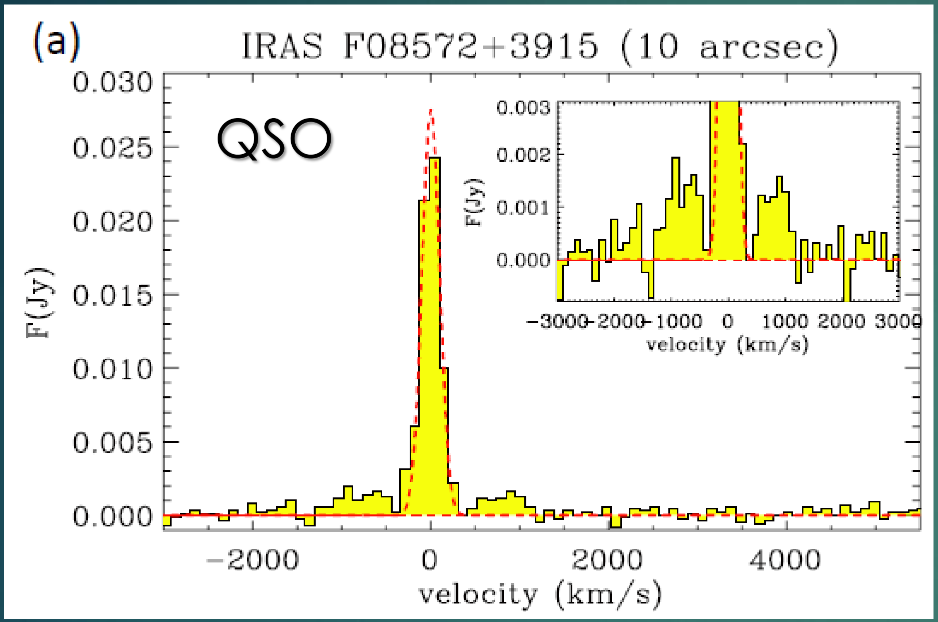
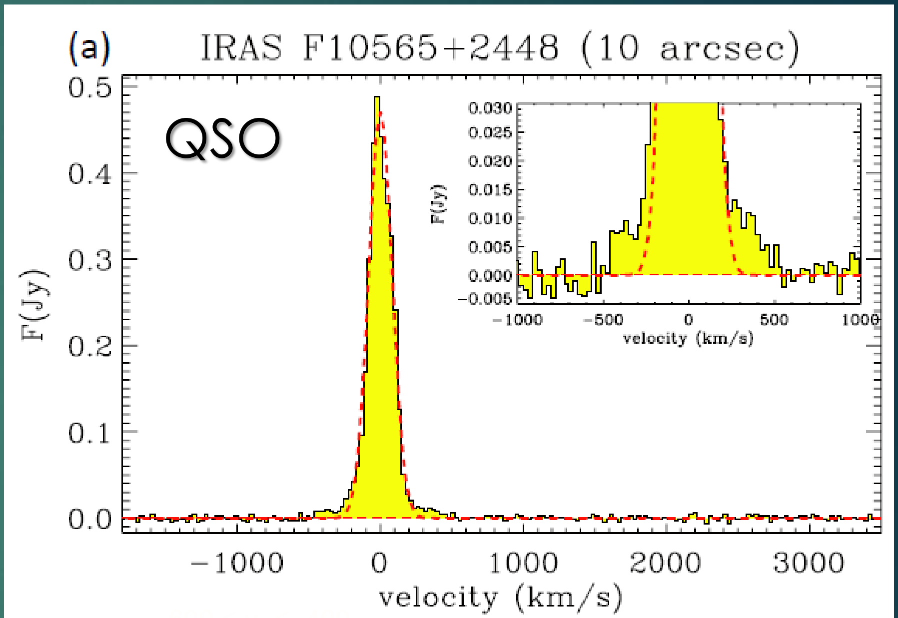
Molecular Gas - AGN Jet Interaction: Near and Far

SATOKI MATSUSHITA (ASIAA)

Introduction: Molecular Outflows in AGNs

Cicone et al. 2014, A&A, 562, A21

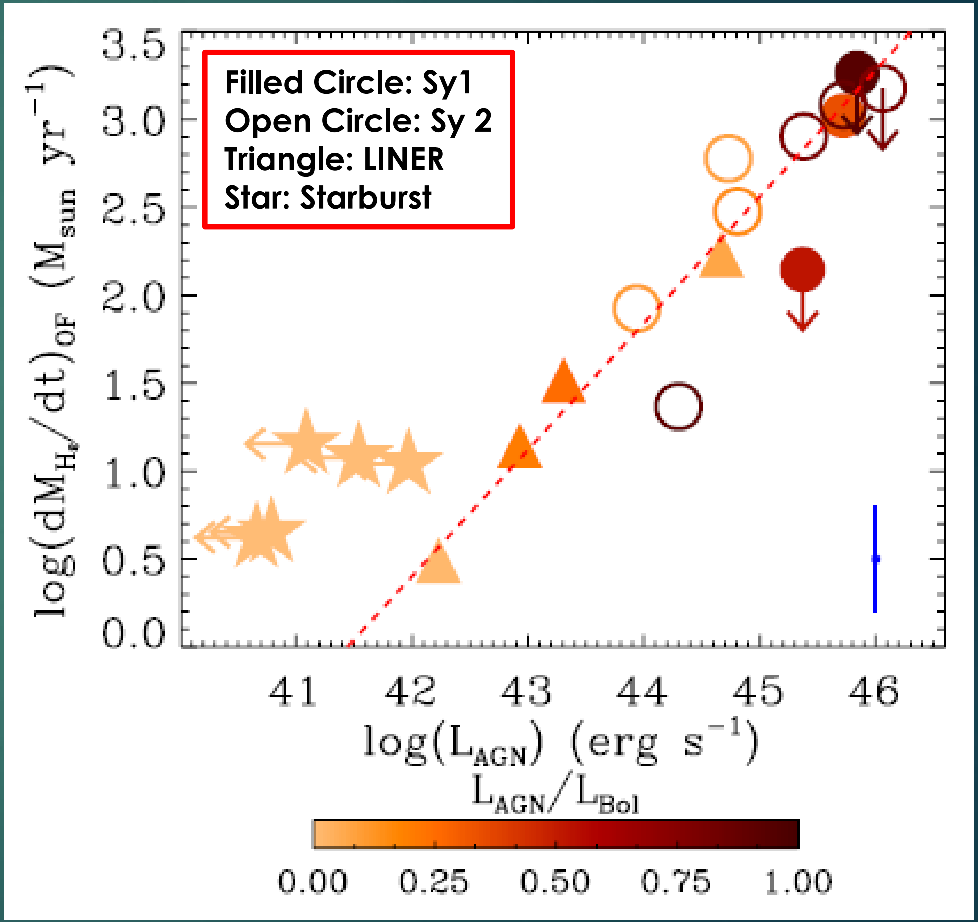




- Most of the past observations are not spatially resolved: Spectrum base studies.
- Broad wing components (> 500 km/s) can be seen in the spectra.

Introduction: Molecular Outflows in AGNs

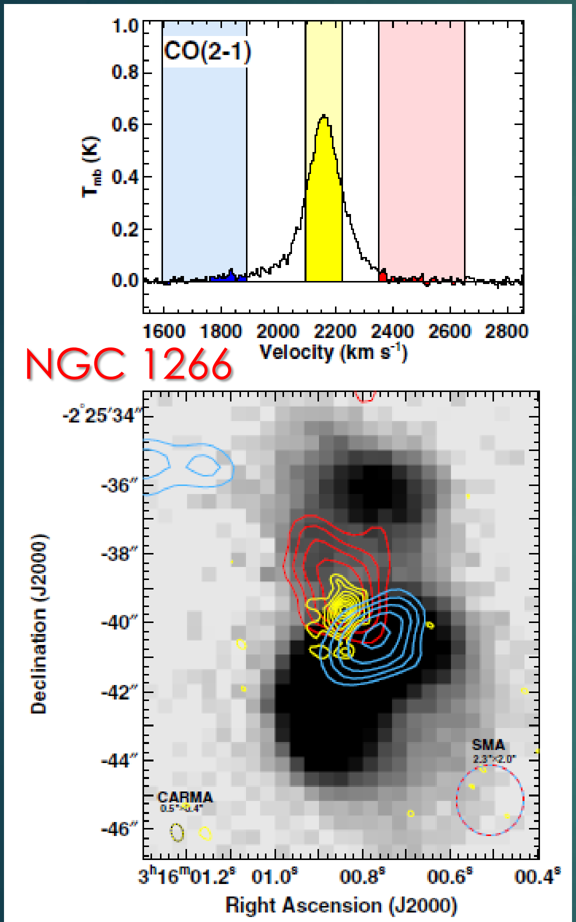
- Limited to the study of energetics.
- Spatial resolution is not enough to discuss about the cause(s) of molecular outflows.



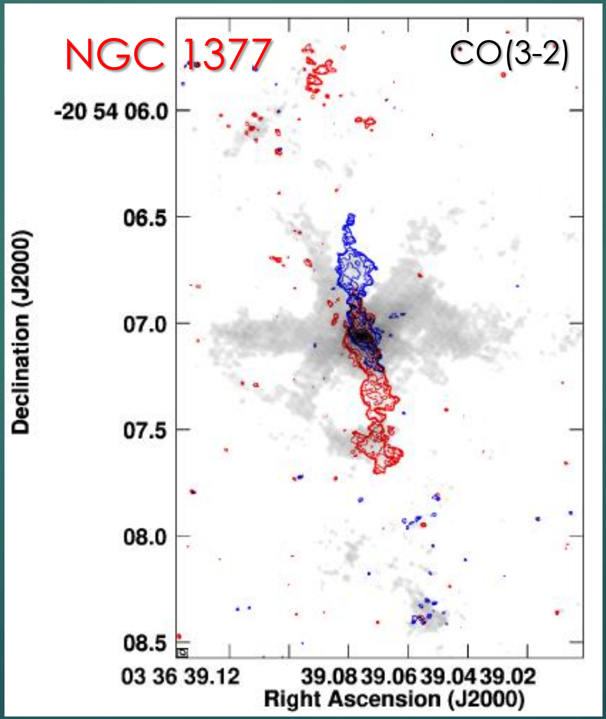
Cicone et al. 2014, A&A, 562, A21

Introduction:
Molecular Outflows in AGNs

- Recent high spatial resolution and high sensitivity observations:
  - Start to resolve molecular outflows from AGNs.
  - But not enough to study the cause(s).

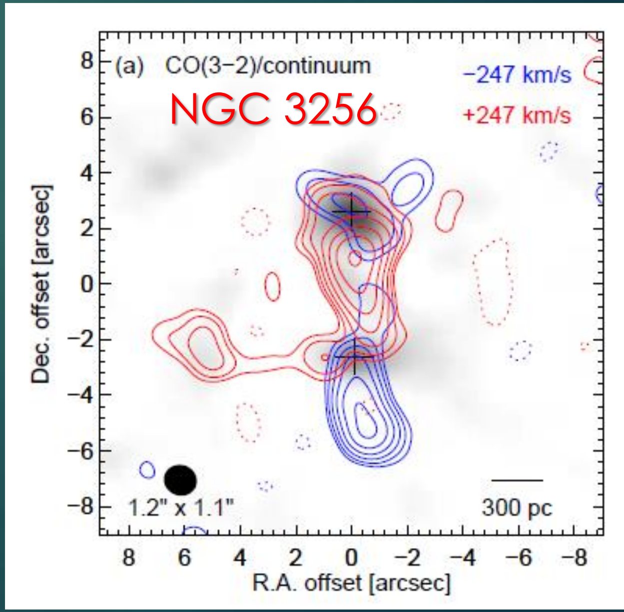


Alatalo et al. 2012, ApJ, 735, 88



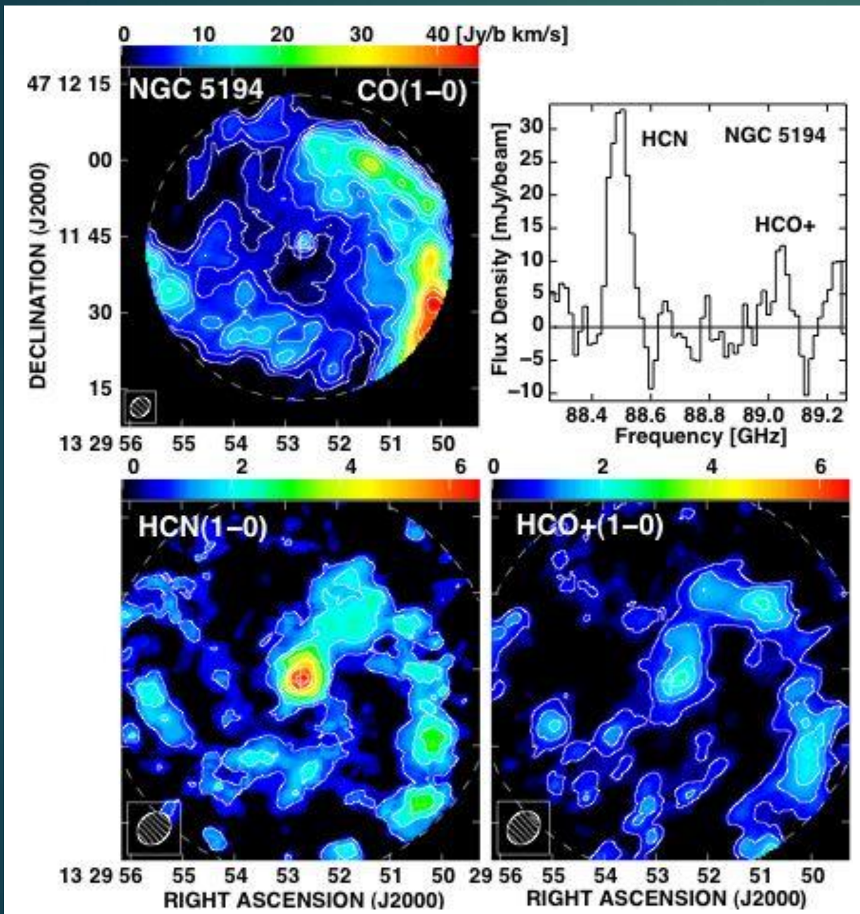
Aalto et al. 2020, A&A, 640, A104

Sakamoto et al. 2014, ApJ, 797, 90



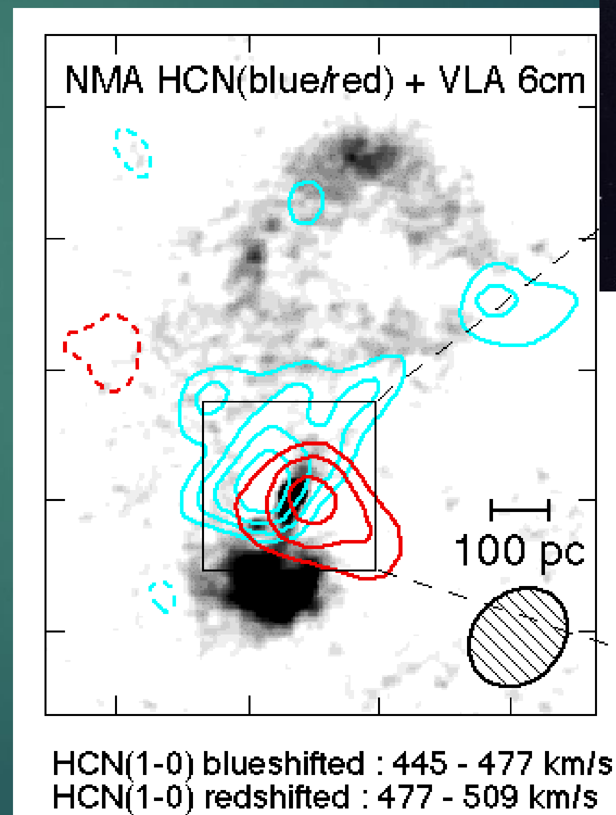
Case Study in Nearby

Molecular Gas - Radio Jet Interaction
Seyfert 2 Galaxy M51



Kohno et al. 2008, ApSS, 313, 279

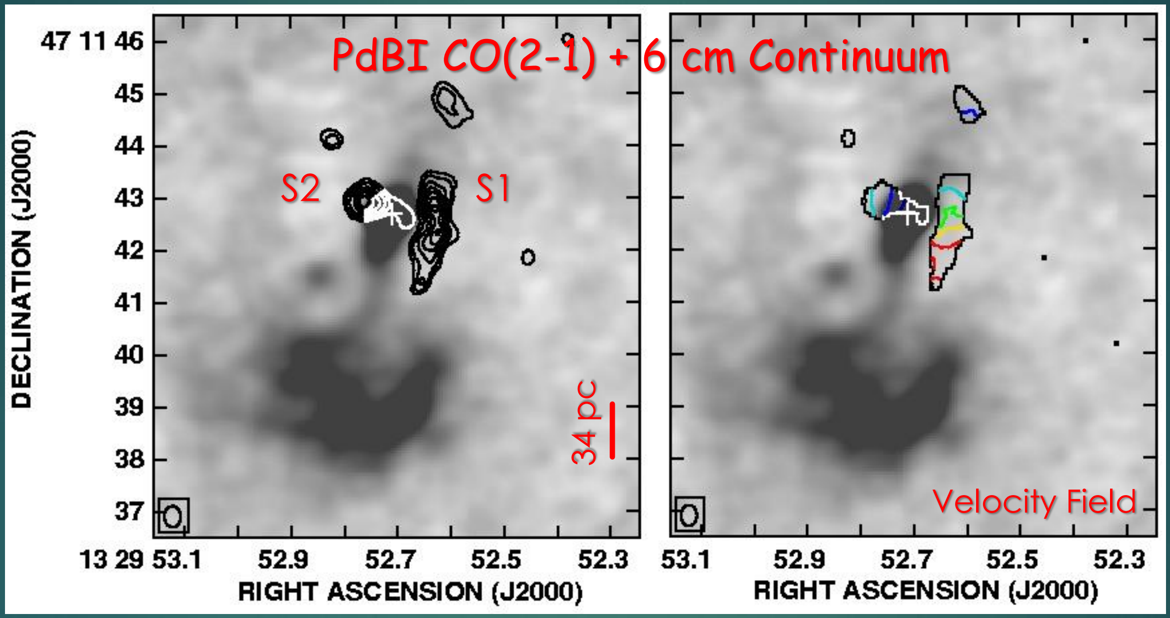
- Distance: 7.1 Mpc
- 1'' ~ 34 pc

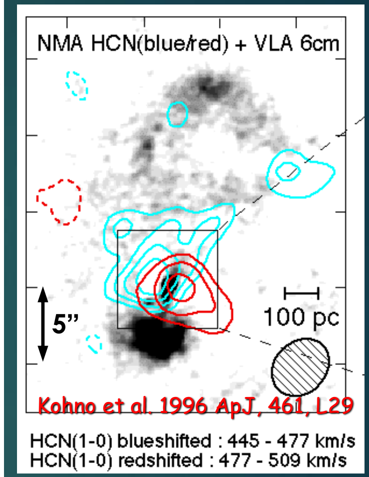


Kohno et al. 1996, ApJ, 461, L29

Molecular Gas - Radio Jet Interaction
Radio Jet Entrained Molecular Outflow

Matsushita et al. 2007
A&A, 468, L49

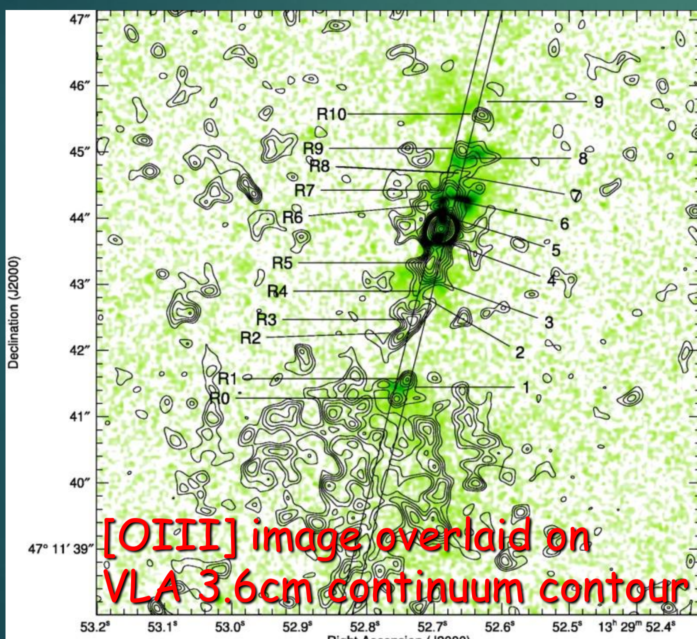




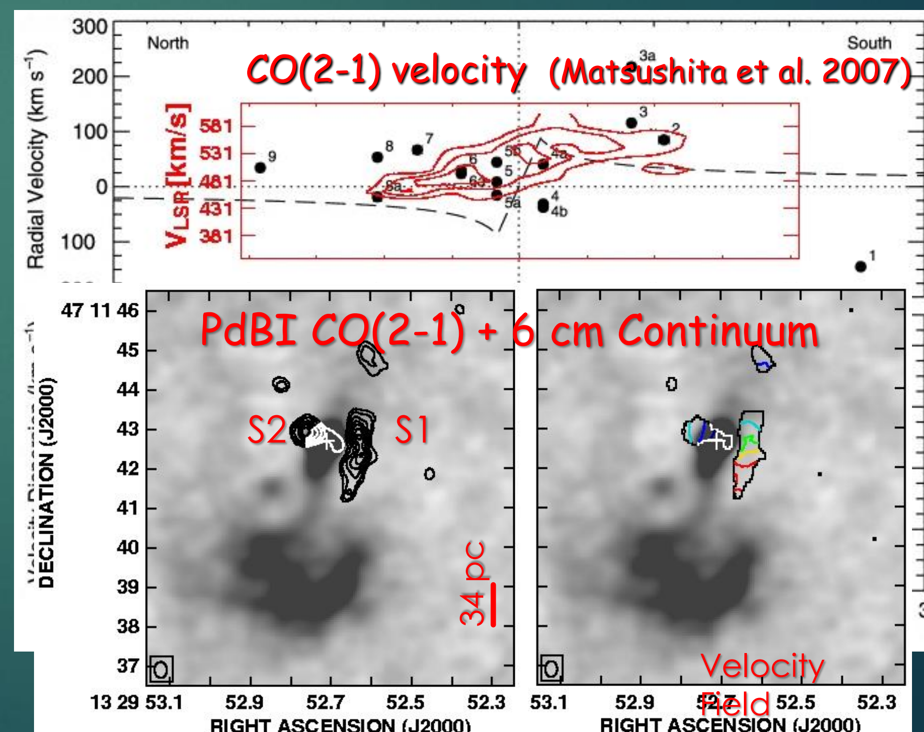
- No clear disk/torus structure.
  - Several ~10-20 pc size molecular clouds.
- Complicated velocity structure.
  - Cloud S1: Velocity gradient toward north-south.
  - Cloud S2: Velocity gradient toward east-west, but opposite sense as the previous observations.

Molecular Gas - Radio Jet Interaction Radio Jet Entrained Molecular Outflow

- Velocity of molecular gas matches well with that of [OIII] emission along the radio jets.
  ⇨ Molecular gas is entrained by the jets.



Bradley et al. 2004, ApJ, 603, 463



Molecular Gas - Radio Jet Interaction
Molecular Outflow Powered by Jets

- Can radio jets drive the molecular outflow?
  - Properties of entrained molecular gas:
    - Mass: 6×10^5 Mo
    - Momentum: 8×10^{45} g cm s^{-1}
    - Energy: 3×10^{52} erg
  - Properties of radio jets:
    - Momentum: 2×10^{41} g cm s^{-1} (assuming the velocity of the relativistic particles are 90% of the speed of light)
    - Energy: $> 6.9 \times 10^{51}$ erg (Crane & van der Hulst 1992)

  ⇨ With spending long time (putting momentum continuously), radio jets are possible to drive the molecular outflow.

- Mass loss rate?
  - Velocity gradient = 2.2 km/s/pc

    ⇨ Timescale = 5×10^5 yr

  ⇨ Mass loss rate = 1.2 Mo/yr

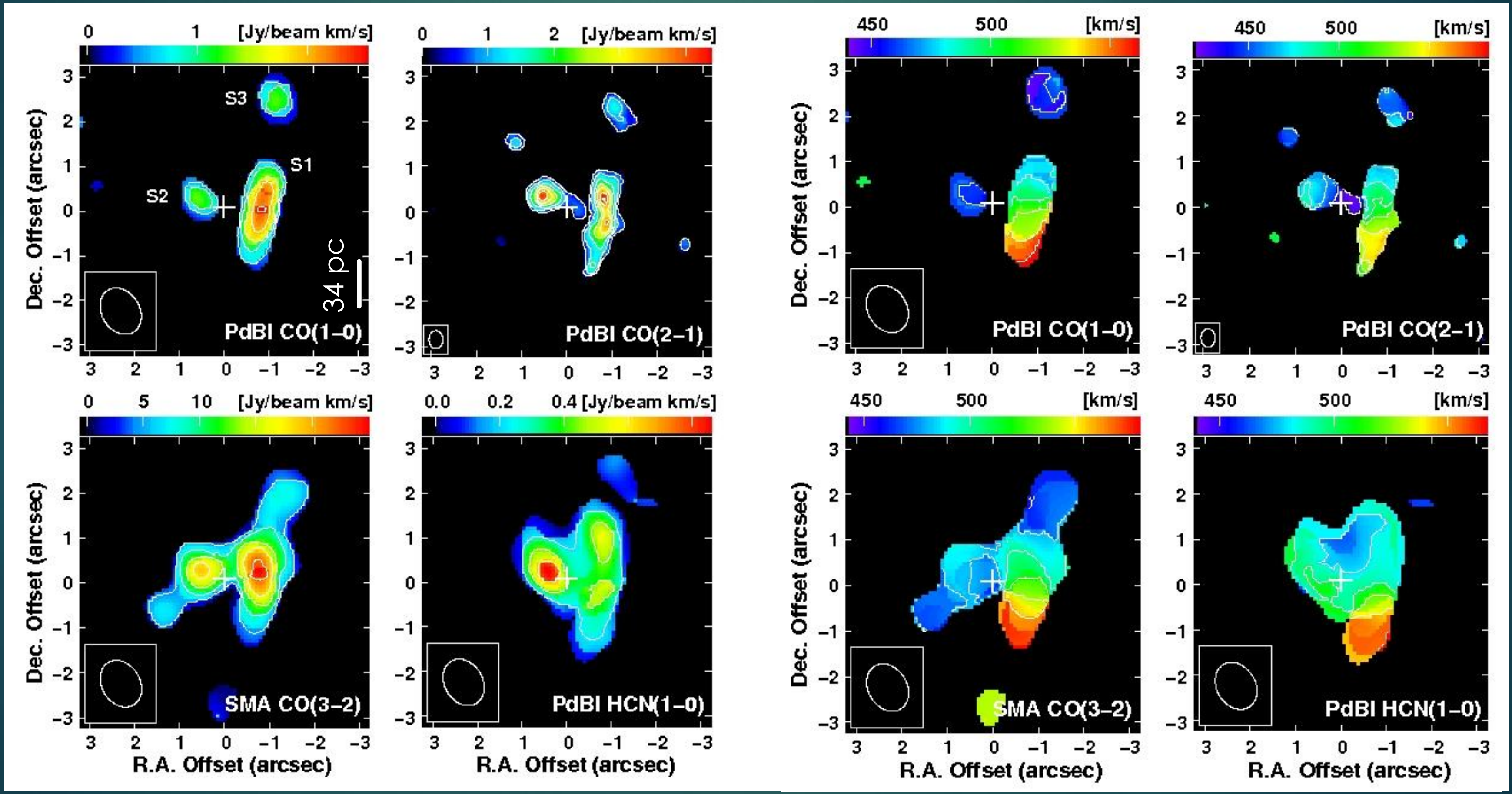
- Molecular gas, which can be the fuel for the AGN activity, is moving out from the AGN.

  ⇨ Negative feedback.
  Self-Regulation.

Matsushita et al. 2004, ApJ, 616, L55
Matsushita et al. 2007, A&A, 468, L49

Molecular Gas - Radio Jet Interaction

- HCN shows similar distribution and kinematics as that of CO lines.
  ⇨ Both dense and diffuse molecular gas are outflowing.



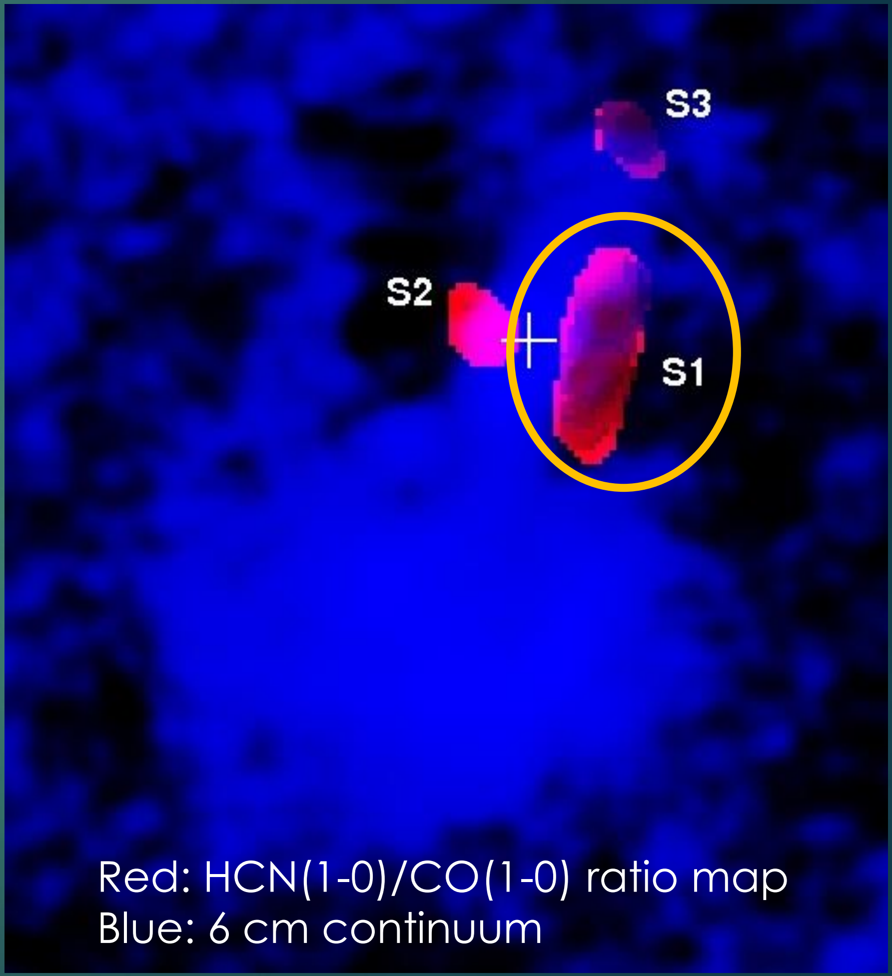
Matsushita et al. 2015, ApJ, 799, 26

Molecular Gas - Radio Jet Interaction
Shocked Molecular Gas along Jets

- HCN(1-0)/CO(1-0) ratio is high (~1) along the jet in S1, and only at the jet side.
- Opposite side is around 0.3. Average of S1 ~ 0.6.

- This high ratio has been observed at shocked molecular gas in outflows from young stellar objects.
  - L1157: HCN(1-0)/CO(1-0) ~ 0.9; Umemoto et al. 1992, ApJL, 392, L83
  - Orion-KL: HCN/CO ~ 0.4-0.5; Wright et al. 1996, ApJ, 469, 216

⇨ High ratio in S1 is highly possible caused by shock due to jet – molecular gas interaction.



Matsushita et al. 2015, ApJ, 799, 26

Molecular Gas - Radio Jet Interaction
Shocked Molecular Gas along Jets

- HCN(1-0)/CO(1-0) ratio is high (~1) along the jet in S1, and only at the jet side.
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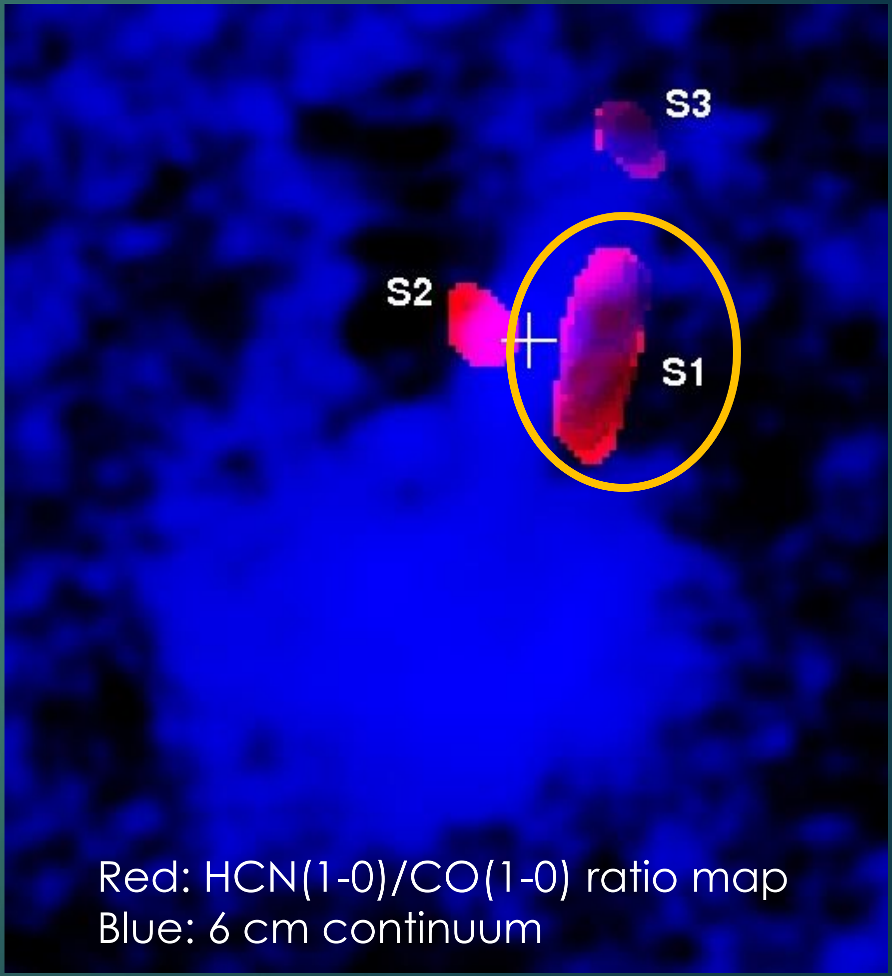
- In normal and starburst galaxies, HCN(1-0)/CO(1-0) < 0.3 (e.g., Gao & Solomon 2004, ApJ, 606, 271)
- At the nuclei of Seyfert galaxies, HCN(1-0)/CO(1-0) can be ~0.6 (e.g., Kohno et al. 2008, EAS Publ. Ser. 31, 65)

⇨ High ratio in S1 is similar to that in Seyfert galaxies. Shocked regions may playing an important role for the high ratio.

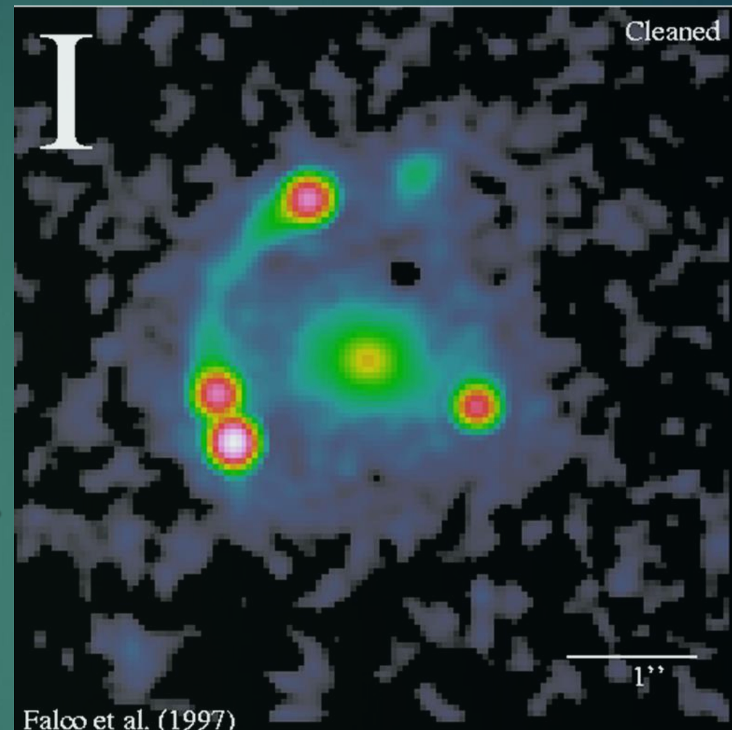


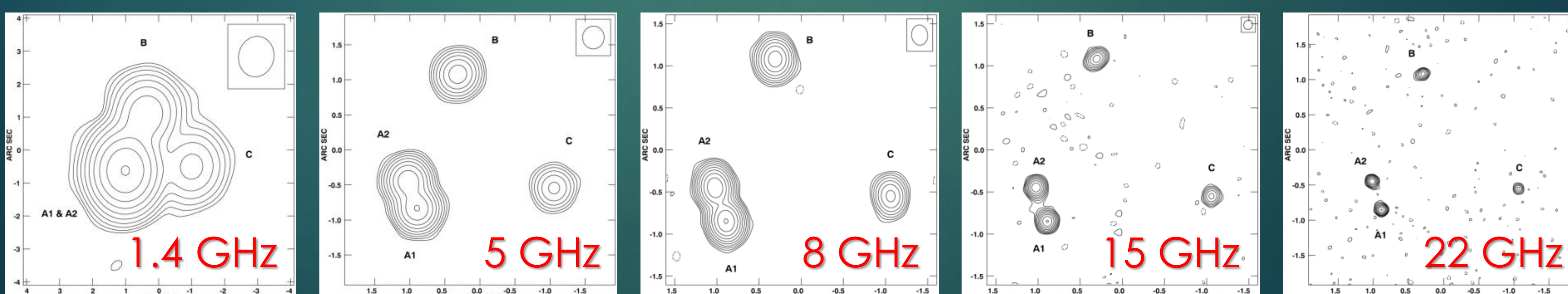
Matsushita et al. 2015, ApJ, 799, 26

Case Study at Far Away

MG J0414+0534

- Quadruply lensed radio-loud quasar.
- Lensed source: z = 2.639. Lensing source: z = 0.9584.
- Only the lensed source emits radio emission.

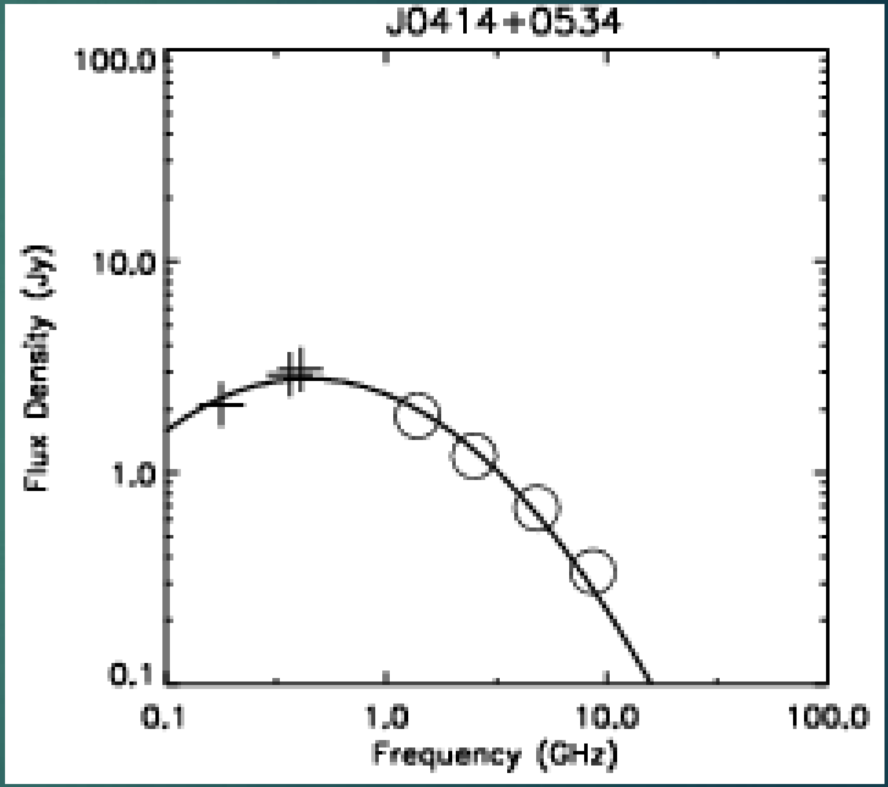




Katz et al. (1997)

MG J0414+0534

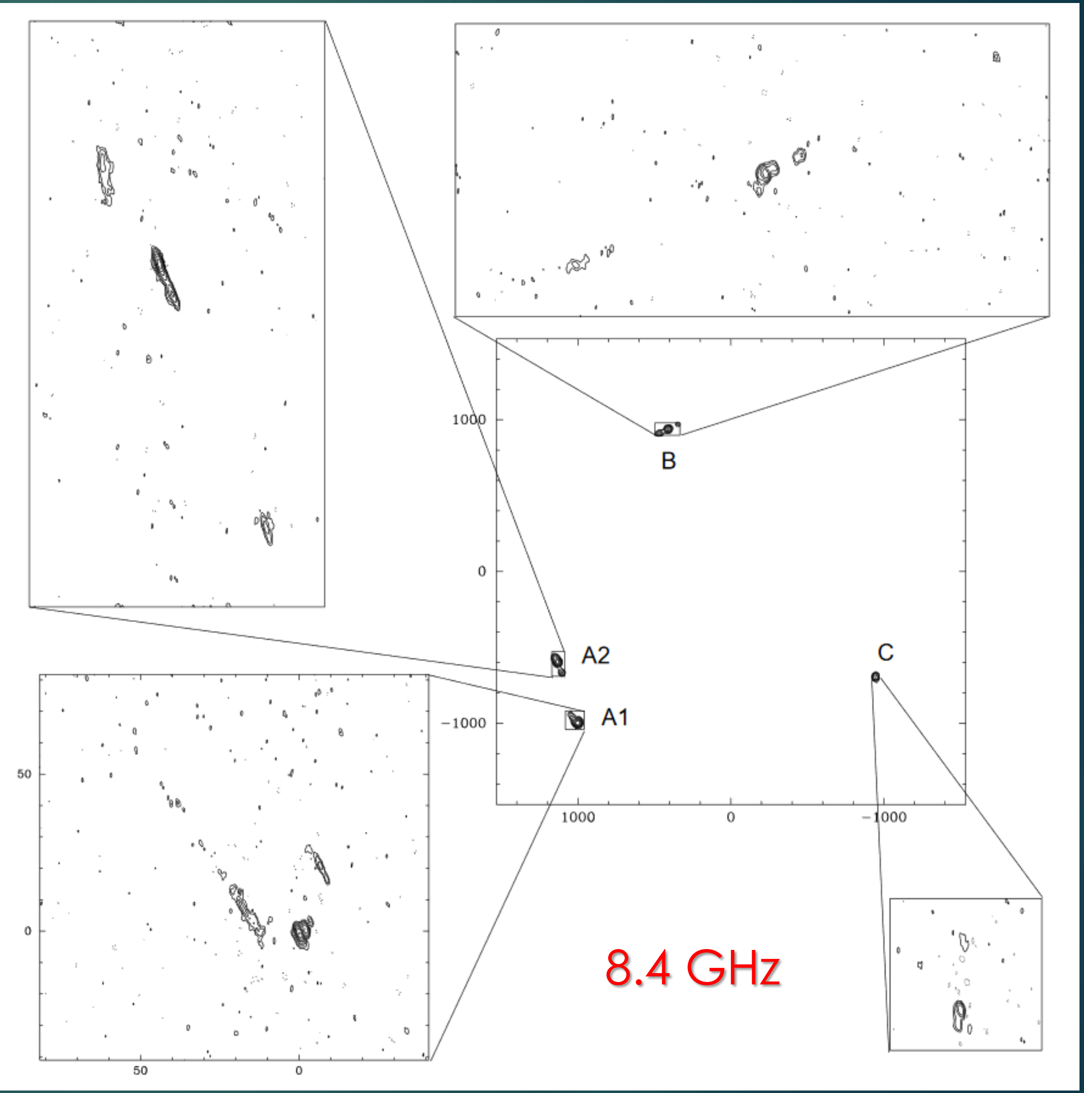
- Continuum emission spectrum peaks around 0.4 – 0.5 GHz
  ⇨ Gigahertz Peaked-Spectrum (GPS) source.
  - GPS sources are possibly in the early phase of the radio sources (O'Dea 1998).



Edwards & Tingey (2004)

MG J0414+0534

- VLBI image shows the resolved jets.
- Size is small, < 1 kpc.



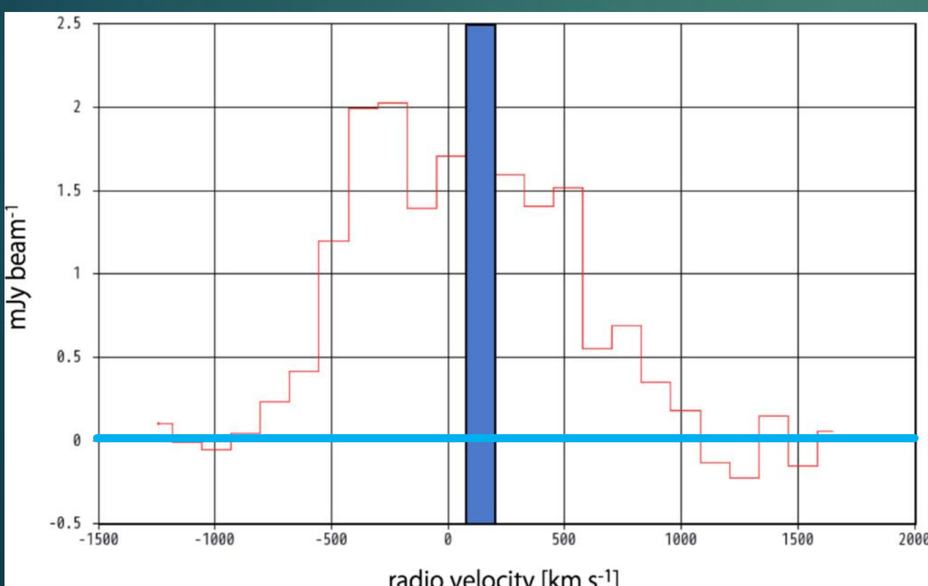
Ros et al. (2000)

ALMA Observations

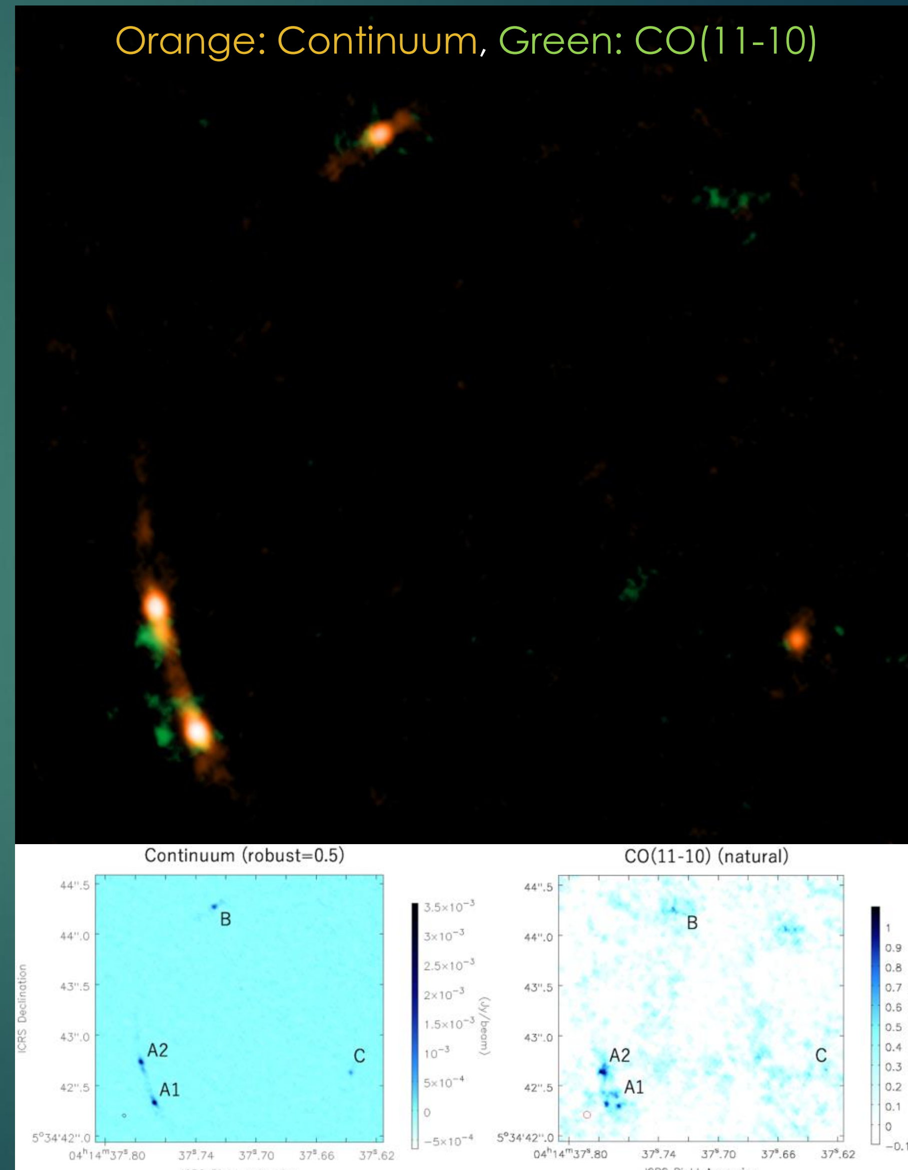
- Data:
  - Cycle 2 (Project ID: 2013.1.01110.S, PI: K.T. Inoue)
    - Baseline length: 15 – 1575 m
  - Cycle 4 (Project ID: 2016.1.00281.S, PI: S. Matsushita)
    - Baseline length: 113 – 13894 m
- CO(11-10): Natural weighting (0.072" × 0.068")
  - 1267.014486 GHz (or 237 μm) at z = 0
  - 348.176556 GHz at z = 2.639
- Continuum: Uniform weighting (0.036" × 0.029")

Continuum + CO(11-10)

- Different distribution between 234 μm continuum emission and the CO(11-10) line.
- CO(11-10) line width is broad ~ ±1000 km/s.

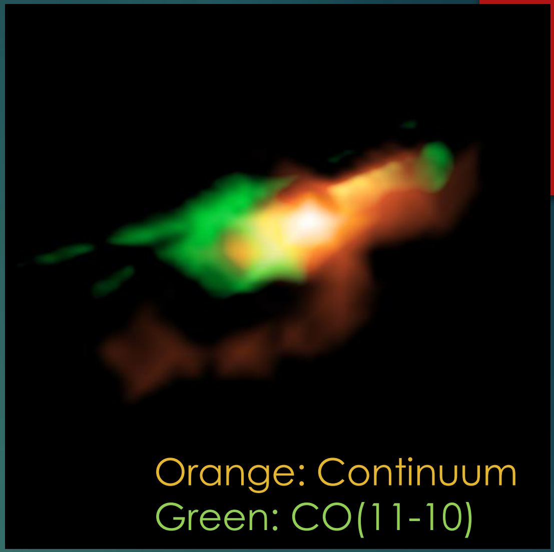


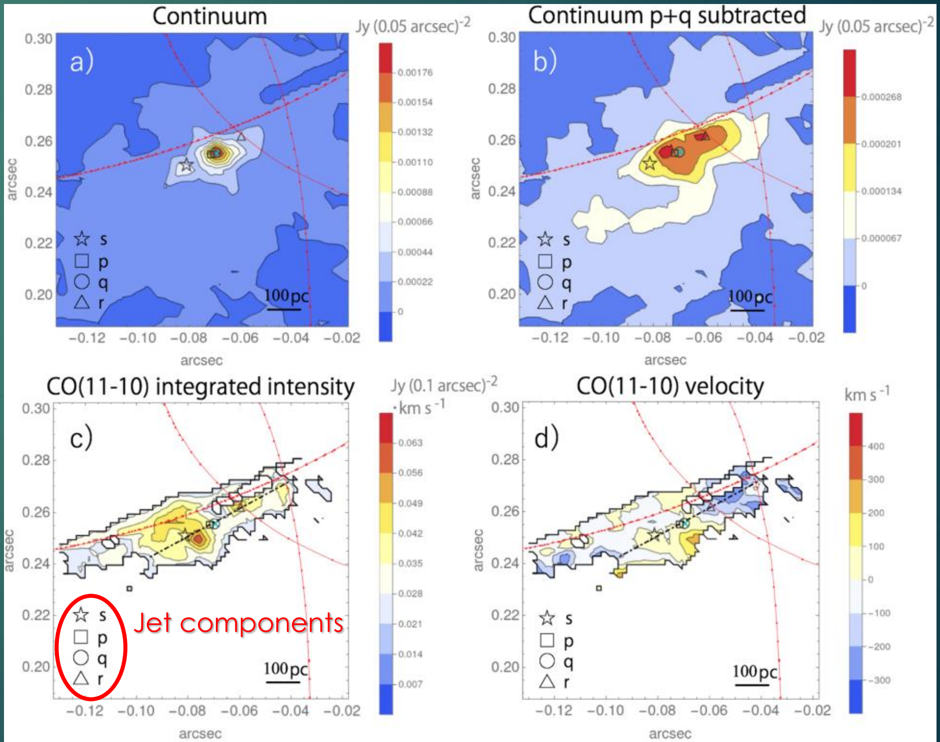
Inoue, Matsushita et al. (2017, 2020)



De-Lensed Image

- Continuum
  - Achieved angular resolution near intensity peak is ~0.007", which is ~50 pc at z = 2.639.
  - Centrally peaked.
  - Weak extended structure along the jet direction.
  - Stream or spiral-arm like feature toward south.
- CO(11-10)
  - No central peak.
  - Extended toward the jet direction.

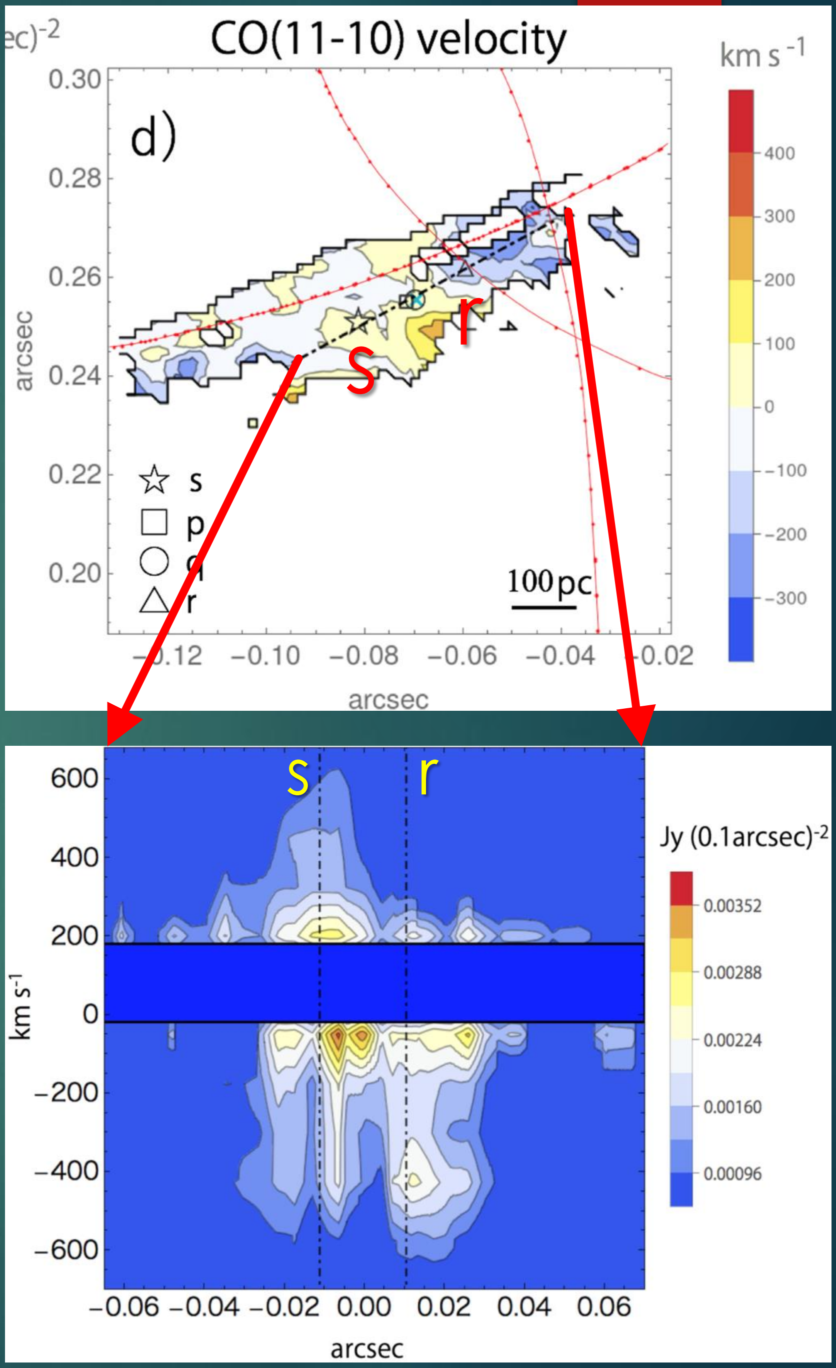




Inoue, Matsushita et al. (2017, 2020)

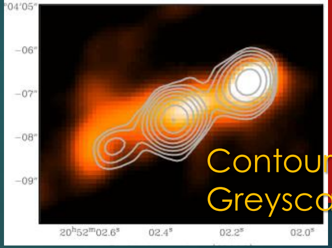
CO Velocity Feature

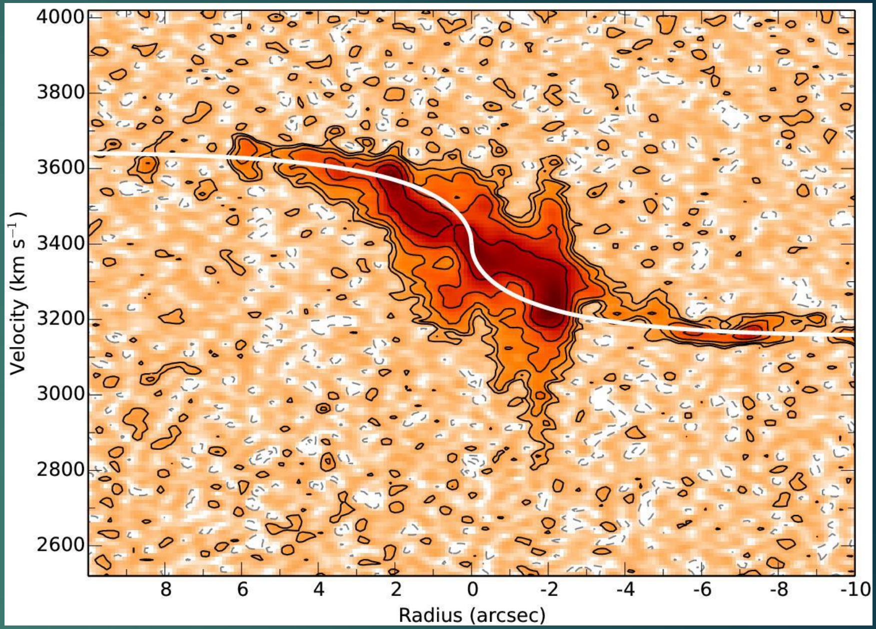
- CO(11-10) velocity gradient can be seen along the jets.
- CO velocity width is wide around the locations of the VLBI jet components.
- Highly possible that the CO and jets are interacting.



Inoue, Matsushita et al. (2017, 2020)

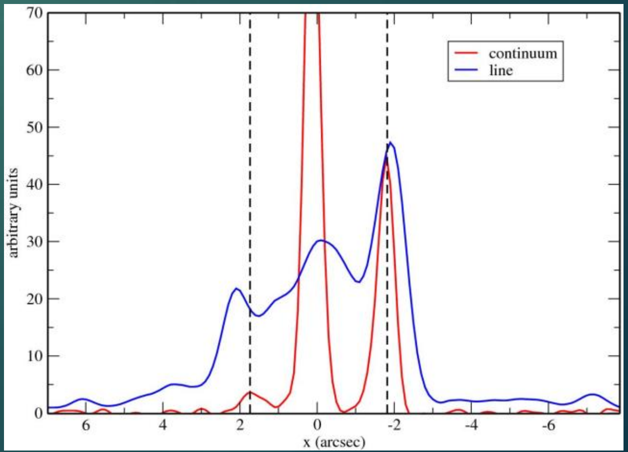
Similar Features with IC 5063





- Relatively nearby (47.9 Mpc) radio-loud Seyfert 2 galaxy.
- 228 GHz continuum is dominated by jets.
- Continuum peaks matches with the CO(2-1) peaks, but CO is located a bit outside.
- CO peaks have broad velocity width.

⇨ Jet – ISM interaction.

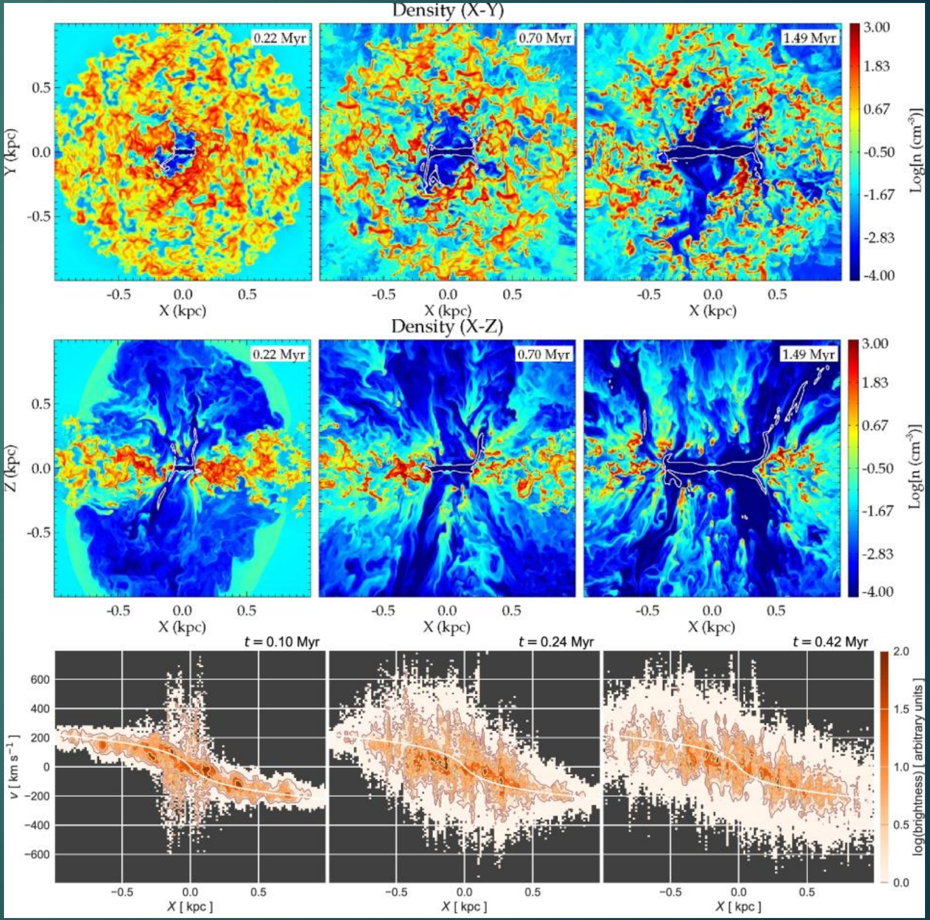


Morganti et al. (2015)

Numerical Simulation of Jet-ISM Interaction

- Relativistic hydrodynamic simulations of the inner kpc region of IC 5063.
- Interaction of the relativistic jets with the inhomogeneous ISM.
- Reproduced many of the observed features in the PV diagram of IC 5063.

⇨ Jet is responsible for the strongly perturbed gas dynamics.

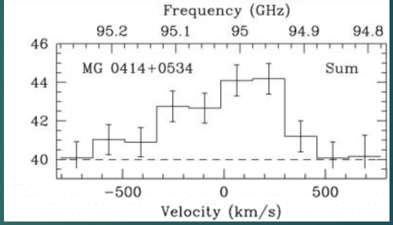


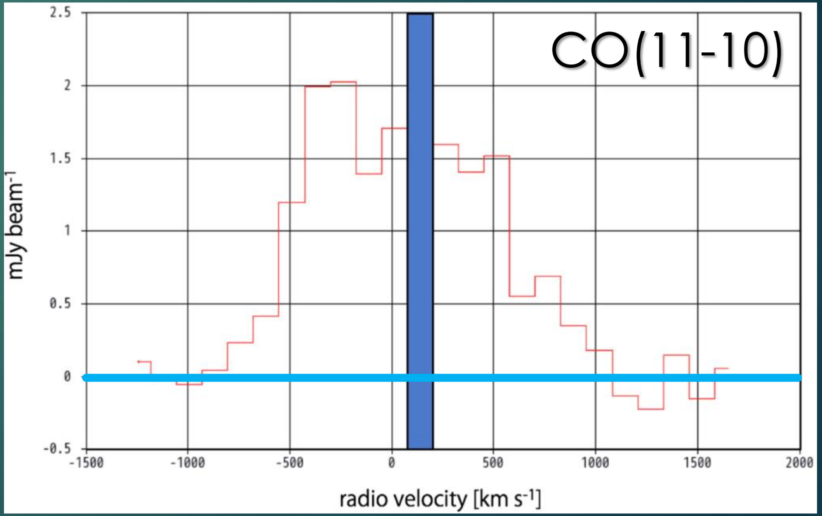
Mukherjee et al. (2018)

CO Intensity Ratios

- CO(3-2) data
  - Barvainis et al. (1998): Very low S/N.
- CO(1-0) data
  - Sharon et al. (2016): Non-detection.
- Brightness temperature ratios:
  - CO(11-10)/CO(3-2) = 0.14 (matched velocity width)
  - CO(3-2)/CO(1-0) > 0.475
- Using RADEX (van der Tak et al. 2007):
  - Kinetic temperature: ~2×10^{2} K
  - H_2 number density: ~5×10^{4} cm^{-3}
- High density and high temperature condition.
- Highly possible due to the jet-ISM interaction.

Barvainis et al. (1998)
CO(3-2)

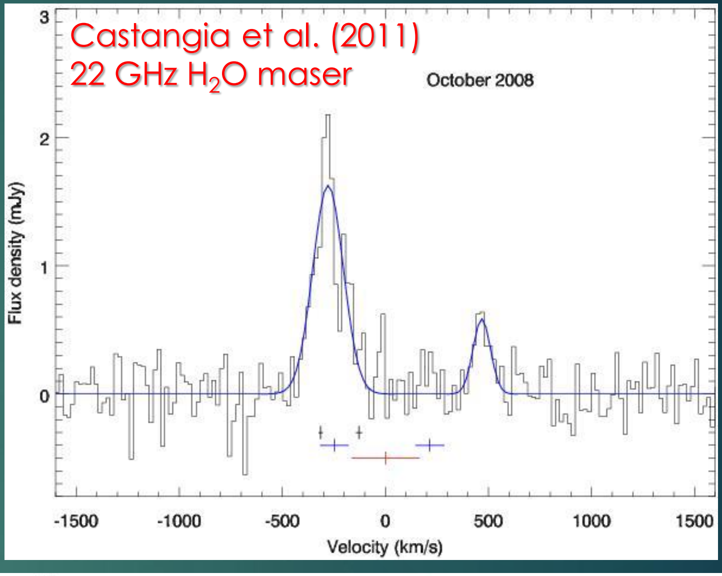


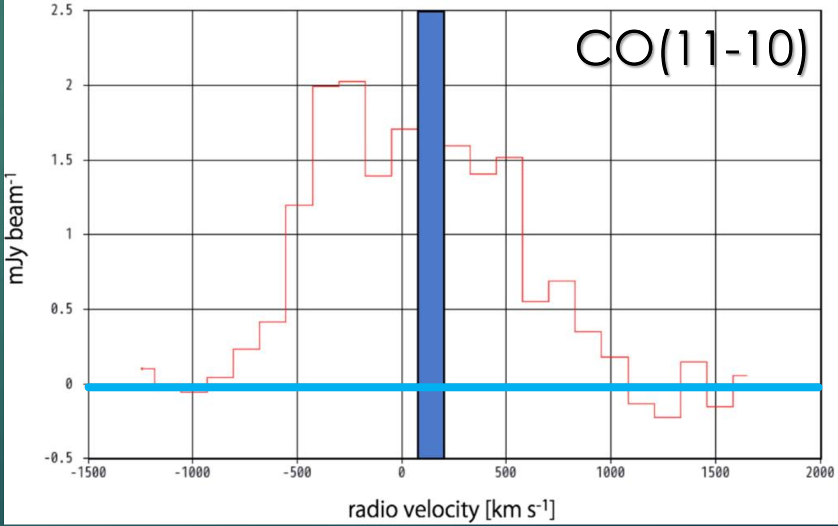


Inoue, Matsushita et al. (2017, 2020)

Water Maser Detection

- 22 GHz water maser has been detected (Impellizzeri et al. 2008; Castangia et al. 2011).
- Velocity range is well within the CO velocity width.
- They suggested that the water maser lines come from the interaction zone of the radio jet and the molecular gas





Inoue, Matsushita et al. (2017, 2020)

MG J0414+0534: Early Stage of Quasar Radio Activity

- Major cause of SED turnover in GPS sources (O'Dea 1998):
  - Synchrotron self-absorption
  - Free–free absorption

  ⇨ Embedded inside dense medium.
- Small size (<1 kpc) of radio emitting regions.

⇨ Radio jets in GPS sources are still interacting with ISM in host galaxies (O'Dea & Baum 1997).

MG J0414+0534: Early Stage of Quasar Radio Activity

- GPS sources are in the young stage of the evolution of radio galaxies on the grounds of their small sizes (O'Dea 1998).
- Numerical simulations of Jet – ISM interaction show that even though dense ISM is surrounding, jets can expand to ~1000 pc within ~10^4 yr (Wagner & Bicknell 2011; Wagner et al. 2012).
- MG J0414+0534 does not have any extended radio emission (also most of GPS sources do not have any extended radio emission; O'Dea 1998).

⇨ We therefore concluded that MG J0414+0534 is possibly in the early stage of quasar radio activity, and just started the radio-mode feedback.
Namely, we are observing the birth of a radio galaxy.

Summary

- For both in M51 and in MG J0414+0534, molecular gas and jets from AGNs are interacting.
- In M51, molecular gas is entrained by the radio jets, and flowing outward. Molecular gas can be the fuel for the AGN activities. So, probably, the AGN activity is self-regulating its own activity (negative feedback).
- In MG J0414+0534, small-scale jets are trying to go out from the host galaxy. Radio-mode feedback just started. We are probably observing the birth of a radio galaxy.