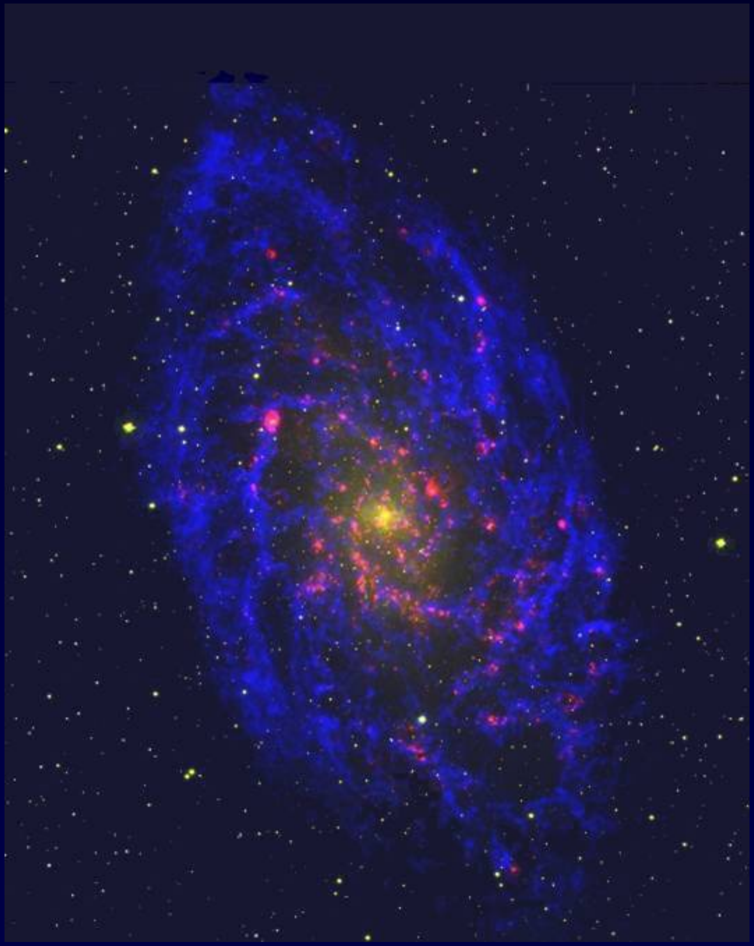
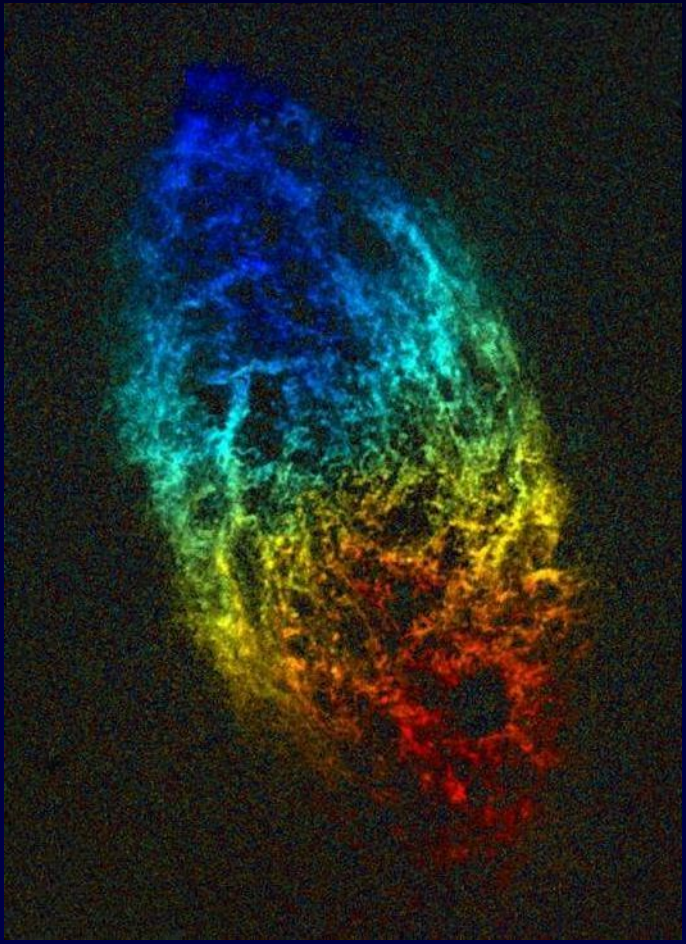
Structure and Kinematics of Galaxies

U. Klein





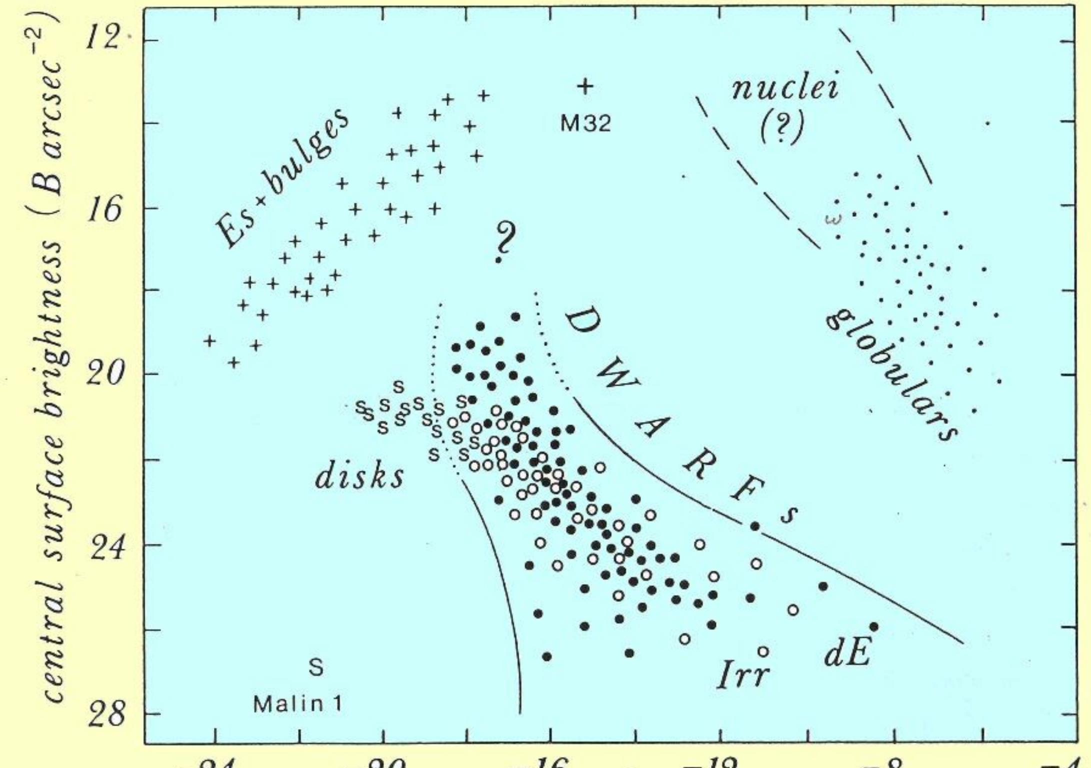
Ringberg, 19 July 2011

Outline

1. Galaxy zoo
2. The structure of disk galaxies
3. Photometry
4. Kinematics of disk galaxies
5. Relation to magnetic fields

Galaxy zoo

Galaxy types: disk galaxies (Sa, Sb, Sc, Sd, Sm, dIrr)
S0s ('interlude'), SBa … have bars
elliptical galaxies (E0 … E7, dE, dSph)

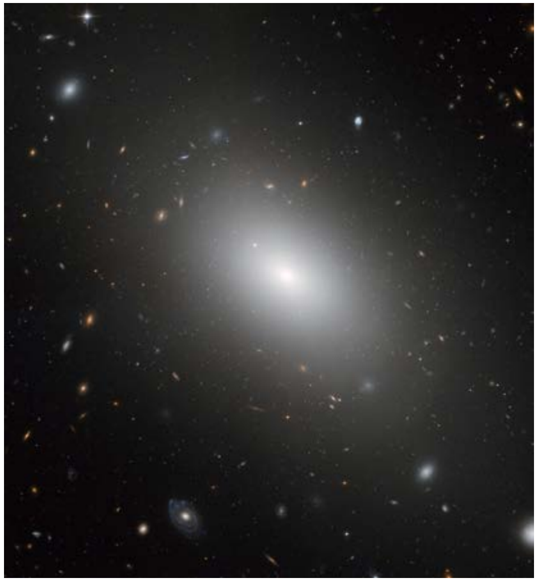


Binggeli (1994)

disk galaxies:

- stellar bulge & disk
- gas disk (HI + H_2)
- hot gaseous corona
- ordered circular rotation of stellar and gaseous disk

elliptical galaxies:



- spherical or elliptical in projection (prolate, oblate, triaxial?)
- entire gas in hot gaseous corona
- dE, dSph: no gas at all
- stars move on random elliptical orbits, no ordered rotation

disk galaxies:

- all prerequisits for B-field generation and sustainment

  cold gas with ionized component

  (differential) rotation, turbulence via SF and SNe

ellipticals:

- may possess B-fields (high conductivity), but

  no SF $\Rightarrow$ no relativistic particles $\Rightarrow$ no synchrotron radiation $\Rightarrow$ no detection

  no SF $\Rightarrow$ no turbulence

  dE, dSph: no gas $\Rightarrow$ no SF $\Rightarrow$ no …

so here focus on disk galaxies!

Constituents of spiral galaxies†

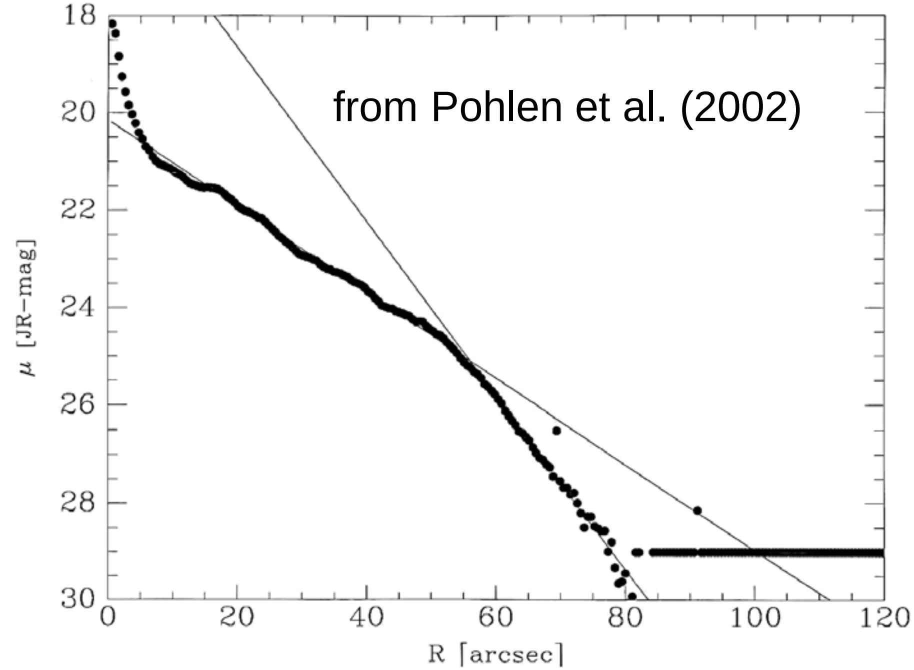
Component	Mass	dynamically
• stellar		
- thin disk	$4.7 \cdot 10^{10}\ M_\odot$	significant
- thick bulge	$6.2 \cdot 10^{10}\ M_\odot$	significant
• gaseous disk		
- atomic neutral hydrogen (HI)	$3.1 \cdot 10^{10}\ M_\odot$	significant
- molecular hydrogen (H_2)	$7.5 \cdot 10^{9}\ M_\odot$	significant (?)
- ionized/hot gas (HII)	$5.0 \cdot 10^{8}\ M_\odot$	insignificant
- dust	$4.0 \cdot 10^{8}\ M_\odot$	insignificant
• relativistic plasma	$10 - 50\ M_\odot$	insignificant
• dark halo	$5.0 \cdot 10^{11}\ M_\odot$	dominant

† e.g. NGC 7331

Structure of disk galaxies

stellar disk: exponential decline of brightness

$$I(R) = I_0 \cdot e^{-R/R_d}$$



I(R) and I_0 have units of mag/③″

conversion to $L_\odot$ pc^{-2} for optical band X via

$$I_X = 4.25 \cdot 10^{8+0.4\left[\left(\frac{M_{\odot,X}}{mag}\right)-\left(\frac{\mu_X}{mag/\text{G''}}\right)\right]} \cos i \quad L_\odot\, \text{pc}^{-2}$$

conversion to mass surface density then via mass-to-light ratio for that band:

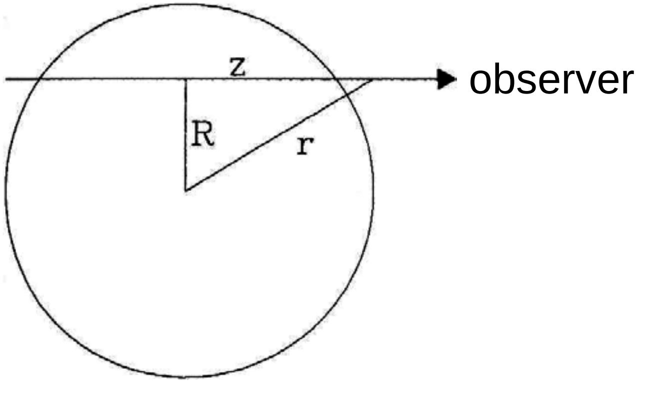
$$\left(\frac{\Sigma_X(R)}{\mathrm{M}_\odot\,\mathrm{pc}^{-2}}\right) = \mathrm{K}_X \cdot \left(\frac{I_X(R)}{\mathrm{L}_\odot\,\mathrm{pc}^{-2}}\right)$$

likewise for mass and luminosity density, respectively:

$$\left(\frac{\rho_X(r)}{\mathrm{M}_\odot\,\mathrm{pc}^{-3}}\right) = \mathrm{K}_X \cdot \left(\frac{j_X(r)}{\mathrm{L}_\odot\,\mathrm{pc}^{-3}}\right)$$

use Poisson equation to convert to circular velocities (see kinematics)

note:
we use R for observed radial brightness and r for intrinsic galacto-centric distance



edge-on view:

truncated disk with finite thickness (Casertano 1983):

$$I(R,z) = I_0\, e^{-\frac{R}{R_d}} \cosh^{-2}(z/z_0)$$

~ exp[-(z/z_0)^2]   for small *z*

with underlying density

$$\rho(R,z) = \rho_0(R) \cosh^{-2}(z/z_0)$$

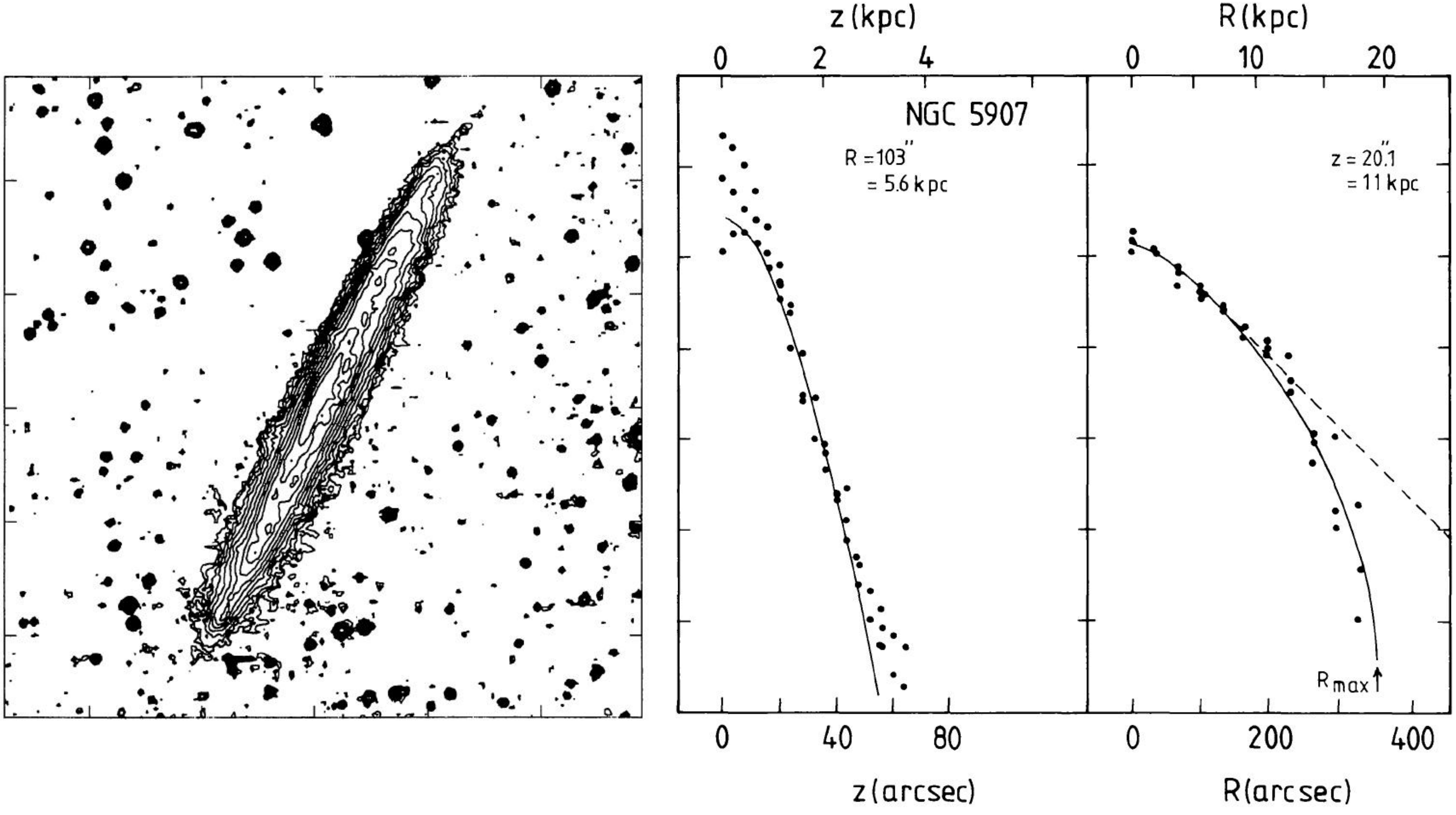
where

$$\rho_0(R) = \begin{cases} \rho_{00}\, e^{-R/R_d} & (R \le R_t) \\ \rho_{00}\, e^{-R/R_d} \left[1 - (R - R_t)/\delta\right] & (R_t \le R \le R_t + \delta) \\ 0 & (R_t + \delta \le R) \end{cases}$$

$\boldsymbol{R_t}$ = truncation radius, $\boldsymbol{\delta}$ = soft-cutoff region

note: sech(x) = cosh(x)$^{-1}$

e.g. NGC5907 (van der Kruit & Searle 1982):



bulge: intensity follows de Vaucouleurs (1948) law

$$I(R) = I_e \cdot e^{-7.67\left[(R/R_e)^{1/4} - 1\right]}$$

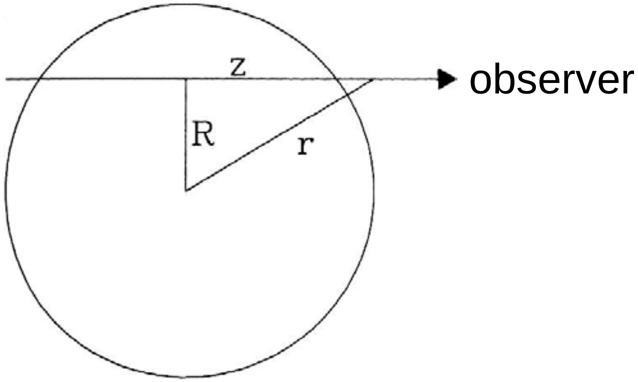
or, its generalized form, a Sersic law

$$I(R) = I_e \cdot e^{-b_n\left[(R/R_e)^{1/n} - 1\right]}$$

where $\boldsymbol{R_e}$ is the effective radius, implying that one-half of the total light is emitted interior to $\boldsymbol{R_e}$.

Intensity distribution of a spheroid needs to be deprojected (Binney & Tremaine 1987; Binney & Merrifield 1998):

$$I(R) = \int_{-\infty}^{+\infty} j(r)\, dz = 2\int_{R}^{+\infty} \frac{j(r)\, r\, dr}{\sqrt{r^2 - R^2}}$$



this Abel integral is readily inverted to yield the luminosity density

$$j(r) = -\frac{1}{\pi}\int_{r}^{+\infty}\frac{dI}{dR}\frac{dR}{\sqrt{R^2 - r^2}}$$

convert luminosity density into matter density of bulge

$$\rho_X(r) = \mathrm{K}_X \cdot j_X(r)$$

and calculate circular velocity using Poisson equation for the spherically symmetric case (see kinematics).

gaseous disks:

e.g. Leroy et al. (2008):

total gas and SFE from

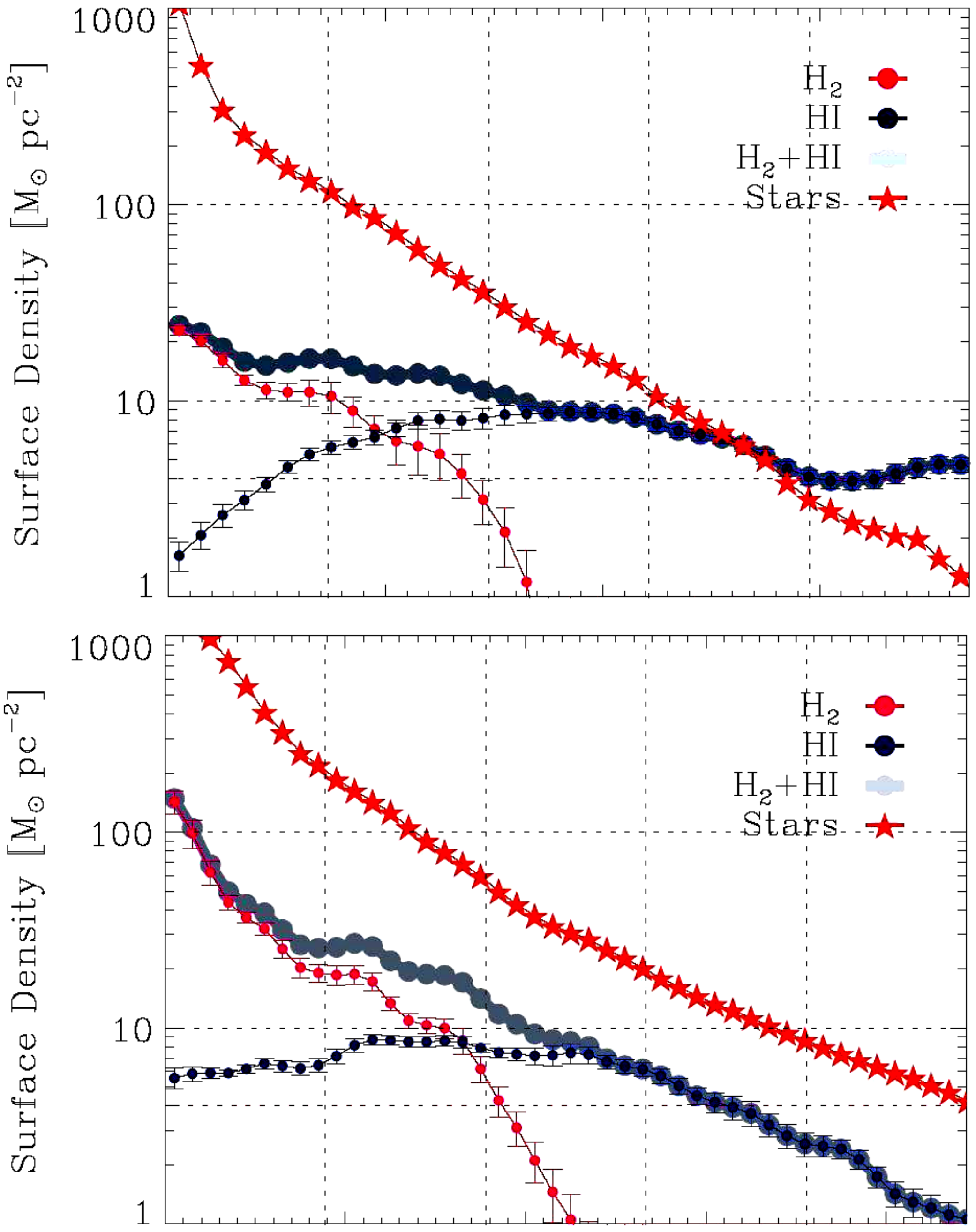
• HI (THINGS)
  34 galaxies, 6″ resolution

• CO (BIMA SONG)
  44 galaxies, 44″ resolution

distribution of molecular gas:

inferred H_2 leads to nearly exponential decline

fills the HI gaps in the centres



Atomic gas

neutral hydrogen

formation: in the first 3 minutes ... (BBNS)

21 cm line radiation of neutral hydrogen at frequency

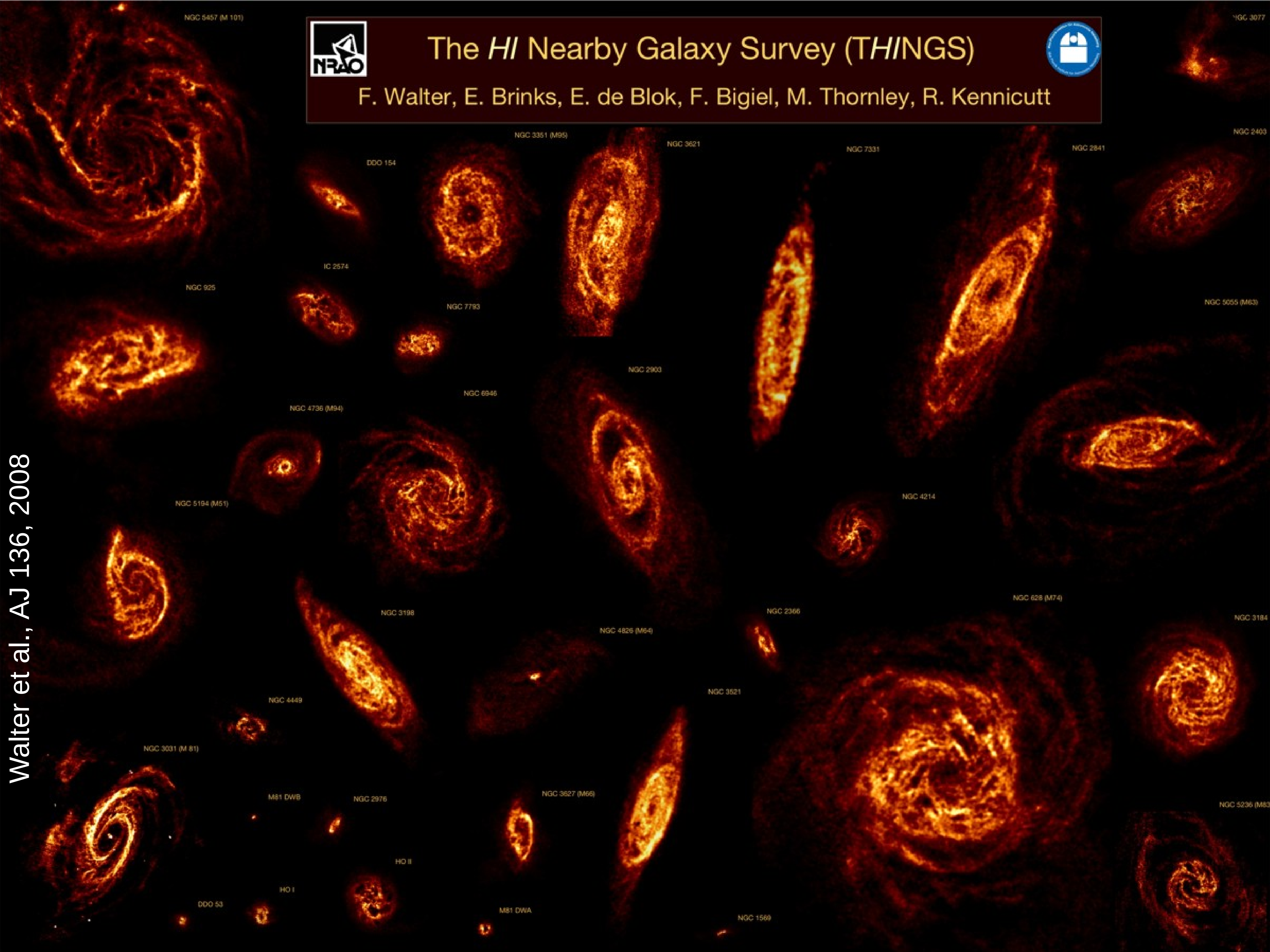
ν_{10} = 1.42040575178(6) GHz

hyperfine transition, interaction of electron and nuclear spin magnetic dipole radiation with

$A_{10} = 2.86888 \cdot 10^{-15}\ s^{-1}$

column densities easily derived via

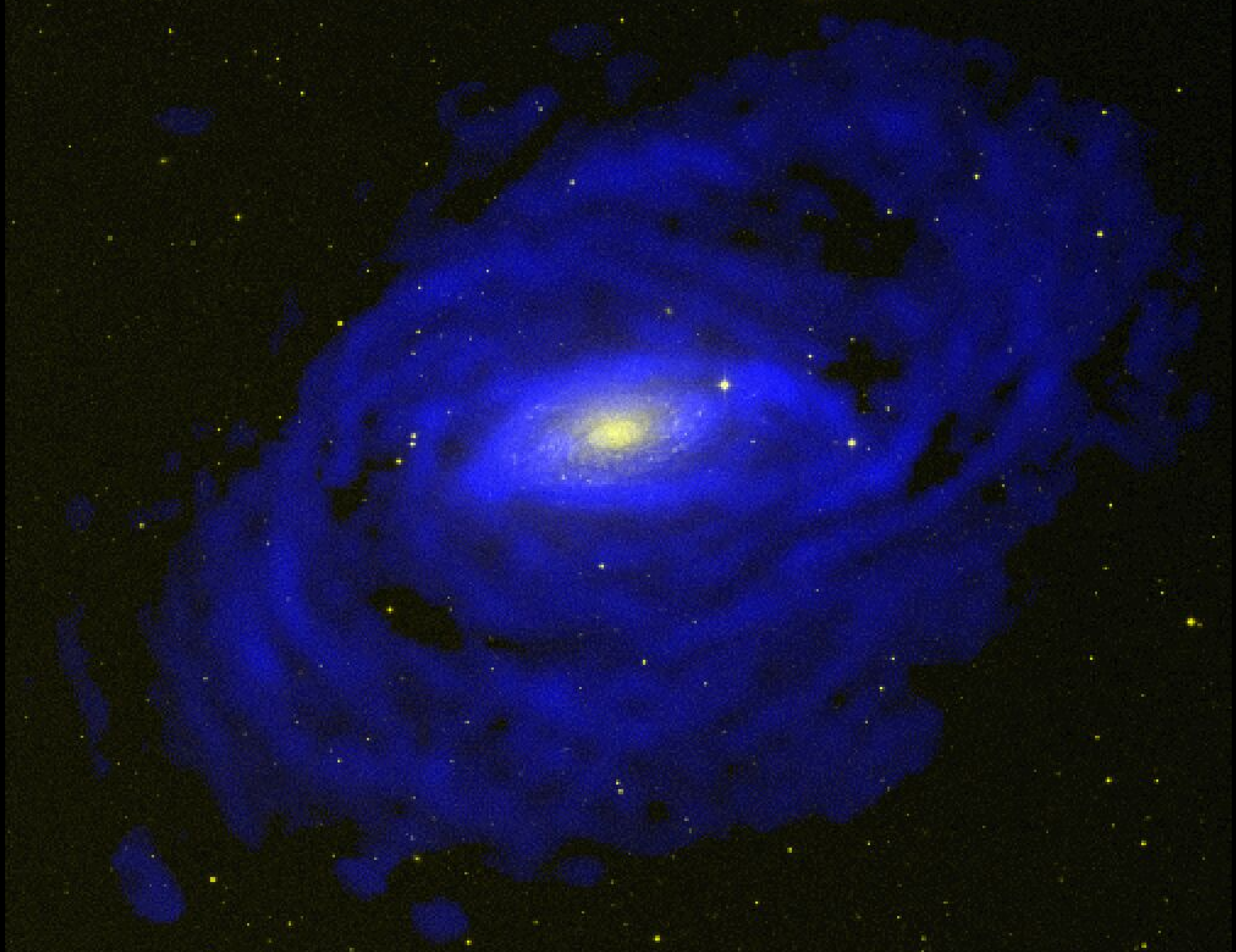
$$N_{HI}(\xi,\eta) = 1.822 \cdot 10^{18} \int_{V_1}^{V_2} \left[\frac{T_b(\xi,\eta)}{K} \right] \left(\frac{dV}{km\ s^{-1}} \right) \ atoms\ \ cm^{-2}$$



Walter et al., AJ 136, 2008

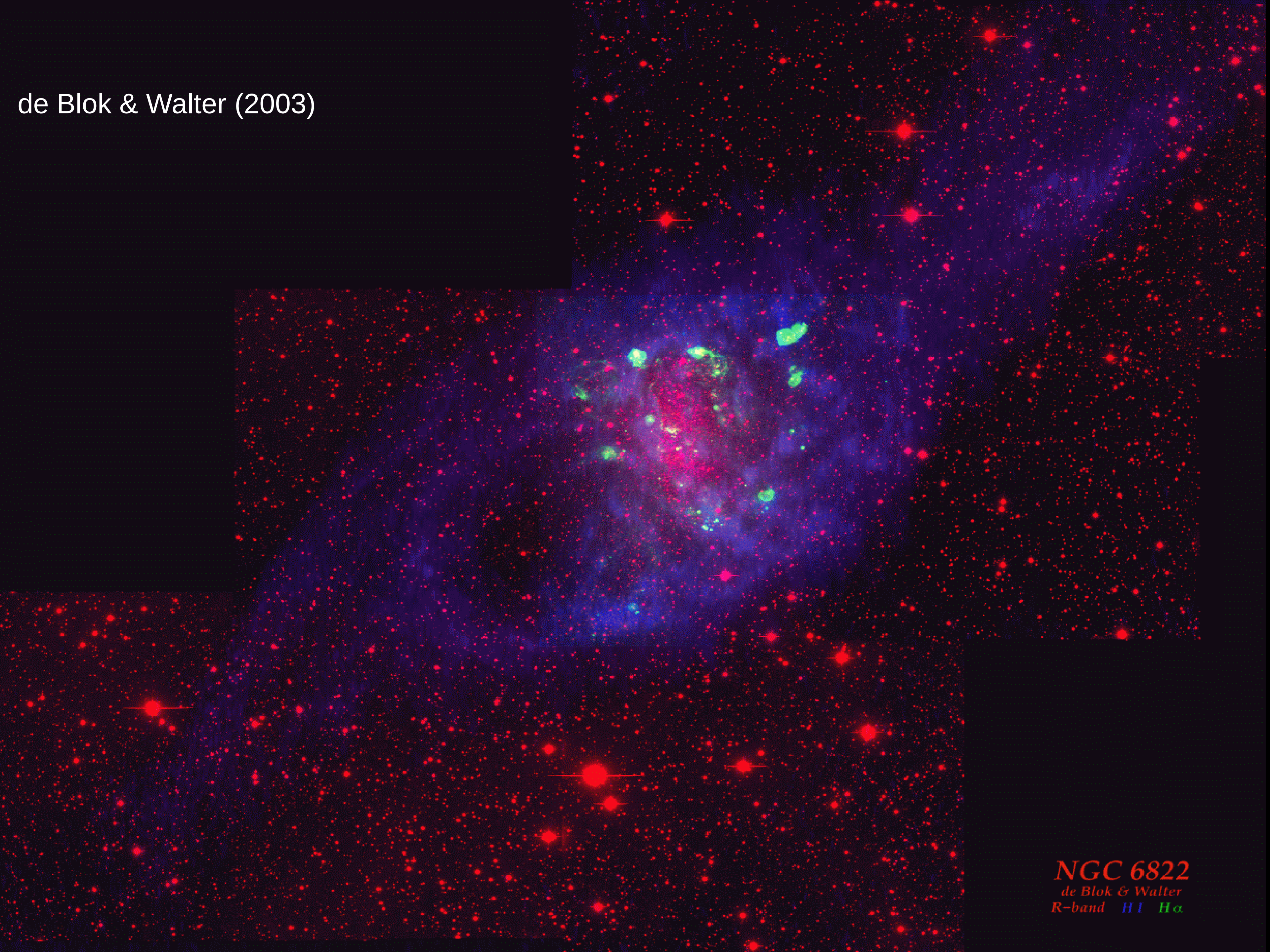
in general: HI disks much larger than stellar ones!

e.g. NGC 5055



Battaglia et al. (2005)

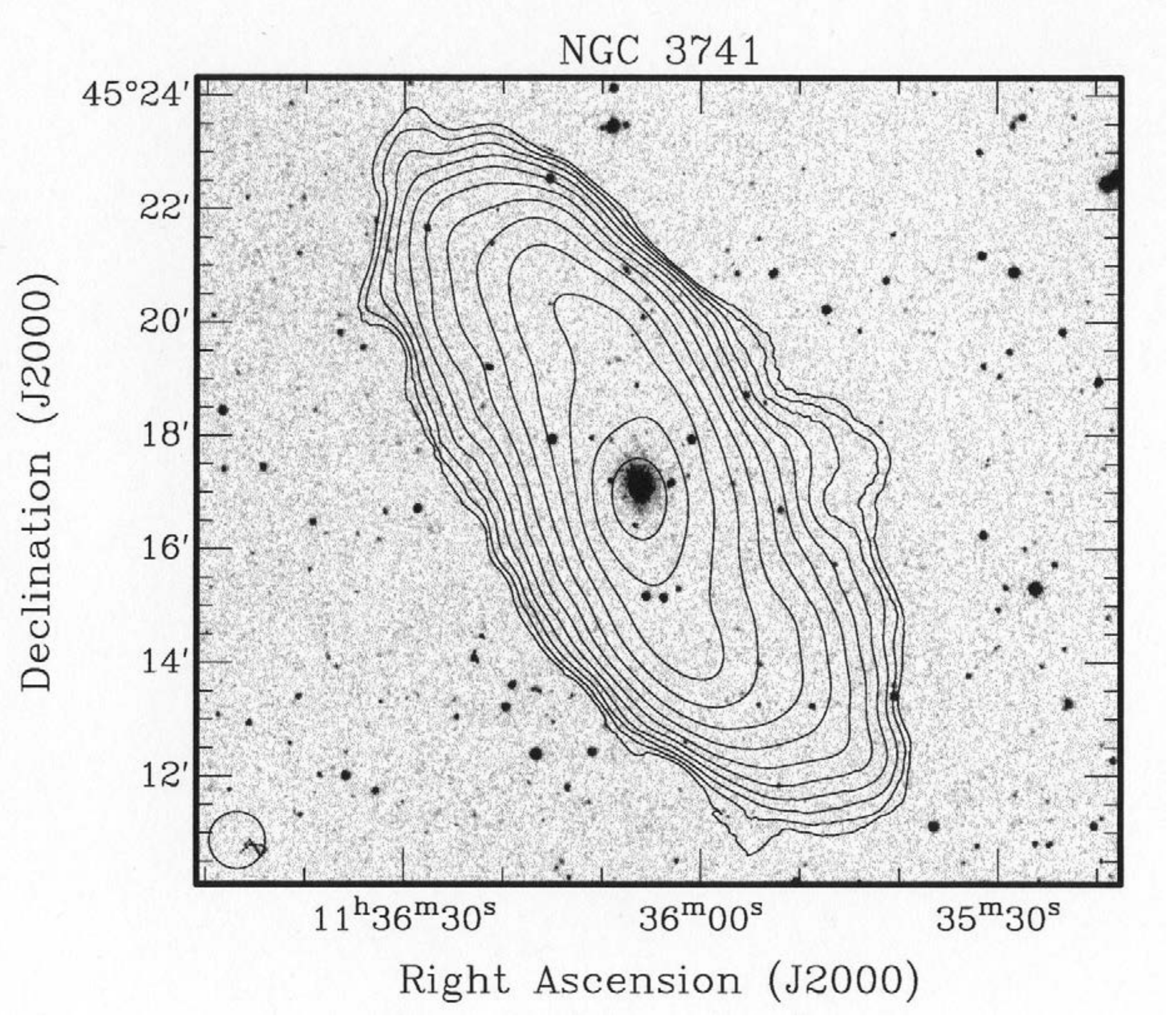
de Blok & Walter (2003)



… and another one: NGC 3741 (Gentile et al. 2007):

WSRT observations; 15“ × 12“ beam ⇒ 220 pc × 170 pc

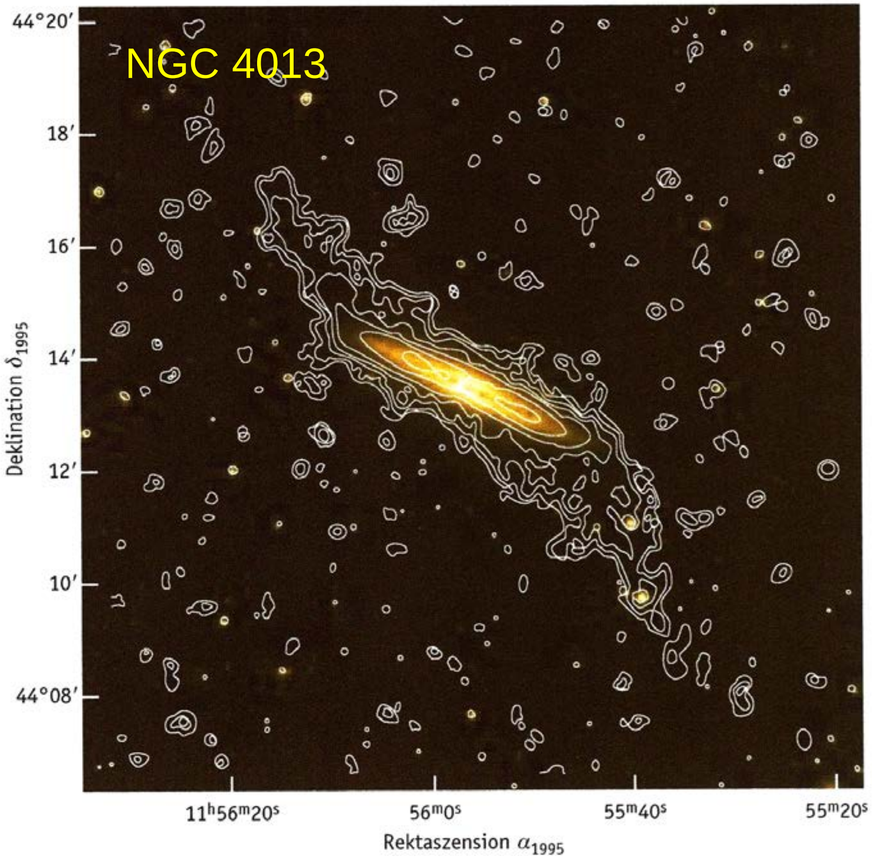
- largest HI disk so far
- out to ~15 × $\boldsymbol{R_{25}}$,
  = 42 B-band scale-lengths!



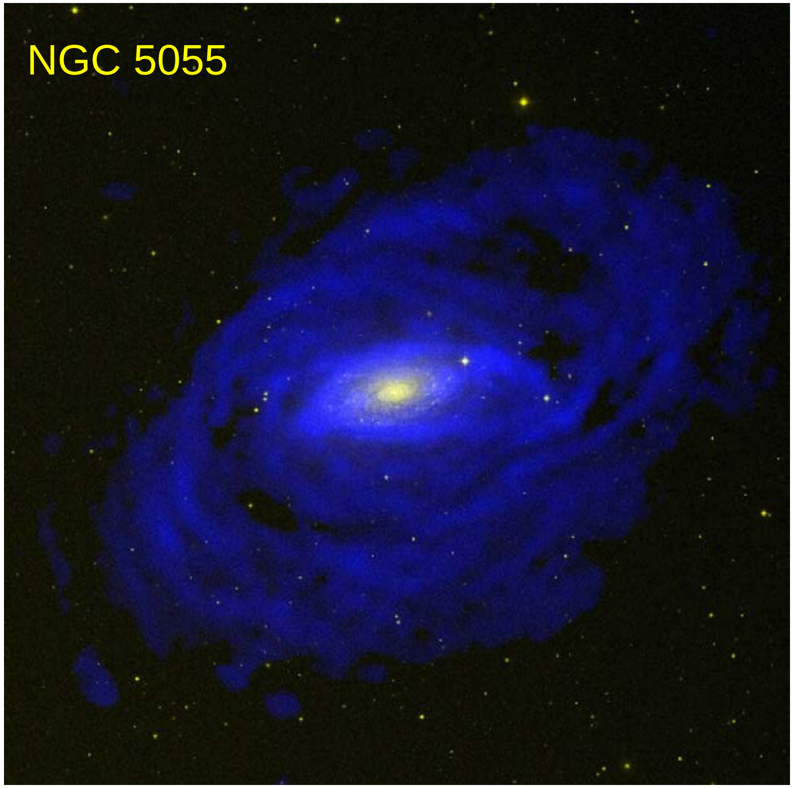
warps:

- most pronounced in HI line
- first seen in edge-on systems (Sancisi 1976; 1983)

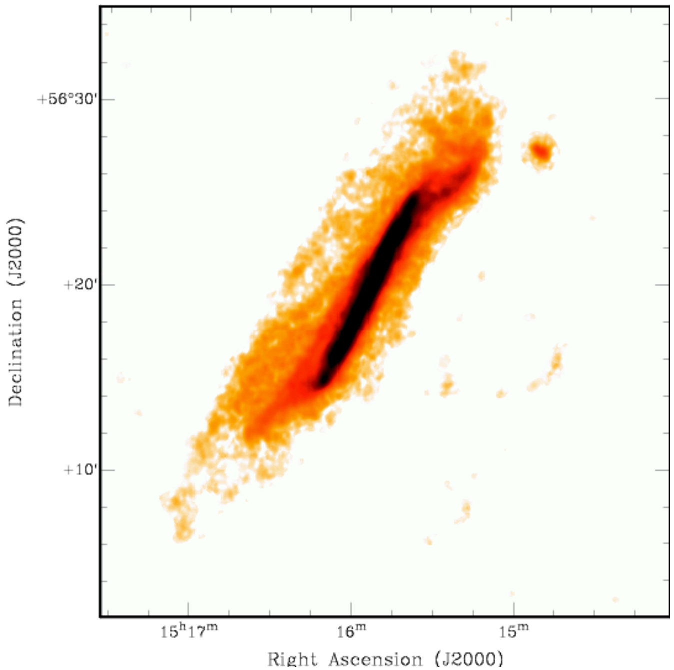
cause: external or internal torques

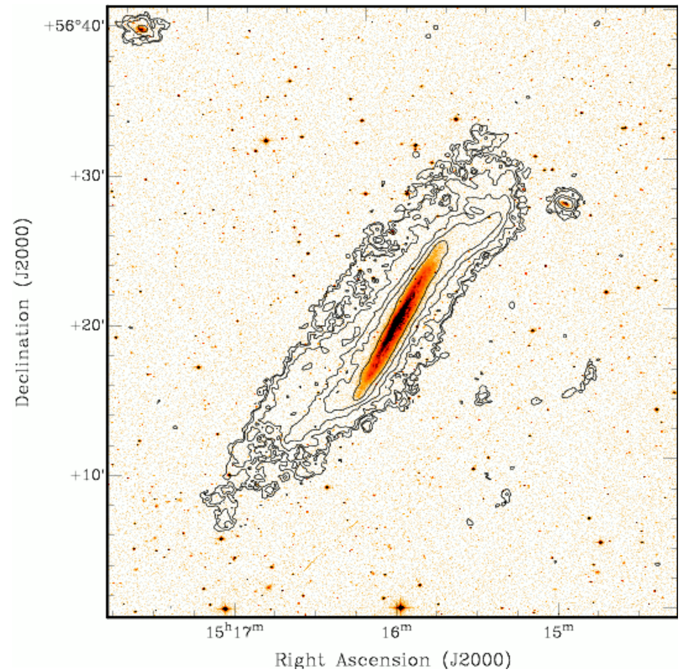


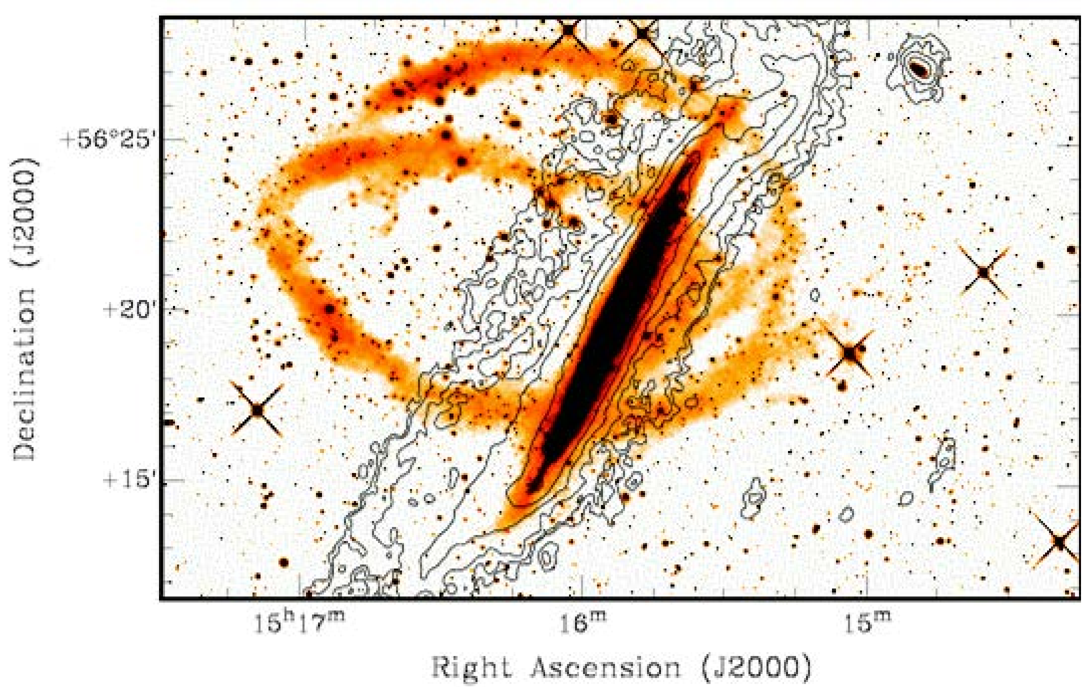
Bottema et al. (1996)



Battaglia et al. (2006)



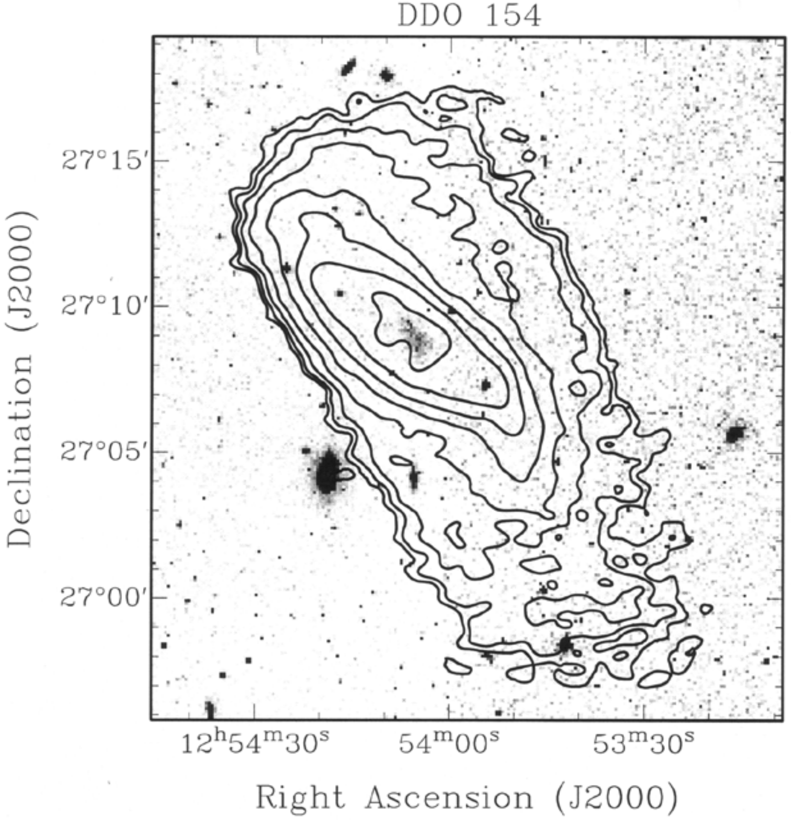


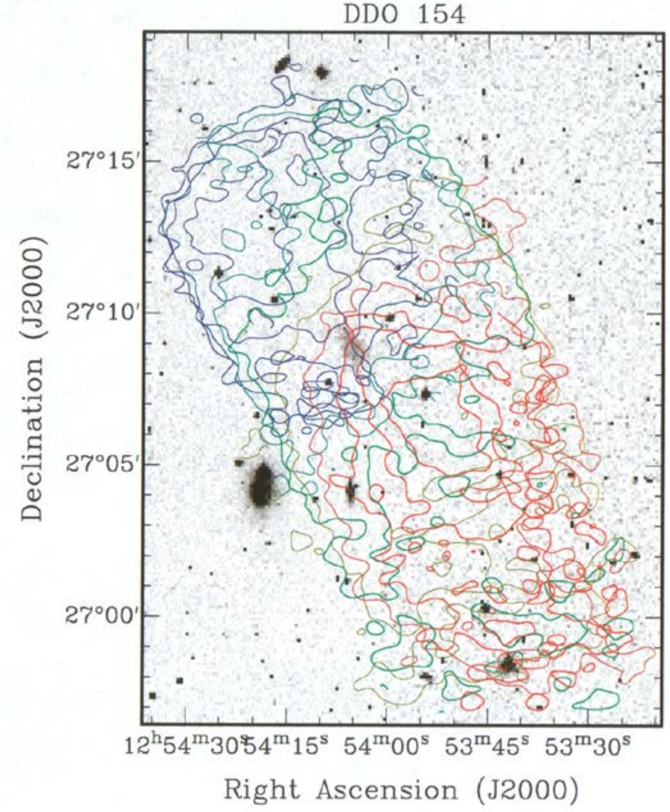


NGC 5907

Józsa et al., in prep.

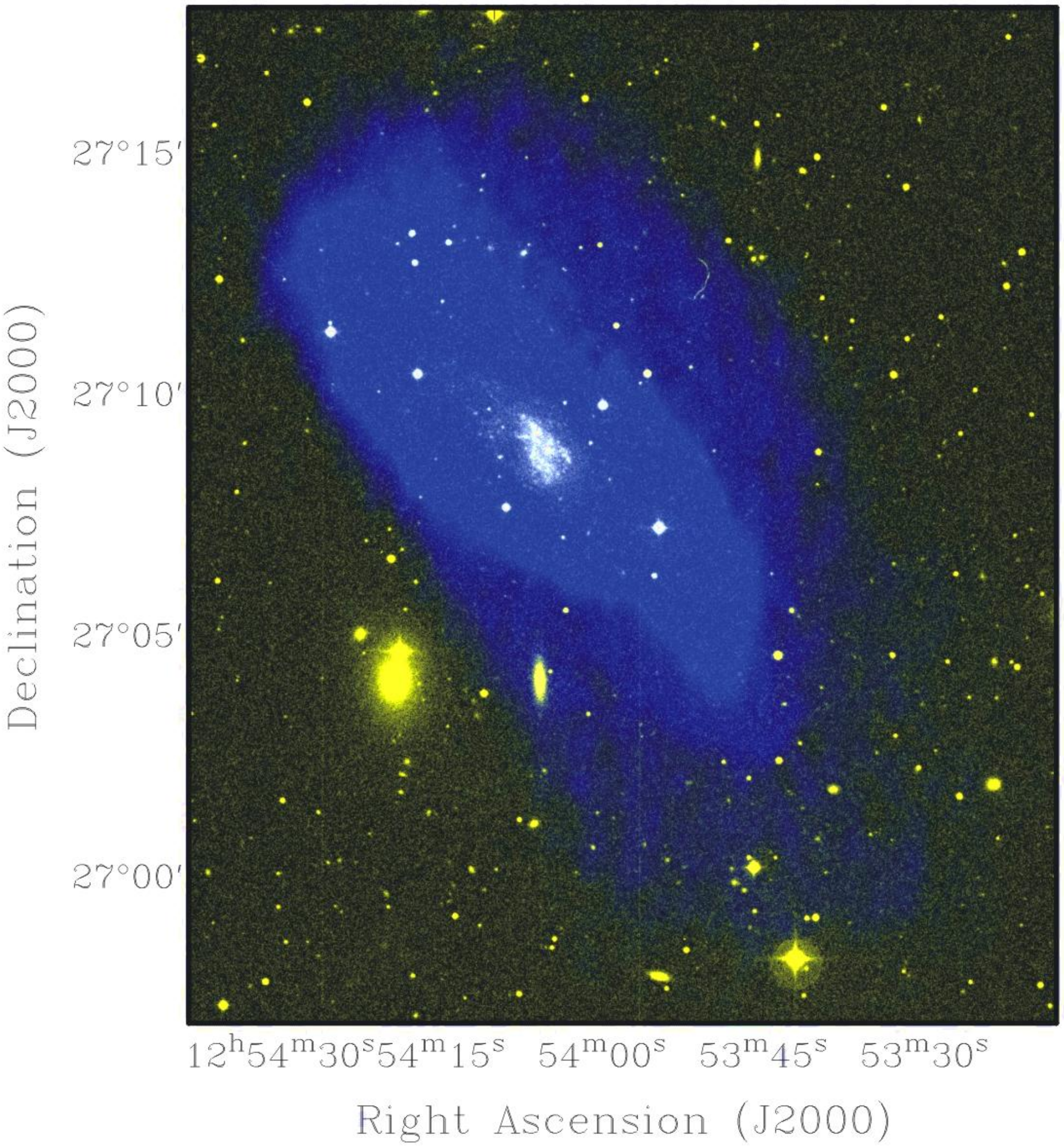
DDO 154: HI out to ~15 × R_{25} (B band)





Gentile et al. (in prep.)

DDO 154: the 3-D gaseous structure (?)



Józsa et al. (in prep.)

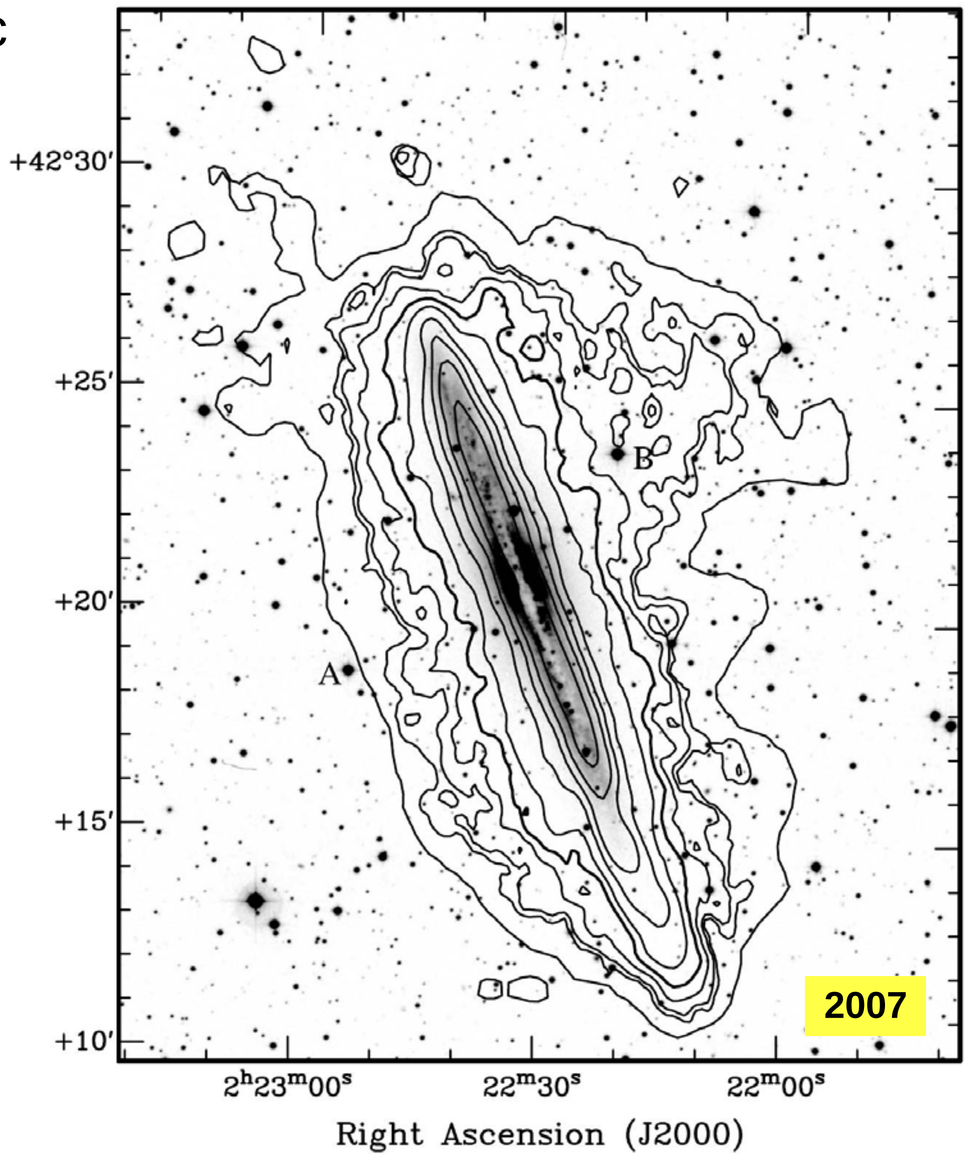
cold halo gas: e.g. NGC 891, a matter of sensitivity …

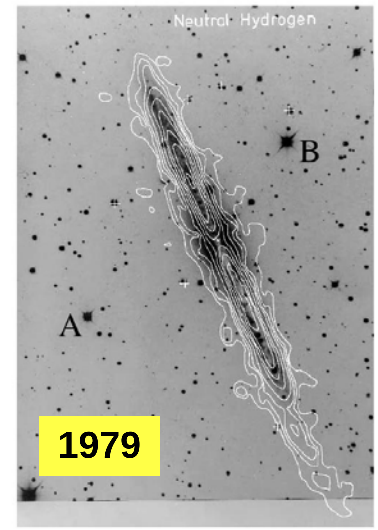
Oosterloo et al. (2007)

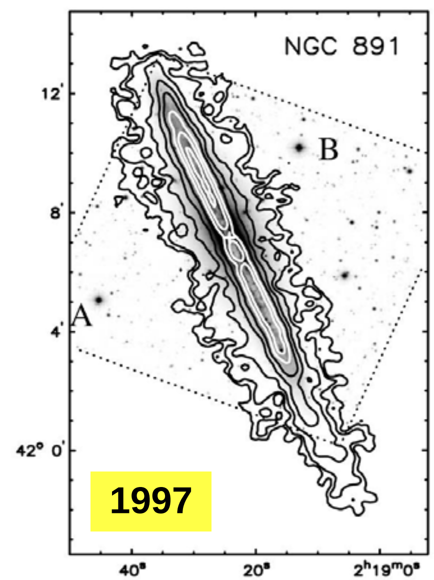
HI out to z = 22 kpc

$M_{HI} = 1.2 \cdot 10^9$ $M_\odot$

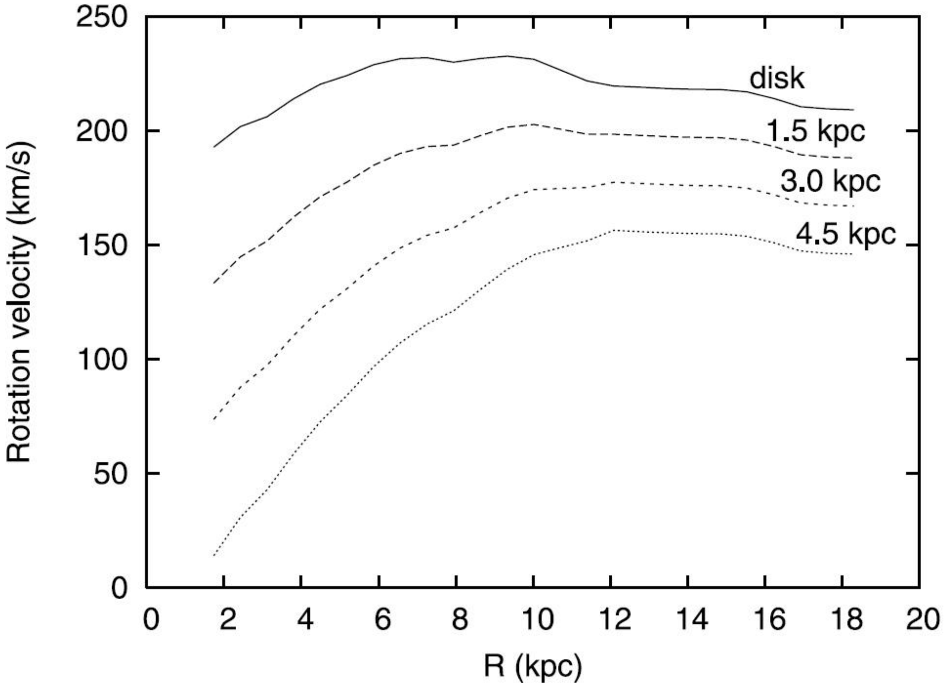
≈ 30% of total HI!



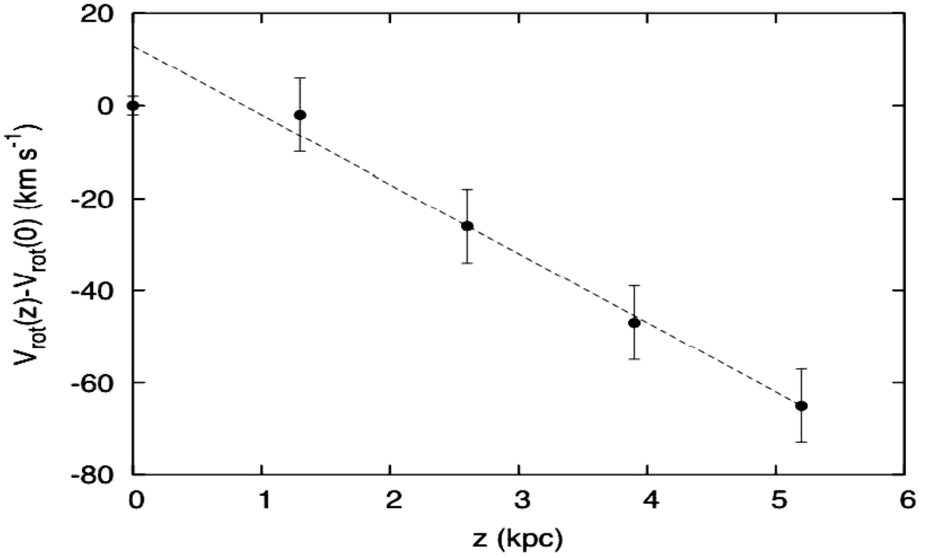




rotation of halo gas:



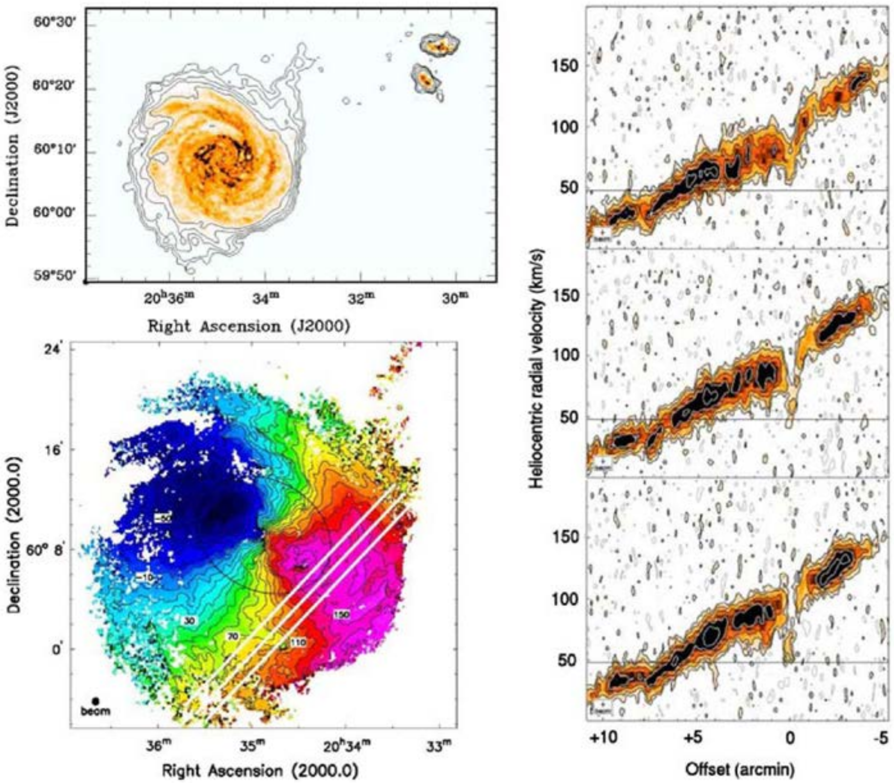
dV_z/dz = 15 km s^{-1} kpc^{-1}



further support for accretion scenario: HI with anomalous velocities

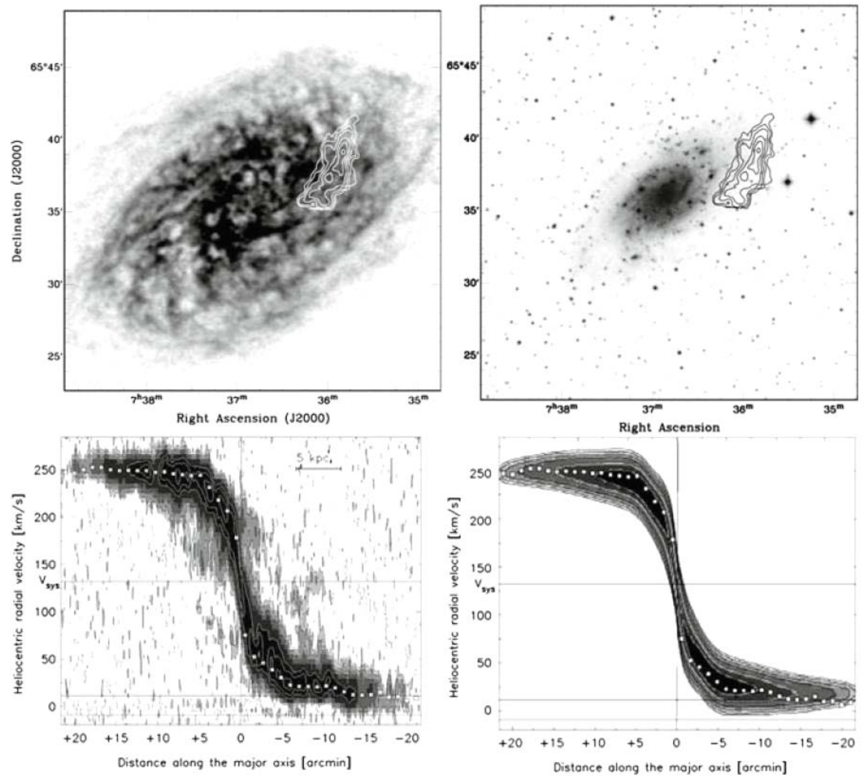
NGC 6946

Boomsma (2007)



NGC 2403

Fraternali et al. (2002)



holes and shells in the ISM

Bagetakos et al. (2010):

• found > 1000 holes (*THINGS*)

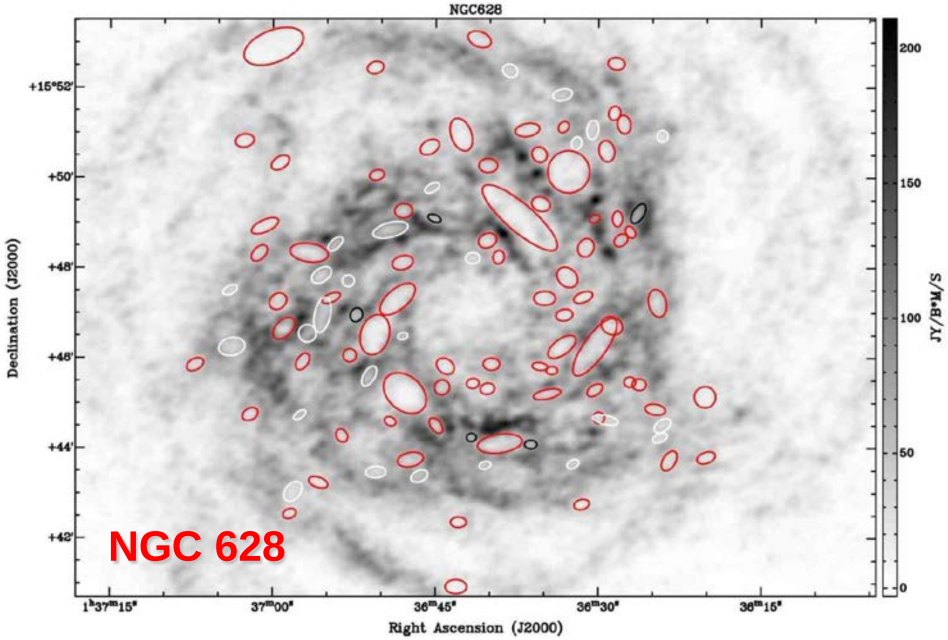
$\varnothing$ = 100 … 1000 pc
v_{exp} = 4 … 34 km s^{-1}
τ_{kin} = 3 … 150 Myr

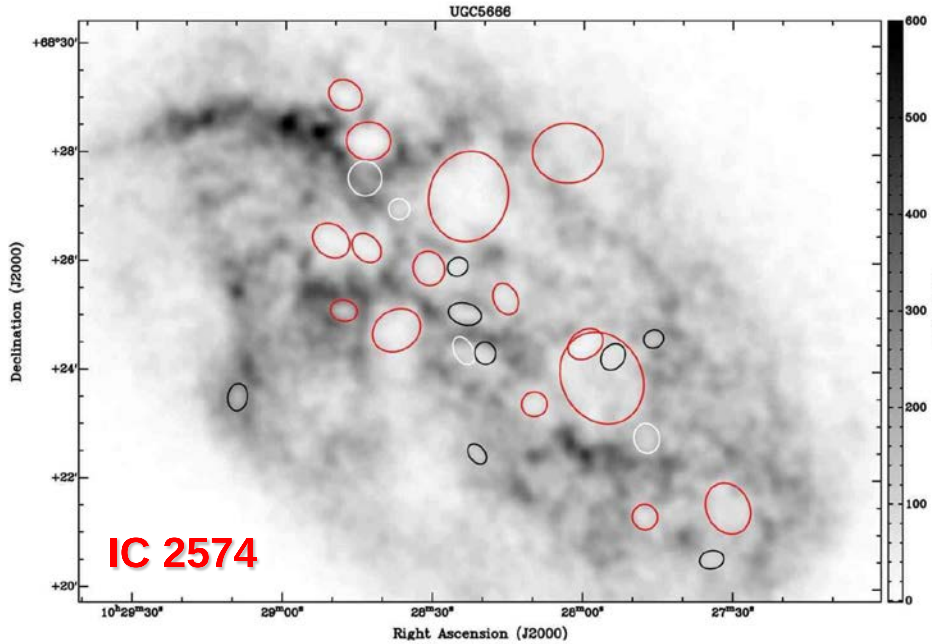
• larger and round holes in dwarfs

origin:

- star formation

- turbulence (Dib & Burkert 2005)





influence of environment:

VLA Imaging of Virgo galaxies in Atomic gas

extended H I tails, almost all pointing away from the cluster center

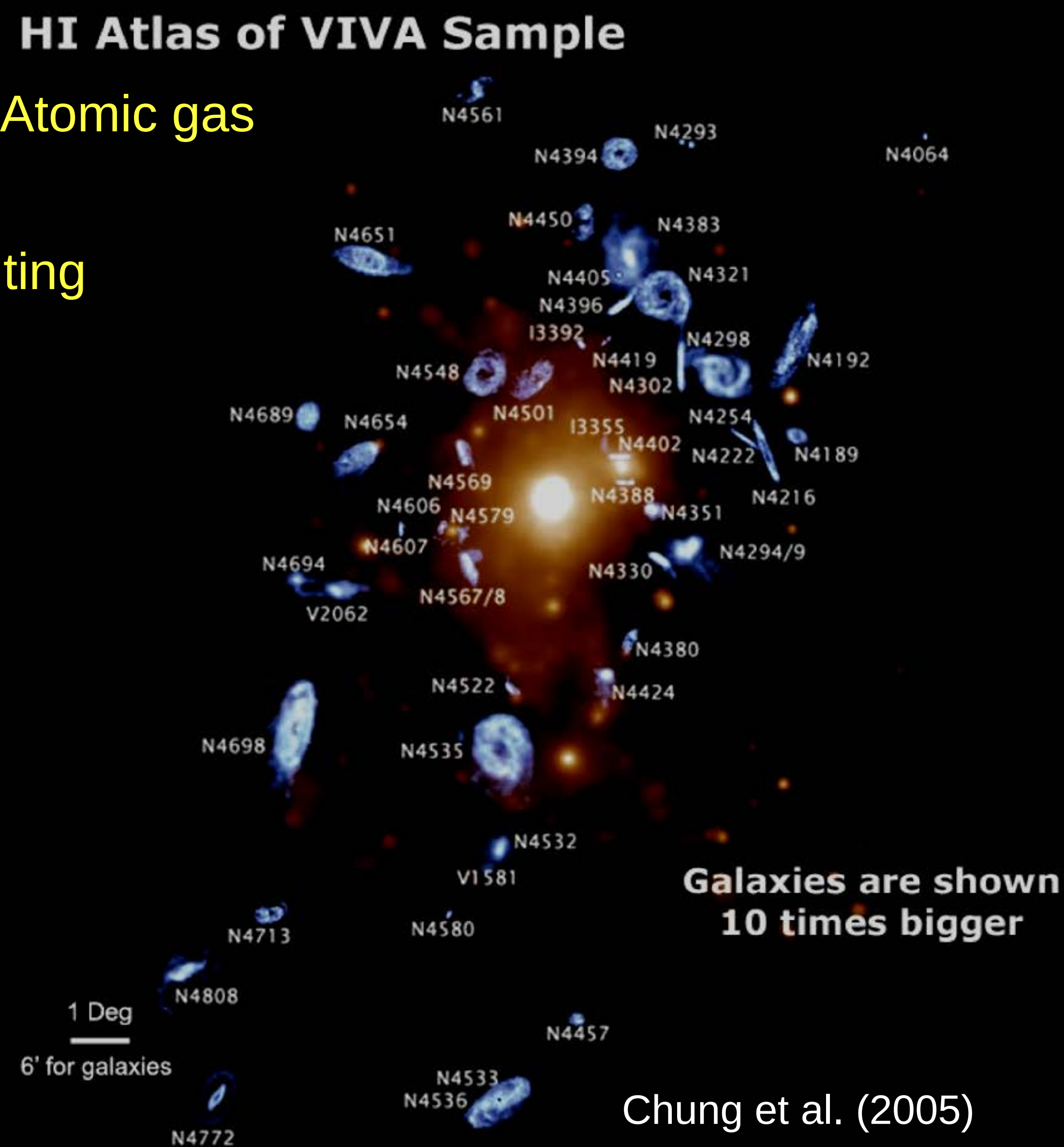
truncated H I disks

near cluster center compression gas on one side

some of the HI extra-planar

variety of environmental effects:

- ICM-ISM interactions
- harassment
- tidal interactions
- mergers



Chung et al. (2005)

molecular gas:

most abundant: H_2 molecule

determination of N_{H2} much more difficult than N_{HI}

lacks dipole moment

$\rightarrow$ quadrupole transitions with $\Delta J = 2$ ($J = 2 \rightarrow 0$)

requires high gas temperatures ($\Delta E / k = 509$ K)

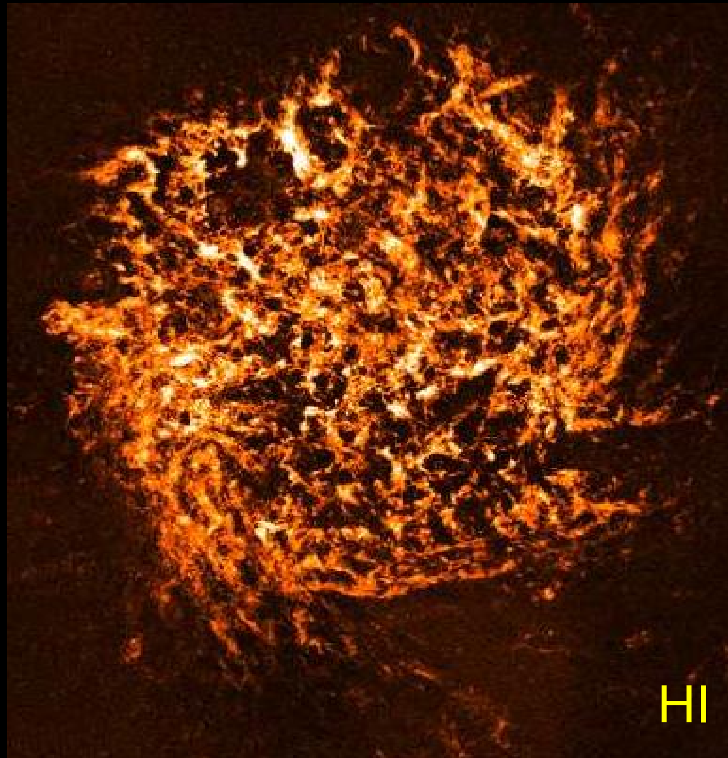
$\rightarrow$ not representative for general ISM (only hot molecular gas)

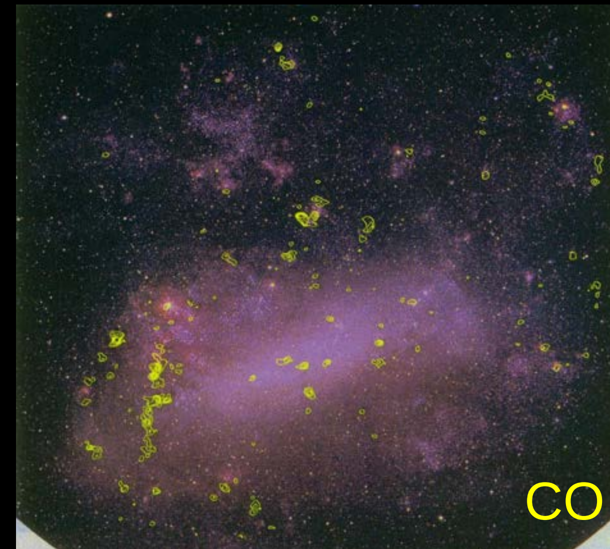
CO molecule:

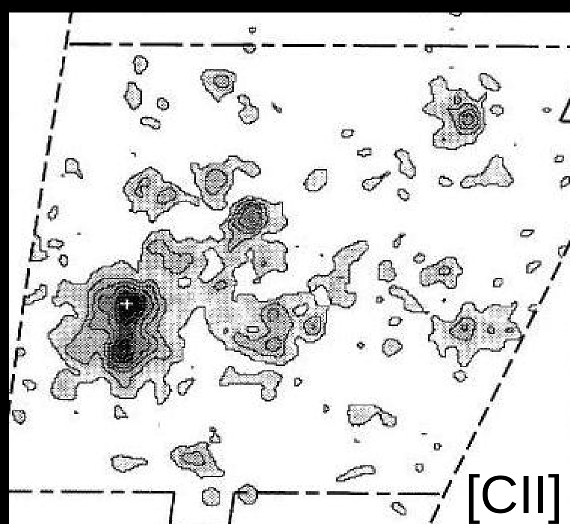
second-most abundant molecule

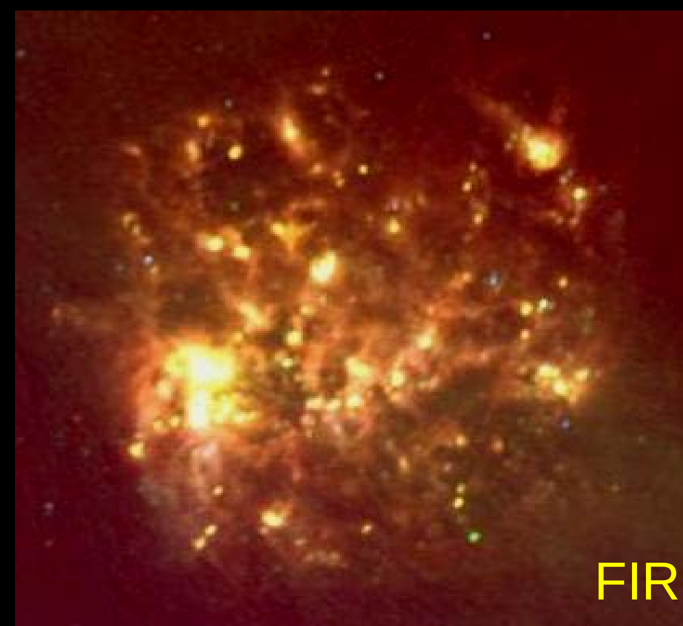
frequent collisions with H_2 $\rightarrow$ information about H_2 (column) density

quite stable: $E_{diss} = 11.09$ eV $\Rightarrow \lambda_{diss} \leq 1118$ Å e.g. LMC:







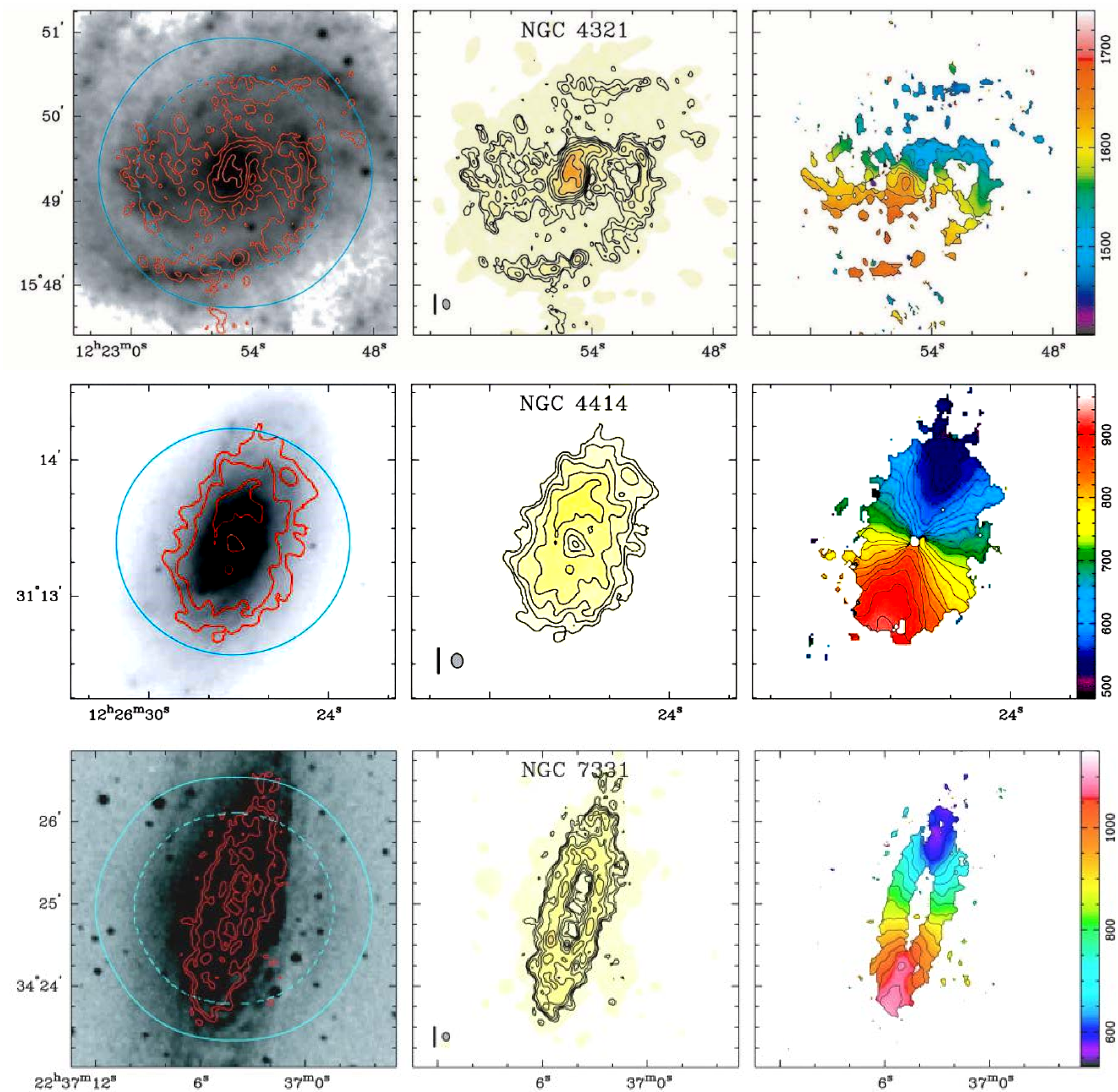


no CO for log(O/H) + 12 $\leq$ 7.9 (Taylor et al. 1998)

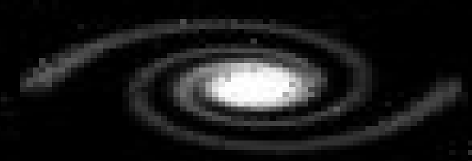
BIMA Survey of Nearby Galaxies (BIMA SONG)

Regan et al. (2001)

Helfer et al. (2003)



and finally the dark-matter halo:

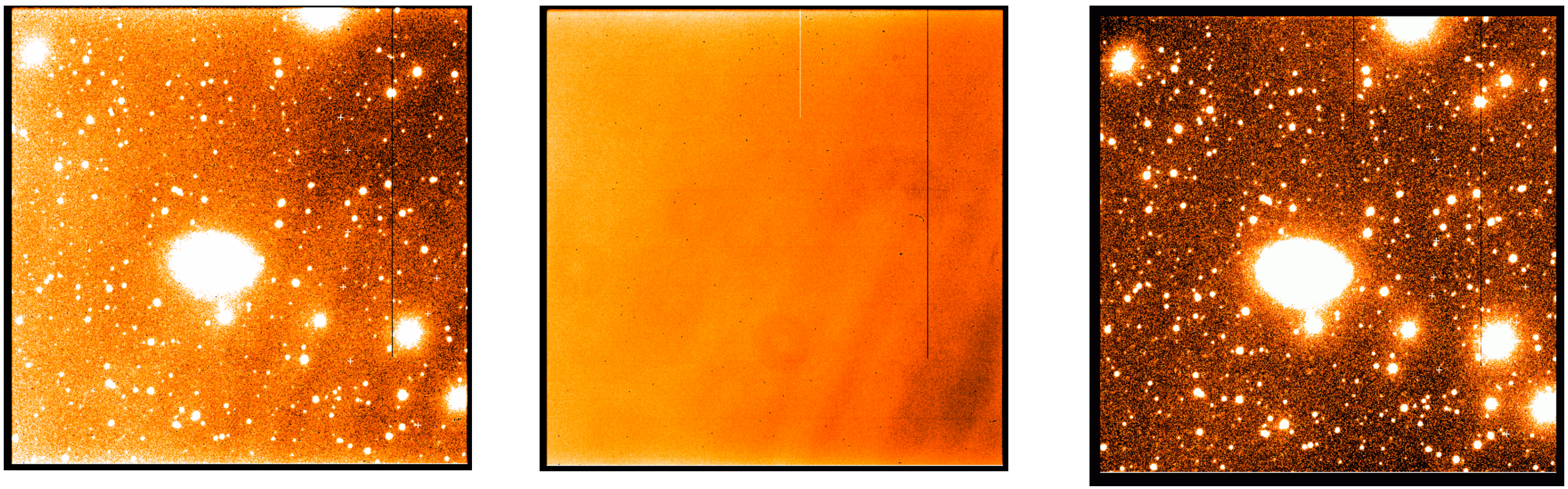


inferred from rotation curves (see kinematics)

Photometry

optical photometry $\Rightarrow$ mass distribution of stellar component (bulge, disk)

calibration is tricky, e.g. “flat-fielding”



raw image : flat-field image = flat-fielded image

then subtract stars and fit elliptical isophotes to galaxy image, with position angle χ and inclination *i* such as to obtain (projected) intensity distribution $I(R)$.

(from A. Pizzella’s home page)

evaluation: e.g. profile fitting

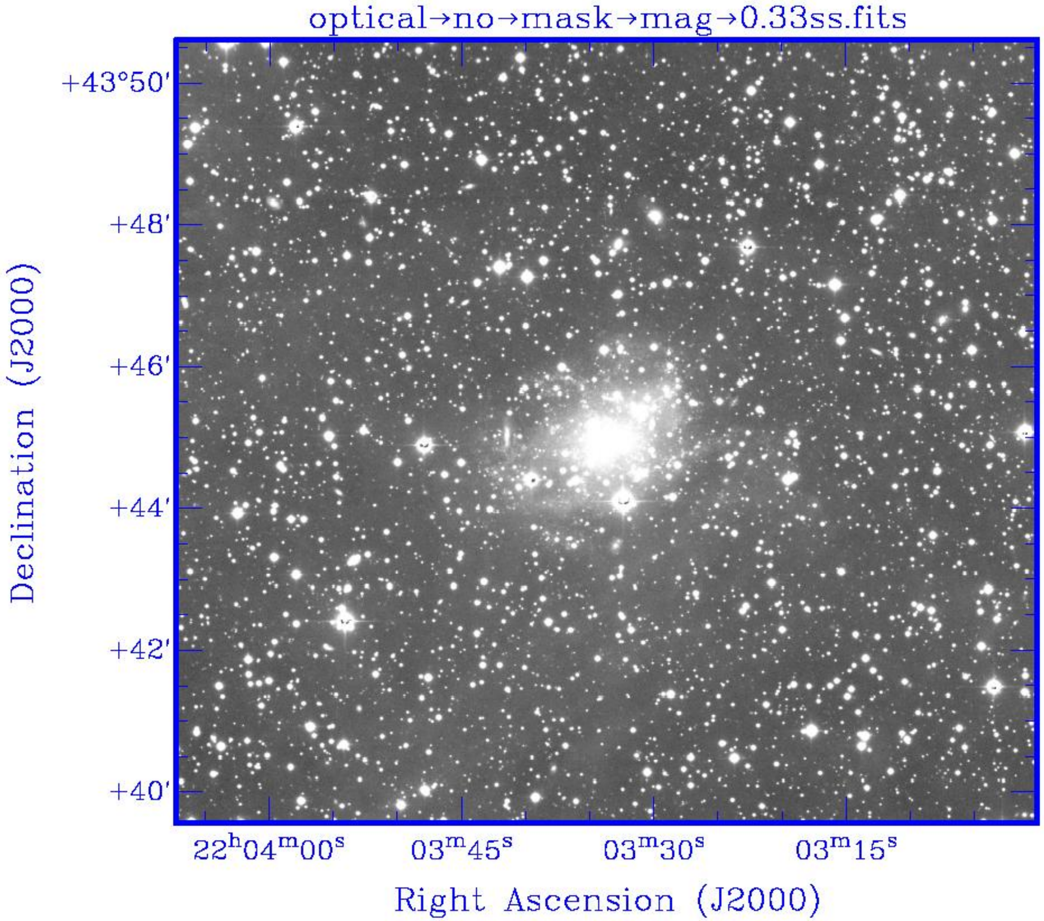
- one-dimensional: average brightness in elliptical rings and fit analytical function to it

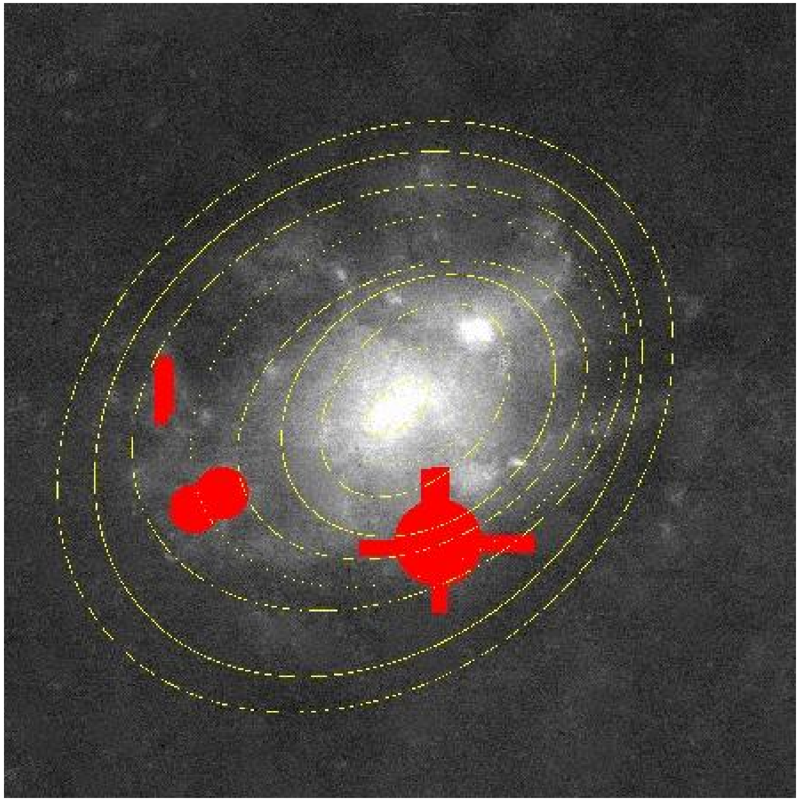
- two-dimensional fit to the photometry

most widely used tool: GALFIT (Peng et al. 2002; 2007; 2010)

provides large set of radial fitting functions

accounts for PSF by convolving galaxy model functions with it a weird thing: star subtraction!





… a real challenge: e.g. UGC 11891 (a ‘smudge’ close to the Galactic plane)

Sersic

$$I(R) = I_e \cdot e^{-b_n\left[(R/R_e)^{1/n} - 1\right]}$$

exponential

$$I(R) = I_0 \cdot e^{-R/R_d}$$

Nuker

$$I(R) = I_b \cdot 2^{(\beta-\gamma)/\alpha} \left(\frac{R}{R_b}\right)^{-\gamma} \left[1 + \left(\frac{R}{R_b}\right)^{\alpha}\right]^{(\gamma-\beta)/\alpha}$$

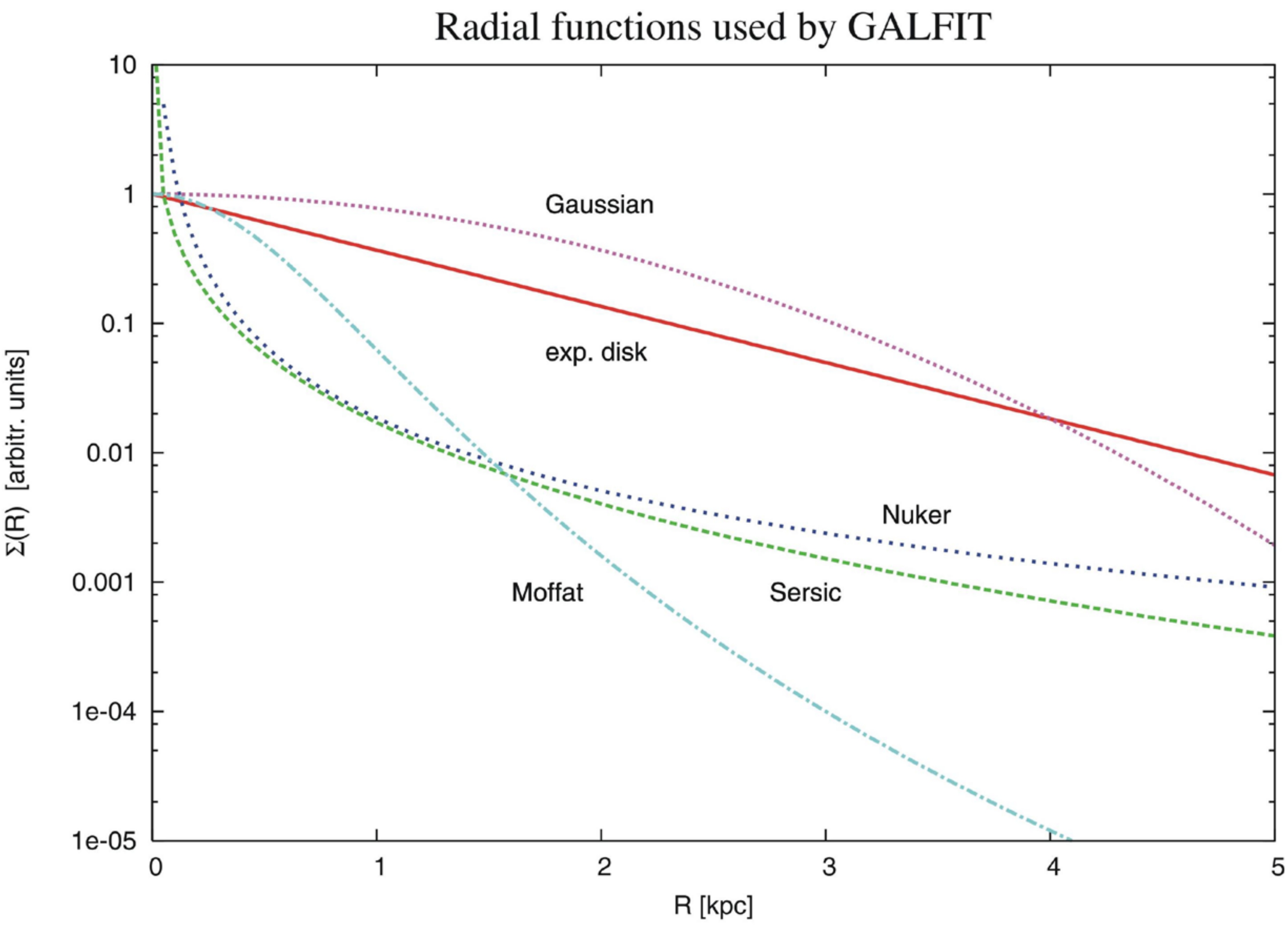
Gaussian

$$I(R) = I_0 \cdot e^{-\left(R^2/2\sigma^2\right)}$$

Moffat

$$I(R) = I_0 \cdot \left[1 + (R/R_d)^2\right]^{-n}$$

Graphical illustration of GALFIT functions



when principal axes of ellipse aligned with coordinate axes, the radial pixel coordinate given by

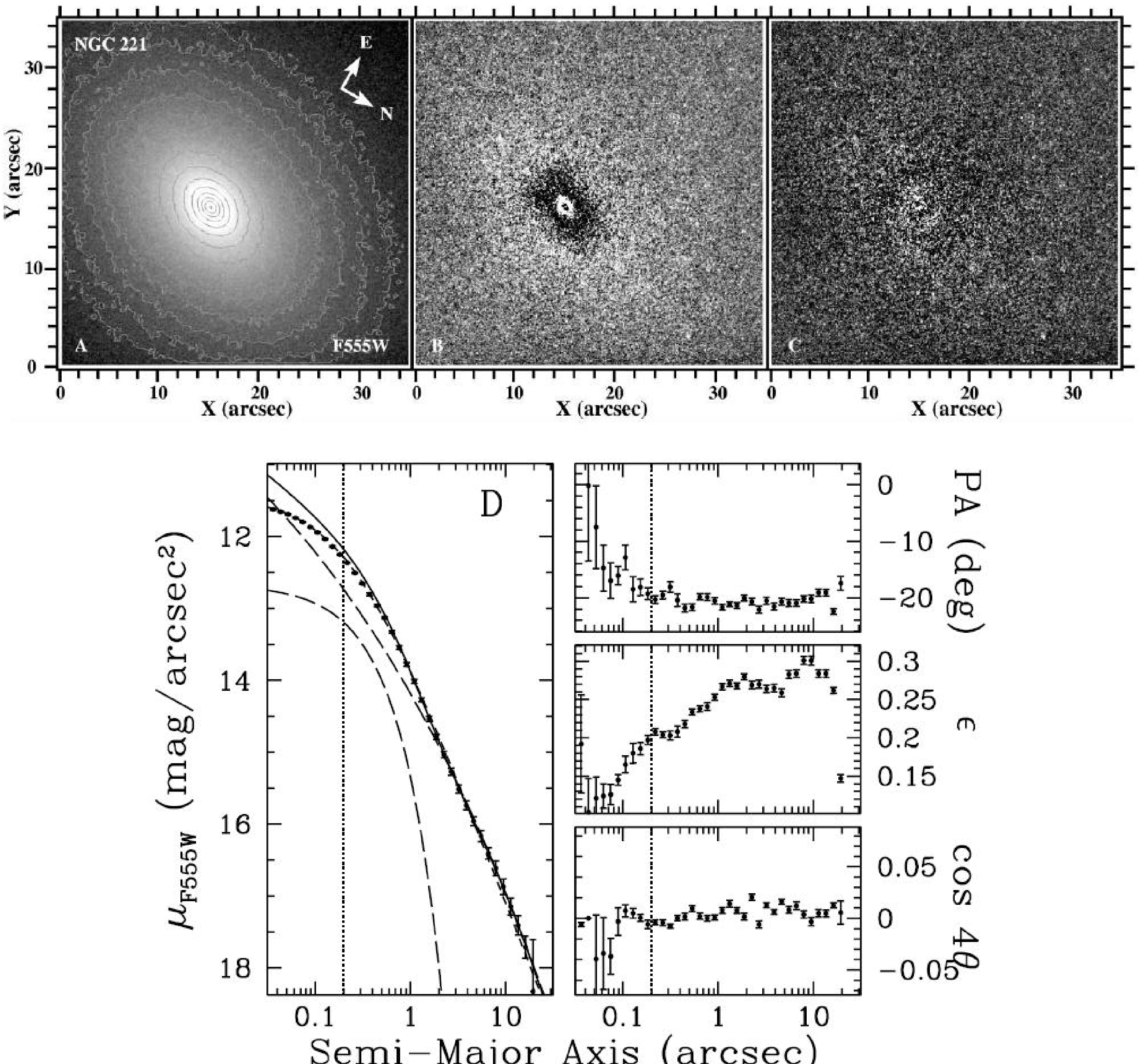
$$R = \left(|x|^{c+2} + \left|\frac{y}{q}\right|^{c+2} \right)^{\frac{1}{c+2}}$$

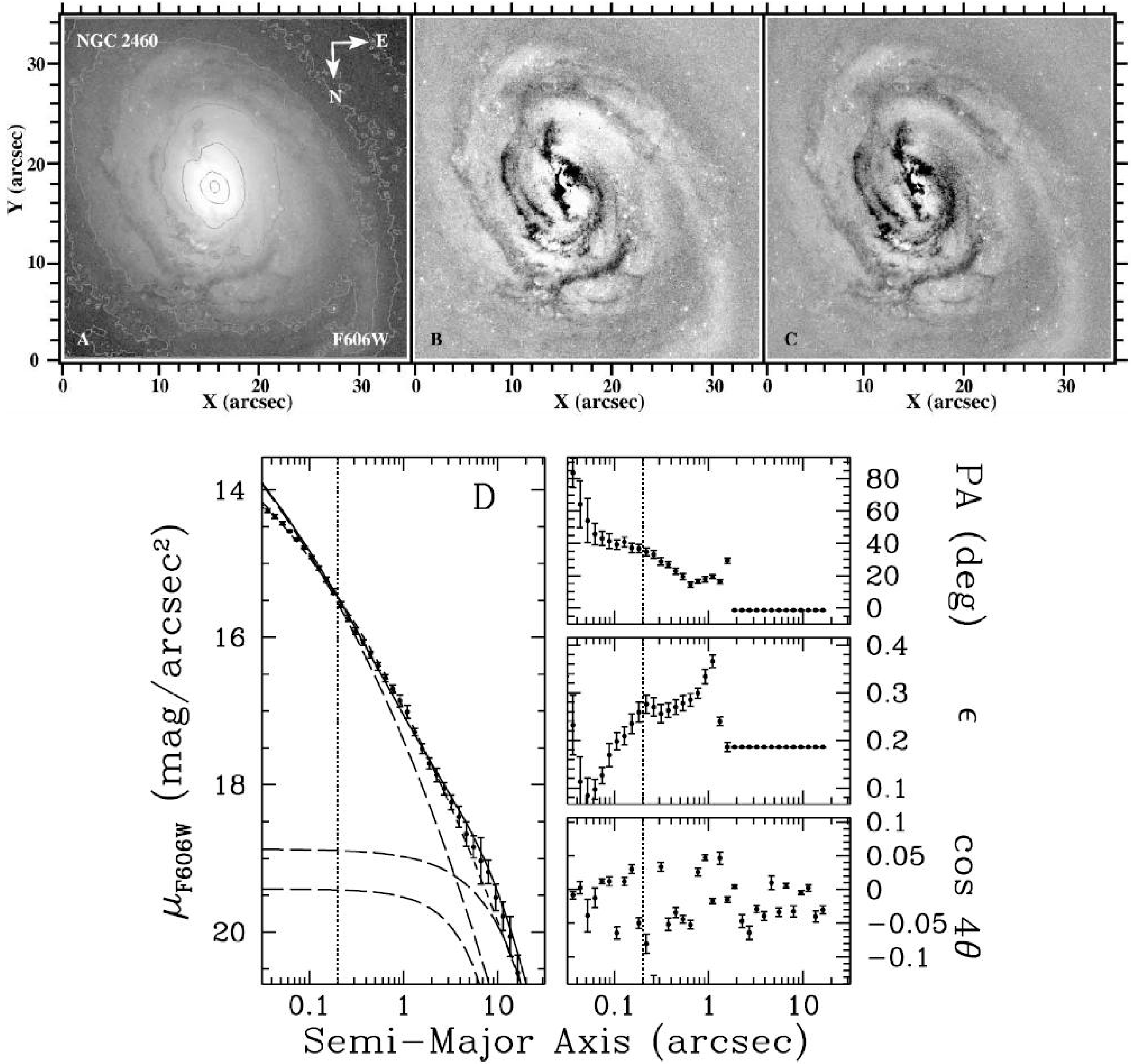
pure ellipse : $c = 0$

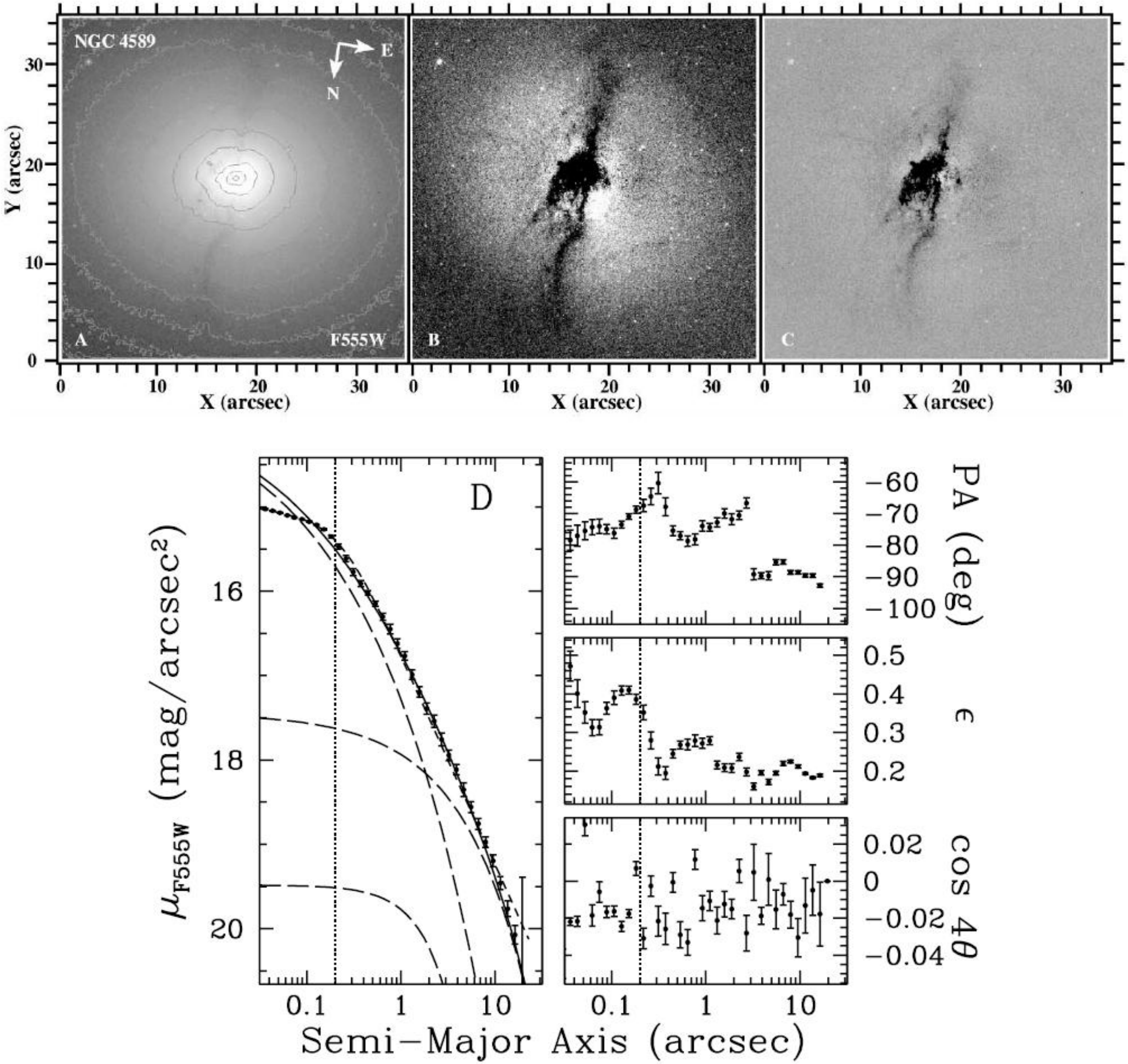
boxy : $c > 0$

disky : $c < 0$

q = minor/major axis ratio


NGC 221
E
N
A
F555W
B
C
Y (arcsec)
X (arcsec)
D
μF555W (mag/arcsec²)
PA (deg)
ε
cos 4θ
Semi−Major Axis (arcsec)


NGC 2460
E
N
A
F606W
B
C
Y (arcsec)
X (arcsec)
D
μ_{F606W} (mag/arcsec^2)
PA (deg)
ϵ
cos 4θ
Semi−Major Axis (arcsec)


NGC 4589
E
N
A
F555W
B
C
Y (arcsec)
X (arcsec)
0
10
20
30
D
μF555W (mag/arcsec²)
16
18
20
0.1
1
10
Semi−Major Axis (arcsec)
PA (deg)
−60
−70
−80
−90
−100
ϵ
0.5
0.4
0.3
0.2
cos 4θ
0.02
0
−0.02
−0.04

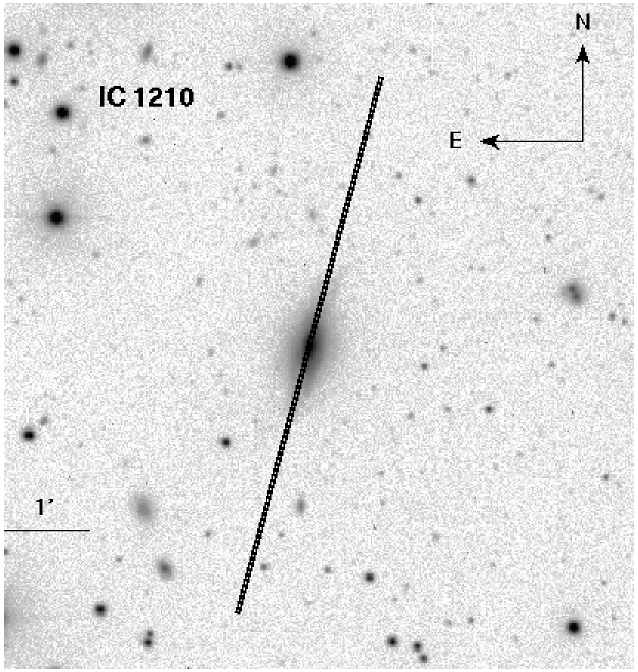
Kinematics of disk galaxies

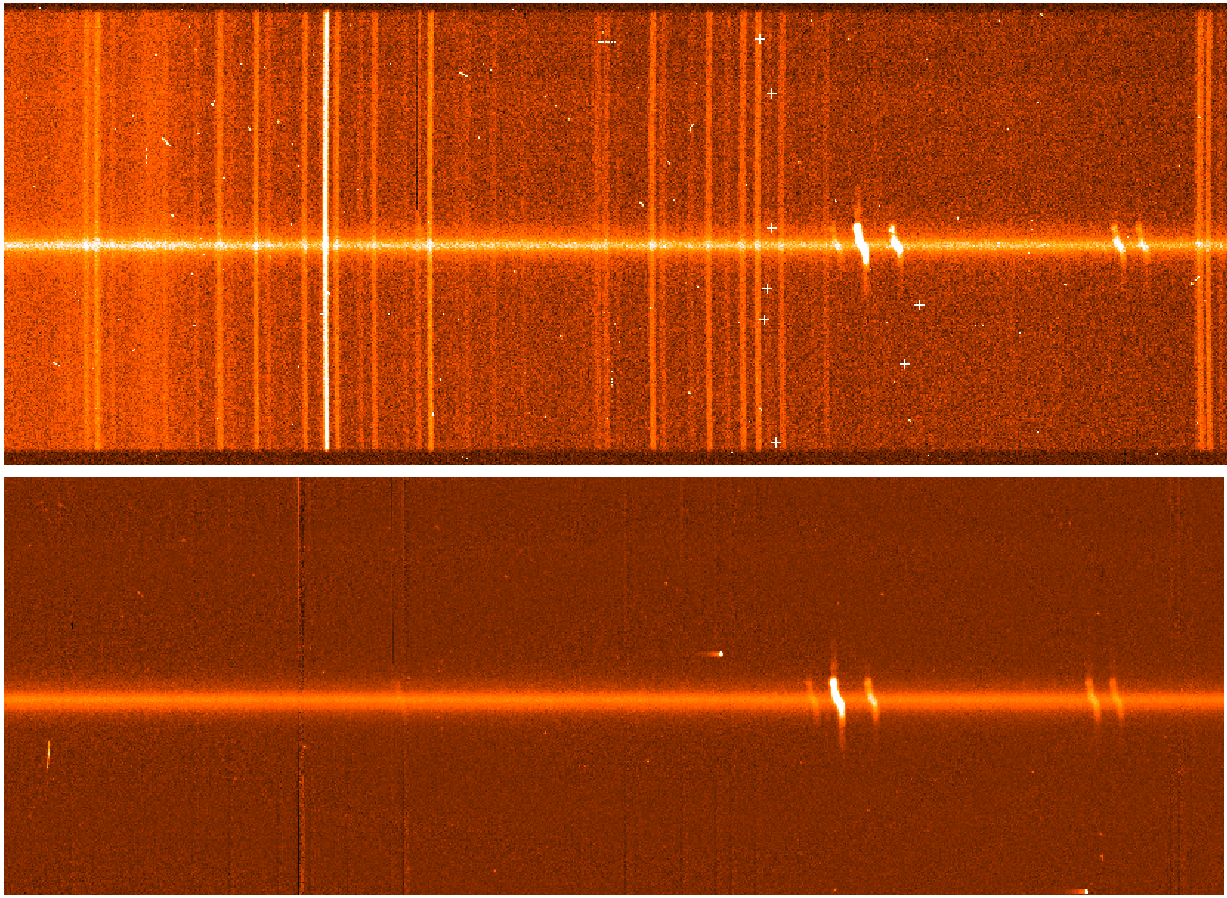
obtain V_{obs} from spectroscopy:
- optical emission lines (Hα etc.)
- neutral hydrogen (HI)
- carbon monoxide (CO)

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

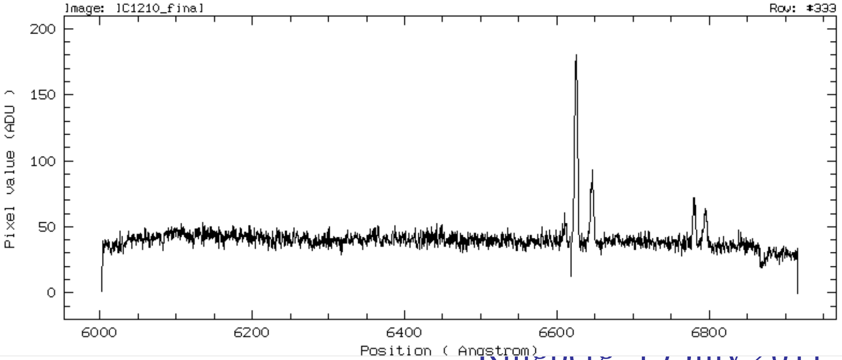
optical spectroscopy ⇒ kinematics of inner galaxy (bulge, disk)

long-slit spectroscopy



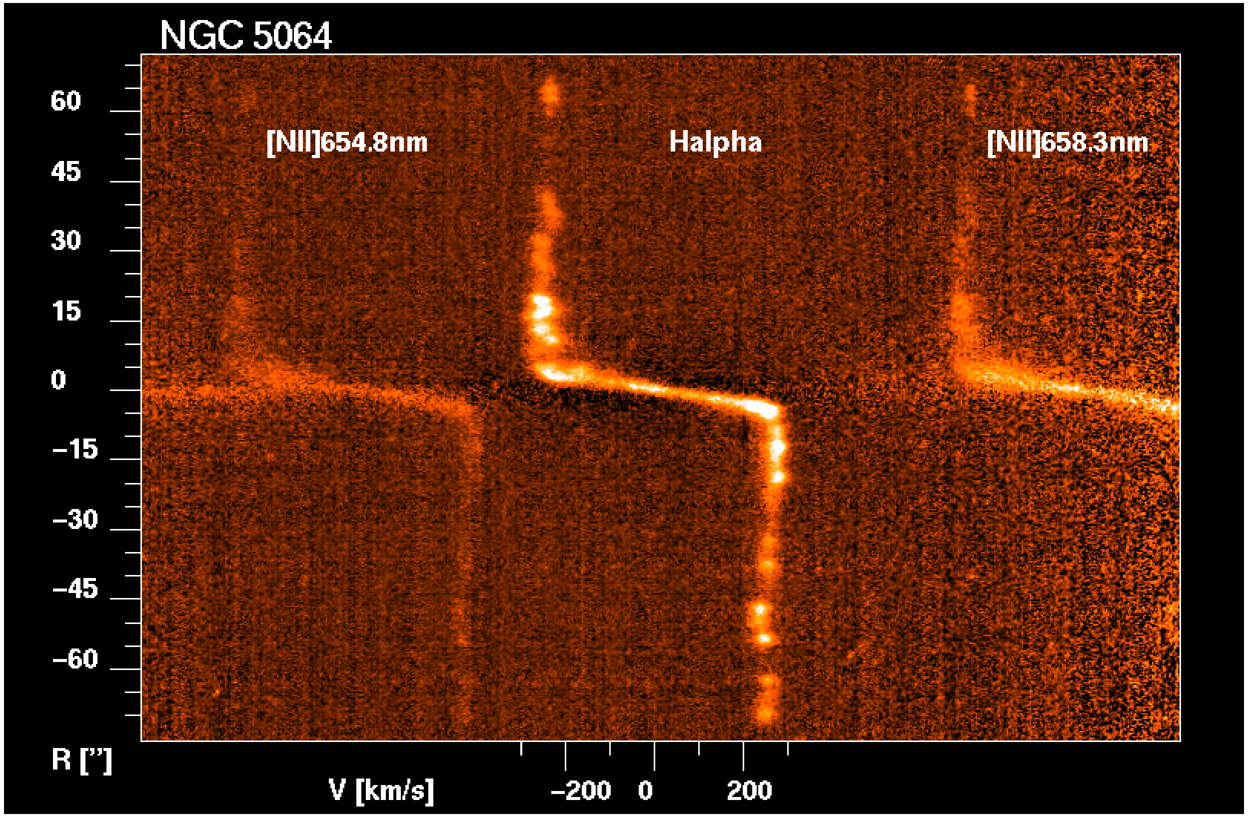


(A. Pizzella's home page)



mainly three lines:	nitrogen	$^3P_1 \rightarrow ^1D_2$	6543 Å
		$^3P_2 \rightarrow ^1D_2$	6583 Å
	hydrogen	$H\alpha$	6563 Å
	sulfur	$^4S_{1/2} \rightarrow ^2D_{5/2}$	6716 Å
		$^4S_{1/2} \rightarrow ^1D_{3/2}$	6731 Å

$$V = c\,\frac{\lambda_{obs}-\lambda_0}{\lambda_0}$$



integral-field spectroscopy

e.g. DensePak on WIYN telescope:

91 fibers (7 fiber x 13 fiber rectangle)

fiber diameter: 300 microns = 3 arcseconds

fiber-to-fiber spacing: 4 arcseconds

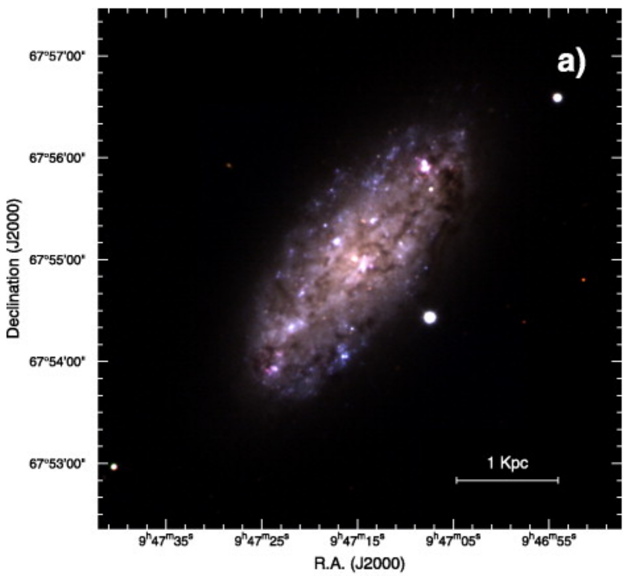
overall dimensions: 30 arcseconds x 45 arcseconds

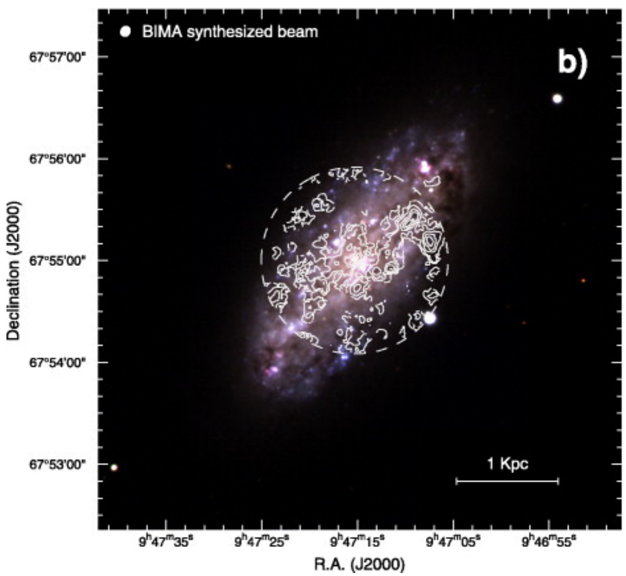
spectral window: 3700 Å to 1.1 μm

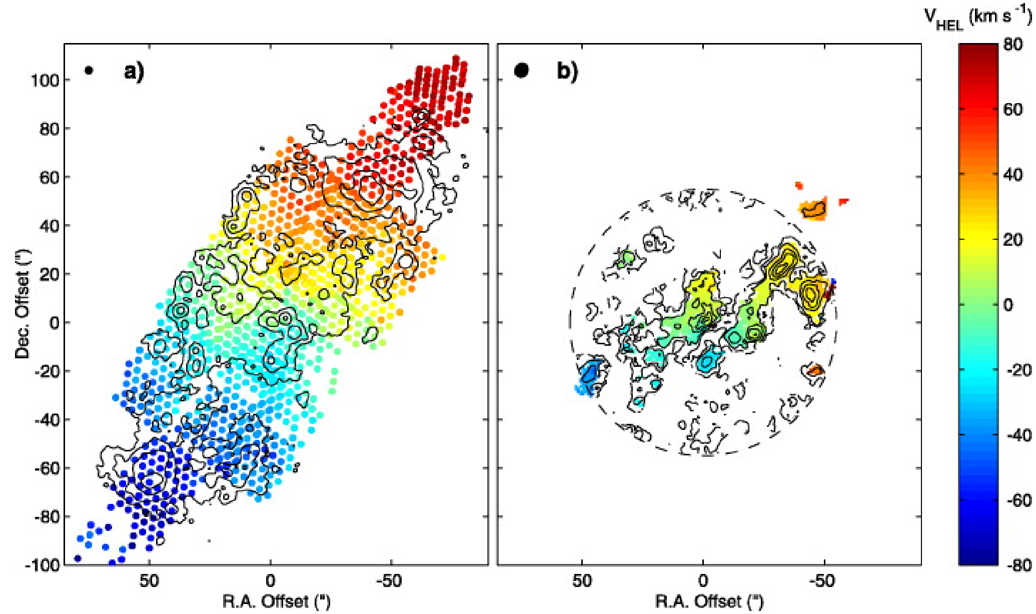
ΔV = 13 km s^{-1} in Hα

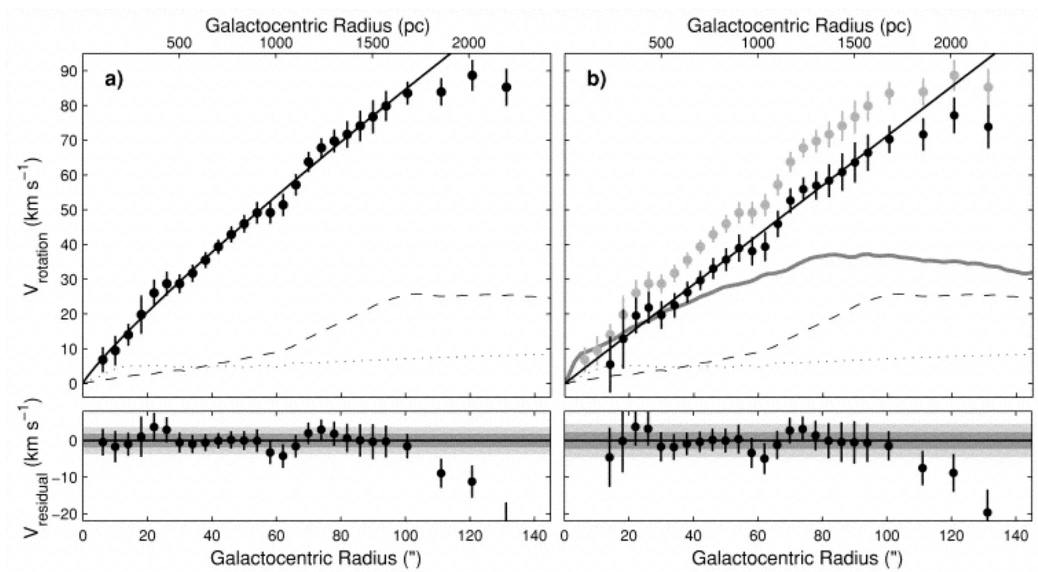
another one: SAURON on the 4.2-m on WHT

Simon et al. (2003): dwarf spiral NGC2976, Hα integral-field + CO





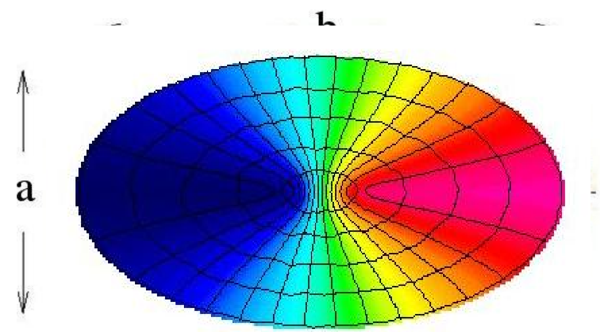




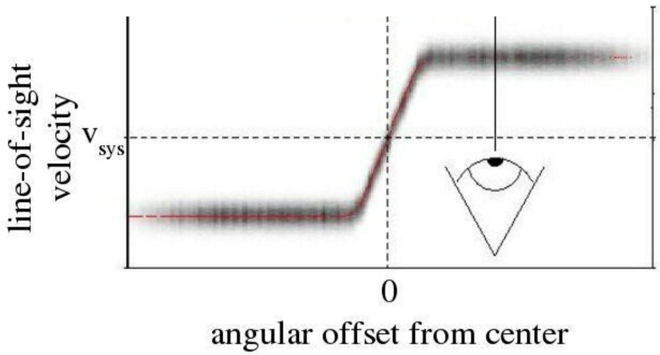
rotation curves: assume symmetric circular rotation of a disk characterized by

- sky coordinates (η_0,ξ_0) of the kinematic centre
- systemic velocity V_{sys}, i.e. the velocity of the galaxy's centre w.r.t. the sun
- circular velocity $V(R)$
- position angle χ of the major axis (clockwise from north)
- inclination angle i between normal to galaxy plane and l.o.s., i.e.

$$i = \arccos\left(\frac{a}{b}\right)$$



now subdivide projected (elliptical) galaxy image into elliptical rings of width ΔR.



radio spectroscopy ⇒ data cubes

e.g. 21-cm line:

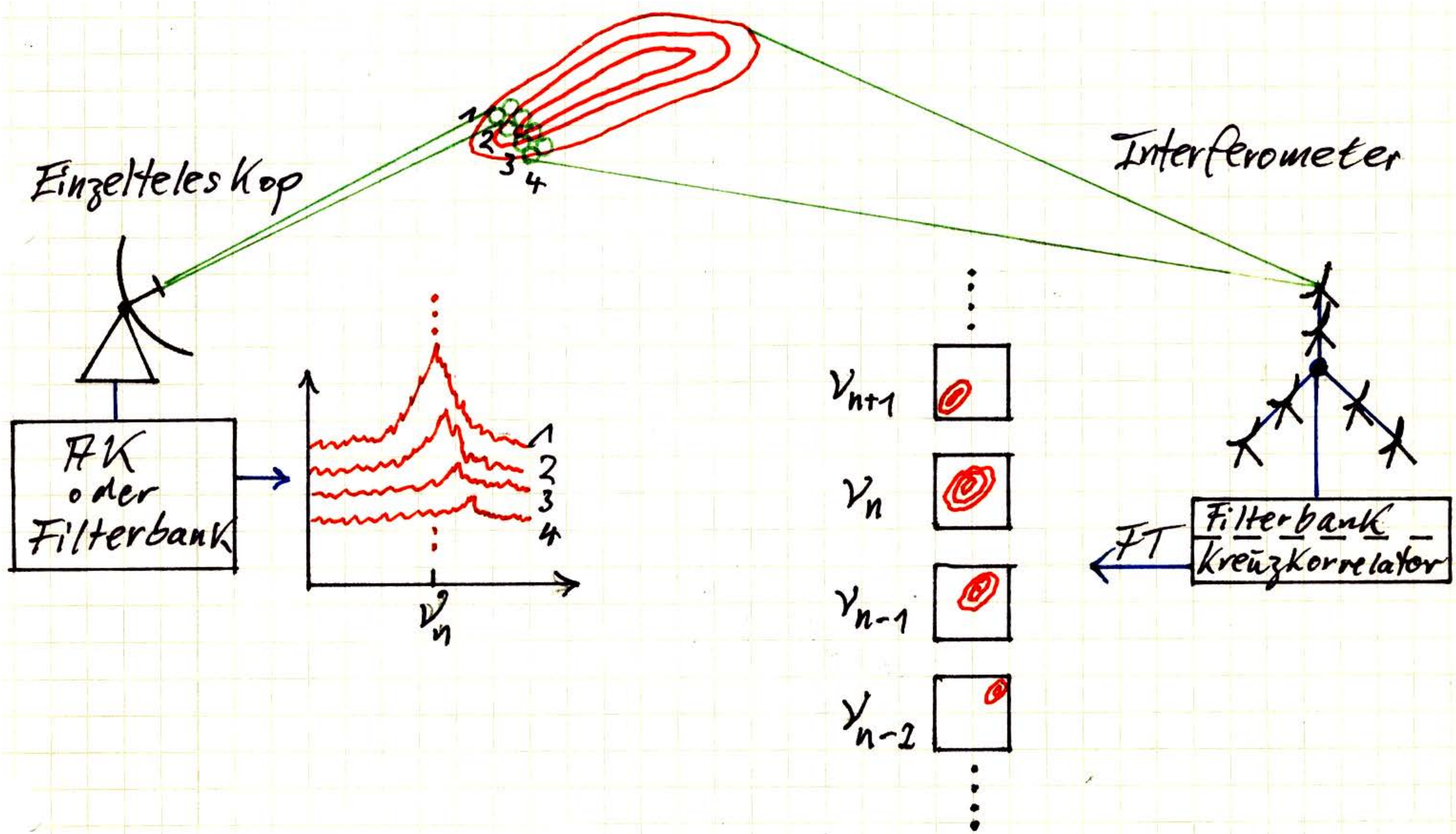
brightness temperature: $T_b = T_b(\xi, \eta, V)$

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

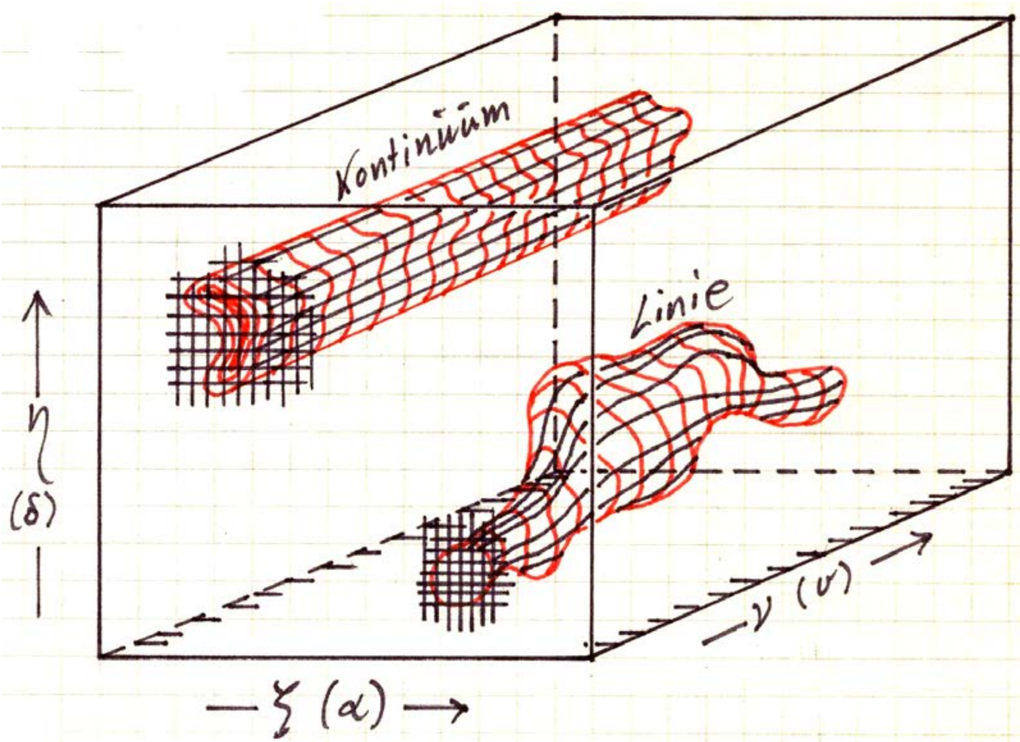
column density (e.g. HI):

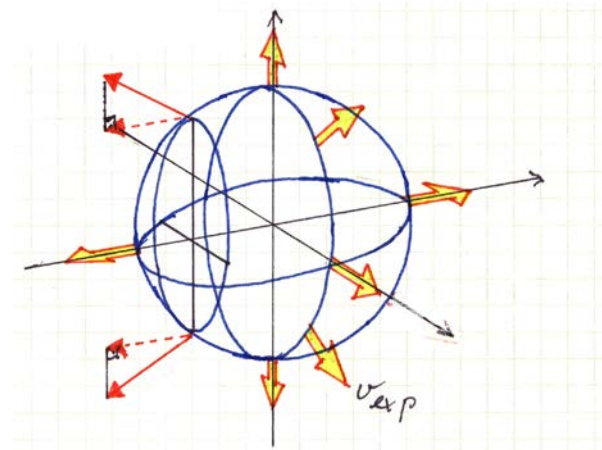
$$N_{HI}(\xi,\eta) = 1.822 \cdot 10^{18} \int_{V_1}^{V_2} \left[\frac{T_b(\xi,\eta)}{K} \right] \left(\frac{dV}{km\ s^{-1}} \right) \quad atoms\ \ cm^{-2}$$

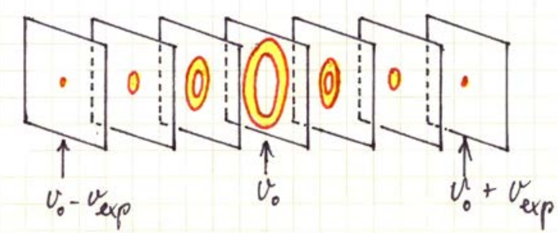
single dish vs. interferometer

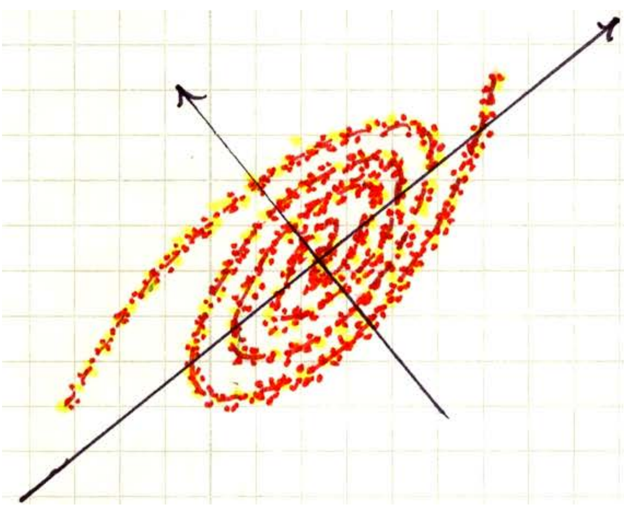


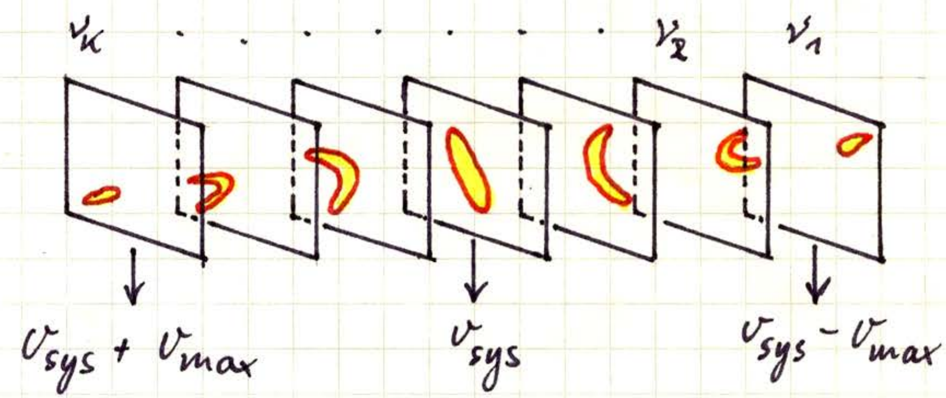
data cubes

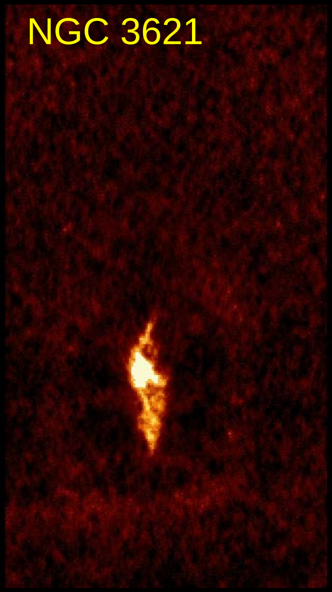

Kontinuum
Linie
η
(δ)
— ξ (α) →
— ν (v) →

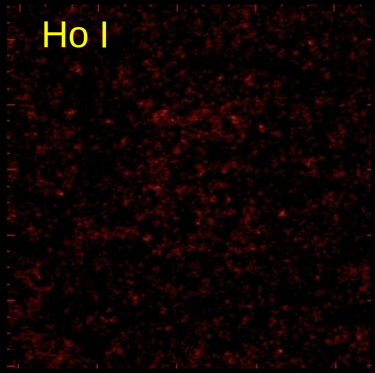

v_{exp}


$v_0 - v_{exp}$
v_0
$v_0 + v_{exp}$




ν_K . . . . ν_2 ν_1
$v_{sys} + v_{max}$
v_{sys}
$v_{sys} - v_{max}$

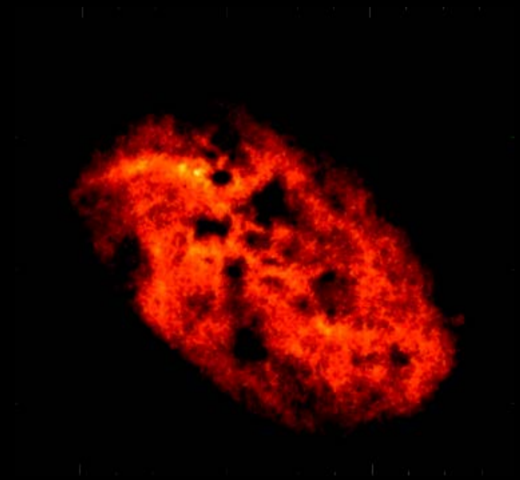


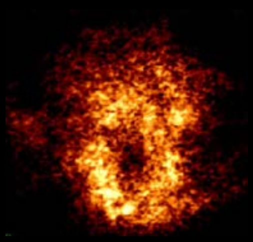


$L_B \sim 0.5 \times \mathrm{L}_*$

$L_B \sim 0.06 \times \mathrm{L}_*$

$L_B \sim 0.005 \times \mathrm{L}_*$





WSRT

ATCA

VLA

PdB Interferometer

ALMA

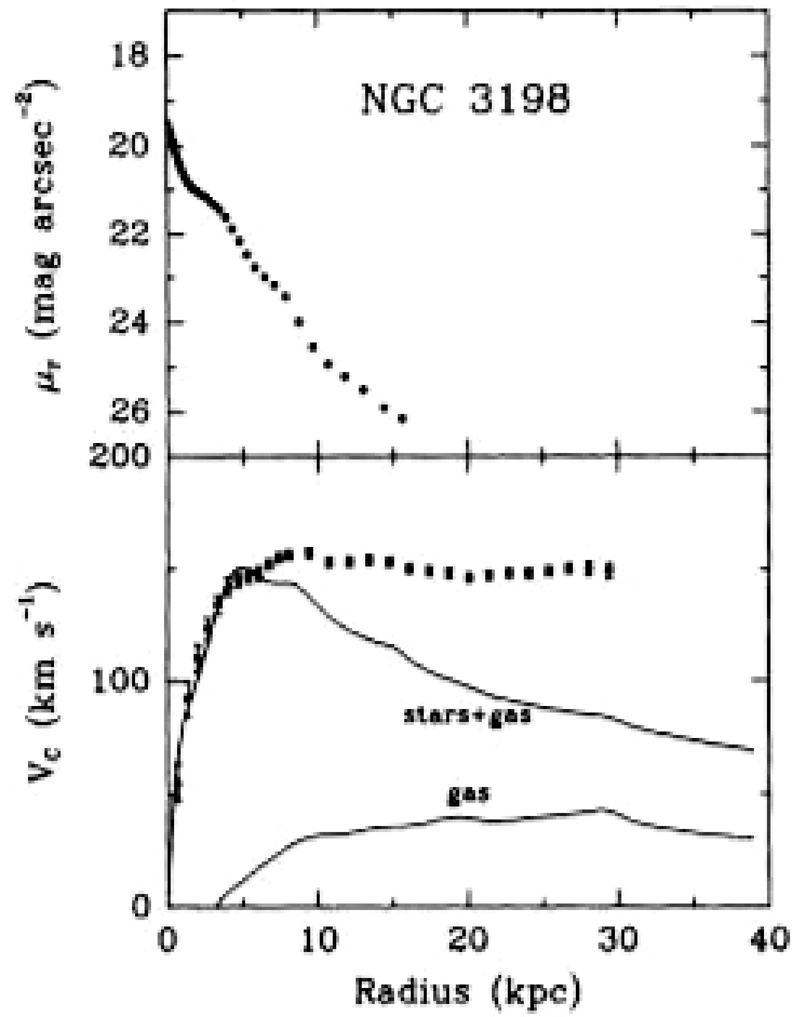
Rotation curves

needed for studies of mass distributions:

rotation curve *V(r)*

problems (see, e.g., Swaters et al. 2003):

- slit position and orientation (Hα)
- distribution of tracers (HI, CO, Hα)
- spectral smoothing
- spatial smoothing (“beam smearing”)
- finite disk thickness, edge-on galaxies
- anomalous velocities
  - non-circular motions
  - star-forming regions (Hα)
- lopsidednes
- warps



Begeman et al. (1989)

tilted-ring analysis of velocity field:

$$V_{obs}(\xi,\eta) = V_{sys} + V(r)\cos\theta\sin i$$

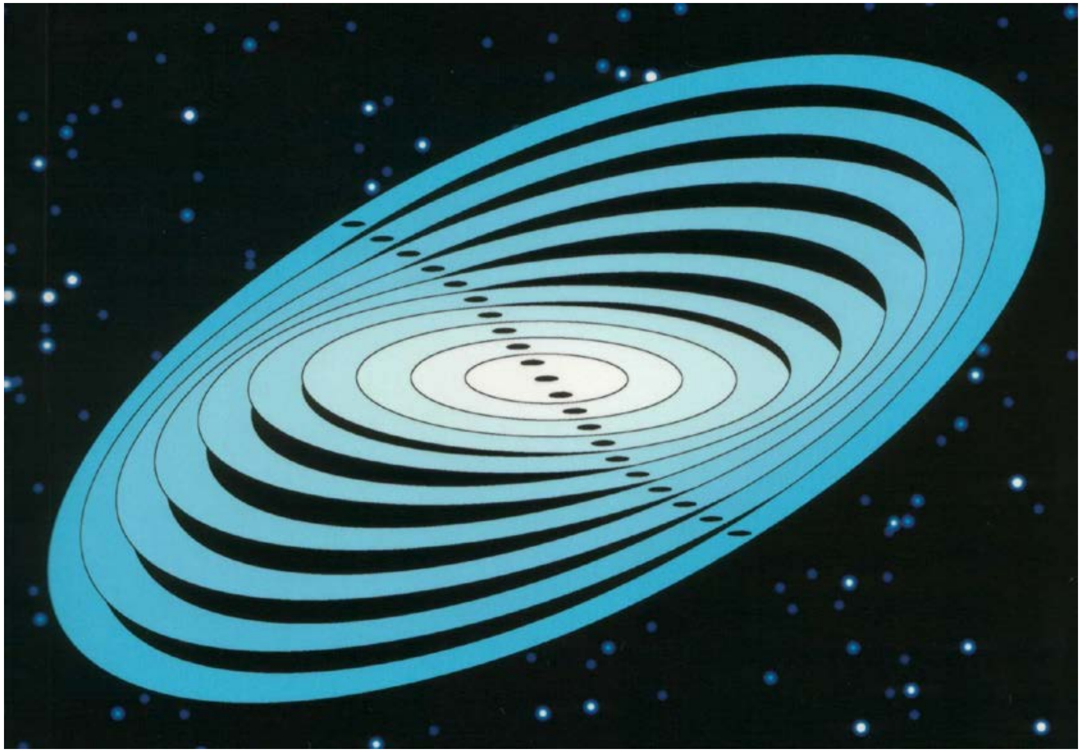
$$\cos\theta = \frac{-(\xi-\xi_0)\sin\chi + (\eta-\eta_0)\cos\chi}{R}$$

$$\sin\theta = \frac{-(\xi-\xi_0)\cos\chi - (\eta-\eta_0)\sin\chi}{R\cos i}$$

$\boldsymbol{i}$ = inclination angle (0º = face-on)

$\boldsymbol{\theta}$ = azimuthal angle

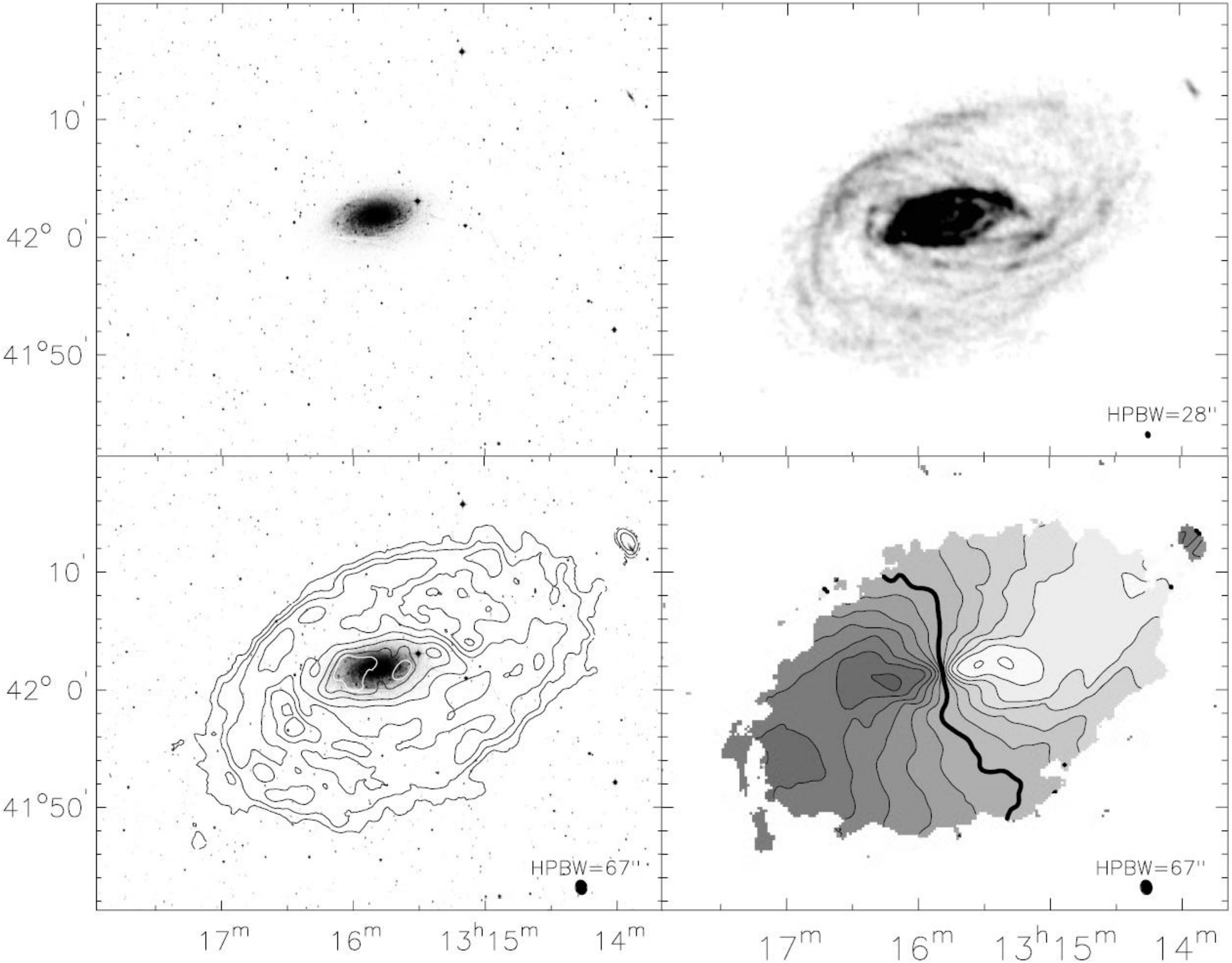
ξ_0, η_0, i, χ and V are expected to vary with R

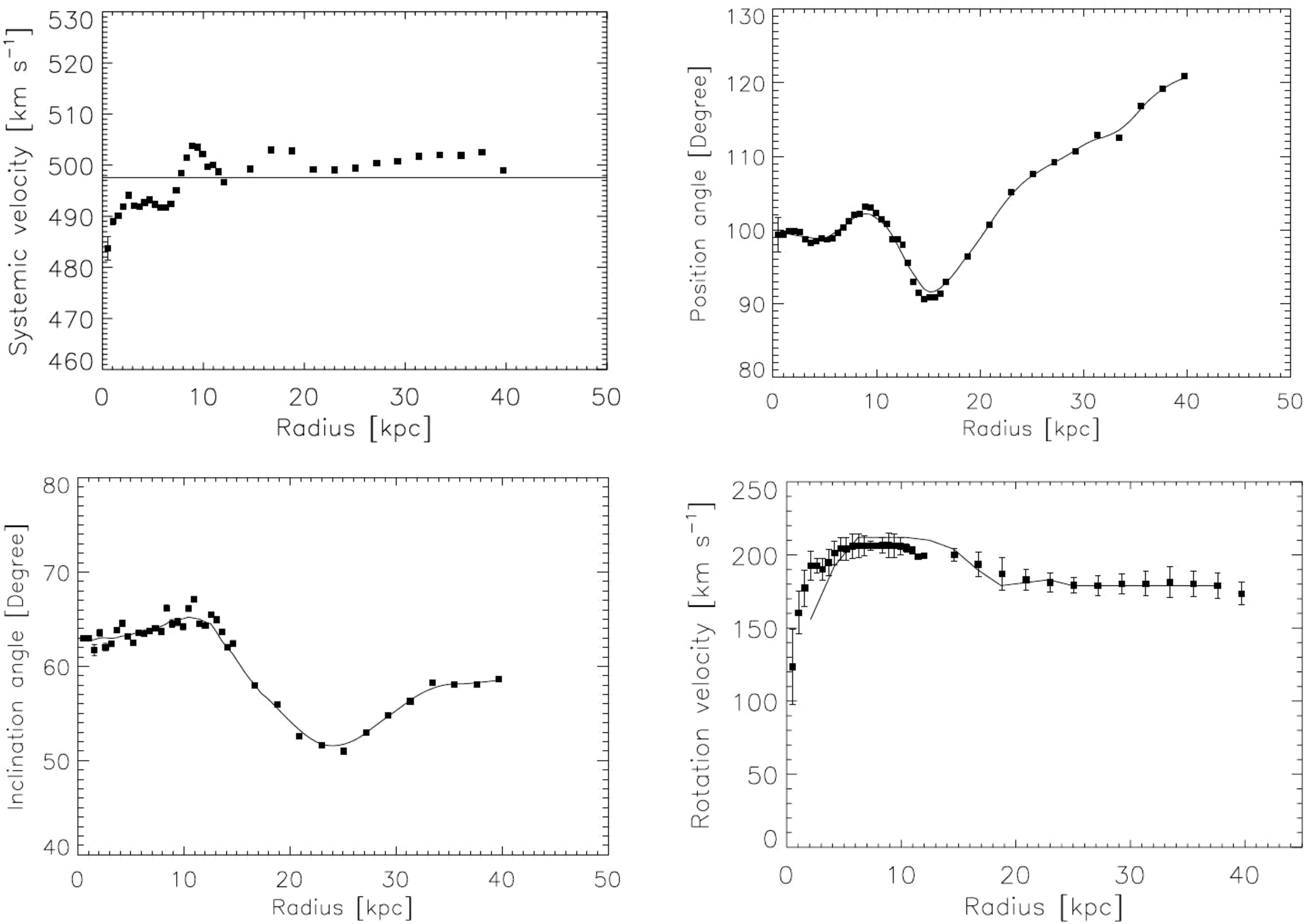


procedure (Begeman 1989):

1. divide galaxy into concentric rings (width ~ 1 beam width)
2. estimate initial values of V_0, ξ_0, η_0, V_c, i and χ
3. calculate initial radial velocities $V(\xi,\eta)$ $\Rightarrow$ 1st moment
4. make least-squares fit for parameters V_0, ξ_0, η_0, V_c, i and χ, using observed velocity field and initial guess determined above
5. improved values of basic parameters define new set of sky coordinates ξ,η; go to 3 until convergence is reached; iteration process is monitored by calculating χ^2

Battaglia et al. (2006)





530
520
510
500
490
480
470
460
Systemic velocity [km s^-1]
0
10
20
30
40
50
Radius [kpc]
130
120
110
100
90
80
Position angle [Degree]
0
10
20
30
40
50
Radius [kpc]
80
70
60
50
40
Inclination angle [Degree]
0
10
20
30
40
50
Radius [kpc]
250
200
150
100
50
0
Rotation velocity [km s^-1]
0
10
20
30
40
Radius [kpc]

fit parameters in RC fitting:

$$V_{rot}^2(r) = V_{DM}^2(r) + V_b^2(r) + V_d^2(r) + V_{HI}^2(r) + V_{H_2}^2(r)$$

stars

mass-to-light ratio of optical band X: 😐$_X$ (disk, bulge)

gas

- HI : straight forward, just account for helium, $X_{He} \approx 1.3 \dots 1.4$
- H_2: conversion from CO brightness to H_2 column density, X_{CO}

dark halo

- core or characteristic radius : r_0, r_s
- central or characteristic density : ρ_0, ρ_s

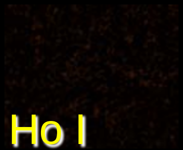
MOND

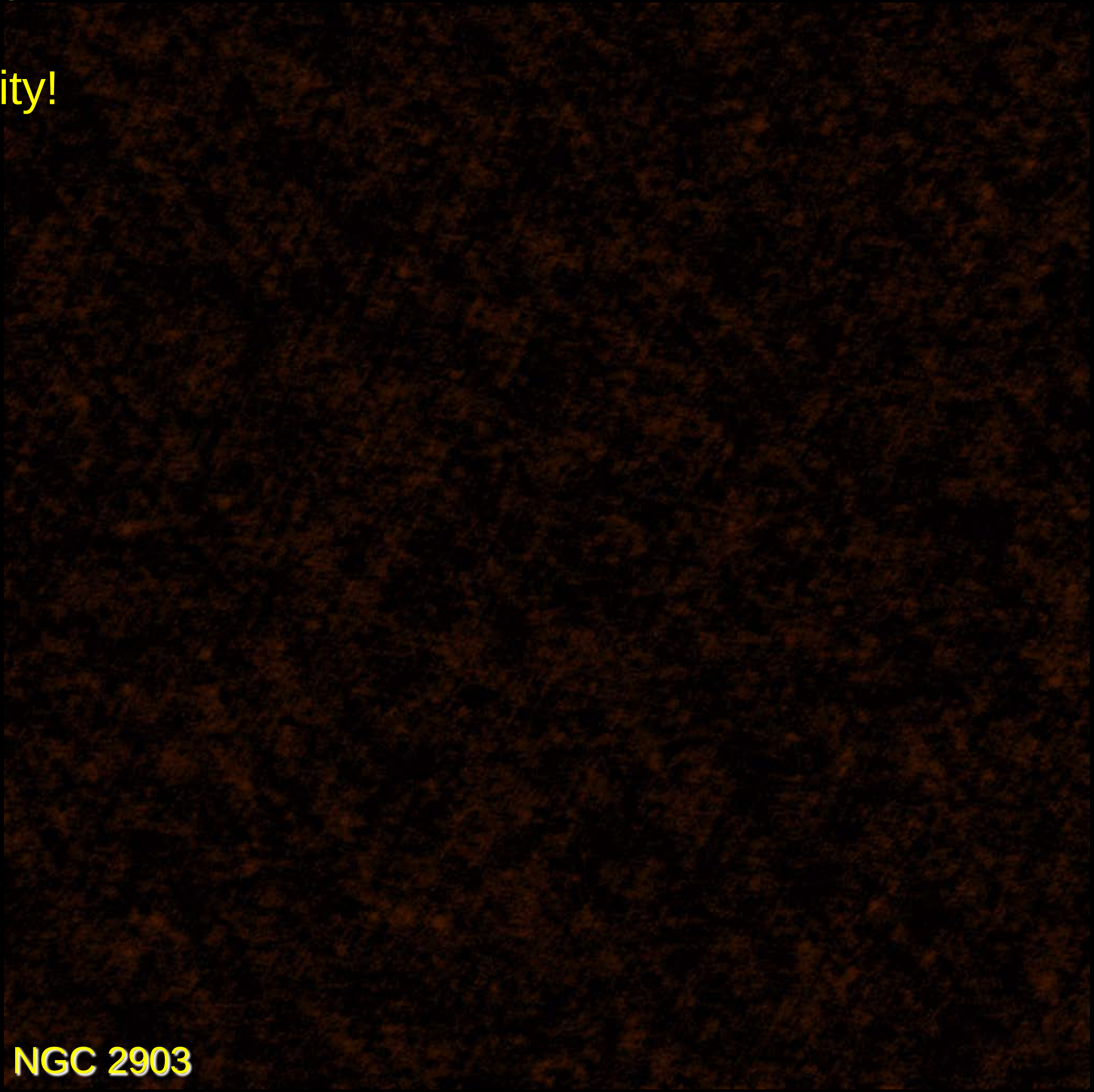
- acceleration : a_0 (although this ought to be a universal constant)
- distance : D

now perform mass decomposition

needs excellent data quality!

from *THINGS*:





Probing the galaxy potential

Poisson equation:

$$\vec{\nabla}^2 \Phi = 4\pi \cdot G \cdot \rho$$

in principle for axi-symmetric potentials: measure circular rotation speed *V* and infer density ρ

for spherical (DM, stellar bulge) potential: measure circular rotation speed $\boldsymbol{V_{DM}(r)}$ and infer $\boldsymbol{\rho_{DM}(r)}$ using

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

$\Rightarrow$ most simple inversion method in case of (e.g.) dominating (spherical) DM halo or, vice versa:

$$M(<r) = \int_0^r 4\pi\, r'^2 \rho(r')\, dr'$$

$$V^2(r) = \frac{G\,M(<r)}{r}$$

e.g. quasi-isothermal halo:

$$\rho(r) = \rho_0 \left(1 + \frac{r^2}{r_0^2}\right)^{-1}$$

i.e.

$$M(<r) = 4\pi\,\rho_0 \int_0^r \frac{r'^2\, r_0^2}{r_0^2 + r'^2}\, dr'$$

$$= 4\pi\,\rho_0\, r_0^2 r \left(1 - \frac{r_0}{r} \arctan \frac{r}{r_0}\right)$$

so: measure $\boldsymbol{V_{rot}(r)}$, calculate $\boldsymbol{V_{stellar}(r)}$, $\boldsymbol{V_{gas}(r)}$, and deduce $\boldsymbol{V_{DM}(r)}$

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

stellar component : bulge (b) and disk (d)

gaseous component : HI and H_2

$$V_{rot}^2 = V_{DM}^2 + V_b^2 + V_d^2 + V_{HI}^2 + V_{H_2}^2$$

high-precision rotation curve delivers $\boldsymbol{V_{rot}(r)}$

mass surface densities yield $\boldsymbol{V_{stellar}(r)}$, $\boldsymbol{V_{gas}(r)}$

$$V_{DM} = \sqrt{V_{rot}^2 - V_b^2 - V_d^2 - V_{HI}^2 - V_{H_2}^2}$$

stellar disk

solution for infinitely thin exponential disk, which has intensity an distribution

$$I(r) = I_0 \cdot e^{-r/r_D}$$

is (Freeman 1970)

$$V_d^2(r) = 4\pi G \Sigma_0 r_d \; y^2 \left[I_0(y) K_0(y) - I_1(y) K_1(y) \right]$$

I(R) and $\boldsymbol{I_0}$ have units of $L_\odot$ pc^{-2}, and $\boldsymbol{y = R / 2\, R_d}$.

with stellar mass-to-light ratio 😐$_*$:

$$\Sigma_0 = \mathrm{K}_* I_0$$

solution for truncated thick disk reads (Casertano 1983)

$$V_d^2(r) = 4\pi G r \int_0^\infty du \int_0^\infty d\varsigma \, \frac{2\sqrt{u}}{\pi\sqrt{r\,p}} \left[\mathcal{K}(p) - \mathcal{E}(p)\right] \frac{\partial}{\partial u} \left[\rho(u,\varsigma)\right]$$

where $\mathcal{K}$ and $\mathcal{E}$ are complete elliptical integrals,

$$p = x - \sqrt{x^2 - 1}$$

and

$$x = \frac{r^2 + u^2 + \varsigma^2}{2Ru}$$

now plug in numerically any density distribution $\rho(R,z)$ and obtain (circular) velocity of the disk component.

gaseous disk

in general not an exponential disk, but rather has arbitrary *Σ(R), s*o use Casertano (1983) formalism:

$$V_{gas}^2(r) = 4\pi G r \int_0^\infty du \int_0^\infty d\varsigma \, \frac{2\sqrt{u}}{\pi\sqrt{r\,p}} \left[\mathcal{K}(\mathrm{p}) - \mathcal{E}(\mathrm{p})\right] \frac{\partial}{\partial u}\left[\rho(u,\varsigma)\right]$$

observed: $N_H(R)$, readily converted into mass surface density $\Sigma_H(R)$

divide by effective thickness of gaseous disk to obtain density ρ

$$\rho_{gas}(r) = 1.4 \cdot \Sigma_{gas}(r) \cdot \left(\int_{-\infty}^{\infty} e^{-z/z_0} \, dz \right)^{-1}$$

factor of 1.4 accounts for presence of helium.

note: N_{HI} results directly from 21-cm line
N_{H2} results indirectly via CO line (s.b.)

Dark halos

Burkert (1995) established empirical law that fits (DM-dominated) dwarf Galaxies best; characterized by central density ρ_0 and core radius r_0

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

test particle has circular velocity

$$V^2(r) = 2\pi G \, \rho_0 \frac{r_0^3}{r}\left[\ln\left(\frac{r + r_0}{r_0}\right) + \frac{1}{2}\ln\left(\frac{r^2 + r_0^2}{r_0^2}\right) - \arctan\frac{r}{r_0}\right]$$

numerical simulations in the (Λ)CDM framework yield halos that are best fitted by analytic function (Navarro, Frenk & White 1997) referred to as "NFW profile"

$$\rho(r) = \frac{\rho_s}{r/r_s\left(1 + r/r_s\right)^2}$$

test particle in such a potential has circular velocity

$$V^2(r) = V_{200}^2 \, \frac{1}{x} \, \frac{\ln(1+cx) - (cx/1+cx)}{\ln(1+c) - (c/1+c)}$$

where $x = r/r_{200}$. V_{200} is the circular velocity at r_{200}, the "virial radius", for which $\langle\rho\rangle = 200\,\rho_{crit}$. c is the concentration parameter defined as

$$c = \frac{r_{200}}{r_s}$$

concentration parameter c, characteristic radius r_s and density ρ_s are connected by

$$c \approx 20 \left(\frac{M_{vir}}{10^{11} \mathrm{M}_{\odot}} \right)^{-0.13}$$

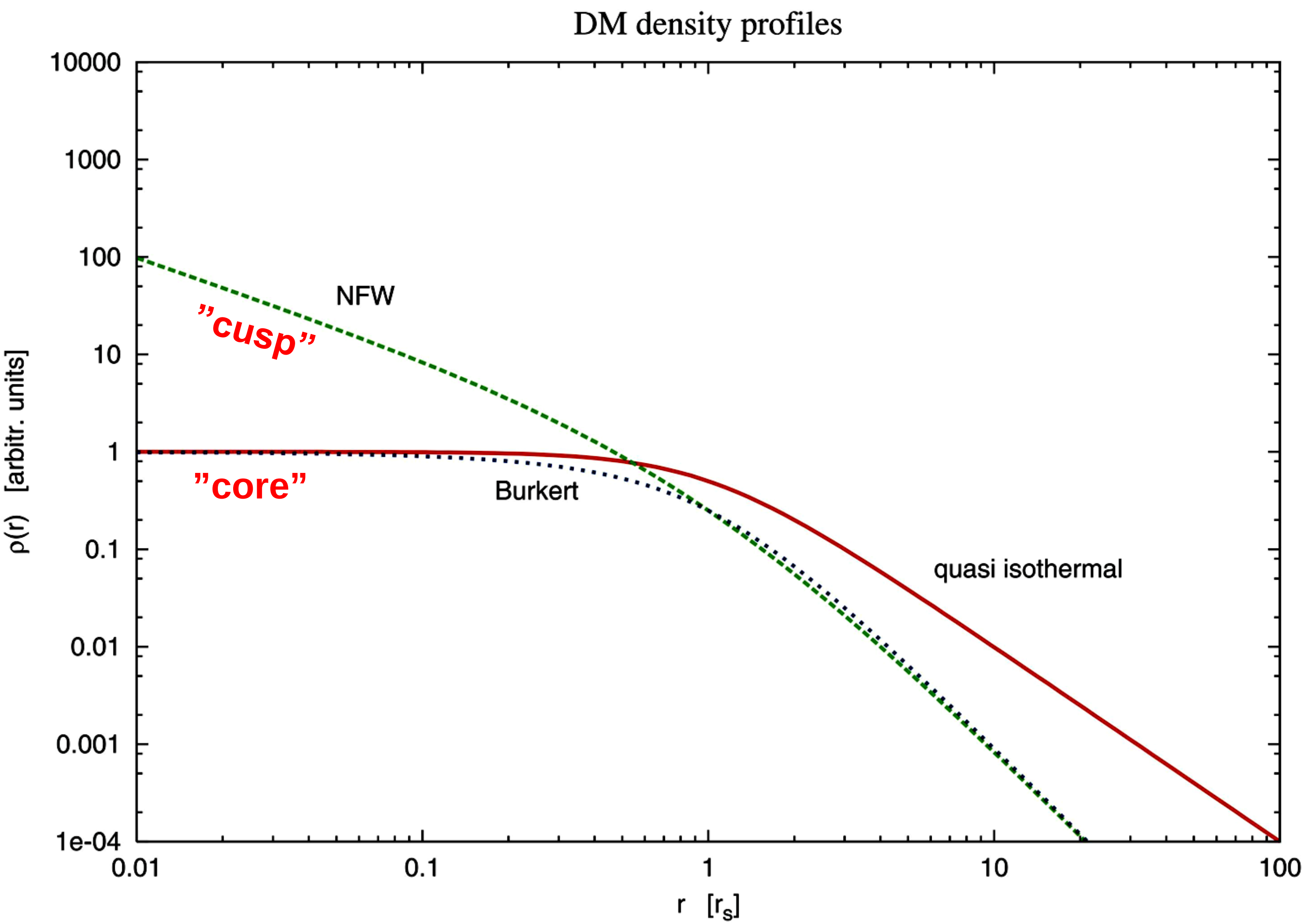
$$r_s \approx 5.7 \left(\frac{M_{vir}}{10^{11} \mathrm{M}_{\odot}} \right)^{0.46} \quad \mathrm{kpc}$$

$$\rho_s \approx \frac{\Delta}{3} \frac{c^3}{\ln(1+c) - c/(1+c)} \rho_{crit}$$

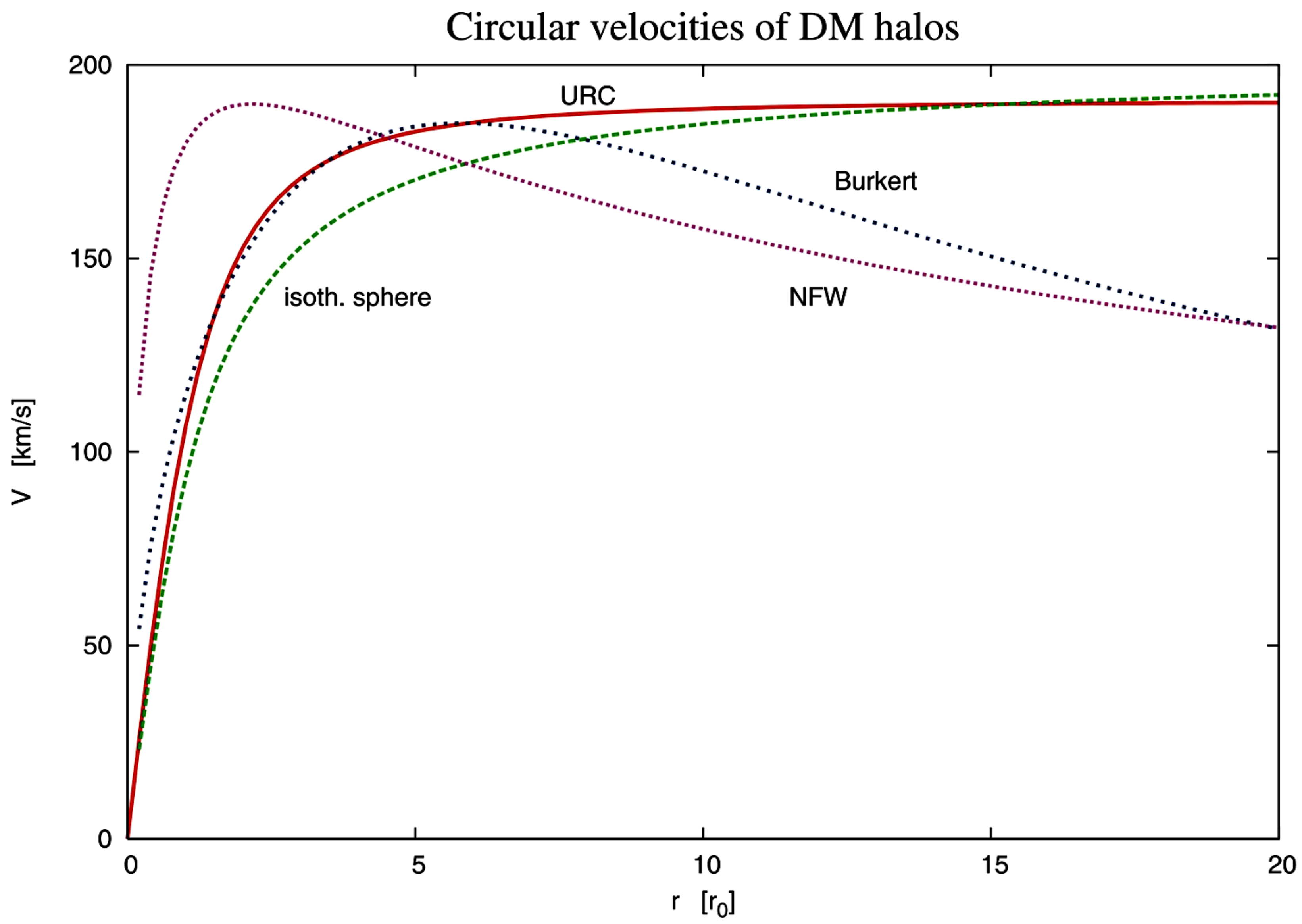
$$M_{\mathrm{vir}} \equiv \frac{4}{3} \pi r_{200}^3 \Delta \cdot \rho_{crit}$$

$\Delta \approx 337$ is the overdensity at $z = 0$ (see Bryan & Norman 1998).

“cuspy” and “cored” density profiles of DM halos



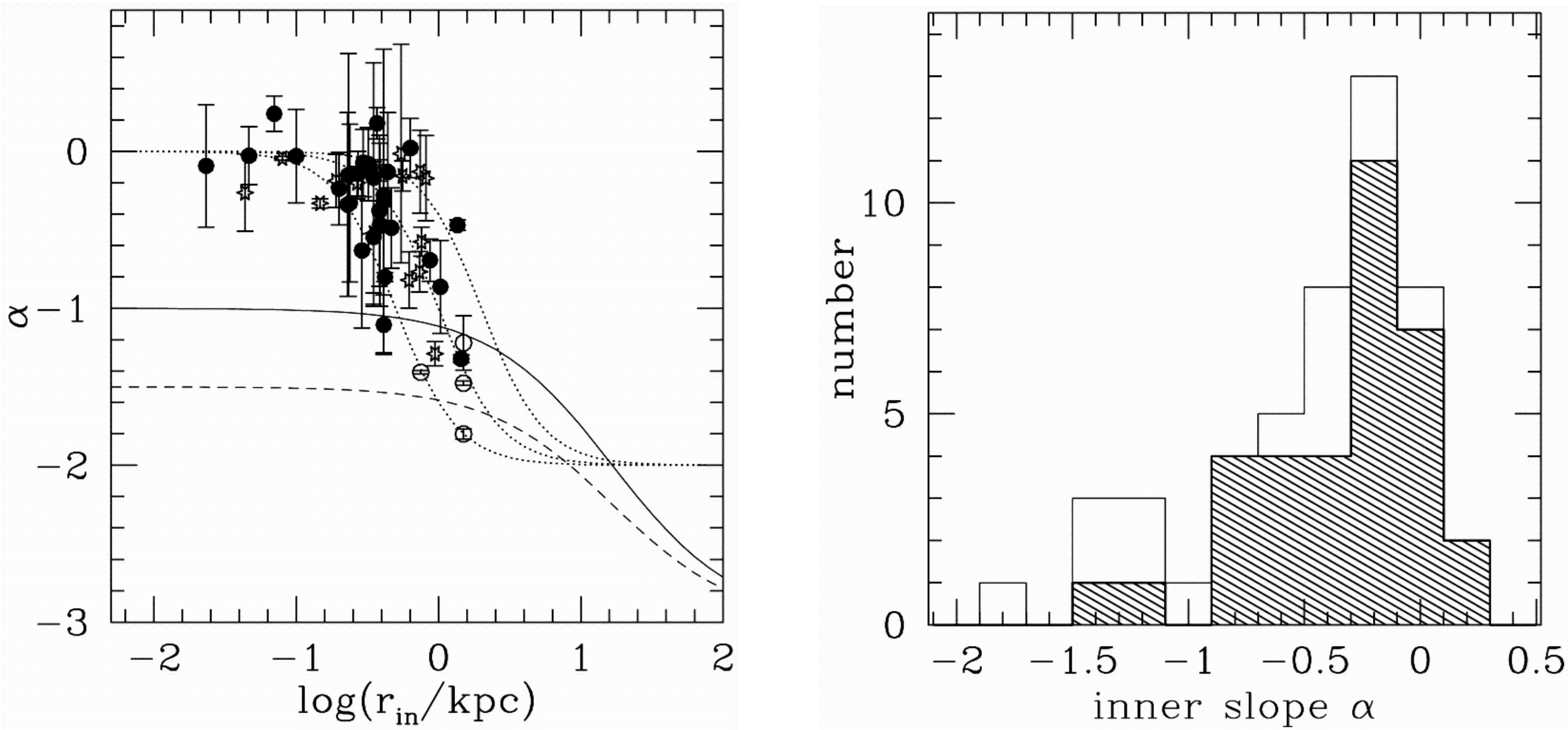
… and the circular velocities of DM halos



e.g. de Blok et al. (2001a): 48 LSB galaxies

high-resolution RCs (Hα + HI)

inner slopes strongly peaked around α = -0.2 for $\rho_{DM} \propto r^{\alpha}$



dotted : isothermal halo, with core radii of 0.5, 1 and 2 kpc

solid : NFW model

dashed : Moore

(solid and dashed): c = 8 and V_{200} = 100 km s^{-1}

Gentile et al. (2004):

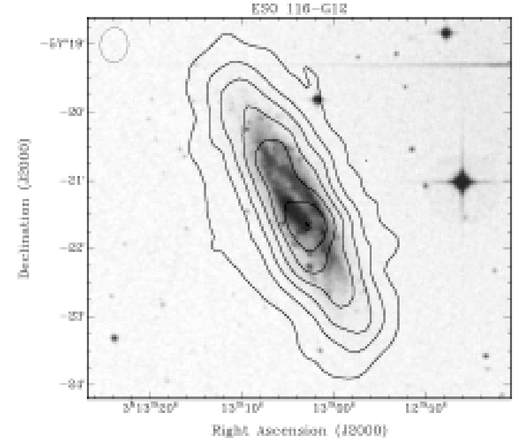
sample of spiral galaxies with

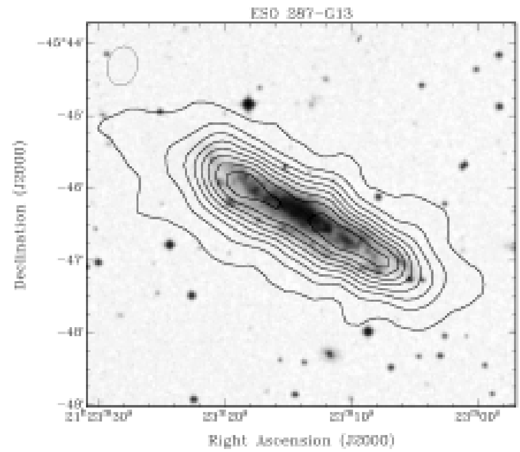
- low luminosities

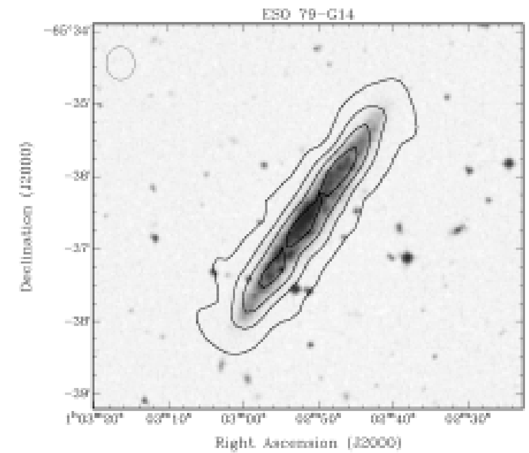
- precise optical RCs available

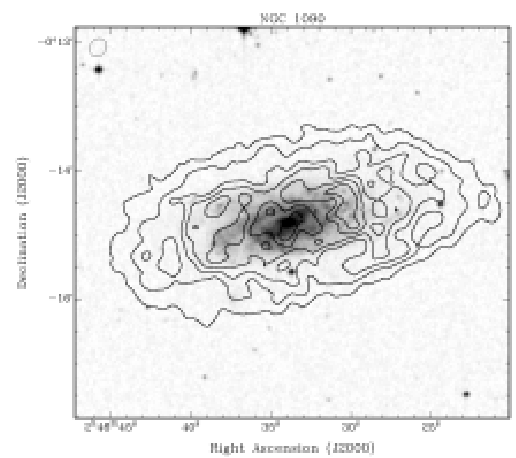
- late type (small or no bulges)

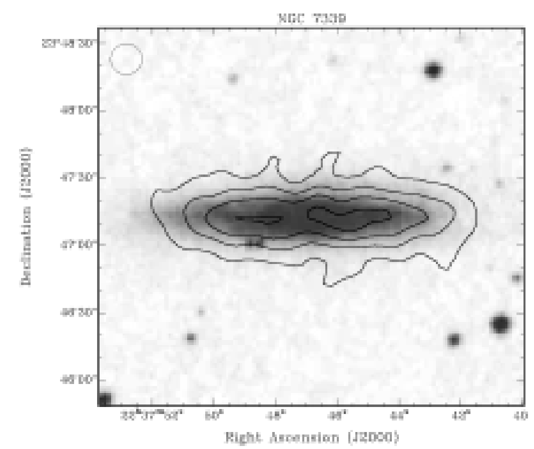
- well known distances



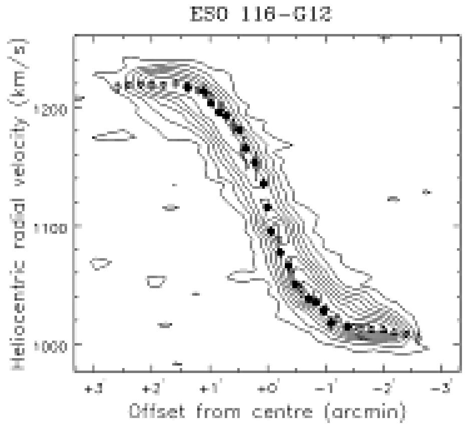


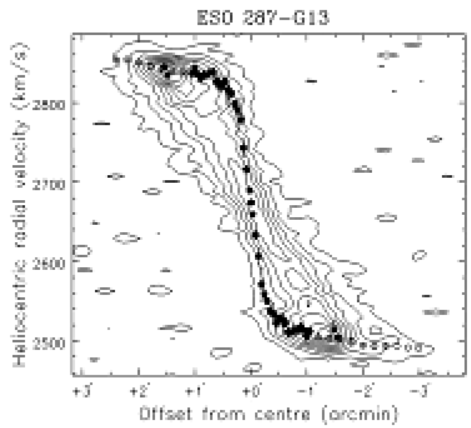


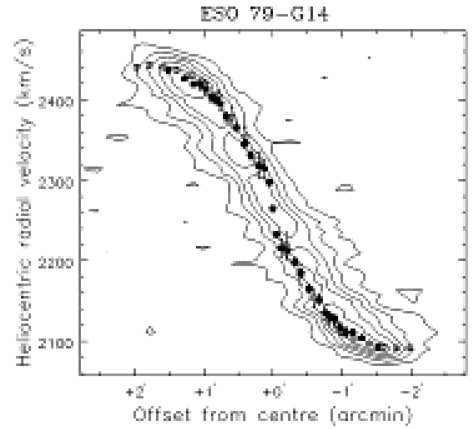


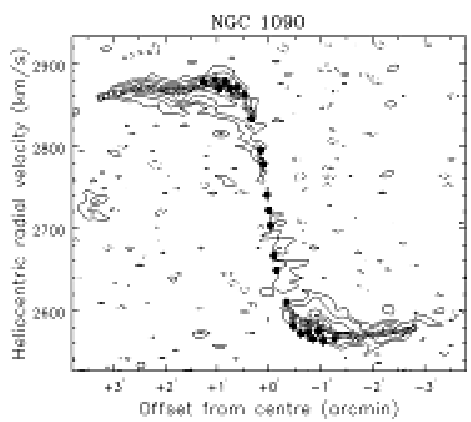


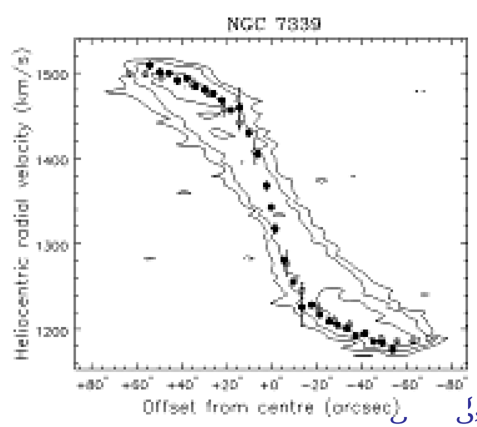
derived rotation curves



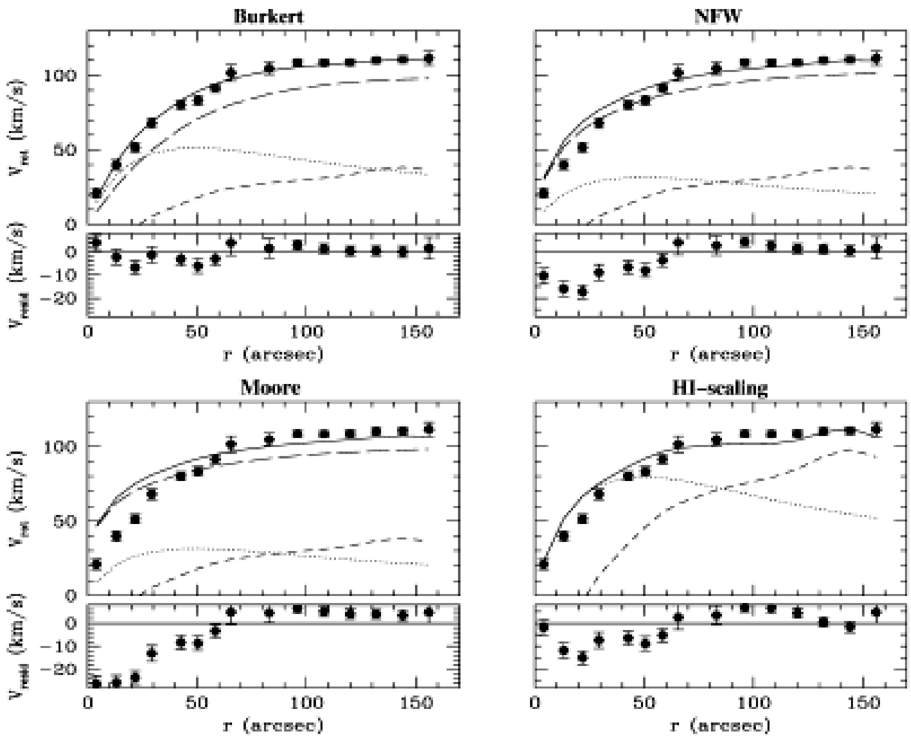


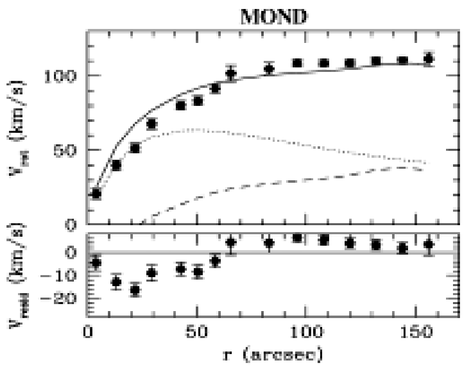






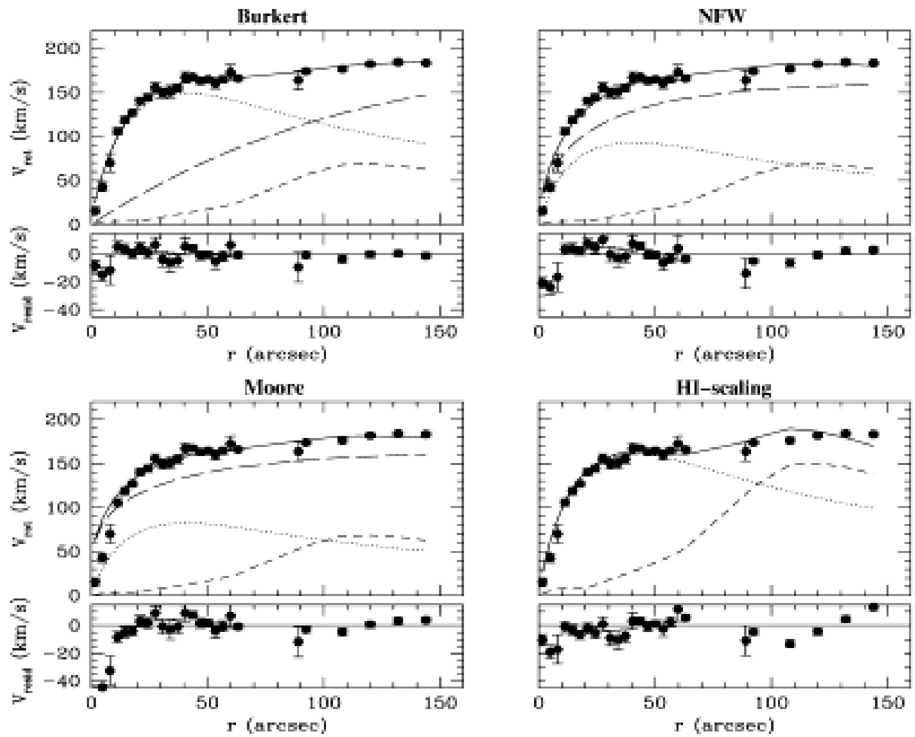
comparison with models

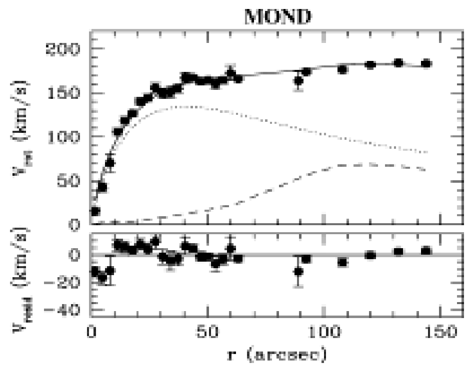




ESO 116–G12

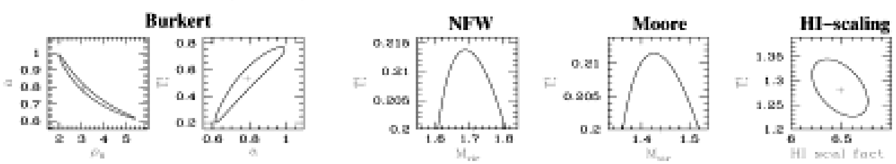
Discrepant points:	2σ	3σ	no. of points
Burkert	1	0	15
NFW	7	2	15
Moore	8	5	15
HI–scaling	8	4	15
MOND	7	2	15

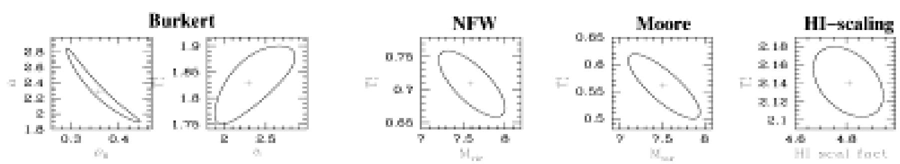




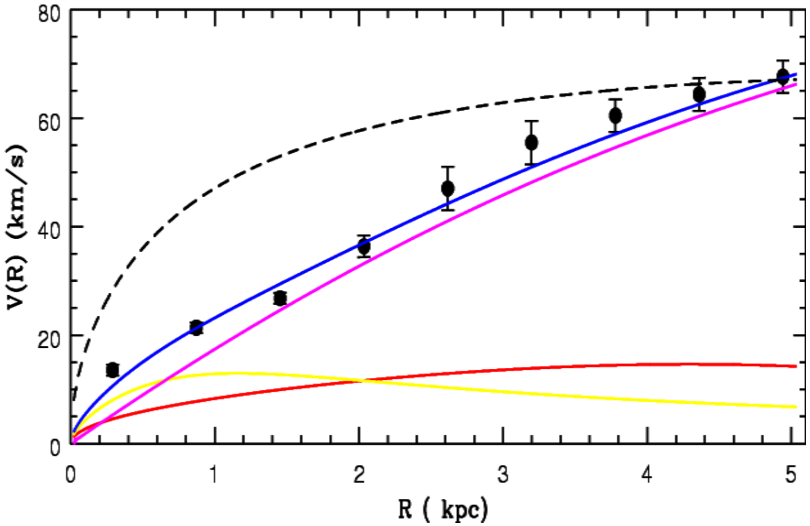
ESO 287–G13

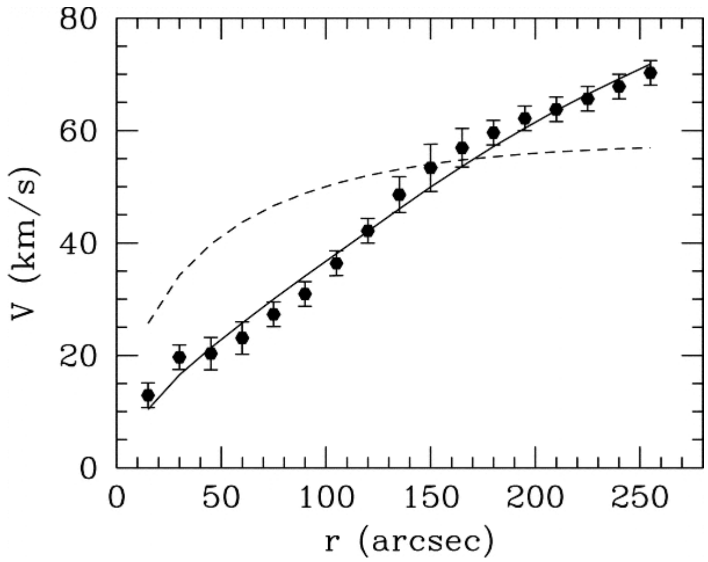
Discrepant points:	2σ	3σ	no. of points
Burkert	2	0	26
NFW	6	2	26
Moore	6	3	26
HI–scaling	8	3	26
MOND	3	2	26





fits with NFW (dashed) and Burkert (magenta & black solid) law





last point matches M_{vir}

c left as free parameter

NFW "flagrantly" bad (c = 25)

Burkert yields: r_0 = 7 kpc

$\rho_0 = 1.4 \cdot 10^{-24}$ g cm^{-3}

Relation to magnetic fields

'flux freezing':

magnetic fields tightly coupled to gas (via ionized component)

$\Rightarrow$ B-field influenced by kinematics!

observations:

B-field follows spiral arms

kinematics:

- galactic rotation
- spiral density waves

B-field influenced by density waves?

Fletcher et al. (2011)

influence by magnetic field on gas kinematics requires

$$\frac{B^2}{8\pi} \approx \rho(\Delta V)^2$$

e.g.

turbulence: $u_{mag}/u_{kin} \approx 3$

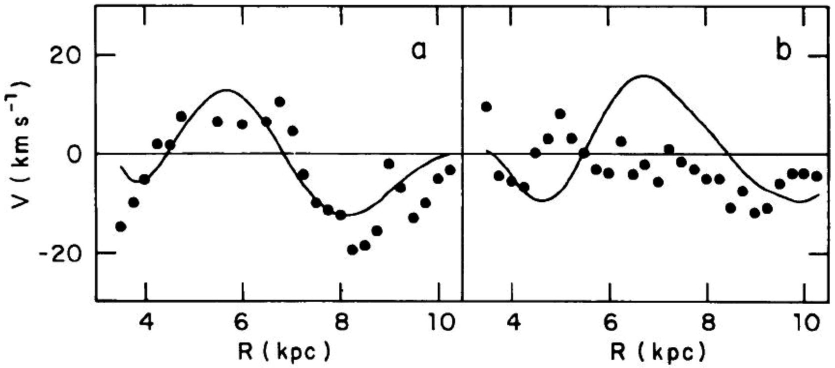
rotation: u_{mag}/u_{kin} 📬 10^{-4}

magnetic field passive on large scales

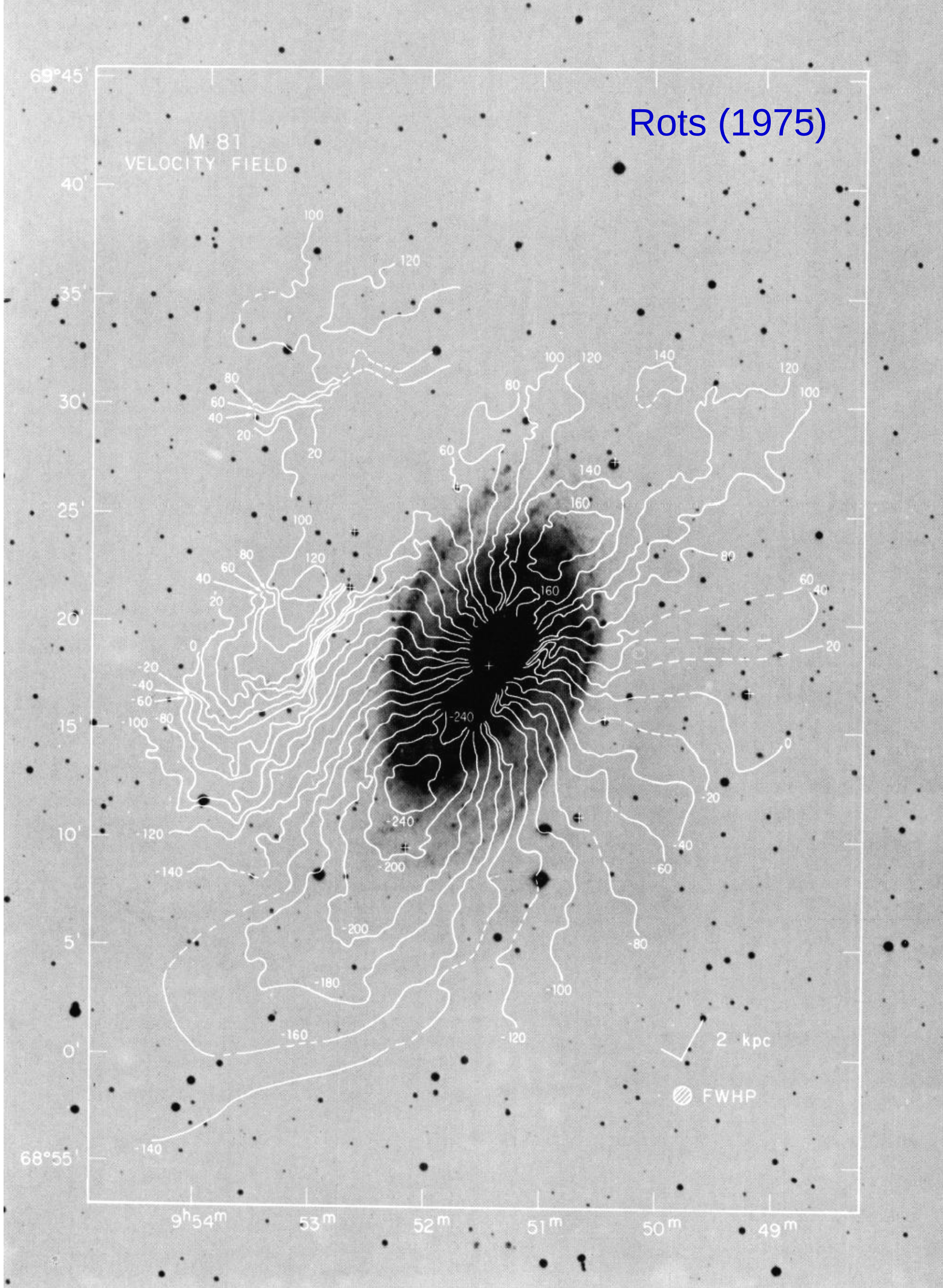
density waves

classical case: M 81 (Rots 1975)

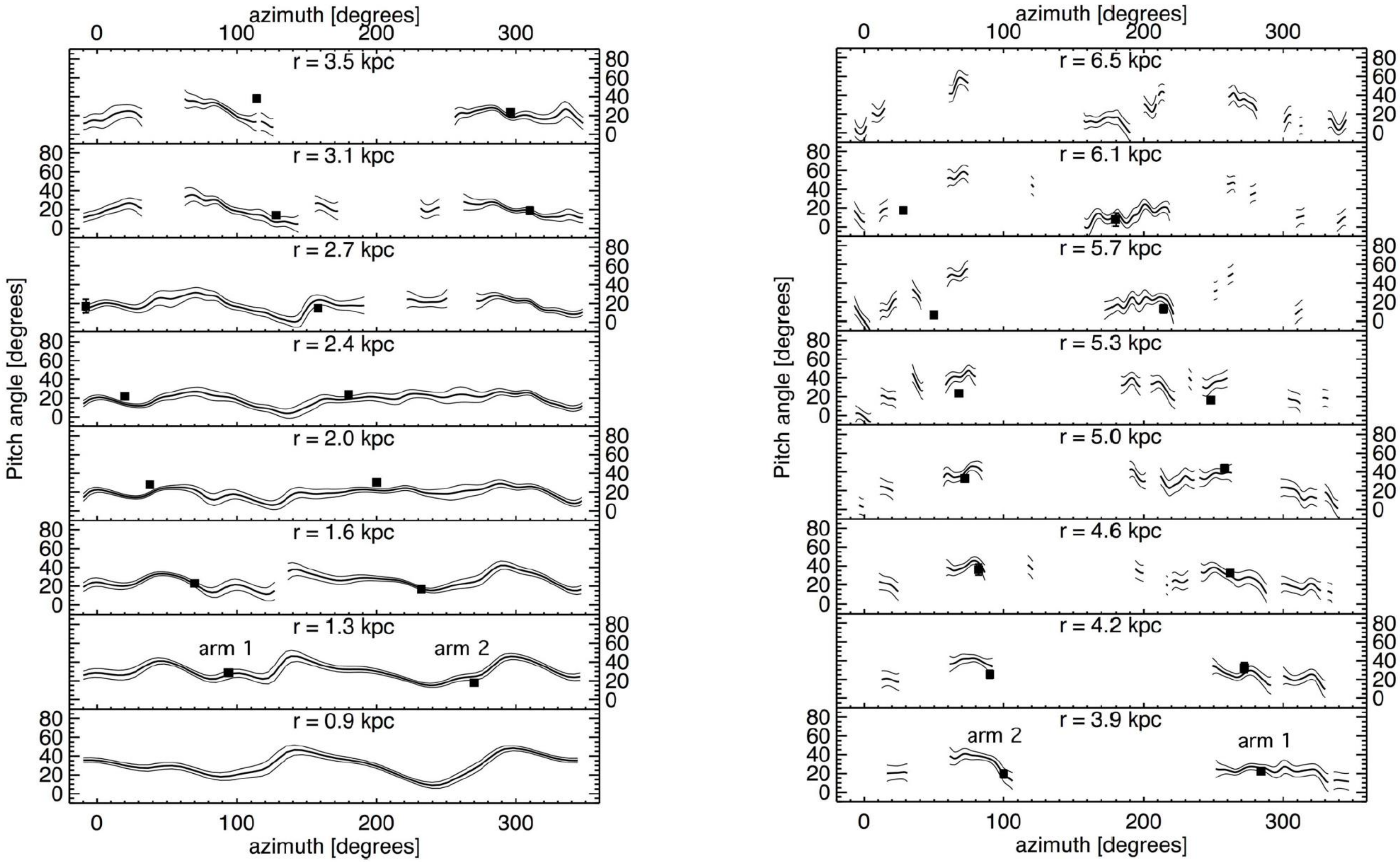
kinematic imprint: |ΔV| ≈ 20 km s^{-1}



does this affect the B-field?

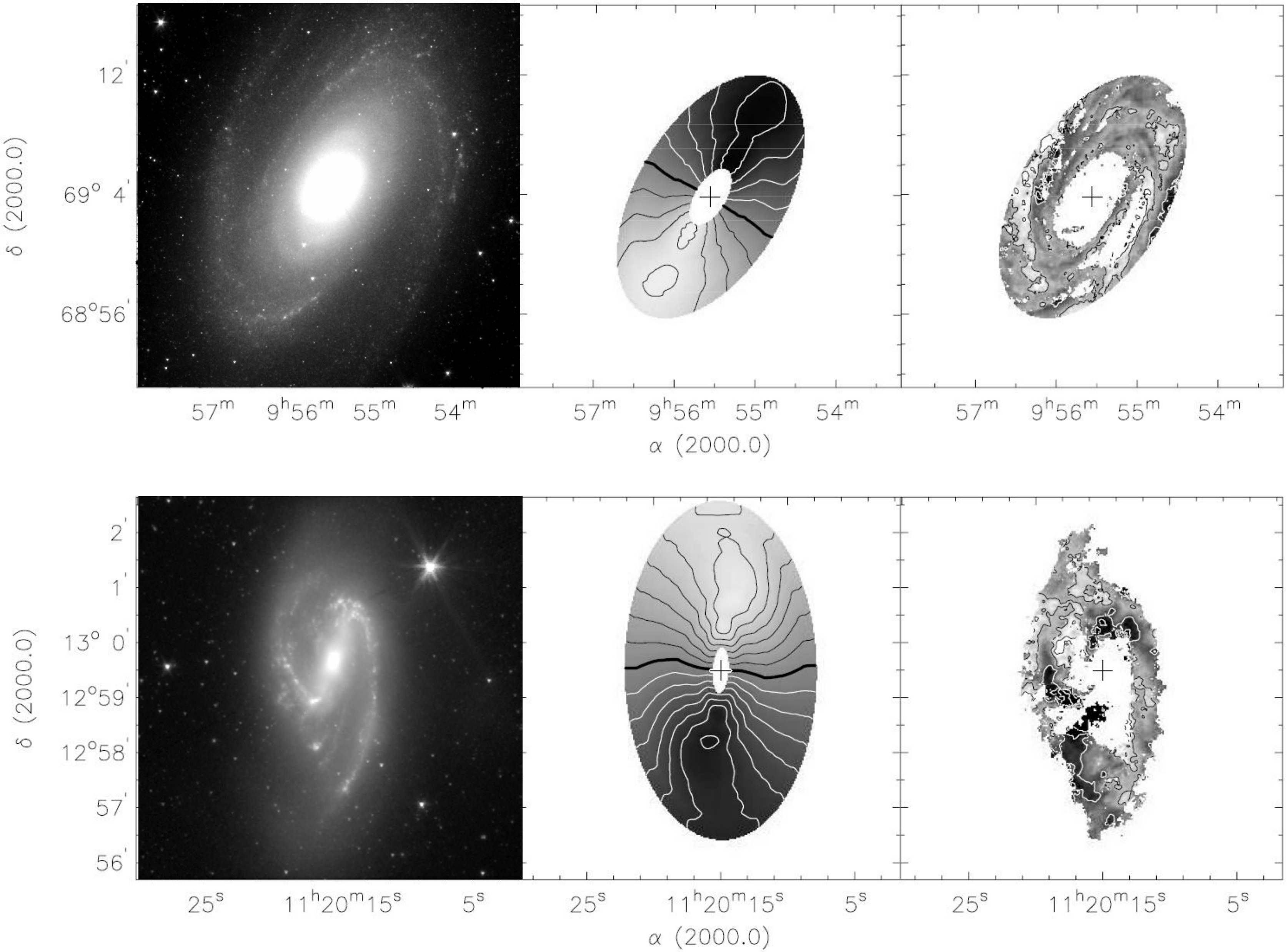


pitch angles of B-field in M 51 (Patrikeev et al. 2006)



⇒ inspect HI data cubes!

de Blok et al. (2008)



construct deprojected velocity vectors from residual velocities and compare with B-field orientation

good candidates:

spirals with pronounced density waves:

M 51, M 81, M 83, NGC 2903

spirals with bars:

NGC 1097, NGC 1365, NGC 3627

THINGS
The HI Nearby
Galaxy Survey
10 kpc
THINGS
Data: Walter et al 2008
Milky Way HI map: Oort et al (1958)
Milky Way art: NASA/JPL, R. Hurt (SSC)