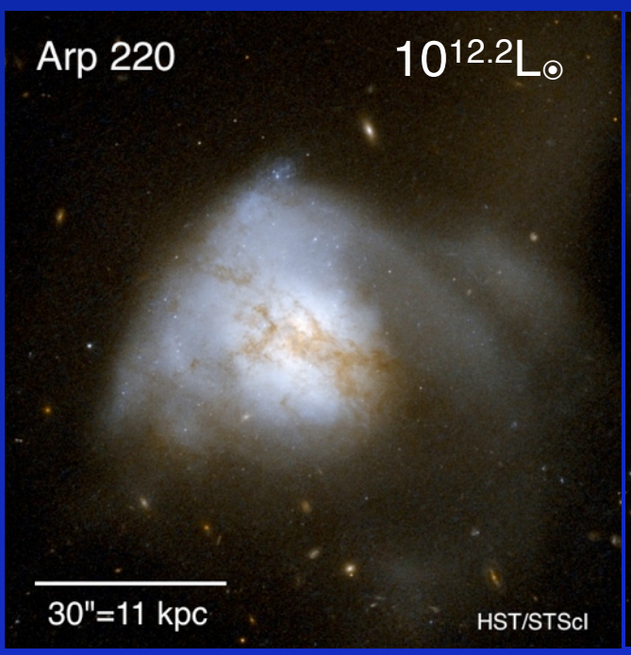
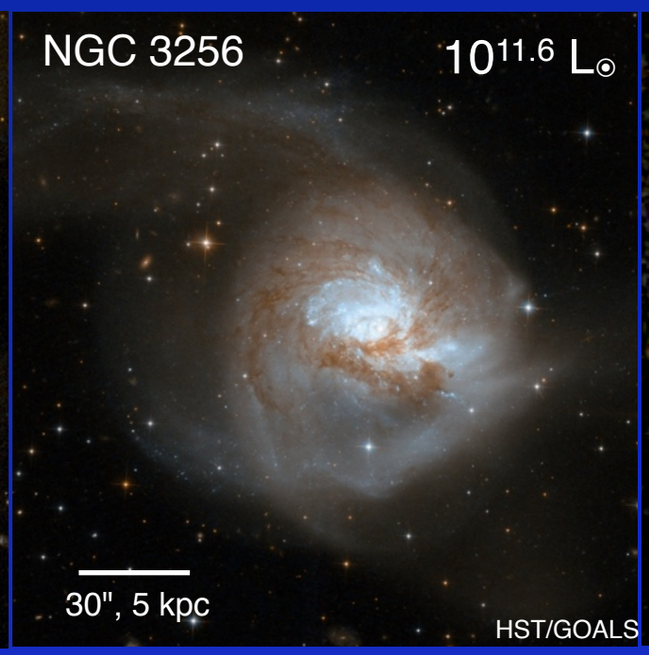
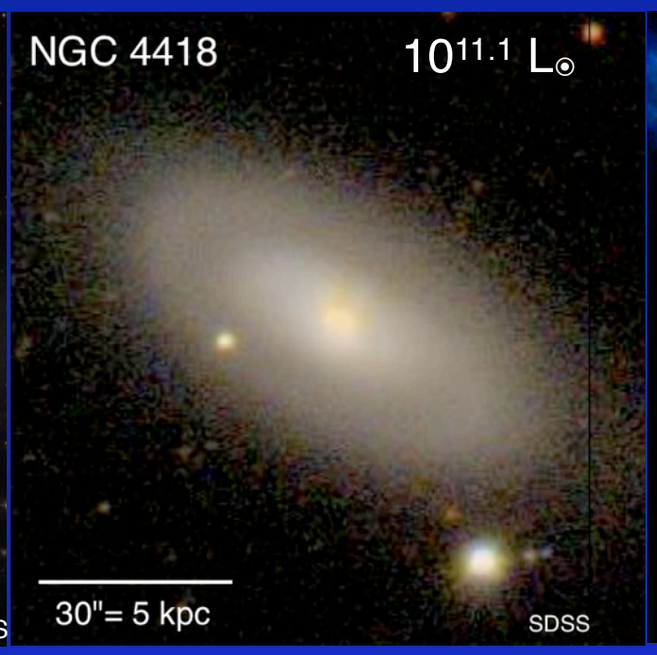
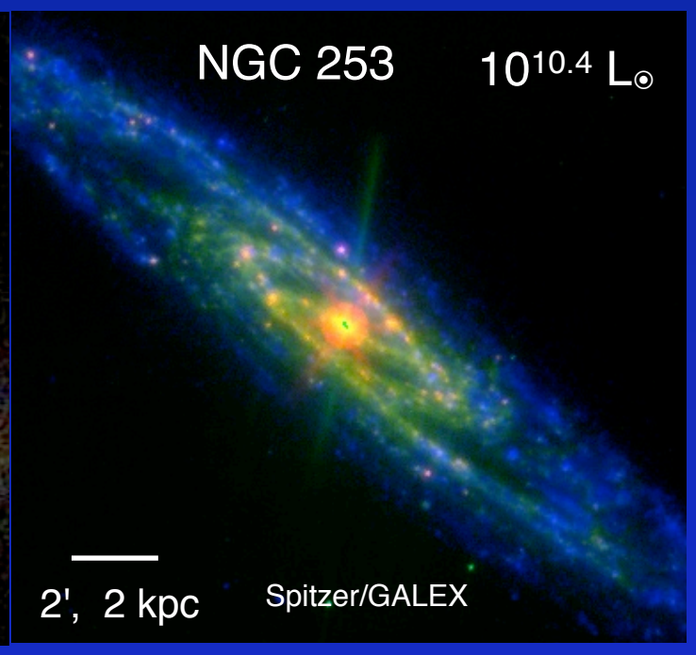
SMA Discoveries in Nearby Galaxies









Kazushi Sakamoto (ASIAA)

in collaboration with

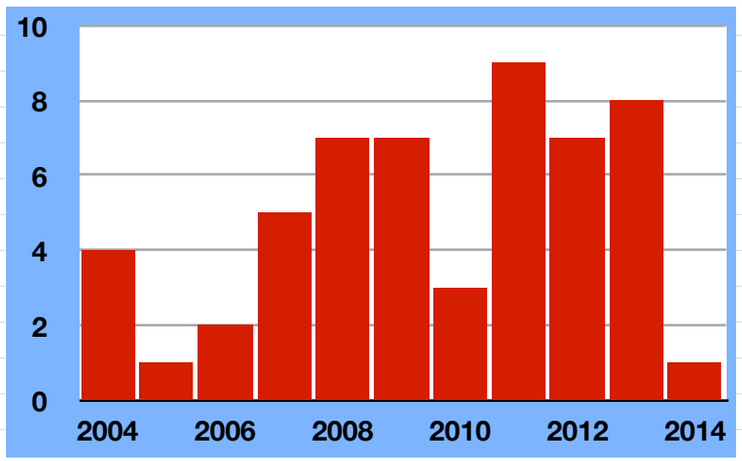
S. Aalto, J. Black, F. Combes, J. Conway, F. Costagliola, A. Evans, P. Ho, D. Iono, E. Keto, R-Q. Mao, S. Martin, S. Matsushita, Y. Ohyama, A. Peck, G. Petitpas, M. Spaans, J. Wang, Z. Wang, M. Wiedner, D. Wilner, Q. Zhan, J-H. Zhao

SMA 10 @ Cambridge, MA, 2014 May

SMA on Nearby Galaxies

54+ papers
920+ cites
~8 % of SMA
as of June 4, 2014
excl. Time-domain, VLBI

2004	Matsushita	Submillimeter Array 12CO (J=3-2) Interferometric Observations of the Central Region of M51
2004	Sakamoto	Molecular Gas around the Double Nucleus in M83
2004	Iono	High-Density Molecular Gas in the Infrared-bright Galaxy System VV 114
2004	Wang	Warm Molecular Gas in Galaxy-Galaxy Merger NGC 6090
2005	Humphreys	First Detection of Millimeter/Submillimeter Extragalactic H2O Maser Emission
2006	Sakamoto	Molecular Superbubbles in the Starburst Galaxy NGC 253
2006	Sakamoto	Imaging Molecular Gas in the Luminous Merger NGC 3256: Detection of High-Velocity Gas and Twin Gas Peaks in the Double Nucleus
2007	Sakamoto	Detection of CO Hot Spots Associated with Young Clusters in the Southern Starburst Galaxy NGC 1365
2007	Sawada-Satoh	Structure and Kinematics of CO J = 2-1 Emission in the Central Region of NGC 4258
2007	Iono	High-Resolution Imaging of Warm and Dense Molecular Gas in the Nuclear Region of the Luminous Infrared Galaxy NGC 6240
2007	Minh	Unveiling the Ongoing Star Formation in the Starburst Galaxy NGC 253
2007	Chou	The Circumnuclear Molecular Gas in the Seyfert Galaxy NGC 4945
2008	Ao	Molecular Gas and Star Formation in ARP 302
2008	Lim	Radially Inflowing Molecular Gas in NGC 1275 Deposited by an X-Ray Cooling Flow in the Perseus Cluster
2008	Hsieh	Interferometric 12CO J = 2-1 Image of the Nuclear Region of Seyfert 1 Galaxy NGC 1097
2008	Papadopoulos	A New Twist to an Old Story: HE 0450-2958 and the ULIRG --> Optically Bright QSO Transition Hypothesis
2008	Sakamoto	Submillimeter Array Imaging of the CO(3-2) Line and 860 μm Continuum of Arp 220: Tracing the Spatial Distribution of Luminosity
2008	Tan	A Search for Molecular Gas in the Nucleus of M87 and Implications for the Fueling of Supermassive Black Holes
2008	Wilson	Luminous Infrared Galaxies with the Submillimeter Array. I. Survey Overview and the Central Gas to Dust Ratio
2009	Aalto	High-resolution HNC 3-2 SMA observations of Arp 220
2009	Santangelo	Resolving the molecular environment of super star clusters in Henize 2-10
2009	Matsushita	SMA 12CO(J = 6 - 5) and 435 μm Interferometric Imaging of the Nuclear Region of Arp 220
2009	Iono	Luminous Infrared Galaxies with the Submillimeter Array. II. Comparing the CO (3-2) Sizes and Luminosities of Local and High-Redshift Luminous Infrared Galaxies
2009	Muller	HCO+ and HCN J = 3-2 Absorption Toward the Center of Centaurus A
2009	Ho	Multiple Radial Cool Molecular Filaments in NGC 1275
2009	Sakamoto	P Cygni Profiles of Molecular Lines Toward Arp 220 Nuclei
2010	Martin	Imaging Carbon Monoxide Emission in the Starburst Galaxy NGC 6000
2010	Espada	Disentangling the Circumnuclear Environs of Centaurus A. II. On the Nature of the Broad Absorption Line
2010	Sakamoto	Vibrationally Excited HCN in the Luminous Infrared Galaxy NGC 4418
2011	Krips	Submillimeter Array/Plateau de Bure Interferometer Multiple Line Observations of the Nearby Seyfert 2 Galaxy NGC 1068: Shock-related Gas Kinematics and Heating in the Central 100 pc?
2011	Boone	High-resolution mapping of the physical conditions in two nearby active galaxies based on 12CO(1-0), (2-1), and (3-2) lines
2011	Martin	The Submillimeter Array 1.3 mm line survey of Arp 220
2011	Lin	The Central Region of the Nearby Seyfert 2 Galaxy NGC 4945: A Pair of Spirals
2011	Sakamoto	Star-forming Cloud Complexes in the Central Molecular Zone of NGC 253
2011	Alatalo	Discovery of an Active Galactic Nucleus Driven Molecular Outflow in the Local Early-type Galaxy NGC 1266
2011	Hsieh	Physical Properties of the Circumnuclear Starburst Ring in the Barred Galaxy NGC 1097
2011	Hirashita	Central free-free dominated 880-μm emission in II Zw 40
2011	Li	The alignment of molecular cloud magnetic fields with the spiral arms in M33
2012	Aalto	Winds of change - a molecular outflow in NGC 1377?. The anatomy of an extreme FIR-excess galaxy
2012	Ueda	Unveiling the Physical Properties and Kinematics of Molecular Gas in the Antennae Galaxies (NGC 4038/9) through High-resolution CO (J = 3-2) Observations
2012	Tsai	Interferometric CO(3-2) Observations toward the Central Region of NGC 1068
2012	Hsieh	Probing Circumnuclear Environments with the HCN(J = 3-2) and HCO+(J = 3-2) Lines: Case of NGC 1097
2012	Wei	Two Populations of Molecular Clouds in the Antennae Galaxies
2012	Sliwa	Luminous Infrared Galaxies with the Submillimeter Array. III. The Dense Kiloparsec Molecular Concentrations of Arp 299
2012	Espada	Disentangling the Circumnuclear Environs of Centaurus A: Gaseous Spiral Arms in a Giant Elliptical Galaxy
2013	Koenig	The NGC 1614 interacting galaxy. Molecular gas feeding a "ring of fire"
2013	Costagliola	High-resolution mm and cm study of the obscured LIRG NGC 4418 . A compact obscured nucleus fed by in-falling gas?
2013	Sakamoto	Submillimeter Interferometry of the Luminous Infrared Galaxy NGC 4418: A Hidden Hot Nucleus with an Inflow and an Outflow
2013	Hsi-An	Formation of Dense Molecular Gas and Stars at the Circumnuclear Starburst Ring in the Barred Galaxy NGC 7552
2013	Hwang	Dust Properties of Local Dust-obscured Galaxies with the Submillimeter Array
2013	Sliwa	Luminous Infrared Galaxies with the Submillimeter Array. IV. 12CO J = 6-5 Observations of VV 114
2013	Hirashita	Properties of free-free, dust and CO emissions in the starbursts of blue compact dwarf galaxies
2013	Izumi	Submillimeter ALMA Observations of the Dense Gas in the Low-Luminosity Type-1 Active Nucleus of NGC 1097
2014	Kuo	Measuring Mass Accretion Rate onto the Supermassive Black Hole in M87 Using Faraday Rotation Measure with the Submillimeter Array



SMA on Nearby Galaxies

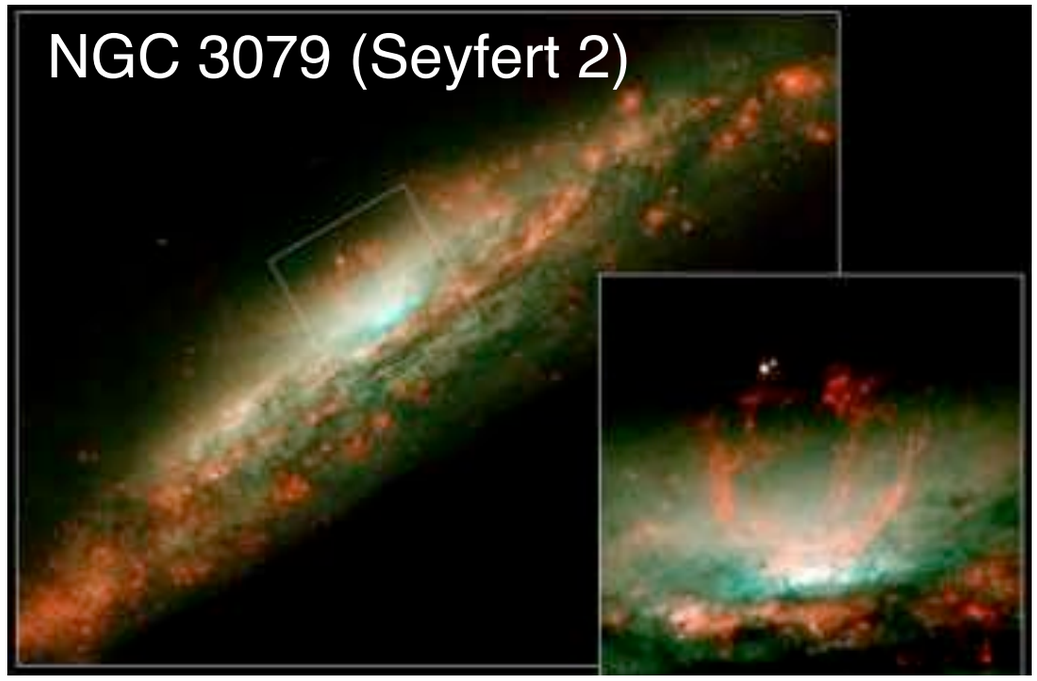
- SMA strengths:
  - sub-mm, sub-arcsec, wide-band, sensitivity, polarimetry, southern+northern sky, ...
  - good at *warm/active sources*, multi-line studies, ...
- Spectroscopy
- U/LIRG Legacy Project
- U/LIRGs at highest resolutions
- Feedback/Outflows
- Warm/Dense Gas in Active Galactic Nuclei
- Polarimetry
- ...

Spectroscopy

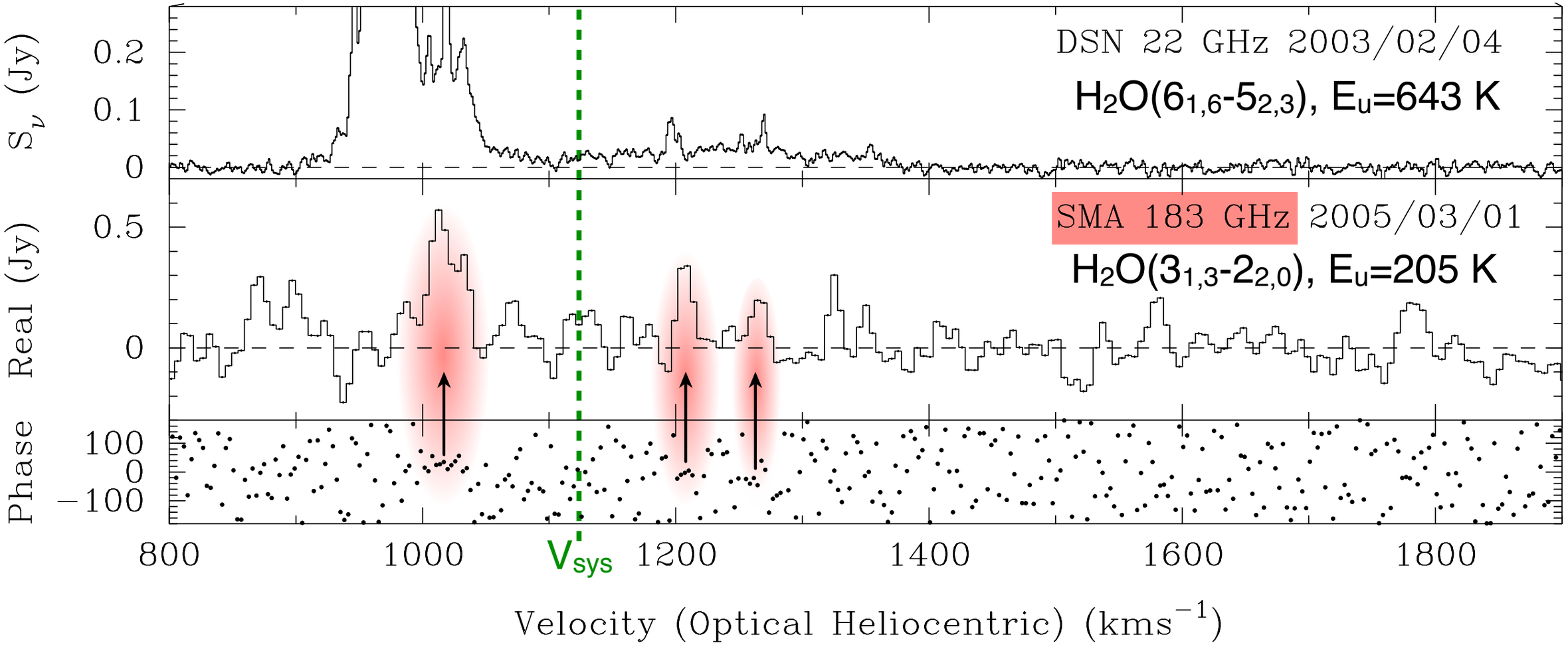
SMA 10 @ Cambridge, MA, 2014 May

New Extragalactic H_2O Maser

Humphreys et al. (2005)

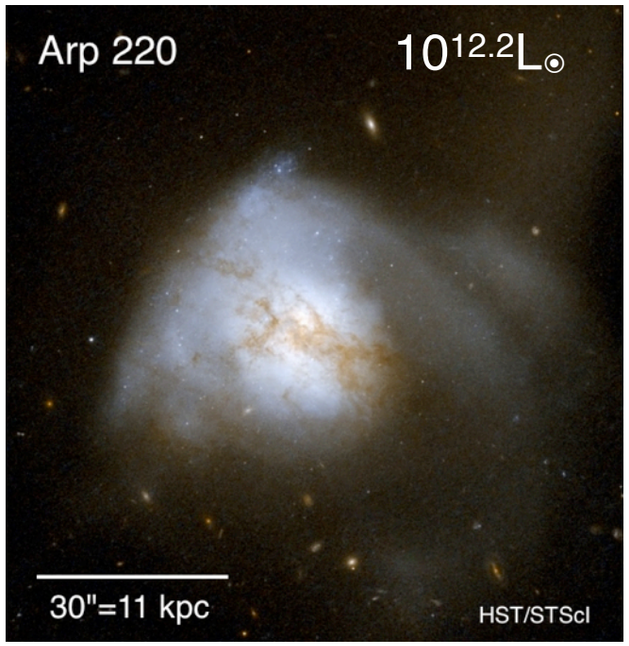


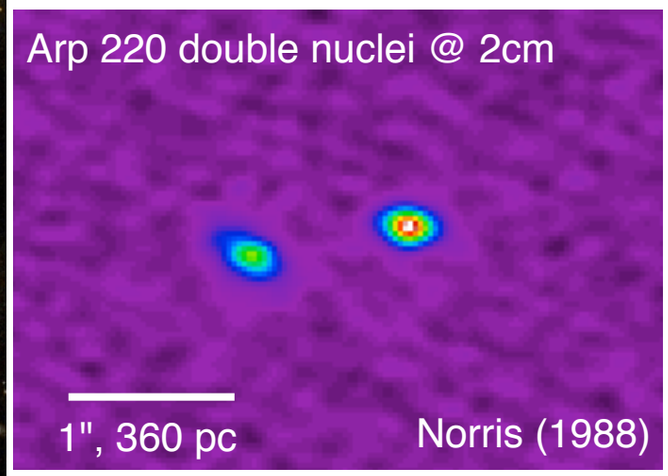
credit: NASA, G. Cecil

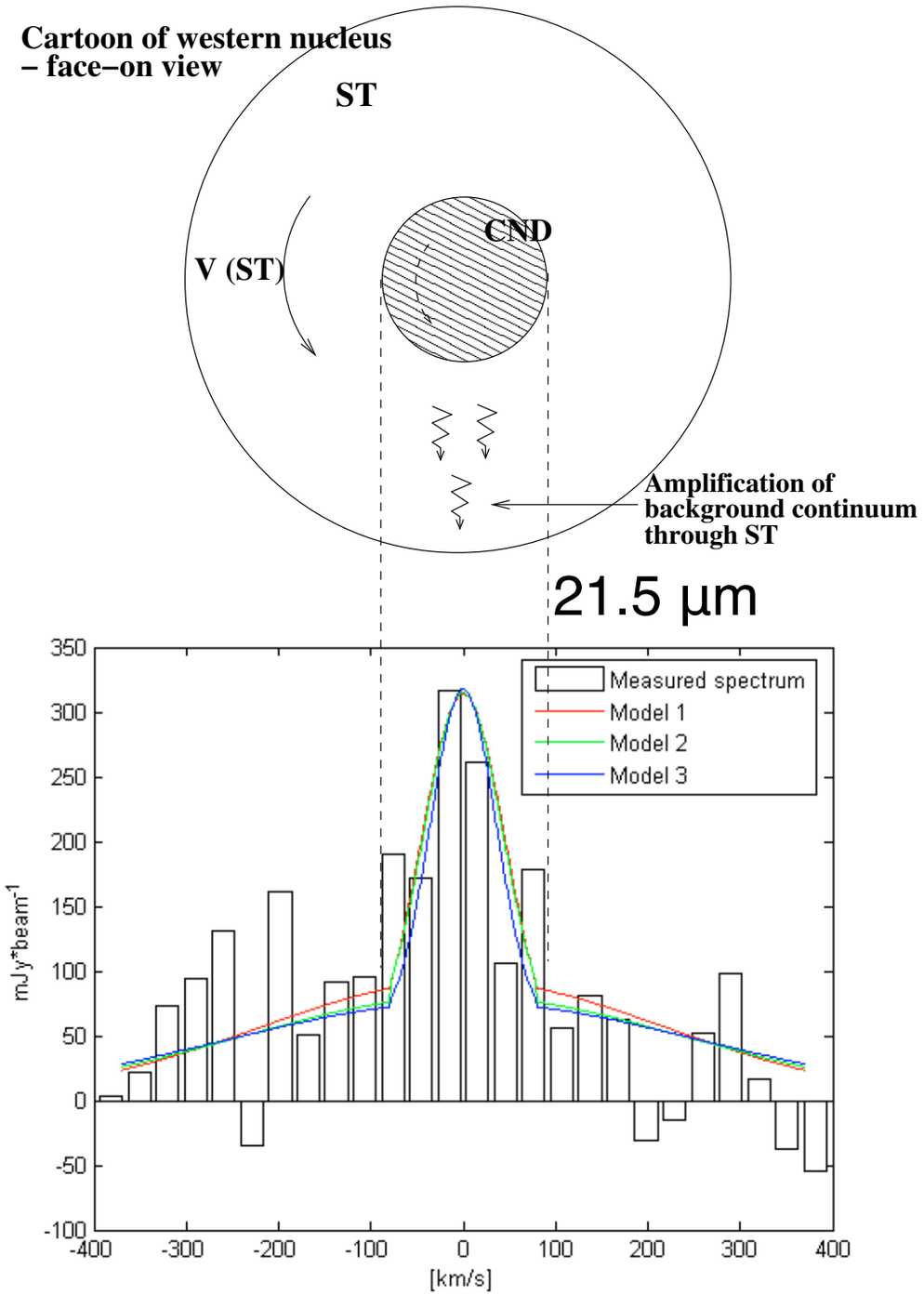


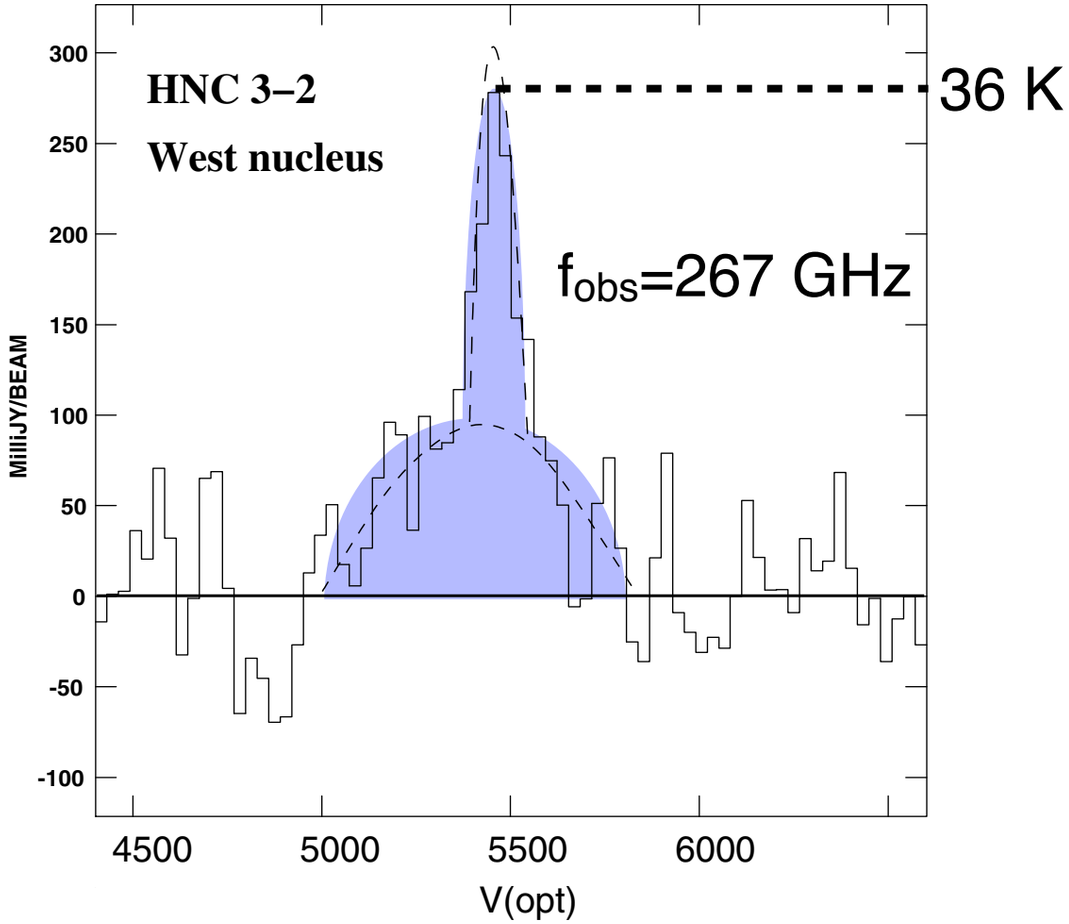
New Extragalactic HNC Maser?

Aalto et al. (2009)



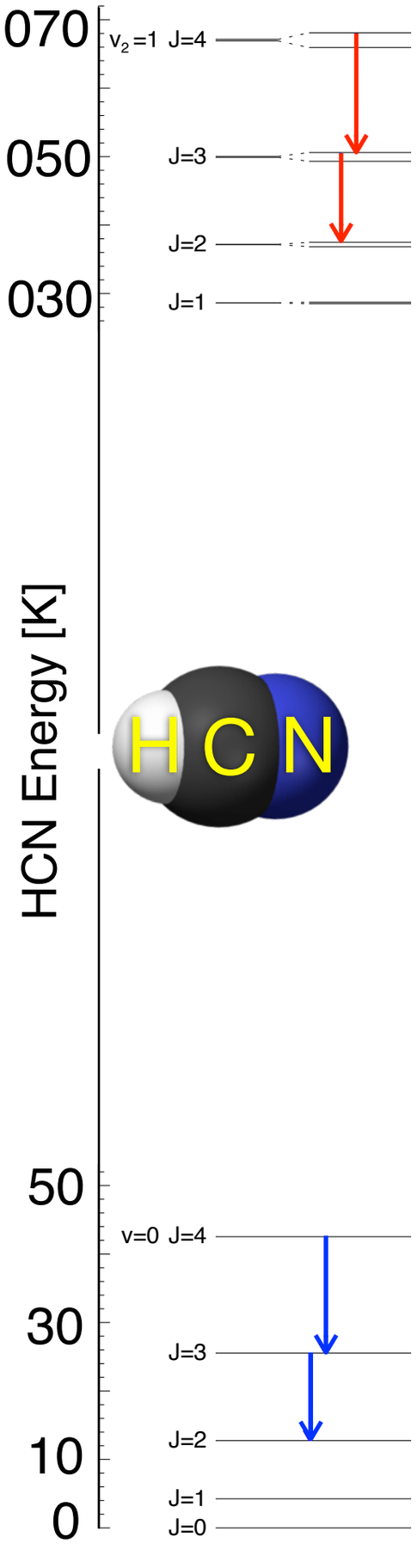


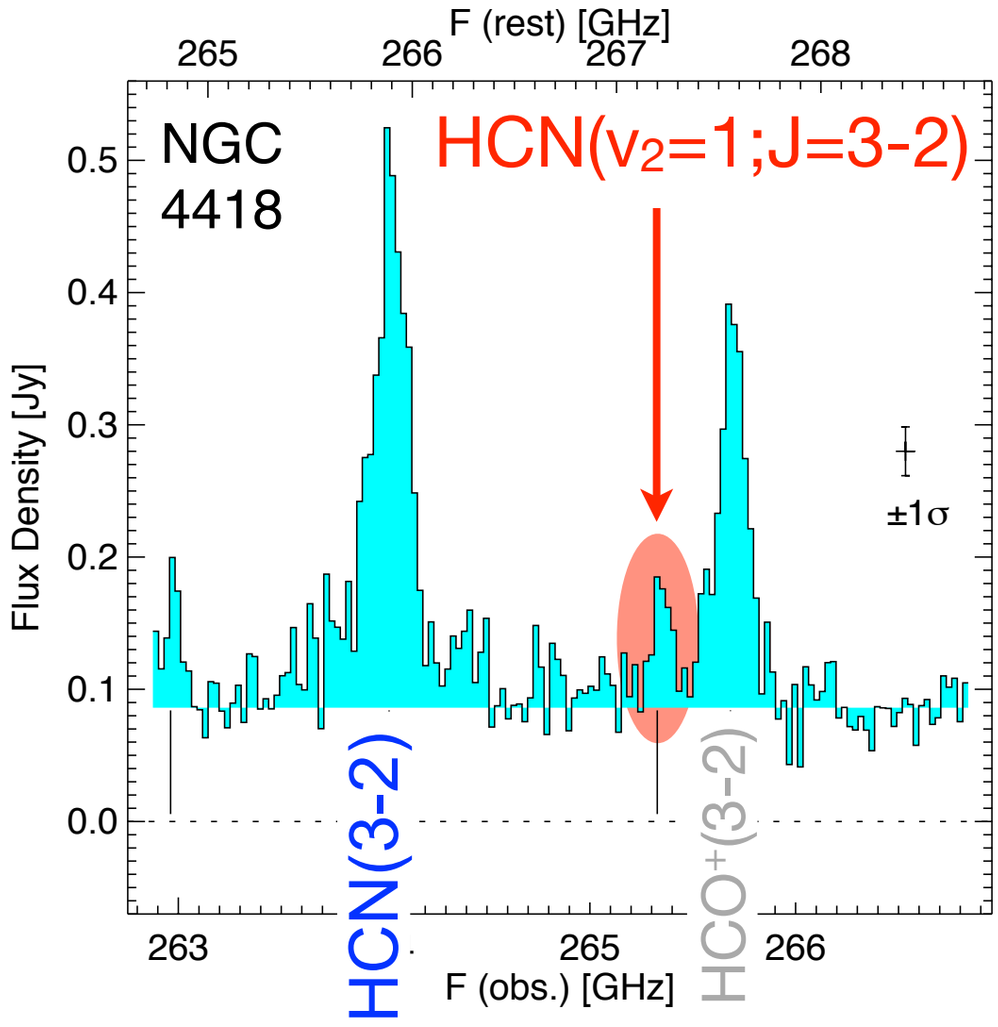


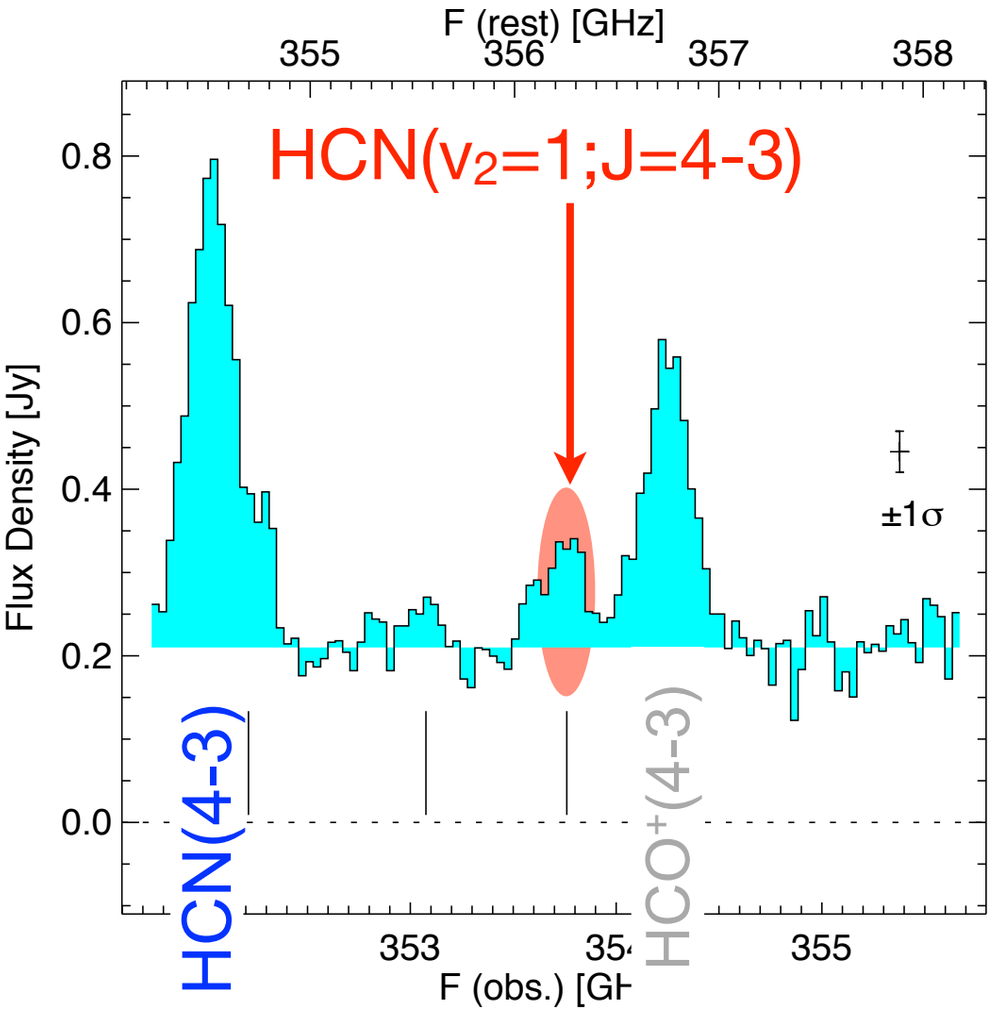


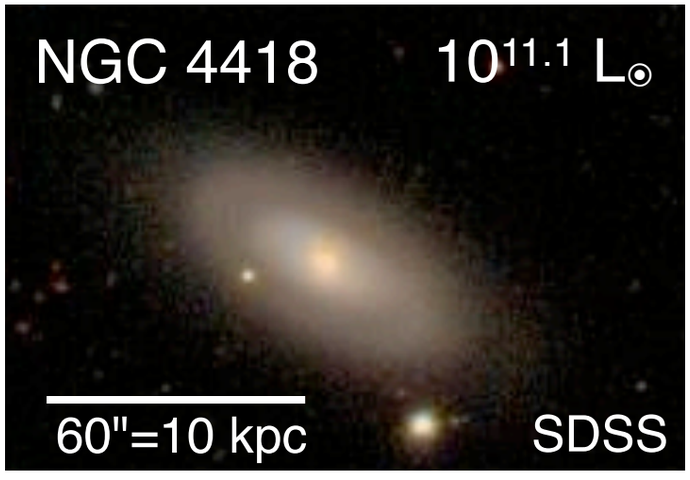
First Extragalactic Rotational lines from Vibrationally Excited HCN

Sakamoto et al. (2011)



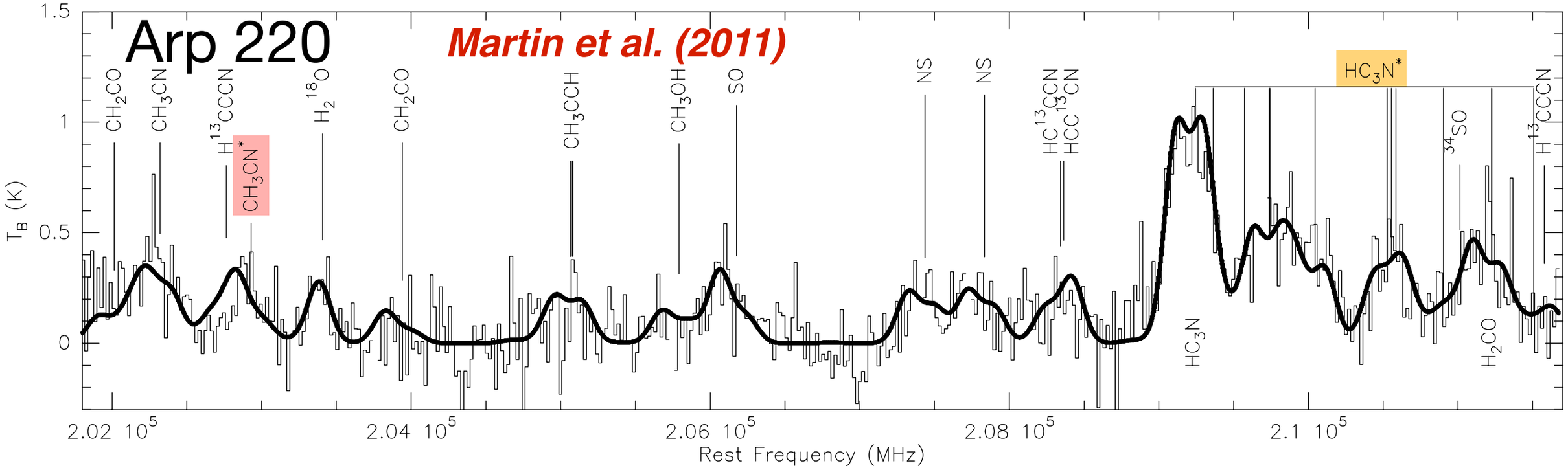






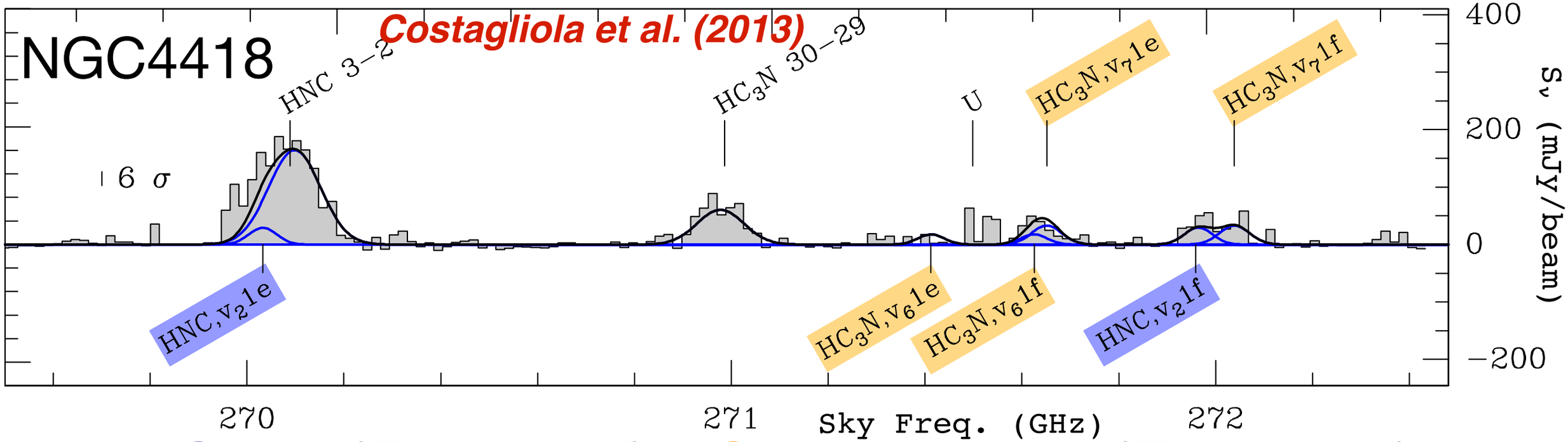
- T_{vib} ~ 230 K
- IR-pumping (14μm)
- Second extragalactic ro-vib line @ sub/mm, after HC_3N

More Vibrationally-Excited Molecules



CH_3CN v_8=1 (T_{vib} ~ 400-450 K), HC_3N v_7=1,2, v_6=1 (T_{vib} ~ 400 K)

(E_u/k ~ 700 K) (E_u/k ~ 450, 700, 850 K)

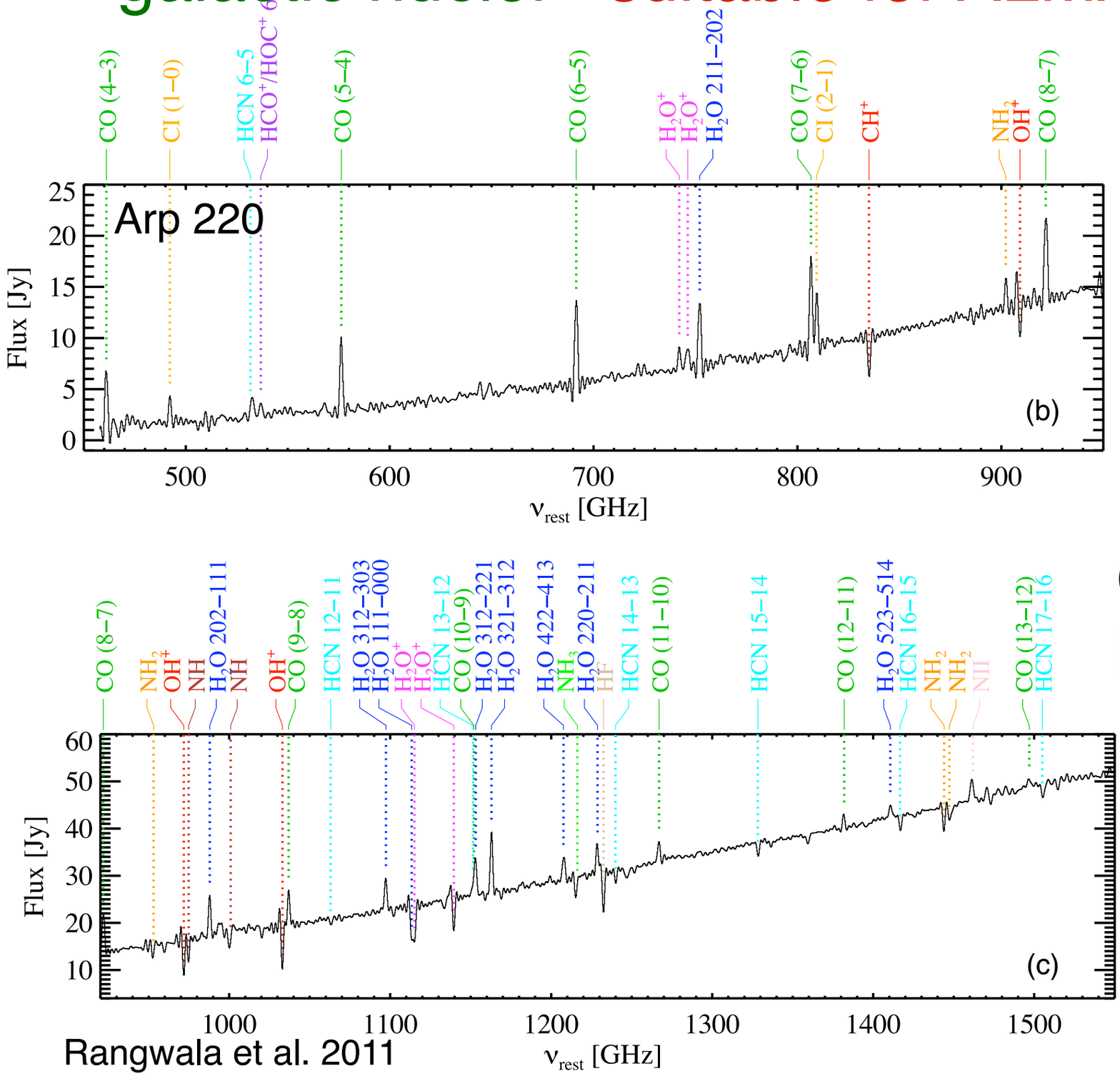


HNC v_2=1 (T_{vib} ~ 350 K), HC_3N v_7=1,2, v_6=1 (T_{vib} ~ 315 K)

(E_u/k ~ 690 K)

Vibrationally-Excited Molecules

New tools to study ***hot molecular gas*** in luminous galactic nuclei - suitable for ALMA high-res imaging



Rangwala et al. 2011

Herschel detection

up to

CO(13-12), E_u/k=503 K

HCN(17-16), E_u/k=650 K

at

1.5 THz

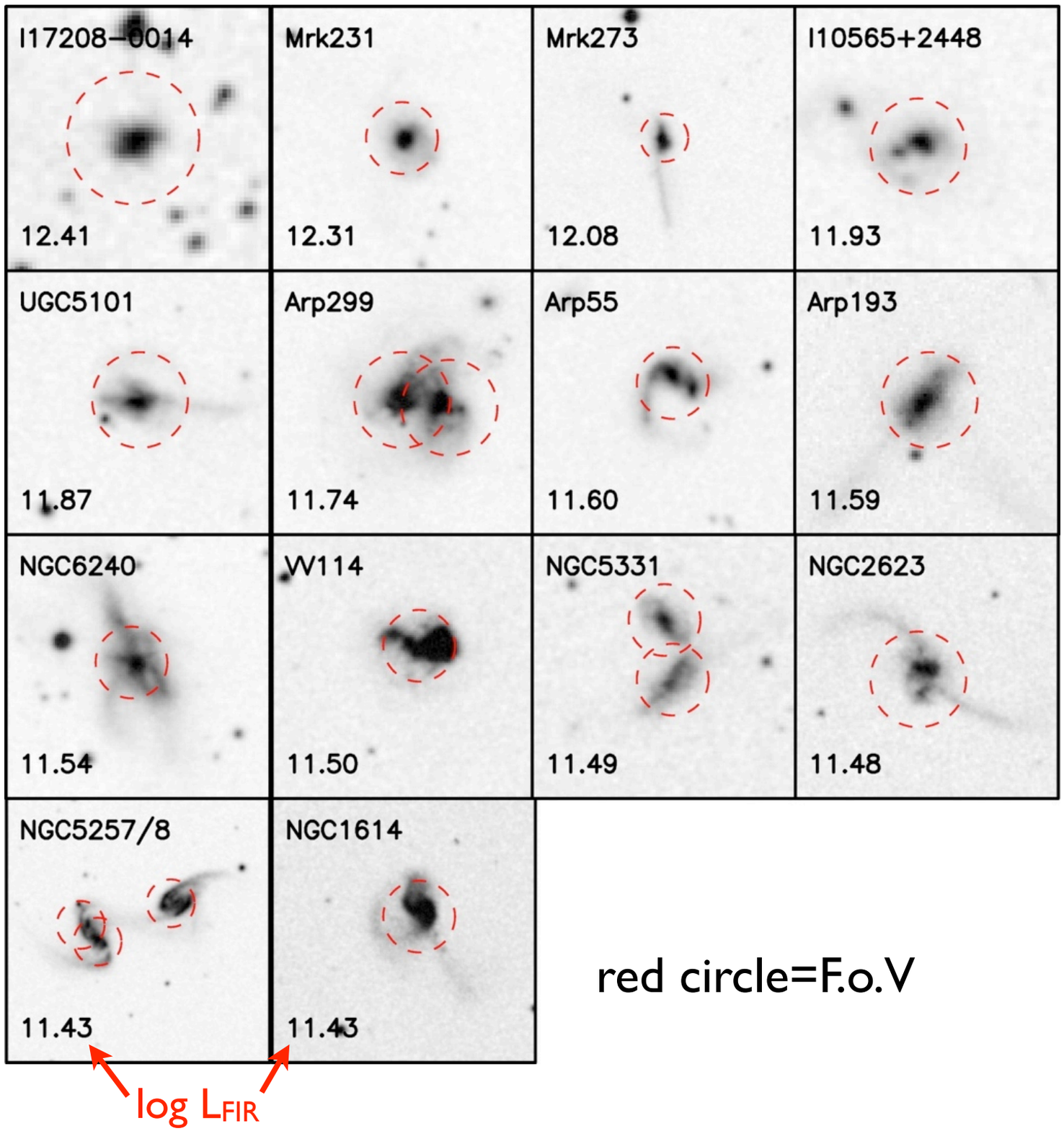
no high-res. imaging at 1.5 THz for some time

U/LIRG Legacy Project

SMA 10 @ Cambridge, MA, 2014 May

SMA Legacy Survey of U/LIRGs

Ultra-Luminous InfraRed Galaxies



red circle=F.o.V

Wilson et al. (2008)
Iono et al. (2009)
Silwa et al. (2012,13)

D_L < 200 Mpc

log L_{FIR} > 11.4

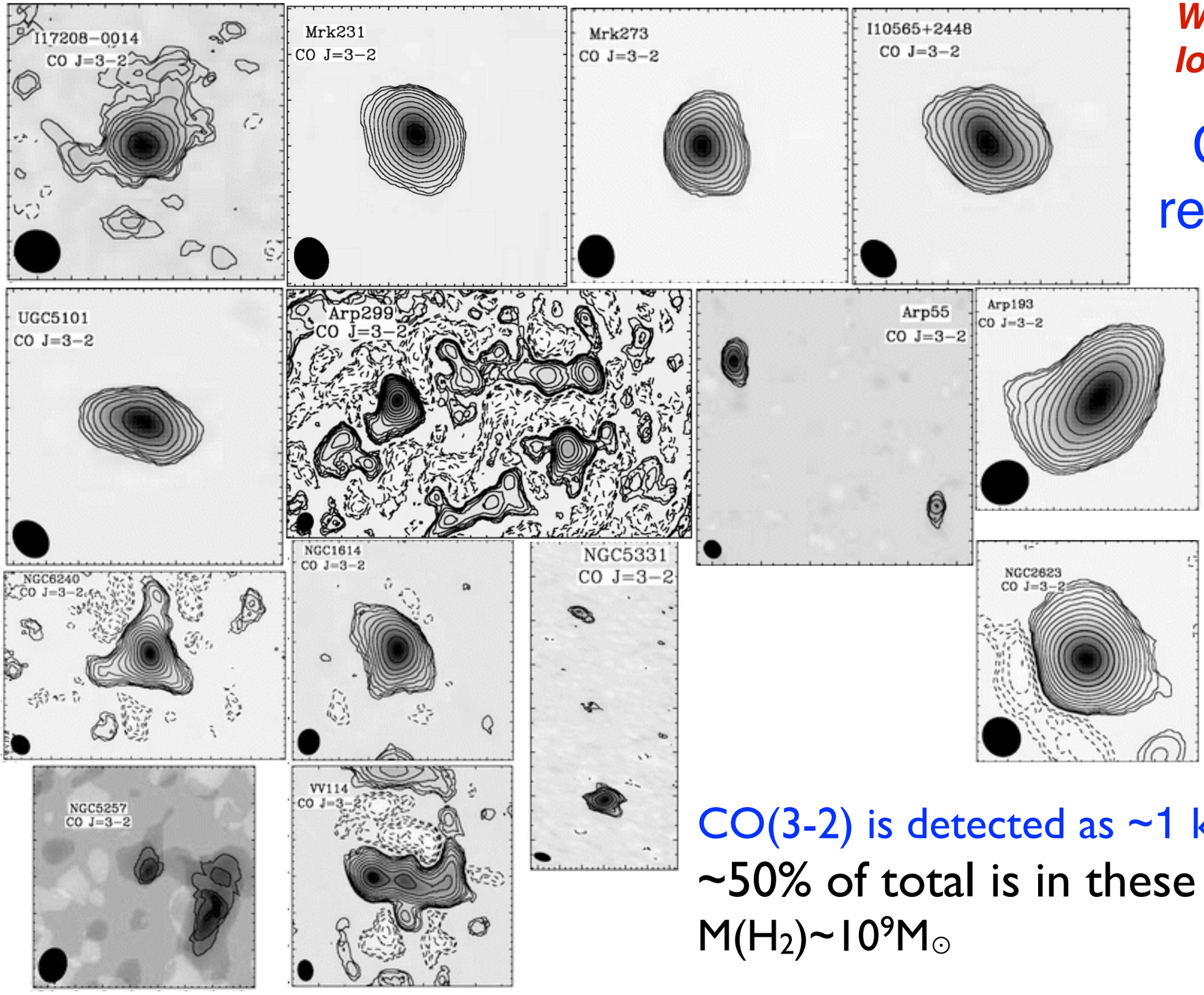
dec. > -20°

Observed 14 (out of 39).

CO(3-2), CO(2-1), HCO^+ (4-3), continuum

~1kpc (1") resolution

SMA Legacy Survey of U/LIRGs



Wilson et al. (2008)
Iono et al. (2009)

CO(3-2)
res. ≈ 1kpc

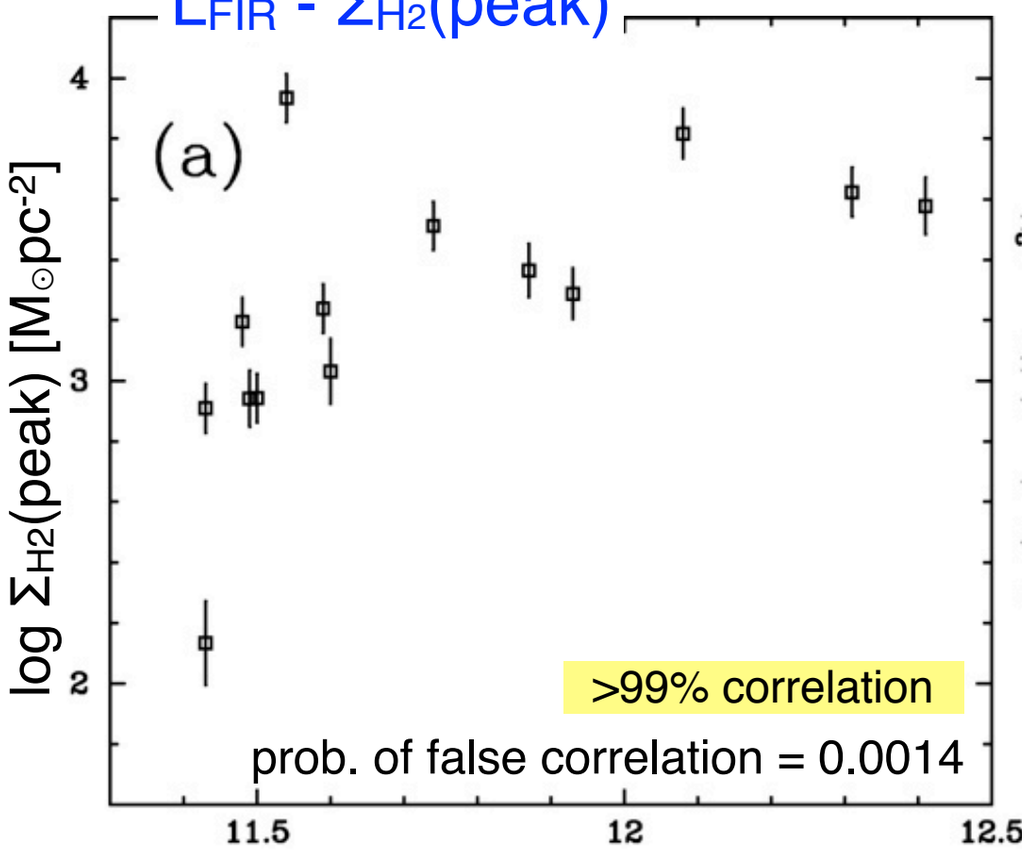
CO(3-2) is detected as ~1 kpc peaks.
~50% of total is in these peaks.
$M(H_2) \sim 10^9 M_\odot$

(Wilson et al. 2008)

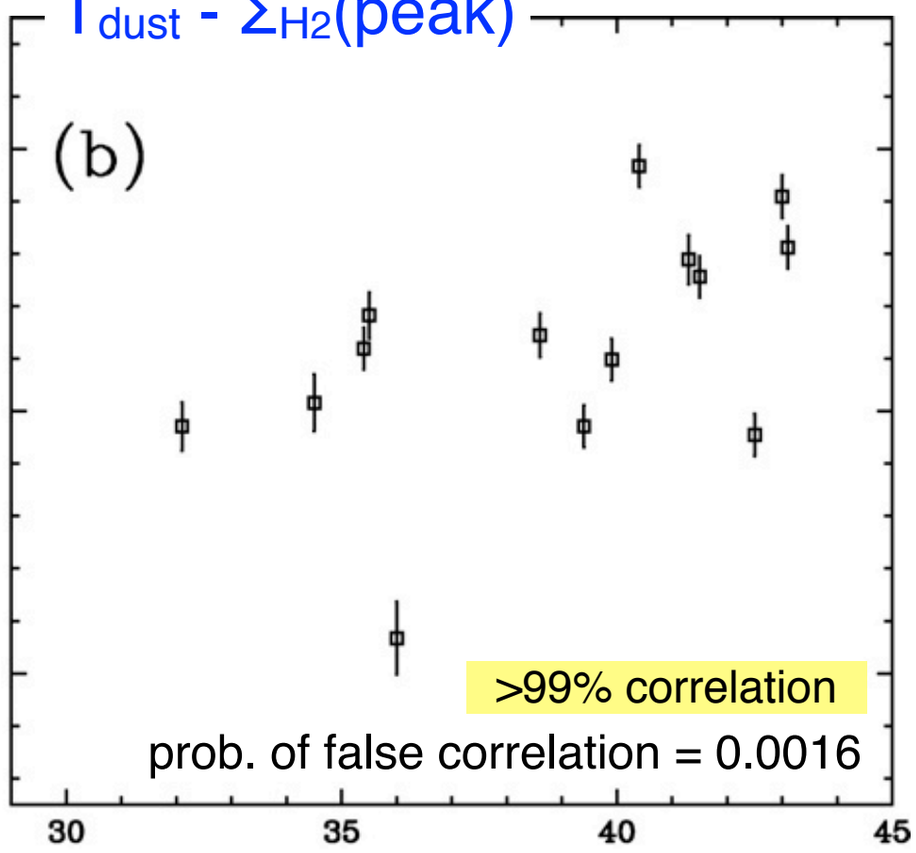
SMA U/LIRG Survey : Correlations

Wilson et al. (2008)

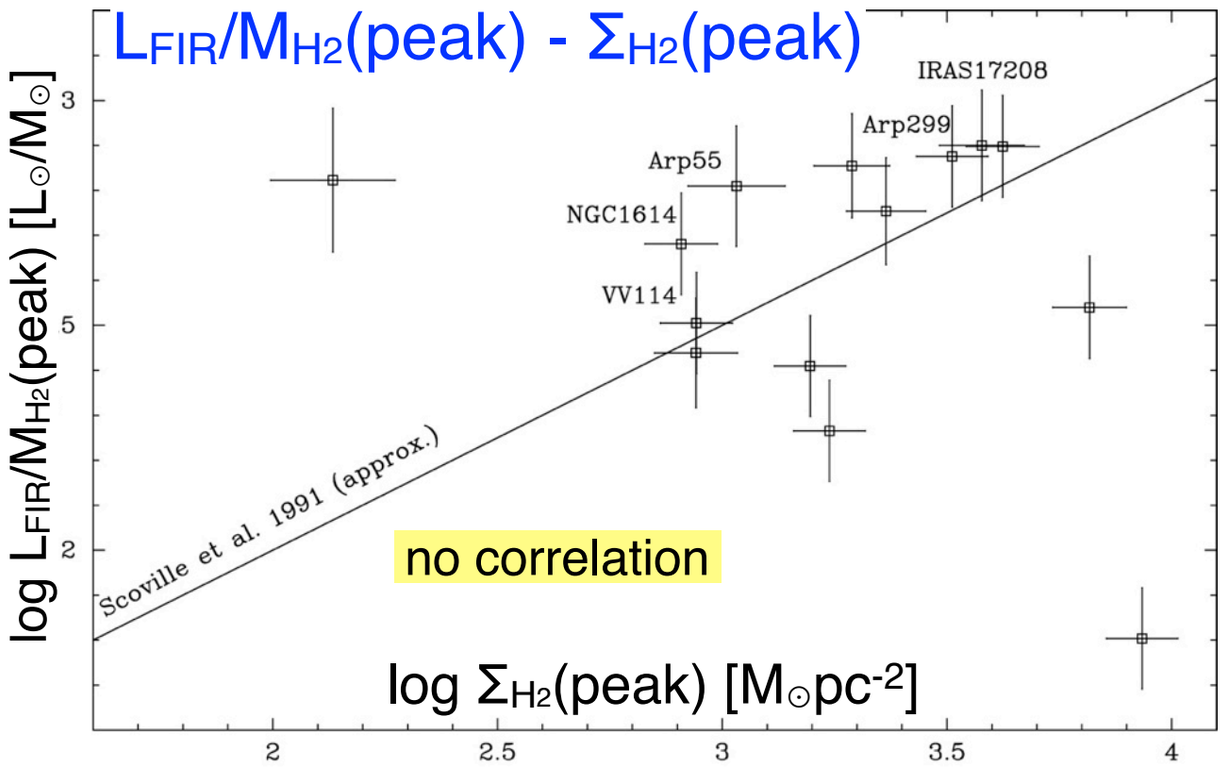
L_{FIR} - Σ_{H_2}(peak)



T_{dust} - Σ_{H_2}(peak)



L_{FIR}/M_{H_2}(peak) - Σ_{H_2}(peak)



More gas to the center (~kpc)

⇒ More Luminous (higher L_{FIR})

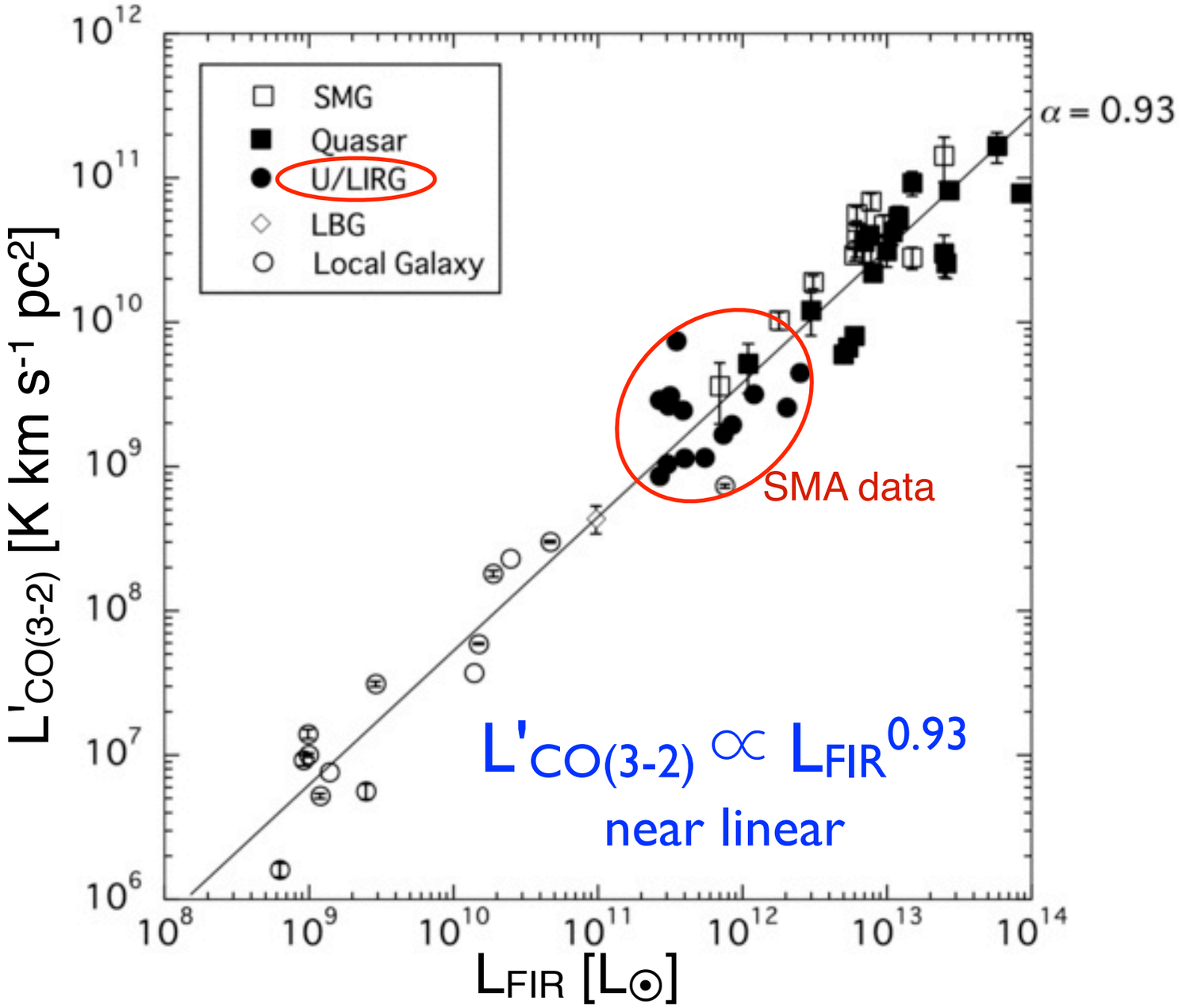
w/o increasing efficiency (M_{gas}/L_{IR})

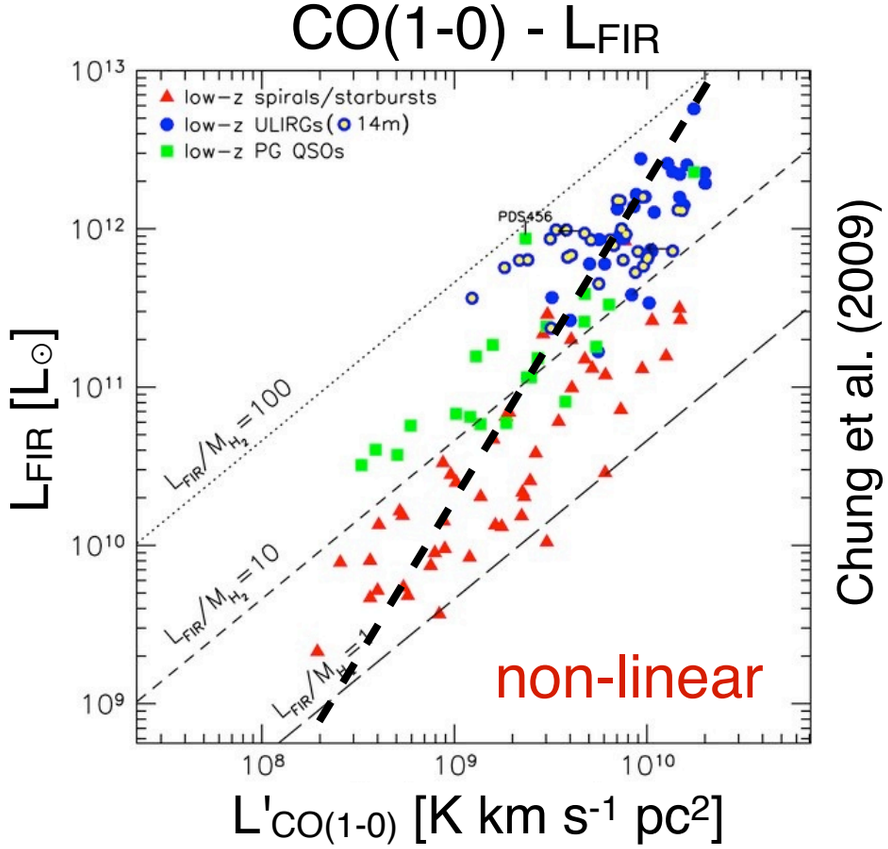
c.p. CO(1-0) studies by
Scoville et al. 1991 (ApJ);
Okumura et al. 1991 (IAUS 146)

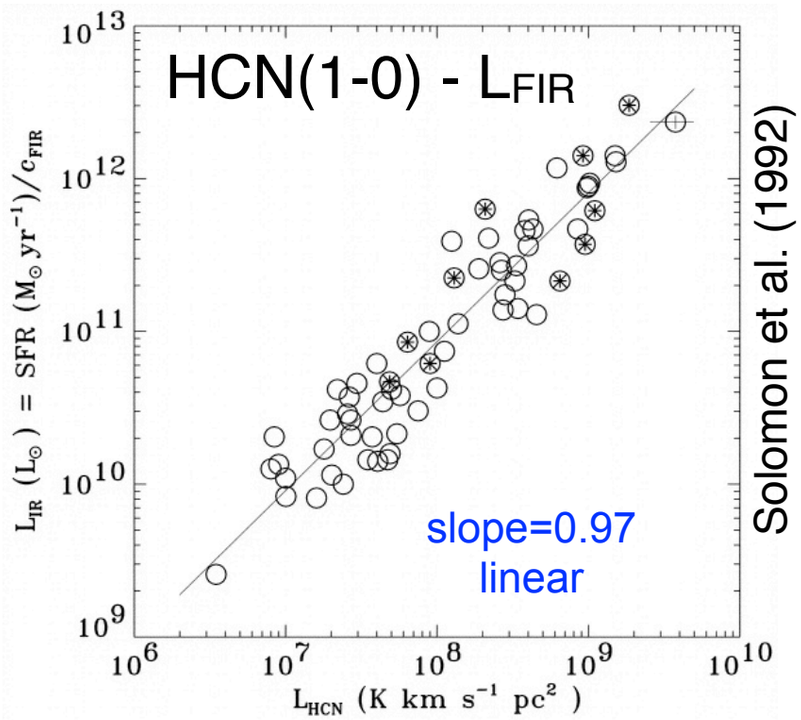
⇒ Warmer ISM (higher T_{dust})

SMA U/LIRG Survey : Correlations

Iono et al. (2009)







LCO(3-2) - LFIR : near linear correlation

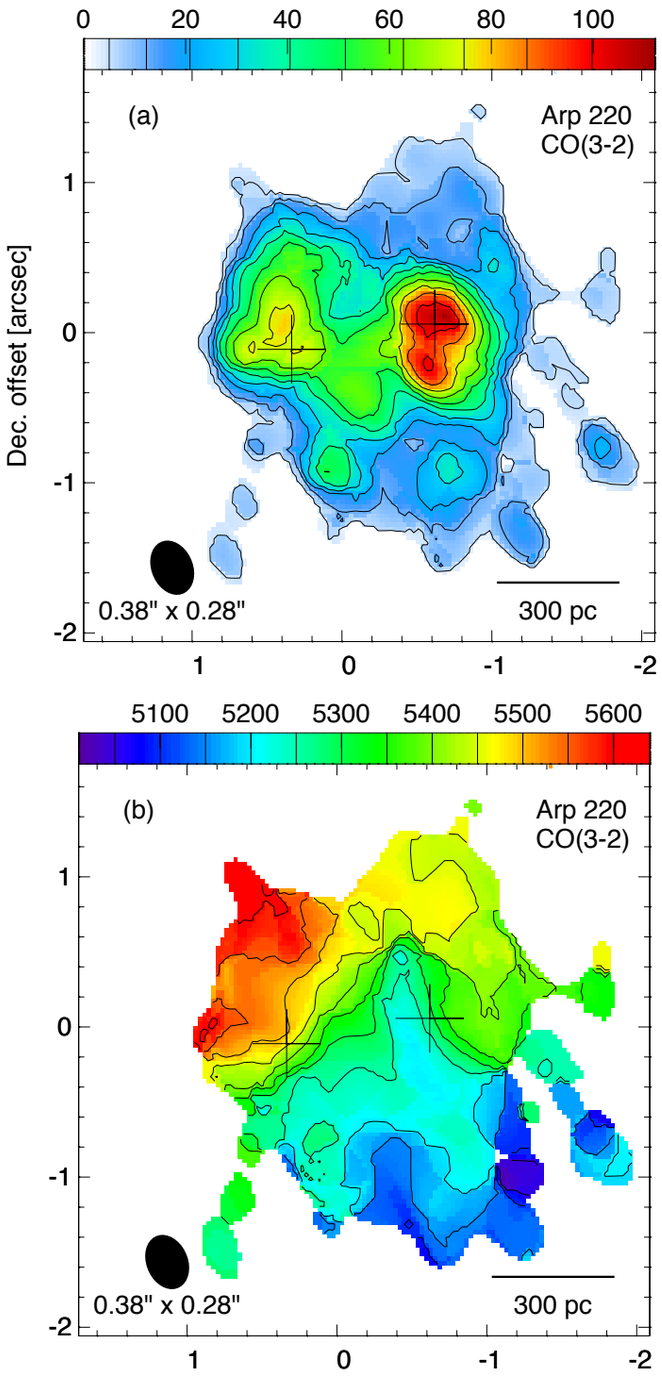
- CO(3-2) traces SF dense mol. gas
- LFIR/LCO(3-2) = (dense gas) SFE ~ constant

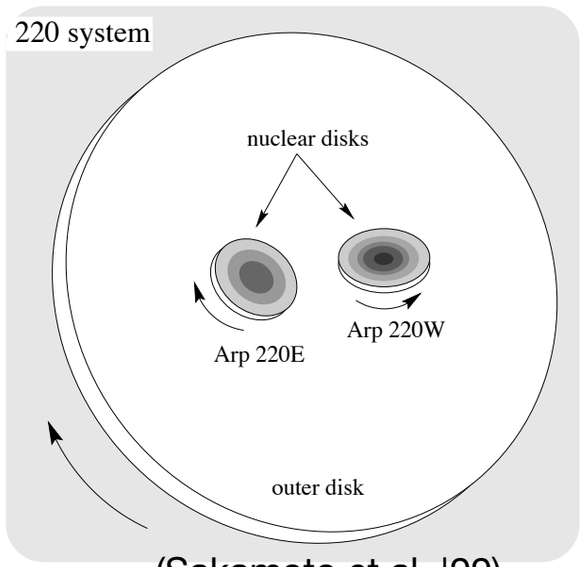
U/LIRG: Highest resolution

SMA 10 @ Cambridge, MA, 2014 May

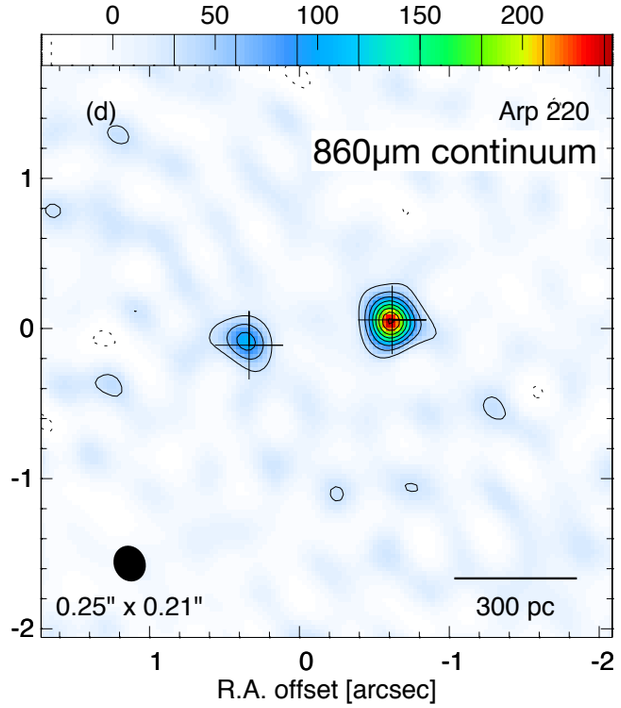
Arp 220 @ 860μm, 0.23"

Sakamoto et al. (2008)





(Sakamoto et al. '99)



Arp 220 W:

Deconvolved Size

d ~ 0.15"-0.22" = 50-80 pc

Deconvolved (peak) T_b

T_b = 90-160 K $\leq T_{dust}$ ($\tau_{860} \sim 1$)

Luminosity

$L_{bol} \approx \sigma T_d^4 \times \pi\, d^2 \geq (2\text{-}3)\times 10^{11}\ L_\odot$

Luminosity surface density

$\Sigma(L_{bol}) \geq 10^{7.6}\ L_\odot\ pc^{-2}$

Dynamical mass (W disk ≈ edge-on)

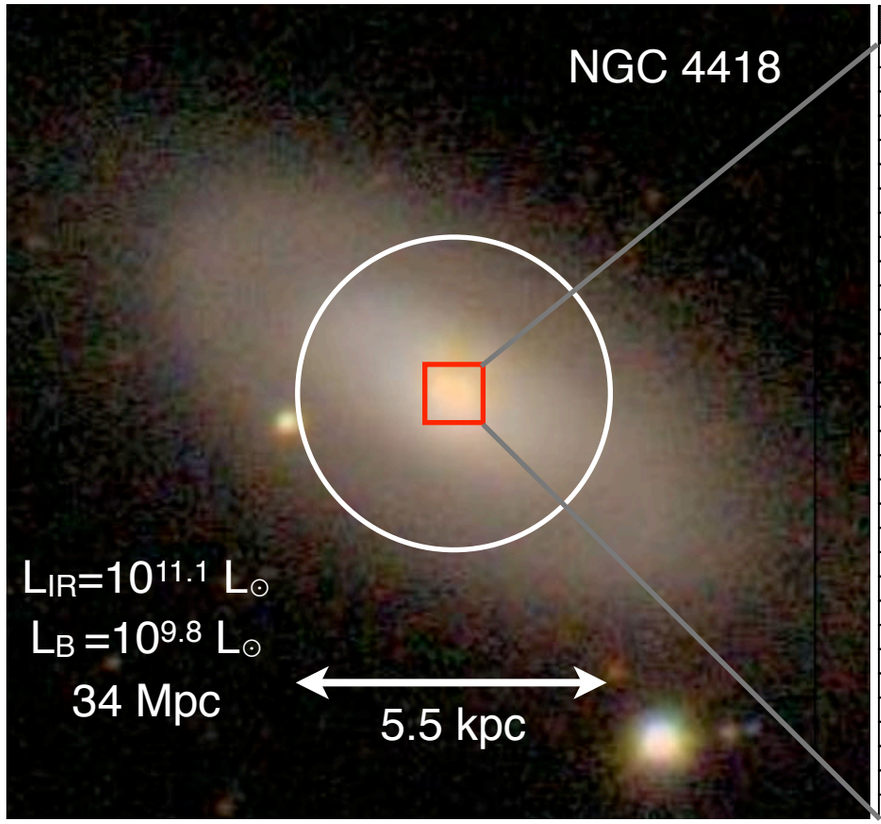
M_{dyn} ($r \leqq 40pc$) ~ $6\times 10^8\ M_\odot$

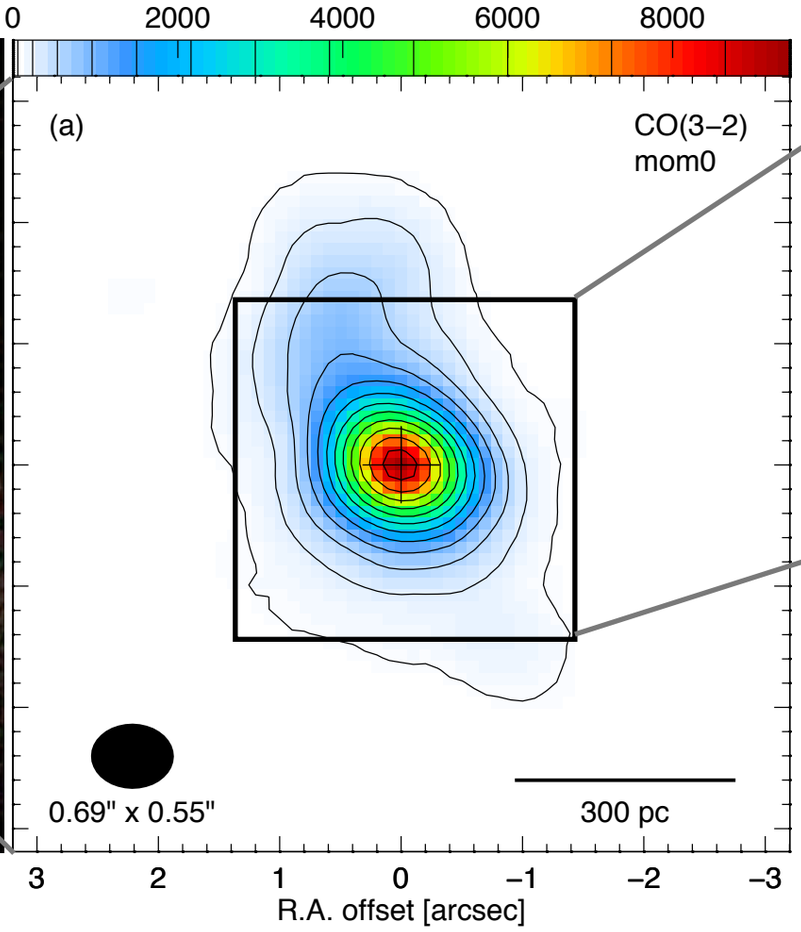
Luminosity-to-Mass ratio

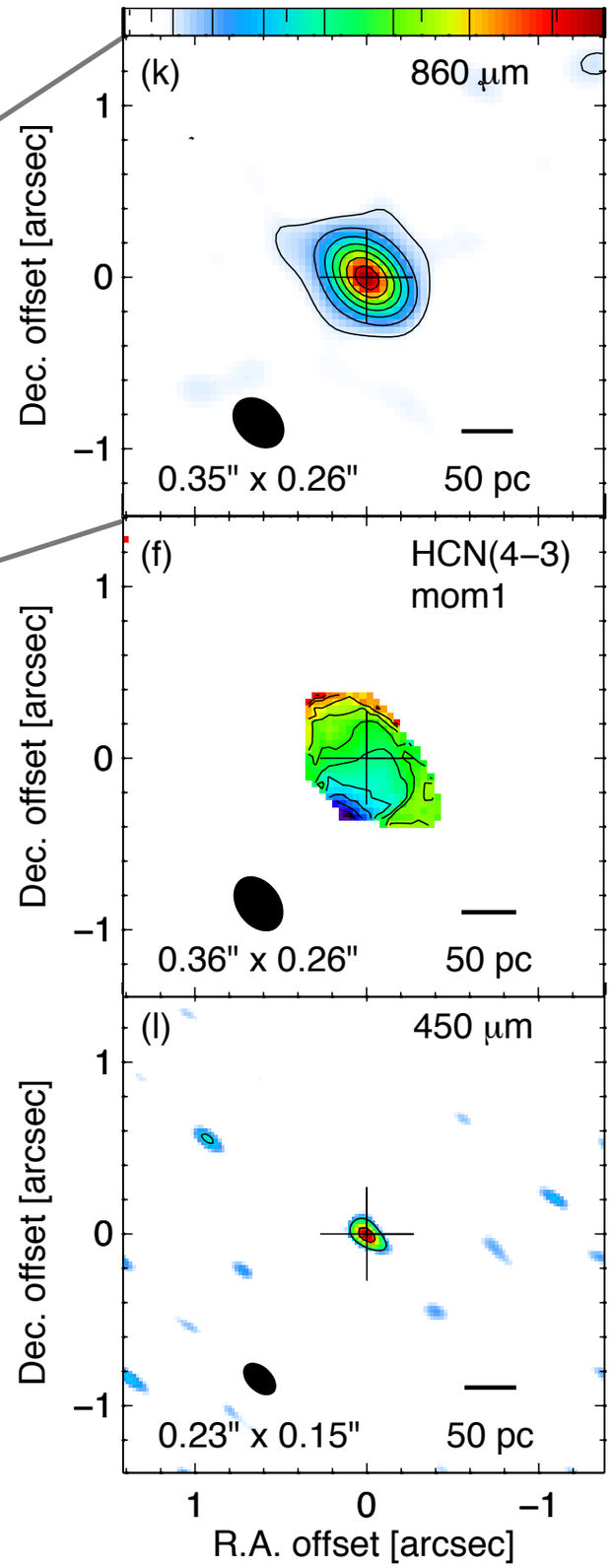
$L/M \gtrsim 400\ L_\odot/M_\odot$ ($r \leqq 40pc$)

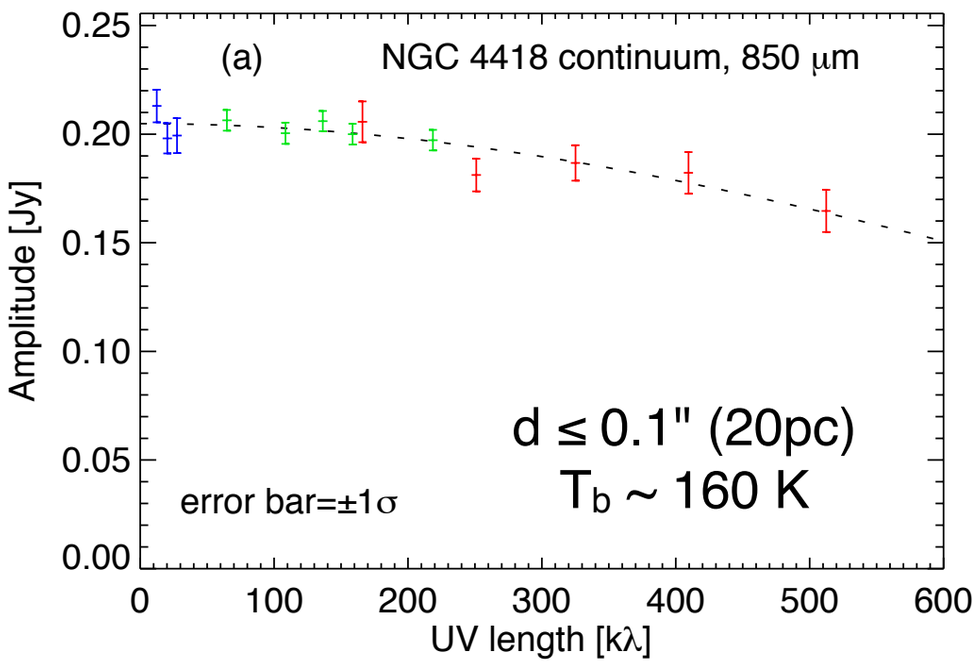
NGC 4418 @ 1300/860/450μm, 0.4/0.3/0.2"

Sakamoto et al. (2013)
Costagliola et al. (2013)









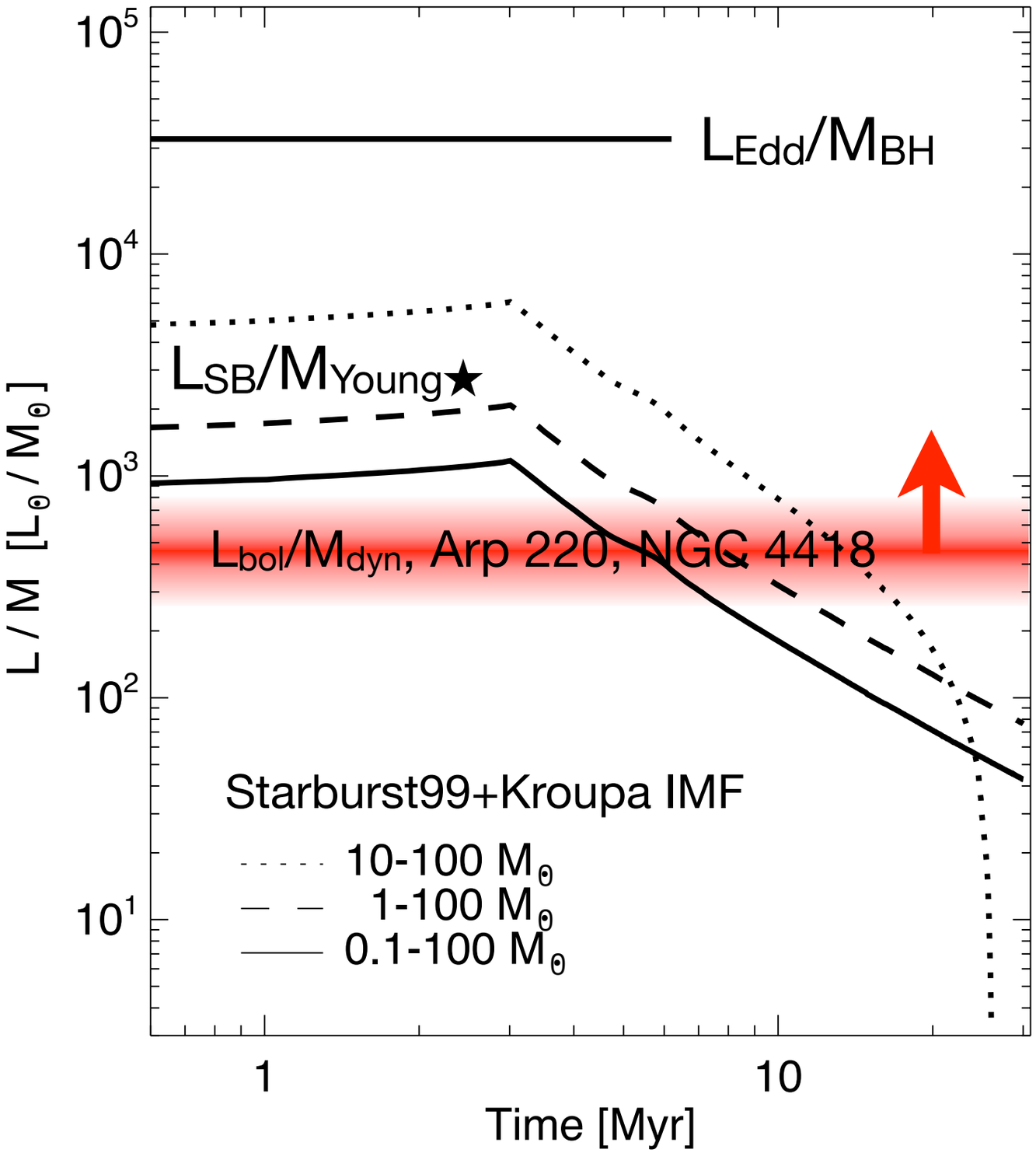
a ~20 pc dusty core

$L_{bol} \sim 10^{11} L_\odot \sim L_{galaxy}$

$L_{bol}/M_{dyn} \sim 500\ L_\odot/M_\odot$

$N_H \geq 10^{25}$ cm^{-2} (Compton thick)

Submm-diagnosis of L_{bol}-source



young SB (<10Myr)
or
AGN+SB

SMA obs.
Arp 220: Sakamoto et al. 2008
N4418: Sakamoto et al. 2013

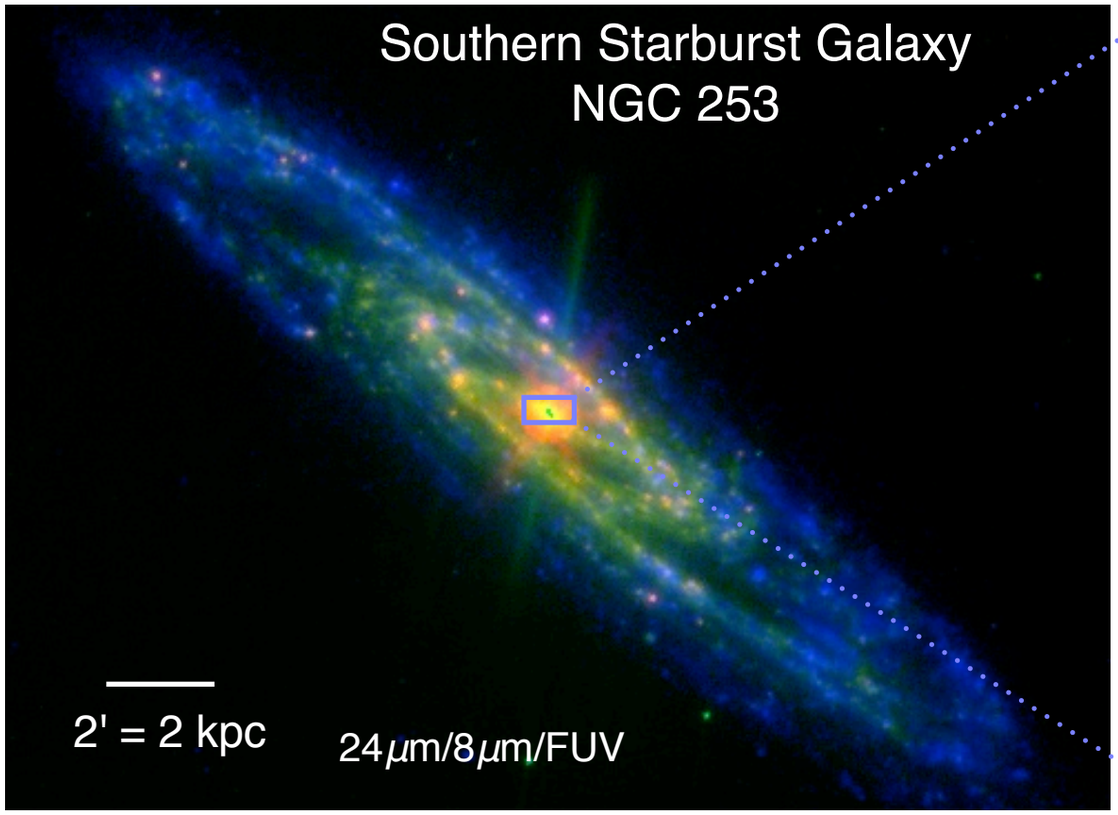
Feedback/Outflows

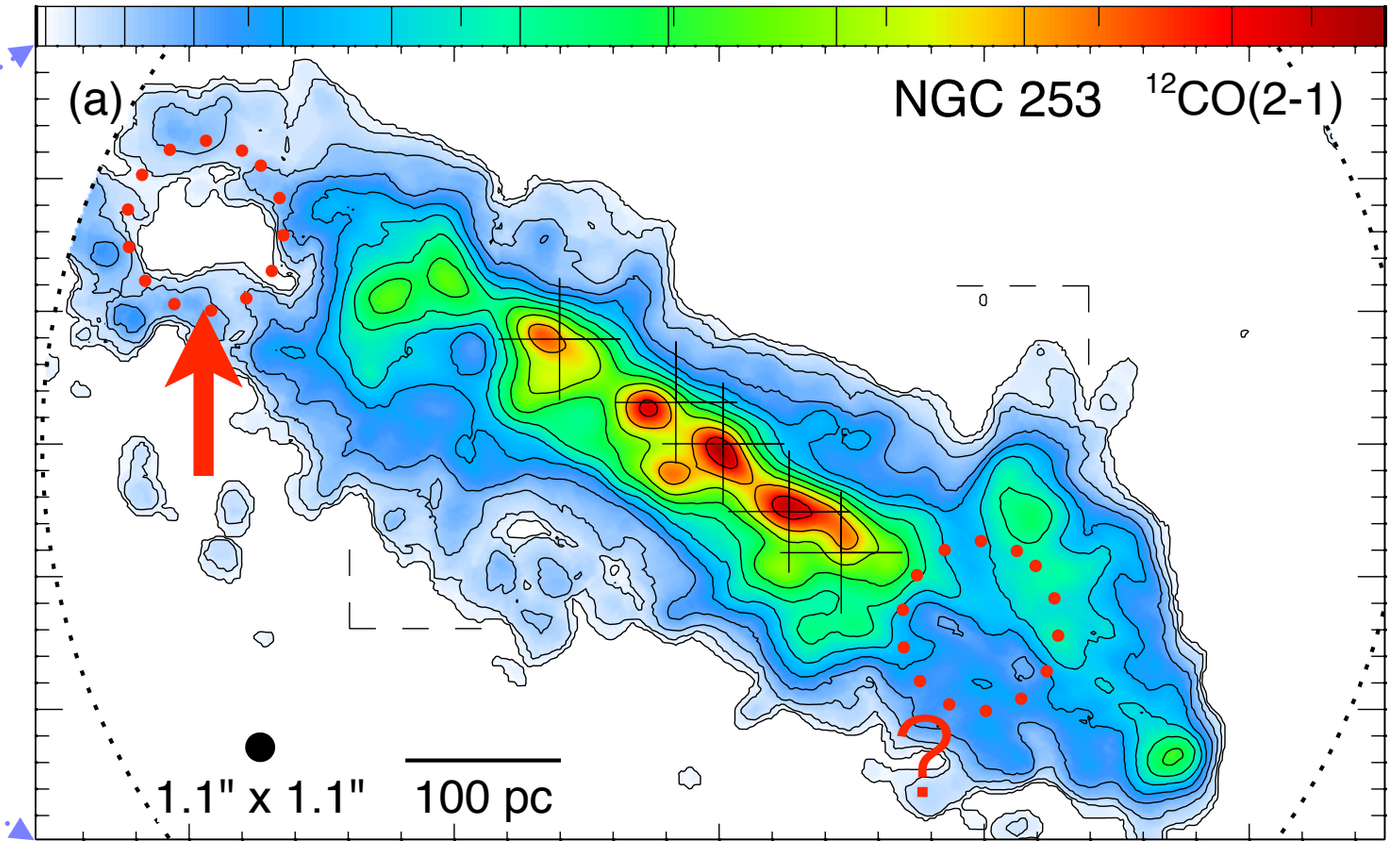
NGC 1266 → Next Talk

SMA 10 @ Cambridge, MA, 2014 May

Feedback: Mol. Superbubbles

Sakamoto et al. (2006, 2011)





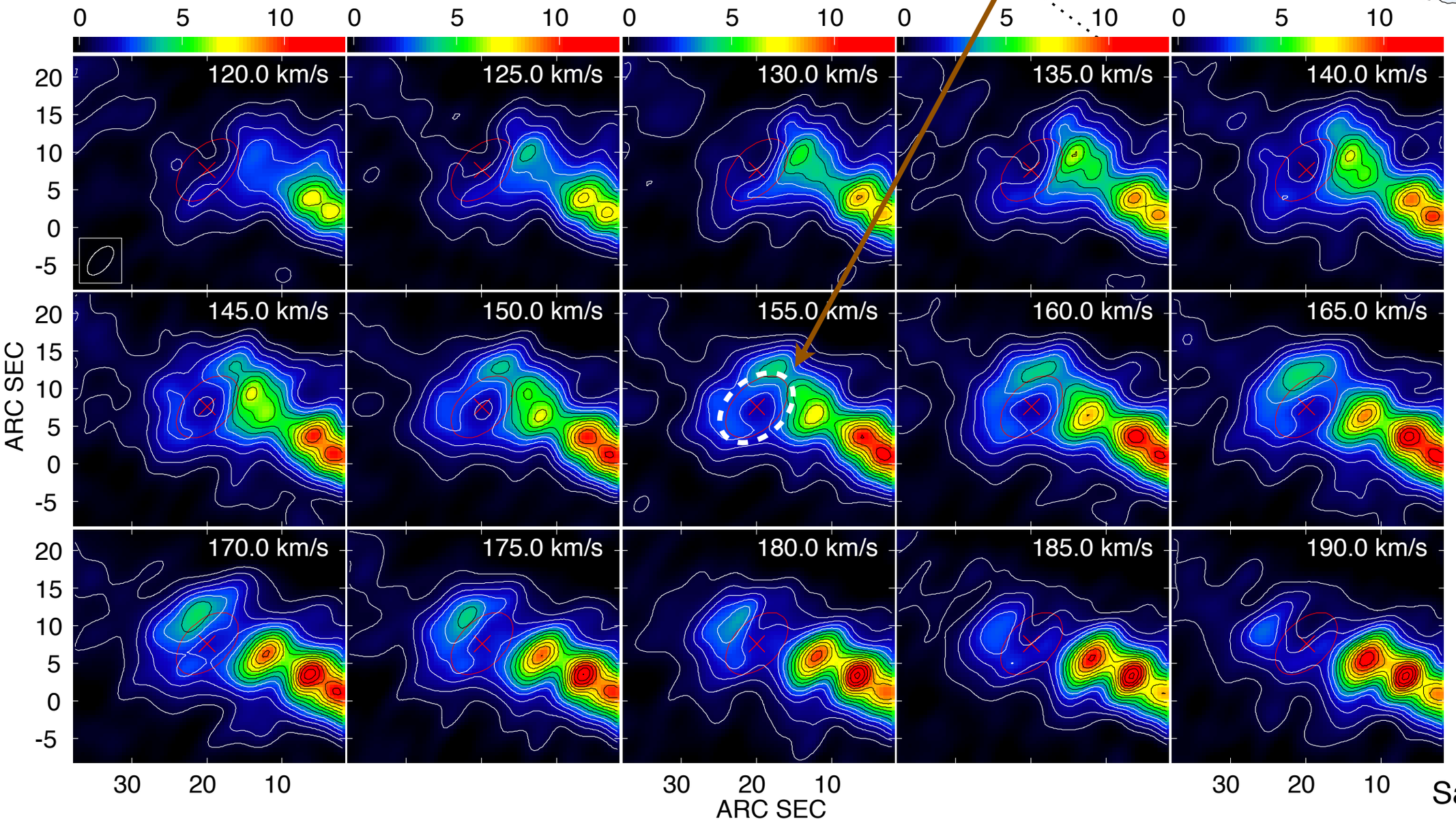
(Sakamoto, Mao, Matsushita et al. 2011)
(Sakamoto, Ho, Iono, Keto, Mao et al. 2006)

Cavities in the central molecular zone

Feedback: Mol. Superbubbles

Cavity
- D ~ 100 pc
- dV ~ 100 km/s

Superbubble ? If so,
- Age ~ 1 Myr
- E ~ 10^{46} J ~ 100 E_{SN}

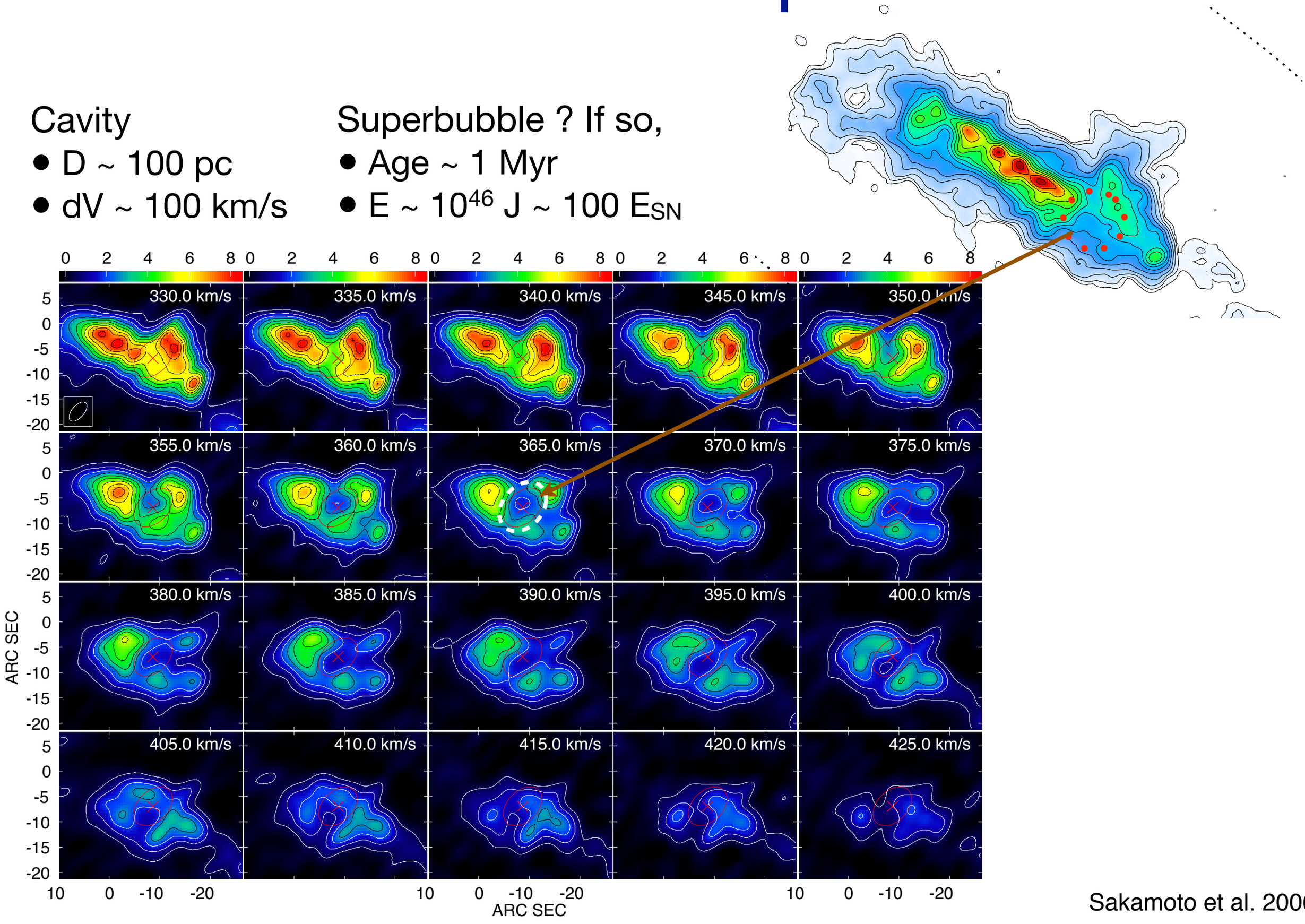


Sakamoto et al. 2006

Feedback: Mol. Superbubbles

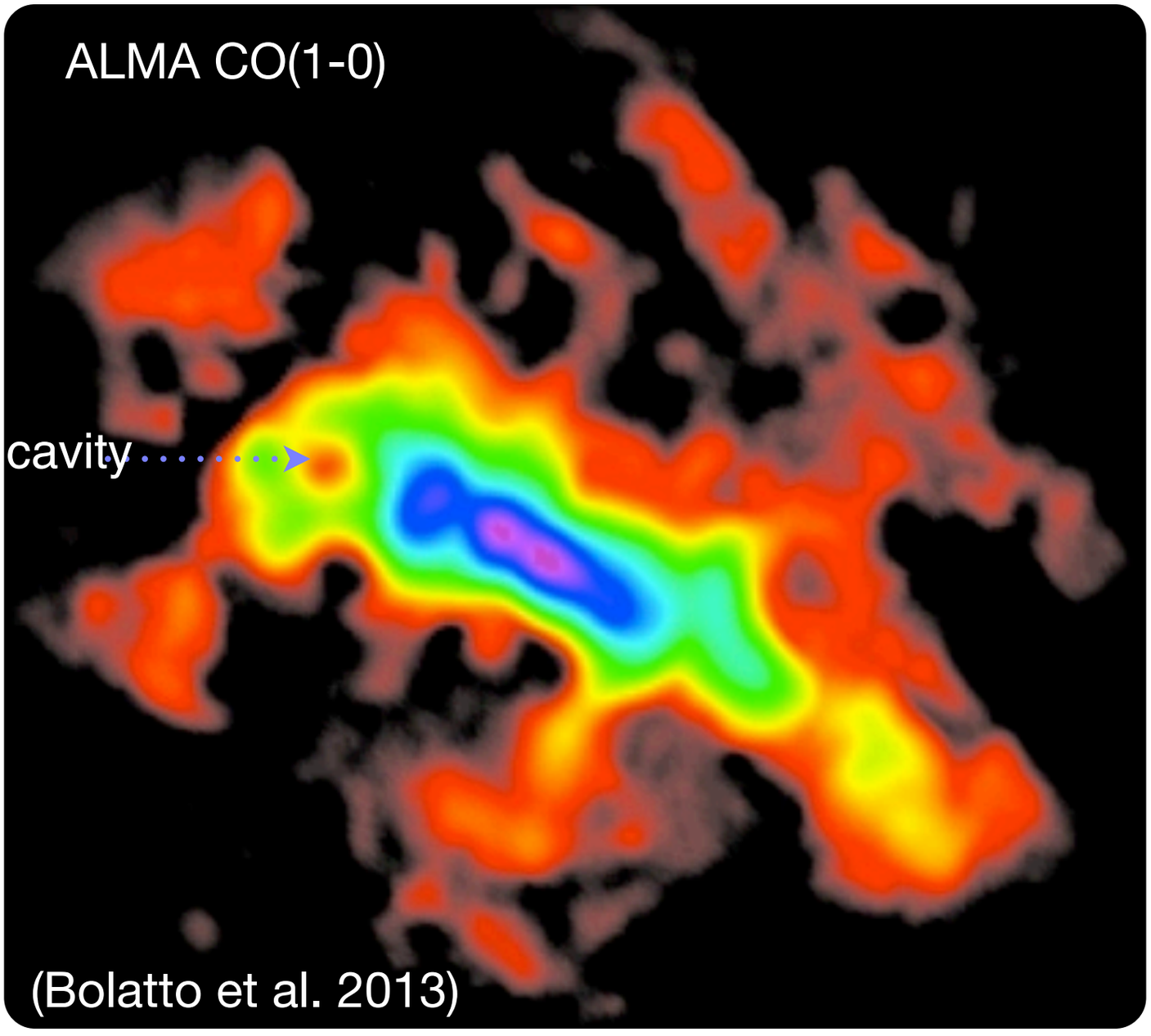
Cavity
- D ~ 100 pc
- dV ~ 100 km/s

Superbubble ? If so,
- Age ~ 1 Myr
- E ~ 10^{46} J ~ 100 E_{SN}



Sakamoto et al. 2006

Feedback: Mol. Outflow

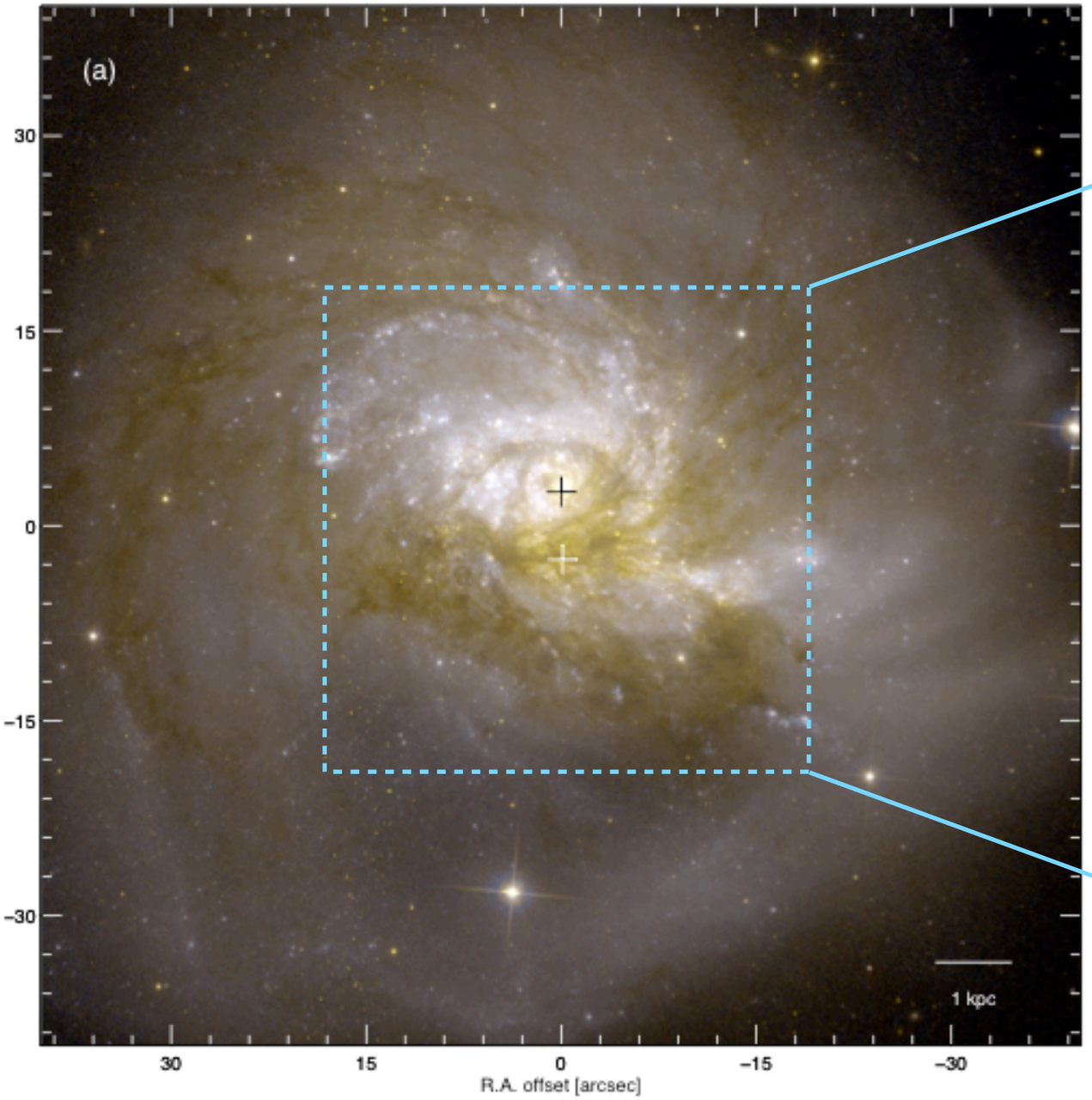


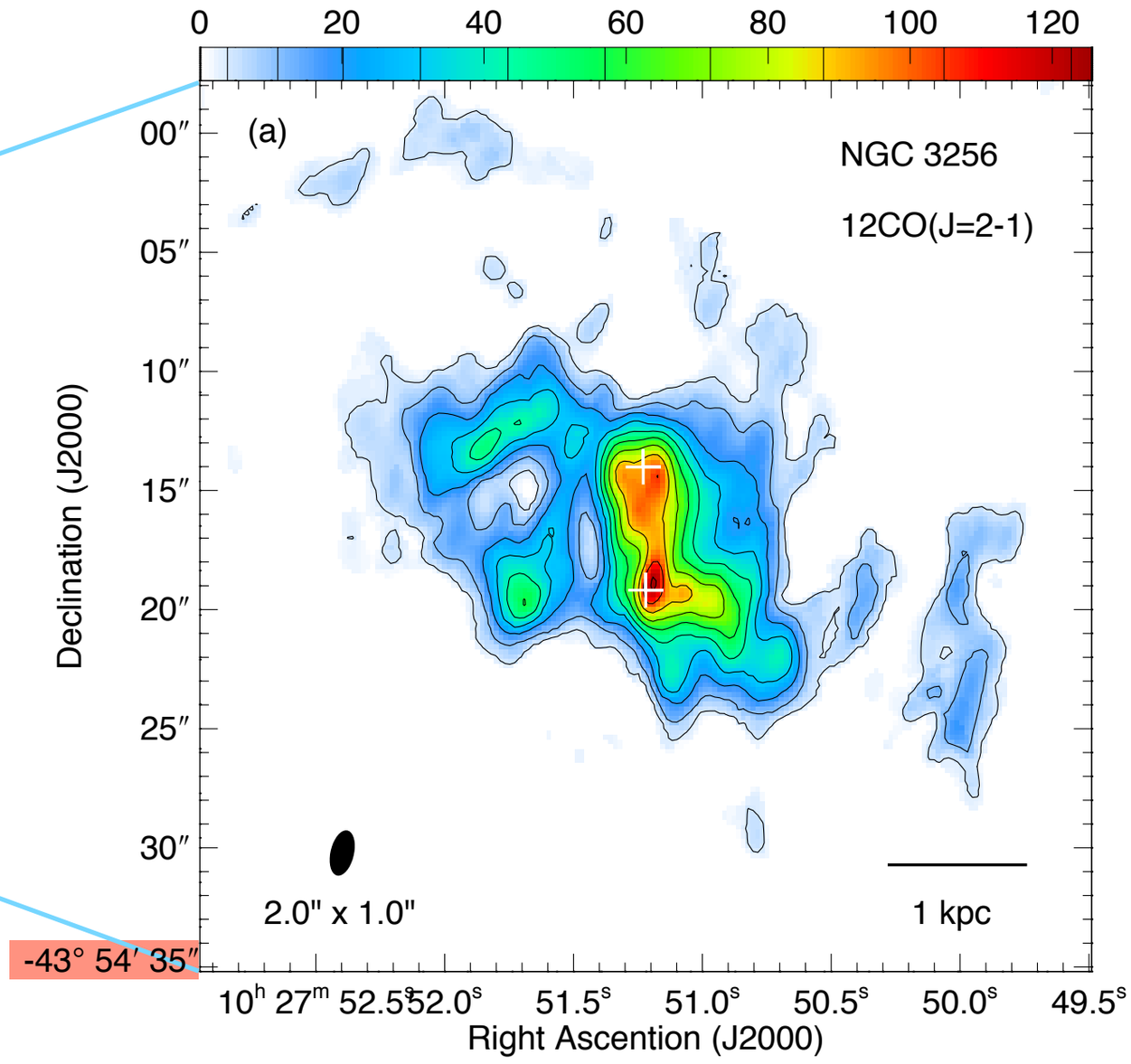
$dM_w/dt \approx 9\ M_\odot\ yr^{-1} \geq SFR$

Galactic Molecular Outflow from CO line wings

Sakamoto, Ho, Peck (2006)

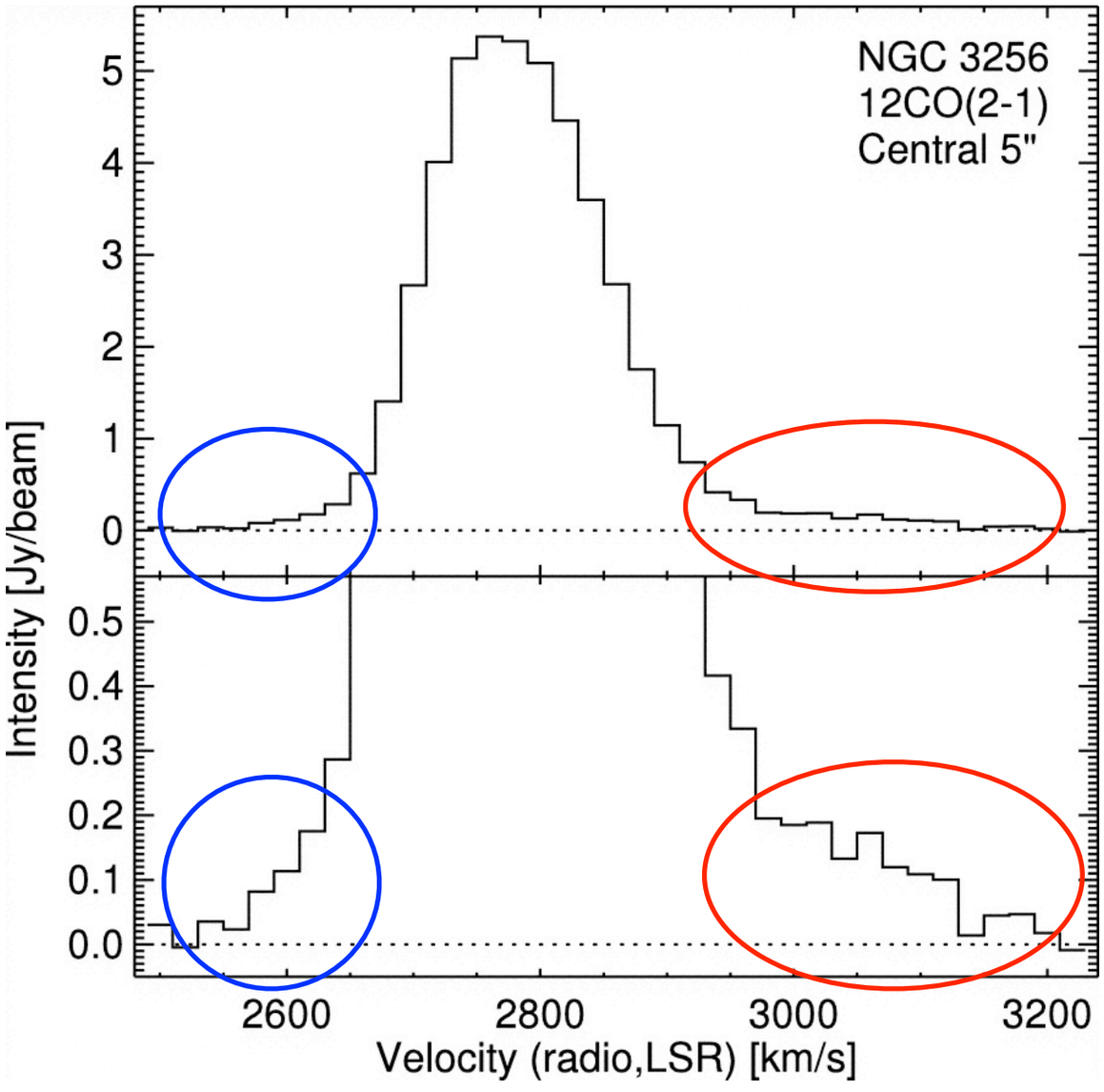
NGC 3256, merger, $L_{IR}=4x10^{11}L_{\odot}$

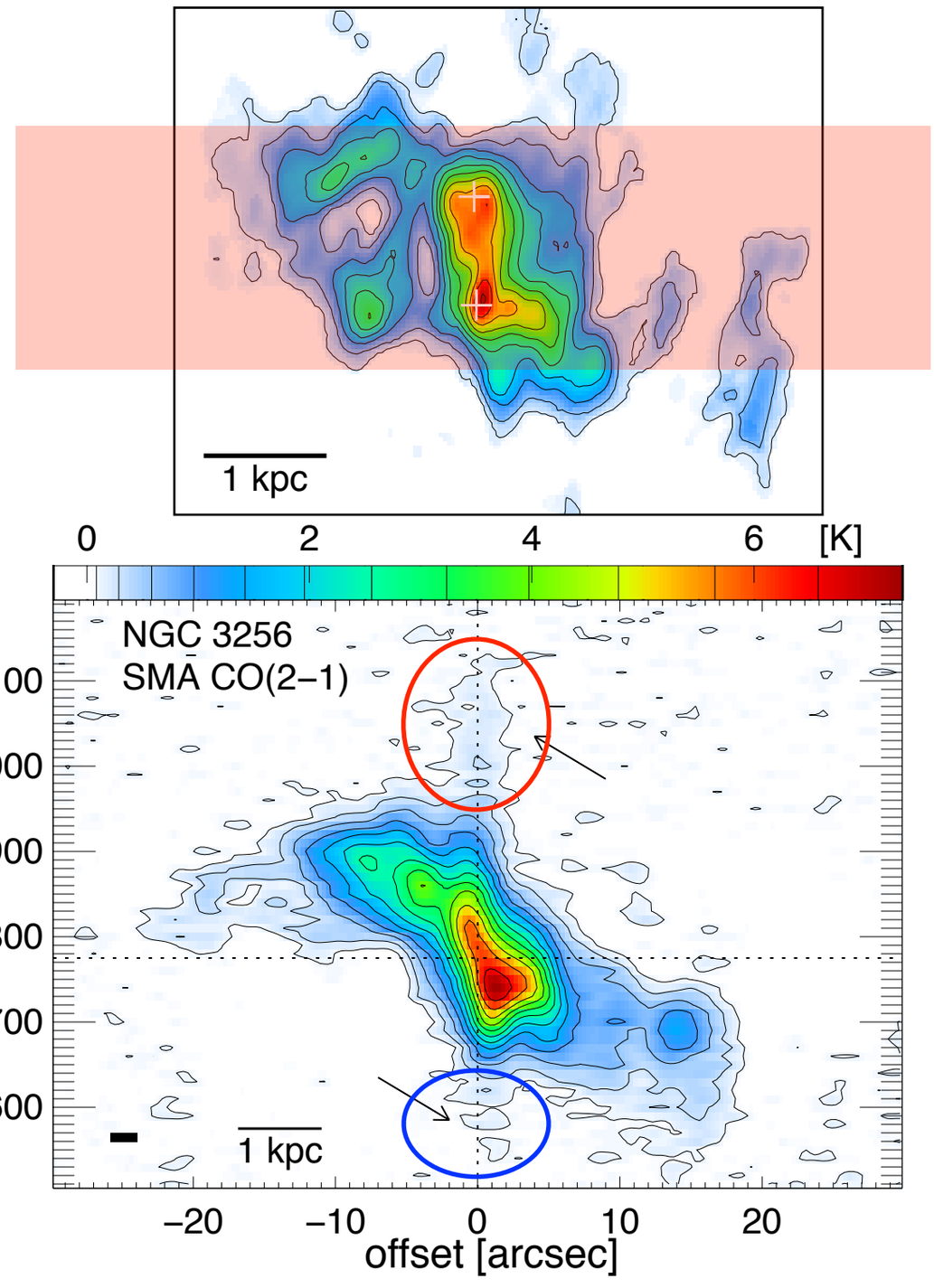




Galactic Molecular Outflow from CO line wings

Sakamoto, Ho, Peck (2006)



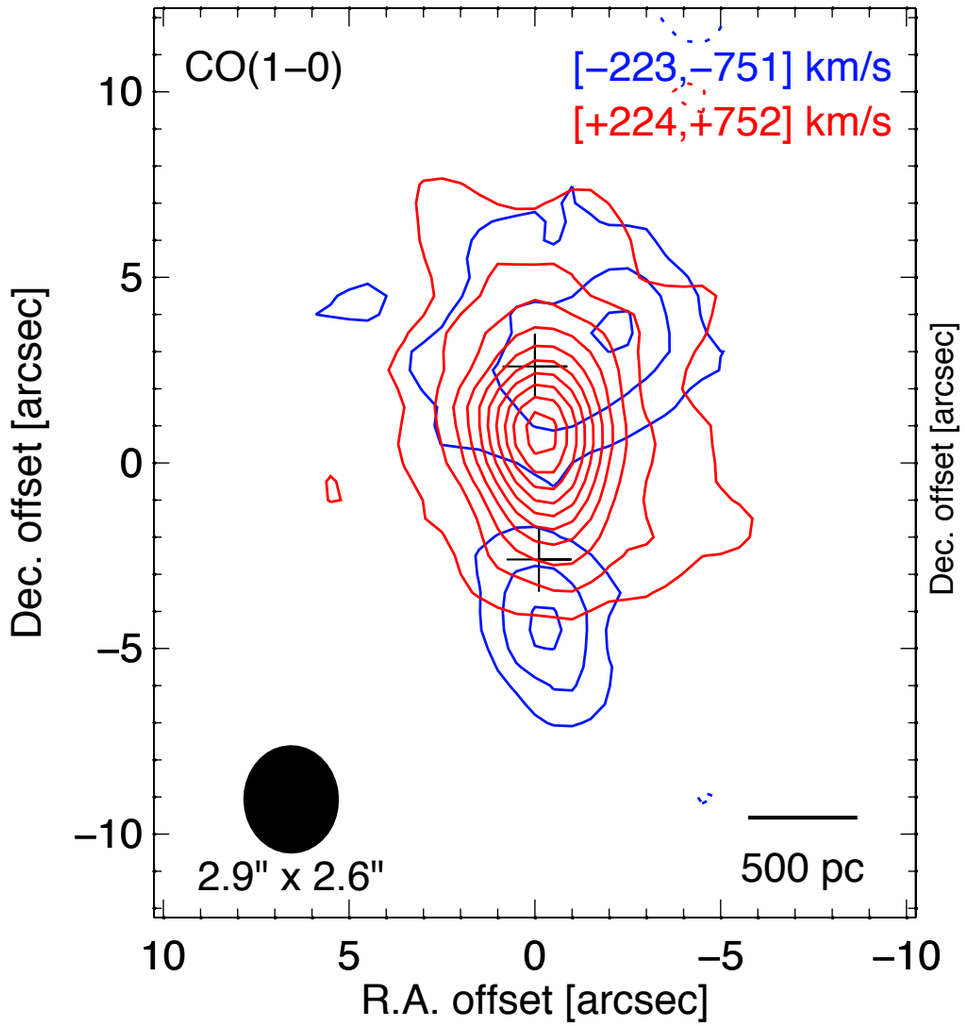


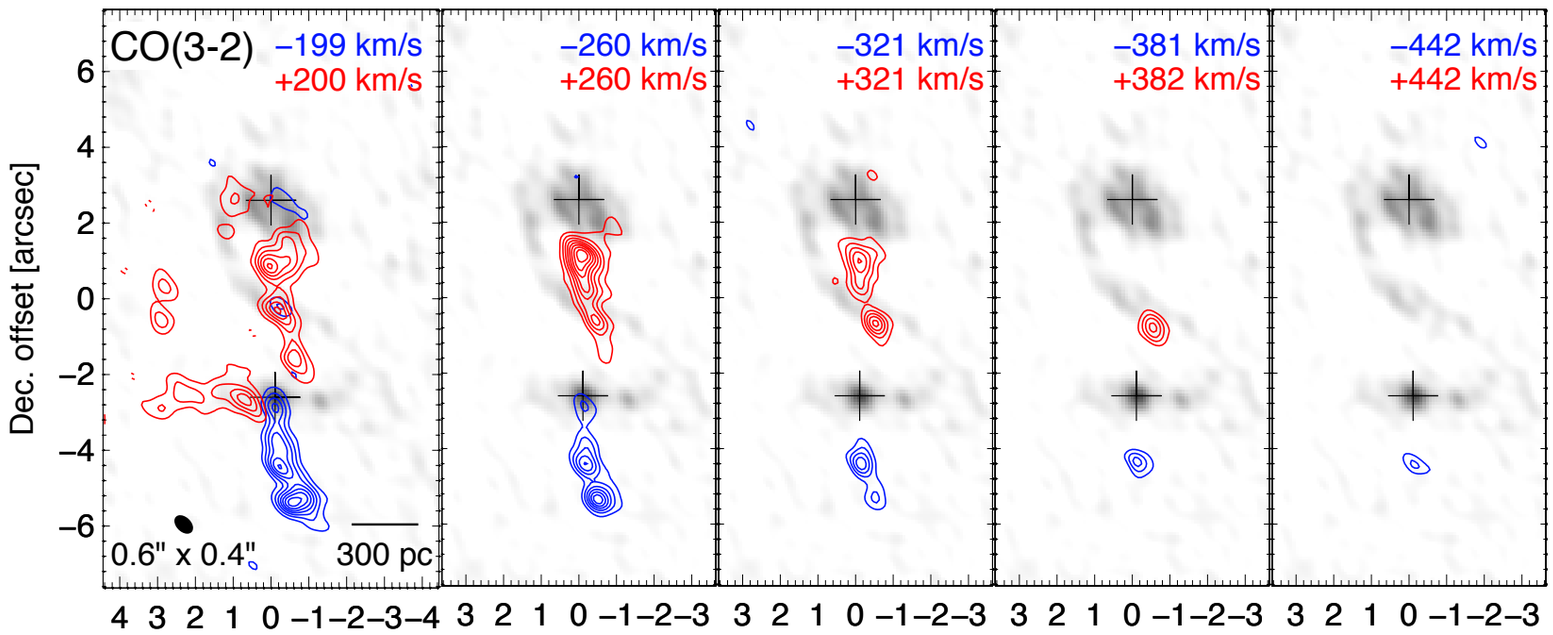
- High-velocity gas (molecular outflow)
  outflow rate ~ 10 $M_\odot$/yr ~ SFR
- First one found from CO line wings

Double-Outflow System

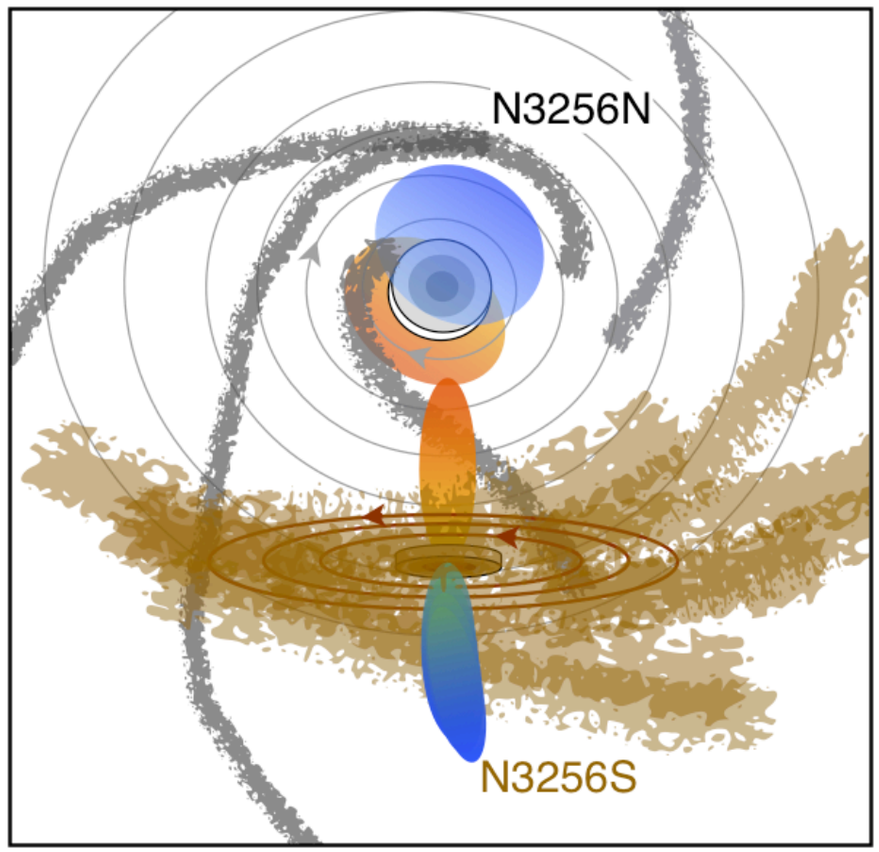
NGC 3256

Sakamoto et al. (2014)
ALMA



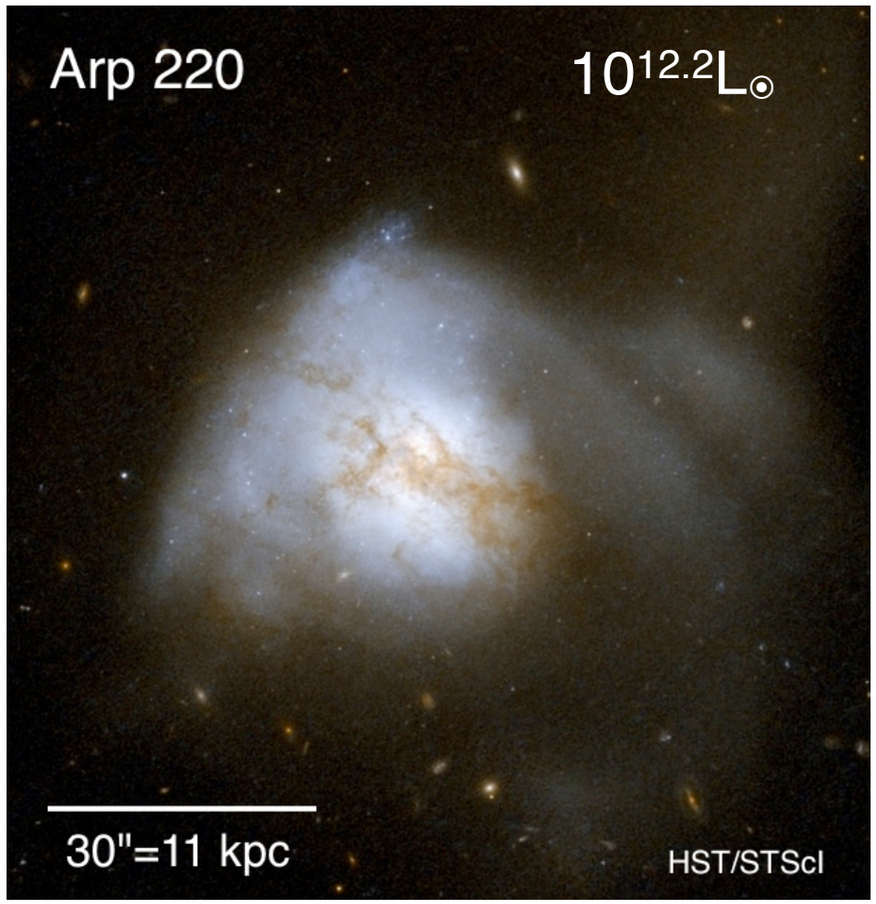


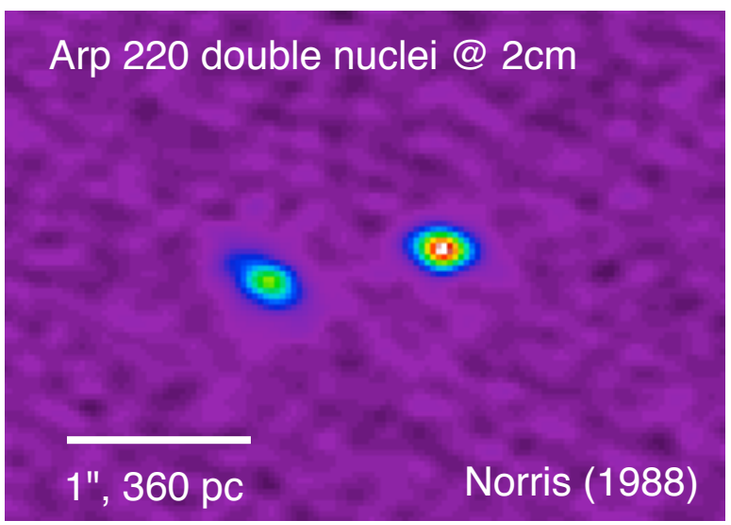
- Two molecular bipolar outflows
- from N nucleus:
  pole-on, wide opening angle
- from S nucleus:
  edge-on, collimated bipolar jet
- total dM/dt ~ 100 $M_\odot$/yr

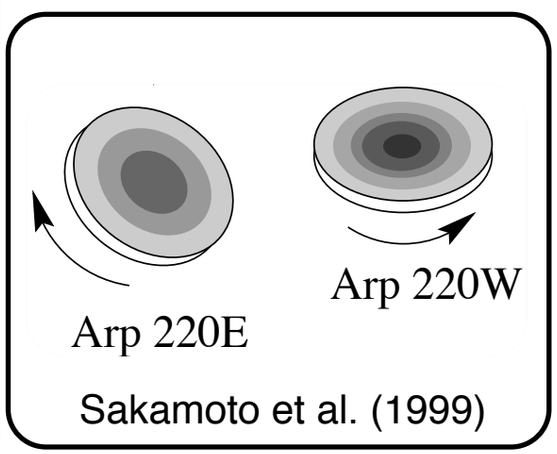


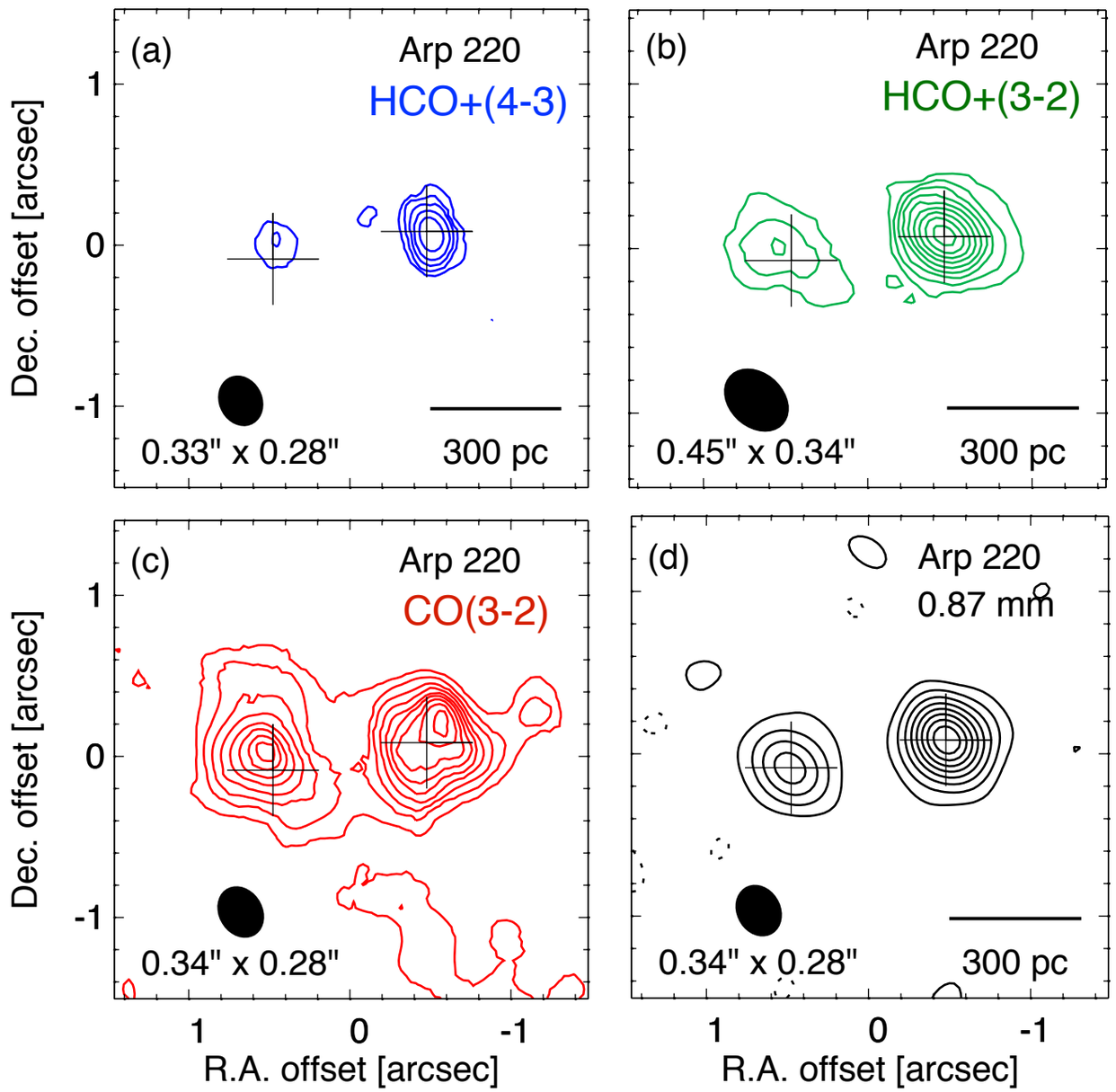
Galactic Molecular Outflows from P-Cygni Line Profiles

Sakamoto et al. (2009)



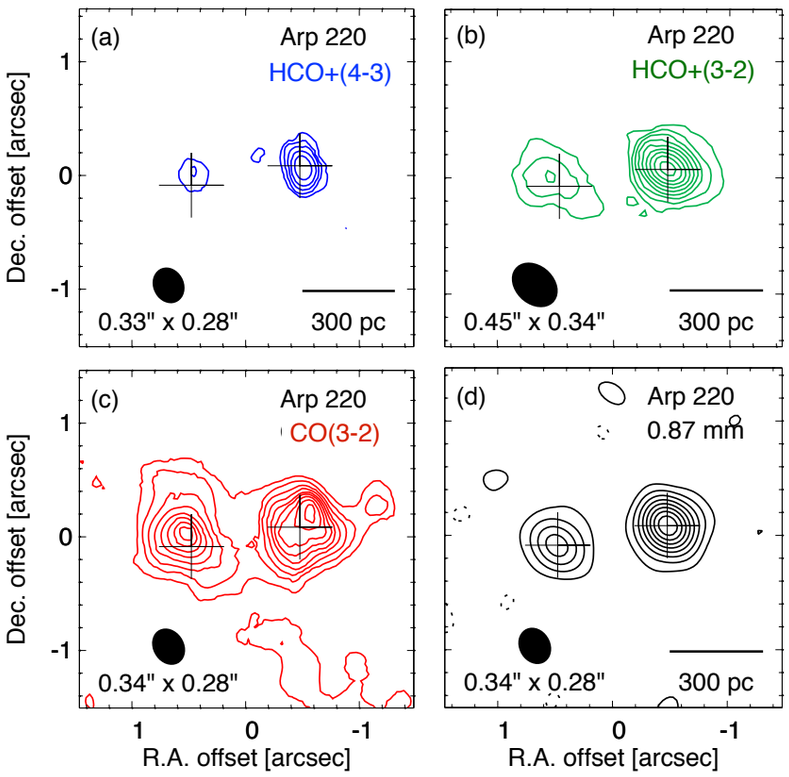


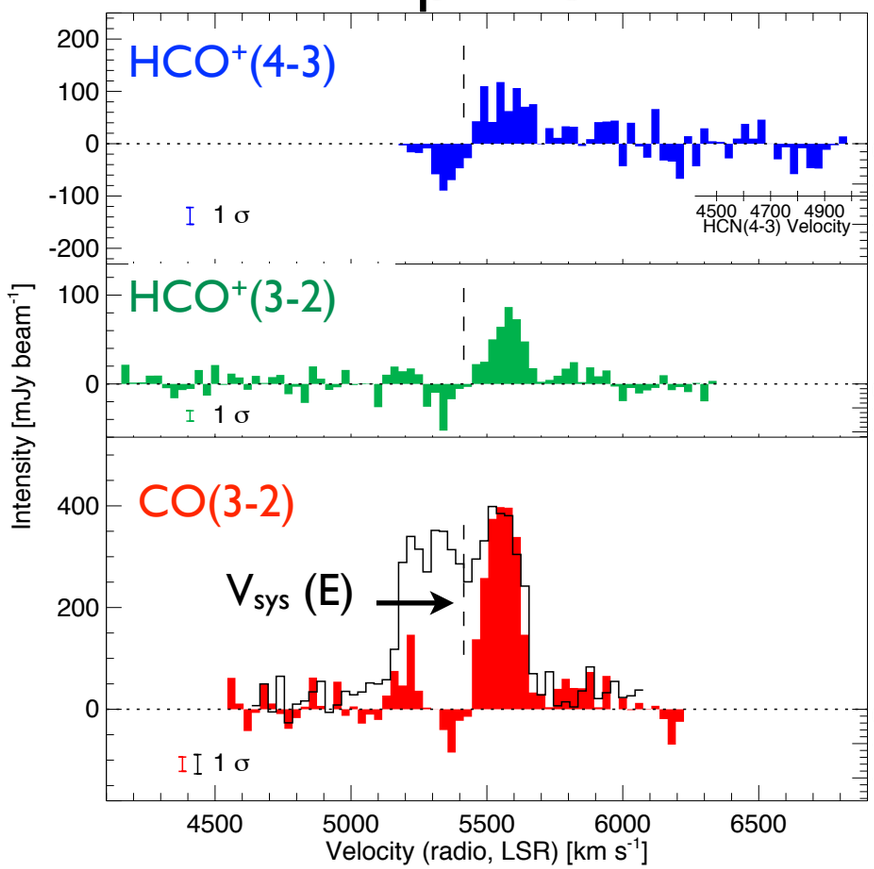


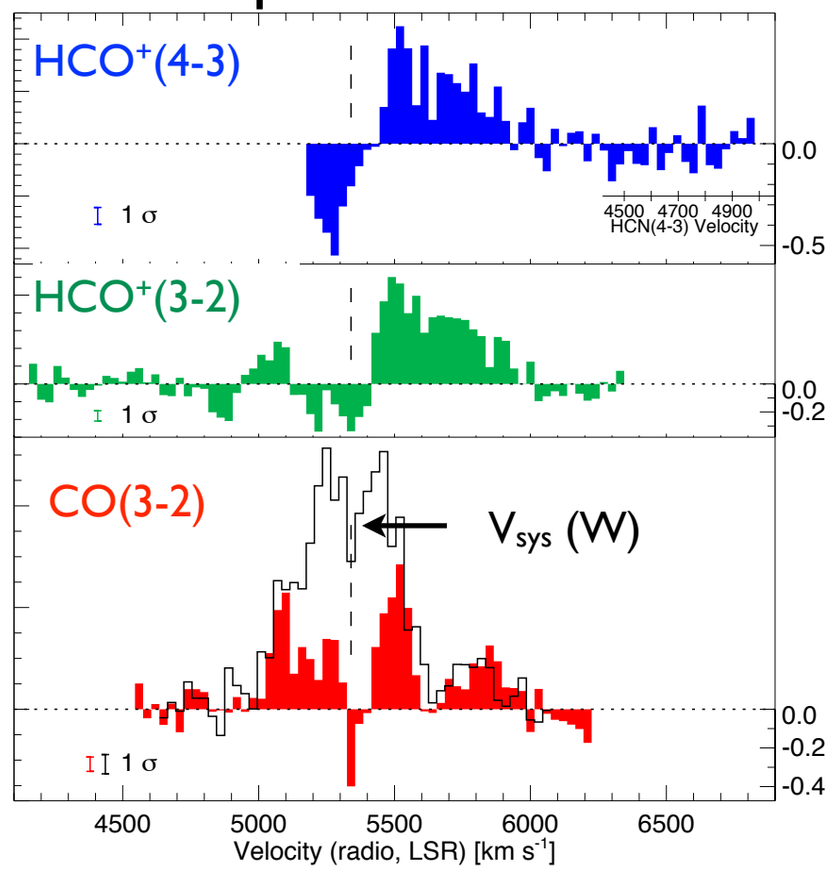


Galactic Molecular Outflows from P-Cygni Line Profiles

Sakamoto et al. (2009)



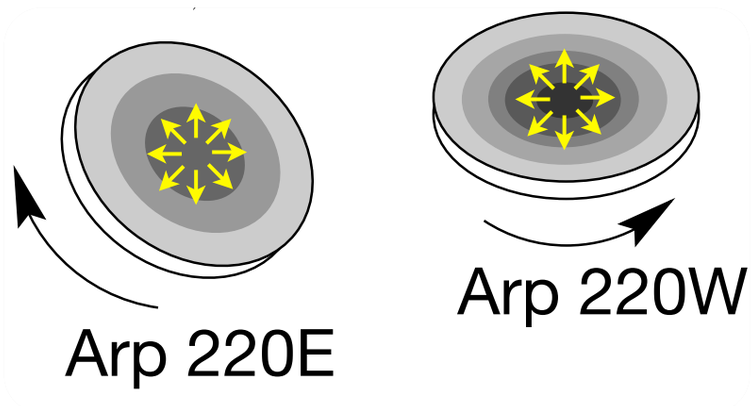




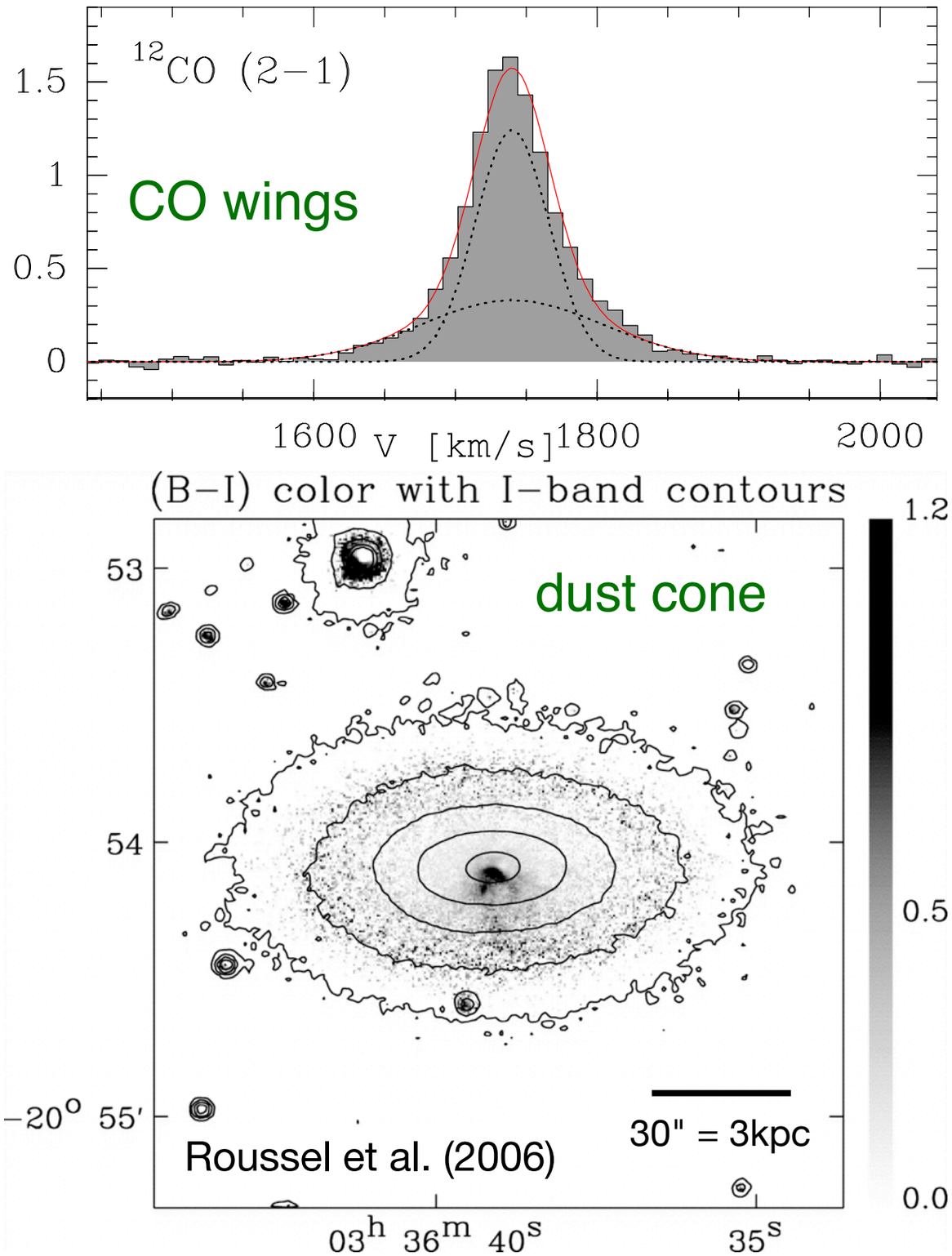
Blueshifted absorption + Redshifted emission

= P-Cygni profile

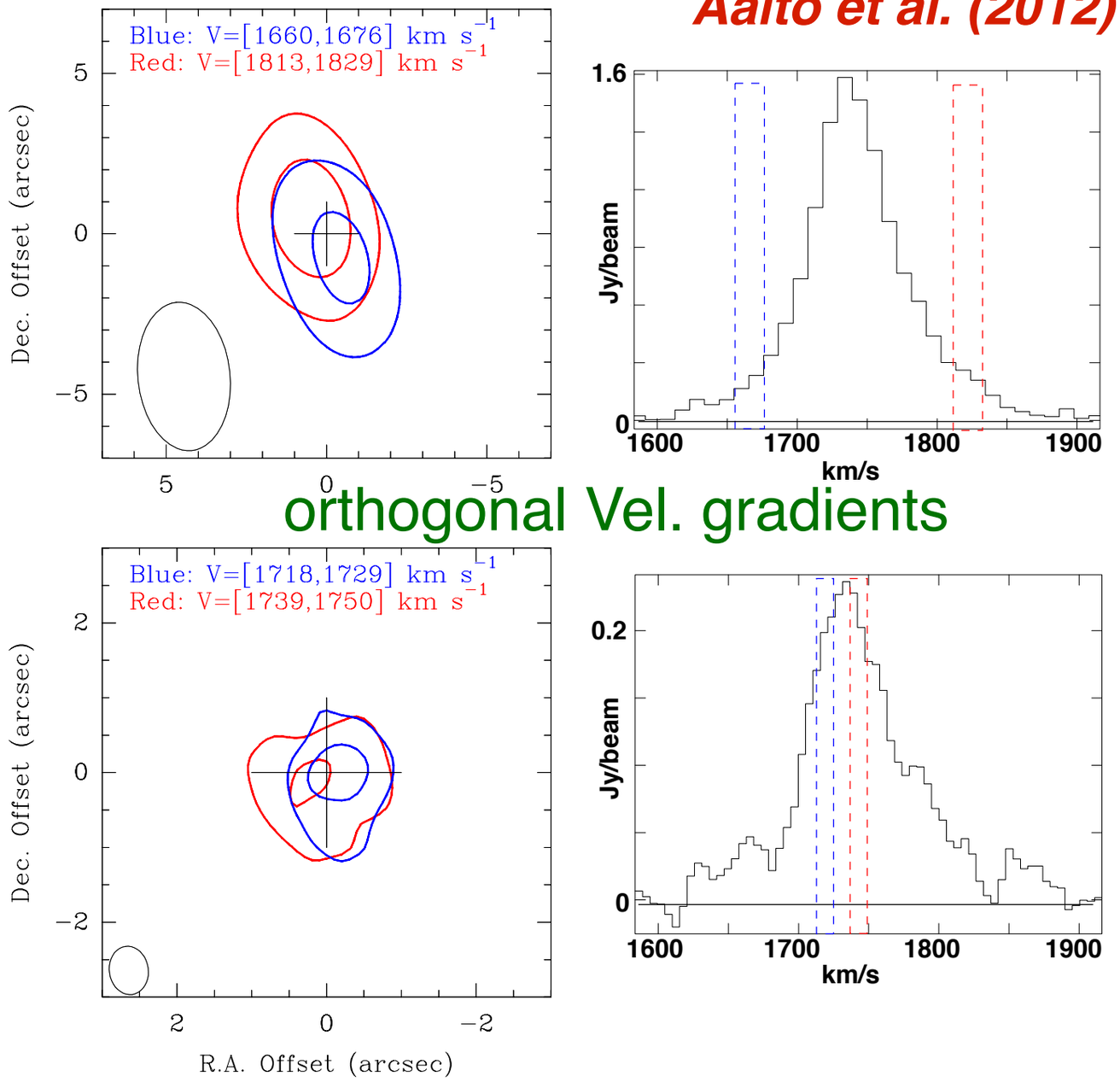
⇒ nuclear outflows/winds



Galactic Molecular Outflow from Orthogonal Vel. Gradients



Aalto et al. (2012)



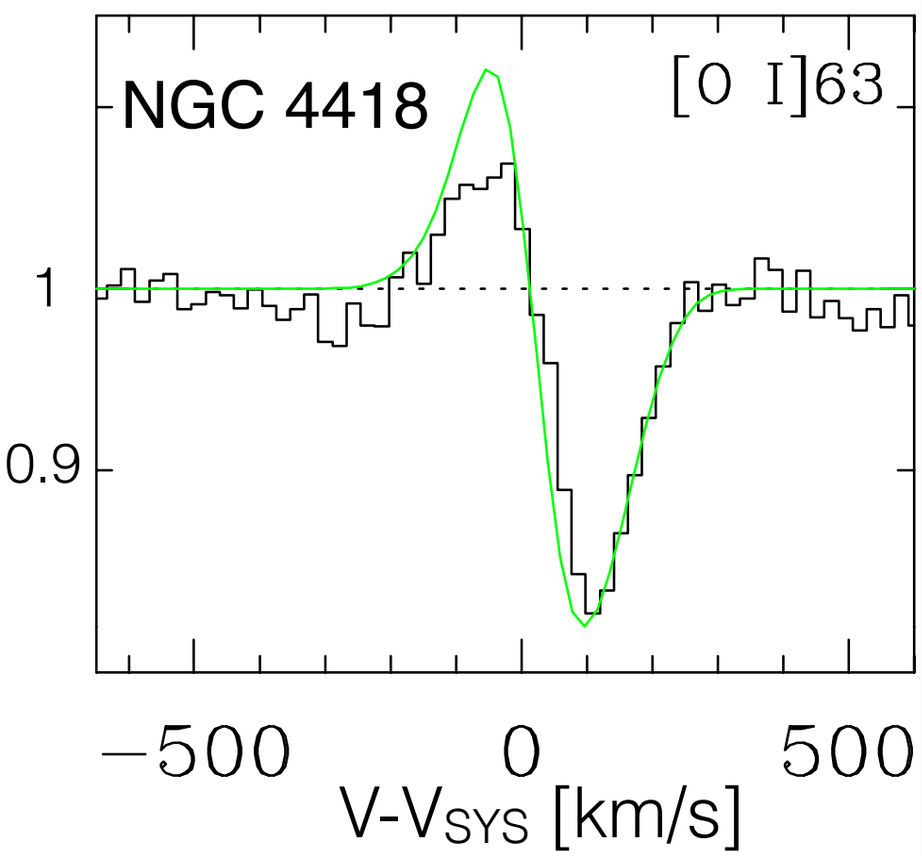
V_{out} = 140 km/s

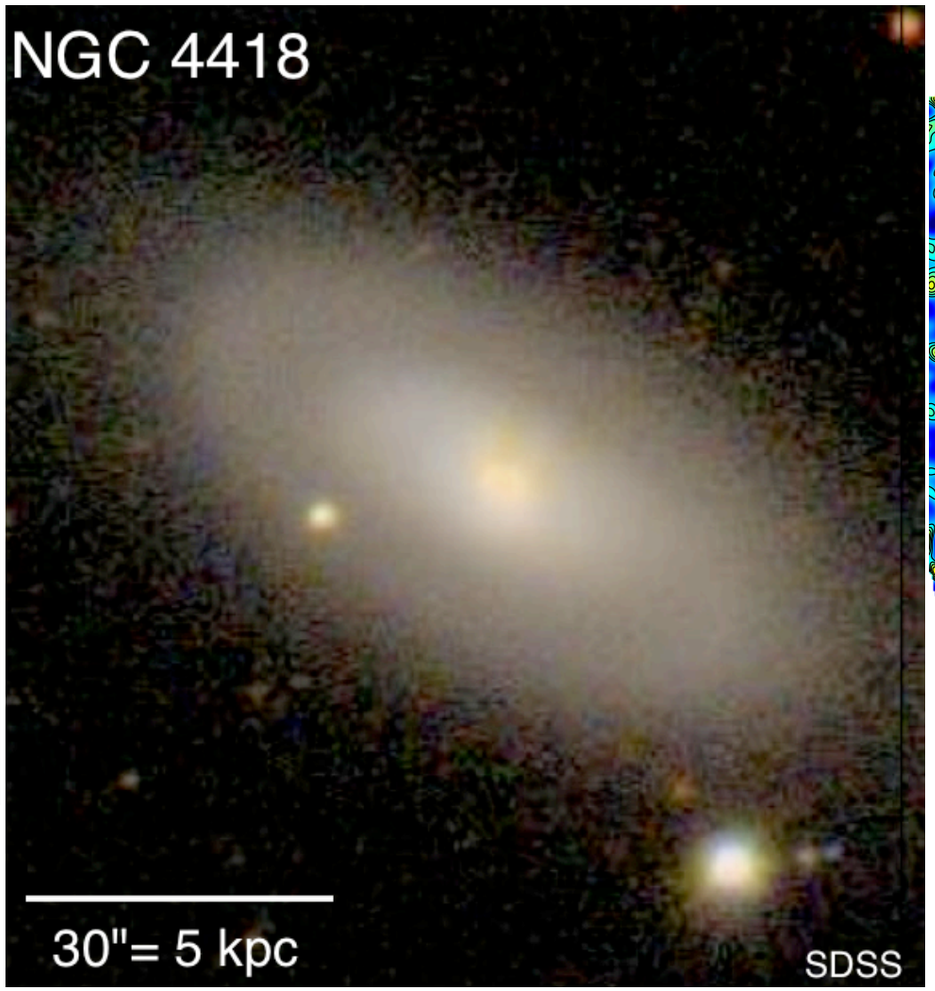
age ~ 1.4 Myr

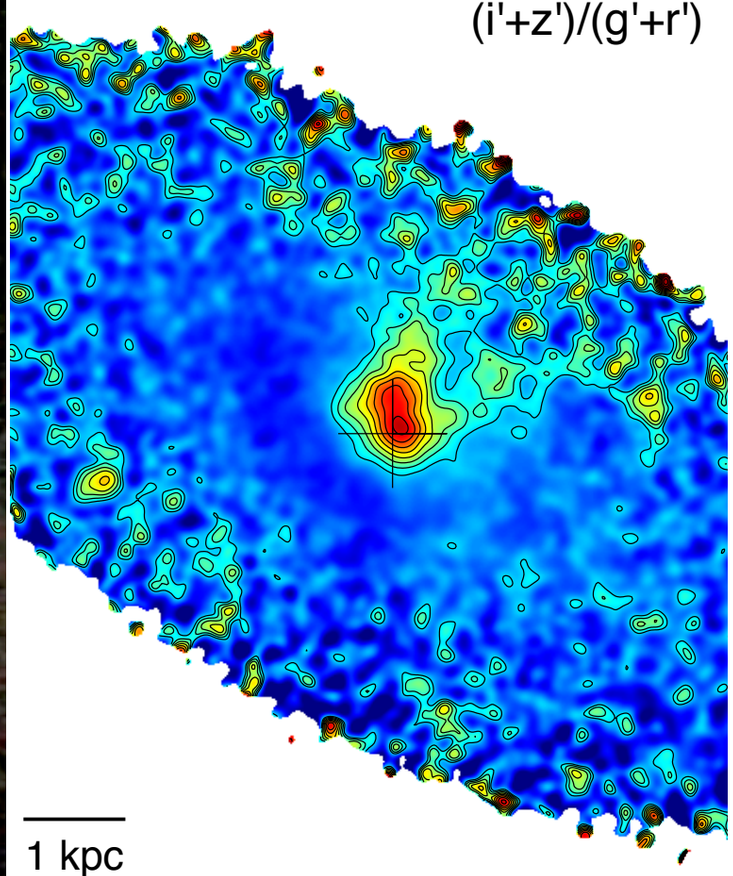
dM/dt > 8 $M_\odot$ yr^{-1}

Inflow+Outflow System

Sakamoto et al. (2013)

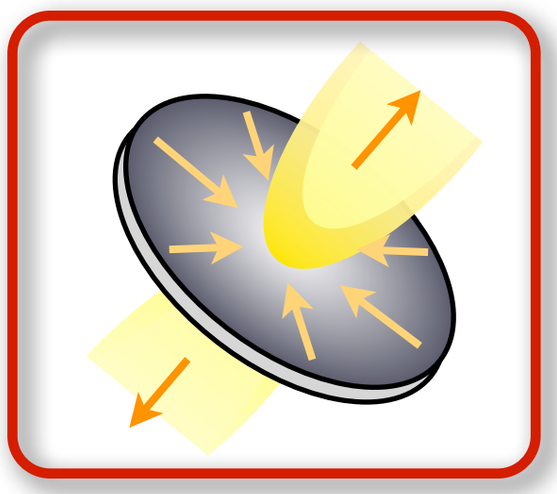






redshift absorption
→ inflow

Gonzalez-Alfonso et al. (2012)

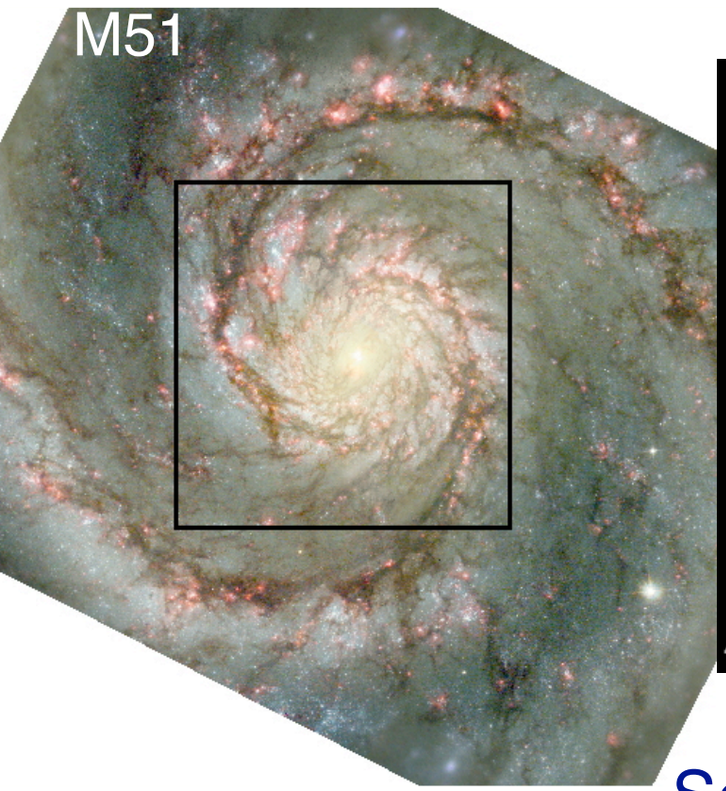


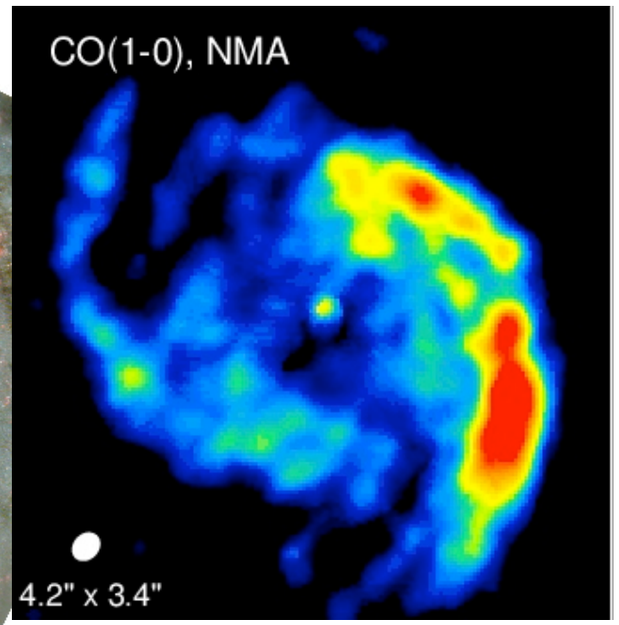
reddening cone
// semi-minor axis
→ outflow

Warm/dense Gas in Active Galactic Nuclei

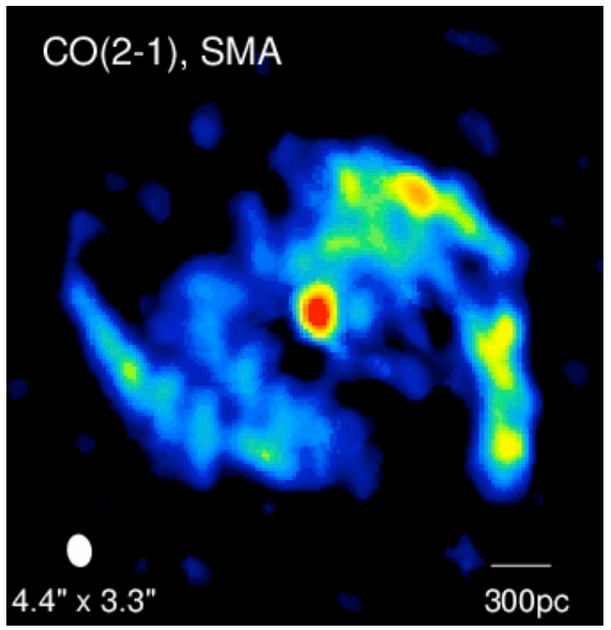
SMA 10 @ Cambridge, MA, 2014 May

Warm Gas in (active) Galaxy Nuclei

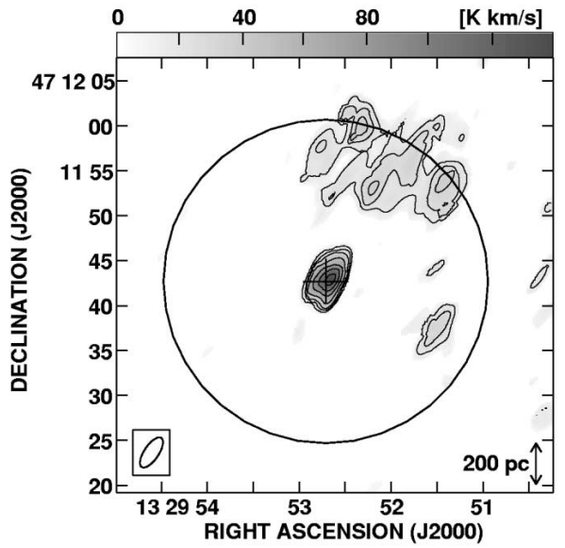




Sakamoto et al 1999



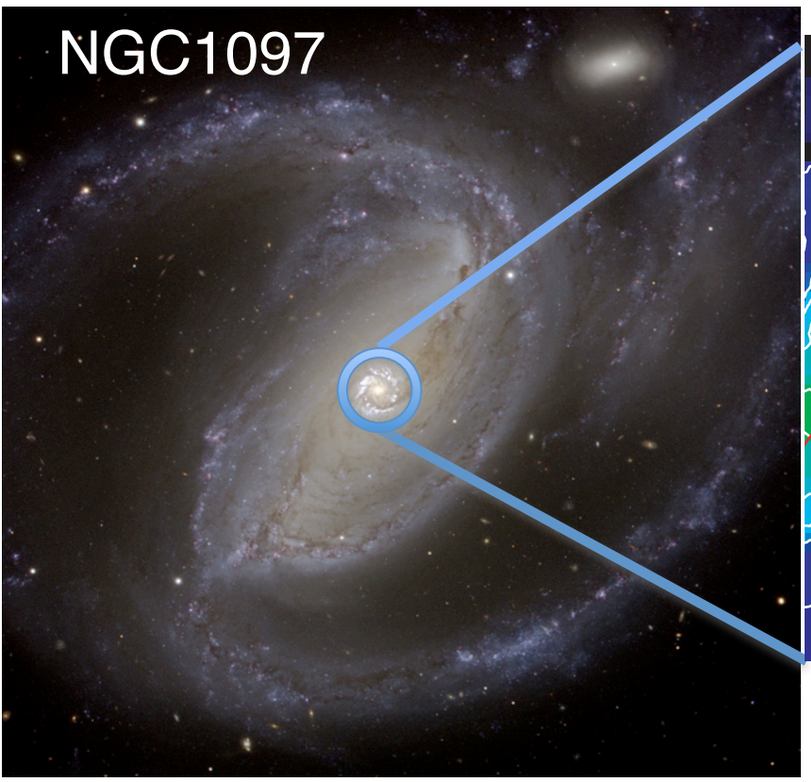
CO(3-2). SMA

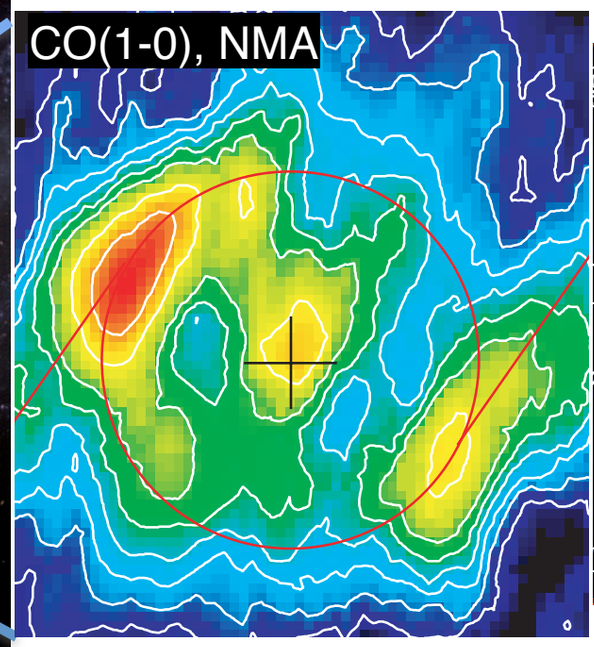


Matsushita et al. (2004)

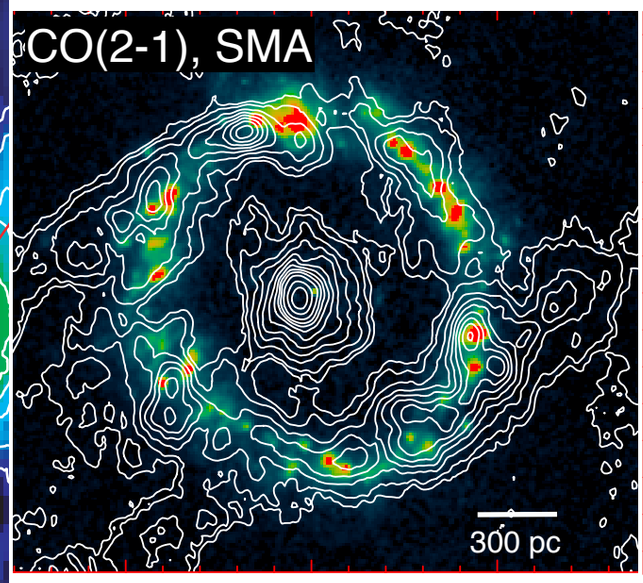
Seyfert nucleus brighter in higher J CO

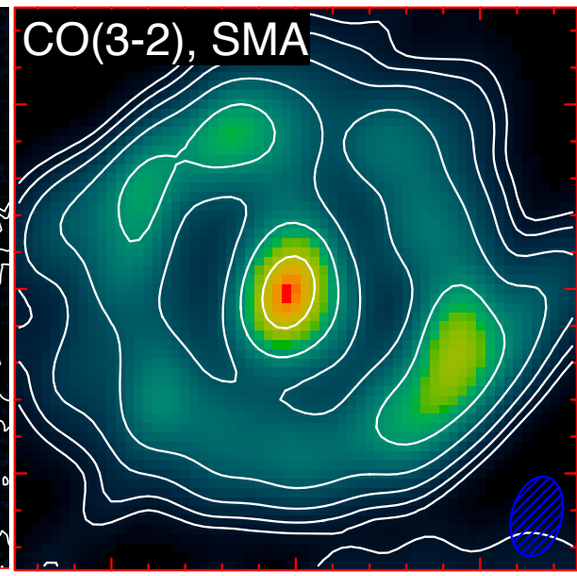
⇒ warm/dense gas at the nucleus





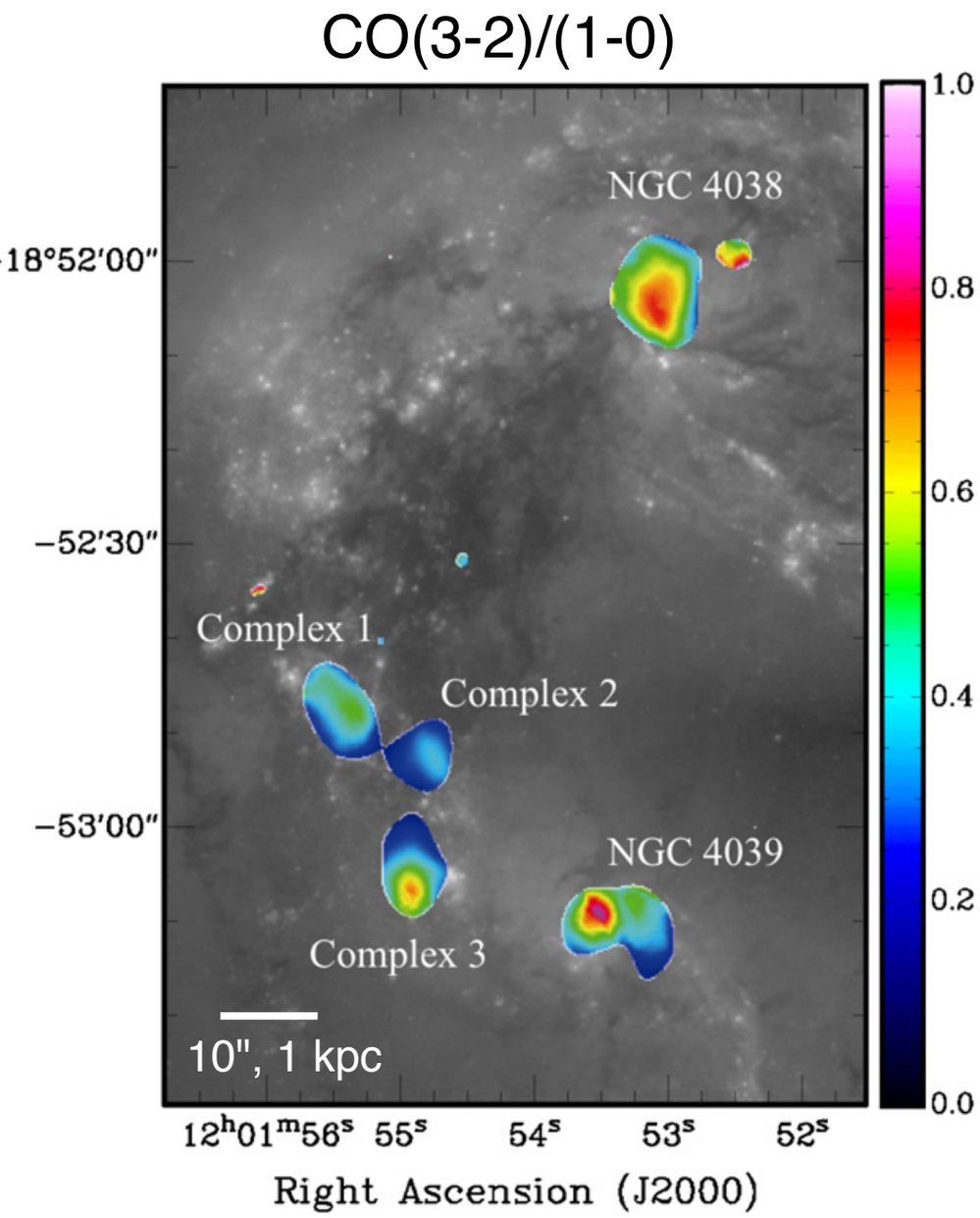
Kohno et al 2003





Hsieh et al. (2008, 2011, 2012)

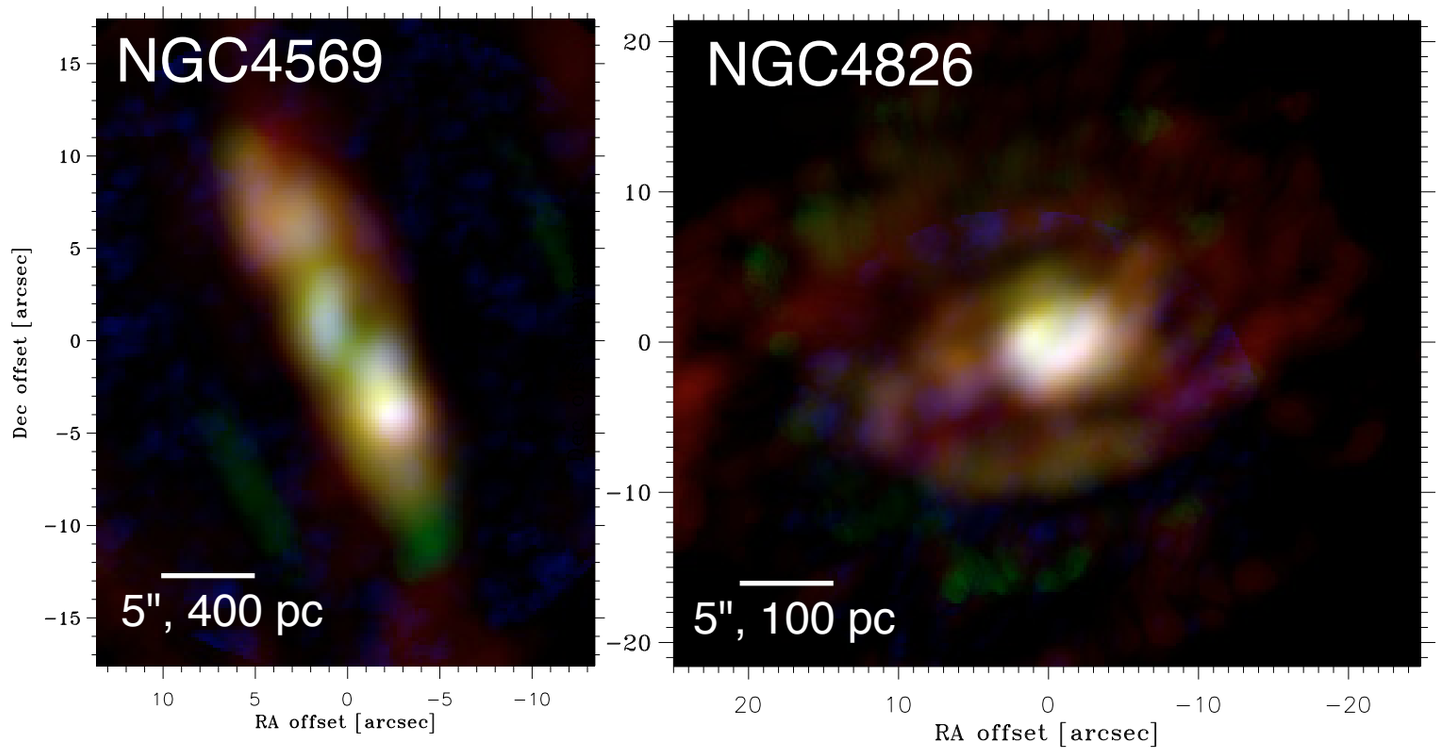
Warm Gas in (active) Galaxy Nuclei



peak CO(3-2) = 0.75 (N4038)
~ 1.0 (N4039)

N4039 has less S.F. and no AGN !?

Ueda et al. (2012)



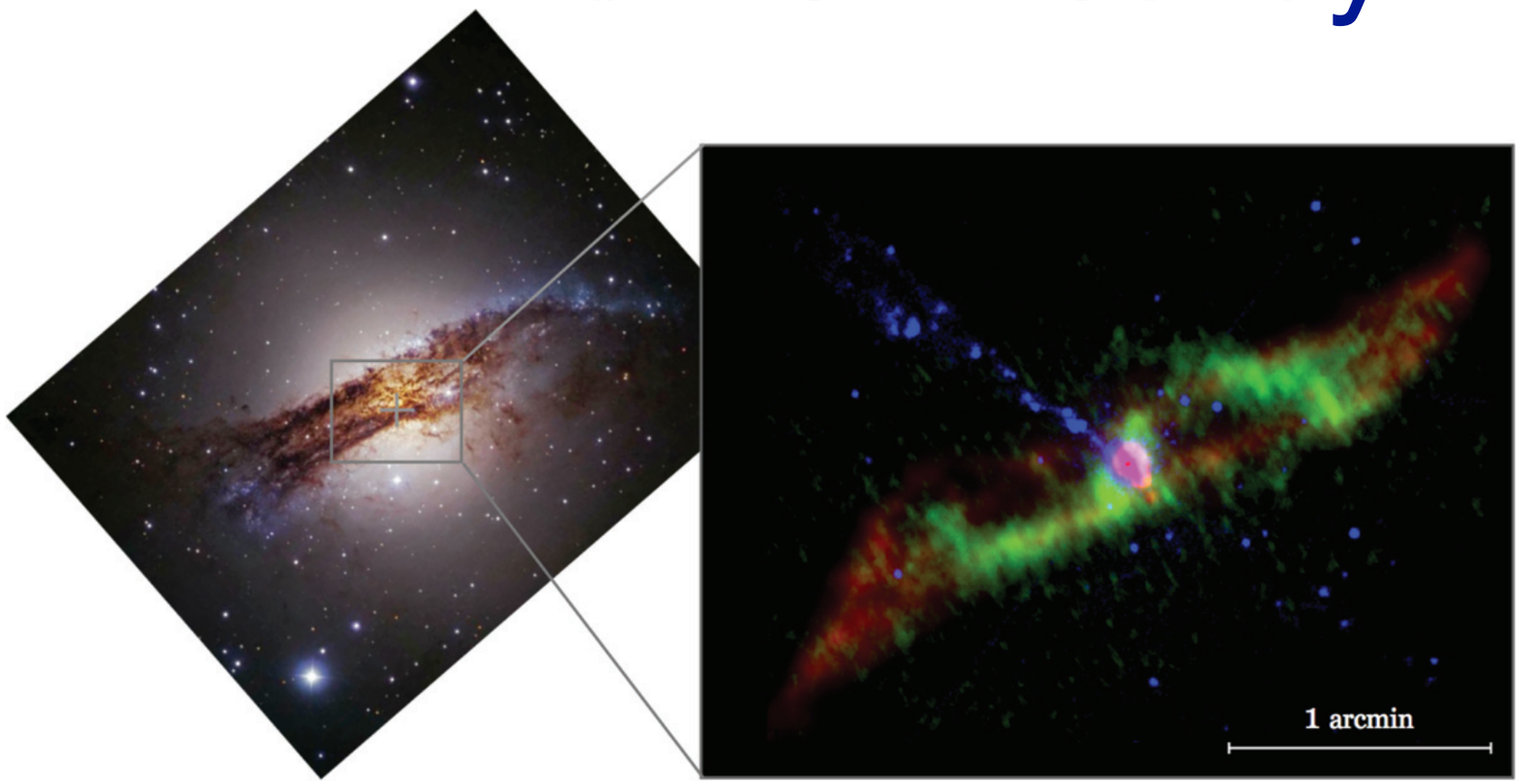
RGB=CO1-0/2-1/3-2; PdBI/PdBI/SMA

Boone et al. (2011)

peak CO(3-2)/(1-0) = 0.45 (N4569)
= 0.60 (N4826)

LINER/transition nuclei incapable
to enhance R(3-2/1-0)

Other Nearby AGNs



Molecular-gas spiral arms
in dust-lane elliptical galaxy

R: 8mm PAH, Spitzer
G: CO(2-1), SMA
B: X-ray, Chandra

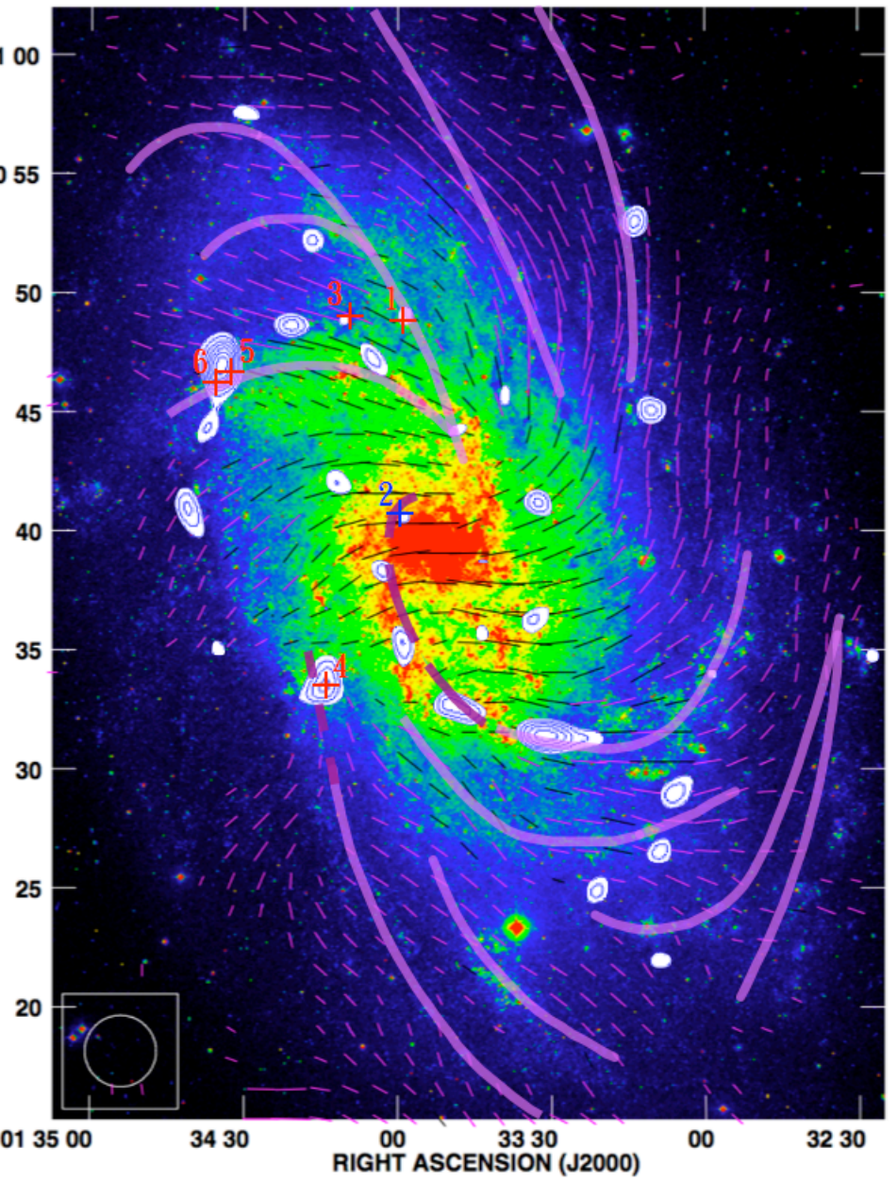
Espada et al. (2012)

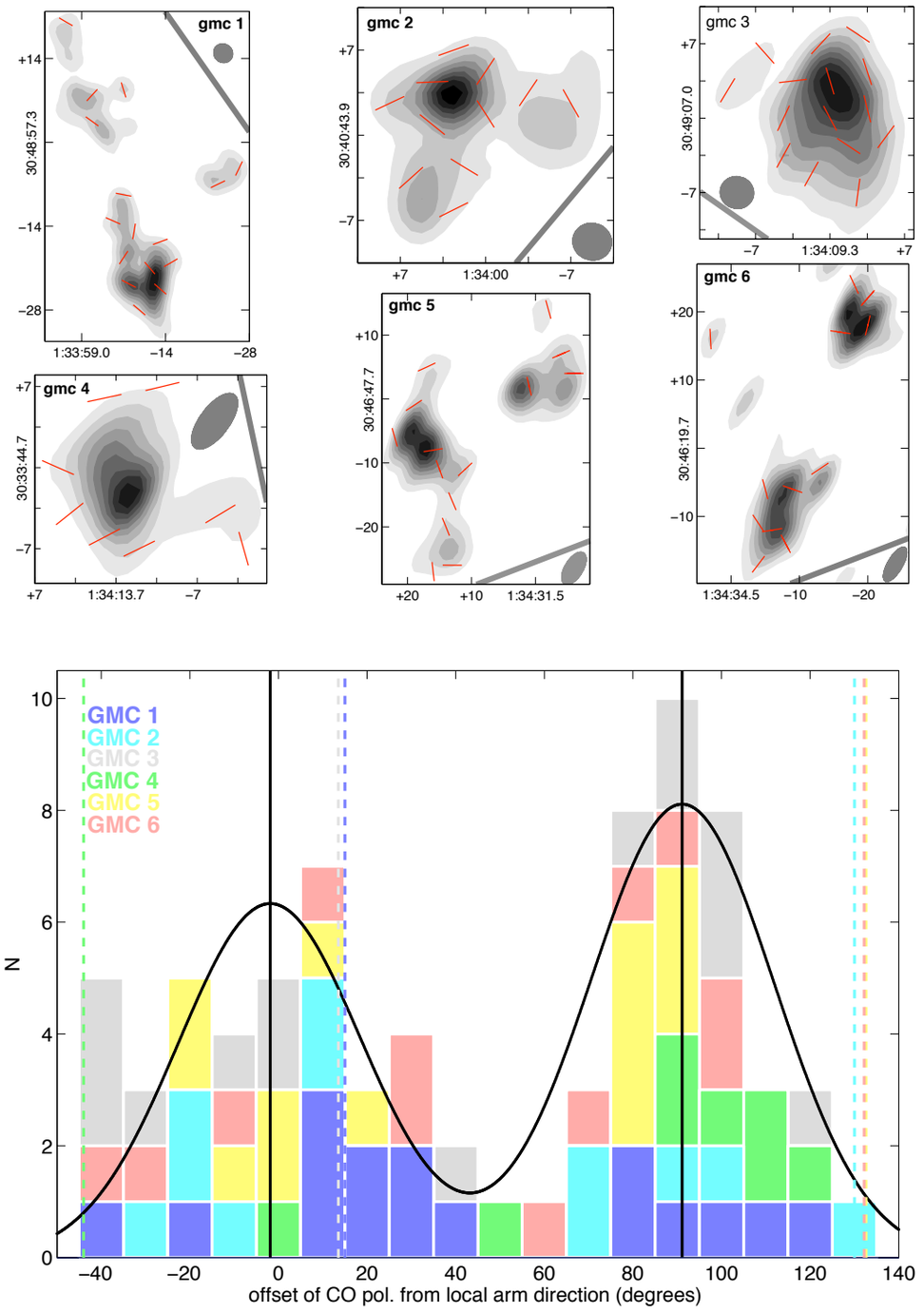
Polarimetry

SMA 10 @ Cambridge, MA, 2014 May

Alignment of Molecular Cloud Magnetic Fields with Spiral arms in M33

Li et al. (2011)



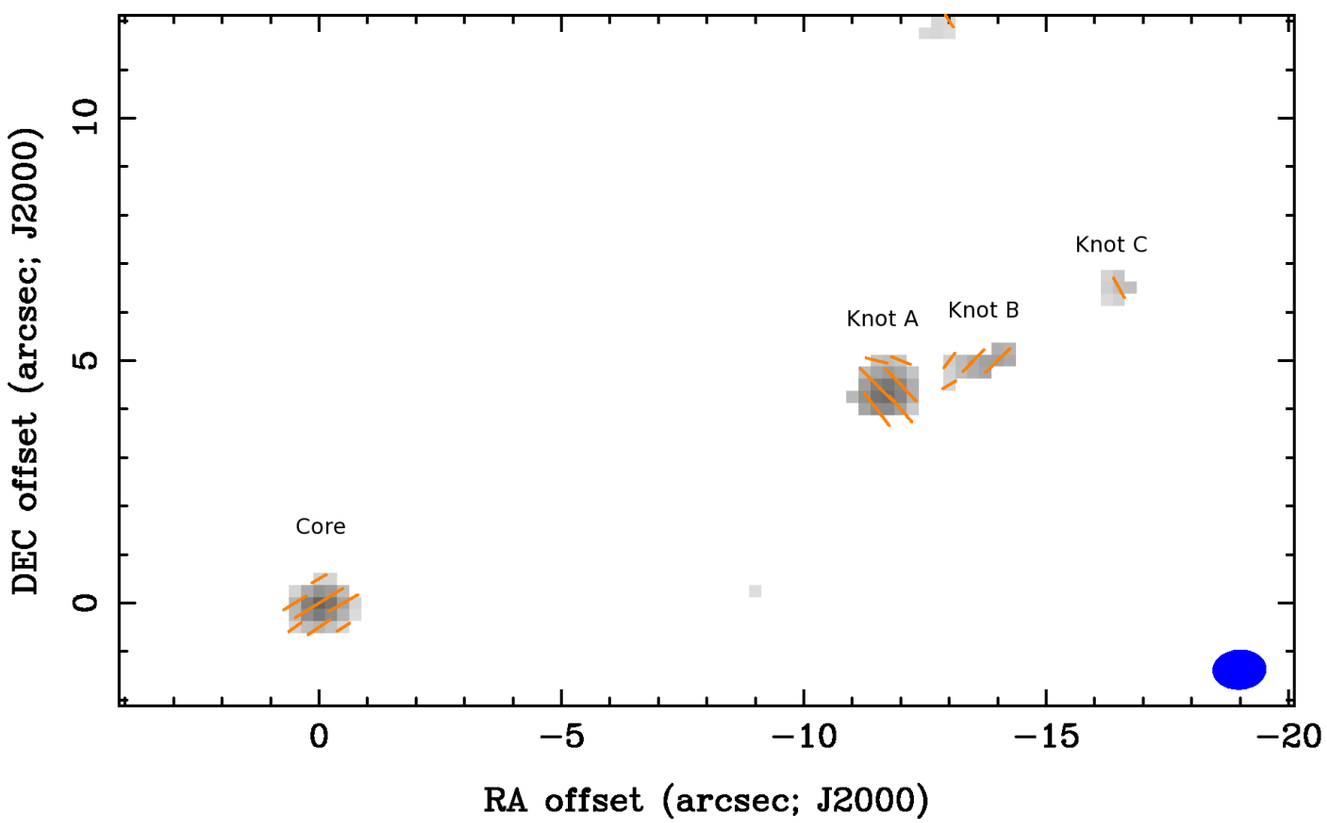


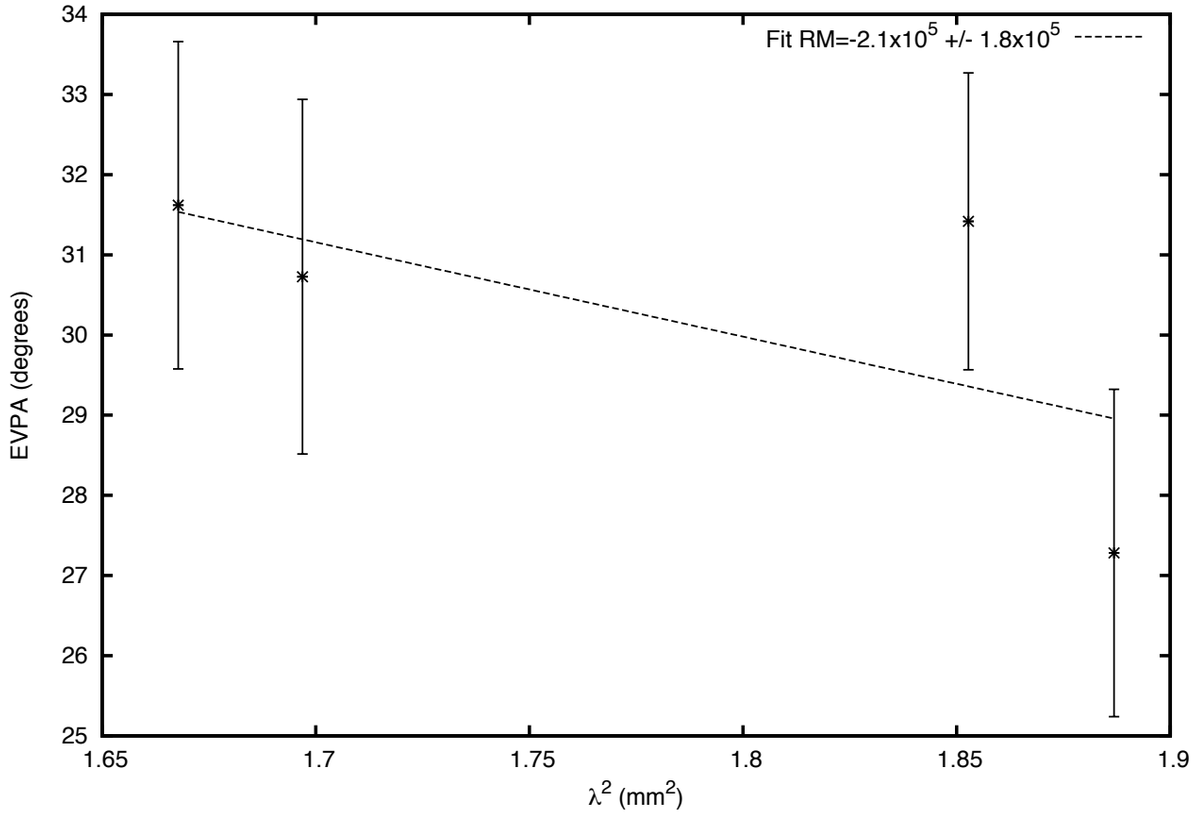
CO line polarization
// or ⊥ with B

Correlation with arm

Mass Accretion Rate to M87 BH from Faraday Rotation Measure

Kuo et al. (2014)





$$RM \Rightarrow dM/dt < 9.2 \times 10^{-4}\ M_{\odot}/yr$$

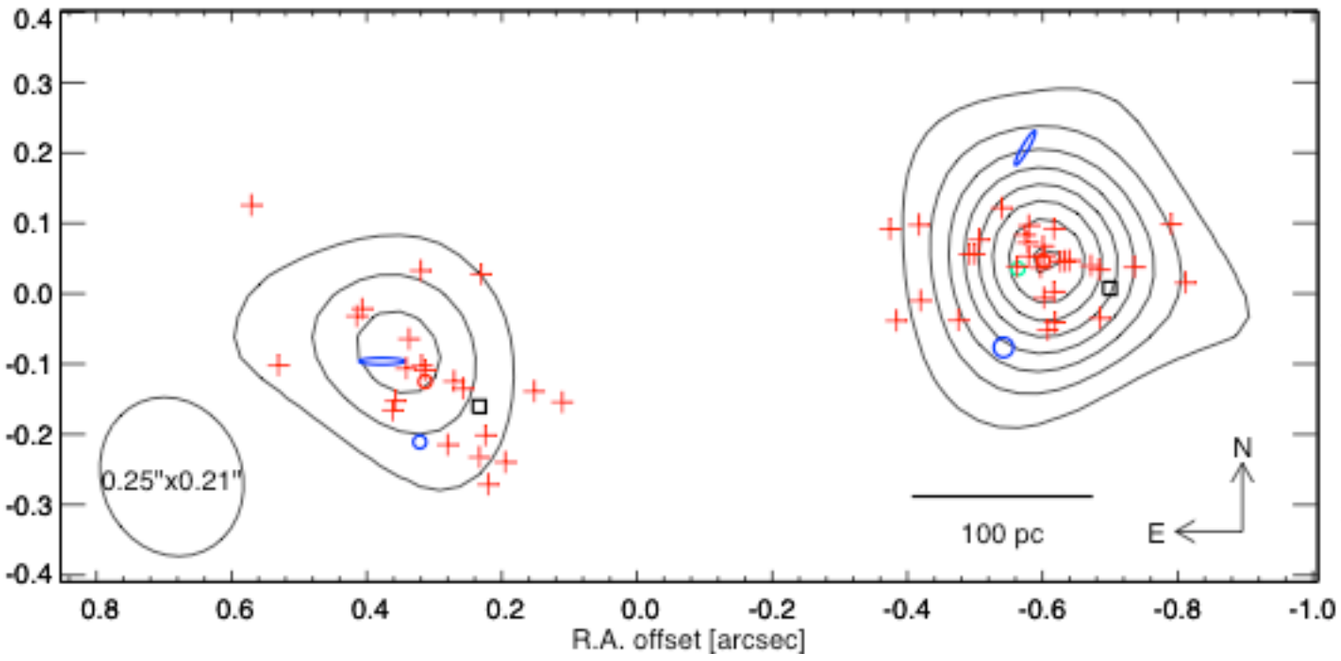
SMA on Nearby Galaxies

- Spectroscopy - new masers, vib-excited lines
- U/LIRG Legacy Project
  - gas concentration → luminosity @ constant dense gas SFE
- U/LIRGs at highest resolutions
  - new AGN/Starburst diagnosis with sub-mm subarcsec obs.
- Feedback/Outflows - new cases, forms, detection methods
- Warm/Dense Gas in AGN - AGN effects on e.g.,high-J CO
- Polarimetry - Magnetic filed in MCs, AGN accretion
- ...

Many discoveries on warm/active sources

Ongoing follow-ups with SMA, ALMA, etc.

SF in Arp 220 and NGC 4418

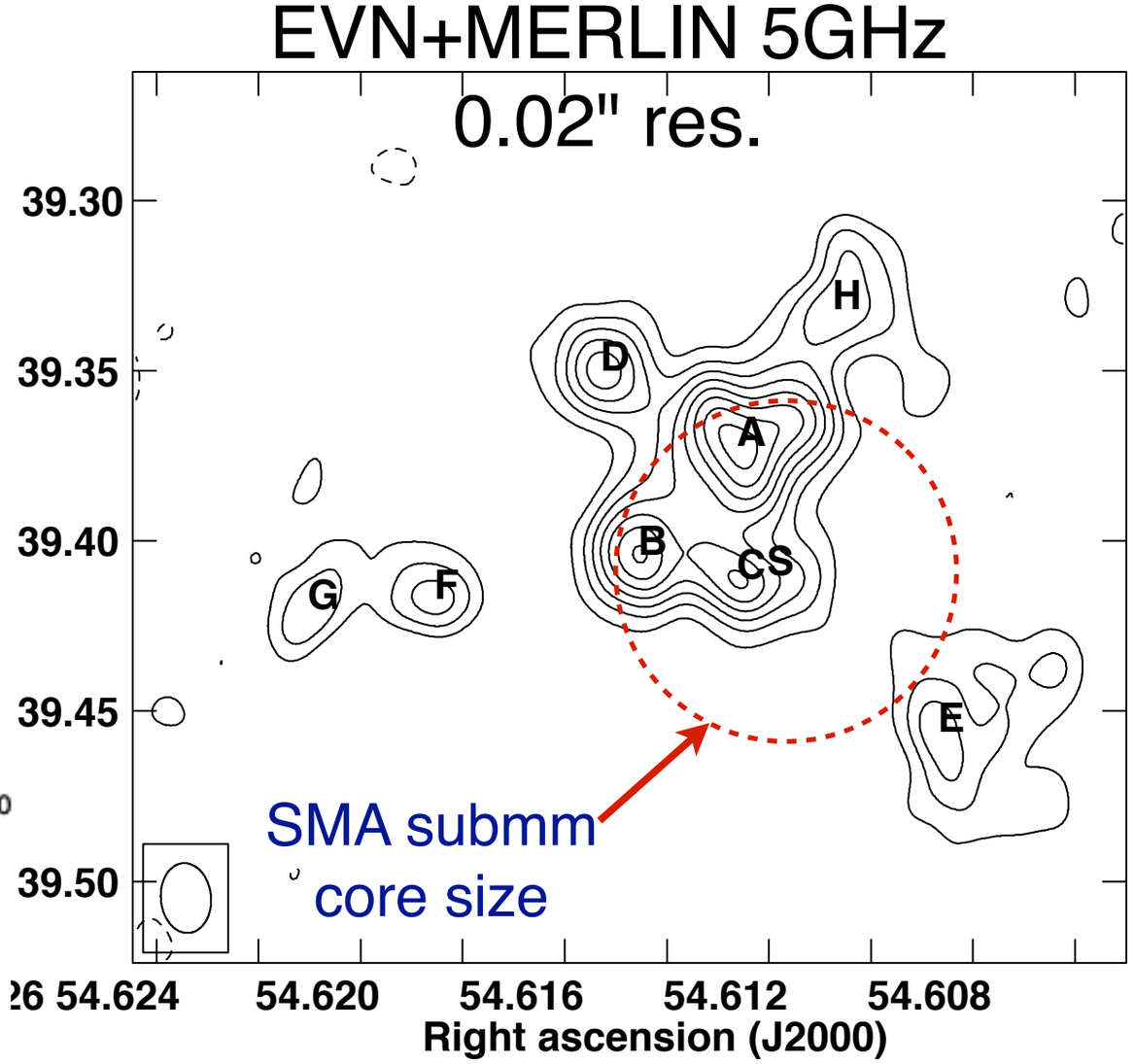


red + : VLBI SNRs & RSNe

(Lonsdale et a. 2006; Parra et al. 2007)

contours : SMA 860μm continuum

(Sakamoto et al. 2008)



clumps (SSCs) with

D ~ 5 pc, $T_b \sim 10^{5.2\pm0.2}$ K

(+ AGN ??)

(Varenius et al. 2014)

SF evident. *Is AGN hidden !?*