Magnetic fields at $\geq$ Galactic scales

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Introduction

- **Possible effects of cosmic magnetic fields on large scales (Galactic, clusters, IGM...)**

o diffuse emission:

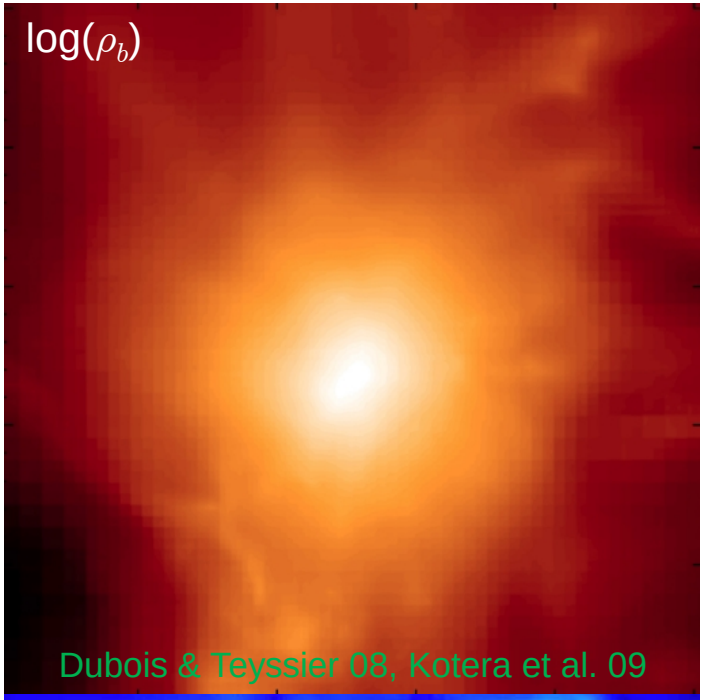
- e.g. energetic electrons radiate through synchrotron in radio, inverse Compton in the X and gamma range...
- in the Galaxy, synchrotron component relatively well known, discussed earlier...
- Galactic high energy diffuse emission also discussed earlier ...
- extra-Galactic: clusters vs less dense IGM?

o cosmic ray transport:

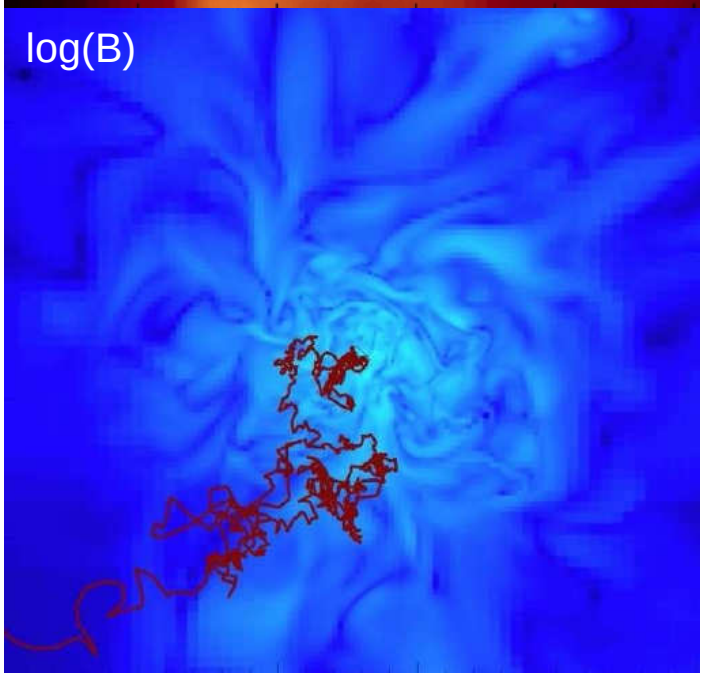
- Galactic CR: to be discussed by Ptuskin / Maurin / Shalchi
- X-Galactic CR: many free parameters... unknown non-thermal content of IGM at energies $\lesssim 10^{18}$ eV...

o structure formation:

- in general, expected to be weak, except (maybe) inside clusters



Dubois & Teyssier 08, Kotera et al. 09



Galactic magnetic field

o observations: Faraday rotation of polarized background sources or pulsars yields

$$\Delta\Psi = 812\,\mathrm{rad}\,\lambda_{\mathrm{m}}^2 \int \mathrm{d}l_{\mathrm{kpc}}\, n_{e,\mathrm{cm}^{-3}} B_{\parallel,\mu\mathrm{G}}$$

(n_e from pulsar dispersion measures)

o large scale component B_0 follows spiral arms with reversal in inter-arm: bisymmetric geometry Han et al. 2005

o turbulent component: coherence scale $l \sim \mathcal{O}$(10-100pc) (?), strength $\delta B \sim B_0$

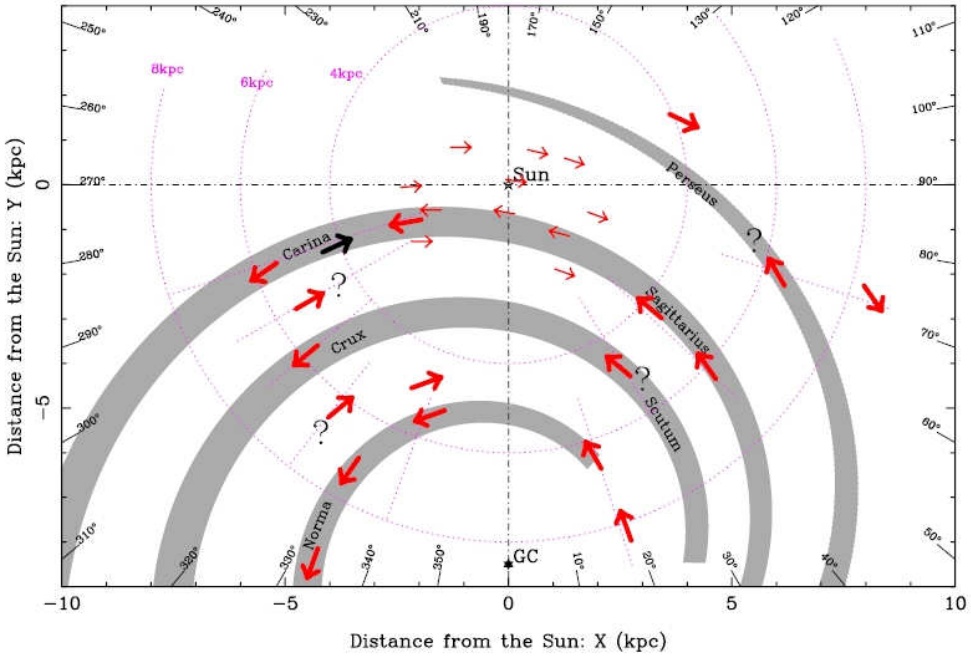
o total $B \sim 6\ \mu$G near the Sun, with a radial scale length of ~10kpc (Beck 08)

o the Galactic center: a diffuse field with $B \sim 30\mu$G with non-thermal magnetized filaments with $B \sim 100\ \mu$G

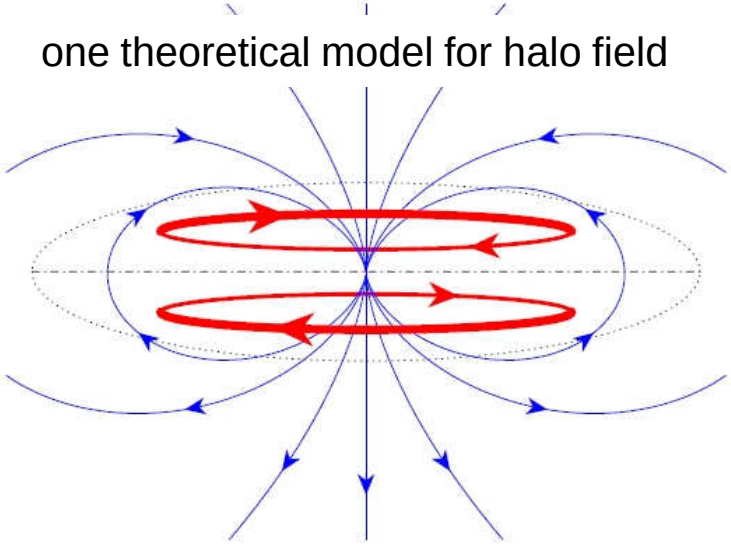
o halo scale height: ~ 2 kpc, poorly known

o Geometry poorly known: dipole-like, quadrupole-like, parity wrt Galaxy plane?

Han et al. 06



one theoretical model for halo field

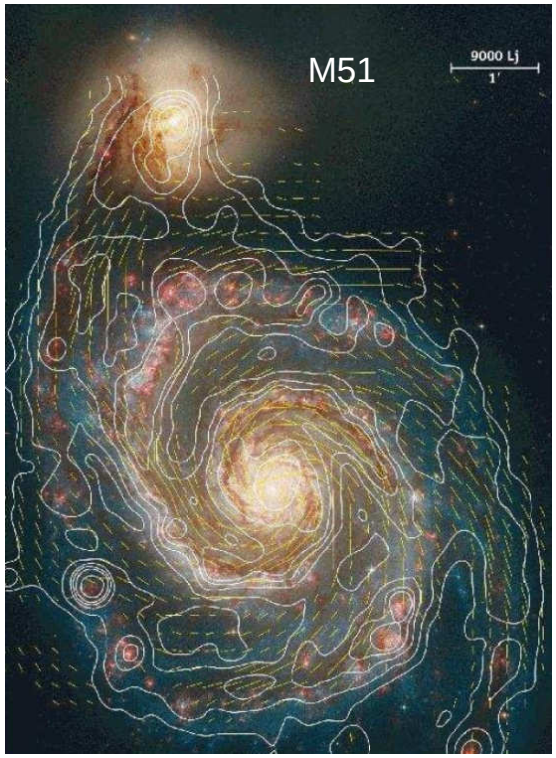


Magnetic field in other galaxies

o observations: synchrotron emission of relativistic electrons

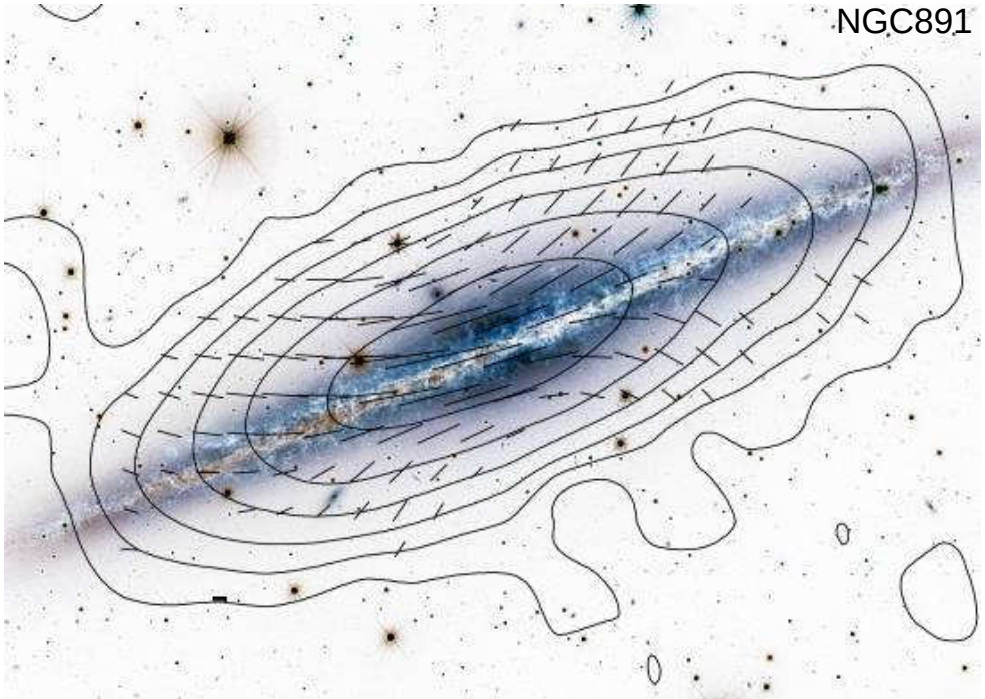
$$j(\nu) \propto n_{e,0}\nu^{(1-s)/2} B_{\perp}^{(1+s)/2}$$

$dn_e/d\gamma = n_{e,0}\,\gamma^{-s}$
if n_e is unknown, one assumes approximate equipartition between electron energy density and magnetic field to estimate B



Beck 08

o all galaxies seem to possess a magnetic field that follows spiral structure, with scale height ~ few kpc (see e.g. Beck 08)



o at high z, galaxies also appear magnetized: detection of an excess rotation measure in halos of galaxies (MgII absorption systems) Kronberg & Perry 82, Bernet et al. 08

... the magnetic field must be powered up/amplified on ~ few Gyr timescales!

Magnetic field in clusters of galaxies

o clusters of galaxies are magnetized with B $\sim\mathcal{O}(\mu$G) in the core, decreasing outwards

o there is no large scale component; the field is tangled on small scales in the core ($\sim$10kpc?), on larger scales towards the outskirts...

o B is sufficiently strong to confine protons on a Hubble time up to E $\sim$ 100 GeV

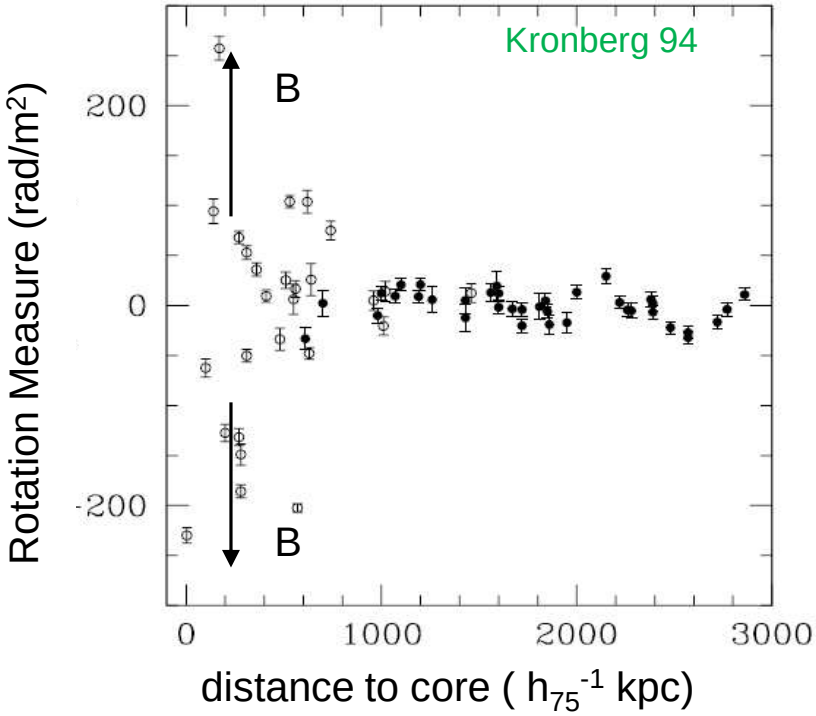
$\frac{R^2}{2D} \approx 10\,\mathrm{Gyr}$ for Kolmogorov D, R$\sim$ 100kpc

$\Rightarrow$ diffuse emission from clusters in radio, X and gamma if relativistic populations are present.

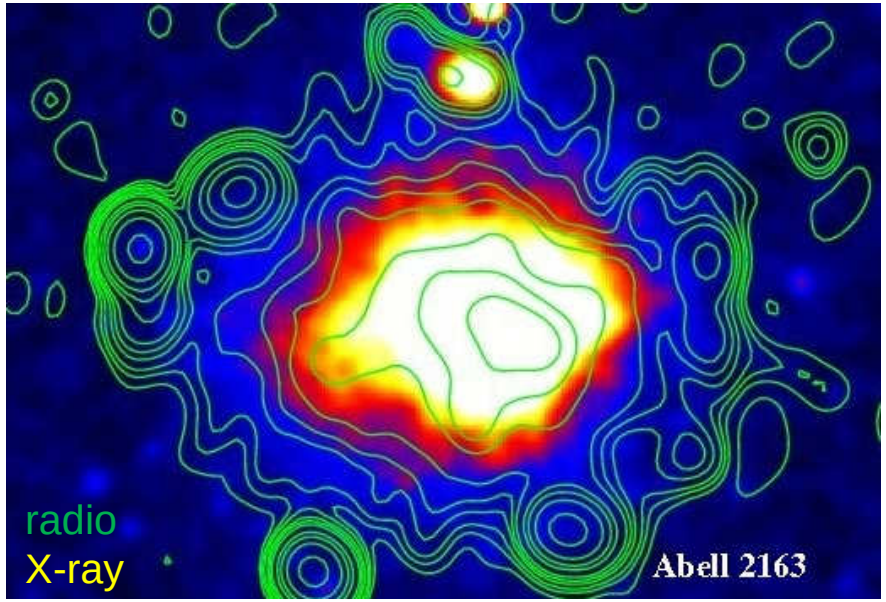
o a fraction of clusters exhibit radio halos, with $\sim$1 μJy/arsec^2 at 1GHz; detailed origin of energetic electrons still debated...

o $B_{cluster}$ has a strong impact on the transport and thermodynamical properties of the gas...

o $B_{cluster}$ may induce B-polarization of CMB anisotropies (Tashiro et al. 08)...



Ferrari 09



Magnetic field on super-cluster scales

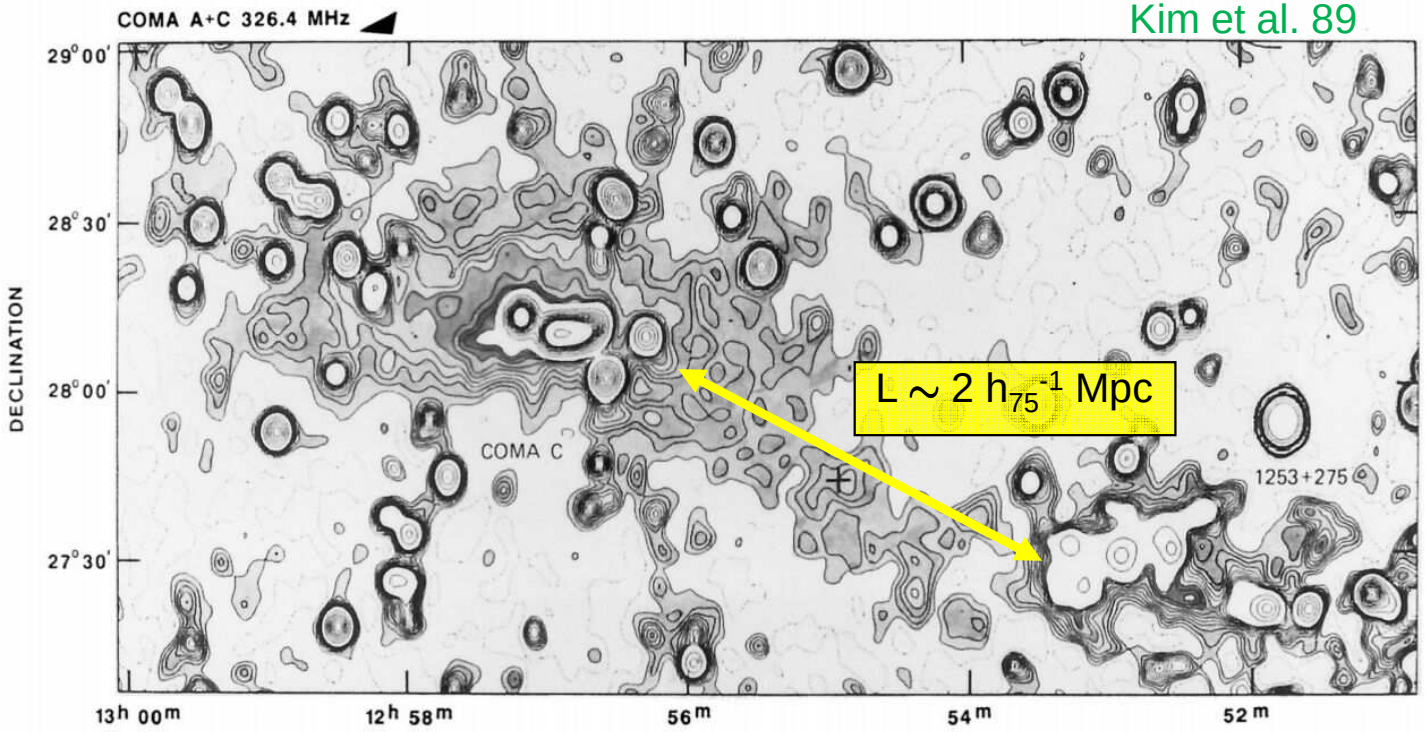
o a non-ambiguous detection of a diffuse magnetic field in the IGM, bridging a cluster with an extended radio source...

equipartition assumption leads to: $B \sim 0.3 \mu G$

o +several claims of detection in synchrotron (e.g. Bagchi et al. 02, Brown & Rudnick 08, ...) and a claim for statistical correlation of RM with large scale structure (Lee et al. 09): $B \sim 3\ 10^{-8} G$ with coherence on Mpc scales ??

o other methods for probing very weak IGM magnetic fields < 10^{-15}G : delayed or dispersed pair echo of gamma-ray bursts or blazars: >TeV γ produces e^- e^+ pair, which turns back to high energy photon below threshold (Plaga 1995, Elyiv et al. 09, Takahashi et al. 09)

Kim et al. 89



flux: ~800 mJy at 325MHz

Origin of the Galactic magnetic field

Ferriere 07

o induction equation for the magnetic field:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} - \eta \nabla \times \mathbf{B})$$

U velocity field, η = resistivity $\propto 1/\sigma$, with σ conductivity.

o ideal MHD: $\eta \rightarrow 0$, B can be amplified from a seed field; B_{Gal} requires $B_{seed} \gtrsim 10^{-18}$ G on Galactic scales ... origin of the seed field?
(e.g. Ruzmaikin et al. 88)

$\rightarrow$ efficiency the Galactic dynamo?
$\rightarrow$ can it explain the high z magnetic fields?

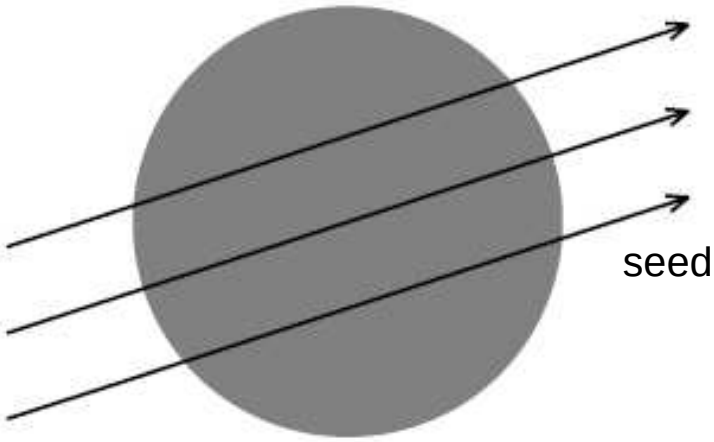
o in the very early Universe ($\ll$ recombination)?

Attractive scenario, but in general very inefficient due to the small causality length H^{-1}.

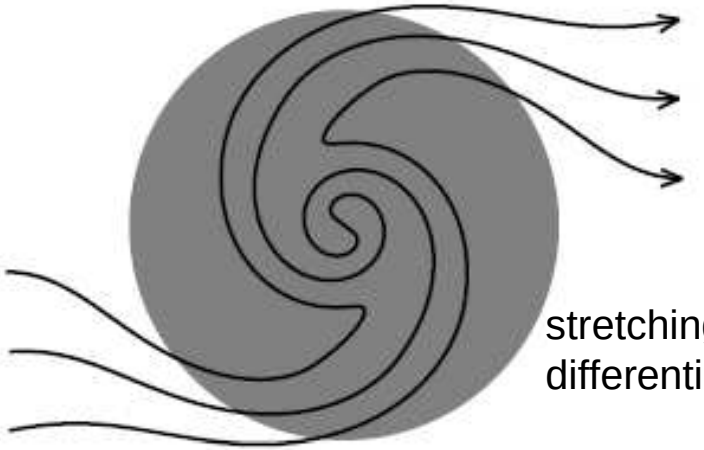
$\rightarrow$ CMB constraints $B \lesssim 10^{-9}$G (Widrow 02)

o in the Galaxy, through the ejection of magnetized material by stars?

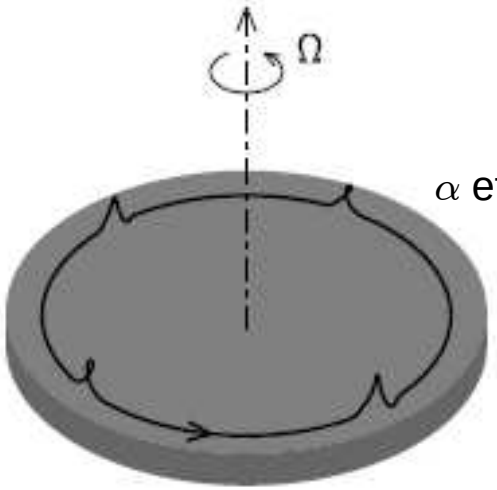
$\rightarrow$ consequence of dynamo on a small scale magnetic field?



seed field



stretching through differential rotation



α effect

Origin of the Galactic magnetic field

o in the late Universe ($\gg$ recombination): many possible scenarios at recombination - reionization - Galaxy formation, in general yield very weak seed fields $\lesssim 10^{-12}$G... no prevalent theory yet...

ex: Langer et al. 03, differential radiation pressure on e-p in inhomogeneous+anisotropic environment (reionization) leads to B $\sim 10^{-12}$ G...

o seed field sufficient for a Galactic dynamo but without influence on structure formation (impact significant for B $\gtrsim 10^{-10}$ -10^{-9} G...?)

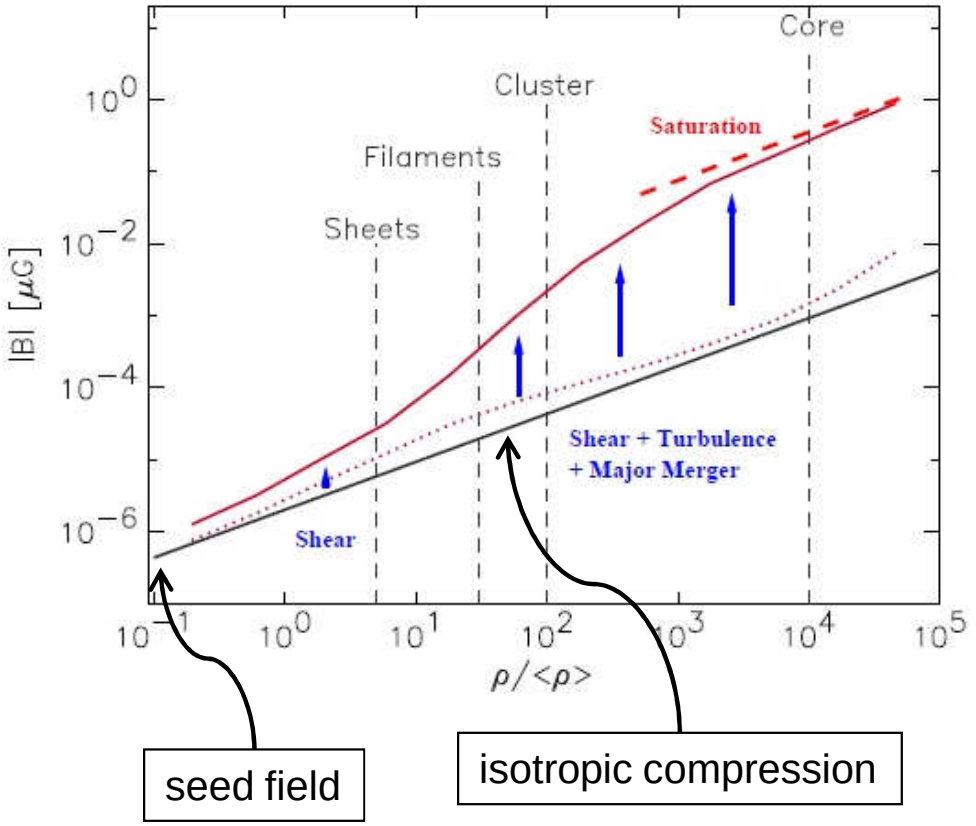
o evolution of the seed fields in the IGM: B $\propto (1+z)^2$ through expansion, but B is amplified during structure formation, B $\propto (\delta\rho/\rho)^\alpha$ with $\alpha\sim$ 0.6 - 1 $\Rightarrow$ B $\lesssim 10^{-8}$ G in filaments, too weak to produce detectable emission...

o seeding of the IGM by magnetized material ejected by other galaxies: galactic winds, radio-galaxy lobes...

$\rightarrow$ origin of the magnetic field in these galaxies?

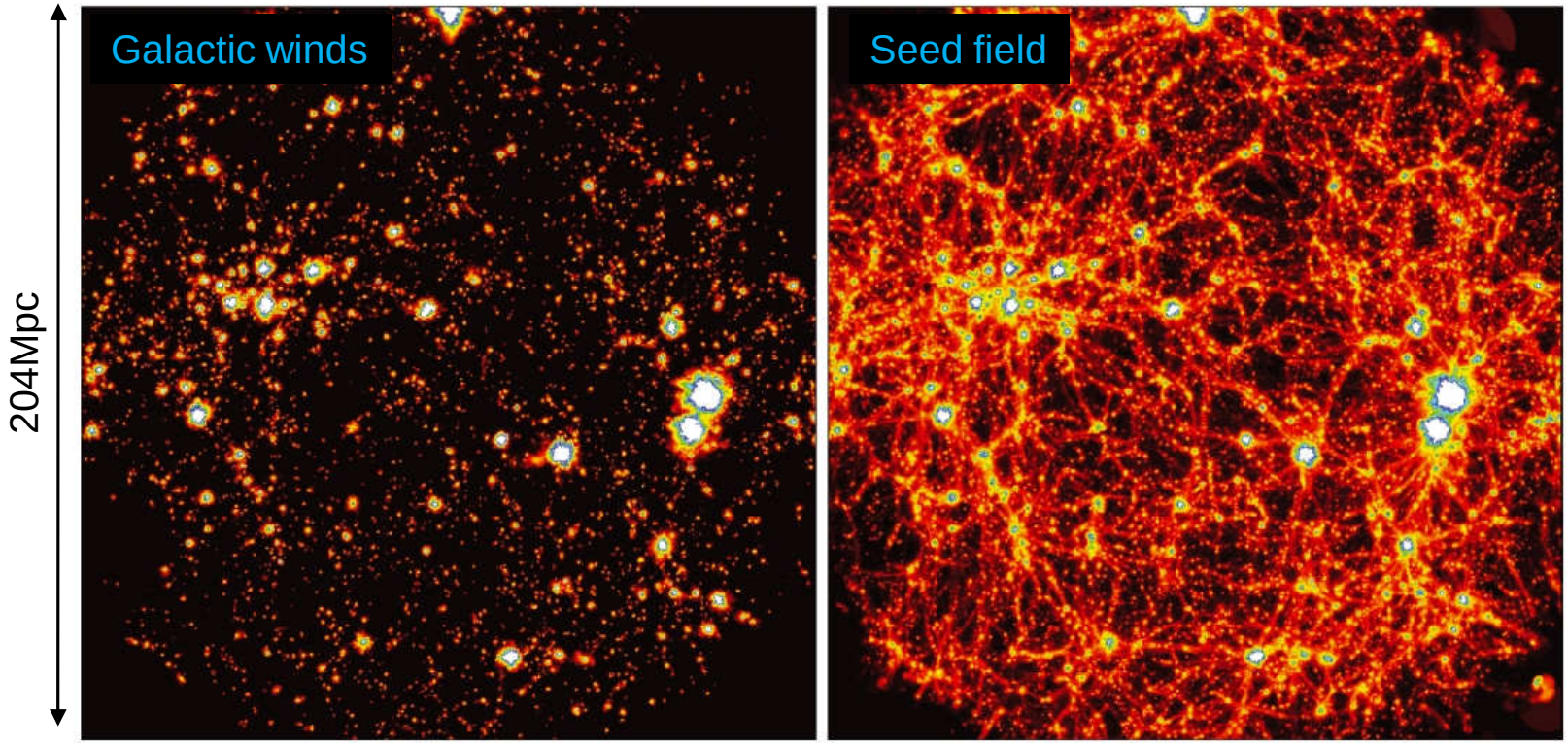
$\rightarrow$ is galactic pollution sufficient to account for cluster magnetic fields?

Dolag 06



Expectations for B on $\geq$ Galactic scales

o modern view: the IGM at low z is seeded by magnetized galactic pollution (just as most of Lyman alpha systems are enriched in metals); for early galaxies, some seed field is necessary...



o magnetic field in the IGM is thus expected to be highly inhomogeneous, patchy, with strength up to 10^{-8} G in some parts of filaments, much weaker in the voids...

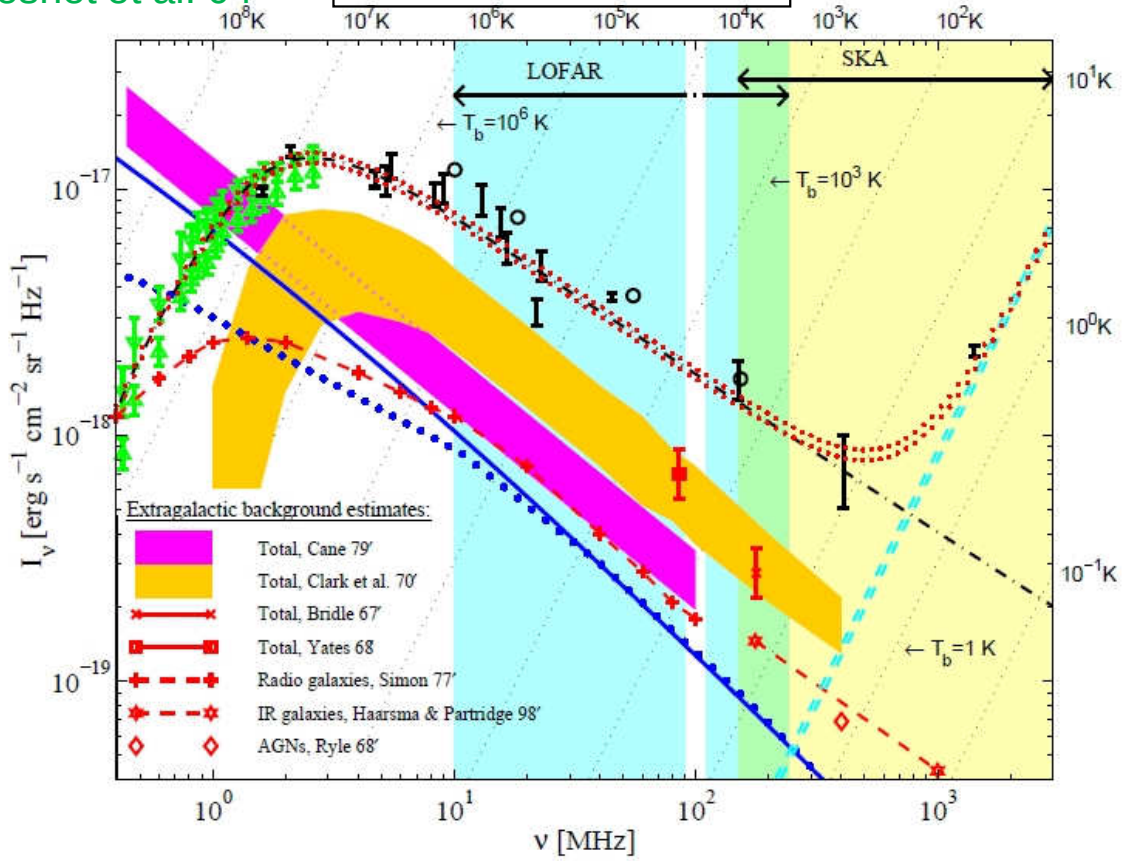
$\rightarrow$ CR transport in the IGM governed by stochastic interactions with magnetized regions...
$\rightarrow$ diffuse emission very weak, except around intergalactic shocks (see below)...
$\rightarrow$ impact on structure formation?

Expectations for B on $\geq$ Galactic scales

o accretion flows produce shocks, which are expected to imply magnetization and particle acceleration: diffuse emission from radio to gamma rays from accelerated electrons (possibly as high as $\sim$ 10% of radio and gamma-ray background, Keshet et al. 03, 04)

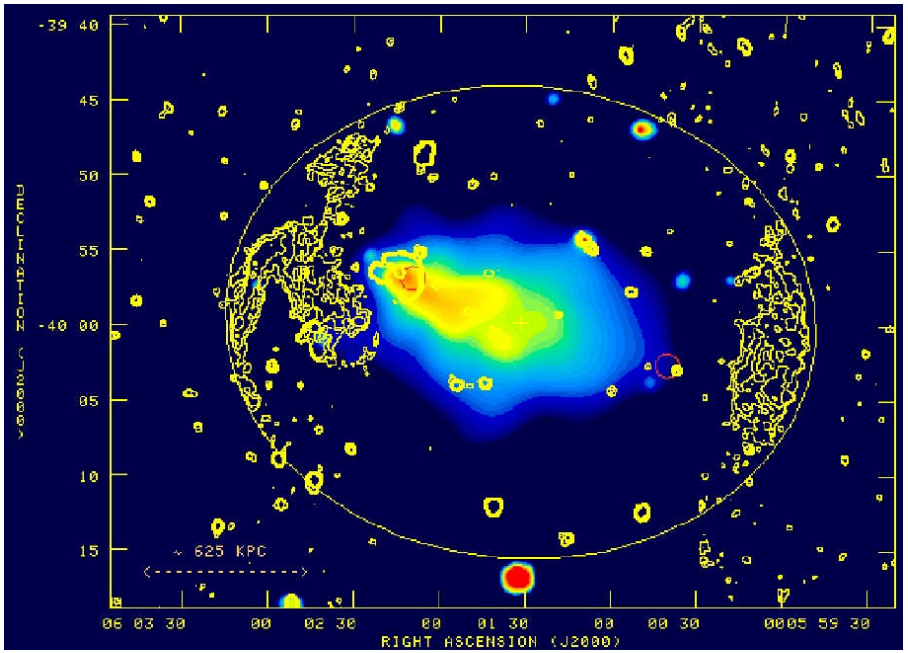
Keshet et al. 04

intergalactic shocks



Bagchi et al. 06

radio relics



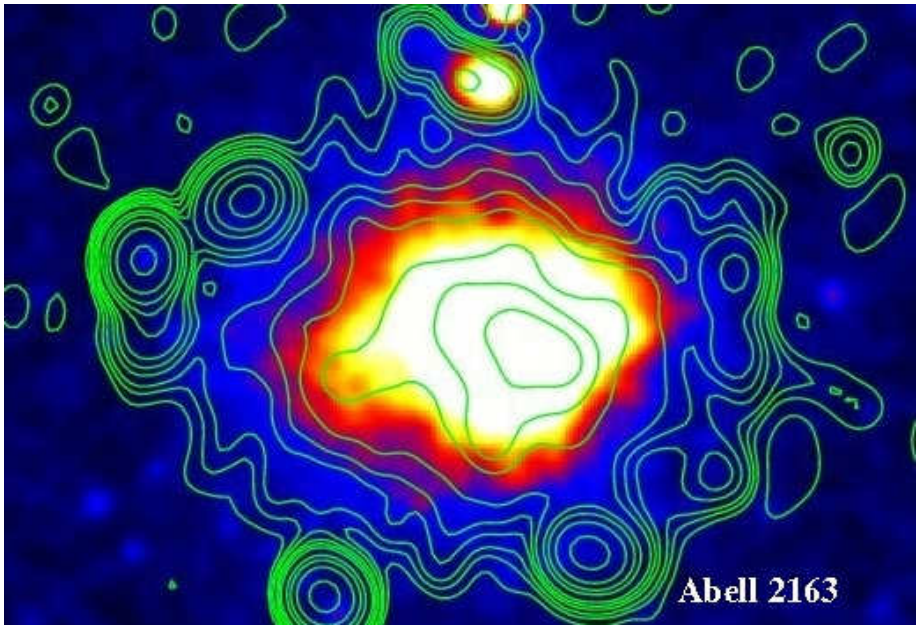
o so far detected: radio relics around clusters of galaxies $\sim$ giant shock waves with R $\sim$ 1Mpc, B as high as 1 μG?

Summary

- **On the effects of cosmic magnetic fields on large scales (Galactic, clusters, IGM...)**

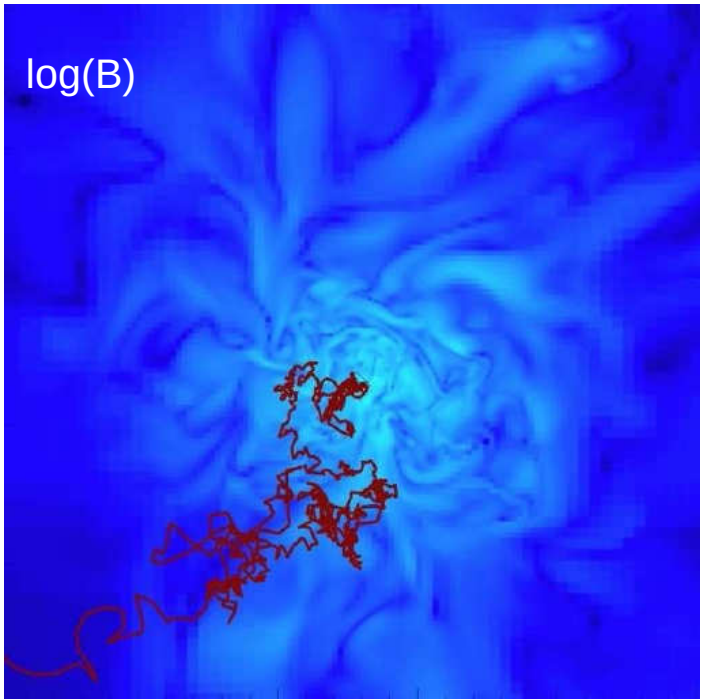
o diffuse emission:

- synchrotron in radio domain, inverse Compton in the X and gamma range: detected or to be soon detected in/around clusters of galaxies
- in less dense IGM, magnetic field is weaker and patchy...
- diffuse emission from accretion shocks could be soon detected in radio



o cosmic ray transport:

- in galaxies/clusters, B governs CR transport
  $\rightarrow$ VHE energy CR escape/modulation?
- X-Galactic CR: unknown non-thermal content of IGM at energies $\lesssim 10^{18}$ eV...
- transport of UHE cosmic rays on $\gtrsim$ 100Mpc scales governed by stochastic interactions with magnetized regions



o structure formation:

- in general, expected to be weak, except (maybe) inside clusters