ALMA CH^+(1-0) detections of starburst galaxies at z ~2.5

Massive turbulent reservoirs unveiled

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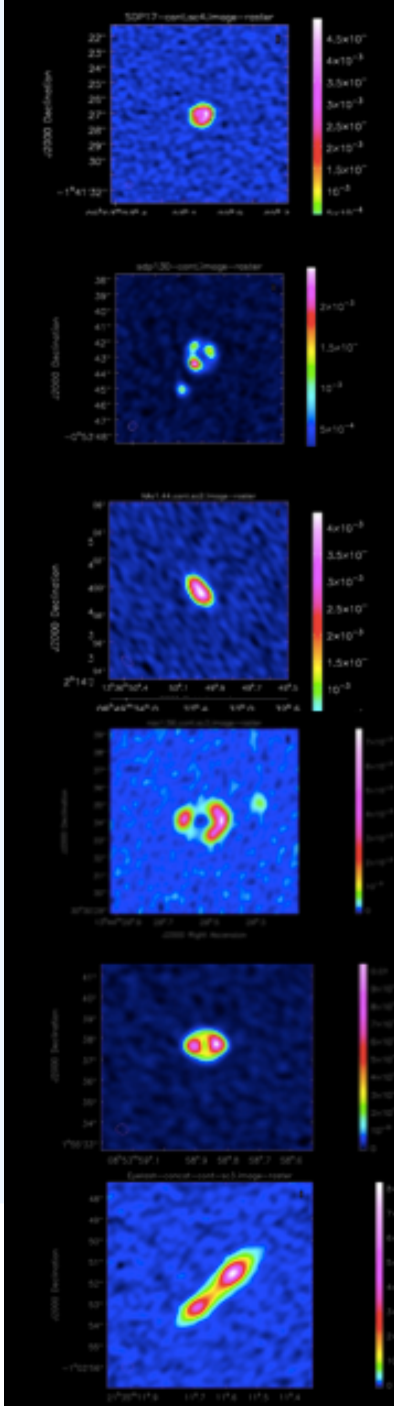


« The Hydride Toolbox »,
Paris, December 12-15, 2016

Cosmic star formation

Peak of cosmic star formation history at z~2: most stars and galaxies seen today formed at that epoch.

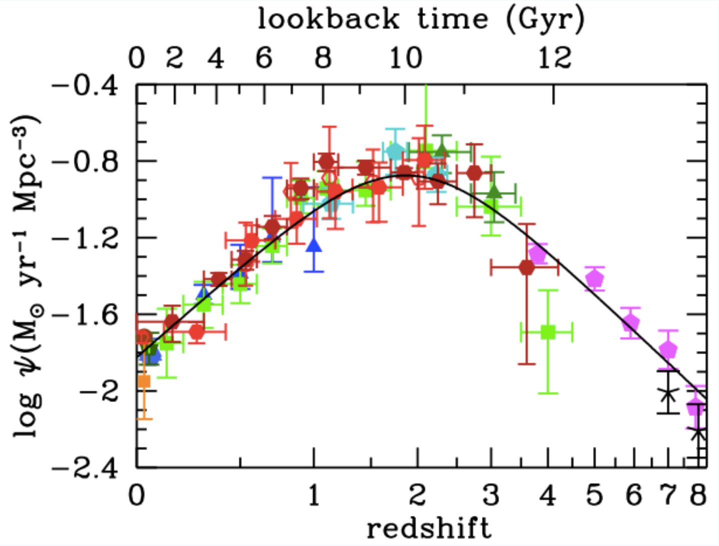
Grand challenges of cosmological simulations:

➪ Star/galaxy formation runs too fast: observed timescales for cosmic star formation ~ 1 to 2Gyr
Schreiber + 2015

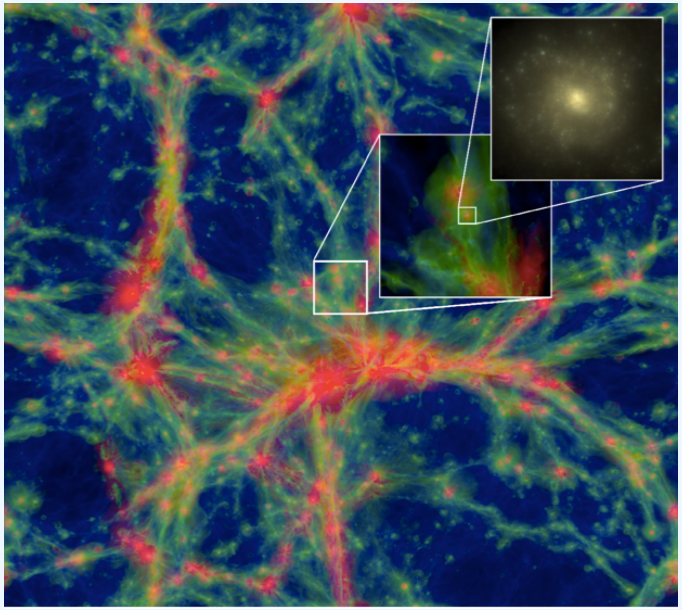
>> timescales imposed by the growth of DM structures Somerville & Davé + 2015

➪ Somewhat alleviated by stellar- and AGN-driven feedback Schaye + 2015

➪ the cold (10^4 K) streams predicted to feed galaxy growth have never been observed Narayanan + 2015

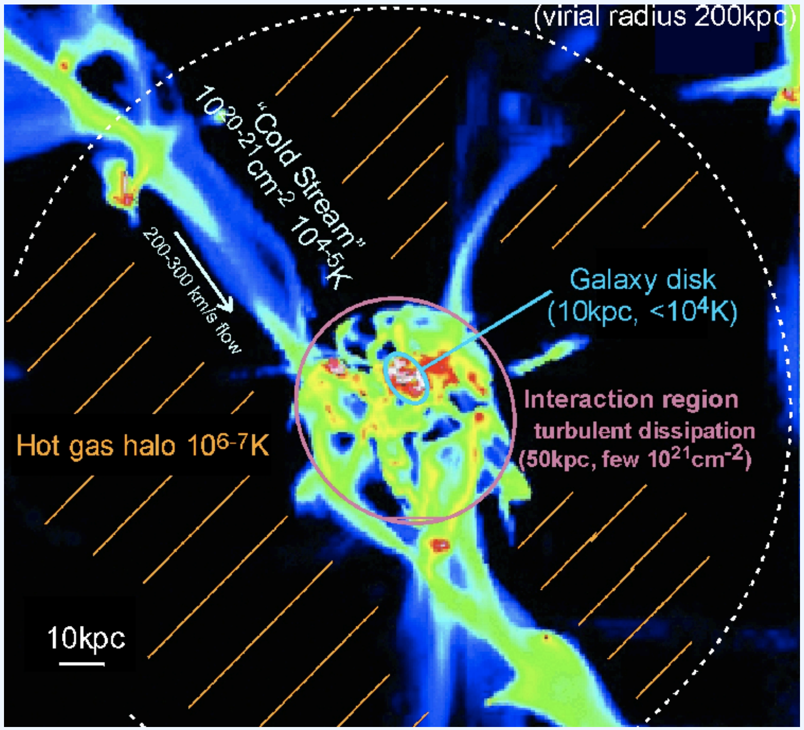


Madau & Dickinson 2014



Schaye + 2015

ALMA CH^+ project: search for large turbulent interfaces



Ceverino + 2010,
Gabor & Bournaud, 2013, 2014

→ Formation of large turbulent interfaces at the interface cold streams-growing galaxy = buffers of mass and energy

6 targets

H-ATLAs and HerMES surveys
Bussmann + 2013

Redshift: z = 2 – 2.6

Lens magnification: μ = 4 – 35
Oteo + in prep.

Starburst galaxies

FIR luminosity: L_{FIR} up to 10^{13} L_{sun}

➪ SFR ~ 280 – 1330 M_{sun}/yr
Kennicutt 1998

SFR ~ 10^3 x galactic average in 10^6 x smaller volume

Why CH^+ ?

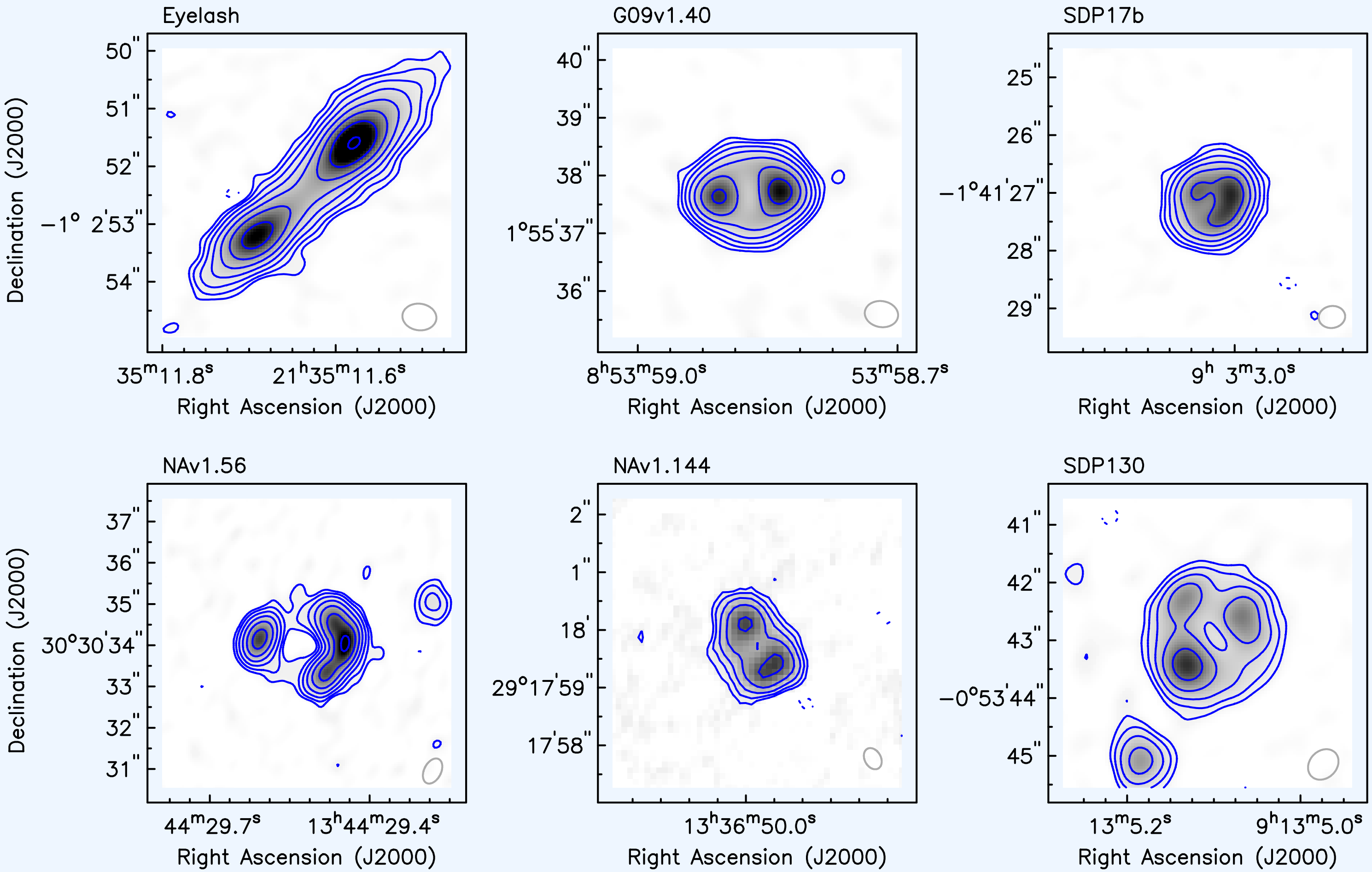
- High critical density = 10^7 cm^{-3}
  ➪ in absorption: $n_H < 100$ cm^{-3}
- Highly endothermic formation : $C^+ + H_2$ ➪ $E_{form} = 0.4$ eV
  → need supra-thermal energy
- Fast destruction by reactive collisions with H and H_2 → CH_3^+
  ➪ lifetime t ~ 1 year in diffuse gas

➪ $$\dot{E} = \mathcal{N}(\mathrm{CH}^+)\frac{E_{\mathrm{form}}}{t}$$ = rate of the energy supply needed to sustain $\mathcal{N}(\mathrm{CH}^+)$ molecules in the beam

$\dot{E}$ ~ 10^{-2} to 10^{-3} turbulent energy transfer rate Godard + 2014

CH$^+$ absorption is a marker of the dissipation sites of supra-thermal energy in diffuse gas

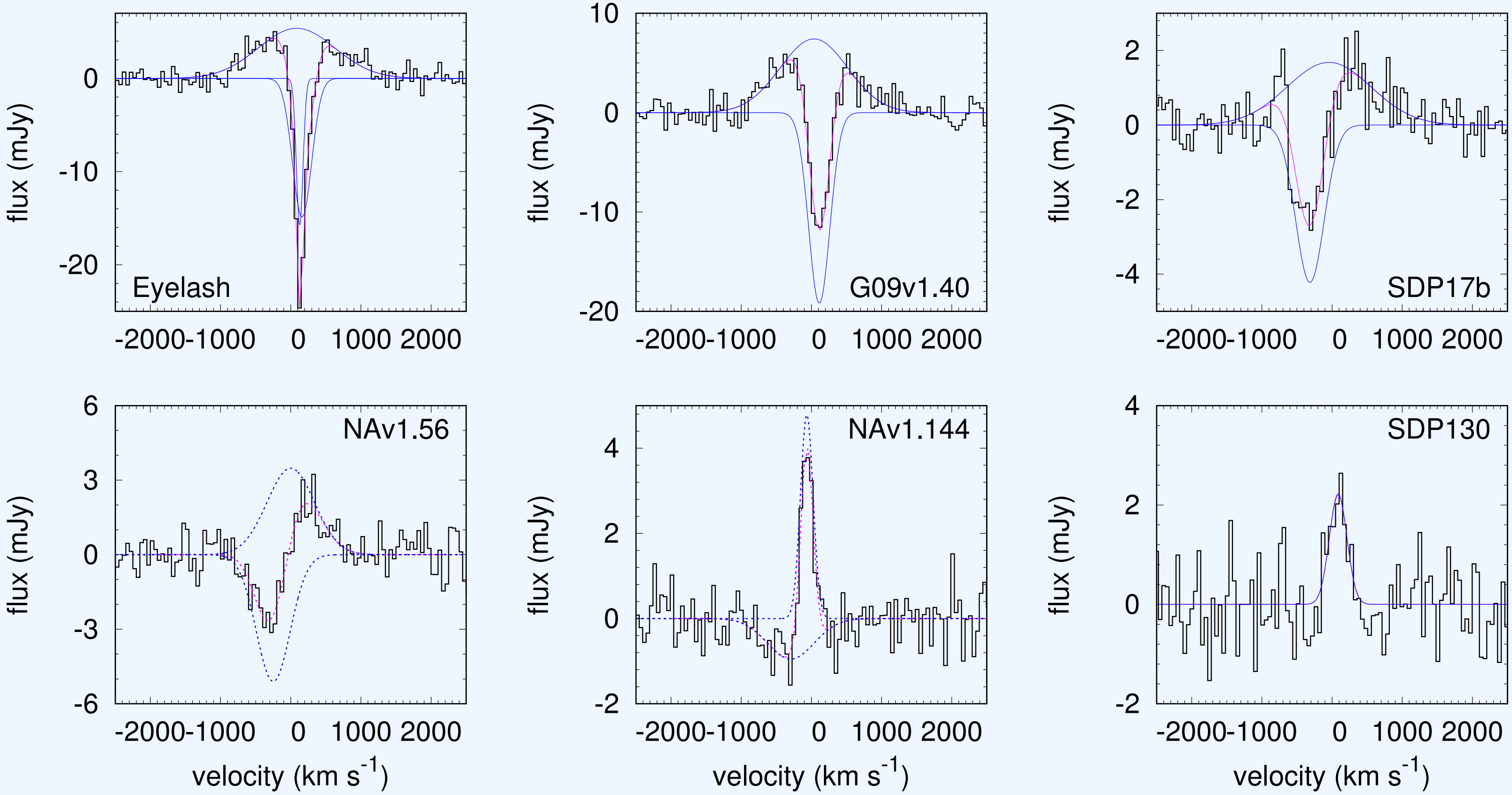
ALMA 350μm rest-frame maps



Lens models → r_{SMG} = 0.5 – 1.2 kpc   Oteo + in prep.

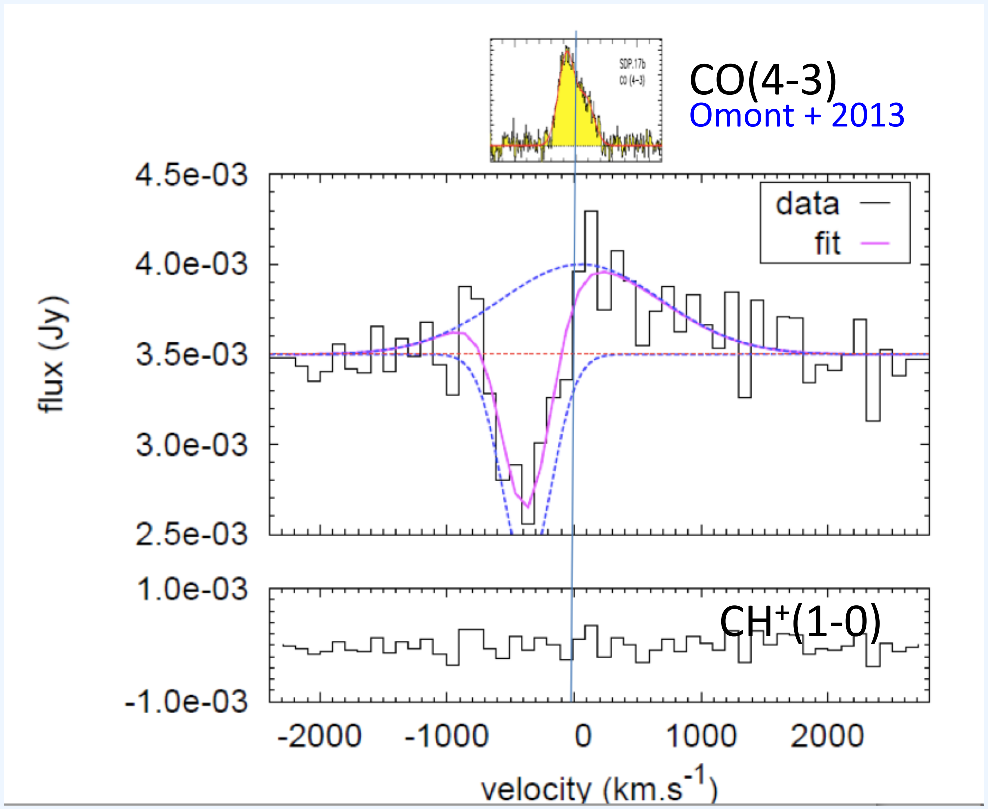
In *Planck* cosmology   0.4 arcsec → 3.3 kpc at z=2.3

ALMA CH^+(1-0) spectra

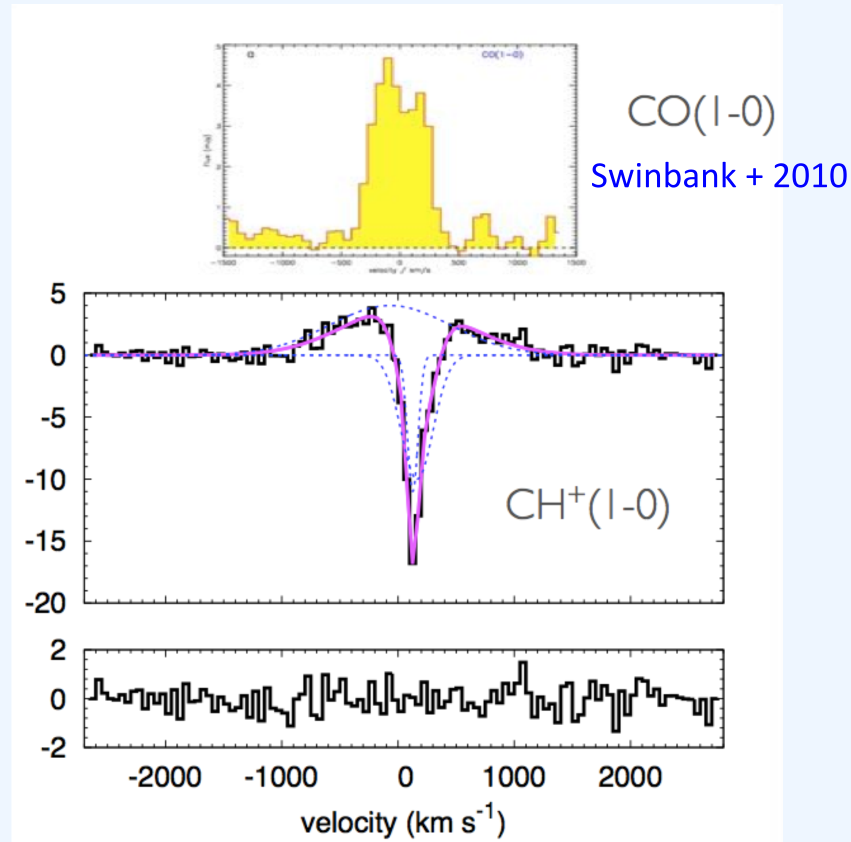


Absorption: detected in 5 sources out of 6→ lifetime ~ t_{SB}
linewidths 230 – 580 km/s, optical depths 0.25 – 1.2 in 100 km/s bins
Broad emission: FWZI up to 2500 km/s

SDP17b



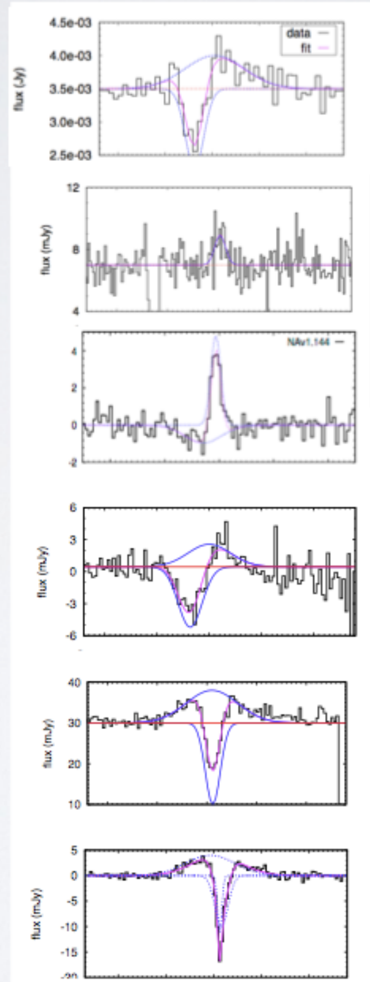
Cosmic Eyelash

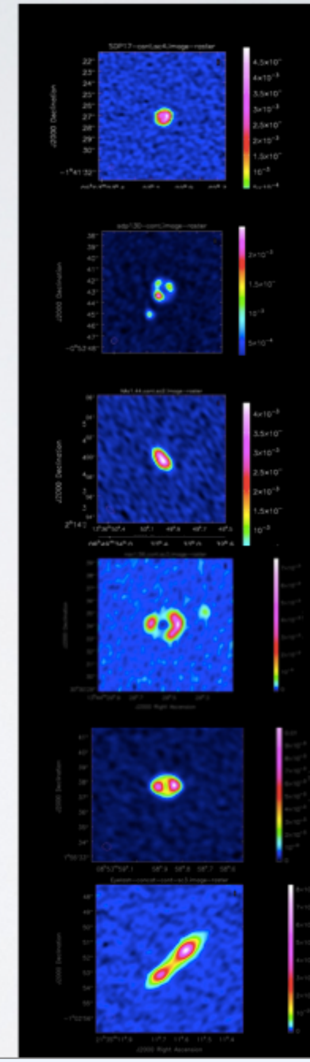


CH^+ emission lines much broader than known CO lines

→ not from PDRs sharing the dynamics of SB cores

Name	CH+ emission	CH+ absorption
SDP17	✔	blue
SDP130	✔	-
NAv1.144	✔	blue centre?
NAv1.56	✔	blue
G09v1.40	✔	centre
Eyelash	✔	red

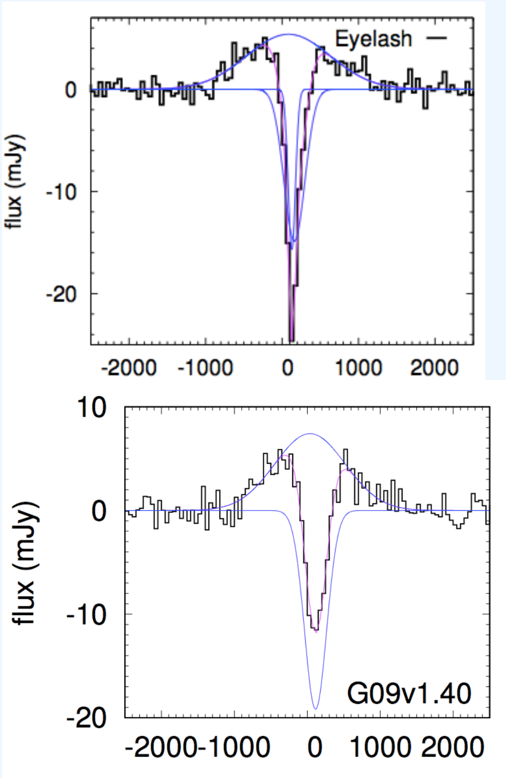




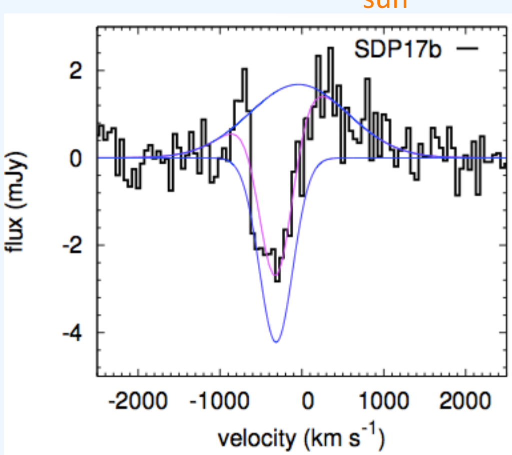
Outflows? Inflows?

→ Turbulence in low density gas likely driven by outflows

$M_* = 3 \times 10^{10}\ M_{sun}$



$M_* = 2.4 \times 10^{11}\ M_{sun}$



What are the lineprofiles telling us?

- Concomitance broad emission / deep absorption → **processes tied together**
- Similar emission linewidths for SFR x 5

→ **hot gas pressure driven outflows**

$$v_{\rm out} \sim \sqrt{3} \times 500\,{\rm km\,s^{-1}} \Big(\frac{T}{4 \times 10^7 {\rm K}}\Big)^{1/2}$$

- Different absorption linewidths

→ **gravitationally bound**

$$\Delta v_{\rm abs} \sim v_{\rm esc}(r) = \Big(\frac{2GM_{\rm tot}}{r}\Big)^{1/2}$$

at $r = \Delta v_{\rm abs}\, t_{\rm SB}$

The diffuse turbulent reservoirs

CH^+ must form within the turbulent gas:
too short a lifetime to be transported from galaxies
→ formation driven by turbulent dissipation :

$$N(\mathrm{CH}^+) = 5 - 8 \times 10^{14}\,\mathrm{cm}^{-2}$$

$$r_{\mathrm{TR}} = 8 - 20\,\mathrm{kpc}$$

$$[\mathrm{CH}^+]/[\mathrm{H}] = 0.4 - 2.5 \times 10^{-8}$$

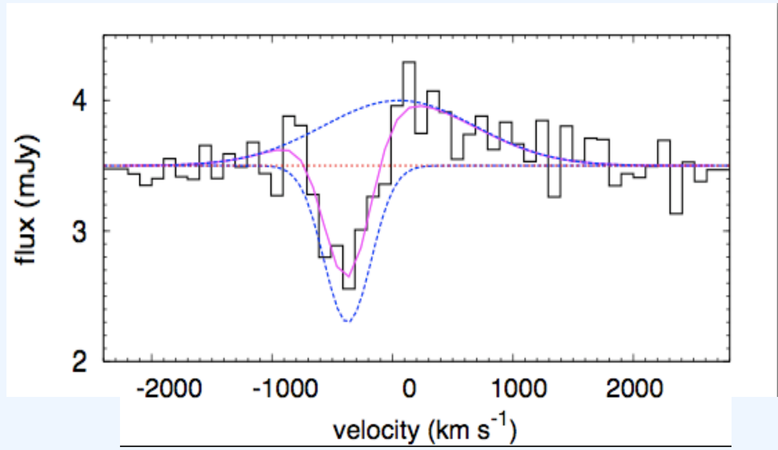
$$M_{\mathrm{TR}} = 5 - 6 \times 10^{10}\,\mathrm{M}_\odot$$

Kinetic luminosity:

$$L_{\mathrm{TR}} \propto \frac{M_{\mathrm{TR}} \Delta v_{\mathrm{abs}}^2}{t_{\mathrm{SB}}} = 0.6 - 2.2 \times 10^9\,\mathrm{L}_\odot \propto \mathrm{SFR}$$

→ mass outflow rate ~ SFR

High velocity gas seen in emission



No shocks v_{sh} > 90 km/s: radiative precursors

→ **Myriads of low velocity v_{sh} < 40 km/s irradiated shocks**

Pre-shock density 10^4 cm^{-3}, v_{sh} = 20 km/s

➪ N(CH^+) = 10^{14} cm^{-2}

Shock density > 10^5 cm^{-3}, optically thin CH^+(1-0) lines

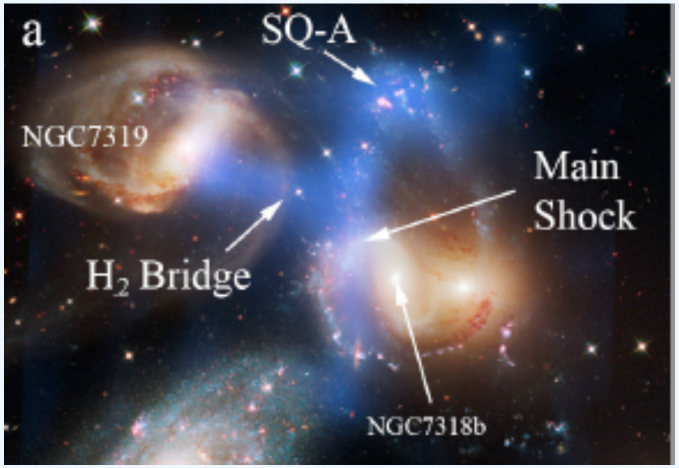
Result depends weakly on density

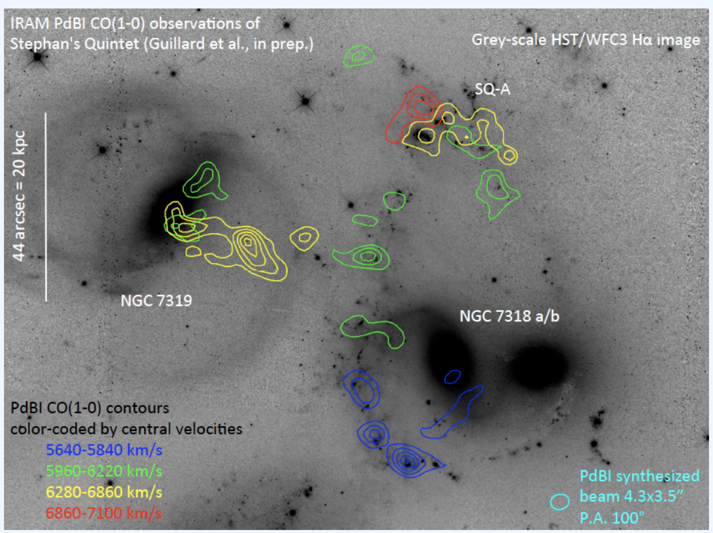
Lesaffre et al. 2013,
Falgarone et al. 2010
Godard + in prep

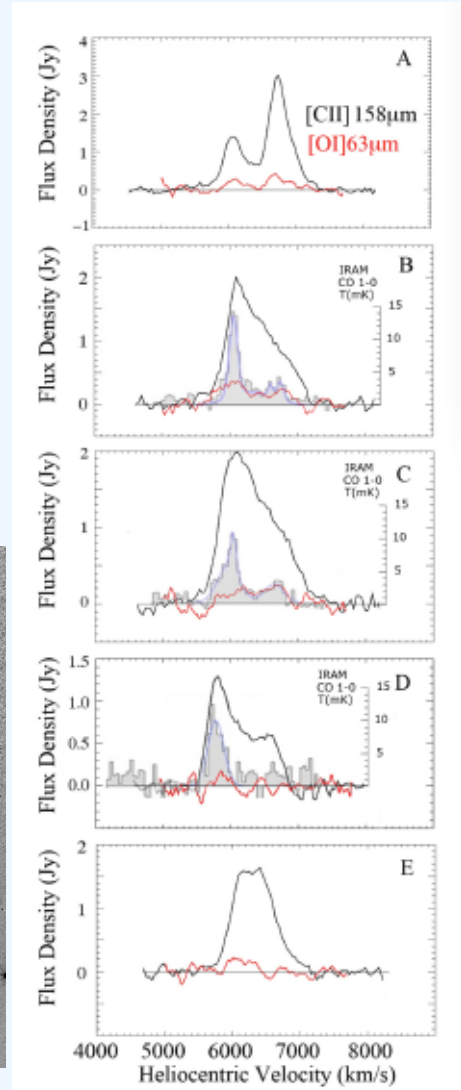
Origin?

Stellar- or AGN-driven outflows within the SB cores, tidal shocks in mergers, cold stream collision with the galaxies?

Kpc-scale shock in the Stephan's quintet







Appleton + 2013
Guillard + 2012 and in prep.

Energy of a large-scale collision

v_{rel} = 500 – 700 km/s

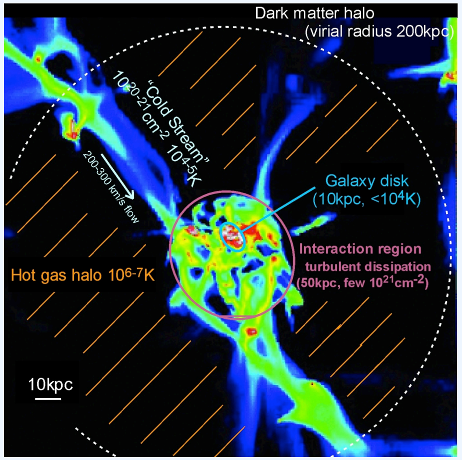
→ **shock heated gas**

25% radiated in X-rays
75% radiated in H_2 pure rotational lines

Cluver + 2010

Shock distribution

Lesaffre + 2013



In summary

Regardless of the energy drivers (feedback from stellar- or AGN-driven outflows, infalling cold streams, major mergers, …)

- ➮ massive turbulent interfaces
  = buffers of mass and gravitational energy
- ➮ turbulence likely driven by outflows
- ➮ multi-phase turbulence (shocks, diffuse halo)

CH^+ being a very specific tracer of
(i) dissipation of turbulent energy in diffuse gas
(ii) highly irradiated dense gas in shocks
opens an entirely new field of investigation of galaxy formation in the high-z universe