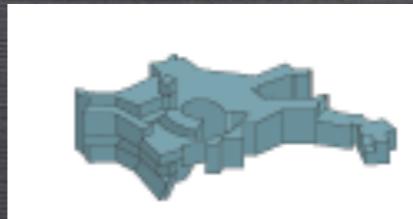


# THE ICM POWER SPECTRUM: PROBING THE GAS PHYSICS OF GALAXY CLUSTERS

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MAX PLANCK INSTITUTE FOR ASTROPHYSICS



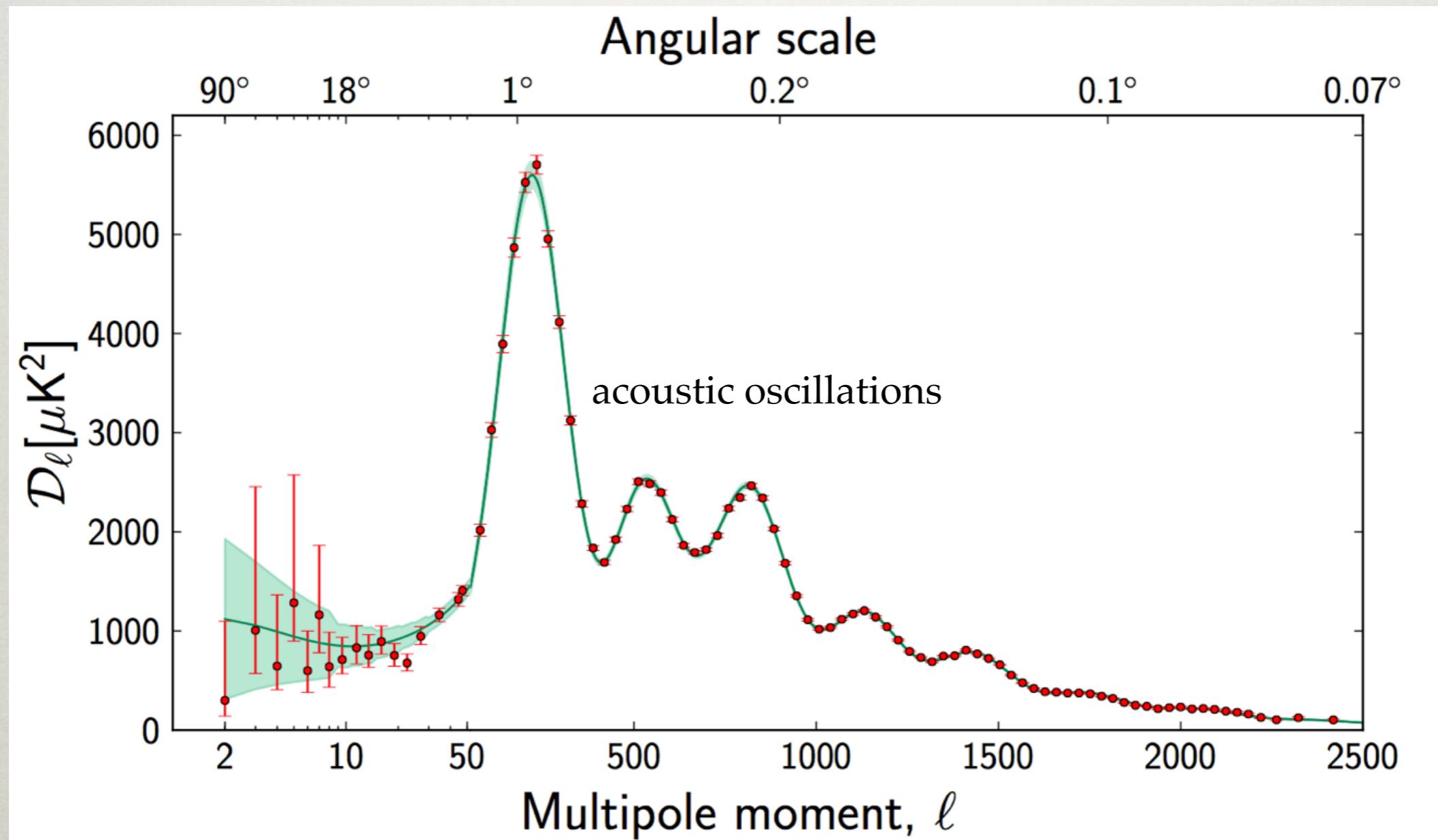
COLLABORATORS: E. CHURAZOV, D. NAGAI, E. LAU, I. ZHURAVLEVA, R. SUNYAEV

# POWER SPECTRUM

## CMB - OBSERVATIONS

Photon-baryon fluid

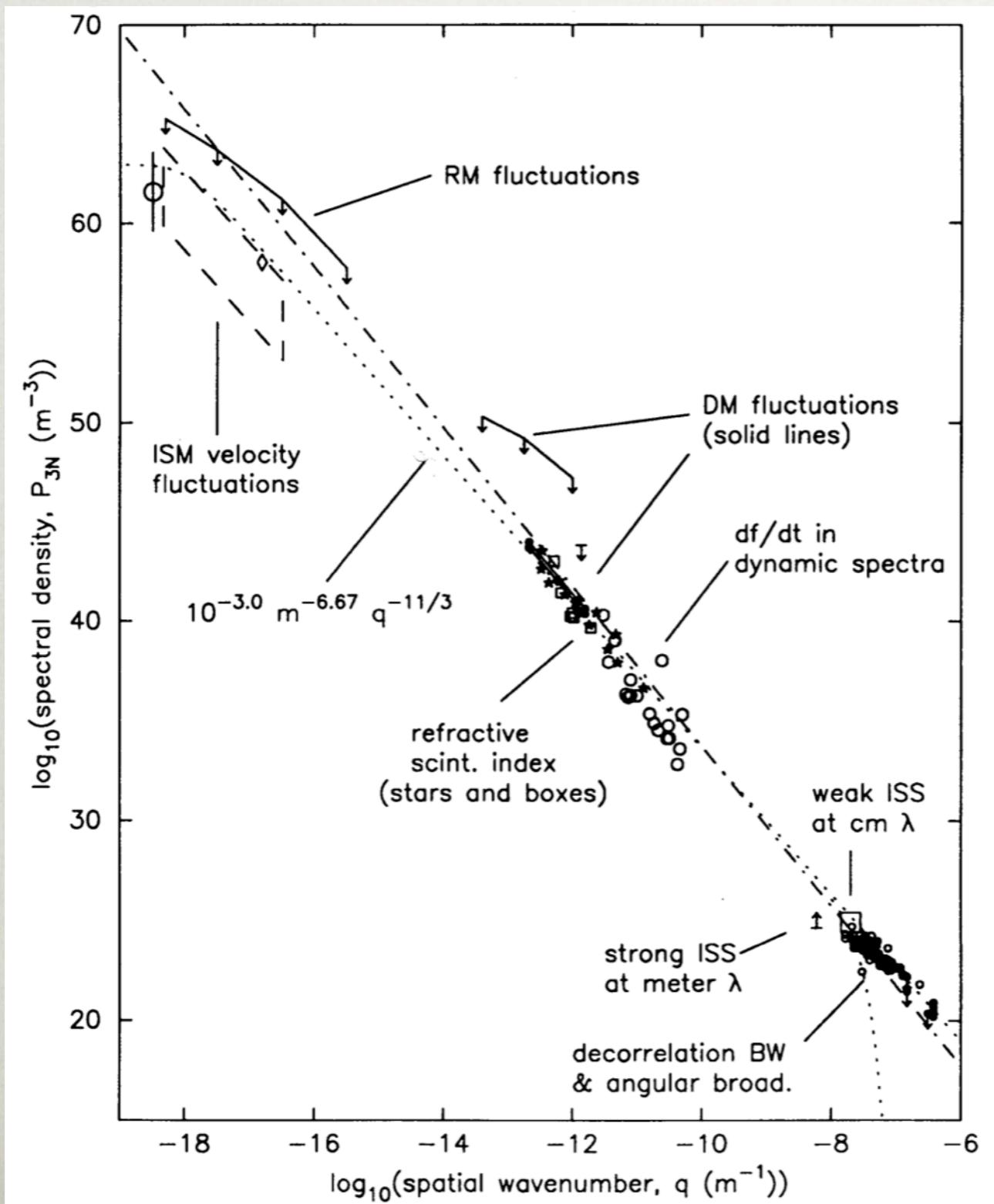
CMB temperature: Planck coll. 2013



If sound waves are synchronized, the same behavior can be simulated in the ICM

# POWER SPECTRUM

## ISM - OBSERVATIONS



ISM density: Armstrong et al. 1995

Kolmogorov slope (classic turbulence)  
over 10 decades in wavenumber!

$$E_k \propto k^{-5/3}$$

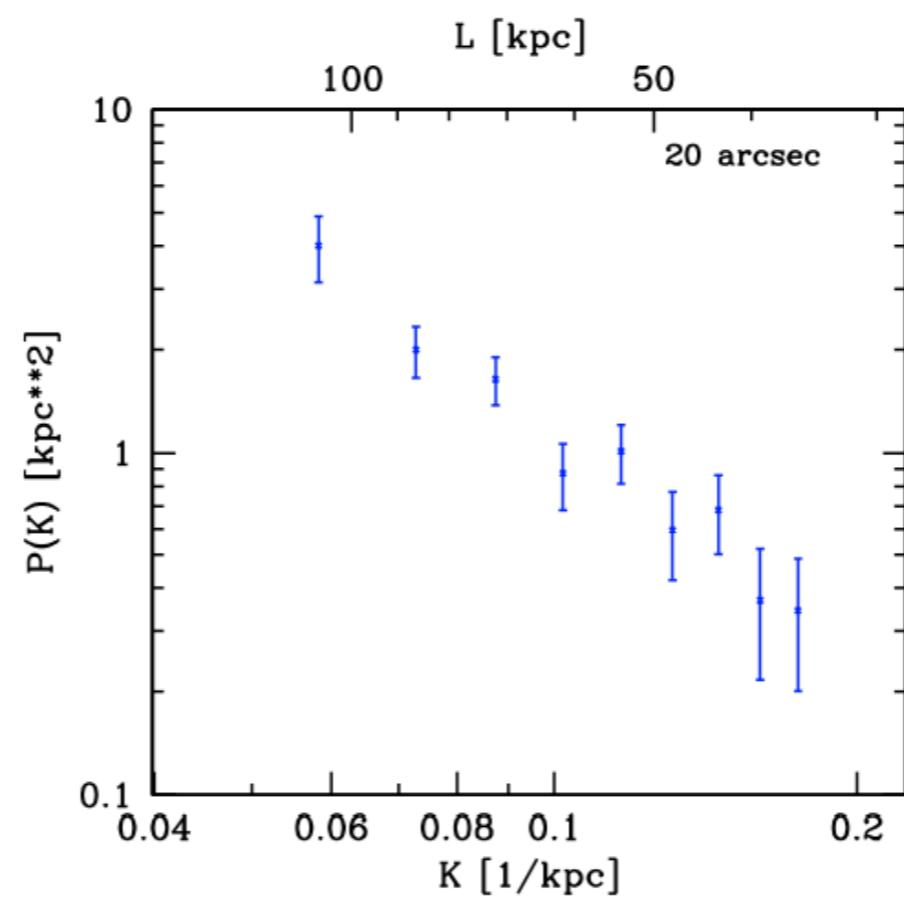
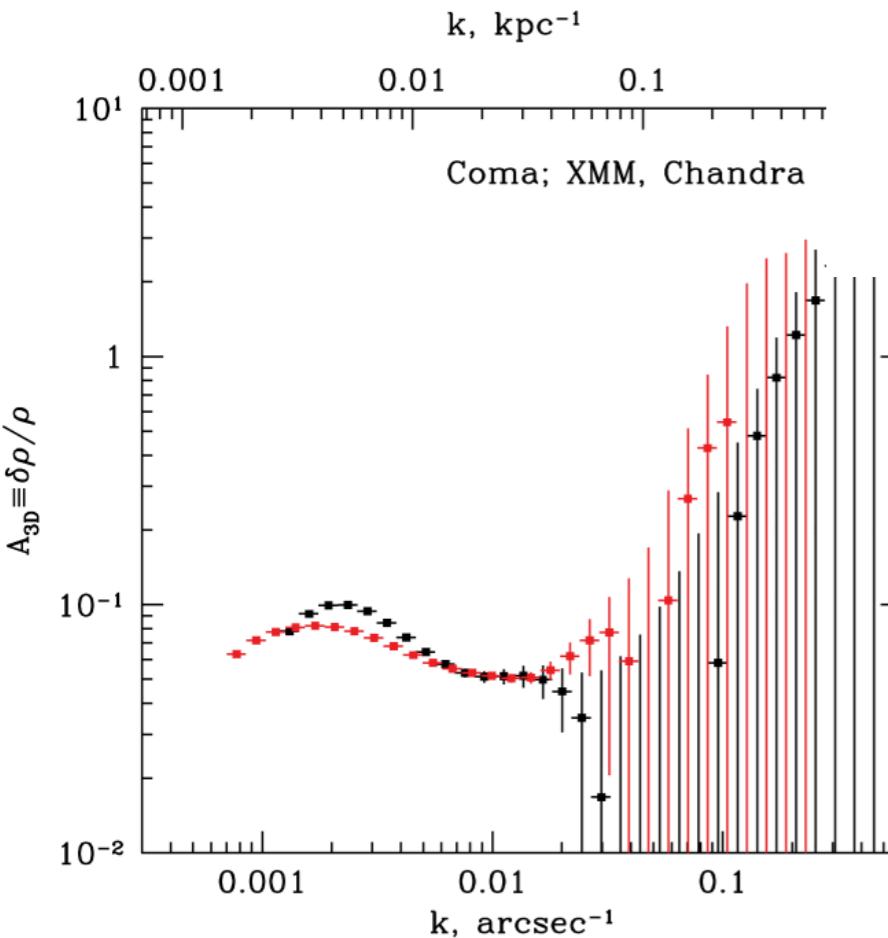
... same for the solar wind:  
Woo & Armstrong 1979,  
Marsch & Tu 1990

# POWER SPECTRUM

## ICM - OBSERVATIONS

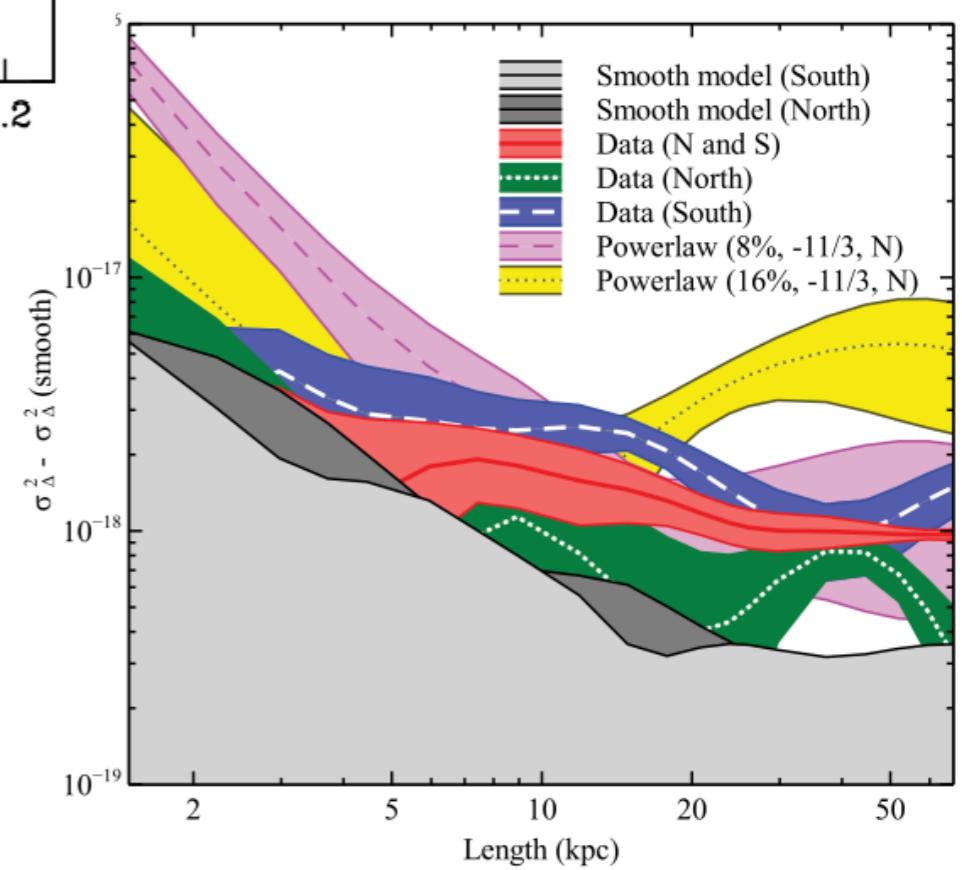
Only a few ICM studies:  
suggest **Kolmogorov trend**  
(or slightly shallower)

ICM density: Churazov et  
al. 2012 (Coma)



ICM pressure:  
Schuecker et al. 2004  
(Coma)

ICM density:  
Sanders et al. 2012 (AWM7)



# 3D HIGH-RES SIMULATIONS

## [ASTROPHYSICAL EXPERIMENT]

Gaspari & Churazov 2013  
Gaspari et al. 2014

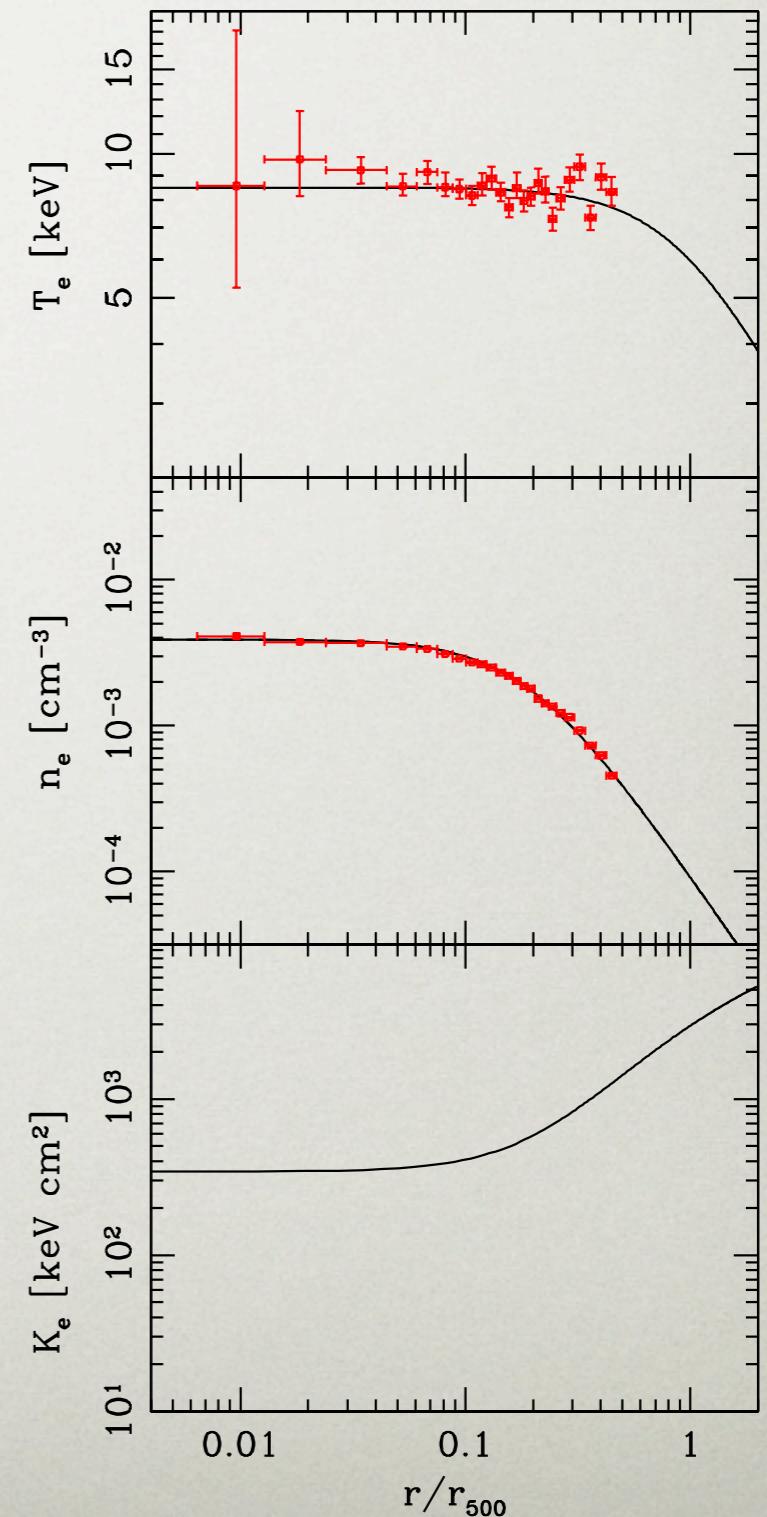
for numerical details

- Massive hot galaxy cluster:  
 $T_0 = 8.5 \text{ keV}$ ,  $M_{\text{vir}} \sim 10^{15} M_\odot$ ,  $R_{500} \sim 1.4 \text{ Mpc}$
- UG 512<sup>3</sup> (100 mil. cells) → avoid AMR diffusion
- $\Delta x \approx 2.6 \text{ kpc}$  ( $\sim$  electron mean free path)
- 3D hydrodynamics: III order PPM (*FLASH4*)

Main physics tested:

- **TURBULENCE:**  $M \sim 0.25 - 0.75$
- **THERMAL CONDUCTION:**  $f \sim 10^{-3} - 10^0$
- **electron - ion equilibration**

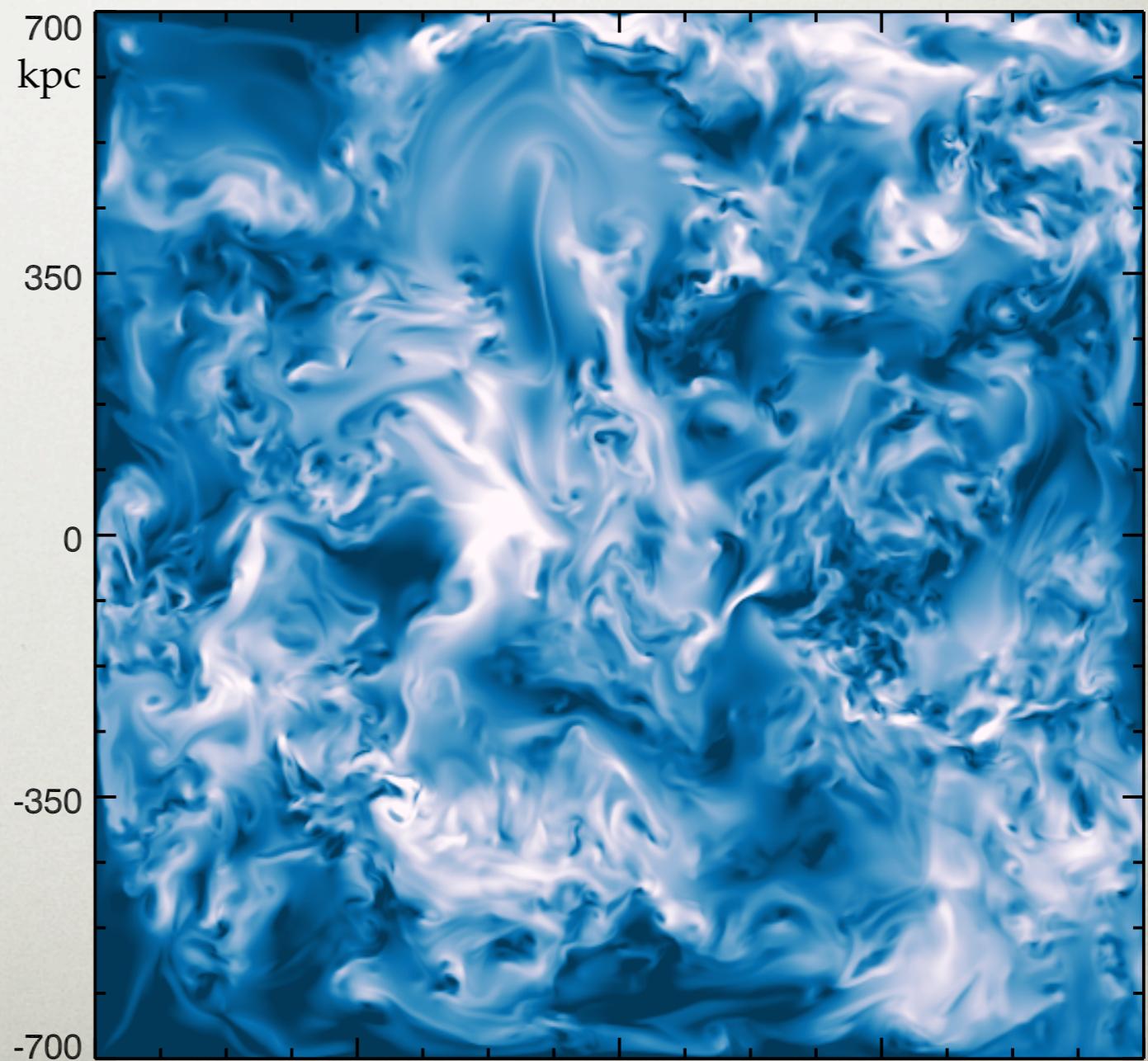
init from observed profiles (Coma)



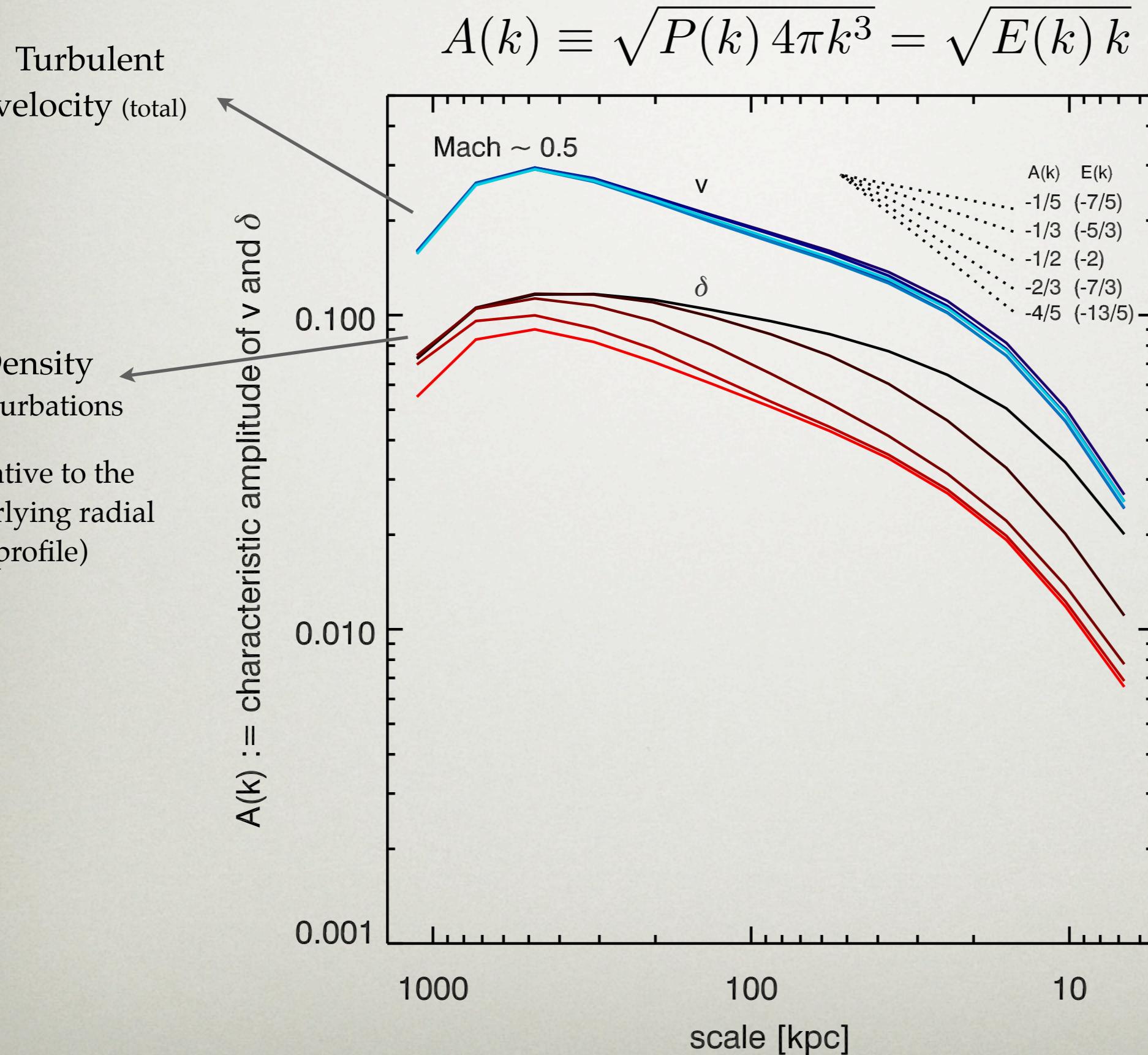
# TURBULENCE

- ICM is never in perfect HSE: mergers, cosmic flows, galaxy motions, feedback processes
- Observations & simulations: e.g. Norman & Bryan 1999, Schuecker et al. 2004, Lau et al. 2009, Vazza et al. 2009, 2011, Churazov et al. 2008, de Plaa et al. 2012, Gaspari et al. 2012, Sanders & Fabian 2013, ...
- $E_{\text{turb}} \sim 3 - 30\% E_{\text{th}}$  → tested range:  
 $\text{Mach} \sim 0.25 - 0.75$
- OU spectral driving in Fourier space  
( $L_{\text{inj}} \sim 100 - 600 \text{ kpc}$ ) → natural turbulent cascade to smaller scales

Gaspari et al. 2014  
 $|v|$  mid-plane slice  
massive galaxy cluster



# ICM POWER SPECTRUM



Gaspari & Churazov 2013  
Gaspari et al. 2014

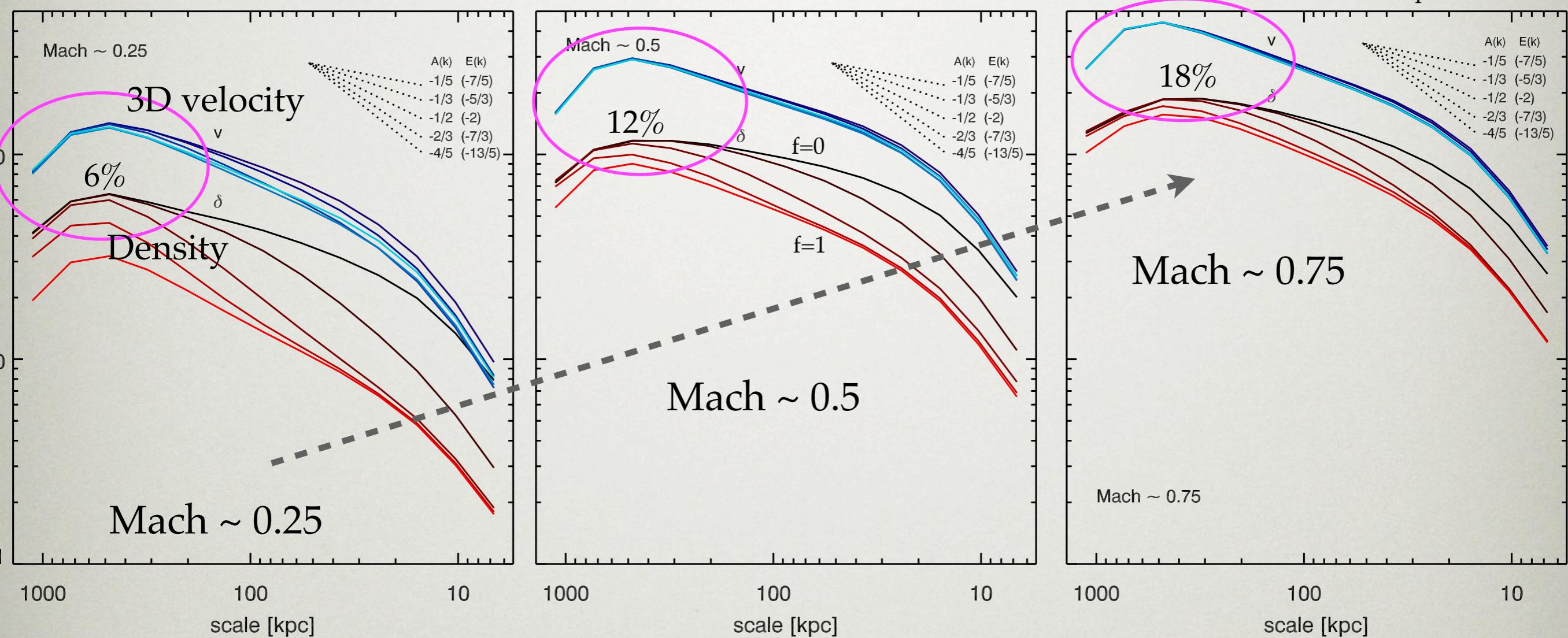
1.

**PS NORMALIZATION:  
RISING WITH TURBULENT  
MOTIONS**

$$\delta\rho/\rho \approx \text{Mach}_{1\text{D}}$$

# PS NORMALIZATION

Gaspari et al. 2014



globally self-similar  
over Mach and  $L_{\text{inj}}$

$$\delta\rho/\rho \approx \text{Mach}_{1D}$$

( $< 1$ )

# G-WAVES vs P-WAVES

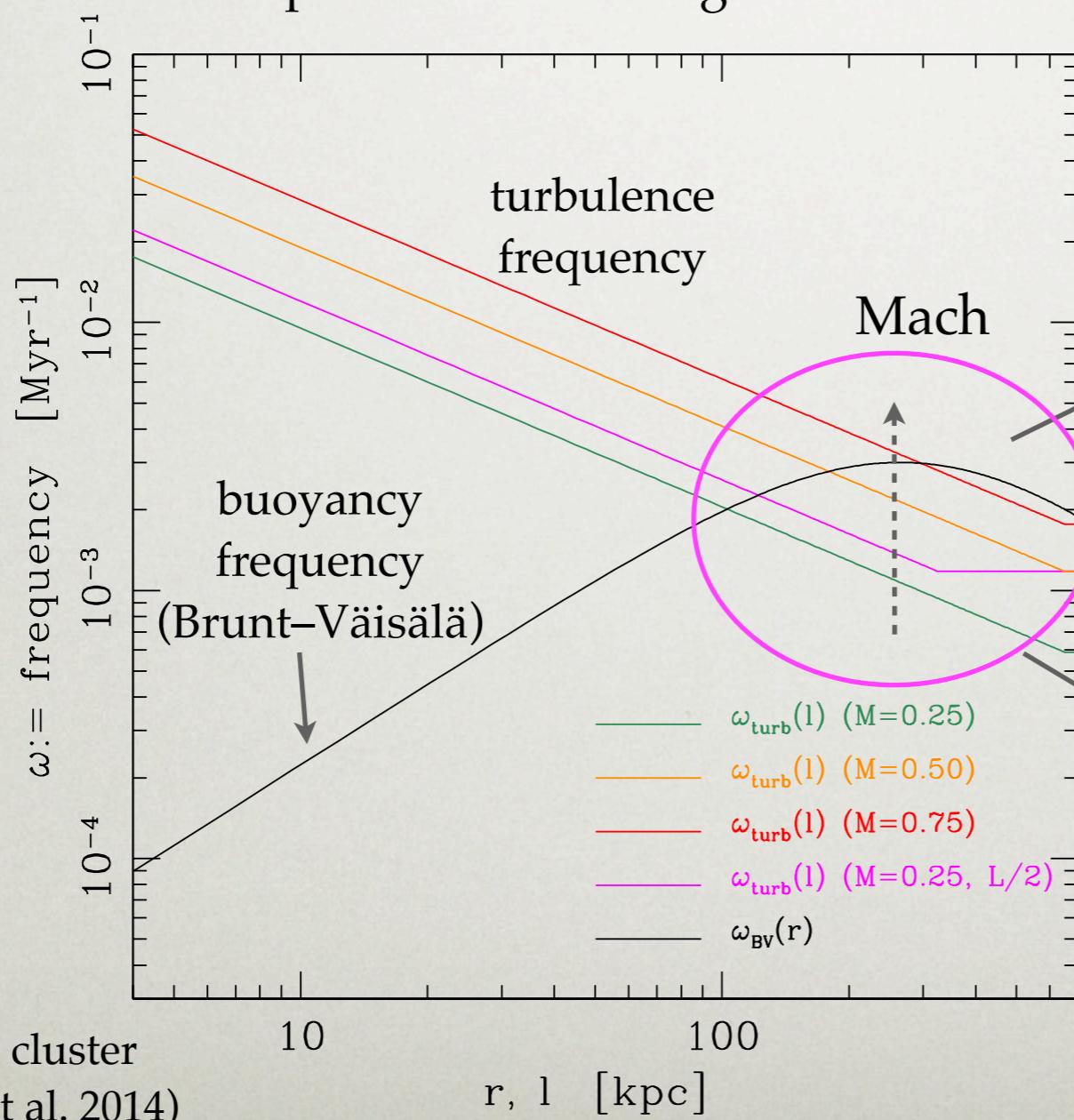
BUOYANCY

SOUND

$$\omega^4 - \omega^2 c_s^2 k^2 + \omega_{BV}^2 c_s^2 k_\perp^2 = 0$$

p-waves                            g-waves

linearized perturbed HD - dispersion relation (Balbus & Soker 1990)



$\delta P/P \sim \text{Mach}_{1D}$   
stronger compression (p-waves)

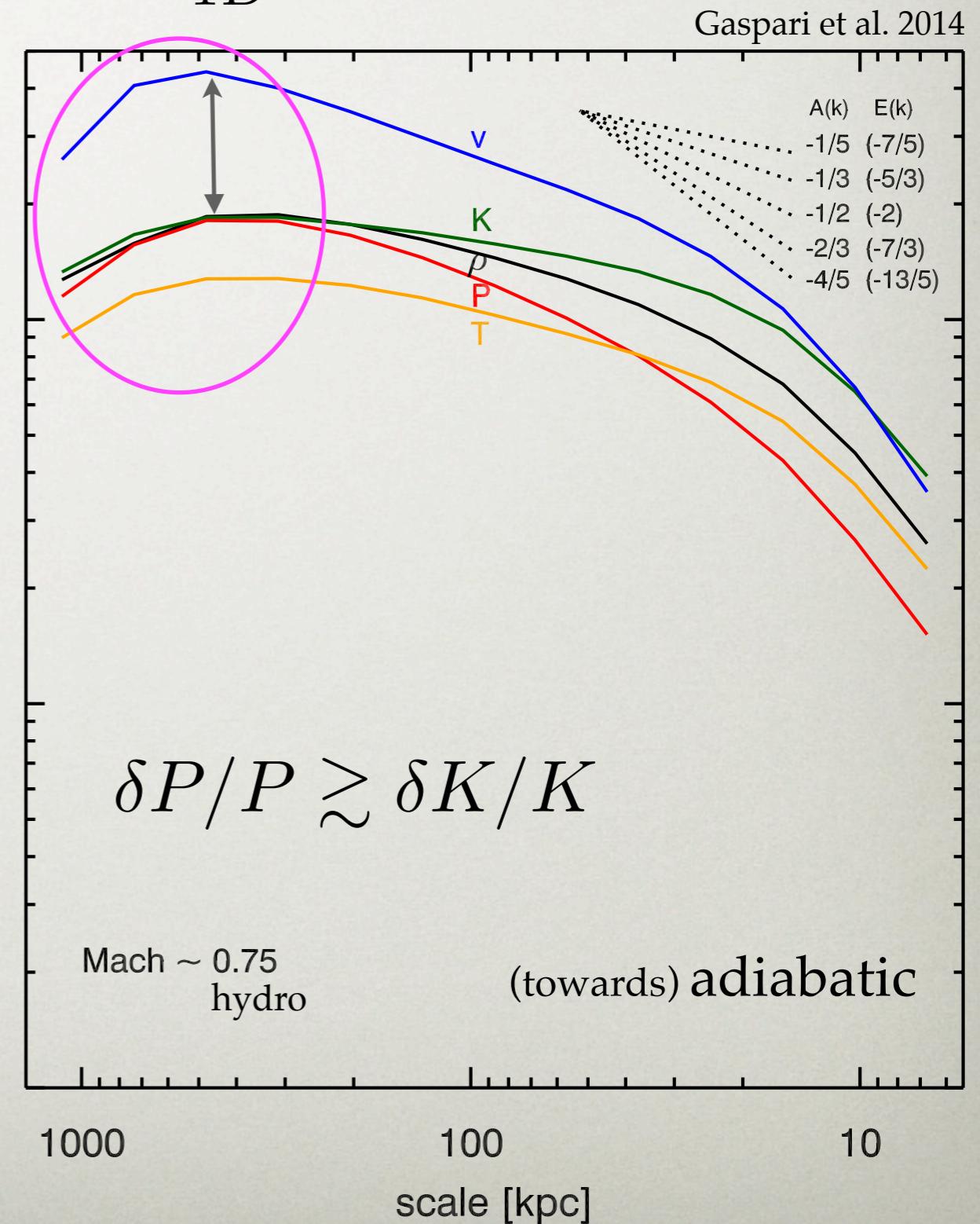
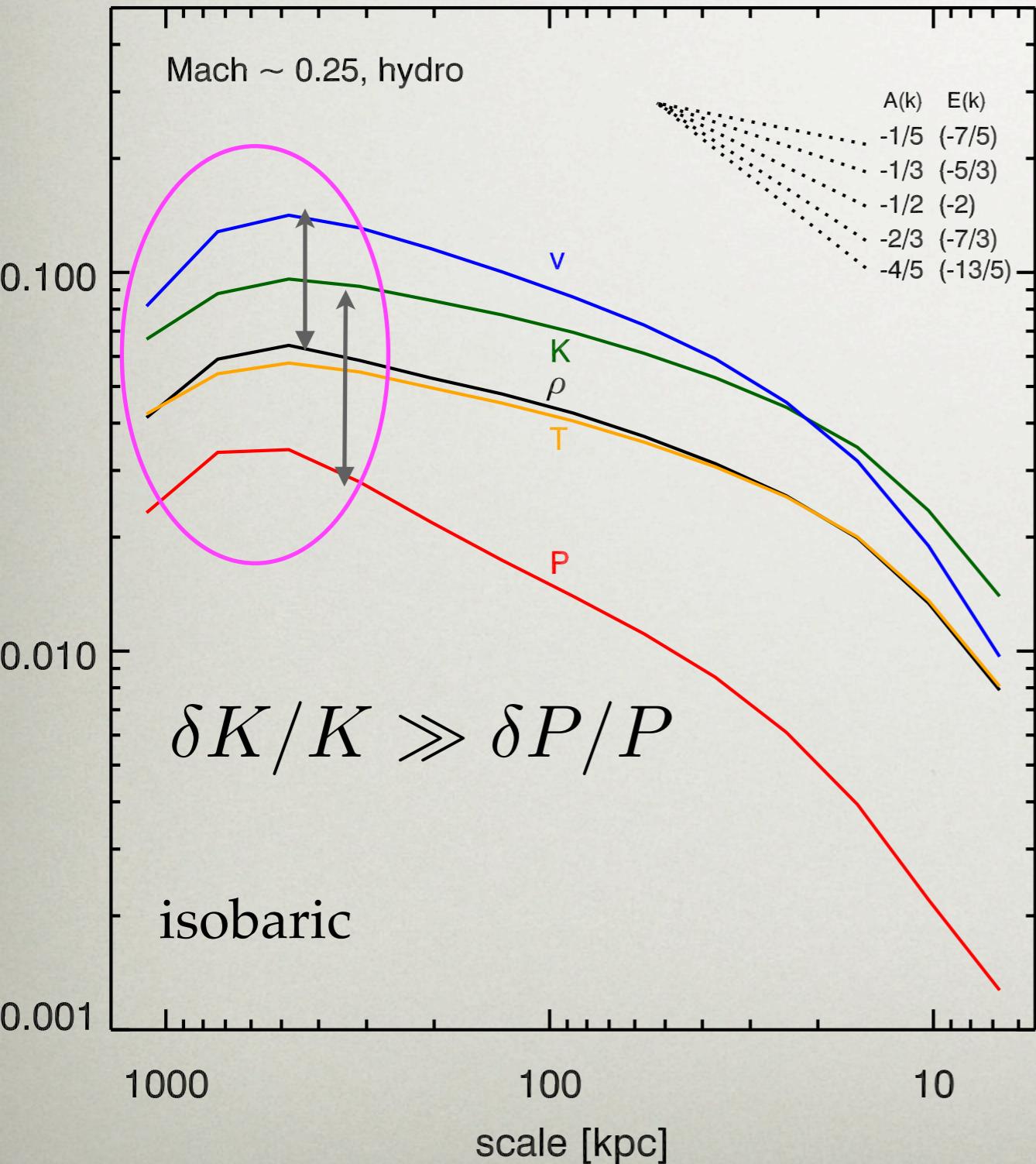
stronger buoyancy (g-waves)

$\delta K/K \sim \text{Mach}_{1D}$   
cluster gradients are radial

**G-WAVES > P-WAVES**

**G-WAVES  $\lesssim$  P-WAVES**

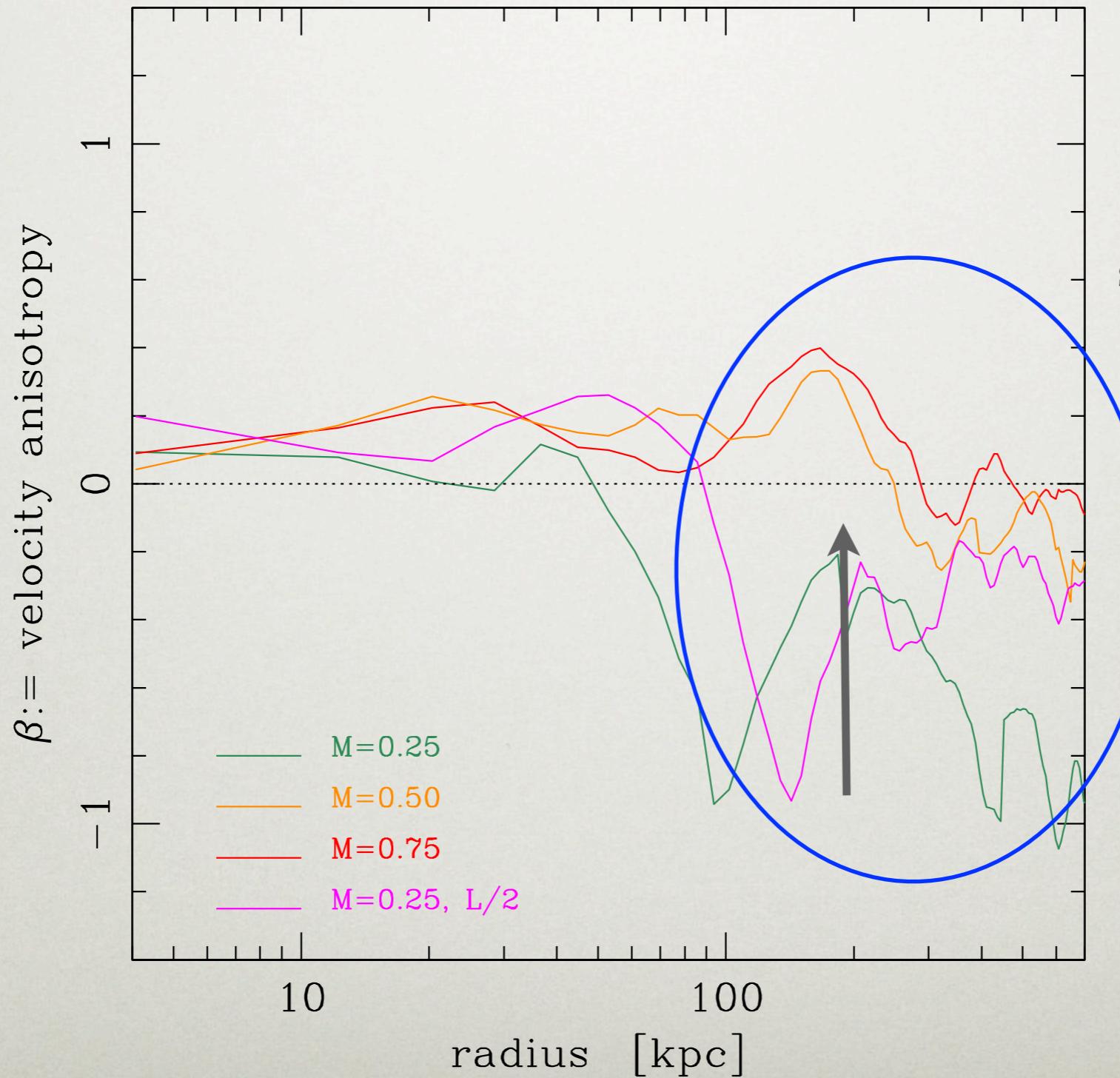
but in both cases  
 $\delta\rho/\rho \approx \text{Mach}_{1D}$



# VELOCITY ANISOTROPY

marker of the dominant regime

Gaspari et al. 2014



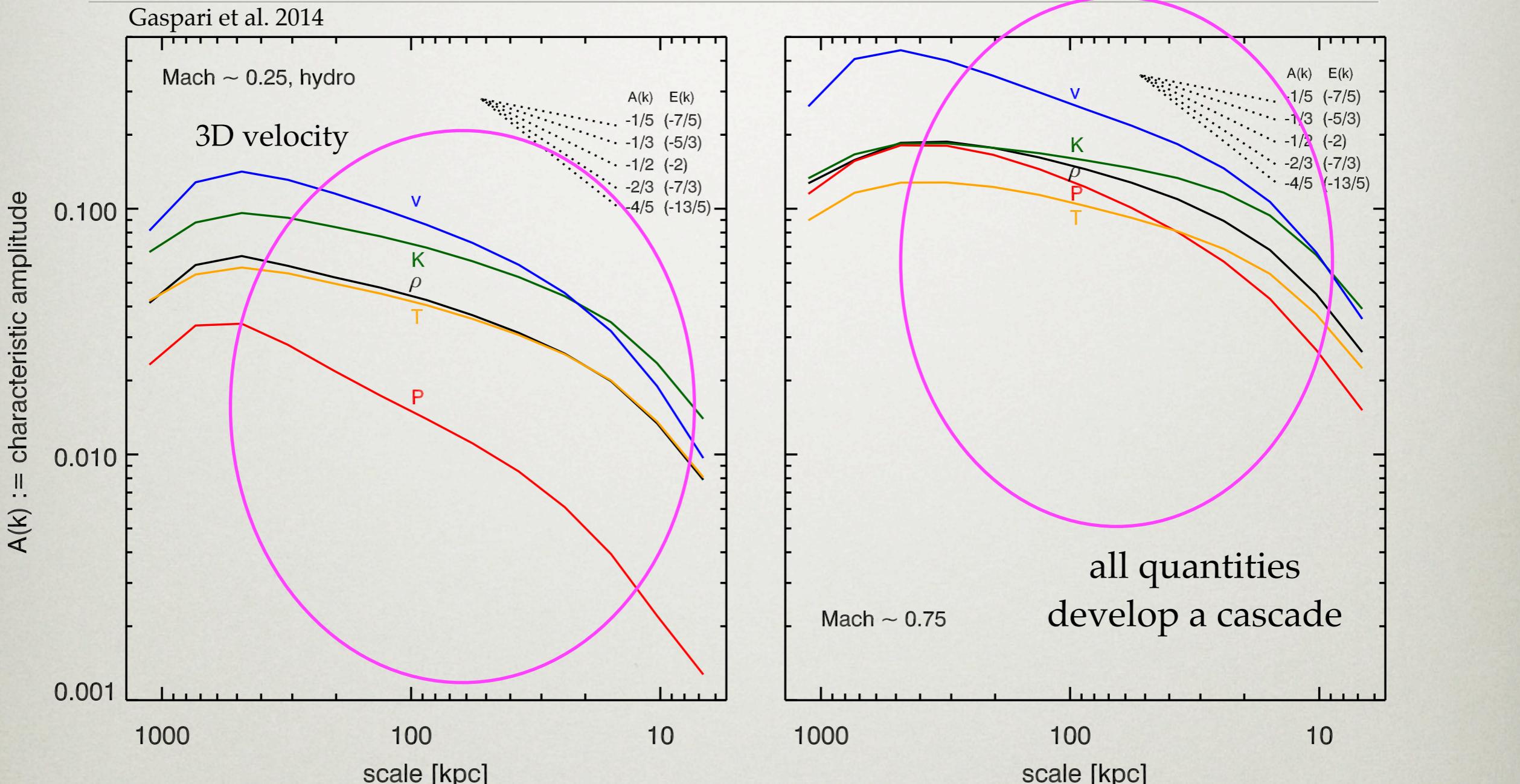
stronger turbulence  
(Mach > 0.5):  
towards isotropy

g-waves (Mach < 0.5):  
mild tangential  
anisotropy

**2.**

**PS SLOPE:  
TRACING VELOCITY FIELD  
&  
SHAPED BY TRANSPORT  
PROCESSES**

# 'TRACERS' OF THE VELOCITY FIELD



Kolmogorov-Obhukov-Corrsin

Extreme / fully passive case:  $E_{\text{tracer}}(k) \propto E_v(k)$

e.g. entropy:  $\rho T \frac{DS}{Dt} \equiv \rho T \left( \frac{\partial S}{\partial t} + \mathbf{v} \cdot \nabla S \right) \sim 0$

... but deviations:  
weak compression, radial  
gradients, different diffusivity  
(nonlinear sims are required)

# THERMAL CONDUCTION

Transfer of heat via plasma electrons:

heating rate per unit volume

$$\nabla \cdot \mathbf{F}_{\text{cond}} = - \nabla \cdot (\kappa \nabla T_e)$$

Spitzer (1962) conductivity:

$$\kappa \approx f \frac{1.84 \times 10^{-5} T_e^{5/2}}{\ln \Lambda_{ei}}$$

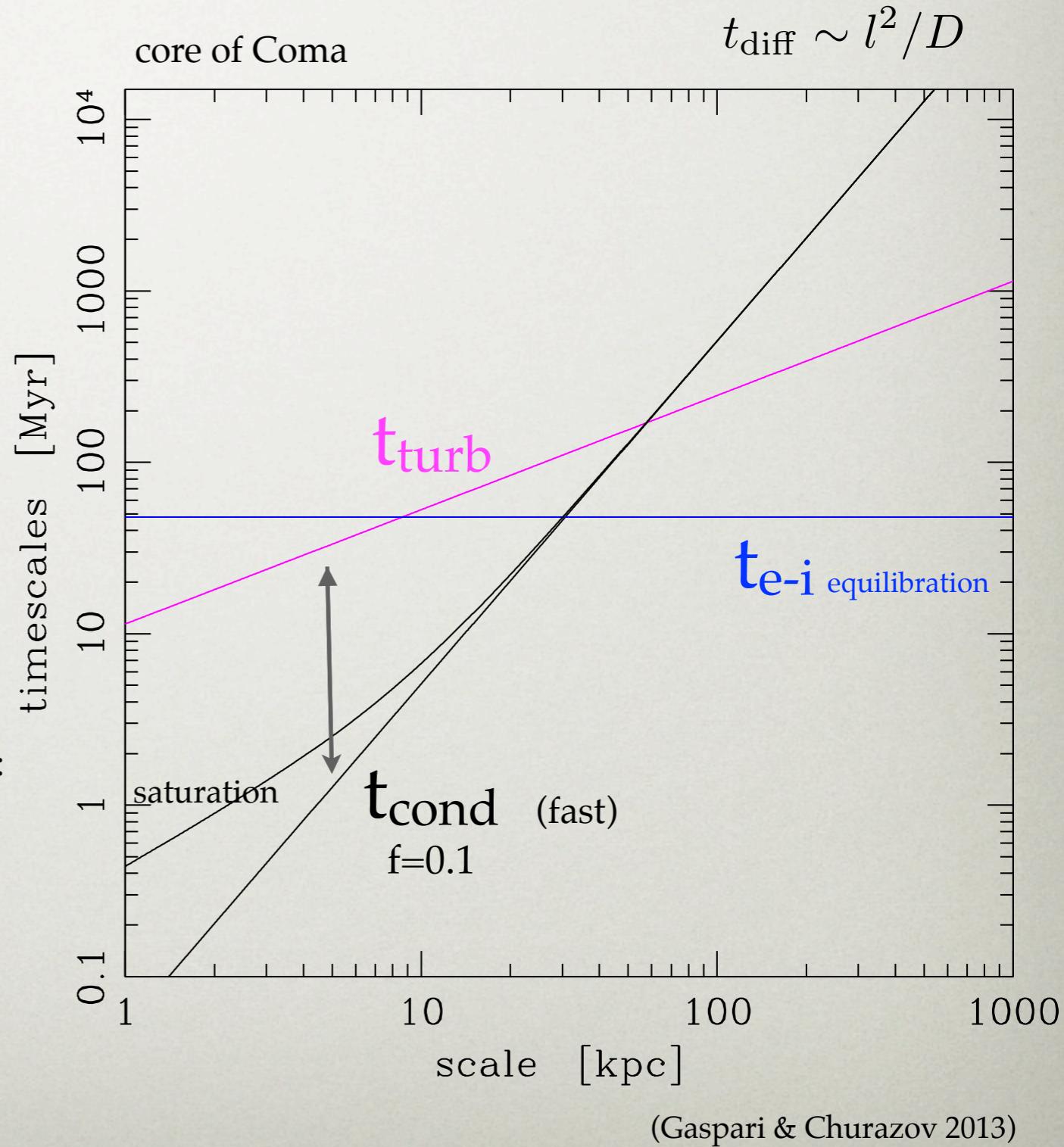
magnetic suppression

(unresolved small scales → highly tangled  $B$ -field):  
Ruszkowski & Oh 2010,11

$$f \sim 10^{-3} - 0.3$$

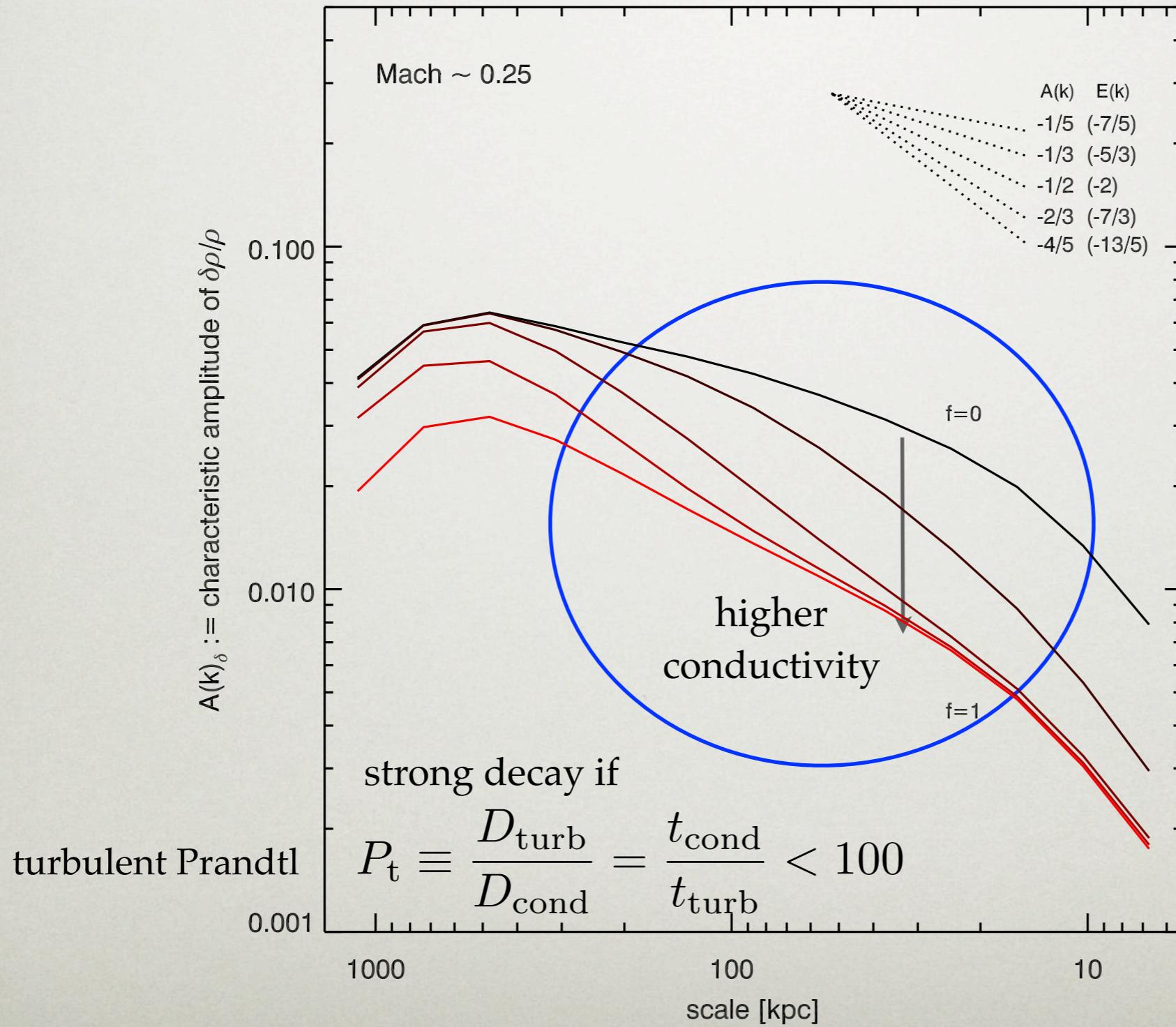
plasma micro-instabilities  
(mirror, firehose, etc.) + line  
divergence

geometric suppression  
(electrons move along  
 $B$ -field lines)

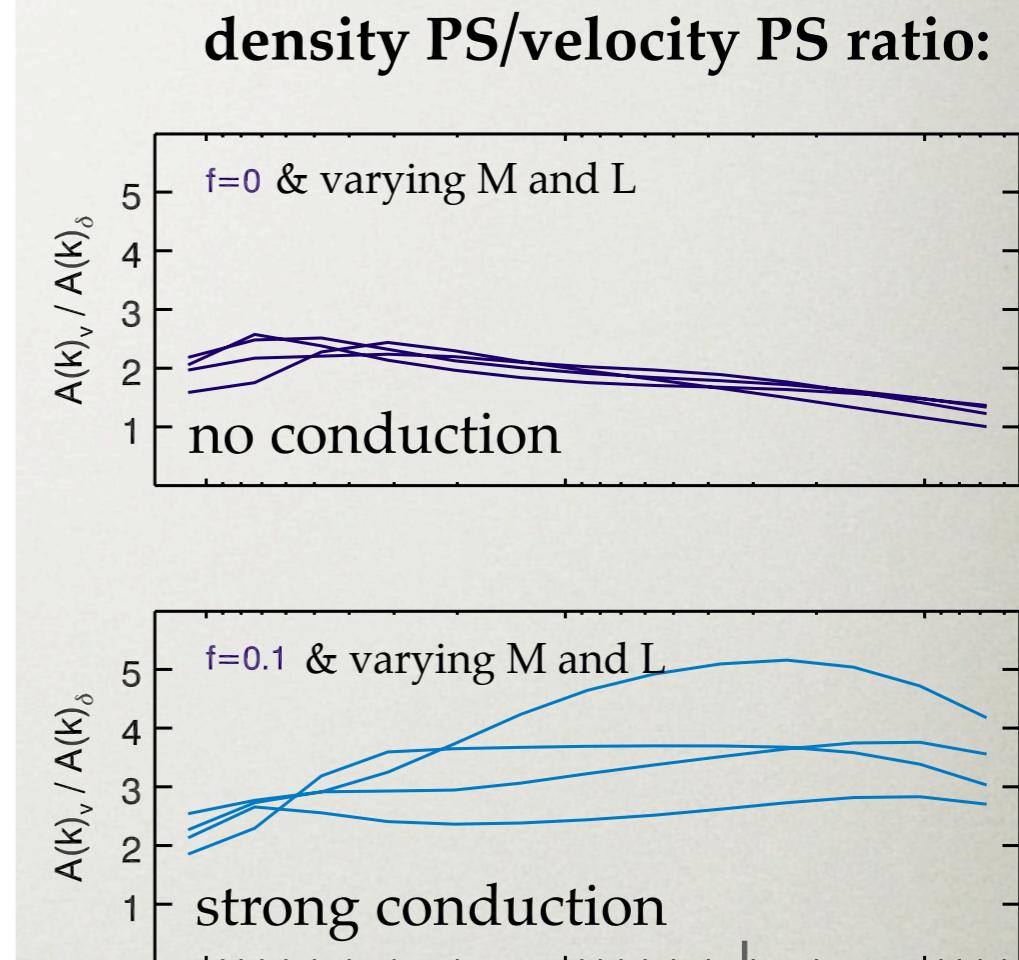
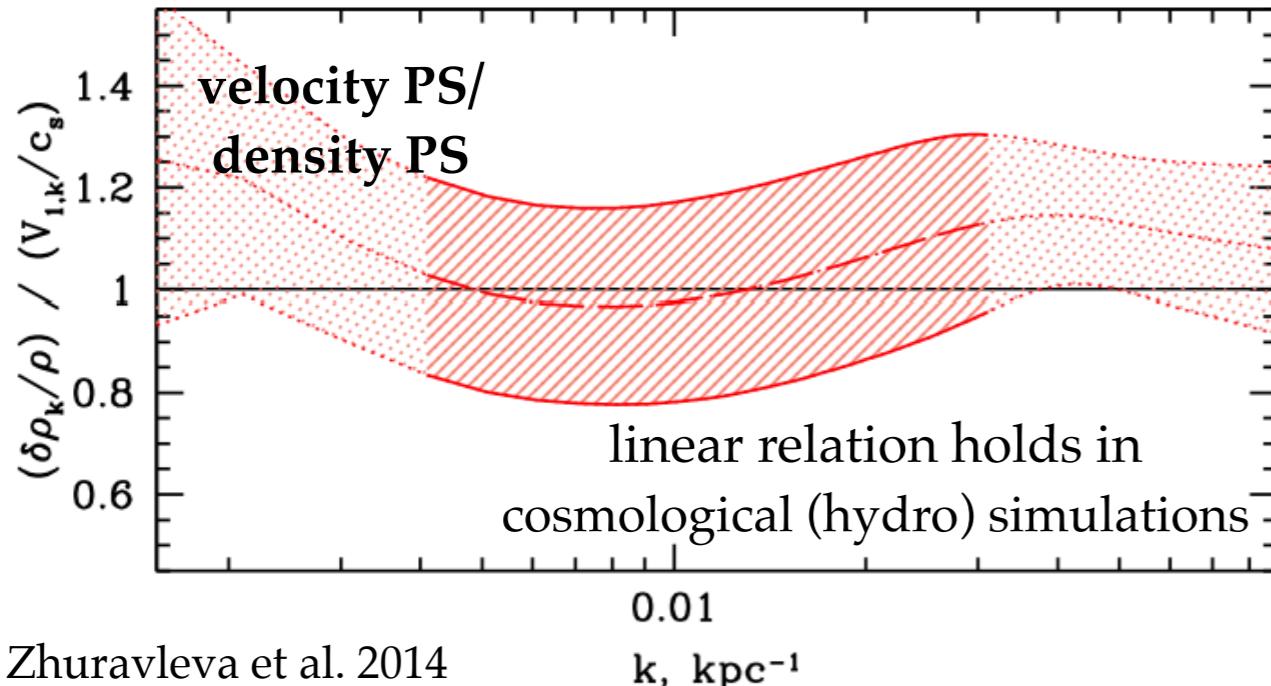
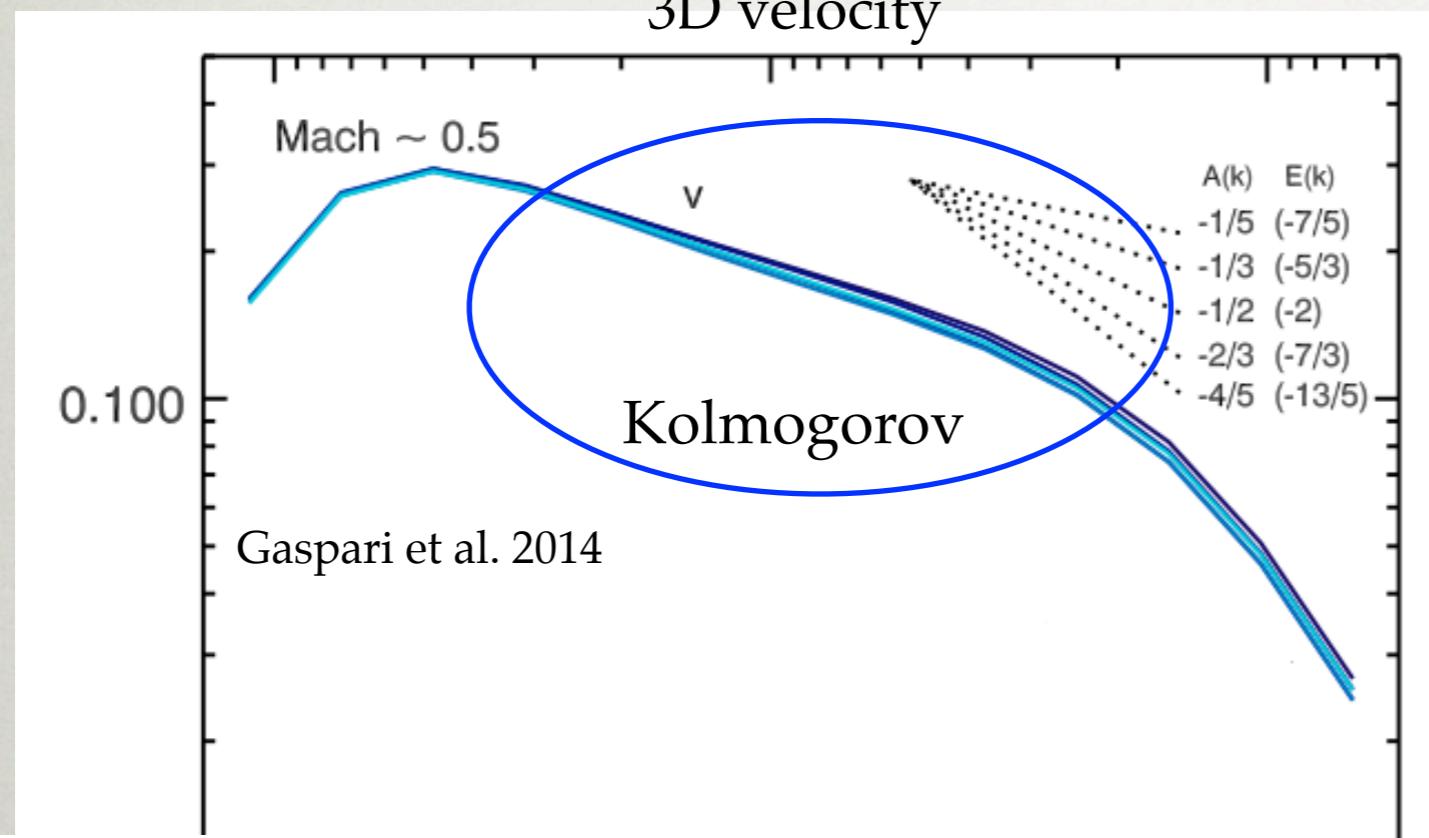


# DENSITY CASCADE DAMPED BY CONDUCTION

Gaspari & Churazov 2013



# VELOCITY CASCADE UNAFFECTED BY CONDUCTION



Decoupling:  
ratio widens up to 5!

# DENSITY FLUCTUATIONS (REAL SPACE)

$\delta\rho / \rho$  mid-plane cuts

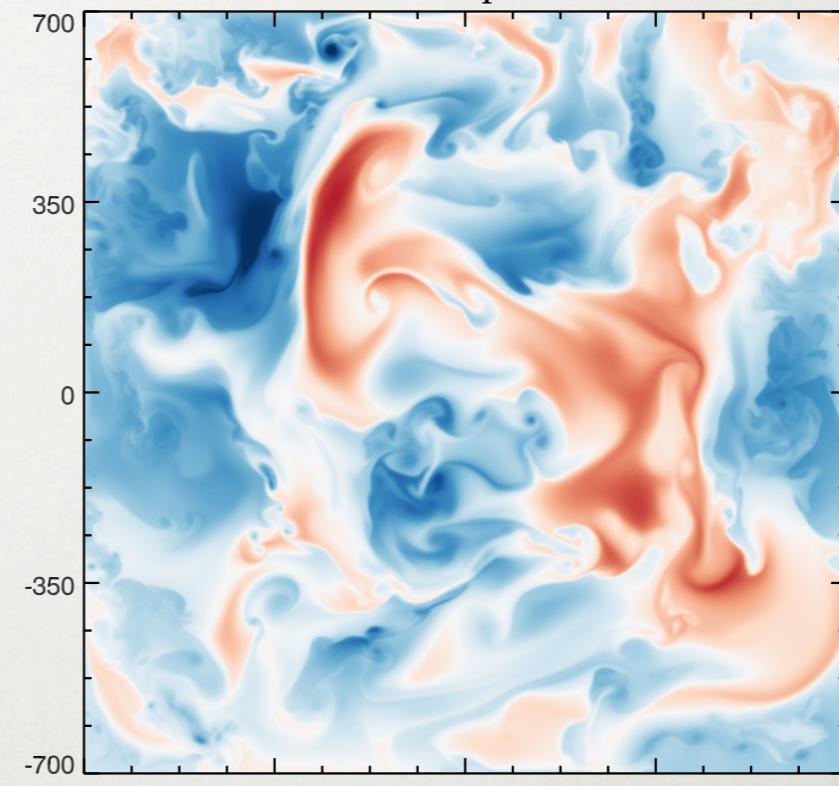
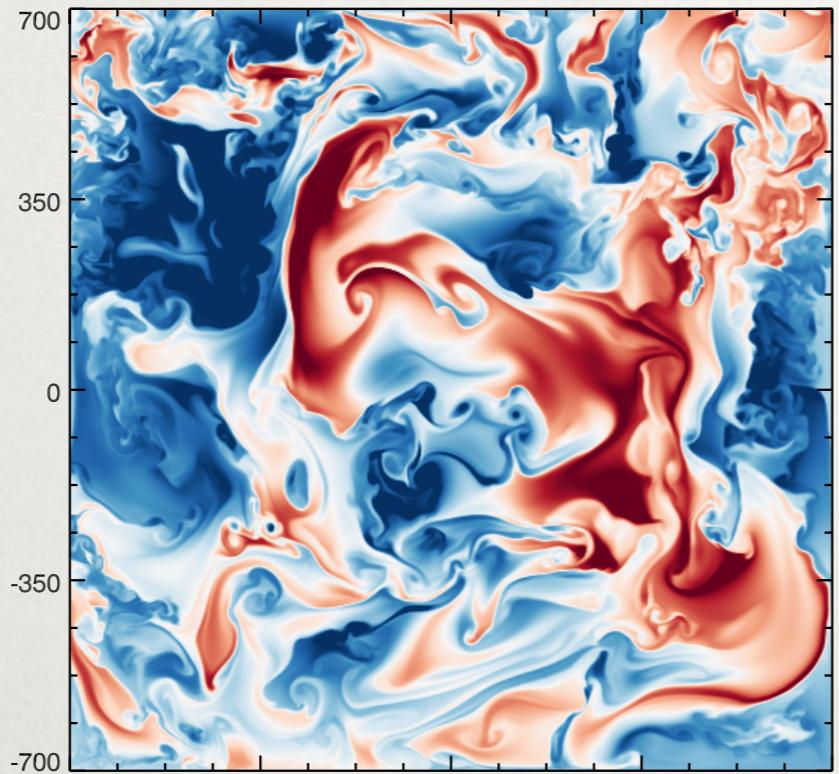
hydro

isobaric  
fluctuations

$M \sim 0.25$

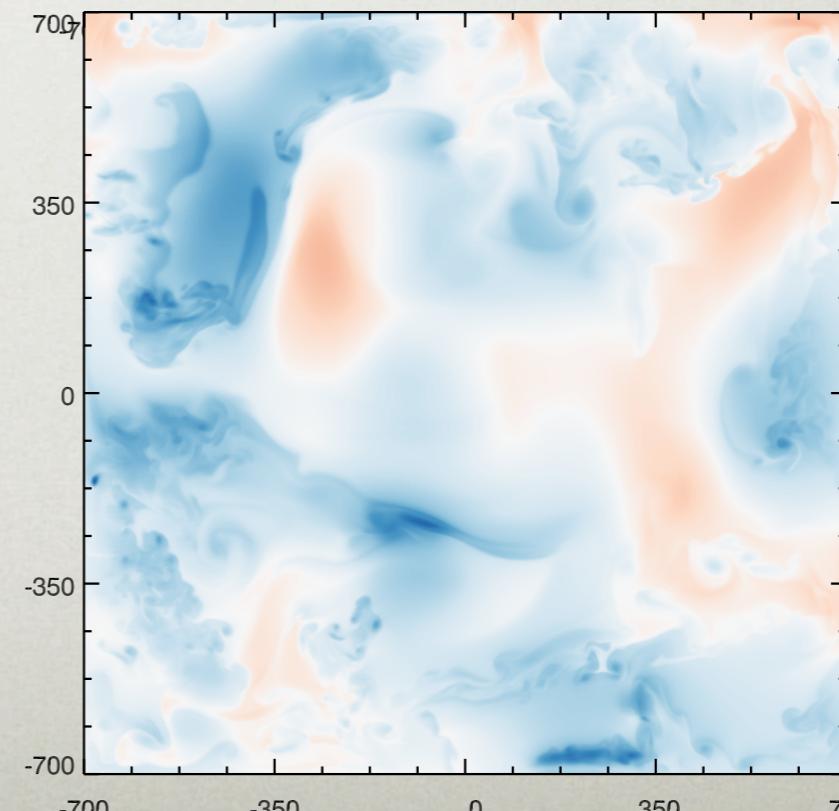
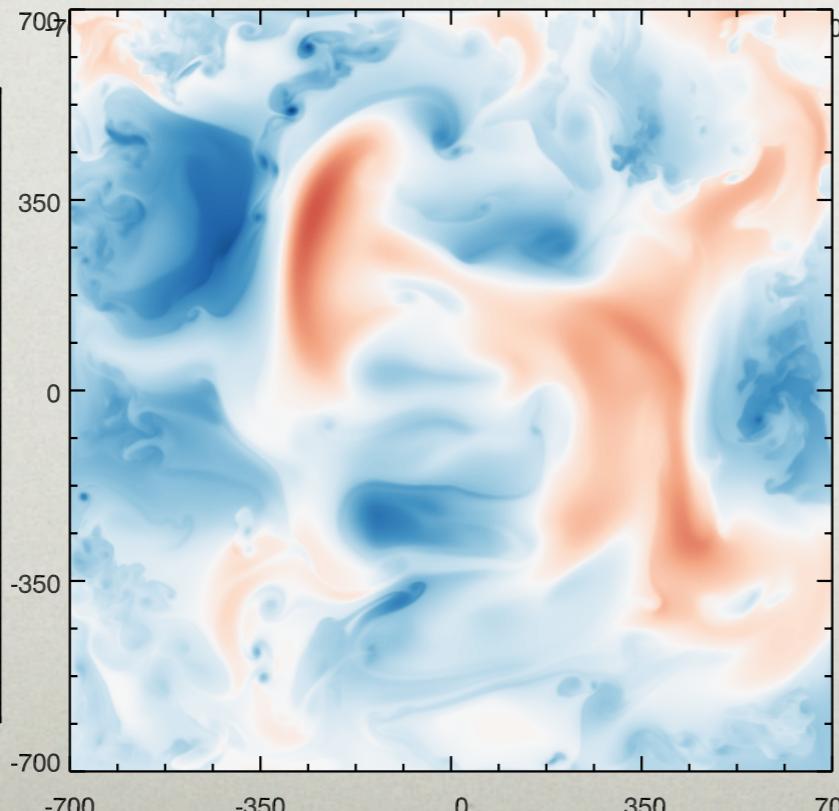
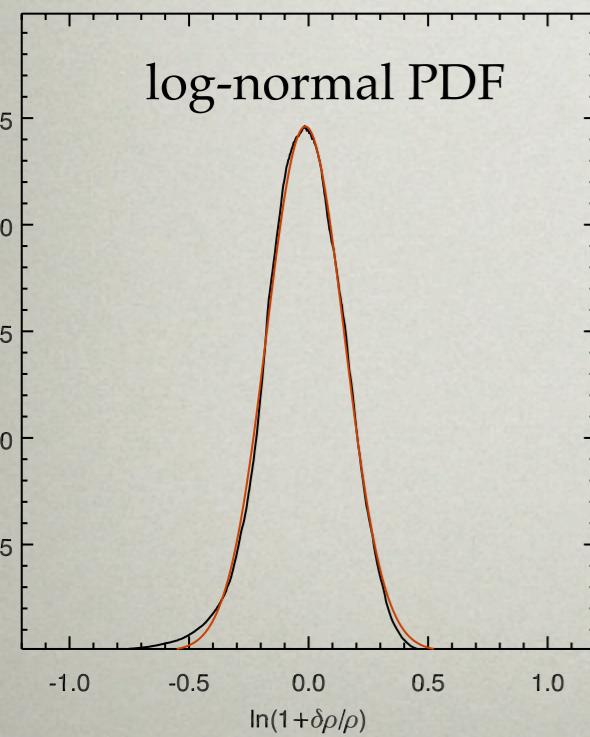
Gaspari & Churazov 2013

$f = 0.001$



$f = 0.01$

log-normal PDF



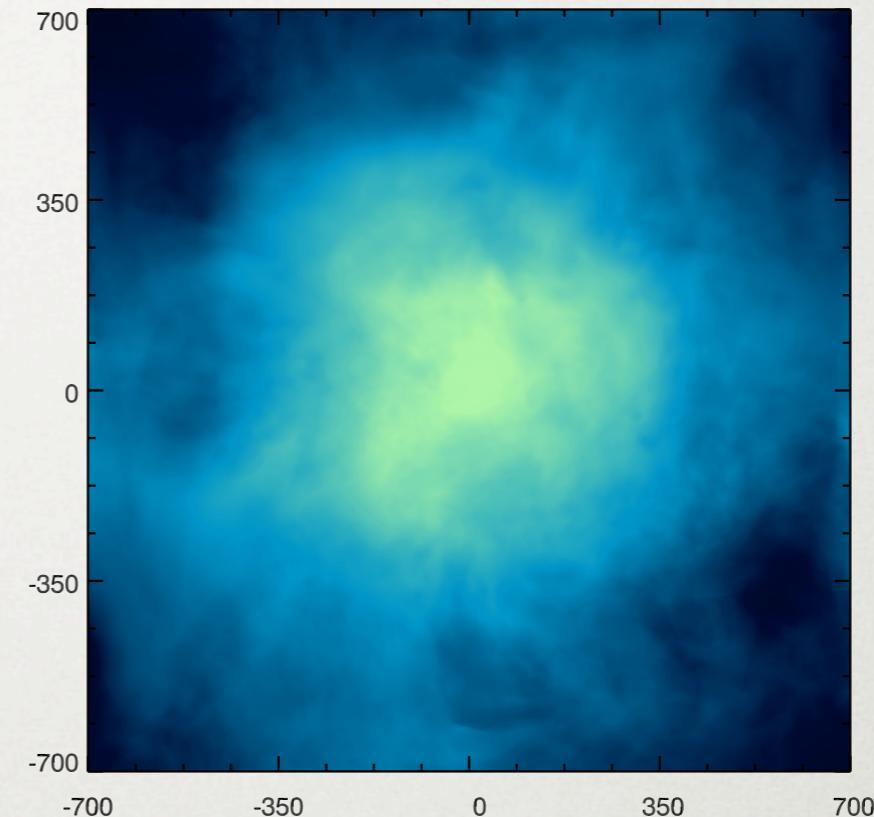
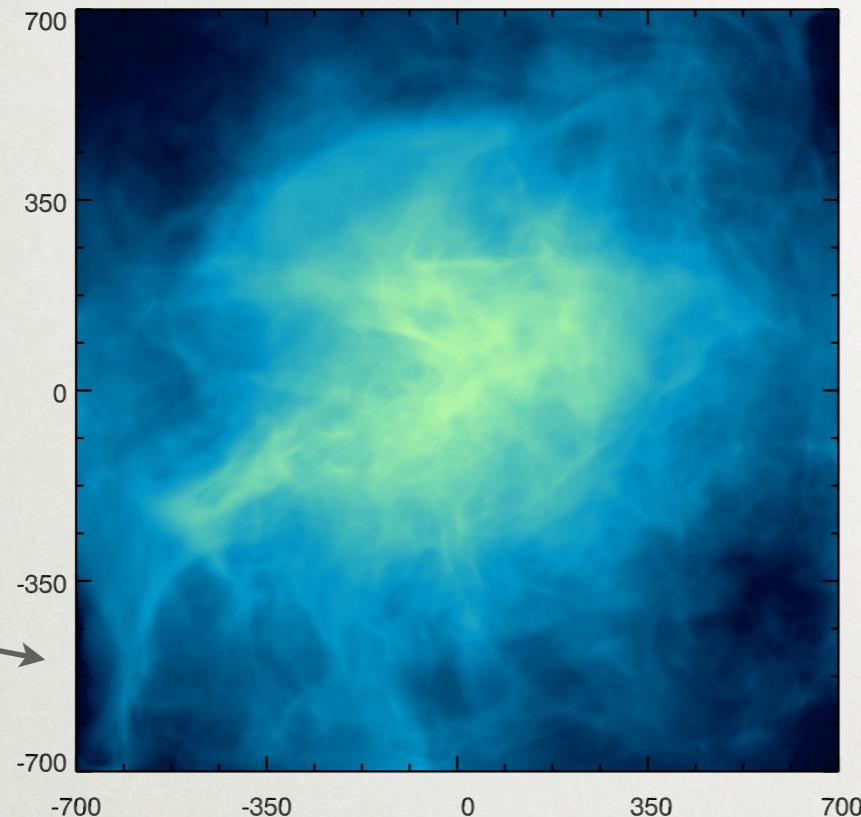
$f = 0.1$

isothermal  
fluctuations

# **SB<sub>x</sub> WEIGHTING**

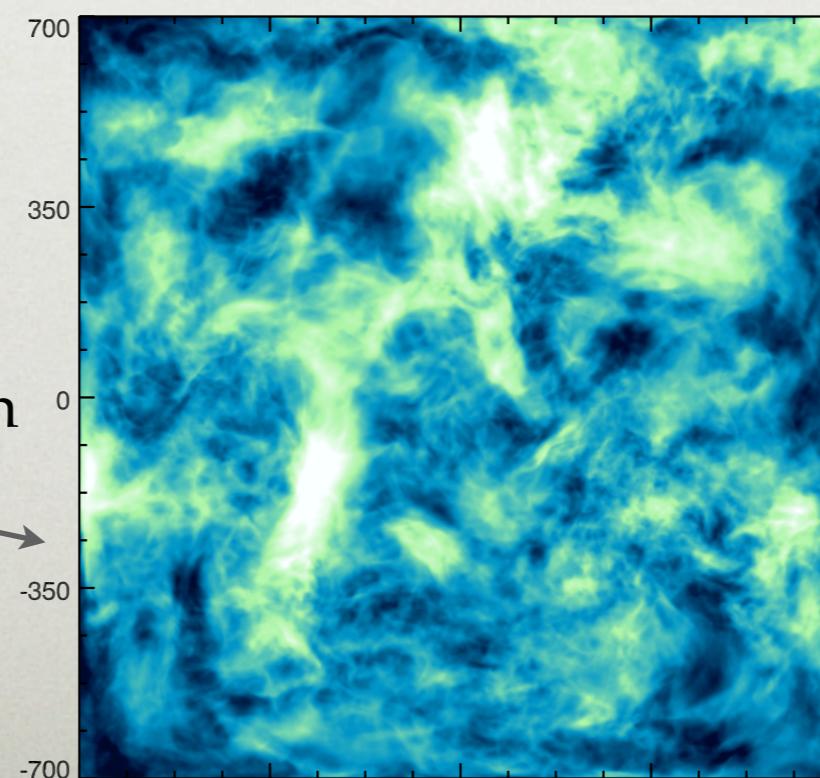
Gaspari & Churazov 2013

hydro  
 $M \sim 0.5$   
SB<sub>x</sub> image  
perturbations +  
global profile



$f = 0.1$   
 $M \sim 0.5$   
smoothening:  
KH + RT rolls  
washed out

X-ray emission-weighted  
(projected) velocity dispersion



non-black regions: *Astro-H* will be able to  
detect turbulent velocities  $> 200 \text{ km s}^{-1}$   
(using the Fe XXV line)

Gaspari et al. 2014

# REAL CASE: COMA CLUSTER

Gaspari & Churazov 2013; Churazov et al. 2014 (in prep.)

mild turbulence:

$$M \simeq 0.45$$

$$E_{\text{turb}} \simeq 0.11 E_{\text{th}}$$

(as in cosmological sims  
& line-broadening constraints)

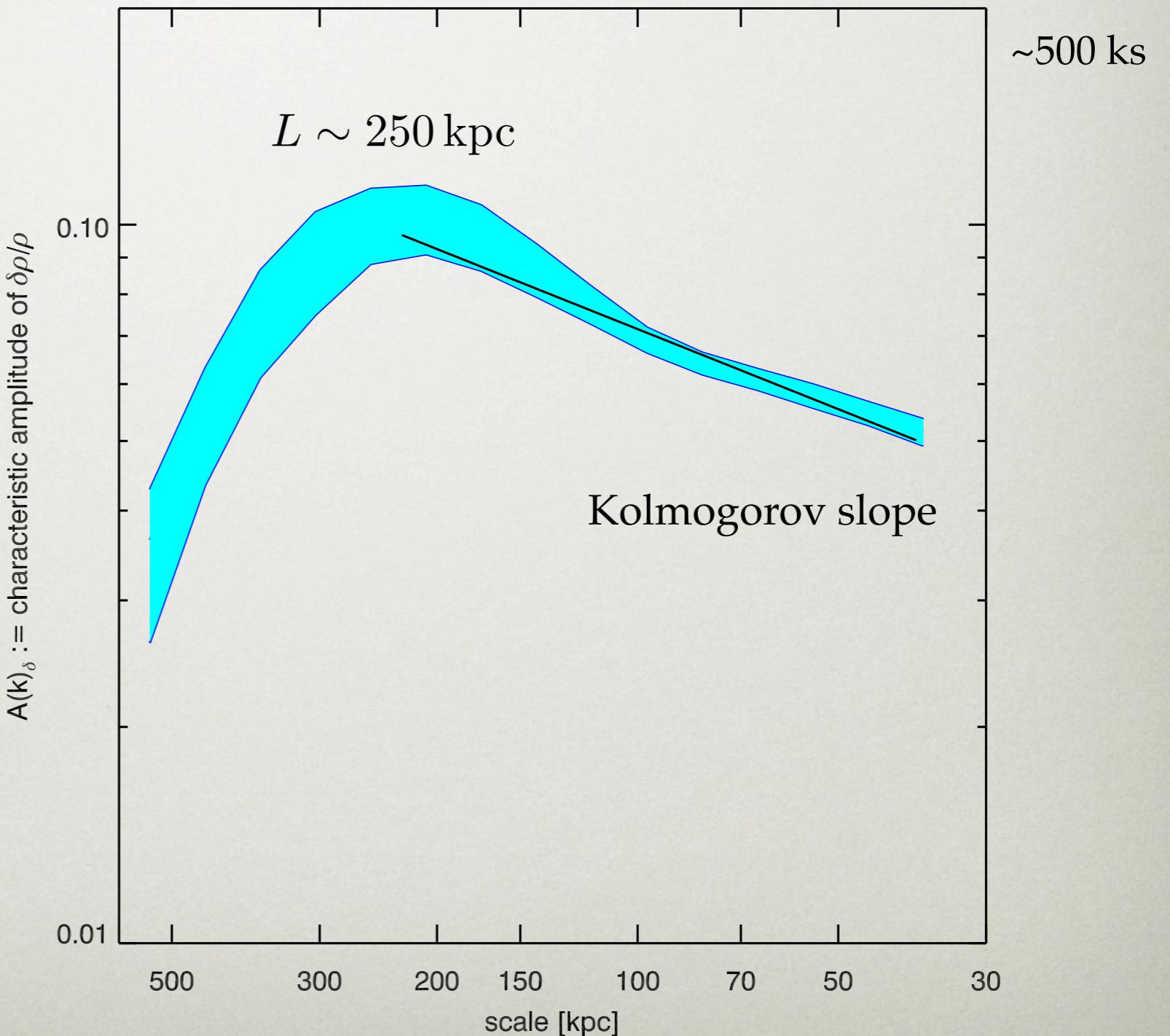
strongly suppressed conduction:

$$f \sim 10^{-3}$$

plasma microinstabilities and line divergence  
below electron mean free path are important

(consistent with cold fronts, filaments, bubbles)

(cooling flows can not be balanced by conduction)



# SUMMARY

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- **Power spectrum of ICM perturbations is a powerful tool to probe baryon physics.**  
Highly unexplored: many deep *XMM/Chandra* observations already available.  
*Astro-H* and *Athena+* major advancements:  $\sigma_v \sim 100 \text{ km/s} \longleftrightarrow \delta\rho/\rho \sim \text{a few \%}$ .  
3D high-res. simulations/experiments: we are working on MHD, viscosity, cooling, other physics.
- **PS<sub>ρ</sub> normalization:** linear relation (easy conversion)  $\rightarrow \delta\rho/\rho \approx \text{Mach}_{1\text{D}}$   
Weak turbulence ( $M < 0.5$ )  $\rightarrow$  gravity-waves (tangential bias; isobaric):  $\delta K/K \sim \text{Mach}_{1\text{D}}$   
Strong turbulence ( $M > 0.5$ )  $\rightarrow$  pressure-waves (isotropic; adiabatic):  $\delta P/P \sim \text{Mach}_{1\text{D}}$
- **PS<sub>ρ</sub> slope** overall traces the velocity cascade (deviations: compressibility, radial gradients),  
but decouples if diffusion processes are not suppressed:  
**conduction** damps  $\rho/T$  perturbations (smooth SB<sub>x</sub> images), not velocities.  
Steepening Kolmogorov to Burgers-like slope (as  $P_t < 100$ ).
- (Real) Coma  $\rightarrow$  mild turbulence:  $\text{Mach} \approx 0.4$  & suppressed conduction:  $f \approx 10^{-3}$ .