CO Rotation Curves

High-velocity Rotation, Deep Potential, & Dense Molecular Cores in Spiral Centers

Sofue, Y.,

Koda, J., Nakanishi, H., Onodera, S., Egusa, F., Komugi, S., Kohno, K.

2006 June 26-30, Ishigaki

’ Mapping the Galaxy and Nearby Galaxies ’

Summary: Normal galaxies

1. Rotation curves & Mass structures are common (universal).

2. Dynamical mass much (~100x gas) dominates in <100 pc.

3. Nuclear gas is stable to produce/maintain dense gas core.

I. Introduction

Rotation Curves and Dark Matter

Ha RC

Rubin .. 80',90'

Mathewson 80'; Persic .. 90'

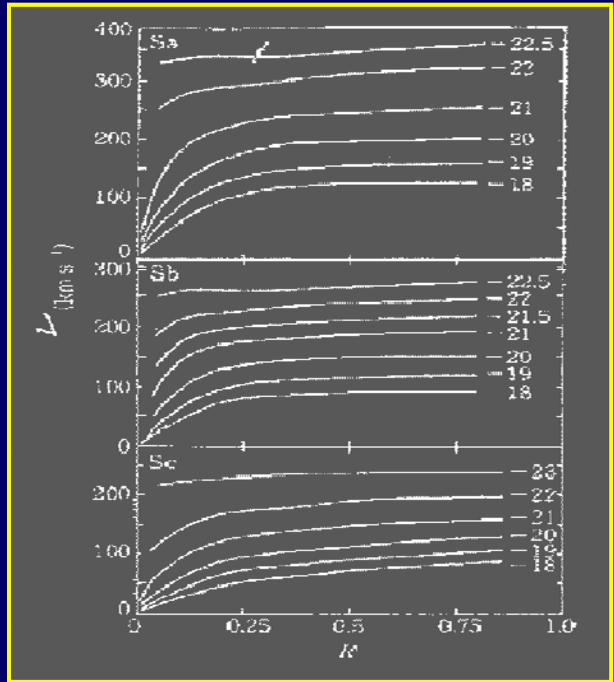
HI RC

Roberts .. 70'

Bosma; Rupen; Sancisi , .. 80'

CO RC

Sofue, et al. .. 1995---



(cf: Sofue & Rubin 2001 ARAA)

M/L Ratio

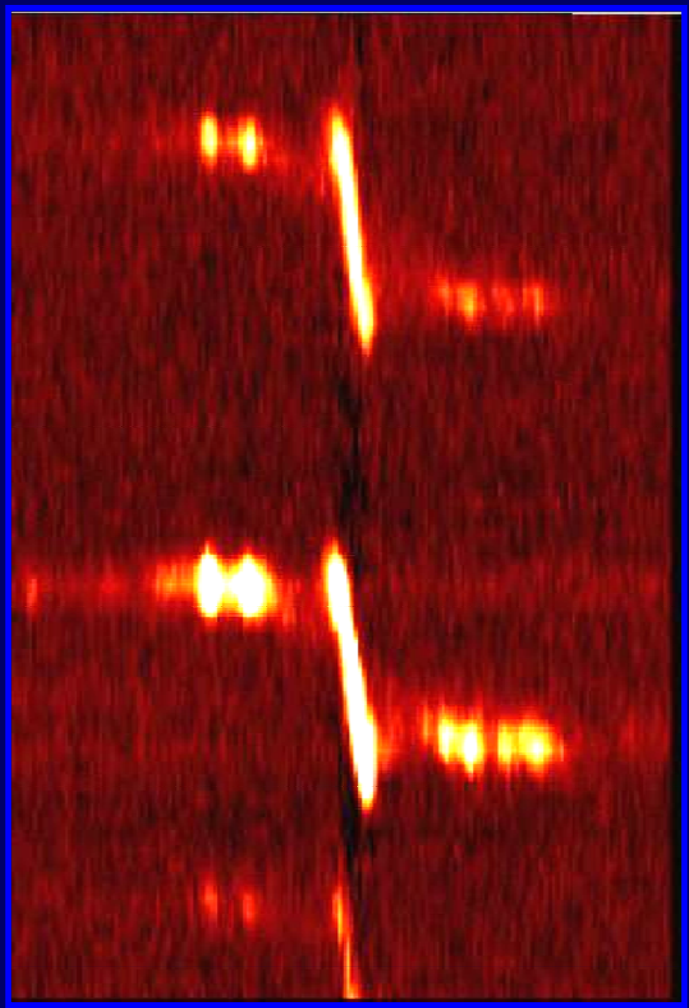
Kent 80'; Persic 80'; Forbes 90'; Heraudeau 90'; Rubin et al. 90'; Takamiya, Sofue 90'

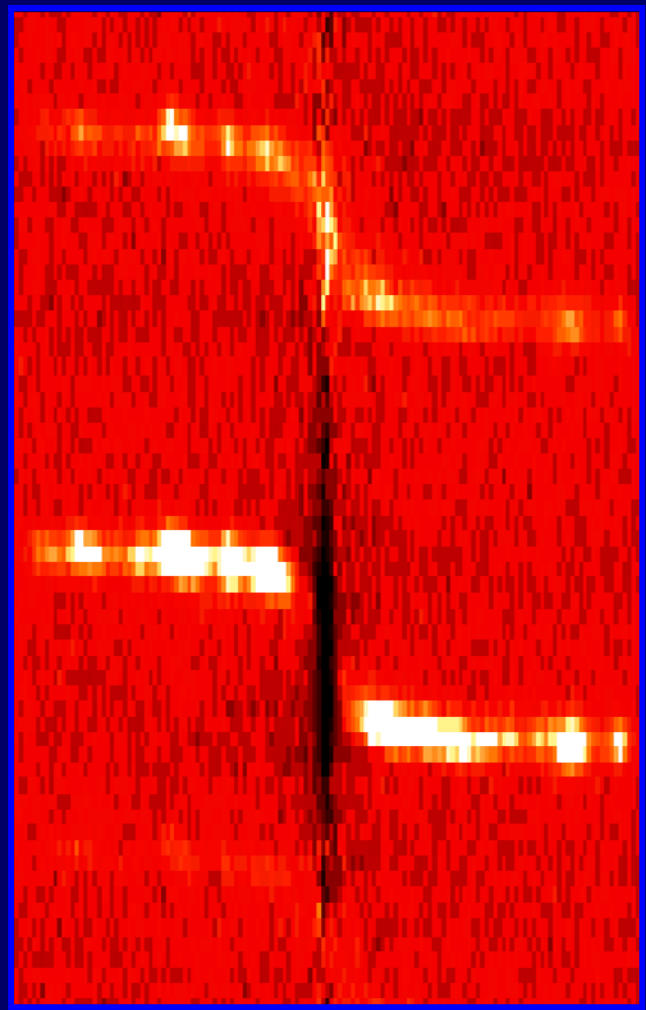
RC, Mass/DM distribution?

	RC	Mass Distri.
Halo	Yes	Yes
Disk	Yes	Yes
Bulge	Yes	Not clear
Core (1-100 pc)	No	No
BH (sub-pc)	Yes	Yes

Optical RCs: sometimes extinction and/or Balmar line absorption

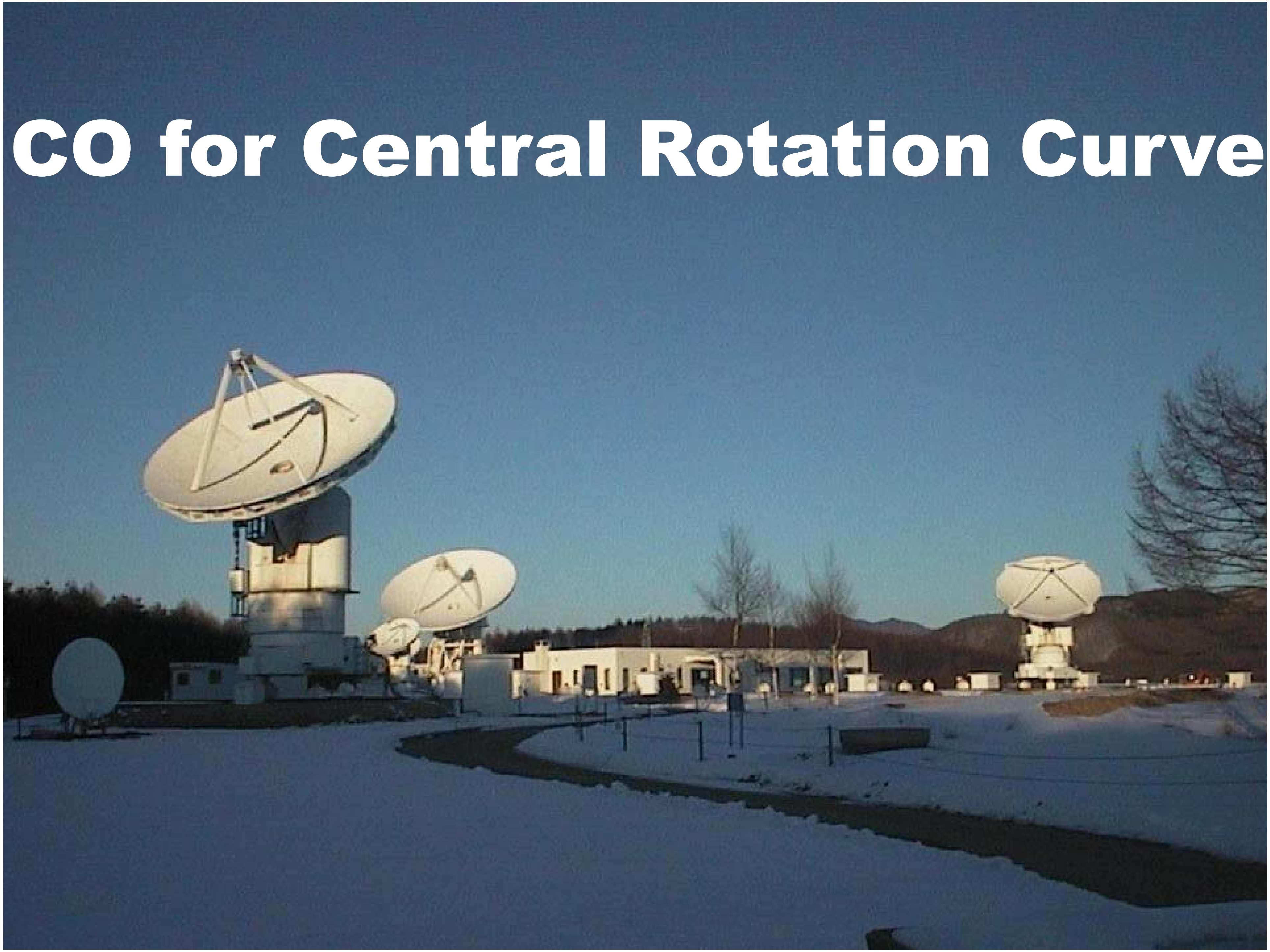
V↑

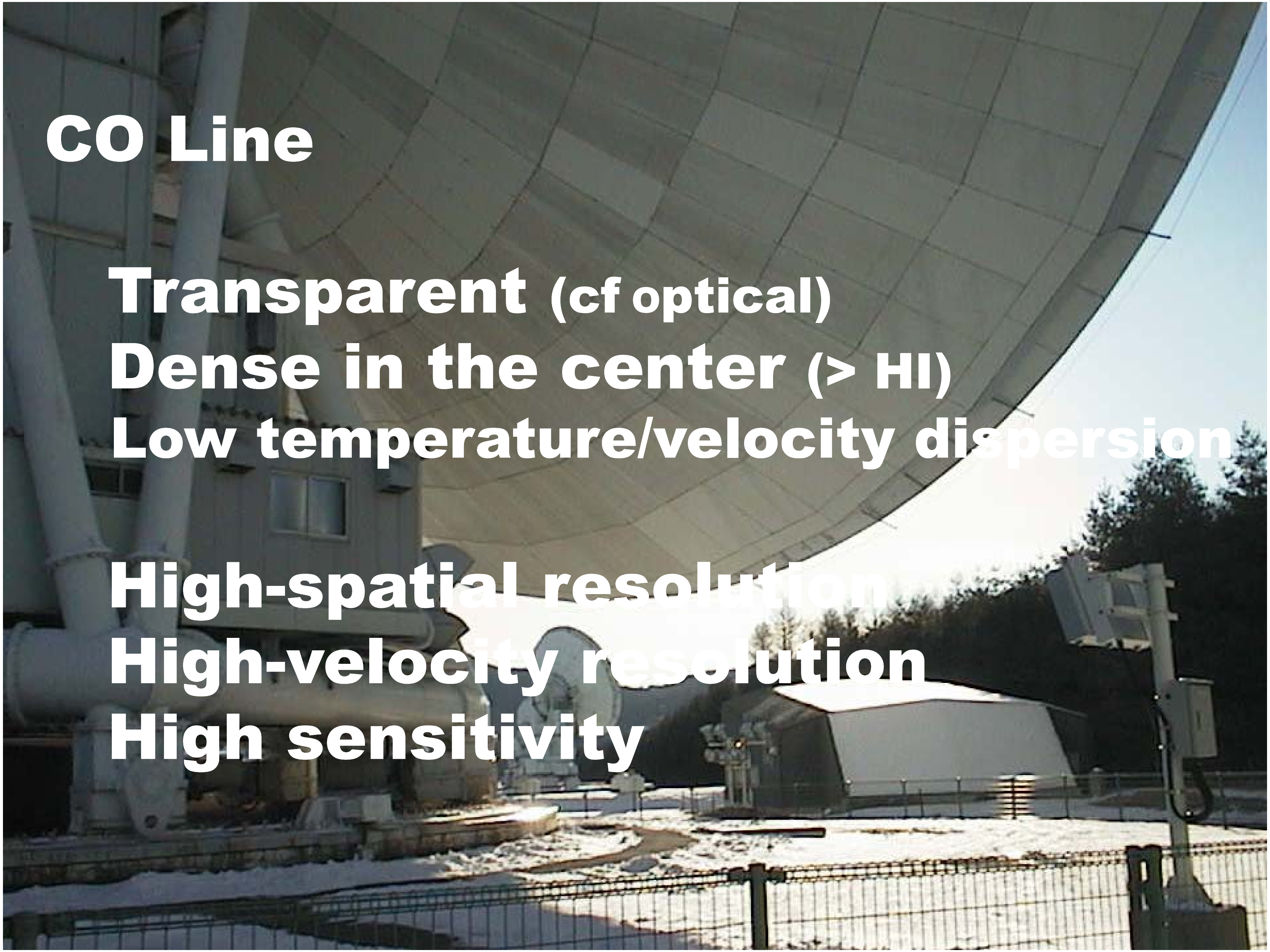




Position along major axis →

CO for Central Rotation Curve

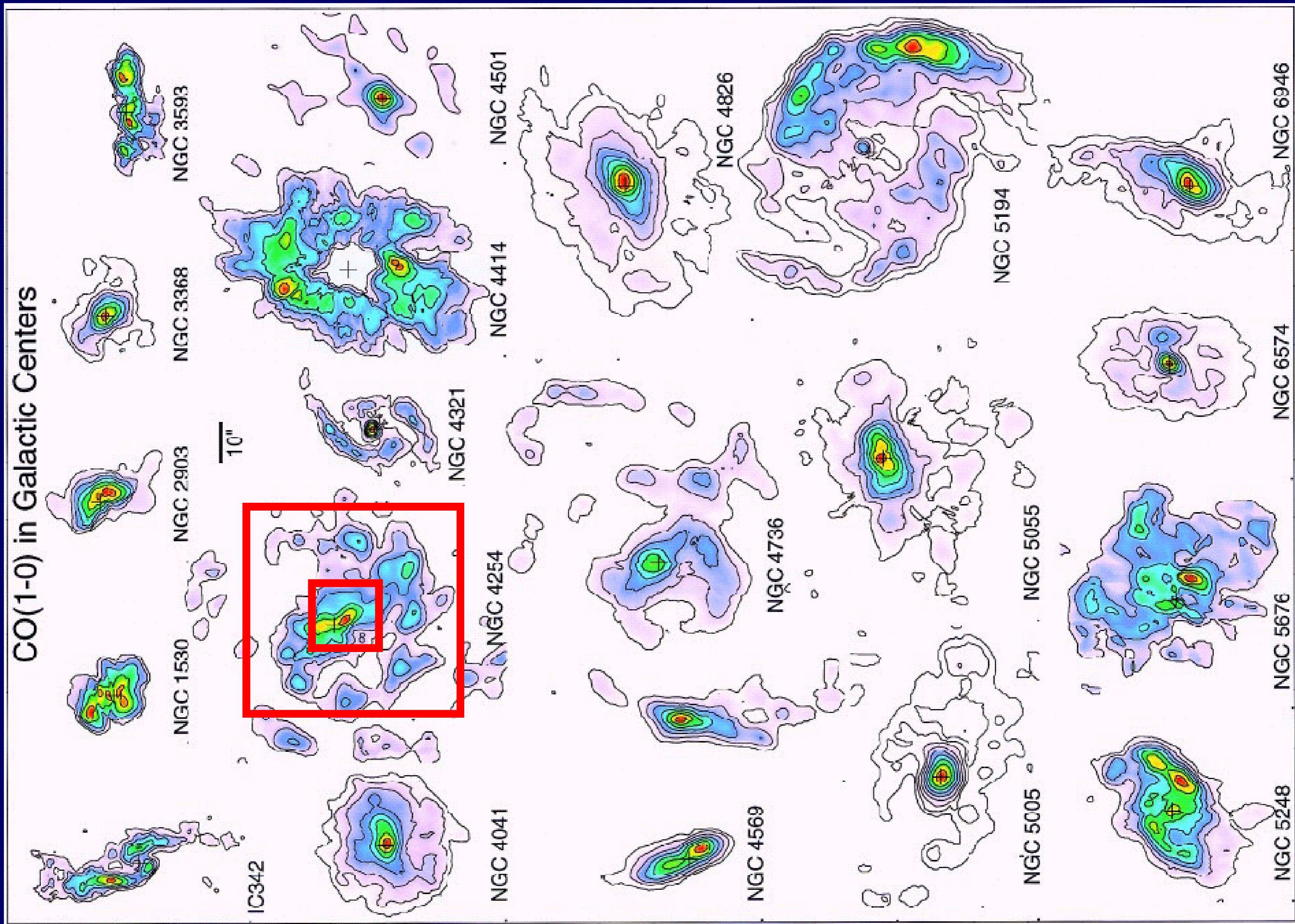



CO Line
Transparent (cf optical)
Dense in the center (> HI)
Low temperature/velocity dispersion
High-spatial resolution
High-velocity resolution
High sensitivity

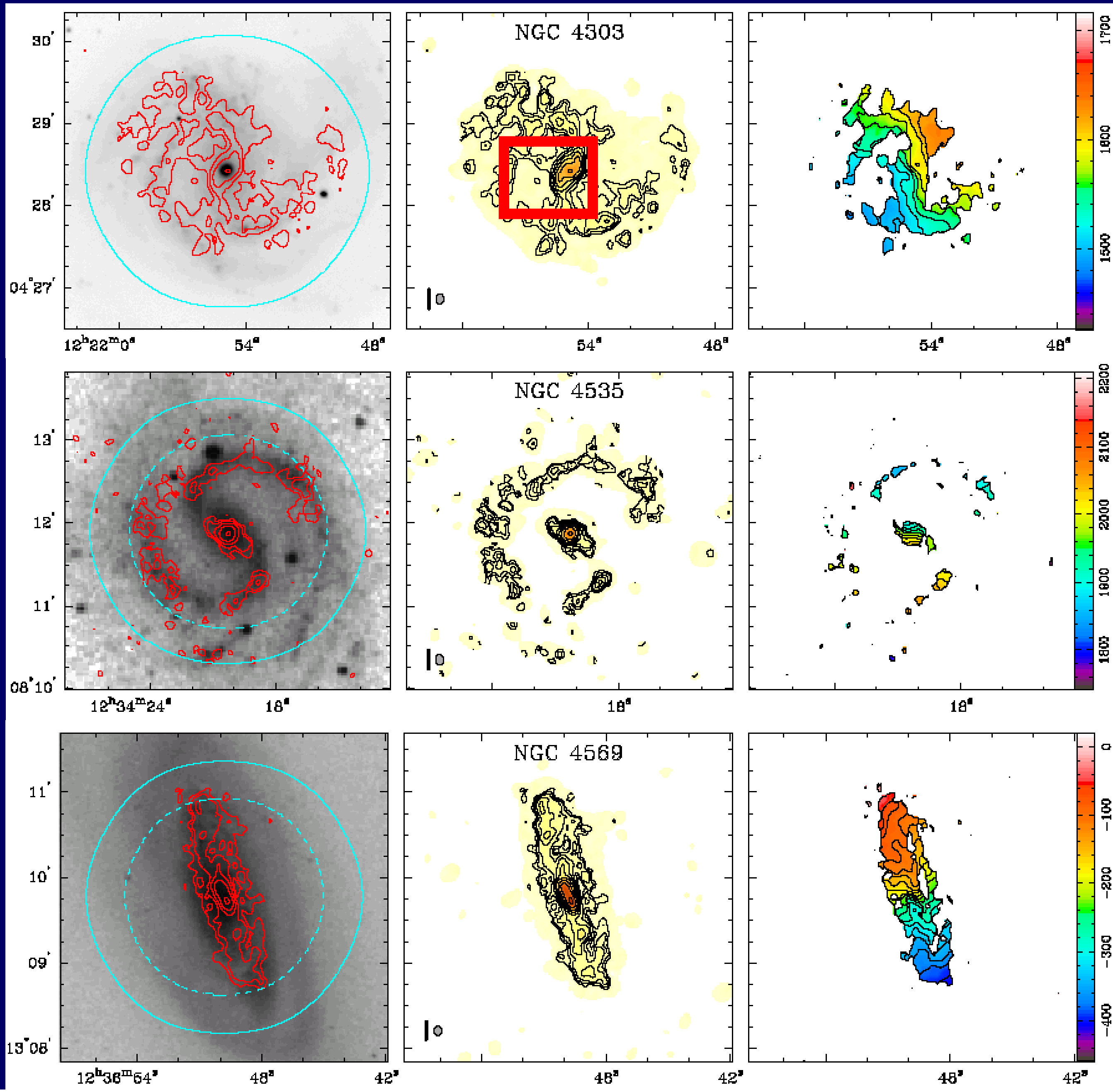
Interferometer CO-line Surveys

OVRO
BIMA
PdB
Nobeyama
etc.

Sakamoto et al. 1999



BIMA SONG



II. Virgo CO Survey

Collaborators

Sofue, Y.

Koda, J.

Nakanishi, H.

Onodera, S.

Kohno, K

Okumura, S.

Tomita, A.

Egusa, F.

Komugi, S.

et. al.

Nobeyama mm Array, 45-m

Future:

SUBARU

ALMA

(Virgo is visible)

Why Virgo?

- Cepheid distance 16.1 Mpc
- Variety of spiral types
- Wealth of data sets
- Visible from ALMA

Observations

1. Nobeyama mm-wave Array
   AB+C+D Arrays (2-4” at 115 GHz)

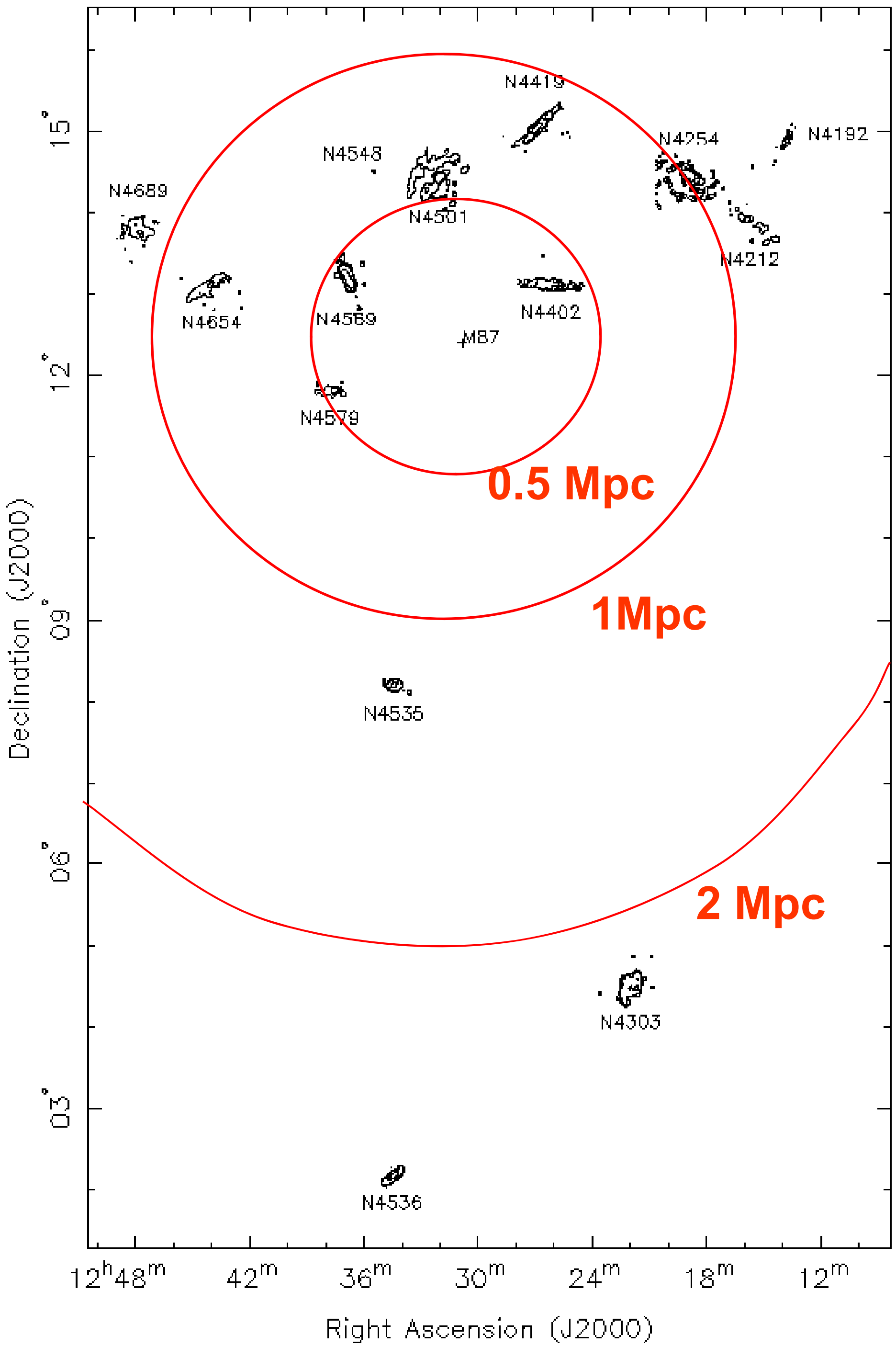
2. ^{12}CO(J=10) line at 115 GHz

3. Normal CO-rich spirals
   (from Kenney & Young ‘s 1988 CO catalog)

4. Long-Term project : 700 h 1999-2003

(1992 – 2006: individ. G. ; accumulated data from past)

Virgo survey galaxies CO images



NGC4254

FITS data available from
http://www.ioa.s.u-tokyo.ac.jp/

Sofue et al. 2003a, b
Onodera et al. 2004
Nakanishi et al., 2004
Koda et al. 2005

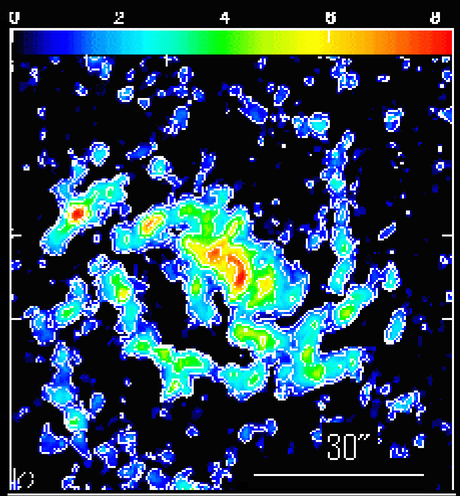
Dec. +14d24m59s

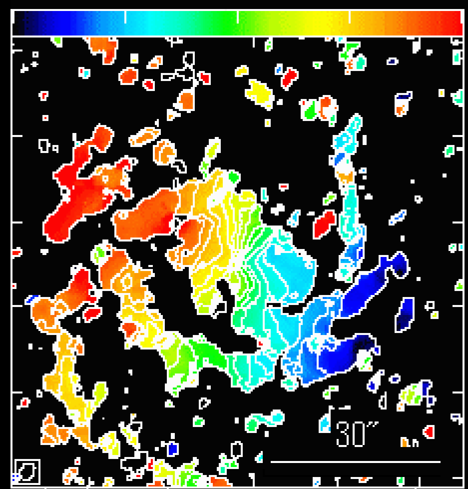
incl. 42 deg.

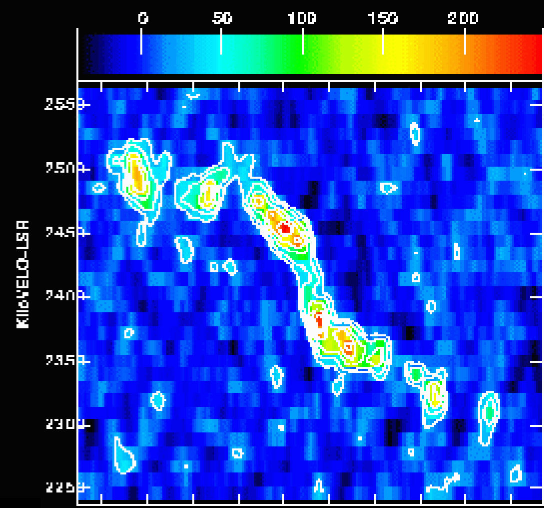
P.A. 68 deg.

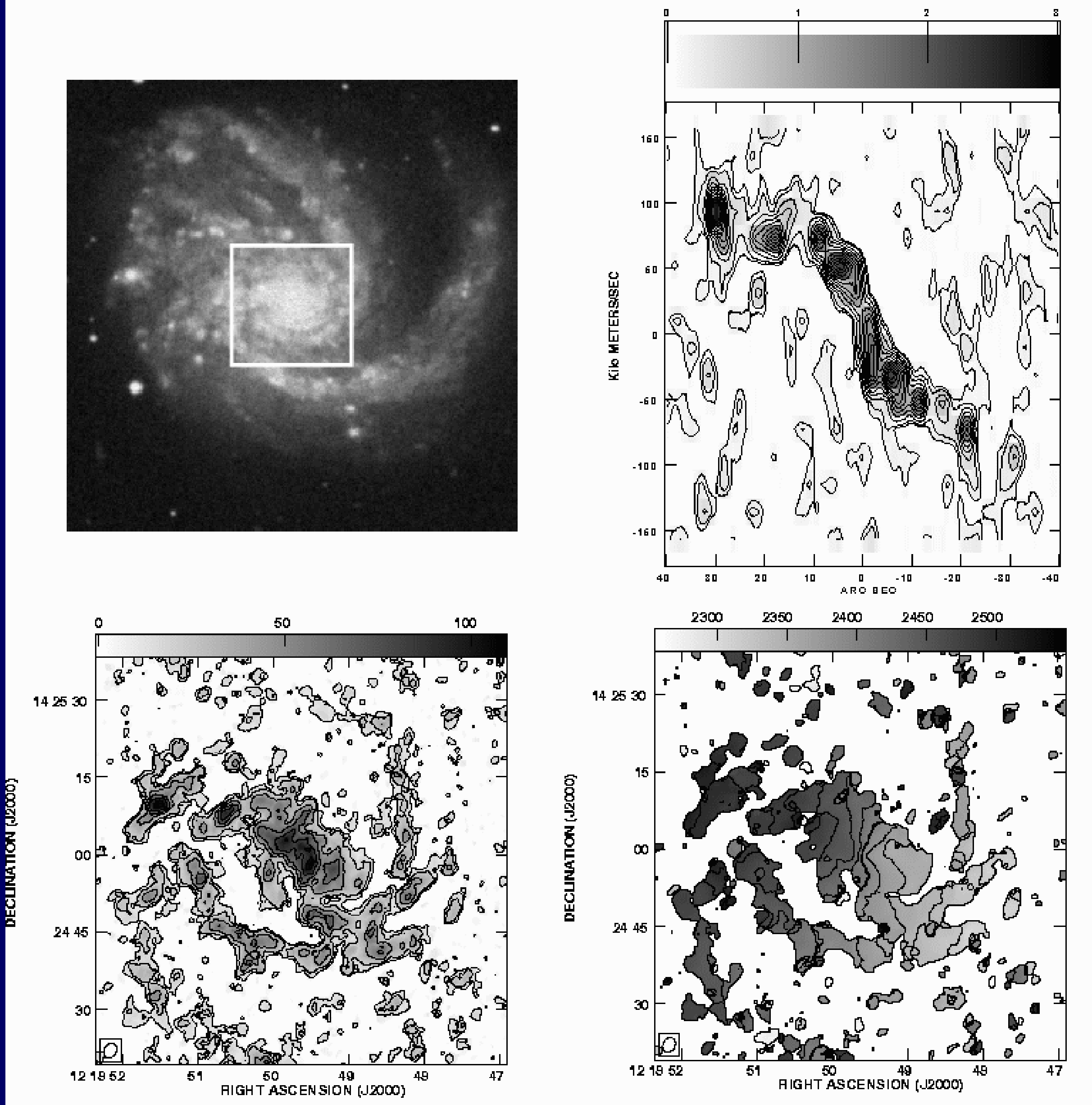
beam size 2.99 x 2.34 asec

rms 16 mJy/Beam



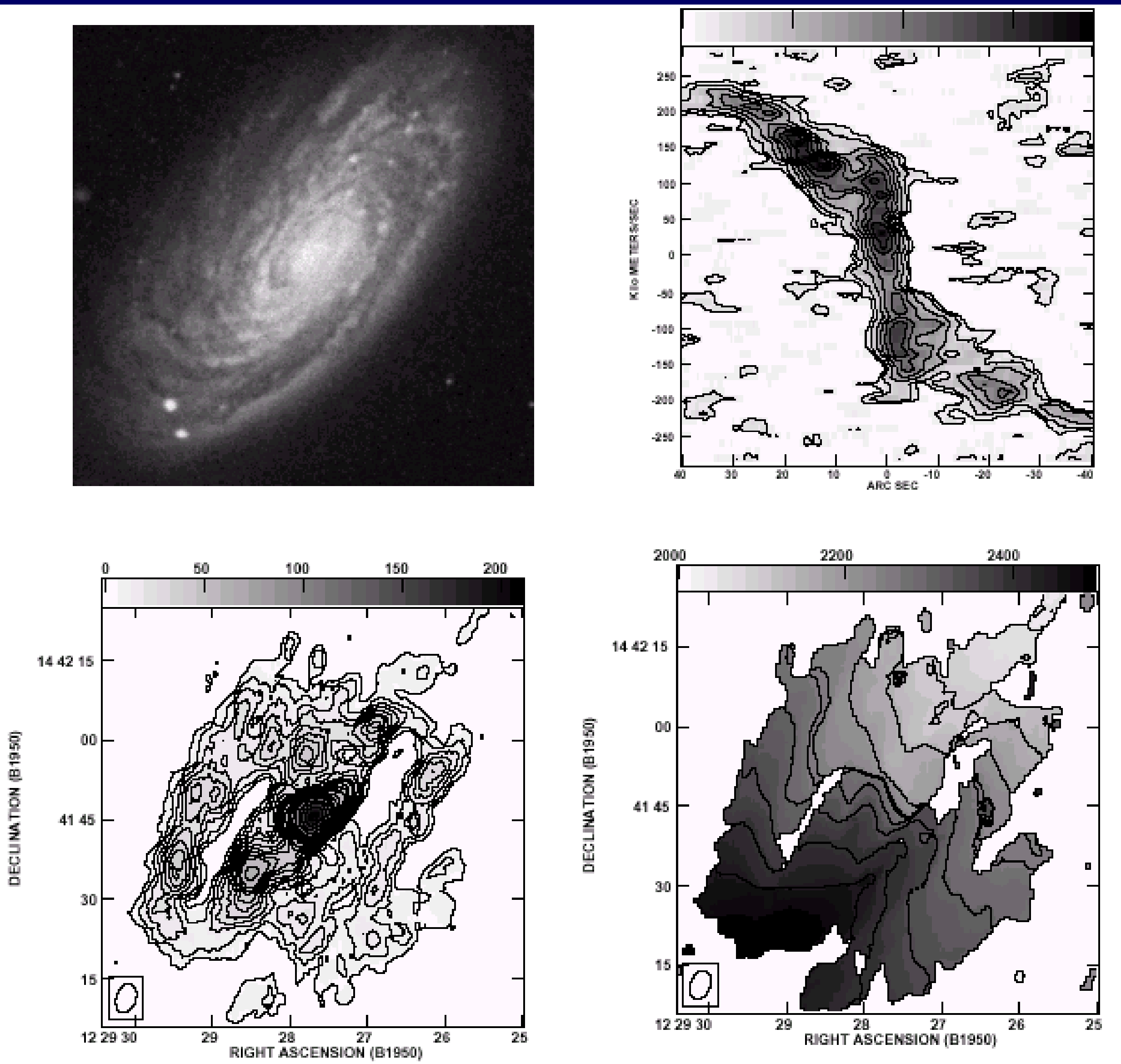






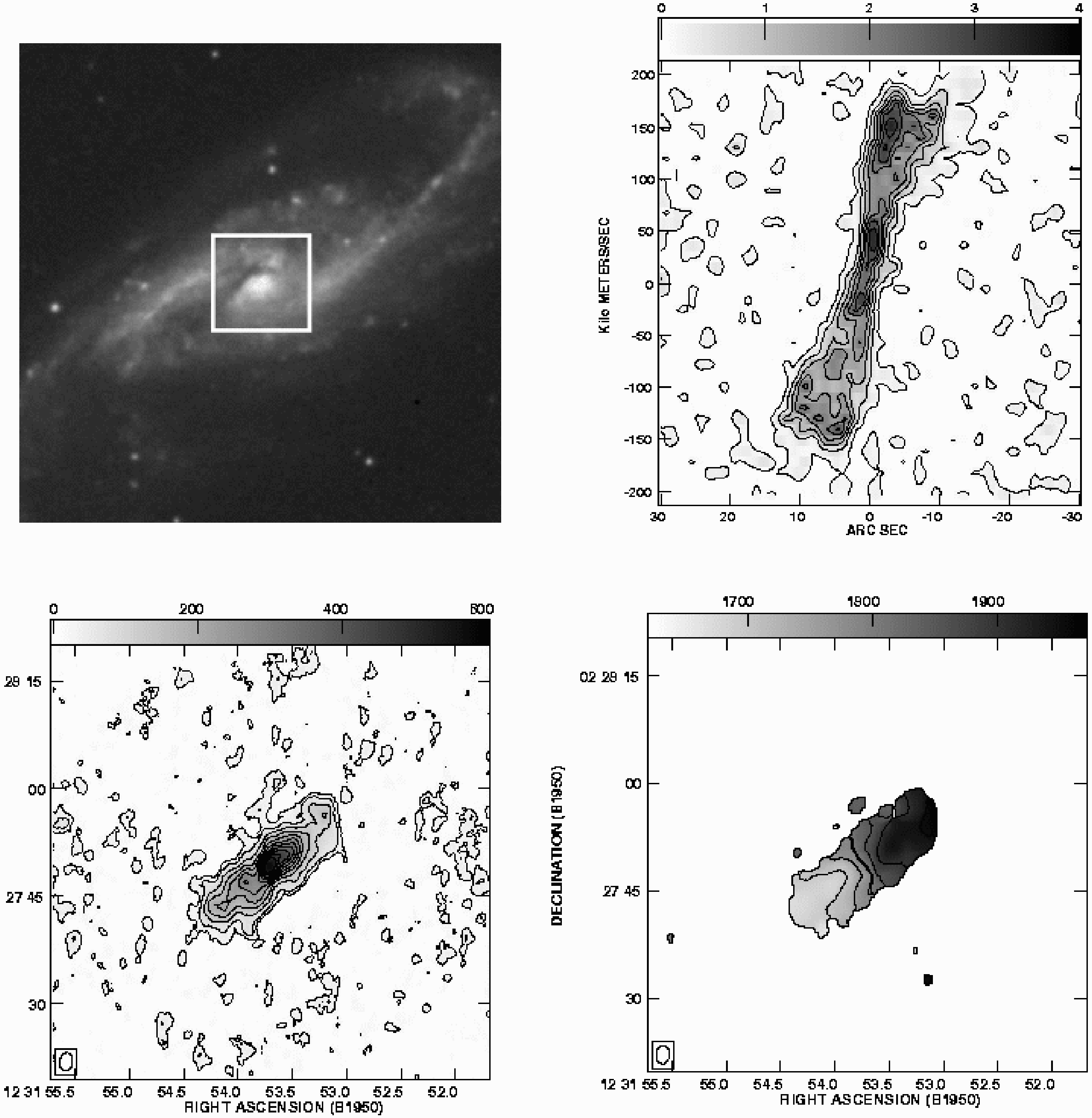
NGC 4254: (tl) DSS b-band 5′ × 5′, i=42°, PA=45°
(bl) Ico: 80″ × 80″; cl= 10 ×(1, 2, ... 12) K km s^{-1}.

(tr) PVD: 1′ × 3″, PA 45°; cl= 0.132 ×(1, 2, ... 12) K.
(br) V-field: 1′ × 1′; cl= 2300 to 2530, every 20 km s^{-1}.



NGC 4501: (tl) DSS b-band $5' \times 5'$; SA(rs)b; Sy 2; $i = 58°$; $PA = 140°$
(bl) Ico: $80'' \times 80''$; Beam $5''.6 \times 3''.7$; cl=5x(1,2,...10,12,...20,25,...40) K km s^{-1}

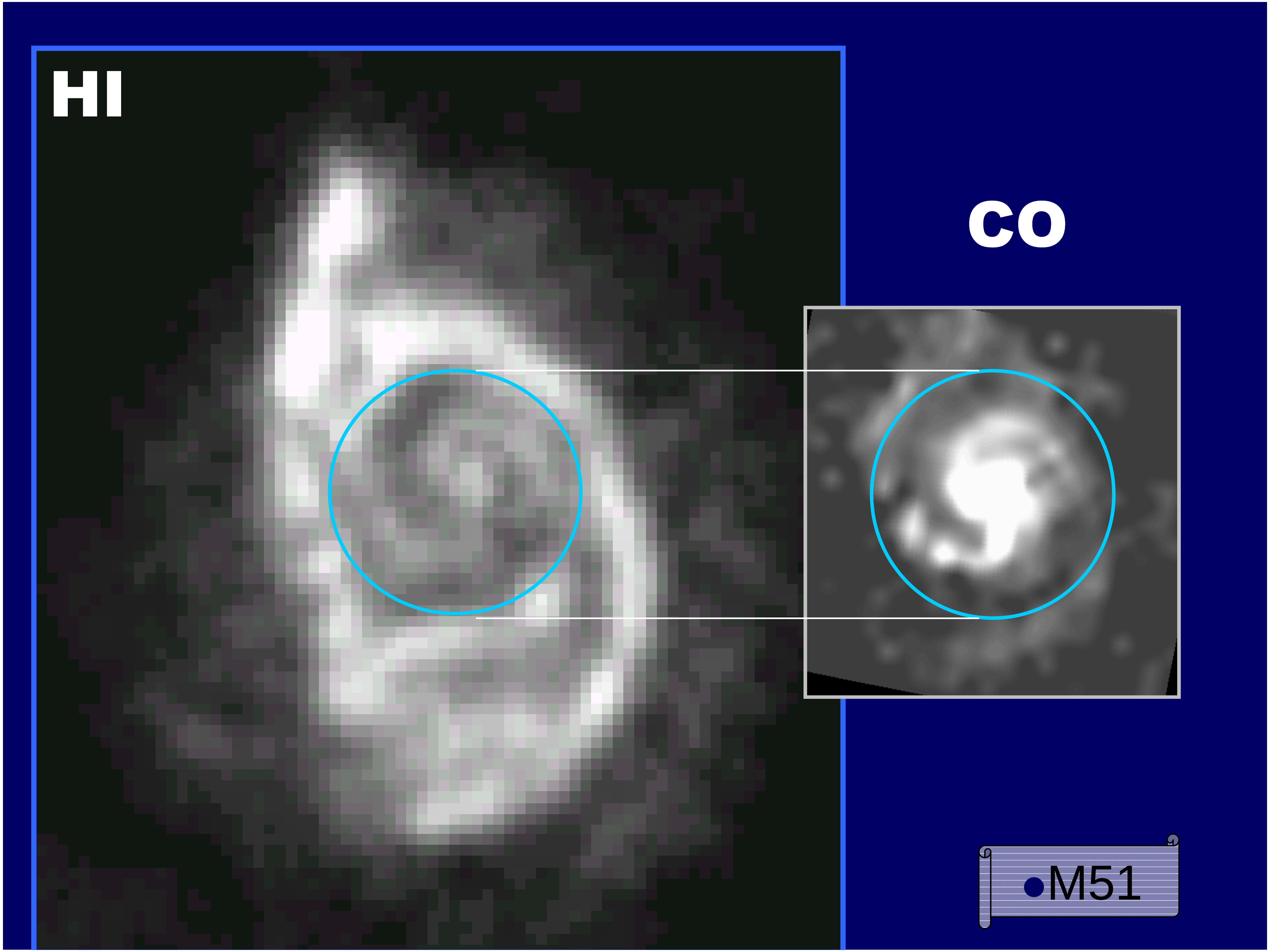
(tr) PVD: $80'' \times 10''$, PA 140°; cl=0.1x(0.5,1,2,...10) K.
(br) V-field: $80'' \times 80''$; cl=-2000 to 2500, every 50 km s^{-1}.



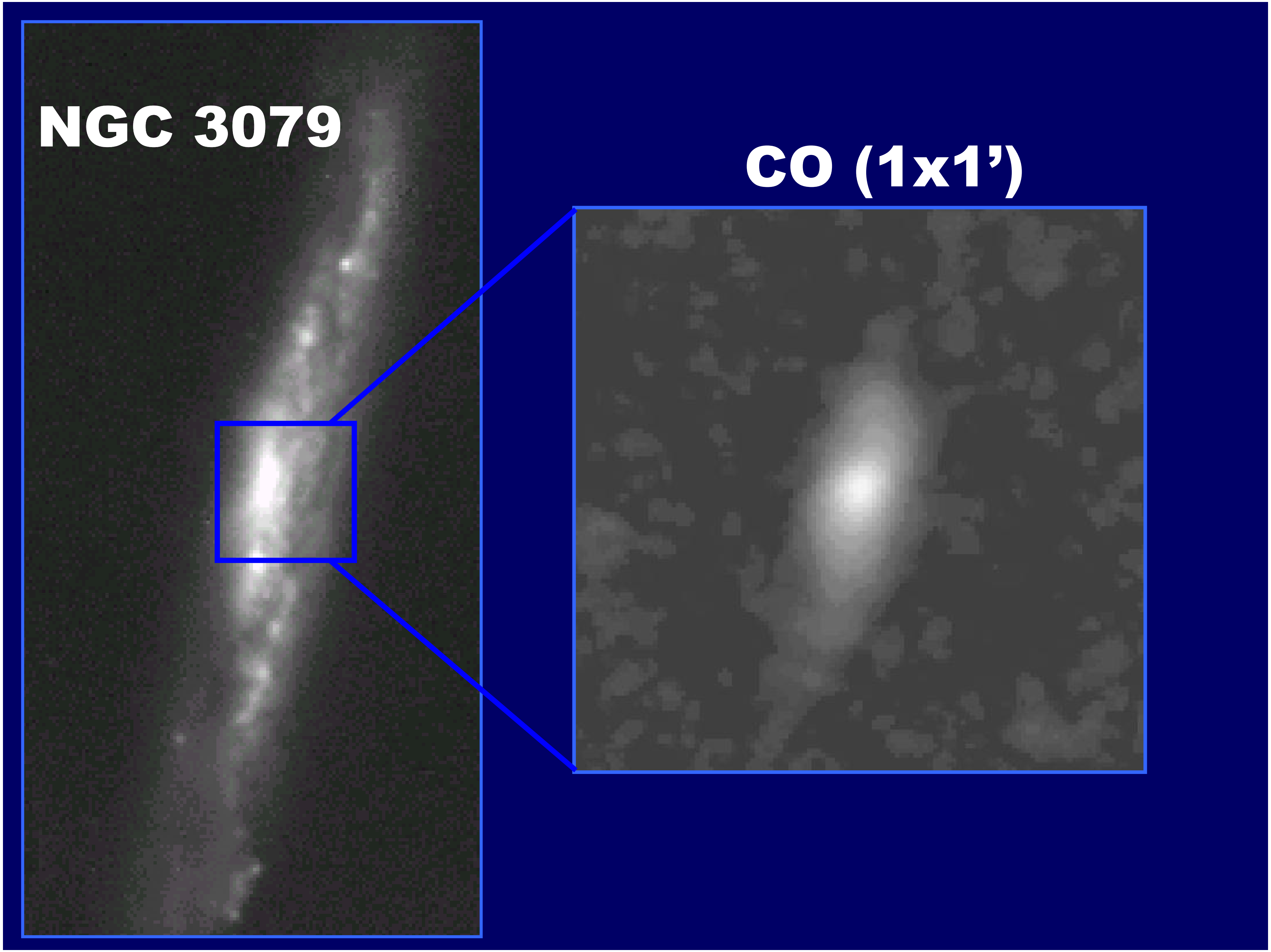
NGC 4536: (tl) DSS b-band 5′ × 5′; $i = 67°$; $PA = 116°$
(bl) Ico: 1′ × 1′; cl=50 x (0.5, 1, 2, 3, ..., 10) K km s^{-1}.

(tr) PVD: 1′×5″, PA 116°; cl=0.5 x (0.25, 1,2,...10) K.
(br) V-field: 1′ × 1′; cl=1600 to 2000, every 50 km s^{-1}.

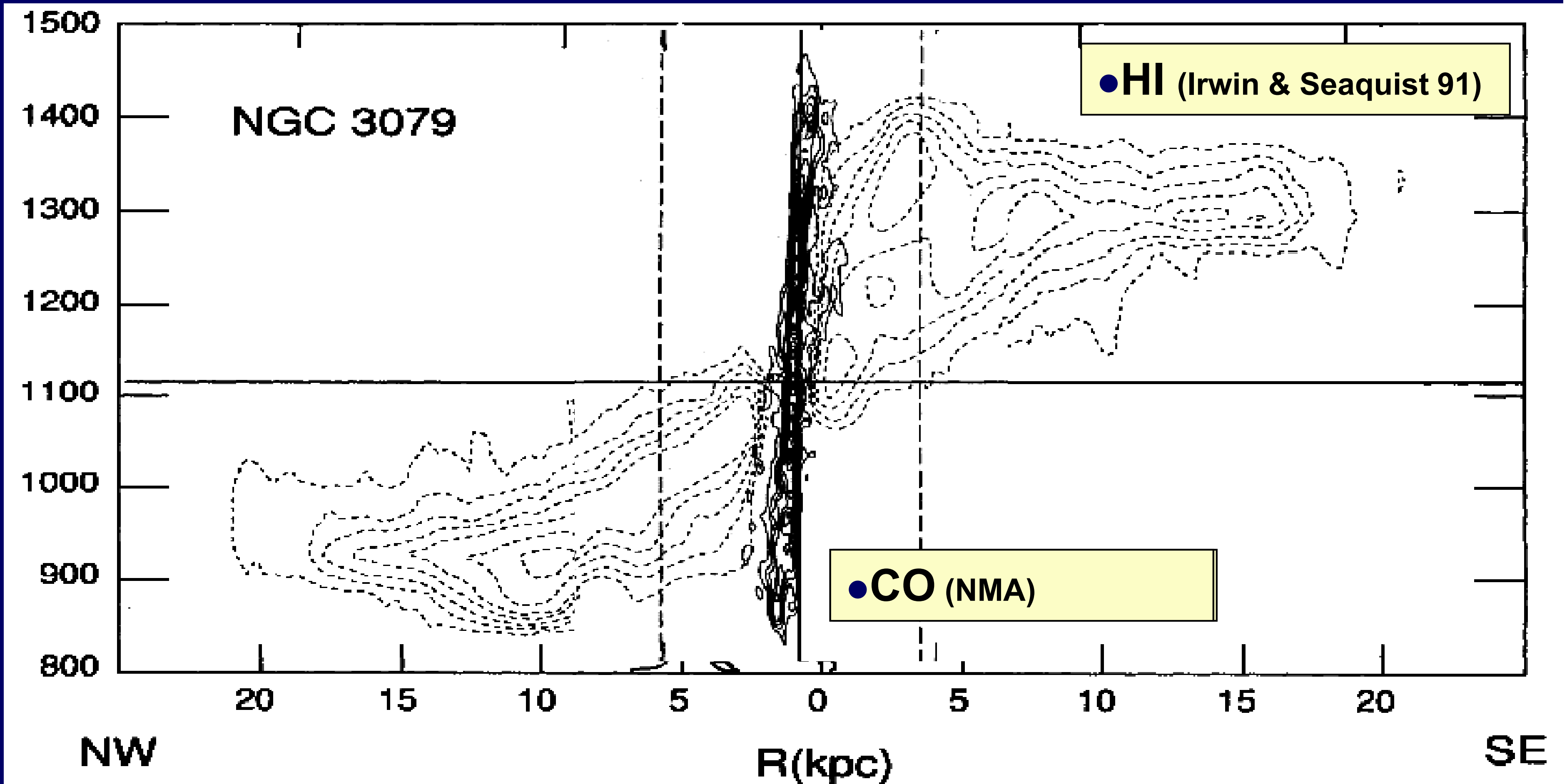
III. Rotation Curves



HI
CO
•M51


NGC 3079
CO (1x1')

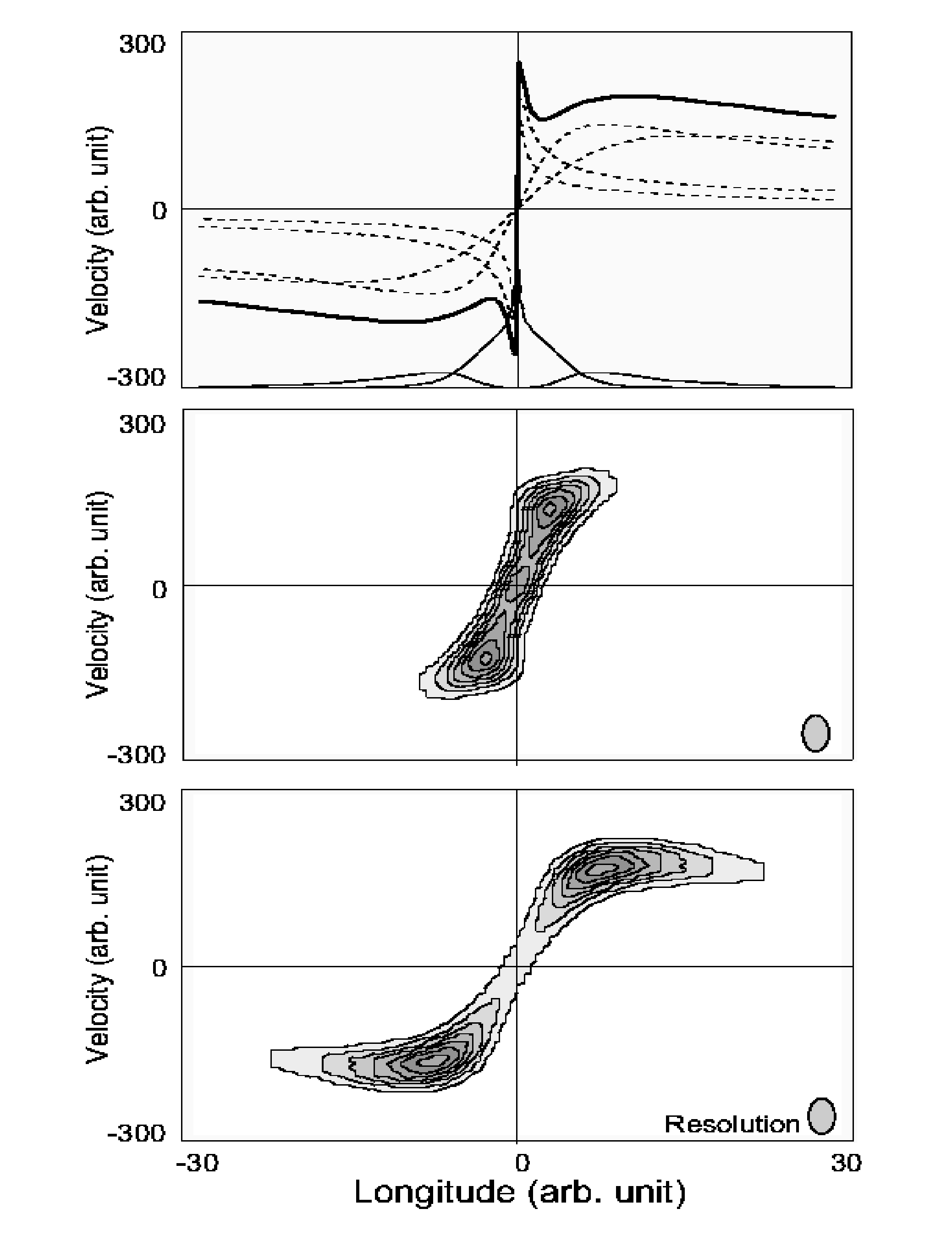
Position-Velocity Diagram
a case for N3079



RC –> PV diagram simulation

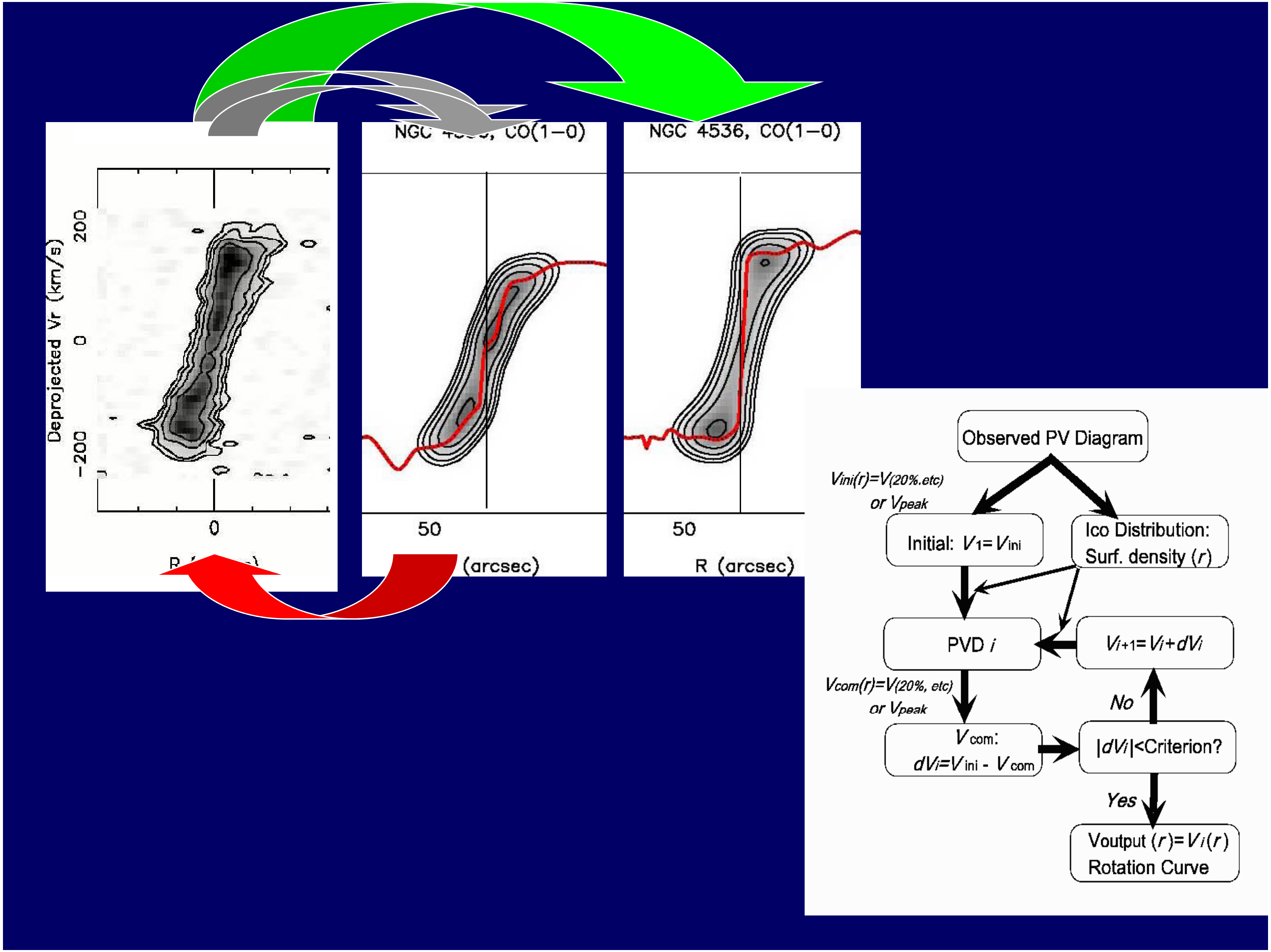
CO

HI



Iteration Method to create RCs

(Takamiya, et al. 2000)



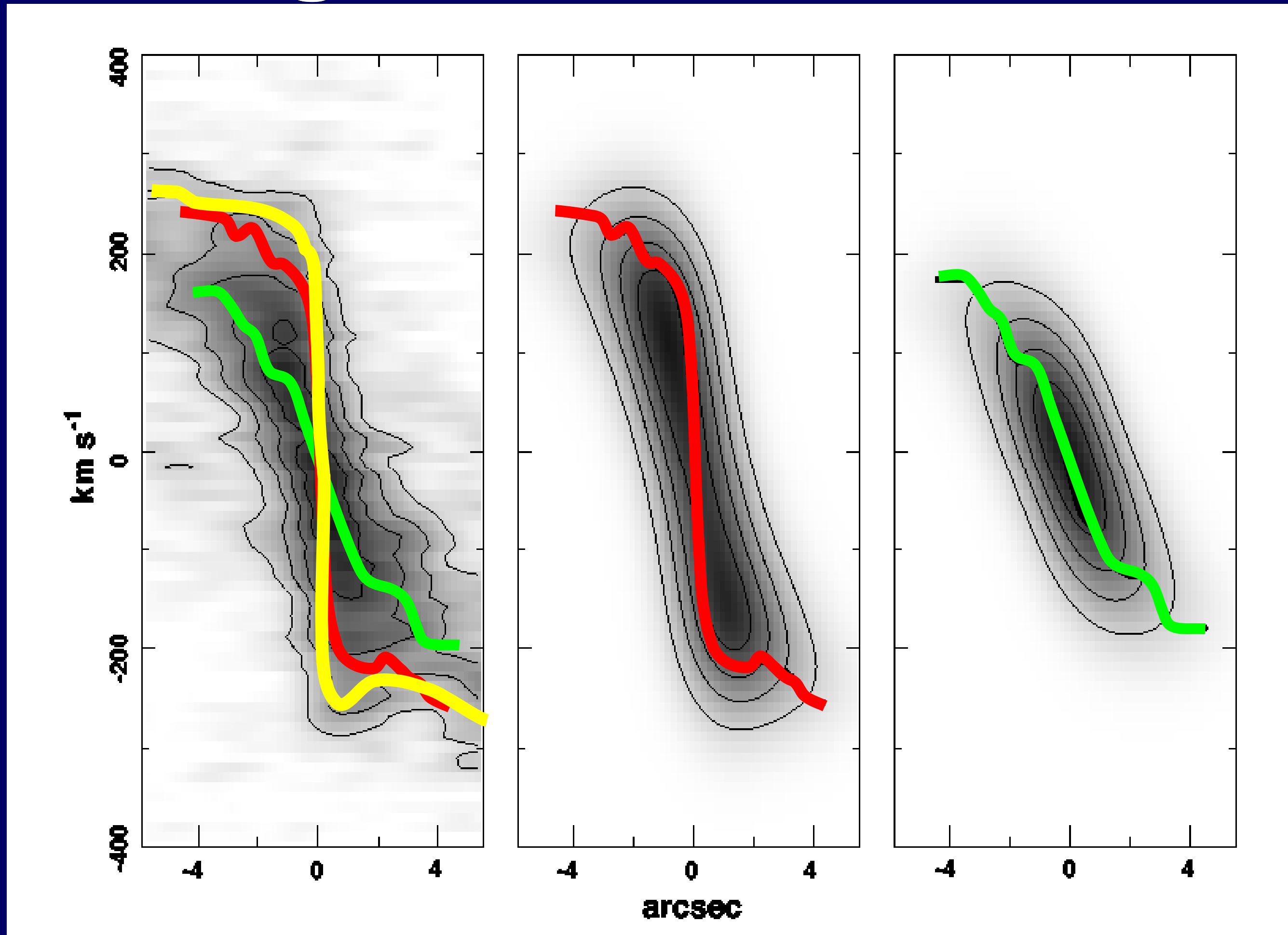
Deprojected Vr (km/s)
200
0
−200
0
50
(arcsec)
NGC 4536, CO(1−0)
50
R (arcsec)
Observed PV Diagram
Vini(r)=V(20%.etc)
or Vpeak
Initial: V1=Vini
Ico Distribution:
Surf. density (r)
PVD i
Vi+1=Vi+dVi
Vcom(r)=V(20%, etc)
or Vpeak
No
V com:
dVi=V ini - V com
|dVi|<Criterion?
Yes
Voutput (r)=Vi(r)
Rotation Curve

Methods for RC

Envelope tracing;

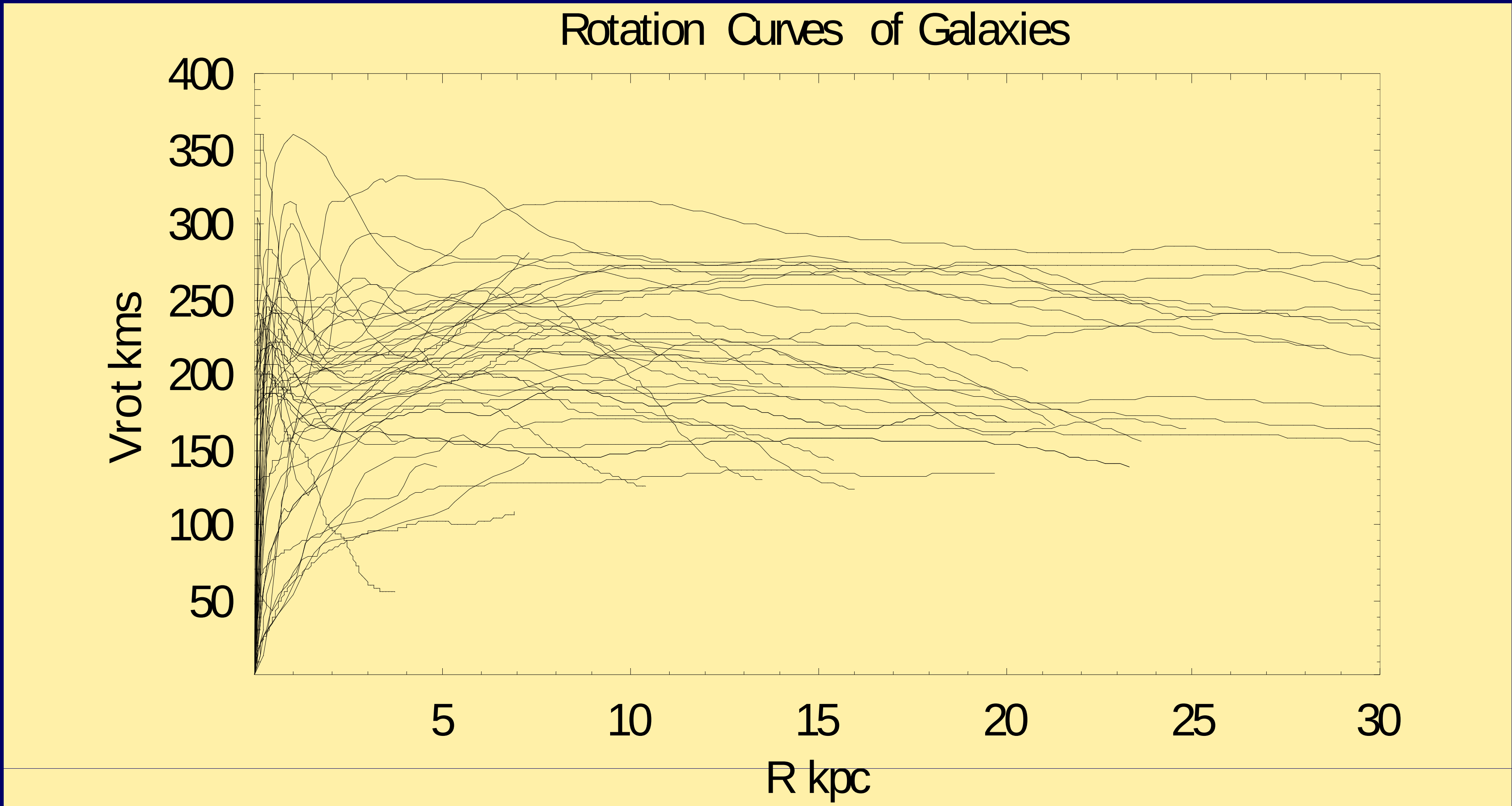
Iteration;

Peak tracing



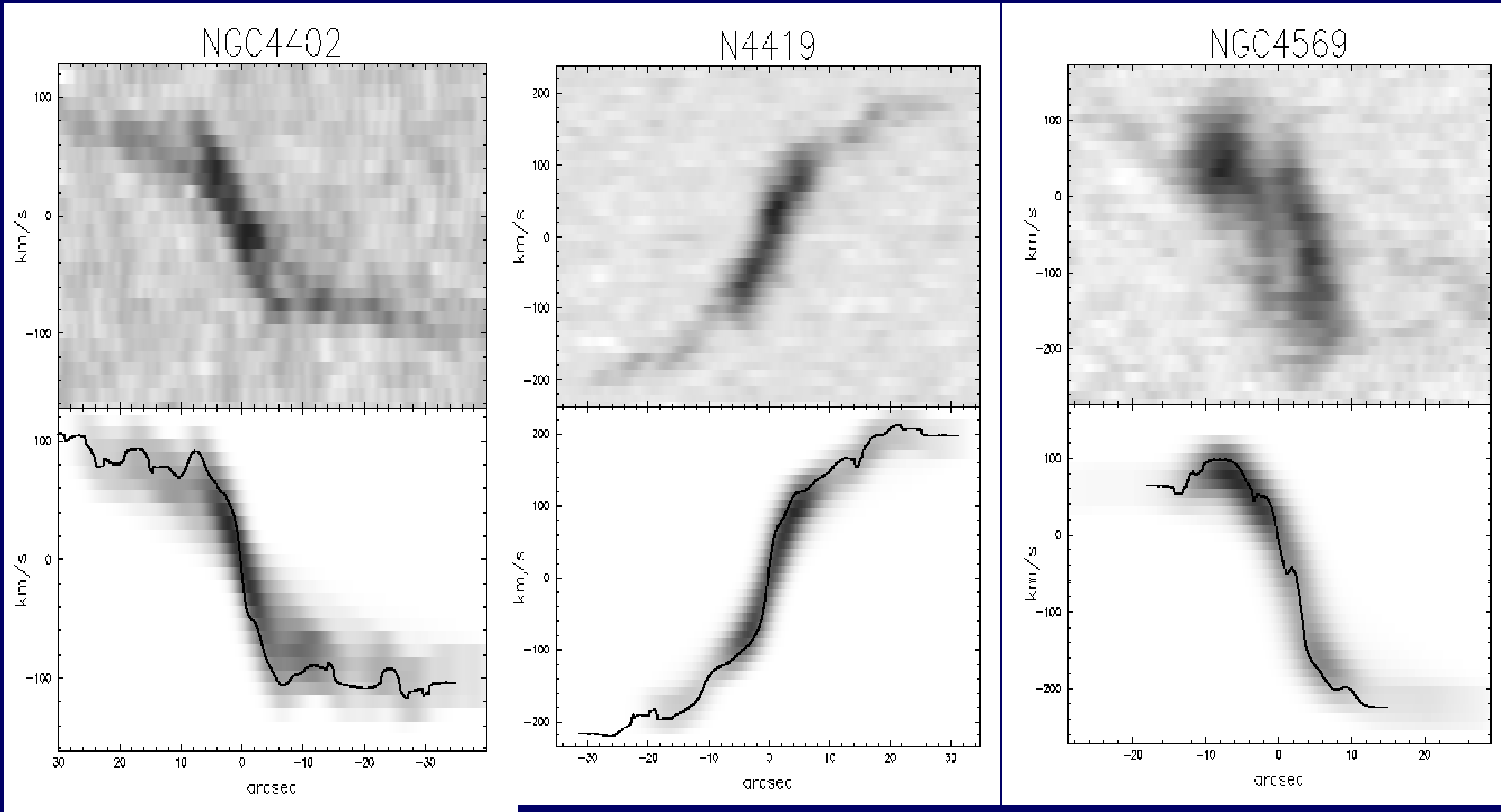
Rotation Curves from single dish data

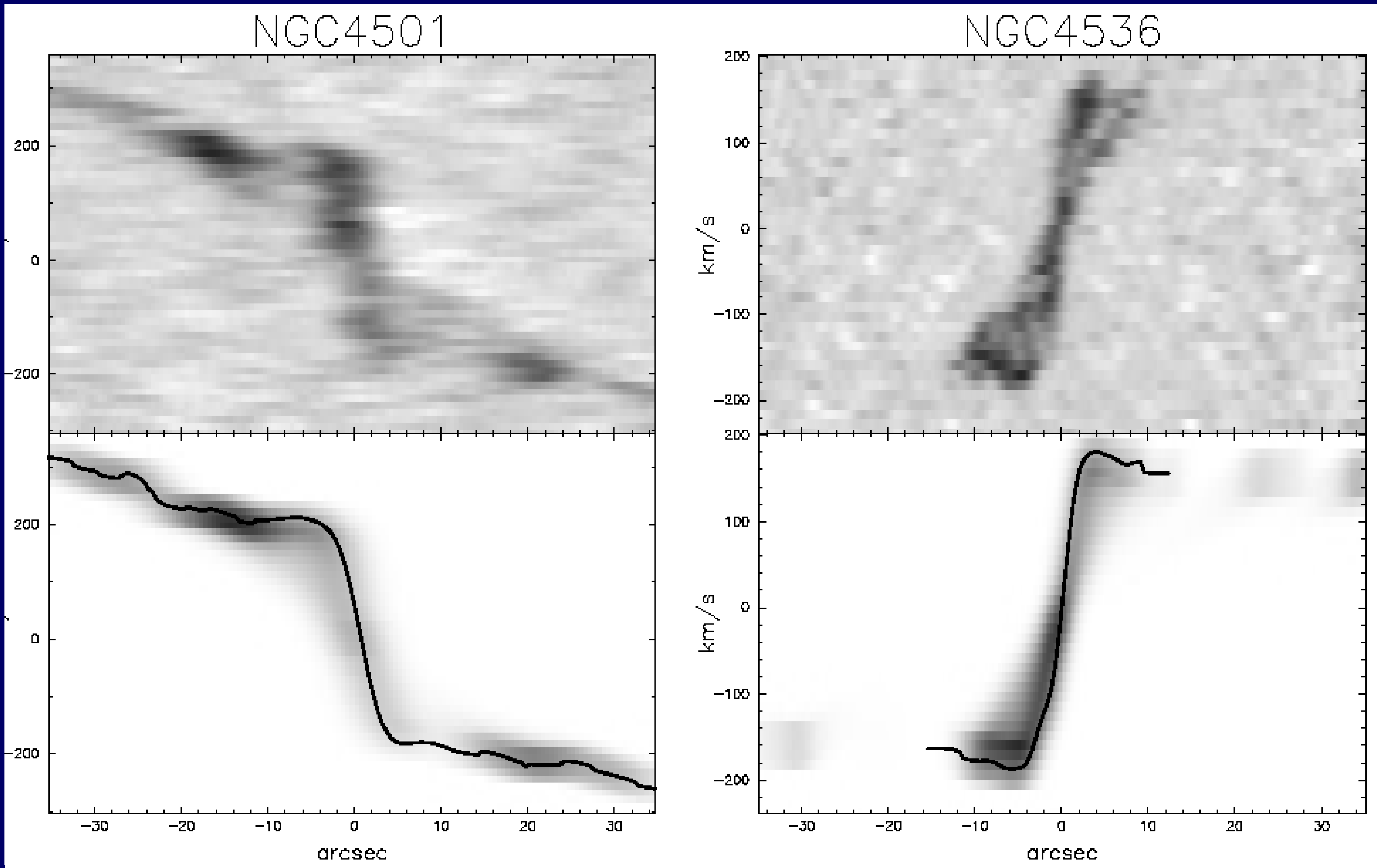
High accuracy RC for nearby galaxies



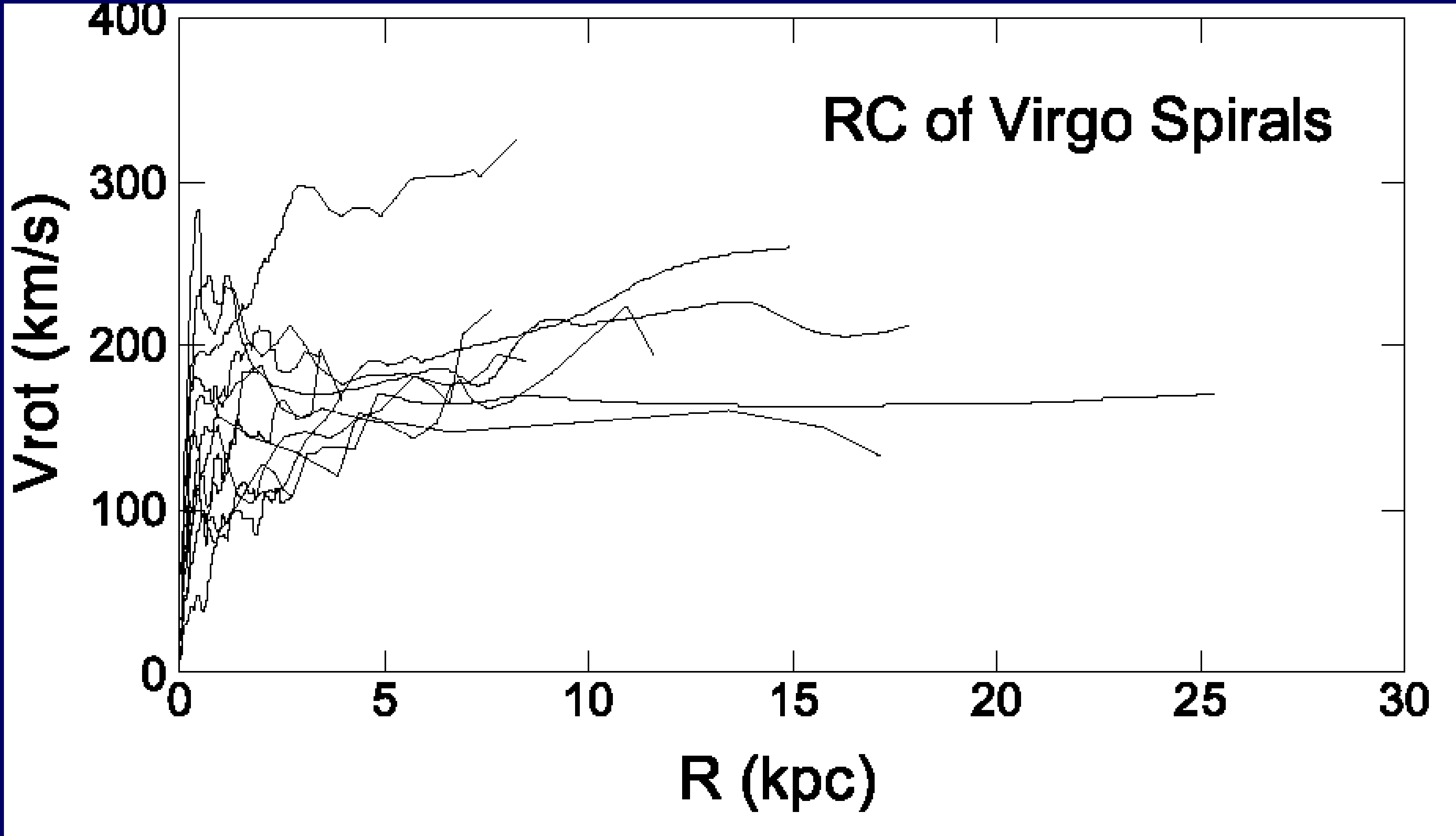
Rotation Curves from NMA

atural weighting (3-5”)


NGC4402
N4419
NGC4569
km/s
arcsec



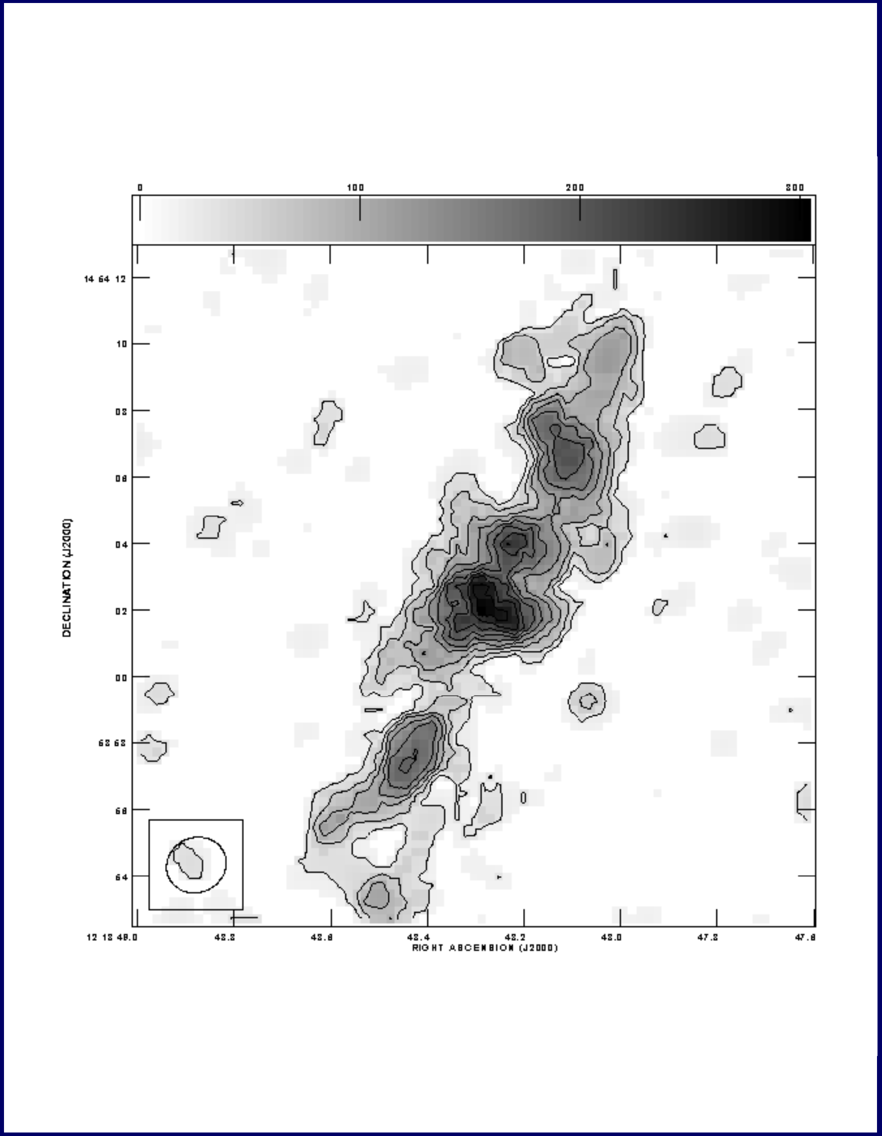
NGC4501
NGC4536
km/s
arcsec


RC of Virgo Spirals
Vrot (km/s)
R (kpc)
0
100
200
300
400
0
5
10
15
20
25
30

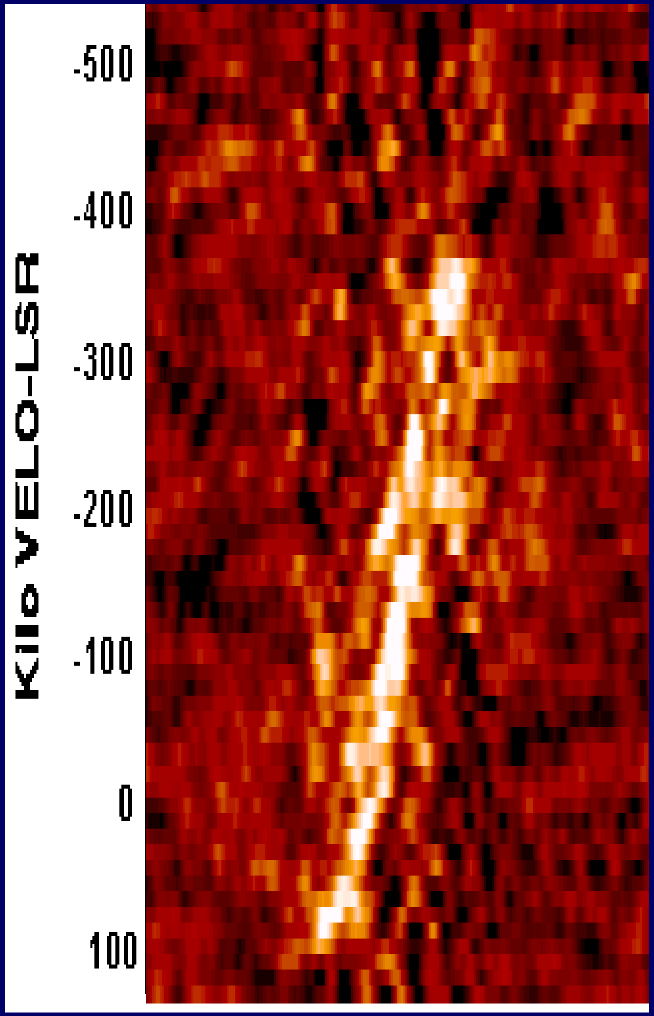
Rotation Curves from NMA

(Uniform weighting 1-2”)

NGC 4192

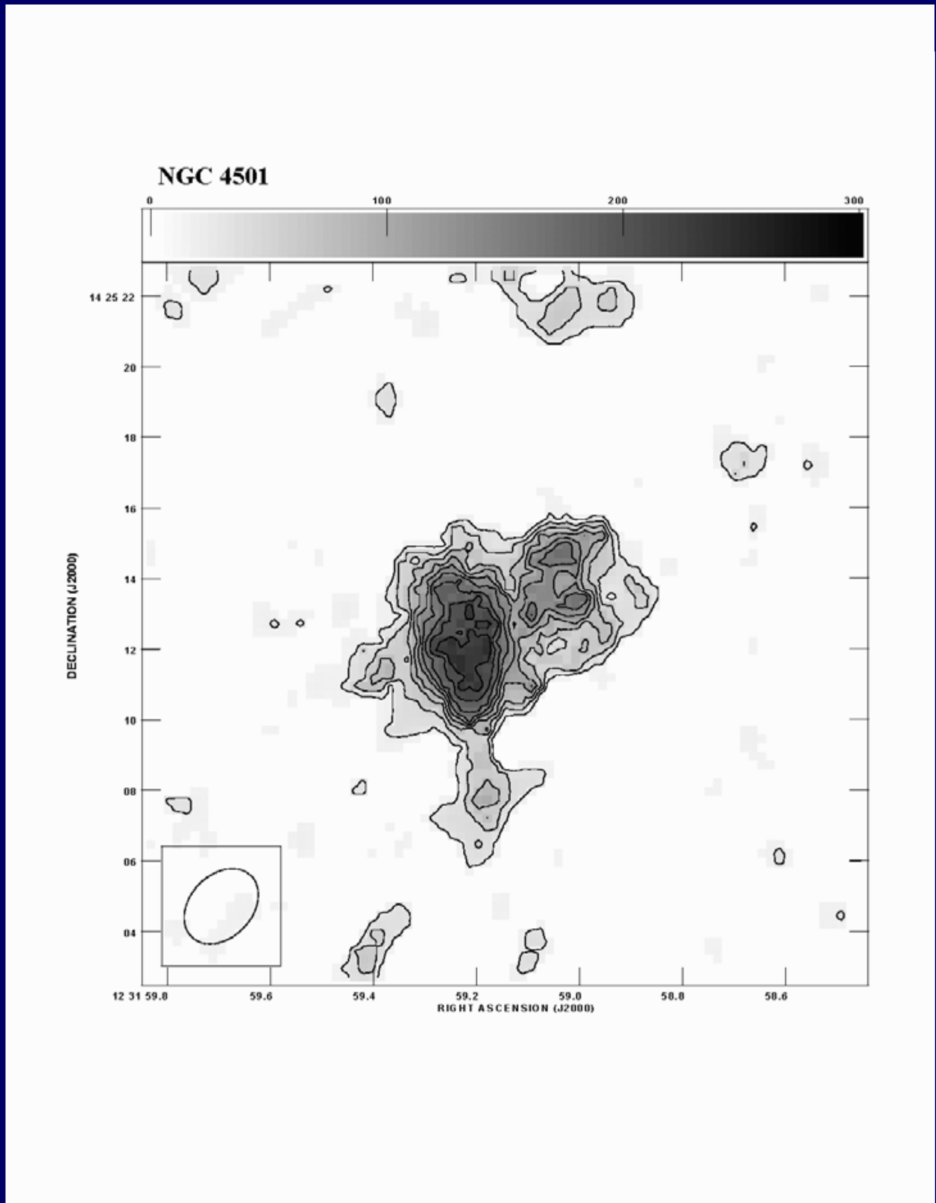


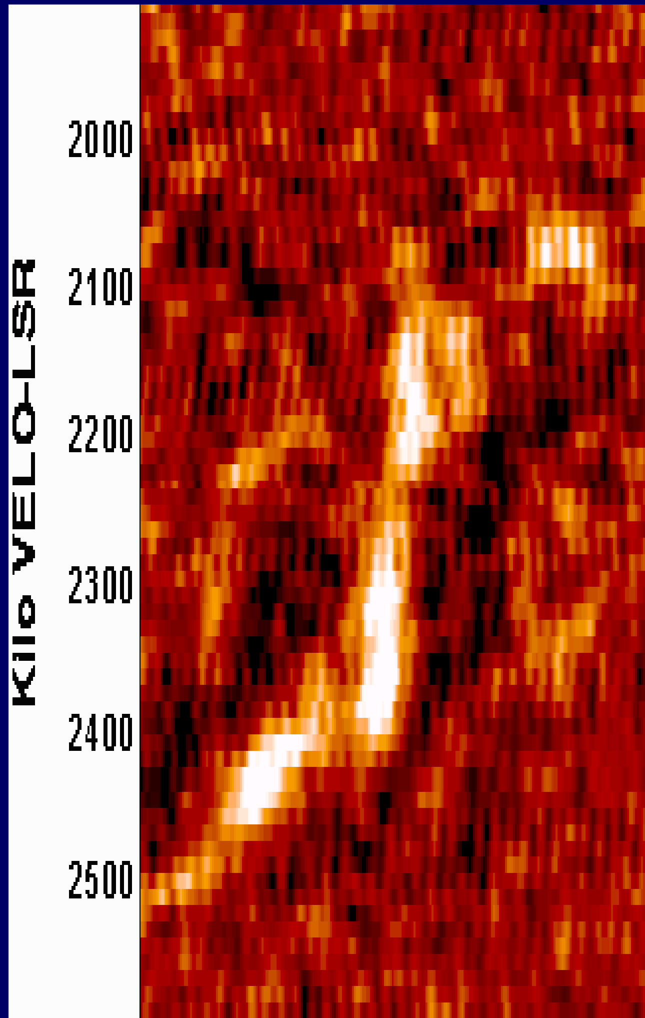
DECLINATION (J2000)
RIGHT ASCENSION (J2000)



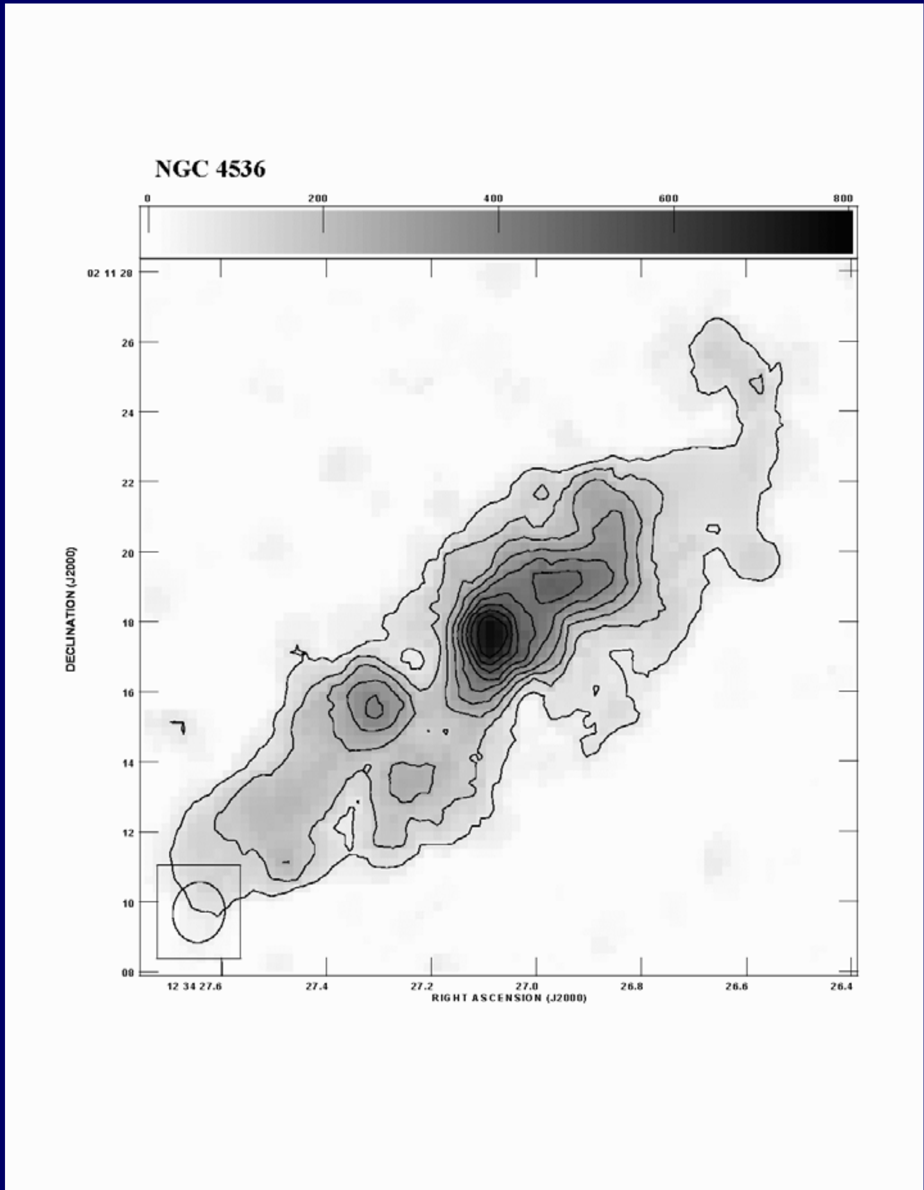
-500
-400
-300
-200
-100
0
100
Kilo VELO-LSR

NGC 4501

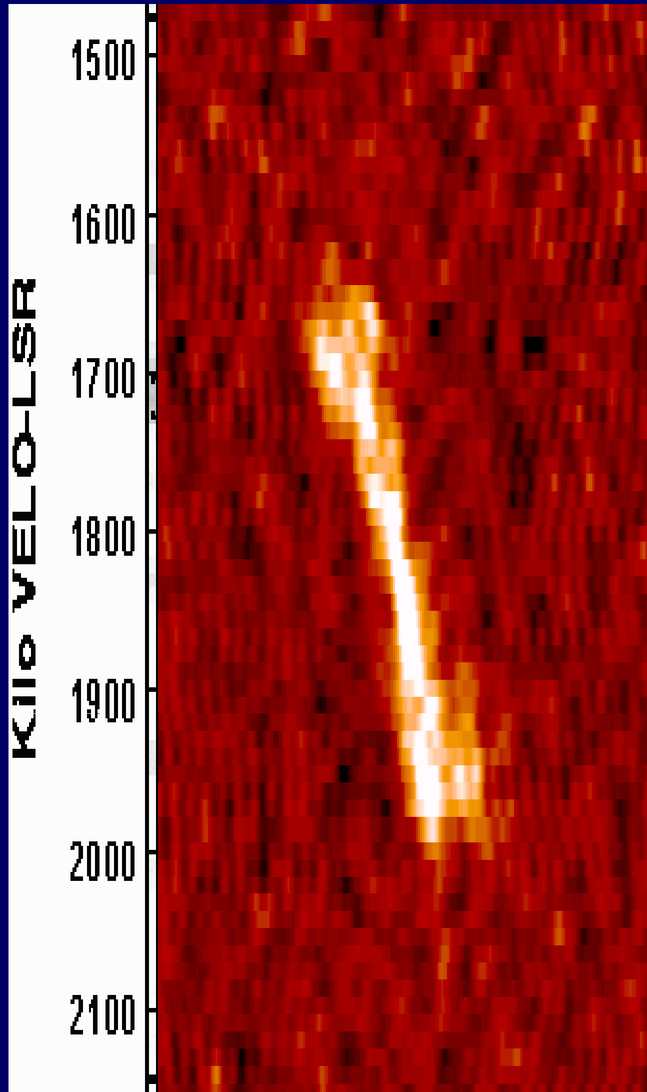

NGC 4501
0
100
200
300
14 25 22
20
18
16
14
12
10
08
06
04
DECLINATION (J2000)
12 31 59.8
59.6
59.4
59.2
59.0
58.8
58.6
RIGHT ASCENSION (J2000)


Kilo VELO-LSR
2000
2100
2200
2300
2400
2500

NGC 4536

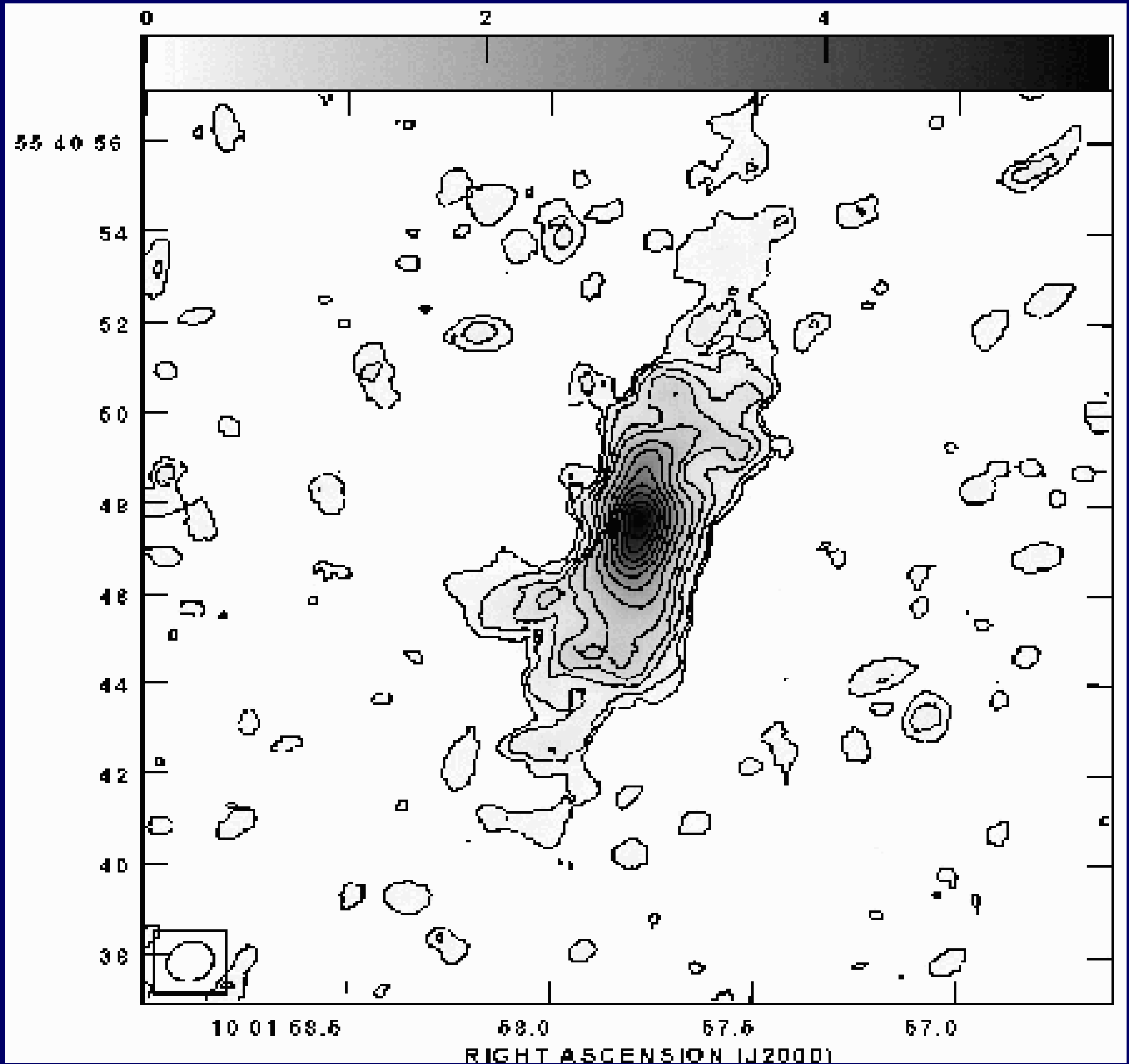


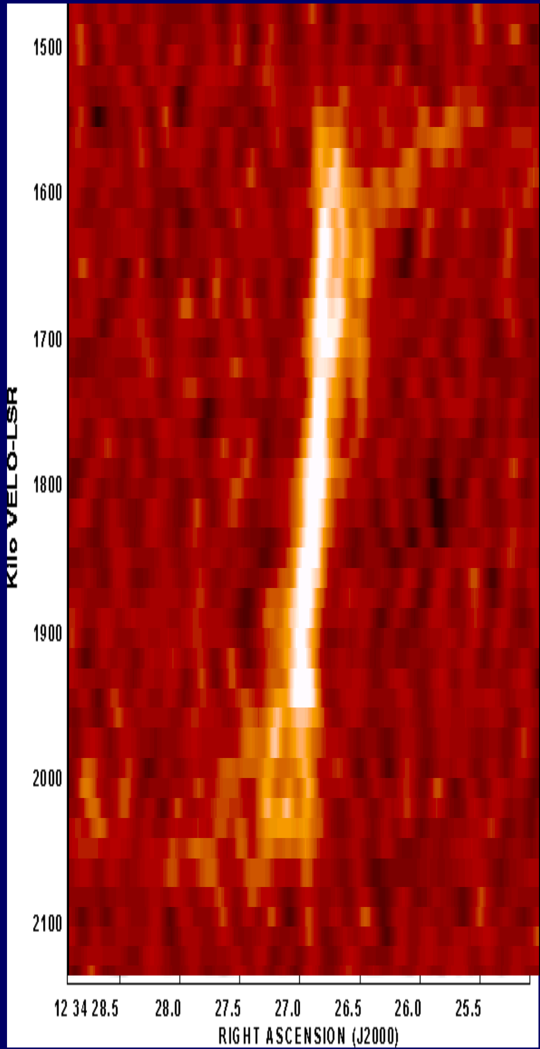
NGC 4536
RIGHT ASCENSION (J2000)
DECLINATION (J2000)



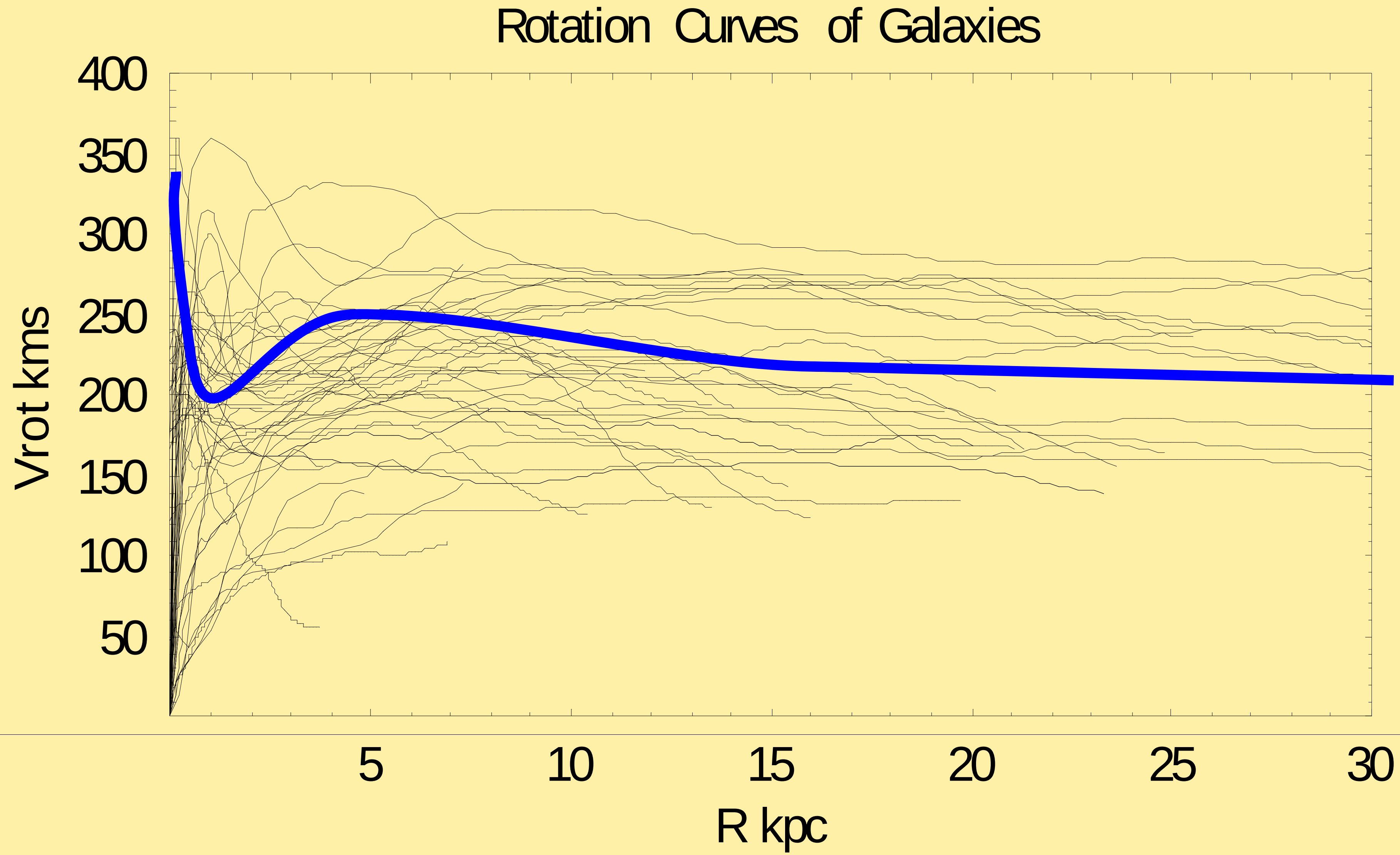
Kilo VELO-LSR
1500
1600
1700
1800
1900
2000
2100

NGC 3079

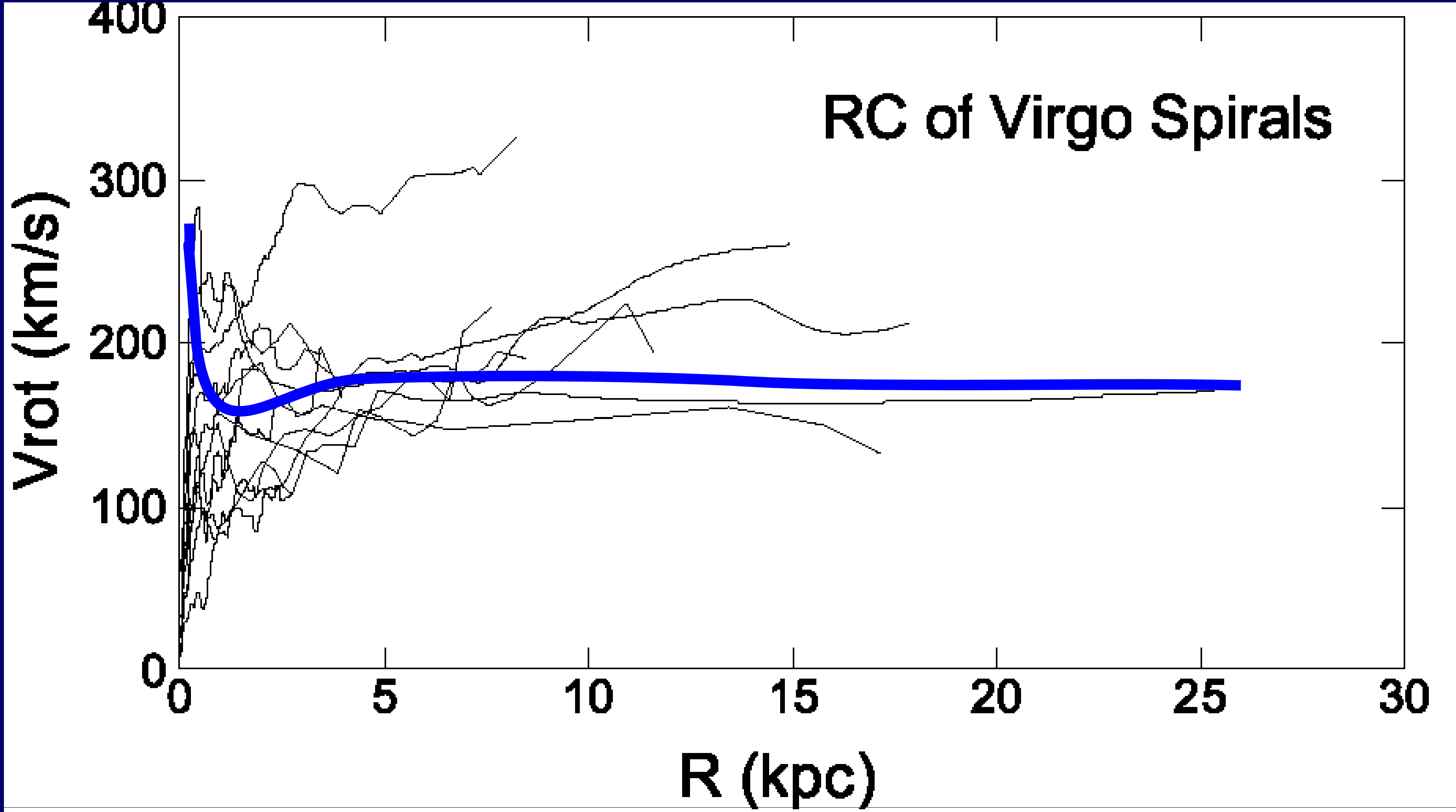

0
2
4
55 40 56
54
52
50
48
46
44
42
40
38
10 01 58.5
58.0
57.5
57.0
RIGHT ASCENSION (J2000)


1500
1600
1700
1800
1900
2000
2100
Kilo VELO-LSR
12 34 28.5
28.0
27.5
27.0
26.5
26.0
25.5
RIGHT ASCENSION (J2000)

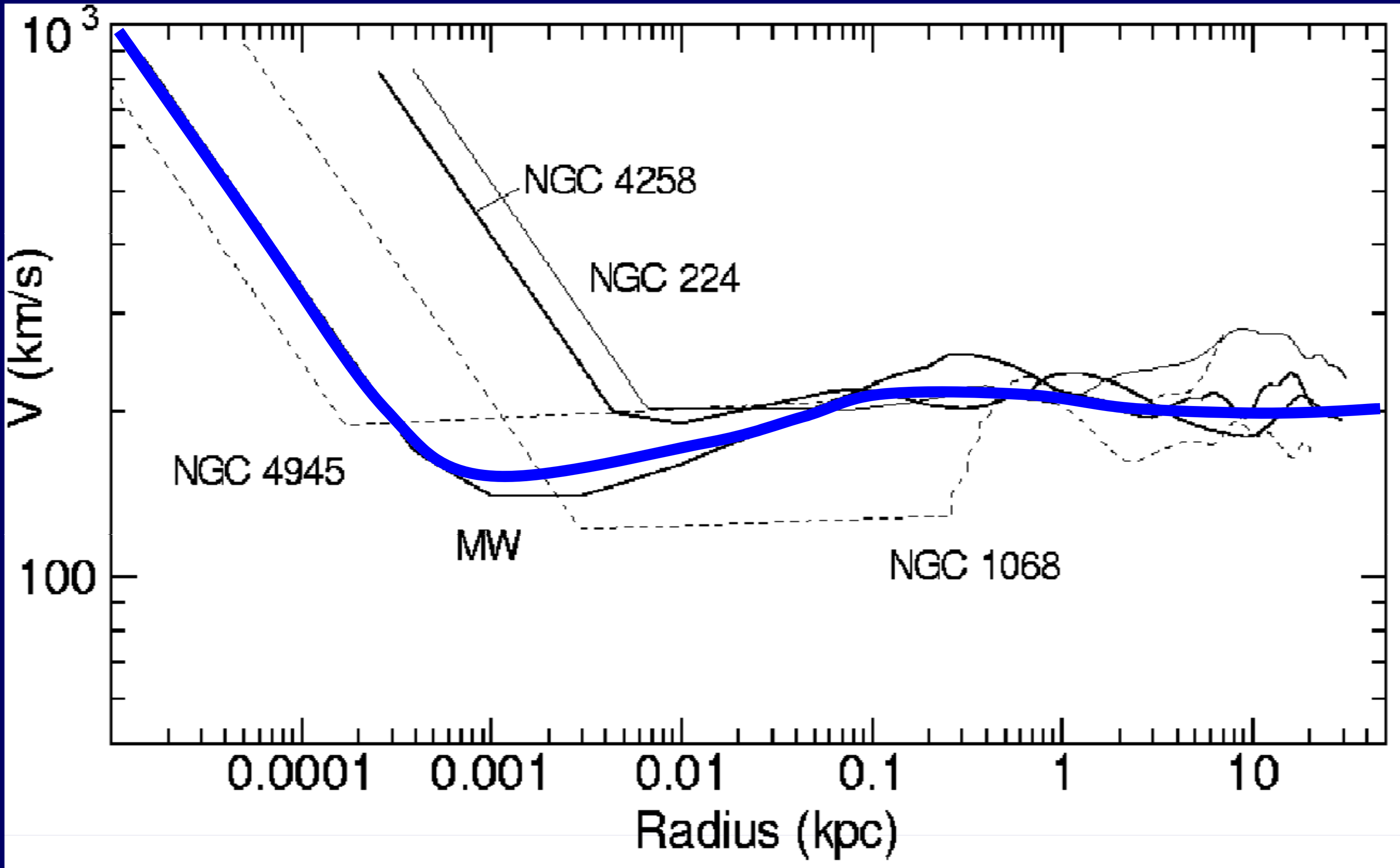
High accuracy RC



High accuracy RC

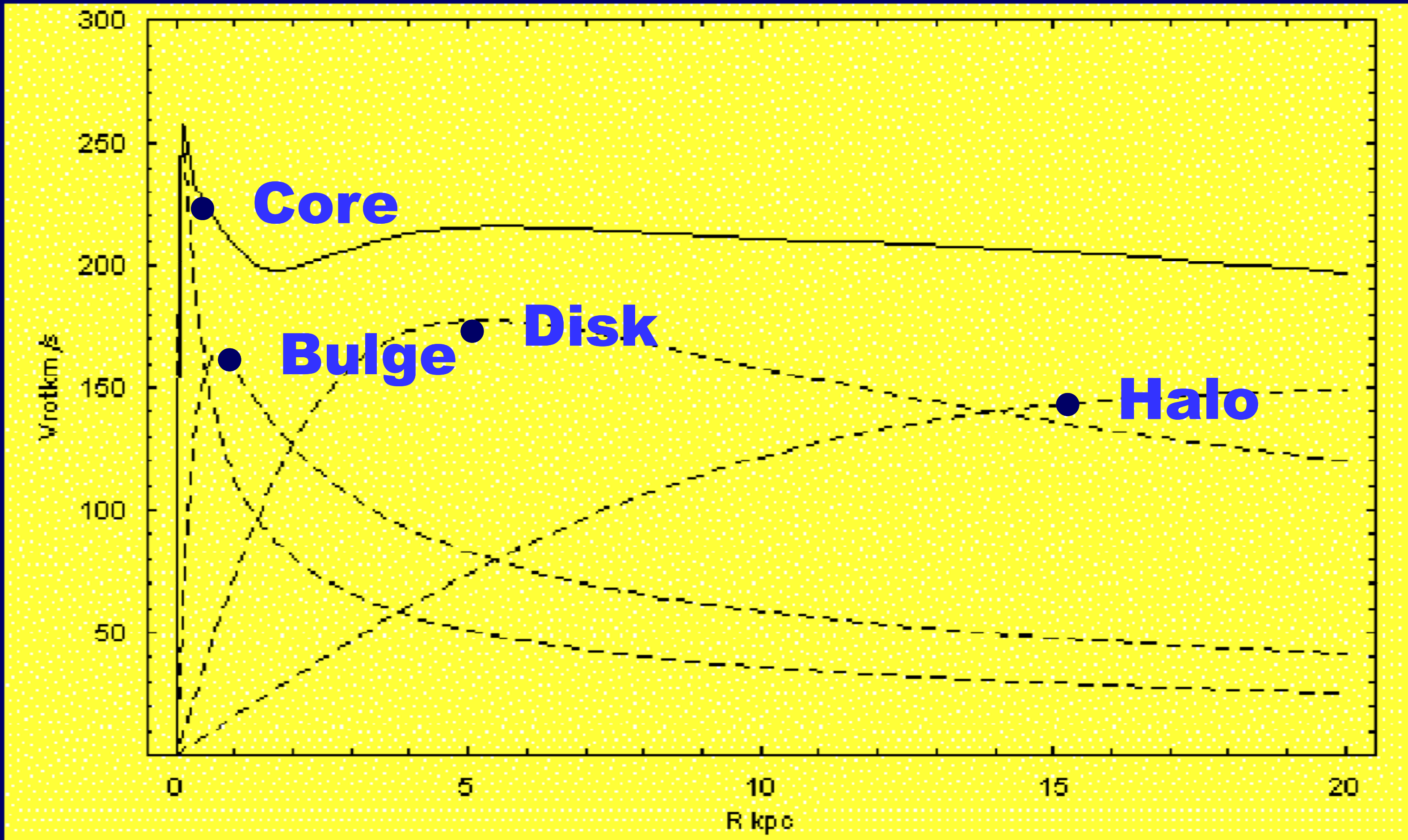


Logarithmic RC

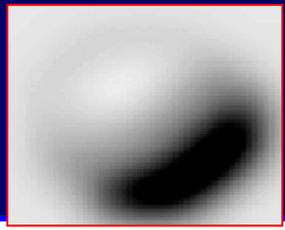
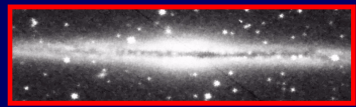
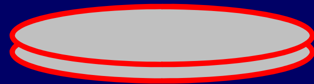


IV. Mass distributions

Fitting by Miyamoto-Nagai Potential



Direct calculation of mass distribution from RC

 >  > 

(a) Spherical Mass Distribution:

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

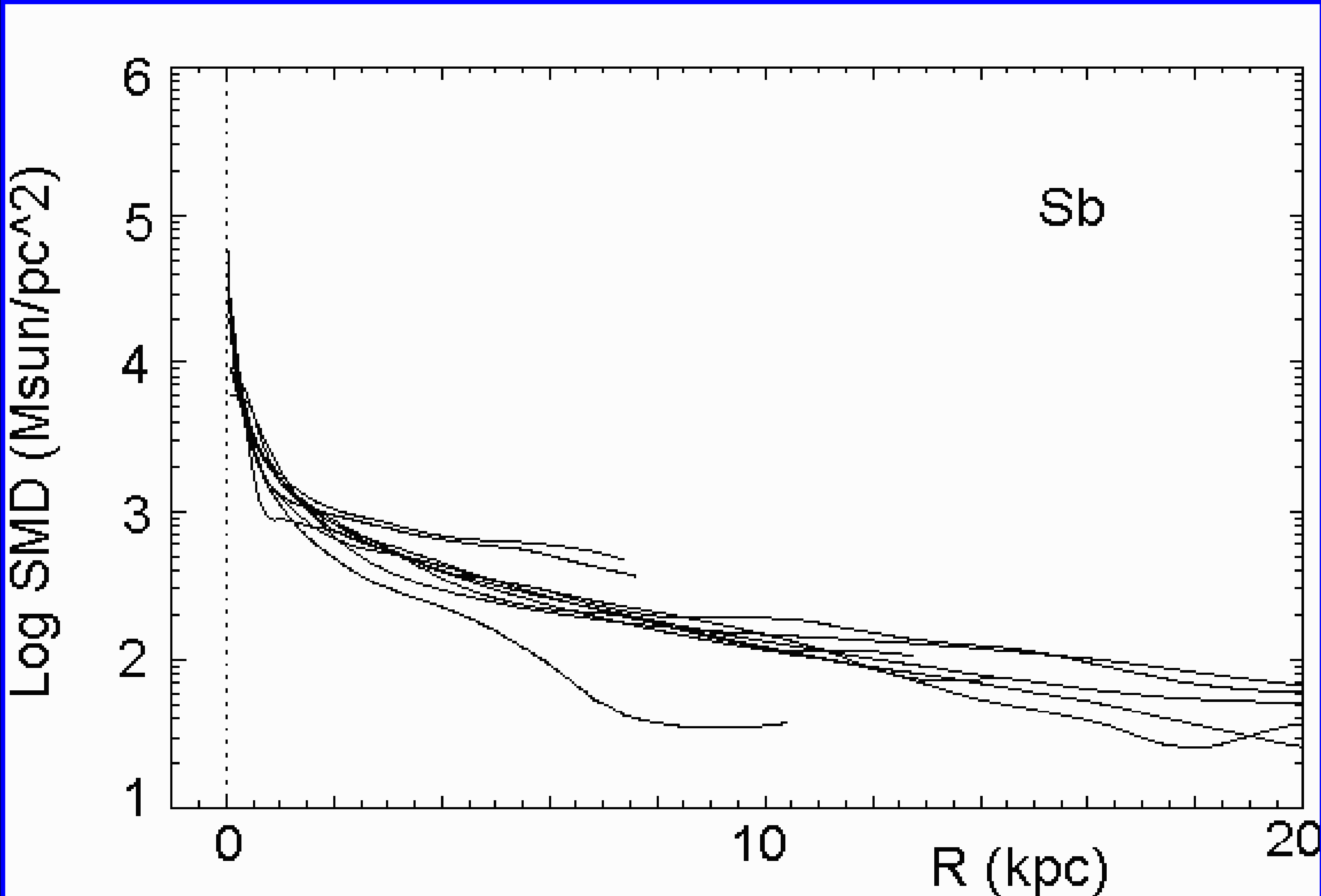
$$\rho(r) = \frac{1}{4\pi r^2}\frac{dM(r)}{dr}.$$

$$\sigma(R)_s = 2\int_0^\infty \rho(r)\,dz = \frac{1}{2\pi}\int_R^\infty \frac{\left(\frac{dM(r)}{dr}\right)_x}{x\sqrt{x^2-R^2}}\,dx,$$

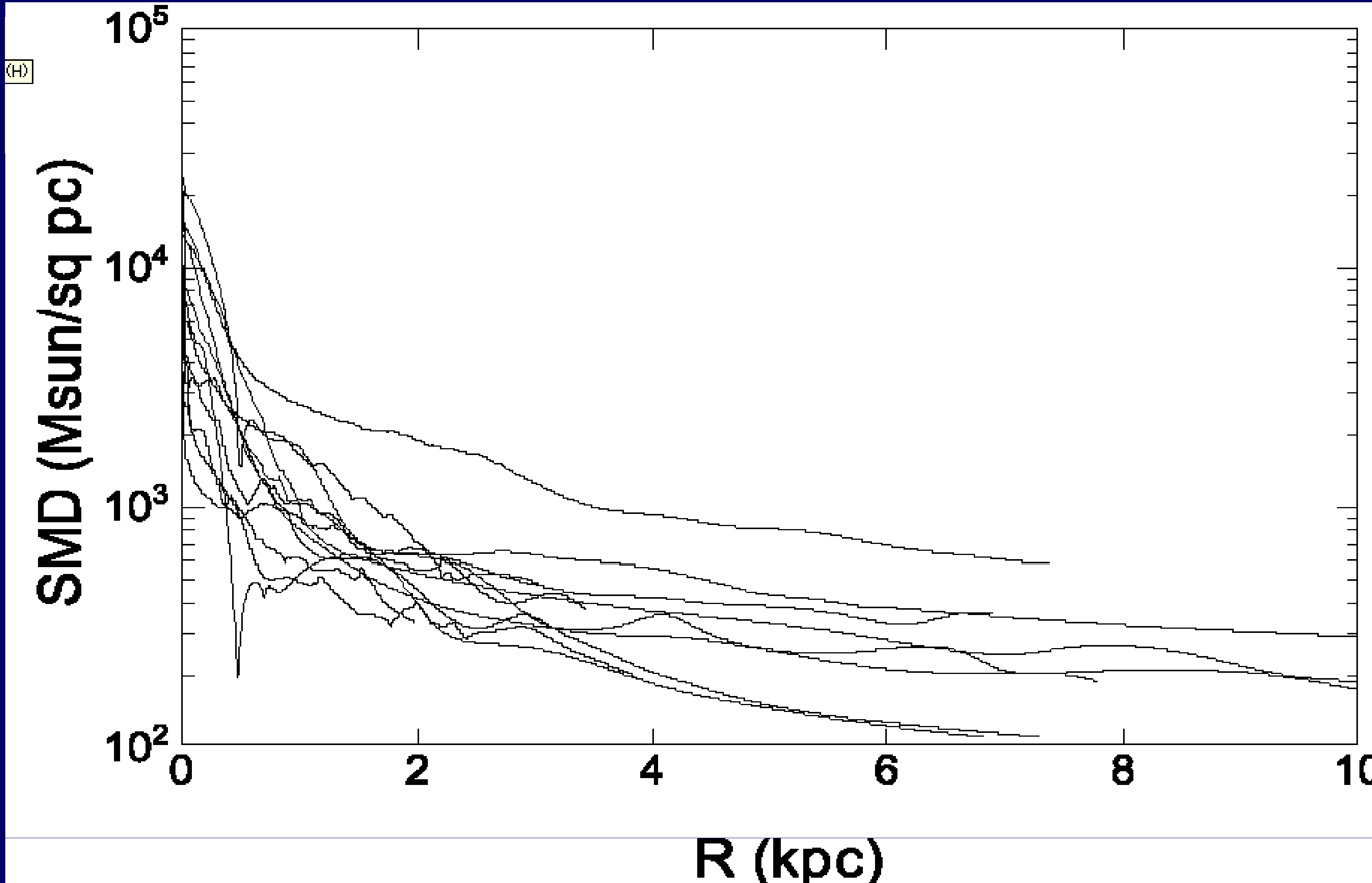
(b) Flat-Disk Mass Distribution: Laplace's equation $\Delta\Phi = 0$:

$$\sigma(R)_f = \frac{1}{\pi^2 G}\left[\frac{1}{R}\int_0^R \left(\frac{dV^2}{dr}\right)_x K\left(\frac{x}{R}\right)dx + \int_R^\infty \left(\frac{dV^2}{dr}\right)_x K\left(\frac{R}{x}\right)\frac{dx}{x}\right],$$

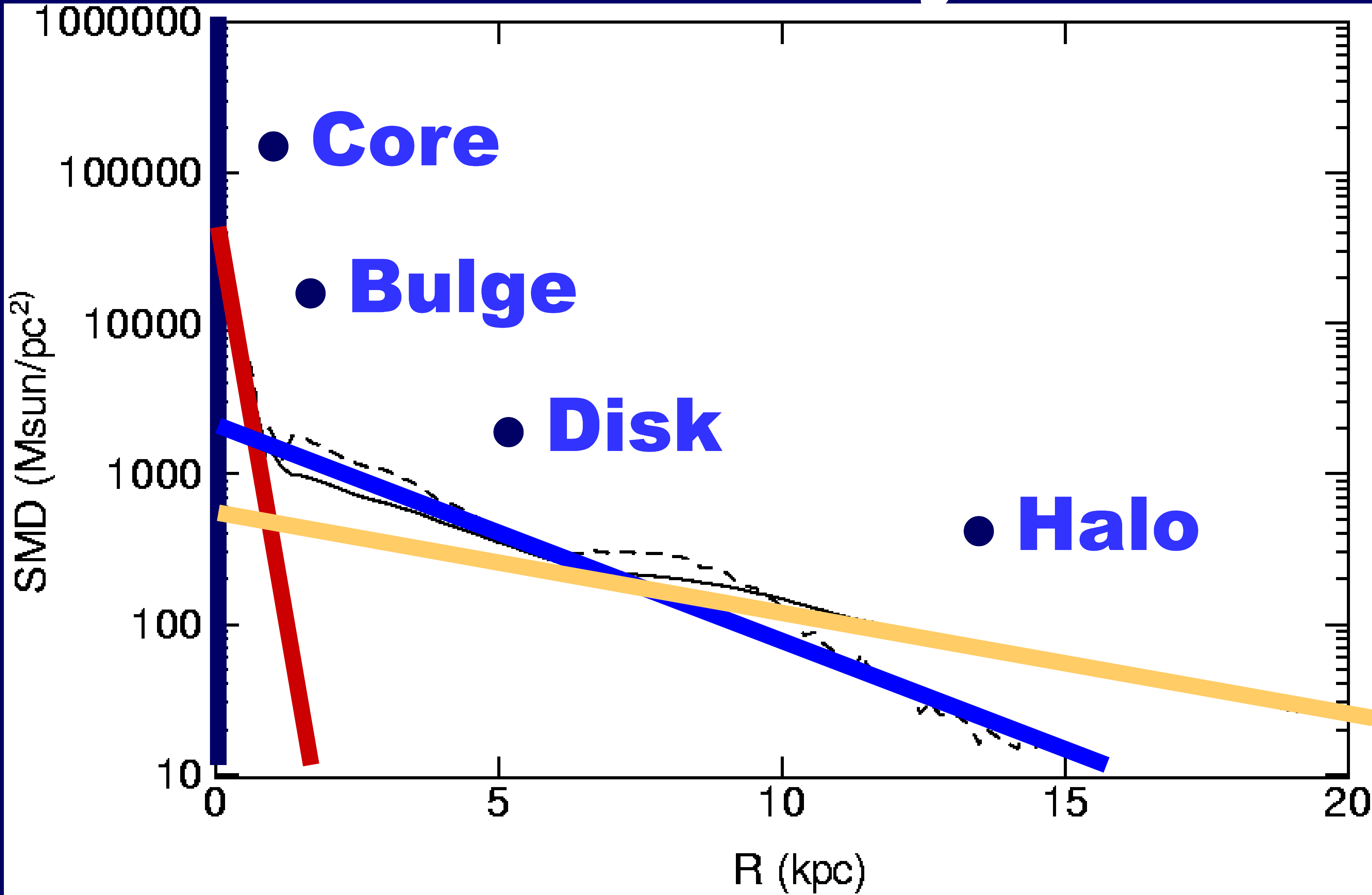
where $K(x)$ is the complete elliptic integral(Binney & Tremaine 1987).


Sb
Log SMD (Msun/pc^2)
1
2
3
4
5
6
0
10
20
R (kpc)

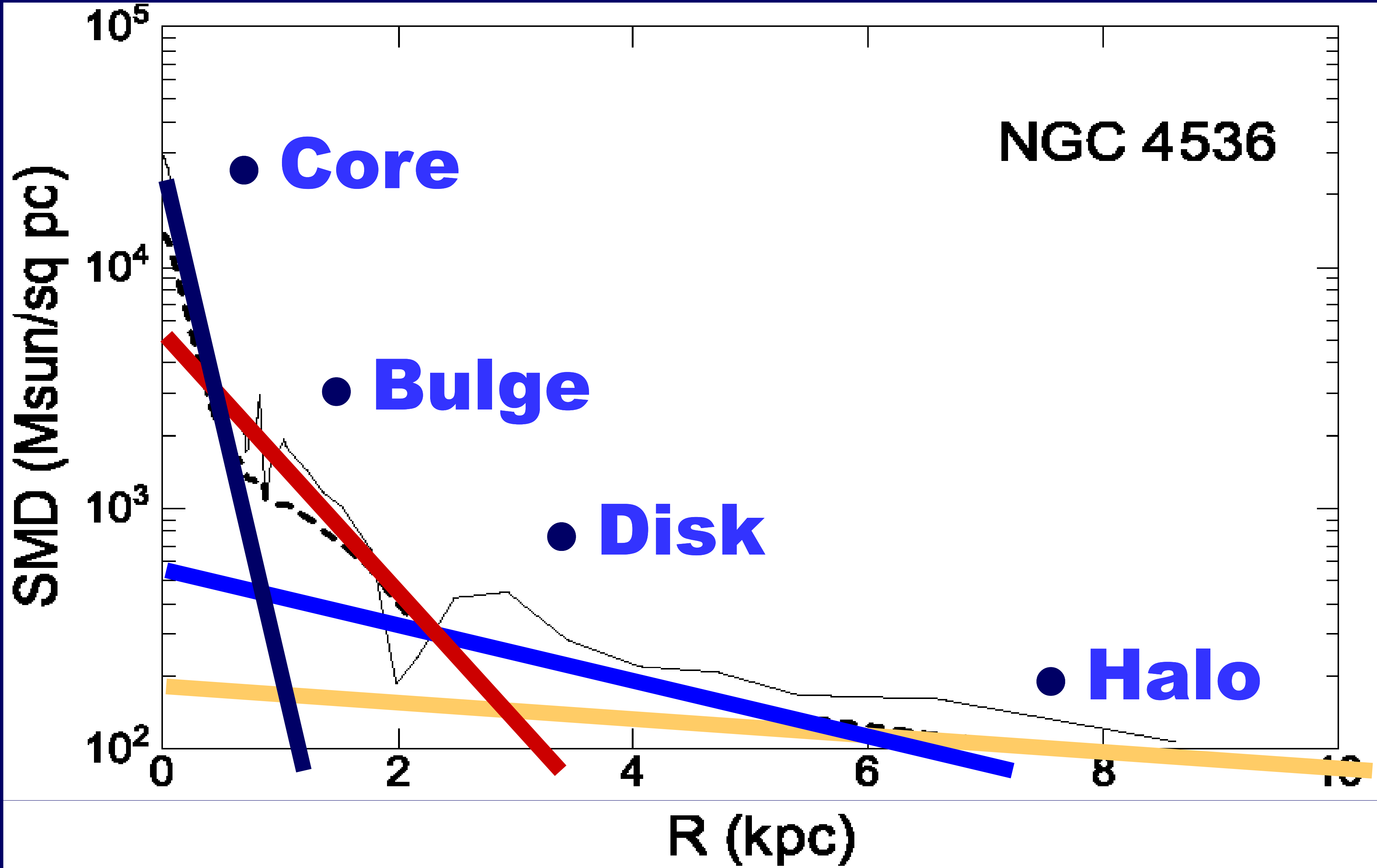
Virgo @ higher resolution



SMD(mass)
Surface mass density



(@ higher resolution)



Fundamental structures of spiral galaxies

- Central BH
- Massive Core
- Bulge
- Disk
- Hallo

Massive Core

10^9 M_{sun} in 100 pc

SMD ~ a few x10^4 M_{sun}/pc^{-2}

Center Cusp (DM/Stellar)

Fundamental mass structures of spiral galaxies

Central BH

Massive Core

Bulge

Disk

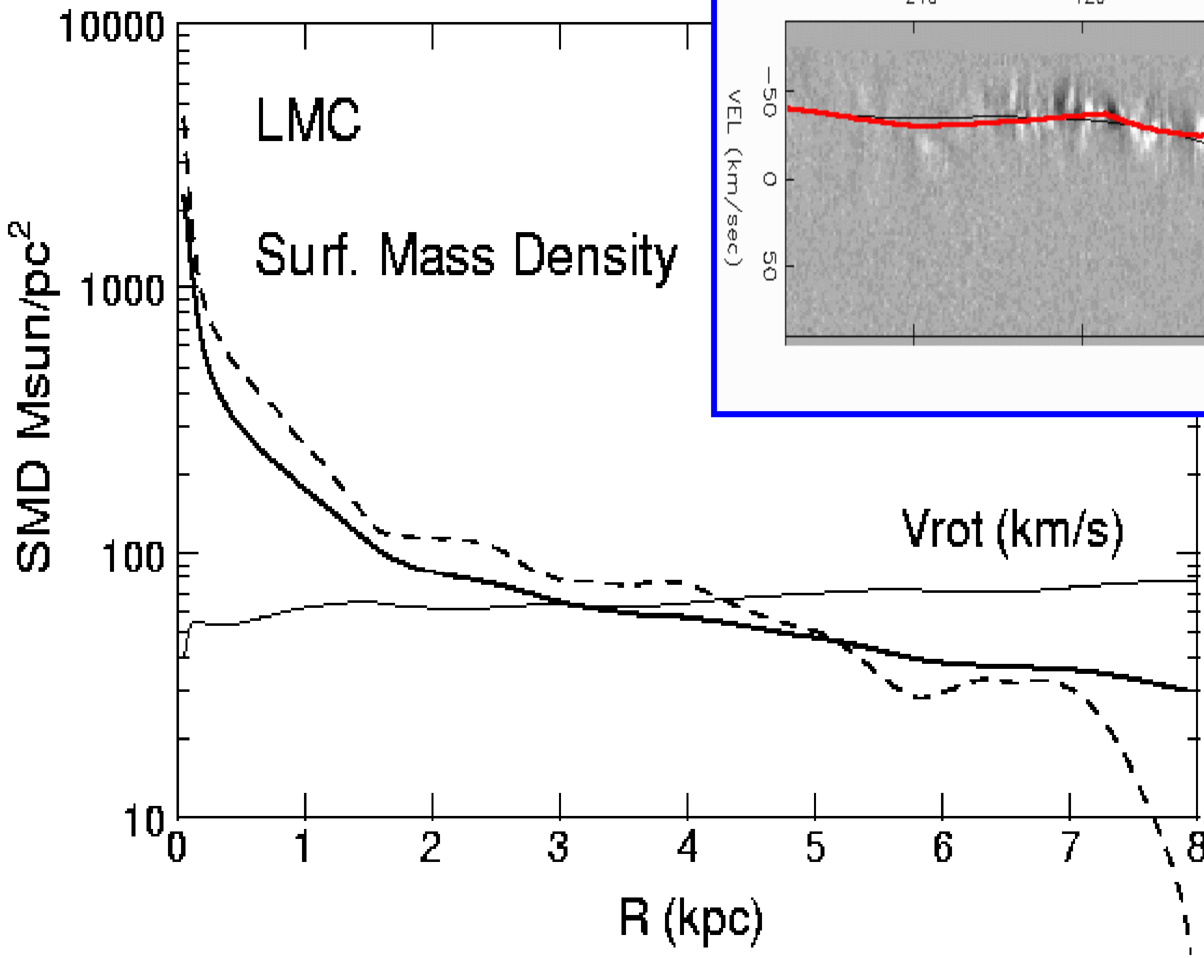
Hallo

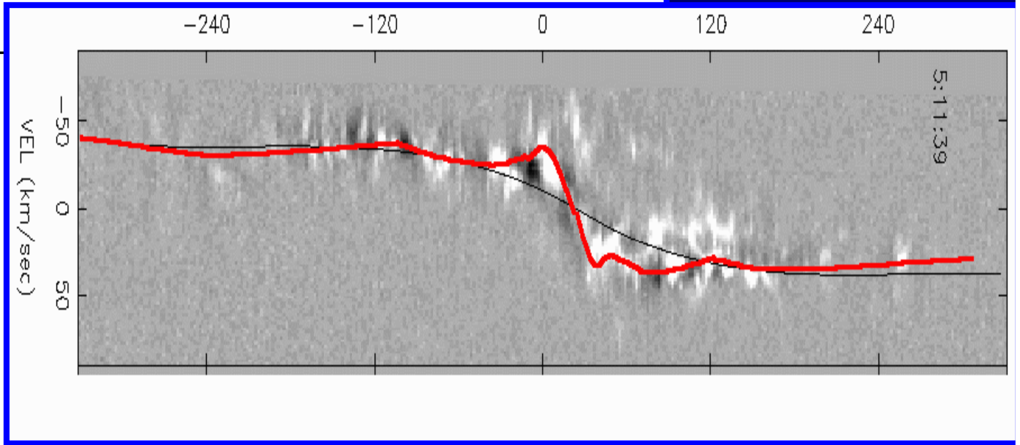
Mass structure is universal.

Milky Way, M31, N253, ... Virgo galaxies, ...

Even LMC, M82(hallo truncated)

LMC =Dark Bulge + Disk + Dark Halo

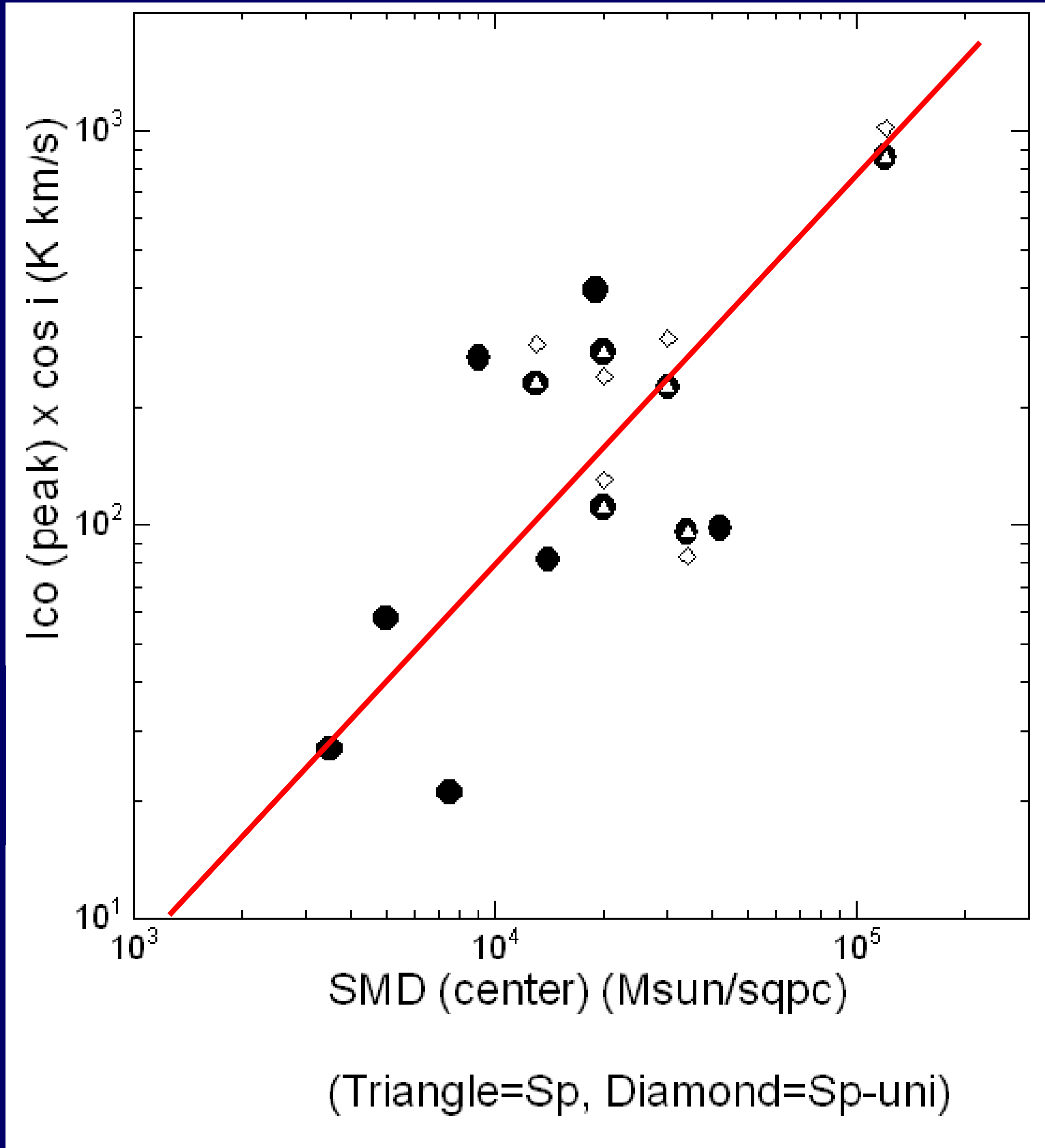




IV. Molecular core in massive core

Center SMD(gas)
vs
SMD(dynamical)

SMD (gas) ~ 0.01 SMD(mass)



1000 $M_{sun}pc^{-2}$

100 $M_{sun}pc^{-2}$

Conversion factor < X_{co} solar

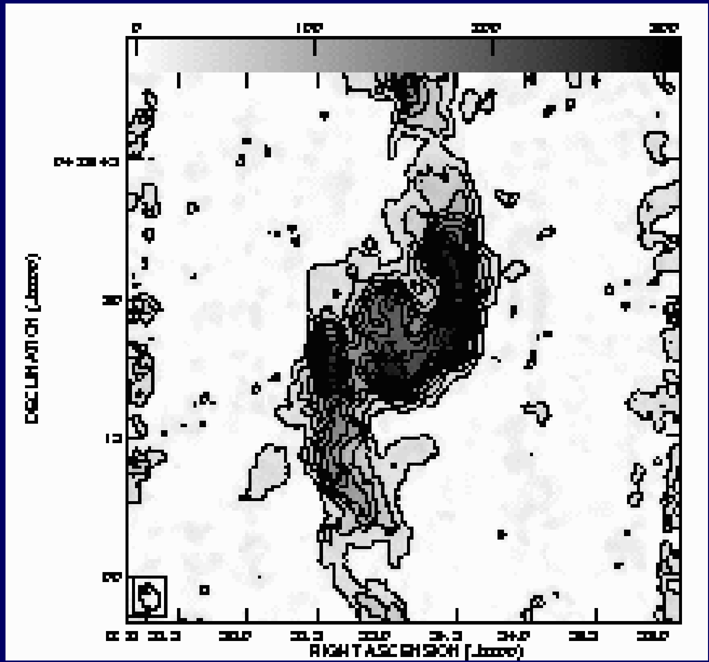
$X_{co} = 1 \times 10^{20}\ H_2\ cm^{-2}/K\ km/s$

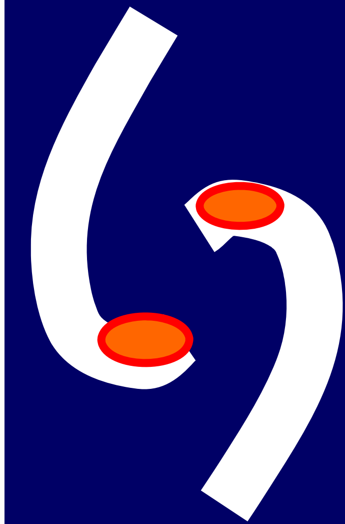
$SMD(H_2) = 0.013\ SMD_{(mass)}$

Gas mass << Dynamical mass
in 100 pc

Central gas distribution:
Twin peaks
vs
Single peak

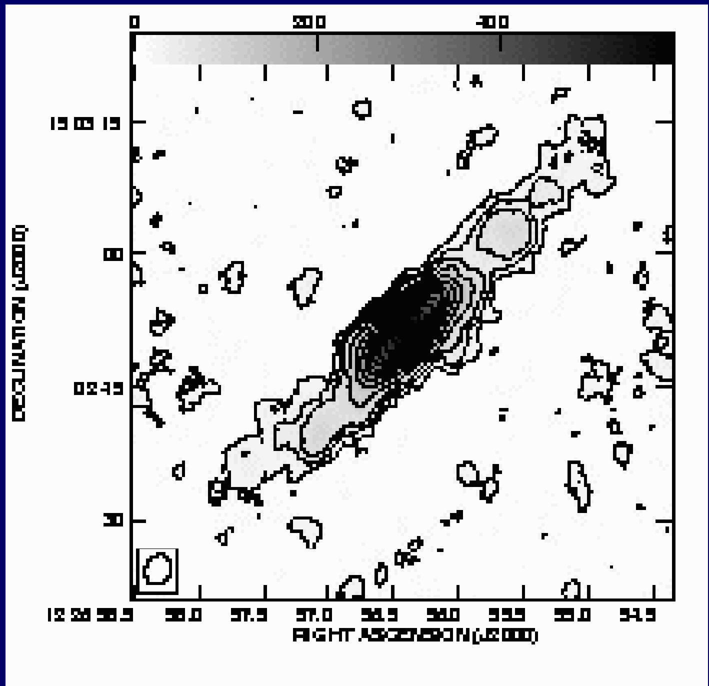
Twin peaks

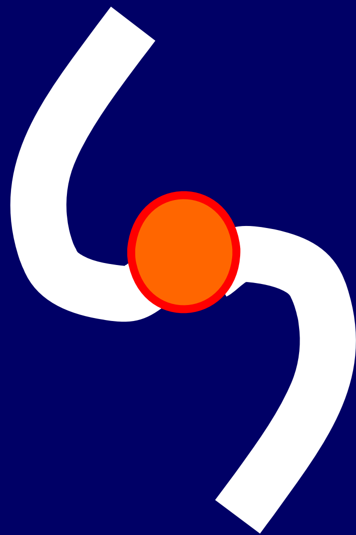




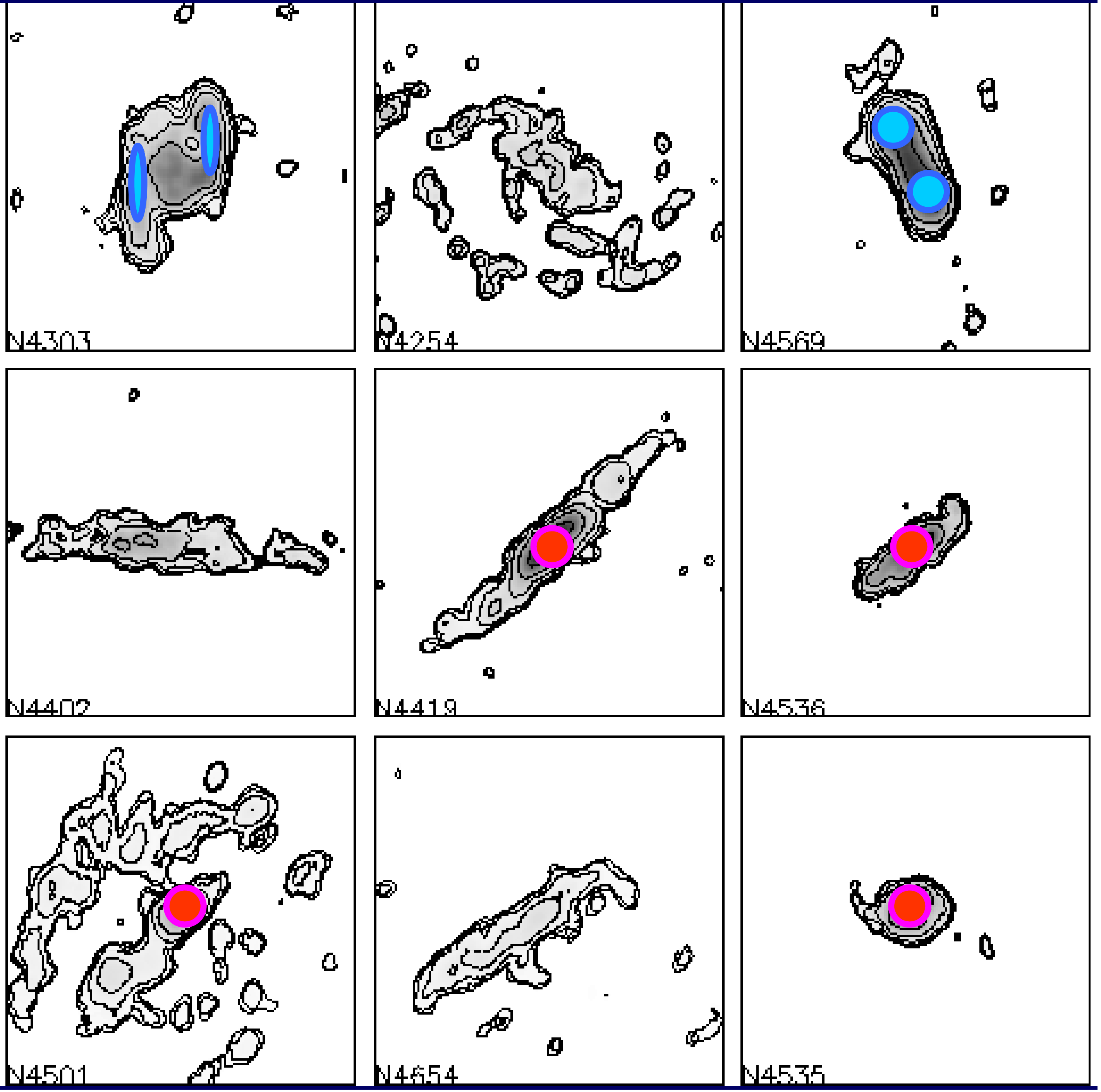
vs

Single peak





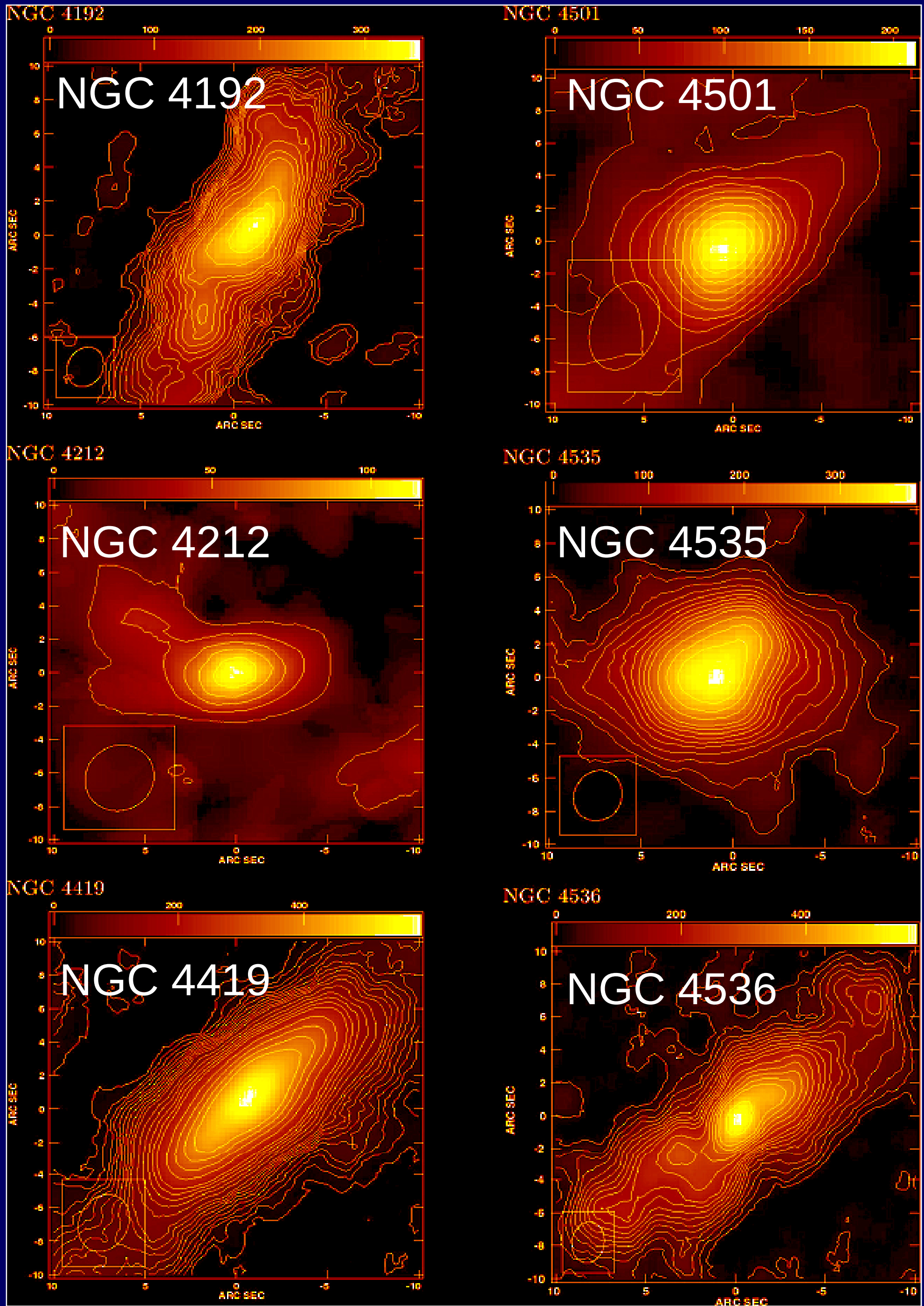
Twin & Single

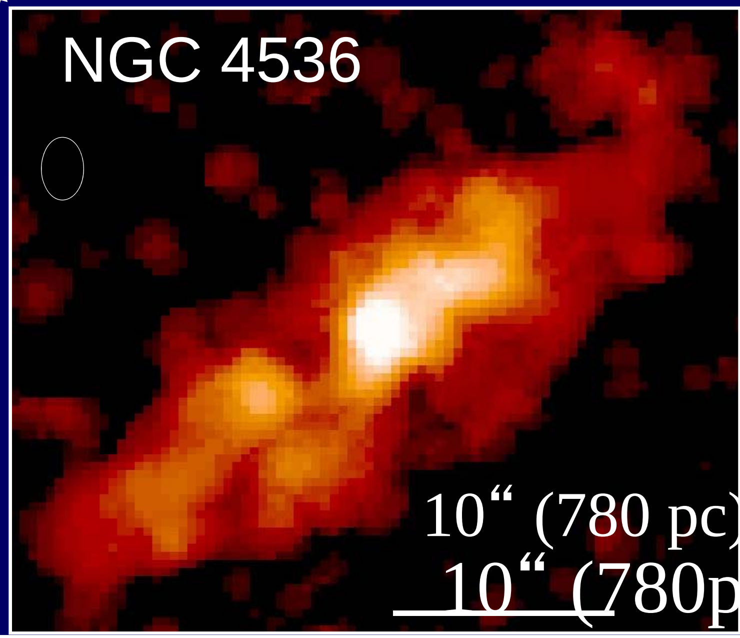


“Single Peaks”

•6 Singles vs 1 Twin

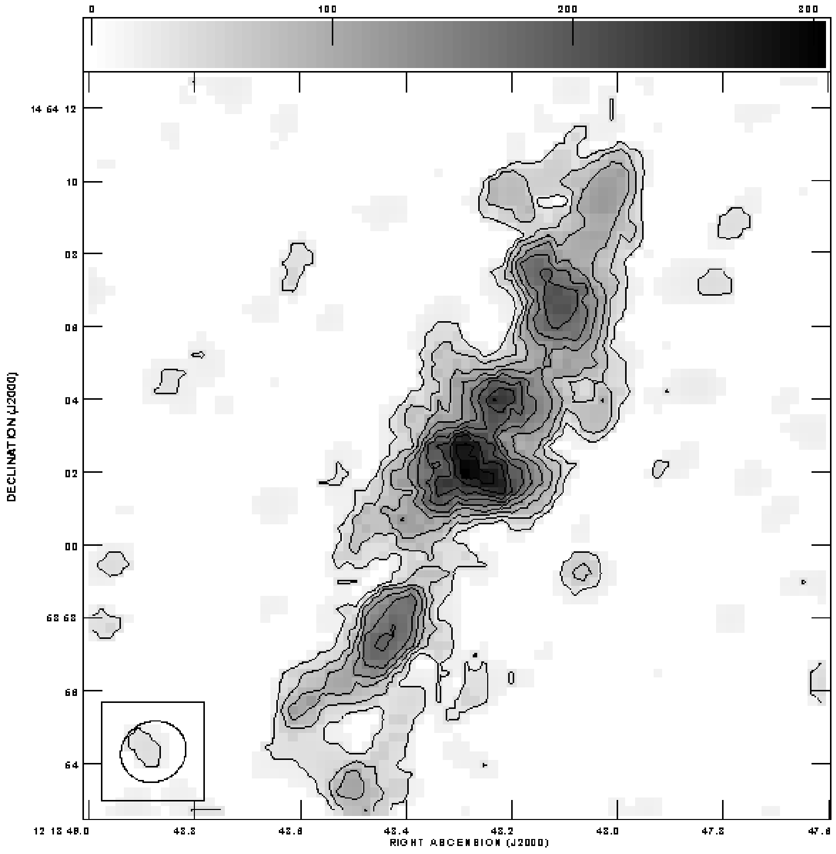
•out of 15 galaxies



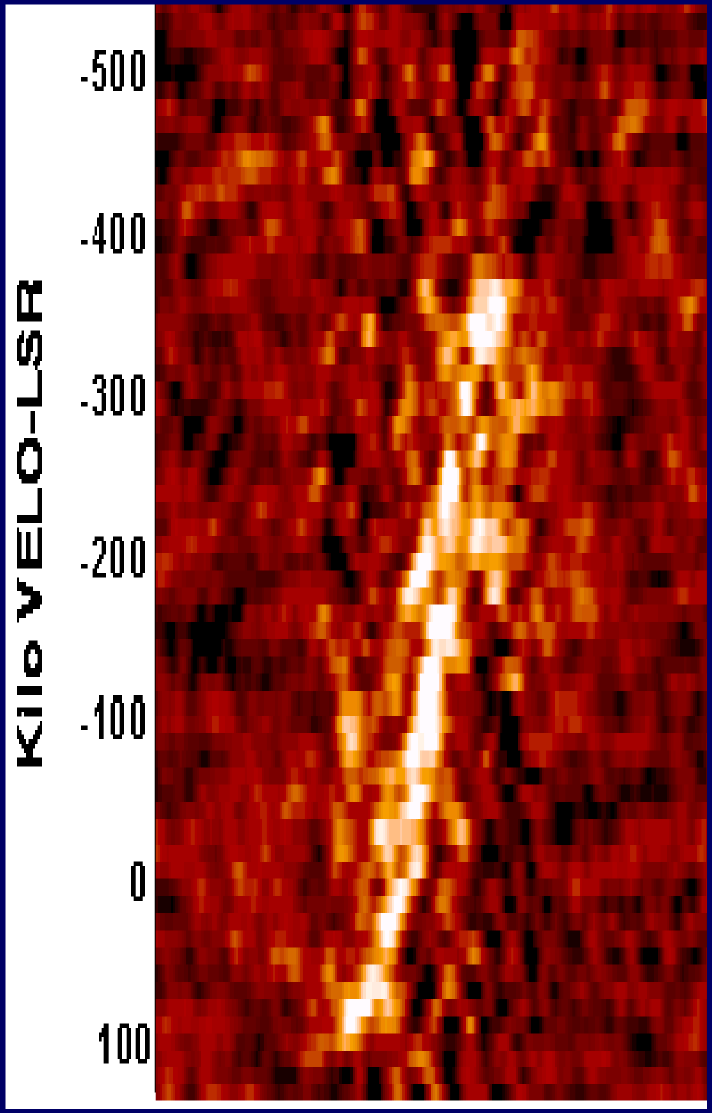


Uniform weighting maps (1-2” resolution)

NGC 4192

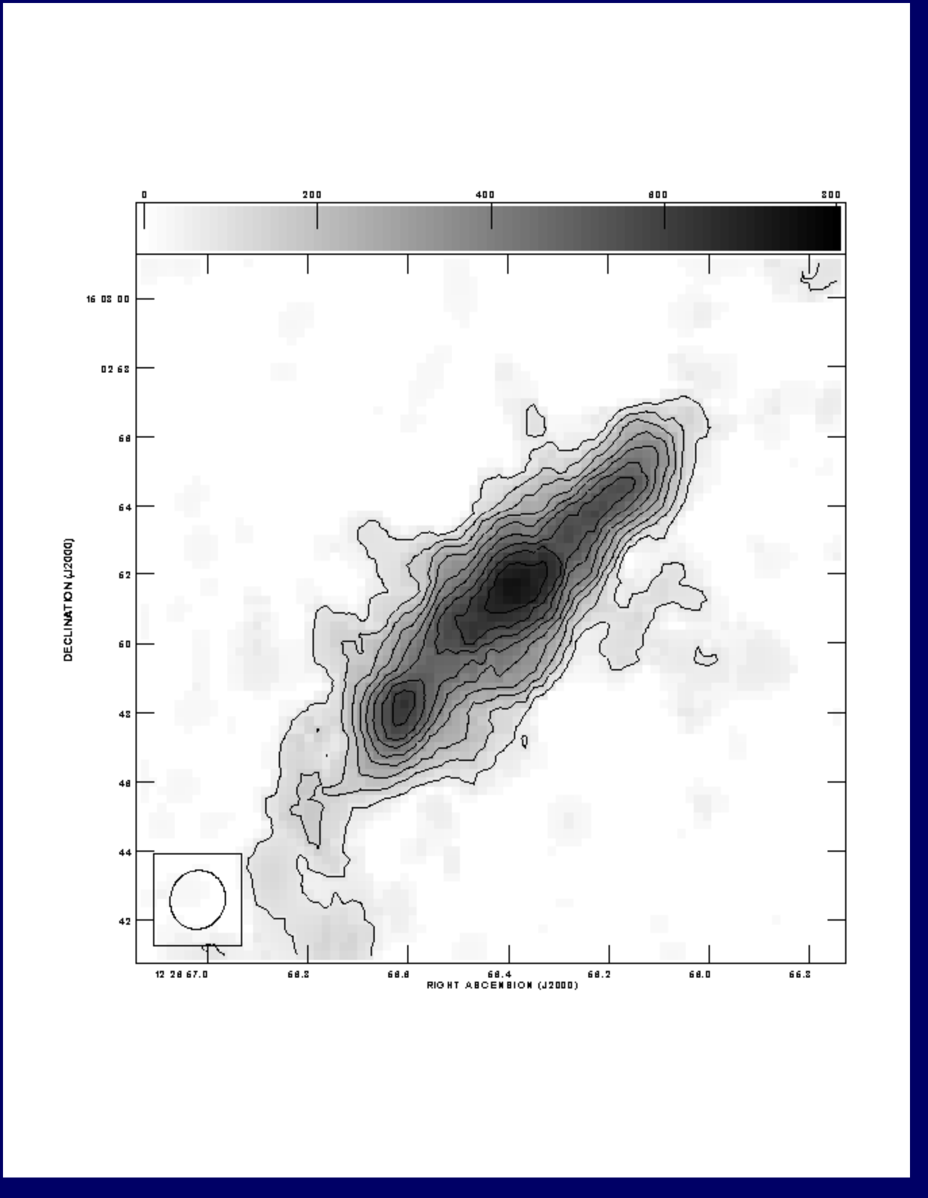


DECLINATION (J2000)
RIGHT ASCENSION (J2000)

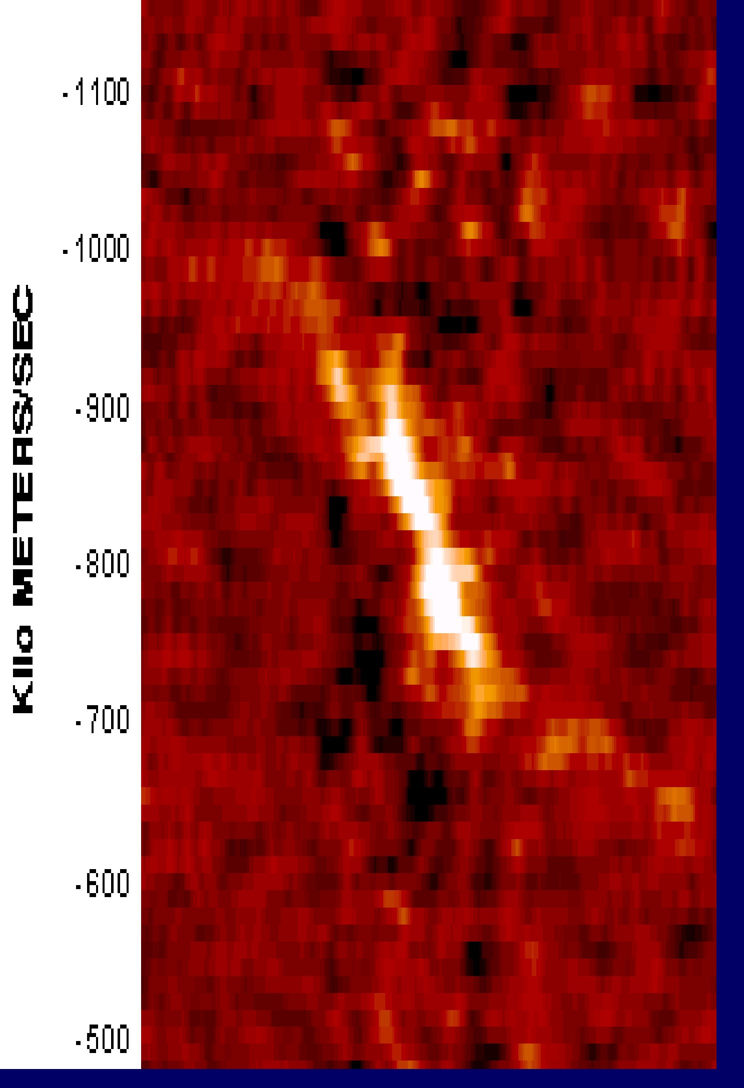


Kilo VELO-LSR
-500
-400
-300
-200
-100
0
100

NGC 4419

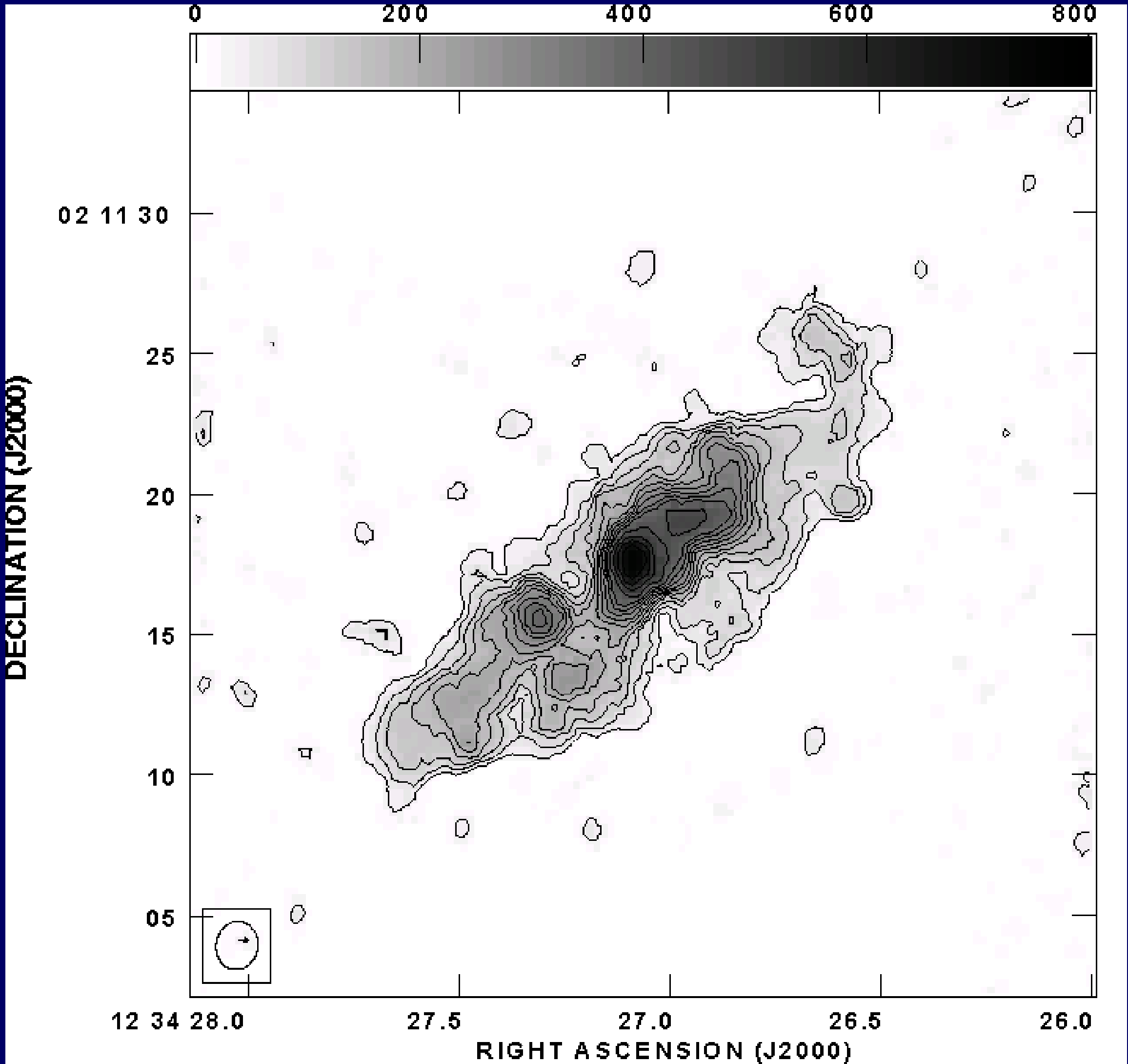


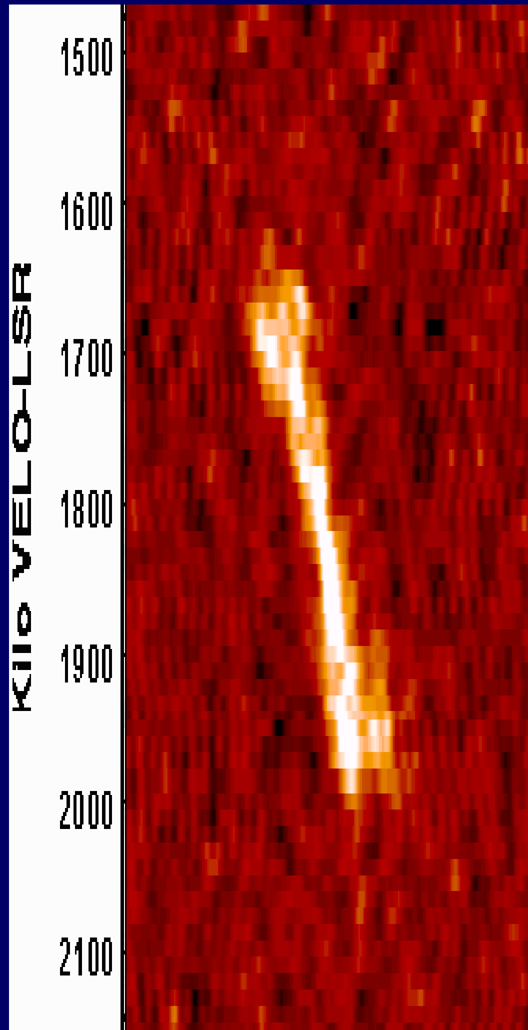
DECLINATION (J2000)
RIGHT ASCENSION (J2000)



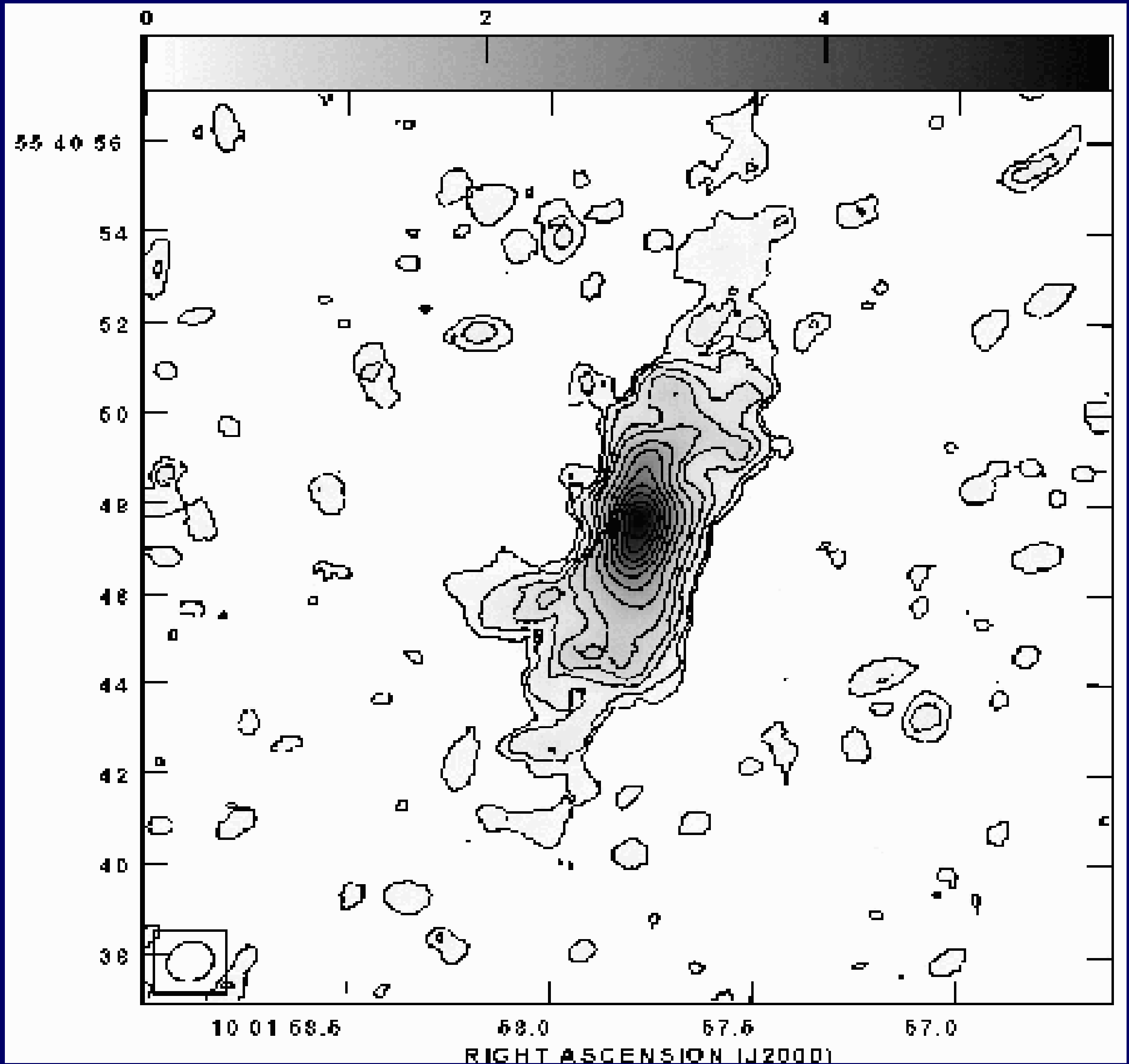
Kilo METERS/SEC
-1100
-1000
-900
-800
-700
-600
-500

NGC 4536

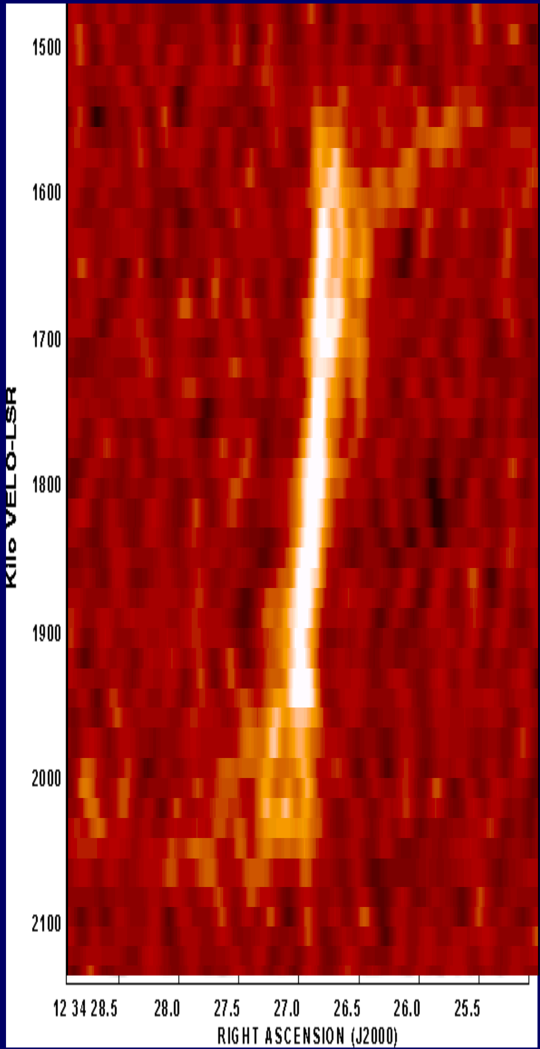

0
200
400
600
800
02 11 30
25
20
15
10
05
DECLINATION (J2000)
12 34 28.0
27.5
27.0
26.5
26.0
RIGHT ASCENSION (J2000)


1500
1600
1700
1800
1900
2000
2100
KILO VELO-LSR

NGC 3079



0
2
4
55 40 56
54
52
50
48
46
44
42
40
38
10 01 58.5
58.0
57.5
57.0
RIGHT ASCENSION (J2000)



1500
1600
1700
1800
1900
2000
2100
Kilo VELO-LSR
12 34 28.5
28.0
27.5
27.0
26.5
26.0
25.5
RIGHT ASCENSION (J2000)

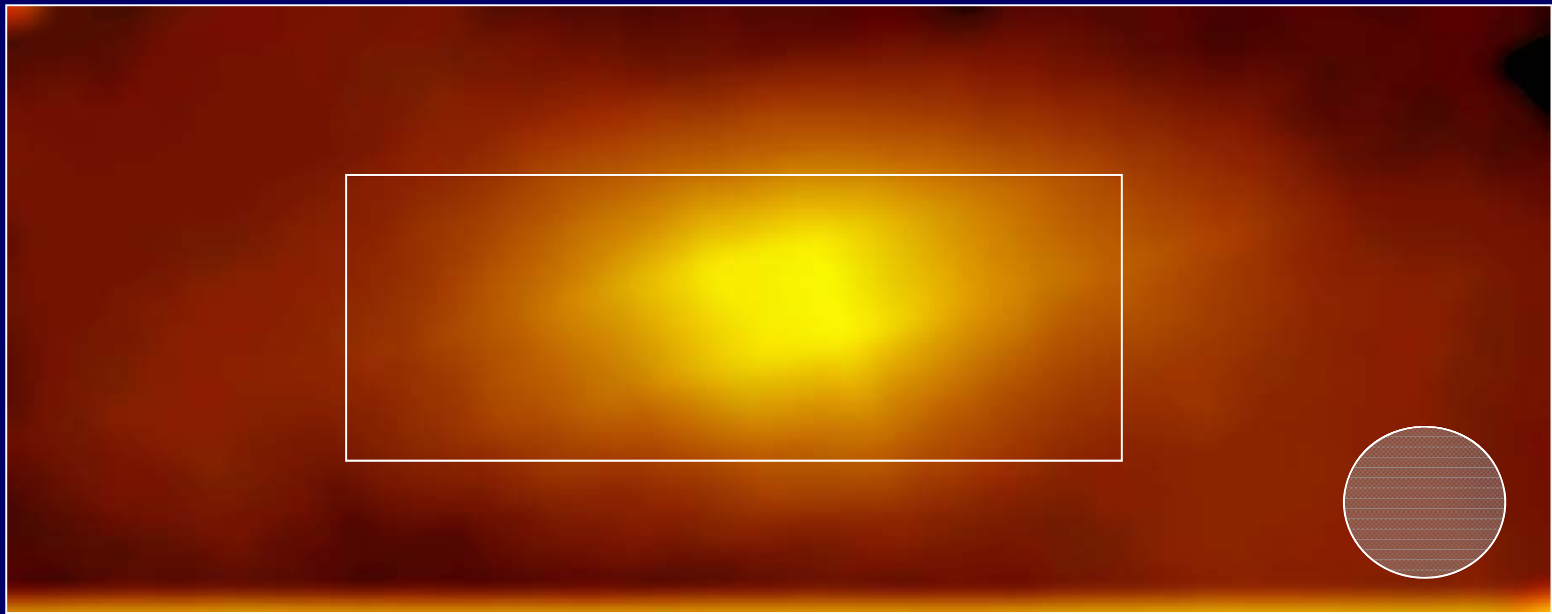
Single peaks are common.

$N_{H2} \sim 10^{22\text{-}23}\ H_2/cm^2$

$\sim 2\times10^3\ M_{sun}/pc^2$

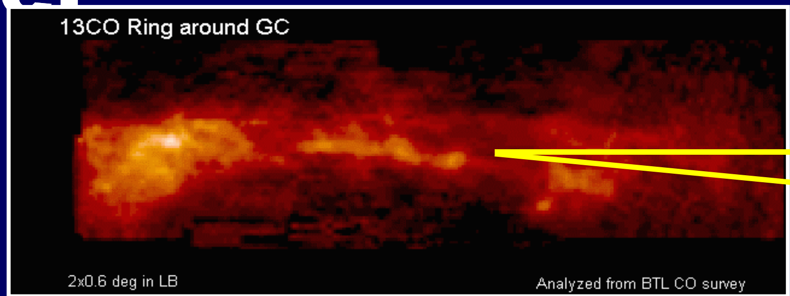
(5 singles against 1 twin)

Molecular core NGC3079



100 pc

MW center



10 pc

If thickness ~10 pc
(like MW center)

n_{H_2} ~ $3x10^3$ H_2 cm^{-3}

Then,

Why stay in gas???

Toomre's Q = Σ_c/Σ

$\Sigma_c = \kappa c/\pi G$

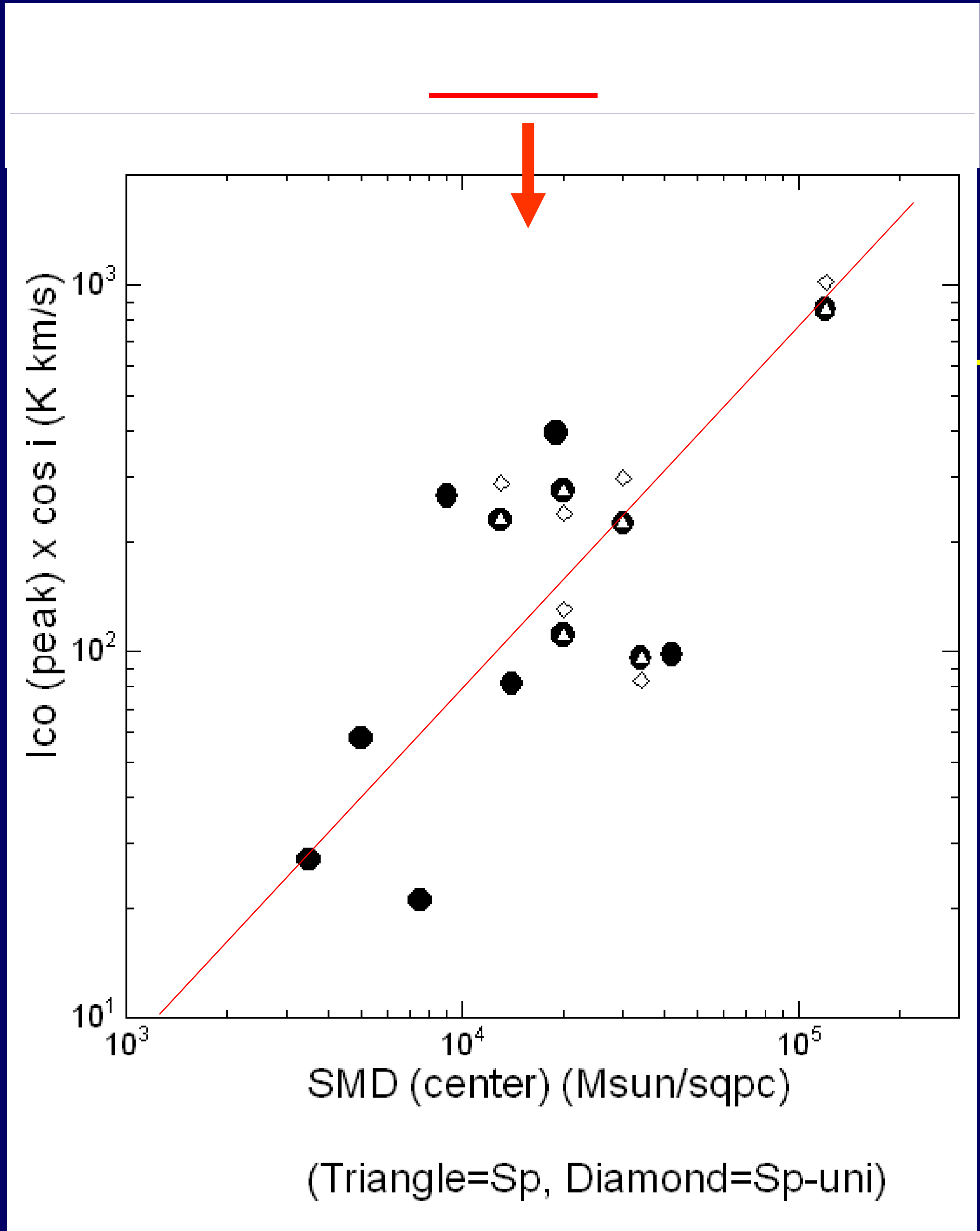
Σ = SMD(gas)

$\kappa \sim O(2\Omega) \sim (0.5\ \mathrm{My})^{-1}$

$c \sim 30$ km/s

$\Sigma_c = 5 \times 10^3\ (V_{200} c_{30} / R_{100})\ M_{sun}\ pc^{-2}$

(Koda et al. 2005)



1000 $M_{sun}pc^{-2}$

100 $M_{sun}pc^{-2}$

$Q > 1$

or

$Q \gg 1$

(Jeans time >> 1/κ)

Gas is stable against gravitational contraction/SF.

Single-peak galaxy centers have

1. Deep potential
   (High SMD, high rotation)

2. High-density molecular core
   (High gas SMD)

3. Gas stable ($Q \gg 1$, $t_J > 1/\kappa$)

“Twin”

↓

“Single peak”

= Stable dense molecular core

Enough time for growth

↓

Burst, activity, ….exhaust gas,…. And cycle

Conclusion

1. Rotation curves & Mass structures are common (universal).

2. Dynamical mass much (~100x gas) dominates in <100 pc.

3. Nuclear gas is stable to produce/maintain dense gas core.

Future work:

1. **Logarithmic Rotation Curves**
   & mass/stability analyses as above,
   100→10→1→0.1 pc

2. **ALMA CO Virgo**
   (Nearest cluster
   with acc. distance)