



**Astronomical
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MOLECULAR GAS IN RAM PRESSURE STRIPPING TAILS

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& J. Kenney, M. Sun, F. Combes, L. Cortese, M. Yagi, E. Roediger et al.

Multi-phase ram pressure stripping tails

- In Virgo:
 - *most* of the ISM missing in Virgo galaxies not revealed in observations (e.g. Vollmer & Huchtmeier 2007; also e.g. Kenney+2014 and Jachym+2013: dwarf galaxy IC3418)
 - only a few long tails observed
 - the bulk of the stripped atomic gas must have been transferred to another phase
 - mixing of the stripped cold ISM with the hot ICM
 - mostly not observed/observable?
 - In (more) massive clusters:
 - many long RPS tails known (H α , X-rays, HI)
 - still a substantial fraction of gas mass not revealed
 - moreover, jellyfish – star formation in the tails
- => There *should* be a molecular component

Search for cold component of RPS tails



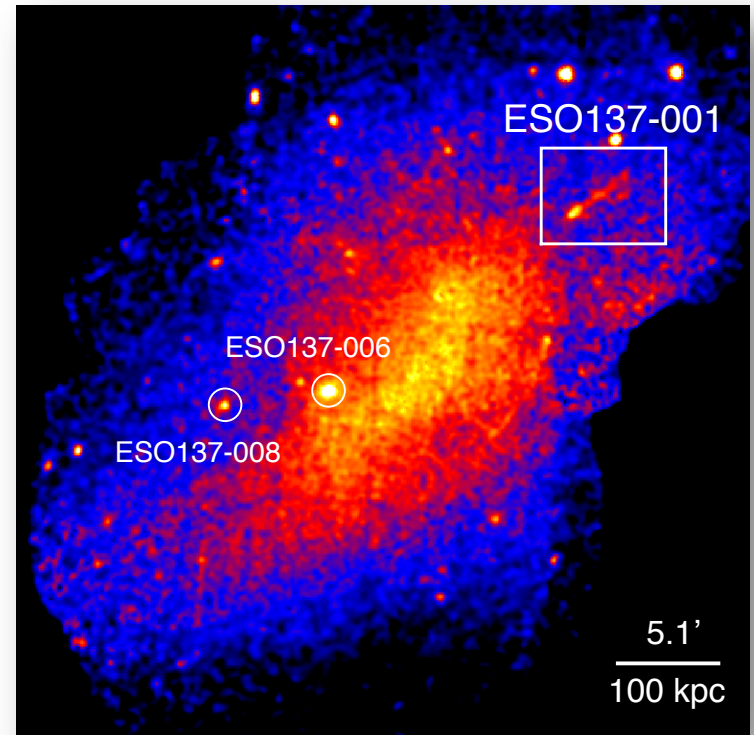
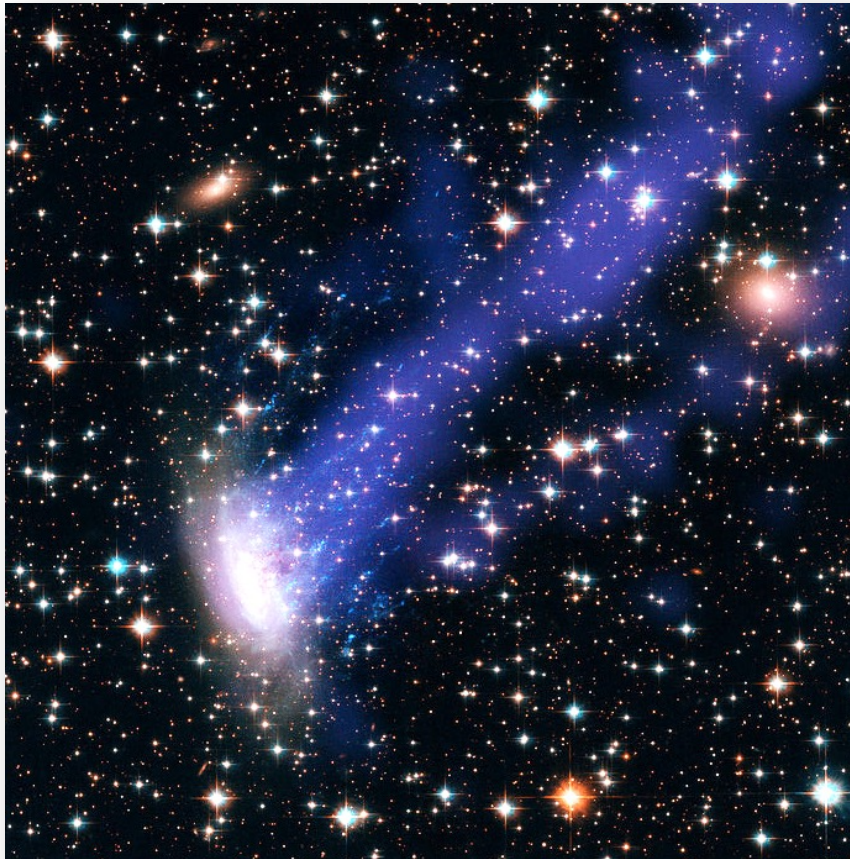
- ESO APEX

- 12 m antenna
- 5100 m elevation
- CO(2-1), CO(3-2)

- IRAM 30m

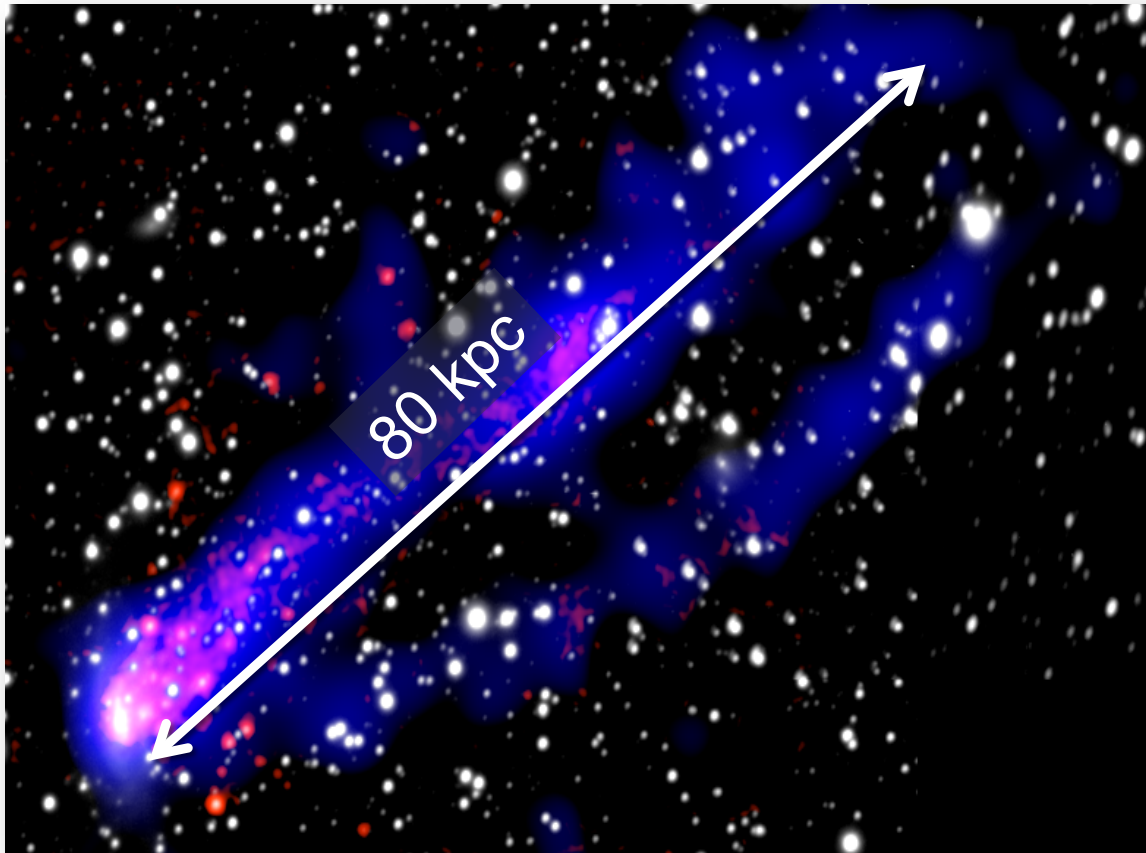
- 30 m antenna
- 2600 m elevation
- CO(1-0), CO(2-1)

Norma cluster galaxy ESO137-001



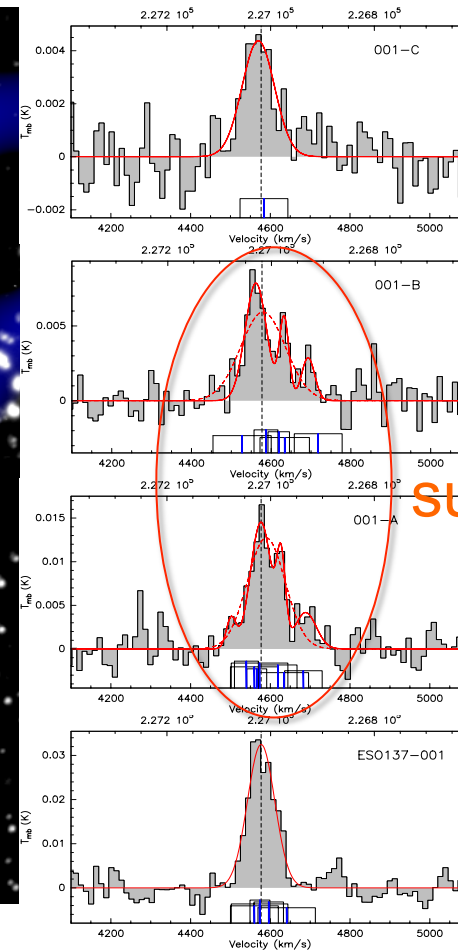
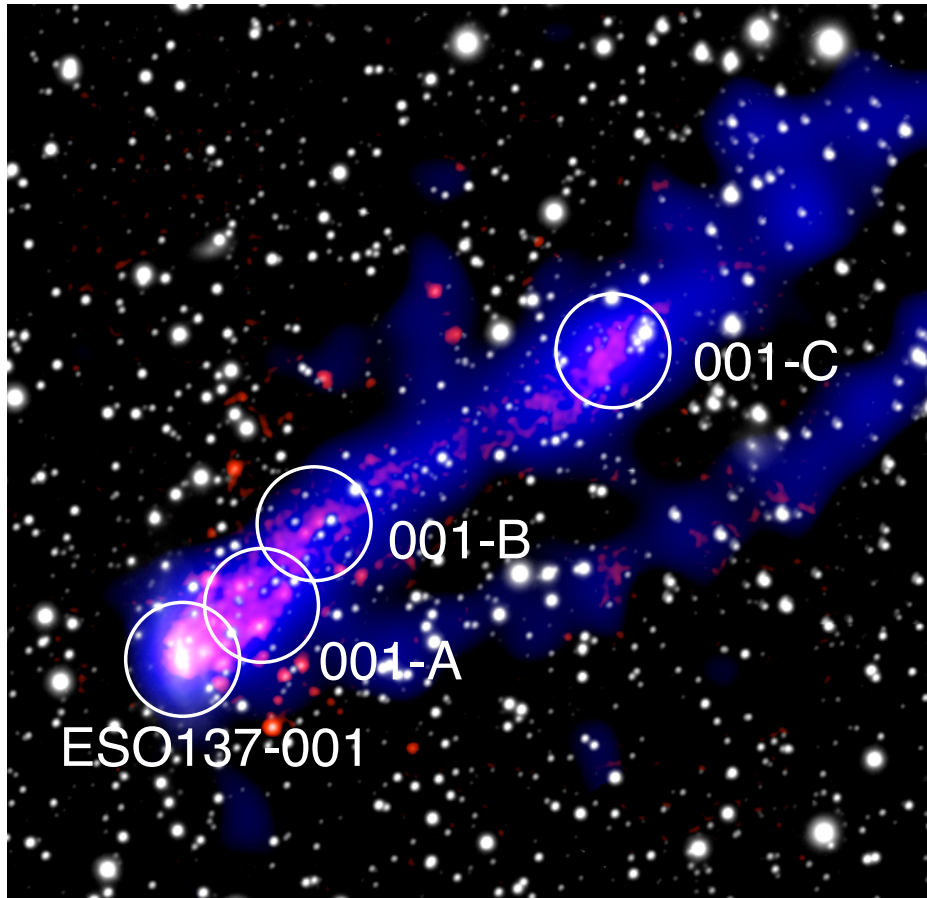
- located ~300 kpc from cluster center
- likely infalling for the first time at a high orbital speed
- at a very high speed (>3000 km/s)
- merging subclusters?

Norma cluster galaxy ESO137-001



- multi-phase gas tail:
 - 80 kpc, narrow, double-structure tail – *Chandra* (Sun+2006, 2010)
 - 40 kpc H α tail with more than 30 giant H II regions; orphaned HII regions – *SOAR* (Sun+2007)
 - H I only to upper limit (ATCA)
 - warm H₂ (*Spitzer*) + dust (*Herschel*) in the inner tail (Sivanandam+in prep.)

APEX observations of ESO137-001



tail C
 $1.5 \times 10^8 M_{\odot}$

tail B
 $3 \times 10^8 M_{\odot}$

substructure

tail A
 $6 \times 10^8 M_{\odot}$

main body
 $1 \times 10^9 M_{\odot}$

- First time detection of a prominent molecular RPS tail!

Gas phases in ESO137-001 tail

Mass budget:

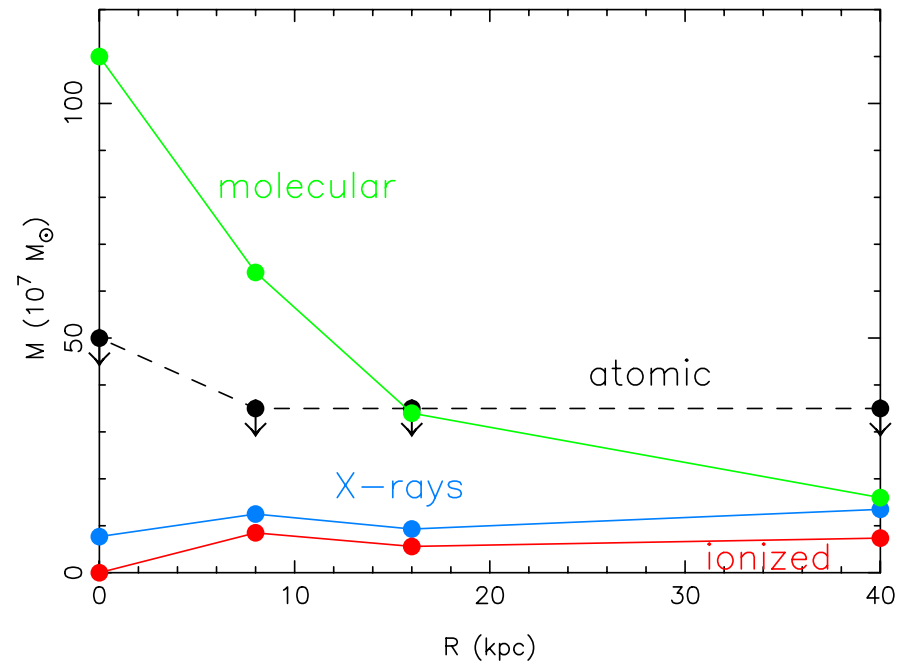
- $> 10^9 M_{\odot}$ of H_2 revealed in the tail
- largest amount found in the inner tail
 - direct stripping of dense gas?
- $\sim 10^9 M_{\odot}$ of hot ($\sim 10^7$ K) X-ray gas
- $< 5 \times 10^8 M_{\odot}$ of HI per 30'' beam with ATCA
- $< 5 \times 10^8 f^{1/2} M_{\odot}$ of ionized, H α -emitting diffuse gas
- $\sim 4 \times 10^7 M_{\odot}$ of warm (130–160 K) H_2 in the galaxy and inner 20 kpc tail (Spitzer) – elevated warm-to-cold (mid-IR-to-CO) H_2 mass fraction

- total gas mass in the tail:

$$2 \times 10^9 M_{\odot} < M_{\text{gas}} < 4 \times 10^9 M_{\odot}$$
- total gas mass in the disk:

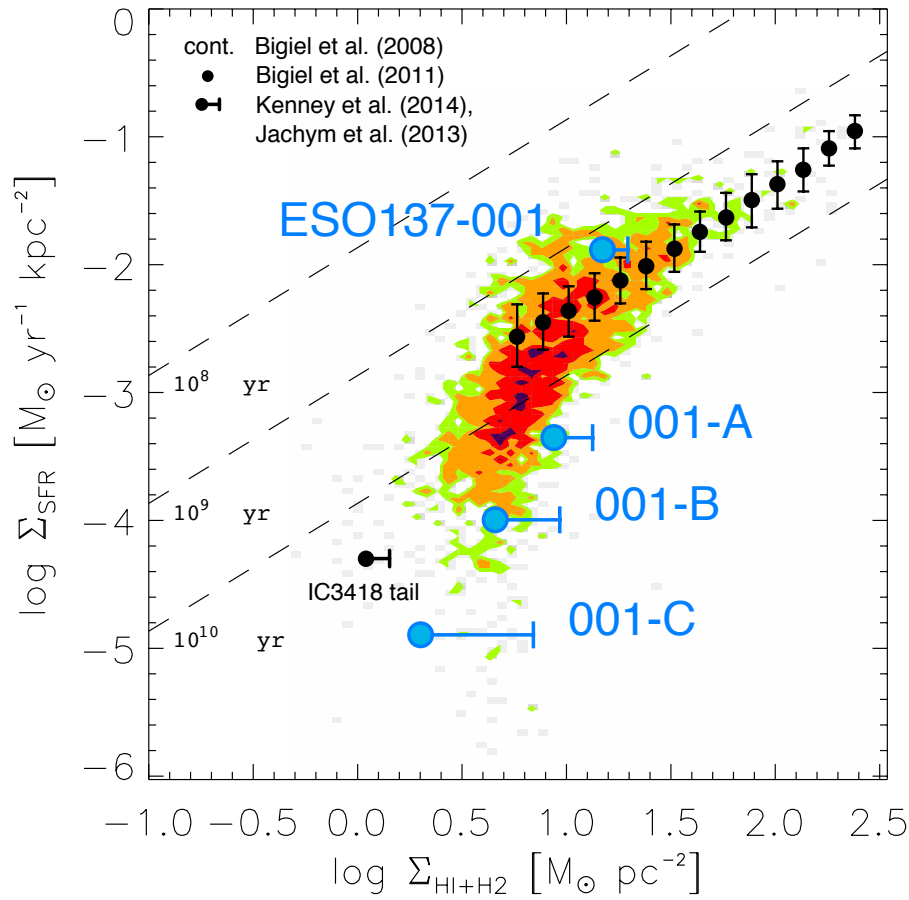
$$\sim 1 \times 10^9 M_{\odot}$$
- original (pre-stripping) gas content:

$$\sim (0.5 - 1) \times 10^{10} M_{\odot}$$



There are large and similar amounts of cold and hot gas that together nearly account for the missing gas from the disk

Very low star formation efficiency

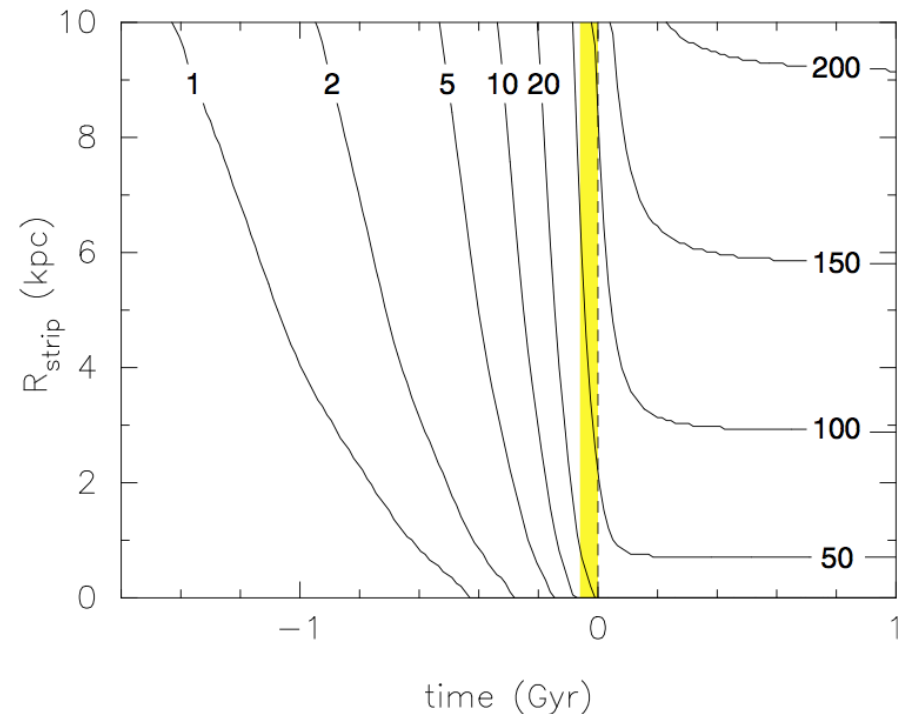


Jachym+2014

- low and decreasing SFE along the tail
- Star formation timescale ($=1/\text{SFE}$) = $M(\text{HI}+\text{H}_2)/\text{SFR}$ is 2-50x longer in stripped gas than in disks
- most of stripped gas does not form stars but remains gaseous and ultimately joins the ICM
 - low average gas density in the tail?
 - turbulent heating induced by RP shock?
- Distinct conditions from typical star-forming ISM in inner parts of nearby galaxies
- Similarly low SFEs found in outer disks where however HI is likely dominant and CO mostly undetected

Ram pressure effects on the ISM

- semi-analytic calculations
- estimate how ISM parcels with different column densities react to a time varying ram pressure
- ESO137-001 may be currently about 100 Myr before peak ram pressure ($\sim 2.1 \times 10^{-10}$ dyne cm $^{-2}$). The FWHM of the ram pressure time profile is ~ 200 Myr.
- gas with $\Sigma_{\text{ISM}} \sim 10 \text{ M}_{\odot} \text{ pc}^{-2}$ is currently completely stripped from the galaxy ($R_{\text{strip}} = 0 \text{ kpc}$), and stripping has proceeded to denser gas (about 20–50 $\text{M}_{\odot} \text{ pc}^{-2}$) at larger disk radii

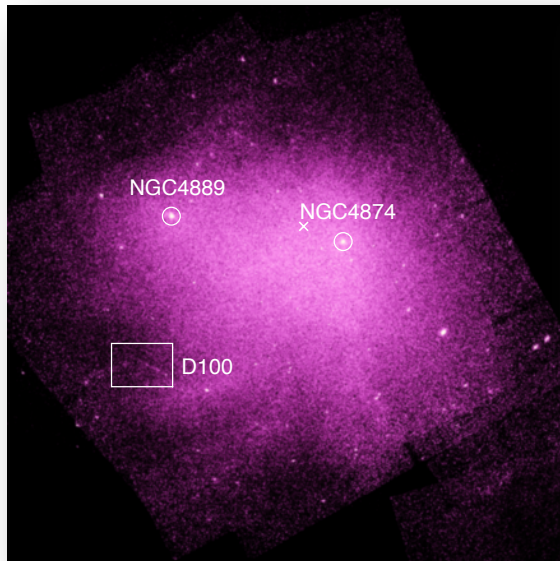
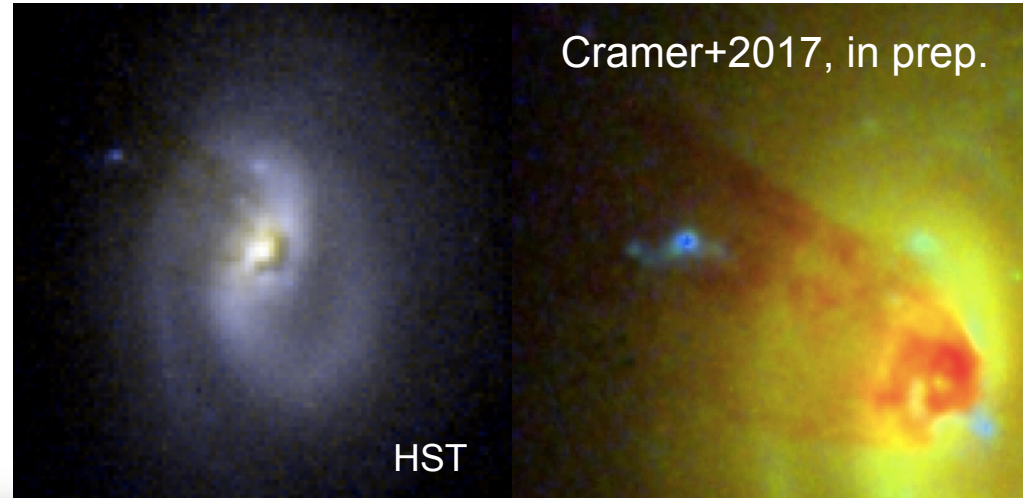


Column Densities of Stripped ISM in Our Model

Vertical Distance	Radius in the Disk		
	2 kpc	6 kpc	10 kpc
tail (80 kpc)	10	17	20
001-C (40 kpc)	15	25	35
001-A (10 kpc)	25	60	90

How common are molecular RPS tails?

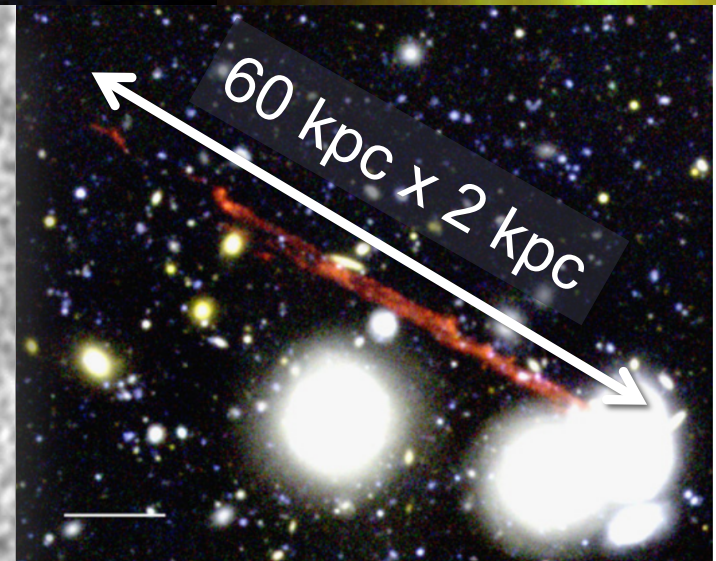
- Galaxy D100 in Coma
 - ~240 kpc from cluster center
 - Stellar mass $\sim 2 \times 10^9 M_{\odot}$
 - (post-)starbursts galaxy
 - Strip. radius $\sim 600\text{pc}$
 - Multi-phase RPS tail
 - 60 kpc H α tail (*Subaru*)
 - 50 kpc X-ray tail (*Chandra*)
 - GALEX 15 kpc UV tail
 - (almost) no SF !



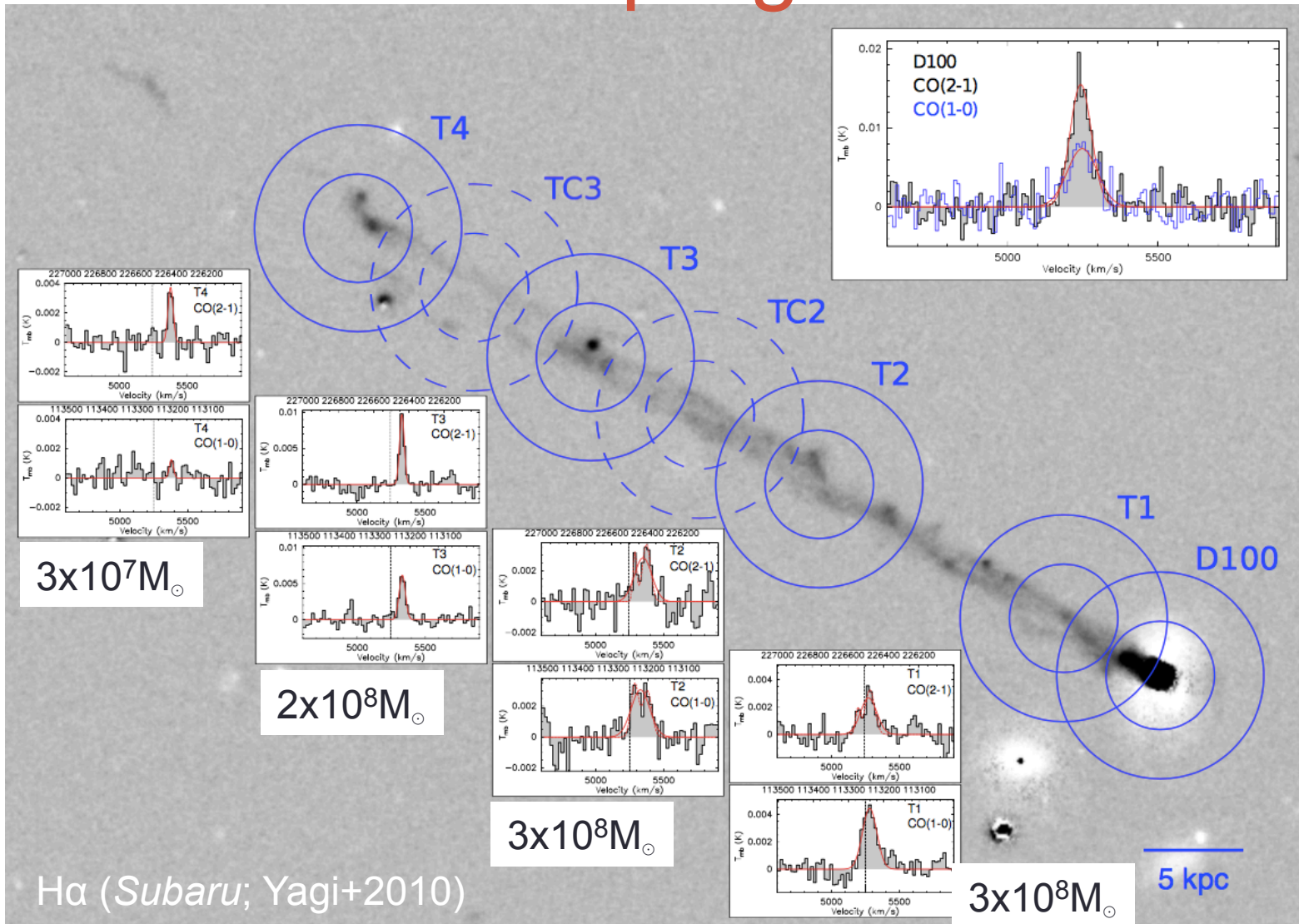
D100
(Chandra)

21.4"

10 kpc



IRAM 30m sampling of D100



$\sim 1 \times 10^9 M_{\odot}$ of H_2

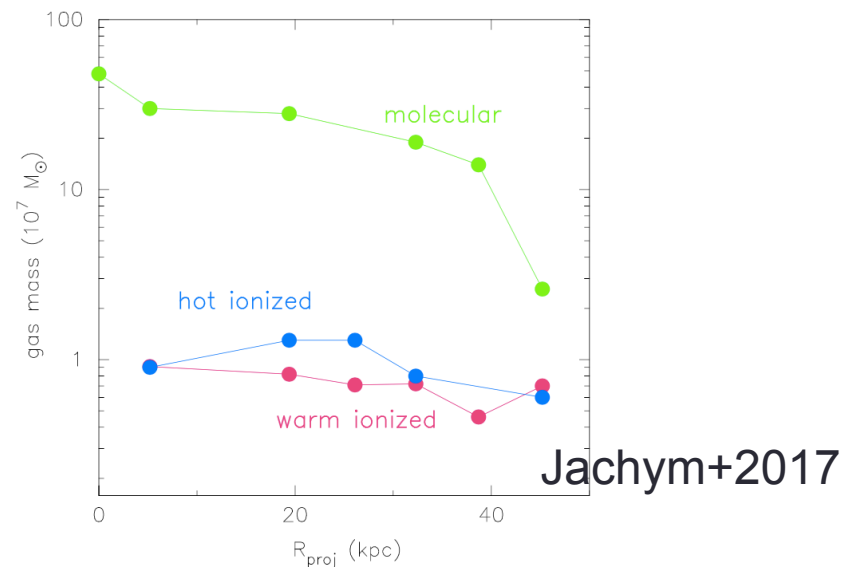
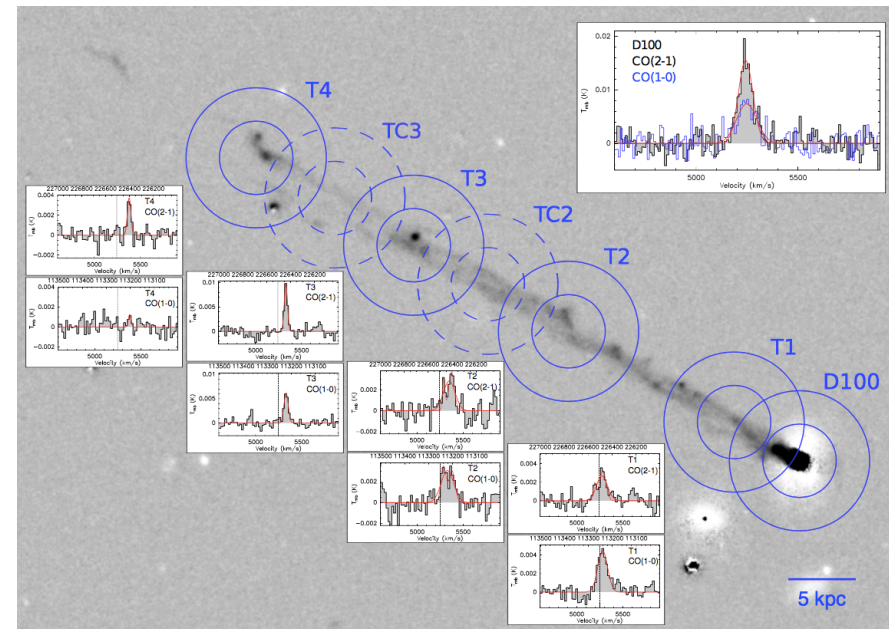
Jachym+2017

IRAM 30m sampling of D100

- $\sim 1 \times 10^9 M_{\odot}$ of H_2
- $\sim 10^8 M_{\odot}$ of X-ray, hot ionized gas
- $\sim 5 \times 10^7 M_{\odot}$ of $H\alpha$, warm ionized gas
- no HI with a limit of $\sim 5 \times 10^7 M_{\odot}$

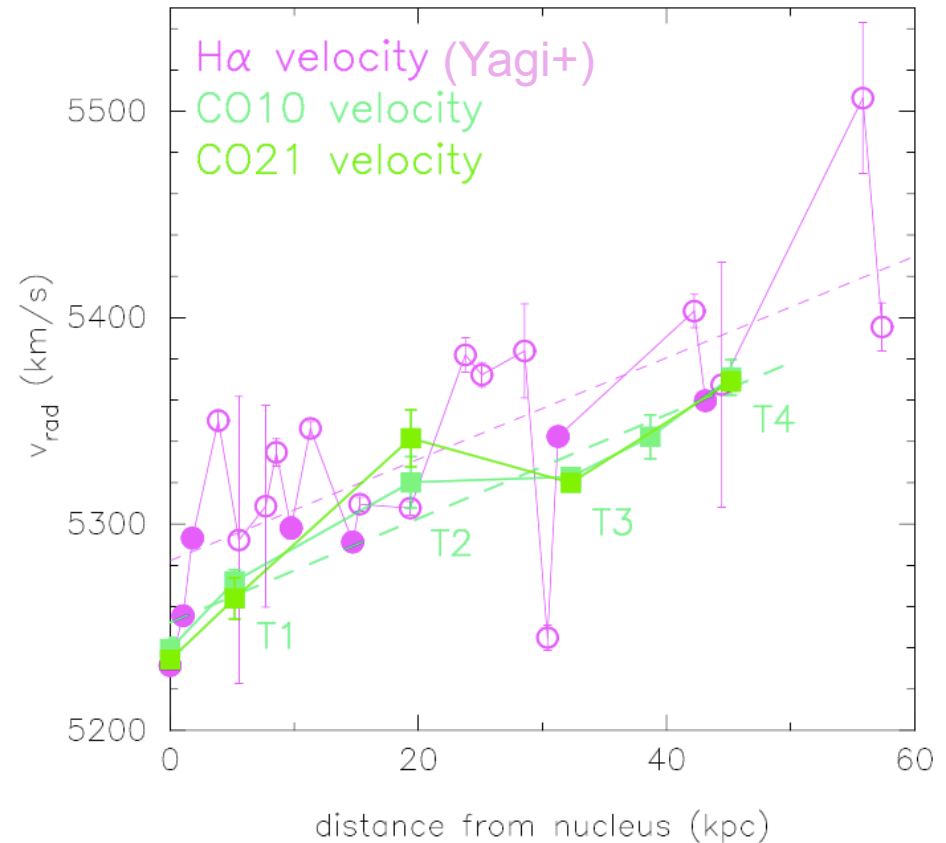
\Rightarrow Tail possibly dominated by cold molecular gas, by a factor of 5-10 !

- Due to uncertainty of the X-factor, the molecular gas fraction may be somewhat smaller (factor of a few), but very likely still exceeding the fraction of the other gas components.



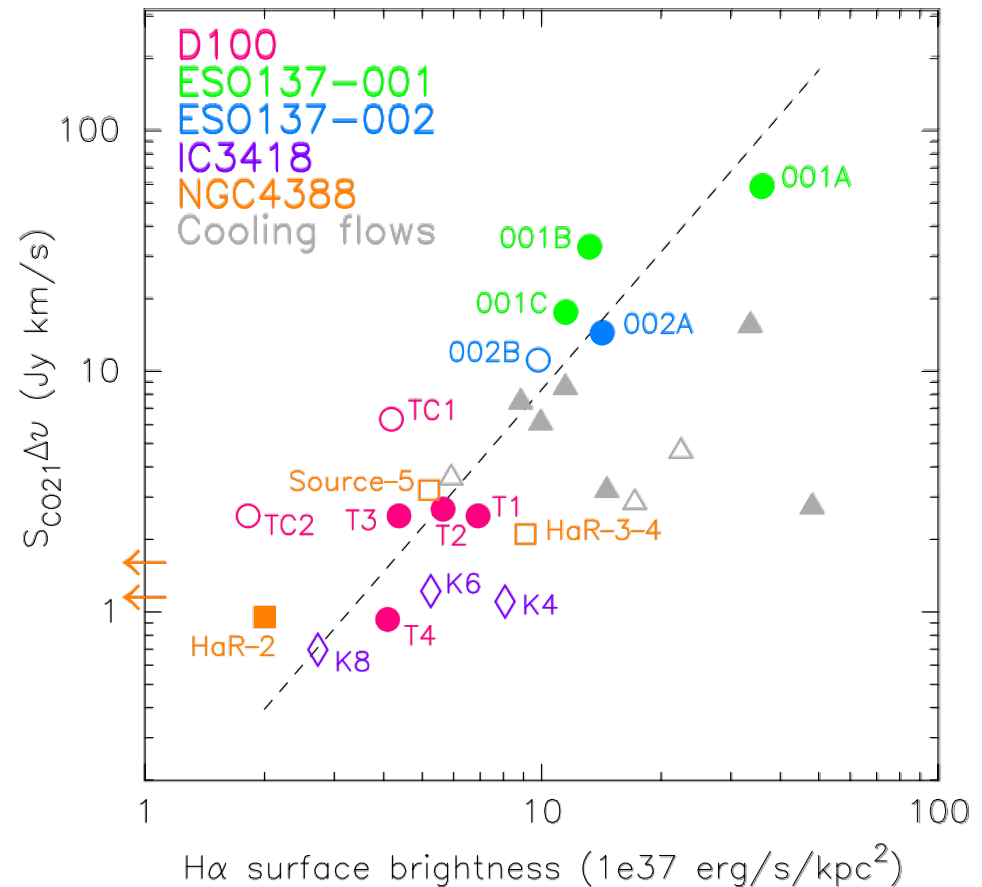
Kinematic separation of gas phases

- Measured offset of ~ 30 km/s between warm ionized and cold molecular gas in the tail, while having a similar slope
- May be due to differential acceleration of gas phases by ram pressure
- radial velocity gradient of about 130 km/s along CO tail and ~ 200 km/s in H α forms only about 10% of the (projected) ICM wind speed
- increase in velocity per unit tail length is constant along the tail, ~ 2.5 km/s/kpc



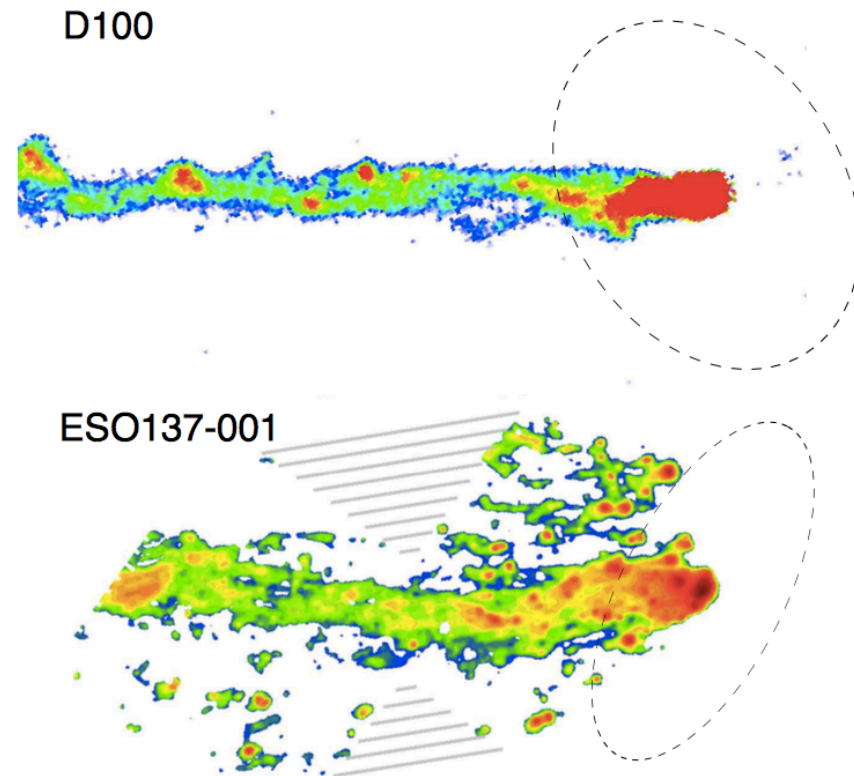
Correlation of gas phases in RPS tails

- A rather tight correlation between warm ionized and cold molecular phases over about 2 dex, at a spatial resolution of ~ 5 kpc
- Presence of H α is good indicator for presence of CO emission – the same excitation process?
- SF levels differ in the tails – ionizing mechanisms other than SF are also at play (shocks)
- The correlation likely evolves with time
- Much looser correlation between hot ionized and cold molecular gas...



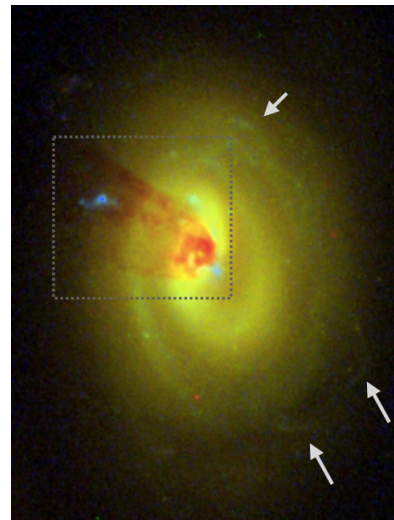
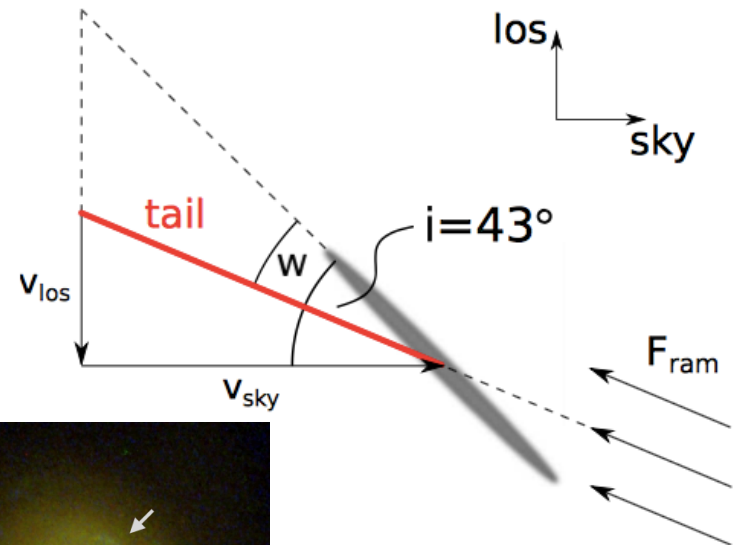
D100 – ESO137-001 comparison

- D100 tail
 - simpler morphology
 - much less substructure perpendicular to its length and it is straighter.
- but also some similarities
 - they are brightest in the innermost parts
 - there are local enhancements along the tail with H α peaks separated by relatively diffuse emission regions
- D100:
 - advanced stripping stage when its stripping radius is small
 - Continuous stripping of nuclear gas?
 - Stronger RP than ESO137-001
 - Effects of viscosity suppressing turbulence? Also magnetic fields aligned with the tail can inhibit instabilities and transport processes.



Constraining the wind angle

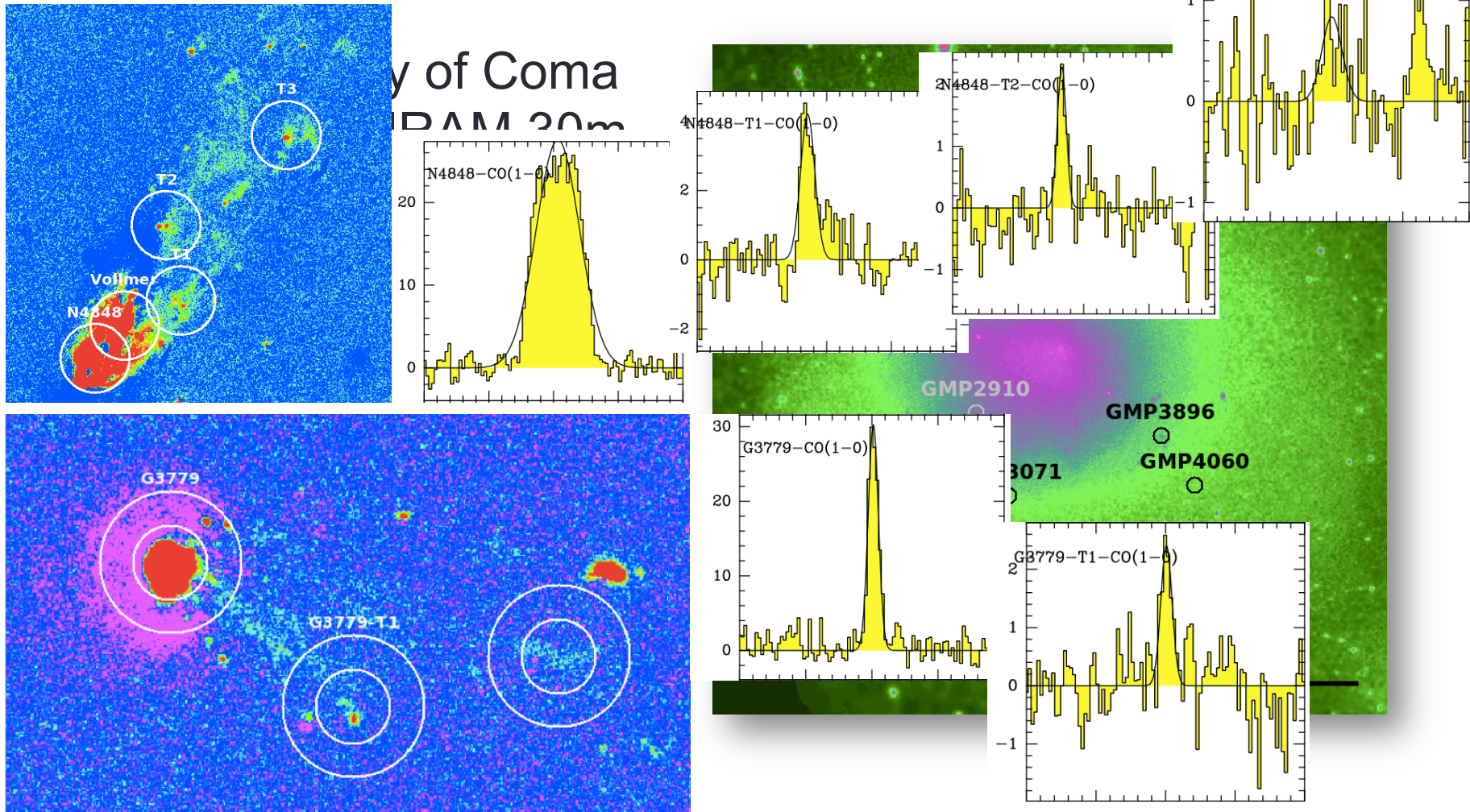
- D100 is blueshifted relative to Coma
- Inclination angle $\sim 45^\circ$
- HST dust extinction suggests: Left disk side = far side
- near edge-on stripping
- wind angle only 11° for total orbital velocity 3000km/s , or 21° for 4000km/s
- tail is oriented perpendicularly to the cluster center direction
 - Near-pericenter passage
 - Near-peak RP
 - Similarly to Virgo IC3418 (Jachym+2013)
- Estimated age of the (visible) tail $\sim 250\text{Myr}$ (160Myr)



Observational strategies following the first detections of H₂ abundant RPS tails:

1. increase the sample
 - single-dish survey of many tails
2. study the details
 - interferometric mapping of best examples

The Coma CORPS - CO survey of Coma Ram Pressure Stripped tails



Mapping cold component in RPS tails



- ALMA

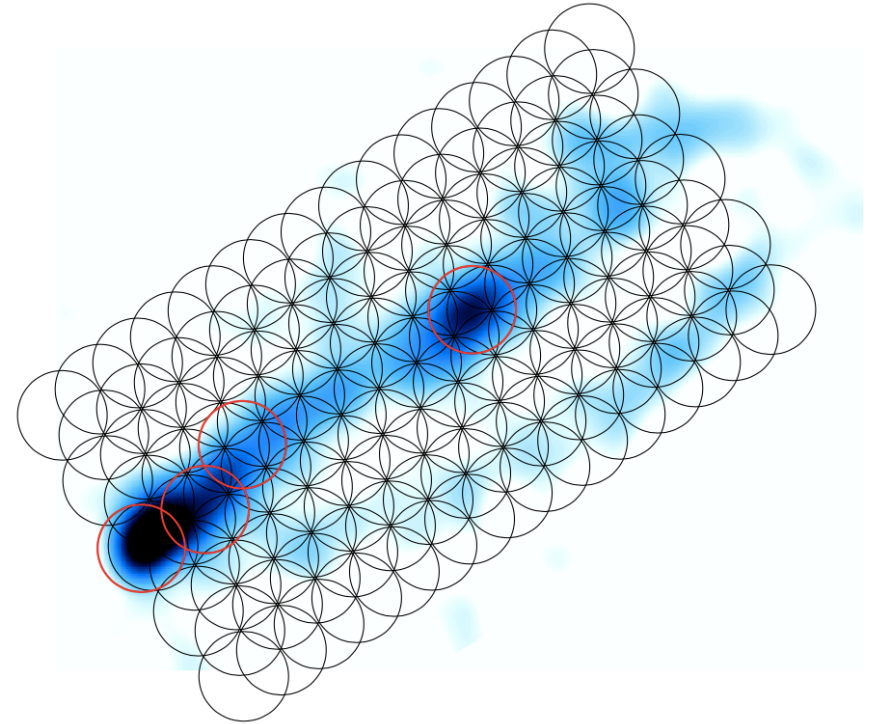
- 40+ 12m antennas
- 5100 m elevation
- CO(2-1), CO(3-2)

- IRAM NOEMA

- 7+ 15m antennas
- 2550 m elevation
- CO(1-0)

Sneak peek on ALMA view of ESO137-001

- B6 and B7 mosaic with $\sim 1''$ ang. resolution, 1.3km/s velocity resolution
- Covering nearly the whole extent of the X-ray tails
- Both 12m and ACA data – 130 and 50 pointings, respectively



=> First map of molecular gas
in a RPS tail !

Sneak peek on ALMA view of ESO137-001



Sneak peek on ALMA view of ESO137-001



ESO137-001 – a complete view?

Coming soon ...

Chandra X-rays

ALMA CO21

MUSE H α

HST

Points for discussion

- how common the phenomena of molecular gas-rich ram pressure stripped tails are?
- Formation and survival of (large quantities of) cold molecular gas
 - Processes able to heat and disperse the stripped cool gas, such as heat conduction, ionizing soft X-ray radiation, cosmic rays or turbulence, are not efficient enough to prevent the gas from cooling and condensing
 - Requires also the presence and survival of dust in the tails
 - Lack of ambient UV photo-dissociating radiation field in the tail further can favor H₂ formation on dust grains.
- Direct stripping of molecular gas or in-situ formation in RPS tails?
 - Possibly combination of both
 - Easy molecularization of dense gas stripped to inner tail
 - Analytical estimates suggest gas clumps with column densities of $\sim 50 M_{\text{sun}}/\text{pc}^2$ could be directly stripped; even larger col. densities can be pushed to inner tail
- Role of ICM viscosity and magnetic fields?
 - With increasing viscosity, the stripped galactic gas mixes less readily with the ambient ICM
 - Magnetic fields if aligned with the tail can further inhibit instabilities and transport processes with the surroundings making the tail smoother than it would be in the absence of magnetic fields.