Virgo CO Survey of Molecular Nuclei

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@ALMA WS Nearby Galaxies, NAOJ 2011 Feb. 10

GAMMA Project with ALMA

Virgo Galaxy MAss MApping

―銀河Dynamics空白地帯を埋める―


技術、サイエンス
12/1/2000

ALMA時代の銀河研究

1. 日米欧：敵情を知れ。

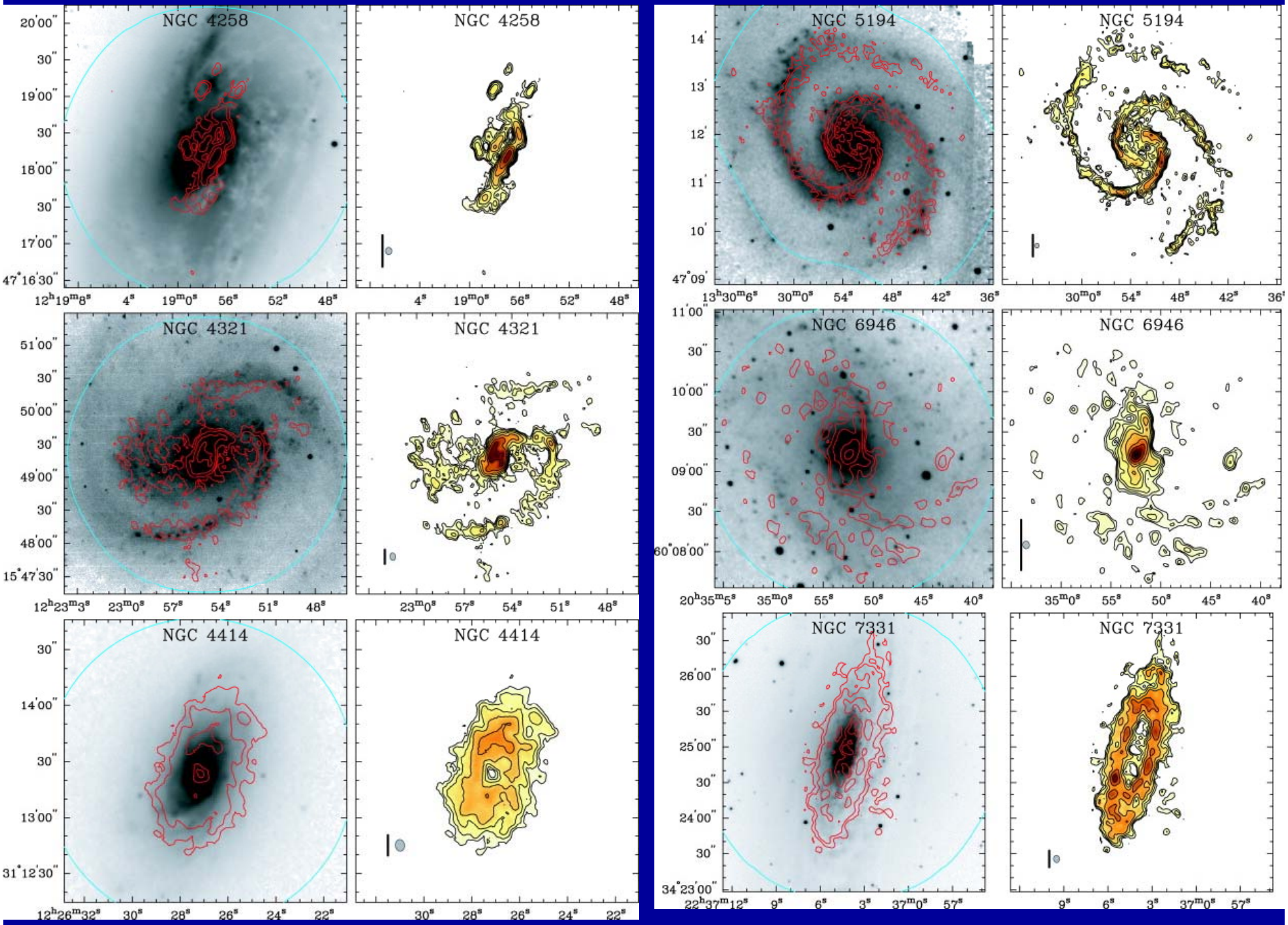
2. ALMAは干渉計である。
(本質的にマッピングマシンである。)

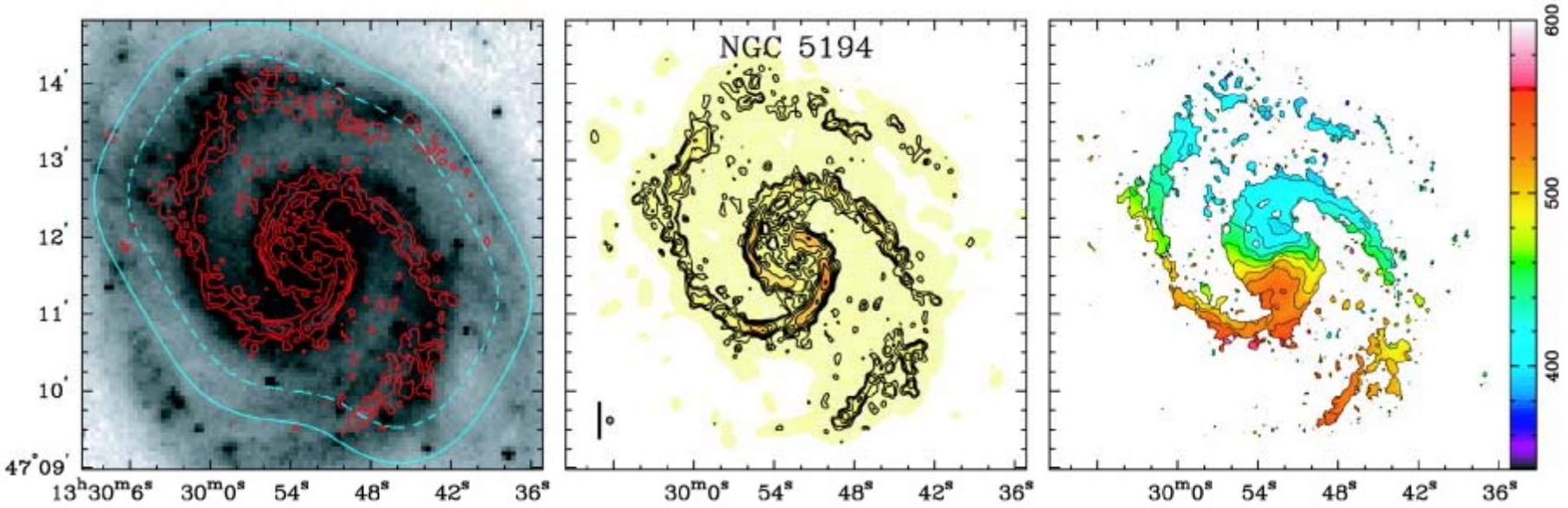
3. NMAでの研究を基盤、正面突破

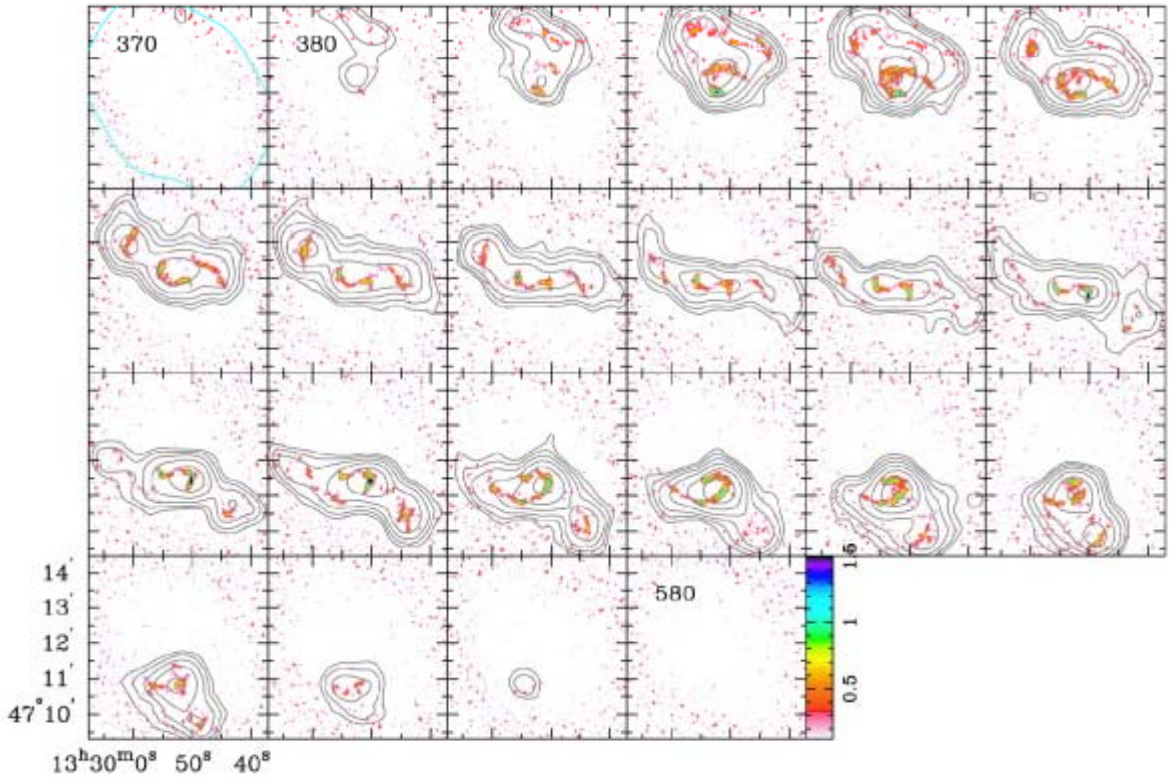
- **BIMA SONG**
- **(BERKELEY ILLINOIS MARYLAND ASSOCIATION**
- **CO Survey of Nearby Galaxies)**

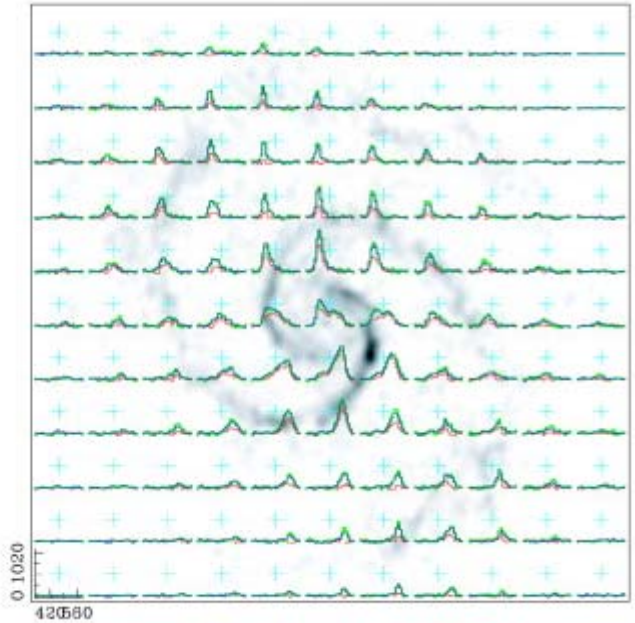
- **OVRO /CARMA**
- **(Owens Valley Radio Observatory)**

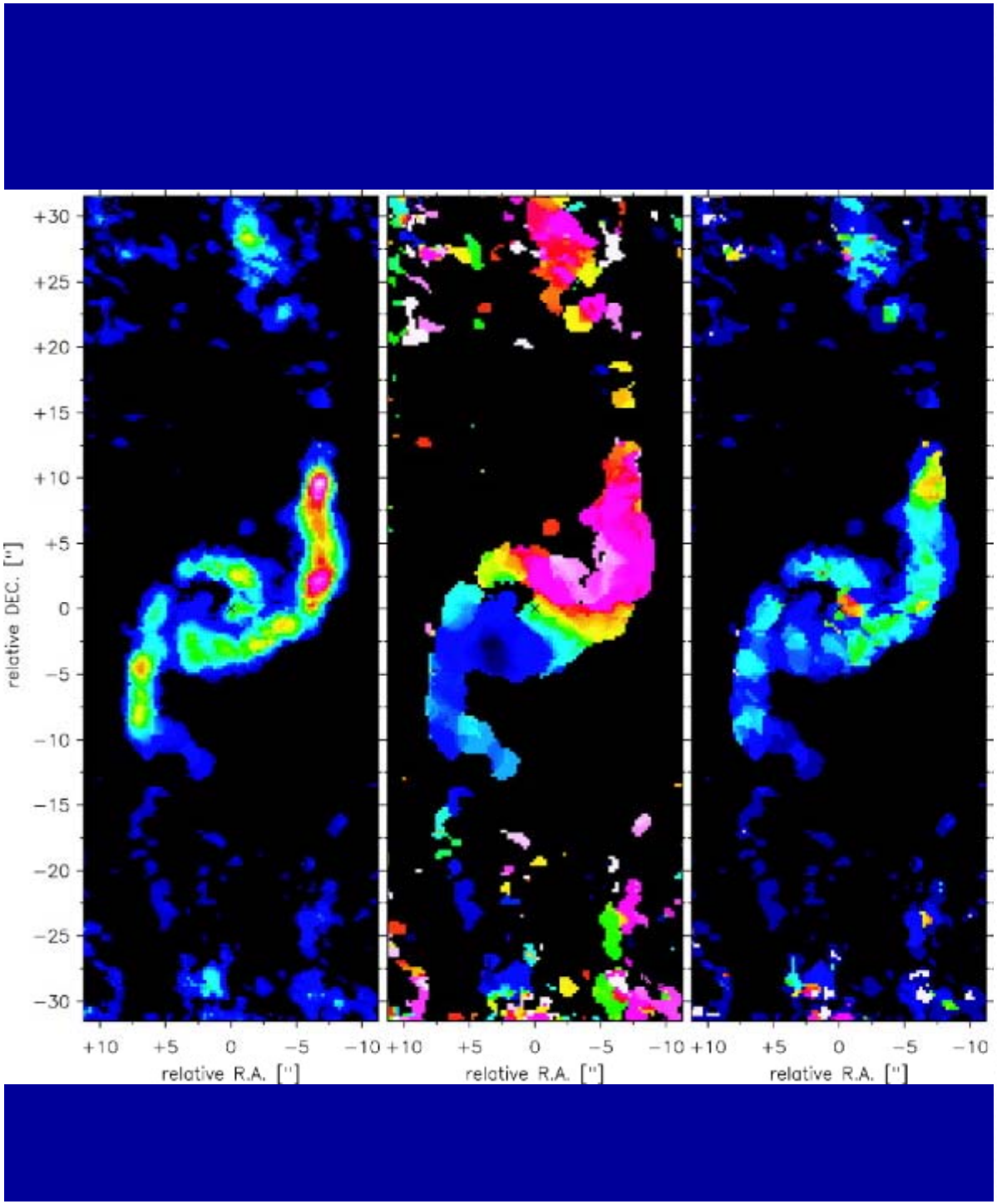
IRAM
Plateau de Bure Interferometer

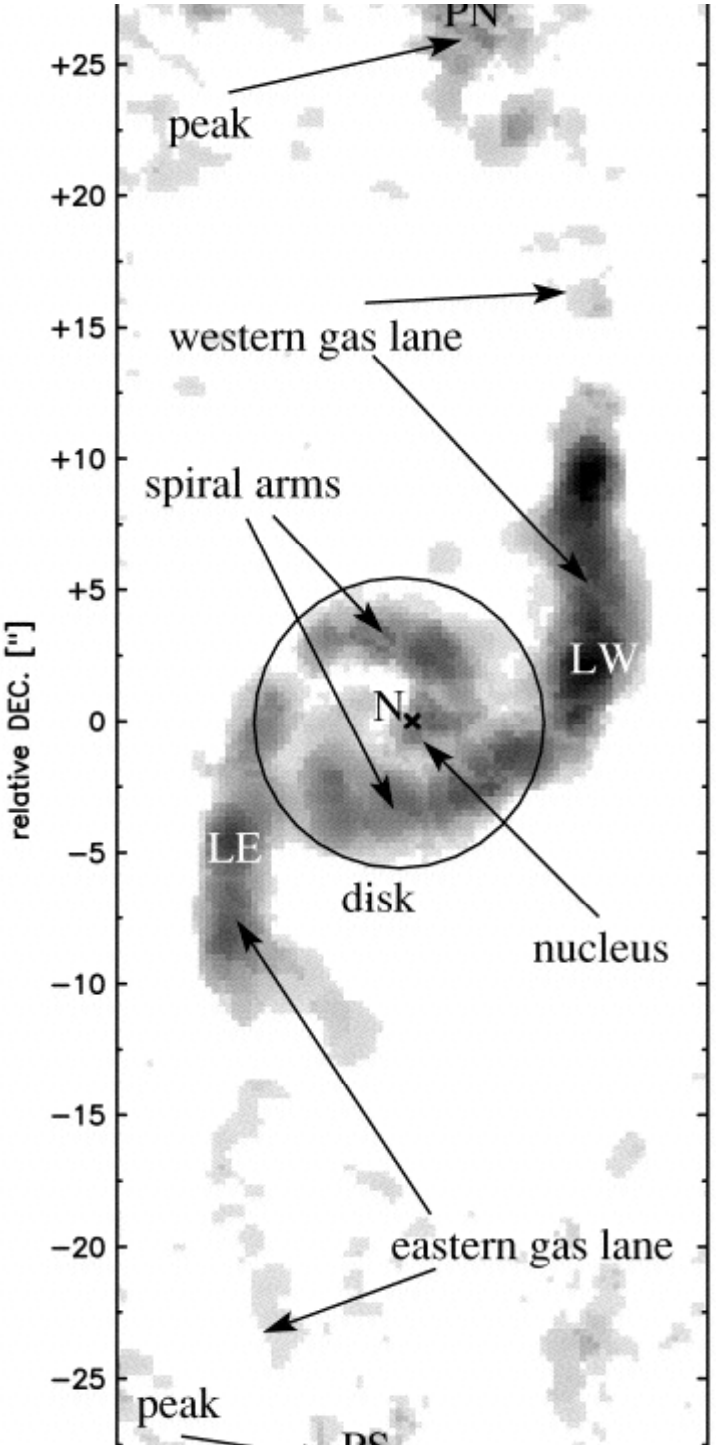

NGC 4258
NGC 4258
NGC 5194
NGC 5194
NGC 4321
NGC 4321
NGC 6946
NGC 6946
NGC 4414
NGC 4414
NGC 7331
NGC 7331


NGC 5194
14'
13'
12'
11'
10'
47°09'
13h30m6s
30m0s
54s
48s
42s
36s
600
500
400


370
380
580
14'
13'
12'
11'
47°10'
13h30m0s
50s
40s
1.5
1
0.5


0 1020
420560


+30
+25
+20
+15
+10
+5
0
−5
−10
−15
−20
−25
−30
relative DEC. ["]
+10
+5
0
−5
−10
relative R.A. ["]


PN
peak
+25
+20
+15
+10
+5
0
−5
−10
−15
−20
−25
relative DEC. ["]
western gas lane
spiral arms
LW
N
LE
disk
nucleus
eastern gas lane
peak

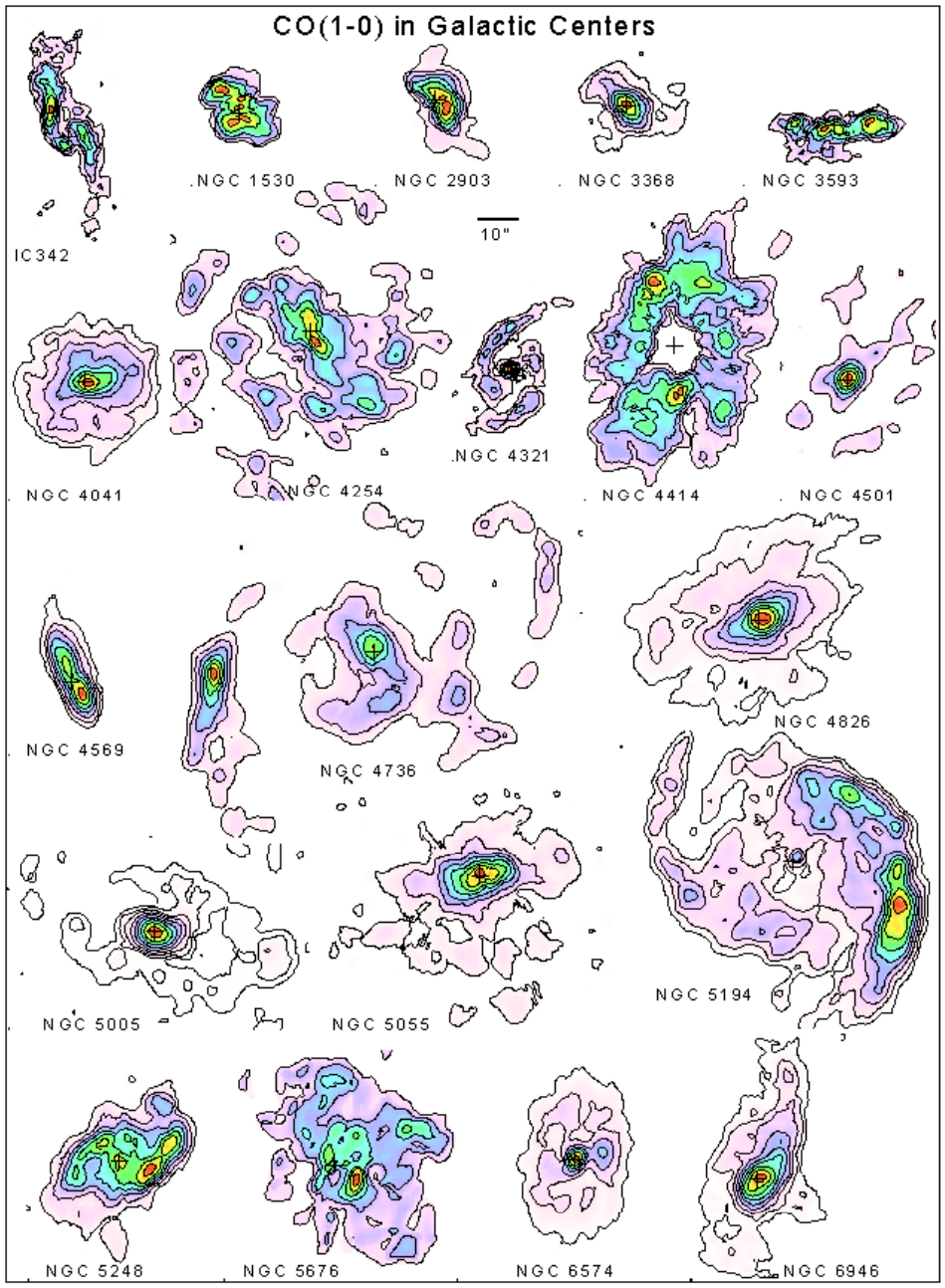
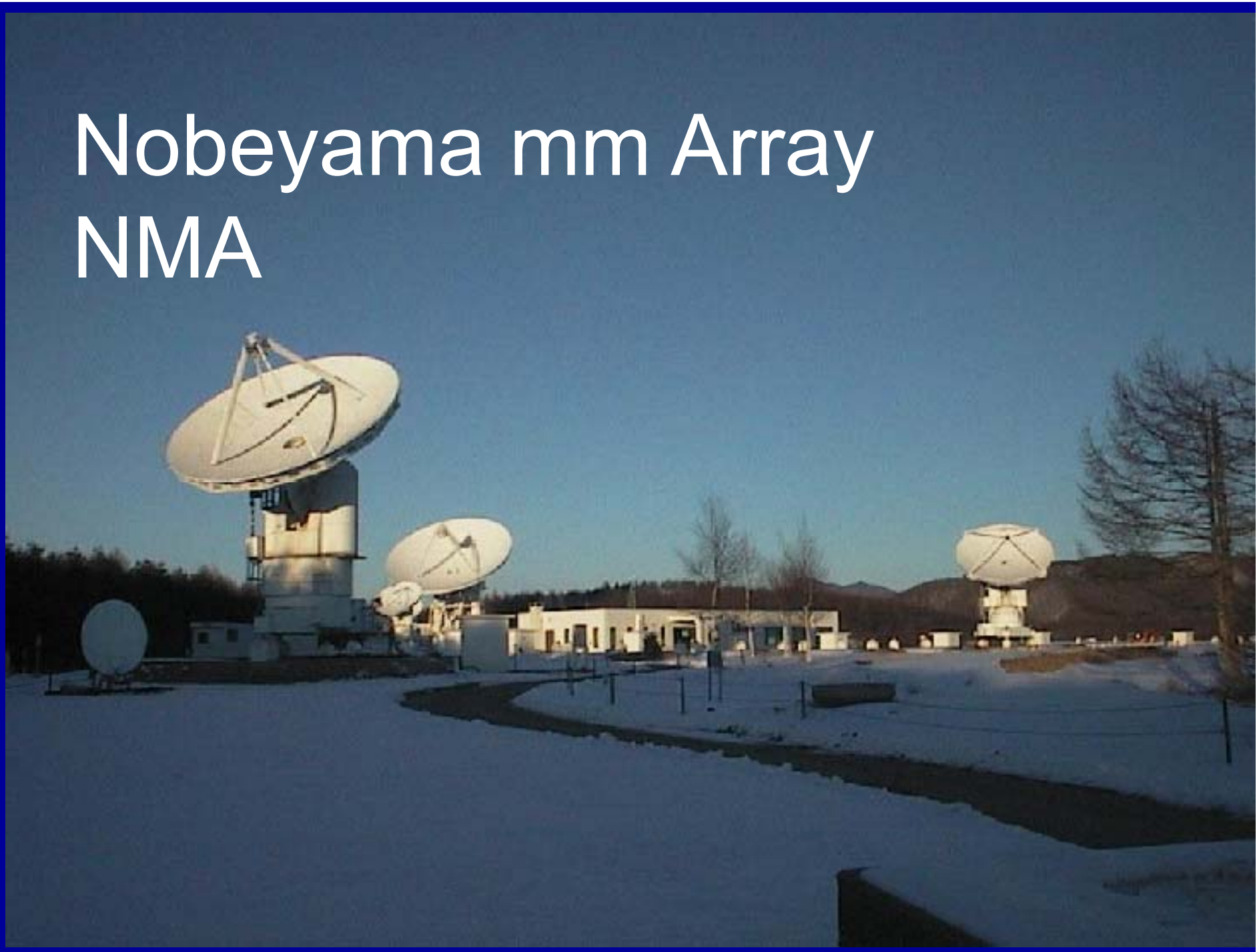
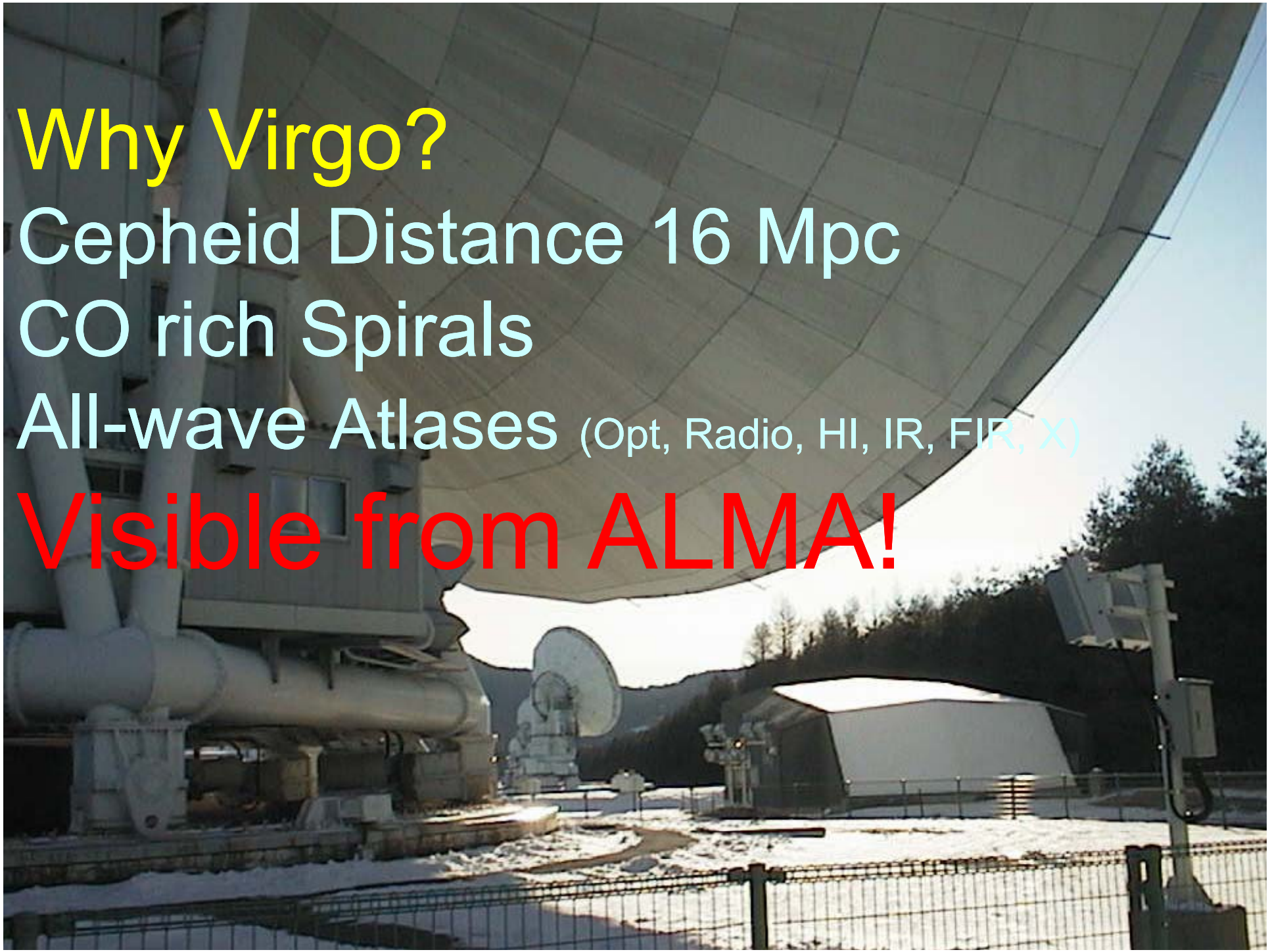


Fig. 1.— CO(J=1–0) in the central regions of 20 spiral galaxies. Maps are shown with the same scale on the sky, with crosses of 300 pc width at the adopted galactic centers. No correction for the primary-beam pattern has been applied except for NGC 4736, which is a mosaic of three fields. Gamma correction, in which normalized intensity

Nobeyama mm Array
NMA

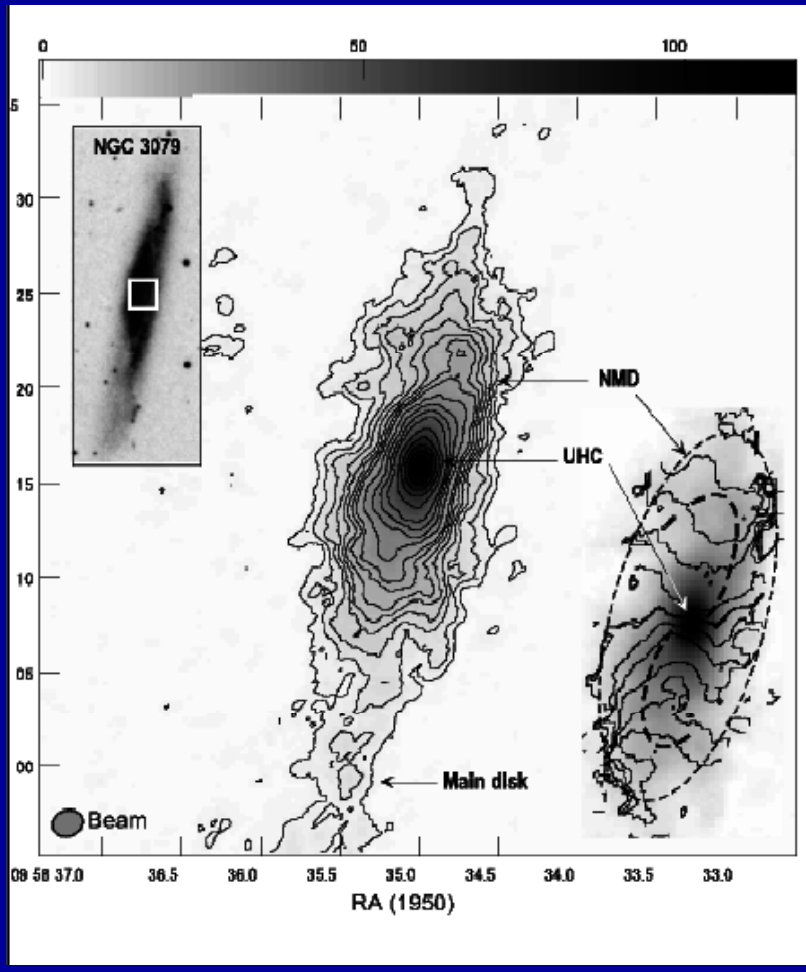



Why Virgo?
Cepheid Distance 16 Mpc
CO rich Spirals
All-wave Atlases (Opt, Radio, HI, IR, FIR, X)
Visible from ALMA!

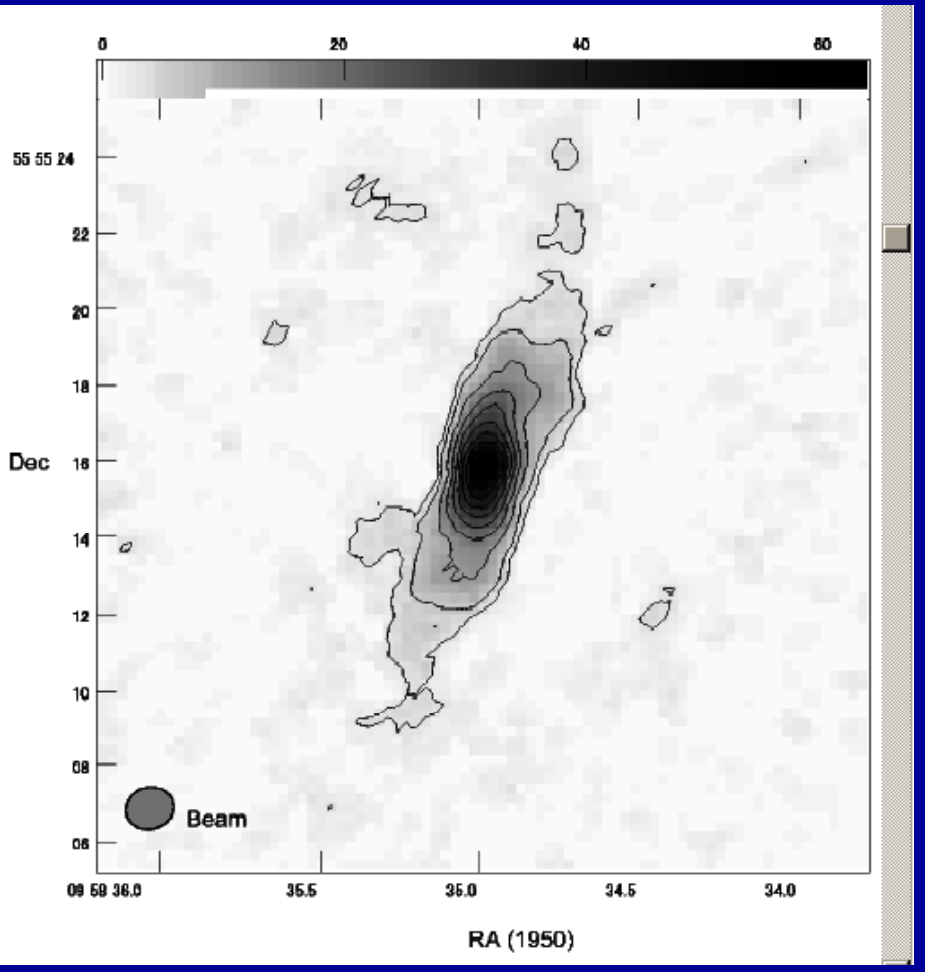
1. Nuclear Dynamics & Massive cores

NGC 3079 RAINBOW

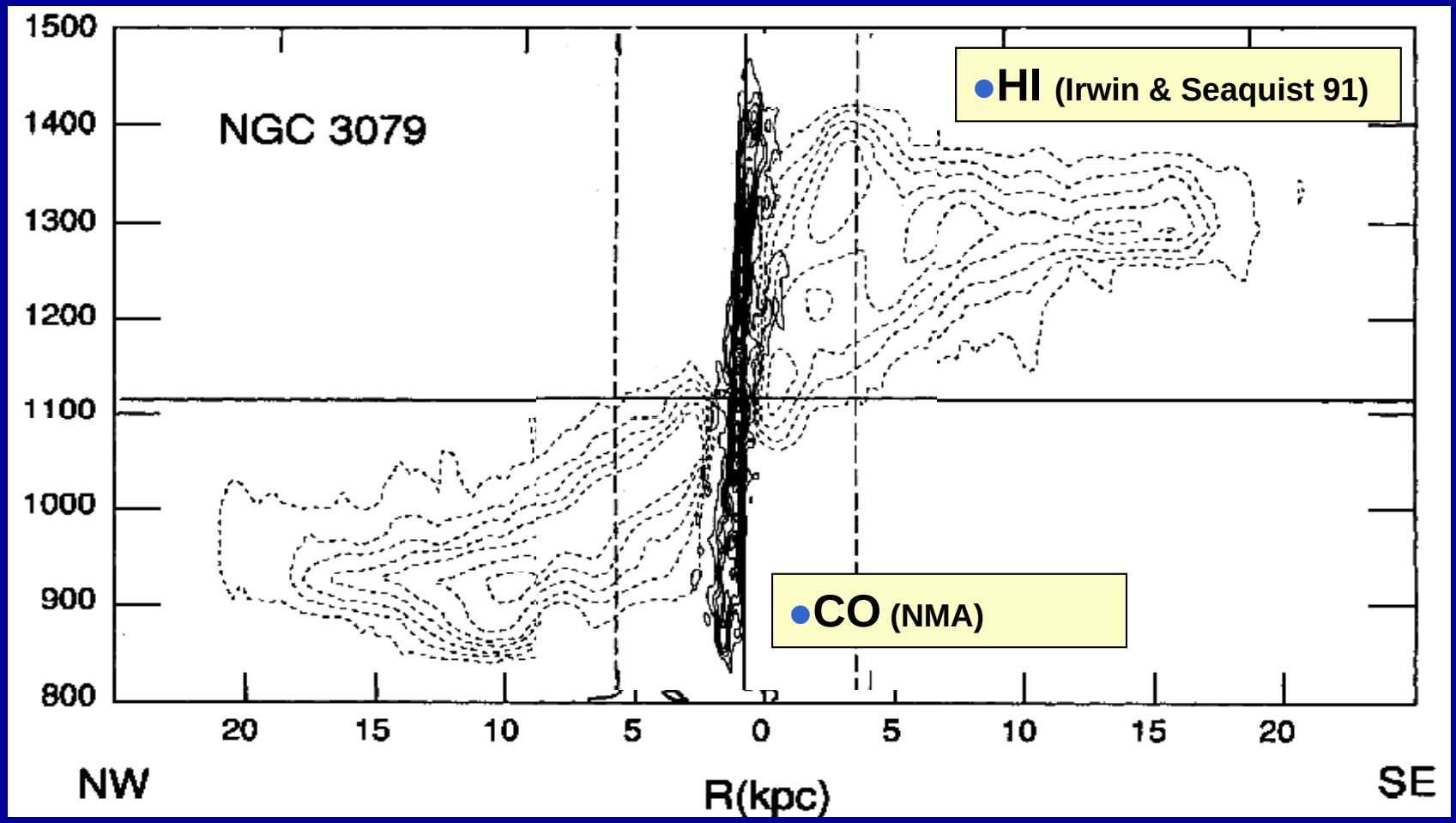
RB+C+D



RB

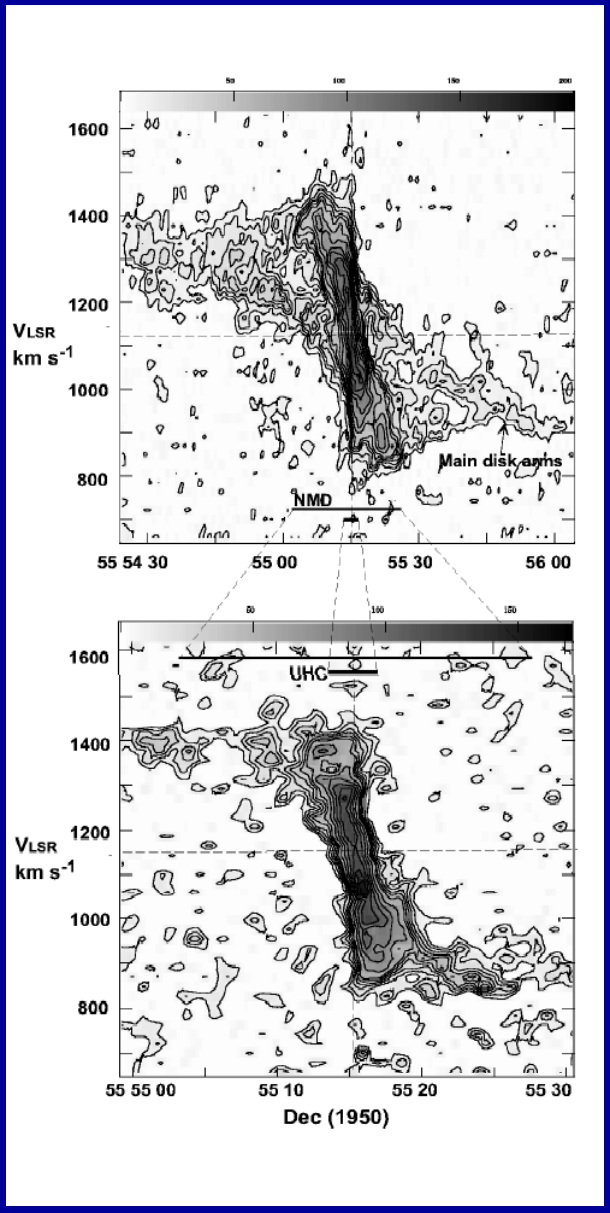


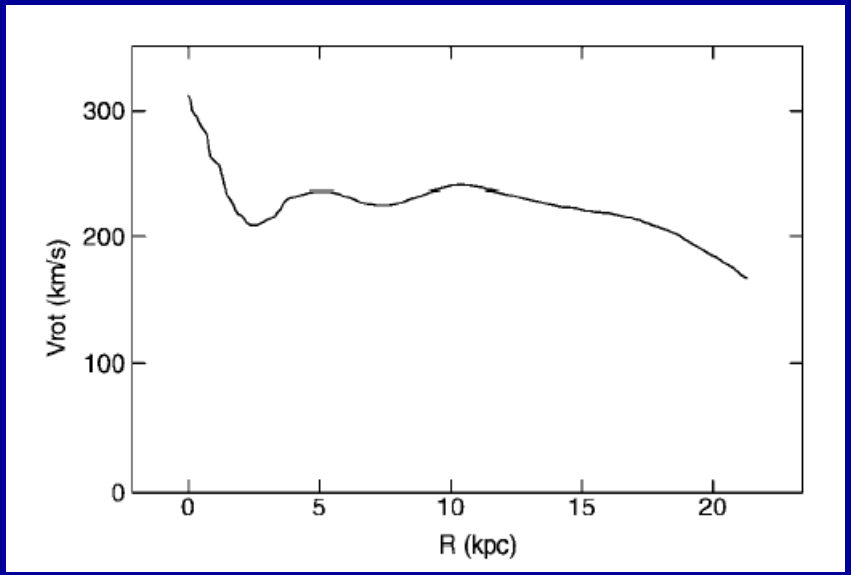
NGC 3079 P-V Diagram: HI vs CO

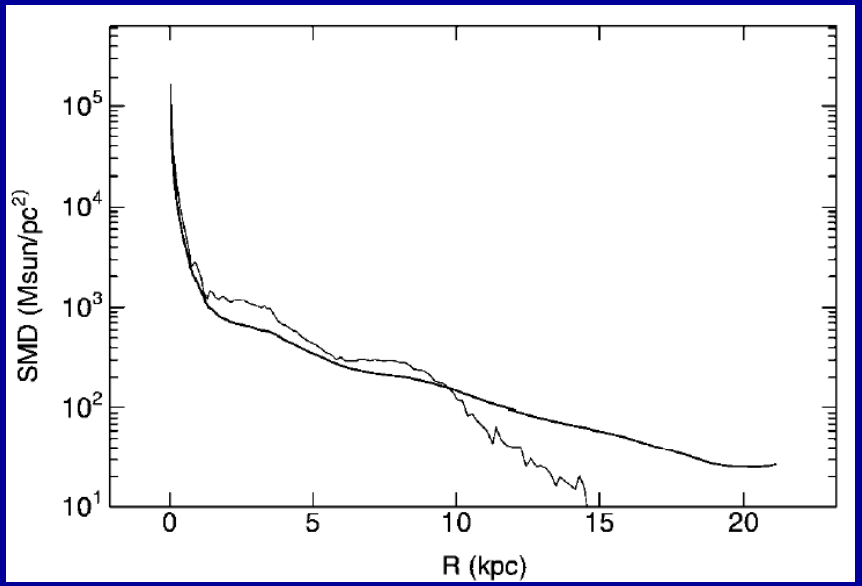


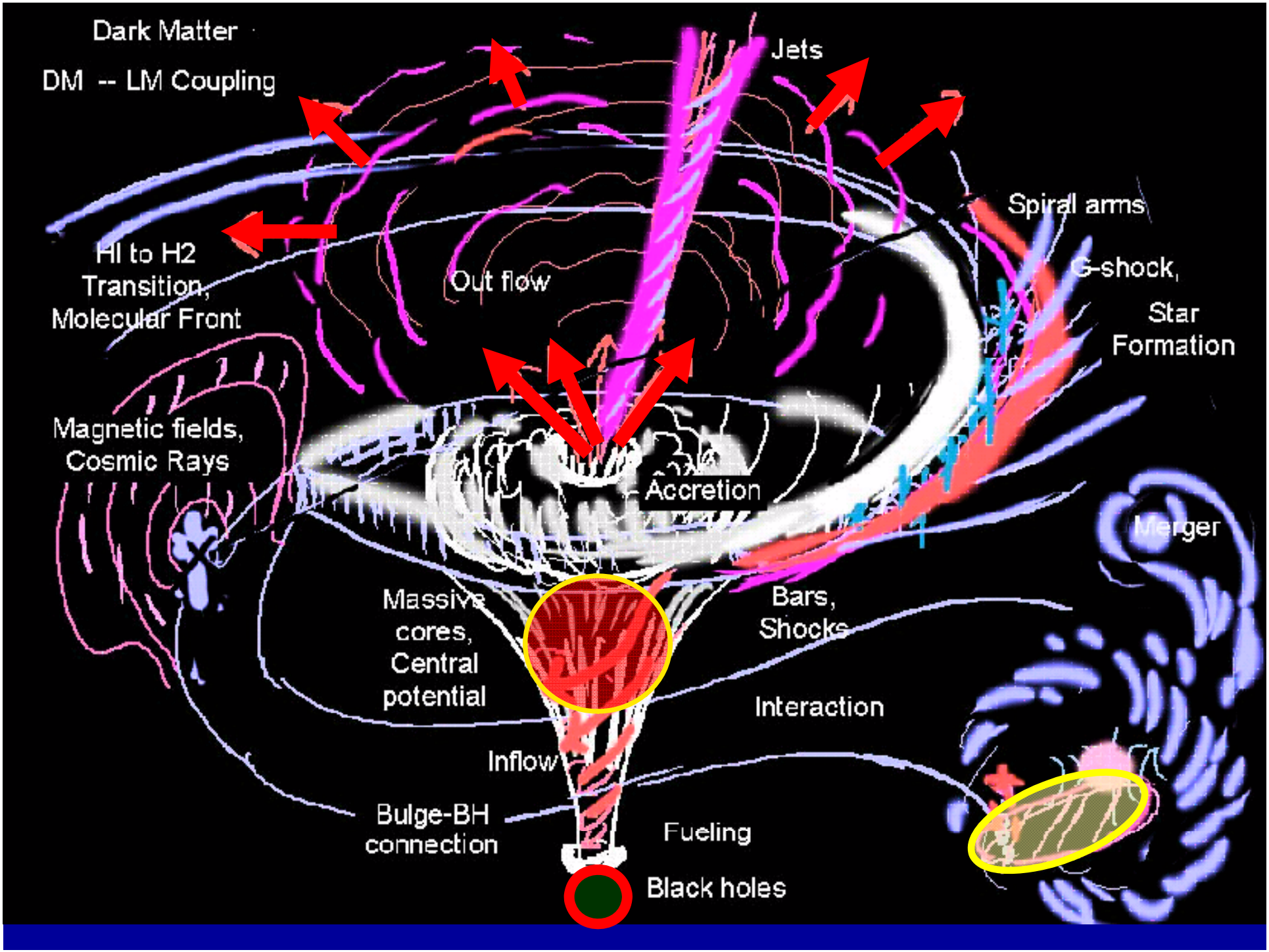
NGC 3079

CO PVD → RC → Mass Distribution

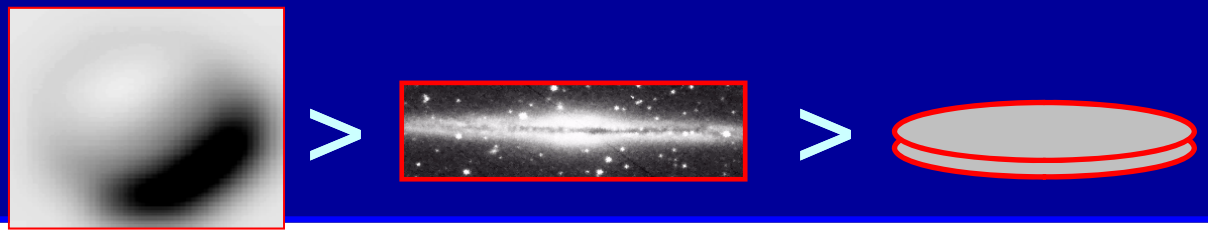







Dark Matter
DM -- LM Coupling
Jets
Spiral arms
HI to H2
Transition,
Molecular Front
Out flow
G-shock,
Star
Formation
Magnetic fields,
Cosmic Rays
Accretion
Merger
Massive
cores,
Central
potential
Bars,
Shocks
Interaction
Inflow
Bulge-BH
connection
Fueling
Black holes

質量分布一直接導出



(a) Spherical Mass Distribution:

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

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

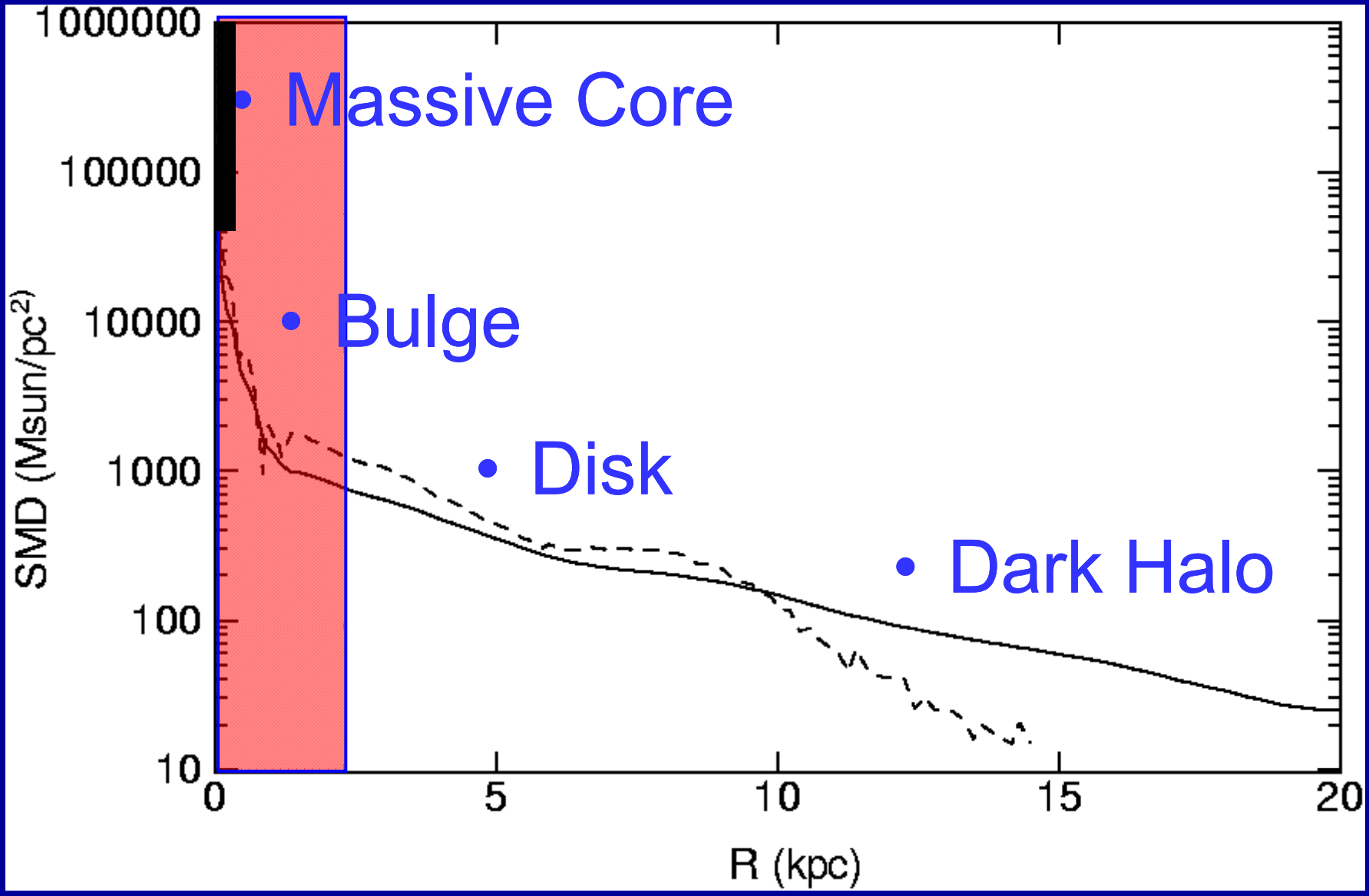
$$\sigma(R)_s = 2\int_0^\infty \rho(r)dz = \frac{1}{2\pi}\int_R^\infty \frac{\left(\frac{dM(r)}{dr}\right)_x}{x\sqrt{x^2-R^2}}dx,$$

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

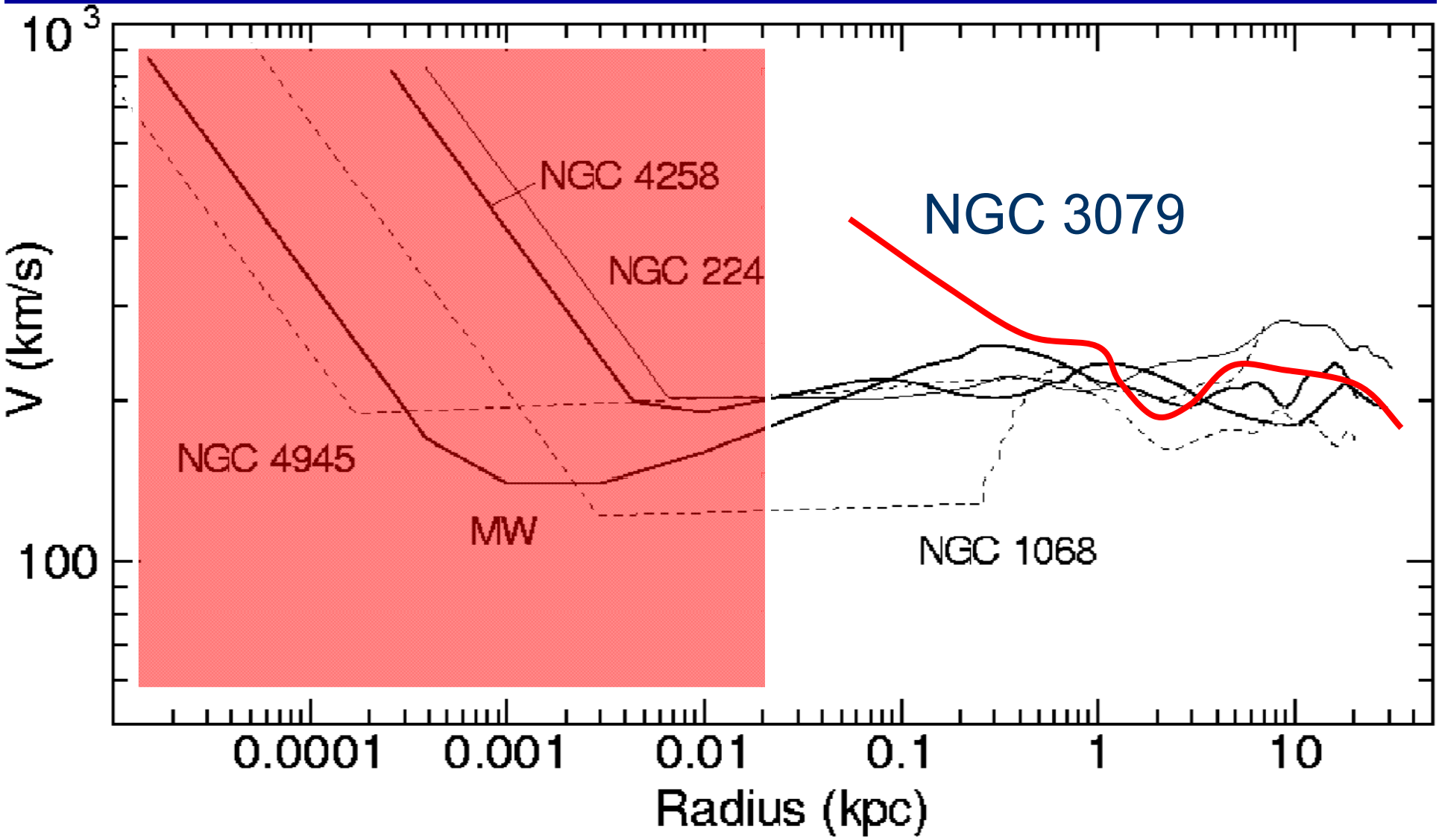
$$\sigma(R)_f = \frac{1}{\pi^2 G}\left[\frac{1}{R}\int_0^R \left(\frac{dV^2}{dr}\right)_x K\left(\frac{x}{R}\right)dx + \int_R^\infty \left(\frac{dV^2}{dr}\right)_x K\left(\frac{R}{x}\right)\frac{dx}{x}\right],$$

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

Surf. Mass Density



Black hole connection



2. “Single peak”

vs

“Twin peaks”

Nuclear ISM Physics

NGC4254

SA(s)c

R.A. 12h16m17.6s

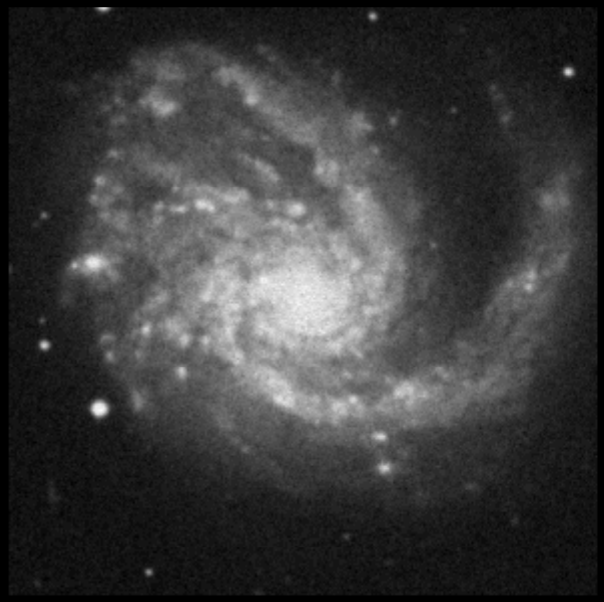
Dec. +14d24m59s

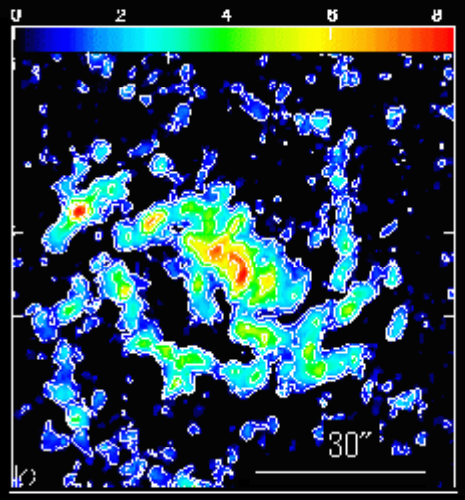
incl. 42 deg.

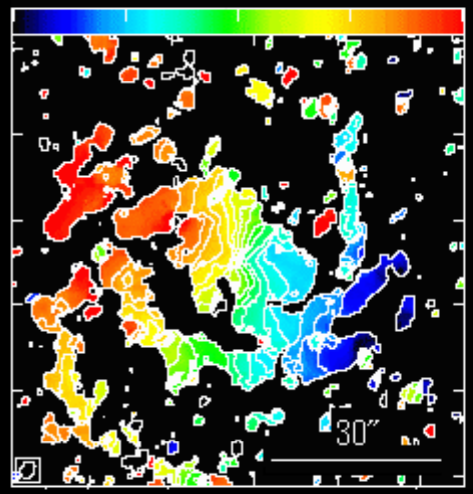
P.A. 68 deg.

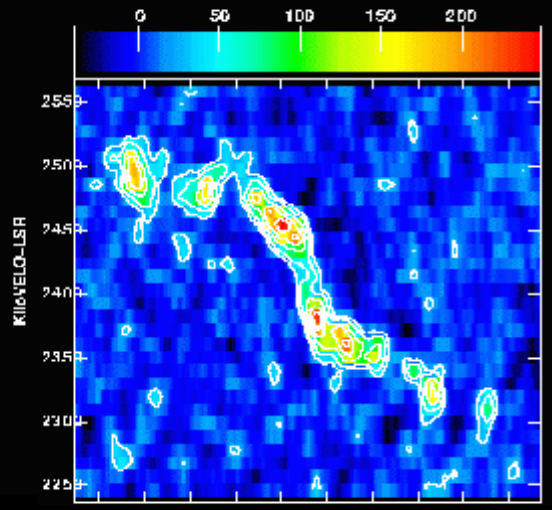
beam size 2.99 × 2.34 asec

rms 16 mJy/Beam









NGC4303

SAB(rs)bc;HII Sy2

R.A. 12h19m21.6s

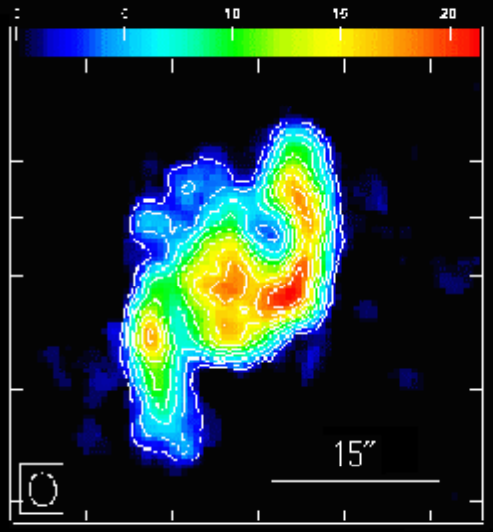
Dec. +04d45m03s

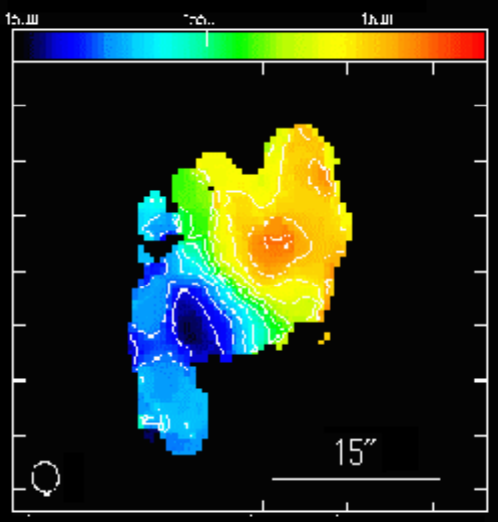
incl. 25 deg.

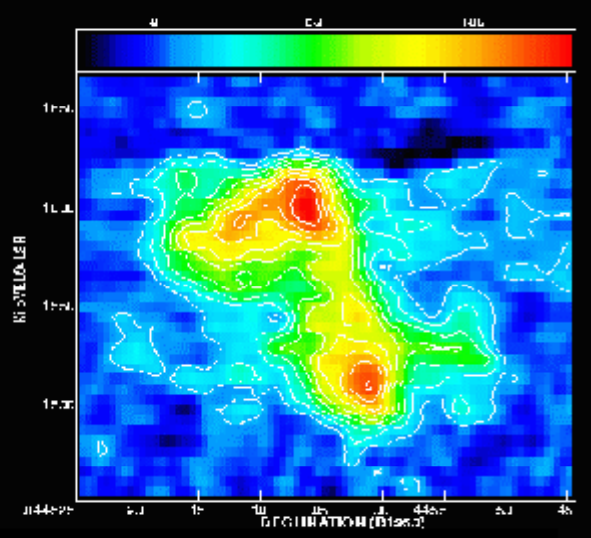
P.A. 0 deg.

beam size 2.9 x 2.3 asec

rms 23 mJy/Beam







NGC4419

SAB(rs)bc HII

R.A. 12h24m24.7s

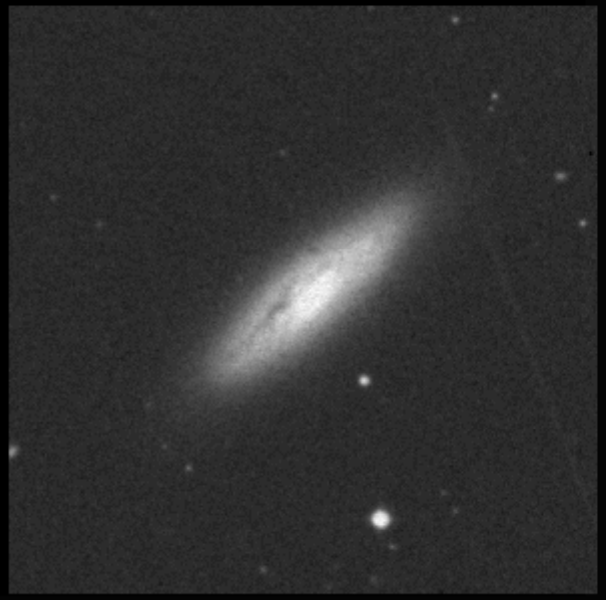
Dec. +15d19m27s

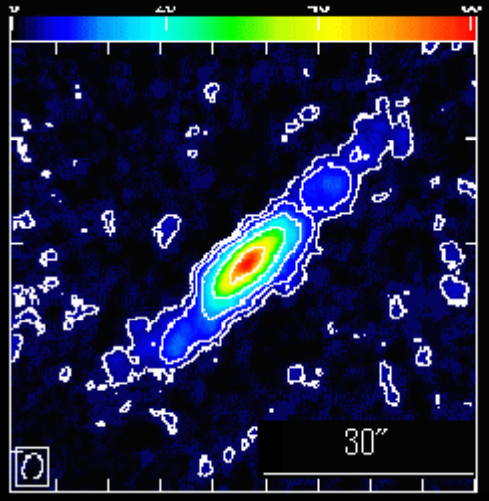
incl. 67 deg.

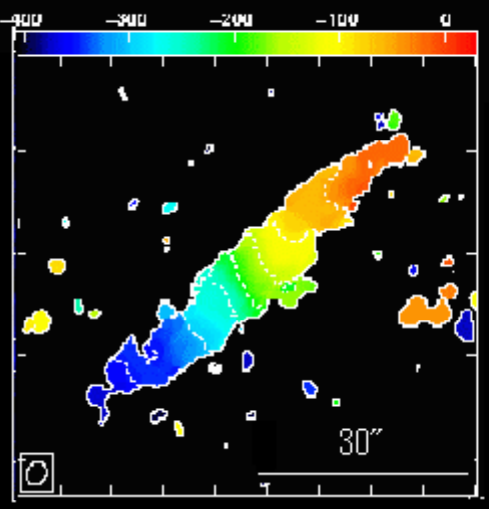
P.A. 133 deg.

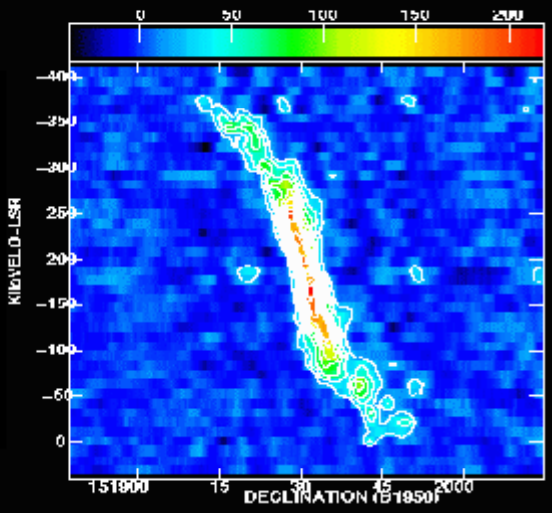
beam size 4.5 × 3.1 asec

rms 23 mJy/Beam









NGC4501

SAB(rs)bc HII

R.A. 12h29m27.7s

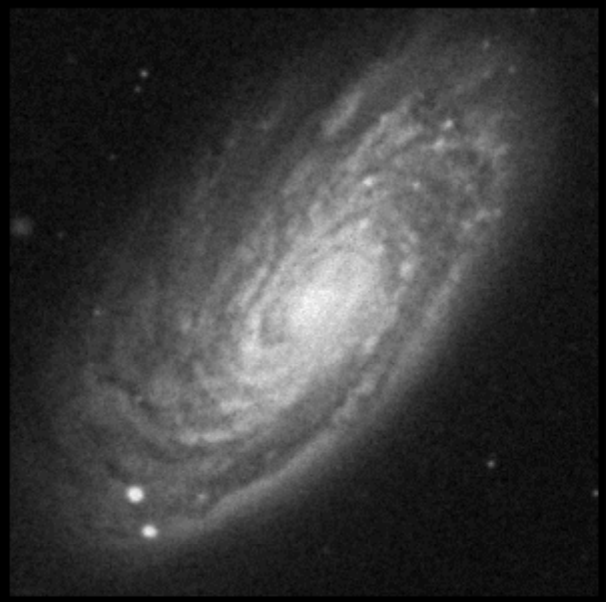
Dec. +14d41m46s

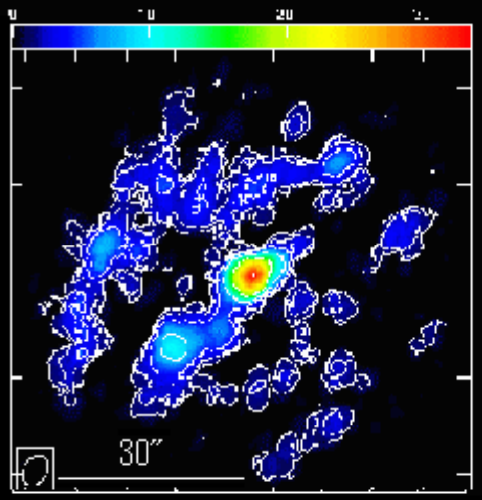
incl. 58 deg.

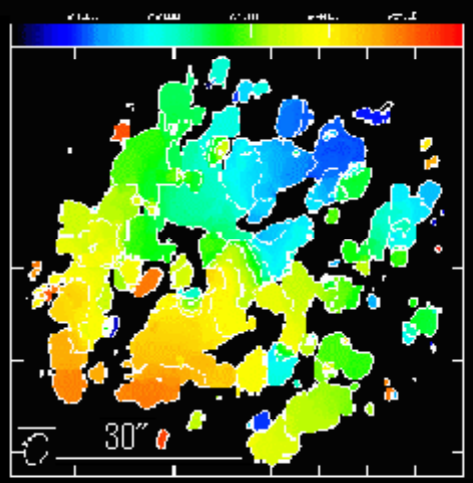
P.A. 140 deg.

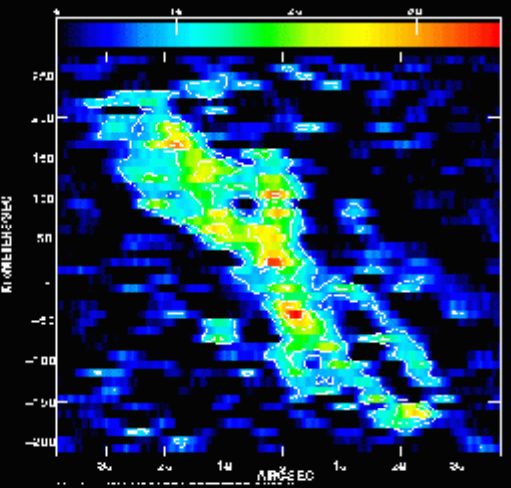
beam size 4.9 × 3.3 asec

rms 18 mJy/Beam









NGC4535

SAB(s)c

R.A. 12h31m47.9s

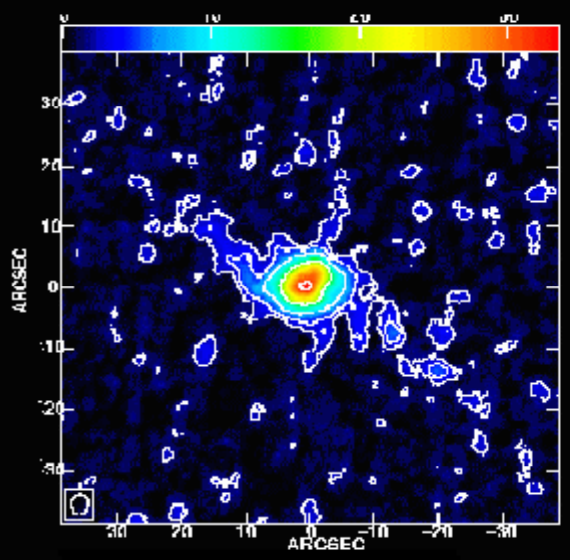
Dec. +08d28m24s

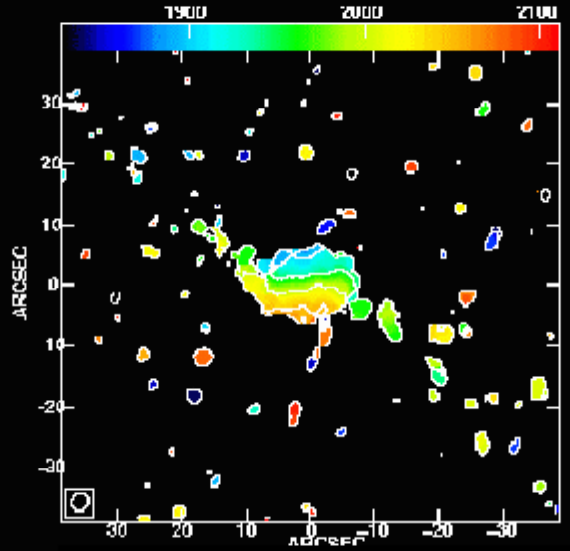
incl. 43 deg.

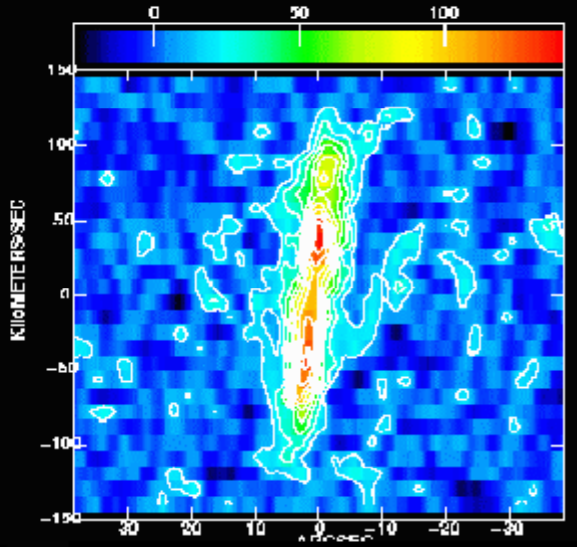
P.A. 0 deg.

beam size 3.1 × 2.6 asec

rms 21 mJy/Beam







NGC4536

SAB(rs)bc HII

R.A. 12h31m53.7s

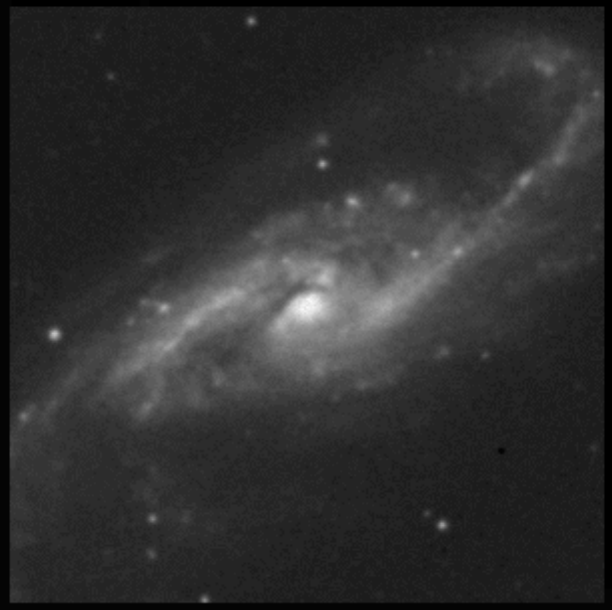
Dec. +02d27m50s

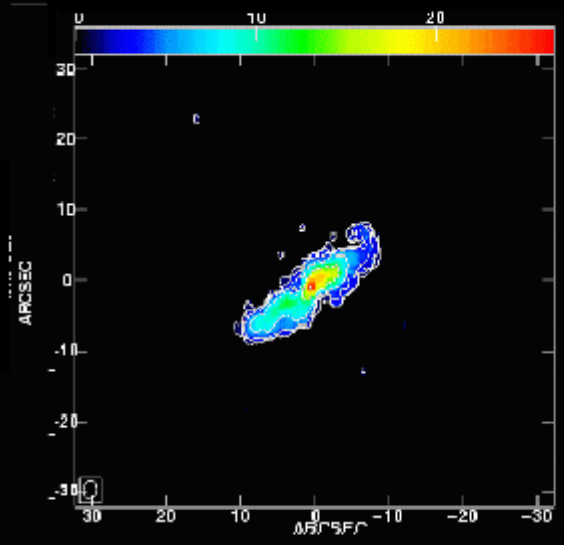
incl. 67 deg.

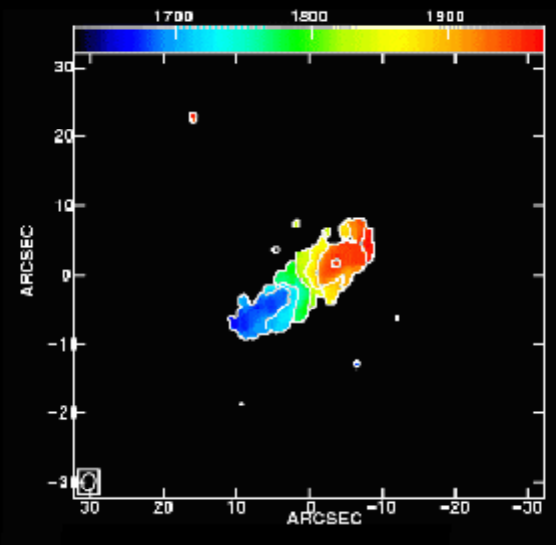
P.A. 116 deg.

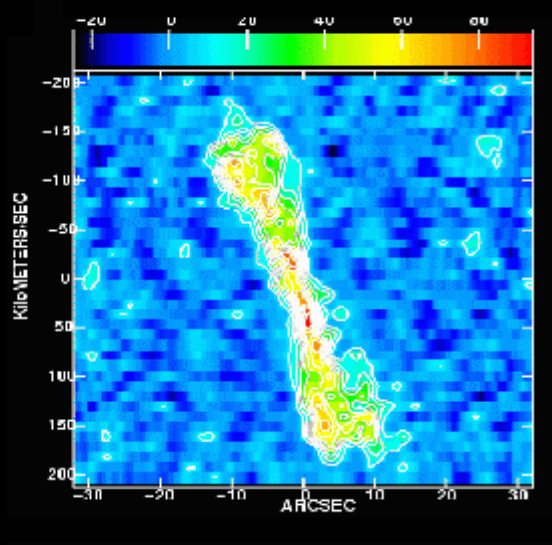
beam size 2.5 × 1.8 asec

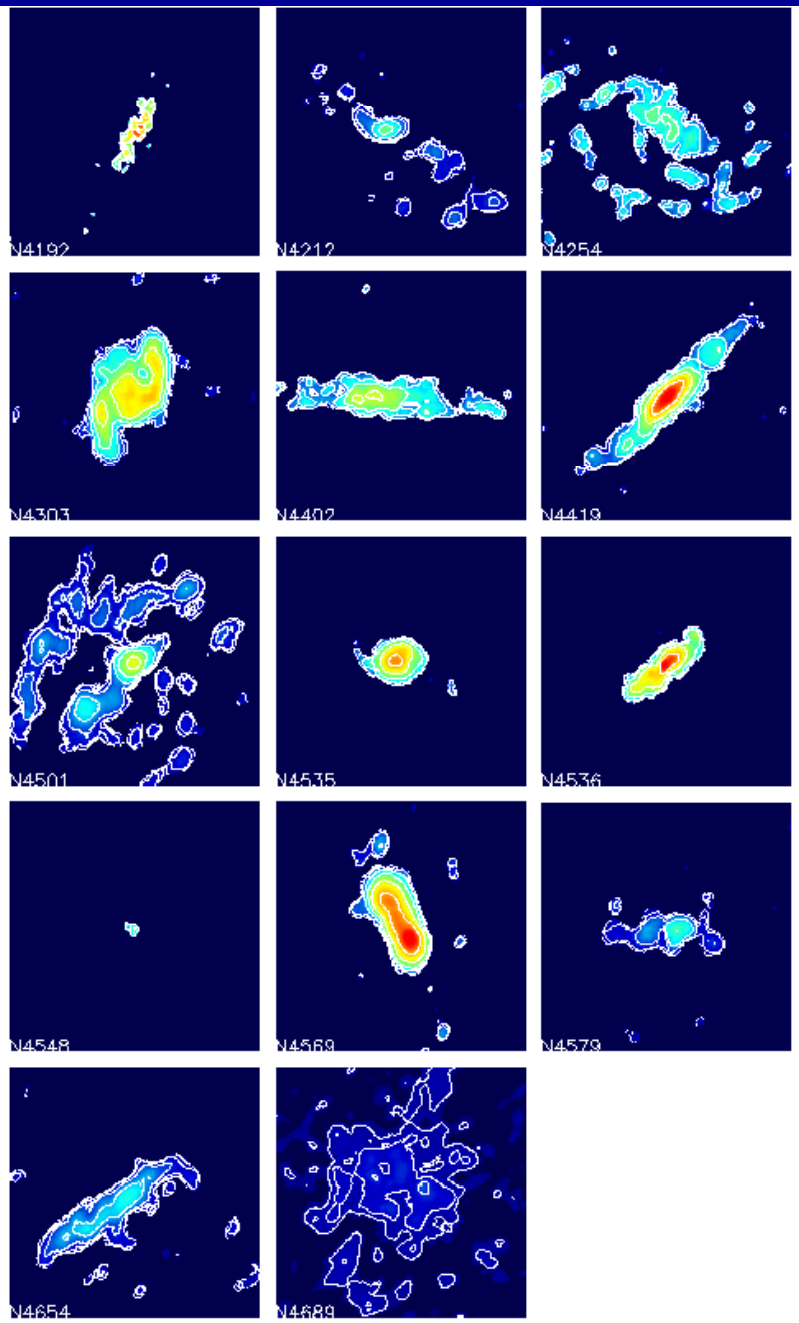
rms 15 mJy/Beam

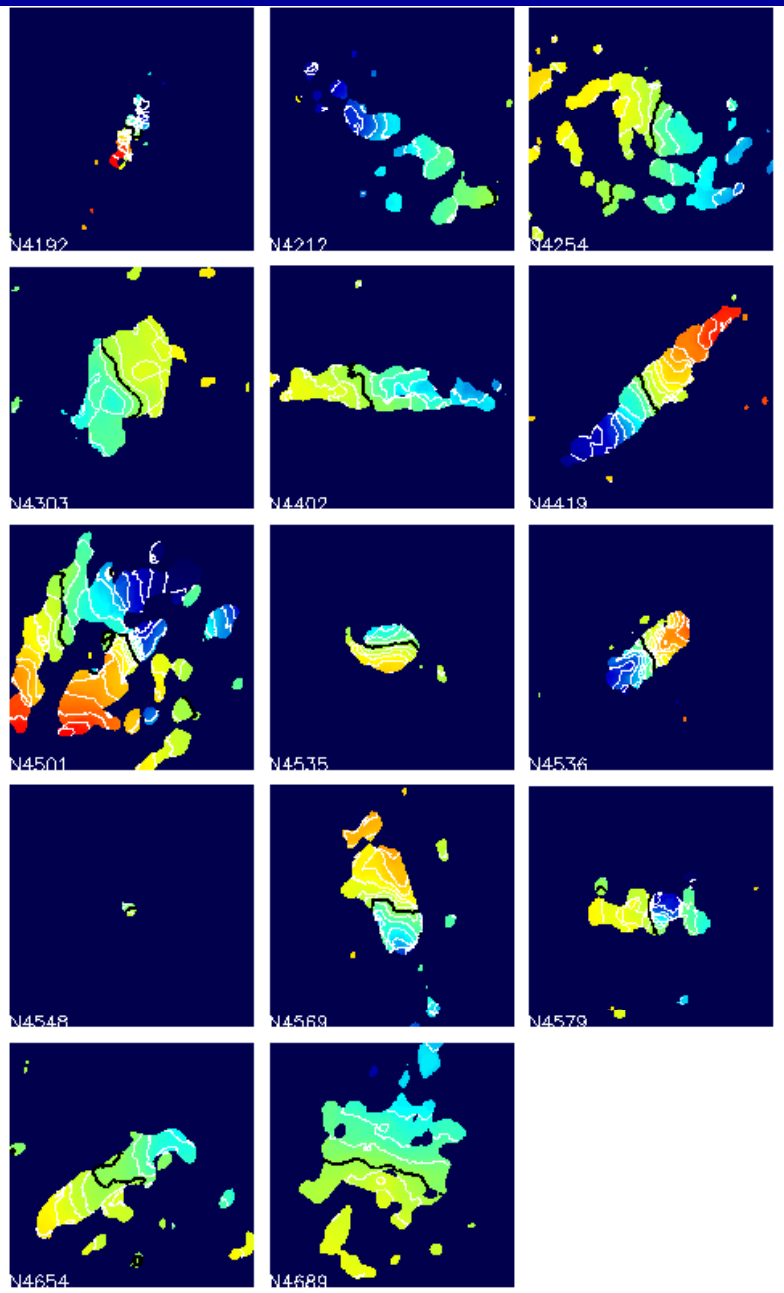









N4192
N4212
N4254
N4303
N4402
N4419
N4501
N4535
N4536
N4548
N4569
N4579
N4654
N4689


N4192
N4212
N4254
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N4419
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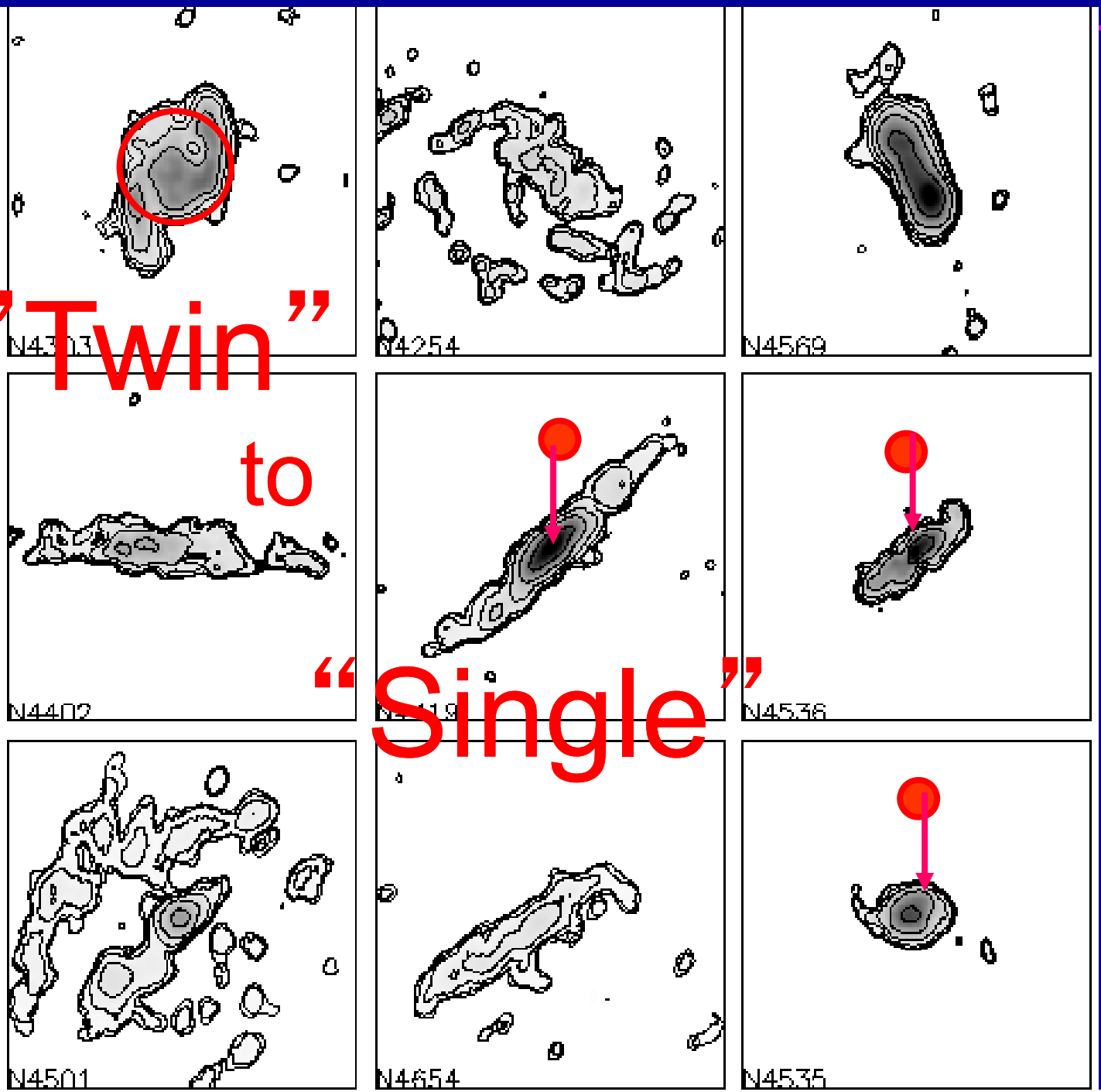
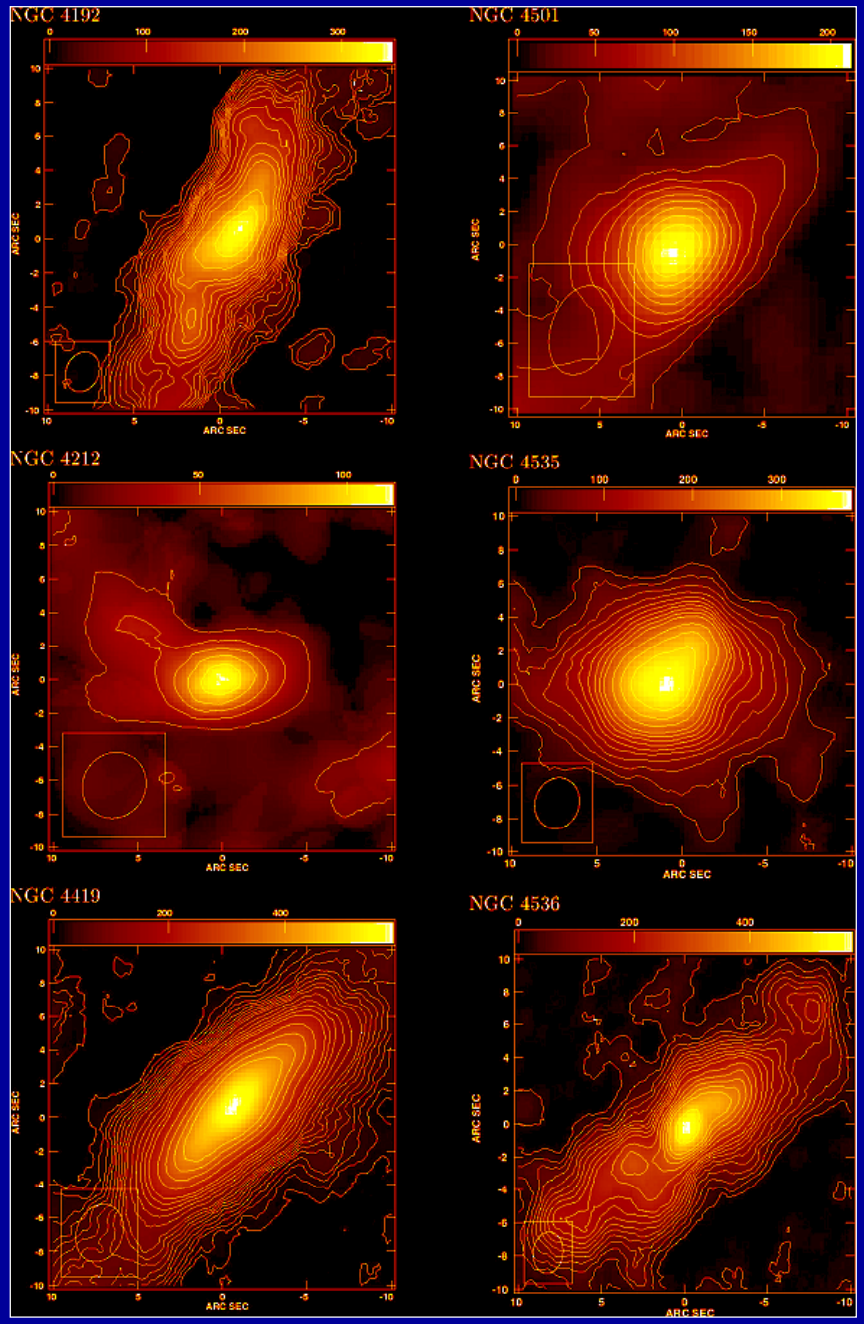
N4689


V
"Twin"
to
"Single"
N4254
N4569
N4402
N4536
N4501
N4654
N4535

“Single peaks”



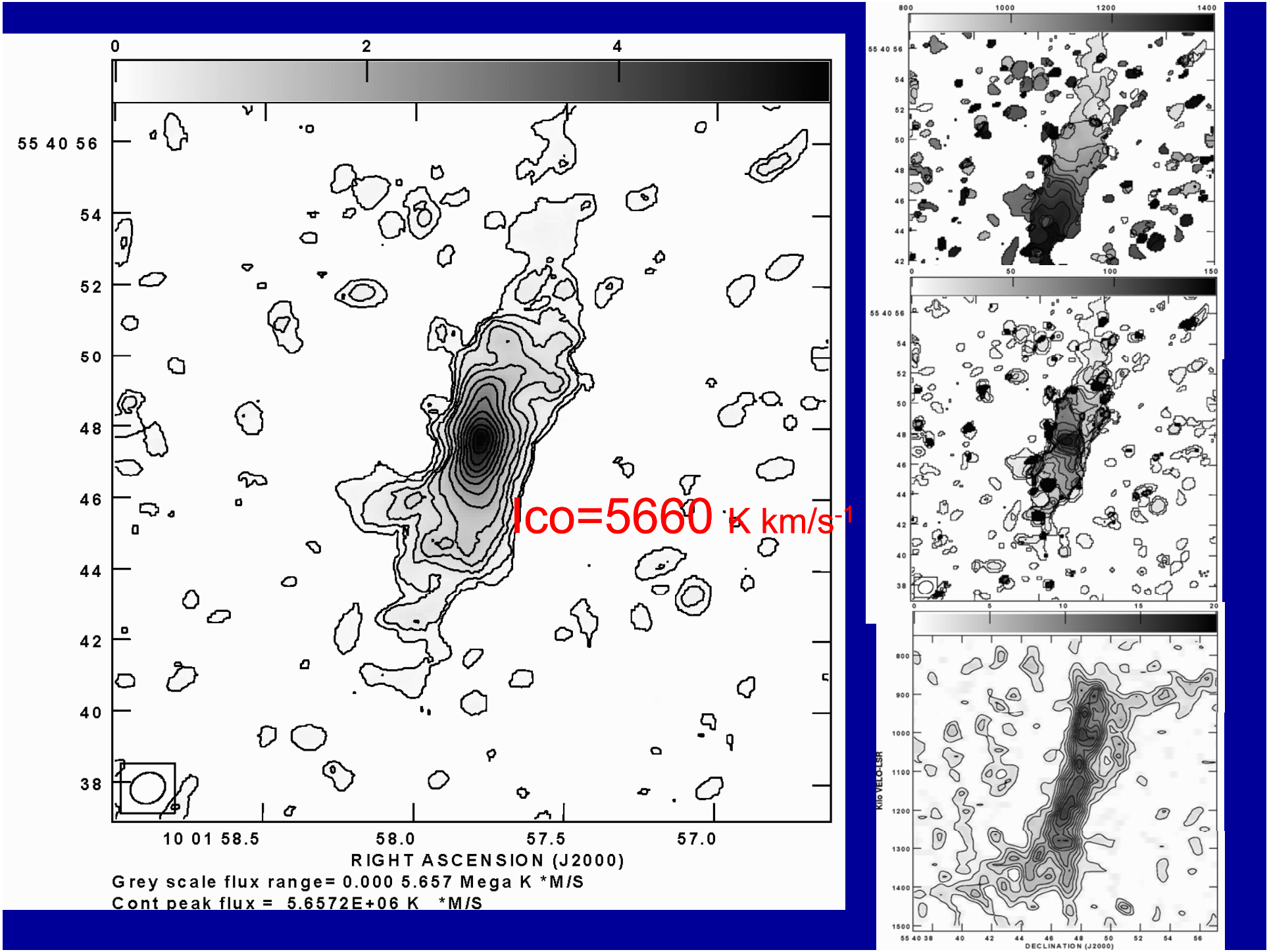
Molecular Nucleus (Single Peaks) Rate

BIMA	5”	32%	(14/44)
NMA-OV	4”	40%	(8/20)
Virgo	3”	33%	(5/15)
NMA Unifo	1.5”	66%	(4/6)

3. Uniform wt maps

in place for

RAINBOW


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)
Grey scale flux range= 0.000 5.657 Mega K *M/S
Cont peak flux = 5.6572E+06 K *M/S
Ico=5660 K km/s-1
800
1000
1200
1400
0
50
100
150
0
5
10
15
20
Kilo VELO-LSR
55 40 38
DECLINATION (J2000)

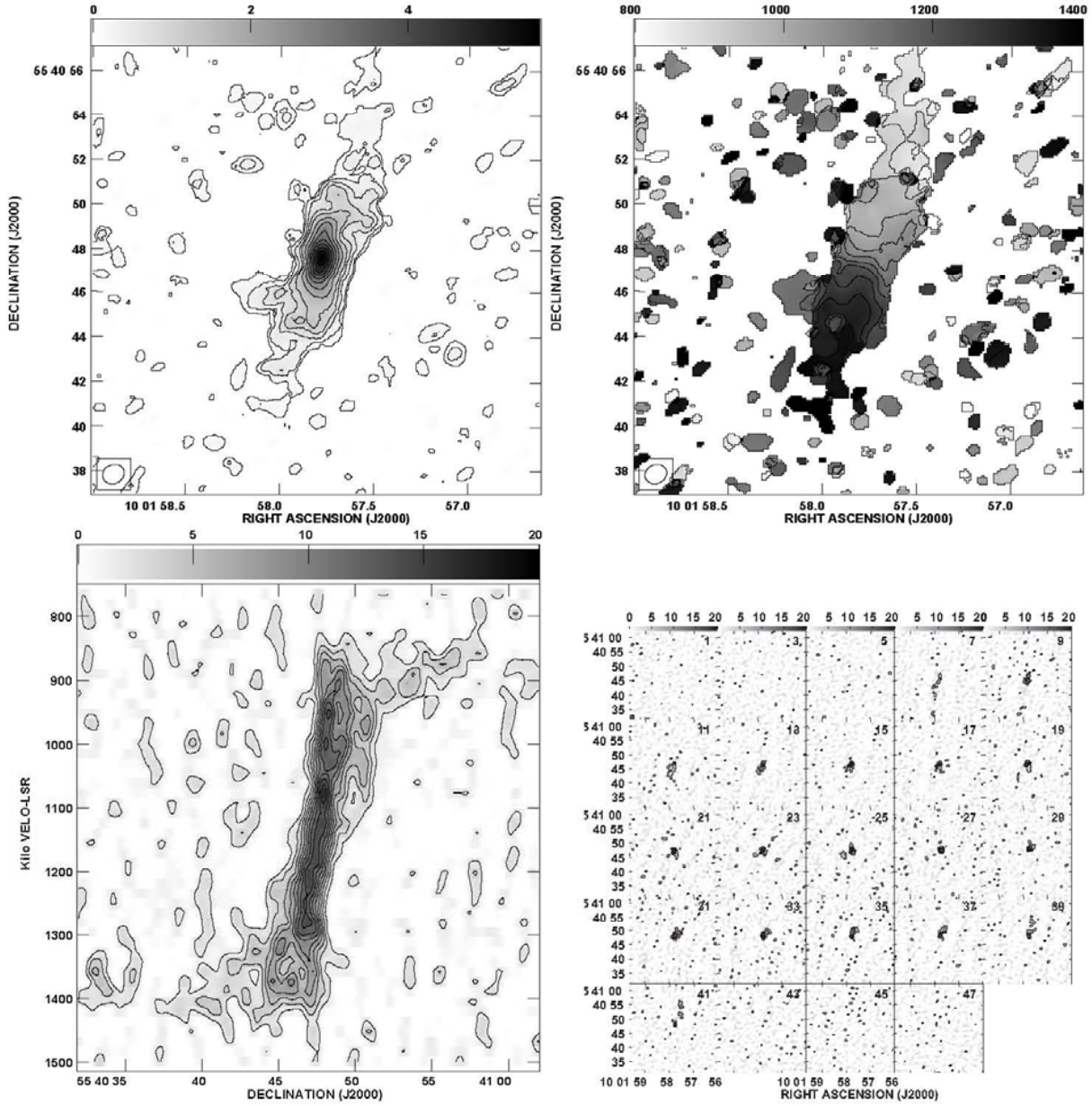


Fig. 2. (a) Uniform weighting integrated intensity maps in the CO line, (b) velocity fields, (c) pv diagrams, and (d) channel maps for NGC 3079. Intensity contour levels are 20 × (1, 2, ..., 10, 12, ... 20, 25, ... 40) K km s^{-1}.

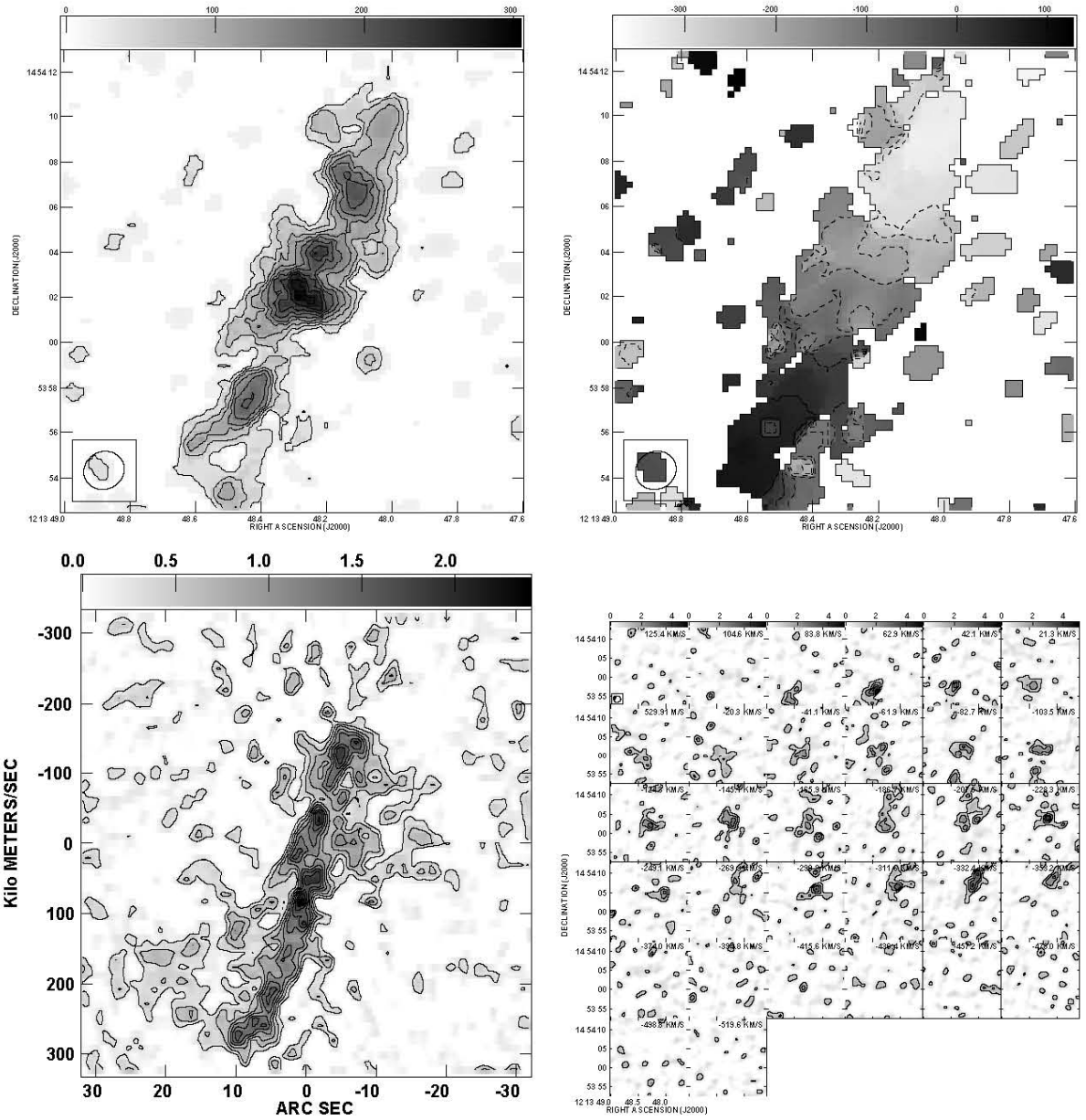


Fig. 3. Same as Fig. 2 but for NGC 4192

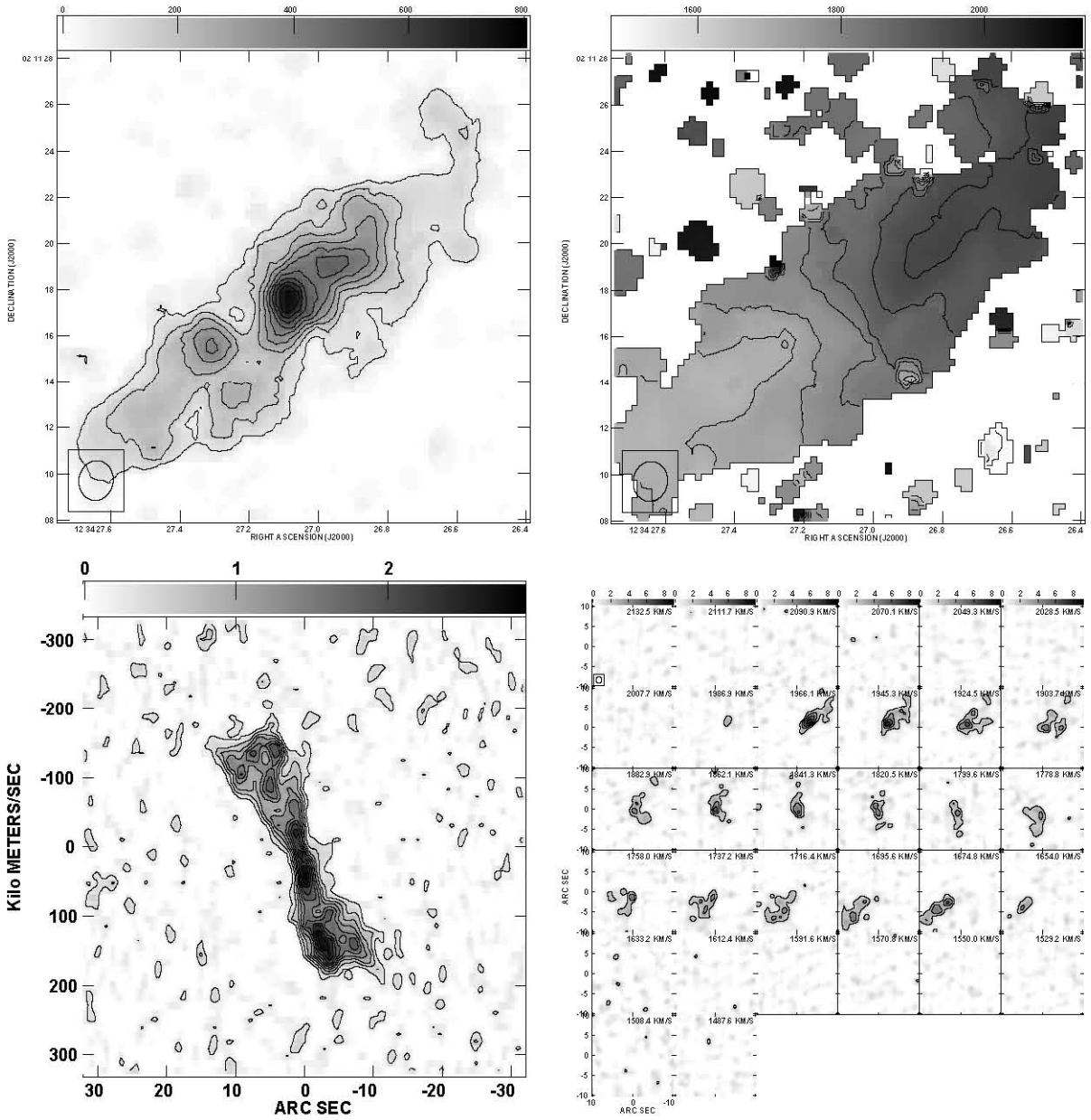


Fig. 7. Same as Fig. 2 but for NGC 4536

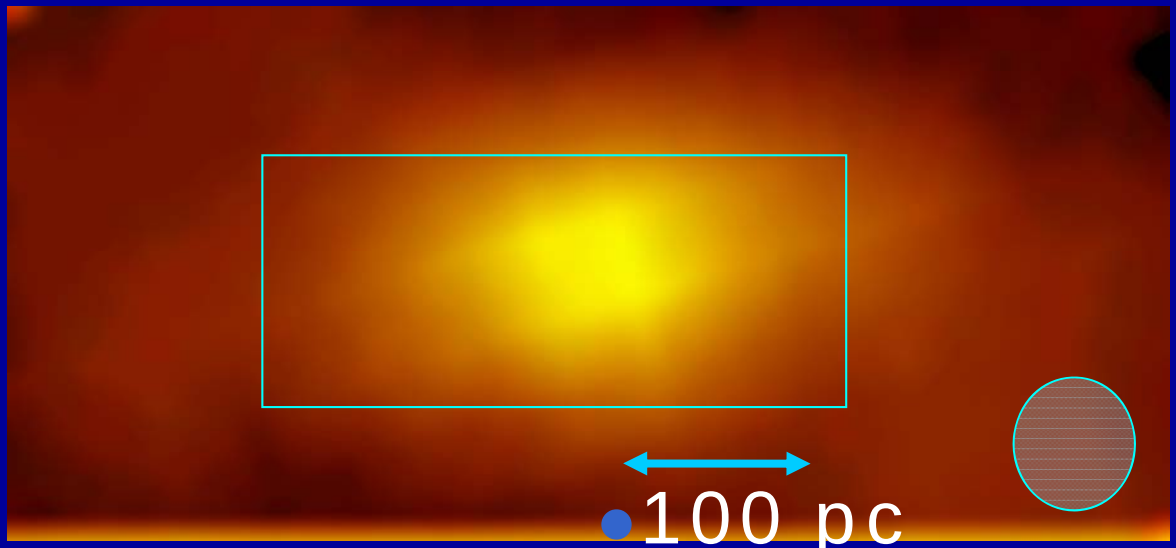
4. ISM Physics of S-peaks

Single Peaks

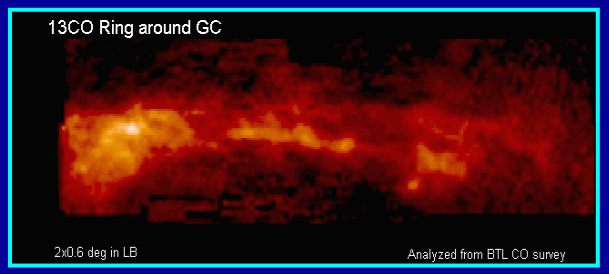
$I_{CO} > 500$ K km/s

$N(H_2) > 10^{23} H_2$ cm^{-2}

超高密度分子コア



銀河系と比較



High-Density Molecular Core in R~100 pc (if conv.X=1x10^{20} H_2/ K km^{-1})

Column Density

$N(H_2) > 10^{23} H_2$ cm^{-2}

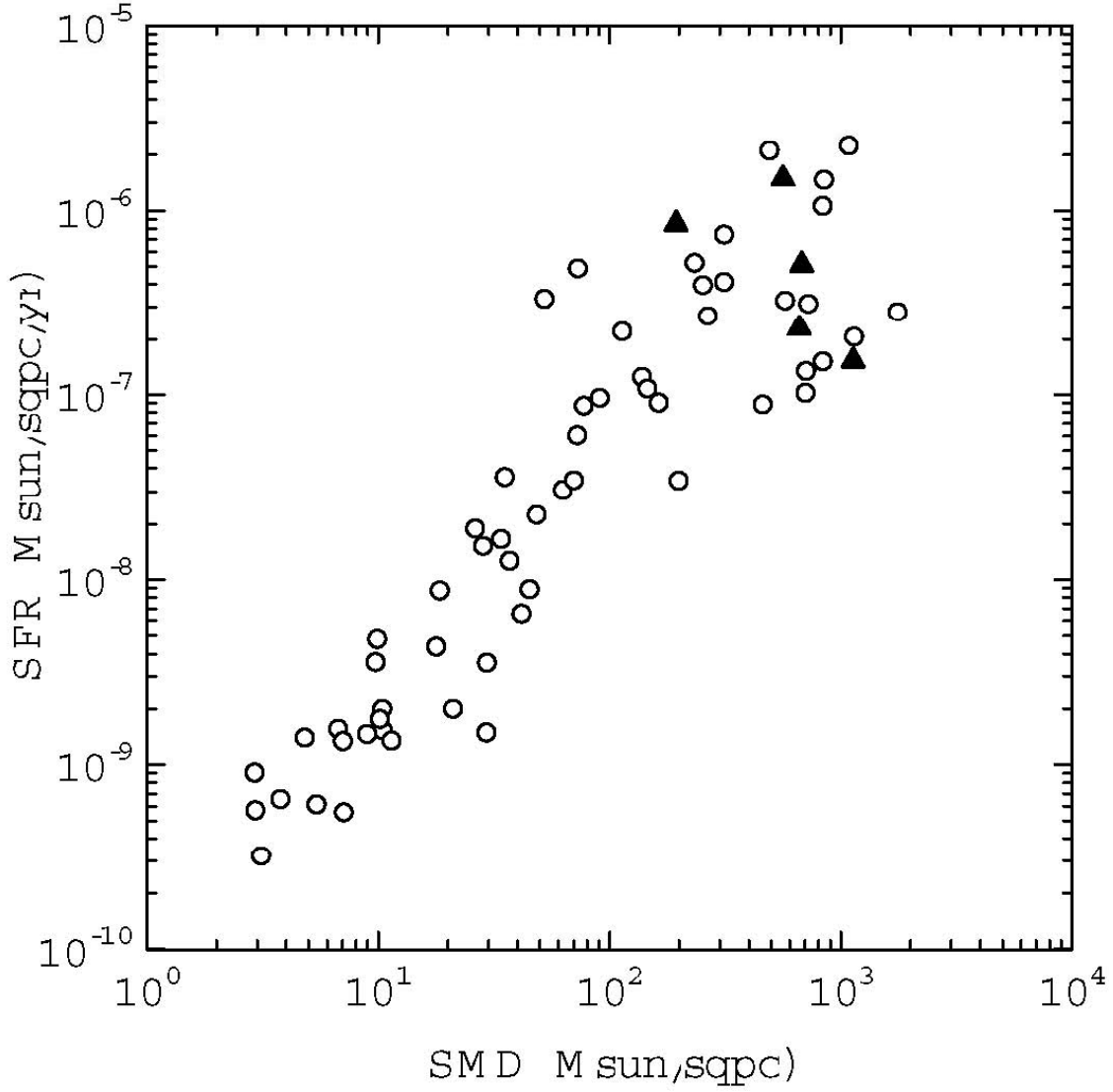
Gass Mass

$M(H_2)$ ~ Several10^8 Msun

Dynamical mass ~ 10^9 Msun

Schimidt Law

SFR$\propto\Sigma^{1.0}$(gas) (Schimidt law)



[1] Bar accretion

"Twin peaks" + Ring

Temporary

[2] Feeding Nuclei

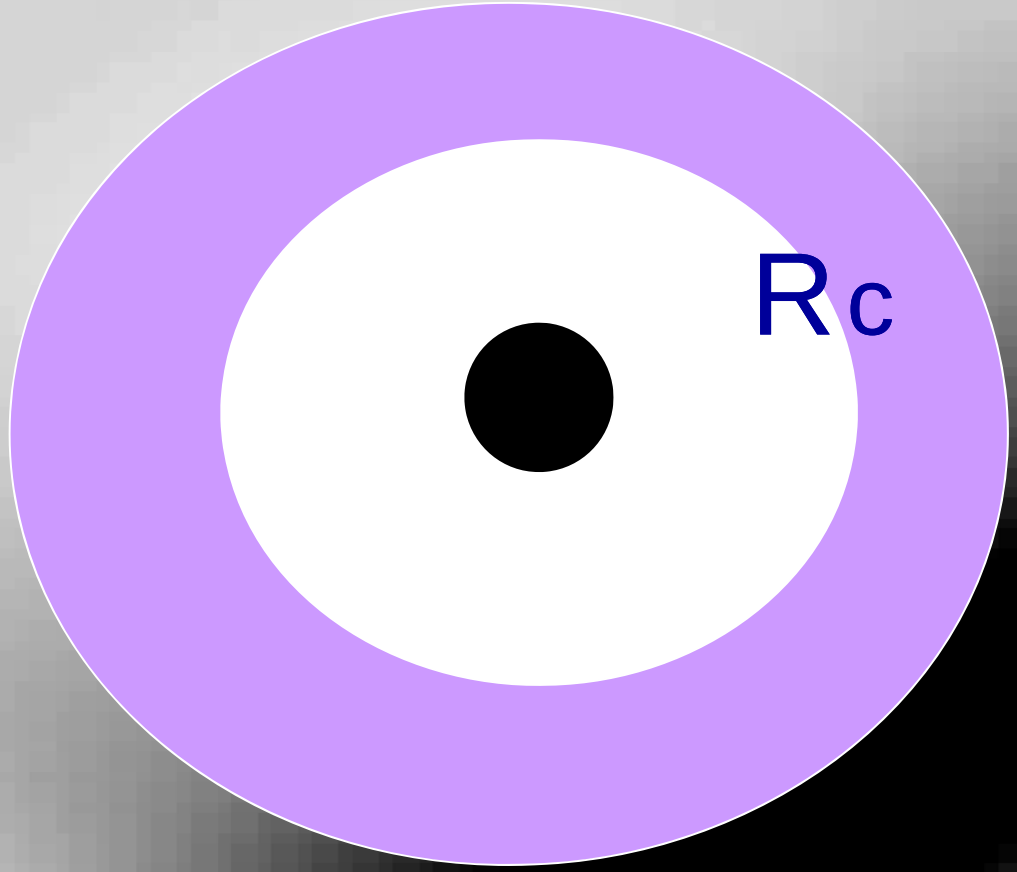
[3] Nucl. Mol. Core,

"Single Peak"

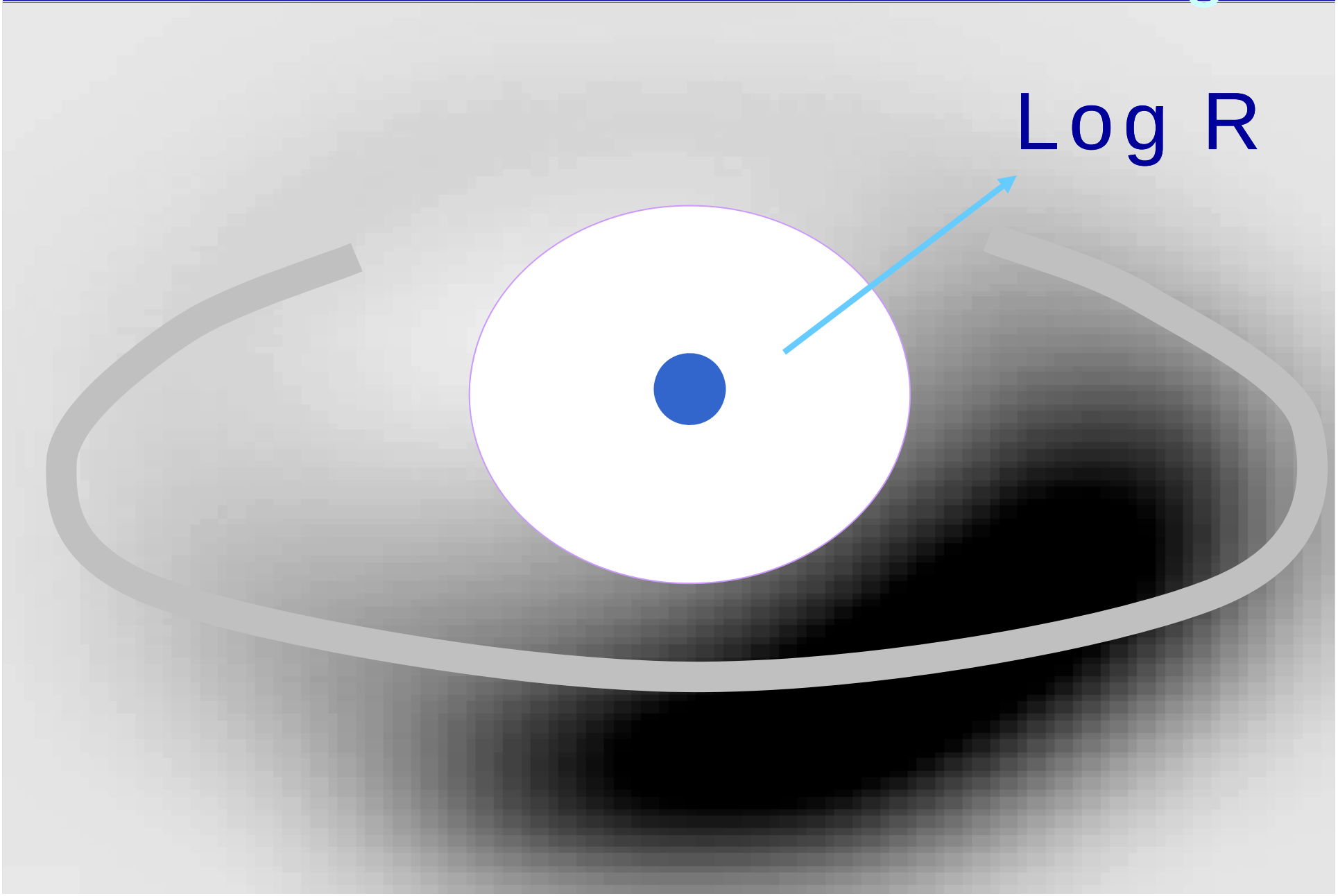
Stationary

SFR=Schmidt / Starburst

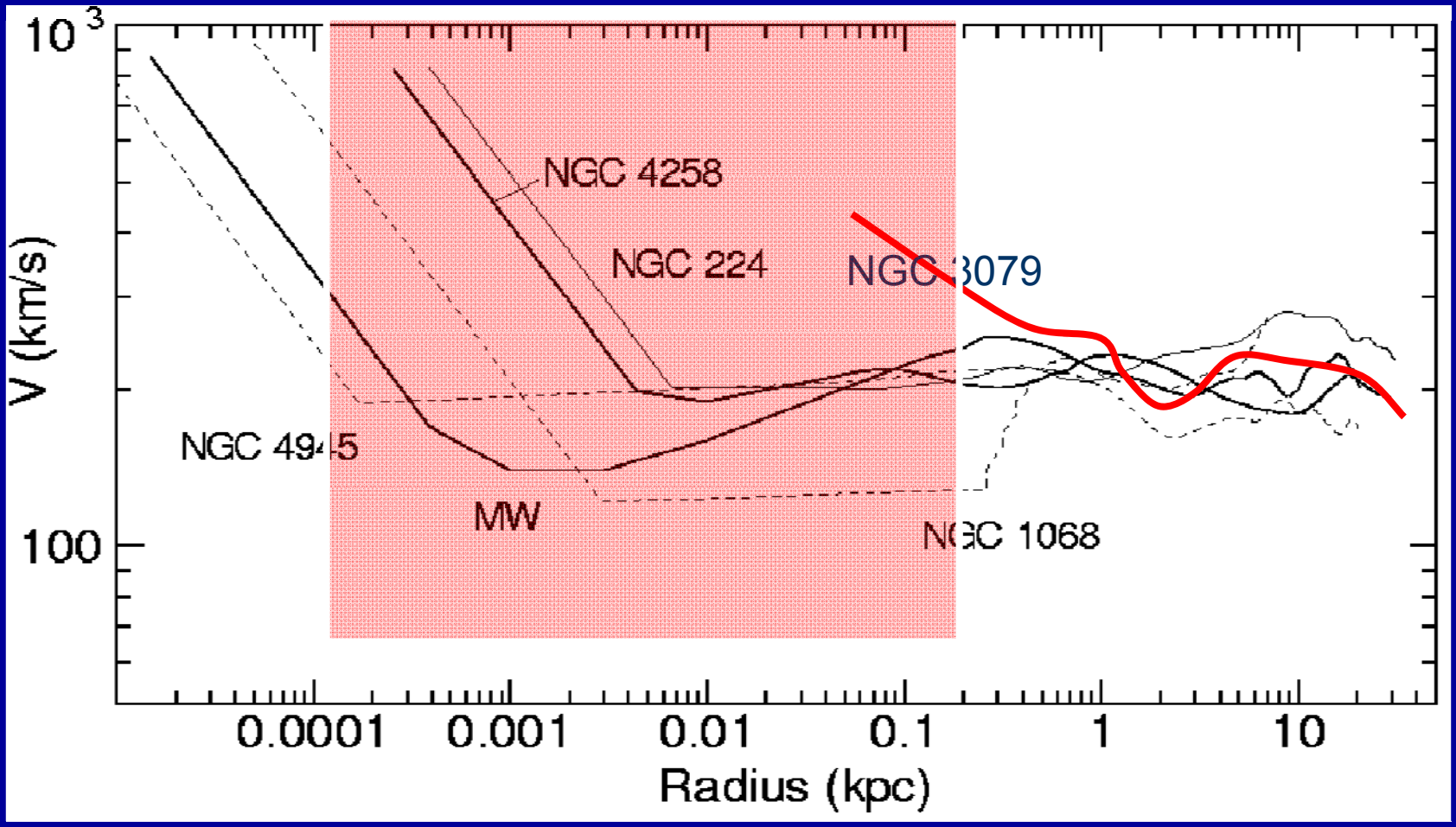
質量空白域 or DM cusp



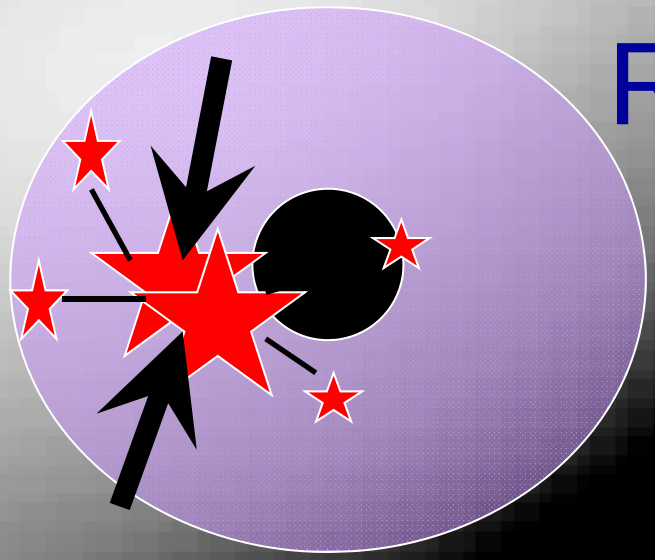
銀河質量研究の空白領域 BH - Bulge



BH – Bulge – Disk



BH formation in core/cusp



作業仮説

Flat RC

(Isothermal)
beyond BH.

Isothermal disk, ρ infinite at center

$$\rho \sim R^{-2}$$

Critical $R_{\rm c}$, $V_{\rm c}$ for BH formation

$$M_\bullet = R_{\rm c} V_{\rm c}^2 G^{-1}$$

$$M_\bullet = (4\pi/3) R_{\rm c}^3 \rho_{\rm s}$$

Time scale of star-star collisions

$$t_{\rm col} = m_{\rm s}/(V a^2 \rho_{\rm s})$$

$m_{\rm s} \sim M_\odot$, $a \sim 10^{11}$cm

$$R_{\rm c} = [(3/4) V^3 t_{\rm H}/mG]^{1/2} a \sim 0.1 [V/200 {\rm kms}^{-1})]^{1.5}$$

We, thus, obtain

$$M_\bullet = R_{\rm c} V_{\rm c}^2/G \sim V_{\rm c}^{3.5}$$

If Rotation curve is flat

$$M_{\rm G} \sim V^4$$

Thus,

$$M_\bullet \sim M_{\rm G}^{0.9}$$

. If total mass $\propto$ B luminosity,

$$\log M_\bullet \sim -1.8 M_{B,{\rm disk}}$$

$$M_{BH} \sim M_G^{0.9}$$

$$\text{Log } M_{BH} \sim -1.8 M_{B,disk}$$

Log $M_{BH} \sim -1.8\ M_{B,disk}$

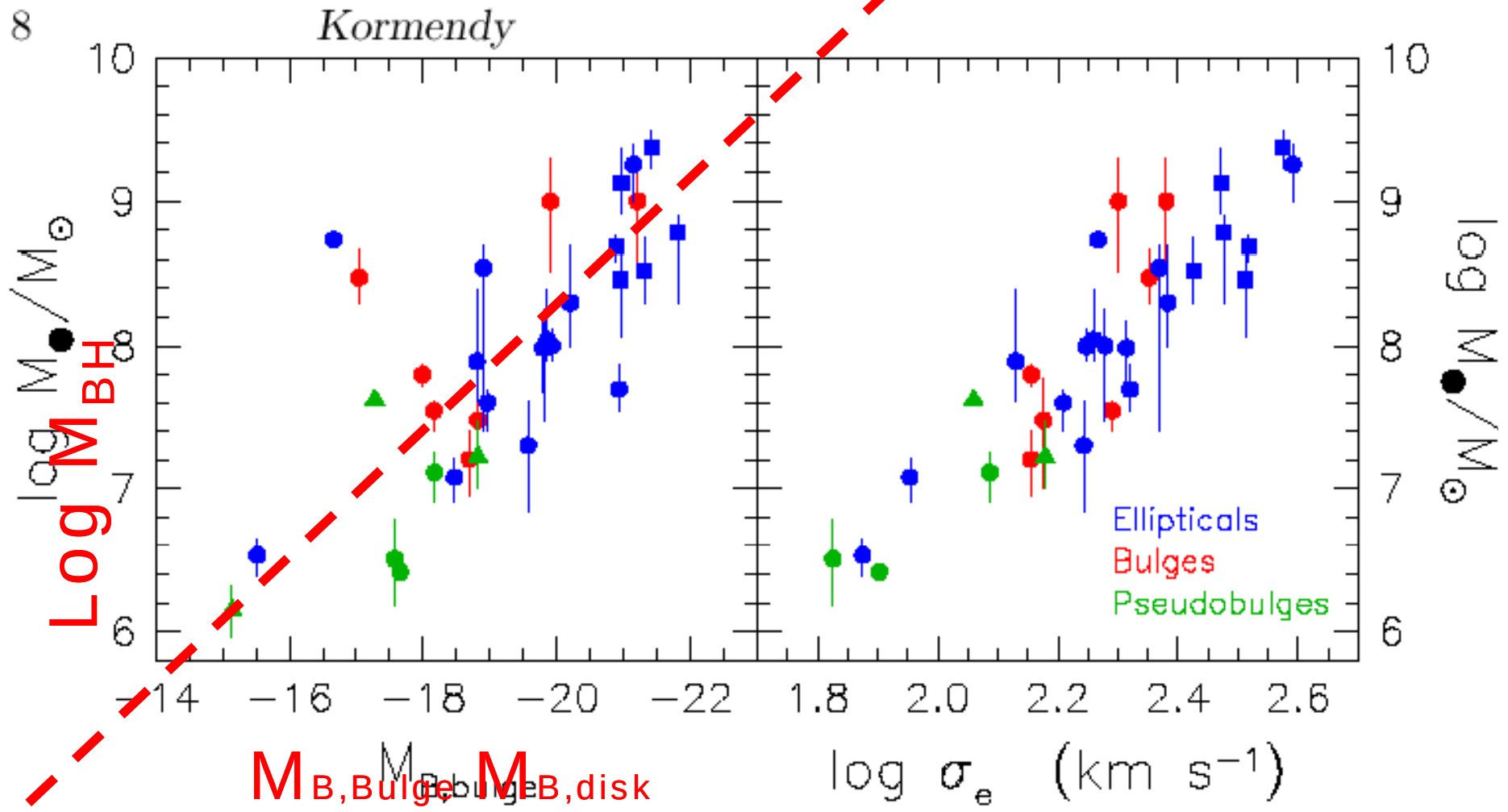
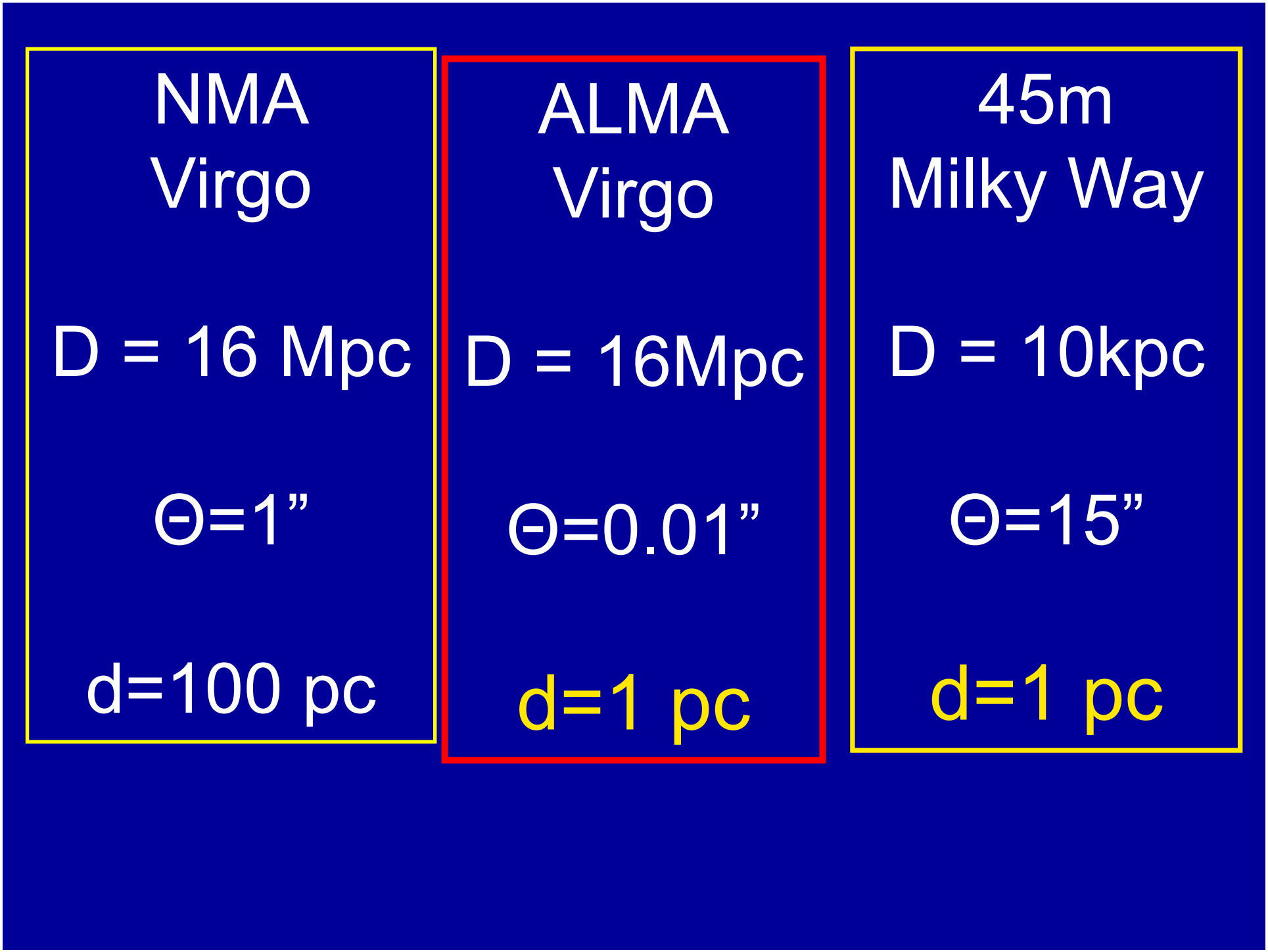
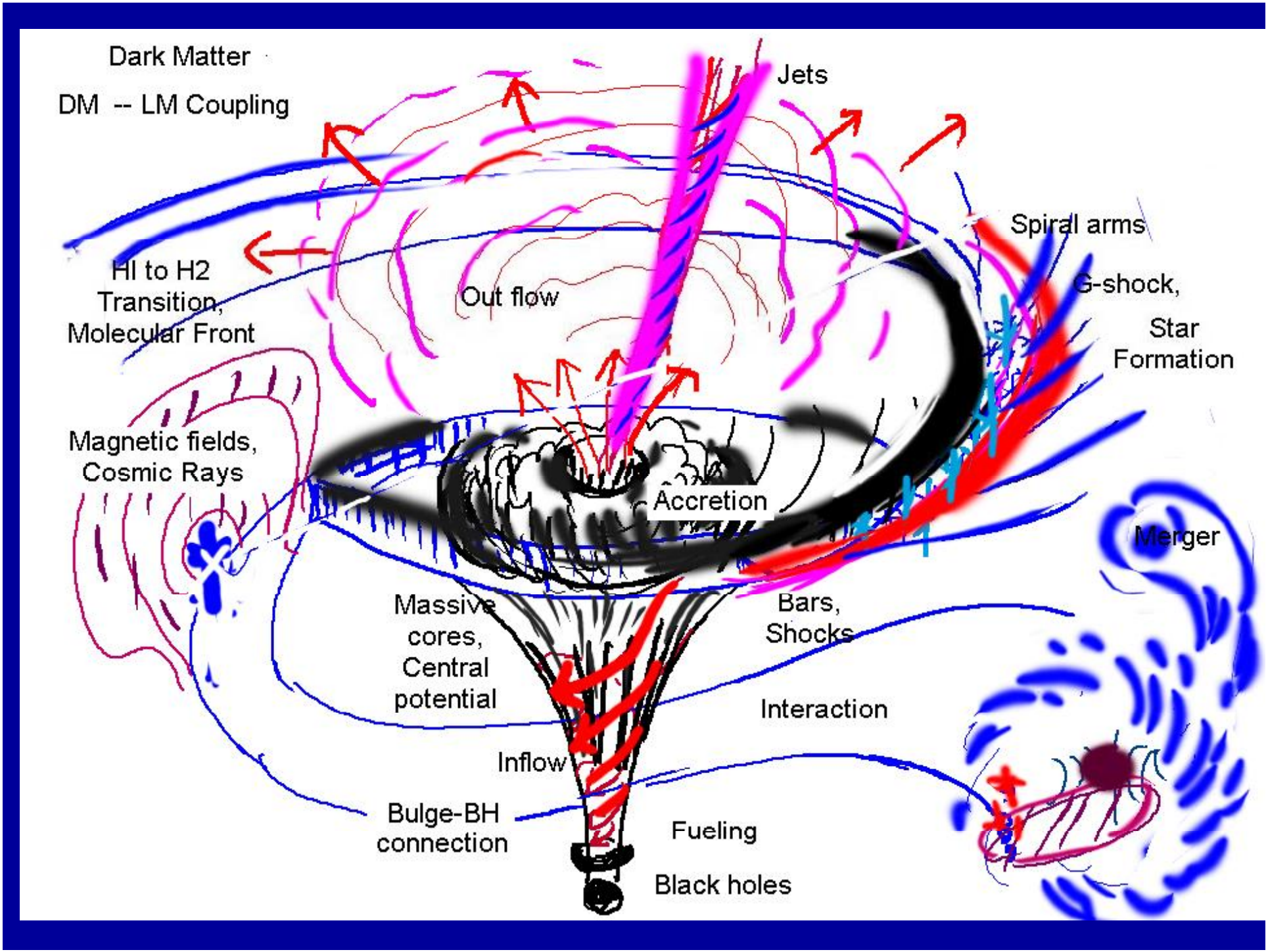


Figure 4. The $M_\bullet - M_{B,\mathrm{bulge}}$ (left) and $M_\bullet - \sigma_e$ (right) correlations for elliptical galaxies (blue symbols), traditional bulges (red) and pseudobulges (green).

Kormendy 2000

1. 野辺山、ALMA　回転曲線
2. 質量分布
3. 銀河研究の空白地帯
4. 対数回転曲線


NMA
Virgo
D = 16 Mpc
Θ=1”
d=100 pc
ALMA
Virgo
D = 16Mpc
Θ=0.01”
d=1 pc
45m
Milky Way
D = 10kpc
Θ=15”
d=1 pc


Dark Matter
DM -- LM Coupling
Jets
Spiral arms
HI to H2
Transition,
Molecular Front
Out flow
G-shock,
Star
Formation
Magnetic fields,
Cosmic Rays
Accretion
Merger
Massive
cores,
Central
potential
Bars,
Shocks
Interaction
Inflow
Bulge-BH
connection
Fueling
Black holes