Astronomical Institute of the Czech Academy of Sciences

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MOLECULAR GAS RAM PRESSURE STRIPPING

Pavel JÁCHYM
(Czech Academy of Sciences, Astronomical Institute)

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

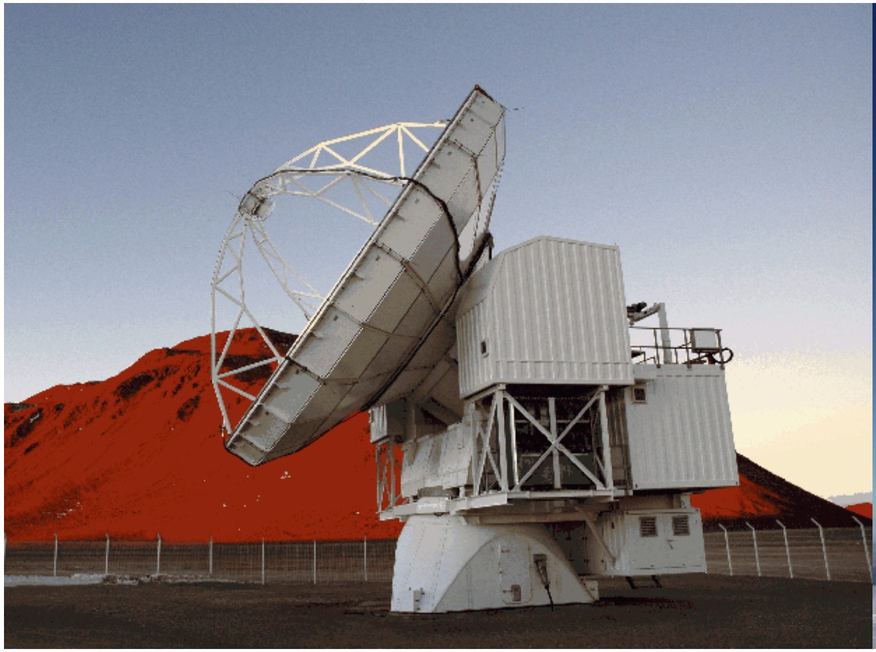
Multi-phase ram pressure stripping tails

- in Virgo, *most* of the ISM missing in Virgo galaxies not revealed in observations (e.g. Vollmer & Huchtmeier 2007; Kenney+2014 and Jachym+2013: dwarf galaxy IC3418)
- the bulk of the stripped atomic gas must have been transferred to another phase
- mixing of the stripped cold ISM with the hot ICM

- In (more) massive clusters, many long RPS tails known
- still a substantial fraction of gas mass not revealed
- jellyfish galaxies – star formation in the tails

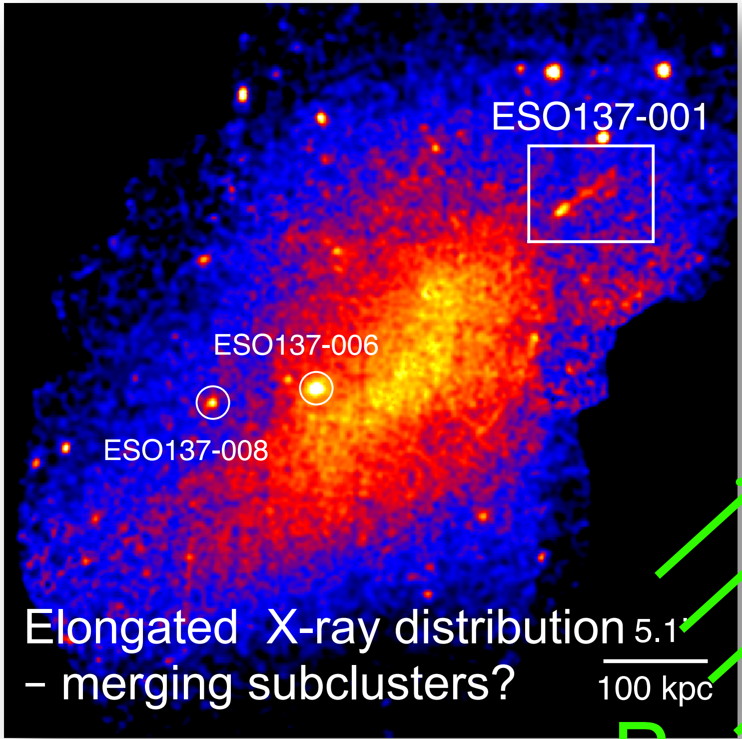
- => There should be a molecular component

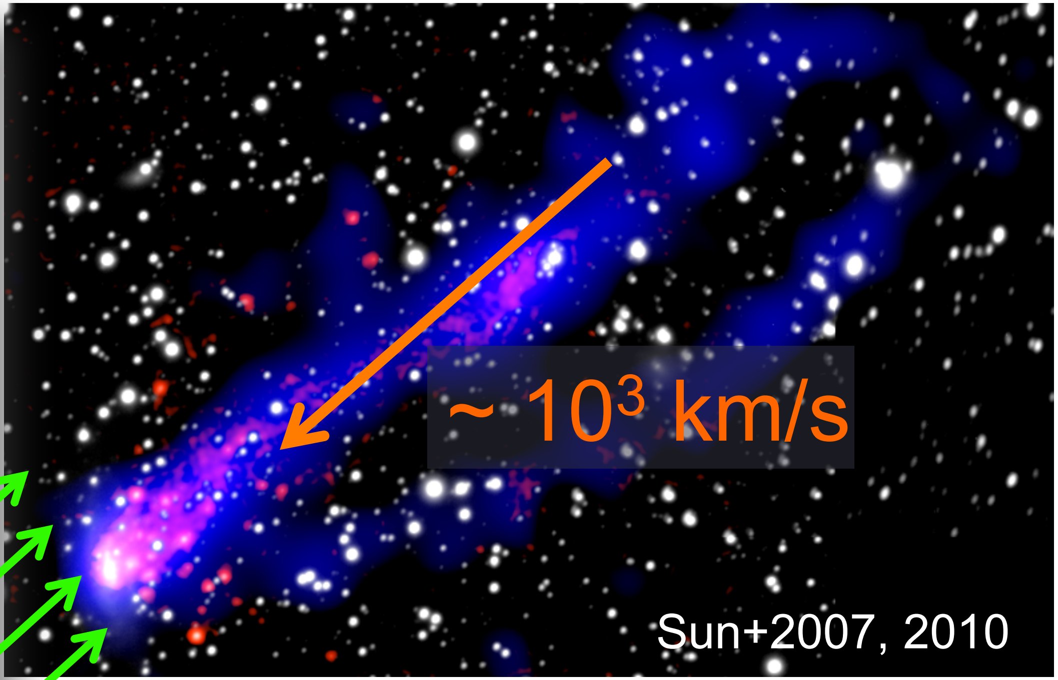
Search for cold component of RPS tails



- 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



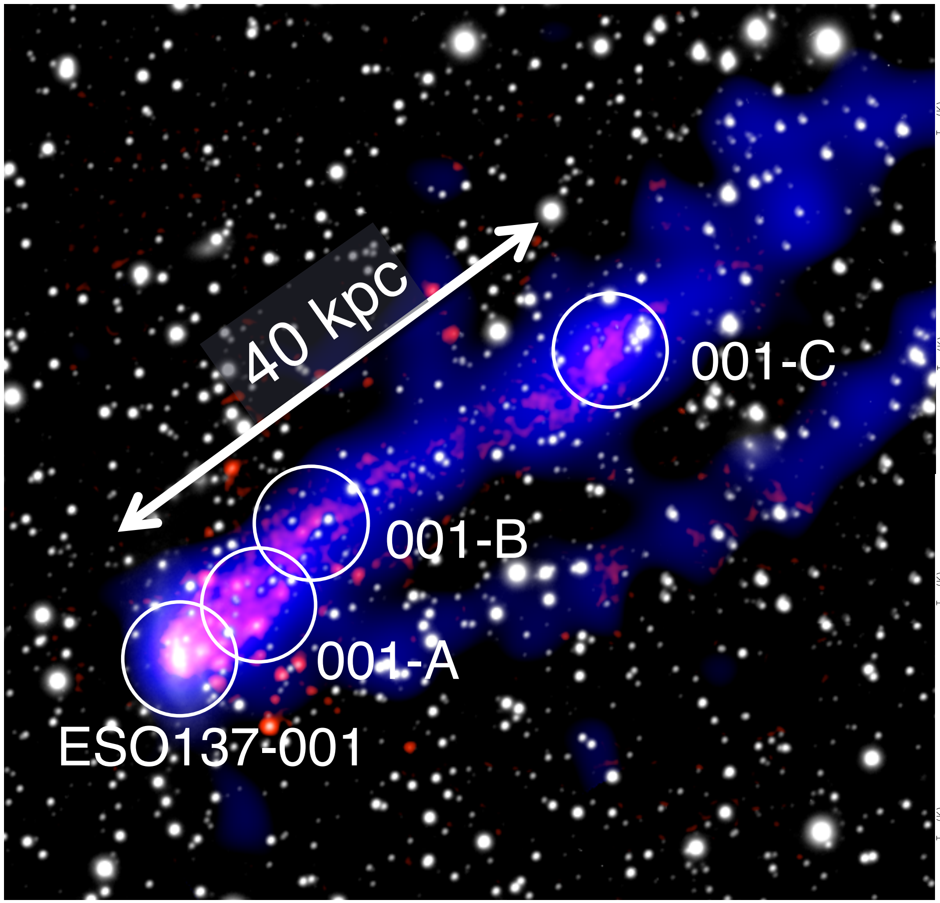


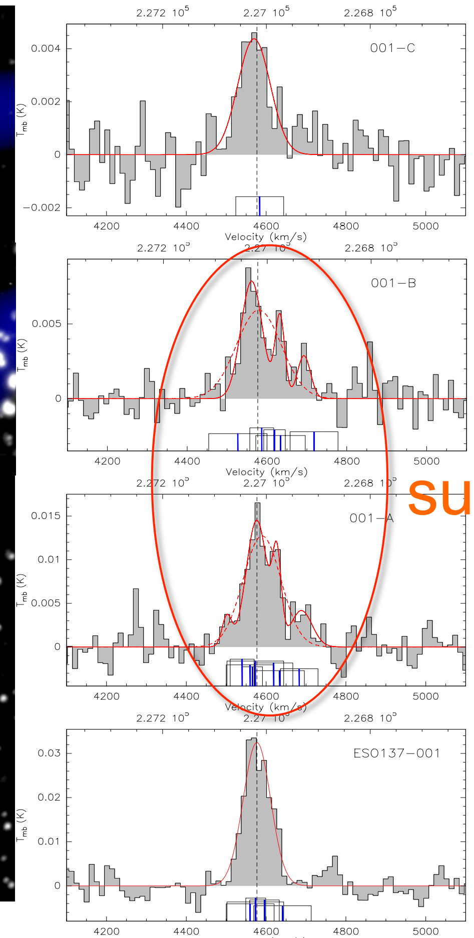
P_{ram}

- located ~300 kpc from cluster center
- likely infalling for the first time at a high orbital speed

- multi-phase gas tail:
  - Chandra and XMM-Newton: 80 kpc, narrow, double-structure tail
  - 40 kpc Hα tail with more than 30 giant H II regions; orphaned HII regions
  - H I only to upper limit (ATCA)
  - warm H_2 (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
$3 \times 10^8\ M_\odot$

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

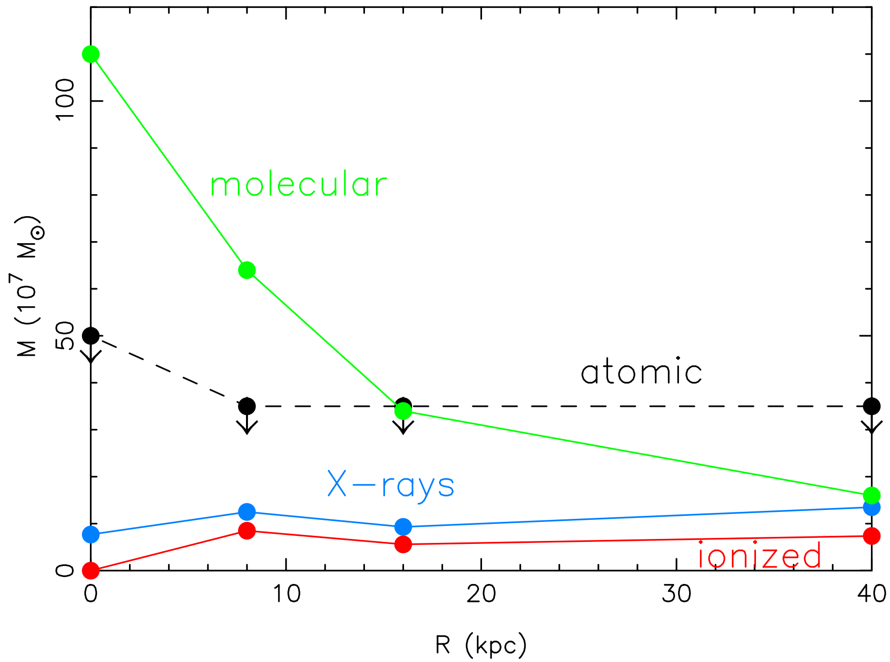
main body
$1 \times 10^9\ M_\odot$

- First time detection of a prominent molecular RPS tail!

Jachym+2014

Gas phases in ESO137-001 tail

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

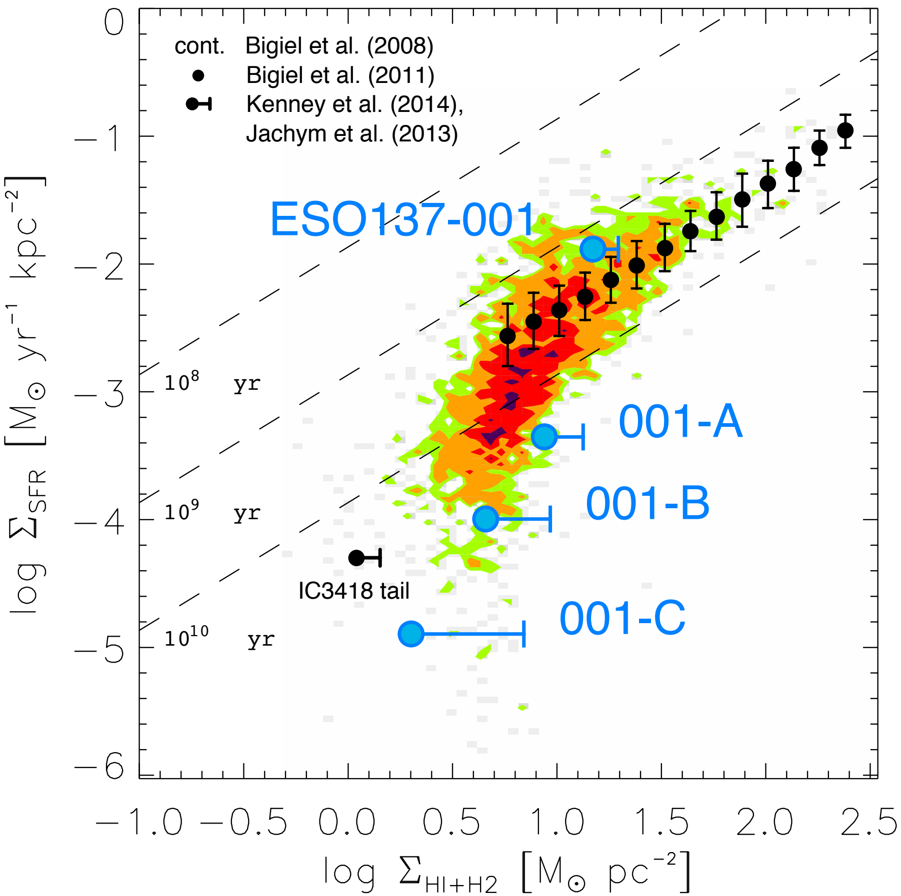


- total gas mass in the tail:
  2 × 10^9 $M_\odot$ < M_{gas} < 4 × 10^9 $M_\odot$
- total gas mass in the disk:
  ~1 × 10^9 $M_\odot$
- original (pre-stripping) gas content:
  ~ (0.5 – 1) × 10^{10} $M_\odot$

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

Jachym+2014

Low star formation efficiency



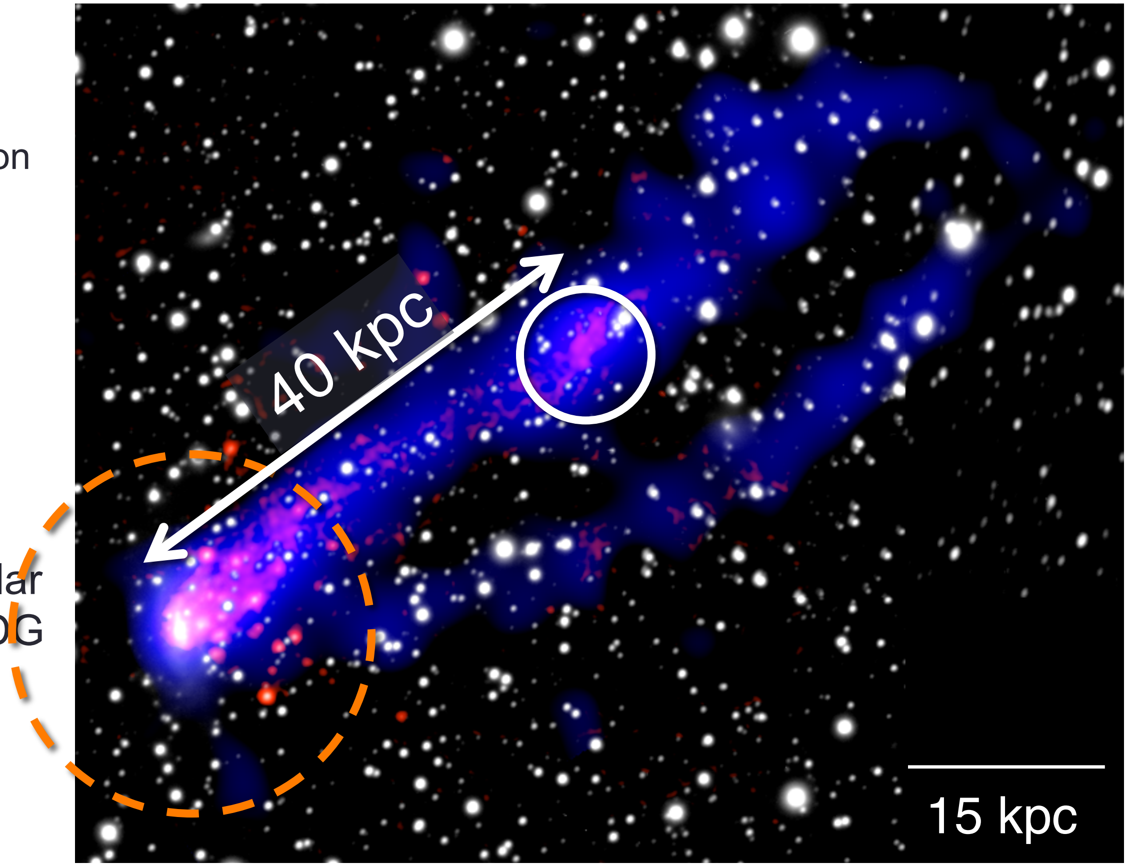
Jachym+2014

- low and decreasing SFE along the tail
- Star formation timescale (=1/SFE) = M(HI+H_2)/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

Jachym+2014

RP dwarf galaxy in formation in the tail?

- IC region at 40kpc with ~ 1.5 x 10^8 $M_\odot$ of H_2
  - young
  - has been formed by condensation of pre-enriched matter that belonged to a parent galaxy
  - it is now (probably) decoupled
  - it may be gravitationally bound
  - no dark matter component
- ram pressure dwarf galaxy (RPDG) forming?
- while in TDGs a typical molecular gas fraction is ~20%, in an RPDG H_2 is likely the dominant gas phase
- Needs more detailed observations to determine total mass, kinematics, and especially self-gravitation



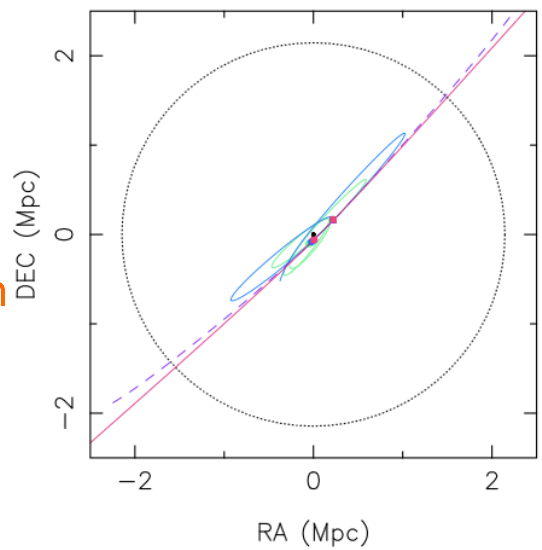
Jachym+2014

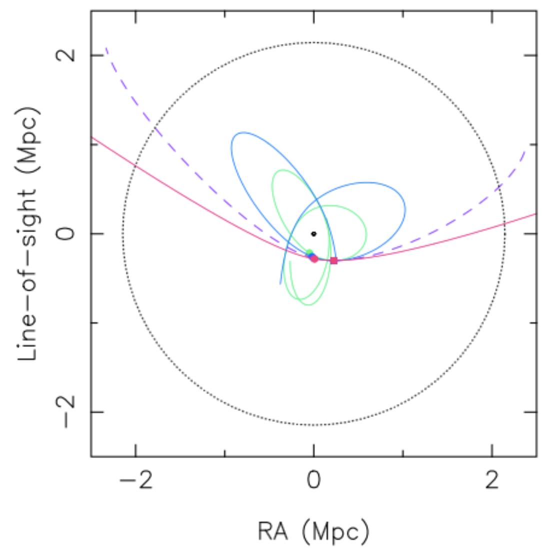
Possible orbit of ESO137-001

- Known orbital parameters:
  - galaxy's current position on the sky,
  - LOS velocity
  - plane of the sky velocity direction (indicated by the projected tail direction)
- Free parameters:
  - current LOS distance relative to the cluster center
  - velocity component in the plane of the sky

Jachym+2014

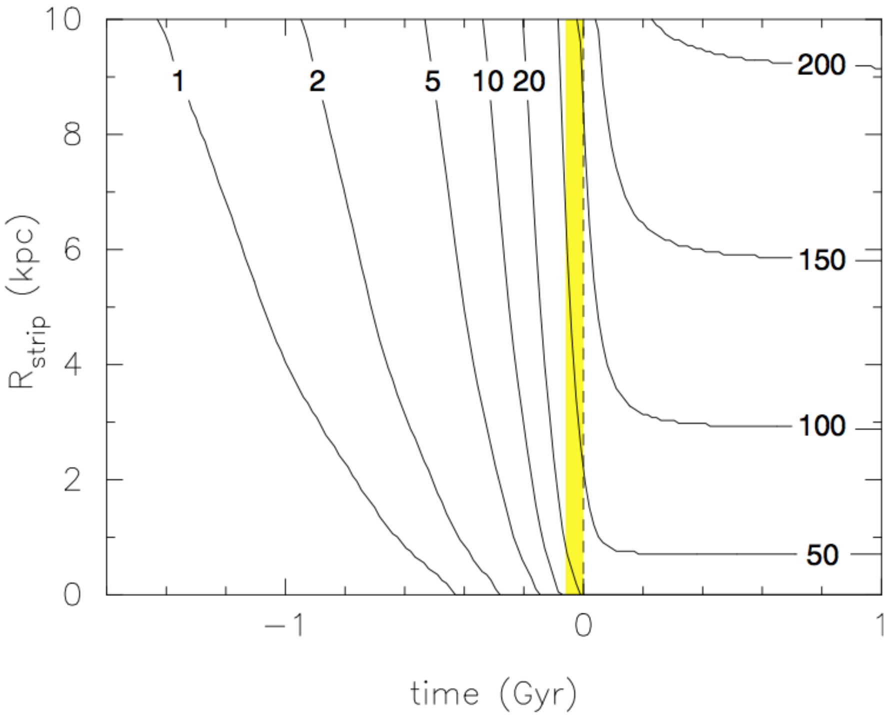
- from comparison with typical orbits of in-falling galaxies in cosmological simulations,
- for a NFW model profile of DM for Norma,
- ESO137- 001 has a rather high orbital velocity 3000 km/s





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 (~2.1×10^{-10} dyne cm^{-2}). The FWHM of the ram pressure time profile is ~200 Myr.
- gas with Σ_{ISM} ~10 $M_{\odot}$ pc^{-2} is currently completely stripped from the galaxy (R_{strip} = 0 kpc), and stripping has proceeded to denser gas (about 20–50 $M_{\odot}$ pc^{-2}) at larger disk radii



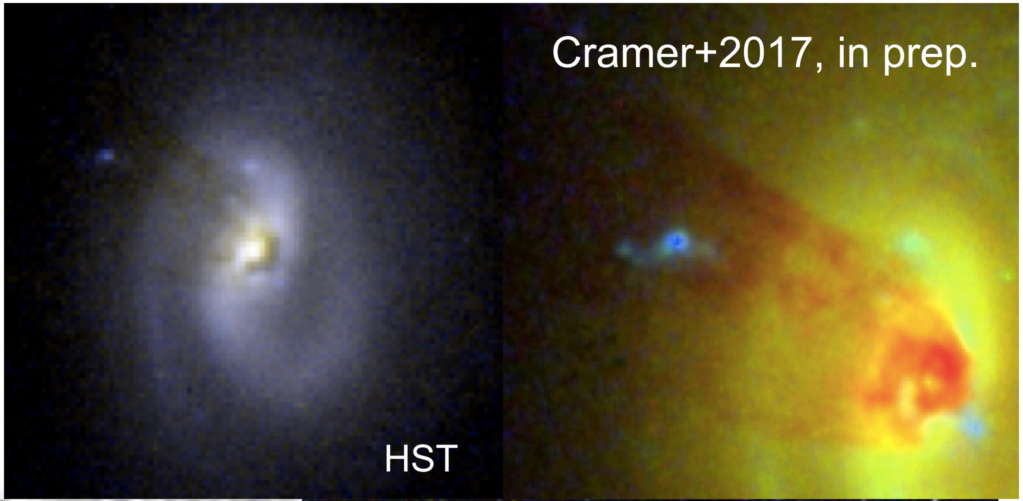
Column Densities of Stripped ISM in Our Model

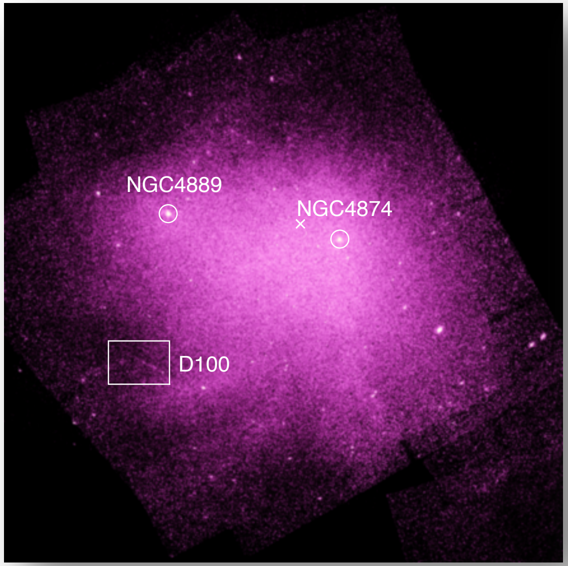
Vertical Distance	Radius in the Disk		
	2 kpc	6 kpc	10 kpc
tail (80 kpc)	10	17	20
001-C (40 kpc)	15	25	35
001-A (10 kpc)	25	60	90

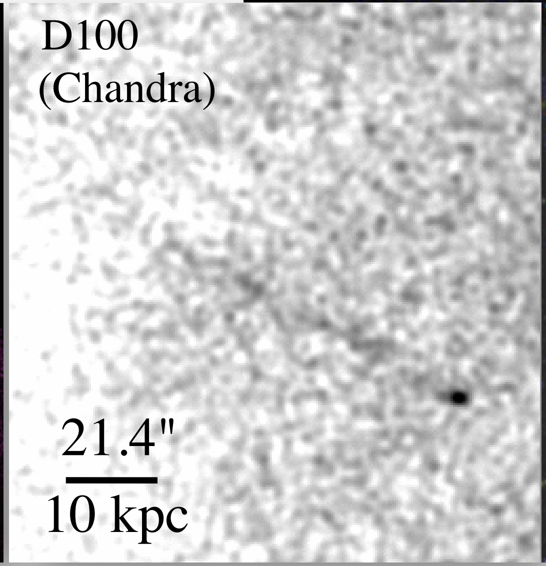
Jachym+2014

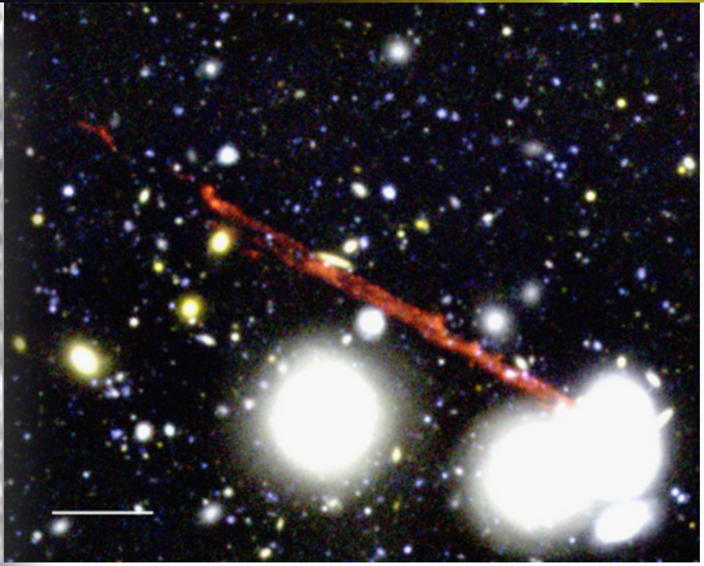
How common is cold gas in RPS tails?

- Galaxy D100 in Coma
  - ~240 kpc from cluster center
  - Stellar mass ~ 2 x 10^9 $M_\odot$
  - Multi-phase RPS tail
    - 60 kpc Hα tail
    - 50 kpc X-ray tail
    - GALEX 15 kpc UV tail



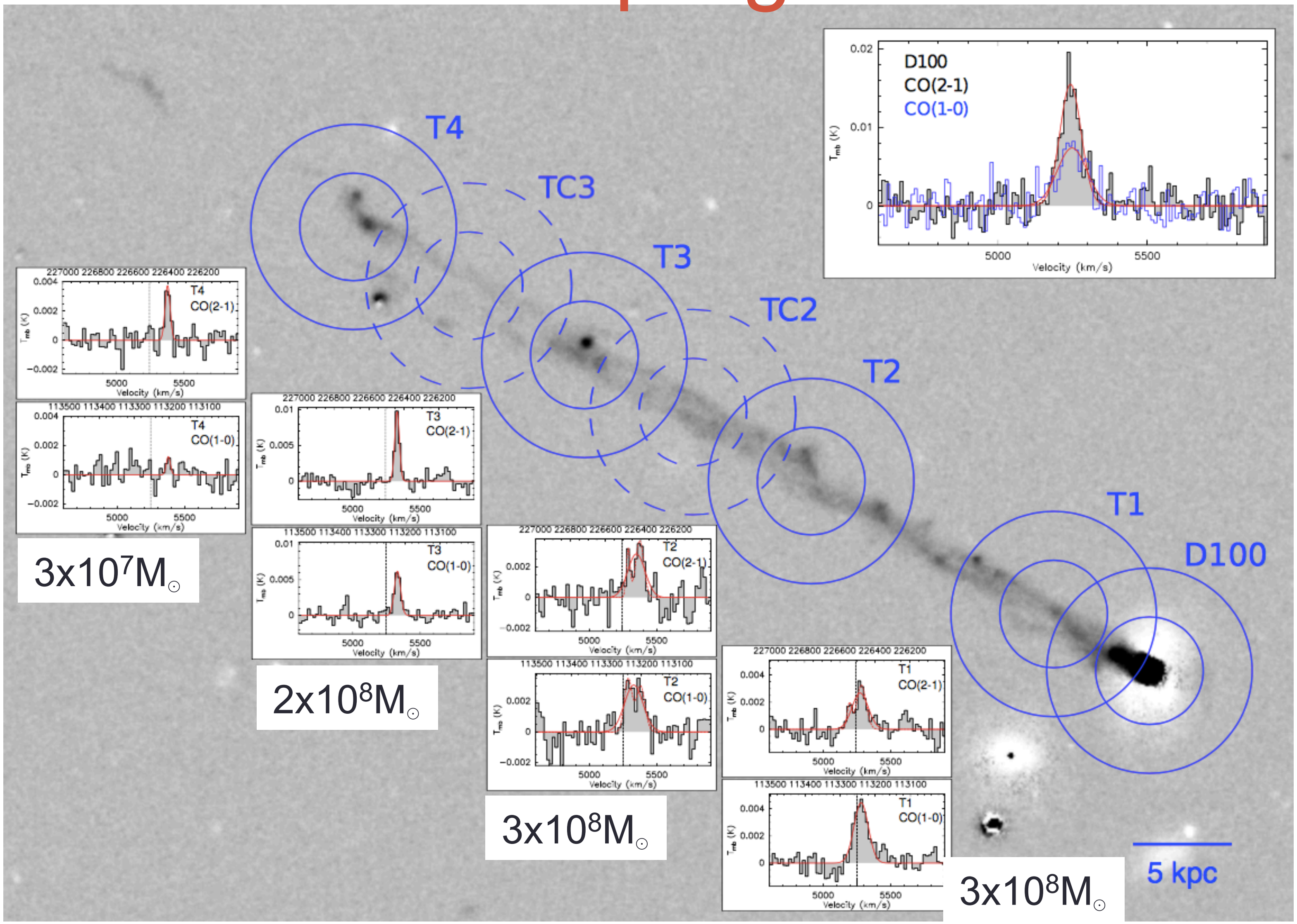






Sanders+2013; Yagi+2010; Caldwell+1999

IRAM 30m sampling of D100



~ $1 \times 10^9\ M_\odot$ of H_2

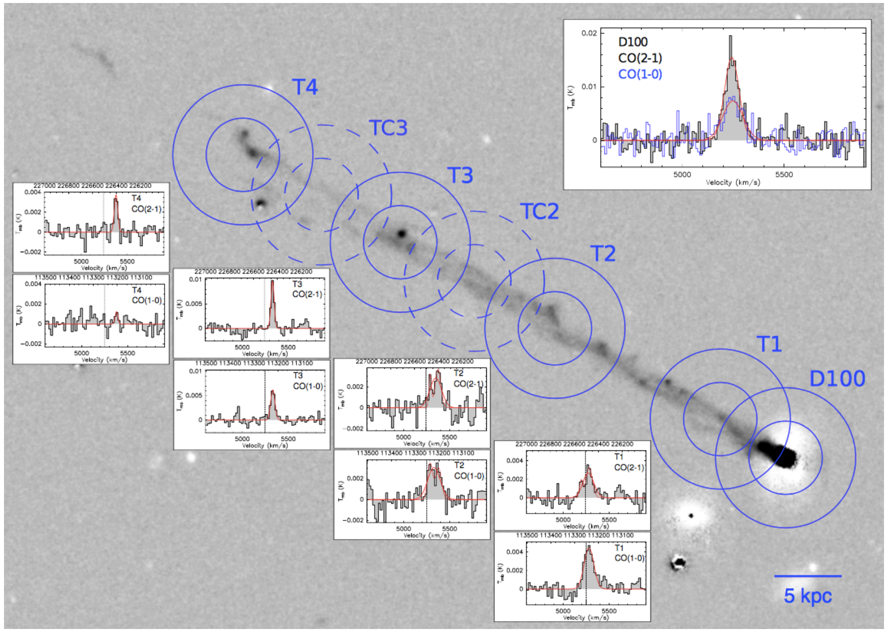
Jachym+2017

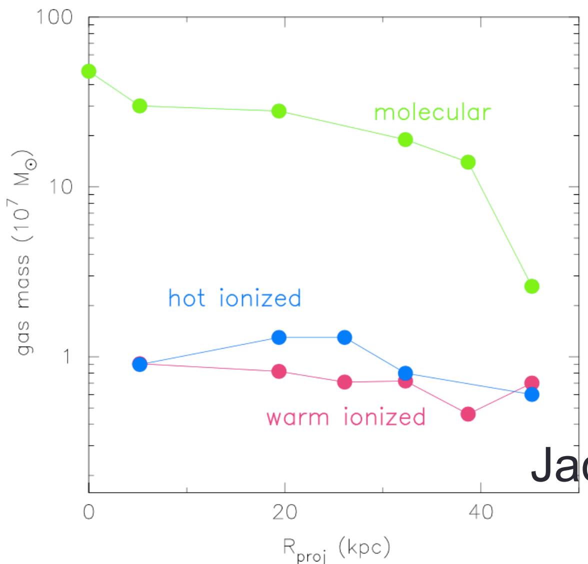
IRAM 30m sampling of D100

- ~ $1x10^9$ $M_\odot$ of H_2
- only ~10^8 $M_\odot$ of X-ray, hot ionized gas
- ~$5x10^7$ $M_\odot$ of Hα, warm ionized gas
- no HI with a limit of ~$0.5x10^8$ $M_\odot$

⇒ 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, but very likely still exceeding the fraction of the other gas components.

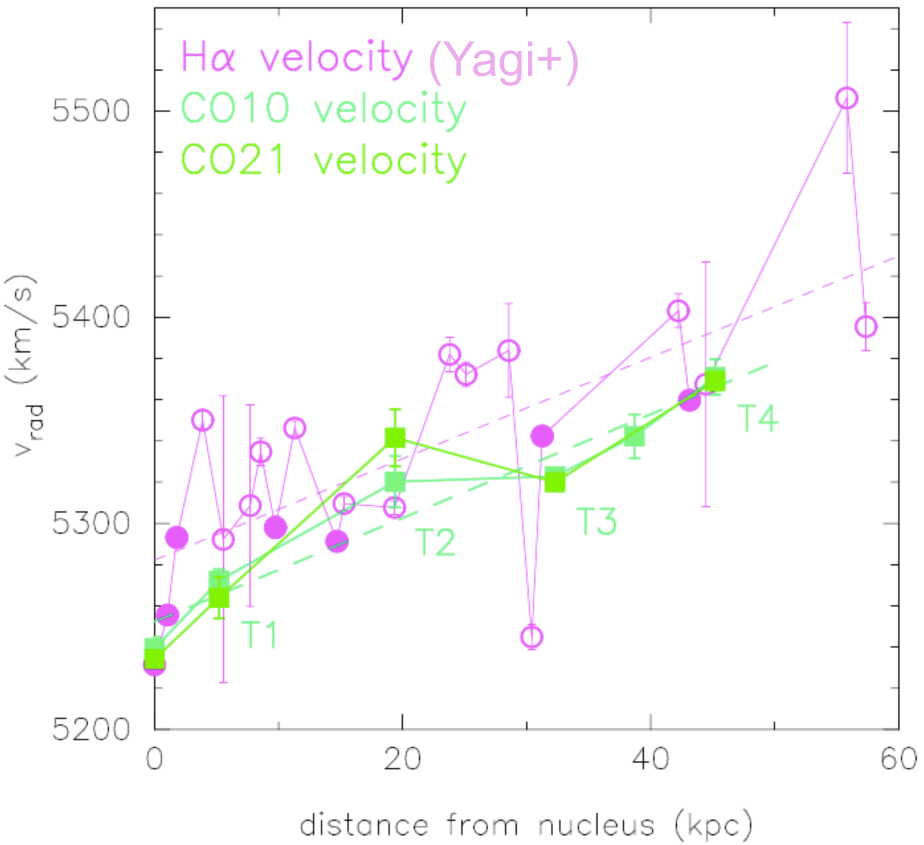




Jachym+2017

Kinematic separation of gas phases

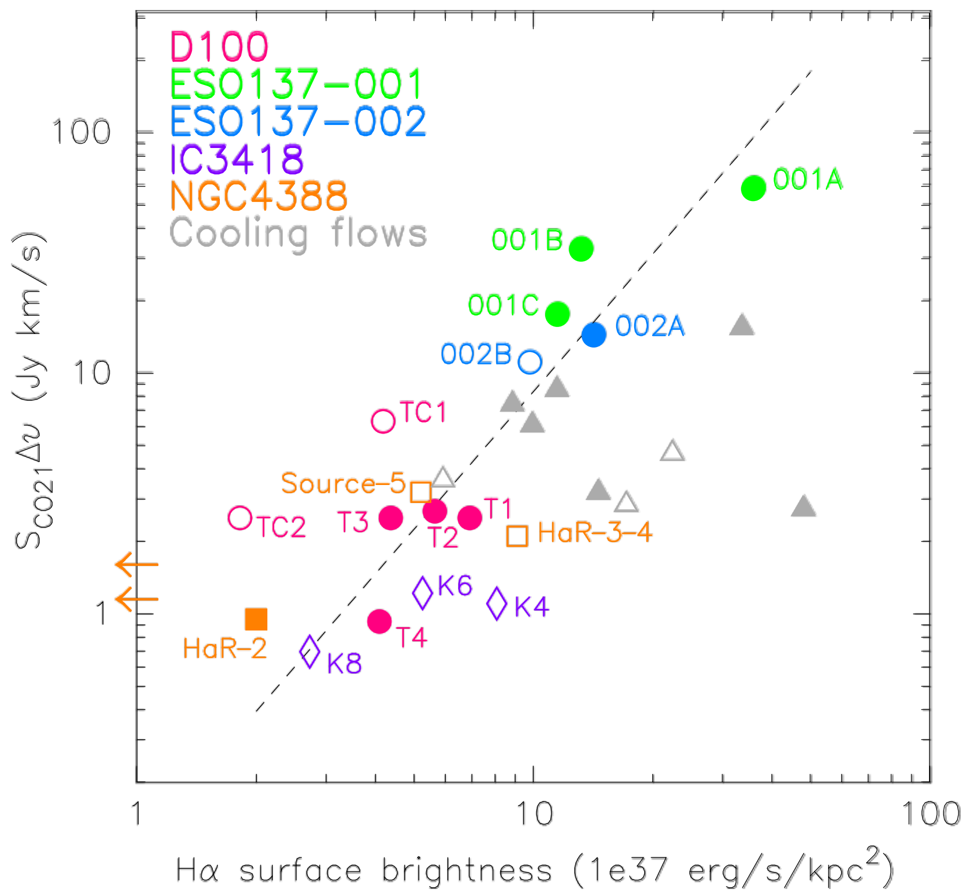
- Measured offset of ~ 30 km/s between warm ionized and cold molecular gas in the tail, while having a similar slope
- May be due to differential acceleration of gas phases by ram pressure
- radial velocity gradient of about 130 km/s along CO tail and ~ 200 km/s in Hα forms only about 10% of the (projected)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



Jachym+2017

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 Hα 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…



Jachym+2017

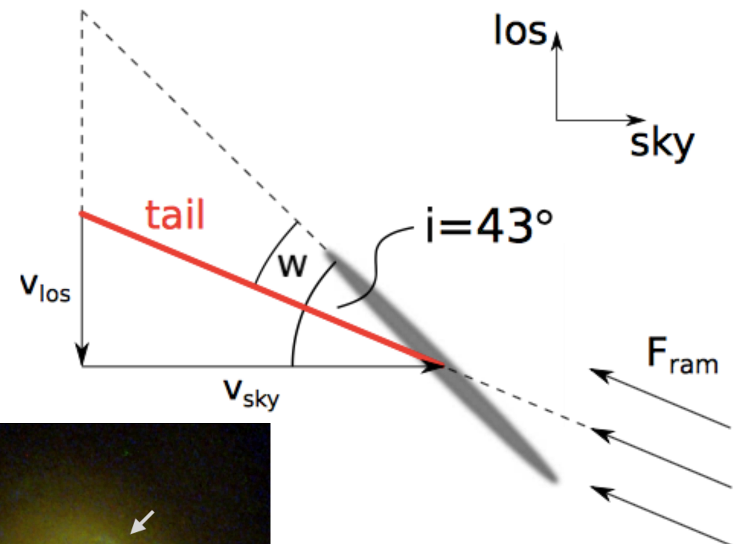
Constraining the wind angle

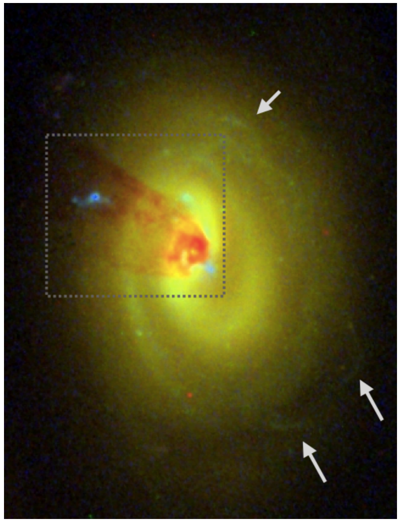
- D100 is blueshifted relative to Coma
- Inclination angle ~45°
- HST dust extinction suggests: Left disk side = far side

- <u>near edge-on stripping</u>
- 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 ~250Myr (160Myr)



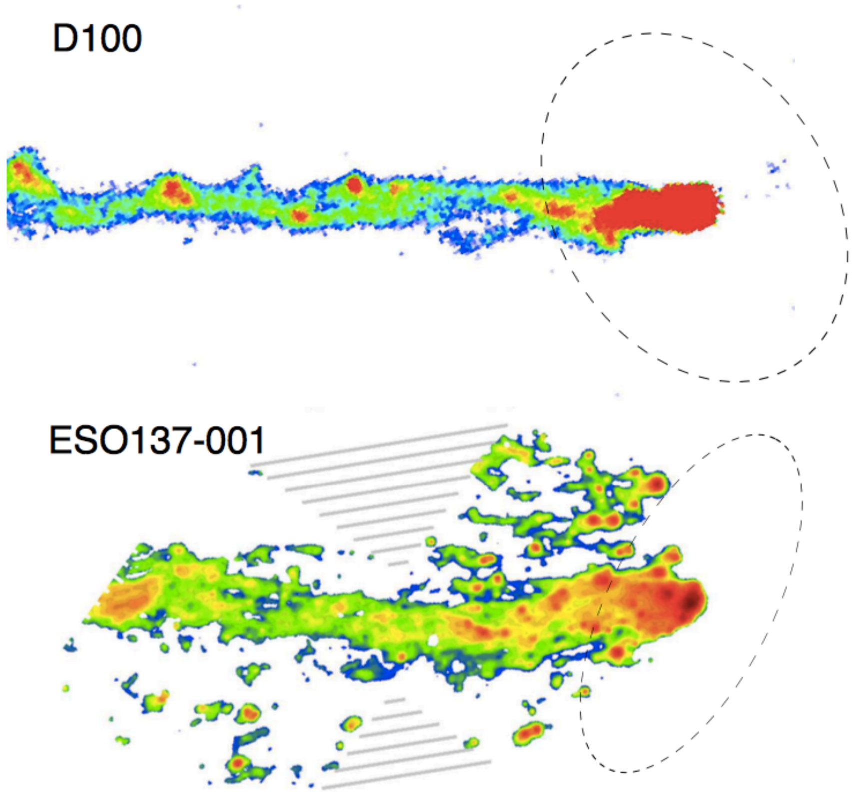


Jachym+2017

D100 – ESO137-001 comparison

- tail of D100 has a simpler morphology
  - much less substructure perpendicular to its length and it is straighter.
- On the other hand, the two tails bear some similarities
  - they are brightest in the innermost parts
  - there are local enhancements along the tail with Hα peaks separated by relatively diffuse emission regions

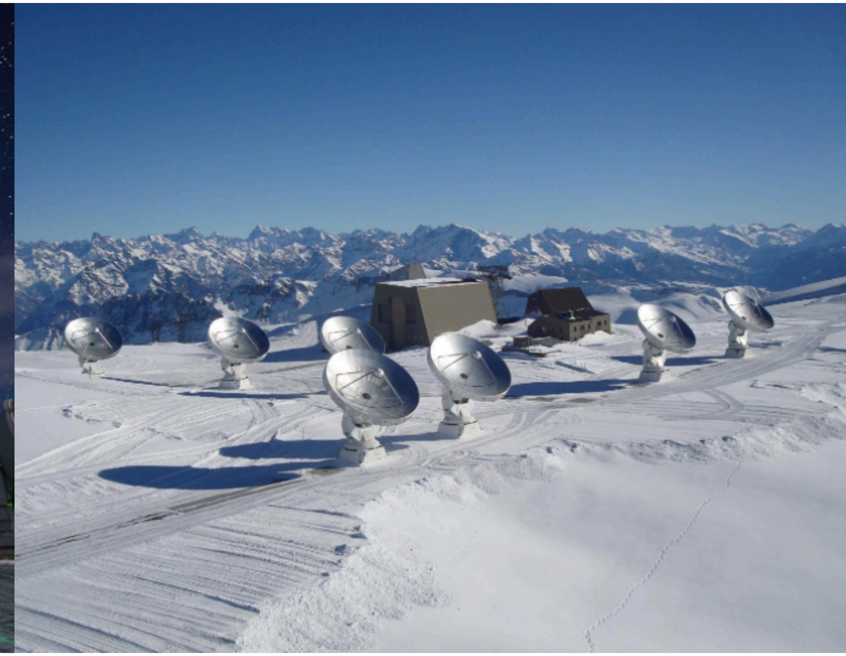
- D100
  - advanced stripping stage when its stripping radius is small
  - Continuous stripping of nuclear gas?
  - Stronger RP than ESO137-001
  - Second RPS event?
  - Effects of viscosity suppressing turbulence?
  - Also magnetic fields can inhibit instabilities and transport processes



Jachym+2017

New and ongoing projects

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)

Jachym+2017, in prep.

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

- First CO survey of Coma RPS tails with IRAM 30m telescope – 50+ hr

Jachym+2017, in prep.

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 H_2 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 ~50 M_{sun}/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.

Conclusions

- RPS tails may be molecular gas-rich – ESO137-001 galaxy in Norma & D100 in Coma
- Cold molecular phase is an important component in (some) RPS tails – may be dominant in D100
- Reveals (a large fraction of) missing stripped gas
- Star formation efficiency in the extreme environments is very low – most of molecular gas does not form stars and may join ICM
- Two directions of further observational study – search for more evidence (single dish surveys), and detailed mapping of the best cases (interferometry)