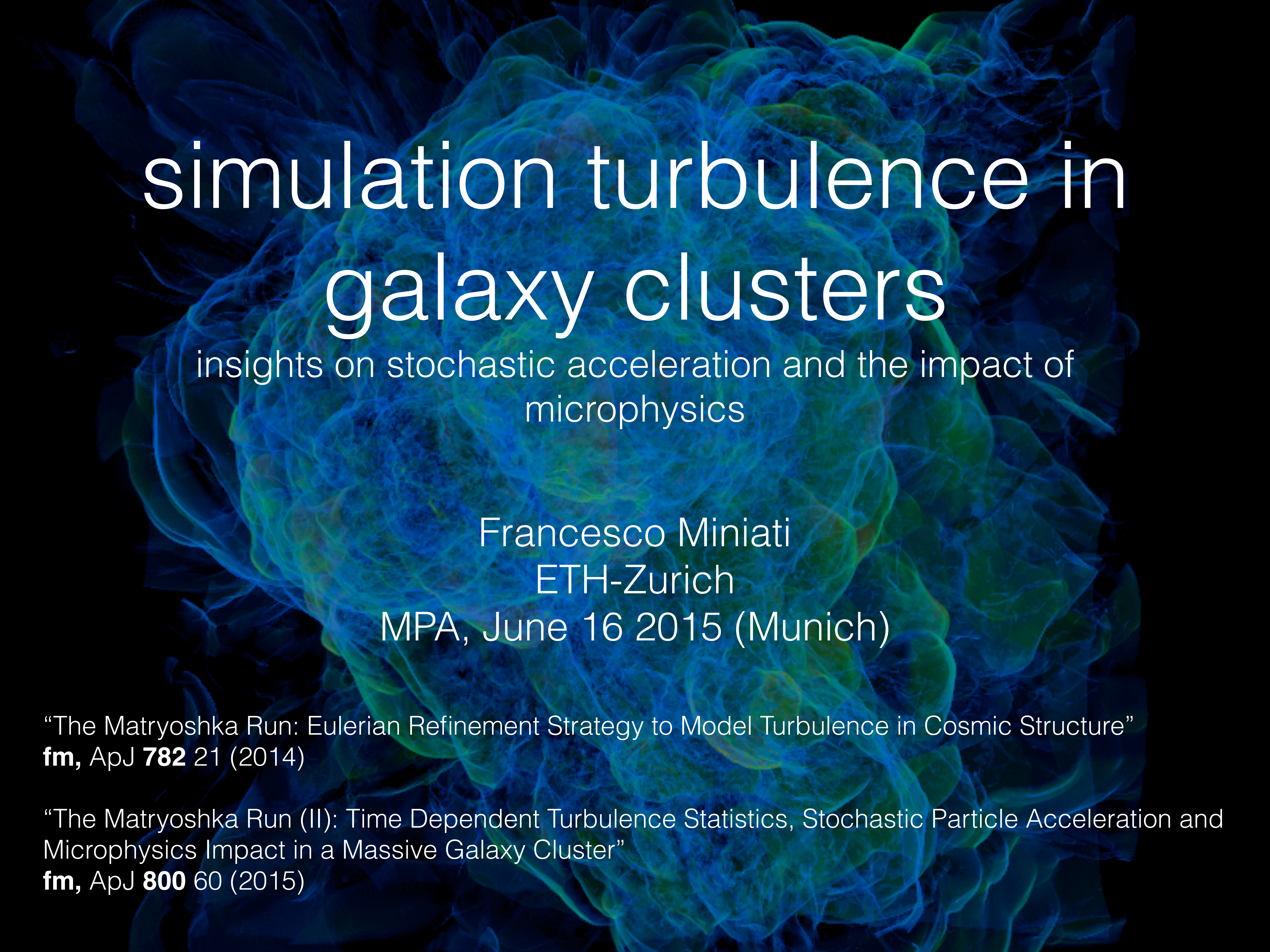


# simulation turbulence in galaxy clusters

## insights on stochastic acceleration and the impact of microphysics


Francesco Miniati
ETH-Zurich


MPA, June 16 2015 (Munich)

“The Matryoshka Run: Eulerian Refinement Strategy to Model Turbulence in Cosmic Structure”
**fm,** ApJ **782** 21 (2014)

“The Matryoshka Run (II): Time Dependent Turbulence Statistics, Stochastic Particle Acceleration and Microphysics Impact in a Massive Galaxy Cluster”
**fm,** ApJ **800** 60 (2015)

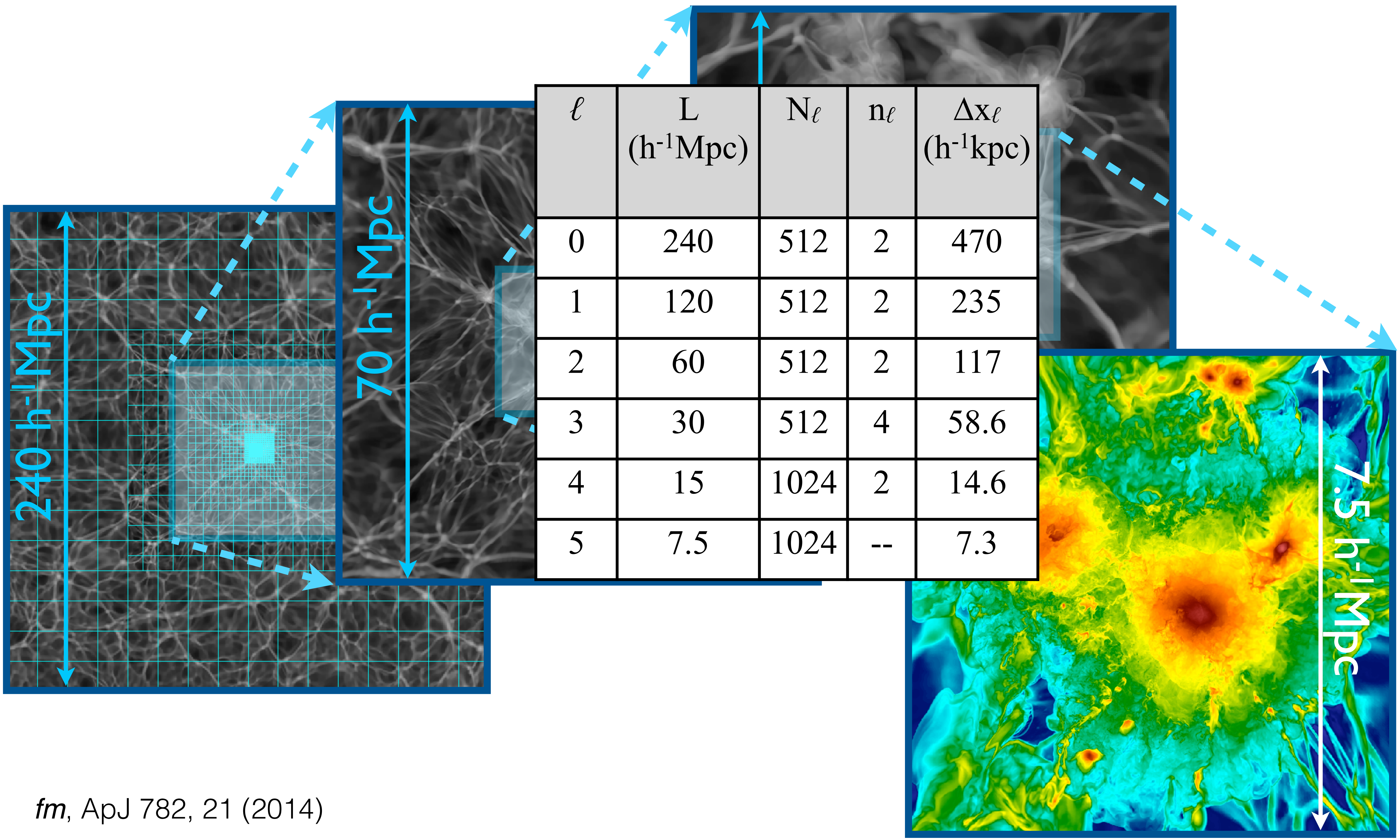
# motivations for turbulence acceleration

- diffuse radio sources appear only in massive systems
- they appear to be triggered by mergers / bi-modality (but see Enßlin+ 2011)
- spectral curvature
- source statistics suggests a lifetime of ca 1 Gyr
- we don't see gamma-rays that would suggest a secondary origin
- other more sophisticated tests but like radial profile requiring some assumption about B or the like

# outline

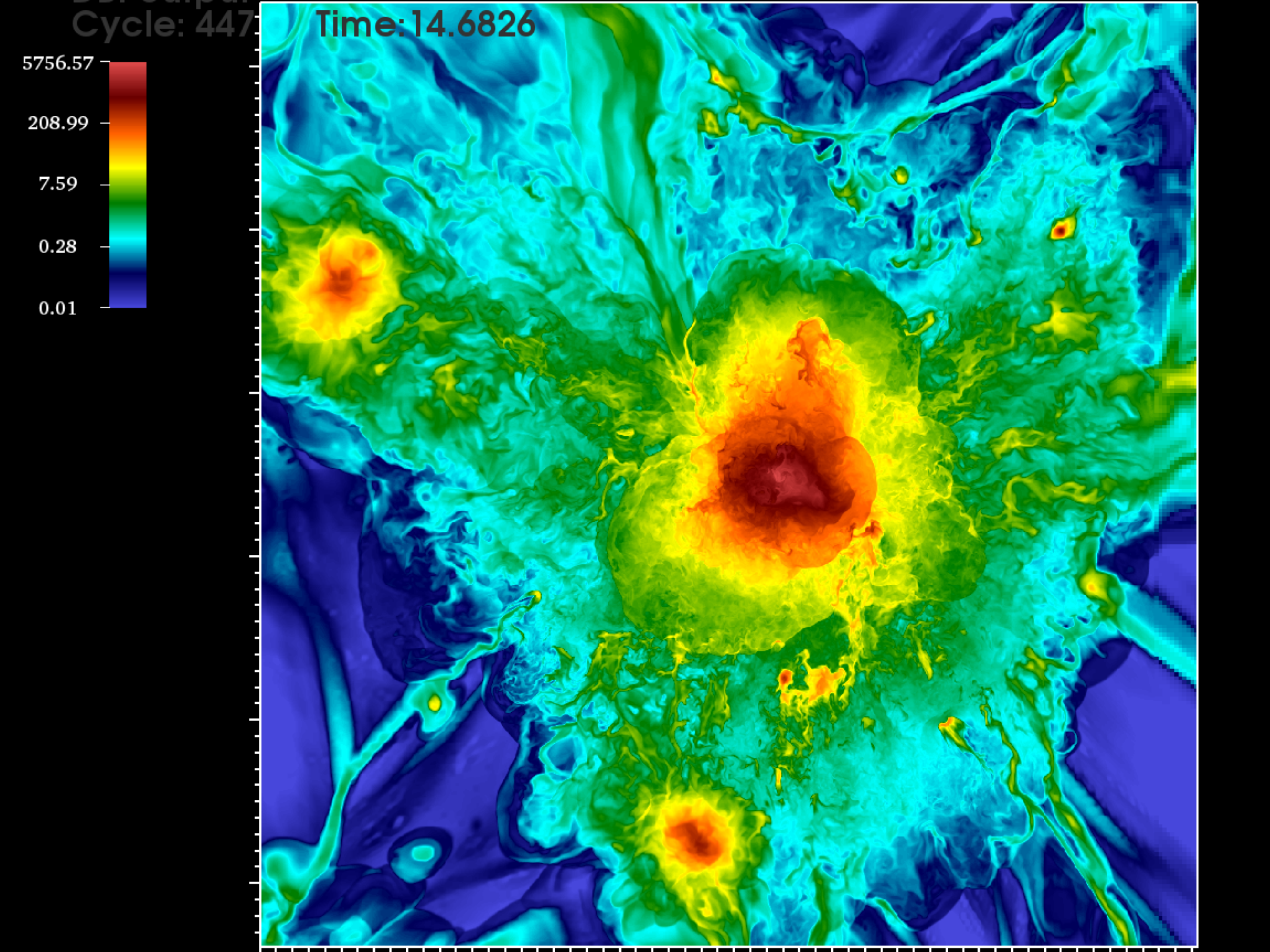
- (computational modeling)
- some properties of turbulence in galaxy clusters
- particle acceleration by turbulence, impact of microphysics of weak shocks

# Eulerian Refinement Strategy: Zoom-in + Matryoshka of grids

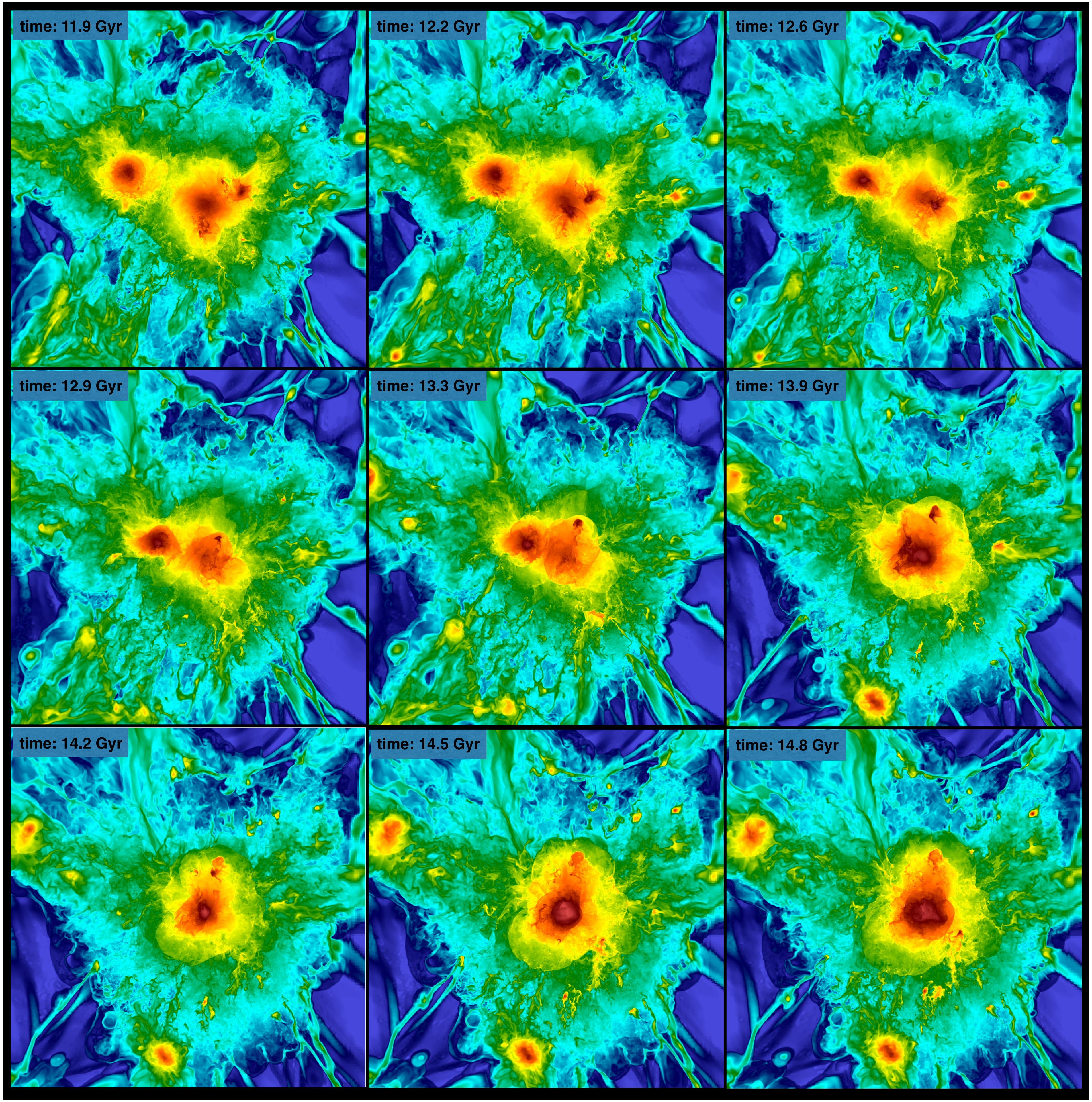



| $\ell$ | L ($h^{-1}$Mpc) | $N_\ell$ | $n_\ell$ | $\Delta x_\ell$ ($h^{-1}$kpc) |
|---|---|---|---|---|
| 0 | 240 | 512 | 2 | 470 |
| 1 | 120 | 512 | 2 | 235 |
| 2 | 60 | 512 | 2 | 117 |
| 3 | 30 | 512 | 4 | 58.6 |
| 4 | 15 | 1024 | 2 | 14.6 |
| 5 | 7.5 | 1024 | -- | 7.3 |

*fm*, ApJ 782, 21 (2014)



Cycle: 447
Time:14.6826
5756.57
208.99
7.59
0.28
0.01


time: 11.9 Gyr
time: 12.2 Gyr
time: 12.6 Gyr
time: 12.9 Gyr
time: 13.3 Gyr
time: 13.9 Gyr
time: 14.2 Gyr
time: 14.5 Gyr
time: 14.8 Gyr

# Statistics

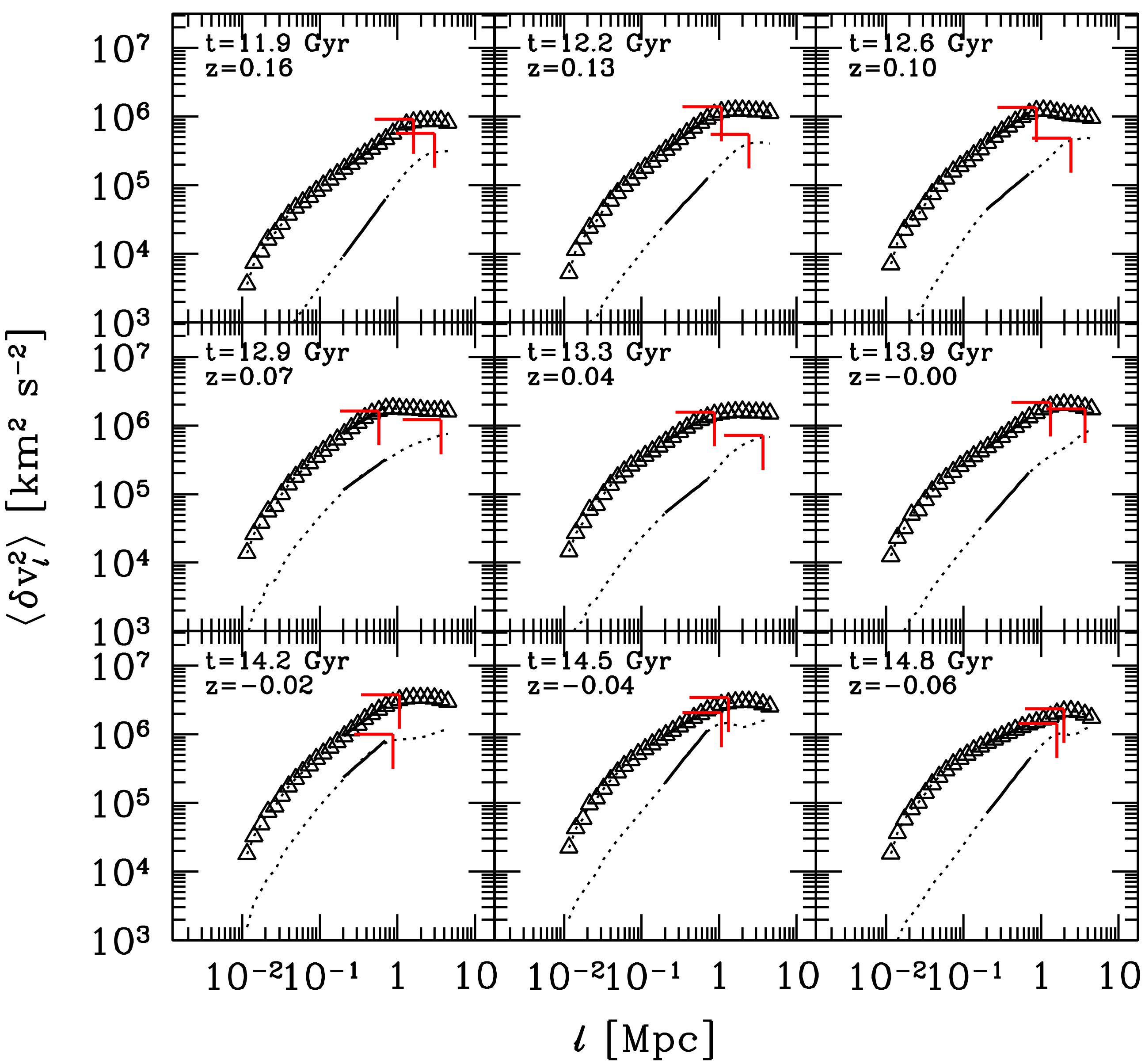
Hodge-Helmholtz decomposition

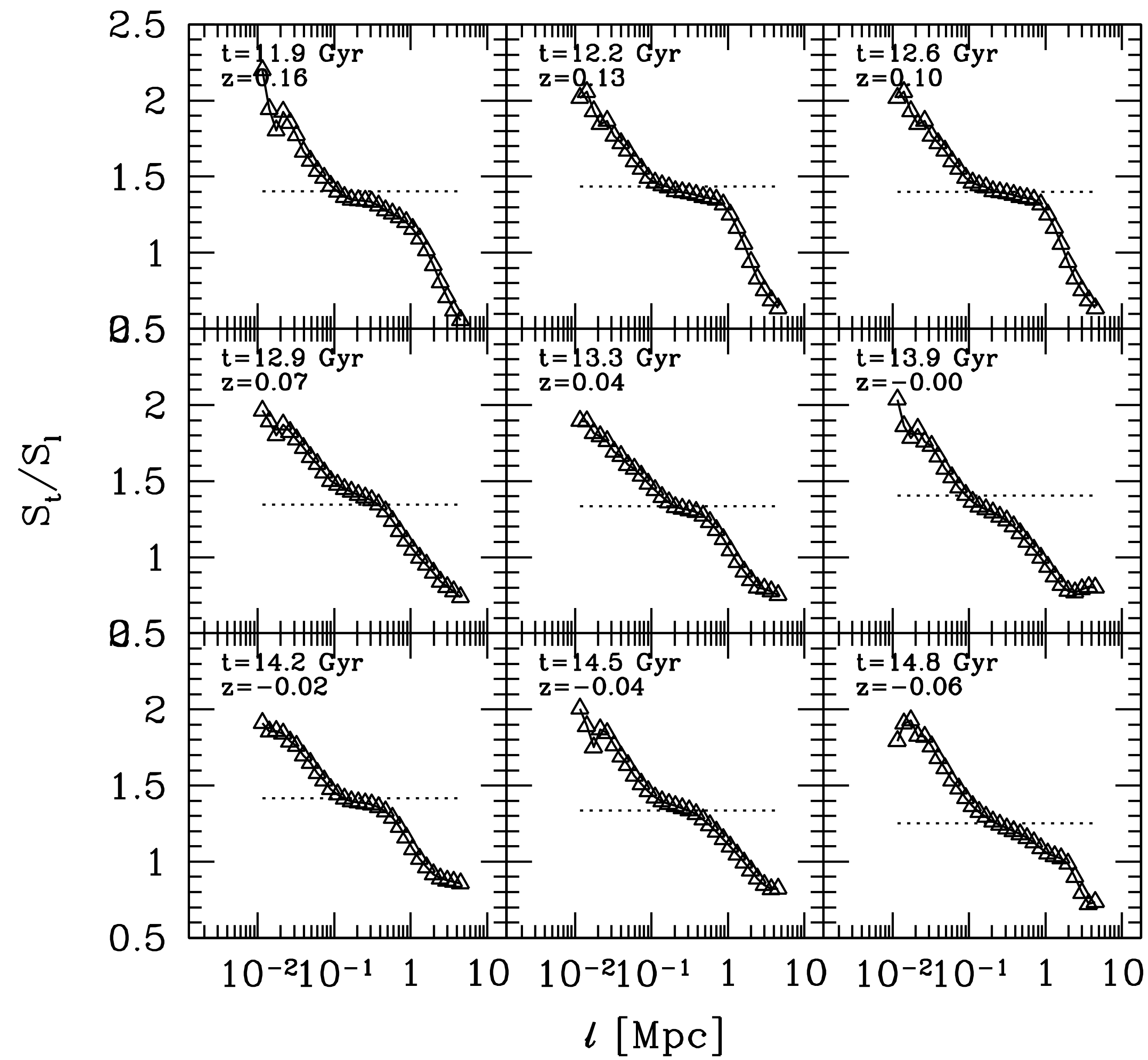
$$\vec{v}_c = -\nabla\phi, \qquad \vec{v}_s = \nabla\times\vec{A}$$

$$\phi = \frac{1}{4\pi}\int\frac{\nabla\cdot\vec{v}}{r}d^3r, \quad \vec{A} = \frac{1}{4\pi}\int\frac{\nabla\times\vec{v}}{r}d^3r$$

$$S^{(2)}_{t,s} = \frac{2+\zeta_2}{2}S^{(2)}_{l,s}$$

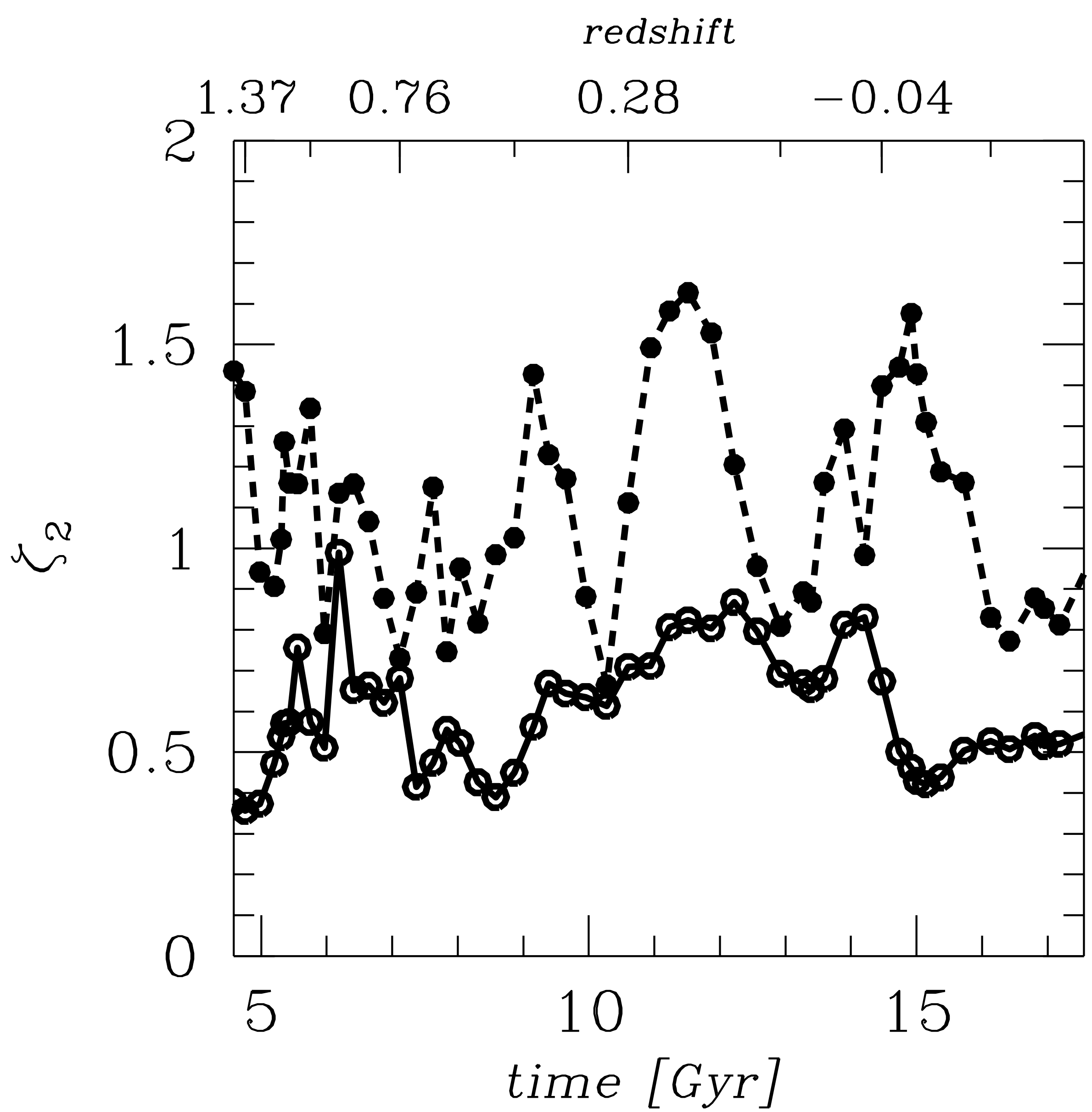
(von Karman & Howarth, 1938)

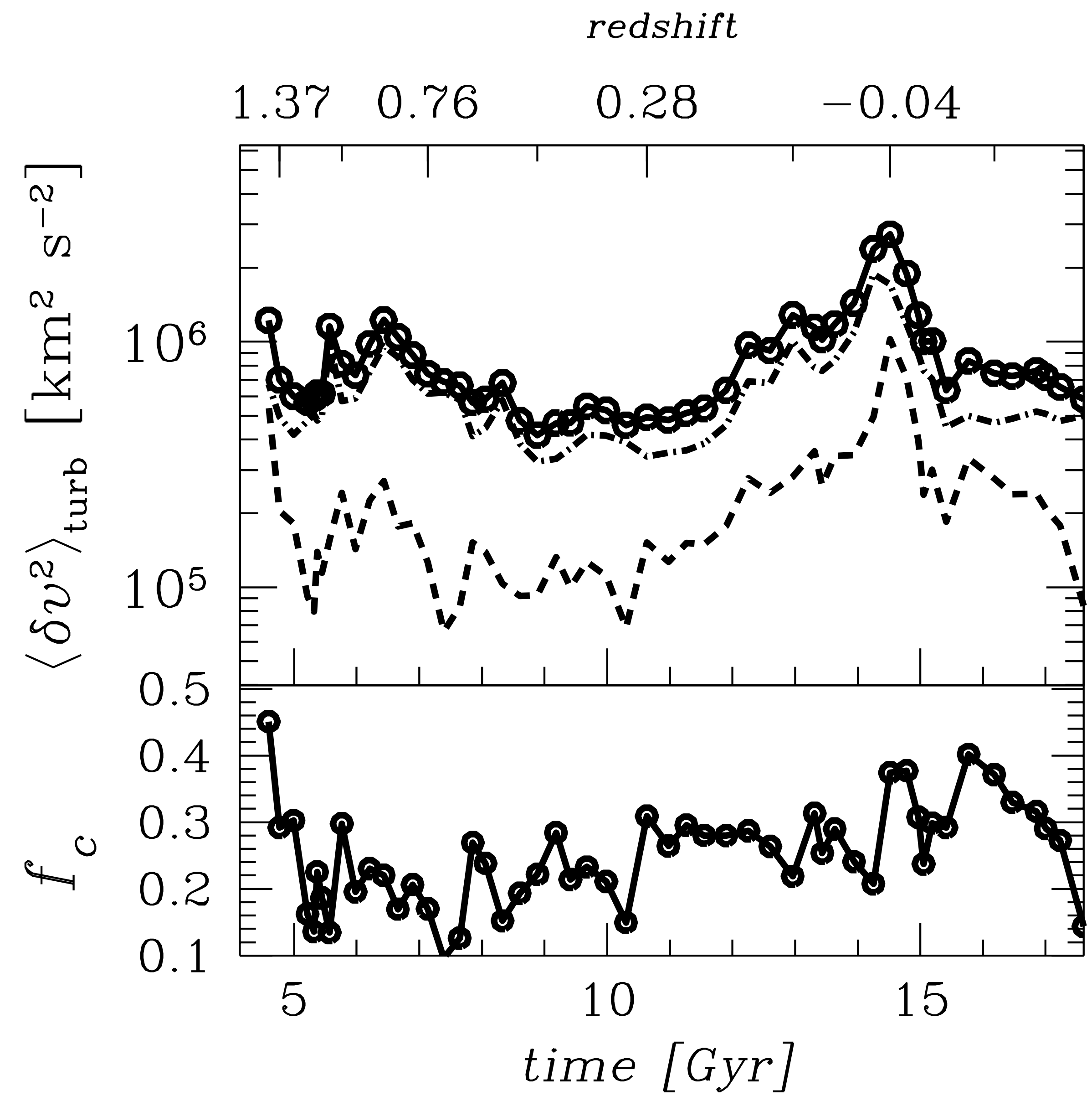



*fm*, ApJ 800, 60 (2015)

# Evolution of Turbulence




*fm*, ApJ 800, 60 (2015)

# Particle Acceleration

transport eq. $$\frac{df}{dt} - \nabla D_{xx} \nabla f - \frac{1}{p^2} \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial f}{\partial p} = 0$$

Fokker-Planck coeff. $$D_{pp} \equiv \left\langle \frac{\Delta p^2}{2\Delta t} \right\rangle, \qquad D_{xx} \equiv \left\langle \frac{\Delta x^2}{2\Delta t} \right\rangle$$

advection rate in p-space $$\Gamma_p \equiv \frac{\dot{p}}{p} = \frac{1}{p^3} \frac{\partial}{\partial p} \left( p^2 D_{pp} \right) = 4 \frac{D_{pp}}{p^2}$$

# Particle Acceleration

$$\frac{\partial f}{\partial t} - \nabla D_{xx} \nabla f - \frac{1}{p^2}\frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial f}{\partial p} = 0$$

- Transit-Time-Damping (Fisk 1976, BL07):

*2nd order Fermi process, particles resonate with fast MHD waves and get reflected by the mirror force*

$$\frac{dp_{\parallel}}{dt} = -\frac{p_{\perp}}{2B^2} \mathrm{v}_{\perp} \left(\vec{B}\cdot\nabla\right)\vec{B}$$

micro macro

$$D_{pp} = p^2 \frac{\pi I_{\vartheta}}{16c} \langle k \rangle_E \left\langle \left(\delta u_c\right)^2 \right\rangle$$

- Non Resonant Mech. (Ptuskin 1988, BL07):

*stochastic acceleration due to velocity divergence according to the adiabatic process*

$$\frac{dp}{dt} = -\frac{p}{3} \nabla \cdot \vec{\mathrm{v}}$$

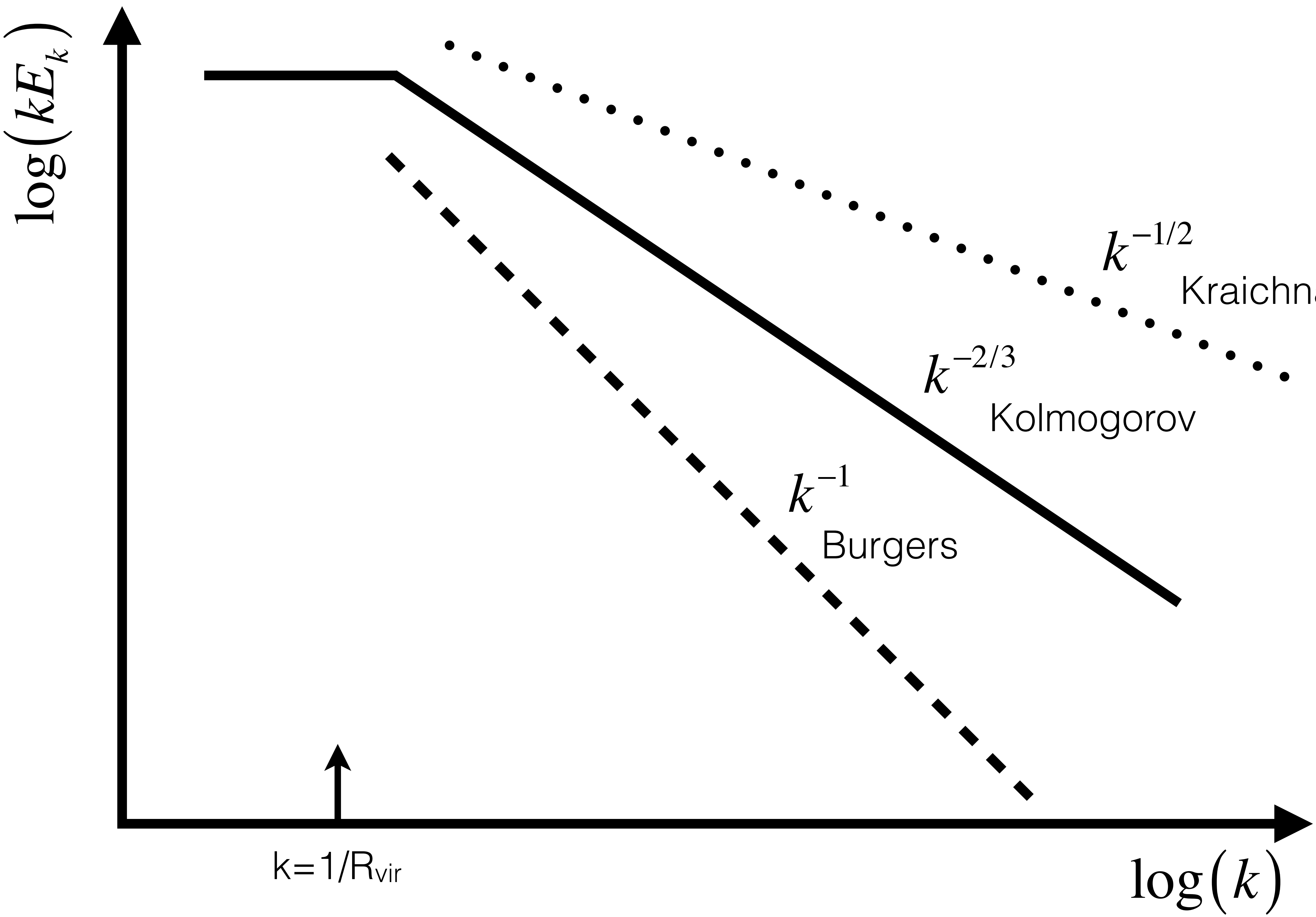
micro macro

$$D_{pp} = p^2 \frac{2}{9} \zeta_2 \frac{I_{\xi}}{D} \left(\frac{k_L D}{c_s}\right)^{\zeta_2} \left\langle \left(\delta u_c\right)^2 \right\rangle$$

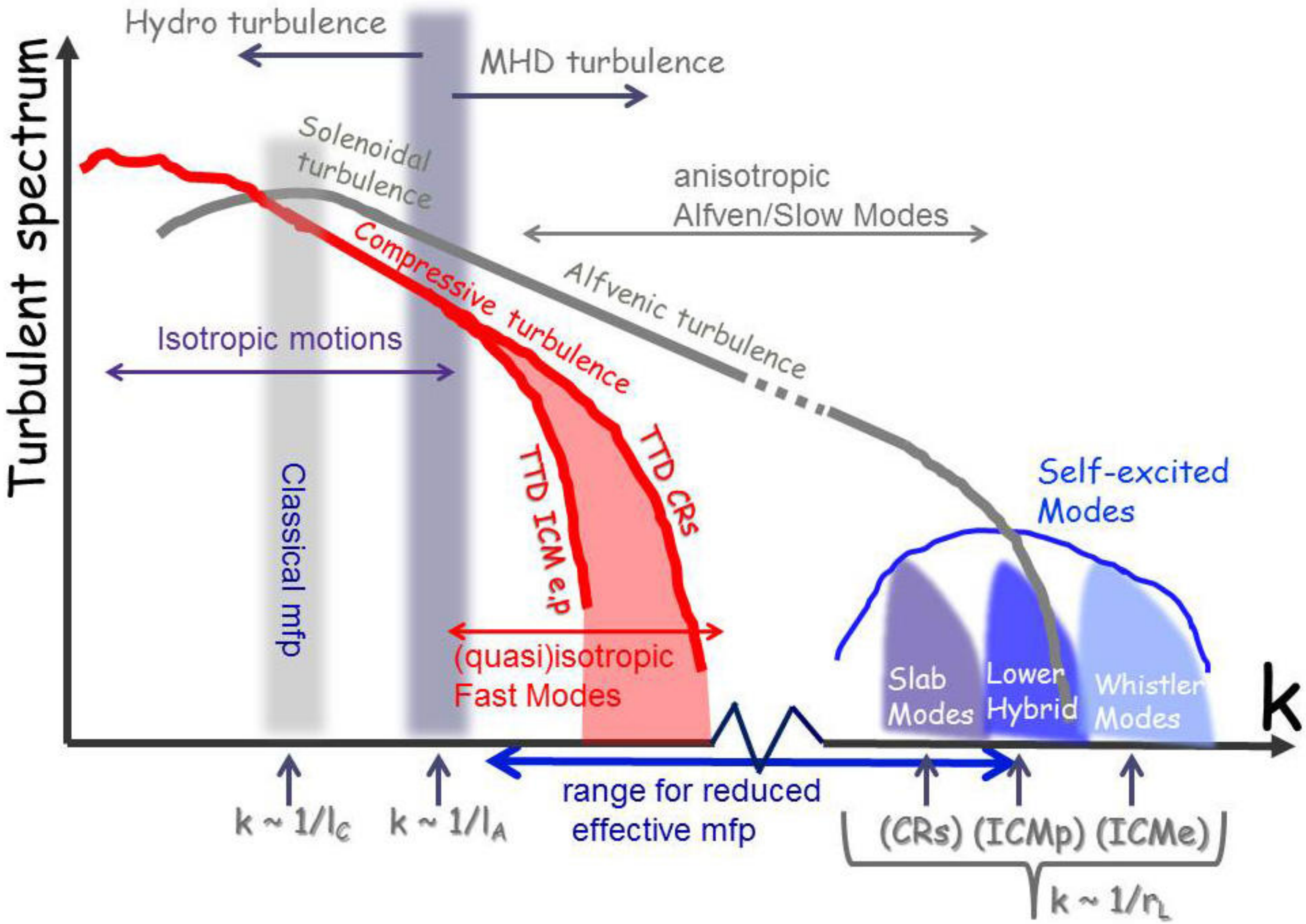
$$\langle k \rangle_E \equiv \frac{1}{\left\langle \left(\delta u_c\right)^2 \right\rangle} \int^{k_c} dk k W(k) \approx \frac{\zeta_2}{1-\zeta_2} k_L \left[ \left(\frac{k_c}{k_L}\right)^{1-\zeta_2} - 1 \right]$$

$$I_{\xi} \equiv \int_{k_L D/c_s}^{k_c D/c_s} d\xi \frac{\xi^{1-\zeta_2}}{1+\xi^2}$$

# Spectra of Turbulent Cascade



# Spectra of Turbulent Cascade




Brunetti & Jones 2014

# Key Cascade Physics

- the cascade of the compressional modes, Alfven vs Burgers: how much dissipation occurs during the cascade ? If enough to steepen the structure functions then the mechanisms become very inefficient

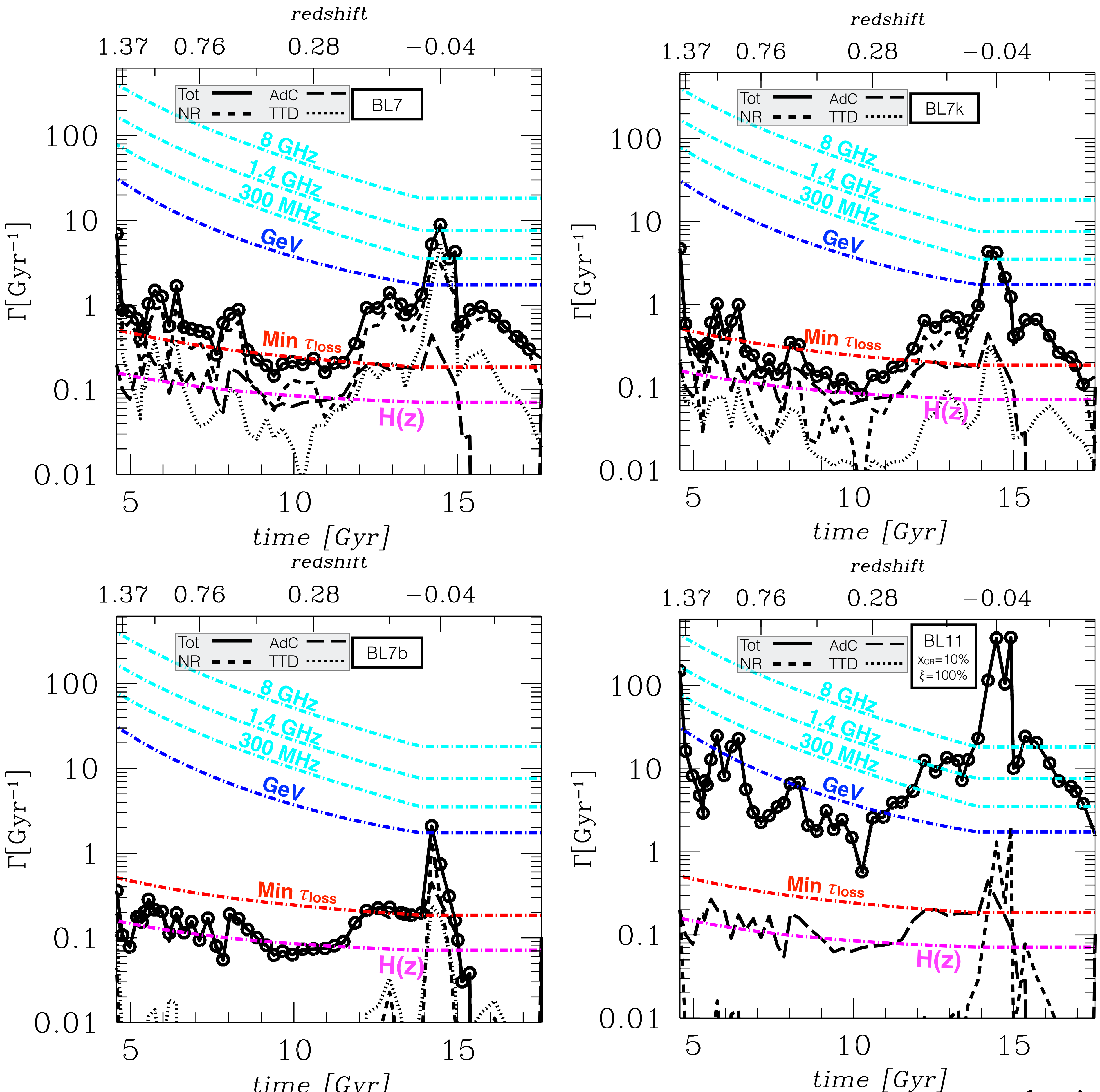
- the slope of the cascade of compressional modes affects
  i) the value of the energy-averaged wave-vector which tends to $k_L$ as $\zeta \longrightarrow 1$
  ii) the cascade cutoff which can become much larger

- the collisionality of the plasma; if thermal particles have their *mfp* reduced by micro instabilities (mirror, firehose…), they won't resonate with and damp the MHD waves anymore, only CRs do, so their acceleration efficiency increases dramatically

$$D_{pp} = p^2 \frac{C_D C_W}{x_{CR}} \xi k_L \frac{\left\langle (\delta u_c)^2 \right\rangle}{c_s^3}$$

kraicknan's cascade for cutoff and <k>E no micro instabilities

kraicknan's cascade for cutoff + burgers' (simulation's) slope for <k>E no micro instabilities




burger's (simulation's) cascade for cutoff and <k>E independent of micro instabilities

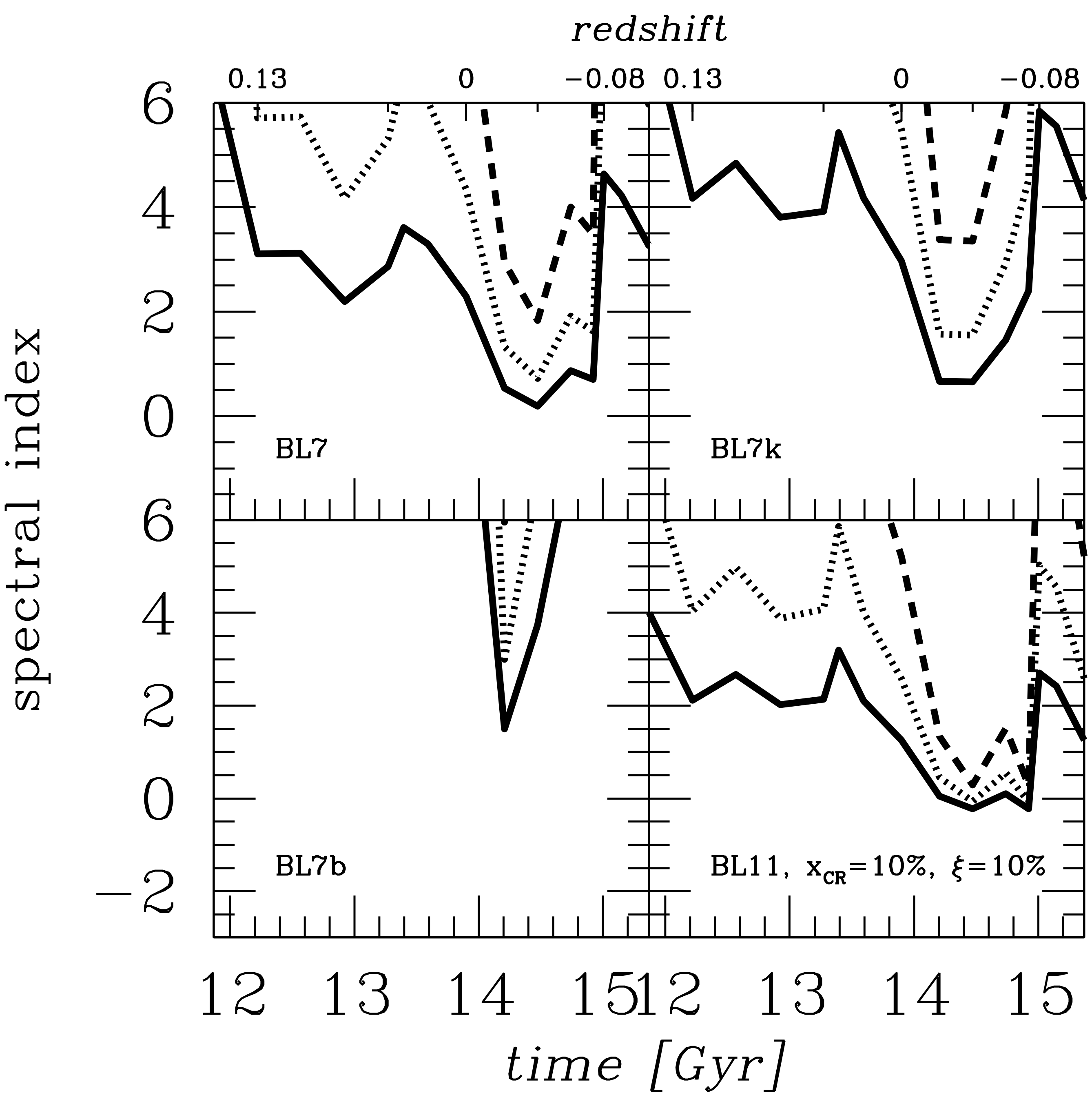
kraicknan's cascade for cutoff and <k>E + micro instabilities set *mfp*

*fm*, ApJ 800, 60 (2015)

# Time evolution of spectral indexes

kraicknan's cascade for cutfoff and $\langle k \rangle_E$ no micro instabilities

burger's (simulation's) cascade for cutfoff and $\langle k \rangle_E$ independent of micro instabilities




kraicknan's cascade for cutfoff + burgers' (simulation's) slope for $\langle k \rangle_E$ no micro instabilities

kraicknan's cascade for cutfoff and $\langle k \rangle_E$ + micro instabilities set *mfp*

# takeaway result

- the simulation model of the turbulence pins down an important ingredient entering the acceleration rate, which is the amount of compressional turbulent energy available for TTD or NR mechanisms

- the microphysics of the ICM plasma, however, also enters the acceleration rates, and because we have fixed the above unknown, we can now expose its impact

- the acceleration rates depend on at least the following microphysics (but possibly other as well) of:

- the cascade of the compressional modes, Alfven vs Burgers: how much dissipation occurs during the cascade ? If enough to steepen the structure functions then the mechanisms become very inefficient

- the collisionality of the plasma; if micro instabilities (mirror, firehose… ) reduce the thermal particles *mfp* then the acceleration efficiency is very high

- we also need to understand the properties of magnetic fields