Extended Molecular Gas Reservoirs are common in a distant galaxy cluster

Submitted to MNRAS

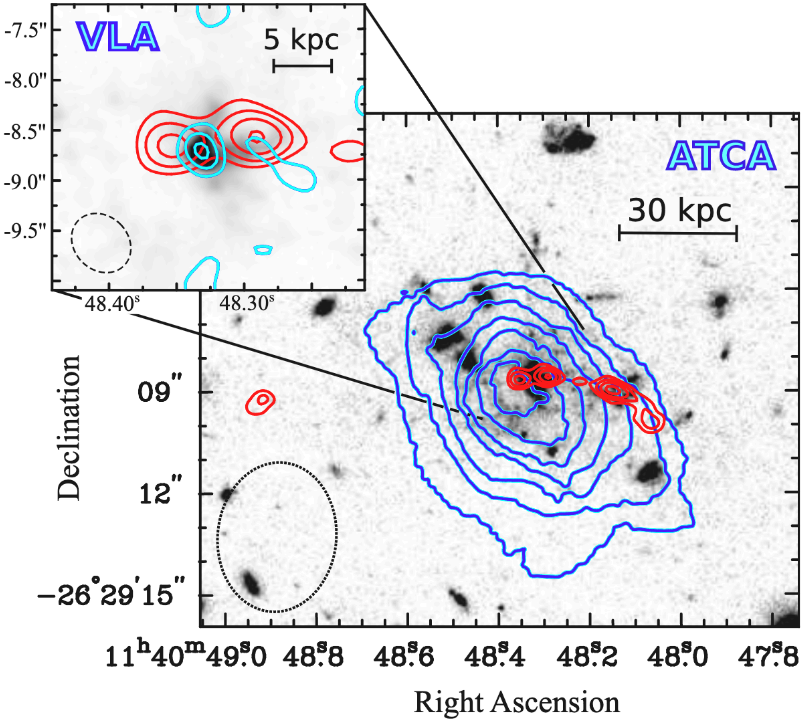
Zhengyi Chen (Nanjing University, China; Instituto de Astrofísica de Canarias, Spain)
Collaborators: H. Dannerbauer, M. Lehnert, B. Emonts, Q. Gu & ATCA Spiderweb Protocluster Team

First Structure 2023 @ Paris
2023.09.06

Motivation:
Large/Extended Molecular Gas Reservoir Discoveries (Rare)

Large molecular gas reservoirs found in Spiderweb Protocluster at z=2.16 with ATCA

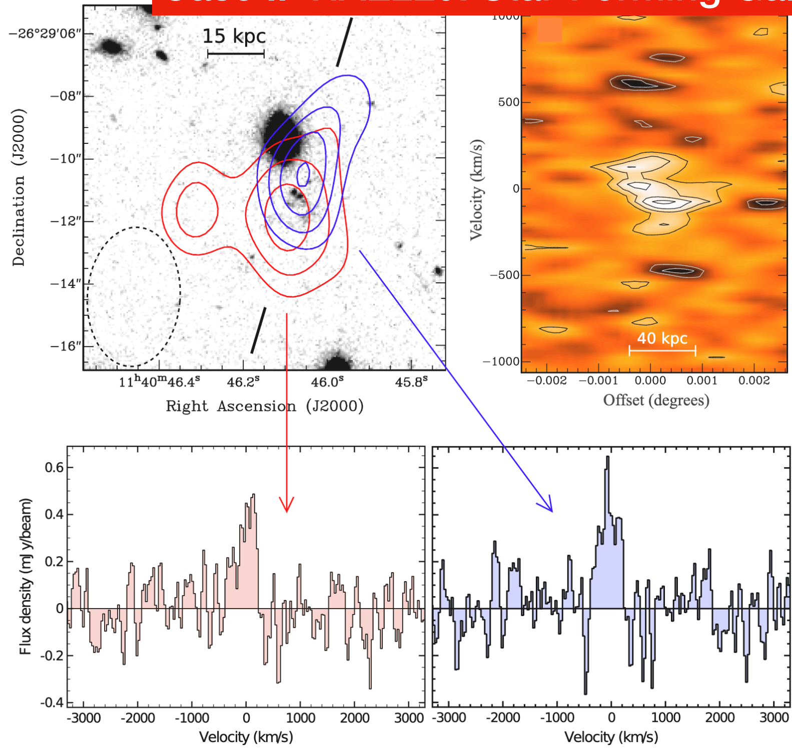
Case I. The Spiderweb Galaxy: Central Radio Galaxy



1. Massive extended **~70 kpc** intergalactic medium are revealed around the radio galaxy MRC1138-262, called the Spiderweb galaxy.

Emonts+2016 Science

Case II. HAE229: Star-Forming Galaxy



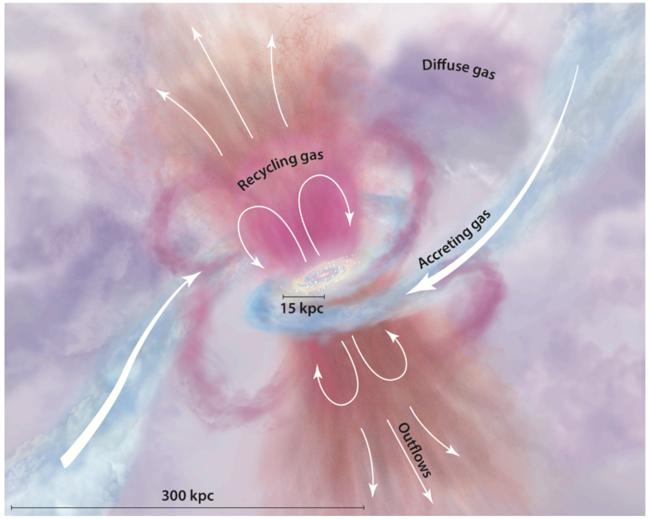
2. Large, extended **~40 kpc** rotating molecular gas disk found in a normal star-forming galaxy,HAE229.

Dannerbauer+2017

see also work by other groups e.g. Ginolfi+2017; D'Amato+20: Emonts+20; Champagne+21

Galaxy - CGM/IGM interplay
Navigating Complexity: Zooming In on Our Area of Interest

Galaxy-surrounding medium Interplay is multiple folded

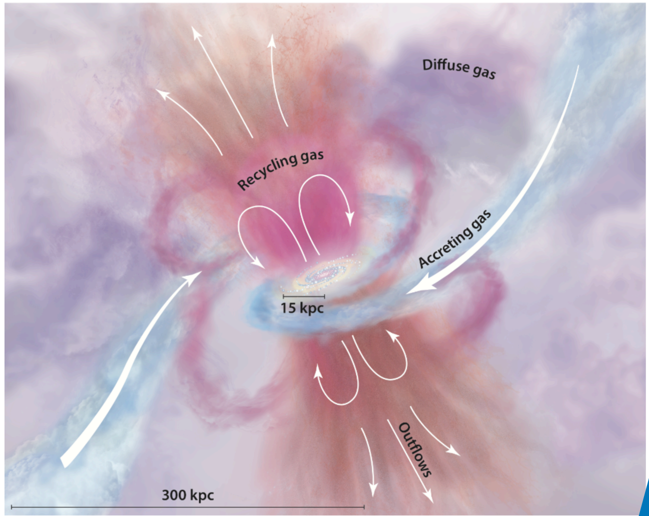


(Tumlinson+2017)

1. **multiple processes**
   1. Inflow: accretion; recycling, etc
   2. Outflow: AGN driven; SN driven; etc
   3. mergers
2. **multiple medium phases**
   1. PAH;
   2. atomic;
   3. molecular;
   4. ionised
3. **multiple scales**
   1. ~kpc,
   2. tens of kpc;
   3. hundreds of kpc; etc

Galaxy - CGM/IGM interplay
Navigating Complexity: Zooming In on Our Area of Interest

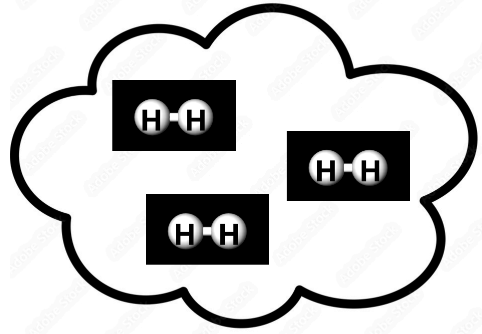
Galaxy-surrounding medium Interplay is multiple folded



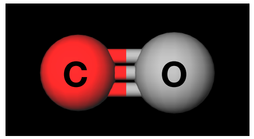
(Tumlinson+2017)

1. **multiple processes**
    1. Inflow: accretion; recycling, etc
    2. Outflow: AGN driven; SN driven; etc
    3. mergers
2. **multiple medium phases**
    1. PAH;
    2. atomic;
    3. **molecular;**
    4. ionised
3. **multiple scales**
    1. ~kpc,
    2. **tens of kpc;**
    3. hundreds of kpc; etc

Molecular gas (H2): the direct fuel of star-formation in galaxies



Tracer:



Multiple Physical Process Behind: A Complex Topic

Unraveling Environmental Effects on various mechanisms: Comparing (Proto)cluster and Field Galaxies to Probe Probable Impacts

Scale: ≳ 40 kpc

- Inspired by Unveiled Extended Molecular Gas Reservoirs (Introduced in Previous Slide)
- Physical Scope: CGM, IGM, etc

Initial Leap: COALAS Survey

— Exploring Cold Molecular Gas in both (Proto)cluster and Field Environments

Focus located.
Next Step:
The Sample & Data???

Initial Leap: COALAS Survey

— Exploring Cold Molecular Gas in both (Proto)cluster and Field Environments

Focus located.
Next Step:
The Sample & Data???

COALAS Survey

Initial Leap: COALAS Survey

— Exploring Cold Molecular Gas in both (Proto)cluster and Field Environments

Focus located.
Next Step:
The Sample & Data???

COALAS Survey

Previous talk by Helmut Dannerbauer

ATCA Large Program COALAS CO(1-0) survey (C3181, PI: H. Dannerbauer)

COALAS (CO ATCA **L**egacy **A**rchive of **S**tar-Forming Galaxies; ~800 hrs.**):** ATCA observation of CO(1-0) transitions in **protocluster (Spiderweb)** & **field** galaxies at z~2.

Offer the opportunity to constrain environmental effects

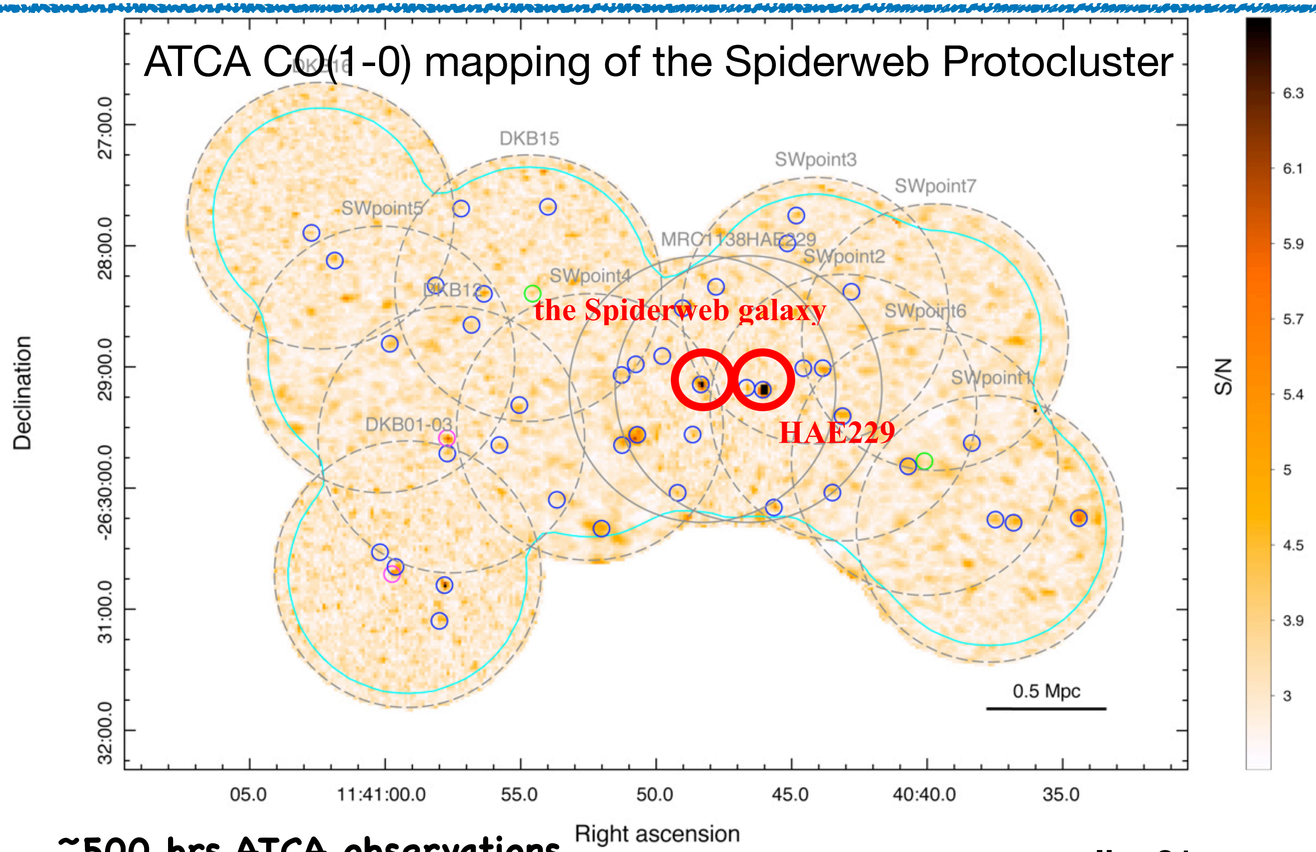
Exclusive Southern Capabilities: Pre-ALMA Cycle 10 Band 1 Launch, ATCA Stands as the ONLY Southern Hemisphere Facility for CO(1-0) Targeting at z~2.

This Work: the Spiderweb Protocluster.

Initial Leap: COALAS Survey

— Exploring Cold Molecular Gas in both (Proto)cluster and Field Environments

The COALAS SpiderWeb Protocluster Observations (COALAS-SW)



~500 hrs ATCA observations

Jin+21

Large Volume Coverage

1. 13-pointing covering 25 arcmin2
2. ±7000 km/s range around z=2.16

The **largest** CO catalogue in cluster: 46 CO(1-0) detections determined

NOTES I. : advantage of employing CO(1-0)

- low T_{ext}: ~5K
- sensitive to low-surface-density molecular gas **(i.e., high-J CO emission could be much more compact than CO(1-0))**
- IN SHORT, GO TO CO(1-0) IF YOU WANT LARGE MOLECULAR GAS RESERVOIRS

NOTES II. Relatively Compact Array required

- To ensure the detection of extended low-surface-brightness emission, relatively compact array configuration needed ("missing flux issue")

Methodology: Novel Approach Developed

via Coarse and High-Resolution Observational Data Comparison

The core of the method: **morphological** and **kinematical** based sizes assessment

(**collapsed images** + **position-velocity diagram**)

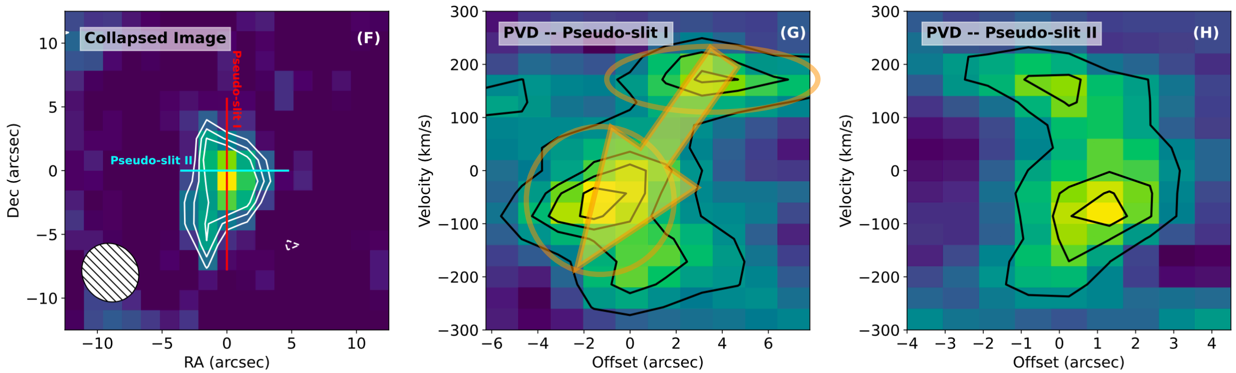
Methodology: Novel Approach Developed
via Coarse and High-Resolution Observational Data Comparison

The core of the method: morphological and kinematical based sizes assessment
(collapsed images + position-velocity diagram)

Collapsed Images | position-velocity diagram

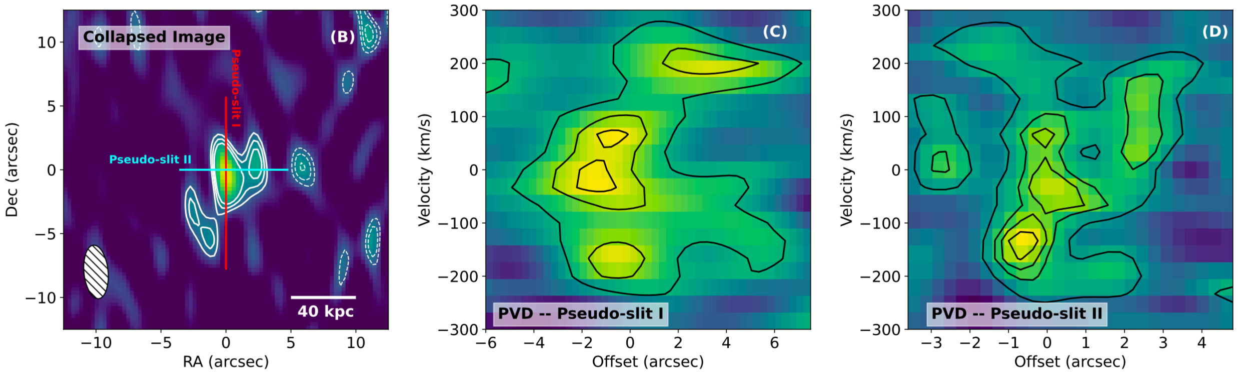
Example on DKB03

Coarse Data
(low-resolution)



To confirm our assessment - large molecular gas reservoir — follow-up observations are conducted.

High-Resolution
@ 3arcsec



Methodology: Novel Approach Developed
via Coarse and High-Resolution Observational Data Comparison

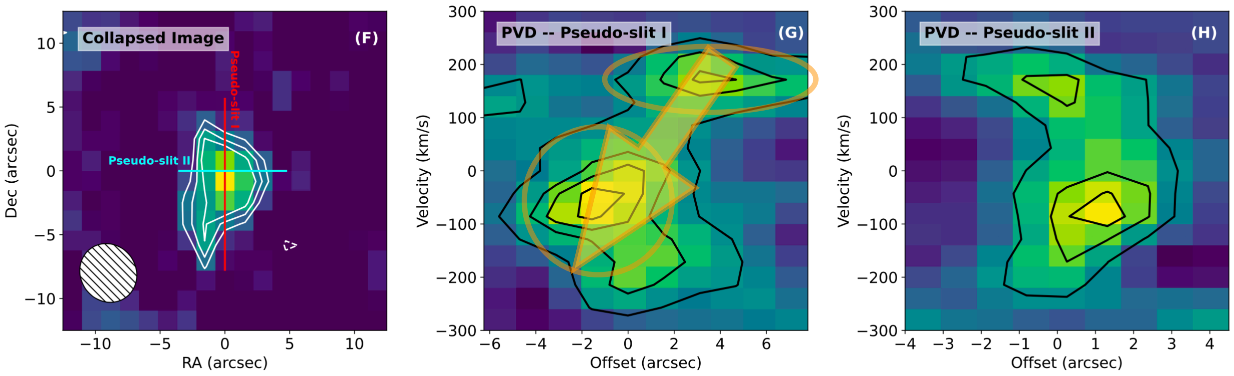
The core of the method: morphological and kinematical based sizes assessment
(collapsed images + position-velocity diagram)

Collapsed Images

position-velocity diagram

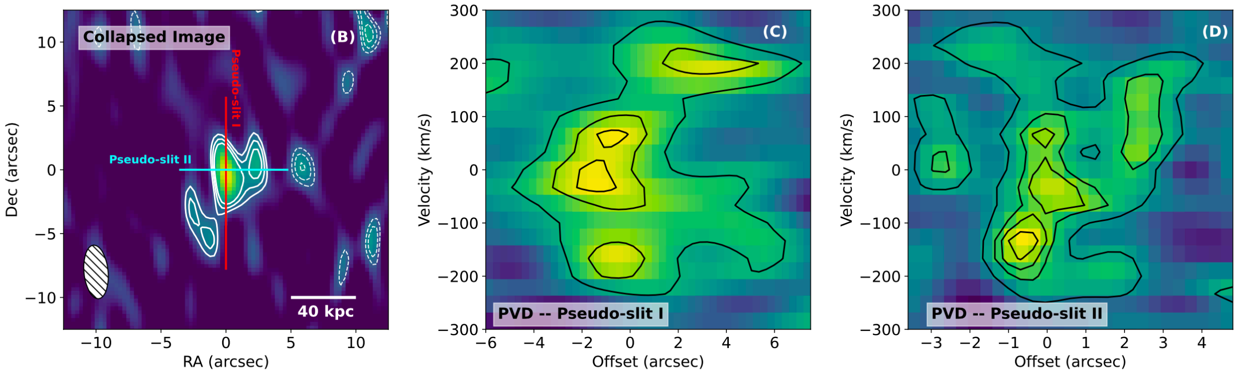
Example on DKB03

Coarse Data
(low-resolution)



To confirm our assessment - large molecular gas reservoir — follow-up observations are conducted.

High-Resolution
@ 3arcsec



Common Features:

1. large size of collapsed image;
2. multiple velocity components and velocity gradients on position-velocity diagrams
3. more details to be discussed

Coarse Data Unveils Extended Gas Features, Despite Reduced Resolution and Detail Compared to High-Resolution Data.

Unlocking Potential with Coarse Observations: Filtering Extended Gas Reservoirs, Less Time, Broader Spatial Range—Beyond Cluster Center Pointings!

Methodology: Novel Approach Developed
"Criterion Binary Ranking"

The core of the method: morphological and kinematical based sizes assessment (collapsed images + position-velocity diagram)

Binary System

A binary number with one bit: "0" or "1":

A binary number with two bits: "00", "01", "10" or "11":

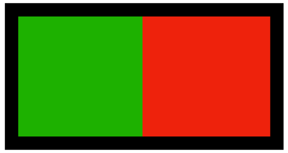
A binary number with three bits: ...

Methodology: Novel Approach Developed
“Criterion Binary Ranking”

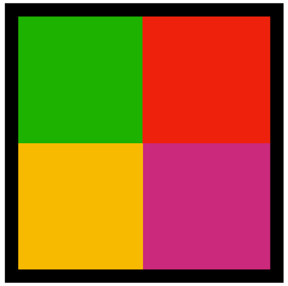
The core of the method: morphological and kinematical based sizes assessment (collapsed images + position-velocity diagram)

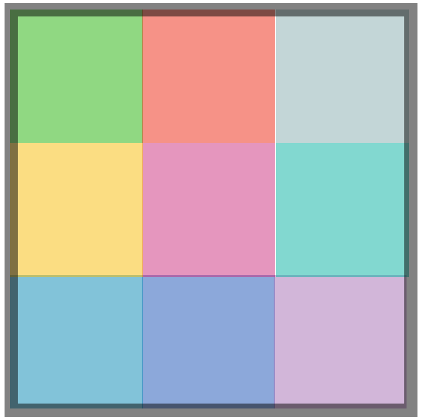
Binary System

A binary number with one bit: “0” or “1”:



A binary number with two bits: “00”, “01”, “10” or “11”:





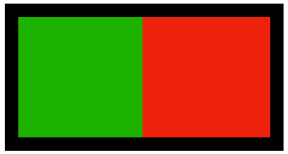
A binary number with three bits: ...

Methodology: Novel Approach Developed
"Criterion Binary Ranking"

The core of the method: morphological and kinematical based sizes assessment
(collapsed images + position-velocity diagram)

Binary System

A binary number with one bit: "0" or "1":



A binary number with two bits: "00", "01", "10" or "11":

A

- Criteria: Define the classes of "properties".
- Assign the binary value ("0"/"1"): Classify properties into classes

Methodology: Novel Approach Developed

"Criterion Binary Ranking"

The core of the method: morphological and kinematical based sizes assessment (collapsed images + position-velocity diagram)

Source Characteristics

Collapsed image size → Features in Position-Velocity Diagram → SNR →

Observational Conditions

Number of Small-Beam-Size Pointings → Fraction of Small-Beam-Size Pointings → Fraction of Small-Beam-Size Pointings

Most Important (weighted the most) → Least Important (weighted the least)

Binary Criteria Ranking Evaluation: Six Criteria Incorporating Source Characteristics and Observational Conditions (each 1-2 bits, i.e., 2-4 classes), Followed by Ranking Using Converted Decimal Values for Each CO emitters

Methodology: Novel Approach Developed

“Criterion Binary Ranking”

The core of the method: morphological and kinematical based sizes assessment (collapsed images + position-velocity diagram)

Source Characteristics

Collapsed image size → Features in Position-Velocity Diagram → SNR →

Observational Conditions

Number of Small-Beam-Size Pointings → Fraction of Small-Beam-Size Pointings → Fraction of Small-Beam-Size Pointings

Binary Criteria Ranking Evaluation: Six Criteria Incorporating Source Characteristics and Observational Conditions (each 1-2 bits, i.e., 2-4 classes), Followed by Ranking Using Converted Decimal Values for Each CO emitters

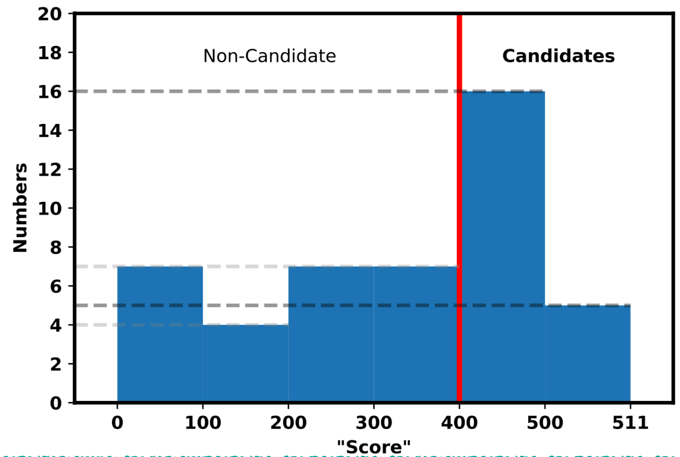
Equation: Obtaining Binary Array and Converting to Decimal Value (“Scores”)

$$[\text{Collapsed size}]\ (x_8) \oplus [\text{PVD}]\ (x_7) \oplus [\text{SNR}]\ (x_6) \oplus [\text{Number SBSP}]\ (x_5\ x_4) \oplus [\text{Fraction SBSP}]\ (x_3\ x_2) \oplus [\text{Fraction E}]\ (x_1\ x_0)$$

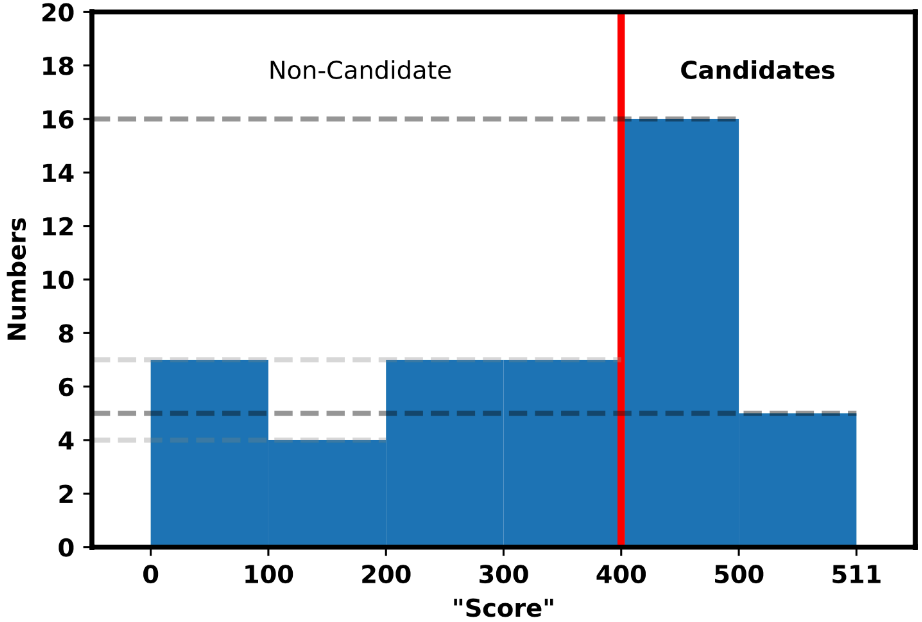
$$= x_8\ x_7\ x_6\ x_5\ x_4\ x_3\ x_2\ x_1\ x_0 \quad \text{(combine)}$$

$$\Rightarrow \sum_{i=0}^{N-1} x_i \cdot 2^i\ (N=9) \quad \text{(convert to decimal)}$$ **“Score”**

Obtain the Extended Gas Reservoir Candidates: Based on Scores



Results I. Widespread Presence of Extended Gas Reservoirs



21 Extended Gas Reservoir Candidates

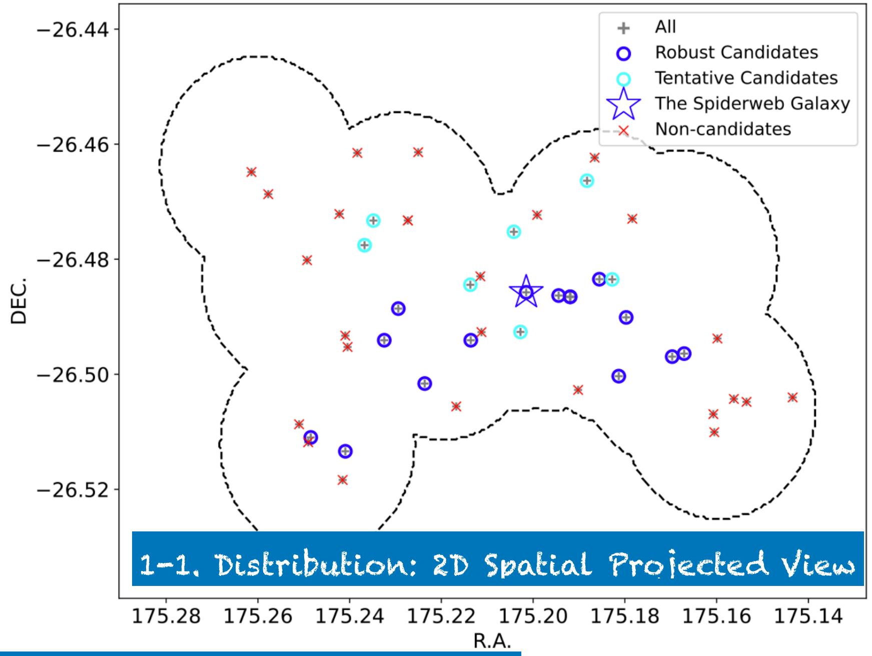
- 14 Robust Candidates
- 7 Tentative Candidates

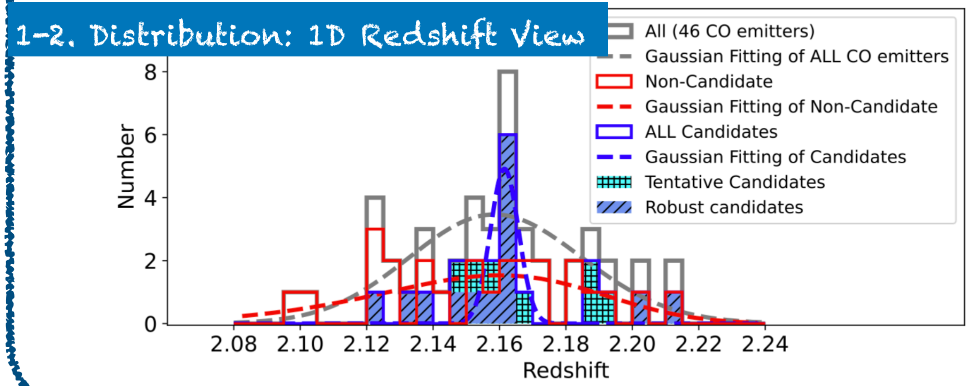
The rate of cluster members containing large gas reservoirs is ~30% (14/46), and up to ~50% (21/46) if including the tentative candidates.

Extended Molecular Gas Reservoirs: Surprisingly Prevalent, Often Overlooked in Prior Studies (Further Discussion in Later Slides)

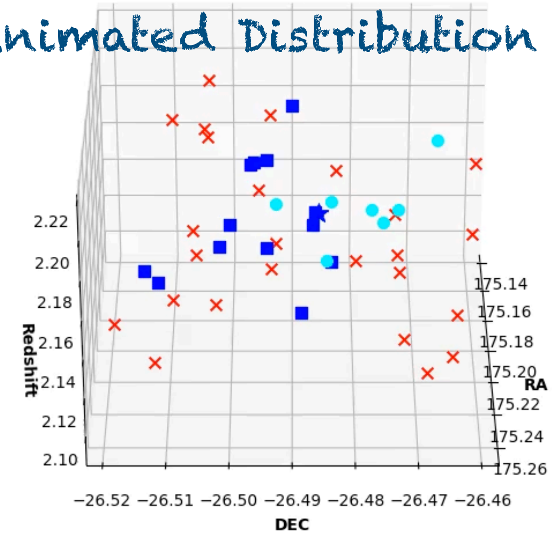
Results II. Distribution Patterns:
Extended Gas Reservoirs Show Preference for Denser Regions

1. Static Distribution View



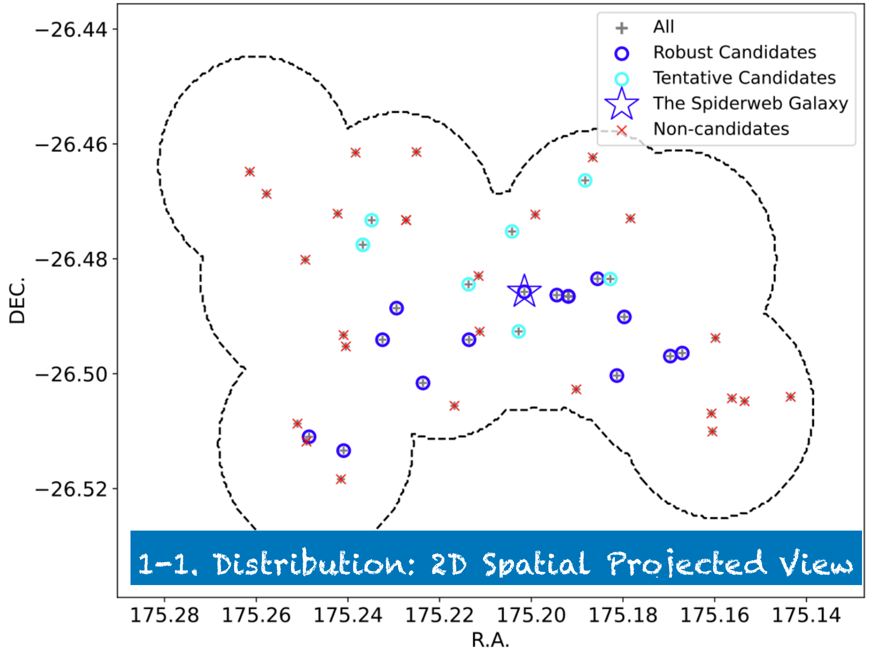


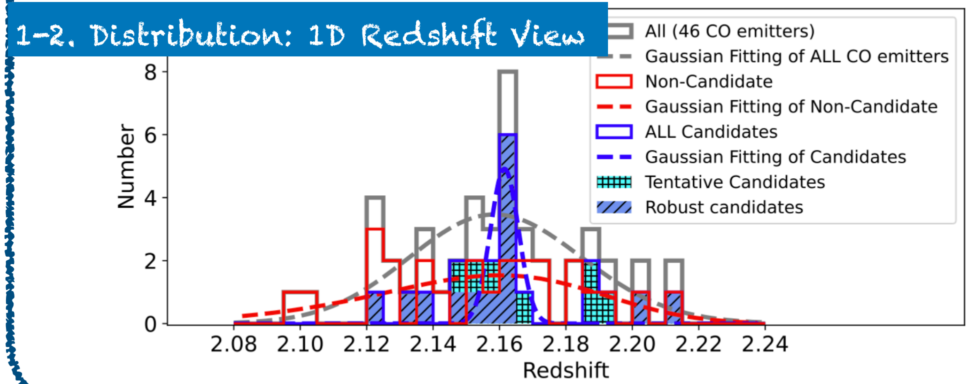
2. Animated Distribution View



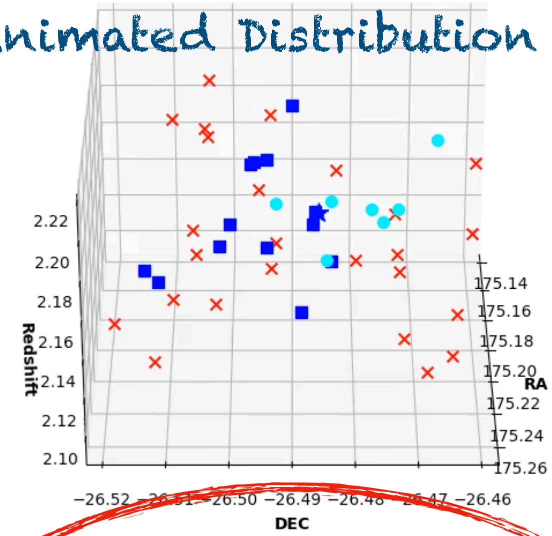
Results II. Distribution Patterns:
Extended Gas Reservoirs Show Preference for Denser Regions

1. Static Distribution View

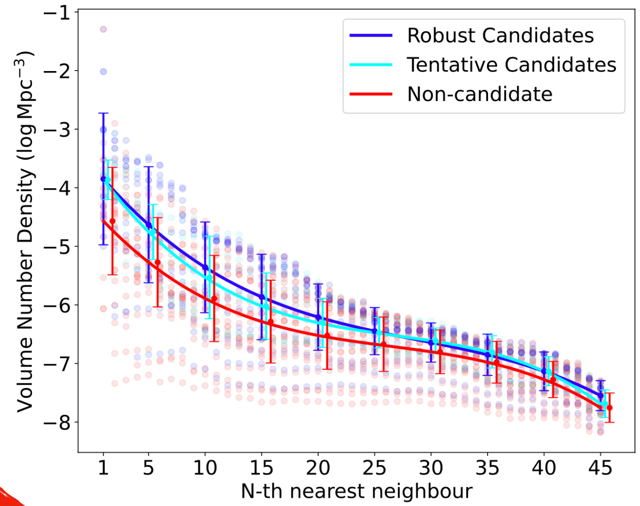




2. Animated Distribution View



3. N-th Nearest Neighbour



Discussion I. Exploring Gas Reservoir Gaps: Ground-transition of CO is Crucial

Protocluster	redshift	Source ID	Emission Lines	Size	Size Given	Reference
Jackpot nebular	2.04	galaxy1	CO(3-2)	~40 kpc	-	Decarli et al. 2021
PKS1138-262 Protocluster (Spiderweb)	2.16	Spiderweb Galaxy	CO(1-0)	~70 kpc	Yes	Emonts et al. (2013, 2014, 2016, 2018)
			CO(4-3)	~50 kpc	Yes	Emonts et al. (2018)
			[CI]	~50 kpc	Yes	Emonts et al. (2018)
		HAE229	CO(1-0)	~40 kpc	Yes	Dannerbauer et al. (2017)
Protocluster ELANe	2.22	QSO Q12287+3128	CO(4-3)	~100 kpc	Yes	Li et al. (2021b, 2023)
Slug nebular	2.28	QSO	CO(3-2)	~50 kpc	-	Decarli et al. (2021)
BOSS1441 Protocluster (MAMMOTH-I)	2.3	Region A (Q0052)	CO(1-0)	~40 kpc	-	Emonts et al. (2019)
			CO(3-2)	$\lesssim$15 kpc	-	Li et al. (2021a)
			CO(4-3)	$\lesssim$15 kpc	-	Li et al. (2023)
CLJ1001 Protocluster	2.5	131077	CO(1-0)	$\lesssim$40 kpc	Yes	Champagne et al. (2021)
			CO(3-2)	$\lesssim$10 kpc	-	Champagne et al. (2021)
			CO(1-0)	~30 kpc	-	Wang et al. (2016)
			CO(5-4)	~30 kpc	-	Wang et al. (2016)
		130933	CO(1-0)	~60 kpc	-	Wang et al. (2018)
		130842	CO(1-0)	~60 kpc	-	Wang et al. (2018)
HXMM20 Protocluster	2.6	S0	CO(1-0)	~45 kpc	-	Gómez-Guijarro et al. (2019)
			CO(3-2)	~30 kpc	-	Gómez-Guijarro et al. (2019)
		S2	CO(1-0)	~40 kpc	-	Gómez-Guijarro et al. (2019)
			CO(3-2)	~30 kpc	-	Gómez-Guijarro et al. (2019)
		S3	CO(1-0)	~40 kpc	-	Gómez-Guijarro et al. (2019)
			CO(3-2)	~30 kpc	-	Gómez-Guijarro et al. (2019)
SSA22 Protocluster	3.1	LAB1	[CII]	~50 kpc	-	Umehata et al. (2017, 2021)
			CO(4-3)	~30 kpc	-	Umehata et al. (2021)
HZ10 Protocluster	5.7	massive dusty starburst	CO(2-1)	~40 kpc	-	Pavesi et al. (2018)

14 Potential Extended Source From Literature.

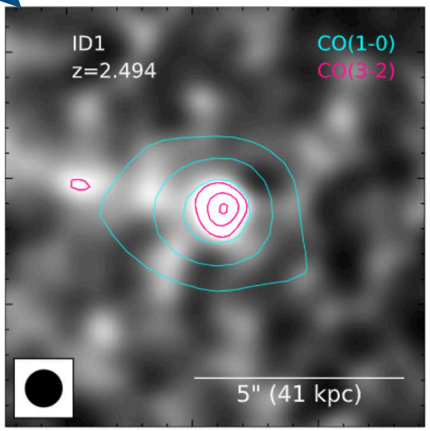
Discussion I. Exploring Gas Reservoir Gaps: Ground-transition of CO is Crucial

Protocluster	redshift	Source ID	Emission Lines	Size	Size Given	Reference
Jackpot nebular	2.04	galaxy1	CO(3-2)	~40 kpc	-	Decarli et al. 2021
PKS1138-262 Protocluster (Spiderweb)	2.16	Spiderweb Galaxy	CO(1-0)	~70 kpc	Yes	Emonts et al. (2013, 2014, 2016, 2018)
			CO(4-3)	~50 kpc	Yes	Emonts et al. (2018)
			[CI]	~50 kpc	Yes	Emonts et al. (2018)
		HAE229	CO(1-0)	~40 kpc	Yes	[illegible]
Protocluster ELANe	2.22	QSO Q12287+3128	CO(4-3)	~100 kpc	Yes	[illegible]
Slug nebular	2.28	QSO	CO(3-2)	~50 kpc	-	Decarli et al. (2021)
BOSS1441 Protocluster (MAMMOTH-I)	2.3	Region A (Q0052)	CO(1-0)	~40 kpc	-	Emonts et al. (2019)
			CO(3-2)	$\lesssim$15 kpc	-	Li et al. (2021a)
			CO(4-3)	$\lesssim$15 kpc	-	Li et al. (2023)
CLJ1001 Protocluster	2.5	131077	CO(1-0)	$\lesssim$40 kpc	Yes	Champagne et al. (2021)
			CO(3-2)	$\lesssim$10 kpc	-	Champagne et al. (2021)
			CO(1-0)	~30 kpc	-	Wang et al. (2016)
			CO(5-4)	~30 kpc	-	Wang et al. (2016)
		130933	CO(1-0)	~60 kpc	-	Wang et al. (2018)
		130842	CO(1-0)	~60 kpc	-	Wang et al. (2018)
HXMM20 Protocluster	2.6	S0	CO(1-0)	~45 kpc	-	Gómez-Guijarro et al. (2019)
			CO(3-2)	~30 kpc	-	Gómez-Guijarro et al. (2019)
		S2	CO(1-0)	~40 kpc	-	Gómez-Guijarro et al. (2019)
			CO(3-2)	~30 kpc	-	Gómez-Guijarro et al. (2019)
		S3	CO(1-0)	~40 kpc	-	Gómez-Guijarro et al. (2019)
			CO(3-2)	~30 kpc	-	Gómez-Guijarro et al. (2019)
SSA22 Protocluster	3.1	LAB1	[CII]	~50 kpc	-	Umehata et al. (2017, 2021)
			CO(4-3)	~30 kpc	-	Umehata et al. (2021)
HZ10 Protocluster	5.7	massive dusty starburst	CO(2-1)	~40 kpc	-	Pavesi et al. (2018)

Extended in CO(1-0) emission while compact for higher transitions

Example I

Example II



14 Potential Extended Source From Literature.

Previous talk by Jaclyn Champagne

Discussion II. Galaxy-CGM/IGM Interplay

Large gas reservoirs in SW protocluster may contribute to the future CGM in Virgo-like galaxy cluster

The Spiderweb Protocluster has ABUNDANT gas (also mentioned in previous talk by Jaclyn Champagne)
The following estimation focus on ONLY on Extended Gas Reservoirs

1. **Molecular gas derivation equation:** $M_{gas} = \alpha\ L'_{CO}$
   - Star-forming mode: $\alpha \equiv 4.6 \mathrm{M}_\odot \left(\mathrm{Kkms}^{-1}\mathrm{pc}^2\right)^{-1}$
   - Starburst mode: $\alpha \equiv 0.8 \mathrm{M}_\odot \left(\mathrm{Kkms}^{-1}\mathrm{pc}^2\right)^{-1}$
2. **Total (large gas reservoir) molecular gas in Spiderweb protocluster**
   - Assume pure star-forming mode: $8.7 \times 10^{13} M_\odot$ (large gas reservoirs: $\underline{2.0 \times 10^{13} M_\odot}$)
   - Assume pure starburst mode: $1.5 \times 10^{13} M_\odot$ (large gas reservoirs: $3.5 \times 10^{12} M_\odot$)
3. **ICM in Virgo galaxy cluster:** $\underline{\sim 3 \times 10^{14} M_\odot}$ (Sparke & Gallagher 2007)
4. Consider a low molecular-to-atomic ratio (~ 0.1; Saintonge+2017; Catinella+2018), and under simple star-forming mode assumption, **the large gas reservoirs in Spiderweb protocluster may be enough to contribute the CGM in a future Virgo-like galaxy cluster (e.g., through "truncation" process)**.

* "truncation" process: galaxy-galaxy encounter or gravitational interactions between galaxies and the (proto)cluster environment can result in the distortion, stripping, and truncation of galaxy halos (Moore+96,98; Fujita 98)

Discussion II. Galaxy-CGM/IGM Interplay

Unveiling the Rationale Behind Extended Gas Reservoirs: Their Origin and Maintenance?

Calculating Dynamical Time: The Timescale over Which Extended Gas Reservoirs May Persist

- Assumption: angular momentum resembles that of a rotating-like system
- Timescale: $t_{orbital} \sim 1.2$ Gyr (r/40 kpc) / (v_{orb}/200 km s^{-1})
- Explanation: The gas cannot inspire into the galaxy potential, through tidal effects due to bars or spiral arms or other disk substructures in less than a dynamical time
- Reasoning: this suggest that these extended gas reservoirs of molecular gas could be long lived if not disrupted by *external force* (e.g., ram pressure stripping, tidal stripping by passing/merging gas, etc). Furthermore, if the extended gas is stable, it can fuel the future growth of these proto-cluster galaxies for a long time, at least 1 Gyr (the star-formation in the galaxies won't stop even if the gas accretion has ceased).

Calculating Dynamical Time for "External Force": crossing/infall time time of galaxies

- Timescale: $t_{crossing} \sim 1$ Gyr (r/Mpc)/(v_{infall}/1000 km s^{-1})

Comparable Timescales (order-of-magnitude).

A Paradox? Are Extended Gas Reservoirs Unexpected?

An open question need to be solved with further observations...

Discussion II. Galaxy-CGM/IGM Interplay

Unveiling the Rationale Behind Extended Gas Reservoirs: Their Origin and Maintenance?

Calculating Dynamical Time: The Timescale over Which Extended Gas Reservoirs May Persist

- Assumption: angular momentum resembles that of a rotating-like system
- Timescale: $t_{orbital} \sim 1.2$ Gyr (r/40 kpc) / (v_{orb}/200 km s^{-1})
- Explanation: The gas cannot inspire into the galaxy potential, through tidal effects due to bars or spiral arms or other disk substructures in less than a dynamical time
- Reasoning: this suggest that these extended gas reservoirs of molecular gas could be long lived if not disrupted by *external force* (e.g., ram pressure stripping, tidal stripping by passing/merging gas, etc). Furthermore, if the extended gas is stable, it can fuel the future growth of these proto-cluster galaxies for a long time, at least 1 Gyr (the star-formation in the galaxies won't stop even if the gas accretion has ceased).

Calculating Dynamical Time for "External Force": crossing/infall time time of galaxies

- Timescale: $t_{crossing} \sim 1$ Gyr (r/Mpc)/(v_{infall}/1000 km s^{-1})

If consider that those sources without extended gas reservoirs were stripped of their material, they may have contributed to the gas in the ICM — Supported by Metal-Rich ICM in Nearby Clusters.

The Scenario: Continuous Material Exchange with Surrounding Large Molecular Gas Reservoirs — Fuelled by Outflows from Young Massive Stars, Type Ia SNe, and AGN via Radiation Pressure and Radio Jets.

Ongoing Follow-up Observations

- **ATCA C3465 Project (PI: Z. Chen)**
  - To validate the extended gas reservoir selection using high-resolution data.
  - 180 hrs observations finished.

Higher resolution but ensure the extended low-surface-brightness emission detected (relatively compact configuration required; the "missing flux issue")

- **ALMA 2023.1.00229.S Project (PI: Z. Chen)**
  - Utilising higher-transition carbon monoxide (CO) observations for the characterisation of gas properties.
  - Approved.

Summary

Method Develop: Criteria Binary Ranking

- Guided by Comparing Coarse and High-Resolution Data, We've Crafted a Binary Ranking System. It Considers Source Characteristics and Observational Conditions, Efficiently Filtering Out Extended Molecular Gas Reservoir Candidates from Coarse Data.

Filtered Out Extended Molecular Gas Reservoir Candidates in the Spiderweb Protocluster

- 14 Robust Candidates + 7 Tentative Candidates.
- The Extended Gas Reservoir is a Prevalent Phenomenon: 30% (50% count in Tentative Candidates).
- Extended Gas Reservoirs Show Preference for Denser Regions.

Previous Studies Might Have Overlooked Potential Large Gas Reservoirs

- Focused Observations: Limited to Central Region of (Proto)clusters;
- Without Ground Transition CO(1-0) Exploration.

Galaxy-IGM/ICM Interplay: The Galaxies has Ongoing Material Exchange with Surrounding Large Molecular Gas Reservoirs Leads to Metal-Enriched Mediums in Local Clusters.

- Further Studies needed.

Take Home Messages

1. Ubiquitous Extended Molecular Gas Reservoirs in (proto)cluster Environments, Preferring Denser Regions.

2. Beyond the Core Regions: Outskirts of (Proto)clusters Deserve Attention Too. Coarse Observations Offer Efficient Coverage for Broader Spatial Areas.

3. Exploring Extended Molecular Gas via CO(1-0) Emission.