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The Evolution of Spiral Galaxies in a Cluster Environment

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On the menu for today…

Virgo Cluster: a lab for studying galaxy evolution

Interaction diagnostics: tools & methods

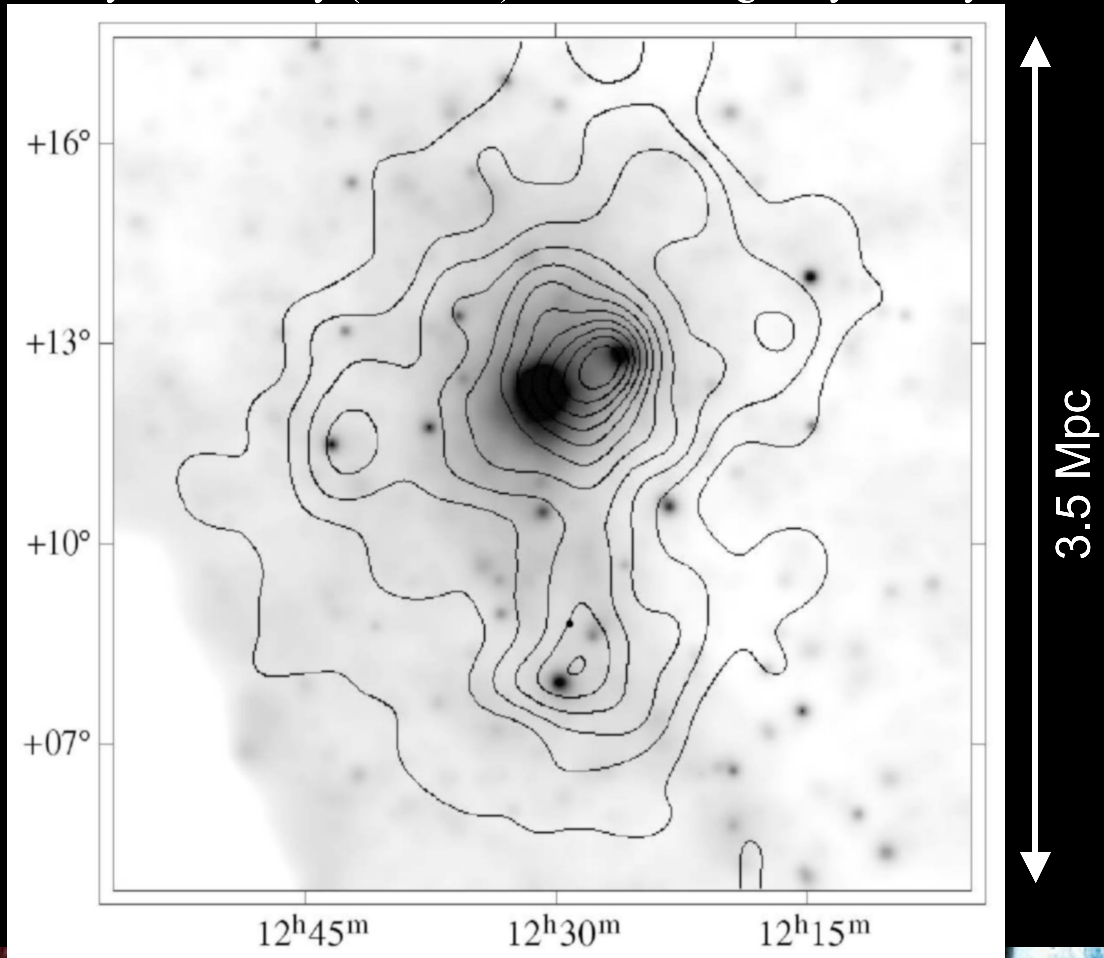
Our sample of Virgo galaxies: radio & X-rays

Summary & Outlook

Introduction: The Virgo Cluster

- Distance: ~17 Mpc
- 1' = 5 kpc
- Velocity dispersion: ~700 km/s
- Dynamically young cluster
- Mass: ~10^{14} M_{solar} at R=1 Mpc
- M_{gas}/M_{tot} ~ 14%
- M_{gal}/M_{tot} ~ 4%
- M/L ~ 500

Greyscale: X-ray (ROSAT) Contours: galaxy density



(Schindler et al. 1999)

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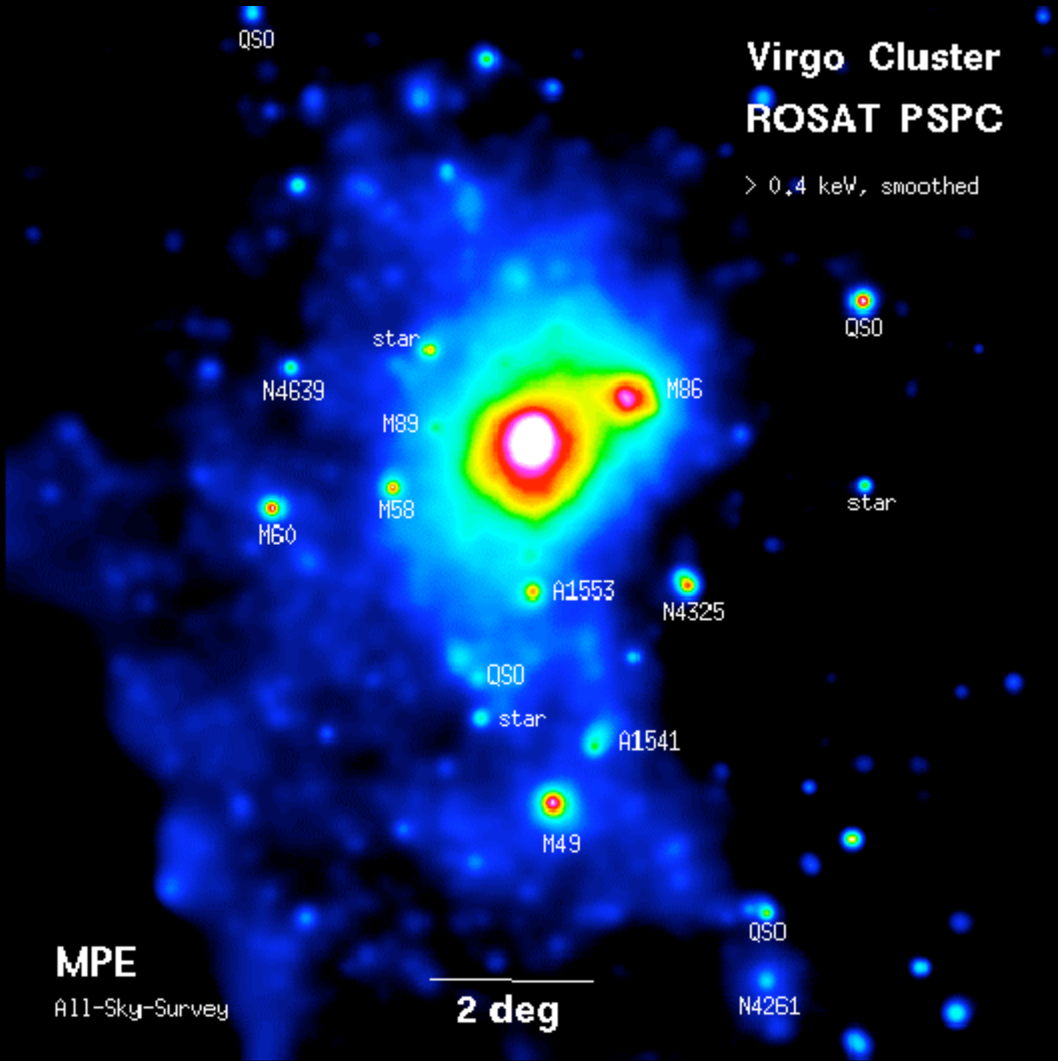
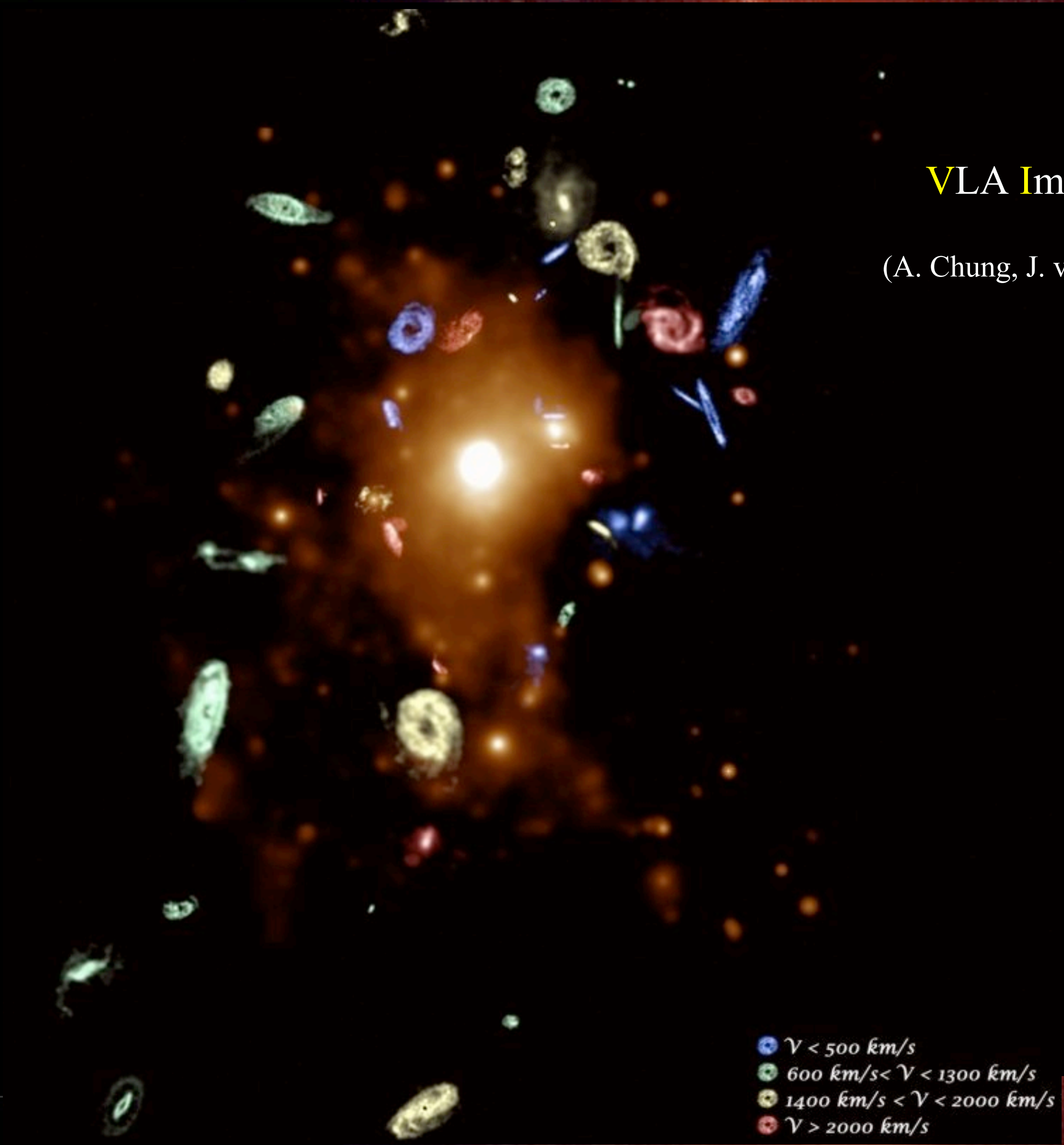


(Böhringer et al. 1994)

- Soft X-ray emission traces hot gas → extended emission helps to examine past or present perturbations of the hot ICM, via spatial and spectral analysis



VIVA

VLA Imaging of Virgo in Atomic Gas

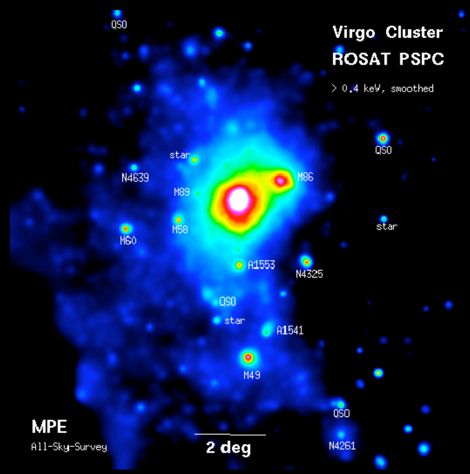
(A. Chung, J. van Gorkom, J. Kenney, H. Crowl, B. Vollmer)

Interaction of a spiral galaxy with its environment

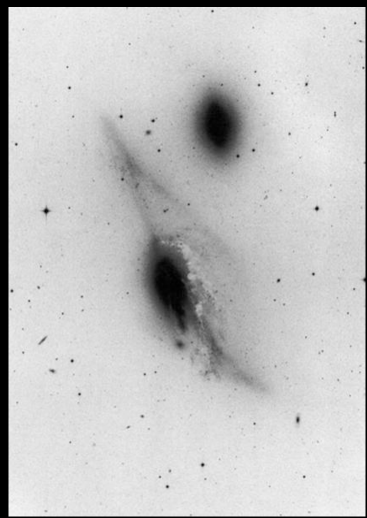
- Gravitational interaction
  galaxy - cluster

- Gravitational interaction
  galaxy - galaxy

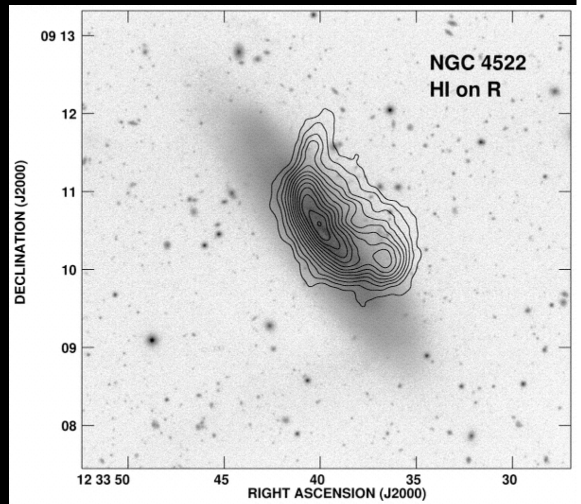
- Ram pressure
  galaxy ISM – intracluster medium (ICM)



(Böhringer et al. 1994)



(Kenney et al. 1995)



(Kenney et al. 2004)

Interaction diagnostics

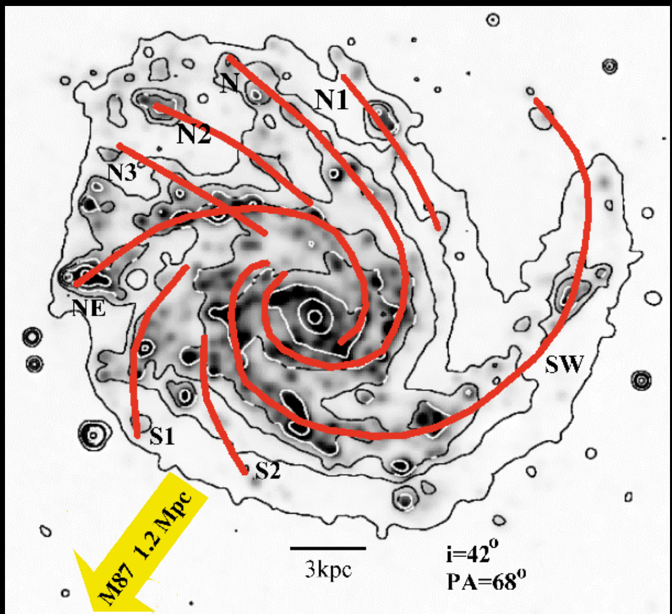
- Which interaction is responsible for the observed distortions/perturbations?
- Determination of the interaction parameters
- Determination of evolutionary path of a galaxy in a cluster
- Means: HI maps and velocity fields, dynamical simulations, polarized radio continuum emission, soft diffuse X-ray emission

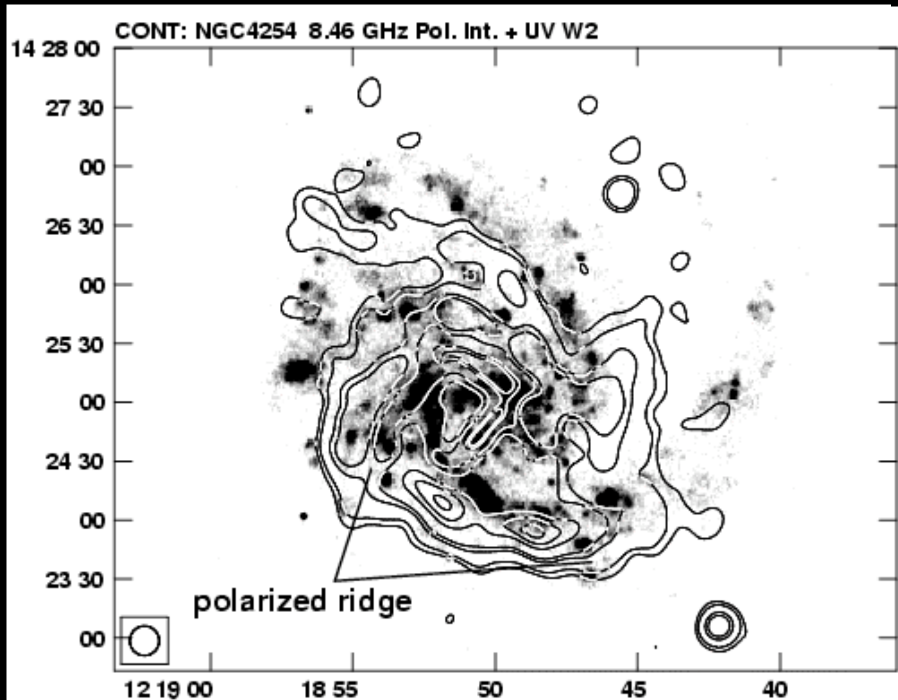
Polarized radio continuum emission – a diagnostic tool for interactions

- Polarized radio continuum emission is proportional to the density of relativistic electrons and the strength of the large-scale regular magnetic field: $PI \sim n_e B^{2-4}$
- Polarized radio continuum emission is sensitive to shear and compression motions

NGC 4254
(Chyzy et al. 2007)

Grey: Hα
Contour: NIR





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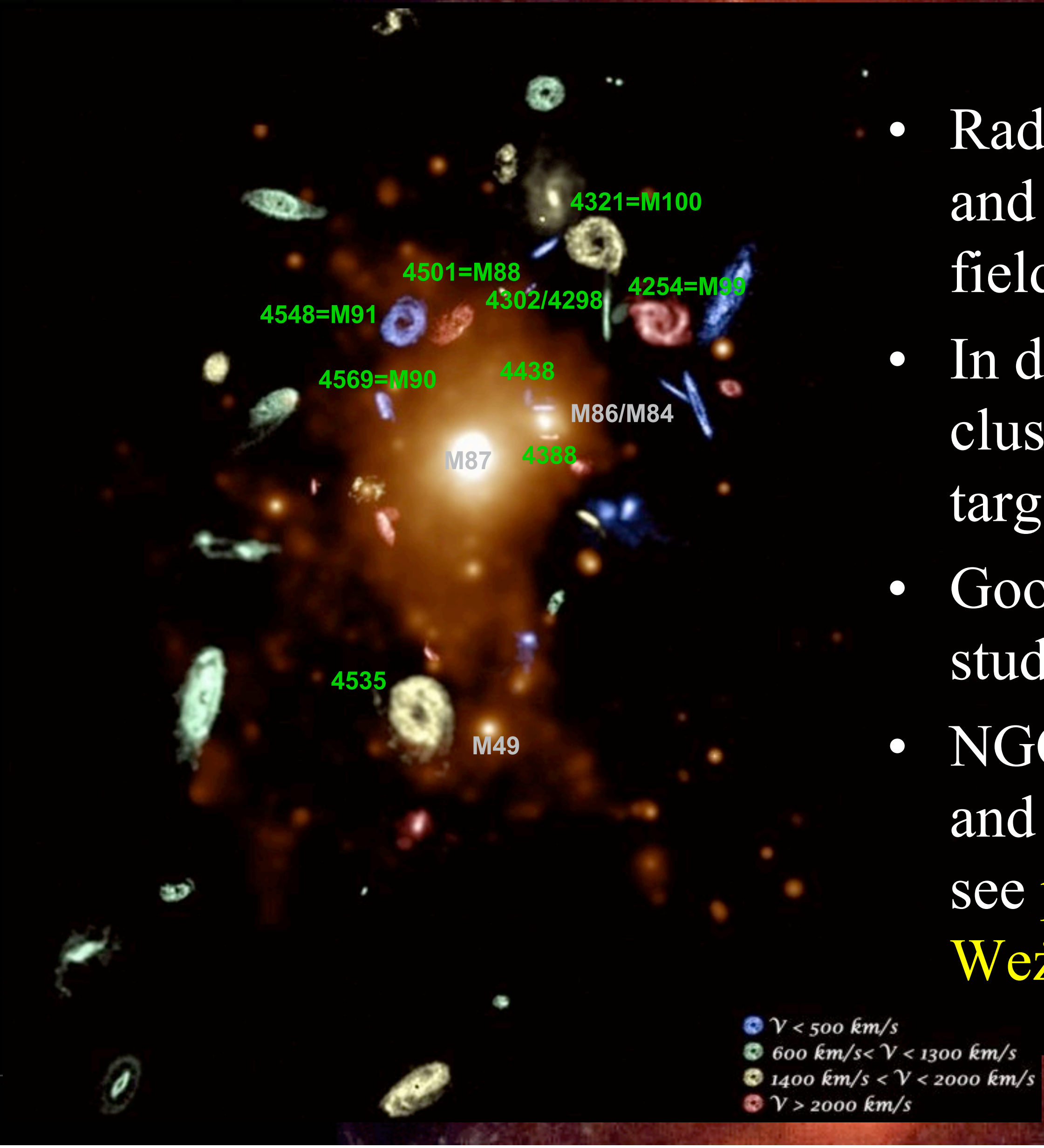
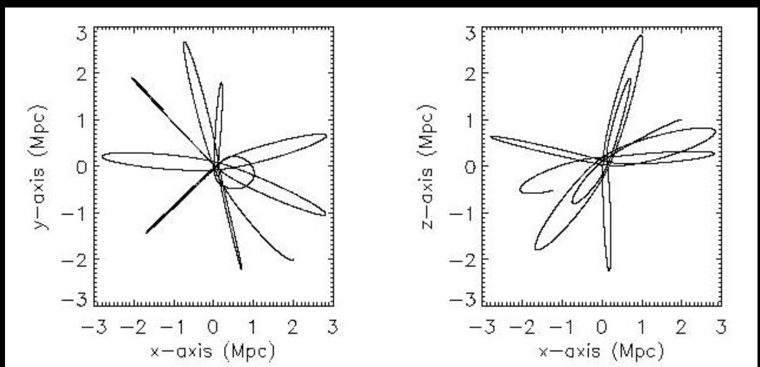


- Radio continuum survey and study of magnetic fields (Ph.D Weżgowiec)
- In different parts of the cluster, see labelled targets
- Good candidates for X-ray studies (XMM-Newton)
- NGC 4254, NGC 4388 and NGC 4438: for details see poster P6.10 by Weżgowiec et al.

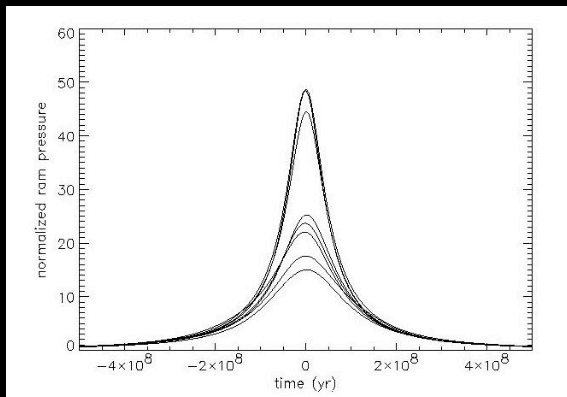
Numerical simulations

- ISM-ICM interaction + gravitational interaction
- turbulent/viscous stripping (Nulsen 1982; timescale ~ 1Gyr)

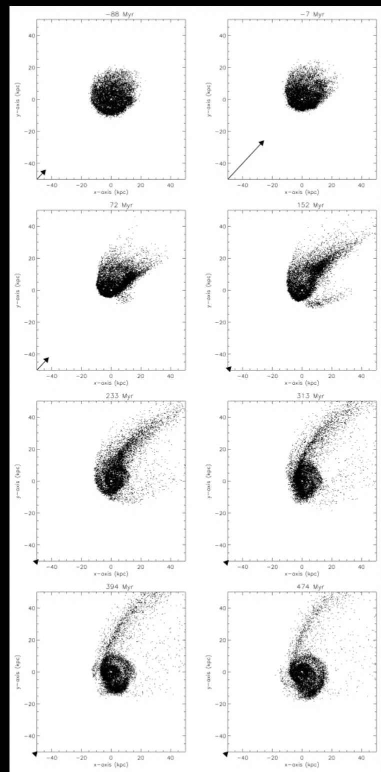
  ⟷ ram pressure stripping (momentum transfer; timescale ~10Myr)
- constant ⟷ time dependent ram pressure
- Models: Eulerian hydro (2D, 3D),
  - Smoothed Particle Hydrodynamics (SPH),
  - Sticky particles (Vollmer et al. 2001, Vollmer 2003)
  - with time dependent ram pressure (Vollmer 2009)



galaxy orbits

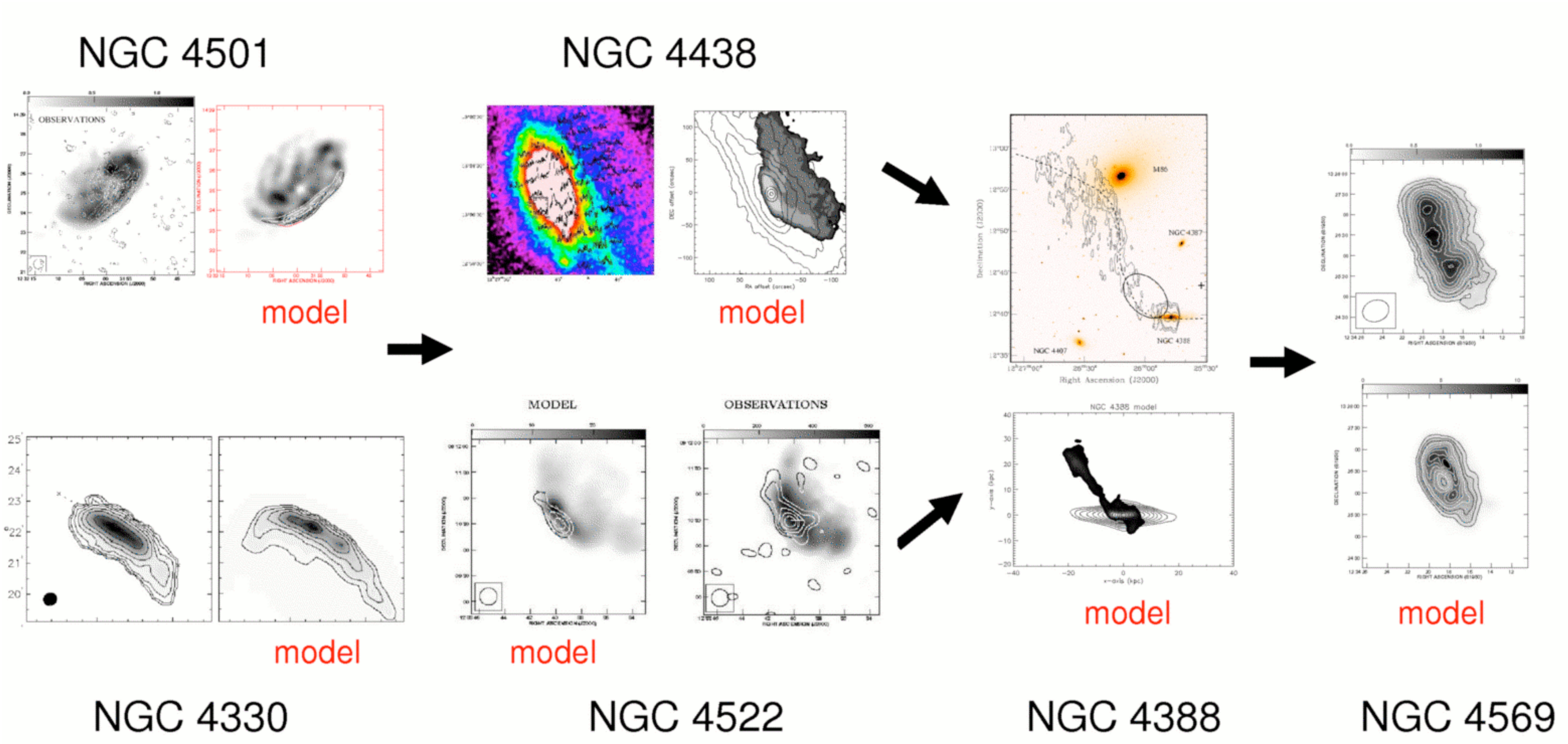


temporal ram pressure profile (ρv^2)



Model-based time sequence for ram pressure stripping in the Virgo cluster

(Vollmer 2009)



pre-peak **near peak** **~150 Myr after peak** **~300 Myr after peak**

Soft diffuse X-ray emission – a new diagnostic tool for interactions

- Diffuse X-ray emission traces distribution of very hot gas from the ISM and ICM: flux ~ $n_e \, n_H$
- Diffuse X-ray emission is also sensitive to shear and compression motions
- Hot gas might be expelled, stripped or trailing
- In addition, spectral analysis allows us to derive temperatures, i.e. trace outflow, and study the interface and mixing at the ISM/ICM border

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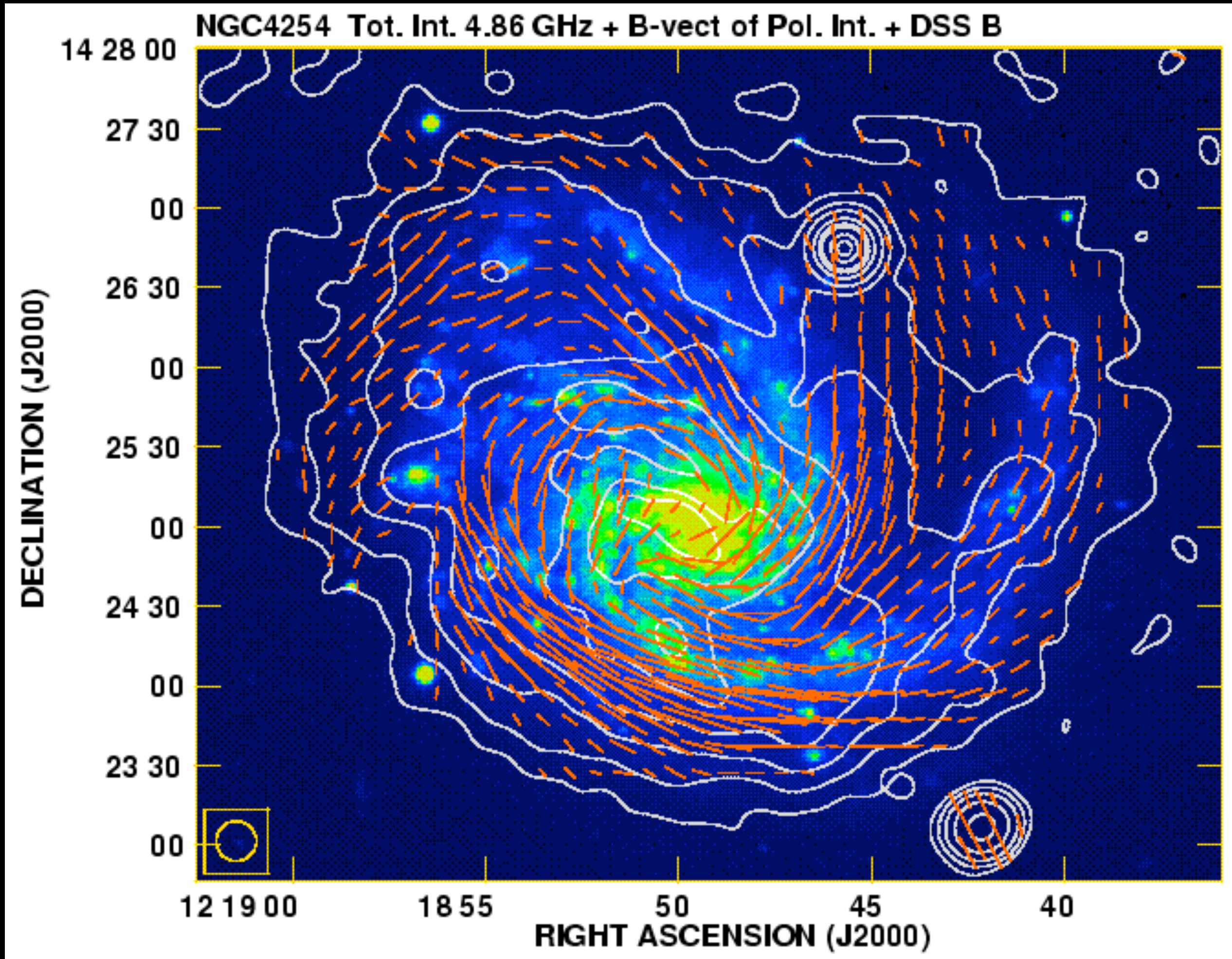

- **NGC 4254:** Sc-type, outside X-ray cloud, normal star-formation, no signs of gas deficiency
- Perturbed (HI tail to the NW, Phookun et al. 1993)
- Radio data discussed in Soida et al. (1996) and Chyzy (2008)
- What is the origin of the polarized ridge?
- Tidal or ram pressure?

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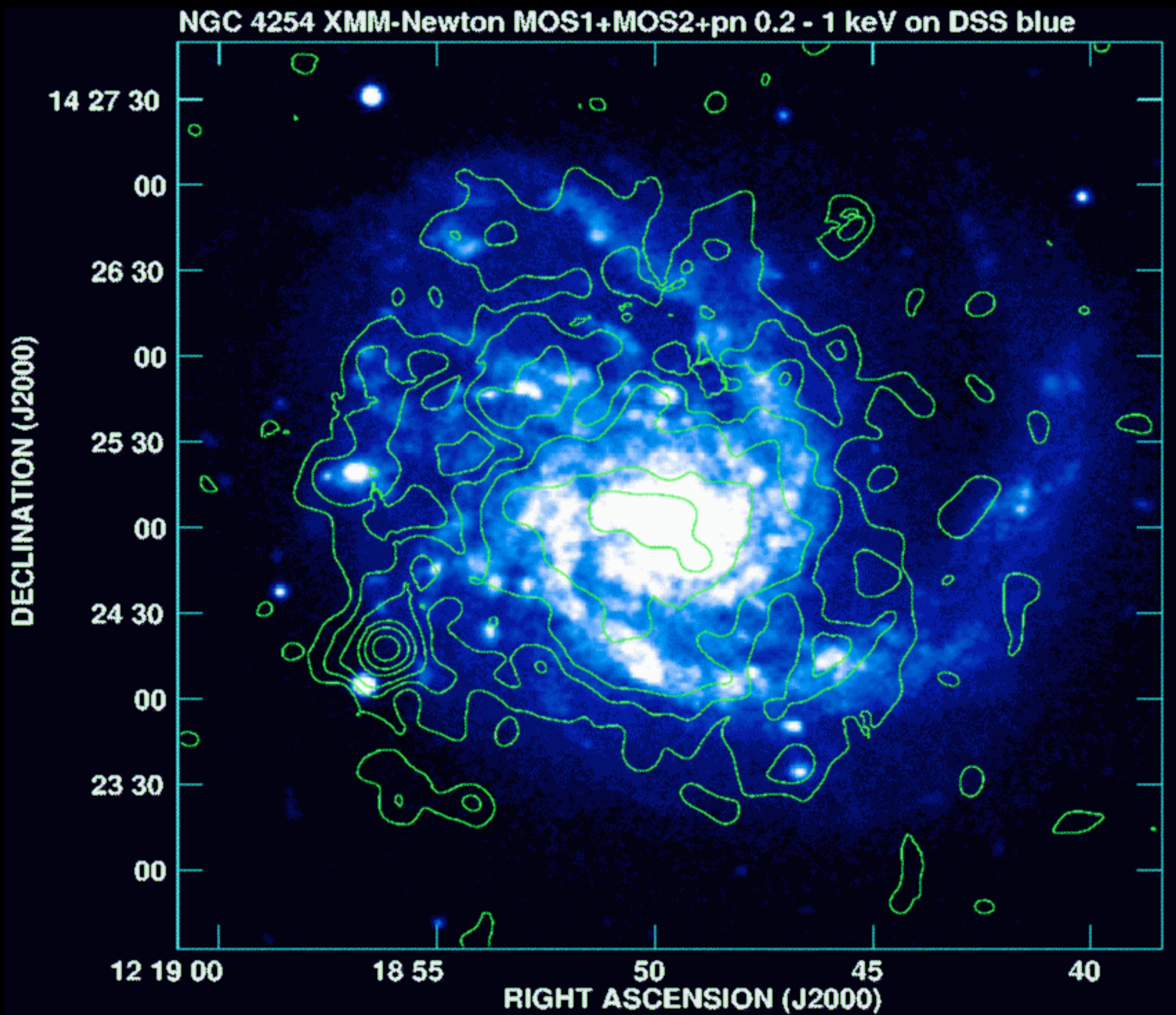

- Extended X-ray emission
- Spectral analysis (details in P6.10): polarized ridge region has similar temperature!

→ no shock heating, most likely tidal interaction

Vollmer et al. 2005: close and rapid encounter ~280 Myr ago, followed by (ongoing) week ram pressure stripping

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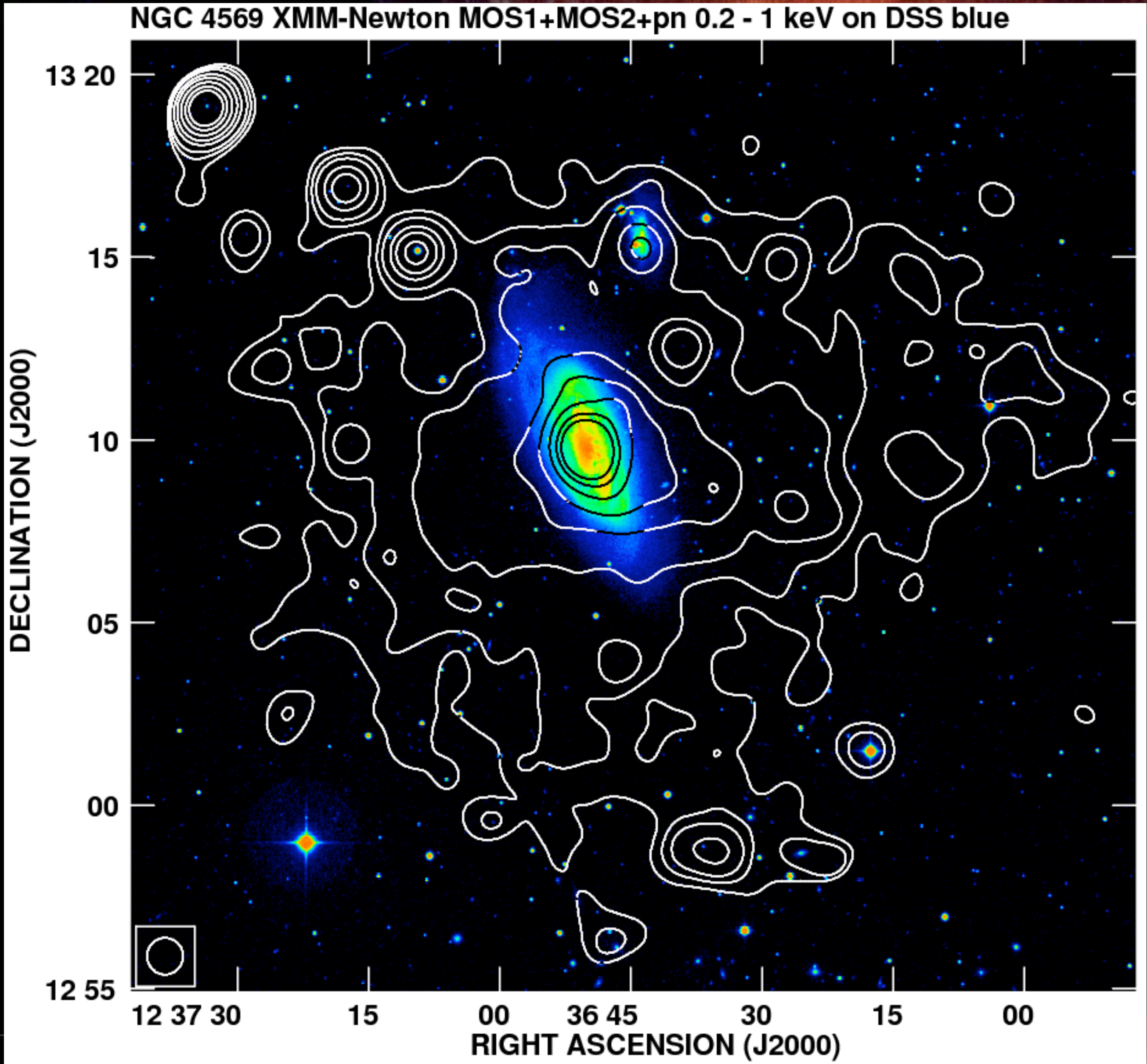

- **NGC 4569** (M90): SABa galaxy, quite close to cluster centre
- giant radio lobes in an otherwise normal spiral (Chyży et al. 2006 & in prep.)
- Extended X-ray emission suggestive for hot gas outflows (Weżgowiec 2009)
- Probably nuclear starburst in the past
- Smoothed version of the X-ray map reveals giant hot gas halo, including IC 3583

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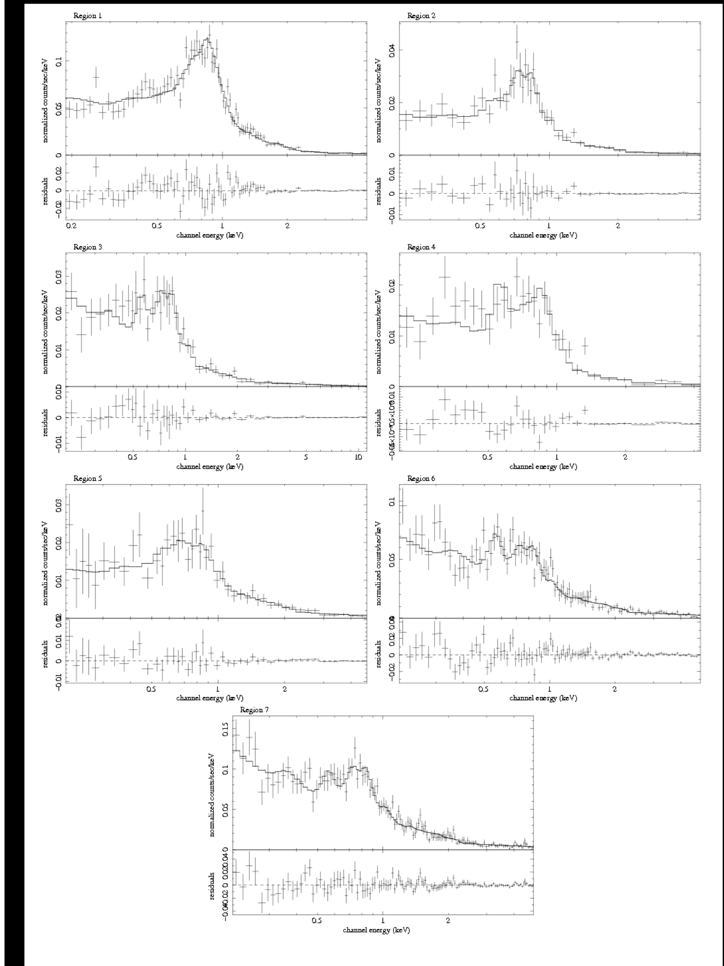
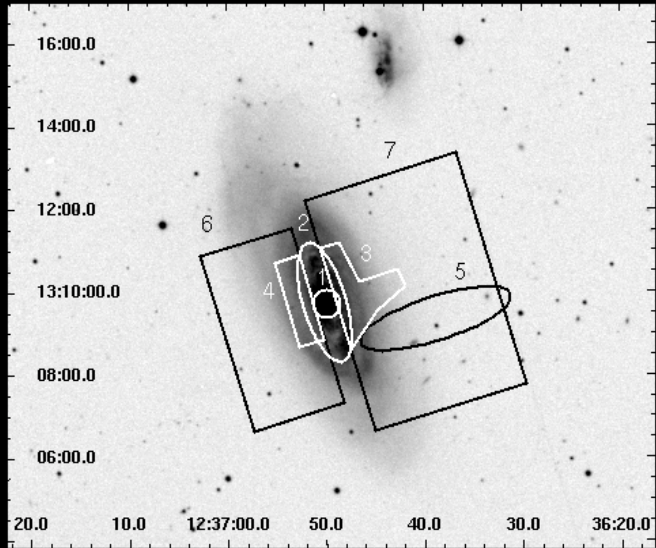
NGC 4569: spectral fits EPIC-pn (Weżgowiec, PhD)



Model fits to the regions of NGC 4569.

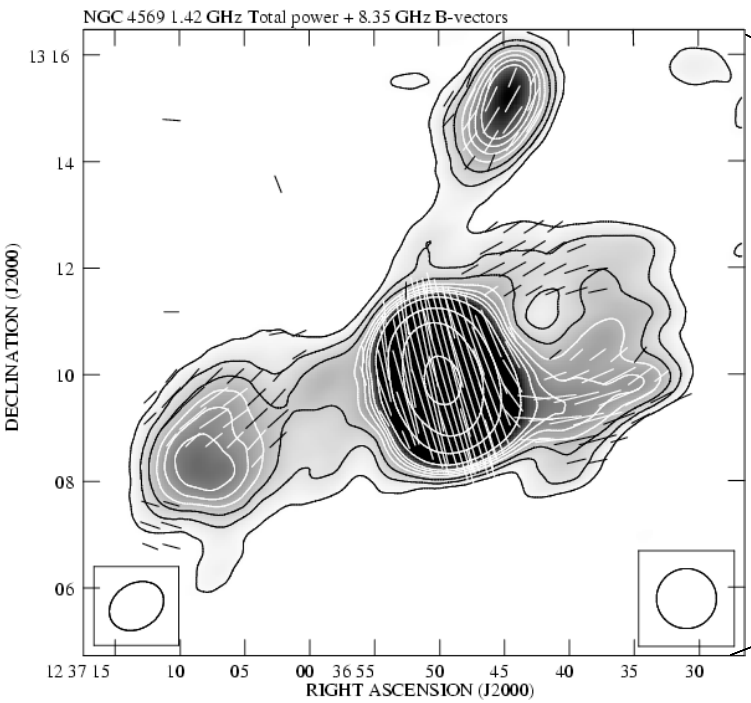


Model fit parameters of selected regions in NGC 4569.

Reg. no.	kT_1 [keV]	kT_2 [keV]	Photon Index
1	0.21 ± 0.05	0.64 ± 0.03	$1.71^{+0.07}_{-0.09}$
2	$0.14^{+0.10}_{-0.04}$	0.46 ± 0.08	$1.26^{+0.25}_{-0.24}$
3	0.12 ± 0.01	0.47 ± 0.08	$1.11^{+0.17}_{-0.16}$
4	$0.15^{+0.06}_{-0.02}$	$0.61^{+0.07}_{-0.15}$	0.77 ± 0.24
5	$0.23^{+0.09}_{-0.08}$	$0.62^{+0.24}_{-0.17}$	$1.33^{+0.20}_{-0.21}$
6	0.12 ± 0.01	$0.48^{+0.07}_{-0.13}$	1.07 ± 0.11
7	0.10 ± 0.01	$0.47^{+0.06}_{-0.08}$	$1.16^{+0.12}_{-0.10}$

- two mekals plus powerlaw
- Similar parameters in all outflow/halo/lobe regions
- Temp. of outflowing gas similar to disk
- But: polarized spur is region with hottest X-ray emission
- Ongoing compression or due to infalling gas (that previously was expelled)?

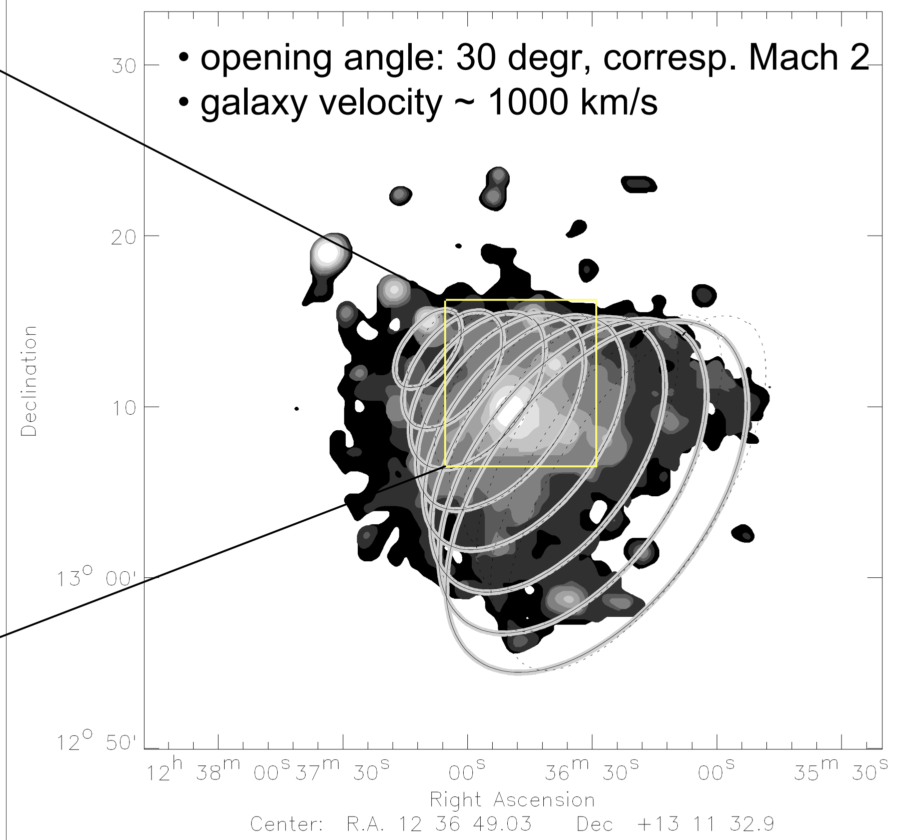
NGC 4569 – a galactic wind in a ram pressure wind?



(Chyzy et al. 2006)

Mach cone (based on Vollmer et al. 2005):

- opening angle: 30 degr, corresp. Mach 2
- galaxy velocity ~ 1000 km/s



(Wezgowiec et al., in prep.)

Summary & Outlook

- Examining compression regions visible in radio polarized intensity also in X-rays can help to distinguish between ram pressure and tidal scenarios
- Radio outflows seem to be accompanied (to some extent) by X-ray ones
- X-ray extended emission is extremely useful in determining evolutionary path of a cluster galaxy
- Future Aims:
  - Obtain X-ray observations of as many as possible of our target galaxies; search for spatial & spectral signatures of interactions in the hot gas
  - Compare the results with radio polarimetry data for better understanding of the past and the future of cluster galaxies
  - Investigate if halo structures agree with model predictions (orbit, ram pressure profile, Mach cones)