Rotation Curves of Disk Galaxies: New Perspectives

Argelander-Institut für Astronomie

Uli Klein

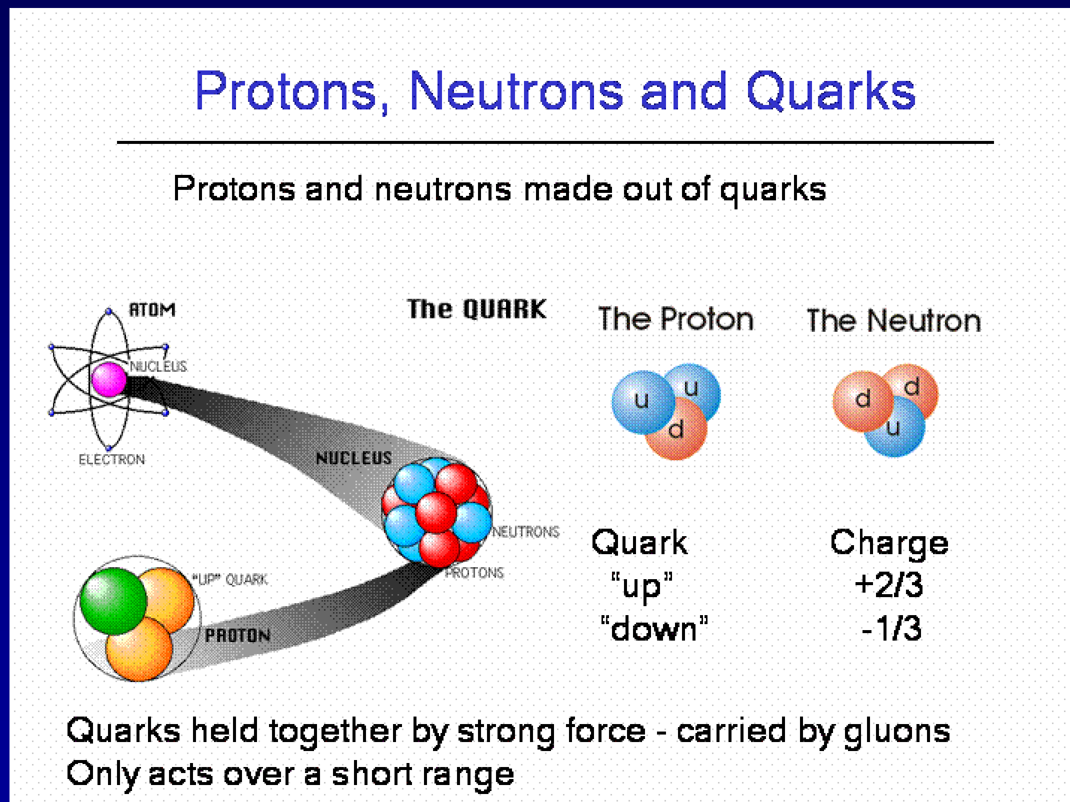
universität bonn

- Introduction
- Rotation curves
- Cusps vs. cores
- Dwarf galaxies
- Giant spirals
- Warps in galaxies
- DM: future perspectives

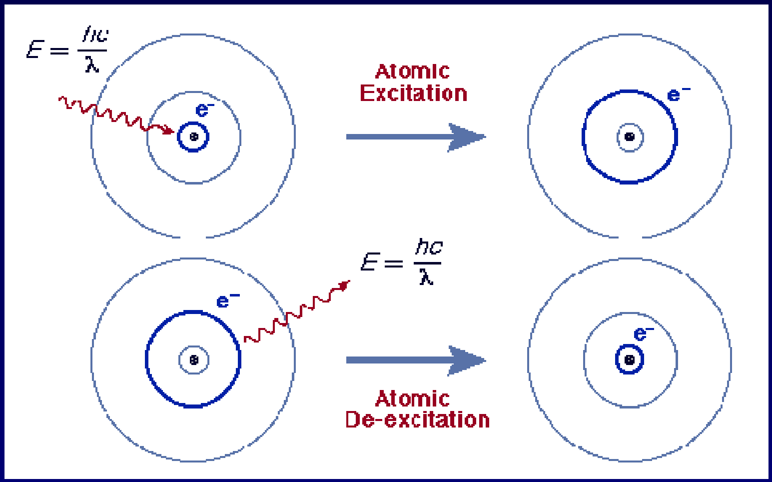
A.	Burkert	LMU
G.	Gentile	UNM
G.	Józsa	AIfA
F.	Kenn	AIfA
T.	Oosterloo	ASTRON
A.	Pizzella	Padova
P.	Sallucci	SISSA
C.	Struve	Univ. Groningen

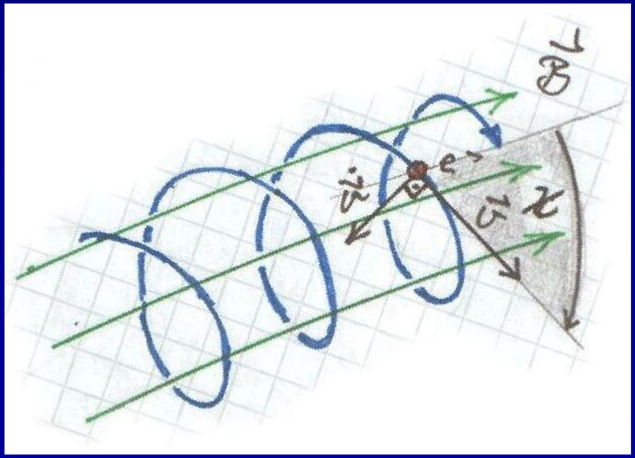
(well) understood: baryonic matter

“baryonic” matter: that’s what we know from ‘every day’s life’

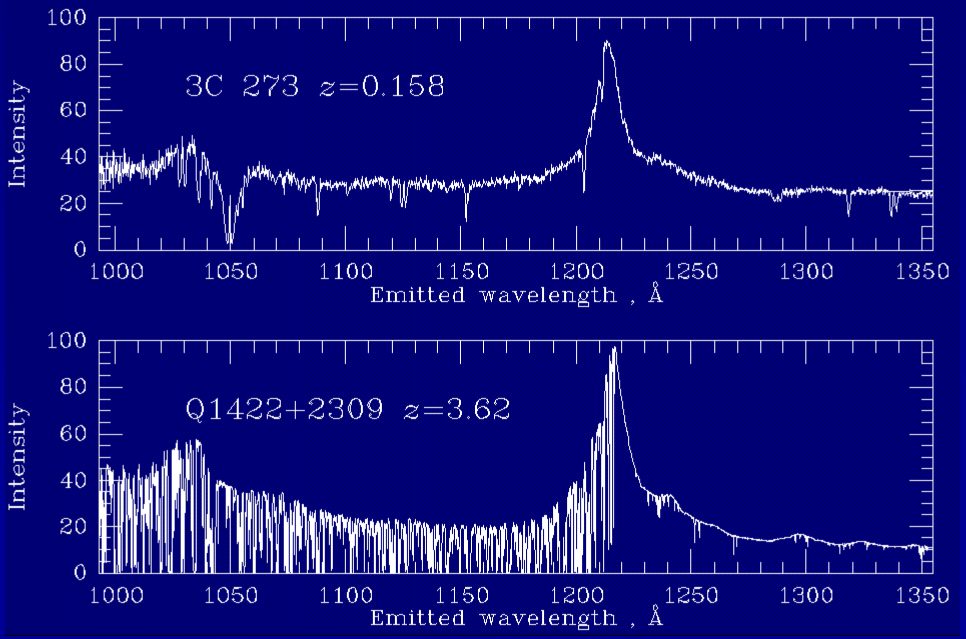


baryons emit photons ….

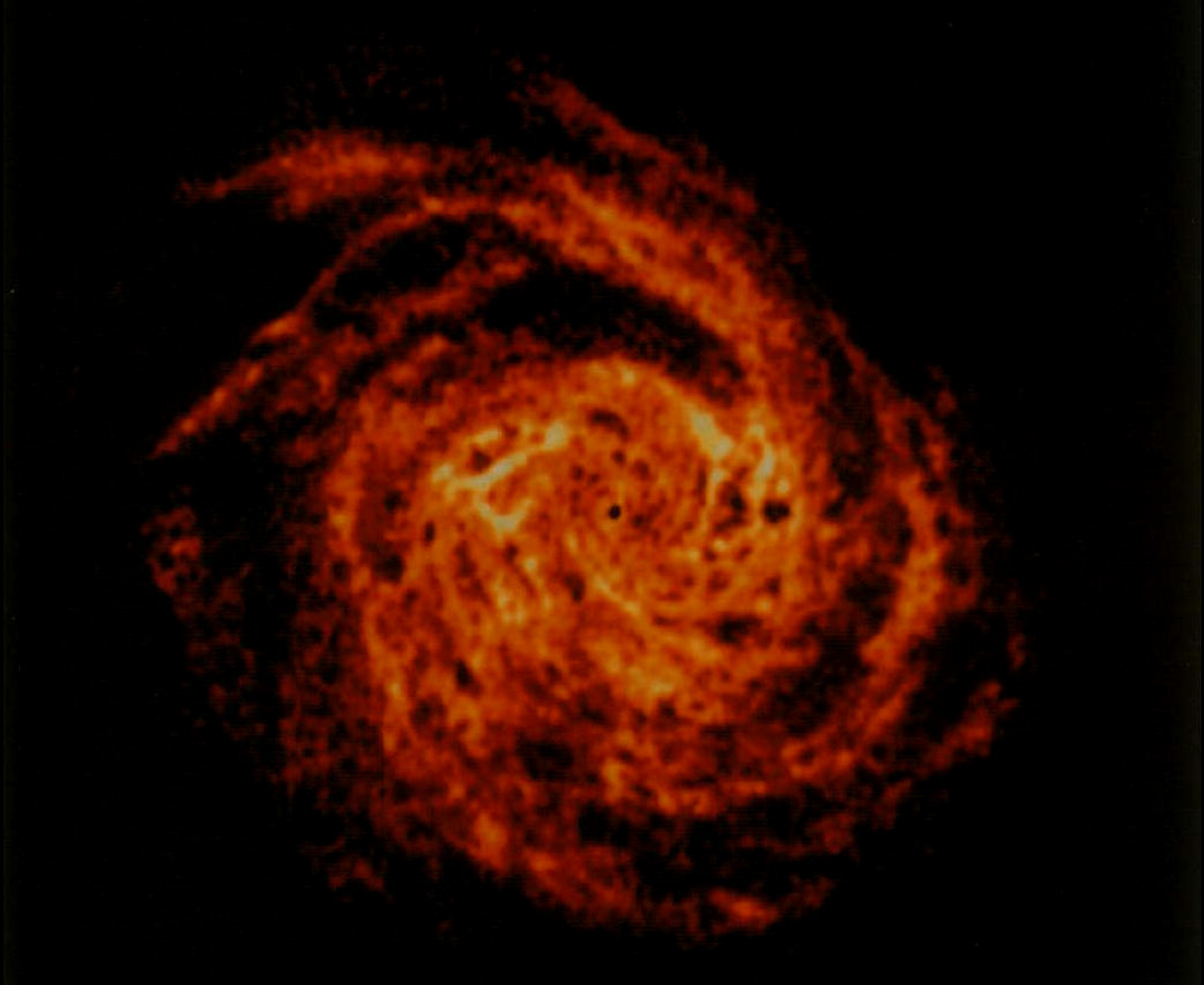




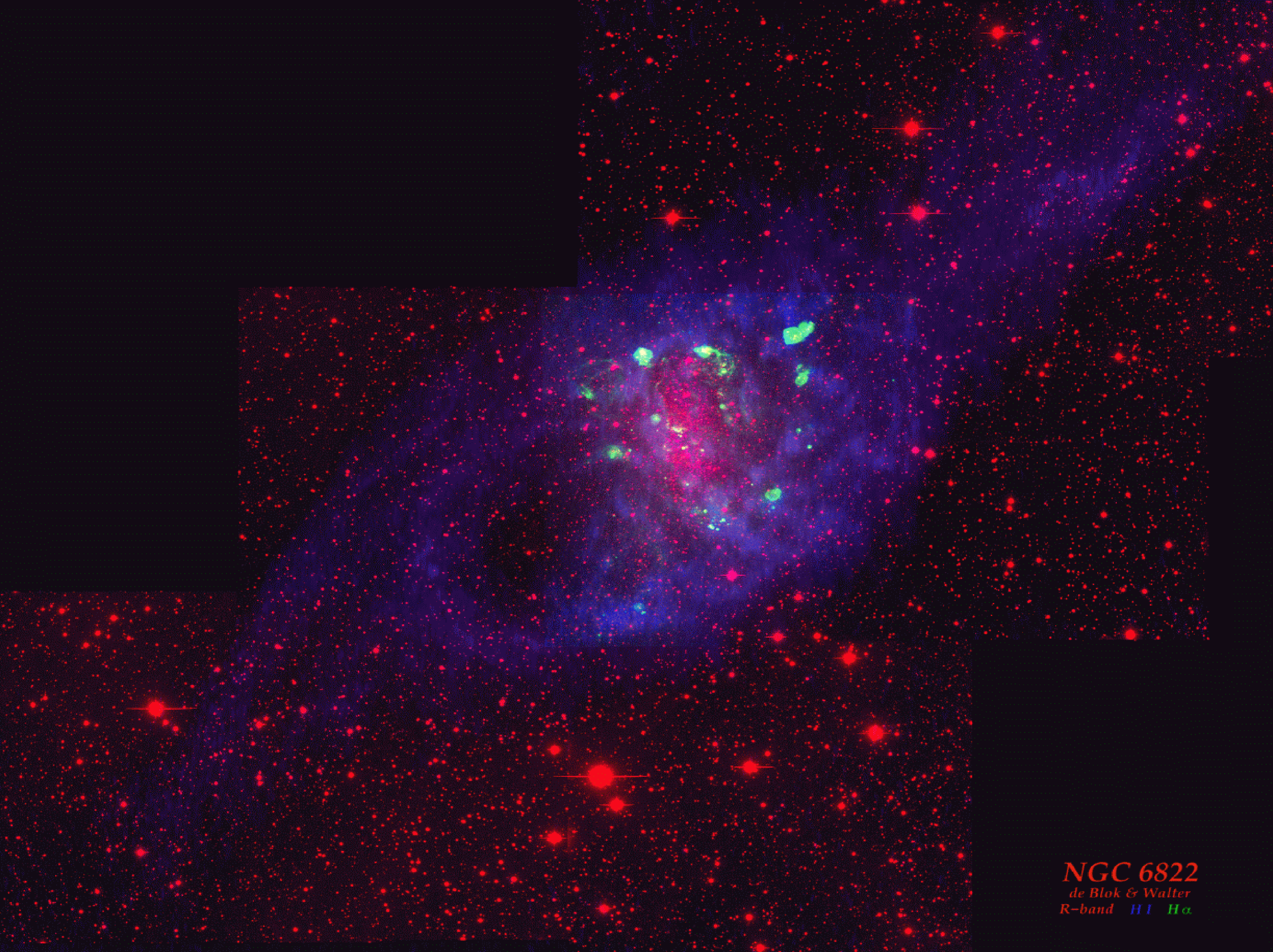
…. or absorb them



gas disks much larger than stellar ones

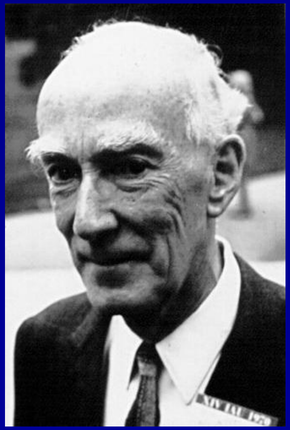
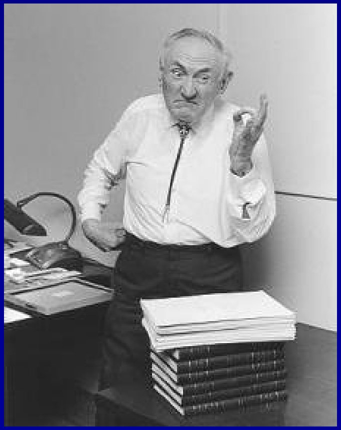


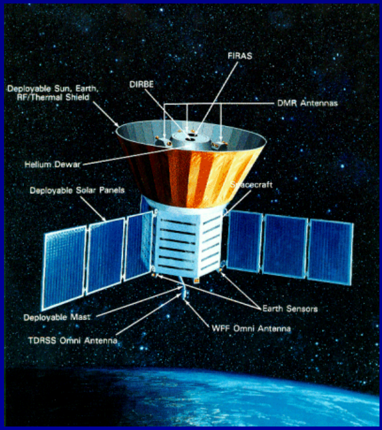
T. Oosterloo


NGC 6822
de Blok & Walter
R-band H I Hα

Dark Matter: some milestones

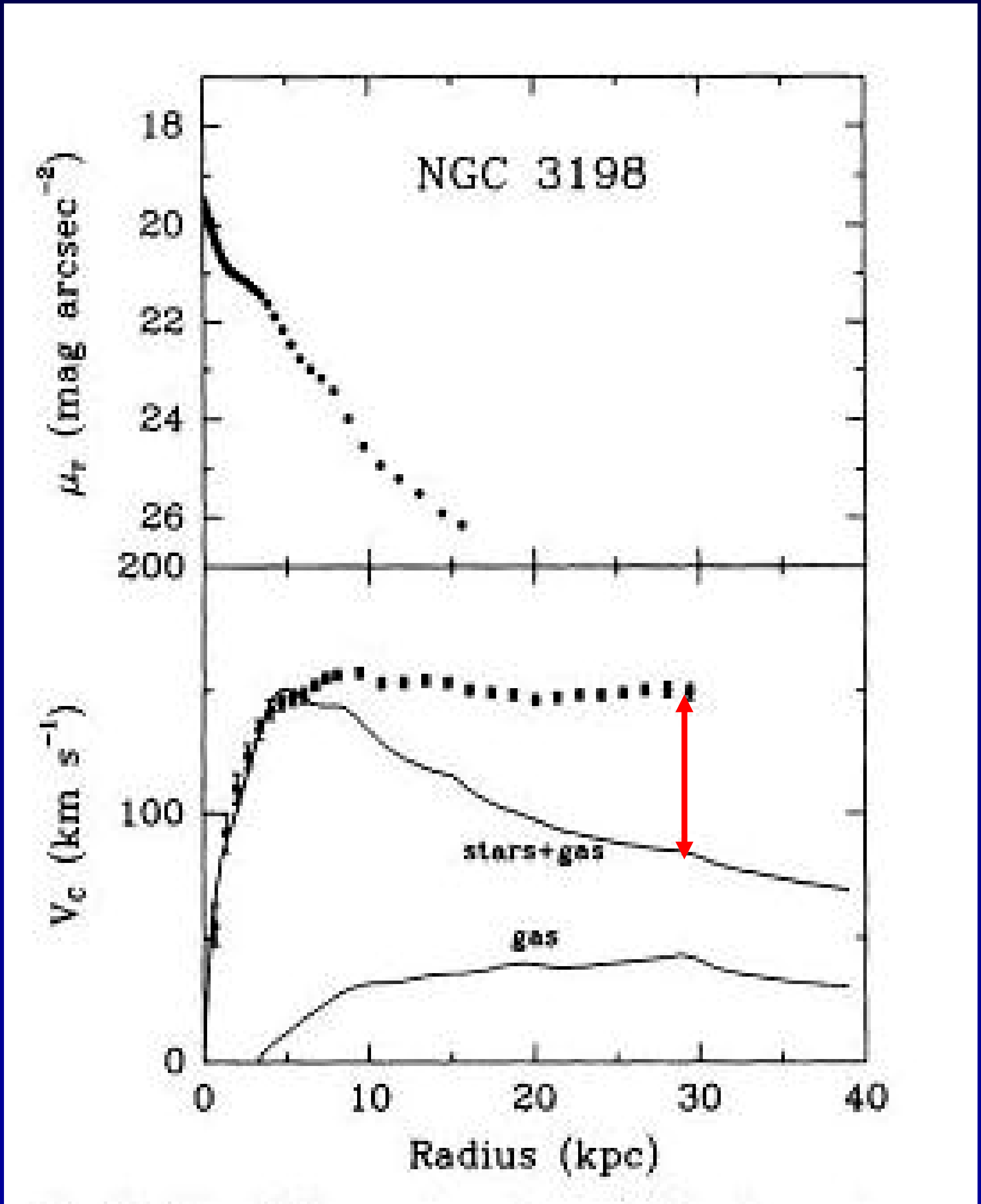
- J. Oort (1933) v_z of stars
- F. Zwicky (1933) σ_v in the Coma cluster of galaxies
- V. Rubin (1980) galaxies: Hα rotation curves
- A. Bosma (1981) galaxies: HI rotation curves
- COBE (1992) CMB: DM on cosmic scales

disk galaxies: circular velocities

$$\frac{m \cdot V^2(R)}{R} = \frac{G \cdot M(R) \cdot m}{R^2}$$



expected: "Kepler rotation"

$$V(R > R_{opt}) = \sqrt{\frac{G \cdot M_{tot}}{R}}$$

observed:

$$V(R > R_{opt}) = const!$$

"Dark Halo"

Numerical simulations with dark matter

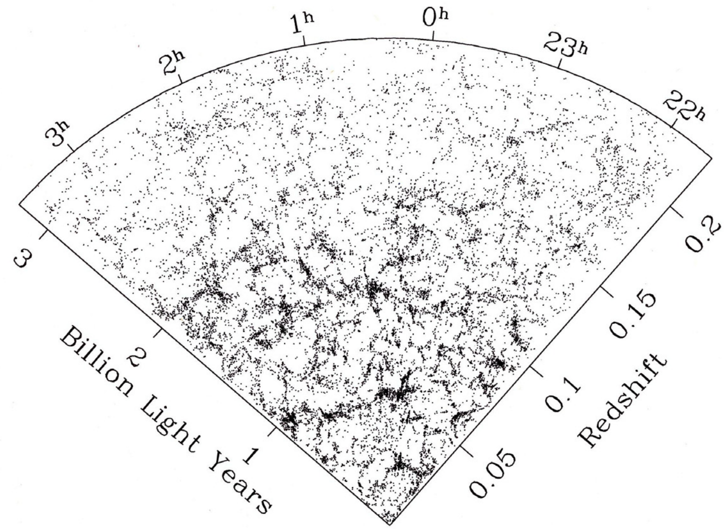
90's: numerical models of cold dark matter (ΛCDM)
Navarro et al. (1996), Moore et al. (1998)

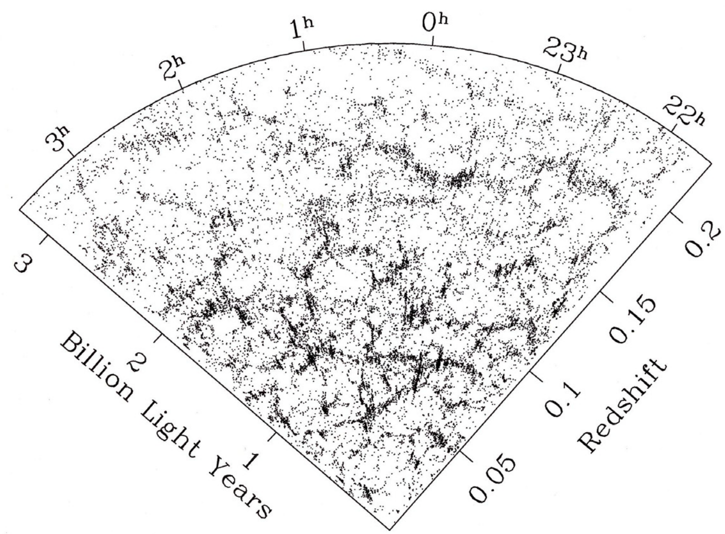
very successful on large scales

⇨ **possibility to test (verify / falsify) something!**
larger number of observational efforts / more focussed

progress: DM exists ⟶ M_{DM}/M_{lum} ⟶ $\rho_{DM}(r)$!

success on large scales:





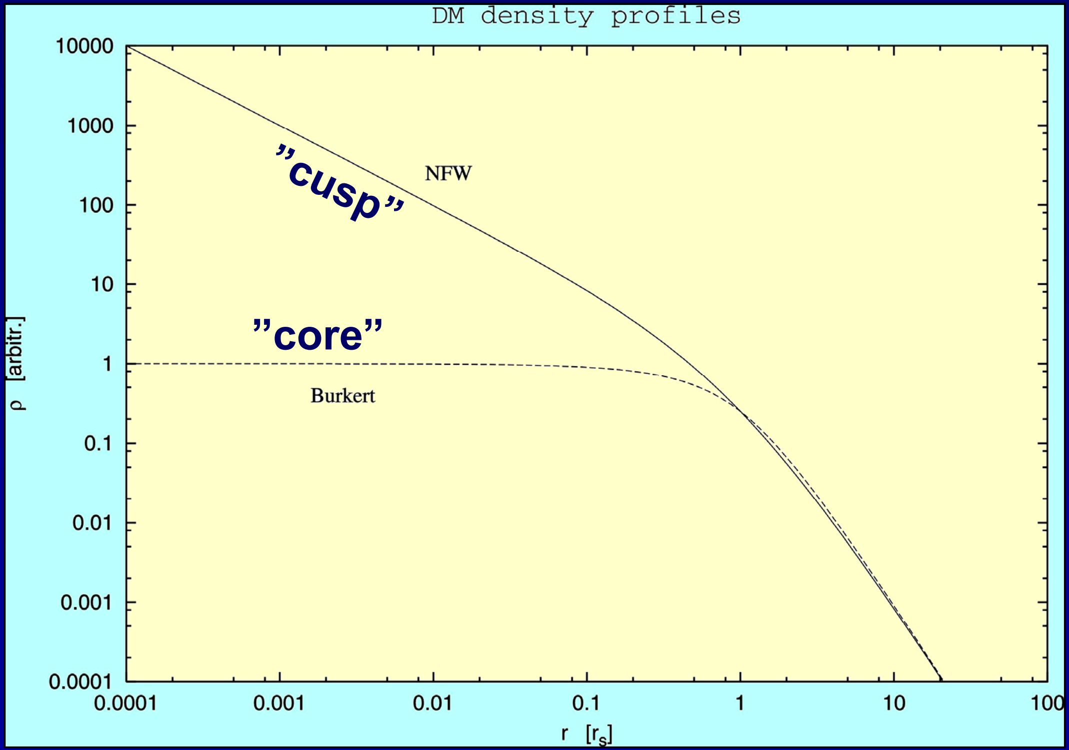
problems on galaxy scales: “cusps” vs. “cores”

$$\rho(r) = \rho_c \cdot \frac{\delta_c}{\left(\frac{r}{r_s}\right)\cdot\left(1+\frac{r}{r_s}\right)^2}$$

NFW

$$\rho(r) = \rho_0 \cdot \frac{r_0^3}{(r+r_0)\cdot(r^2+r_0^2)}$$

Burkert



shape of inner density profile

↕

properties of Dark Matter (?)

For spherical DM potential in galaxies:

measure circular rotation speed $V_{DM}(R)$ and infer $\rho_{DM}(R)$ using

$$\vec{\nabla}^2 \Phi_{DM}(R) = 4\pi \cdot G \cdot \rho_{DM}(R)$$
$$= \left(\frac{V_{DM}}{R}\right)^2 + 2 \cdot \left(\frac{V_{DM}}{R}\right) \cdot \frac{\partial V_{DM}}{\partial R}$$

So: measure $V_{tot}(R)$, $V_{stellar}(R)$, $V_{gas}(R)$, and deduce $V_{DM}(R)$

$$V_{rot}^2 = V_{DM}^2 + V_*^2 + V_{gas}^2$$

Rotation curves

Three main tracers:

- **HI** λ = 21 cm
- **Hα** λ = 6563 Å
- **CO** λ = 2.6, 1.3, ... mm

} **data cube:**

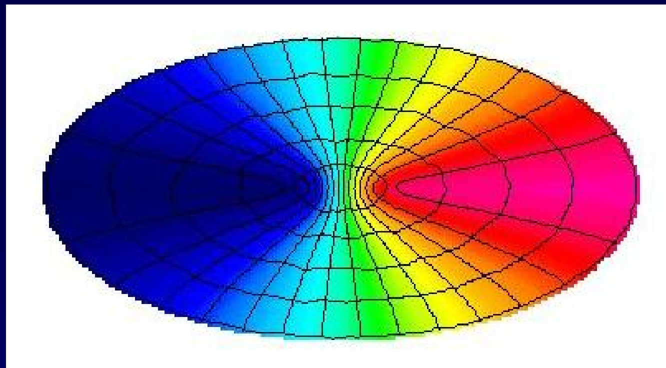
$$I_\nu = I(\xi, \eta, V)$$

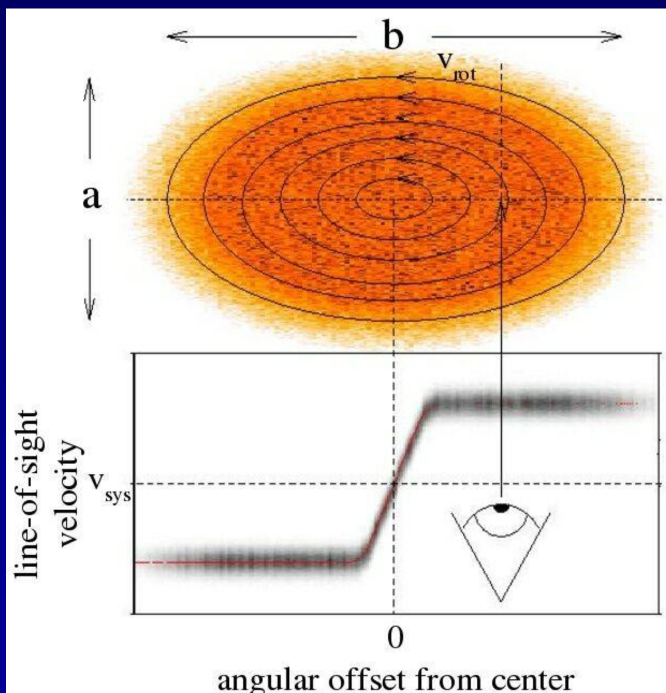
e.g. HI line: velocity
(peak, Gauss fit, 1st moment)

$$\langle V(\xi,\eta) \rangle = \frac{\int_{V_1}^{V_2} T_b(\xi,\eta)\, V(\xi,\eta)\, dV}{\int_{V_1}^{V_2} T_b(\xi,\eta)\, dV}$$

column density

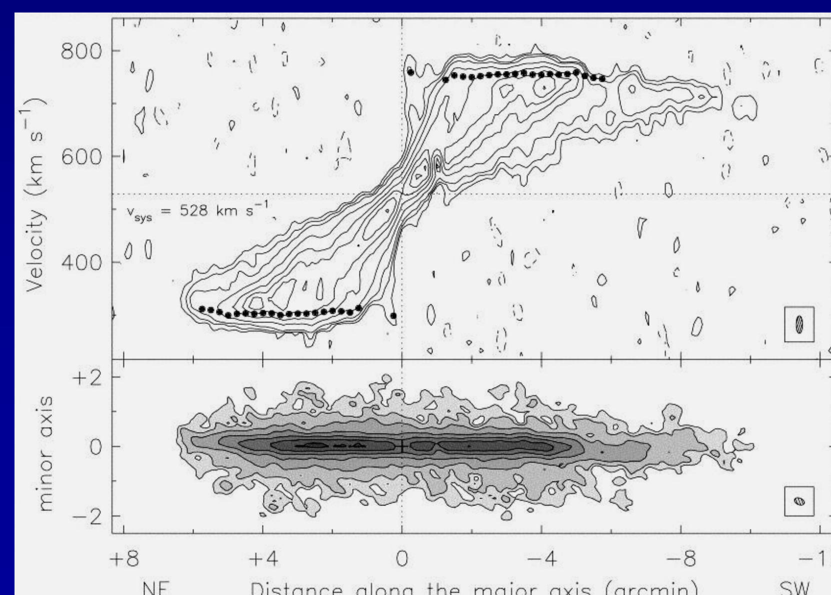
$$N_{HI} = 1.822 \cdot 10^{18} \int_{V_1}^{V_2} \left(\frac{T_b}{K}\right)\left(\frac{dV}{km\ s^{-1}}\right) \quad atoms\ cm^{-2}$$





$$V_{rot} = \frac{|V_{los} - V_{sys}|}{\sin(i)} \qquad i = \arccos\left(\frac{a}{b}\right)$$

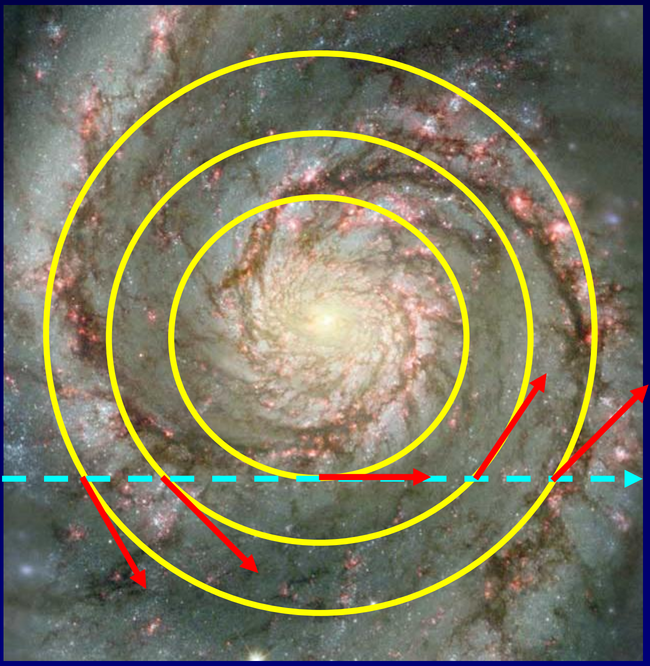
analysis in elliptical rings ('tilted-ring analysis') yields rotation curve *V(R)*



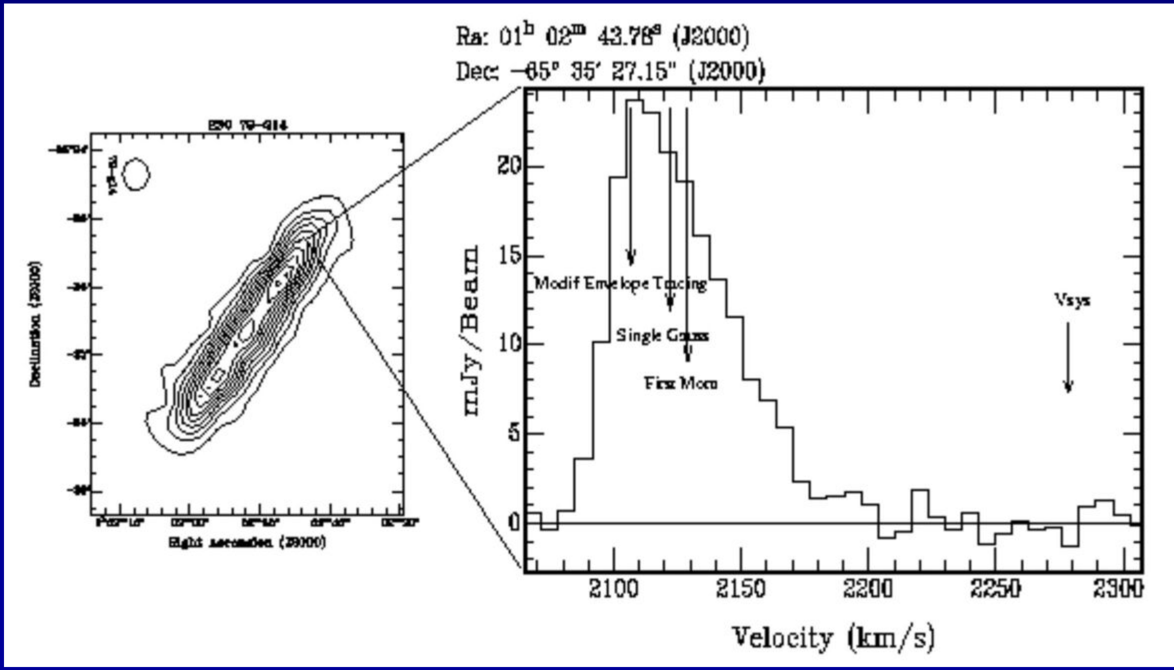
rotation curves, traditionally via

- tilted-ring analysis yields
  - V_{sys}
  - position angle
  - inclination

  constant with radius

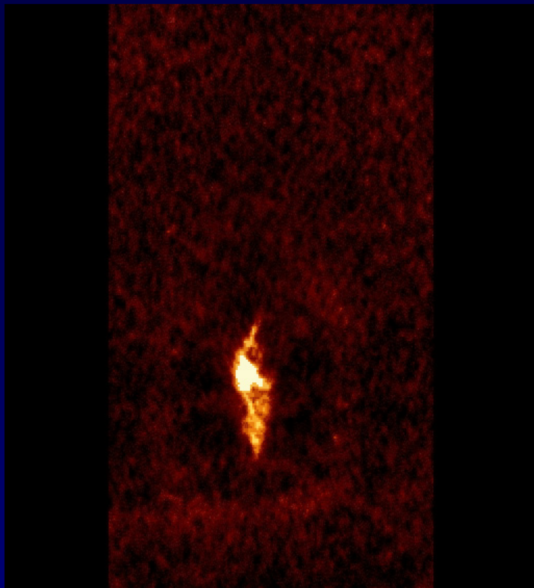


- asymmetric HI line profiles:
  - tails towards systemic velocity
  - projected emission from thick disk

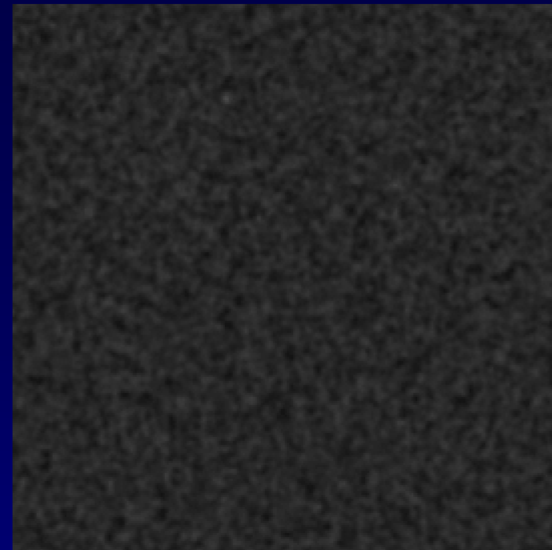


- need to account for
  - instrum. ΔV broadening
  - beam smearing
  - interst. turbulence

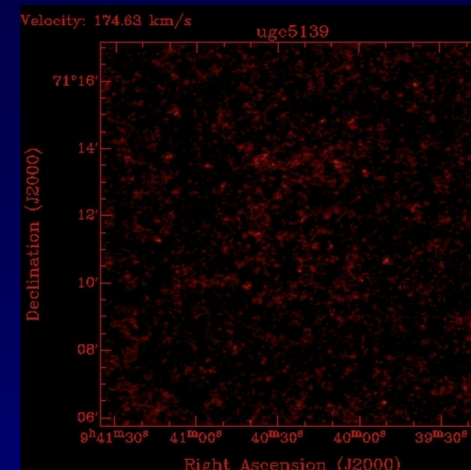
Tracer	angular resolution	spectral resolution
HI	7" … 30"	2 … 10 km s^{-1}
CO	1.5" … 8"	2 … 10 km s^{-1}
$H\alpha$, …	0.5" … 1.5"	10 … 30 km s^{-1}



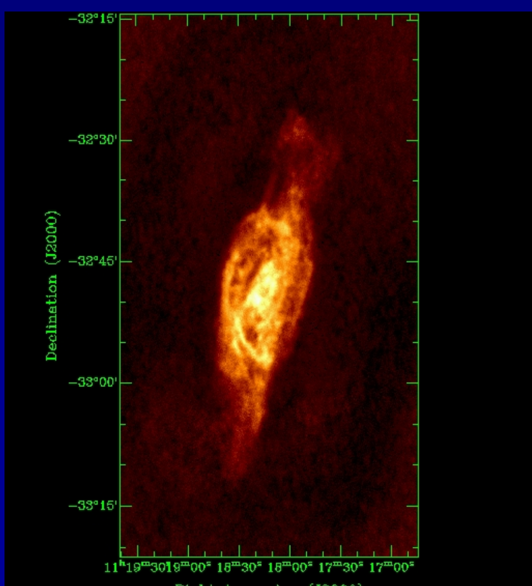
$L_B \sim 0.5 \times L_*$

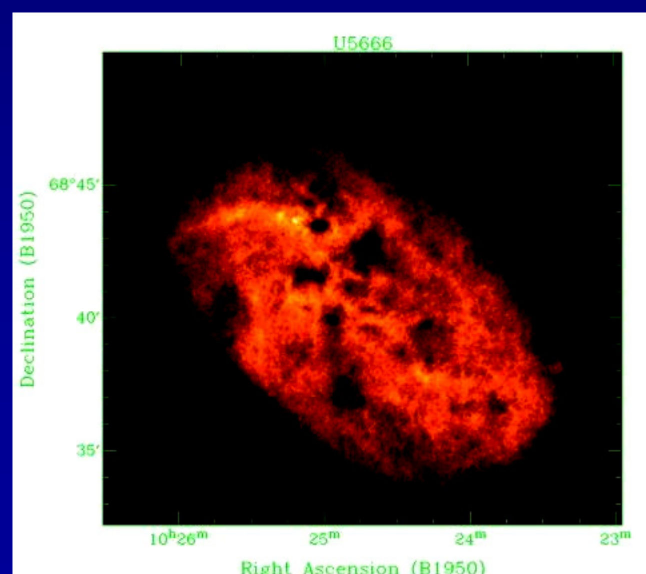


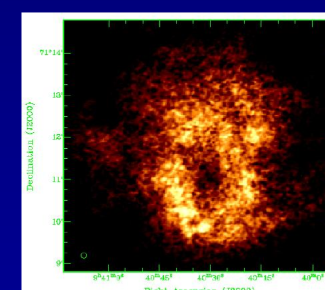
$L_B \sim 0.06 \times L_*$



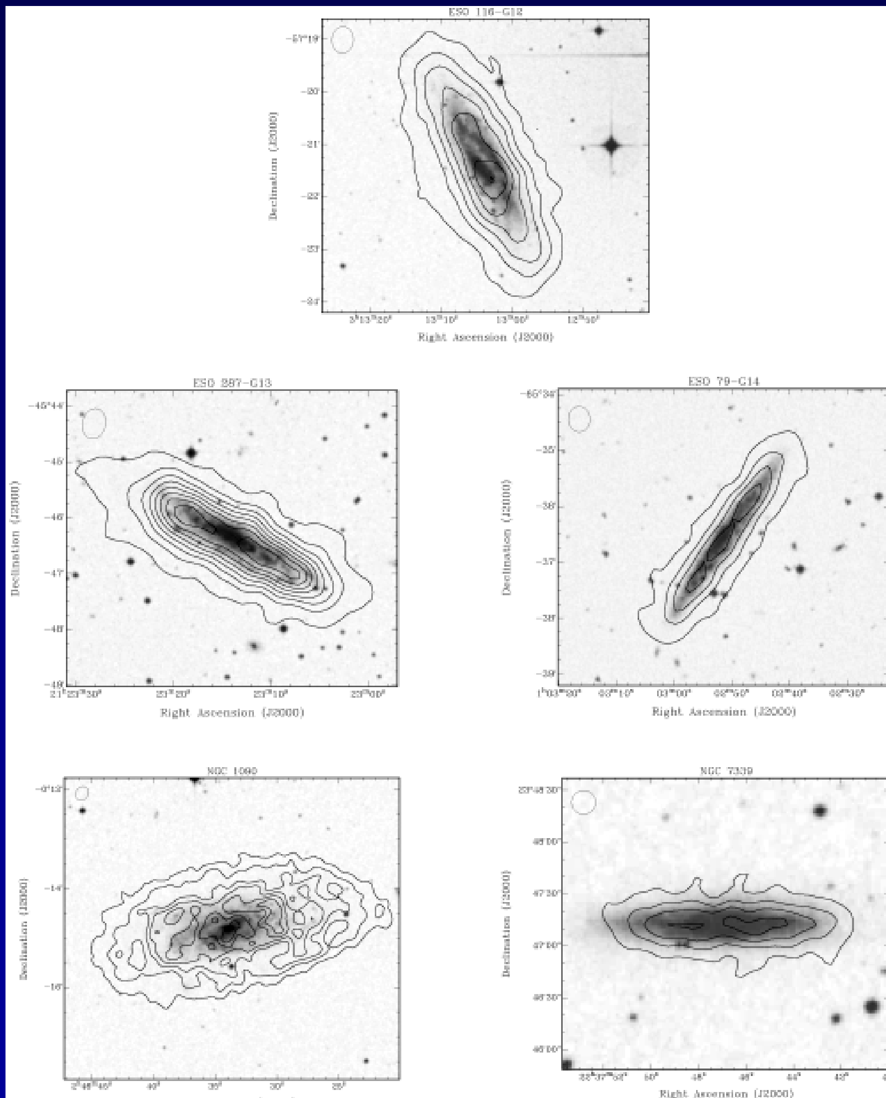
$L_B \sim 0.005 \times L_*$







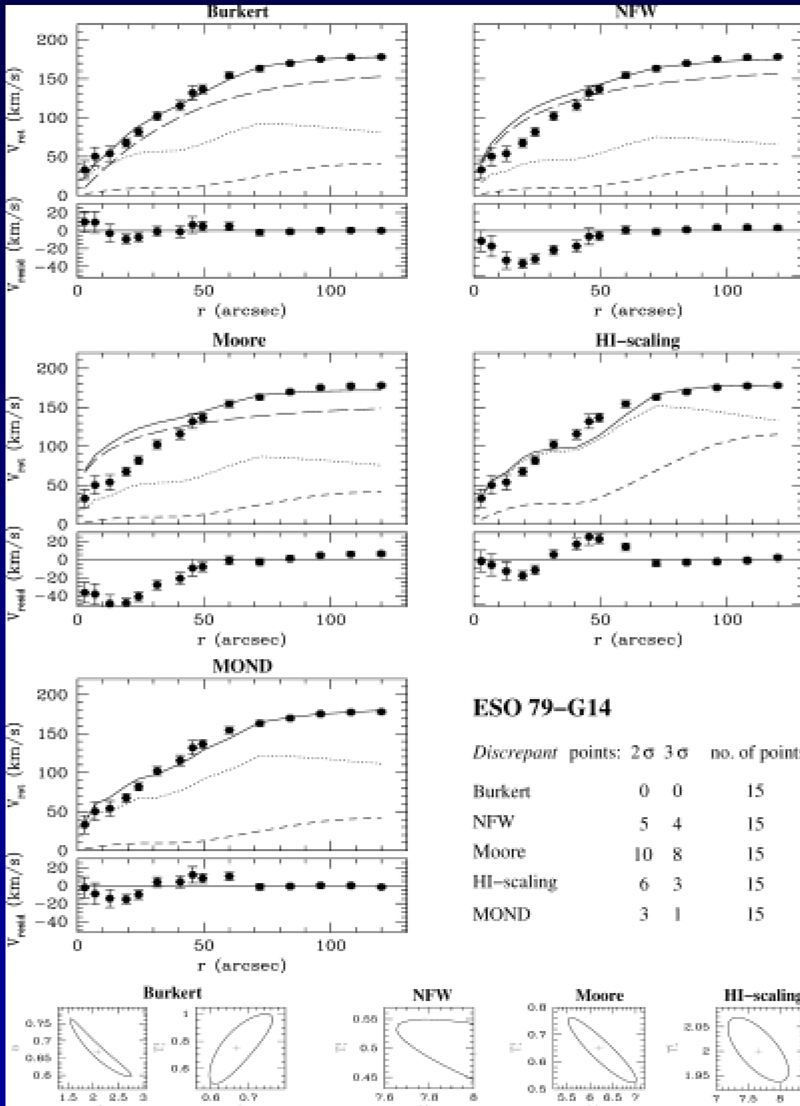
Cusps or cores?

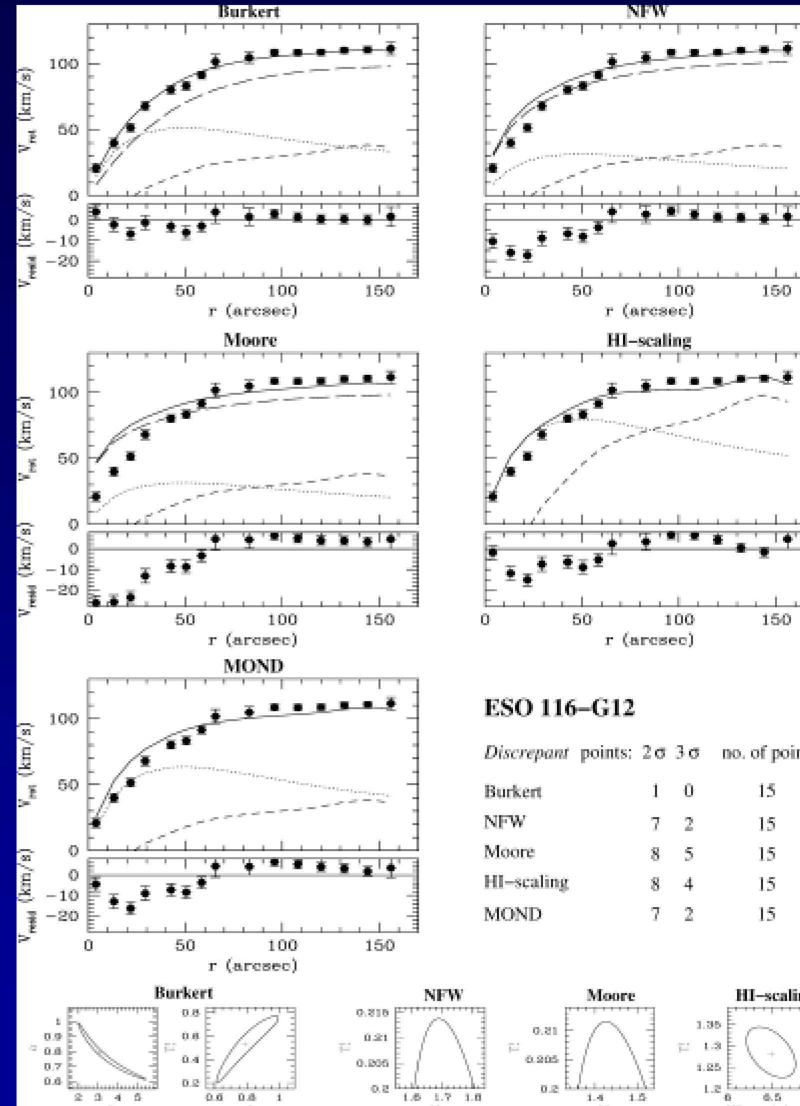


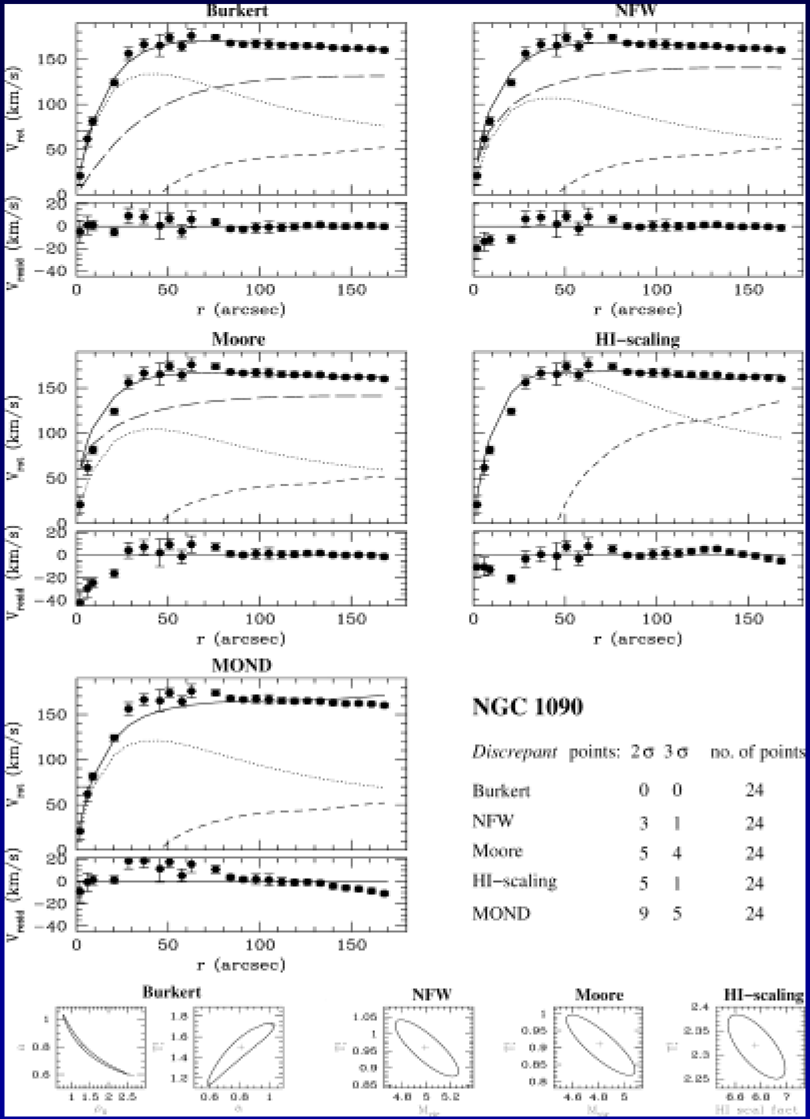
Gentile et al. (2004)

sample of spiral galaxies with

- **moderate ($L < L_*$) luminosities**
- **precise optical RCs**
- **late type (small or no bulges)**
- **well known distances**


Burkert
NFW
Moore
HI-scaling
MOND
V_rot (km/s)
V_resid (km/s)
r (arcsec)
ESO 79-G14
Discrepant points: 2σ 3σ no. of points
Burkert 0 0 15
NFW 5 4 15
Moore 10 8 15
HI-scaling 6 3 15
MOND 3 1 15


Burkert
NFW
Moore
HI-scaling
MOND
V_rot (km/s)
V_resid (km/s)
r (arcsec)
ESO 116-G12
Discrepant points: 2σ 3σ no. of points
Burkert 1 0 15
NFW 7 2 15
Moore 8 5 15
HI-scaling 8 4 15
MOND 7 2 15



- **Burkert profiles fit well throughout**
- **CDM halos produce worse fits**
- **MOND and HI scaling produce bad fits in some cases**

Dwarf galaxies

DDO 47

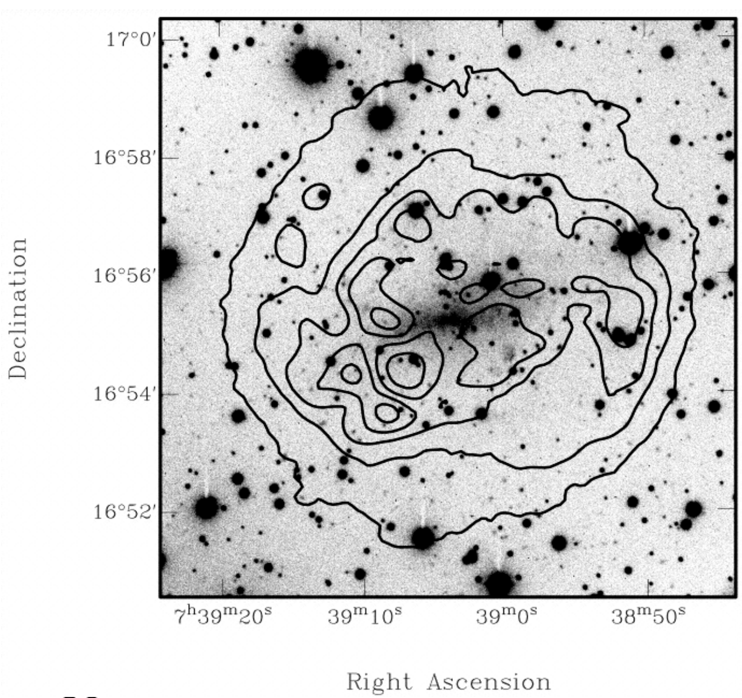
P. Salucci, F. Walter, A. Borriello (2003)

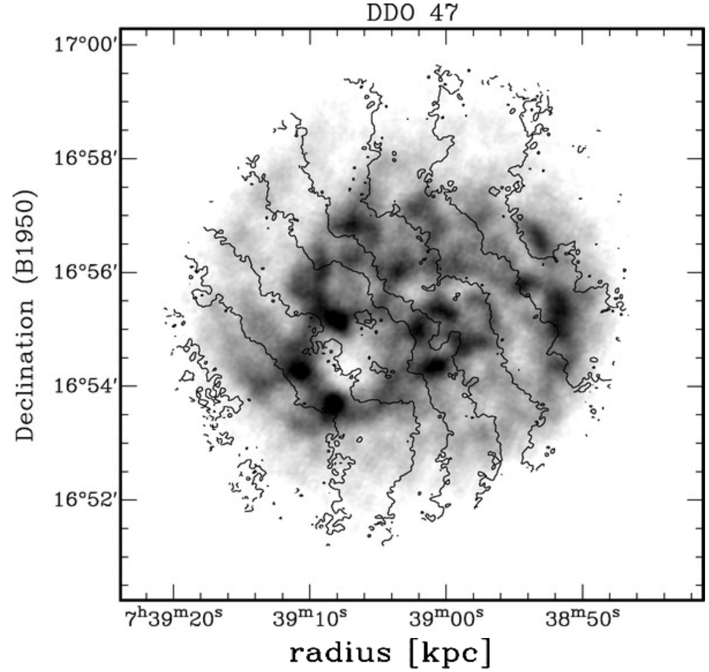
G. Gentile, A. Burkert, P. Salucci, U. Klein, F. Walter (2005)

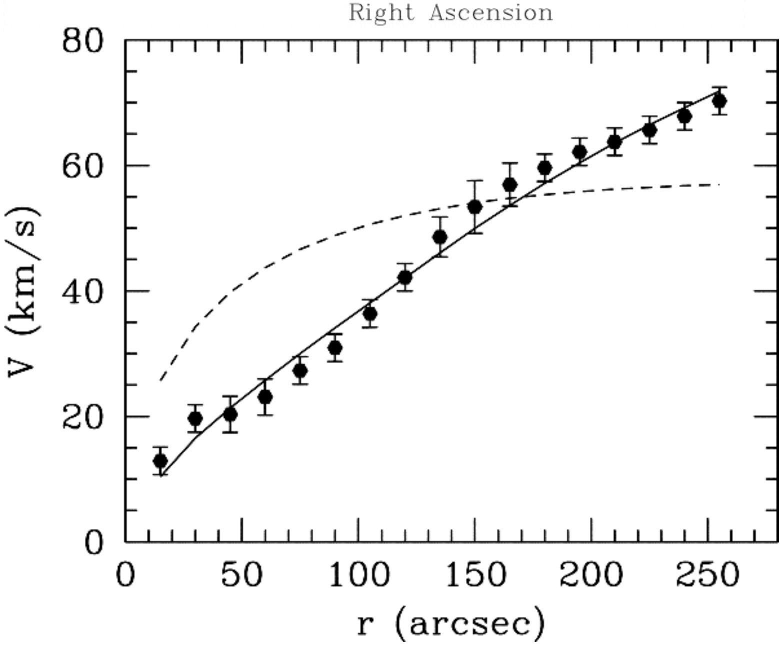
NGC 3741

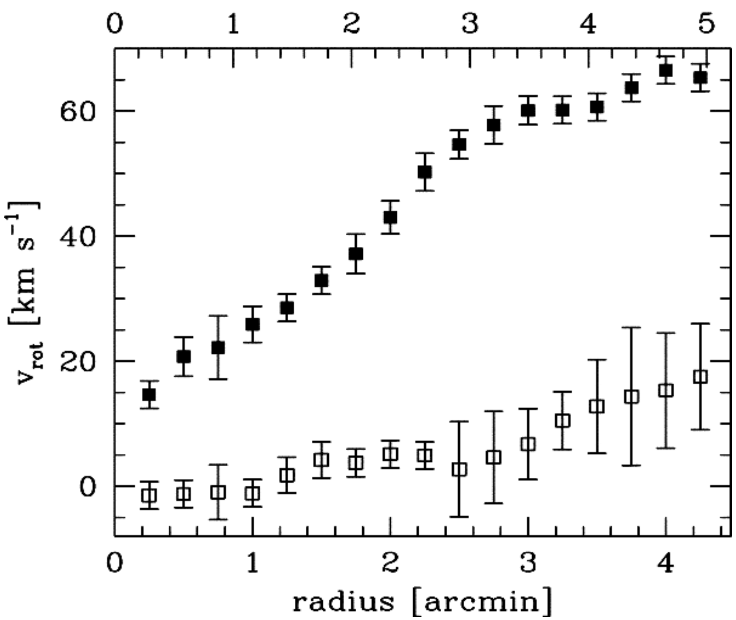
G. Gentile, P. Salucci, U. Klein, G. L. Granato (2007)

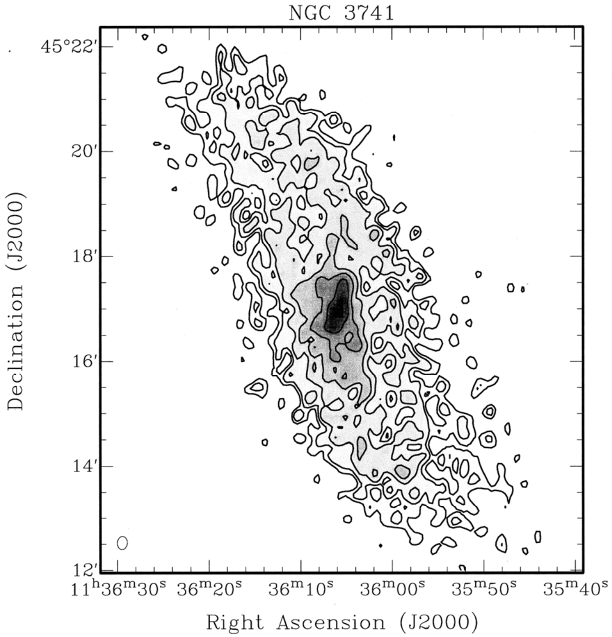
HI out to ~43 blue scale lengths!

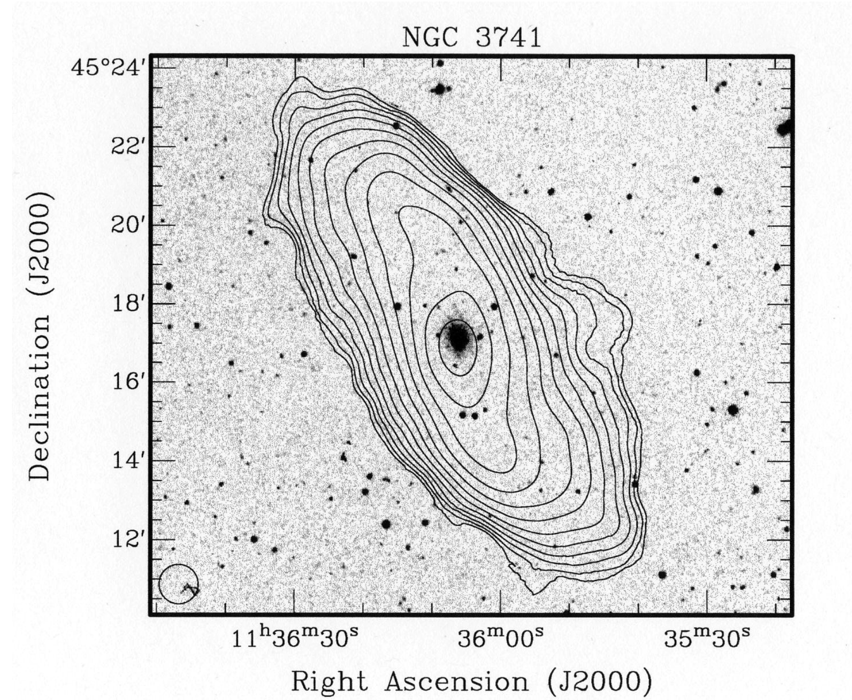

17°0′
16°58′
16°56′
16°54′
16°52′
Declination
7h39m20s
39m10s
39m0s
38m50s
Right Ascension

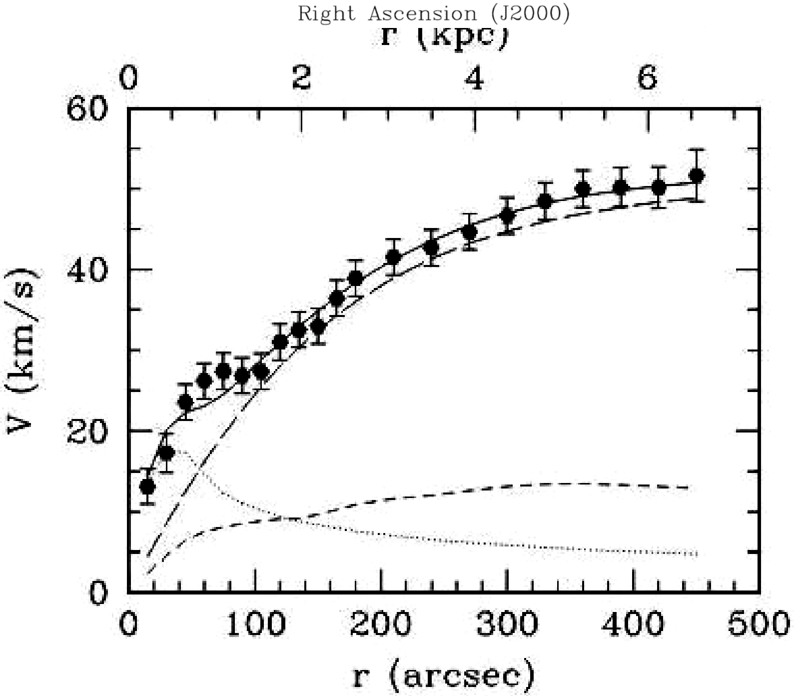

DDO 47
17°00′
16°58′
16°56′
16°54′
16°52′
Declination (B1950)
7h39m20s
39m10s
39m00s
38m50s
radius [kpc]

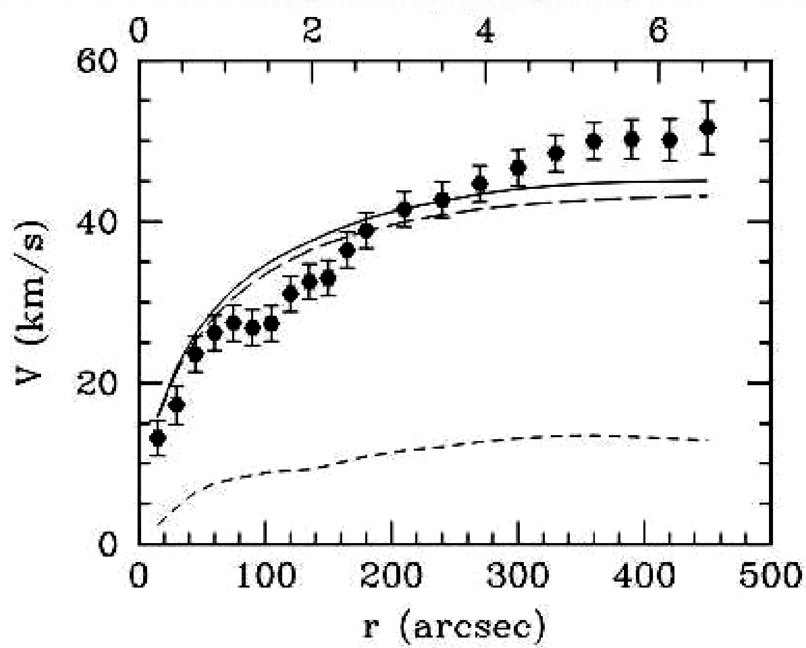

V (km/s)
0
20
40
60
80
0
50
100
150
200
250
r (arcsec)


0
1
2
3
4
5
v_rot [km s^-1]
0
20
40
60
0
1
2
3
4
radius [arcmin]


NGC 3741
45°22′
20′
18′
16′
14′
12′
Declination (J2000)
11h36m30s 36m20s 36m10s 36m00s 35m50s 35m40s
Right Ascension (J2000)


NGC 3741
45°24′
22′
20′
18′
16′
14′
12′
Declination (J2000)
11h36m30s 36m00s 35m30s
Right Ascension (J2000)


r (kpc)
0 2 4 6
60
40
20
0
V (km/s)
0 100 200 300 400 500
r (arcsec)


0 2 4 6
60
40
20
0
V (km/s)
0 100 200 300 400 500
r (arcsec)

harmonic decomposition: non-circular motions:

Fit line-of-sight velocity V_{los} by

$$V_{los} = c_0 + \sum_{j=1}^{n} \left[c_j \cos(j\psi) + s_j \sin(j\psi) \right]$$

ψ = azimuthal angle in galaxy

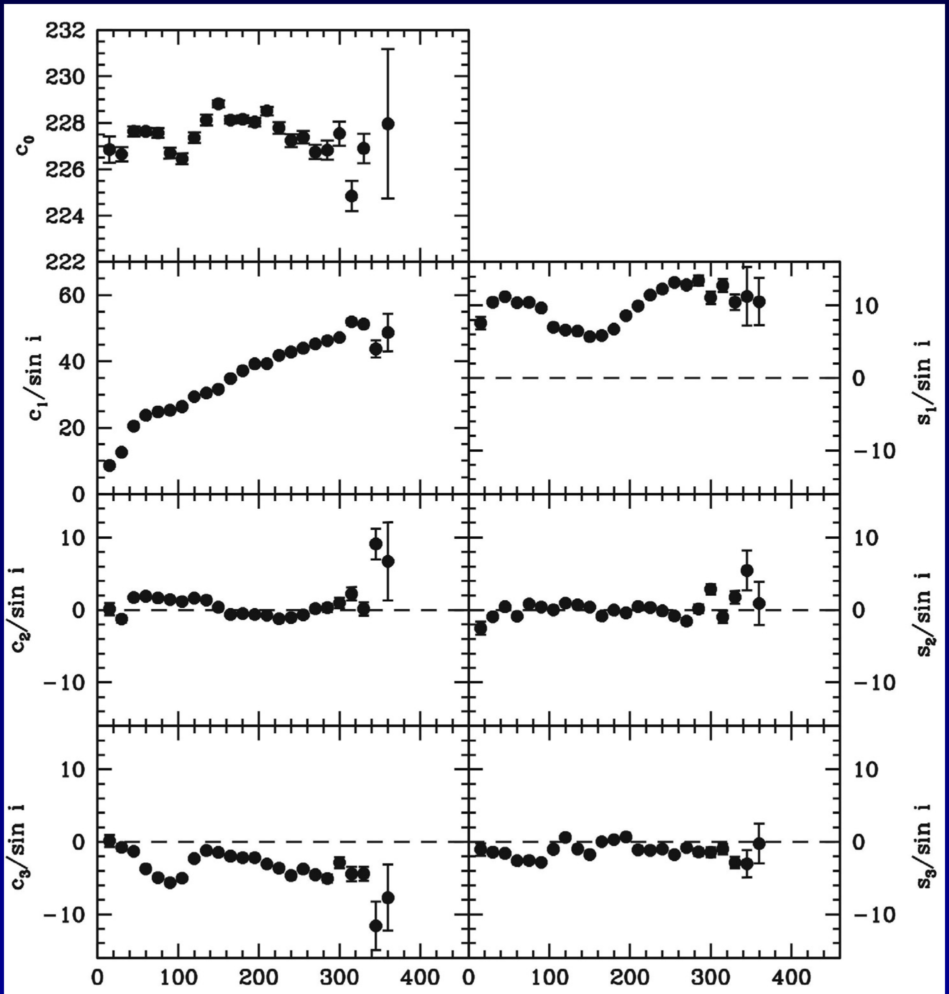
pure circular rotation:

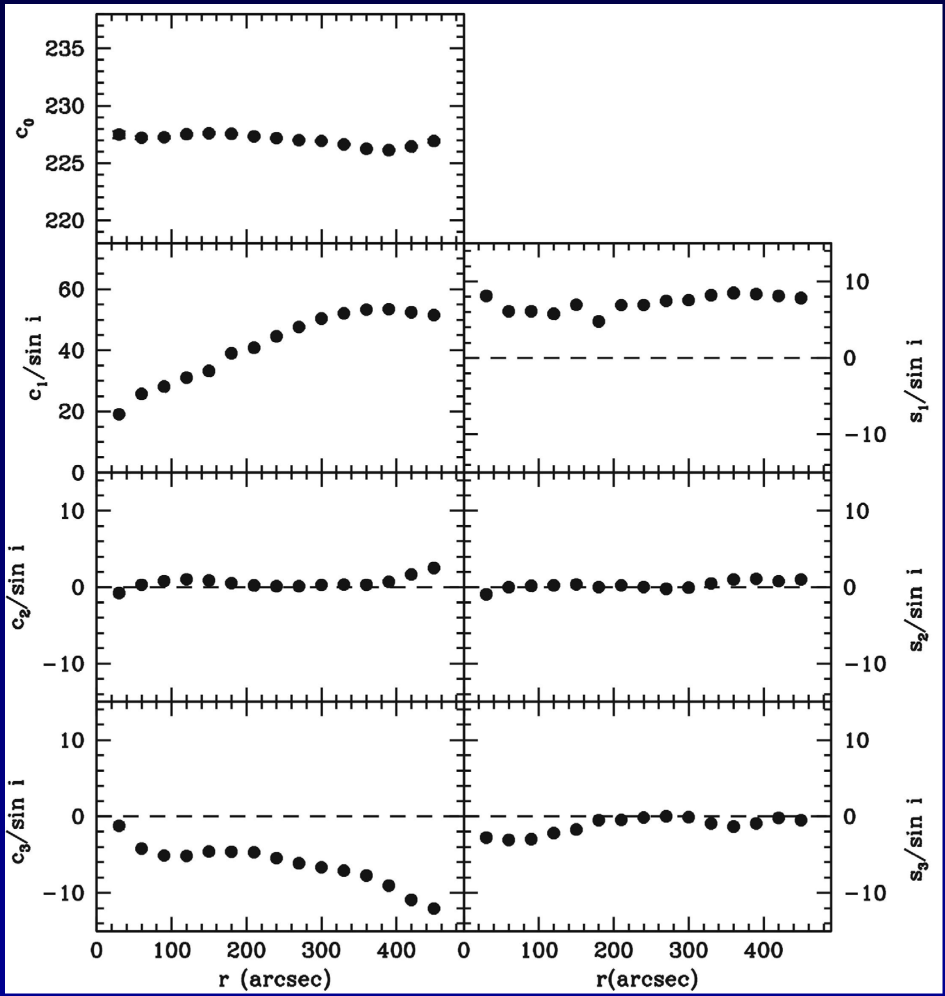
$c_0 = V_{sys}$ and $c_1 = v_c \sin i$, with all other coefficients = 0

$s_j \neq 0$ $(j > 1)$, $c_j \neq 0$ $(j > 2)$: shift of systemic velocity or kinematic centre

radial motions

vertical motions

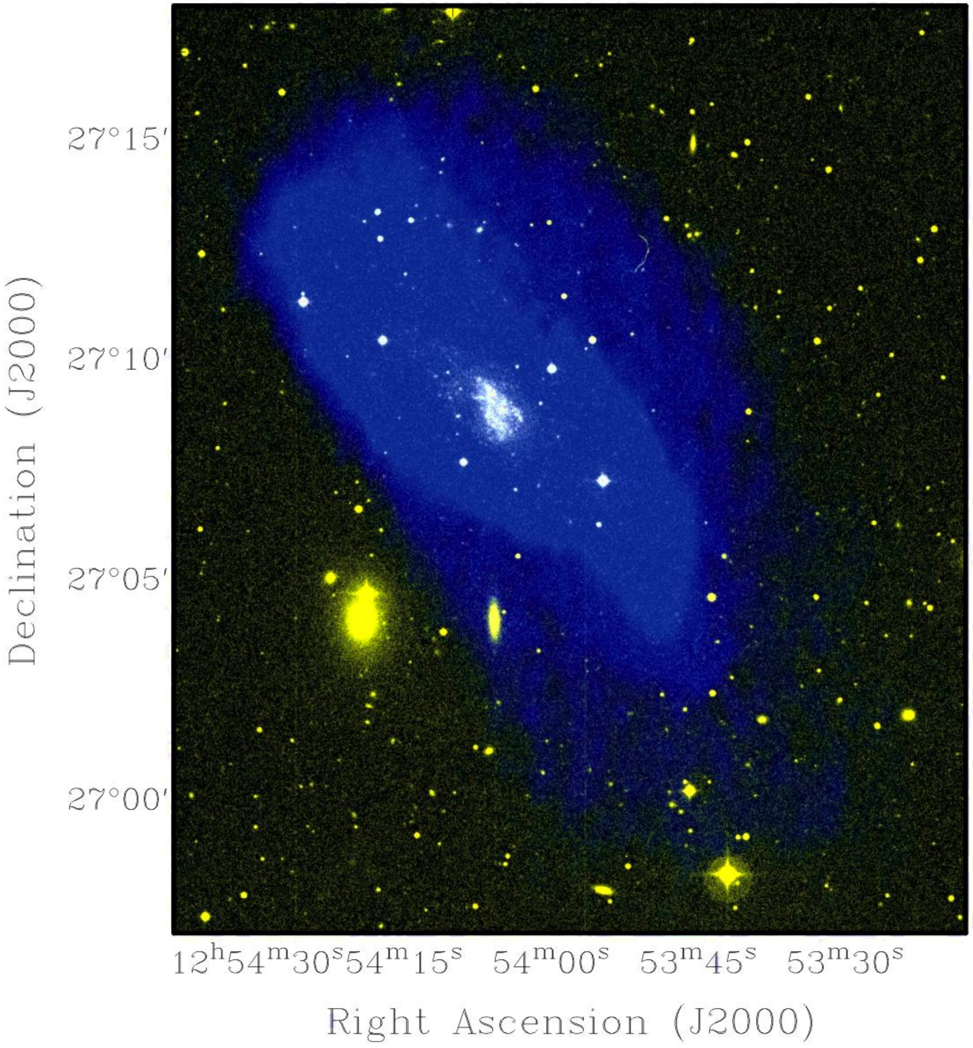




s_1 non-zero: some radial motions in NGC 3741

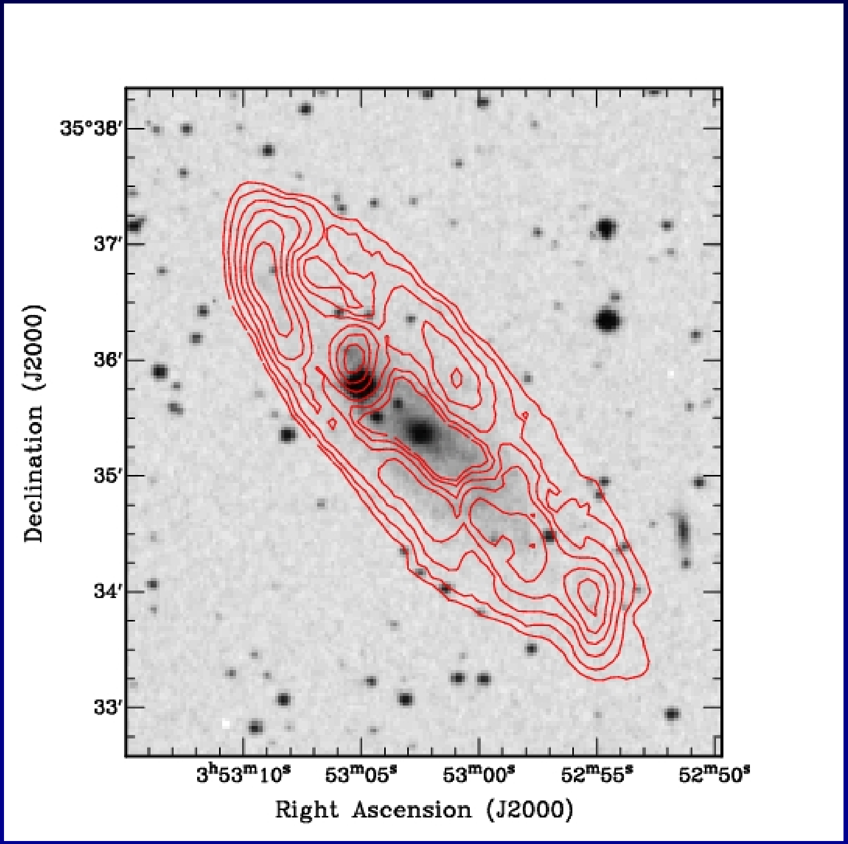
⇒ bar?

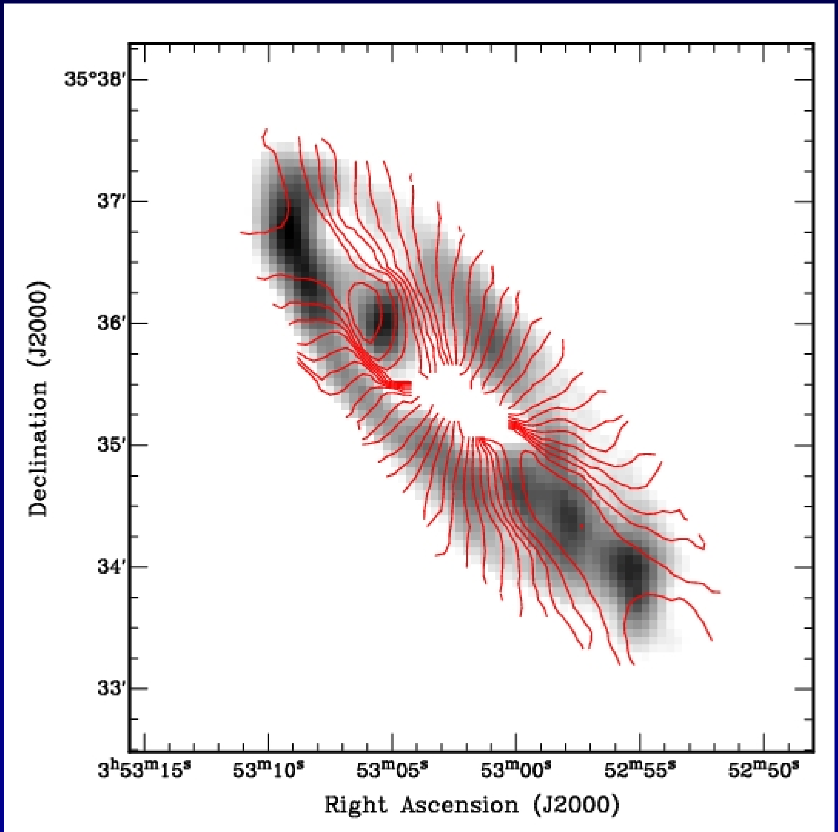
DDO 154: HI out to ~12 × r_{25} (B band)



Analysis by new tilted-ring fitting code (Jozsa et al., in prep.)
⇒ evidence for gas infall

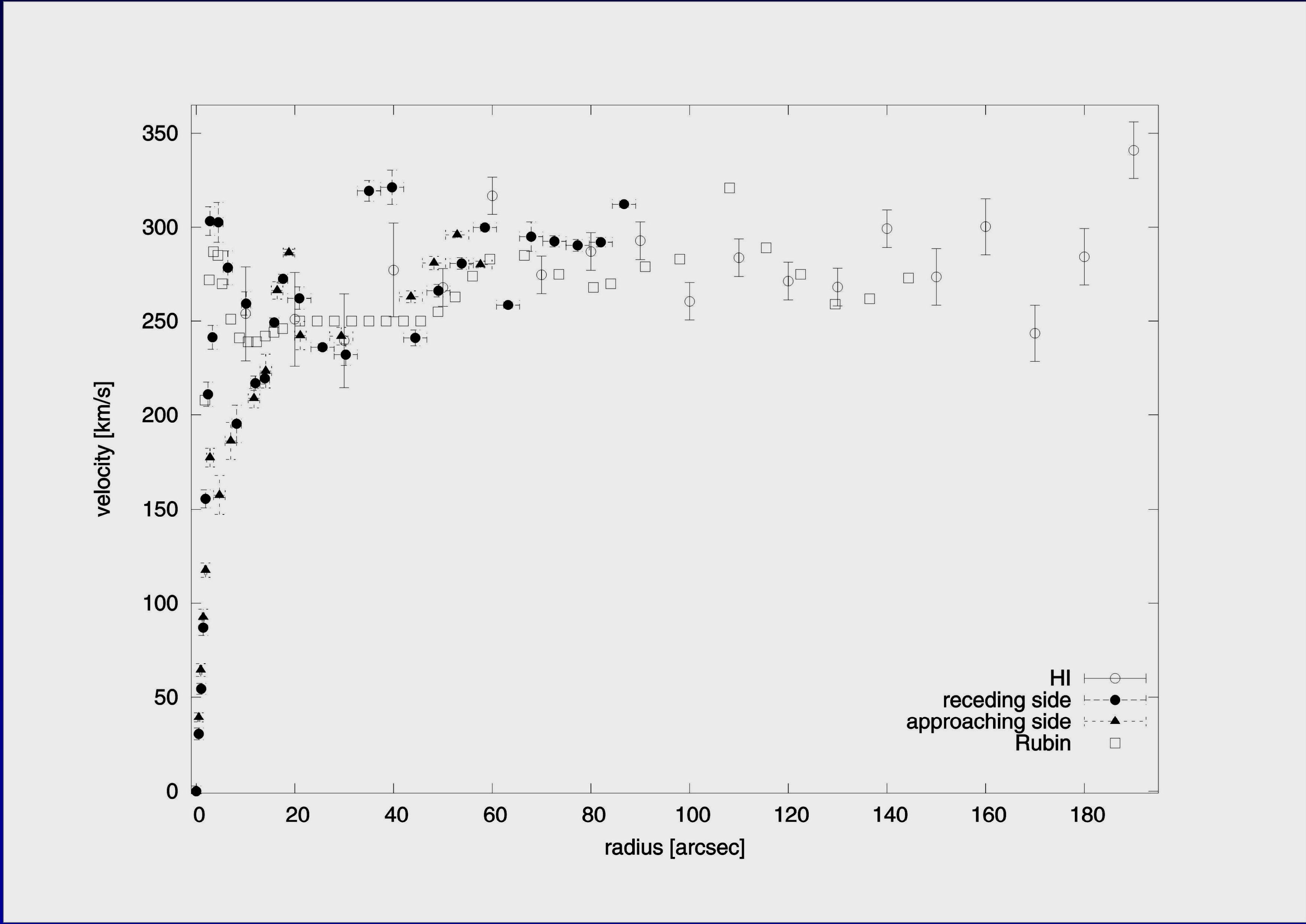
Giant spiral galaxies





e.g. UGC 2885: flat rotation curve out to ~ 100 kpc!

(Struve et al., in prep.)



Hα and HI measurements

Conclusions:

1. **galaxies are dominated by DM**

2. **… into the inner disk for low-mass / low-luminosity galaxies**

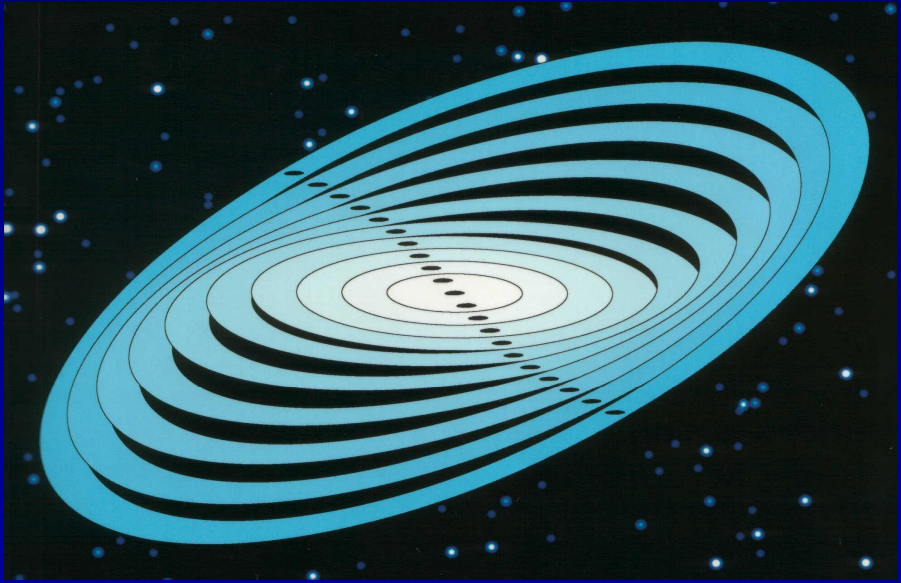
3. **CDM simulations do not reproduce the central *ρ(R)***

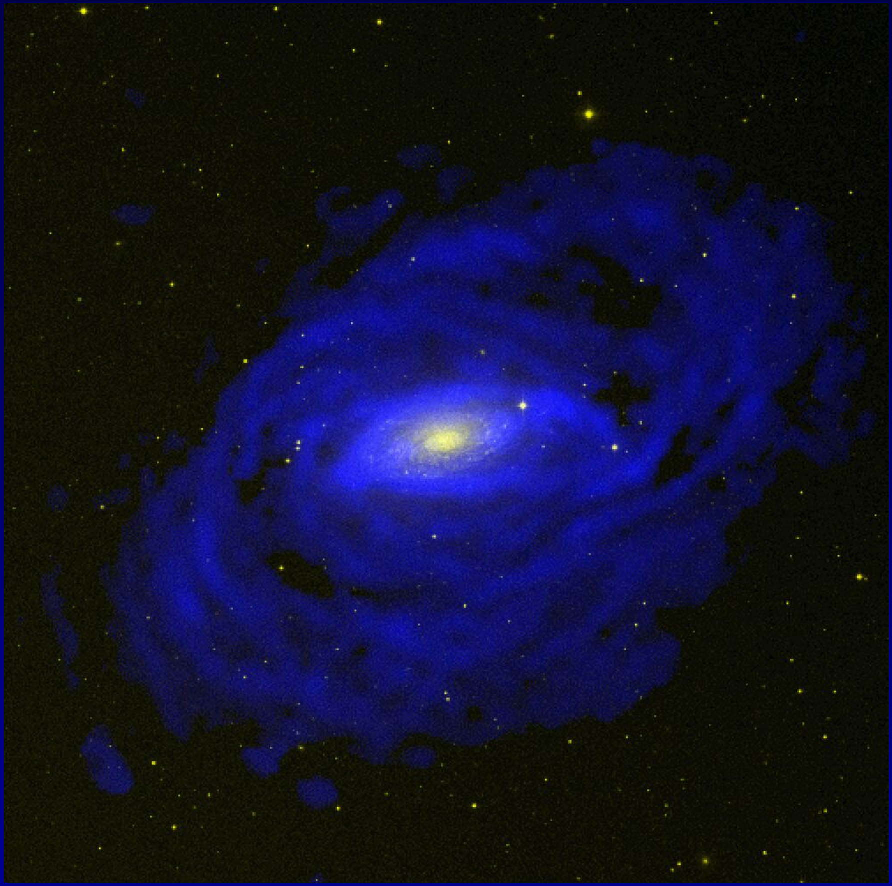
4. **MOND does not fit *V(R)* in many cases**

Warps in galaxies

possible causes:

- tidal forces
- IGM (gas infall)
- (non-spherical) DM halos





Battaglia et al. (2006)

Warps in galaxies: a frequent phenomenon!

- **Reshetnikov & Combes (1998; 1999):**

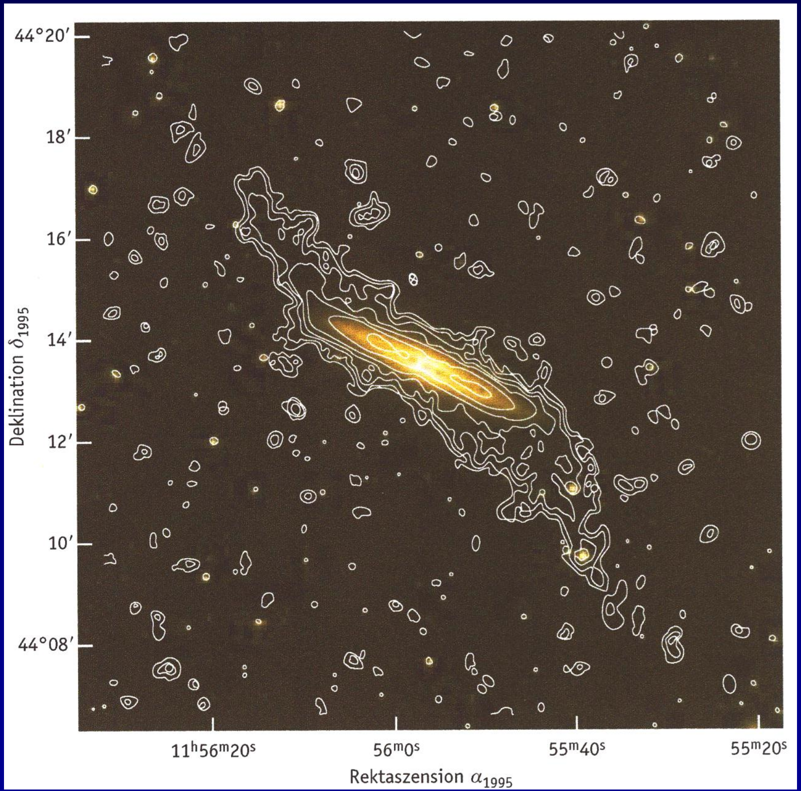
  - about 40% of late-type galaxies exhibit ∫-shaped warps
  - tidal interaction a likely cause

- **García-Ruiz (2001):**

  - all galaxies with an HI disk that is more extended than the optical are warped (corollary: all disk galaxies are warped)
  - stronger and more asymmetric warps in more rich environments
  - but also warps in isolated galaxies ⇒ other mechanisms

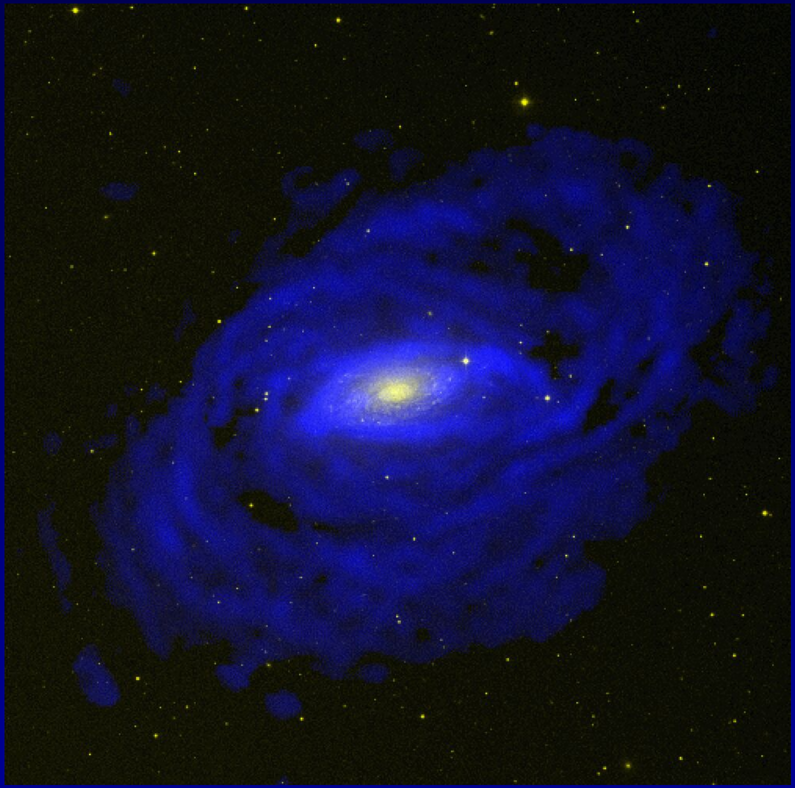
most pronounced in the HI line!

NGC 4013



Bottema et al. (1996)

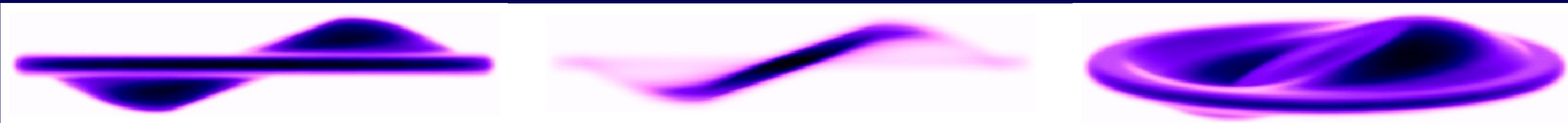
NGC 5055



Battaglia et al. (2006)

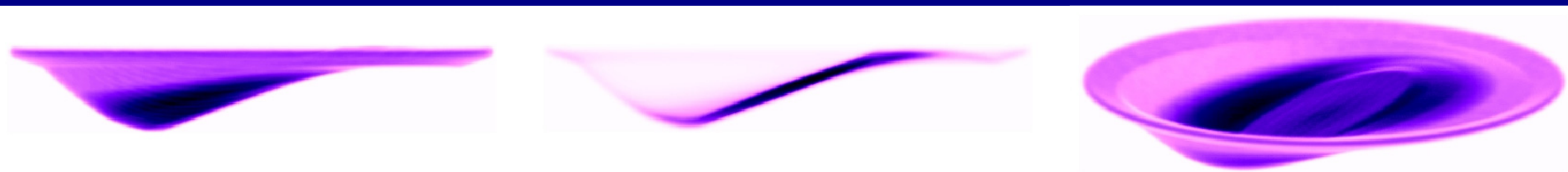
Warp shapes

edge-on, opaque | edge-on, translucent | inclined, opaque



S-shaped (antisymmetric, integral-signed) warp

U-shaped (symmetric, bowl-shaped) warp



L-shaped (asymmetric) warp

Most warps are grand-design S-shaped warps
(García-Ruiz et al. 2002, Sánchez-Saavedra et al. 2003)

TIRIFIC

(G. Józsa, Ph.D. thesis 2006)

measured (HI) data cube $\Rightarrow$ velocity field

$B(\xi, \eta, V)$ $\Rightarrow$ tilted-ring analysis

$\Rightarrow$ initial model

- systemic velocity
- inclination
- position angle

model cube ← – – – – – – – – –

$\Downarrow$

convolution

$\Downarrow$

subtract data cube

$\Downarrow$

check χ^2 – – – – – – → better / worse?

new parameters, each ring
(V_{sys}, V_{rot}, centre, *i*, *p.a.*, *w.a.*)

Kinematics and morphology of warped disk galaxies

Józsa (2007)
Józsa, Kenn, Klein, Oosterloo (2007)

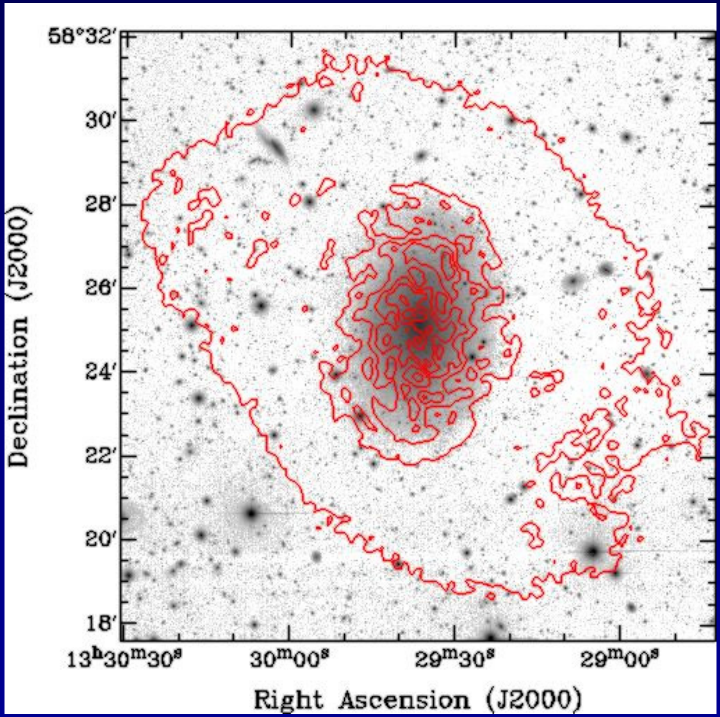
- isolated galaxies with strong symmetric HI warps
- no bars
- HI observations with WSRT
- optical photometry with INT

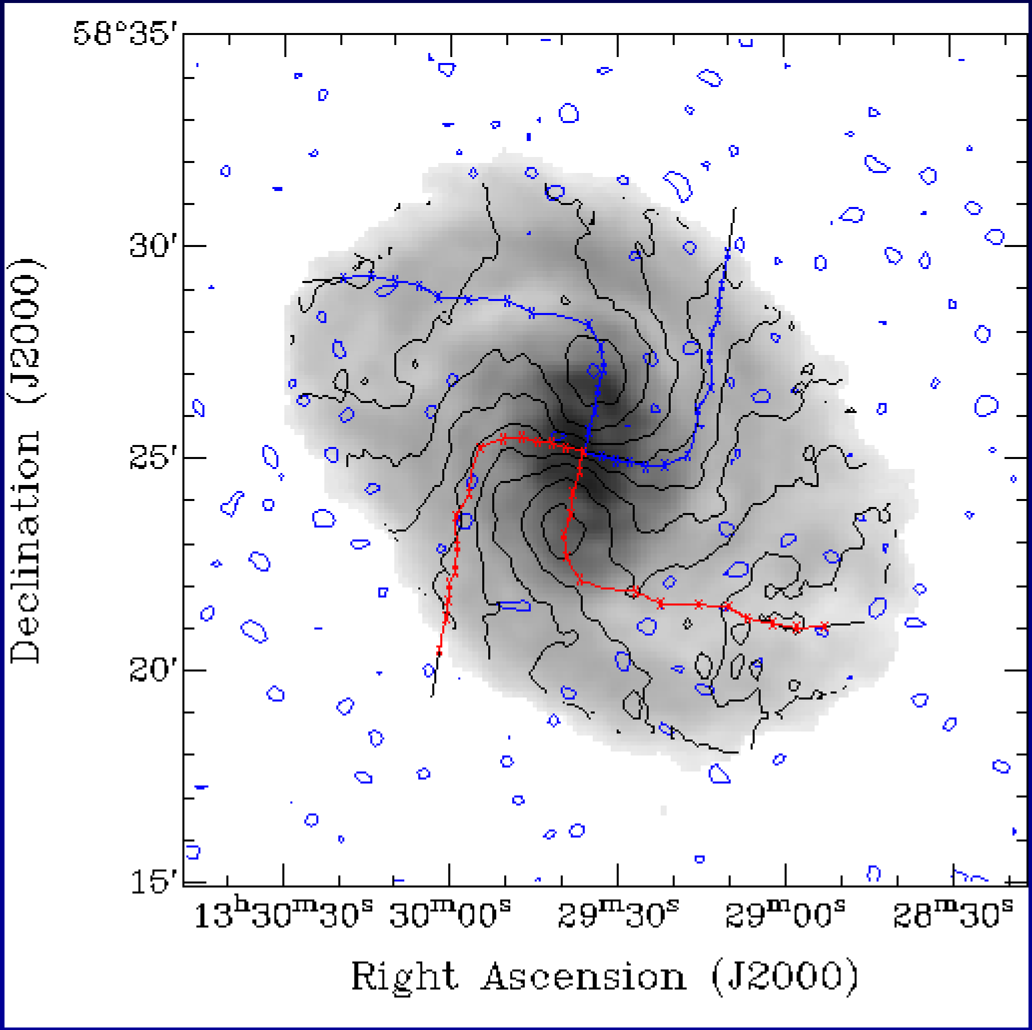
study of galaxies in 3 dimensions, i.e. determine

- centre $\xi_0\ (R), \eta_0\ (R)$
- inclination $i\ (R)$
- position angle $p.a.\ (R)$
- systemic velocity $V_{sys}\ (R)$
- warp angle $w.a.\ (R)$

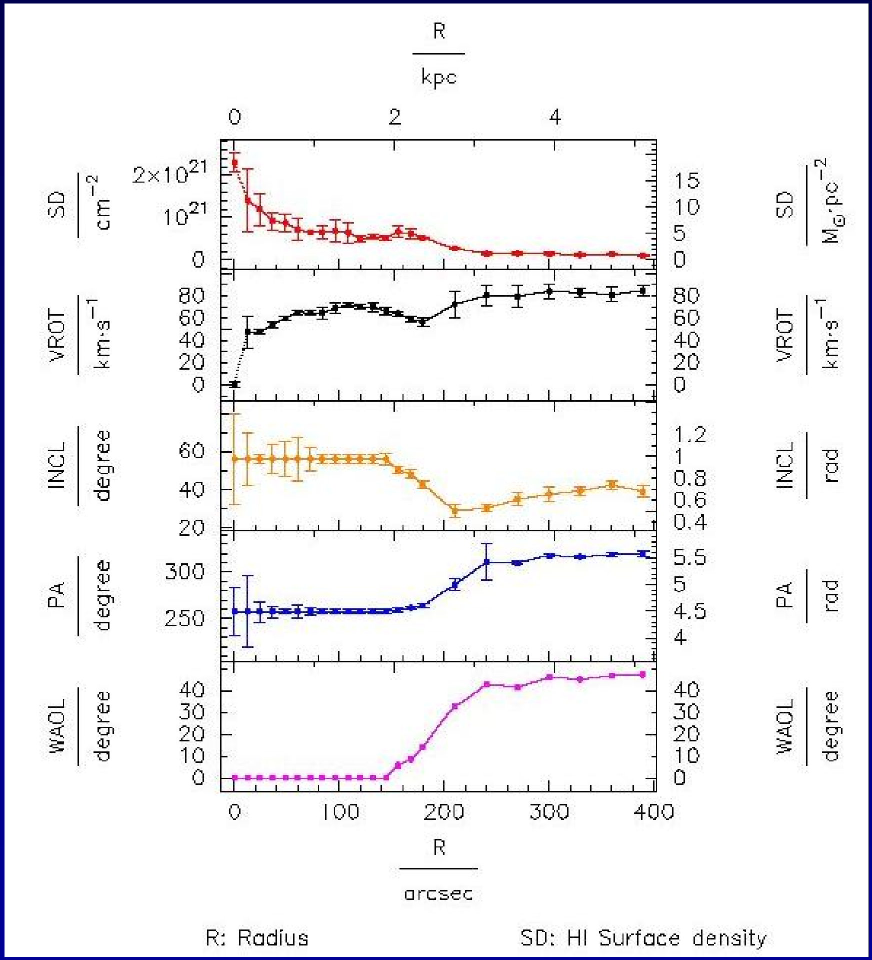
ample (successful) tests with “mock galaxies”

strong warps: e.g. NGC 5204

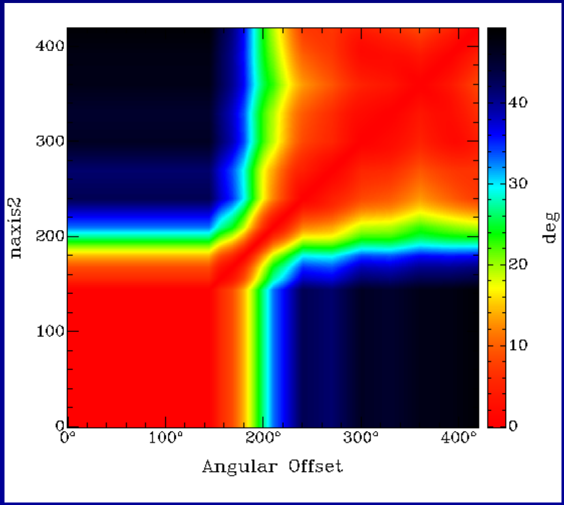




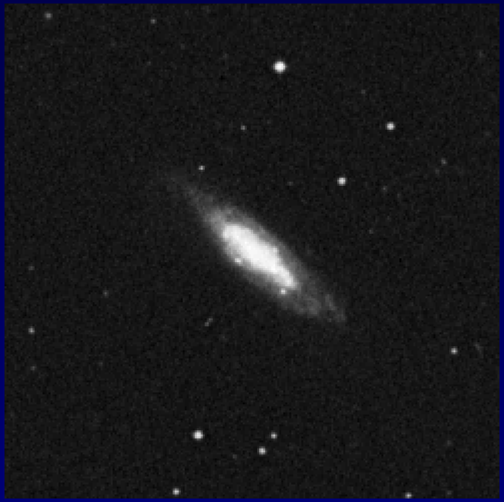
NGC 5204

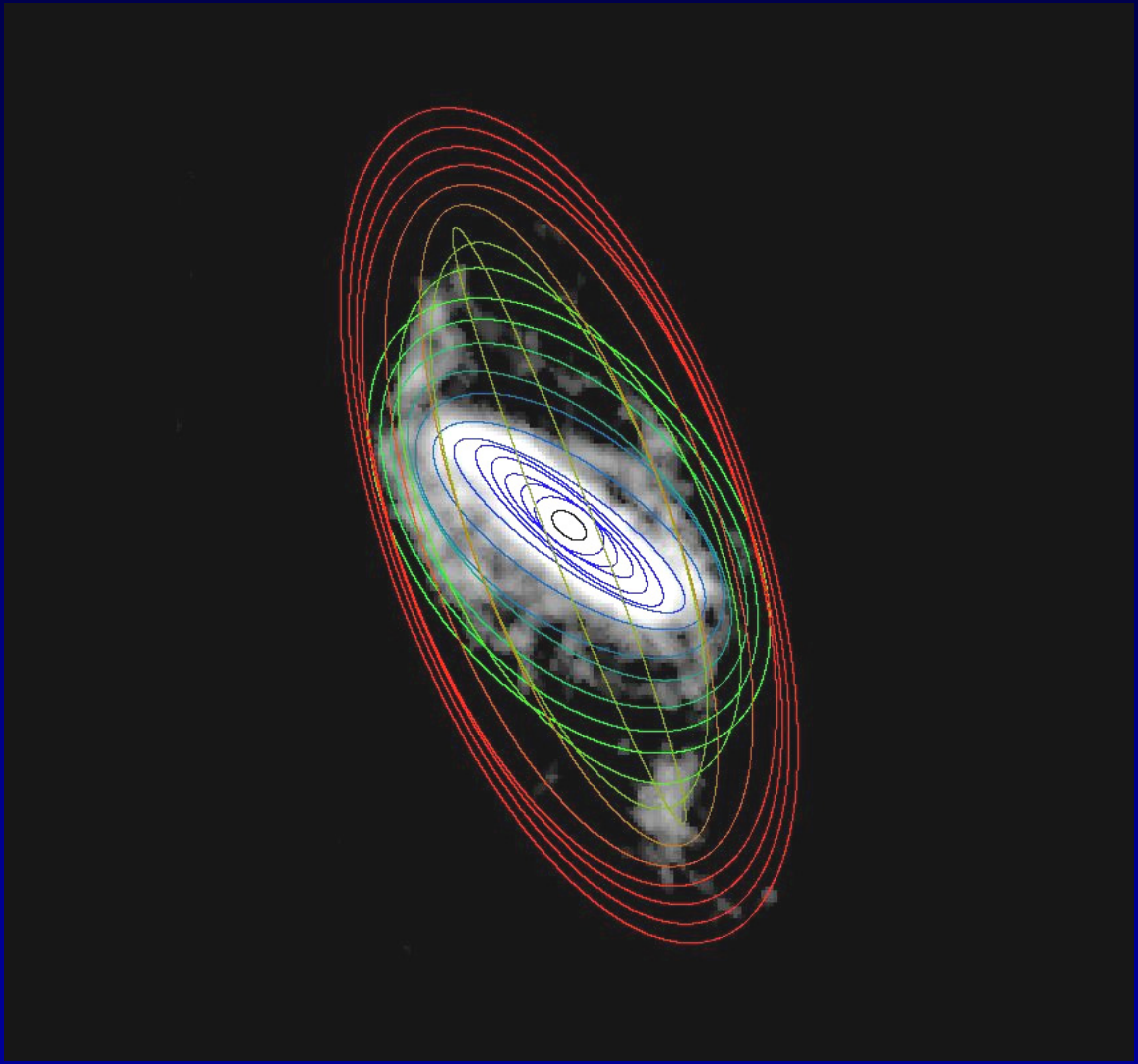


R
kpc
SD cm^-2
VROT km·s^-1
INCL degree
PA degree
WAOL degree
SD M☉·pc^-2
INCL rad
PA rad
R
arcsec
R: Radius
SD: HI Surface density



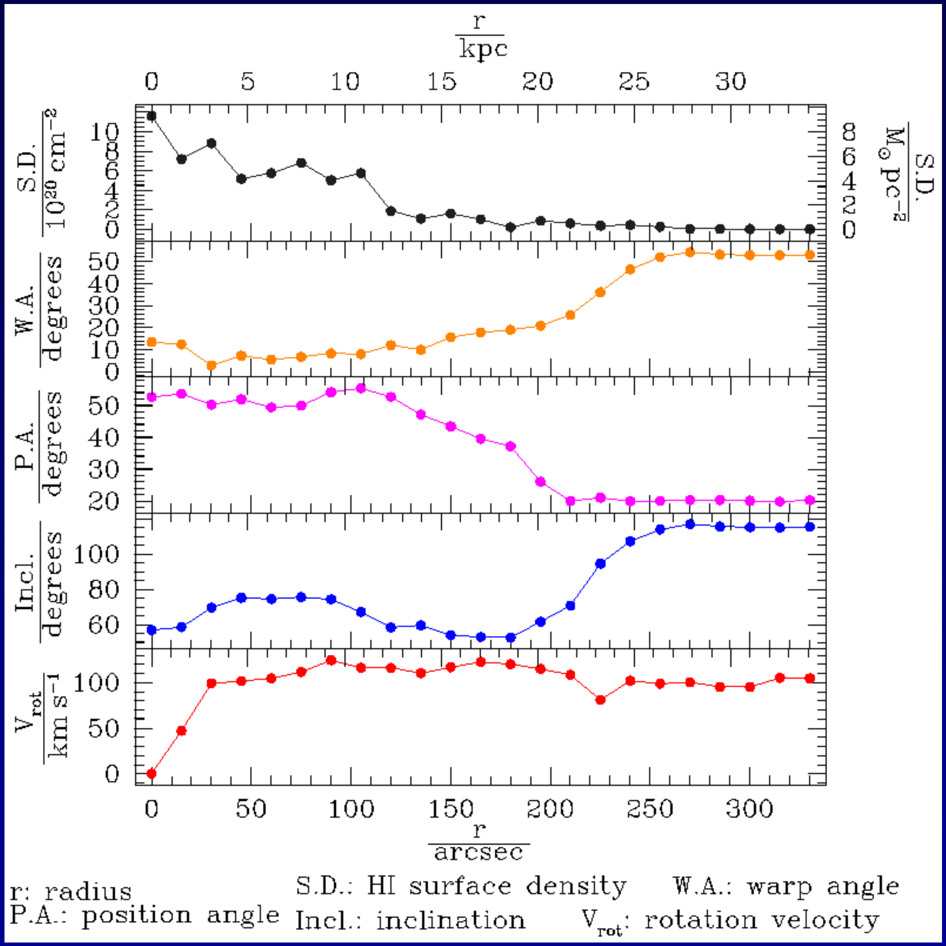
naxis2
Angular Offset
deg





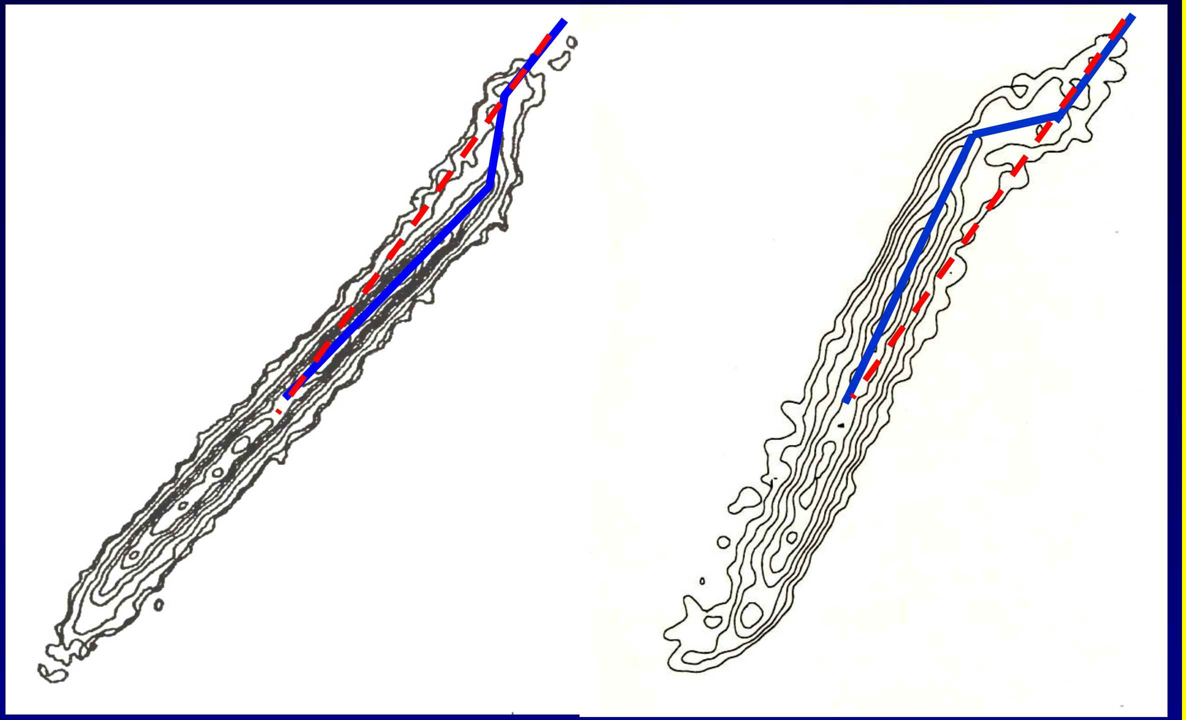
NGC 755

NGC 755

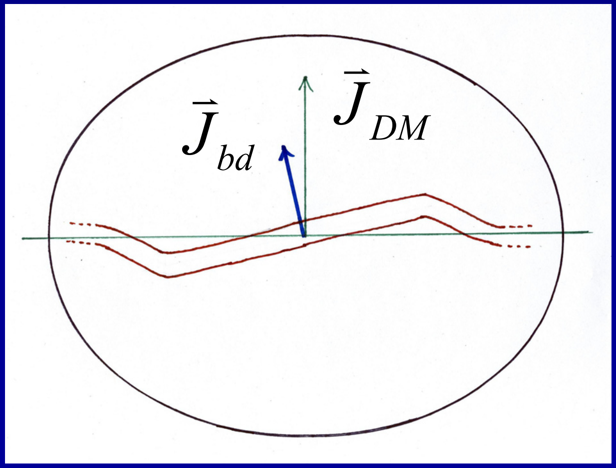


r
kpc
S.D.
10^{20} cm^{-2}
W.A.
degrees
P.A.
degrees
Incl.
degrees
V_{rot}
km s^{-1}
S.D.
$M_\odot$ pc^{-2}
r
arcsec
r: radius
P.A.: position angle
S.D.: HI surface density
Incl.: inclination
W.A.: warp angle
V_{rot}: rotation velocity

an intriguing interpretation:



… maybe:



Sharma & Steinmetz (2005):

misalignment between angular momentum of disk and dark halo

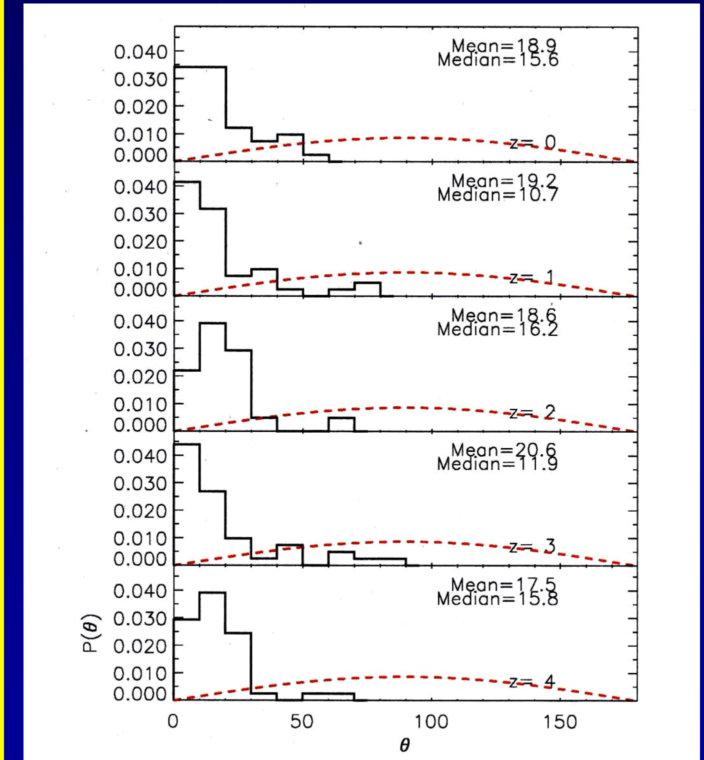


FIG. 4.— Distribution of misalignment angle θ for various redshifts. The dashed line is the expected distribution if the angle is completely random or uncorrelated.

Conclusions:

1. warps are a frequent phenomenon in galaxies
2. warped galaxies possess flat inner disk
3. warps start where
   - optical disk has faded away
   - HI surface brightness reaches a constant, low level
4. rotation velocity changes with orientation of the disk
   $\Rightarrow$ non-spherical DM halo?
5. two coherent kinematic regimes, each with constant line of nodes

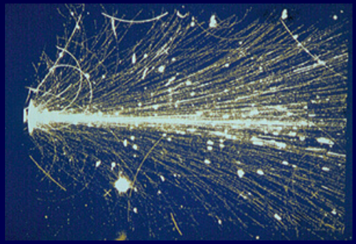
DM: where do we go?

Close collaboration physics/astrophysics:

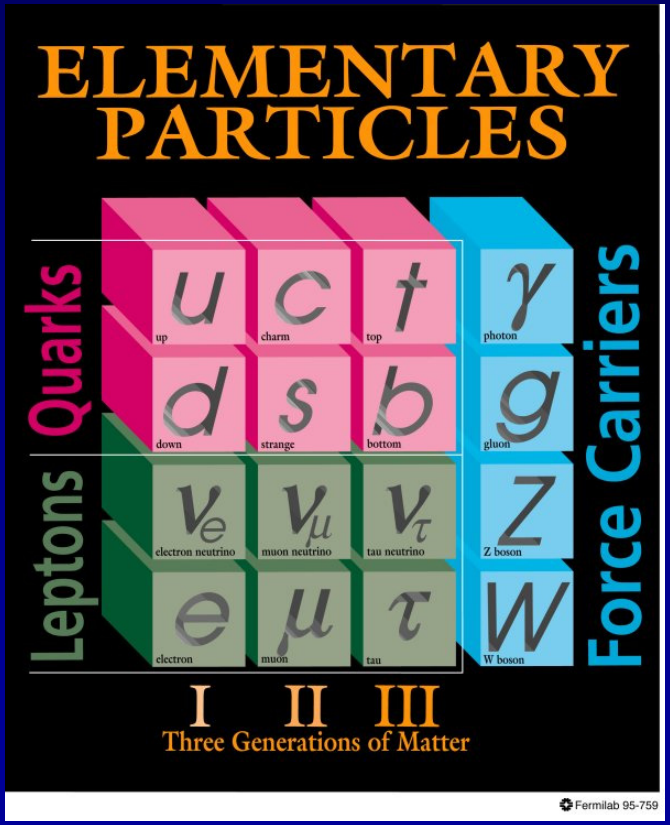
- **derivation of quality rotation curves**
- **improved numerical simulations**
- **collider experiments in the TeV regime (LHC)**
- **direct DM detection experiments**
- **theoretical models of DM candidates**

Collider physics:

Large Hadron Collider (LHC) @ Cern



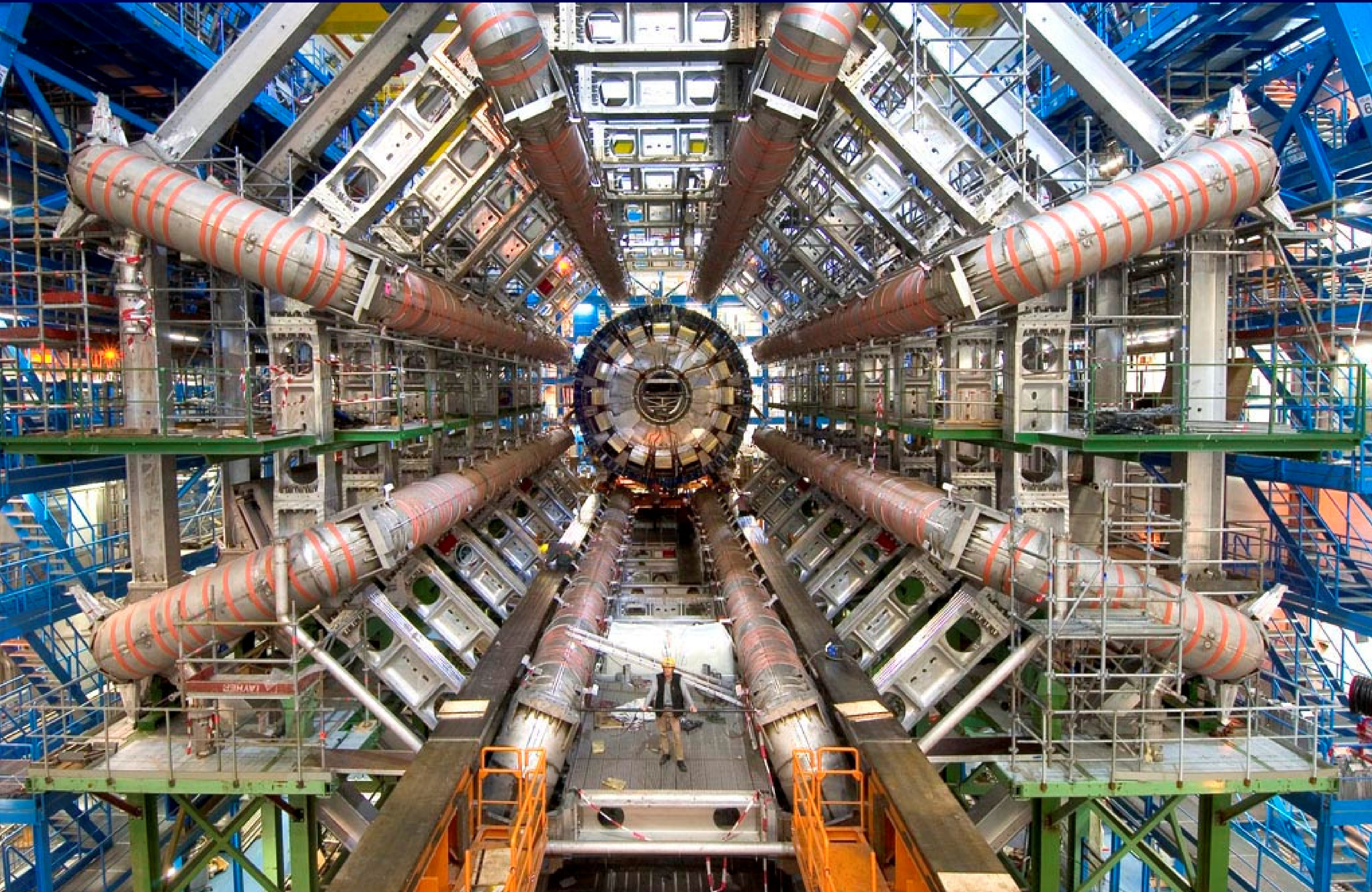
- circular tunnel 27 km in circumference, 50 m to 175 m underground
- designed to have two counter-rotating beams of protons or heavy ions collide
- p-p collisions are foreseen at an energy of 7 TeV per beam
- start-up in 2008



detectors: e.g. ATLAS

- test of Standard Model
- search for Higgs particle
- search for SUSY particles

ATLAS: 7000 metric tons, 5 storeys high



Direct DM detection: e.g. XENON @ Gran Sasso

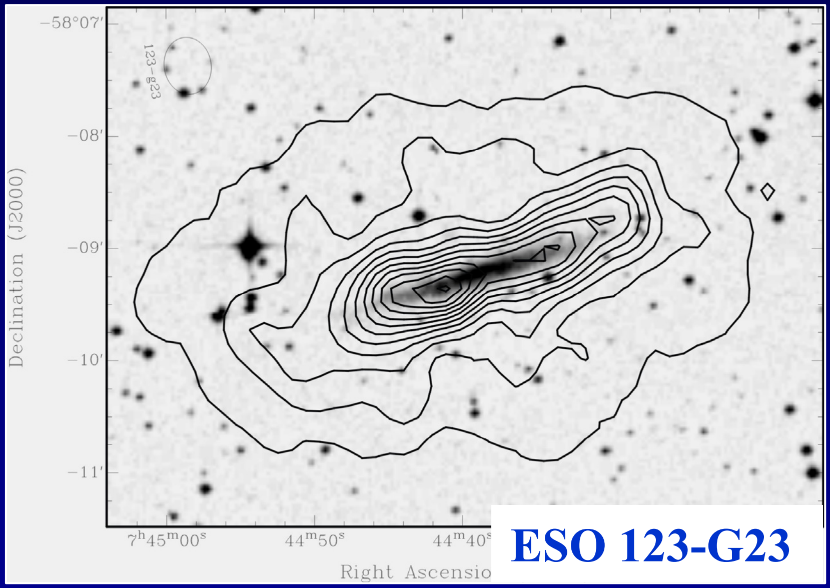
goal: detect small charge and light signal after a dark matter particle interacts with a xenon nucleus

1 ton of xenon!

Grazie per l'invito!

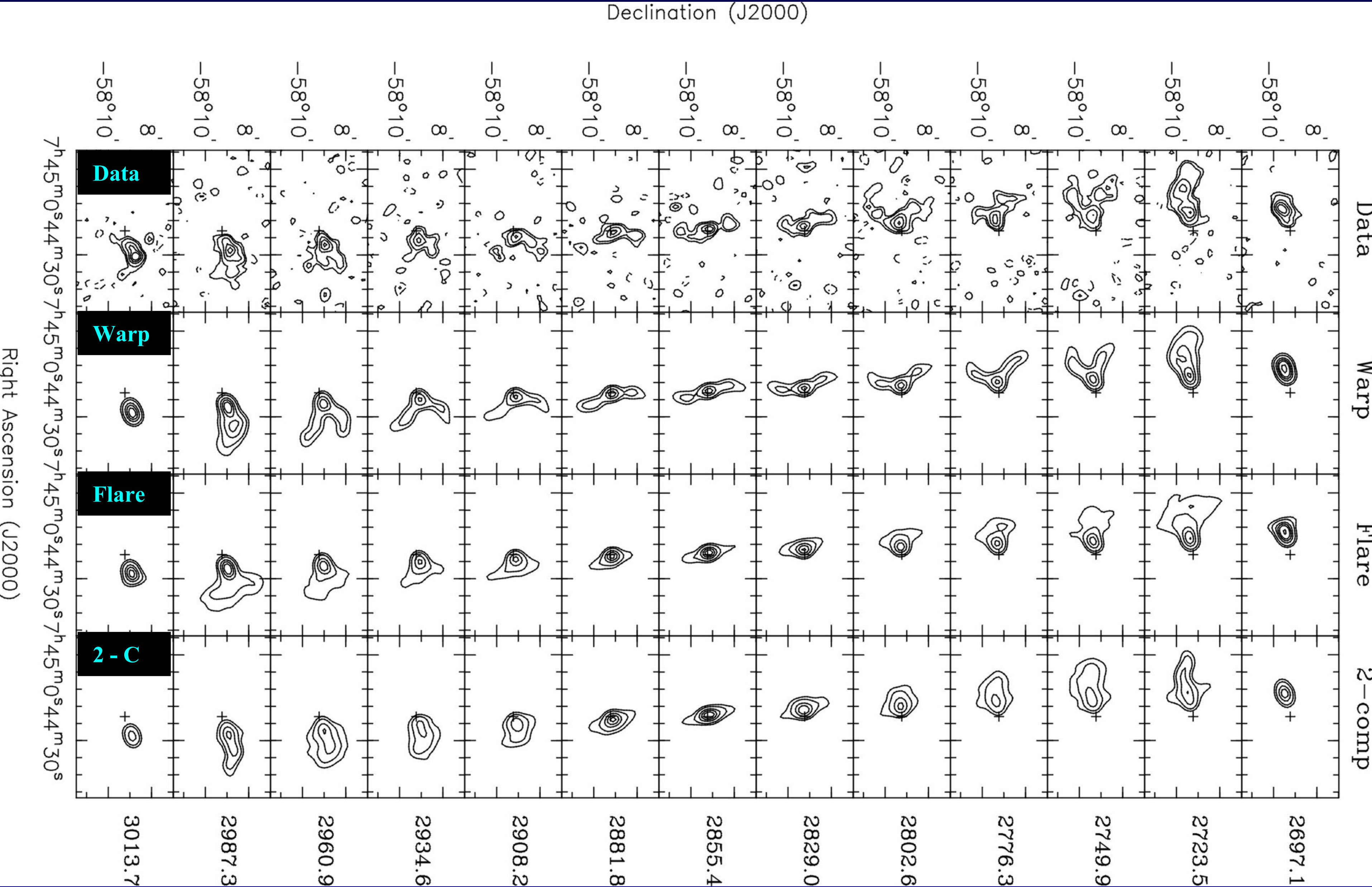
the conspicuous galaxy ESO 123-G23

HI gas 15 kpc out of the plane??

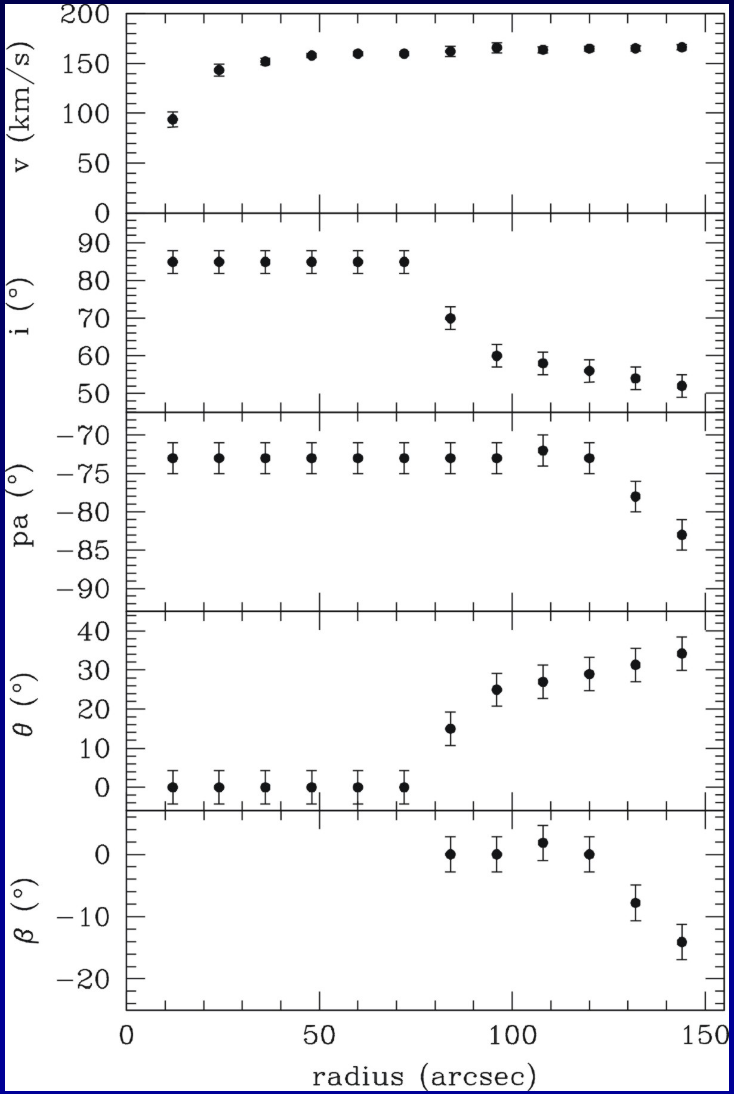


Gentile et al. (2003)

Data and models



G. Gentile, Fraternali, P., Klein, U., P. Salucci, P. (A&A 405, 969, 2003)



parameters:

θ ~ 35º (strong warp!)

β ≈ 0º (close to l.o.s)

view of warp