A Thermally Stable Heating Mechanism for the ICM

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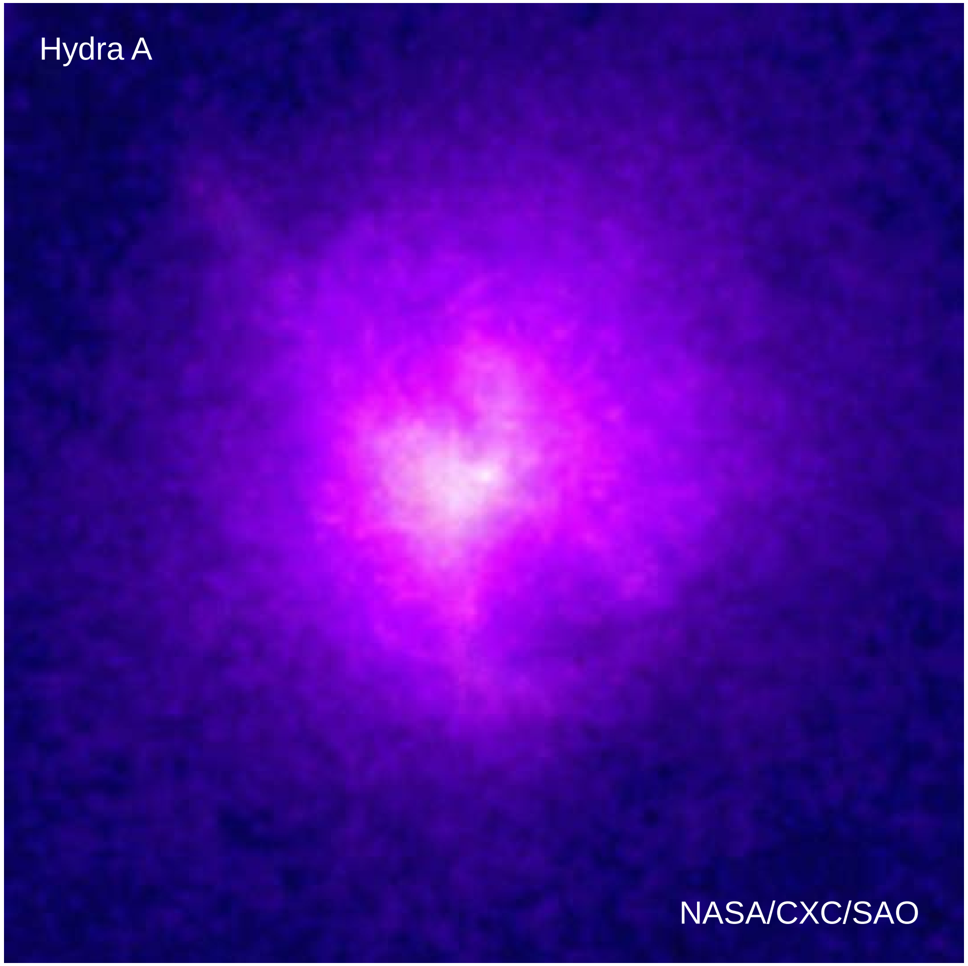
with many thanks to Helen Russell (*Cambridge*)
and Annalisa Bonafede (*Bologna*) for sharing data

Kunz *et al.*, *MNRAS* submitted; arXiv:1003.2719

Check out revision tomorrow morning on astro-ph!

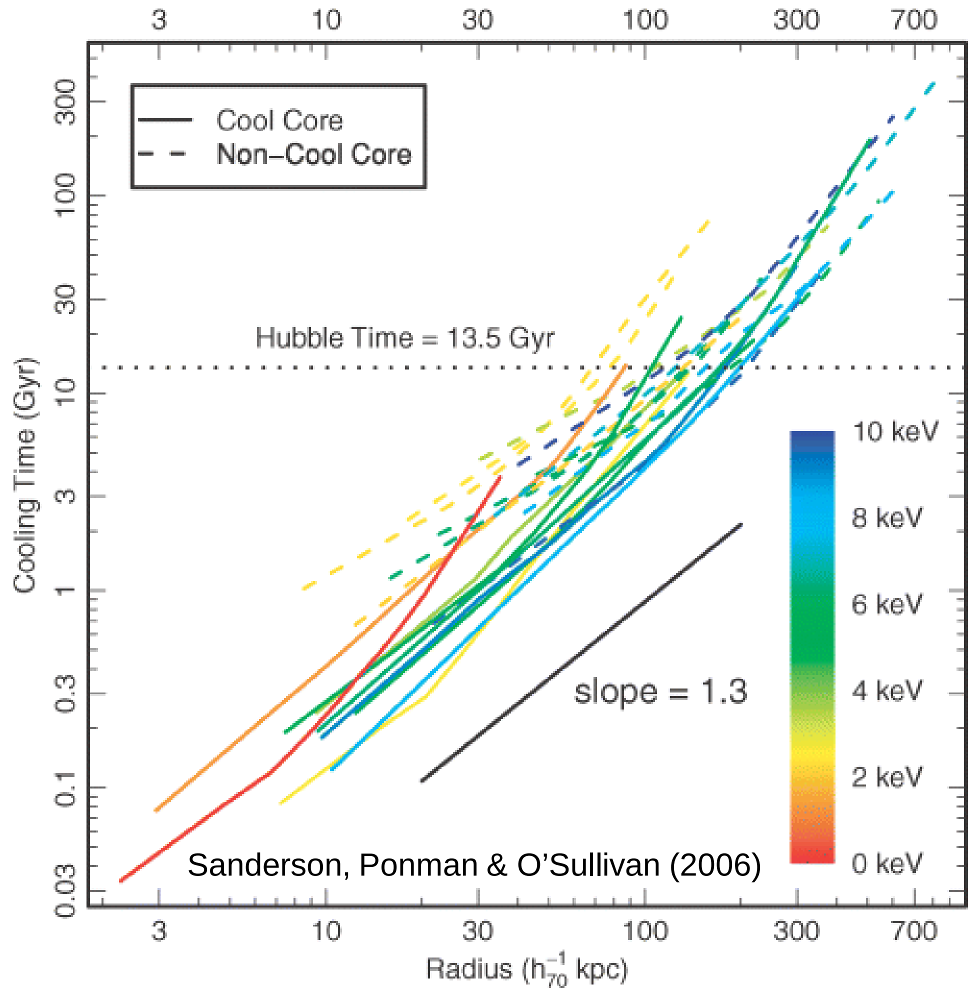
You all know the problem…

$$Q^{-} = 1.4 \times 10^{-25} \left(\frac{n_{\rm e}}{0.1\ {\rm cm}^{-3}}\right)^{2} \left(\frac{T}{2\,{\rm keV}}\right)^{1/2} {\rm erg\ s^{-1}\ cm^{-3}}$$



You all know the problem…

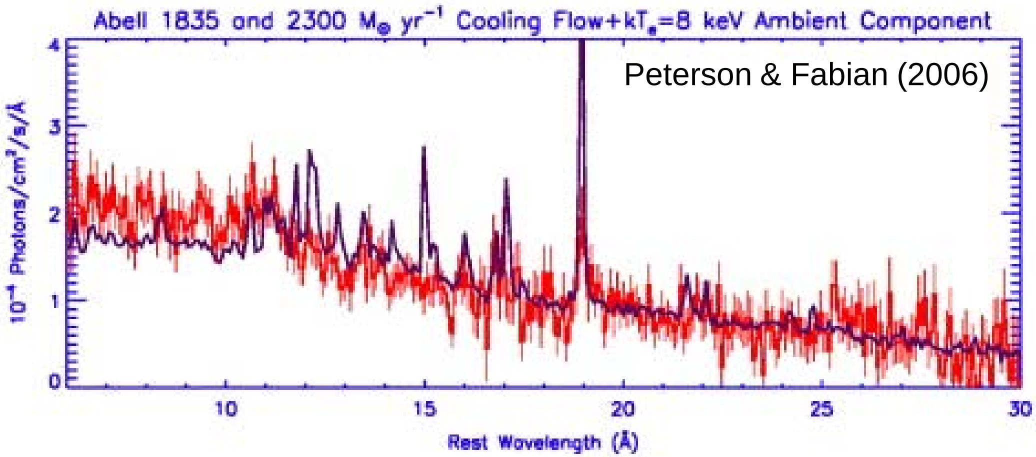
$$\Rightarrow \quad t_{\rm cool/heat} = \frac{3}{2}\frac{nT}{Q^-} = 0.21\left(\frac{n_{\rm e}}{0.1\ {\rm cm}^{-3}}\right)^{-1}\left(\frac{T}{2\ {\rm keV}}\right)^{1/2}\ {\rm Gyr},$$

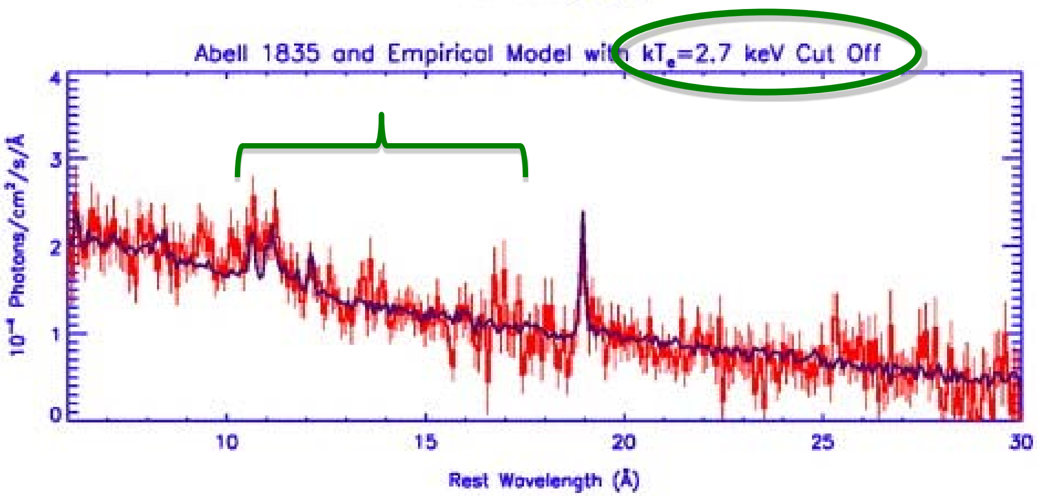


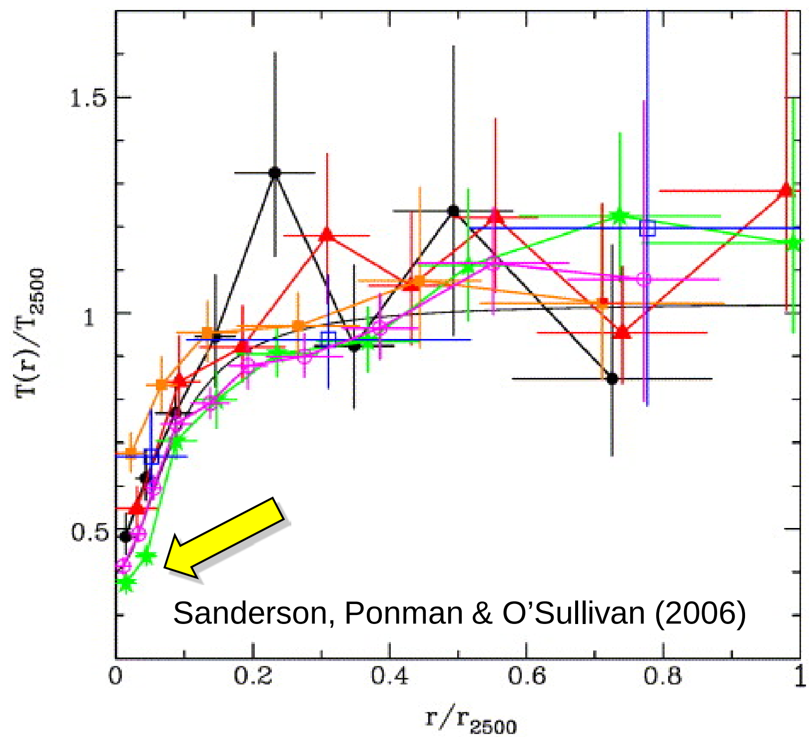
You all know the problem…

$$\Longrightarrow \quad L_{\rm cool} = \frac{5}{2}\frac{\dot{M}}{\mu m}kT \quad \Longrightarrow \quad \dot{M} = 50\text{–}100\, M_\odot\, {\rm yr}^{-1}$$

sometimes $\dot{M} \gtrsim 500\, M_\odot\, {\rm yr}^{-1}$





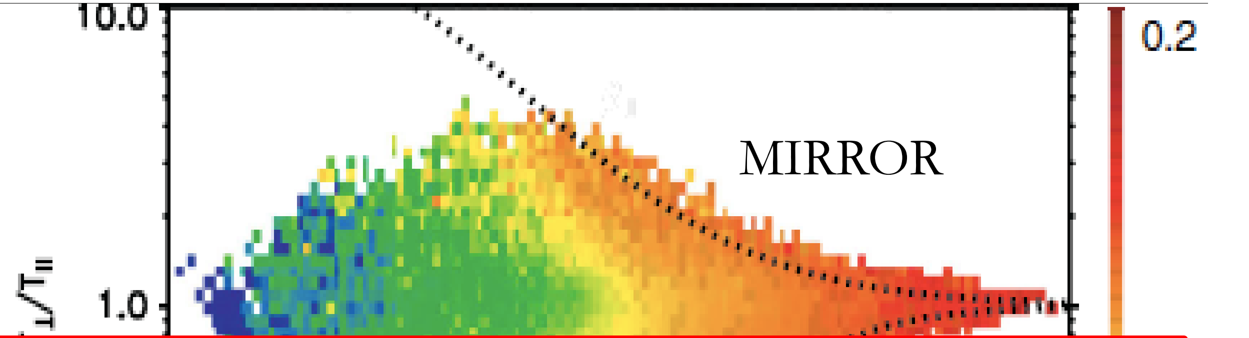


So what keeps the gas from cooling below $\sim T_{\rm vir}/3$?

…picking up where we left off…

A Macrophysical Fudge: Marginal ICM

Despite progress,
a complete *ab initio*
microphysical theory
of transport
is s
of
and



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Why are we returning to Alex's talk?

Because the transport properties of the ICM are dependent on both the geometry and strength of the magnetic field, as well as on microscale plasma instabilities that are likely to occur ubiquitously in the ICM.

Magnetic field increases: Δ>0

$$\text{MIRROR:} \quad \gamma = \frac{|k_{||}|v_{\text{th}i}}{\sqrt{\pi}}\left(\Delta - \frac{1}{\beta_i}\right)$$

$$\Delta = \frac{2\xi}{\beta_i}, \quad \xi \in [-1, 0.5]$$

Heating in Marginal ICM

$$\frac{3}{2} n \frac{dT}{dt} = -nT\nabla\cdot\boldsymbol{u} - \boldsymbol{\sigma}_{\rm i}{:}\nabla\boldsymbol{u} - \nabla\cdot\boldsymbol{q}_{\rm e} - n_{\rm i} n_{\rm e}\Lambda$$

heating Q^+

cooling Q^-

$\Lambda \propto T^{1/2}$

$$Q^+ = -\overline{\boldsymbol{\sigma}_{\rm i}{:}\nabla\boldsymbol{u}} = p_{\rm i}\Delta_{\rm i}\,\overline{\left(\boldsymbol{bb}{:}\nabla\boldsymbol{u} - \frac{1}{3}\nabla\cdot\boldsymbol{u}\right)} = 0.35\, p_{\rm i}\nu_{\rm ii}\Delta_{\rm i}^2$$

$$-\boldsymbol{\sigma}_{\rm i} = -\left(\boldsymbol{bb} - \frac{1}{3}\mathsf{I}\right) p_{\rm i}\Delta_{\rm i}$$

viscous stress tensor

$$\nu_{\rm ii}\Delta_{\rm i} = 2.9\,\overline{\left(\boldsymbol{bb}{:}\nabla\boldsymbol{u} - \frac{1}{3}\nabla\cdot\boldsymbol{u}\right)}$$

[Kunz *et al.*, submitted (2010)]

Heating in Marginal ICM

$$\frac{3}{2} n \frac{dT}{dt} = -nT\nabla\cdot u - \sigma_i : \nabla u - \nabla\cdot q_e - n_i n_e \Lambda$$

heating Q^+

cooling Q^-

$\Lambda \propto T^{1/2}$

$$Q^+ = 0.35\, p_i \nu_{ii} \Delta_i^2 = 0.35\, \frac{\nu_{ii}}{p_i} \left(\frac{\xi B^2}{4\pi} \right)^2$$

To leapfrog having to do an honest microphysical job, simply assume closure (fudge)

$$\Delta = \frac{2\xi}{\beta_i}, \quad \xi \in [-1, 0.5]$$

[Kunz *et al.*, submitted (2010)]

Heating in Marginal ICM

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heating Q^+

cooling Q^-

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$$Q^+ = 0.35\, p_{\rm i}\nu_{\rm ii}\Delta_{\rm i}^2 = 0.35\,\frac{\nu_{\rm ii}}{p_{\rm i}}\left(\frac{\xi B^2}{4\pi}\right)^2$$

$$= 10^{-25}\,\xi^2\left(\frac{B}{10\,\mu{\rm G}}\right)^4\left(\frac{T}{2\,{\rm keV}}\right)^{-5/2}\ {\rm erg\,s^{-1}\,cm^{-3}}$$

Compare this with Bremsstrahlung cooling:

$$Q^- = 1.4\times10^{-25}\left(\frac{n_{\rm e}}{0.1\ {\rm cm}^{-3}}\right)^2\left(\frac{T}{2\,{\rm keV}}\right)^{1/2}\ {\rm erg\,s^{-1}\,cm^{-3}}$$

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Heating vs. Cooling in Marginal ICM

$$Q^{+} = 10^{-25}\,\xi^{2}\left(\frac{B}{10\,\mu\mathrm{G}}\right)^{4}\left(\frac{T}{2\,\mathrm{keV}}\right)^{-5/2}\ \mathrm{erg\,s^{-1}\,cm^{-3}}$$

$$Q^{-} = 1.4\times 10^{-25}\left(\frac{n_{\mathrm{e}}}{0.1\ \mathrm{cm^{-3}}}\right)^{2}\left(\frac{T}{2\,\mathrm{keV}}\right)^{1/2}\ \mathrm{erg\,s^{-1}\,cm^{-3}}$$

Rates are similar …

… so let's explore what $Q^{+} \sim Q^{-}$ implies

and check *a posteriori* if the results are

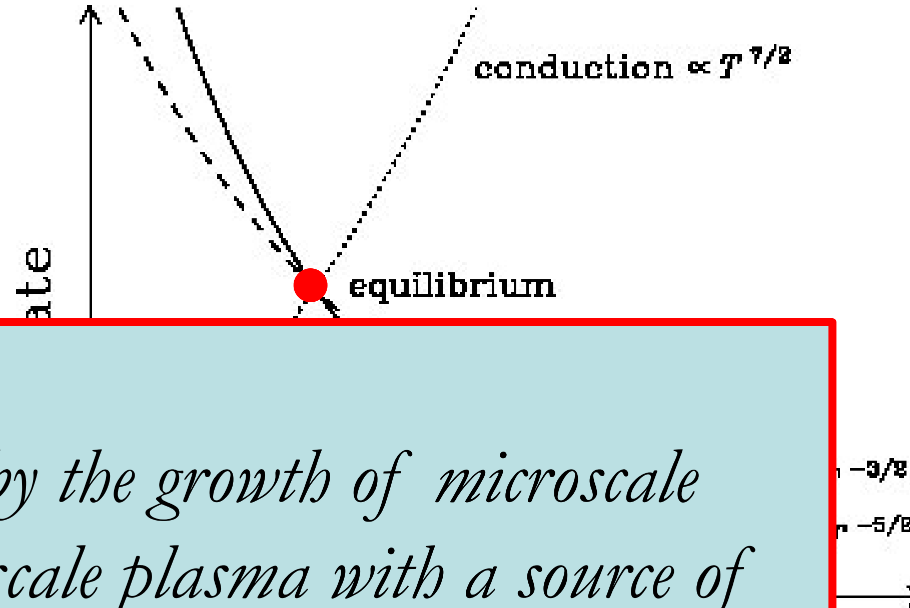
observationally permissible and theoretically sensible.

If they are, then we might be onto something…

Thermal Stability

First thing to notice :

The balance between heating and cooling is **thermally stable**, while balance between cooling



Parallel viscosity, regulated by the growth of microscale instabilities, endows the large-scale plasma with a source of viscous heating that makes the plasma thermally stable.

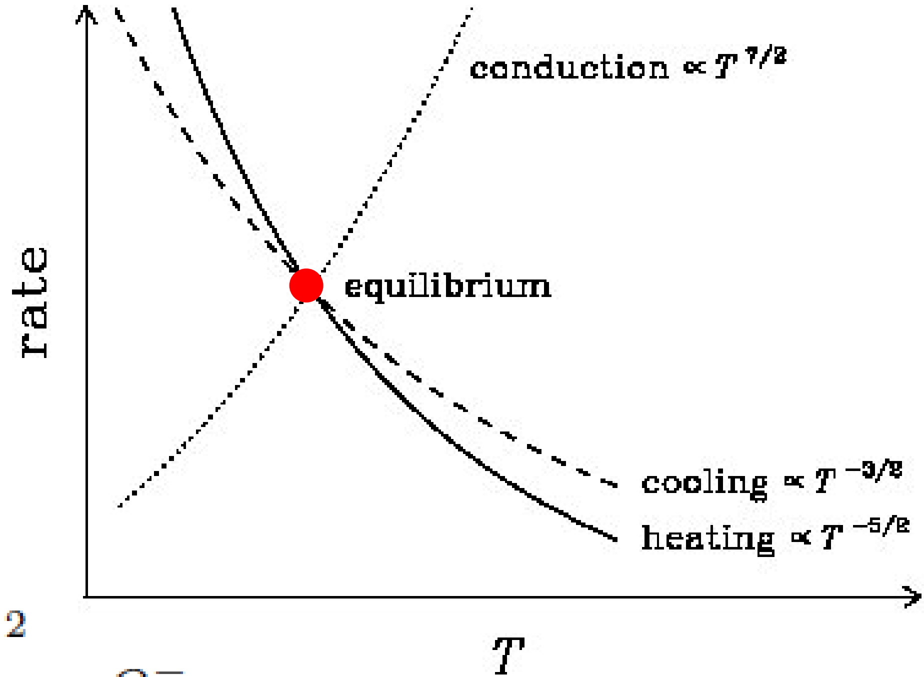
Compare this with Bremsstrahlung cooling:

$$Q^- = 1.4 \times 10^{-25} \left(\frac{n_e}{0.1\ \mathrm{cm}^{-3}} \right)^2 \left(\frac{T}{2\ \mathrm{keV}} \right)^{1/2} \mathrm{erg\ s}^{-1}\ \mathrm{cm}^{-3}$$

[Kunz *et al.*, submitted (2010)]

Corollary: B vs. n and T

The balance between heating and cooling is thermally stable, while balance between cooling and conduction is not.



$$Q^+ = 0.35\, p_i \nu_{ii} \Delta_i^2 = 0.35\, \frac{\nu_{ii}}{p_i} \left(\frac{\xi B^2}{4\pi} \right)^2 = Q^-$$

$$B \simeq 11\, \xi^{-1/2} \left(\frac{n_e}{0.1\ \mathrm{cm}^{-3}} \right)^{1/2} \left(\frac{T}{2\ \mathrm{keV}} \right)^{3/4} \mu\mathrm{G}$$

NB: Magnetic field is a function both of density *and* temperature!

[Kunz *et al.*, submitted (2010)]

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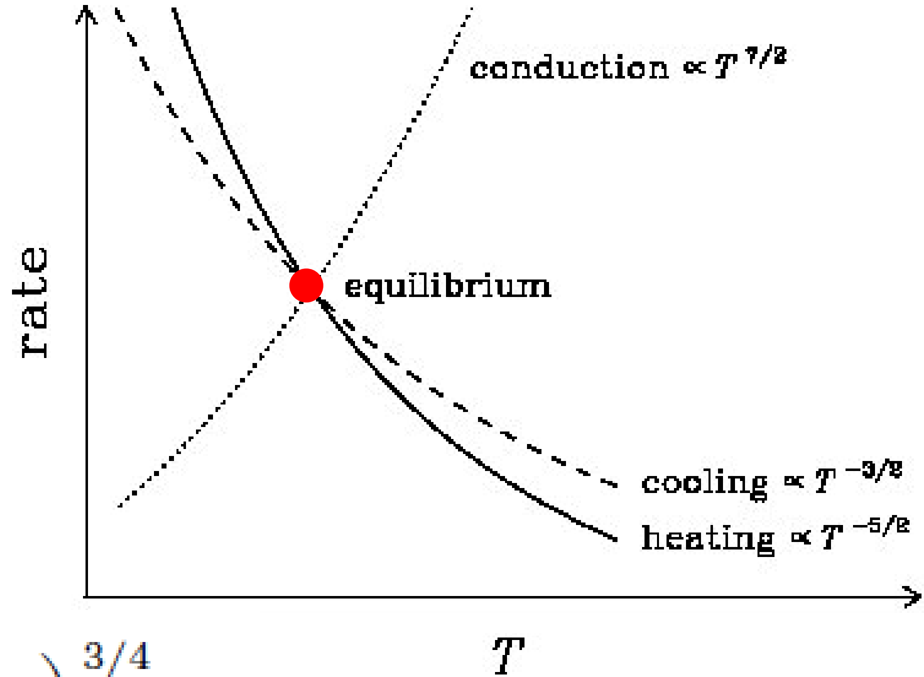

$$B \simeq 11\,\xi^{-1/2}\left(\frac{n_{\rm e}}{0.1\ {\rm cm}^{-3}}\right)^{1/2}\left(\frac{T}{2\ {\rm keV}}\right)^{3/4}\ \mu{\rm G}$$

or, for conditions near the temperature maximum…

$$B \cong 2\ \xi^{-1/2}\left(\frac{n_{\rm e}}{10^{-3}\ {\rm cm}^{-3}}\right)^{1/2}\left(\frac{T}{5\ {\rm keV}}\right)^{3/4}\ \mu{\rm G}$$

[Kunz *et al.*, submitted (2010)]

Corollary: B vs. n and T

Cluster name	$n_{e,c}$ (10^{-2} cm^{-3})	T_c (keV)	$B_{c,\rm theory}$ ($\xi^{-1/2}\mu$G)	$B_{c,\rm obs}$ (μG)
Cool-core clusters				
A1835	10	2.85	13.8	–
Hydra A	7.2	3.11	12.4	12^a
A478	15.2	1.72	12.1	–
A2199	10	$\simeq 2$	$\simeq 11$	15^b
M87	10.8	1.62	9.8	35^b
A1795	5.4	2.26	8.6	9.7^b
Centaurus	9.5	1.24	7.7	8
A262	3.7	1.54	5.5	–
Non-cool-core clusters				
A2142	1.87	8.8	13.0	RM^c
Ophiucus	0.80	10.3	9.5	RM^c
A401	0.70	8.3	7.6	RM^c
A2382	0.50	2.9	3.1	3
A2634	0.28	3.7	2.7	3.5^b
A2255	0.2	3.5	2.2	2.5
A400	0.24	2.3	1.8	2.9^b

Corollary: Properties of Turbulence vs. n and T

1) Heating ~ cooling

$$\boxed{Q^+ = Q^-} \Longrightarrow B \simeq 11\,\xi^{-1/2}\left(\frac{n_e}{0.1\ \mathrm{cm}^{-3}}\right)^{1/2}\left(\frac{T}{2\ \mathrm{keV}}\right)^{3/4}\ \mu\mathrm{G}$$

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2) Dynamo saturates at equipartition

$$\frac{1}{2}m_i n_i U_{\mathrm{rms}}^2 \simeq \frac{B^2}{8\pi} \Longrightarrow$$

$$U_{\mathrm{rms}} \simeq 70\,\xi^{-1/2}\left(\frac{T}{2\ \mathrm{keV}}\right)^{3/4}\ \mathrm{km\,s^{-1}}$$

$$M \equiv \frac{U_{\mathrm{rms}}}{c_s} = 0.18\,\xi^{-1/2}\left(\frac{T}{2\ \mathrm{keV}}\right)^{1/4}$$

[Kunz *et al.*, submitted (2010)]

Corollary: Properties of Turbulence vs. n and T

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3) Turbulent energy absorption adjusts to heating rate

$$m_\mathrm{i}n_\mathrm{i}\frac{U_\mathrm{rms}^2}{\tau_\mathrm{turb}} \simeq Q^+ \Longrightarrow \tau_\mathrm{turb} \simeq 2\,\xi^{-1}\left(\frac{n_\mathrm{e}}{0.1\ \mathrm{cm}^{-3}}\right)^{-1}\left(\frac{T}{2\ \mathrm{keV}}\right)\ \mathrm{Myr}$$

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$$L \equiv U_{\mathrm{rms}}\,\tau_{\mathrm{turb}} \simeq 0.2\,\xi^{-3/2}\left(\frac{n_e}{0.1\ \mathrm{cm}^{-3}}\right)^{-1}\left(\frac{T}{2\ \mathrm{keV}}\right)^{7/4}\ \mathrm{kpc}$$

$$\kappa_{\mathrm{turb}} \sim U_{\mathrm{rms}}^2\tau_{\mathrm{turb}} \simeq 3\times 10^{27}\,\xi^{-2}\left(\frac{n_e}{0.1\ \mathrm{cm}^{-3}}\right)^{-1}\left(\frac{T}{2\ \mathrm{keV}}\right)^{5/2}\ \mathrm{cm^2\,s^{-1}}$$

[Kunz *et al.*, submitted (2010)]

Corollary: Properties of Turbulence vs. n and T

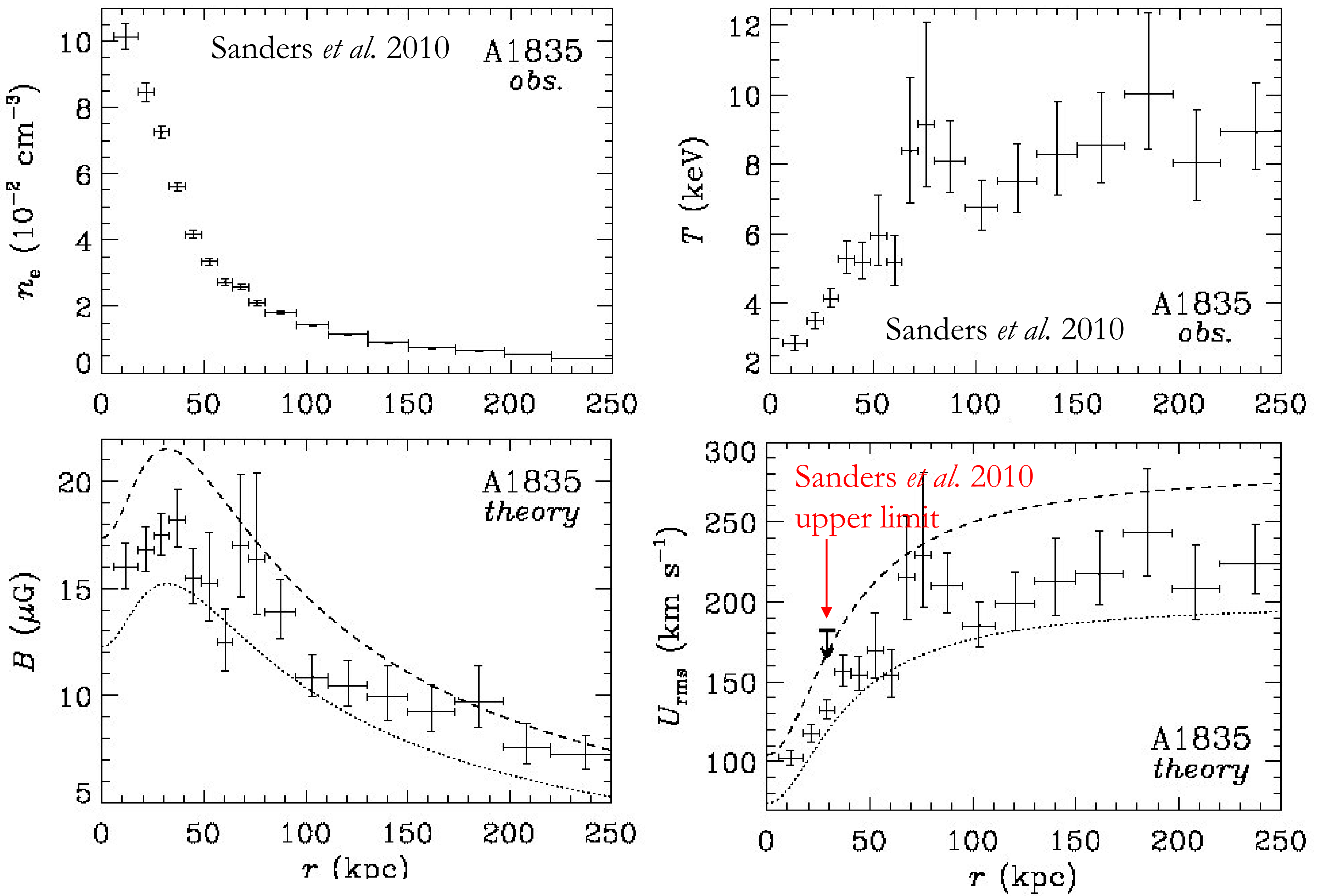
5 parameters: B, U_{rms}, L, n_{e}, T

If observations provide 2 of these, we can predict the other 3;
usually n_{e} and T provided, so we'll predict B, U_{rms}, L

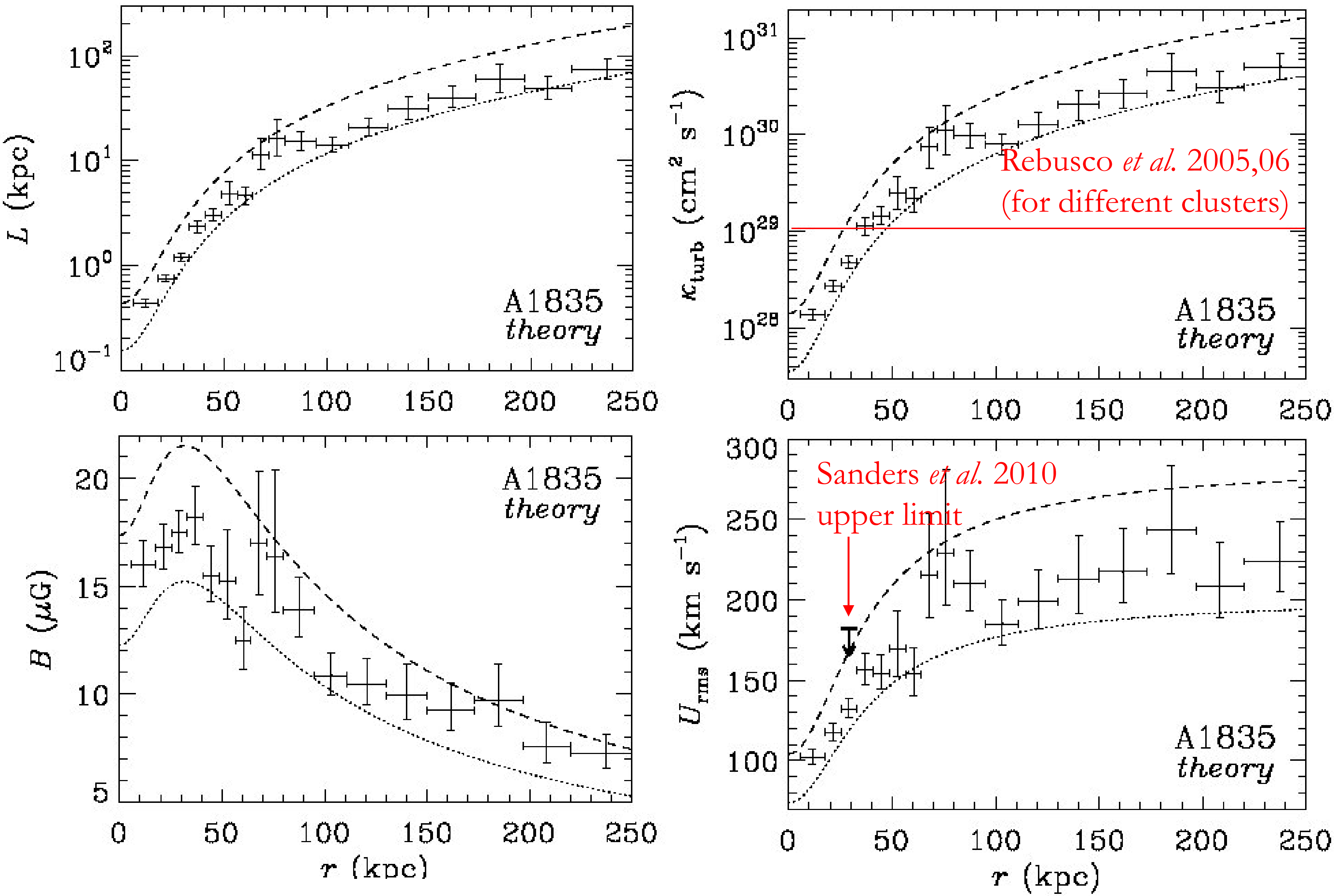
N.B. But no specific causal relationship is implied!

[Kunz *et al.*, submitted (2010)]

Example: A1835



Example: A1835

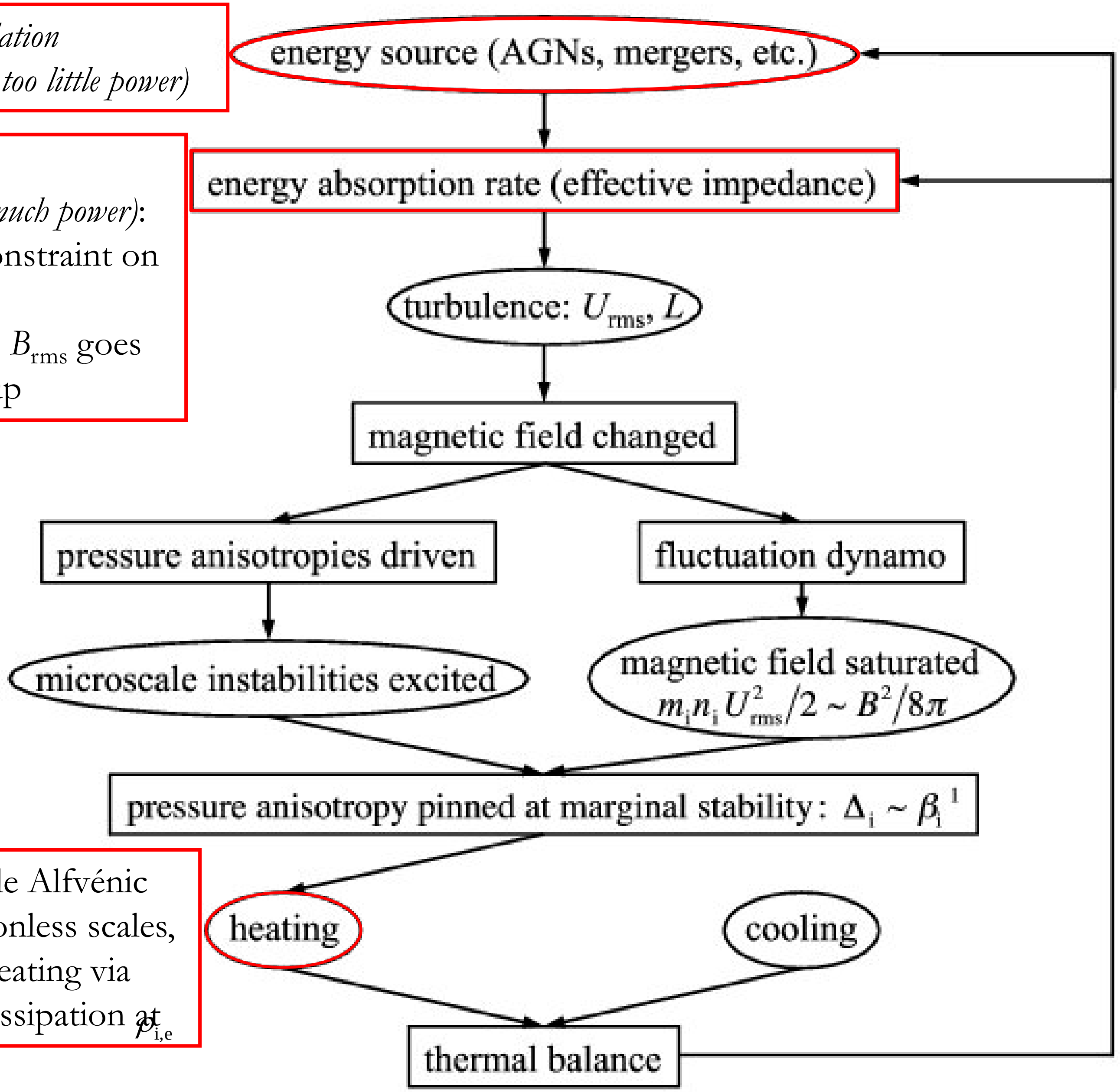


Summary of What Is Proposed

Global self-regulation
(how to deal w/ too little power)

Local self-regulation
(how to deal w/ too much power):

a. Microscale constraint on rate of strain
b. U_{turb} goes up, B_{rms} goes up, Q^+ goes up



neglects possible Alfvénic cascade to collisionless scales, with plasma heating via microphysical dissipation at $\rho_{i,e}$

Morals of the Story

1. Microscale plasma physics controls macroscopic transport properties
2. ICM viscosity responds to local changes in *T*, *n*, and *B*; can prevent runaway heating/cooling; possible solution to cooling-flow problem?
3. Pick two radial profiles from *B*, U_{rms}, *L*, *n* and *T*, we'll predict the other three
4. Magnetic field depends on both *n* and *T*: $B \propto n_e^{1/2} T^{3/4}$
5. Conduction is not as simple as one might think (see Schekochihin *et al.*, *MNRAS* 405, 291)
6. Need a good theory for saturation of microscale instabilities (marginality?) and effect on macroscales (magnetoviscous transport)

Kunz *et al.*, arXiv:1003.2719v2 Rosin *et al.*, arXiv:1002.4017