Molecular gas properties of three Virgo spirals experiencing ram pressure

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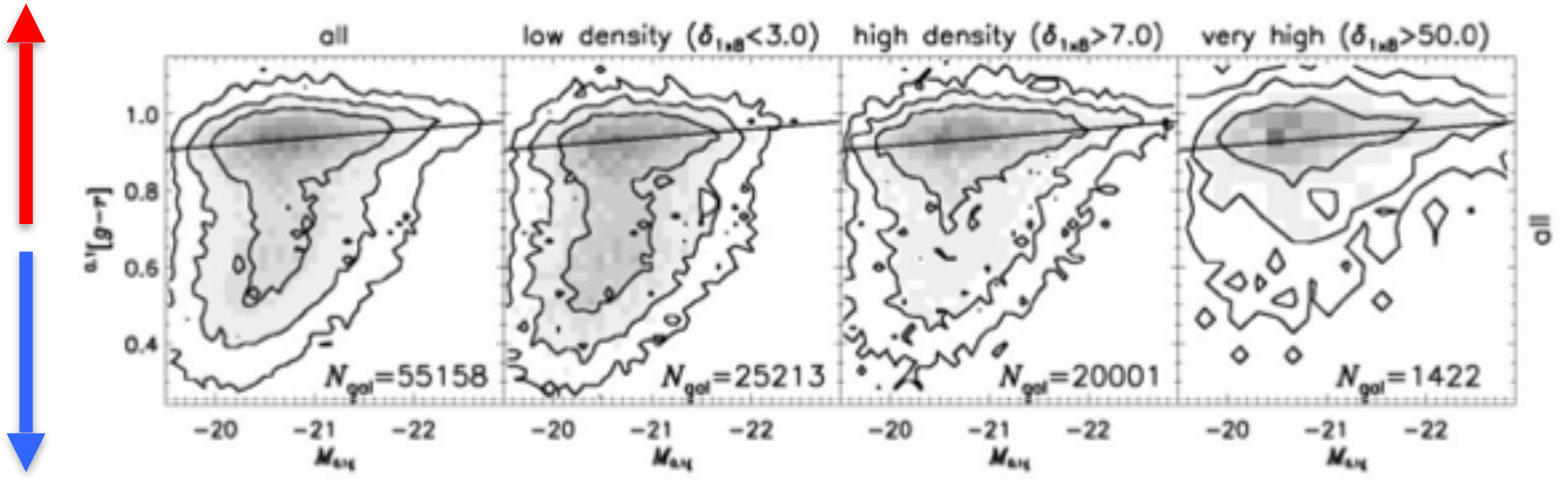
Cluster Environments

Red

Density



Blue

Low

high

Cluster galaxy population: passive and red

Hogg et al. 2004

Ram pressure stripping

- **Gravitation interaction**

Tidal interactions among galaxies, galaxy mergers

- **ICM (The intracluster medium) - ISM (The interstellar medium) interaction**

Ram pressure stripping (Gunn & Gott 1972)

$$P_{Ram} = \rho_{ICM} v_{gal}^2$$

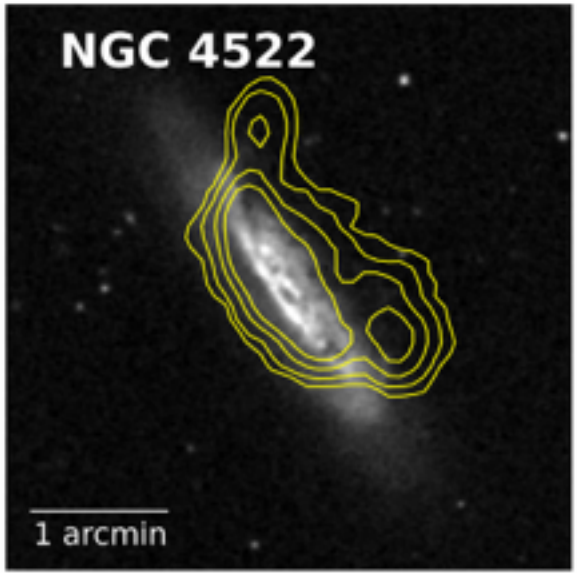
ρ_{ICM} : the density of ICM
v_{gal} : the velocity of a galaxy relative to ICM

$P_{Ram} > F_{grav,gas}$ → **gas is stripped**

Normal spiral galaxy → Red S0 galaxy

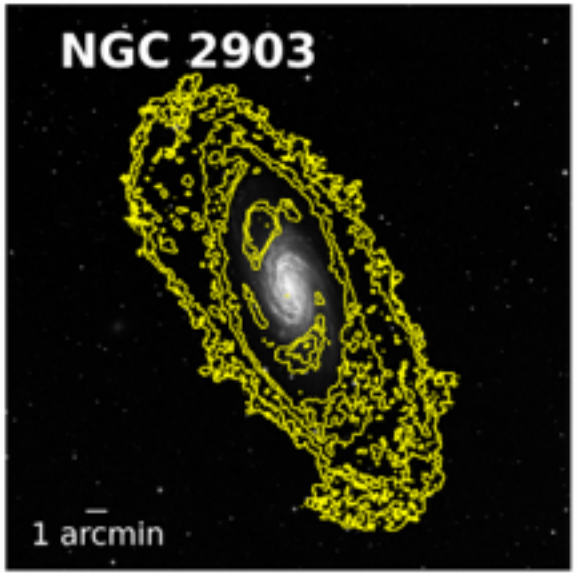
Ram pressure stripping & HI gas

Cluster spiral



Chung et al. 2009

Field spiral

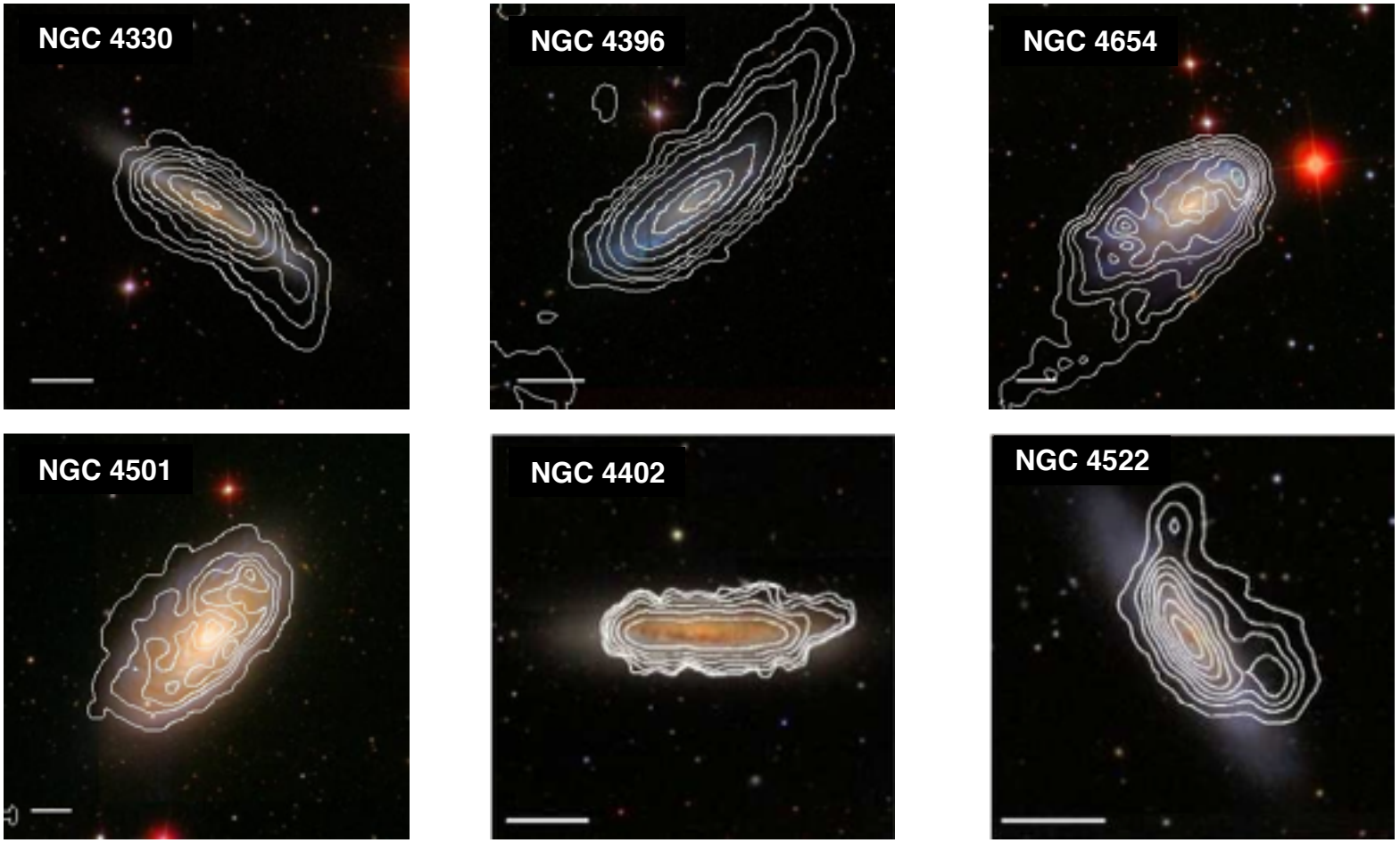


Walter et al. 2008

Yellow contours: HI gas
Grey scale: the stellar disk

HI gas of many cluster spirals:
highly disturbed morphology and/or truncation within the stellar disk.
(Warmerls 1988; Cayatte et al. 1990; Chung et al. 2009)

Ram pressure stripping & HI gas



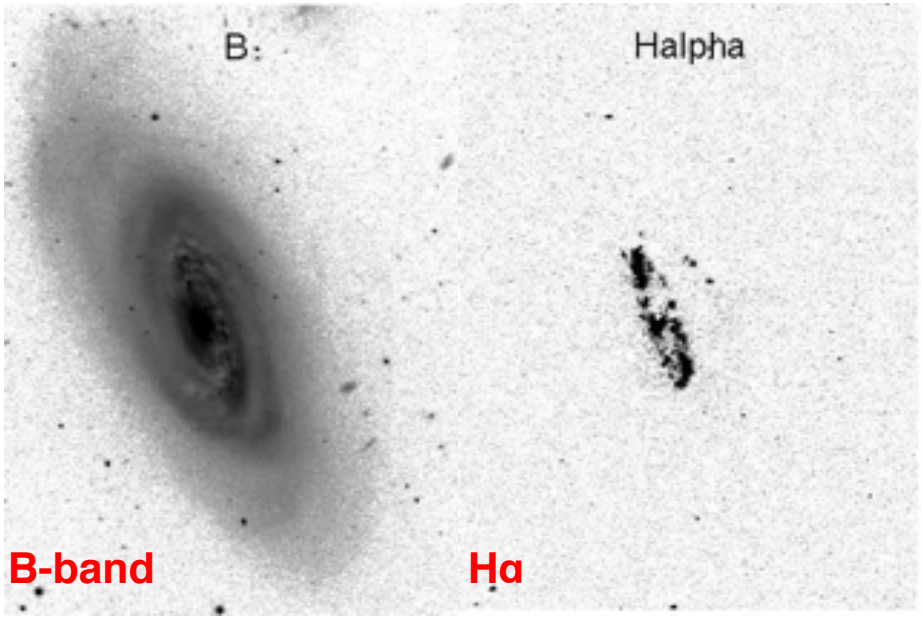
Chung et al. 2009

HI deficient compared to field counterpart,
with highly disturbed morphology and/or truncation within the stellar disk.
(Davies & Lewis 1973; Warmerls 1988; Cayatte et al. 1990; Chung et al. 2009)

Star formation activity in cluster environments

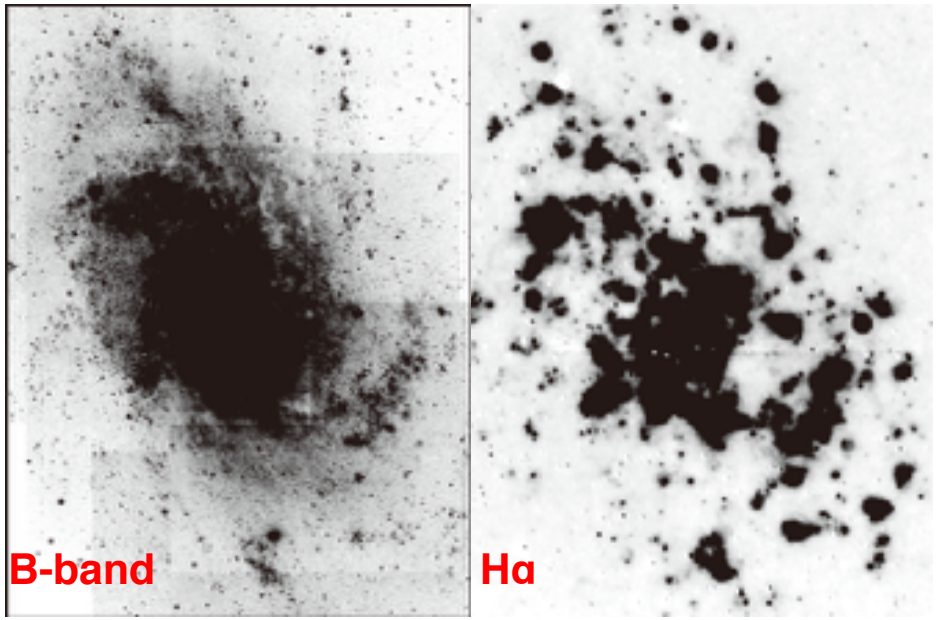
Cluster spiral, NGC4569

(Boselli et al. 2006)



Field spiral, M33

(Hinz et al. 2004)



Star formation activity in Virgo spirals:

A smaller Hα extent and truncated star-forming disk within the stellar disk

DEEP IMPACT:

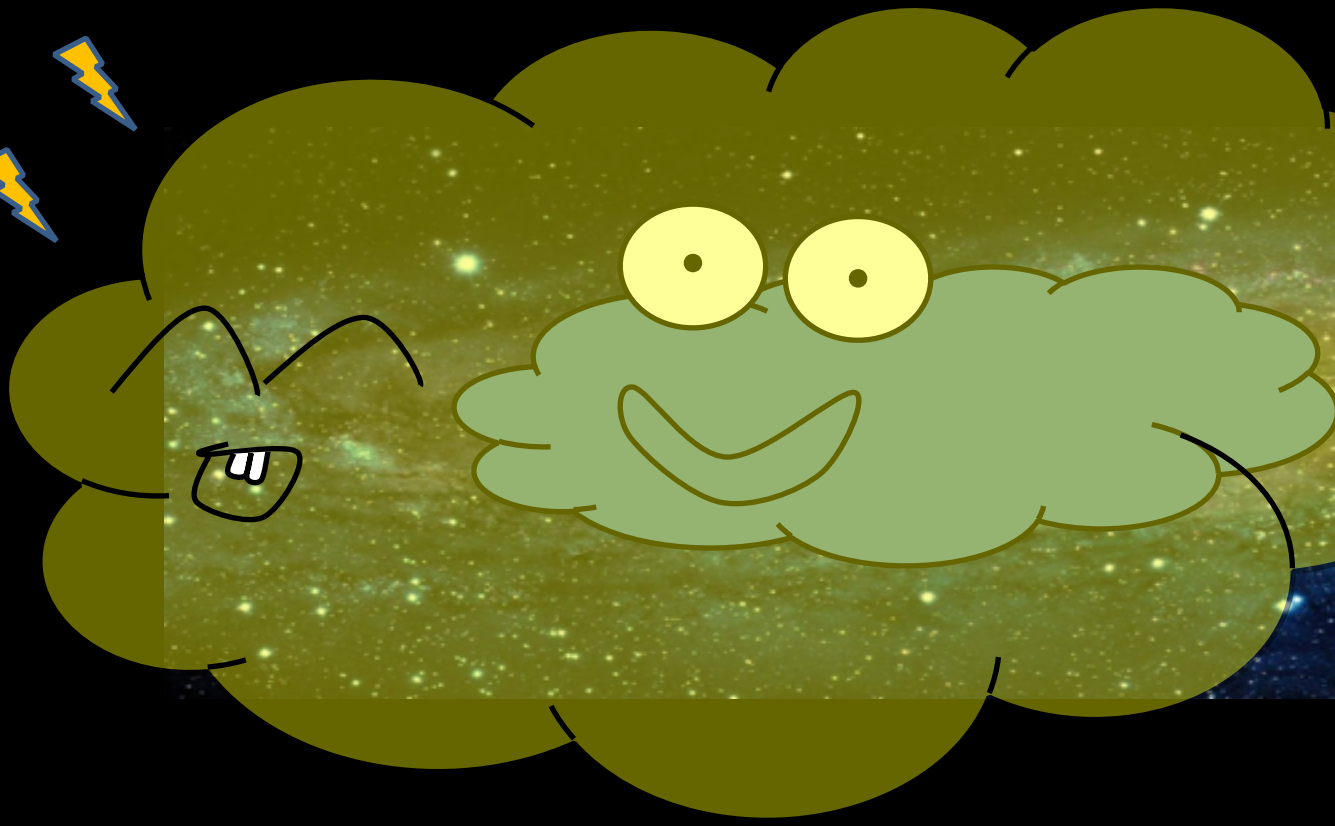
√ ICM BOMBARDS A GALAXY

THE DESTINY OF MOLECULAR GAS UNDER STRONG RAM PRESSURE

Molecular gas

HI gas

ICM



DEEP IMPACT:

√ ICM BOMBARDS A GALAXY

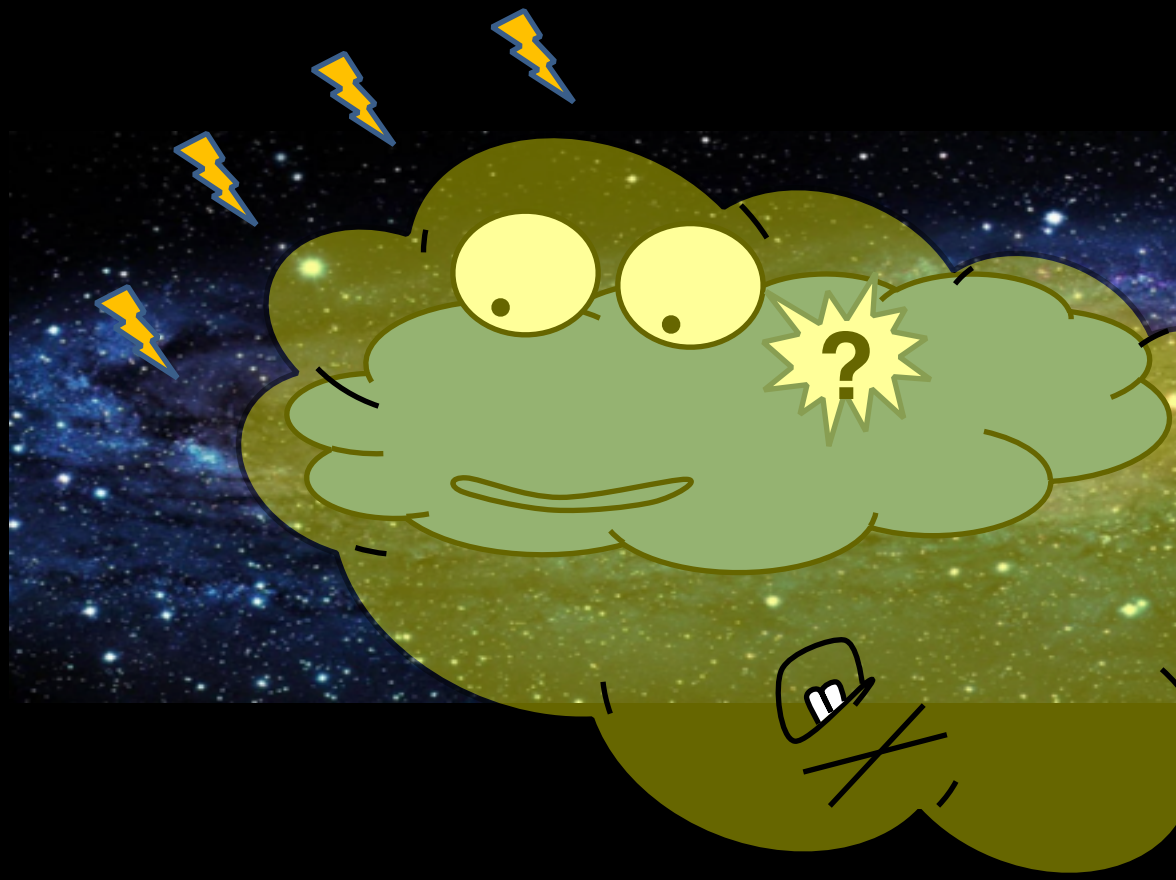
√ HI GAS IS STRIPPED

THE DESTINY OF MOLECULAR GAS UNDER STRONG RAM PRESSURE

Molecular gas

HI gas

ICM



DEEP IMPACT:

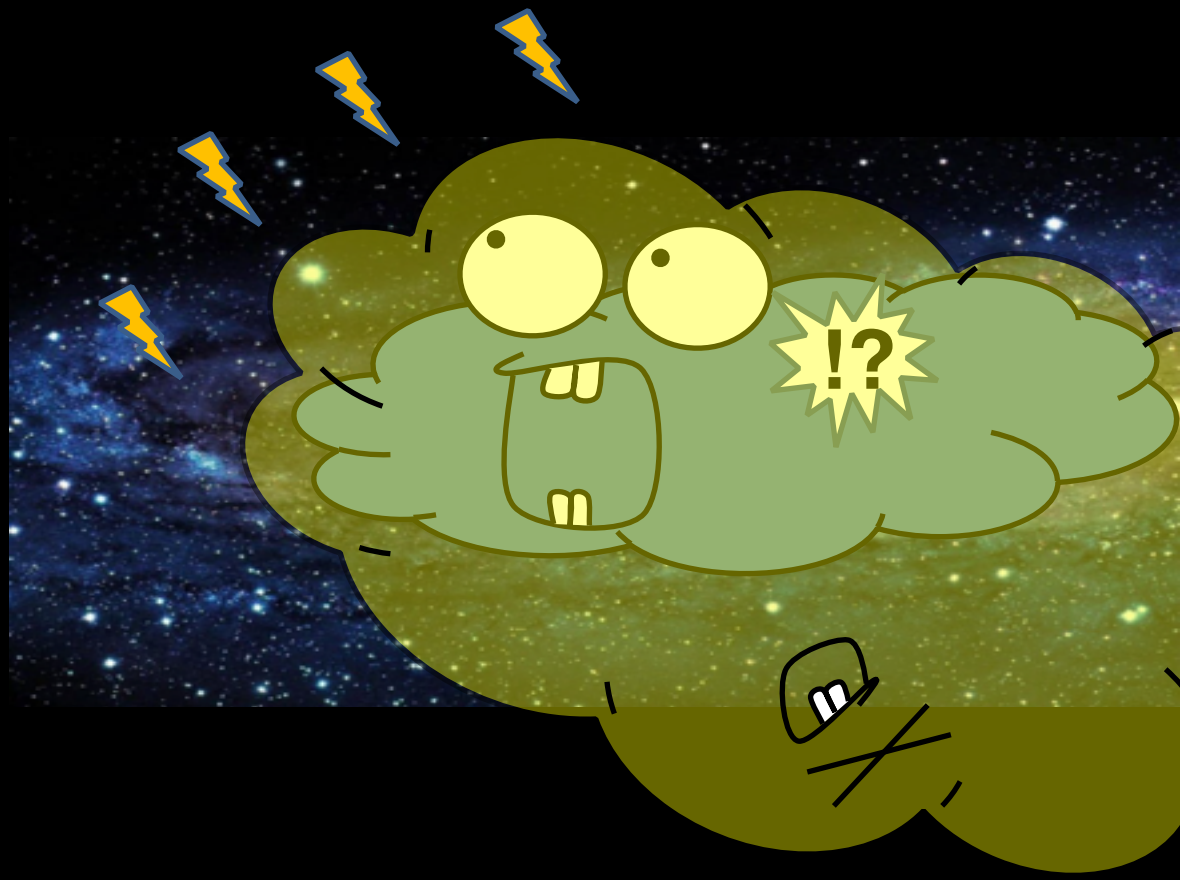
THE DESTINY OF MOLECULAR GAS UNDER STRONG RAM PRESSURE

- Molecular gas
- HI gas
- ICM

√ ICM BOMBARDS A GALAXY

√ HI GAS IS STRIPPED

√ MOLECULAR GAS SURVIVES?



Ram pressure also affects Molecular gas???

Q. Can ram pressure also strip molecular gas?

Q. Can ram pressure change the molecular gas properties?

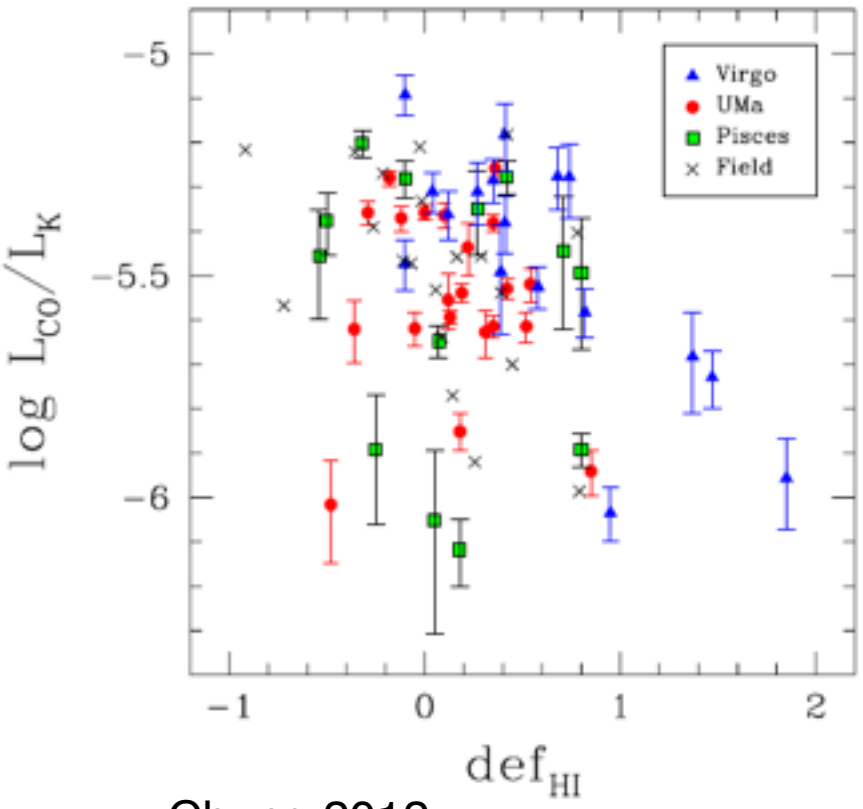
Q. If so, does star formation activity change?

Q. Are cluster galaxies deficient in molecular?

1) No significant difference in molecular gas mass between cluster and non-cluster galaxies
(Stark et al. 1986, Kenney & Young 1989)

2) HI deficient galaxies → Deficient in molecular gas
(Fumagalli et al. 2009, Boselli et al. 2014)

Ram pressure also affects Molecular gas???



Chung 2012

It is hard to define how deficient one galaxy is in molecular gas.

The CO brightness ranges widely for galaxies in high and low-density environments

H2 deficiency cannot be defined in the same way as HI deficiency.

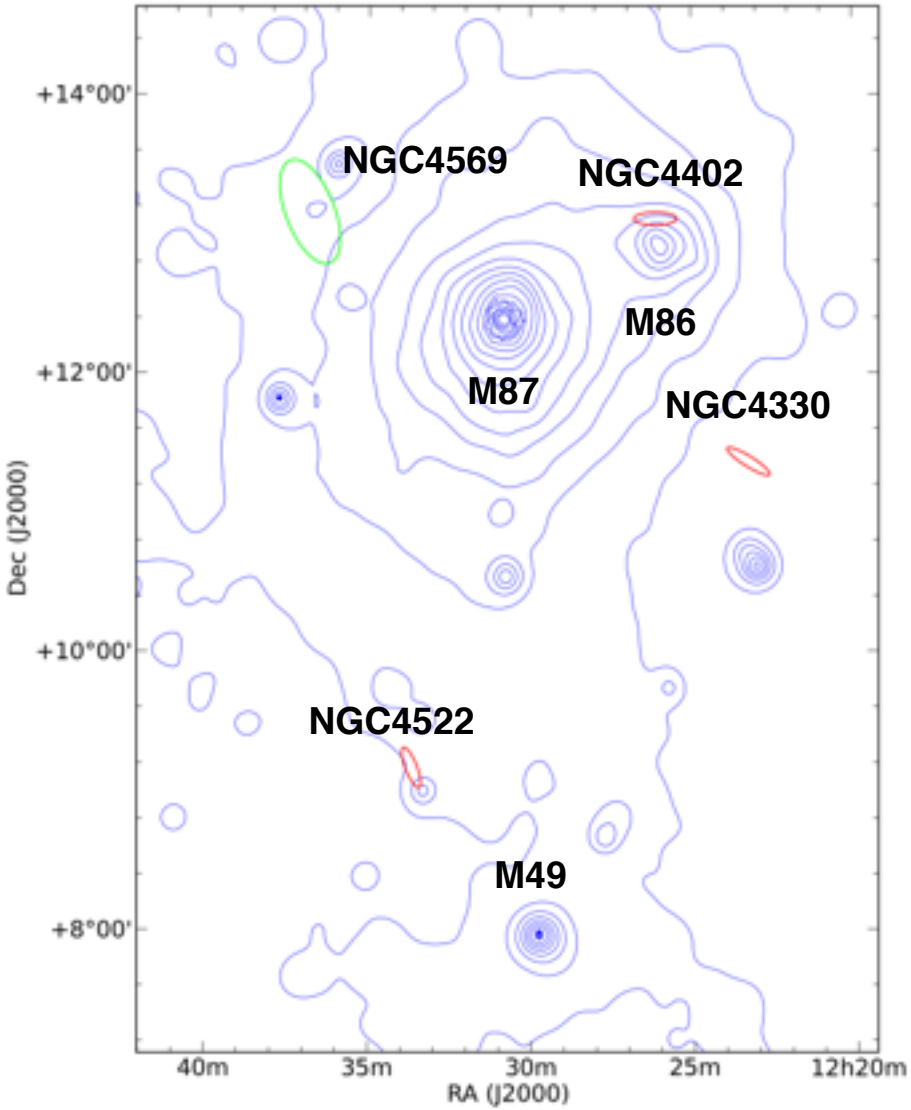
Scientific Goals

- Investigate detailed properties (CO morphology and CO kinematics) of molecular gas of galaxies experiencing ram pressure

- Study how star formation activity changes together with ISM using multi-wavelength data (optical, HI, UV, Hα)

- Study how the physical and chemical conditions (density and temperature) of molecular gas are changed due to ram pressure

Virgo cluster & Sample galaxies



Virgo cluster

a distance of 16 Mpc

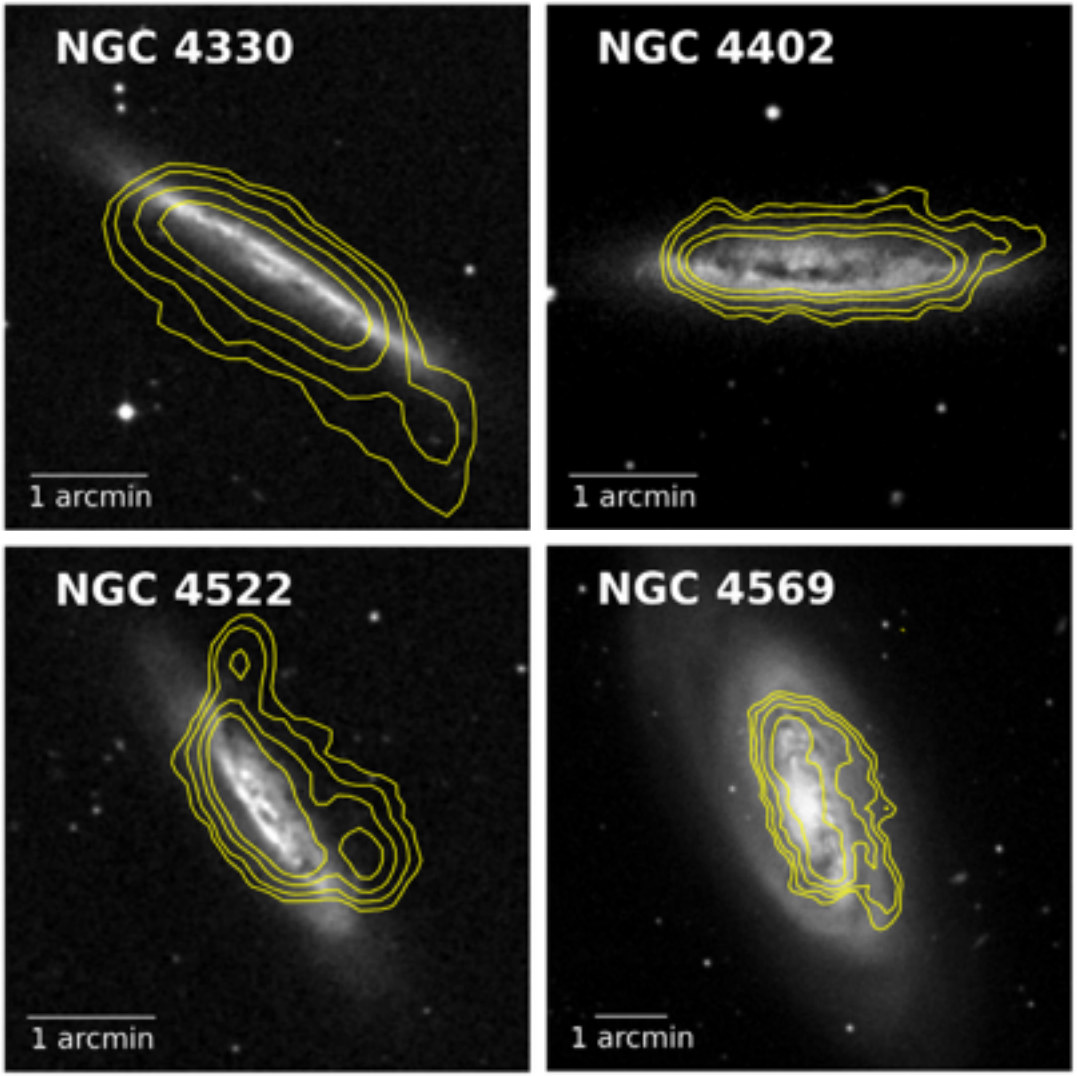
Different HI stripping stages :

Early to active ram pressure stage
NGC4330, NGC 4402, NGC4522

Past ram pressure stage
NGC4569

X-ray : blue, Böringer et al. 1994
Optical : gray, DSS2 blue
HI : yellow, Chung et al. 2009

Virgo cluster & Sample galaxies



Virgo cluster

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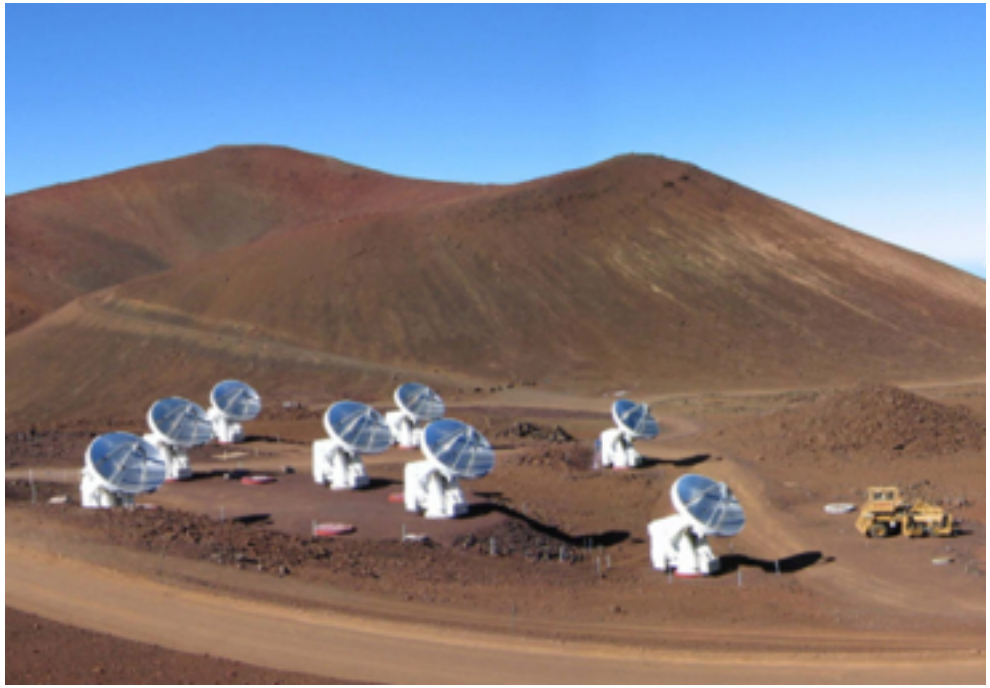
Observations



The Submillimeter Array (SMA)

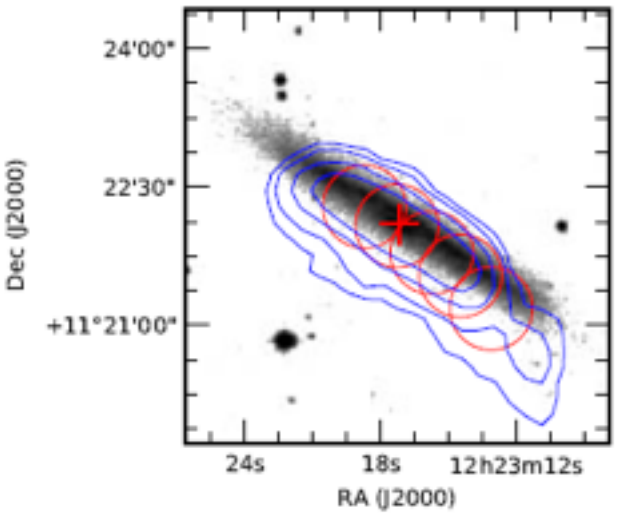
Array configuration : Subcompact

NGC4330, NGC4402, NGC4522,
except for NGC 4569

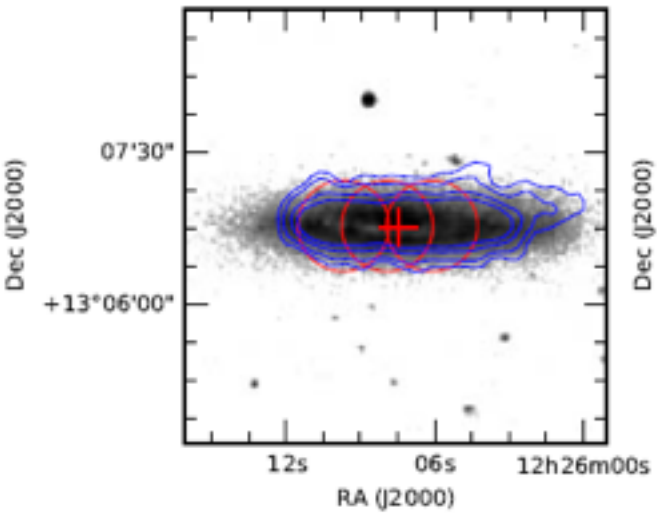
12CO (2-1), 230.538GHz
13CO (2-1), 220.398GHz

Observations

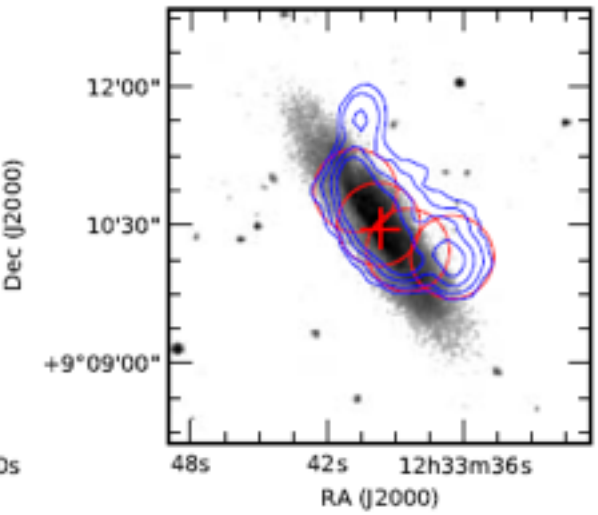
NGC 4330



NGC 4402



NGC 4522



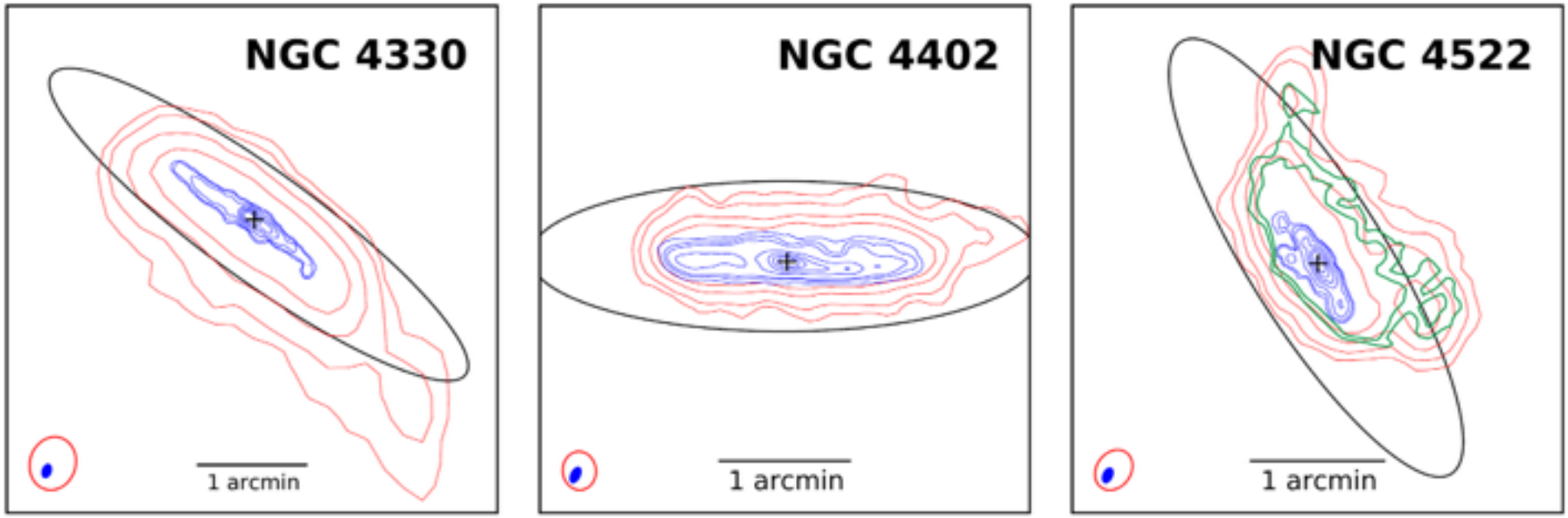
The SMA observation points : red circles Optical : gray, DSS2 blue
HI : blue contours, Chung et al. 2009

The primary beam size:
~54 arcsec at 230 GHz

Mosaic observation:3-5 points

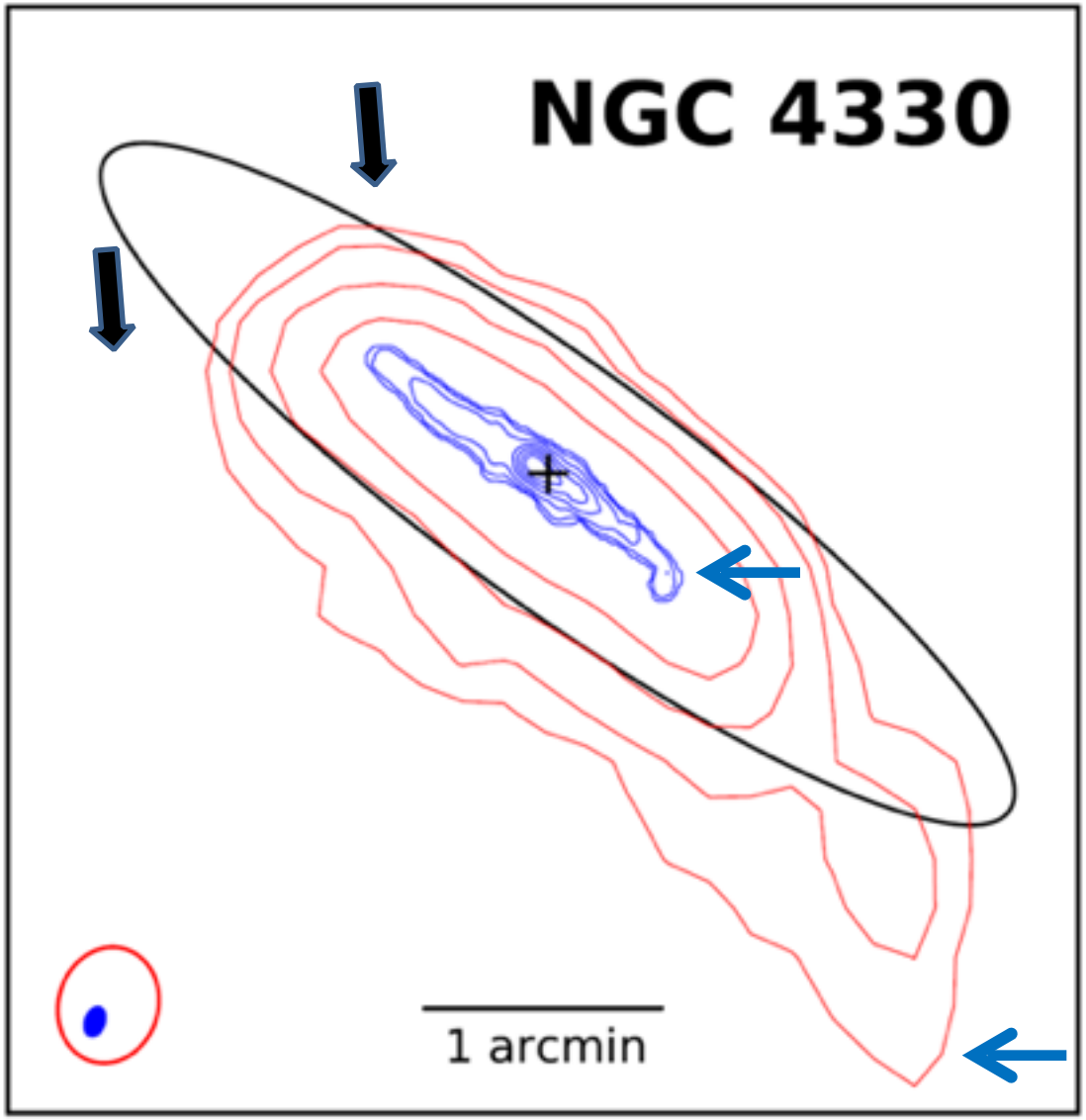
Asymmetric CO morphology

CO morphology → highly asymmetric and disturbed
→ closely related to the HI morphology

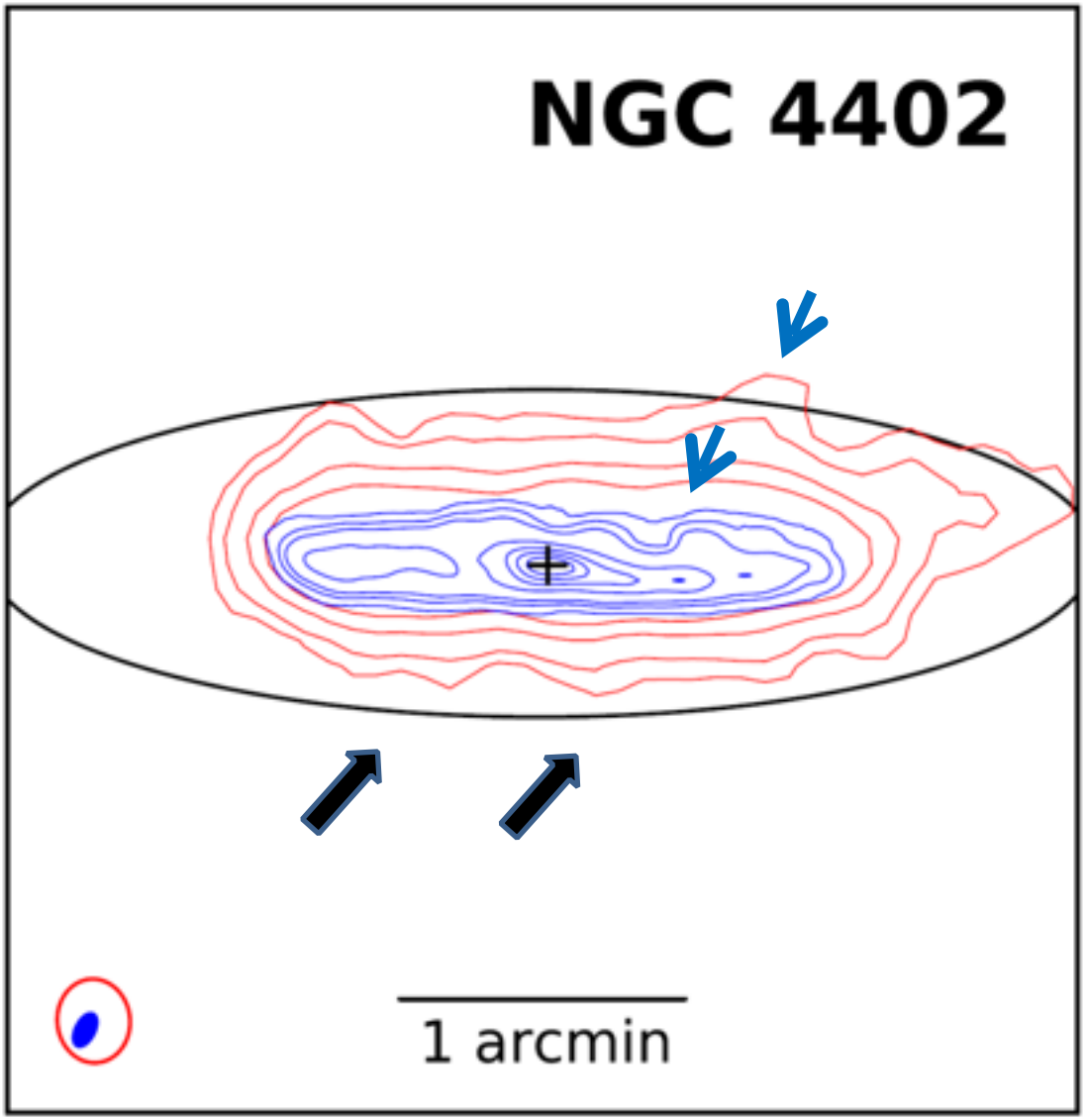


12CO (2-1): blue, SMA, Lee et al. in preparation
12CO (2-1): green, IRAM 30m, Vollmer et al. 2008
HI: red, Chung et al. 2009
D_{25} in the optical B band: black ellipse, RC3
Synthesized beam size of the VLA and SMA: red and blue ellipse

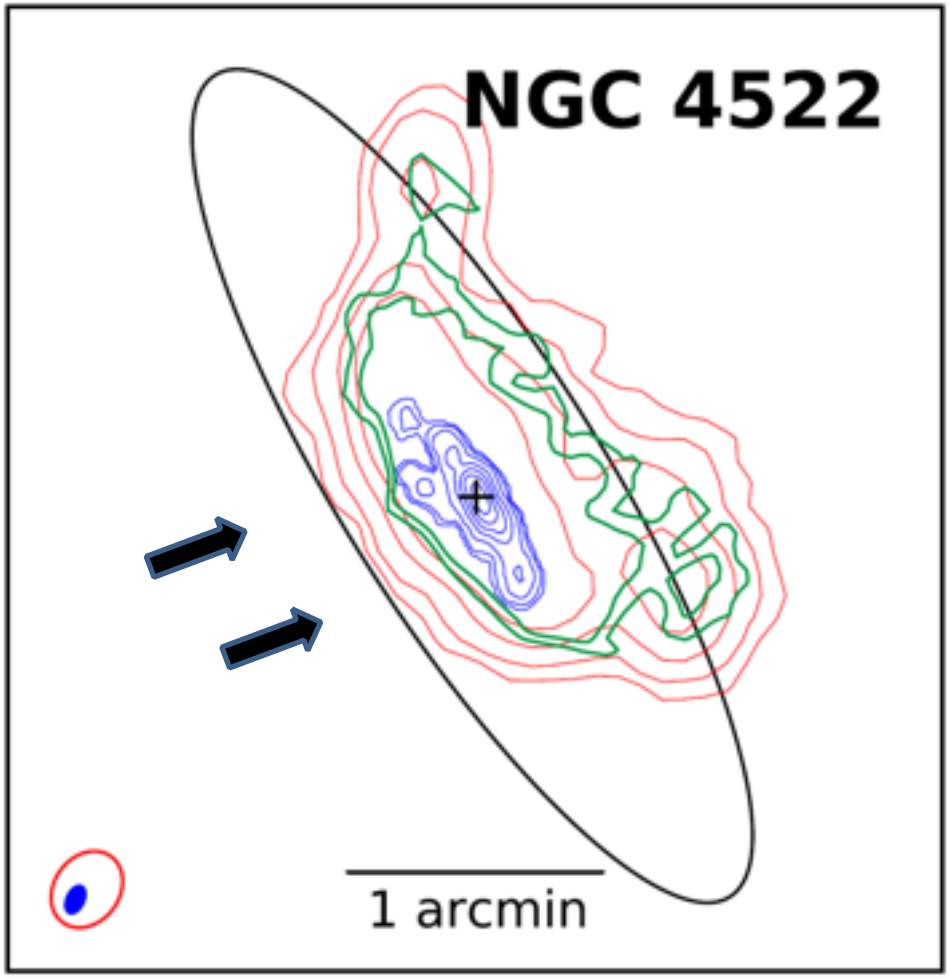
Asymmetric CO morphology



Asymmetric CO morphology



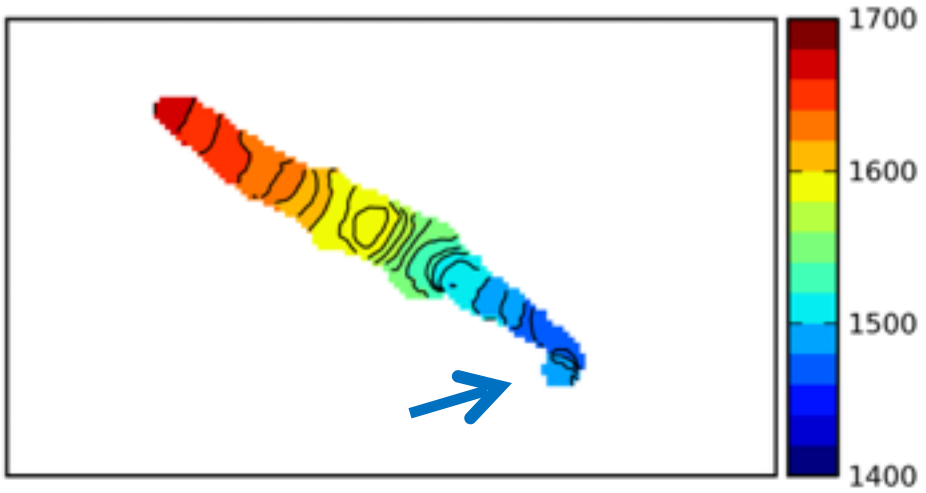
Asymmetric CO morphology



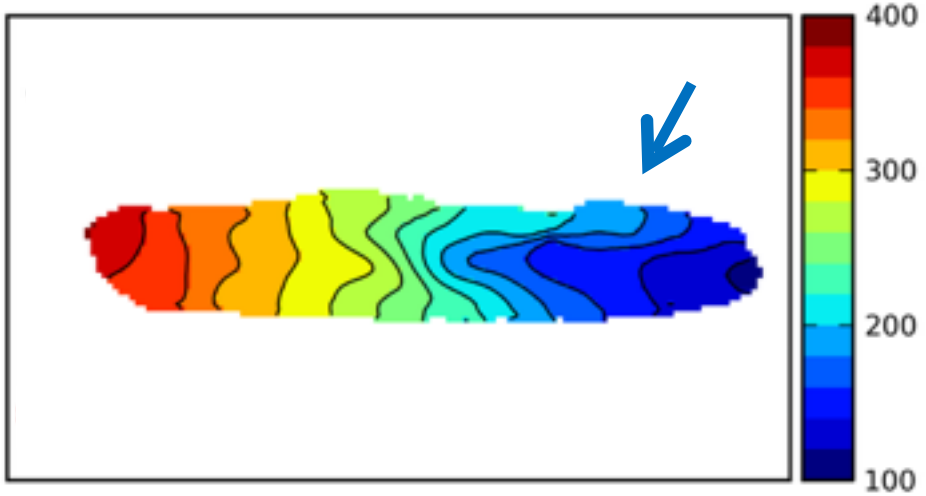
Molecular gas has been influenced by ram pressure.

Peculiar CO kinematics

Velocity field (NGC 4330)



Velocity field (NGC 4402)

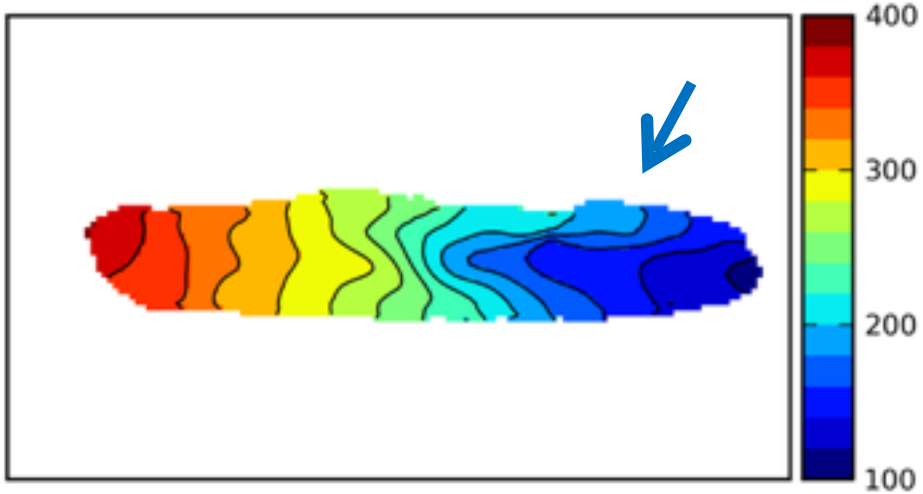


Color scale: velocity range (km/s)

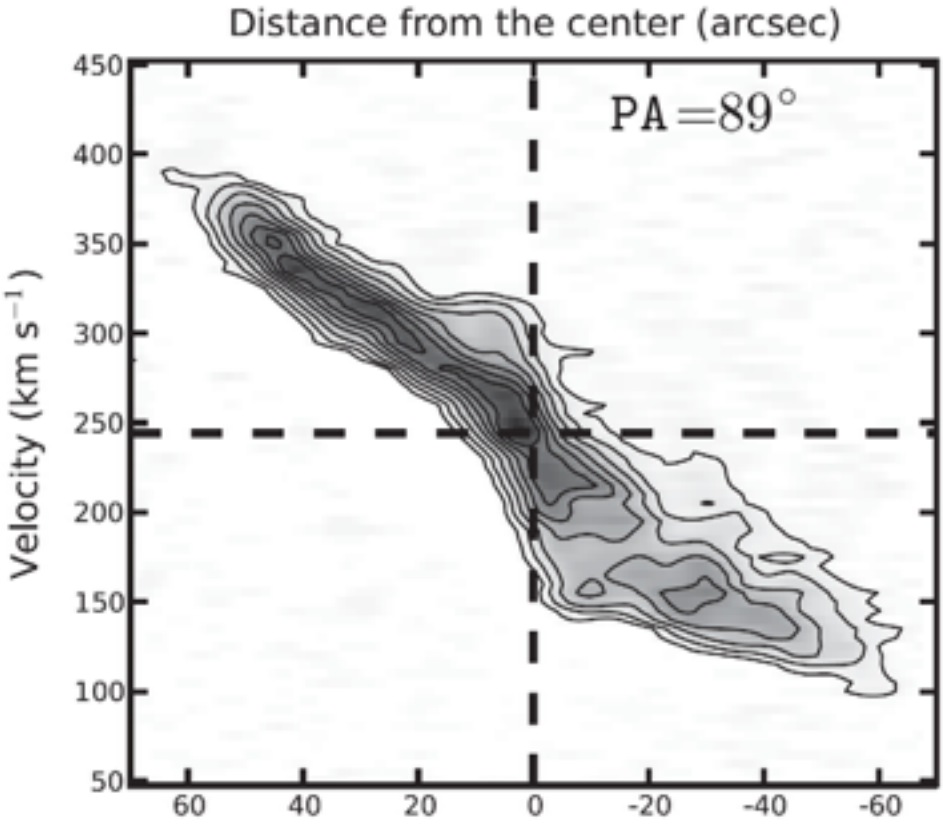
1) Deviated from galactic rotation
2) Asymmetric kinematical structure

Peculiar CO kinematics

Velocity field (NGC 4402)

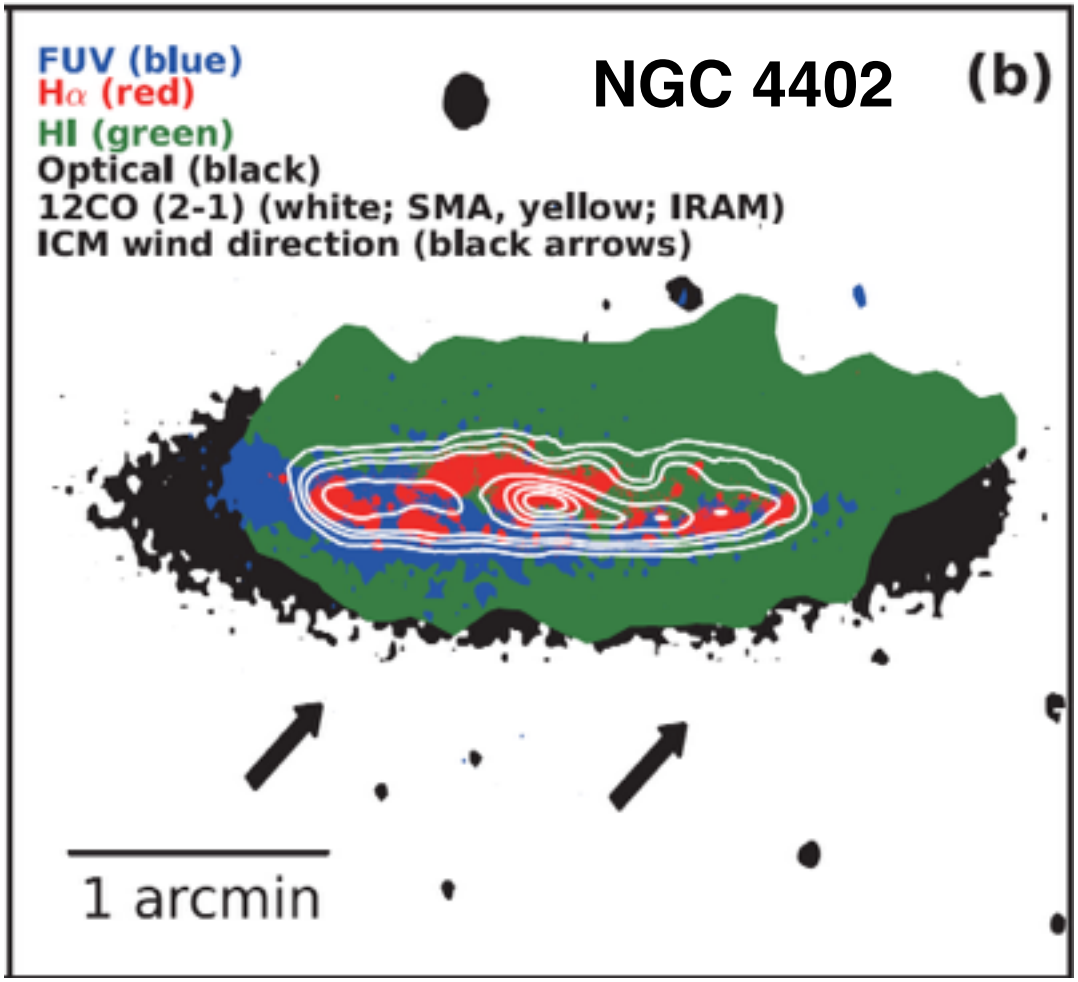


Position-velocity diagram (NGC 4402)



Evidence for the influence of ram pressure on the kinematics of molecular gas

Comparisons with multi-wavelength data

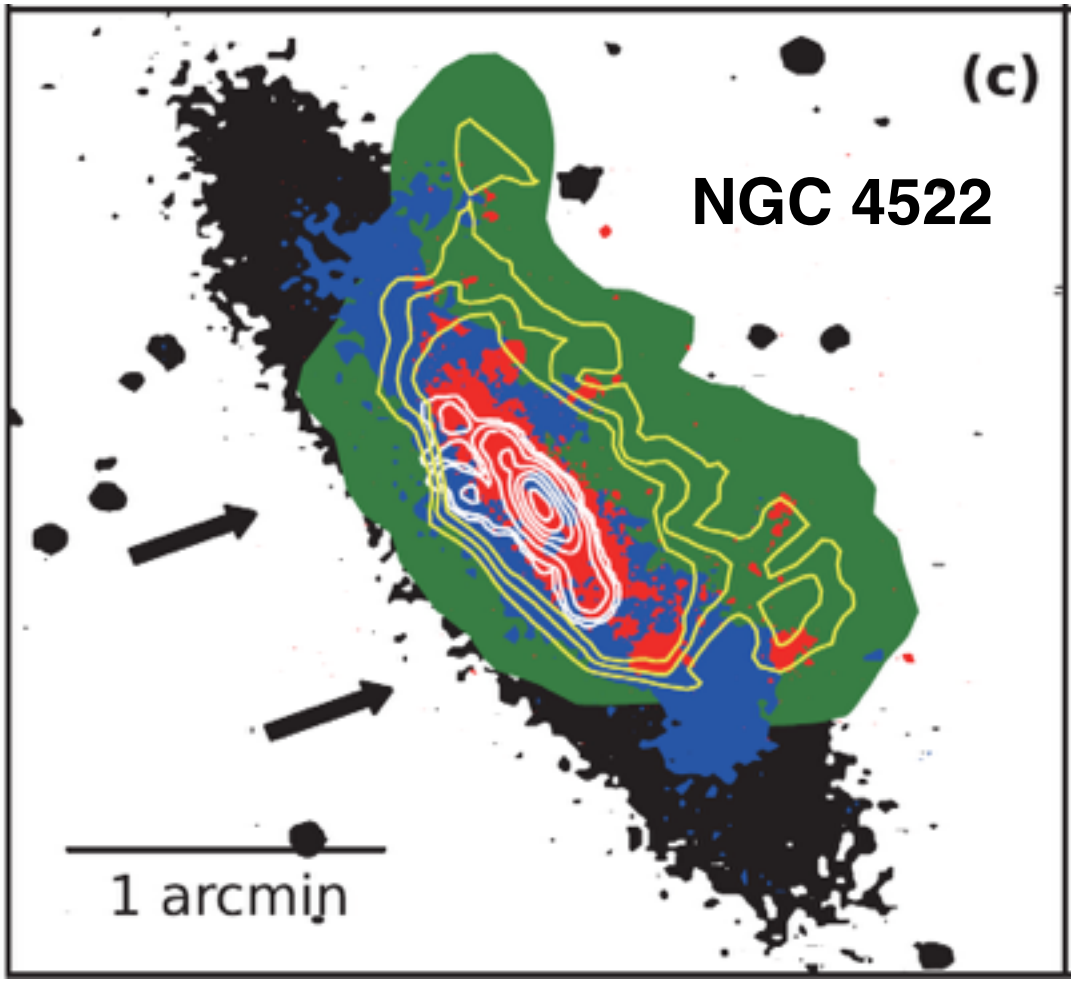


Morphological correlation among multi-wavelength data

Hα: ~20 Myr
FUV: ~100 Myr
Kennicutt 1998

- A similar distribution and extent between CO and Hα
- FUV, distinct morphology from those of Hα/CO
- The FUV enhancement along the CO compression

Comparisons with multi-wavelength data



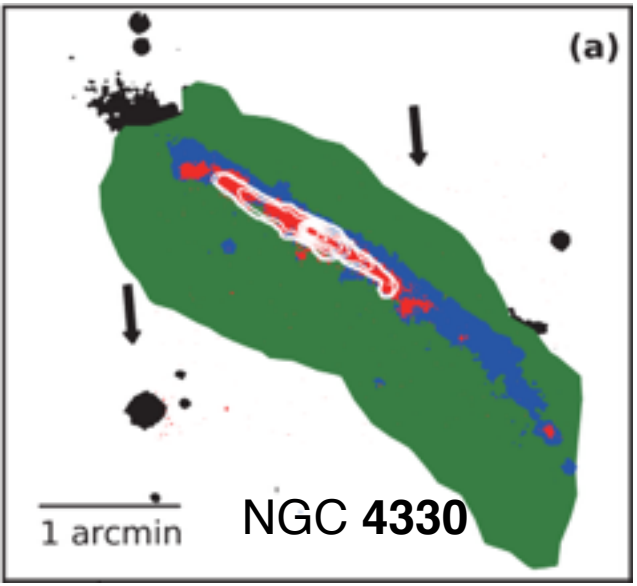
Morphological correlation among multi-wavelength data

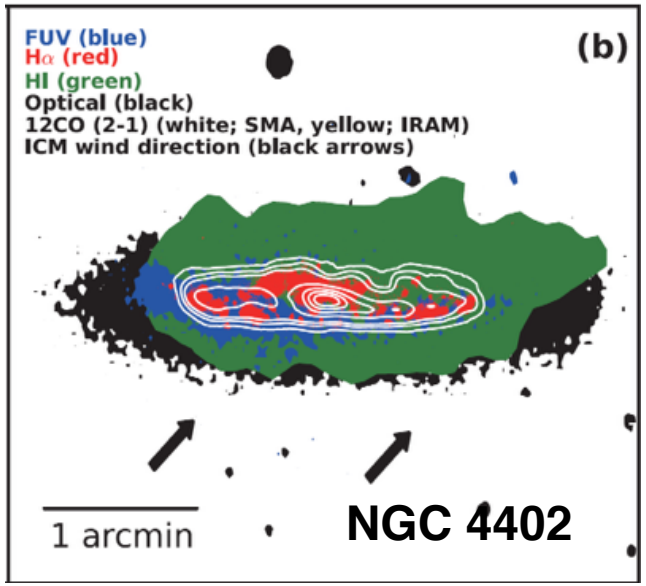
Hα: ~20 Myr
FUV: ~100 Myr
Kennicutt 1998

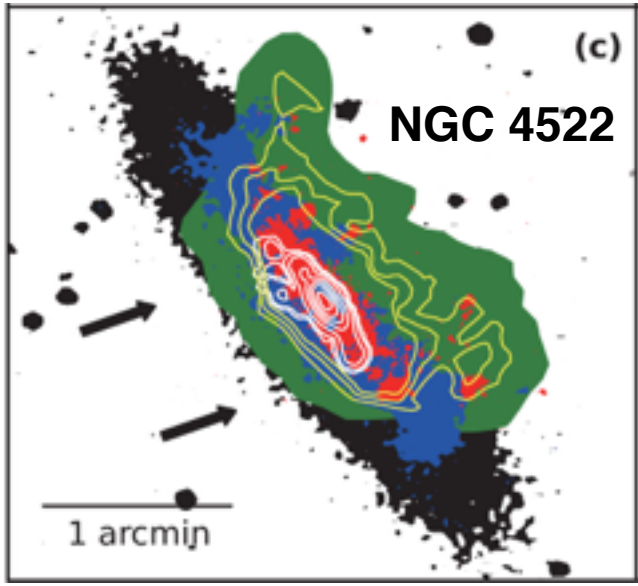
12CO (2-1) (white: SMA, yellow: IRAM)

- FUV, more extended than CO and Hα
- FUV and Hα in the extraplanar gas

Ongoing ram pressure stripping stage







The relationship between molecular gas and star formation activity in three galaxies

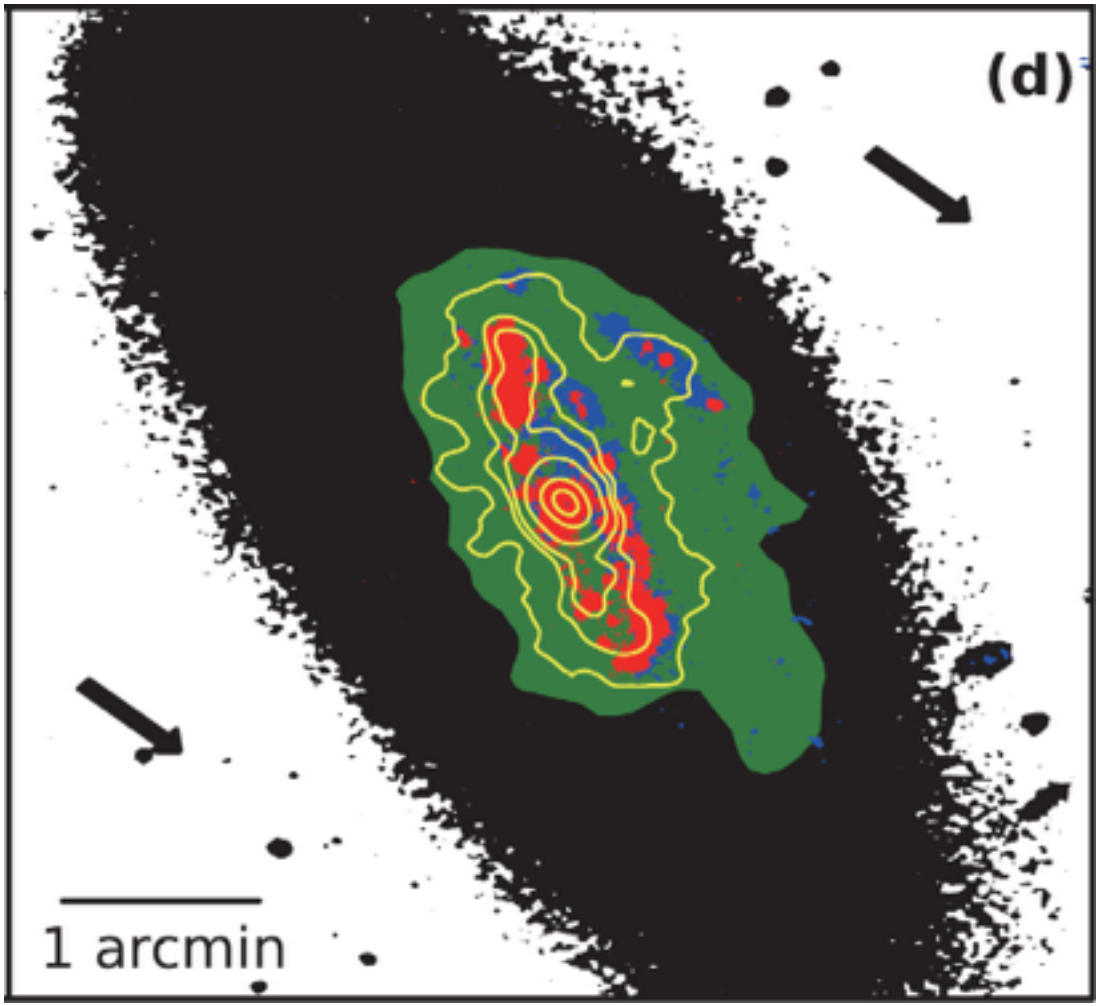
- **Hα and CO are overall in good agreement.**
- **The FUV extent is similar to the HI extent or larger than the HI extent.**
- **Local FUV enhancements found near CO compression in the upstream side**

→ **locally induced star formation due to ram pressure (e.g. Fujita & Nagashima 1999)**

- **FUV shows distinct morphology and extent from those of Hα/CO**

→ **Recently quenched star formation in the last 100 Myr**

Past ram pressure stripping stage



NGC 4569

Moving away from the cluster center after crossing core

SF quenching time >> 300 Myr

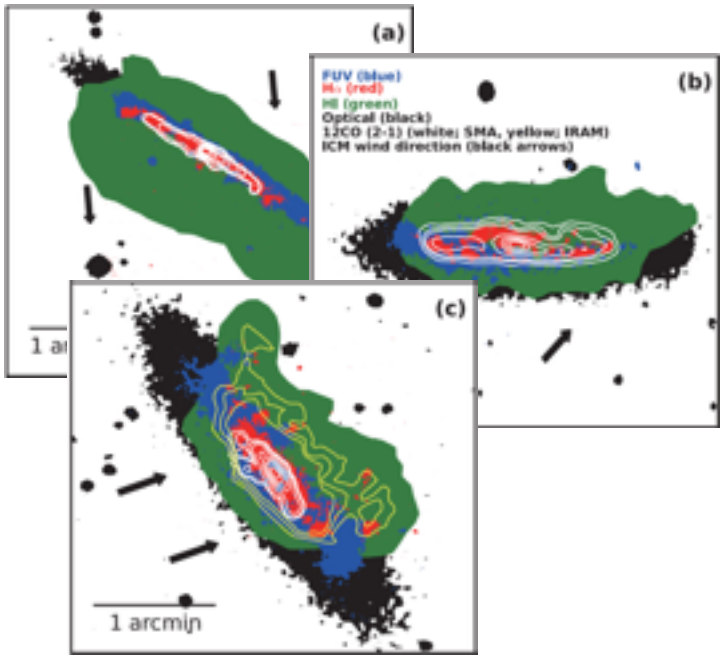
- **The extent of FUV disk is comparable to that of Hα and CO/HI.**

→ The FUV emission fade as time goes by

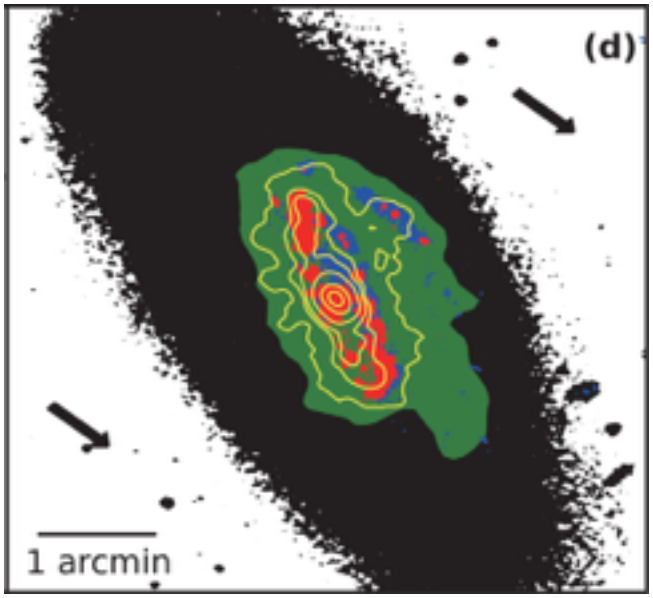
→ The FUV extent can decrease to the Hα extent

Galaxy evolution in the galaxy cluster

Ongoing ram pressure stripping stage



Past ram pressure stripping stage



Cluster galaxy become passive and red

Work in progress

Physical properties of molecular gas

Studying physical properties in molecular gas with line ratios (12CO, 13CO) & non-LTE model (RADEX, Van der Tak et al. 2007**)**

Temperature and density distribution of CO gas of NGC 4402

IRAM 30m telescope

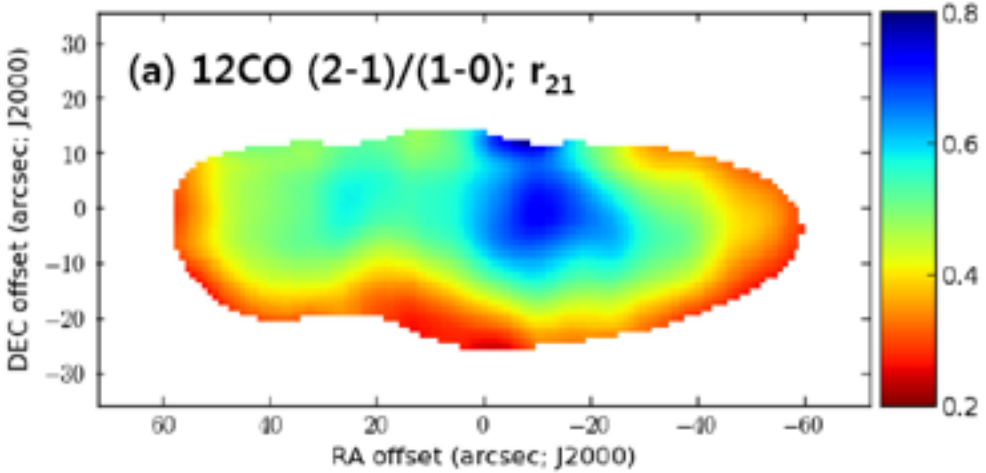
OTF (on the fly) mode

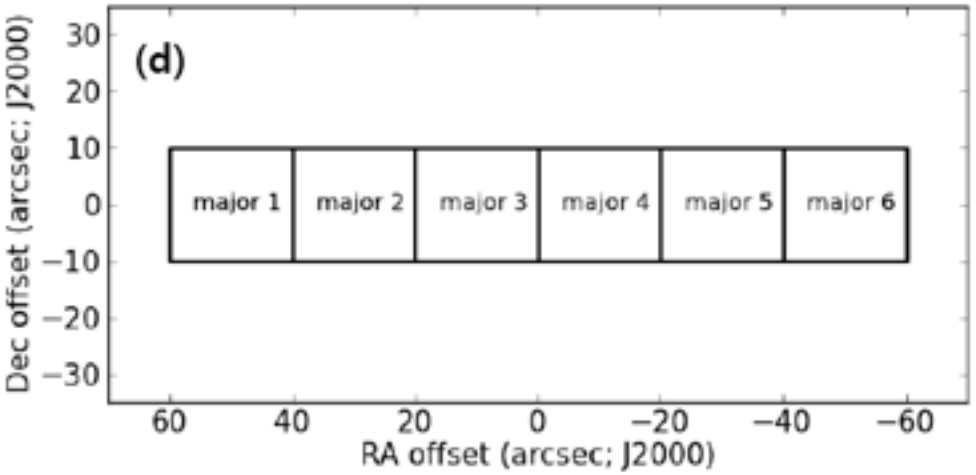
NGC4402

12CO (1-0), 115.271 GHz
13CO (1-0), 110.201 GHz
12CO (2-1), 230.538 GHz
13CO (2-1), 220.398 GHz

Work in progress

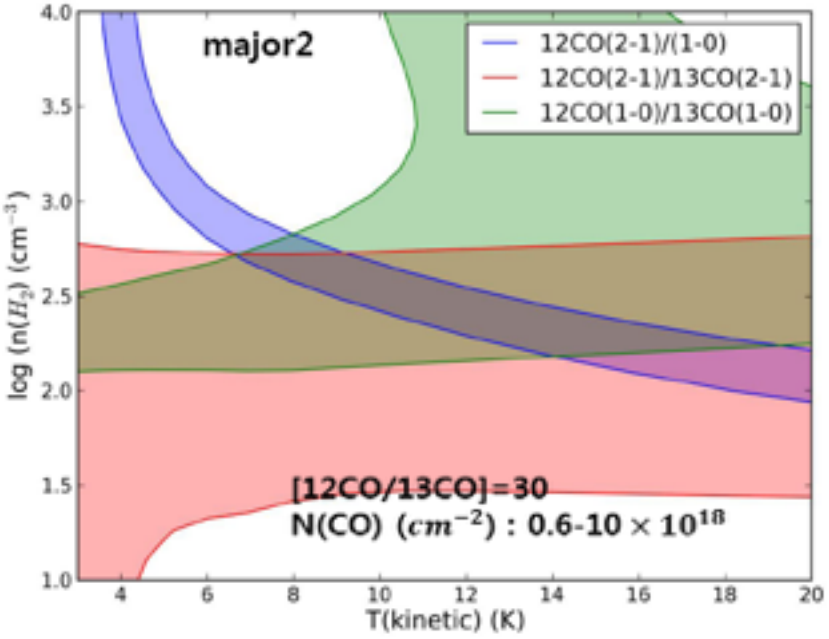
Physical properties of molecular gas

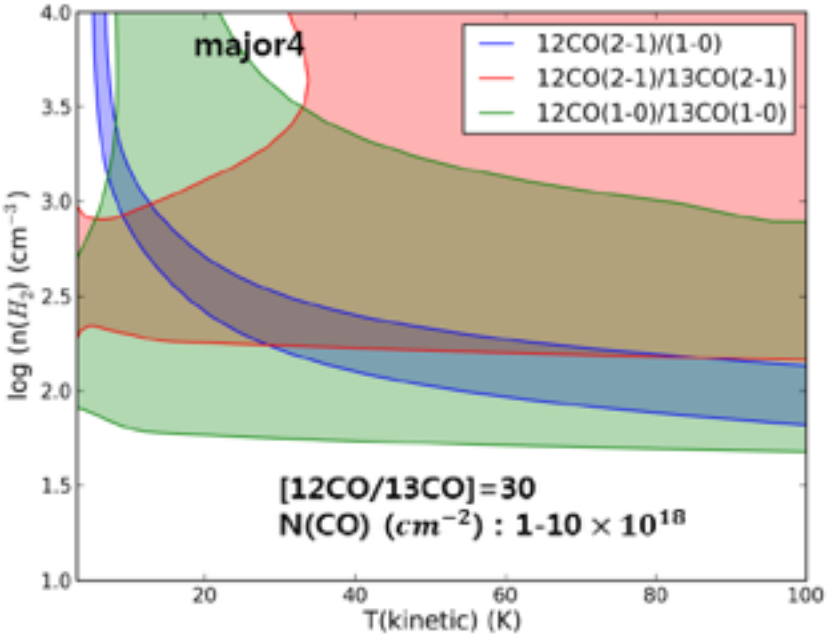




Work in progress

Physical properties of molecular gas





T_{KIN} (K): ~5.7 – 14.3
n(H_2, cm^{-3}) : ~$10^{1.3}$ – $10^{2.8}$

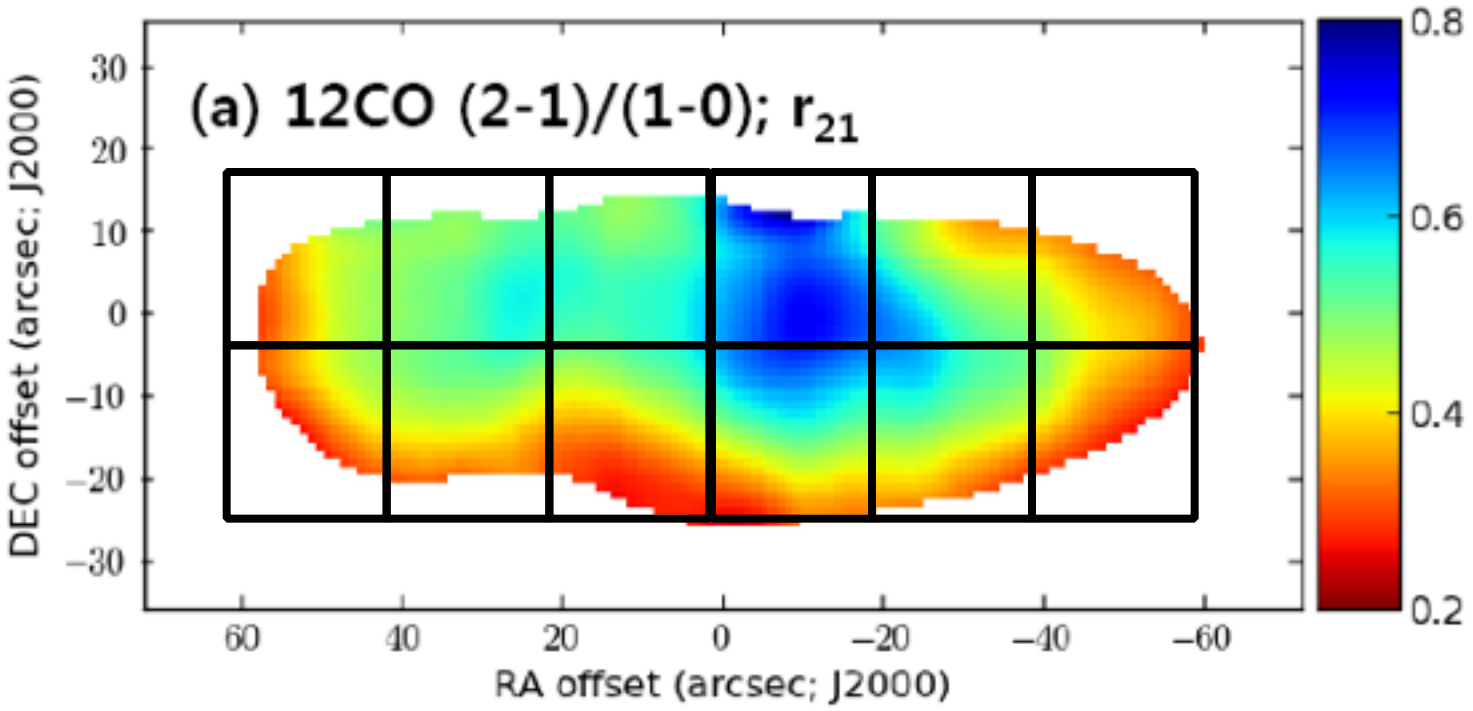
T_{KIN} (K): ~5.5 – 170.0
n(H_2, cm^{-3}) : ~$10^{1.8}$ – $10^{3.4}$

Work in progress

Physical properties of molecular gas

Temperature and density distribution of molecular gas in NGC 4402

Understand the star formation quenching process in the cluster galaxies



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THE DESTINY OF MOLECULAR GAS UNDER STRONG RAM PRESSURE

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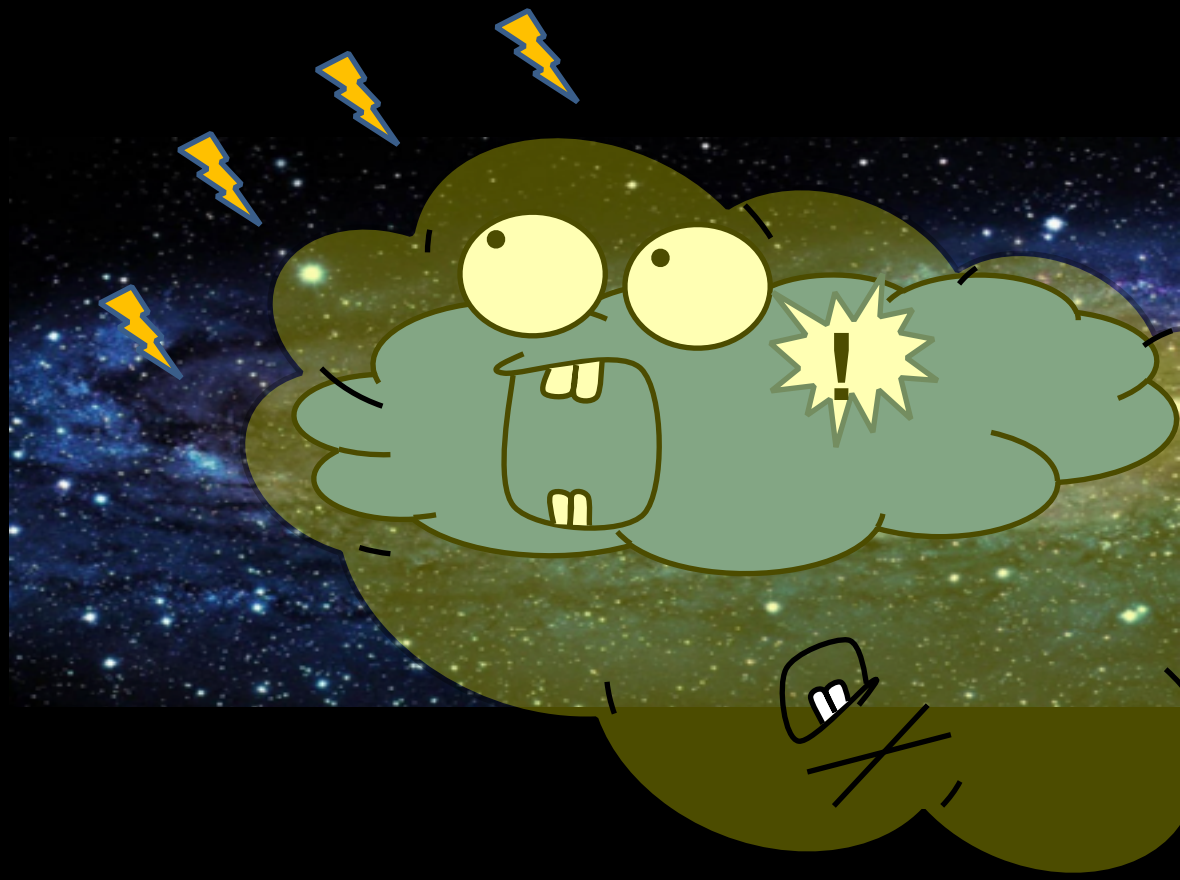
√ HI GAS IS STRIPPED

√ MOLECULAR GAS SURVIVES?

Molecular gas

HI gas

ICM



DEEP IMPACT:

THE DESTINY OF MOLECULAR GAS UNDER STRONG RAM PRESSURE

√ ICM BOMBARDS A GALAXY

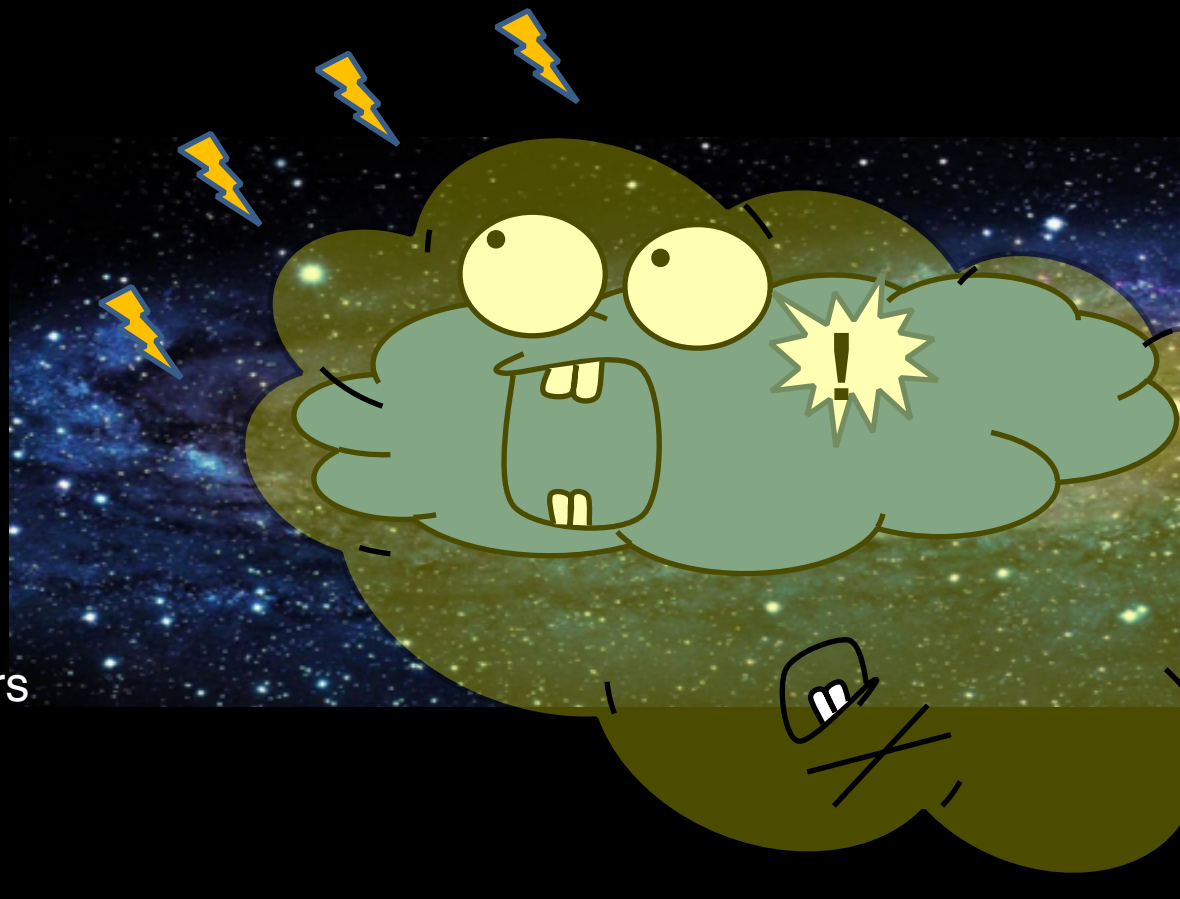
√ HI GAS IS STRIPPED

√ MOLECULAR GAS IS DISTURBED!!

Molecular gas

HI gas

ICM



Recent CO study using JCMT:
(Mok et la. 2016)
Molecular gas enhancement
among the Virgo cluster members

Summary

- The overall morphology and kinematics of molecular gas are **asymmetric and disturbed due to ram pressure.**

- Peculiarities in molecular gas is **closely connected to that in diffuse atomic gas**, reflecting the effects of ram pressure.

- **FUV enhancement** is found along the **CO compression** region in the ICM wind front. It is **locally induced star formation** by ram pressure.

- FUV shows **distinct morphology and extent from those of Hα/CO**. This indicates that **star formation has been recently quenched** in the last 100 Myr.

- We are currently probing the **physical and chemical status of molecular gas** of NGC 4402 using multiple CO transitions.