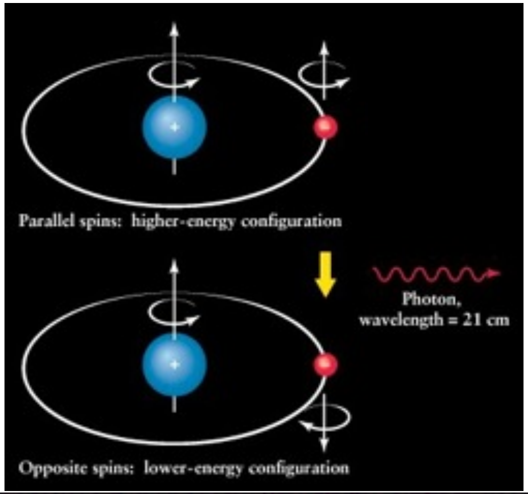
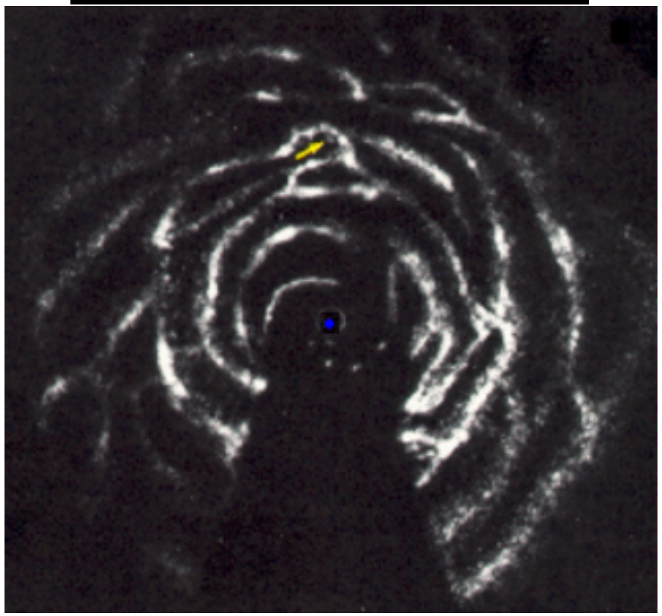
Spectral line radio astronomy

Prediction & detection of HI

- HI - neutral hydrogen hyperfine line - was predicted by van de Hulst (1944)
- Detected at 21 cm by Ewen & Purcell in 1951, and shortly thereafter by Oort & Muller (at Kootwijk, NL)

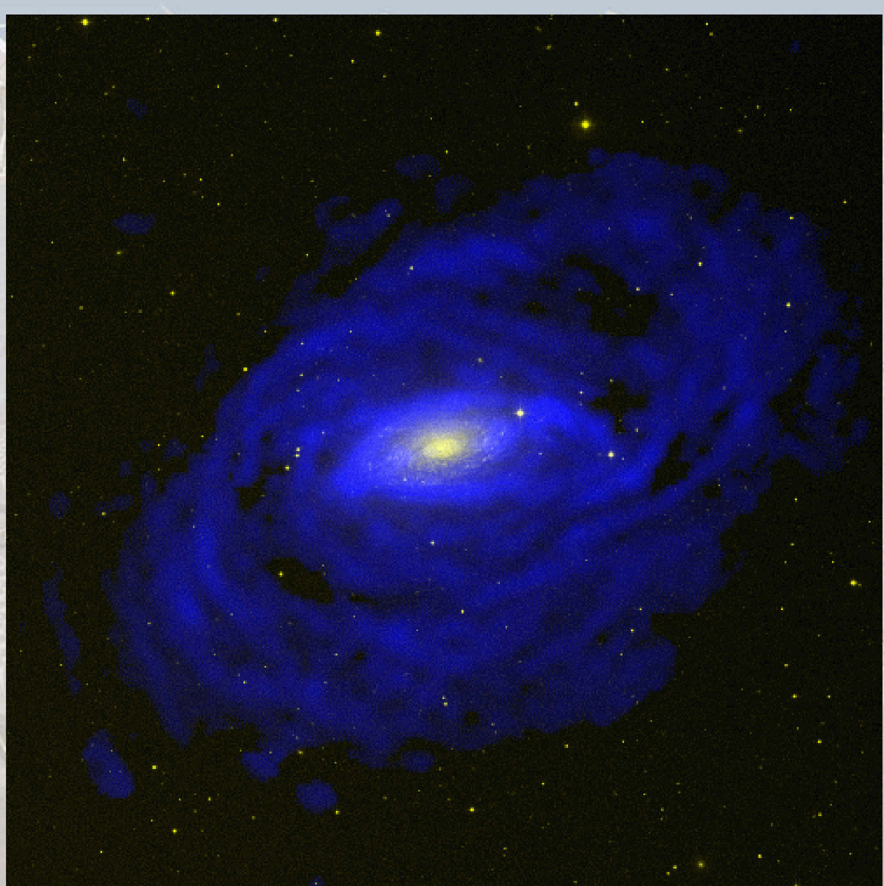




Wurzburg "Riese" Radar Antenna, 7.5 m diameter

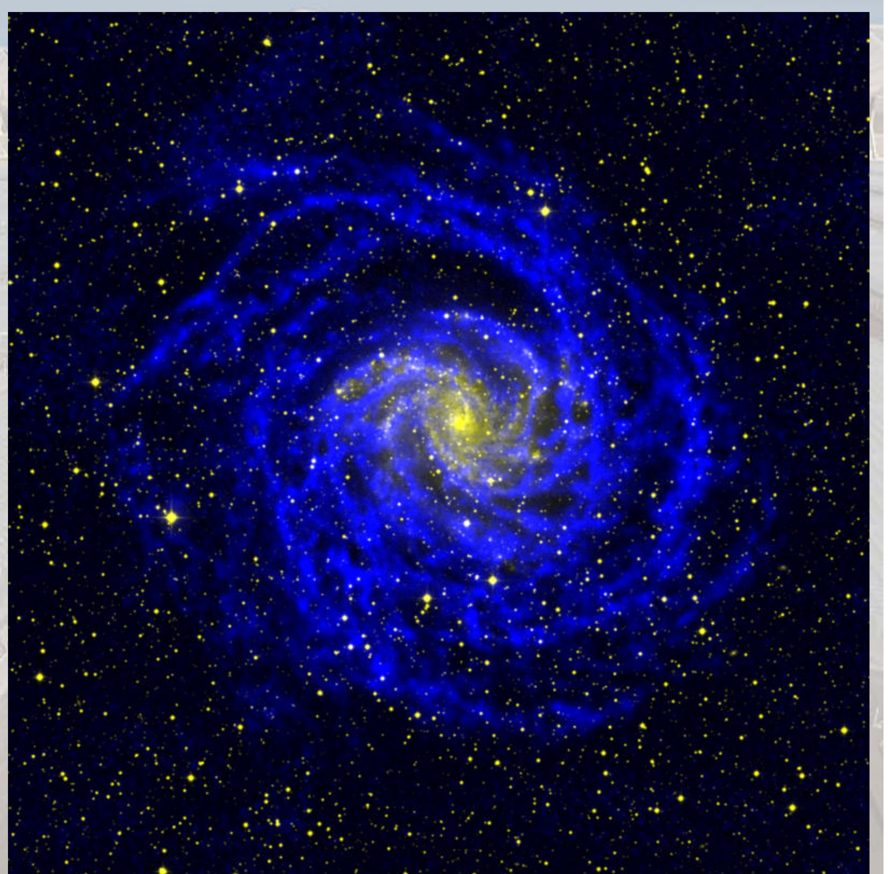
HI in galaxies

NGC 5055



Battaglia, Fraternali, Oosterloo and Sancisi 2006 A&A, 447, 49

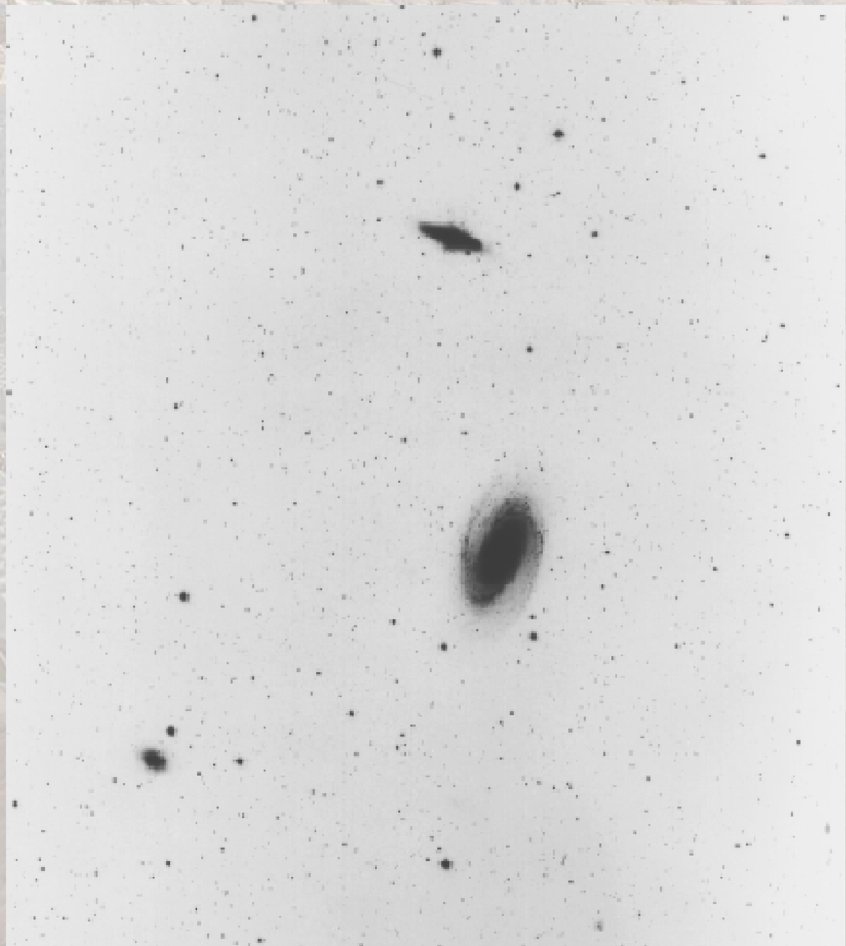
NGC 6946



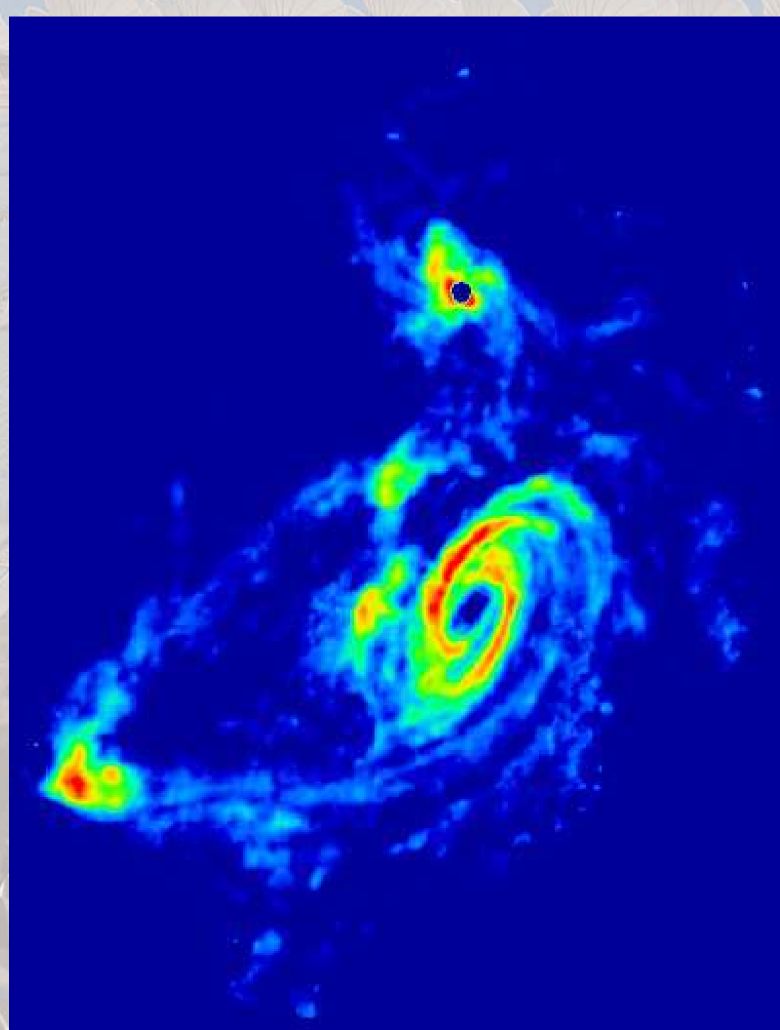
Boomsma, Oosterloo, Sancisi and van der Hulst, 2008 A&A, 490, 555

Messier 81

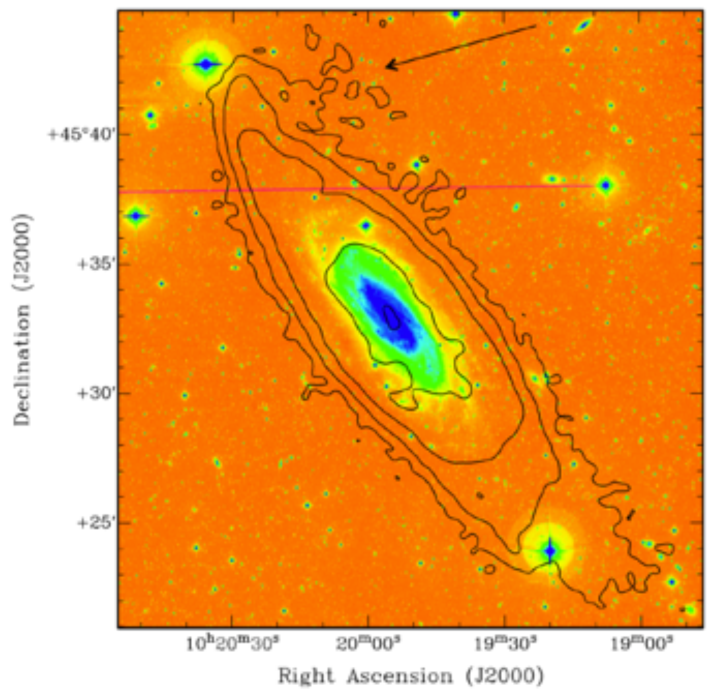
Optical

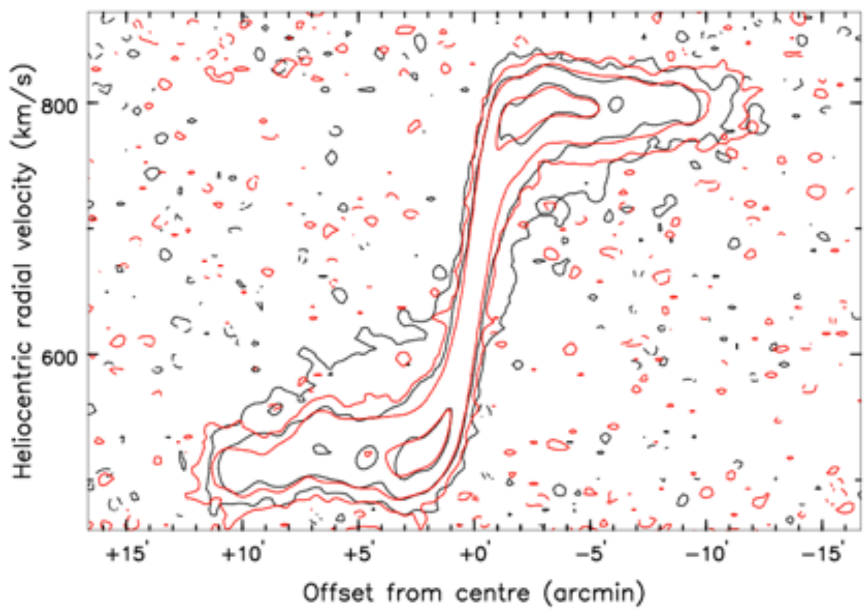


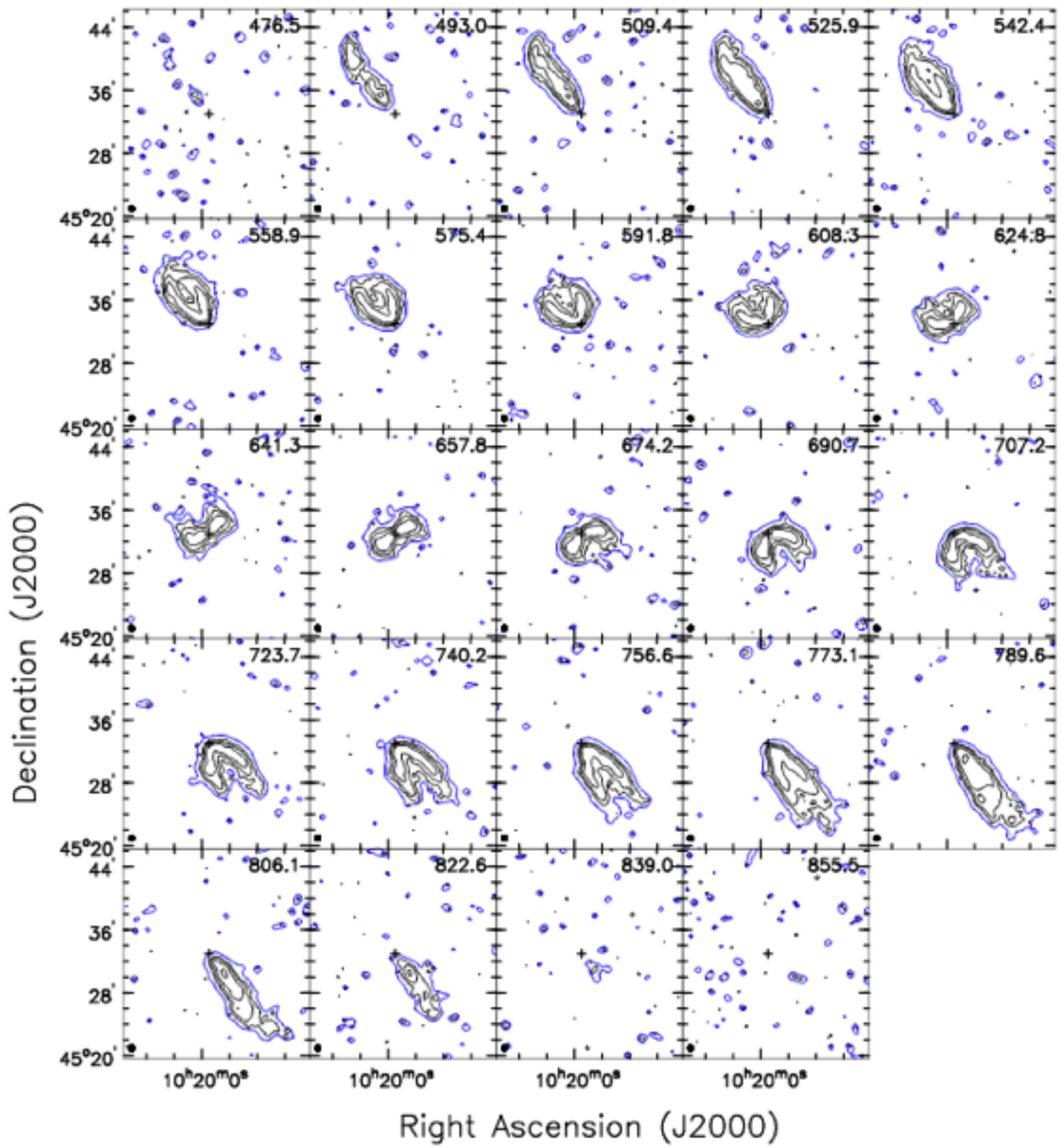
Neutral Hydrogen

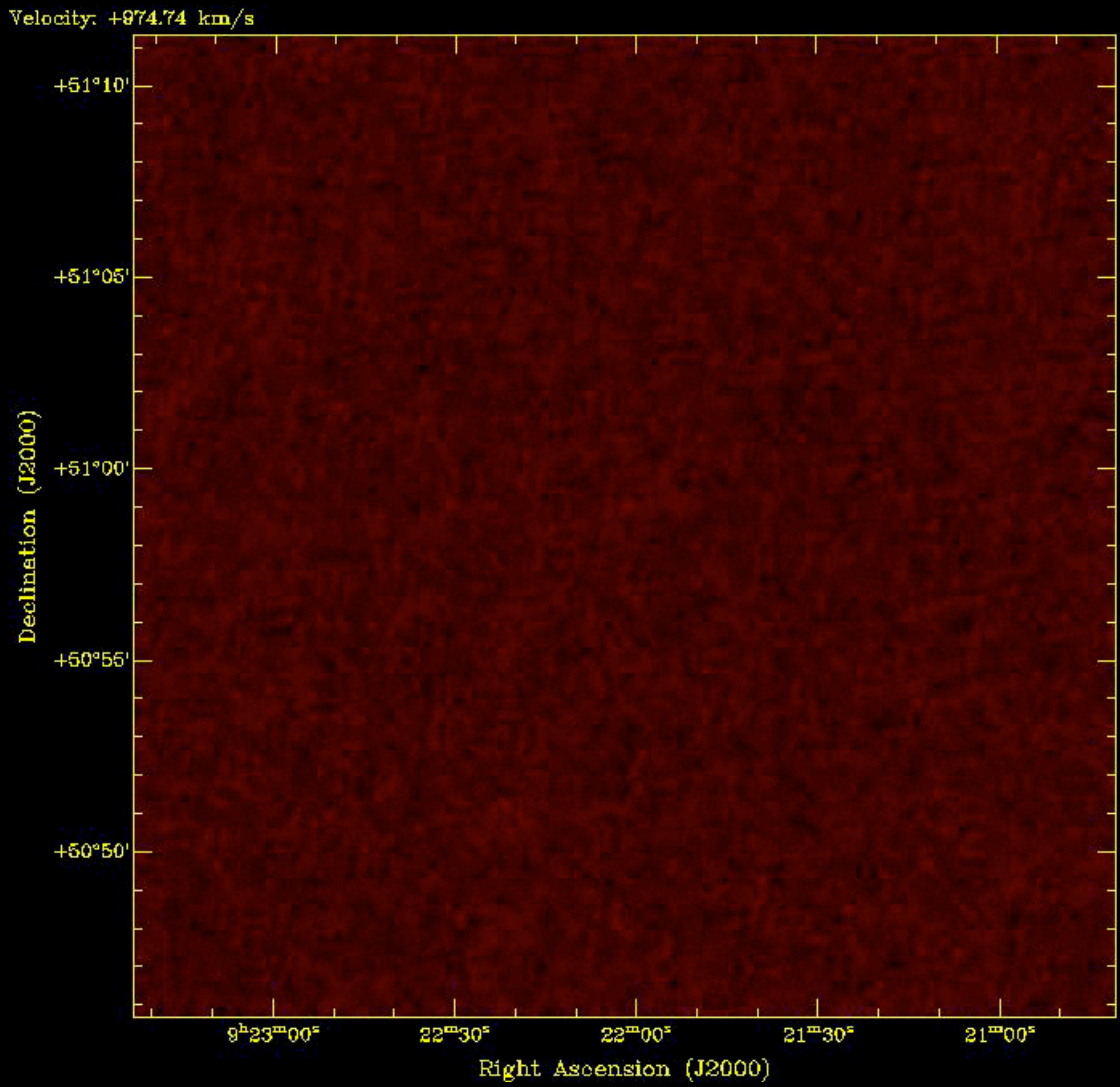


Galaxies in HI: Velocity information

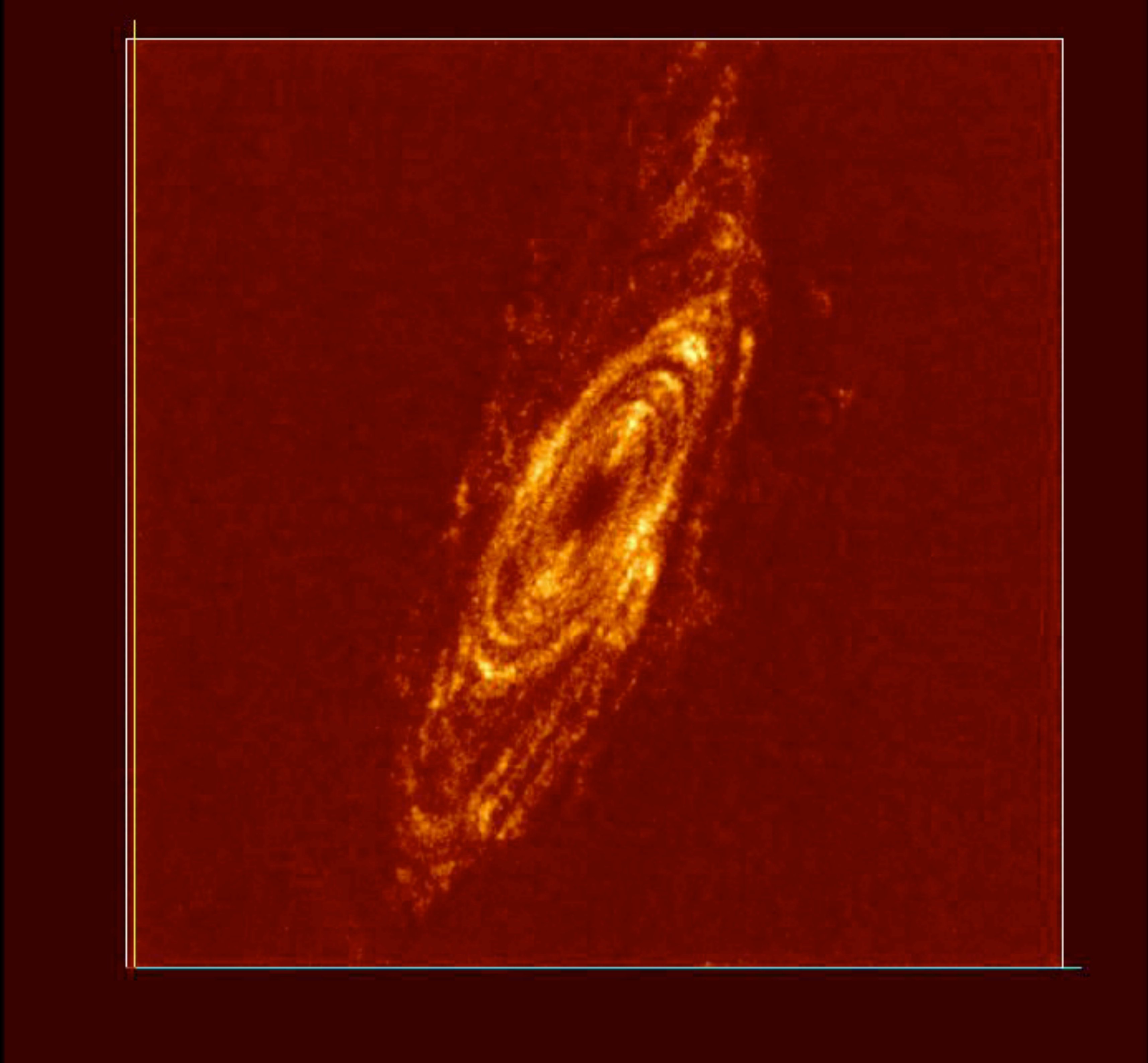








NGC 2841 THINGS
natural weighted data cube



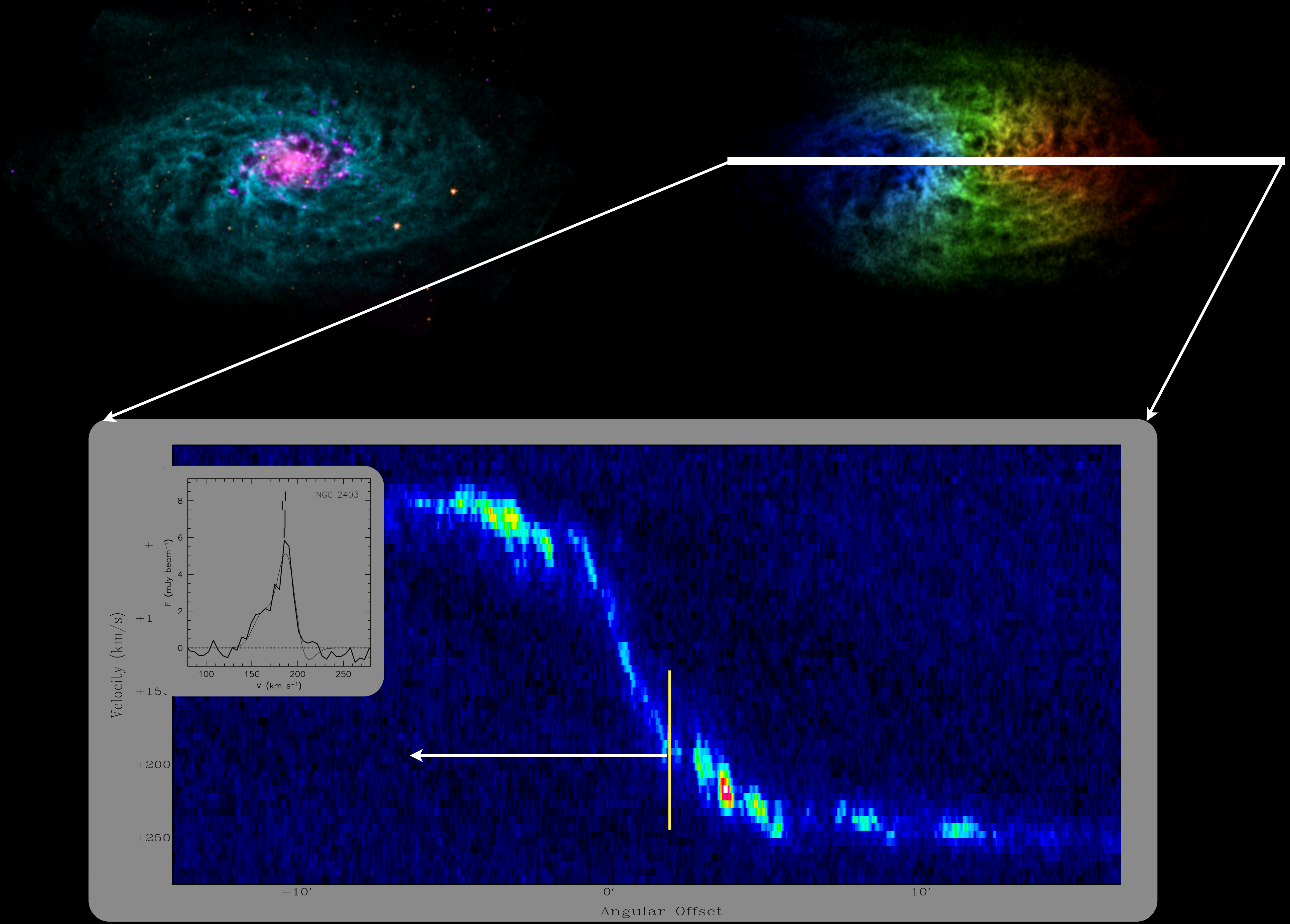
Moments

- How to characterise the kinematics of a galaxy?

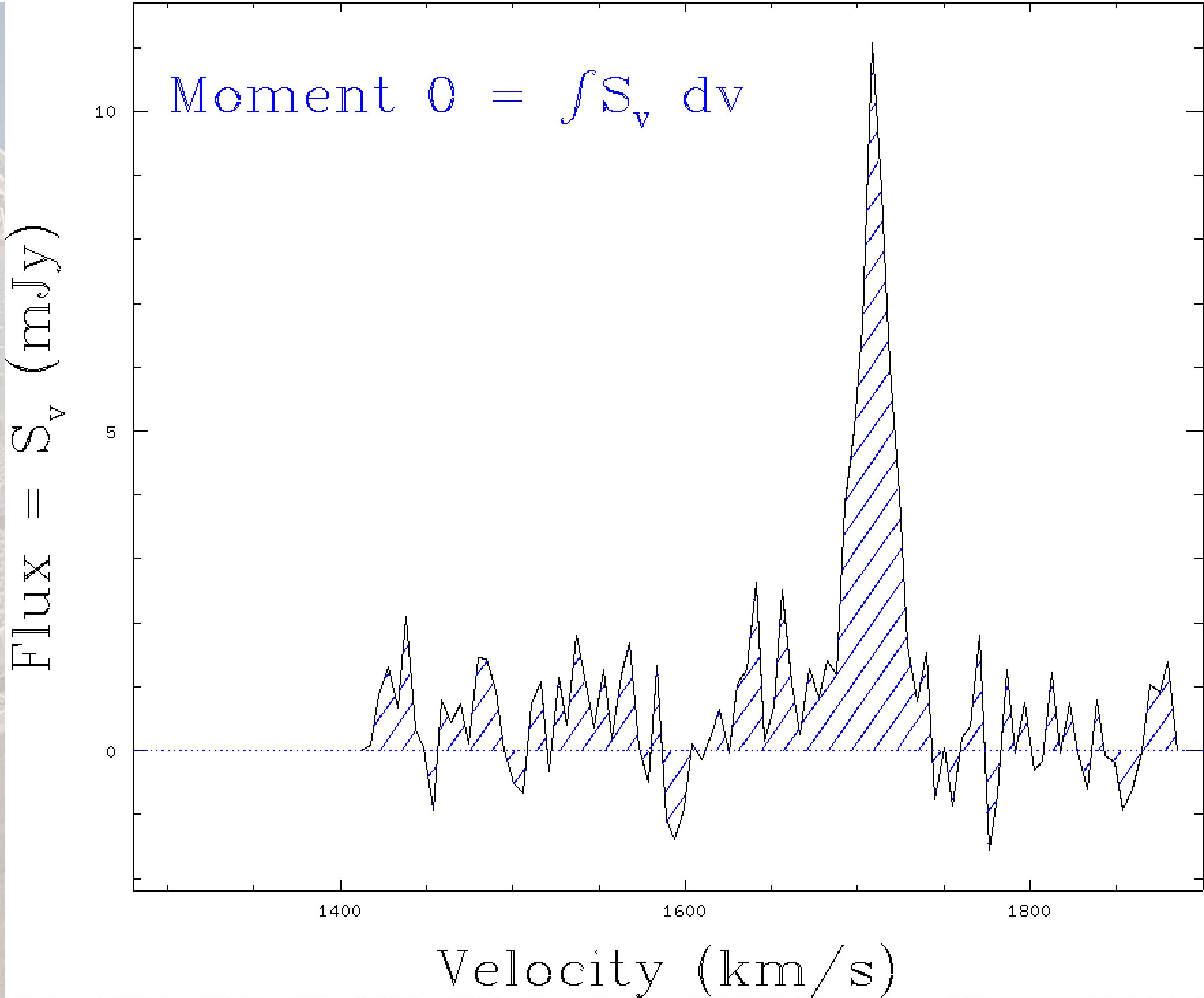
- Can use full 3D modelling, but expensive and many free parameters

- Use velocity profile moments
  - mom0 : flux
  - mom1 : velocity
  - mom2 : dispersion

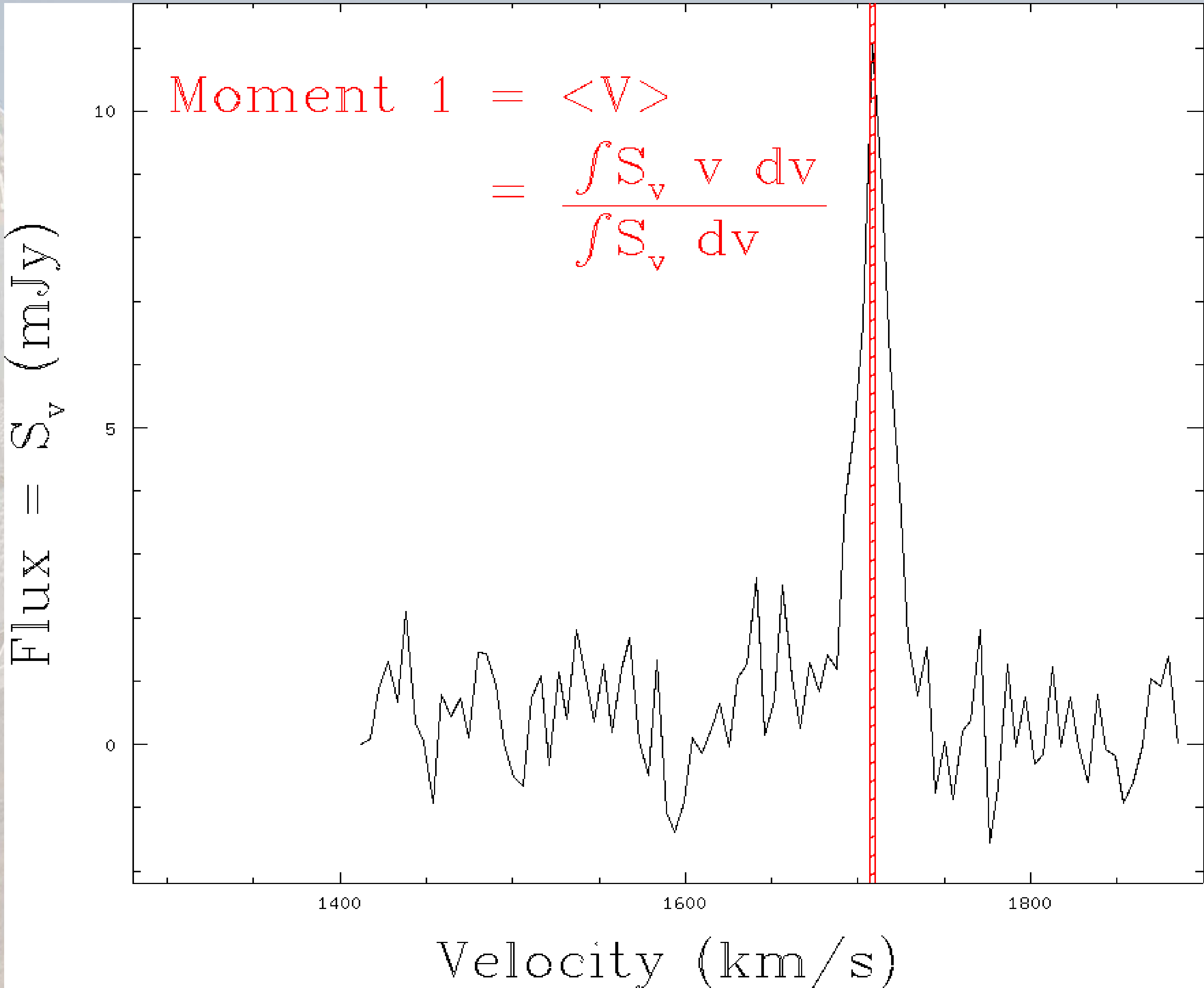
major axis position velocity diagram of NGC 2403



Moment 0

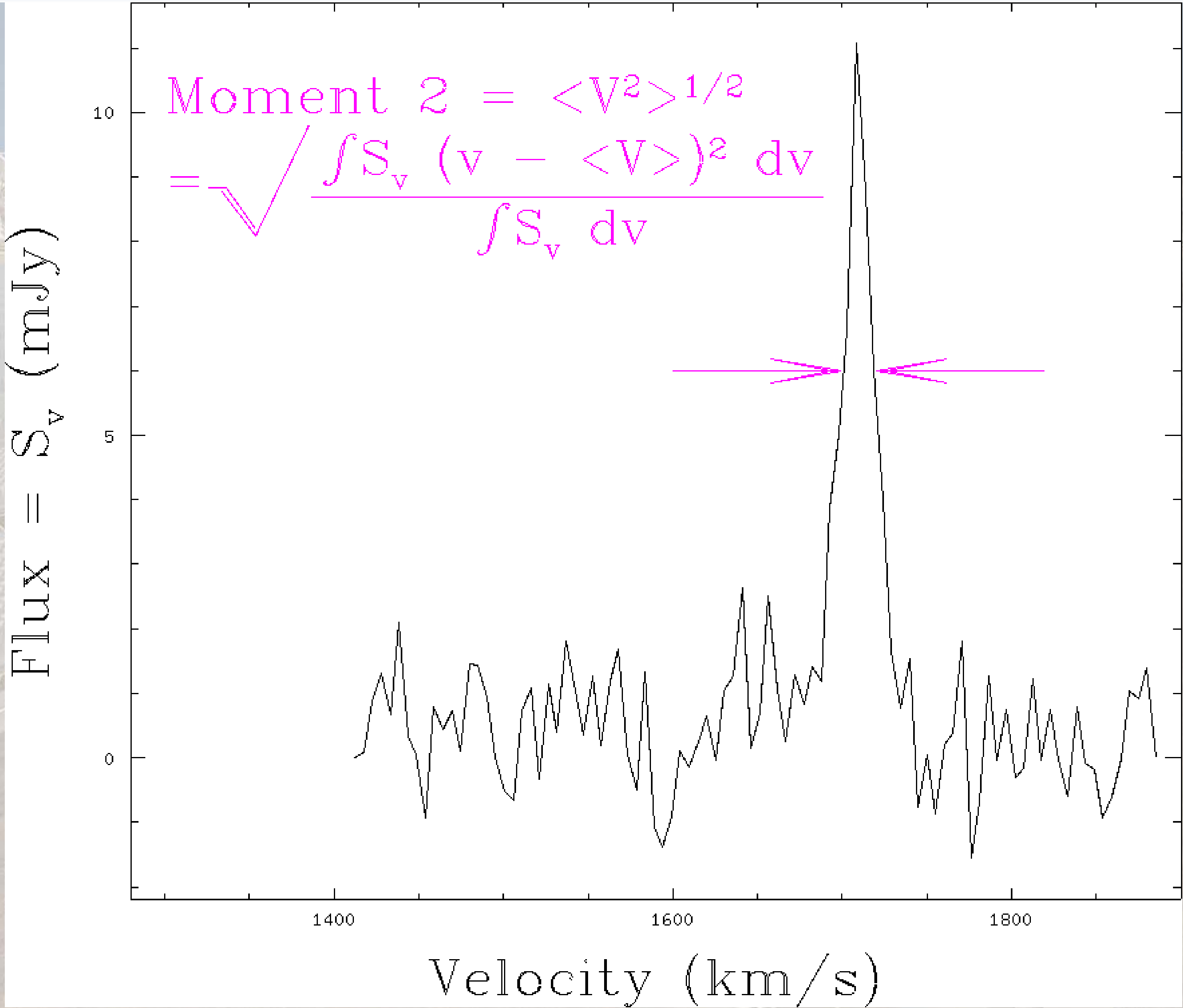


Moment 1



Moment 1 = <V>
$= \frac{\int S_v \, v \, dv}{\int S_v \, dv}$
Flux = S_v (mJy)
Velocity (km/s)
10
5
0
1400
1600
1800

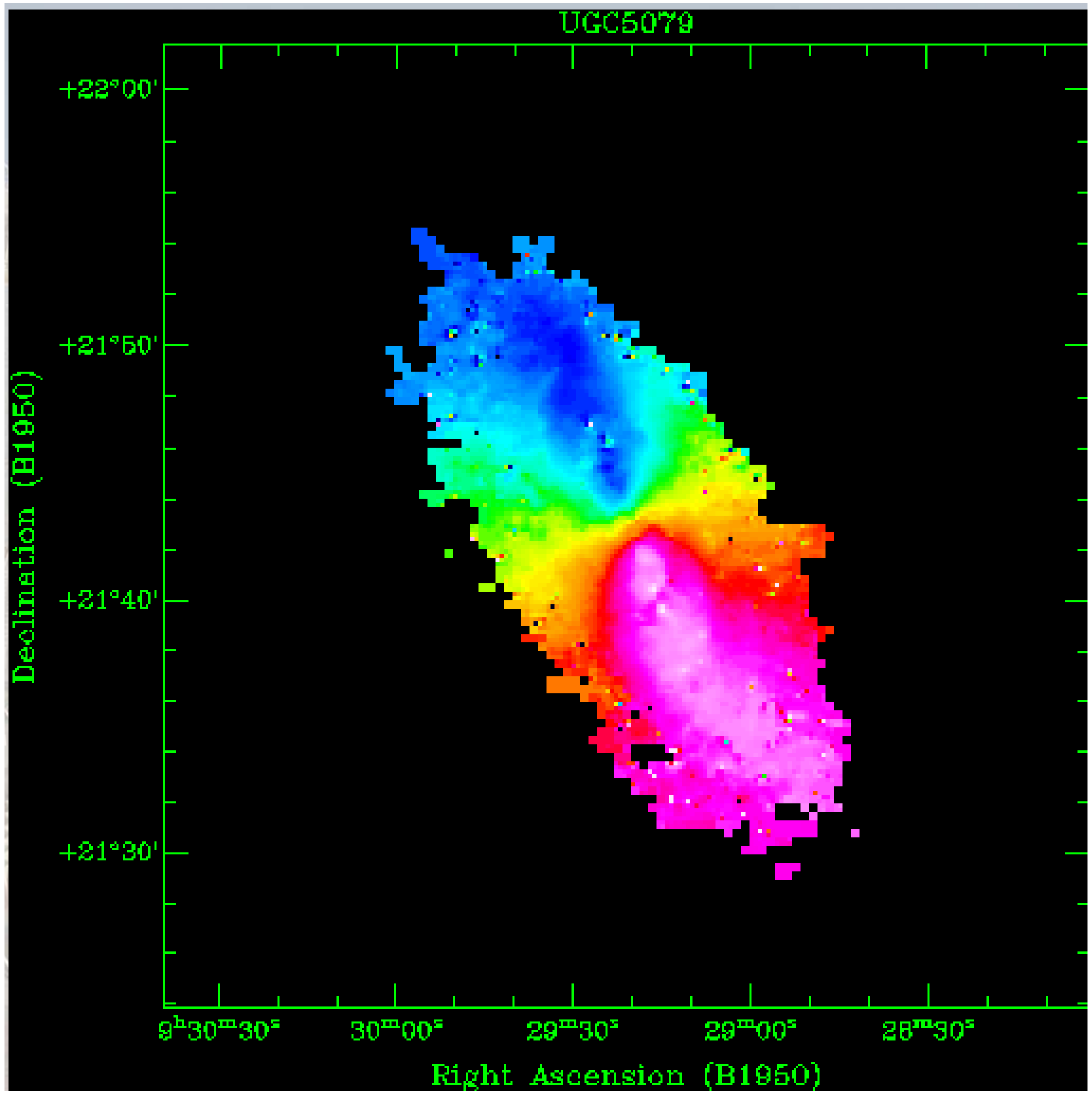
Moment 2



Moment 2 = <V²>^1/2
= √(∫S_v (v − <V>)² dv / ∫S_v dv)
10
5
0
1400
1600
1800
Flux = S_v (mJy)
Velocity (km/s)

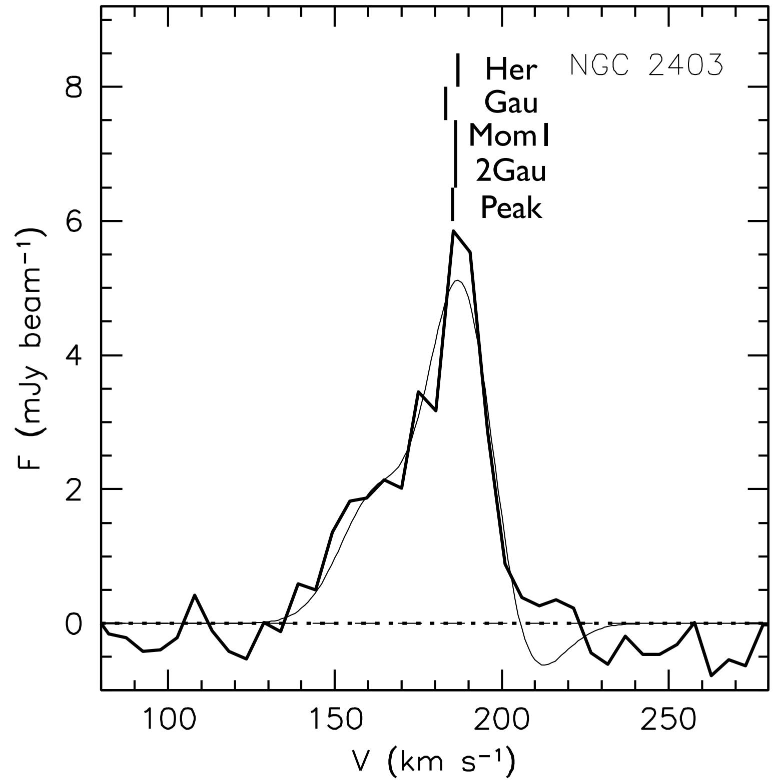
Velocity field

- Map of first-moment values is the “velocity field”
- Used for modelling kinematics

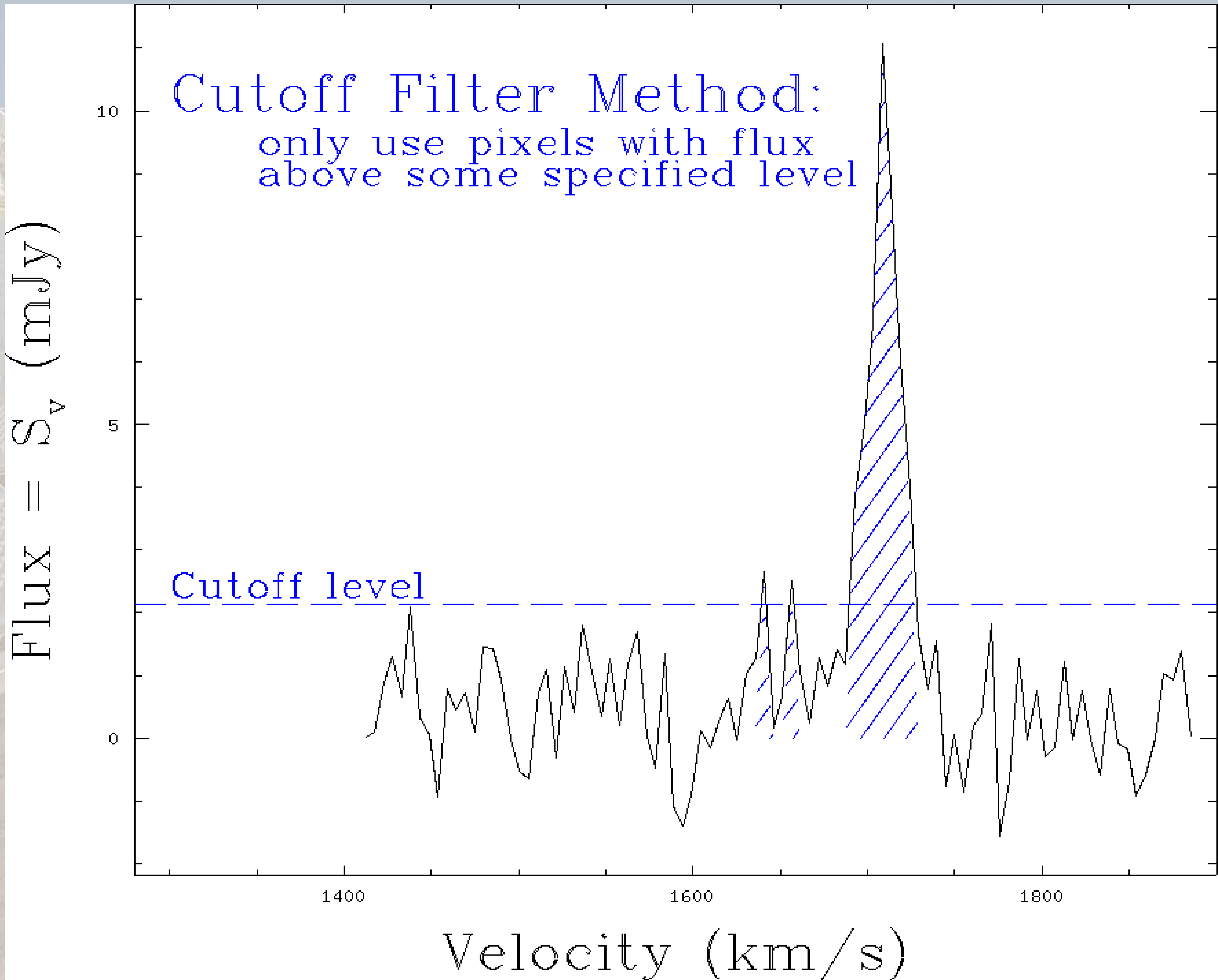


From 3D to 2D

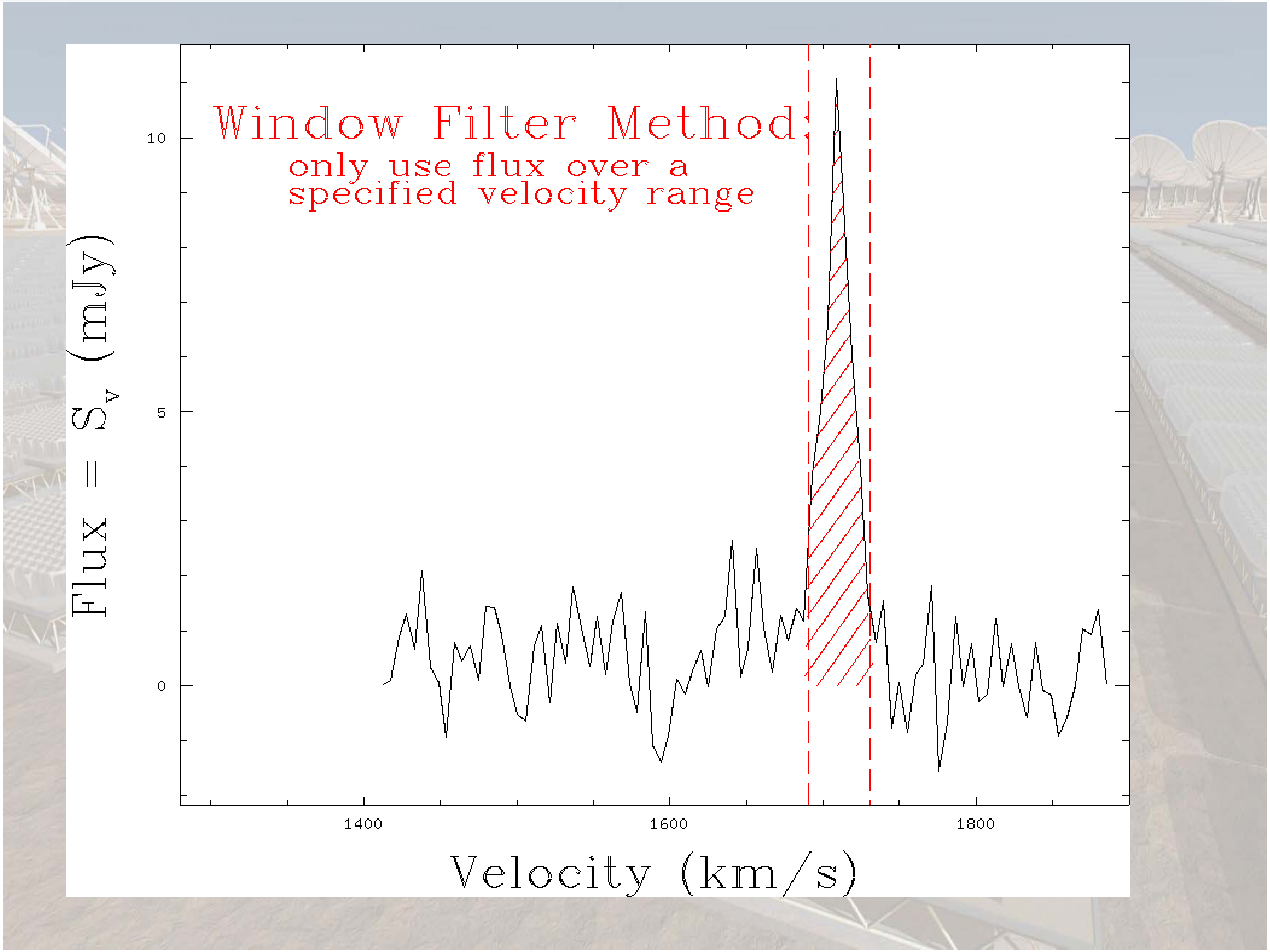
- Not all profiles symmetrical
- Need to define a "typical" velocity
- Choice has impact on velocity field
- Consider:
  - first-moment
  - single gaussian
  - double gaussian
  - peak velocity
  - third-order hermite polynomial



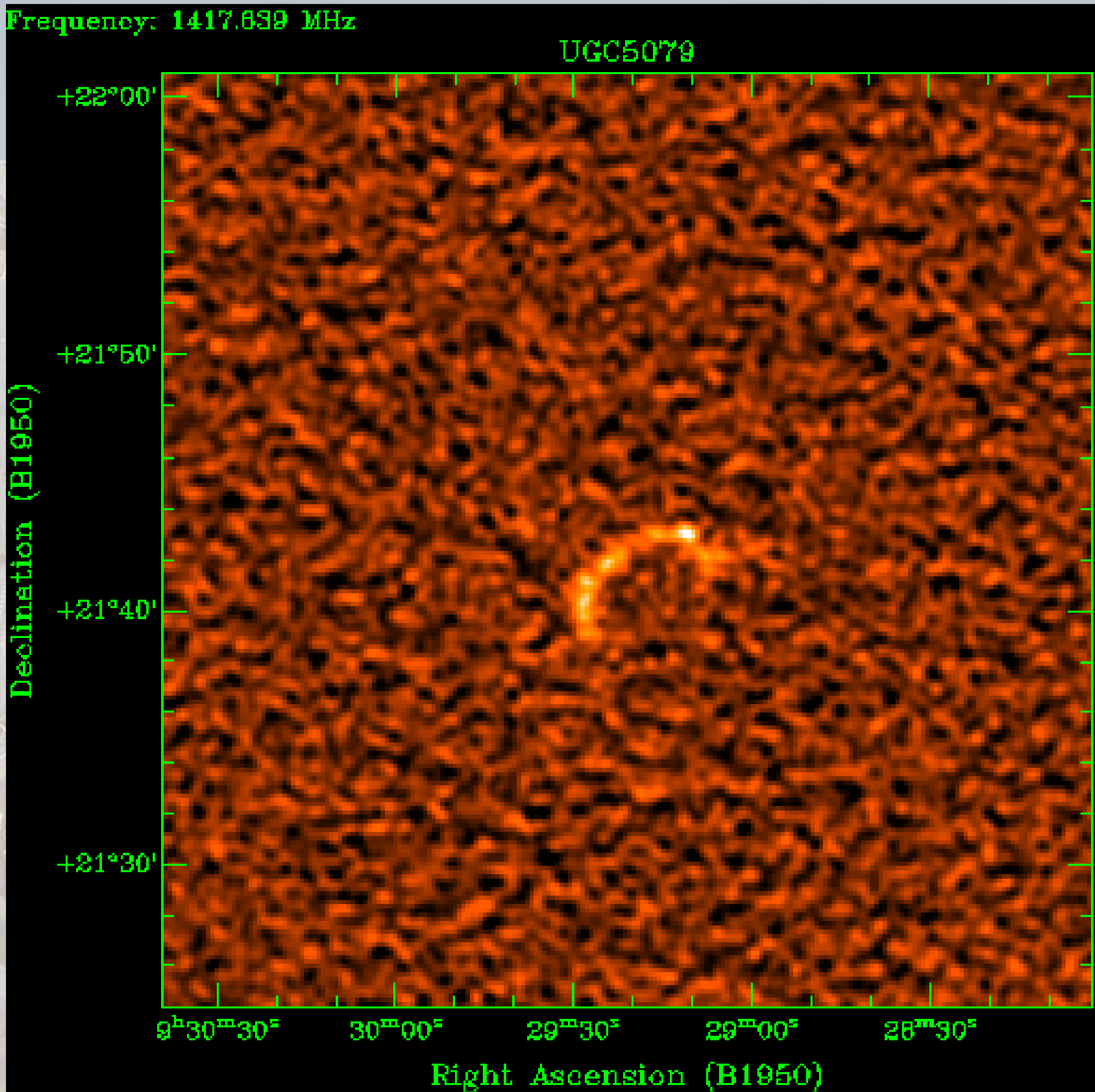
Making velocity fields I



Making velocity fields II

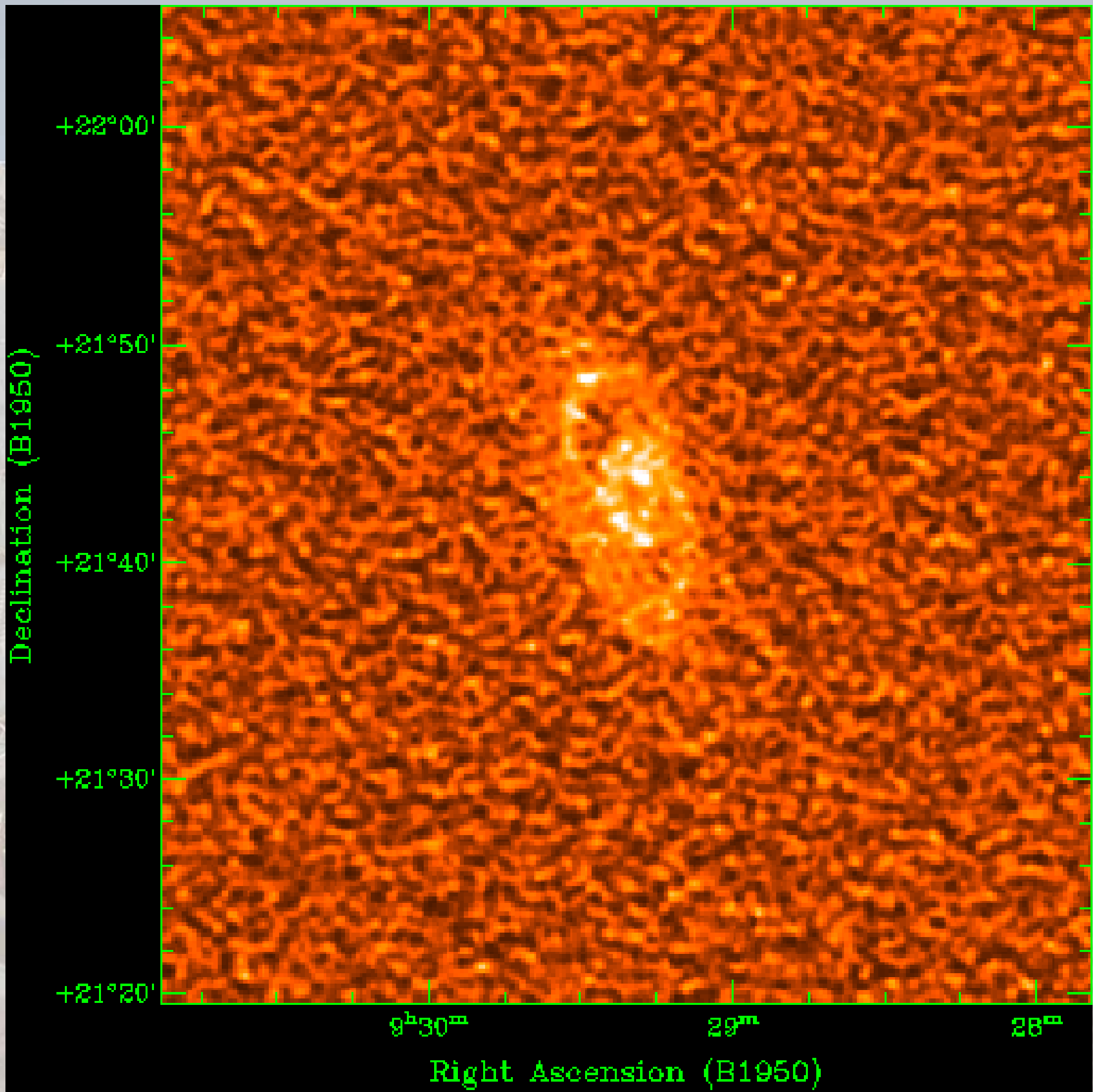


cleaned
line map



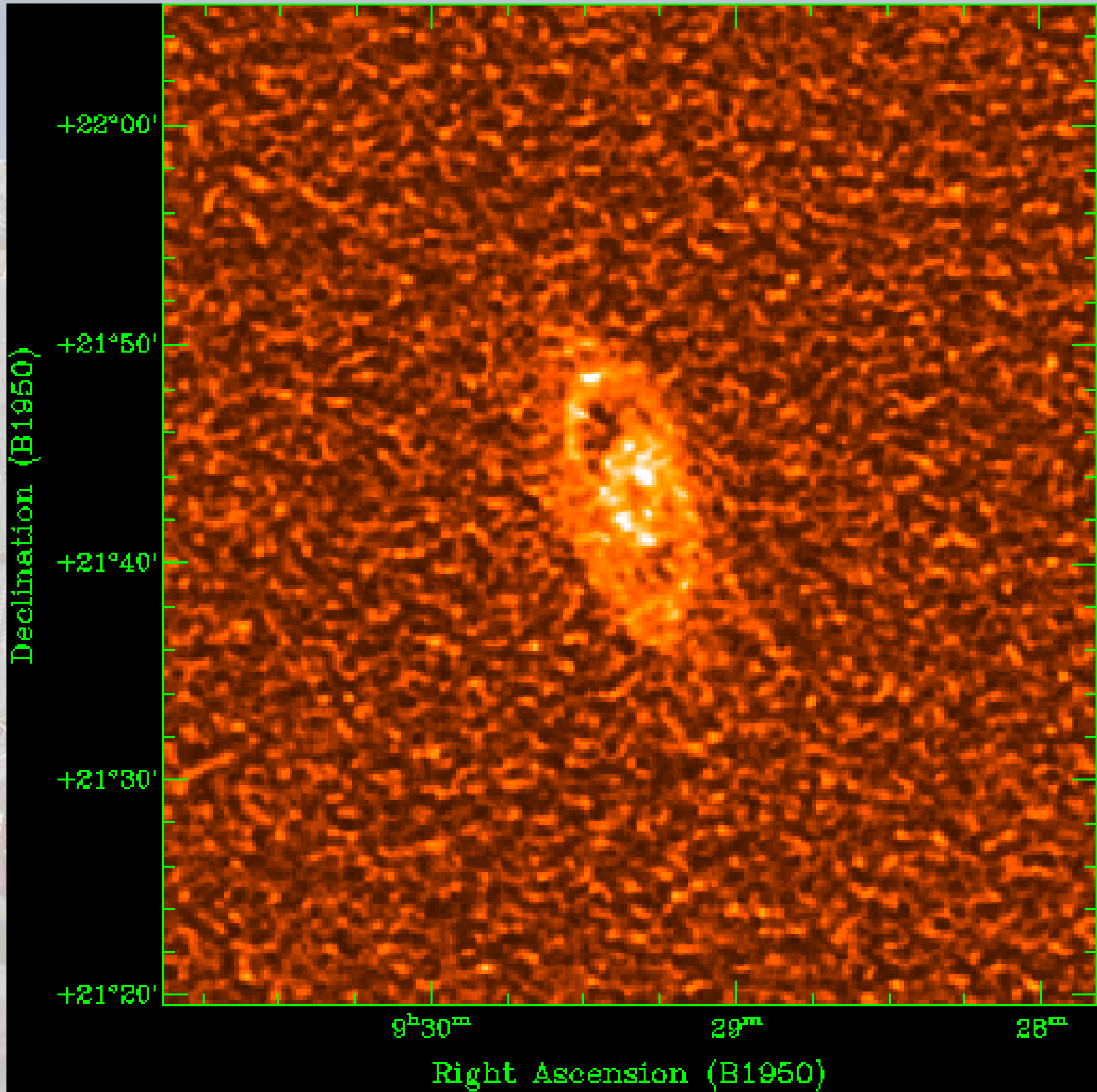
cut-off

1σ



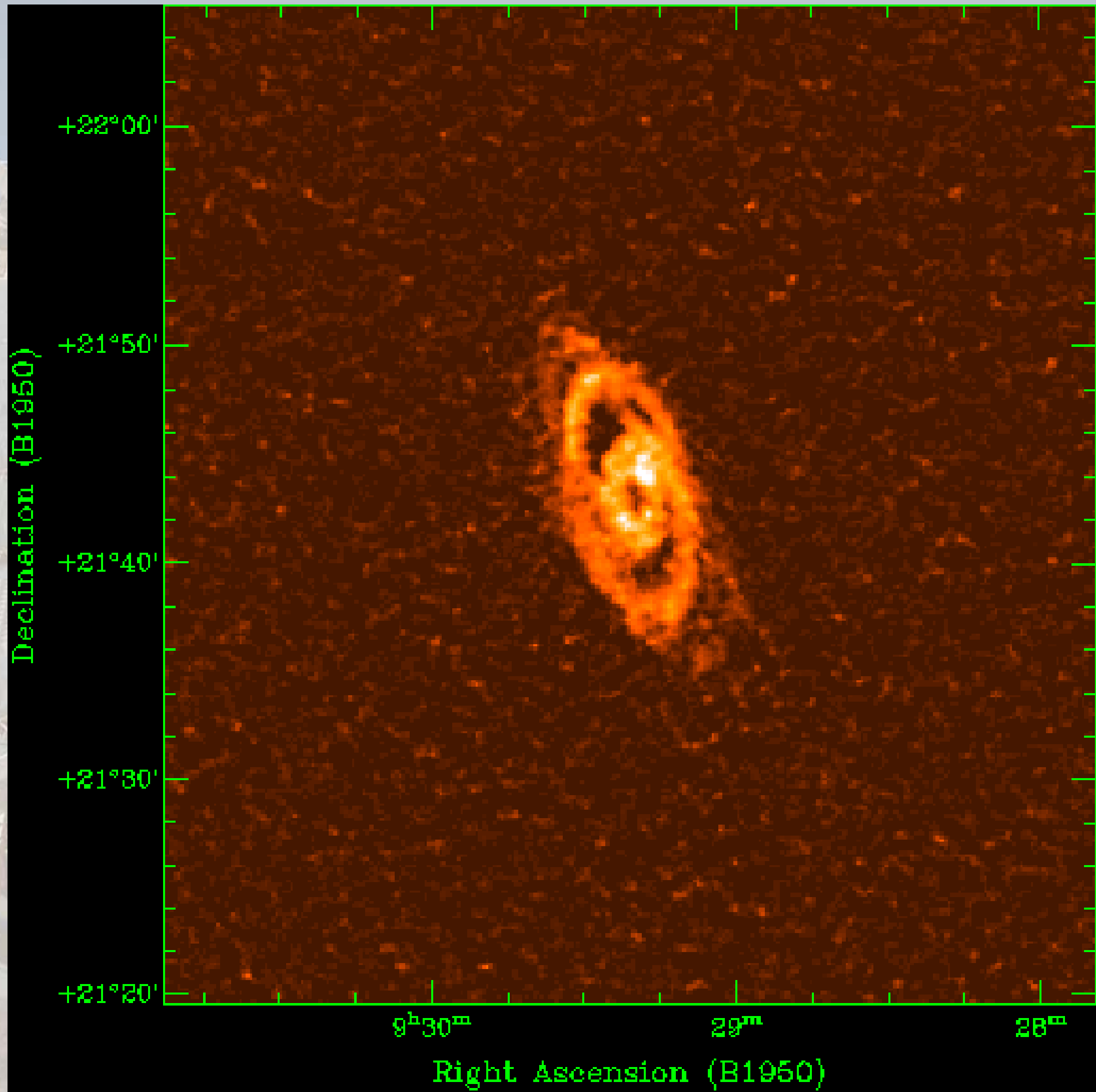
cut-off

2σ



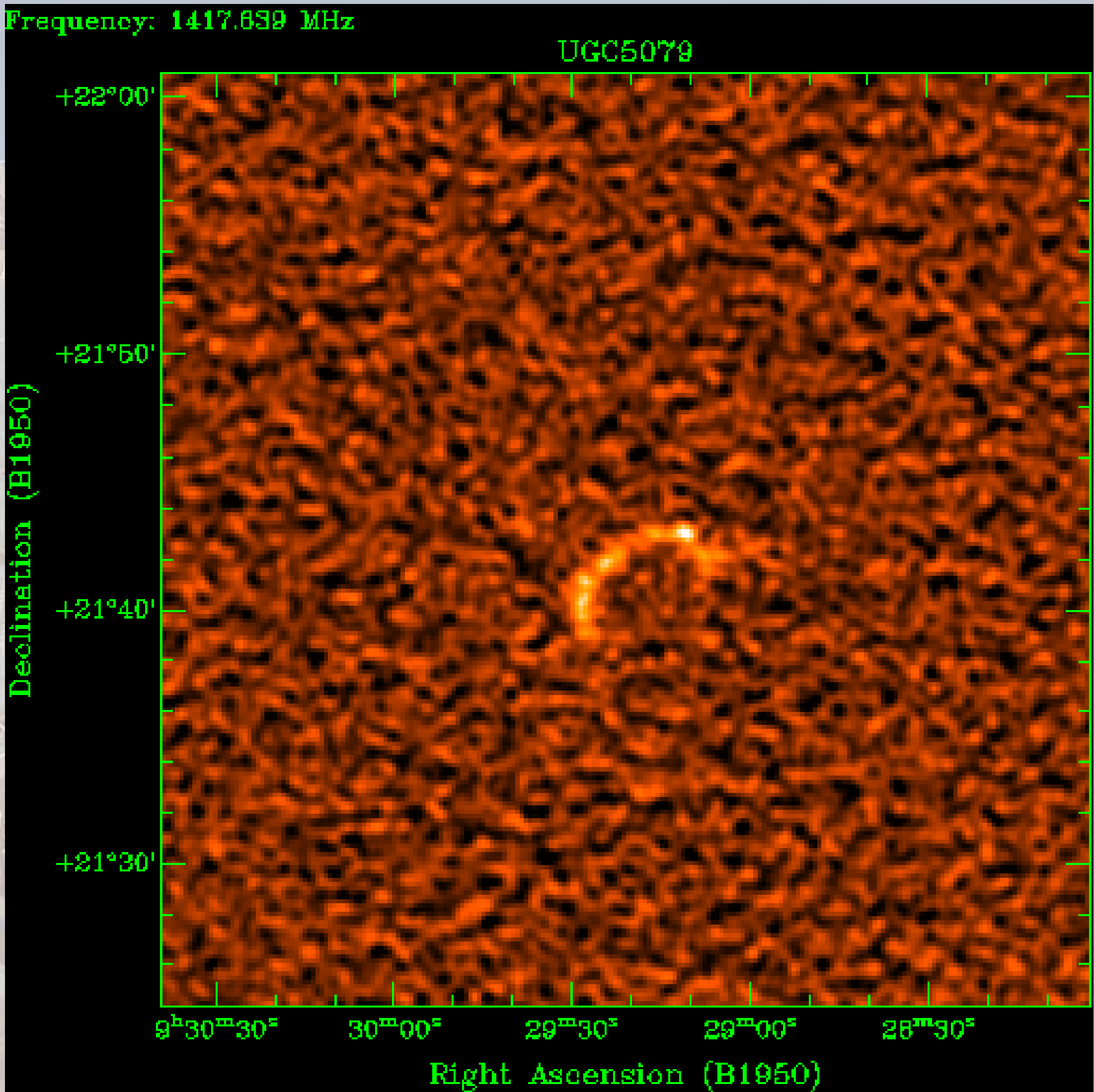
+22°00'
+21°50'
+21°40'
+21°30'
+21°20'
Declination (B1950)
9h30m
29m
28m
Right Ascension (B1950)

cut-off
4σ

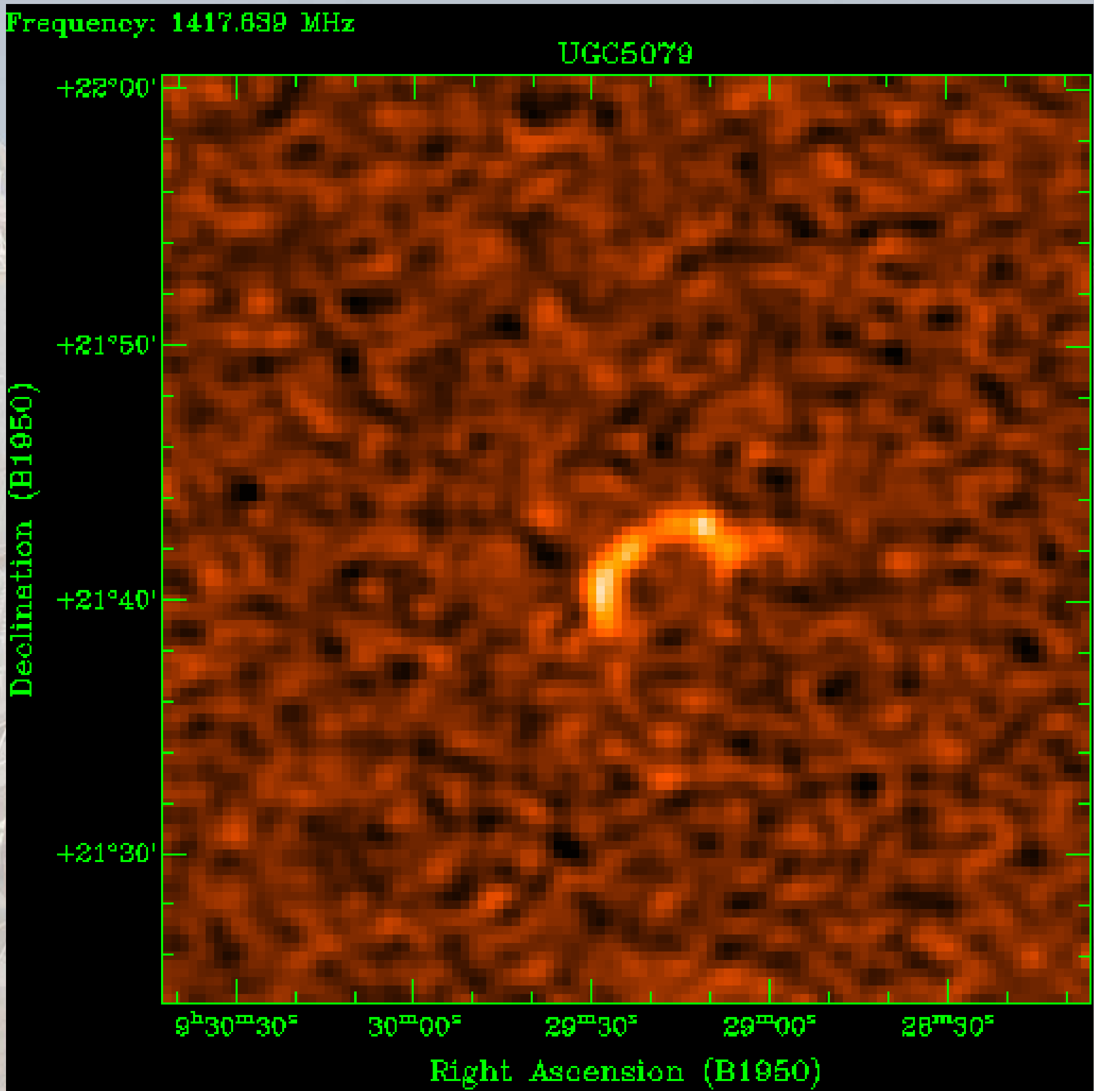


+22°00'
+21°50'
+21°40'
+21°30'
+21°20'
Declination (B1950)
9h30m
29m
28m
Right Ascension (B1950)

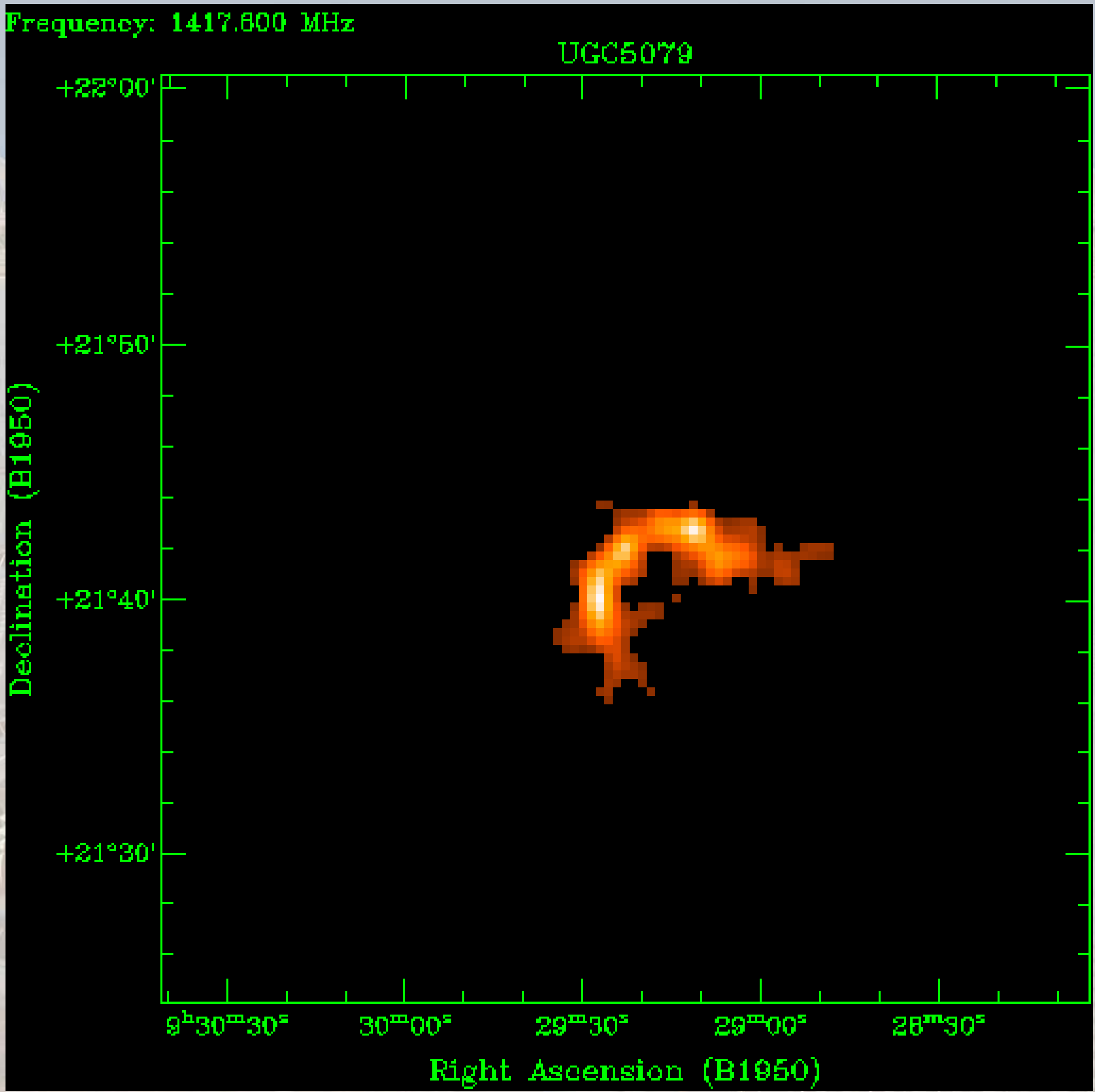
cleaned
line map



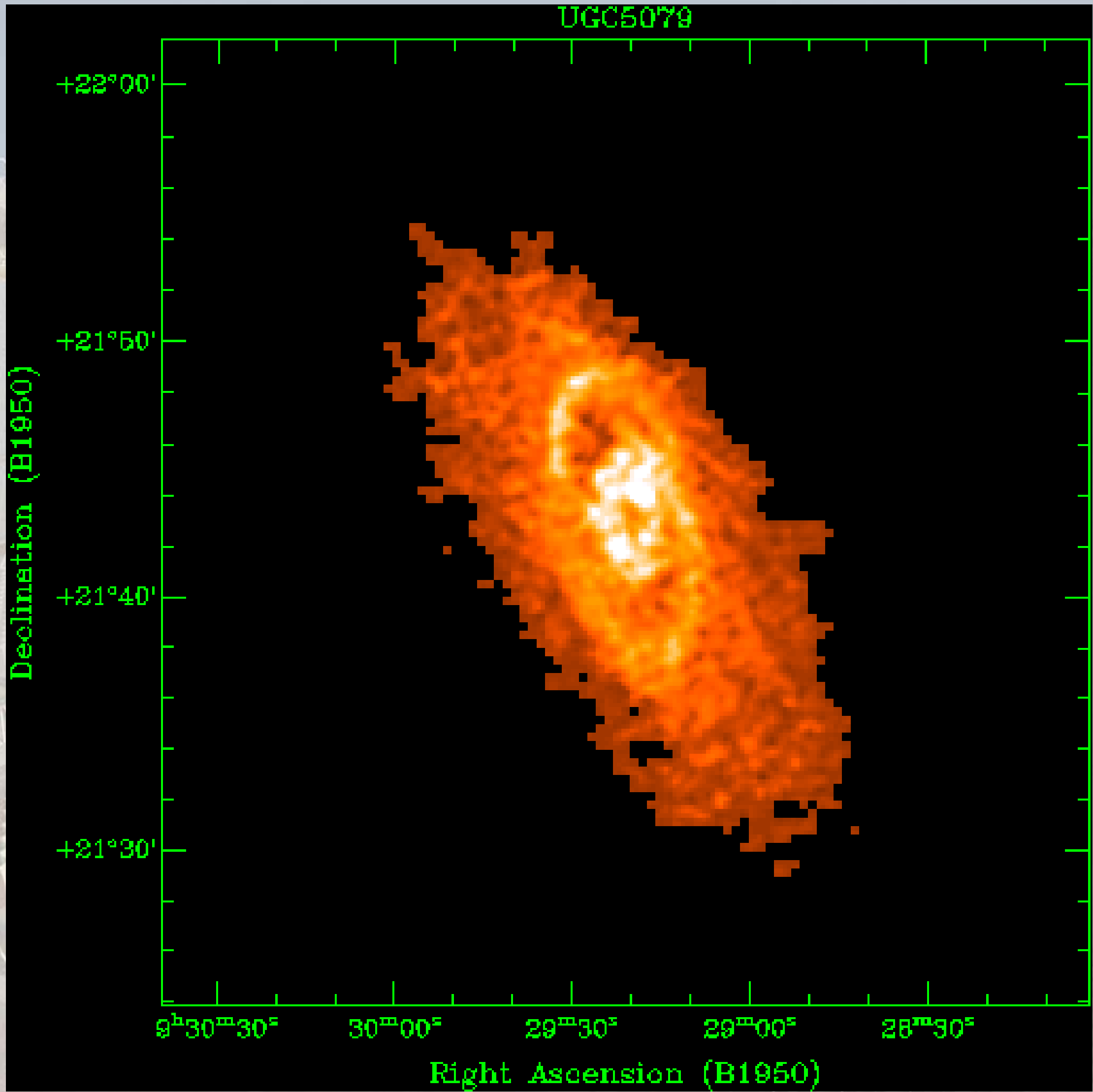
smoothed line map



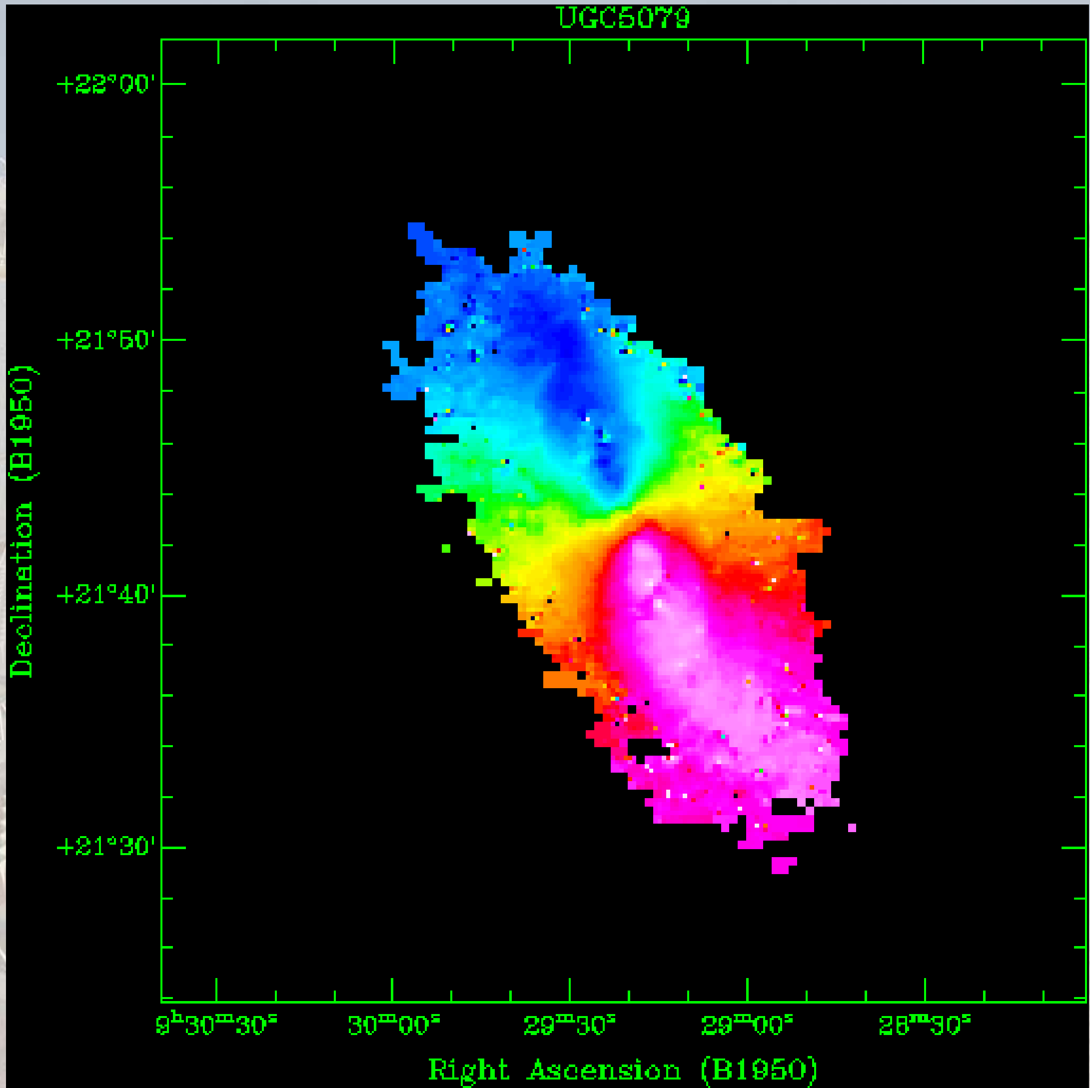
mask from smoothed map



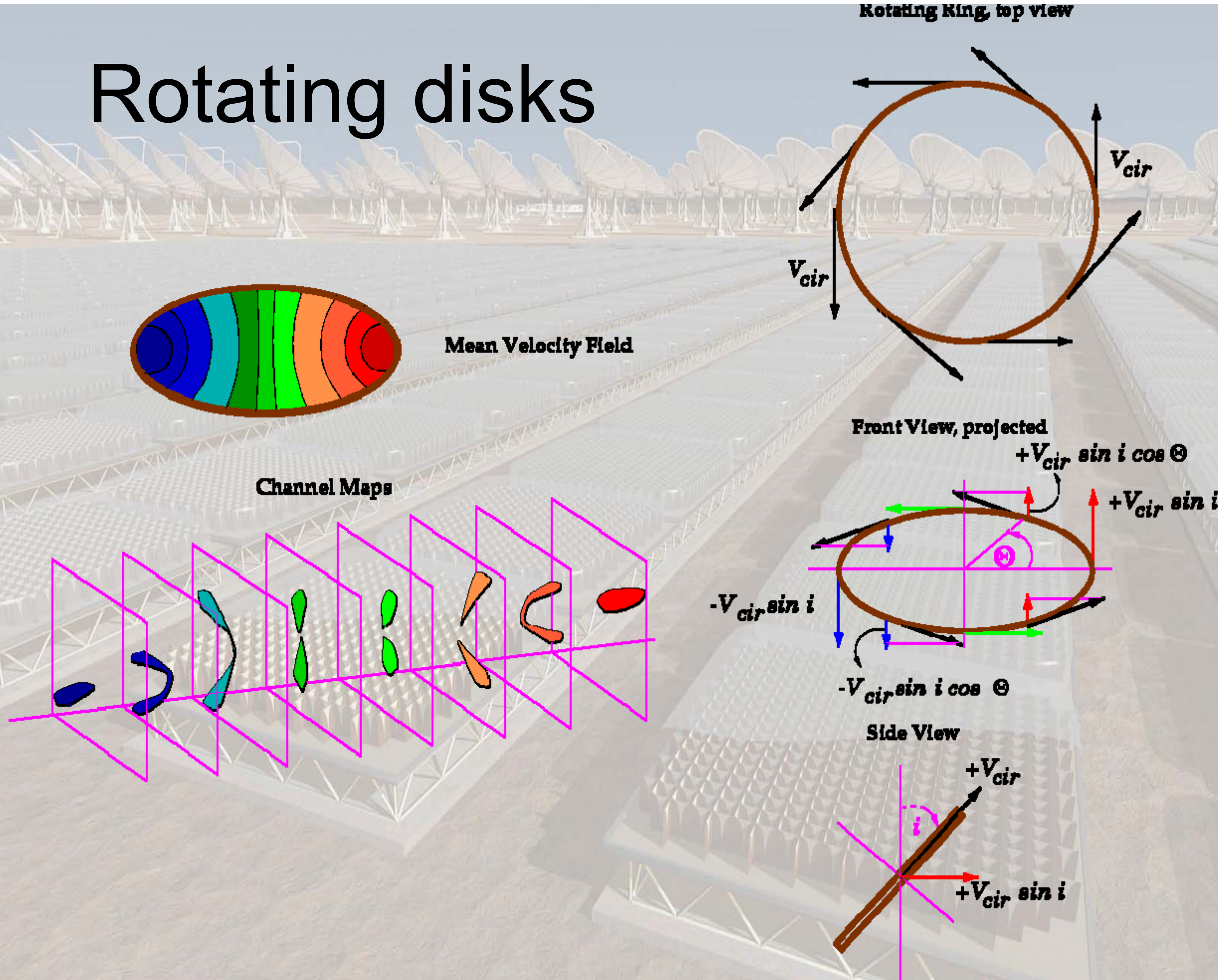
0^{th} moment + masking



1st moment
+ masking



Rotating disks



But the moment analysis is restrictive.

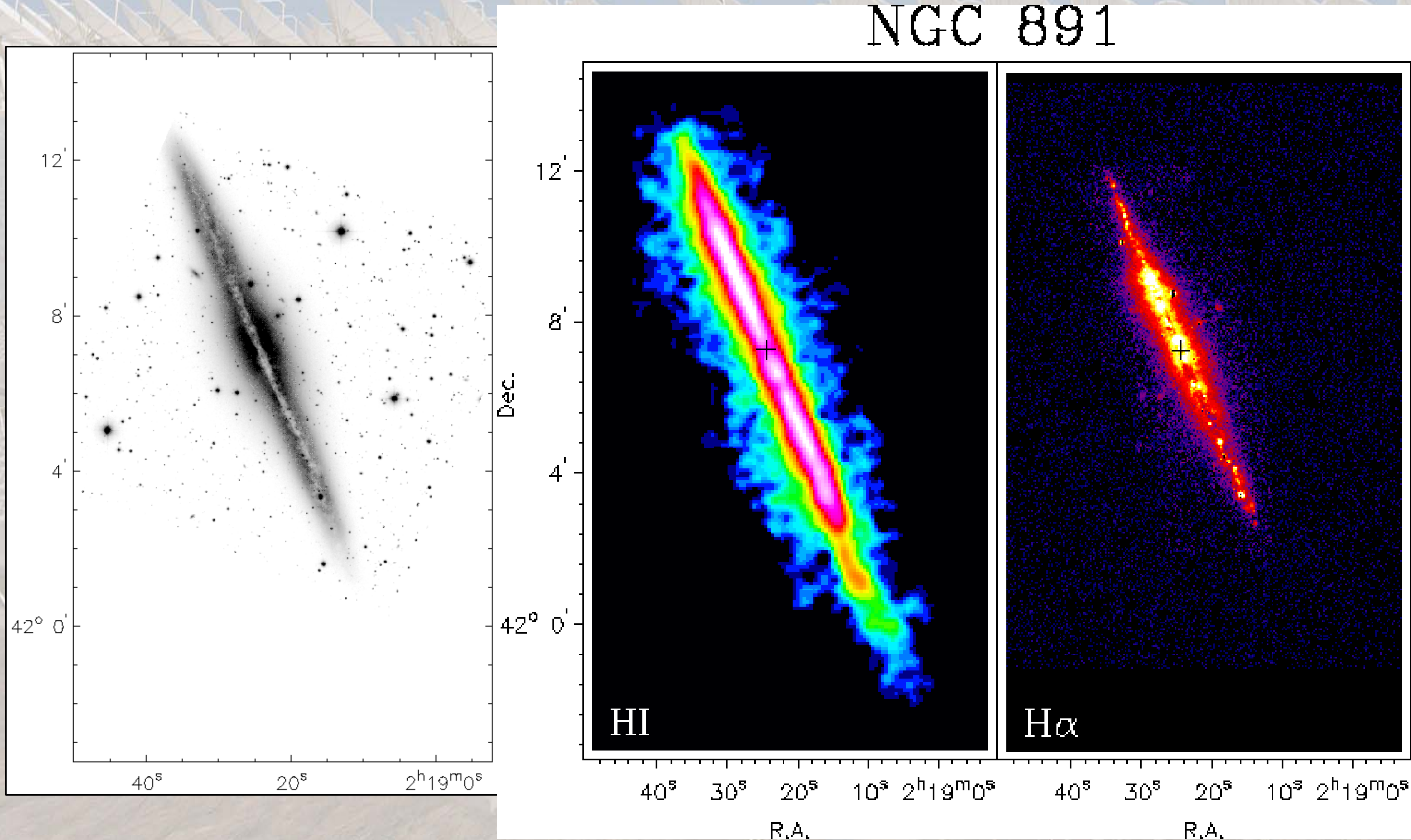
- It does not describe complex profiles
  (asymmetries, double profiles)
- it does not always define mean velocities well
  (especially when S/N ratio is low,
  when beam-smearing is important,
  and in case of edge-on galaxies)

Alternatives:

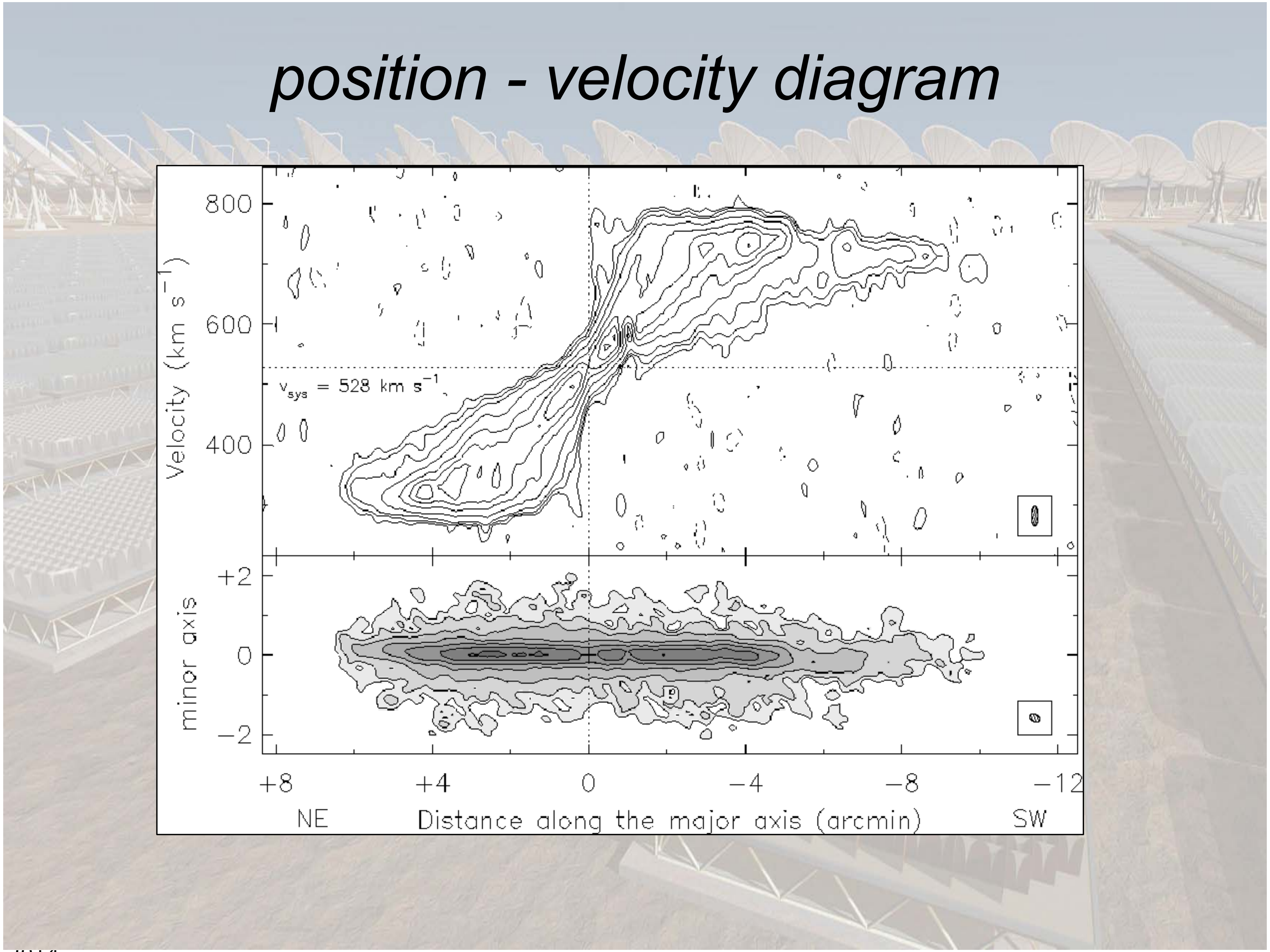
- multiple Gauss fitting, fitting of Hermitian functions
- special visualisation and treatment of the 3D data

examples: derotation, position – velocity diagrams along well chosen directions

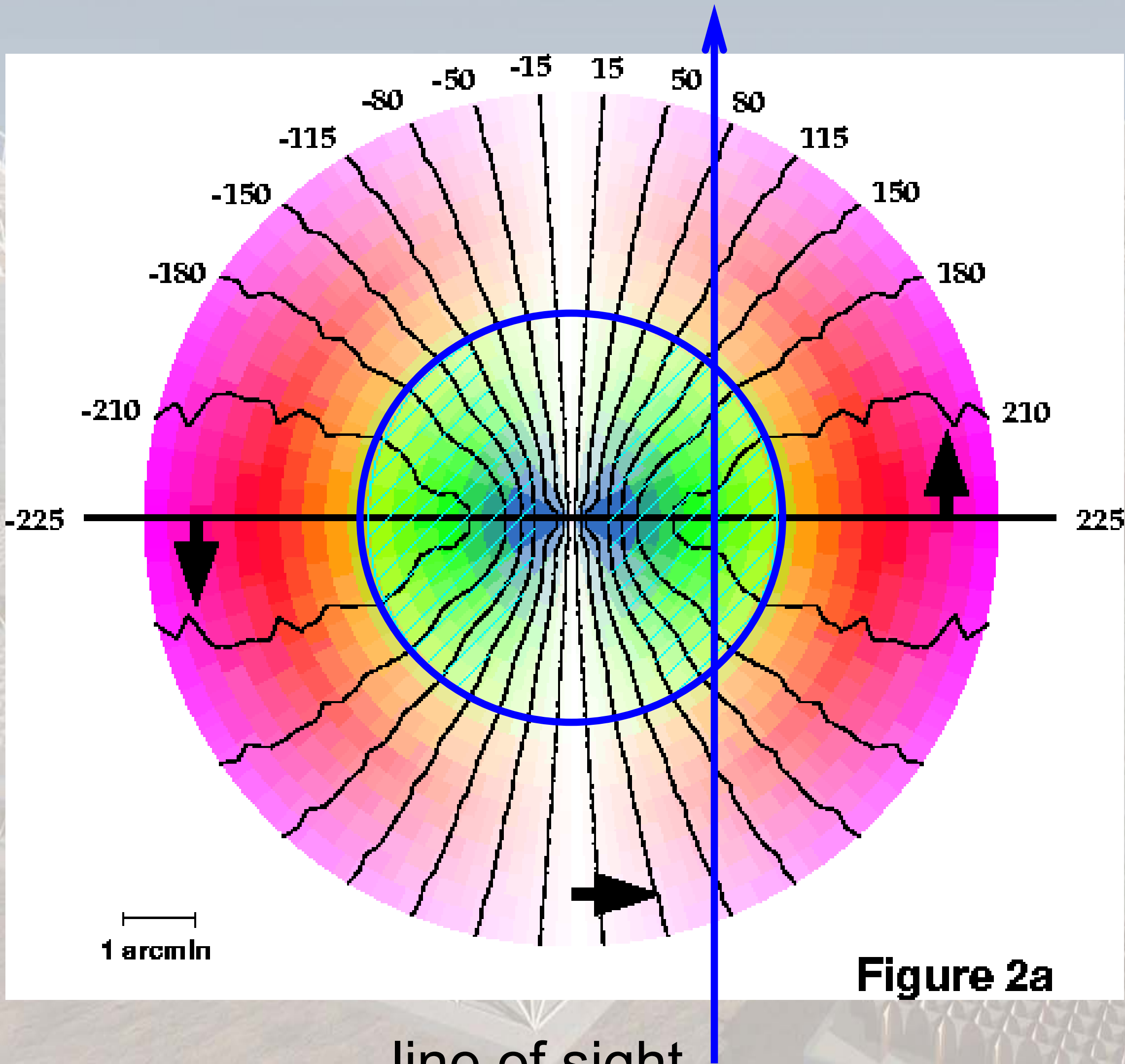
Use of position -velocity diagrams



pV diagrams


position - velocity diagram
800
600
400
Velocity (km s^{-1})
v_{sys} = 528 km s^{-1}
+2
0
−2
minor axis
+8
+4
0
−4
−8
−12
NE
Distance along the major axis (arcmin)
SW

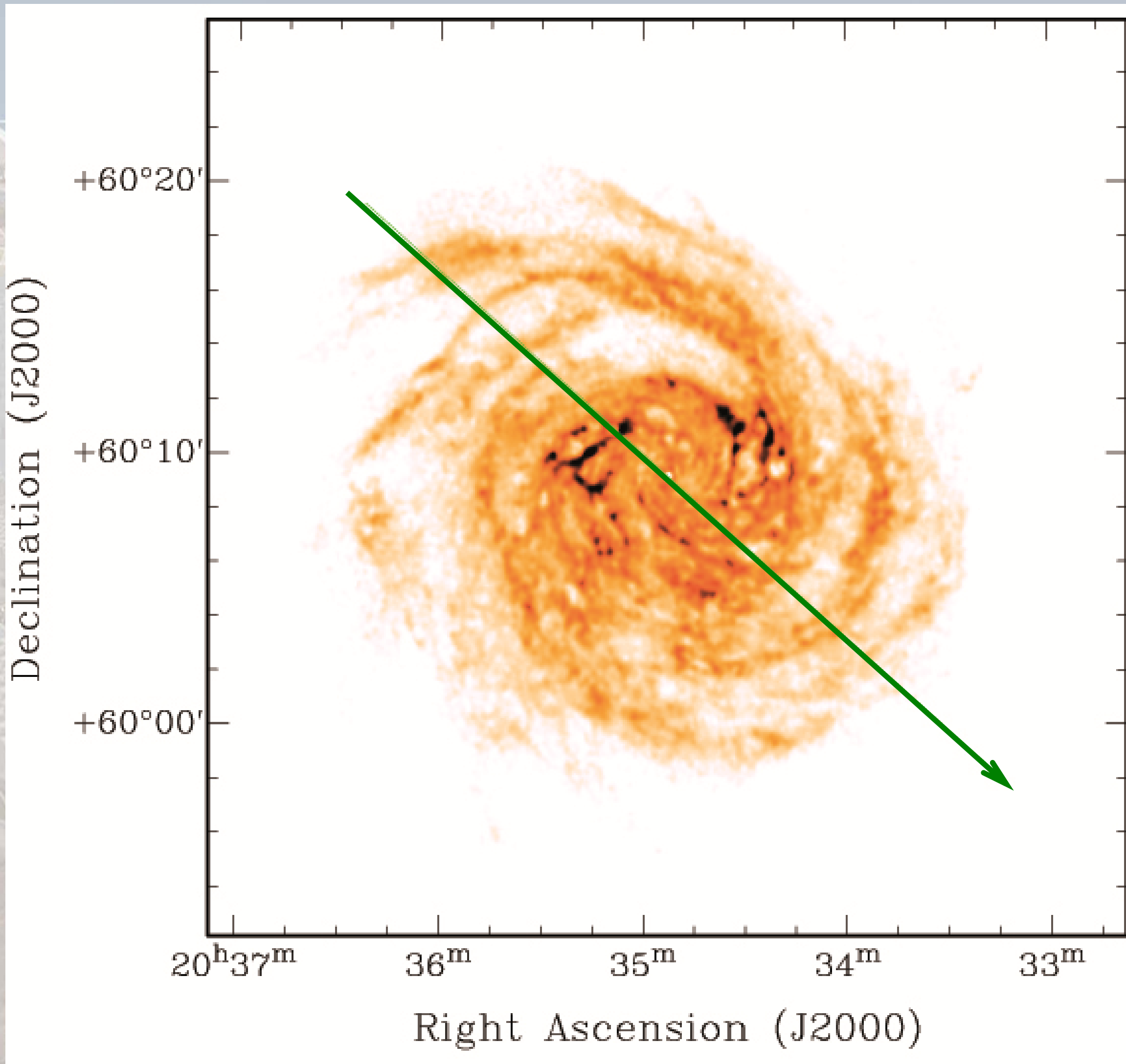
Velocity fields….



line of sight

Velocity Field:

velocities in inner region are all higher than in the outer parts along a single line of sight

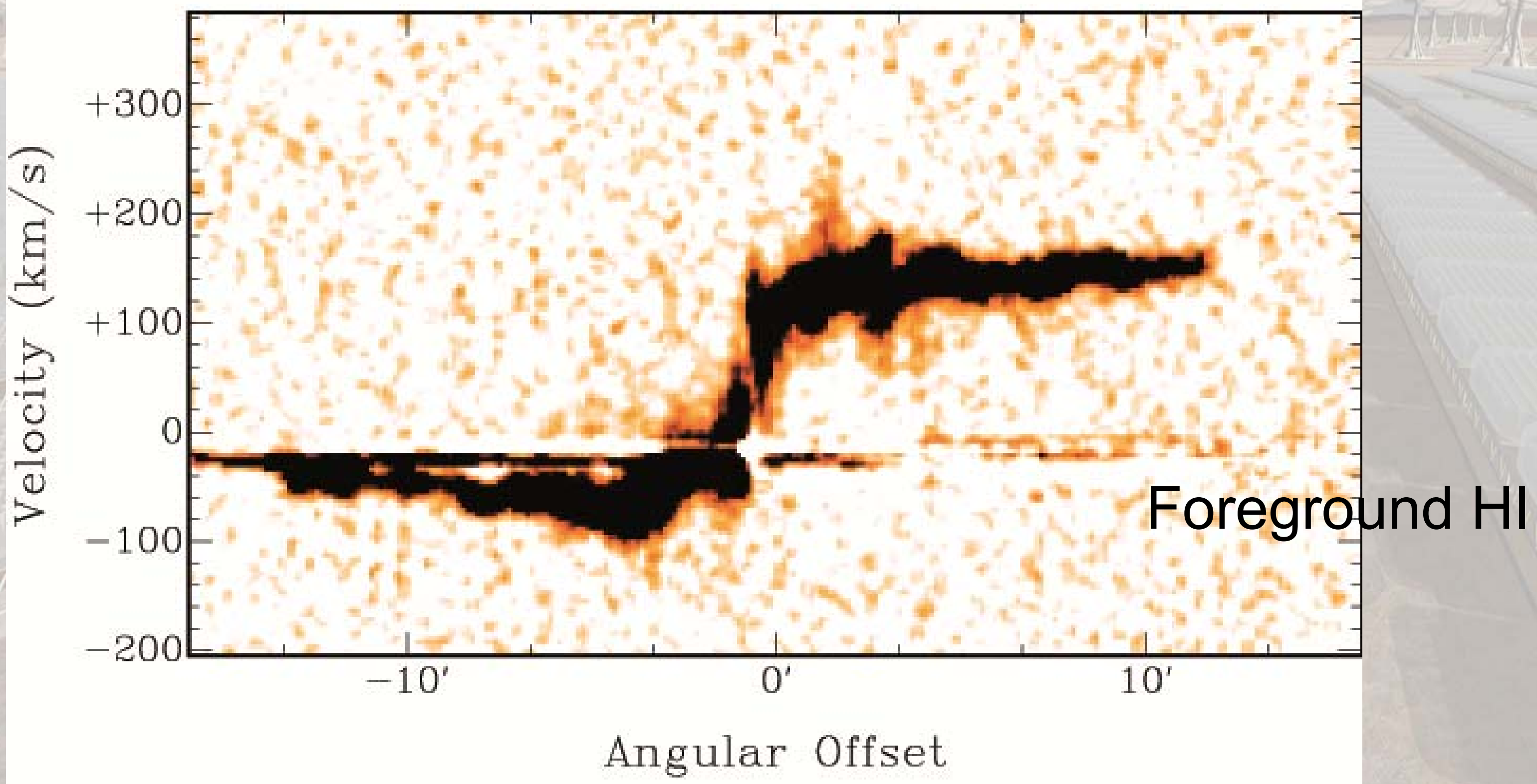


NGC 6946

To inspect the data:

make a position velocity slice along the green arrow

Result: rotating gas disk plus gas at anomalous velocities



The big question

- Now that we are all experts in radio telescopes and neutral hydrogen in galaxies:
- What can we say about dark matter in galaxies?

Stars, gas, galaxy evolution

- Galaxies are more than dark matter alone
- Gas cools, forms stars, stars live and die
- "Feedback" and "accretion" affect the ISM and possibly DM distribution
- Galaxies more than the sum of their parts
- Understanding interplay is the next challenge

Governato et al. http://www-hpcc.astro.washington.edu/

The HI Nearby Galaxy Survey

What is THINGS?

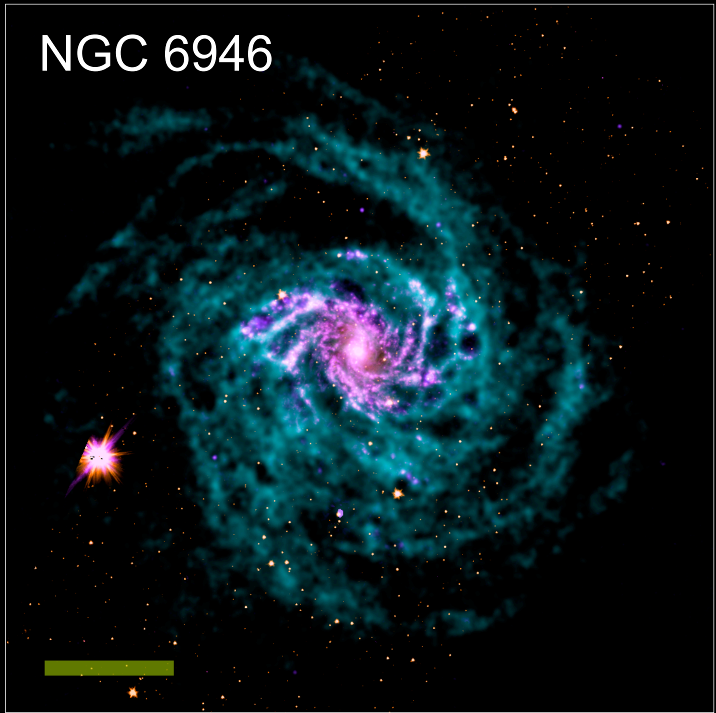
- Large NRAO VLA program (2003-2006)
- ~500 hours: B, C and D arrays
- 34 galaxies: Sa - Irr, 3-10 Mpc
- Resolution ~ 6" (100-300 pc)
- Velocity Resolution ~ 5 km s^{-1}
- Sensitivity ~ 5 x 10^{19} cm^{-2}
- total: 1 Tbyte
- Targets overlap SINGS *Spitzer* Legacy Survey and GALEX Nearby Galaxy Survey

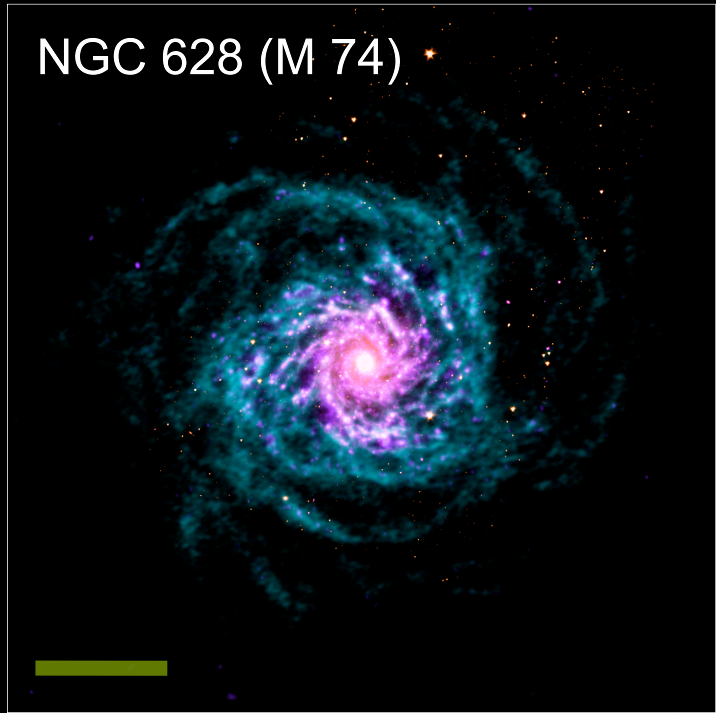
www.mpia.de/THINGS

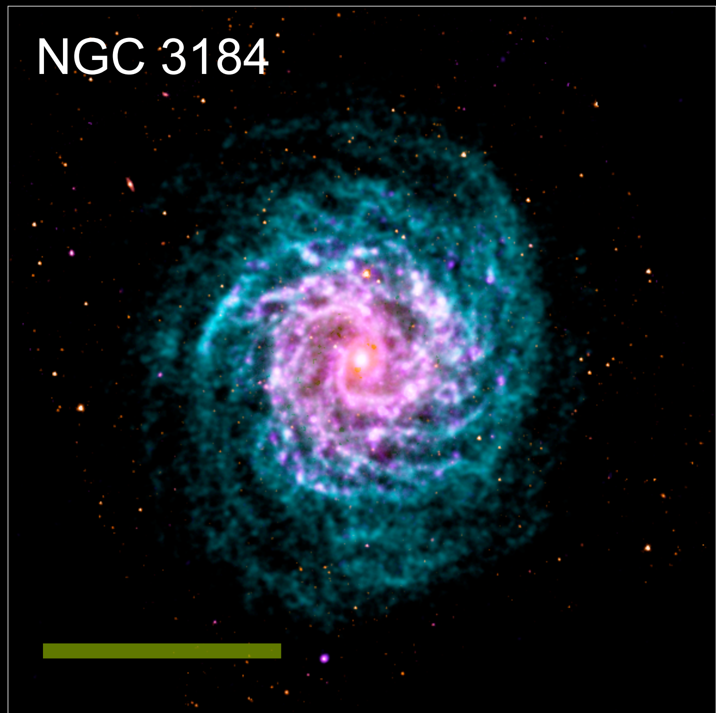

THINGS
The HI
Nearby
Galaxy Survey
10 kpc
Data: Walter et al 2008
Milky Way HI map: Oort et al (1958)
Milky Way art: NASA/JPL, R. Hurt (SSC)


THINGS
The HI
Nearby
Galaxy Survey
NGC 2841
NGC 3621
NGC 7331
NGC 4826
(M64)
NGC 3198
NGC 6946
NGC 3184
NGC 925
NGC 3351
(M95)
NGC 5194
(M51)
NGC 4214
NGC 2976
DDO 53
NGC 1569
NGC 3521
NGC 5236
(M83)
NGC 2366
M81dwB
Our Galaxy
HI
stars
M81dwA
NGC 4449
IC 2574
NGC 3627
(M66)
Holmberg II
NGC 7793
DDO 154
NGC 4736
(M94)
NGC 3077
Holmberg I
NGC 5055
NGC 2903
NGC 628
(M74)
NGC 5457
(M101)
NGC 3031
(M81)
NGC 2403
10 kpc
Data: Walter et al 2008
Milky Way HI map: Oort et al (1958)
Milky Way art: NASA/JPL, R. Hurt (SSC)

Spiral Galaxies in T*HI*NGS — The *HI* Nearby Galaxy Survey







'Face-on'
Spiral Galaxies
in T*HI*NGS

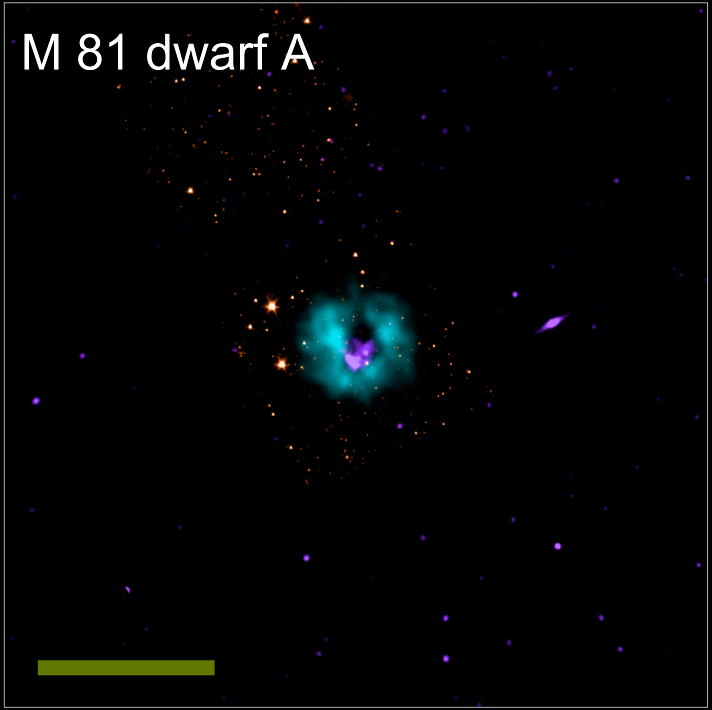
scale:
10 kpc
30.000 light years

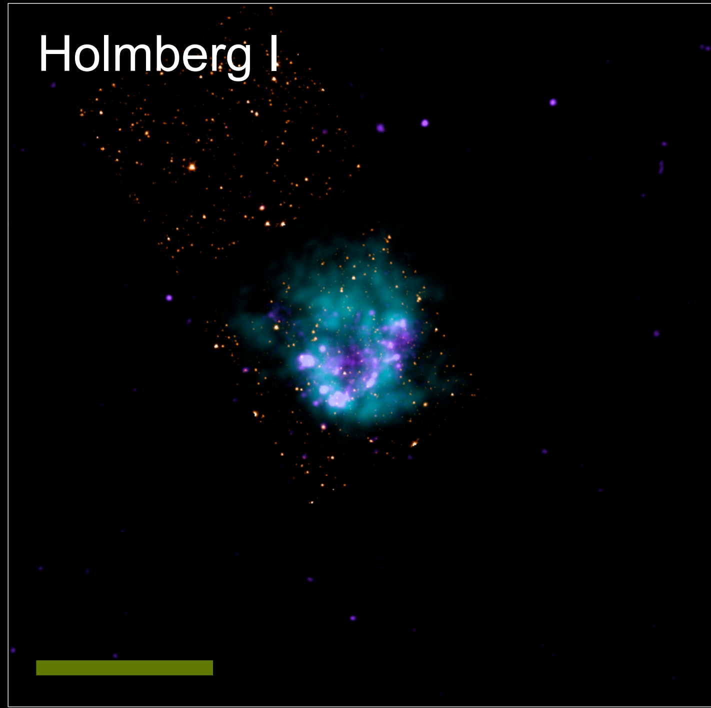
Color Coding:

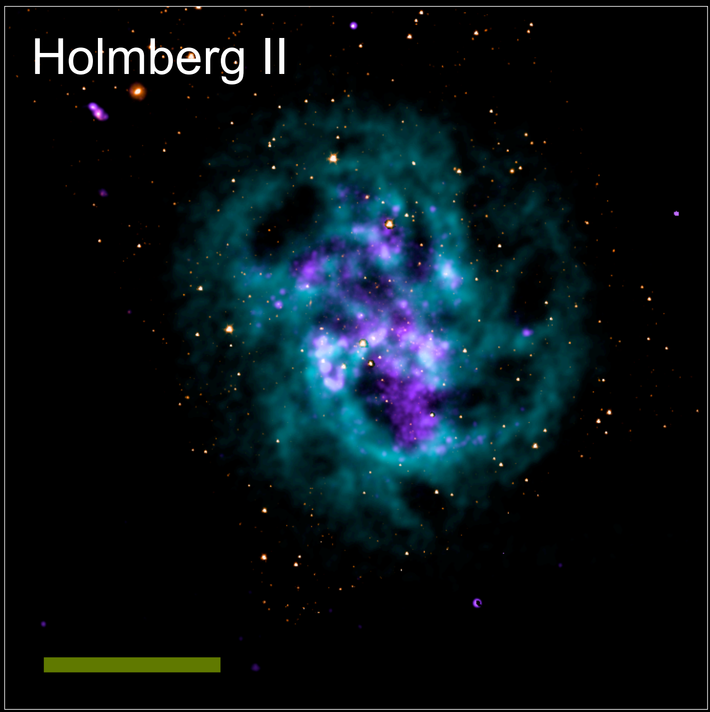
Atomic Hydrogen (HI)
(Very Large Array)
Old stars
(Spitzer)
Star Formation
(Galex & Spitzer)

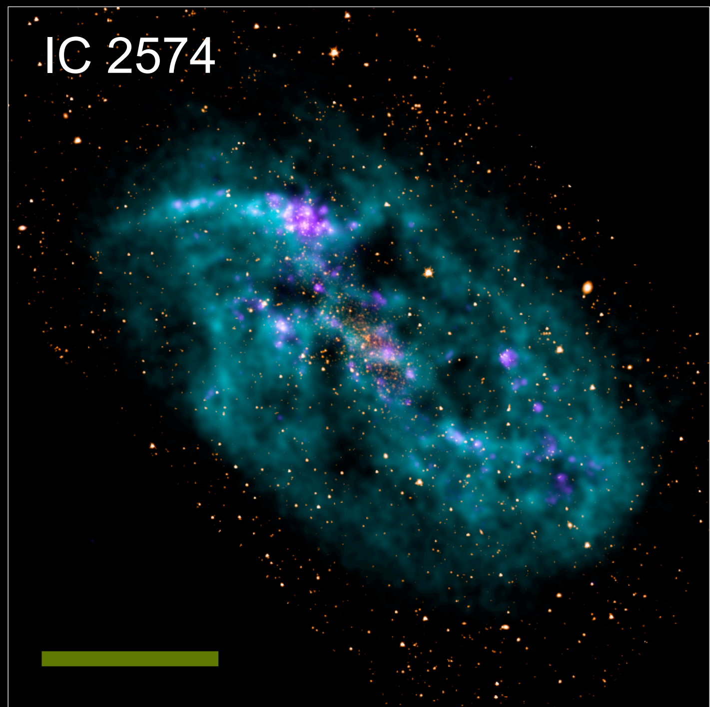
Image credits:
VLA THINGS: Walter et al.
Spitzer SINGS: Kennicutt et al.
Galex NGS: Gil de Paz et al.

Dwarf Galaxies in T*HI*NGS -- The *HI* Nearby Galaxy Survey









Dwarf Galaxies of the M81 group in T*HI*NGS

scale:
5 kpc
15.000 light years

color coding:

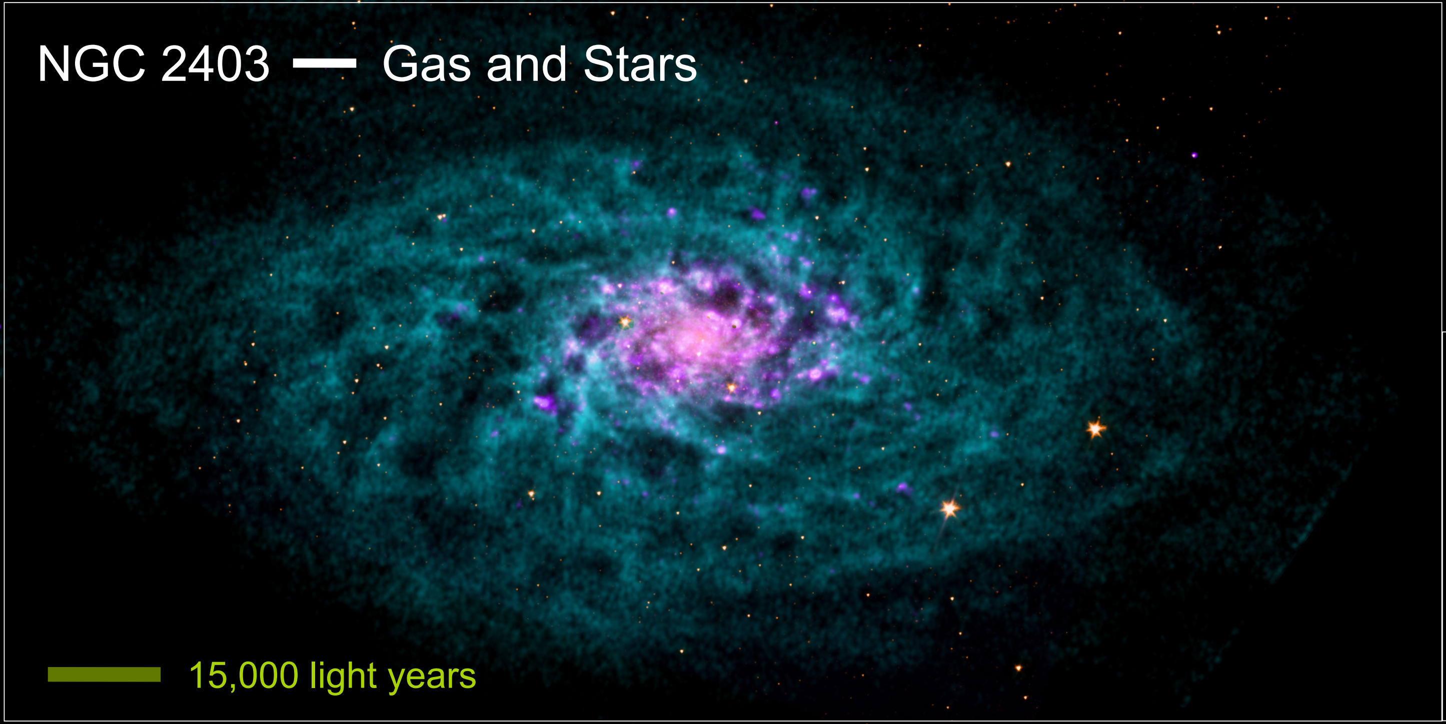
Atomic Hydrogen (HI)
(Very Large Array)

Old stars
(Spitzer)

Star Formation
(Galex & Spitzer)

Image credits:
VLA THINGS: Walter et al.
Spitzer SINGS: Kennicutt et al.
Galex NGS: Gil de Paz et al.

Galaxy Dynamics in THINGS — The HI Nearby Galaxy Survey

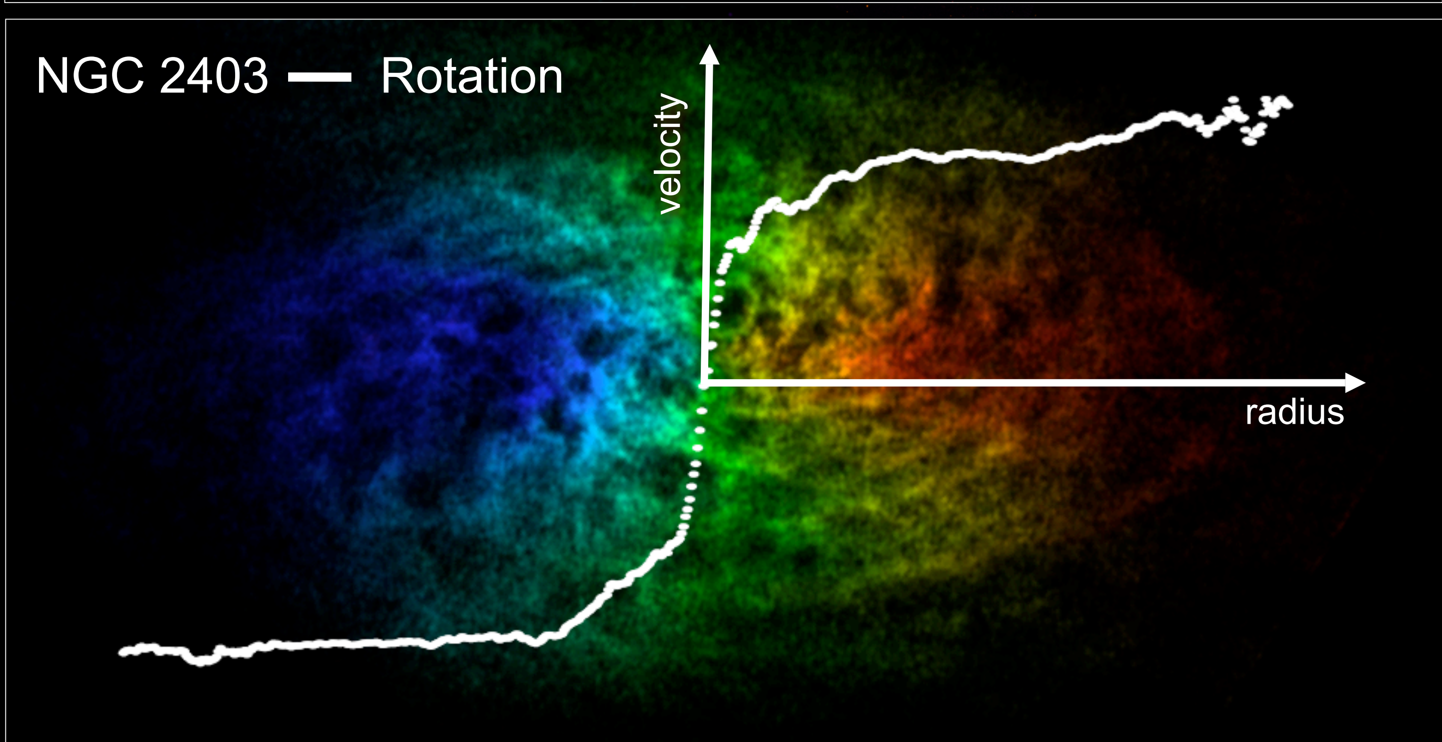


THINGS

The HI Nearby Galaxy Survey

Color Coding:

THINGS Atomic Hydrogen
(Very Large Array)
Old stars
(Spitzer Space Telescope)
Star Formation
(GALEX & Spitzer)

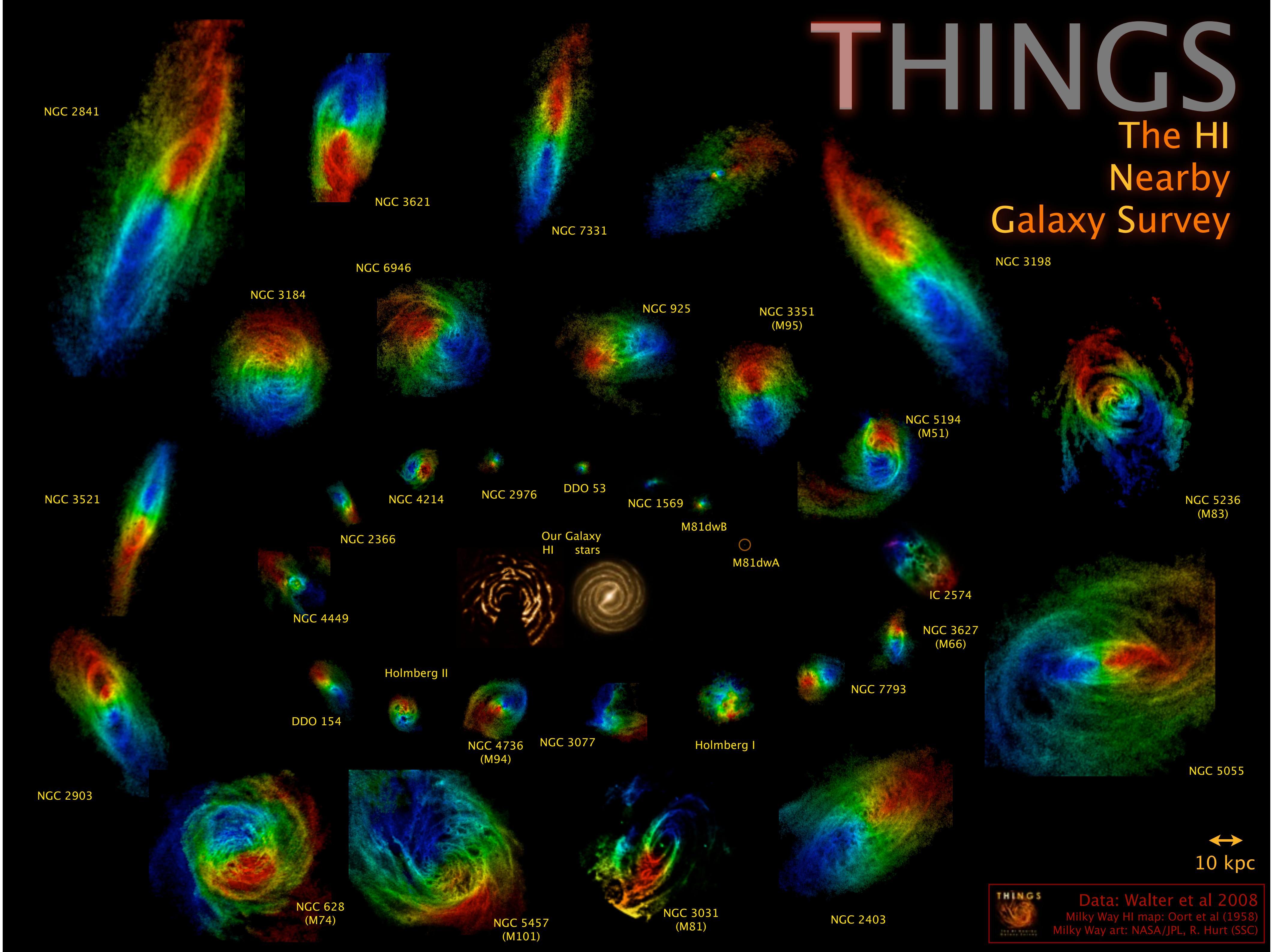


Color coding:
THINGS HI distribution:
Red-shifted (receding)
Blue-shifted (approaching)
Rotation Curve

Max-Planck-Institut für Astronomie Heidelberg · Max Planck Institute for Astronomy Heidelberg

NRAO

Image credits:
VLA THINGS: Walter et al. 08
Spitzer SINGS: Kennicutt et al. 03
GALEX NGS: Gil de Paz et al. 07
Rotation Curve: de Blok et al. 08


THINGS
The HI
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NGC 2841
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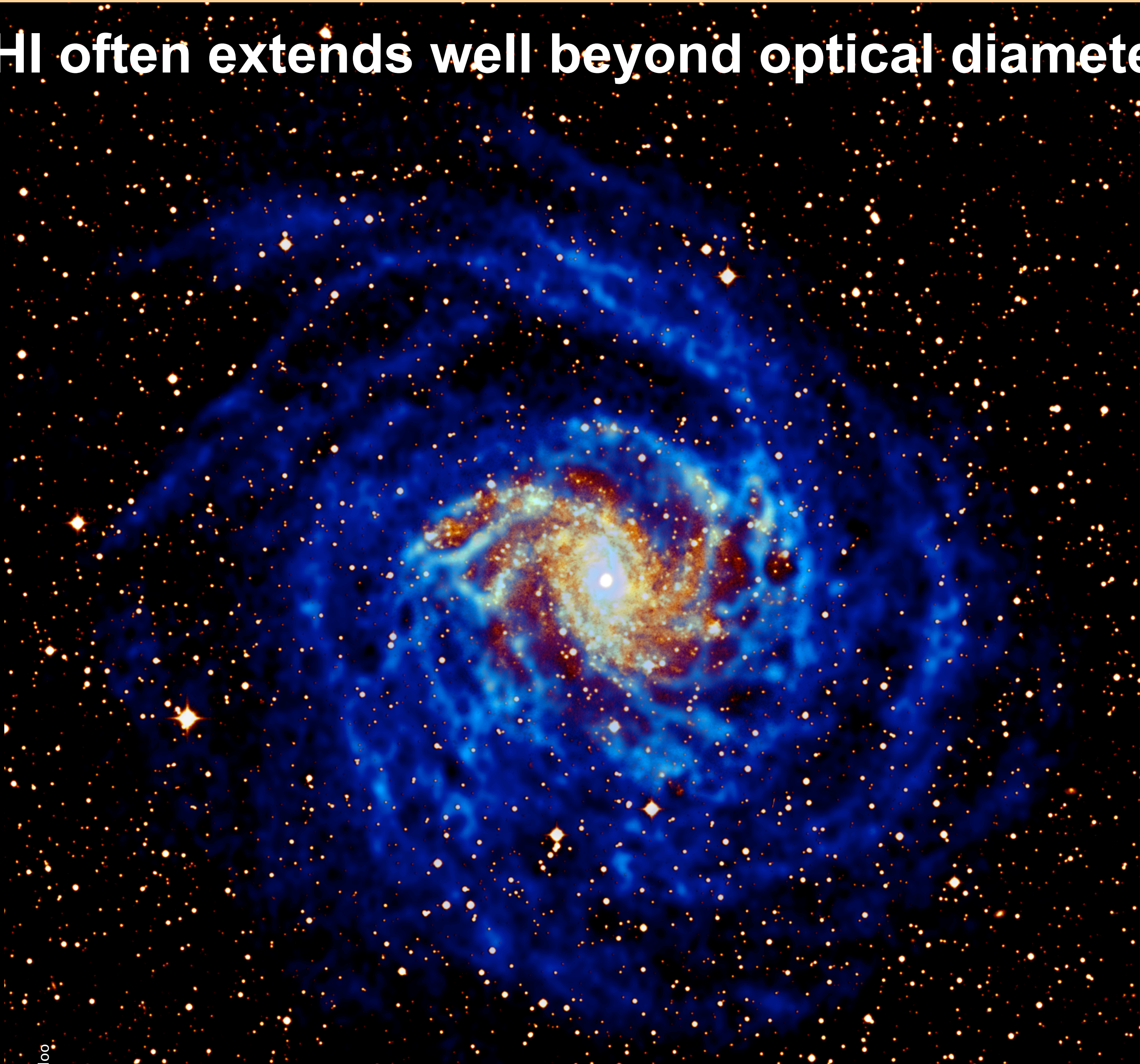
NGC 3077
Holmberg I
NGC 5055
NGC 2903
NGC 628
(M74)
NGC 5457
(M101)
NGC 3031
(M81)
NGC 2403
10 kpc
THINGS
Data: Walter et al 2008
Milky Way HI map: Oort et al (1958)
Milky Way art: NASA/JPL, R. Hurt (SSC)

HI extent

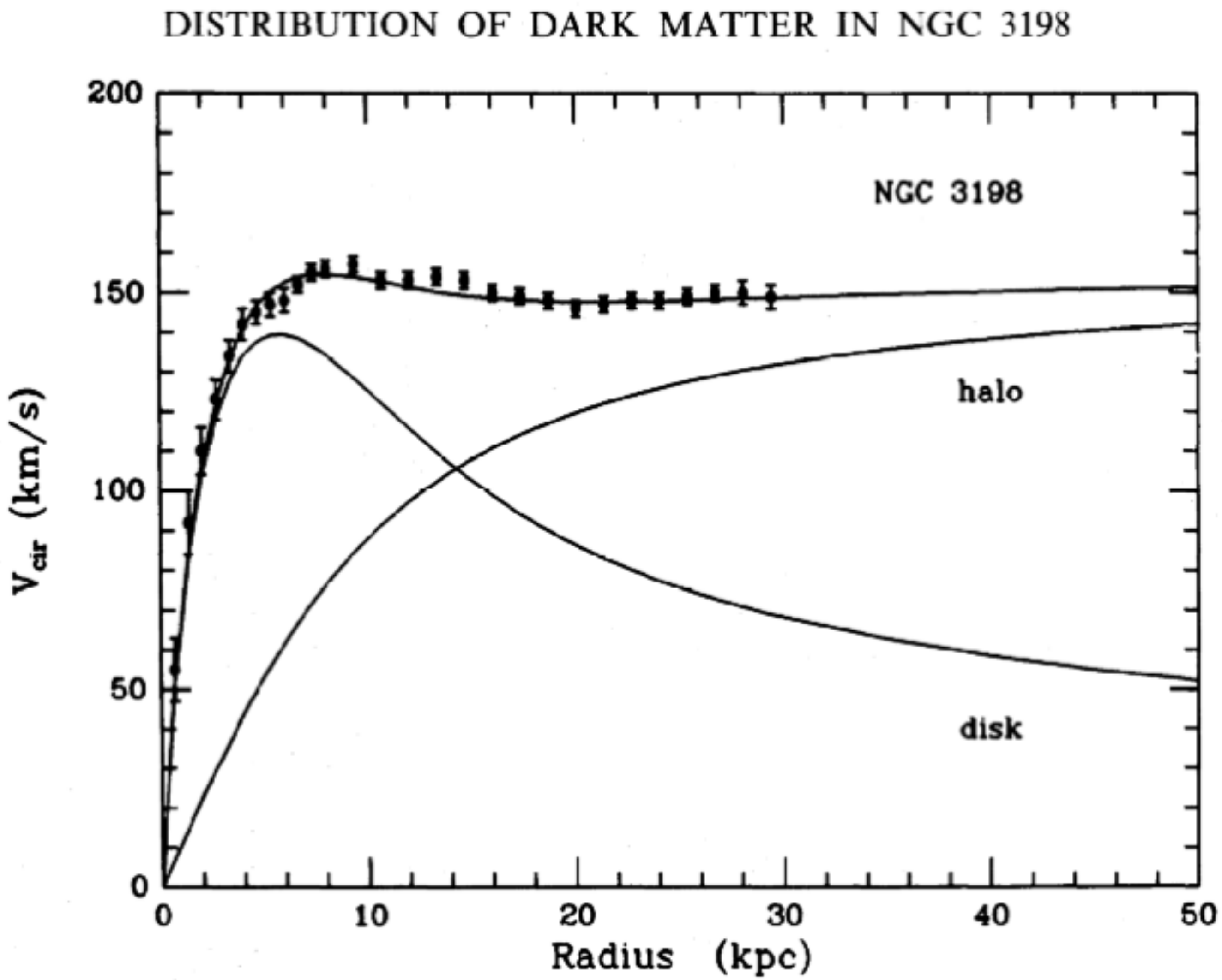
HI often extends well beyond optical diameter



NGC 6946
HI (blue) and optical DSS (orange)
credit: T. Oosterloo (ASTRON)

Rotation curves: *Why?*

- Rotation curves classic evidence for dark matter



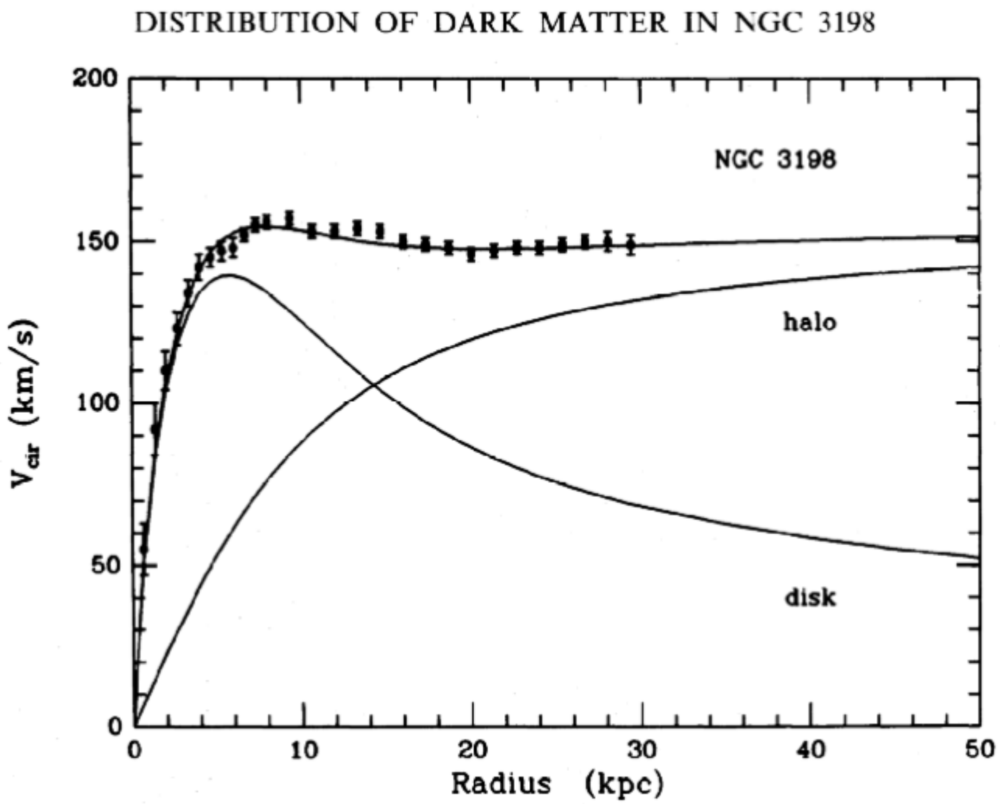
van Albada et al 1985

Rotation curves: *Why?*

- Efficient way of describing dynamics of galaxies
- In combination with baryonic distribution give information on presence and distribution of dark matter

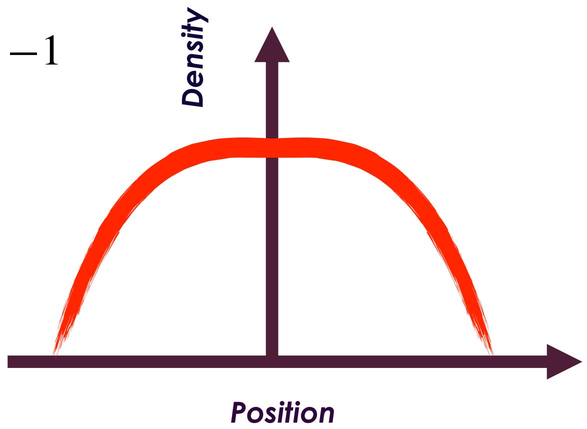
Cores

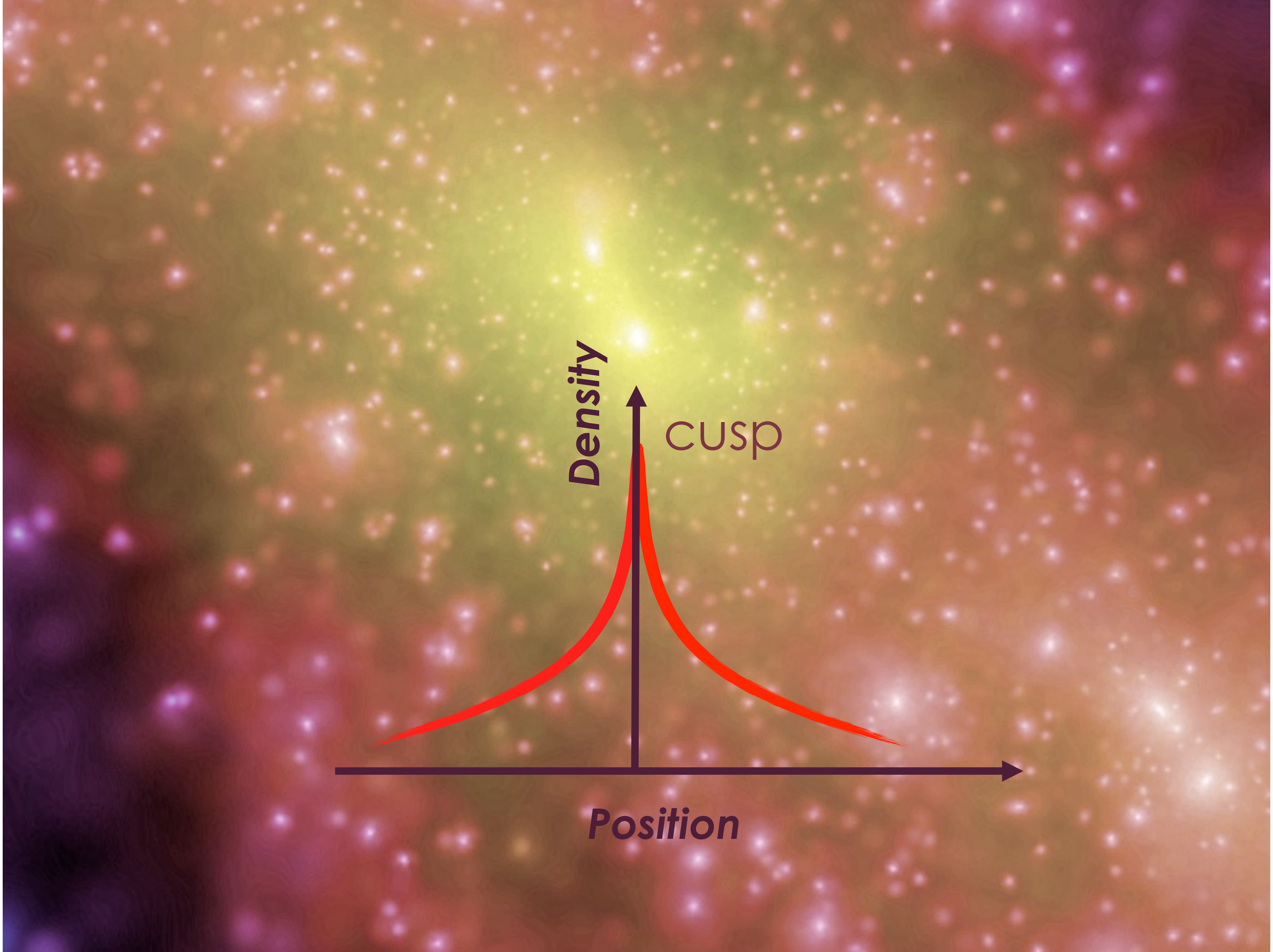
- Rotation curves classic evidence for dark matter
- Flat rotation curves and inner solid-body rise led to pseudo-isothermal halo model
- Constant density core and isothermal density fall-off



van Albada et al 1985

$$\rho_{\rm ISO}(R) = \rho_0 \left[1 + \left(\frac{R}{R_C}\right)^2\right]^{-1}$$

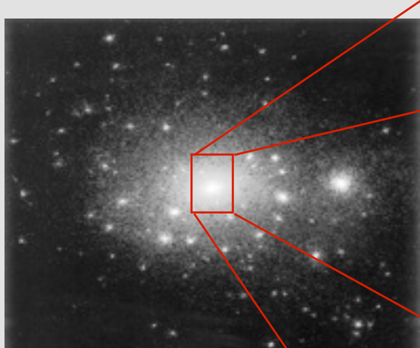


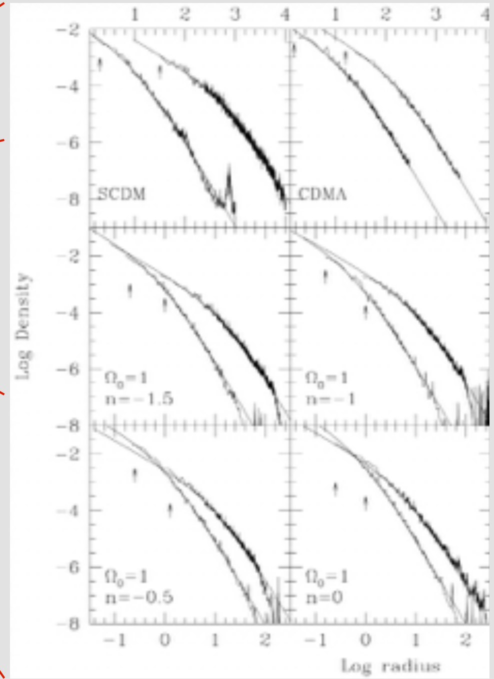

Density
cusp
Position

Cold Dark Matter on Small Scales

- universal mass density profile from CDM simulations
- dominated by central steep density cusp
- cusp causes steep inner rotation curve

$$\rho_{\mathrm{NFW}}(R) = \frac{\rho_i}{(R/R_s)\,(1+R/R_s)^2}$$





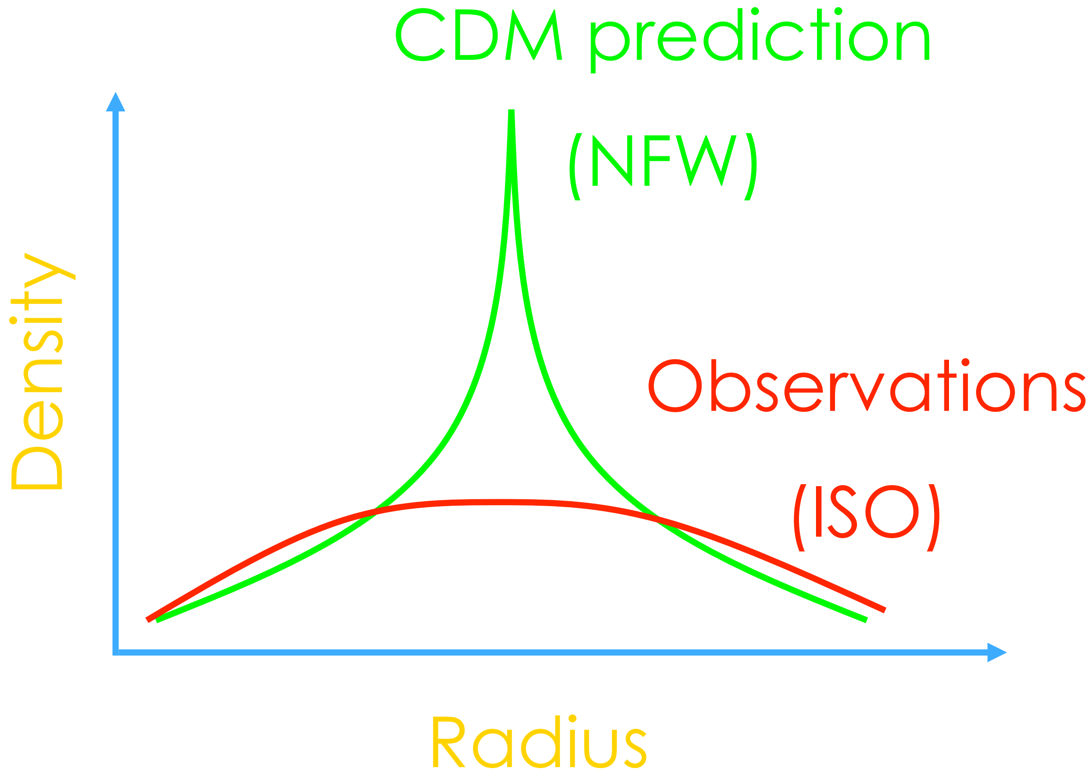
ρ ~ $\mathbf{R^{-1}}$ for small R

ρ ~ R^{-3} for large R

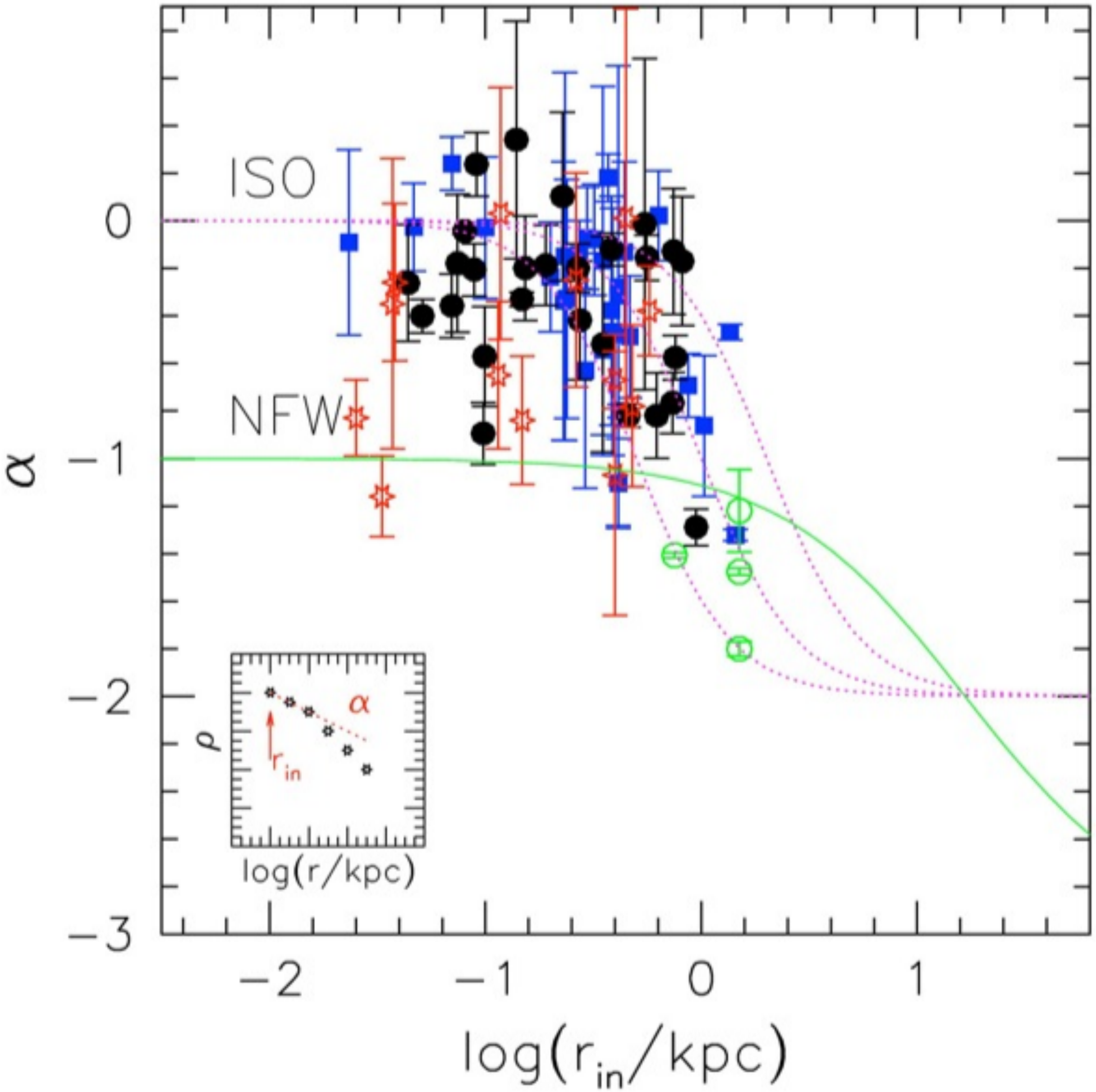
NFW96,97

Dark Matter on Small Scales

- observations indicate that the DM halos of late-type galaxies have a ~constant-density core (pseudo-isothermal or ISO)
- "there are no density cusps in the centres of disk galaxies"



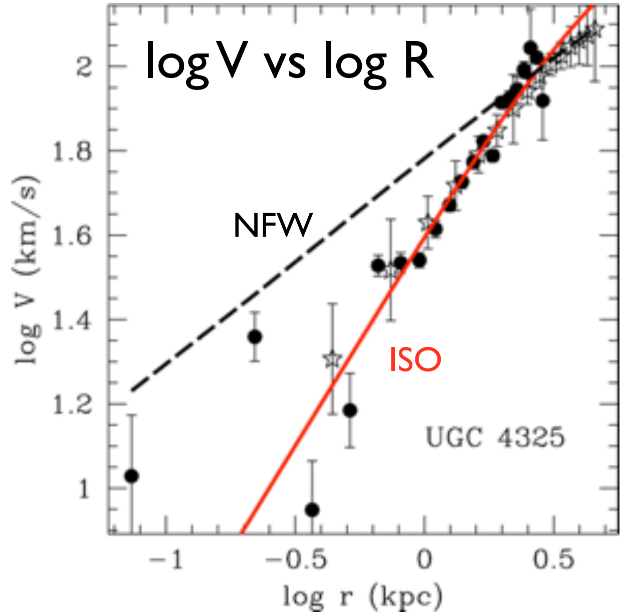
Dark Matter on Small Scales



dB et al 2001

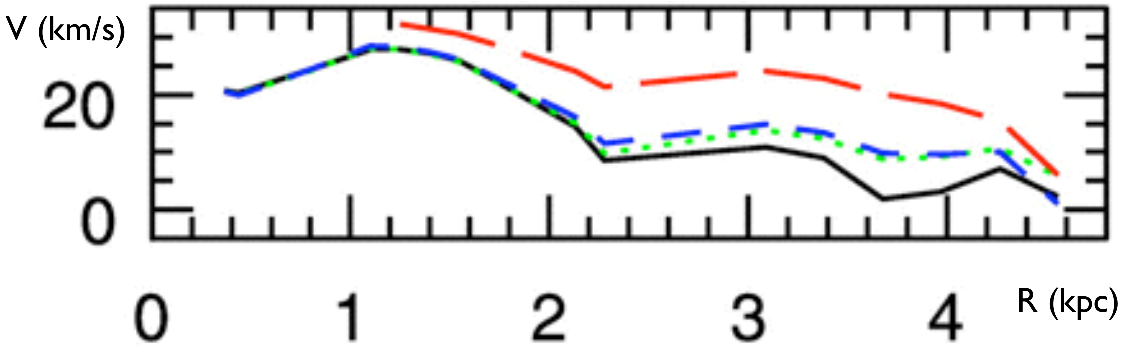
Dark Matter on Small Scales

- observations indicate that the DM halos of late-type galaxies have a ~constant-density core (pseudo-isothermal or ISO)
- "there are no density cusps in the centres of disk galaxies"
- systematic effects? offsets? non-circular motions?

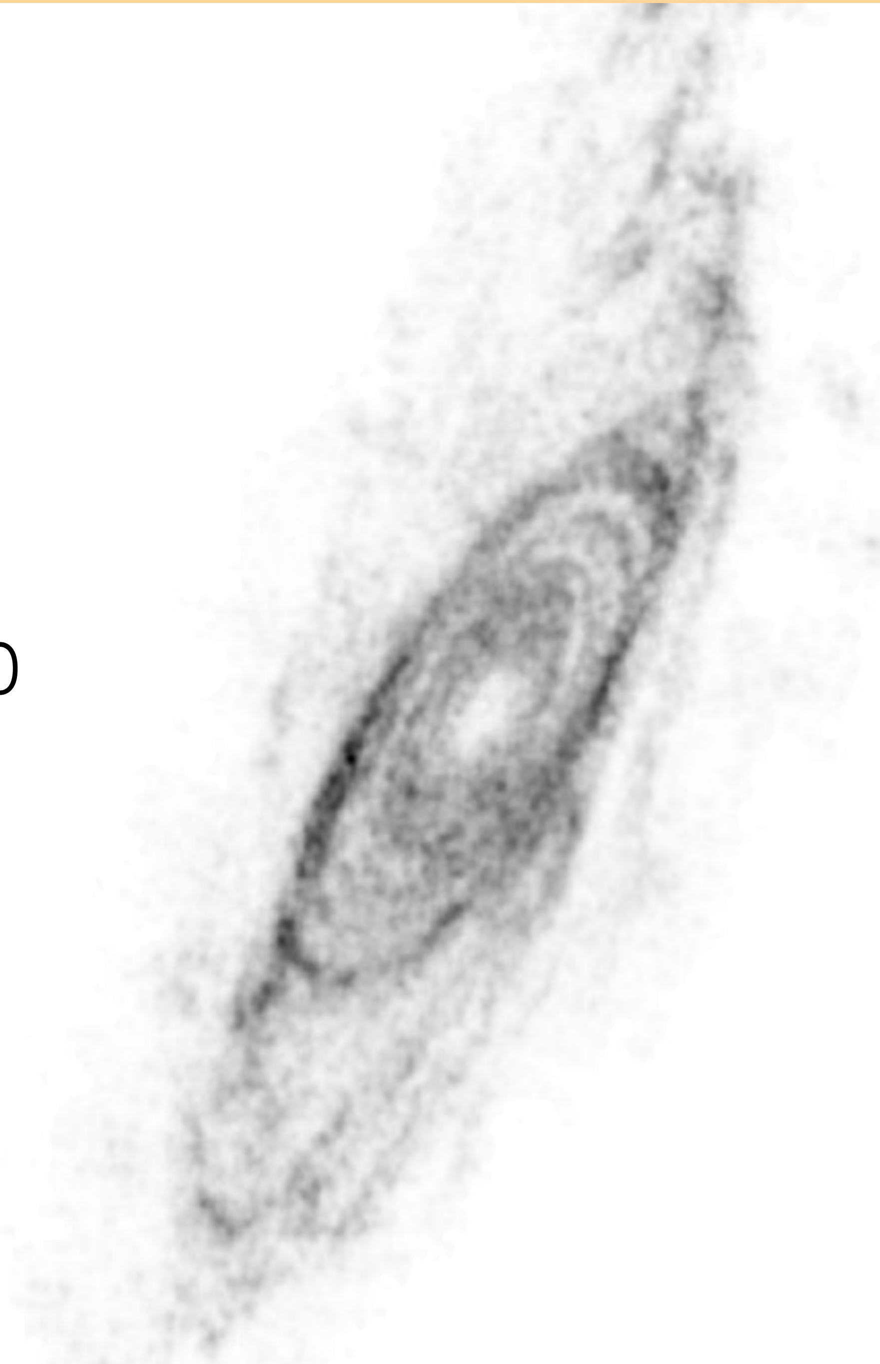


McGaugh et al 2008

Required non-circular motions to make NFW work



What to do…



- Derive dynamical models without using external information on inclination etc.
- These can be derived for i > 40 degrees
- 19 galaxies in rotation curve sample


THINGS
The HI
Nearby
Galaxy Survey
NGC 2841
NGC 3621
NGC 7331
NGC 4826
(M64)
NGC 3198
NGC 6946
NGC 3184
NGC 925
NGC 3351
(M95)
NGC 5194
(M51)
NGC 5236
(M83)
NGC 3521
NGC 4214
NGC 2976
DDO 53
NGC 1569
M81dwB
M81dwA
NGC 2366
Our Galaxy
HI
stars
IC 2574
NGC 4449
NGC 3627
(M66)
Holmberg II
NGC 7793
DDO 154
NGC 4736
(M94)
NGC 3077
Holmberg I
NGC 5055
NGC 2903
10 kpc
NGC 628
(M74)
NGC 5457
(M101)
NGC 3031
(M81)
NGC 2403
THINGS
Data: Walter et al 2008
Milky Way HI map: Oort et al (1958)
Milky Way art: NASA/JPL, R. Hurt (SSC)


THINGS
The HI
Nearby
Galaxy Survey
NGC 2841
NGC 3621
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DDO 154
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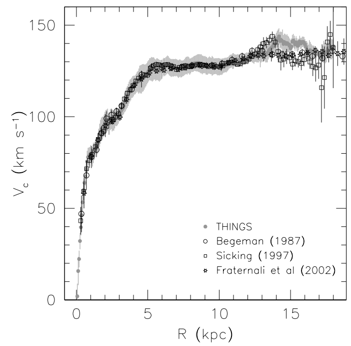
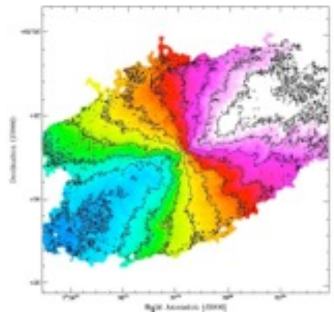
(M94)
NGC 5055
NGC 2903
NGC 3031
(M81)
NGC 2403
10 kpc
Data: Walter et al 2008
Milky Way HI map: Oort et al (1958)
Milky Way art: NASA/JPL, R. Hurt (SSC)

Standard method

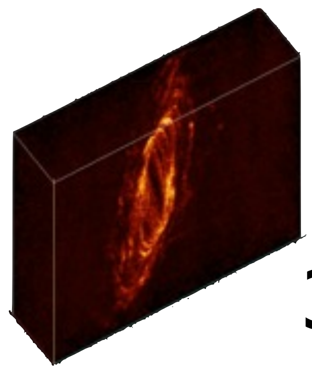
- Standard technique
- Rotation curve: $V = V(R)$
- Derived from velocity field using tilted rings
- $V(x,y) = V_{sys} + V_C(R) \sin(i) \cos(\theta)$
- Velocity field $V(x,y)$ derived from data cube $I(x,y,v)$



1D

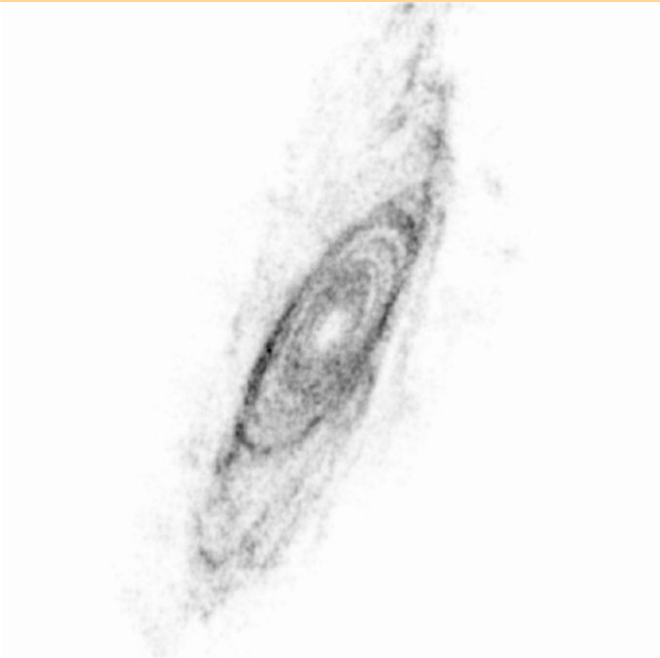


2D



3D

Tilted rings

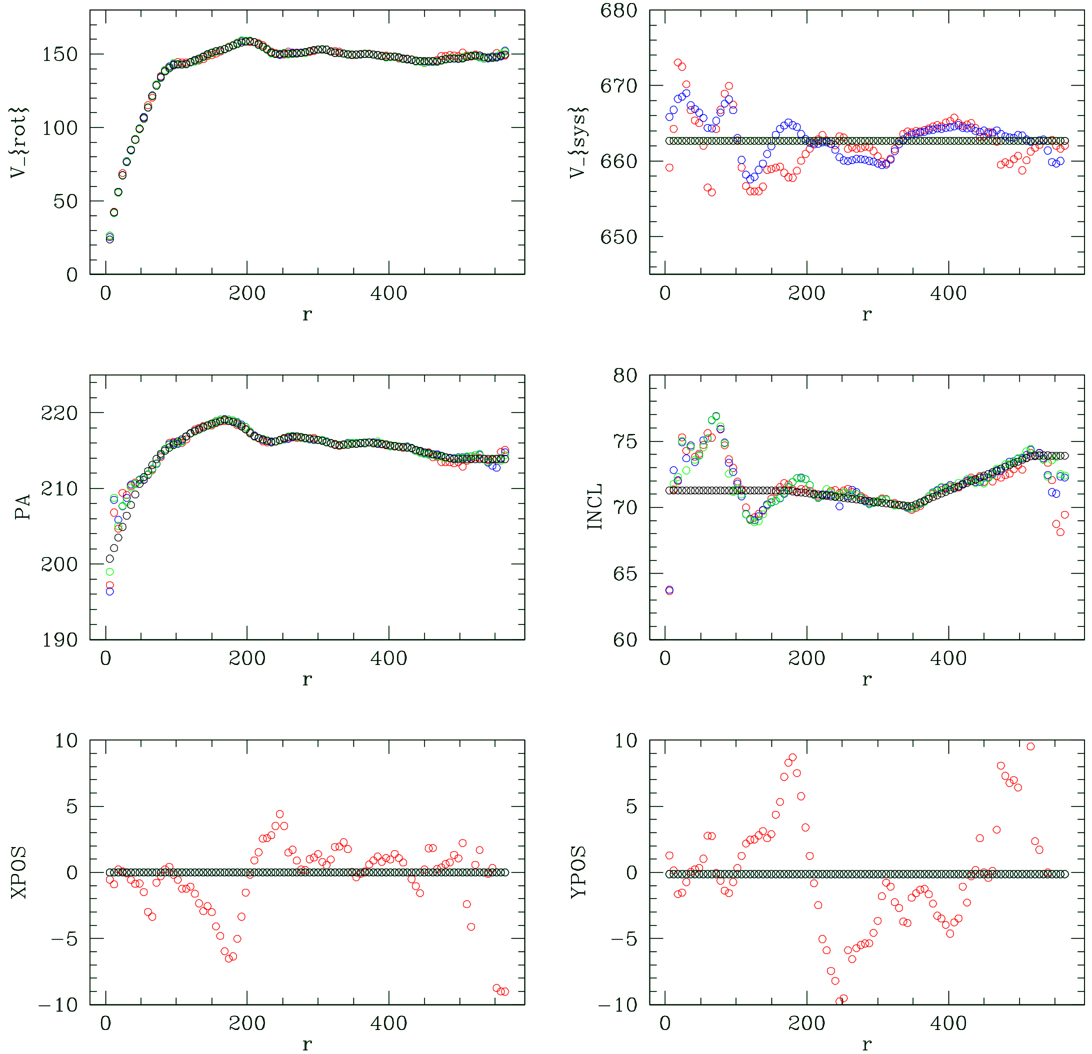


- Model galaxy with concentric rings with center (xpos, ypos) and systemic velocity V_{sys} each with their own i, PA, and V

$V(x,y) = V_{sys} + V_C(R)\sin(i)\cos(\theta)$.

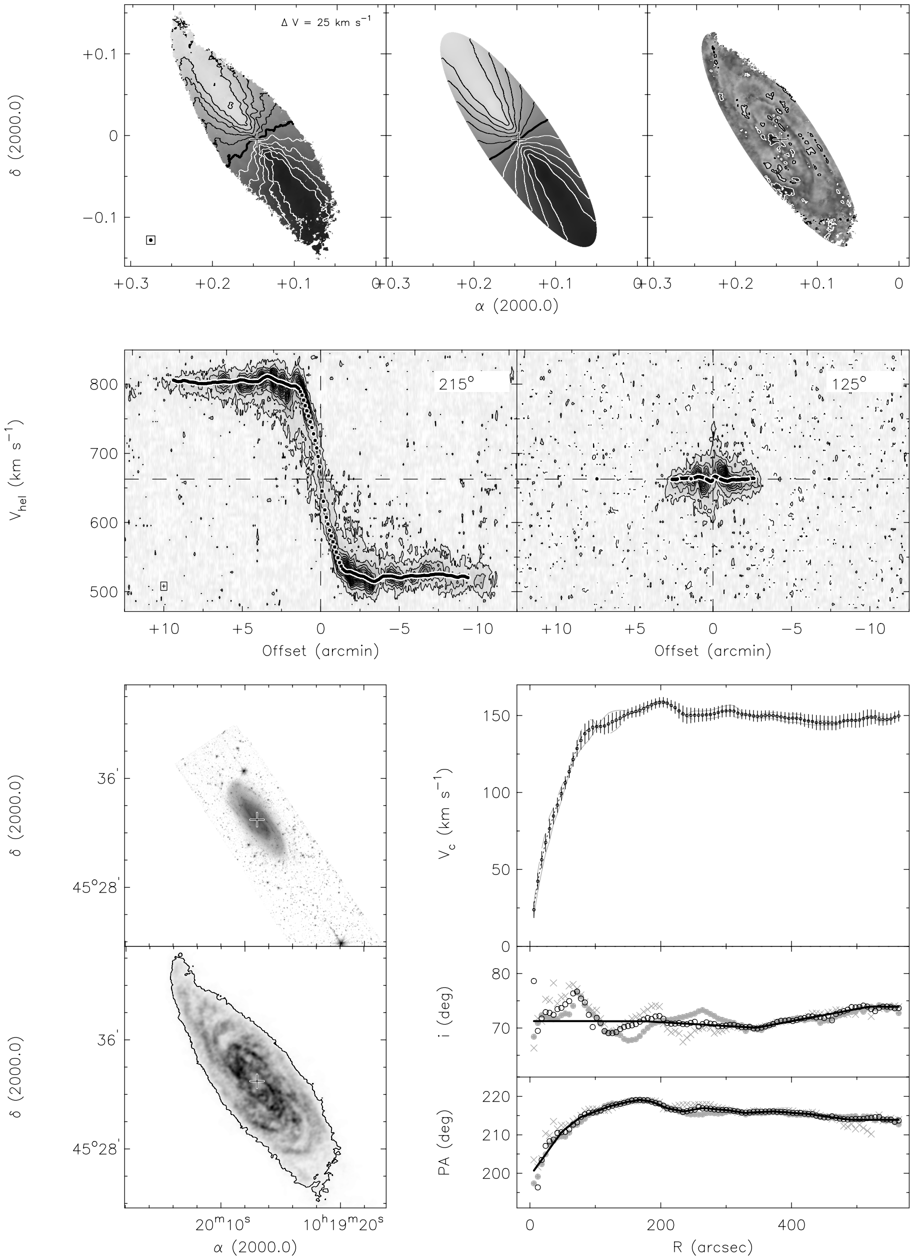
Tilted rings example: NGC 3198

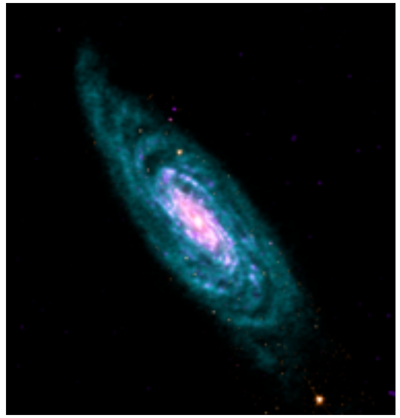
V | Vsys
PA | i
xpos | ypos

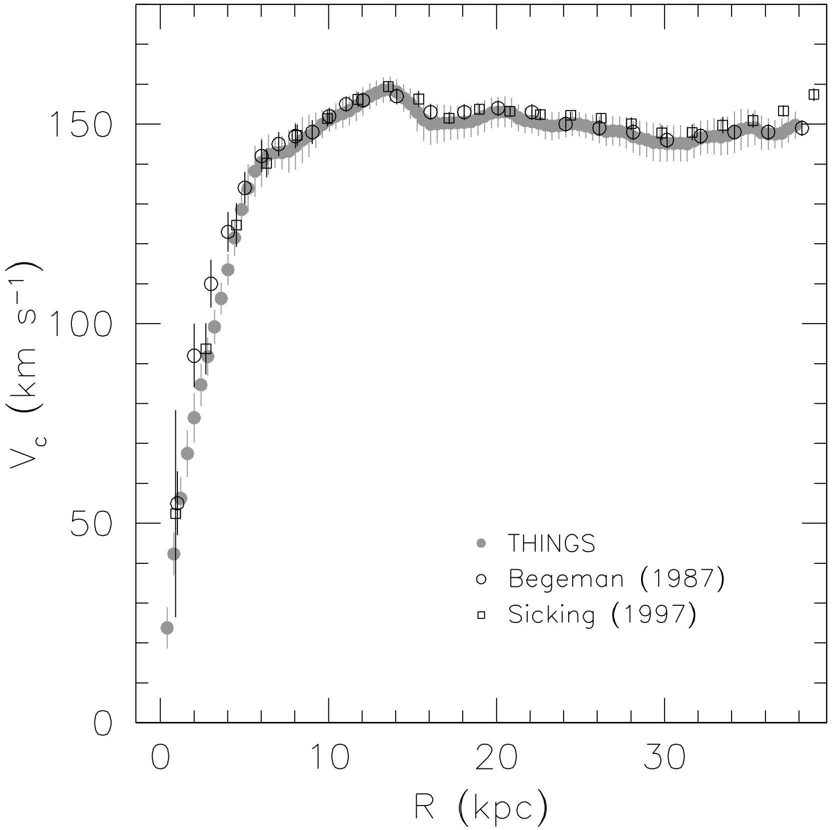


radius

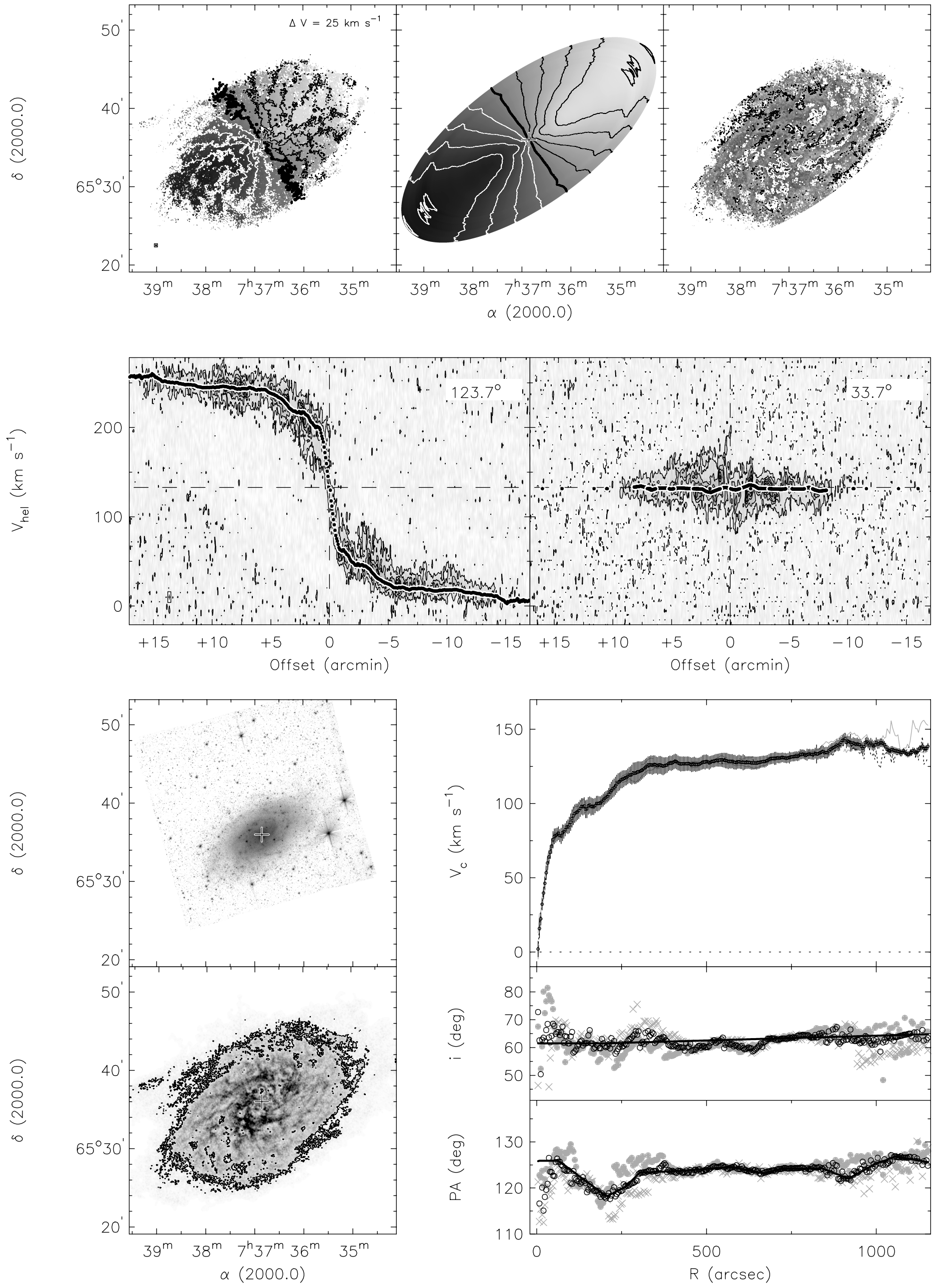
NGC 3198


Δ V = 25 km s⁻¹
δ (2000.0)
α (2000.0)
+0.1
0
−0.1
+0.3
+0.2
+0.1
0
V_{hel} (km s^{-1})
800
700
600
500
215°
125°
+10
+5
0
−5
−10
Offset (arcmin)
36'
45°28'
20^{m}10^s
10^{h}19^{m}20^s
V_c (km s^{-1})
150
100
50
0
i (deg)
80
70
PA (deg)
220
210
200
R (arcsec)
400

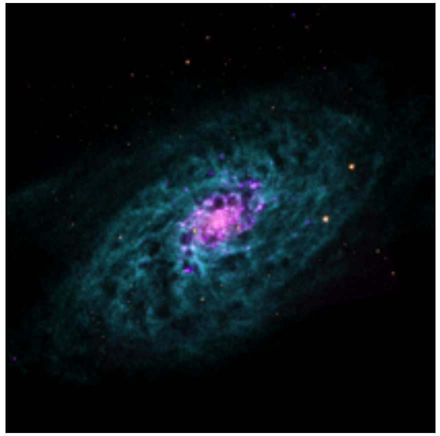


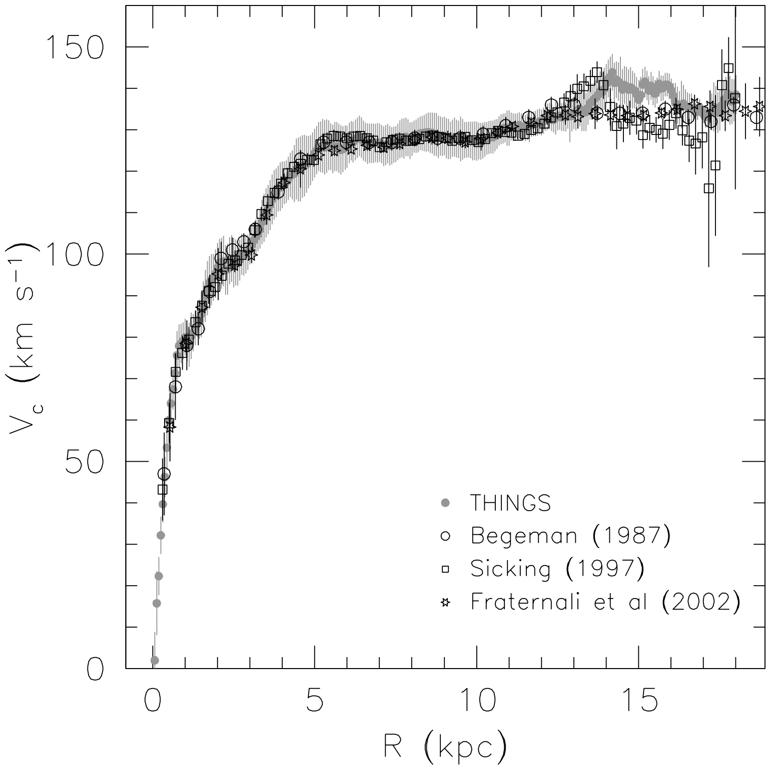

V_c (km s^{-1})
150
100
50
0
10
20
30
R (kpc)
THINGS
Begeman (1987)
Sicking (1997)

NGC 2403



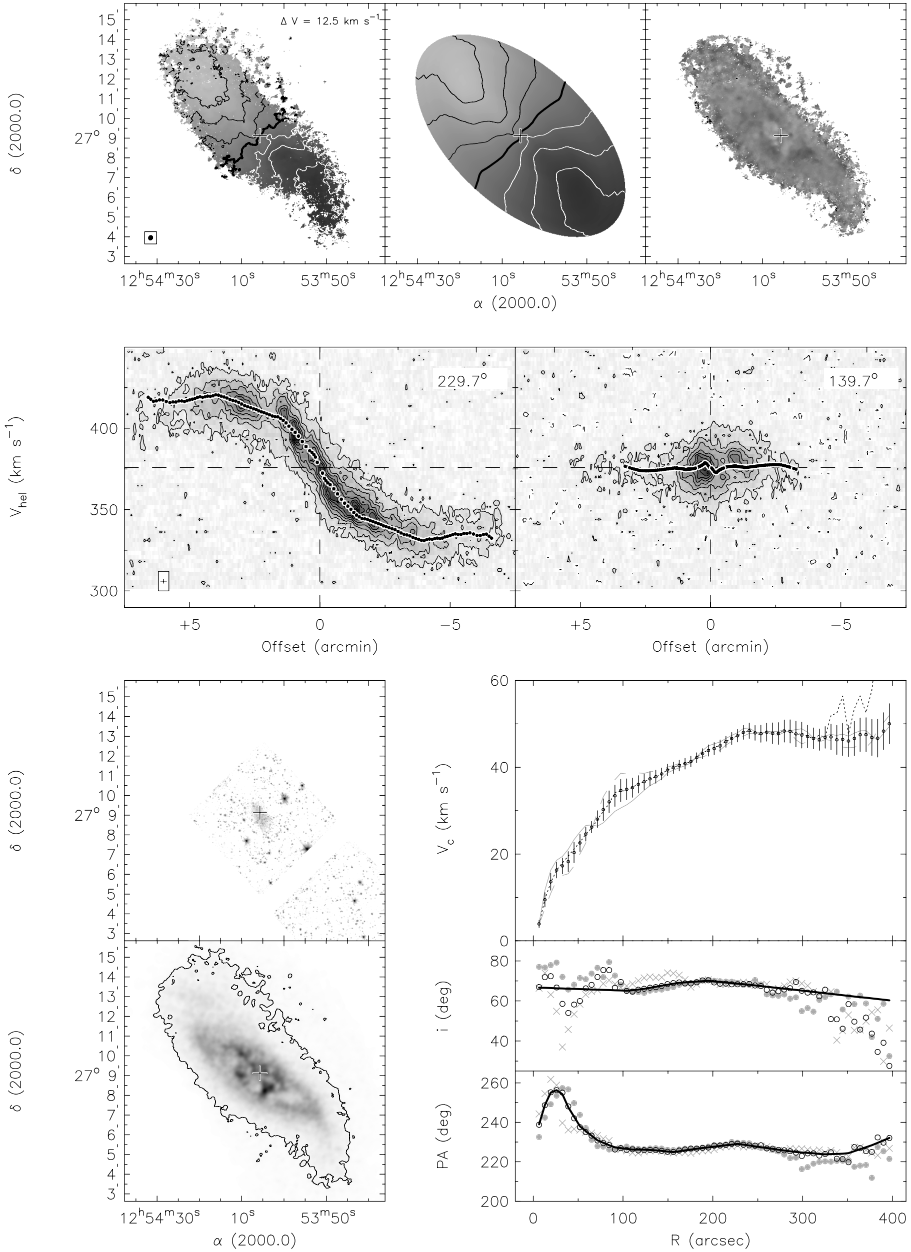
ΔV = 25 km s⁻¹
δ (2000.0)
α (2000.0)
V_hel (km s⁻¹)
123.7°
33.7°
Offset (arcmin)
V_c (km s⁻¹)
i (deg)
PA (deg)
R (arcsec)

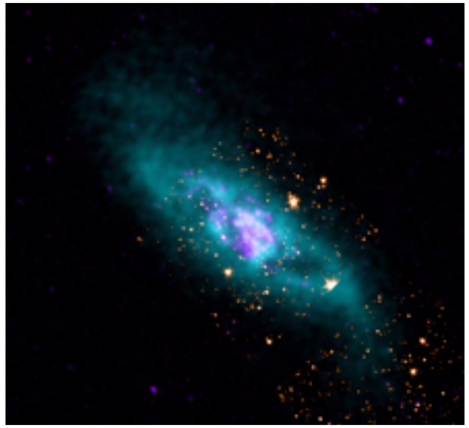


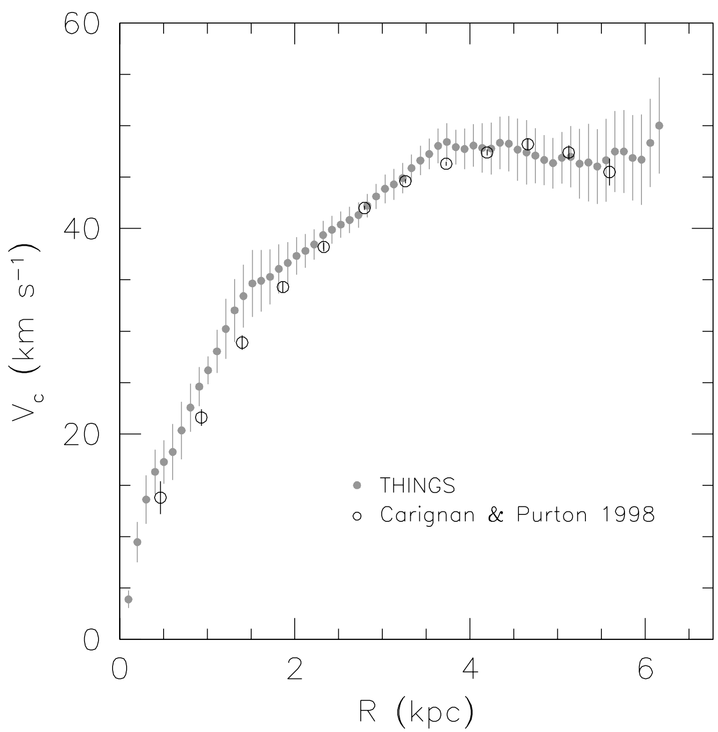


V_c (km s⁻¹)
R (kpc)
THINGS
Begeman (1987)
Sicking (1997)
Fraternali et al (2002)

DDO 154

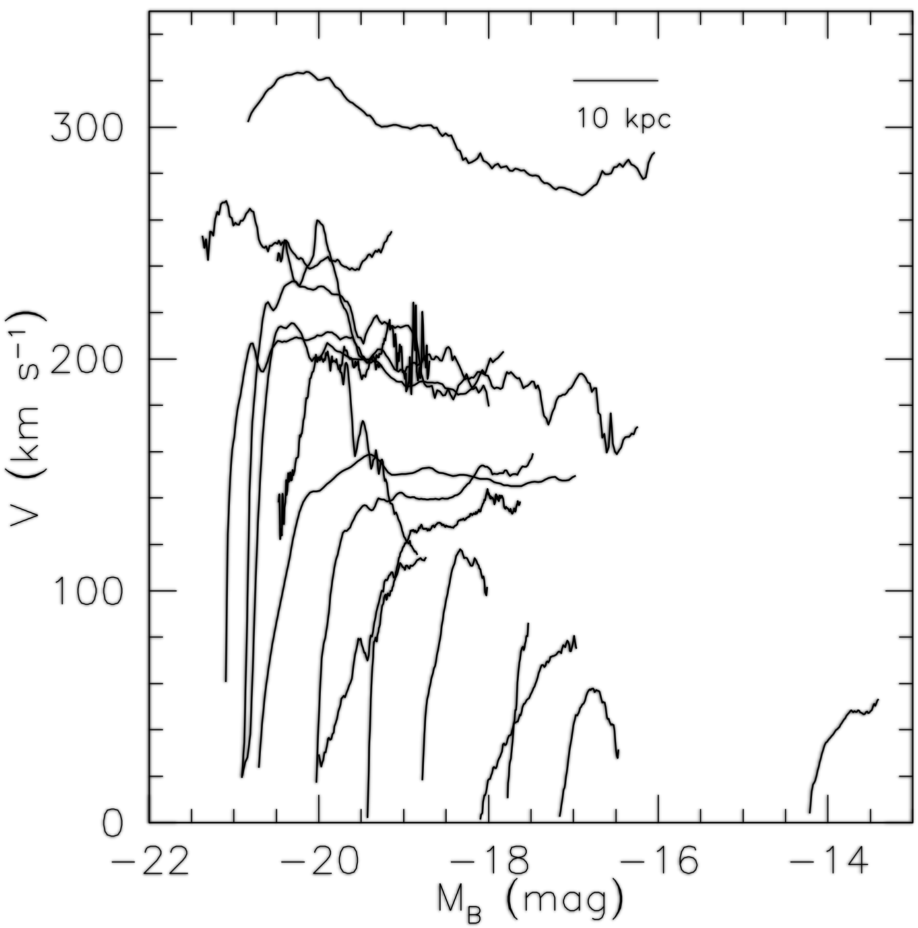


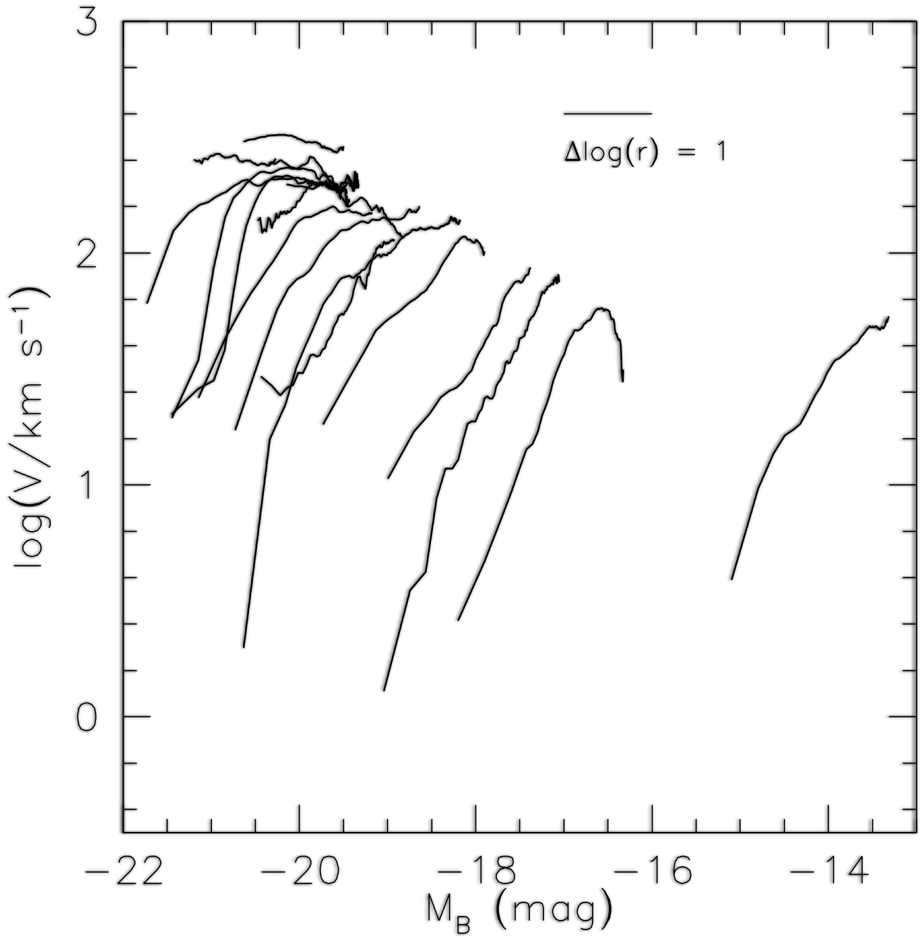




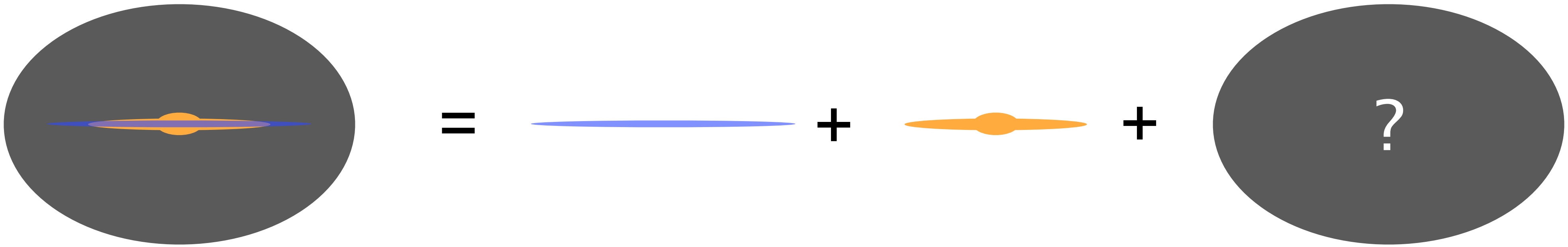
and 16 more...

All together...





Mass Models: Stars and gas

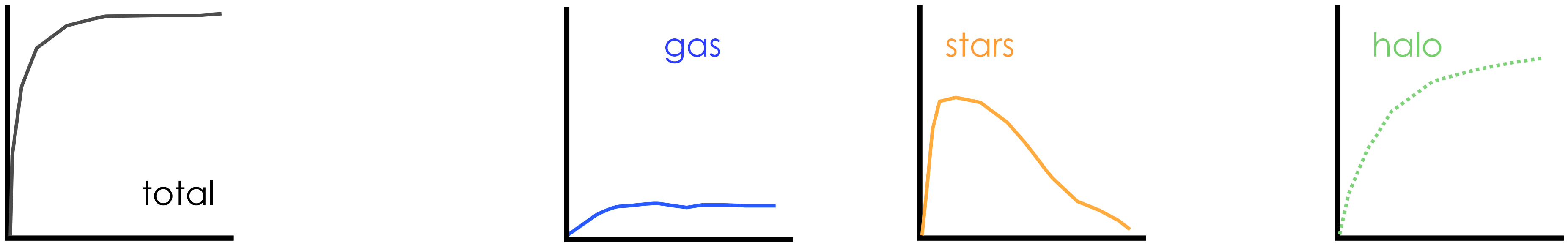


$$M_{tot} = M_{gas} + M_{disk} + M_{halo}$$

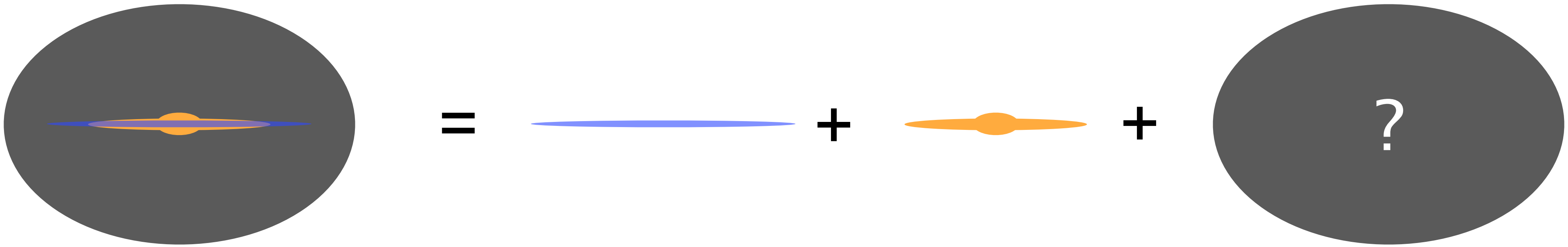
$1.4M_{HI}$

Υ_*

$$V^2_{tot} = V^2_{gas} + V^2_{disk} + V^2_{halo}$$



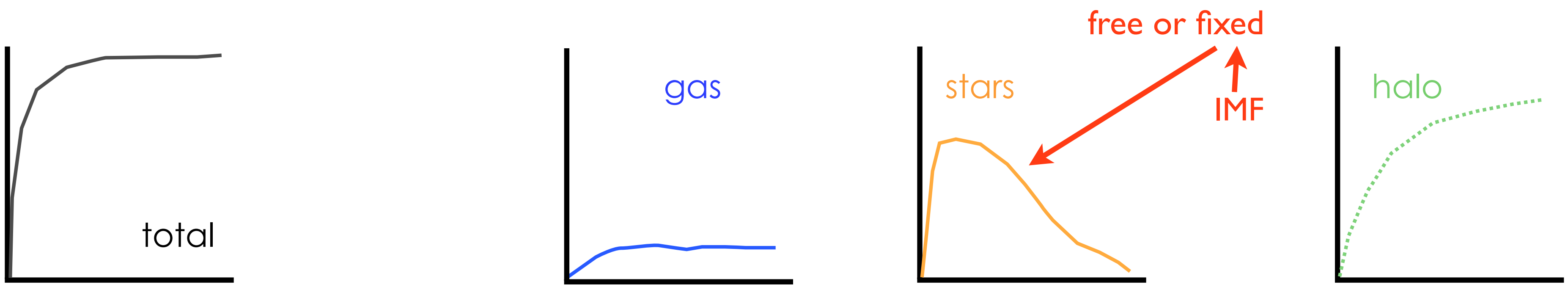
Mass Models: Stars and gas



$$M_{tot} = M_{gas} + M_{disk} + M_{halo}$$

$1.4 M_{HI}$ (gas), Υ_* (disk)

$$V^2_{tot} = V^2_{gas} + V^2_{disk} + V^2_{halo}$$



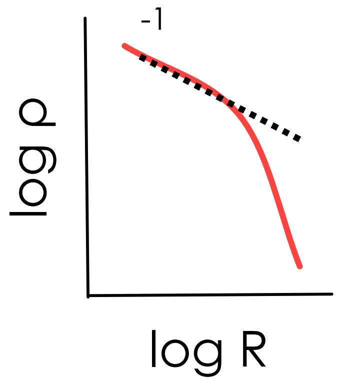
Dark Matter Halo Models

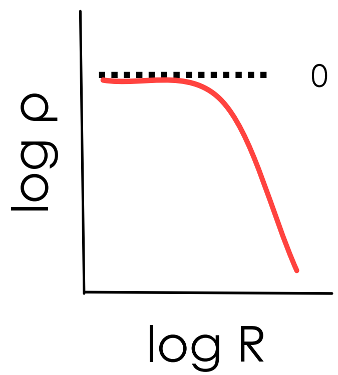
Cold Dark Matter (NFW)

- Universal Mass Density profile
- Most prominently parametrized by NFW
- Dominated by steep, central density "cusp": $\rho \sim R^{-1}$
- "Universal'' cusp gives "universal'' rotation curve
- Steep slope confirmed by many, many simulations

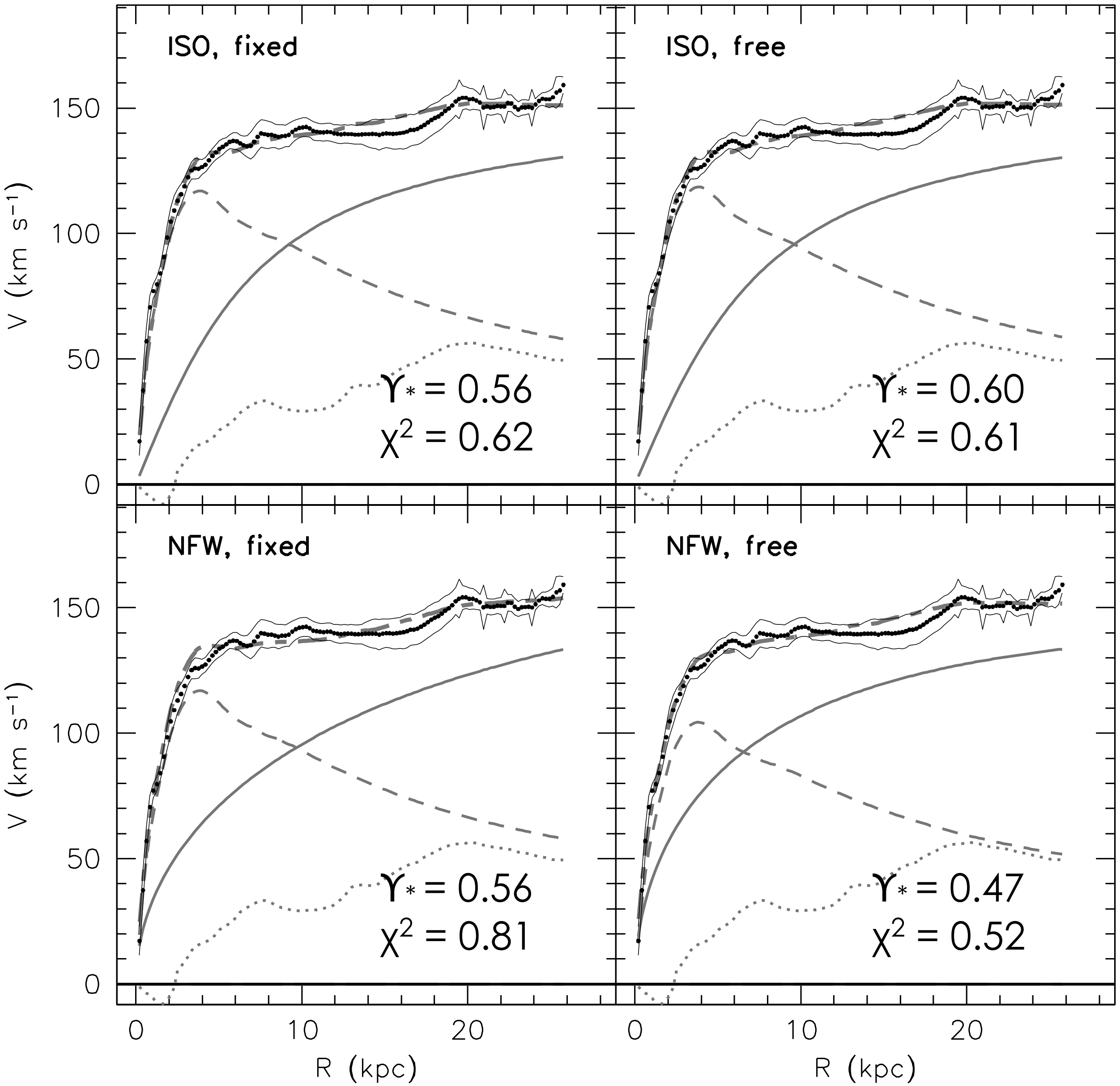
Empirical (ISO)

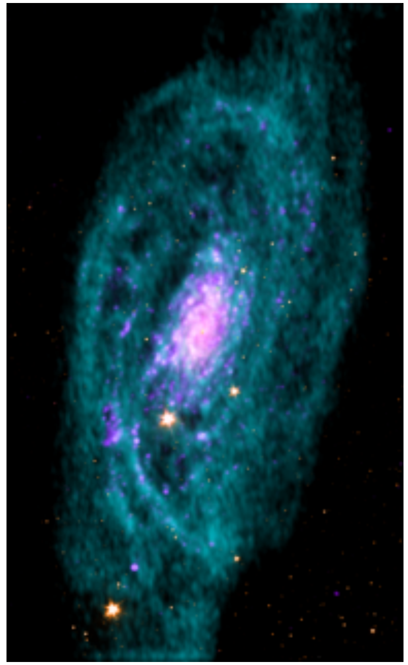
- Most observed rotation curves show inner linear rise and outer flattening
- Best described by central constant-density core: $\rho \sim R^{0}$
- Pseudo-isothermal halo
- Observationally motivated, best description of data
- No cosmological motivation





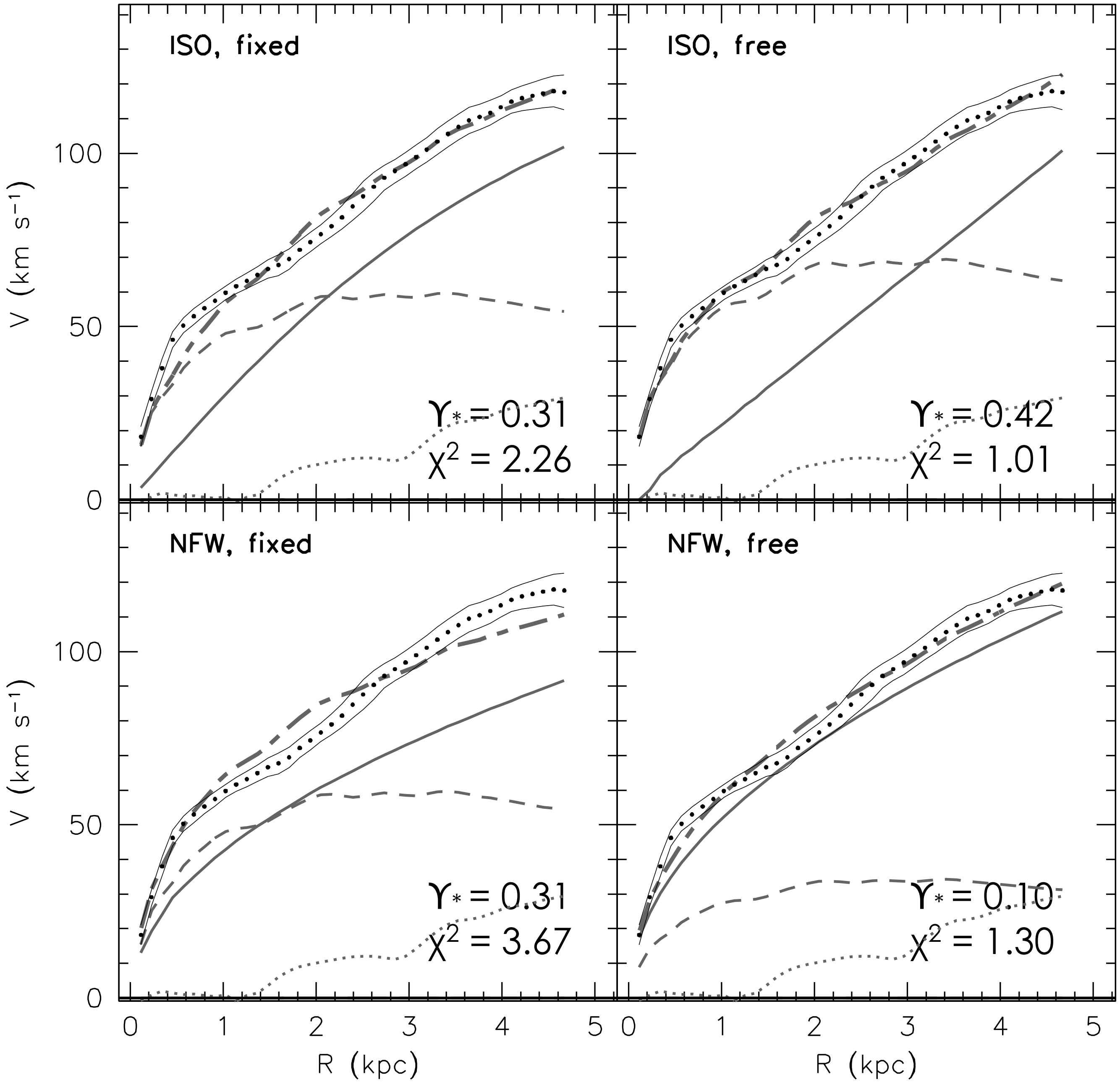
Mass models example: NGC 3621

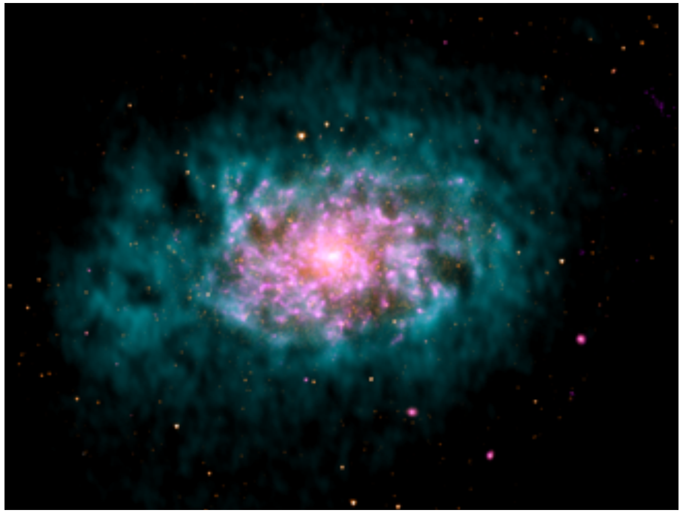




For every galaxy produce models with Υ_* fixed to predicted value and with Υ_* free

Mass models example: NGC 7793

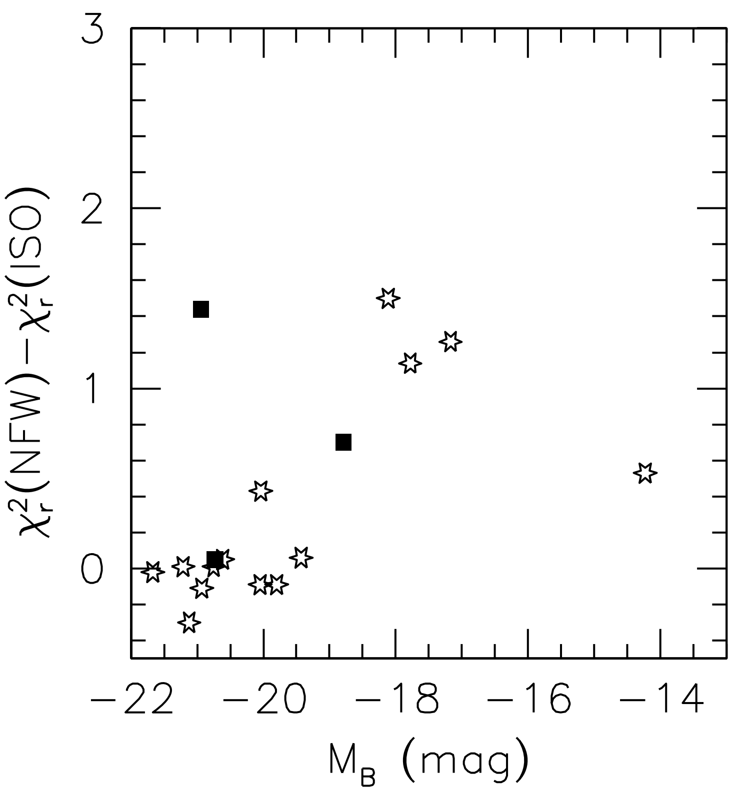




For every galaxy produce models with Υ* fixed to predicted value and with Υ* free

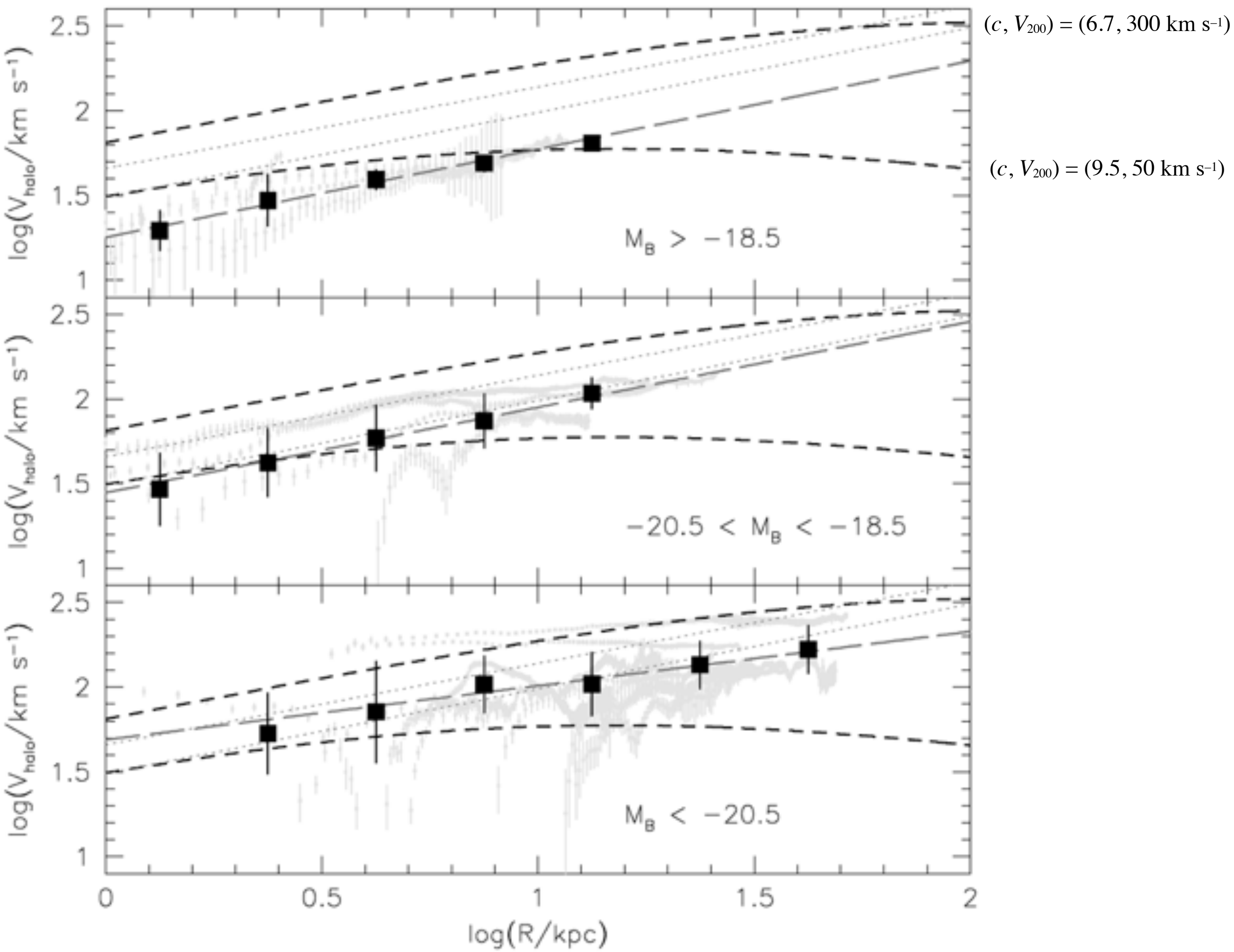
Ɛcetera

Does it fit?



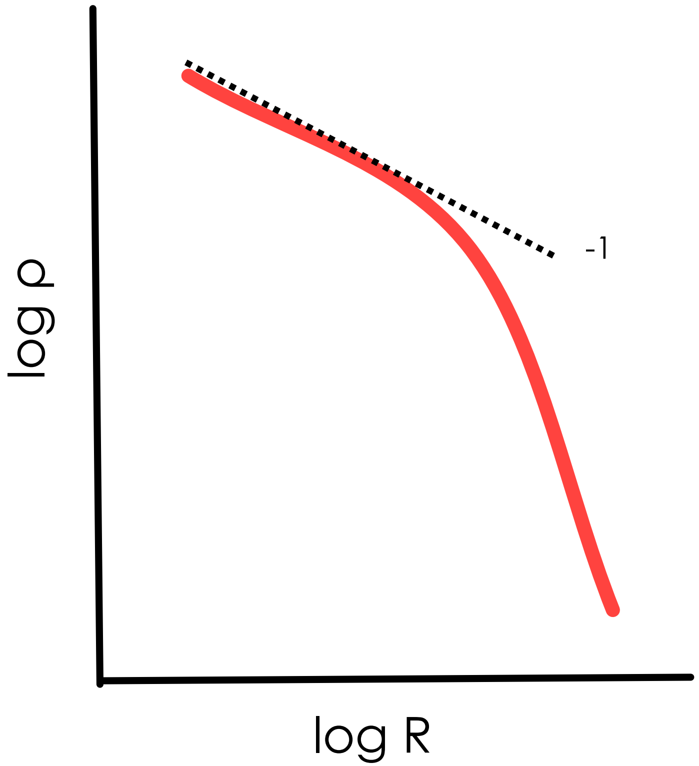
- For M_B < -19 ISO and NFW fit ~equally well
- But dominated by stars
- For M_B > -19 large differences; ISO best
- Dominated by dark matter
- Looking only at good fits: clear break at M_B~-18.5
- Non-circular motions?

Halo Rotation Curves

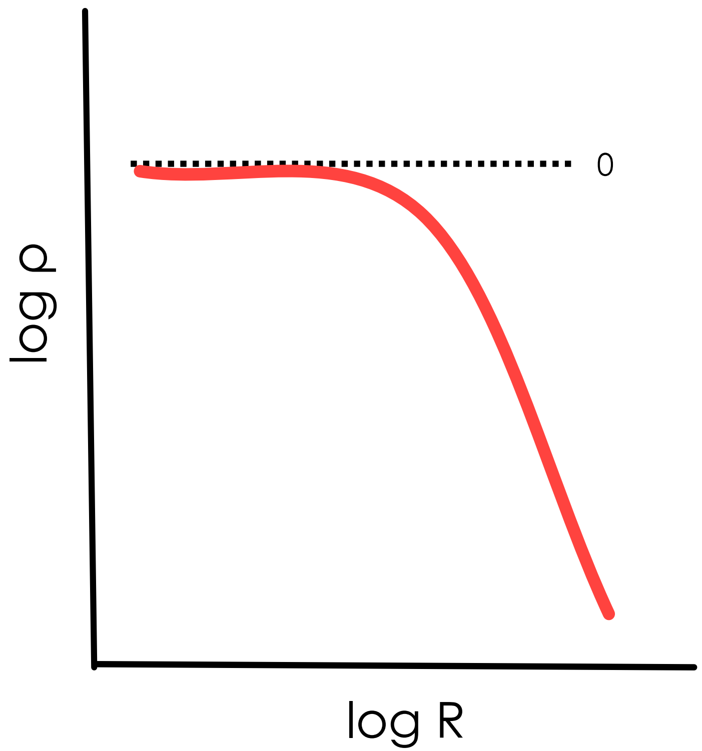


Dark Matter Halo Models

Cold Dark Matter (NFW)

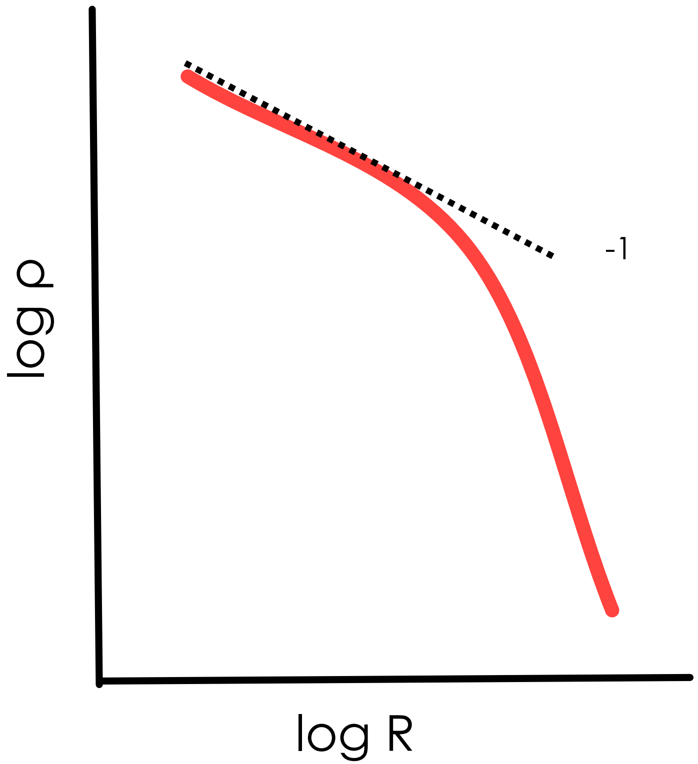


Empirical (ISO)

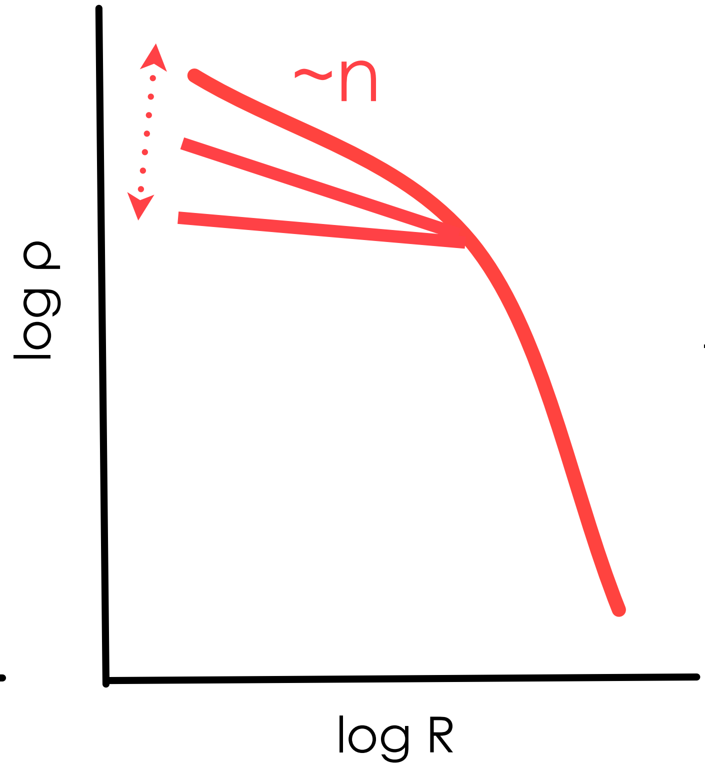


Dark Matter Halo Models

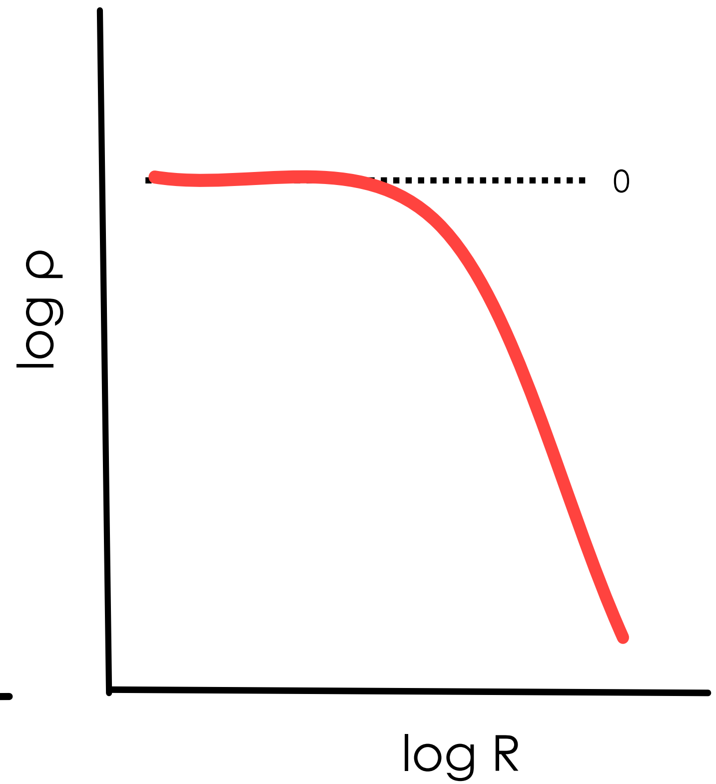
Cold Dark Matter (NFW)



Einasto



Empirical (ISO)



$$\rho_{\mathrm{E}}(r) = \rho_{-2} \exp\left\{-2n\left[\left(\frac{r}{r_{-2}}\right)^{1/n} - 1\right]\right\}$$

r_{-2} = radius where d(log ρ)/d(log r) = -2; $\rho_{-2} = \rho(r_{-2})$

Einasto mass profile (Cardone et al 2005; Mamon and Łokas 2005)

The Einasto Halo

Proposed as superior model for CDM simulated halos (Navarro et al 2004, Merritt et al 2006)

Previously used for surface photometry of galaxies by Einasto (1965, 1968, 1969) [cf. Sersic profile]

$$\rho_{\rm E}(r) = \rho_{-2}\, \exp\left\{-2n\left[\left(\frac{r}{r_{-2}}\right)^{1/n} - 1\right]\right\}$$

r_{-2} = radius where $d(\log \rho)/d(\log r) = -2$; $\rho_{-2} = \rho(r_{-2})$

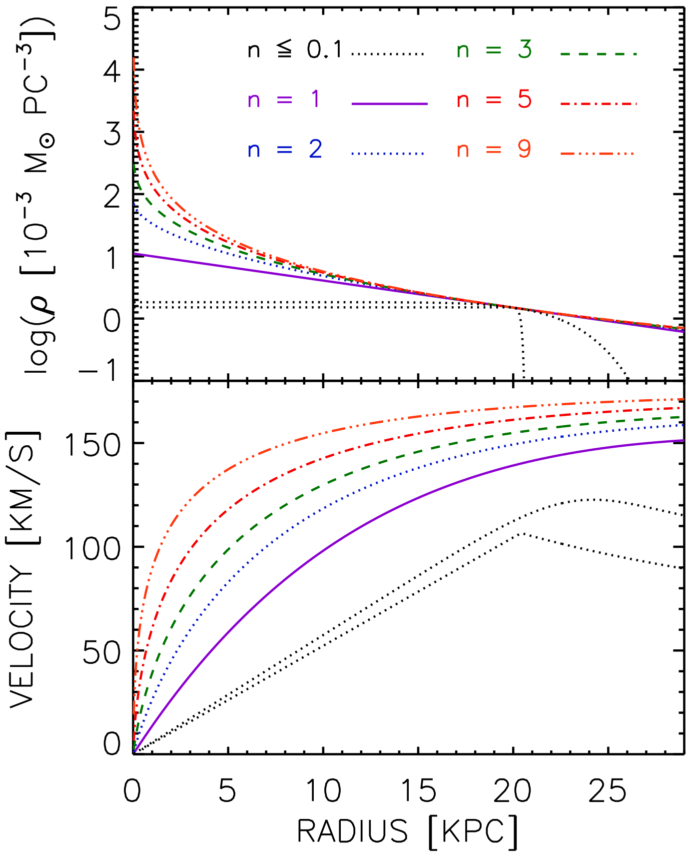
Einasto mass profile (Cardone et al 2005; Mamon and Łokas 2005)

$$M_{\rm E}(r) = 4\pi n r_{-2}^{3} \rho_{-2}\, {\rm e}^{2n}\, (2n)^{-3n} \gamma\left(3n, \frac{r}{r_{-2}}\right)$$

where $\gamma(3n, x) = \int_0^x {\rm e}^{-t} t^{3n-1} {\rm d}t$ is the incomplete gamma function.

The Einasto Halo

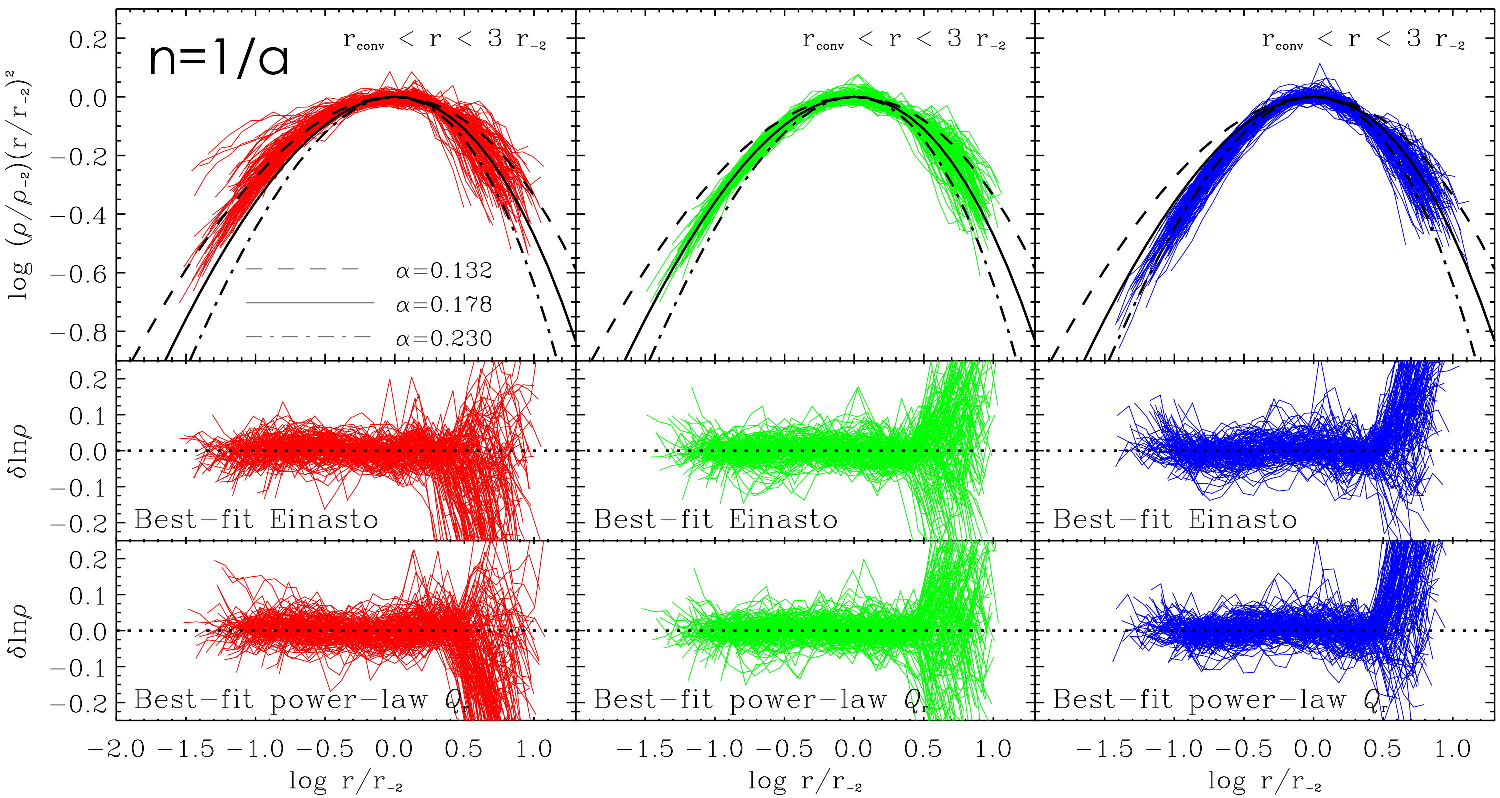
Index n regulates inner slope of density and rotation curve



$$\rho_{\mathrm{E}}(r) = \rho_{-2}\ \exp\left\{-2n\left[\left(\frac{r}{r_{-2}}\right)^{1/n} - 1\right]\right\}$$

Einasto and CDM

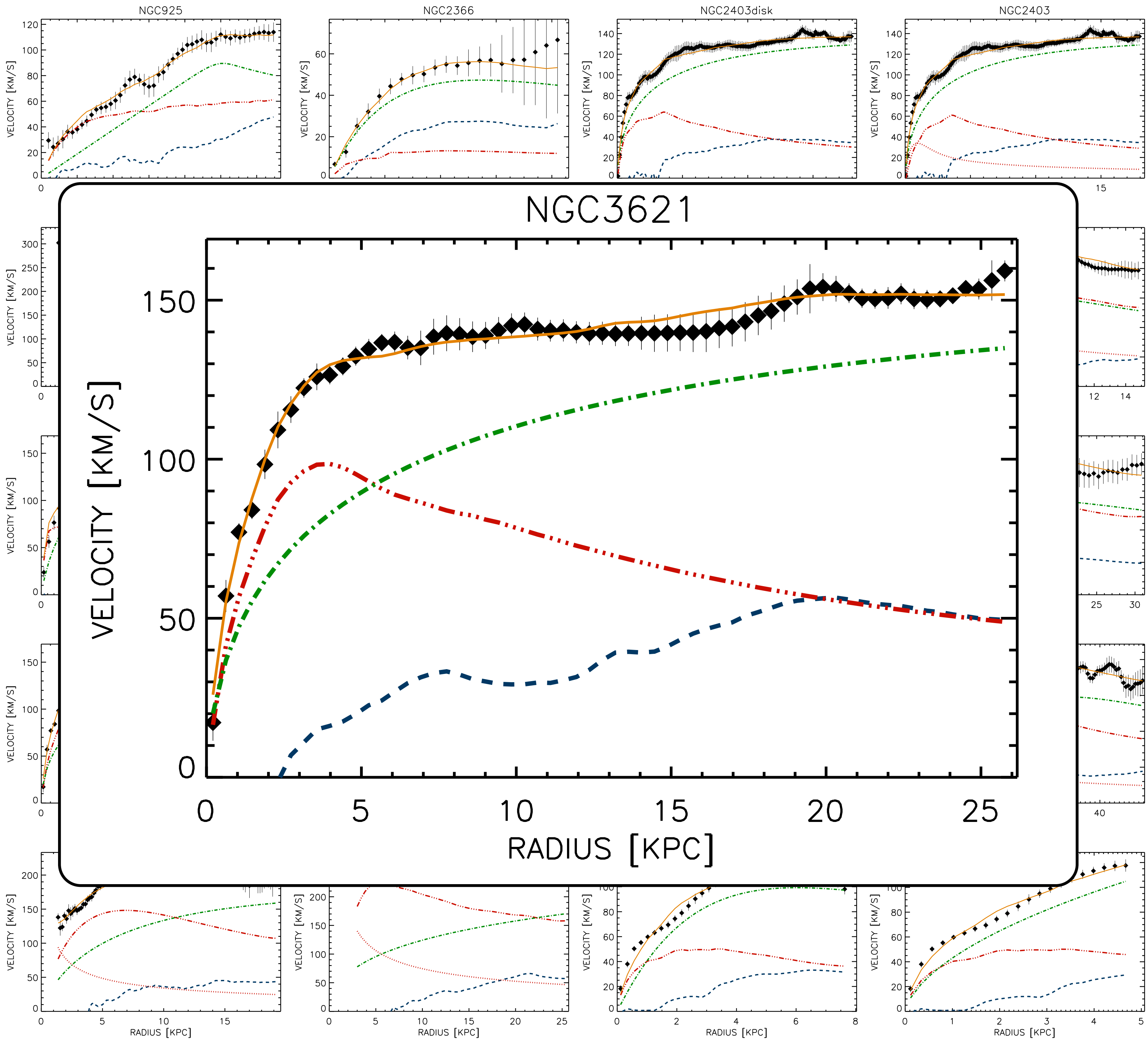
Einasto halo gives good description of CDM halos



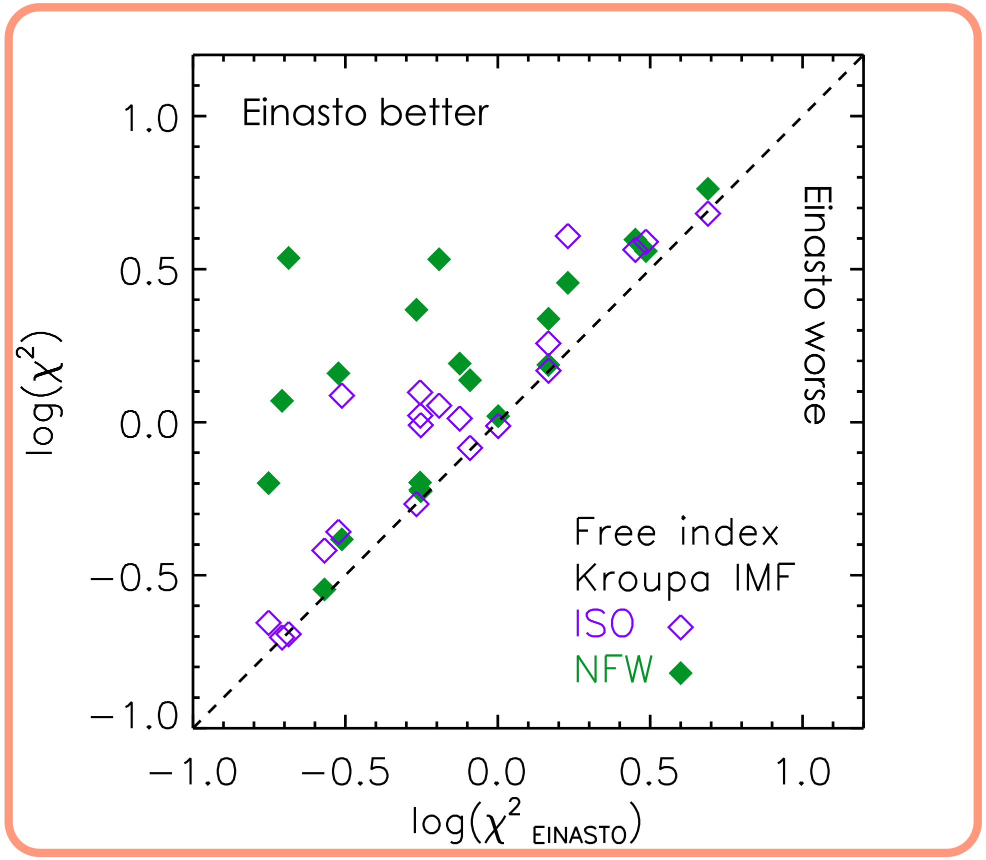
Ludlow et al 2011

CDM halos yield fairly narrow range in n.
Navarro et al (2004): $n = 6.2 \pm 1.2$.
Generally one finds $5 \lesssim n \lesssim 10$

Einasto halo, Kroupa IMF, free n

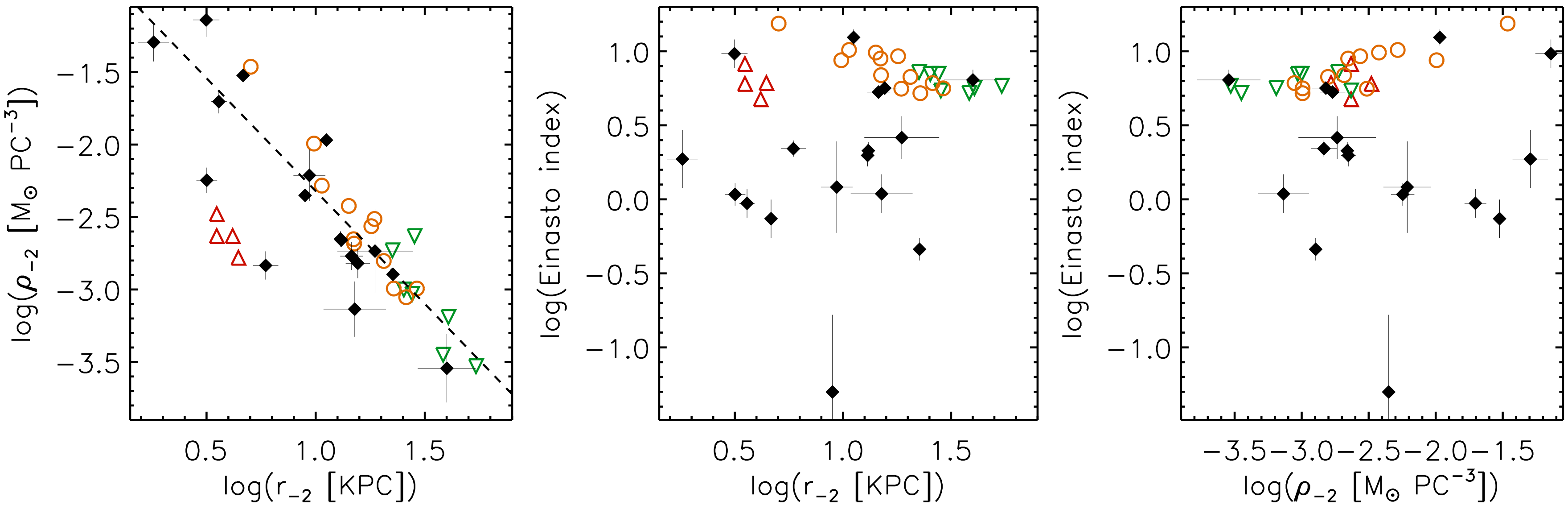


Comparison with ISO and NFW



Einasto halos provide better fits, also to observed rotation curves

Einasto Halo Parameters



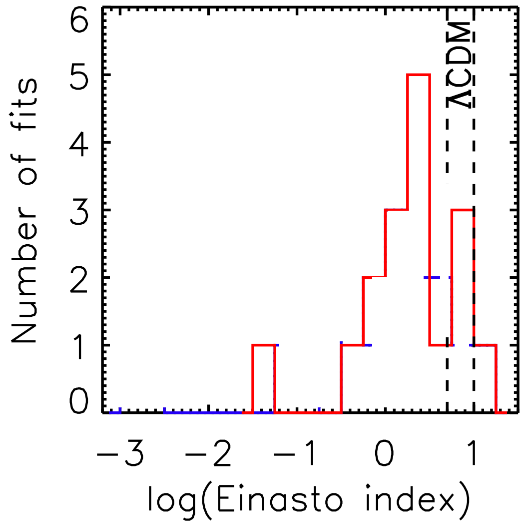
Kroupa IMF

△ dwarf-sized halos (Navarro et al 2004)

▽ galaxy-sized halos (Navarro et al 2004)

○ galaxy-sized halos with baryons (Tissera et al 2010)

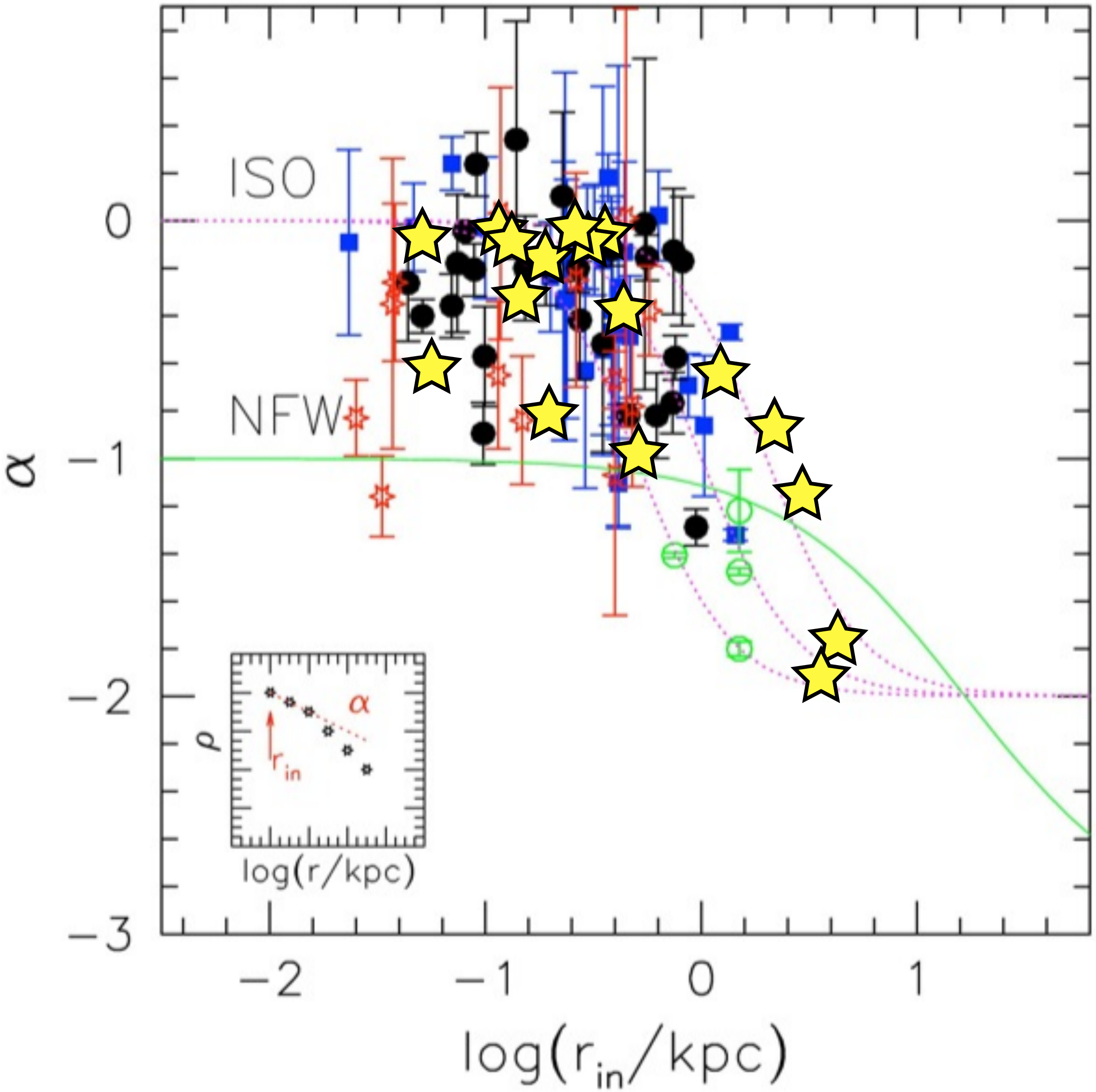
degenerate fits not shown



No single index or simple relation can describe observations

Observed indices smaller than simulations

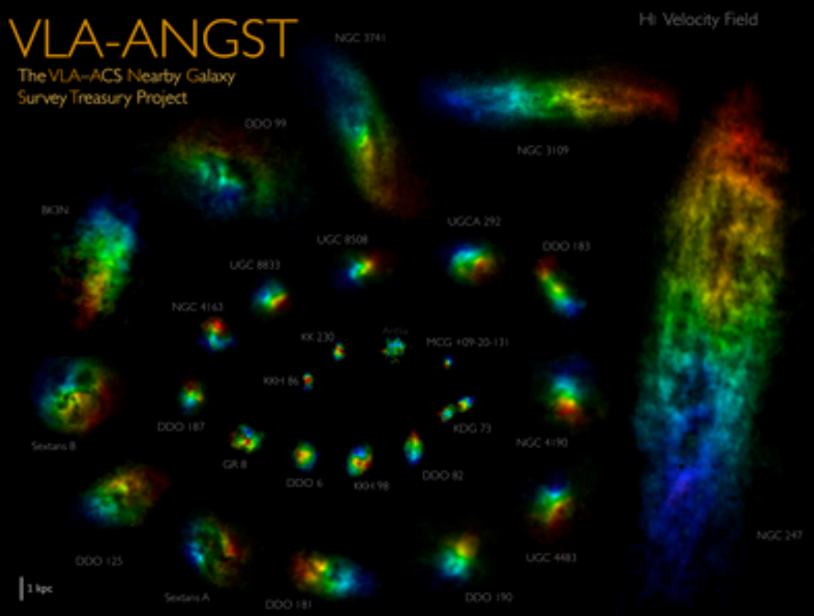
Einasto slope and resolution



THINGS,
Einasto halo,
free n,
Kroupa IMF

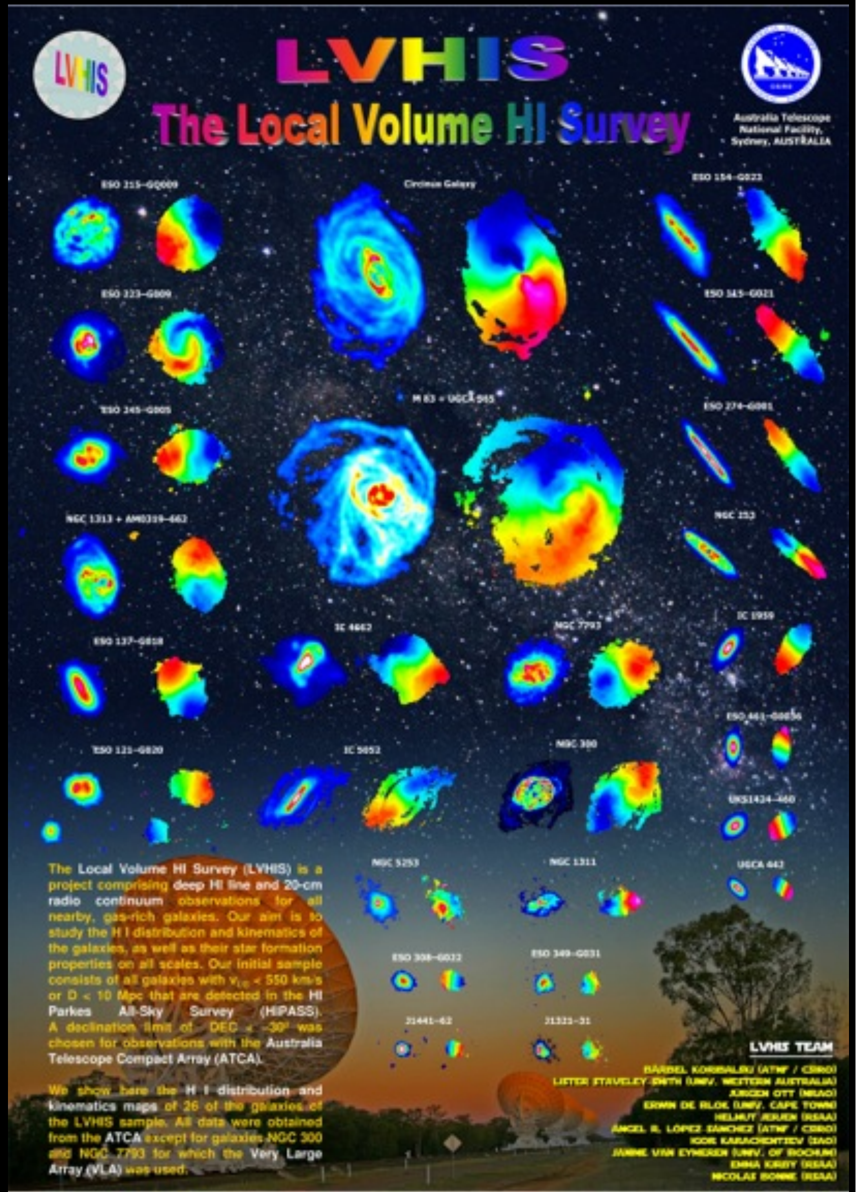
Einasto Results

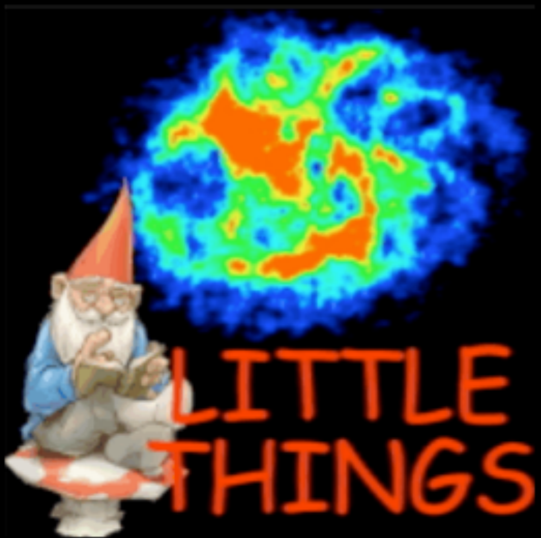
- Einasto fits better than ISO or NFW
- However, no unique n-value, no scaling between masses
- No universal Einasto halo in THINGS galaxies
- Typically smaller n-value than CDM halos. n>4 is rare



VLA-ANGST:
35 nearby local
volume galaxies
PI : J. Ott

LVHIS:
all HIPASS detected
D<10Mpc galaxies
PI: B. Koribalski





LITTLE THINGS
41 gas-rich dwarf galaxies
PI: D. Hunter

LITTLE THINGS

Local Irregulars That Trace Luminosity Extremes
The HI Nearby Galaxy Survey
Hunter et al. (2012)

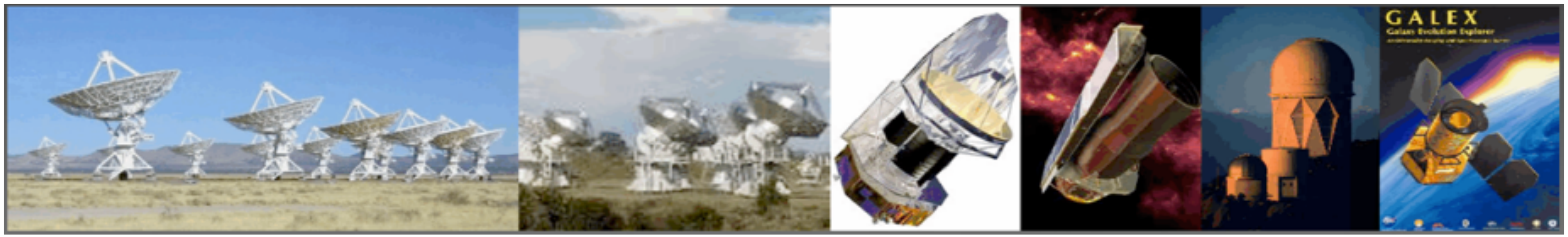
• "THINGS-like" (~6"; < 5.2 km/s) high-resolution VLA HI 21cm survey (B+C +D; 376 hours) for 41 nearby (< 10 Mpc) dwarf (dIm, BCD) galaxies

• Commensality with Spitzer (+ Herschel) optical, GALEX uv, CO data etc.)

• VLA observations ended in 2009

• Data available at:
https://science.nrao.edu/science/surveys/littlethings

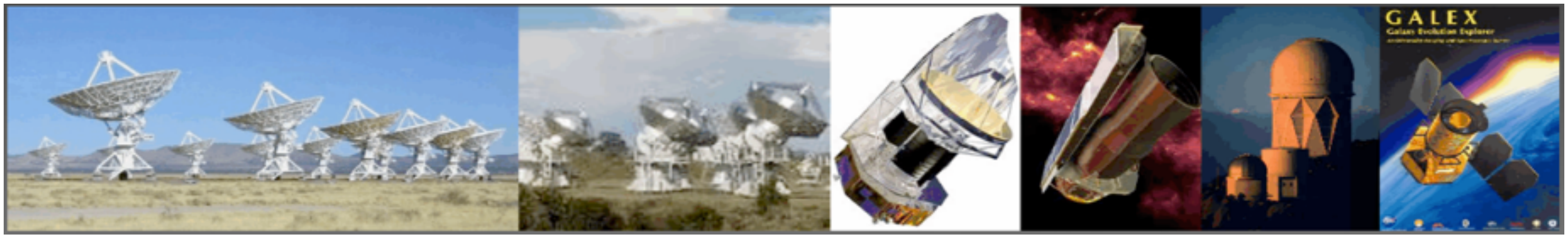
• Further observations with EVLA, CARMA, APEX, Herschel etc.



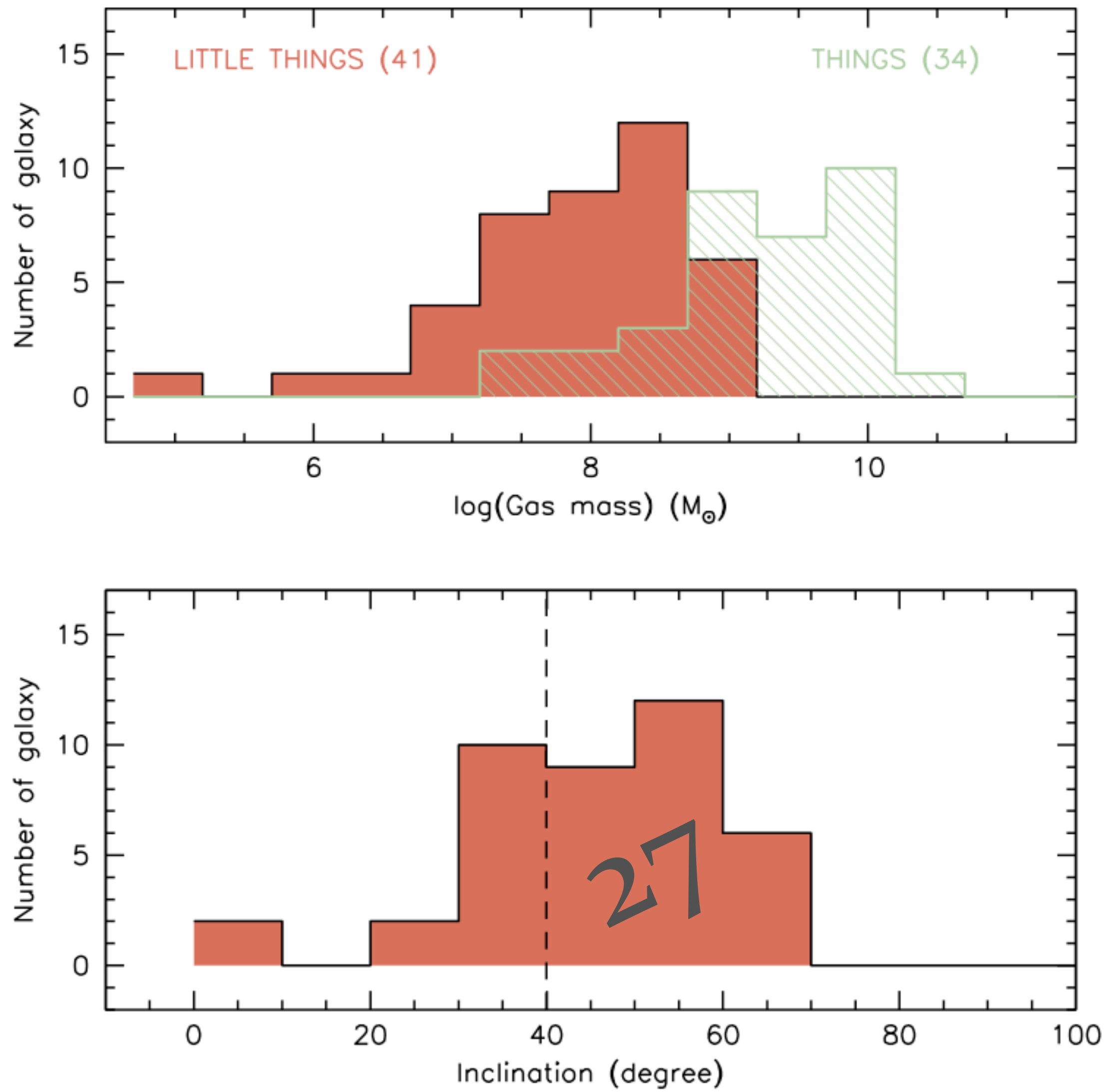
LITTLE THINGS

Main Science Drivers

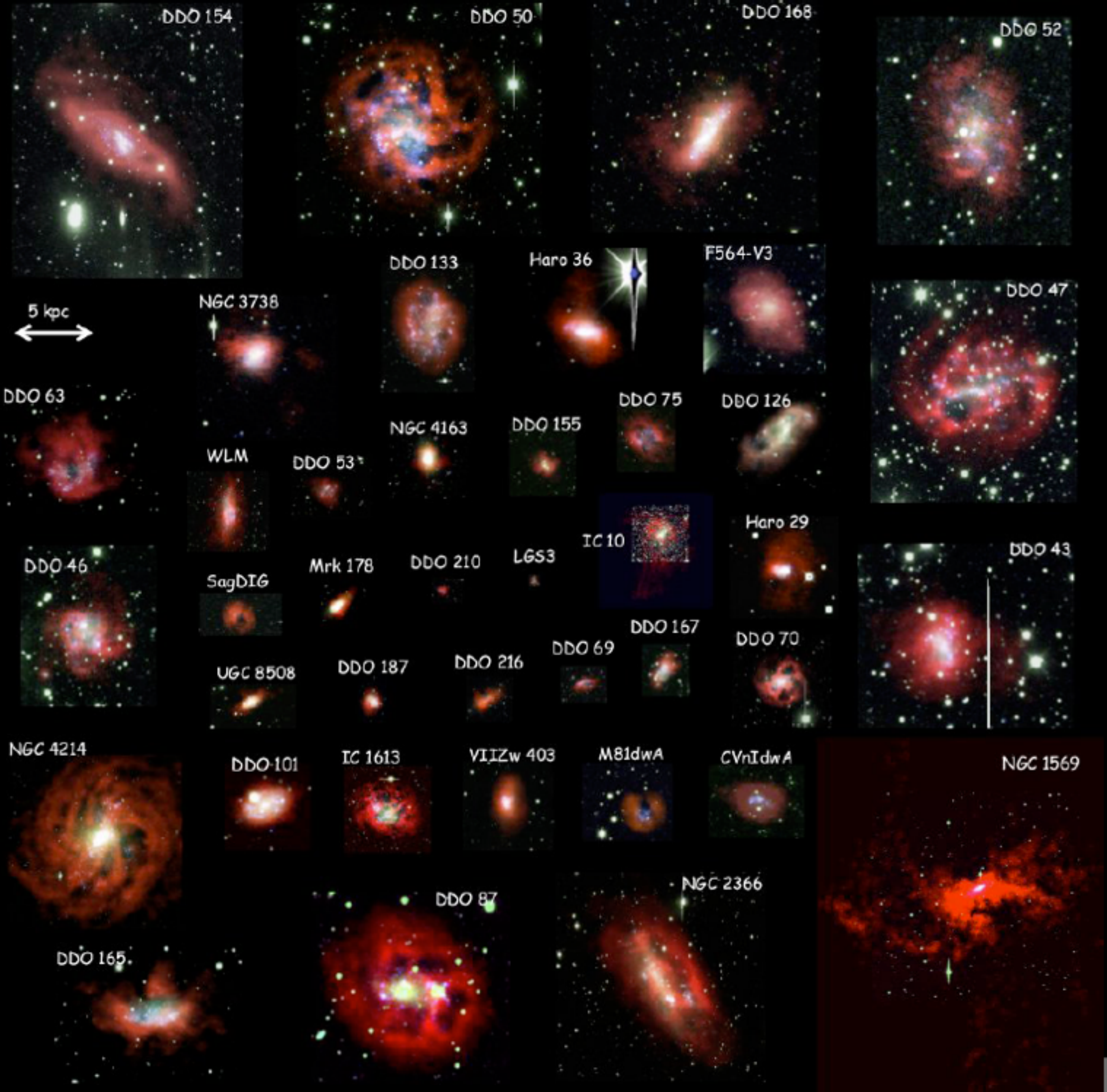
- What regulates **star formation** is dwarf galaxies?
- What is the **relative importance of sequential triggering** for star formation in dwarf galaxies?
- How **(dark) matter** is distributed in dwarf galaxies?
- What is the relative importance of triggering by **random turbulence compression** in dwarf galaxies?
- What is happening in the **far outer parts** of dwarf galaxies?
- What happens to the star formation process **at breaks in the exponential light profile**?
- What happens in **Blue Compact Dwarf (BCD) galaxies**?



Little THINGS



Oh et al. in prep.

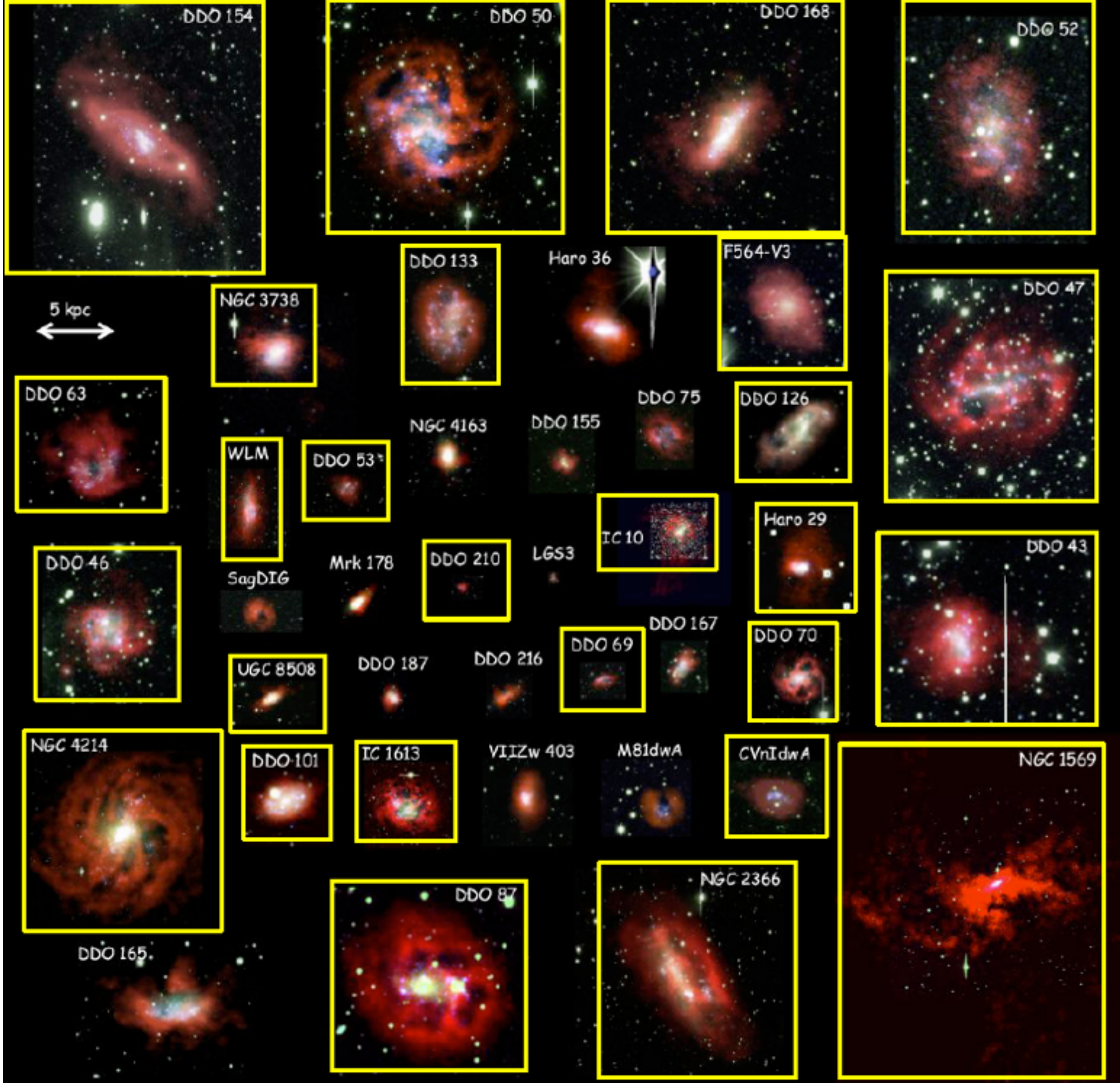


LITTLE THINGS

HI (red)

V (green)

FUV (blue)



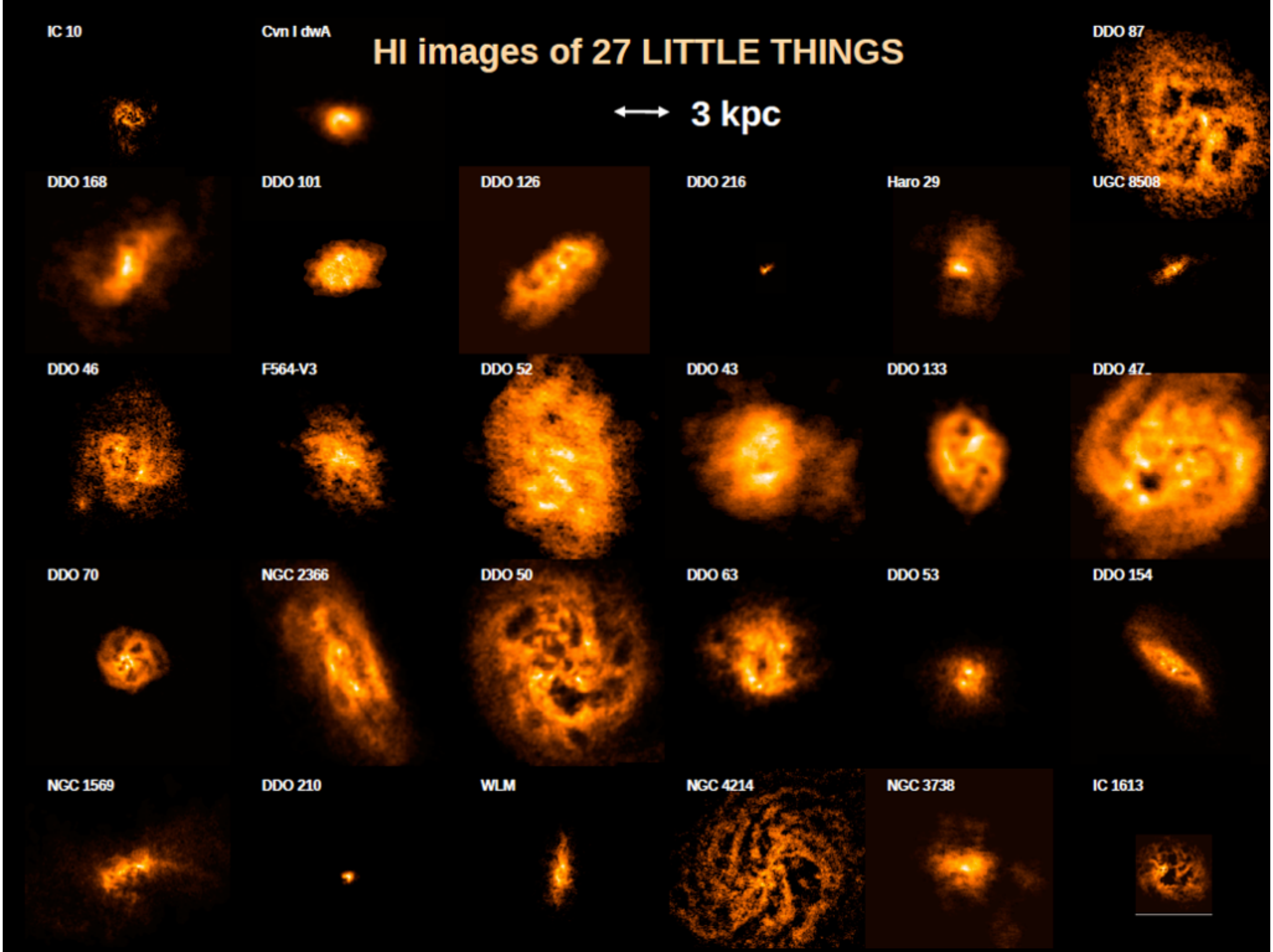
LITTLE THINGS

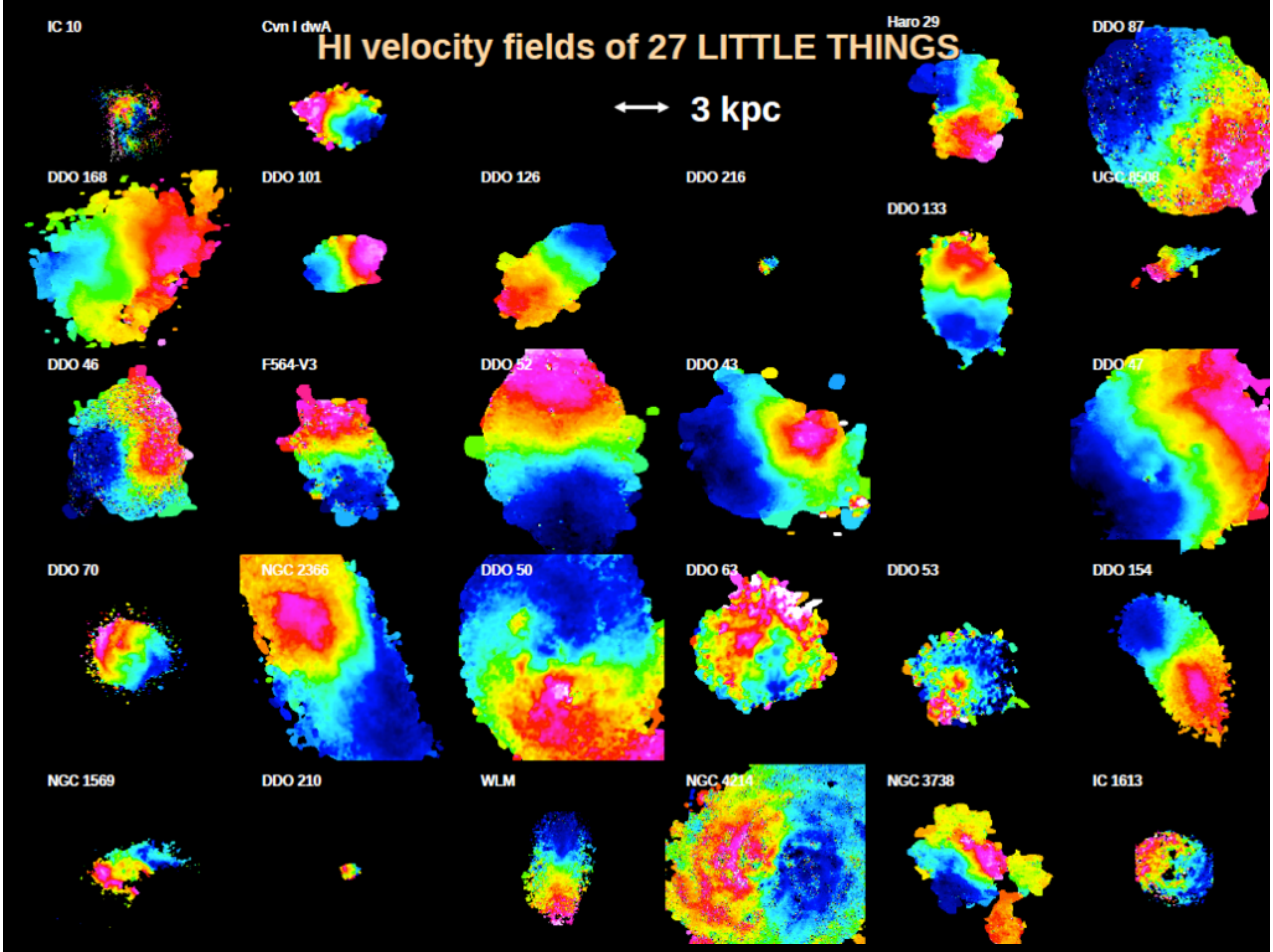
27 sample galaxies, circular rotation dominated

HI (red)

V (green)

FUV (blue)


HI images of 27 LITTLE THINGS
3 kpc
IC 10
Cvn I dwA
DDO 87
DDO 168
DDO 101
DDO 126
DDO 216
Haro 29
UGC 8508
DDO 46
F564-V3
DDO 52
DDO 43
DDO 133
DDO 47
DDO 70
NGC 2366
DDO 50
DDO 63
DDO 53
DDO 154
NGC 1569
DDO 210
WLM
NGC 4214
NGC 3738
IC 1613


HI velocity fields of 27 LITTLE THINGS
3 kpc
IC 10
Cvn I dwA
Haro 29
DDO 87
DDO 168
DDO 101
DDO 126
DDO 216
DDO 133
UGC 8508
DDO 46
F564-V3
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DDO 50
DDO 63
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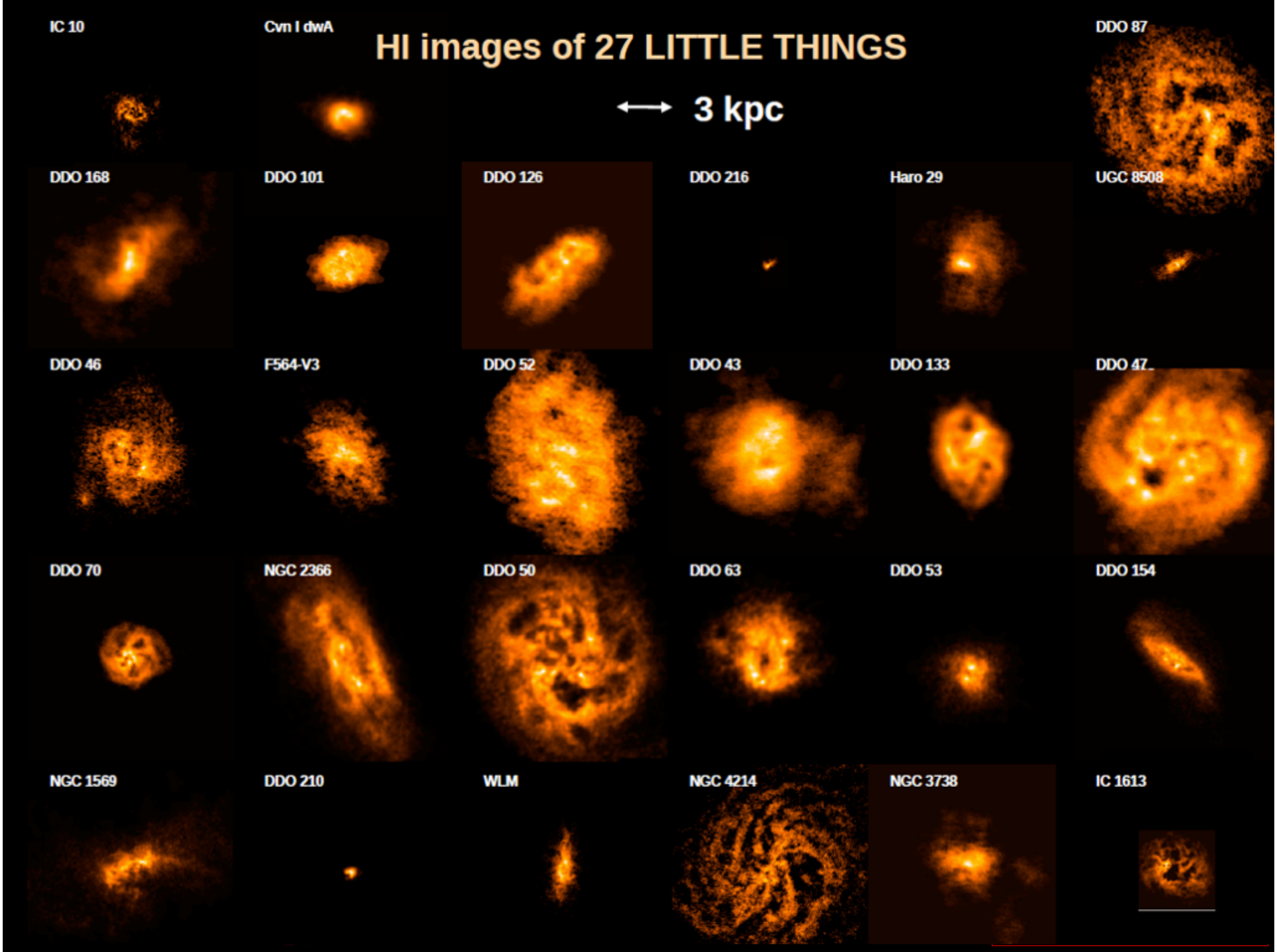

HI images of 27 LITTLE THINGS
3 kpc
IC 10
Cvn I dwA
DDO 87
DDO 168
DDO 101
DDO 126
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UGC 8508
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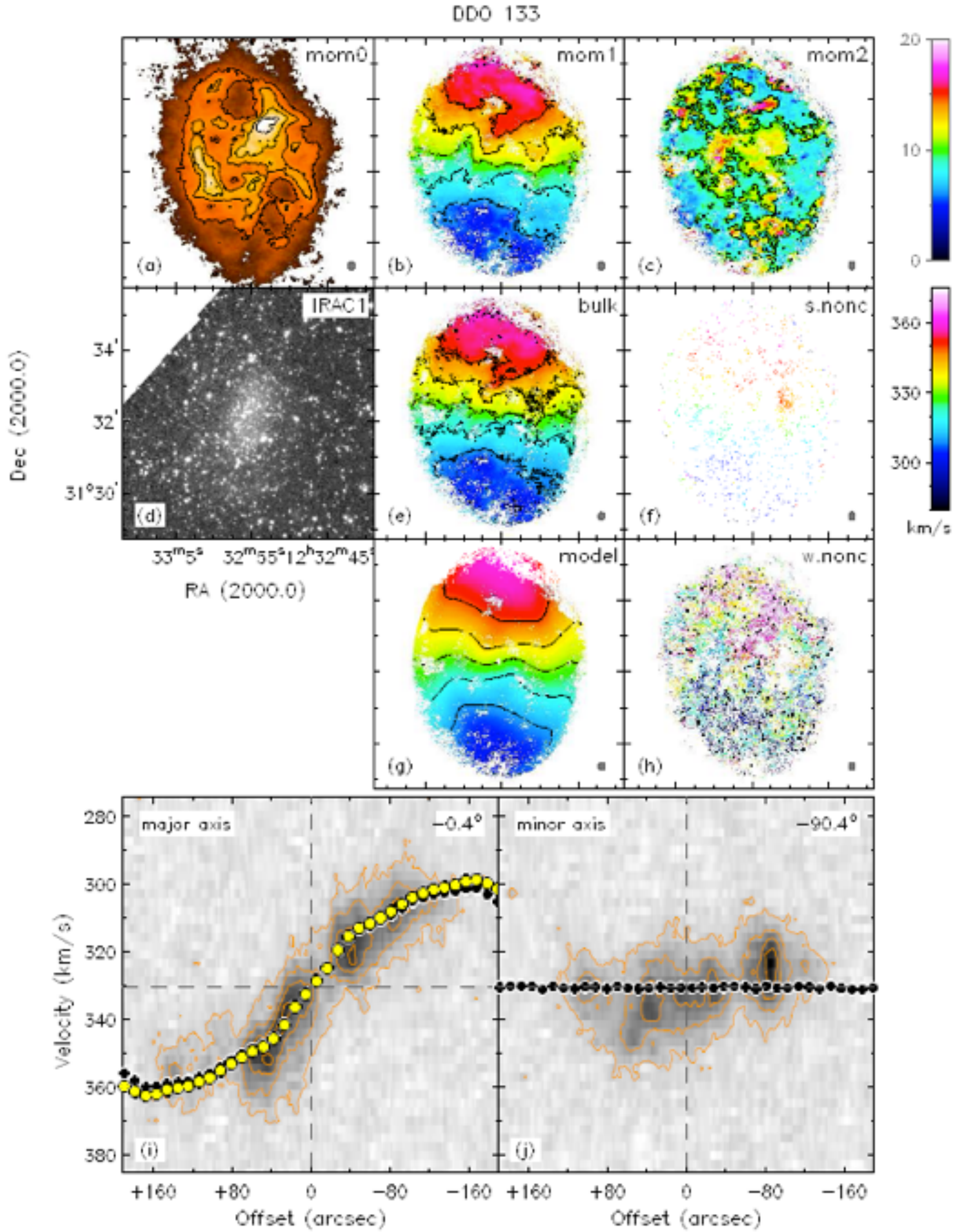
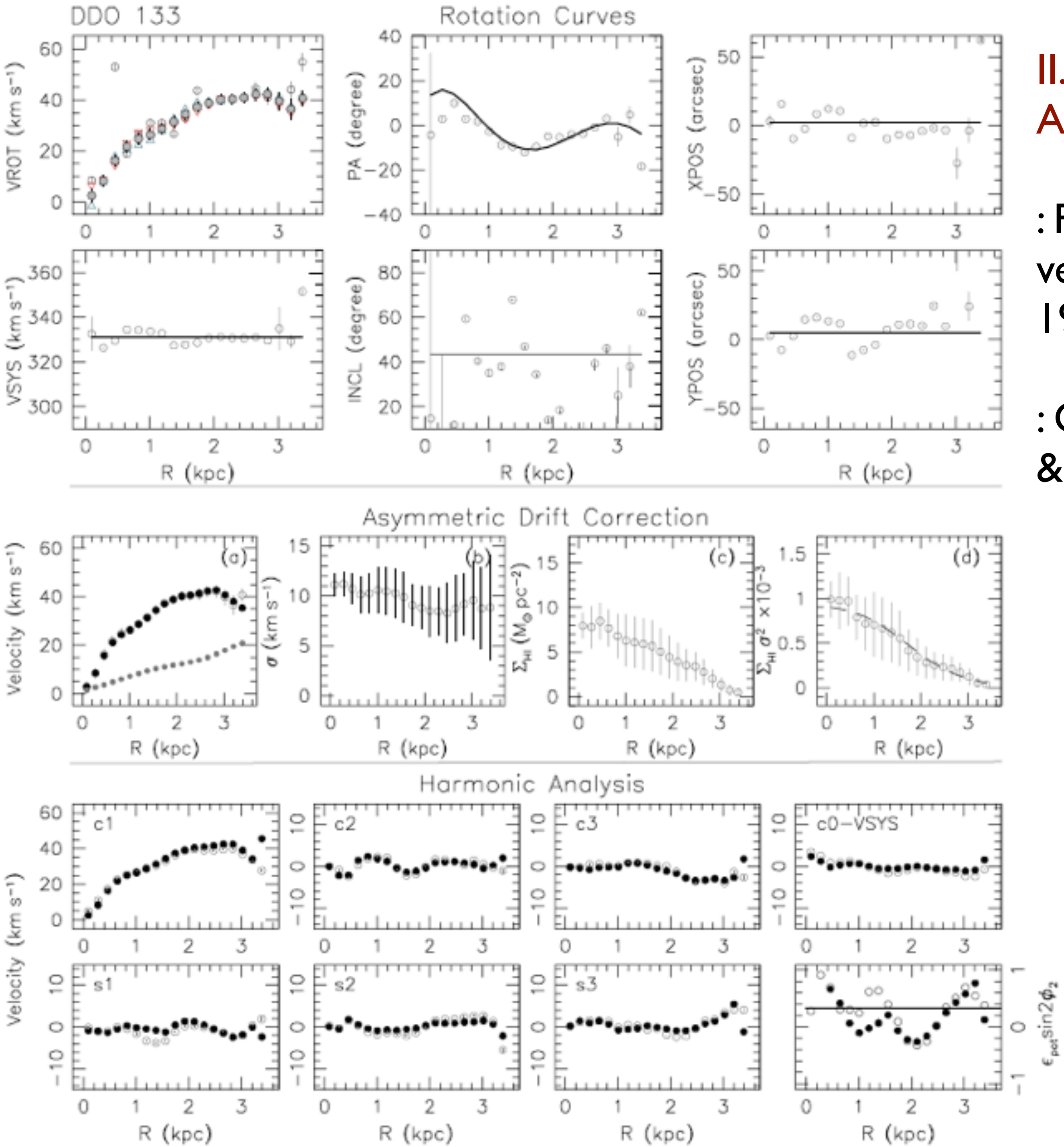
DDO 70
NGC 2366
DDO 50
DDO 63
DDO 53
DDO 154
NGC 1569
DDO 210
WLM
NGC 4214
NGC 3738
IC 1613

I. Data (e.g., DDO 133)

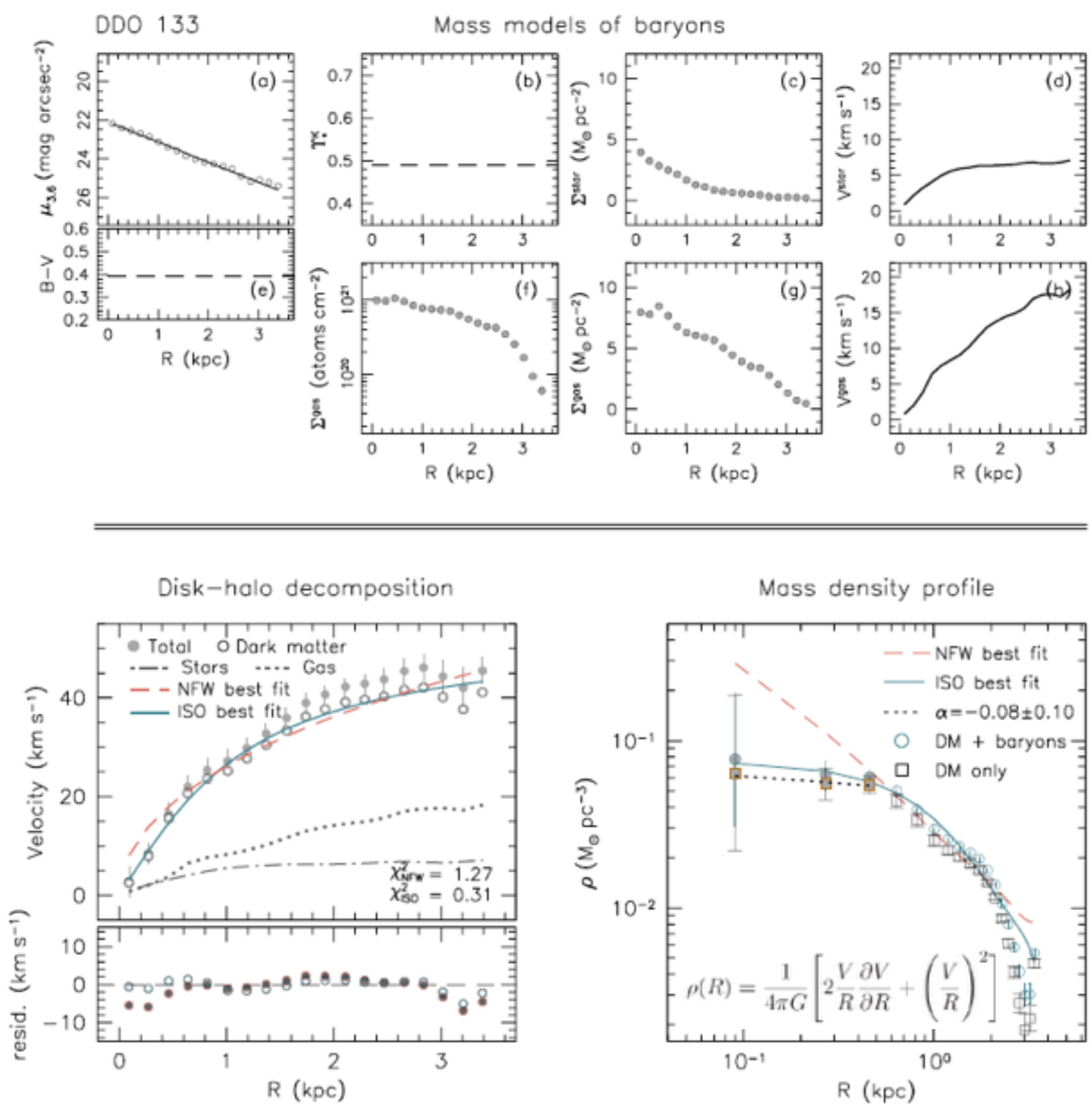




II. Rotation curves & Asymmetric drift correction

: Fit 2D tilted-ring models to velocity fields (Rogstad et al. 1974; "rotcur" task in GIPSY)

: Gas drift correction (Bureau & Carignan 2002)



III. Disk-halo decomposition & Dark matter density profile

: derive mass models of gas and stellar components using gas intensity map (corrected for He+metals) and Spitzer 3.6 micron images

: M/L based on stellar population synthesis models

: Fit two halo models (ISO & NFW)

: Matter density profiles (DM +baryons; DM-only) derived assuming a spherical halo potential

: Measure the inner density slope, α

SPH Simulations of Dwarfs

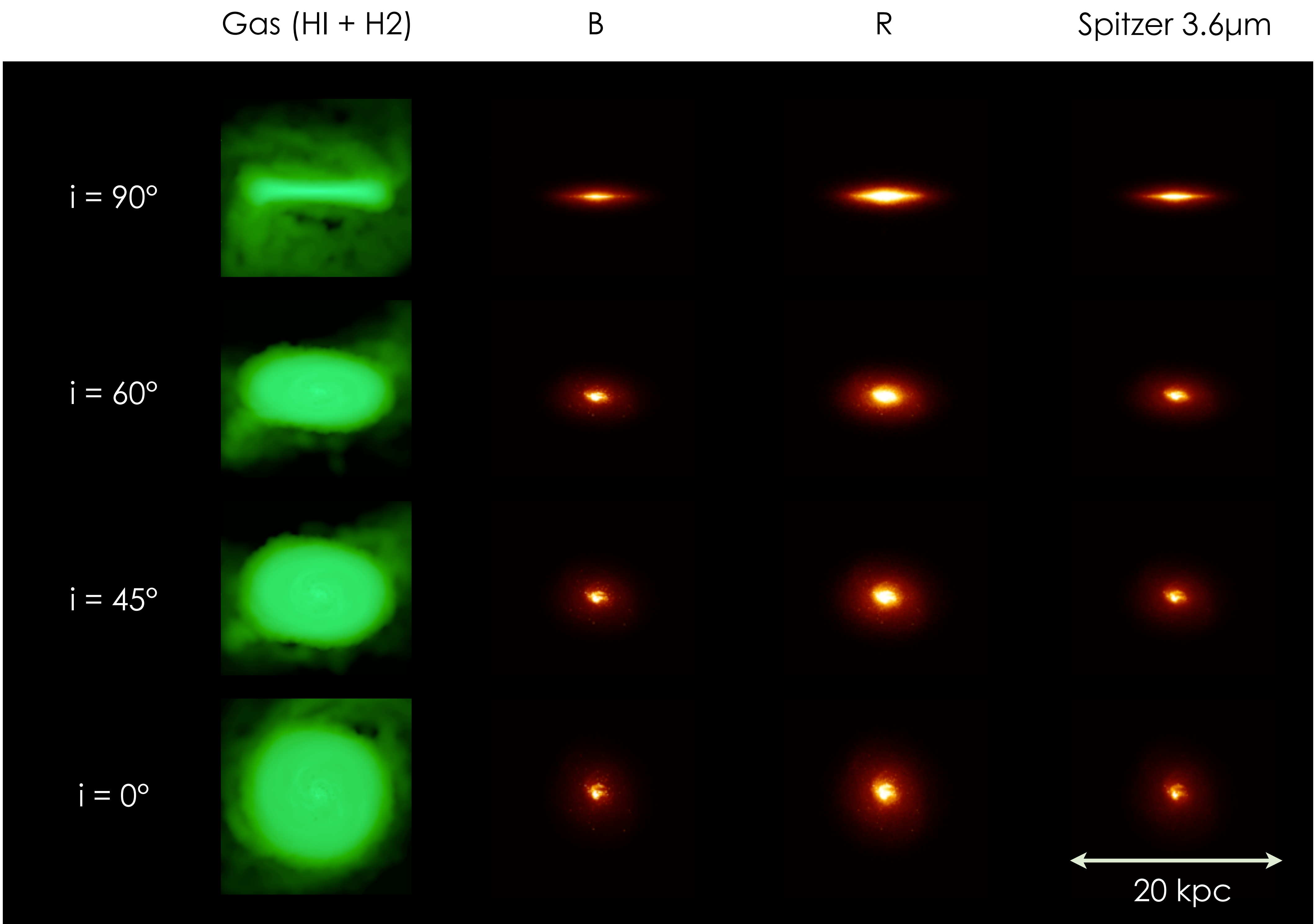
- Governato et al. (2010, 2012)
- N-body+SPH tree-code GASOLINE
- Flat Λ-dominated cosmology
- Baryonic processes are included such as,
  - gas cooling
  - cosmic UV field heating
  - star formation
  - SNe-driven gas heating
- There are ~3.3 million particles within the virial radius at $z = 0$.
- DM particle mass is $1.6\times10^4\ M_\odot$, and gas particle mass is $3.3\times10^3\ M_\odot$.
- The force resolution (gravitational softening) is 86 pc.

THE FORMATION OF A BULGELESS GALAXY WITH A SHALLOW DARK MATTER CORE

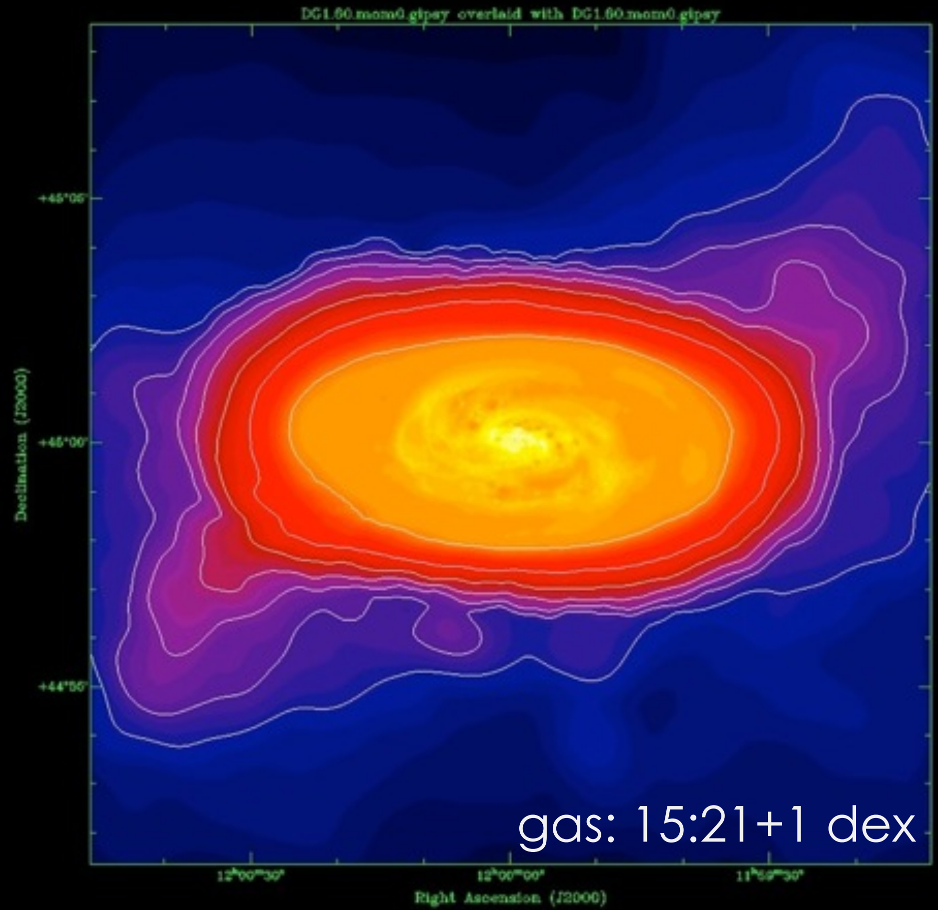
Fabio Governato (University of Washington)
Chris Brook (University of Central Lancashire)
Lucio Mayer (ETH and University of Zurich)
and the N-Body Shop

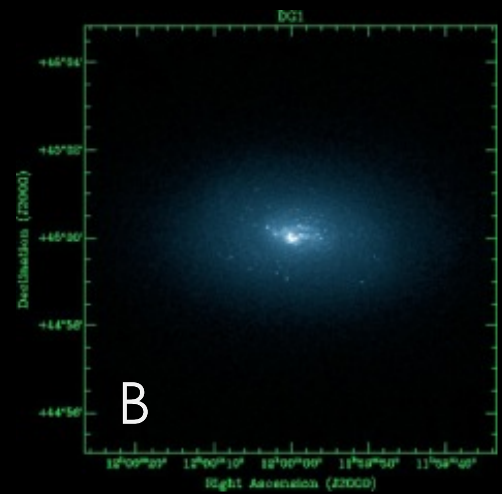
KEY: Blue: gas density map. The brighter regions represent gas that is actively forming stars. The clock shows the time from the Big Bang. The frame is 50,000 light years across.

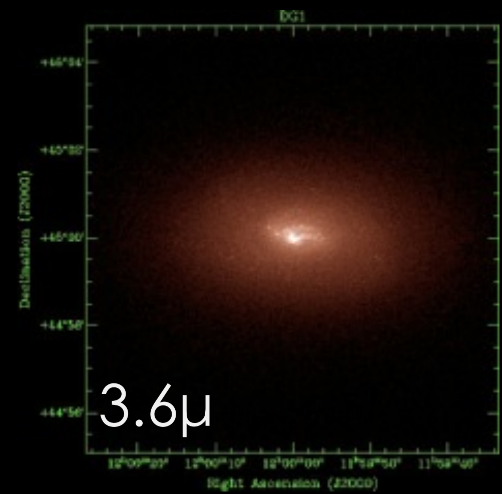
Simulations were run on Columbia (NASA Advanced Supercomputing Center) and at ARSC

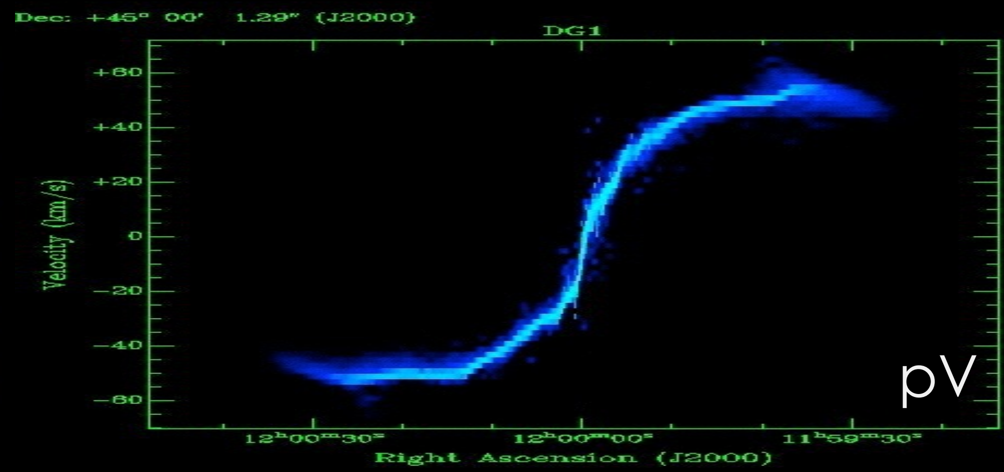

Gas (HI + H2)
B
R
Spitzer 3.6μm
i = 90°
i = 60°
i = 45°
i = 0°
20 kpc

DG1 observed

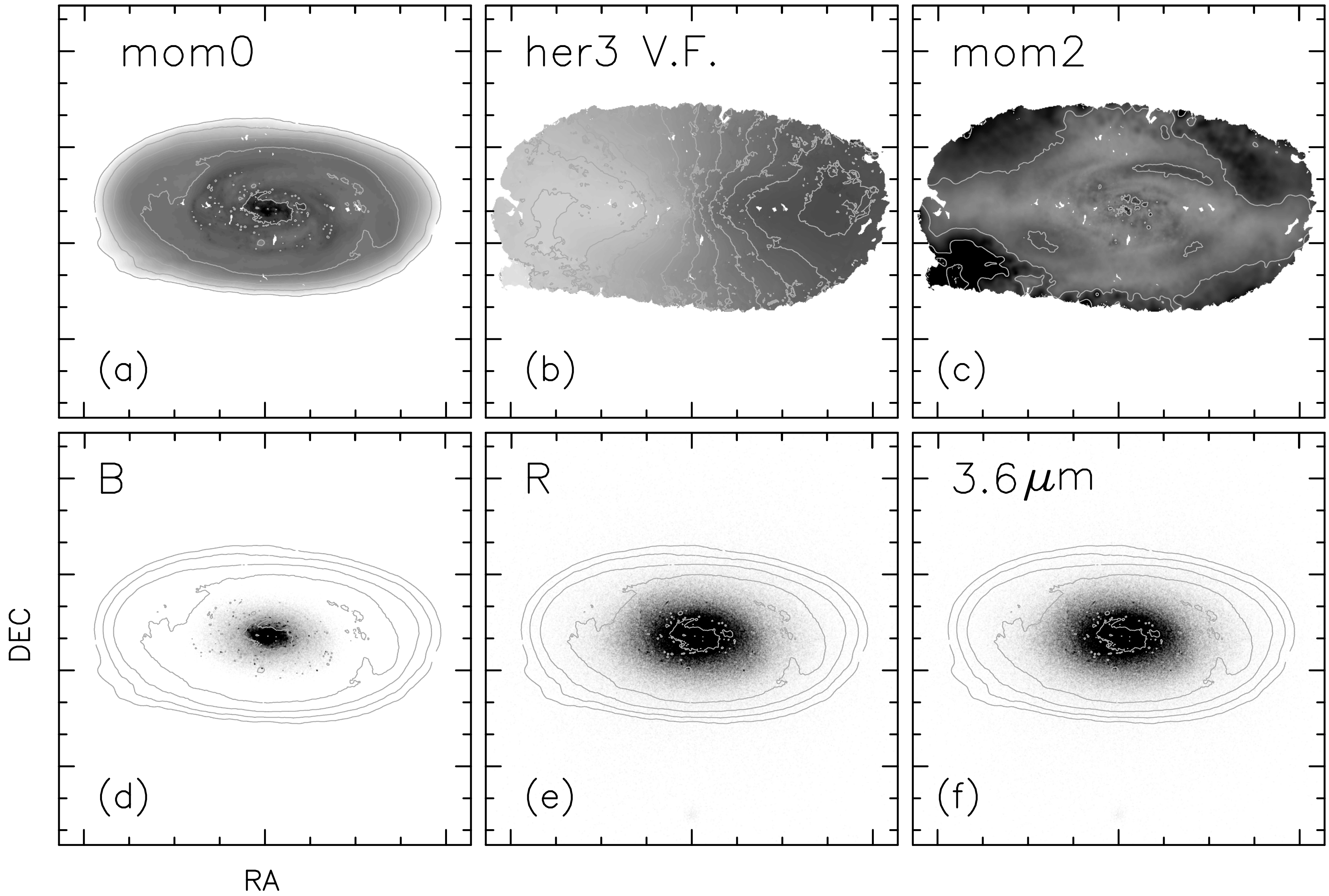








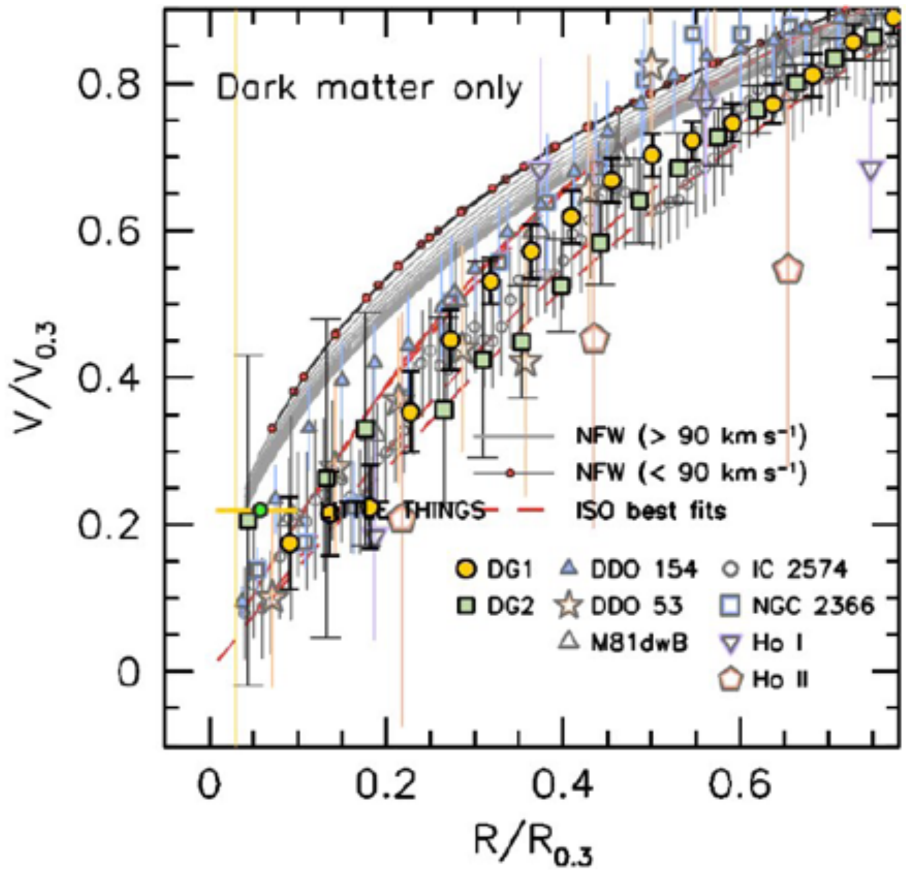
DG1 observed



Oh et al. (2011).

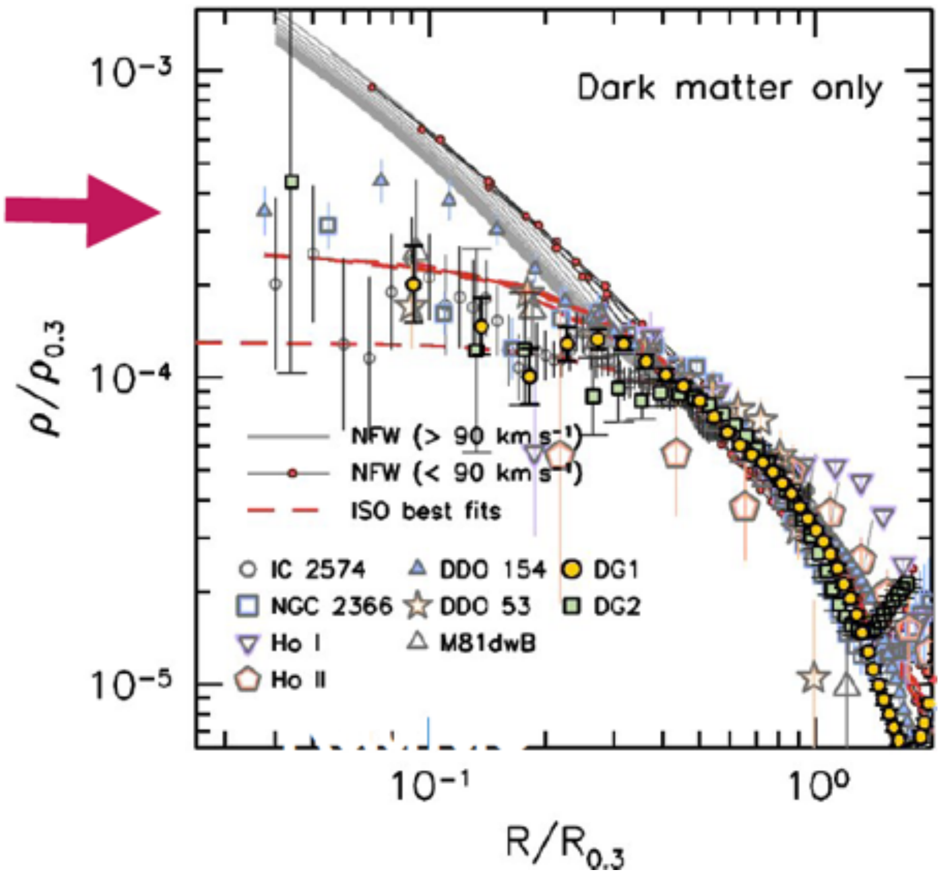
Comparison with THINGS + Simulations

Rotation curve shape



Radius

Density profile



Radius

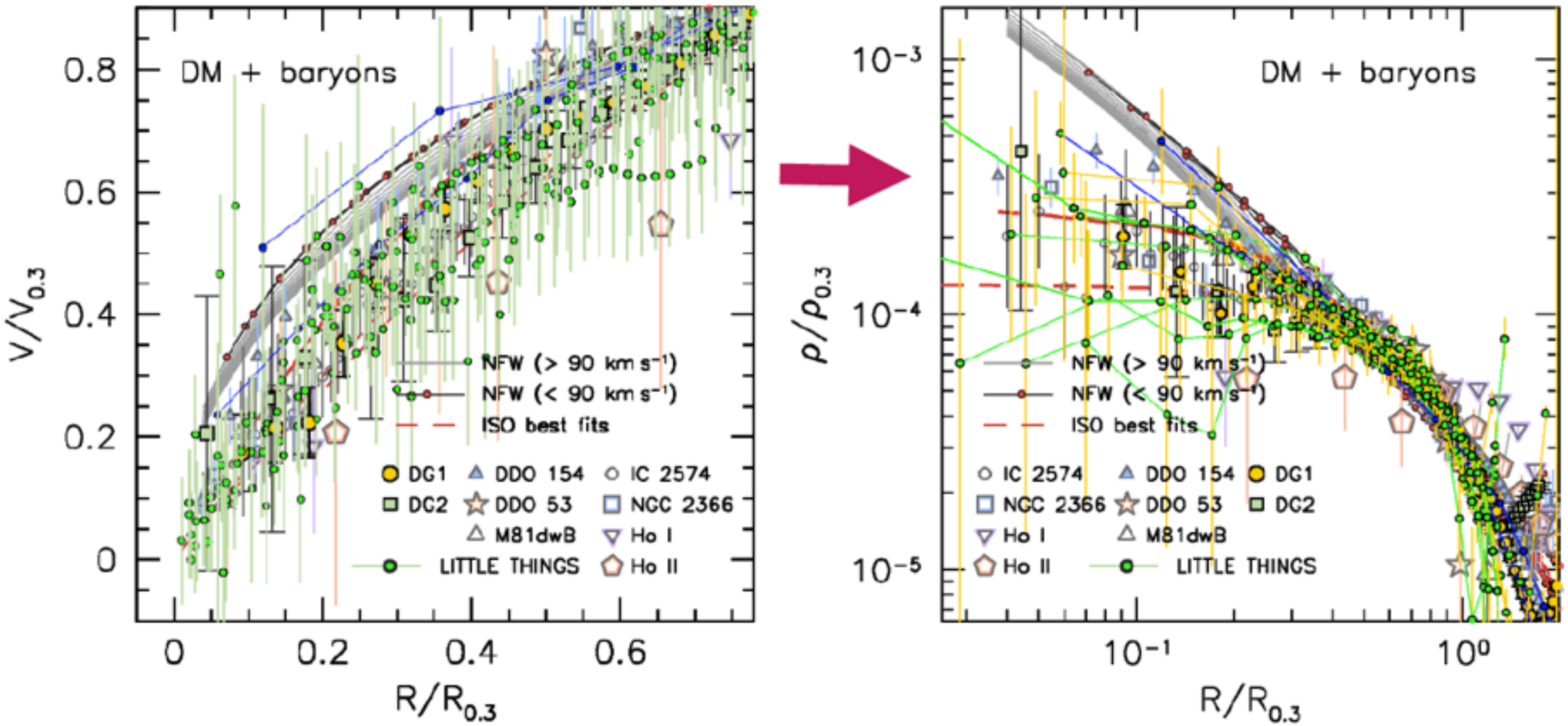
$R_{0.3} \rightarrow d \log V / d \log R = 0.3$

Oh et al (2011).

Comparison with LITTLE THINGS + Simulations

Rotation curve shape

Density profile

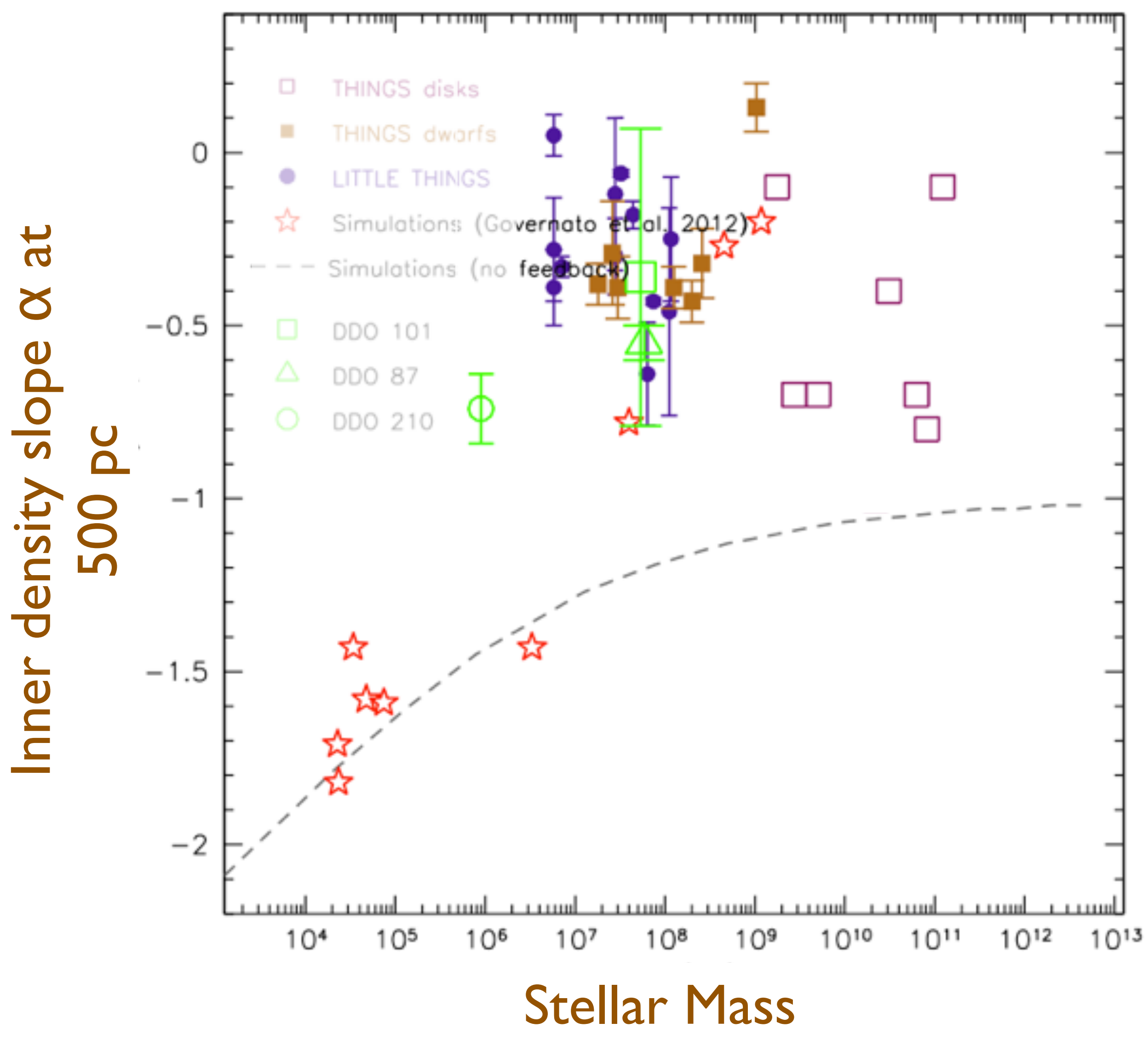


Oh et al. in prep.

- Scaled rotation curves too shallow compared with CDM
- Slope based on 19 galaxies: $\alpha = -0.3 \pm 0.1$
- Consistent 7 dwarfs from THINGS (Oh et al. 2011)
- Agrees well with simulated dwarfs from Governato et al (2011)

Density slope vs. Stellar mass

Oh et al. in prep.

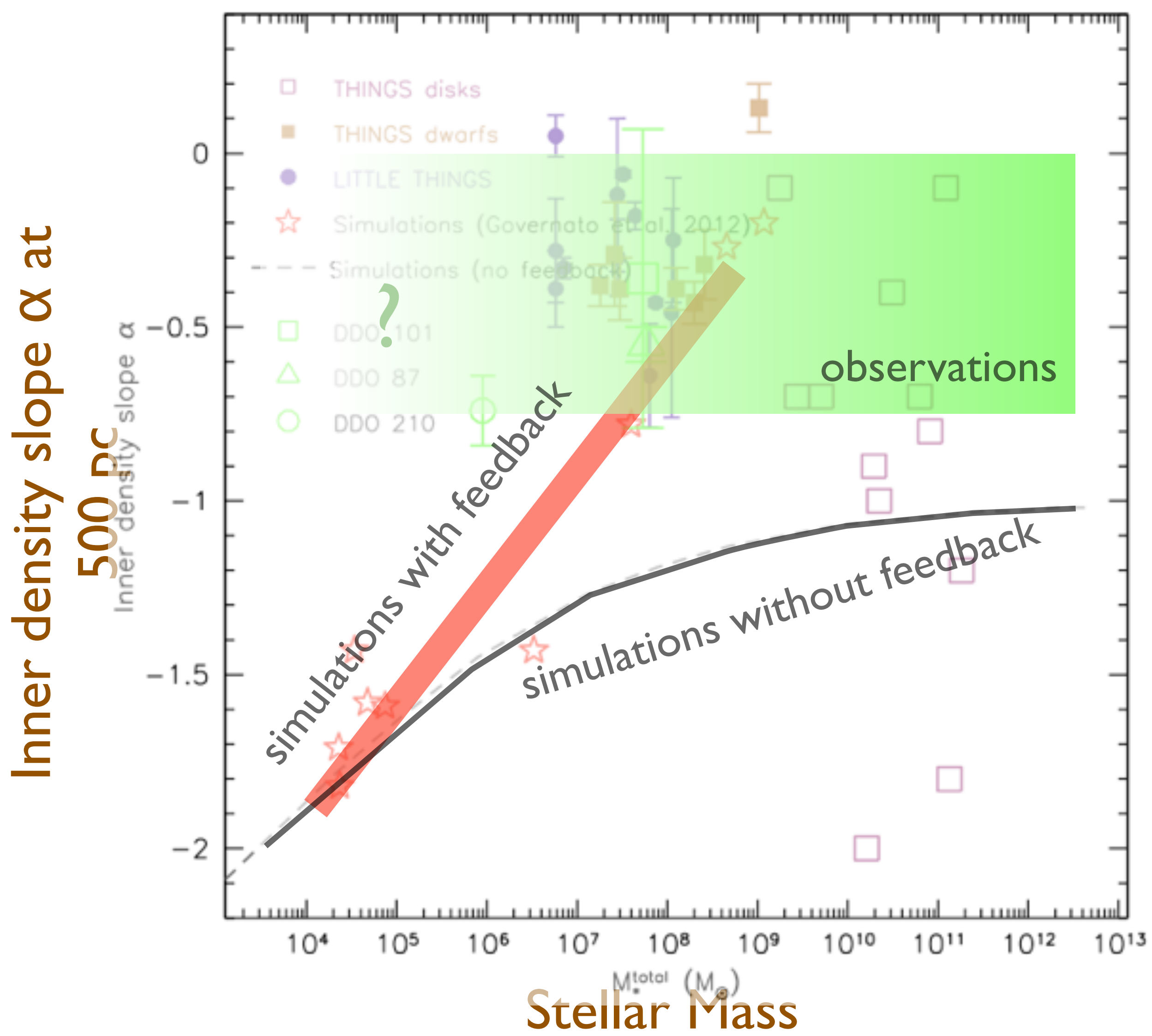


- **Simulations:**
Gas outflows become less efficient in smaller galaxies so primordial DM distribution less affected

- **Observations:**
DM distribution in low mass dwarf galaxies would be a key for the central DM problem

Density slope vs. Stellar mass

Oh et al. in prep.



- **Simulations:**
  Gas outflows become less efficient in smaller galaxies so primordial DM distribution less affected

- **Observations:**
  DM distribution in low mass dwarf galaxies would be a key for the central DM problem

Conclusions

- Radio observations show disk and dwarf galaxies show a cored dark matter distribution.
- Feedback must be invoked to explain this
- Observations of ultra-low mass dwarfs will provide a crucial test

www.mpia.de/THINGS