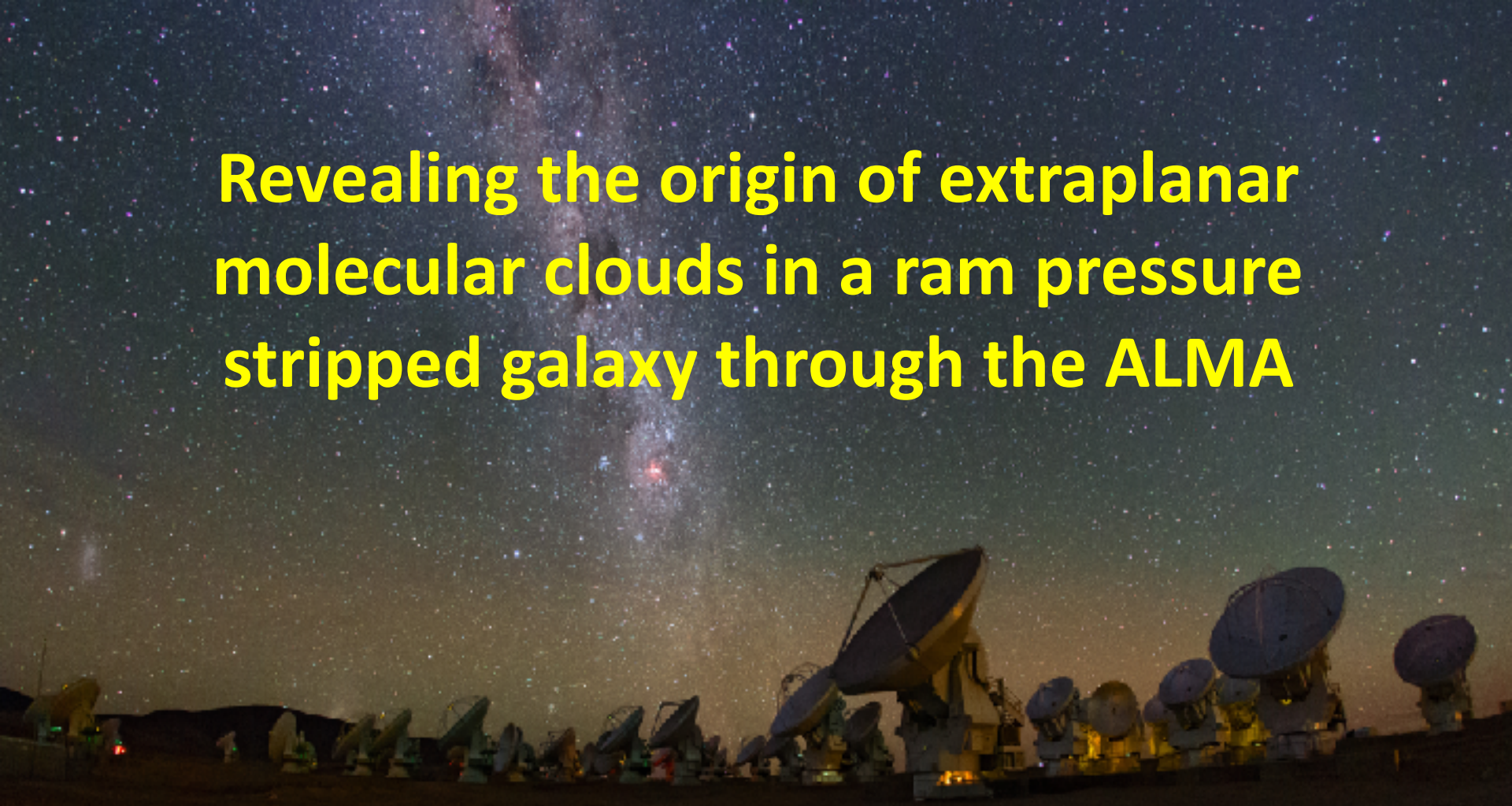
Revealing the origin of extraplanar molecular clouds in a ram pressure stripped galaxy through the ALMA



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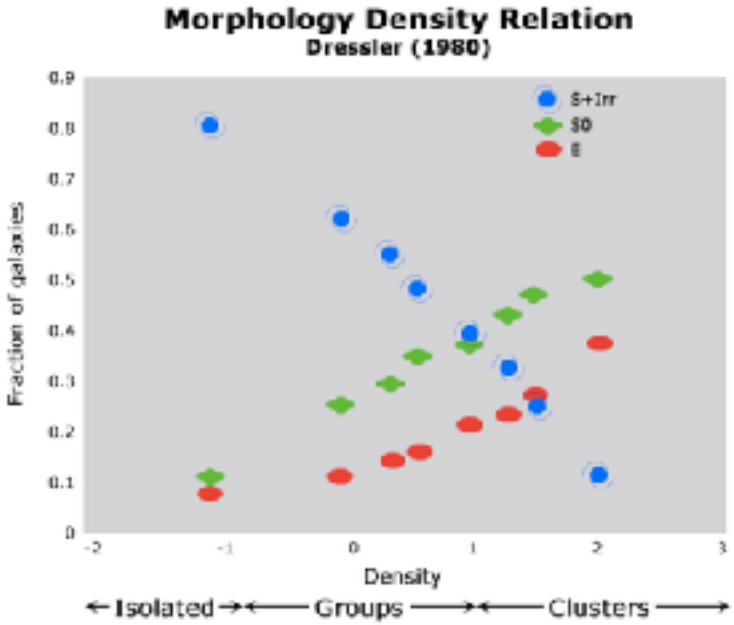
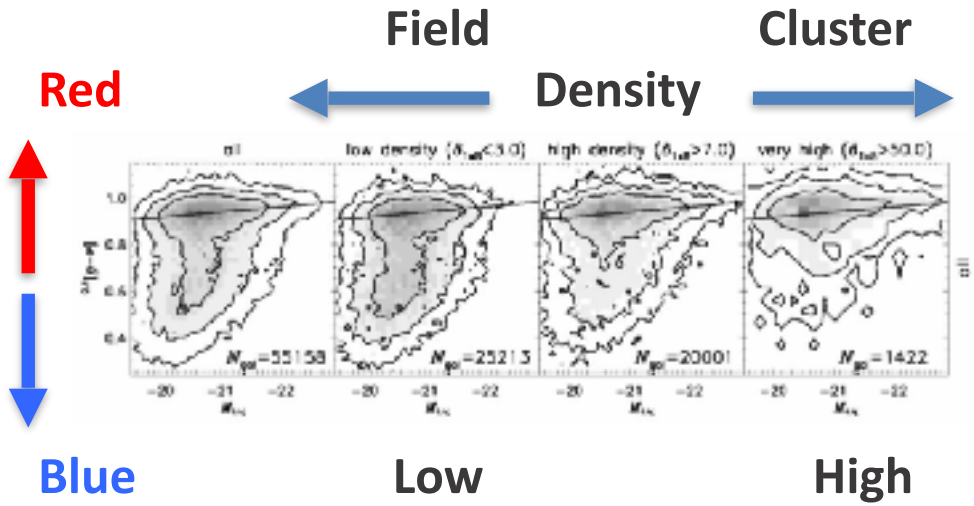
East-Asia ALMA Science Workshop 2017 - Korea, November 27-29, 2017

Credit: ESO/B. Tafreshi (twanight.org)

Galaxy evolution in cluster environment





Hogg et al. 2004

- **Elliptical & S0 galaxies:**

90% in the cluster environment

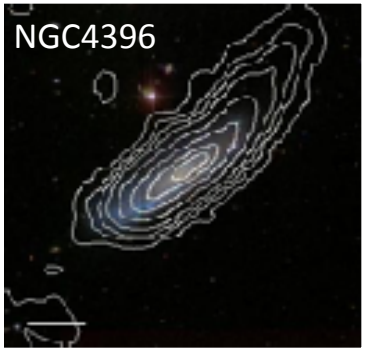
- **Cluster population:**

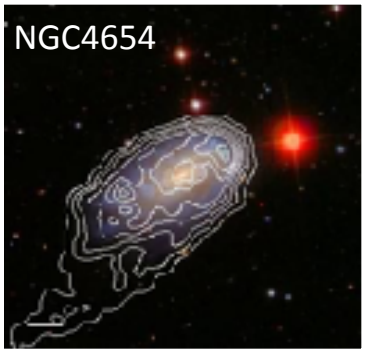
passive and **red**

Ram pressure stripping

✓ ICM (the intracluster medium) – ISM (the interstellar medium)

Ram pressure stripping (RPS, Gunn & Gott 1972)
ram pressure > restoring force
→ gas is stripped → red & passive galaxy?





Chung et al. 2009

✓ HI gas stripping (e.g. Cayatte et al. 1990; Chung et al. 2007, 2009)
✓ Star formation quenching (Koopmann & Kenney 2004a,b)

Molecular gas → a direct ingredient for star formation

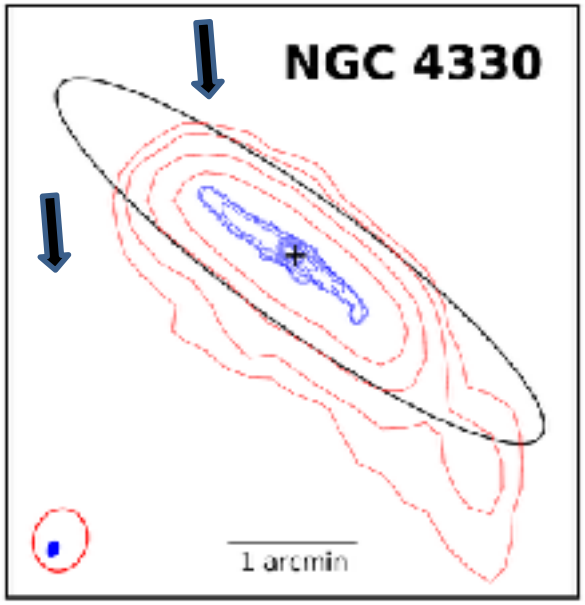
Q. Whether molecular gas is stripped/disturbed by the ram pressure

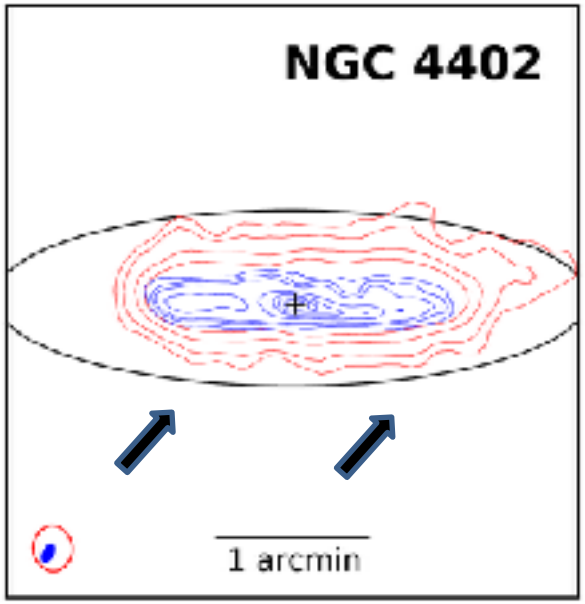
Q. Whether cluster are deficient in molecular gas
(Stark et al. 1986, Kenny & Young 1989 vs. Fumagalli et al. 2009, Boselli et al. 2014)

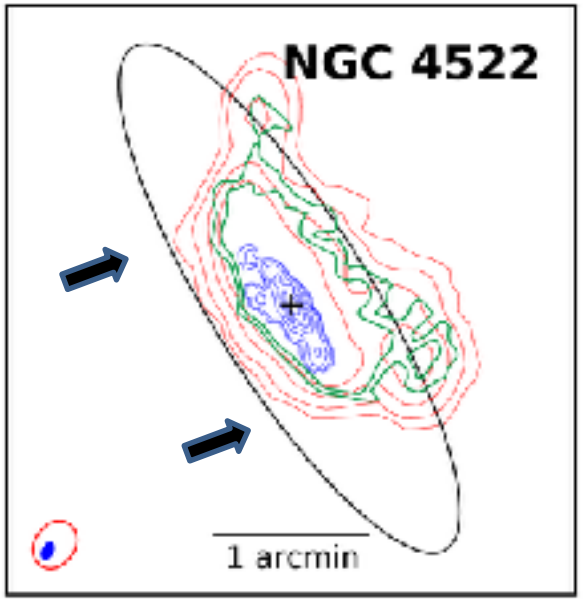
Molecular gas under strong ram pressure

Lee & Chung et al. 2017, MNRAS, 446, 1382

SMA observations in order to investigate detailed CO properties







12CO (2-1): blue, SMA, Lee & Chung et al. 2017
12CO (2-1): green, IRAM 30m, Vollmer et al. 2008
HI: red, Chung et al. 2009
D_{25} in the optical image, RC3
The ICM wind direction: black arrows

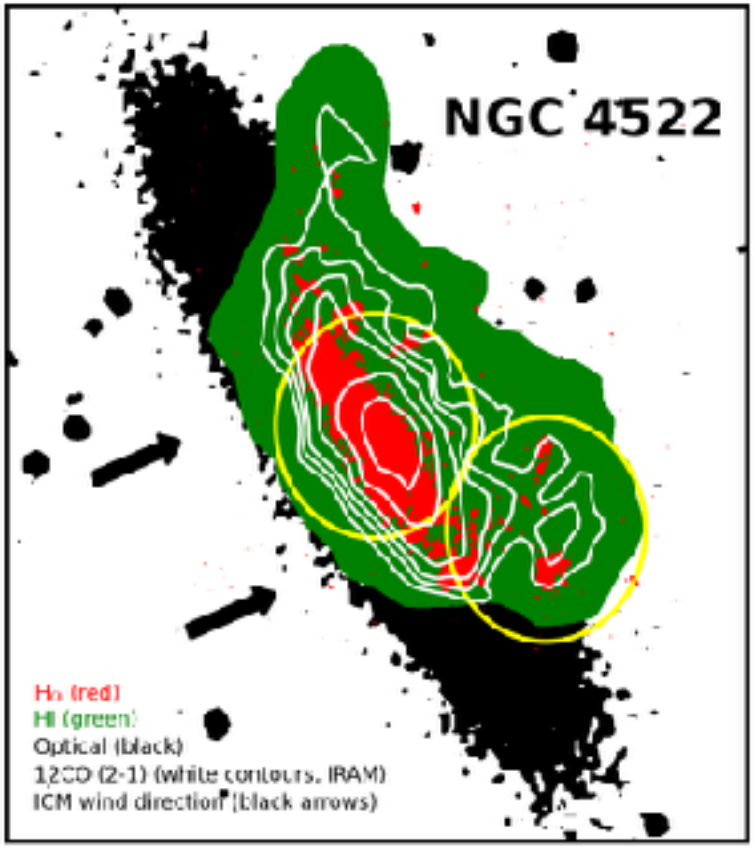
Virgo cluster (16 Mpc), three spirals in active RPS

Using SMA 12CO (2-1) data,

✓ **12CO morphology**
→ **highly asymmetric and disturbed**
→ **closely related to the HI morphology**

▶**Strong ram pressure can affect properties of molecular gas (even within a few kpc of stellar disk)**

Extraplanar CO gas in NGC 4522



- Active ram pressure stripping stage
- Only 25% of expected HI gas mass
- 40% of total HI gas (green) in the extraplanar
- 25% of total CO gas (white contour) in the extraplanar
- **Extraplanar CO gas & extarplanar Hα patches** (Kenney et al. 2004; Vollmer et al. 2008; Chung et al. 2009)

✓ **An interesting case, as the nearest example among only the few galaxies found with extraplanar molecular gas**

✓ **Molecular gas properties and star formation activities inside & outside the disk with the follow-up ALMA observations**

Scientific questions in the ALMA observations

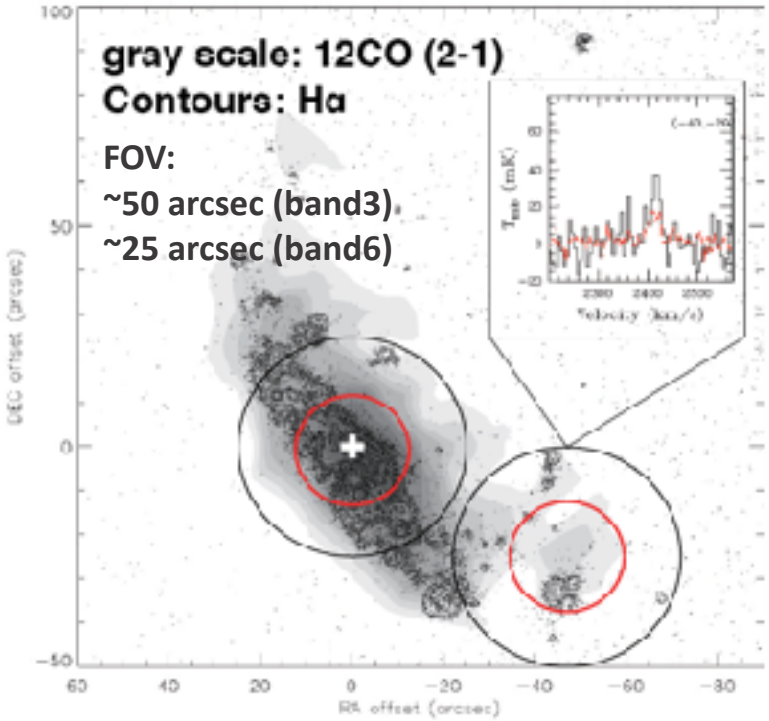
Q1. What are properties of extraplanar molecular clouds? (e.g. mass, linewidths, velocity field, 12/13CO line ratio)

Q2. Can the molecular gas get stripped by ram pressure due to the ICM? If so, is it stripped as cloud or is it re-crumpled after stripping? In addition, can the molecular gas be newly formed from stripped atomic gas outside the stellar disk?

Q3. How efficiently do stars form in a RPS galaxy?

✓ **A relation between the molecular gas surface density and the star formation rate (i.e. the Kennicutt-Schmidt law) at sub-kpc scale**

The ALMA observations (Cycle 3, PI: Lee, B)




Credit: ALMA(ESO/NAOJ/NRAO), B. Tafreshi

Using 12m array,

- January 12, 2016, 12CO, 46 antennas
- January 19, 2016, 13CO, 43 antennas

In band 3 and band 6 (Multi CO lines),

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

In two regions,

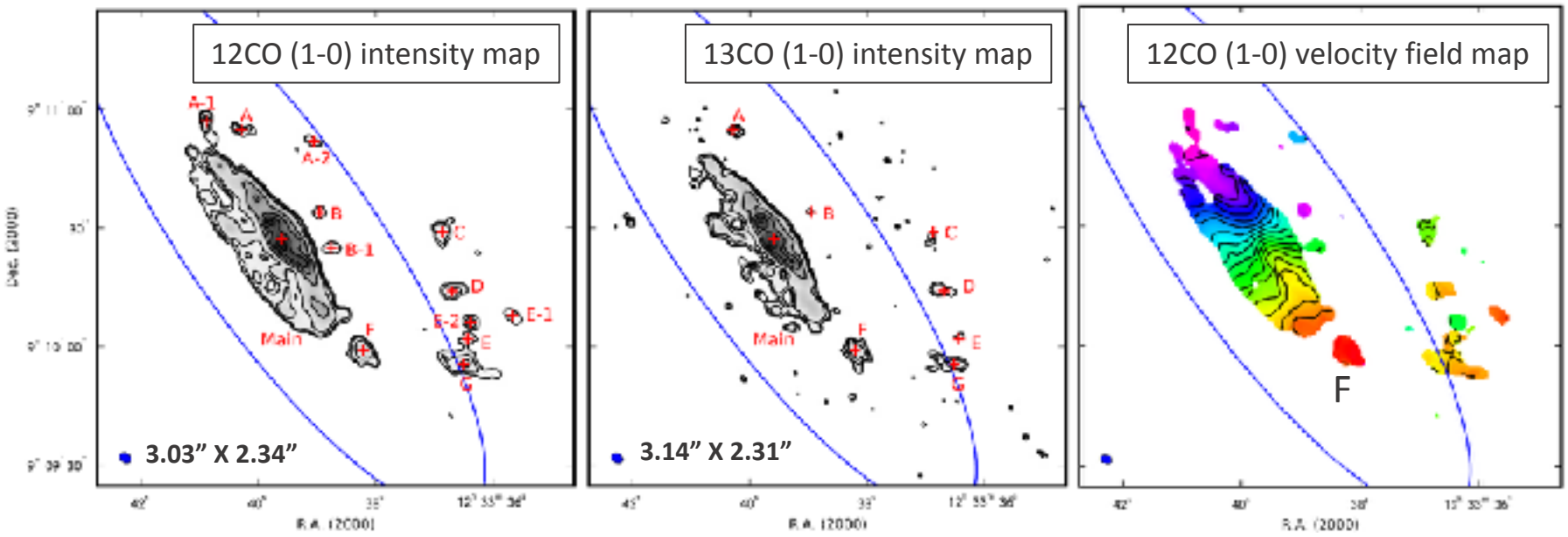
- one around the center of NGC 4522
- One centered on the peak of the extraplanar CO gas

On-source time:

- 12CO (1-0): 0.9 hrs, 13CO (1-0): 4.6 hrs
- 12CO (2-1): 0.3 hrs

In total observation time: ~5.8 hrs

The ALMA data of NGC 4522

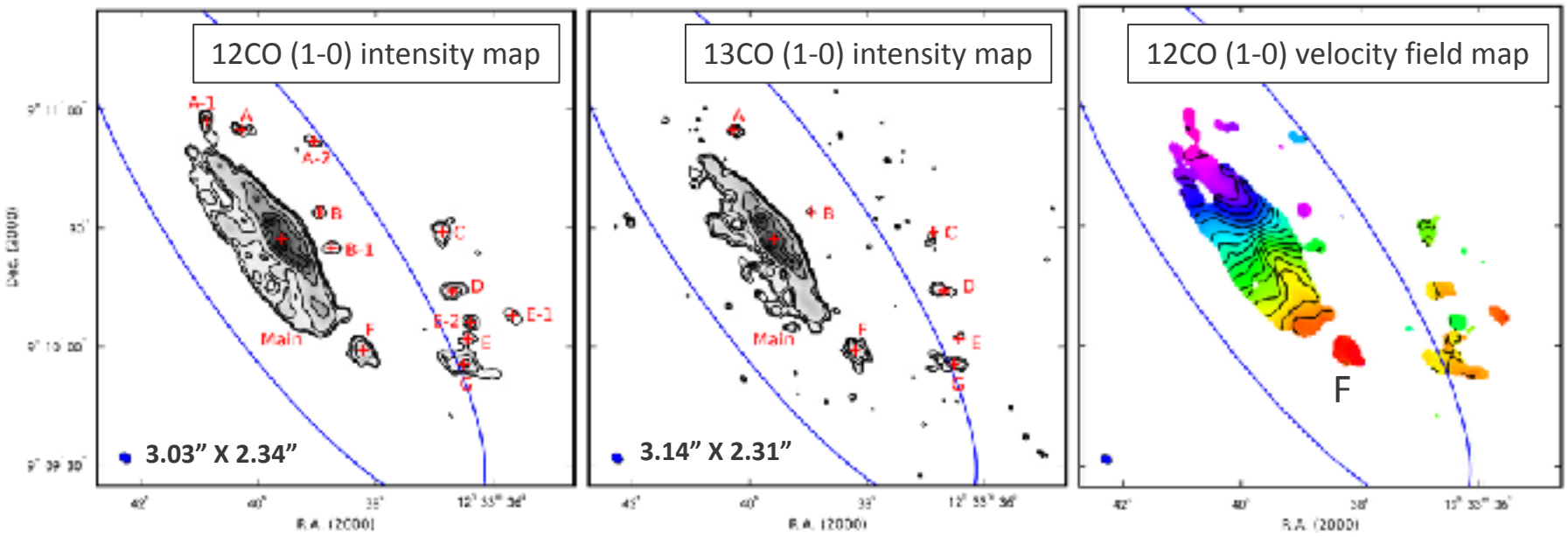


✓ Extraplanar clouds detected in both 12CO and 13CO (C, D, E, G)

✓ **The first report for extraplanar 13CO detection in a RPS galaxy, using ALMA**
→ important data to constrain the origin of extraplanar clouds and their physical states

Lee et al. in prep.

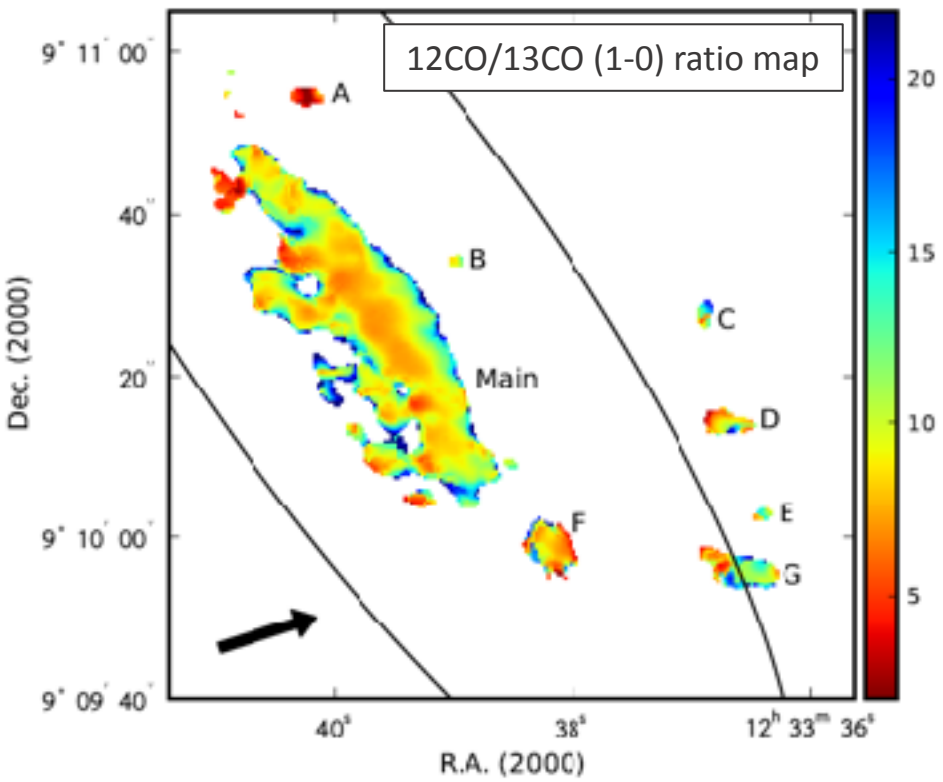
The ALMA data of NGC 4522



- ✓ The mass of extraplanar molecular clouds: ~$10^5 - 10^6 M_\odot$, comparable to the GMCs
- ✓ The linewidth of extraplanar molecular clouds: ~20 km/s, larger than the GMCs
- ✓ Radial velocity of extraplanar clouds: ~2388 km/s vs. 2429 km/s (Clump F)
  → **accelerated (40 km/s blueshift) toward Virgo cluster due to the ram pressure**

Lee et al. in prep.

Line ratio of 12CO & 13CO



Arrow: the ICM wind direction
Ellipse: the optical disk

- ✓ Mean line ratio of extraplanar clouds: **~11.1** (i.e. comparable to the line ratio of the main disk: **~10.8**)
- ✓ UGC 12914/5 interacting system: **~50** in the tidal bridge (cf. **~15** in the center of UGC 12915)

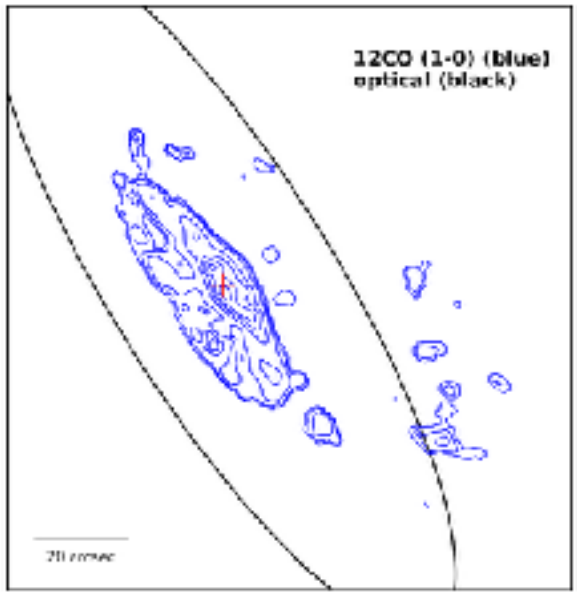
▶ **The external pressure: ram pressure?**
(Alatalo et al. 2015)

- ✓ Line ratio gradient in extraplanar clouds (C, D, E, G; east to west)
- ✓ Low in east → high in west

▶ **Diffuse CO gas is stripped?**
(Alatalo et al. 2015)

Two potential origins of extraplanar clouds

1. Molecular gas formation from stripped HI gas



2. Stripping molecular gas
as cloud OR reassemble
(Sivanandam et al. 2010)

✓ HI surface density for H2 formation (4-10 $M_{\odot}pc^{-2}$): ~5 $M_{\odot}pc^{-2}$ around the extraplanar CO in NGC 4522
(Burkhart & Loeb 2016)

✓ Ram pressure > restoring force for molecular clouds in the stellar disk
→ stripping molecular clouds
(Lee et al. 2017)

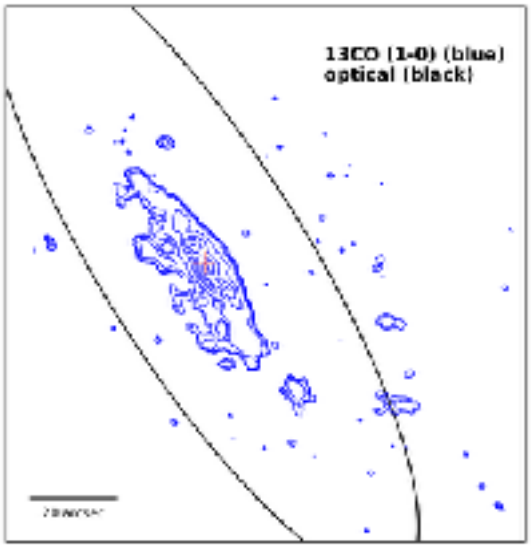
✓ Considering various timescales (e.g. GMC formation timescale (30 Myr), stripping timescale (100 Myr)) (Vollmer et al. 2006; Crowl & Kenney 2008)

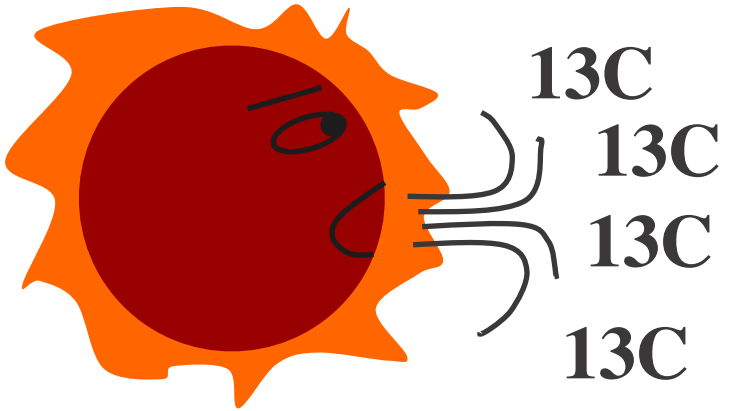
✓ **The combination of two potential origins?**

Lee et al. in prep.

Two potential origins of extraplanar clouds

✓ **13CO detection → a hint for the origin of the extraplanar molecular gas?**





✓ **13C from the AGB stage of intermediate-mass stars (3−4$M_\odot$)**

Marigo 2006

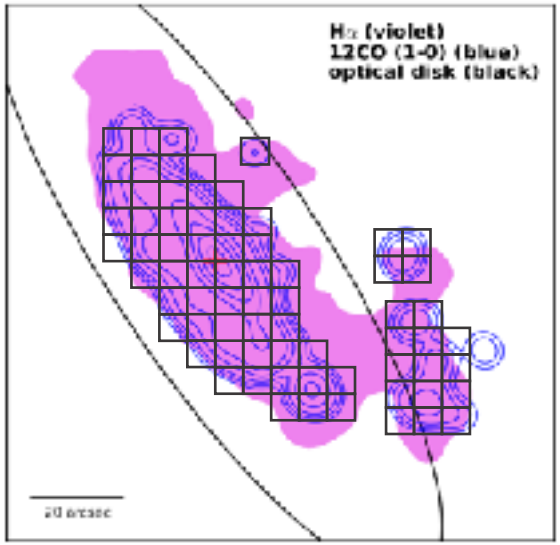
✓ The formation timescale of 13C: at least, **> 300 Myr**
(e.g. main sequence lifetime: ~300 Myr @ 4 $M_\odot$)
cf. stripping timescale: **~100 Myr**

→ **Not enough time to produce 13CO from new stars in the extraplanar space**

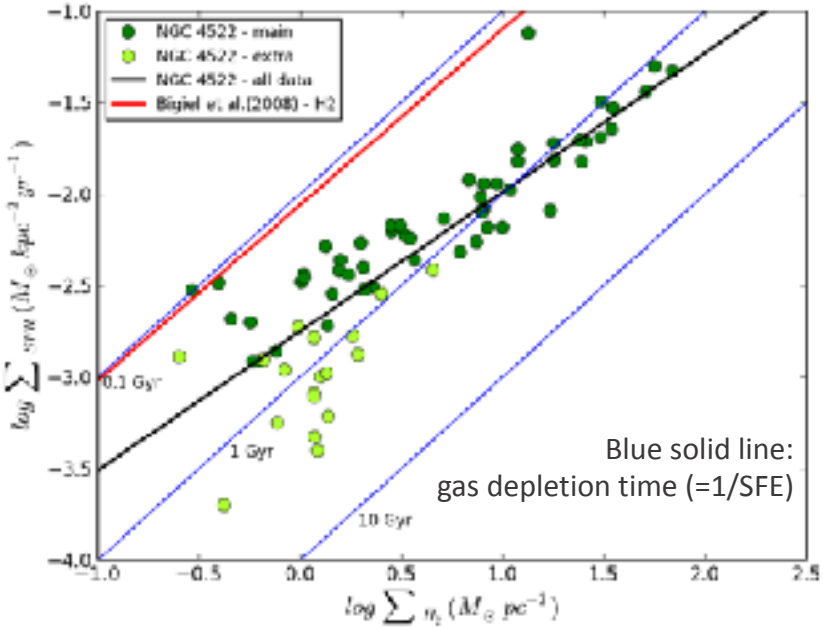
▶ **The existence of extraplanar 13CO suggests that the extraplanar moleucular clouds of NGC 4522 is likely to be stripped from the galactic disk**

Lee et al. in prep.

The Kennicutt-Schmidt (KS) relation of NGC 4522



$$SFR[M_{\odot}yr^{-1}] - 5.3 \times 10^{-42}[L(H\alpha)_{obs} + 0.031\,L(24\mu m)]$$



✓ Measuring Σ_{SFR} and Σ_{H2} in 6 arcsec (~500 pc) box (low spatial resolution in IR data)

$$\log \Sigma_{\rm SFR} = 0.76 \pm 0.05 \log \Sigma_{\rm H2} - 2.75 \pm 0.04 \text{ (our work)}$$

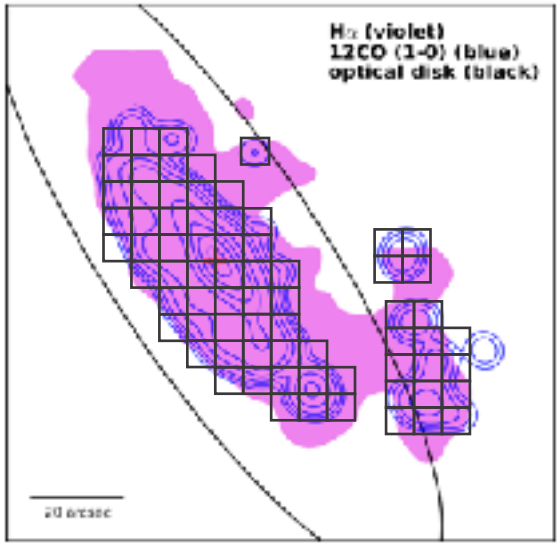
$$\text{Cf. } \log \Sigma_{\rm SFR} = 0.96 \pm 0.07 \log \Sigma_{\rm H2} - 2.06 \pm 0.17 \text{ (Bigiel et al. 2008)}$$

1) Sub-linear relation (slope: 0.76) on the KS plot

✓ **Inefficient star formation activity** due to injecting turbulence into molecular gas by ram pressure Alatalo et al. 2015, Lee et al. 2017, Shetty et al. 2013

Lee et al. in prep.

The Kennicutt-Schmidt (KS) relation of NGC 4522



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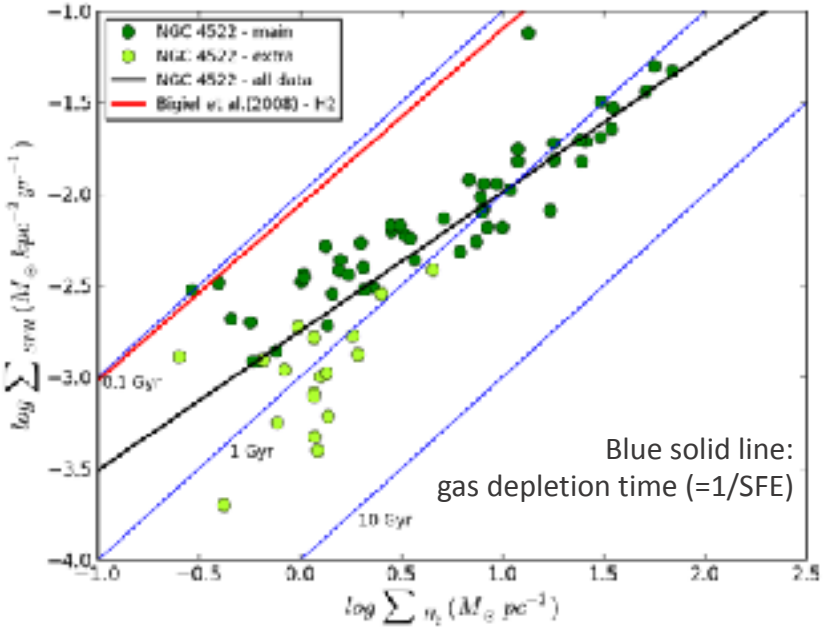


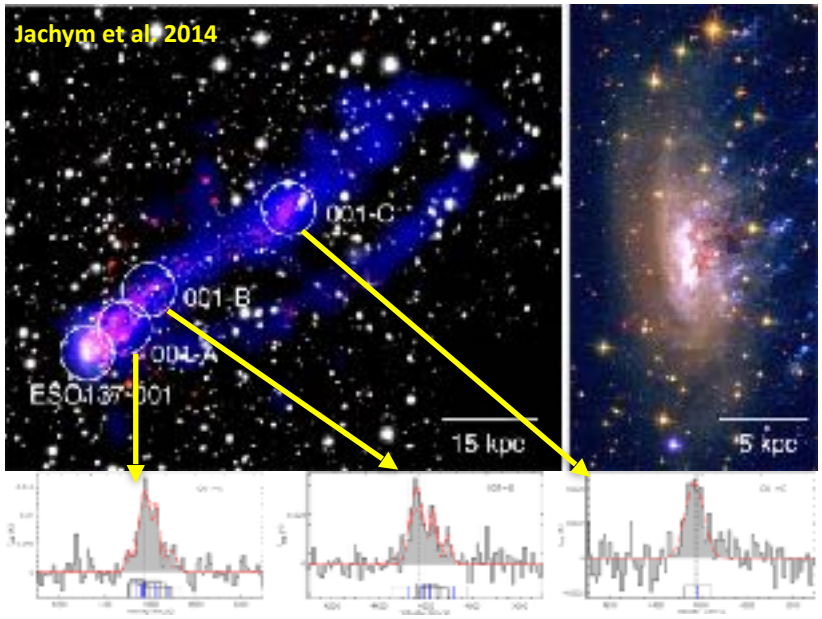
2) Relatively long gas depletion time in extraplanar molecular clouds

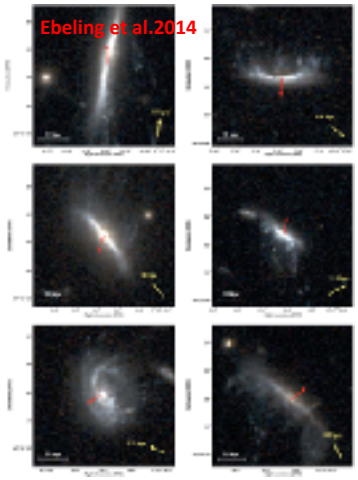
- ✓ Long gas depletion time (H2 mass/ SFR) at low gas surface density ($\log \sum_{H2}$: 0-0.5), main disk: 458 ± 55 Myr vs. extraplanar clouds: 1274 ± 251 Myr
- ✓ No gravitational confinement in the extraplanar space & increasing thermal and turbulent pressure due to ram pressure induced shock Jachym et al. 2014, Vollmer et al. 2012
- ✓ Low star formation efficiency as seen in other RPS galaxies (e.g. NGC 4388 and ESO 137-001) Jachym et al. 2014, Verdugo et al. 2015

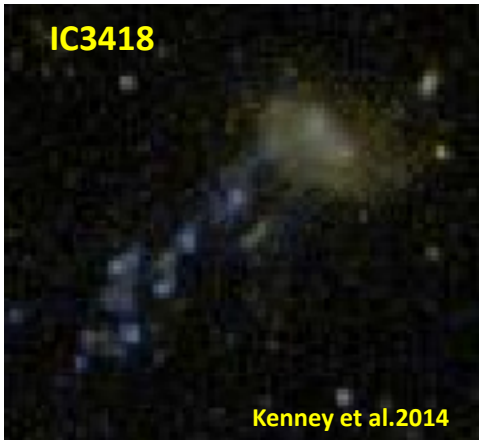
Lee et al. in prep.

Summary

Recent studies for many jellyfish galaxies







- ✓ The first report for 13CO detection outside the main disk of the RPS galaxy thanks to high-sensitivity of ALMA
- ✓ Extraplanar molecular clouds are accelerated (40 km/s blueshifted) toward Virgo cluster
- ✓ Line ratio gradient, east (low) to west (high) in extraplanar clouds, diffuse CO gas is stripped?
- ✓ Two potential origins of extraplanar clouds, but extraplanr 13CO → extraplanr molecular clouds are stripped by ram pressure
- ✓ Sub-linear slope in the KS plot and relatively long gas depletion time in extraplanar molecular clouds

This ALMA data will give an opportunity to better understand the fate of ISM and star formation activity in the extraplanar space

Thank you