Magnetic Fields in the Cosmic Web

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with

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and etc

- A brief review on what we know about cosmic B
- A model for cosmic magnetic fields
- Possibility of detecting of cosmic B through RM with SKA

Magnetic field is ubiquitous in the Universe!

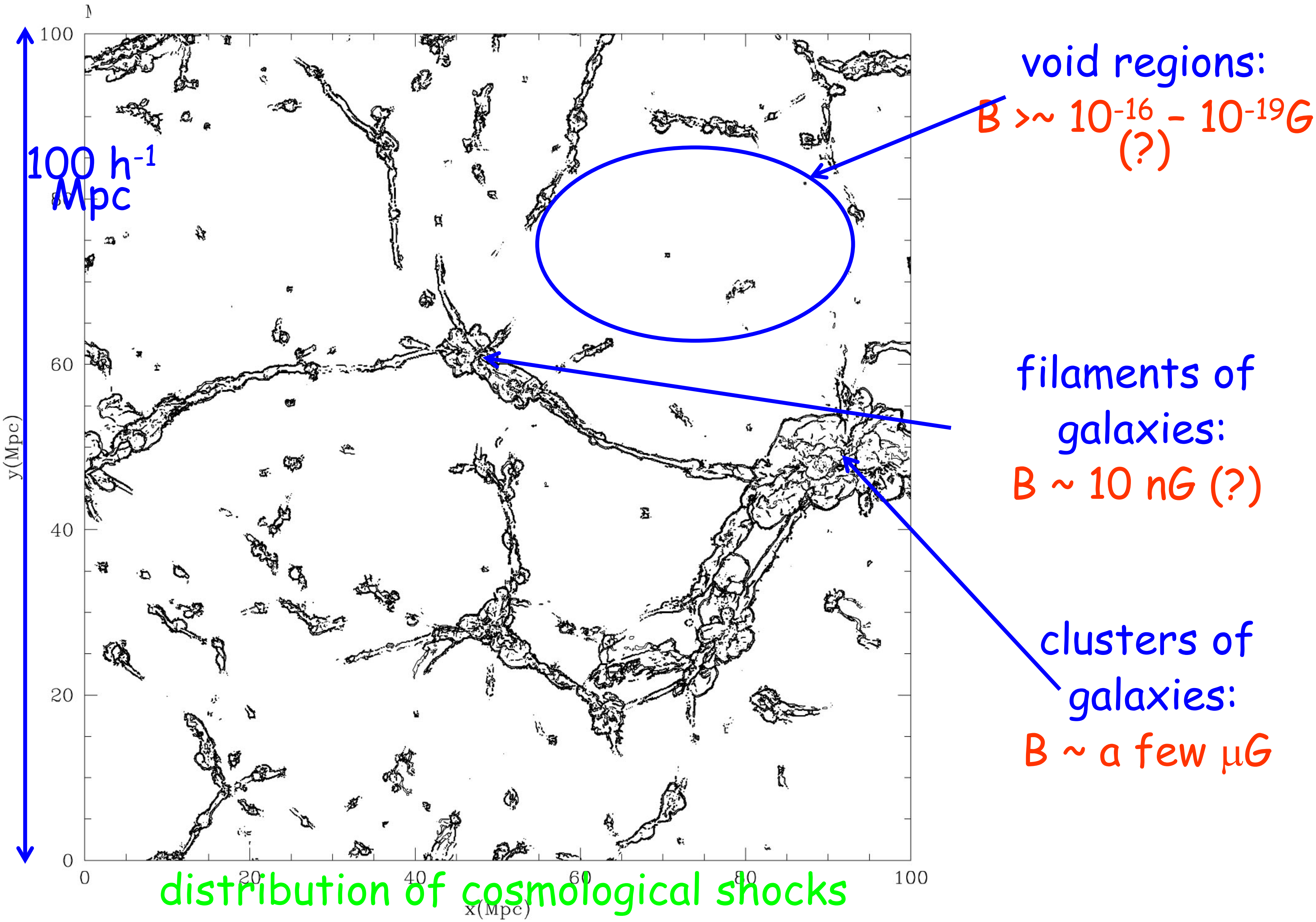
Star	
Magnetar	$\sim 10^{13}$ - 10^{15} G
Neutron star	$\sim 10^{11}$ - 10^{13} G
White dwarf	$\sim 10^{6}$ G
Ap/Bp star	$\sim 10^{3}$ G
Normal star	~ 1 G
Molecular cloud	$\sim 10^{-3}$ G
Interstellar medium	$\sim$ several $\times 10^{-6}$ G
Cluster of galaxies	$\sim$ a few $\times 10^{-6}$ G
Filament of galaxies	$\sim 10^{-10}$ G (?)
Void	$\sim 10^{-16}$ G (?)
Early universe	$\sim 10^{-20}$ G (?)
Planck mass monopole	$\sim 10^{55}$ G

↑ stronger field

↓ larger scale

Cluster of galaxies, Filament of galaxies, Void → cosmic magnetic fields

Cosmic magnetic fields

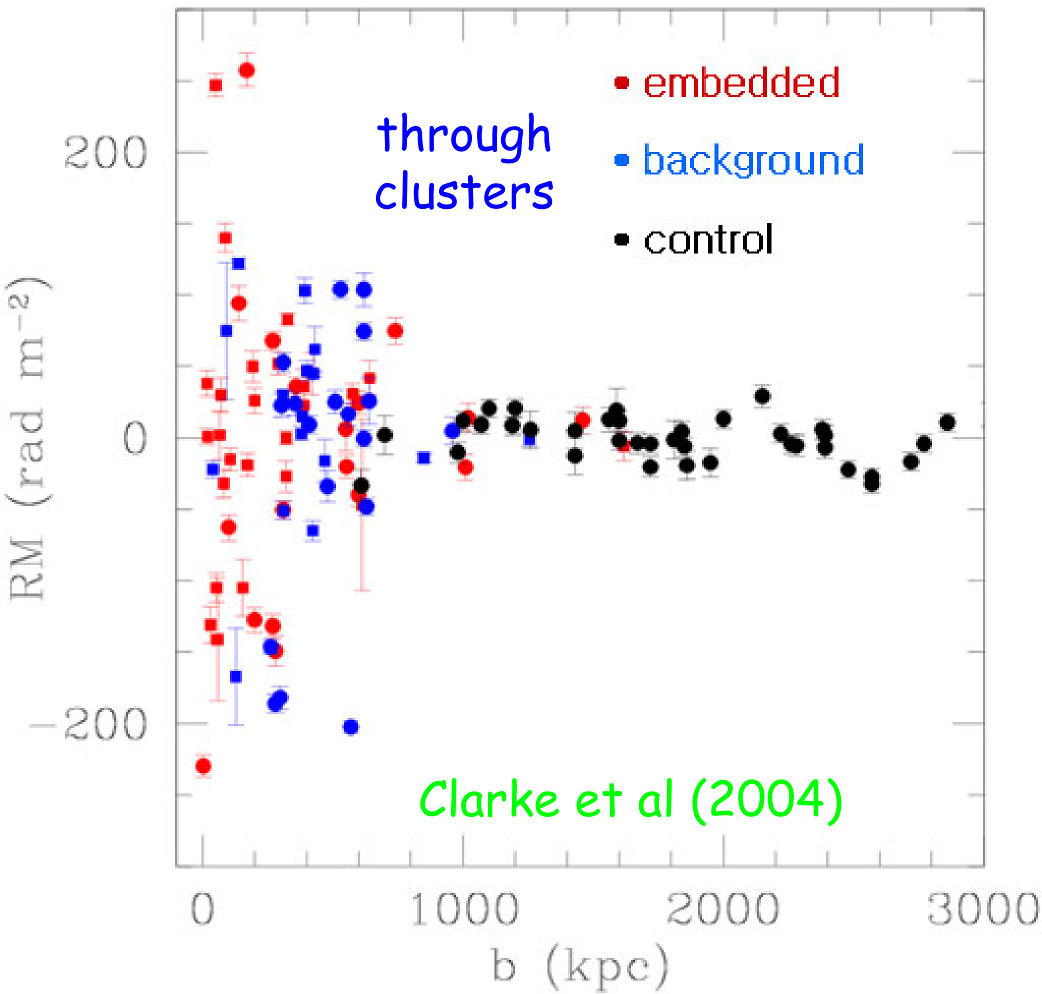


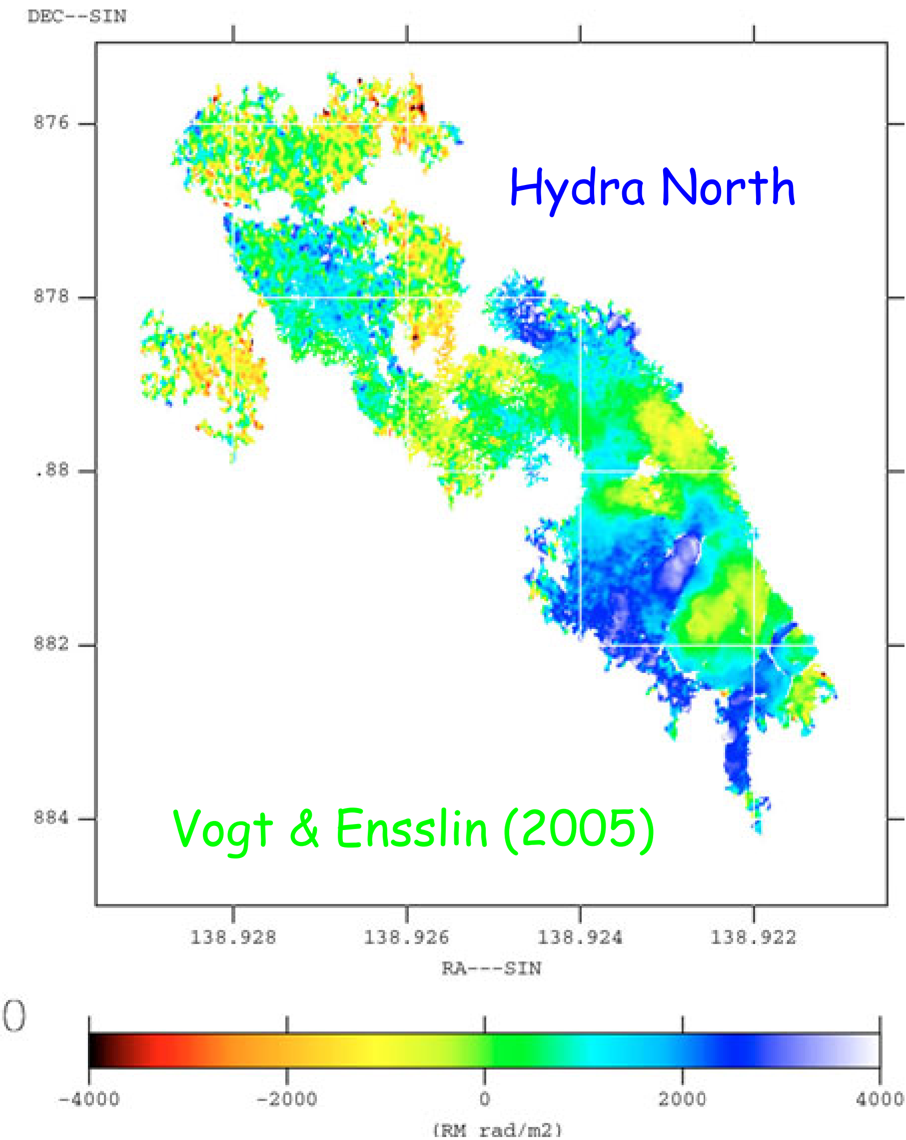
distribution of cosmological shocks

Clusters of galaxies - magnetic fields

Faraday rotation measure of a few x 100 rad/m^2

-> B ~ a few μG





Clusters of galaxies – numbers and energetics

density of baryonic matter	$n \sim 10^{-2}\,\mathrm{cm}^{-3}$
flow velocity	$\upsilon \sim \mathrm{several} \times 10^{2}\ \mathrm{km/s}$
gas temperature	$T \sim 10^{8}\,\mathrm{K}$
magnetic fields	$B \sim \mathrm{a\ few}\ \mu\mathrm{G}$

gas thermal energy	$E_{\mathrm{thermal}} \sim 10^{-10}\,\mathrm{erg/cm}^{3}$
gas kinetic energy	$E_{\mathrm{kinetic}} \sim 10^{-11}\,\mathrm{erg/cm}^{3}$
cosmic-ray energy	$E_{\mathrm{cosmic\text{-}ray}} \sim 10^{-11}\,\mathrm{erg/cm}^{3}$
magnetic energy	$E_{\mathrm{magnetic}} \sim \mathrm{a\ few} \times 10^{-12}\,\mathrm{erg/cm}^{3}$

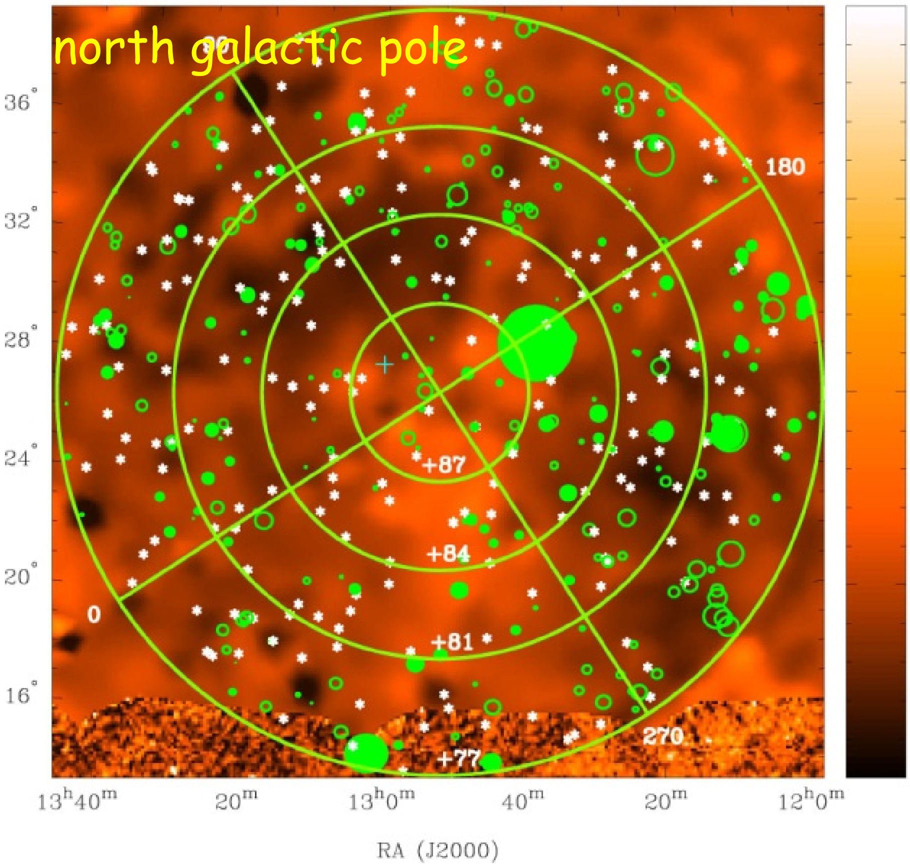
magnetic fields
<- turbulence dynamo + feedbacks from galaxies

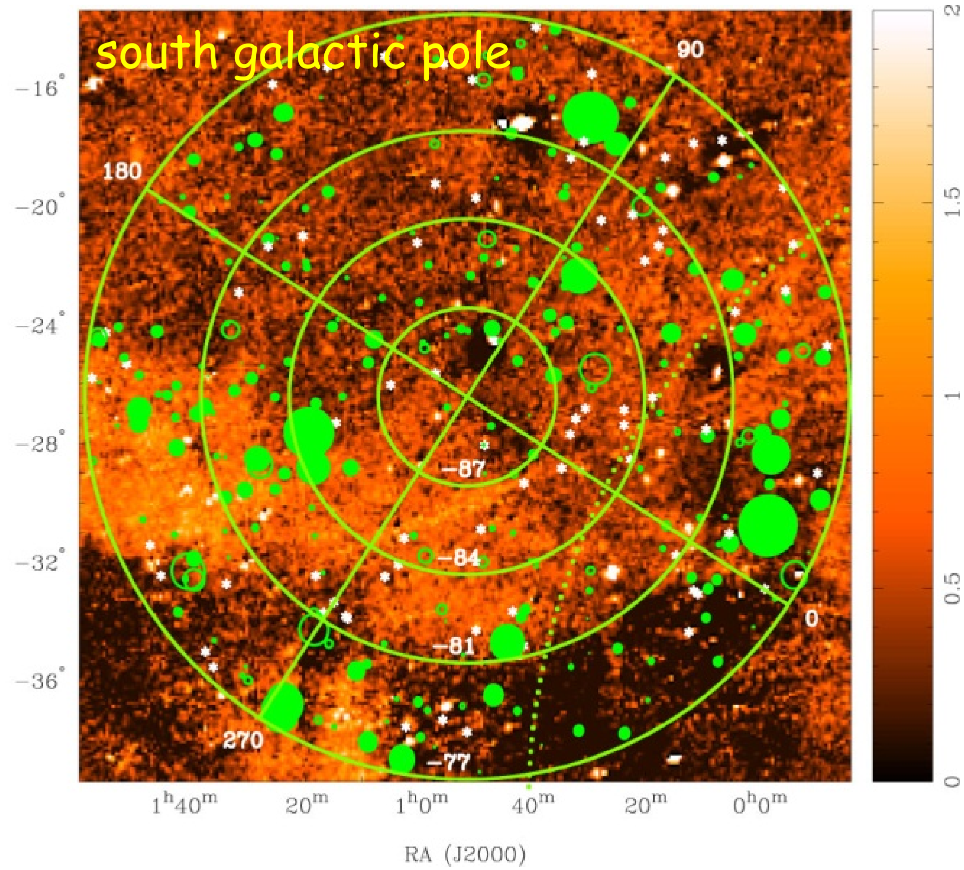
Filaments of galaxies - magnetic fields

Faraday rotation measure of several rad/m^2

-> B ~ 10 nG

Mao et al (2010), Stil et al (2011)





-> extragalactic contribution of ~6 rad/m^2

Schnitzeler et al (2010)

Filaments of galaxies – numbers and energetics

density of baryonic matter $n \sim 10^{-5}\,\mathrm{cm}^{-3}$

flow velocity – divergent comp. $\upsilon_{\mathrm{div}} \sim \text{a few} \times 10^{2}\ \mathrm{km/s}$

flow velocity – curl comp. $\upsilon_{\mathrm{curl}} \sim 10^{2}\ \mathrm{km/s}$

gas temperature $T \sim 10^{6}\,\mathrm{K}$

magnetic fields $B \sim 10\,\mathrm{nG}\ (?)$

gas thermal energy $E_{\mathrm{thermal}} \sim 10^{-15}\,\mathrm{erg/cm}^{3}$

gas kinetic energy – divergent motion $E_{\mathrm{div}} \sim 10^{-14}\,\mathrm{erg/cm}^{3}$

gas kinetic energy – turb. motion $E_{\mathrm{turb}} \sim 10^{-15}\,\mathrm{erg/cm}^{3}$

cosmic-ray energy $E_{\mathrm{cosmic\text{-}ray}} \sim 10^{-15}\,\mathrm{erg/cm}^{3}\,(?)$

magnetic energy $E_{\mathrm{magnetic}} \sim 10^{-17}\,\mathrm{erg/cm}^{3}\,(?)$

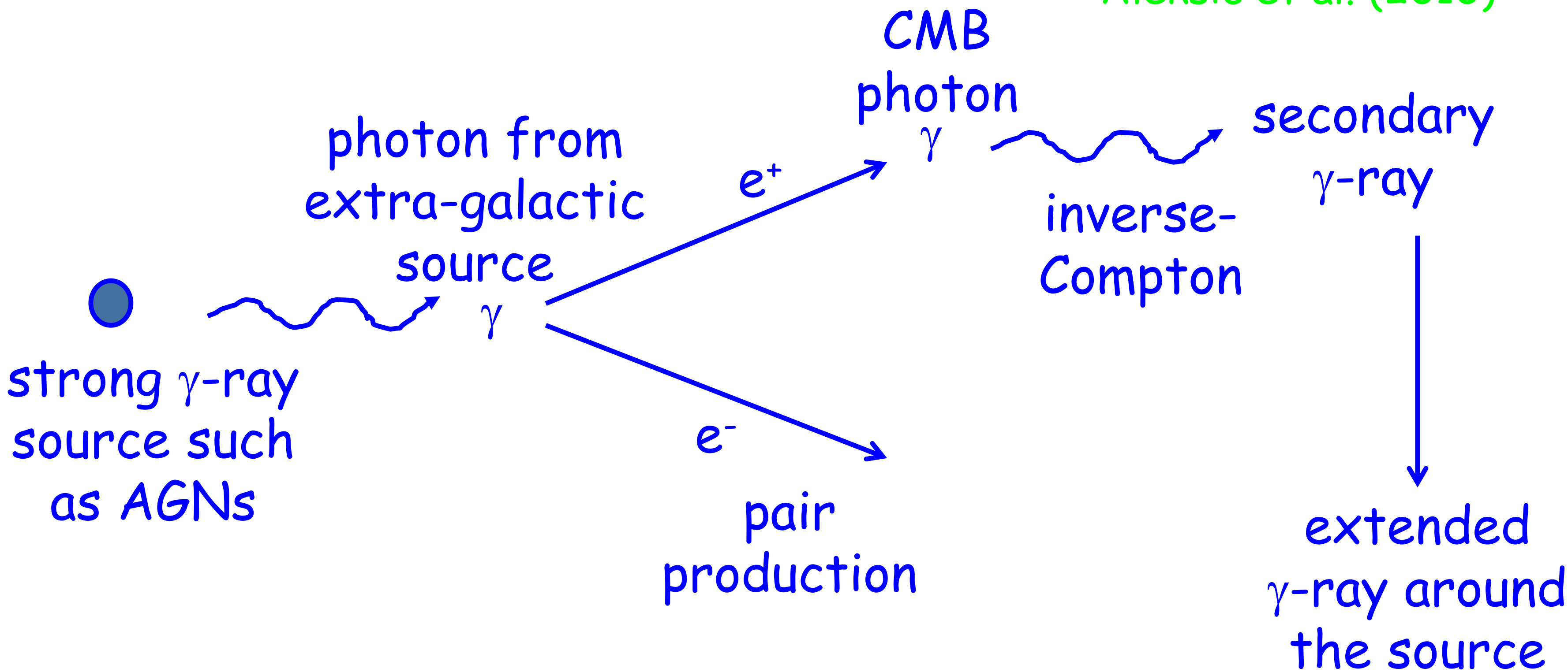
magnetic fields <- turbulence dynamo ?

Void regions - magnetic fields

Lack of extended GeV γ-ray emission around AGNs

-> $B \gtrsim 10^{-16}$ G

Neronov & Vovk (2010)
Aleksic et al. (2010)



no observation of extended γ-ray around sources
-> evidence of magnetic defection along the path
from the source to the observer

$B \gtrsim 10^{-16}$ or 10^{-19}G in void regions!

Void regions - numbers and energetics

density of baryonic matter	$n \sim 10^{-8}\,\mathrm{cm}^{-3}$
flow velocity - divergent comp.	$\upsilon_{\mathrm{div}} \sim 10^{2}\ \mathrm{km/s}$
flow velocity - curl comp.	$\upsilon_{\mathrm{curl}} \sim 1\,\mathrm{km/s}\ \ (?)$
gas temperature	$T \sim 10^{4}\,\mathrm{K}$
magnetic fields	$B \sim 10^{-16}\ \mathrm{G}\ (?)$
gas thermal energy	$E_{\mathrm{thermal}} \sim 10^{-20}\,\mathrm{erg/cm}^{3}$
gas kinetic energy - divergent motion	$E_{\mathrm{div}} \sim 10^{-18}\,\mathrm{erg/cm}^{3}$
gas kinetic energy - turb. motion	$E_{\mathrm{turb}} \sim 10^{-22}\,\mathrm{erg/cm}^{3}\ \ (?)$
cosmic-ray energy	$E_{\mathrm{cosmic\text{-}ray}} \sim 10^{-22}\,\mathrm{erg/cm}^{3}\ \ (?)$
magnetic energy	$E_{\mathrm{magnetic}} \sim 10^{-33}\,\mathrm{erg/cm}^{3}\,(?)$

origin and nature of magnetic fields <- not yet known !!

Magnetic field is ubiquitous in the Universe!

Star	
Magnetar	~ 10^{13} - 10^{15} G
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Planck mass monopole	~ 10^{55} G

stronger field ↑ larger scale ↓

main foucs

Origin of cosmic magnetic fields

- **<u>turbulence induced at shocks in the LSS of the universe</u>**

  <u>+ turbulence dynamo with weak seed fields</u> (Ryu et al 2008)

  → probably energetically most important

- AGN outflows, galactic winds, … (Kronberg et al 2001)

  → <B> ~ 10 - 100 nG in the cosmic web (?)

- microscopic instabilities such as mirror instab, fire-hose instab,
  macroscpic instabilities such cosmic-ray induced instab,
  cosmic-ray flux,
  and etc

  → not yet clear!

A model for B in clusters and filaments:
B from the large-scale structure formation

large-scale structure formation

gravitational collapse & flow motions

cosmological shocks

shock dissipation

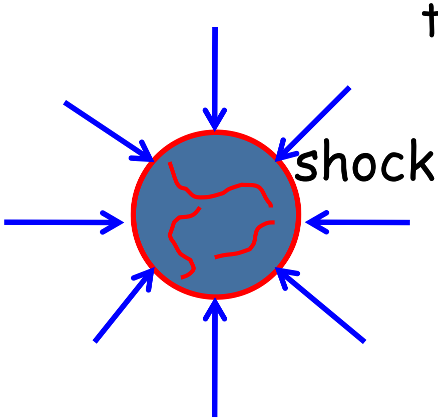
generation of heat
fresh acc. & re-acc. of CRs
genera. of magnetic fields
generation of vorticity

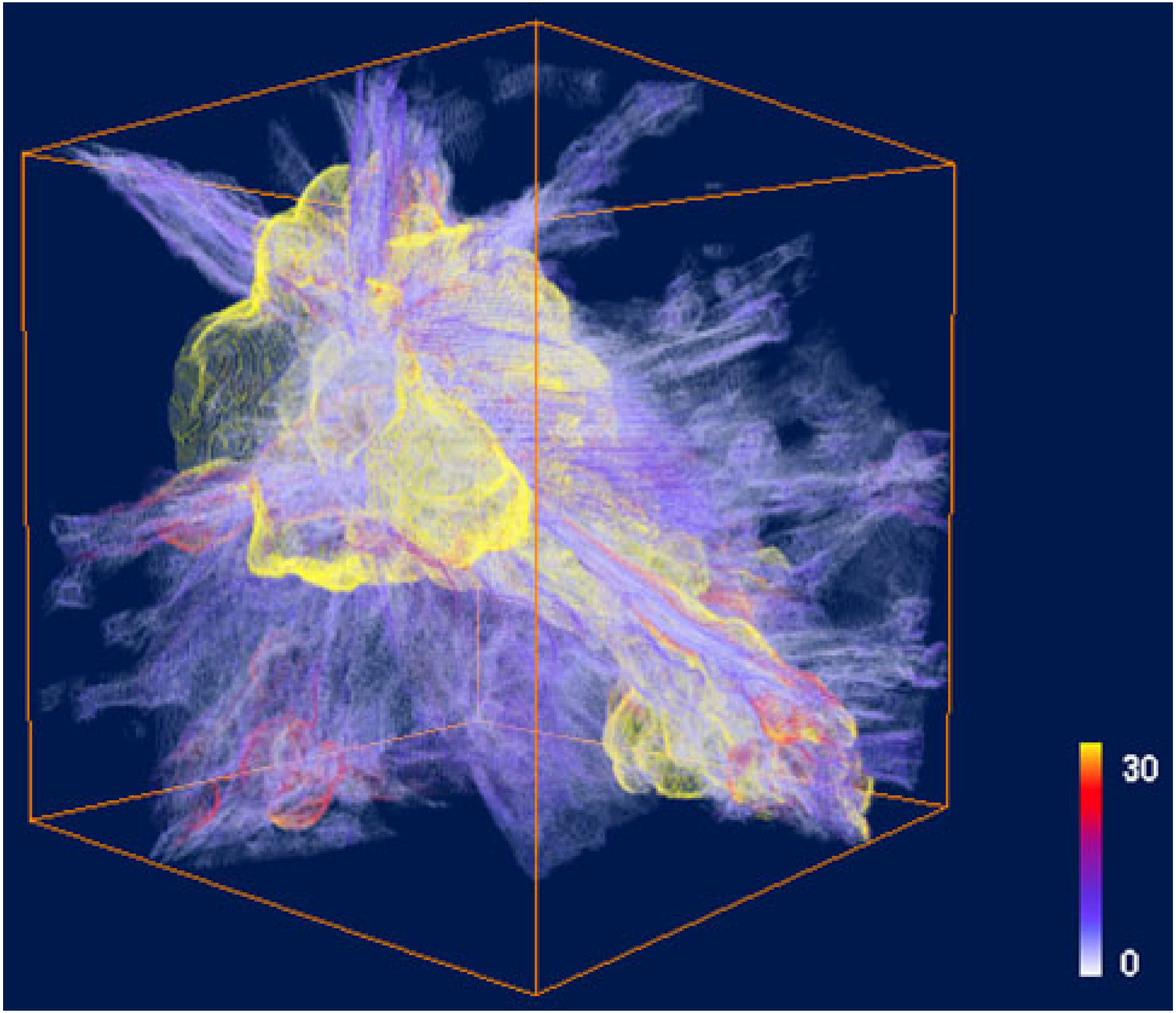
cascade into turbulence

turbulent amp. of mag. fields
turbulent acceleration of CRs

the main channel to flow the gravitational energy to the intergalactic medium

(gravity is the ultimate source of energy in astrophysics!)



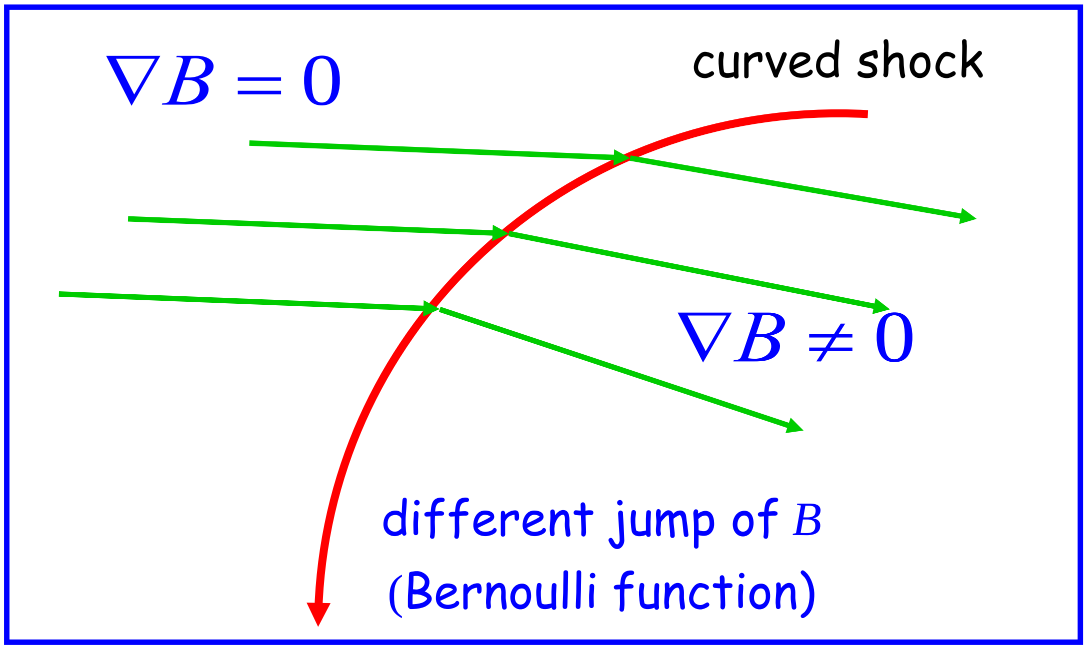


Mach number distribution of shocks around the cluster complex

Ryu et al (2003)

Vorticity generated at cosmological shocks

directly at curved shocks

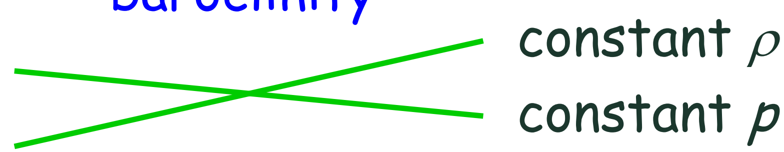


⟹ at postshock

$$\varpi_{\rm cs} \sim \frac{(\rho_2 - \rho_1)^2}{\rho_2 \rho_1} \frac{\vec{U} \times \vec{n}}{R}$$

ρ_1 preshock density
ρ_2 postshock density
$\vec{U}$ preshock flow speed
$\vec{n}$ unit normal to shock surf.
R curvature radius of surf.

baroclinity



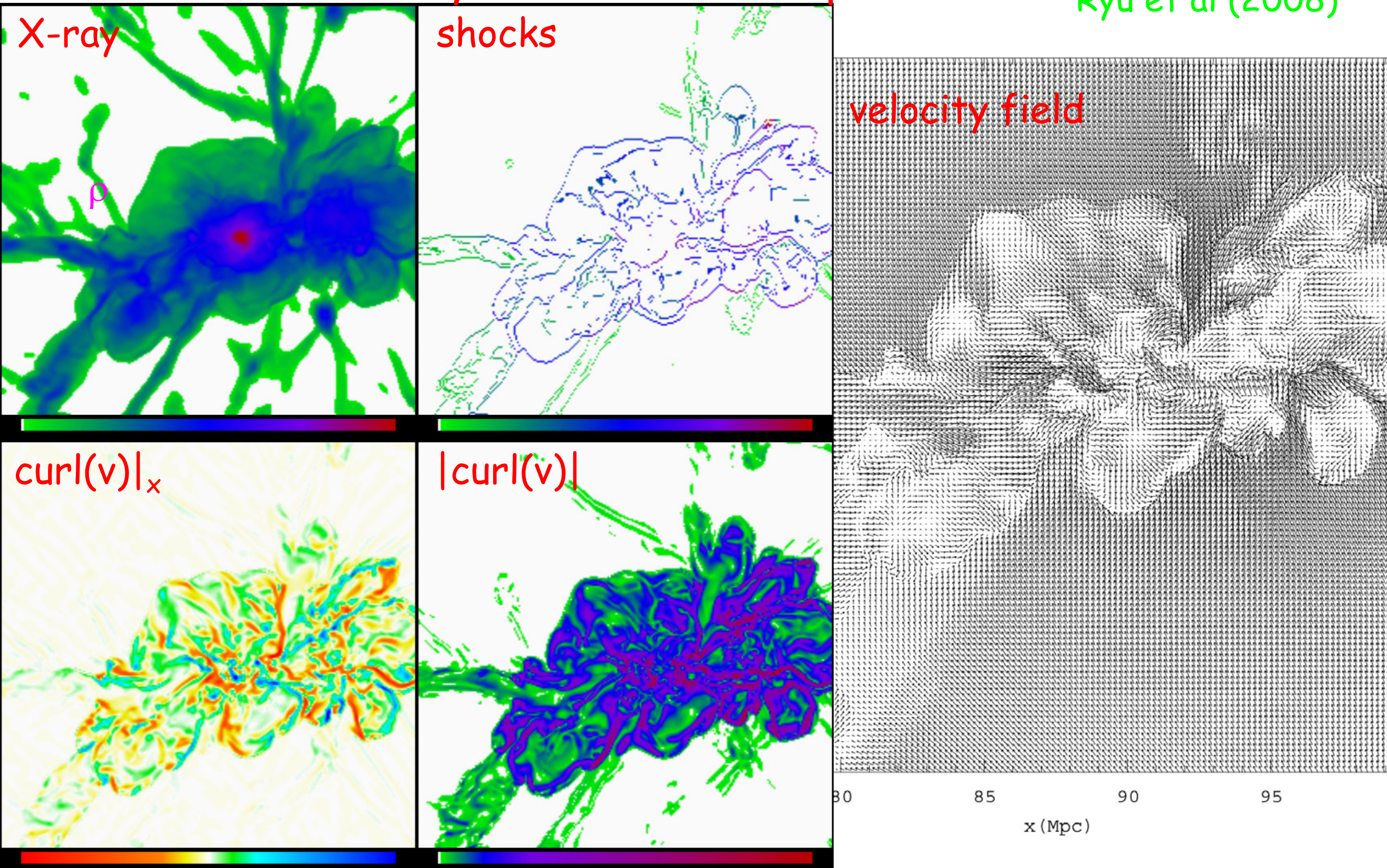
by the baroclinic term

$$\dot{\varpi}_{\rm bc} = \frac{1}{\rho^2} \vec{\nabla}\rho \times \vec{\nabla} p$$

⟸ due to entropy variation induced at shocks

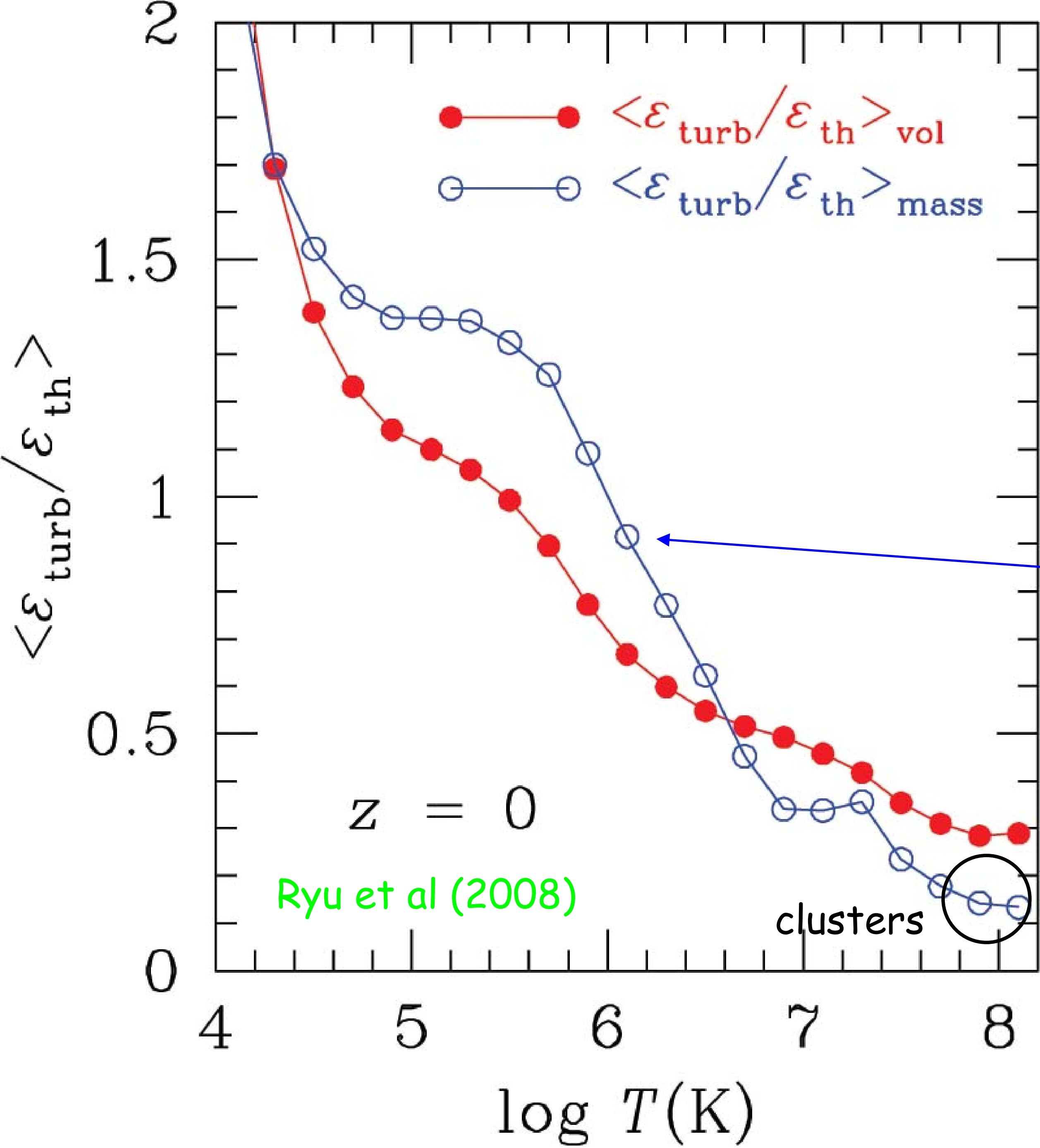
Vorticity in a cluster complex

Ryu et al (2008)



-1500 kms^{-1} / 300 kpc 1500 kms^{-1} / 300 kpc 6 kms^{-1} / 300 kpc 2000 kms^{-1} / 300 kpc

(25 h^{-1}Mpc)^2 2D slice



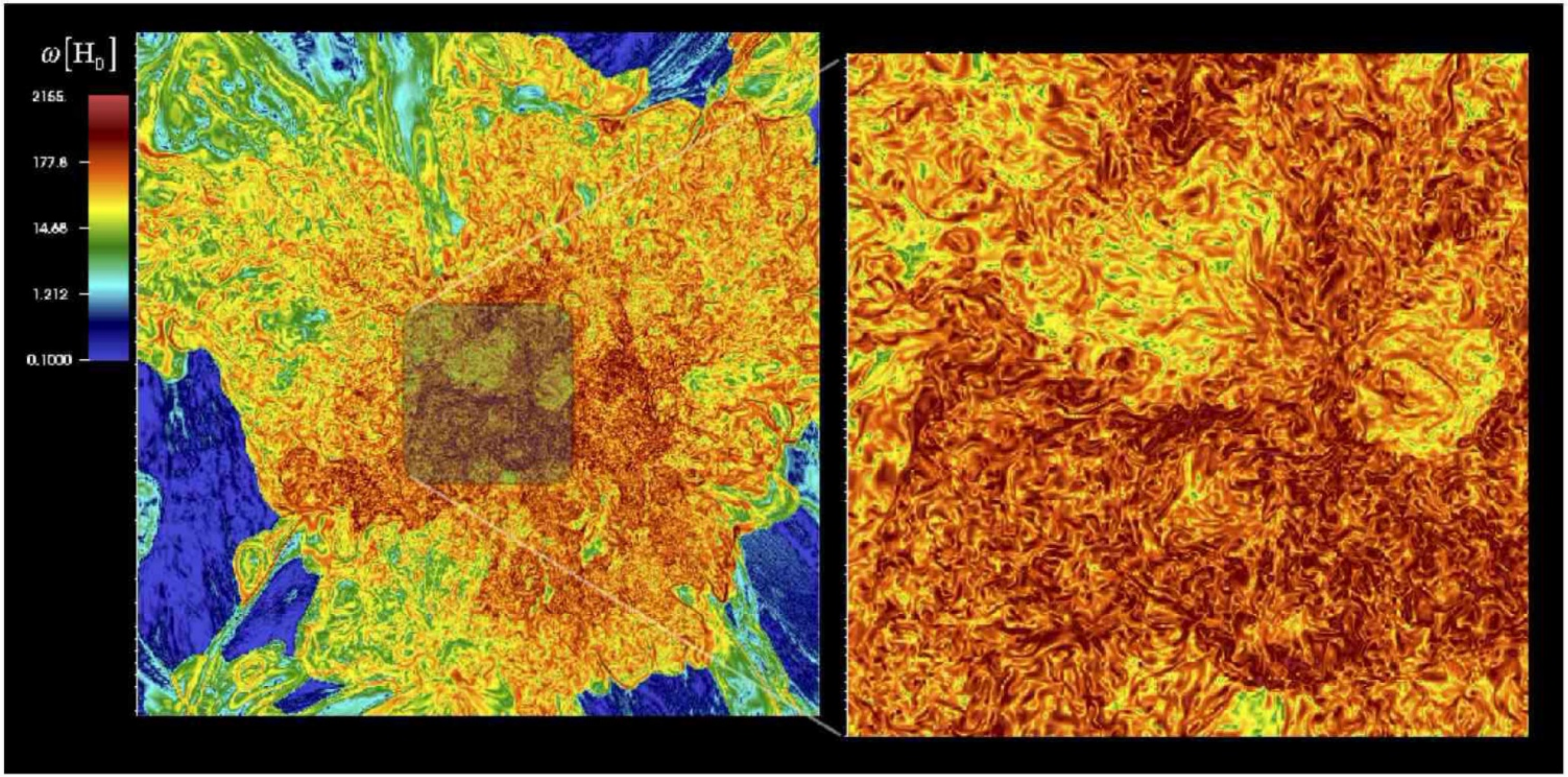
Turbulence energy of in the ICM

assuming that vorticity cascades down to induce turbulence

M_{turb} ~ 1
(transonic turbulence)
in filaments

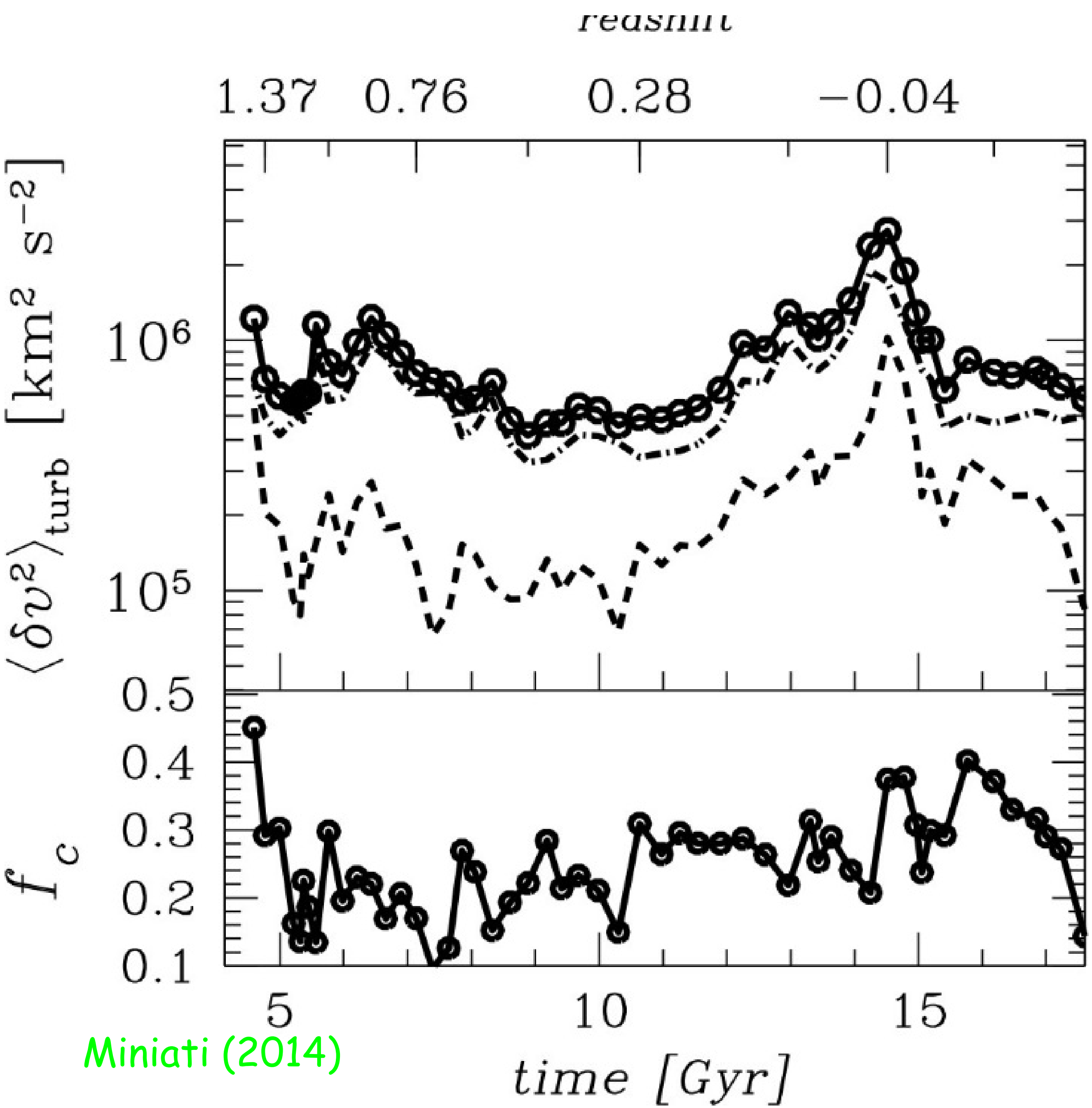
M_{turb} < 1
(subsonic turbulence)
E_{turb}/E_{therm} ~ 0.1 – 0.2
inside and outskirts of clusters

Turbulence in high resolution simulations of galaxy clusters



vorticity in the plane through the cluster center

Miniati (2013)



Miniati (2014)

fraction of compressional component ~ 20 - 30%

→ compression play a role

(in controlled box turbulence, fraction ~ 10%)

Origin of cosmic magnetic fields

- **turbulence induced at shocks in the LSS of the universe**

  + turbulence dynamo with weak seed fields (Ryu et al 2008)

  → probably energetically most important

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  → <B> ~ 10 - 100 nG in the cosmic web (?)

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  macroscpic instabilities such cosmic-ray induced instab,
  cosmic-ray flux,
  and etc

  → not yet clear!

Seed magnetic fields in the large-scale structure (LSS) of the universe

Suggestions include:

- generation in the early universe(e.g., see Widrow, Ryu et al 2012 for review)
  - e.g.) during the electroweak phase transition ($t \sim 10^{-12}$sec)
  - during the quark-hadron transition ($t \sim 10^{-5}$sec)

  → uncertain but maybe challenging (?)

- generation before the formation of the LSS of the universe through plasma physical processes (e.g., see Ryu et al 2012 for review)
  - e.g.) Biermann battery at shocks (Kulsrud, Ryu et al 1997)
  - instabilities, thermal fluctuations, photo-ionization and etc …

  → weak ($\sim 10^{-20}$ G) and some at small scales, yet most promising(?)

- astrophysical processes
  - e.g.) magnetic fields from the first stars

  → maybe not the first magnetic field

Origin of seeds for comic magnetic fields is uncertain!

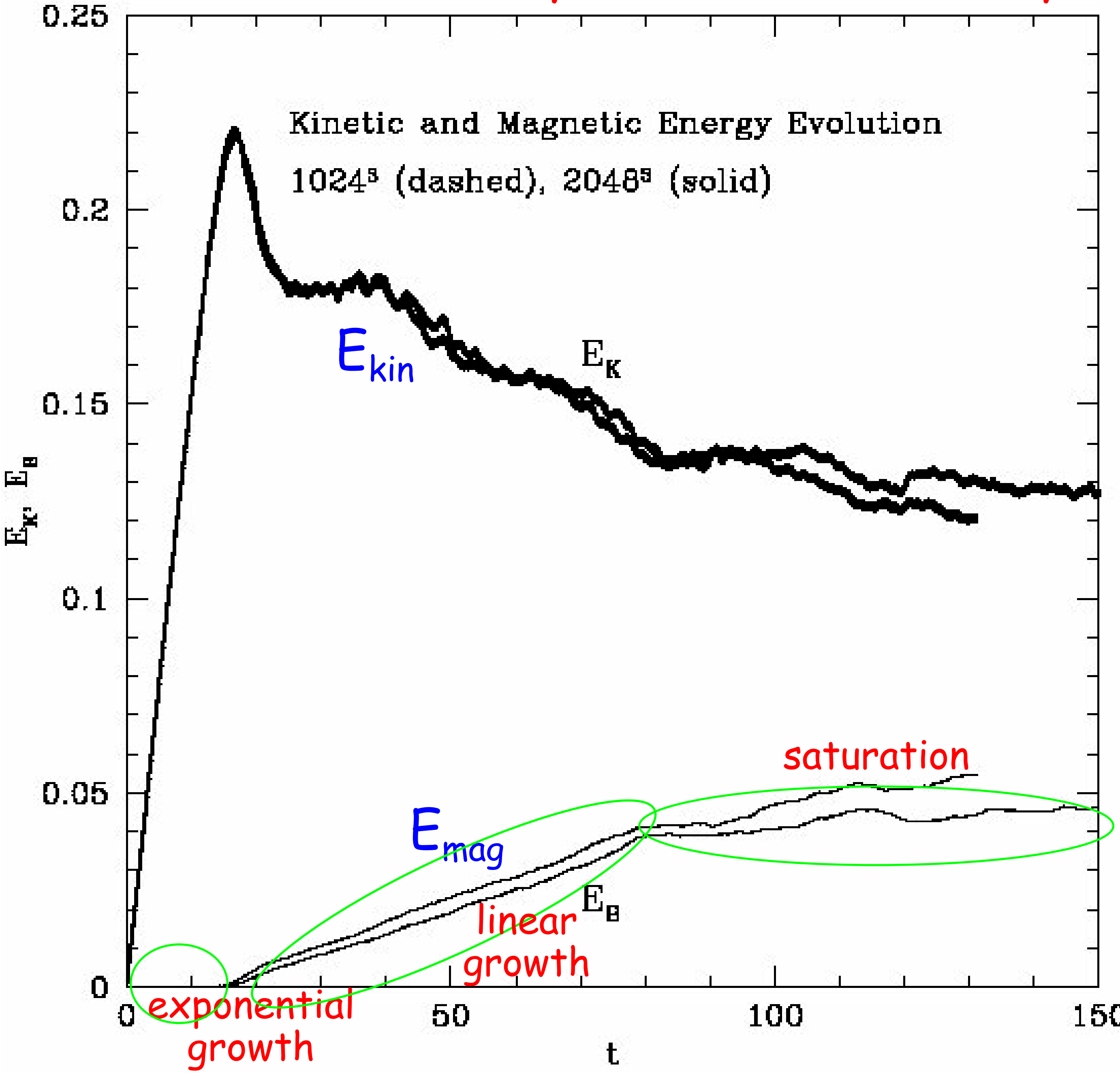
Turbulence + magnetic field

→ Magnetohydrodynamic turbulence

Magnetic fields can be amplified by turbulence from weak seed fields

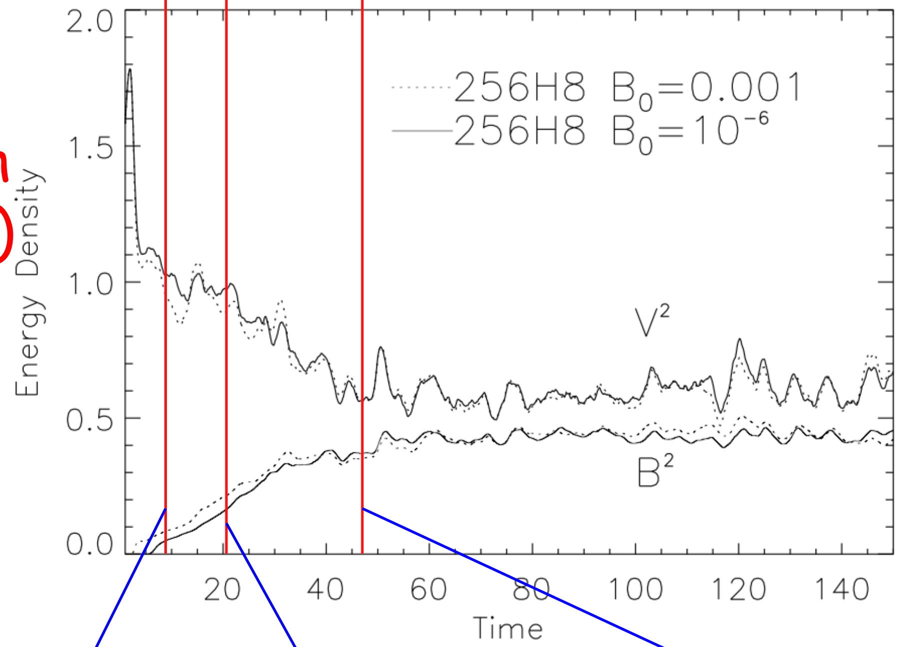
→ Turbulence dynamo or small-scale dynamo

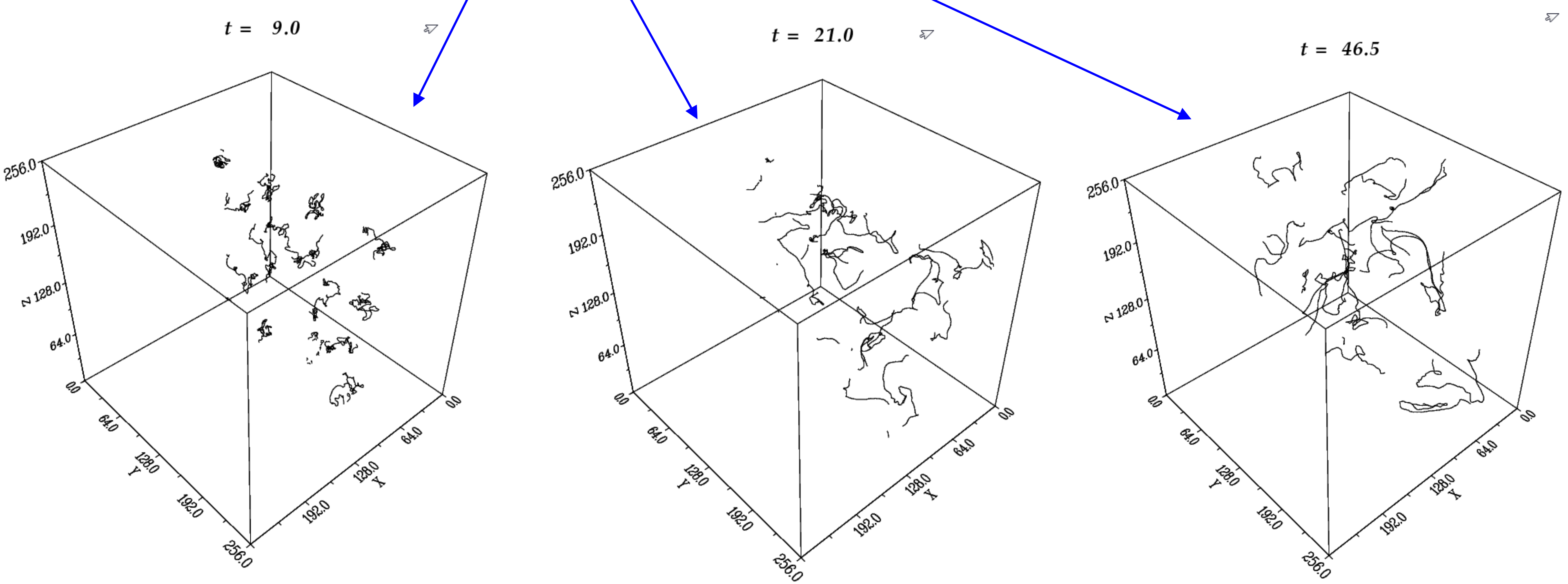
Turbulence dynamo (small-scale dynamo)



at saturation $E_{mag}/E_{kin} \sim 1/2$ in 2048^3 run, while $E_{mag}/E_{kin} \sim 2/3$ in incompressible run

Growth of coherence length (inverse cascade)





A model for the intergalactic magnetic field (IGMF)

(Ryu et al 2008)

- vorticity generated at curved shocks and also due to baroclinity
- cascades into turbulence
- produce the IGMF by turbulence dynamo

$$E_B = \frac{B^2}{8\pi} = \phi(\omega \cdot t) E_{turb}$$

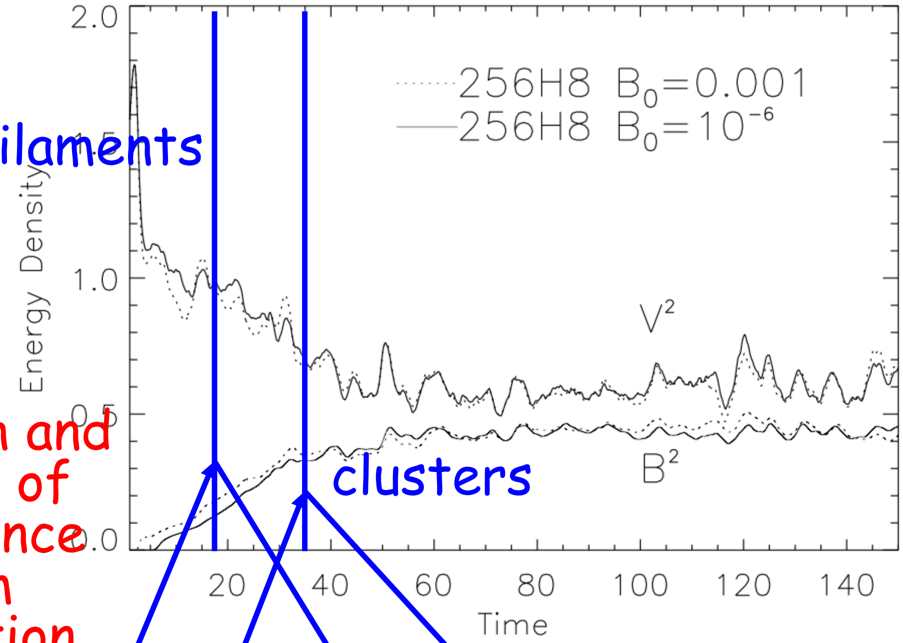
conversion factor from separate MHD turbulence simulations

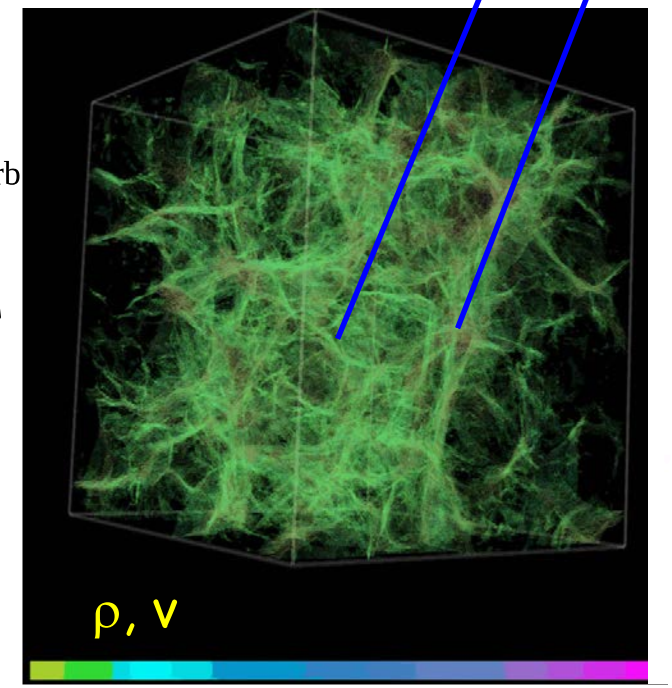
no fine tuning to normalize B !

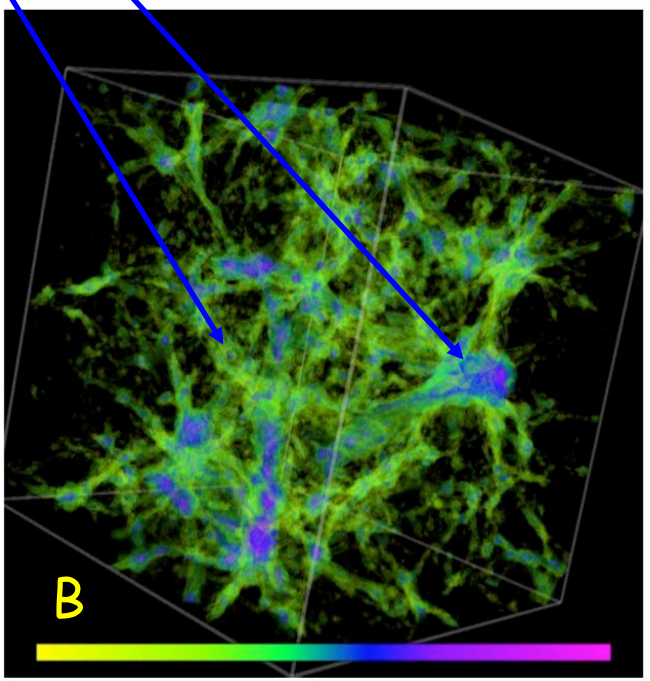
strength and energy of turbulence from simulation

filaments

clusters







Magnetic fields in the large-scale structure

averaged strength and integral scale of magnetic fields at z = 0 predicted from the turbulence dynamo

- inside clusters

  $\langle B \rangle \sim$ a few μG, $L_{int} \sim$ a few x 10 kpc

- outskirts of clusters ($T > 10^7$ K)

  $\langle B \rangle \sim 0.1\ \mu$G

- in filaments (10^5 K < T < 10^7 K, or WHIM)

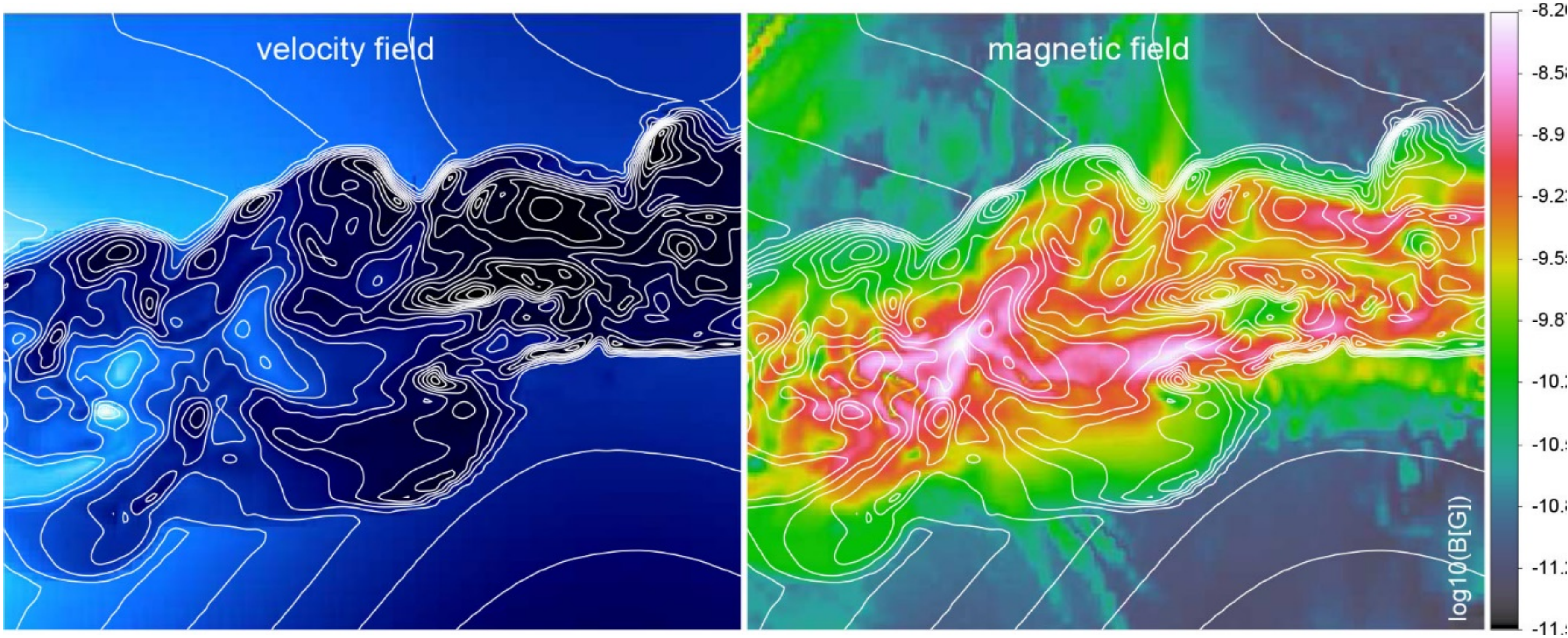
  $\langle B \rangle \sim 10$ nG, $L_{int} \sim$ a few x 100 kpc

the integral scale is a length scale of magnetic field, which would be relevant to Faraday rotation measure

$$L_{\rm int} = 2\pi \int (E_B / k) dk \Big/ \int E_B dk$$

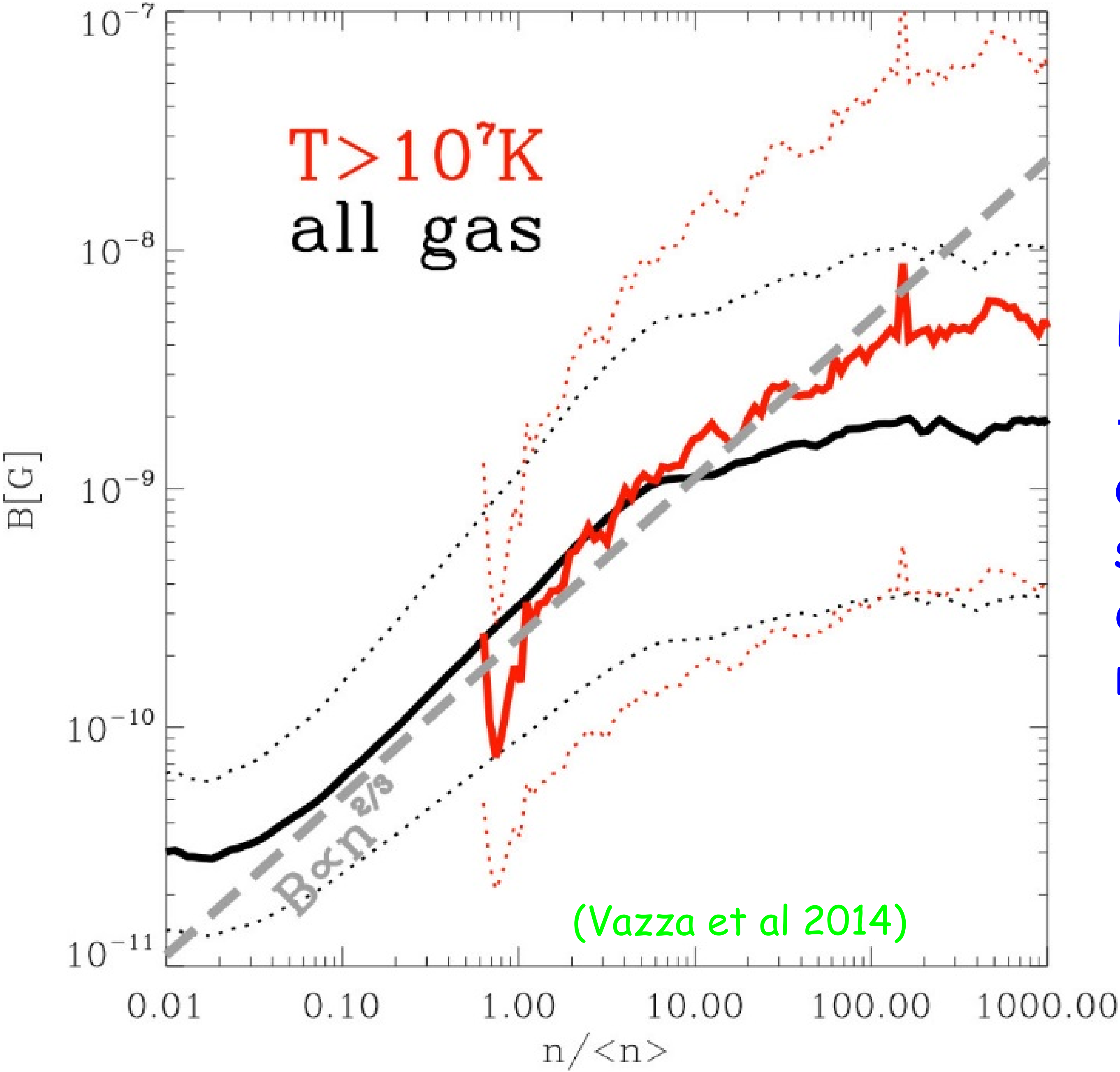
(Cho & Ryu 2009)

Simulations of magnetic field amplification in the cosmic web



(Vazza et al 2014)

magnetic field in filaments ~ a few nG



$B \sim \rho^{2/3}$

→ compression on the top of small scale dynamo plays a role

Some scales in the intracluster medium

size of clusters of galaxies $l_{\text{clusters}} \sim 1\,\text{Mpc} = 1000\,\text{kpc}$

mean free-path for electron-electron & proton-proton collisions

$$l_{p-p} \sim l_{e-e} \sim \frac{10^5}{\ln\Lambda}\frac{T^2(\text{K})}{n_e(\text{cm}^{-3})}\text{cm} \sim \text{a few kpc}$$

1 kpc = 3,261 light-years
= 3.1 x 10^{21} cm

mean free-path for electron-proton relaxation

$$l_{e-p} \sim l_{p-p} \times \left(\frac{m_p}{m_e}\right)^{\frac{1}{2}} \sim 100\,\text{kpc}$$

gyro-radius of protons

$$r_{\text{gyro},p} \sim \frac{\sqrt{T(\text{K})}}{B(\text{G})}\text{cm} \sim 10^6\ \text{km}$$

gyro-radius of elections

$$r_{\text{gyro},e} = r_{\text{gyro},p} \times \frac{m_e}{m_p} \sim 10^3\ \text{km}$$

$L > l_{e-p}$ ⟹ fluid regime $(T_p = T_e)$

$L > l_{p-p}$ ⟹ fluid regime $(T_p \neq T_e)$

$L < l_{p-p}$ ⟹ viscous regime?

$L < r_{\text{gyro},p}$ ⟹ resistive regime?

Viscosity and resistivity the ICM

kinetic viscosity $\nu \sim \upsilon_{p-p}^{\text{therm}} l_{p-p} \sim \frac{l_{p-p}^2}{t_{p-p}}$ (?)

or substantially smaller ?

resistivity $\eta \sim \frac{(c/\omega_p)^2}{t_{e-p}} \quad \left(\omega_p = \left(\frac{4\pi\, n_e e^2}{m_e} \right)^{1/2} \right)$ (?)

much smaller than viscosity?

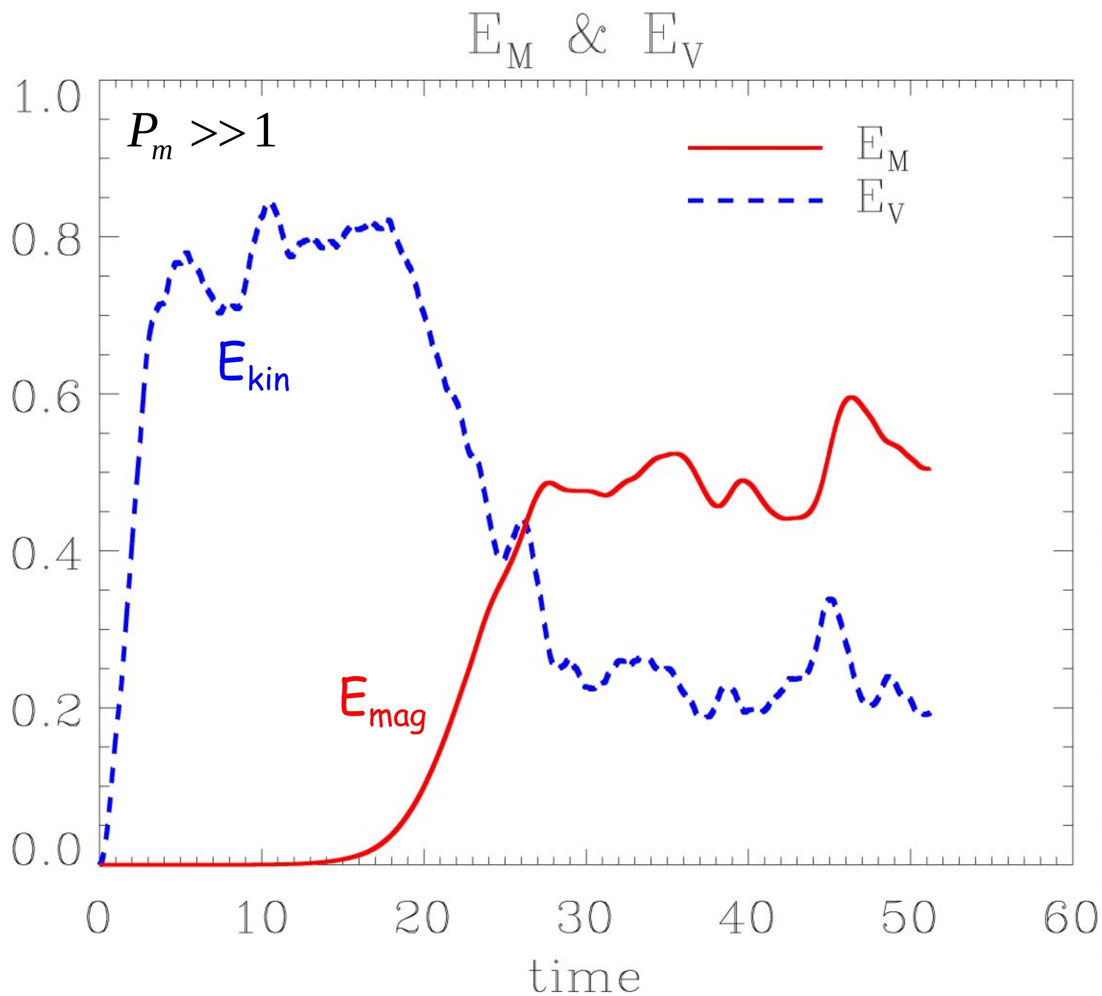
⟹ high magnetic Prandtle number ?

$$P_m = \frac{\nu}{\eta} \sim 10^{20} \text{ or larger ?}$$

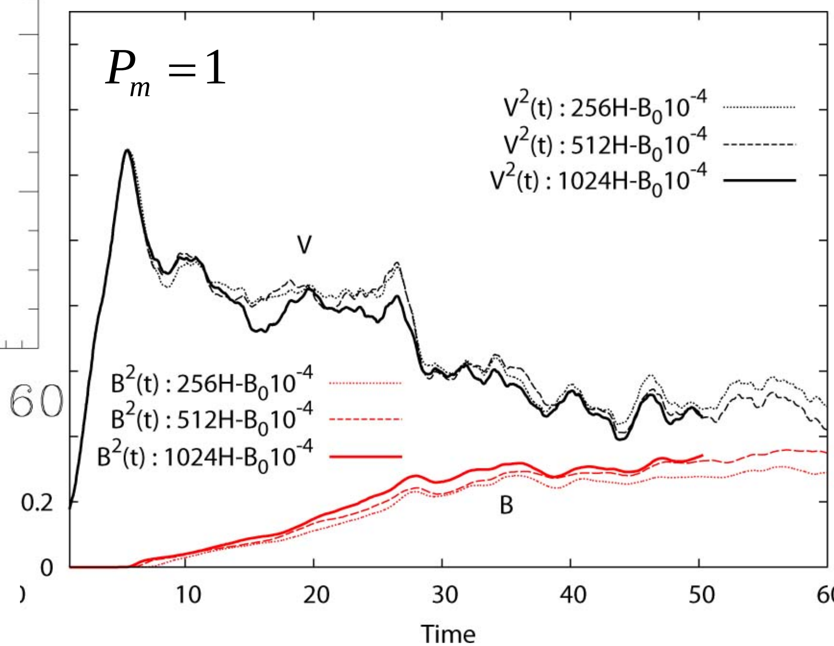
Turbulence with $B_0 << \delta B$ and large P_m

1. Time evolution of kinetic and magnetic energies

Park, Ryu, et al
(in preparation)

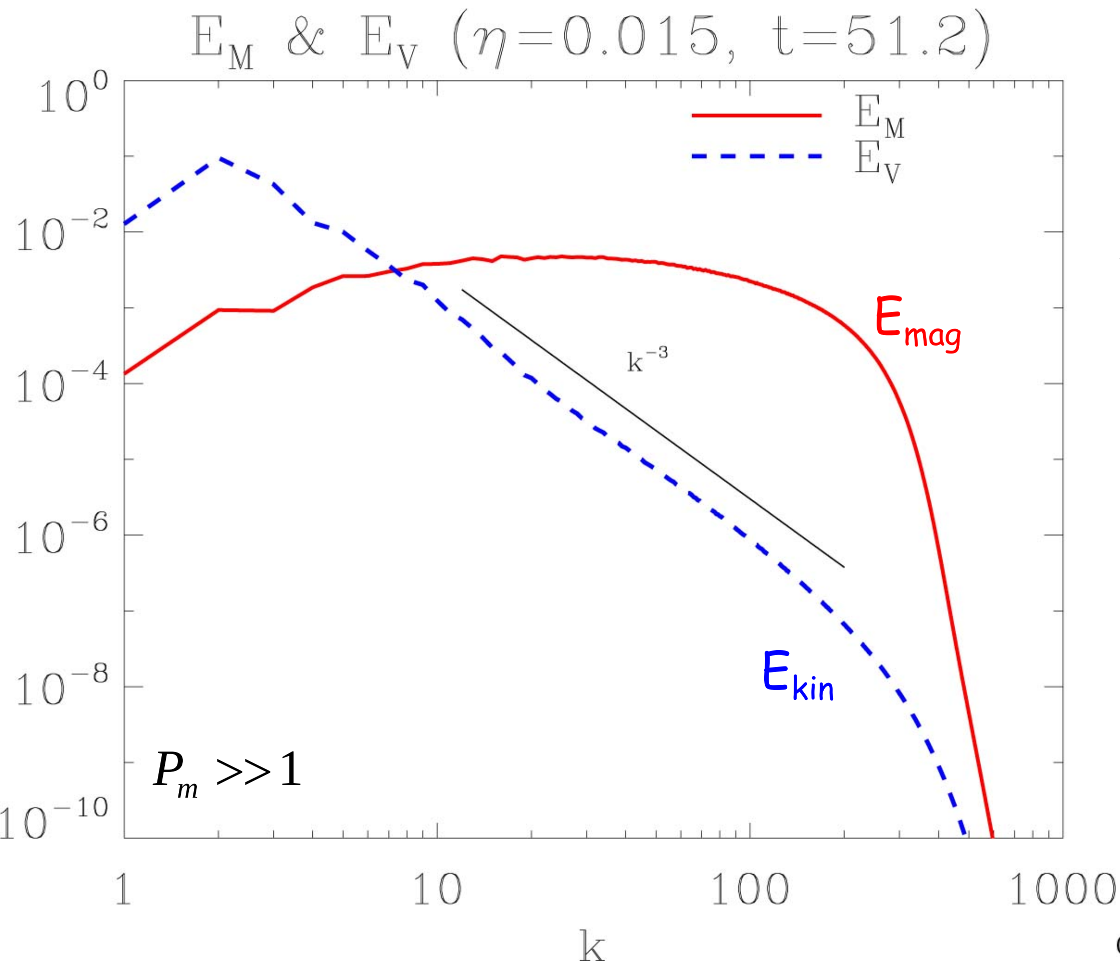


at saturation
magnetic energy
>> kinetic energy



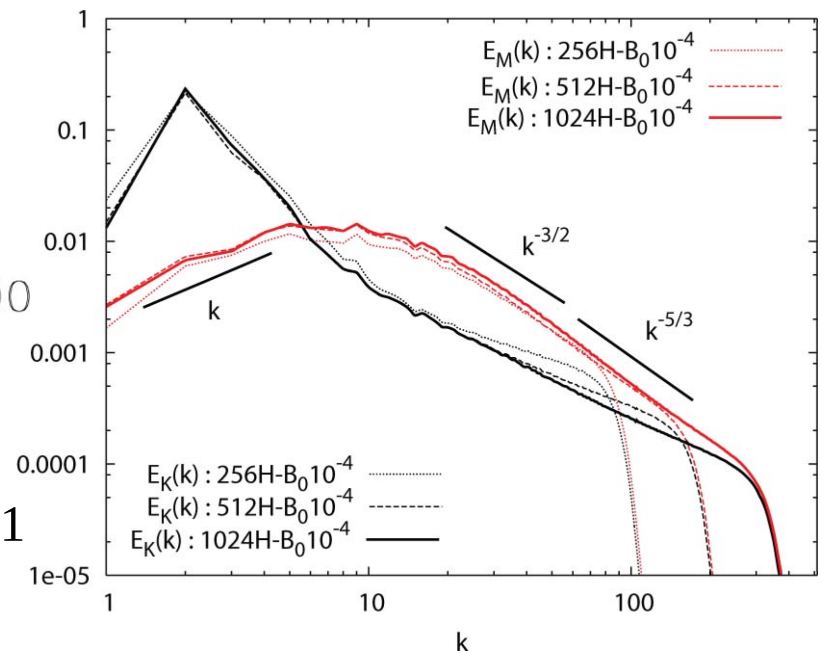
2. Power spectrum at saturation

with $\nu >> \eta, \quad V_k << B_k$



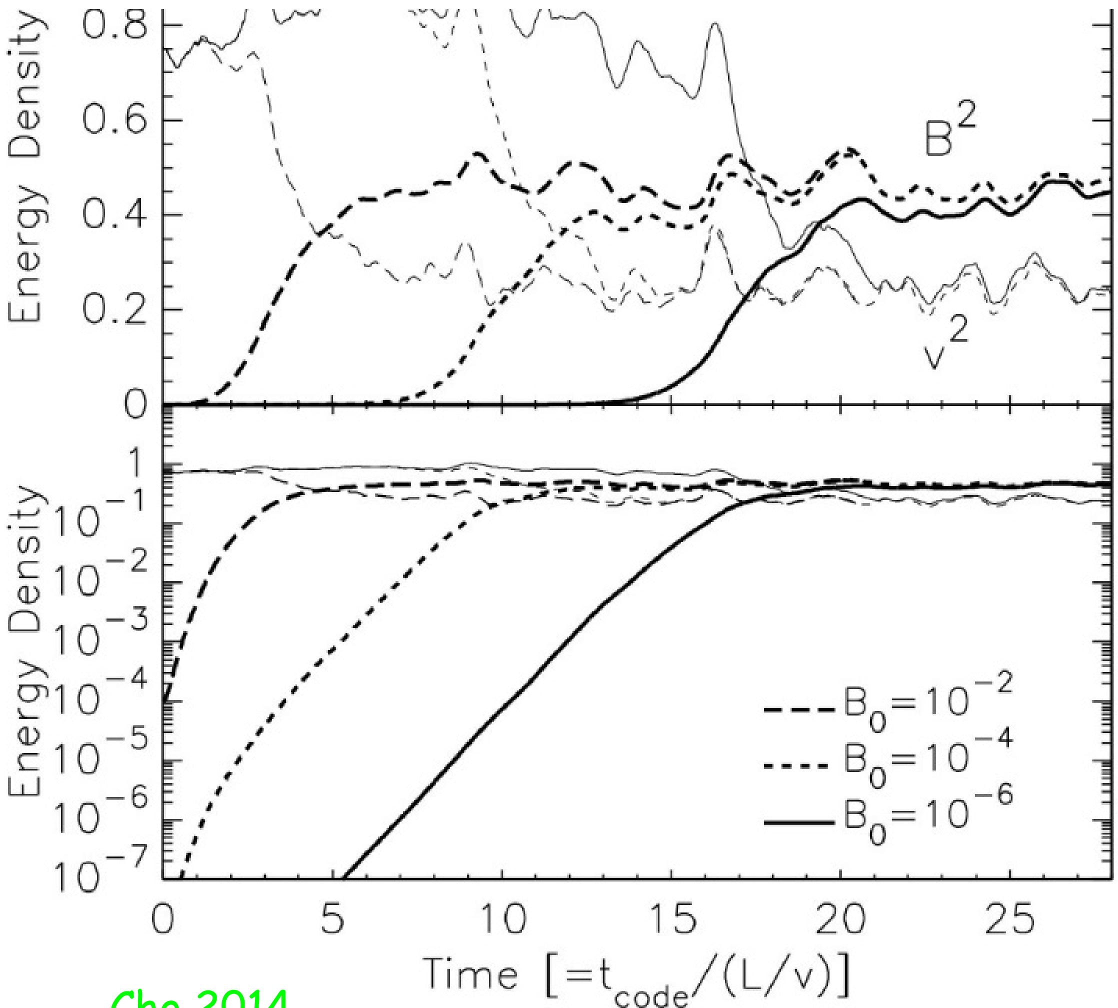
$E_M \sim$ constant, $E_K \sim k^{-3}$

in the inertial range



$P_m = 1$

Turbulent amplification of weak, uniform seed magnetic field, B_0, in high P_m plasmas

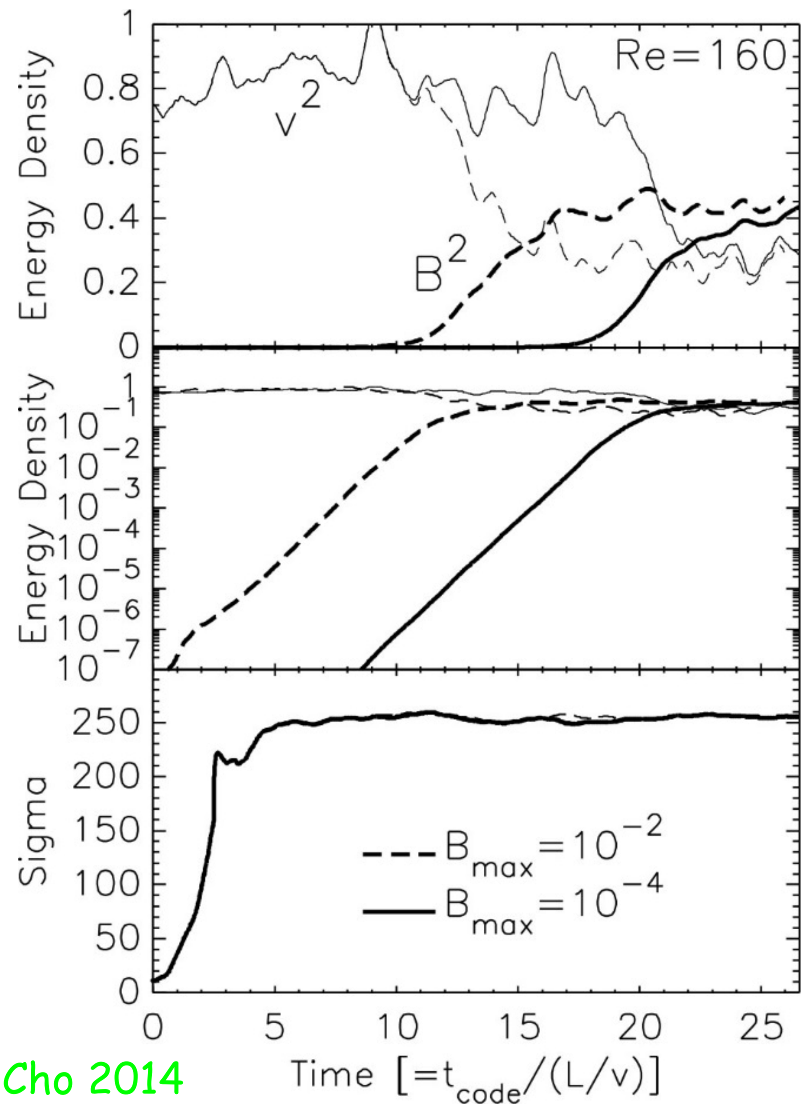


Cho 2014

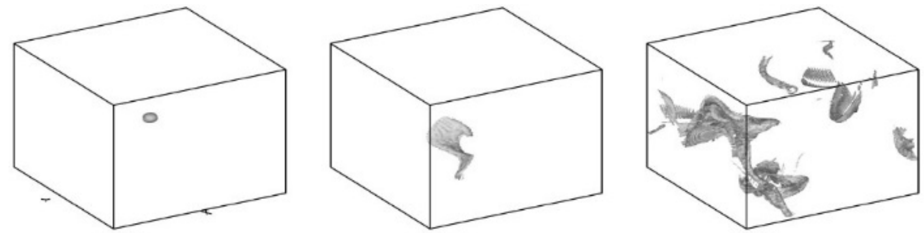
to produce B ~ a few μG in clusters

- if τ_{eddy} ~ 10^9 years (L ~ 400 kpc, v ~ 400 km/s), B_0 ~ 10^{-11} G required
- if τ_{eddy} ~ 10^8 years (L ~ 100 kpc, v ~ 800 km/s), B_0 ~ 10^{-16} G required

Turbulent amplification of localized seed magnetic field, B_0, in high P_m plasmas

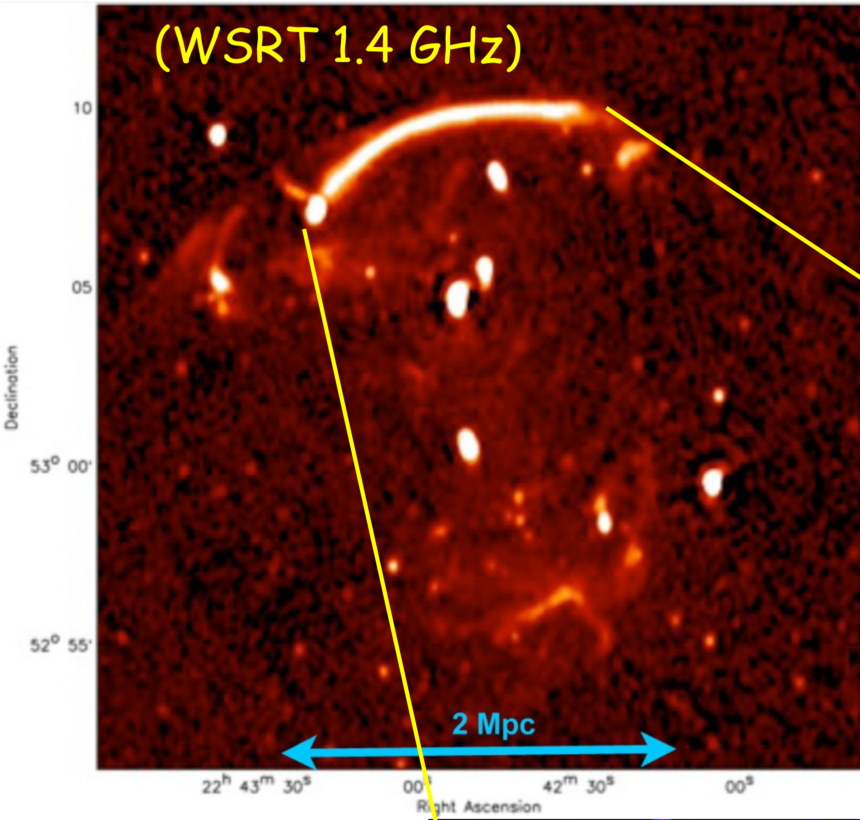


Cho 2014



(a) t=0 (b) t=1.4 (c) t=2.7

- spread of B is fast, faster than scalar quantity
- to produce B ~ a few μG in clusters, if τ_{eddy} ~ 10^9 years (L ~ 400 kpc, v ~ 400 km/s), B_0 ~ 10^{-9} G would be OK



Radio relic in CIZA J2242.8+5301

(van Weeren et al)

shock Mach number

M ~ 4.5 (too strong ?)

strong magnetic field:

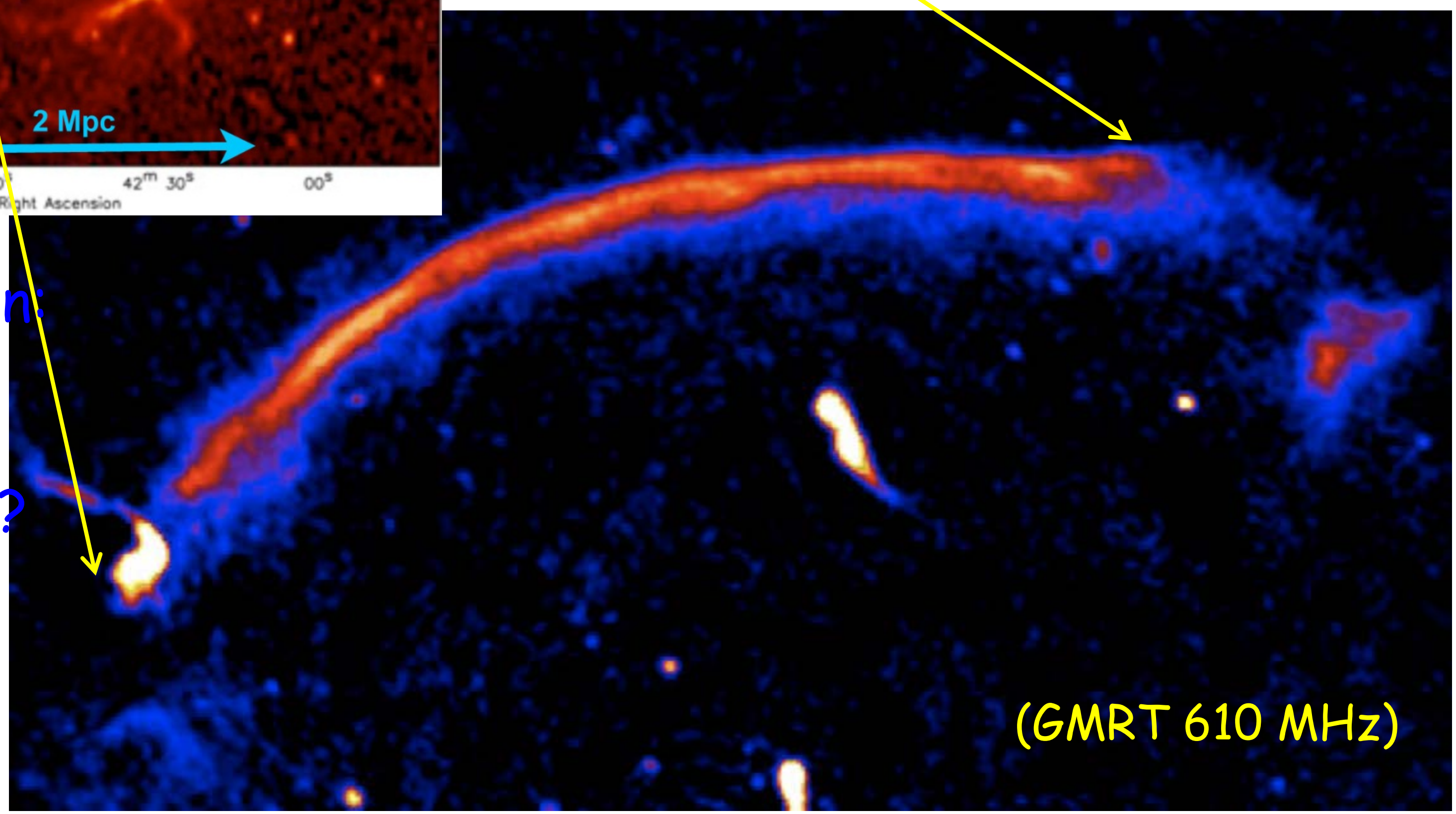
B ~ 6 or 1.2 μG (strong !)

high polarization:

~ 70% or so

→ uniform B ???

→ need large-scale dynamo???

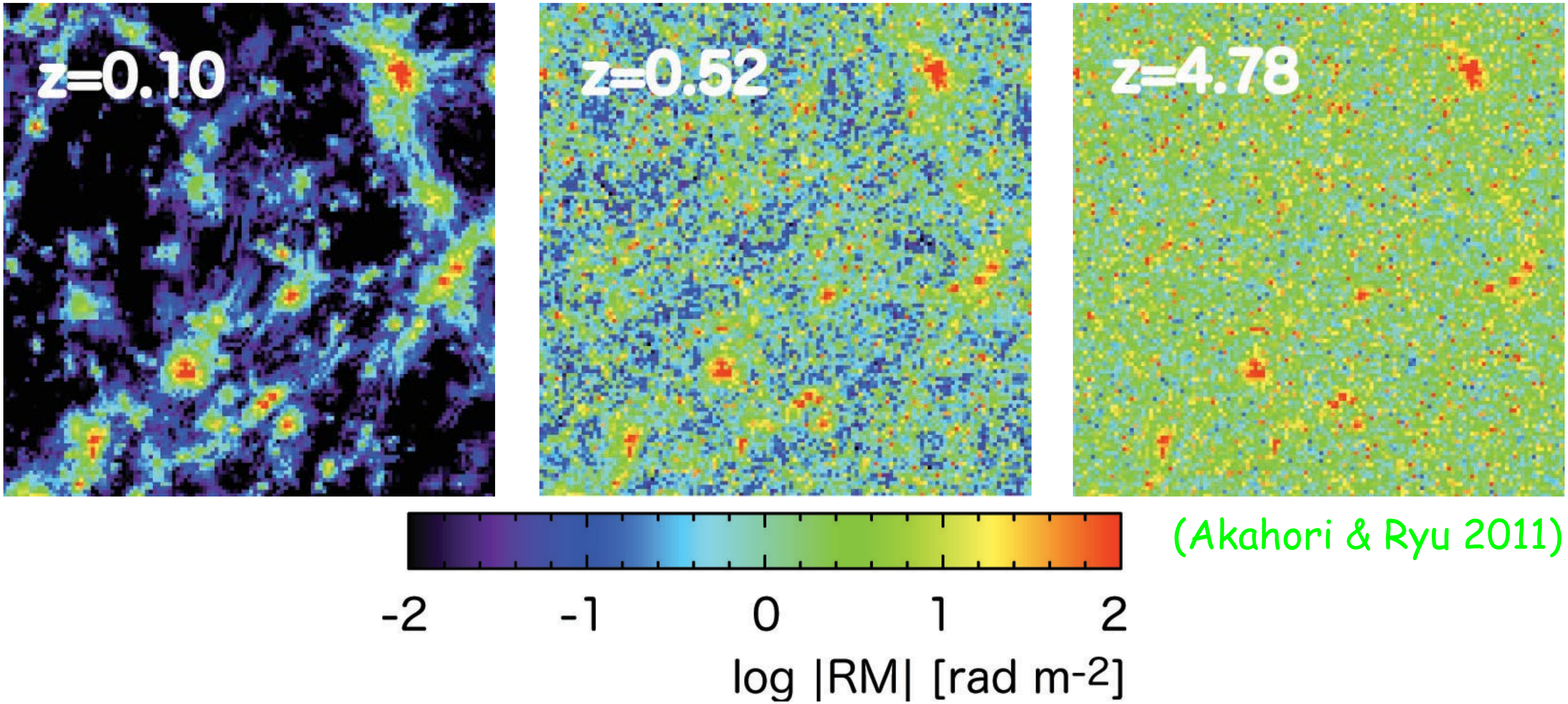


Possibility of detection of B in filaments through RM observation with SKA

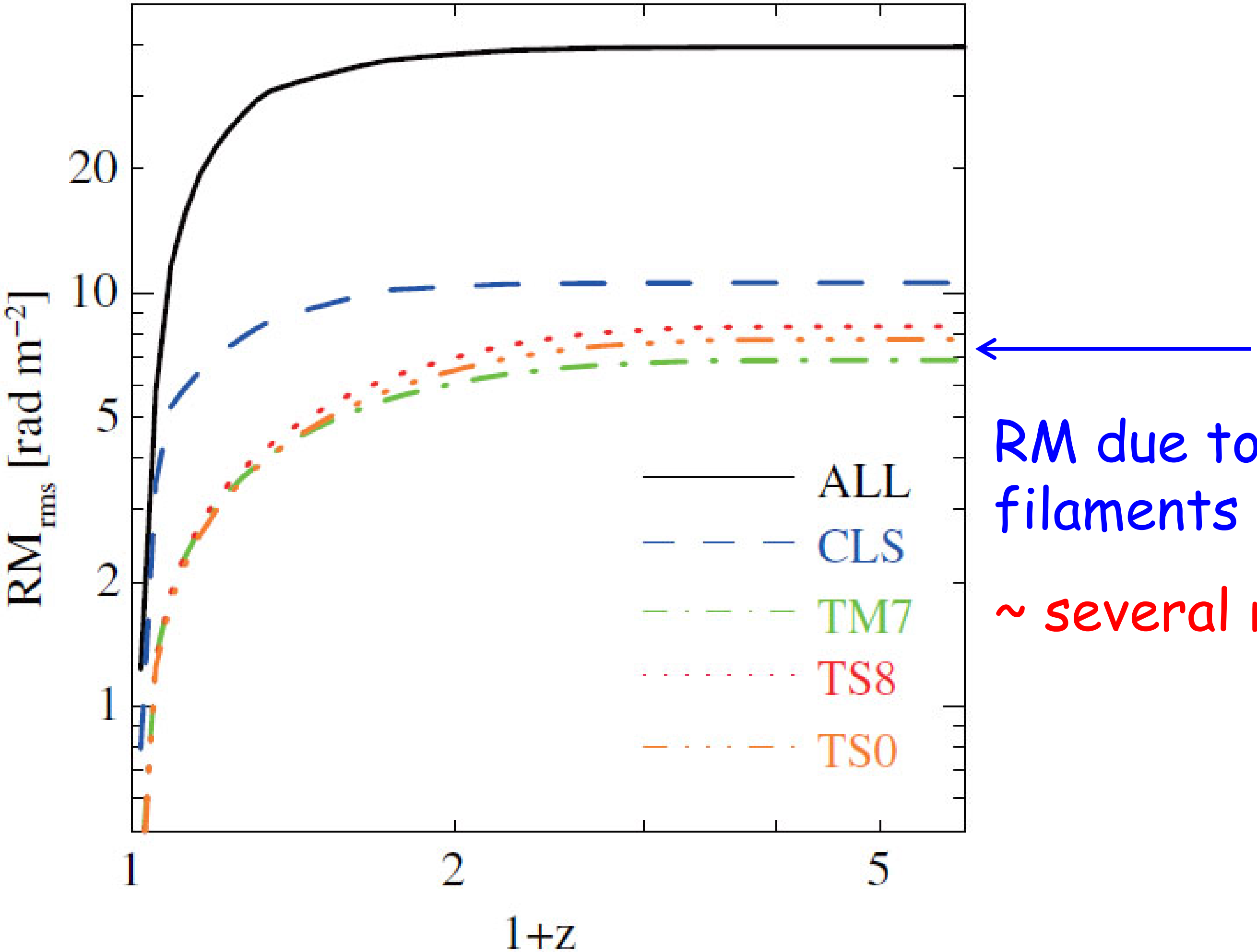
- **Statistical Approach (Akahori, Gaensler, Ryu, 2014, ApJ)**
- RM Synthesis (Akahori, Kumazaki, Takahashi, Ryu, 2014, PASJ)
- QU-Fitting (Fisher analysis) (Ideguchi, Takahashi, Akahori, Kumazaki, Ryu, 2014, PASJ)

Faraday rotation induced by the model intergalactic magnetic field

area of the region – (100 h^{-1} Mpc)^2, integrated up to redshift z



(Akahori & Ryu 2011)



RM due to B in filaments

~ several rad/m^2

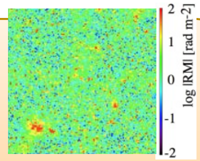
rms of RM up to redshift z

Multiple RM components in observation of extra galactic sources

- Observed RM contains multiple RM contributions
  - INT: intrinsic RM associated with polarized sources
  - IGM: RM due to magnetic fields in filaments
  - EXG: RM of B in intervening extra-galaxies/clouds
  - ISM: RM due to the galactic magnetic field
  - ERR: RM of ionosphere, instruments, etc
- COM: combined RM (observed RM)
  - $\mu_{COM} = \mu_{INT} + \mu_{IGM} + \mu_{EXG} + \mu_{ISM} + \mu_{ERR}$ (average)
  - $\sigma_{COM}^2 = \sigma_{INT}^2 + \sigma_{IGM}^2 + \sigma_{EXG}^2 + \sigma_{ISM}^2 + \sigma_{ERR}^2$ (dispersion)

Statistical Approach

IGM Map



σ_{IGM} = 7 rad/m^2

INT map

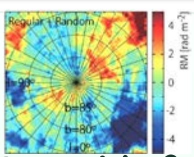
$\sigma_{INT} = \sigma_{INT0}(1+z)^{-2}$

σ_{INT0} = 10 rad/m^2

EXG map

σ_{EXT} = 10 rad/m^2

ISM Map

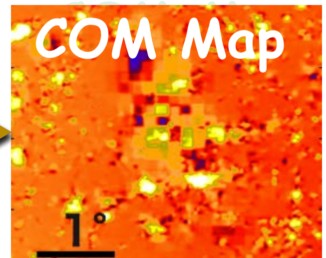


σ_{IGM} = 9 rad/m^2

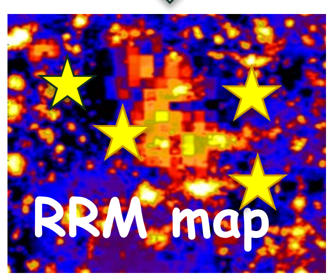
μ_{IGM} = 7 rad/m^2

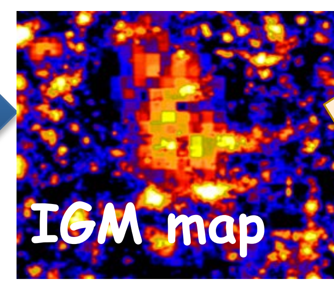
ERR map

σ_{ERR} = 1 rad/m^2



- INT filter
- EXG filter
- ISM filter
- ERR filter





using high-z sources at z=2, σ_{INT} ~ 1

~ 50 % of sources, no EXG choosing sources with no EXG

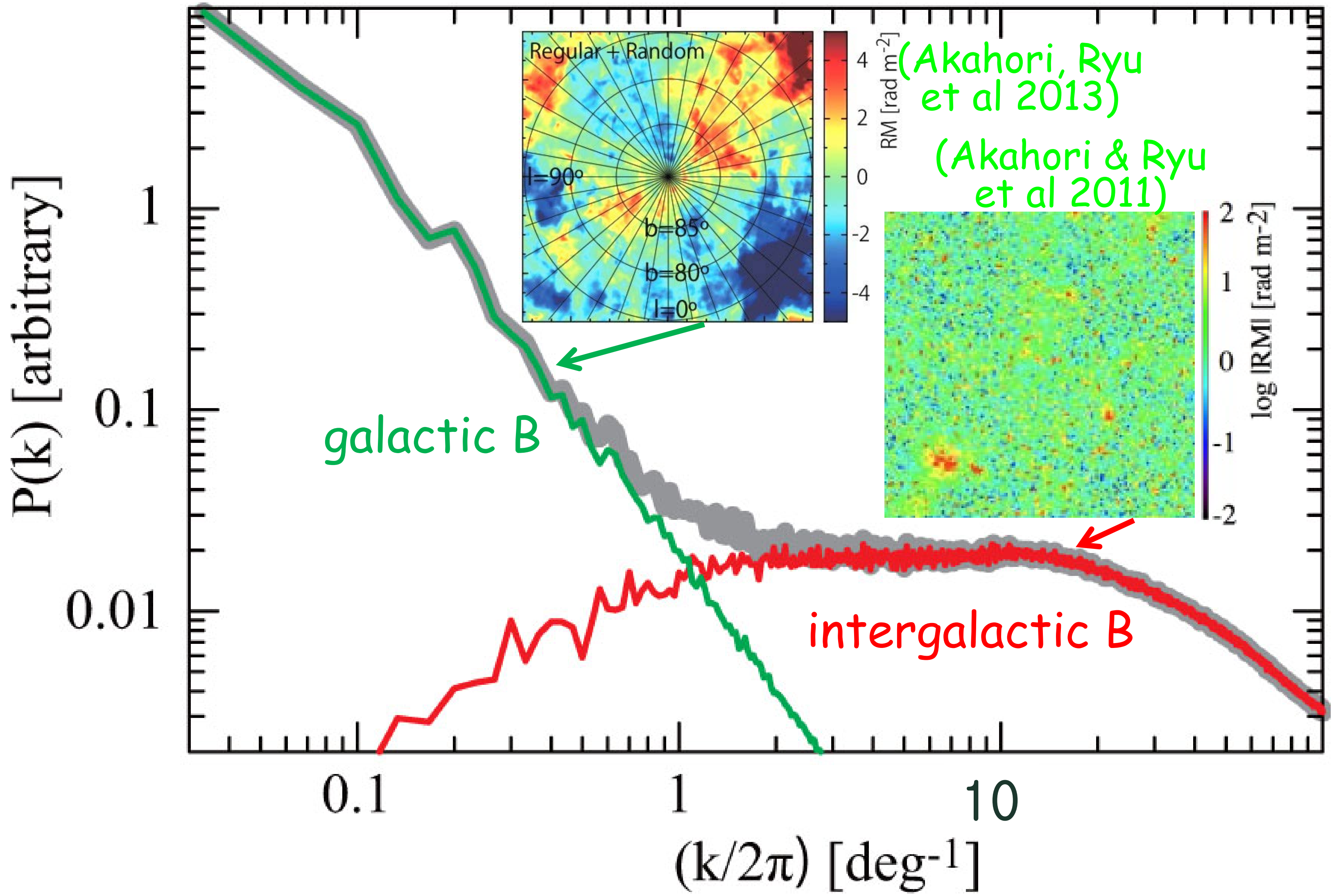
pointing the Galactic Poles subtracting μ_{IGM} (if non-zero) filtering σ_{IGM} at scale ~1°-2°

assuming small error σ_{ERR} ~ 1 (would become possible)

How many sources do we need to extract the statistics of RM due to the IGMF?

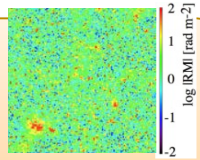
(Akahori, Gaensler, Ryu 2014)

power spectrum of RM



Statistical Approach

IGM Map



σ_{IGM} = 7 rad/m^2

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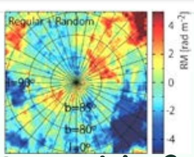
$\sigma_{INT}=\sigma_{INT0}(1+z)^{-2}$

σ_{INT0}=10 rad/m^2

EXG map

σ_{EXT} = 10 rad/m^2

ISM Map



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μ_{IGM} = 7 rad/m^2

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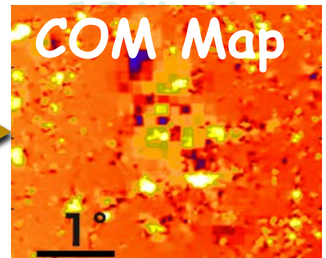
σ_{ERR} = 1 rad/m^2



INT filter

EXG filter

ISM filter

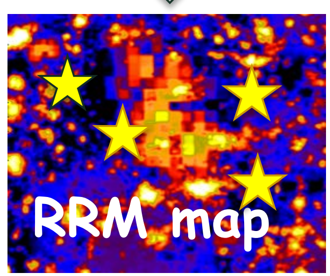
ERR filter

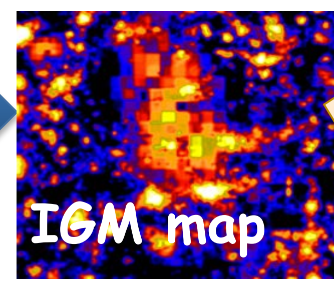
using high-z sources
at z=2, σ_{INT} ~ 1

~ 50 % of sources, no EXG
choosing sources with no EXG

pointing the Galactic Poles
subtracting μ_{IGM} (if non-zero)
filtering σ_{IGM} at scale ~1°-2°

assuming small error σ_{ERR} ~ 1
(would become possible)



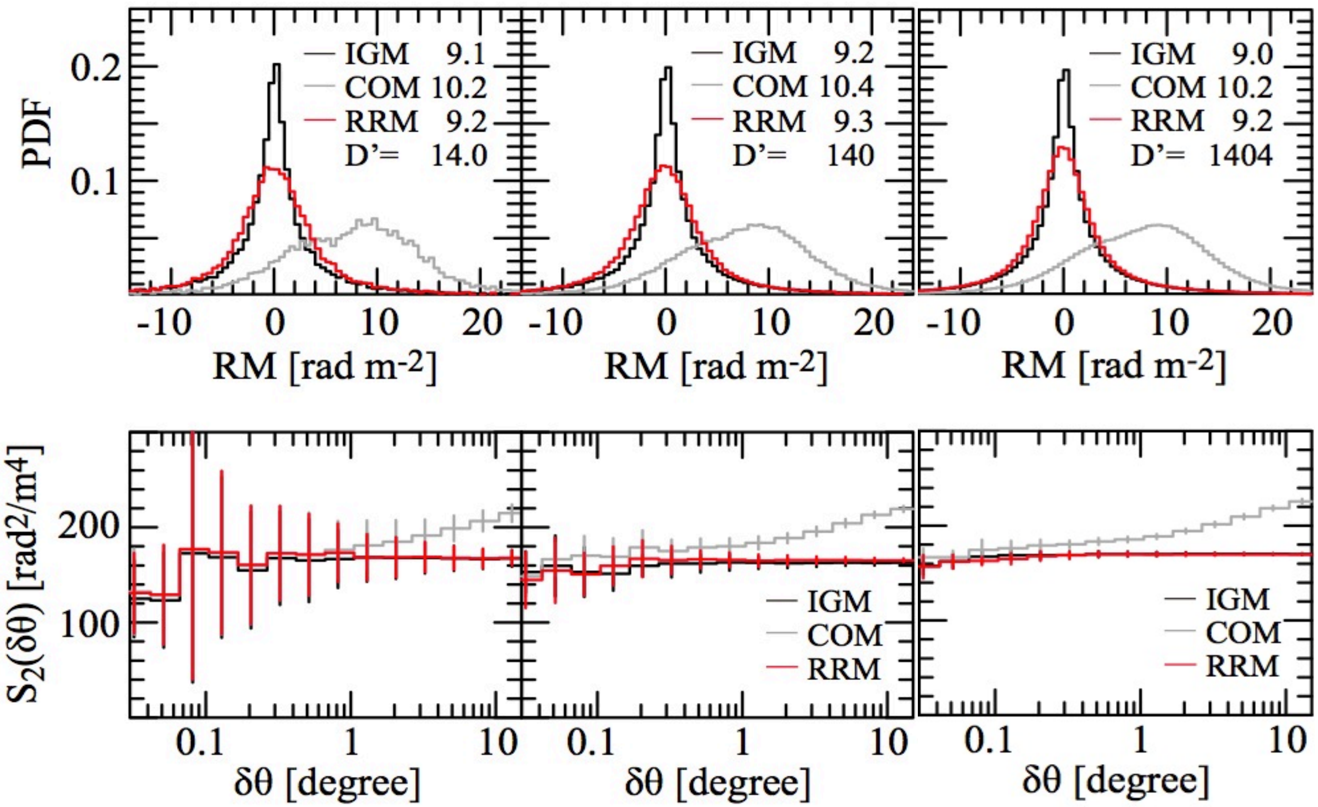


How many sources do we need to extract the statistics of RM due to the IGMF?

(Akahori, Gaensler, Ryu submitted)

900 deg² FOV, south Galactic pole, z>2 sources with no EXE
— IGM — COM — RRM

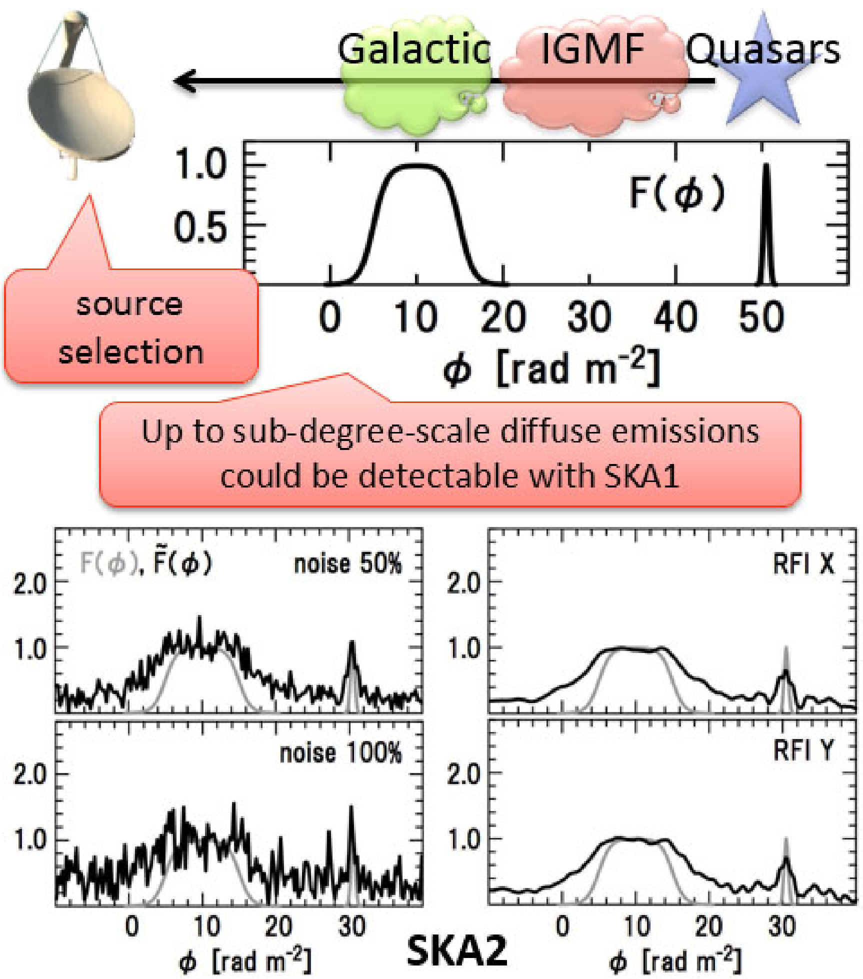
SKA1-Sur	SKA1-Sur	SKA2 Deep?
100 RM/deg²	1000 RM/deg²	10000 RM/deg²
3h, 2 μJy/bm, S/N=8	300h,0.2μJy/bm,S/N=8	

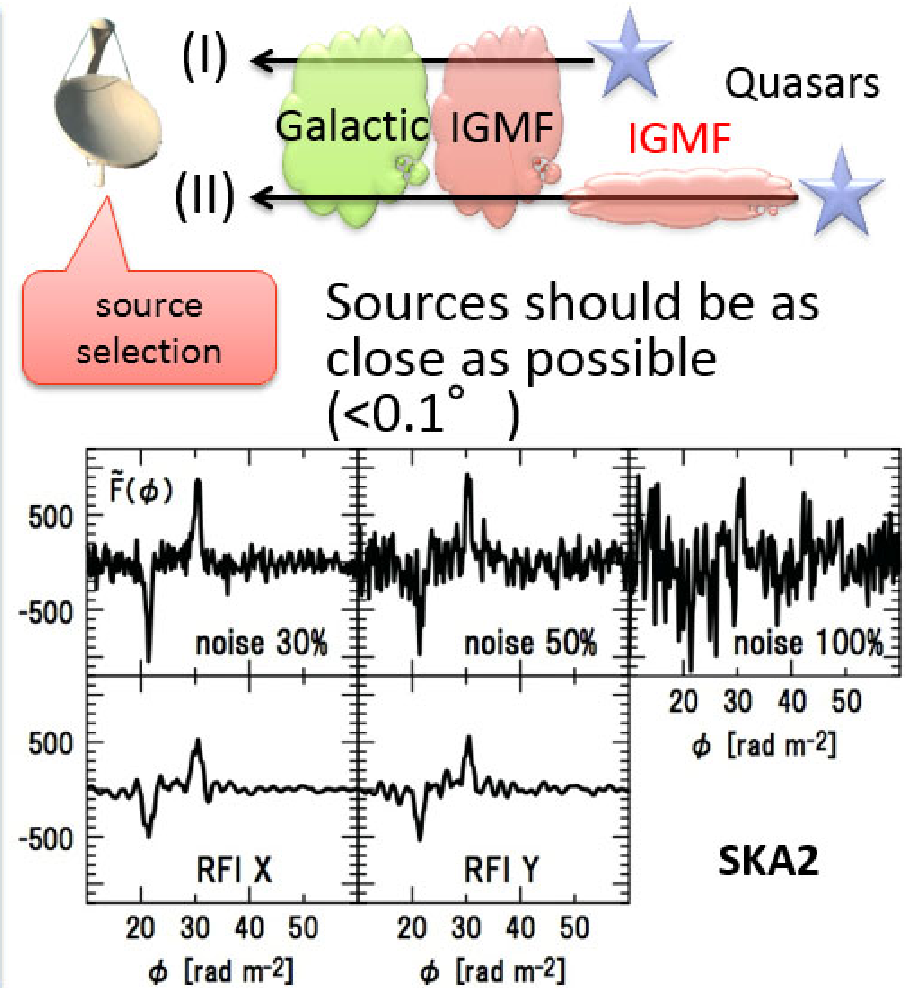


- with our selection criteria, ~14% of sources are usable
- **100 RM/deg²** data may allow to extract σ_{IGM},
- **1000 RM/deg²** data may allow to extract **$S_{2,IGM}$ down to ~0.1°**

RM Synthesis: Strategies

❖ **RM$_{IGMF}$~10 rad/m^2** could be detectable



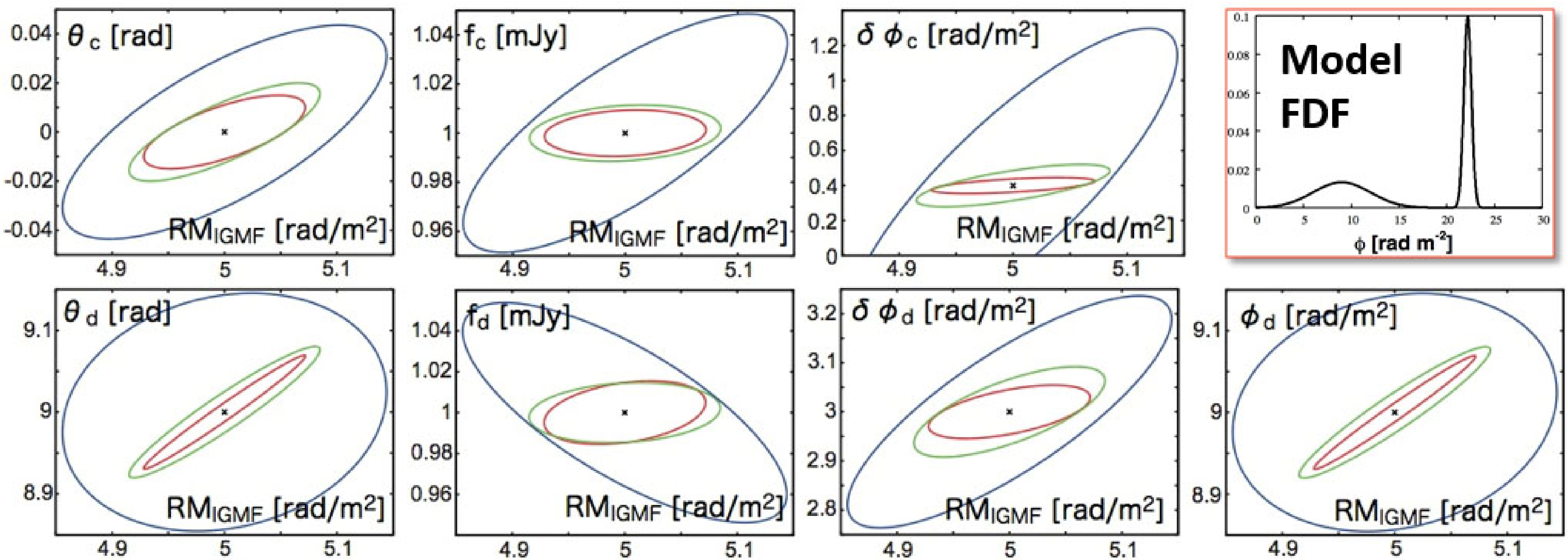


Akahori, Kumazaki, Takahashi, Ryu, PASJ

RM Synthesis: QU-fit

- Going to lower frequencies is better for RM synthesis, since we gain a wider λ^2 coverage

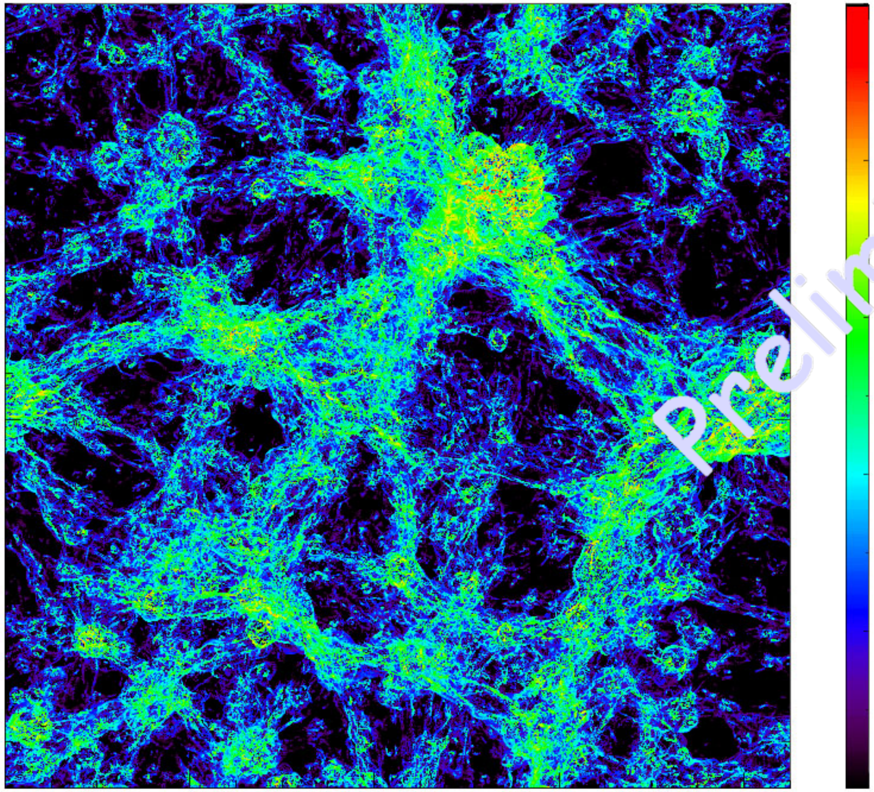
Strategy A, SKA1-Survey, 1 hr, 1 mJy source, RM_{IGMF}= 5 rad/m^2, 3σ confidence
—650-1670 MHz —500-1500 MHz —350-1350 MHz



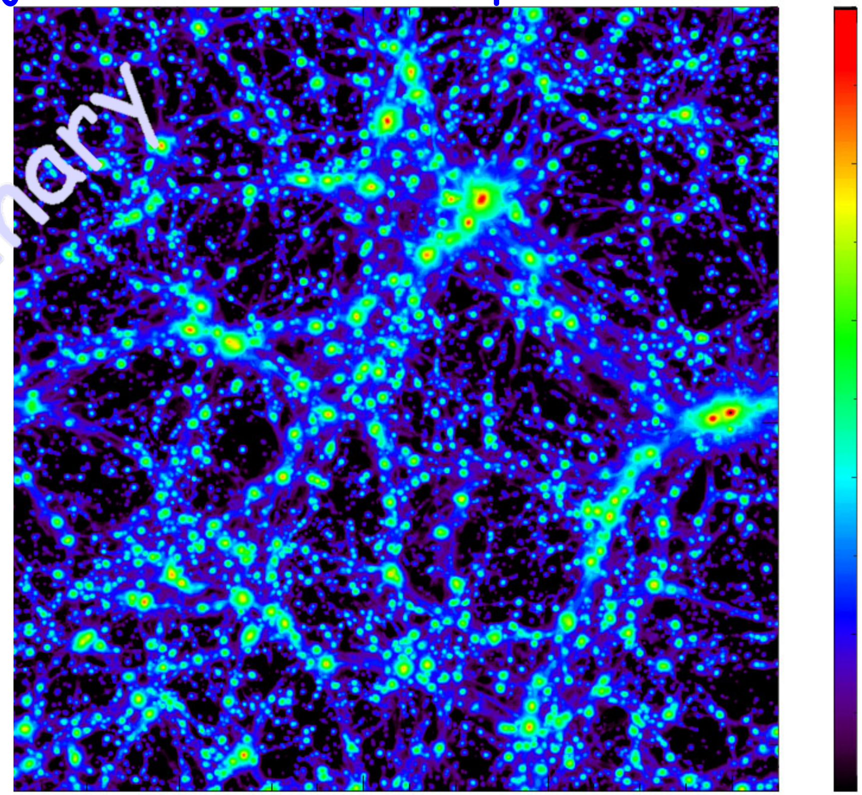
Ideguchi, Takahashi, Akahori, Kumazaki, Ryu, PASJ

Synchrotron emission induced by the model intergalactic magnetic field

area of the region – (85 h^{-1} Mpc)^2 projected over the depth of 85 h^{-1} Mpc



synchrotron from
primary CR electrons



thermal bremsstrahlung

synchrotron emission from clusters – radio relic & radio halo
synchrotron emission from filaments – yet to be observed

Main results

- Magnetic fields are ubiquitous in astrophysical environments including the large-scale structure of the universe.
- Magnetic fields in the large-scale structure of the universe:

Cluster of galaxies	~ 10^{-6} G
Filament of galaxies	~ 10^{-10} G (?)
Void	~ 10^{-16} G (?)

- The magnetic fields in filaments could be detected through RM observation with the SKA.
- Synchrotron emission from filaments could be detected too, but need to be further studied

Thank you !