Science Working Group for SKA in Korea
and
Magnetic Fields in the Intergalactic Space

Dongsu Ryu (Chungnam National U, Korea)

Korean involvement to SKA

- participation of SSEC
  - as an observer from 2009 - M. Choi
  - as a full member from 2010 - J. Kim
- participation of ASG from 2010
- participation of RadioNet (EU-FP7) from 2008
  - B. W. Sohn
- participation of PrepSKA (EU-FP7) from 2009
  - J. Kim
- joined POSSUM
  - D. Ryu, T. Akahori

...

Science Working Group for SKA in Korea

- members
  - about 25
  - including staffs
  - and students

- activities
  - 1st meeting – August 20, 2010
    - introduction of the SKA to community
  - 2nd meeting – April 5, 2011
    - kick of SWG and study of the SKA document
  - 3rd meeting – August 4 – 5, 2011
    - review of the SKA key science

- fields of interests

HI science – 5 science talks on yesterday

Kyungjin Ahn
Sunghye Baek
Hansik Kim
} HI in EoR

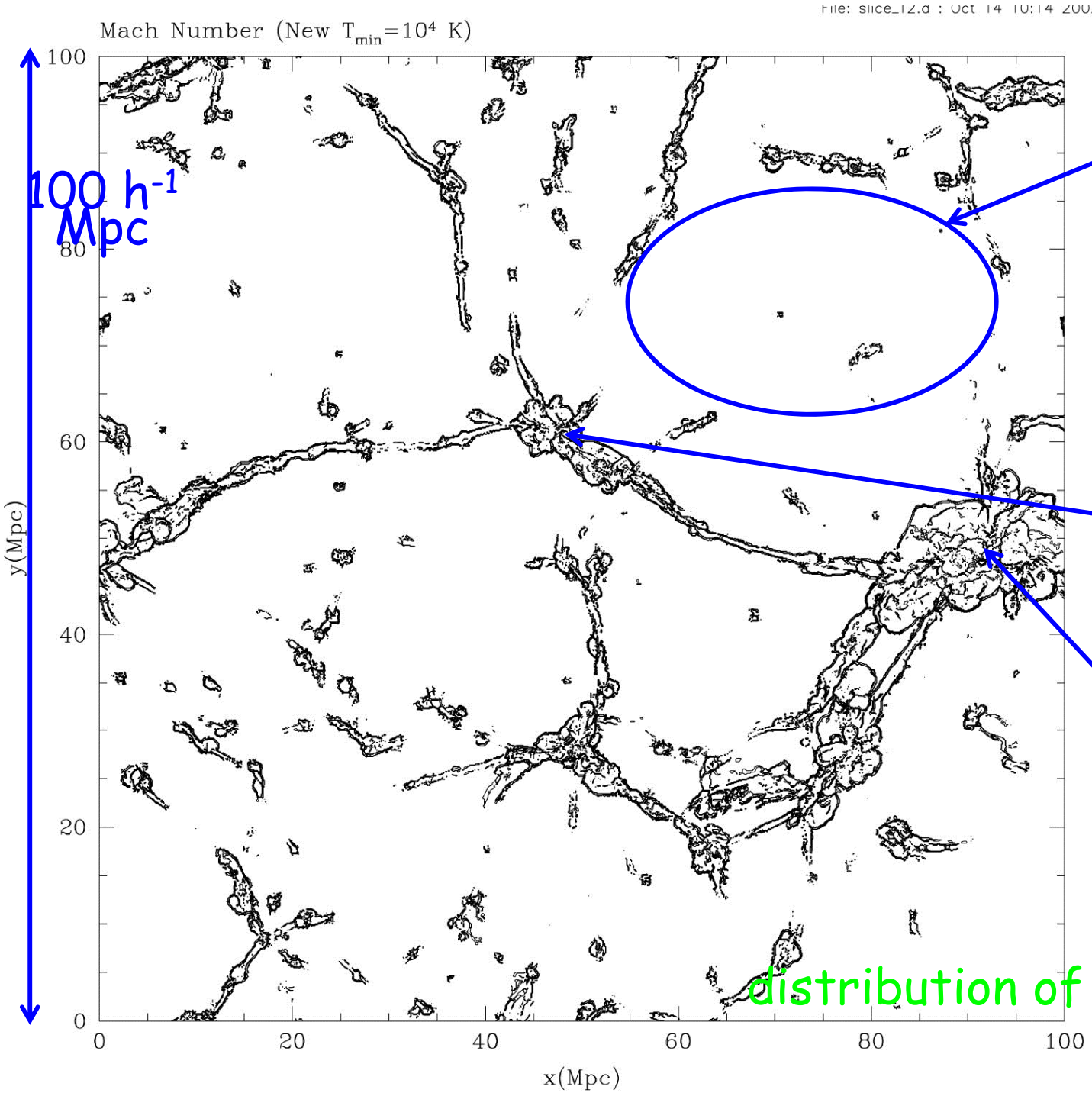
Se-Heon Oh
Aeree Chung
} HI in galaxies

cosmic magnetism - 2 science talks on today

Dongsu Ryu
Takuya Akahori
} B in the cosmic web

radio halo/relics, pulsar, etc…

Magnetic fields in the intergalactic space



void regions:
B >~ 10^{-16} G (?)

filaments of galaxies:
B ~ 10 nG

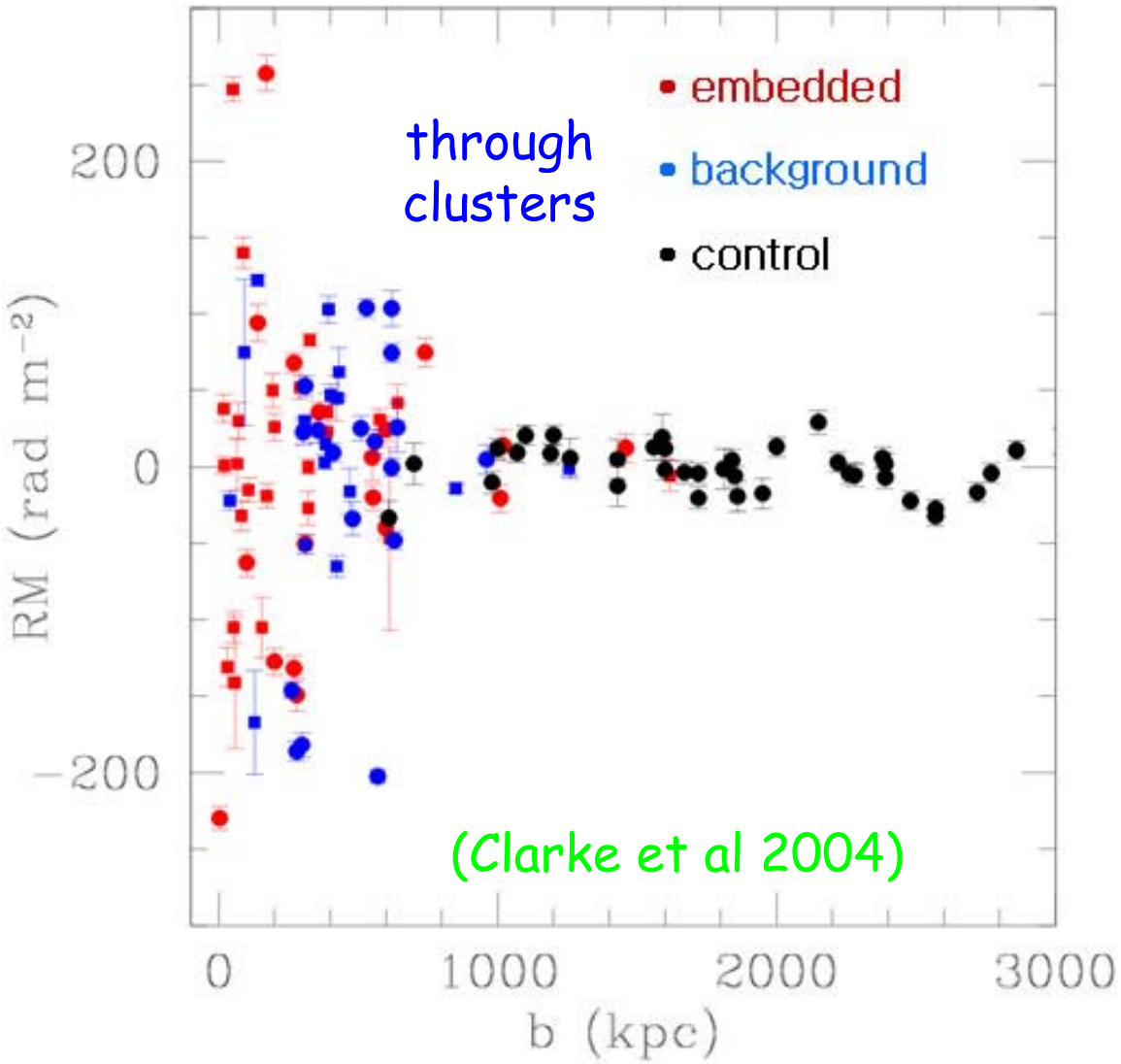
clusters of galaxies:
B ~ a few μG

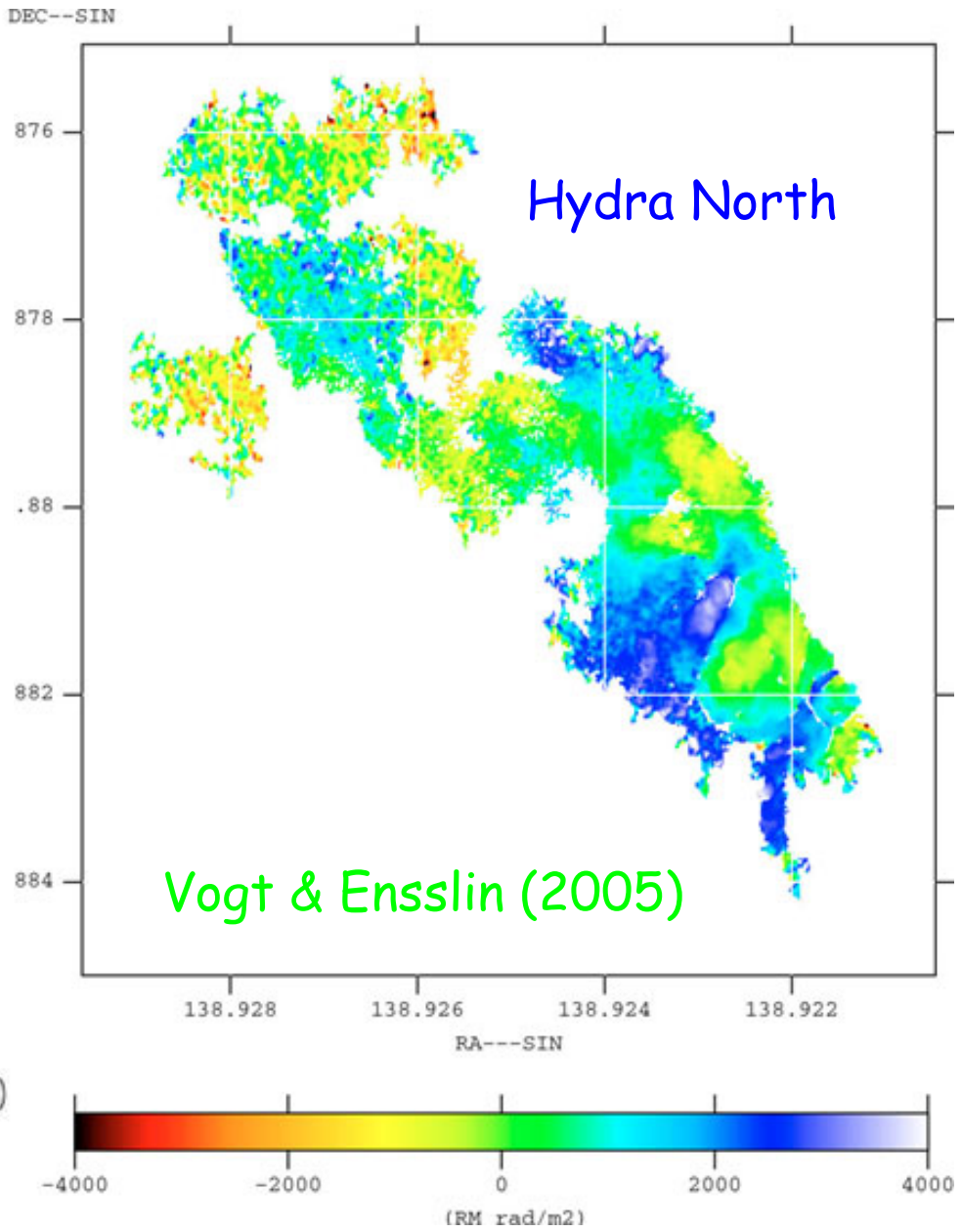
distribution of cosmological shocks

Clusters of galaxies - magnetic fields

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

-> B ~ a few μG (core region)





Clusters of galaxies - 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 $B \sim$ a few μG

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 $E_{\mathrm{magnetic}} \sim 10^{-12}\,\mathrm{erg/cm}^{3}$

magnetic fields

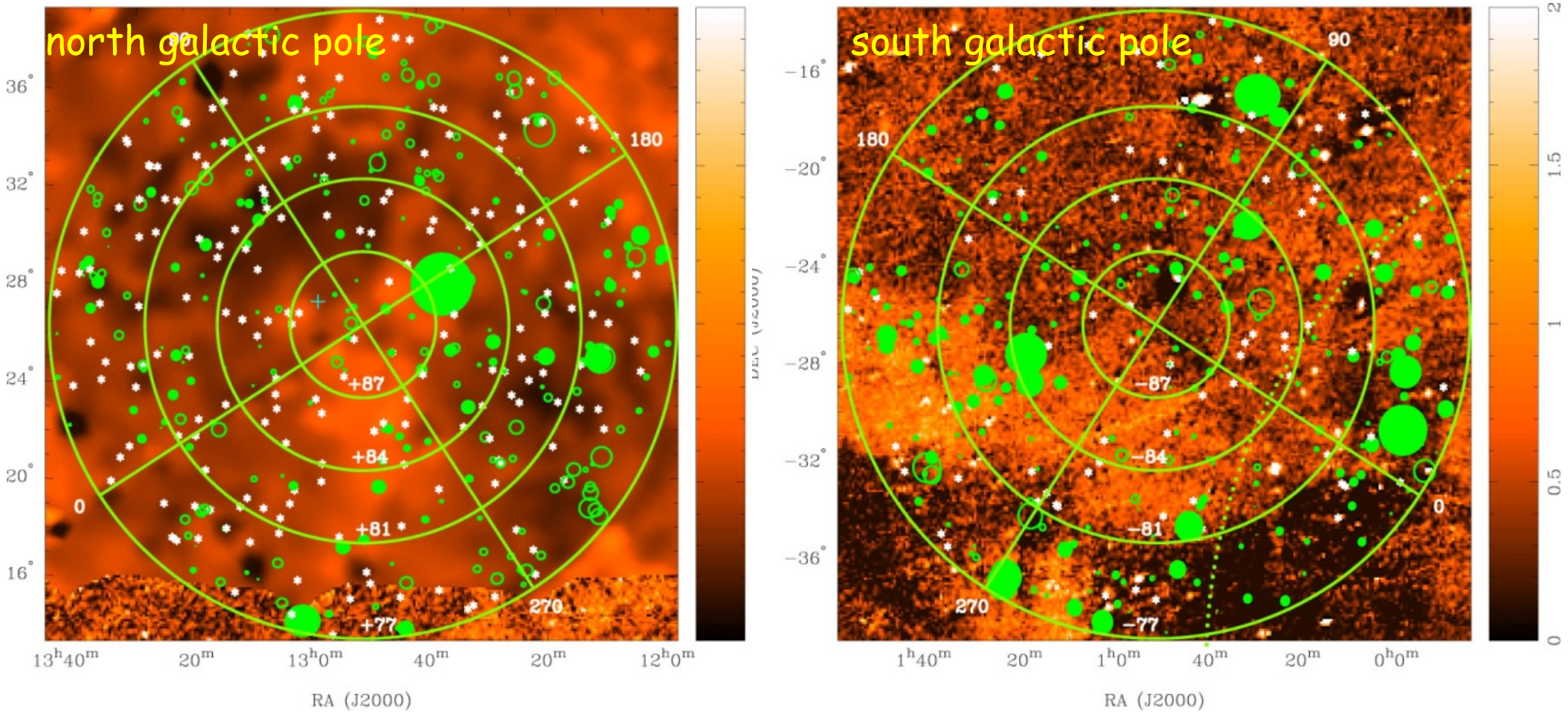
<- turbulence dynamo + feedbacks from galaxies ?

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

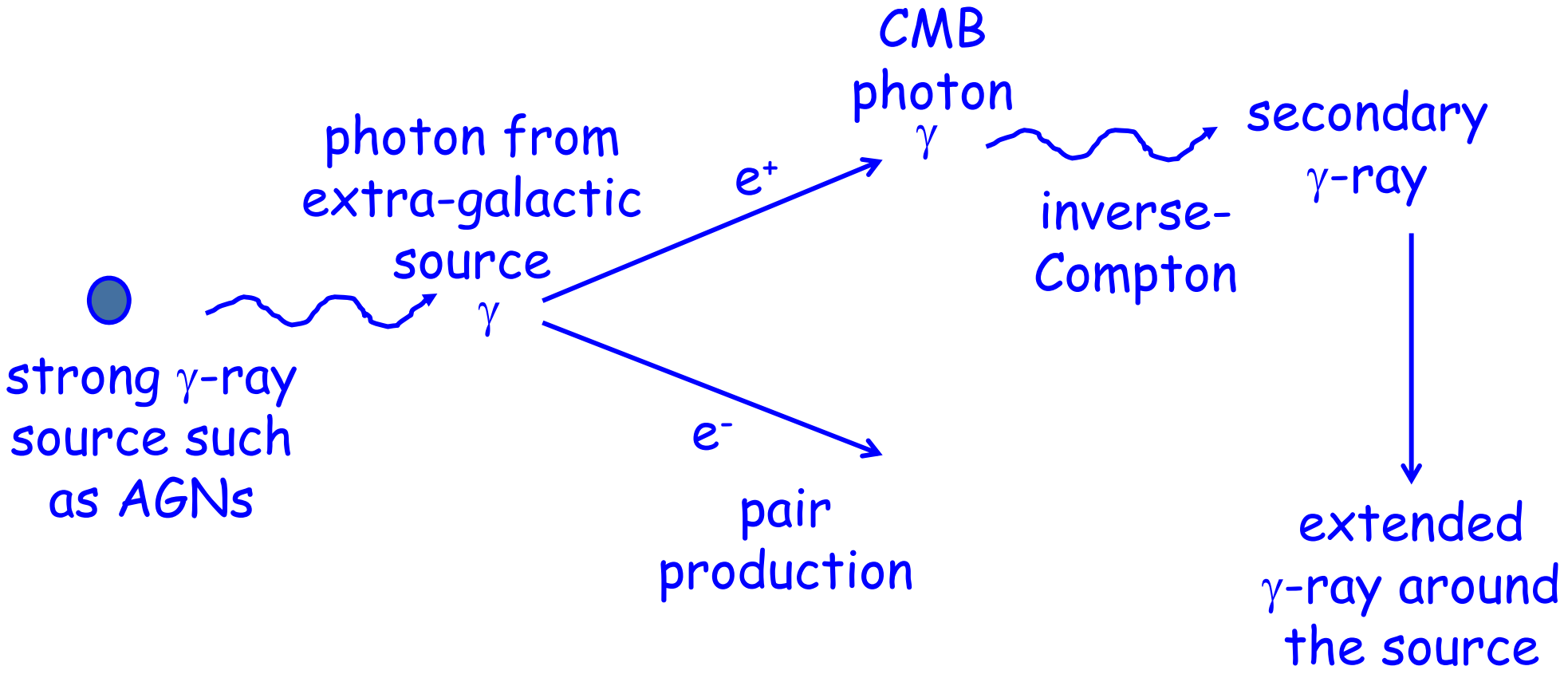
magnetic energy $E_{\mathrm{magnetic}} \sim 10^{-17}\,\mathrm{erg/cm}^{3}$

magnetic fields <- turbulence dynamo ?

Void regions - magnetic fields

Lack of extended γ-ray emission around AGNs

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



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

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

(Neronov & Vovk 2010
Aleksic et al. 2010)

Void regions - 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 $E_{\mathrm{cosmic\text{-}ray}} \sim 10^{-20}\,\mathrm{erg/cm}^{3}\ (?)$

magnetic energy $E_{\mathrm{magnetic}} \sim 10^{-33}\,\mathrm{erg/cm}^{3}(?)$

origin and nature of magnetic fields <- unknown !!

Exploration of magnetic fields in the cosmic web
using the SKA

-> Faraday rotation measure

see the next talks by Akahori

Kumazaki

-> **synchrotron**

this talk

Synchrotron radiation

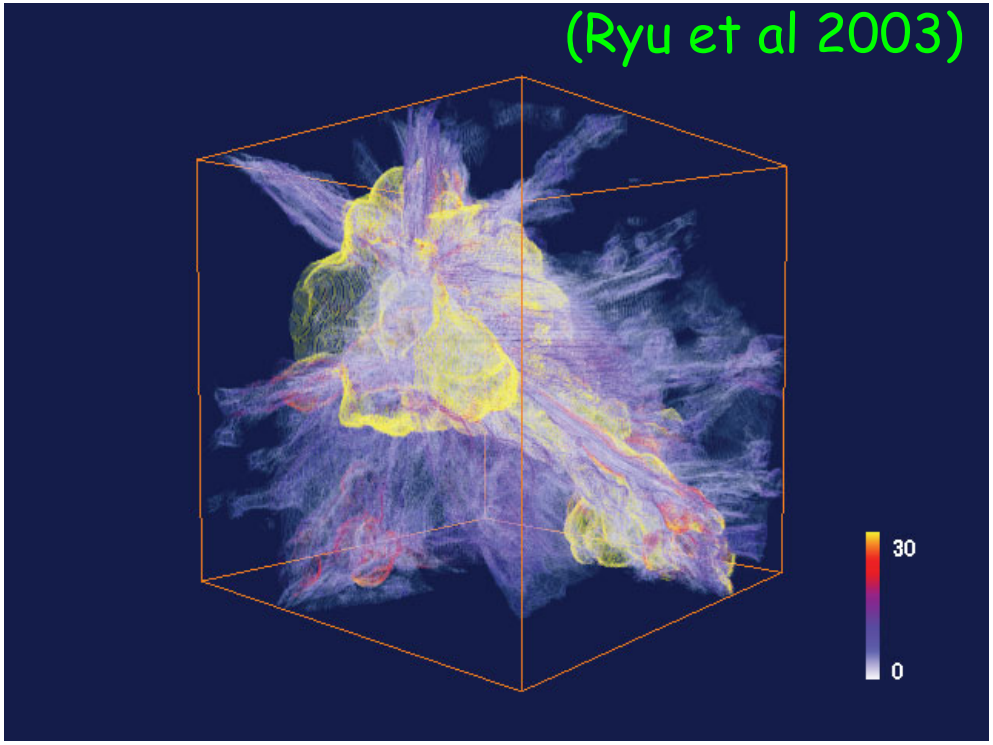
requires

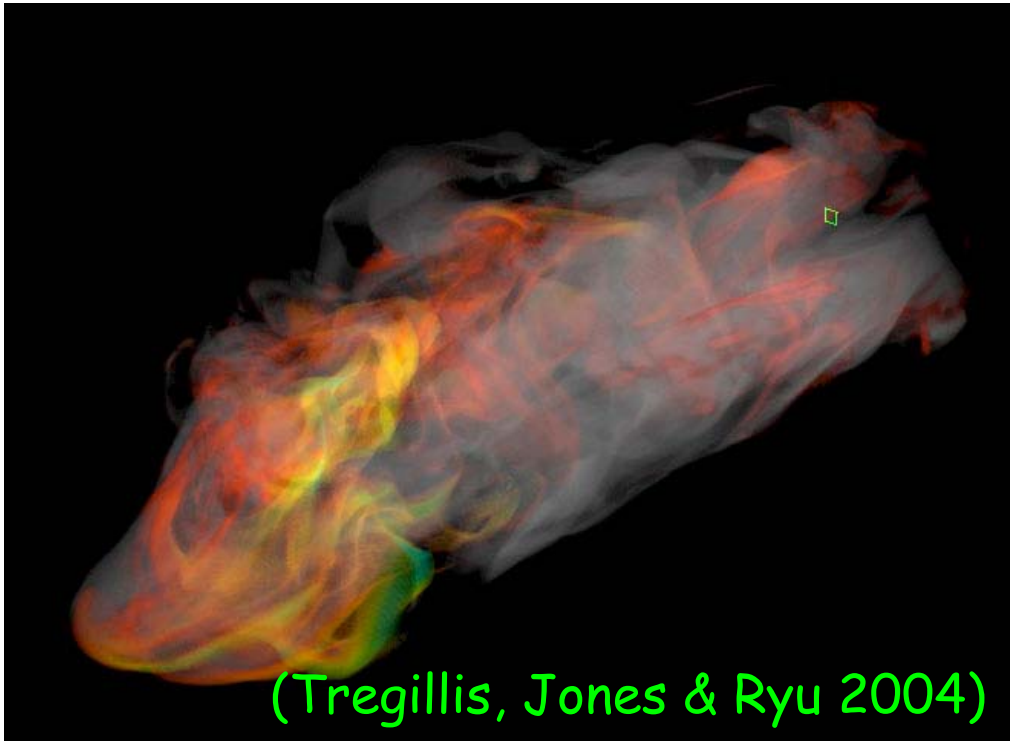
cosmic ray particles

\+ **magnetic fields**

Sources of B and CRs

- **formation of large-scale structure**
  - **-> shocks from merger, accretion, …**
  - **turbulence**
- AGN outflows, galactic winds, …
- macroscopic, microscopic instabilities





Overall picture for cosmological shocks

large-scale structure formation

gravitational collapse & flow motions

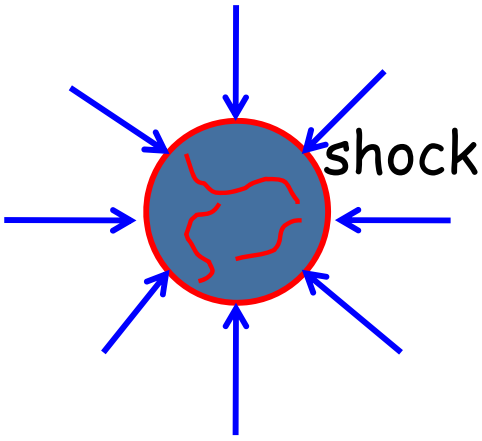
other sources, such as AGNs of heat, CRs, turbulence and magnetic fields

cosmological shocks

shock dissipation

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

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



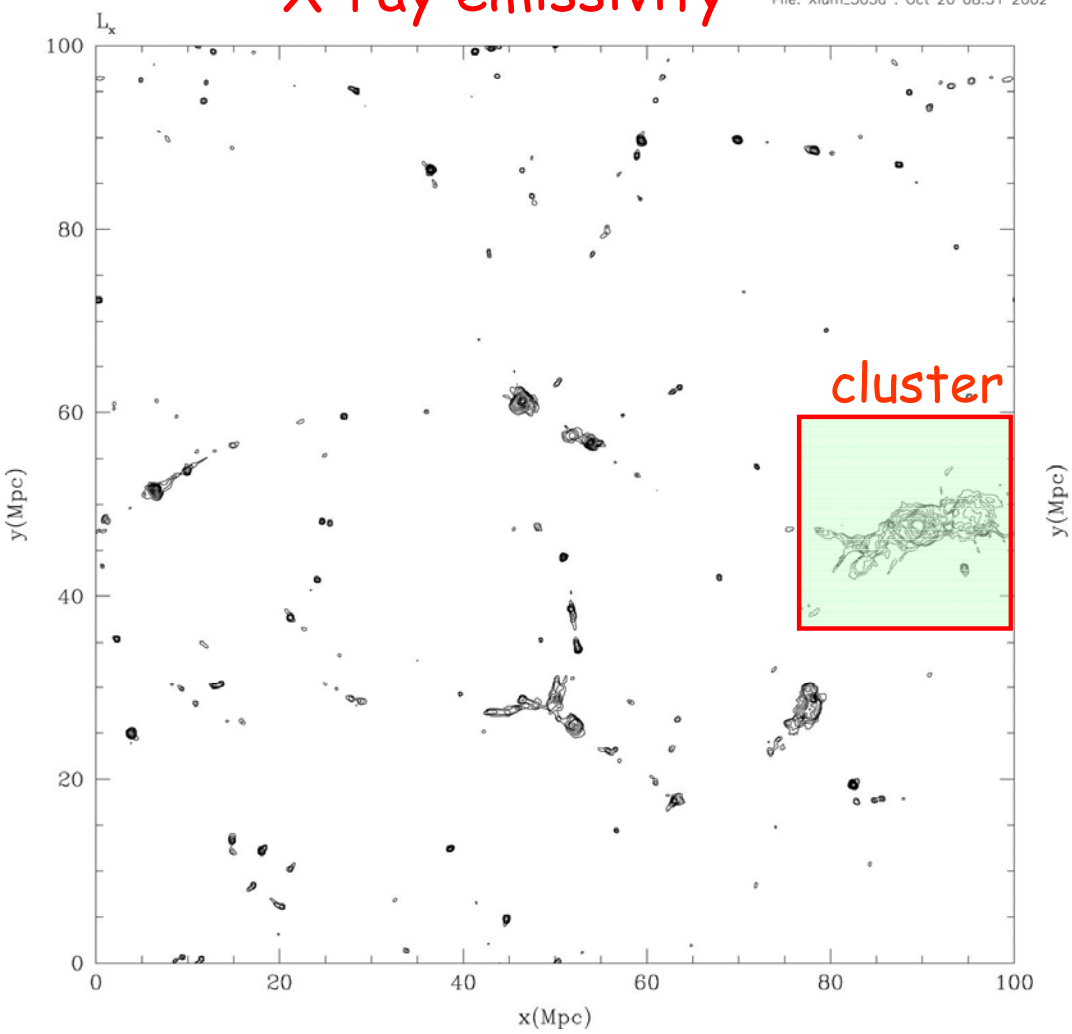
cascade into turbulence

turbulent amp. of mag. fields
turbulent acceleration of CRs

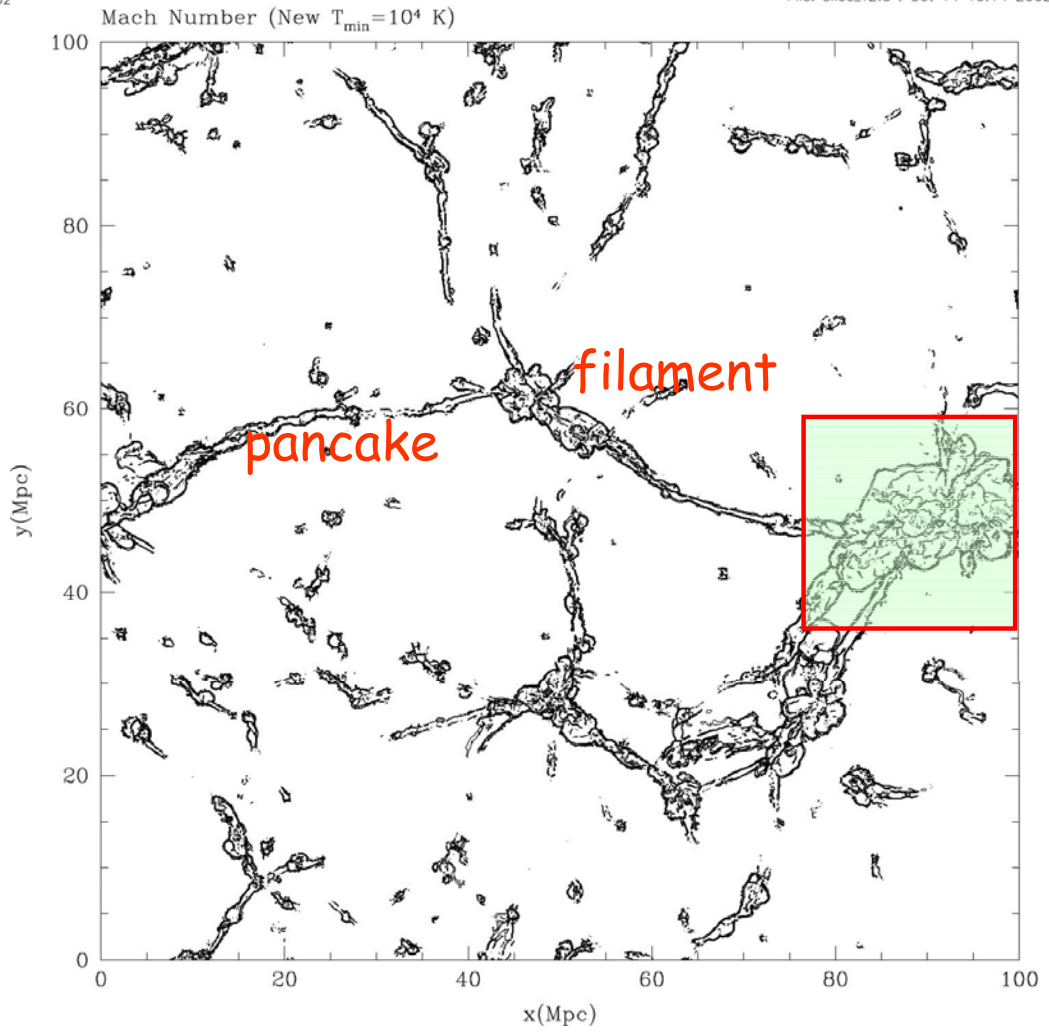
Spatial distribution of cosmological shocks in the large-scale structure of the universe

(Ryu et al 2003)

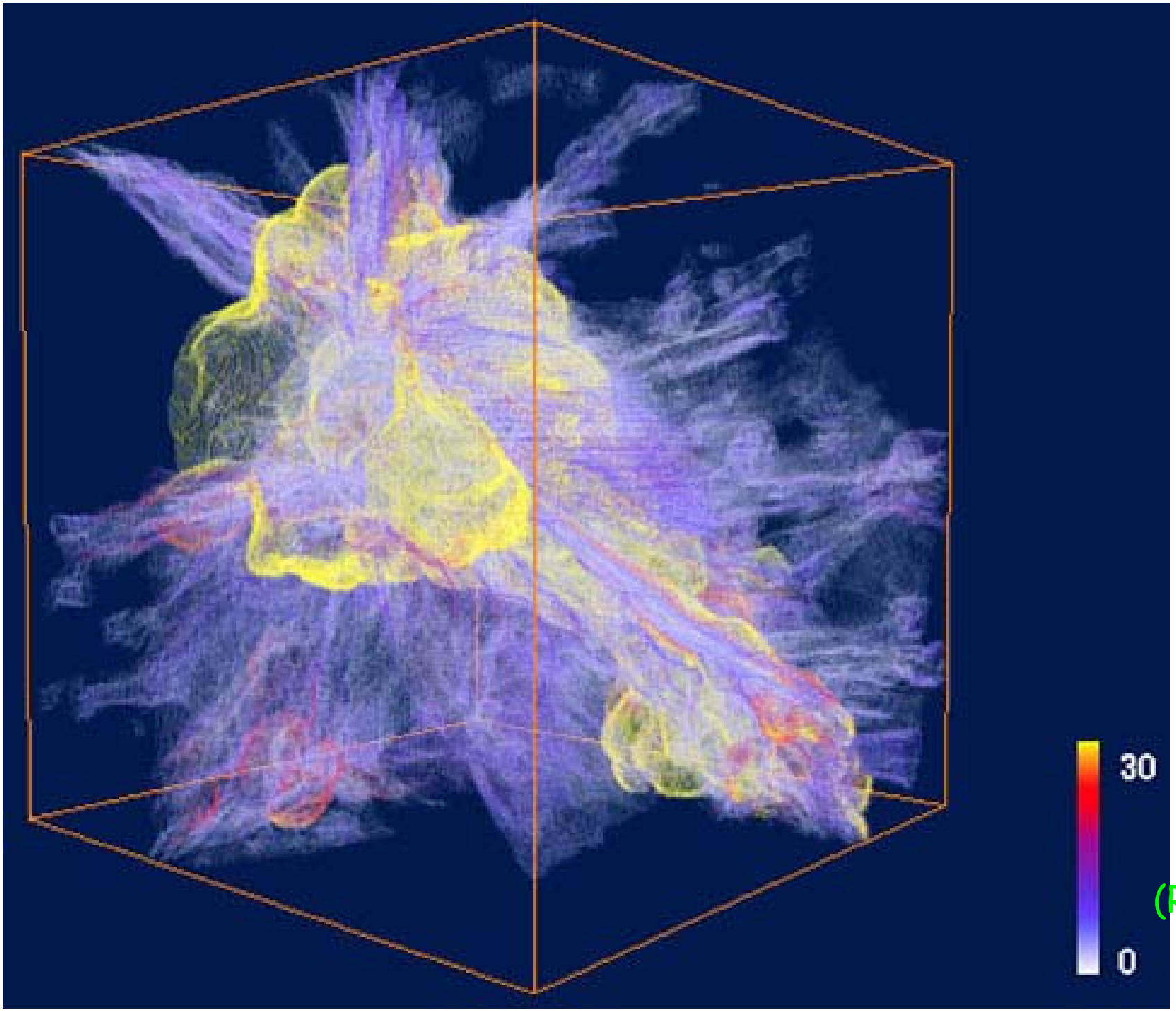
X-ray emissivity



shock waves



rich, complex shock morphology:
shocks "reveal" filaments and sheets (low density gas)



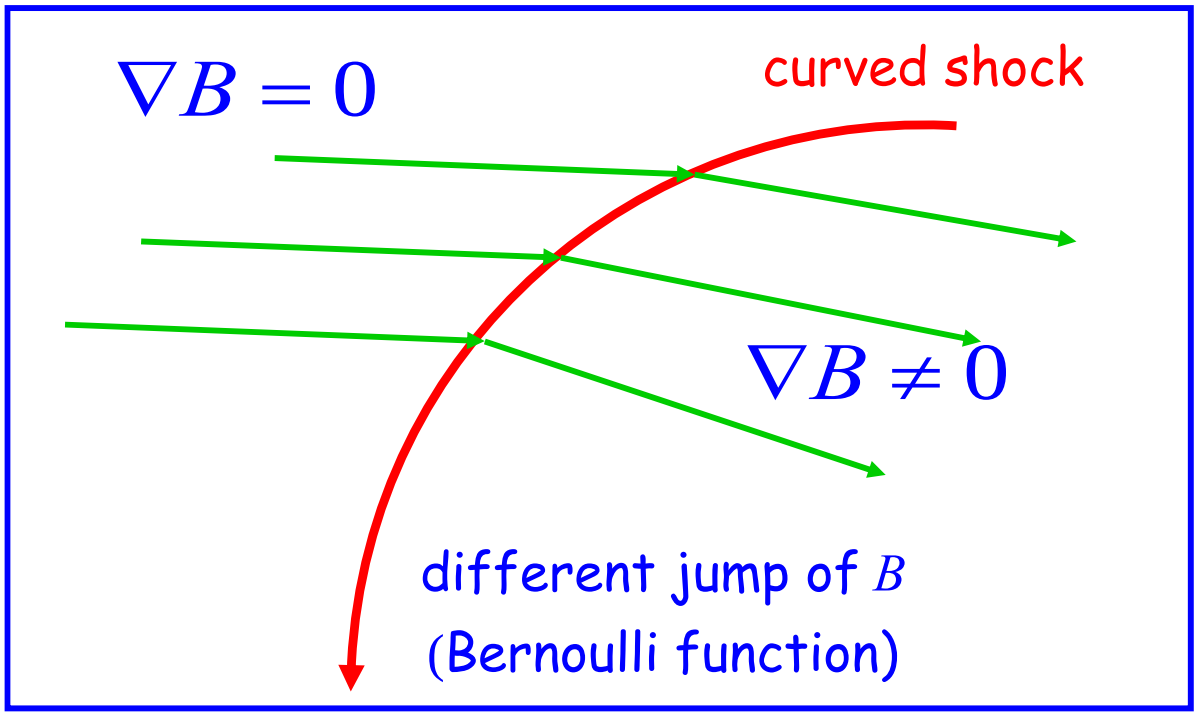
Mach number distribution of shocks around the cluster complex

(Ryu et al 2003)

Turbulence

Vorticity generated at cosmological shocks

directly at curved shocks



$\Longrightarrow$ at postshock

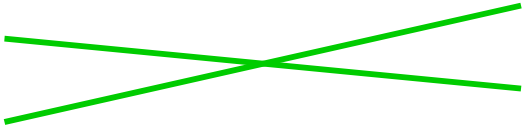
$$\varpi_{cs} \sim \frac{(\rho_2 - \rho_1)^2}{\rho_2 \rho_1} \frac{\vec{U} \times \vec{n}}{R}$$

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.

by the baroclinic term

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

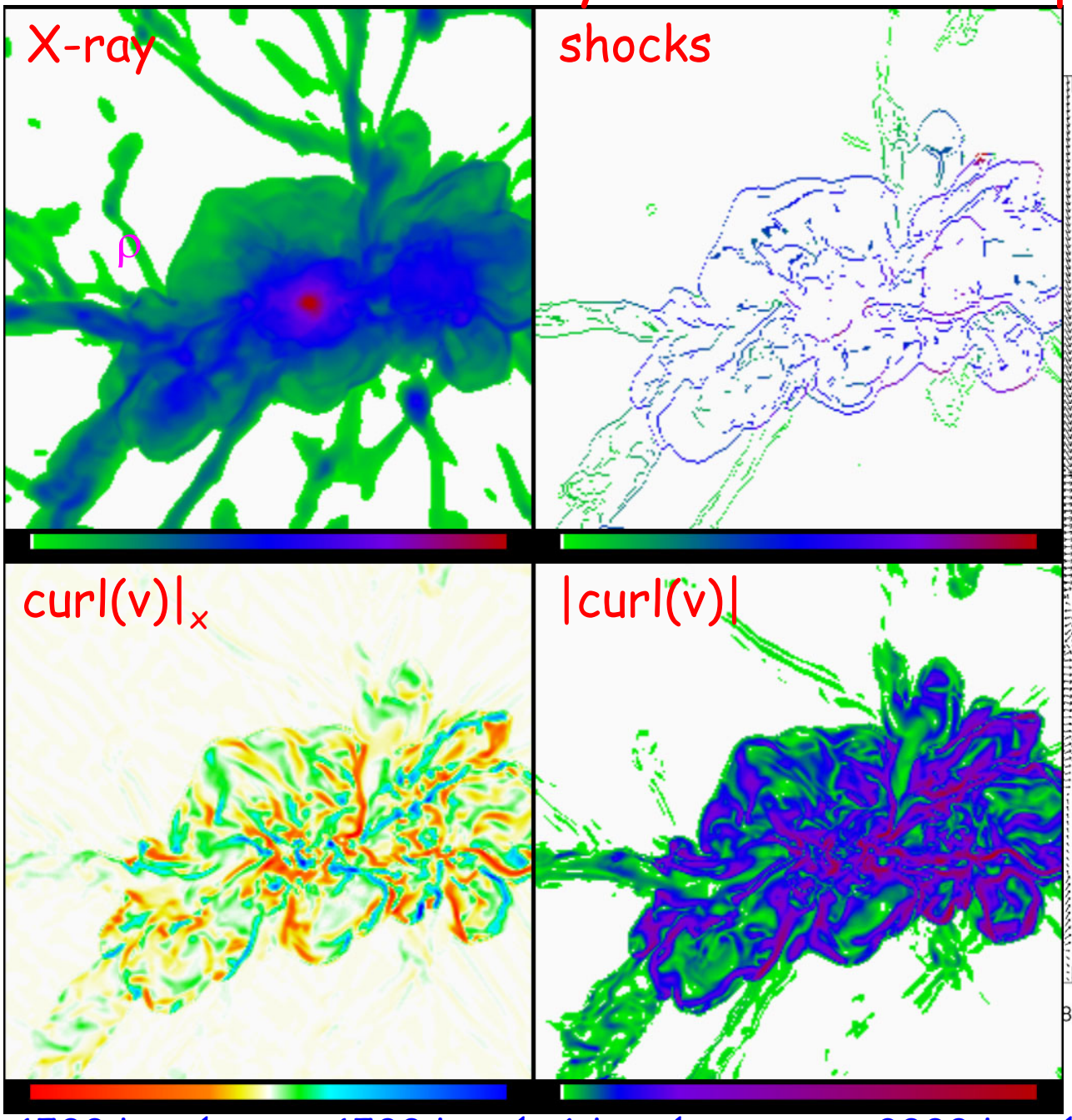
baroclinity



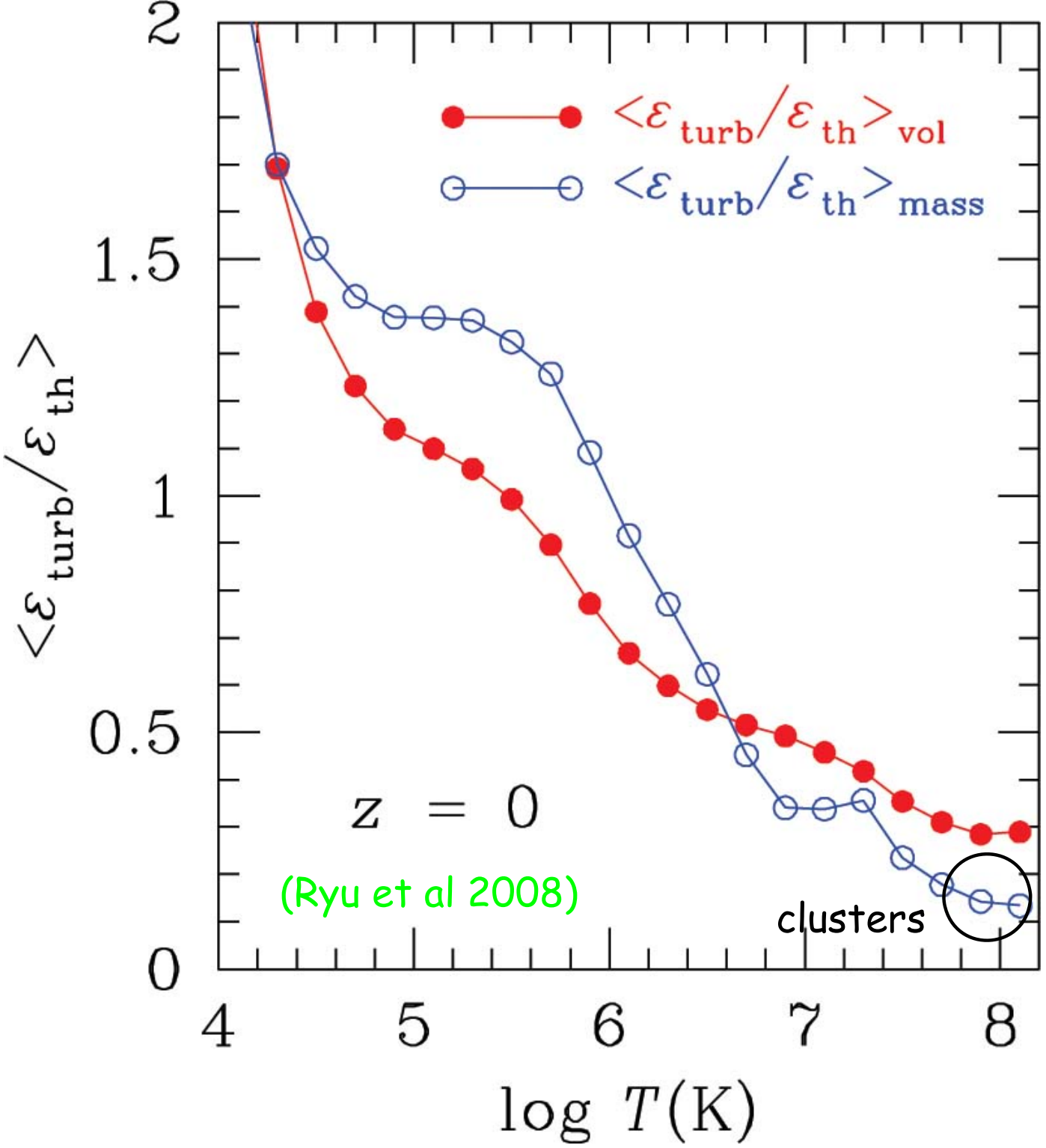
$\Longleftarrow$ due to entropy variation induced at shocks

Vorticity in a cluster complex

(Ryu et al 2008)



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



Turbulence energy of in the ICM

assuming that all the energy of vortical motions goes to turbulence

$M_{turb} < 1$
(subsonic turbulence)
inside and outskirts of clusters
$E_{turb}/E_{therm} \sim 0.1 - 0.2$
inside and outskirts of clusters
-> agrees with obs.
$M_{turb} \sim 1$
(transonic turbulence)
in filaments

Magnetic fields in the LSS of the universe

Seed magnetic fields

Origin of seeds for comic magnetic fields is uncertain.

some suggestions:

1. generation in the early universe

   e.g.) during the electroweak phase transition ($t \sim 10^{-12}$sec)?

   during the quark-hadron transition ($t \sim 10^{-5}$sec)?

2. generation before cluster formation

   e.g.) plasma processes such as thermal fluctuations

   or at shocks

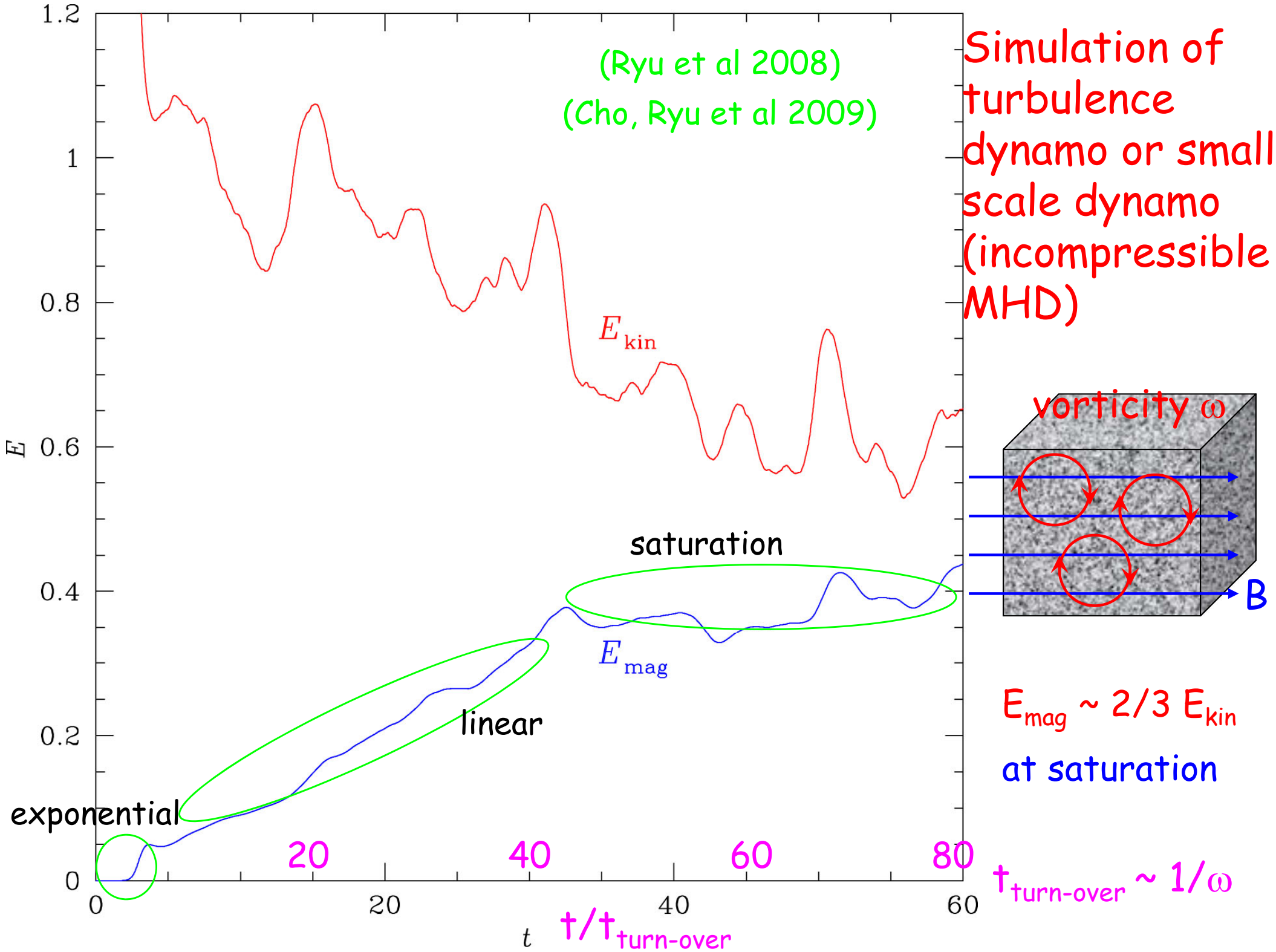
3. magnetic fields from the first stars and active galaxies

...

-> expected to be very weak

Amplification through turbulence dynamo ?

<- observed magnetic fields


(Ryu et al 2008)
(Cho, Ryu et al 2009)
Simulation of turbulence dynamo or small scale dynamo (incompressible MHD)
E_{kin}
E_{mag}
saturation
linear
exponential
vorticity ω
B
E_{mag} ~ 2/3 E_{kin}
at saturation
$t_{turn-over}$ ~ 1/ω
E
t
t/$t_{turn-over}$
0
0.2
0.4
0.6
0.8
1
1.2
0
20
40
60
80

Resulting magnetic fields in the large-scale structure of the universe at z = 0

(Ryu et al 2008)

averaged magnetic field

strength at z = 0

- inside clusters

  $\langle B \rangle \sim$ a few μG

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

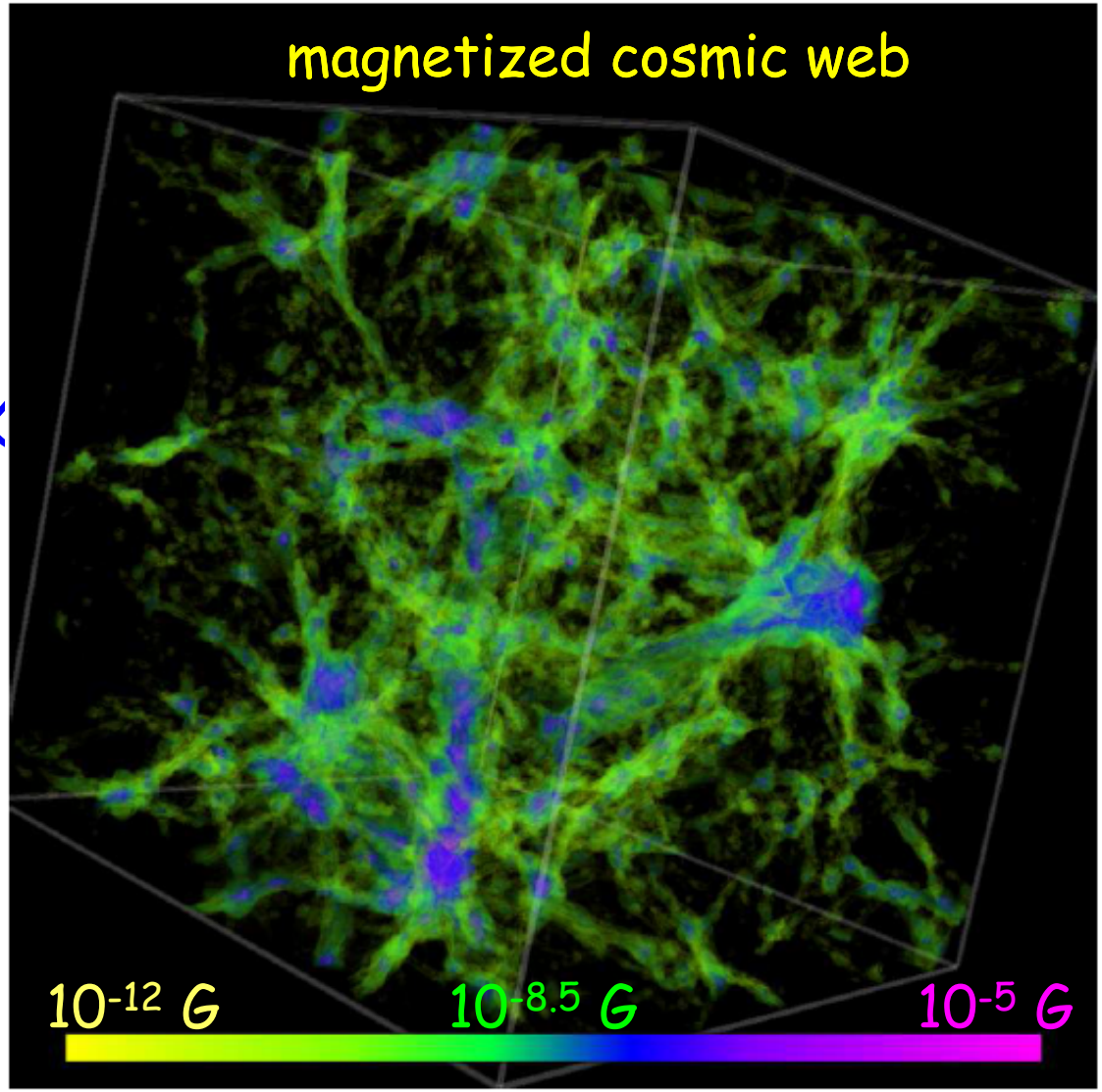
  $\langle B \rangle \sim 0.1\ \mu G$

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

  $\langle B \rangle \sim 10$ nG

⟵ energetics

distribution of the intergalactic magnetic field in a $(\sim 100\ h^{-1}\ \mathrm{Mpc})^3$ box



Cosmic rays accelerated at cosmological shocks

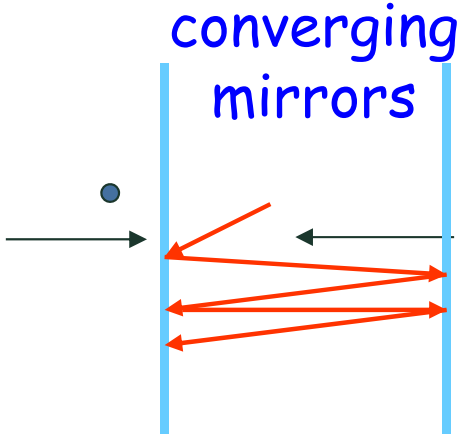
key ideas behind DSA
(diffusive shock acceleration)

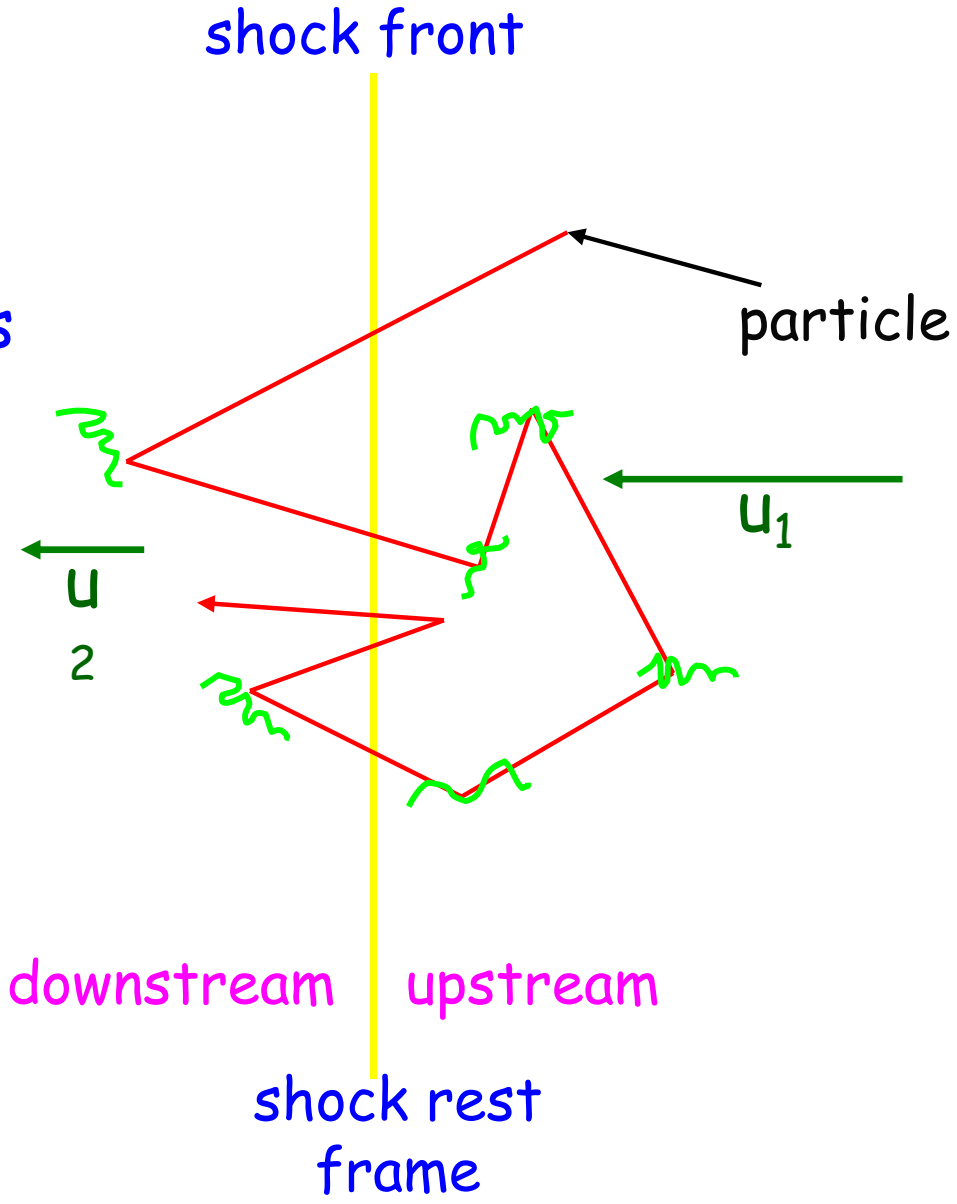
- Alfven waves in a converging flow act as converging mirrors
→ particles are scattered by waves
→ cross the shock many times

"Fermi first order process"

$$\frac{\Delta p}{p} \sim \frac{|\Delta u|}{u}$$

energy gain at each crossing



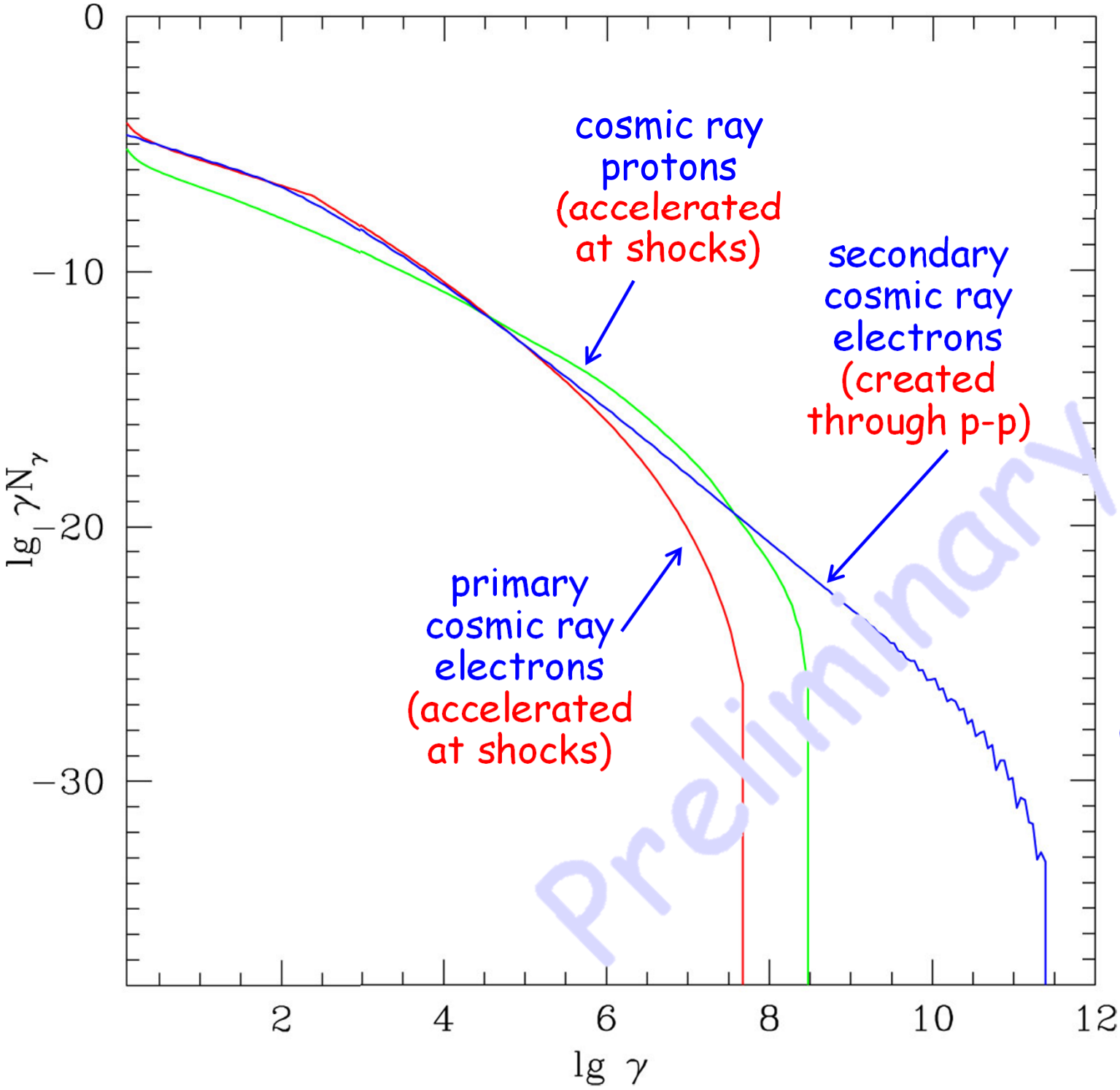


Cosmic ray electrons responsible for synchrotron

- **primary CR electrons: directly accelerated or re-accelerated at shocks**

- **secondary CR electrons: created through collisions between cosmic ray protons and gas thermal protons**

- turbulence-accelerated CR electrons: accelerated in turbulence through the second-order Fermi process



Resulting spectrum of CRs

the ratio of E_{CRe}/E_{CRp} at shocks is arbitrary in this plot

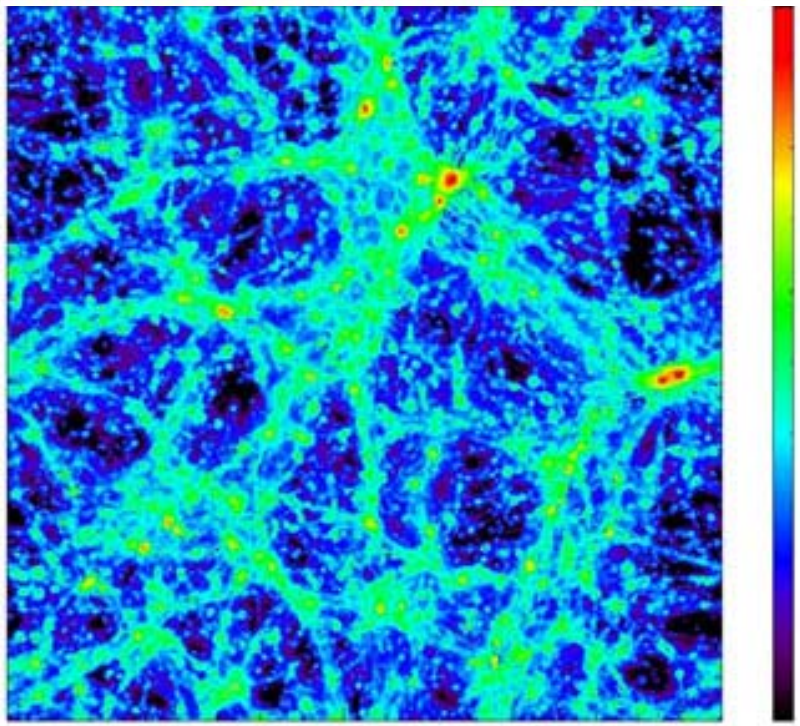
Spatial distribution of CRs at z=0

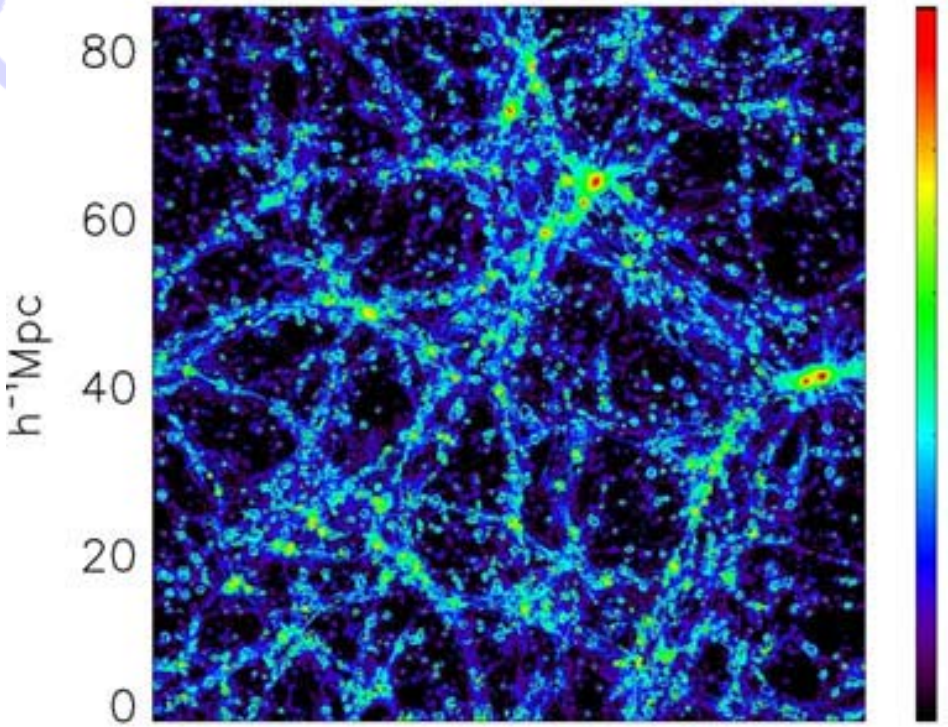
primary cosmic ray electrons follows the distribution of shocks

projected over the depth of 85 h^{-1} Mpc

cosmic ray protons follows the distribution of matter - concentrated

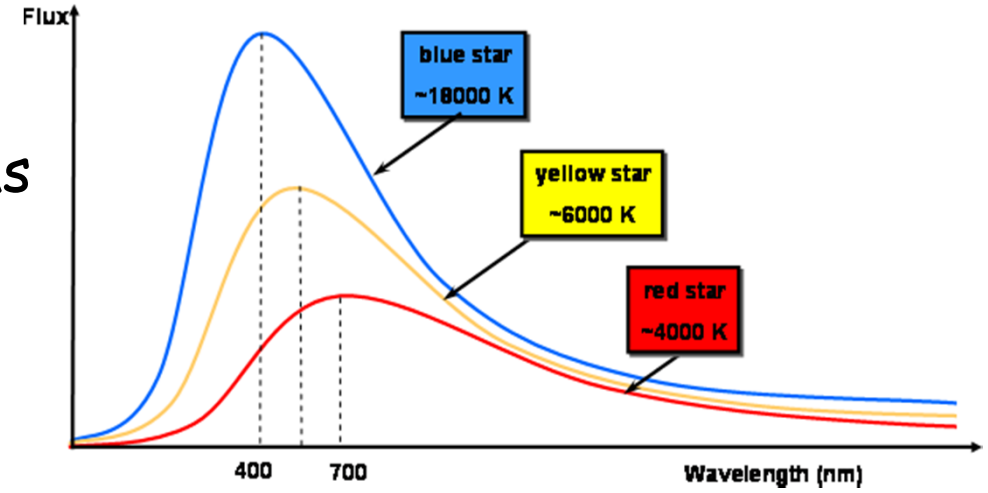
secondary cosmic ray electrons from p-p





Thermal radiation

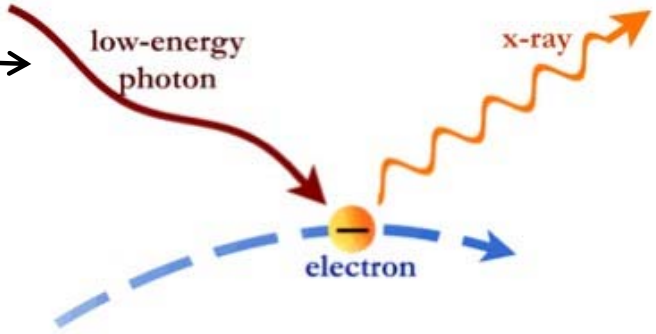
having a continuous spectrum of wavelength or frequency, referred to as blackbody radiation, which is mostly produced by **thermal particles**



Non-thermal radiation

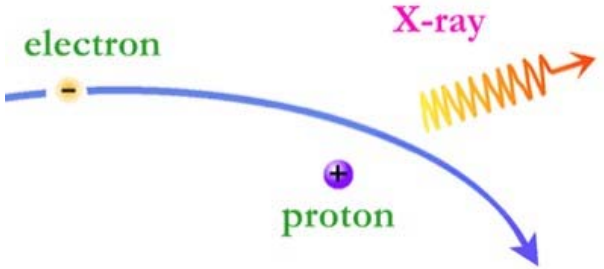
emitted by **non-thermal particles, or cosmic rays**, including

- synchrotron radiation
- inverse-Compton
- non-thermal bremsstrahlung
- γ-ray from p-p, photo-pair, photo-pion



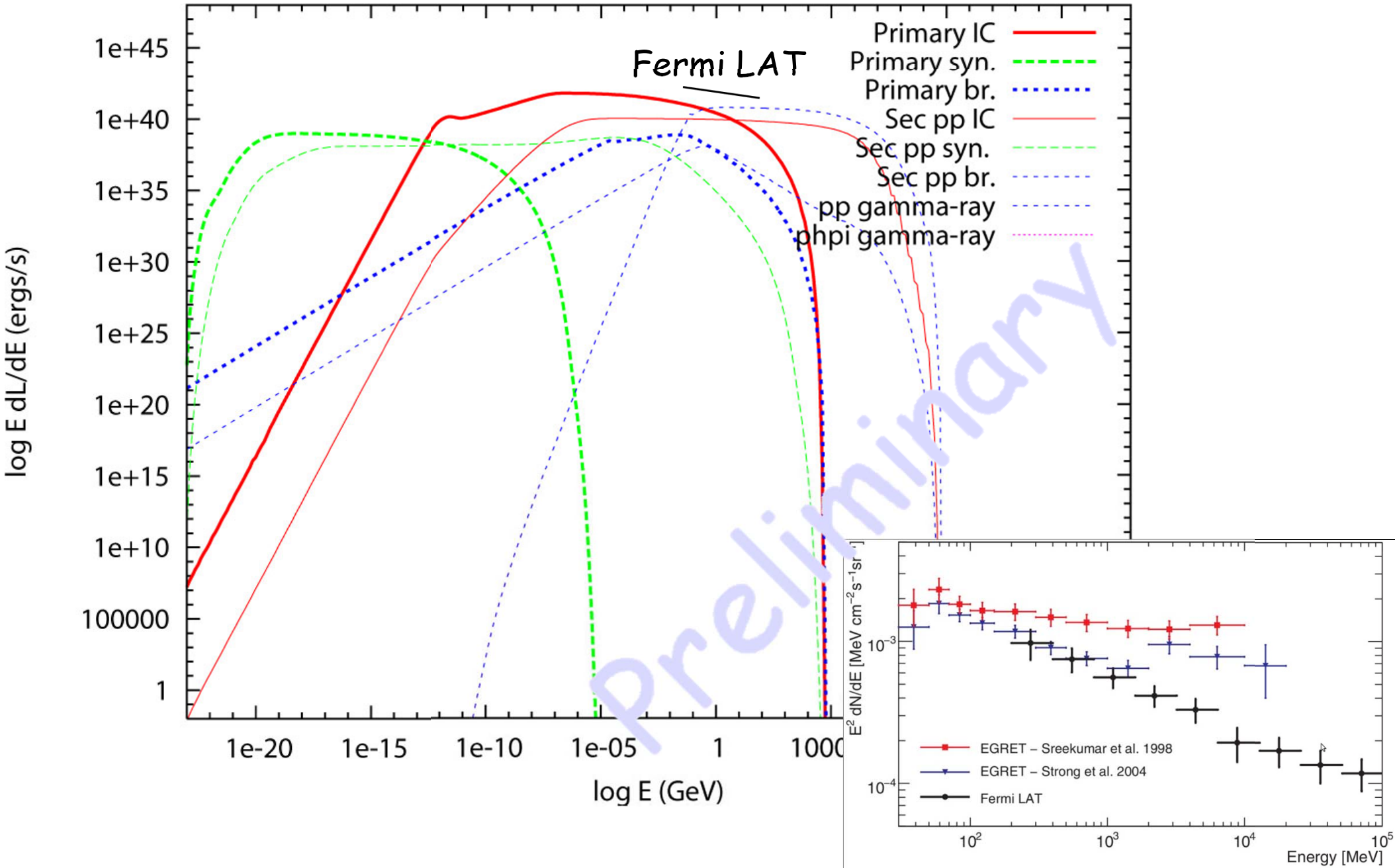
Non-thermal processes

involving non-thermal components, such as cosmic rays, magnetic fields, turbulence, shock waves, and etc



Nonthermal radiation from the intergalactic CRs

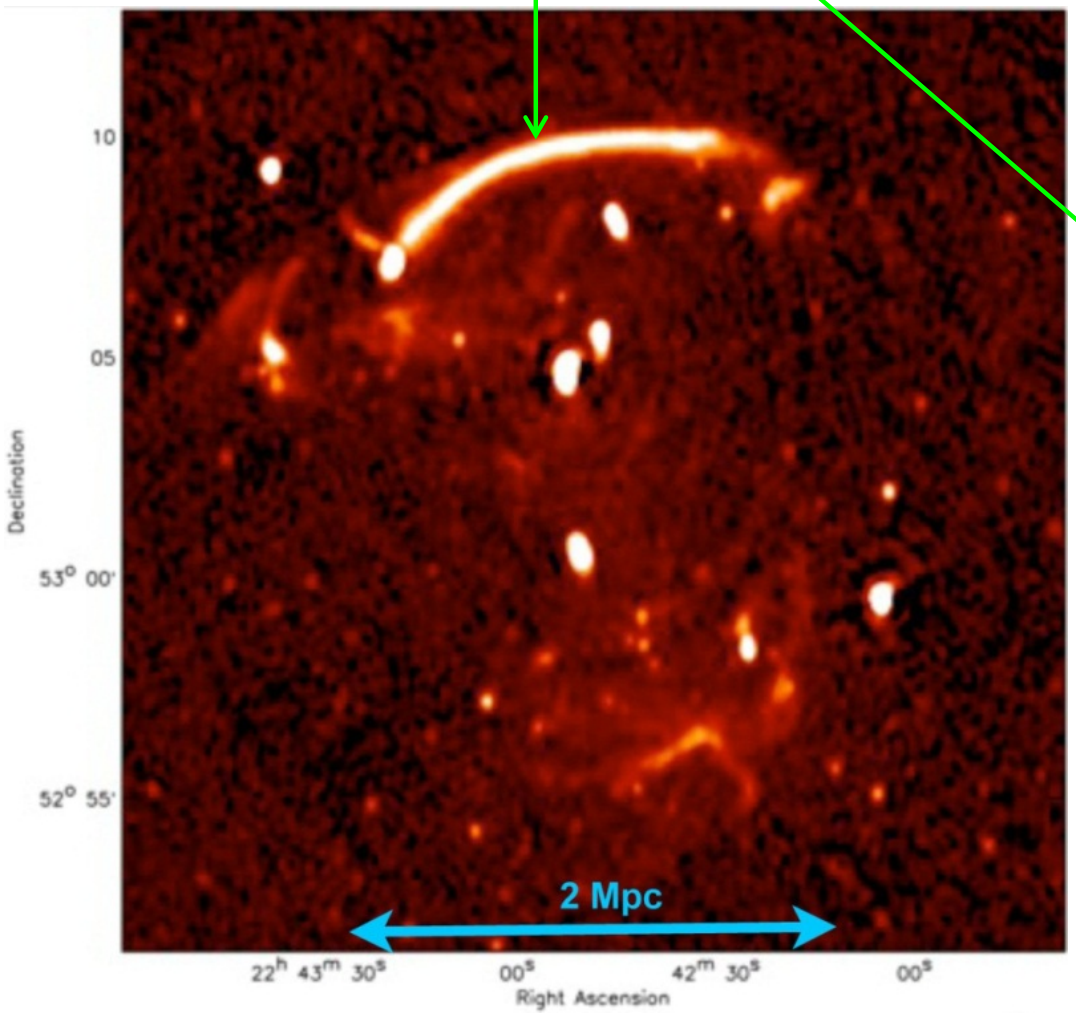
$E_{prim\ CRe}/E_{second\ CRe} \sim 5$

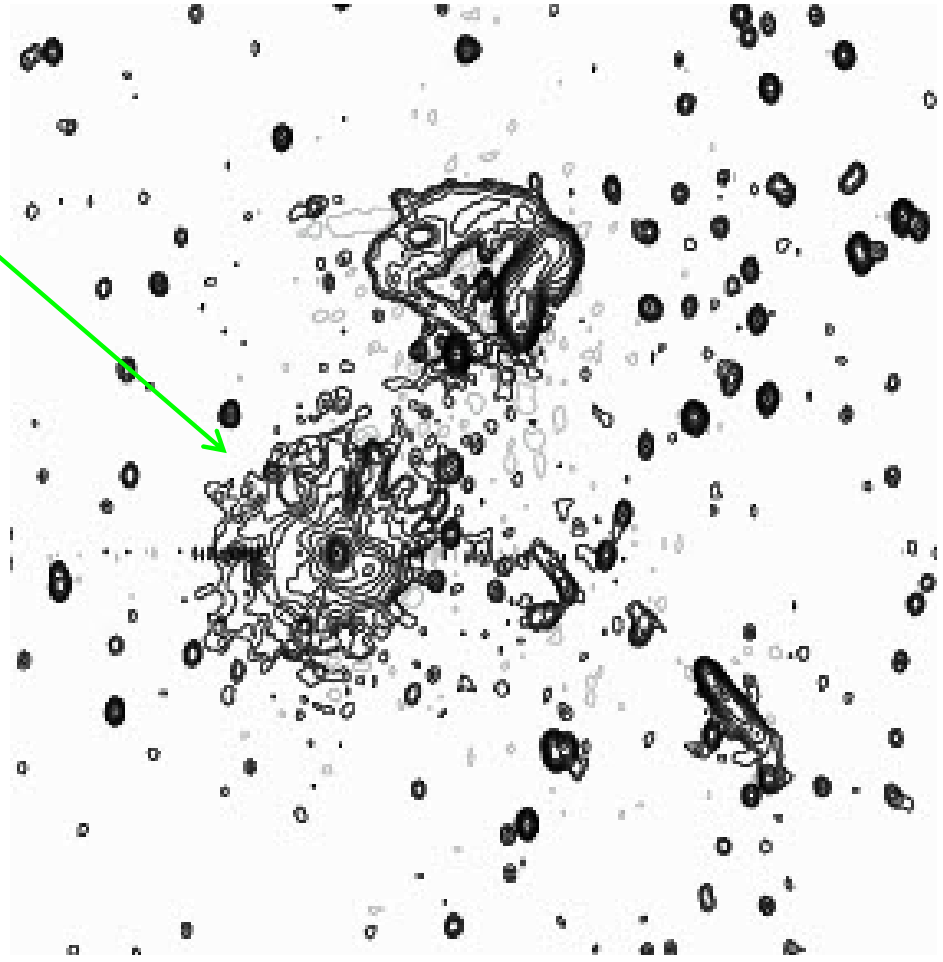


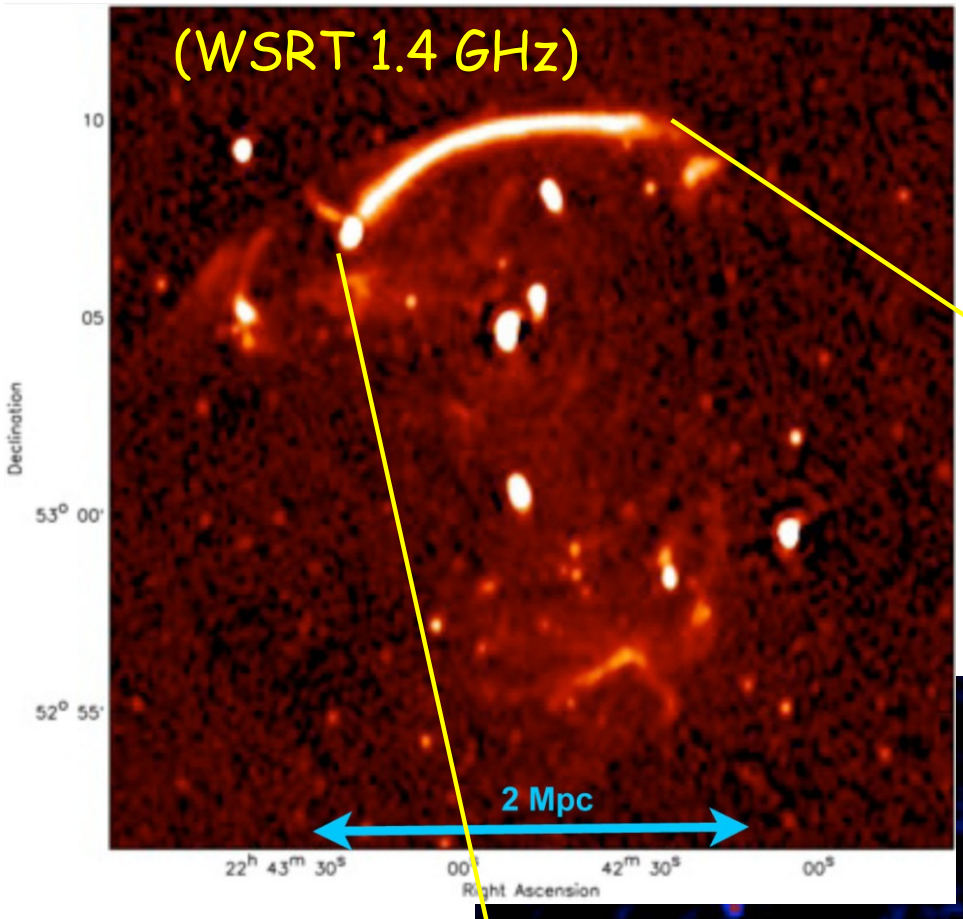
Observation of synchrotron in the LSS of the universe I

In clusters of galaxies

- primary electrons -> radio relics (highly polarized)
- secondary electrons or electrons accelerated through turbulence
  -> radio halos (diffuse, and a few percent polarized)







Radio relic in CIZA J2242.8+5301

shock Mach number

M ~ 4.5 (too strong ?)

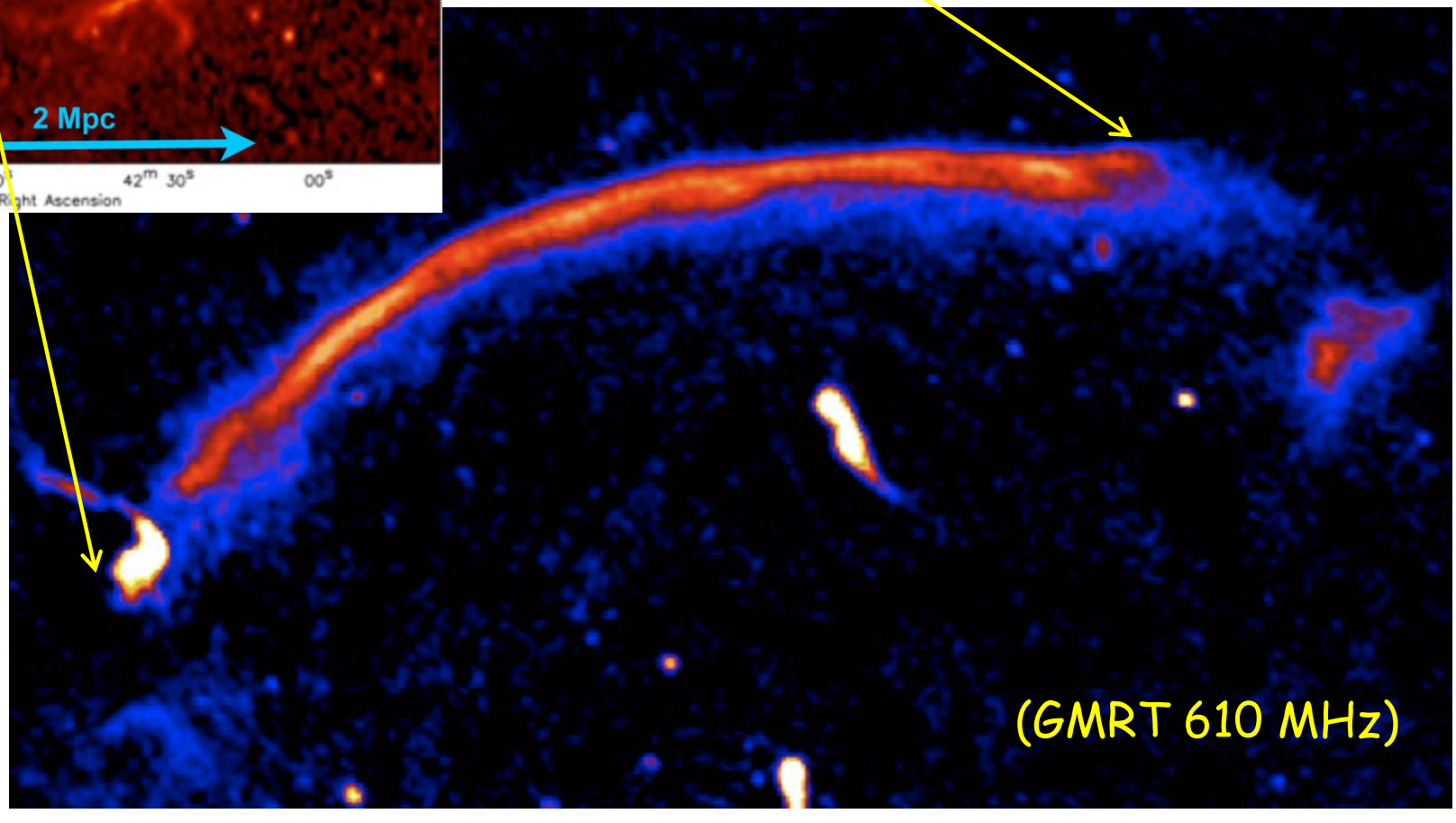
strong magnetic field:

B ~ 6 μG (strong, but OK !)

high polarization:

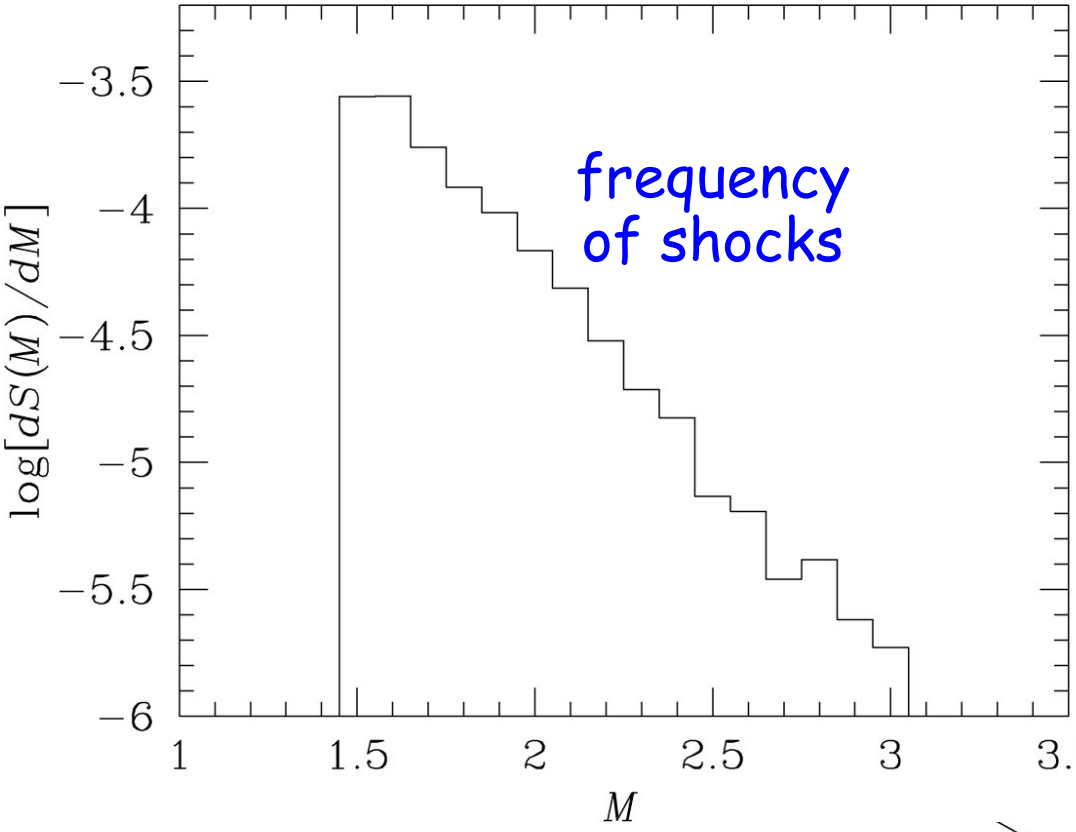
~ 70% or so (uniform B !)

(van Weeren et al 2010)



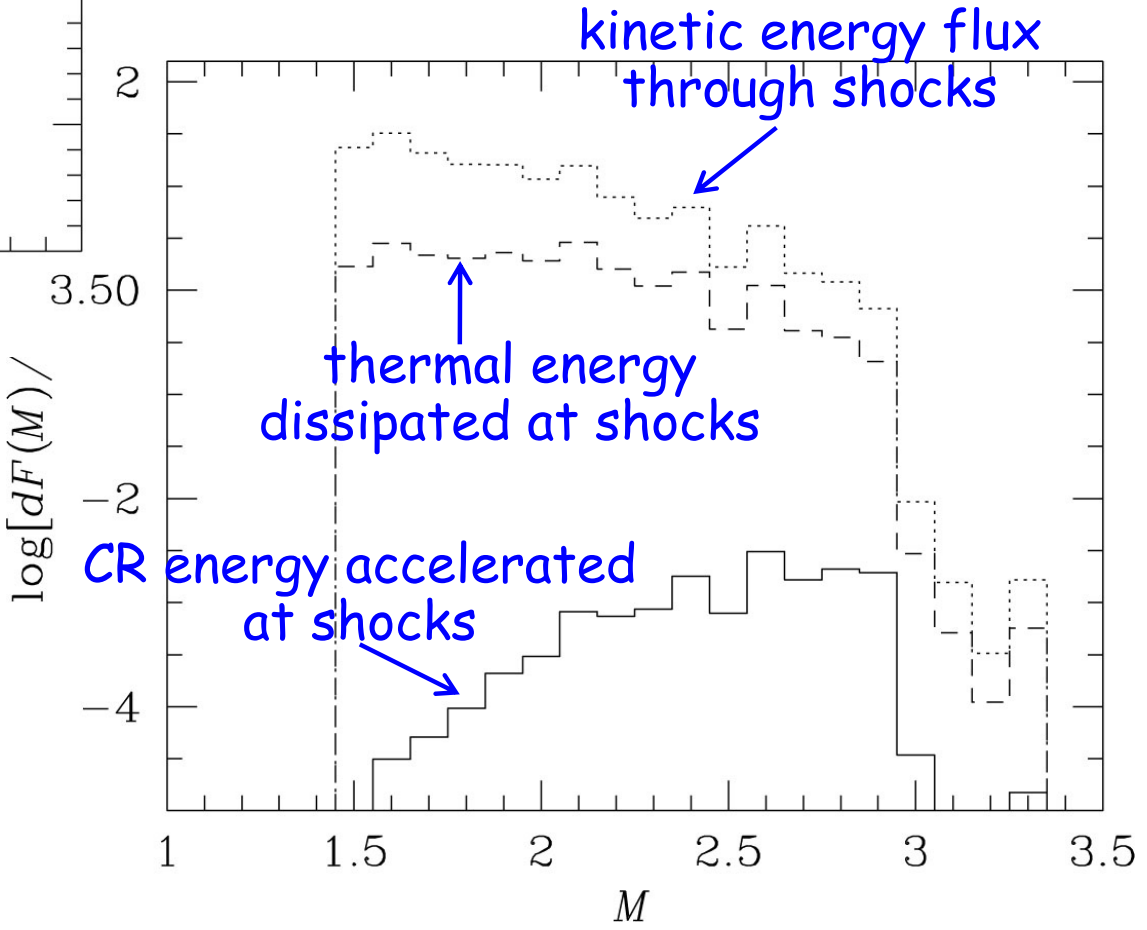
Shocks statistics

Kang & Ryu (2011)

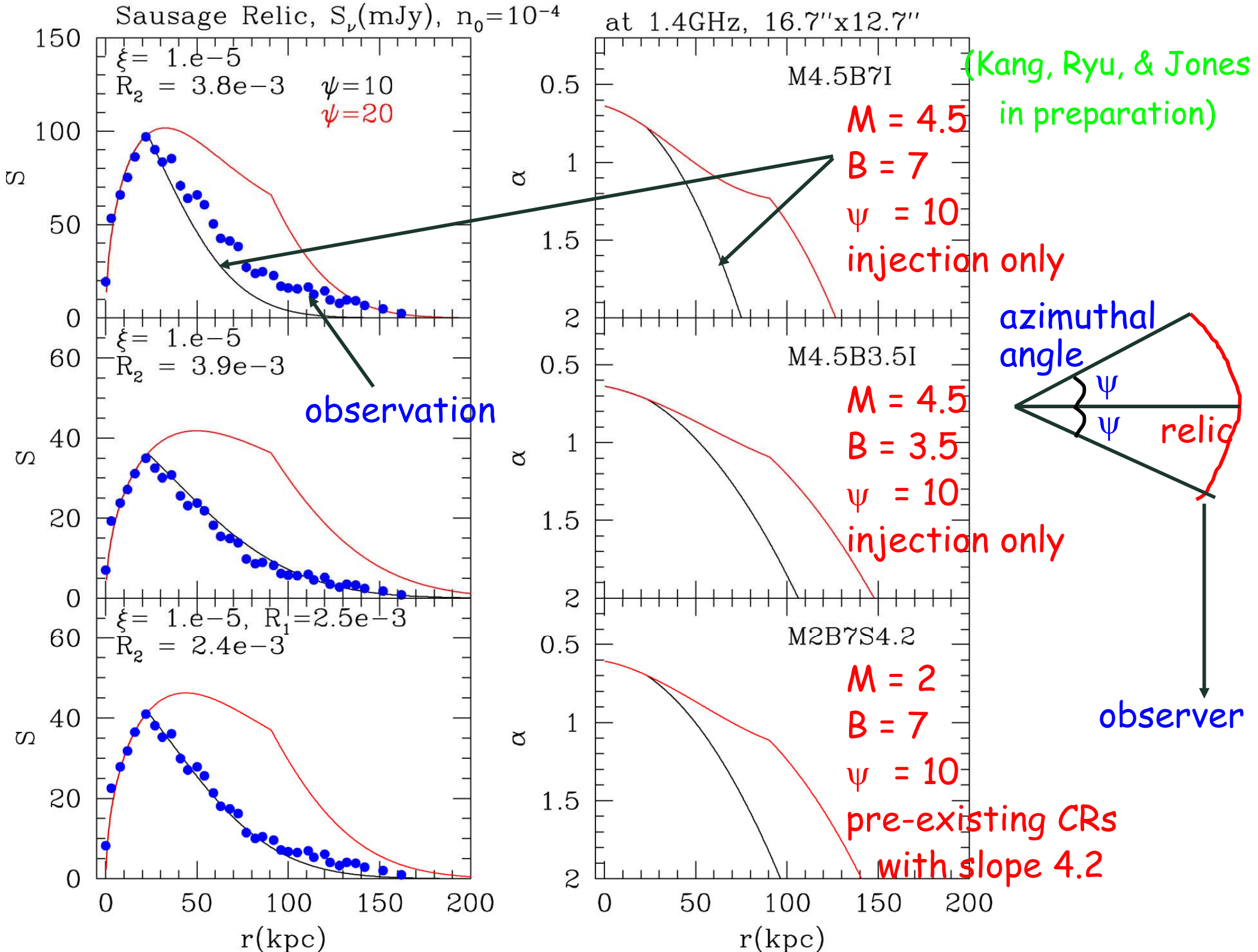


in hot gas with $T > 10^7$

(inside and outskirts of clusters)



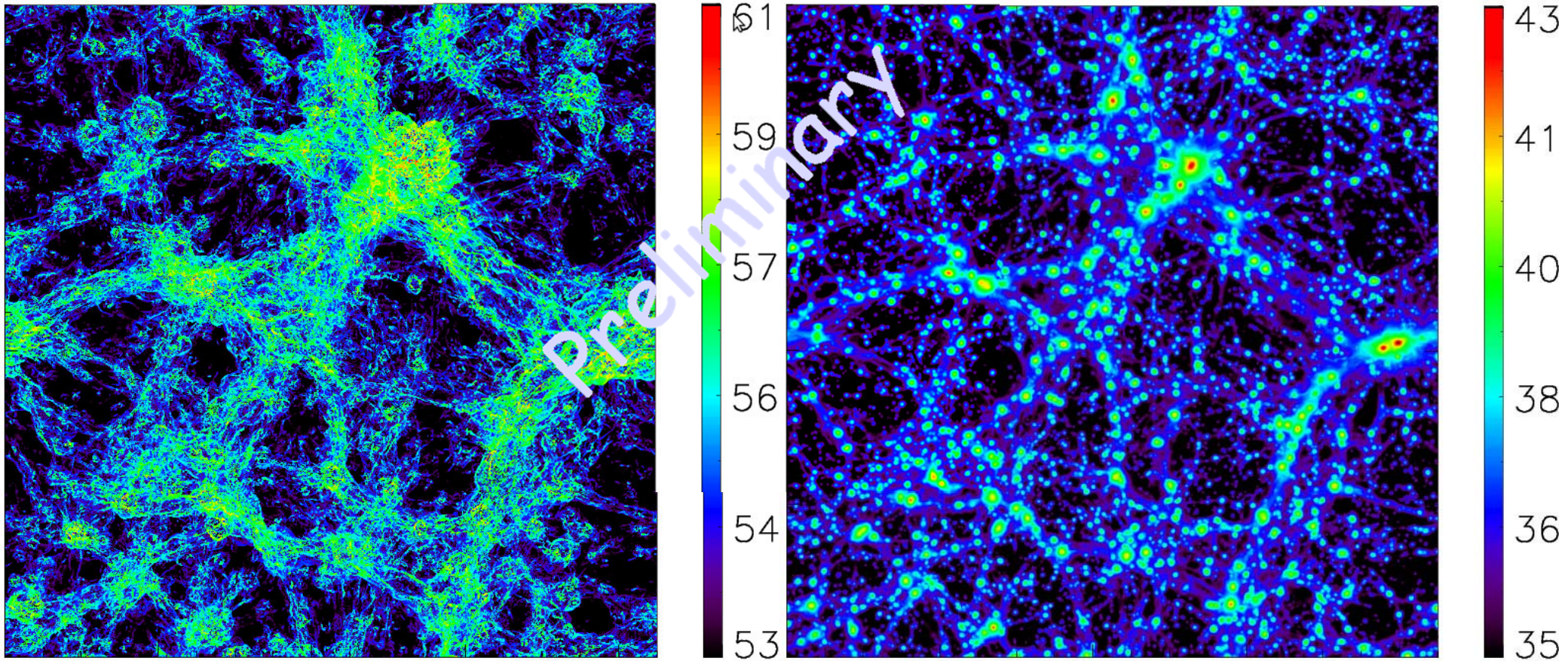
shocks with small Mach number are common and energetically important inside and outskirts of clusters


Sausage Relic, S$_\nu$(mJy), n$_0$=10^{-4}
at 1.4GHz, 16.7″x12.7″
ξ= 1.e−5
R$_2$ = 3.8e−3
ψ=10
ψ=20
ξ= 1.e−5
R$_2$ = 3.9e−3
ξ= 1.e−5, R$_1$=2.5e−3
R$_2$ = 2.4e−3
S
α
r(kpc)
observation
M4.5B7I
M4.5B3.5I
M2B7S4.2
(Kang, Ryu, & Jones in preparation)
M = 4.5
B = 7
ψ = 10
injection only
M = 4.5
B = 3.5
ψ = 10
injection only
M = 2
B = 7
ψ = 10
pre-existing CRs with slope 4.2
azimuthal angle
ψ
ψ
relic
observer

Observation of synchrotron in the LSS of the universe II

In the cosmic web: synchrotron from **primary** electrons -> traces shocks

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



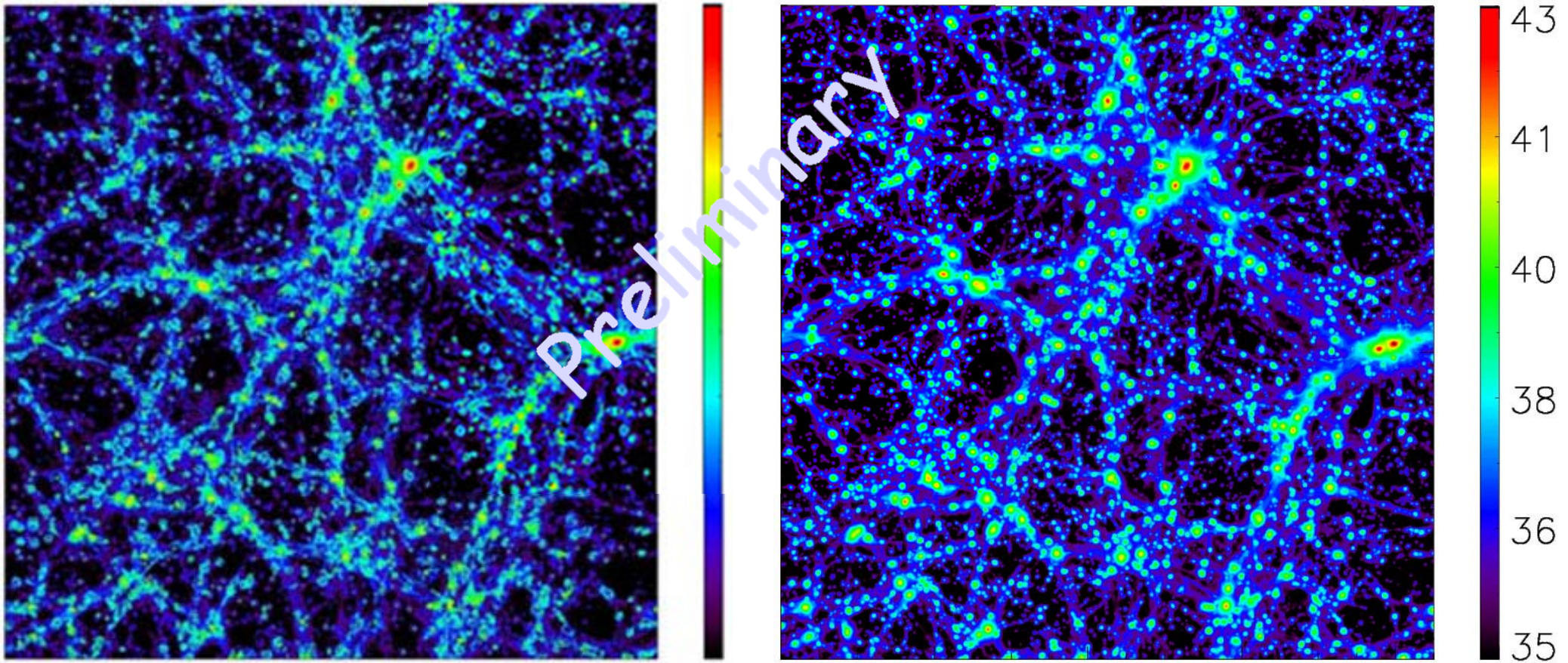
synchrotron (CRe + B) thermal bremsstrahlung

- strength of ~ 1 – 0.1 of the Galactic foreground toward poles ?
- to be confirmed through correlation with diffuse X-ray ?
  but separation of a few Mpc ?
- continuum in EMU and LADUAM ?
- another foreground to EoR HI 21cm ?

Observation of synchrotron in the LSS of the universe II

synchrotron from **secondary** electrons -> traces density peaks

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



synchrotron (CRe + B)

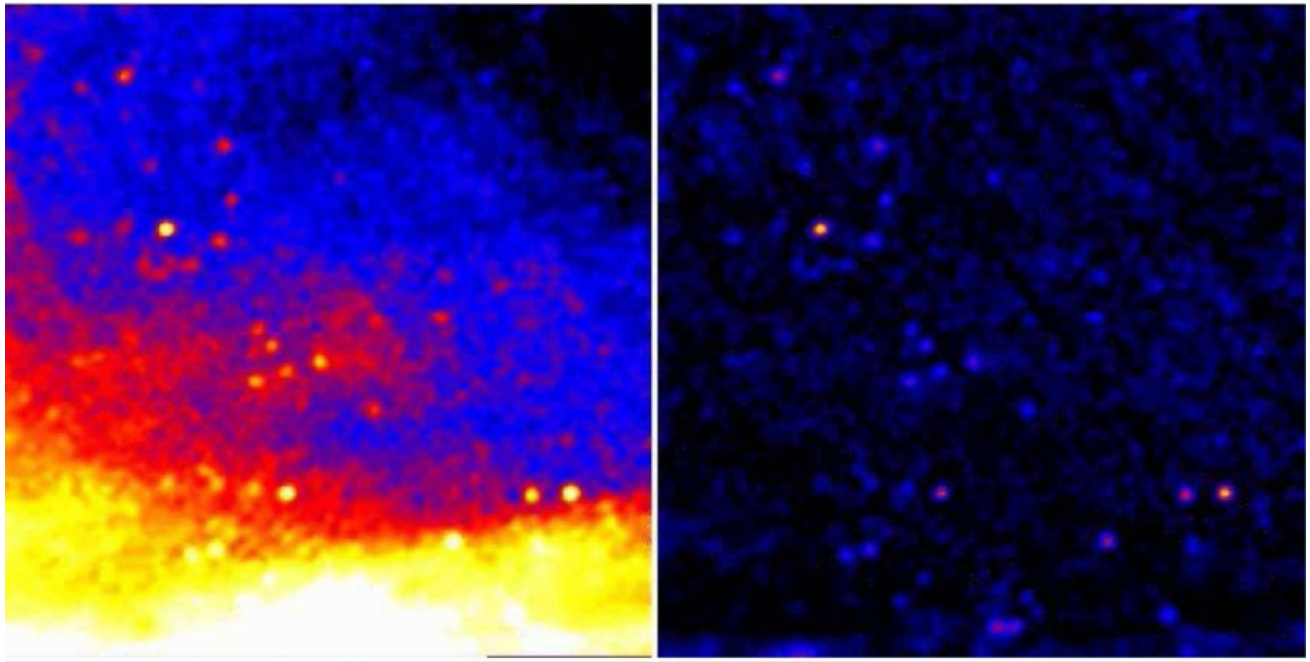
thermal bremsstrahlung

- an order of magnitude smaller than that from primary electrons ?
- to be confirmed through correlation with galaxies ?
  synchrotron from galaxies ?
- continuum in EMU and LADUAM ?
- a foreground to EoR HI 21cm ?

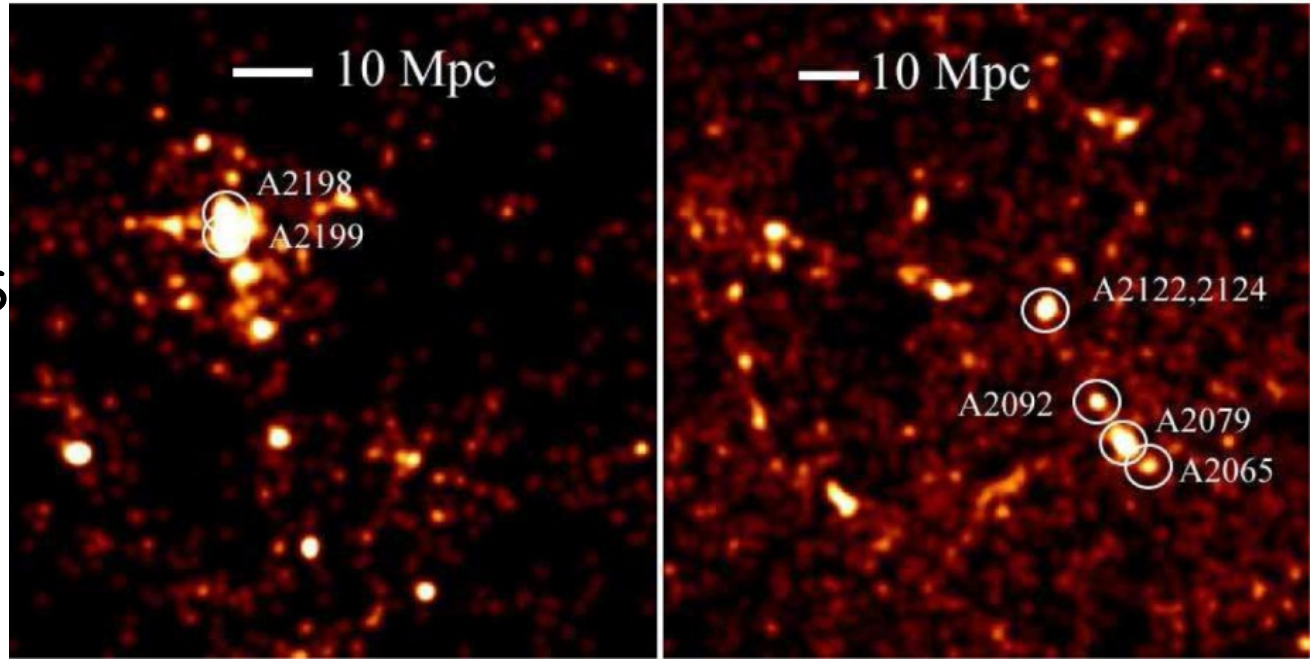
1.4 GHz

1.4 GHz with the Galactic foreground removed

Bonn survey



2MASS



galaxies z = 0.03 – 0.04

galaxies z = 0.06 – 0.07

Cross-correlation analysis of 1.4 GHz Bonn survey and 2MASS galaxies

-> a null result

<= we would need a good strategy !

(Brown et al 2010)

Summary

I hope to be able to explore magnetic fields in the cosmic web using the SKA through observation of synchrotron.

in clusters of galaxies – a few μG

primary CR electrons -> radio relics

secondary/turbulence-accelerated CR electrons -> radio halo

=> have been observed, and will be further explored !

in filaments of galaxies - ~10 nG

primary CR electrons -> traces shocks

secondary CR electrons -> traces density peaks

turbulence-accelerated CR electrons -> ???

=> yet to be observed with the SKA precursors and SKA !!