High-energy astrophysics and cosmology with galaxy clusters

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in collaboration with

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Outline

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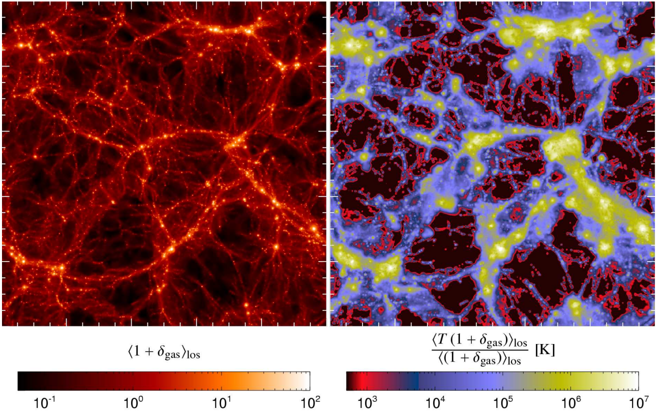
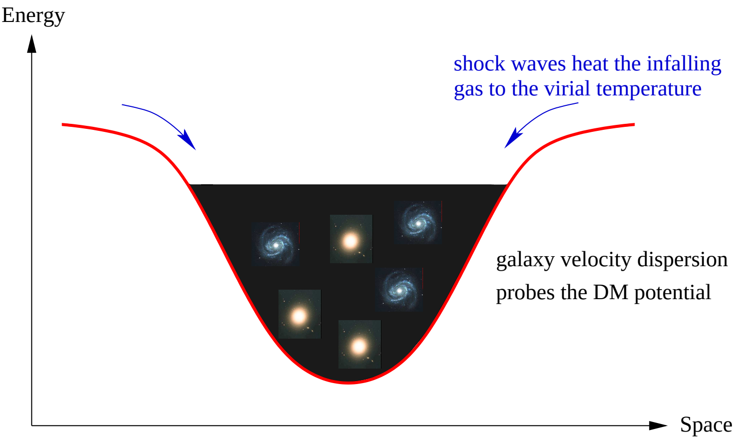
The structure of our Universe



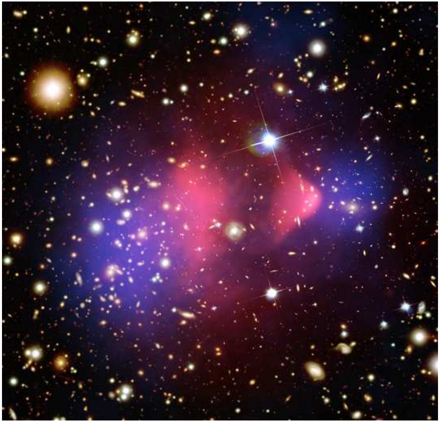
The "cosmic web" today. *Left:* the projected gas density in a cosmological simulation. *Right:* gravitationally heated intracluster medium through cosmological shock waves (C.P. et al. 2006).

A theorist's perspective of a galaxy cluster . . .

Galaxy clusters are dynamically evolving dark matter potential wells:

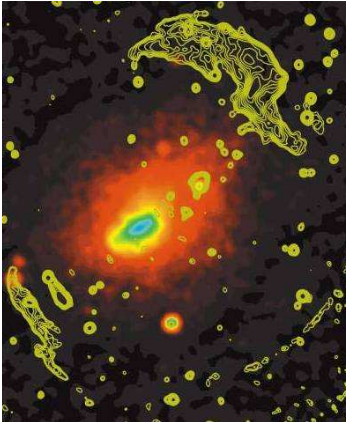


. . . and how the observer's Universe looks like



1E 0657-56 ("Bullet cluster")

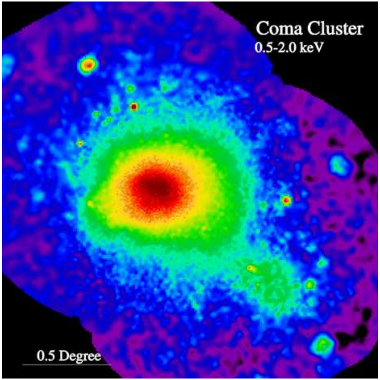
(X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.)



Abell 3667

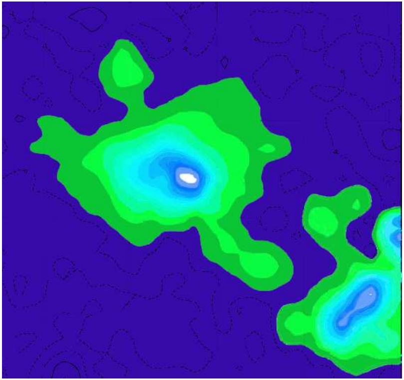
(radio: Johnston-Hollitt. X-ray: ROSAT/PSPC.)

Giant radio halo in the Coma cluster



thermal X-ray emission

(Snowden/MPE/ROSAT)



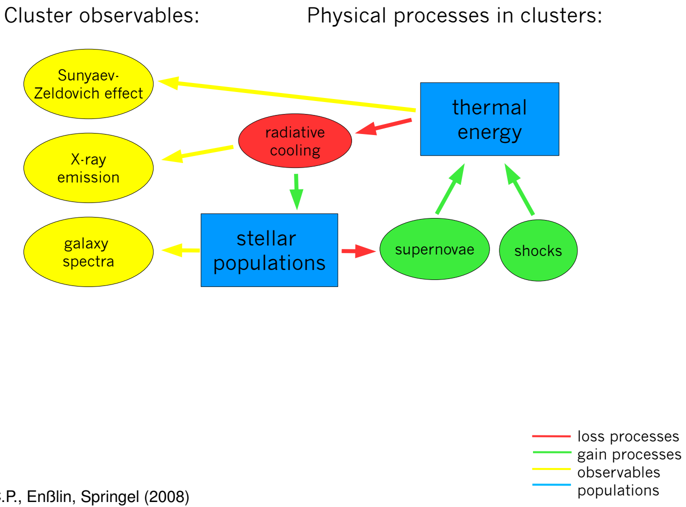
radio synchrotron emission

(Deiss/Effelsberg)

Galaxy cluster astrophysics: the big questions

- What powers these non-thermal processes in galaxy clusters?
  $\rightarrow$ illuminating the process of structure formation
  $\rightarrow$ history of individual clusters: cluster archeology
- Can we separate the cluster physics from the pure cosmological signal?
- How can we learn about the nature of dark matter in the presence of astrophysical γ-ray foregrounds?
- What can we learn about fundamental plasma physics?
  - process of shock acceleration
  - origin and evolution of large scale magnetic fields

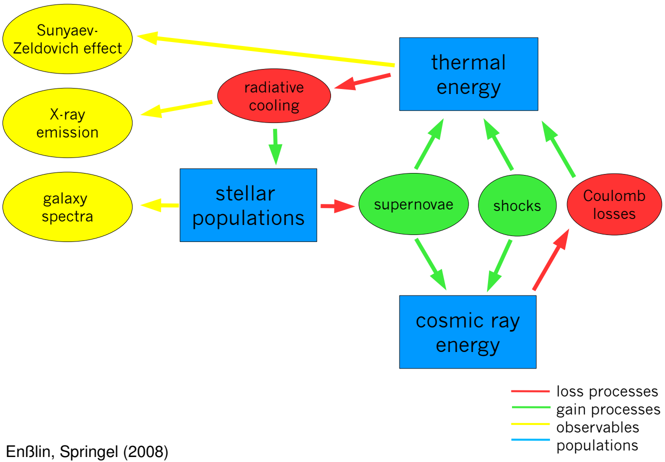
Cosmological simulations – flowchart



C.P., Enßlin, Springel (2008)

Cosmological simulations with cosmic ray physics

Cluster observables: Physical processes in clusters:



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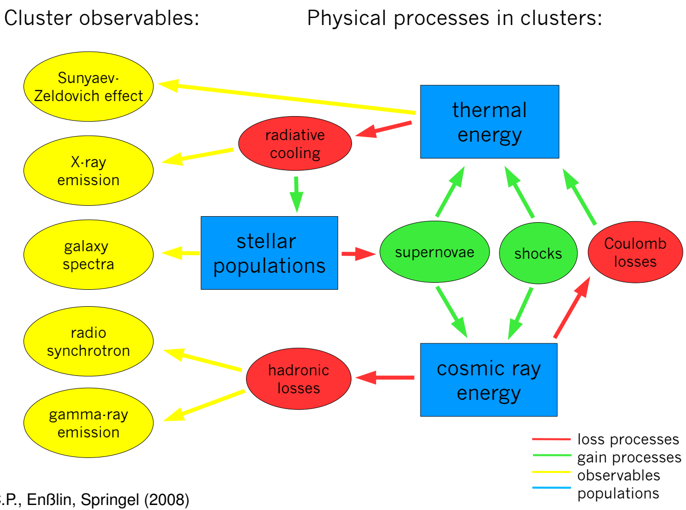
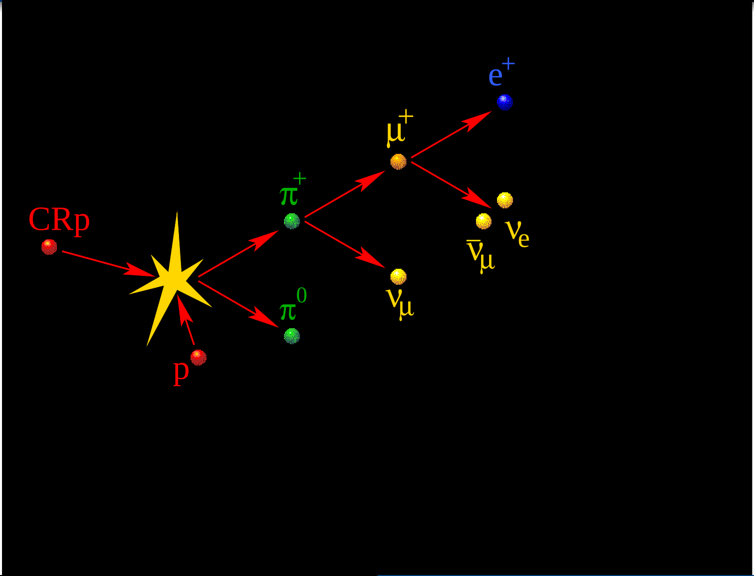


C.P., Enßlin, Springel (2008)

Hadronic cosmic ray proton interaction



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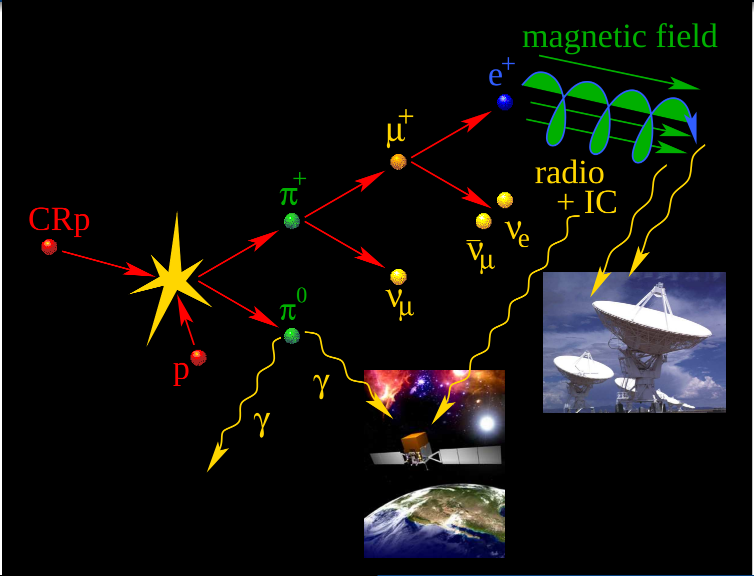
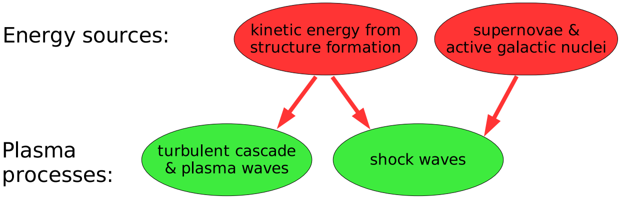


Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:



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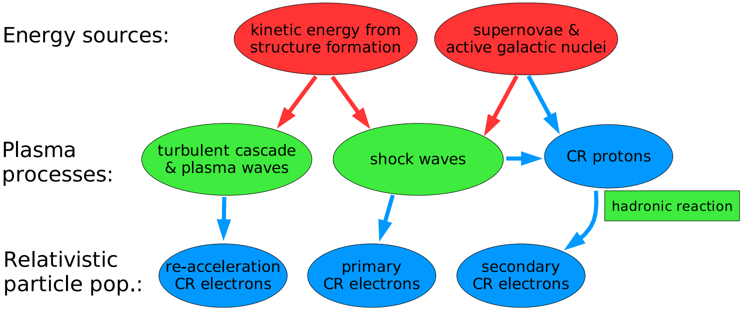

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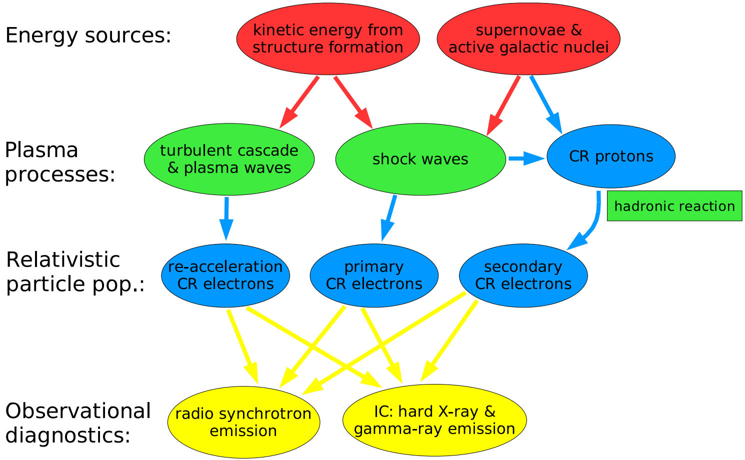

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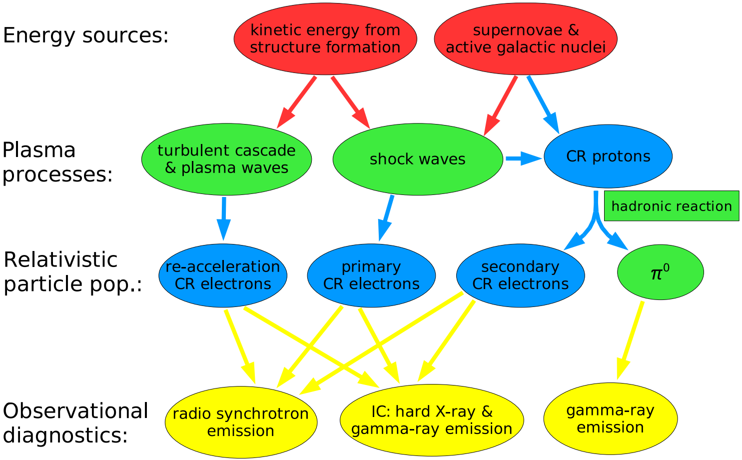
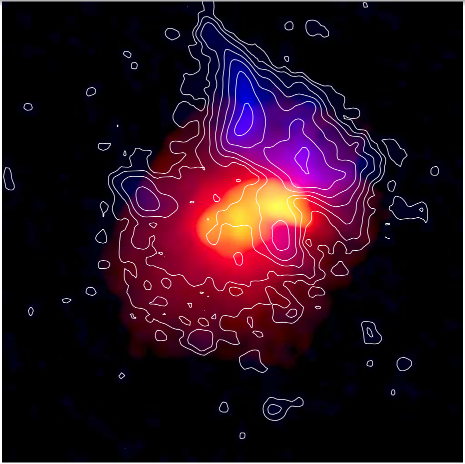
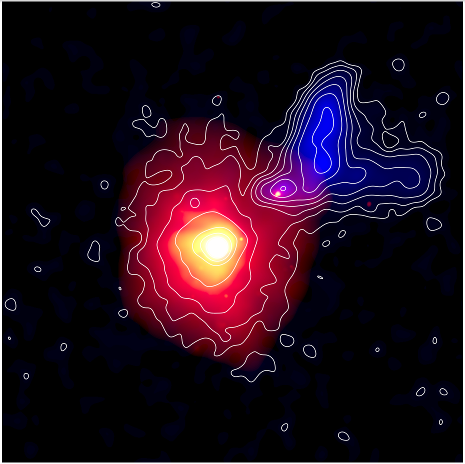


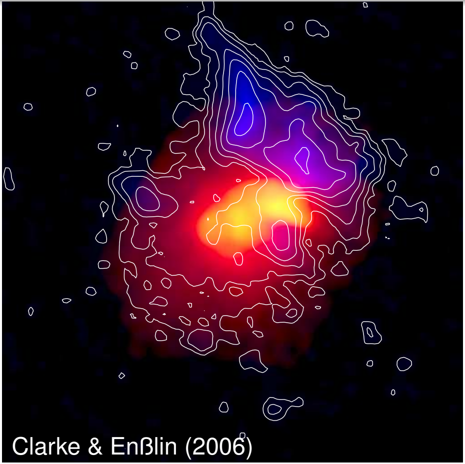
Which one is the simulation/observation of A2256?

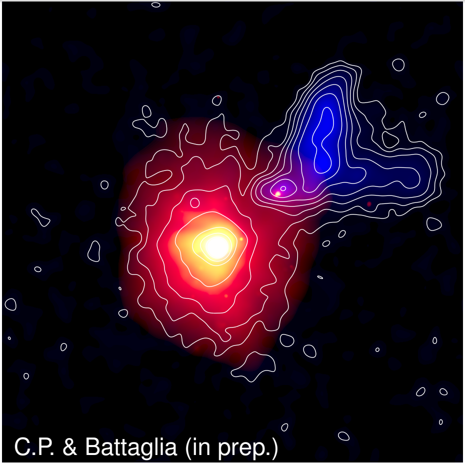




red/yellow: thermal X-ray emission,
blue/contours: 1.4 GHz radio emission with giant radio halo and relic

Observation – simulation of A2256





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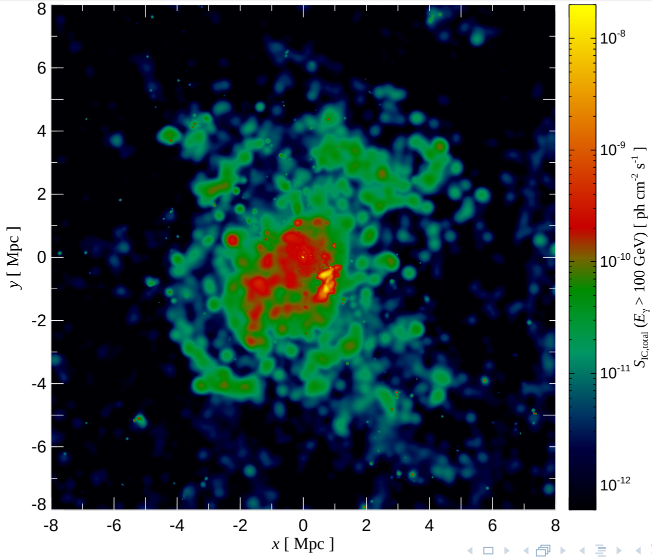
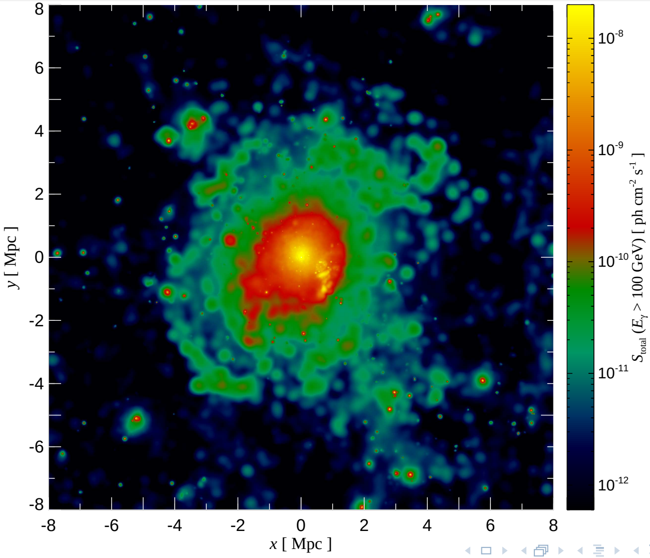
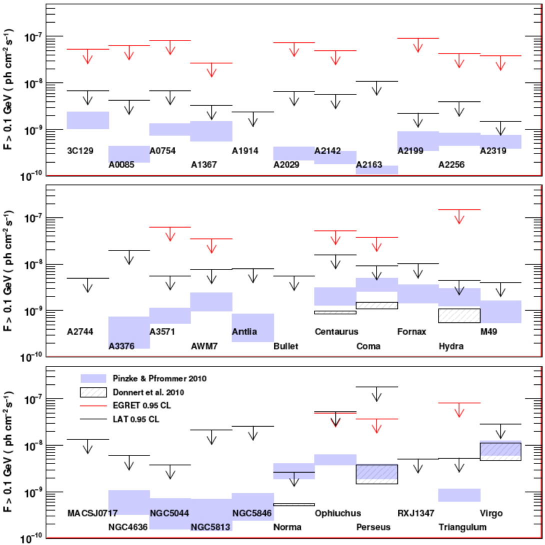
Inverse Compton emission, $E_{\mathrm{IC}} > 100$ GeV



Total γ-ray emission, $E_\gamma > 100$ GeV



γ-ray limits and hadronic predictions (Ackermann et al. 2010)



Conclusions on high-energy astrophysics in clusters

Exploring the memory of structure formation

1. Cosmological hydrodynamical simulations are indispensable for understanding non-thermal processes in galaxy clusters
$\rightarrow$ illuminating the process of structure formation
2. Multi-messenger approach including radio synchrotron, hard X-ray IC, and HE γ-ray emission:
    - fundamental plasma physics: diffusive shock acceleration, large scale magnetic fields, and turbulence
    - nature of dark matter
    - gold sample of clusters for precision cosmology

Conclusions on high-energy astrophysics in clusters

New generation of observatories

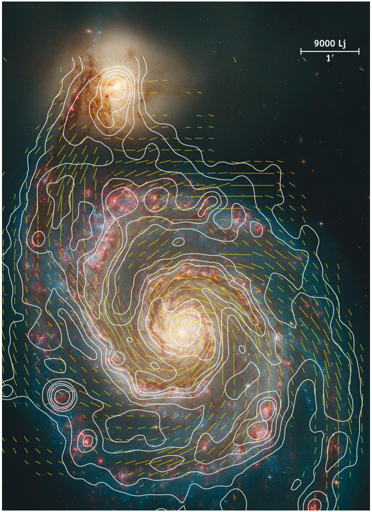
How can we read out this information about non-thermal populations?
$\rightarrow$ new era of multi-frequency experiments, e.g.:

- LOFAR, GMRT, MWA, LWA, SKA: interferometric array of radio telescopes at low frequencies ($\nu \simeq (15 - 240)$ MHz)
- NuSTAR: future hard X-ray satellite ($E \simeq (1 - 100)$ keV)
- Fermi γ-ray space telescope ($E \simeq (0.1 - 300)$ GeV)
- MAGIC, H.E.S.S., Veritas, CTA: imaging air Čerenkov telescopes ($E \simeq (0.1 - 100)$ TeV)

Outline

1. High-energy phenomena in galaxy clusters
   - Introduction and Motivation
   - Cosmological cluster simulations
   - Non-thermal emission from clusters
2. Magnetic draping on spiral galaxies
   - Radio emission in galaxies
   - Physics of magnetic draping
   - Implications for cosmology

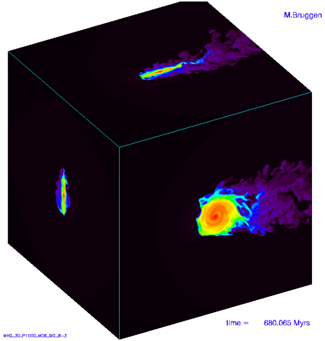
Polarized synchrotron emission in a field spiral: M51



MPIfR Bonn and Hubble Heritage Team

- grand design ‘whirlpool galaxy’ (M51): optical star light superposed on radio contours
- polarized radio intensity follows the spiral pattern and is strongest in between the spiral arms
- the polarization ‘B-vectors’ are aligned with the spiral structure

Ram-pressure stripping of cluster spirals

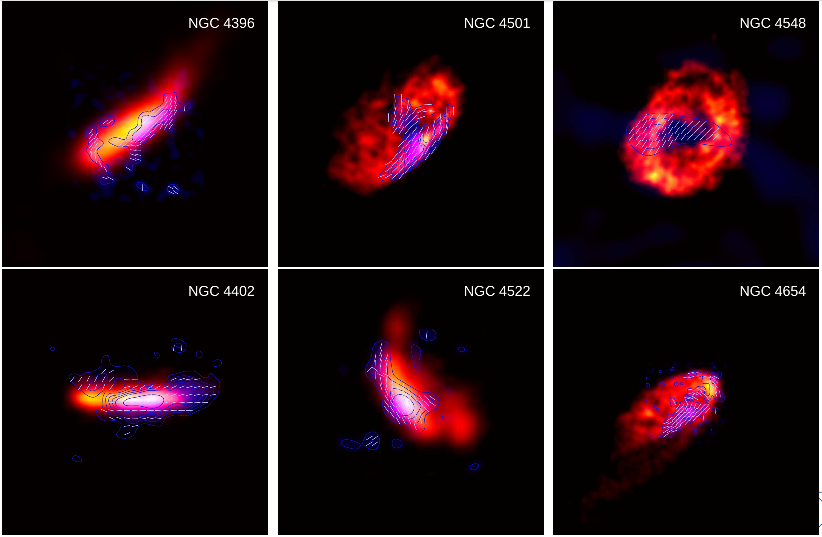


Brueggen (2008)

- 3D simulations show that the ram-pressure wind quickly strips the low-density gas in between spiral arms (Tonnesen & Bryan 2010)
- being flux-frozen into this dilute plasma, the large scale magnetic field will also be stripped

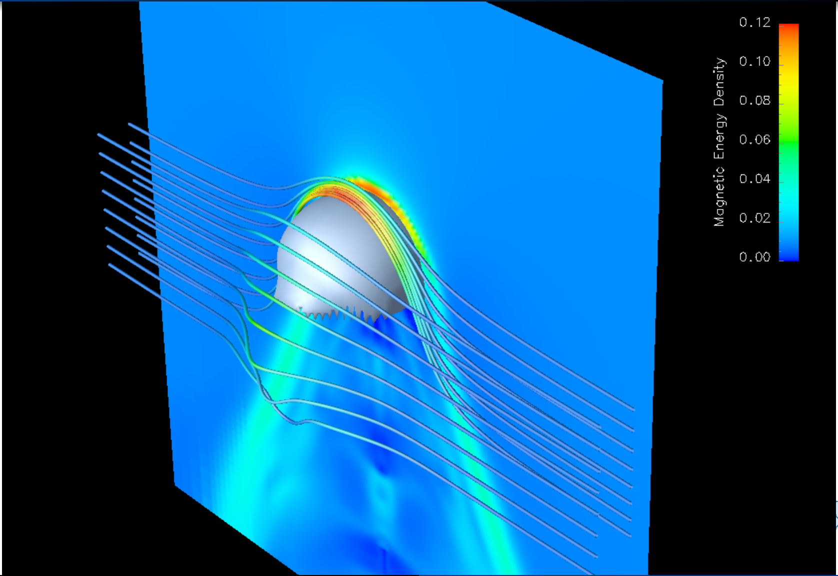
→ resulting radio emission should be unpolarized

Polarized synchrotron ridges in Virgo spirals

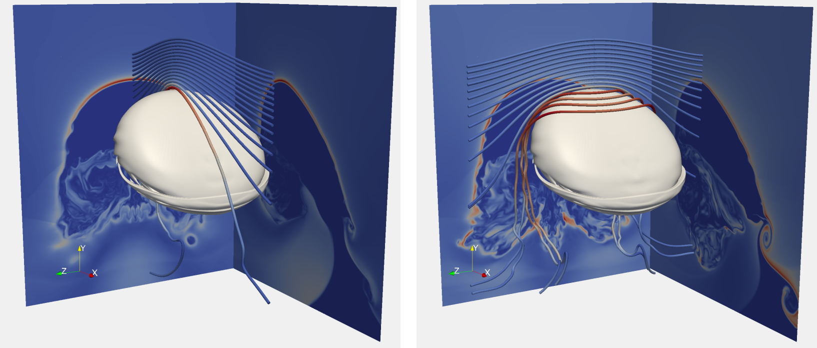


Vollmer et al. (2007): 6 cm PI (contours) + B-vectors; Chung et al. (2009): HI (red)

Draping field lines around a moving object



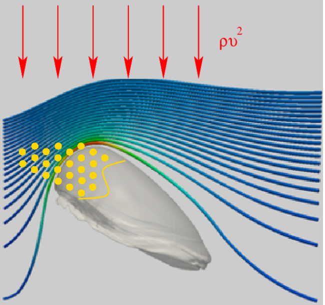
Magnetic draping around a spiral galaxy



Athena simulations of spiral galaxies interacting with a uniform cluster magnetic field. There is a sheath of strong field draped around the leading edge (shown in red).

C.P. & Dursi, 2010, Nature Phys.

Magnetic draping around a spiral galaxy – physics

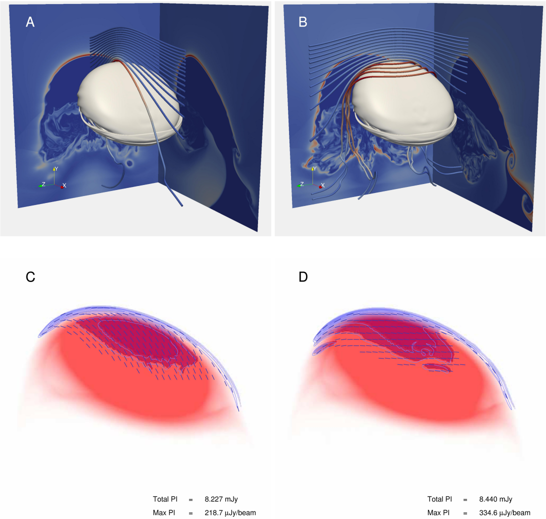


- the galactic gas is pushed back by the ram pressure wind $\sim \rho v^2$
- the stars are largely unaffected and lead the gas
- the draping sheath is formed at the contact of galaxy/cluster wind
- as stars die, their supernova remnants accelerate CRes that populate the draped field lines

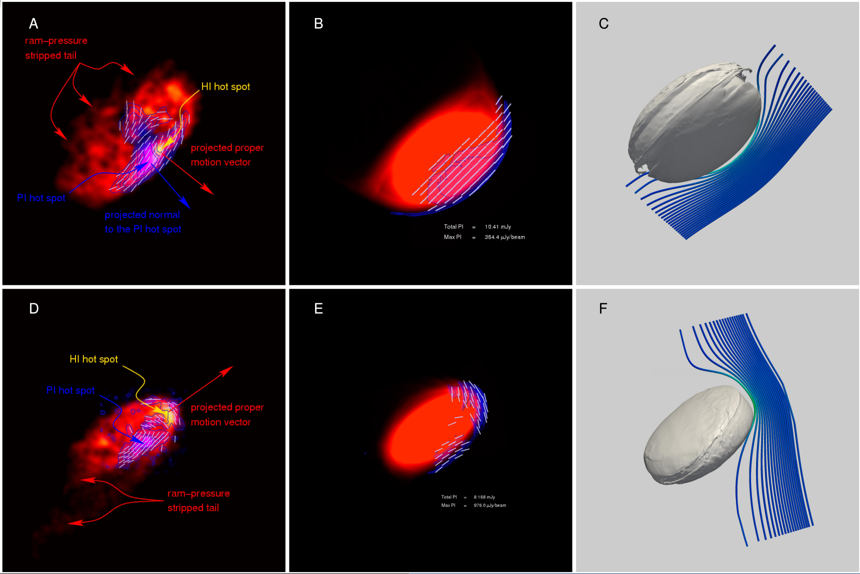
- CRes are transported diffusively (along field lines) and advectively as field lines slip over the galaxy
- CRes emit radio synchrotron radiation in the draped region, tracing out the field lines there $\rightarrow$ coherent polarized emission at the galaxies' leading edges

Magnetic draping and polarized synchrotron emission

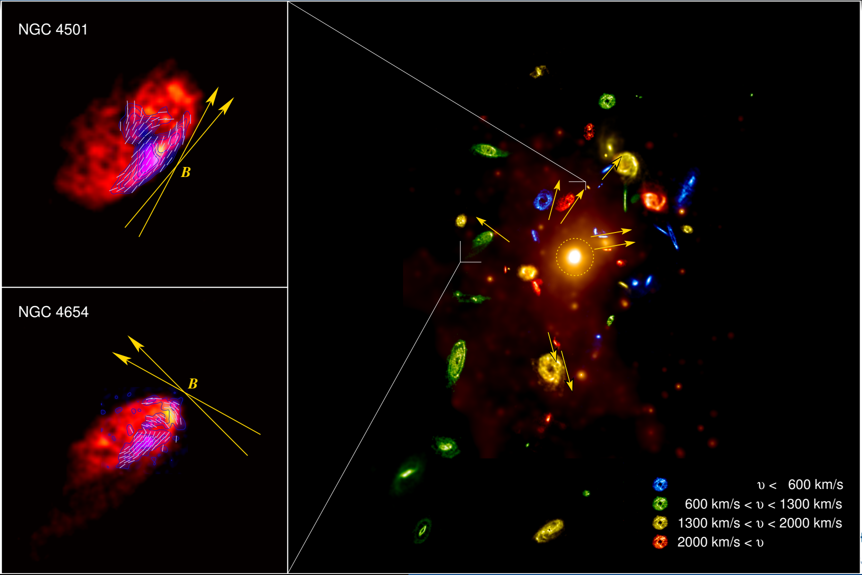
Synchrotron B-vectors reflect the upstream orientation of cluster magnetic fields



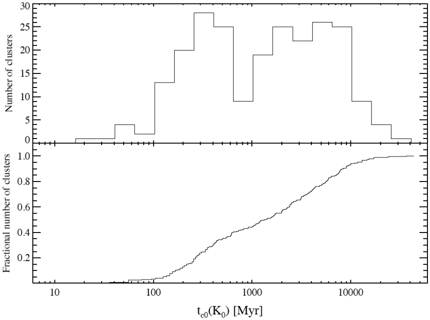
Observations versus simulations



Mapping out the magnetic field in Virgo



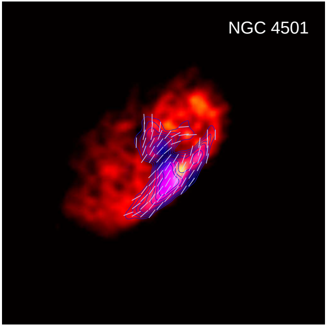
Implications for galaxy clusters (probing cosmology)



Cavagnolo et al. (2009)

- *How are galaxy clusters thermally stabilized?*
  → radial magnetic field in non-cool core clusters implies efficient thermal conduction that stabilizes these systems against entering a cooling catastrophe
  → thermal history + clusters as cosmological probes
- current cosmological cluster simulations fail to reproduce these clusters
  → magnetic fields + anisotropic conduction

Conclusions on magnetic draping around galaxies



- draping of cluster magnetic fields naturally explains polarization ridges at Virgo spirals

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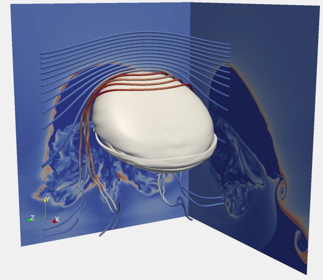

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- this represents a new tool for measuring the in situ orientation of cluster magnetic fields

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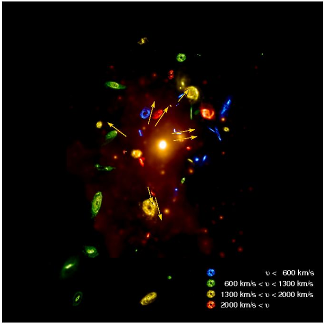

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- application to the Virgo cluster shows that the magnetic field is preferentially aligned radially

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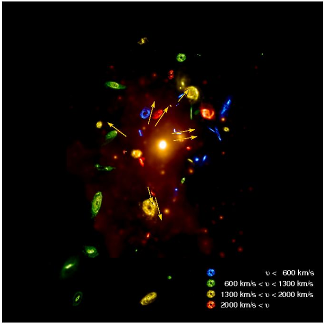

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- this finding implies efficient thermal conduction across clusters that stabilizes these non-cool core systems
- important implications for thermal cluster history → galaxy cluster cosmology