X-raying the Mach cones of Virgo Cluster spiral galaxies

Matthias Ehle
XMM-Newton Science Operations Centre,
European Space Astronomy Centre, ESA, Madrid

M. Weżgowiec, B. Vollmer, R.-J. Dettmar, D. J. Bomans,
K. T. Chyży, M. Urbanik and M. Soida

X-raying the Mach cones of Virgo Cluster spiral galaxies

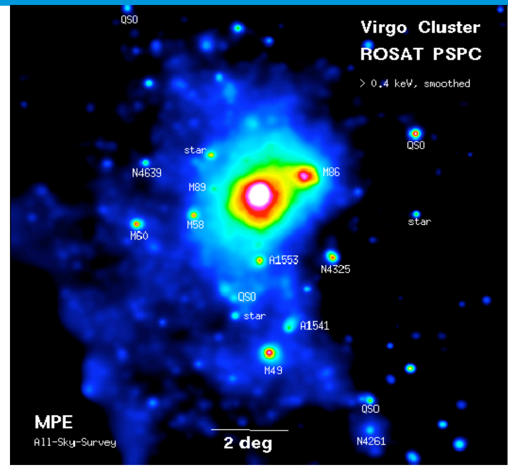
Menu of the Day:

- The Frame Work: Galaxy Evolution by Interactions
- Our Laboratory: Galaxies in the Virgo Cluster
- Numerical Models
- Expectations: Mach cones
- Method, targets and observational results: 3 spiral galaxies
- Conclusions

The Frame Work: Galaxy Evolution by Interactions

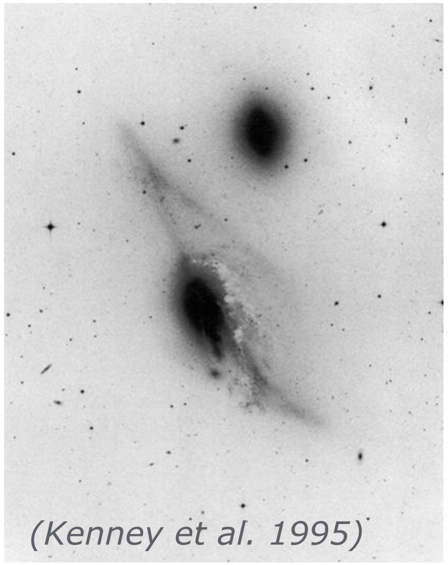
Interaction of a spiral galaxy with its environment

- Gravitational interaction
  galaxy - cluster



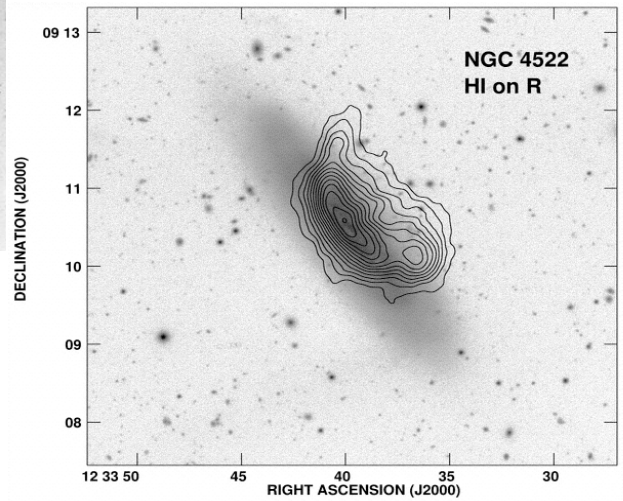
(Böhringer et al. 1994)

- Gravitational interaction
  galaxy - galaxy



(Kenney et al. 1995)

- Ram pressure
  galaxy ISM – intracluster medium (ICM)



(Kenney et al. 2004)

The Frame Work: Galaxy Evolution by Interactions

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

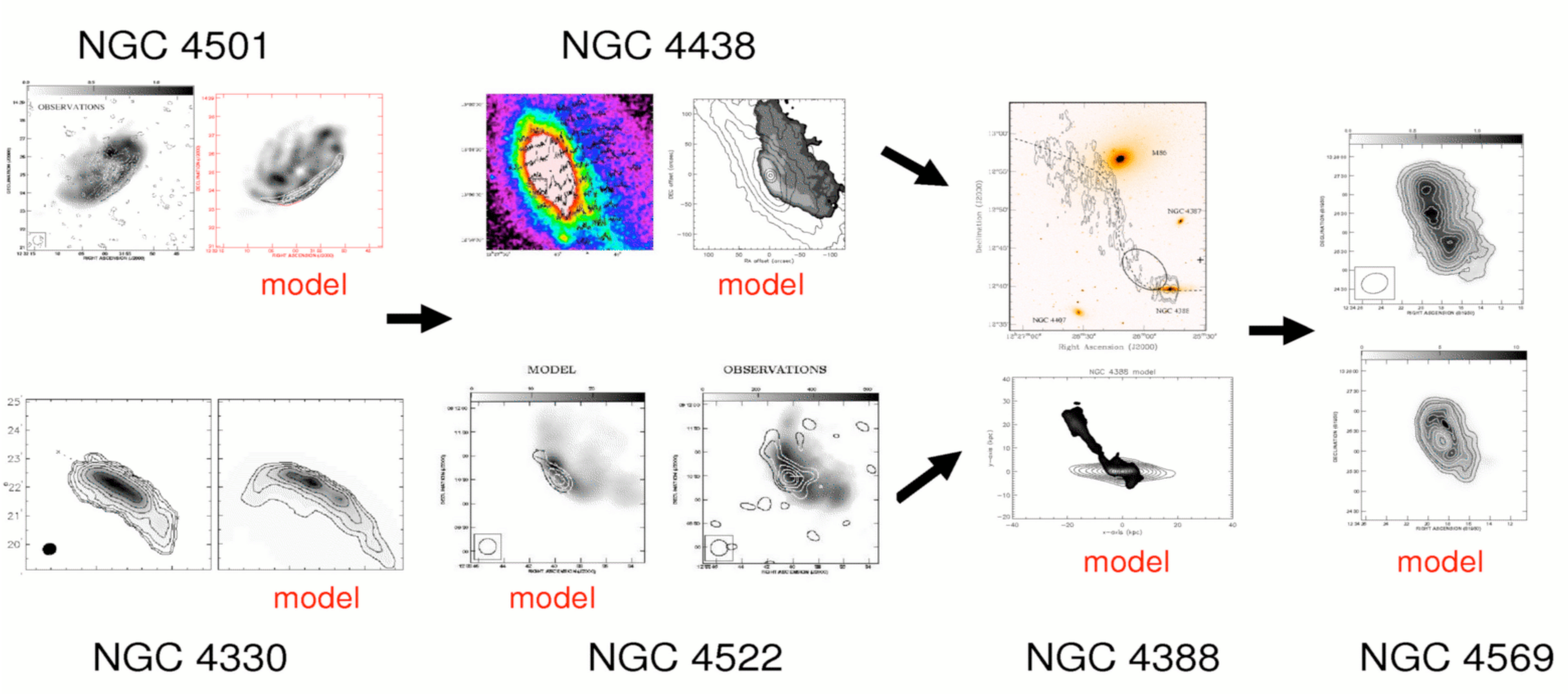
Our Laboratory: Galaxies in the Virgo Cluster

- Radially truncated gas disks *(Cayatte et al. 1990, Chang et al. 2009)*
- Long HI tails *(Chung et al. 2007)*
- Asymmetric polarized radio ridges marking gas compressions and shear motions *(Weżgowiec et al. 2007, Vollmer et al. 2007)*

Numerical Models

Model-based time sequence for ram pressure stripping in the Virgo cluster *(Vollmer 2009)*

- Snapshots of 3D models including ram pressure compared to observed HI gas distribution & velocity fields
- 3D velocity vectors and time steps are matched with observed projected position and radial velocity of the galaxy



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

Observing Interactions: The X-ray Method

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

- Diffuse X-ray emission traces distribution of very hot gas from the ISM and ICM:
  flux ~ $n_e\ n_H$
- In addition, spectral analysis allows us to derive temperatures, i.e. trace outflow, and study the interface and mixing at the ISM/ICM border

Expectations:

- Hot gas might be expelled, stripped or trailing
- Ram pressure stripping heats gas to X-ray temperatures (shocks, heat conduction, mixing of stripped ISM with intracluster medium) *(Stevens et al. 1999, Roediger et al. 2006)*
- Supersonic velocities of cluster galaxies cause **bow shocks with associated Mach cones**

Method, targets and observational results

Search for Hot Gas in Mach cones around Virgo Cluster spiral galaxies:

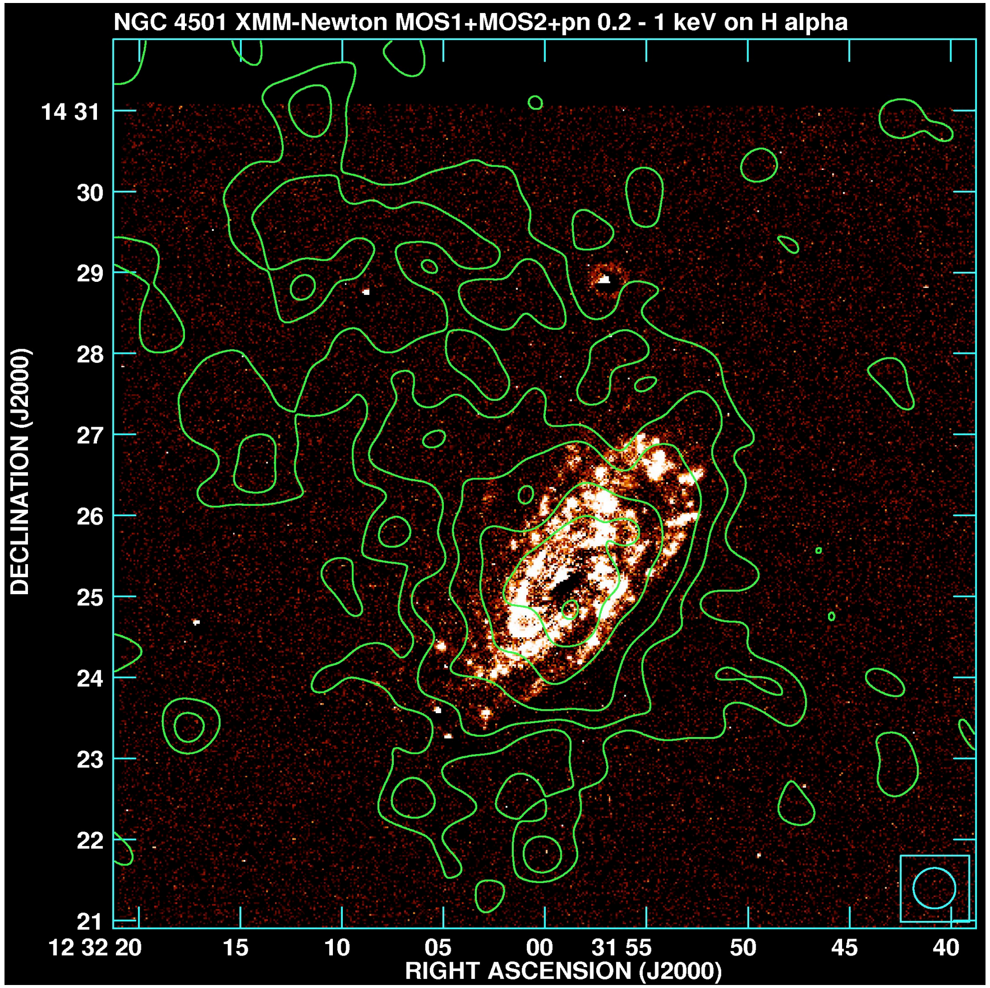
- Detailed comparison between observations and simulations of ram pressure stripped spiral galaxies in the Virgo cluster
- Can derived Mach cone geometries be seen in hot gas?
- Look at low resolution maps of diffuse extended X-ray emission
- Study X-ray spectra to derive gas temperatures for comparison with ICM

Done, with XMM-Newton, for 3 galaxies: NGC 4501, NGC 4388 and NGC 4569…

(full details in our recent paper: *Weżgowiec et al. A&A 531, 44, 2011)*

Observational results (1/4)

NGC 4501:



- Strong compression of B-field in the SW *(Weżgowiec et al. 2007, Vollmer et al. 2007)*
- Sharply truncated HI disk

In X-rays:

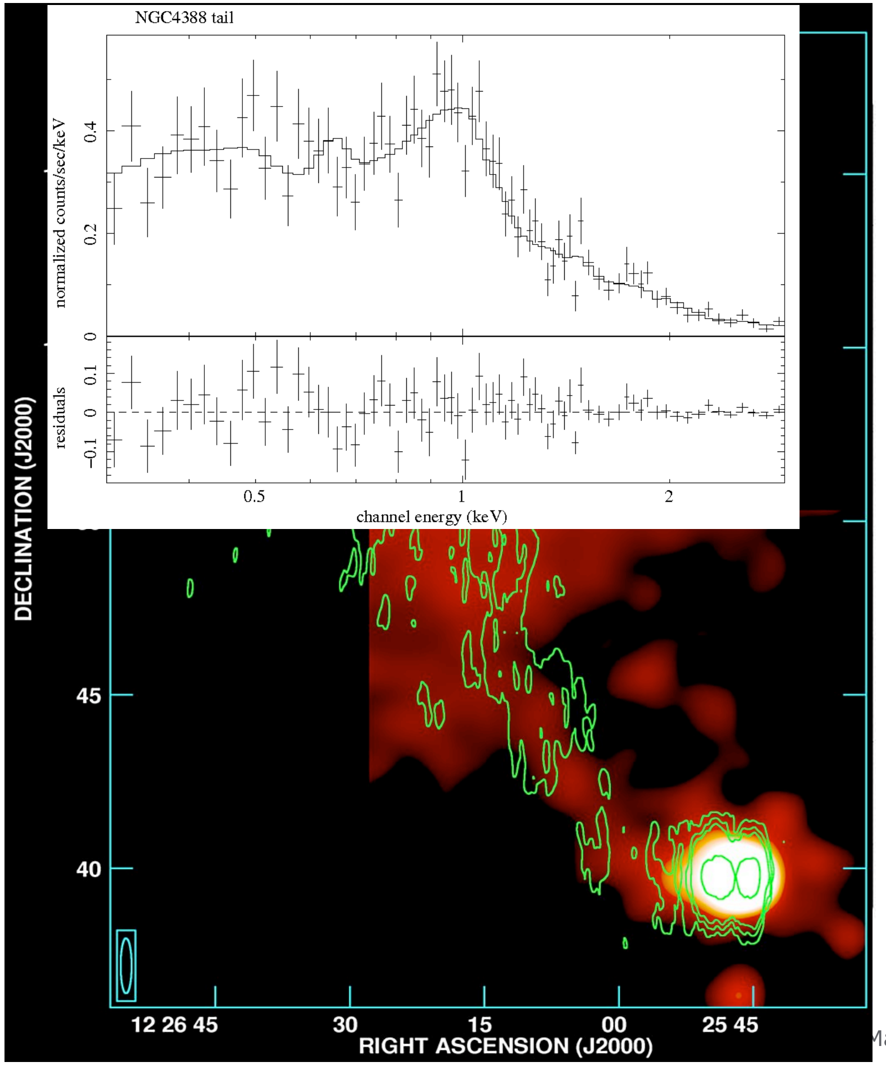
- Moderately extended hot gas halo
- Hot gas tail at ~ 0.7 keV

Conclusions:

- Distribution fits ram pressure stripping model
- Extra-planar X-rays due to stripped gas mixed with intracluster medium and/or galactic wind from SF?

Observational results (2/4)

NGC 4388:



- Impressive hot gas tail associated with Hα plume *(Yoshida et al. 2002)*
- Huge HI tail discovered by *Oosterloo & van Gorkom (2005)*

In X-rays:

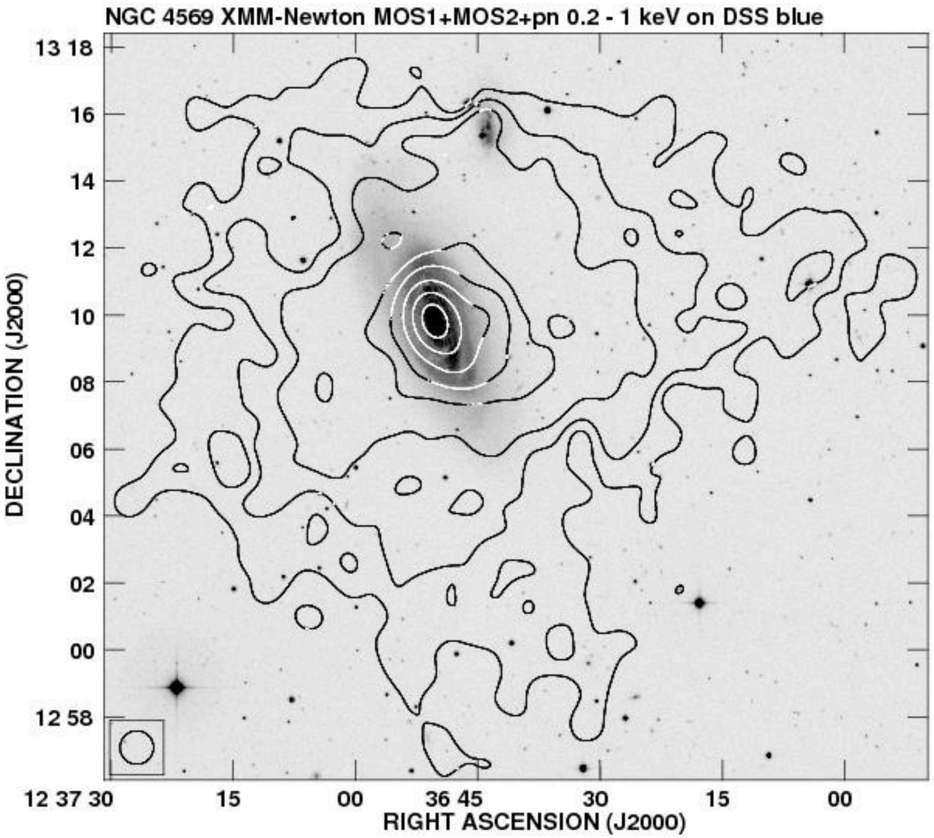
- Map cut where contributions from M86 halo start to dominate
- Spectrum of hot gas tail: two temp MEKAL: hot ISM (~0.9 keV) plus ICM (~2.3 keV)

Conclusions:

- Thermal pressure in tail a few times lower than estimated ram pressure
- Estimates total gas mass of tail (~6x10^{8} M_{sun}) << stripped gas mass; HI deficiency (2x10^{9} M_{sun})
- Strong ISM-ICM mixing & initial stripping of outer gas disk *(Vollmer & Huchtmeier, 2007)*

Observational results (3/4)

NGC 4569:



- One of the largest & most HI deficient galaxies *(Solares et al. 2001)*
- Large radio lobes (Chyży et al. 2006)

In X-rays:

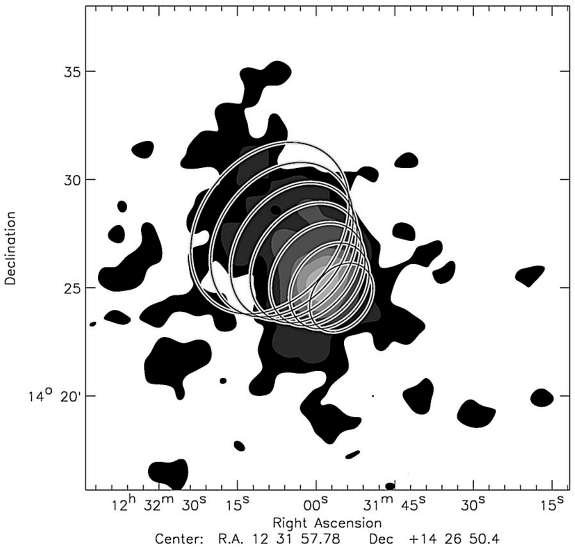
- Giant hot gas diffuse halo (100x100 kpc)
- Spectrum of hot gas: ~0.5 keV MEKAL; pressure 2x lower cosmic rays and B-fields

Conclusions:

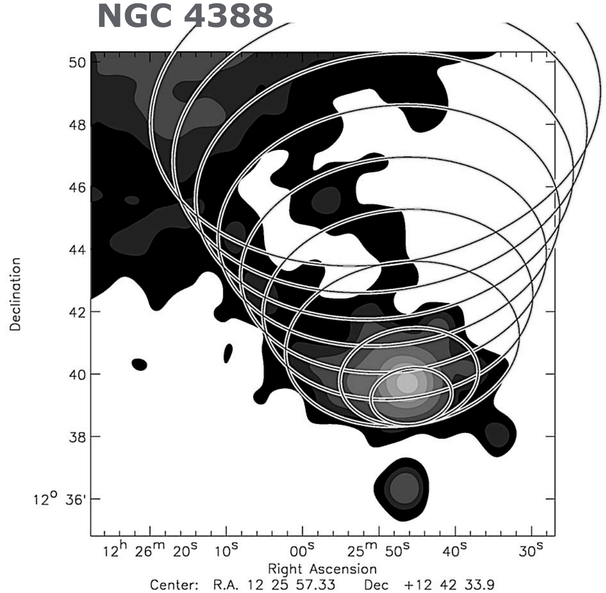
- Radio lobes & hot gas halo likely due to galactic superwind, driven by cosmic rays

Observational results (4/4): The Mach Cones

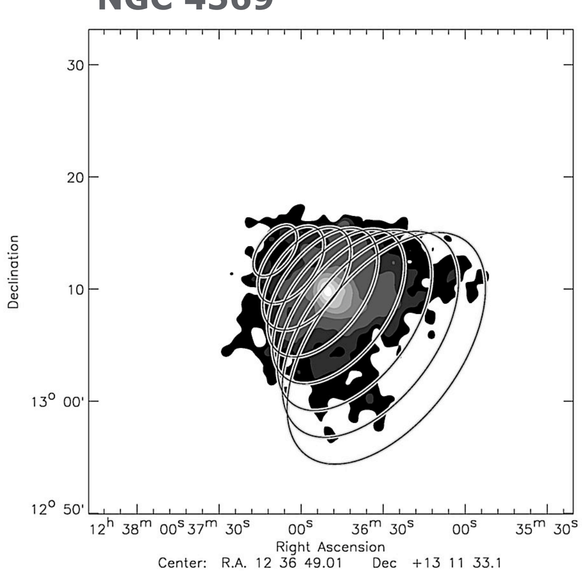
NGC 4501



NGC 4388



NGC 4569

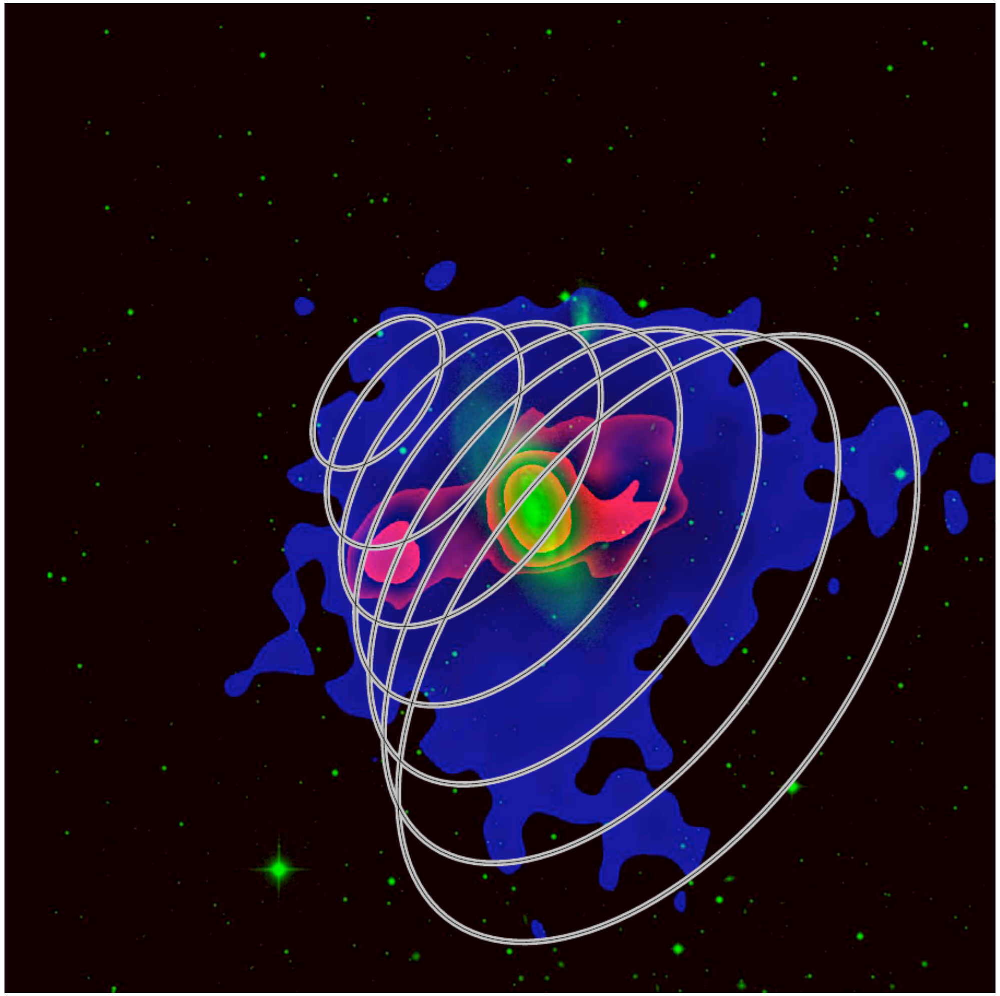


- Assumption: all extra-planar X-ray emission is confined by Mach cones ⇒ can ‘fit’ cones: directions based on dynamical model; opening angles ‘adjusted’
- Mach cone opening angles ⇔ Mach number: $\alpha = \sin^{-1}(1/M)$ ($M = v_{gal} / c_S$)

What the Cones can tell us...

- The **case NGC 4569** (other galaxies: cf. paper):
  - *Expectations:*
    v_{gal} = 1500 km/s (estimated)
    c_s = 550-700 km/s (ICM, depending on adiabatic index)
    $\Rightarrow$ M ~ 2.1-2.7 $\Rightarrow$ α = 22-28 deg
  - *Observations:*
    α = 37.5 deg, adding projection (velocity vector) $\Rightarrow$ true α = 30 deg (+/- 10)

- Consistent but somewhat high…we can do better:
  - ICM ionized & magnetized $\Rightarrow$ not c_s but magnetosonic velocity is important:
    v_{ms}=sqrt ($c_s^2 + v_a^2$);
    v_a=B/sqrt(4πnm_p) Alfvén speed
  - To reach α=30-32 deg (with v_{gal}, c_s, n=10^{-4} cm^{-3}) one needs v_a=300-600 km/s



$\Rightarrow$ B(cluster) ~1-3 μG (at location of NGC 4569), consistent with e.g. *Ferrari et al. 2008*

Conclusions

Summary:

- first time detection of Mach cones of a cluster spiral galaxy which moves supersonically in a cluster atmosphere (Mach number 2-3).
- Mach cone of NGC 4569 filled with hot gas from galactic outflow, detected in X-rays and radio continuum
- XMM-Newton data represent direct proof of the dynamical model predictions.
- Based on Mach cone opening angle it is possible to determine the galaxy velocity and to estimate the strength of the intracluster magnetic field.
- Based on the X-ray spectra it is possible to separate the different components of the hot gas (ISM, outflow, ICM) and to determine their densities and temperatures.
- Results are important for the understanding of the evolution of cluster spiral galaxies and clusters as a whole.

Thanks for your attention.