# Magnetic fields in galaxy clusters

Christoph Pfrommer

Heidelberg Institute for Theoretical Studies, Germany

Jul 30, 2014 / *Inhomogeneities in the Intracluster Plasma, Stanford*

# Outline

1. Intracluster magnetic fields
   - Origin and evolution
   - Faraday rotation measures
   - Minimum field estimates
2. Fields at cluster shocks
   - Radio relics
   - Radio and X-rays
   - Cooling lengths
3. Magnetic draping
   - Mechanism
   - Observations
   - MHD Simulations

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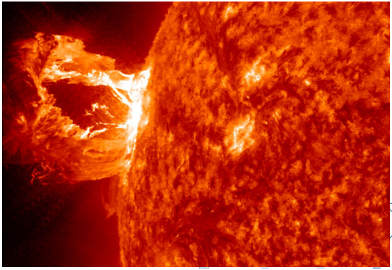
# Origin and evolution of cluster fields

possible origin:

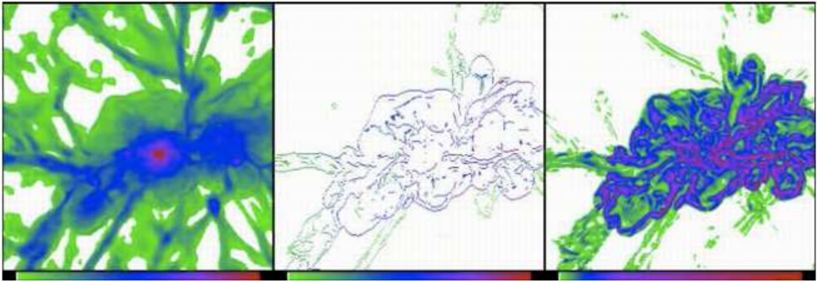
- stellar winds or AGN jets
- plasma instabilities or battery effects in shock waves, in ionization fronts, or in neutral gas-plasma interactions
- primordial generation in early universe processes, such as phase transitions during the epoch of inflation

evolution:

- amplification in a (small-scale turbulent) dynamo
- expectation: saturation at a fraction of $P_{\rm kin}$



# Origin of turbulence and magnetic fields

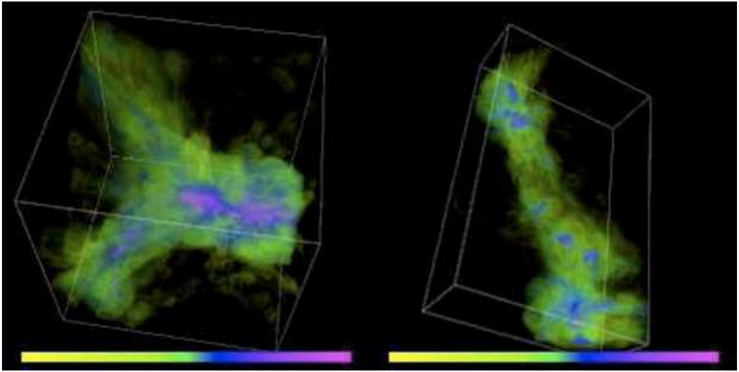


gas density, locations of shocks, vorticity = curl of flow velocity (Ryu et al. 2008)

model for the origin of intra-cluster magnetic fields:

- turbulent flow motions are induced via the cascade of the vorticity generated at cosmological formation shocks
- the turbulence amplifies weak seed magnetic fields of any origin

# Volume rendered magnetic field strengths



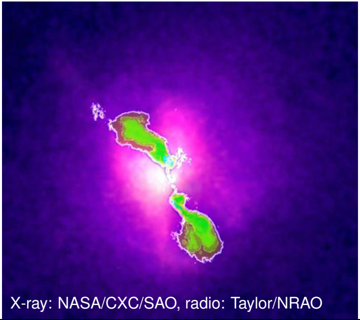
distribution of the resulting inter-galactic magnetic fields around a cluster and a filament that includes a number of groups (Ryu et al. 2008)

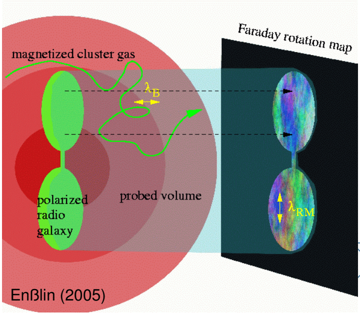
# Faraday rotation measurements

magnetic birefringence causes rotation of plane of polarization

$$\chi(\boldsymbol{x}_\perp, \lambda) = \chi_0 + \lambda^2 \frac{e^3}{2\pi m_e^2 c^4} \int_0^{z_s} \mathrm{d}z\, n_e(\boldsymbol{x}_\perp, z) B_z(\boldsymbol{x}_\perp, z)$$

- need to model $n_e$ and window function $\rightarrow$ statistics of $B_z(\boldsymbol{x}_\perp)$
- assuming statistical isotropy $\rightarrow$ deprojection and statistics of $B$

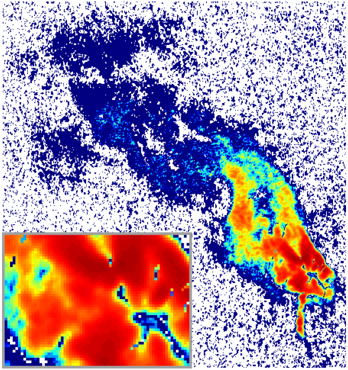

X-ray: NASA/CXC/SAO, radio: Taylor/NRAO



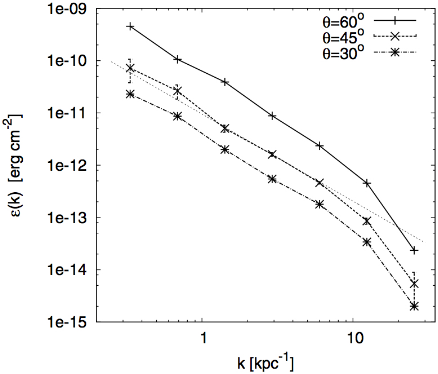
Enßlin (2005)

# Faraday rotation measurements: Hydra A

- inferred power spectrum compatible with Kolmogorov slope
- $B_0 = 36\,\mu$G (45°) and coherence scale $> 8$ kpc



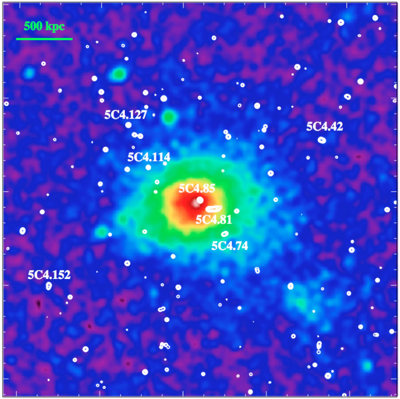
Vogt+ (2005)

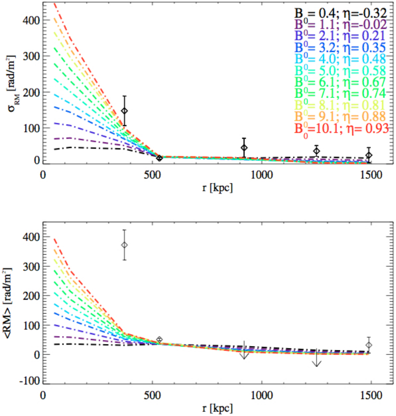



Kuchar & Enßlin (2011)

# Faraday rotation measurements: Coma

- forward modeling of 3D magnetic (Kolmogorov) power spectra
- varying $B_0$ and radial magnetic decline ($B \propto n_e^{\eta}$): $B_0 \simeq 5\,\mu$G, $\eta \simeq 0.5$

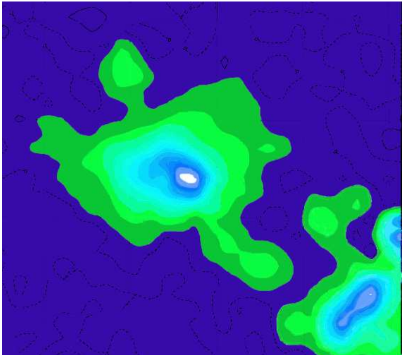



Bonafede+ (2010)

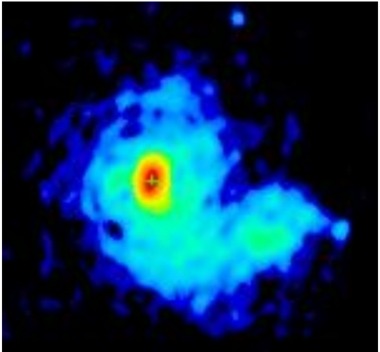
# Radio (mini-)halos: Coma and Perseus

Coma radio halo:



Deiss/Effelsberg, emission diameter ∼ 3 Mpc

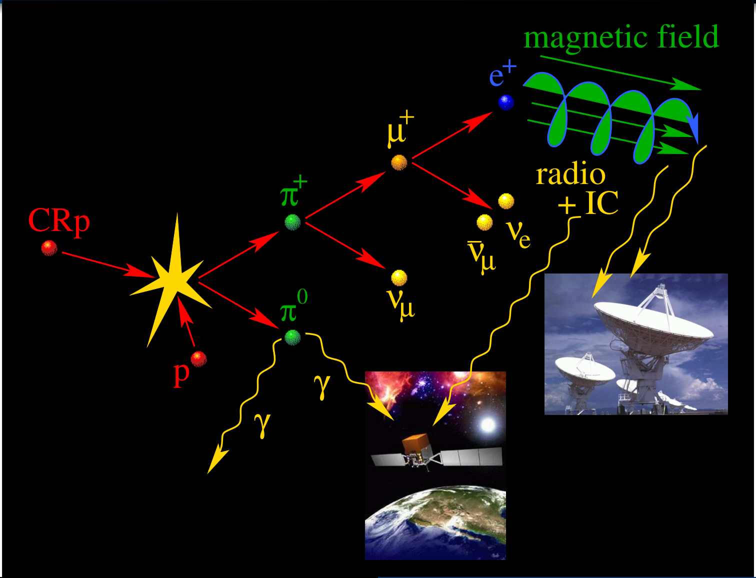
Perseus mini-halo:



Pedlar/VLA, emission diameter ∼ 300 kpc

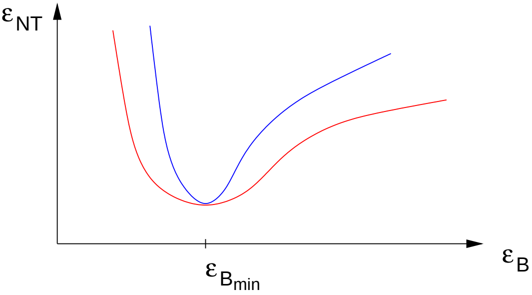
emission models: turbulent re-acceleration or hadronic cosmic ray interactions?

# Hadronic cosmic ray proton interaction



# Minimum energy criterion (MEC): the idea

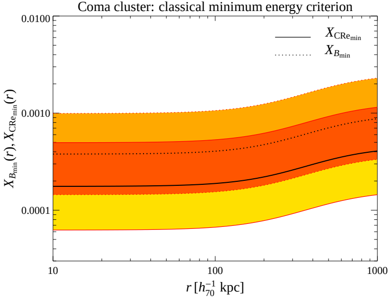
- $\varepsilon_{\rm NT} = \varepsilon_B + \varepsilon_{\rm CRp} + \varepsilon_{\rm CRe}$
  $\rightarrow$ minimum energy criterion: $\left.\frac{\partial \varepsilon_{\rm NT}}{\partial \varepsilon_B}\right|_{j_\nu} \stackrel{!}{=} 0$
- classical MEC: $\varepsilon_{\rm CRp} = k_{\rm p} \varepsilon_{\rm CRe}$
- hadronic MEC: $\varepsilon_{\rm CRp} \propto (\varepsilon_B + \varepsilon_{\rm CMB})\varepsilon_{\rm CRe} \propto (\varepsilon_B + \varepsilon_{\rm CMB})\varepsilon_B^{-(\alpha_\nu+1)/2} j_\nu$

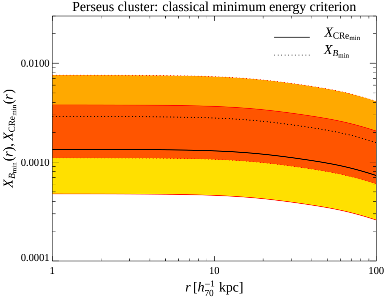



define tolerance levels: deviation from minimum by one e-fold

# Classical minimum energy criterion

$$X_{\mathrm{CRp}}(r) = \frac{\varepsilon_{\mathrm{CRp}}}{\varepsilon_{\mathrm{th}}}(r), \quad X_B(r) = \frac{\varepsilon_B}{\varepsilon_{\mathrm{th}}}(r)$$



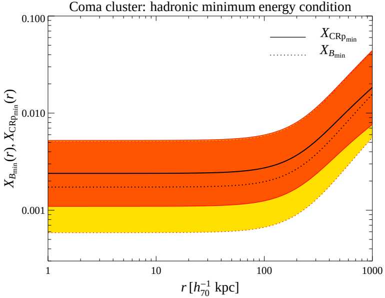



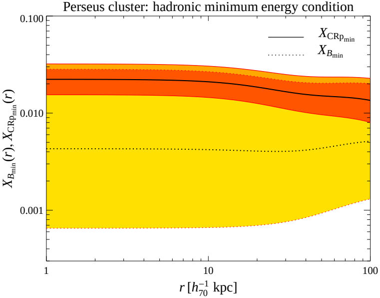

C.P. & Enßlin (2004)

$$B_{\mathrm{Coma}}(0) = 1.1^{+0.7}_{-0.4}\,\mu\mathrm{G} \qquad B_{\mathrm{Perseus}}(0) = 7.2^{+4.5}_{-2.8}\,\mu\mathrm{G}$$

# Hadronic minimum energy criterion

$$X_{\mathrm{CRp}}(r) = \frac{\varepsilon_{\mathrm{CRp}}}{\varepsilon_{\mathrm{th}}}(r), \quad X_B(r) = \frac{\varepsilon_B}{\varepsilon_{\mathrm{th}}}(r)$$



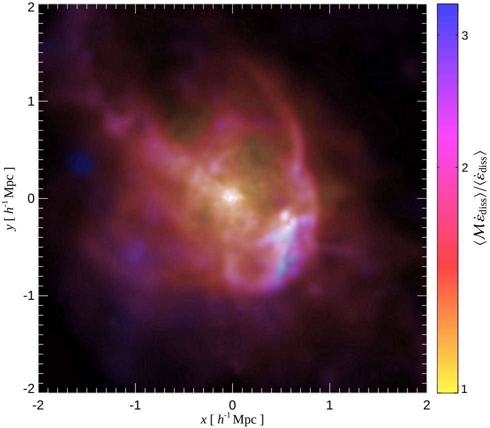




C.P. & Enßlin (2004)

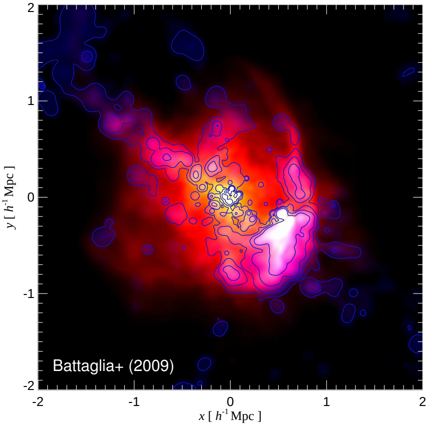
$$B_{\mathrm{Coma}}(0) = 2.4^{+1.7}_{-1.0}\,\mu\mathrm{G} \qquad B_{\mathrm{Perseus}}(0) = 8.8^{+13.8}_{-5.4}\,\mu\mathrm{G}$$

# Outline

# Radio gischt illuminates cluster magnetic fields




structure formation shocks triggered by a recent merger of a large galaxy cluster.




red/yellow: shock-dissipated energy, blue/contours: 150 MHz radio gischt emission from shock-accelerated CRe

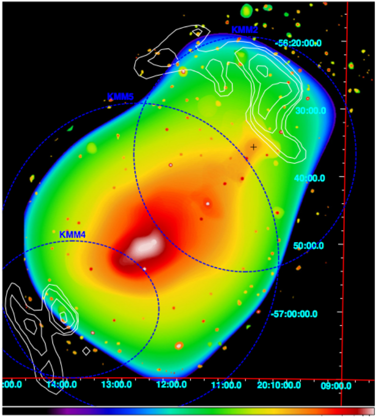
# Synchrotron and inverse Compton emission

detection of hard X-ray emission at the northern relic of A3667:

$$\frac{F_{\mathrm{sync}}}{F_{\mathrm{IC}}} \propto \frac{\varepsilon_B^{(\alpha_e+1)/4}}{\varepsilon_{\mathrm{CMB}}} \left(\frac{\nu_{\mathrm{sync}}}{\nu_{\mathrm{IC}}}\right)^{(1-\alpha_e)/2}$$

- if X-ray emission due to thermal bremsstrahlung: lower $B$ limit
- if X-ray emission due to inverse Compton: estimate for $B$ provided the radio emitting regions correlate with the volume occupied by $B$

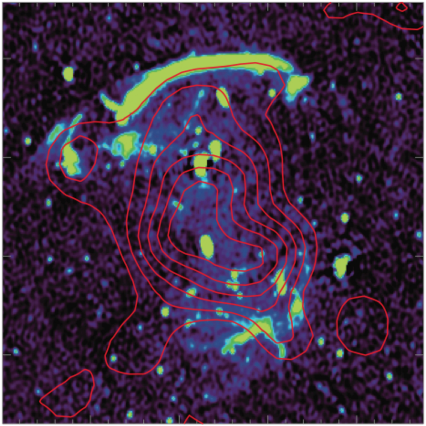
$\rightarrow B > 3\mu$G at the relic, i.e. at $R_{200}$!




Finoguenov+ (2010)

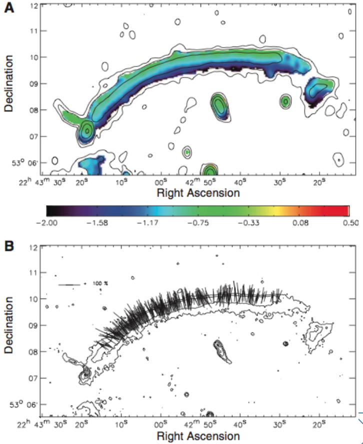
# Radio gischt probes acceleration and magnetic fields

double relic in CIZA J2242:



van Weeren+ (2010)

spectral index + *E* polarization:

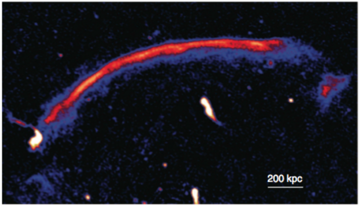


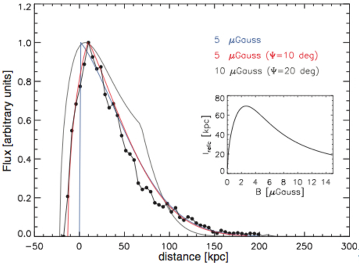
# Radio gischt probes acceleration and magnetic fields

- synchrotron cooling length of equilibrium electron distribution:

$$l_{\rm sync} = v_{\rm adv}\tau_{\rm sync} \propto \frac{\sqrt{B}}{B^2 + B_{\rm CMB}^2}$$

- allows for 2 solutions: $B \geq 5\,\mu$G or $B \leq 1.2\,\mu$G accounting for projection effects
- van Weeren+ argue for $B \geq 5\,\mu$G solution based X-ray limits in A3667




van Weeren+ (2010)

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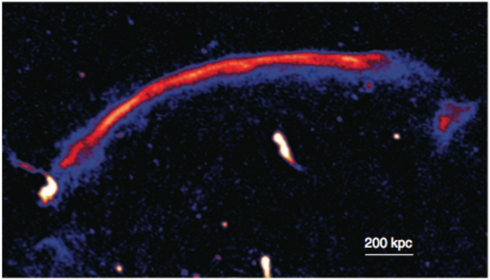


van Weeren+ (2010)

- how are these strong magnetic fields at the center out to $R_{200}$ generated?
- why is the magnetic field perpendicular to the shock normal?
- how can particle acceleration proceed at perpendicular shocks?

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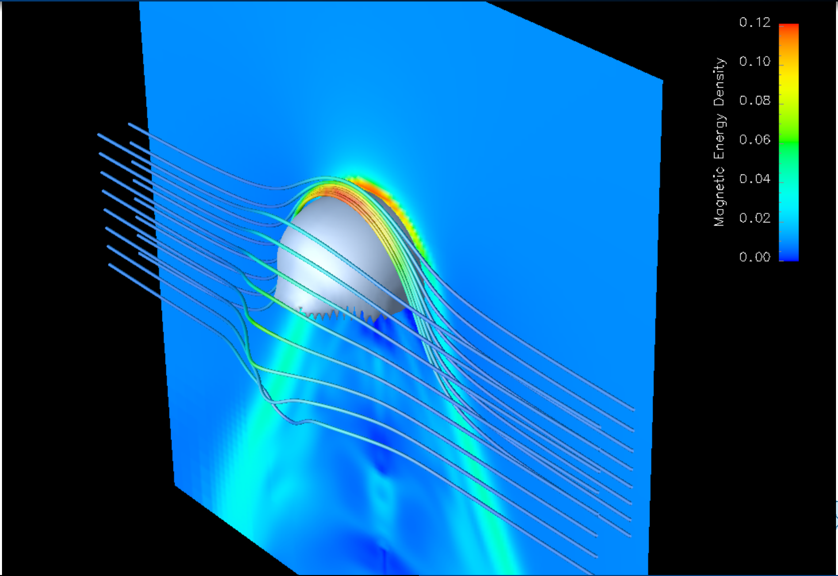
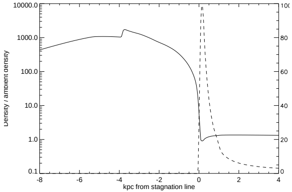
# What is magnetic draping?



# What is magnetic draping?

- is magnetic draping (MD) similar to ram pressure compression?
  $\rightarrow$ no density enhancement for MD
  - analytical solution of MD for incompressible flow
  - ideal MHD simulations *(right)*



# What is magnetic draping?

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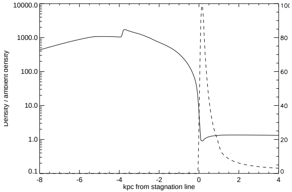
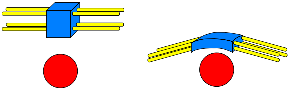
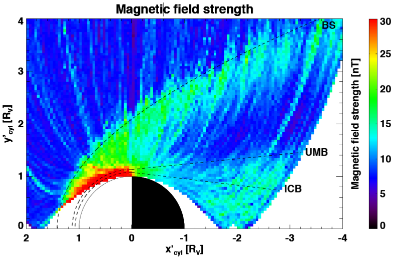
  → no density enhancement for MD
  - analytical solution of MD for incompressible flow
  - ideal MHD simulations *(right)*
- is magnetic flux still frozen into the plasma?
  yes, but plasma is pulled into the direction of the field lines while field lines get stuck at the obstacle



# Draping of the interplanetary field over Venus

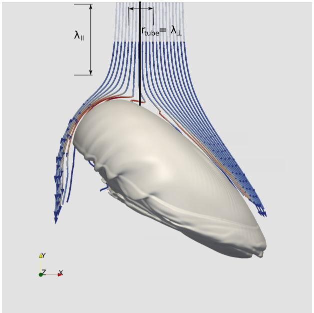
- Venus and Mars do not have a global magnetic field
- *Venus Express:* amplification of solar wind field by a factor $\sim$ 6 at the side facing the Sun




Guicking et al. (2010)

- draping of solar wind magnetic field around Venus/Mars leads to the formation of magnetic pile-up region and the magneto tail $\rightarrow$ enhanced magnetic field strength in the planets' wake

# Streamlines in the rest frame of the galaxy




- Stokes function $p(s, \theta) = \sqrt{3sR}\,\sin\theta$ $\rightarrow$ critical impact parameter for $\theta = \pi/2$, $s = l_{\rm drape}$: $p_{\rm cr} = R/(2\mathcal{M}_A)$
- only those streamlines initially in a narrow tube of radius $p_{\rm cr} \simeq R/20 \simeq 1$ kpc from the stagnation line become part of the magnetic draping layer (color coded) $\rightarrow$ constraints on $\lambda_B$

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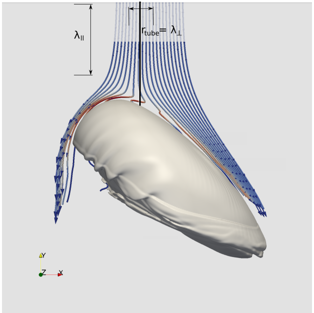


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- only those streamlines initially in a narrow tube of radius $p_{\rm cr} \simeq R/20 \simeq 1$ kpc from the stagnation line become part of the magnetic draping layer (color coded) $\rightarrow$ constraints on $\lambda_B$
- the streamlines that do not intersect the tube get deflected away from the galaxy, become never part of the drape and eventually get accelerated (Bernoulli effect)
- note the kink feature in some draping-layer field lines due to back reaction as the solution changes from the hydrodynamic potential flow solution to that in the draped layer

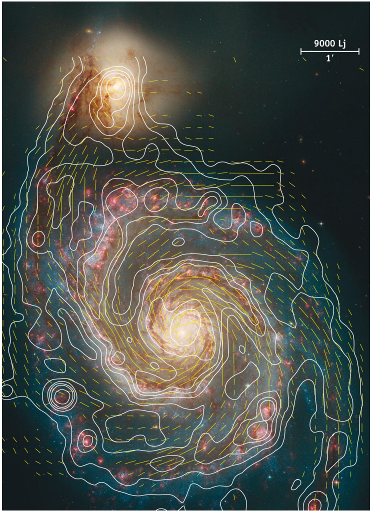
# Conditions for magnetic draping

- ambient plasma sufficiently ionized such that flux freezing condition applies
- super-Alfvénic motion of a cloud through a weakly magnetized plasma: $\mathcal{M}_A^2 = \beta\gamma\mathcal{M}^2/2 > 1$
- magnetic coherence across the “cylinder of influence”:

$$\frac{\lambda_B}{R} \gtrsim \frac{1}{\mathcal{M}_A} \sim 0.1 \times \left(\frac{\beta}{100}\right)^{-1/2} \quad \text{for sonic motions,}$$

Here $R$ denotes the curvature radius of the working surface at the stagnation line.

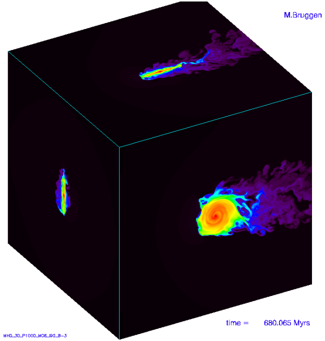
# Polarized synchrotron emission in a field spiral: M51




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

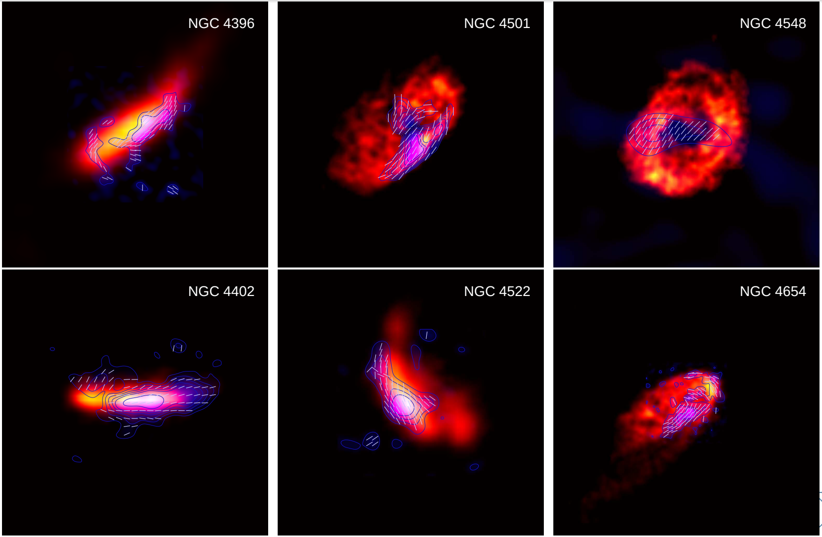



Brueggen (2008)

- 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)

# Observational evidence and model challenges

- asymmetric distributions of polarized intensity at the leading edge with extraplanar emission, sometimes also at the side
- coherent alignment of polarization vectors over $\sim 30$ kpc
- HI gas only moderately enhanced (factor $\lesssim 2$), localized 'HI hot spot' smaller than the polarized emission region:
  $n_\mathrm{compr} \simeq n_\mathrm{icm}\, v_\mathrm{gal}^2 / c_\mathrm{ism}^2 \simeq 1\,\mathrm{cm}^{-3} \simeq \langle n_\mathrm{ism} \rangle$

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- flat radio spectral index (similar to the Milky Way) that steepens towards the edges of the polarized ridge
- no or weak Kelvin-Helmholtz instabilities at interface detectable

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$\rightarrow$ previous models that use ram-pressure compressed galactic magnetic fields fail to explain most of these points!

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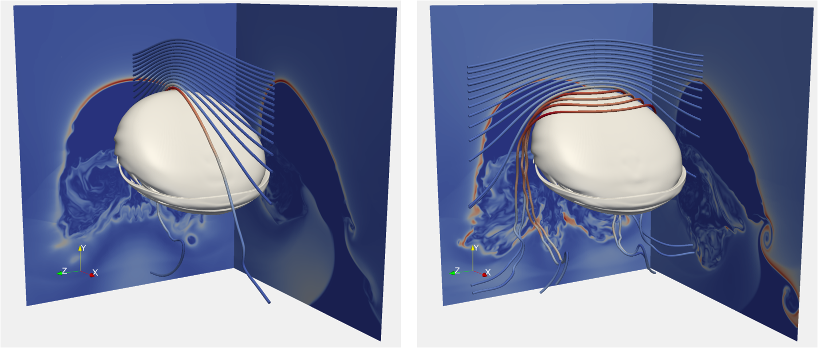
$\rightarrow$ need to consider the full MHD of the interaction spiral galaxy and magnetized ICM !

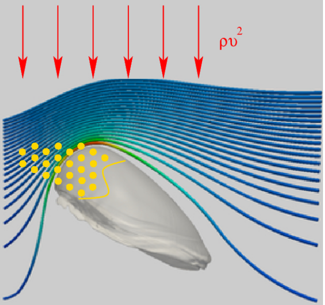
# Magnetic draping around a spiral galaxy



*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.

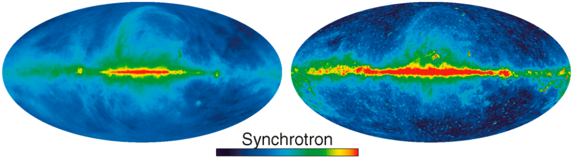
# Magnetic draping around a spiral galaxy – physics




- the galactic ISM 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 become SN, their remnants accelerate CRes that populate the field lines in the draping layer

- 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

# Modeling the electron population




- typical SN rates imply a homogeneous CRe distribution (WMAP)
- FIR-radio correlation of Virgo spirals show comparable values to the solar circle $\rightarrow$ take CRe distribution of our Galaxy:

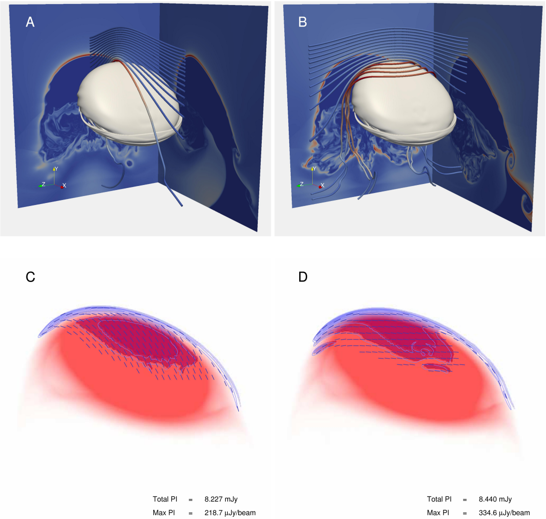
$$n_{\rm cre} = C_0\, e^{-(R-R_\odot)/h_R}\, e^{-|z|/h_z}$$

with normalization $C_0 \simeq 10^{-4}\,\mathrm{cm}^{-3}$,
scale heights $h_R \simeq 8\,\mathrm{kpc}$ and $h_z \simeq 1\,\mathrm{kpc}$ at Solar position

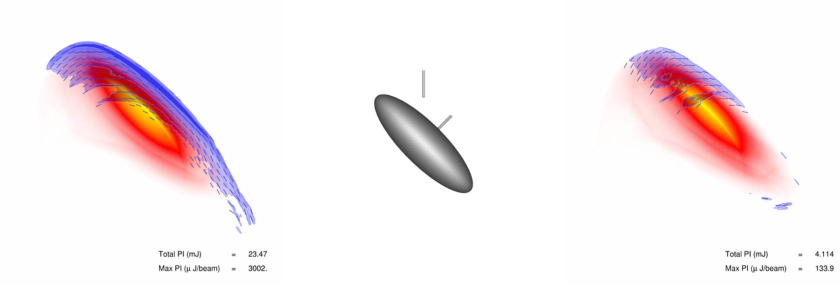
- truncate at contact of ISM-ICM, attach exp. CRe distribution $\perp$ to contact surface with $h_\perp \simeq 150$ pc (max. radius of Sedov phase)

# Magnetic draping and polarized synchrotron emission

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



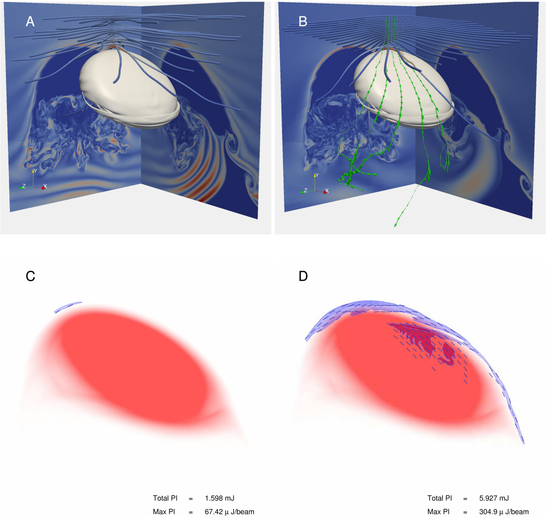
# Simulated polarized synchrotron emission



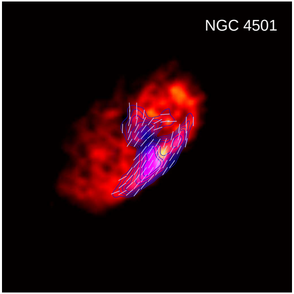

Movie of the simulated polarized synchrotron radiation viewed from various angles and with two field orientations.

# Magnetic draping of a helical B-field

## (Non-)observation of polarization twist constrains magnetic coherence length



# Magnetic coherence scale estimate by radio ridges



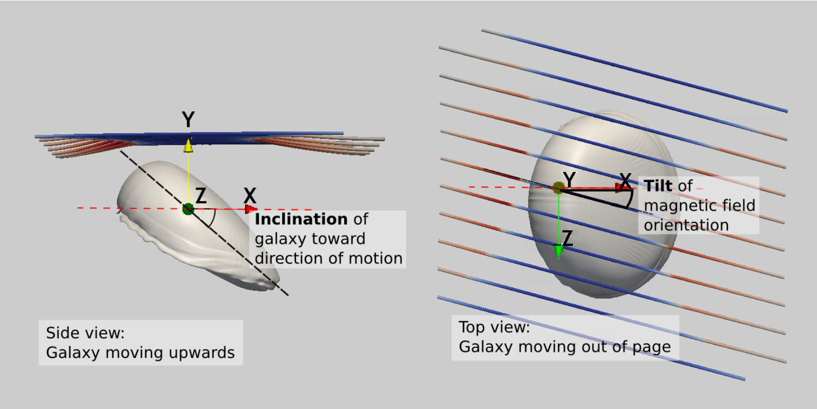

- observed polarised draping emission $\rightarrow$ field coherence length $\lambda_B$ is at least galaxy-sized
- if $\lambda_B \sim 2R_{\rm gal}$, then the change of orientation of field vectors imprint as a change of the polarisation vectors along the vertical direction of the ridge showing a 'polarisation-twist'

- the reduced speed of the boundary flow means that a small $L_{\rm drape}$ corresponds to a larger length scale of the unperturbed magnetic field ahead of the galaxy NGC 4501

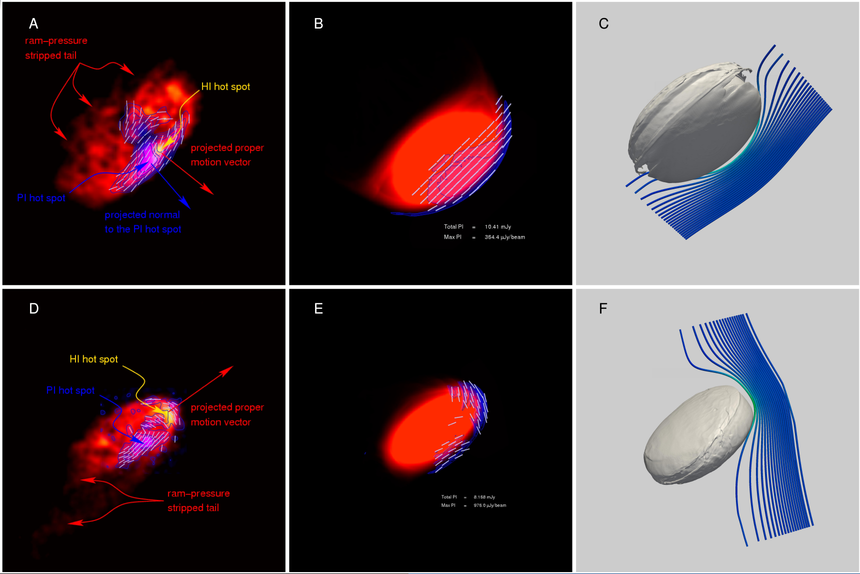
$$L_{\rm coh} \simeq \eta L_{\rm drape} v_{\rm gal}/v_{\rm drape} = \eta \tau_{\rm syn} v_{\rm gal} > 100\,{\rm kpc},$$

with $\tau_{\rm syn} \simeq 5 \times 10^7$ yr, $v_{\rm gal} \simeq 1000\,{\rm km/s}$, and a geometric factor $\eta \simeq 2$

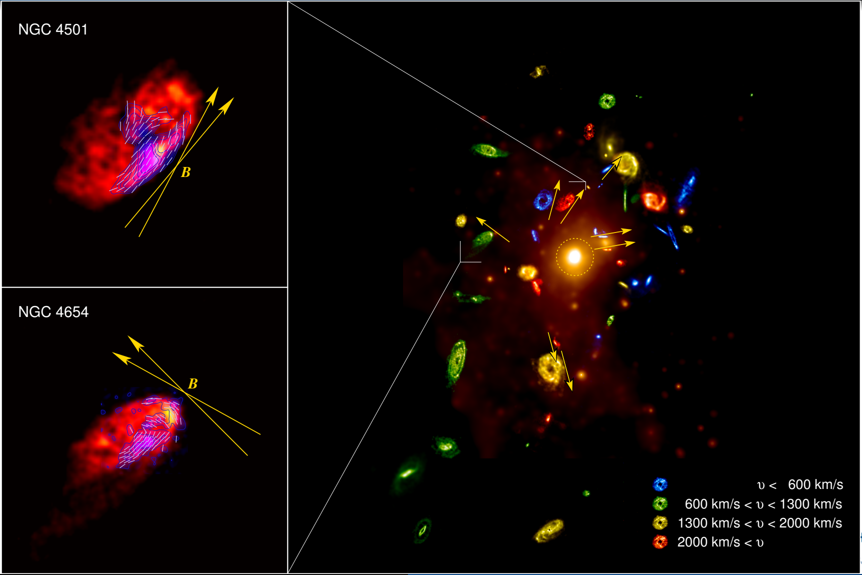
# Varying galaxy inclination and magnetic tilt



# Observations versus simulations



# Mapping out the magnetic field in Virgo



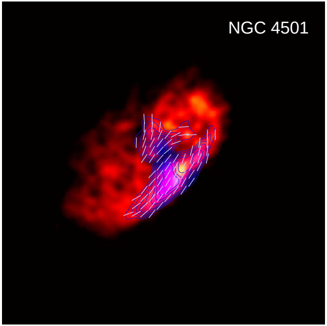
# Discussion of radial field geometry

- The alignment of the field in the plane of the sky is significantly more radial than expected from random chance. Considering the sum of deviations from radial alignment gives a chance coincidence of less than 1.7% ($\sim 2.2\,\sigma$).
- For the three nearby galaxy pairs in the data set, all have very similar field orientations.

$\rightarrow$ Which effect causes this field geometry?

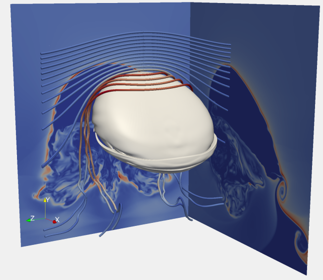
Magneto-thermal instability? (Parrish+2007)
Radial infall? (Ruszkowski+2010)

# Conclusions on magnetic draping around galaxies




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

# Conclusions on magnetic draping around galaxies

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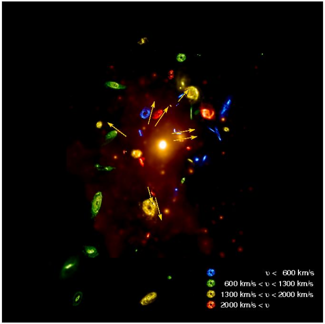
- this represents a new tool for measuring the in situ 3D orientation and coherence scale of cluster magnetic fields

# Conclusions on magnetic draping around galaxies

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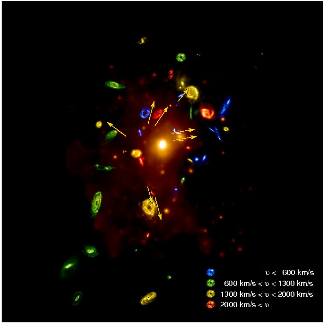
- this represents a new tool for measuring the in situ 3D orientation and coherence scale of cluster magnetic fields
- application to the Virgo cluster shows that the magnetic field is preferentially aligned radially

# Conclusions on magnetic draping around galaxies




- draping of cluster magnetic fields naturally explains polarization ridges at Virgo spirals
- this represents a new tool for measuring the in situ 3D orientation and coherence scale of cluster magnetic fields
- application to the Virgo cluster shows that the magnetic field is preferentially aligned radially

- this finding implies efficient thermal conduction across clusters
  $\rightarrow$ thermal cluster history & cluster cosmology
- prospects for studying microphysics of transport processes, issues: magnetic reconnection with ISM fields

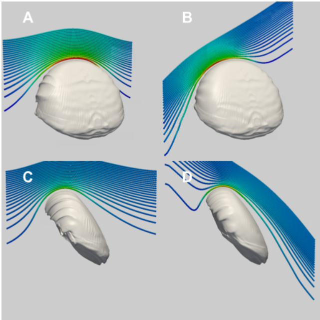
# Literature for the talk

- Pfrommer & Dursi, 2010, Nature Phys., 6, 5206, *Detecting the orientation of magnetic fields in galaxy clusters*
- Dursi & Pfrommer, 2008, ApJ, 677, 993, *Draping of cluster magnetic fields over bullets and bubbles - morphology and dynamic effects*

# Additional slides

# Biases in inferring the field orientation

- uncertainties in estimating the 3D velocity: $v_r$, ram-pressure stripped gas visible in HI morphology $\rightarrow \hat{\boldsymbol{v}}_\mathrm{t}$
- *direction-of-motion asymmetry:* magnetic field components in the direction of motion bias the location of $B_{\mathrm{max,\ drape}}$ (figure to the right): draping is absent if $\boldsymbol{B} \parallel \boldsymbol{v}_\mathrm{gal}$




- *geometric bias:* polarized synchrotron emission only sensitive to traverse magnetic field $B_\mathrm{t}$ ($\perp$ to LOS) $\rightarrow$ maximum polarised intensity may bias the location of $B_{\mathrm{max,\ drape}}$ towards the location in the drape with large $B_\mathrm{t}$