Galaxy-IGM workshop 2021
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Recent observations of IGMs/CGMs

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Outline

- ❖ Introduction
- ❖ Case1: Lyα-filaments at z=3 proto-cluster
  + other examples
- ❖ Case2: A bright Lyα Blob at z=3
  + some works on “molecular” CGMs
- ❖ Summary

Cosmic Evolution in a simulation

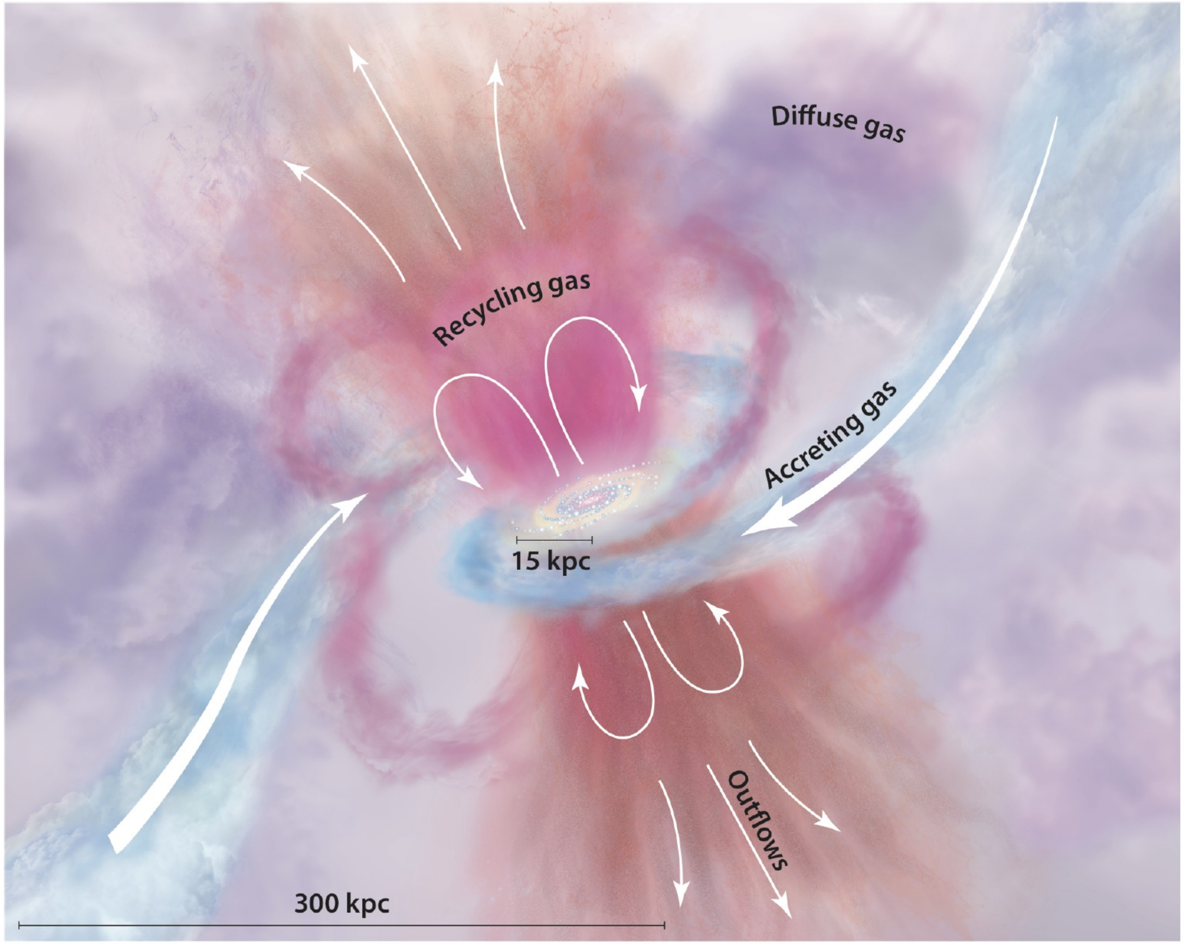
Gas | Dark Matter | Stellar | Magnetic Field

Temperature | Gas Metallicity | Gas Velocity Field | OVI Column Density

https://www.tng-project.org/

- ❖ Galaxies are not isolated systems, and stars are one of various phases.
- ❖ Observing the gas network directly is of importance.

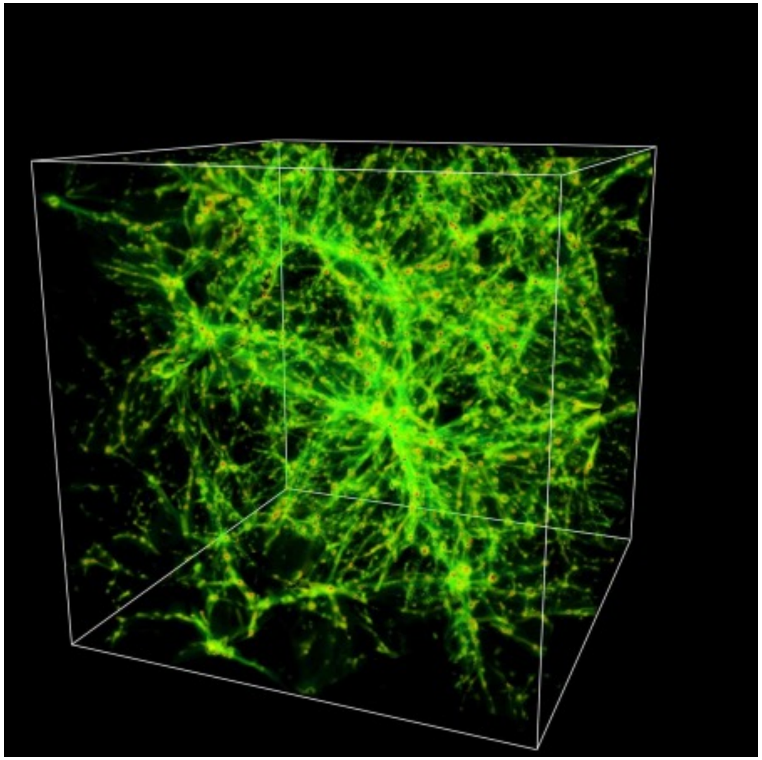
Baryon Cycling around Galaxies



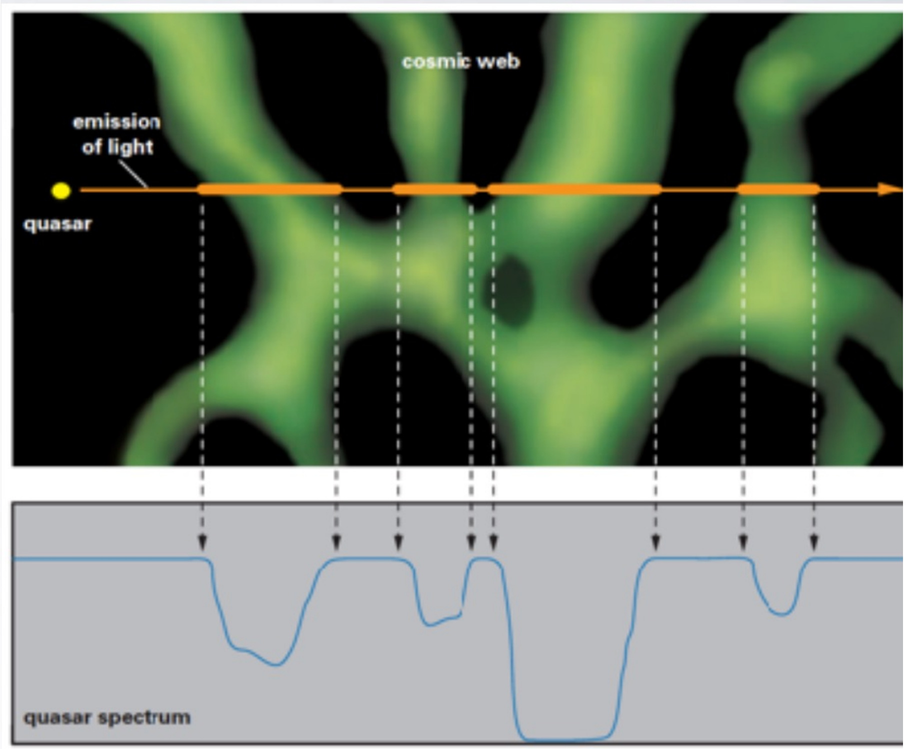
Tumlinson et al. 2017, ARAA, 1, 46

- ❖Active baryon cycle is predicted around a galaxy.
- ❖One need to trace phases (outflow, accreting gas, recycling gas...) to comprehend it.

How to trace the IGMs/CGMs?



(c) Cen & Ostriker



(c) Rob Simcoe

❖ Both emission and absorption have been utilized.

How to trace the IGMs/CGMs?

Method	Emi./Abs.	Pros. and Cons.
Lyα Stacking / Intensity mapping	Emission	✔ Sensitivity, statistical properties △ detailed picture, individual properties
Lyα (direct) mapping	Emission	✔ details picture, individual properties △ kinematics, physical parameters
QSO/Galaxy Absorption system	Absorption	✔ sensitivity, physical parameters △ extent, detailed picture
HI Tomography	Absorption	✔ large-scale picture △ detailed picture
Molecular line mapping e.g., [CII], CO, CH+, ...	Emission/ Absorption	✔ kinematics, information of molecular gas △ field of view, sensitivity

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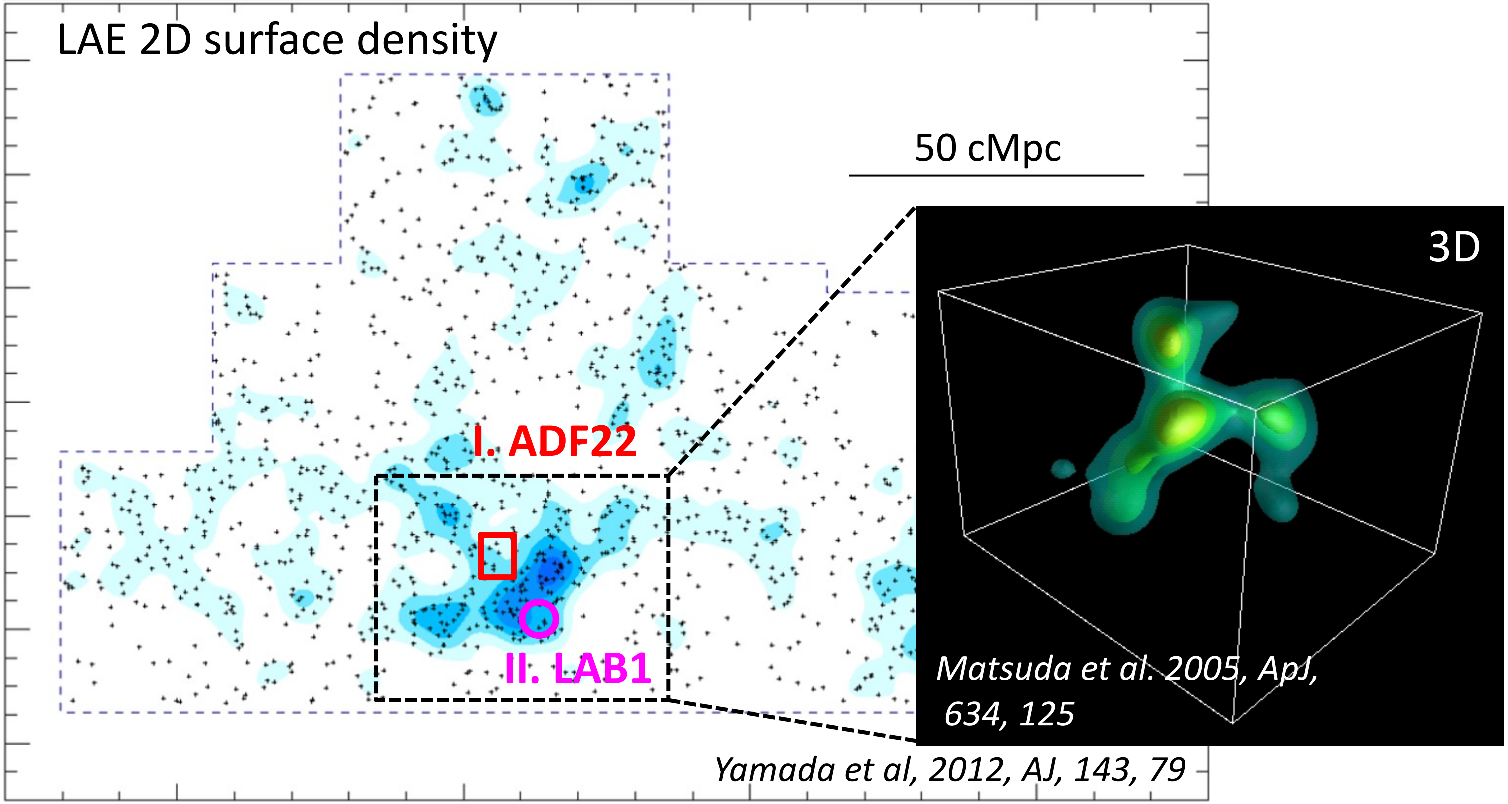
❖To observe IGMs, on top of Lyα stacking, direct imaging and HI tomography recently provides relatively novel tool.

❖To observe CGMs, individual Lyα halos has been detected. Molecular lines also provides a tool.

I. Lyα Filaments connecting starbursts and SMBHs

Umehata et al. 2019, Science, 336, 97 (Arxiv: 1910.01324)

SSA22 Proto-cluster at z=3.1



❖The SSA22 proto-cluster has a 3D structure traced by LAEs at z=3.1.
❖One of the most significant overdensity at z>2.
=> A unique laboratory to investigate 'environmental effect' in galaxy formation and evolution.

ADF22: ALMA Deep Field in SSA22

Obscured SF

ALMA 1mm, 3mm

JVLA 5cm, 10cm, 20cm

(Herschel/SCUBA2/MIPS)

Stars

MOIRCS/SWIMS NIR

HST F814W, F160W

(Suprime-Cam, IRAC)

Ionized Gas

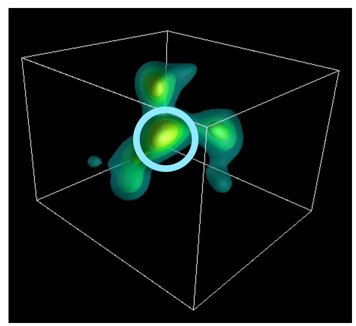
MOSFIRE NIR

(MOIRCS)

AGN

Chandra X-ray

JVLA 5cm



Cold Gas Reservoir

JVLA CO(1-0)

ALMA CO(3-2), CO(9-8)

[CII]158

IGM/CGM

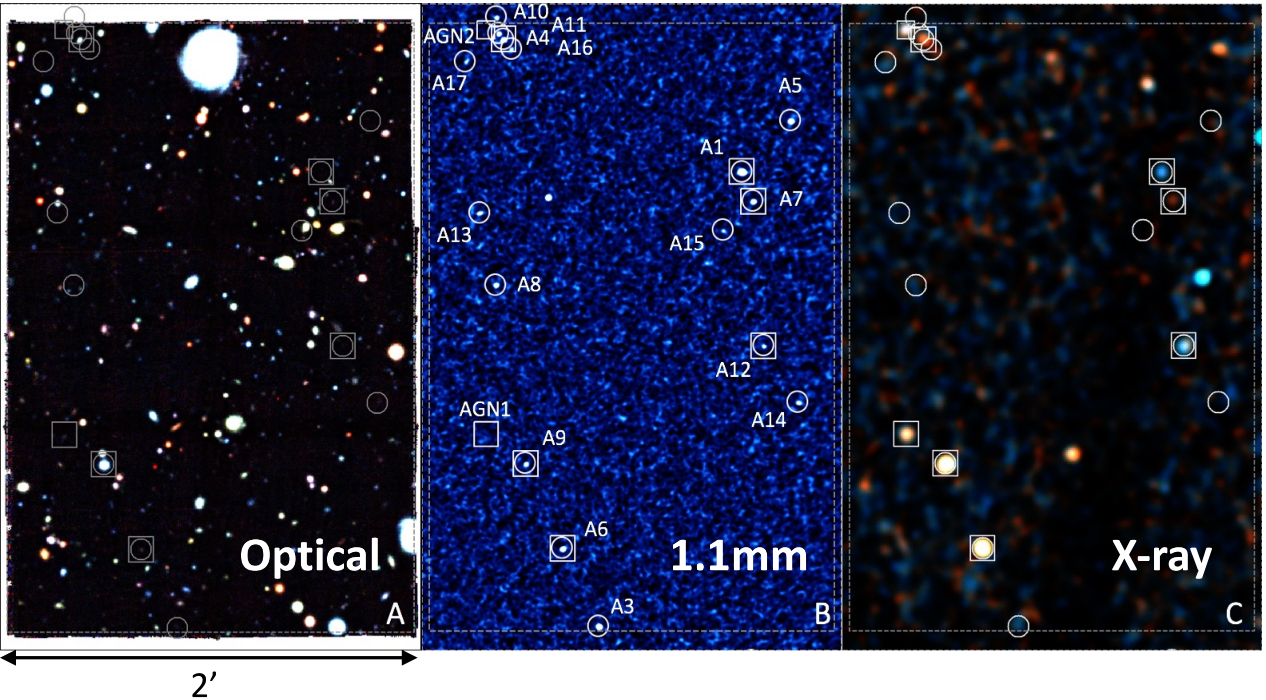
S-Cam, **MUSE Lyα**

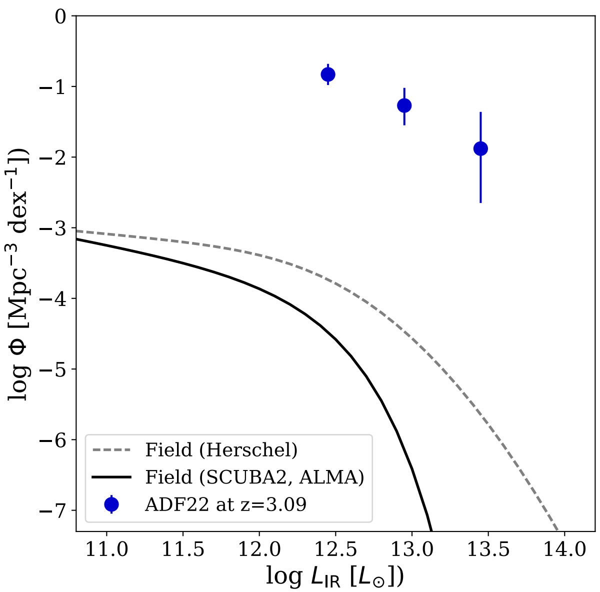
ALMA OH+

Umehata et al. 2015, ApJ, 815, L8
Umehata et al. 2017, ApJ, 835, 98
Umehata et al. 2018, PASJ, 70, 65
Umehata et al. 2019, Sci, 366, 97
Umehata et al. 2020, A&A, 640, L8
Hayatsu et al. 2017, PASJ, 69, 45
Kubo et al. 2017, MN, 469, 2235
Kubo et al. 2021, ApJ, in press
Monson et al. 2021, ApJ, in press
... and more to come!

Enhanced SF/AGN activity at the core

Umehata et al. 2019, Science, 336, 97





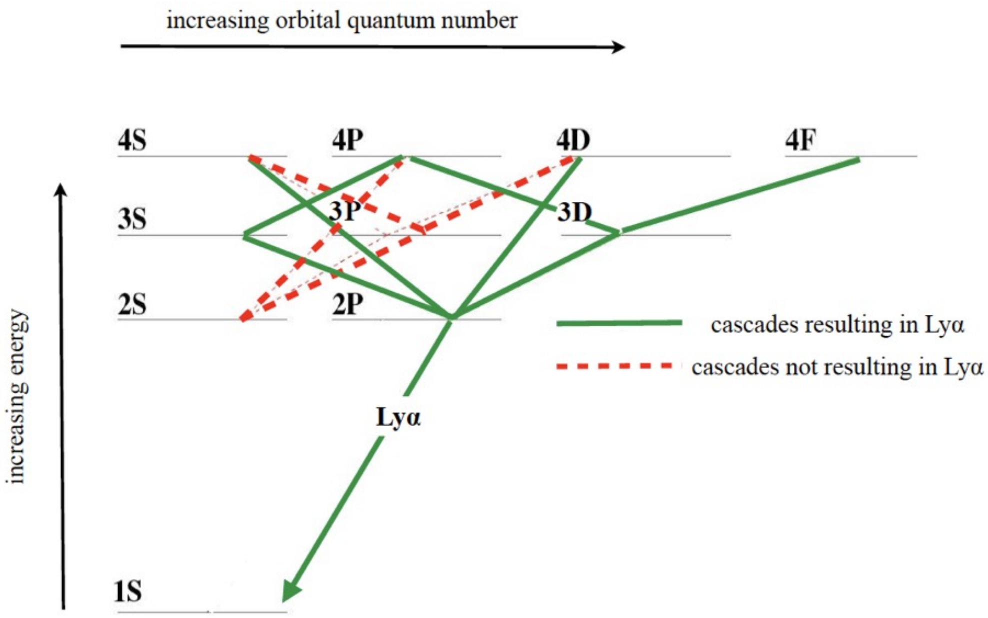
Umehata et al. in prep

❖ We mapped a 2'x3' are 'contiguously' in ALMA Band6 (e.g., Umehata et al. 2015).
- Among the 18 brightest 1mm sources, 16 sources have found to be at z=3.1.
- This is 2-3 orders of magnitudes higher than the general field.

❖ The field is also covered by a 400ks Chandra survey (Lehmer et al. 2009).
- X-ray AGNs (Lx~10^{44} erg/s) are similarly exceptionally overdense (x~2 orders).

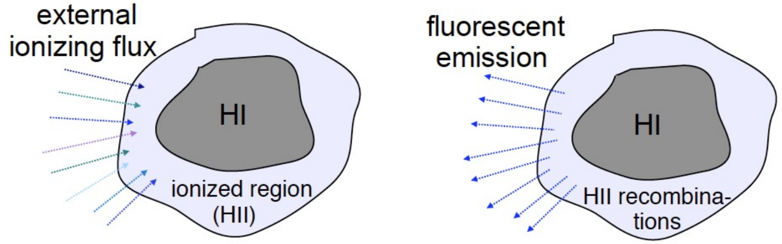
=> There must be a mechanism to enhance SF/AGN at the node of the z=3.1 LSS.

Mechanisms to generate Lyα

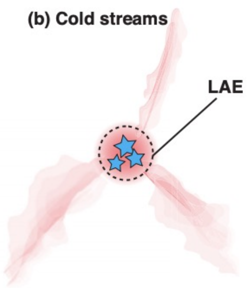


Fluorescence

(c) S. Cantalupo

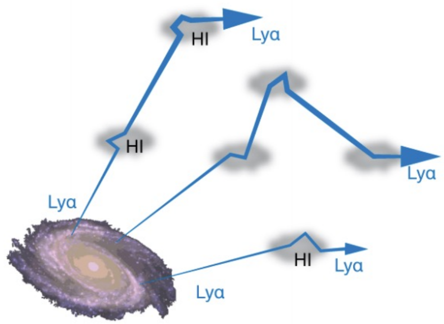


Cold stream



(c) R. Momose

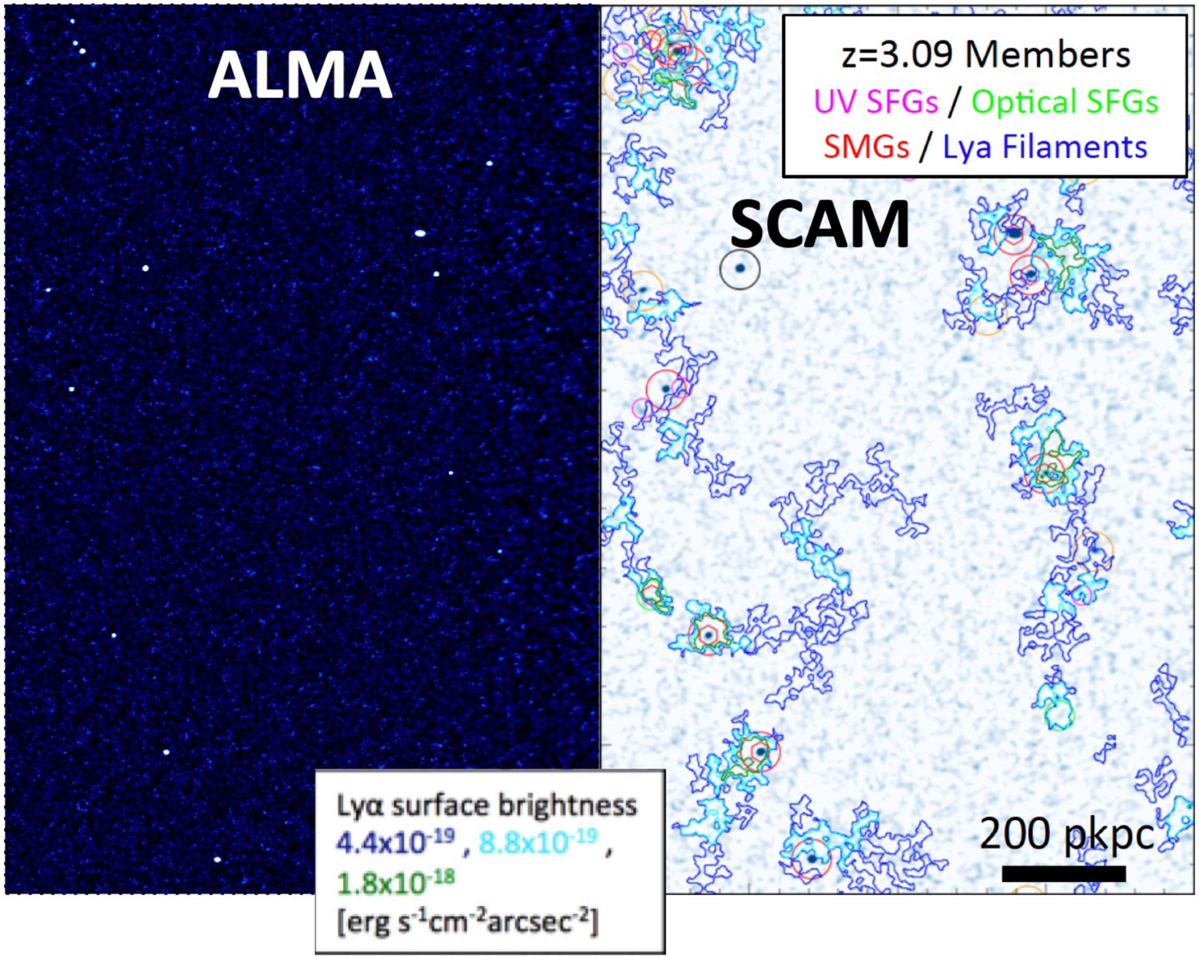
Scattering



(c) S. Mukae

- ❖ The Hydrogen Lyα-line (2p->1s) has (rest frame) 1215.67A (or 10.2 eV)
- ❖ Major scenarios to cause extended Lyα emission so far proposed includes:
  - Fluorescence: ionization and recombination at the surface of HI.
  - Cold stream: collisional excitation and de-excitation in accreting gas
  - Scattering: scattered light of Lyα caused by star-formation in galaxies

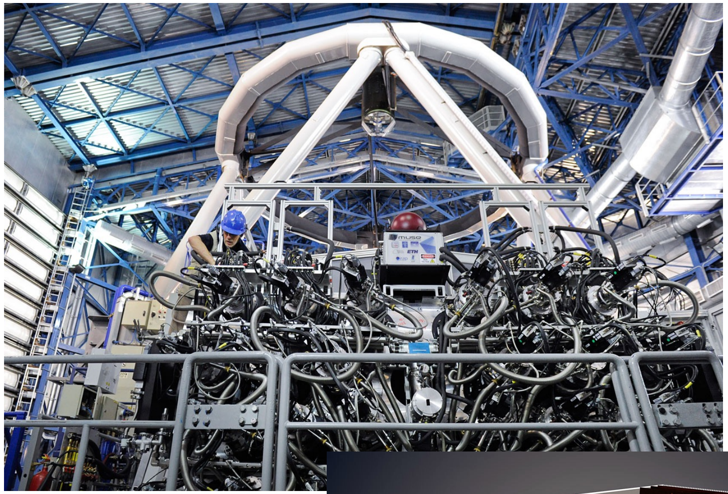
A hint from Suprime-Cam



- ❖ We revisited an archival NB image taken with S-Cam.
- ❖ Lyα "filaments" on a Mpc-scale are "suggested".

=> We headed to 'confirm' the tantalizing structure.

MUSE Observation



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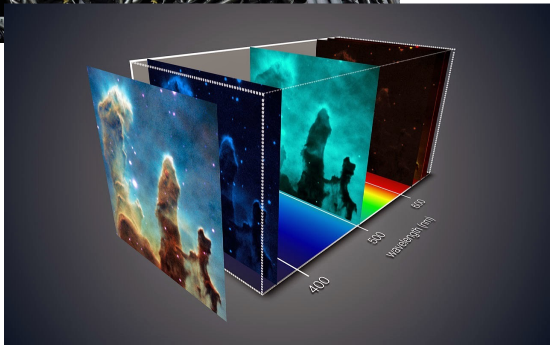
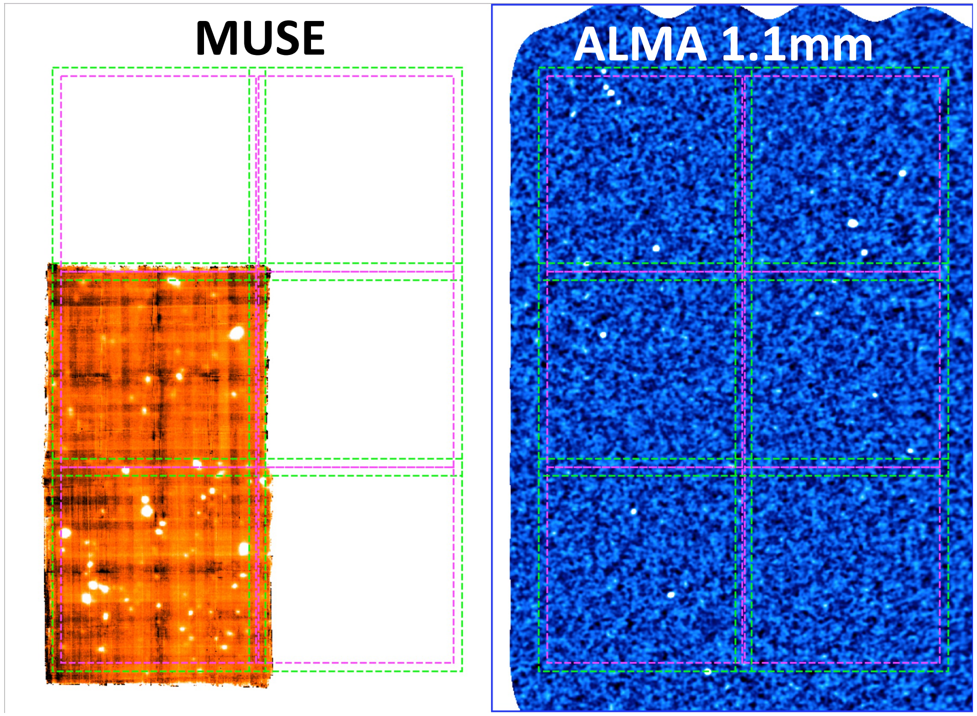
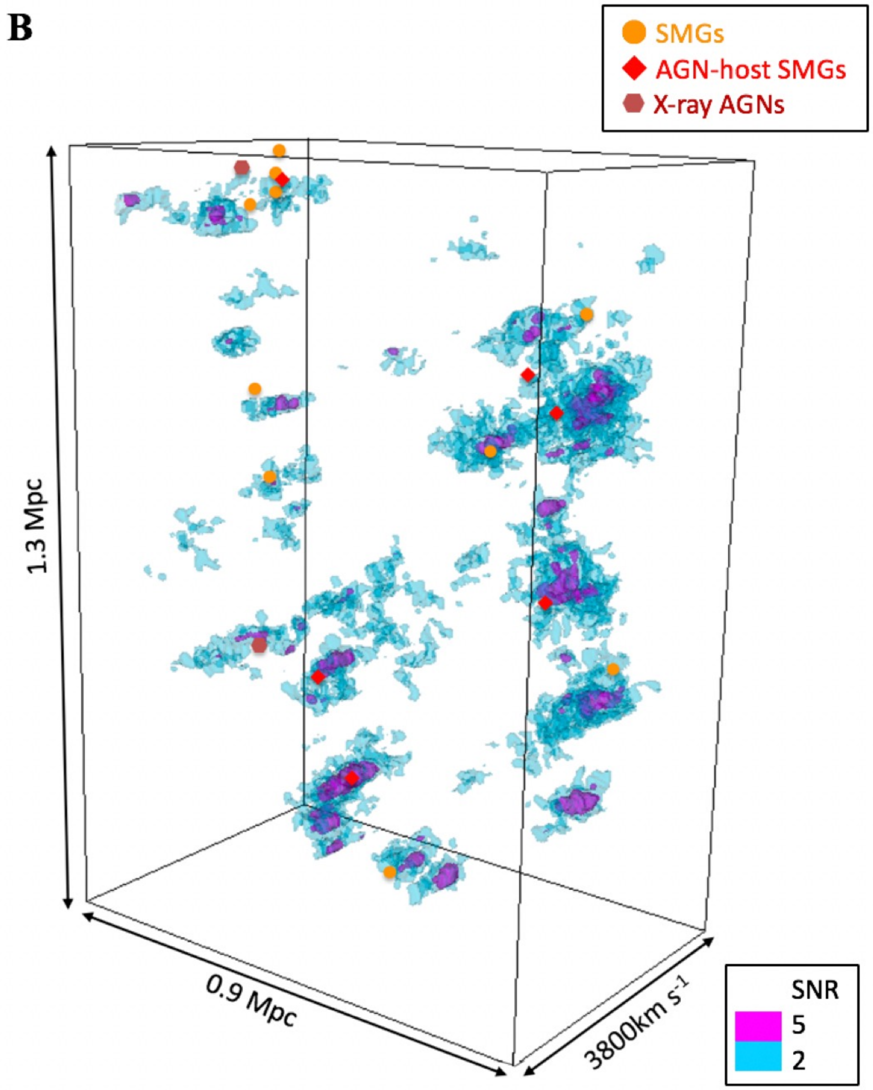


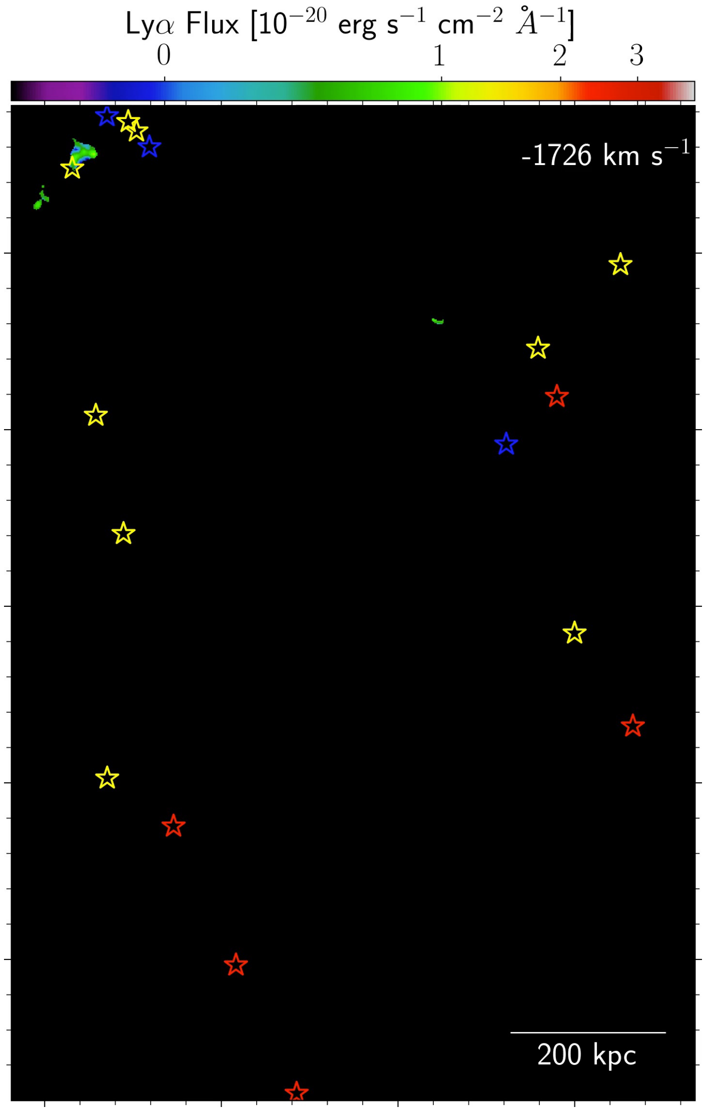


❖MUSE/VLT is one of the most powerful instrument for the study of IGM/CGM. We can trace Lyα emission in 3D.

❖A 6-pts mosaic cube was obtained to cover the nearly entire ADF22 field.

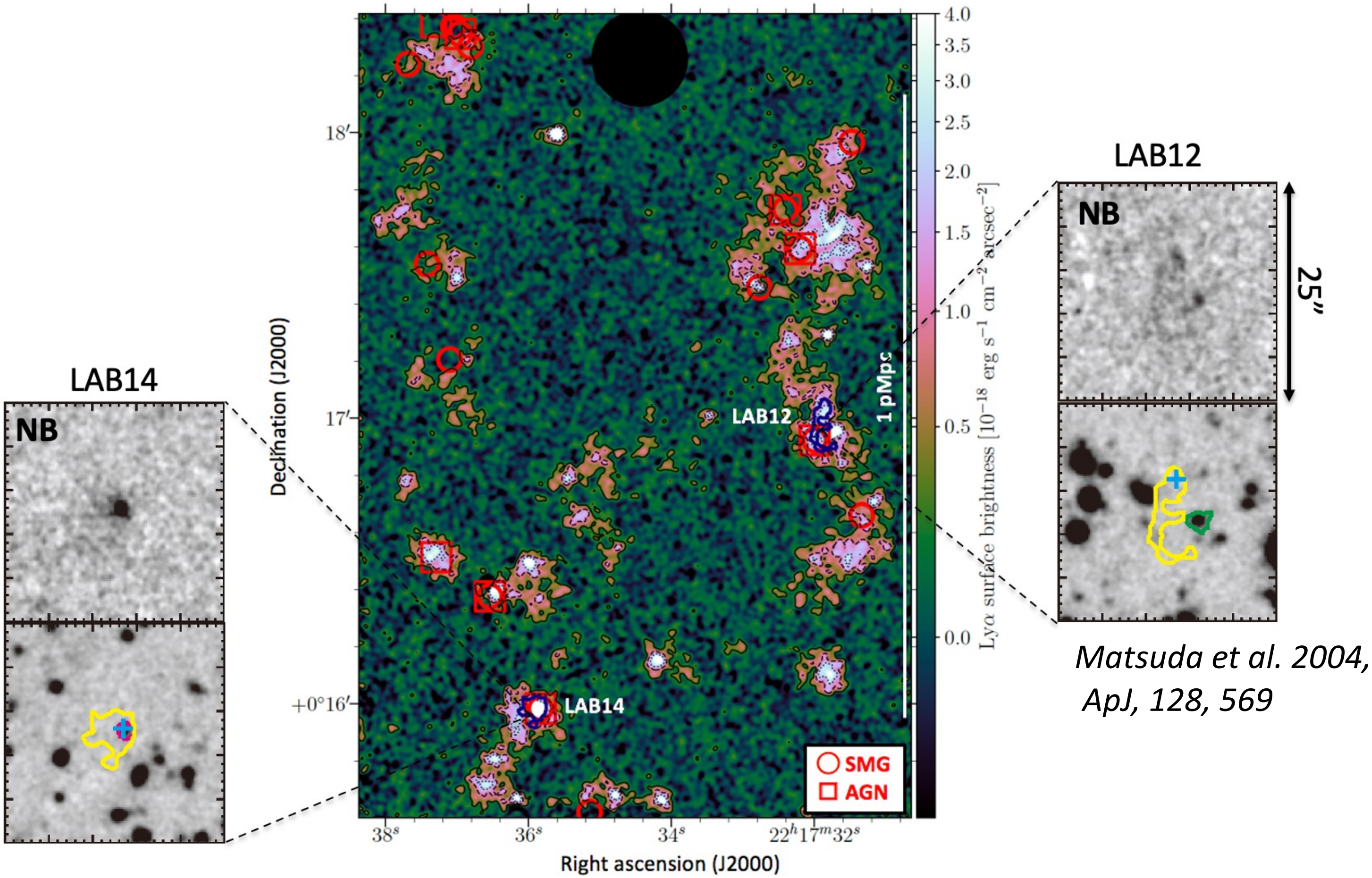
3D views of galaxies/nuclei/filaments





Umehata et al. 2019, Science, 336, 97

Extended Lyα Emission in ADF22

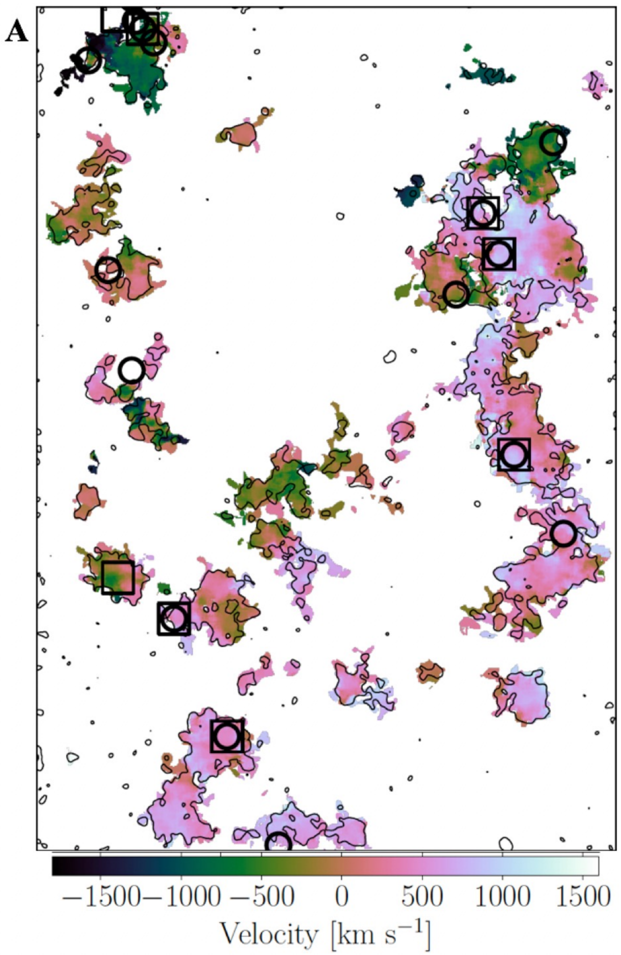


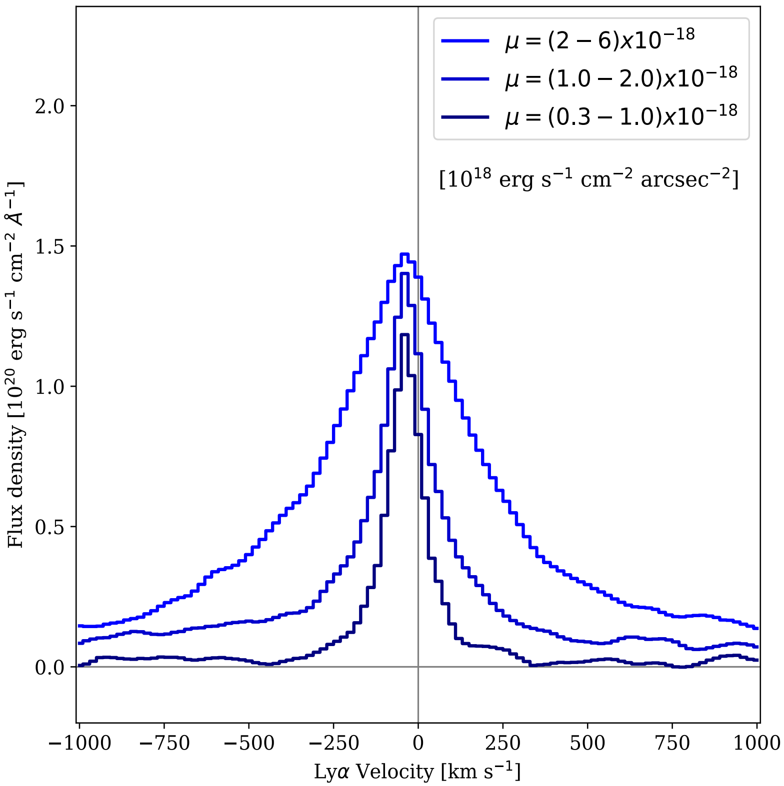
Matsuda et al. 2004, ApJ, 128, 569

❖The MUSE Lyα map shows two major filaments on a Mpc scale, expanding to the intergalactic space.

❖Previously found LABs are likely to be the tip of the iceberg.

Kinematics of the filaments

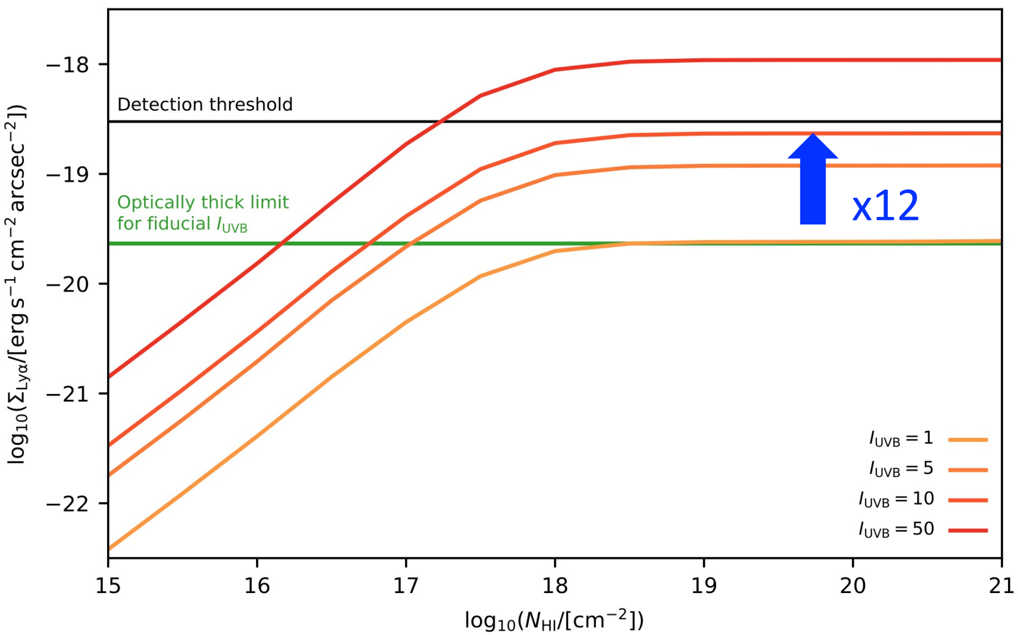




- ❖ The Lyα emission shows a coherent structure with a velocity range of ~1500 km/s.
- ❖ Stacking analysis suggests that lower SB parts have lower velocity widths.

  => Faint filaments are kinematically cooler, which is in contrast with classical LABs.

Fluorescence as a plausible power source



<u>geometry</u>: slabs of constant density

Intensity of the radiation field (variable)

Ionizing radiation

HI

Column Density (variable)

<u>ionizing radiation field spectra</u>: similar to the UVB

<u>metallicity</u>: scaled to 1% of solar abundance

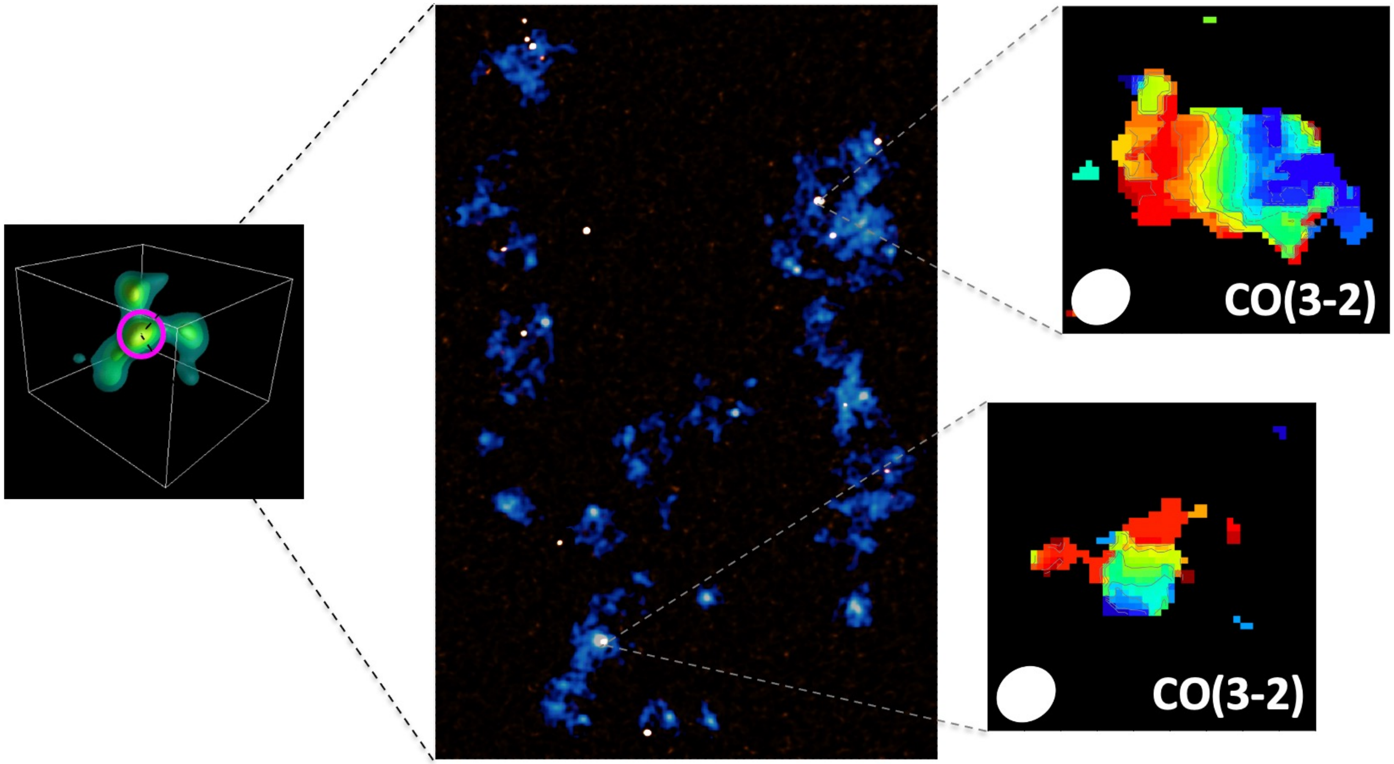
❖Based on a simple Cloudy modeling, we suggest that the Lyα emission can be explained by fluorescence if the radiation field is boosted (x>12).

❖Since there are 16 SMGs and 8 X-ray AGNs, they can provide sufficient amounts of ionizing photons.

Caveats:

- escape fraction of ionizing photons is unclear.
- other power sources are not excluded.

The role of the filaments in galaxy growth



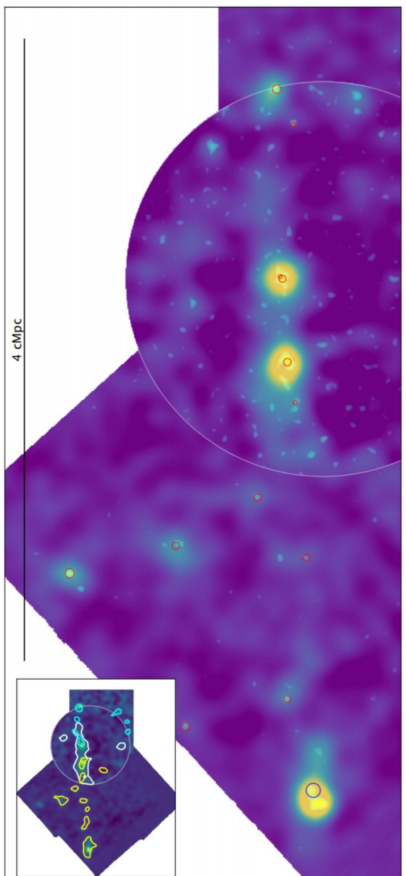
❖The Lyα filaments are found at the proto-cluster core that would have a deep potential well.
❖The massive filaments (>10^{12} Msun, with assumptions) connects starbursts (and massive molecular gas reservoirs) and X-ray AGNs (i.e., growing SMBHs).

=> We could be seeing a growing site of galaxies and SMBHs fed by cosmic web filaments.

Recent Progress in other fields

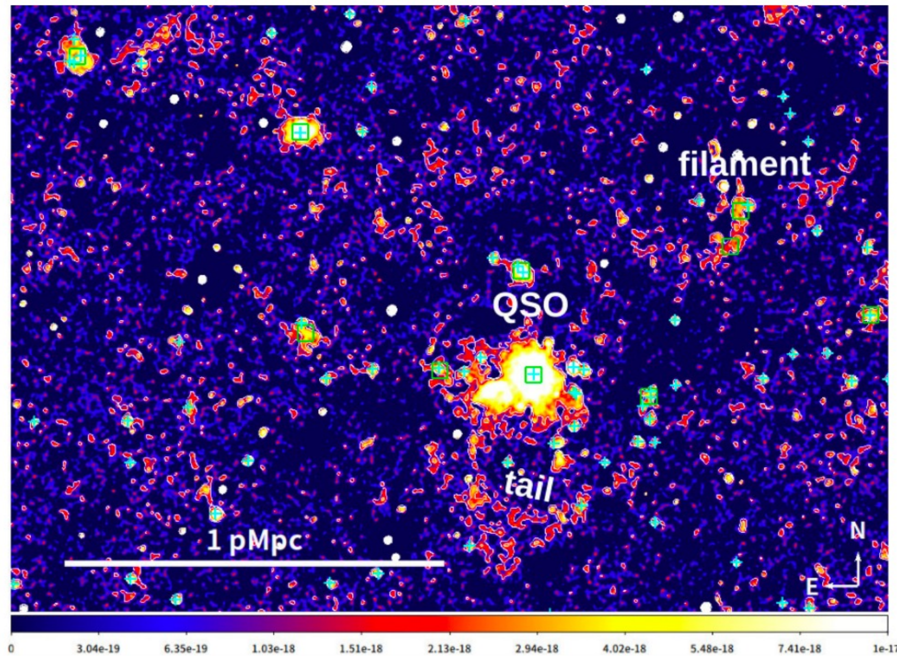
❖ Lyα filaments could be ubiquitous.

Lyα filaments at z=3.1, illuminated by a number of low-luminous LAEs?



Bacon et al. 2021, A&A, 647, 107

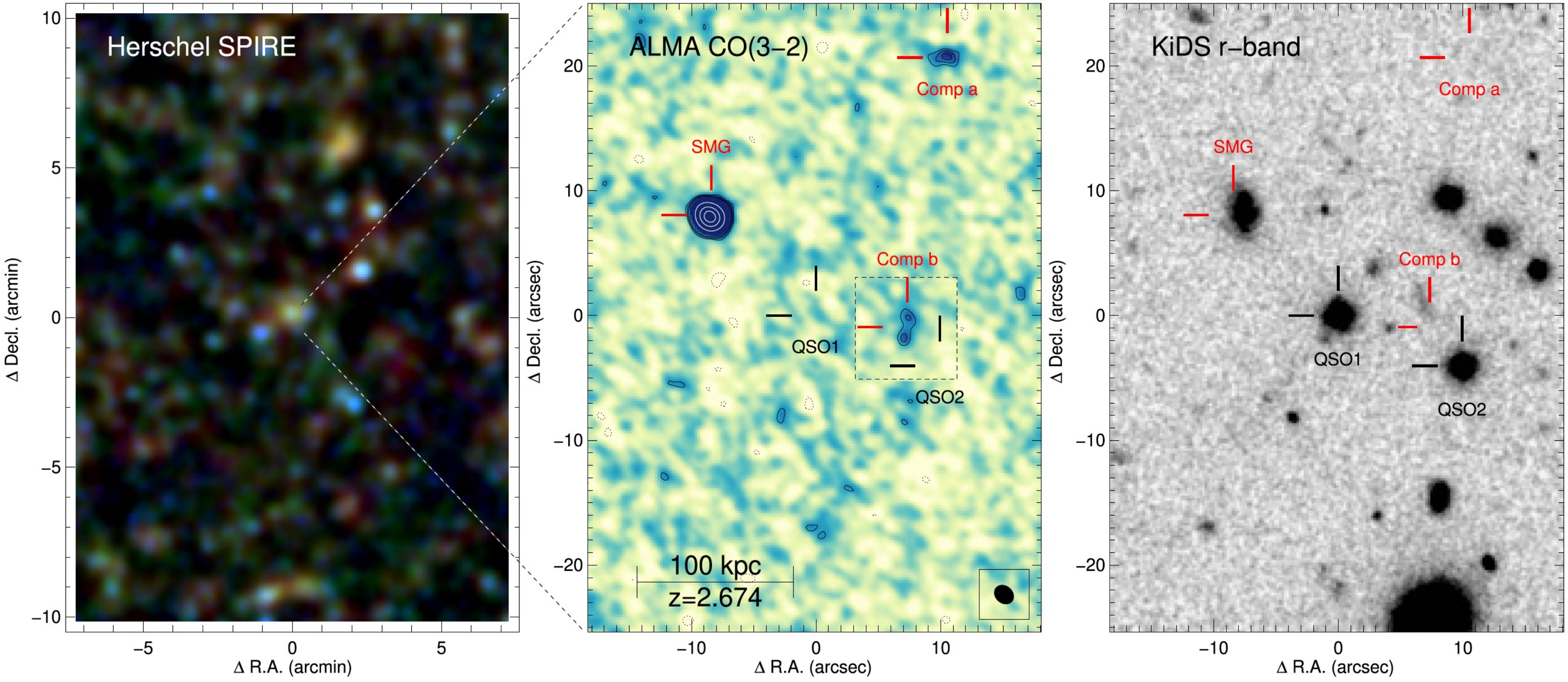
Lyα filaments at z=2.8, illuminated by a bright QSO?



Kikuta et al. 2019, PASJ, 71, L2

HI absorber associated with SMGs

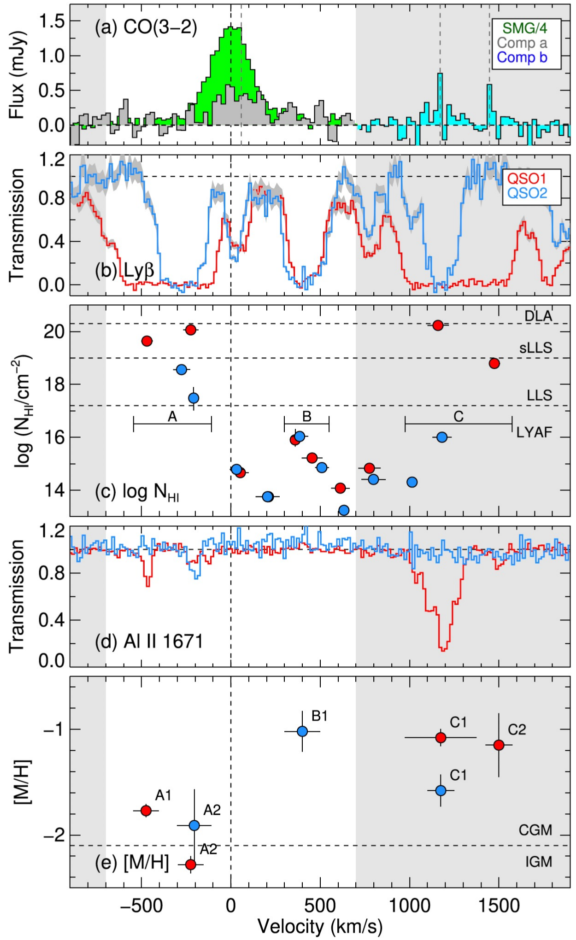
Fu et al. 2021, ApJ, 908, 188

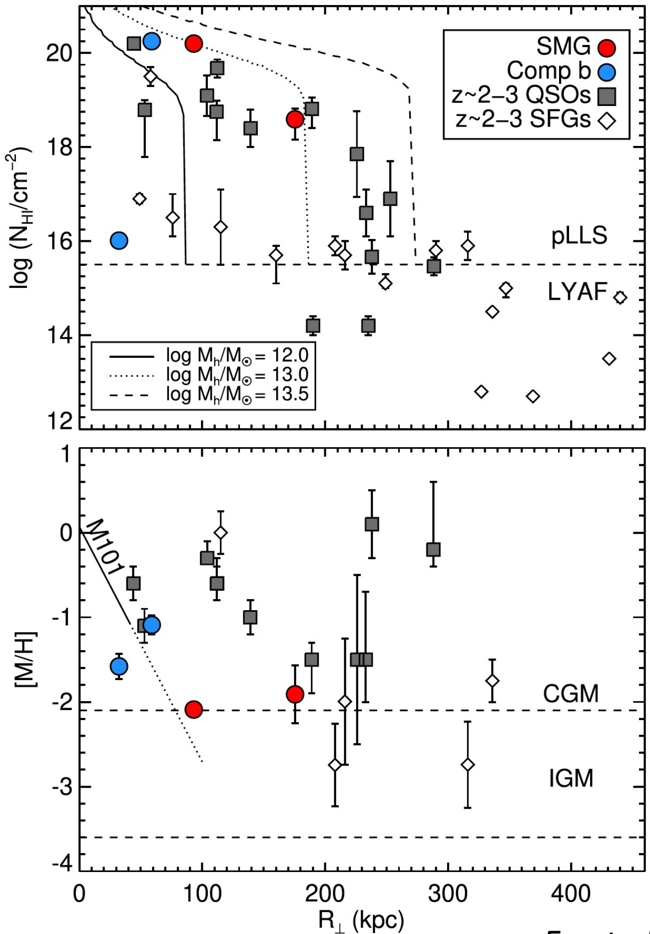


❖The target is a SMG at z=2.7 which has two QSO sight lines.

❖The SMG was originally selected as a Herschel source near a known QSO, and then its redshift was confirmed by ALMA (and NIR spectroscopy).

HI absorber associated with SMGs



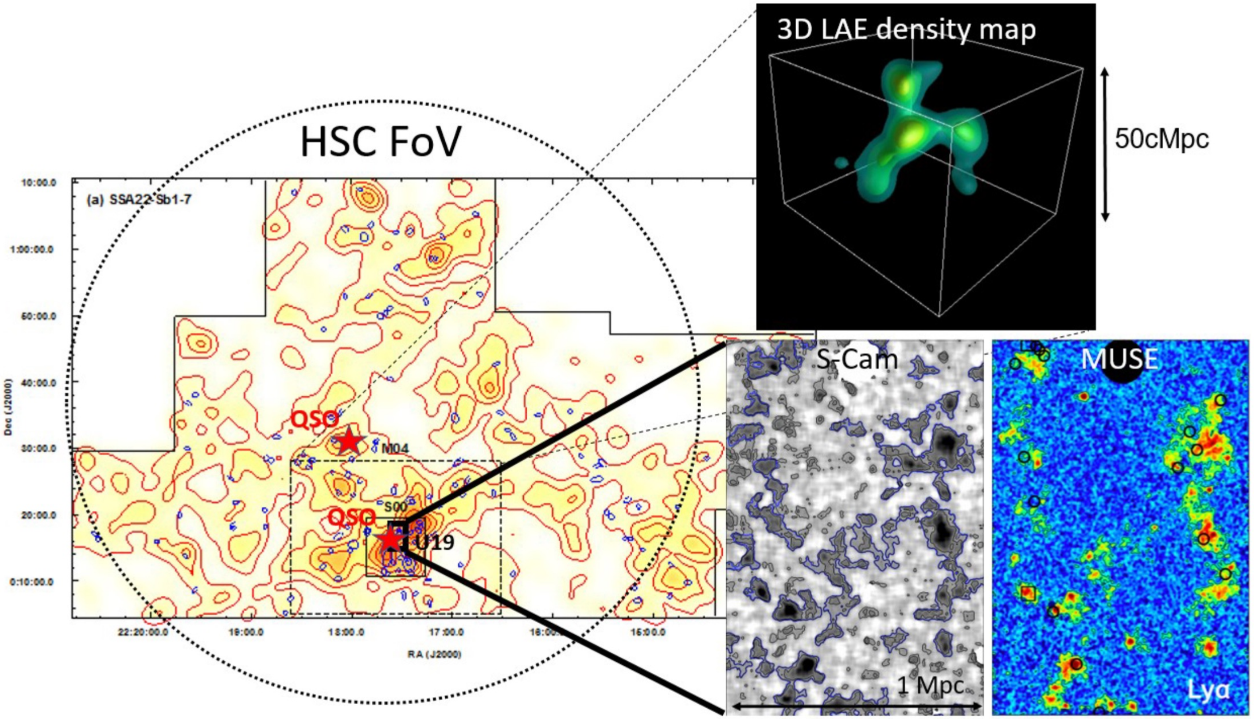


Fu et al. 2021, ApJ, 908, 188

❖The absorber has a) high HI column density, b) low metallicity, and c) nearly the same radial velocity.

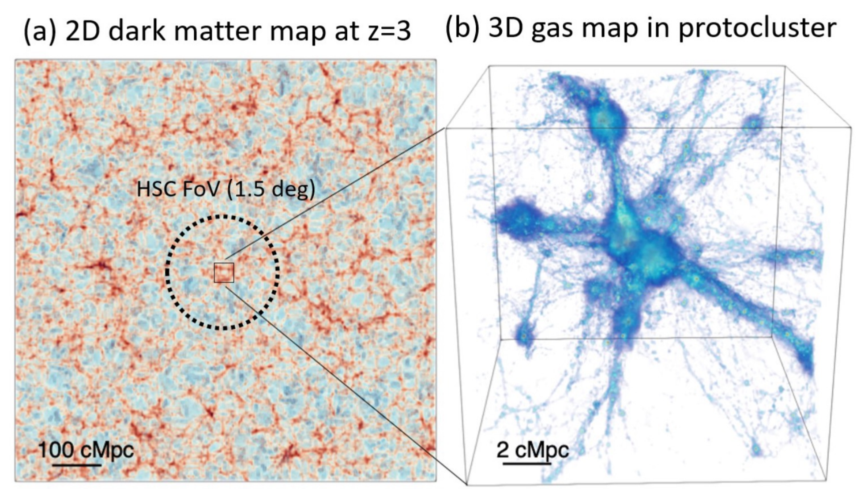
❖The absorber may be cold streams, the authors argued.

MIRACLES



❖MIRACLES (Mapping of Ionizing RAdiation on the Cosmic Web with Lyα Emission and Shadow) has been started (PI. Matsuda).

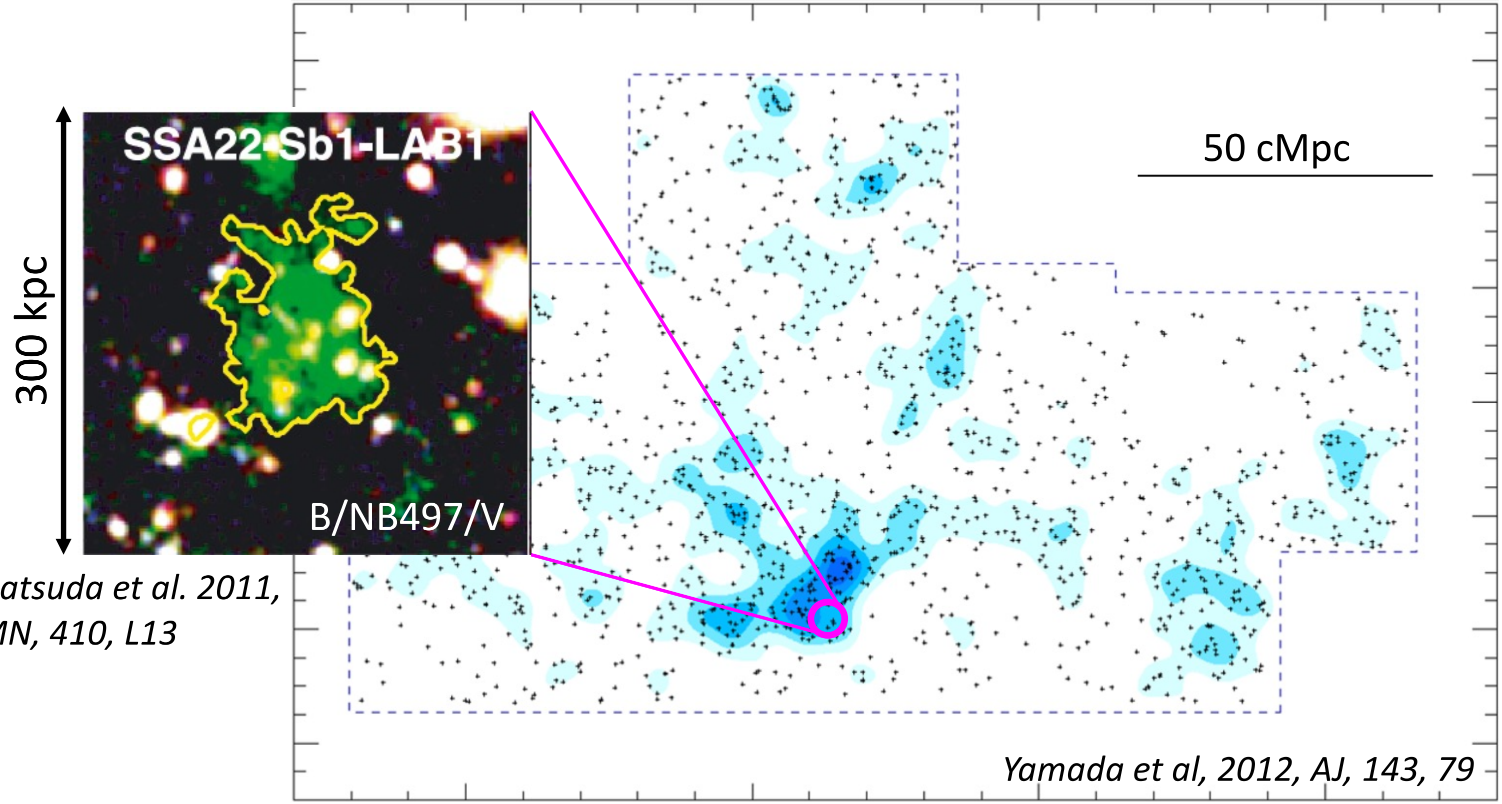
❖Using ~100 hrs of the HSC time, we will map the cosmic web on a 100 Mpc scale.



II. Extended [CII] and dust continuum in a giant LAB

Umehata et al. 2021, ApJ, in press (Arxiv: 2107.01162)

LAB1: A Giant Lyα Blob



Matsuda et al. 2011, MN, 410, L13

Yamada et al, 2012, AJ, 143, 79

❖LAB1 is a bright ($L_{Ly\alpha}$ ~ 10^{44} ergs/s) and extended (200 kpc) LAB located at the SSA22 proto-cluster, firstly discovered by Steidel et al. (2000).

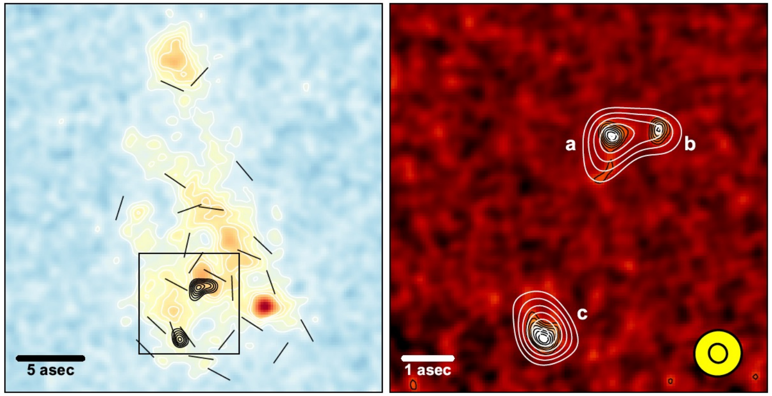
❖It is one of the most spectacular LABs and has been investigated intensively.

Questions for LAB1

❖What is the power source of the extended Lyα emission?

- Dust-obscured star-formation activity can be a power source (Geach et al. 2014; 2016).

- Obstacles:
  1. Extended dust continuum emission?
  2. Spectroscopic redshift?

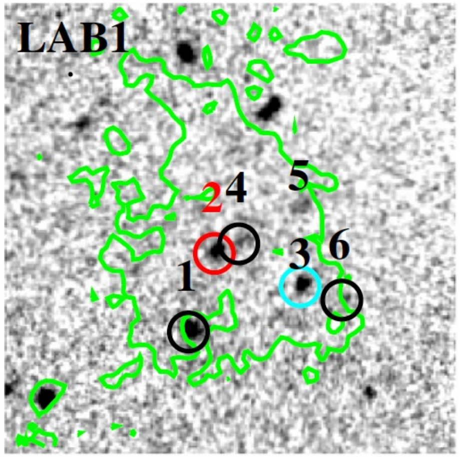


Geach et al, 2016, ApJ, 832, 37

❖What phase of galaxy formation are we seeing?

- MOIRCS imaging and spectroscopy suggests massive galaxy formation in LAB1 (Uchimoto et al. 2012, Kubo et al. 2015; 2016).

- Obstacles:
  1. Overall membership
  2. Information of the cold ISM



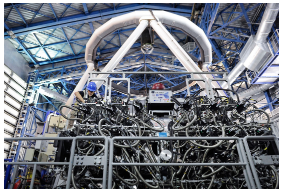
Uchimoto et al, 2012, ApJ, 750, 116

Observation

❖ALMA (Umehata+, Hine+)

- [CII]158 and rest frame ~160um in Band8
- [NII]205 and rest frame ~210um in Band7
- CO(4-3) and rest frame ~690um in Band3

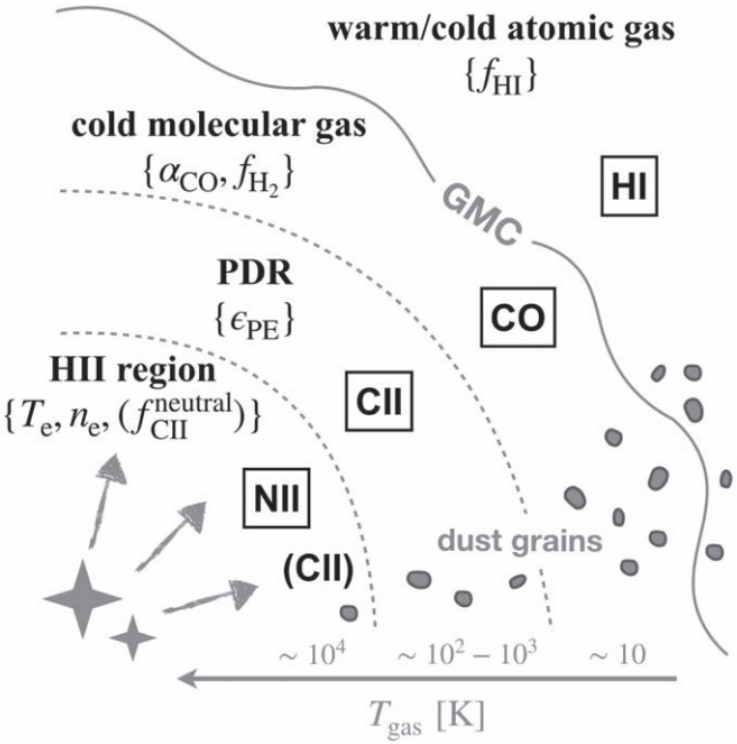
=> We can trace multi-phase ISM in LAB1.



❖VLT/MUSE (Swinbank+)

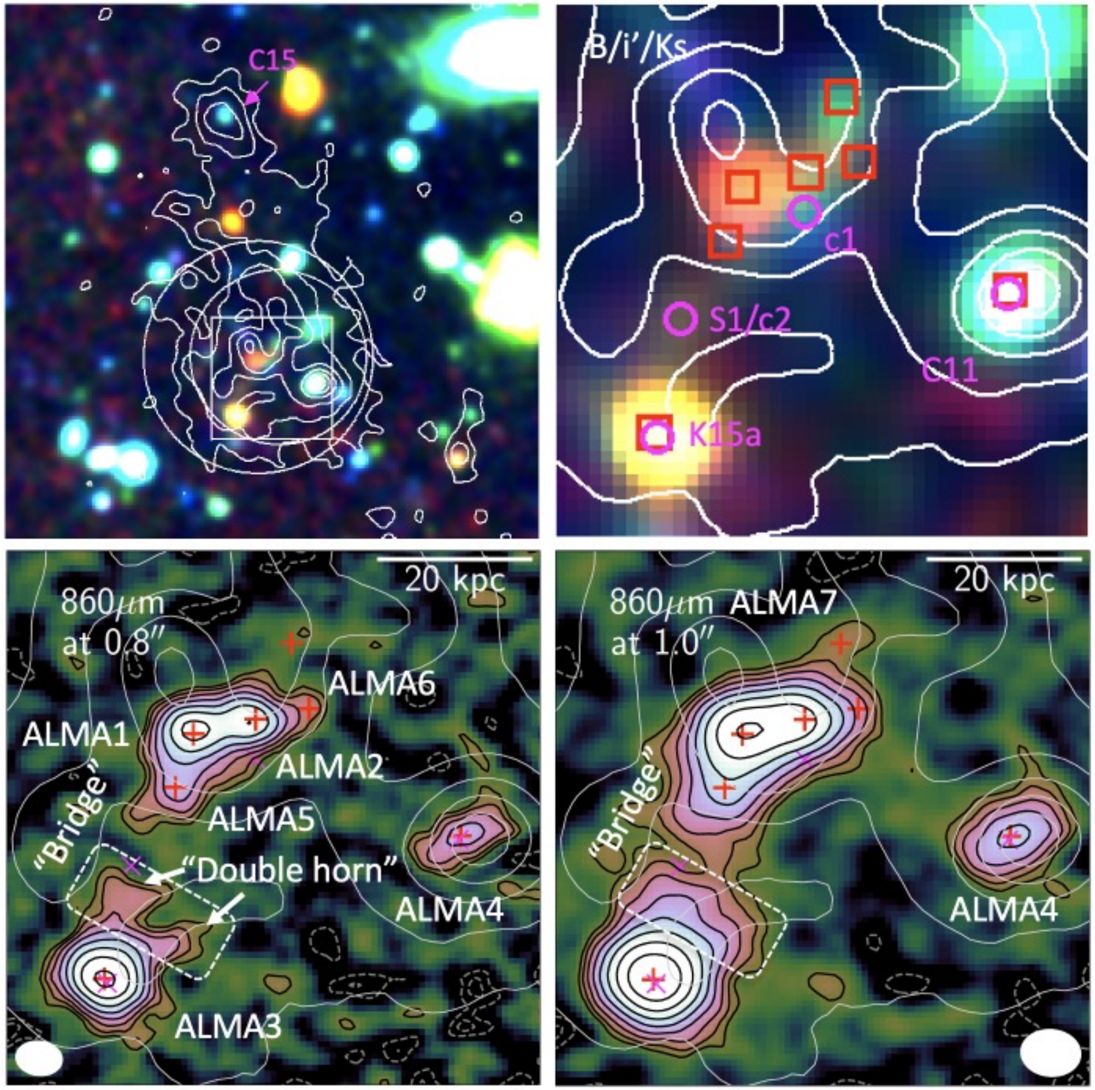
- Lyα

=> We can trace HI Lyα emission in 3D.



Sun et al, 2019, ApJ, 887, 142

Dust Continuum



❖ Dust continuum emission is extended across LAB1.

❖ Source decomposition shows eight individual components.

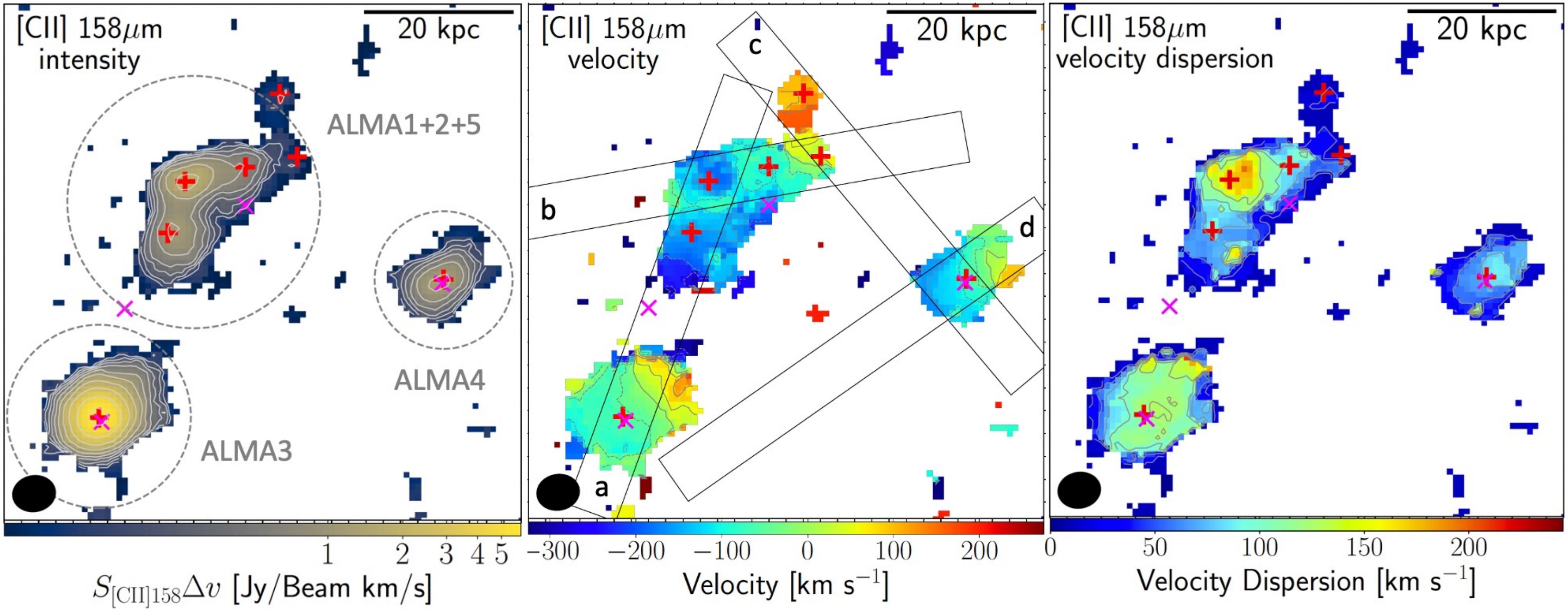
- ALMA1~ALMA5
- ALMA6~ALMA7, Bridge

❖ ALMA1~ALMA5 have

S_{860} = 0.2-1.0 mJy

SFR_{IR}=20-100 Msun/yr.

[CII] Moment Maps

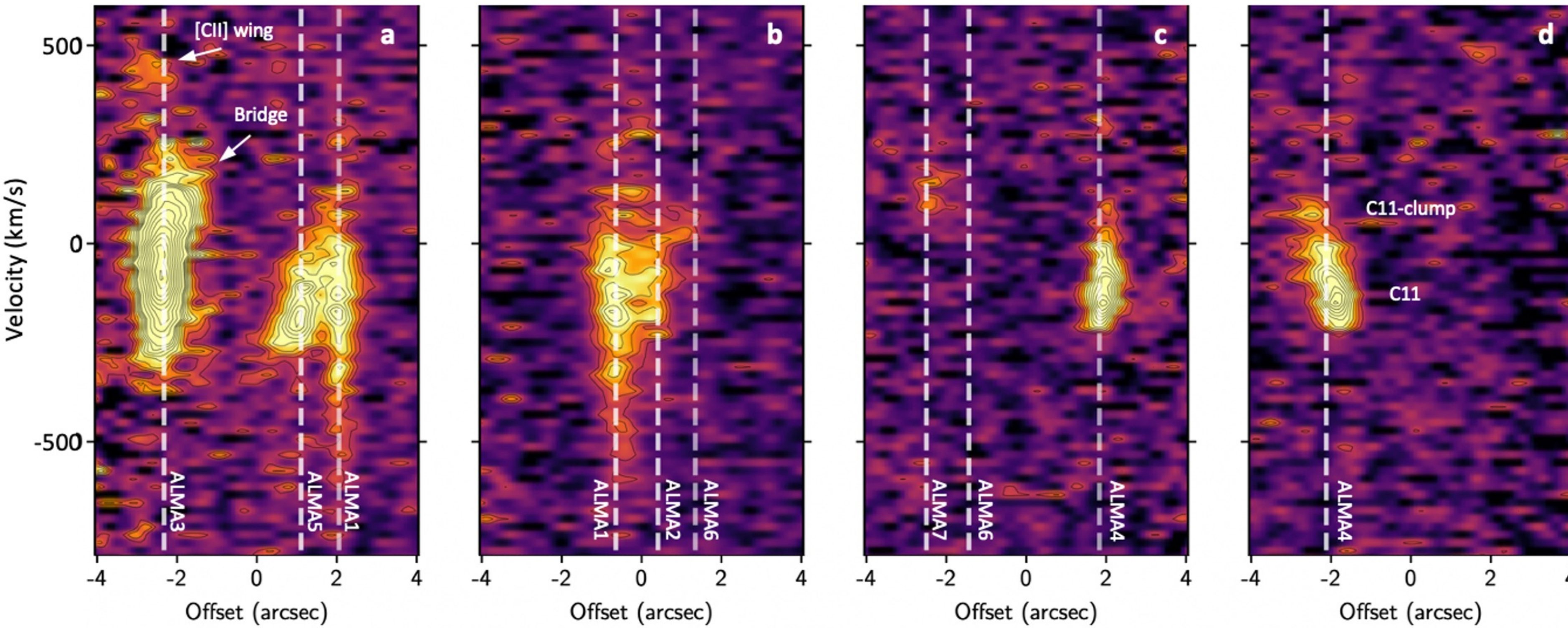


❖[CII] emission is also very extended, which is generally co-spatial with dust continuum. This confirms that dust continuum emission is exactly at z=3.1.

❖[CII] shows coherent velocity structure at a very narrow velocity range. ALMA1~ALMA7 has a redshift of 3.0987-3.1006.

❖A range of velocity dispersion is observed, suggesting turbulent nature in some regions.

[CII] P-V Diagram

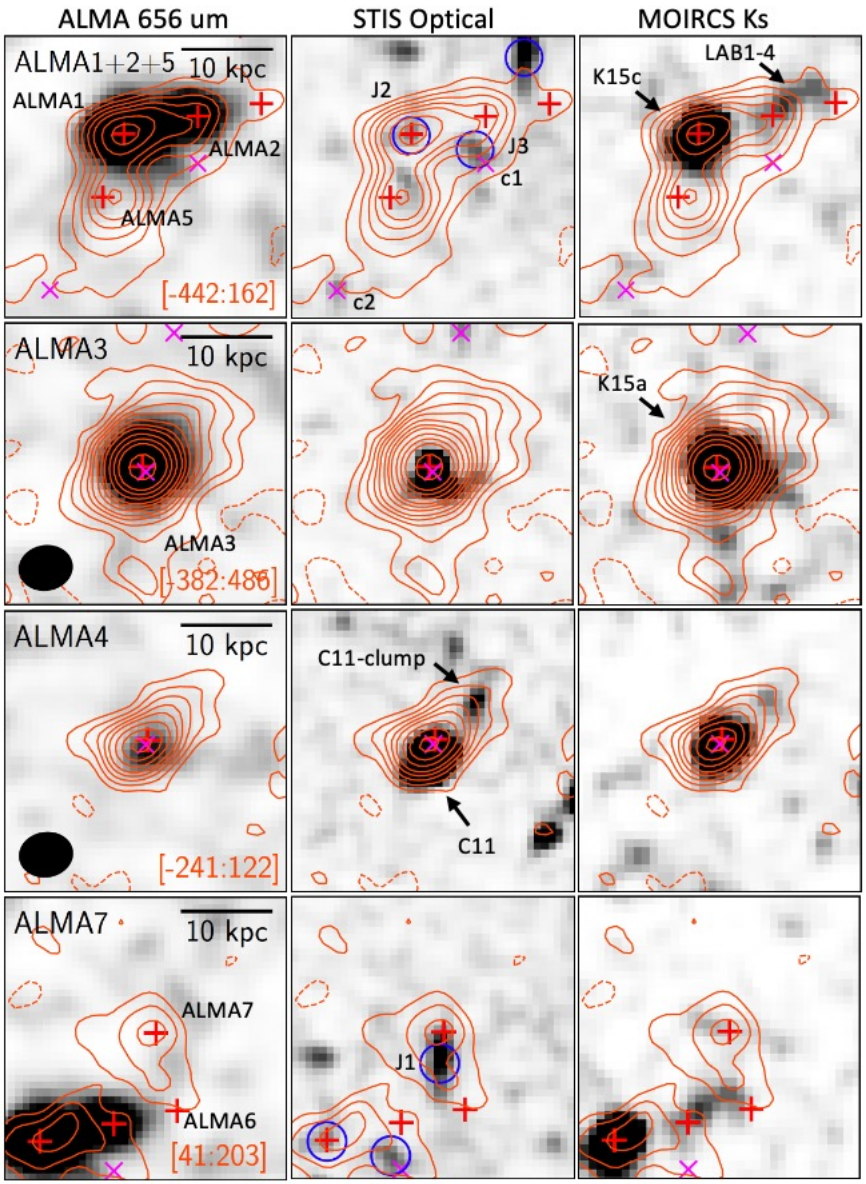


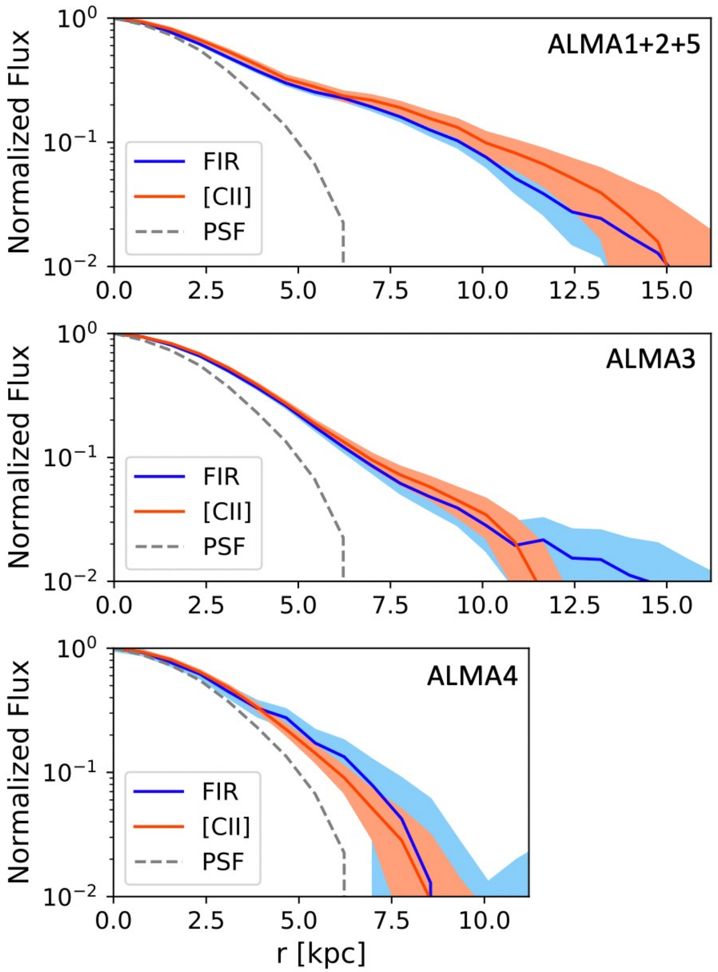
❖ALMA5, which is blank at any optical/NIR wavelengths, is likely to have a rotating disk.

❖ALMA2 shows highly disturbed morphology. This could be due to merging process with ALMA1, and ALMA6/ALMA7 may be a tidal component.

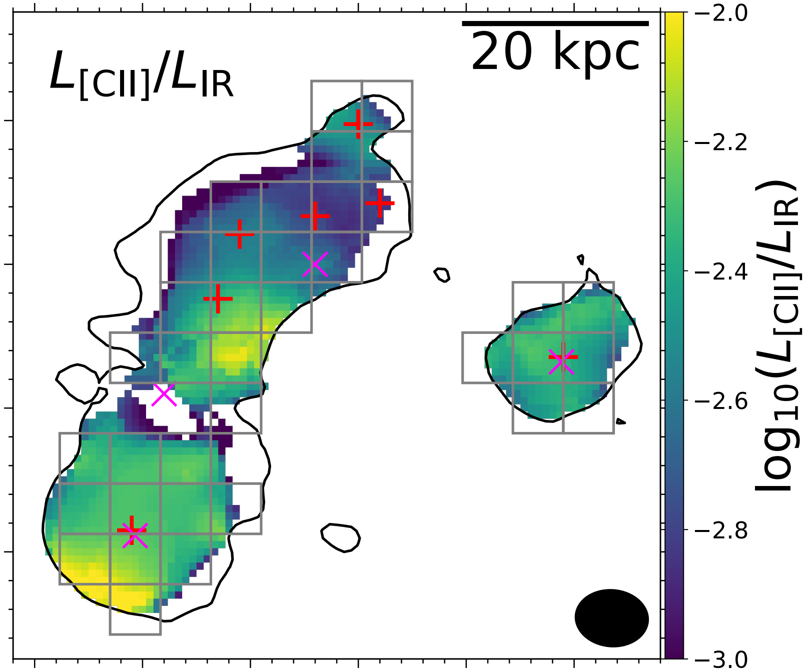
❖ALMA3 have a red wing. This can be an outflow or a companion.

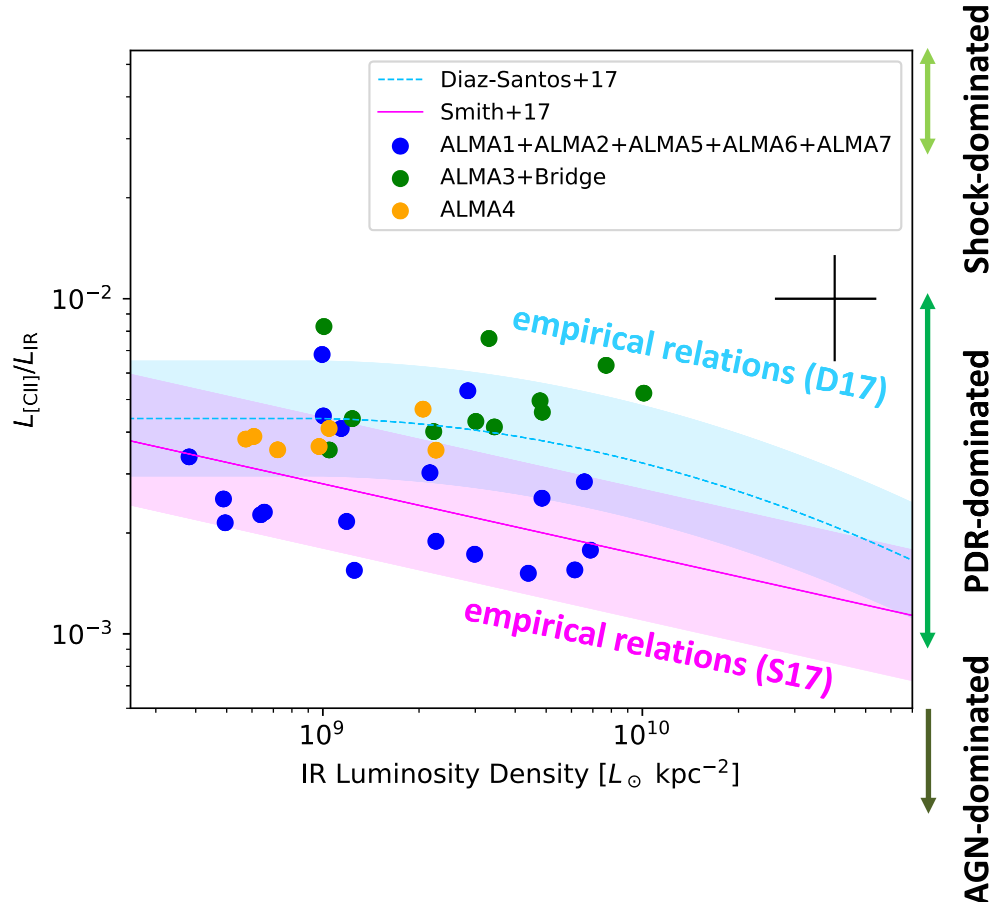
Extended [CII] emission





[CII] / IR Ratio





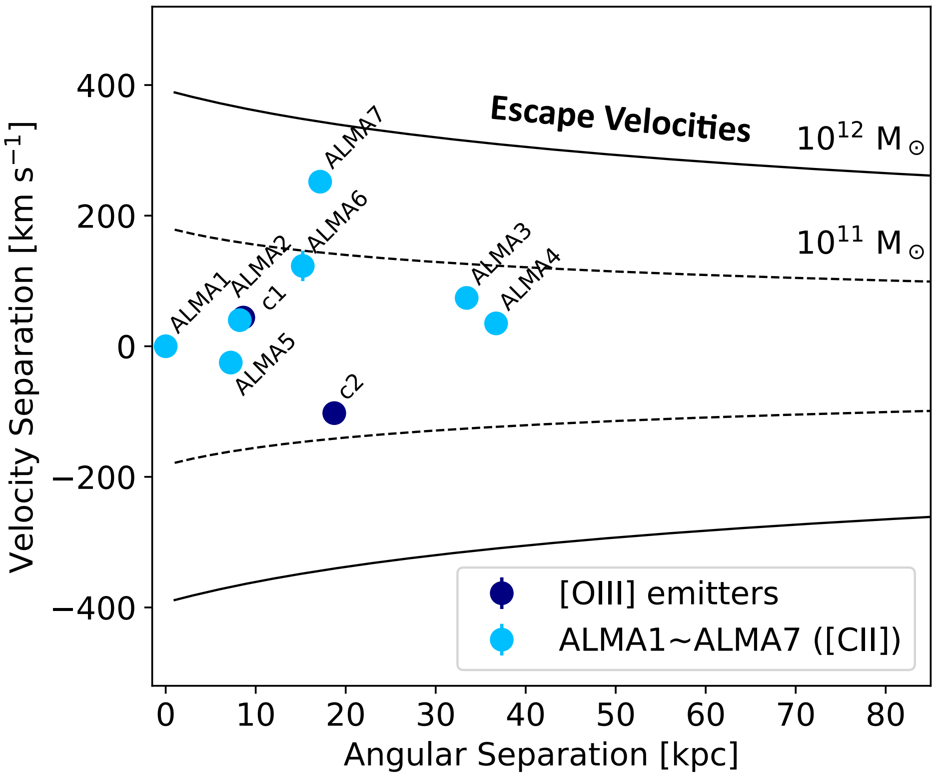
❖ The [CII] and IR luminosity ratio is derived in a ‘resolved’ manner.

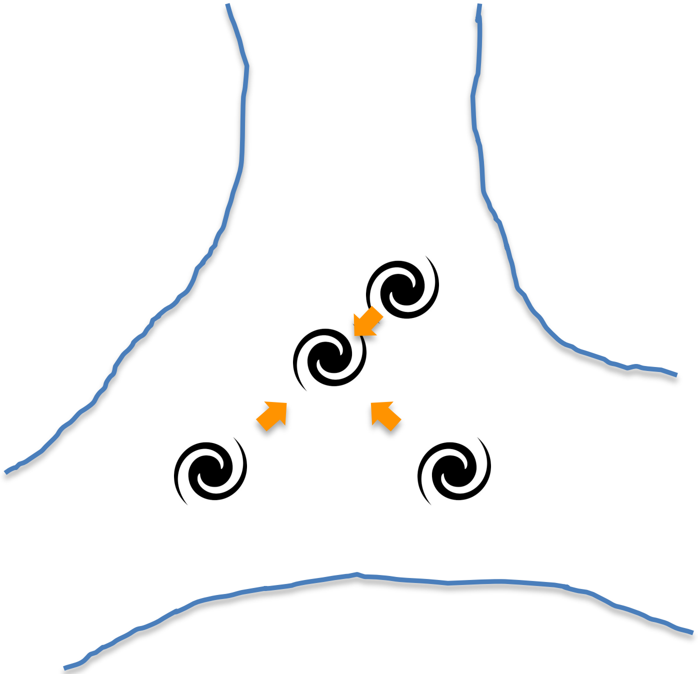
- The ratio has a significant range, which suggests a variety of ISM properties (e.g., radiation field strength, gas density, metallicity, etc) across LAB1.

❖ The ratio is generally explainable as PDR-origin.

❖ The extended [CII] may be contributed by companion, tidal component, and recycling gas.

Velocity Dispersion as a system



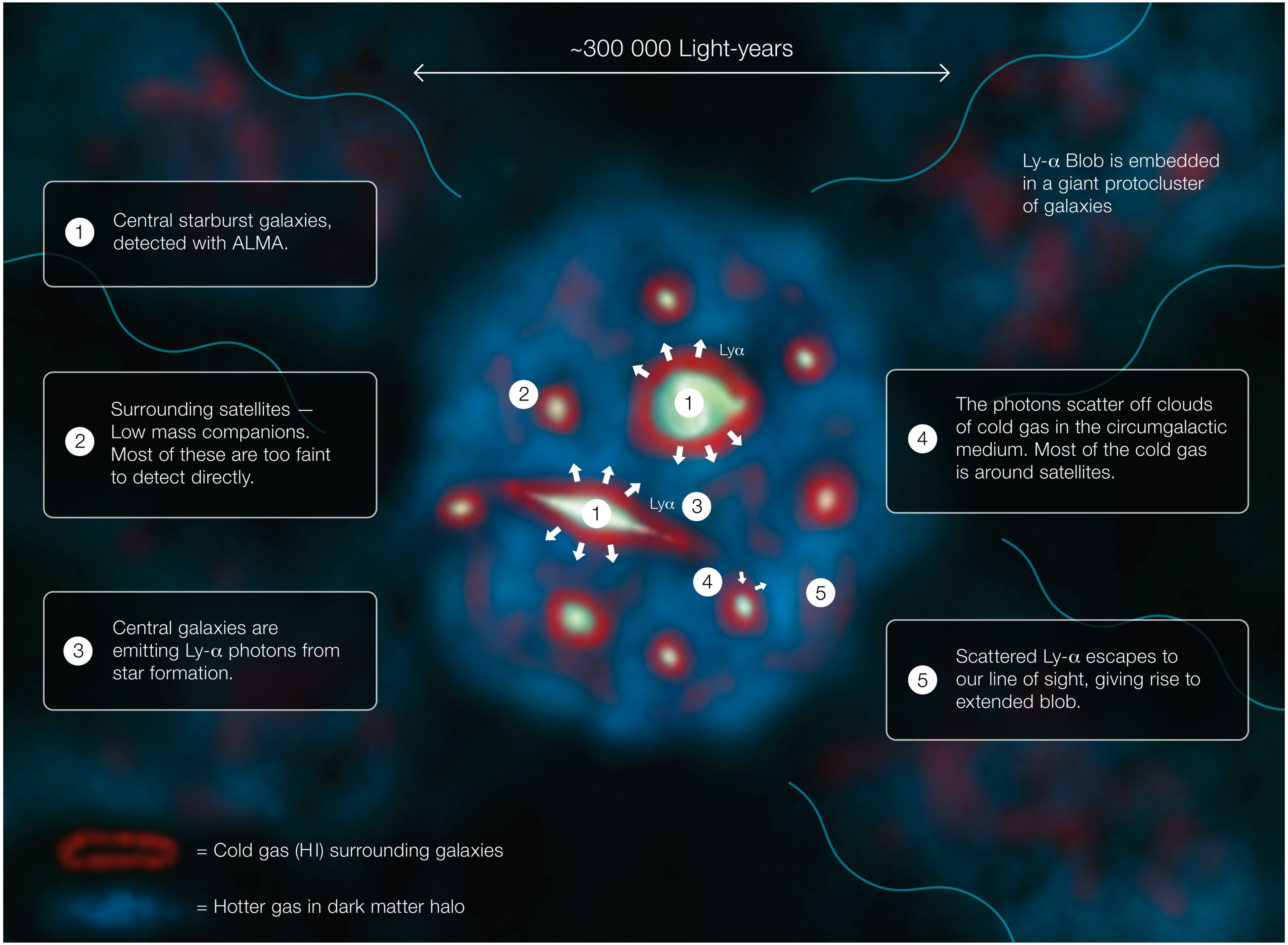


❖While M*-M_{halo} relation suggests M_{halo}>10^{13} Msun, the velocity separation is narrower than the corresponding M_{halo}.

❖The galaxy group in LAB1 would be in a merging phase during hierarchical galaxy assembly in the node of the cosmic web (as expected for progenitors of BCGs).

(Caveat: line of sight effect.)

The Origin of Lyα Emission



Geach et al, 2016, ApJ, 832, 37

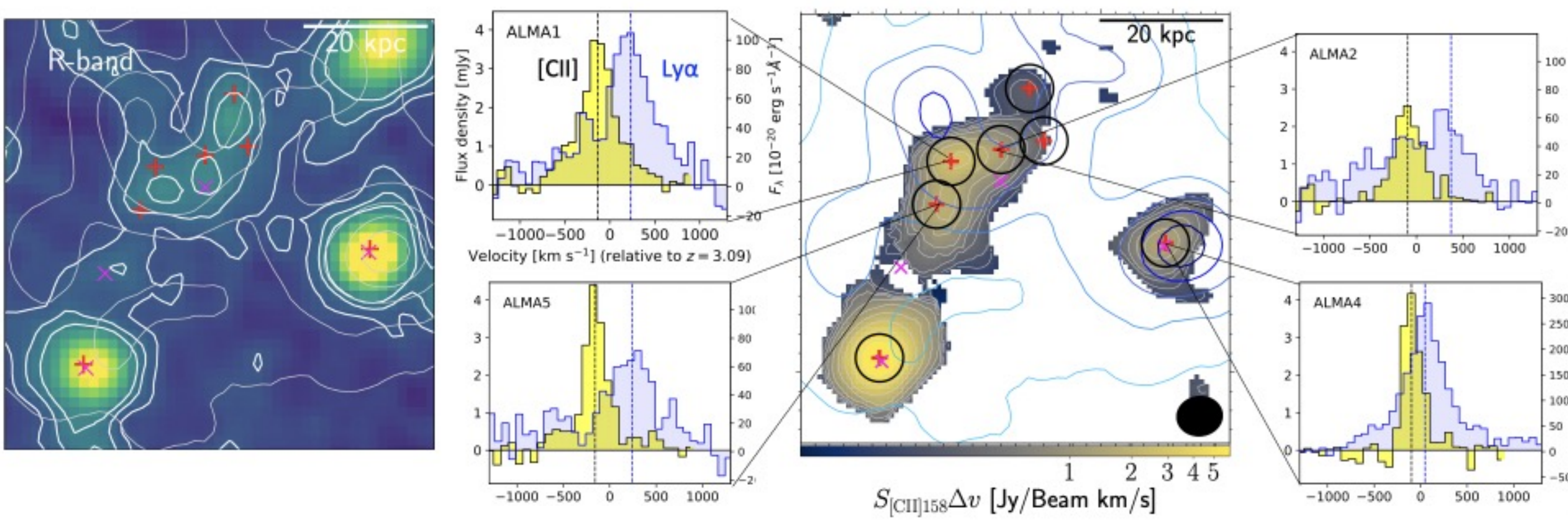
The Origin of Lyα Emission

❖Our ALMA results support the “central heating source” scenario (e.g., Hayes et al. 2011, Geach et al. 2016).

I. Spectroscopically confirmed dusty star-forming galaxies as a LAB1 member.
II. The total SFR (UV+IR, 300 Msun/yr) may account for the observed Lyα luminosity.

$$L_{\rm Ly\alpha}[{\rm erg\ s^{-1}}] = f_{\rm esc,Ly\alpha} \times 1.89 \times 10^{42} \times {\rm SFR}[M_\odot {\rm yr}^{-1}]$$

III. The Lyα profile shows a dominant red peak and a blue bump. This can be interpreted as an outflow (and extinction at the systemic redshift).



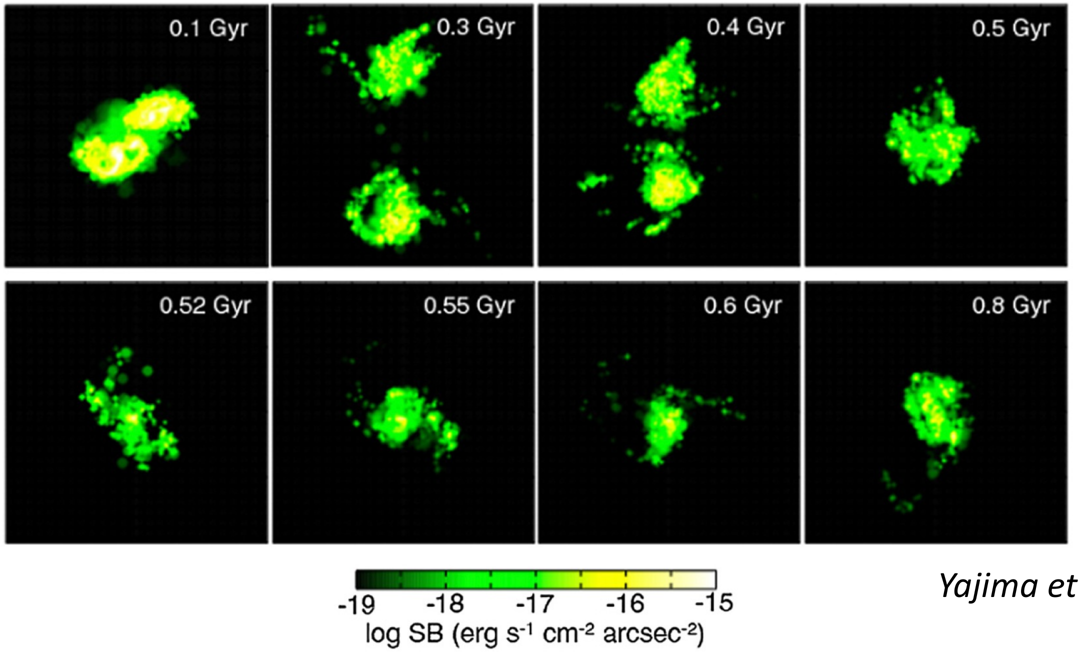
The Origin of Lyα Emission

❖ ...But there are also caveat.

I. fesc, Lyα 20% may be difficult, considering the dusty nature.

II. More bright SMGs in ADF22 (with SFR up to 2000 Msun/yr) are generally associated with fainter Lyα emission.

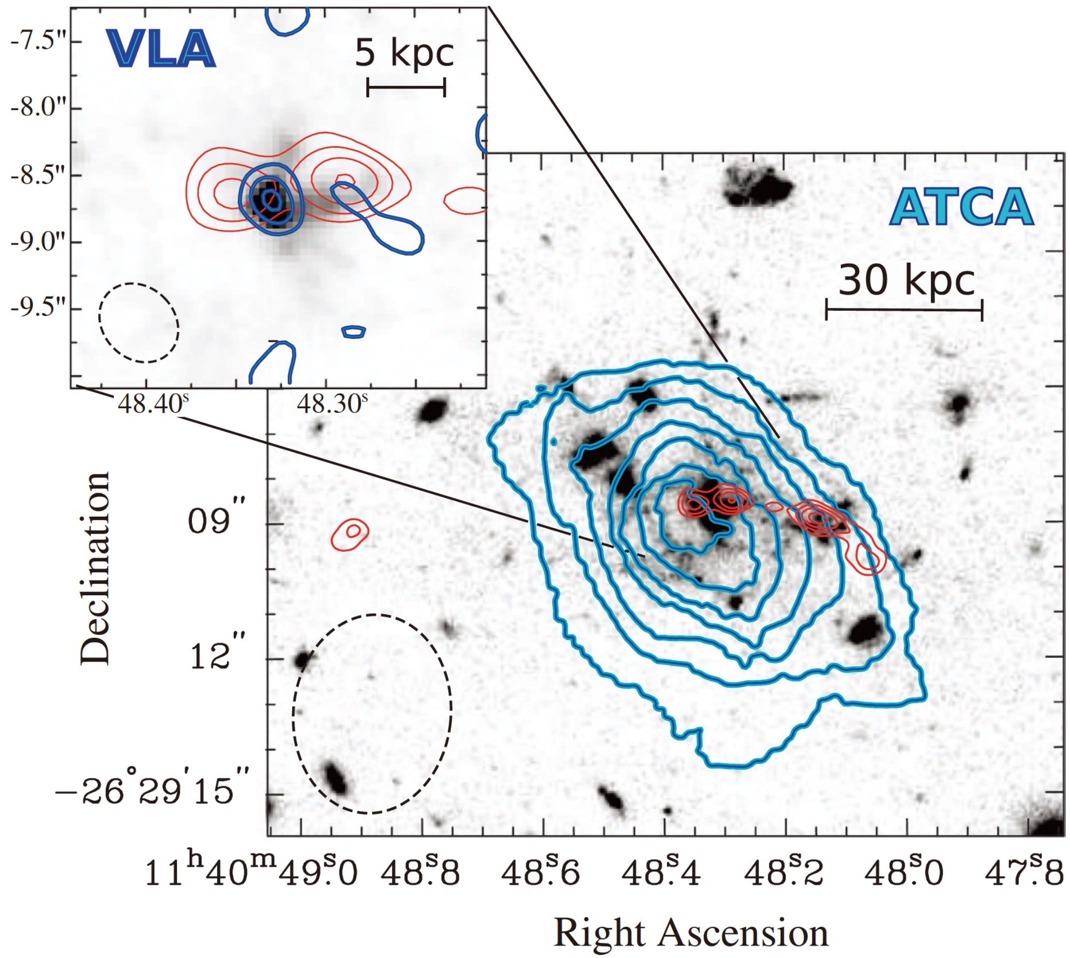
❖ We suggest cooling radiation induced by gravitational interactions an additional power source.

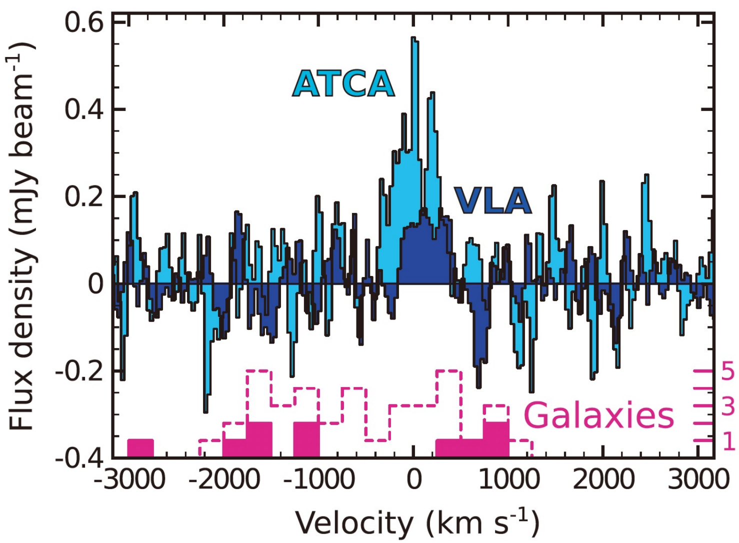


Yajima et al, 2013, ApJ, 773, 151

Extended Molecular Gas Emission

Emonts et al, 2016, Science, 354, 6316





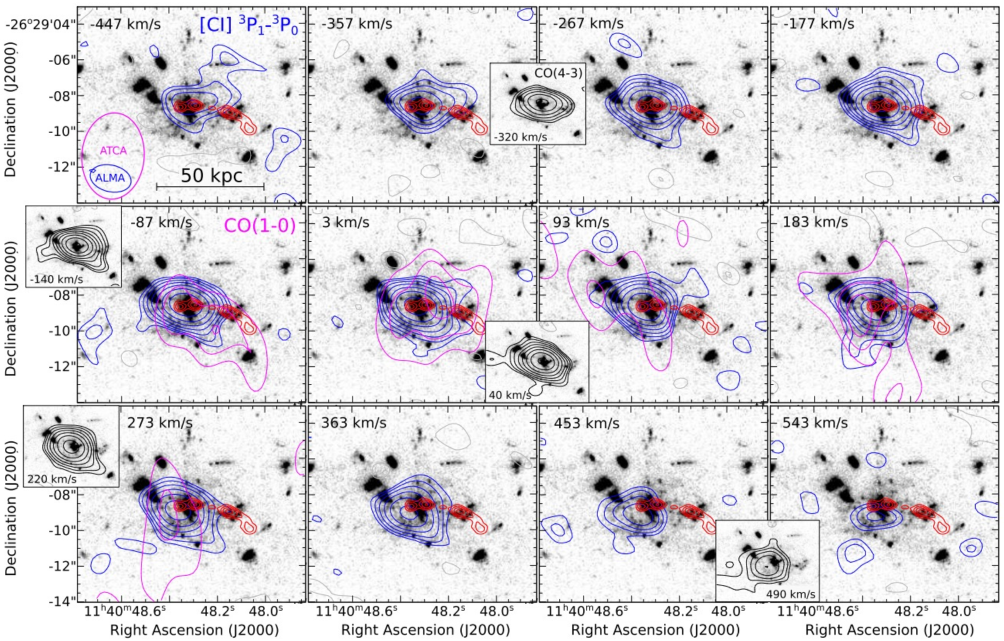
❖A large reservoir of molecular gas has been found in the Spiderweb proto-cluster.

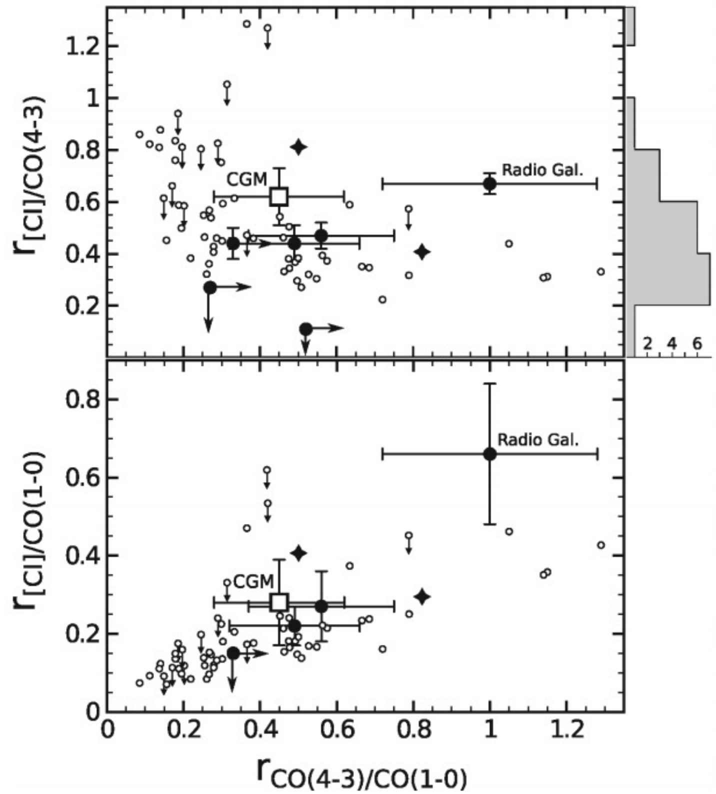
❖Most of the molecular gas lies between the proto-cluster galaxies and has low velocity dispersion.

=> "indicating that it is part of an enriched intergalactic medium."

Extended Molecular Gas Emission

Emonts et al, 2017, MNRAS, 477, L60





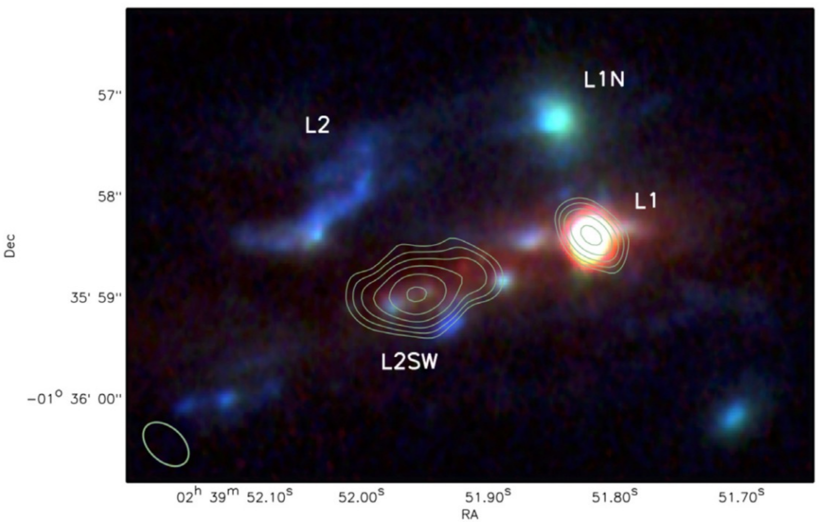
❖ For the Spiderweb, [CI](1-0) and CO(4-3) are also detected across ~50 kpc.

❖ The line ratio is similar to the ISM of member galaxies and other star-forming galaxies.

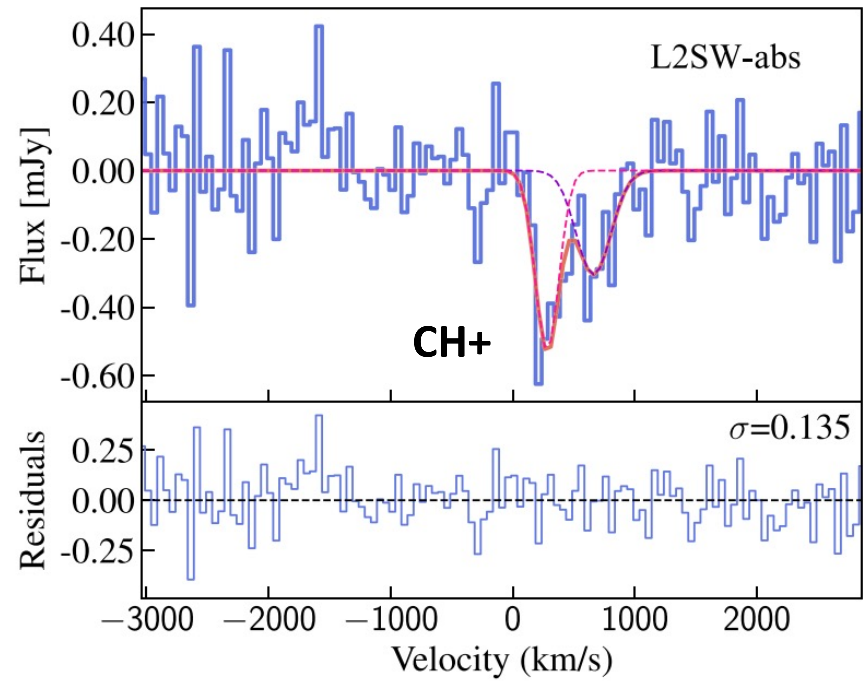
=> the Spiderweb may grow not directly through accretion of gas from the cosmic web. but from recycled gas in the CGM.

❖ Possible caveat: contributions from previously missed gas-rich galaxies?

Low-dense, turbulence gas reservoir



Vidal-Garcia et al, 2021, MNRAS, 2551, 2573
(See also Falgarone et al. 2017, Nature, 548, 430)



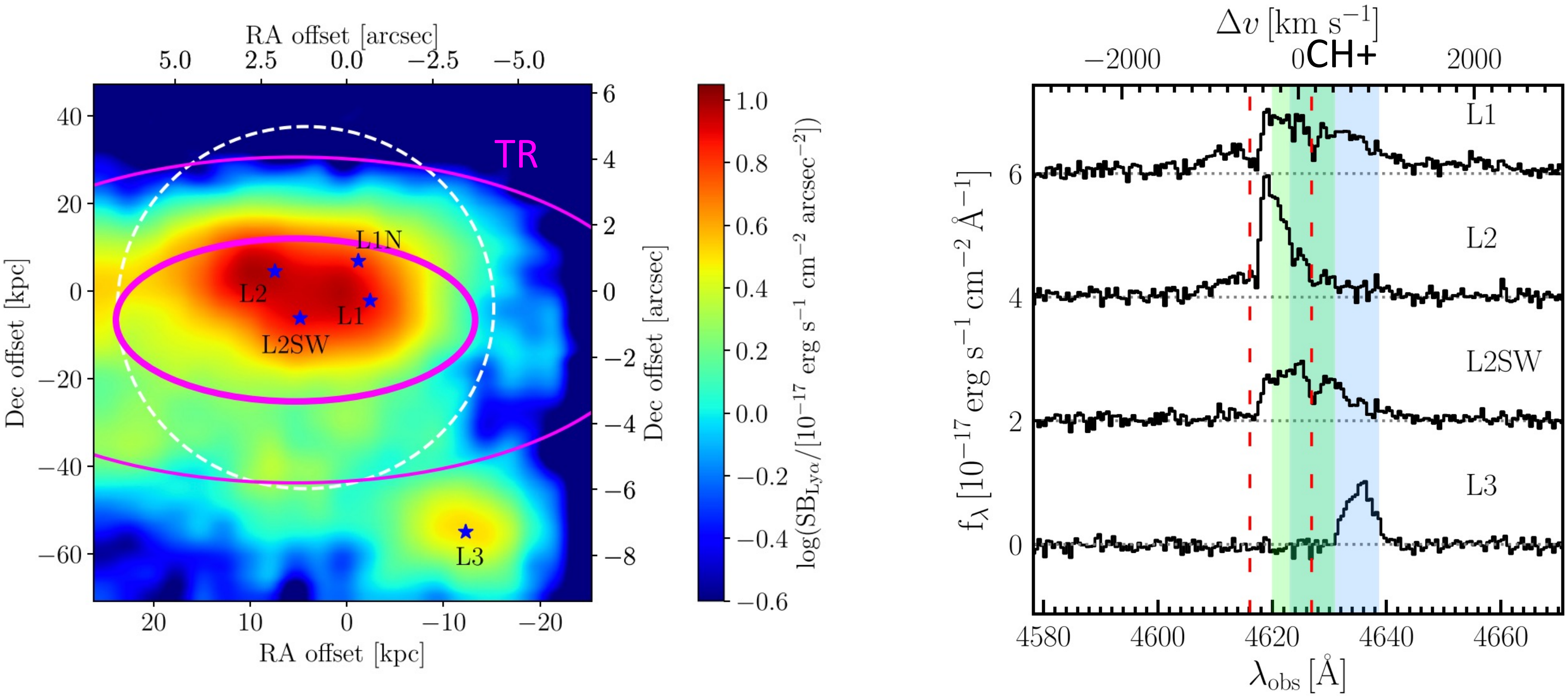
❖CH+(J=1-0) is detected in absorption for the bright SMG, SMMJ02399.

❖CH+ absorption is a marker of the dissipation sites of kinetic energy in diffuse gas.

- the formation of CH+ is highly endothermic (C^{+}+H_2=> E_{form} = 0.5eV).
- its lifetime is extremely short due to fast destruction by reactive collisions (w/ H and H_2).

Low-dense, turbulent gas reservoir

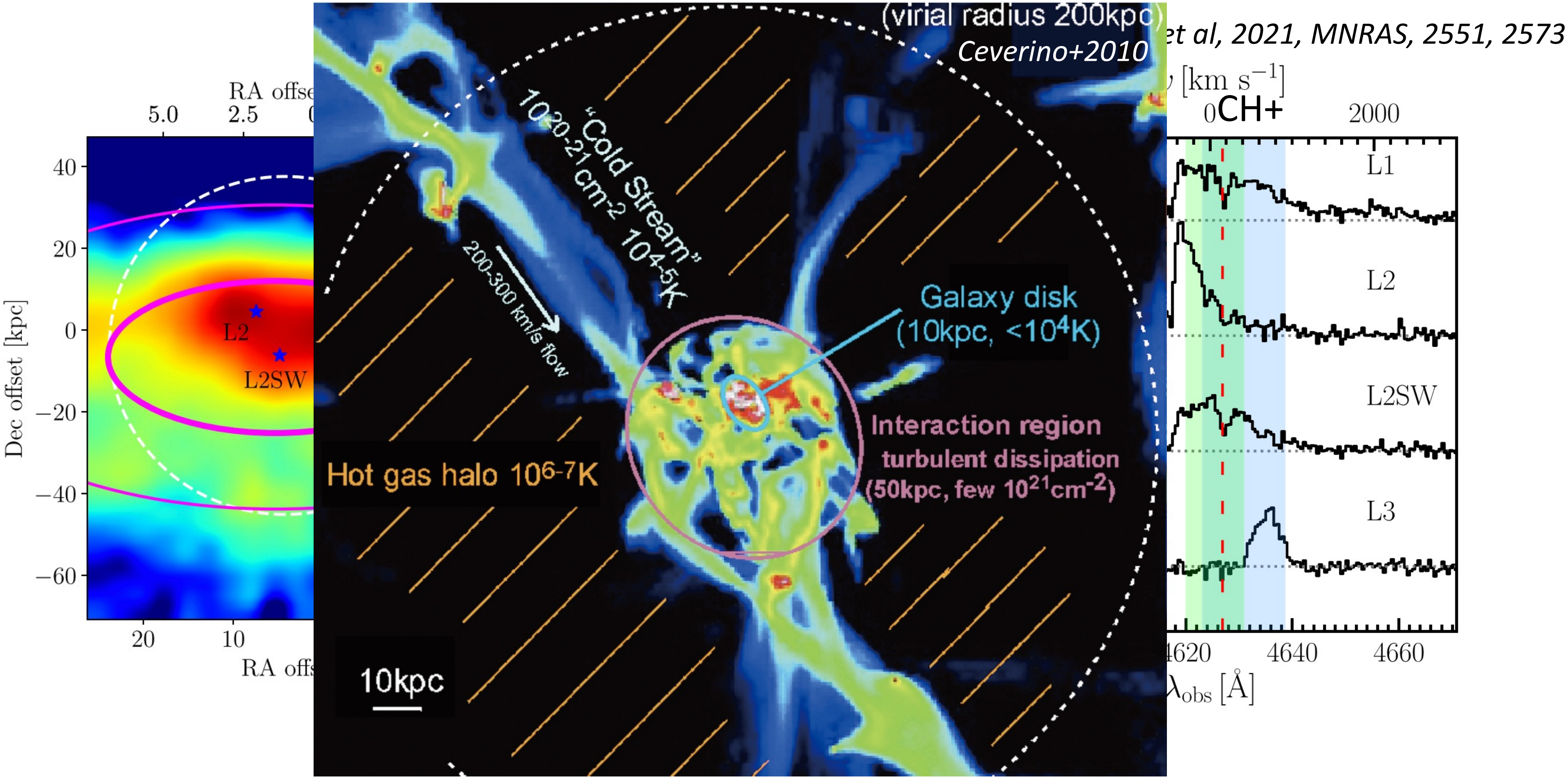
Vidal-Garcia et al, 2021, MNRAS, 2551, 2573



❖In the case of SMMJ02399, the turbulent gas reservoir is cospatial with extended Lyα emission. The velocity of CH+ absorption is also consistent with that of Lyα.

❖The turbulent gas reservoir may lie at the interface of the inflowing CGM and the high-velocity outflowing gas.

Low-dense, turbulent gas reservoir



❖In the case of SMMJ02399, the turbulent gas reservoir is cospatial with extended Lyα emission. The velocity of CH+ absorption is also consistent with that of Lyα.

❖The turbulent gas reservoir may lie at the interface of the inflowing CGM and the high-velocity outflowing gas.

Summary

❖To trace the IGMs/CGMs in the early Universe, we have multiple ways. Each has pros. and cons, and we should select/combine them, according to what we want to know.

❖Mpc-scale Lyα filaments have been found at the z=3 proto-cluster core, which could provide fuels for starbursts and SMBHs. The number of large-scale Lyα filaments is increasing.

❖ALMA uncovers unprecedentedly extended [CII] and dust continuum emission within LAB1, which is the most spectacular LAB in the field. We would be uncovering active baryon cycle during galaxy assembly in the active era.

❖ALMA can play an important role in the IGM/CGM studies.