Star formation efficiency in the outer filaments of Centaurus A
(Salomé et al., accepted to A&A; Salomé et al., in prep.)

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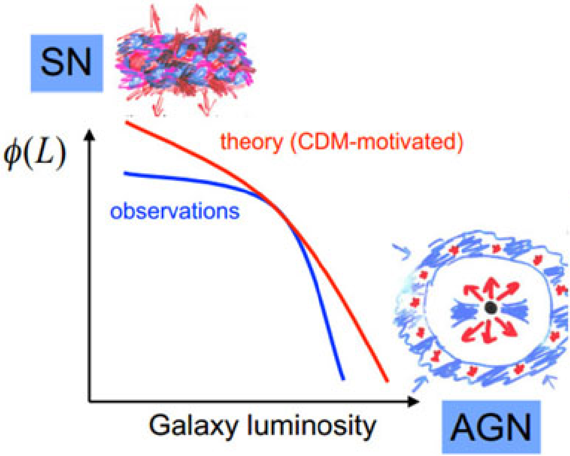
Laboratoire d'Étude du Rayonnement et de la Matière en Astrophysique

Introduction: AGN feedback



Supernovae reduce SF efficiency through galactic fountains. But this process is too weak to regulate star formation in massive galaxies.
AGN feedback: interaction between energy generated by accretion, and the gas in the host galaxy. It maintains a heating/cooling balance.

Introduction: AGN feedback

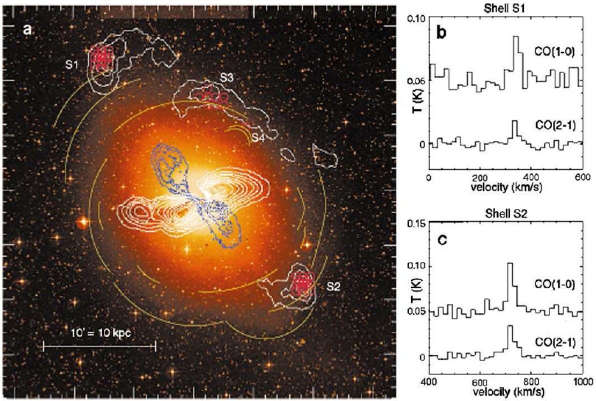
Accreting gas, the central SMBH emits energy. Depending on how this energy is released, there are two kinds of AGN feedback:

- Radiative mode $\rightarrow$ large amount of radiation
- Jet mode $\rightarrow$ kinetic energy

The radiative mode produces winds of gas due to the radiative pressure.
In the jet mode, the energy is released through jets of particles $\rightarrow$ sometimes observed in radio.

Some examples suggest that AGN feedback may also trigger star formation. The filaments of Centaurus A is often invoked as an example of star formation triggered by the radio jet.

Introduction: Centaurus A



Schiminovich et al. (1994)
Charmandaris et al. (2000)

- 1.5×10^8 $M_\odot$ of **HI in shells**
- 4.3×10^7 $M_\odot$ of H_2 associated with the shells
- CO gas **aligned with** the shells and the radio jet
- Optical filaments **along the jet**

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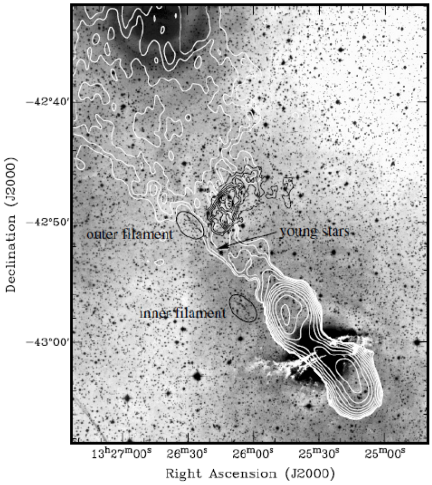

- HST observation of the inner filament
- Strong Hα emission: $M_{H\alpha} = 2.1 \times 10^5$ $M_\odot$
- **Young stellar population** near the SW tip
- Mass of young stars: $M_* \sim (2-8) \times 10^3$ $M_\odot$
- A weak shock have **compressed** a molecular gas cloud, **triggering** the observed SF?

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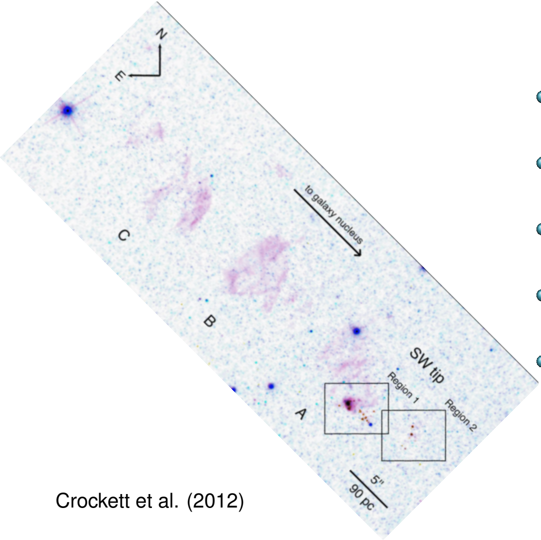

Crockett et al. (2012)

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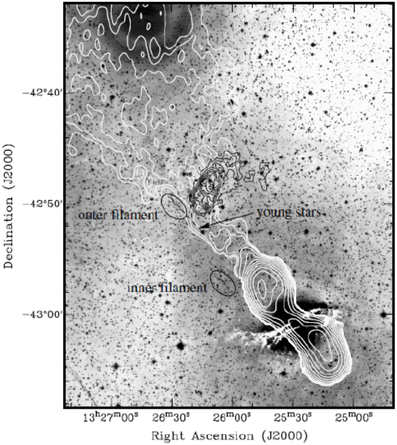
A multi-wavelength study

We gathered archival data of the outer filaments in FUV, IR and CO. We also searched for HCN and HCO^+ and observed optical emission lines.
The filament extend on ~ 8 kpc at a distance of ~ 13.5 kpc from the galaxy, at the interaction of the radio jet with an HI shell.



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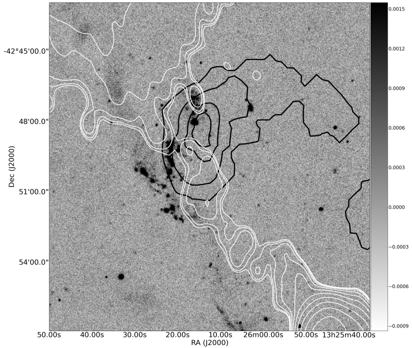

I do not discuss the origin of the gas!!!
I focus on the effect of the jet on the gas located along its direction.

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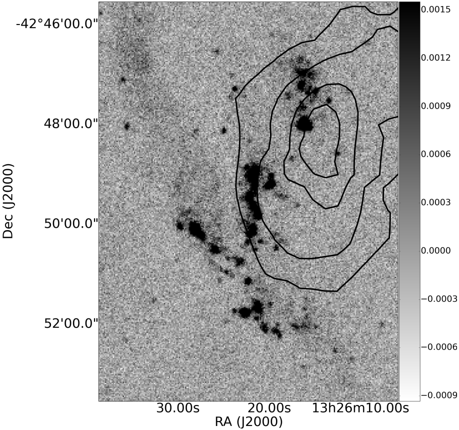

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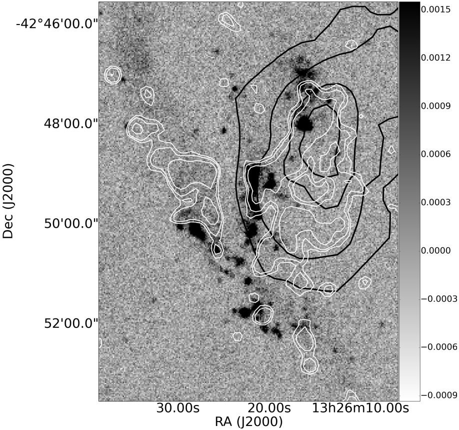

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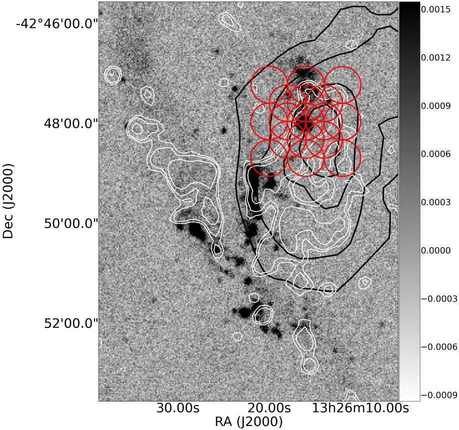

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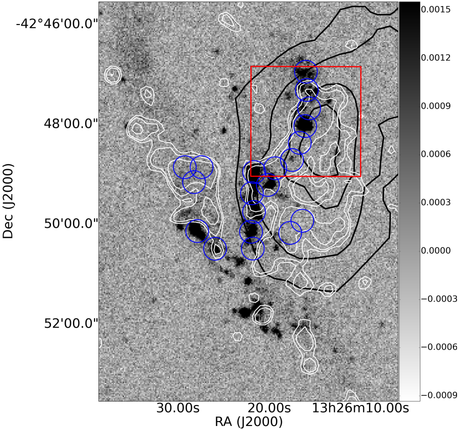

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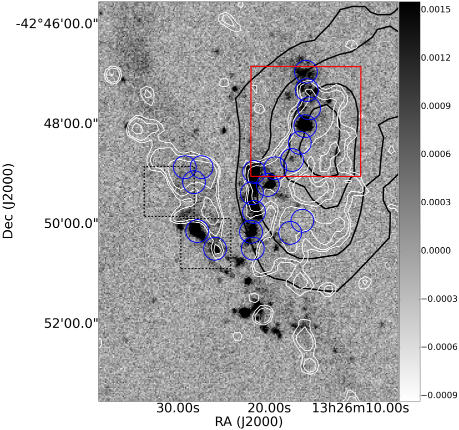

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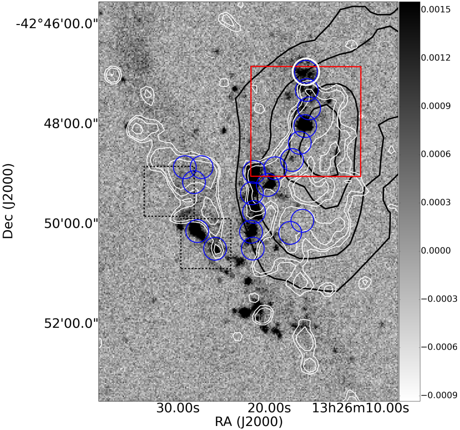

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- **MUSE observations** on the VLT
- **HCN(1-0) and HCO^+(1-0)** with ATCA on June 2014
- **ALMA archive** CO(2-1) data

Star formation tracers

The SFR was estimated via the FUV (GALEX) and IR (Herschel) emission. The IR luminosity was computed by fitting the SED with a modified black-body.

- uncertainties about the IR fluxes is $\sim 10\%$ (background extraction)
- dust mass very sensitive to the uncertainties on the background extraction
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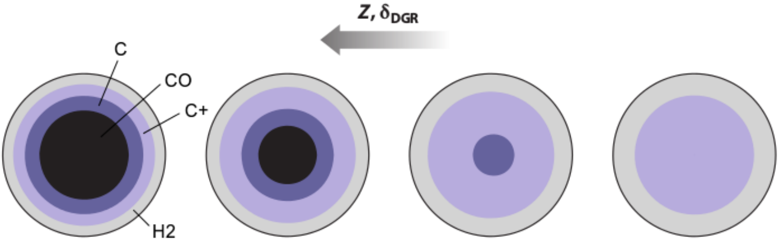
- uncertainties on the SFR is of the order of $\sim 10 - 30\%$
- in the whole region $(8.7 \times 5.8\ \mathrm{kpc})$: $\mathrm{SFR} \sim 4 \times 10^{-3}\ \mathrm{M_{\odot}.yr^{-1}}$
- for each CO pointing: $\mathrm{SFR} \sim 10^{-5} - 10^{-4}\ \mathrm{M_{\odot}.yr^{-1}}$

CO properties

- The SEST data consist in a map of 17 pointings. CO emission detected for 10 positions (including 2 in CO(2-1) only).
- The CO data from APEX contain 20 pointings. All the positions except one are detected in CO(2-1).
- The CO luminosity L'_{CO} is estimated with the formula from Solomon et al. (1997).
- For the CO(2-1) emission, a factor CO(2-1)/CO(1-0)~ 0.55 (Charmandaris et al. 2000) is applied.
- $M_{H_2} \sim 2.5 \times 10^5 - 3 \times 10^6$ $M_\odot$ in $44'' \sim 725$ pc (SEST);
  $M_{H_2} \sim 6 \times 10^5 - 1.3 \times 10^7$ $M_\odot$ in $27'' \sim 450$ pc (APEX)

Metallicity correction

In the case of low-metallicity environments, the cold molecular gas mass could be under estimated. The CO/H_2 conversion factor must be corrected by a factor that depends on the gas-to-dust ratio (Leroy et al. 2013).



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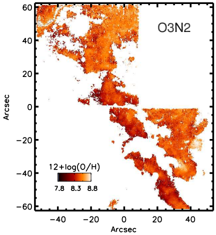
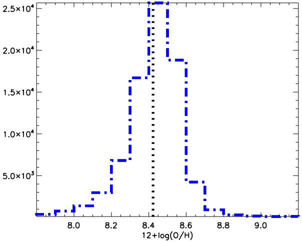
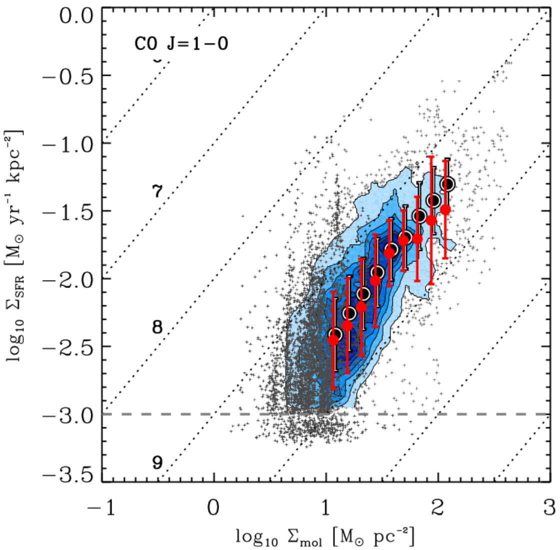




Santoro et al. (2015)

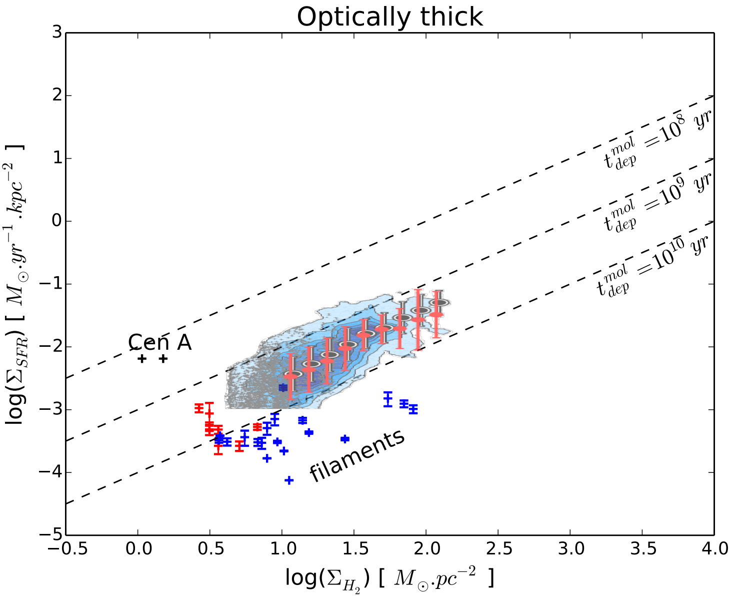
Metallicity slightly subsolar, with local variations of $12 + \log(\mathrm{O/H})$ between 8.3 and 8.6. Lead to gas-to-dust ratio of $\sim 200 - 400$ (Rémy-Ruyer et al. 2014).

Star formation law: a correlation between H_2 and SFR



Leroy et al. (2013)

Gas and SFR surface densities in the filaments



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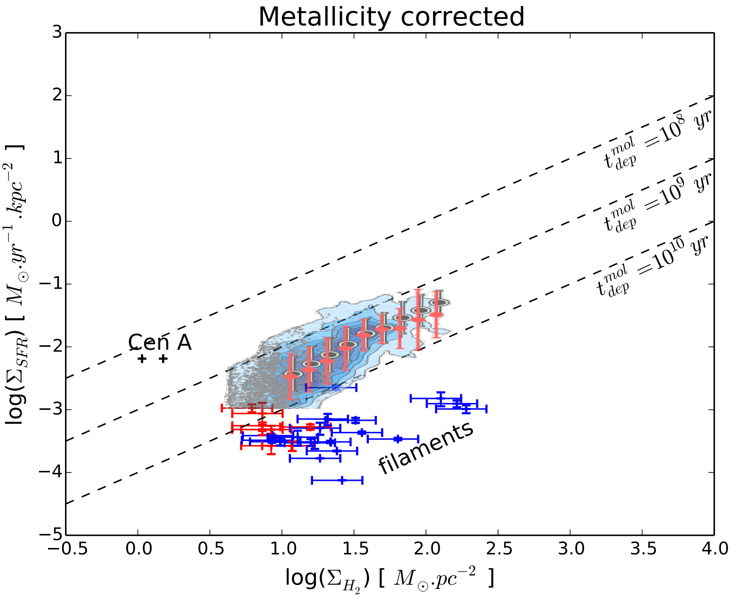
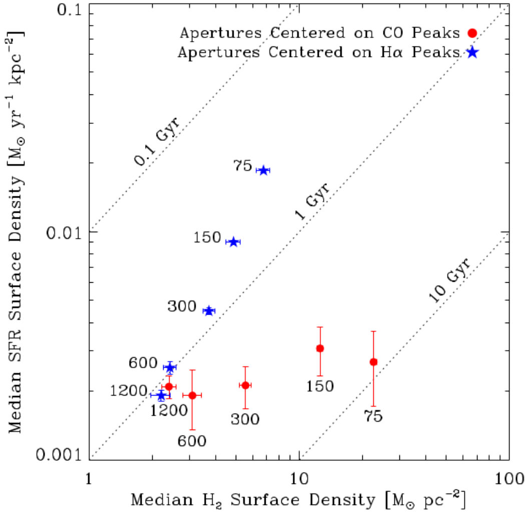
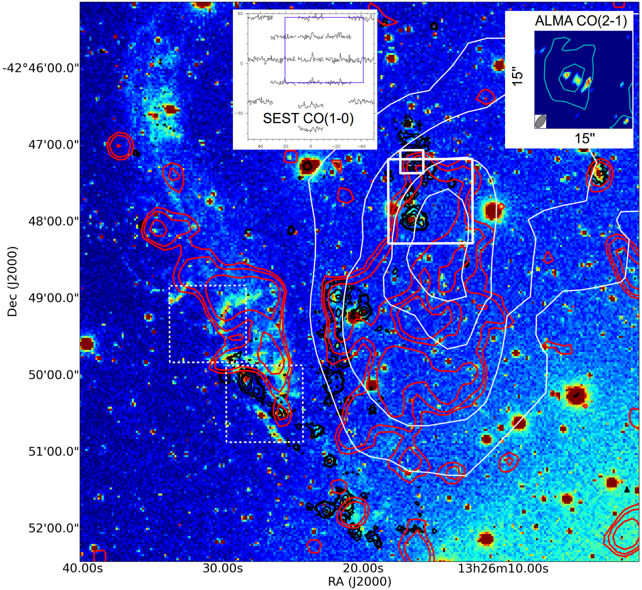


Star formation law: scale dependency



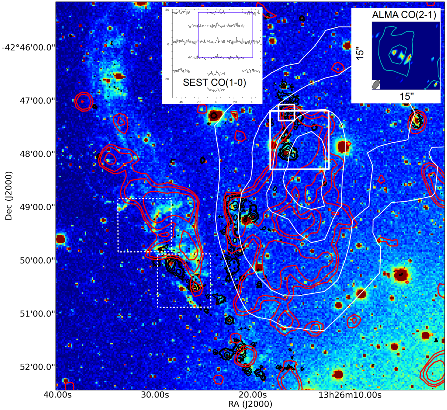
Schruba et al. (2010)

ALMA resolved molecular gas map



ALMA resolved molecular gas map

Cycle 1 observations; 16 antennas



- $S_{CO}\Delta v \sim 3.0$ Jy.km.s^{-1} $\Rightarrow$ $M_{H_2} \sim 8.7 \times 10^4$ $M_\odot$
- HCN not detected: $S_{HCN}\Delta v < 33.5$ mJy.km.s^{-1} ($f_{dense} \lesssim 23\%$)
- $\alpha_{vir} = 5\sigma_c^2 R_c/(GM_c) \sim 10 - 16$ $\Rightarrow$ no gravitational collapse, turbulent gas?

Clump	v_0 ($km.s^{-1}$)	Δv ($km.s^{-1}$)	M_{H_2} (10^4 $M_\odot$)
1	−231	12.5	4.0 ± 1.7
2	−222	8.0	2.6 ± 1.7
3	−214	7.5	2.1 ± 1.5

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

Conclusion and outlook

Conclusion:

- whole region 8.7×5.8 kpc: $\mathrm{SFR} = 2 \times 10^{-3}\ \mathrm{M_\odot.yr^{-1}}$, $\mathrm{M_{gas}} = 2 \times 10^{7}\ \mathrm{M_\odot}$ $\Rightarrow \mathrm{t_{dep}} \sim 10\ \mathrm{Gyr}$
- star formation seen in $\mathrm{H}\alpha$ along the filaments
- if we assume $\mathrm{t_{dep}} \sim 2\ \mathrm{Gyr}$ then only 10% of the molecular gas form stars
- need high spatial resolution to explore the jet/gas interaction in details

Outlook/prospect:

- ALMA proposal for Cycle 3 (grade C; filler project)
- KMOS proposal to observe $\mathrm{H_2}$ emission and look for turbulence contribution
- Kaneda et al. (2008): galaxies with turbulence that may suppress SF (NOEMA; B rated)
- NGC4258: the radio jet within the ISM produces a shock and a cavity (NOEMA; B rated)

Prospect: ALMA Cycle 4 pre-announcement

ALMA Cycle 4 will start in October 2016 (for 12 months): $\sim 3000\,\mathrm{h}$ of 12m Array science observations. Key dates for Cycle 4:

22 March 2016	Call for Proposals and observing tool
21 April 2016	Proposal deadline
August 2016	Results of the proposal review
October 2016	Start of ALMA Cycle 4 observations
September 2017	End of Cycle 4 observations

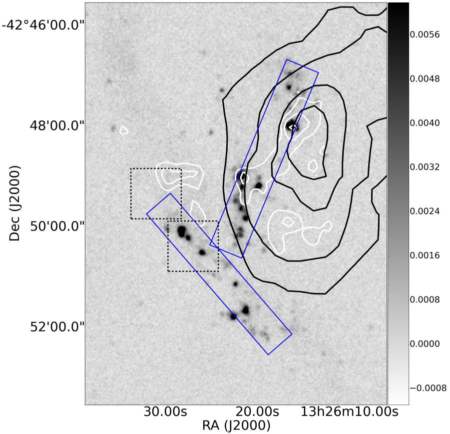
Detailed information on the capabilities in Cycle 4 will be published in the Call for Proposals. Anticipated capabilities include:

- At least **40×12m** Array + **10×7m** antennas (short baselines) + **3×12m** antennas (single-dish maps) in the ACA
- Bands 3, 4, 6, 7, 8, 9, 10 (wl: 3.1, 2.1, 1.3, 0.87, 0.74, 0.44, and 0.35 mm)
- Nine configurations with maximum baselines **from 155 m to 12.6 km**
- **Large programs (>50 h)**

https://almascience.eso.org/news/alma-cycle-4-pre-announcement

Appendix: High resolution and large scale map of the outer filaments

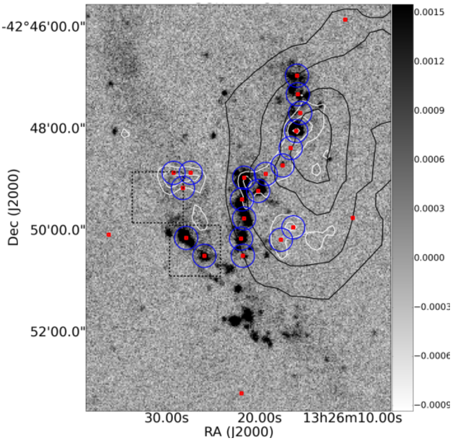
ALMA proposal (Cycle 3); filler project



- Mapping CO(1-0) emission with ALMA in configuration C36-3 ($1.2''$, ie 20 pc)
- First **high resolution map of the gas in the filaments**
- **Statistical study of the clumps**, based on their mass and size; study the stability
- **Determine the large scale dynamics** of the gas along the $6'$ (6 kpc) filaments
- Size of the interaction? in small located regions or in a coherent large-scale structure?

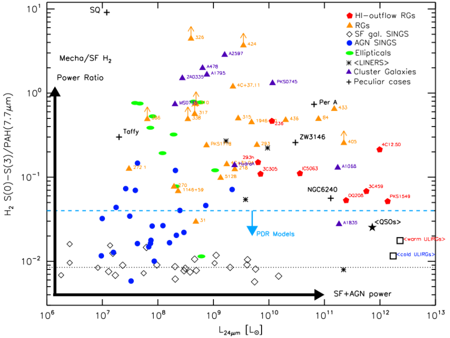
Appendix: The origin of SF quenching in the outer filaments

KMOS proposal



- combine H_2 KMOS observations with the CO(2-1) emission from APEX
- Warm molecular gas mass present and local kinematic information
- Study the effect of turbulent kinetic energy
- Proposal made during period 97A: request 3h

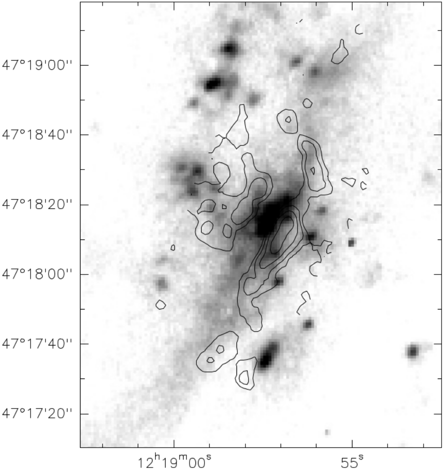
Appendix: Kaneda sample with NOEMA



Guillard et al. (2012)

- Radio galaxies with fast outflows and strong H_2 emission
- We proposed to map 4 galaxies of the sample in CO(2-1)
- CO distribution → fraction of cold to warm molecular gas
- CO kinematics → rate of energy dissipation
- ~ 20.5h on-source with NOEMA (7 antennas); B rated

Appendix: NGC 4258 with NOEMA



- unique example of jet-ISM interaction in the plane
- narrow tunnel excavated in the molecular gas disc
- dense gas pushed to the cavity walls
- aim to determine the physical processes at the jet-ISM interface