The Molecular Baryon Cycle of M82

John Chisholm (Univ. Geneva / Univ. Wisconsin-Madison)
& Satoki Matsushita (ASIAA)

Chisholm & Matsushita 2016, ApJ, 830, 72
Matsushita et al. 2005, ApJ, 618, 712
Matsushita et al. 2000, ApJL, 545, L107

ASIAA Summer Student Program

- Provide forefront research f or mainly undergraduates, b ut graduate students are als o fine.
- Every Year, Jul.1-Aug.31.
- Salary will be paid.
- Travel fee will not be provic ed.
- Very competitive now.
- Contact me, if you are inter ested.

Introduction
Baryon Cycle of Galaxies

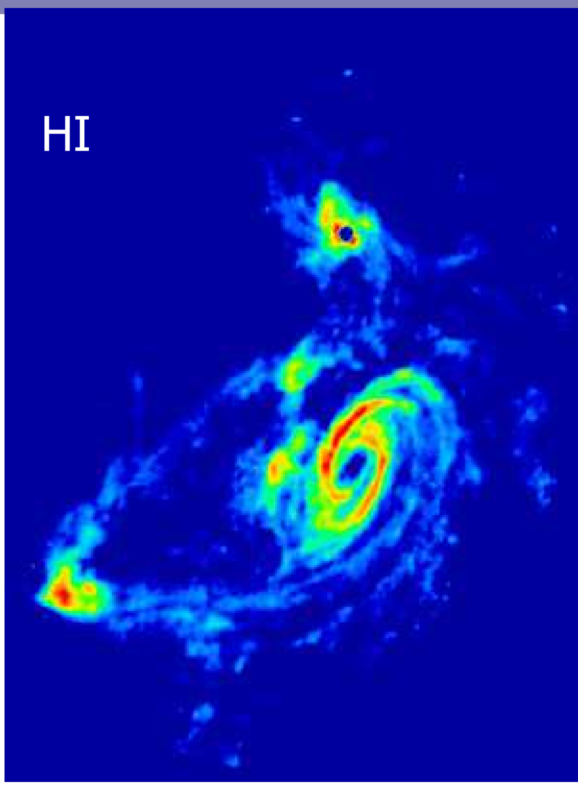
- Galaxies lose gas by:
  - Forming stars.
  - High energy photons and cosmic rays from high-mass stars.
  - Galactic outflows caused by supernovae.
- Galaxies gain gas by:
  - Low velocity outflows recycle back.
  - Accretion from circumgalactic medium.
  - Major/minor mergers.

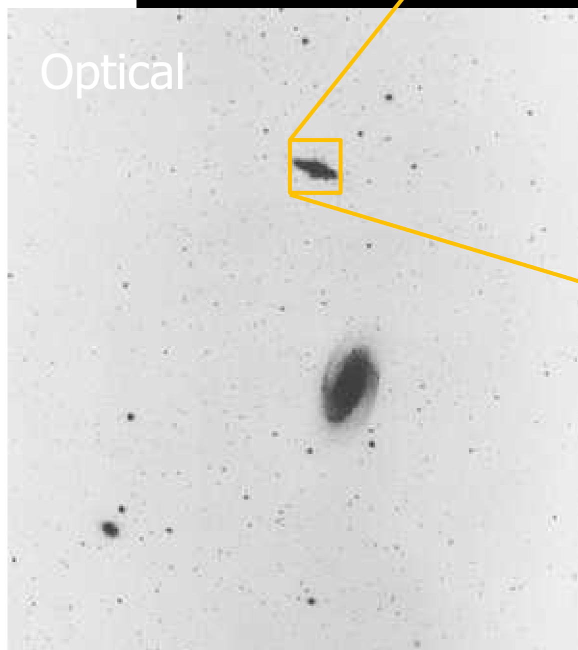
Introduction
Molecular Gas

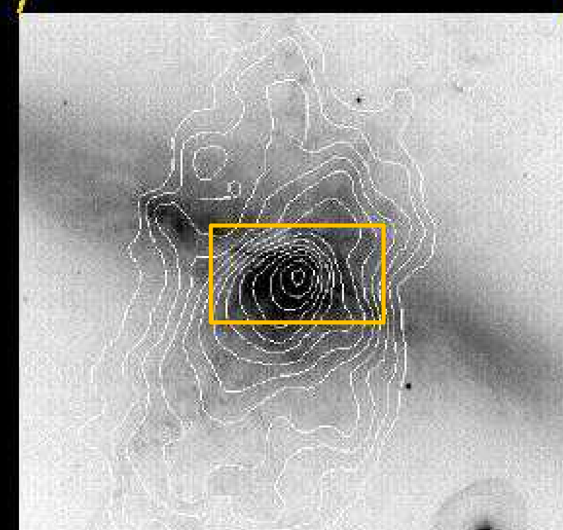
- Molecular gas makes stars.
  - Existence of (dense) molecular gas means the (future) location of star formation.
  - Molecular gas outflows take away the fuel f or star formation.
  - Molecular gas inflows supply the fuel for st ar formation.
- Molecular gas observations will tell us th e baryon cycle of galaxies.

Introduction
Prototypical Starburst M82

- One of the Nearest st arburst galaxies (3.6 Mpc).
- H∈, X-ray, Molecular G as, & Dust Outflows.
- Many observations at various wavelengths i n the past.





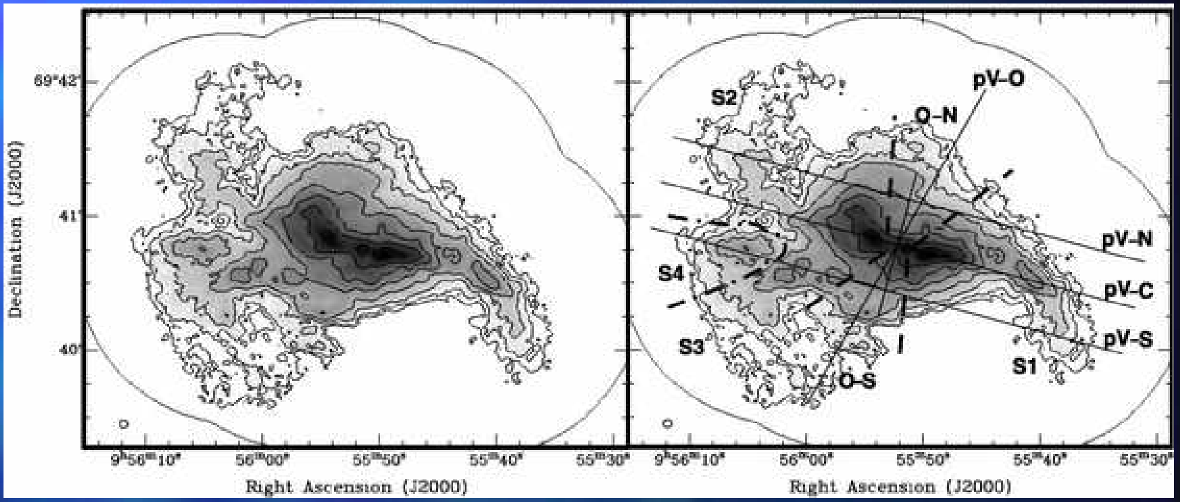


372, 530

H∈(Greyscale; Shopbell et al. 1998)
X-ray (Contours; Bregman et al. 1995)

Introduction
Molecular Gas Filaments

- Due to the tidal interaction and active star formation, many molecular filaments exist around M82.



Walter et al. 2002, ApJL, 580 L21

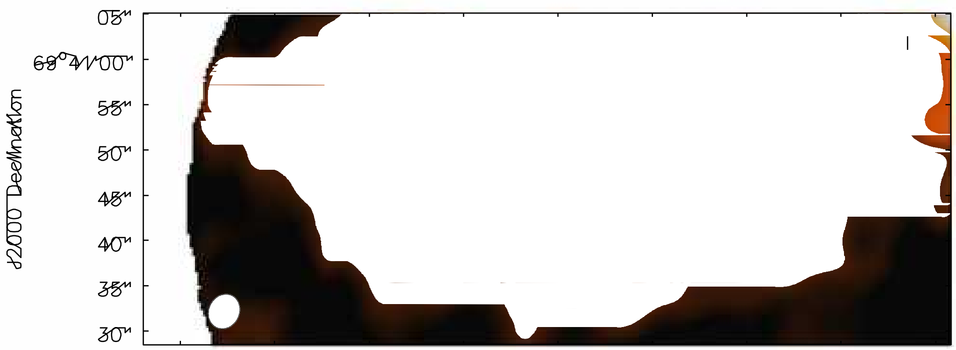
- We try to derive physical conditions and kinematics of the filaments.

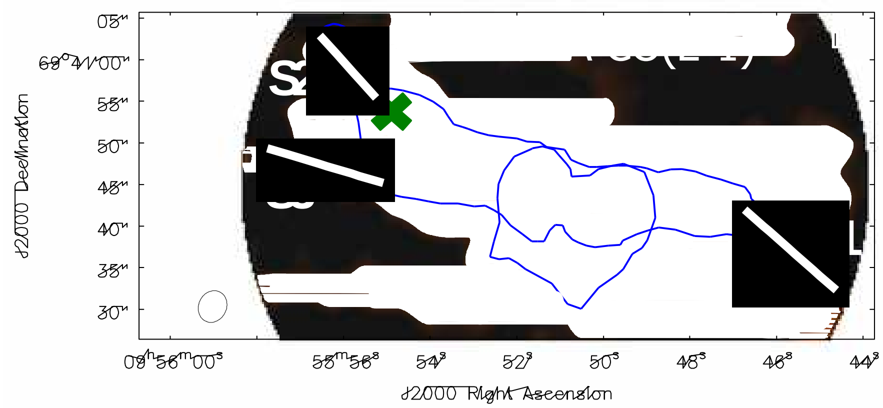
Results

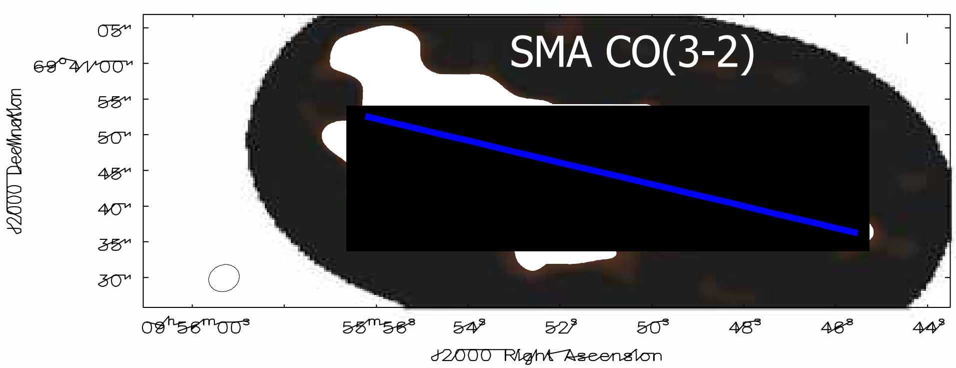
Results

Multi-J CO Maps

- Central region of M82 has been observed in CO J=1-0, 2-1, & 3-2.

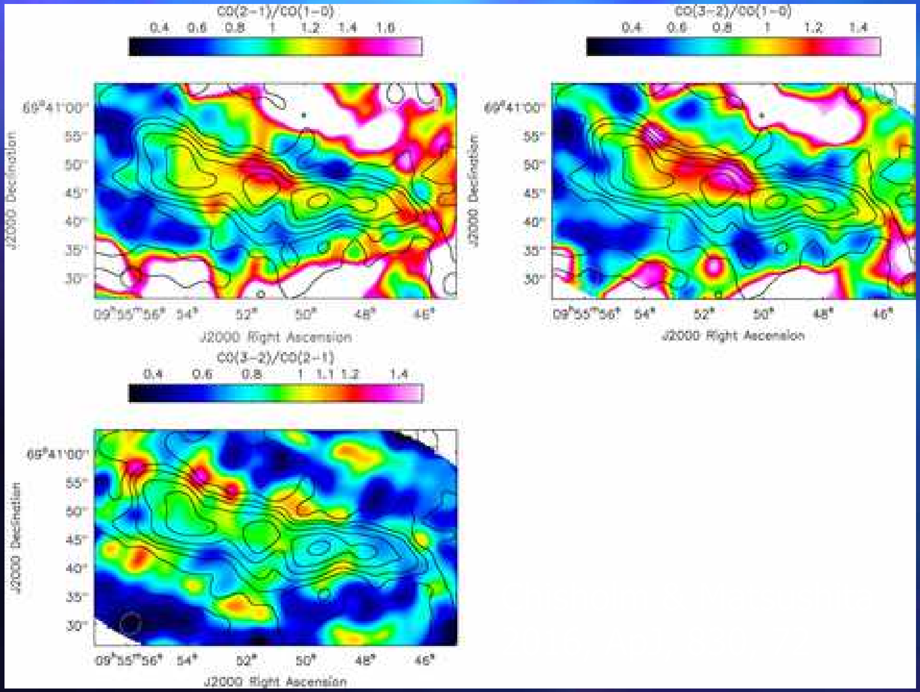


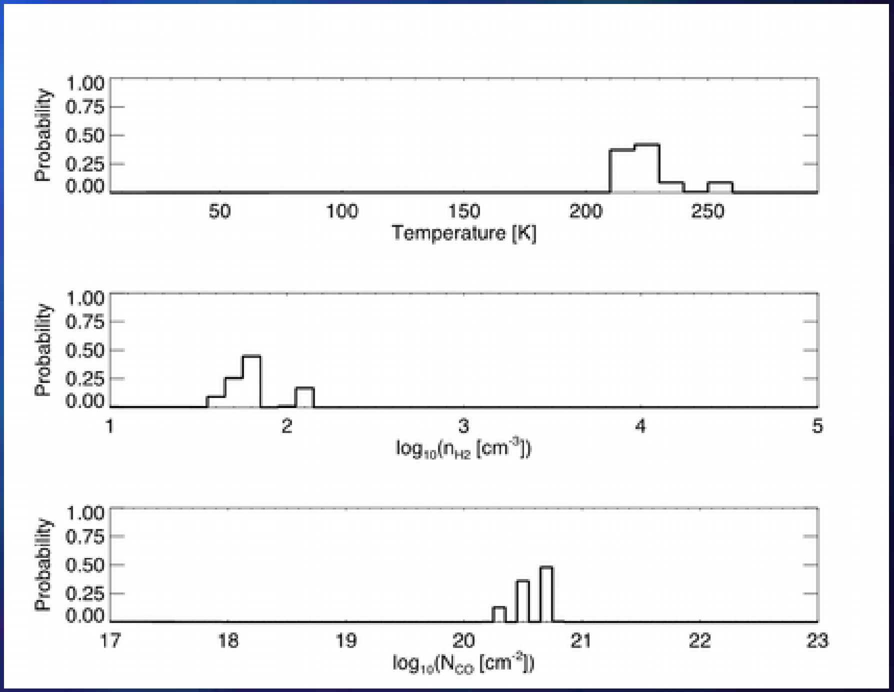




RADEX + Bayesian Analysis

- To derive the physical conditions (density, tempe rature, and column density) of molecular gas, we used RADEX + Bayesian Analysis.

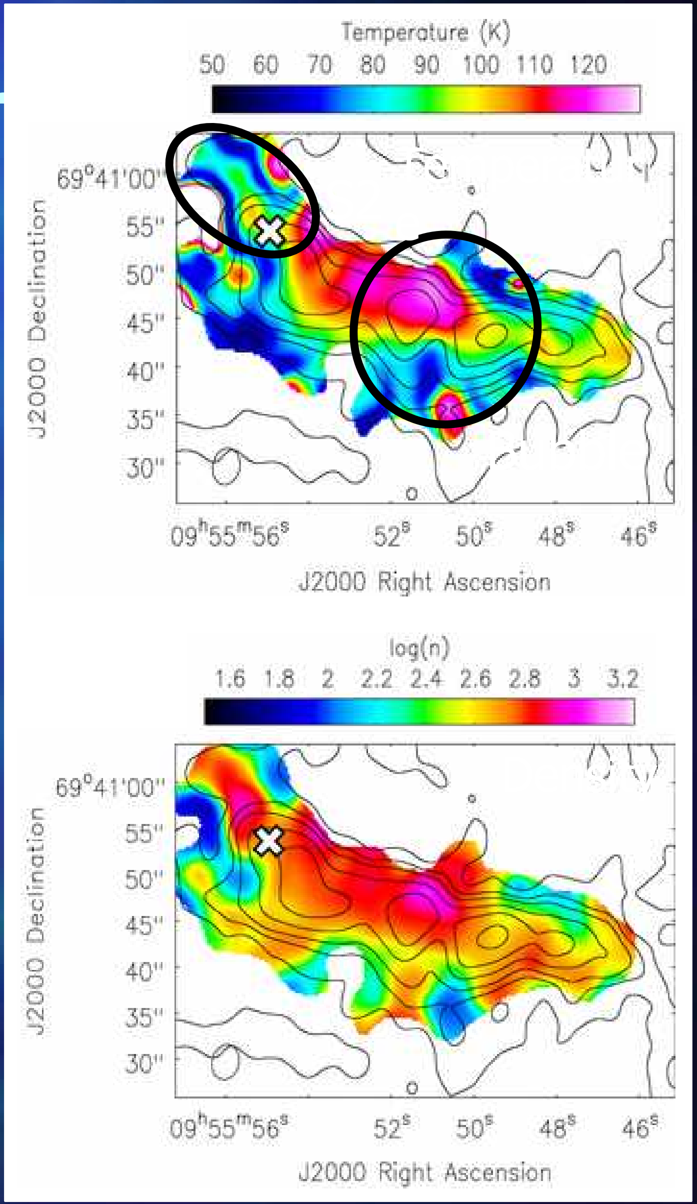




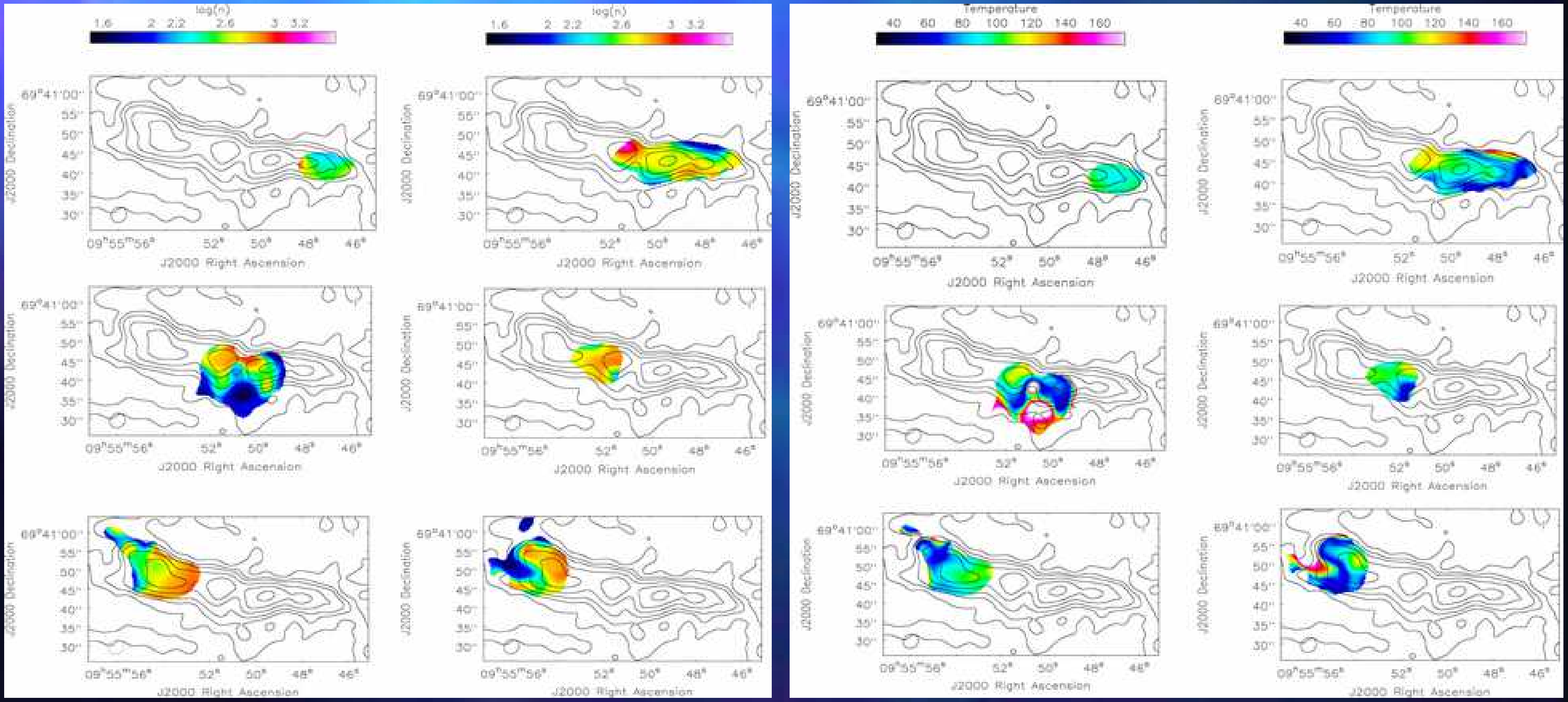
Density & Temperature

- Overall
  - Density: 101.8 - 3.1 cm-3
  - Temperature: 61-175 K
- Each Component
  - Disk
    - Density: 102.6 +- 0.5 cm-3
    - Temperature: 104 +- 36 K
  - Superbubble
    - Inside Disk
      - Density: 102.64 +- 0.18 cm-3
      - Temperature: 82 +- 17 K
    - Outside Disk
      - Density: 101.93 +- 0.15 cm-3
      - Temperature: 159 +- 30 K
  - Filament S2
    - Density: 102.3 cm-3
    - Temperature: 128 K

Chisholm & Matsushita 2016, ApJ, 830, 72

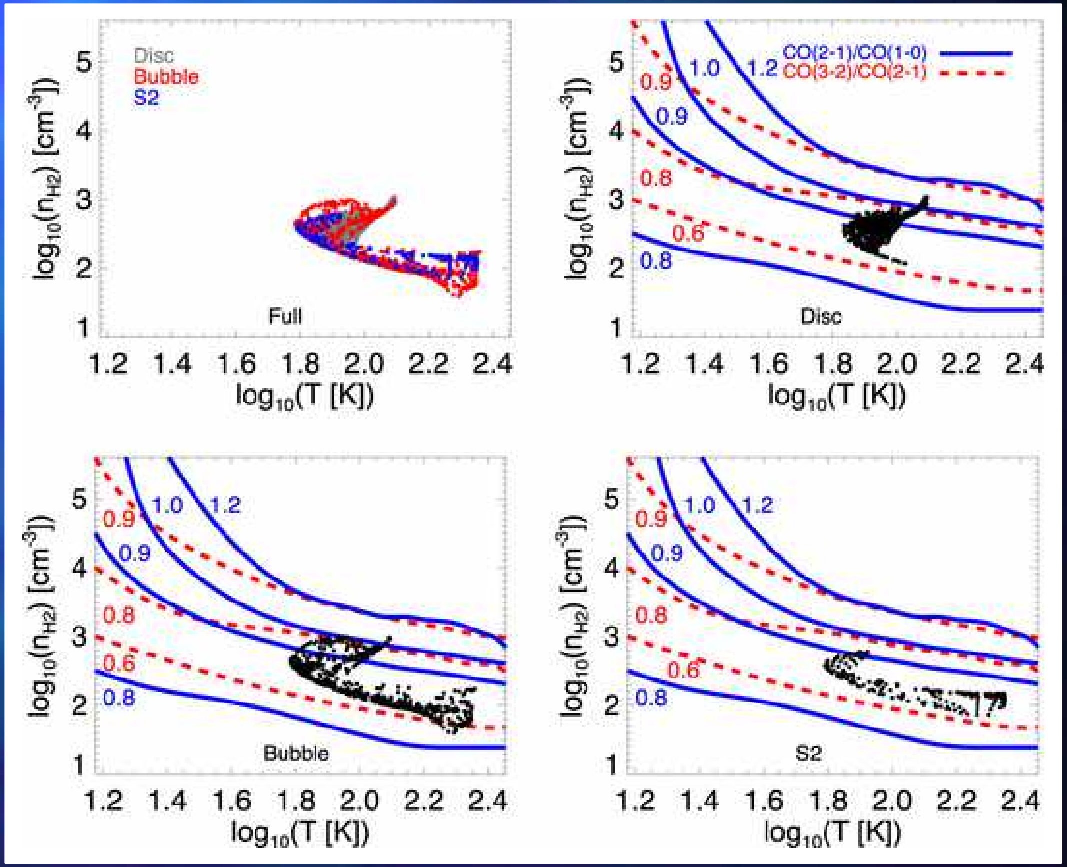


Density & Temperature Channel Map



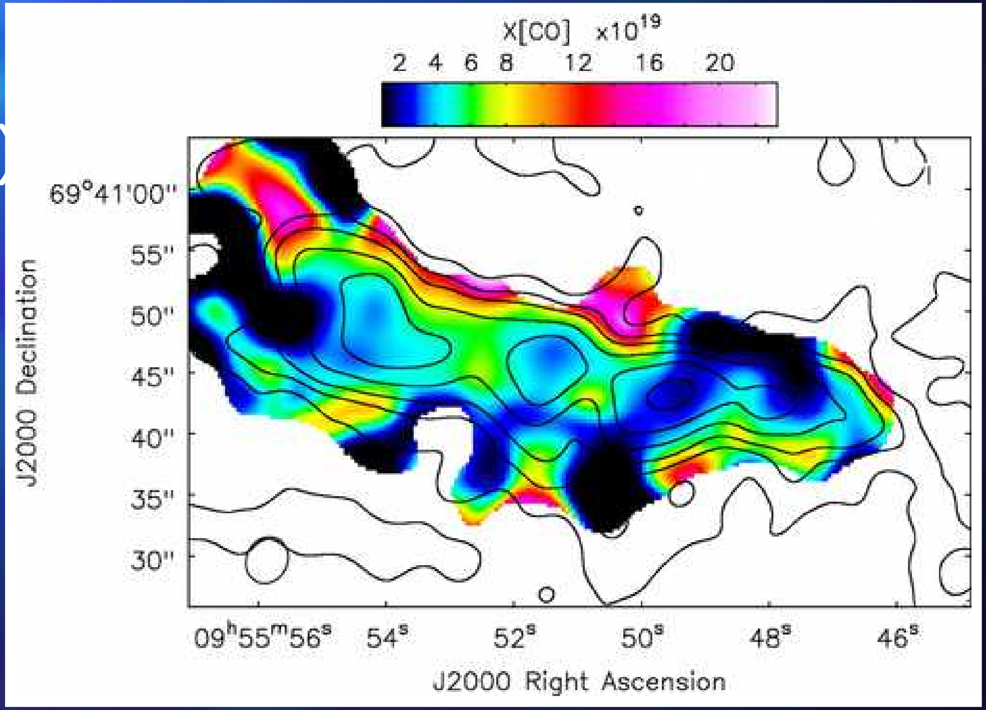
Density vs Temperature

- Superbubble and the streamer S2 have diffuse and high temperature components.



CO-to-H2 Conversion Factor XCO

- NH2 = XCO x (ICO x dv)
  ⇨XCO = (NCO / dv) / {Z(CO) x ICO} = n(H2) x {Z(CO)/(dv/dr)} / {Z(CO) x ICO}
  (Sakamoto et al. 1999)
- Median XCO
  ~ 4 x 1019 cm-2 /(K km/s)
  - An order of magnitude smaller than that in our Galaxy.
- Total Molecular Gas Mass
  ~ 2 x 108 Msolar

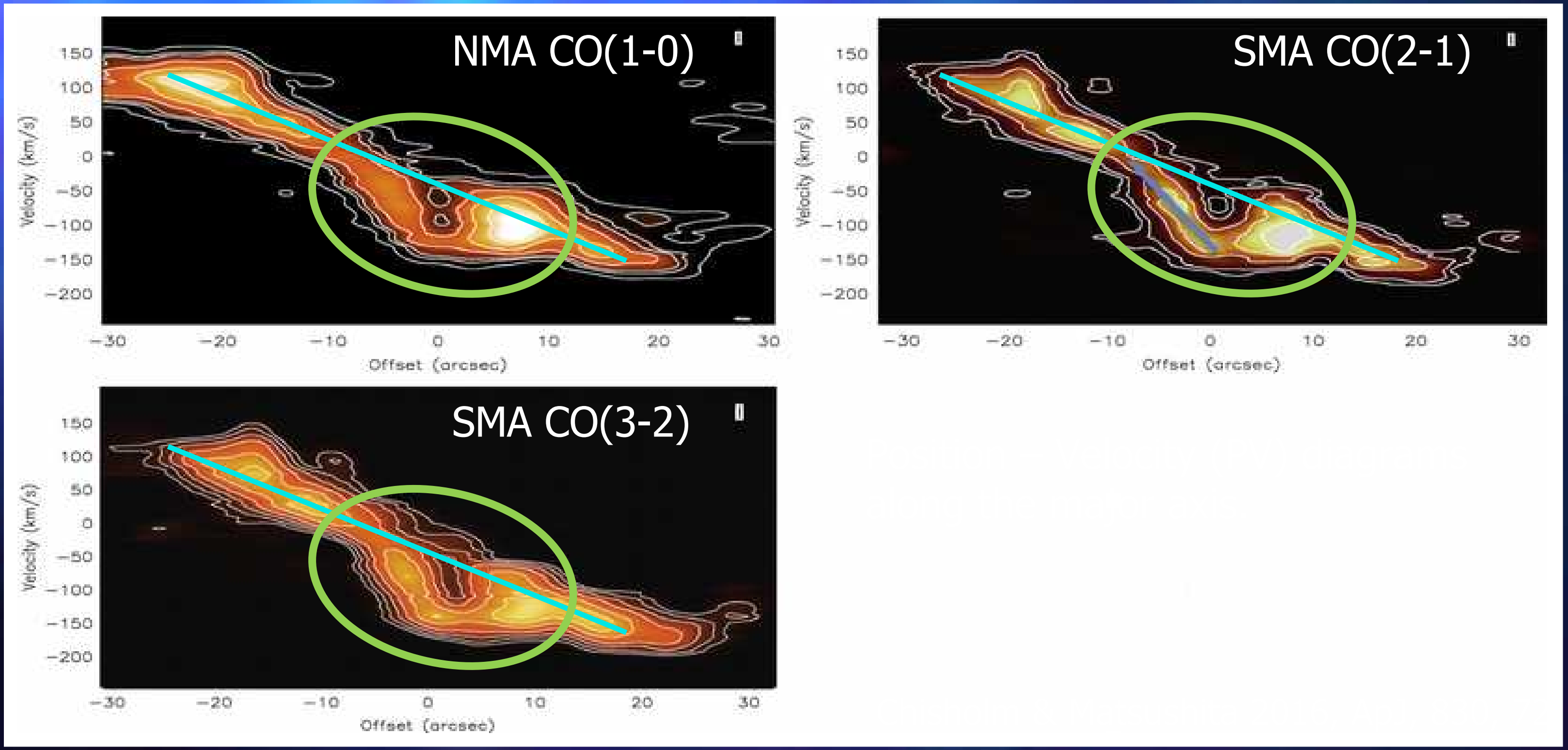


Chisholm & Matsushita 2016, ApJ, 830, 72

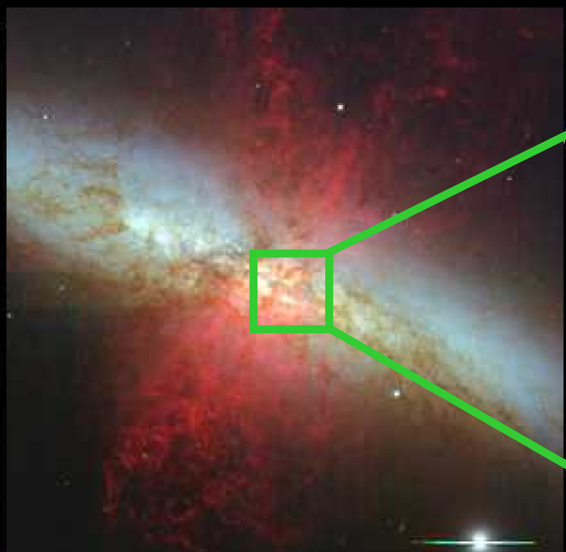
Self-Induced Starburst inside the Molecular Superbubble

Molecular Gas Kinematics

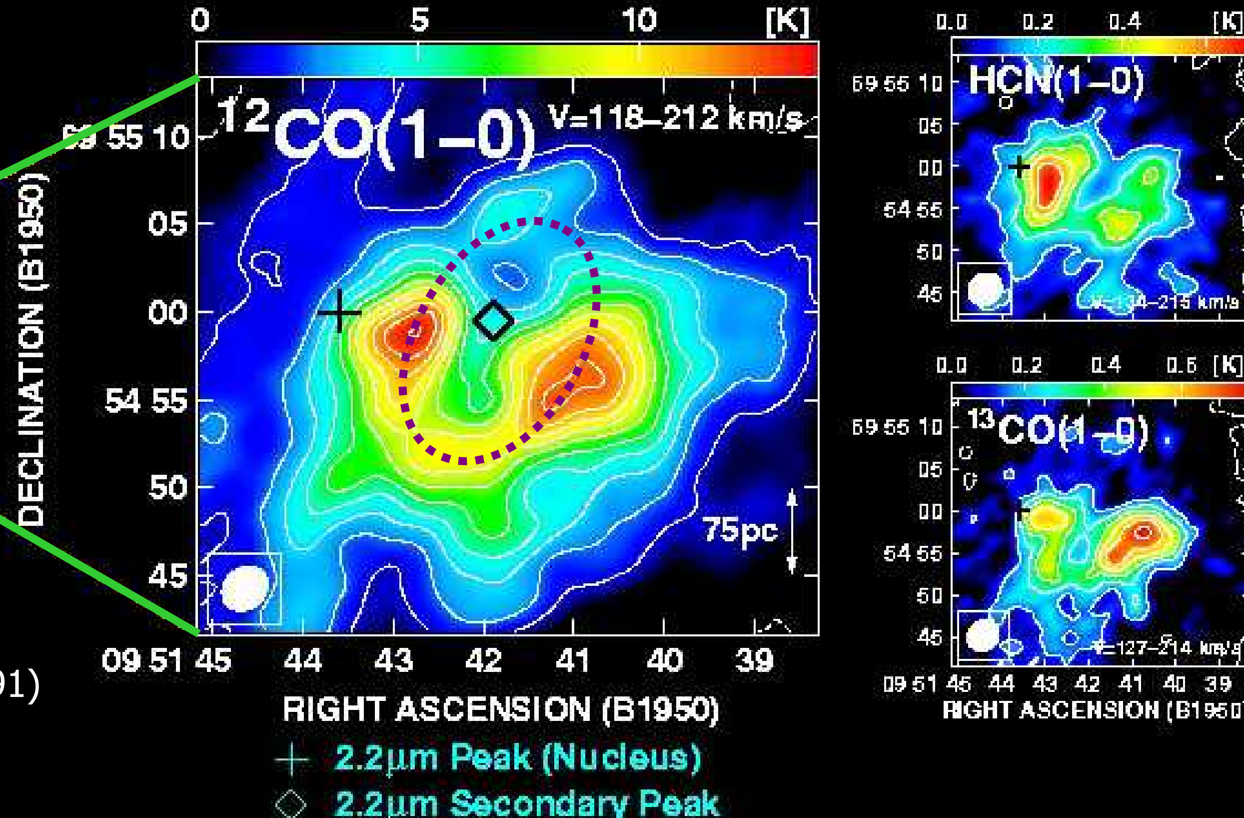
- There is a significant offset from the rigi d rotation near the galactic center.



Molecular Superbubble in M82



Subaru H∈+ B-,V-band
(Ohyama et al. 2002, PASJ, 54, 891)

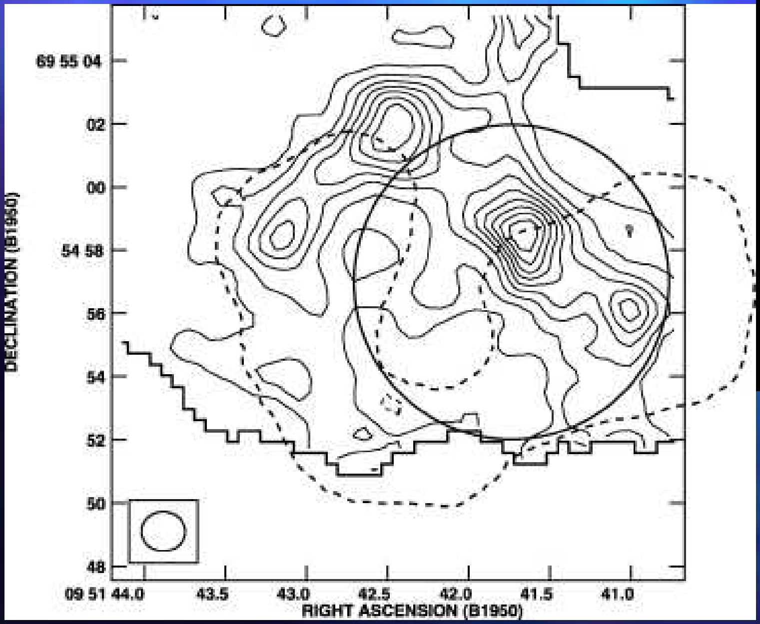


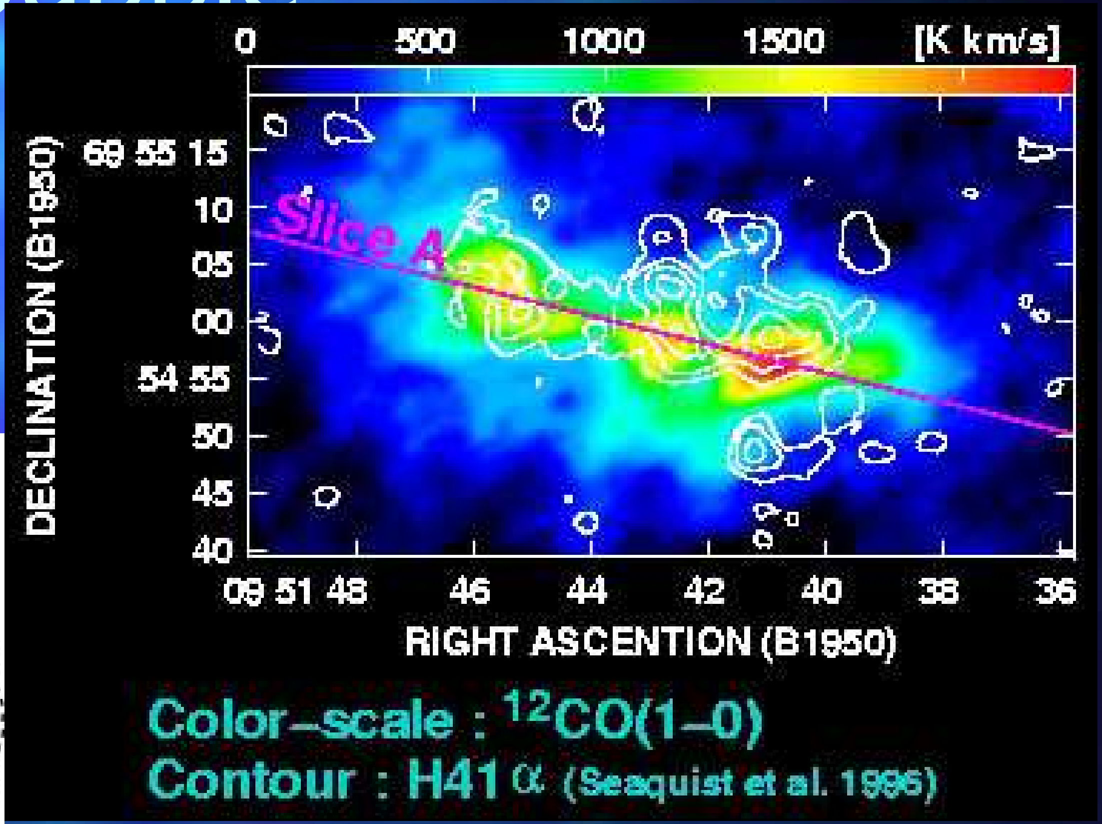
Nobeyama Millimeter Array
Matsushita et al. (2000)

- 140 pc offset from the galactic center.
  - Localized.
- Visible in both diffuse and dense molecular gas
  - Most of the molecular gas is associated with the bubble.

Atomic and Ionized Gas at the Superbubble

- Different distribution
  - South part : Mainly molecular gas
  - North part : Mainly a tomic/ionized gas





Contour : HI Absorption

(Wills et al. 2002, MNRAS, 331, 313)

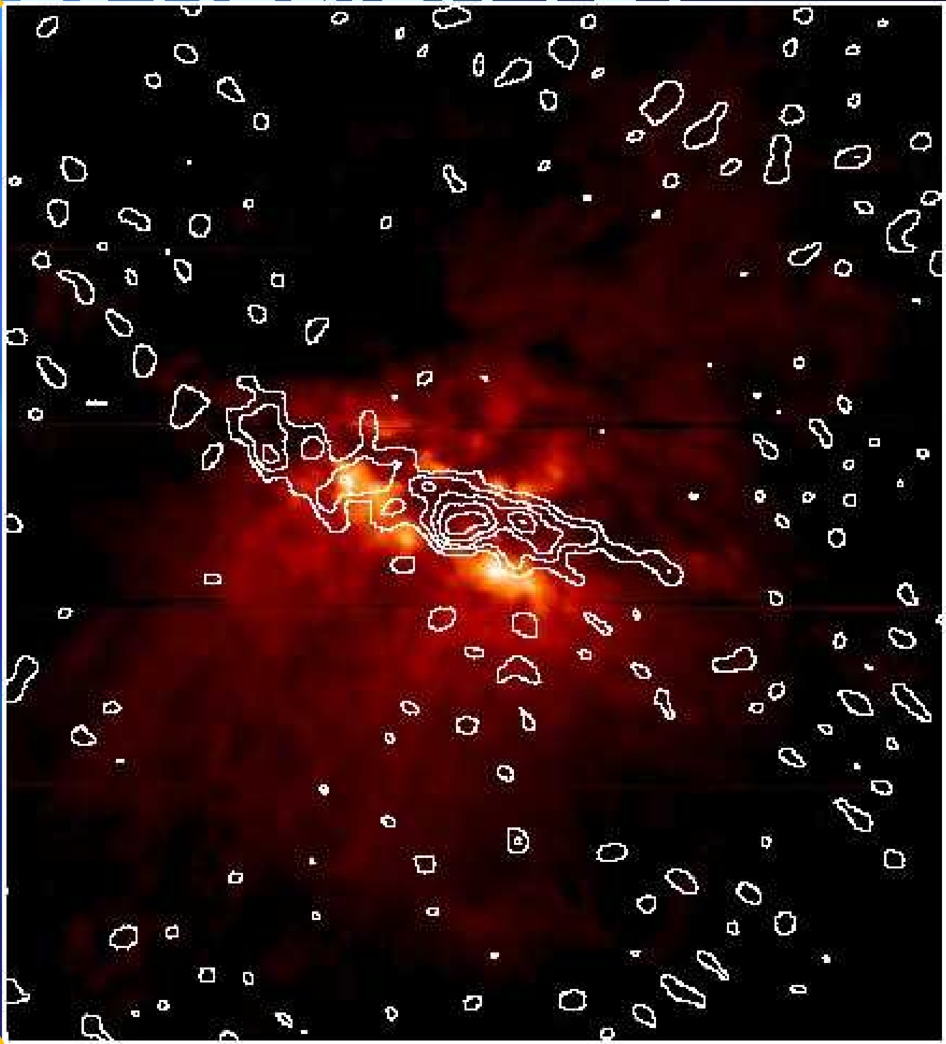
Dashed Line : CO Superbubble

Molecular Superbubble in M82 Properties

- Size ~ 210 x 140 pc
  - Elongated perpendicular to the galactic disk.
- Expansion Velocity ~ 50 - 100 km/s
- Age ~ (1-2) x 106 yr
- Mass ~ (1-3) x 108 Msolar
- Energy ~ (0.5-2) x 1055 erg
  - Equivalent to 103-104 supernovae energy.
- Mass Outflow Rate ~ 17 Msolar/yr

Starbursts inside the Superbubble
Present Starburst Region (1)

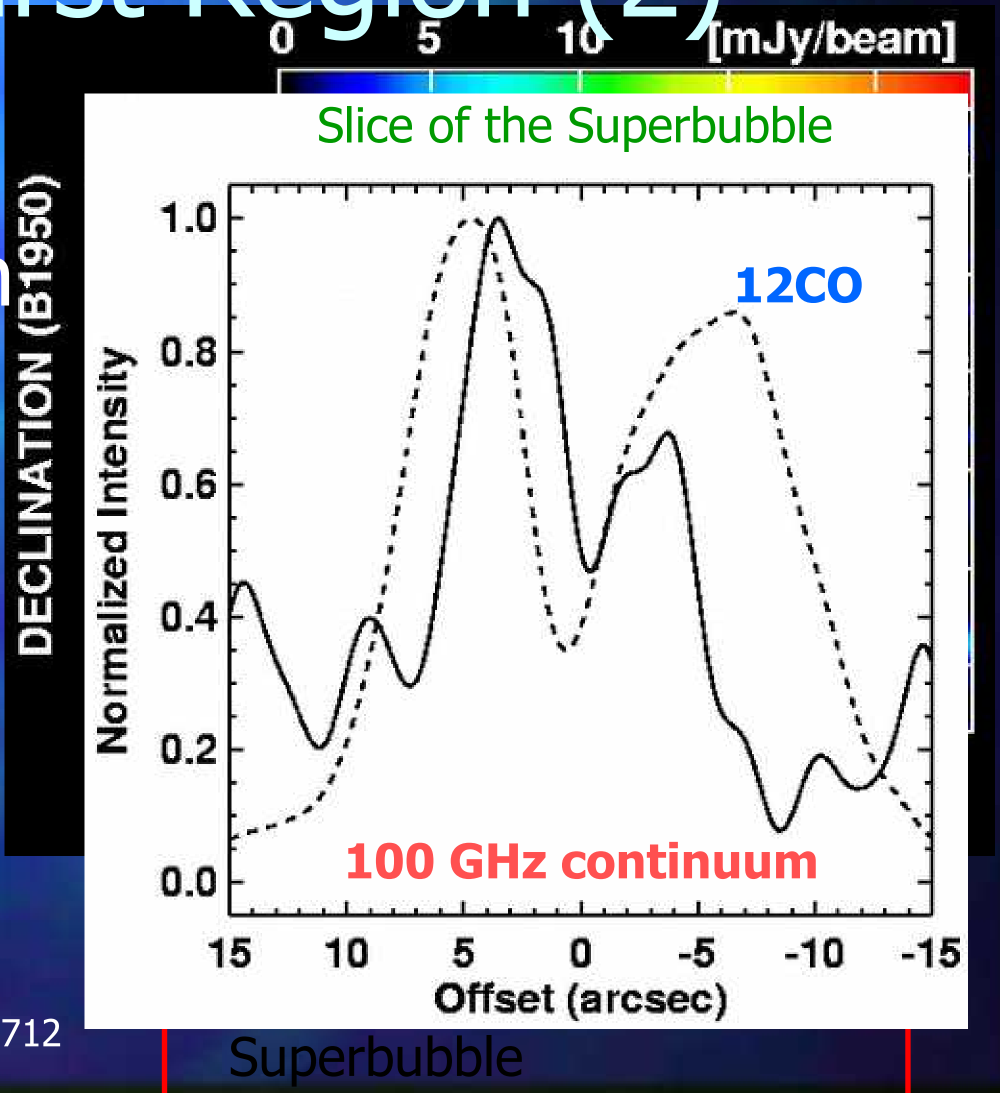
- Most of the starburst regions are obscured by dust.



- Color : H∈emission
  (Ohyama et al. 2002, PASJ, 54, 891)
- Contour : 100 GHz continuum
  (Matsushita et al. 2005, ApJ, 618, 712)

Starbursts inside the Superbubble
Present Starburst Region (2)

- Peak positions of 100 GHz continuum are offset from the nucleus.
- Starburst regions are inside edge of the superbubble.
- Starburst is weak at the bubble center.



Matsushita et al. 2005, ApJ, 618, 712

Self-Induced Starburst in M82
Termination of Starburst

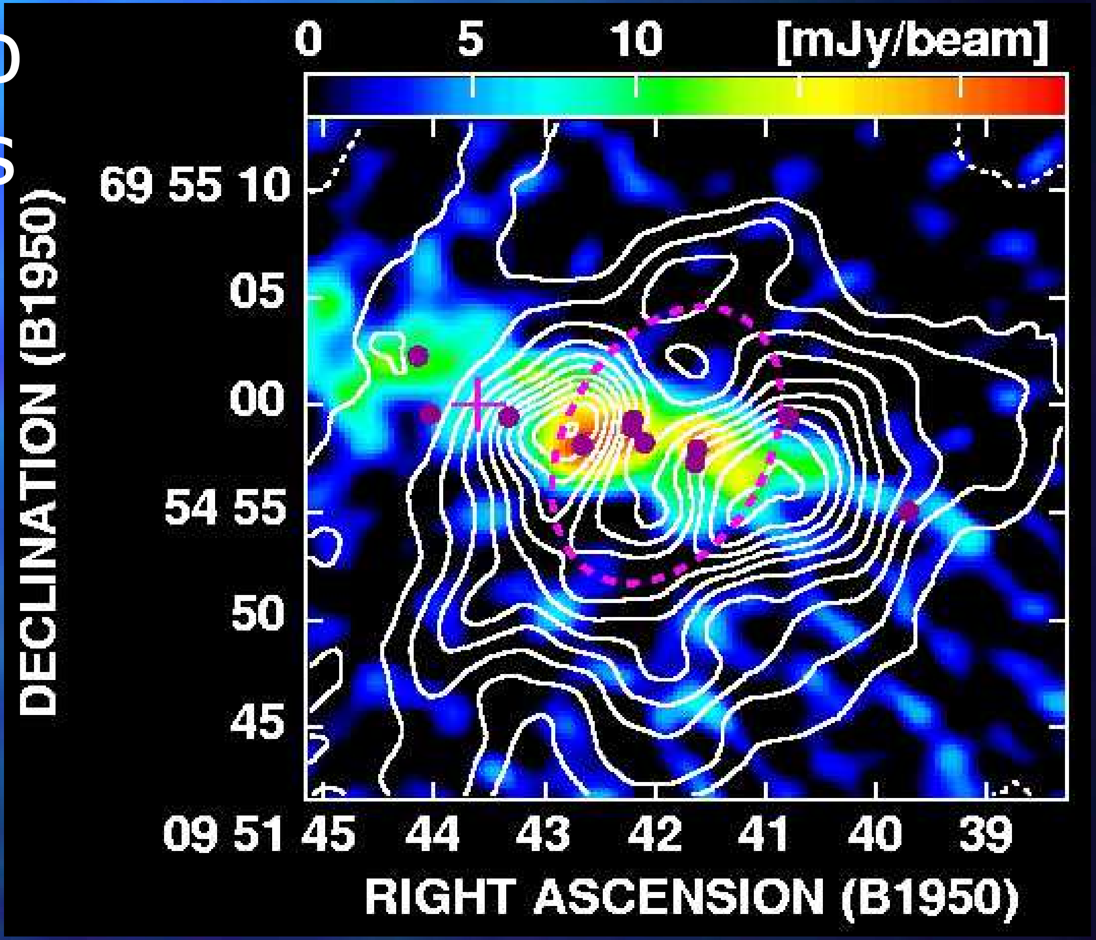
- Stars are made from (dense) molecular gas.
- Small amount of molecular gas at the center of th e superbubble.
- Free-free emission is also weak.
- Red supergiant dominated star cluster locates at t he center of the superbubble.

↓

- Starburst at the center of the superbubble begins t o cease.
- Number of massive stars is decreasing by superno va explosions.

Starbursts inside the Superbubble
Atomic, Ionized Gas, & Masers (1)

- Masers are well co rrelated with the s tarburst regions.

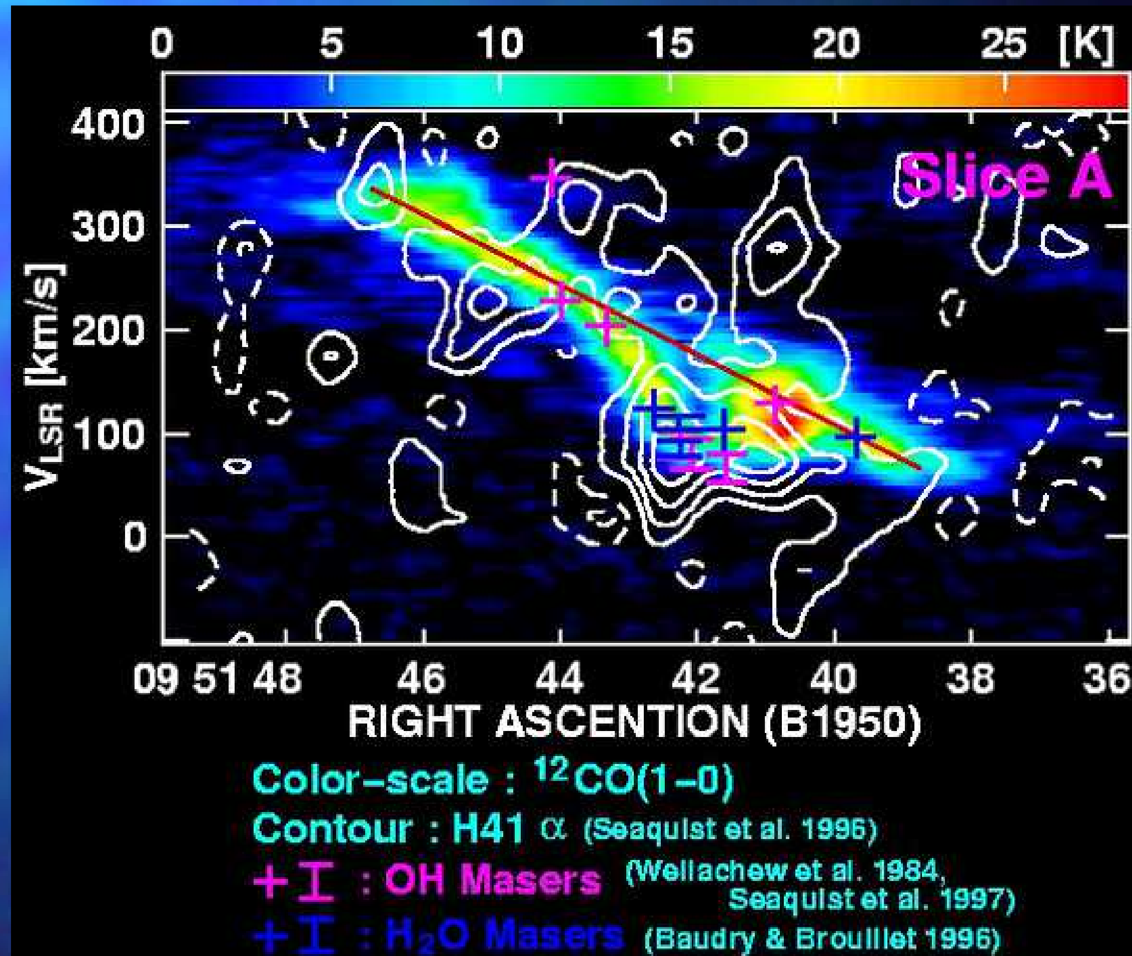


- Color : 100 GHz continuum
  (Matsushita et al. 2005, ApJ, 618, 712)
- Contour : 12CO Superbubble
  (Matsushita et al. 2000, ApJL, 545, L107)
- Dots : OH & H2O Masers
  (Wellachew et al. 1984; Seaquist et al. 1997;
  Baudry & Boulliet 1996)

Starbursts inside the Superbubble Atomic, Ionized Gas, & Masers (2)

- Ionized gas expa nds faster.
- Many masers at t he superbubble.

- Ionized gas is
  - in the bubble.
  - expanding toward outside.
  - interacting with molecular gas.

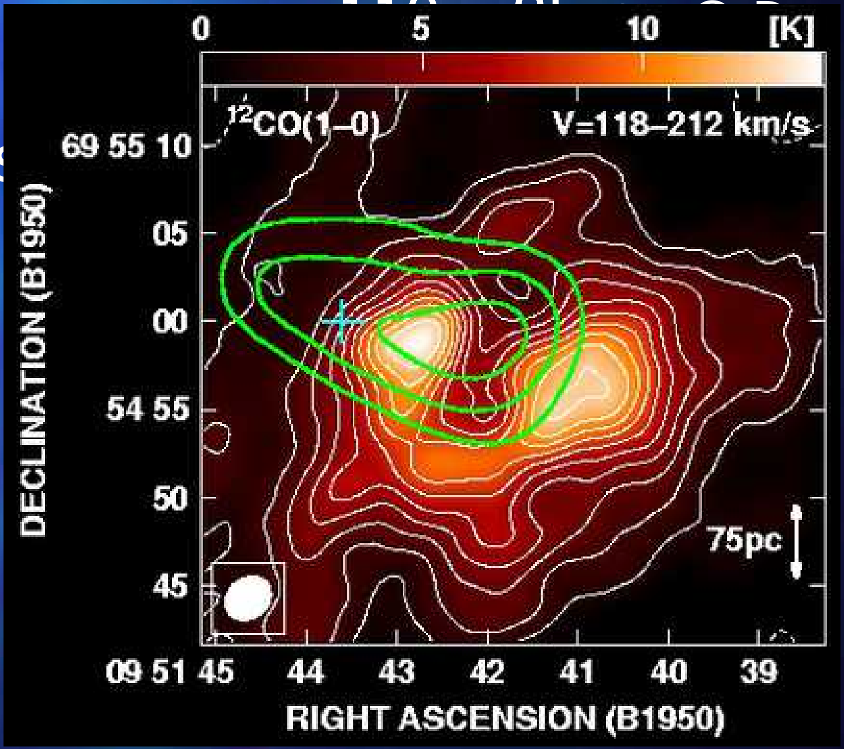


Starbursts inside the Superbubble Atomic, Ionized Gas, & Masers (3)

- Diffuse hard X-ray (2-8 keV; Griffiths et al. 2000, Science, 290, 1325) emits from inside the superbubble
  - Size = 7.2" x 5.4" = 3.25 Mpc
  - LX (2-10 keV) = 2.2x1039 erg/s
  - kT ~ 2.4 - 4.1 keV
  - Overpressurized cm-3).

↓

- Bounded in the bubble.
- Consistent with the results s and masers.



Green Contour: Diffuse Hard X-ray

Starbursts inside the Superbubble Diffuse Hard X-ray (2)

- Soun d Speed of Plasma Proton cpp ~ √(kT/mp) ~ (5-6) x 102 km/s
- Expansion Timescale tex ~ r/cpp ~ (1-2) x 105 yr

↓

- Faster expanding velocity & short expansion ti mescale than the molecular superbubble

↓

- Consistent with the results of ionized gas and masers.

Self-Induced Starburst in M82

Self-Induced Starburst

- Existence of the expanding molecular superbubble.
- Bright supergiants (late OB stars) are at the center.
- Overpressurized hot gas & high-velocity ionized gas.
- Masers are concentrated.
- Free-free emission is strong (= many massive stars exist) at the edge of the superbubble.

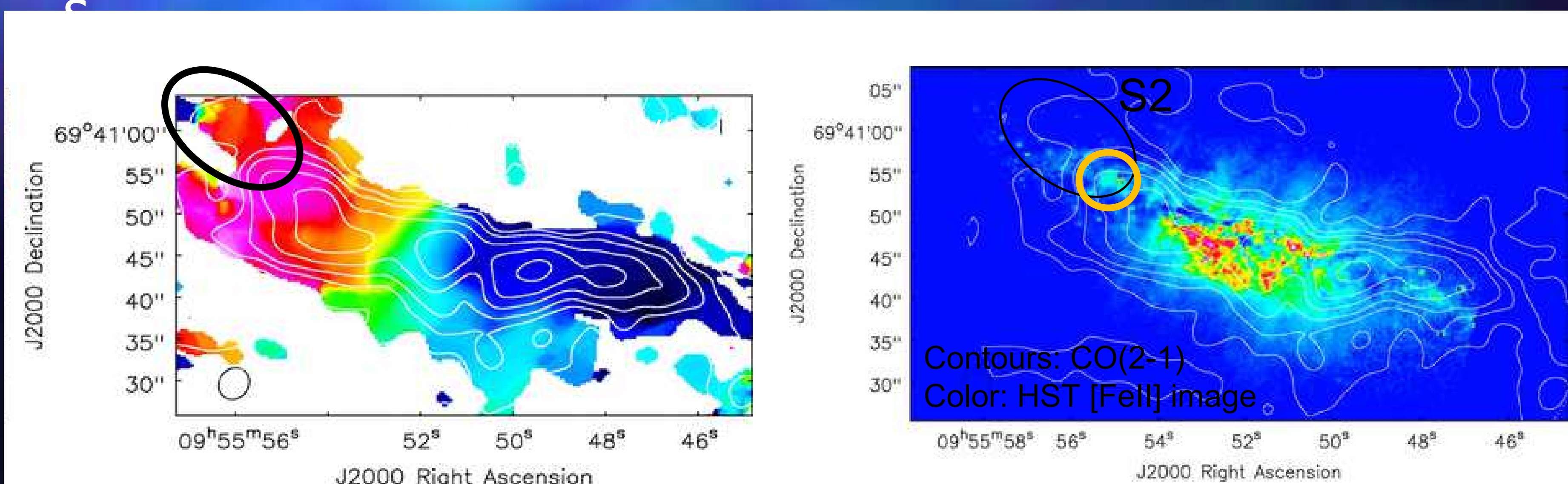
⇒

- Past starburst produced the high-velocity gas, swept surrounding gas, and produced the superbubble.
- The compression of surrounding gas induced new st arburst regions (Self-Induced Starburst).

Inflowing Filament S2

Inflowing Filament S2

- Filament S2 is blueshifted (-37 km/s) from the galactic rotation.
  - If far-side, it is coming toward us, so “inflow”.
  - If near-side, it is moving away from us, so “outflow”.
- S2 has AV ~ 28mag, but no absorption feature in optical images



Inflowing Filament S2 Properties

- Mass ~1.5 x 106 Msolar
- Velocity Gradient ~ 9 x 10-7 yr-1
- Mass Inflow Rate ~ 1.4 Msolar/yr

Molecular Baryonic Cycle of M82

- Total Molecular Gas Mass ~ 2 x 108 Msolar
- Inflow Rate
  - Filament S2
    - H2 + HI Gas Mass Inflow Rate ~ 3.5 Msolar/yr
- Consumption/Outflow Rate
  - Star Formation Rate ~ 13 Msolar/yr (Förster Schreiber et al. 2003)
  - Superbubble Outflow Rate ~ 17 Msolar/yr
- M82 will consume or expel all of the observed molecular gas in 7.8 Myr.

Molecular Baryonic Cycle of M82 Summary

- We observed the starburst region of M82 in CO J=1-0, 2-1, & 3-2.
- Density, temperature, XCO, and total mol ecular gas mass have been derived.
- Self-induced starburst has been observed at the superbubble.
- Observed gas inflow rate is much smaller than the consumption/outflowing rate, so that it will be consumed/expel in 7.8 Myr.