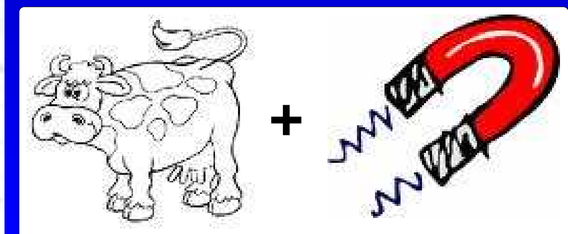
Lecture I
Magnetic Fileds in Clusters
RMs and Radio emission

Klaus Dolag

Universitäts-Sternwarte München, LMU



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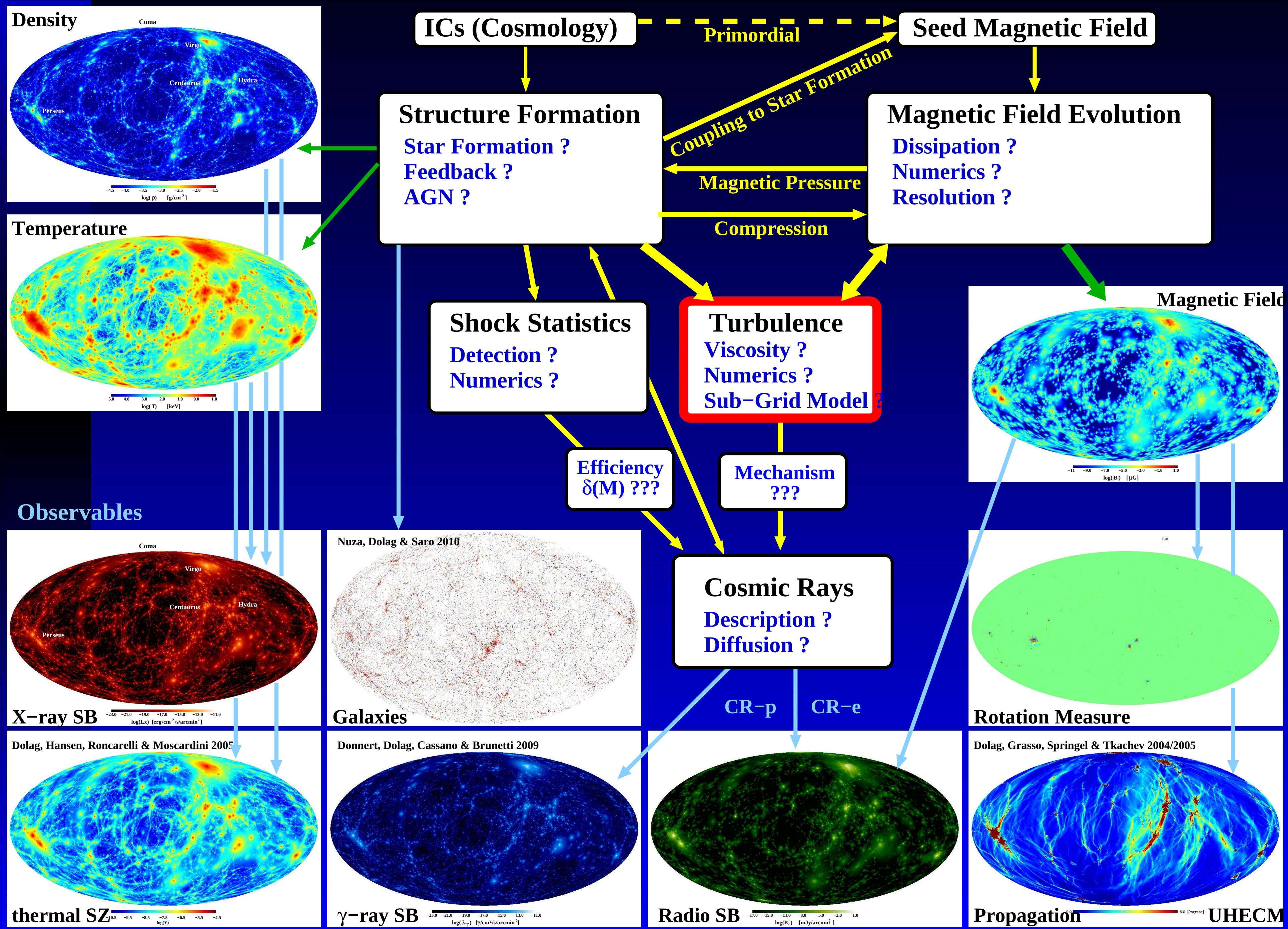

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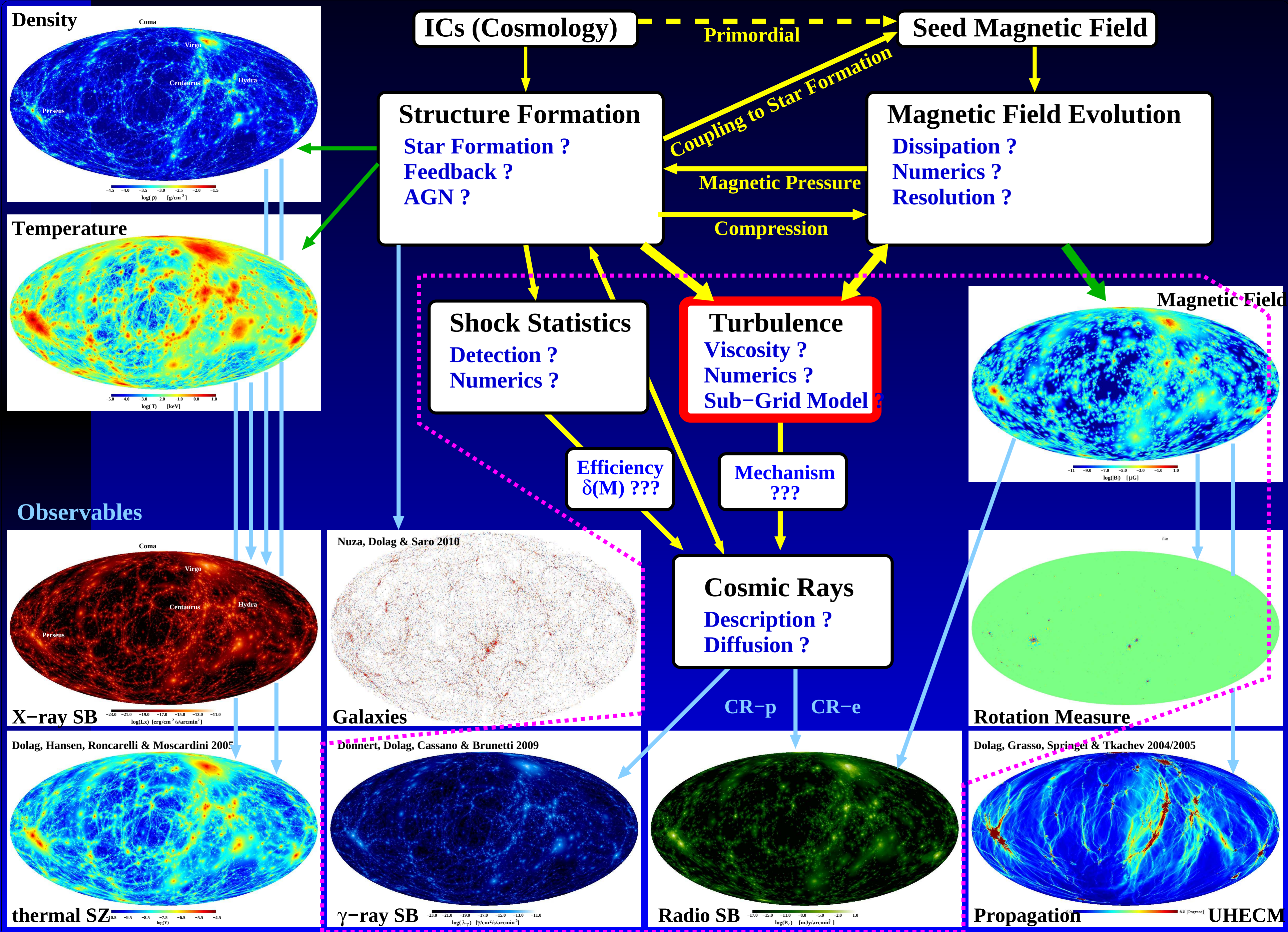
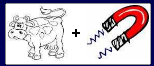
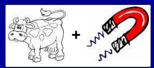
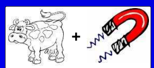
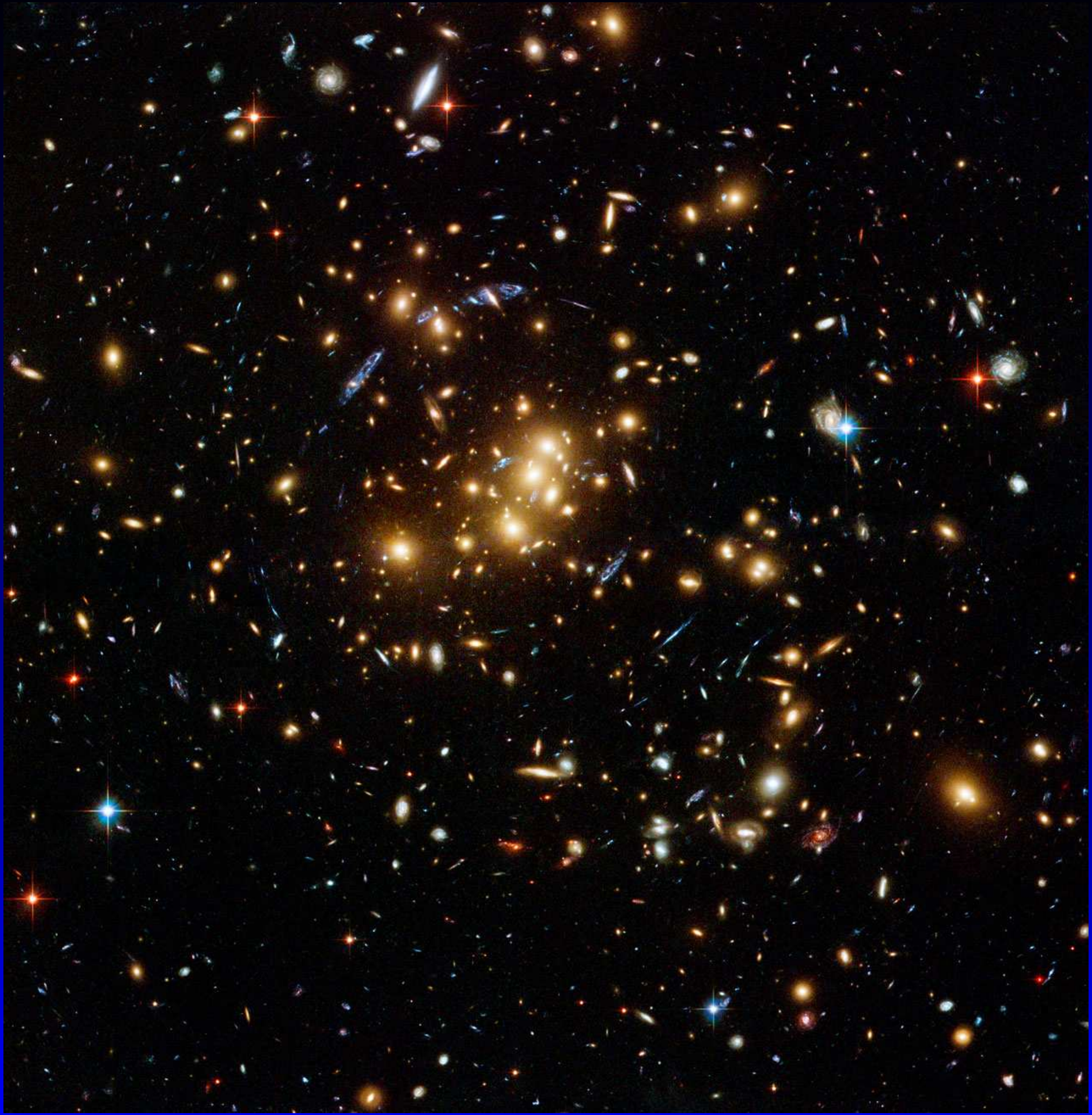


Outline

- Introduction
  Historic Milestones (Example: Coma cluster)
  Observations
  The Big Picture
   part 1
- Faraday Rotation Measures
  Cluster Samples
  Individual Clusters
  Constraing Magnetic Field properties
   part 2
- Diffuse Radio emission
  Radio Haloes
  Radio Relics
  Scaling relations
- Summary
   part 3



Cl 0024+17

NASA, ESA, M.J. Jee and H. Ford (Johns Hopkins University)

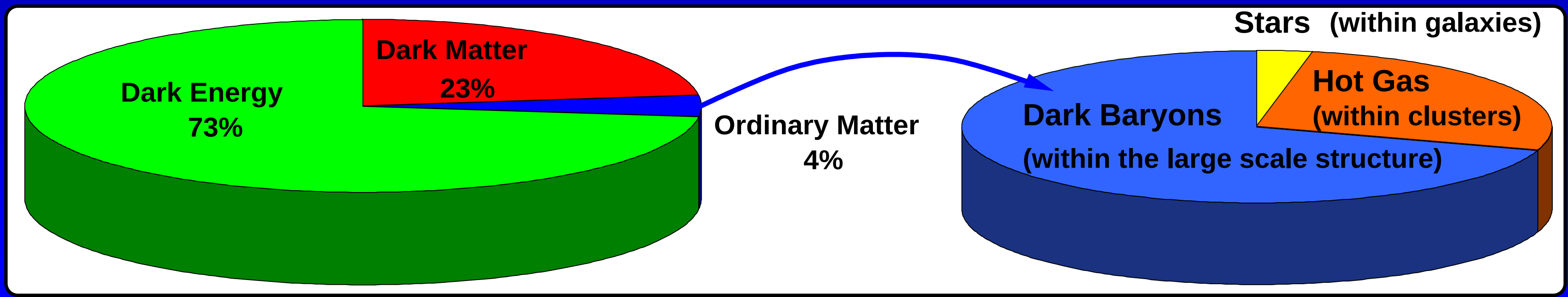
Galaxy Clusters in Numbers

Galaxy clusters are the largest, gravitationally bound objects in the Universe and represent an almost fair sample of the cosmological composition.

- Up to thousands of galaxies with $\sigma_{\rm gal}$ up to $1000\ {\rm km/s}$
- Size ($R_{\rm cluster}$) of several Mpc
- Large Reynolds numbers ($\Rightarrow$ turbulence)
- Total mass ($M_{\rm tot}$) up to several $10^{15} M_\odot$ ($\Rightarrow$ dark matter)
- Nearly cosmic baryon fraction ($\approx 95\%$)
- ICM temperatures ($T_{\rm ICM}$) higher than 10^8K

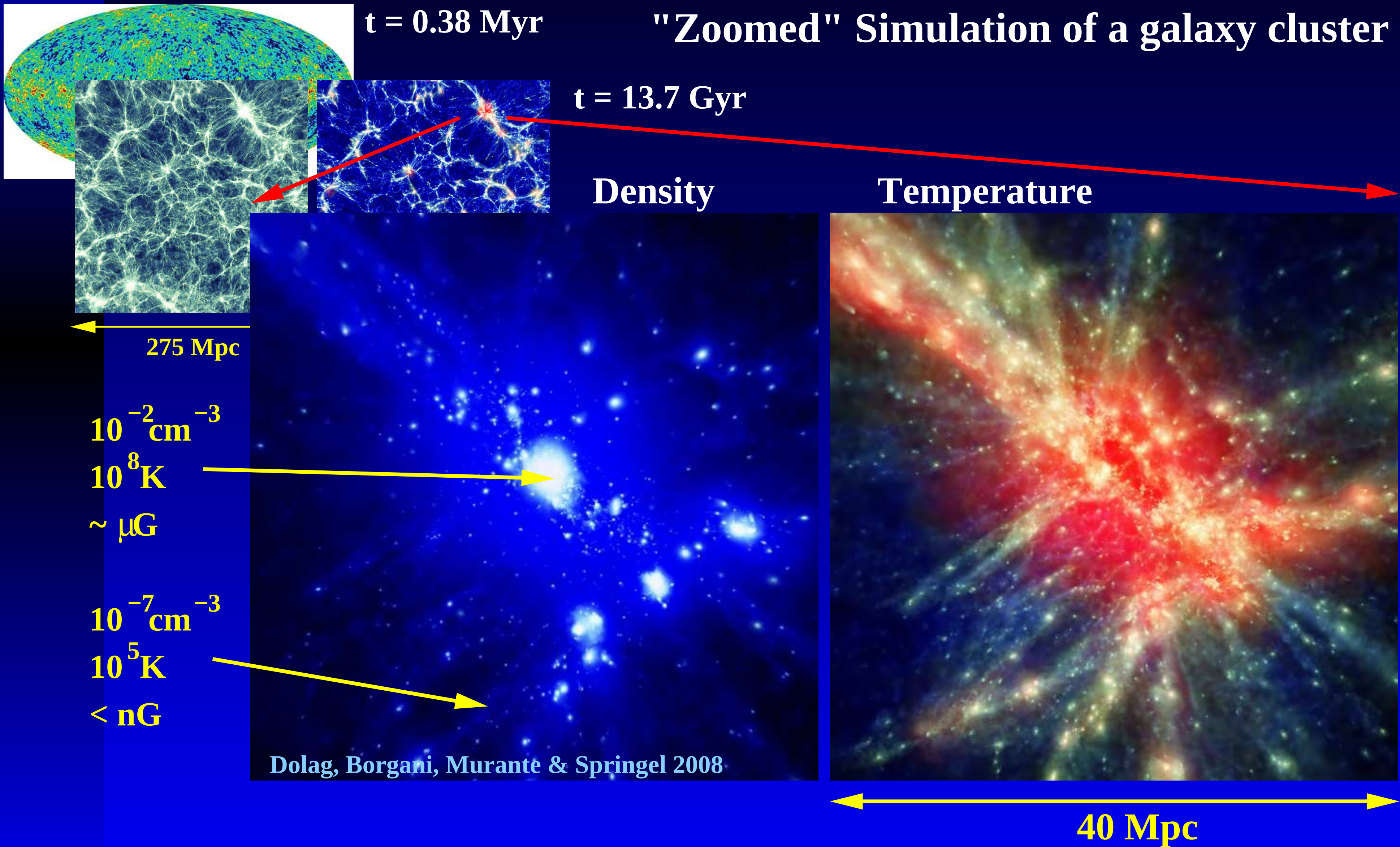
Observed to be virialized:

$$3\sigma^2_{\rm galaxies} \approx \frac{GM_{\rm tot}}{R_{\rm cluster}} \approx \frac{3kT_{\rm ICM}}{2\mu m_p}$$



Galaxy Clusters in Numbers

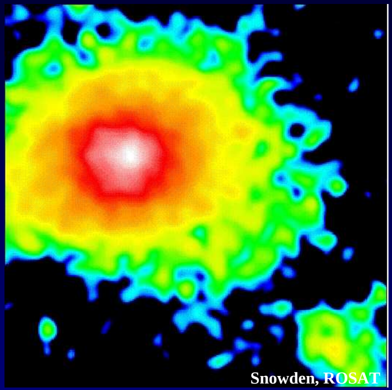
Clusters form at the nodes of the cosmic web and may be utilized to investigate the physical state of diffuse baryons.



$$v_{\mathrm{sound}} \approx 1500 > \sigma_{\mathrm{gal}} \approx 1000 > v_{\mathrm{turb}} \approx 300 > v_{\mathrm{Alfven}} \approx 100\ \mathrm{km/s}$$

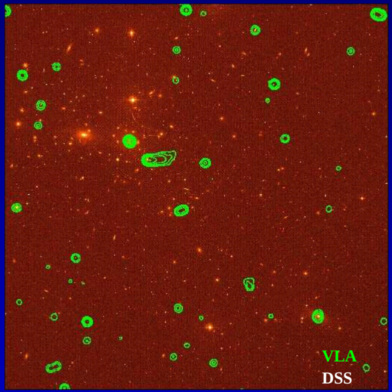
Galaxy Clusters in Numbers

Observations ($\Rightarrow$), Simulations ($\Leftarrow$) and the role of $\vec{B}$:



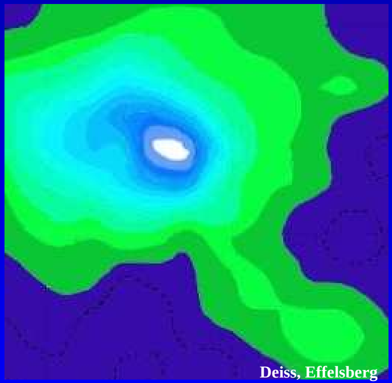
ICM (X-ray, $T \approx 10^8$K, Bremsstrahlung):

- $\Rightarrow$ Dynamical state of ICM
- $\Leftarrow$ Non thermal **pressure** support
- $\Leftarrow$ **Turbulence**, **Viscosity**, Shocks



Galaxies (optical, radio, $N_{\rm gal} > 1000$):

- $\Rightarrow$ Interaction with the ICM
- $\Leftarrow$ Galaxies in dense environment (**stripping**, distribution of metals)
- $\Leftarrow$ Magnetic field **seeding** (outflows)



ICM (radio, synchrotron radiation, RM):

- $\Rightarrow$ Distribution of $\vec{B}$, CRs (diffuse + RM)
- $\Leftarrow$ **Evolution** and **buildup** of $\vec{B}$
- $\Leftarrow$ **Acceleration** and **propagation** of CRs

110 Years Coma Cluster

	0m	59m	58m	57m	56m	55m	54m	53m	52m	51m	50m	49m	48m	47m	46m	45m	44m	43m	42m	41m	40m	39m	38m	37m	36m	35m	
59° 15′	—	—	—	—	—	1	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	—	—	—	—	—
30	—	—	—	—	0	0	2	1	3	1	2	1	3	2	1	1	2	0	0	2	1	0	0	—	—	—	—
45	—	—	—	0	1	4	2	0	1	1	3	1	0	1	2	0	1	2	0	1	1	0	0	1	—	—	—
60° 0′	—	—	0	0	2	1	0	1	1	2	2	1	0	2	3	0	1	3	5	0	0	2	0	0	0	—	—
15	—	0	0	2	3	3	7	3	5	5	2	1	4	1	3	1	2	0	0	0	3	5	0	1	0	0	—
30	—	0	2	3	4	3	2	3	5	3	1	3	0	0	0	2	4	1	0	0	0	3	2	0	0	2	0
45	0	1	4	5	9	16	12	15	5	3	1	4	2	1	4	1	2	1	1	0	1	2	4	0	1	0	0
61° 0′	0	1	5	15	19	10	23	15	19	8	4	3	4	2	1	0	1	1	1	0	1	1	1	2	0	0	4
15	0	0	9	17	11	14	36	68	10	7	3	7	0	2	1	2	3	1	1	3	0	4	4	3	0	2	1
30	1	2	2	9	6	12	13	17	20	16	6	7	1	2	1	1	1	1	4	1	1	5	3	1	6	3	1
45	0	5	5	10	8	8	12	9	10	11	4	5	4	2	5	2	6	5	2	1	2	2	1	3	2	2	3
62° 0′	0	2	1	3	6	8	3	10	7	3	5	4	2	4	6	8	3	2	2	5	0	3	9	10	10	2	2
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30	—	—	0	0	4	0	0	8	0	2	0	0	0	2	4	3	3	4	4	2	8	2	2	2	0	0	—
45	—	—	—	0	2	0	1	4	1	1	1	6	4	2	0	0	5	4	2	1	5	1	1	3	0	—	—
64° 0′	—	—	—	—	0	3	0	0	0	0	1	7	1	2	6	4	3	7	2	4	0	0	0	—	—	—	—
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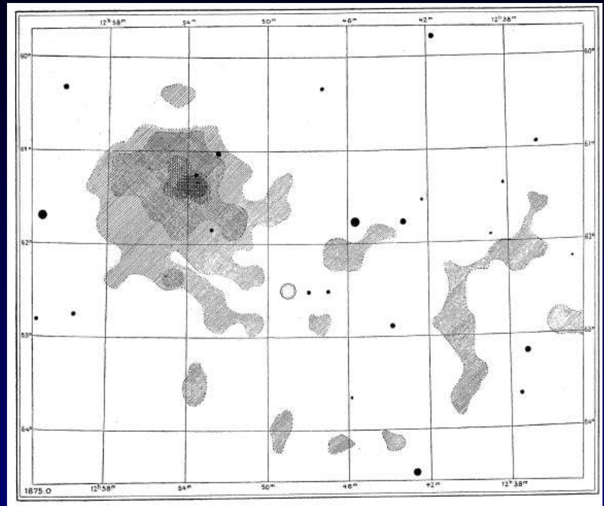

Nebelvertheilung um den Pol der Milchstrasse

Max Wolf, 1901/1902

Ein merkwürdiger Haufen von Nebelflecken.

Auf zwei mit dem Bruce-Teleskop genommenen Aufnahmen vom 24. März dieses Jahres, welche die Umgebung von 31 Comae Berenices darstellen, findet sich eine sehr interessante Gegend des Himmels. Um die Stelle

$$\alpha = 12^h\,52^m\!.6 \quad \delta = +28°\,42' \quad (1855.0)$$

stehen nämlich zahlreiche kleine Nebelflecken so dicht beisammen, dass man beim Anblick der Gegend förmlich über das merkwürdige Aussehen dieses »Nebelhaufens« erschrickt. Ich habe die Anzahl der Nebel in einem Kreis von 30′ Durchmesser um die angegebene Stelle bestimmt und finde, dass mindestens 108 Nebelflecken auf dieser Fläche beisammen stehen, also auf einer Fläche etwa von der Grösse des Vollmondes. Darunter sind vier oder fünf grössere ausgedehnte und centralverdichtete Nebel, sowie mehrere langgestreckte. Die weitaus meisten haben aber rundliche Form und sind kleiner. *)

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59° 15′	—	—	—	—	—	1	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	—	—	—	—	—
30	—	—	—	—	0	0	2	1	3	1	2	1	3	2	1	1	2	0	0	2	1	0	0	—	—	—	—
45	—	—	—	0	1	4	2	0	1	1	3	1	0	1	2	0	1	2	0	1	1	0	0	1	—	—	—
60° 0′	—	—	0	0	2	1	0	1	1	2	2	1	0	2	3	0	1	3	5	0	0	2	0	0	0	—	—
15	—	0	0	2	3	3	7	3	5	5	2	1	4	1	3	1	2	0	0	0	3	5	0	1	0	0	—
30	—	0	2	3	4	3	2	3	5	3	1	3	0	0	0	2	4	1	0	0	0	3	2	0	0	2	0
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45	—	0	1	5	2	3	1	3	6	4	6	2	0	6	2	4	3	5	2	6	10	5	3	1	1	7	6
63° 0′	—	0	2	2	2	3	0	0	0	0	1	1	1	1	2	4	0	2	4	2	7	5	0	4	0	2	2
15	—	1	1	2	0	3	0	8	1	1	0	0	0	2	2	1	0	5	3	5	3	8	4	1	2	1	—
30	—	—	0	0	4	0	0	8	0	2	0	0	0	2	4	3	3	4	4	2	8	2	2	2	0	0	—
45	—	—	—	0	2	0	1	4	1	1	1	6	4	2	0	0	5	4	2	1	5	1	1	3	0	—	—
64° 0′	—	—	—	—	0	3	0	0	0	0	1	7	1	2	6	4	3	7	2	4	0	0	0	—	—	—	—
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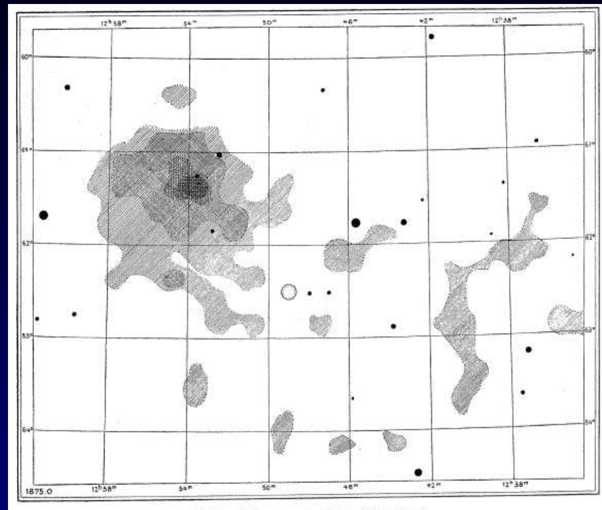

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numerous small nebulae are standing such close together, that once literally frightens in sight of the remarkable appearance of this cluster of nebulae.

110 Years Coma Cluster

	0m	59m	58m	57m	56m	55m	54m	53m	52m	51m	50m	49m	48m	47m	46m	45m	44m	43m	42m	41m	40m	39m	38m	37m	36m	35m	
59° 15′	—	—	—	—	—	1	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	—	—	—	—	—
30	—	—	—	—	0	0	2	1	3	1	2	1	3	2	1	1	2	0	0	2	1	0	0	—	—	—	—
45	—	—	—	0	1	4	2	0	1	1	3	1	0	1	2	0	1	2	0	1	1	0	0	1	—	—	—
60° 0′	—	—	0	0	2	1	0	1	1	2	2	1	0	2	3	0	1	3	5	0	0	2	0	0	0	—	—
15	—	0	0	2	3	3	7	3	5	5	2	1	4	1	3	1	2	0	0	0	3	5	0	1	0	0	—
30	—	0	2	3	4	3	2	3	5	3	1	3	0	0	0	2	4	1	0	0	0	3	2	0	0	2	0
45	0	1	4	5	9	16	12	15	5	3	1	4	2	1	4	1	2	1	1	0	1	2	4	0	1	0	0
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45	0	5	5	10	8	8	12	9	10	11	4	5	4	2	5	2	6	5	2	1	2	2	1	3	2	2	3
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15	0	3	1	6	5	10	11	9	1	10	7	1	5	3	4	4	3	2	3	3	6	4	1	5	2	3	1
30	—	0	1	4	4	1	2	4	8	4	2	1	2	1	2	3	4	2	1	3	9	4	3	2	4	5	3
45	—	0	1	5	2	3	1	3	6	4	6	2	0	6	2	4	3	5	2	6	10	5	3	1	1	7	6
63° 0′	—	0	2	2	2	3	0	0	0	0	1	1	1	1	2	4	0	2	4	2	7	5	0	4	0	2	2
15	—	1	1	2	0	3	0	8	1	1	0	0	0	2	2	1	0	5	3	5	3	8	4	1	2	1	—
30	—	—	0	0	4	0	0	8	0	2	0	0	0	2	4	3	3	4	4	2	8	2	2	2	0	0	—
45	—	—	—	0	2	0	1	4	1	1	1	6	4	2	0	0	5	4	2	1	5	1	1	3	0	—	—
64° 0′	—	—	—	—	0	3	0	0	0	0	1	7	1	2	6	4	3	7	2	4	0	0	0	—	—	—	—
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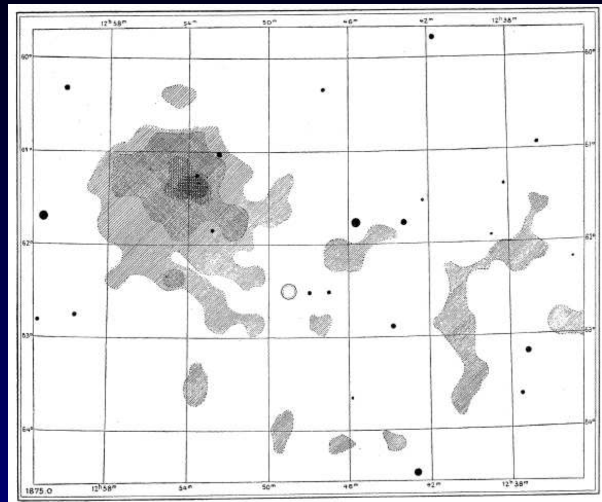


Nebelvertheilung um den Pol der Milchstrasse

Max Wolf, 1902

the regular behavior within the arrangement of these distant worlds

Es ist sofort zu sehen, wenn man die Tabelle oder die Tafel betrachtet, dass das Zusammendrängen der Nebel immer stärker wird, je weiter man in's Innere der Hauptinsel eindringt. Je näher man dem Puncte grösster Dichtigkeit kommt, umso dichter treten auch die Nebel an einander, so dass auf dem innersten Quadratgrad mehr als 320 einzelne Nebelflecken beisammen stehen. An der dichtesten Stelle dieses »Weltpoles« finden sich mehr als 70 Nebel auf der Fläche von $^1/_{16}$ Quadratgrad.

Wir finden also hier ein völlig gesetzmässiges Verhalten in der Anordnung dieser fernen Welten; und dieser ungeheure Reichthum führt uns so eine Ordnung im Weltsystem vor Augen, die sicher für die Erkenntniss des Universums von allergrösster Bedeutung ist, von der wir uns aber auch zugestehen müssen, dass wir noch lange keine erschöpfende Erklärung für sie werden finden können.*)

of greatest significance for understanding the universe

Historical Milestones

$\approx$70 Years ago:

Unvisible matter needed to explain cluster dynamics

Zwicky 1936

$\approx$50 Years ago:

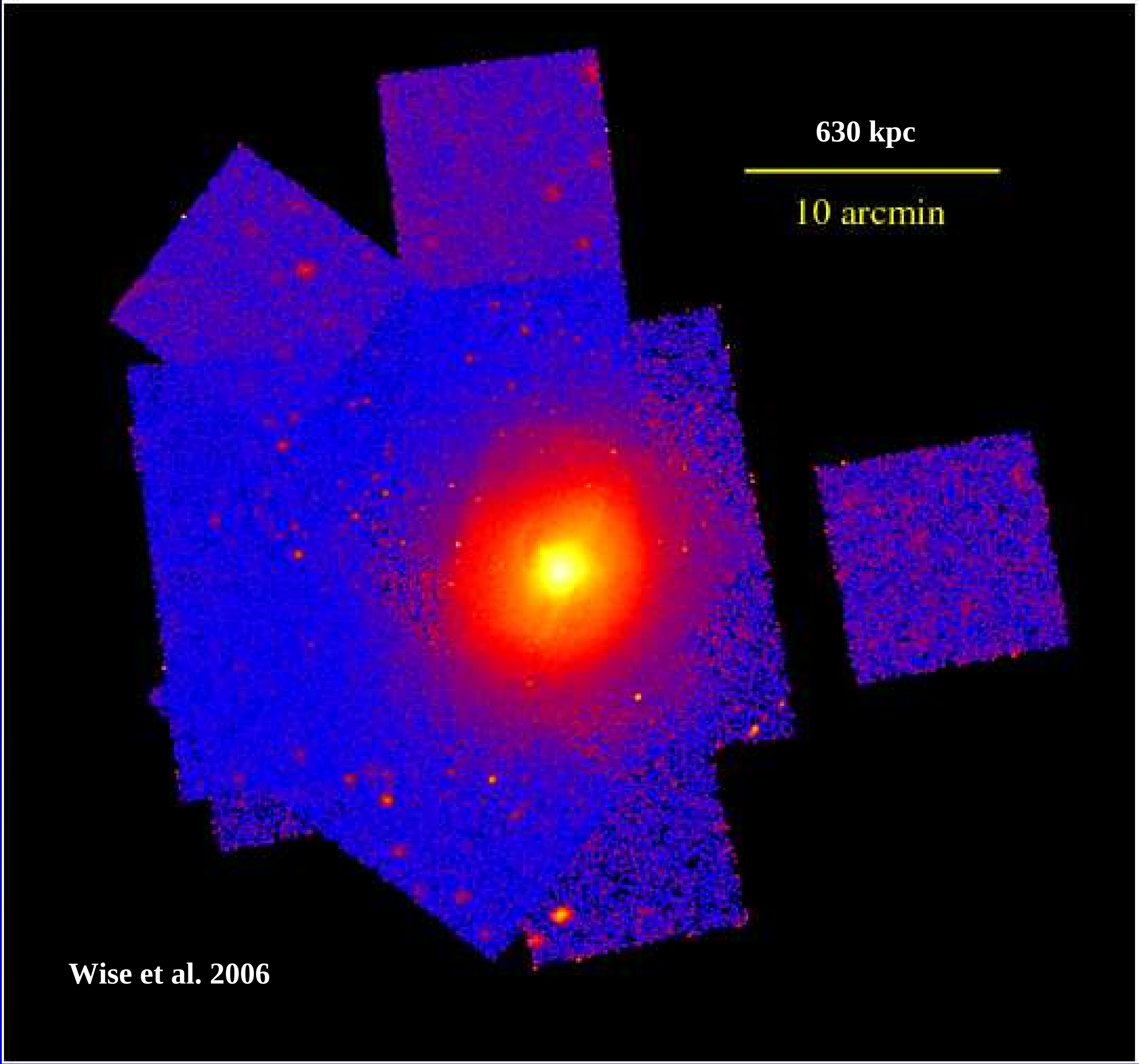
- Coma C detected as extended radio source
  Large, Masthewson & Haslam 1959
- Confirmed to be diffuse radio emission
  Willson 1970 $\Rightarrow$ problem of large extend Jaffe 1977
- Diffuse X-ray emission detected
  Meekins, Fritz, Chubb & Friedman 1971
- Faraday Rotation (RM) of ICM detected
  Dennison 1979
- No similar emission found in 72 rich clusters
  Hanisch 1982

$\Rightarrow$ What is the origin of the magnetic field ?

$\Rightarrow$ What causes the diffuse radio emission ?

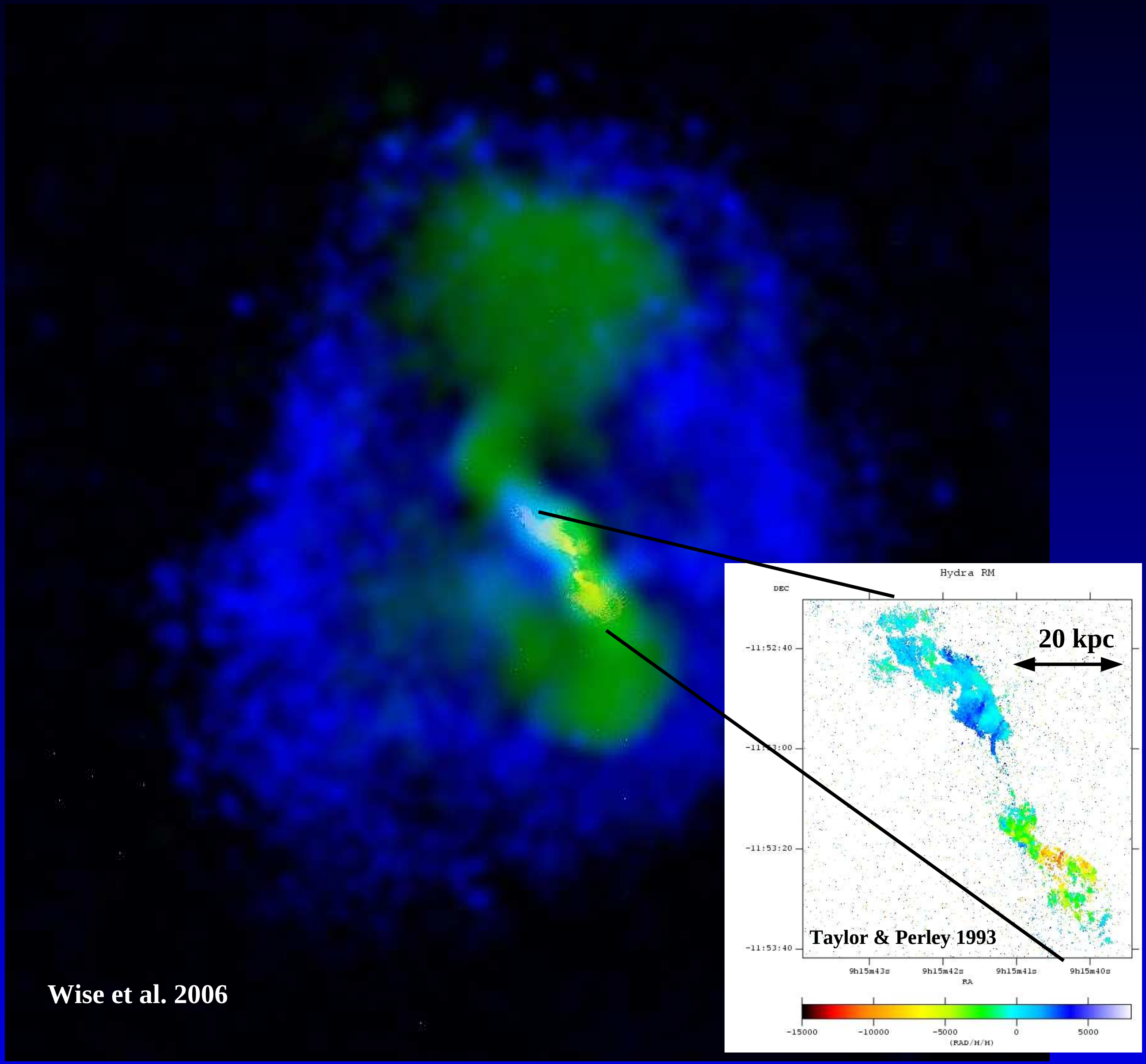
$\Rightarrow$ Magnetic fields on larger scales ?

Cool core clusters



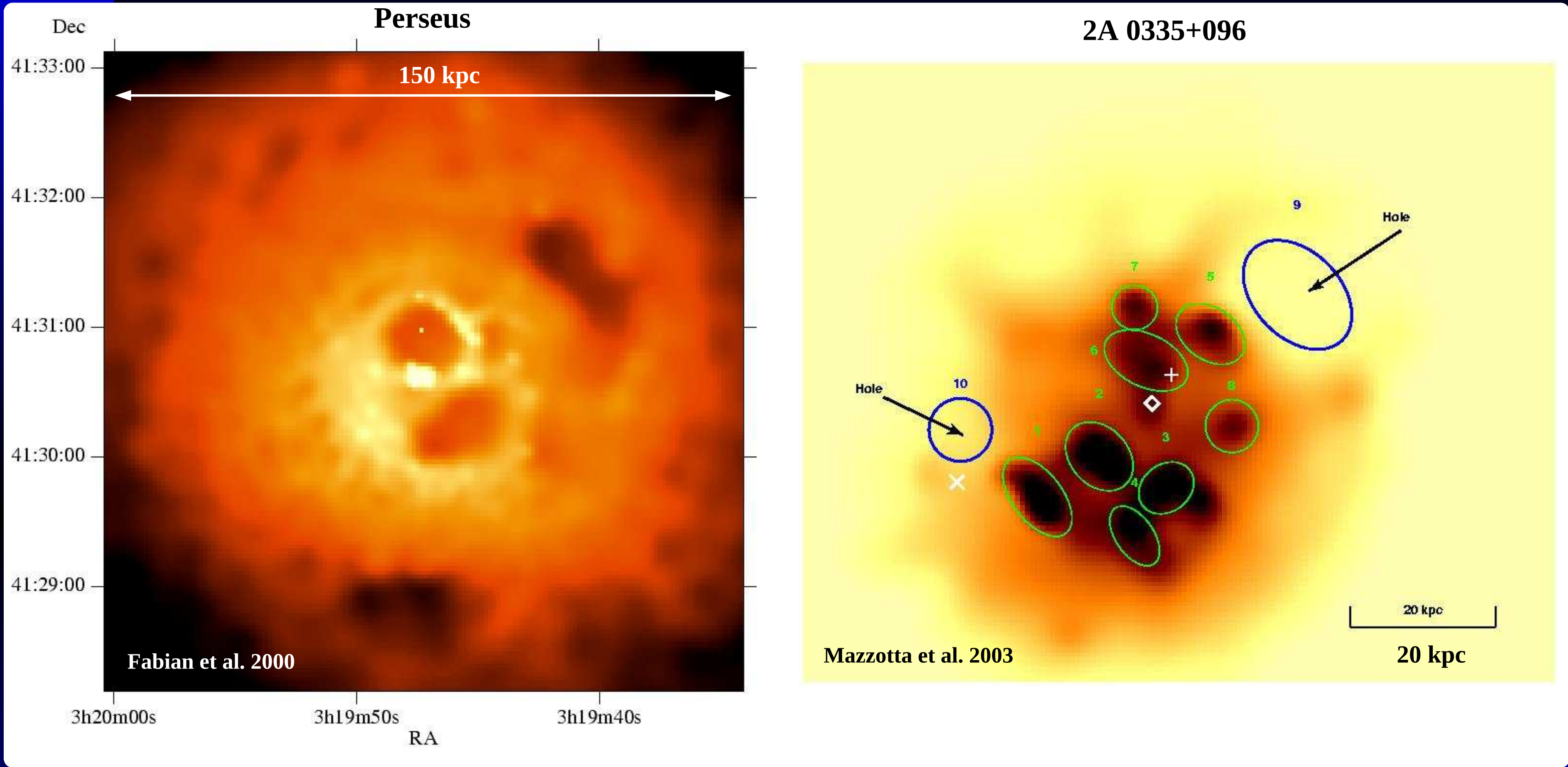
Chandra **X-ray** image (**ICM**) of the Hydra cluster (cool core)

Cool core clusters



Composite image to illustrate the **connection** between the **X-ray cavity** (blue) and 330Mhz **radio emission** (green).

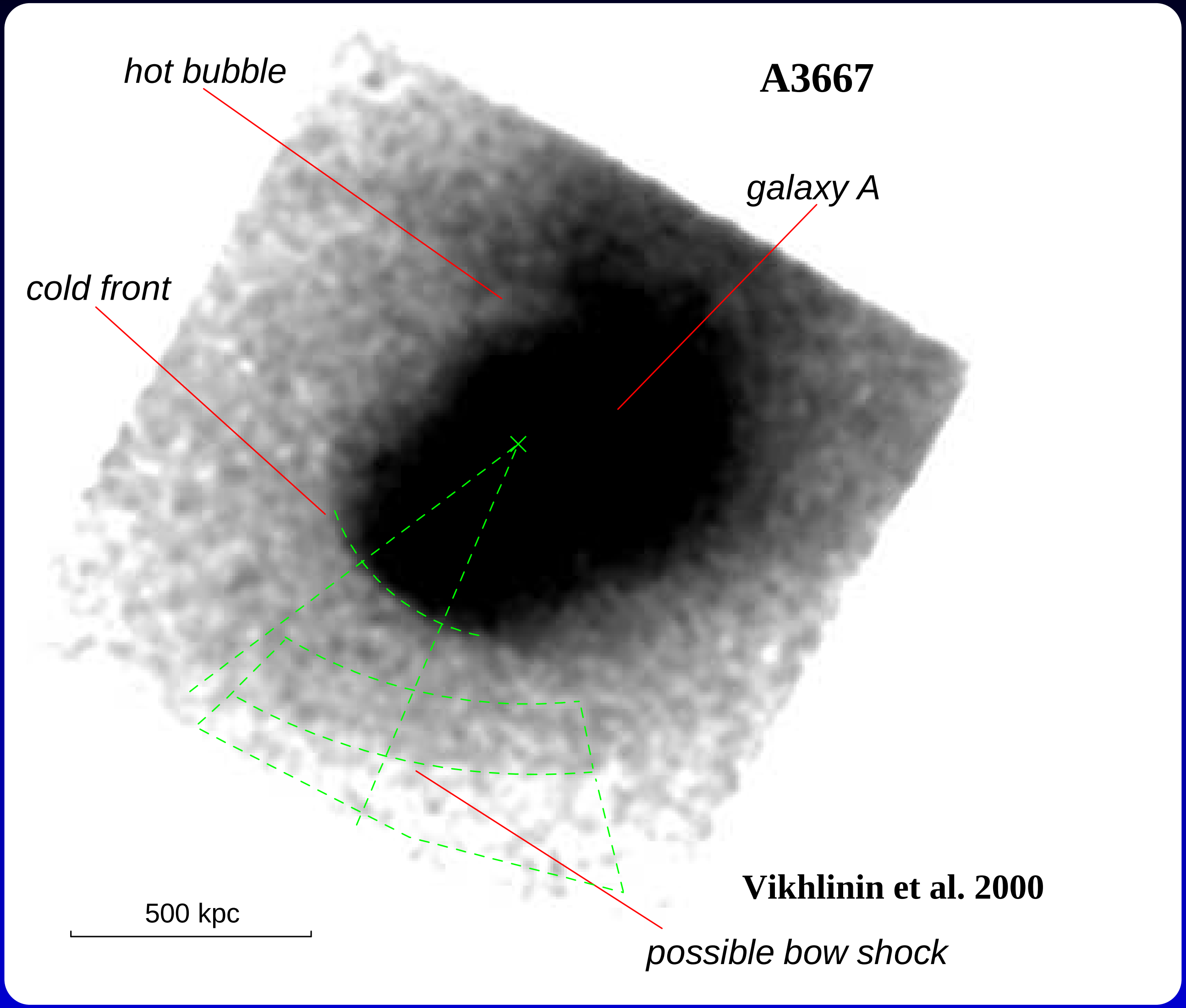
Cool core clusters



X-ray cavity in the cool core center of Perseus cluster (left) and 2A 0335+096 cluster (right). See work by E. Churazov.

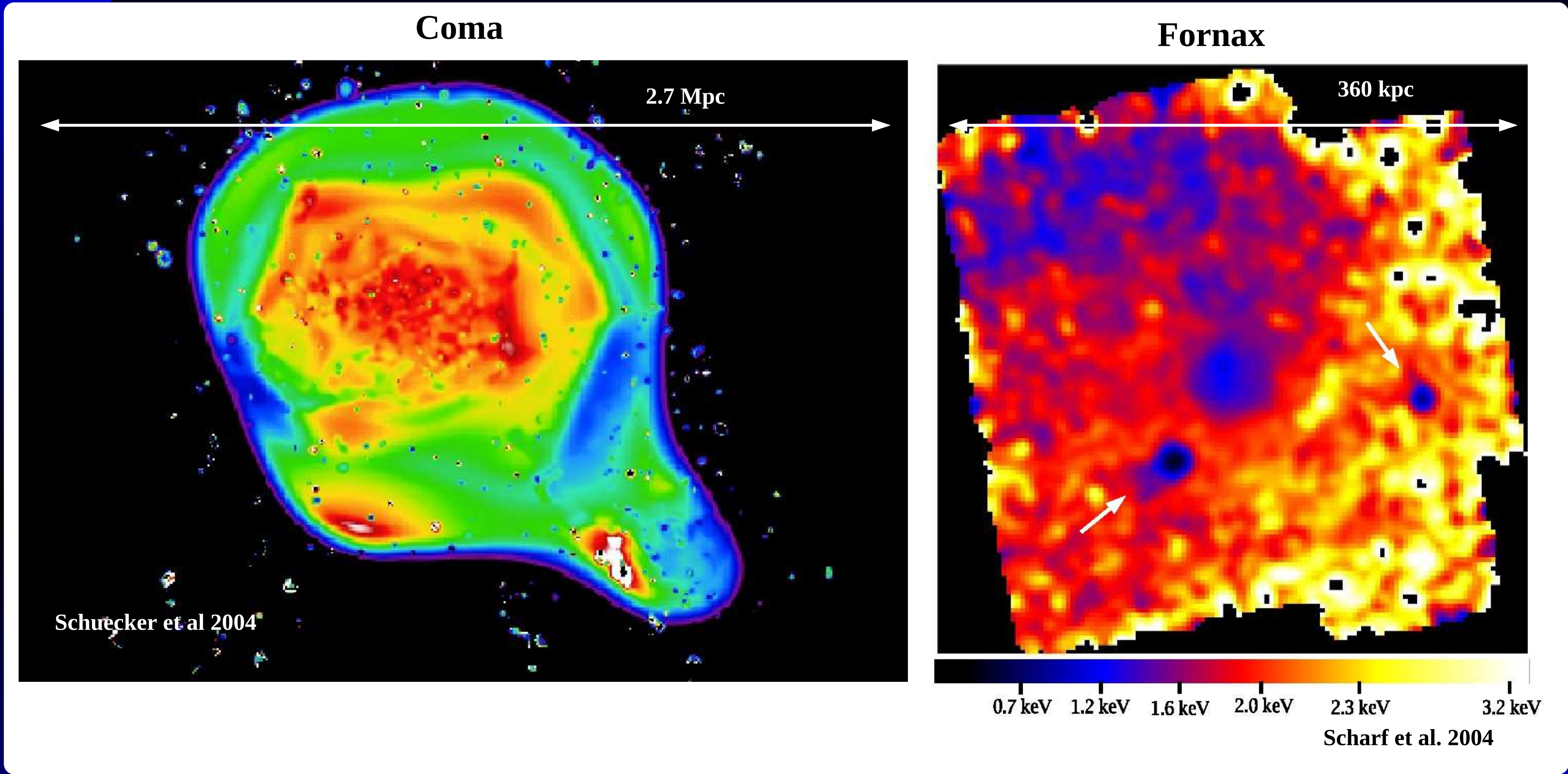
- Does energy injected by the AGN heats the cool core ?
- Does the motion of cores induce mixing ?
- Details remain jet unclear (viscosity, turbulence, instabilities (RT,KH) ...) ⇒ **magnetic field**

X-ray Clusters



X-ray image of the A3667 cluster, illustrating the sloshing of gas on large scales. Sharp fronts indicate suppression of thermal conduction. ⇒ **magnetic field**

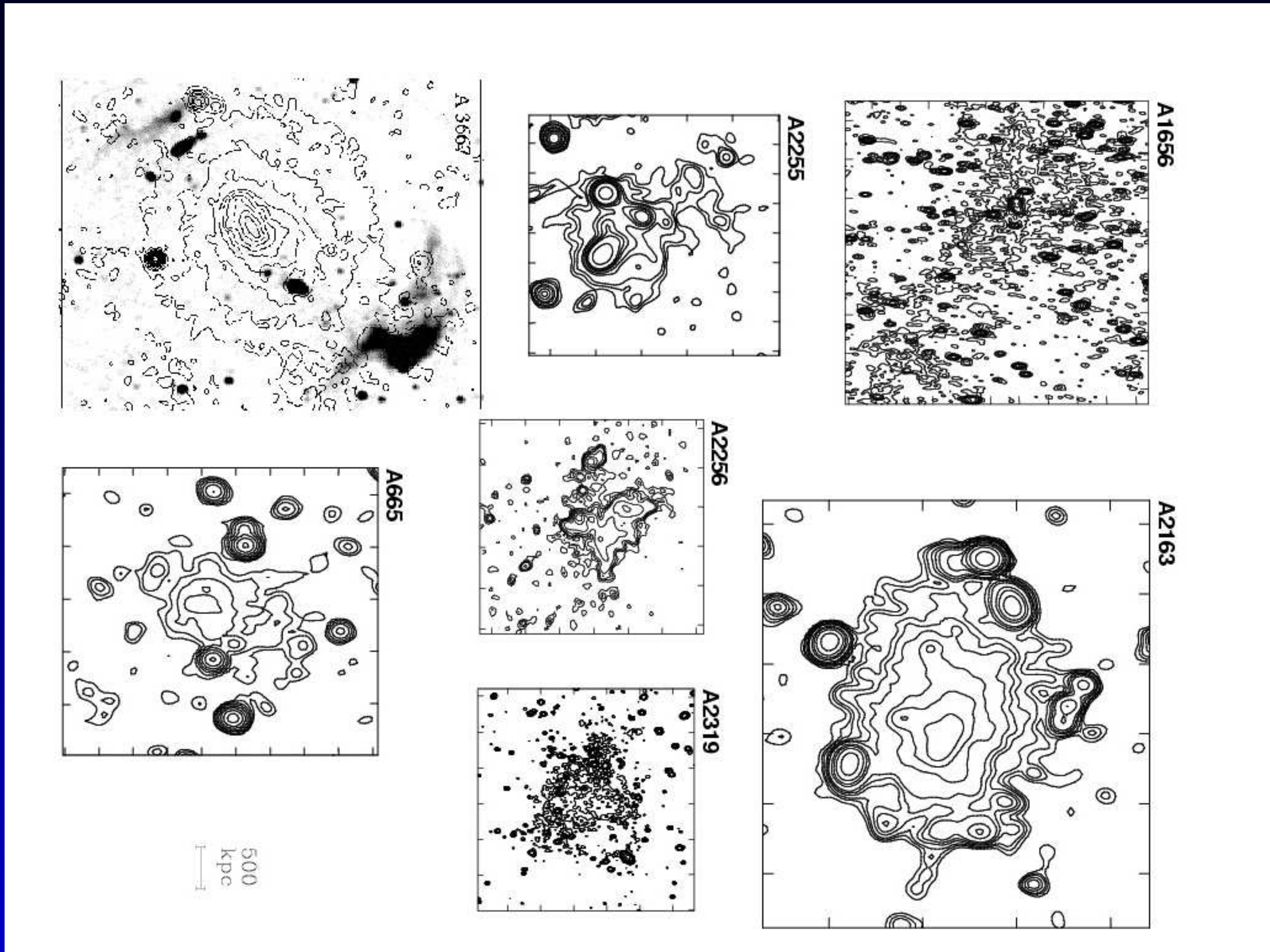
X-ray Clusters



X-ray temperature map of Coma (left) and Fornax cluster (right).

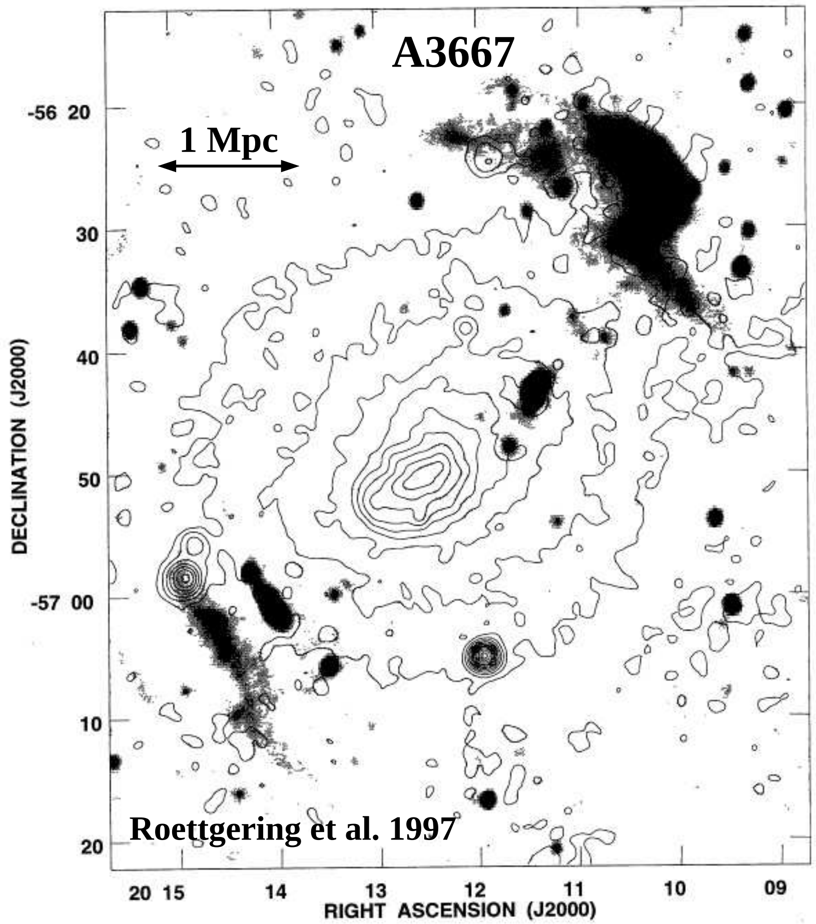
- How much turbulence is present in galaxy clusters ?
- How effective does gas stripping work ?
- Details still unexplored, again viscosity and instabilities depend on **magnetic field**

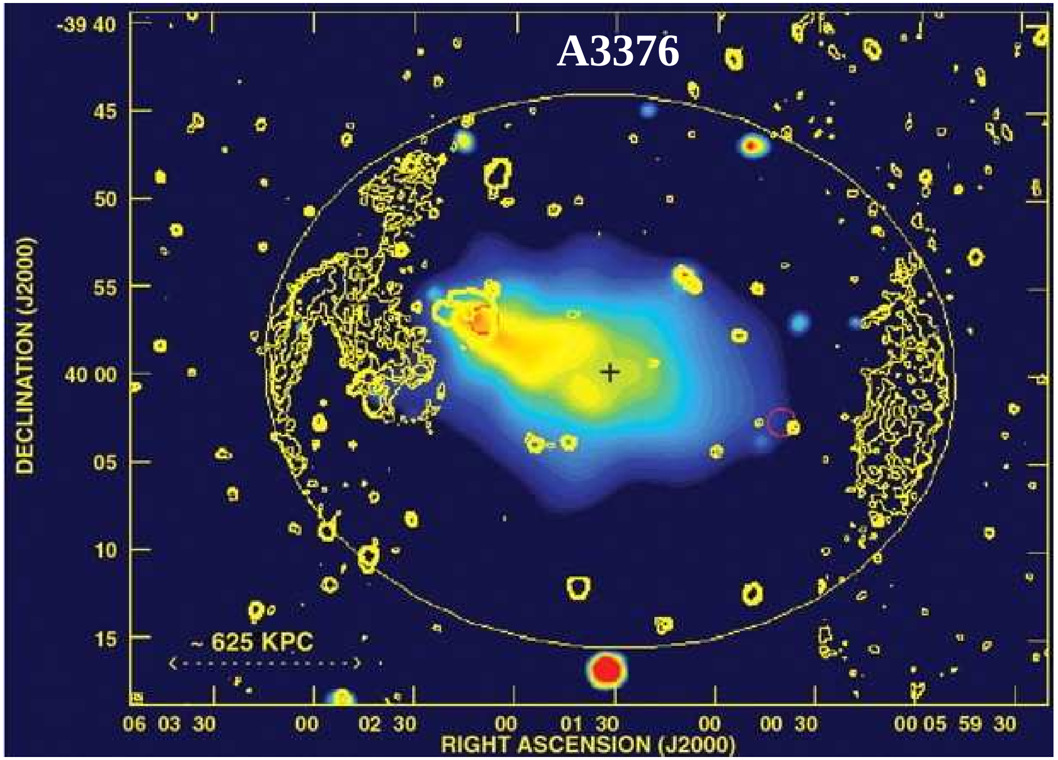
Radio Clusters



Cluster wide diffuse synchrotron emission (radio halos) of relativistic electrons in cluster magnetic fields. **Origin of relativistic electrons** (secondary, shocks, turbulence, ...) ?

Radio Clusters





Bagchi et al. 2006

Peripheral synchrotron emission (radio relics) of A3667 (left) and A3376 (right).

- Related to **merger** or accretion **shock** ?
- Acceleration of electrons in shock ?
- Revival of (old) relativistic plasma ?

Magnetic Field Questions

- Strength, Structure, Origin, Evolution

$\Rightarrow$ Common Origin ?
Filament vs. Cluster, Cluster vs. cool Core, ...

$\Rightarrow$ Relation to other LSS "properties" ?

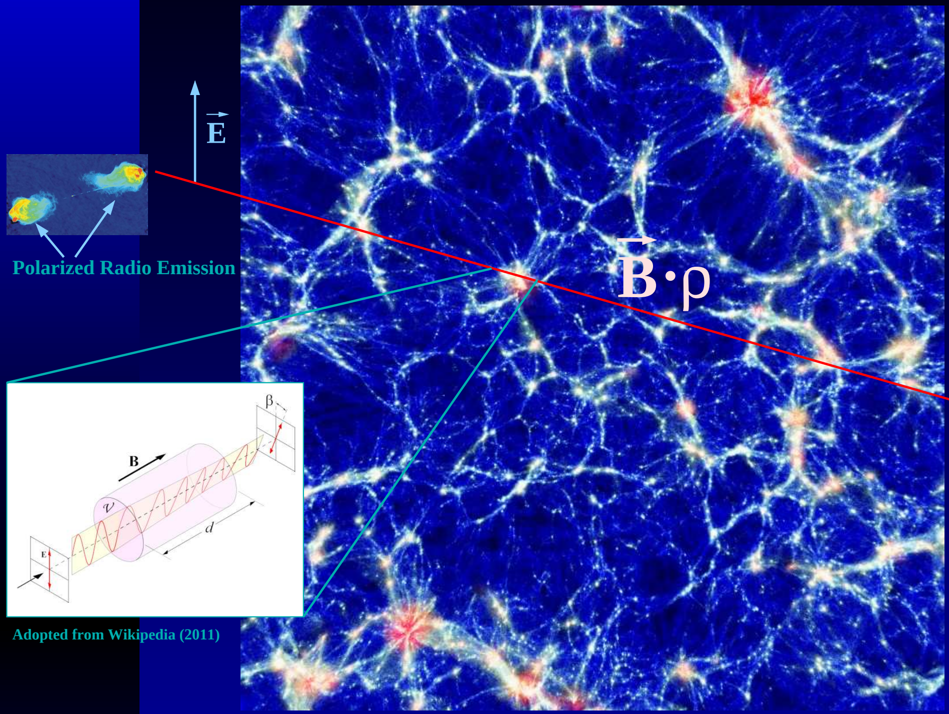
  - scaling with density ($\propto \rho^\alpha$) ?
  - scaling with temperature/mass ($\propto T^\beta$) ?
  - length scales, $P_B(k)$ (Filaments, Cluster, cool Core) ?

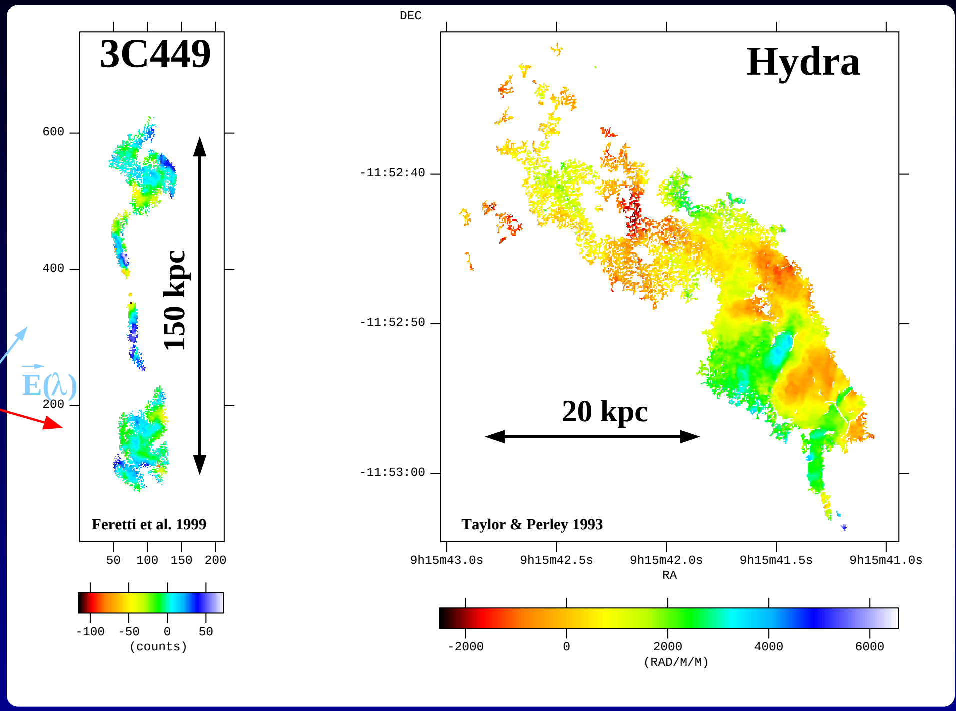
$\Rightarrow$ Relation to dynamics ?

  - Merger, Turbulence, cool Core, Bubbles ?

- Observations:
  - RM in clusters
  - Radio emission (halo and relics)

What do we know ?





High quality Rotation Measure maps across the lobes of the central radio source in 3C449 (left) and Hydra (right).

$$\mathrm{RM} \propto \int n_\mathrm{e}\, B_{\|}\, \mathrm{d}l \approx B_{\|}\sqrt{l}$$

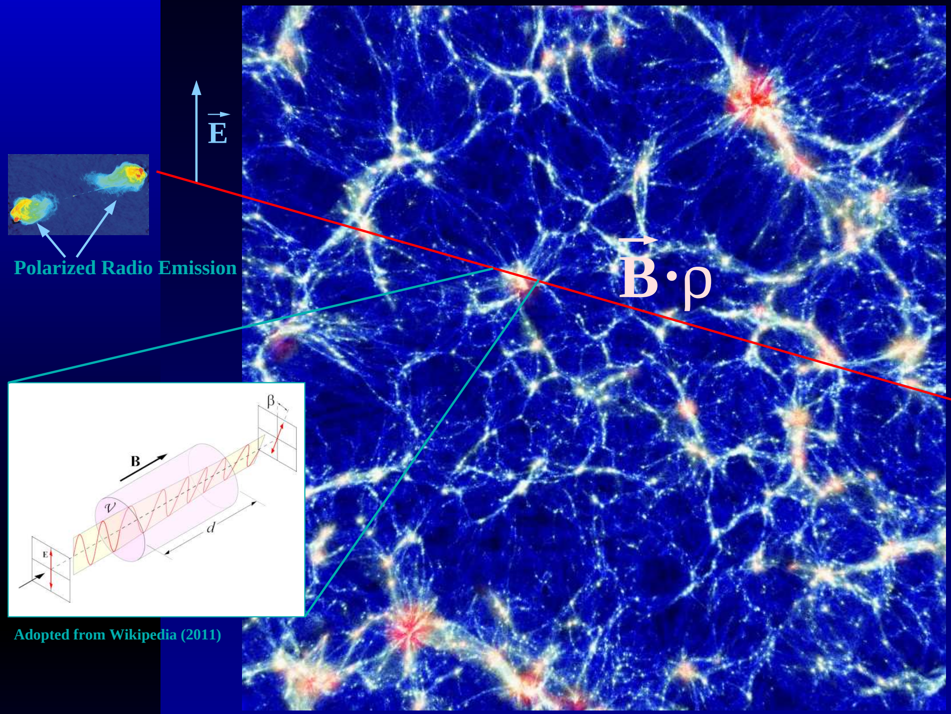
$\approx$20 Years ago:

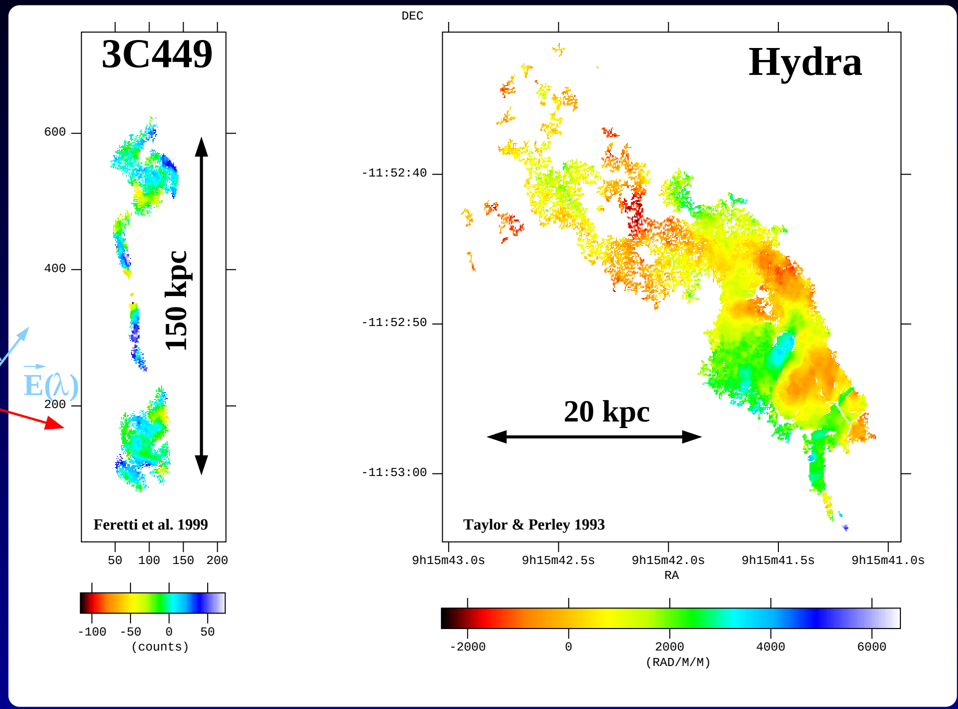
$<$ 10 extended RM sources within clusters

$<$ 100 point sources behind various clusters

$\Rightarrow$ very simplified models: $\sim (0.1 - 10)\mu\mathrm{G}$, $l \sim (4 - 100)\mathrm{kpc}$.

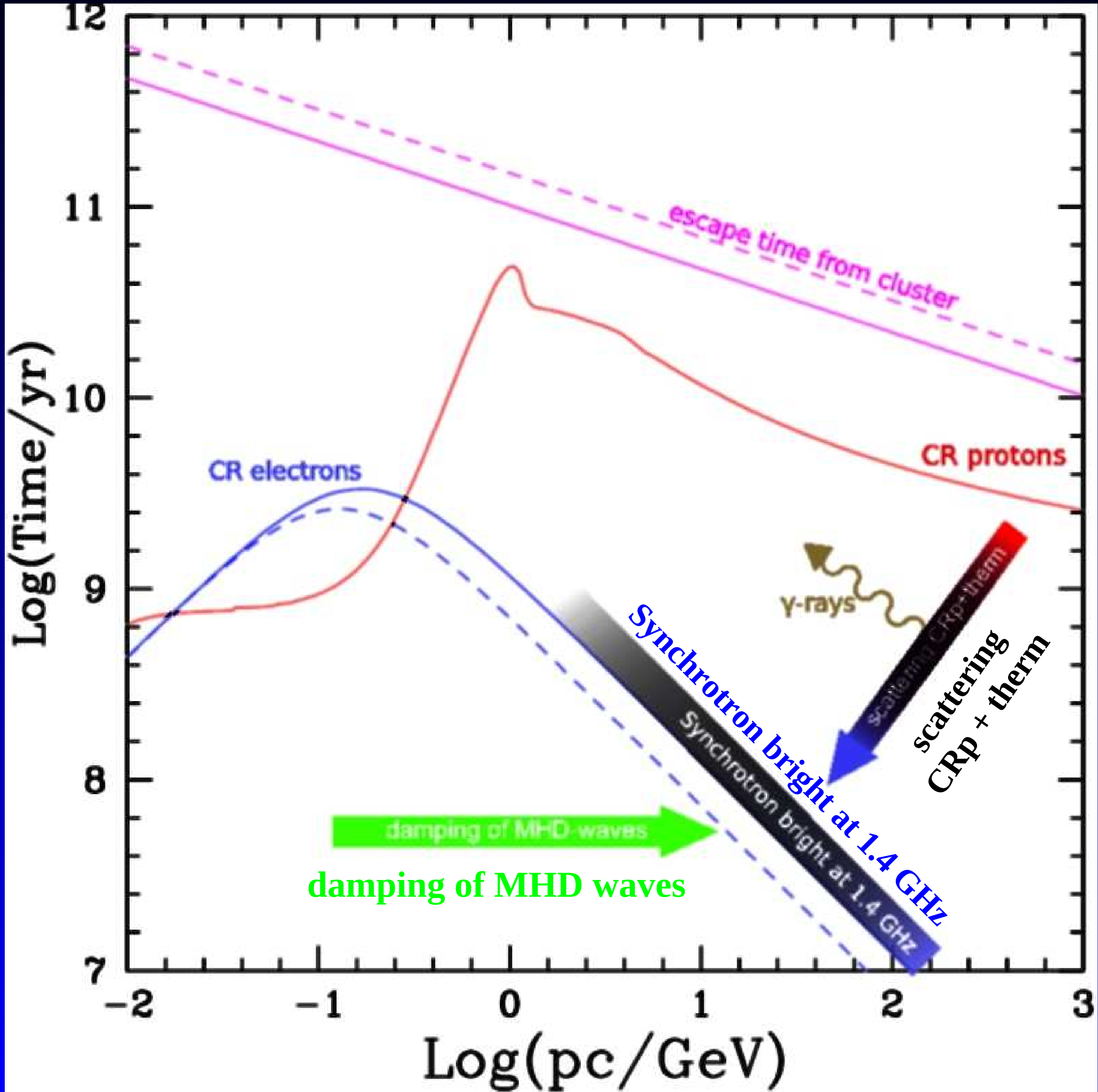
What do we know ?





- A119: $\vec{B}$ with radial declining profile and fixed power spectrum (Murgia et al. 2004)
- Hydra: direct reconstruction of power spectrum (e.g. $|B_k|^2$) (Vogt & Ensslin 2005, Kuchar & Ensslin 2010)
- A2255: $\vec{B}$ with radial declining profile and variable power spectrum (Govoni et al. 2006)
- Coma: RMs from 7 extended sources constraining magnetic field and power spectrum (Bonafede et al. 2009)
- A401, A2142, A2065, Ophiuchus: magnetic field for clusters with different temperature (Govoni et al. 2009)

What do we know ?

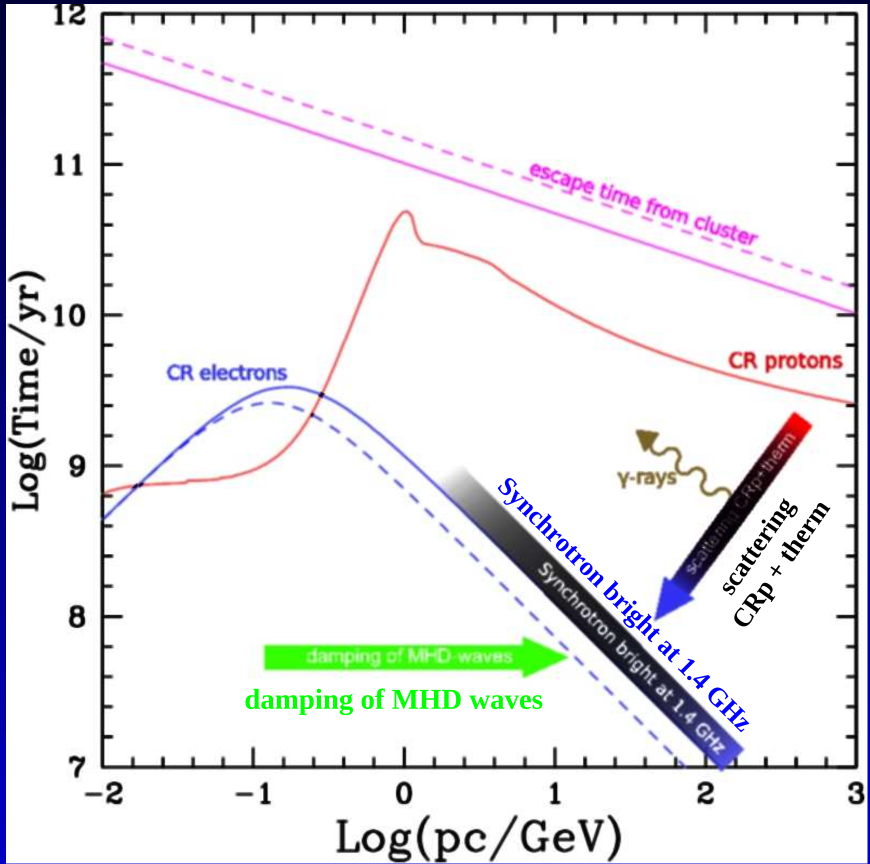


taken from Donnert 2013

What do we know ?

- Early work on radio halos (individual clusters)

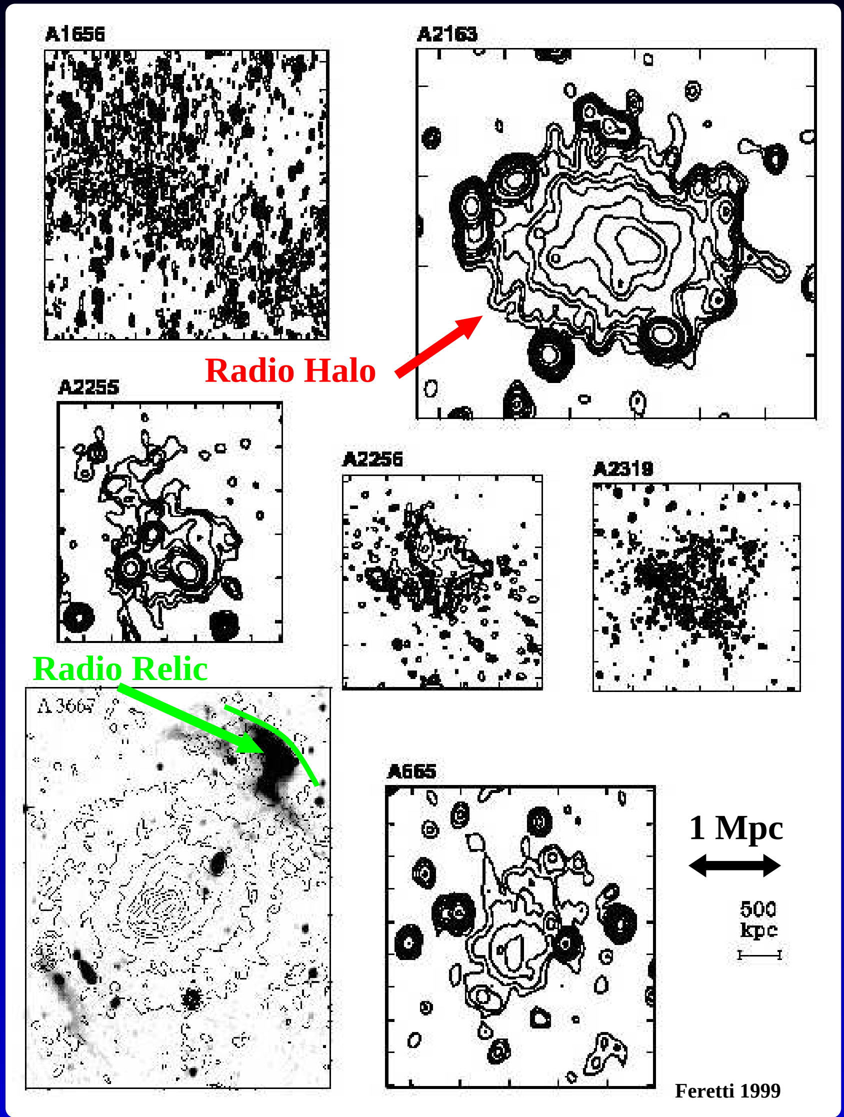
≈ 10 clusters with diffuse emission: $> (0.05 - 0.5)\mu\mathrm{G}$

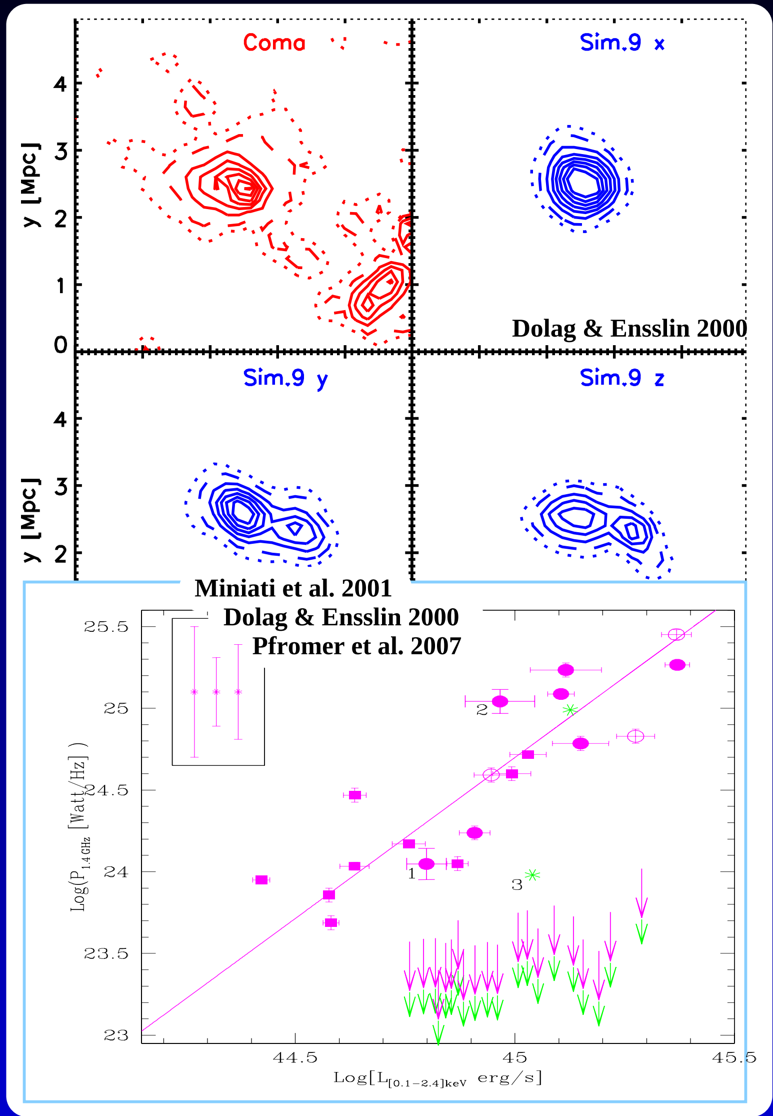


⇒ **Increased numbers and complexity:**

- Global spectral index steepening / local index maps
- Radial radio emission profile for many clusters
- Probability for clusters to host a radio halo

What do we know ?



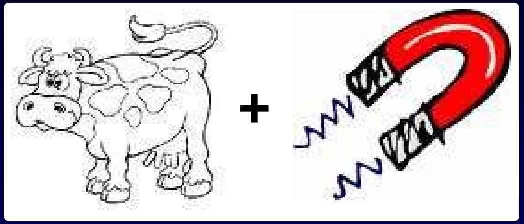


Cluster wide **diffuse synchrotron emission** connected to **merger** events, **periferal** emission directly connected to **shocks**.

- **Radio halo**: Turbulence, shocks, secondary ?
- **Relics**: Primary from shocks or compressed radio plasma ?

Note on magnetic fields

Always be careful, as things can be much more complicated as you think !



Example: **Magnetic Cows**: “Magnetic alignment in grazing and resting cattle and deer”, Begall et al. 2008

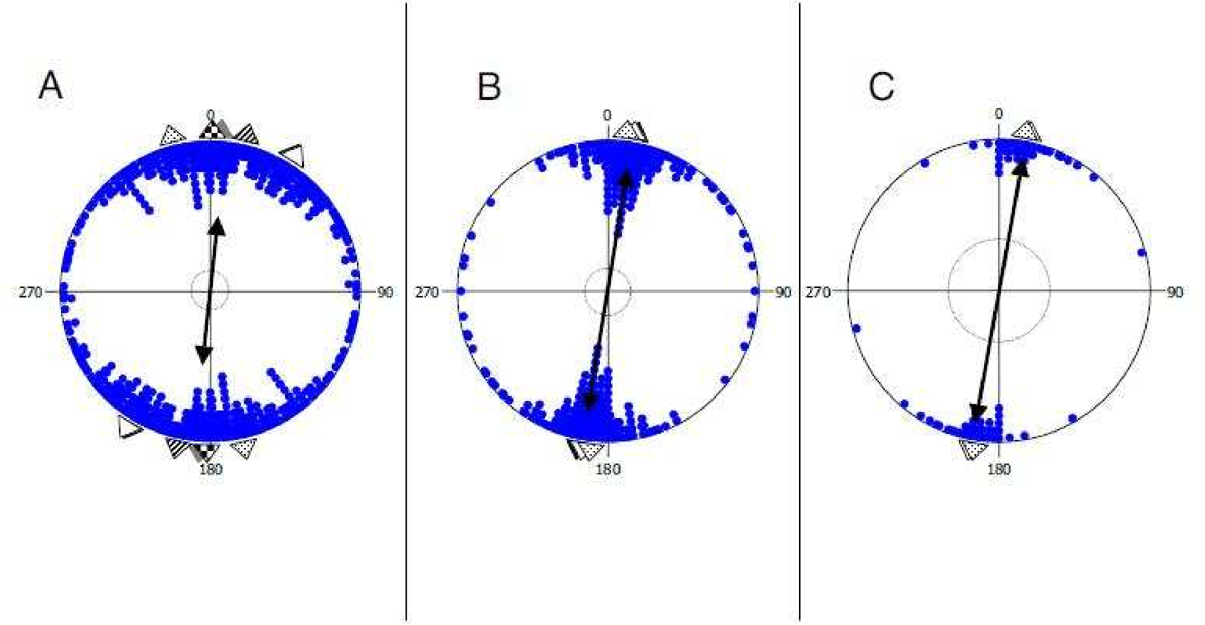
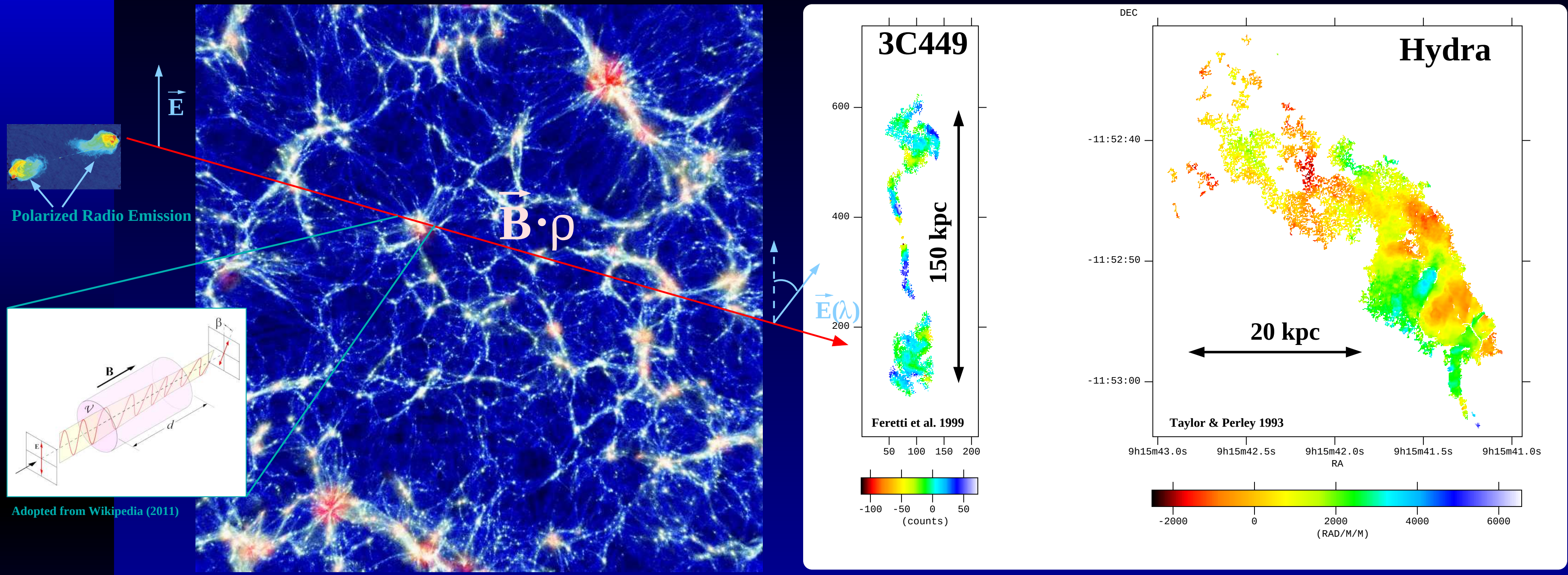


Fig. 1. Axial data revealing the N-S alignment in three ruminant species under study. (*A*) Cattle. (*B*) Roe deer. (*C*) Red deer. Each pair of dots (located on opposite sites within the unit circle) represents the direction of the axial mean vector of the animals' body position at one locality. The mean vector calculated over all localities of the respective species is indicated by the double-headed arrow. The length of the arrow represents the *r*-value (length of the mean vector), dotted circles indicate the 0.01-level of significance. Triangles positioned outside the unit circle indicate the mean vectors of the cattle data subdivided into the six continents (dotted: North America; gray: Asia; checkered: Europe; striped: Australia; black: Africa; white: South America) (*A*) and the mean vectors of resting (black) and grazing (white) deer, and of deer beds (dotted) (*B*: roe deer; *C*: red deer).

Observations

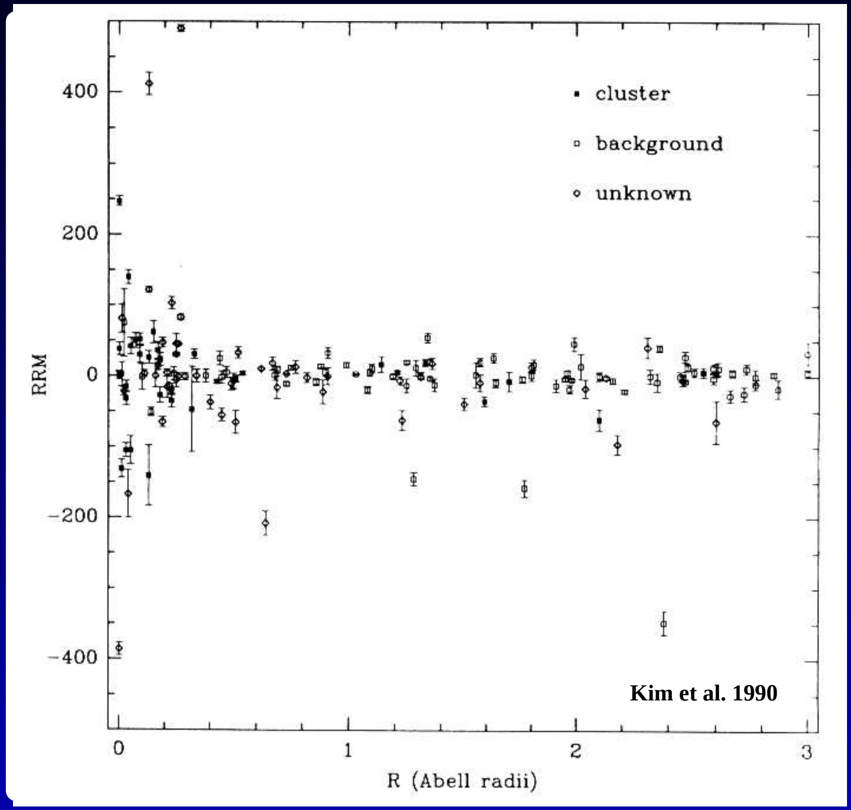


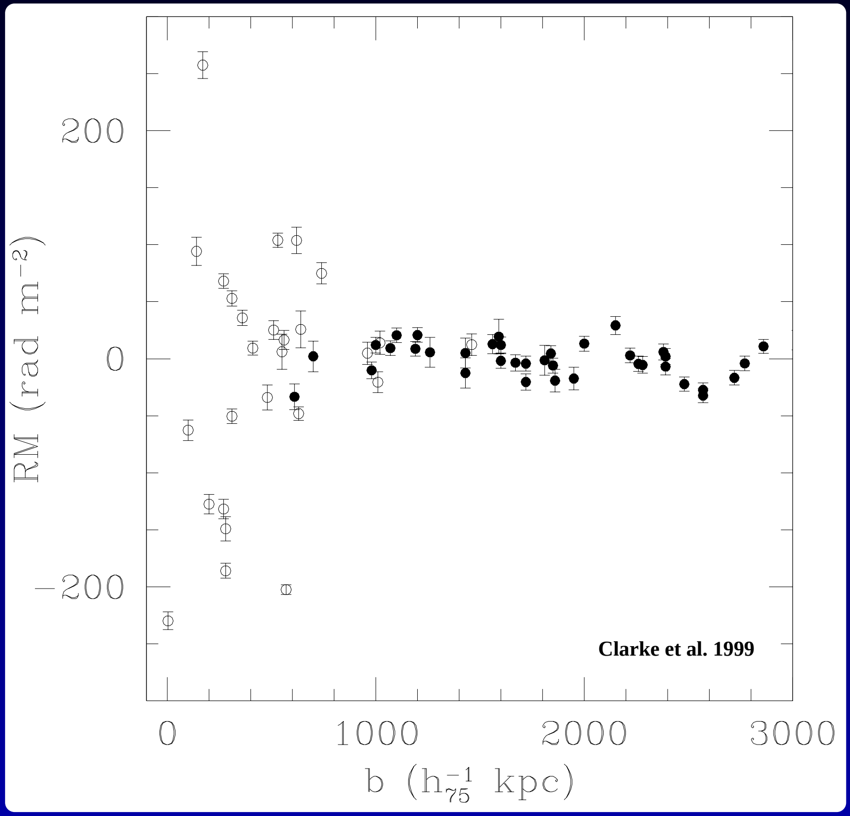
High quality Rotation Measure maps across the lobes of the central radio source in 3C449 (left) and Hydra (right).

$$\mathrm{RM} \propto \int n_e B_{\|}\, \mathrm{d}l \approx B_{\|} \sqrt{l}$$

- **Simple interpretation**
- **Direct inversion**
- **Modeling**
- Simulations (Lecture III)

Observations





Rotation Measure as function of distance to the center of galaxy clusters.

$$\mathrm{RM} = 812 \, \frac{\mathrm{rad}}{\mathrm{m}^2} \int \frac{n_\mathrm{e}}{\mathrm{cm}^{-3}} \, \frac{B_\|}{\mu\mathrm{G}} \, \frac{\mathrm{d}l}{\mathrm{kpc}}$$

Clear signature of **cluster magnetic fields** !

Observations

From **HIFLUGCS** (Reiprich & Böringer 2002)

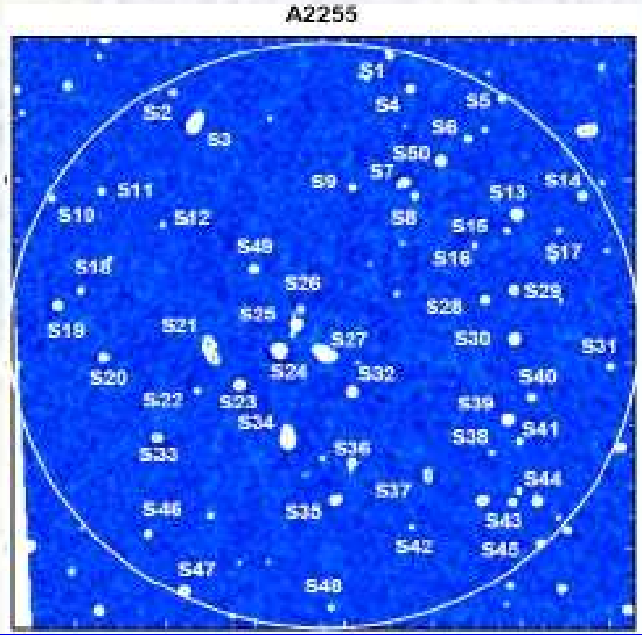
→ clusters with $L_x > 1.5\ 10^{44}$ erg/s [0.1 – 2.4 keV] – $M_{200} > 5\ 10^{14}$ M⊙

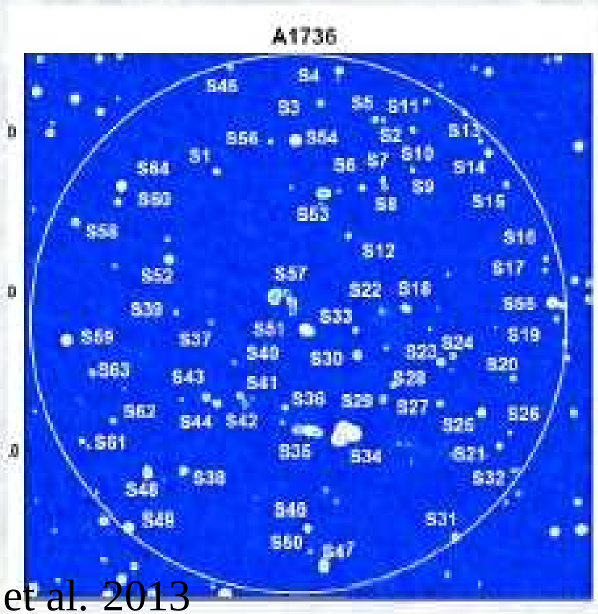
39 clusters

Radio Images → I Q and U Stokes parameters out of 10 core radii from **NVSS**

(1.4 GHz, 100 MHz bandwidth)

Total sample of **33 clusters**

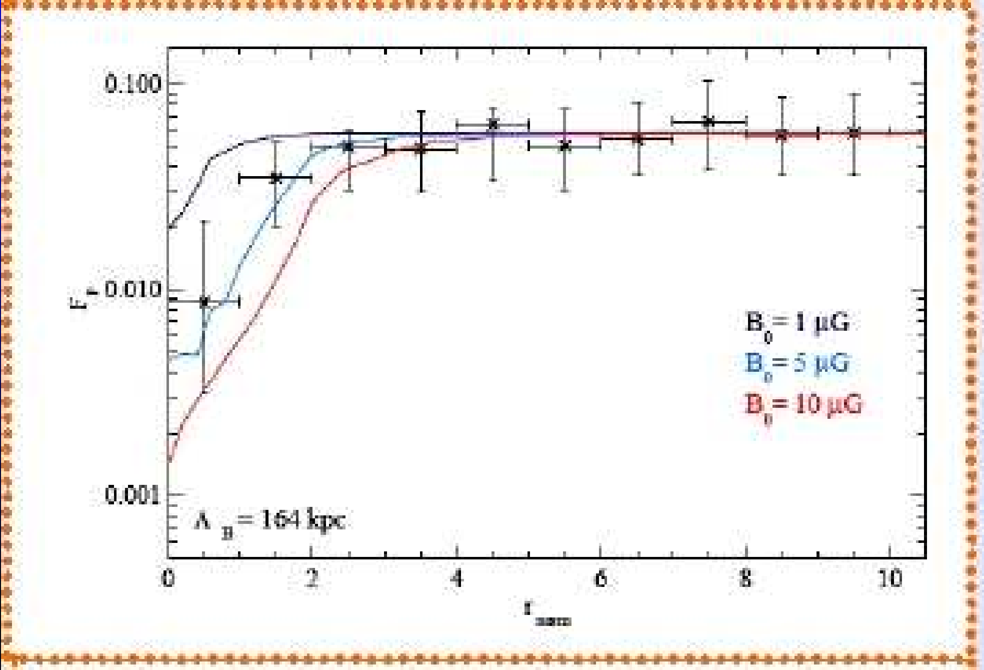


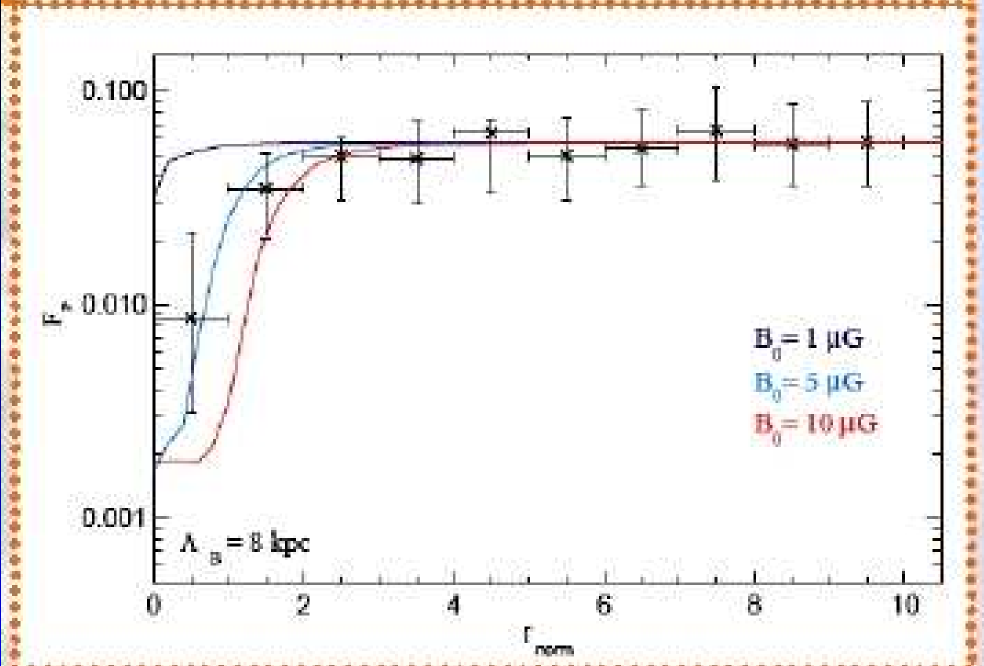


Bonafede et al. 2013

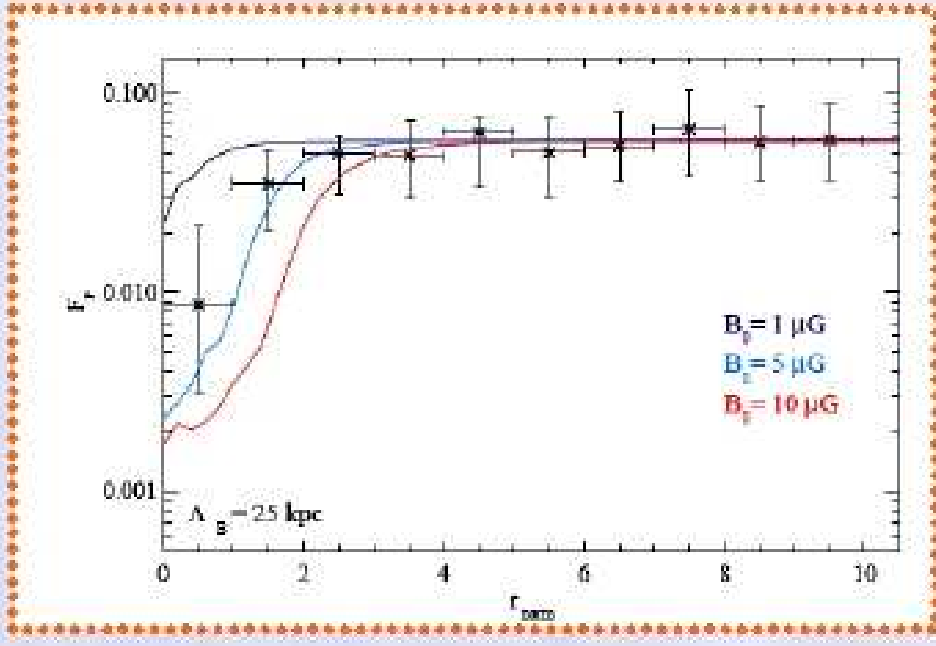
Fractional **polarization** data of radio sources as function of distance to the center of massive galaxy clusters.

Observations





$$\langle B \rangle (r) = \langle B_0 \rangle \left(\frac{n_e}{n_0} \right)^{0.5}$$



$$\langle B_0 \rangle \approx 5 \mu G$$

Bonafede et al. 2013

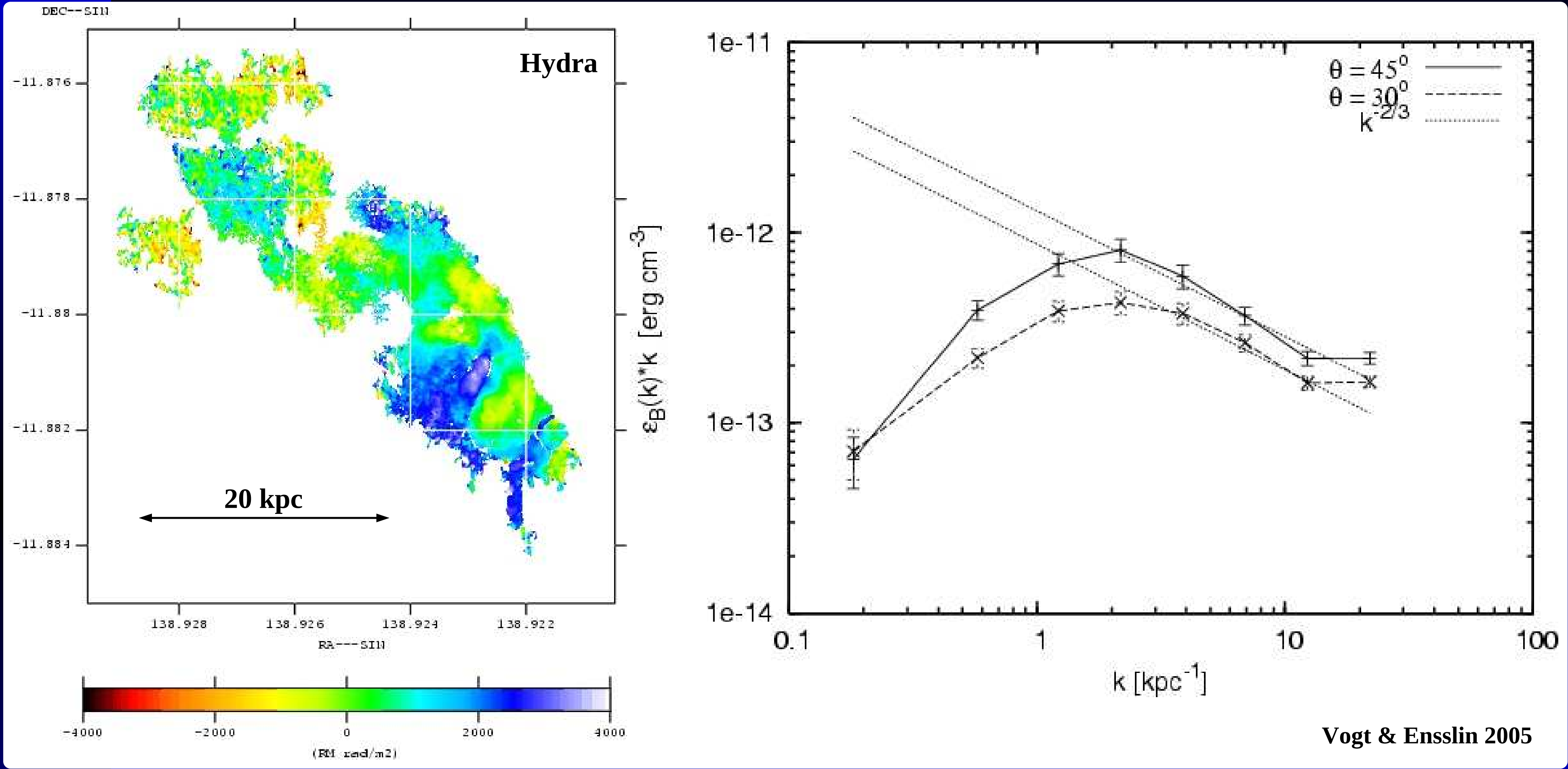
Clear signature of **cluster magnetic fields** !

Observations

Jets in realistic galaxy clusters environment

Mendygral, Jones & Dolag 2012

Observations

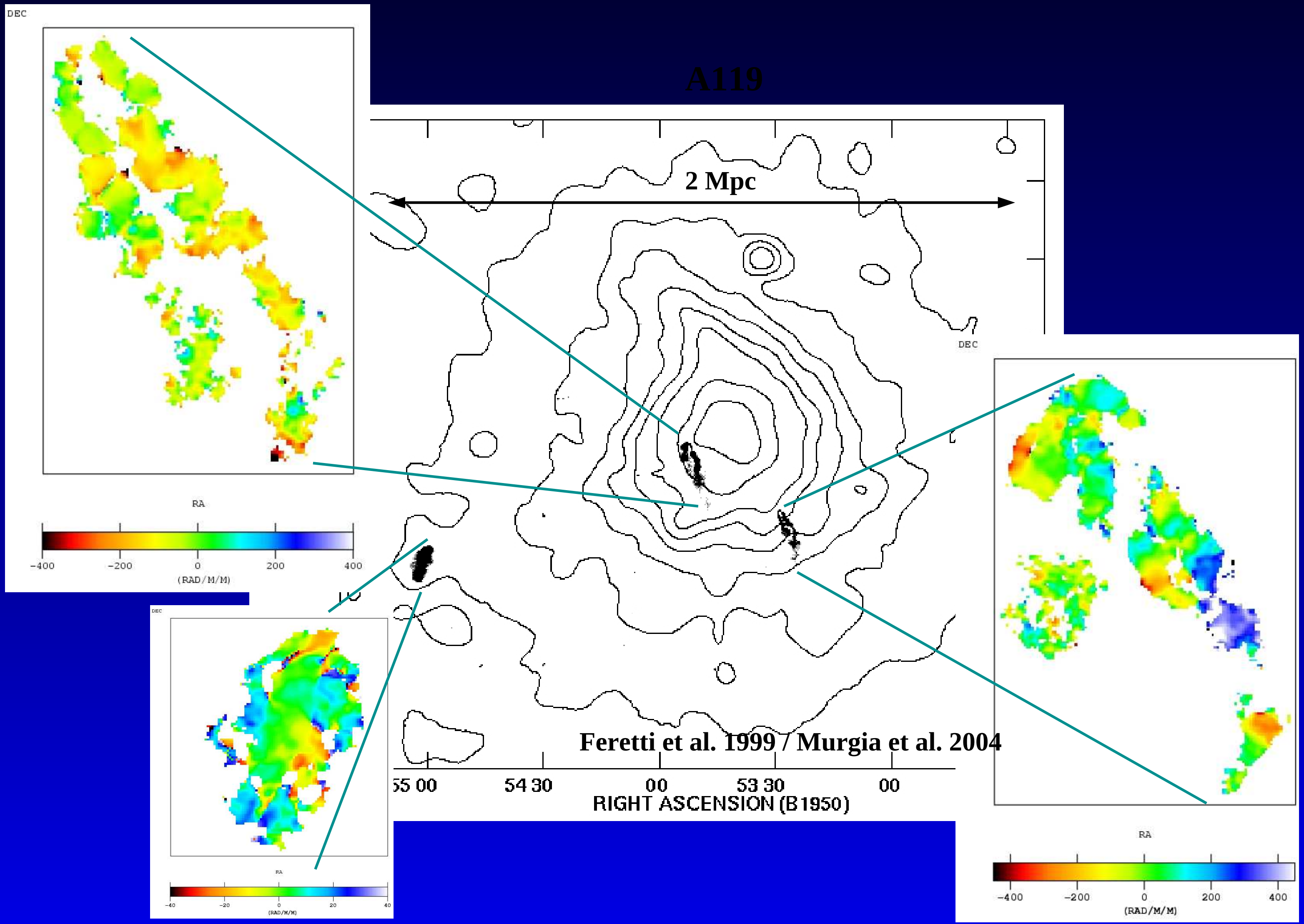


Rotation Measure of Hydra (left) and inferred power spectrum of the underlying magnetic field (Vogt & Ensslin 2005).

- Follows a **Kolmogorov-like** power spectrum !
- Magnetic field correlation length ≈ 3 kpc !
- Cool core turbulence or cluster wide field ?

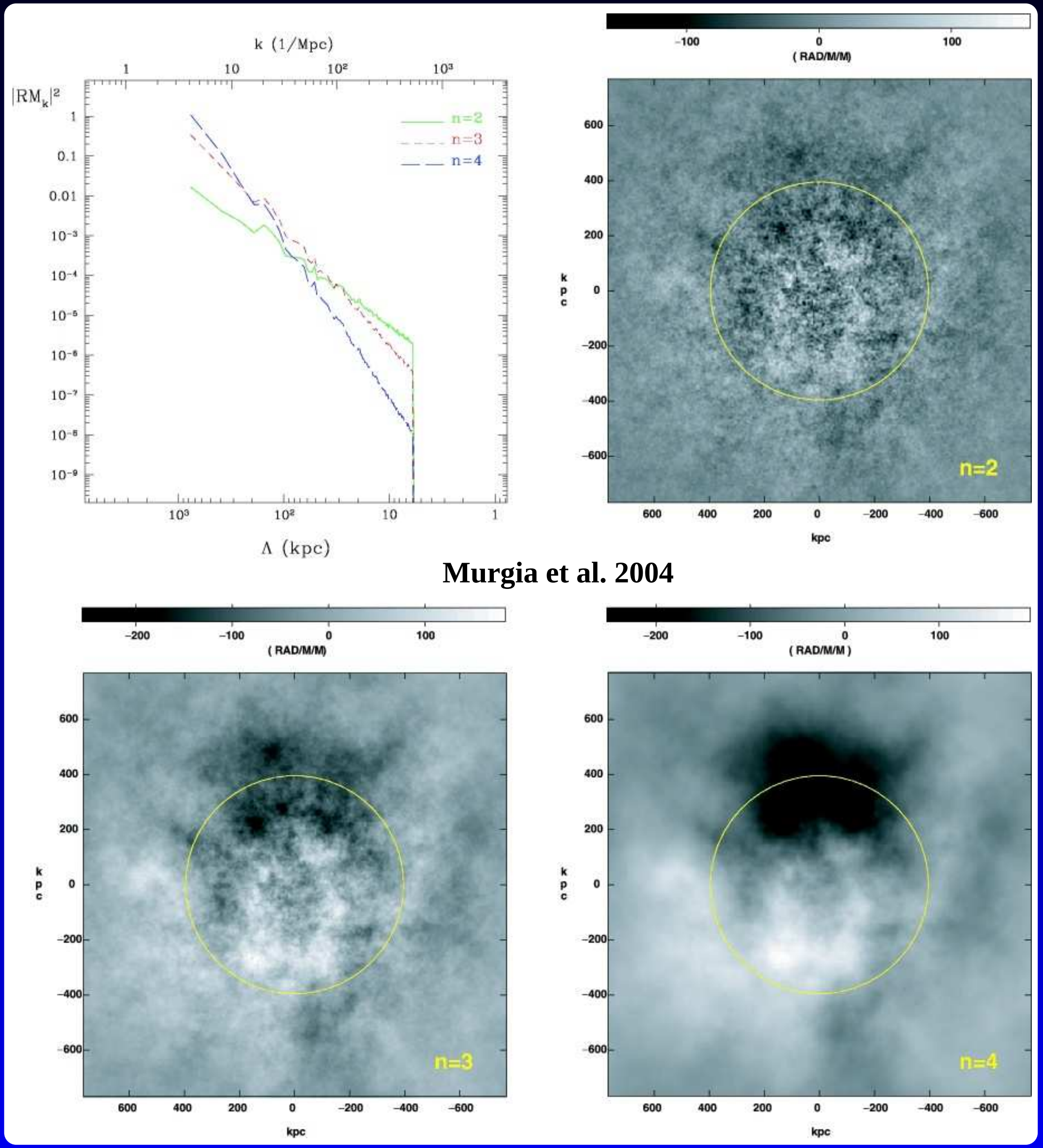
Observations

$$B(r) = B_0 \left(1 + (r/r_c)^2\right)^{-1.5\eta}, \quad |B_k|^2 \propto k^{-n}$$



Composite of X-ray map and Rotation Measure in 3 extended radio sources in A119.

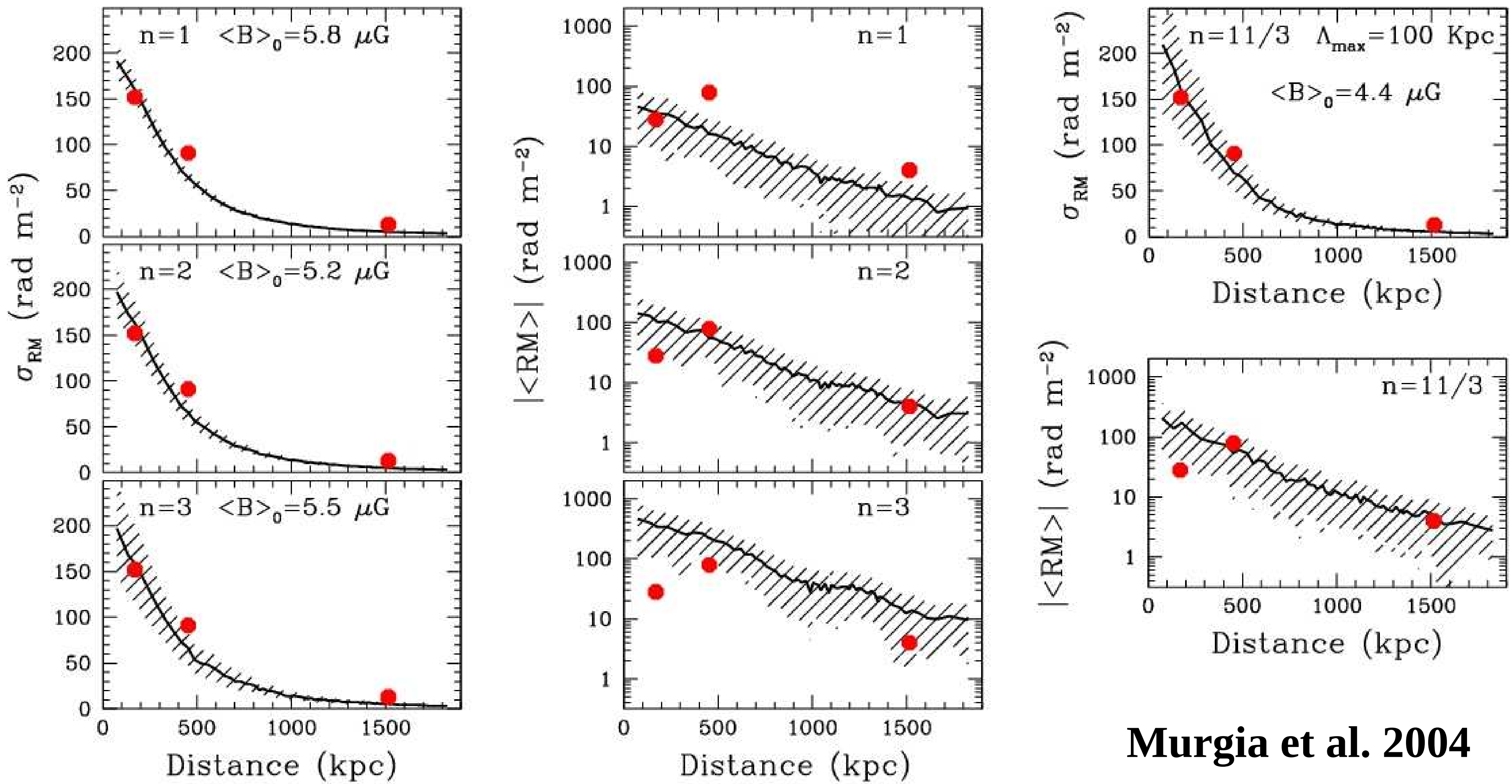
Observations



Murgia et al. 2004

Modeling the magnetic field in A119.

Observations

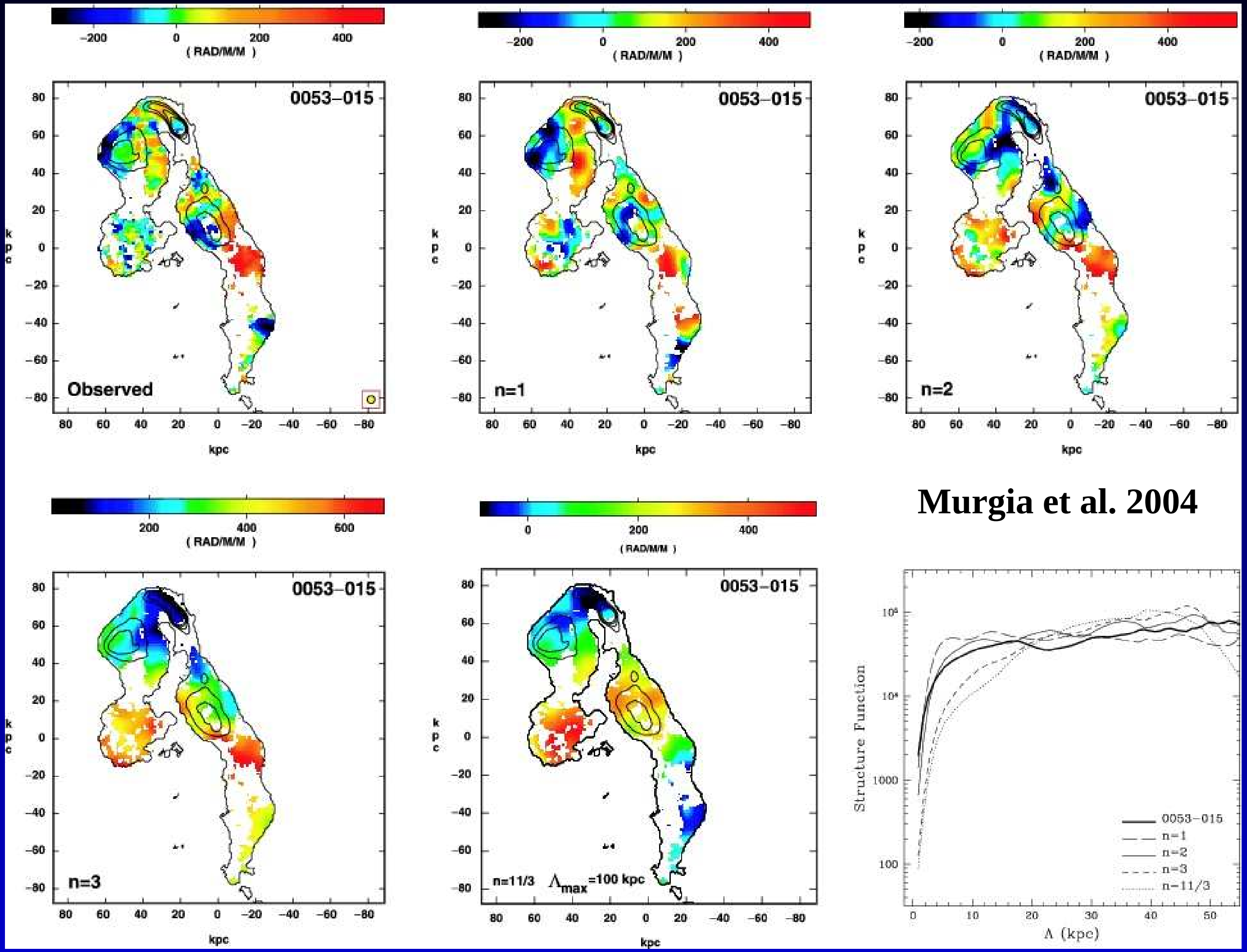


Murgia et al. 2004

Profile of σ (left) and $<>$ (middle) Rotation Measure for A119.

- $(\lambda_{min},\lambda_{max})$ = (6,768) kpc $\Rightarrow$ n=-2 best fit !
- Kolmogorov-like $(-11/3)$ fits only for $\lambda_{max} \approx$ 100 kpc !

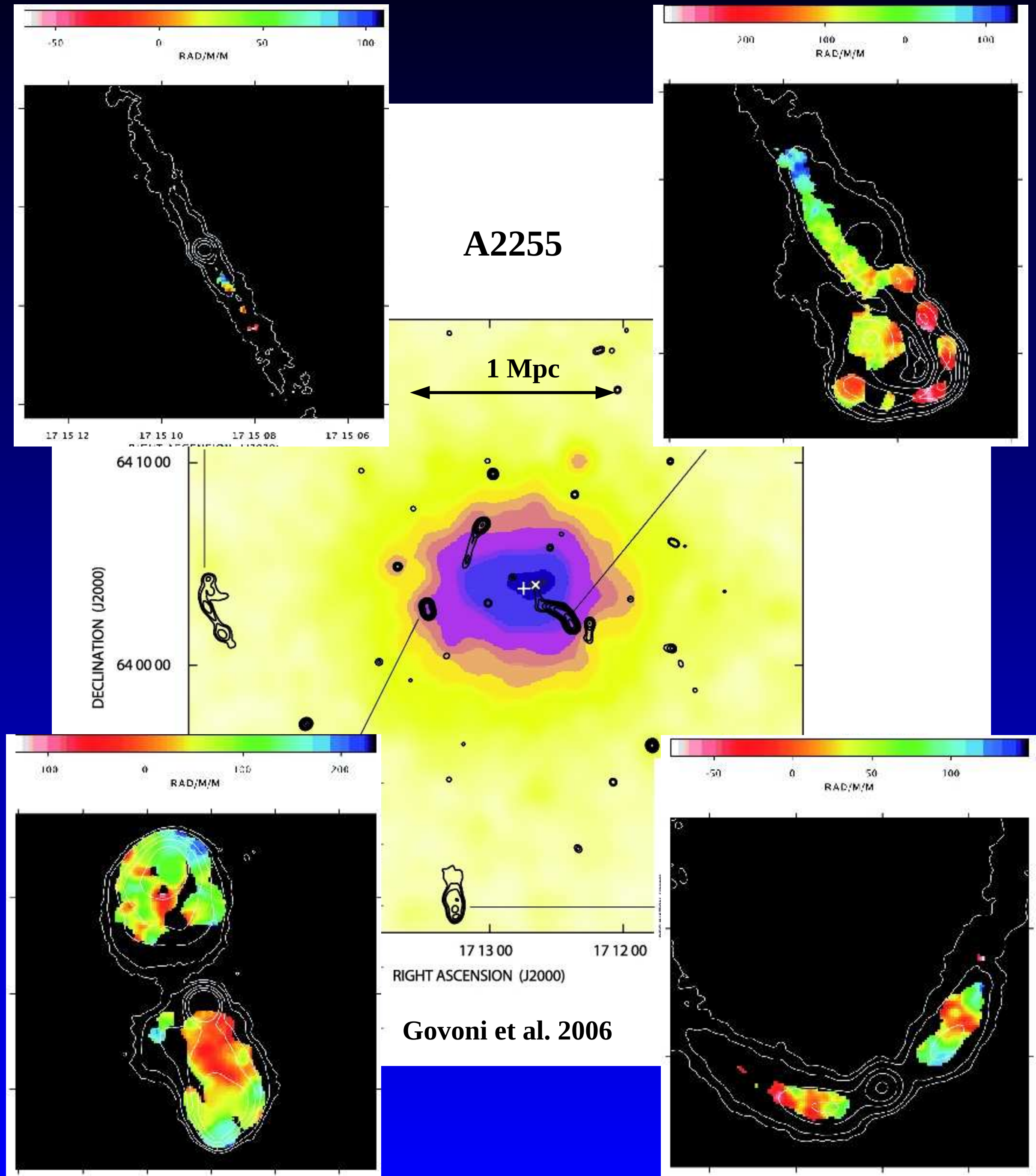
Observations



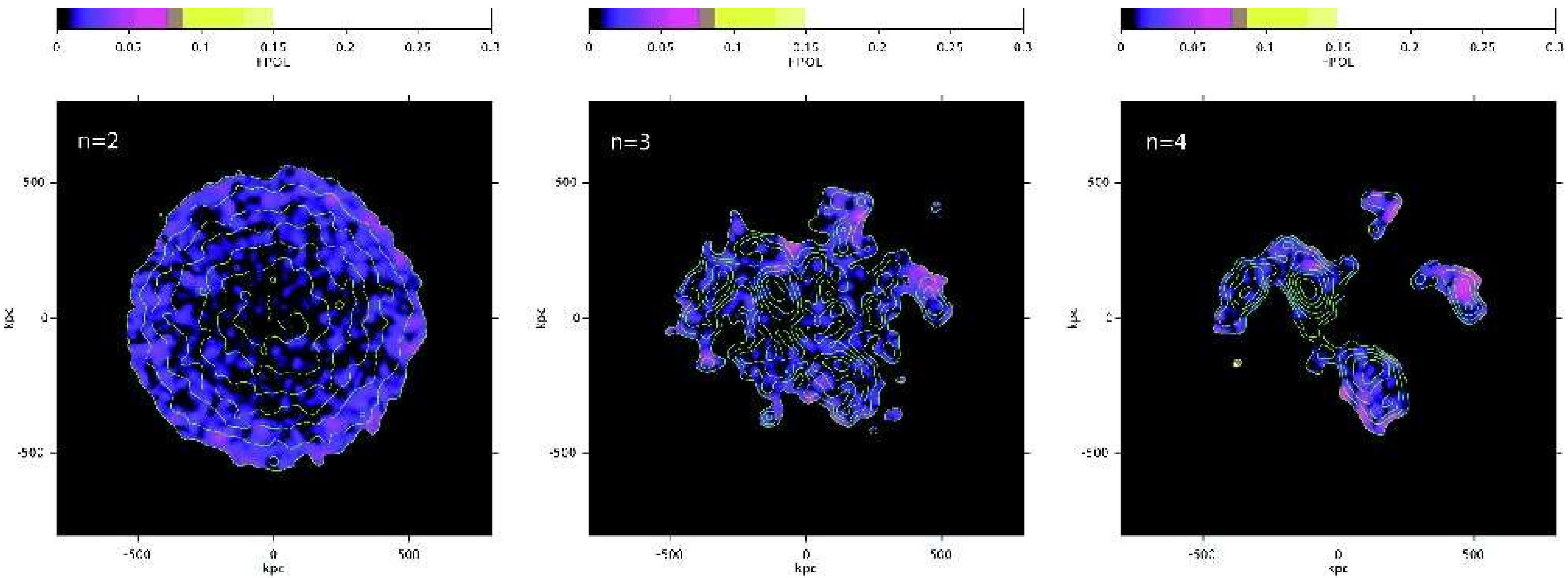
Synthetic Rotation Measure maps and structure function.

- Prefers n=-2 compared to Kolmogorov-like
- Can we include more observations (e.g. radio halo) ?

Observations



Observations

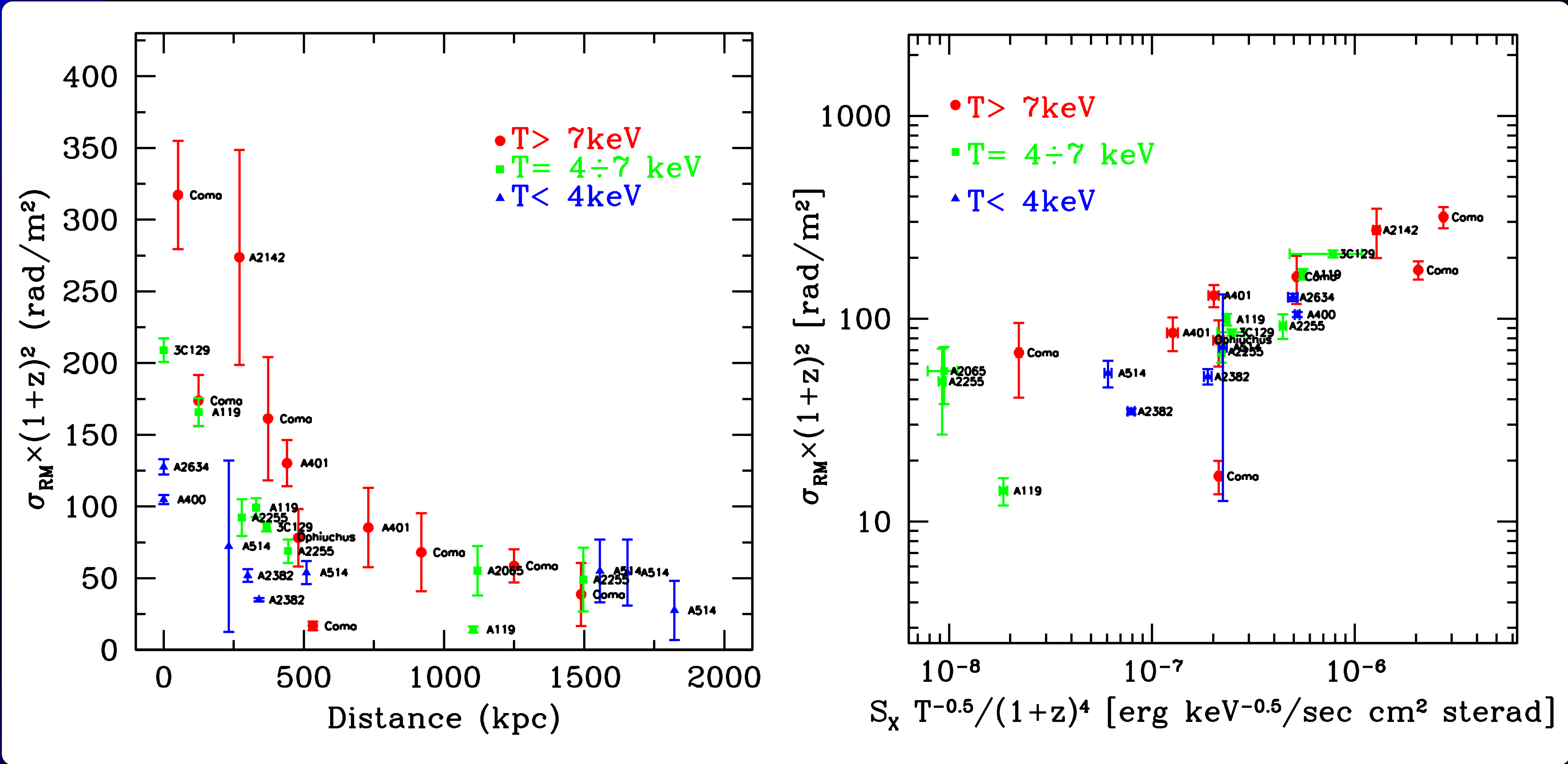


Govoni et al. 2006

Modeled radio halo and fractional polarization for A2255

- **Rotation Measure** alone leads to n≈-3.
- **Radio halo** and **polarization** needs varying from -2 to -4 when going from center to periphery.
- Signature of cluster dynamics ?
- Signature of turbulence/decay of magnetic field ?

Observations

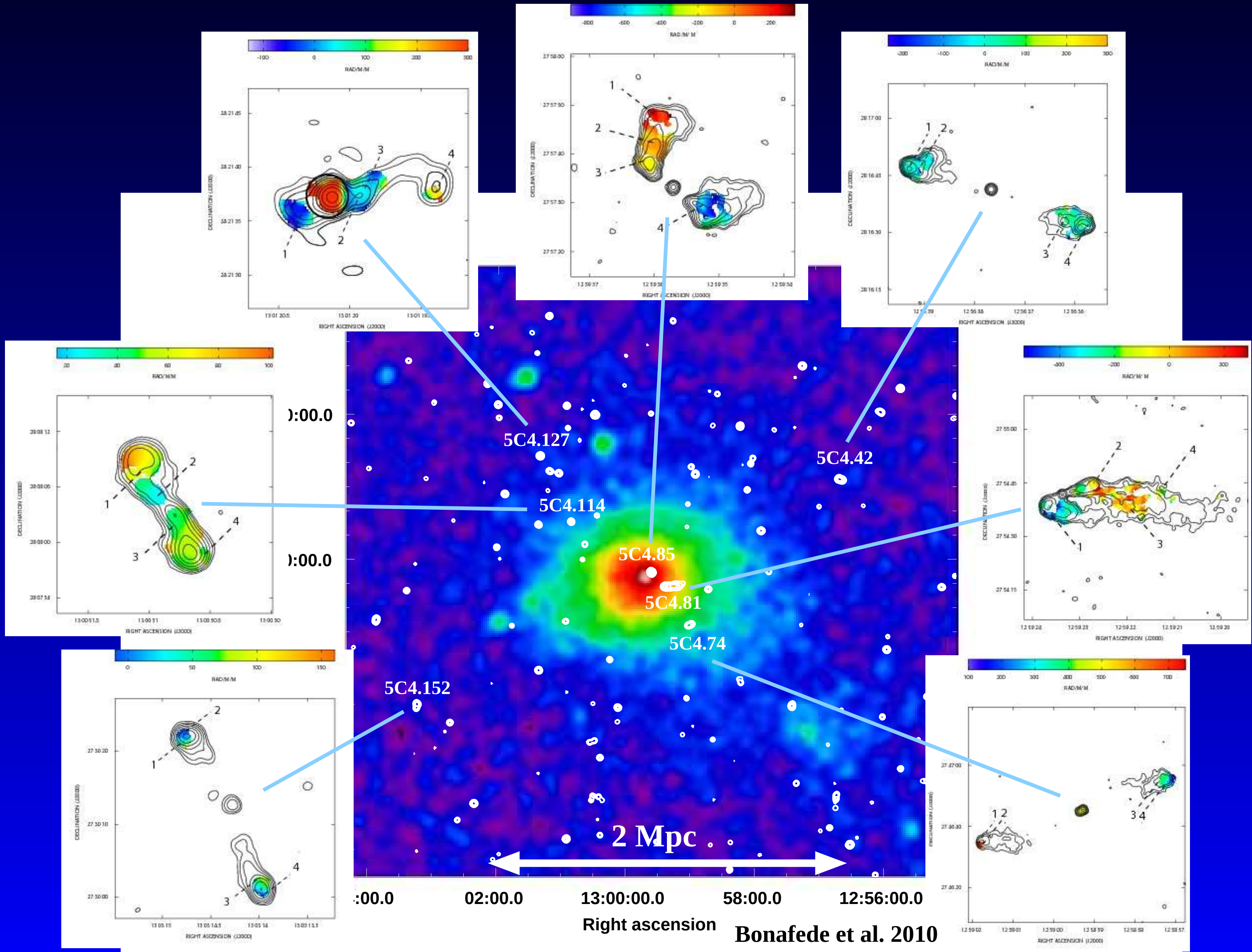


Govoni et al. 2010

- **Combination** of RM measured in **many clusters**.
- How does $\vec{B}$ scale with cluster temperature ?
- Magnetic Field in Radio quiet/active clusters ?

Observations

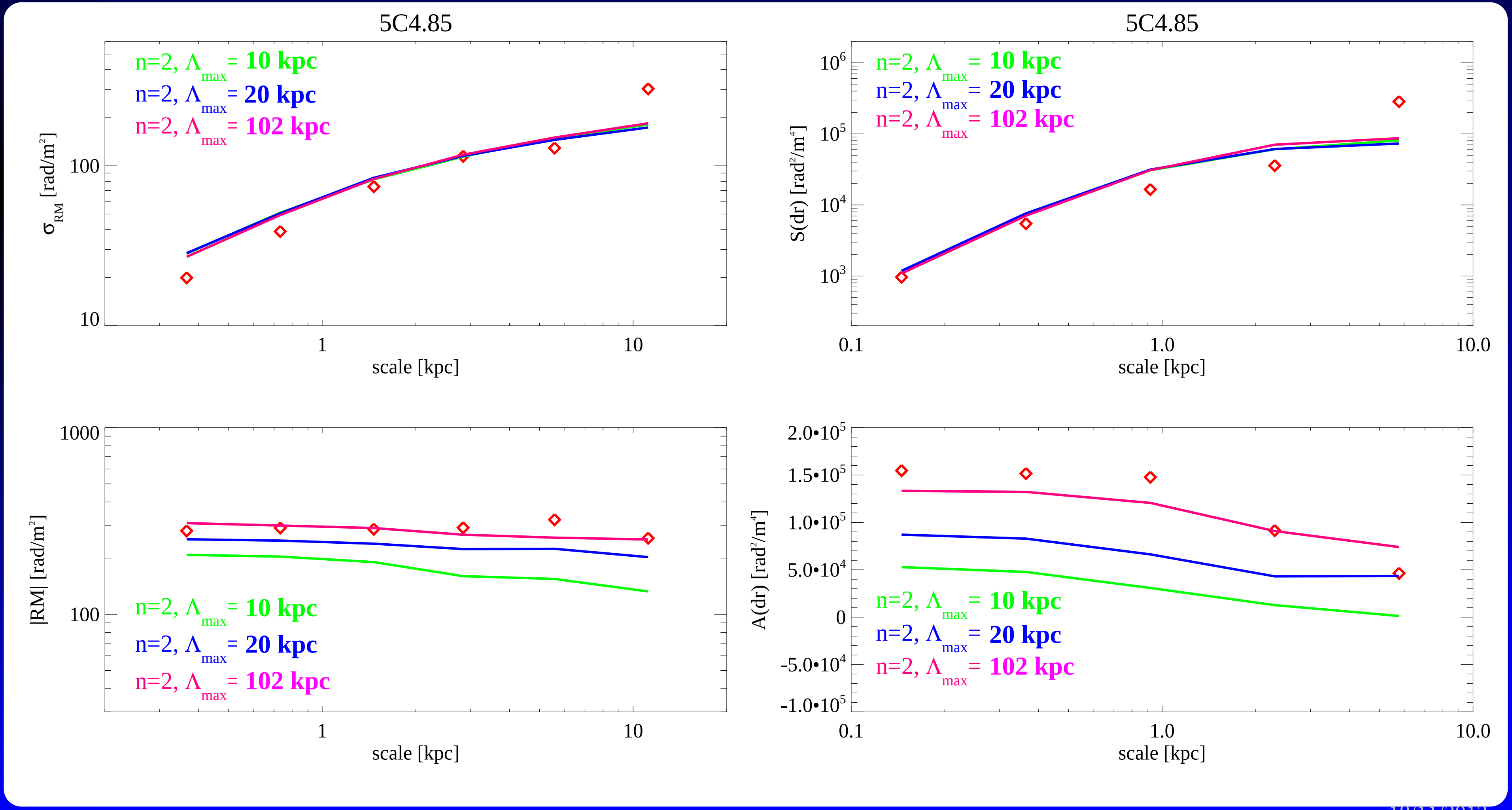
$$B(r) = B_0 \left(1 + (r/r_c)^2\right)^{-1.5\eta}, \quad |B_k|^2 \propto k^{-n}, \quad (k_{\min}, k_{\max})$$



Bonafede et al. 2010

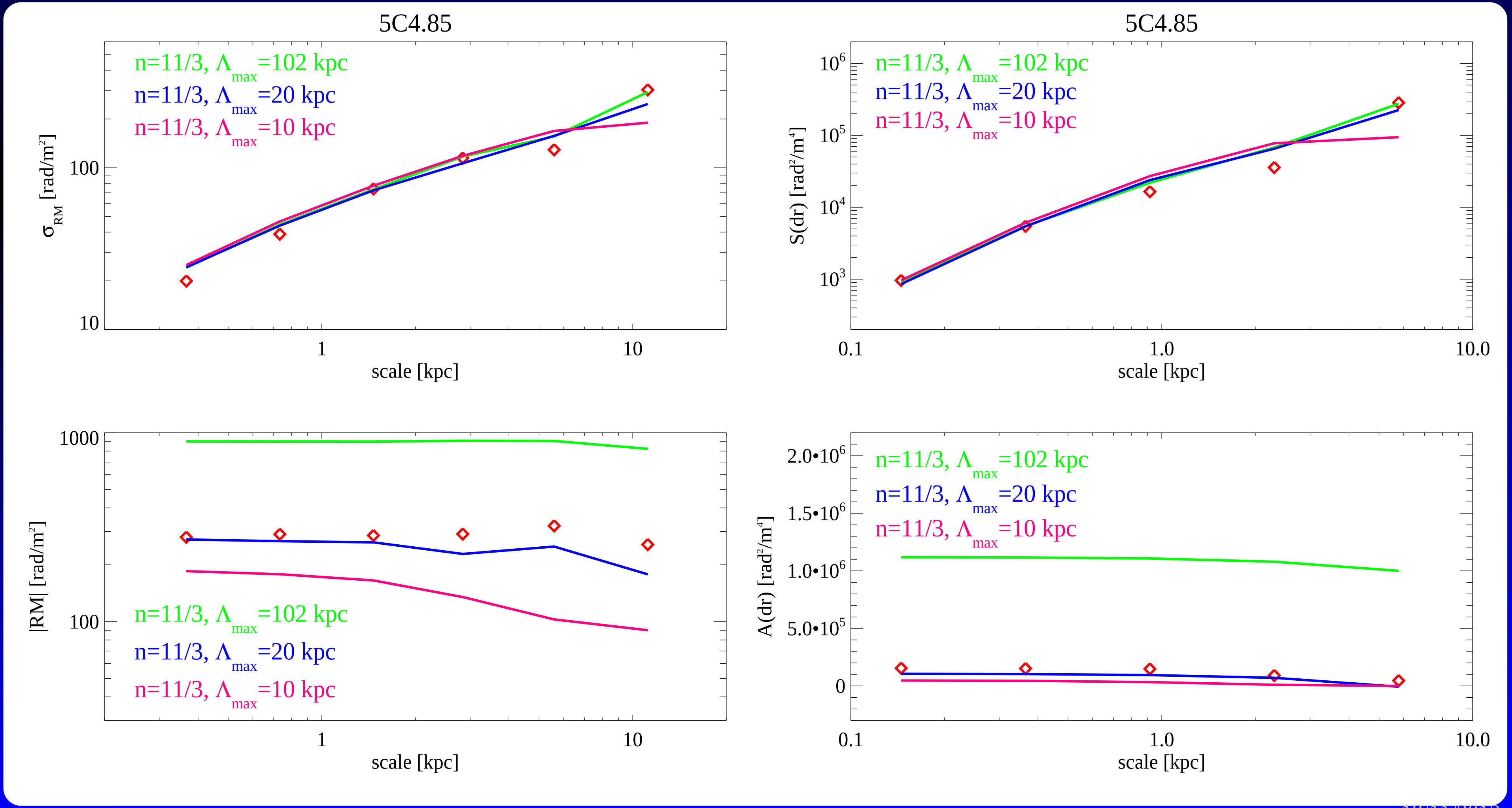
Observations

- $S(dx, dy) = \langle [RM(x, y) - RM(x + dx, y + dy)]^2 \rangle$
- $A(dx, dy) = \langle RM(x, y) \times RM(x + dx, y + dy) \rangle$
- $\langle |RM| \rangle_{\text{scale}}$, $\langle \sigma_{\text{RM}} \rangle_{\text{scale}}$, $n = 2, \Lambda_{\max} = 102\text{kpc}$



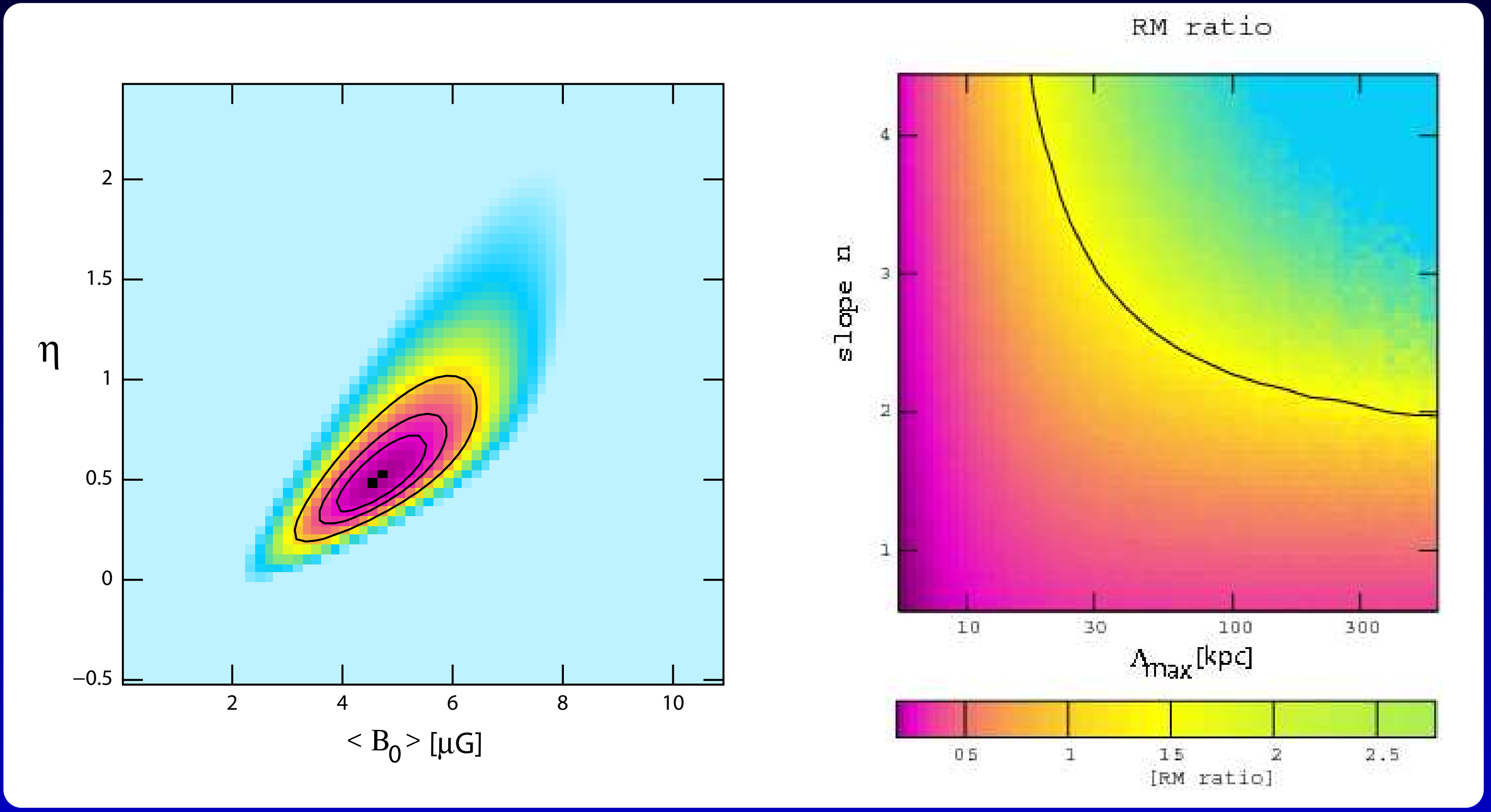
Observations

- $S(dx, dy) = \langle [RM(x,y) - RM(x+dx, y+dy)]^2 \rangle$
- $A(dx, dy) = \langle RM(x,y) \times RM(x+dx, y+dy) \rangle$
- $\langle |RM| \rangle_{\mathrm{scale}}$, $\langle \sigma_{\mathrm{RM}} \rangle_{\mathrm{scale}}$, $n = 11/3, \Lambda_{\mathrm{max}} = 24\mathrm{kpc}$



Observations

$$B(r) = B_0 \left(1 + (r/r_c)^2\right)^{-1.5\eta}, \quad |B_k|^2 \propto k^{-n}, \quad (k_{\min}, k_{\max})$$

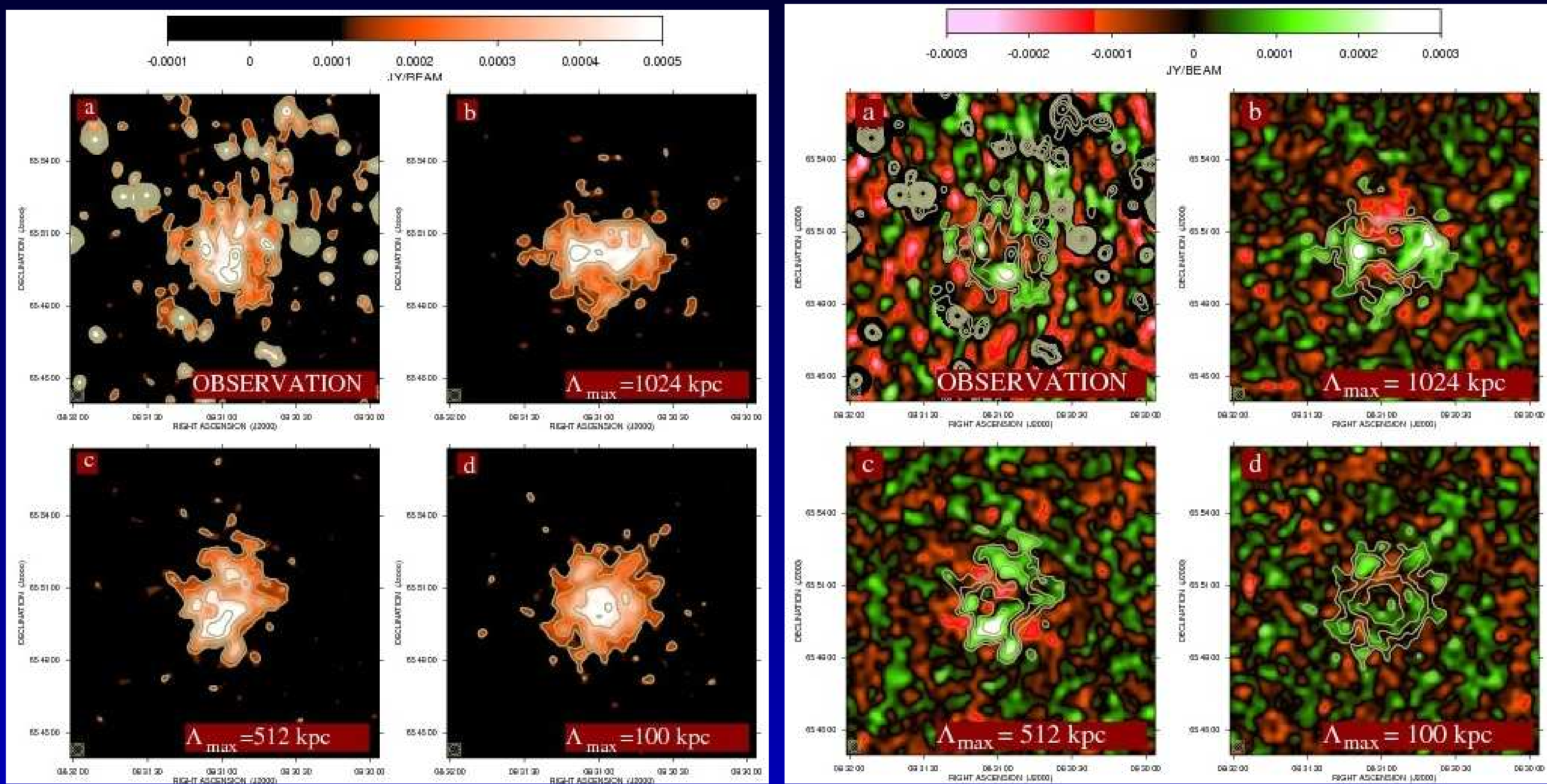


- Degeneration of injection scale $k_{\min}$ and spectral index n
- Knowledge of the spectrum constrains magnetic field
- How does $\vec{B}$ scale with cluster temperature ?

⇒ Cosmological MHD simulations (Lecture III)

Observations

$$B(r) = B_0 \left(1 + (r/r_c)^2\right)^{-1.5\eta}, \quad |B_k|^2 \propto k^{-n}, \quad (k_{\min}, k_{\max})$$



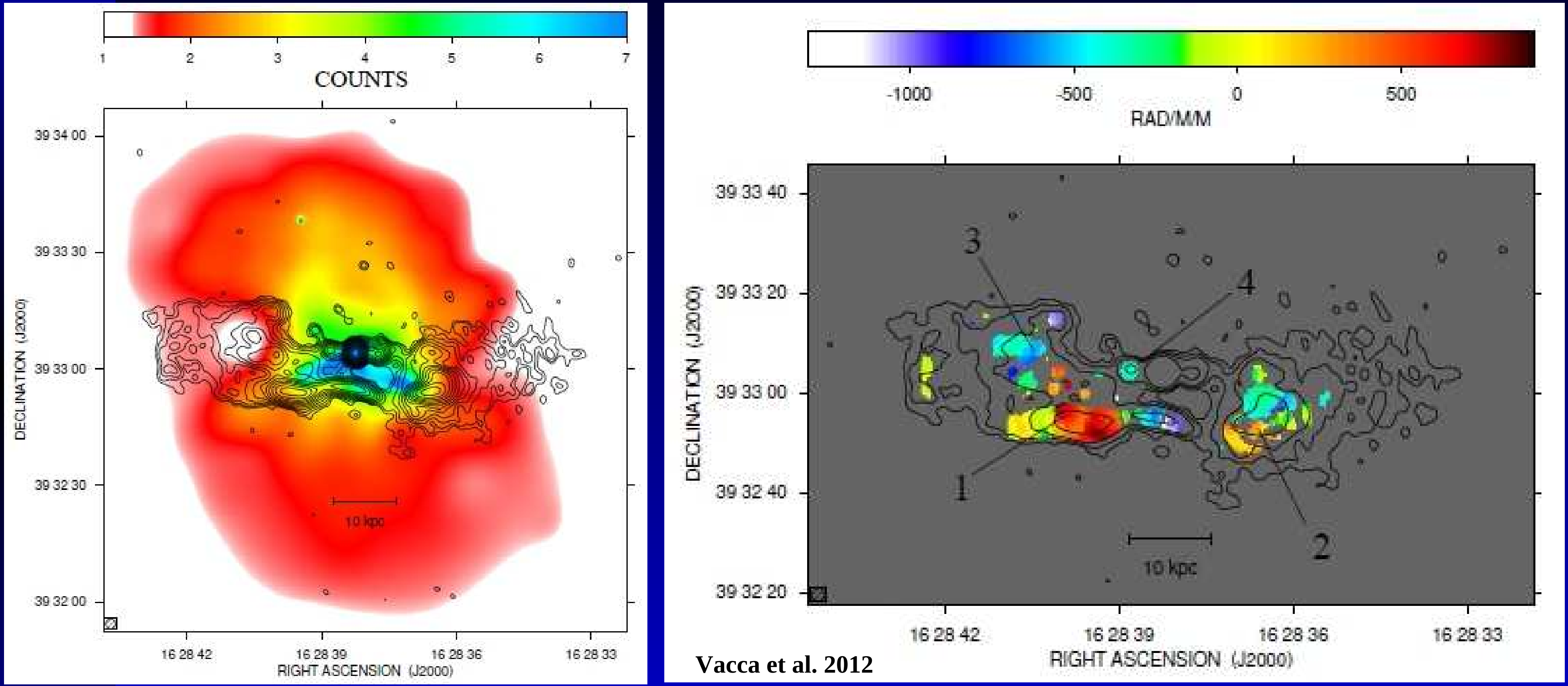
$\Rightarrow$ A655: Inferred outer scale $\approx$450 kpc (Vacca et al. 2010) !

- **Depolarization** indicates truncation at small scales !

$\Rightarrow$ **No** fluctuations at **scales below** $\approx (.1 - .5)$ kpc !

Observations

$$B(r) = B_0 \left(1 + (r/r_c)^2\right)^{-1.5\eta}, \quad |B_k|^2 \propto k^{-n}, \quad (k_{\min}, k_{\max})$$



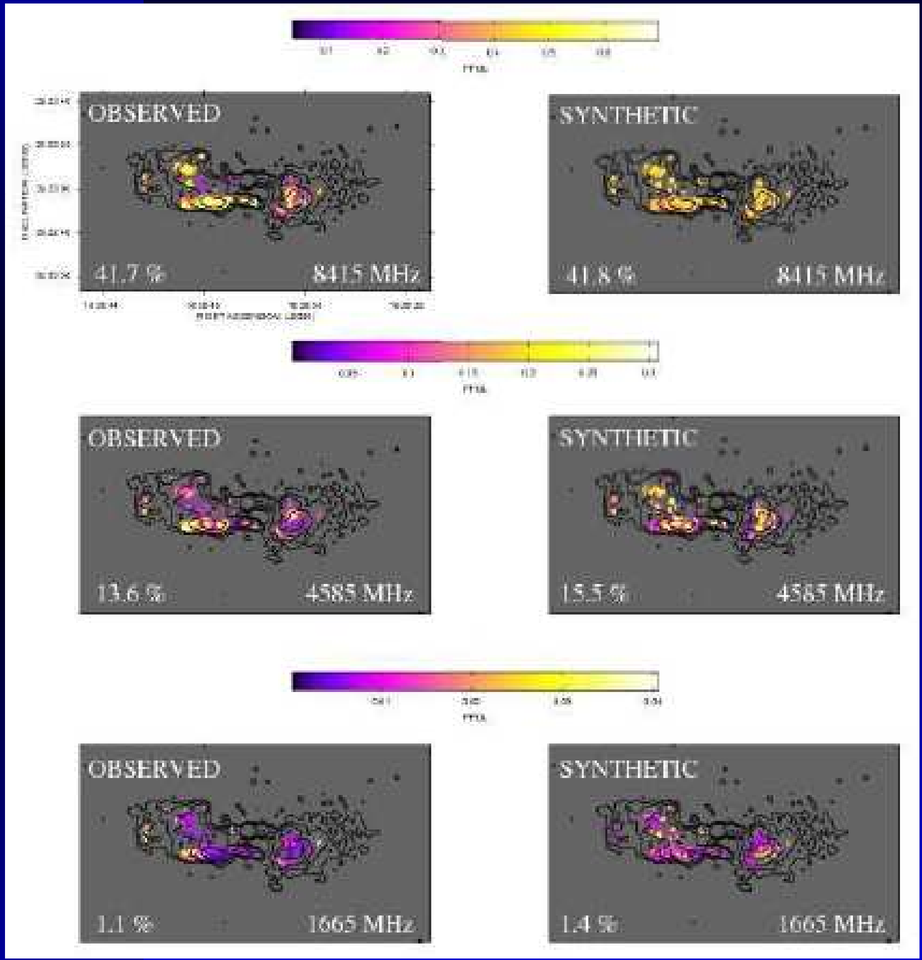
Vacca et al. 2012

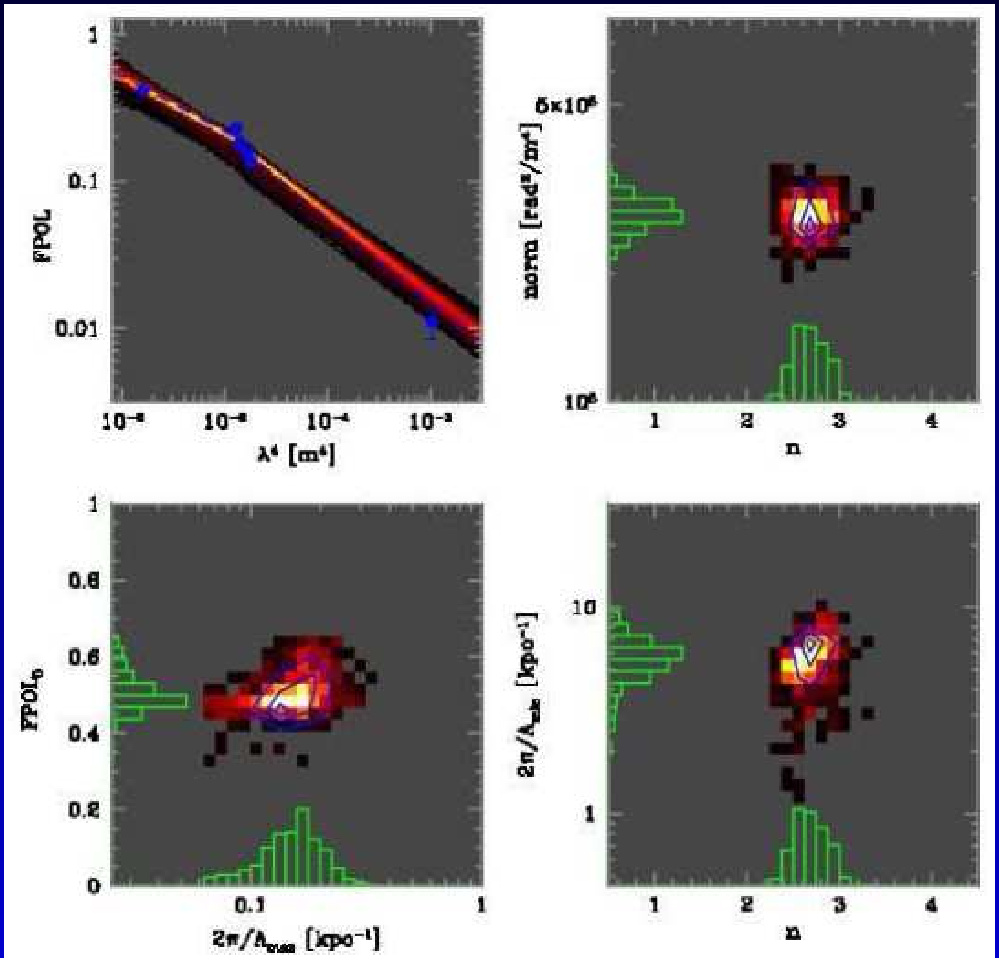
A2199 (Vacca et al. 2012):

- ICM model (double β model)
- Model for cavities
- RM and **depolarization** analysis

Observations

$$B(r) = B_0 \left(1 + (r/r_c)^2\right)^{-1.5\eta}, \quad |B_k|^2 \propto k^{-n}, \quad (k_{\min}, k_{\max})$$



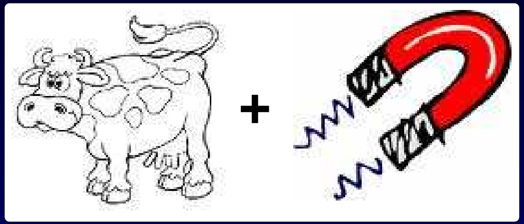


Vacca et al. 2012

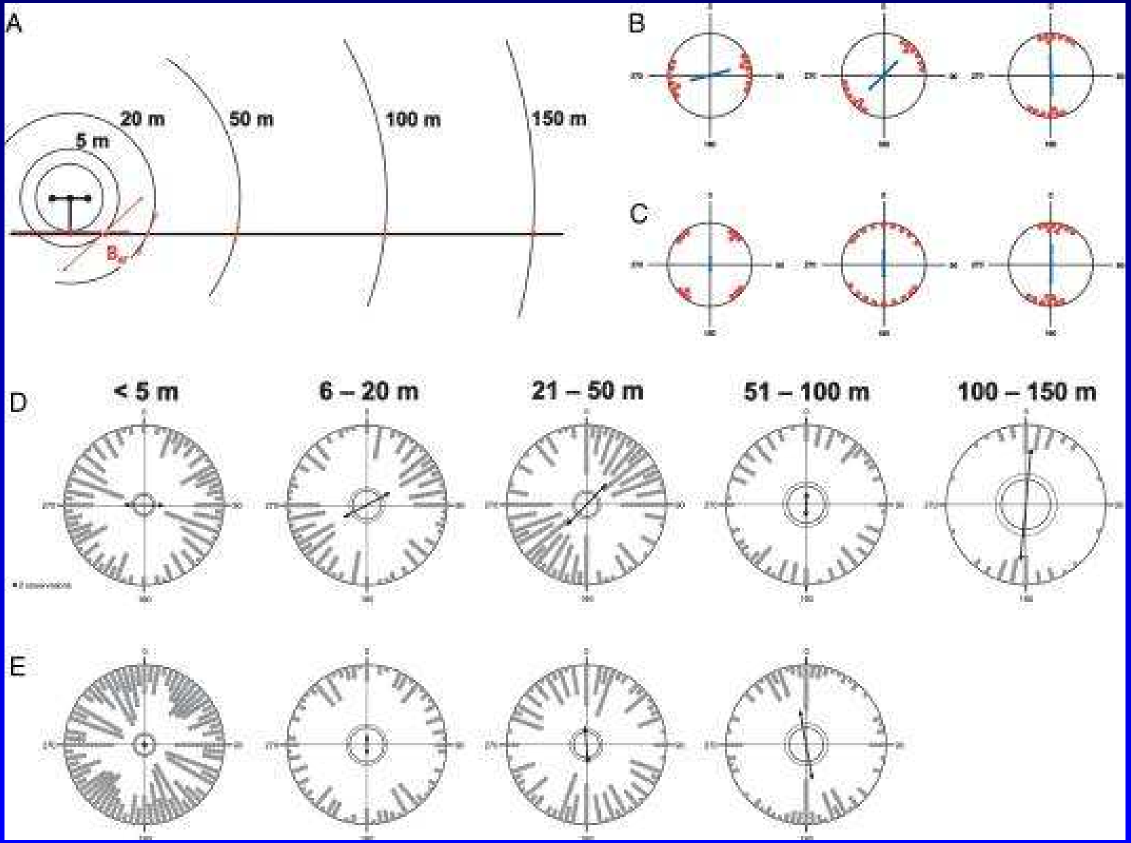
- $B_0 = (11.7 \pm 9.0)\mu$G
- $n = (2.8 \pm 1.3)$
- $\eta = (0.9 \pm 0.5)$
- $\Lambda_{\max} = (35 \pm 28)$kpc
- $\Lambda_{\min} = (0.7 \pm 0.1)$**kpc**

Note on magnetic field structure

Details in magnetic field structure can reveal interesting effects !

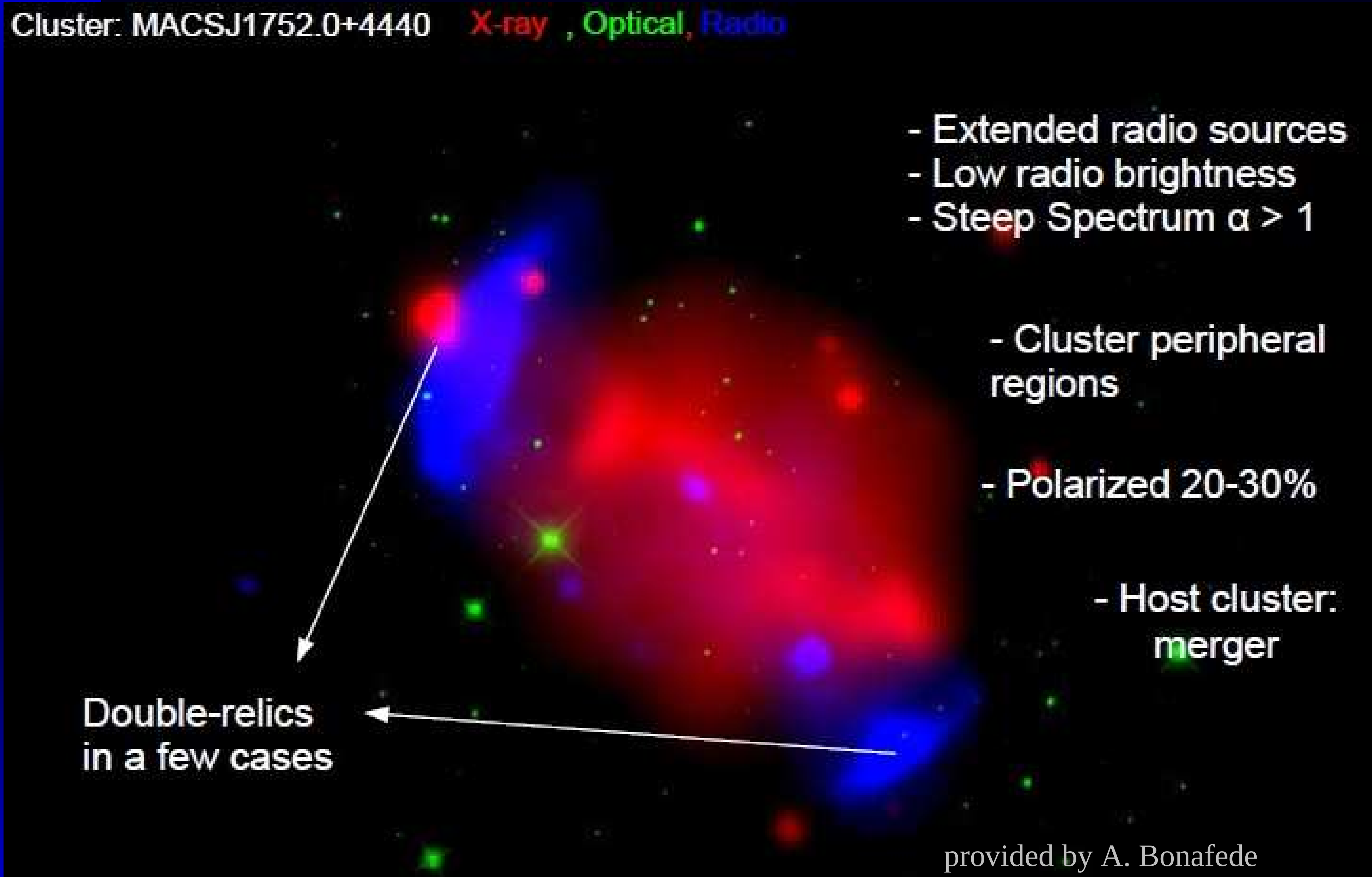


Example **Disturbed Magnetic Cows**: “Extremely low-frequency electromagnetic fields disrupt magnetic alignment of ruminants”



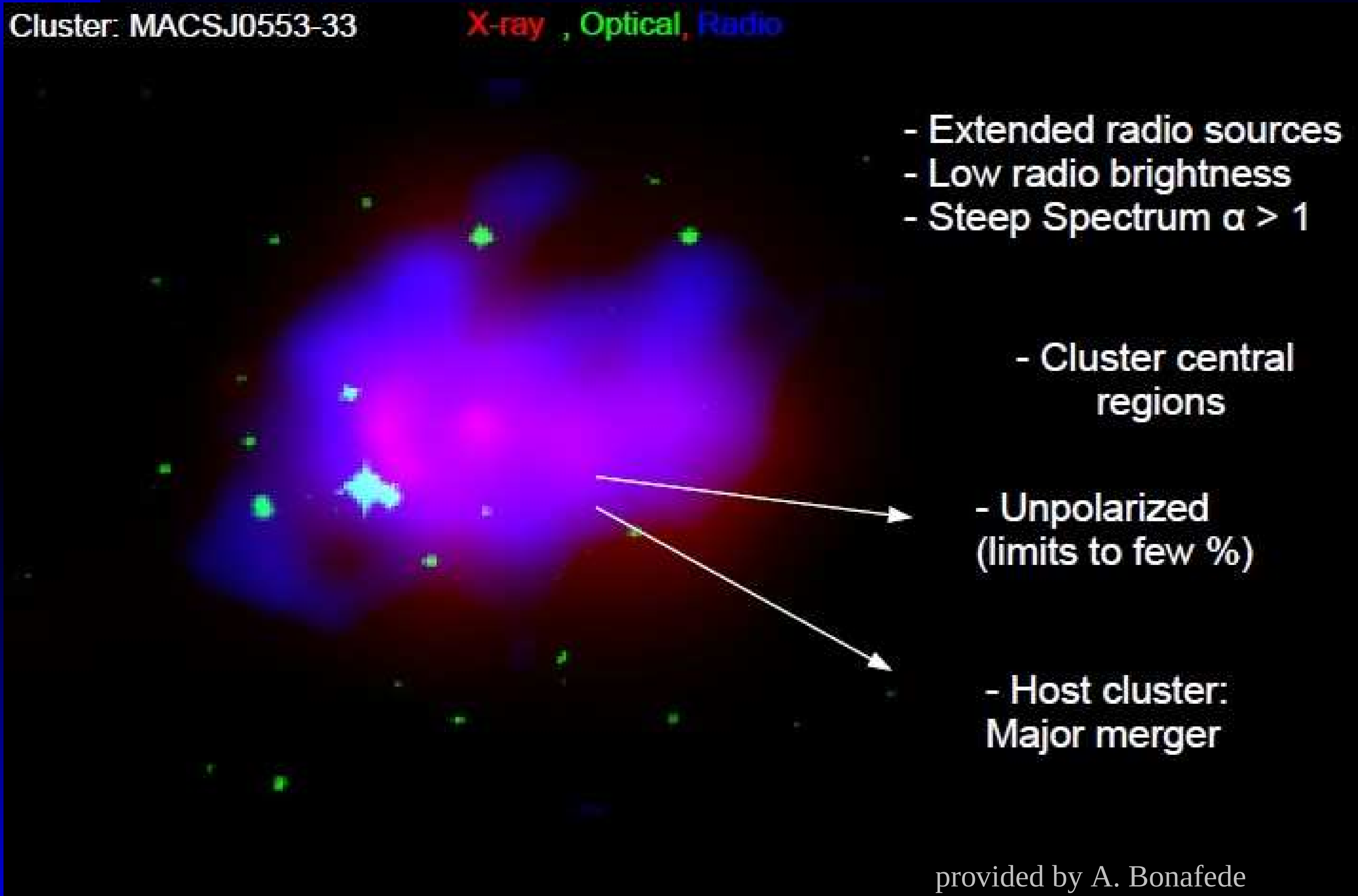
Burda et al. 2009

Cluster non-thermal Emission

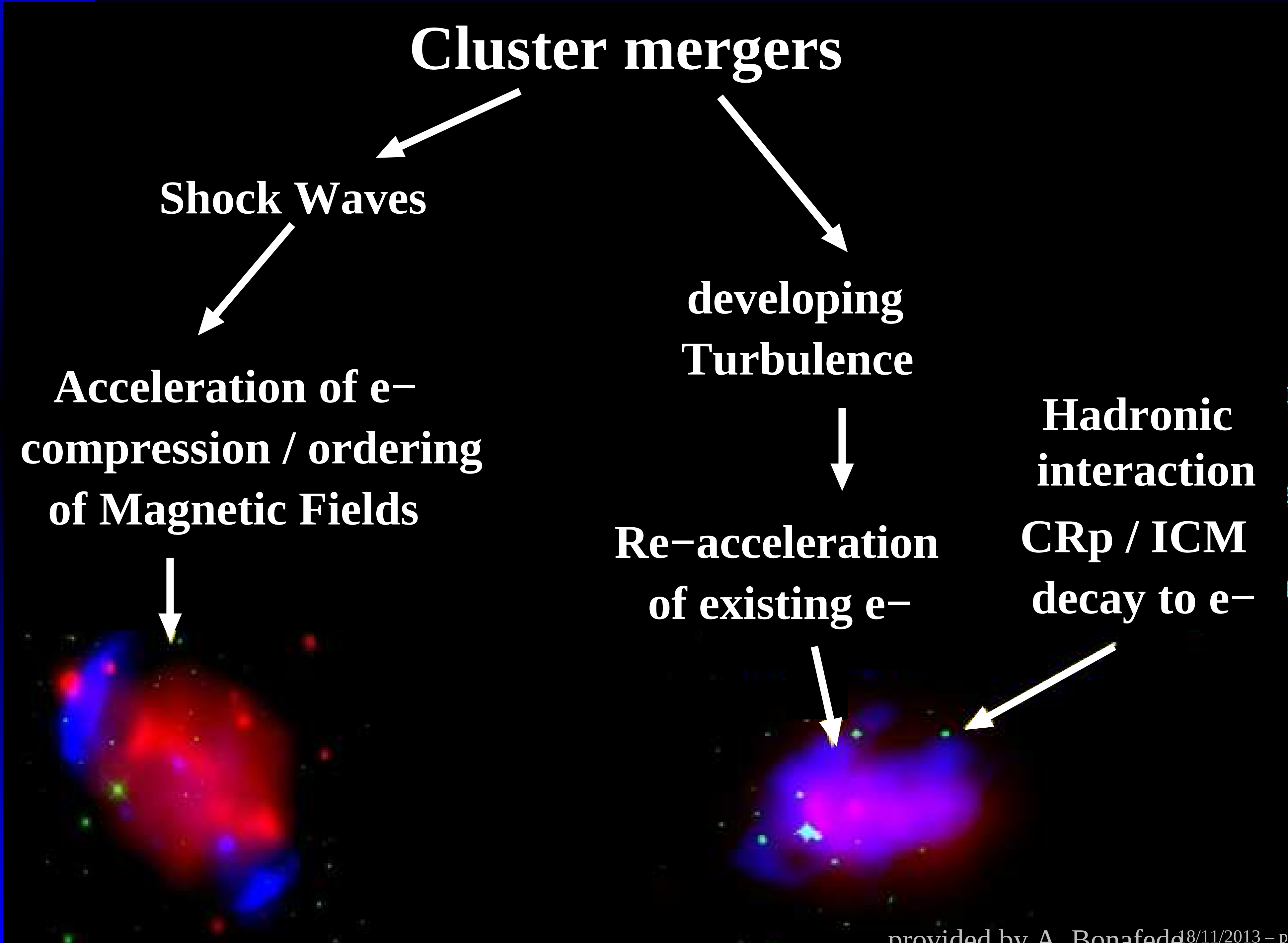


provided by A. Bonafede

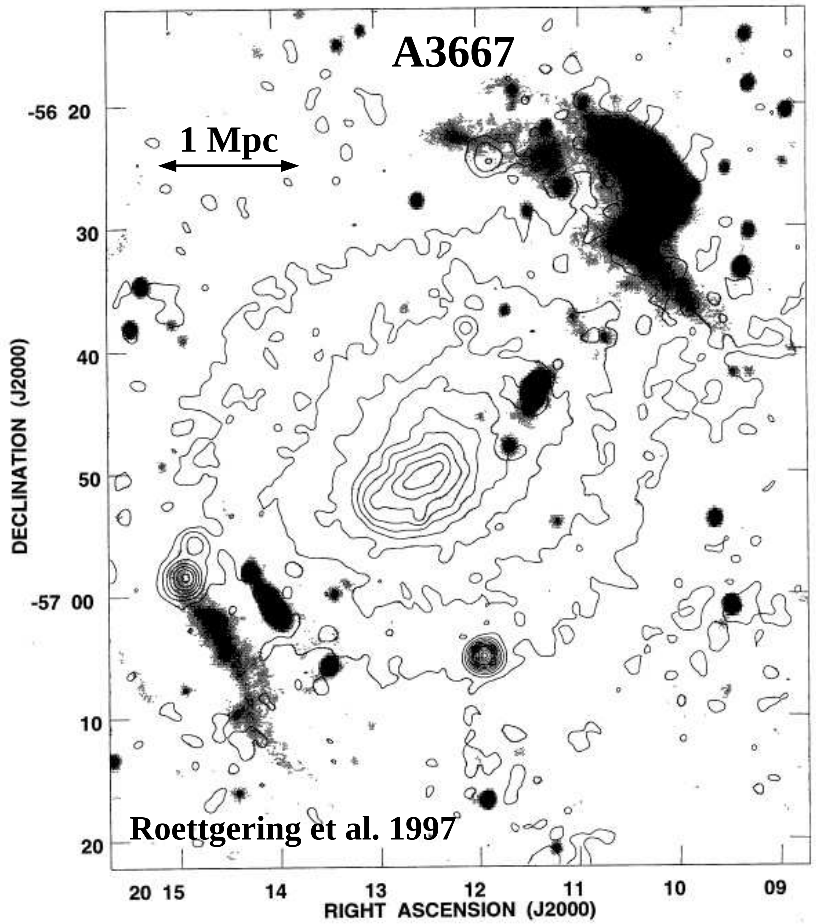
Cluster non-thermal Emission

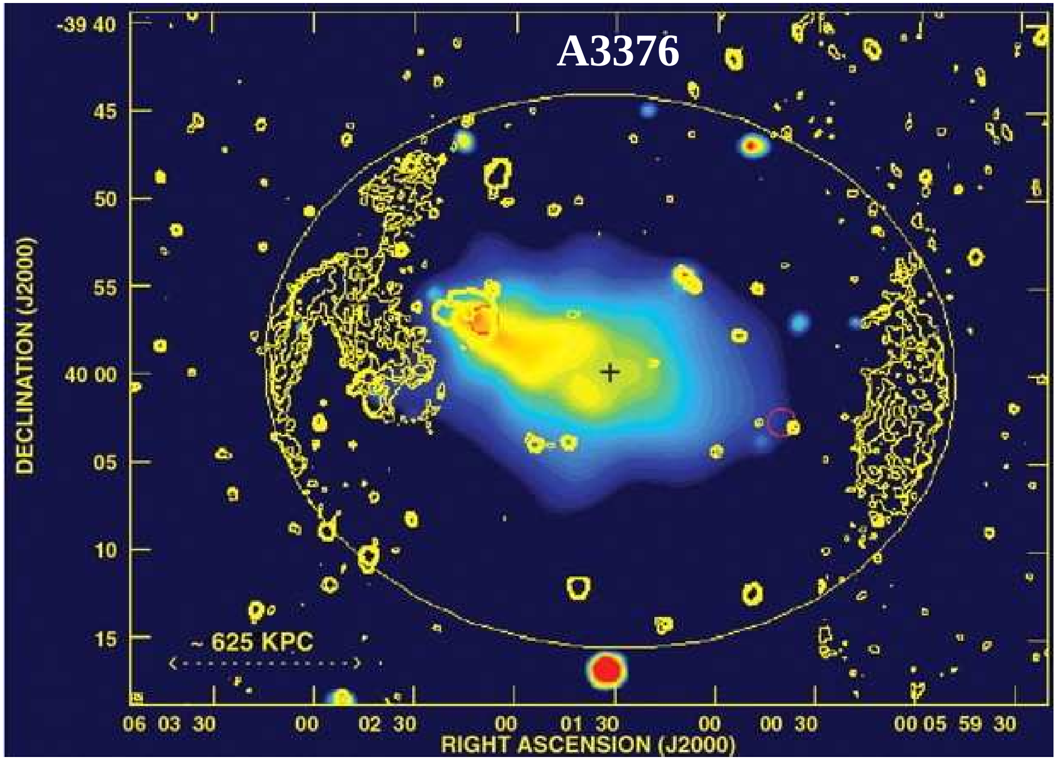


Cluster non-thermal Emission



Cluster Radio Relics



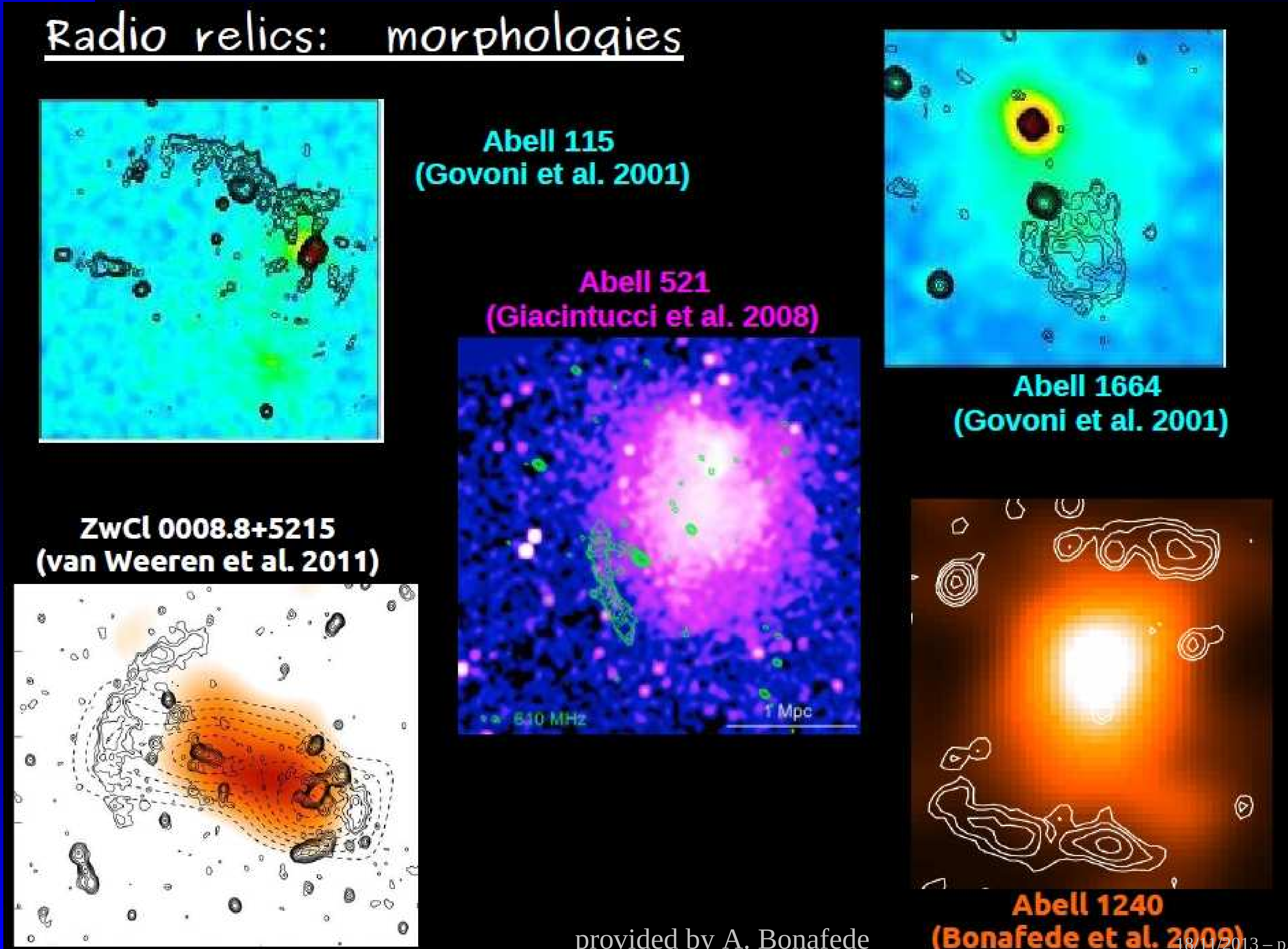


Bagchi et al. 2006

Peripheral synchrotron emission (radio relics) of A3667 (left) and A3376 (right).

- Modeling of A3667 (Roettgering 1997)
- emission zone width ⇒ $\vec{B} \approx 1\mu$G

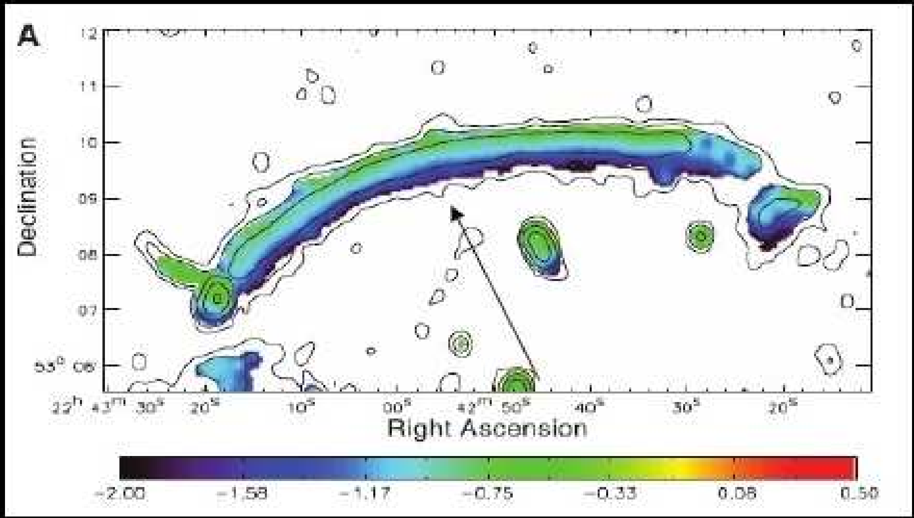
Cluster Radio Relics



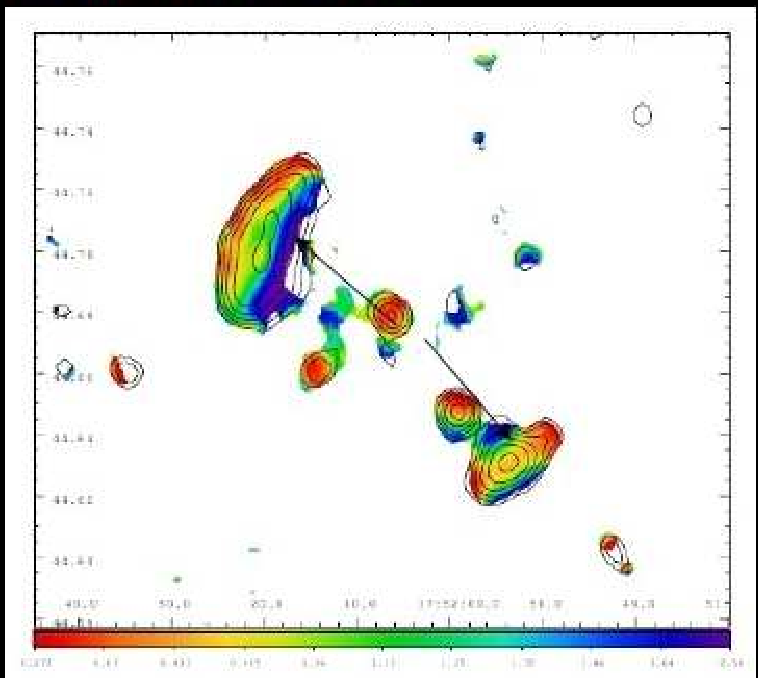
provided by A. Bonafede

Cluster Radio Relics

Van Weeren et al. 2010



Bonafede et al. 2012



Spectral steepening

↓

particle aging

Diffusive Shock
Acceleration regime

$$\alpha_i = -\frac{1}{2} + \frac{M^2+1}{M^2-1}$$

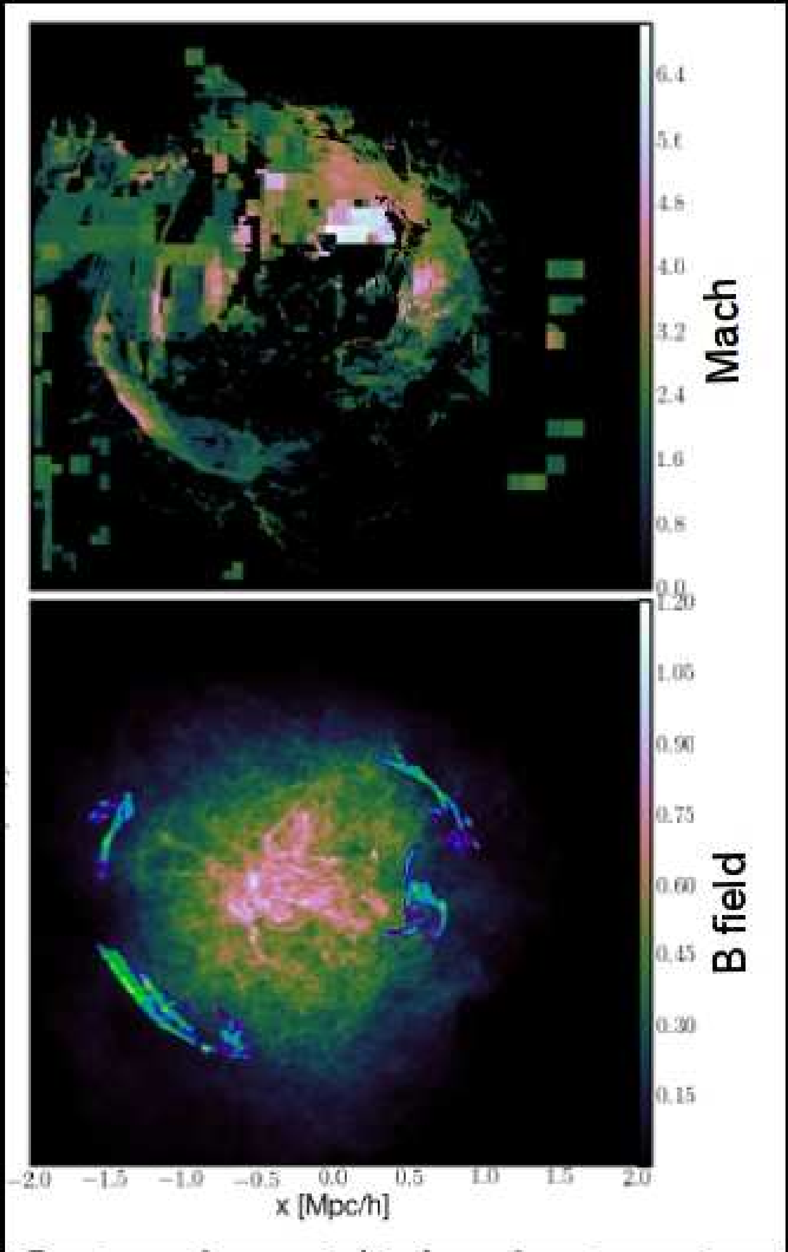
Blandford & Eichler 87

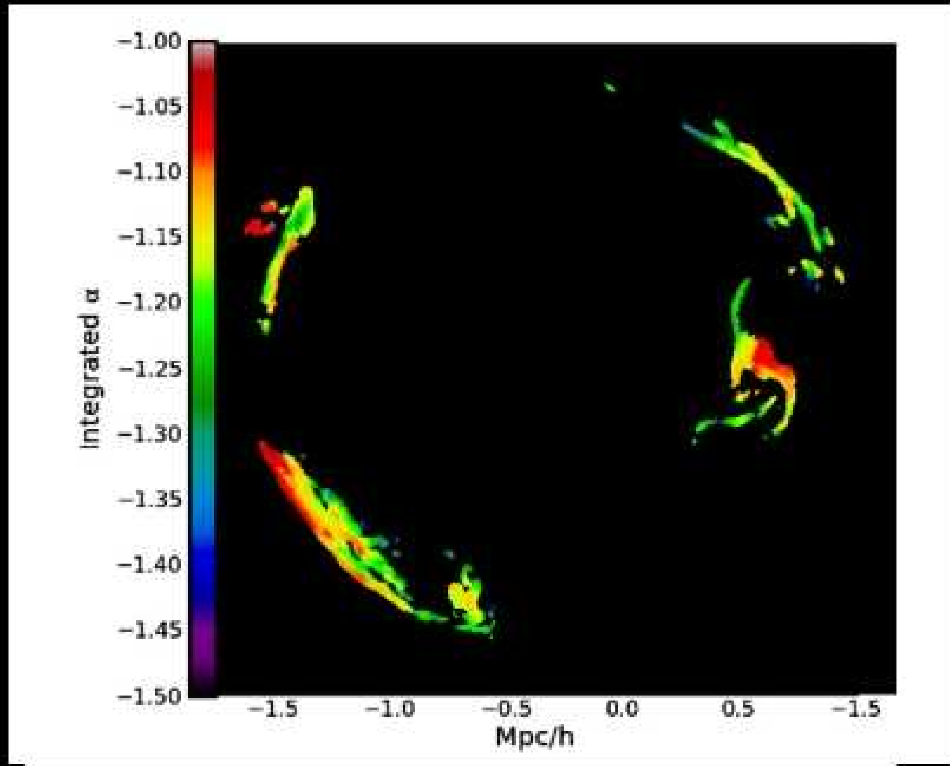
Mach numbers ~
2 - 4

provided by A. Bonafede

Cluster Radio Relics

From cosmological simulations



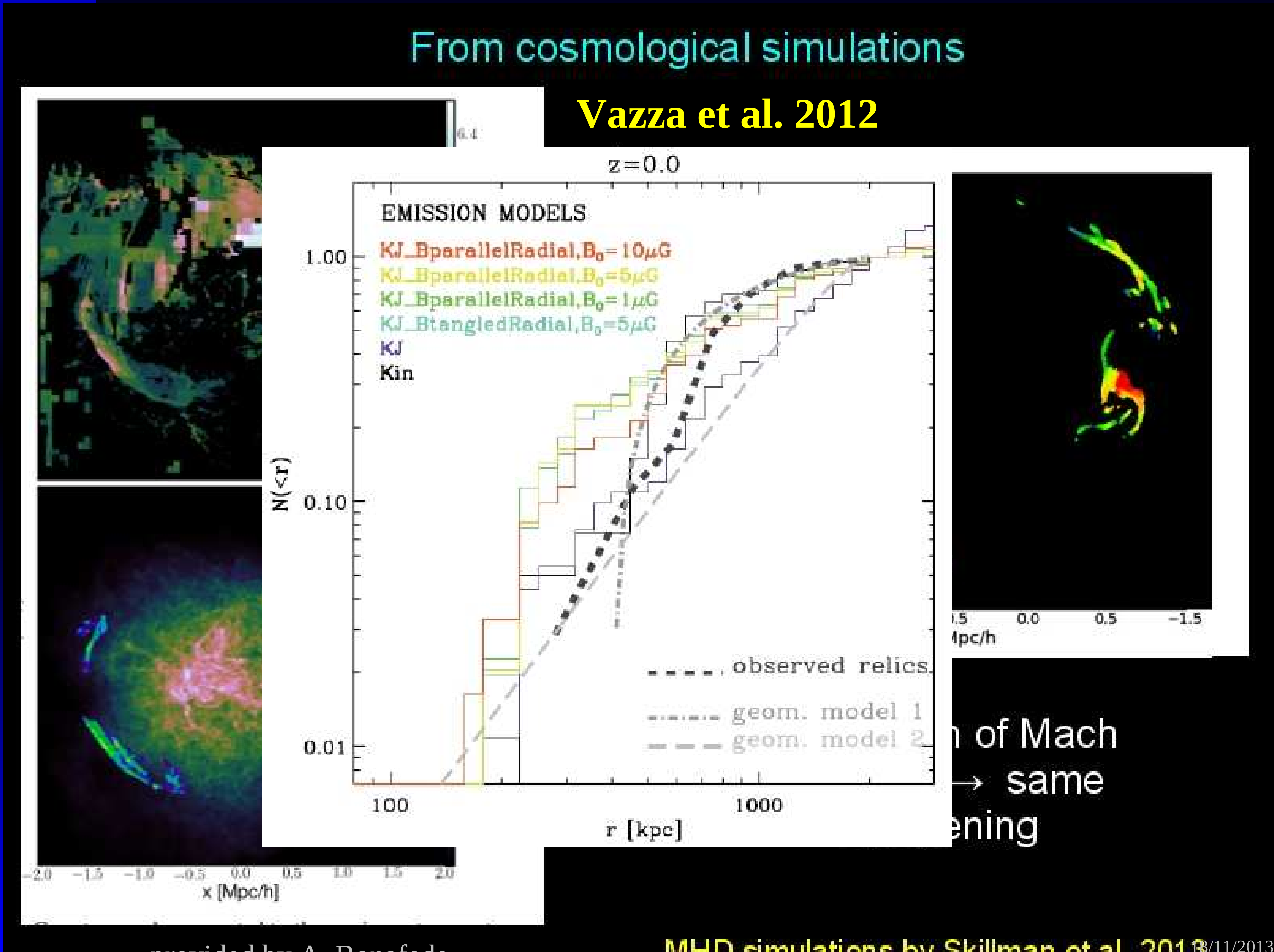


Distribution of Mach numbers → same steepening

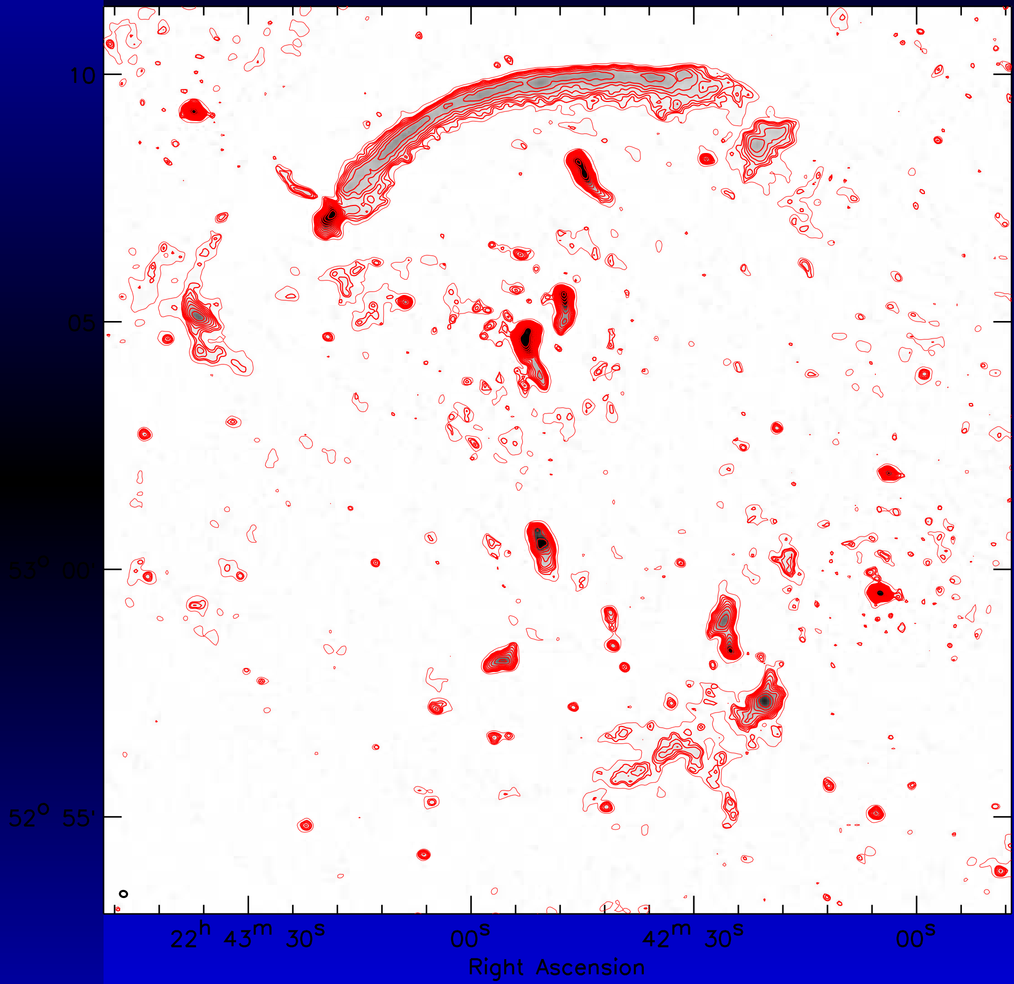
provided by A. Bonafede

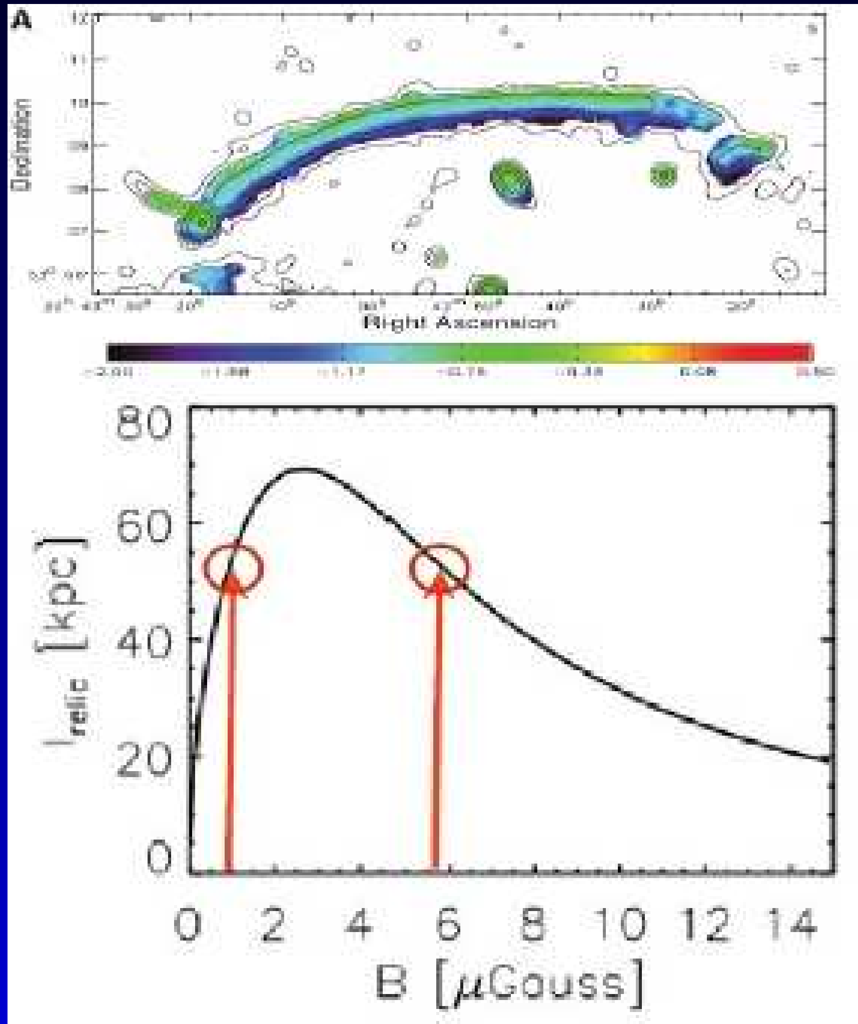
MHD simulations by Skillman et al. 2013

Cluster Radio Relics



Cluster Radio Relics

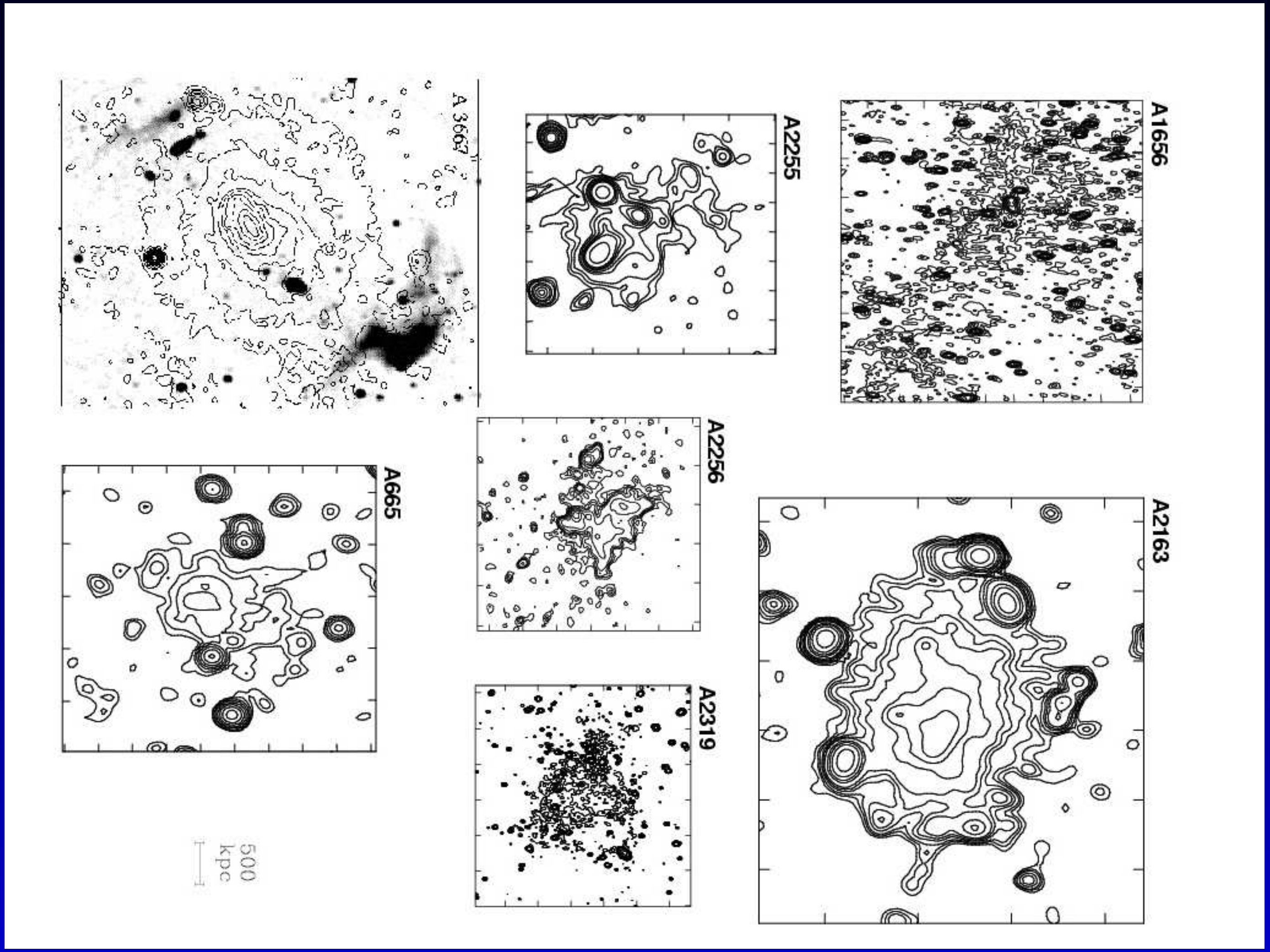




van Weeren et al. 2010

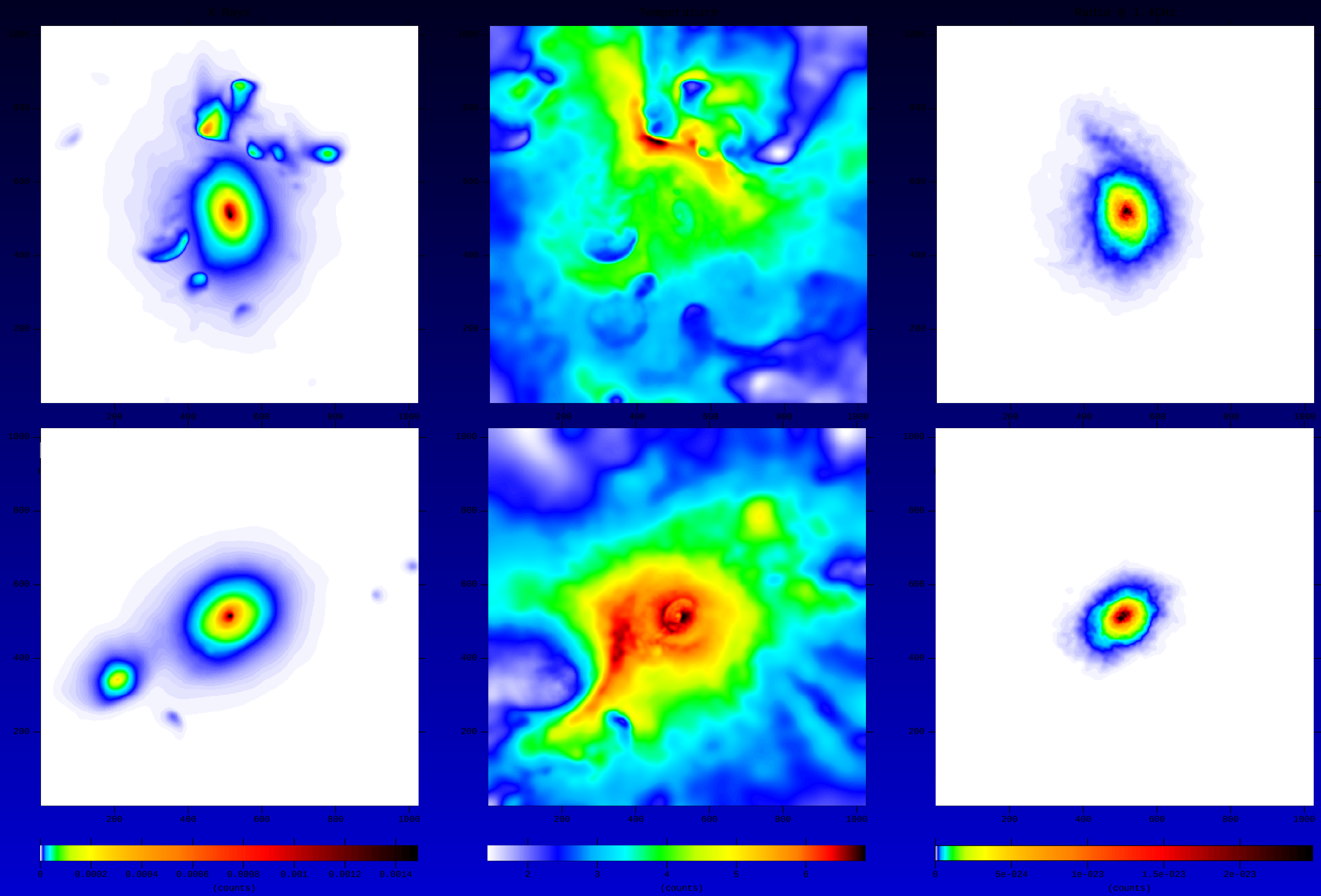
With of the relic suggest $\vec{B} \approx 1\mu\text{G}$ or $5 - 7\mu\text{G}$!

Cluster Halos (hadronic)



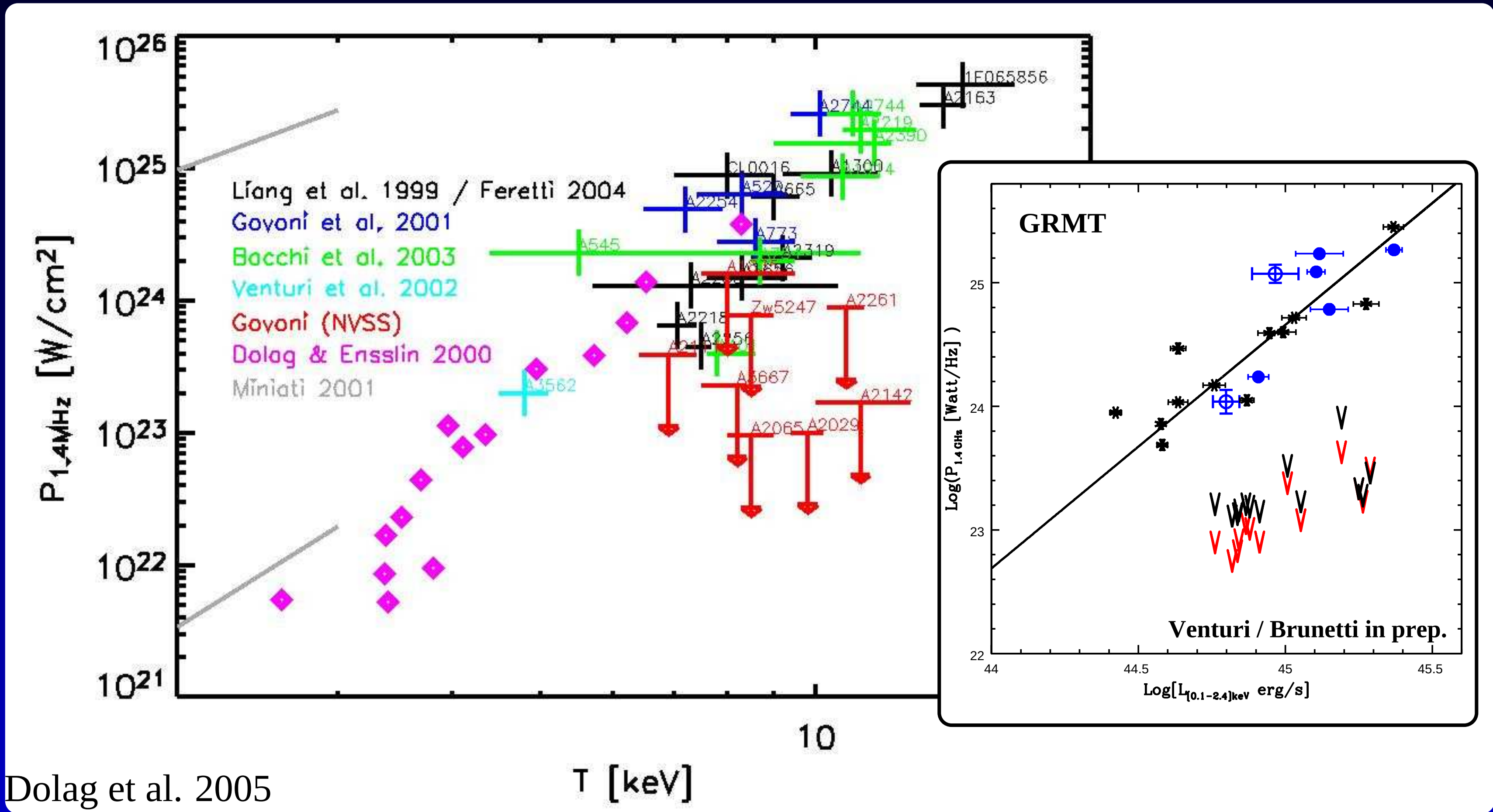
Cluster wide diffuse synchrotron emission (radio halos) of relativistic electrons in cluster magnetic fields. **Origin of relativistic electrons** (secondary, shocks, turbulence, ...) ?

Cluster Halos (hadronic)



X-Ray (left), Temperature (middle) and Radio emission (right) from 2 simulated clusters. Radio emission is derived from **simple secondary model**, see Dolag & Ensslin 2000.

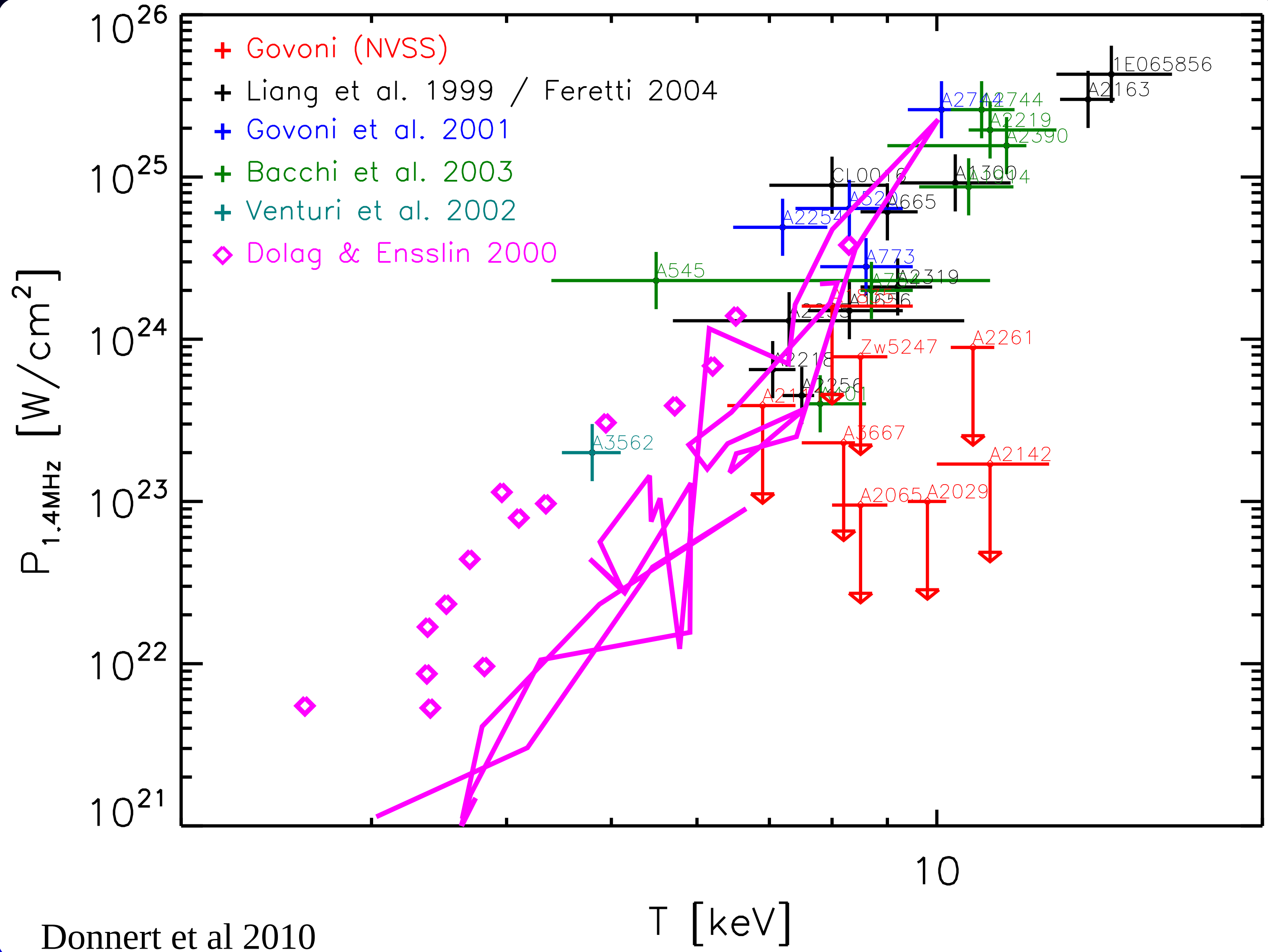
Cluster Halos (hadronic)



Dolag et al. 2005

- Assuming energy fraction of CR$p^+ \propto$ to thermal energy.
- Secondary (CR$p^+ \rightarrow \pi^{\pm,0} \rightarrow e^-$) **predict correlation** !
- But **fail** to reproduce **probability** !

Cluster Halos (hadronic)



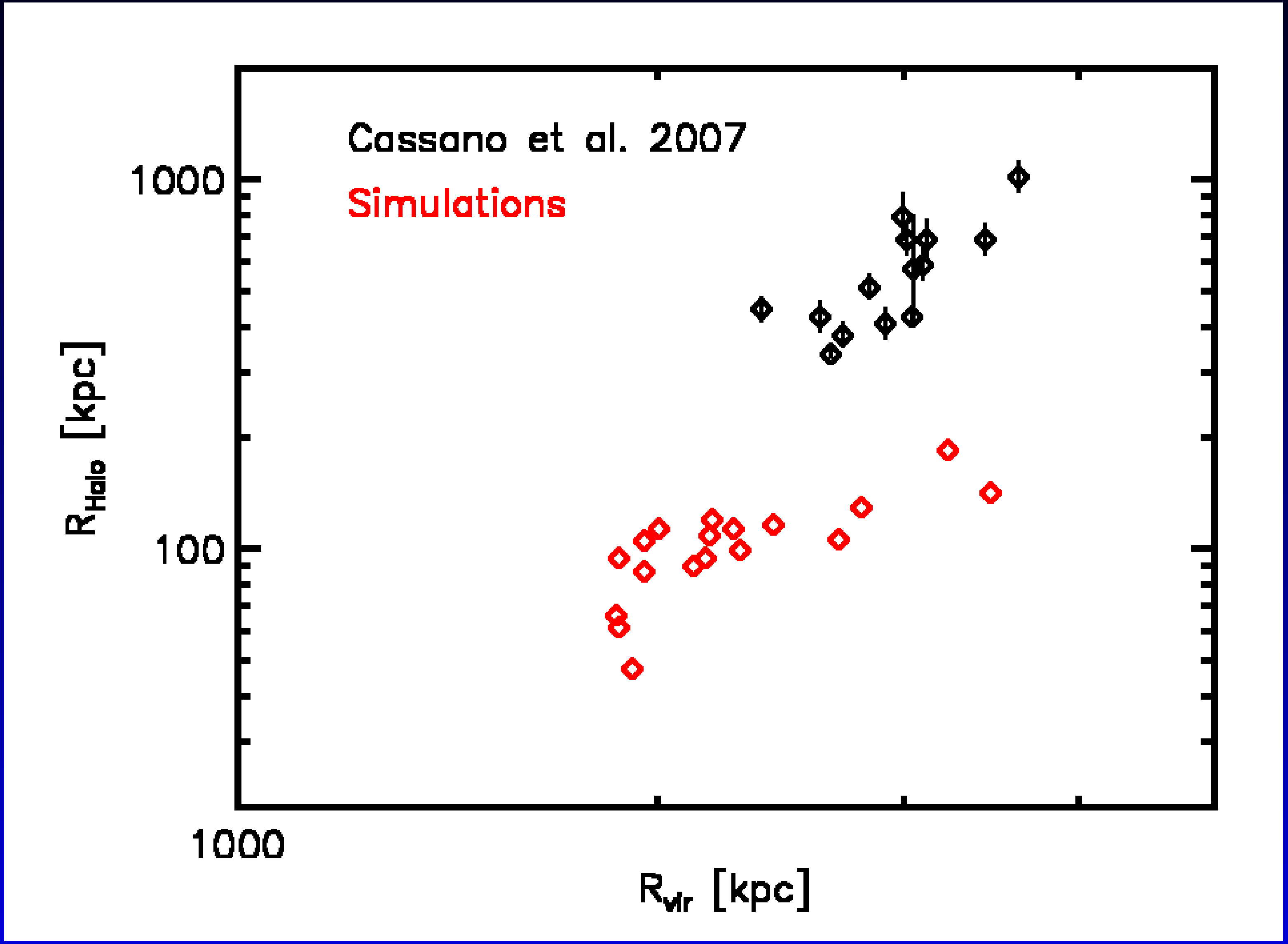
Donnert et al 2010

Evolution **track** relative **parallel** to correlation.

$\Rightarrow$ Strong dissipation of magnetic fields is needed for models.

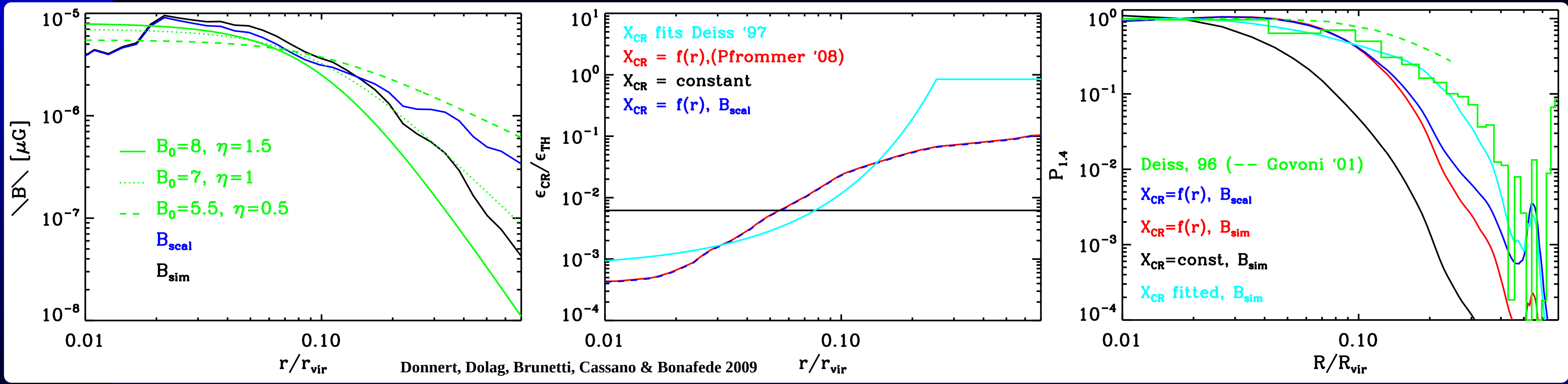
$\Rightarrow$ Or strong diffusion for CRp needed !

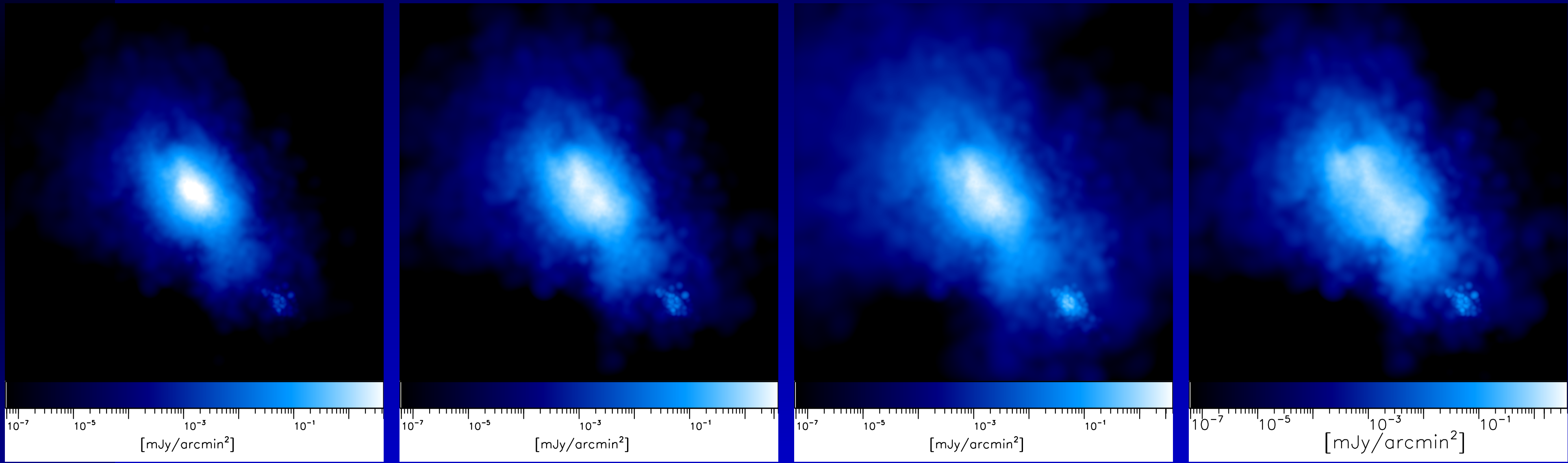
Cluster Halos (hadronic)



Models also **fail** to predict the observed, **large extension** of the diffuse radio emission.

Cluster Halos (hadronic)

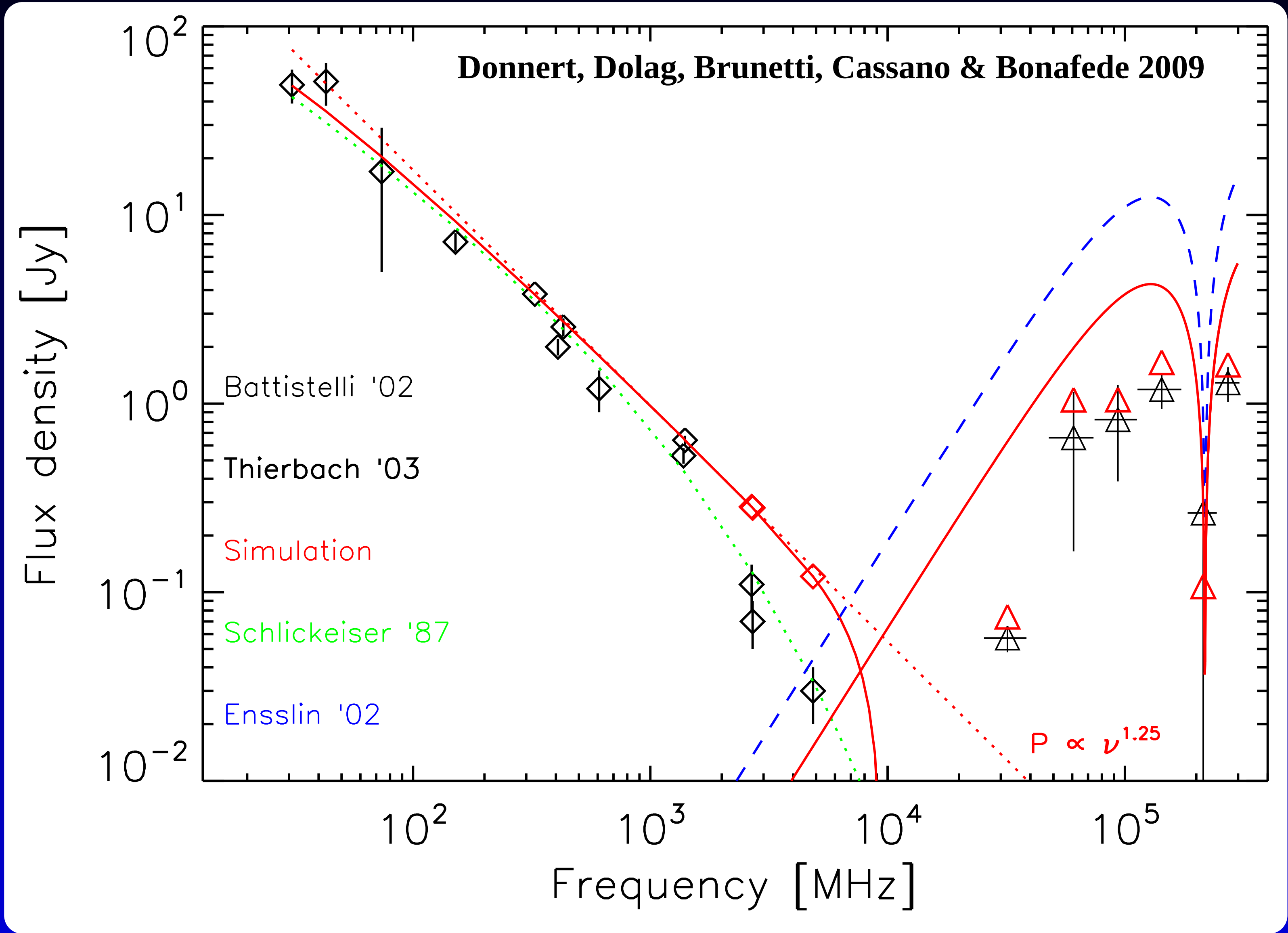




Hadronic interactions of CR-p^+ (>GeV) with ICM-p^+ will produce pions. The charged pions decay into secondary electrons producing synchrotron emission.

$\Rightarrow$ Radial **energy distribution** / emission **disfavors model** !

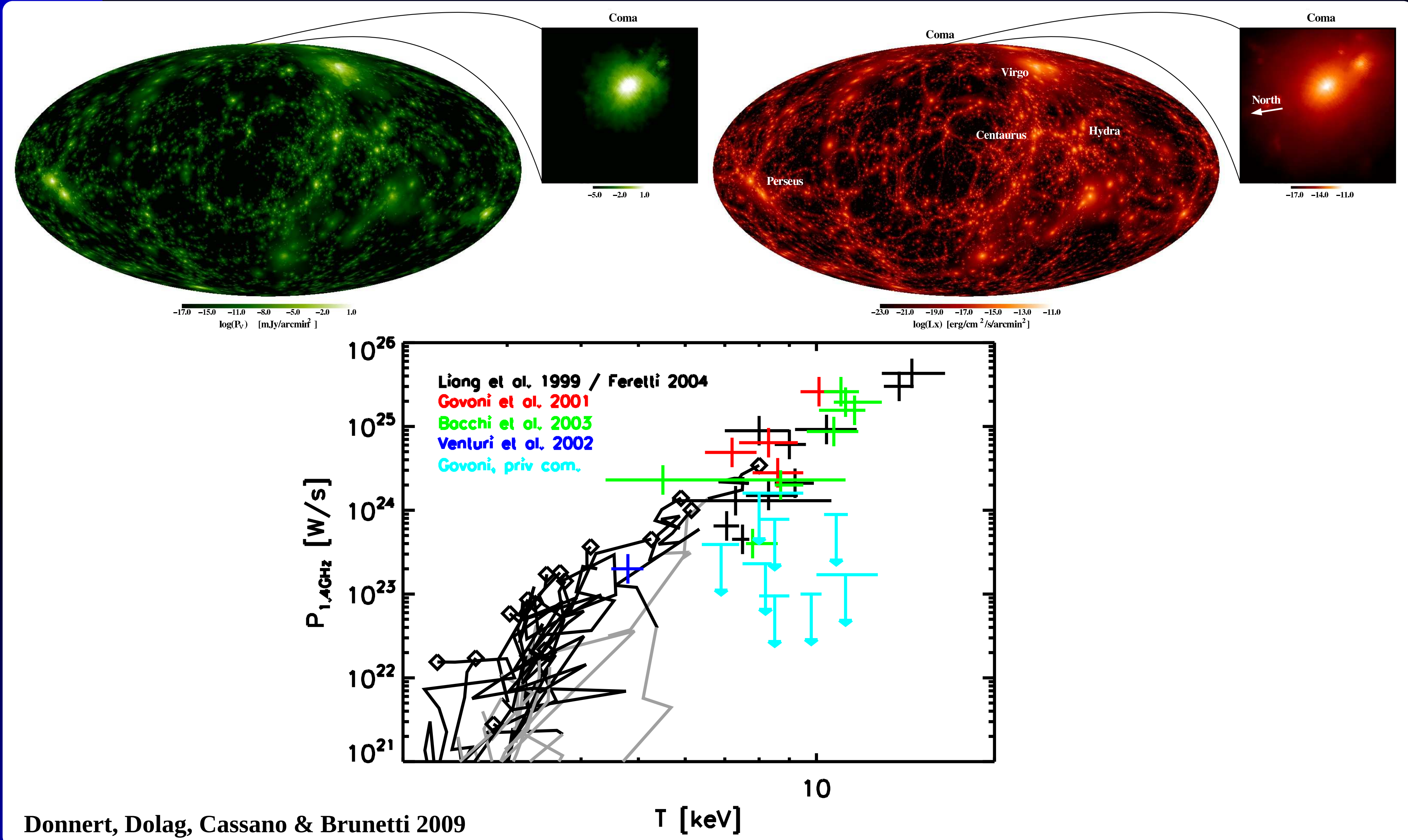
Cluster Halos (hadronic)



CR-p^+ will have power law distribution ⇒ power law spectra, and negative SZ flux steepens spectra not enough

⇒ Sign of aging (e.g. **indicates primary** CR-e^-)

Cluster Halos (hadronic)



Donnert, Dolag, Cassano & Brunetti 2009

Evolution track parallel to correlation

$\Rightarrow$ Strong evolution in CR-e^- needed

$\Rightarrow$ Secondaries from CR-p^+ disfavored

$\Rightarrow$ Need to investigate **turbulent re-acceleration**

Cluster Halos (turbulence)

⇒ Solve Fokker-Planck equation for CRe population

$$\frac{\partial n}{\partial t} = \frac{\partial}{\partial p}\left(D_{\mathrm{pp}}\frac{\partial n}{\partial p} + H(p)n\right) - \frac{n}{T(t)} + Q(t)$$

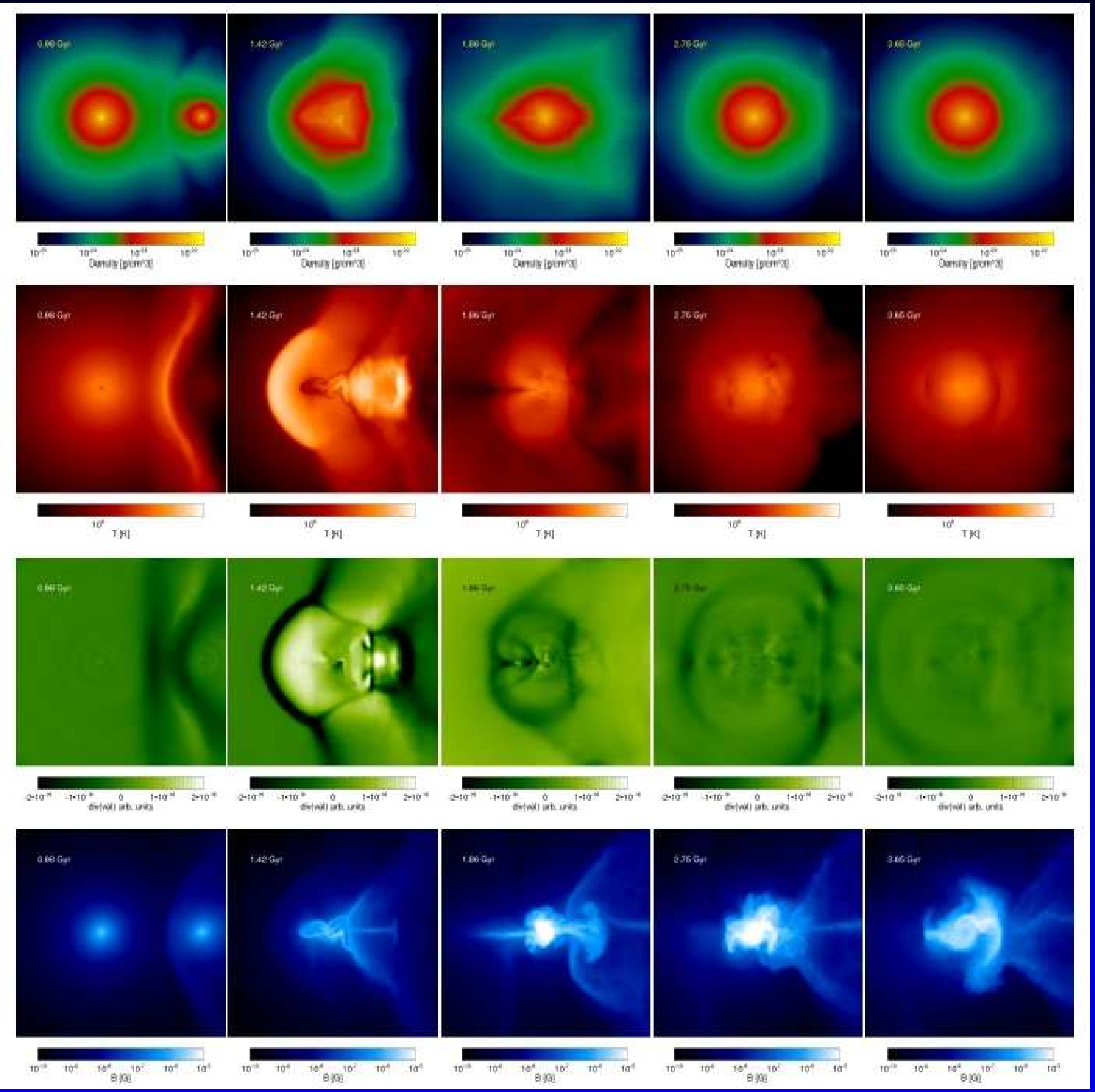
- 10% turbulent energy in fast mhd modes and reacceleration by those only
- Momentum Diffusion Coefficient

$$D_{\mathrm{pp}} \propto v_{\mathrm{turb}}^4 / h_{\mathrm{sml}} / c_{sound}$$

- cooling with inverse compton, synchrotron and bremsstrahlung
- See also Cassano & Brunetti 05, Brunetti & Lazarian 2007
- 1% CRp as seed for CRe (hadronic background)

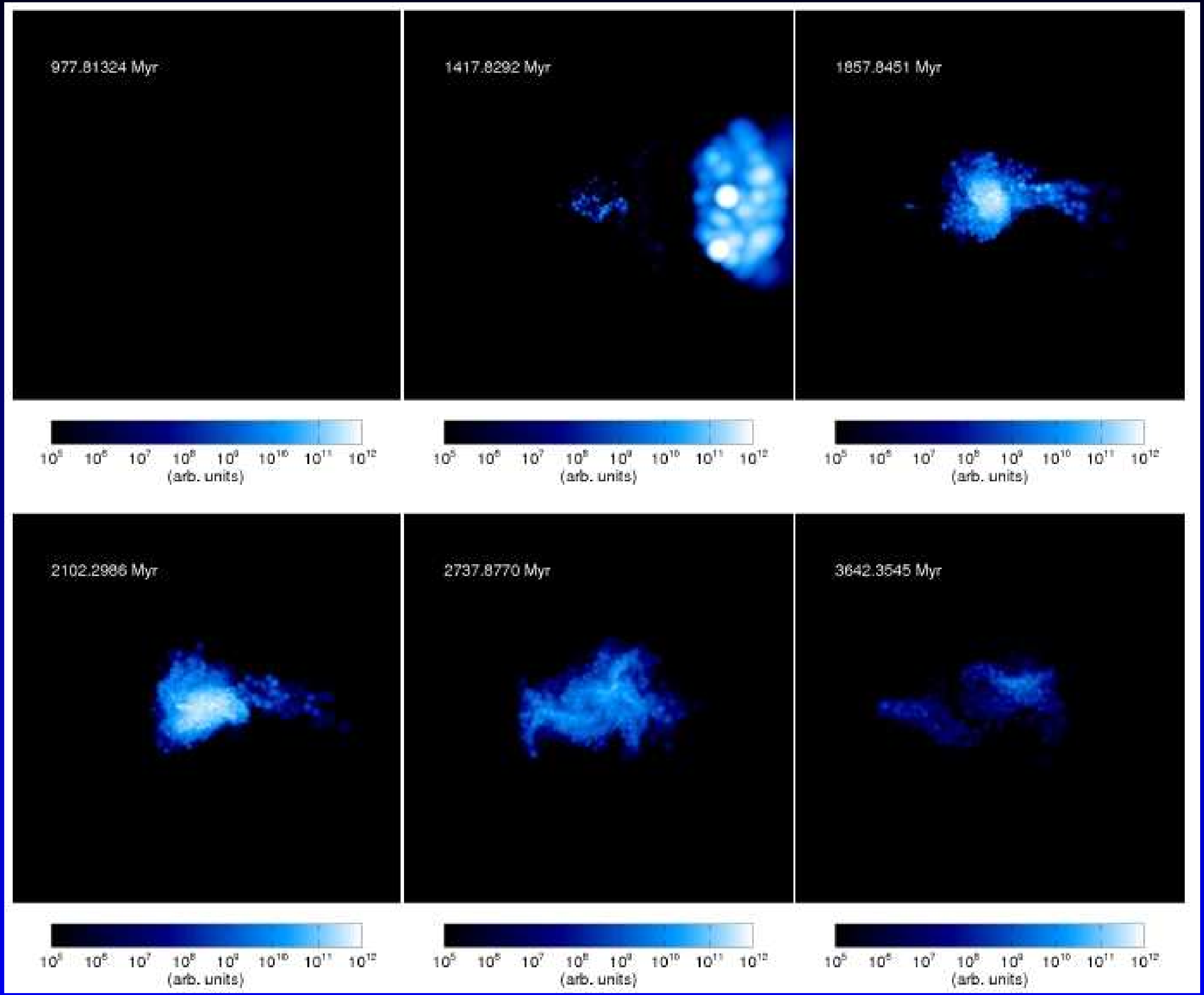
Donnert et al. 2012

Cluster Halos (turbulence)



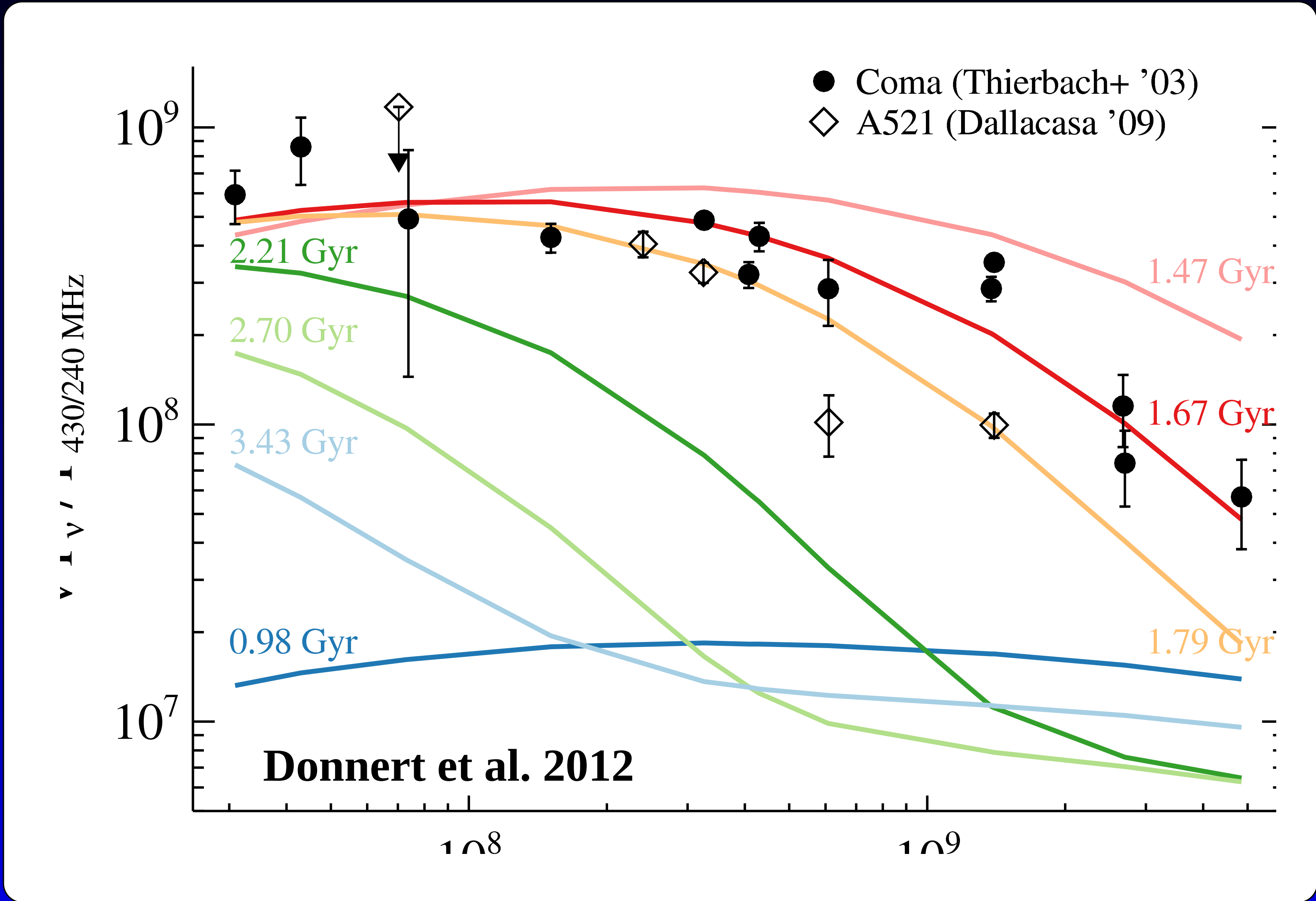
Idealized 1:4 merger, solving Fokker-Planck equation for all particles (2x128^3) (Donnert et al. 2012)

Cluster Halos (turbulence)



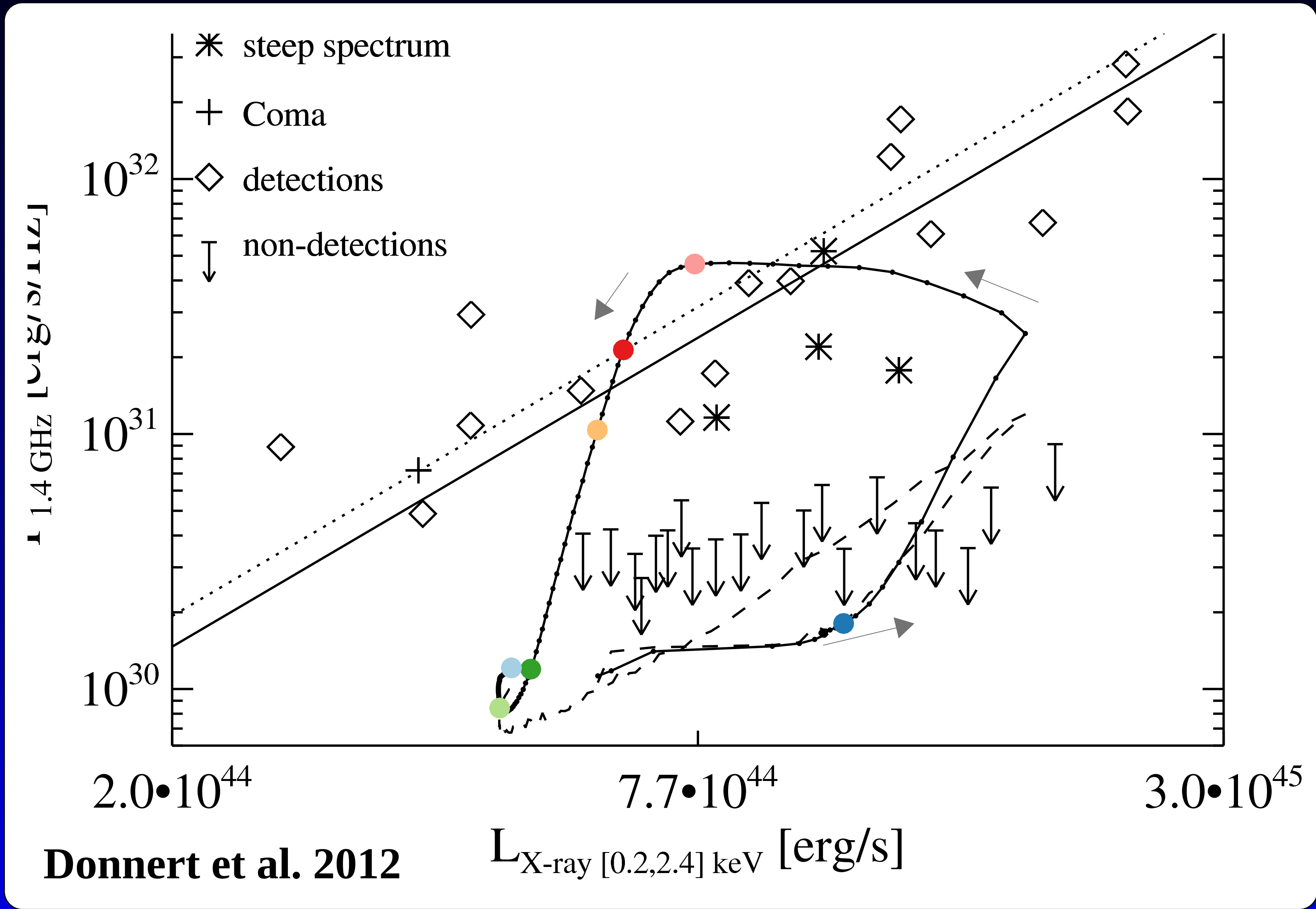
Evolution of synthetic radio emission (Donnert et al. 2012)

Cluster Halos (turbulence)



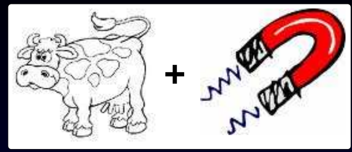
Evolution of the spectrum of the radio emission (Donnert et al. 2012)

Cluster Halos (turbulence)



Evolution of the Lx-P1.4 relation (Donnert et al. 2012)

Are we done ?



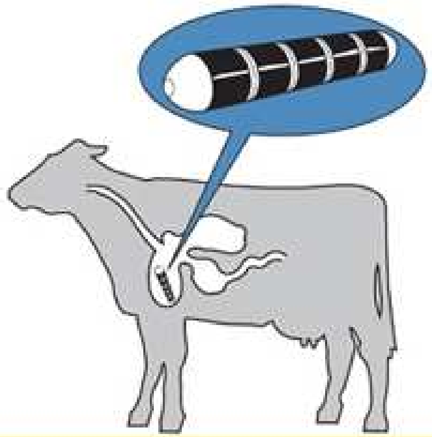
- *"Magnetic alignment in grazing and resting cattle and deer"*, Begall et al. 2008
- *"Extremely low-frequency electromagnetic fields disrupt magnetic alignment of ruminants"*, Burda et al. 2009
- *"No alignment of cattle along geomagnetic field lines found"*, Hert et al. 2011a
- *"Further support for the alignment of cattle along magnetic field lines: reply to Hert et al."*, Begall et al. 2011
- *Authors's respnose*, Hert et al. 2011b

COW MAGNETS

What are Cow Magnets?

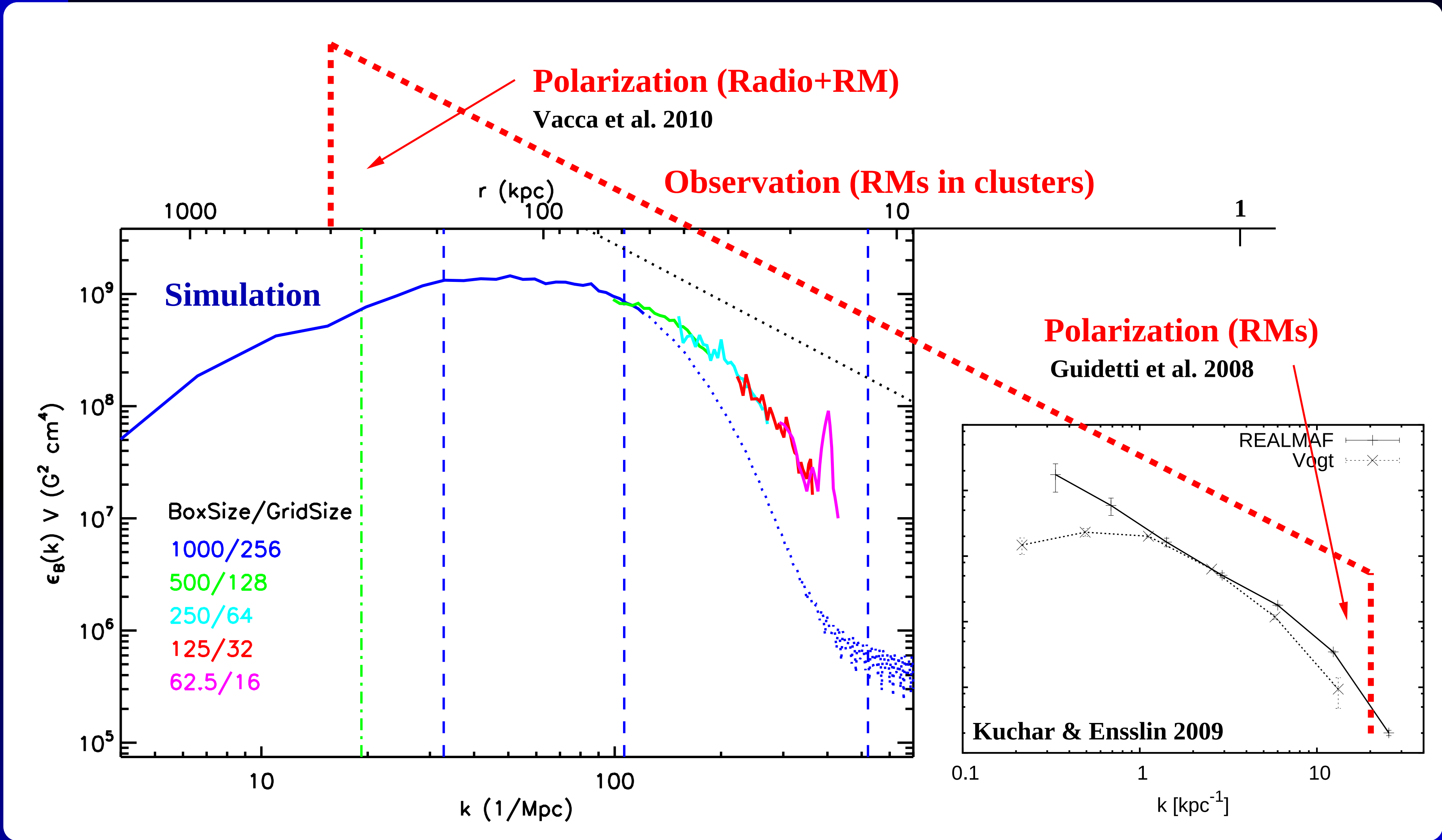
Cow magnets are popular with dairy farmers and veterinarians to help prevent Hardware Disease in cattle. While grazing, cows eat everything from grass and dirt to nails, staples and bits of bailing wire (referred to as tramp iron). Tramp iron tends to lodge in the honeycombed walls of the reticulum, threatening the surrounding vital organs and causing irritation and inflammation, known as Hardware Disease. The cow loses her appetite and decreases milk output (dairy cows), or her ability to gain weight (feeder stock). Cow magnets help prevent this disease by attracting stray metal from the folds and crevices of the rumen and reticulum. One magnet works for the life of the cow!

Purchase Cow Magnets at Our Online Store.



- Science for Europe (US farmers feed cow magnets to their cattle)

Summary (I)



- Measurement of magnetic field power spectra
- Clear indication of magnetic field topology
- Indications for minimum/maximum length scale

Summary (2)

Radio Relics:

- Diffuse, periferal emission
- Related to shocks from mergers
- Spectral index relates to Mach number
- Polarization indicates magnetic field alignment
- Width of emission region constrains $\vec{B}$

Radio Halos:

- Diffuse, central emission
- Related to merger events
- Morphology related to thermal gas
- Secondary model disfavored
- Most likely driven by turbulent re-acceleration