A new insight of the outer filaments of Centaurus A

(Salomé Q. et al. 2016; Salomé Q. et al., accepted)

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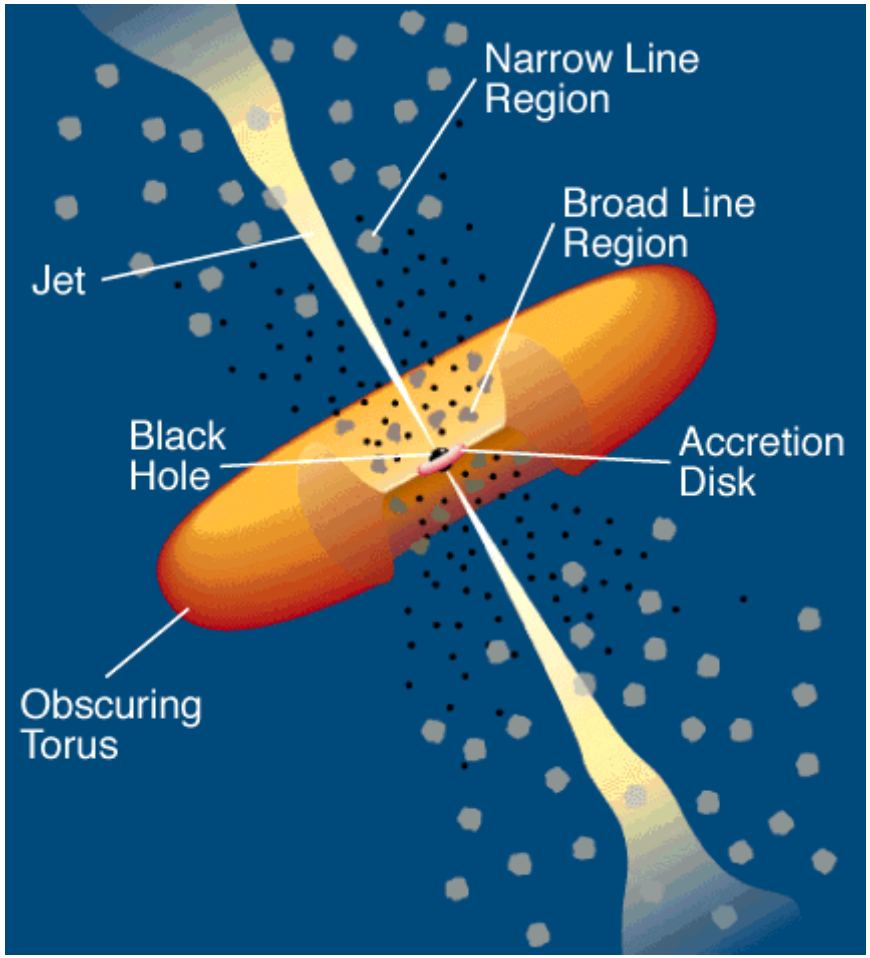
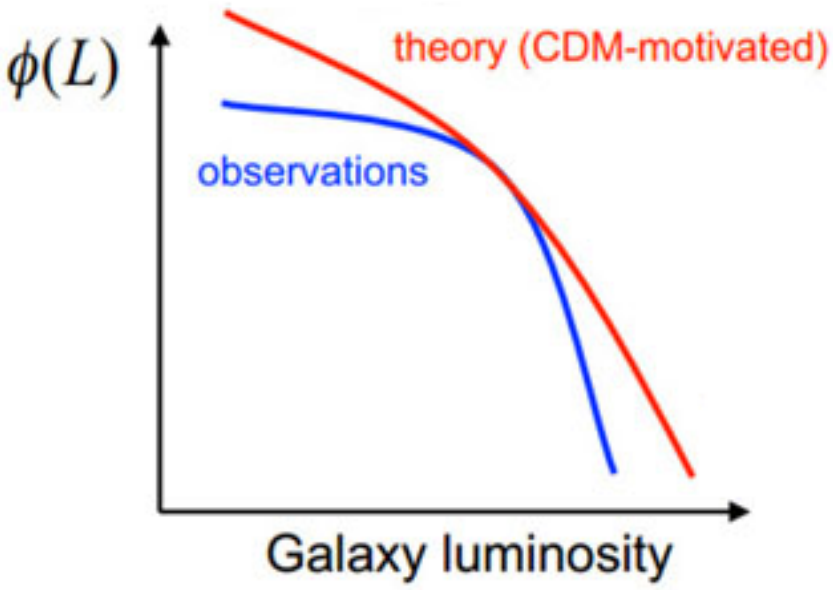
Introduction: AGN feedback



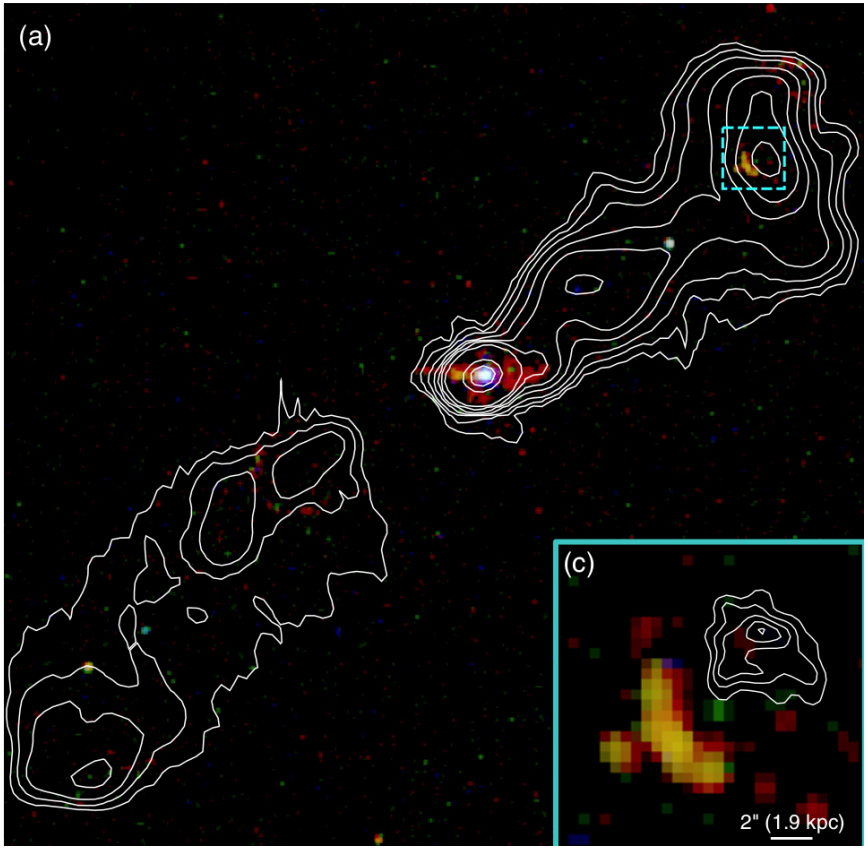


- Radiative mode → large amount of radiation
- Jet mode → kinetic energy

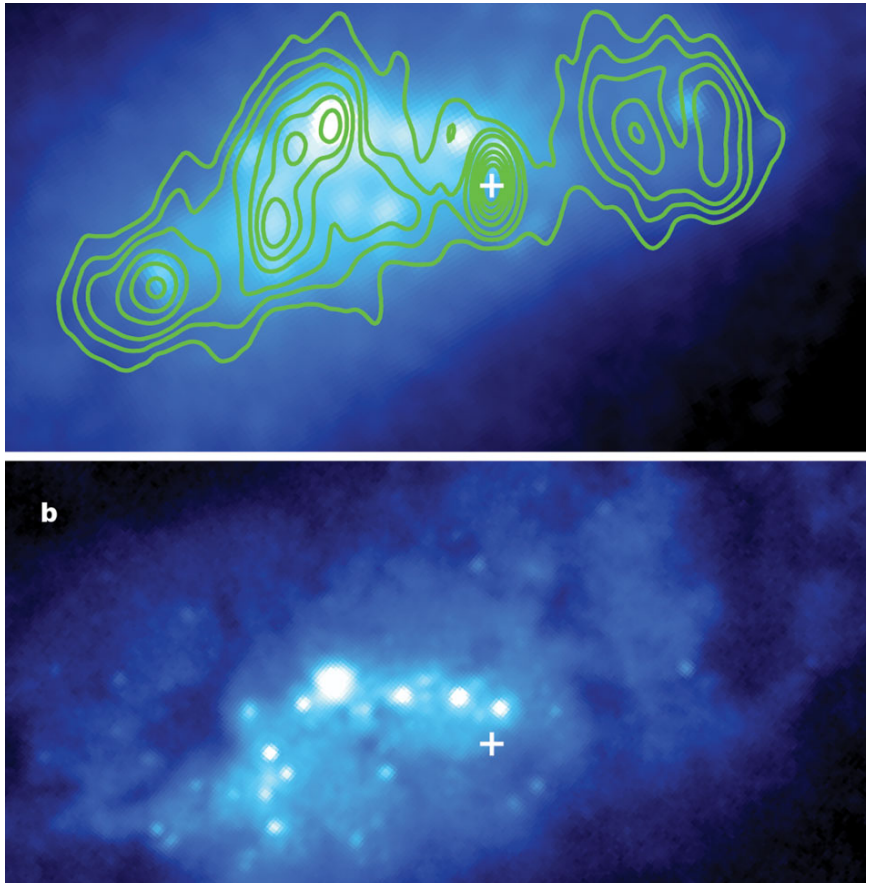
AGN feedback: interaction between energy generated by accretion and gas.

Introduction: jet-induced star formation

Some examples suggest that AGN feedback may also trigger star formation.



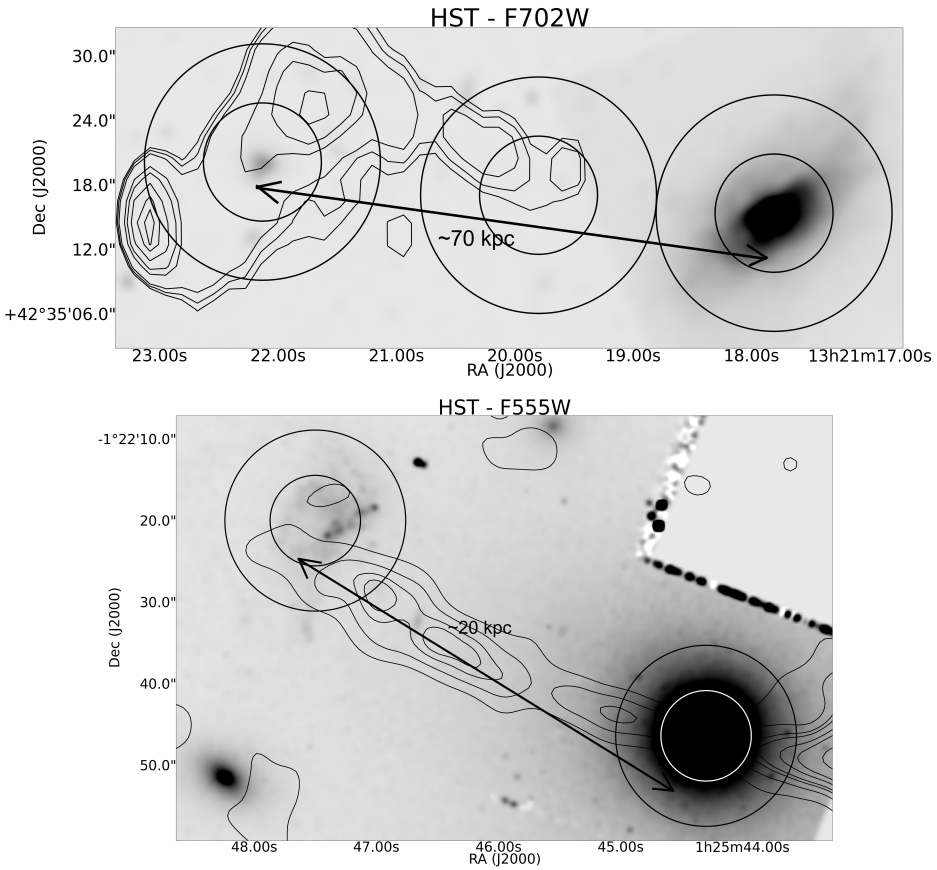
3C 293 by Lanz et al. (2015):
X-ray emission is aligned with the radio jet at $\sim 80\,\mathrm{kpc}$ from the centre



Henize 2-10 by Reines et al. (2011):
near-IR clumps within $\sim 50\,\mathrm{pc}$ along the radio jet in a dwarf starburst galaxy

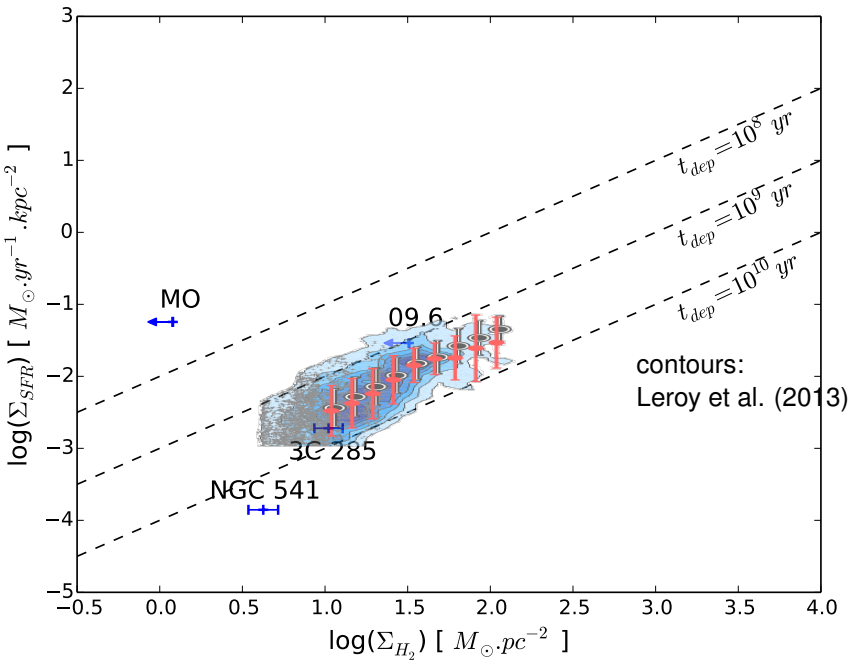
Introduction: 3C 285/Minkowski's Object

Two star-forming regions at tens of kpc of radio galaxies along the radio jet
→ Is star formation more efficient in the shocked region along the jets?

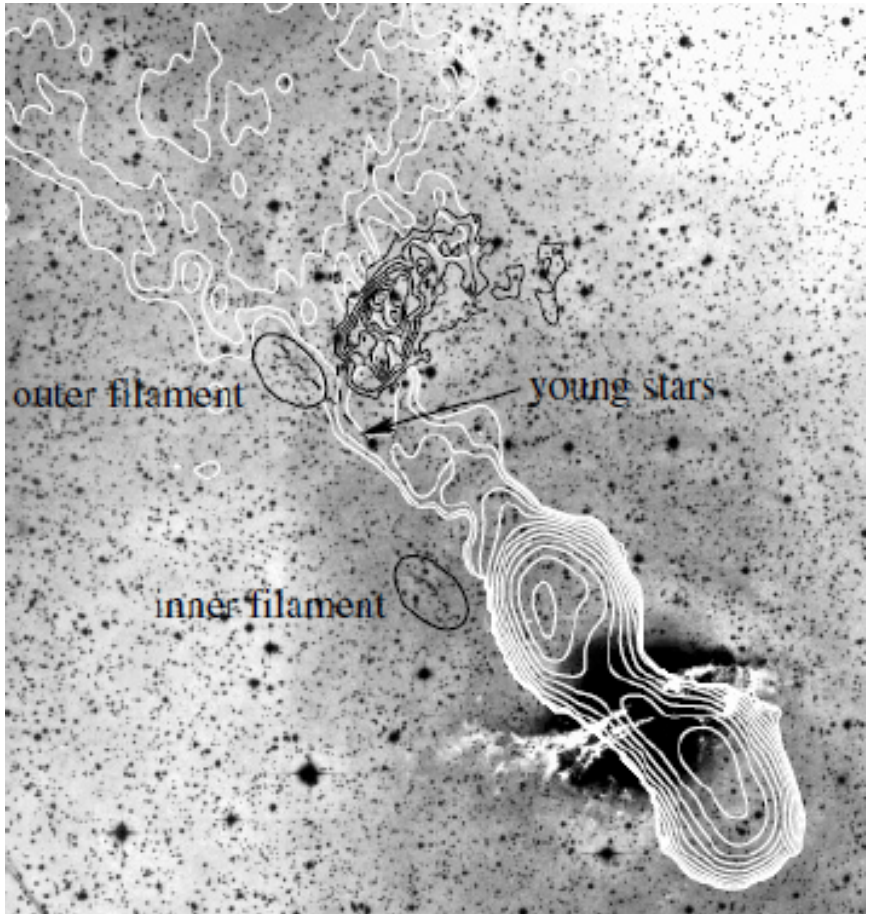


Salomé et al. (2015), A&A, 574, A34

- CO(1-0) and CO(2-1) with the IRAM 30m telescope
- $M_{H_2} < (0.01 - 6) \times 10^8\ M_\odot$
- $SFR = 0.43 - 0.56\ M_\odot.yr^{-1}$



Centaurus A, an example of jet-gas interaction

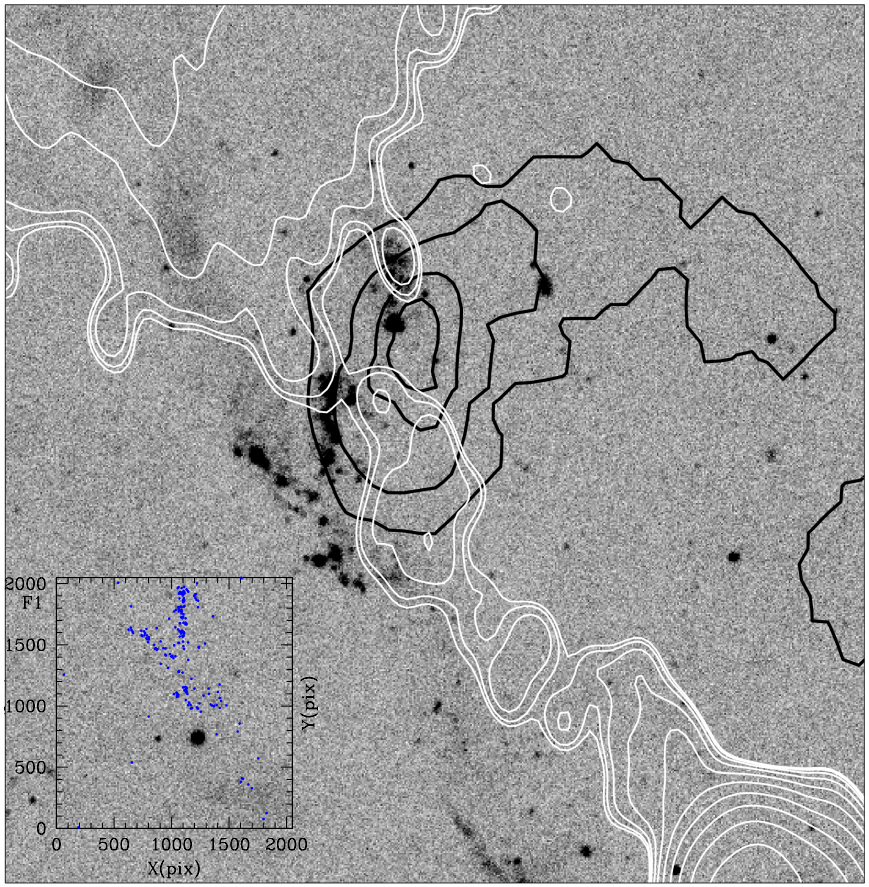


Oosterloo & Morganti (2005)

- The jet encounters a HI shell (Schiminovich et al. 1994)
- The nearest example of jet-gas interaction

⇒ Enables to look at small scales

Centaurus A, an example of jet-gas interaction



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- FUV emission (Neff et al. 2015), young stars (Rejkuba et al. 2001)

⇒ Recent (triggered?) star formation

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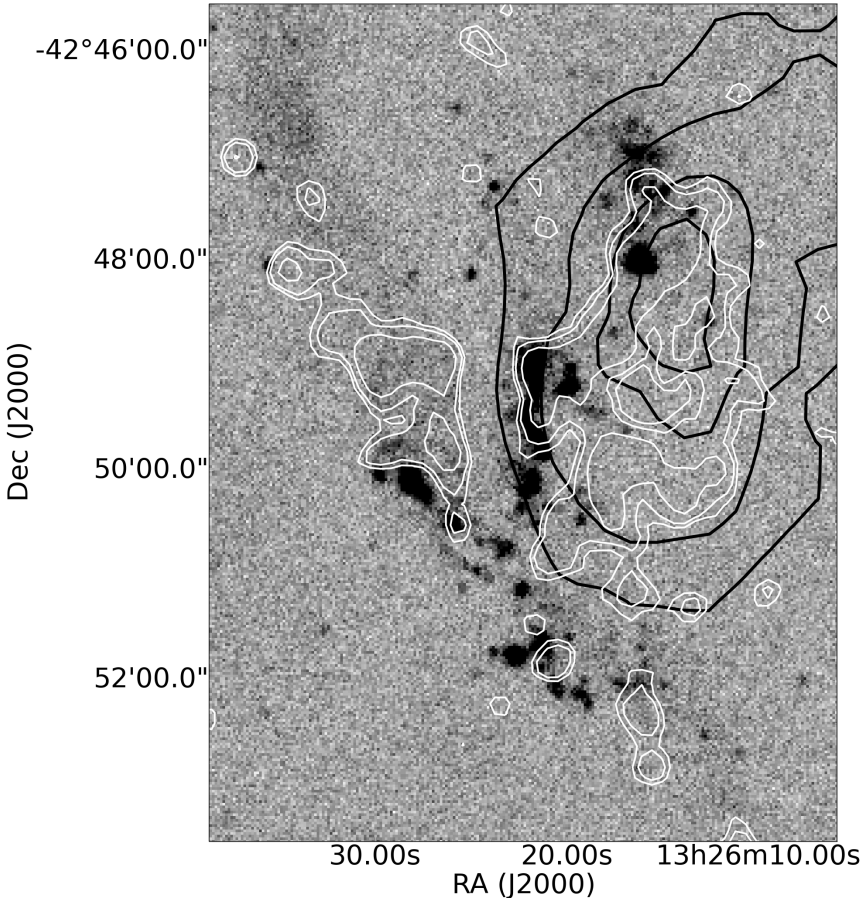

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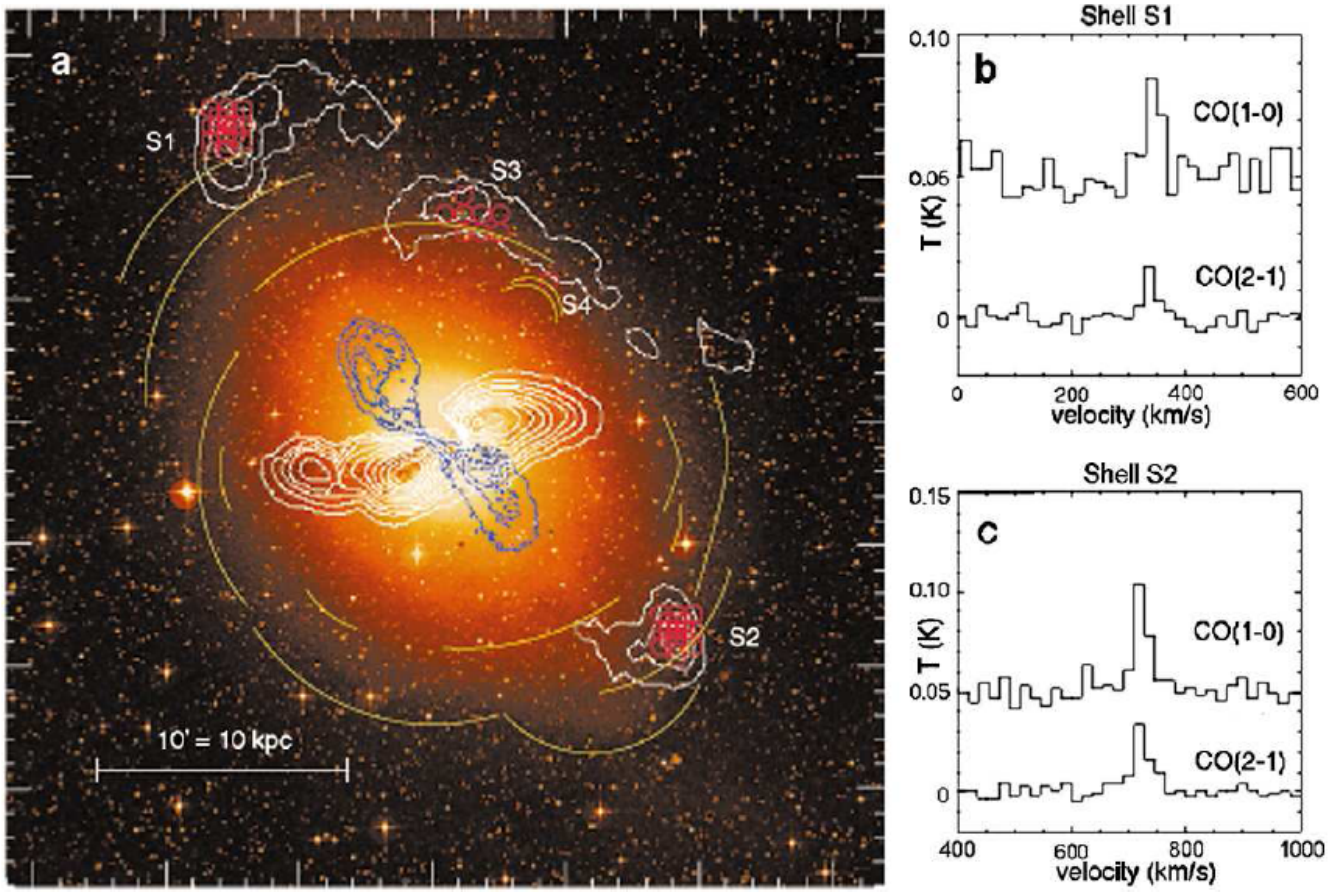
- Dust emission (Auld et al. 2012)

⇒ Molecular gas?

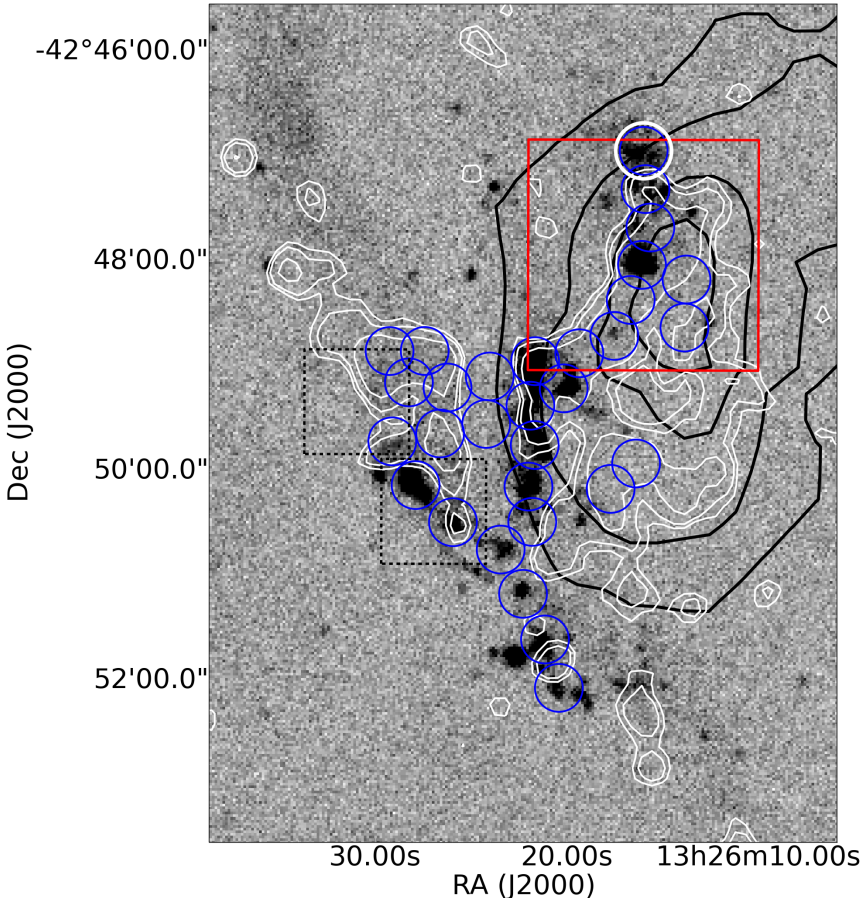
Molecular gas in the shell

Charmandaris et al. (2000)



CO emission in the shells aligned with the jet, but not in the other (S3)

A multi-wavelength study



CO(2-1) with APEX and ALMA (archive), HCN/HCO$^+$(1-0) with ATCA, MUSE data

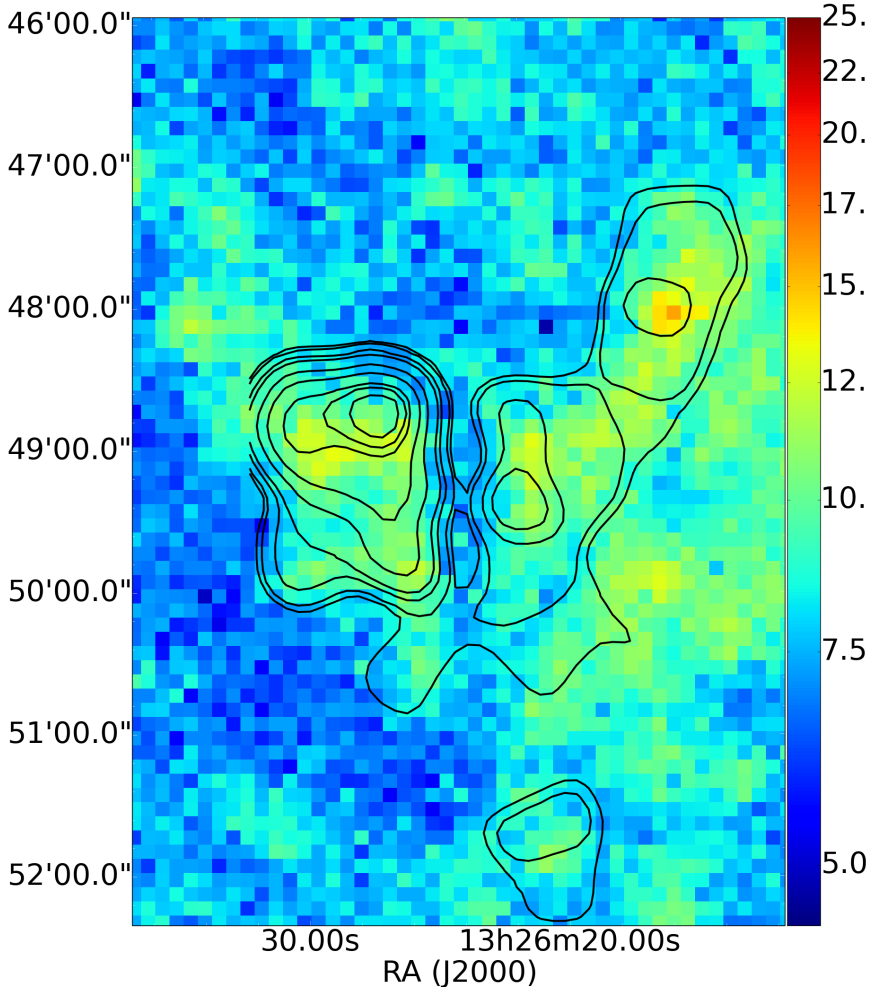
We extended the region and covered three regions:

1. One within the HI cloud
2. One outside the HI and within the dust emission
3. One outside the HI with FUV emission only

Salomé et al. (2016), A&A, 586, A45
Salomé et al. (2016), arXiv:1605.05986

CO properties

CO emission in contours on the FIR map



- The molecular gas follows the dust emission
- It is detected outside the HI cloud
- Surprisingly stronger on the east
- $M_{H_2}^{tot} = (8.2 \pm 0.5) \times 10^7\ M_\odot$

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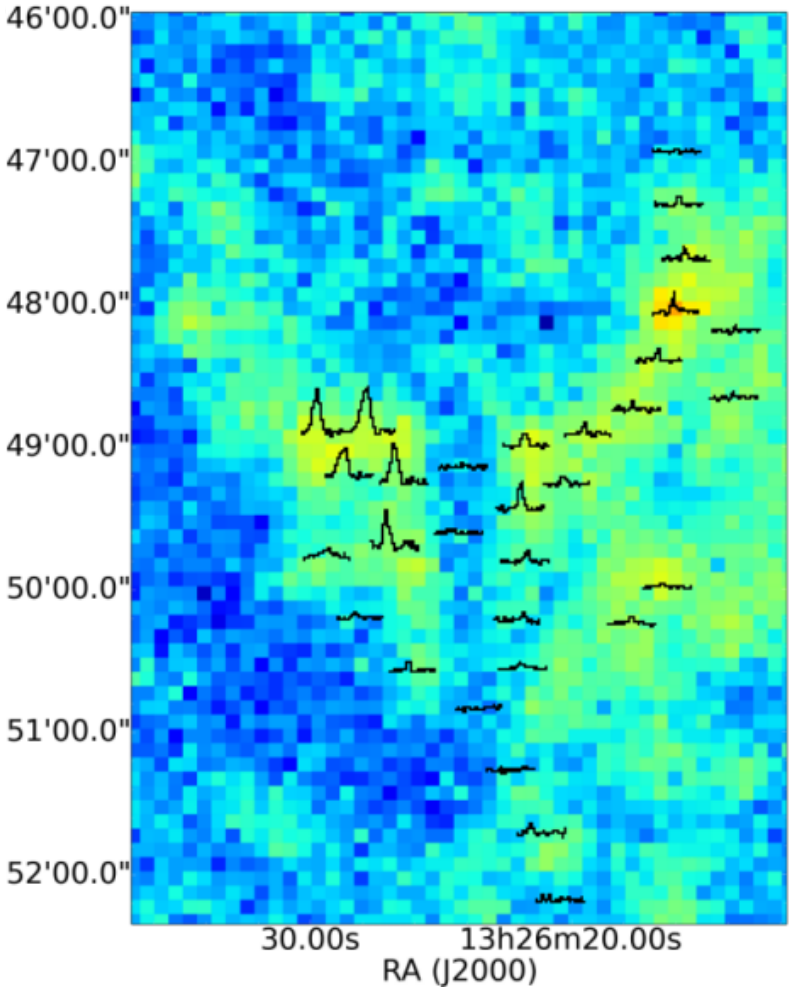

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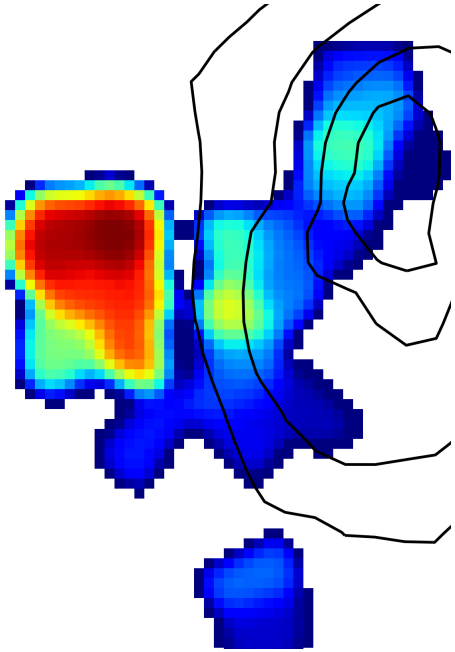
Molecular-to-atomic mass ratio

We compared the APEX CO data with VLA HI data and derive H_2/HI mass ratios. Lower resolution for VLA ($40'' \times 78''$) $\Rightarrow$ combination of several APEX pointings contained in a single VLA beam.

East		
M_{HI}	M_{H_2}	M_{H_2}/M_{HI}
$< 9.2 \times 10^5$	3.2×10^7	> 35.1
$< 9.3 \times 10^5$	9.0×10^6	> 9.73
5.5×10^5	$< 1.0 \times 10^7$	< 18.2
2.4×10^6	5.1×10^7	~ 21.3

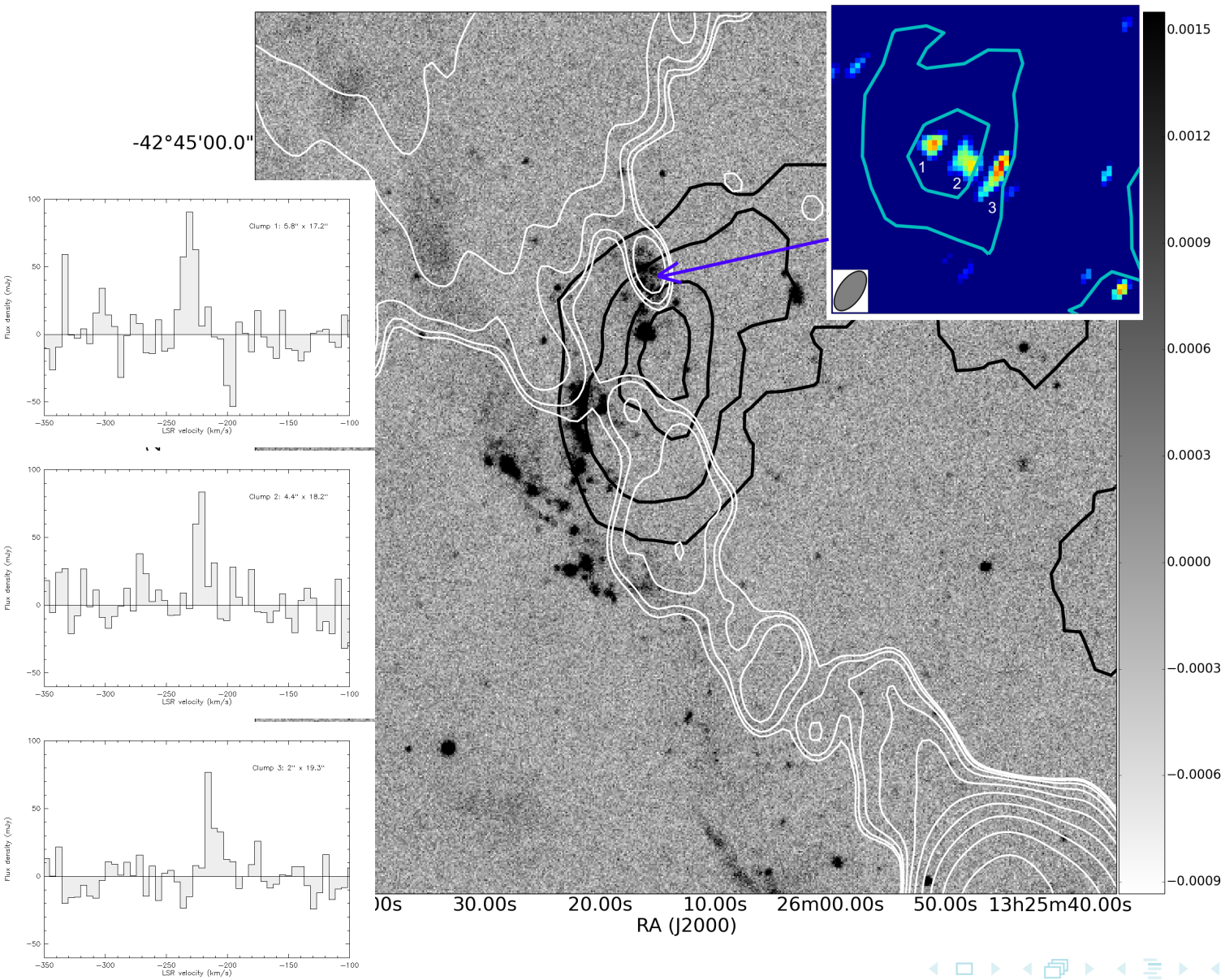


West		
M_{HI}	M_{H_2}	M_{H_2}/M_{HI}
2.8×10^6	$< 2.8 \times 10^6$	< 1.00
4.6×10^6	4.6×10^6	1.00
1.7×10^6	9.4×10^6	5.42
2.6×10^6	1.8×10^6	0.69
8.2×10^5	4.5×10^6	5.49
5.5×10^6	1.1×10^6	0.20
5.9×10^5	$< 1.8 \times 10^6$	< 3.04
1.9×10^7	2.6×10^7	~ 1.37

The full region contains $M_{H_2} = 7.7 \times 10^7\ M_\odot$ and $M_{HI} = 2.1 \times 10^7\ M_\odot$ (ratio of 3.66) $\Rightarrow$ the filaments are mostly molecular.

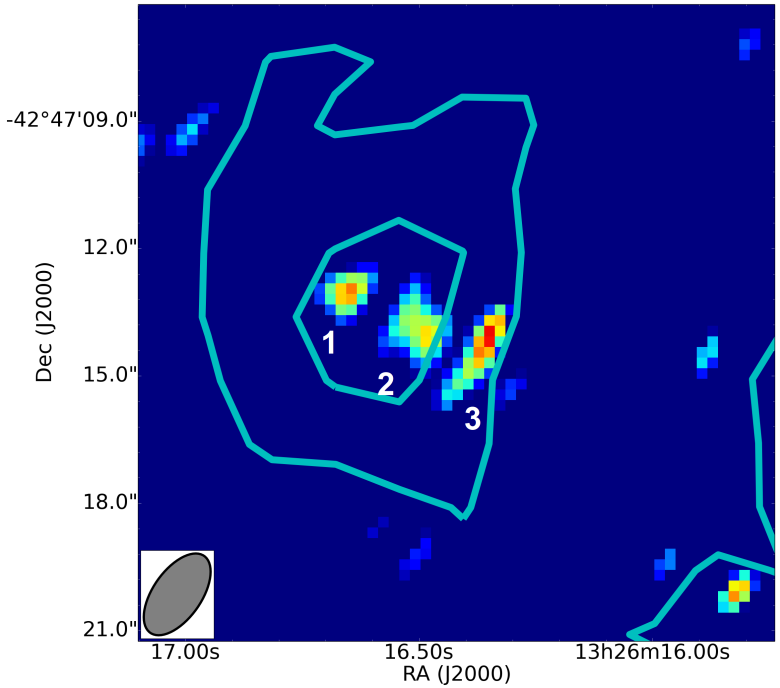
$\Rightarrow$ HI-to-H_2 phase transition triggered by the radio jet?

ALMA resolved molecular gas



ALMA resolved molecular gas

Cycle 0 observations; 16 antennas
unpublished archival data:
project 2011.0.00454.S



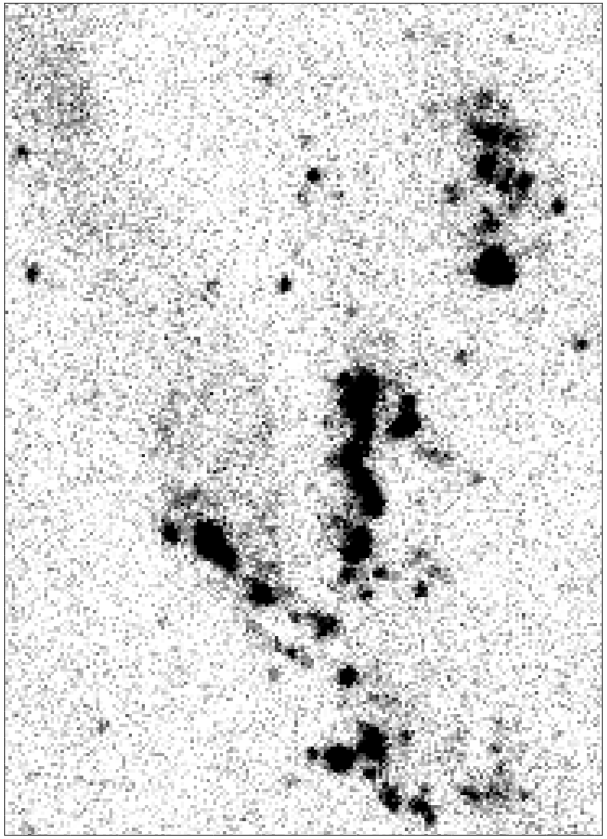
3 clumps ($d = 2'' \sim 30\,\mathrm{pc}$) in CO(2-1)

- $S_{CO}\Delta v \sim 3.0\ \mathrm{Jy.km.s^{-1}} \Rightarrow M_{H_2} \sim 1.6 \times 10^5\ M_\odot$
- HCN not detected: $S_{HCN}\Delta v < 33.5\ \mathrm{mJy.km.s^{-1}}$ ($f_{dense} \lesssim 12\%$)
- $\alpha_{vir} = 5\sigma_c^2 R_c/(GM_c) \sim 15 - 25$ $\Rightarrow$ no gravitational collapse, turbulent gas?

Clump	v_0 ($\mathrm{km.s^{-1}}$)	Δv ($\mathrm{km.s^{-1}}$)	M_{H_2} ($10^4\ M_\odot$)
1	~ 230	~ 12.5	7.3 ± 3.1
2	~ 220	~ 8.0	4.8 ± 3.1
3	~ 210	~ 7.5	3.8 ± 2.7

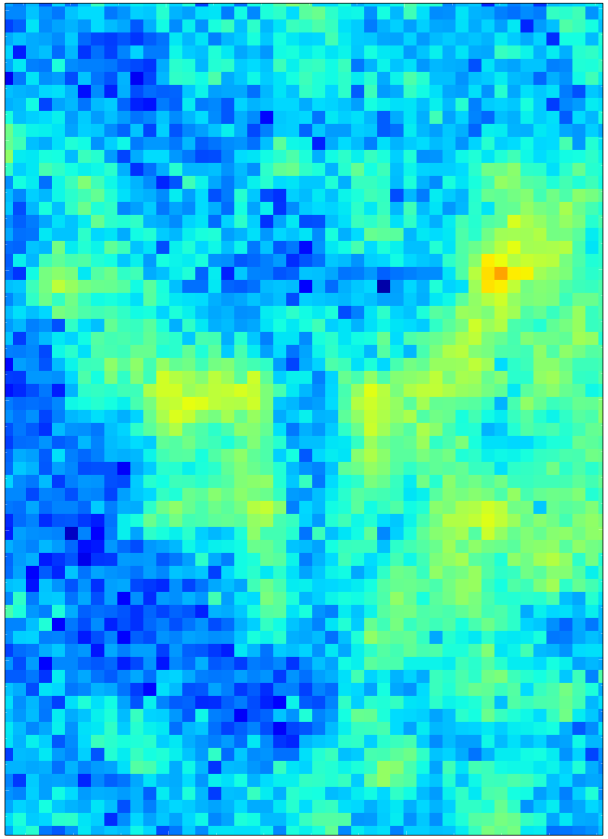
Star formation tracers

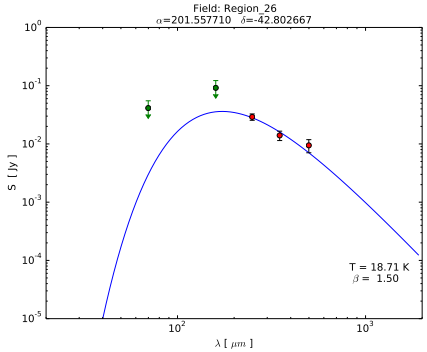
FUV - GALEX



+

$250\mu m$ Herschel



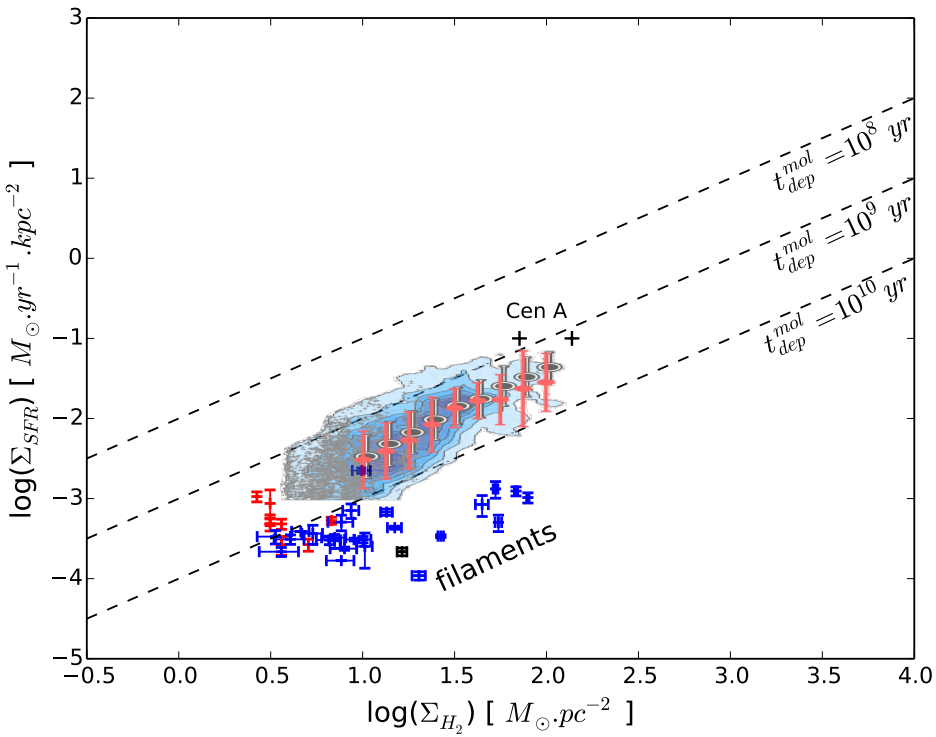


$\Rightarrow$ **SFR**

- $\sim 10\%$ uncertainties on IR fluxes (bgd extraction)
- uncertainties on the SFR: $\sim 10 - 30\%$
- whole region (8.7×5.8 kpc): $\mathrm{SFR_{tot}} \sim 1.1 \times 10^{-3}\ \mathrm{M_{\odot}.yr^{-1}}$

$\Rightarrow$ $\mathrm{t_{dep}^{mol}} \sim 75$ Gyr (normal spiral galaxies: ~ 2 Gyr)

Gas and SFR surface densities in the filaments

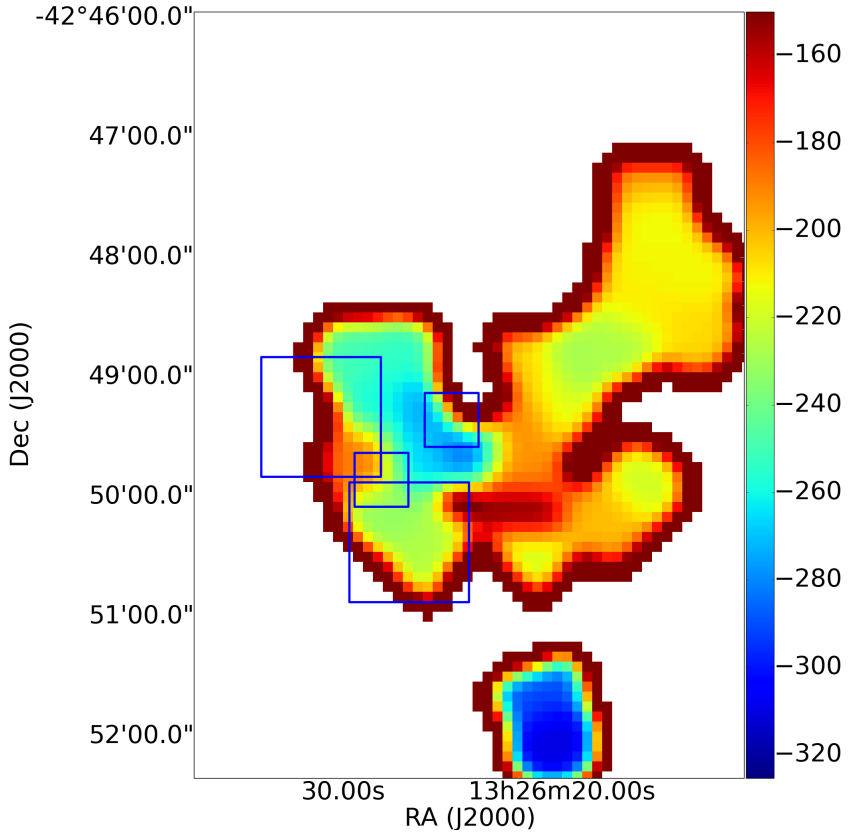


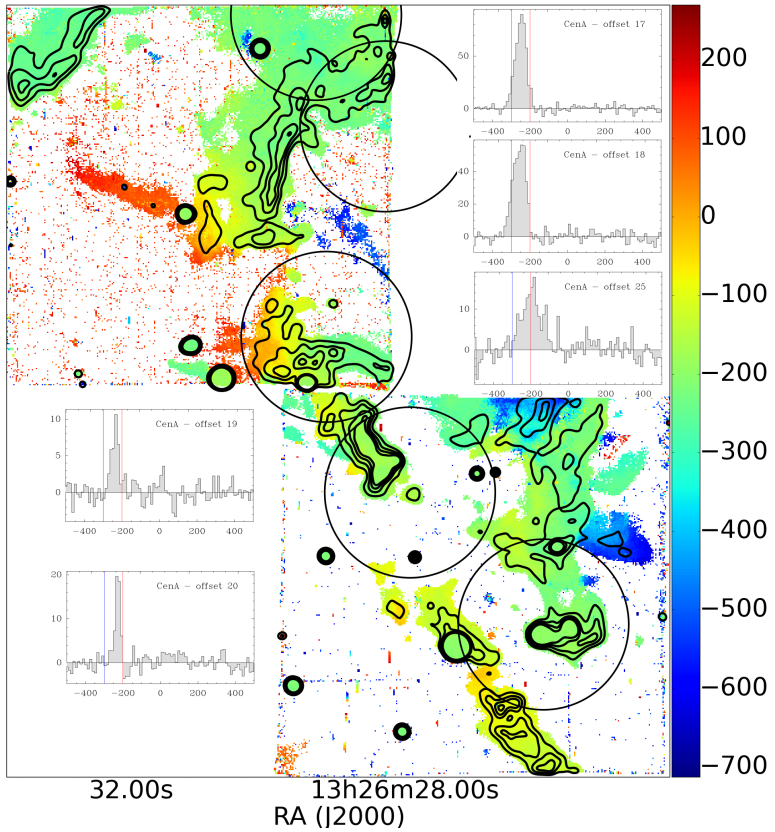
contours: Leroy et al. (2013)

- Recent star formation within the filaments
- Higher H_2/HI ratio along the jet direction
- Star formation efficiency is very low

⇒ Consistent with star formation triggered by the jet (via H_2 formation) within a large molecular gas reservoir

Dynamics of the filaments





CO(2-1) emission is blueshifted and show velocity gradients with the top being bluer. PV diagrams show a change in velocity for both the atomic and molecular gas → Due to the interaction of the radio-jet with the gas?

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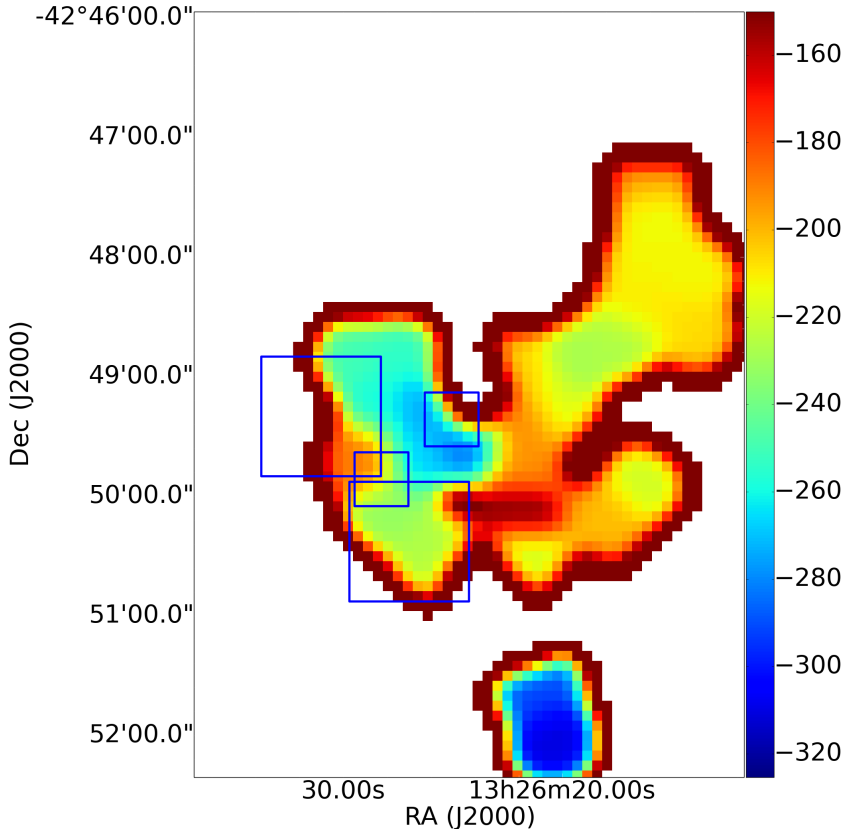
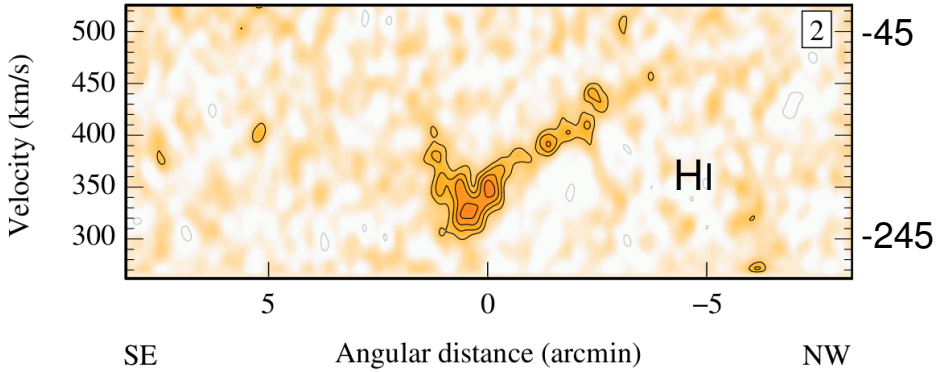
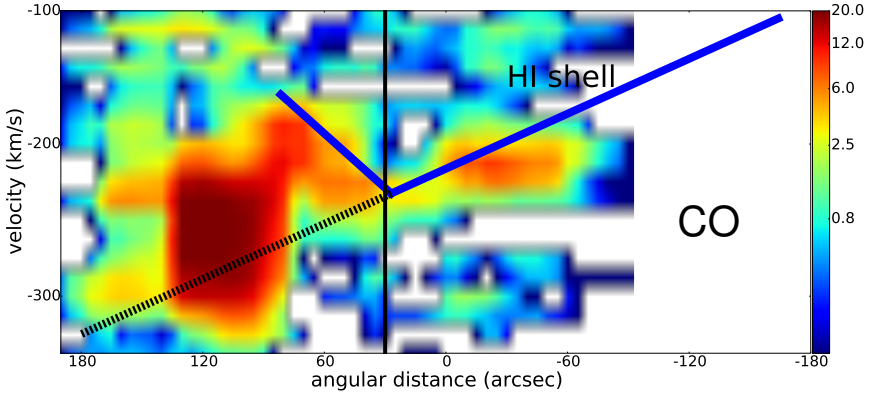


Oosterloo & Morganti (2005)





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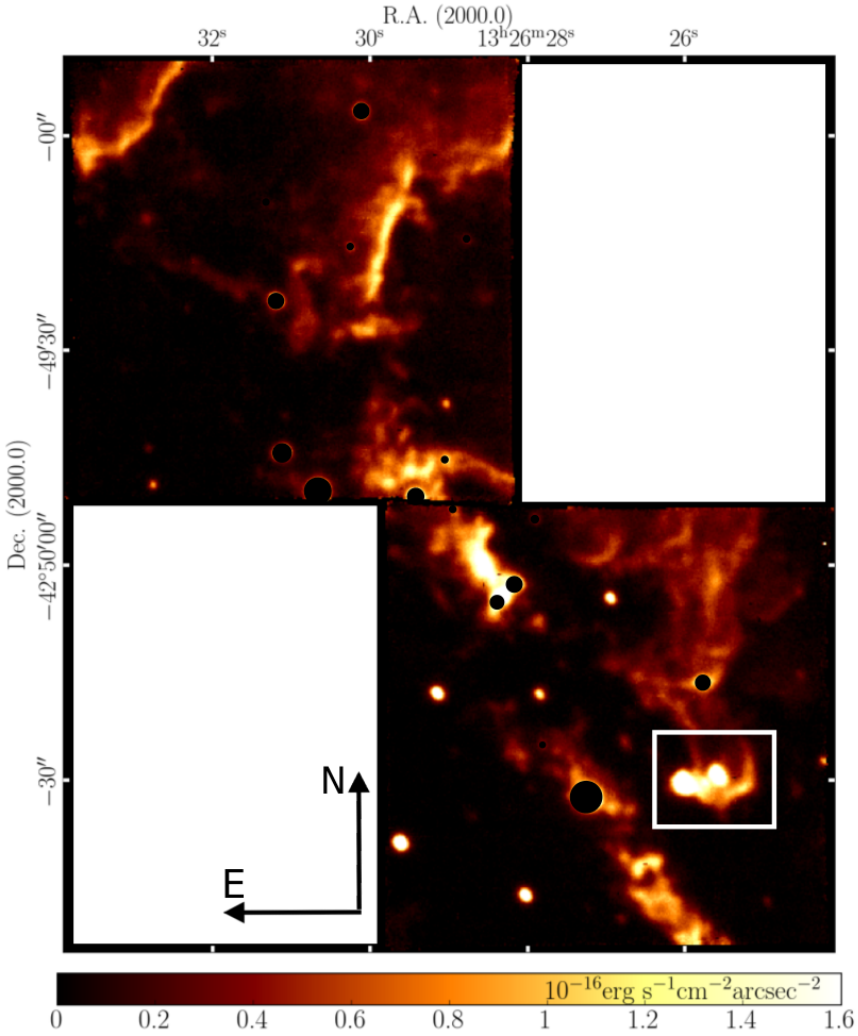
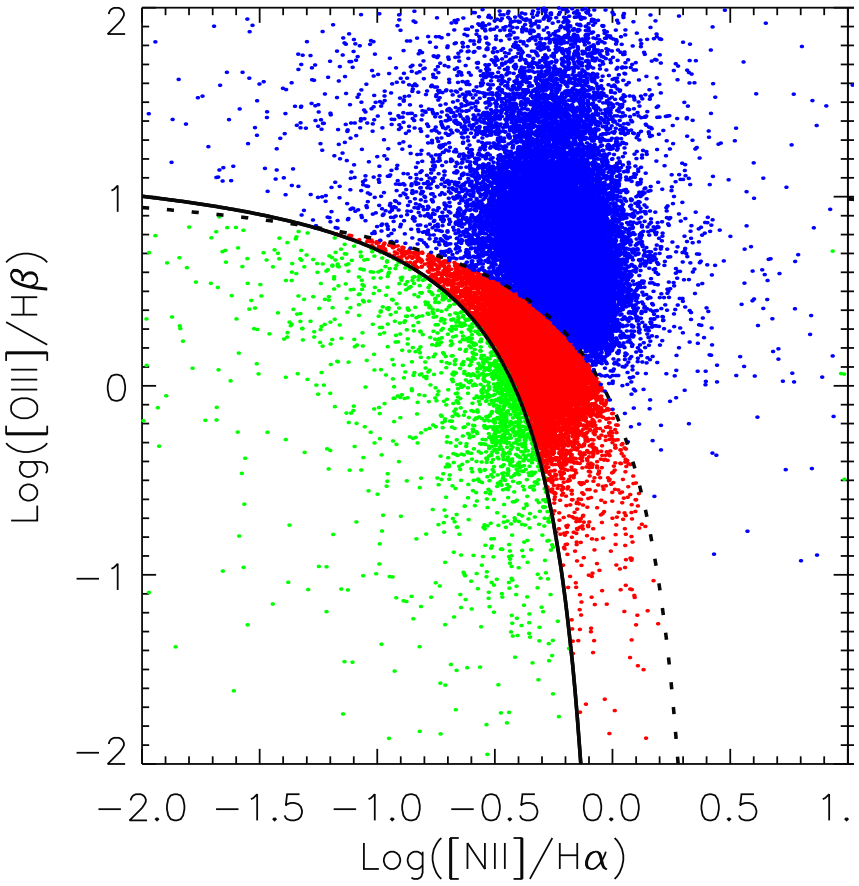
Excitation of the filaments

Santoro et al. (2015)

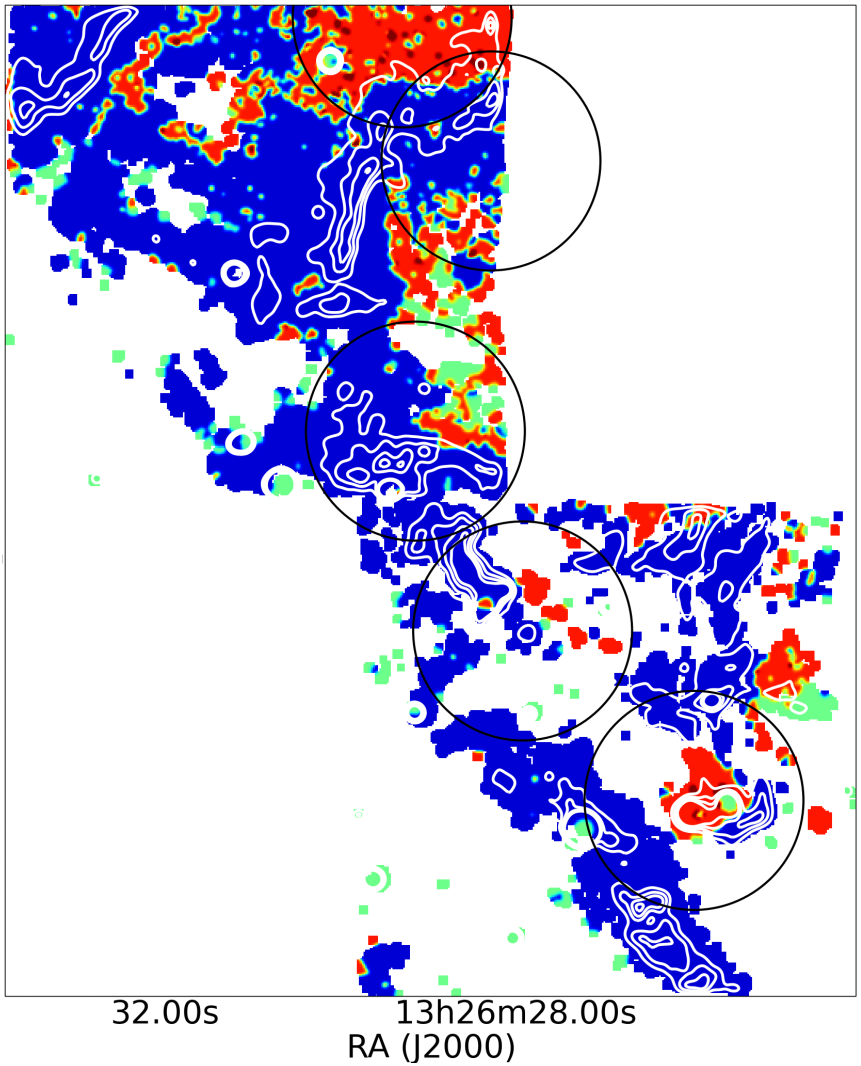


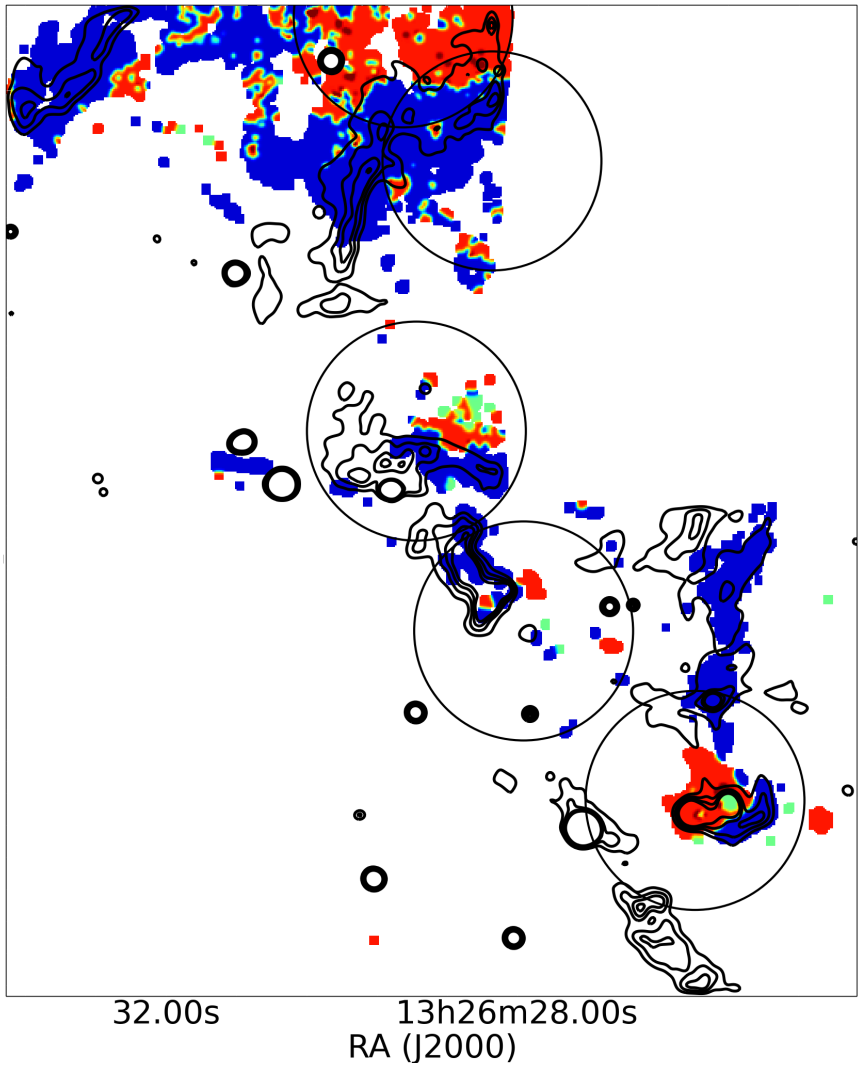
Salomé et al. (2016)



Excitation of the filaments

blue: AGN/shock; green: SF; red: comp.





Mostly excited by energy injection from radio jet or shocks, with small inclusions of star formation. Our APEX pointings contain both excitation processes.

Conclusions

CO distribution in the outer filaments:

- Large scale map along the optical, UV and dusty filaments with APEX
- Clumpy molecular gas in two separated structures, with CO(2-1) emission in between
- The eastern region is CO brighter than the western

Jet-gas interaction:

- Kinetic energy injection from large scale dynamics?
- Velocity shears → direct effect of the jet interaction on the gas distribution?
- Different excitation mechanisms: AGN/shocks dominated, with localised HII regions
- High molecular-to-atomic gas fraction → the jet compresses the gas and triggers the phase transition?

Star formation inefficiency:

- The filaments recently SF but, from a huge molecular gas reservoir
- SFE is very low in the northern filaments: total $t_{dep}^{mol} \sim 75$ Gyr

⇒ Some processes may prevent SF in the cold gas