Molecular gas stripping with APEX

and prospects for ALMA

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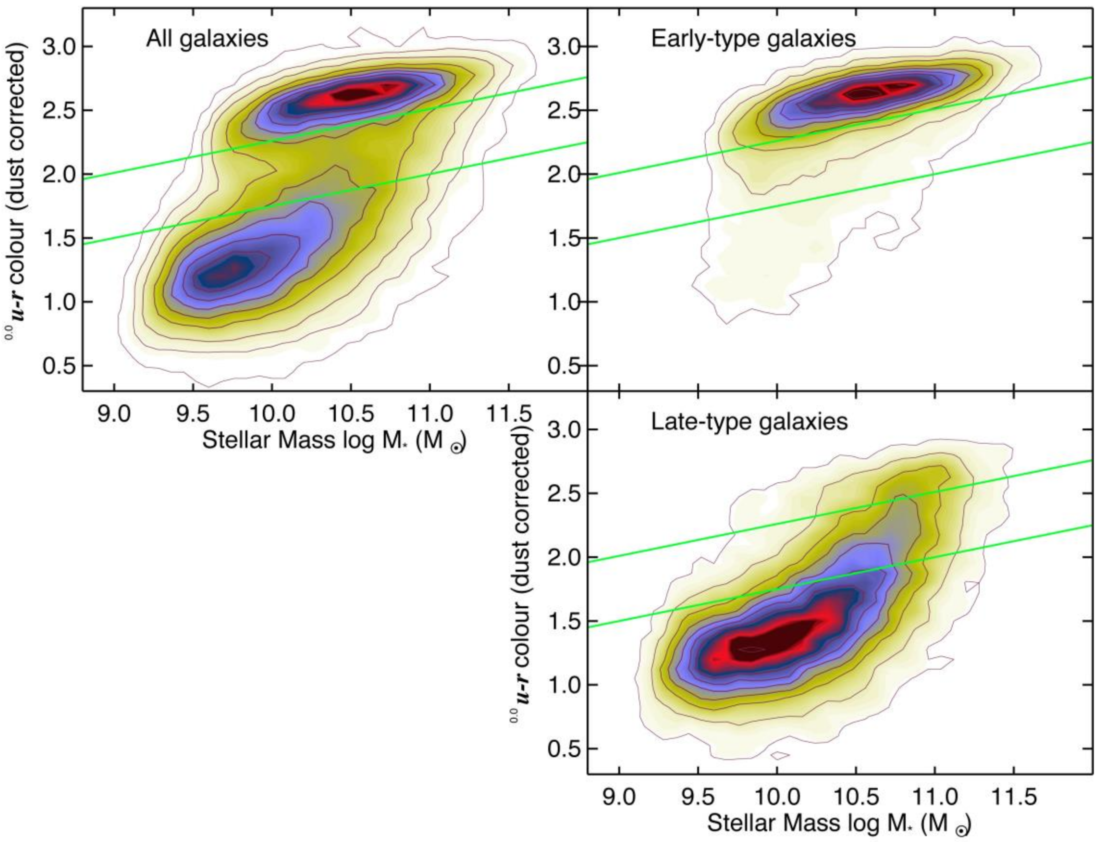
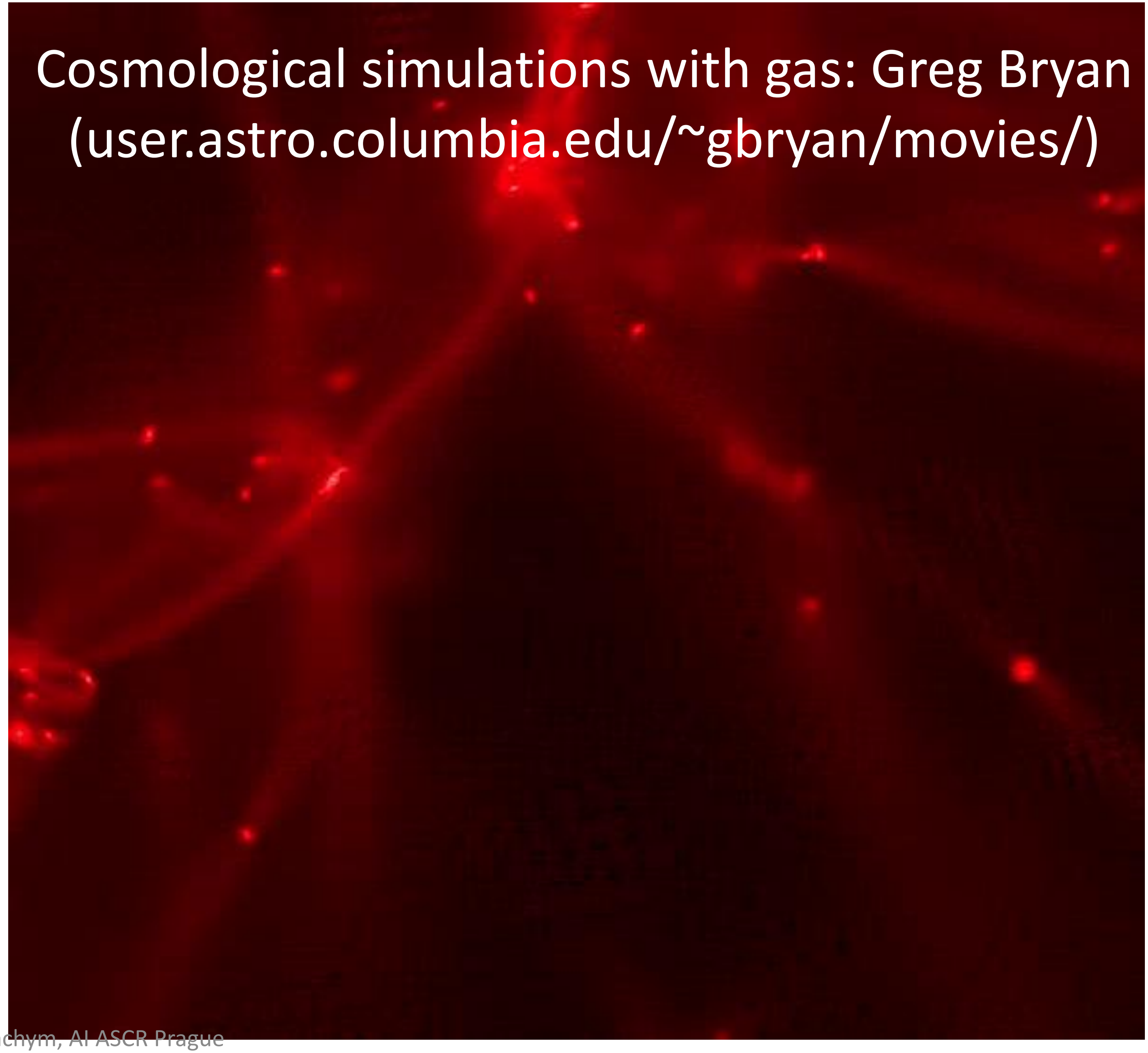
Evolution of galaxies in clusters

- Large surveys of galaxies have revealed a bimodal color distribution: most galaxies tend to be red or blue, leaving a gap in the middle known as the green valley
- Blue, spiral galaxies are transformed into red, Es by migration across the green valley
- due to <u>quenching of the star formation</u>
- primarily in galaxies falling into the clusters (and also in groups and looser structures)
- the physical mechanisms that appear most likely to be behind the migration are harassment & ram pressure stripping



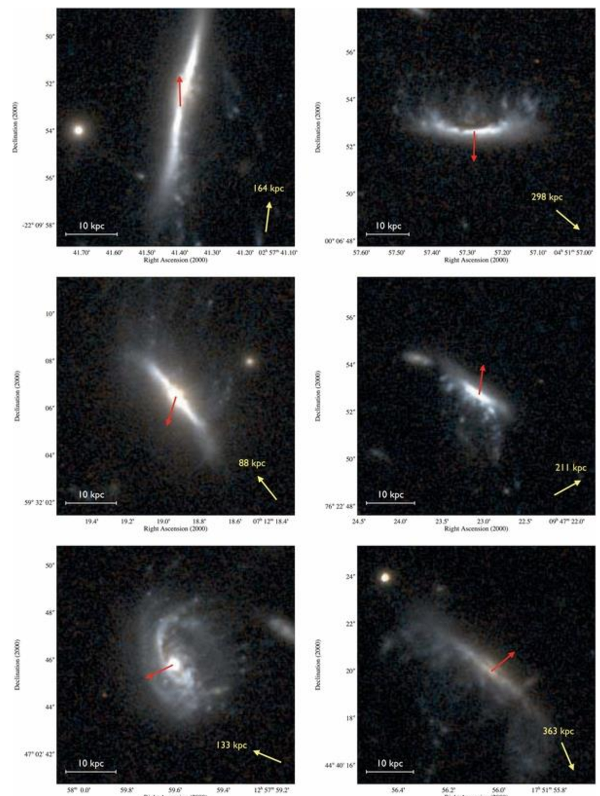
Schawinski et al. (2014)

Cosmological simulations with gas: Greg Bryan (user.astro.columbia.edu/~gbryan/movies/)



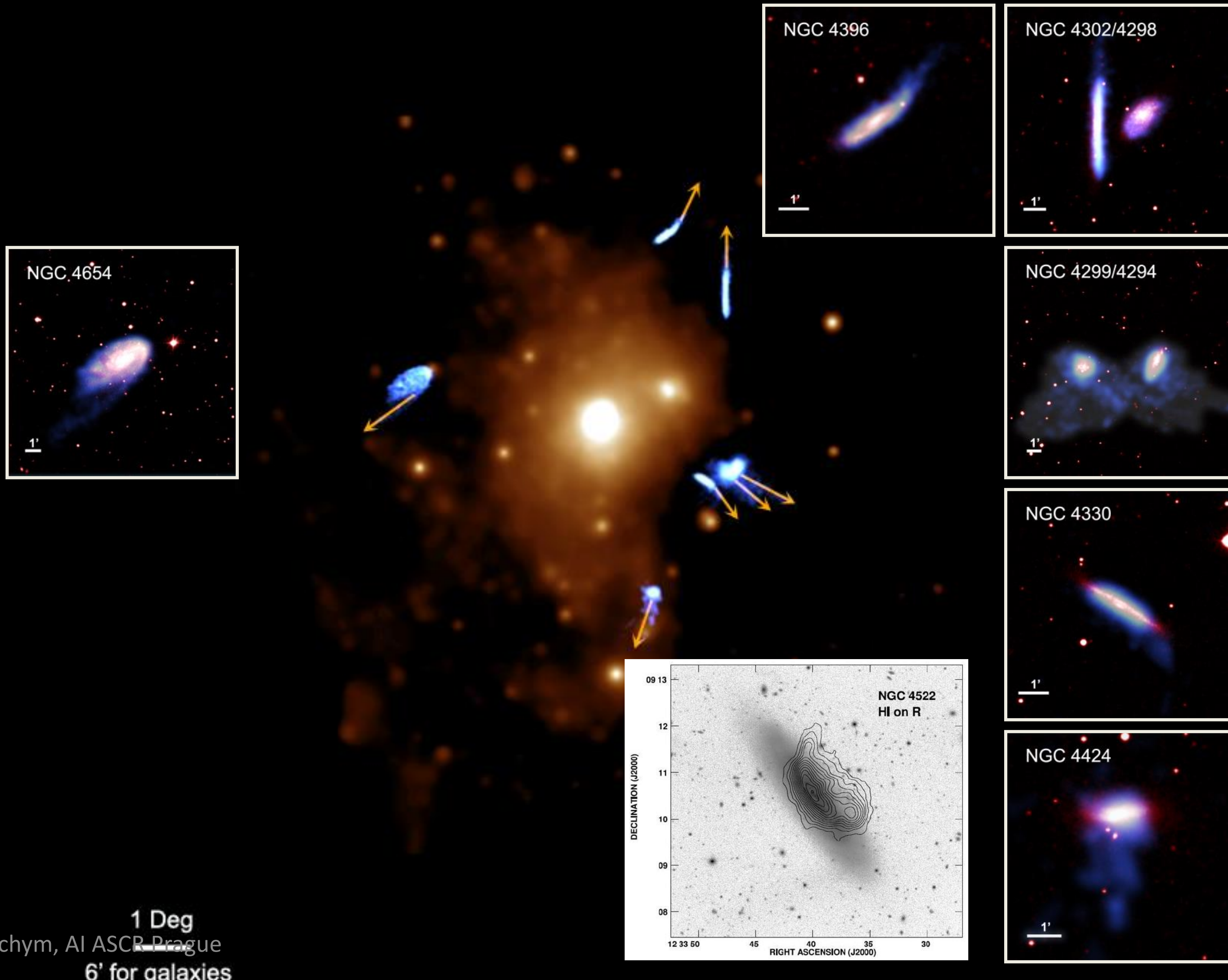
Ram pressure stripping of galaxies in clusters

- Crucial questions:
  - How do galaxies loose the cool gas?
  - When do they stop forming stars?
  - When and where do galaxies stop accreting cool gas?
- Many observation of one-sided tails in HI, soft X-rays, Hα, molecular gas in nearby and distant clusters
  - What is the fate of the stripped cool gas?
  - Where is the stripped cool gas?
  - When X-ray emitting tails do form?
  - Under what conditions stars can form in the tails?
- Many numerical simulations



Ebeling et al. (2014)

Virgo cluster – closest RPS laboratory



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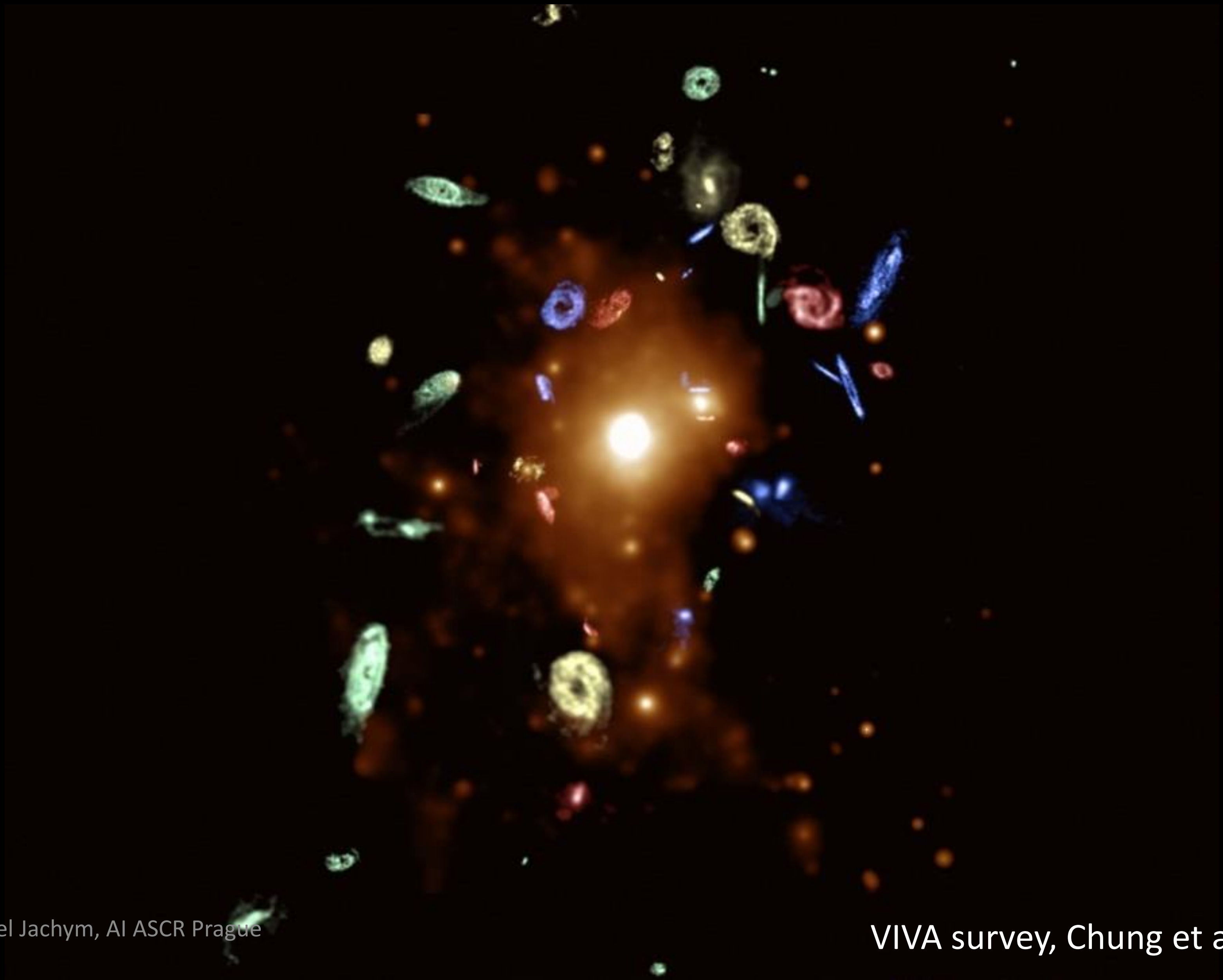
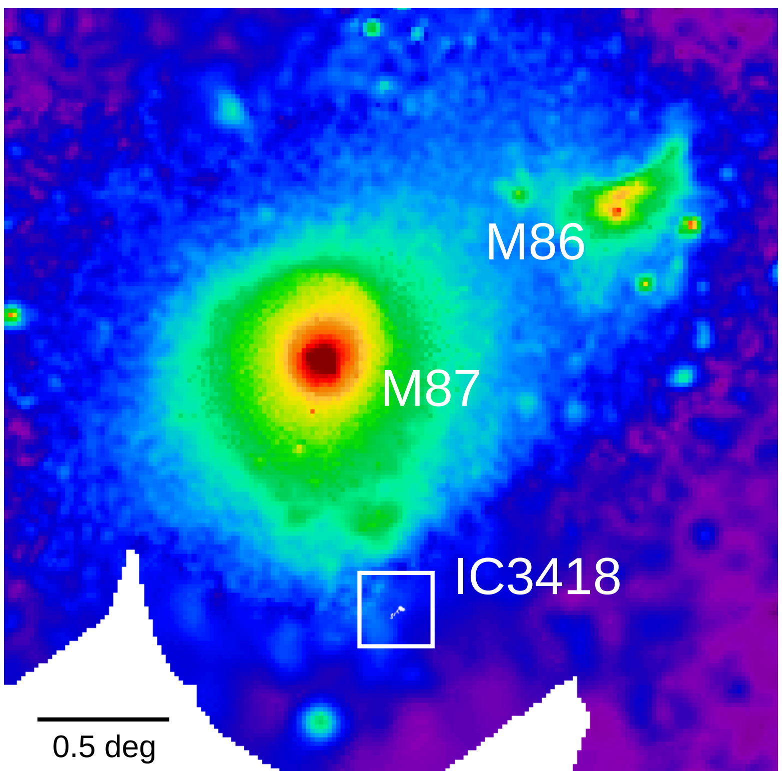
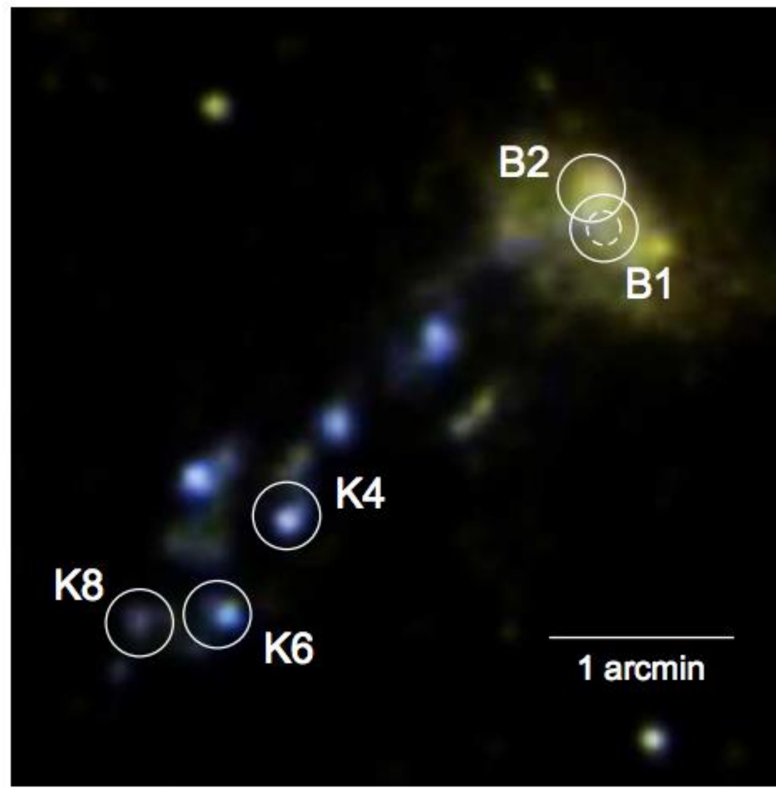


VIVA survey, Chung et al. 2009

RPS galaxies with SF tails

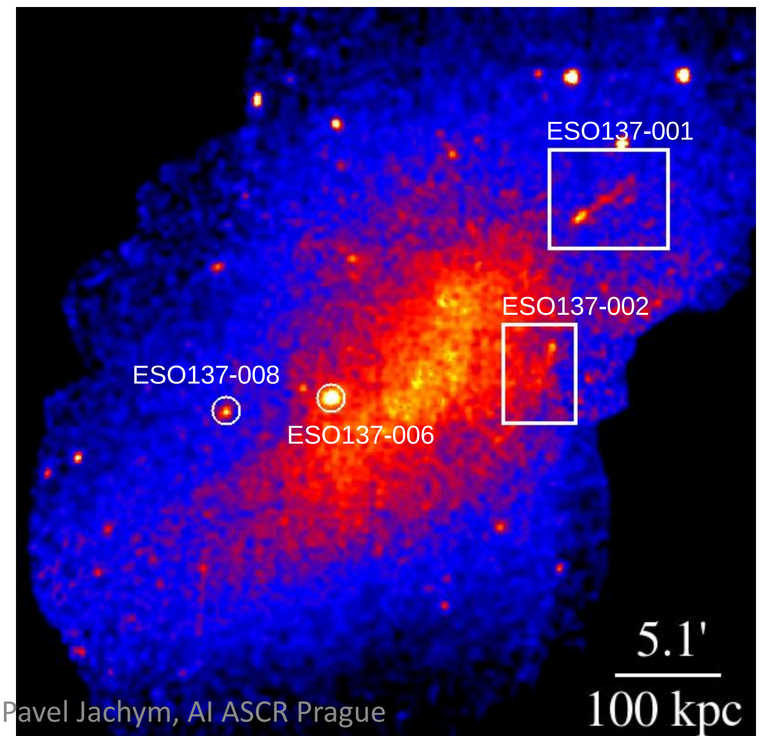
- Virgo dwarf IC3418 with prominent SF tail (Hester et al. 2010)
- Search for cold (<u>molecular, IRAM 30m</u>) and hot (X-ray, Chandra) gas – Jachym et al. (2013)
- Dwarf transformation – Kenney, Geha, Jachym et al. (2014)

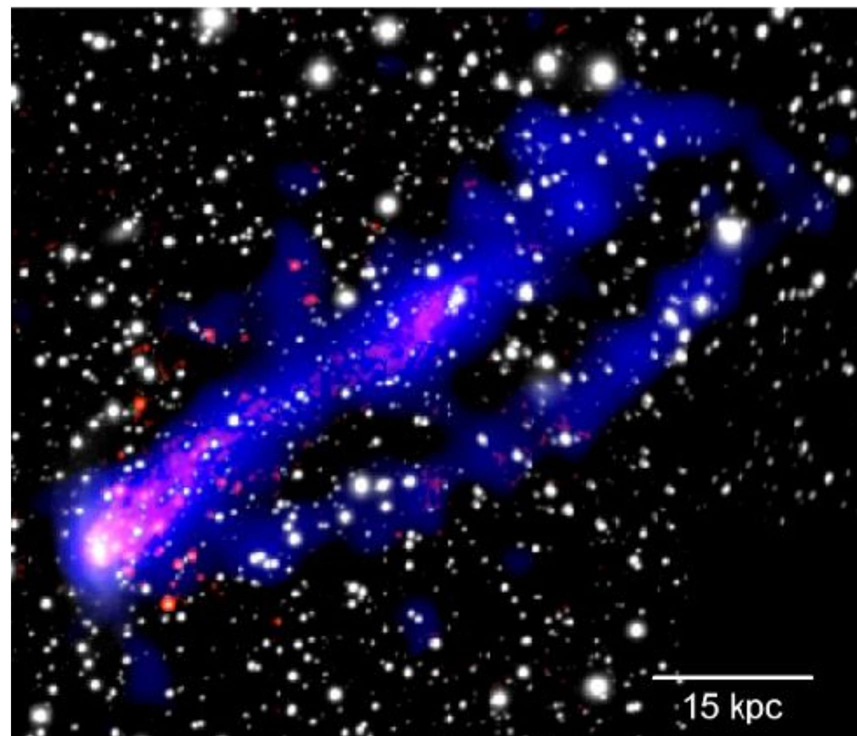




ESO 137-001 galaxy

- Norma (Abell 3627) cluster – nearest (z=0.016, D=70 Mpc) rich cluster
- ESO137-001: excellent candidate for recent transformation from a blue to a red, gas-poor galaxy due to violent RPS
- one-sided tail in X-ray, Hα, warm H_2
- Sun et al. (2006, 2007, 2010), Sivanandam et al. (2010)
- **most dramatic X-ray tail of a late-type galaxy ever observed**



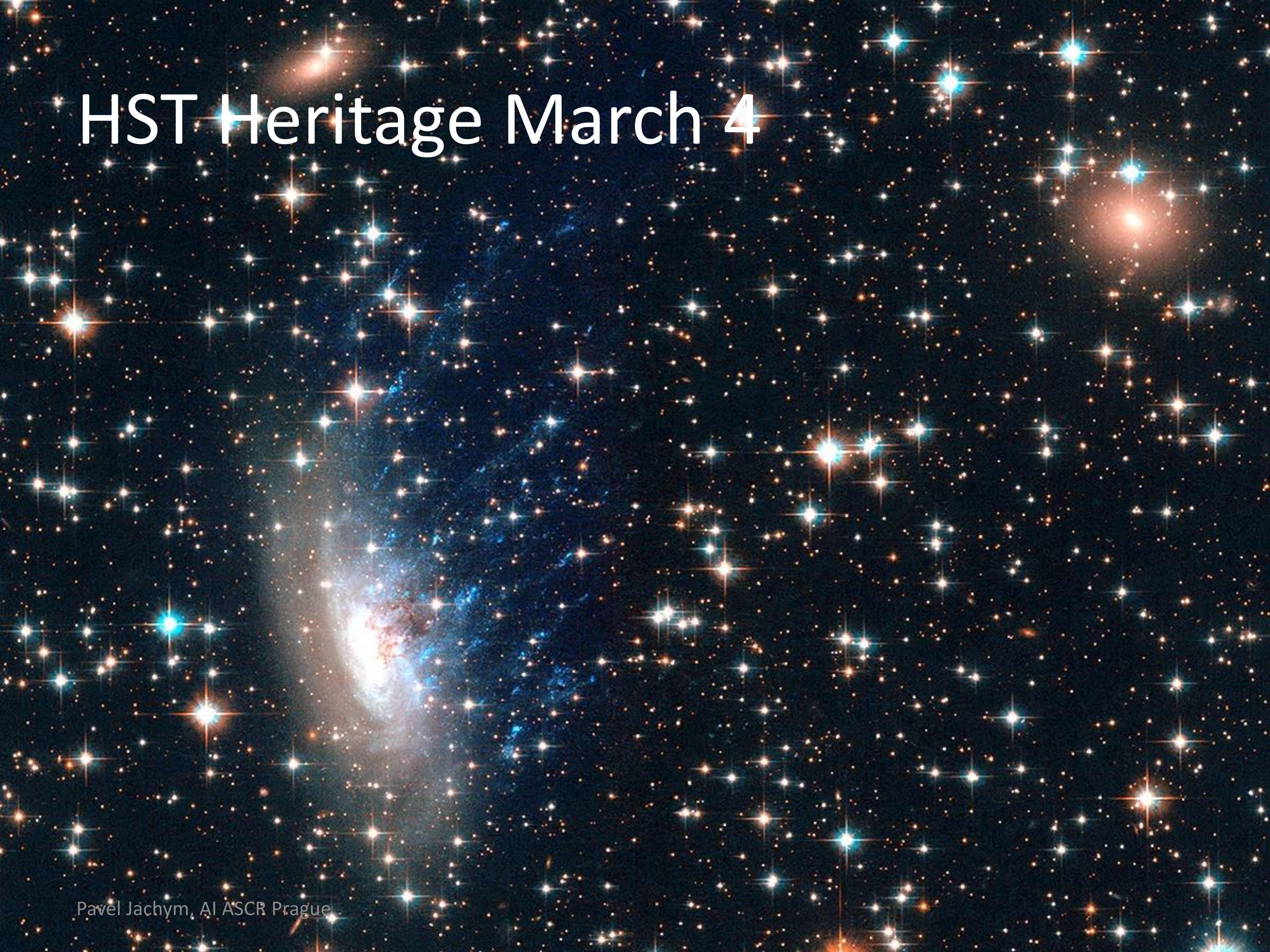


Chandra

APOD March 28

Pavel Jachym, AI ASCR Prague

HST Heritage March 4

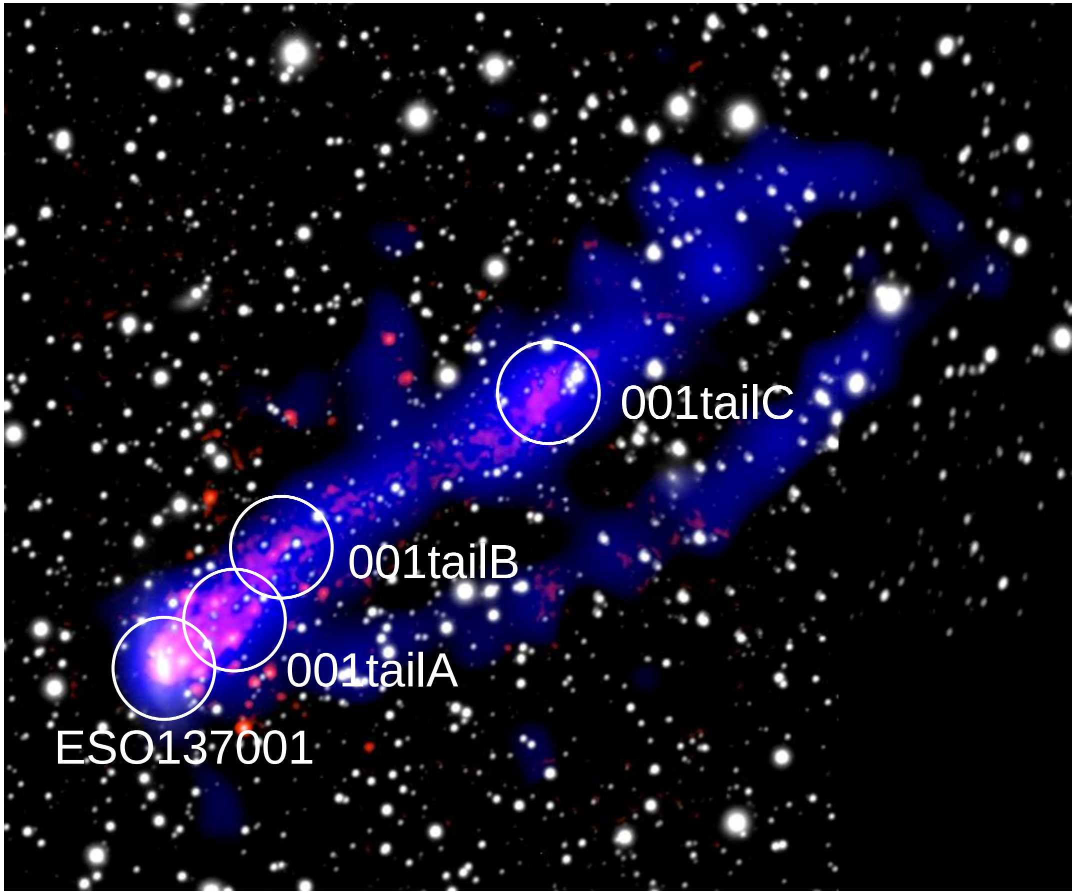


ESO 137-001

- SBc, $M_B = 14.31$,
- $M_* = 10^{10}\ M_\odot$
- low radial velocity with respect to Norma mean
- Chandra and XMM-Newton: 80 kpc, narrow, double-structure tail
- HI only to upper limit
- 40 kpc Ha tail
- <u>more than 30 giant discrete HII regions</u>

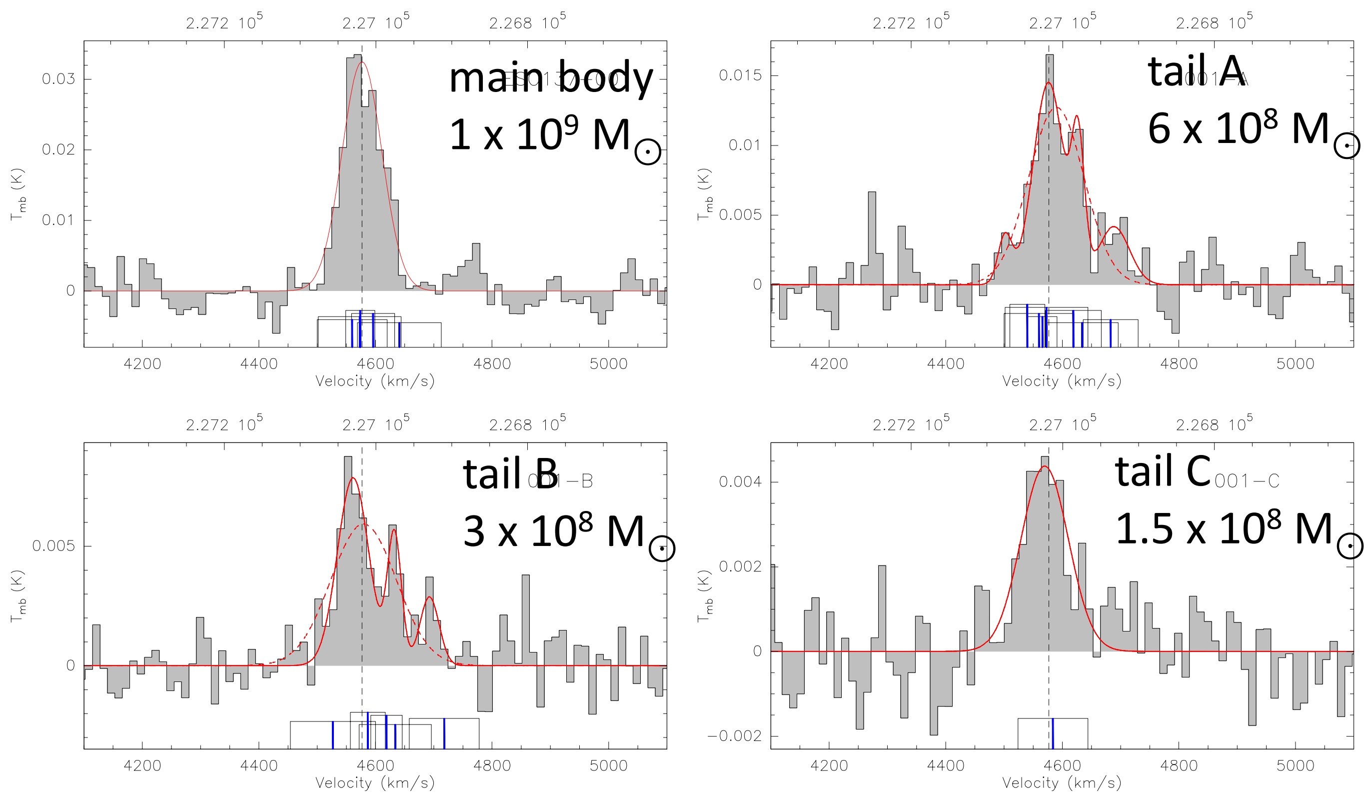
  $\Rightarrow$is there molecular gas?

  $\Rightarrow$APEX



ESO P88: APEX CO(2-1)

- Strong detection even in the most distant (40 kpc) region:



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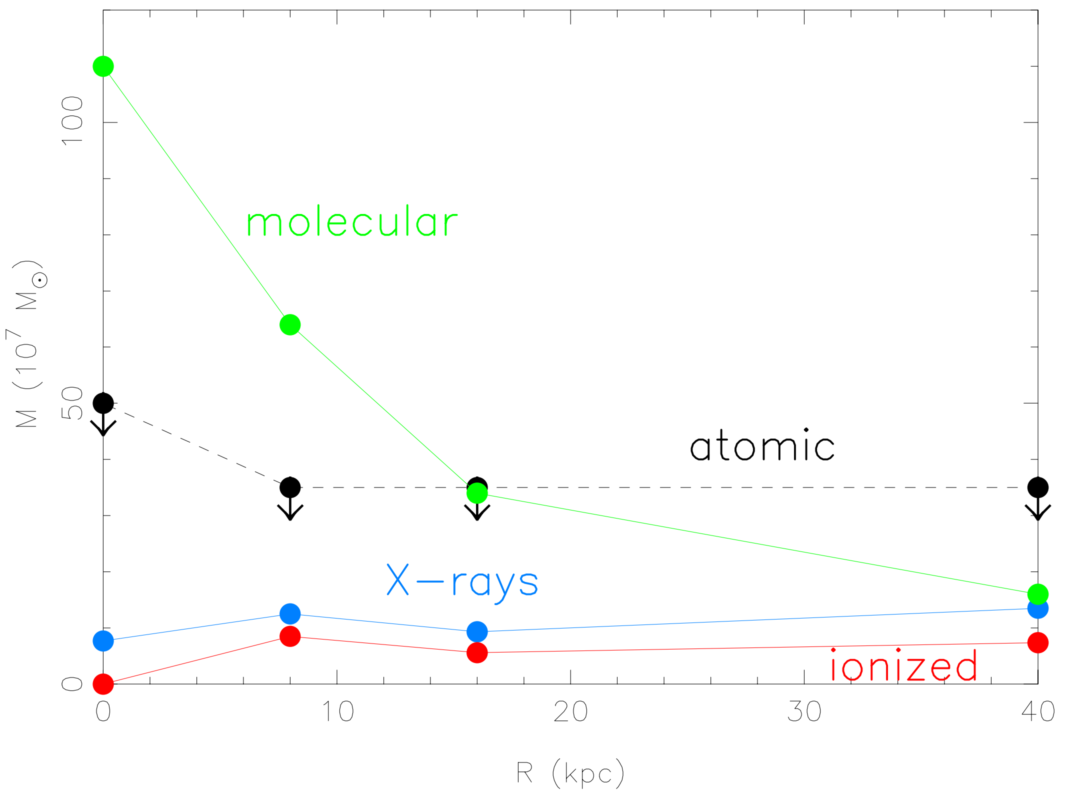
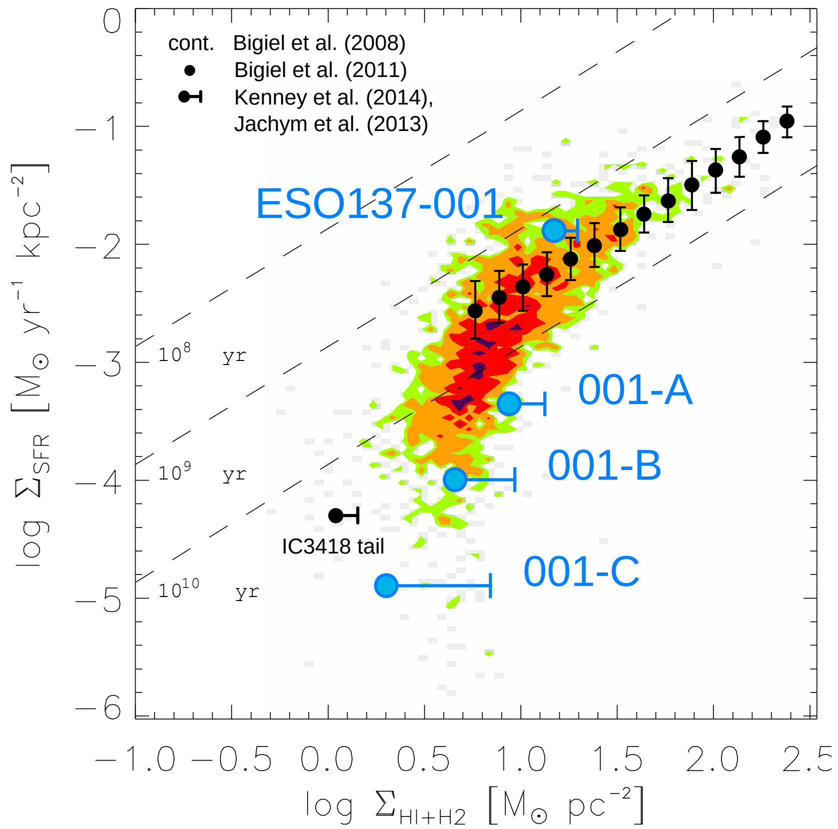
Stripped gas phases



- No HI detected to an upper limit of $2x10^9$ $M_\odot$
- Spitzer: about $4x10^7$ $M_\odot$ of warm (130 – 160 K) H_2 in the galaxy and inner tail
- Up to $5x10^8$ $f^{1/2}$ $M_\odot$ of ionized, Ha emitting diffuse gas
- ~$1x10^9$ $M_\odot$ of soft X-ray emitting gas
- Mass ratio of cold (H_2+HI) –to– hot (X-rays) spans from 1:1 to 3:1
- <u>There are large and similar amounts of cold and hot gas that together nearly account for the missing gas from the disk</u>

Star formation efficiency

- Main body (Ha + WISE band 4)-based SFR = 1 $M_\odot yr^{-1}$
- Tail (Ha-based SFRs): from 0.03 $M_\odot yr^{-1}$ (in 001-A) down to 0.001 $M_\odot yr^{-1}$ (in 001-C)
- Low and decreasing SFE along the tail
- mol. gas depletion times over 10^{10} yr
- 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)



APEX – Conclusions

Jachym et al. (2014, ApJ submitted): <u>for the first time, we reveal large amounts of cold molecular gas in a ram pres- sure stripped tail, out to a large, intracluster distance from the galaxy</u>

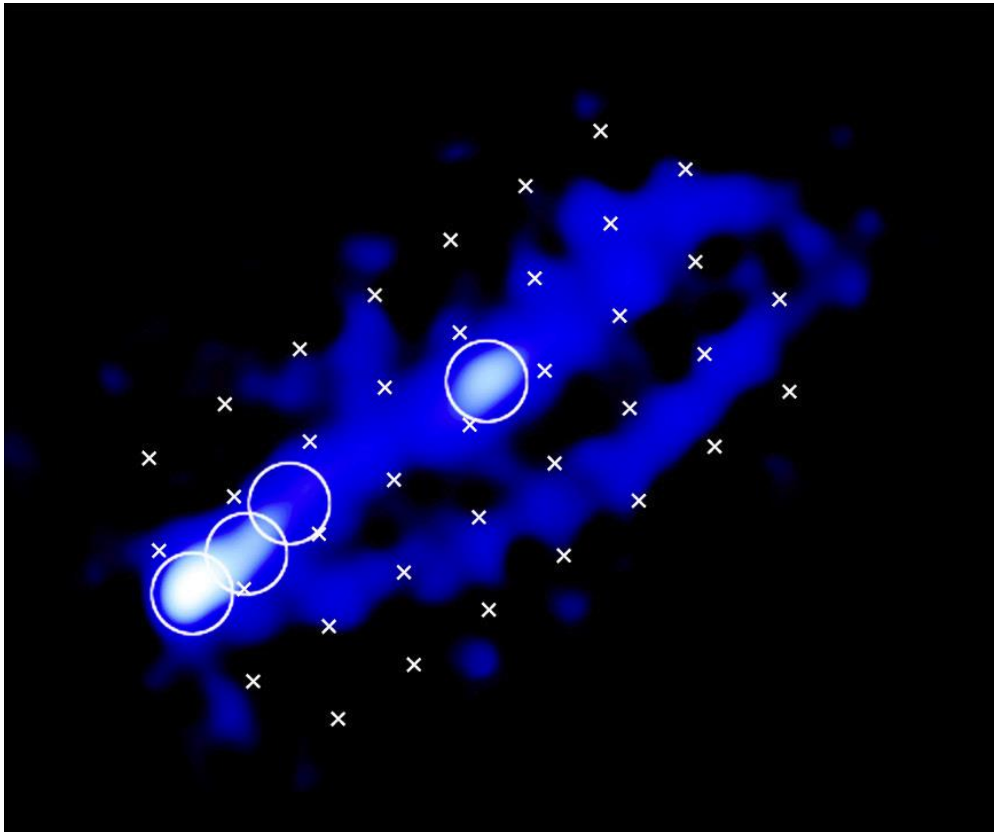
- More than 10^9 $M_\odot$ of molecular gas was detected in the three APEX 230 GHz apertures along the tail of ESO 137-001
- more than 10^8 $M_\odot$ of H_2 revealed in the 40 kpc distant intra-cluster region – a ram pressure dwarf galaxy (RPDG) may be forming in this location?
- H_2, Hα, and X-ray emission can be at observable levels in a single ram pressure stripped tail. The amounts of cold and hot gas in the tail are large and similar ($\sim 10^9$ $M_\odot$) and together nearly account for the missing original gas in the disk.
- The star formation efficiency was found to be very low in the tail environment ($\tau_{dep,H2} > 10^{10}$ yr), while it is consistent with other spiral galaxies in the main body of ESO 137- 001.

<u>ESO P92</u>: new APEX observations of ESO137-001 (Jachym et al., in prep.)

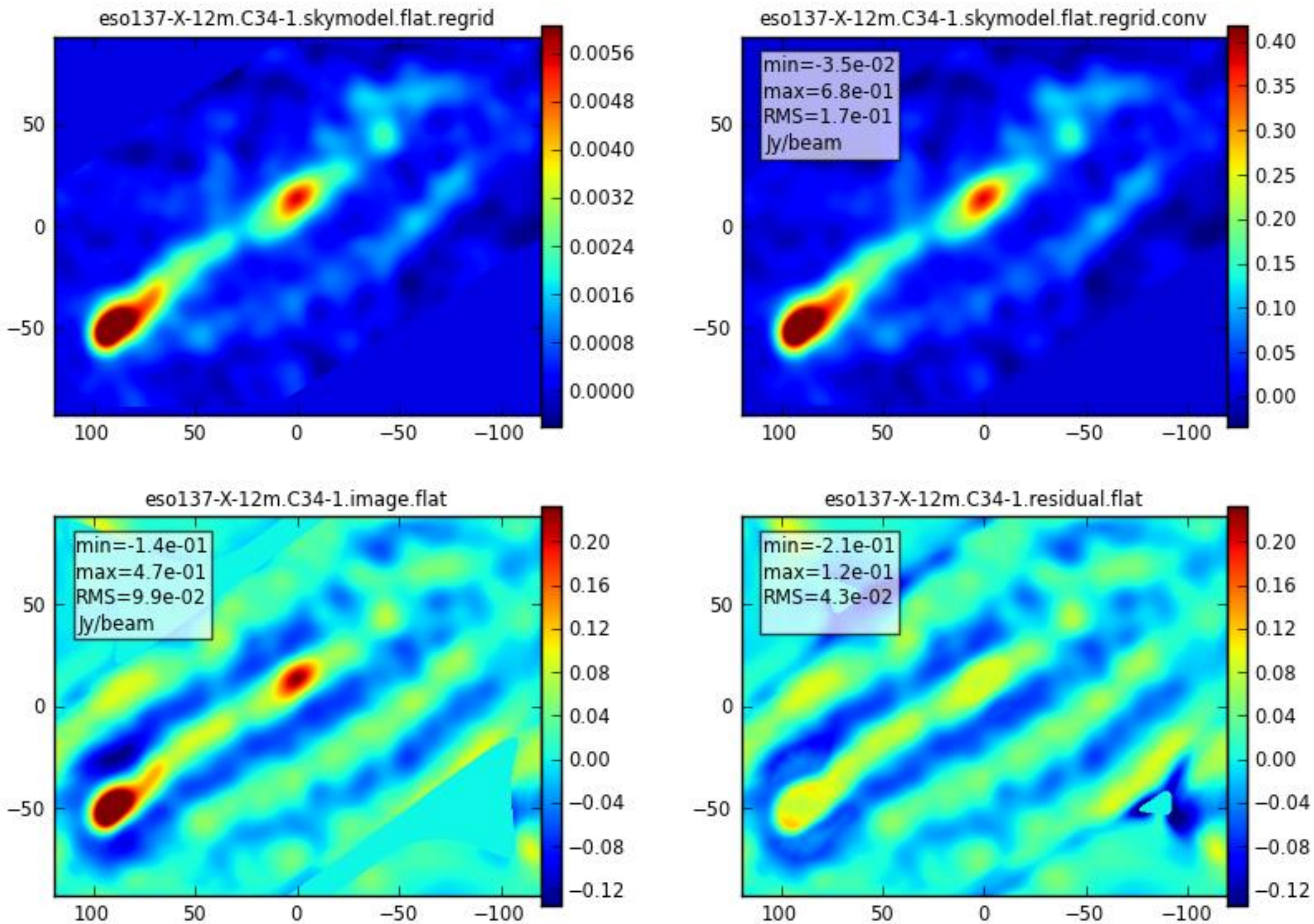
  – CO(3-2) and ^{13}CO(2-1) to learn about physical conditions in the tail

Prospects for ALMA:
Cycle 2 proposal submitted for ESO137-001

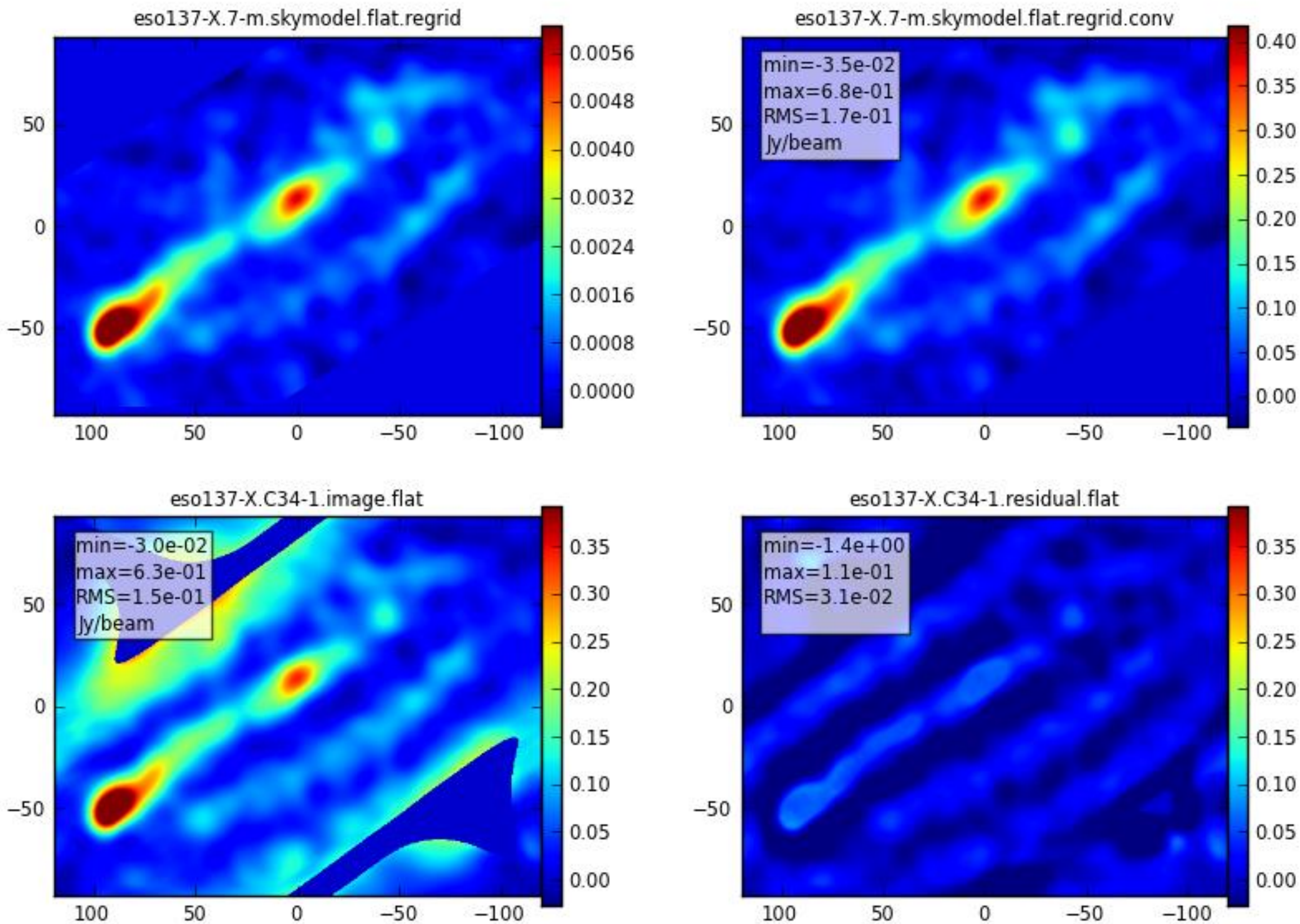
- Mosaic of 37 CO(1-0) fields covering the whole galaxy
- 3.3'' angular resolution (compact config. C34-1)
- + compact array (ACA)
- ~5 hr total (main array)
- Science goals:
  1. Distribution of molecular gas – global trends and small-scale structures
  2. Intra-cluster star formation
  3. Kinematics and intra-cluster turbulence
- great potential for publicity



CASA simulations – C34-1



CASA simulations – C34-1 + ACA



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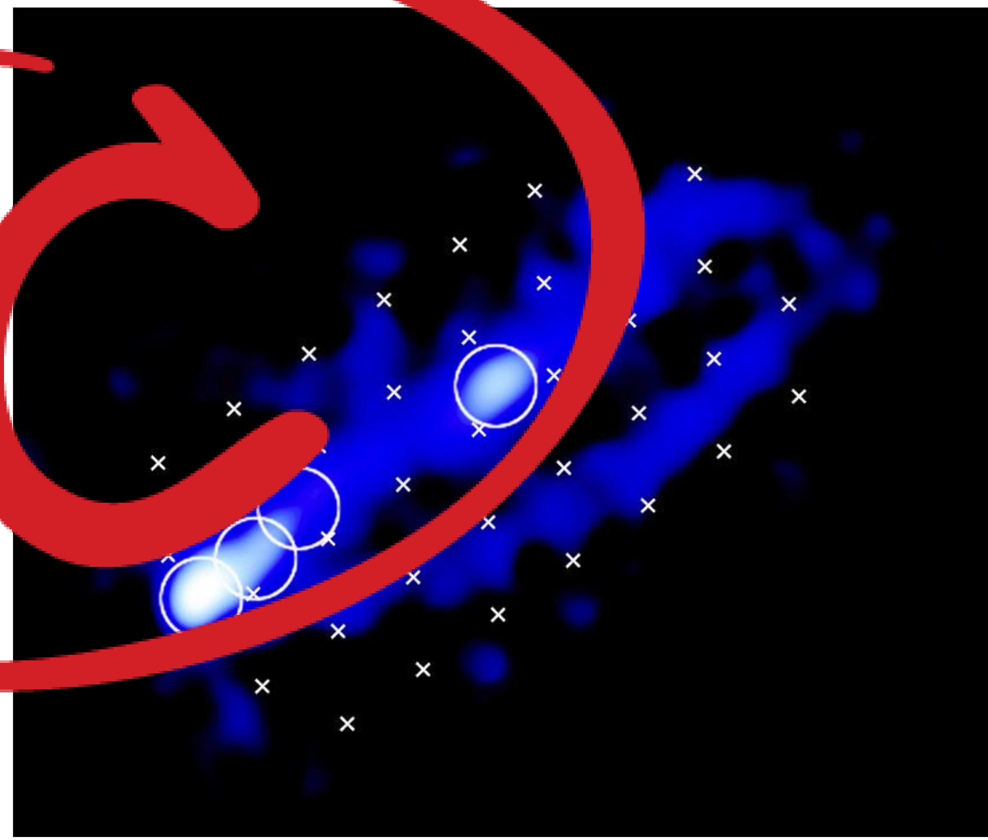

Prospects for ALMA?

- Dear Dr. Jachym,
- The ALMA Early Science Cycle 2 Proposal Review Process has now been completed.
- Following its scientific assessment by the ALMA Proposal Review Committee (see below), your ALMA proposal 2013.1.0xxxx.S was ranked in the 20-40% band of all submitted proposals
- As a result of its ranking, and taking into account the distribution of the observing time between the ALMA regions, your proposal has been assigned priority grade C. Accordingly, it is in the group of filler projects, which will be observed only if the conditions do not allow any higher priority project to be executed.
- At the bottom of this email, you will find a "consensus report" presenting comments on your proposal from the assessors. These comments are intended to provide you with constructive feedback. We hope that they are helpful. Should you have queries or comments, please submit them to the ALMA Helpdesk (http://help.almascience.org).

Prospects for ALMA?

- PROPOSAL REVIEW PROCESS & CYCLE 1 OBSERVATIONS

- The proposals have been assessed by seventy-eight independent scientists from all over the world through a unified process coordinated by the Joint ALMA Observatory.
- For more details about the proposal review process, and the implementation of its outcome, please refer to Section 7 of the Proposer's Guide.
- The estimated amount of 12-m Array time requested in the submitted proposals exceeds the amount of time available for science operations in Cycle 2 by a factor greater than four.
- It follows that many very good projects will not be observed.
- In addition, Cycle 2 observations will be conducted on a best effort basis, with priority given to the completion of the full ALMA capabilities.

- You will be contacted by staff from your ALMA Regional Center to discuss the preparation of scheduling blocks for your project and any other action that may be required from you. The timing of that contact will be determined by ALMA operational progress and needs. You need take further steps only when and if you are explicitly requested to do so.

HST – Virgo RPS galaxies