Molecular gas ram pressure stripping and inefficient intra-cluster SF

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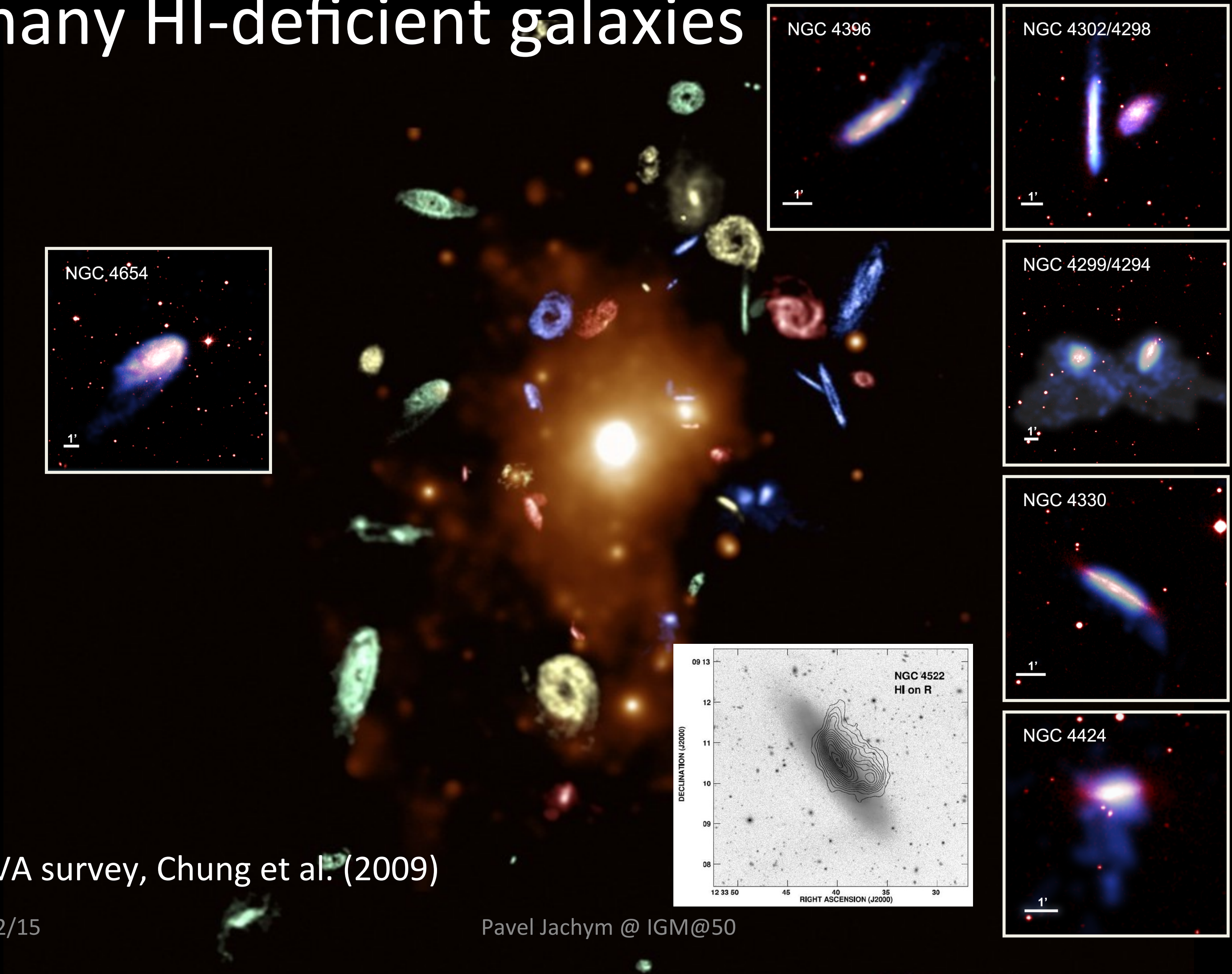
Evolution of galaxies in clusters

- dense environments of galaxy clusters and groups have been identified as places where transformations of galaxies from blue gas-rich to red gas-poor systems occur
- ram pressure of the intra-cluster medium (ICM) can efficiently remove star-forming cool ISM reservoirs from infalling galaxies (Gunn & Gott 1972) and thus cause sudden quenching of SF, while not affecting their stellar disks

- in Virgo cluster, the closest rich galaxy cluster, a number of clearly RP stripped galaxies have been observed with
  - truncated gas disks with normal stellar disks; removal of gas from outside in
  - quenched star formation
  - extra-planar, one-sided features, mostly HI

Virgo cluster – closest RPS laboratory
many HI-deficient galaxies



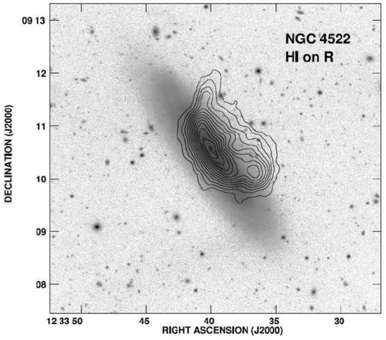
VIVA survey, Chung et al. (2009)

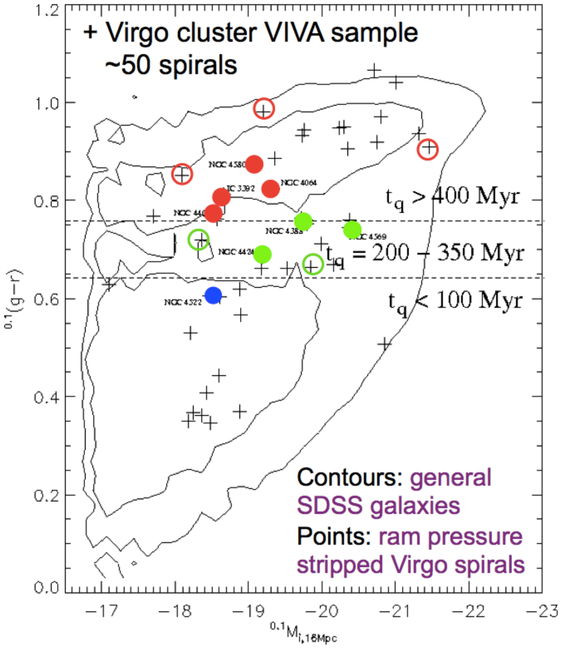
Ram pressure stripping

- Gunn & Gott (1972): ISM element is stripped from galaxy when ram pressure of the intra-cluster medium (ICM) exceeds the gravitational restoring force of the galaxy:

$$\rho_{ICM} v^2 > \Sigma_{ISM}\, d\Phi/dz$$

- HI is expected to be more easily stripped than dense (molecular) clouds, and stars are not affected at all
- RPS is (at least partly) responsible for cluster spirals in green valley and red sequence due to <u>quenching of star formation</u>
- RPS can completely strip dwarf galaxies and partially large spirals in ~10^{14} M_{sun} (Virgo-like) clusters
- RPS can completely strip massive galaxies in ~10^{15} M_{sun} (Coma-like) clusters
- *Starvation* = removal of gas halo (outer disk) reservoir by either tidal or RP stripping => no supply of gas into inner disk



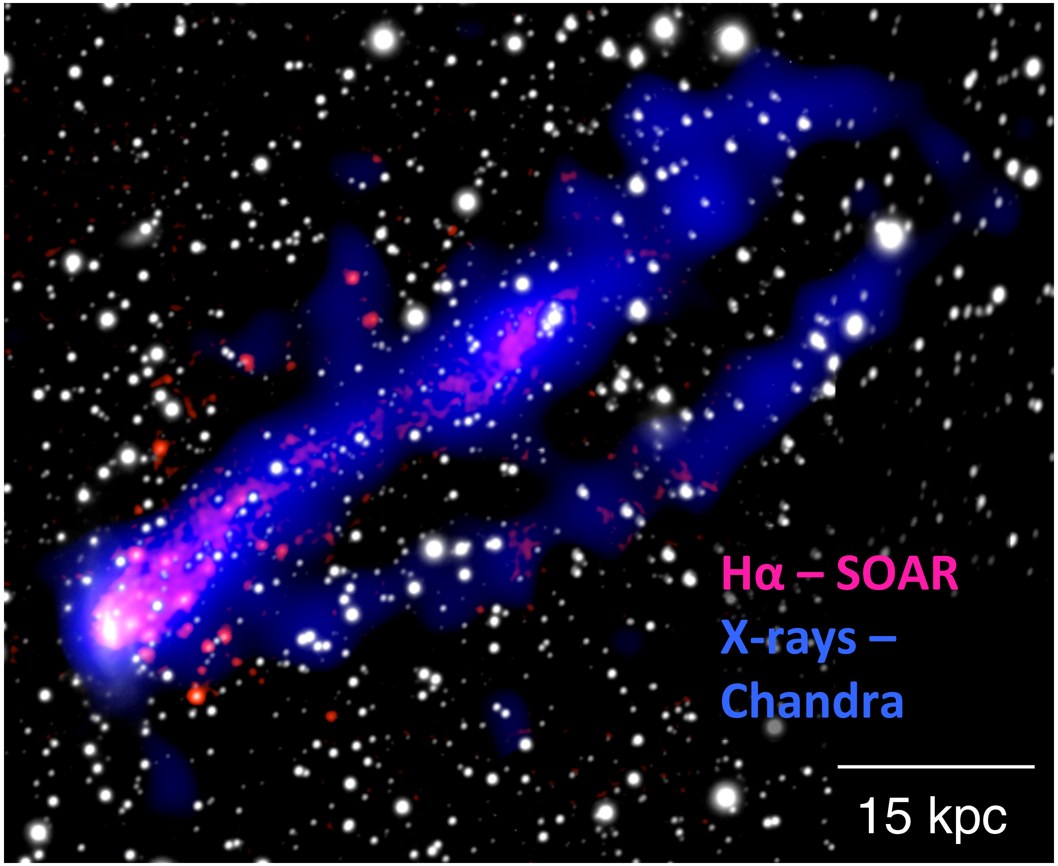


Where is the stripped gas?

- *most* of the ISM missing in Virgo galaxies is not revealed in observations, e.g. Vollmer & Huchtmeier (2007); Kenney et al. (2014) + Jachym et al. (2013) : dwarf galaxy IC3418
- the bulk of the stripped atomic gas must have been transferred to another phase
- one-sided tails in other wavelengths revealed, such as Hα or X-rays
  - in Virgo only few: e.g. NGC4388 or IC3418 (Oosterloo & van Gorkom 2005; Hester et al. 2010)
  - many in more massive clusters with higher ICM pressure (Gavazzi et al. 2001; Cortese et al. 2006, 2007; Sun et al. 2007; Yagi et al. 2007; Yoshida et al. 2004, 2008; Kenney et al. 2008; Fossati et al. 2012; Wang et al. 2004; Finoguenov et al. 2004; Machacek et al. 2005; Sun & Vikhlinin 2005; Sun et al. 2006, 2010)
- mixing of the stripped cold ISM with the hot ICM produces multi-phase gas. Prominent soft X-ray emission may be produced, as well as Hα emission.
- Star-forming RPS tails discovered (Cortese et al. 2006; Sun et al. 2007; Yoshida et al. 2008; Smith et al. 2010; Hester et al. 2010; Yagi et al. 2013; Ebeling et al. 2014)

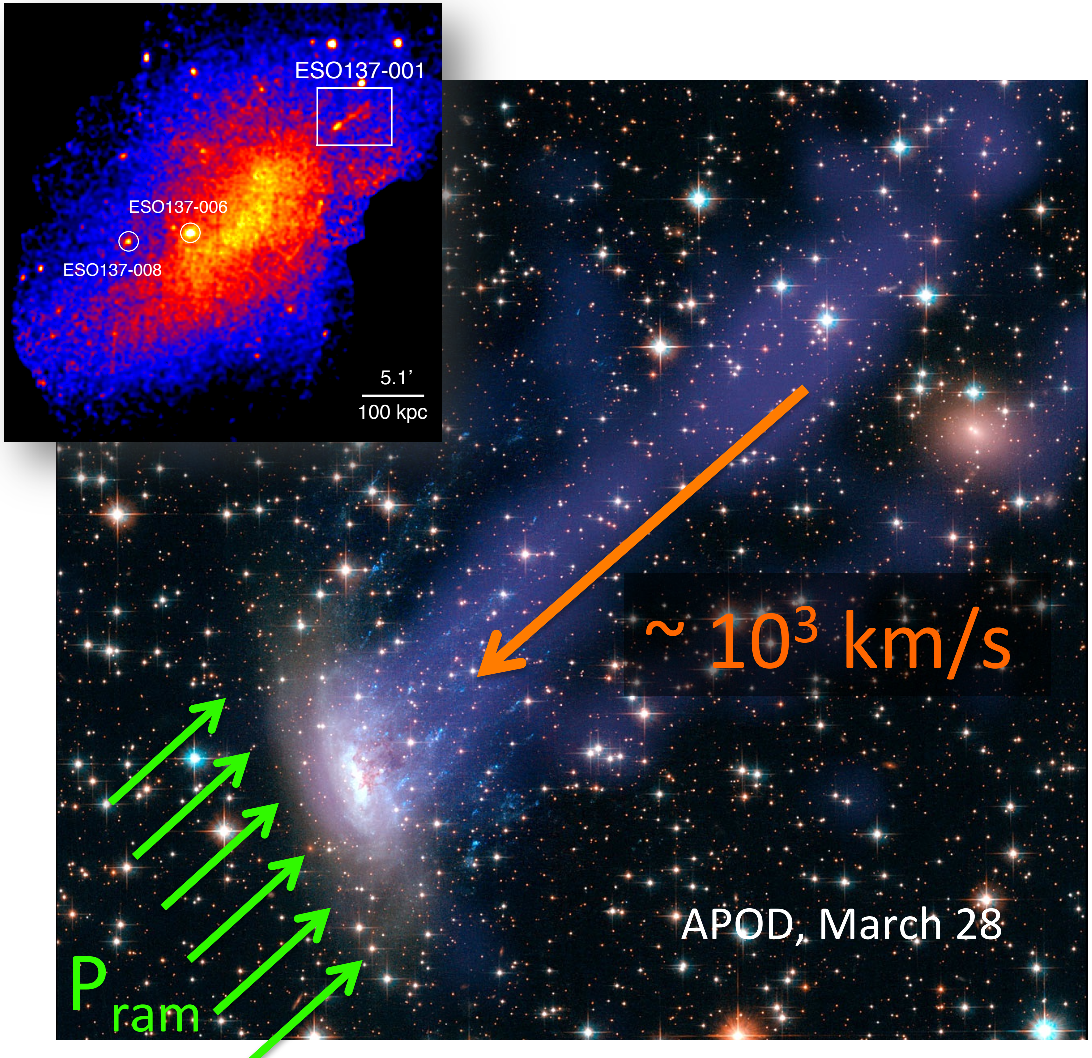
Norma cluster: ESO137-001

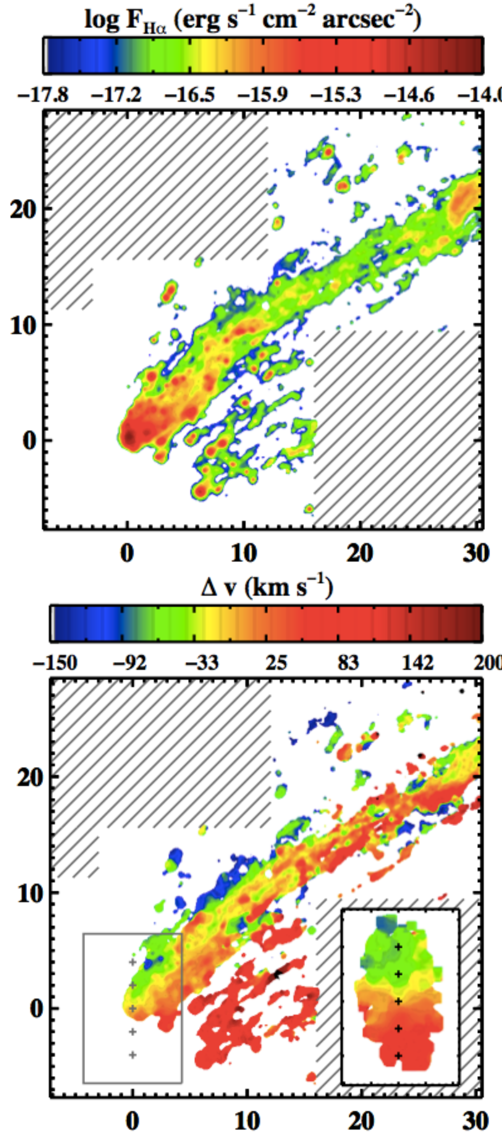
- Norma cluster (A 3627) – nearest (z=0.016, D≈70 Mpc) rich cluster
- ESO 137-001: $M_{*} \sim 1 \times 10^{10}\ M_{sun}$
- infalling for the first time to the cluster center at a high orbital speed, mostly in the plane of the sky
- the most dramatic gas stripped tail of a late-type galaxy ever observed
- multi-phase gas tail:
  - Chandra and XMM-Newton show a 80 kpc, narrow, double-structure tail
  - 40 kpc Hα tail
  - more than 30 giant discrete H II regions
  - H I only to upper limit (ATCA)



Sun et al. (2007, 2010)

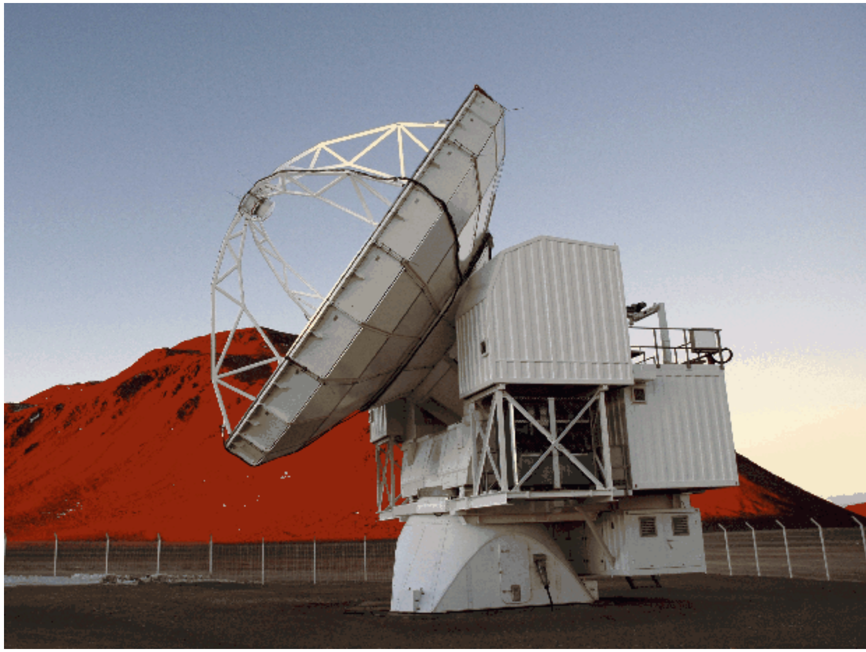
Norma cluster: ESO137-001





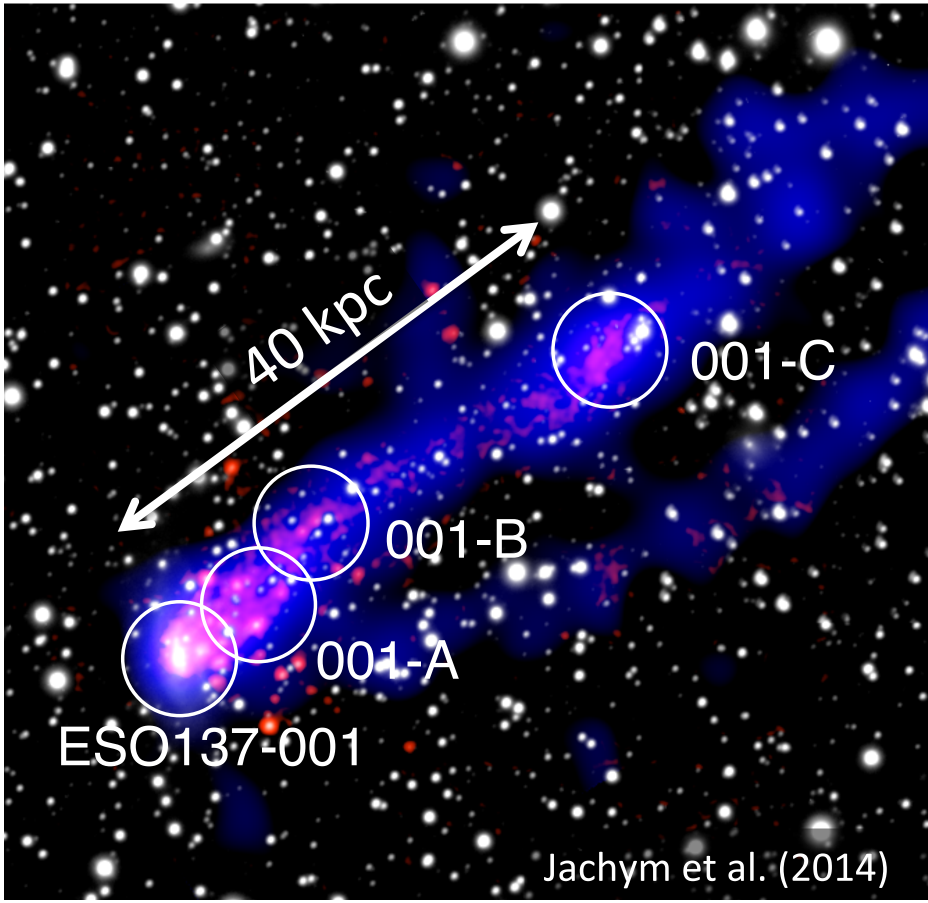
Fumagalli et al. (2014)

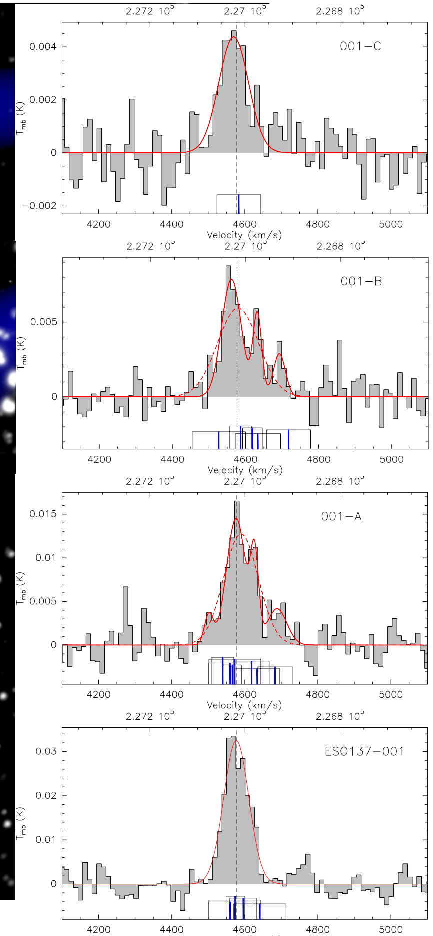
Searching for molecular gas



- ESO APEX
  - 12 m antenna
  - 5600 m elevation
  - CO(2-1), CO(3-2)
- IRAM 30m
  - 30 m antenna
  - 2600 m elevation
  - CO(1-0), CO(2-1)

Searching for molecular gas





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!

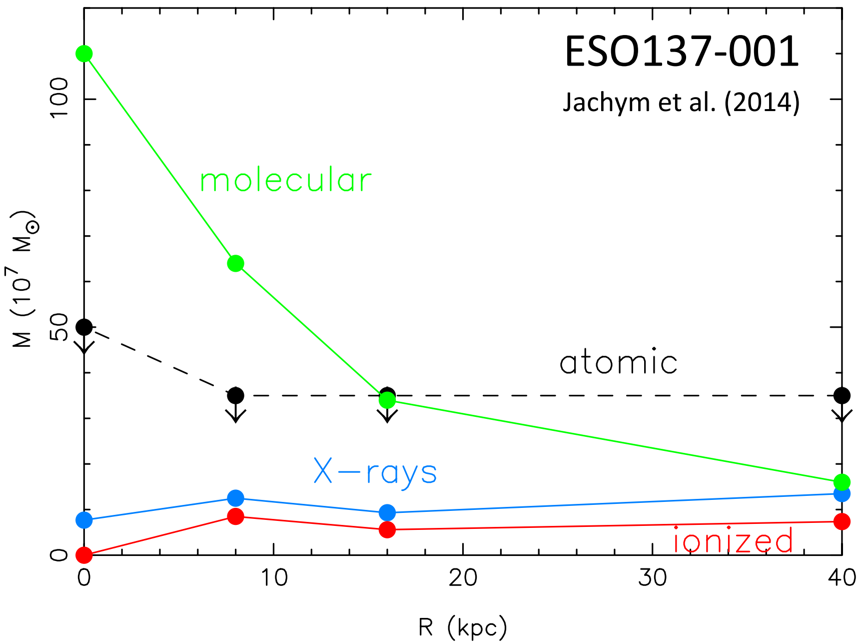
The presence of cold gas is surprising

Gas phases in the stripped tails

- > 10^9 $M_\odot$ of H_2 revealed in the tail
- largest amount found in the inner tail
  - direct stripping of dense gas?
- ~ 10^8 $M_\odot$ found in the 40 kpc tail region
  - in-situ molecular gas formation

- ~ 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 × 10^7 $M_\odot$ < 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} $M_\odot$

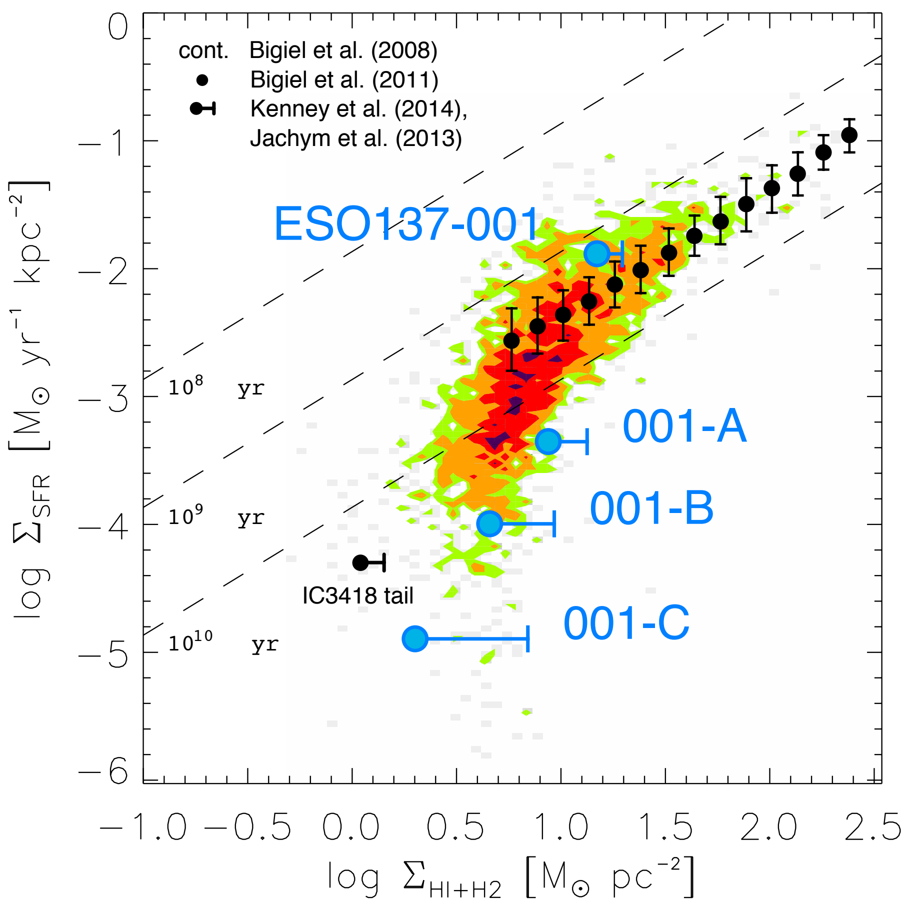


- There are large and similar amounts of cold and hot gas that together nearly account for the missing gas from the disk
- Our observations show for the first time that H_2, Hα, and X-ray emission can be at observable levels in a single ram- pressure-stripped tail

Origin of molecular gas in the tail

- Large fraction of stripped ISM can cool down and turn molecular – in-situ H_2 formation
  - strong ram pressure may push/strip rather dense gas clumps
  - these can transform more readily into molecular gas than stripped diffuse gas (the density of the stripped gas determines the timescale for condensation and H_2 formation following an inverse relation; Guillard et al. 2009)
  - higher-density clumps can then radiatively cool down more easily and eventually form molecular gas, while the low-density stripped phase is compressed by the ICM, starts to mix with it, and likely accounts for the X-ray emitting hot gas in the tail (Tonnesen et al. 2011)
- Can some stripped gas survive in the molecular phase? – direct stripping of H_2
  - absence of UV photo- dissociating radiation & effects of magnetic fields
  - could contribute to the unprecedented CO brightness of the gas stripped tail of the galaxy, especially in its inner parts
- In ESO137-001 possibly combination of both: H_2 revealed in the outer tail is more likely to originate from in situ transformation of stripped diffuse atomic gas
- dust is crucial for H2 formation – *Herschel* revealed a dust trail
  - dust ram pressure stripping studied by Abramson & Kenney

Very low star formation efficiency in the special environment of a RPS tail

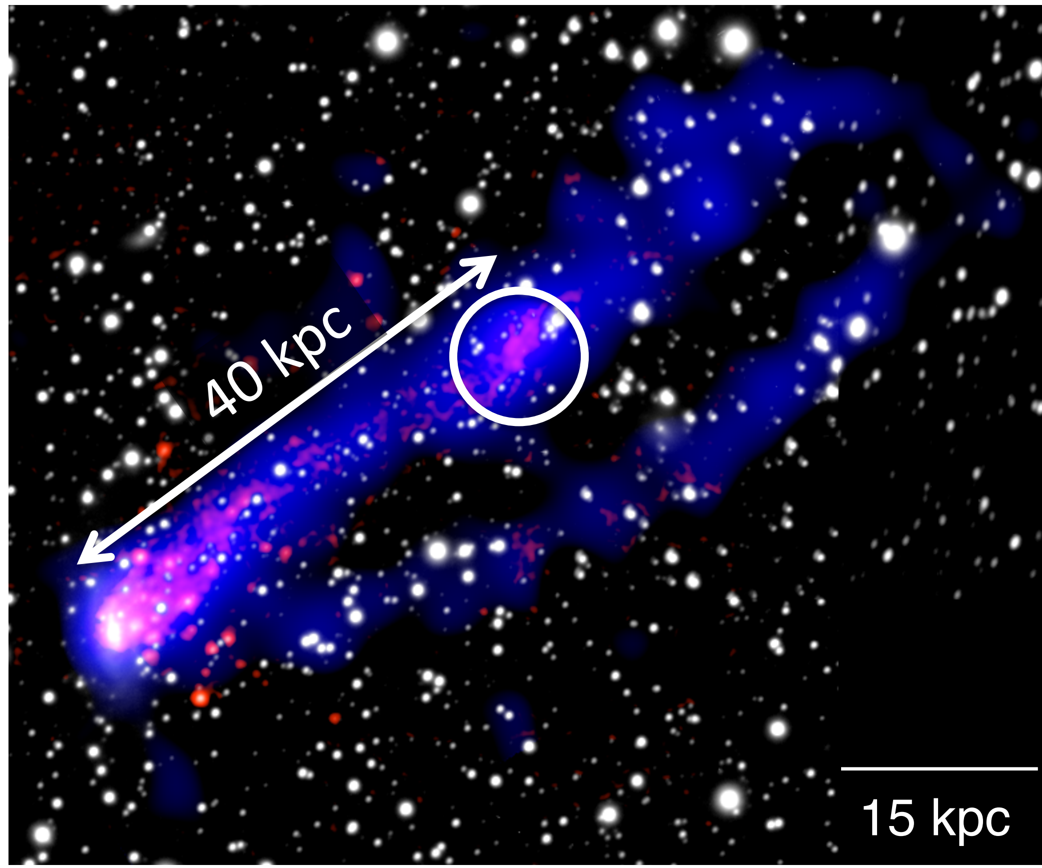


Jachym et al. (2014)

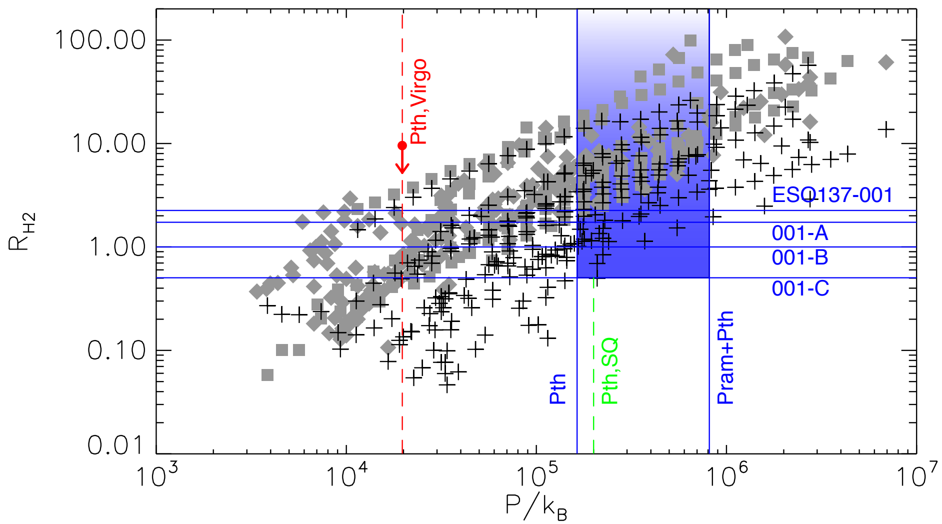
- low and decreasing SFE along the tail
- Star formation timescale (=1/SFE) = $M(HI+H_2)/SFR$ is 2-50x longer in stripped gas than in disks
- most of stripped gas does not form stars but remains gaseous and ultimately joins the ICM
  - low average gas density in the tail?
  - turbulent heating induced by RP shock?
- distinctly different 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

RP dwarf galaxy in formation?

- 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
- a 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



Molecular gas fraction vs. local ICM pressure in the tail

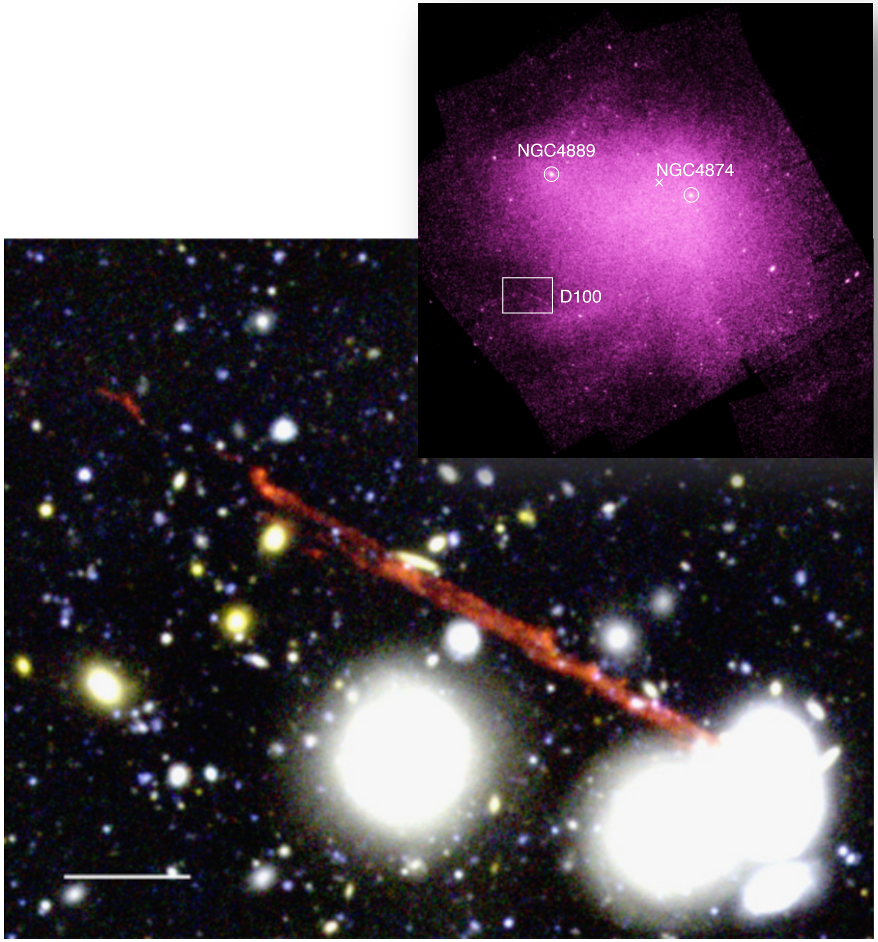


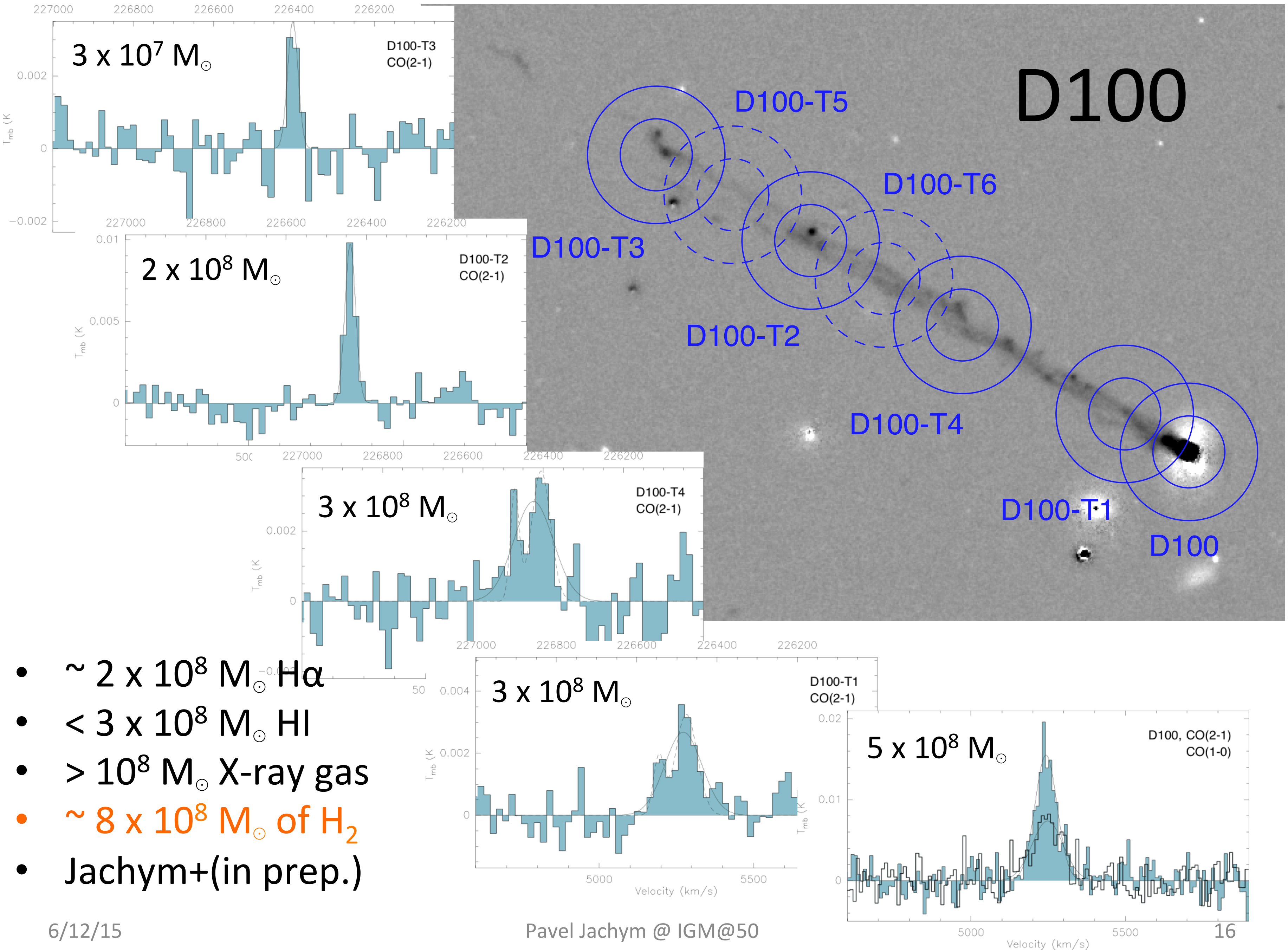
$R_{H2} = \Sigma_{H2}/\Sigma_{HI}$, as a function of midplane pressure in observations of nearby galaxies (squares – Blitz & Rosolowsky 2006; diamonds – Leroy et al. 2008) and theoretical predictions of Krumholz et al. (2009, plus signs)

- ICM thermal (+ ram) pressure at the location of ESO 137-001 in the Norma cluster is similar to midplane gas pressures that occur in the (inner) disks of galaxies
- lower limits on the molecular-to-atomic gas ratio in the tail of ESO 137-001 (corresponding to our APEX detections and the ATCA H I upper limits) are consistent with values measured in galactic disks
- nevertheless, the star formation efficiency in the tail is much lower than in the galaxies
- This could be due to a low average gas density in the tail, or turbulence driven from interaction with the surrounding ICM

How common is the presence of H_2 in RPS tails?

- D100 in Coma
  - $M_* = (1 – 7) \times 10^9 M_\odot$ post-starburst galaxy
  - core starburst and extended Hα connected to core
  - ~ 240 kpc from cluster center
  - multiphase RPS tail:
    - 60 kpc Hα tail shows substructure and bifurcation
    - 48 kpc X-ray tail
    - GALEX 15 kpc UV tail

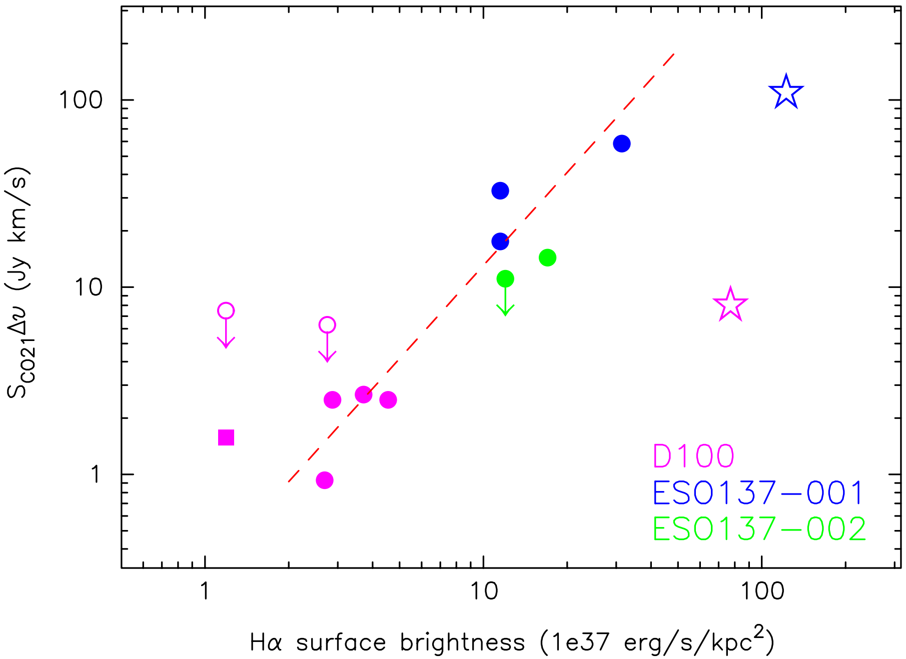




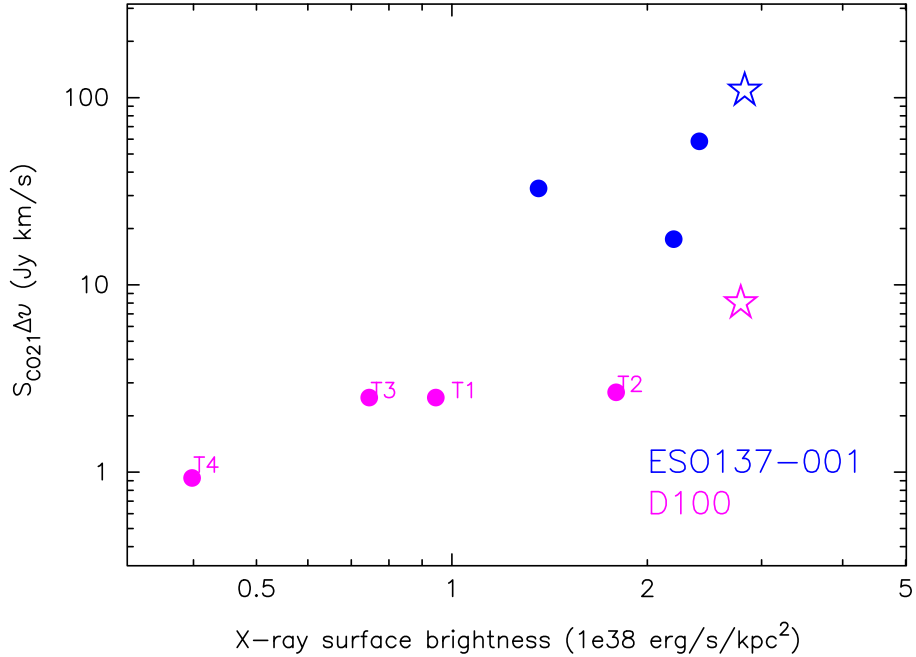
- ~ 2 x 10^8 $M_\odot$ Hα
- < 3 x 10^8 $M_\odot$ HI
- > 10^8 $M_\odot$ X-ray gas
- ~ 8 x 10^8 $M_\odot$ of H_2
- Jachym+(in prep.)

How do gas phases in RPS gas tails correlate?

- H_2 vs. Hα



- H_2 vs. X-rays



Jachym+(in prep.)

Near future prospects

- Build up the database – search for molecular gas in many more RPS galaxies (IRAM, APEX, …)
- High-resolution observations with NOEMA (upcoming) and ALMA (hopefully upcoming) will let us better understand local physical conditions – effects of cooling, in-situ formation of molecular gas and SF, mixing of stripped cool gas with the surrounding ICM
- RPS tails are unique laboratories where stars may form in completely different environments than in galactic disks

Conclusions

- First detections of abundant H_2 in RPS tails including distant, IC regions
- First observations of RPS tails seen in X-rays, Hα, and H_2
- We believe H_2 tails are a widespread phenomenon
- Unified model of RPS: multi-wavelength observations of RPS tails all sample the same stripped ISM that mixes with ICM and changes phases
- Our observations are consistent with numerical simulations that have suggested that ICM pressure strongly affects the formation of X-ray emission and star formation (Tonnesen & Bryan 2010, 2012; Kapferer et al. 2009)