Viscosity and Origin of Magnetic Field in the ICM

Origin of magnetic fields in clusters and filaments

➔ If Spitzer viscosity, it's astrophysical!

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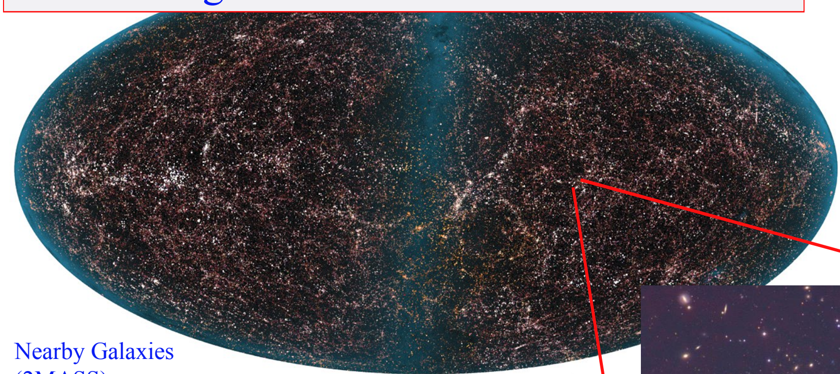
Cho & Yoo (2012; ApJ)
Cho (2013; PRD)
Cho (2014, ApJ)

B in the large-scale structure of the universe?



Nearby Galaxies (2MASS)

Observations: ~μG in clusters
~nG in filaments???

➔Turbulence can amplify magnetic fields

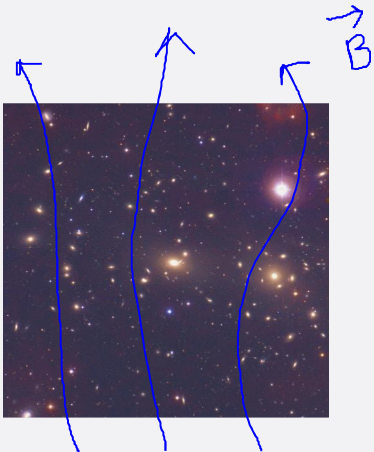
TABLE 1 Cluster magnetic fields

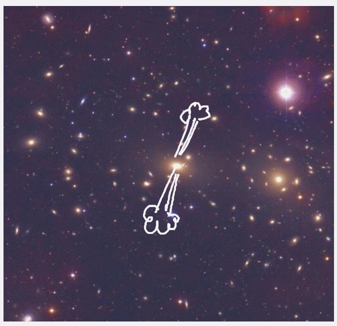
Method	Strength μG	Model parameters
Synchrotron halos	0.4–1	Minimum energy, $k = \eta = 1$, $\nu_{low} = 10$ MHz, $\nu_{high} = 10$ GHz
Faraday rotation (embedded)	3–40	Cell size = 10 kpc
Faraday rotation (background)	1–10	Cell size = 10 kpc
Inverse Compton	0.2–1	$\alpha = -1$, $\gamma_{radio} \sim 18000$, $\gamma_{xray} \sim 5000$
Cold fronts	1–10	Amplification factor ~3
GZK	>0.3	AGN = site of origin for EeV CRs

Carilli & Taylor 2002

* Note: In typical clusters, $B_{eq} \leq O(10\mu G)$ ← $B^2/4\pi \sim \rho v^2$

Origin of cosmic seed magnetic fields is uncertain





Primordial?

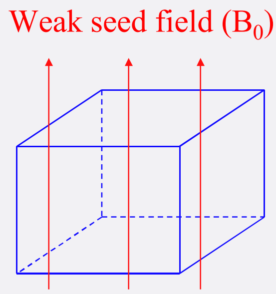
Astrophysical?
(jets, winds, stripped gases, …)

⇧
B from the early universe?
Battery effects during the large-scale structure formation?

Numerical simplification

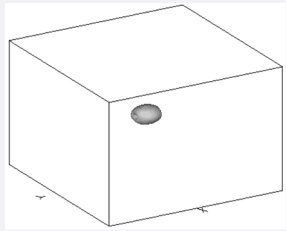
-Primordial seed

➔Uniform seed field at t=0

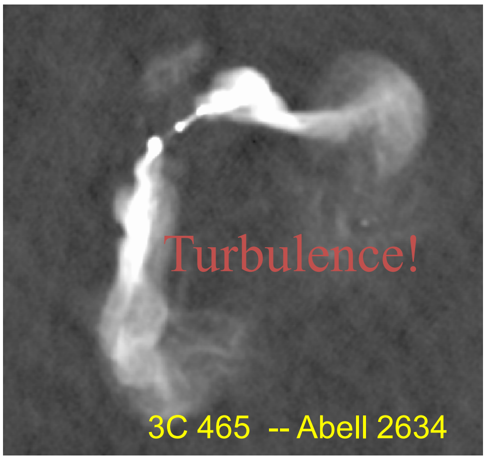


-Astrophysical seed

➔Localized seed field at t=0



ICM (intracluster medium) is turbulent



$\sigma_v \sim 10^2$-10^3 km/sec

Turbulence and Reynolds number

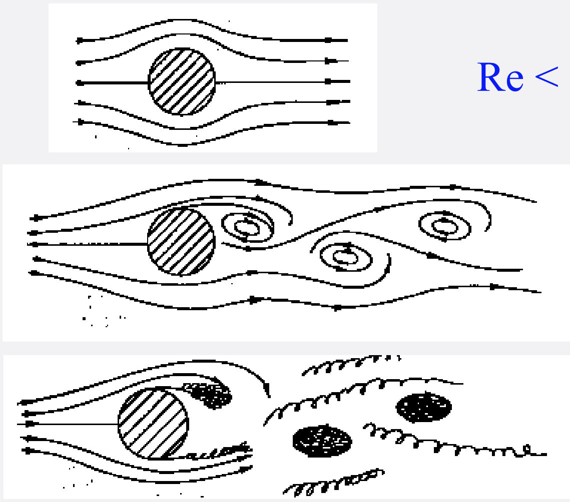
- Reynolds number: Re=VL/ν ← (V²/L) / (νV/L²)

$$\frac{\partial \mathbf{v}}{\partial t} = -(\mathbf{v}\cdot\nabla)\mathbf{v} + \nu\nabla^2\mathbf{v}$$

$(\mathbf{v}\cdot\nabla)\mathbf{v}$ ↑ V^2/L $\nu\nabla^2\mathbf{v}$ ↑ $\nu V/L^2$

- When Re << $Re_{critical}$, flow = laminar
  When Re >> $Re_{critical}$, flow = turbulent

Onset of turbulence



Re < 1

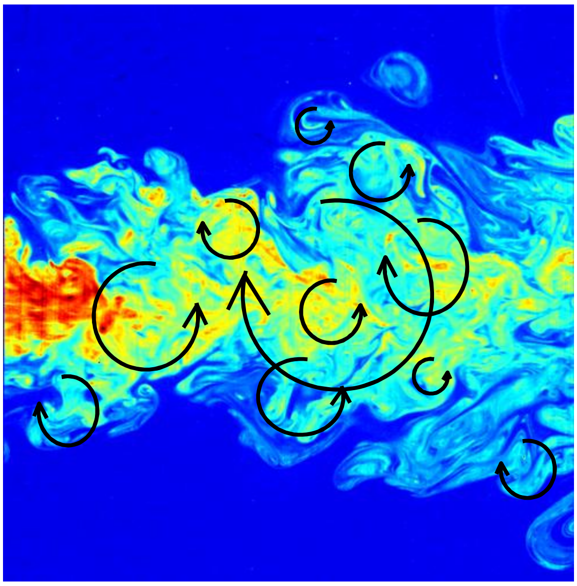
Re ~ 40

Re ~ 10^4

Turbulence develops in large-Re systems!

www-pgss.mcs.cmu.edu

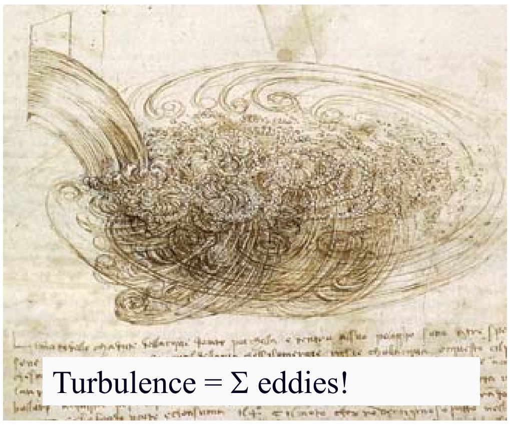
Turbulence = Σ eddies!



C. Fukushima and J. Westerweel

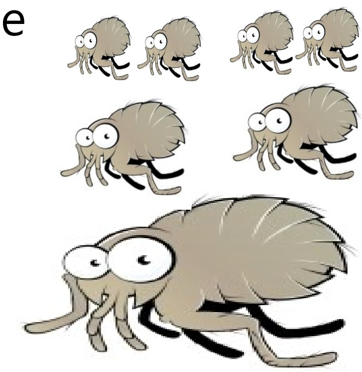
Turbulence = Σ eddies!

-Da Vinci's view



Eddies and Energy Cascade

…
a Flea Hath smaller Fleas that on him prey,
And these have smaller Fleas to bite 'em,
And so proceed *ad infinitum*. [1733 Swift]



-Richardson (1920's): concept of eddy and energy cascade

Big whorls have little whorls / That feed on their velocity

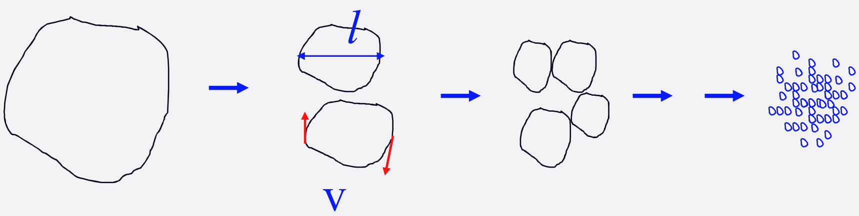
And little whorls have lesser whorls / And so on to viscosity

-Kolmogorov (1941, 1960) : Kolmogorov model

Kolmogorov theory: incompressible hydrodynamic turbulence

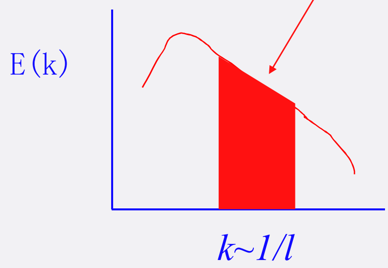
$$\left.\begin{array}{l}\dfrac{v_l^2}{t_{cas}} = \text{const} \\ t_{cas} = l/v_l\end{array}\right\} \dfrac{v_l^3}{l} = \text{const} \rightarrow v_l \propto l^{1/3}$$

Or, $v_l^2 \propto l^{2/3}$



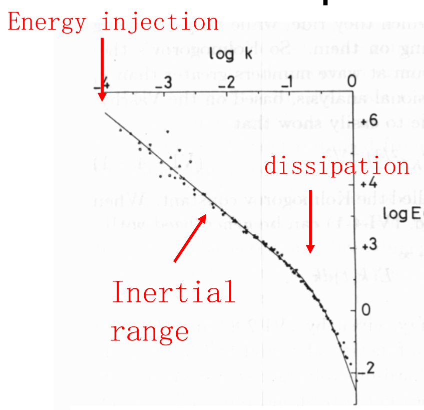
What does $v_l^2 \propto l^{2/3}$ mean?

Kinetic energy near l : v_l^2 = area ~ kE(k),
if E(k) = power law



➔ $kE(k) \propto l^{2/3}$ ➔ $E(k) \propto k^{-5/3}$

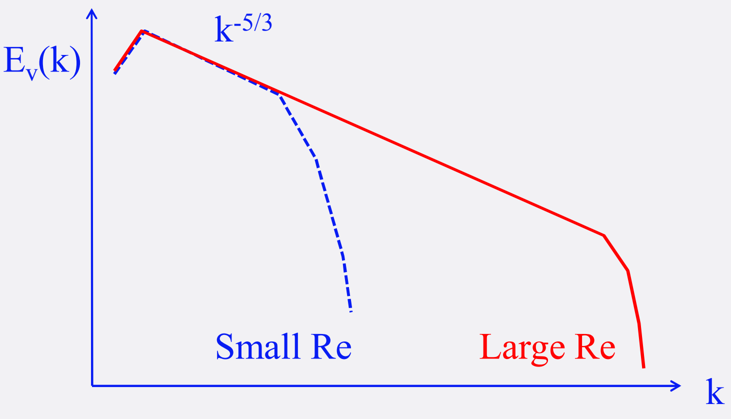
Measured spectrum (on the Earth)



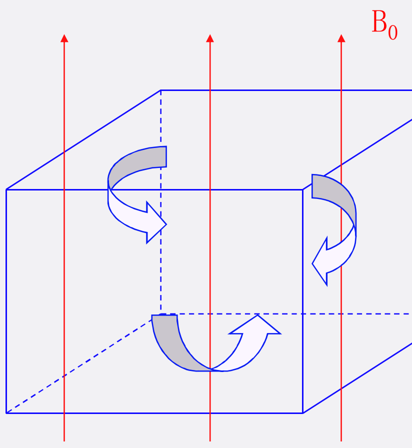
$E(k) \propto k^{-5/3}$

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

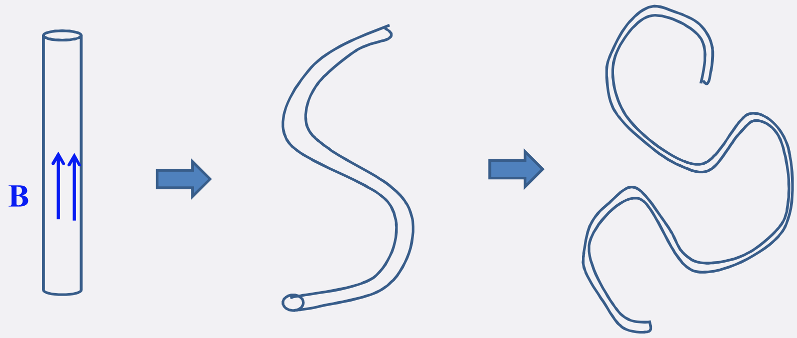
Spectrum of turbulence



Turbulence can amplify magnetic fields!



Turbulence → Stretching of flux tubes

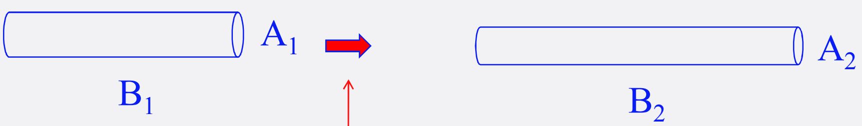


Magnetic flux tube

*In this talk, I'll assume incompressibility

Stretching → Increase of E_B

(Suppose that the fluid is incompressible)



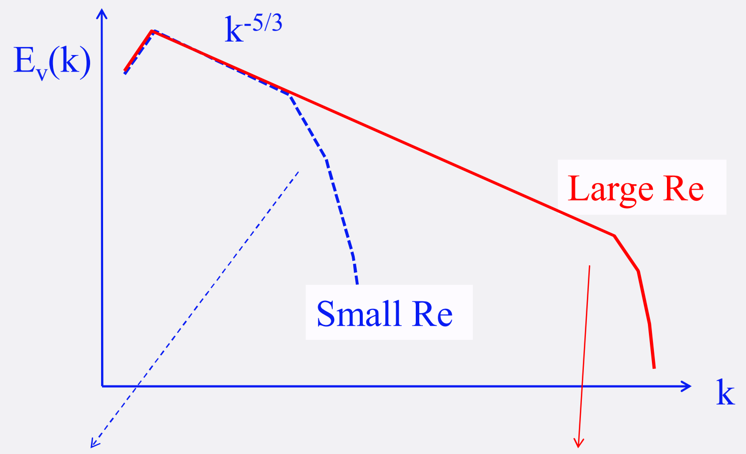
$B_1A_1=B_2A_2$

-$B_2=(A_1/A_2)B_1 > B_1$

-$B_2/8\pi > B_1/8\pi$

⇨ $B(t) \propto$ length

Turbulence dynamo and Re



Slow large-scale motions amplify B inefficiently

Fast small-scale motions amplify B very efficiently

Viscosity in the ICM: Spitzer or not?

*Efficiency of turbulence dynamo depends on viscosity

Spitzer viscosity ~ $l_{mfp}\, v_{th}$ ← l_{mfp} from Coulomb interactions

In the ICM, the mean free path can be > kpc .

e.g.) $l_{pp} > 10$kpc, $l_{ee} > 1$kpc

➔ Viscosity can be large

➔ Turbulence is not fully developed

➔ Turbulence dynamo is inefficient!

Re in the ICM

In the ICM, the Coulomb mean free path can be > kpc
e.g.) $l_{pp} > 10\text{kpc}$, $l_{ee} > 1\text{kpc}$

➔ Viscosity (~ lv) can be large

➔ $$Re \approx 28 \left(\frac{v}{400km/s}\right)\left(\frac{L}{400\ kpc}\right)\left(\frac{k_B T}{8\ keV}\right)^{-2.5}\left(\frac{n}{0.001cm^{-3}}\right)\left(\frac{\ln\Lambda}{40}\right)$$

cf) Brunetti & Lazarian (2007)

* But magnetic diffusivity is still very small

Outline

B in the ICM: Primordial or Astrophysical?

⇓

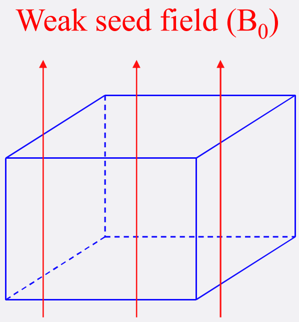
ν in the ICM: Spitzer or Not?

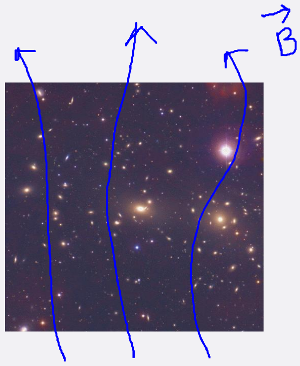
$\nu \sim \nu_{Spitzer}$ → B in the ICM =Astrophysical!

$\nu << \nu_{Spitzer}$ → B in the ICM =?

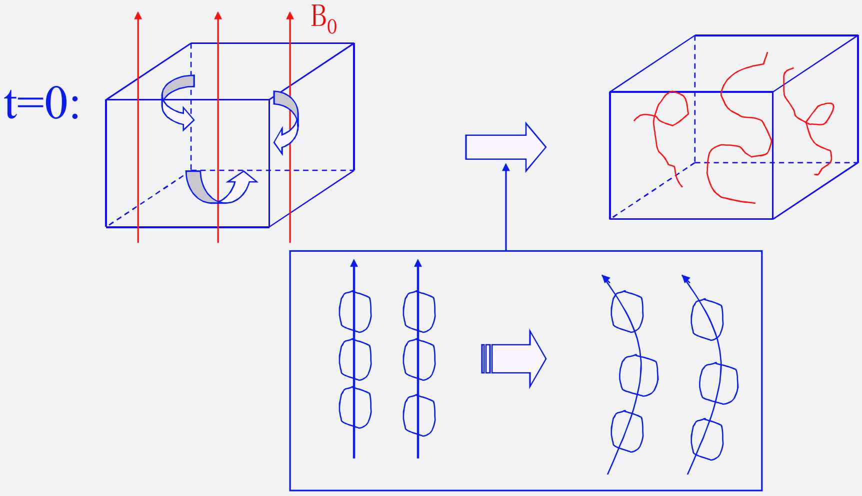
Topic 1: Turbulence dynamo in the limit of $\nu \rightarrow 0$ ($Re \rightarrow \infty$)

- Let's first consider a primordial seed first
  ➔ How can MHD turbulence amplify the seed fields?





Stretching of field lines

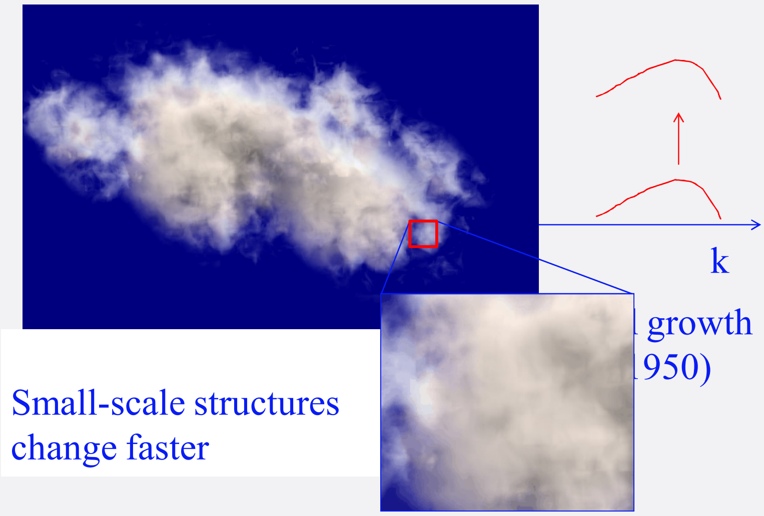


Fluid elements and field lines move together

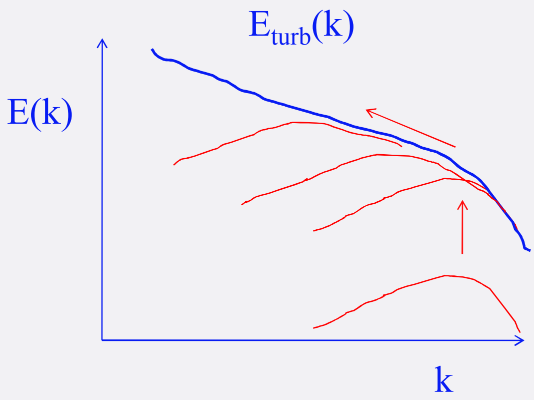
*Back reactions are negligible if $E_{mag} < E_{kin}$

Expectations:

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



Expectations:



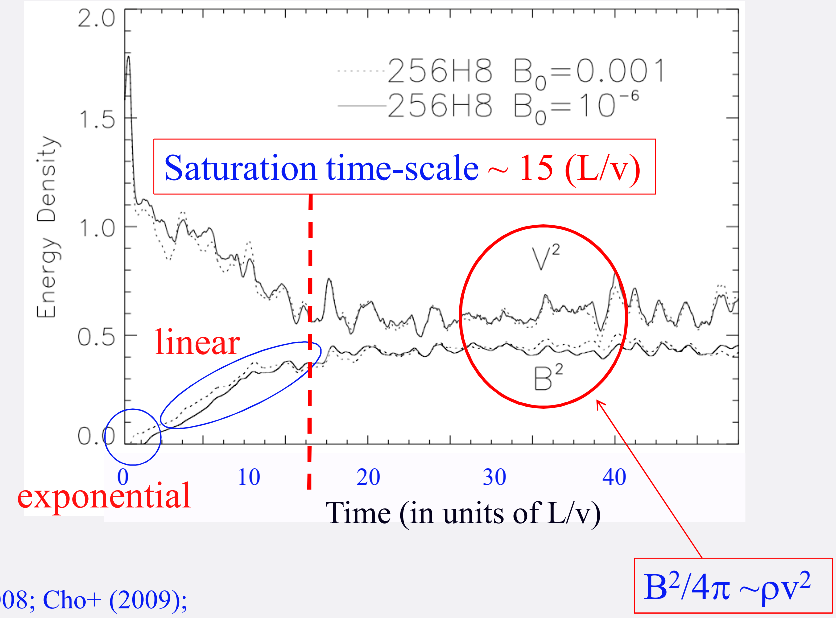
What will happen when $E_{turb} \sim E_{mag}$ on the dissipation scale?

➔ Exponential growth stage will end!

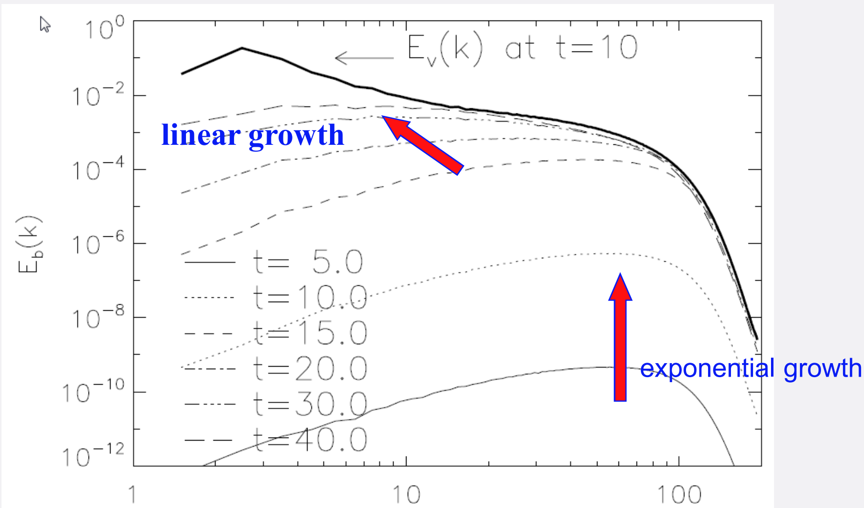
➔ Stretching scale gradually moves to larger scales.

(see, for example, Cho & Vishniac 2000)

Results of simulations



Ryu+2008; Cho+ (2009);
See also Schlueter & Bierman (1950)



Cho et al. (2009)

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

Conclusions for Topic 1

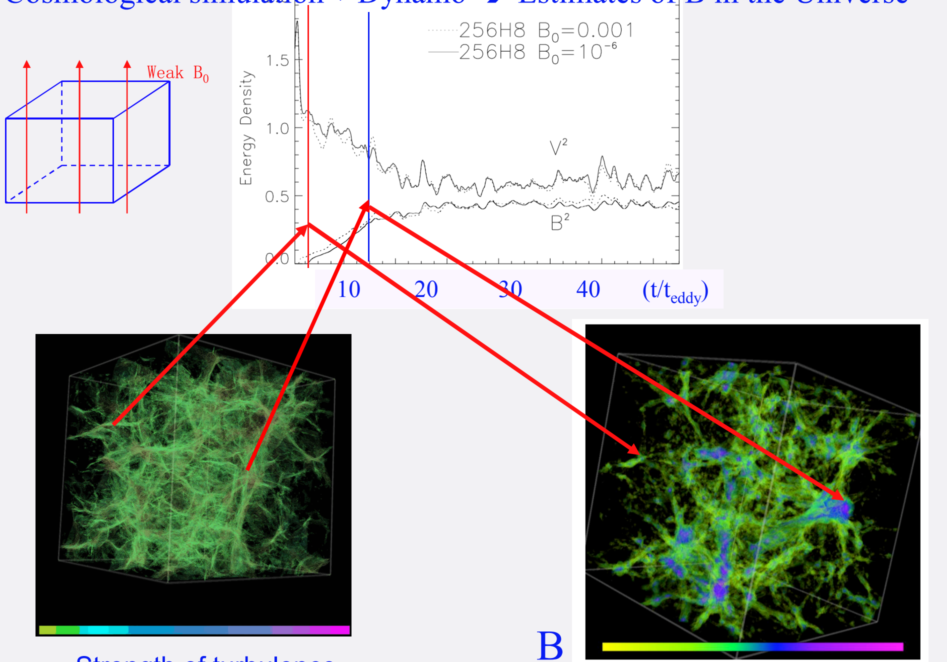
-Turbulence can amplify any uniform weak seed B fields
-Two stages of amplification: exp. and linear
-Saturation time-scale ~15 (L/v)
(Strength of B_0 doesn't matter much when Re →∞)

Example) Cluster with a driving scale of 300kpc:
L~300kpc, v~300km/s ➔ L/v ~ 1 billion years

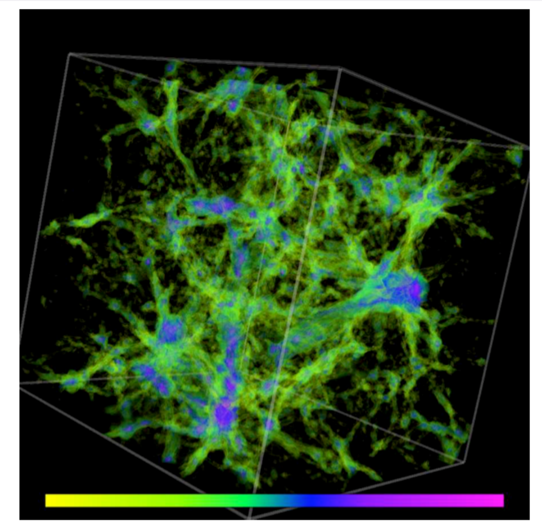
➔ Growth of B ends in t ~ 15(L/v) ~ 15 billion years!

➔ $B_{saturation}$ ~ 10 μG ← $B^2/4\pi \sim \rho v^2$

Cosmological simulation + Dynamo ➔ Estimates of B in the Universe



Strength of turbulence



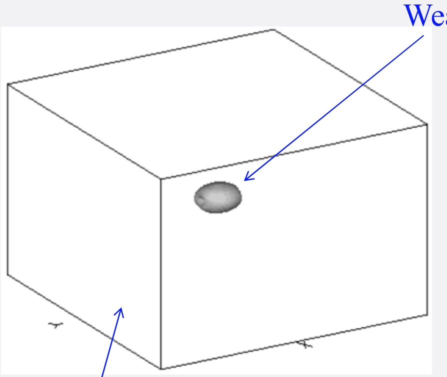
0.1nG 10μG

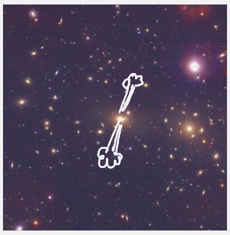
Ryu et al (2008)

Observed strength of B:
In clusters: ~ μG
In filaments: ~10 nG (?)
In voids: ?

Topic 1-2: Growth of a localized seed field in the limit of $\nu \rightarrow 0$ ($Re \rightarrow \infty$)

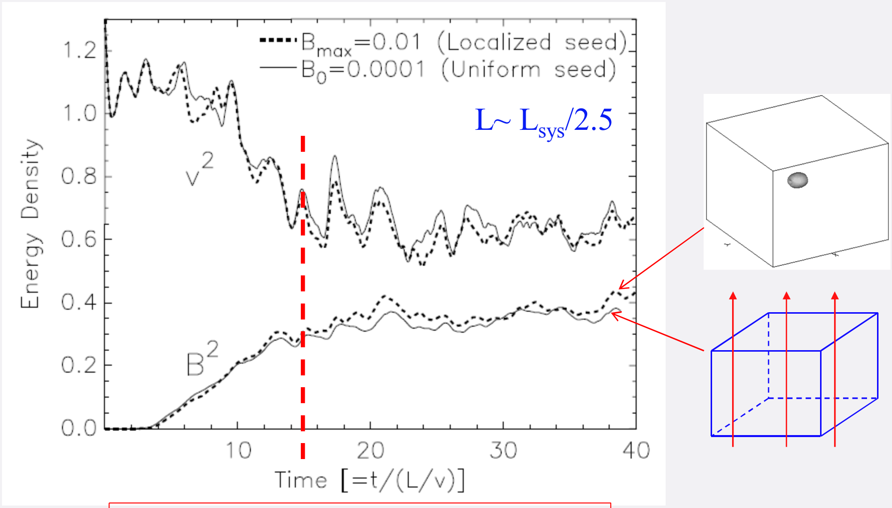
Weak localized seed field





Fully-developed turbulence

If L ~ L_{sys}, results are similar for a localized seed & a uniform seed !



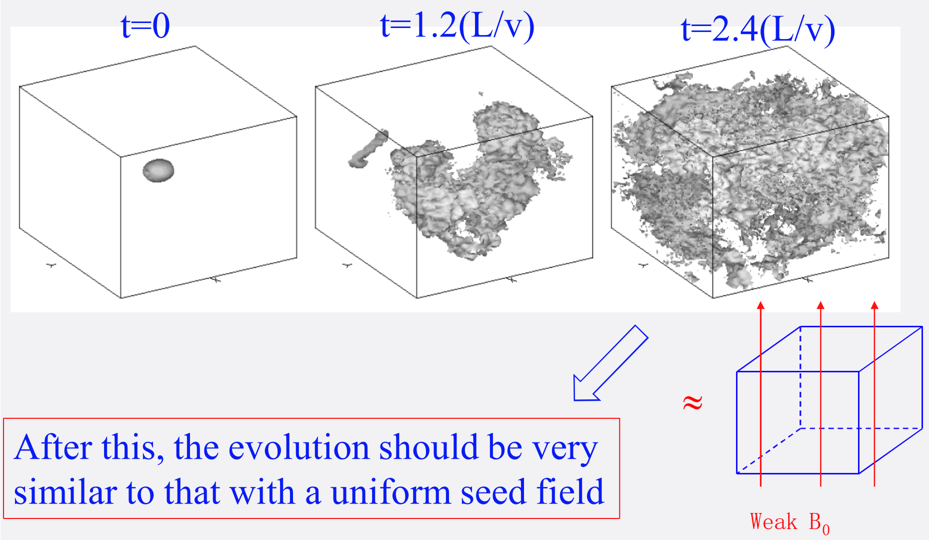
Saturation time-scale ~ 15 (L/v)

Cho & Yoo (2012)

ν=η=small

Why are the results so similar?

➔ Answer: fast magnetic diffusion or fast homogenization!



After this, the evolution should be very similar to that with a uniform seed field

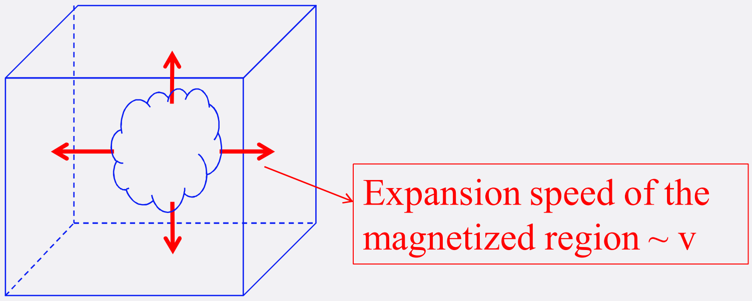
Homogenization time

-For a cluster with v~300km/s, L=300kpc, and L_{sys}=1Mpc,

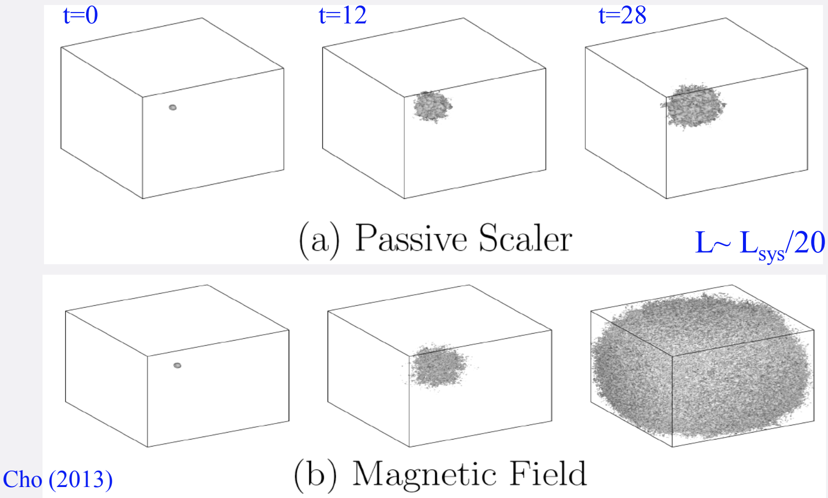
➔ Homogenization time ~ 3 (L/v) ~ 3×10^9 yrs

-In general, homogenization time ~ $L_{sys}/v = (L_{sys}/L)(L/v)$

➔ If $L \sim L_{sys}$, homogenization is fast



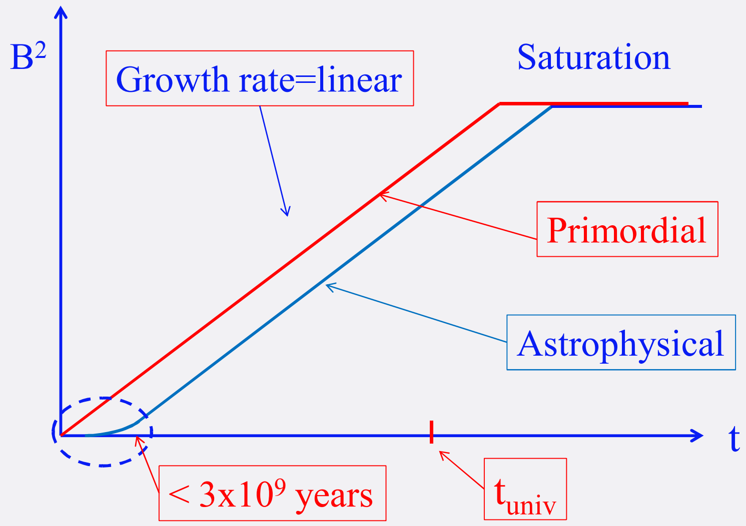
Homogenization time-scale?



$V_{exp} \sim v$ ➔ Homogenization time ~ $L_{sys}/v = (L_{sys}/L)(L/v)$

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

Summary for Topic 1: If viscosity→0 (or Re →∞),…



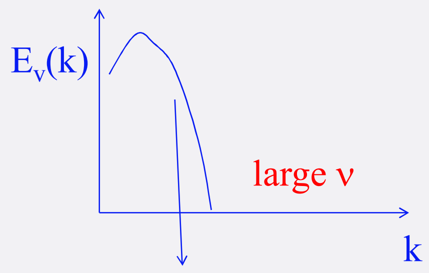
→Initial conditions are wiped out in clusters!
→It's difficult to know the origin in clusters

Implications for observations

- Homogenization time-scale (L_{sys}/v) is important
- For a cluster of size 1Mpc:
  - If $v > 75$ km/s, $L_{sys}/v <$ age of the universe
  - → It is difficult to tell the origin.
- For a filament of size 4Mpc:
  - If $v > 300$ km/s, $L_{sys}/v <$ age of the universe
  - So, if $v<300$ km/s, B field in the filament can be inhomogeneous
    - → RM measurements for filaments will be useful!

$\nu=\eta=$small

Topic 2. Turbulence dynamo in fluids with large ν



Slow large-scale motions amplify B inefficiently

* Exponential growth stage most of the time
  ← e-folding time ~ O(L/v)
* Dynamo stops when $B^2/4\pi \sim \rho v^2$
  → $B_{saturation}$ ~ 10 μG for a cluster with v~300km/s

Expectations

At the exponential growth stage we have

$B^2(t) \propto B_0^2 \exp(t/\tau_d)$ ⇐ $\tau_d \propto l_d/v_d$

→At saturation stage, we have $B_{eq}^2 \propto B_0^2 \exp(t/\tau_d)$

* $B_{eq}^2/4\pi \sim \rho v^2$

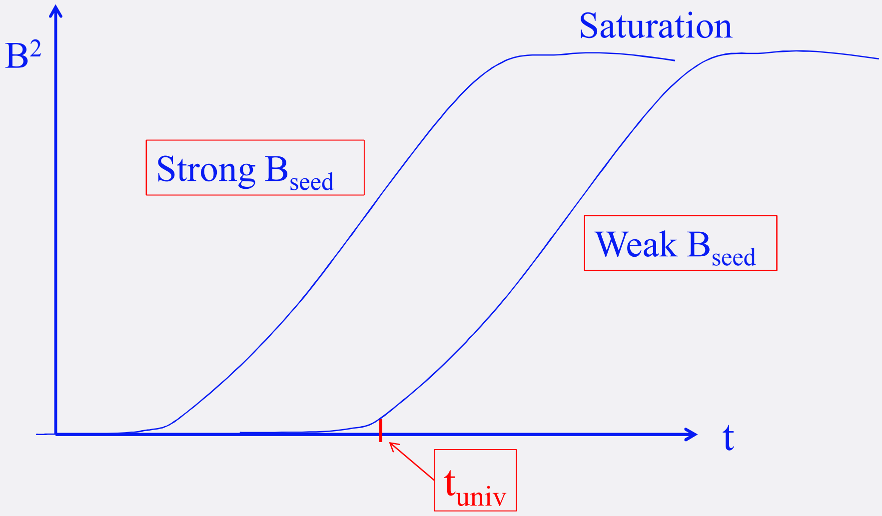
→If Re ~ O(1), we have $t \sim (L/v) \ln B_{eq}^2/B_0^2$

→ $t=t_H$ (=Hubble time) gives $B_{0,crit} \sim B_{eq} \exp(-t_H v/2L)$

→If (L/v)~10^9 years and B_{eq}~10μG, we have

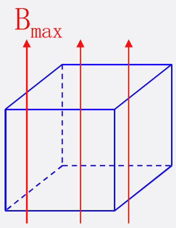
$B_{0,crit} \sim 0.1\mu G$

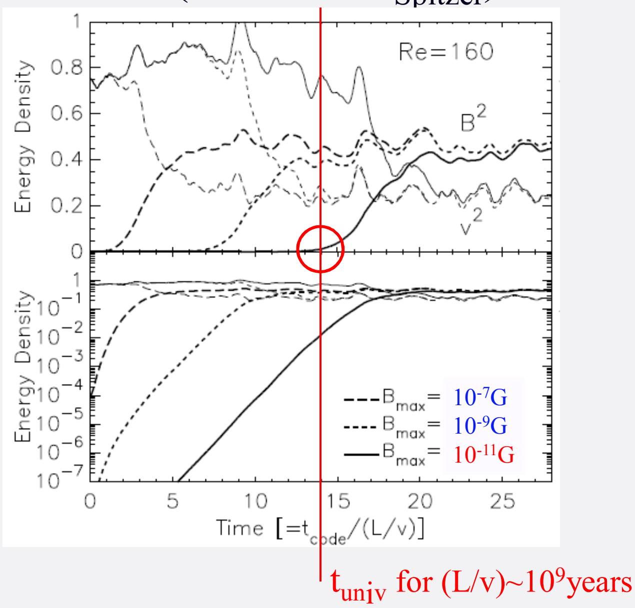
If Spitzer, strength of B_{seed} matters!



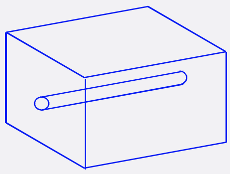
* Note : If $\nu \ll \nu_{Spitzer}$, the strength of B_{seed} doen't matter much

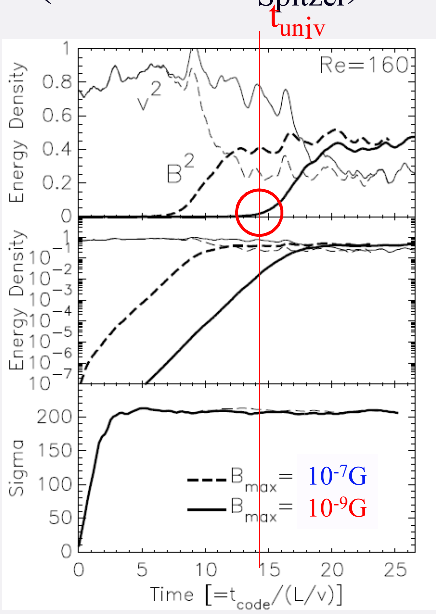
Simulation results (for $\nu \sim 0.2 \nu_{Spitzer}$)

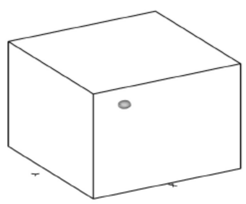




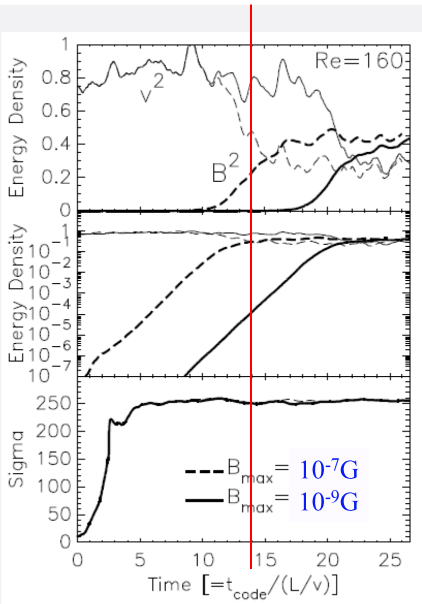
Simulation results (for $\nu \sim 0.2 \nu_{Spitzer}$)





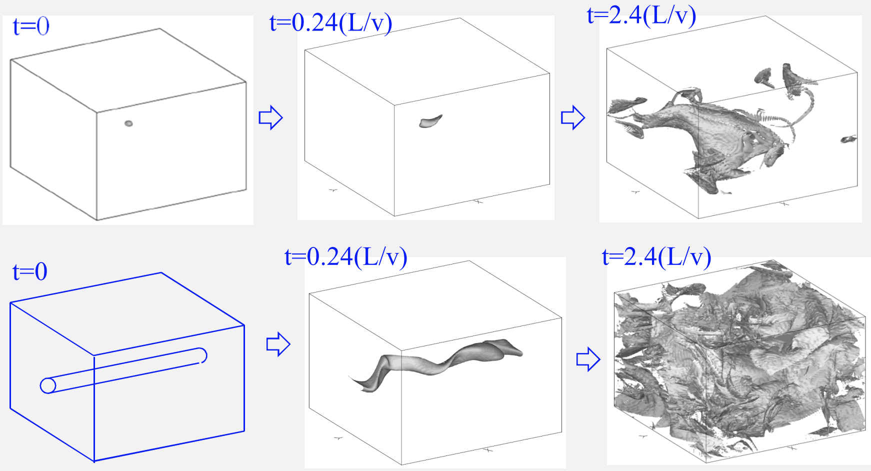


(a) t=0



The shape doesn't matter much

-Homogenization of a localized seed field is fast!



Cho (2014)

Conclusions for Spitzer viscosity

- Turbulence dynamo is inefficient

  ➔ Strength of the seed field matters

- ~~Primordial B should be stronger than 10^{-11}G~~

  ~~➔ It's close to the upper limit of 10^{-9}G~~ ← CMB

- Astrophysical B should stronger than 10^{-9}G

  ➔ It may be easy to satisfy the condition!

- **Therefore, if the Spitzer viscosity is correct, primordial seed B may not be the origin!**

Conclusion for Topic 2

If Re~ O(100), B_0 less than 10^{-11}G cannot be the origin of cosmic B field!

Note 1) If Re ~ 1000, B_0 can be as small as 10^{-13}G

Note 2) Biermann battery can generate seed fields of order 10^{-20} G…

Note 3) CMB observations : upper limit for B_0 ~10^{-9}G

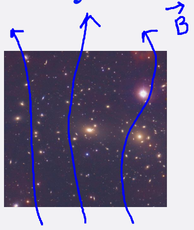
Effects of compression

In galaxy clusters, shocks and mergers can compress fluids and influence growth of magnetic field (Roettiger + 1999; Dolag+ 1999, 2002; Iapichino & Bruggen 2012)

Simulations (e.g. Dolag+ 99) show that the effects enhance the strength of B by a factor of ~30

➔ Strength of B_{seed} can be a bit smaller

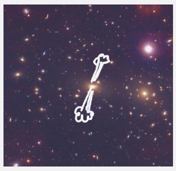
Summary of the Talk



Primordial?

⇨ If $\nu \sim \nu_{Spitzer}$, it's almost ruled out

⇨ If $\nu << \nu_{Spitzer}$, it can be the origin



Astrophysical?

⇨ It can be the origin in any case