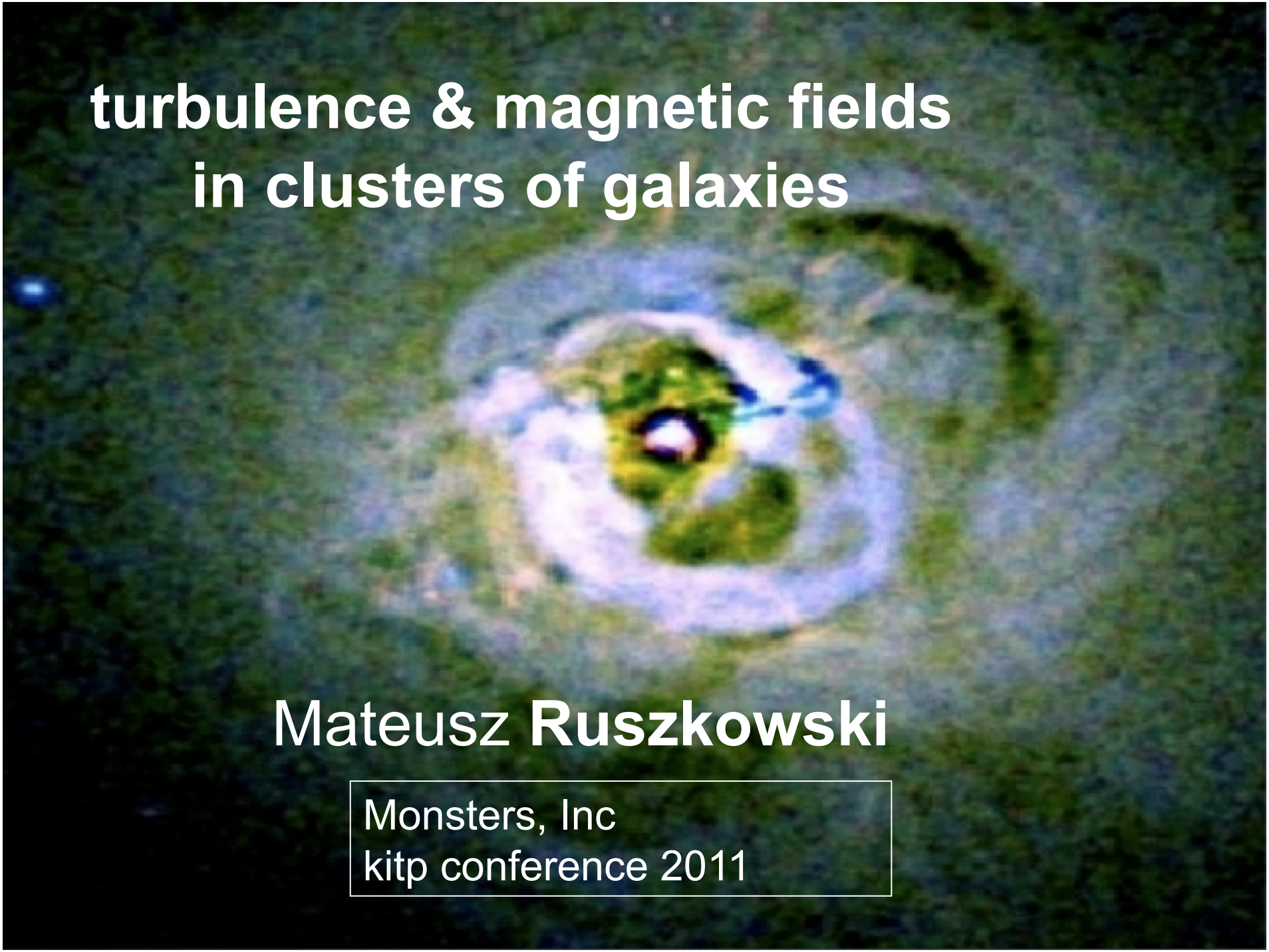
turbulence & magnetic fields in clusters of galaxies

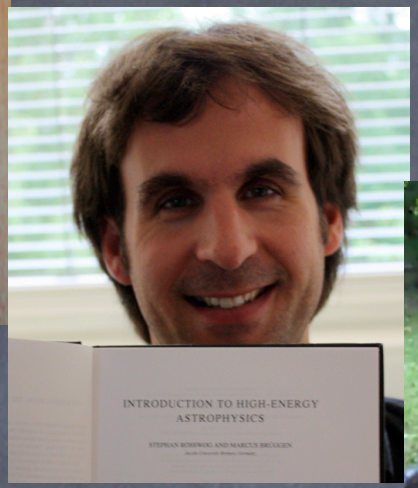


Mateusz **Ruszkowski**

Monsters, Inc
kitp conference 2011

In order of appearance

Peng Oh



Marcus Bruggen

Dongwook Lee

Ian Parrish

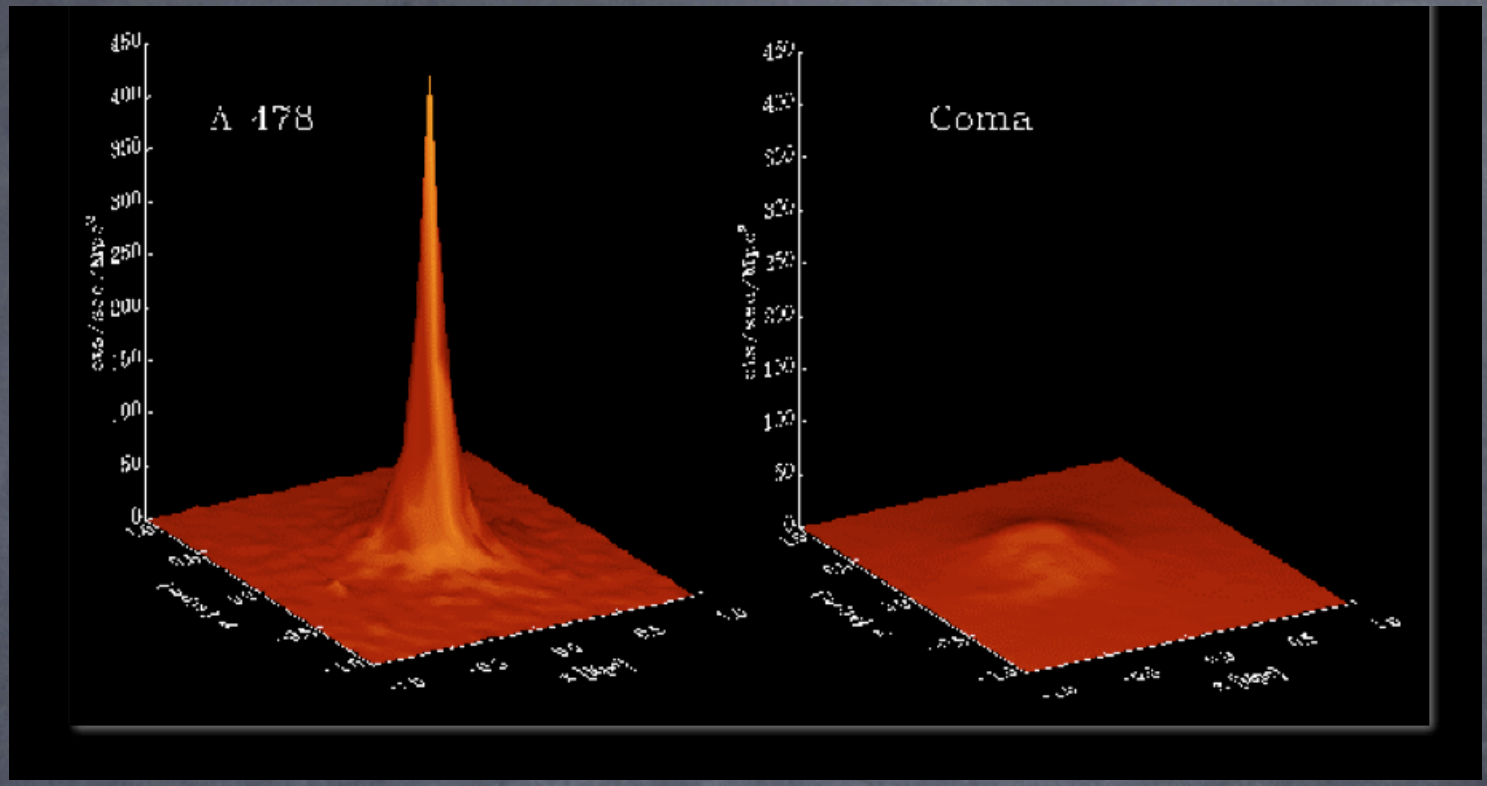
Heating of cool cores by
Turbulent mixing & anisotropic Conduction

Simulation with
anisotropic conduction

Pleiades

Michigan Academic Computing Center

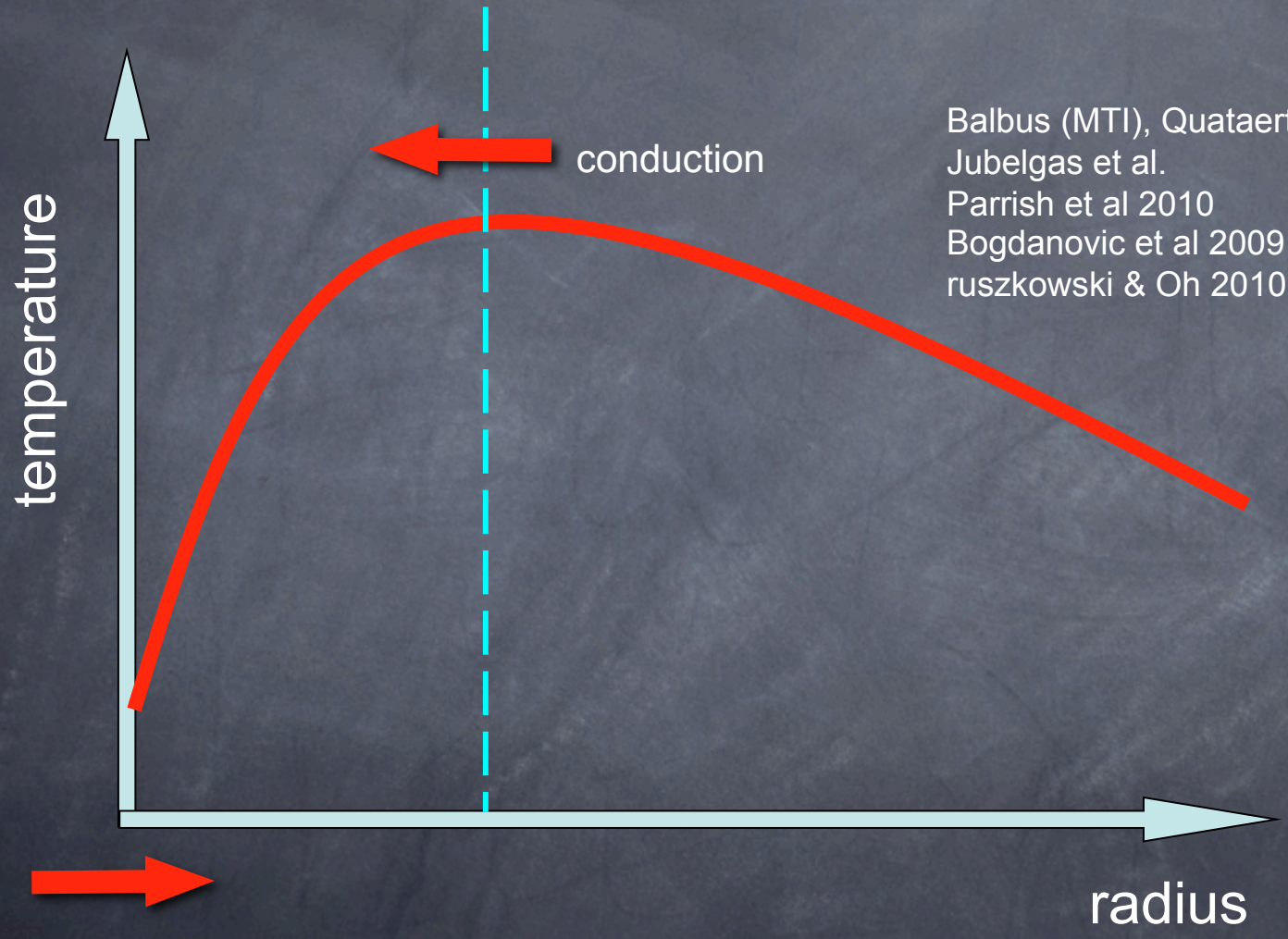
Flash Code



cool core cluster non-cool core cluster

50-70% of clusters have cool cores

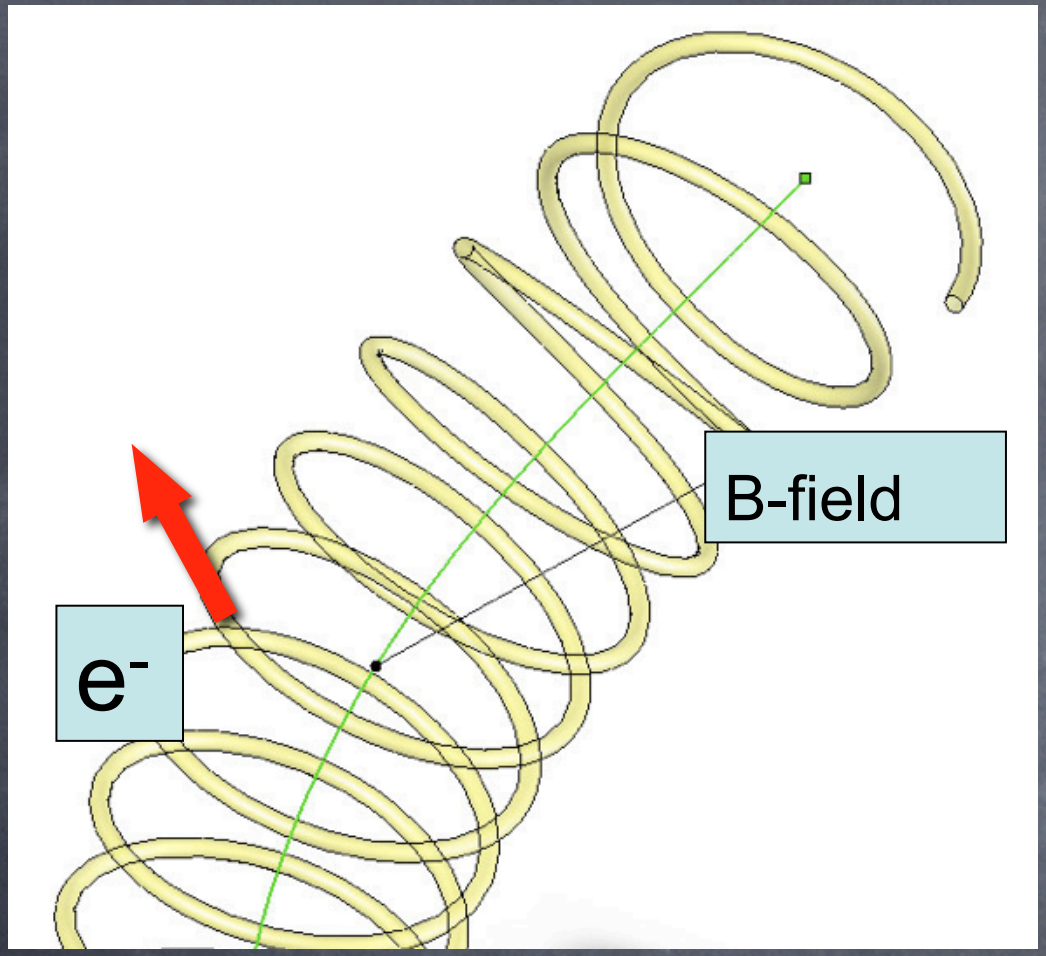
Most common heating mechanisms



Balbus (MTI), Quataert (HBI)
Jubelgas et al.
Parrish et al 2010
Bogdanovic et al 2009
ruszkowski & Oh 2010, 2011

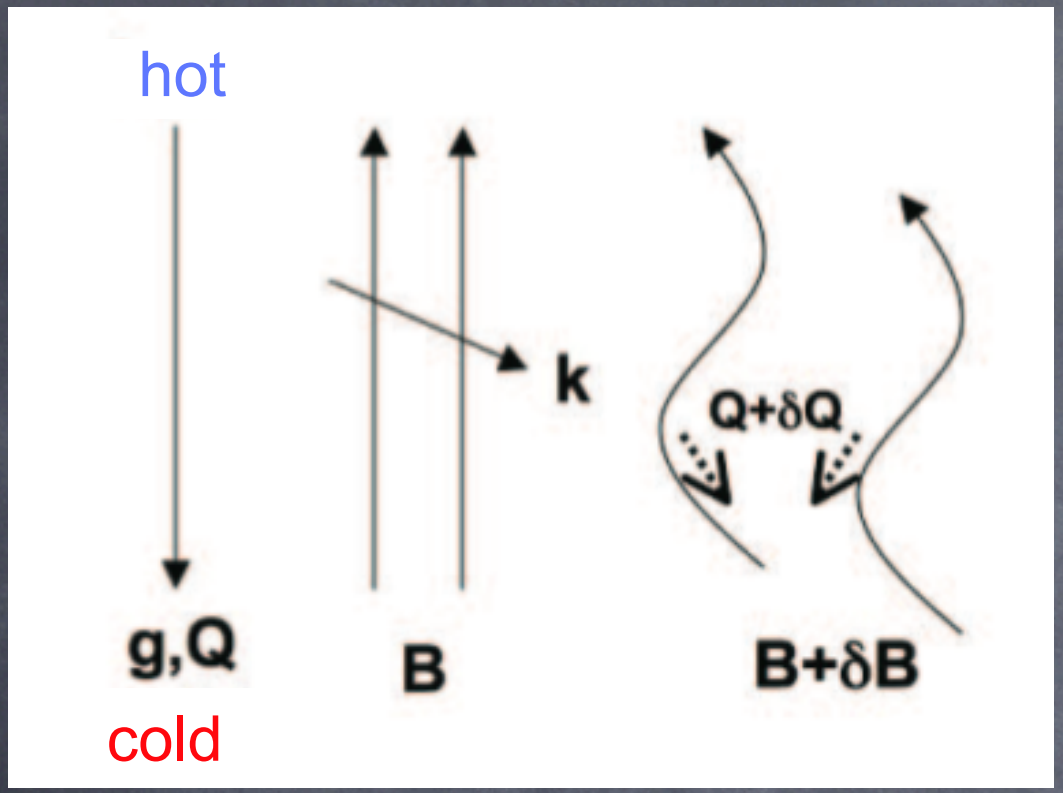
Black holes

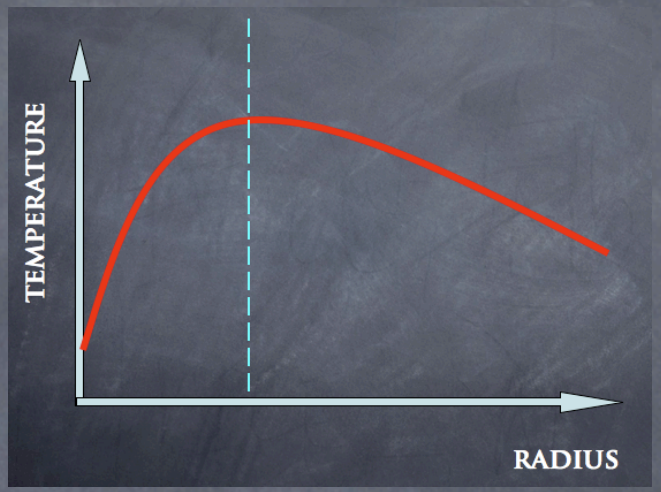
Scannapieco & Bruggen 2009, Ruszkowski et al. 2004a,b, 2007, Dubois & Teyssier



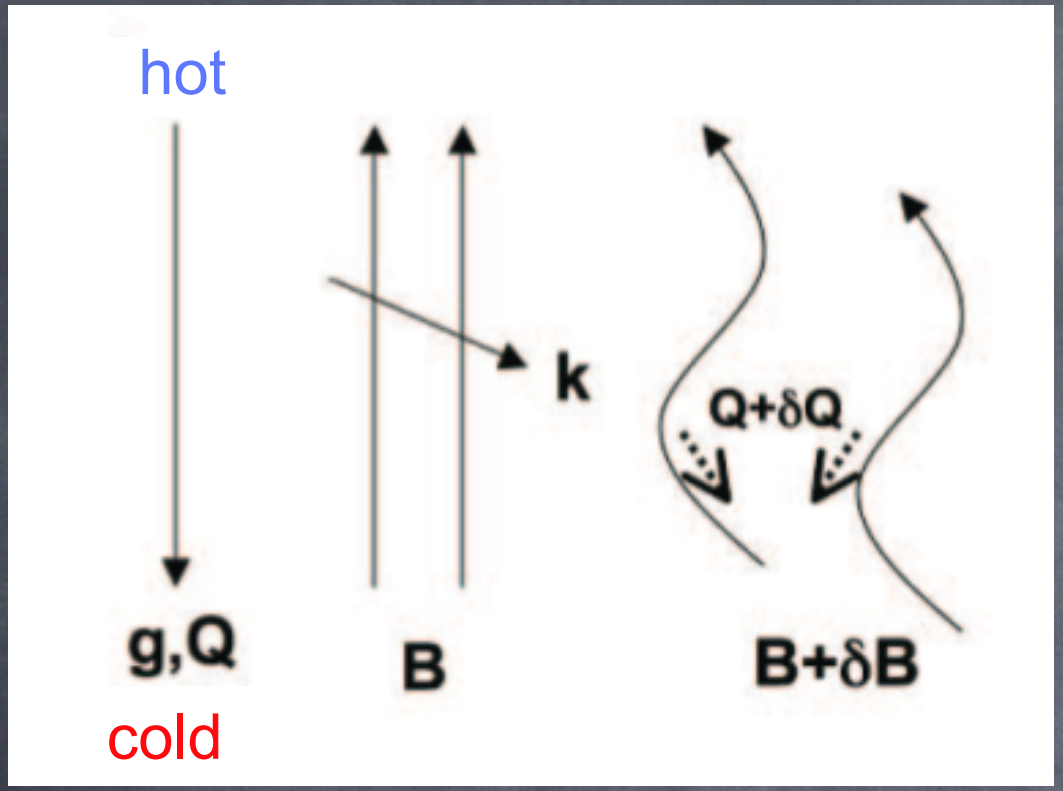
$$r_g = \frac{3.1\times10^8 \text{ cm}}{Z}\left[\frac{T_g}{10^8 \text{ K}}\right]^{1/2}\left[\frac{m}{m_e}\right]^{1/2}\left[\frac{B}{1\,\mu\text{G}}\right]^{-1}$$

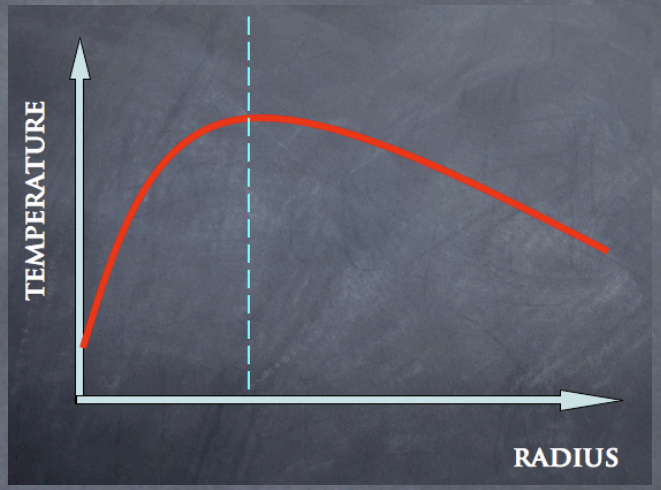
$$\lambda_e = \lambda_i \approx 23 \text{ kpc}\left[\frac{T_g}{10^8 \text{ K}}\right]^{2}\left[\frac{n_e}{10^{-3} \text{ cm}^{-3}}\right]^{-1}$$





Quataert (2008)

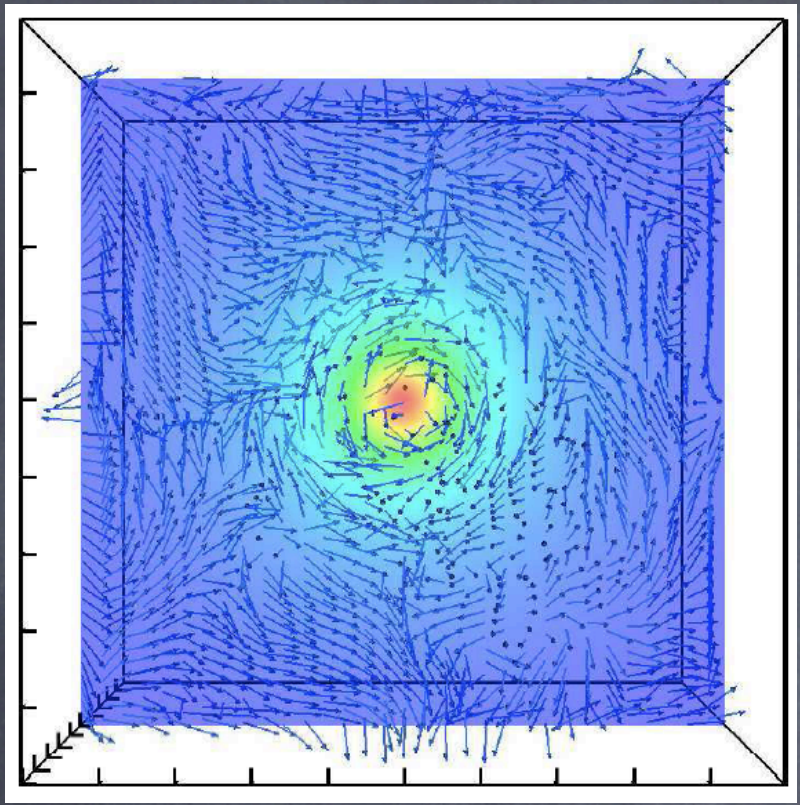




Quataert (2008)

B-field perpendicular to the radial direction

Conduction shuts down

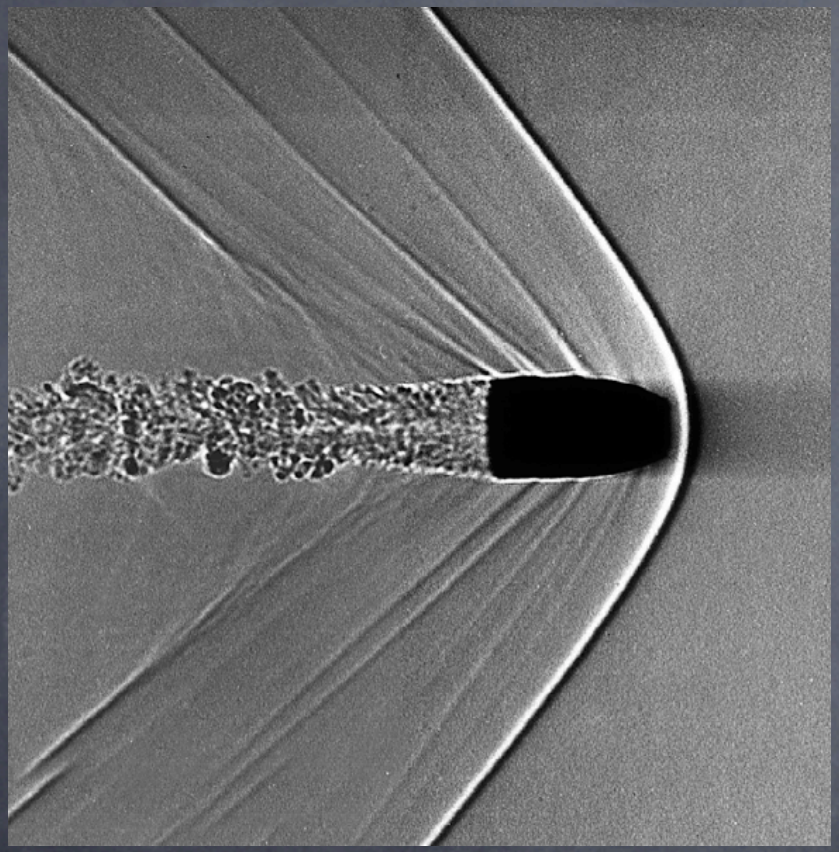


Ruszkowski & Oh 2010a

See Also: Bogdanovic et al. 2009,
Parrish et al. 2010

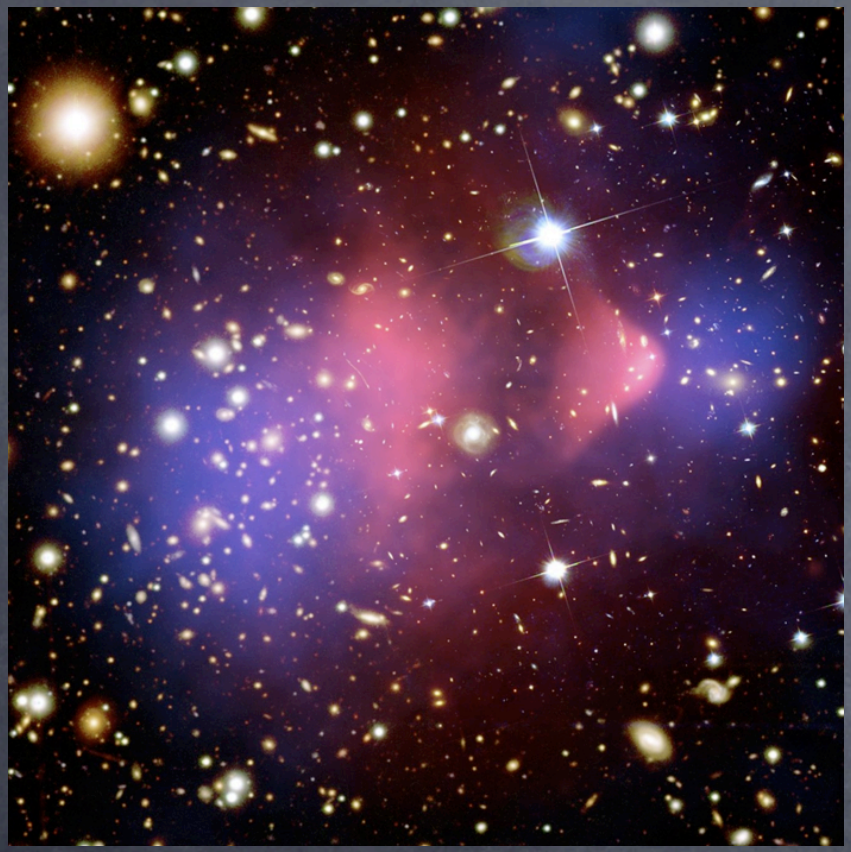
What conditions must be met
for the HBI to operate ?

Lack of perfect hydrostatic equilibrium



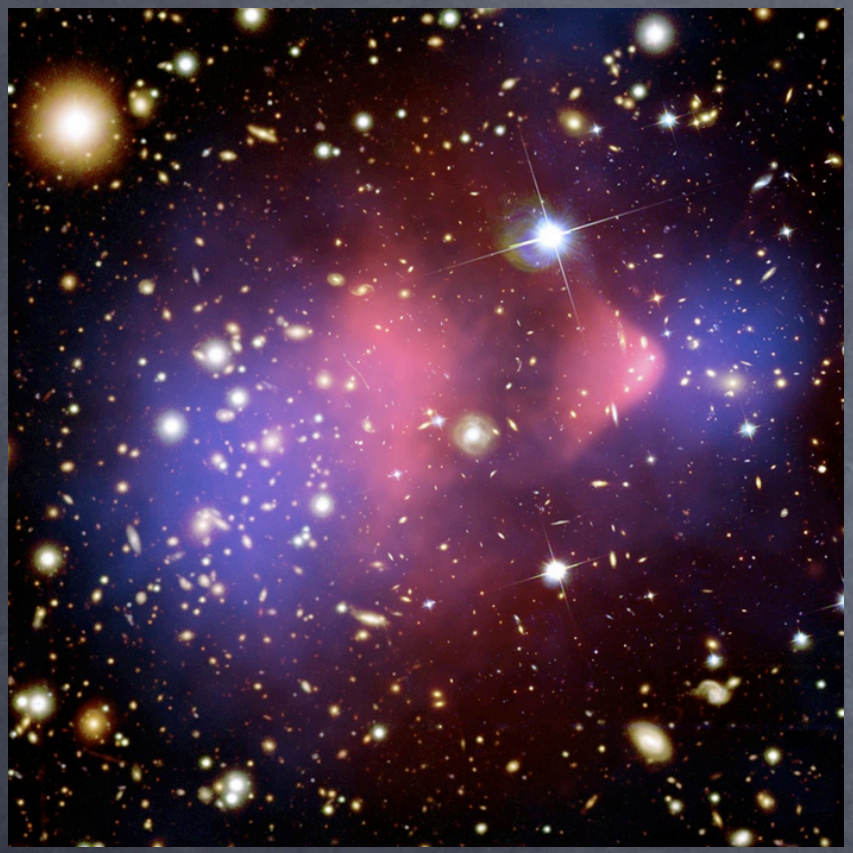
Markevitch et al. 2004
Clowe et al. 2004

Lack of perfect hydrostatic equilibrium



Markevitch et al. 2004
Clowe et al. 2004

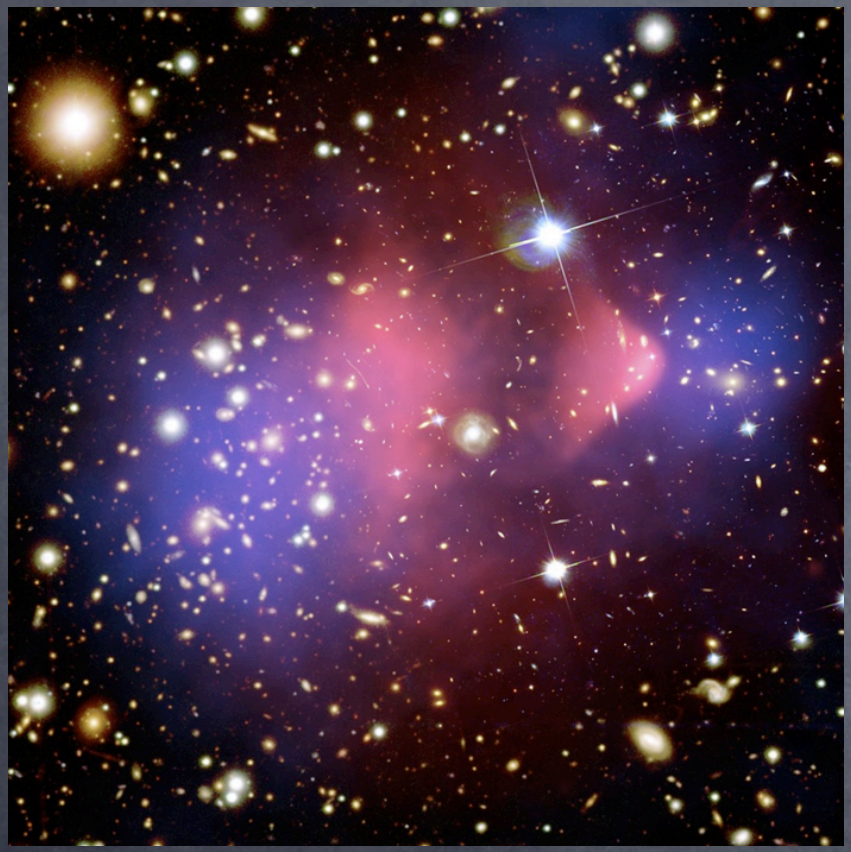
Lack of perfect hydrostatic equilibrium



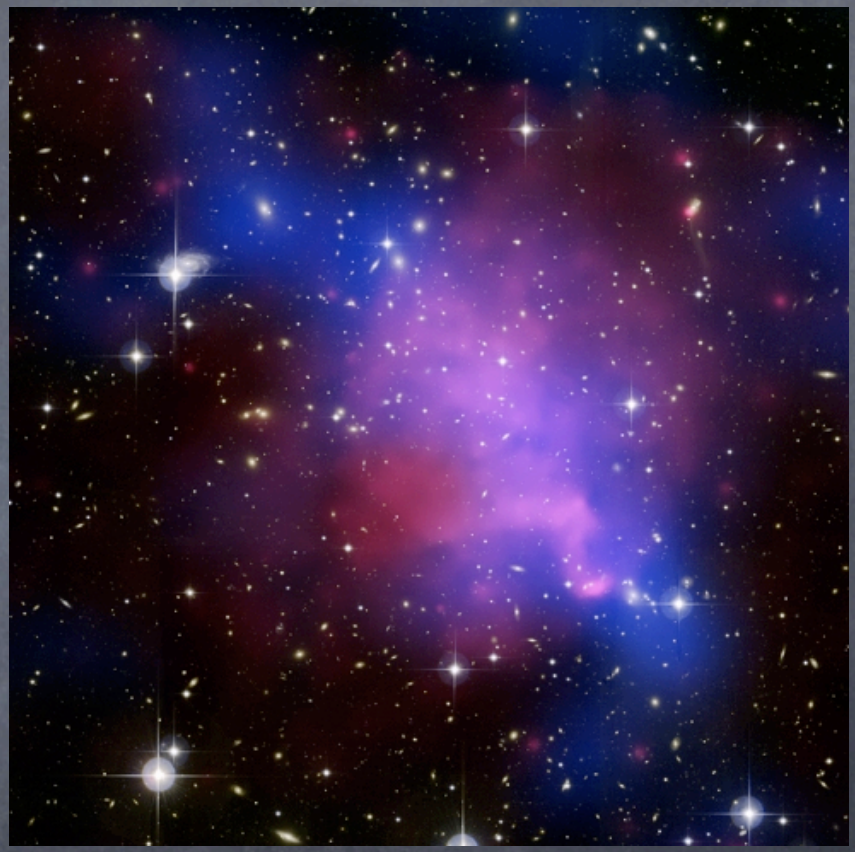
Markevitch et al. 2004
Clowe et al. 2004

Mahdavi et al 2007

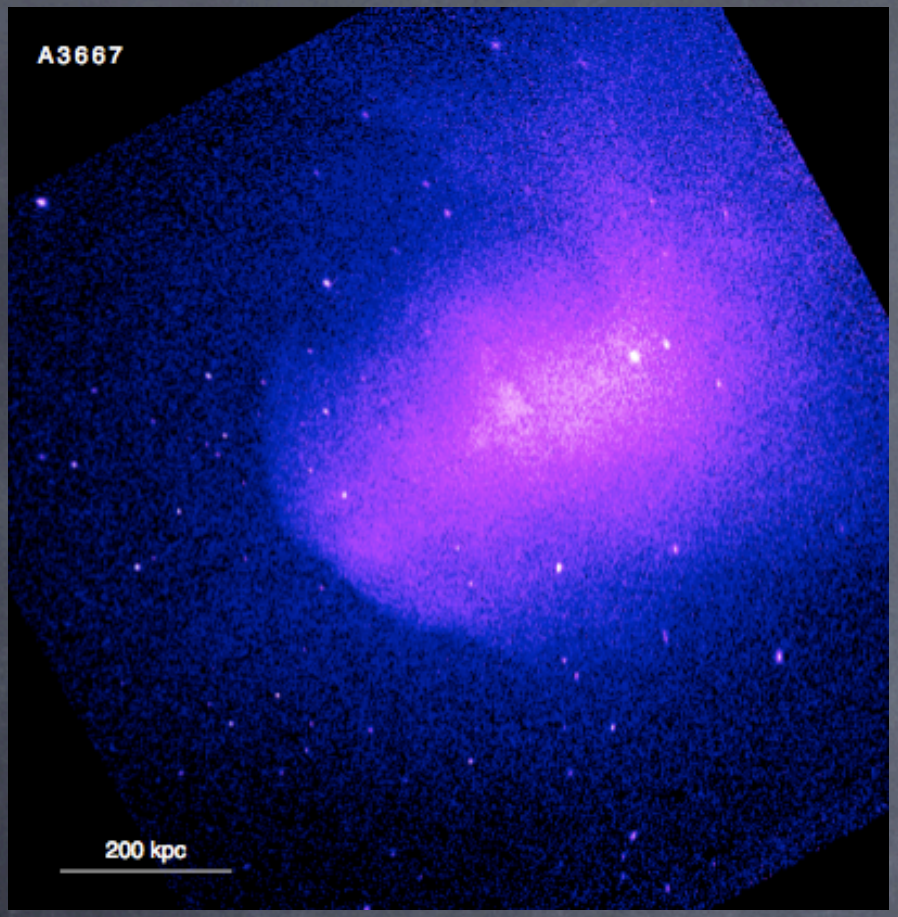
Lack of perfect hydrostatic equilibrium



Markevitch et al. 2004
Clowe et al. 2004



Mahdavi et al 2007

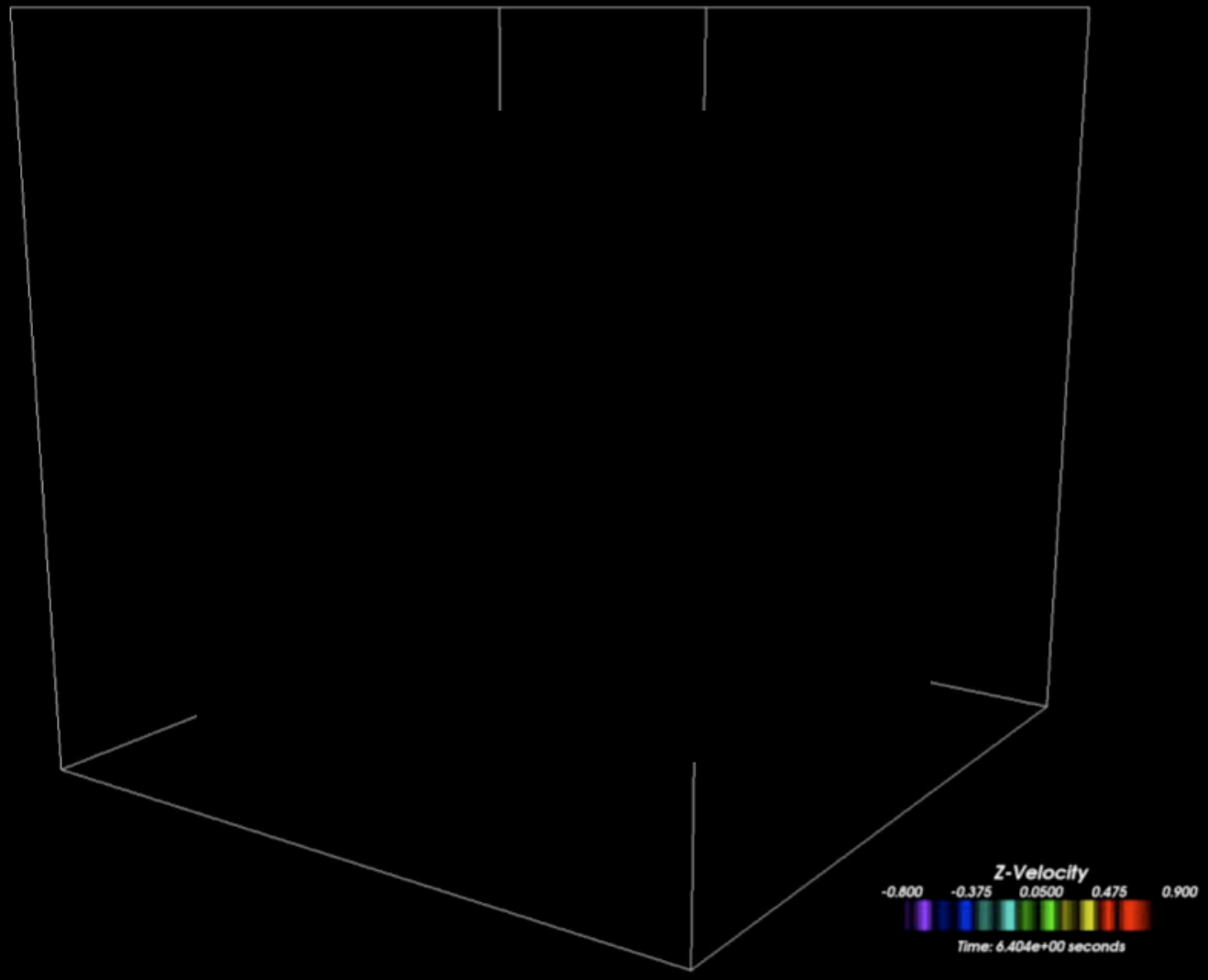


Markevitch et al. 2000
Viklinin et al. 2001

Fig. 16. The origin of cold fronts in the dense cluster cores.

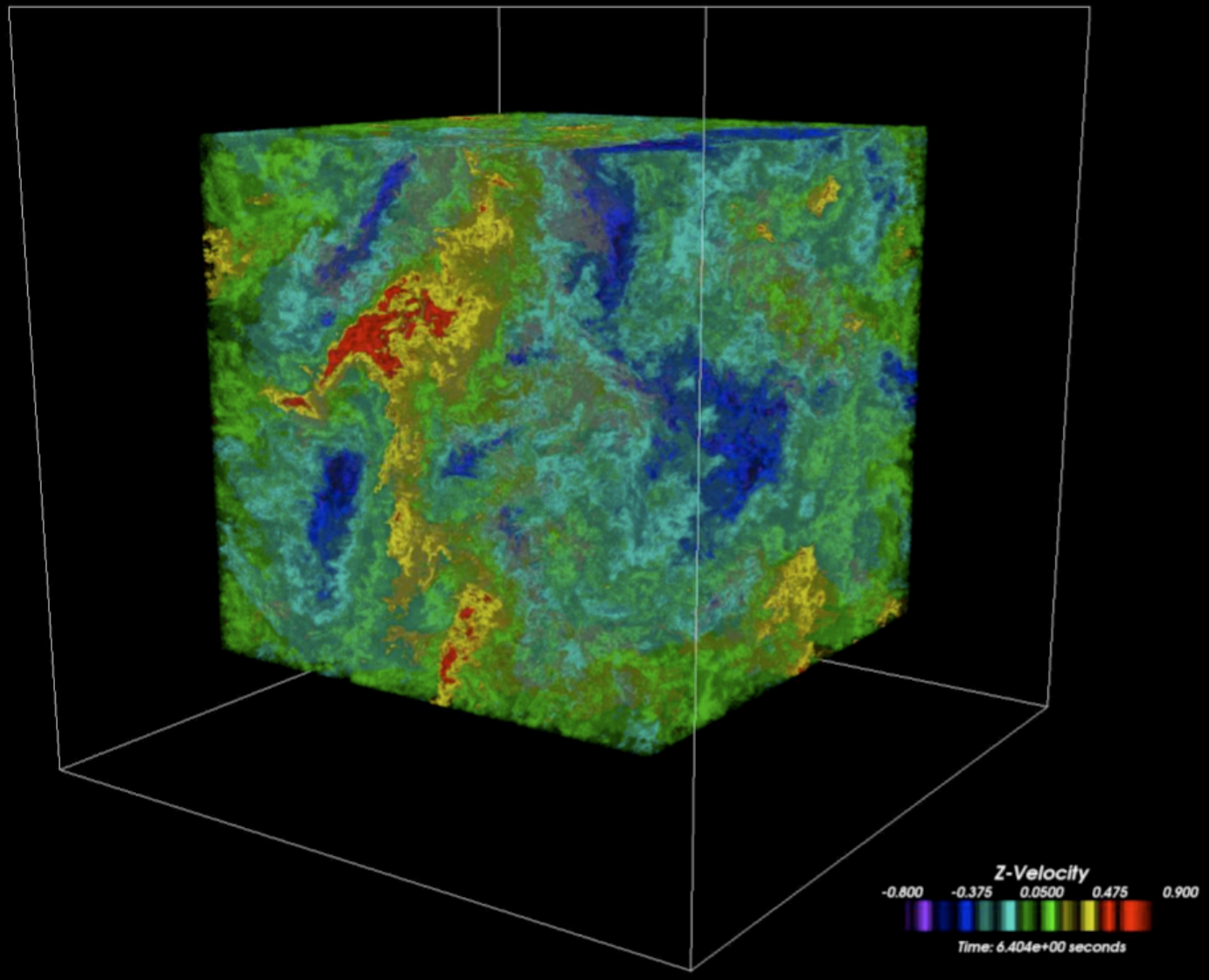
From the **review article** by
Markevitch & Vikhlinin 2007

Terascale Turbulence Computation at LLNL

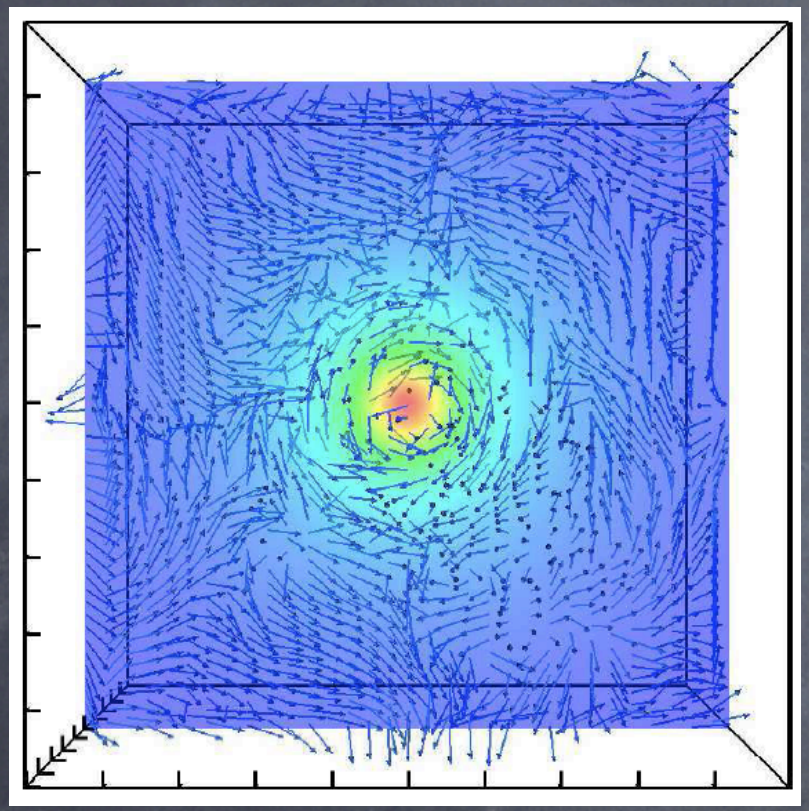


Fisher et al. 2008 flash code

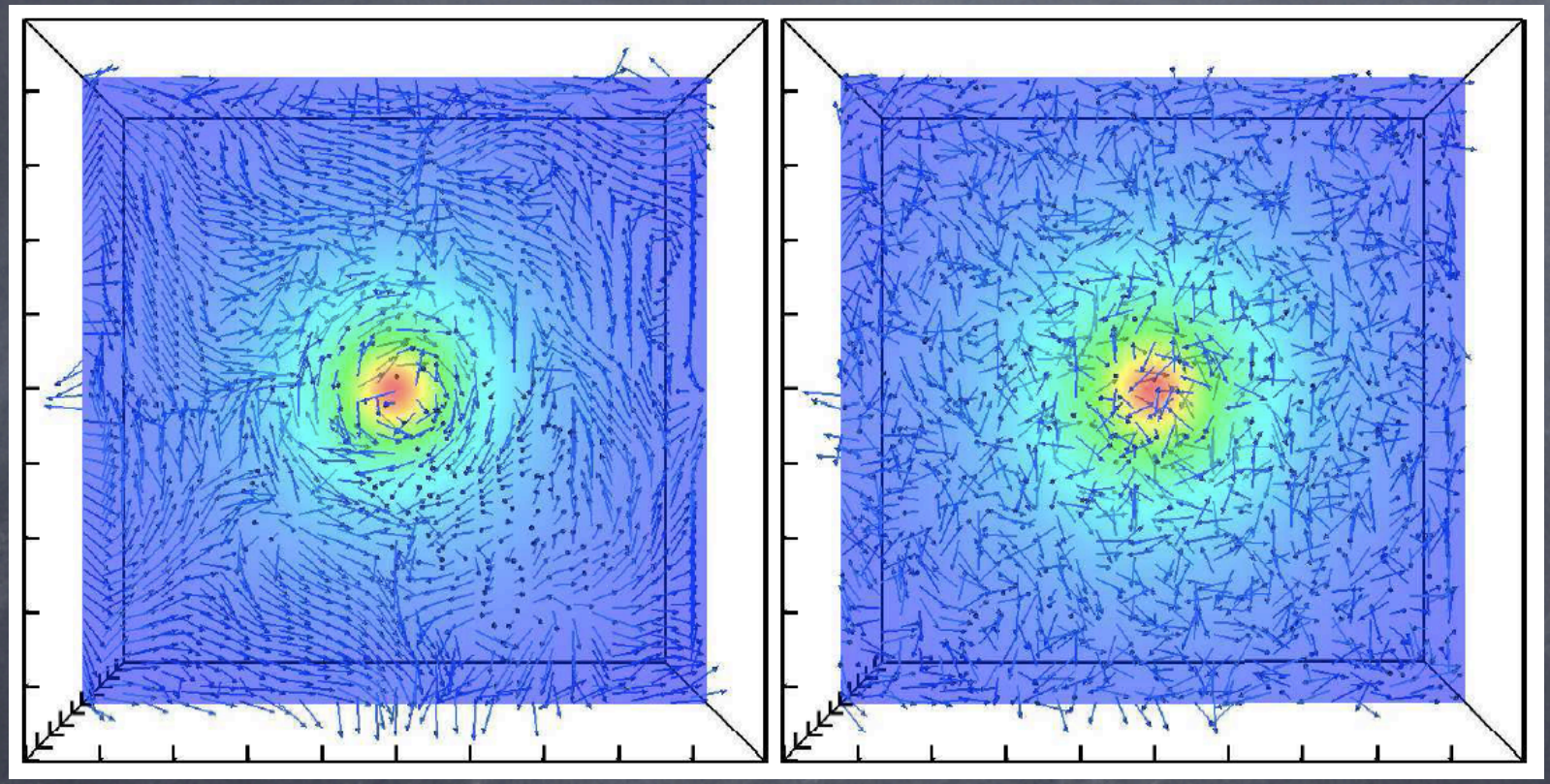
Terascale Turbulence Computation at LLNL



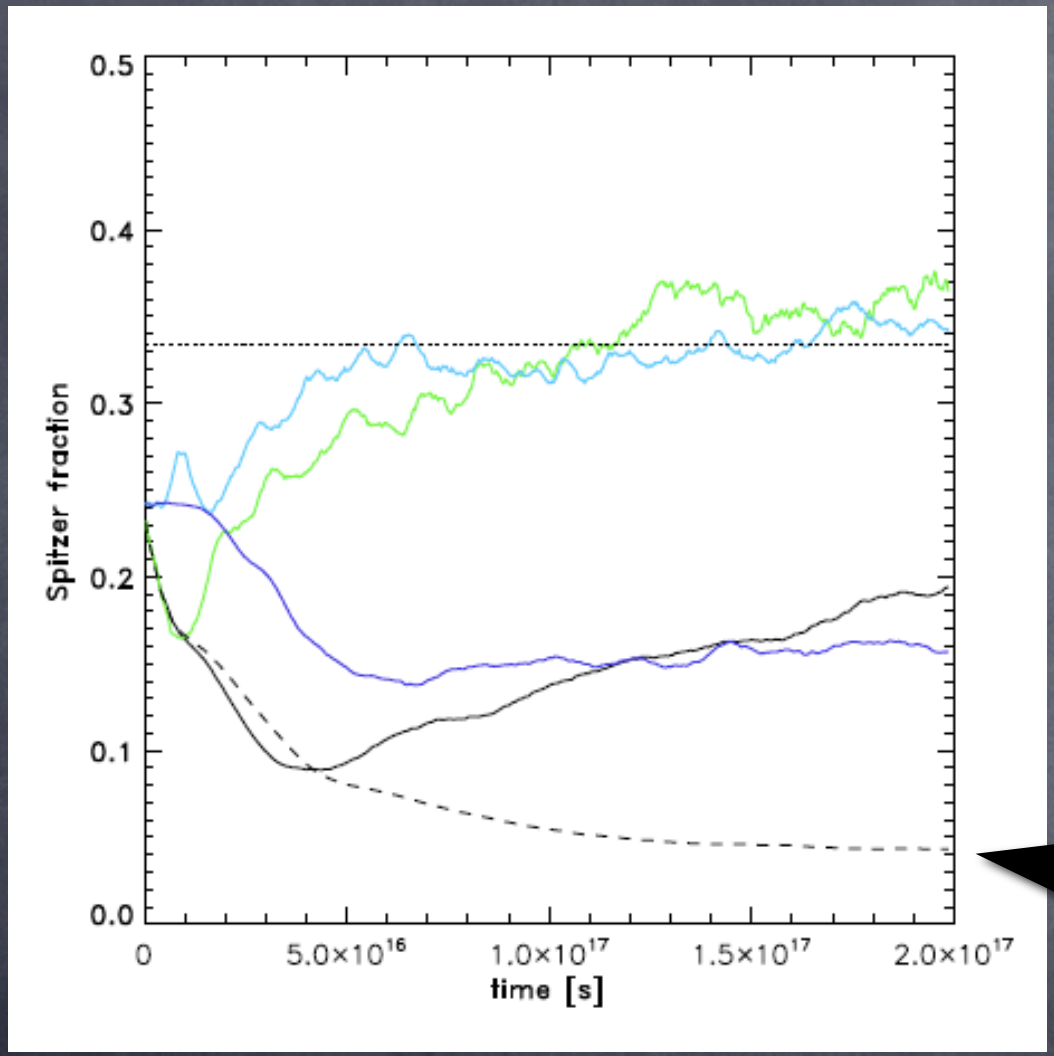
Fisher et al. 2008 flash code



Ruszkowski & Oh 2010a



Ruszkowski & Oh 2010a
See also Parrish et al. 2010



Strong stirring

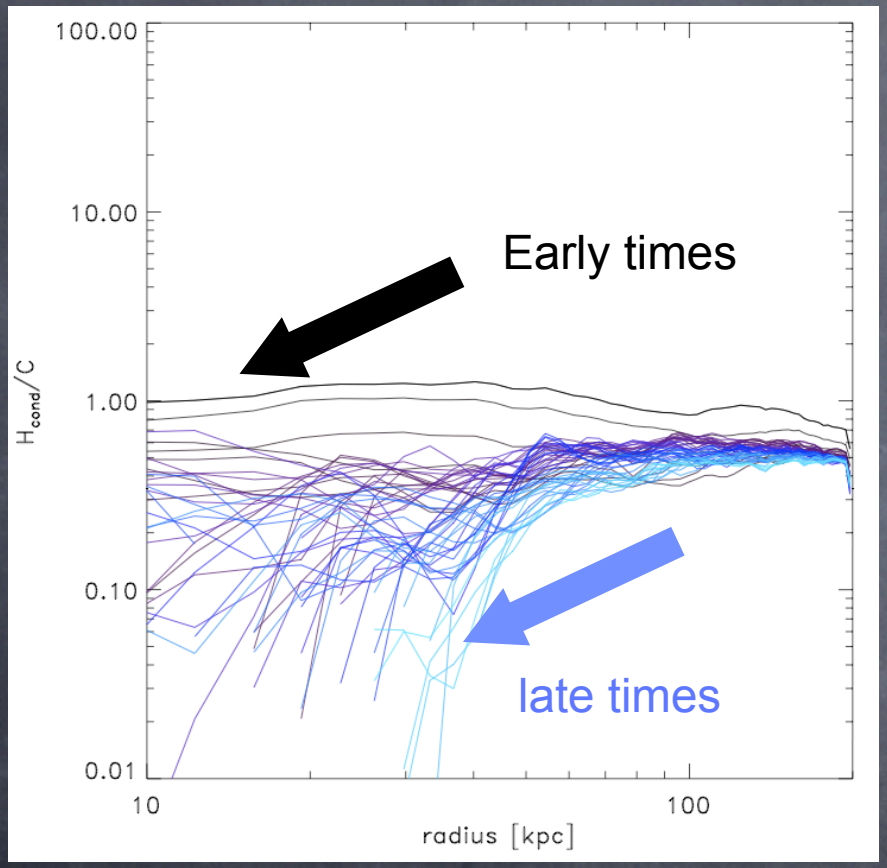
150 km/s

Weak stirring

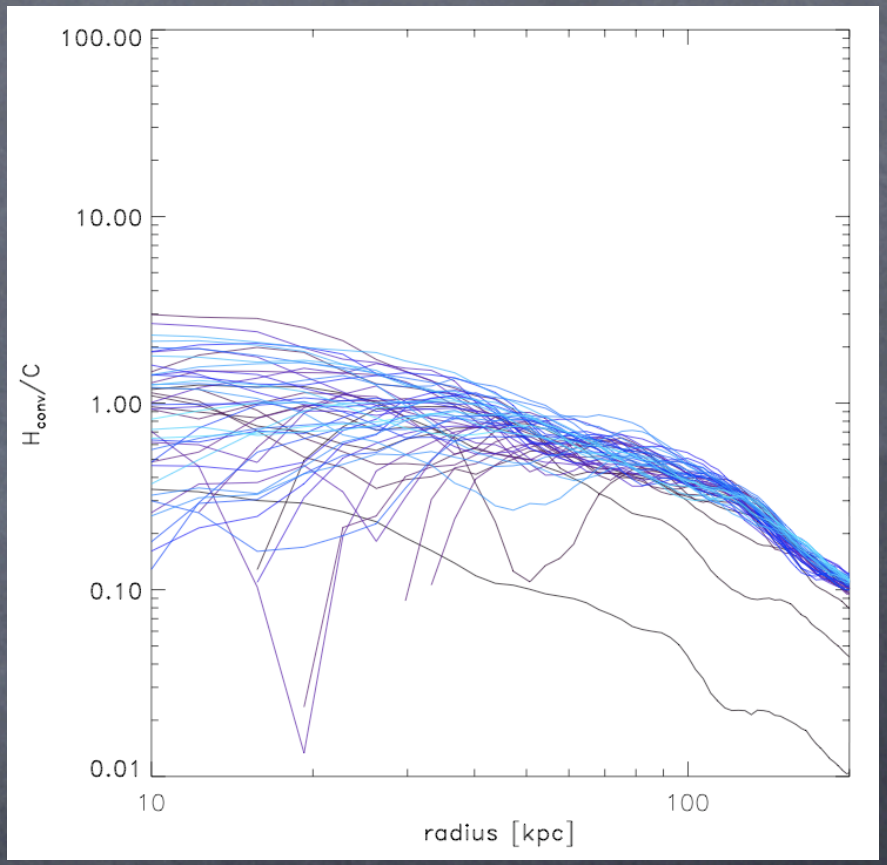
50 km/s

Pure hbi

Conductive

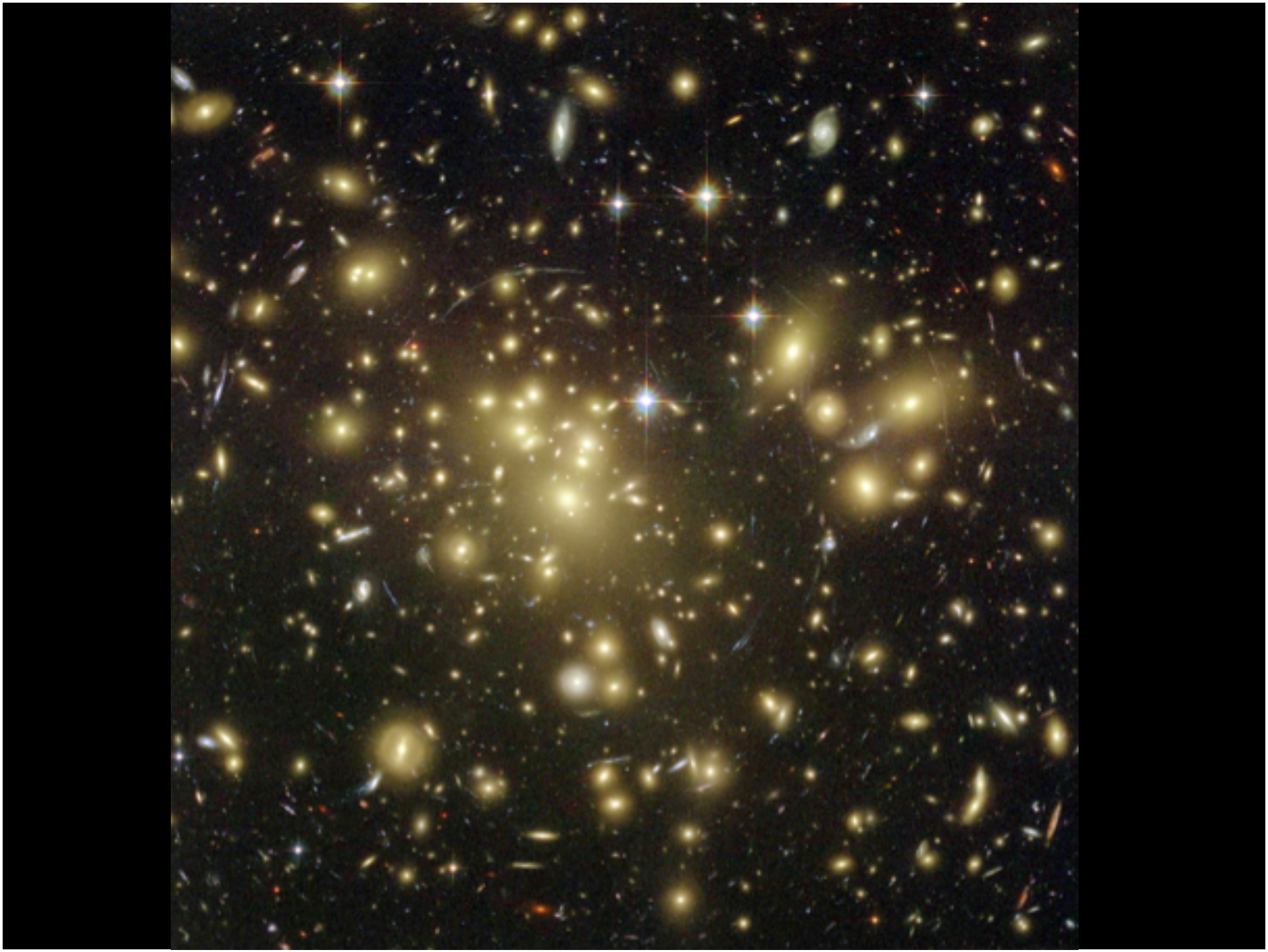


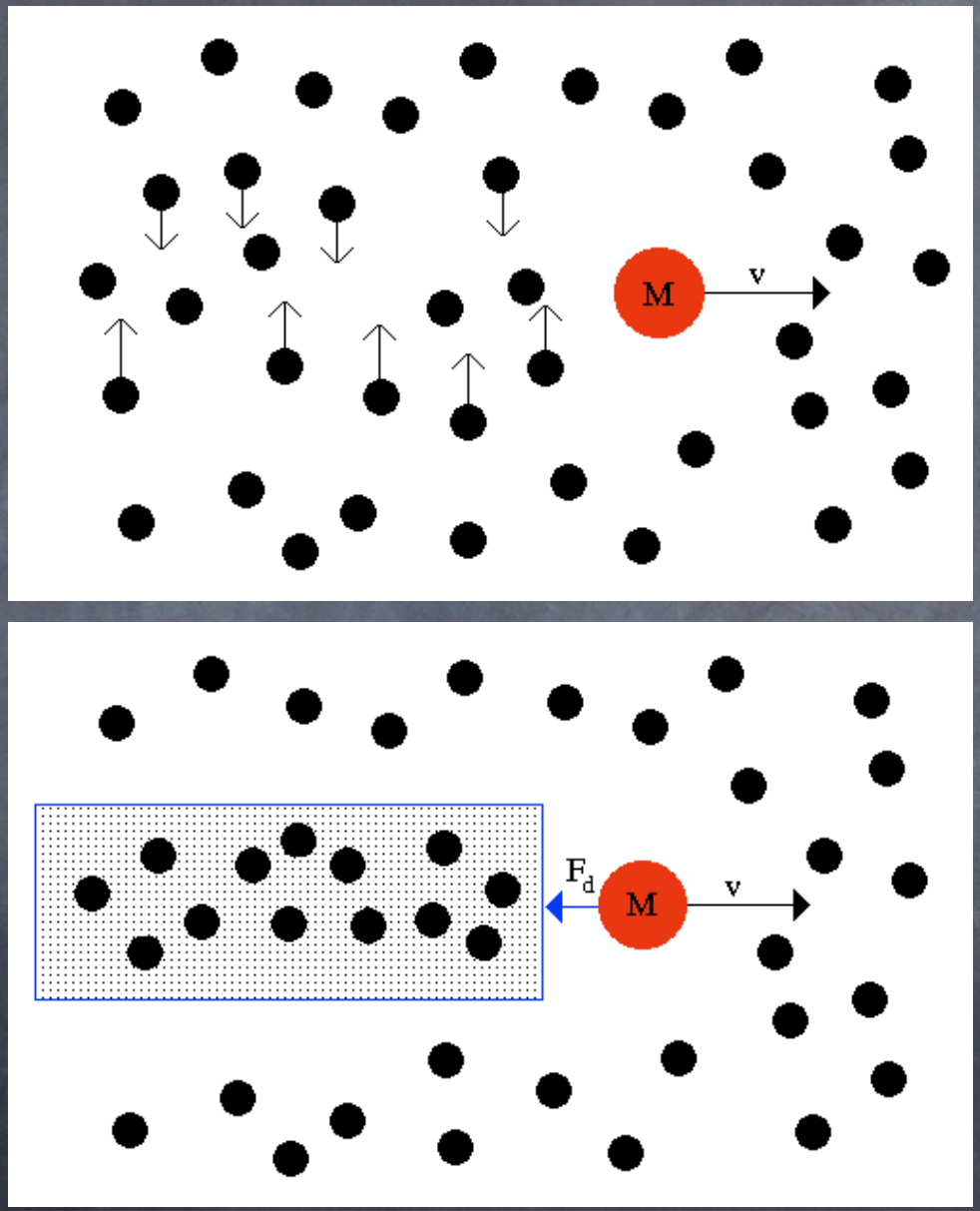
Turbulent

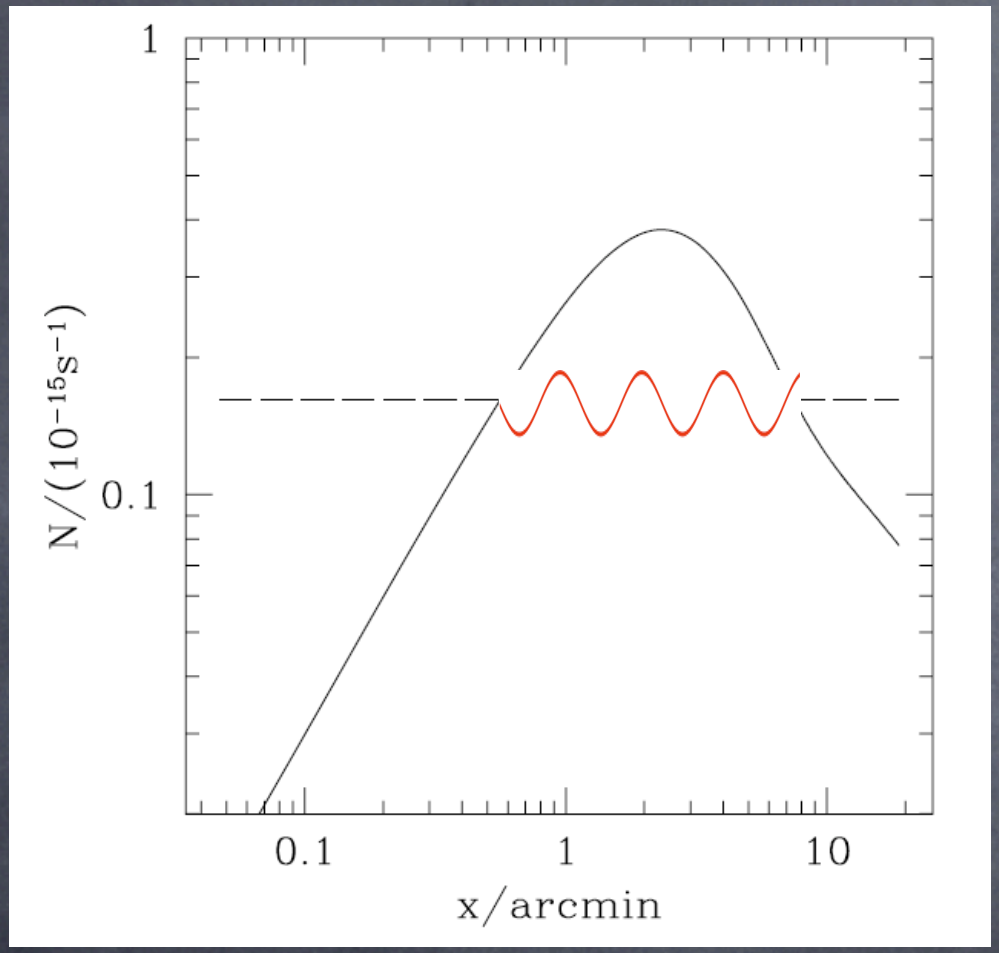


Ruszkowski & oh, 2010b

How can we drive the turbulence
more realistically ?

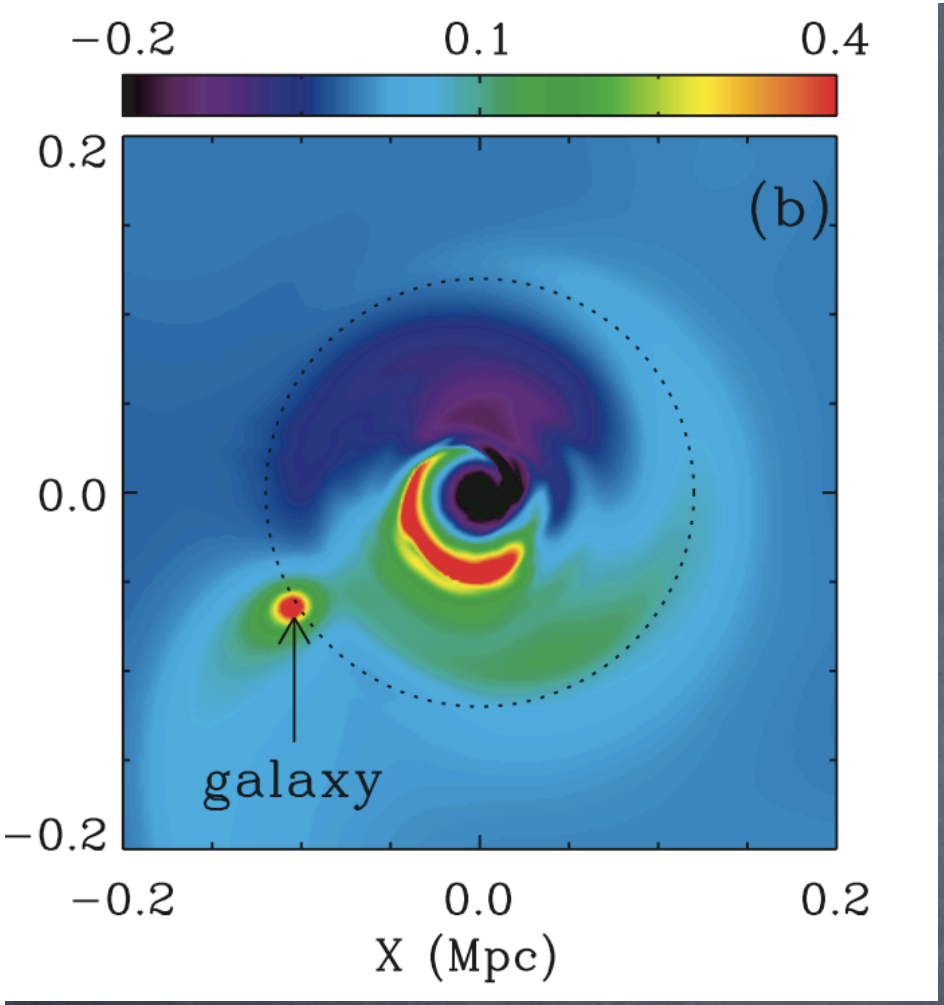



M
v
F_d
M
v

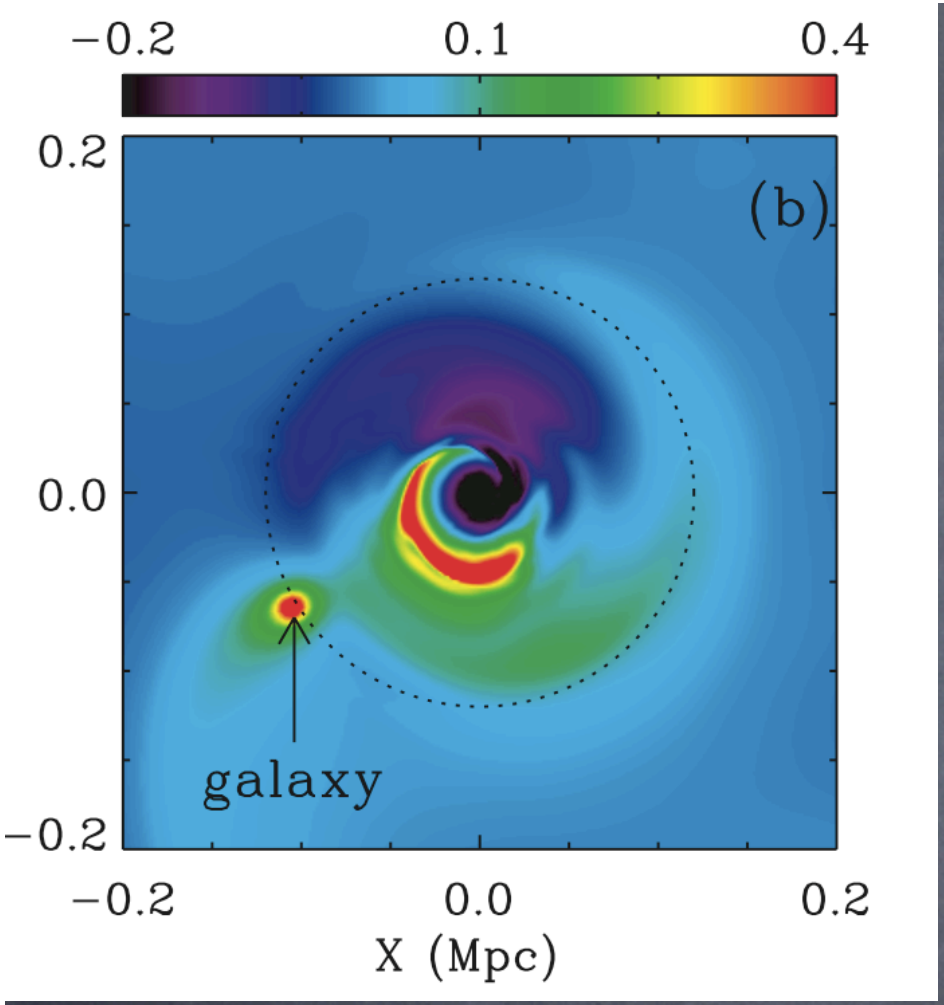


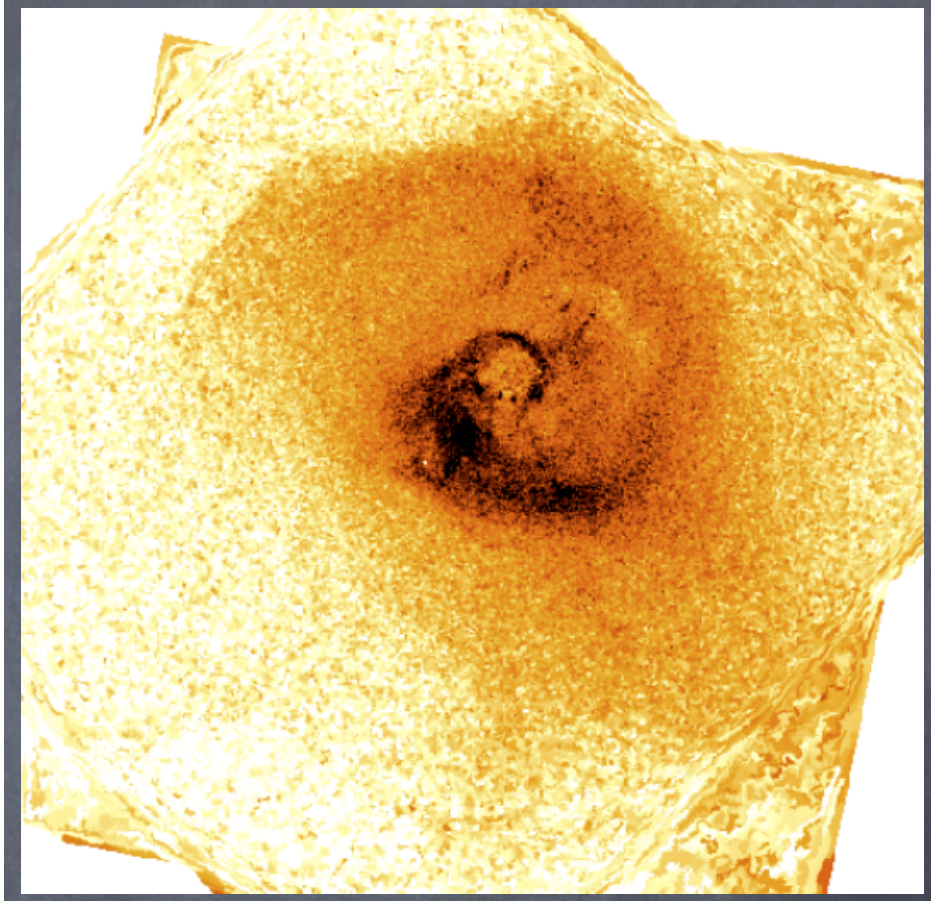
$$\sigma/\lambda \lesssim \omega_{BV}$$

Rebusco, Churazov, Sunyaev, Bohringer, Forman 2008
Lufkin, balbus, hawley 1995



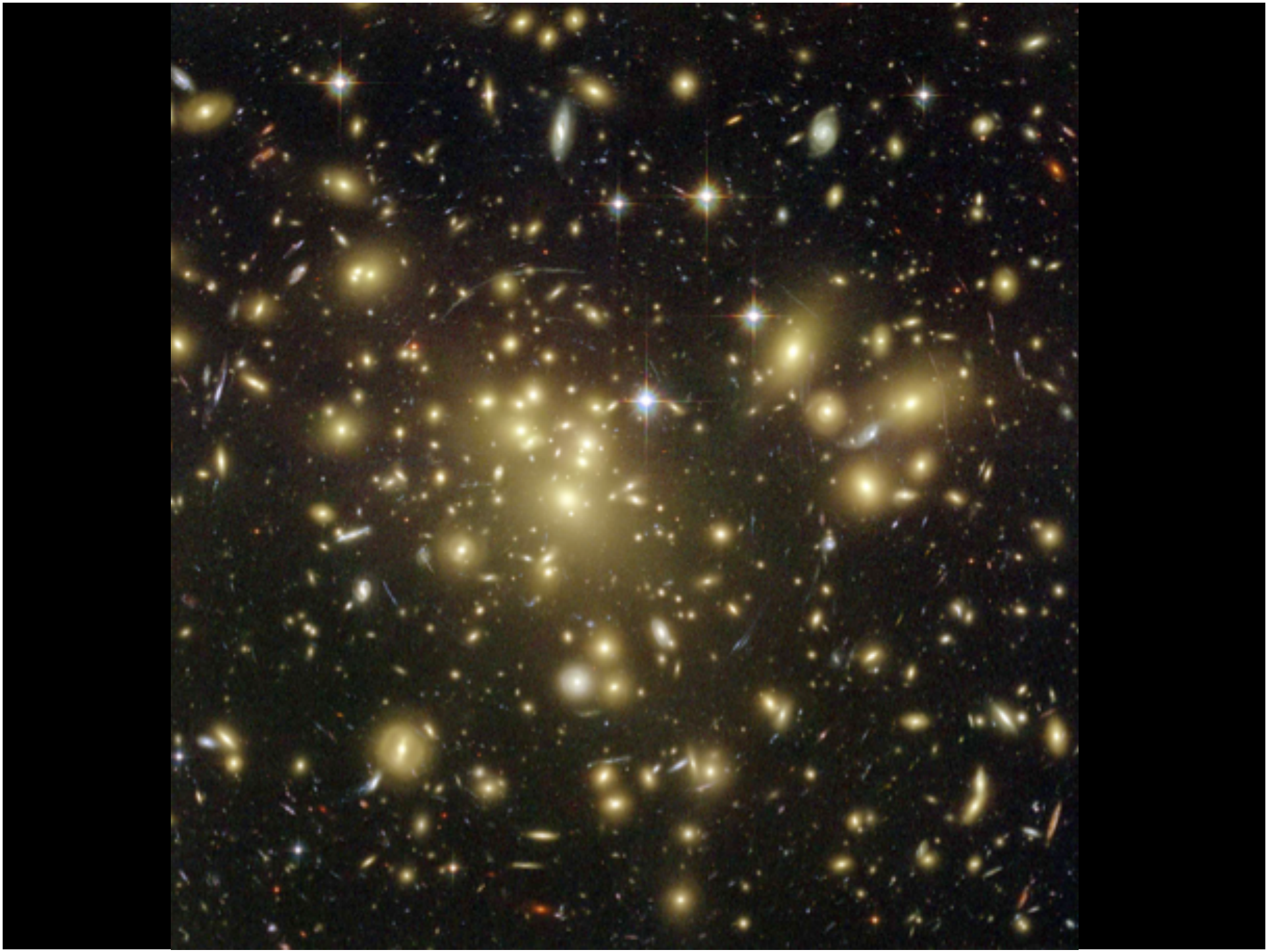
Kim W.-T. (2007)





Kim W.-T. (2007)

Fabian et al. (2005)



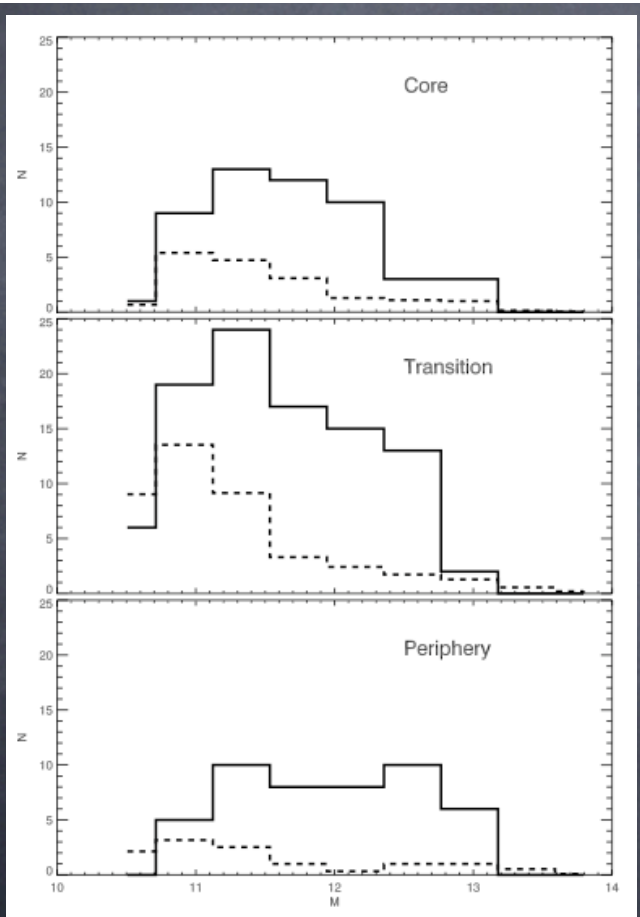
Jeans equation

$$\frac{1}{n_{\rm gal}}\frac{\mathrm{d}}{\mathrm{d}r}\left(n_{\rm gal}\sigma_r^2\right)+2\beta\frac{\sigma_r^2}{r}=-\frac{\mathrm{d}\phi}{\mathrm{d}r}$$

Positions, velocities

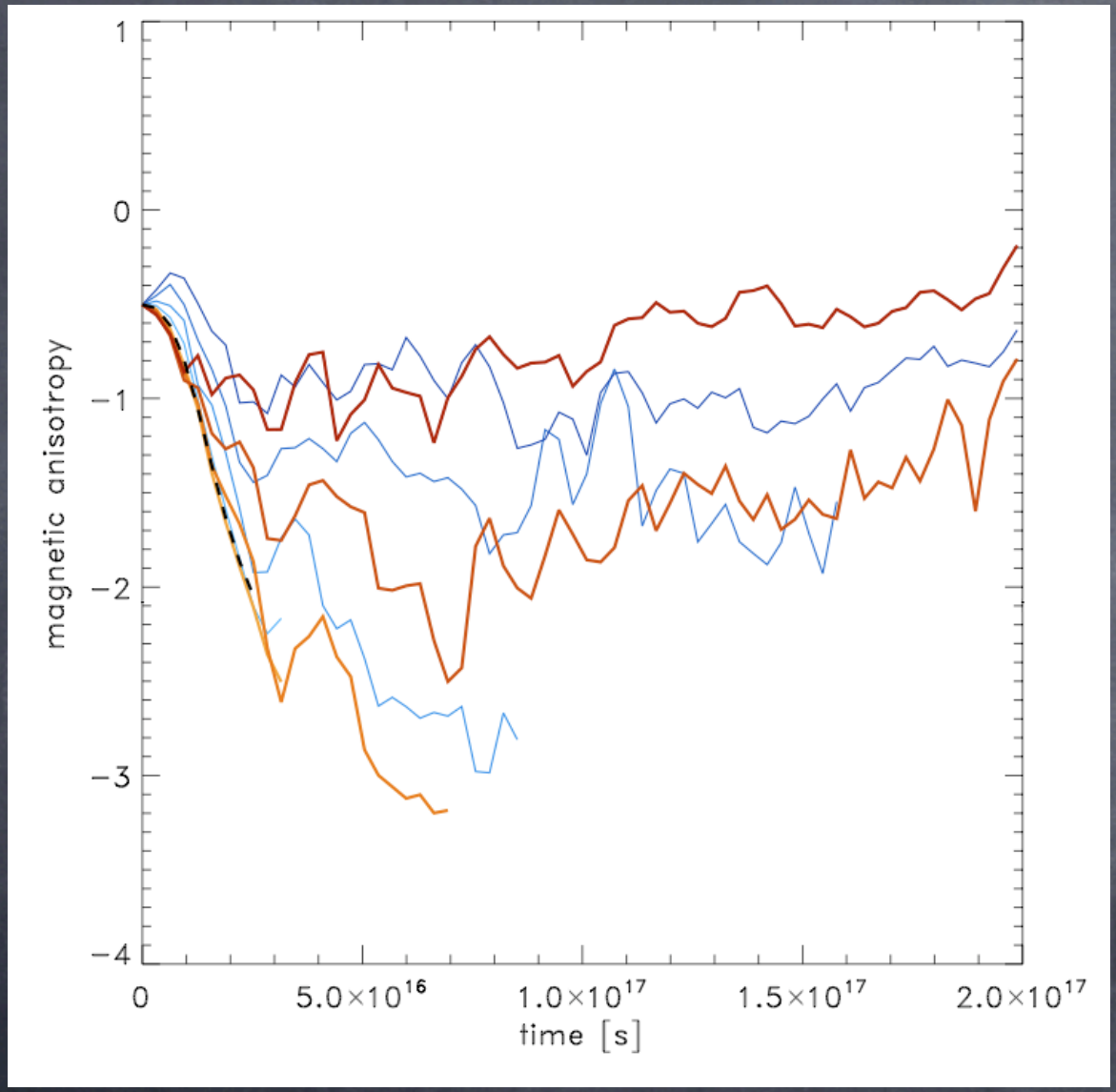
Galaxy masses

Number of galaxies



Galaxy mass

Natarajan et al. 2009



isotropic

~ 150 km/s

Conduction restored

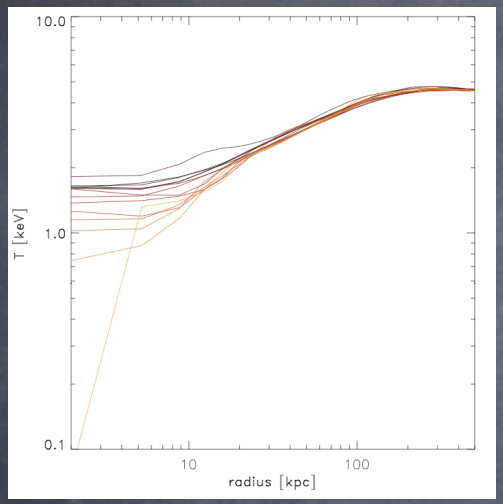
tangential

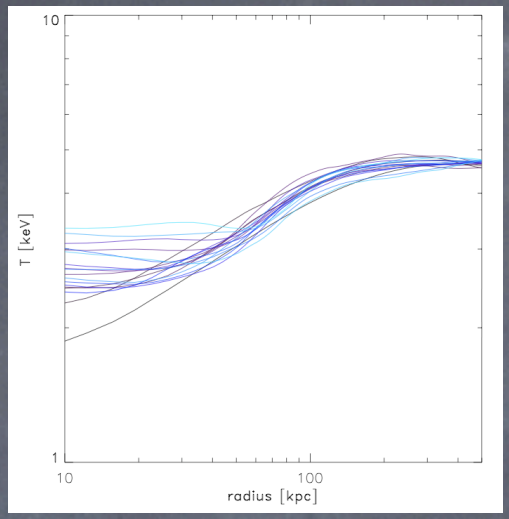
~ 50 km/s

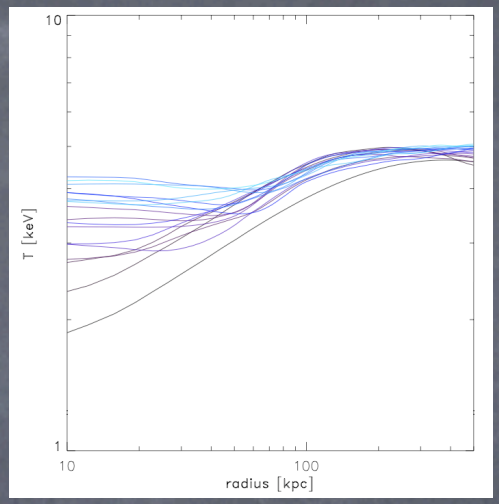
Conduction supressed

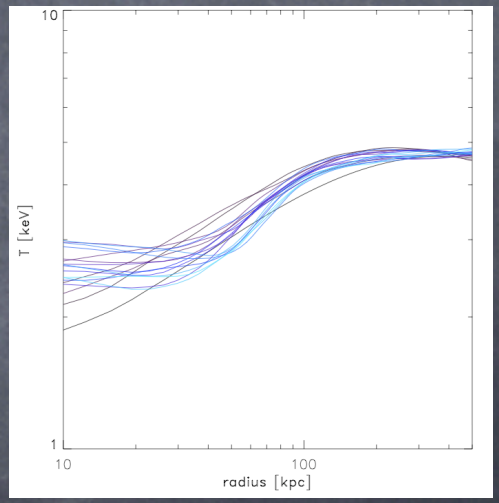
Ruszkowski & Oh 2011

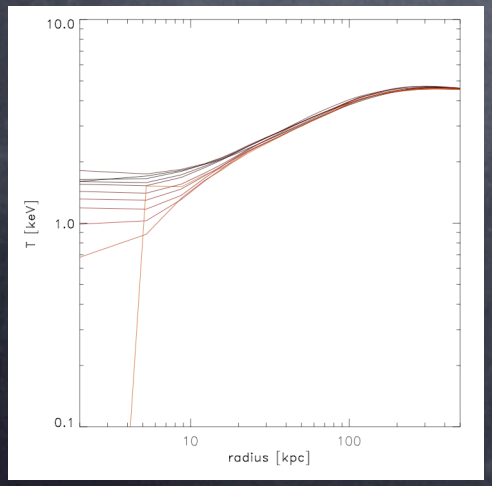
Galaxy mass

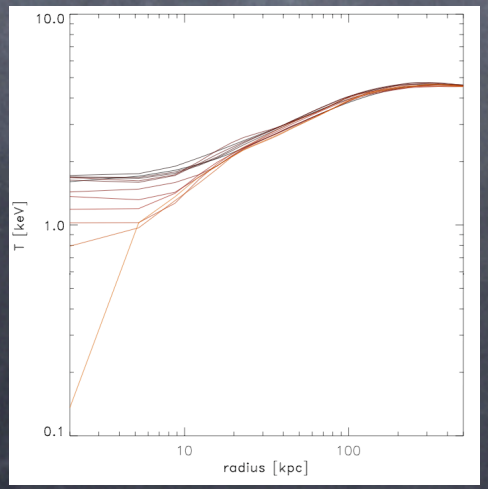






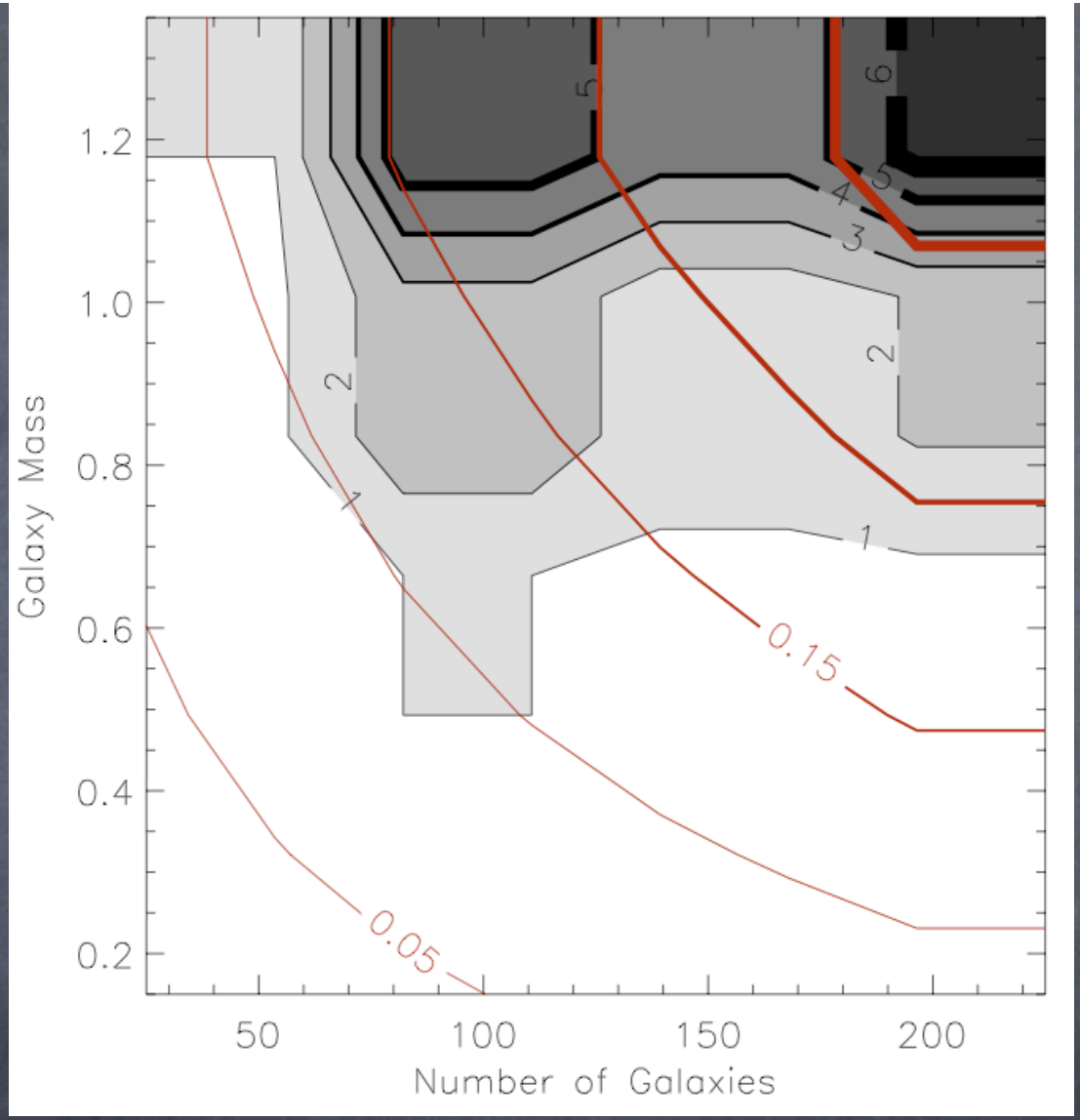






Number of galaxies

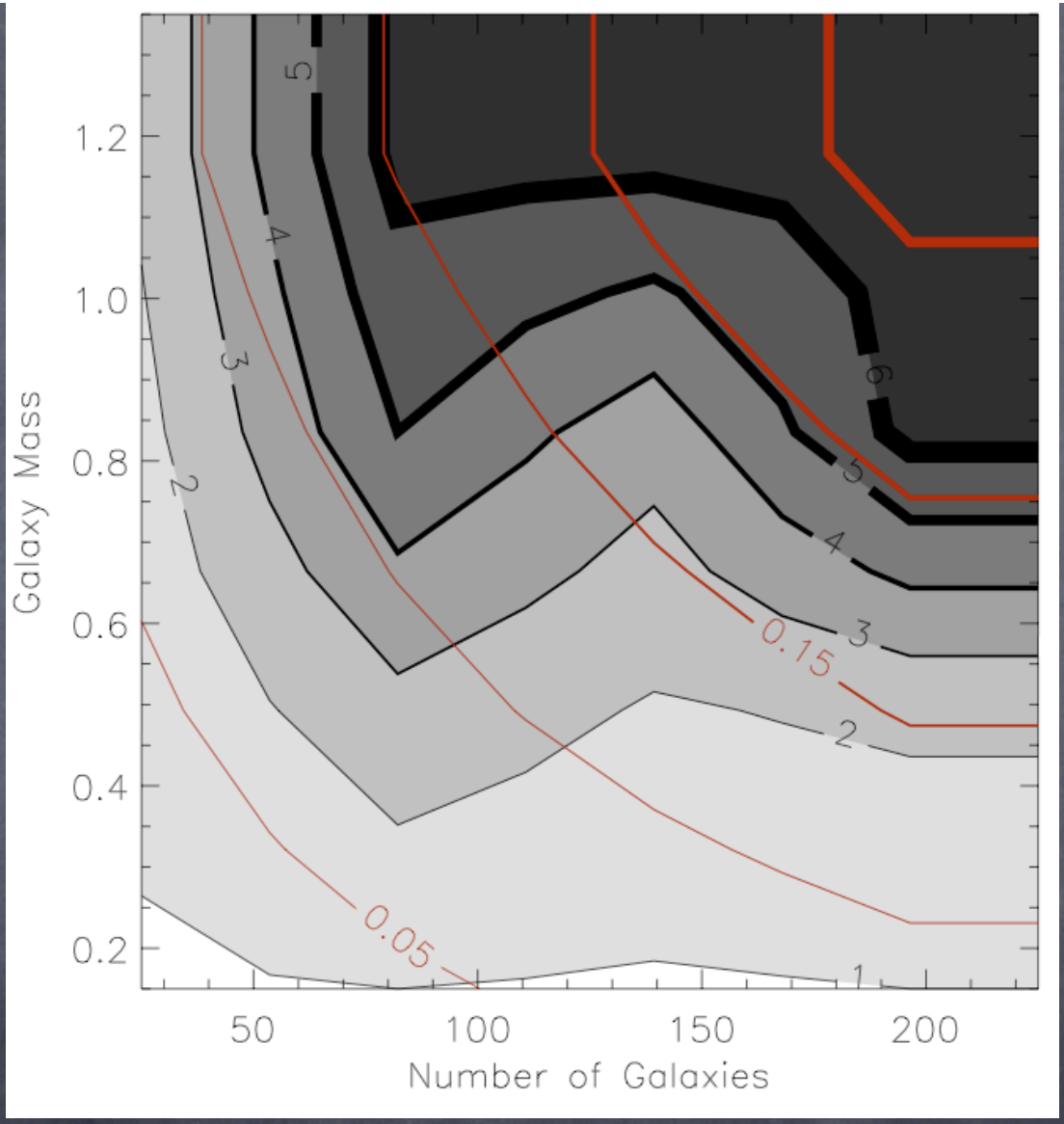
Galaxy mass



Number of galaxies

Ruszkowski & oh, 2010b

Galaxy mass

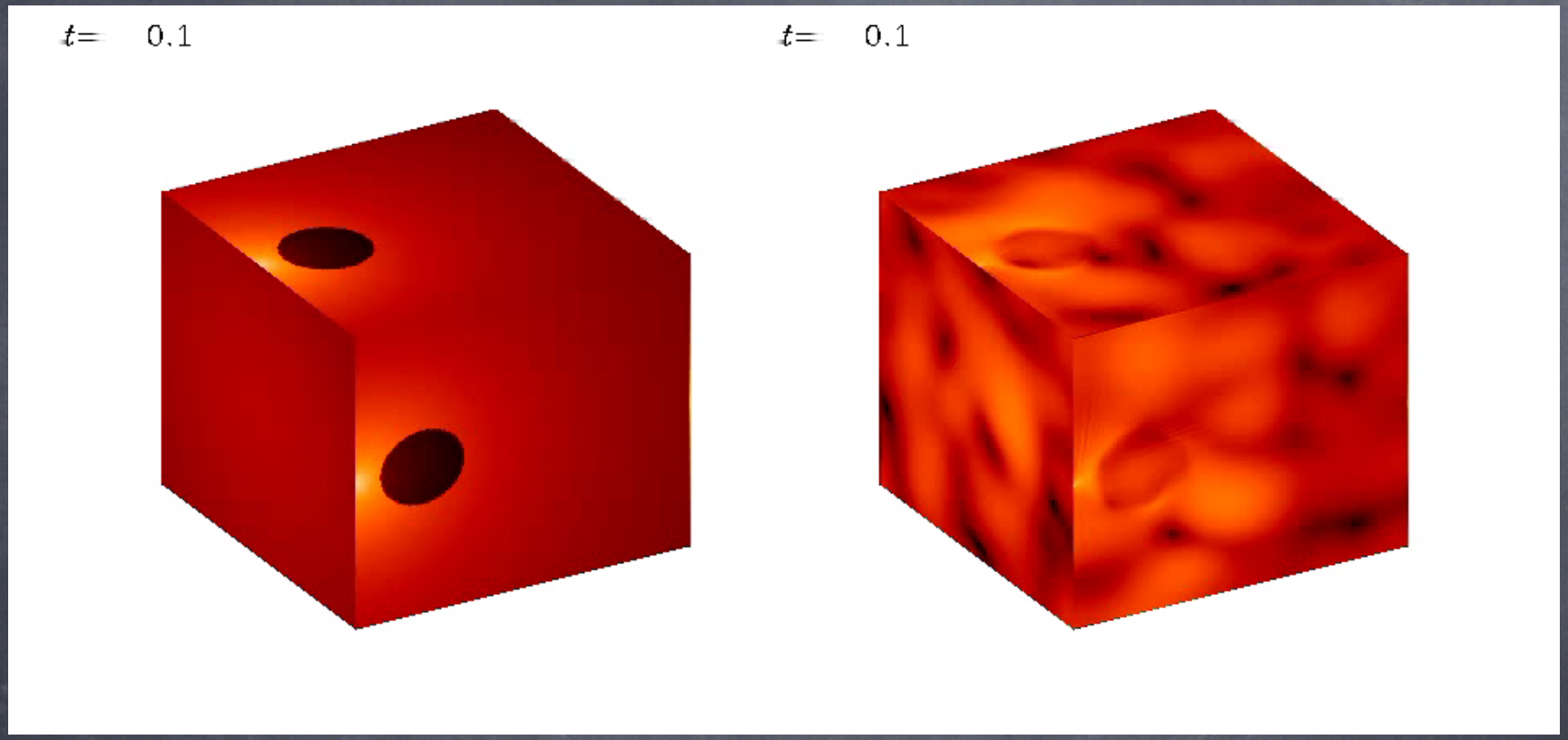


Number of galaxies

Ruszkowski & oh, 2010b

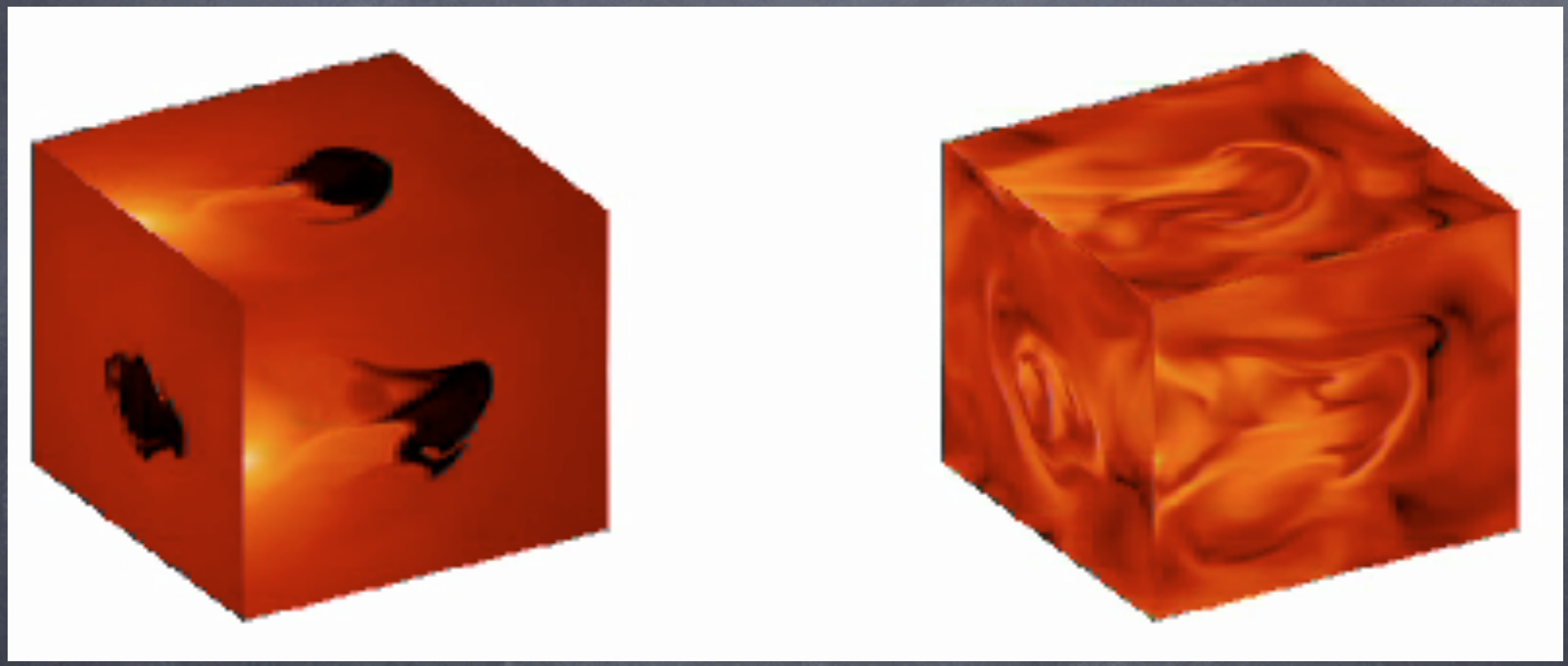

McNamara & Nulsen 2007
Forman et al.
Jones et al.
Finoguenov et al.
Fabian et al.
Sanders et al.
Churazov et al.
Peterson et al.
Blanton et al.
Croston et al.
Kraft et al.

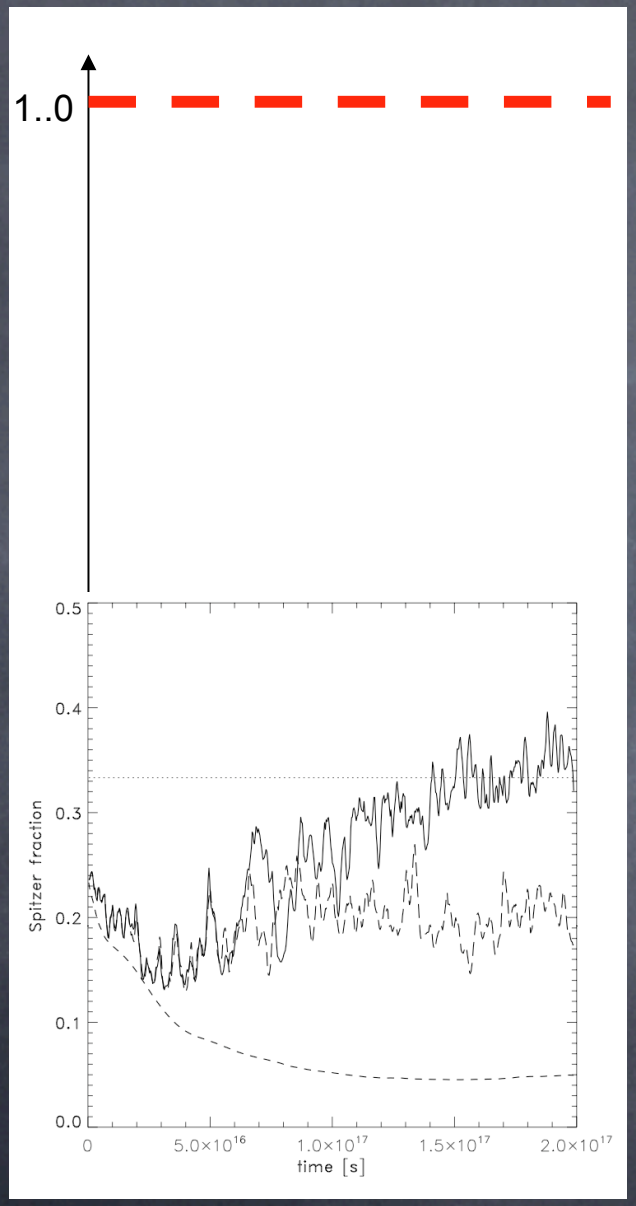
3D MHD simulations with the *PENCIL* code



Note: plasma $\beta >> 1$

Ruszkowski, Ensslin, Bruggen, Heinz, Pfrommer 2007




1..0
0.5
0.4
0.3
0.2
0.1
0.0
Spitzer fraction
0
5.0×10^16
1.0×10^17
1.5×10^17
2.0×10^17
time [s]

THE ASTROPHYSICAL JOURNAL, 525:554–582, 1999 November 10

THE SANTA BARBARA CLUSTER COMPARISON PROJECT: A COMPARISON OF COSMOLOGICAL HYDRODYNAMICS SOLUTIONS

C. S. FRENK,[1] S. D. M. WHITE,[2] P. BODE,[3] J. R. BOND,[4] G. L. BRYAN,[5] R. CEN,[6] H. M. P. COUCHMAN,[7] A. E. EVRARD,[8] N. GNEDIN,[9] A. JENKINS,[1] A. M. KHOKHLOV,[10] A. KLYPIN,[11] J. F. NAVARRO,[12] M. L. NORMAN,[13,14] J. P. OSTRIKER,[6] J. M. OWEN,[15,16] F. R. PEARCE,[1] U.-L. PEN,[17] M. STEINMETZ,[18] P. A. THOMAS,[19] J. V. VILLUMSEN,[2] J. W. WADSLEY,[4] M. S. WARREN,[20] G. XU,[21] AND G. YEPES[22]

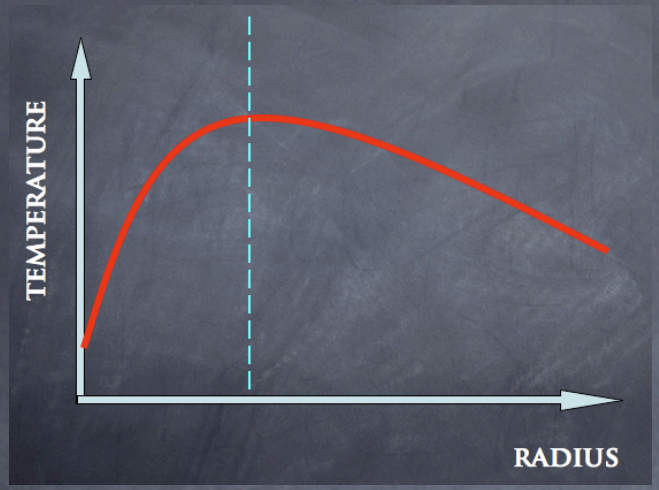
Received 1998 April 9; accepted 1999 June 25

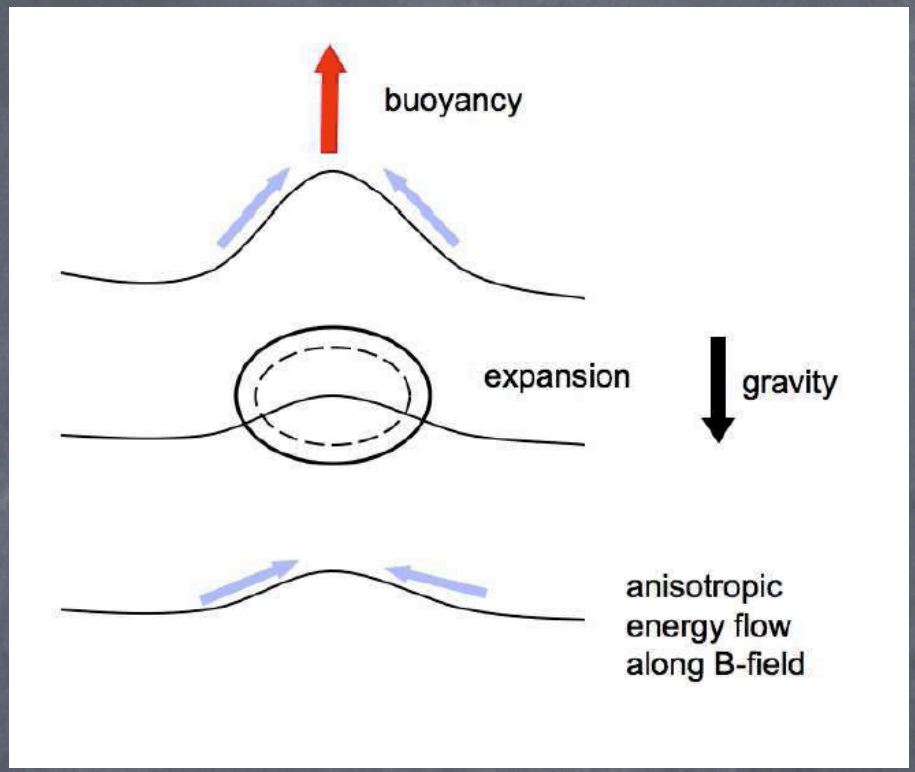
ABSTRACT

We have simulated the formation of an X-ray cluster in a cold dark matter universe using 12 different codes. The codes span the range of numerical techniques and implementations currently in use, including

Dark matter, gas, radiative cooling,
magnetic fields, anisotropic thermal conduction

Ruszkowski, Lee, Bruggen, Parrish, Oh 2011

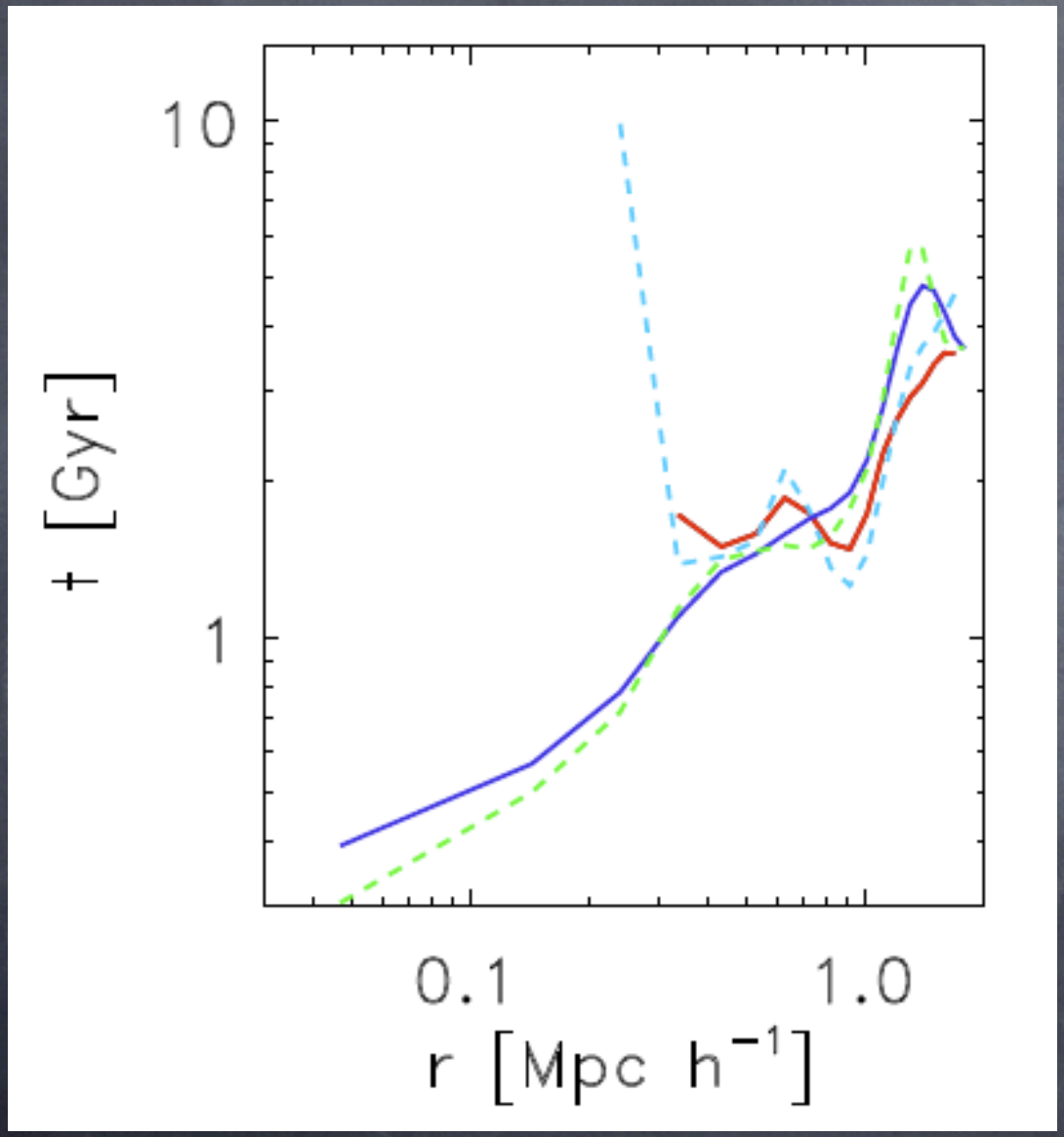




cold

hot

Balbus (2000)



ADIABATIC

ANISOTROPIC CONDUCTION

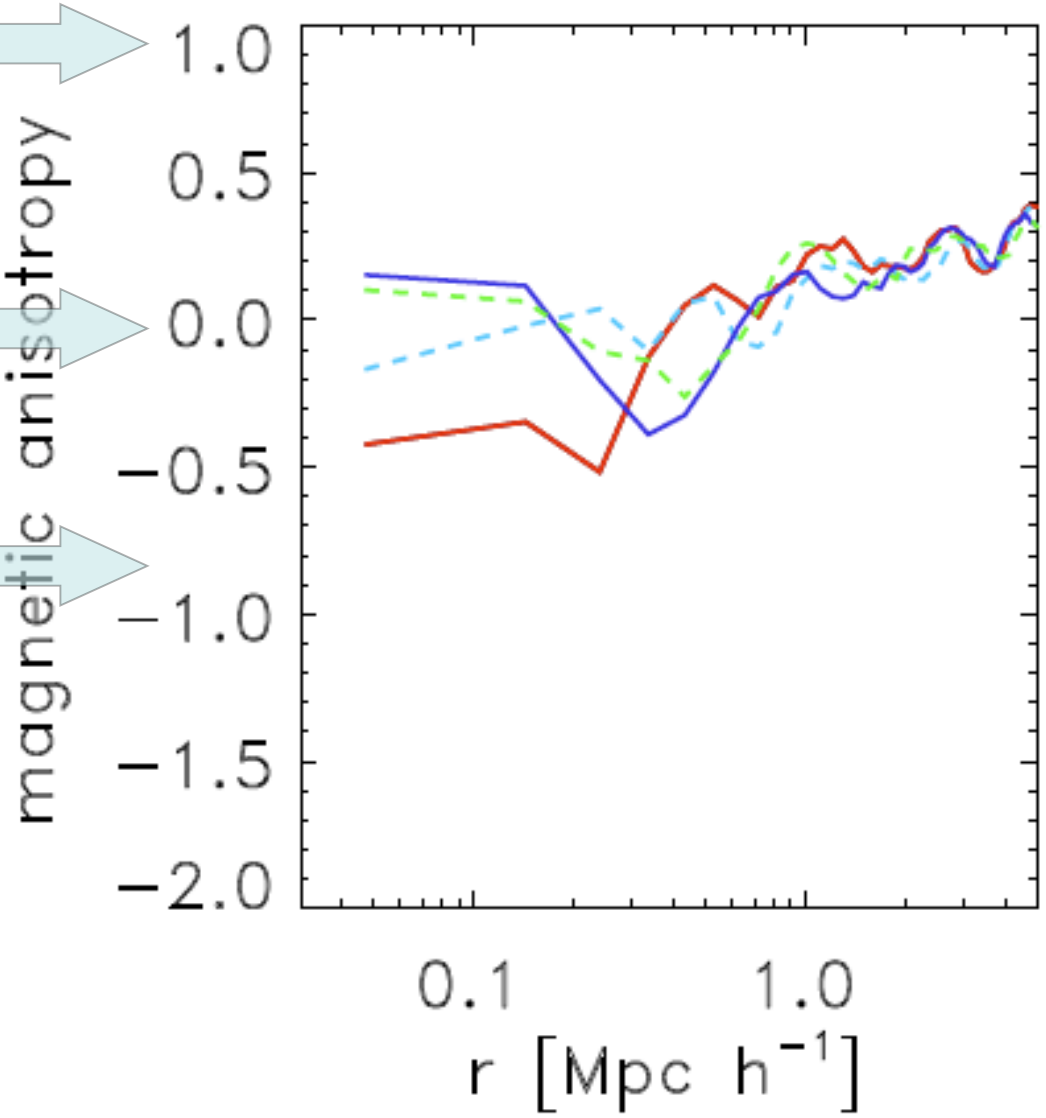
COOLING

COOLING + ANISOTROPIC CONDUCTION

radial

isotropic

tangential



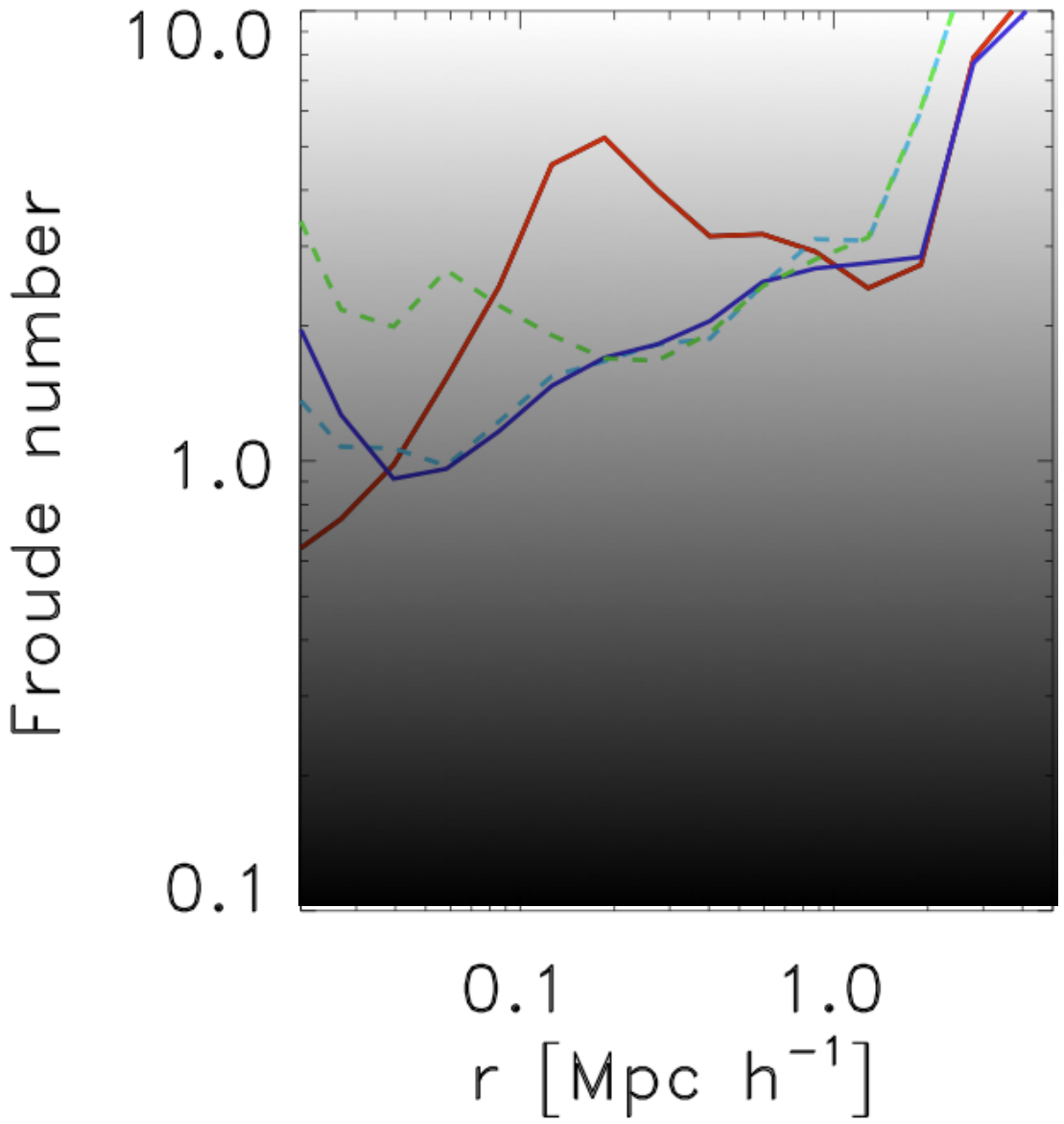
ADIABATIC

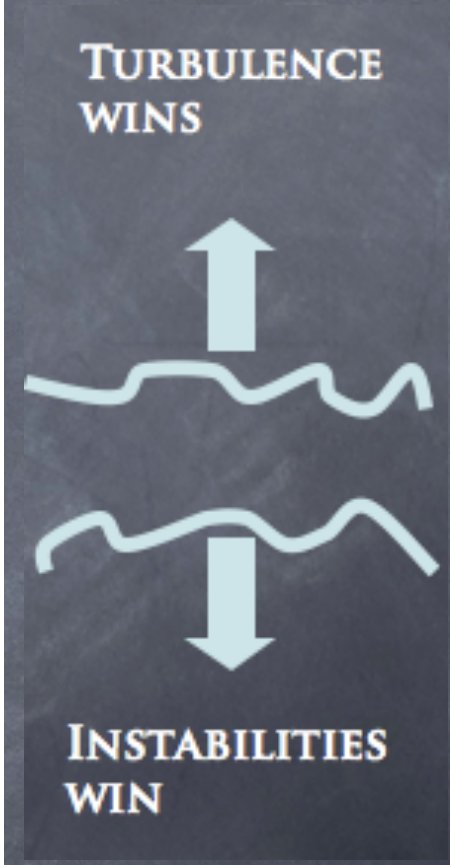
ANISOTROPIC CONDUCTION

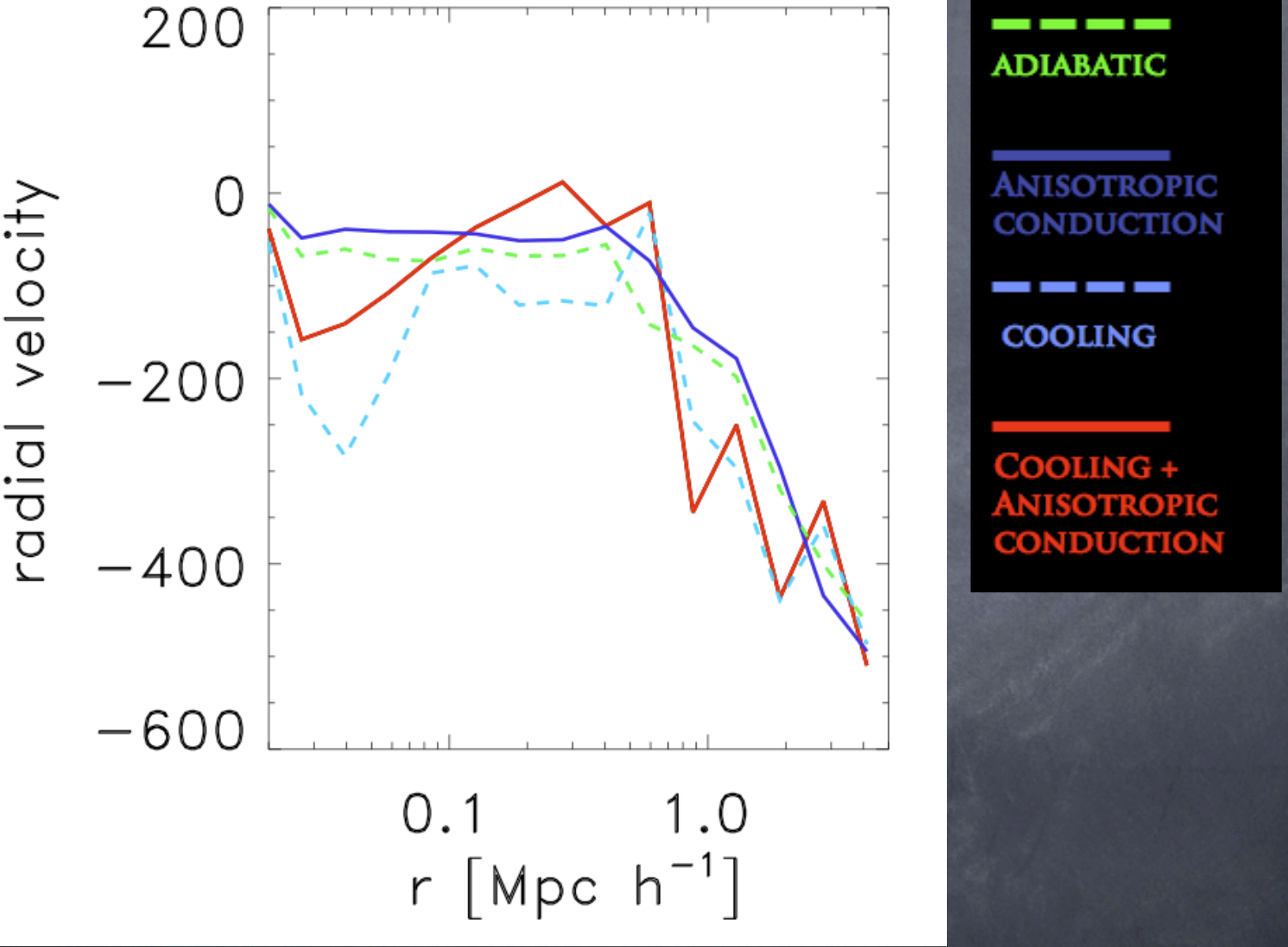
COOLING

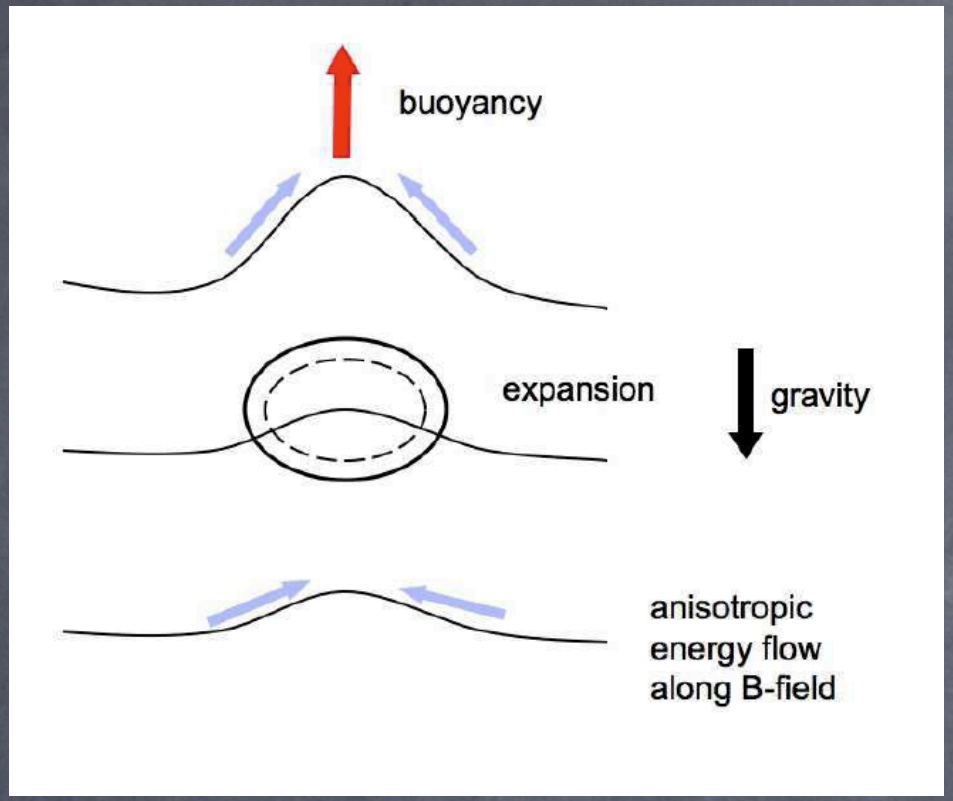
COOLING + ANISOTROPIC CONDUCTION

See Pfrommer & Dursi 2010 *Nature* paper


10.0
1.0
0.1
Froude number
0.1
1.0
r [Mpc h^{-1}]


TURBULENCE WINS
INSTABILITIES WIN


200
0
−200
−400
−600
radial velocity
0.1
1.0
r [Mpc h^{-1}]
ADIABATIC
ANISOTROPIC CONDUCTION
COOLING
COOLING + ANISOTROPIC CONDUCTION



cold

hot

$$\frac{\partial T}{\partial r} < 0 \rightarrow \frac{\partial T}{\partial r} \rightarrow 0 \rightarrow$$ Neutral buoyancy

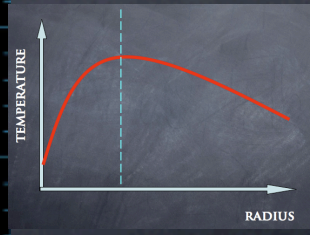
Magnetic pressure

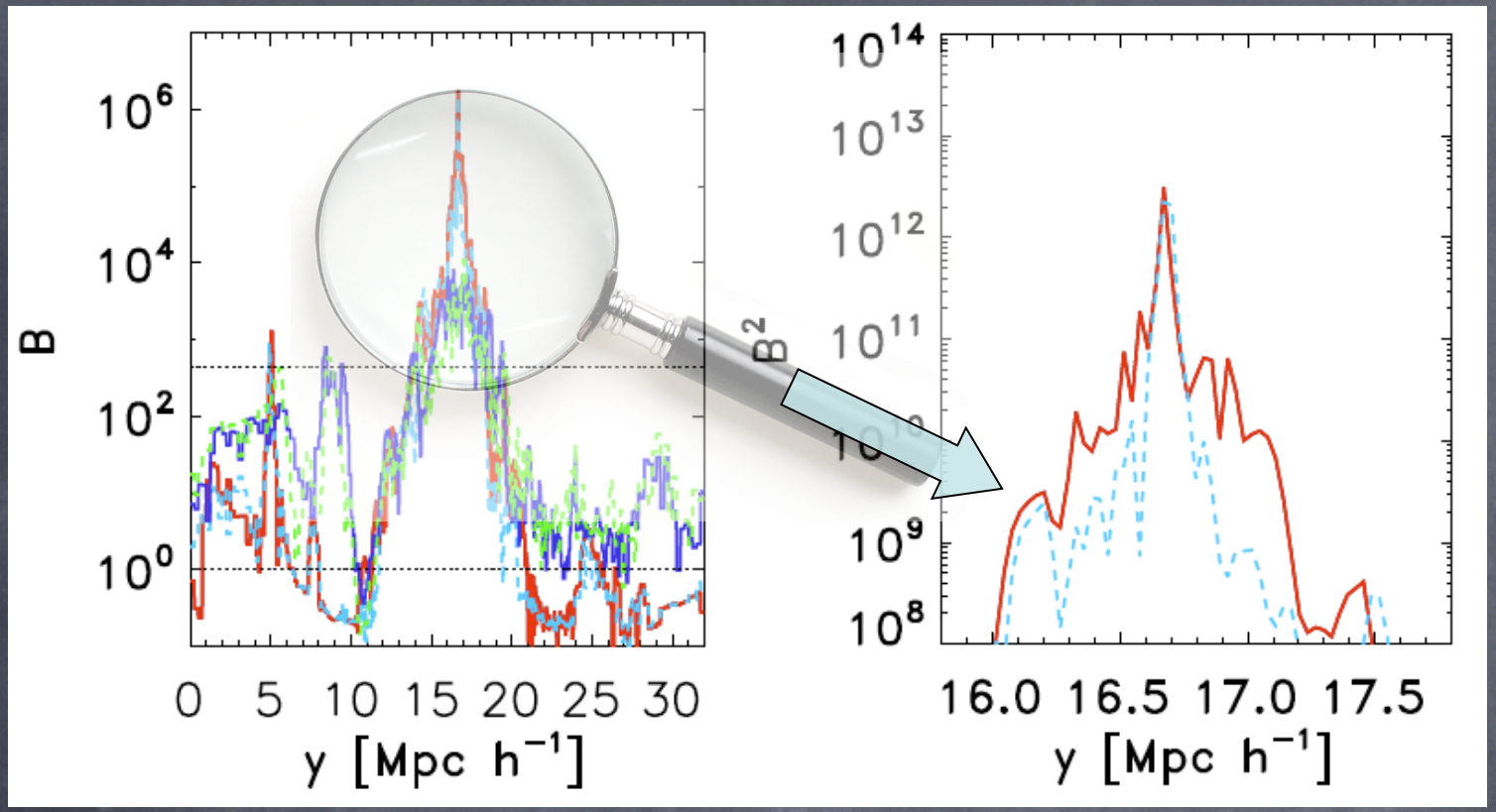
adiabatic

cooling

Anisotropic conduction

Cooling + Anisotropic conduction





Bruggen, Ruszkowski, Simionescu, hoeft, dalla vecchia 2005
Dubois & Teyssier 2008
Dolag & stasyszyn 2009
Li et al. (Los Alamos group)
Collins et al. 2009

Conclusions

hbi instability changes B-field topology
And **shuts down conduction**

ICM motions can **restore conduction**

overcooling can be prevented by
conduction and turbulent mixing (e.g., due to galaxies)

BH feedback can boost the level of thermal conduction
In the ICM

Radial bias in magnetic field

Neutral buoyancy makes MTI suppression easier and may boost B-field