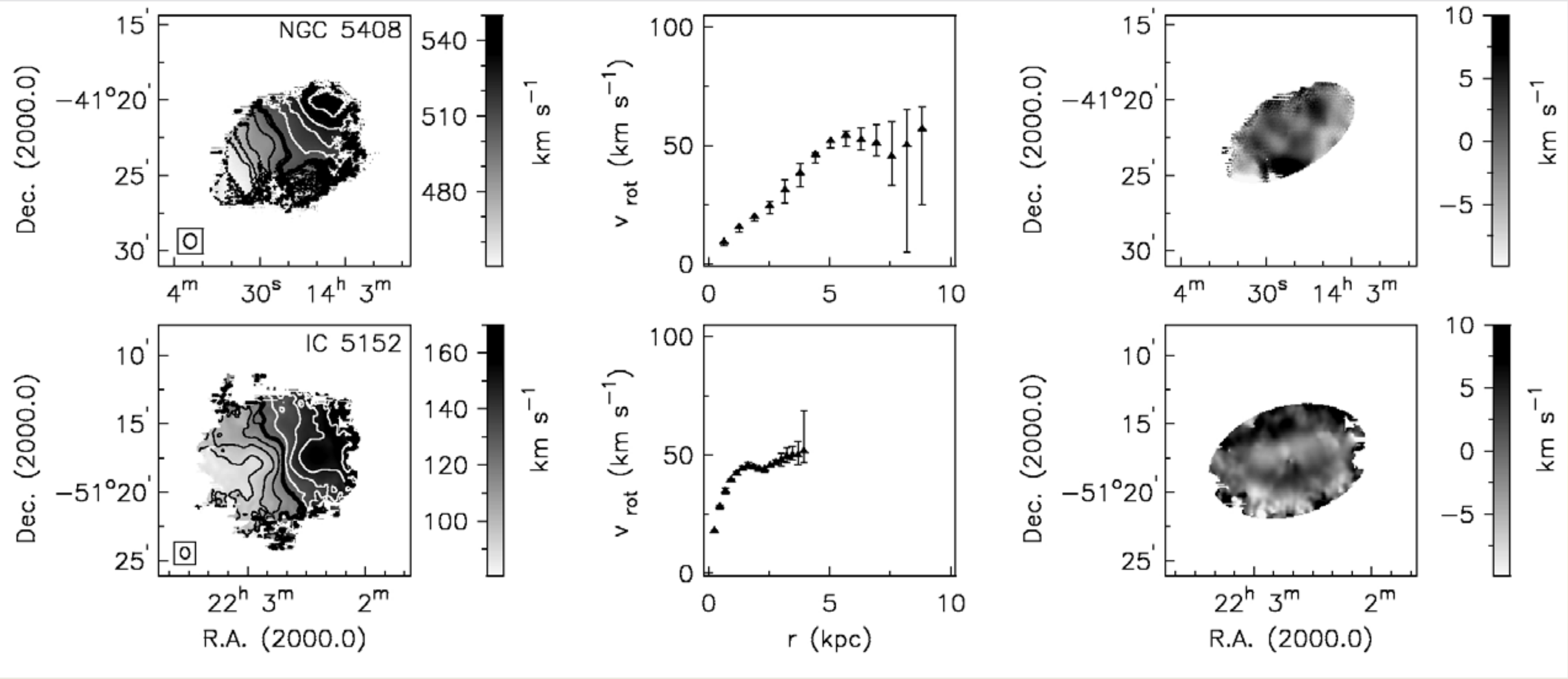




(3) Rotation curves
(Example: NGC 2366)

- Initial estimates for kinematic parameters (v_{sys}, xpos, ypos, incl, pa) from fitting ellipses to the HI intensity distribution
- Tilted-ring analysis on Hermite velocity field (GIPSY task *rotcur*, assumes circular orbits)
- Kinematic parameters iteratively defined


ESO059−G001
ESO215−G?009
NGC 4861
Dec. (2000.0)
v_{rot} (km s^{-1})
km s^{-1}



NGC 5408
IC 5152
Dec. (2000.0)
R.A. (2000.0)
km s^{-1}
v$_{rot}$ (km s^{-1})
r (kpc)

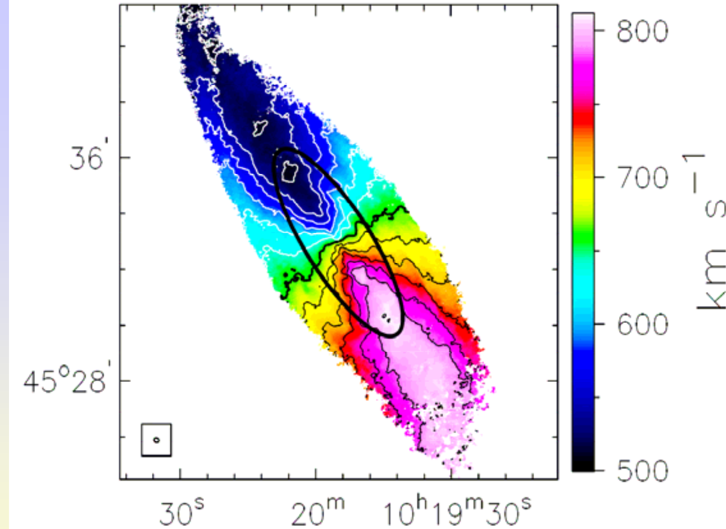
(4) Harmonic decomposition:

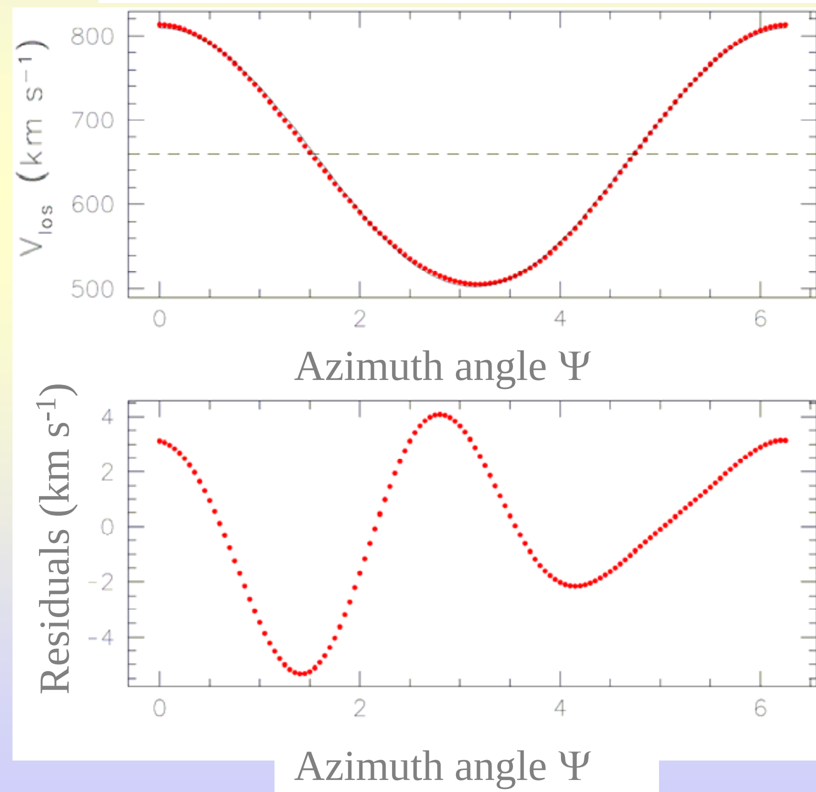
$$v_{\rm los}(r) = c_0(r) + \sum_{m=1}^{3} c_m(r)\cos(m\psi) + s_m(r)\sin(m\psi)$$

- c_0: systemic velocity
- c_1: rotation velocity (circular)
- c_2, c_3, s_1, s_2, s_3: non-circular components
- Ψ: azimuth angle

$$A_r(r) = \sqrt{s_1^2(r) + c_2^2(r) + s_2^2(r) + c_3^2(r) + s_3^2(r)}$$

- Tilted-ring analysis (GIPSY task *reswri*, takes systematic non-circular motions into account)





Credit: C. Trachternach

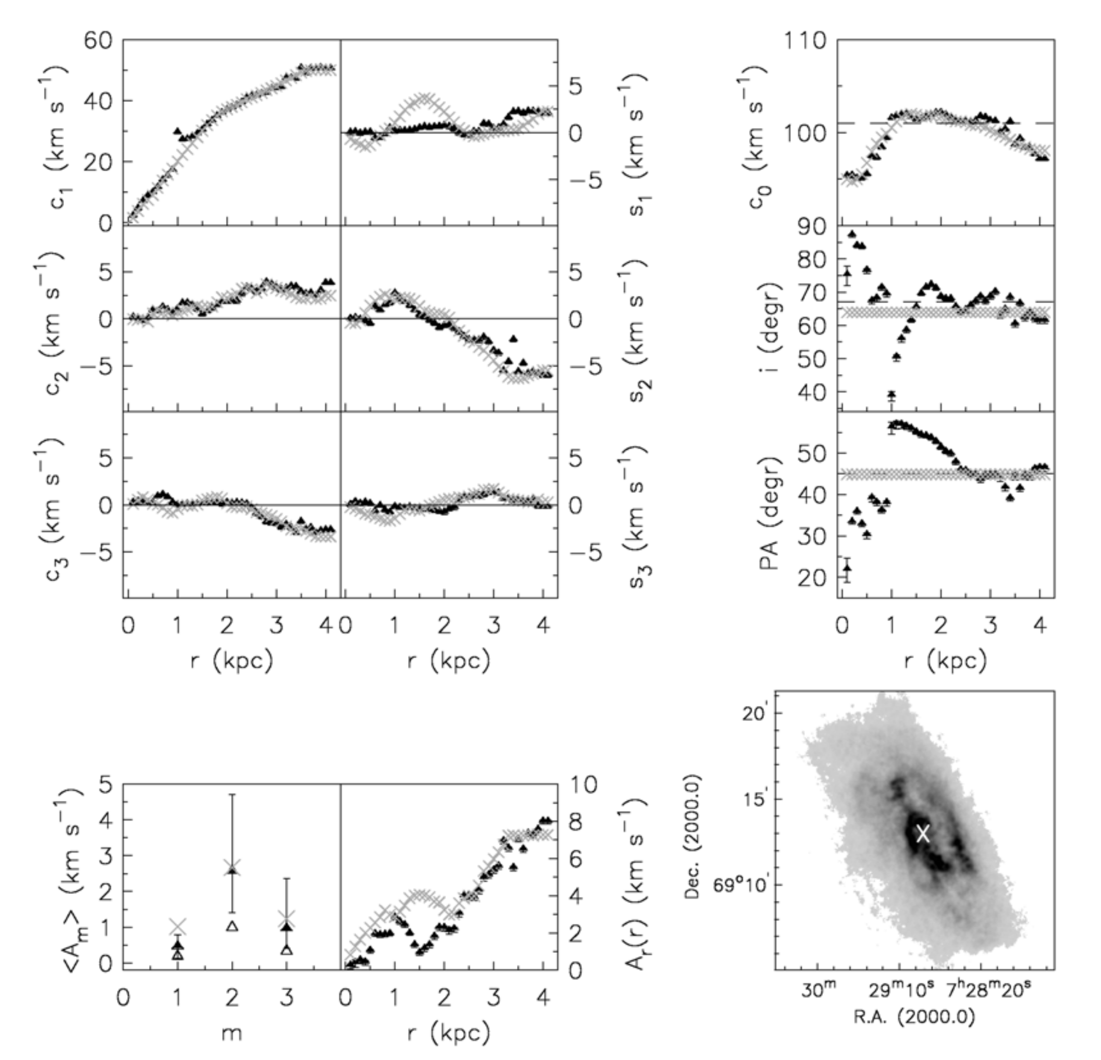
Two approaches:

-xpos, ypos (values from *rotcur*) fixed: unconstrained case (black symbols);

-xpos, ypos, i, pa fixed: constrained case (grey symbols)

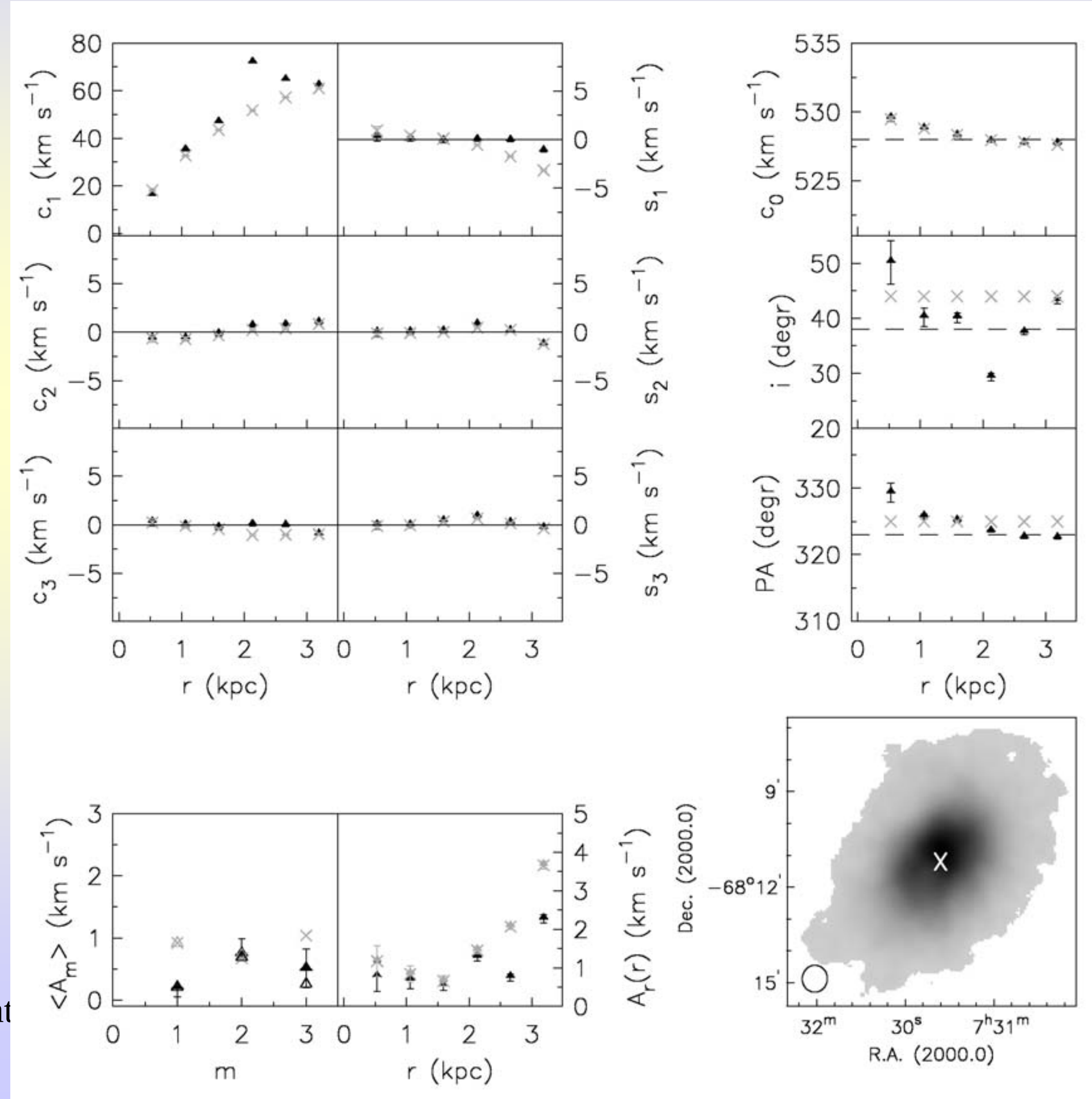
Example 1: NGC 2366

- Unconstrained and constrained case in good agreement
- $\langle A_m \rangle$ below 3 km s^{-1} (< 1 kpc even below 1 km s^{-1})
- $A_r(r)$ below 3 km s^{-1} in the inner 2.5 kpc



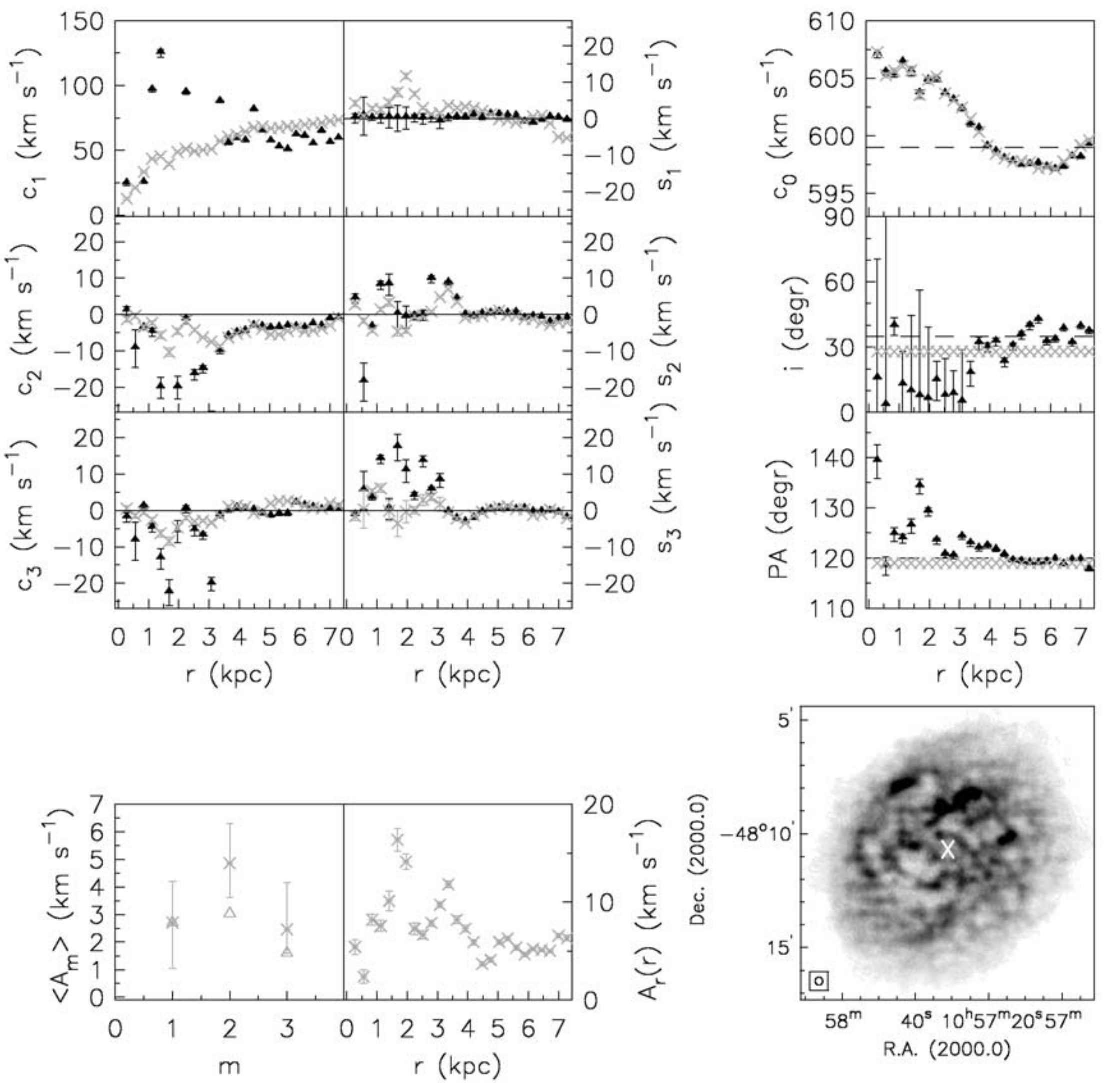
Example 2: ESO 059-G001

- Unconstrained and constrained case in good agreement
- $\langle A_m \rangle$ below 1 km s^{-1}
- $A_r(r)$ below 3 km s^{-1} for all radii
- Amplitudes of the non-circular components are the smallest of all sample galaxies



Example 3: ESO 215-G?009

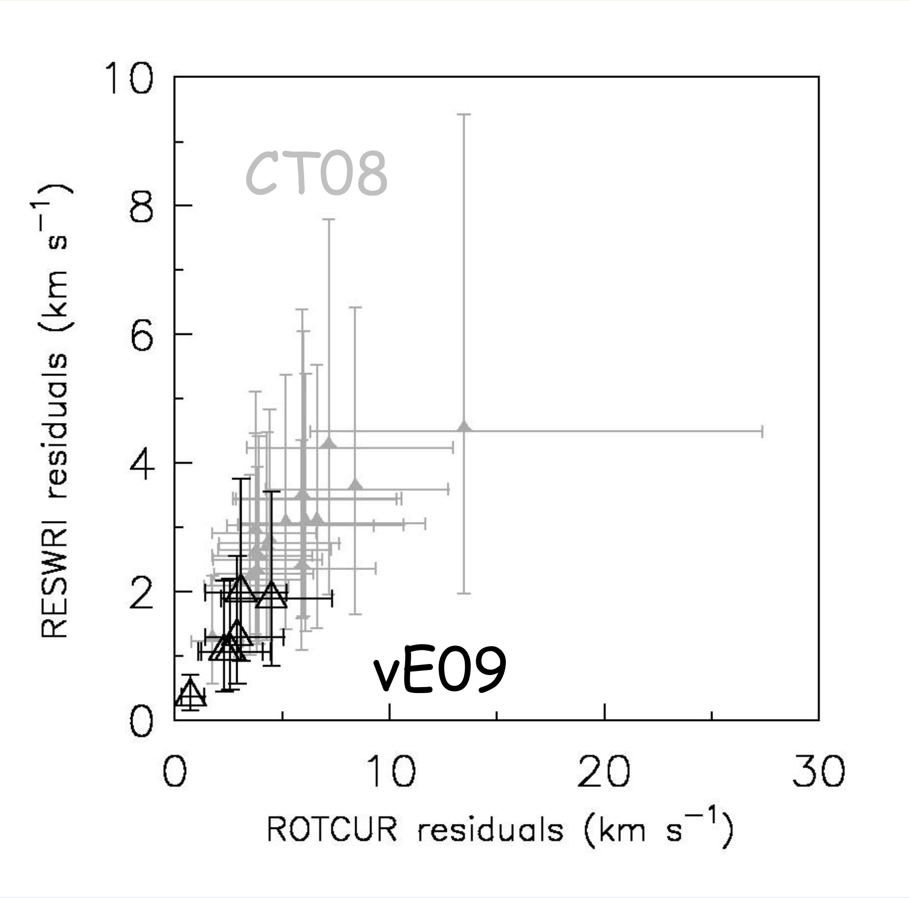
- Very low inclination in the inner 3.5 kpc, leads to large scatter in the harmonic components
- $\langle A_m \rangle$ below 5 km s^{-1}
- $A_r(r)$ mostly below 10 km s^{-1}



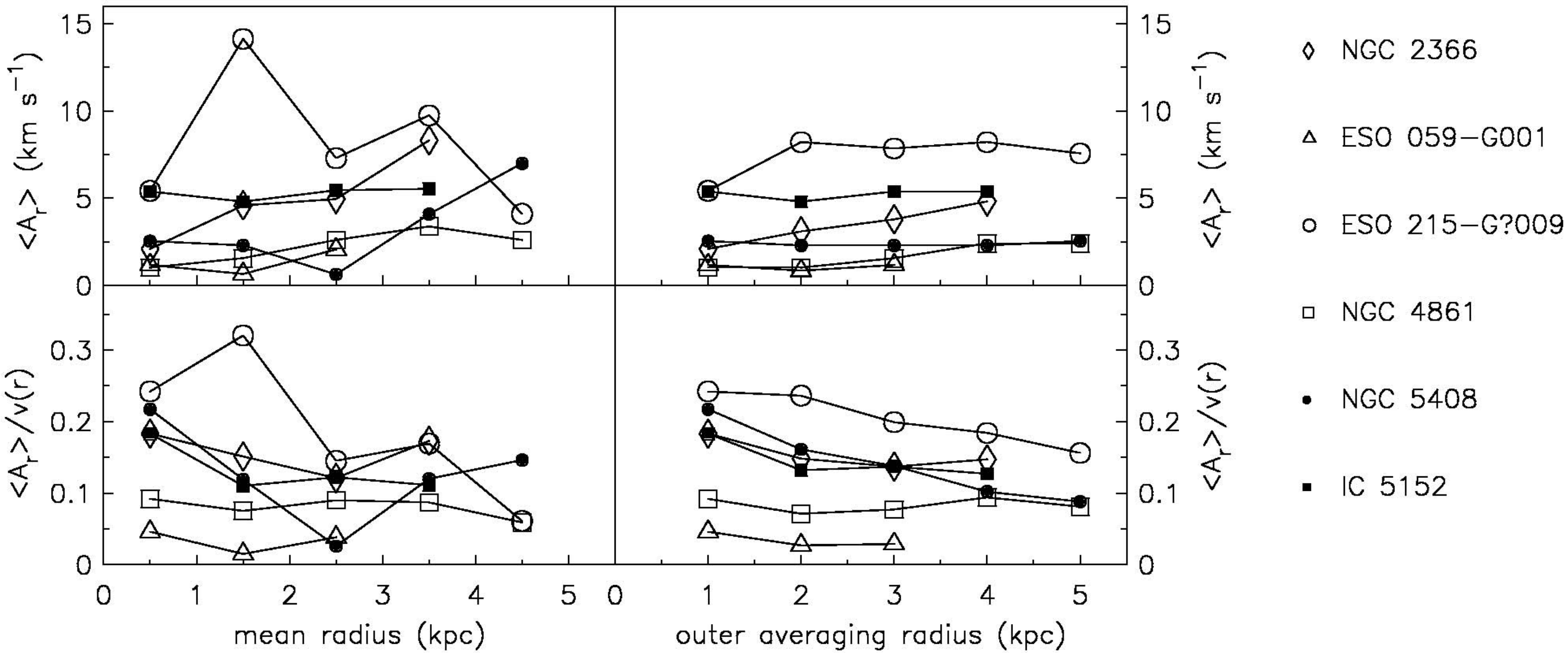
Is the harmonic decomposition able to quantify most of the non-circular motions?

- Median of the *rotcur* residuals (absolute values) *vs.* the median of the *reswri* residuals (absolute values)
- Median of the *reswri* residuals below 2 km s^{-1}

→ Harmonic decomposition up to 3rd order has captured most of the non-circular motions (see also Trachternach et al. 2008)



Non-circular motions *vs.* radius and normalised by the local rotation velocity



- Constrained case as upper limit
- Non-circular motions typically of the order of a few km s^{-1}
- Contribute less than 25% to the local rotation velocity

(5) Mass decomposition

$$v_{\mathrm{obs}}^2 = v_{\mathrm{stars}}^2 + v_{\mathrm{gas}}^2 + v_{\mathrm{halo}}^2$$

- **Minimum-disc case**: simplest case, ignoring all baryonic contributions
- **Minimum-disc + gas case**: + contribution of the gas (HI intensity maps + scaling factor for metals, molecular gas neglected)
- **Maximum-disc case**: + contribution of stars (surface photometry, issues: extinction, mass-to-light ratio)

- GIPSY task *rotmod*: rotation curve for each component under the assumption of an infinitesimally thin disc
- GIPSY task *rotmas*: v_{obs}, v_{gas}, and v_{stars} as input + halo model, χ^2 minimisation

Halo models

NFW: $$v_{\mathrm{rot}}(r) = v_{200}\sqrt{\frac{\ln(1+cx)-(cx)/(1+cx)}{x[\ln(1+c)-c/(1+c)]}},\ \text{with } x = \frac{r}{r_{200}}$$

c : concentration parameter (a function of v_{200})

v_{200} : circular velocity at r_{200}

r_{200} : virial radius

Mass decomposition: $v_{200}=v_{rot}$, c (9-10, in agreement with cosmological predictions), r_{200} free parameter

ISO: $$v_{\mathrm{rot}}(r) = \sqrt{4\pi G\rho_0 r_c^2\left(1+\frac{r_c}{r}\arctan\left(\frac{r}{r_c}\right)\right)}$$

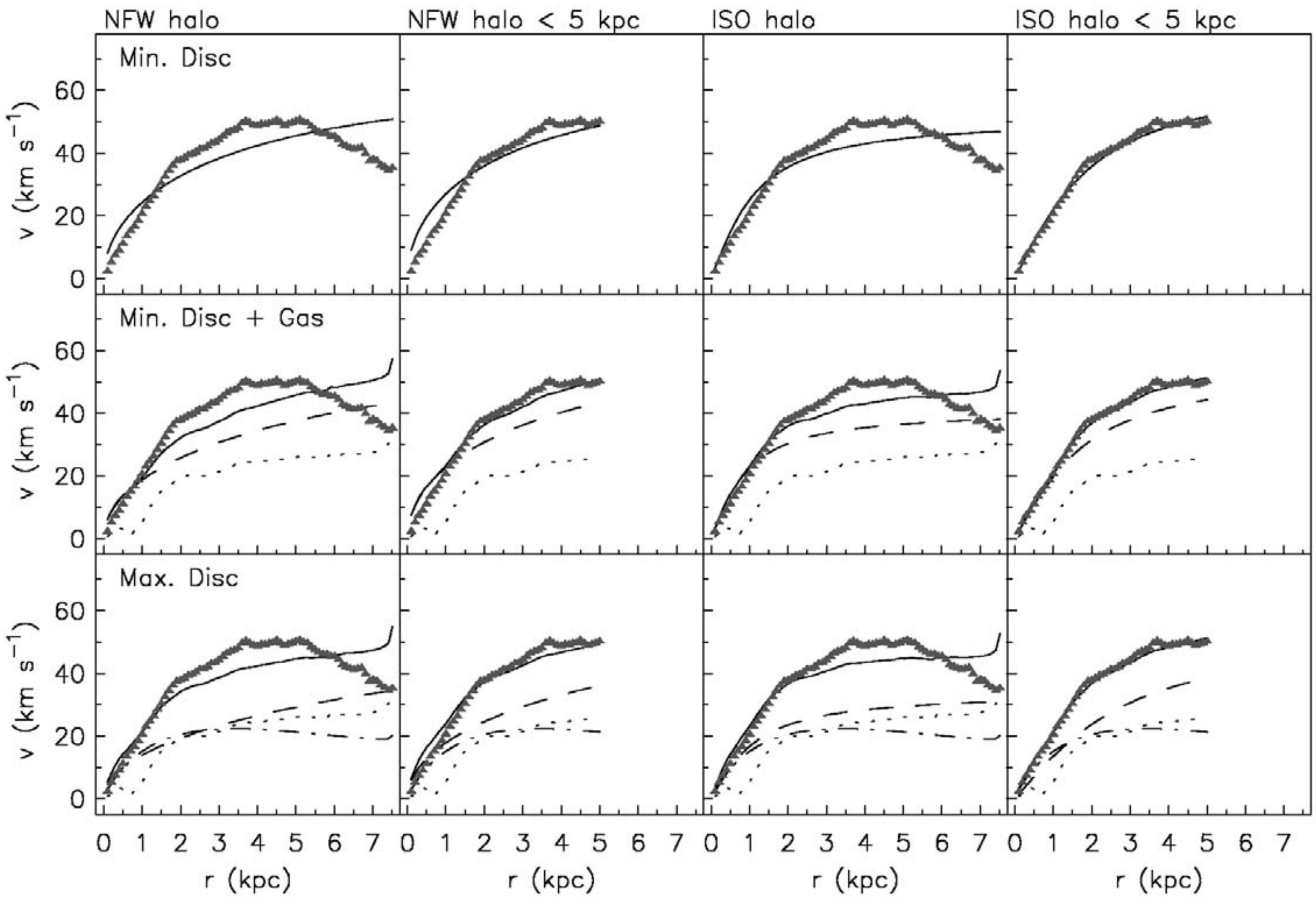
ρ_0 : core density, r_c : core radius

Mass decomposition: ρ_0, r_c free parameters

Example: NGC 2366

$\chi_{red}^2 \rightarrow$

	NFW_{full}	NFW_{part}	ISO_{full}	ISO_{part}
Min. disc	47.47	19.88	27.82	1.79
Md+gas	51.76	8.19	30.27	0.88
Max. disc	36.27	7.81	24.99	1.24



dark matter

dark matter
gas

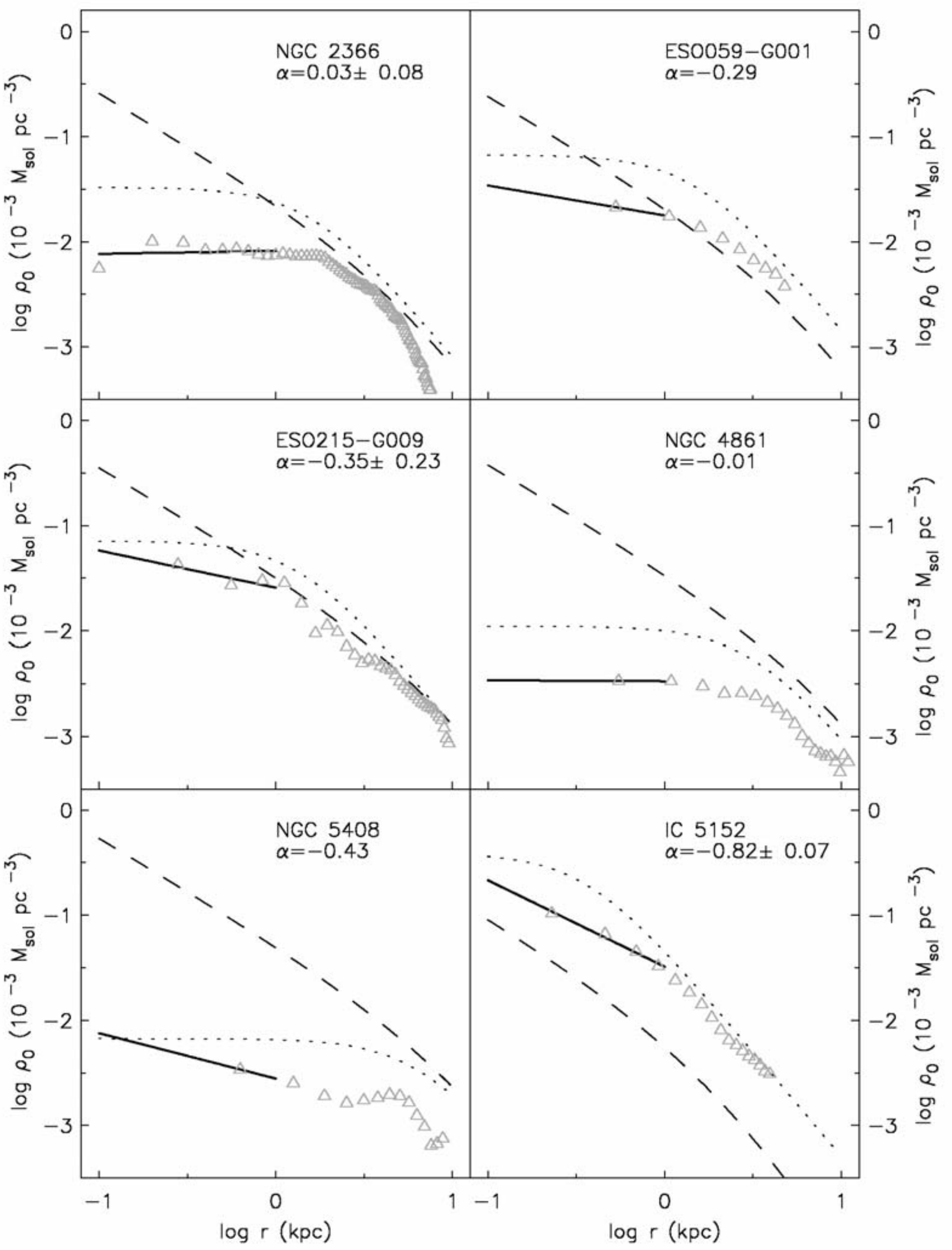
dark matter
gas
stars

What we found…

- χ_{red}^2 much larger for the NFW model
- Improved fits for reduced rotation curve (independent of the used halo model)
- Often improved fits when including the baryons
- Plausible values for ρ_0 and r_c, in fact they follow the finding by Donato et al. (2009) of a constant surface density $\rho_0 * r_c$

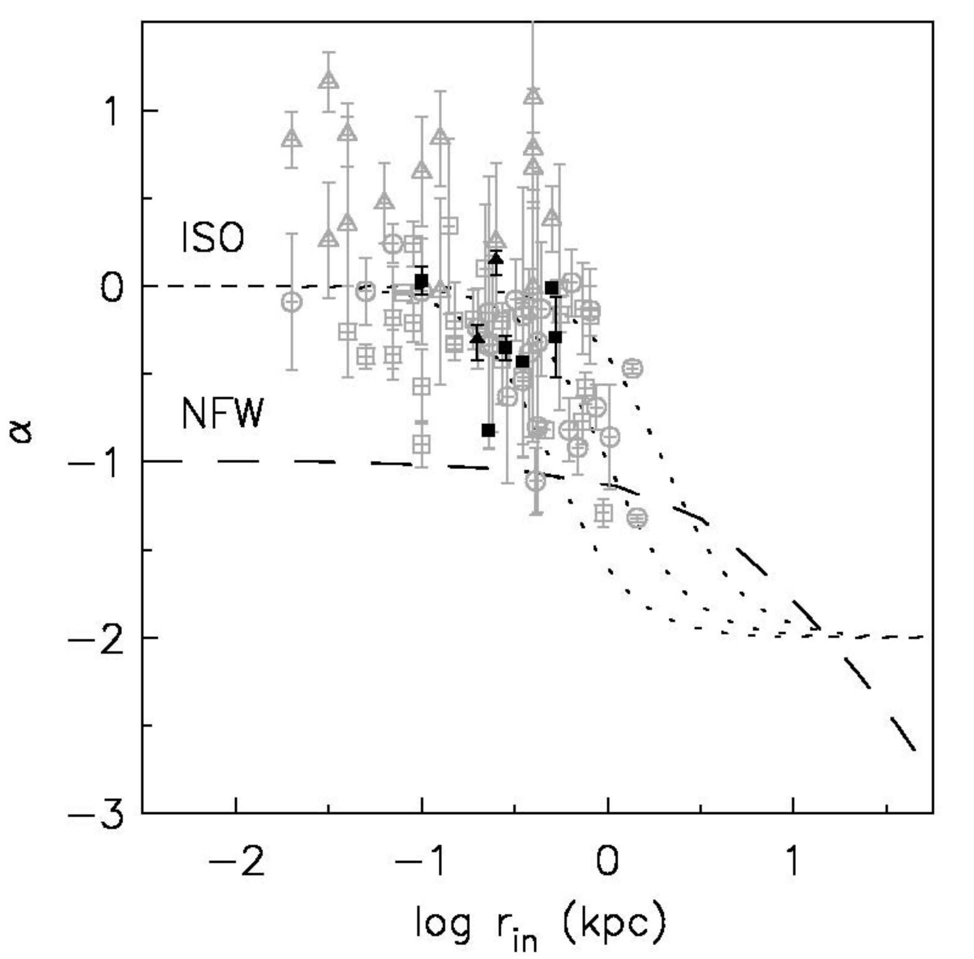
Density profiles of all sample galaxies

- Dashed (NFW) and dotted (ISO) lines represent profiles of the minimum-disc case
- Measure α in inner 1 kpc
- α lies between -0.43 and 0.03, i.e., within the uncertainties of de Blok et al. (2001) measurement (exception: IC 5152)



Measurement of slope α

- Open circles: de Blok et al. (2001)
- Open squares: de Blok & Bosma (2002)
- Open triangles: Swaters et al. (2003)
- Solid triangles: Oh et al. (2008)
- Solid squares: our values



Summary

- The rotation curves of dwarf galaxies can better be described by the empirically derived pseudo-isothermal halo model
- Non-circular motions are negligible in dwarf galaxies, their amplitudes are usually below 10 km s^{-1}, often even below 5 km s^{-1}. They contribute less than 20% to the local rotation velocity.

The measured cores are not hidden cusps!

Outlook

- de Blok (2010): "...studies which, constrained and informed by the high-quality observations now available, self-consistently describe and model the interactions between the dark matter and the baryons in a cosmological context are likely the way forward in resolving the core/cusp problem."