CH^+(1-0) in a z~2.8 galaxy group: probe of multi-phasic turbulent gas reservoirs

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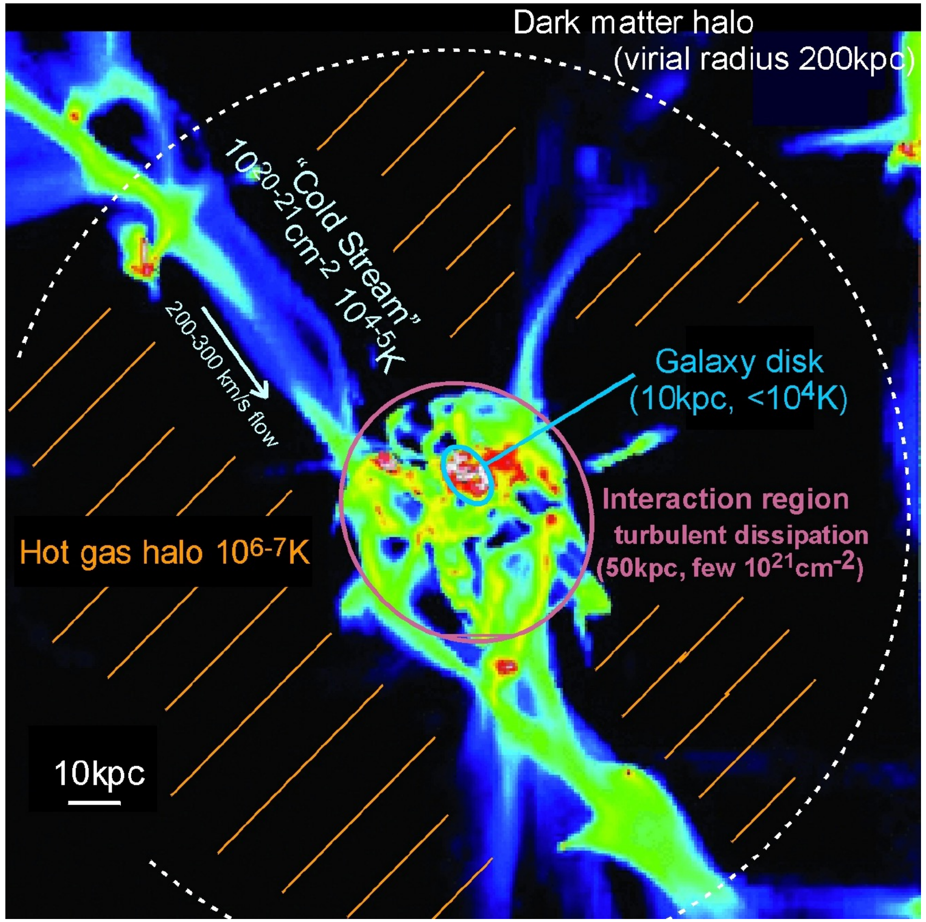
Large interaction regions: signposts of infall



Ceverino+2010, Gabor&Bournaud 2013, 2014

Growth of galaxies in simulations

➡ **accretion of gas**

Feedback from AGN and SF

➡ ejection of matter

Outflows observed, **inflows elusive**

(Dekel+2009)

Observation of **accretion**

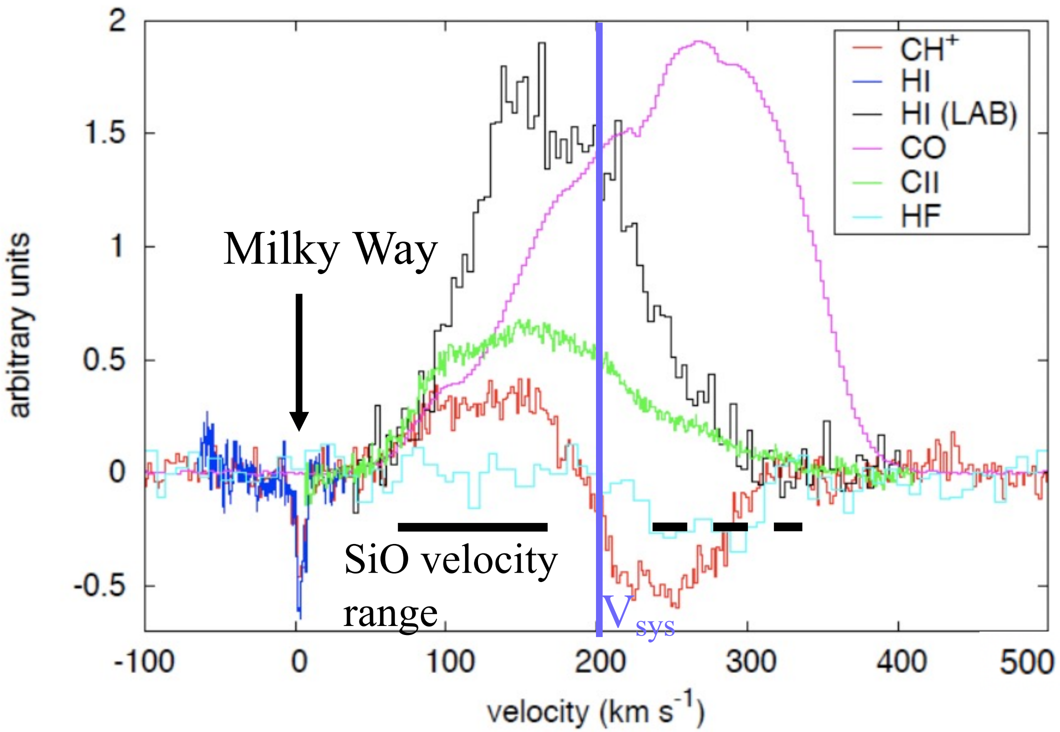
➡ **redshifted absorption** lines ✓

CH^+ profile of 2 local starbursts

M82

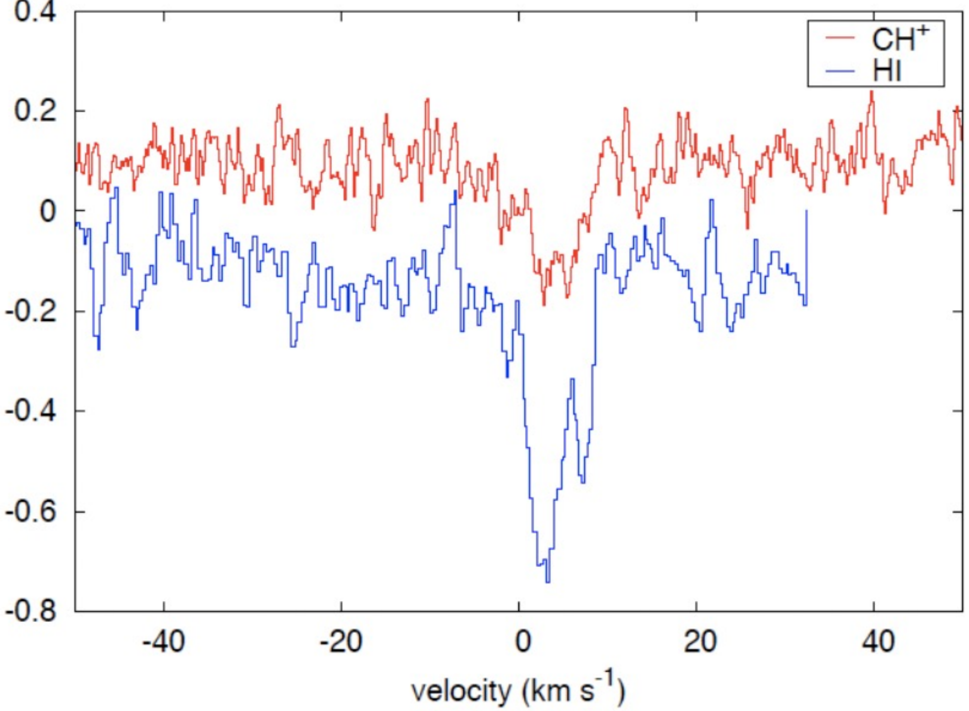
Chandra, HST, Spitzer

SFR~9.8 $M_\odot$/yr



CO(2-1) IRAM-PdBI Weiss+2010
CII Herschel/HIFI Loenen+2010
HF Herschel/HIFI Monje (priv. comm.)

Milky Way



Galactic absorption of CH^+ and HI:

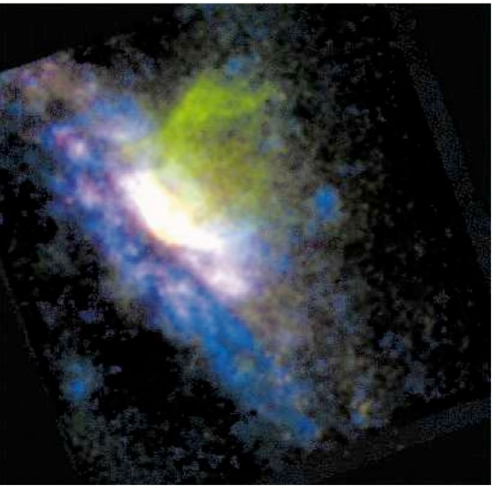
- Similar velocity coverage ~ 15km/s

Inverse P Cygni profile in M82:

- Redshifted absorption: **inflow**
- **Emission** at same velocity as SiO in **shocks** (García-Burillo+2001)

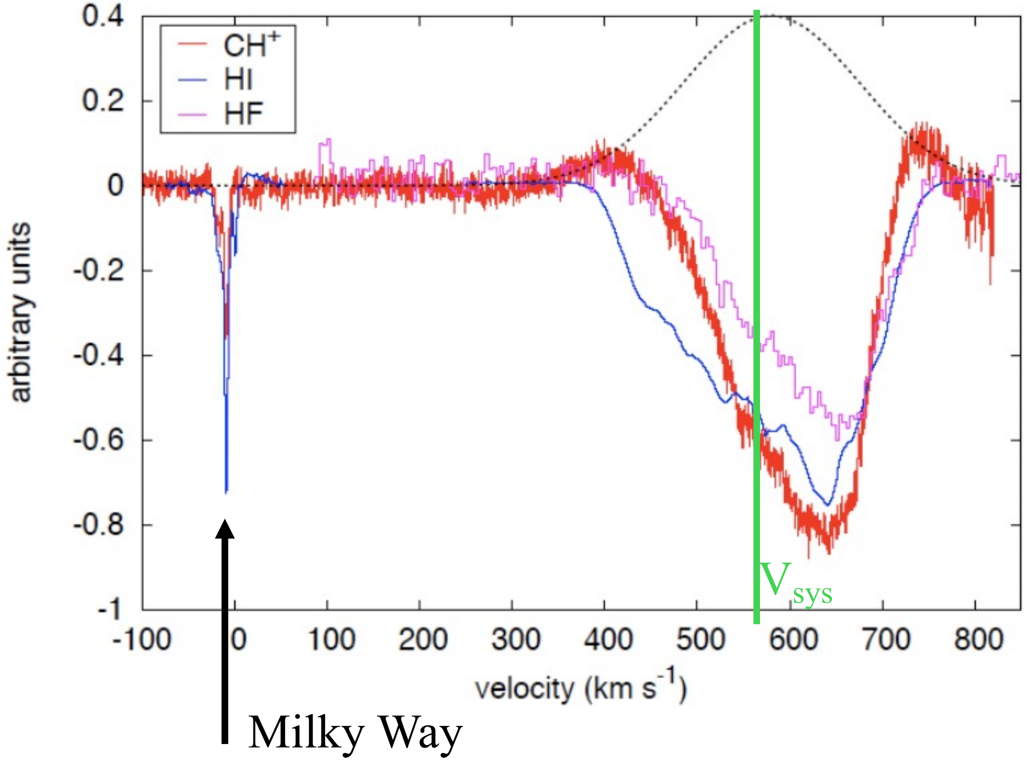
(Vidal-García+in prep.)

NGC 4945

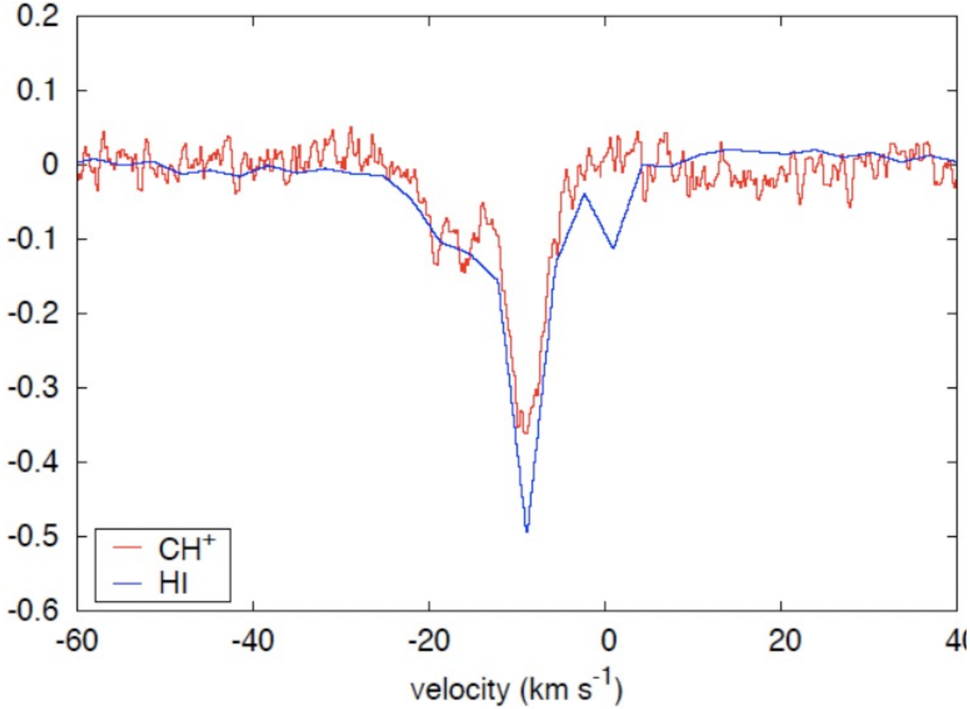


K-band, H_2, Paα
Marconi+2000

SFR~0.4 $M_\odot$/yr



Milky Way



- Nuclear HI absorption (Ott+2001)
- HF inflow rate ~ a few $M_\odot$/yr (Monje+2013)

- Similar shapes CH^+ and HI absorption profiles

(Vidal-García+in prep.)

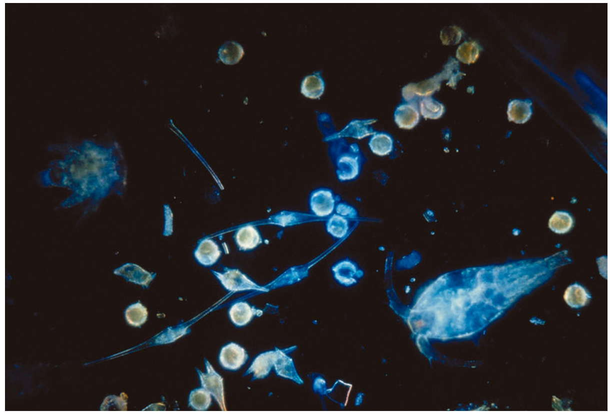
Why CH^+? Most fragile but precious tracer

- Highly **endothermic** formation: E_{form}~ 0.5eV ➡ supra-thermal energy needed
- Highly **reactive** ➡ short lifetime (~1 year at n_{CNM}) ➡ <u>**observed where it forms**</u>
- Enhanced by UV photons instead of photodissociated
- High dipole moment ➡ J=1-0 transition high ρ_{crit}:

➢ **Absorption** line: **diffuse gas** ($n_H < 10^3$ cm^{-3})
➢ **Emission** line: **high density gas** (shocks and PDRs, $n_H > 10^4$ cm^{-3})

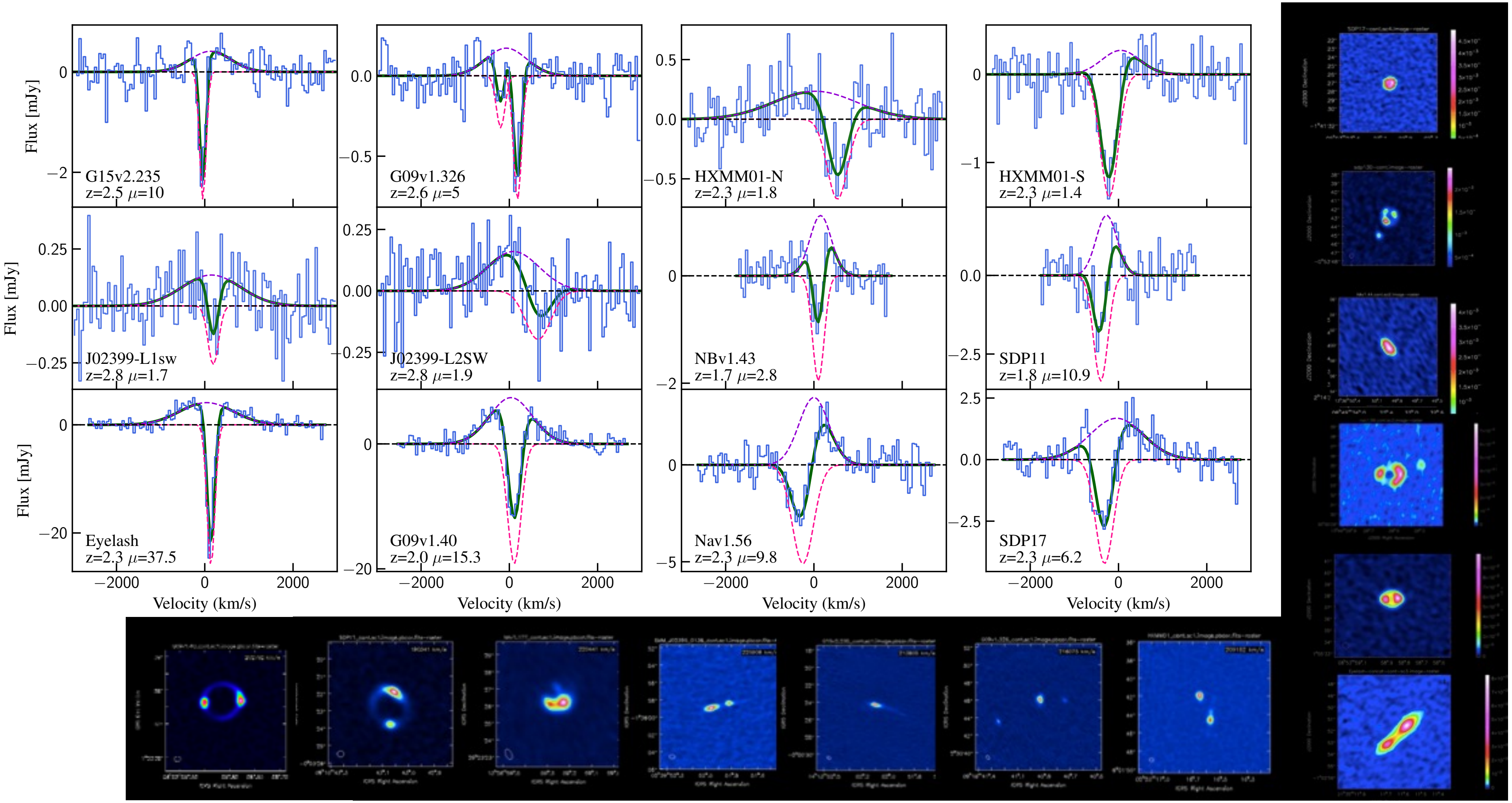
Tracer of turbulent dissipation

Counter of molecules <u>**formed**</u> in absorption beam



Paul Zahl

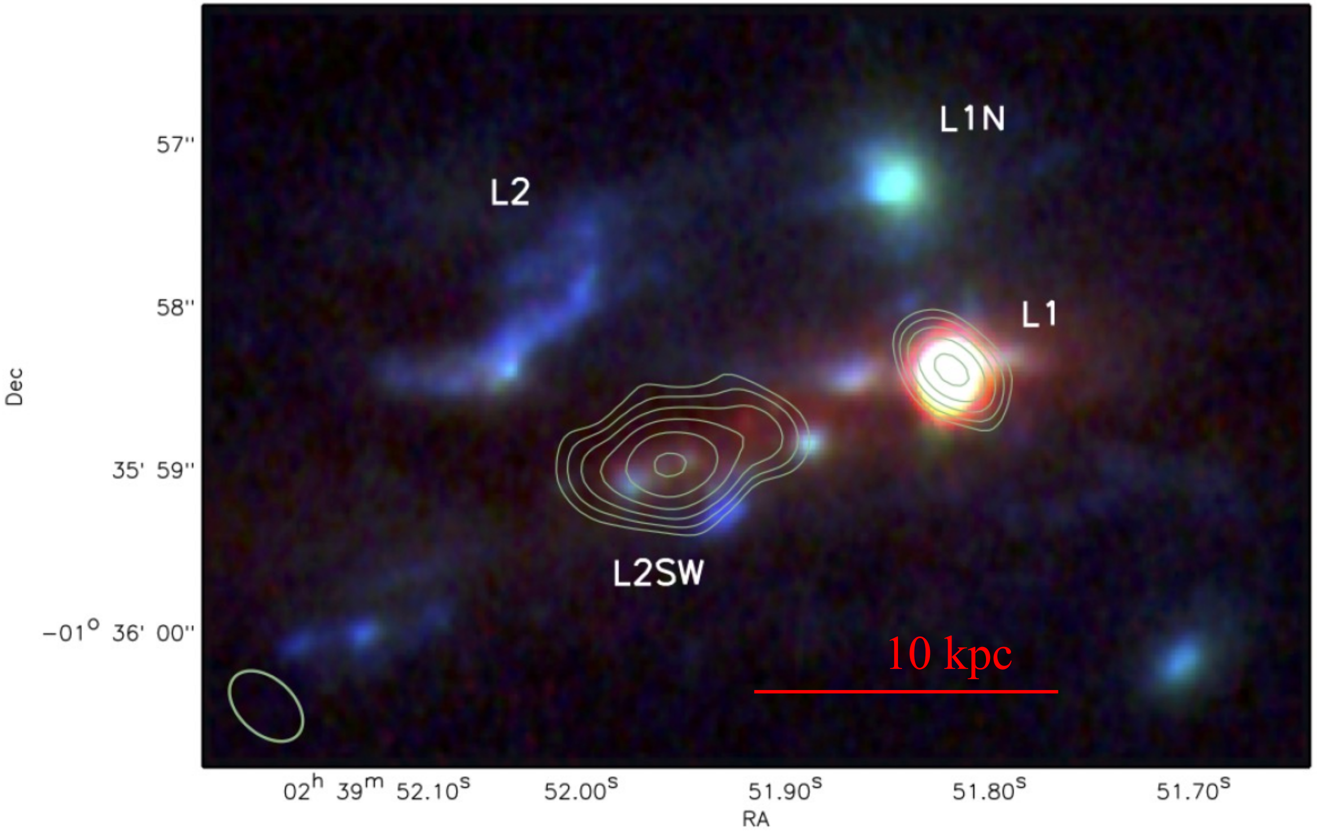
CH$^+$(1-0) in high-z lensed starburst galaxies



Falgarone+2017,
V-G+ in prep.

- 16/18 starburst galaxies observed in absorption CH$^+$(1-0) with ALMA: diffuse phase and starburst phase coeval

SMM J02399-0136 galaxy group



False color HST composite of SMM J02399-0136 galaxy group at z=2.8 and ALMA dust continuum contours

1arcsec at z=2.8 ~8kpc in source frame

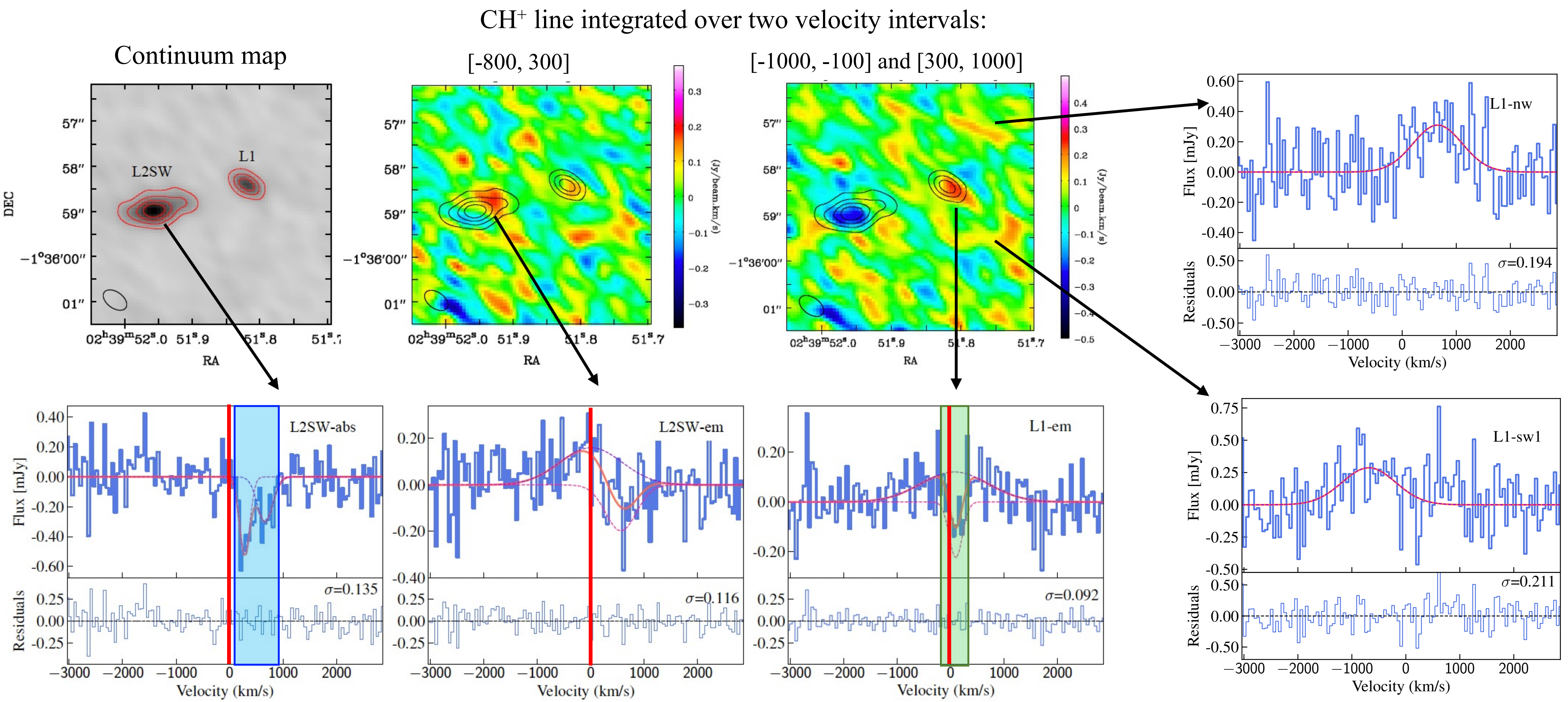
Components (Ivison+1998) :

- **Starburst** galaxy L2SW
- **AGN** L1
- L1N and L2 visible in UV, undetected in the FIR

Properties:

- $L_{bol} = 1.2 \times 10^{13} L_{\odot}$
- SFR (L2SW) = 870 $M_{\odot}$/yr
- μ~2 (Abell 370)
- $t_{dep} = M_{H2}/SFR$=66 Myr (Frayer+2018)

CH^+(1-0) ALMA observations



Redshifted absorption lines against the continuum sources:

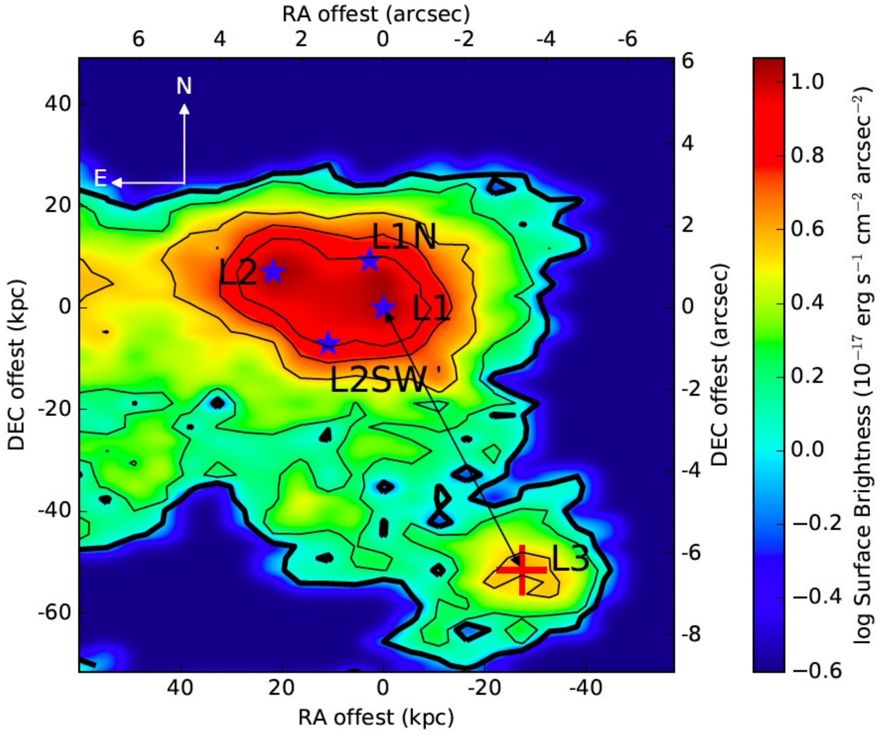
- ➢ **inflowing** low-density turbulent CGM
- ➢ **mass ~ a few 10^{10} $M_\odot$, radius ~20 kpc** inferred from the link: CH^+ abundance - turbulent dissipation

Broad emission lines FWHM ~1400 km/s at the position of the galaxies and in their environment

(Vidal-García+2021)

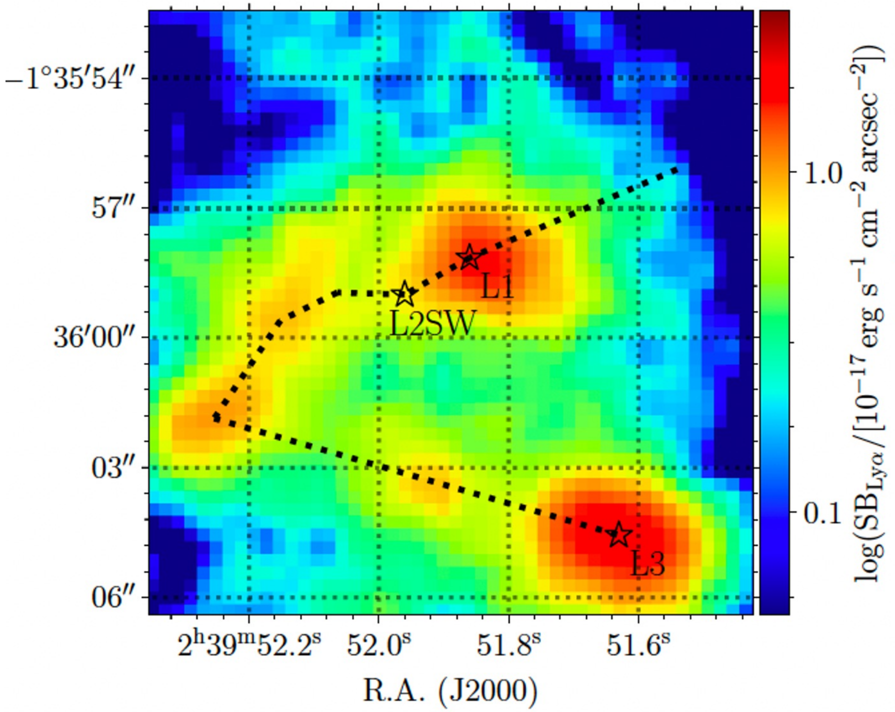
Keck/KCWI Lyα observations

Lyα integrated emission

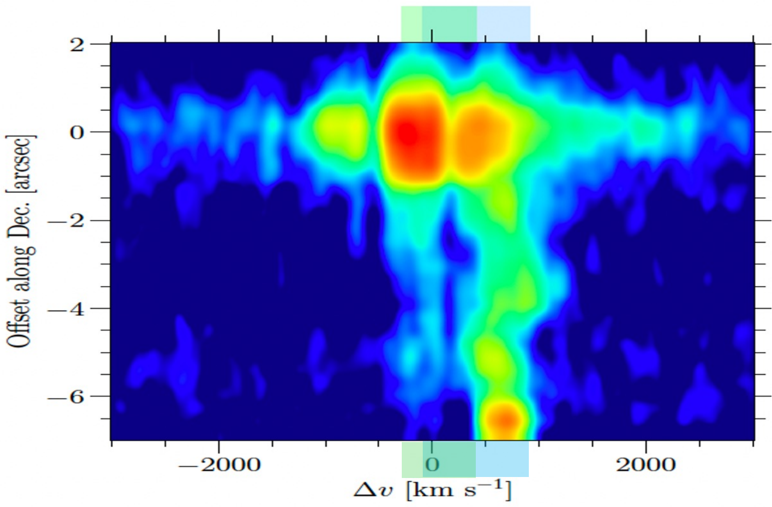


Li+2019

Position-velocity cut's path



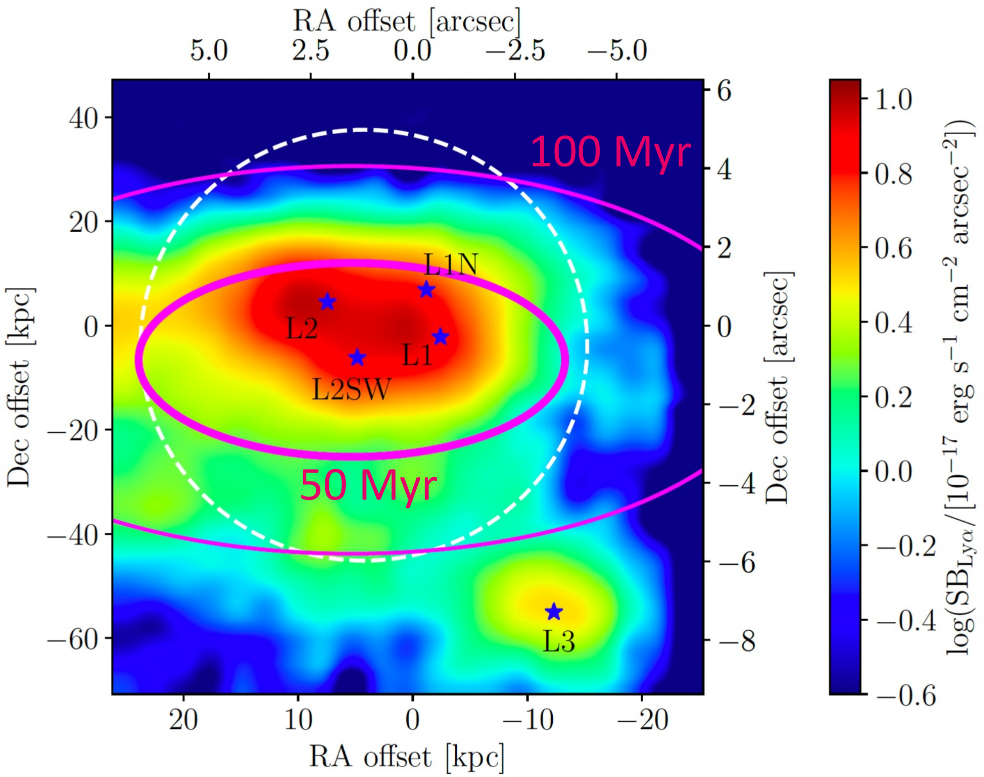
Position-velocity cut

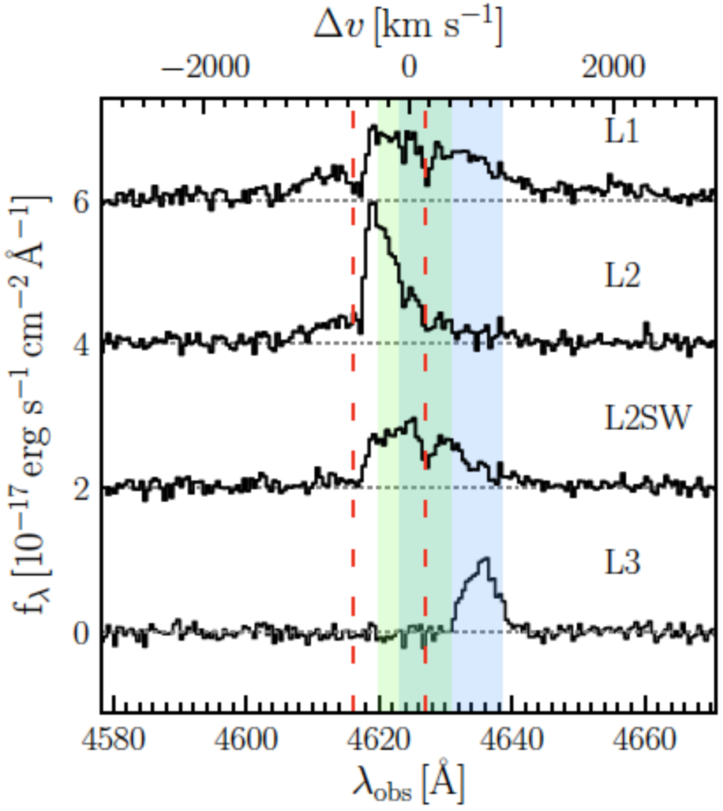


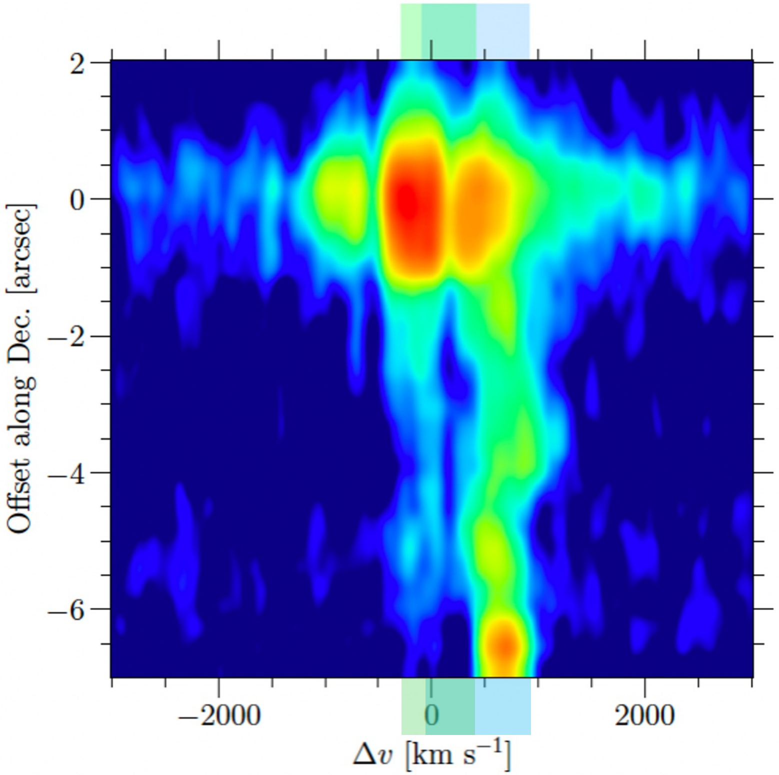
Lyα nebula size >80 kpc

- **Inner part**: extremely **large widths** FWZI≳6000km/s, **outflows**~1000km/s
- **Extended part**: lines **narrower and redshifted** by up to ~750km/s

Comparison of CH^+ and Lyα observations







Lensed radius of the CGM seen in $CH^+(1\text{-}0)$ absorption

- Projection agrees with Lyα nebula

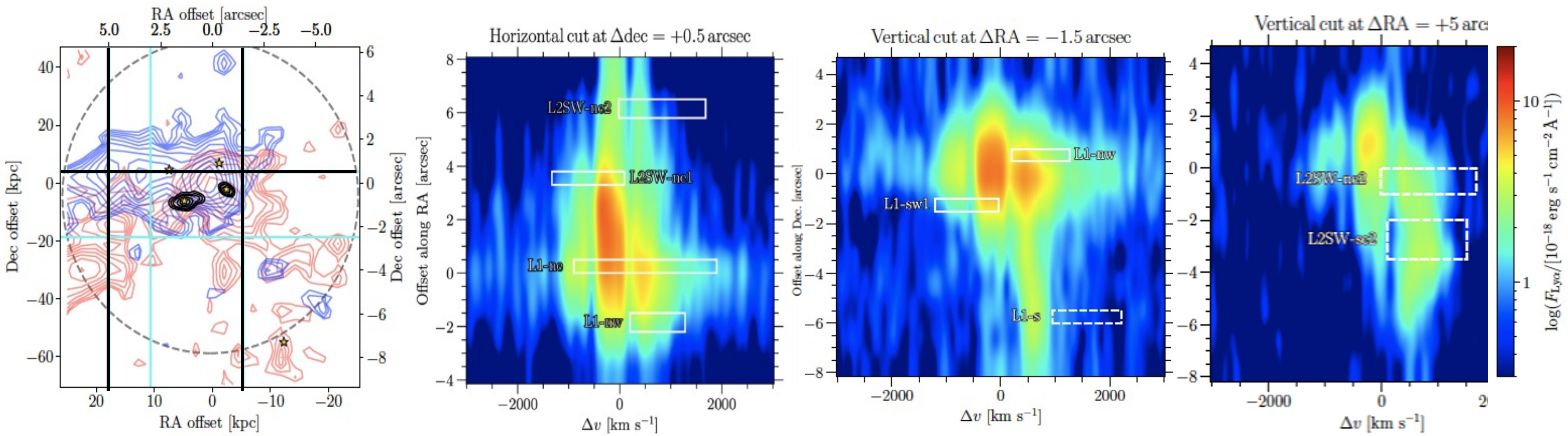
Vertical bands: velocity ranges of **redshifted** absorption of CH^+ towards L2SW and L1

- Lyα self-absorbed at same velocities

- Velocity of extended Lyα nebula same as CH^+ absorption → **whole nebula inflowing**

Multiphasic inflowing CGM

Lyα and CH^+ emission co-spatial

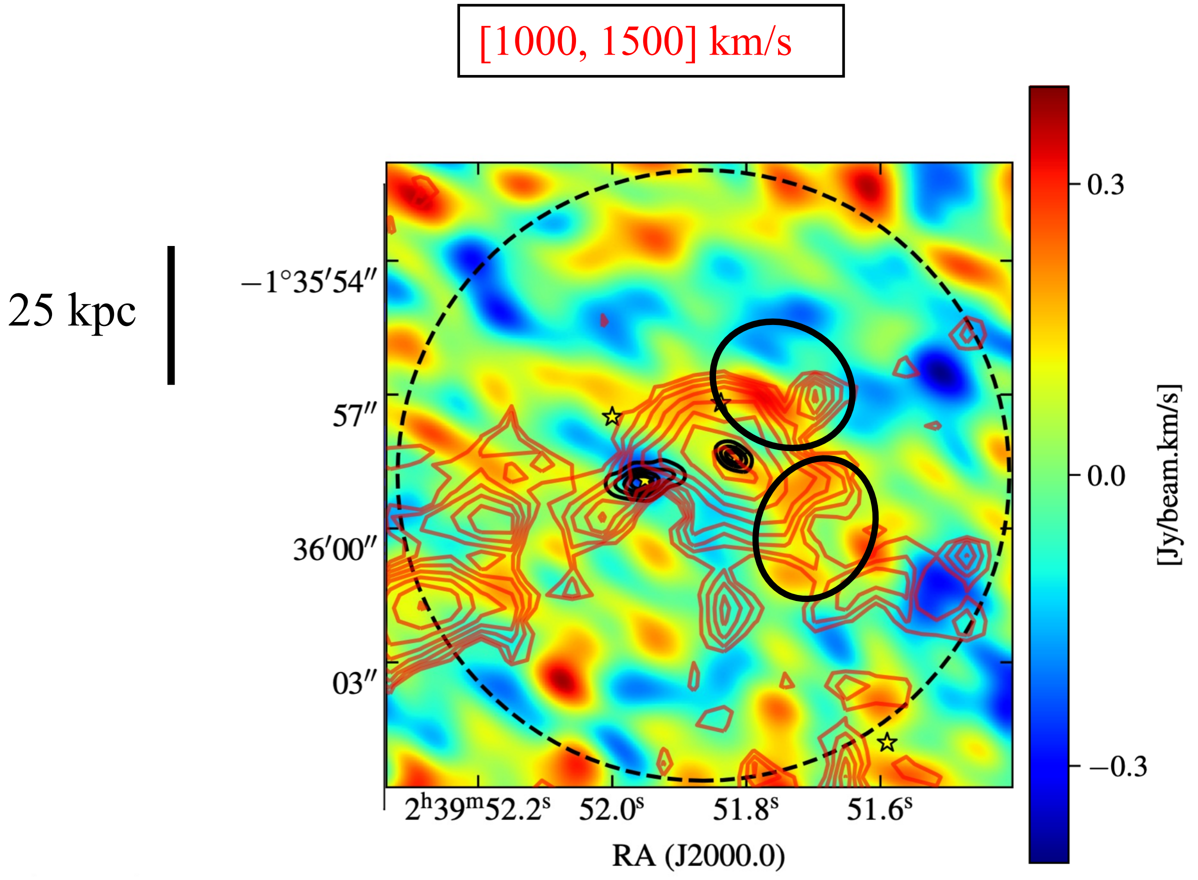


Position-velocity cuts across Lyα nebula. High-velocity Lyα outflows: negative and positive contours
White boxes: velocity, FWHM and position of CH^+ emission lines

- The **CH^+ emission velocities, FWHM and positions agree with** those of the **Lyα wings**
- Reminder: **CH^+ emission traces UV irradiated shocks** (Godard+2019, Lehmann+2021, 2022)

Shock contribution to Lyα emission

CH^+ and high-velocity Lyα emission



Smoothed moment-0 map integrated over [500, 1500] km/s superposed to the Lyα emission integrated over [1000,1500] km/s

➢ **CH^+ emission at edges of high-velocity Lyα** contours

kpc-scale shocks at the interface outflows and inflowing CGM

Shocks at interface between inflow and outflows

Spatial distribution of CH^+ emission structures and high-velocity Lyα emissions ⟹ kpc scale shocks (average linewidth ~1400 km/s) located at interface of AGN- and starburst-driven outflows (~1000 km/s) with inflowing (~ 400 km/s) CGM

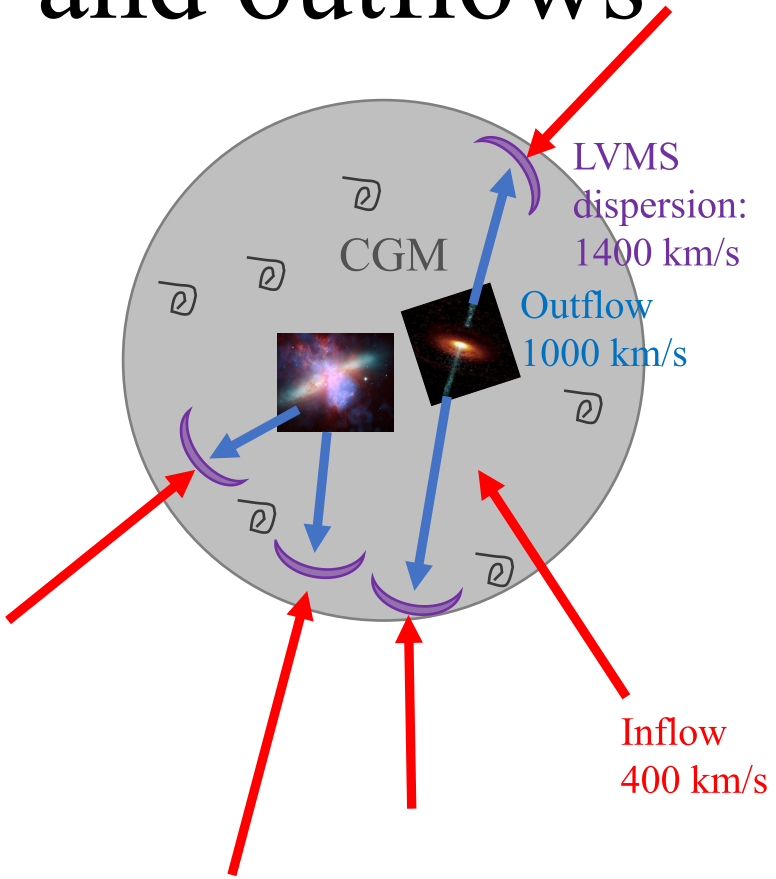
In shocks, post-shocked gas thermalizes at T~ $5{\times}10^7 \left(\frac{v_{shock}}{1400 km/s}\right)^2$ K:

⟹ no molecules

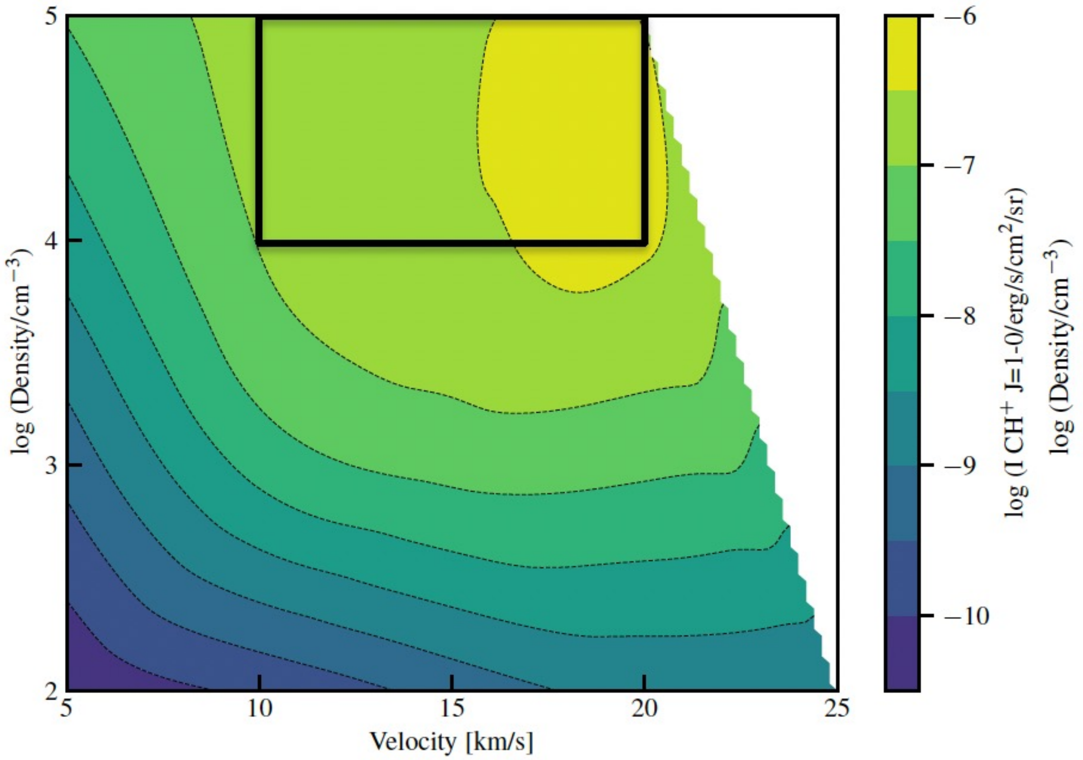
⟹ CH^+ linewidth = velocity dispersion of low-velocity (~20 km/s) molecular shocks (LVMS) (Godard+2019)

⟹ multiphasic turbulent cascade

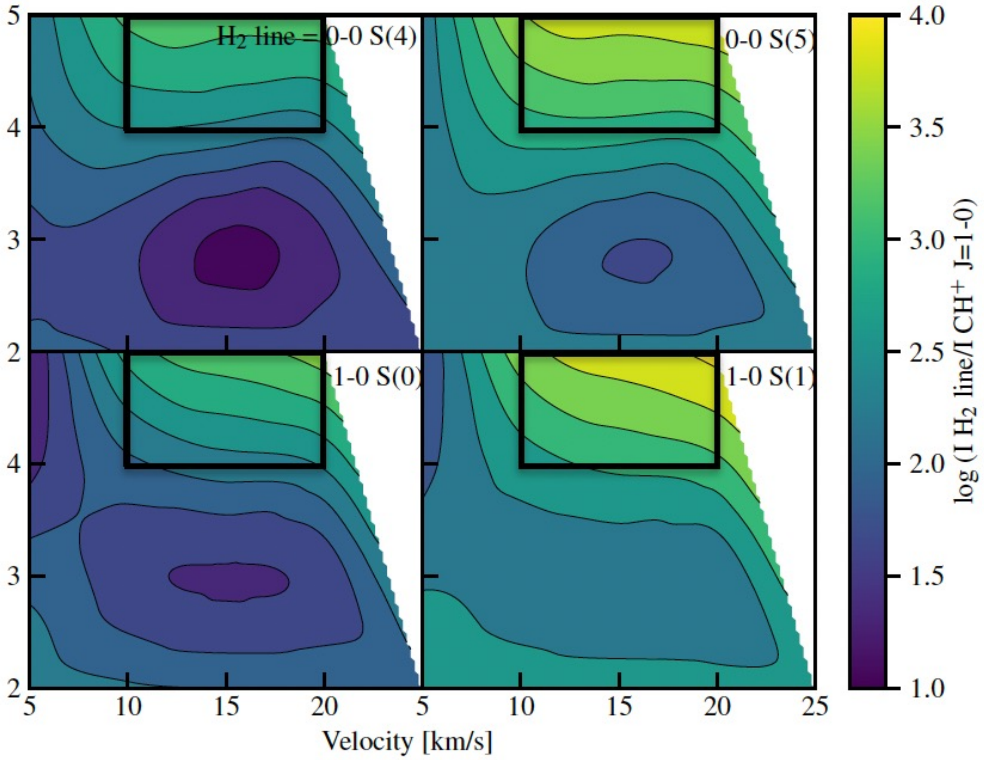
Shocks up to ~20 kpc from the galaxies



CH^+ and H_2 lines from UV-irradiated shock models



Intensity of CH^+(1-0) line computed with UV-Irradiated shock models (Lehmann+2022) as a function of pre-shock density and shock velocity.



Intensity ratios of the pure-rotational S(4), S(5) and ro-vibrational S(0), S(1) H_2 lines to that of CH^+(1-0).

- **At least x300 brighter** than CH^+(1-0)
- Measurement of radiative losses of kinetic energy in CGM shocks.

Observable with JWST

Summary

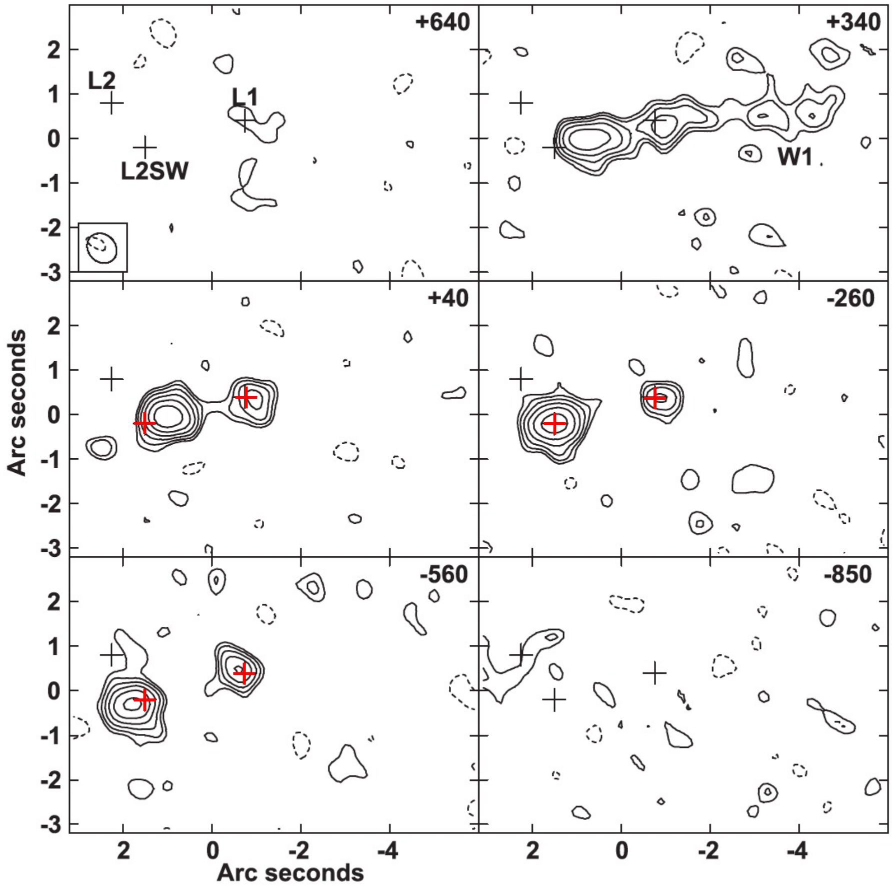
- Redshifted CH^+(1-0) absorption ⟹ inflow of diffuse molecular CGM at ~400 km/s
- Linewidth of CH^+(1-0) absorption ⟹ radius ~20kpc and mass ~ $4x10^{10}$ $M_\odot$ of turbulent CGM
- Co-spatiality and dynamic coupling of CH^+(1-0) and Lyα:

⟹ Multiphasic CGM also inflowing towards the galaxies

⟹ Thermal cooling and shock contributions to Lyα emission

- Broad CH^+(1-0) emission lines at edge of HV Lyα ⟹ scattered kpc-scale shocks at interface between inflow and outflows
- H_2 JWST measurement of radiative losses of kinetic energy in CGM shocks.

Starburst and AGN rotation in SMM J02399

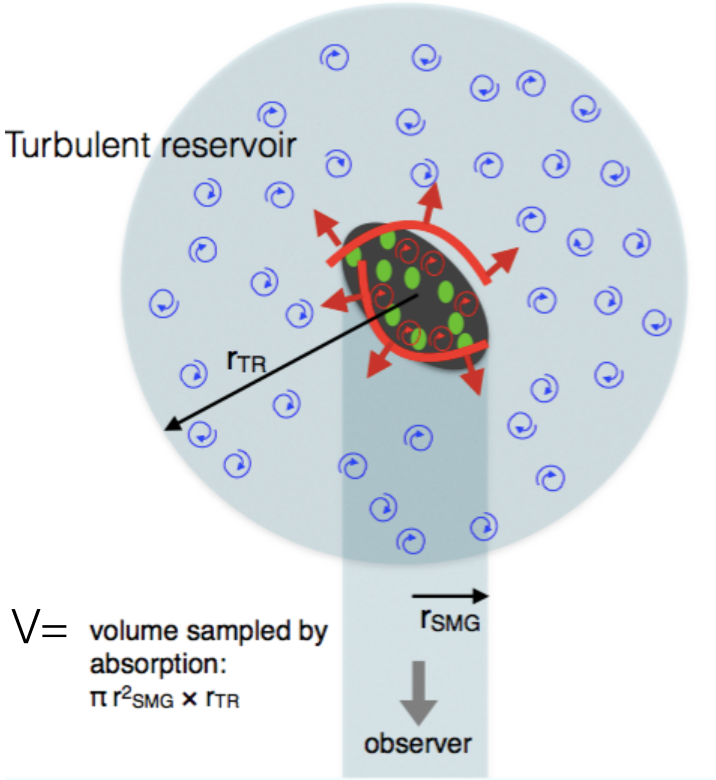


Frayer+2018

ALMA CO(3–2) maps
De-lensed SMG radius ~1-2 kpc
The CGM reservoir few tens kpc

- ➢ Even if the disk galaxies rotate, not clear that the CGM does

Why is CH+ absorption providing the CGM mass?



Energy injection rate to sustain the number of molecules in the beam →

$$\dot{E} = \mathcal{N}(\mathrm{CH}^+)\frac{E_{\mathrm{form}}}{t}$$

← Molecule lifetime ~ 1 year

↑ Number of molecules formed in the beam = $N(CH^+) \times \pi r_{bg}^2$

$$\dot{E} \sim 10^{-2} \text{ to } 10^{-3} \text{ x turbulent energy transfer rate x V}$$

Godard + 2014

Calibration on Milky Way Herschel/HIFI data

$$\dot{E} = \alpha \epsilon \mathrm{V}$$

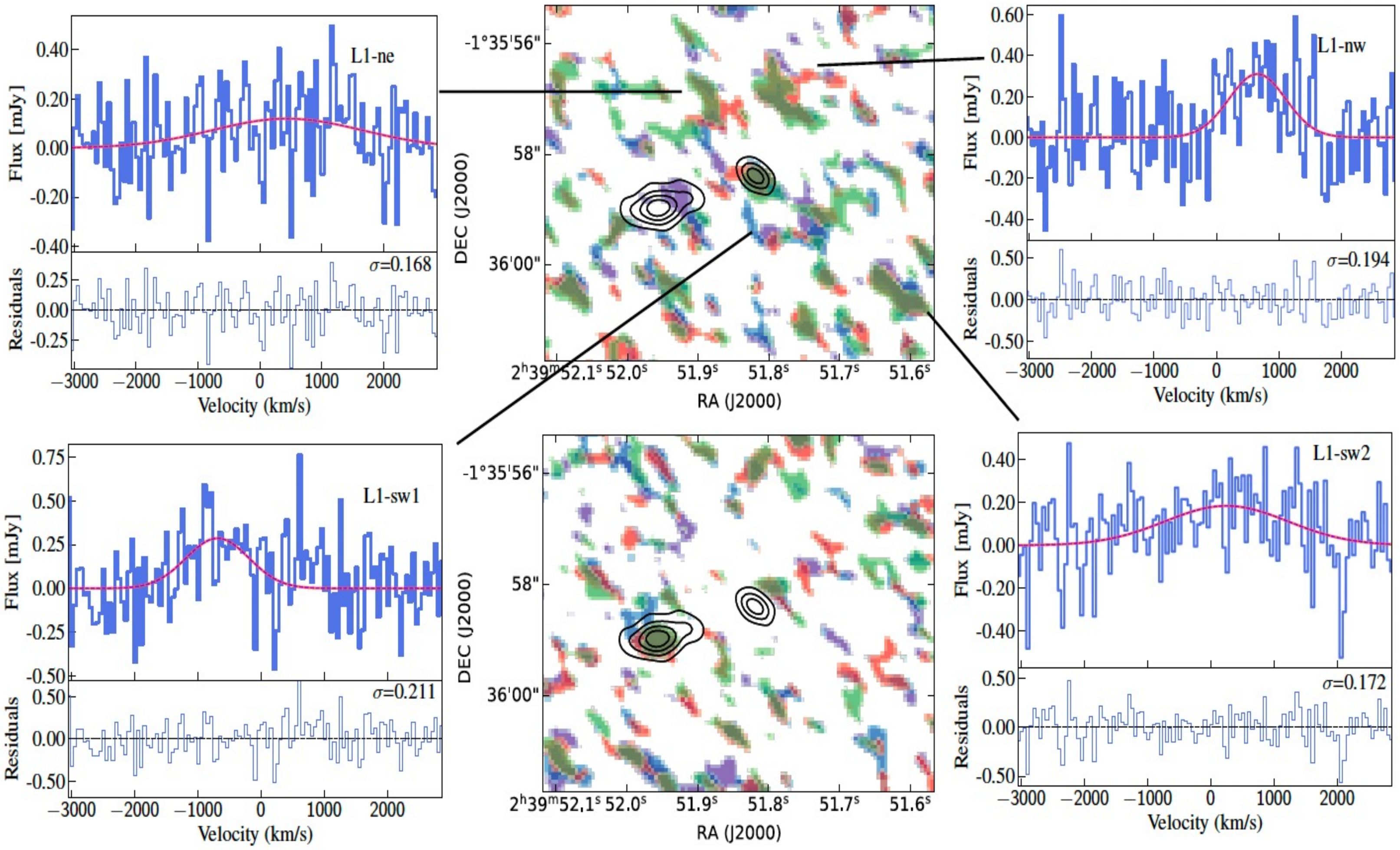
$$\epsilon = \frac{1}{2}\overline{\rho}\sigma^3_{\mathrm{turb}}/r_{\mathrm{TR}}$$

$$\overline{\rho} = \mathrm{M_{abs}}/\mathrm{V}$$

$$\rightarrow \mathrm{M_{abs}} = \frac{\dot{E} r_{\mathrm{TR}}}{\alpha\sigma^3_{\mathrm{turb}}}$$

Total mass assuming $\rho(r) \propto r^{-2}$

13 tentative emissions



- Line integrated intensity in velocities

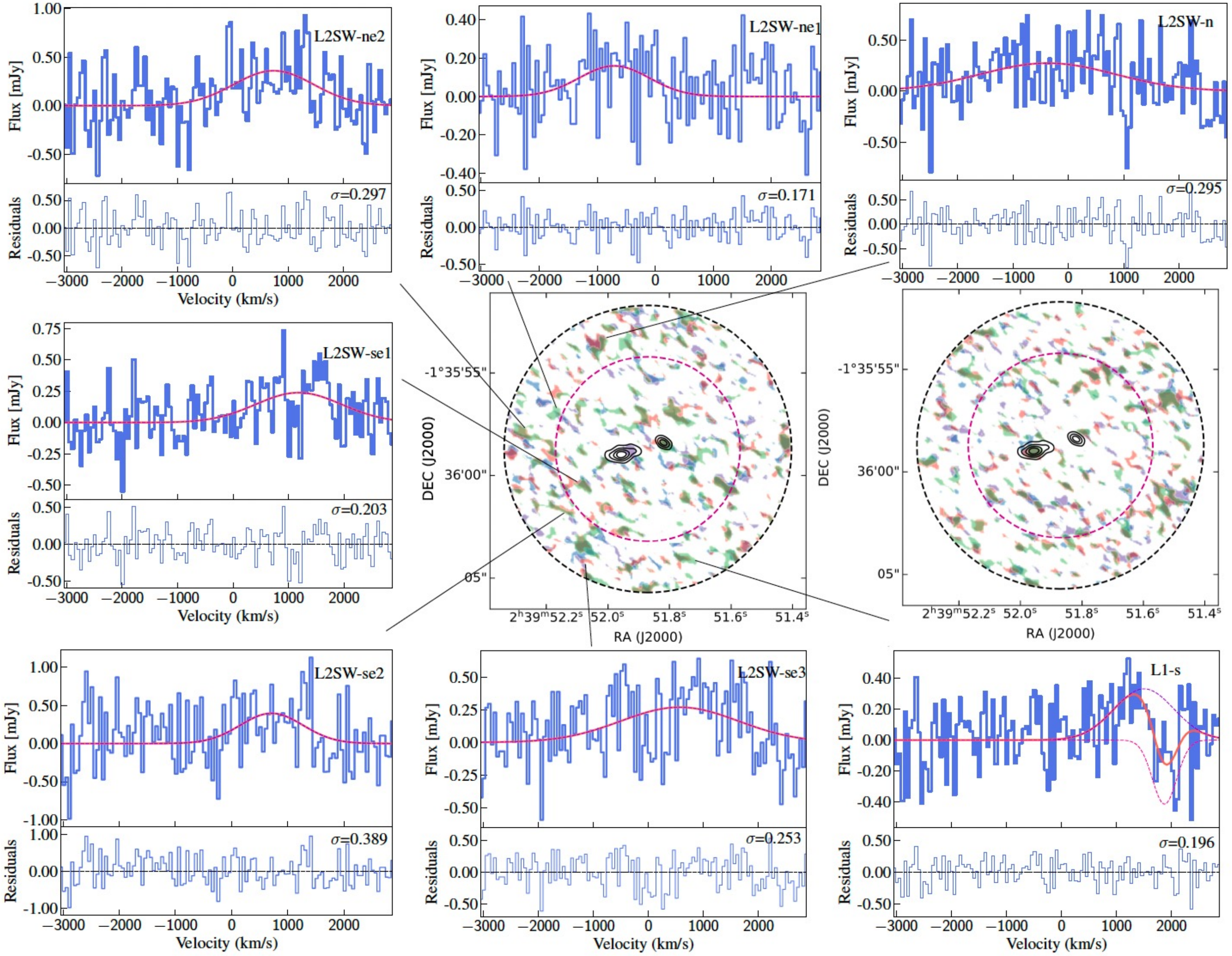
[-1350,250] km/s,
[-1000,-100] and [300,1000] km/s,
[0,1000] km/s
[500,1500] km/s

- Top: Positive σ_{m0}; bottom: negative σ_{m0}

- Not exhaustive search but:

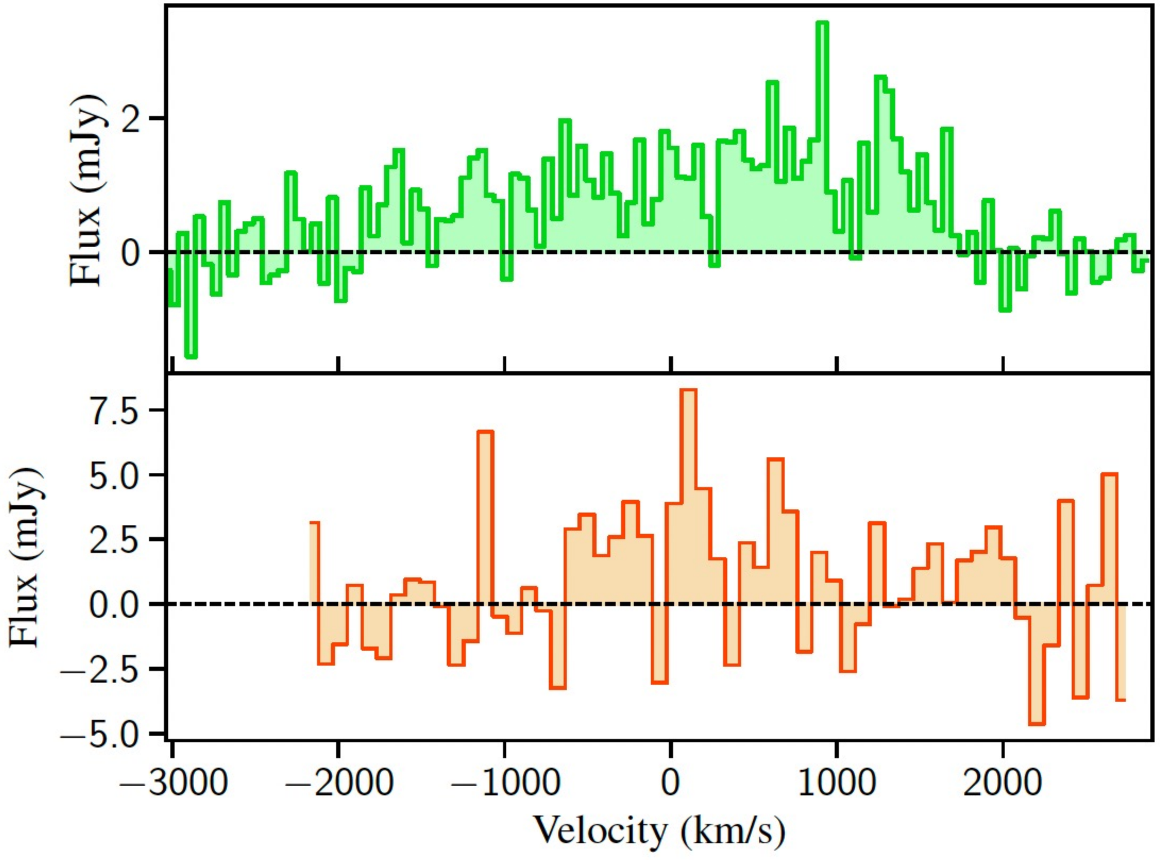
(i) Line integrated intensity brighter than the rms
(ii) More extended than the synt. beam
(iii) localized within the 1/3-primary beam area where noise is minimum

13 tentative emissions



Name	Flux density mJy	σ [a] mJy	v_{em} [b] km s^{-1}	Δv_{em} [b] km s^{-1}	S/N [c]	d [d] arcsec	d [e] kpc	Ω [f] arcsec^2
L1-em	0.12 ± 0.05	0.09	60 ± 240	1350 ±440	2.8	1.1	3.9	0.34
L2SW-em	0.16 ± 0.12	0.12	40 ±380	1280±640	3.0	1.1	3.9	0.38
L1-ne	0.12 ± 0.11	0.17	530 ± 1200	2900±3100	2.7	1.7	5.7	0.46
L1-nw	0.31±0.17	0.19	740 ± 290	1070±690	3.8	2.5	8.4	0.42
L1-sw1	0.29±0.17	0.21	-600±330	1160 ± 775	3.3	2.0	6.7	1.03
L1-sw2	0.18 ± 0.11	0.17	340 ± 720	2290± 1700	3.6	4.5	15.1	0.32
L2SW-ne1	0.16 ± 0.15	0.17	-620± 655	1420 ± 1540	2.5	3.8	12.8	0.44
L2SW-se1	0.24 ± 0.13	0.20	1270 ± 500	1820± 1210	3.6	3.2	10.8	0.54
Average	0.25	–	170 ±540[g]	1330±270 [g]	–		8.4	0.49
L1-s [h]	0.34 ± 0.24	0.20	1590± 766	1275± 940	2.8	5.6	42.3	0.48
L2SW-n	0.27 ± 0.15	0.30	-285 ± 545	2860 ± 1315	3.4	5.4	25.4	1.85
L2SW-ne2	0.36 ± 0.13	0.30	825 ± 320	1700 ± 750	3.5	5.0	17.8	1.03
L2SW-se2	0.48± 0.15	0.40	805 ± 215	1390 ± 500	3.2	5.0	16.8	0.67
L2SW-se3	0.27± 0.11	0.25	655 ± 525	2510± 1270	3.8	5.3	17.8	1.00
Average[i]	0.25	–	412 ±550[g]	1450±390 [g]	–		28.8	0.75

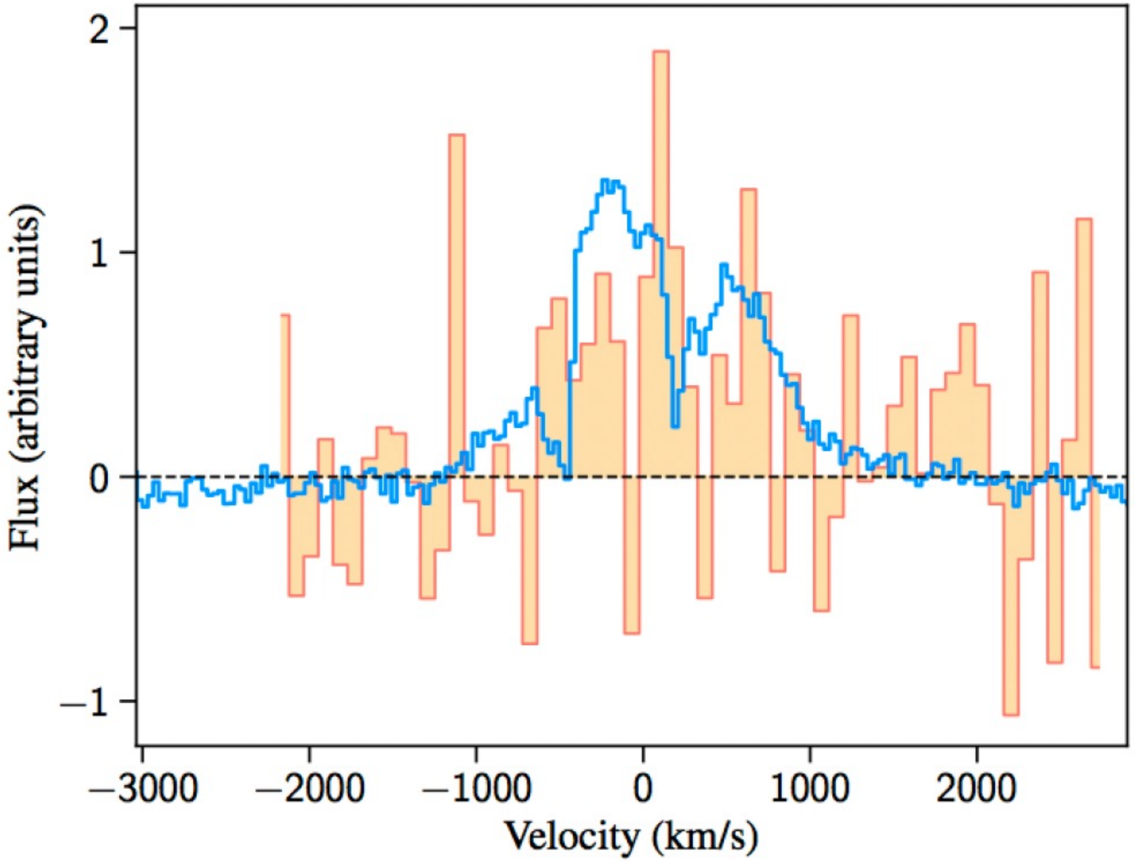
Tentative detections of ALMA with CH^+(1-0) IRAM 30-m observations



Sum of most plausible CH^+ line fluxes, weighted by the IRAM-30m beam profile
Line integrated flux of 1.4+/-0.4 Jy/km/s [-1000,1000]

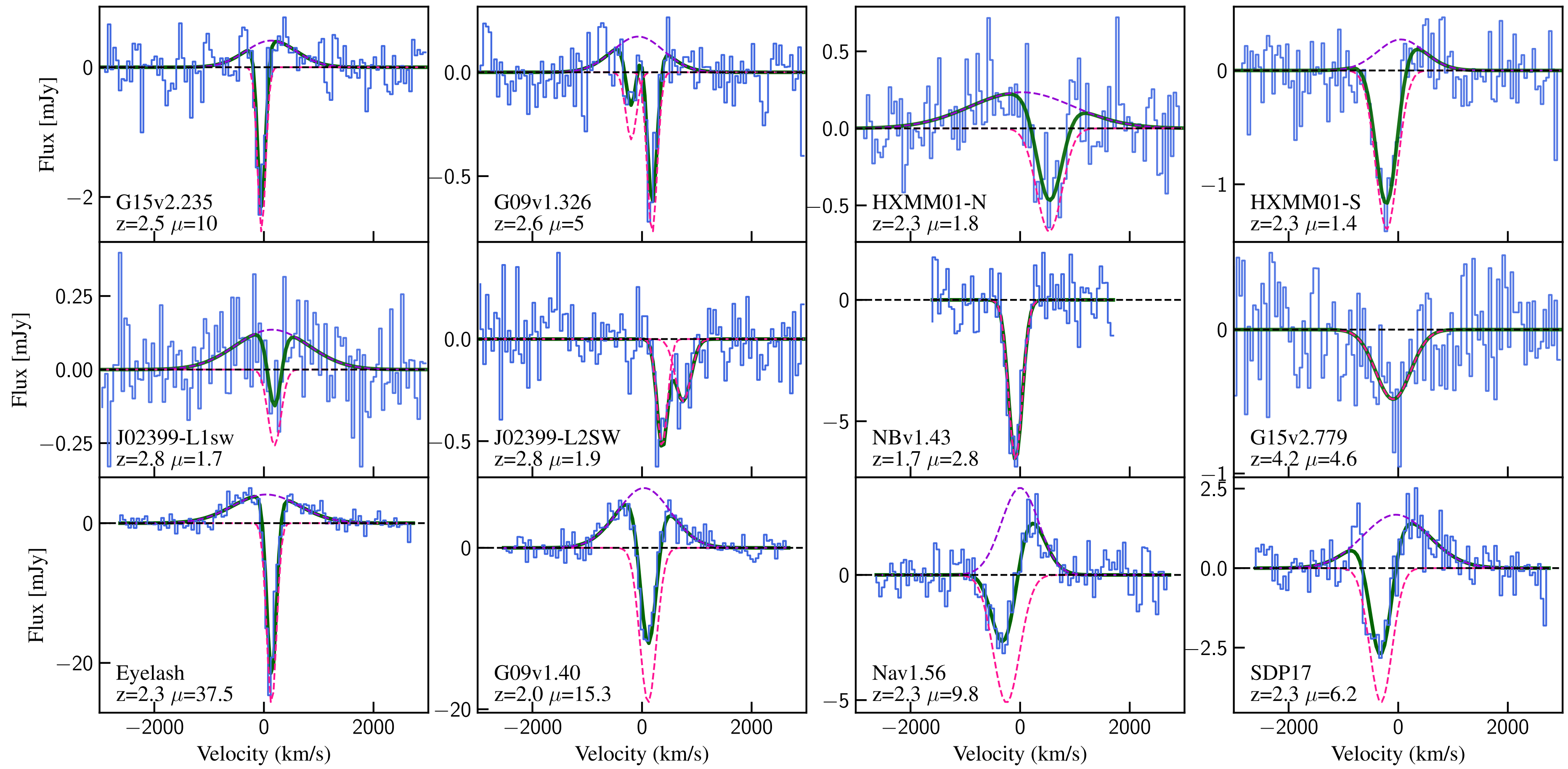
IRAM 30-m tentative detection of CH^+ (1-0)
FWHM~1300km/s
Line integrated flux of 3.5+/-1.4 Jy/km/s [-1000,1000]
V_0=100 km/s

IRAM 30-m CH^+(1-0) and Lyα spectrum



- Ly-α and IRAM 30m co-spatial spectrum in arbitrary units
- Velocity (FWZI ~3000 km/s) in both: supports shock contribution to Lyα

Some examples of CH^+(1-0) observed with ALMA



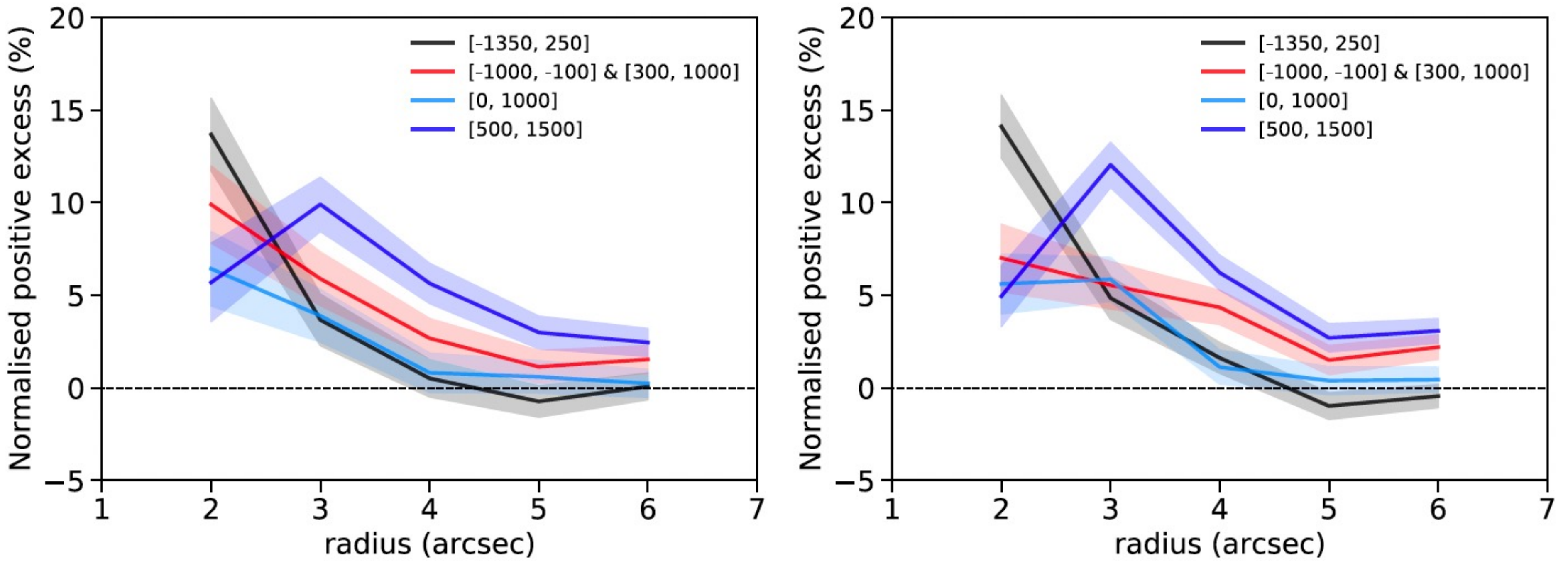
- Starburst galaxies at z~2-4
- μ~1.4-37.5
- Broad absorptions
- Broad emission lines

Lens model

- Sl_fit (Gavazzi+2011)
- Metropolis-Hastings algorithm (MCMC)
- Posterior probability distribution functions of set of parameters describing the mass profile of lens and luminosity profile of source
- Lens: singular isothermal ellipsoid mass distribution centered at cluster position obtained by Richard+2010.
- Background source: Sérsic profile of sources

- μ(L2SW)= 1.9+-0.1   r(L2SW)=1.8+-0.1kpc and μ(L1)= 1.7+-0.1 r(L1)=0.8+-0.1kpc

Statistical confirmation of structures in space and velocity



- Excess number of pixels with positive moment-0 values over those with negative values, normalized to the total number of pixels within a given radius as a function of radius
- The left panel displays this excess for all the connected structures above σ_{m0} (and weaker than $-\sigma_{m0}$)
- Right panel only the pixels in structures larger than one synthesized beam area: excess of positive structures above those negative statistically significant within 4.5 arcsec from the centre.
- Limit depends on the moment-0 map, [500, 1500] km/s remains significant up to 6 arcsec.
- Velocity interval where the CH+ emission is most intense

Energy and mass flow trail

- Are outflows able to sustain observed turbulence in such massive cold CGM over t_{dep}? YES

L_{turb} in CGM (from CO and CH^+ abs): $\sim 5\times10^{43}$ erg/s

L_{kin} of outflows (from L_{CH+} and shock models from Lehmann+2021): $> 6.5\times10^{44}$ erg/s

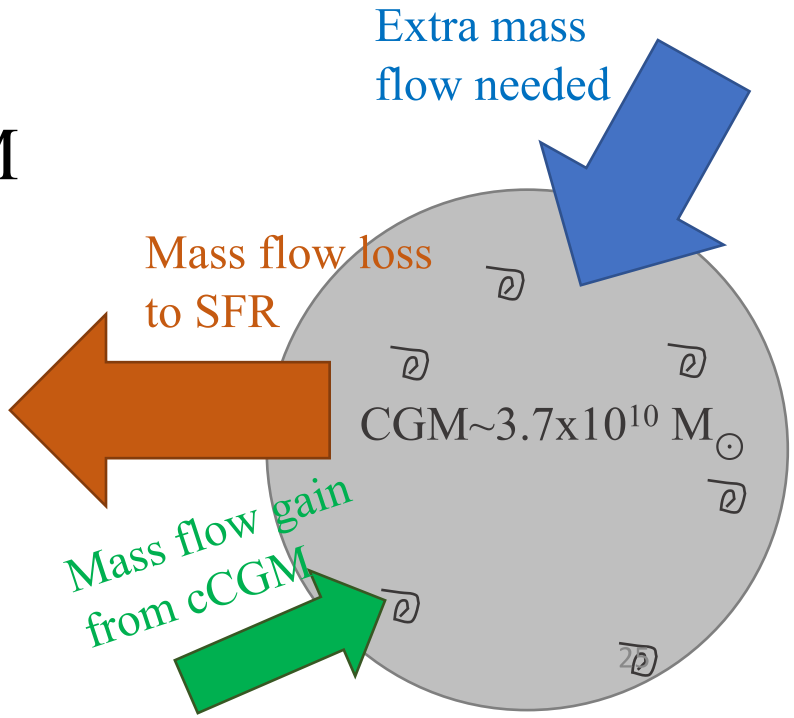
L_{kin} >10x larger than that needed to sustain CGM turbulence

- Are they able to compensate mass drain of cold CGM due to high SFR? NO

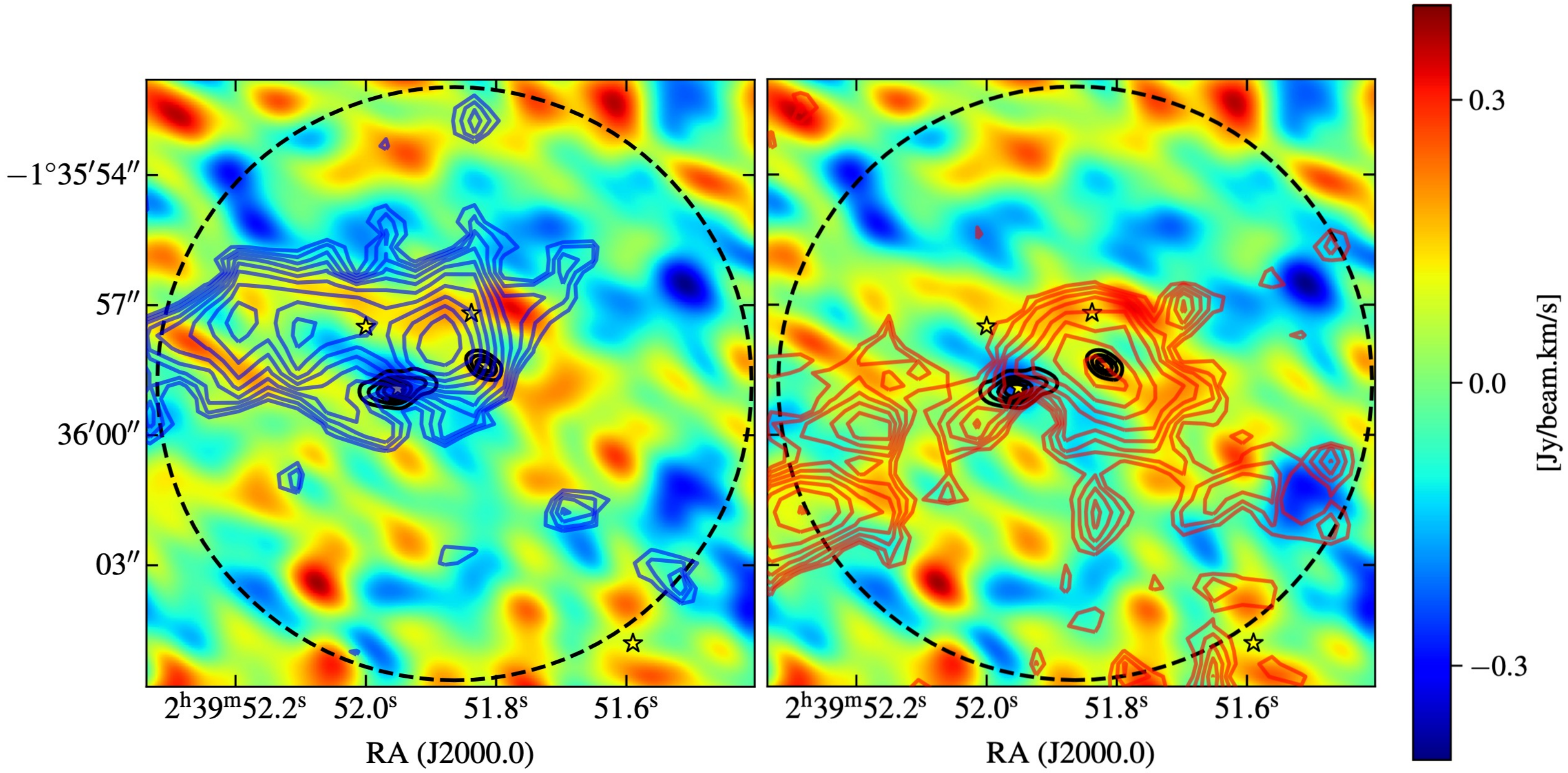
Drain by SFR $\sim 870 M_\odot$/yr

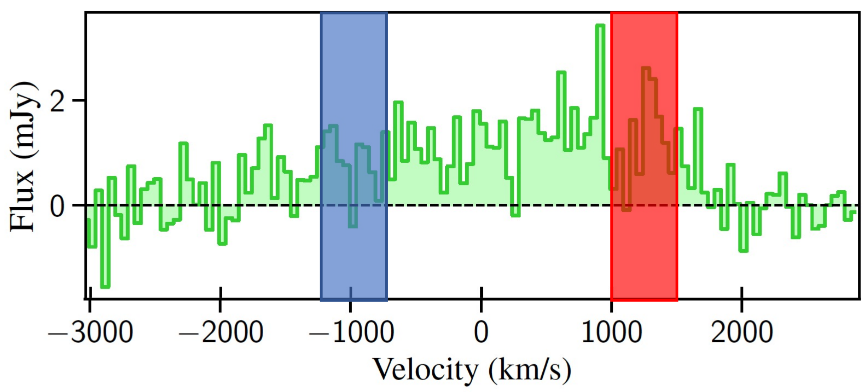
$\dot{M}_{out}$ feeding L_{turb} $\sim 150 M_\odot$/yr

We need extra $\dot{M}_{in}$ $\sim 720 M_\odot$/yr to compensate SFR



Lyα and CH^+ emission co-spatial

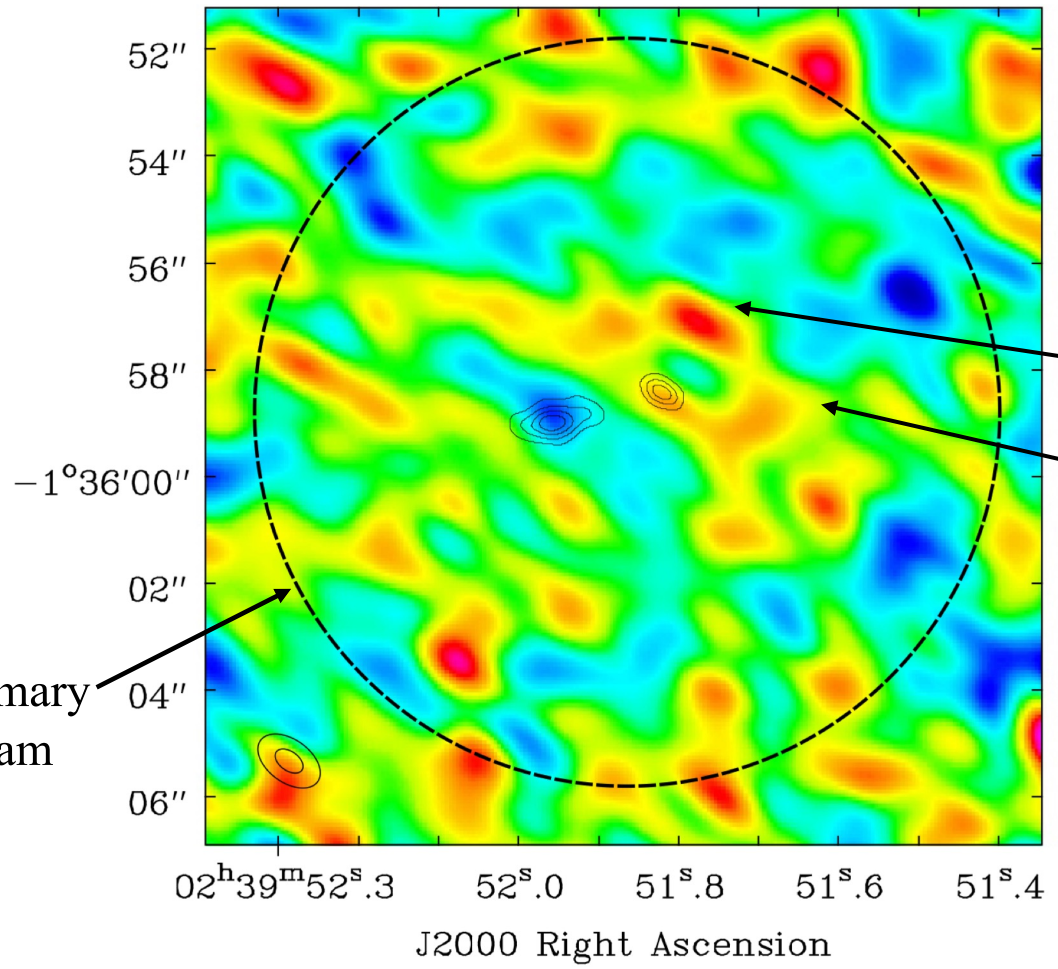




- Weighted sum of most plausible CH^+ line fluxes in ALMA data
- Line integrated flux:
  - Over [-1000, 1000] km/s: 1.4 Jy.km/s
  - Over [-1900, 2200] km/s: 2.2 Jy.km/s

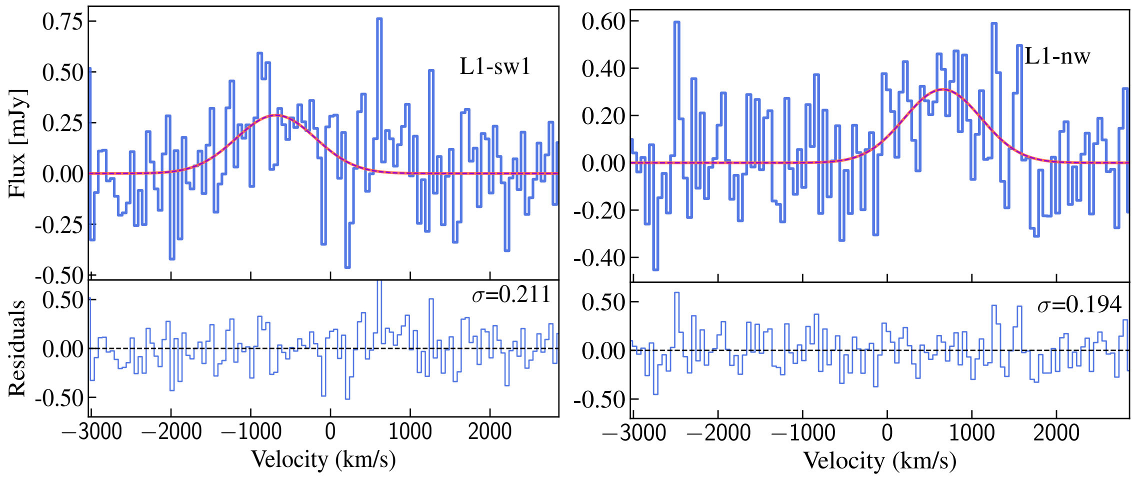
- Smoothed moment-0 maps superposed to the Lyα SB integrated over [-1200, -700] km/s and [1000,1500] km/s
- CH^+ emission at edges of high-velocity contours

Tentative CH^+ emission detections



1/3 primary beam

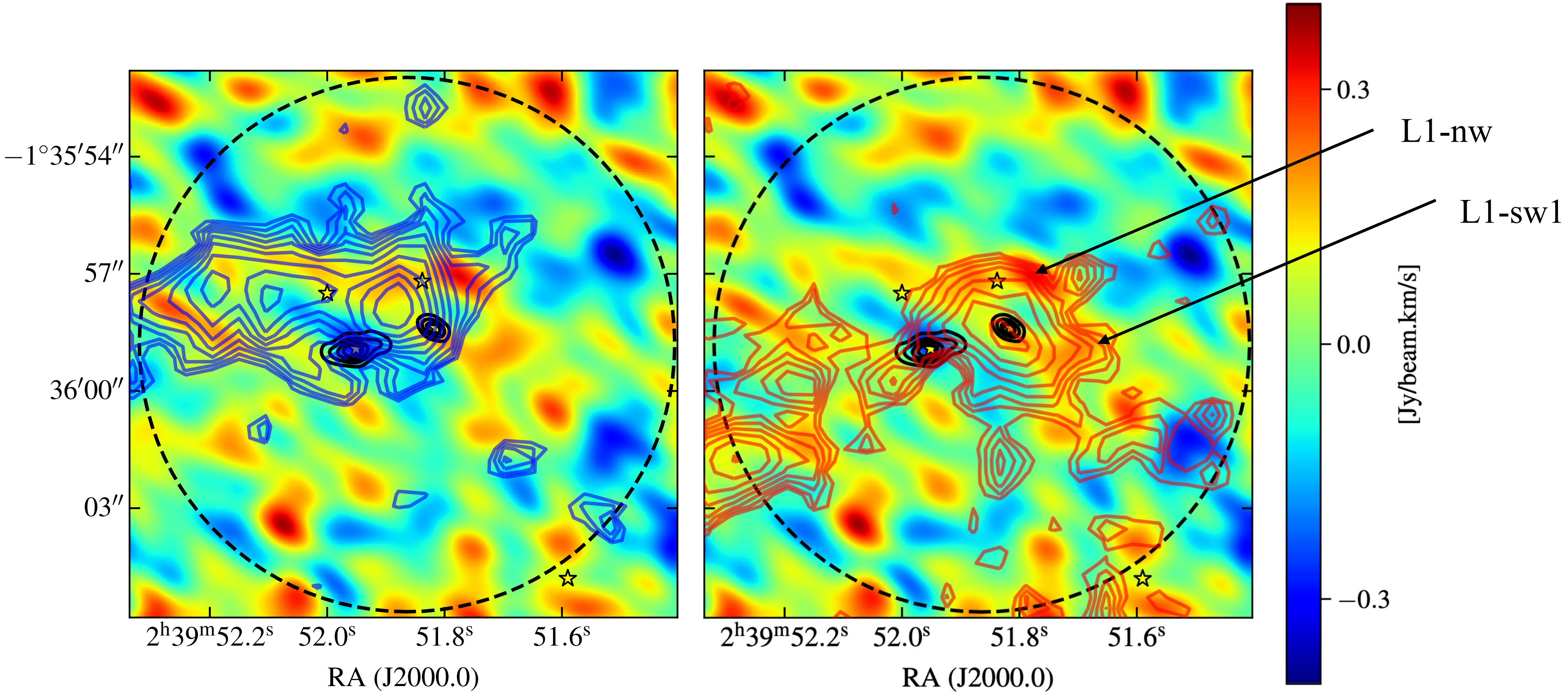
- 13 tentative detections of $CH^+(1\text{-}0)$ emission up to ~40 kpc
- Inner structures: excess of pixels in emission
- Half in vicinity of AGN (L1) (L1-nw, L1-sw1, …)
- On average 3x more extended than synthesized ALMA beam



- Smoothed moment-0 map (line integrated area) in the velocity range [500, 1500] km/s

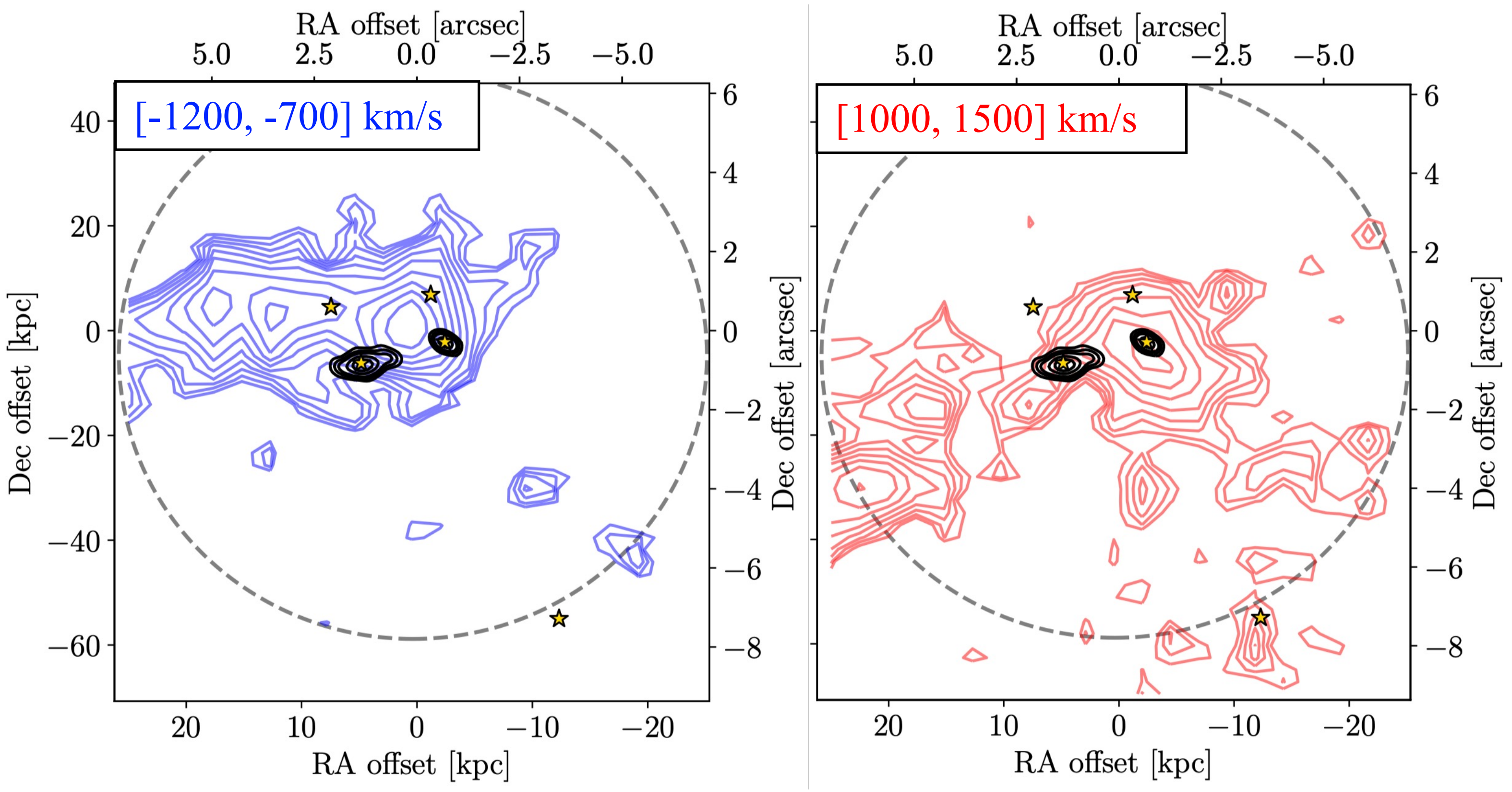
- 2 examples of spectra of CH^+ emitting structures
- Average CH^+ linewidth of 13 CH^+ emitting structures ~ 1400 km/s, σ=300 km/s

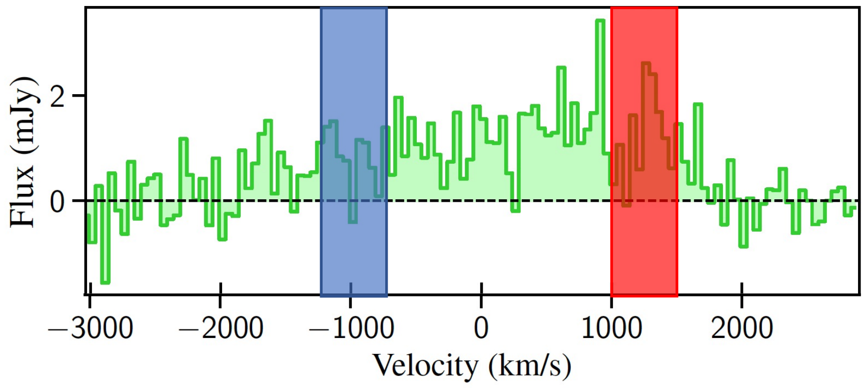
Tentative CH^+ emission detections



- Smoothed moment-0 maps superposed to the Lyα SB integrated over [-1200, -700] km/s and [1000,1500] km/s
- CH^+ emission at edges of high-velocity contours

Lyα outflows: blue and red wings

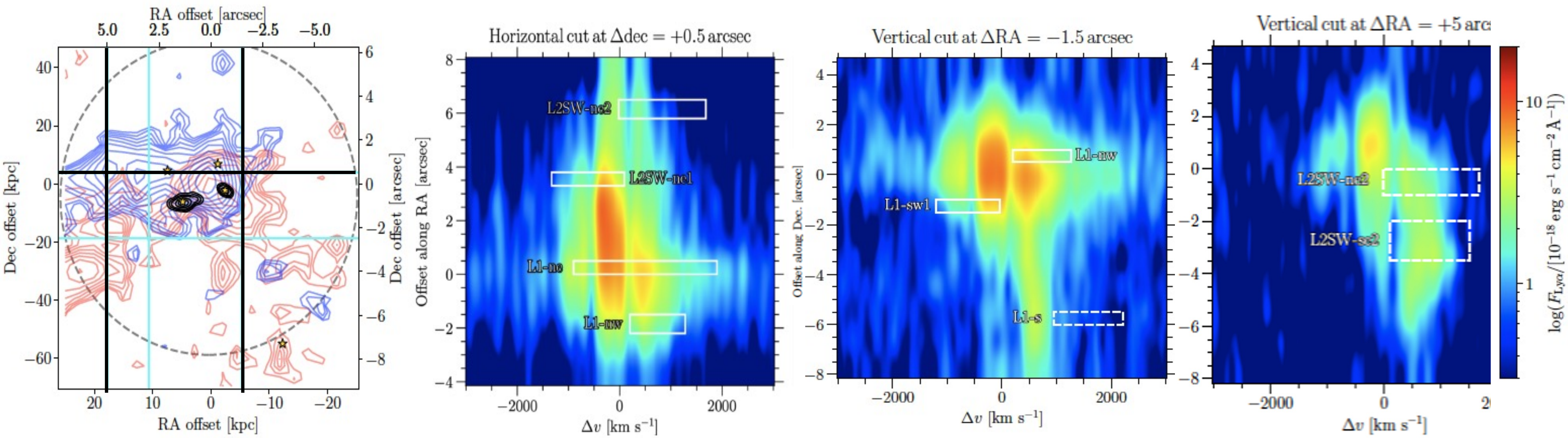




- Weighted sum of most plausible CH^+ line fluxes in ALMA data
- Line integrated flux:
  - Over [-1000, 1000] km/s: 1.4 Jy.km/s
  - Over [-1900, 2200] km/s: 2.2 Jy.km/s

- Contours of Lyα high-velocity emission integrated over [-1200, -700] km/s and [1000,1500] km/s
- Highly structured

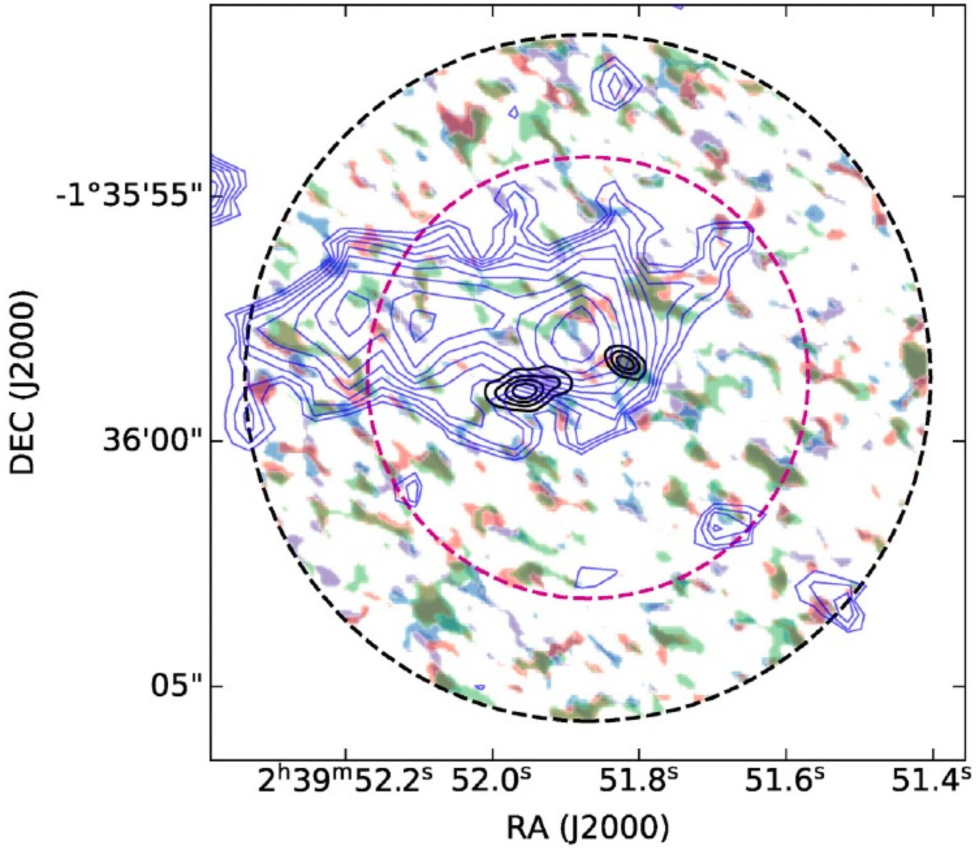
Tentative CH^+ emission detections

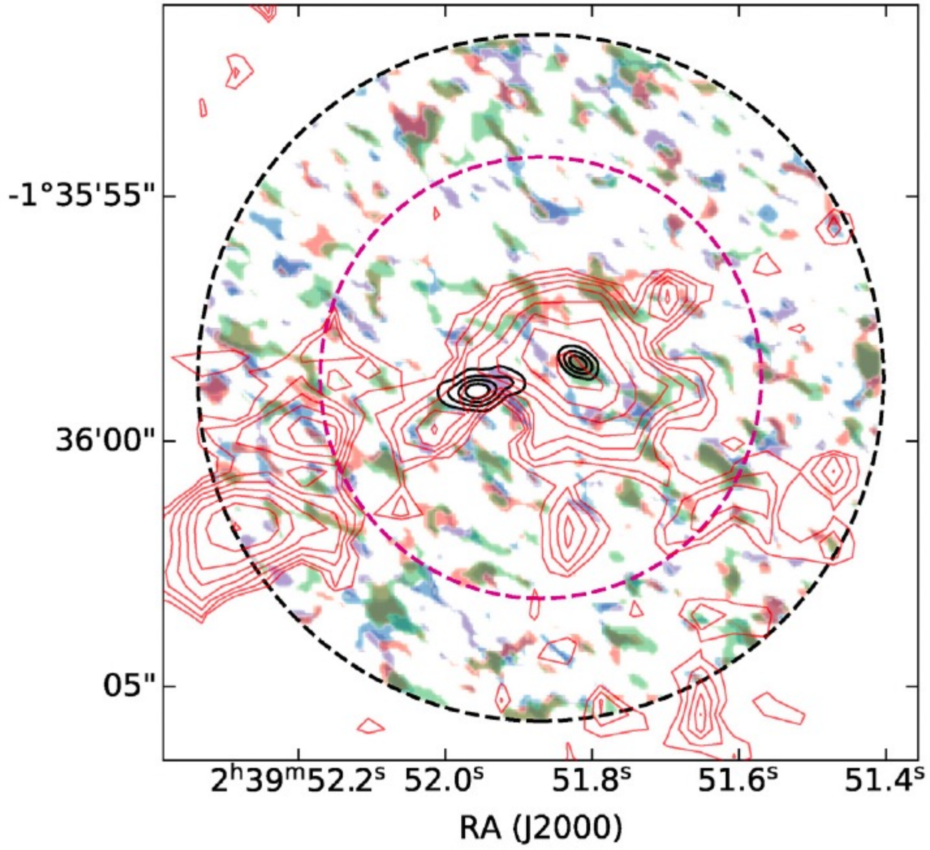


- Position-velocity cuts across Lyα nebula and space-velocity positions of CH^+ emission (white boxes)
- The CH^+ emission velocities coincide with those of the Lyα wings ⟹ shock contribution (Lehmann+2021, 2022)

Starburst and diffuse-gas phase coevolution

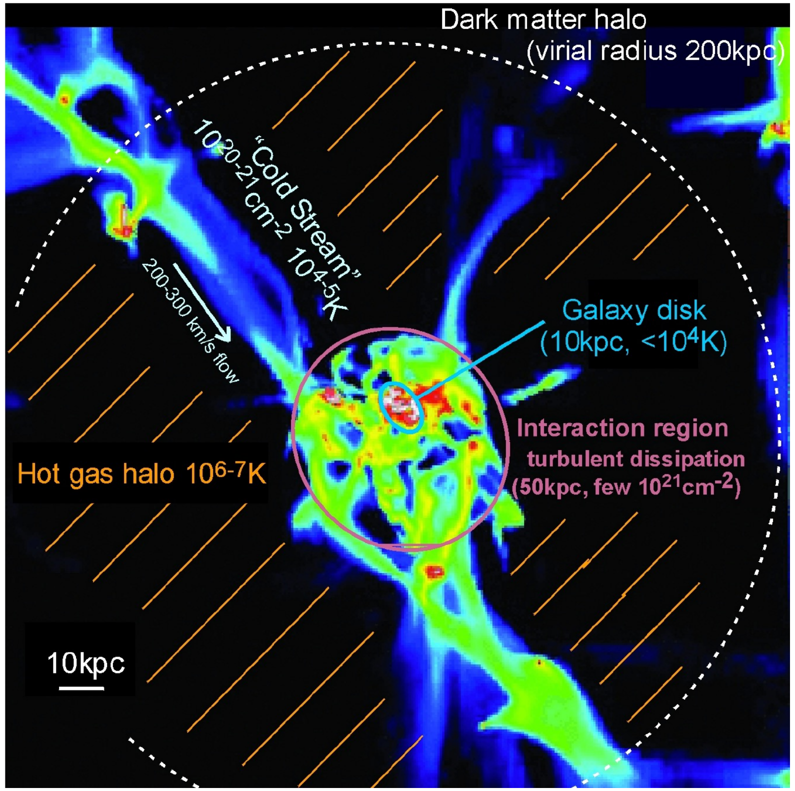
Co-spatiality of CH^+ emitting structures and HV Ly-α emission





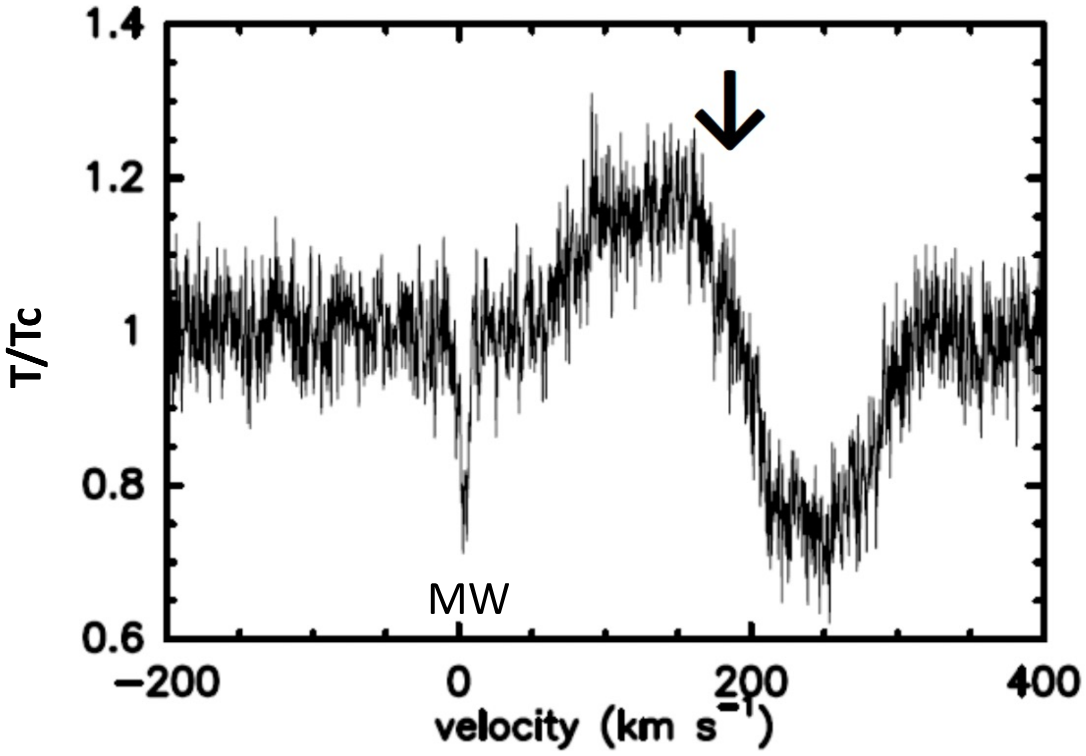
- Weighted: it’s the gaussian at the distance of the region divided by the sigma of the iram beam: exp(-D**2/2 x sigma**2) with sigma=HPBW/2.35
- (name of dE/dt=alpha*epsilon*v)
- Cleaning images: standard procedure. Flagged an antenna over a period of time for bad amplitude. Clean with tclean and hogbom algorithm. Deconvolve image masking galaxies with a contour selected in the continuum image.

Large interaction regions: signposts of infall



Ceverino+2010, Gabor&Bournaud 2013, 2014

Herschel/HIFI CH$^+$(1-0) in M82



Growth of galaxies in simulations: **accretion of gas**
Feedback from AGN and SF: ejection of matter
Outflows observed, **inflows elusive** (Dekel+2009)

Inverse P Cygni profile in a local starburst:

- Redshifted absorption: **inflow**
- **Emission** at same velocity as SiO in **shocks** (García-Burillo+2001)

Power of CH$^+$ spectroscopy in high-redshift lensed starburst galaxies