Turbulence and Magnetic Field in the Large-scale Structure of the Universe

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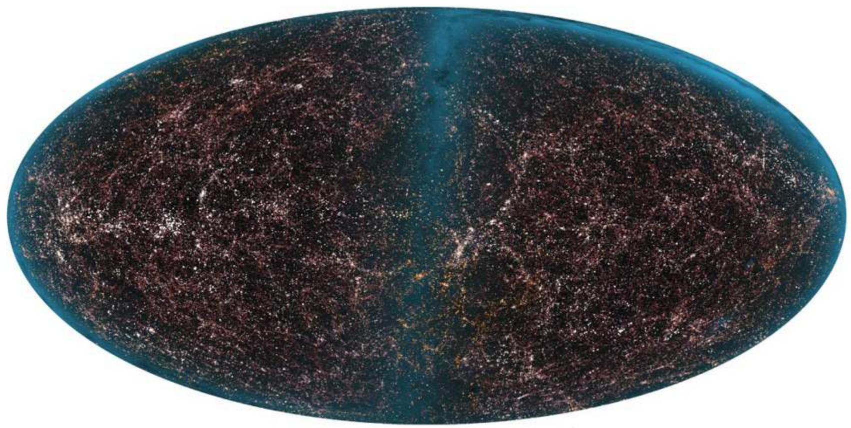
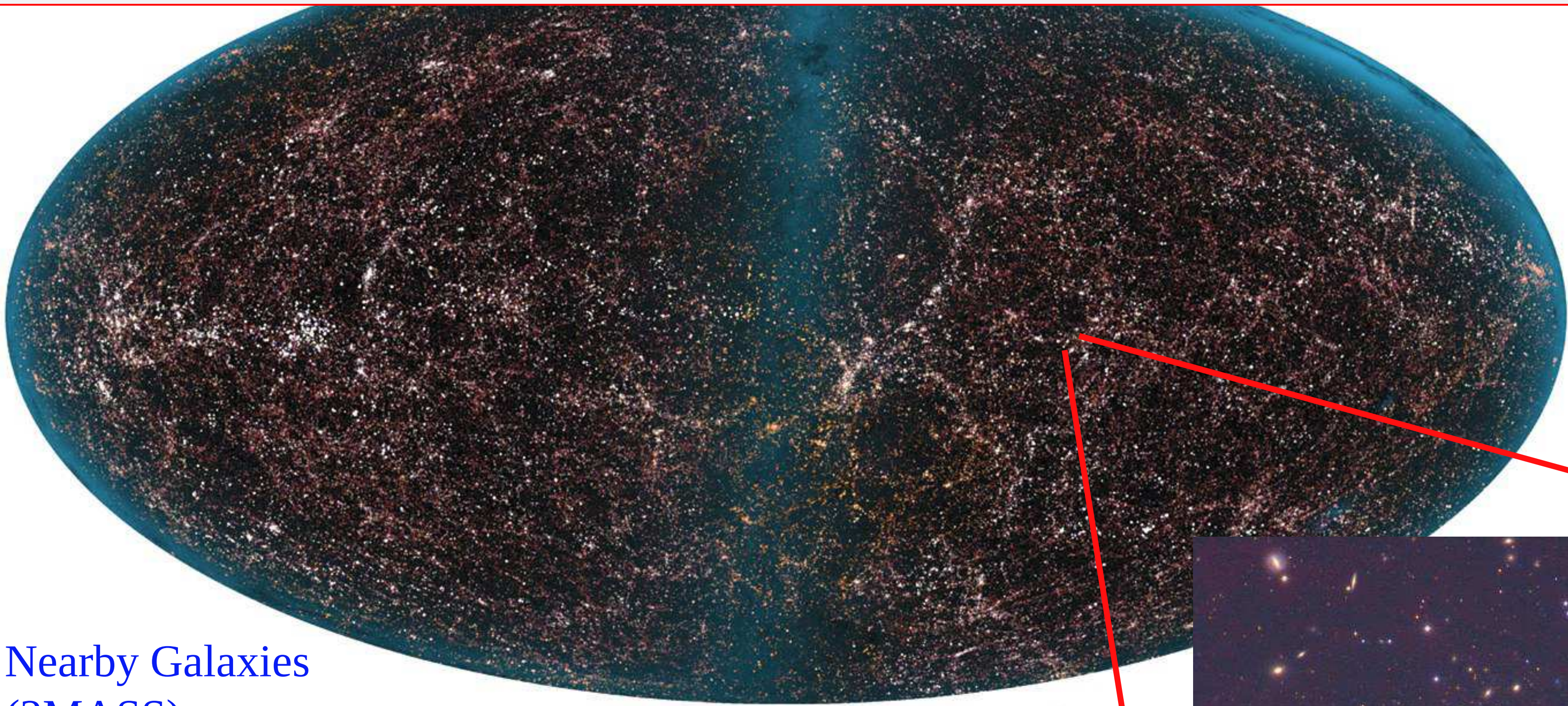
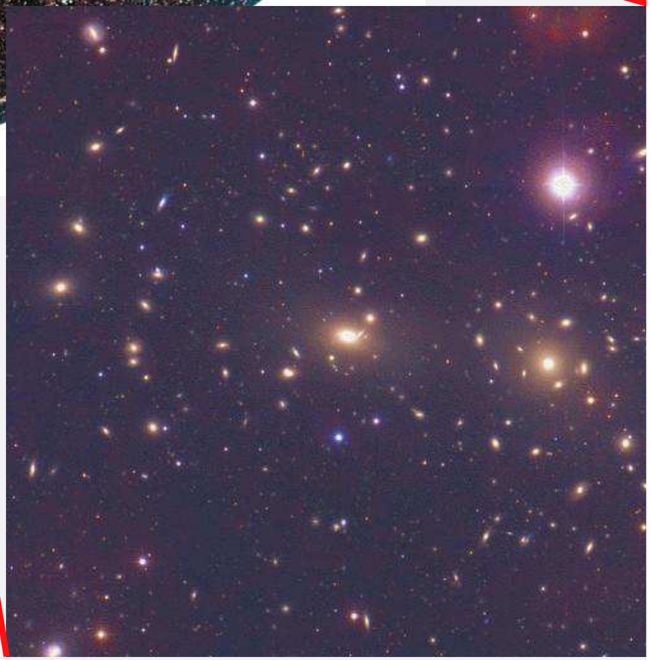
Ryu (+Cho) et al (2008; Science)
Cho, Vishniac, Beresnyak, Lazarian, Ryu (2009; ApJ)
Cho & Yoo (2012; ApJ)
Cho (2013; PRD)



Turbulence plays important roles in origin of cosmic B



Nearby Galaxies
(2MASS)

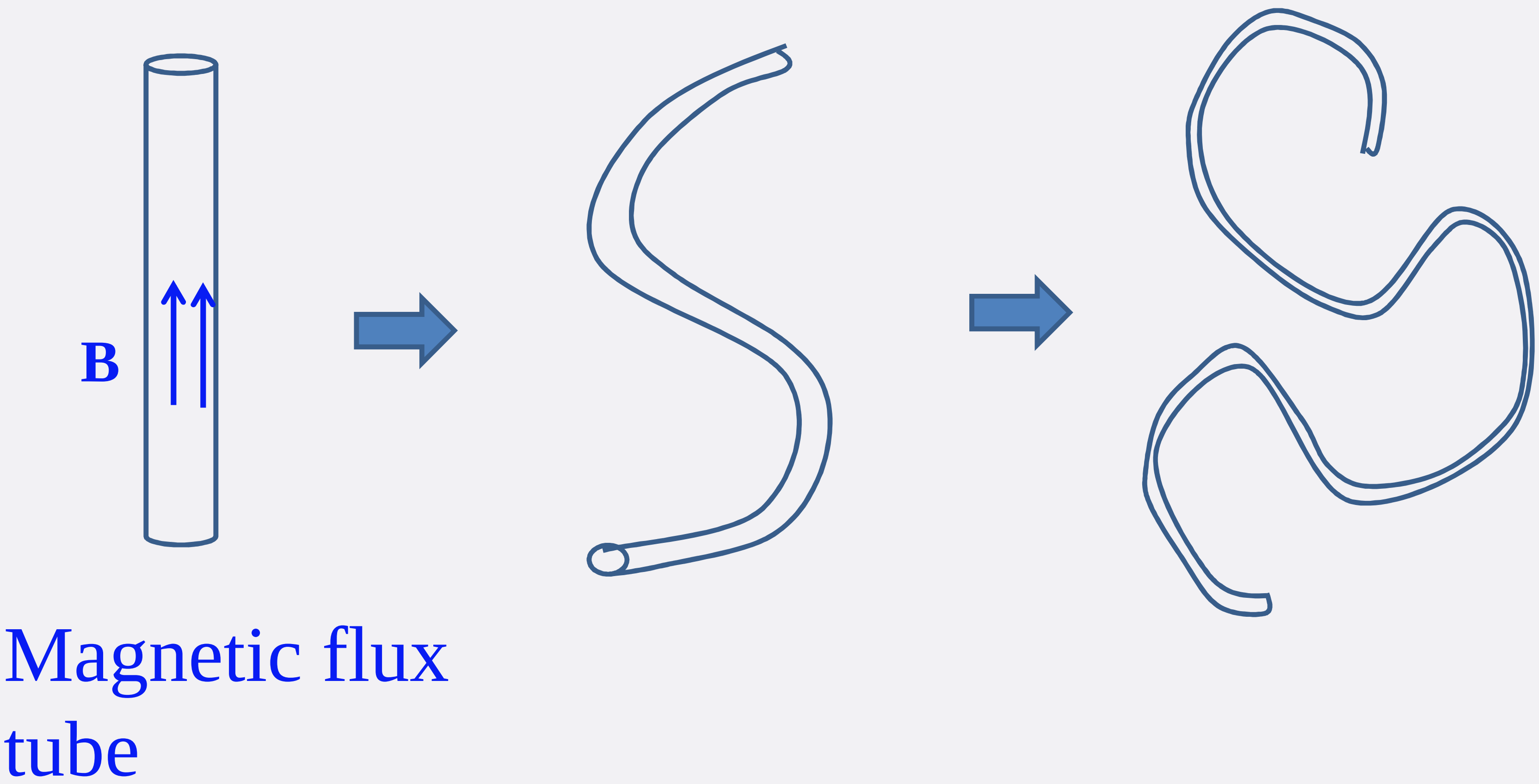


Weak seed field → Strong B

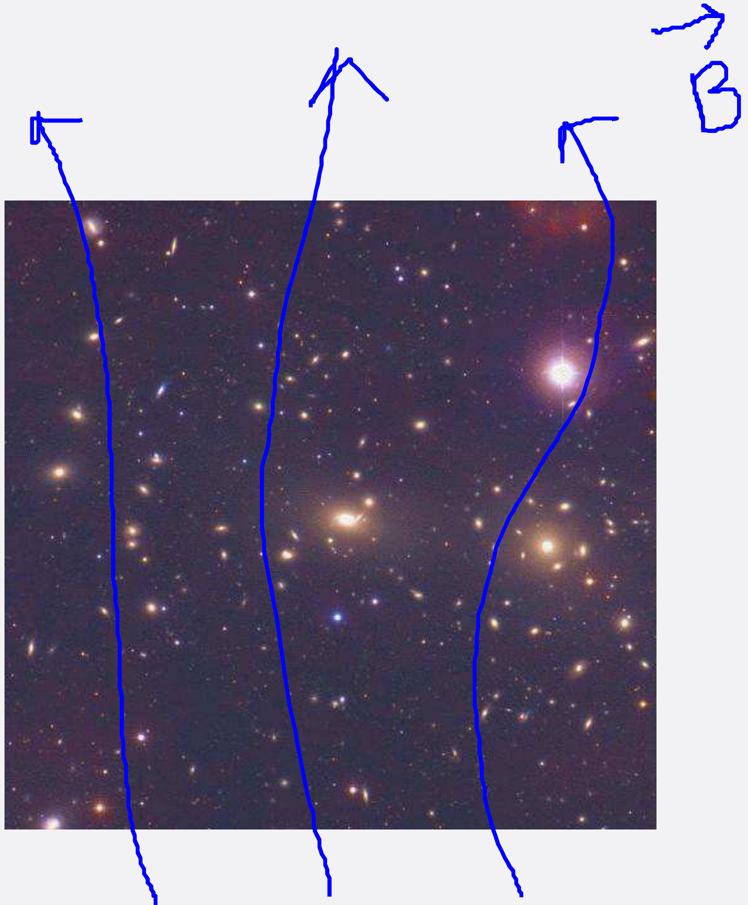
↑

Turbulence

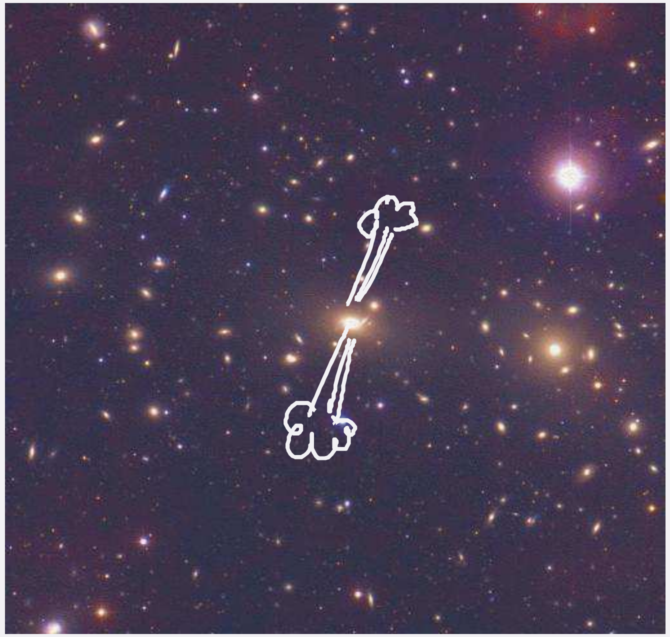
Turbulence ➔ Stretching of flux tubes



Origin of cosmic seed magnetic fields is uncertain.

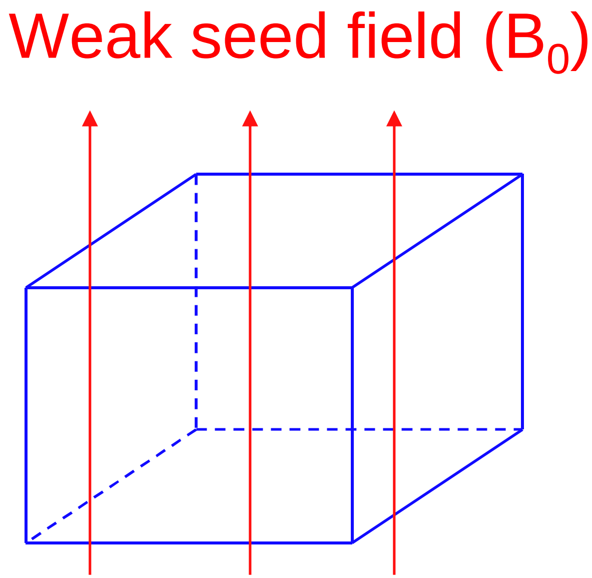


Cosmological?



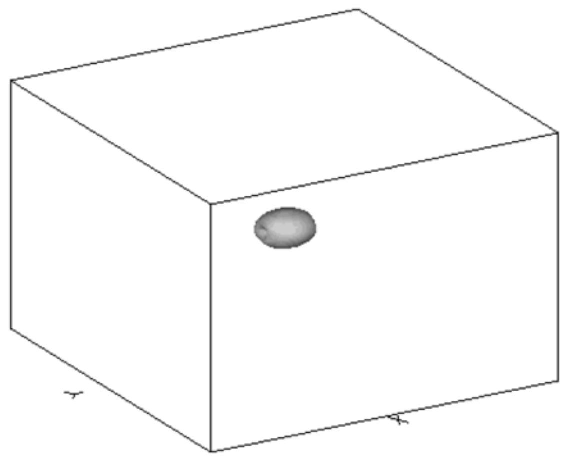
Astrophysical?

Plan



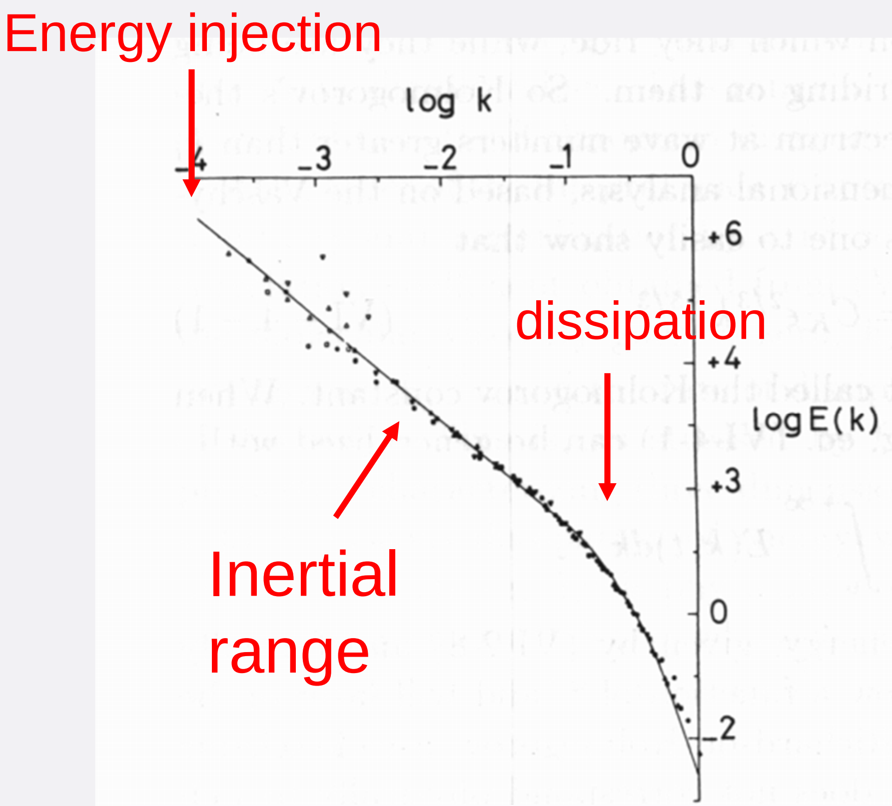
-Uniform seed field case

-Localized seed field case



A spectral code is used

Kolmogorov spectrum (for hydro turb)



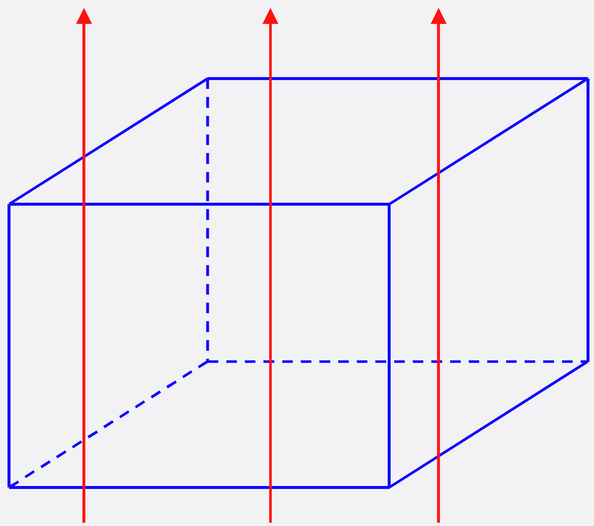
$$E(k) \sim k^{-5/3}$$

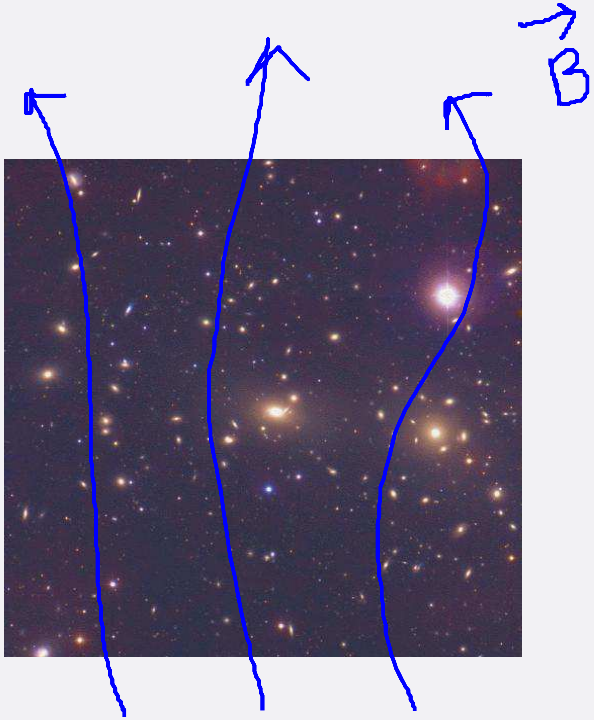
exhibit a three-decade Kolmogorov $k^{-5/3}$ inertial range (from Gargett et al., 1984, courtesy J. Fluid Mech.).

Topic 1. Amplification of a uniform seed field in turbulence

- How can MHD turbulence amplify B fields?

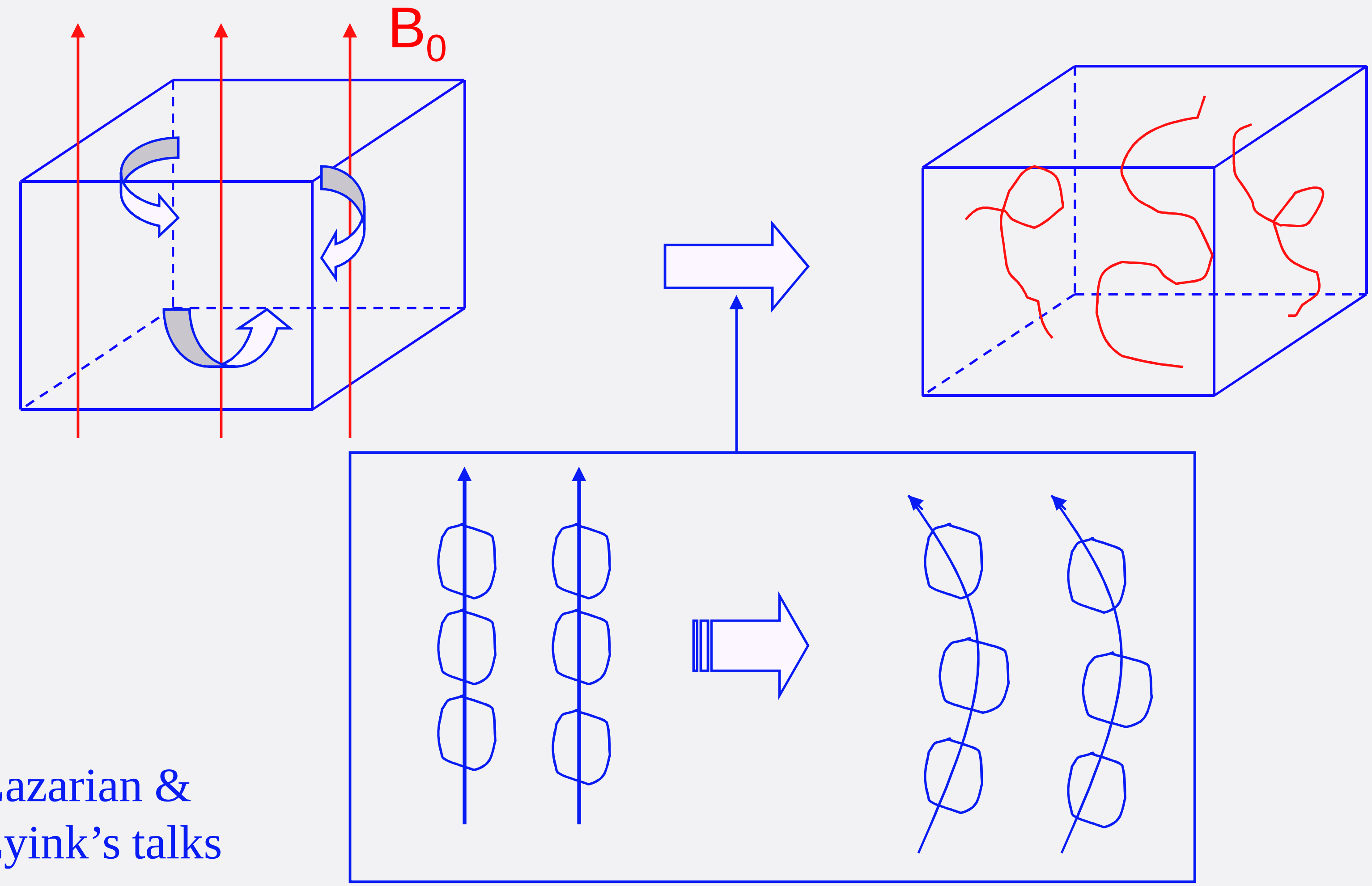
Weak seed field (B_0)





Stretching of field lines

t=0:



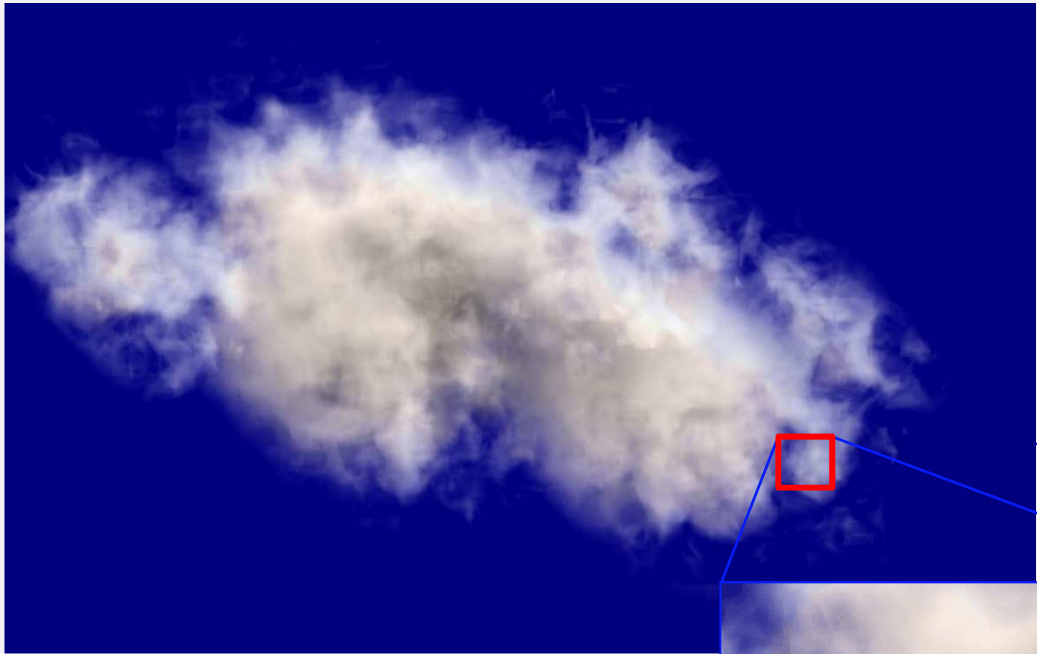
Cf) A. Lazarian &
G. Eyink's talks

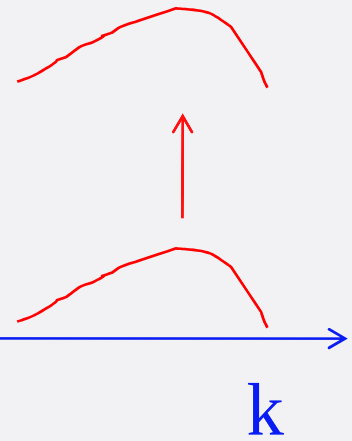
Fluid elements and field lines move together

*Back reactions are negligible if $E_{mag}<E_{kin}$

Expectations:

Stretching on the dissipation scale will occur first because eddy turnover time is shortest there

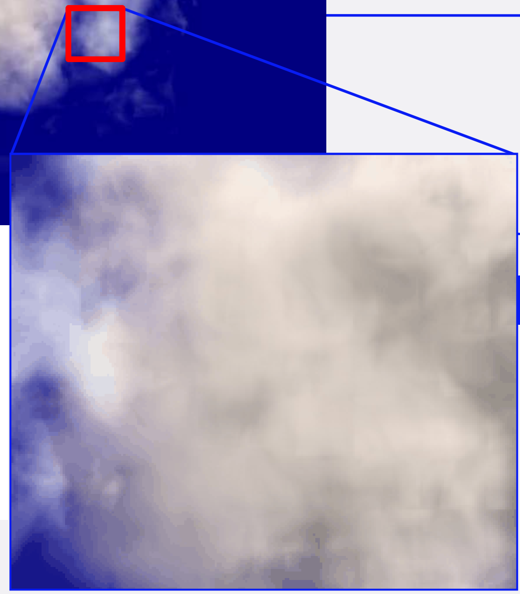




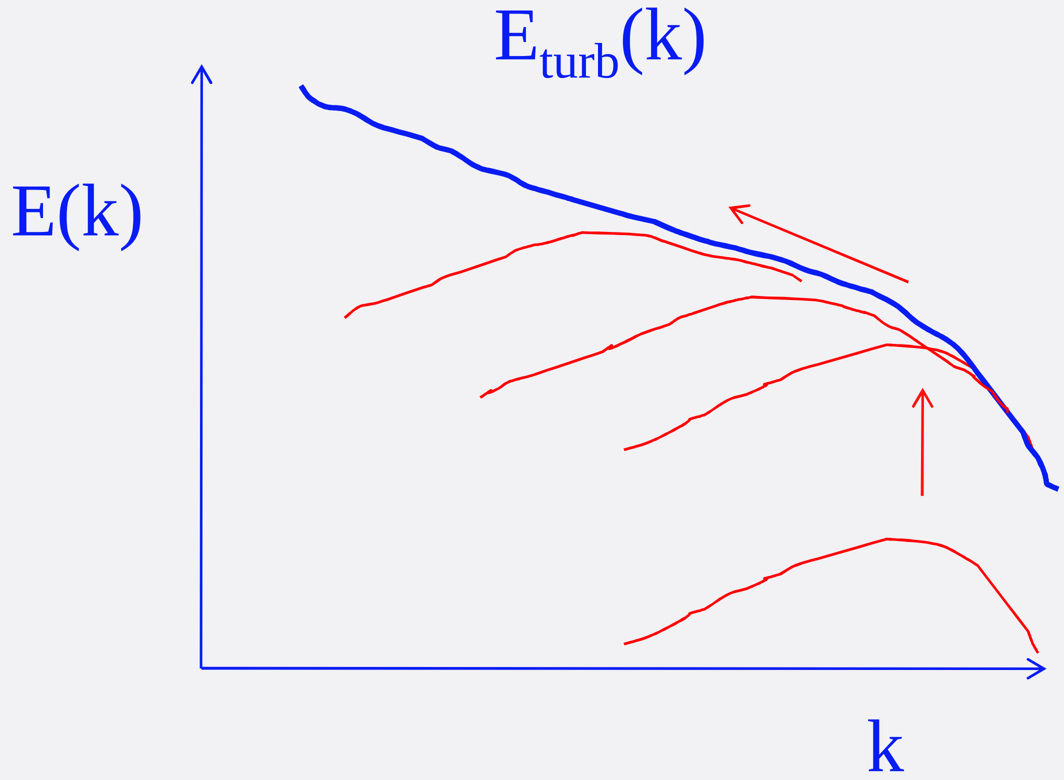
growth

1950)

Small-scale structures change faster



Expectations:



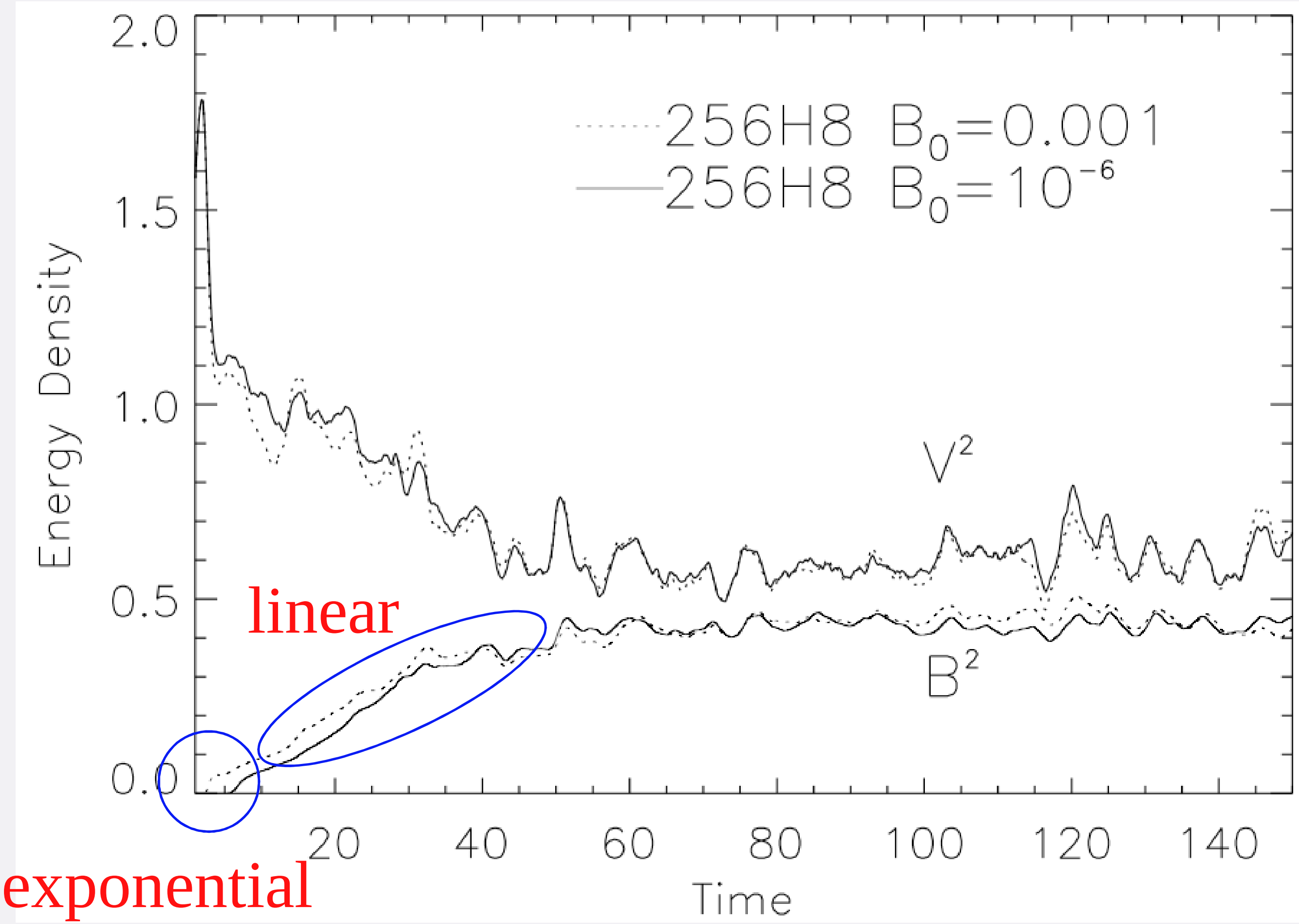
What will happen when $E_{turb} \sim E_{mag}$ on the dissipation scale?

➔ Exponential growth stage will end!

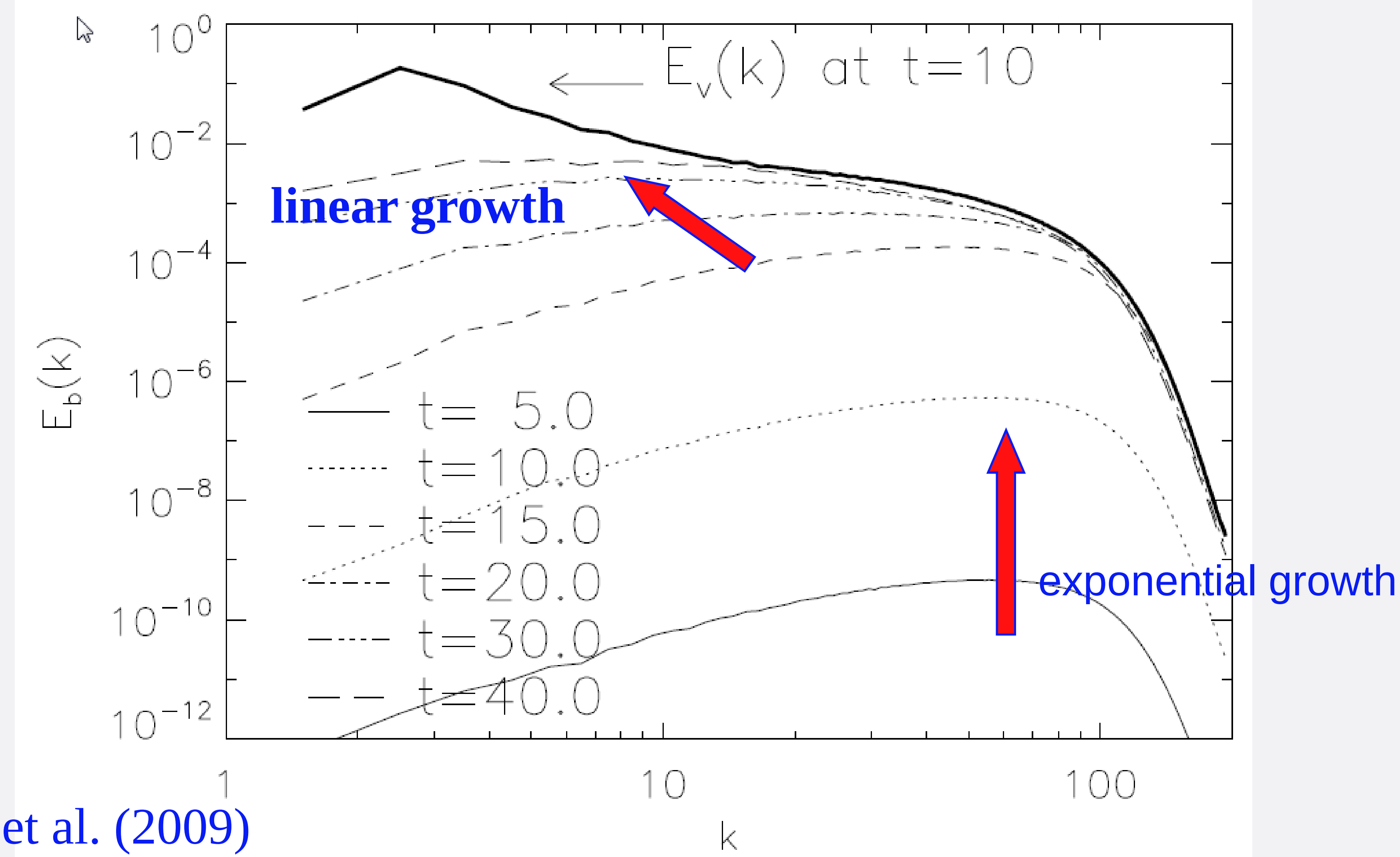
➔ Stretching scale gradually moves to larger scales.

(see, for example, Cho & Vishniac 2000)

Results of simulations



Ryu+2008; Cho, Vishniac, Beresnyak, Lazarian, Ryu (2009); see also Schekochihin et. al. (2006); Cho & Vishniac (2000)



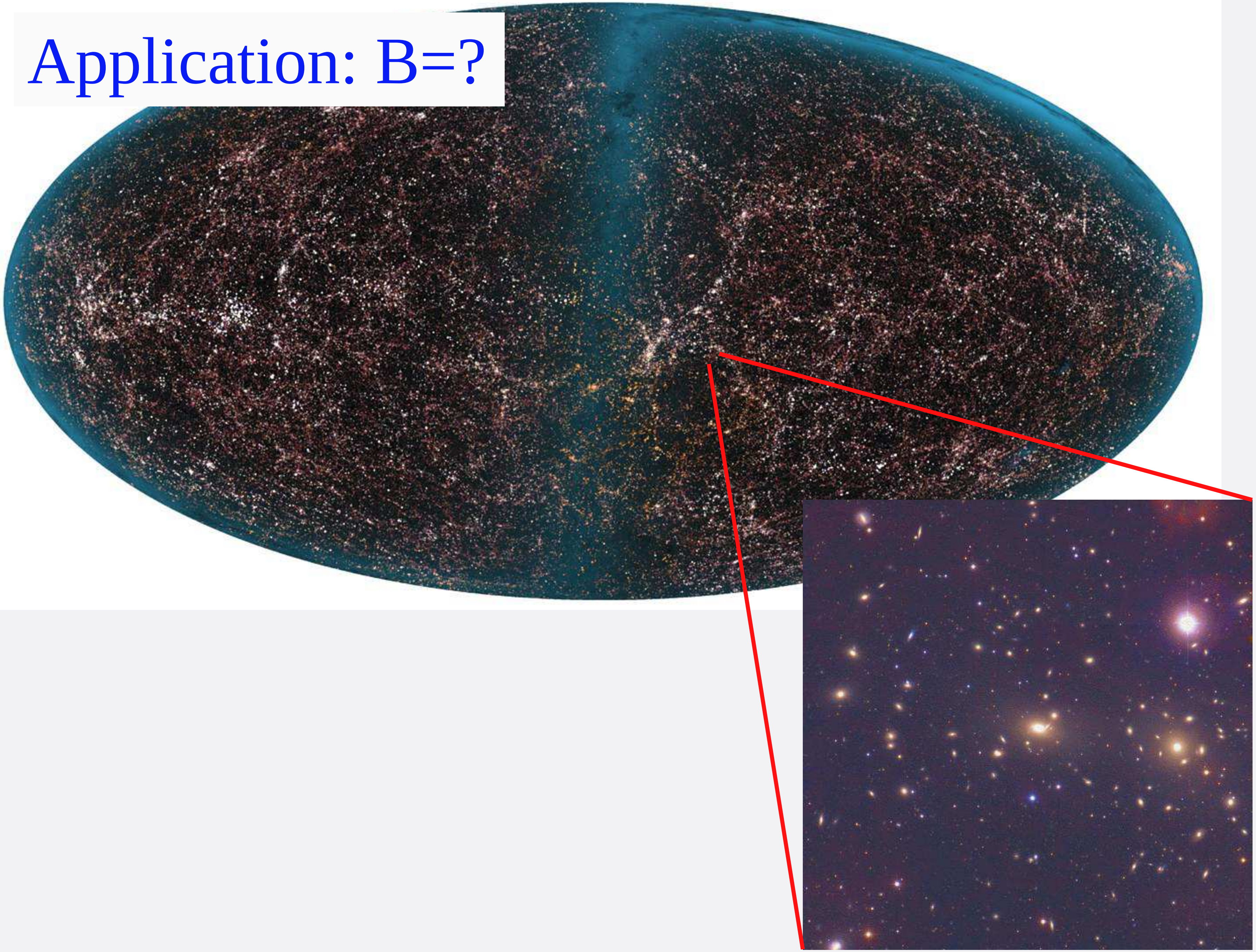
Cho et al. (2009)

* See also Schekochihin et al (2006); Cho & Vishniac (2000)

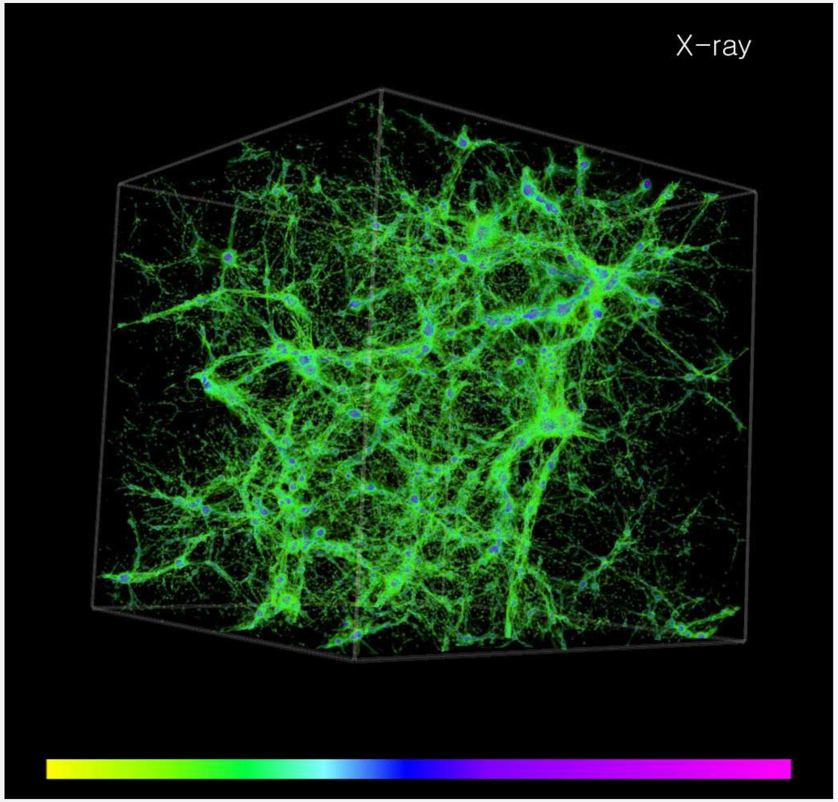
Conclusions for Topic 1

-Turbulence can amplify uniform weak seed B fields
-Two stages of amplification: exp. and linear

Application: B=?

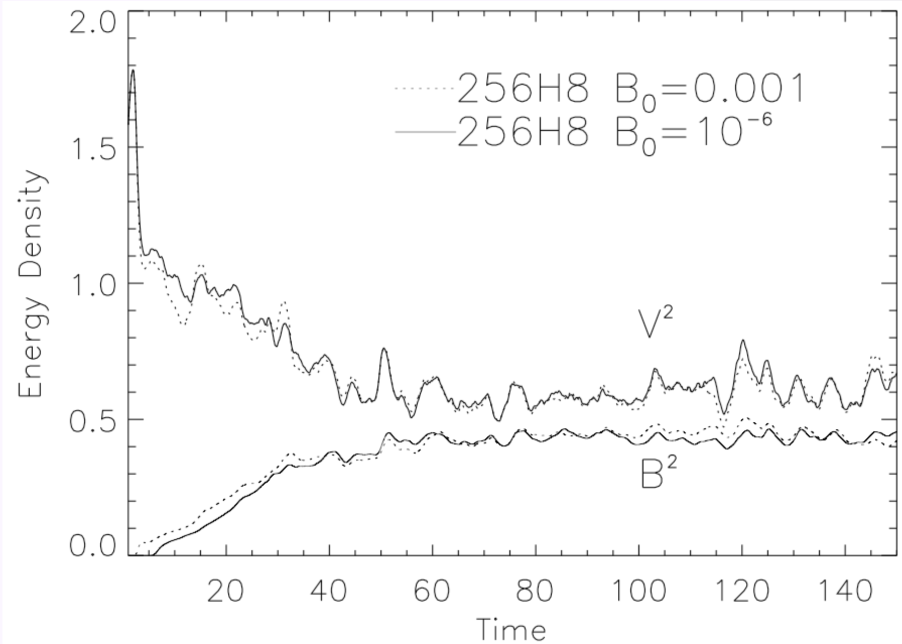


Using the turbulence dynamo model, we can estimate strengths of cosmic B fields



Cosmological simulation
(Ryu et al 2003)

+

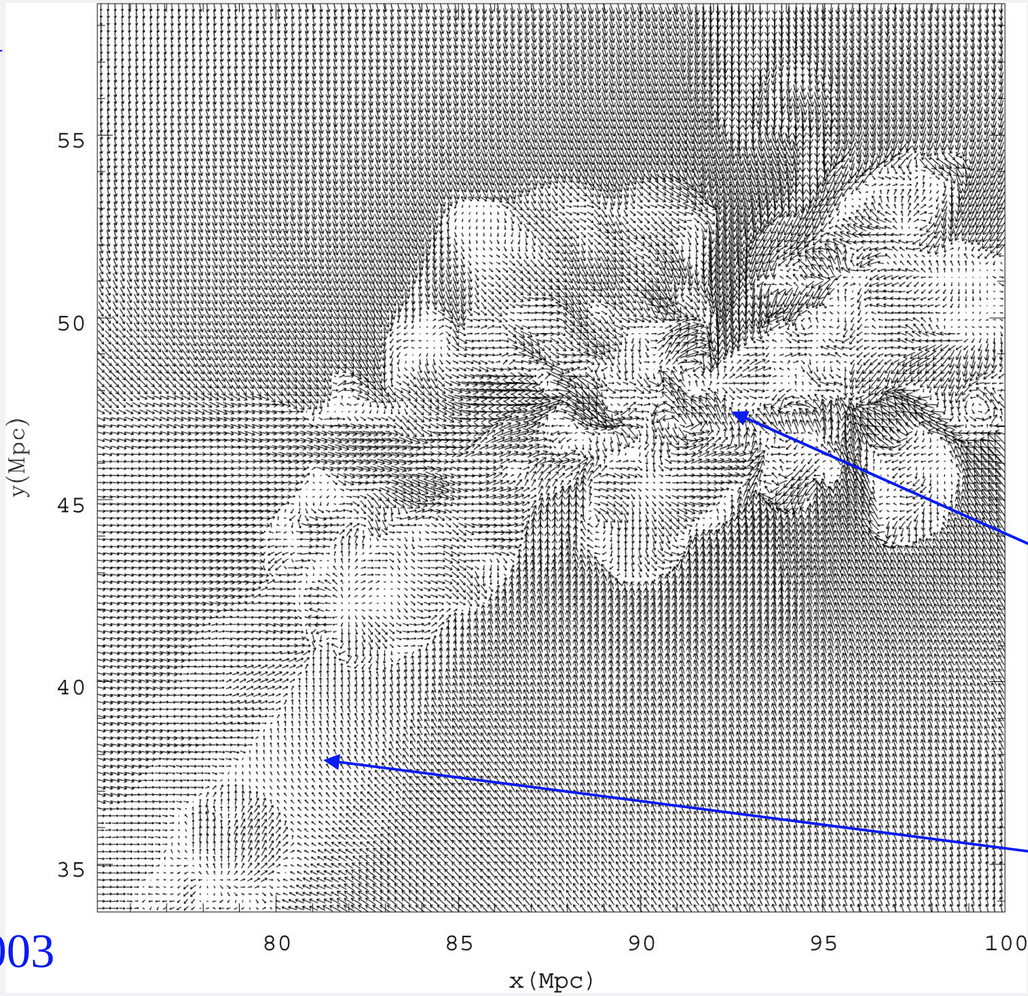


Turbulence dynamo model

Turbulence in clusters and filaments

Cf) F. Miniati's talk, yesterday

velocity

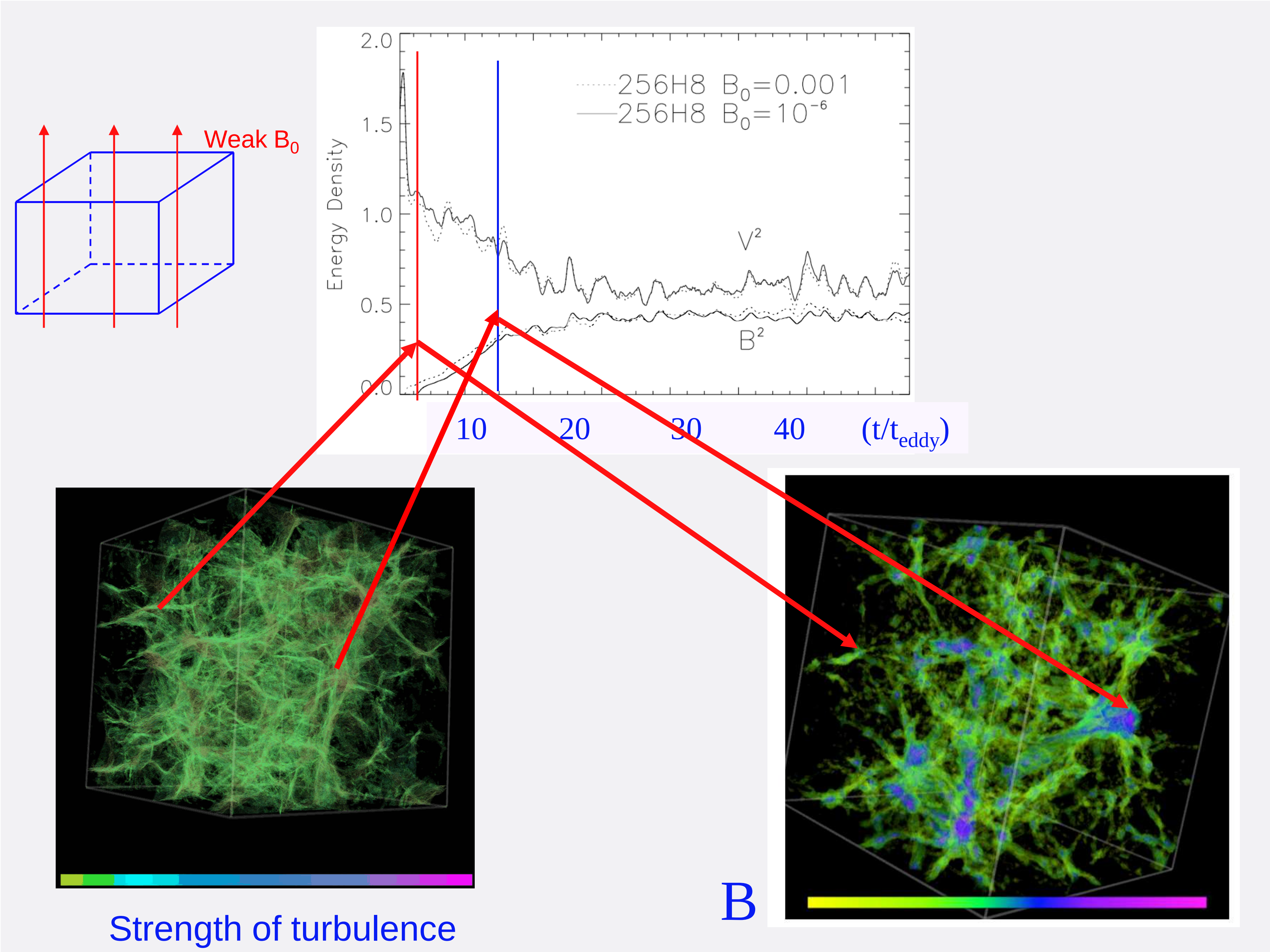


Ryu et al 2003

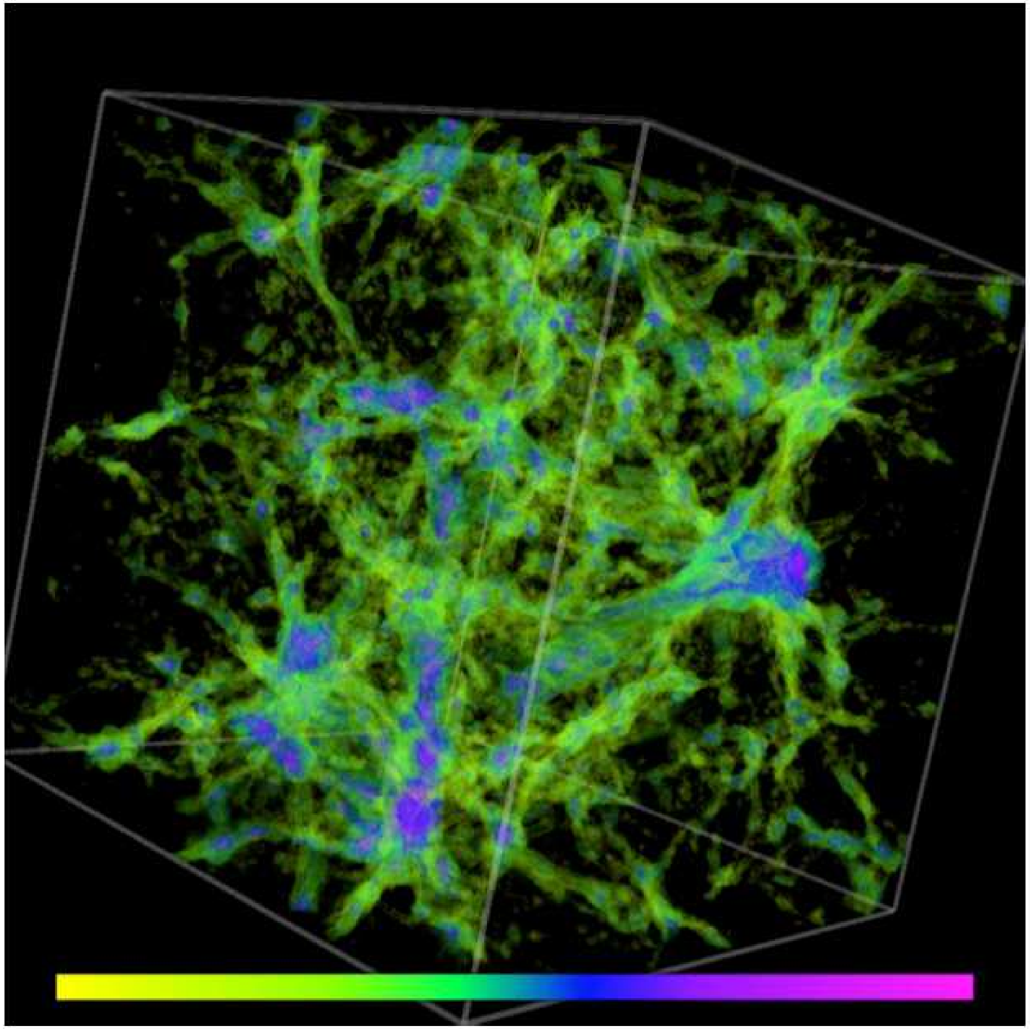
Turbulence is strong in clusters

Turbulence is weak in filaments

We measured strengths of turbulence using vorticity



Weak B_0
Energy Density
2.0
1.5
1.0
0.5
0.0
256H8 B_0=0.001
256H8 $B_0=10^{-6}$
V^2
B^2
10
20
30
40
(t/t_{eddy})
B
Strength of turbulence



0.1nG 10μG

Ryu (+Cho) et al (2008)

Observed strength of B:

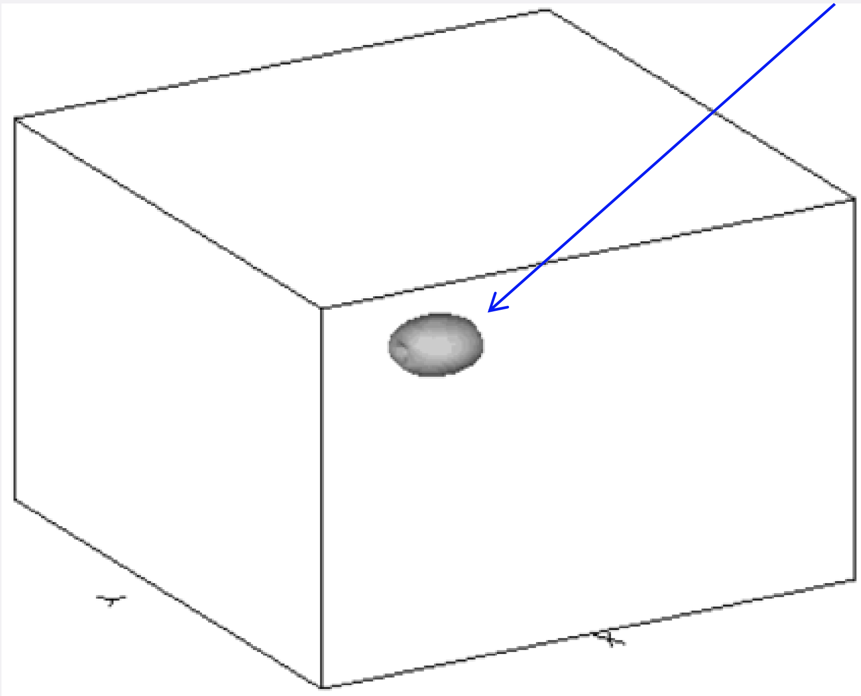
In clusters: ~ μG

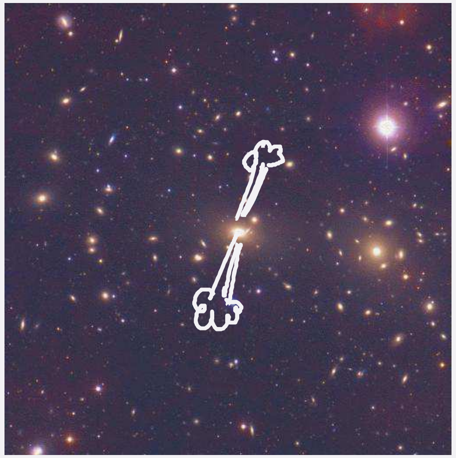
In filaments: ~10 nG (?)

In voids: ?

Topic 2: Growth of a localized seed field in turbulence

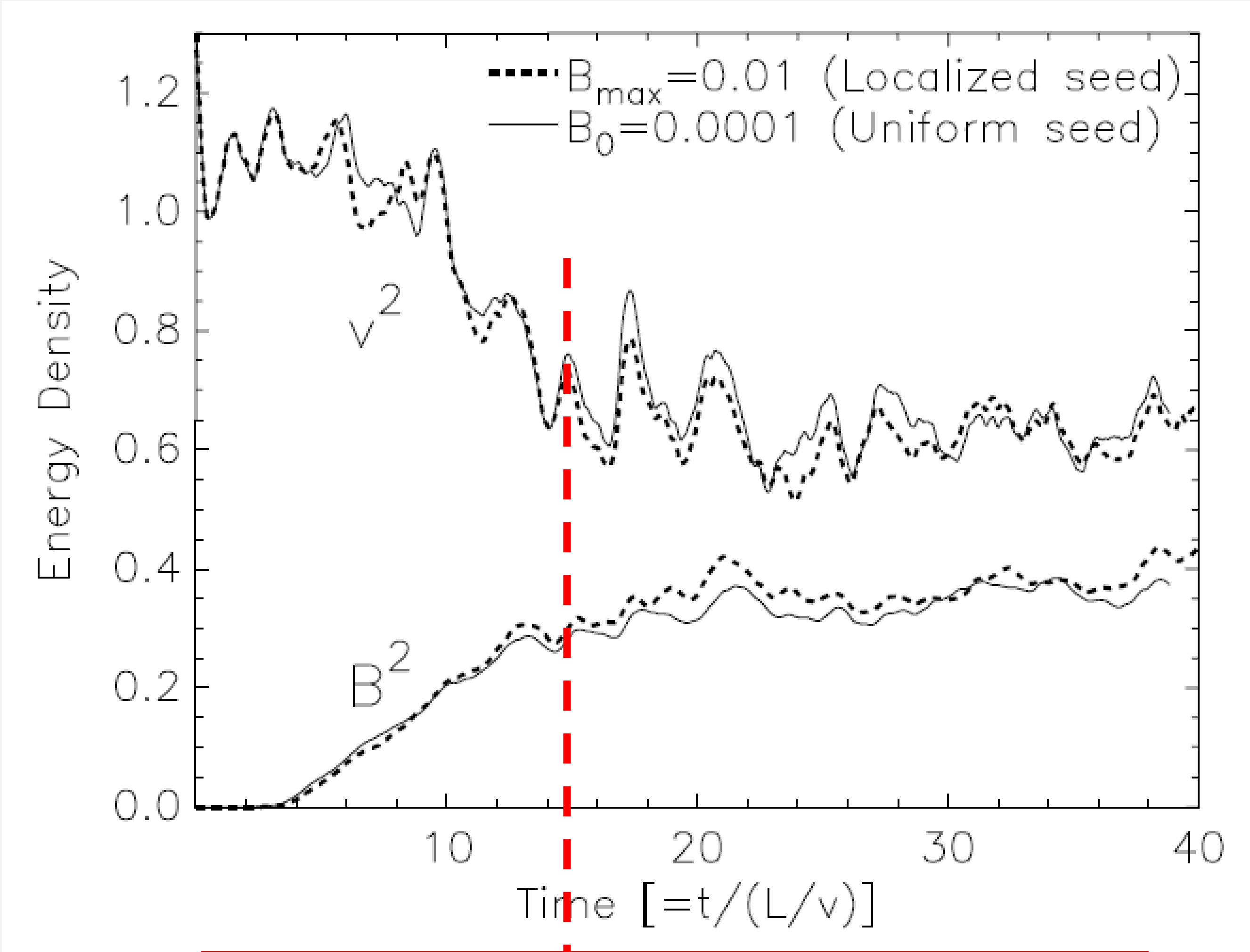
Weak localized seed field





Assumption: driving scale (L) ~ box size (L_{sys})

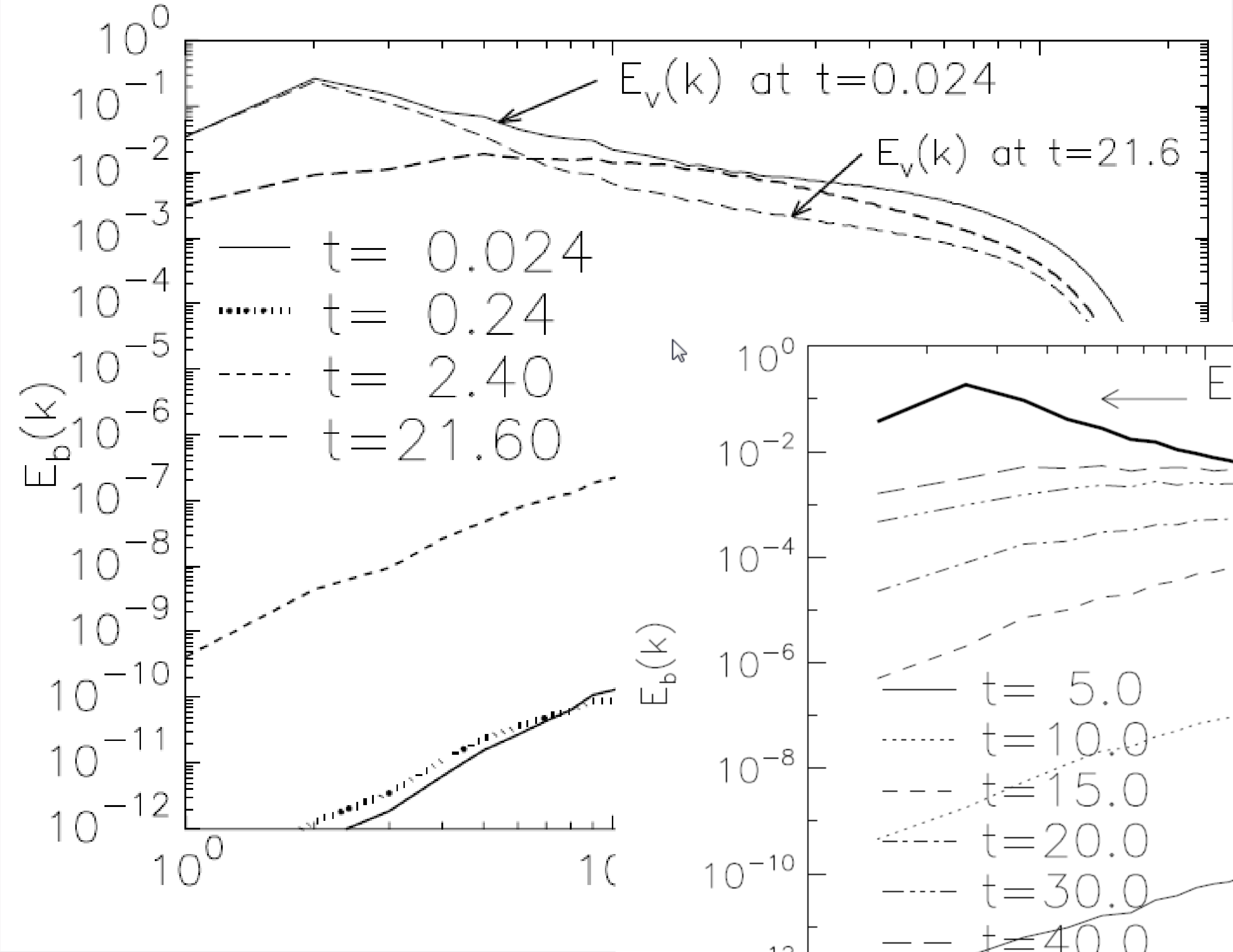
Time evolution of B^2 and v^2 : very similar to uniform seed field cases

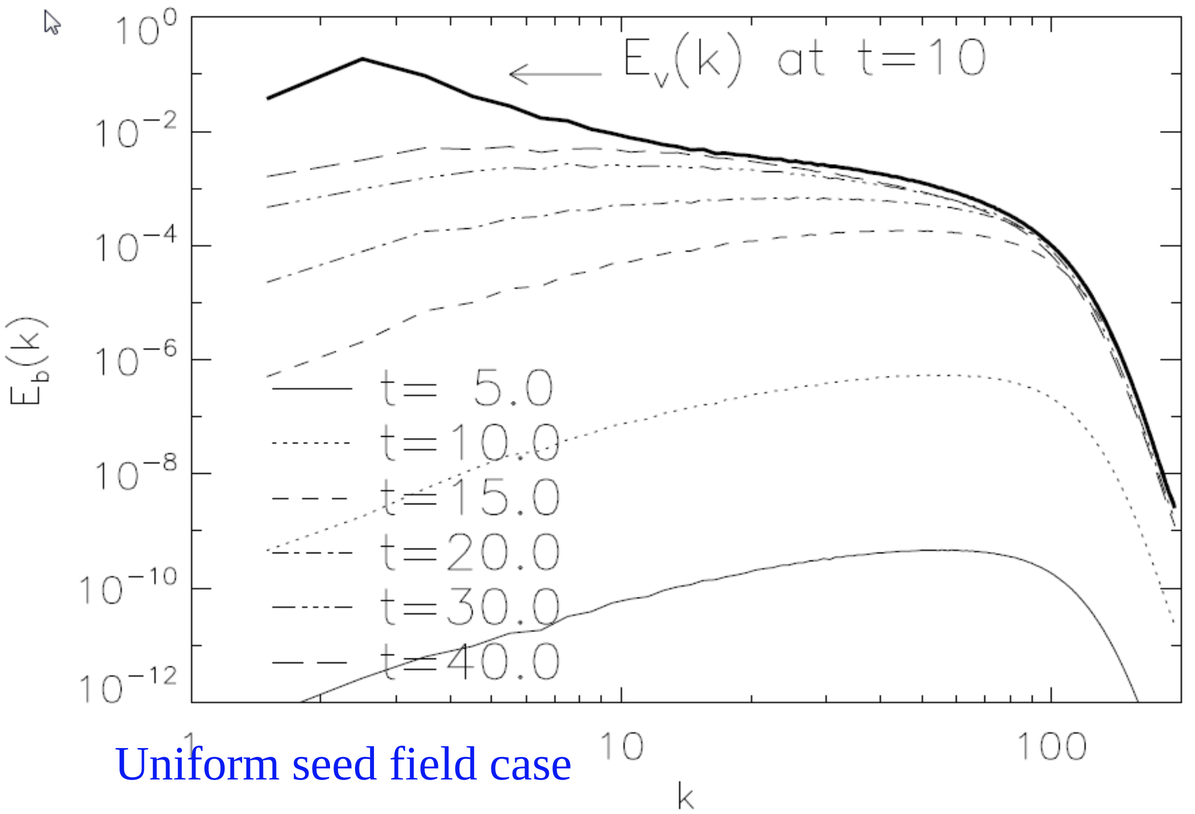


Cho & Yoo (2012)

Saturation time-scale ~ 15 (L/v)

Time evolution of $E_b(k)$: also very similar to uniform seed field cases

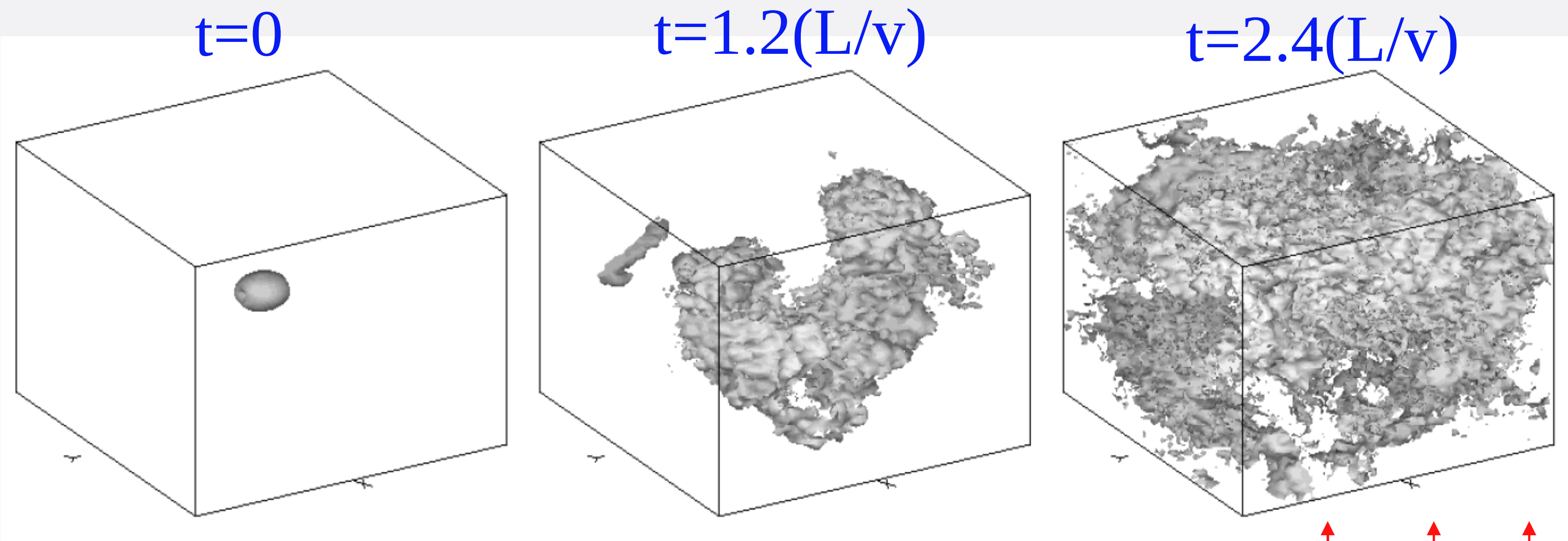




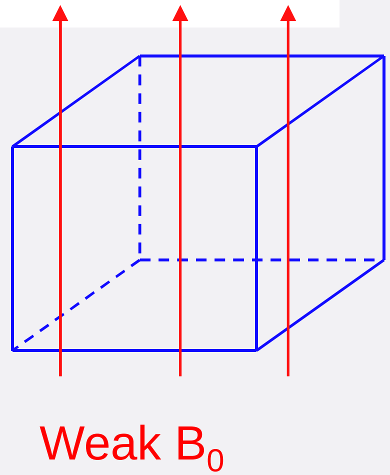
Uniform seed field case

Why are the results so similar?

➔ Answer: fast magnetic diffusion



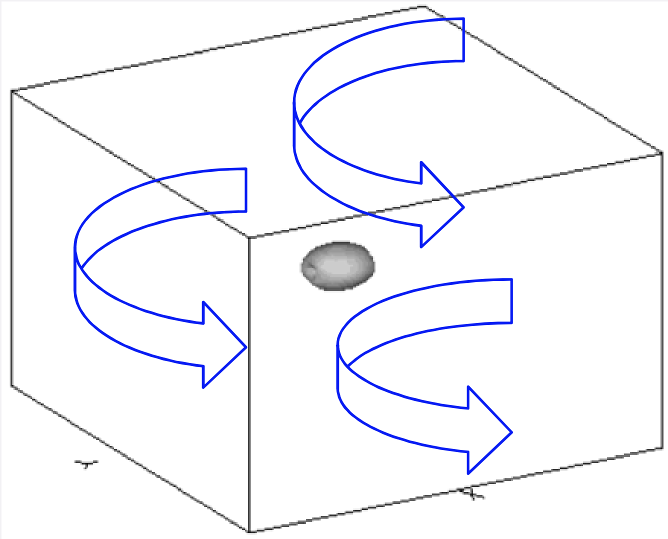
After magnetic field fills the whole system, the subsequent evolution should be very similar to uniform seed field cases ≈



Is magnetic diffusion fast in general?

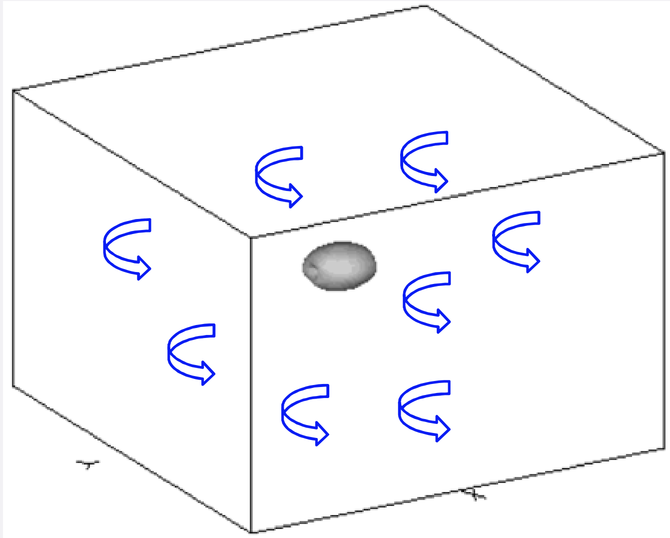
So far, we assumed $L \sim L_{sys}$:

If ICM turbulence is driven by cosmological shocks or major mergers, we expect $L \sim L_{sys}$

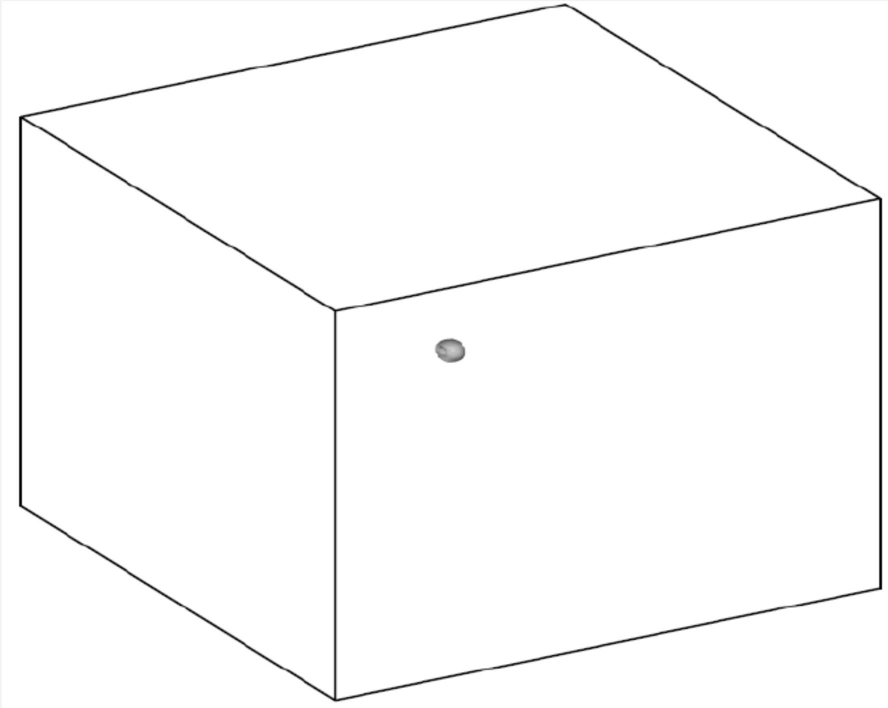


What if $L \ll L_{sys}$?

If ICM turbulence is driven by galaxy motions or accretion of minor bodies, we expect $L \ll L_{sys}$



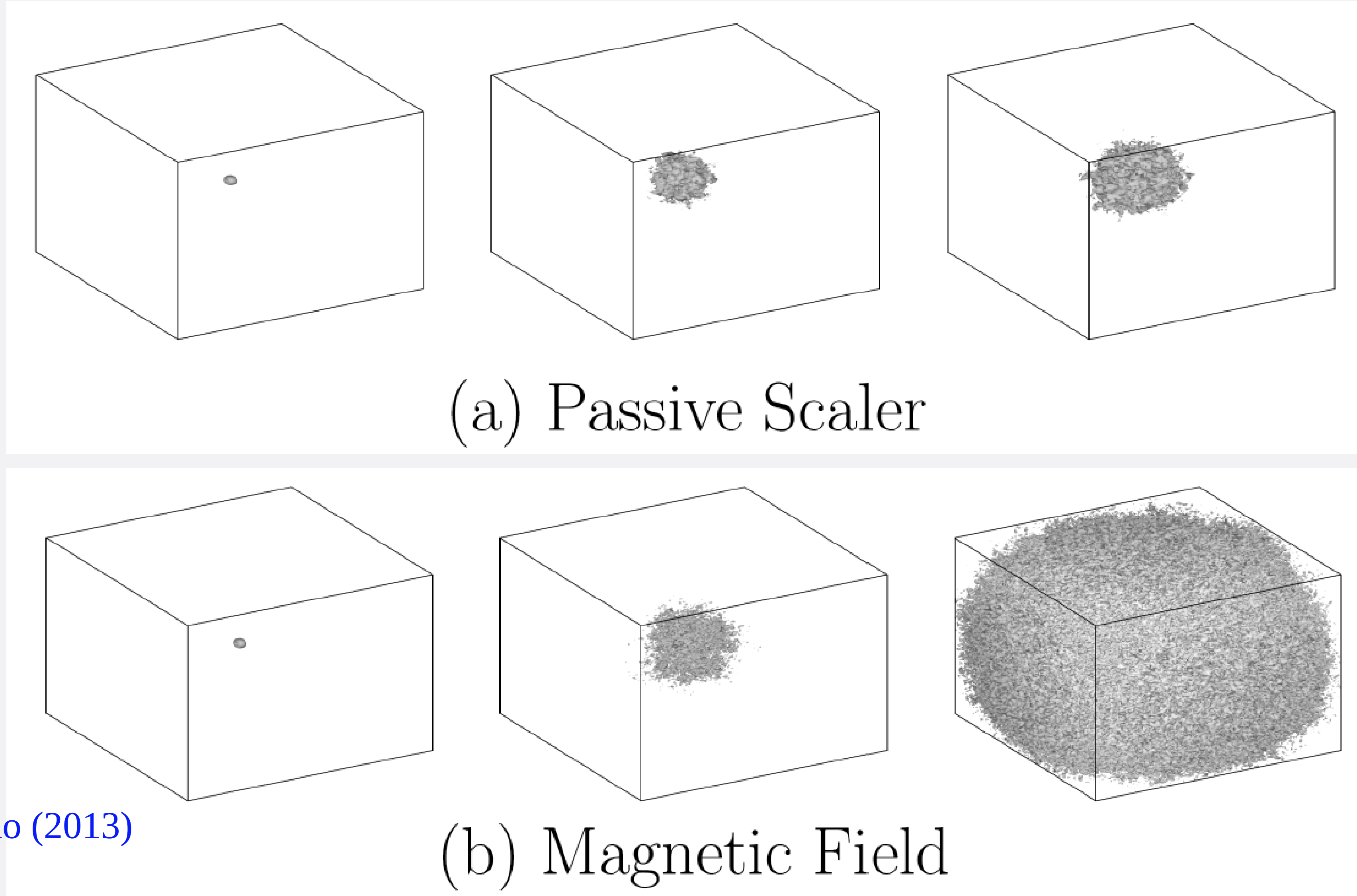
Simulation with $L \sim L_{sys}/20$



512^3

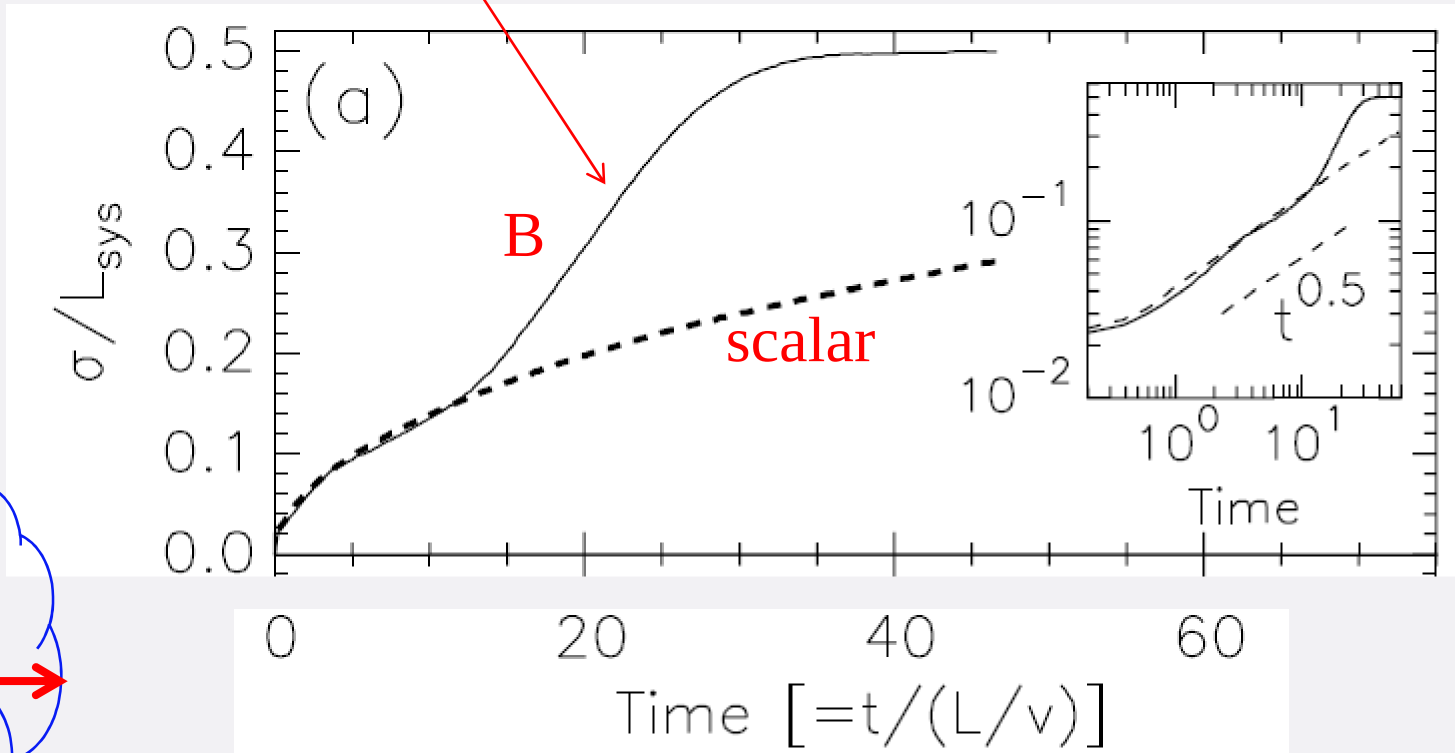
We compare diffusion of a passive scalar and a magnetic field

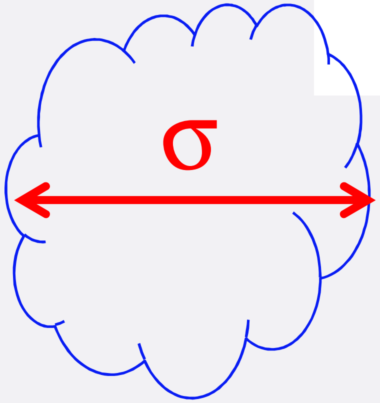
Diffusion of magnetic field is fast!



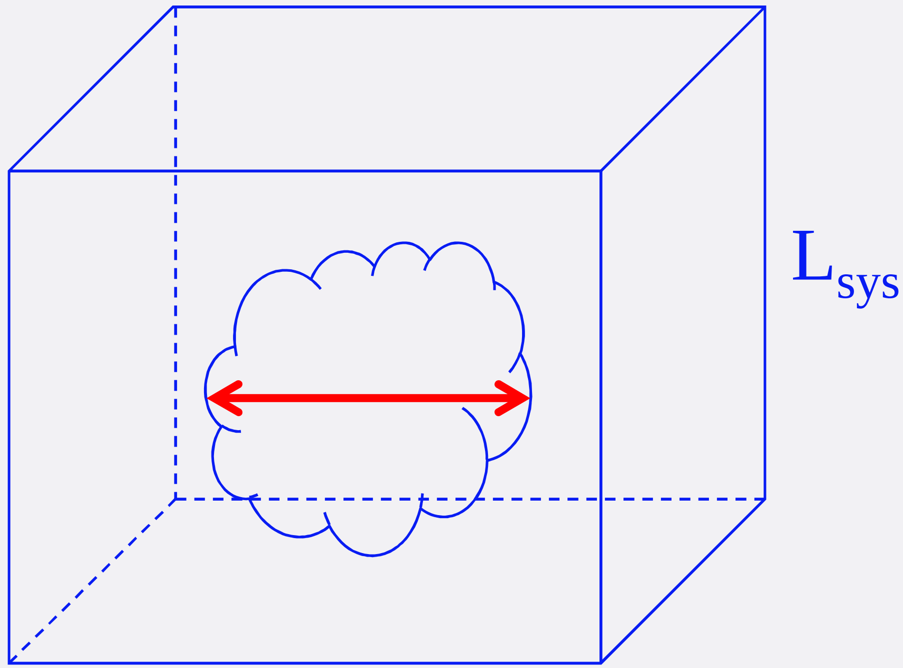
Cho (2013)

Linear growth of the magnetized region!





The speed of expansion is ~v



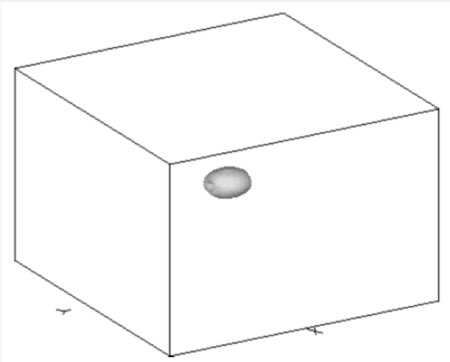
The diameter increases at a speed of ~v

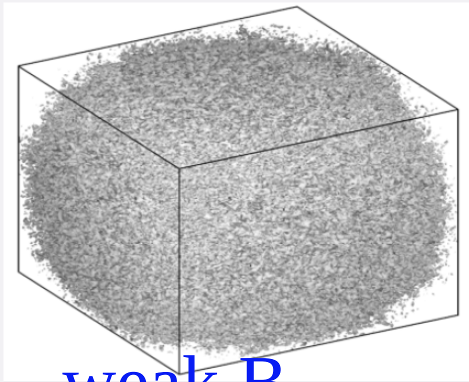
➔ **Full magnetization time-scale** ~ L_{sys}/v ~$(L_{sys}/L)(L/v)$

Cf) **Saturation time-scale** ~ 15 (L/v)

Two timescales: ~(L_{sys}/L)(L/v) & ~15 (L/v)

1. If $L_{sys}/L < \sim 15$: Growth of B ends in ~15(L/v)

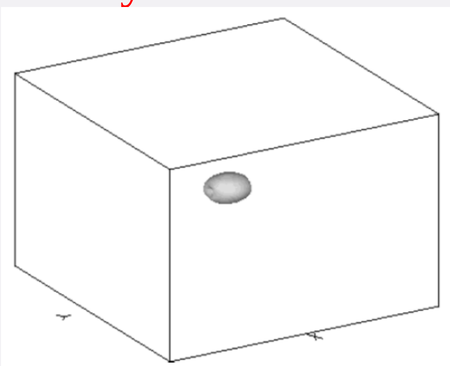


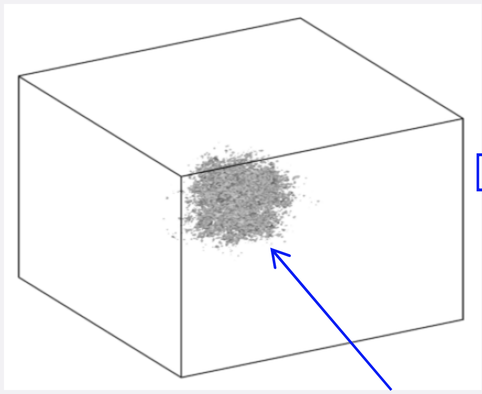


weak B

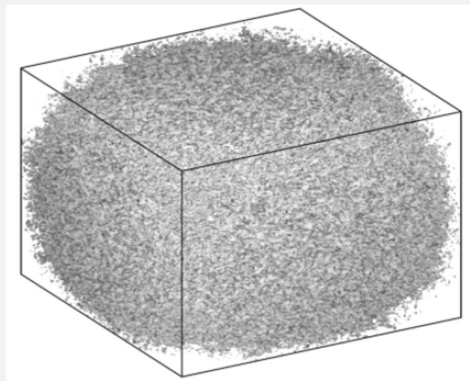
Saturation (strong B)

2. If $L_{sys}/L > \sim 15$: Growth of B ends in ~(L_{sys}/L)(L/v)





strong B



strong B

Examples

1. Cluster with small-scale driving ($L_{sys}/L=20$)

    L_{sys}~1Mpc, L~50kpc, v~100km/s

    ➔ Growth of B ends in t~ 10^{10} years!

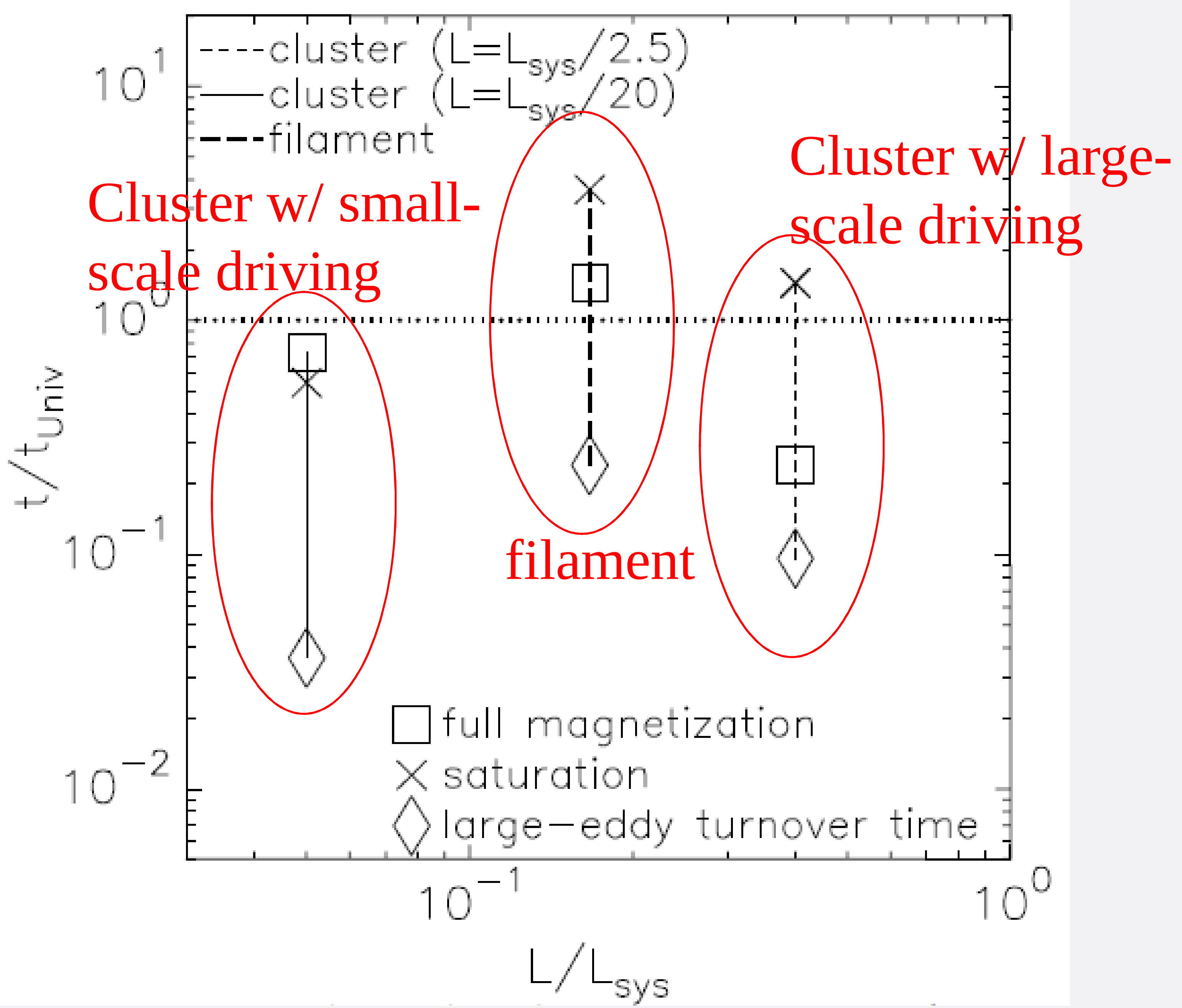
2. Filament with large-scale driving ($L_{sys}/L=6$)

    L_{sys}~3Mpc, L~500kpc, v~150km/s

    ➔ Magnetization time-scale ~ t_{Univ}

    ➔ B fills the whole volume in t ~ t_{Univ}

    * But, B is still very weak



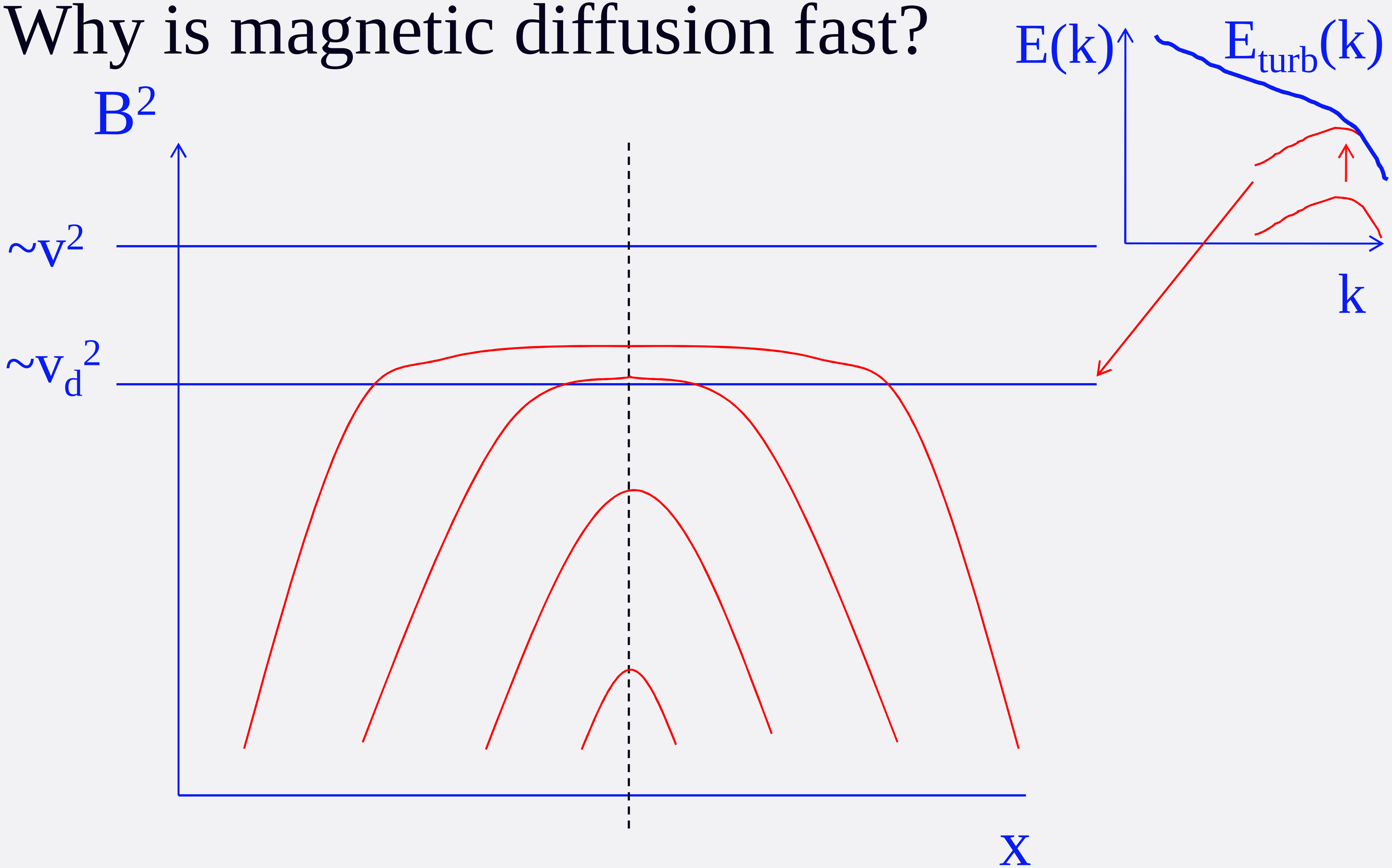
----cluster (L=L_sys/2.5)
——cluster (L=L_sys/20)
- - - filament
Cluster w/ small-scale driving
filament
Cluster w/ large-scale driving
t/t_Univ
L/L_sys
full magnetization
saturation
large−eddy turnover time

Conclusion for Topic 2

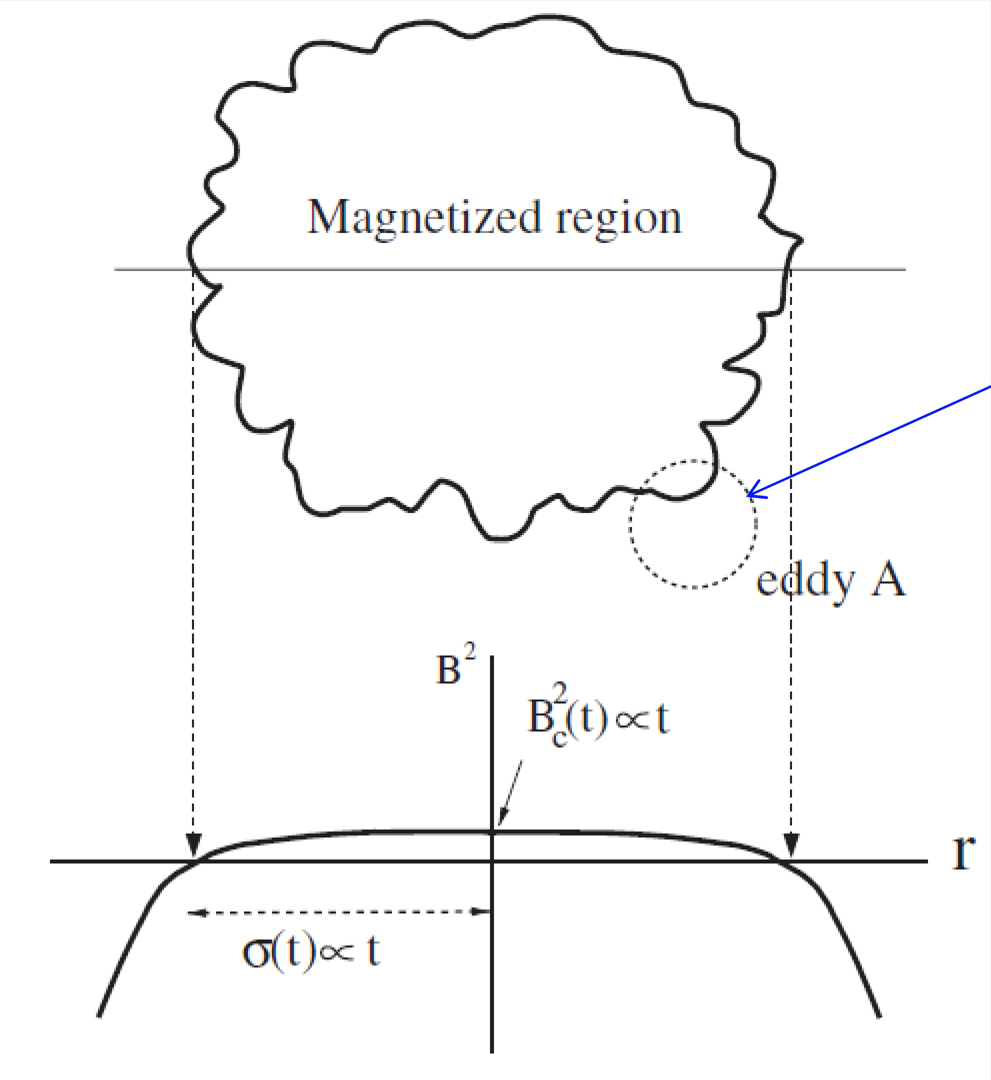
- If $L \sim L_{sys}$, a localized seed magnetic field fills the whole system very fast. Subsequent evolution is very similar to weak uniform seed field cases.

- In general, growth of a localized seed field ends in $\sim \max(15, L_{sys}/L)(L/v)$

Why is magnetic diffusion fast?



Why is magnetic diffusion fast?



1 eddy turnover time is enough to completely magnetize this eddy

Conclusion

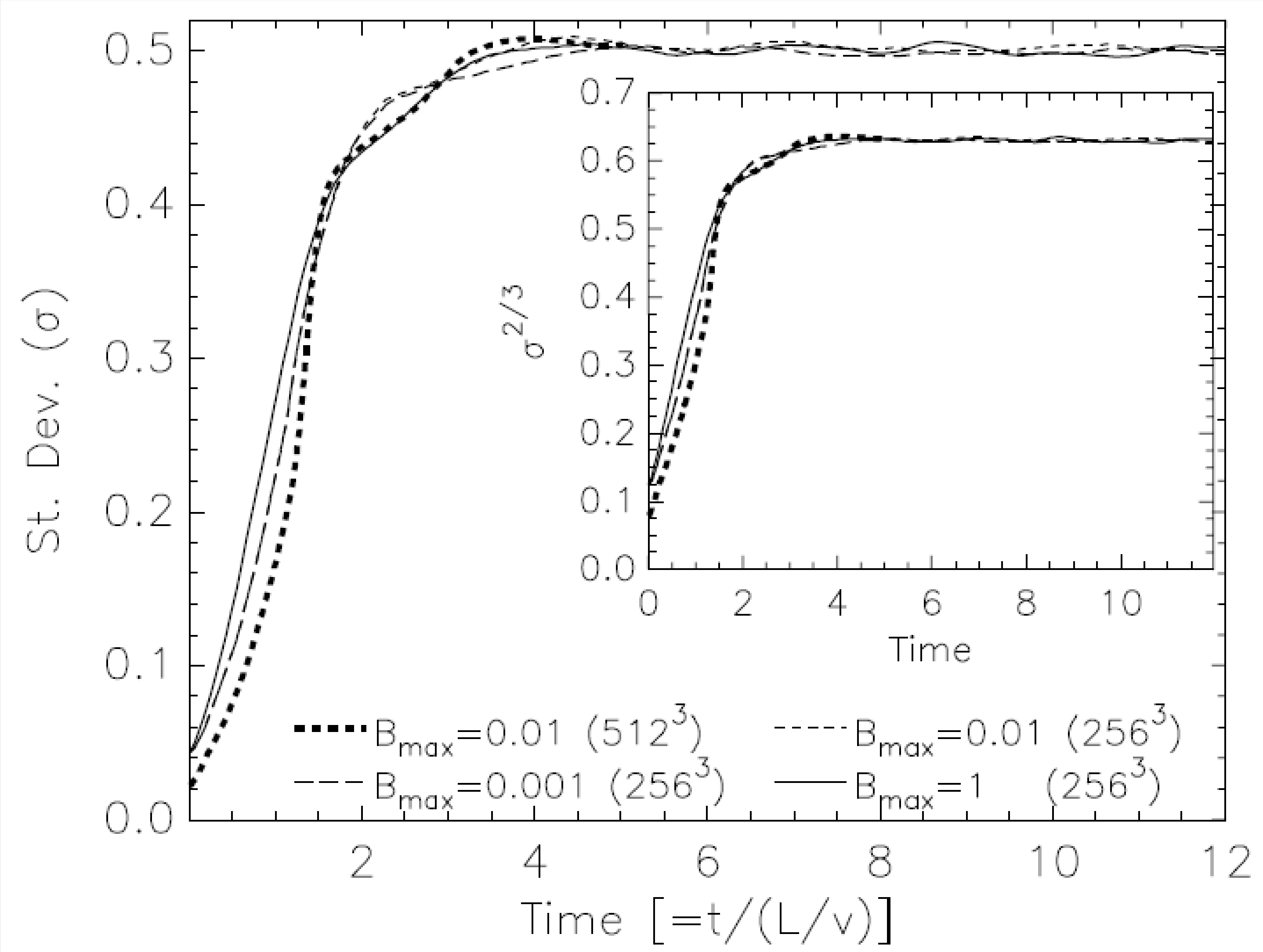
- If a seed fined is uniform, then it takes

$$\sim 15(L/v)$$

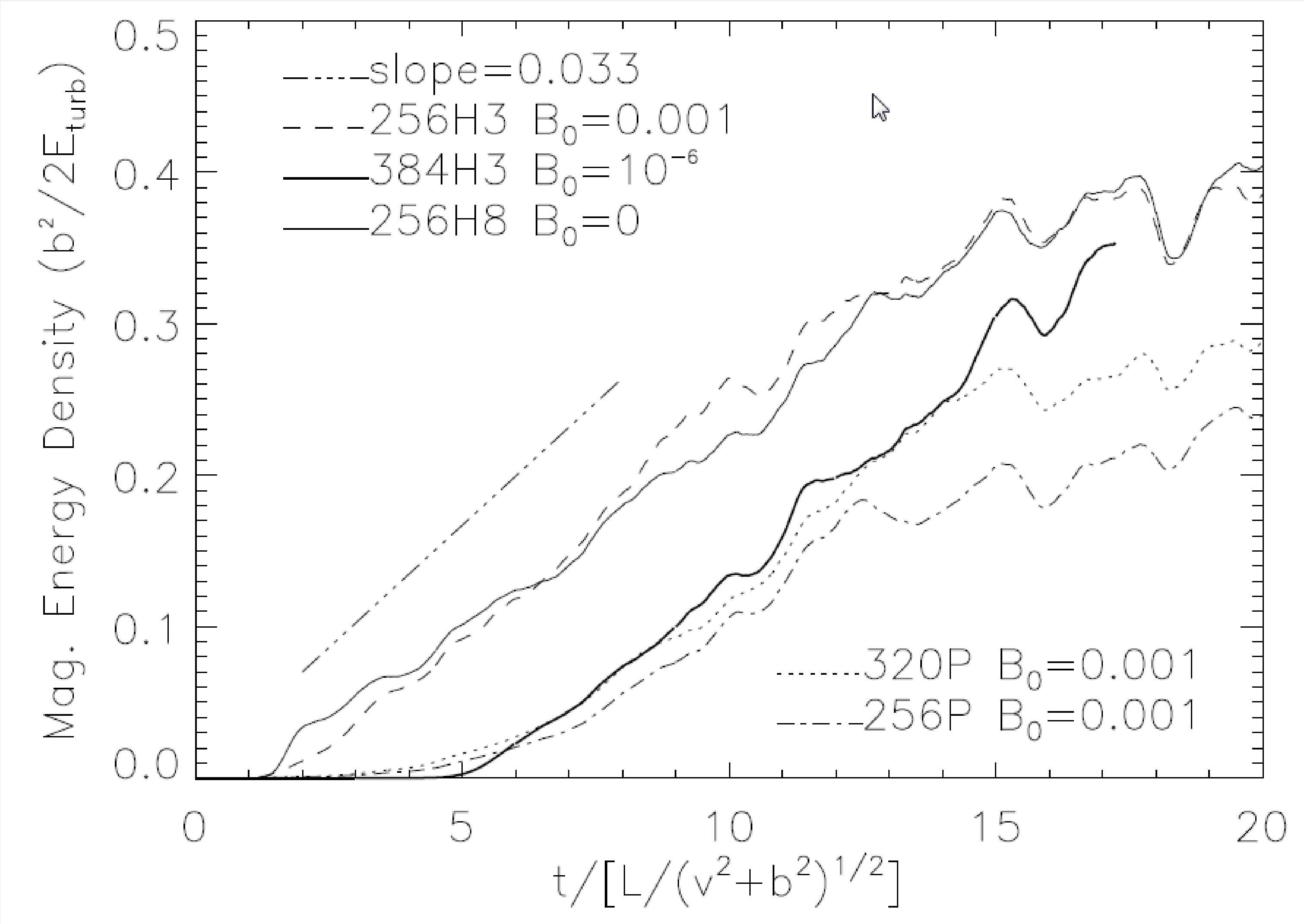
- If a seed field is localized, then it takes

$$\sim \max(15, L_{sys}/L)(L/v)$$

St. dev. of B field distribution follows Richardson's law

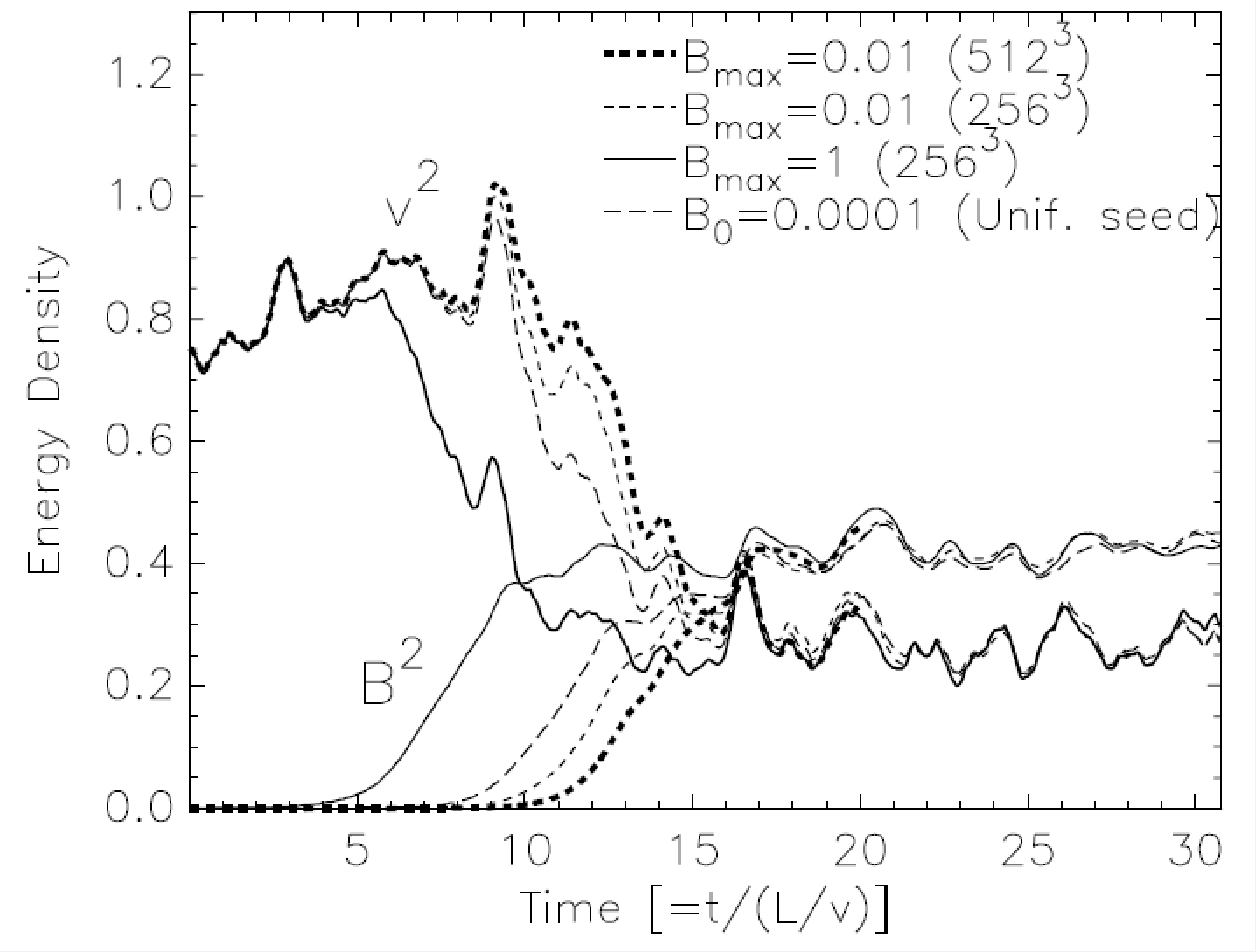


The growth rate seems to be universal



Cho et al (2009)

Growth of a localized magnetic field in turbulence with a high magnetic Prandtl number (i.e. ν >> η)



Cho & Yoo (2012)

Magnetic field fills the whole system fast