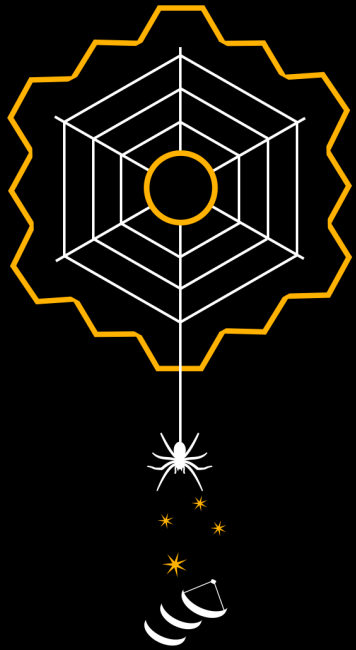




# *Extended Molecular Gas in Protoclusters: A Science Case for AtLAST*



*Helmut Dannerbauer  
Instituto de Astrofísica de Canarias*



MINISTERIO  
DE CIENCIA, INNOVACIÓN  
Y UNIVERSIDADES



AGENCIA  
ESTATAL DE  
INVESTIGACIÓN

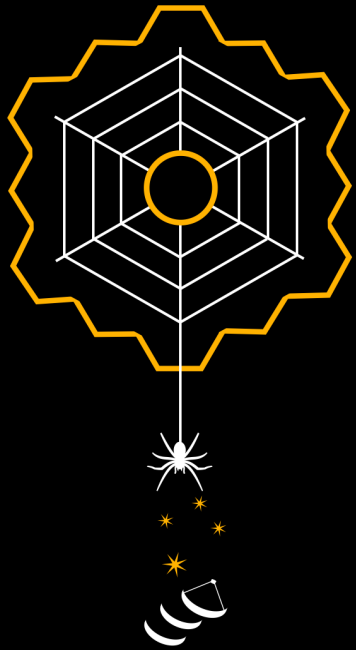


Unión Europea

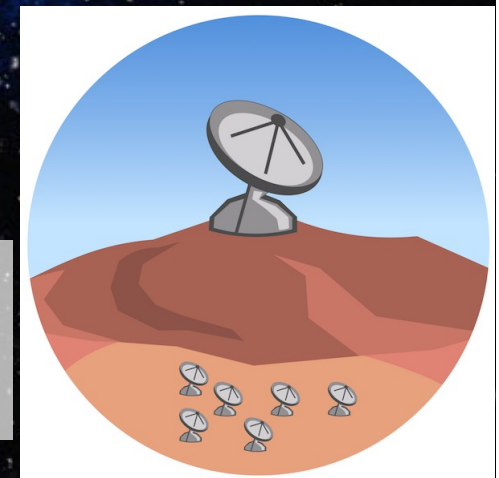
Fondo Europeo  
de desarrollo Regional  
"Una manera de hacer Europa"



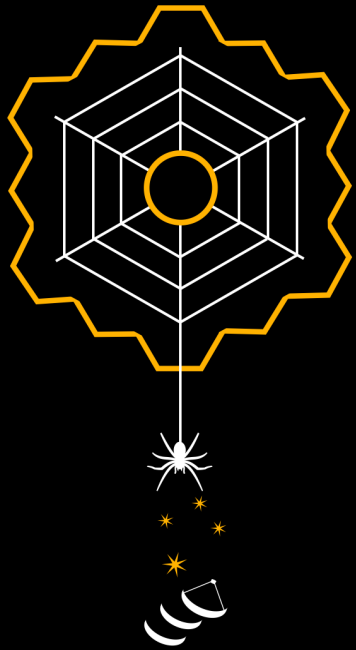
# *Extended Molecular Gas in Protoclusters: A Science Case for AtLAST*



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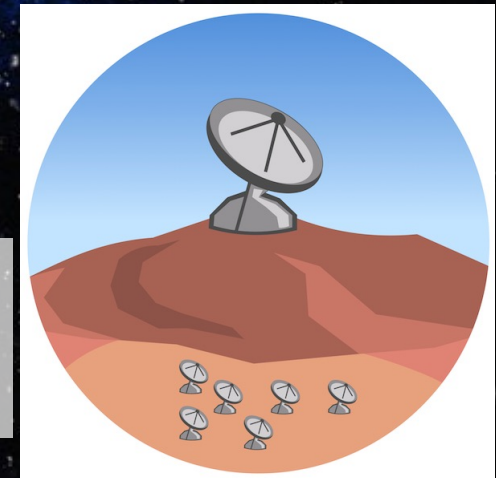


# *Extended Molecular Gas in Protoclusters: A Science Case for AtLAST*



**Science case white paper CGM:  
Lee + AtLAST coll., 2024, ORE,  
arXiv: 2403.00924**

**WG1-2 Charting the gas flows  
around early galaxies with AtLAST  
(Lagos & Pensabene)**



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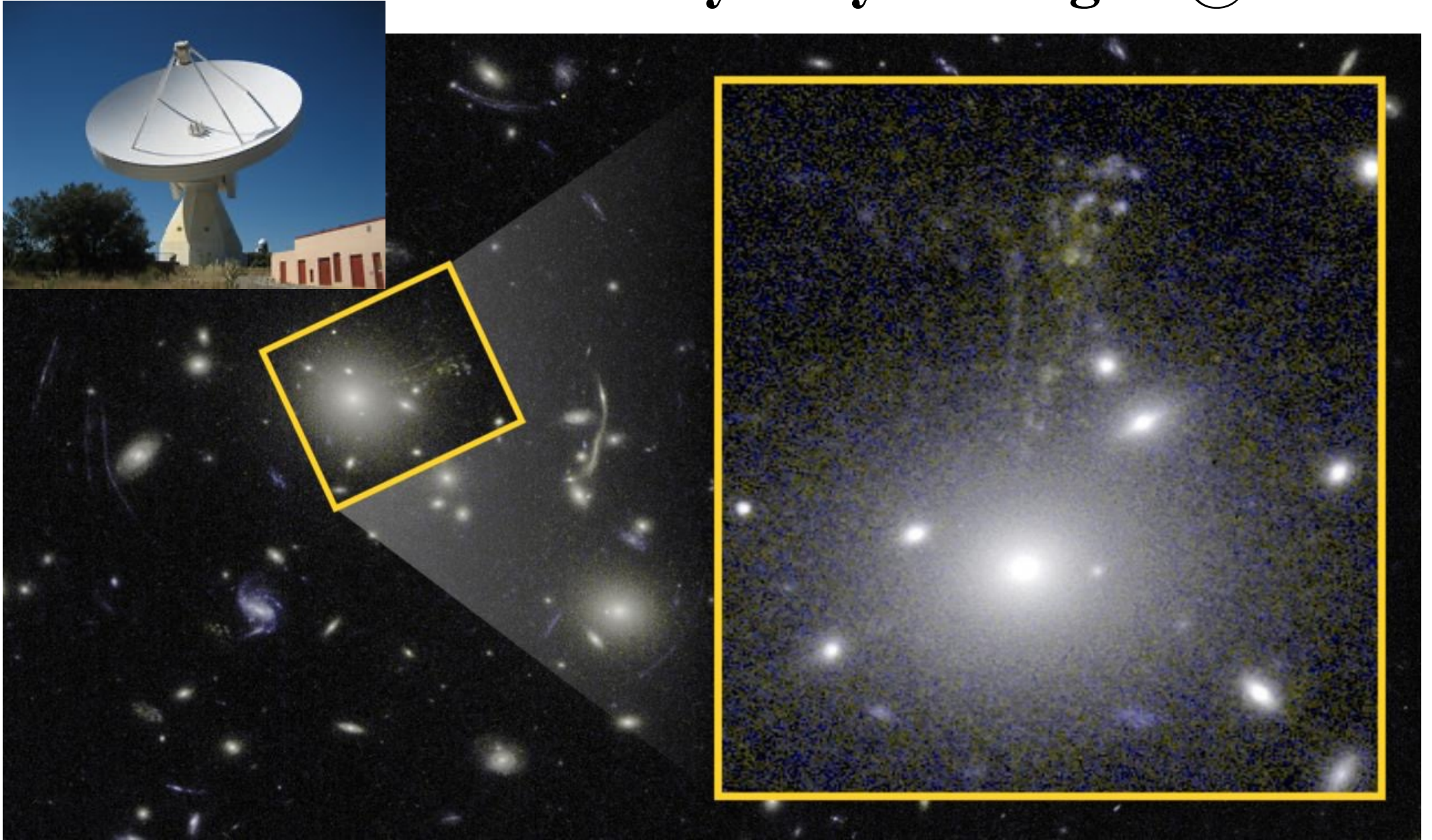
AGENCIA  
ESTATAL DE  
INVESTIGACIÓN



Unión Europea

Fondo Europeo  
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"Una manera de hacer Europa"

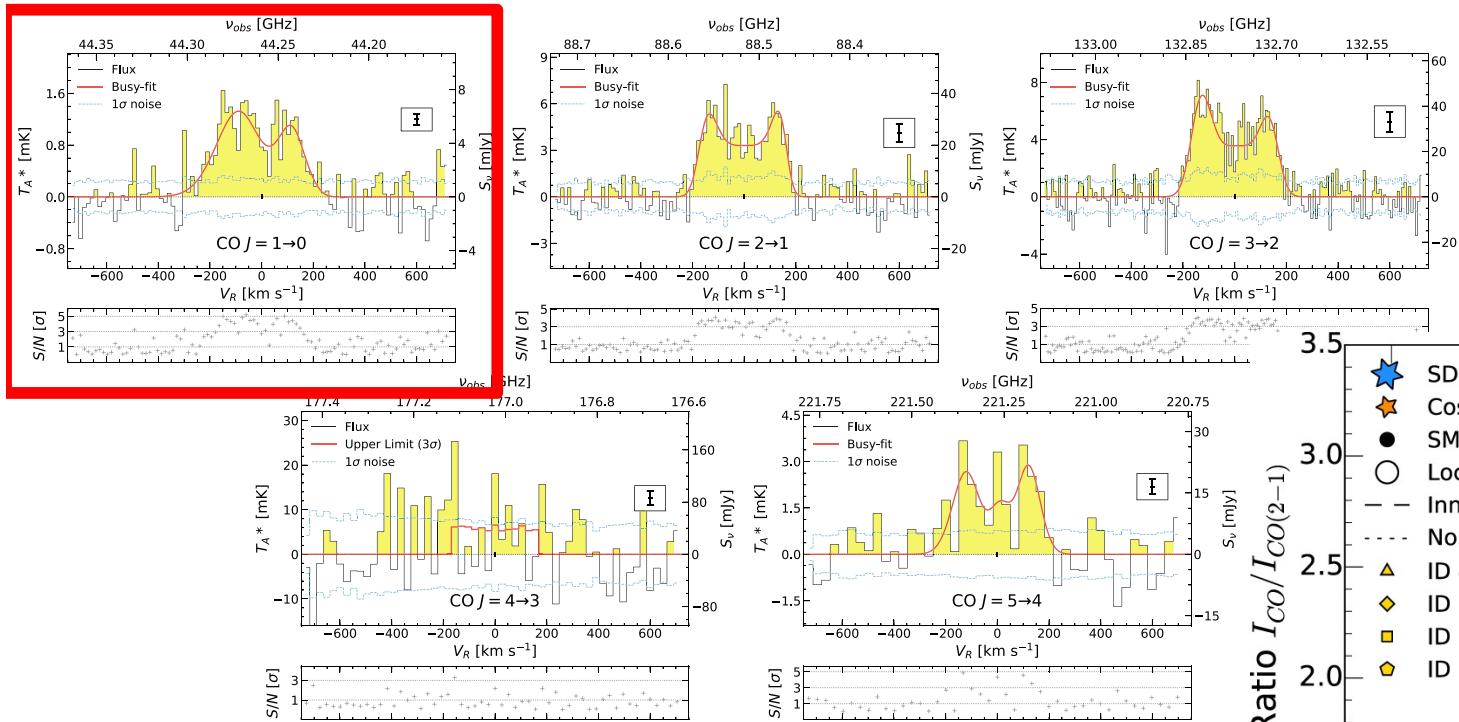
# Cosmic Seahorse – Milky Way Analogue @ $z=1.6$



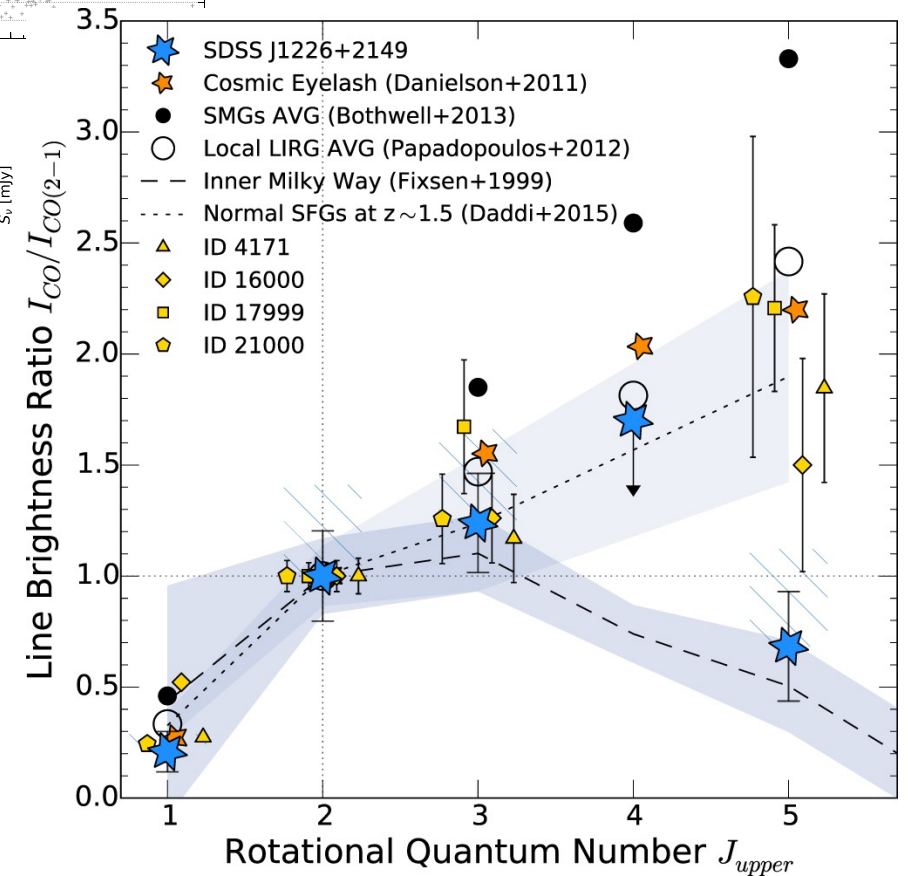
Sulzenauer, Dannerbauer et al. 2021

# Cosmic Seahorse – Milky Way Analogue @ $z=1.6$

37.2hrs on-source



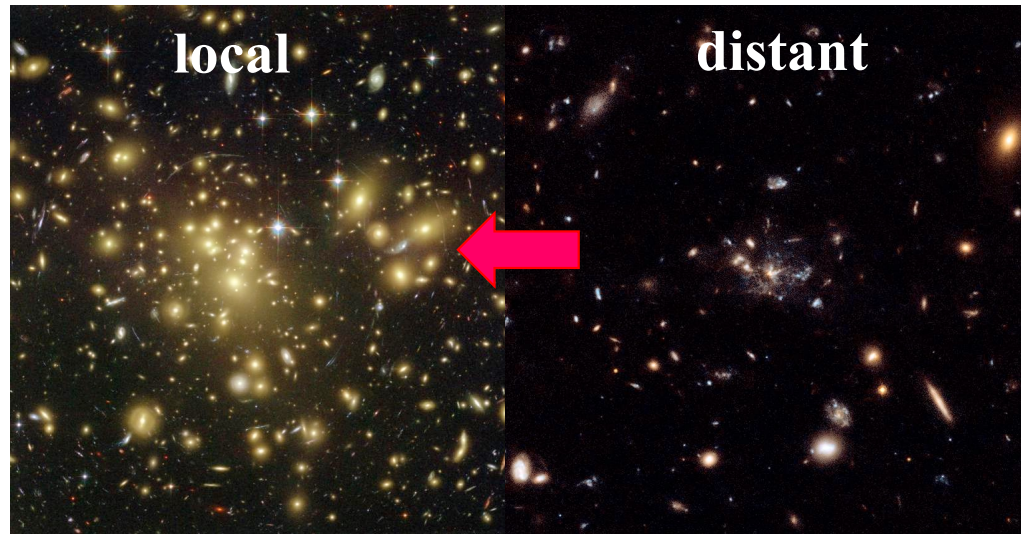
- Cold gas excitation is very low in SDSSJ1226. High density, high temperature component typical for high-redshift normal SF galaxies (Daddi+2015) seems to be missing.
- First ever detection of ultra-bright Milky Way-like gas excitation at high-redshift!



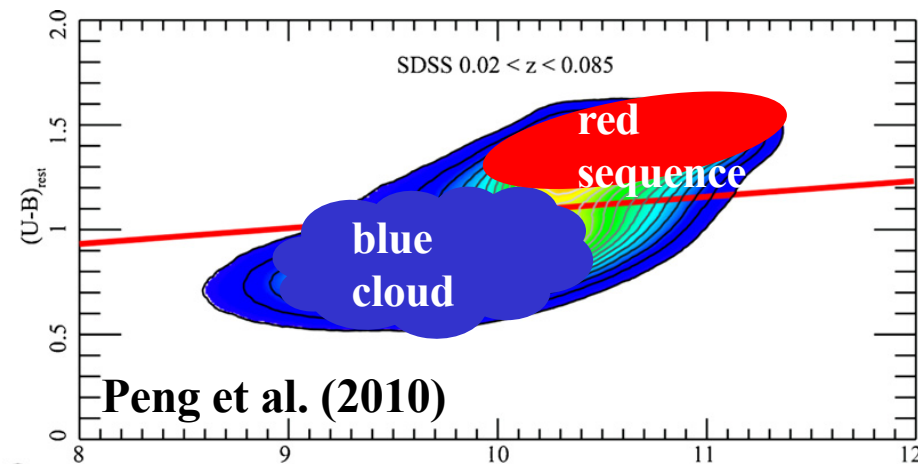
CO Spectral Line Energy Distribution

# Main Scientific Questions

- assembly, formation and evolution of the progenitors of local galaxy clusters and its galaxy members



- formation of red sequence galaxies (in clusters)



# Galaxy Protoclusters

**not yet an official definition, isn't it?!**

**see also José's  
and Itziar's  
talks tomorrow 😊**

## Popular Science

„Clusters of galaxies have back-stories worthy of a Hollywood blockbuster: their existences are marked by violence, death and birth, arising after extragalactic pile-ups where groups of galaxies crashed into each other“

*by N. Seymour in on-line journal*

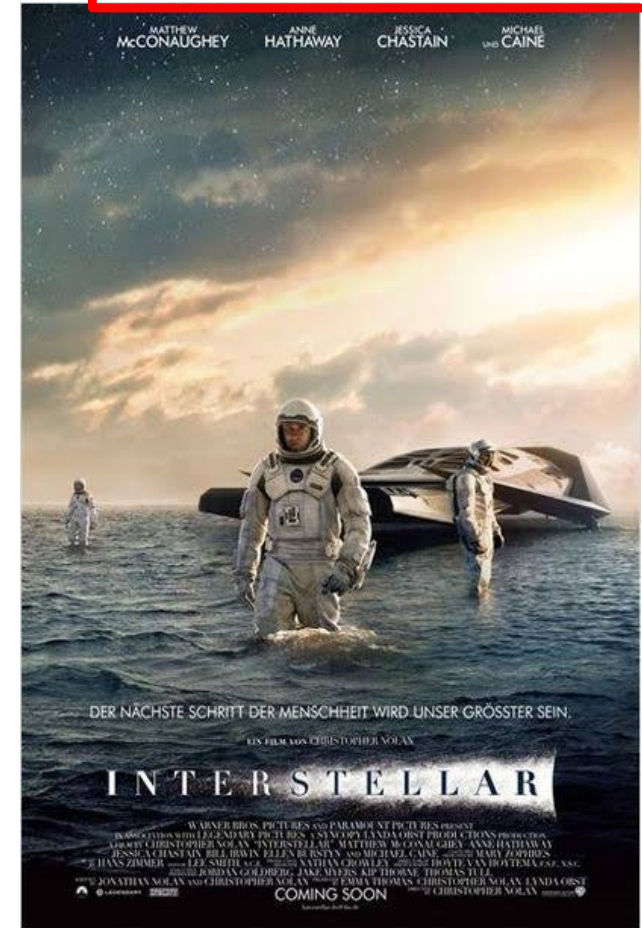
*„The Conversation“*

## Scientific Definition

“a non-virialized structure in the distant universe which will finally collapse into a typical local galaxy cluster, a virialized system of a mass larger than  $10^{14} M_{\text{sun}}$ ”

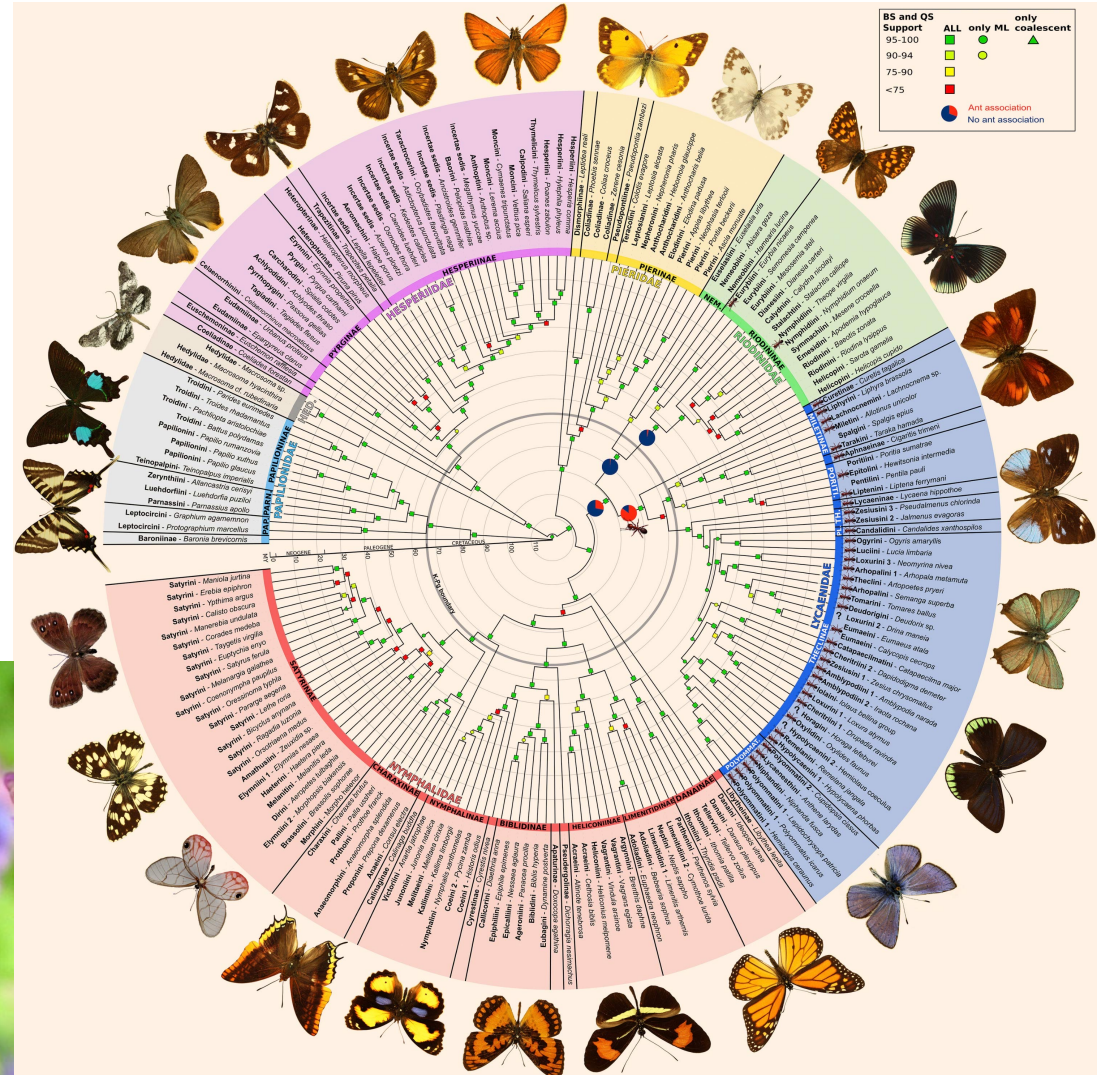
R. Overzier, 2016, A&ARv, 24, 14

*popular one, widely accepted 😊*



# increase sample sizes: cluster AND their members

Espeland+2018, Current Biology



#

from butterfly collecting...



galaxy members

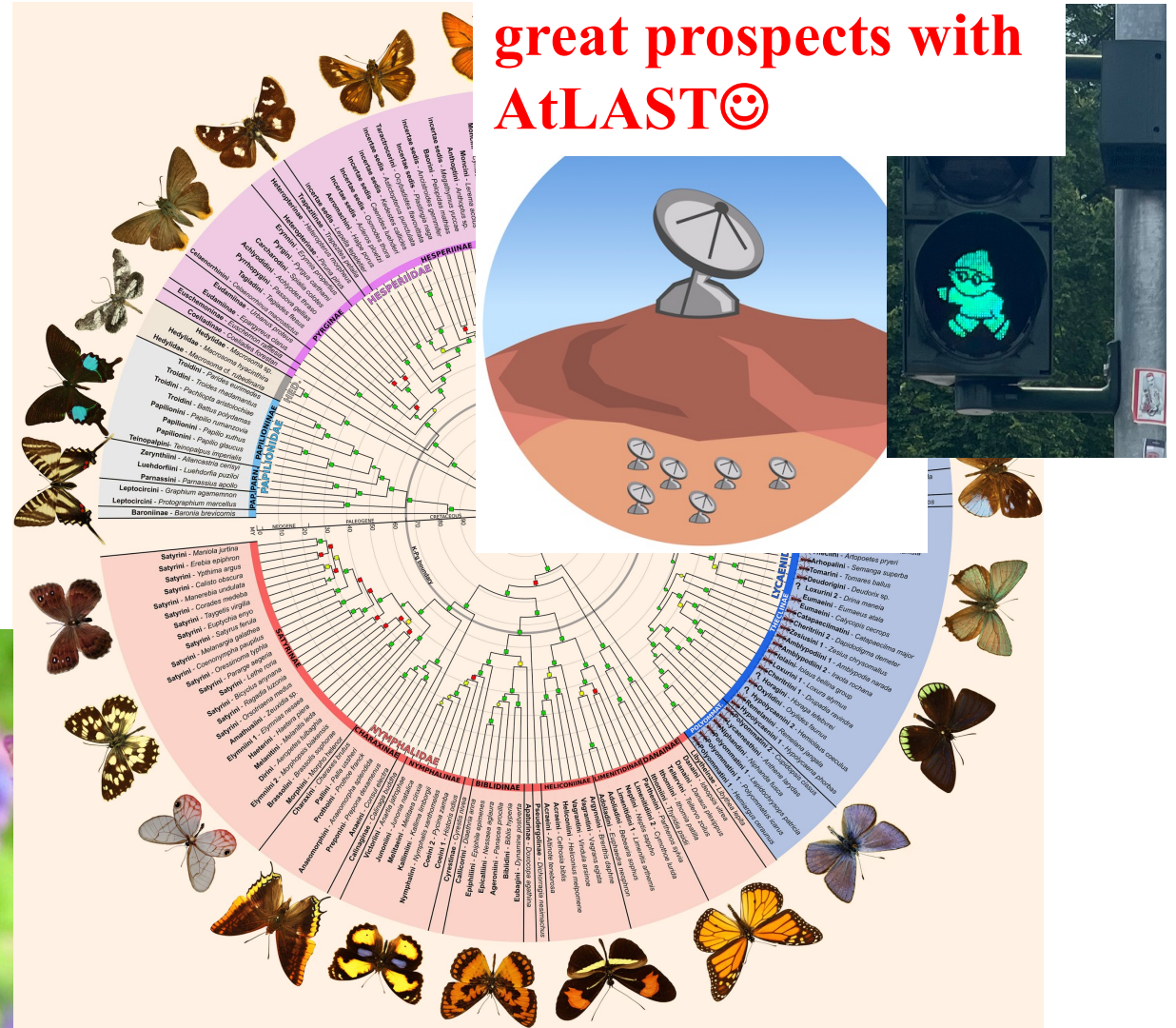
.....to evolutionary biology

(proto)galaxy cluster at high-z# *adapted (inspired) from (by) Roderik Overzier*

# increase sample sizes: cluster AND their members

Espeland+2018, Current Biology

great prospects with  
**AtLAST** 😊



#

from butterfly collecting...



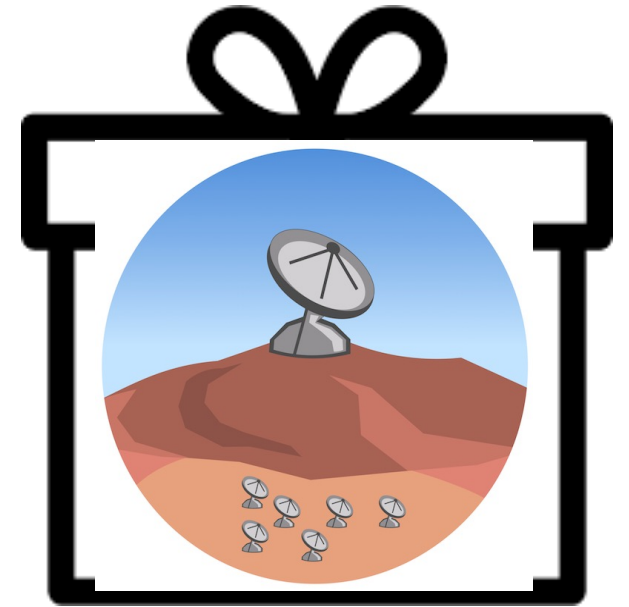
galaxy members

.....to evolutionary biology

(proto)galaxy cluster at high-z# *adapted (inspired) from (by) Roderik Overzier*

# Helmut's Wish List

- large field of view  $> \text{deg}^2$
- multi-object spectroscopy (crowded field)
- (sub)mm IFU
- simultaneous multi-band continuum imaging
- sensitive to low-surface brightness emission
- Sunyaev-Zeldovich effect detection beyond  $z=2$



Funded by  
the European Union

# *HzRG: MRC1138-262 alias Spiderweb Galaxy*

*→ will evolve into a Brightest Cluster Galaxy*

*Carilli et al 1997*

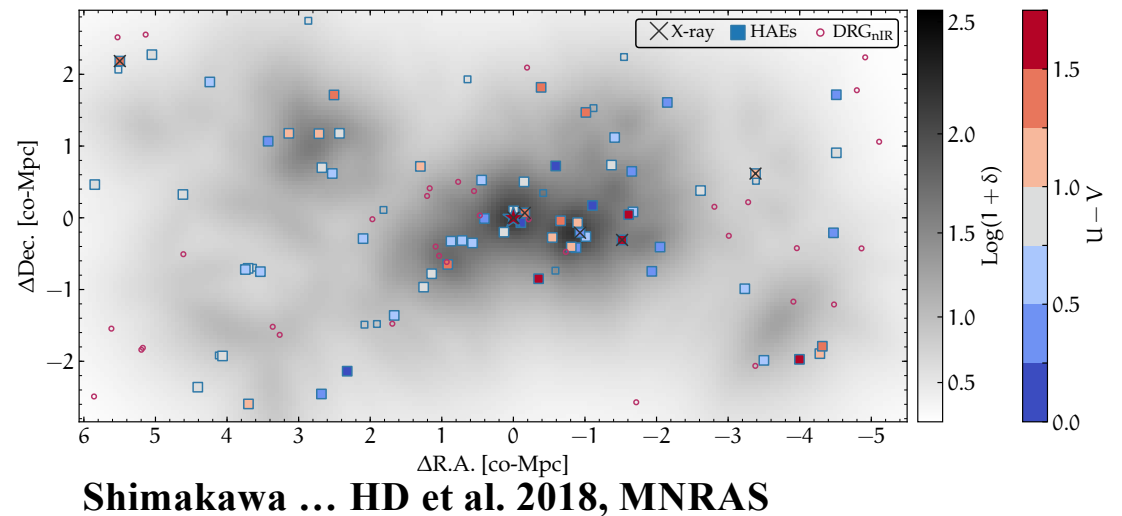
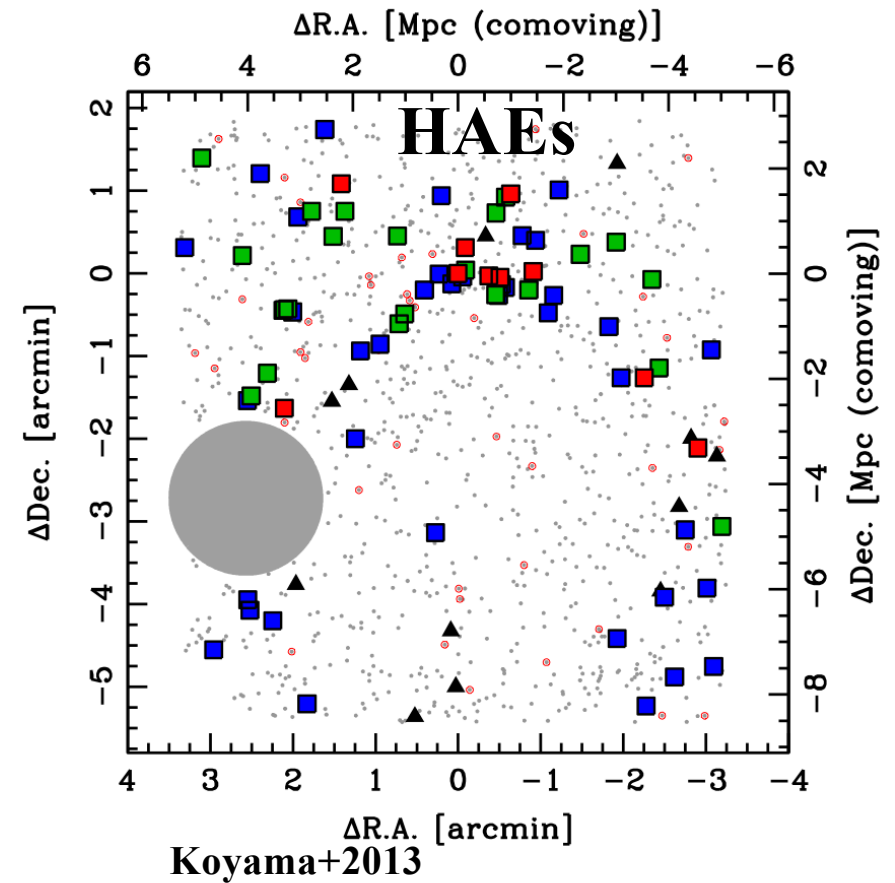
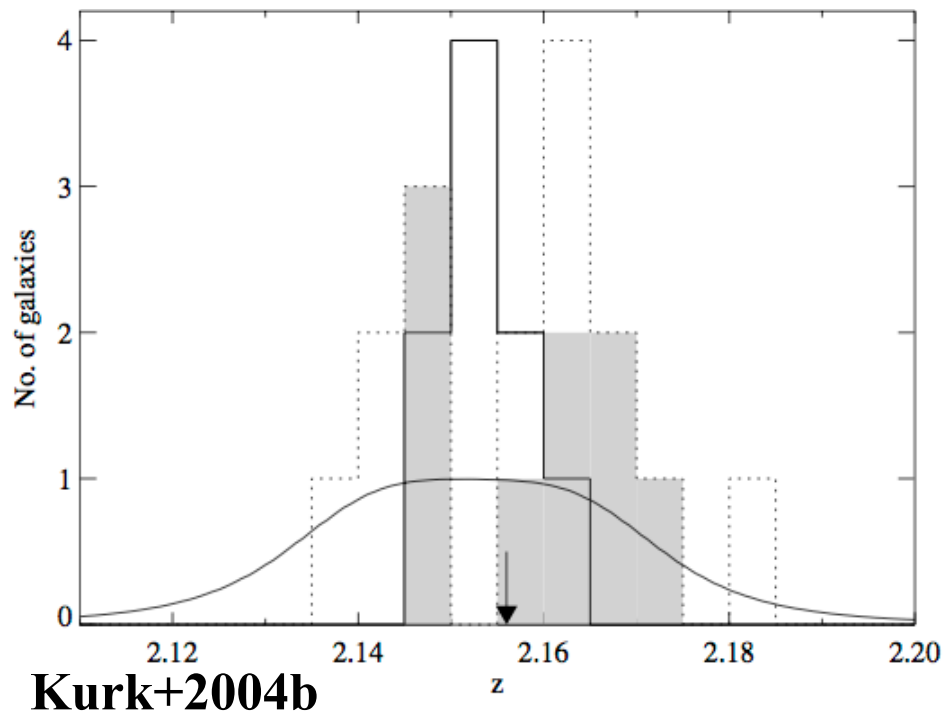
25 kpc

---

$z = 2.16$   
(23% of age Universe)

**Miley et al. 2006** (Credits: NASA, ESA, George Miley and Roderik Overzier (Leiden Observatory, NL))

# Protocluster MRC1138 @ $z=2.16$





# Astronomers witness the birth of a very distant cluster of galaxies from the early Universe

29 March 2023



Di Mascolo, Saro..a.o. HD.. et al. 2023, Nature

ESO PR: „Finding a large reservoir of hot gas in the Spiderweb protocluster would indicate that the system is **on its way to becoming a proper, long-lasting galaxy cluster** rather than dispersing.“

# The Spiderweb protocluster @ $z=2.16$

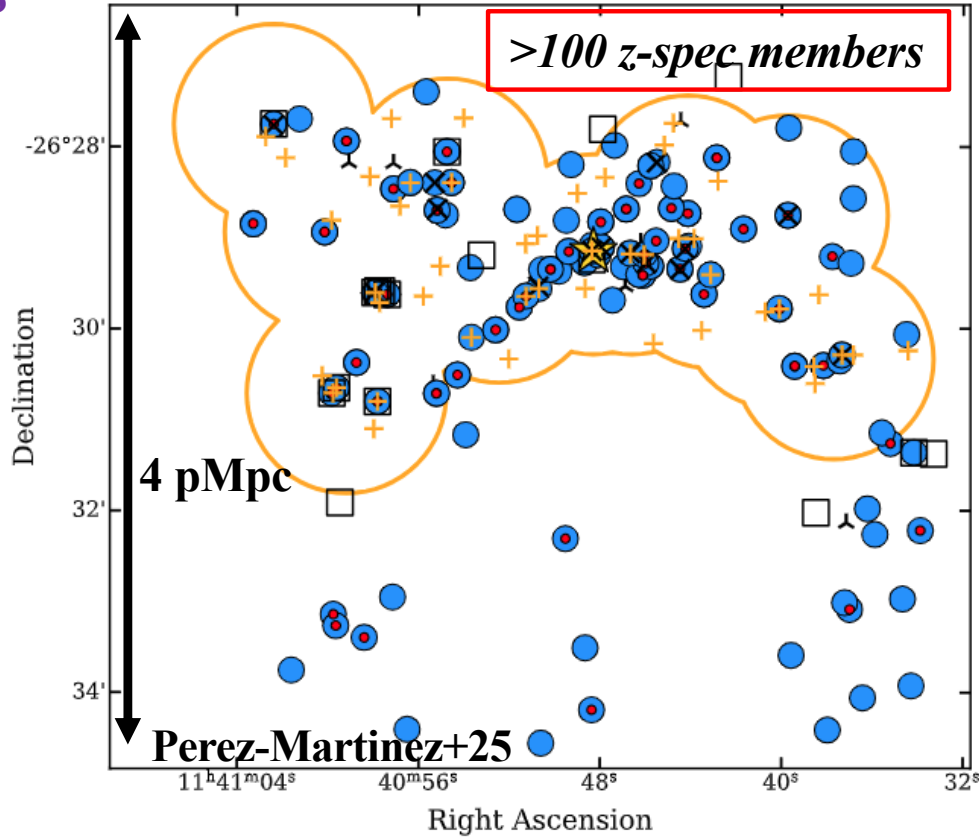
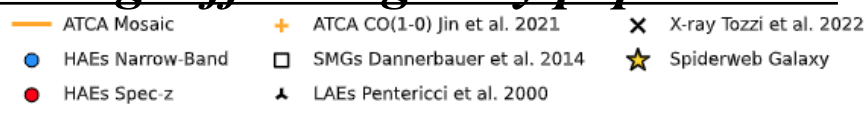
*revealing different galaxy populations*

Spiderweb Radio Galaxy  
 Van Ojik+95, Pentericci+98  
 Miley+06, Emonts+16,+18  
 Anderson+22

Ly $\alpha$  Emitters  
 Kurk+00, Pentericci+00

Red Sequence  
 Kurk+04, Kodama+07  
 Zirm+08, Tanaka+13  
 Naufal+24  
 D'Eugenio+ *subm.*

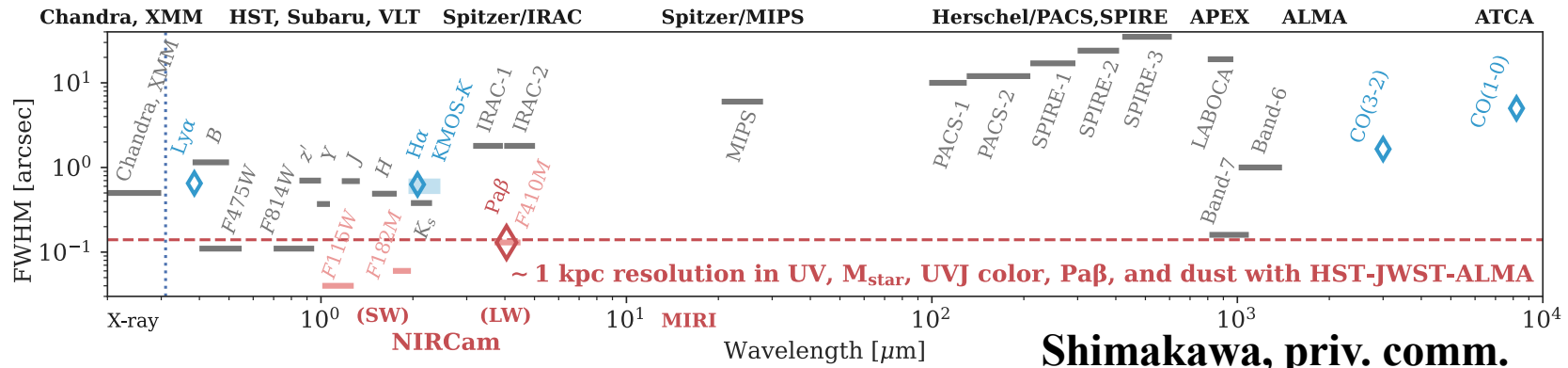
Dusty/SMG  
 Rigby+14  
 Dannerbauer+14  
 Zeballos+18  
 Zhang+24, 26



H $\alpha$  Emitters (PCL-backbone)  
 Kurk+04ab, Koyama+13  
 Shimakawa+18,+24ab,  
 Perez-Martinez+23,+24  
 Daikuhara+24

Molecular Gas  
 Dannerbauer+17  
 Emonts+18, Tadaki+19,  
 Jin+21, Chen+24,  
 Perez-Martinez+25

X-ray  
 Tozzi+22ab, Carilli+23  
 Lepore+24  
SZ-effect  
 Di Mascolo+23

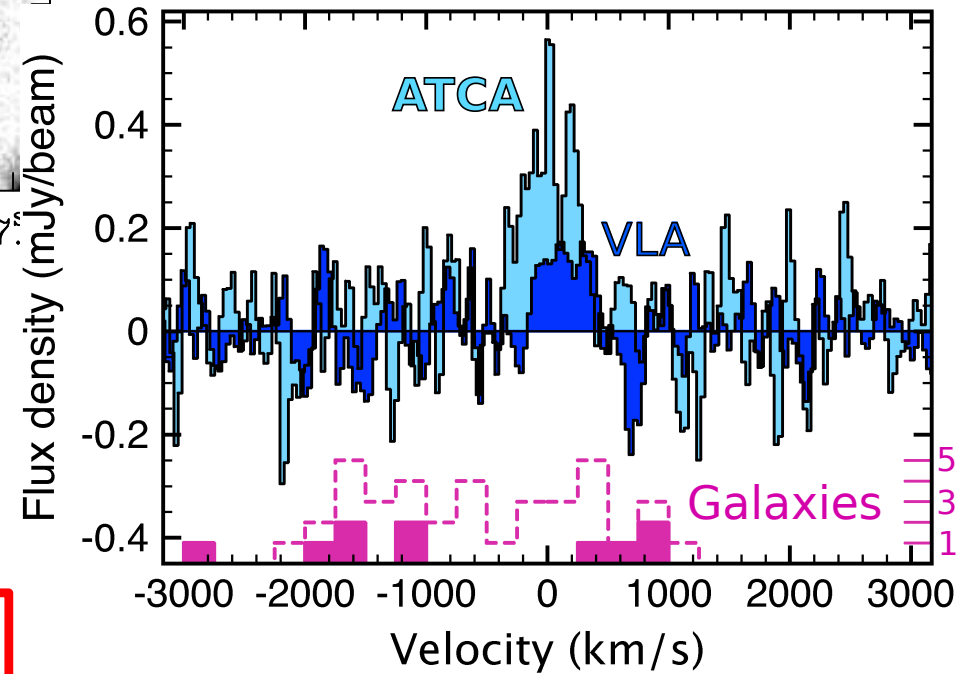
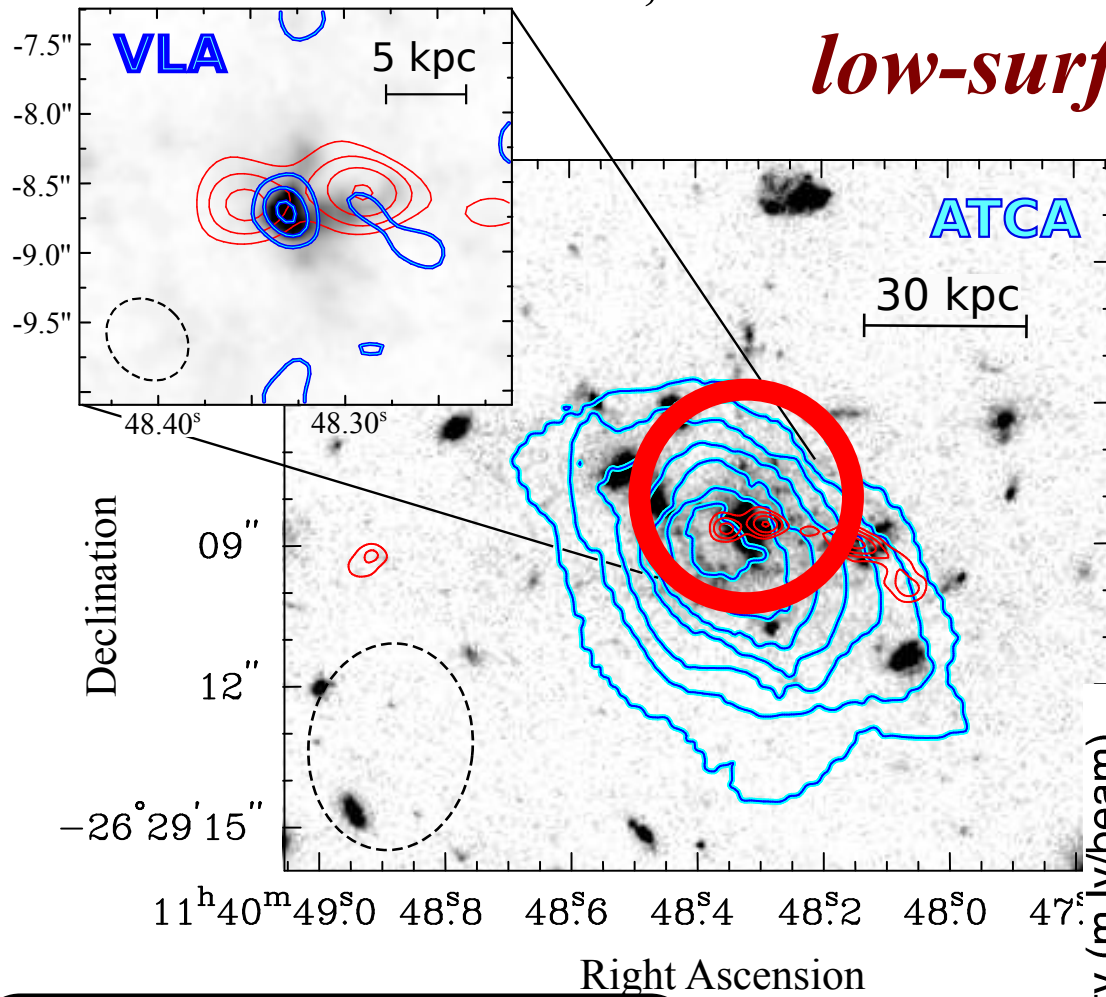


Shimakawa, priv. comm.

# Spiderweb Galaxy: Cold Molecular IGM

Emons ... HD et al. 2016, Science

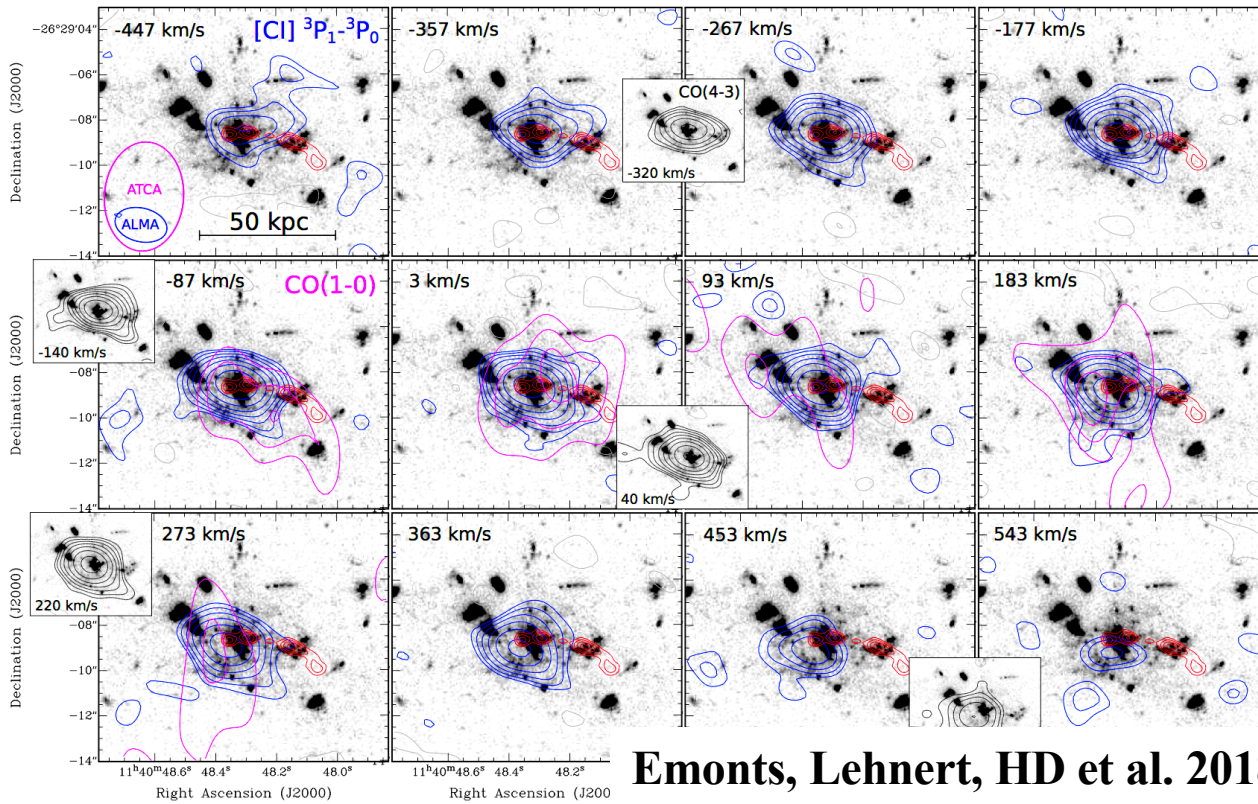
*low-surface-brightness emission!*



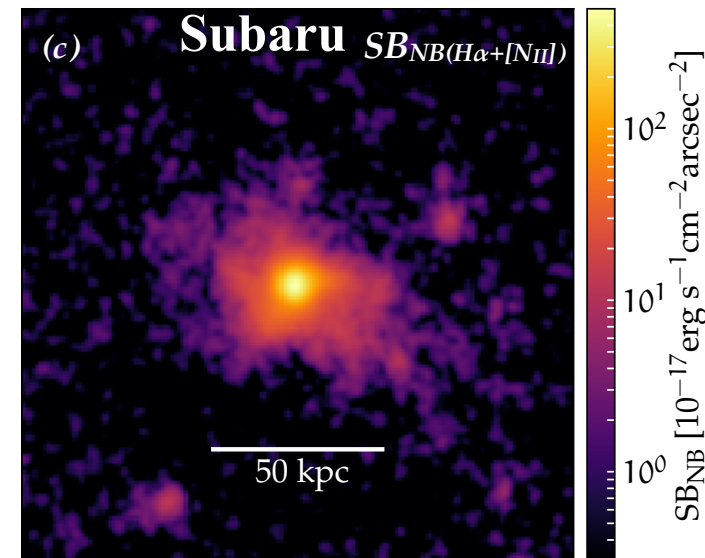
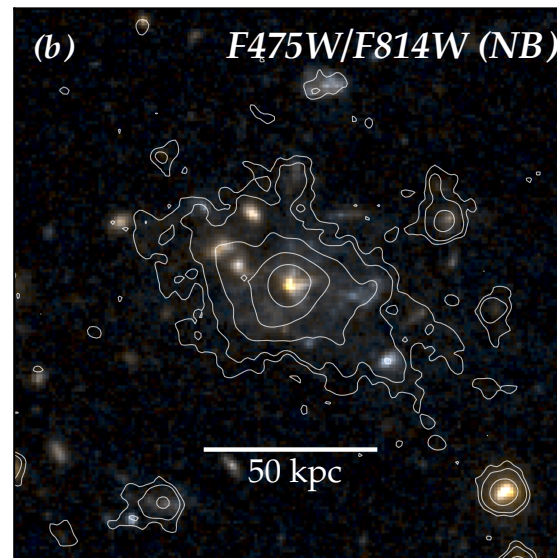
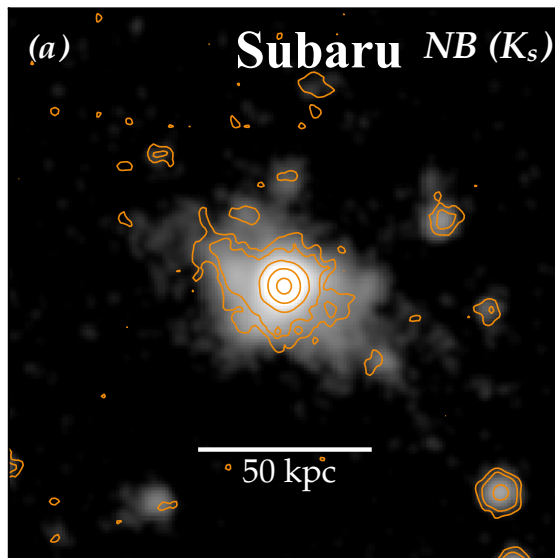
*VLA sees only  
~33% of ATCA flux!!*

**WG1-15 Missing Flux (Andreani)**

# Extended Cold IGM in the Spiderweb Galaxy



Emonts, Lehnert, HD et al. 2018, MNRAS, 477, 60

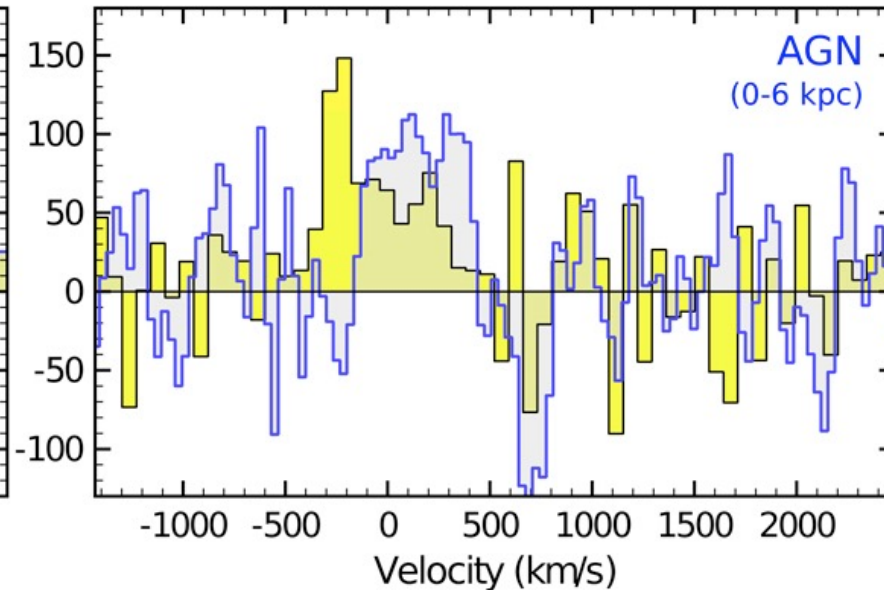
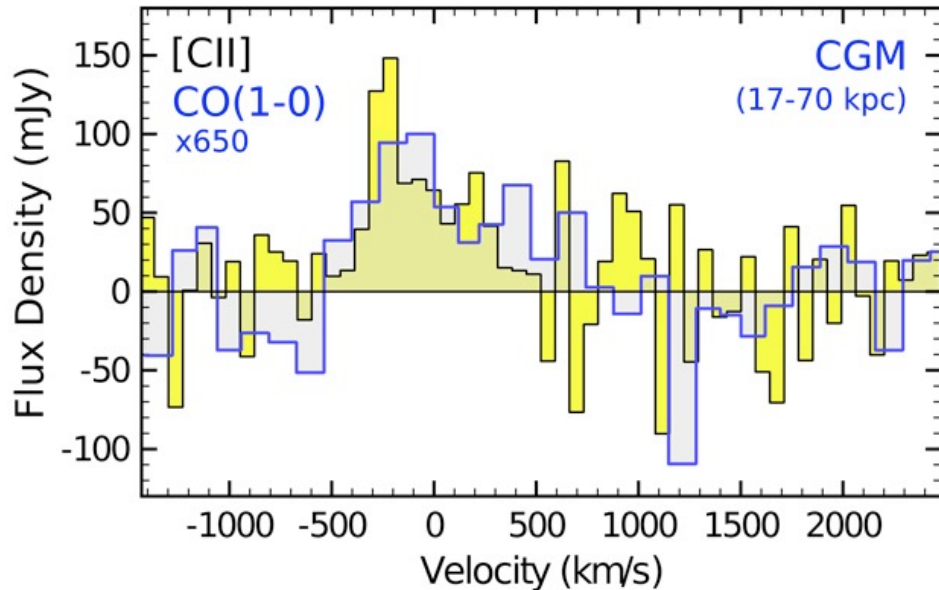
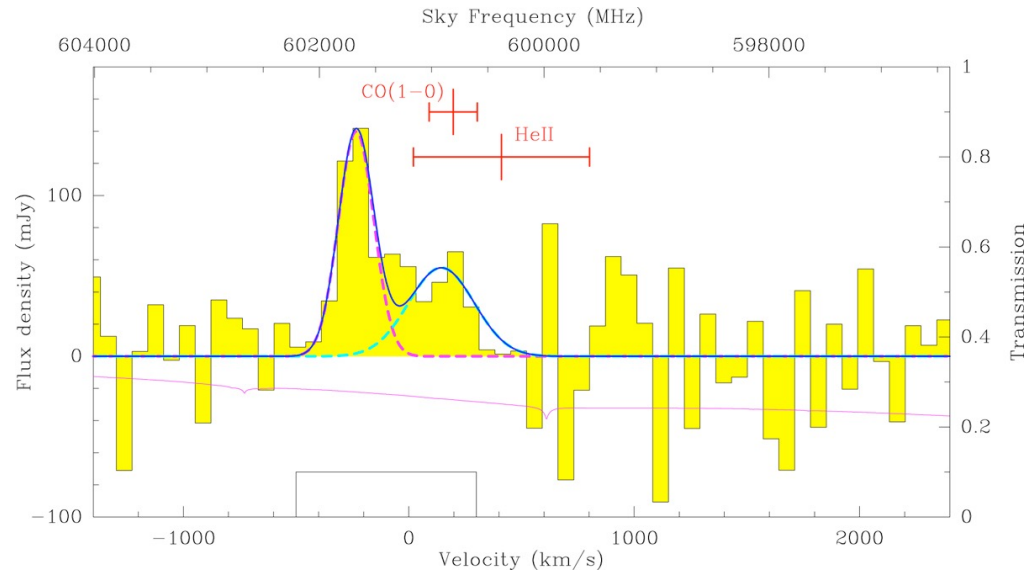


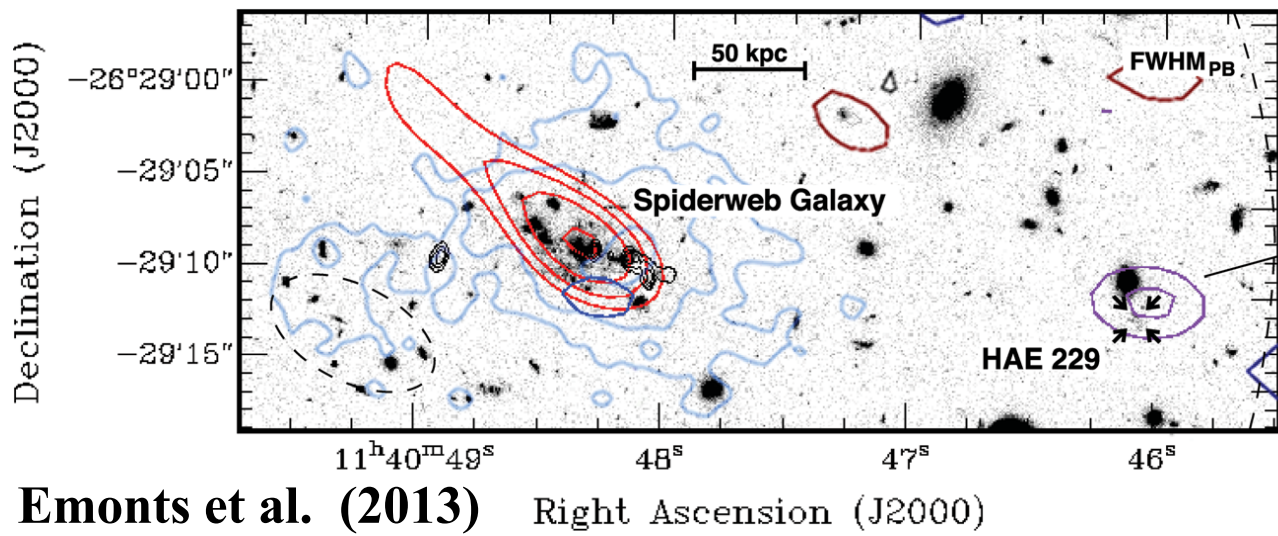
Shimakawa ... HD et al. 2018, MNRAS, 481, 5630

# [CII] is extended too

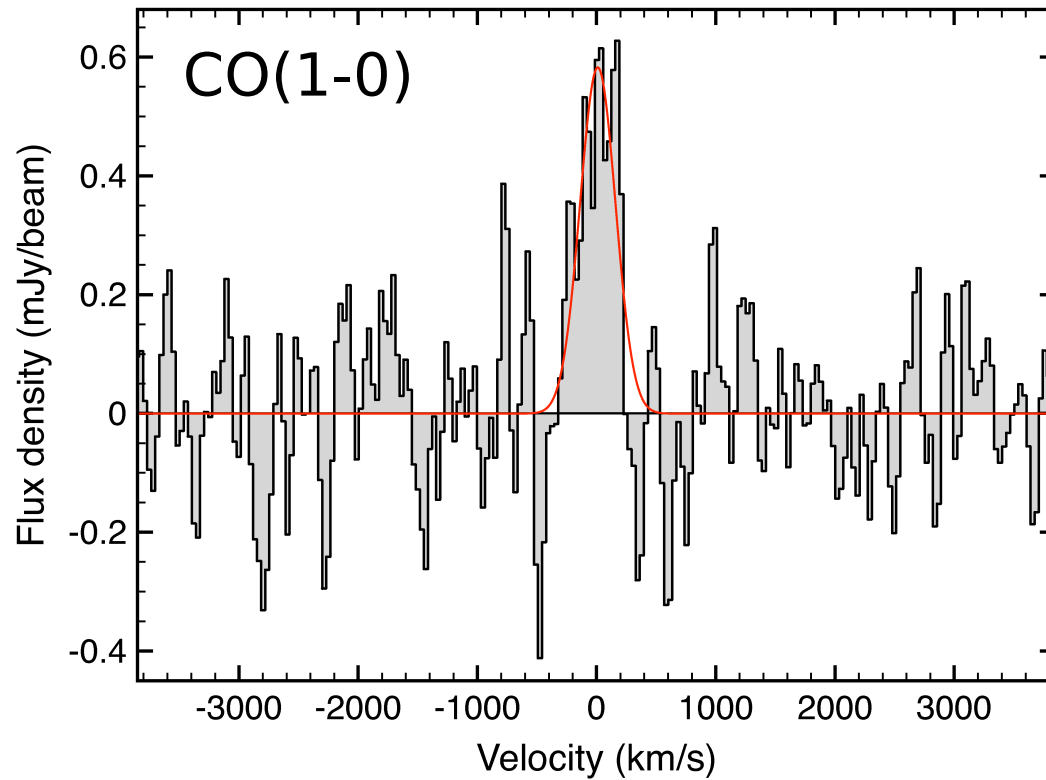
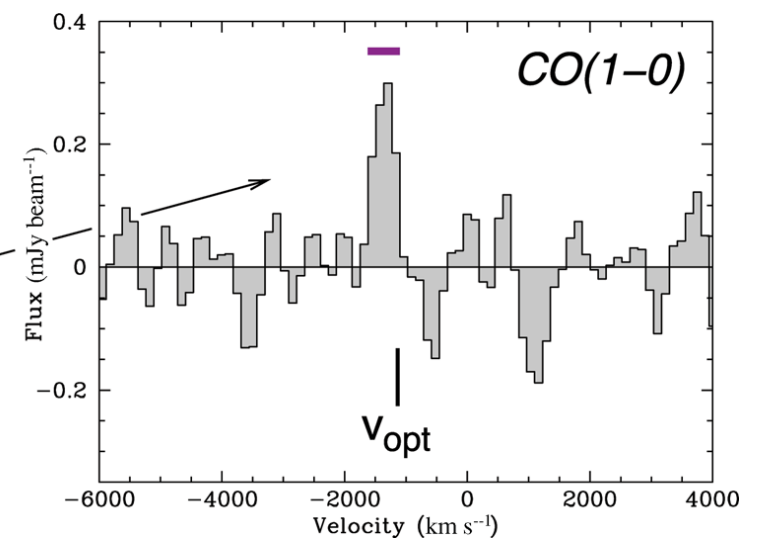
**APEX observations**

**[CII] line cannot be done with ALMA!**



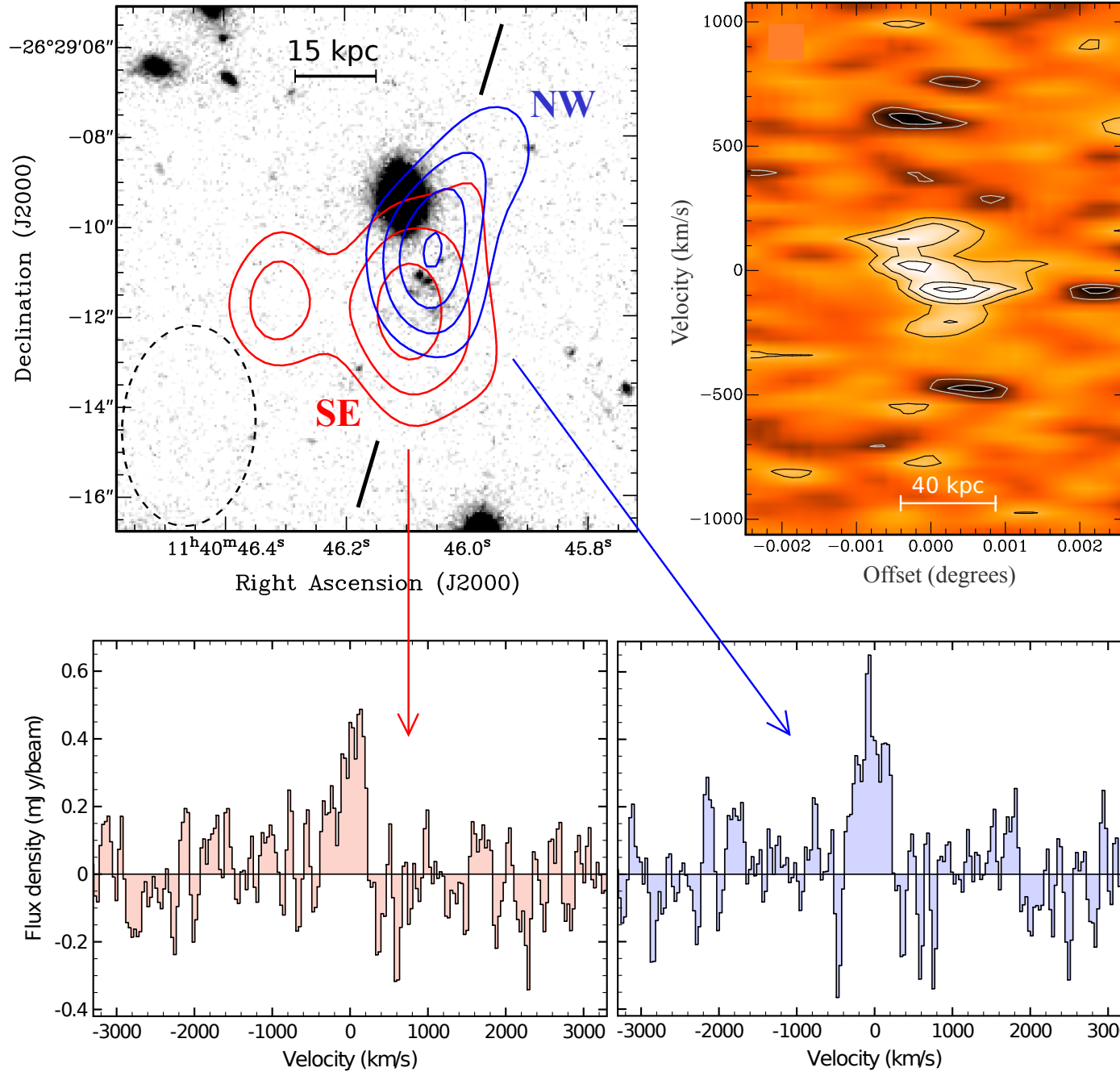


**Emonts et al. (2013)** Right Ascension (J2000)



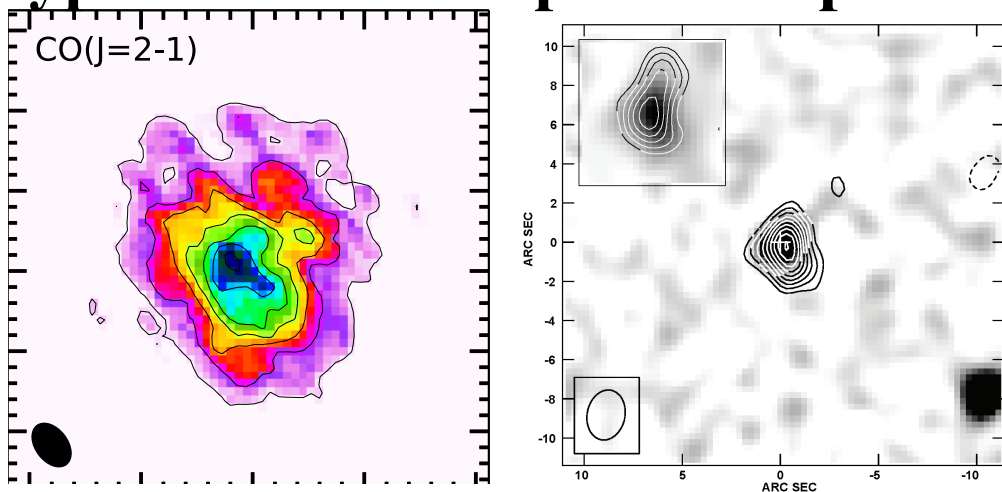
**Dannerbauer, Lehnert, Emonts et al. 2017, A&A, 608, 48**

# CO(1-0): 40kpc large molecular gas reservoir



# Extended molecular gas reservoirs

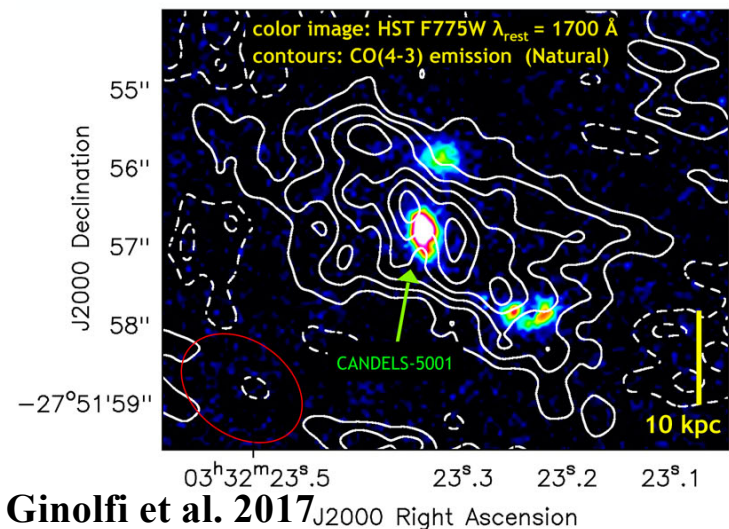
typical sizes are up to 6-8 kpc



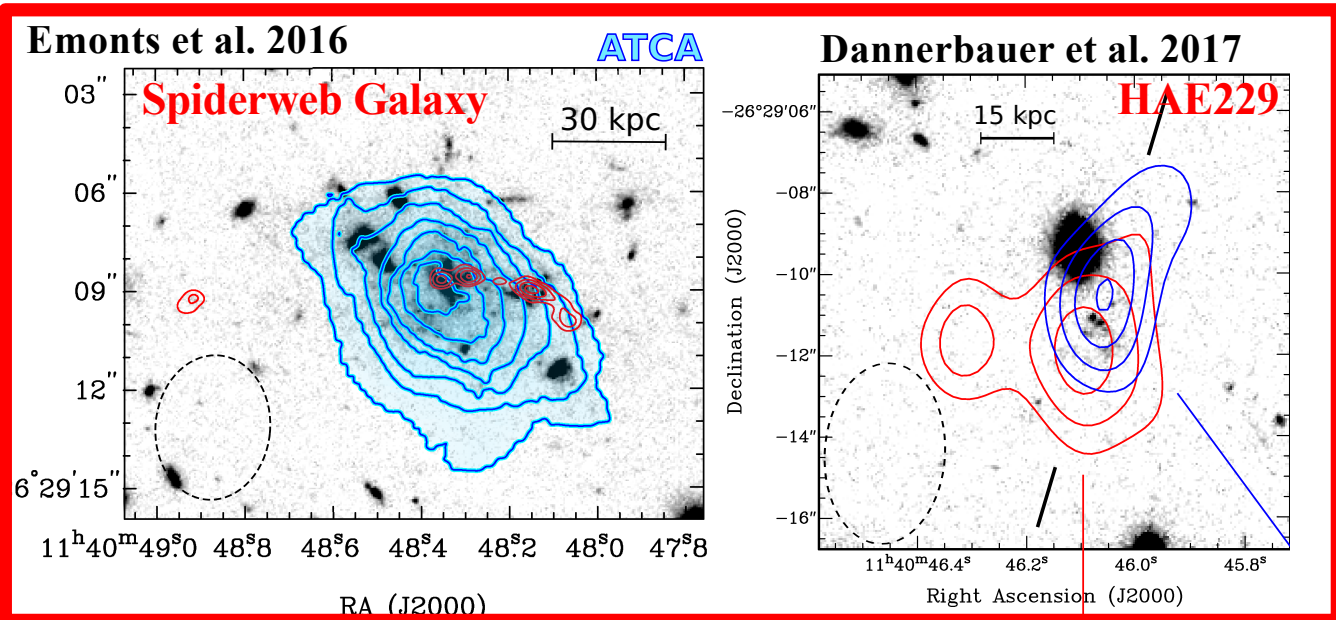
Hodge et al. 2015; Ivison et al. 2011

large molecular gas reservoirs could feed the ICM through “truncation”

in Spiderweb Protocluster



Ginolfi et al. 2017





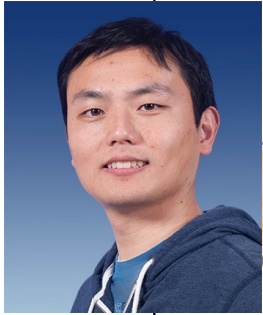
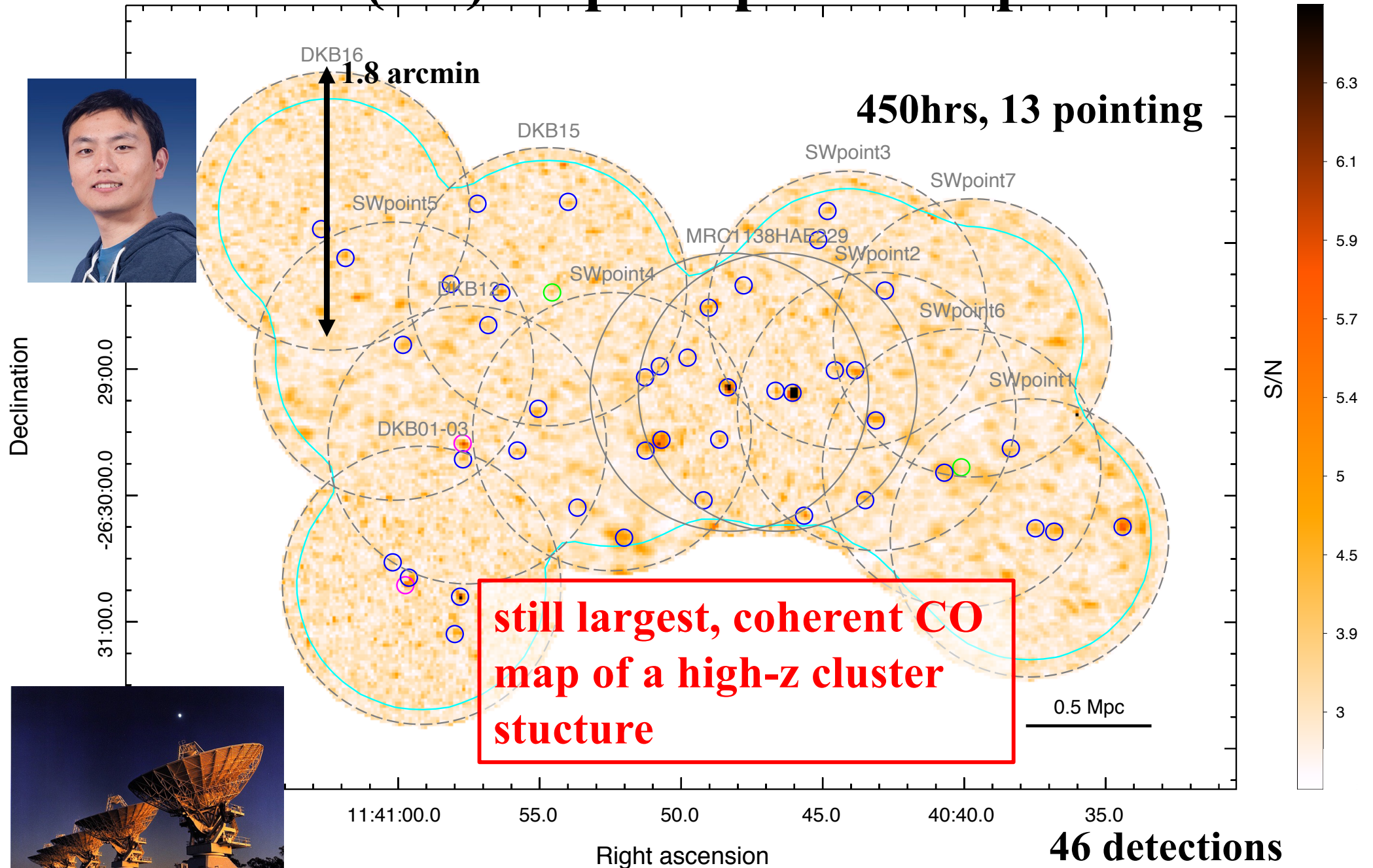
# COALAS

## CO ATCA Legacy Archive of Star-Forming Galaxies

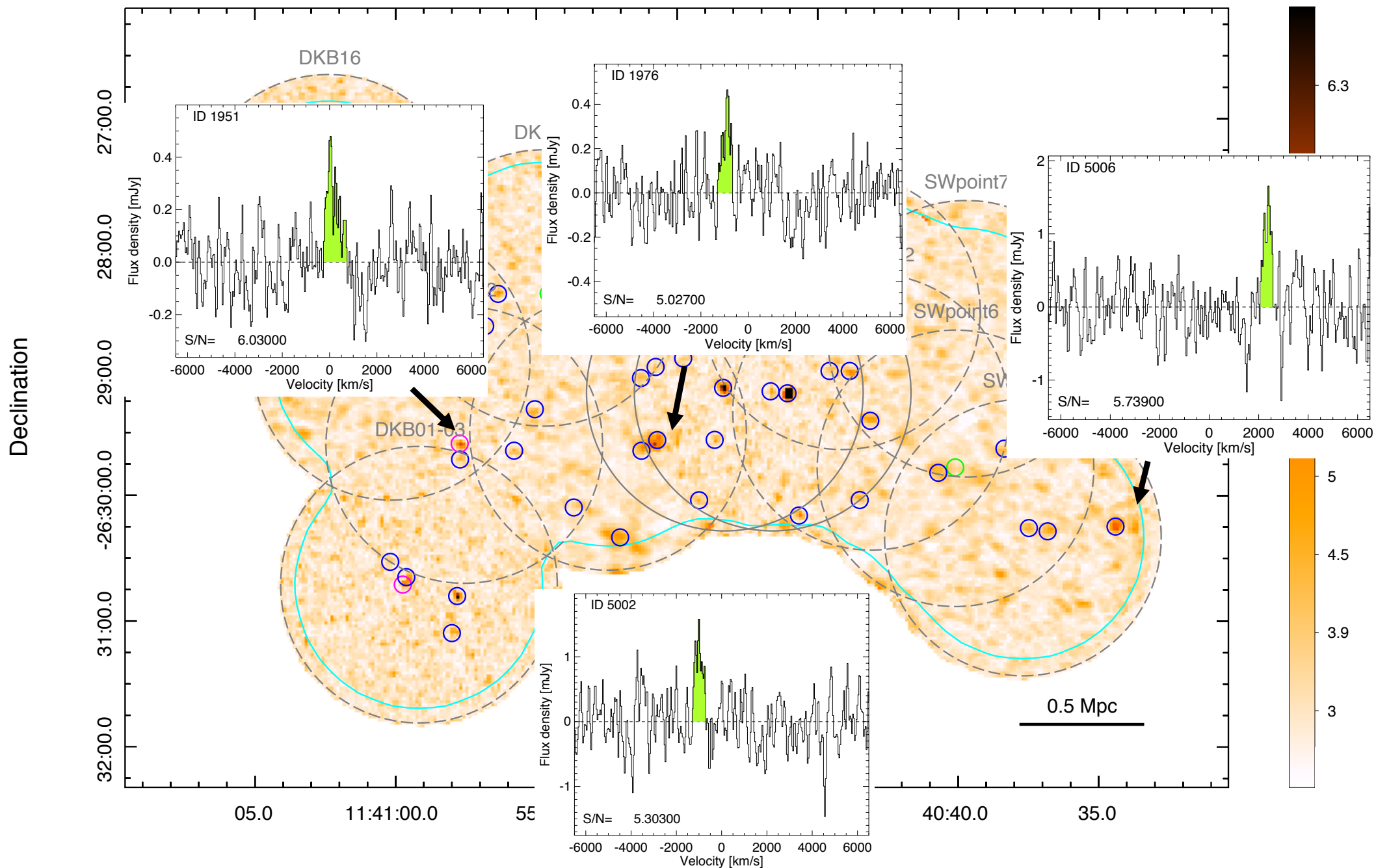


- **ATCA Large Program (PI: Dannerbauer)**
- **Team:** Zhengyi Chen, Bjorn Emons, Shuowen Jin, Matthew D. Lehnert, José M. Pérez Martínez, Alasdair Thomson, James Allison, Bruno Altieri, Itziar Aretxaga, Jack Birkin, Niel Brandt, Scott Chapman, Caitlin Casey, Jackie Champagne, Carlos De Breuck, Guillaume Drouart, Nina Hatch, Jackie Hodge, Minh Huynh, Balt Indermuehle, Amy Kimball, Tadayuki Kodama, Yusei Koyama, Claudia Lagos, Peter MacGregor, George Miley, Desika Narayanan, Ray Norris, Huub Roettgering, Eva Schinnerer, Paolo Serra, Nick Seymour, Rhythm Shimakawa, James Simpson, Mark Swinbank, Ivan Valtchanov, Fabian Walter, Julie Wardlow
- **>800 hrs approved, observations finished in March 2020**
- **CO(1-0) observations of (dusty) star-forming galaxies**
- **selected from the **Spiderweb Protocluster** field and ALESS (APEX-LABOCA survey of the Extended Chandra Deep Field South) field**
- **complementing ALMA molecular gas and dust observation**
- **GOAL: impact of environment on molecular gas reservoir**

# COALAS survey: ATCA CO(1-0) map of Spiderweb protocluster

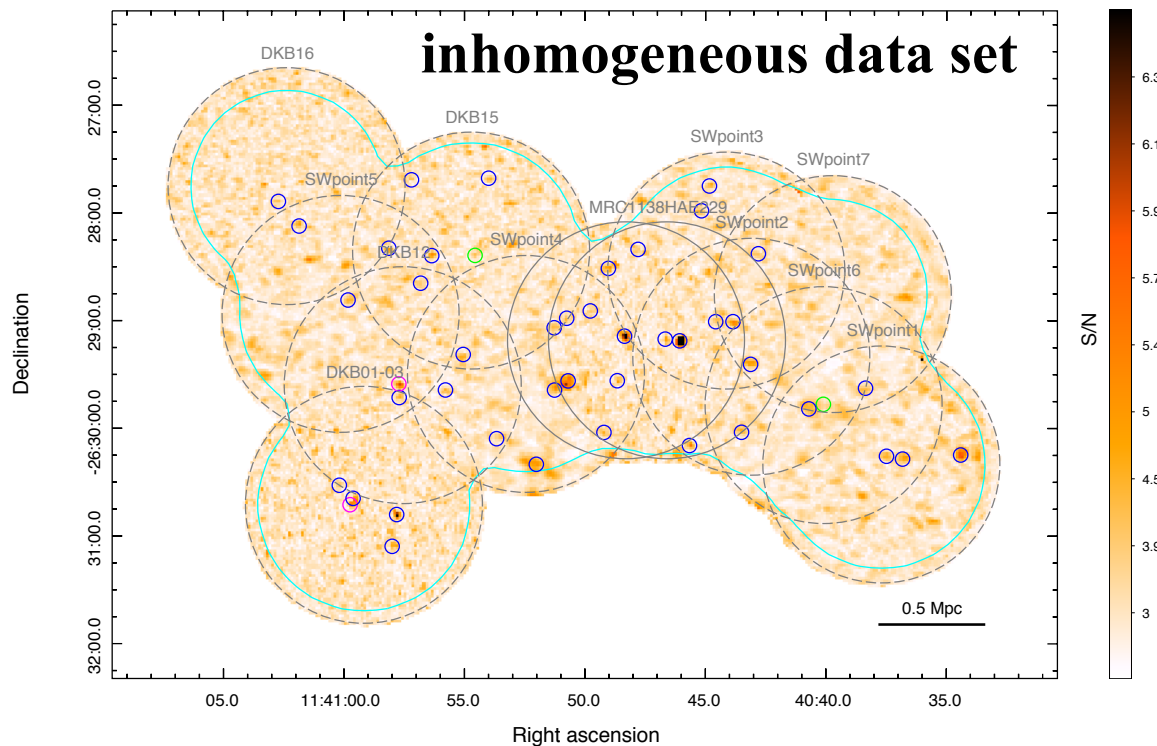


# COALAS survey: ATCA CO(1-0) map



# Search for large molecular gas reservoirs $> 40\text{kpc}$

carried out by former PhD student *Zhengyi Chen*,  
Nanjing U + IAC (through CSC fellowship)



## Assessment of data quality:

- SNR of the CO emission detection
- beam spatial resolution
- location in the pointing

## Criterion Binary Ranking



**9 bits**

# Search for large molecular gas reservoirs > 40kpc

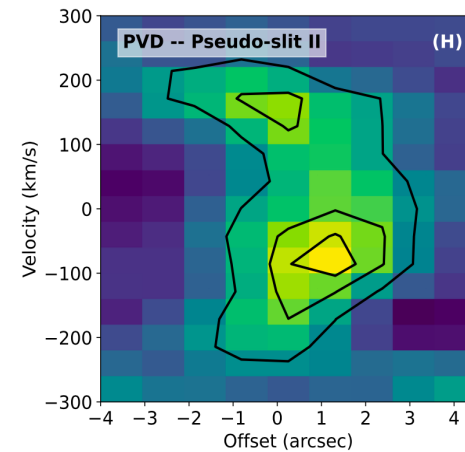
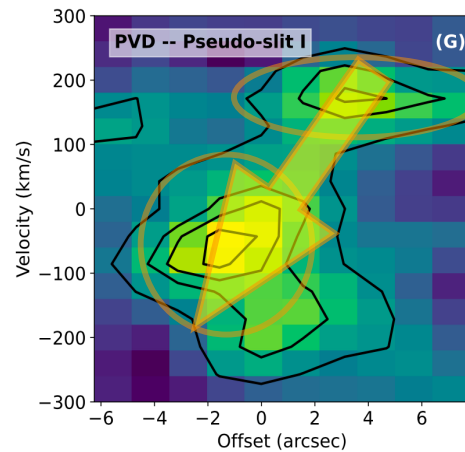
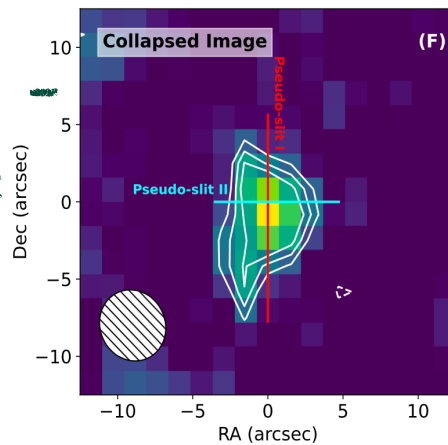
The core of the method: **morphological** and **kinematical** based sizes assessment

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

collapsed images

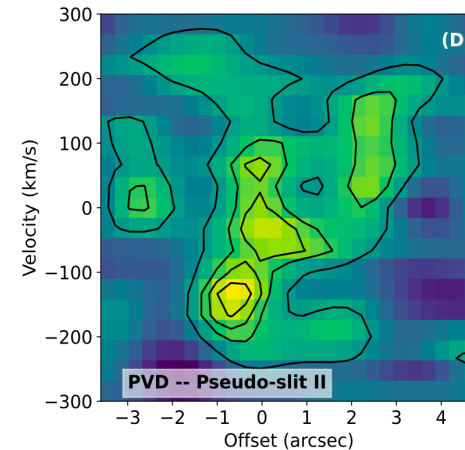
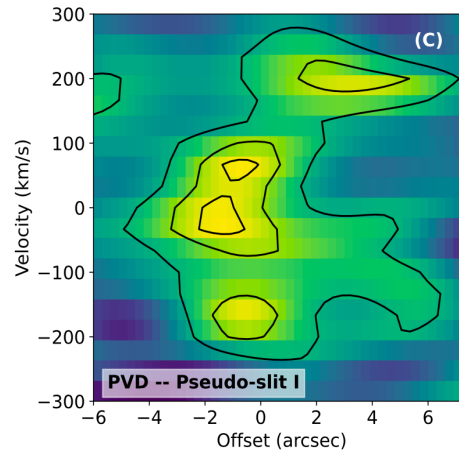
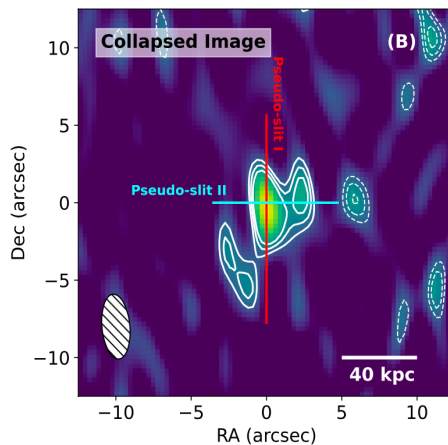
position-velocity diagram

Coarse Data -  
map/mosaic  
(low-resolution;  
7-10 arcsec)



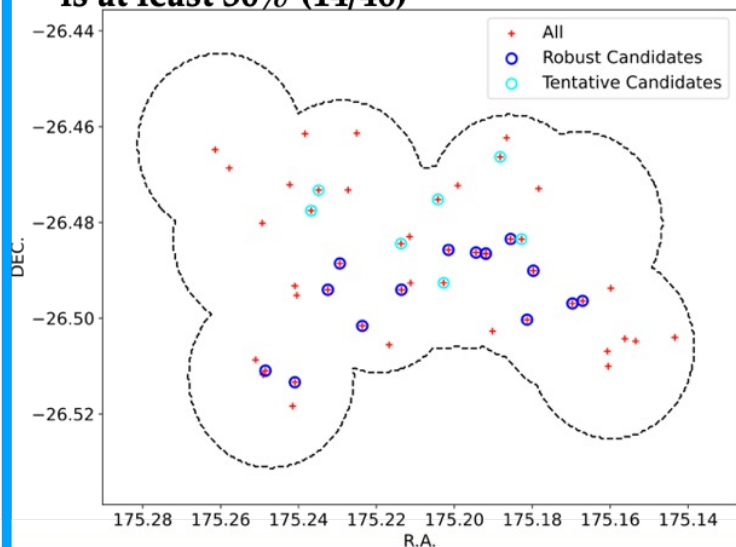
**To confirm our assessment - large molecular gas reservoir  
— follow-up observations have been conducted.**

High  
resolution  
@ 3 arcsec

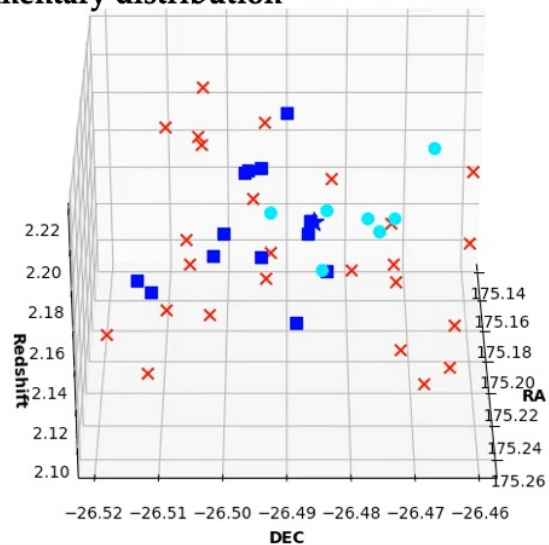


# Search for large molecular gas reservoirs $> 40\text{kpc}$

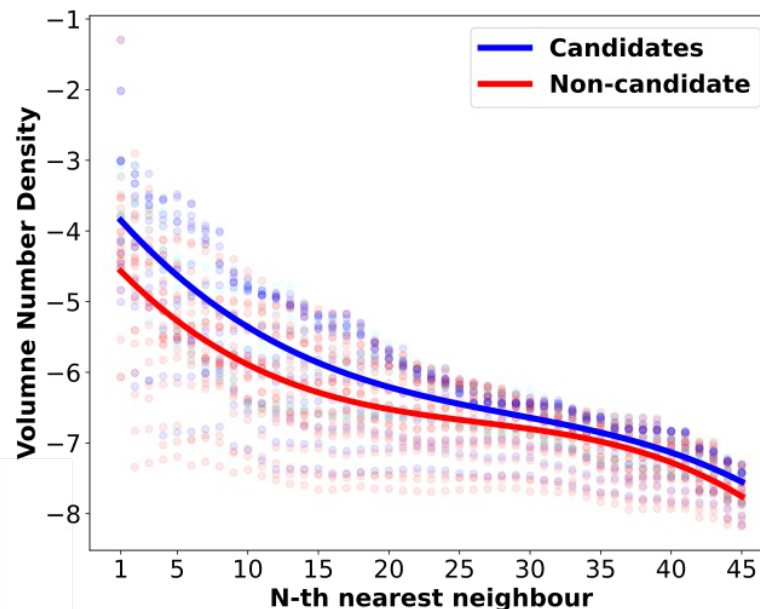
1. The frequency of large gas reservoir phenomenon in Spiderweb protocluster is at least 30% (14/46)



2. The large gas reservoirs mainly located in the core region of Spiderweb protocluster, and show filamentary distribution



3. Large gas reservoir candidates tend to locate on local denser environment.



Possible scenarios of large reservoirs in (proto)clusters:

- gas accretion along filamentary structure
- mergers

# Can the large molecular gas reservoirs feed the future ICM?

1. Molecular gas derivation equation:  $M_{gas} = \alpha L'_{CO}$

- Star-forming mode:  $\alpha \equiv 4.6 M_{\odot} (\text{Kkms}^{-1} \text{pc}^2)^{-1}$
- Starburst mode:  $\alpha \equiv 0.8 M_{\odot} (\text{Kkms}^{-1} \text{pc}^2)^{-1}$

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:  $2.0 \times 10^{13} M_{\odot}$ )
- 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:  $\sim 3 \times 10^{14} M_{\odot}$

4. Consider a low molecular-to-atomic ratio ( $\sim 0.1$ ; Saintonge+2017; Catinella+2018), and under simple star-forming mode assumption,

**→ the large molecular gas reservoirs in the SW protocluster may be enough to contribute to the ICM in a future Virgo-like galaxy clusters (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)*

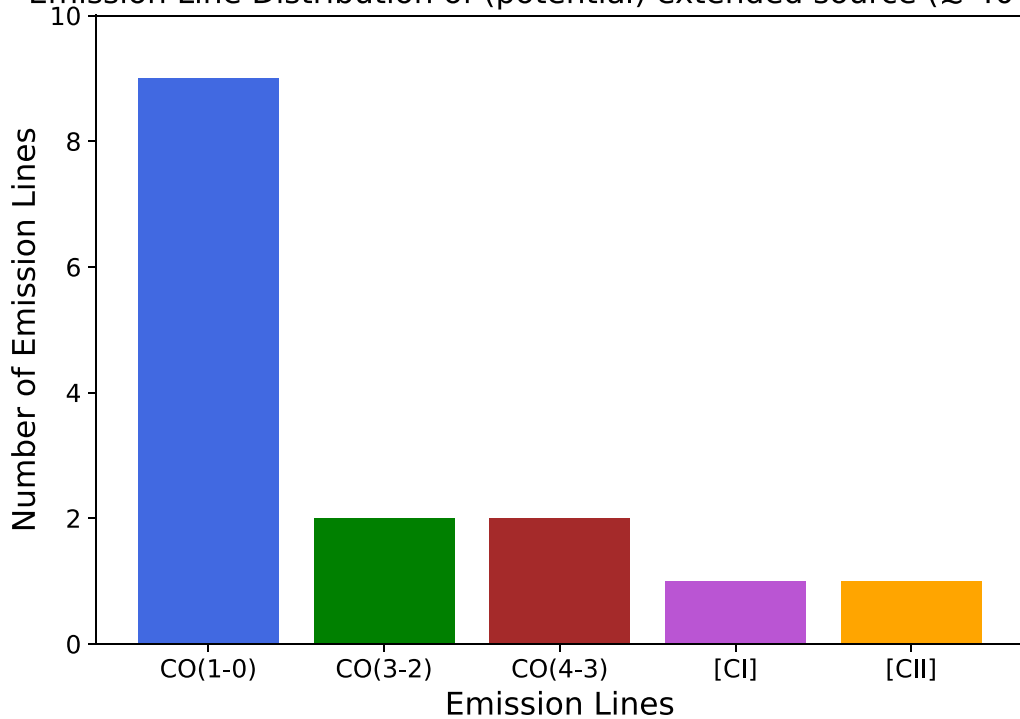
# Literature Search

**Table 1.** Collection from the literature of potential extended molecular gas reservoirs with scale  $\gtrsim 40$  kpc. In addition to emission lines indicative of a scale above 40 kpc, other relevant emission lines of the same sources are also listed exhibiting compact or less extended behaviour.

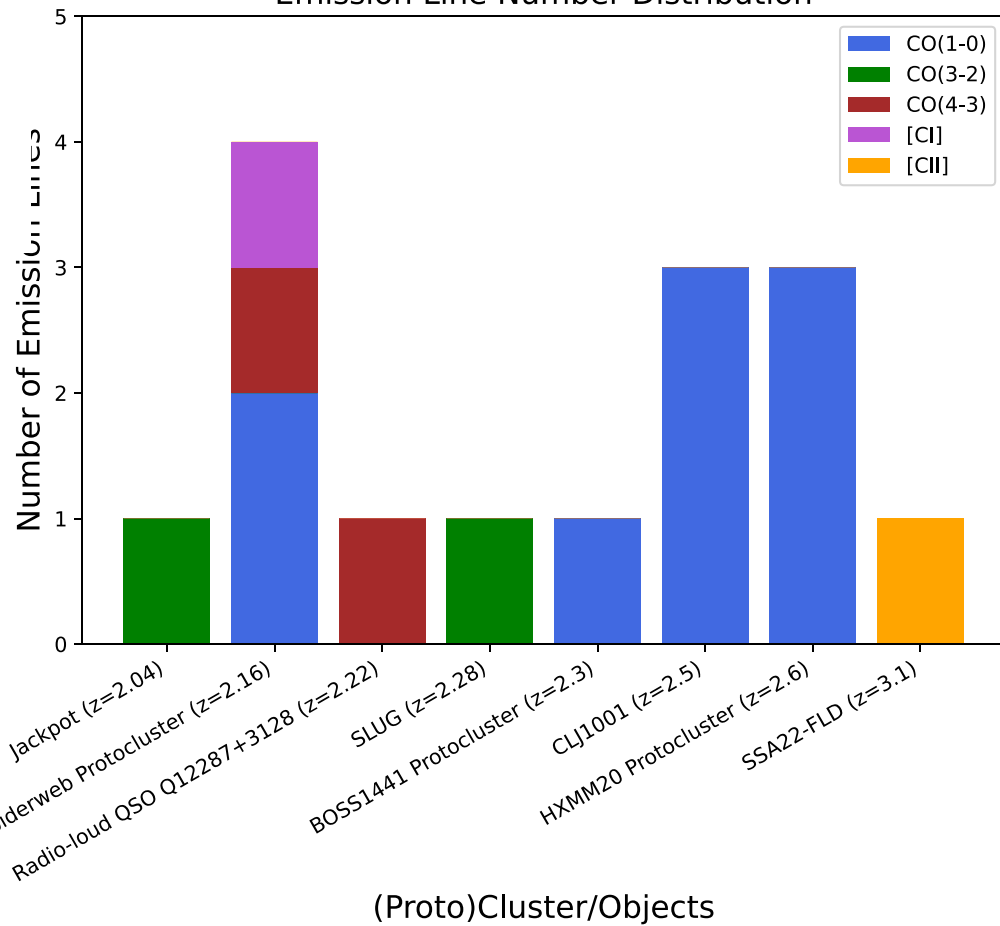
Protocluster	Redshift	Source ID	Emission lines	Size	Size given	Reference	
Jackpot nebular	2.04	Galaxy1	CO(3–2)	$\sim 40$ kpc	–	Decarli et al. (2021)	
PKS1138–262 protocluster (Spiderweb)	2.16	Spiderweb Galaxy	CO(1–0)	$\sim 70$ kpc	Yes	Emonts et al. (2013, 2014, 2016, 2018)	
			CO(4–3)	$\sim 50$ kpc	Yes	Emonts et al. (2018)	
			[CI]	$\sim 50$ kpc	Yes	Emonts et al. (2018)	
			HAE229	$\sim 40$ kpc	Yes	Dannerbauer et al. (2017)	
Protocluster ELANe	2.22	QSO Q12287 + 3128	CO(4–3)	$\sim 100$ kpc	Yes	Li et al. (2021b, 2023)	
Slug nebular	2.28	QSO	CO(3–2)	$\sim 50$ kpc	–	Decarli et al. (2021)	
BOSS1441 protocluster (MAMMOTH-I)	2.3	Region A (Q0052)	CO(1–0)	$\sim 40$ 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	131 077	CO(1–0)	$\lesssim 40$ kpc	Yes	Champagne et al. (2021)	
			CO(3–2)	$\lesssim 10$ kpc	–	Champagne et al. (2021)	
			CO(1–0)	$\sim 30$ kpc	–	Wang et al. (2016)	
			CO(5–4)	$\sim 30$ kpc	–	Wang et al. (2016)	
			130 933	CO(1–0)	$\sim 60$ kpc	–	Wang et al. (2018)
			130 842	CO(1–0)	$\sim 60$ kpc	–	Wang et al. (2018)
HXMM20 protocluster	2.6	S0	CO(1–0)	$\sim 45$ kpc	–	Gómez-Guijarro et al. (2019)	
			CO(3–2)	$\sim 30$ kpc	–	Gómez-Guijarro et al. (2019)	
		S2	CO(1–0)	$\sim 40$ kpc	–	Gómez-Guijarro et al. (2019)	
			CO(3–2)	$\sim 30$ kpc	–	Gómez-Guijarro et al. (2019)	
		S3	CO(1–0)	$\sim 40$ kpc	–	Gómez-Guijarro et al. (2019)	
SSA22 protocluster	3.1	LAB1	CO(3–2)	$\sim 30$ kpc	–	Gómez-Guijarro et al. (2019)	
			[C II]	$\sim 50$ kpc	–	Umehata et al. (2017, 2021)	
			CO(4–3)	$\sim 30$ kpc	–	Umehata et al. (2021)	

# Literature Search

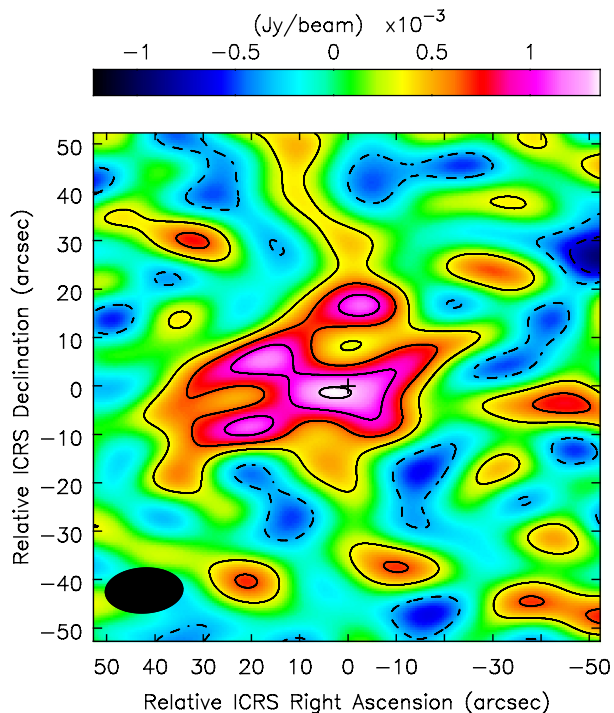
Emission Line Distribution of (potential) extended source ( $\geq 40$  kpc)



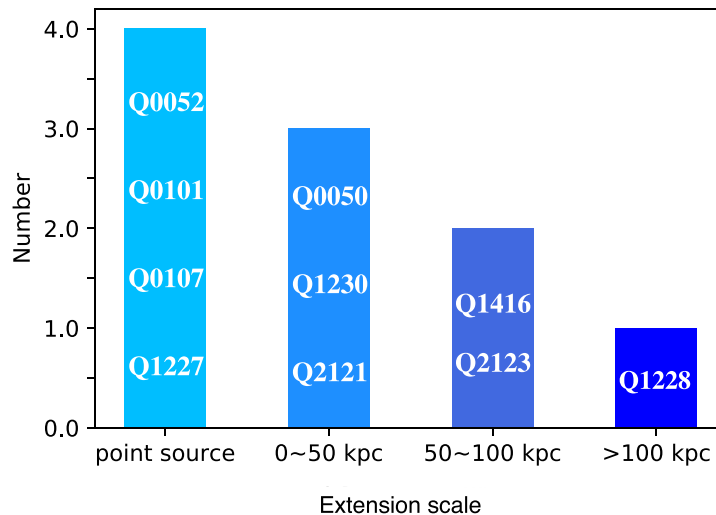
Emission Line Number Distribution



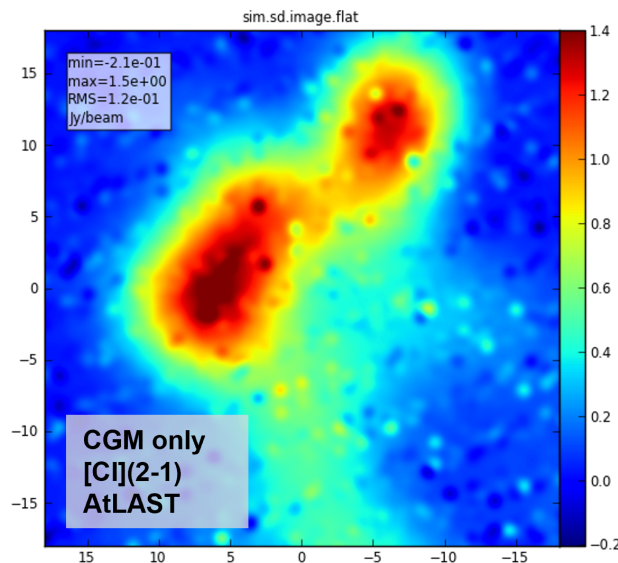
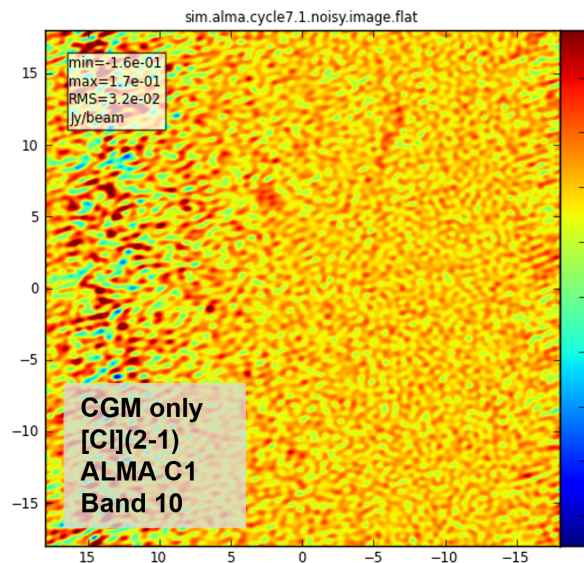
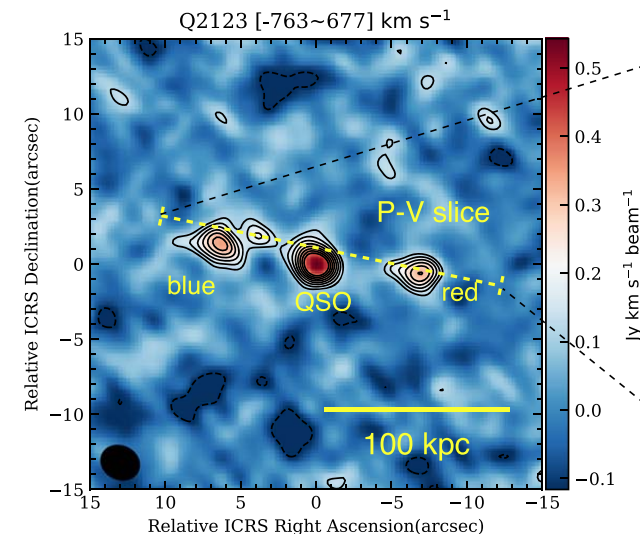
# More Studies ☺



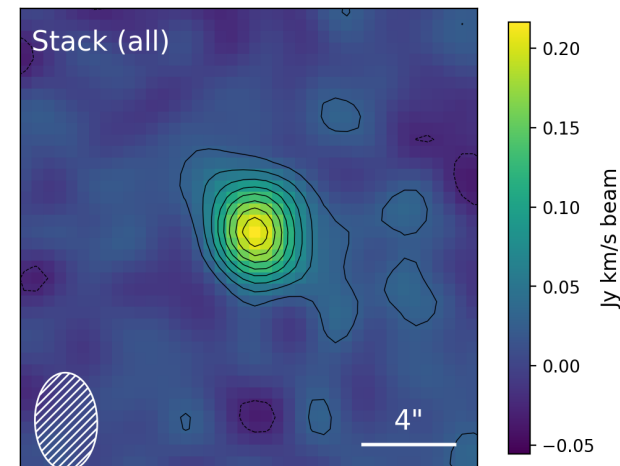
Cicone et al. 2021, A&A



Li, Emonts et al. 2023, ApJ

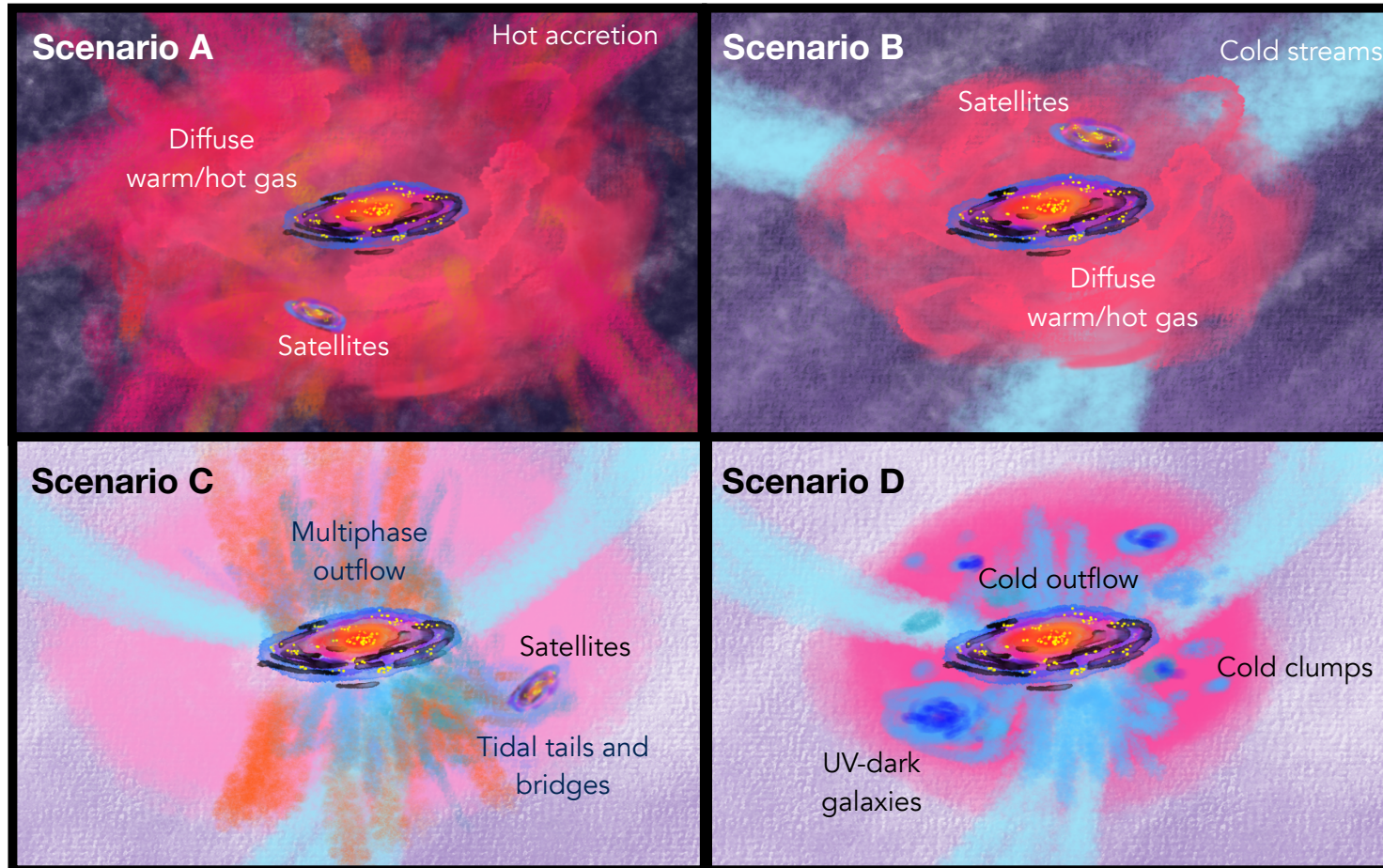


Lee, Schimek et al. 2024, A&A



Rybak et al. 2025, A&A

# Science Case for AtLAST



white paper CGM: Lee + AtLAST coll., 2024, ORE, 4, 177 (arXiv: 2403.00924)



Funded by  
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# Conclusions and Remarks

- **Discovery of large molecular gas reservoirs appears to be a common feature in galaxy protoclusters.**
- **These large molecular gas reservoirs could significantly contribute to the formation of the future ICM.**
- **How frequent is this phenomenon?**
- **Does it depend on environment?**
- **Systematic studies are still scarce.**
- **Large-number statistics are needed, but with current instrumentation such studies remain very demanding and time-consuming.**
- **AtLAST would be a true game changer. 😊**