Magnetic fields at > Galactic scales

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Questions related to large scale magnetic fields

➢ origin of large scale magnetic fields:

• physics of the early Universe?

• plasma astrophysics in the late Universe?

➢ diffuse emission:

• e.g. energetic electrons radiate through synchrotron in radio, inverse Compton in the X and gamma range...

• extra-Galactic: emission from clusters vs less dense IGM?

➢ cosmic ray transport:

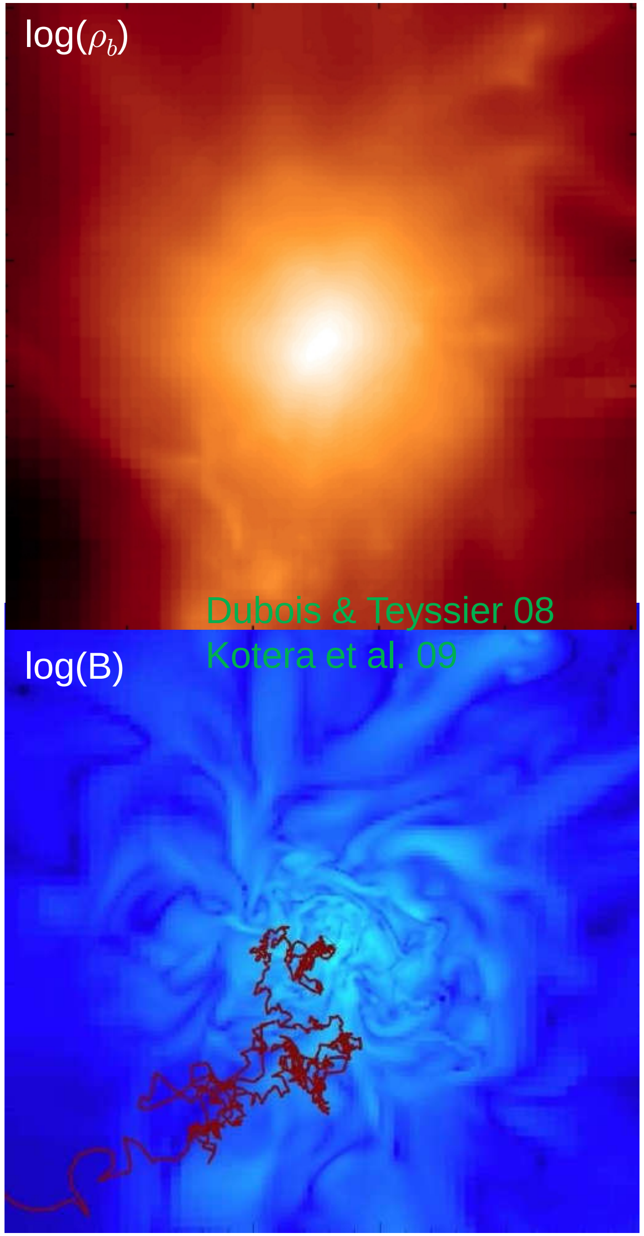
• intimate relationship between cosmic rays and galactic magnetic fields...

• Extra-galactic cosmic rays: transport governed by intergalactic B...

➢ structure formation/dynamics:

• in general, weak effect expected for structure formation, except (maybe) inside clusters

•substantial role in dynamics at equipartition



Outline

1. **Observational data on galactic and extra-galactic magnetic fields**
    a. from the Milky way...
    b. to clusters of galaxies...
    c. to intergalactic magnetic fields

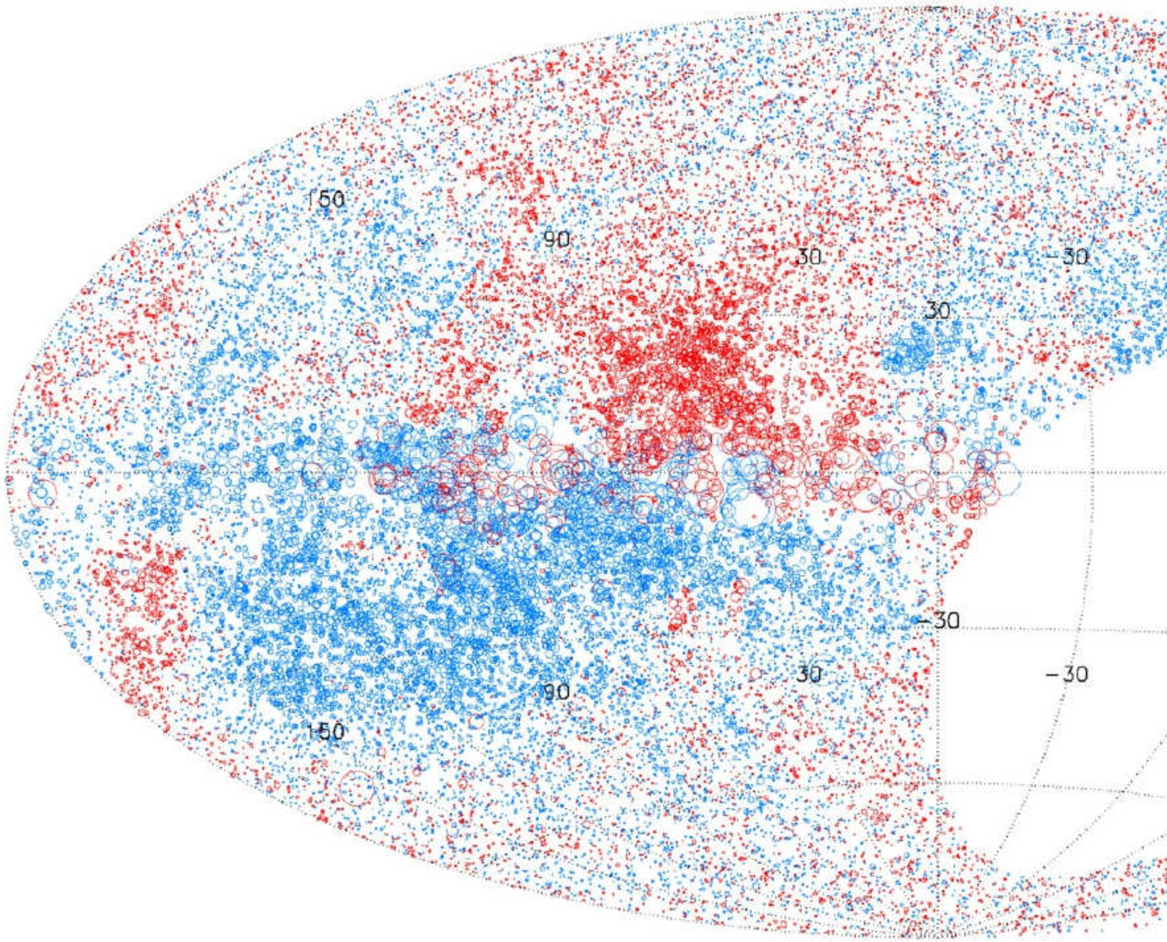
2. **Origin of large scale magnetic fields**
    a. general principles
    b. exotic models: origin in the inflationary Universe, in the early Universe...
    c. astrophysical models: supernovae, winds, dynamos, radio-galaxies, shock waves...

3. **Other constraints on large scale magnetic fields**
    a. constraints from GeV-TeV observations of blazars
    b. other constraints

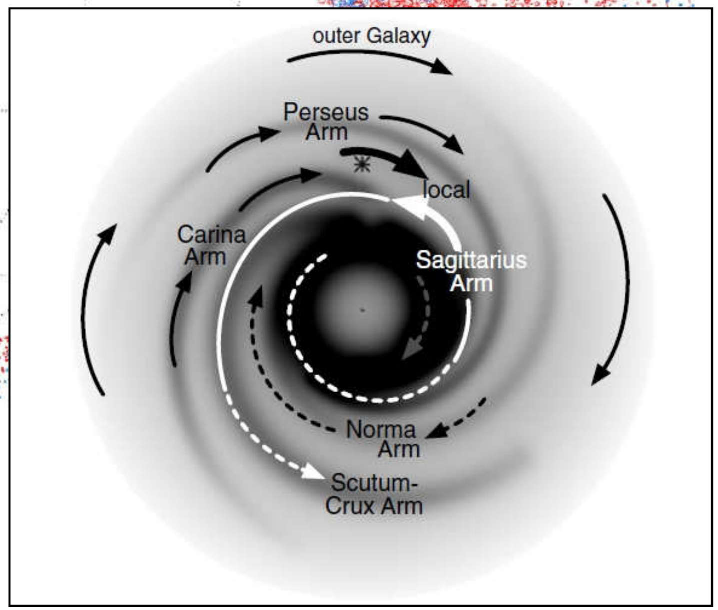
Observational data - Faraday RM map of the Galaxy

➢ Faraday rotation of linear polarization angle of distant sources:

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



NVSS survey (Taylor et al. 09)

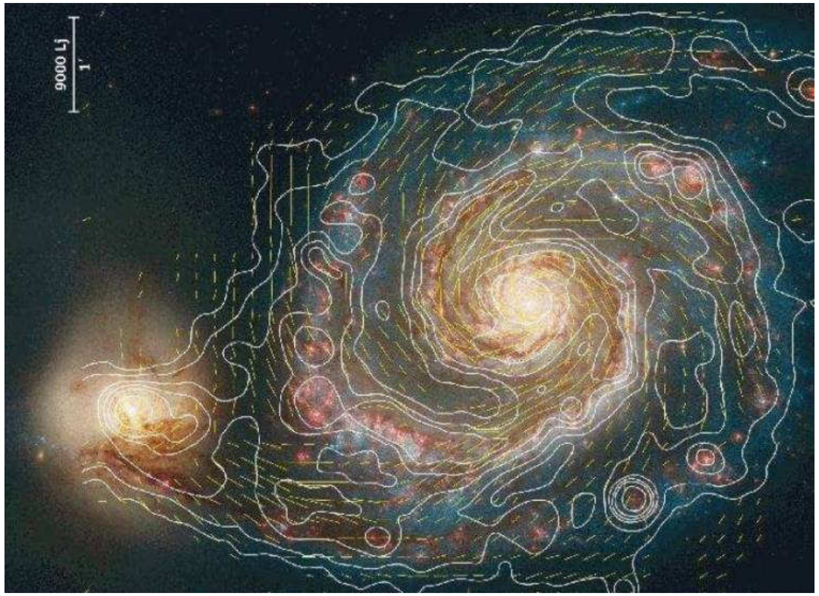


Observational data - Magnetic fields in galaxies

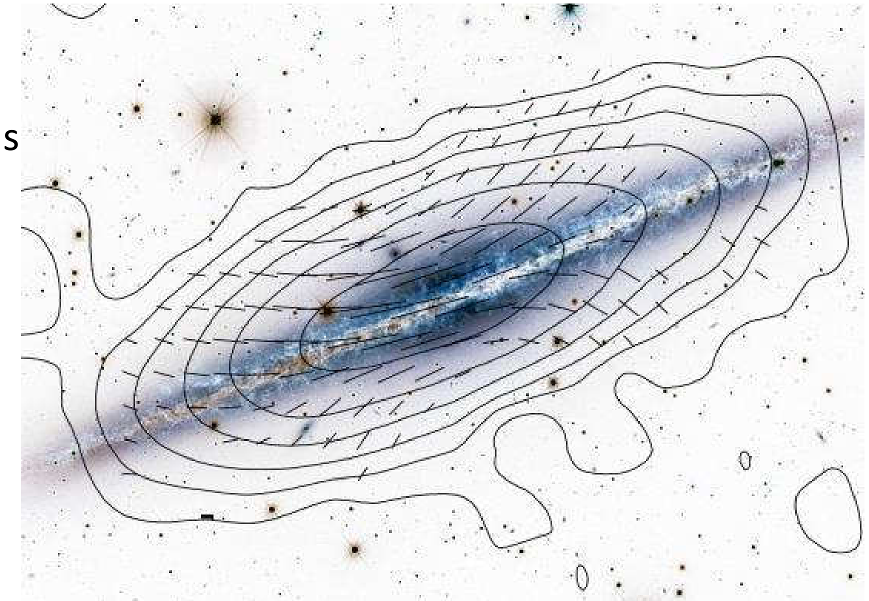
➢ observations: synchrotron emission of relativistic electrons

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

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



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



➢ in the Milky Way, B is at equipartition with the gas and the cosmic rays: $\varepsilon_B \sim \varepsilon_{th} \sim \varepsilon_{cr}$

➢ in star-forming galaxies, B can reach values of 100μG... → connection with star-formation
(→ cosmic ray injection?)

Observational data - Magnetic fields in clusters

➢ observations: clusters of galaxies are magnetized with B ~ O(μG) in the core, decreasing outwards

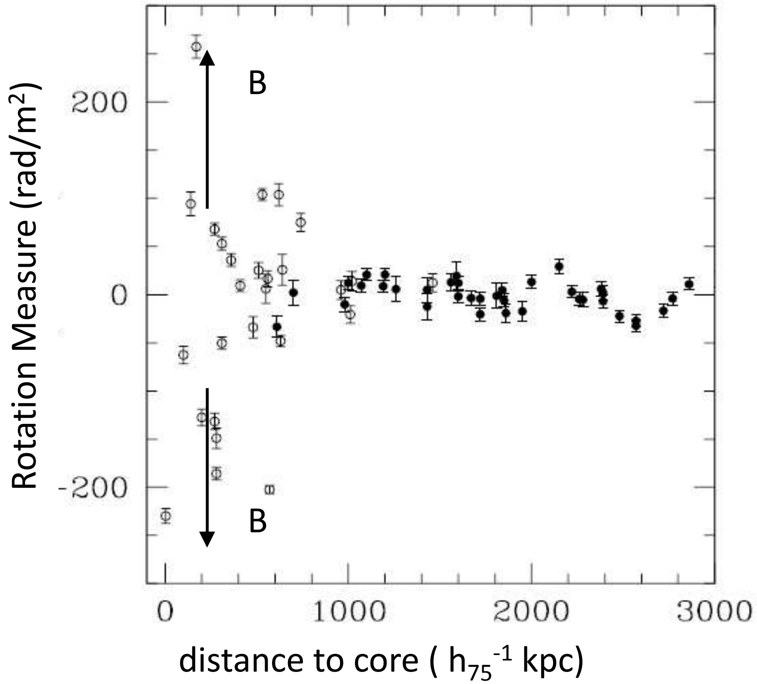
➢ there is no large scale component; the field is tangled on small scales in the core (~ 10kpc?), on larger scales in the outskirts...

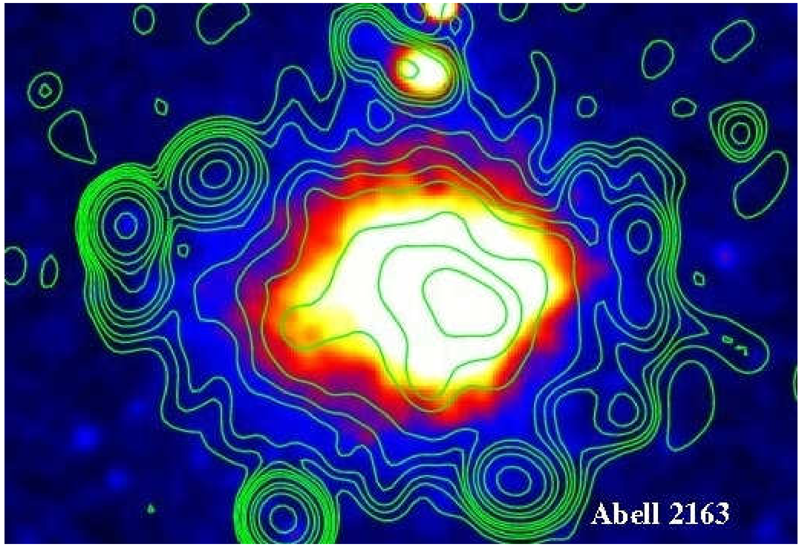
➢B is sufficiently strong to confine protons on a Hubble time up to E ~ 100 GeV

⇒ diffuse emission from clusters in radio, X and gamma...

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

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



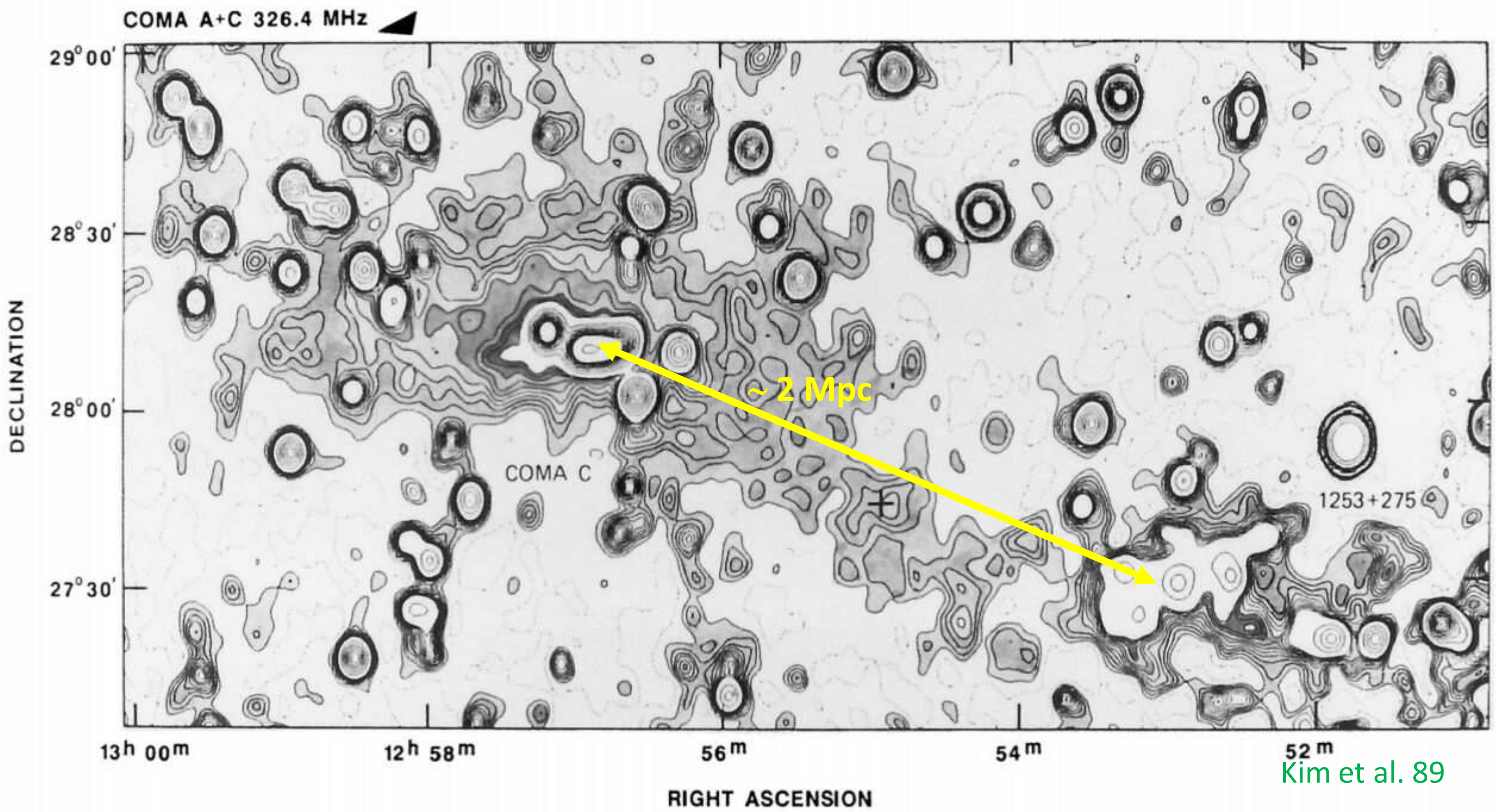


Observational data - on supra-cluster scales

➢ a non-ambiguous detection of a diffuse magnetic field in the IGM, bridging a cluster with an extended radio source... (Kim et al. 89)

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

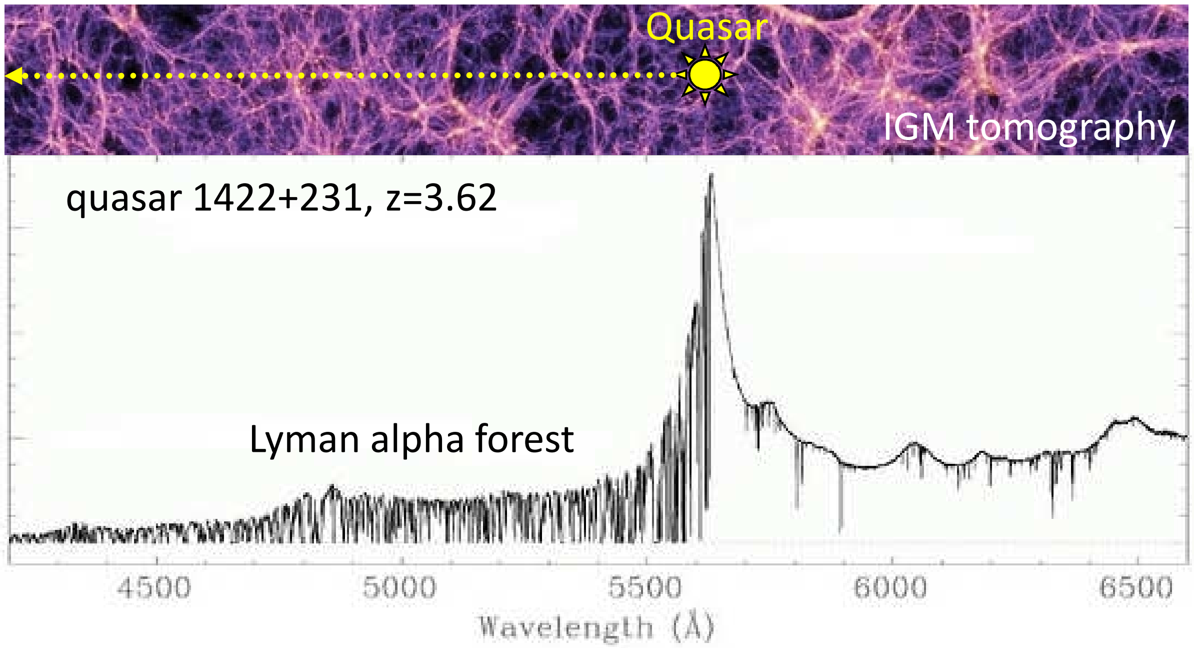
➢ +several claims of detection in synchrotron (e.g. Bagchi et al. 02, Brown & Rudnick 08, ...)

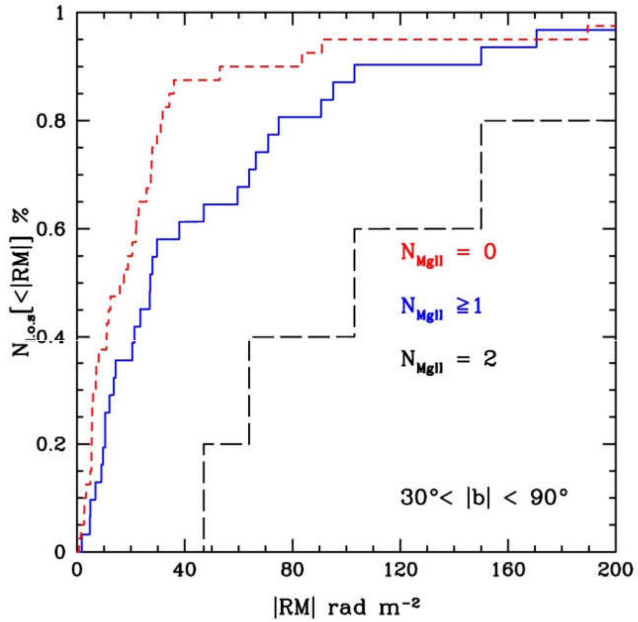


Kim et al. 89

Observational data - at high redshift

- at high z, galaxies also appear magnetized:
  - Kronberg et al. 90: detection of RM in an absorber at z=1.95
  - Kronberg & Perry 82, Bernet et al. 08: detection of an excess rotation measure in MgII absorbers





- upper limit on homogeneous B field from RM (e.g. Kronberg 94, Ryu et al. 98, Blasi et al. 99):
  - homogeneous magnetic power : $B < 10^{-8}$ G, for coherence scale λ=1Mpc, scaling as $\lambda^{-1/2}$
  - more realistically, B < 1 μG in dense parts of large scale structure

- limits on primordial magnetic fields, e.g. from cosmic microwave background anisotropies:
  - $B < 3\ 10^{-9}$ G for an all pervasive field (Barrow et al. 97)
  - on smaller scales... many studies... e.g. Kashniashvili, Caprini

Origin of magnetic fields - principles

➢Ohm's law: $\mathbf{j} = \sigma\,(\mathbf{E} + \mathbf{v} \times \mathbf{B}/c) + \ldots$

[**v** velocity field, $\sigma \equiv$ conductivity $\propto 1/\eta$, η resistivity]

$\Rightarrow$ induction equation: $\frac{\partial}{\partial t}\mathbf{B} = \nabla \times (\mathbf{v} \times \mathbf{B}) - \nabla \times (\eta \nabla \times \mathbf{B}) + \ldots$

amplification of a seed field through twisting, shear etc., but no generation!

dissipation of magnetic field on very small scales

generation?

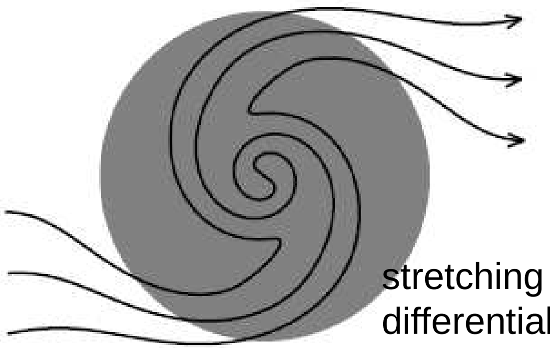
(Parker 79)

➢galactic dynamo: B can be exponentially amplified from a seed field (?), up to equipartition, with e-folding timescales $\sim$ few 10^8 yr...

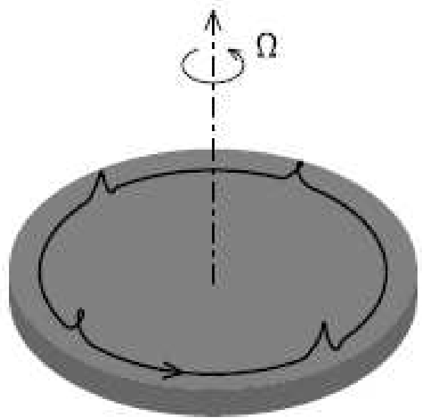
- B_{Gal} requires at least B_{seed} $\sim 10^{-18}$ G on Galactic scales ...

$\rightarrow$ **origin of the seed field?** (e.g. Ruzmaikin et al. 88)

(Ferrière 97)



stretching through differential rotation



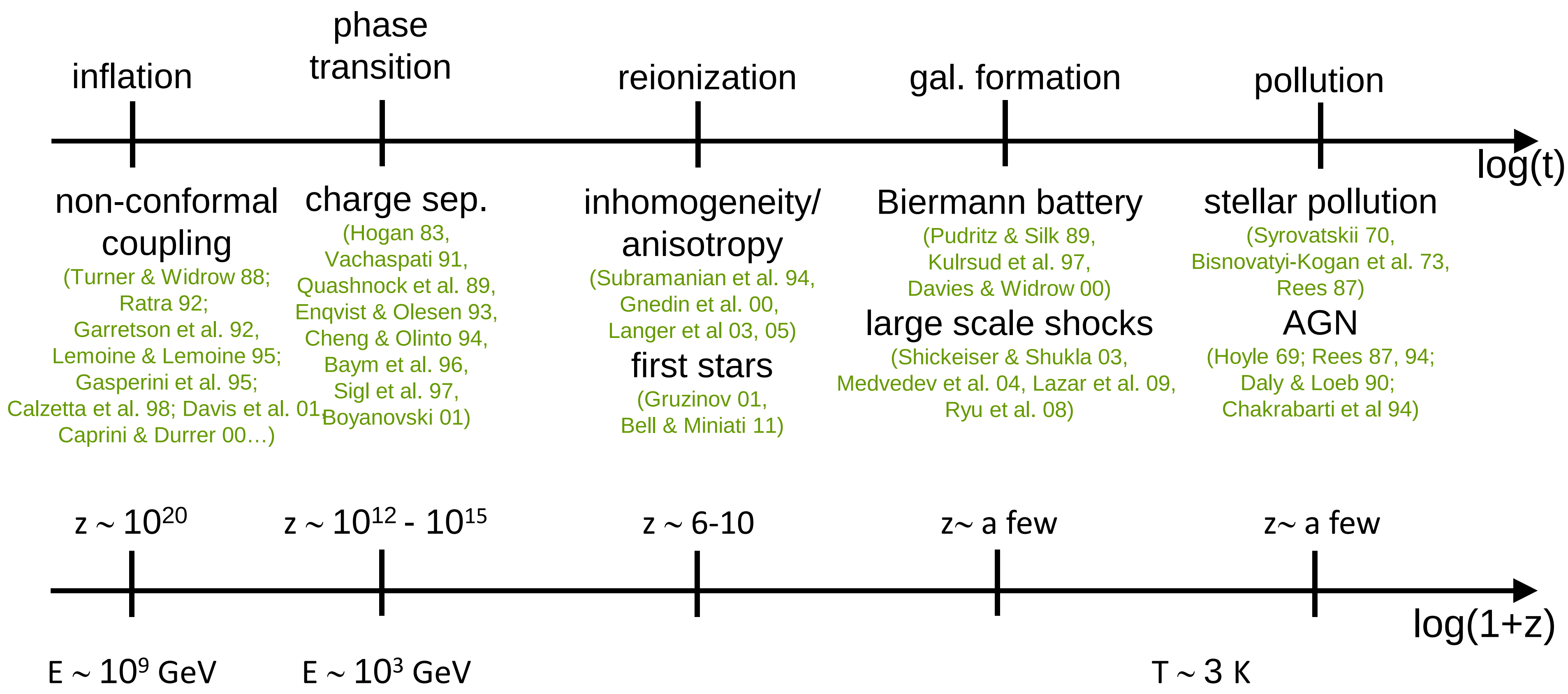
α effect

$\rightarrow$ efficiency the Galactic dynamo?

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

Origin of magnetic fields - models and cosmology

- The origin of cosmic magnetic fields is a long-standing problem (Hoyle 58)...
  ... even the origin of the Galactic magnetic field is not well understood...



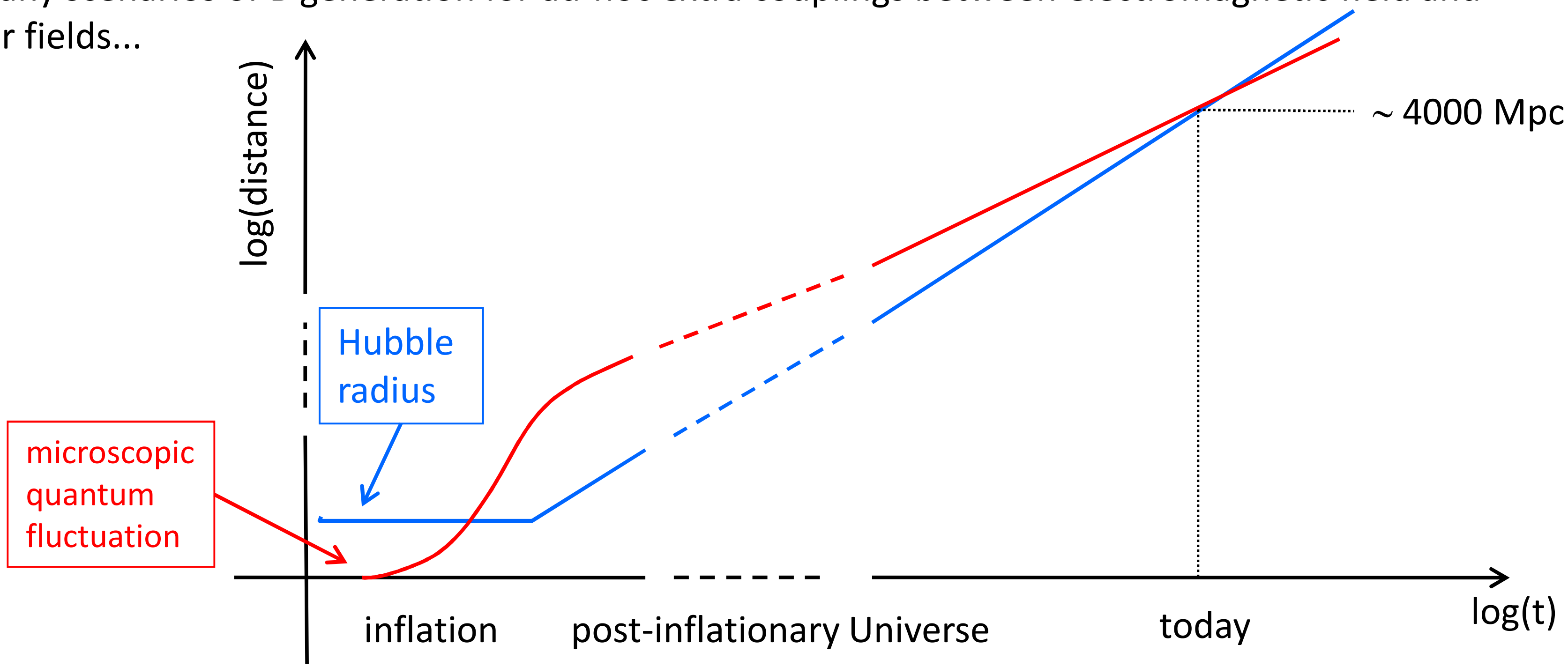
Origin of magnetic fields - Inflationary models

- Schwinger effect: e^+e^- pair production through pumping of the vacuum for $E \geq \frac{m_e^2 c^4}{e\hbar c} \sim 10^{18}\,\mathrm{V/m}$
  (Schwinger 1960)

- in inflationary cosmology, gravitational pumping of the vacuum leads to particle production, e.g. production of cosmological density perturbations, production of gravitational waves... with exponential stretching from microscopic to cosmological scales!
  (e.g. Mukhanov, Bardeen, Starobinsky, Grishchuk...)

- however: the electromagnetic field is conformally invariant, hence particle production cannot take place in conformally flat spacetimes (such as inflationary de Sitter) (Turner & Widrow 88, Ratra 88,...)

- many scenarios of B generation for ad-hoc extra couplings between electromagnetic field and other fields...



Origin of magnetic fields - early Universe

- non inflationary sources in the early Universe: e.g. in first order phase transitions, through currents seeded by moving charge carrying boundaries... (Quashnock et al. 89, Cheng & Olinto 94,...)

- however: causal mechanism on microscopic scales $\Rightarrow$ typical coherence scales is smaller than the horizon scale at that time, which itself is very small even today:

$$\frac{a_0}{a} c H^{-1} \sim 10^{-10}\,\mathrm{Mpc}\,(T/1\,\mathrm{TeV})^{-1}$$

(today scale corresponding to horizon scale at temperature T)

- furthermore: very strong magnetic fields on microscopic scales are strongly constrained by big-bang nucleosynthesis (limits on extra energy density)...
... either directly or through the production of gravitational waves (Caprini & Durrer 02, Caprini 11)

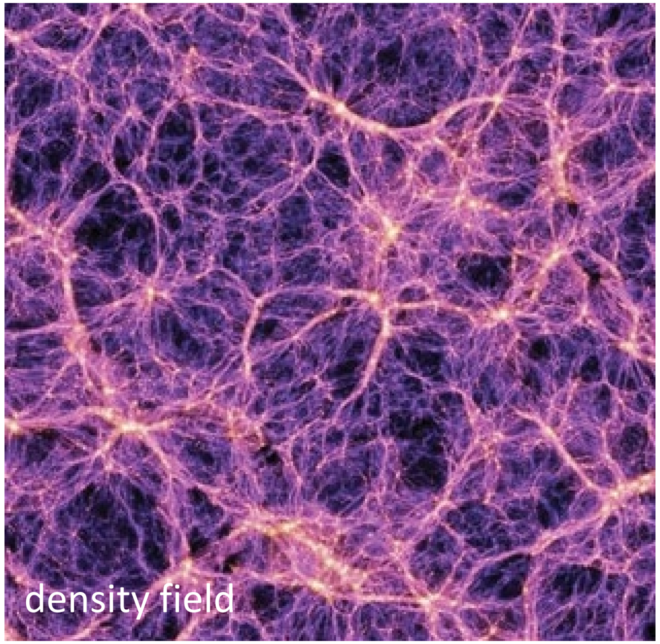
- note that the evolution of magnetic fields on small scales is subject to dissipation and turbulent cascading $\Rightarrow$ evolution in the early Universe non-trivial (e.g. Banerjee & Jedamzik 04)

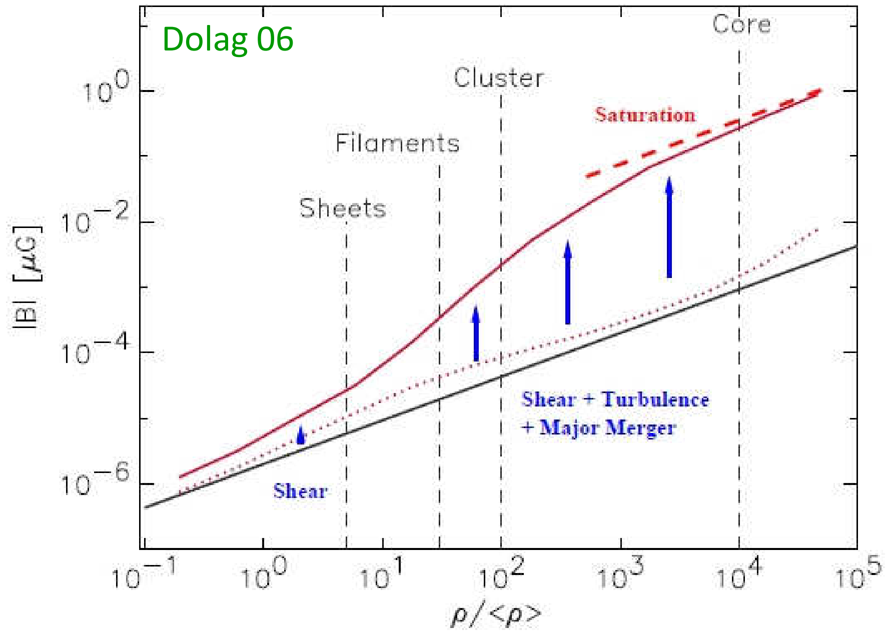
Origin of magnetic fields - late Universe

➢late Universe: many possible sources... and a rather complex evolution in the nonlinear phase of structure formation...

(ideal MHD) $\frac{\mathrm{d}B^i}{\mathrm{d}t} = \frac{2}{3}\frac{B^i}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}t} + B^j\sigma_{ij}$ $\sigma_{ij} = \partial_j v_i - \frac{1}{3}\delta_{ij}\partial_k v_k$

compression shear + vorticity





➢sources: → no seed: reionization (Gnedin et al. 00, Langer et al. 03), first cosmic rays (Bell & Miniati 11) , battery effects at large scale structure formation (Kulsrud et al. 97), AGN winds (Rees 67, Furlanetto & Loeb 01), large scale structure shocks (Ryu et al. 08, Schlickeiser & Shukla 03)...

→ with seed: winds from dwarf galaxies (Bertone et al. 06, Donnert et al. 09, Dubois & Teyssier 09)

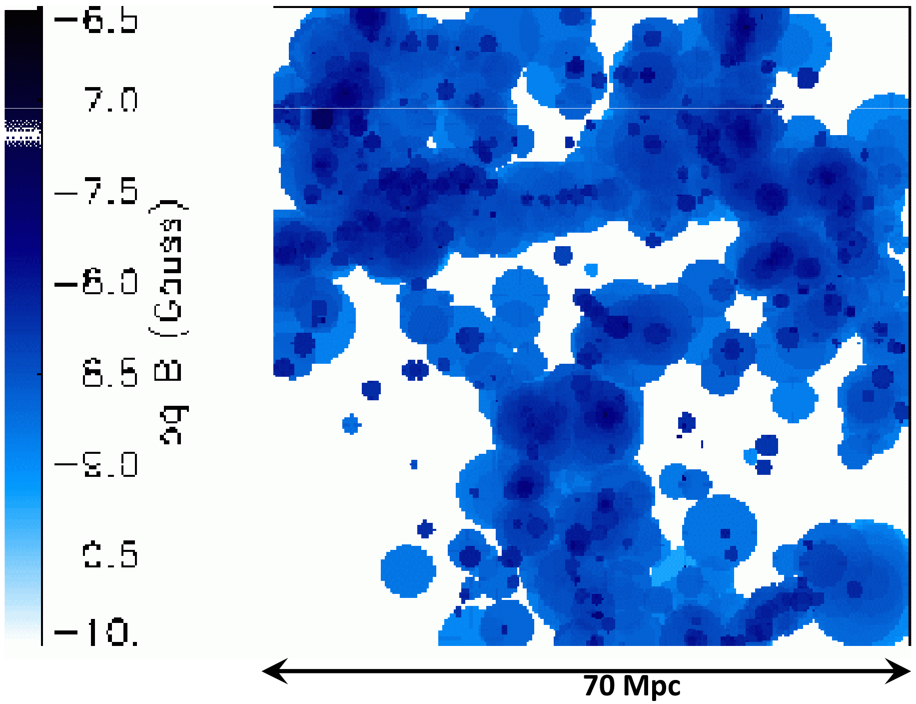
Origin of magnetic fields - Winds of galaxies

- supernovae: expel self-generated magnetic fields, further amplified by cosmic ray streaming...

  Crab supernova remnant: B ~ 300 μG out to 1pc ⇒ B ~ 3 μG in $(10pc)^3$ through expansion...

  ... each galaxy: 1 SN/30yrs ⇔ 3 10^8 SNe in 10Gyrs ⇔ 1 SN/$(10pc)^3$ ...
  ... however, the field would be tangled on short scales ⇒ dynamo?

- a connection with other astrophysical problems: e.g., galactic winds: enrichment of the intergalactic medium in metals (→ metal line systems)?



Bertone, Vogt, Ensslin 06:
pollution by magnetized galactic winds from small starburst galaxies.

→ typical wind radius ~ 1 Mpc
with B ~ $10^{-8} – 10^{-7}$ G

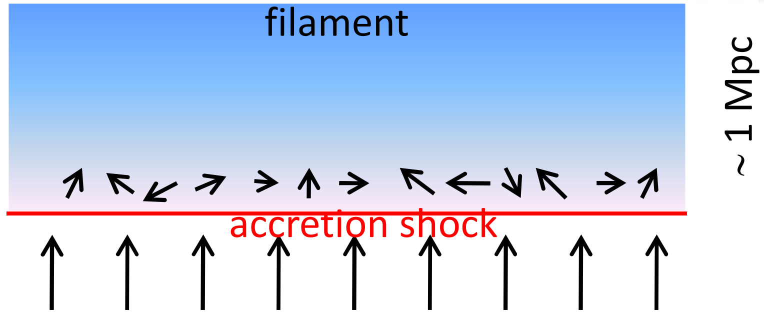
percolation picture, with most of the enrichment in filaments and walls of large scale structure

- radio-galaxies : feedback on the intra-cluster medium?

Origin of magnetic fields - large scale structure shocks

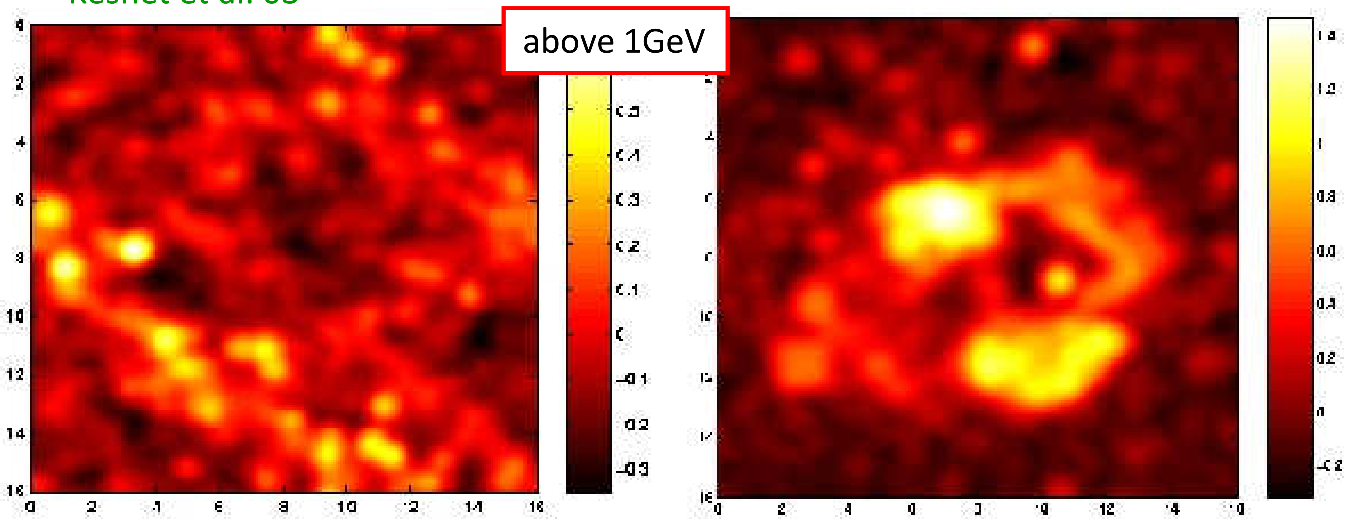
➢ Possible sources of magnetic field at shocks:

→ filamentation instability at the shock
(Shlickeiser & Shukla 03, Medvedev et al. 04, Lazar et al. 09)
→ Biermann battery at curved shocks, vorticity
(Kulsrud et al. 97, Ryu et al. 08)
→ turbulent dynamo behind shock
(Ryu et al. 08)



➢ Radiative signatures: particles can be accelerated at the shock wave through the Fermi mechanism ⇒ magnetized accretion shocks might be possibly seen at GeV energies and above...

Keshet et al. 03



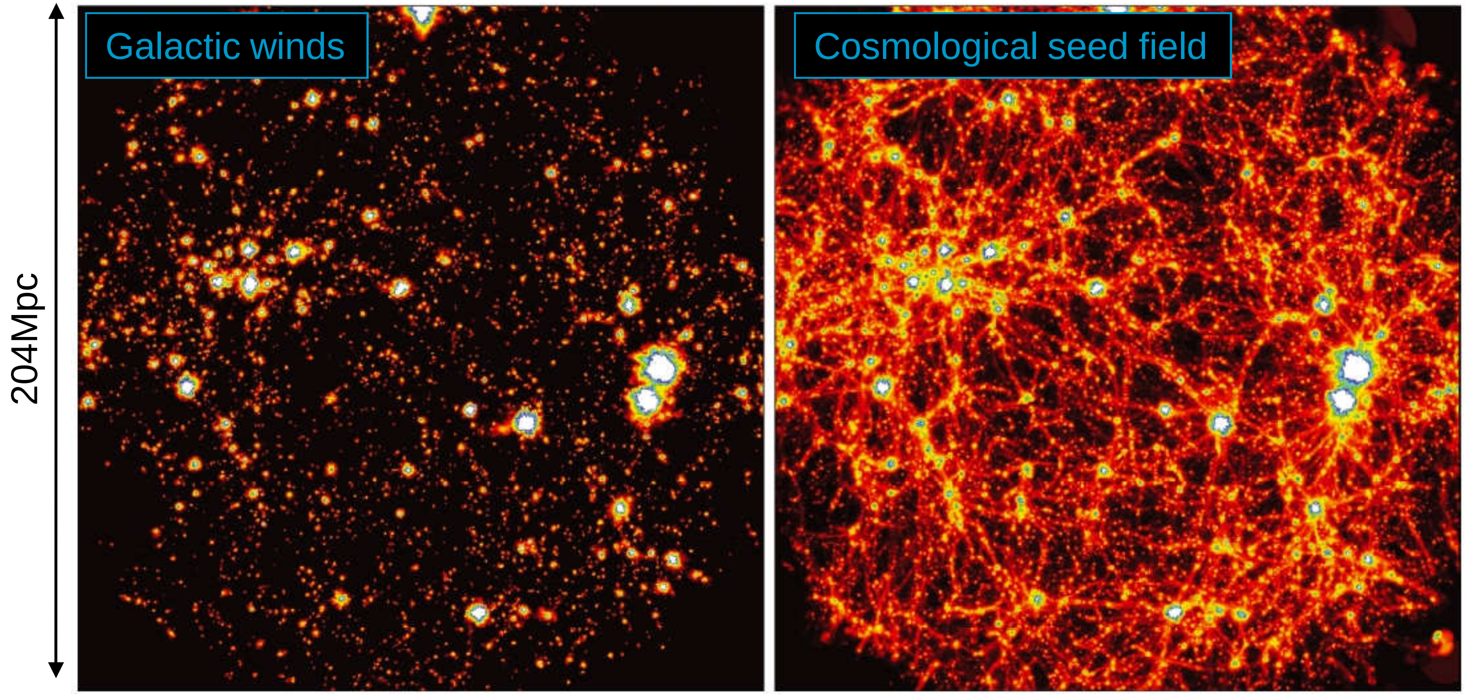
$\log_{10}(J/J_0)$ (>1 GeV)

$J_0 \sim 10^{-7}$ cm^{-2} s^{-1} sr^{-1}

Origin of magnetic fields - a complex picture

➢the IGM at low z is likely seeded by magnetized galactic pollution from a variety of sources...
... just as most Lyman alpha systems are enriched in metals...

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



Donnert et al. 06

➢ **in high density regions, memory of the initial conditions has probably been lost...**
... the field in the voids is probably more representative of the seeds at high z...

Constraints - the Universe as a calorimeter

- the Universe is opaque to >100GeV photons due to pair production on cosmic diffuse backgrounds...

$\gamma + \gamma_b \rightarrow e^+ + e^-$

$$\lambda_\gamma \simeq 80\,\mathrm{Mpc}\,(E_{\gamma,0}/10\,\mathrm{TeV})^{-1}$$

(interaction/cooling length)

electron energy: $E_e \simeq E_\gamma/2$

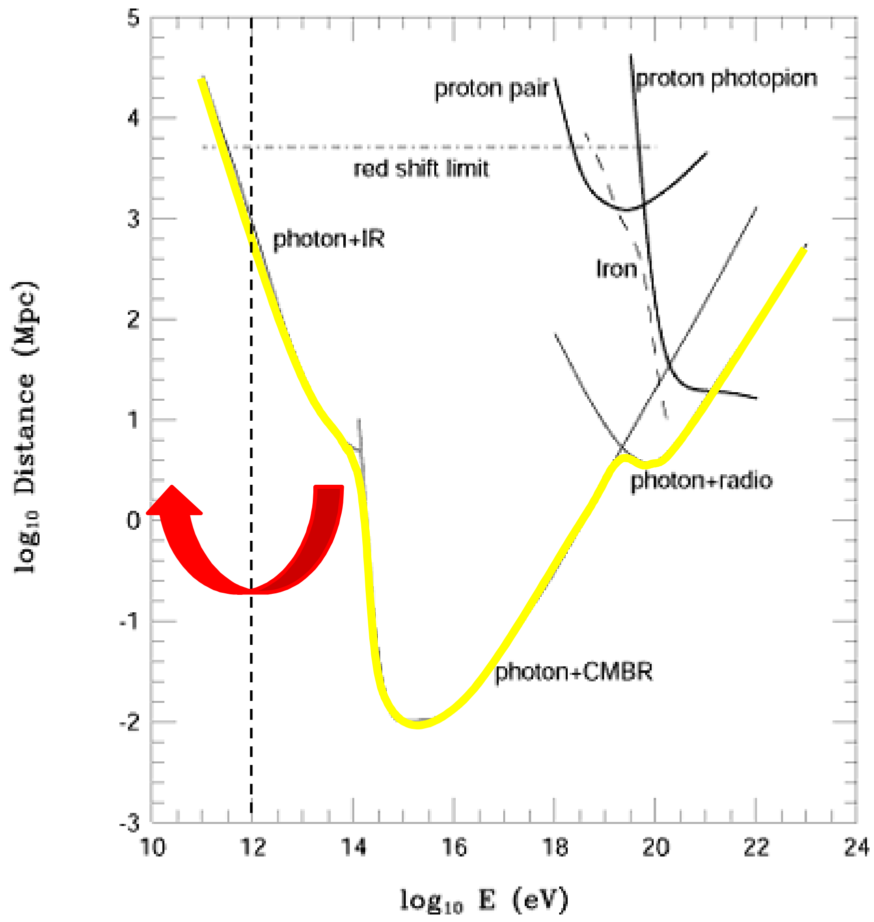
$e + \gamma_b \rightarrow e + \gamma$

e cooling length through inverse Compton on the cosmic microwave background:

$$\lambda_e \simeq 0.07\,\mathrm{Mpc}\,(E_e/5\,\mathrm{TeV})^{-1}$$

energy of upscattered photons:

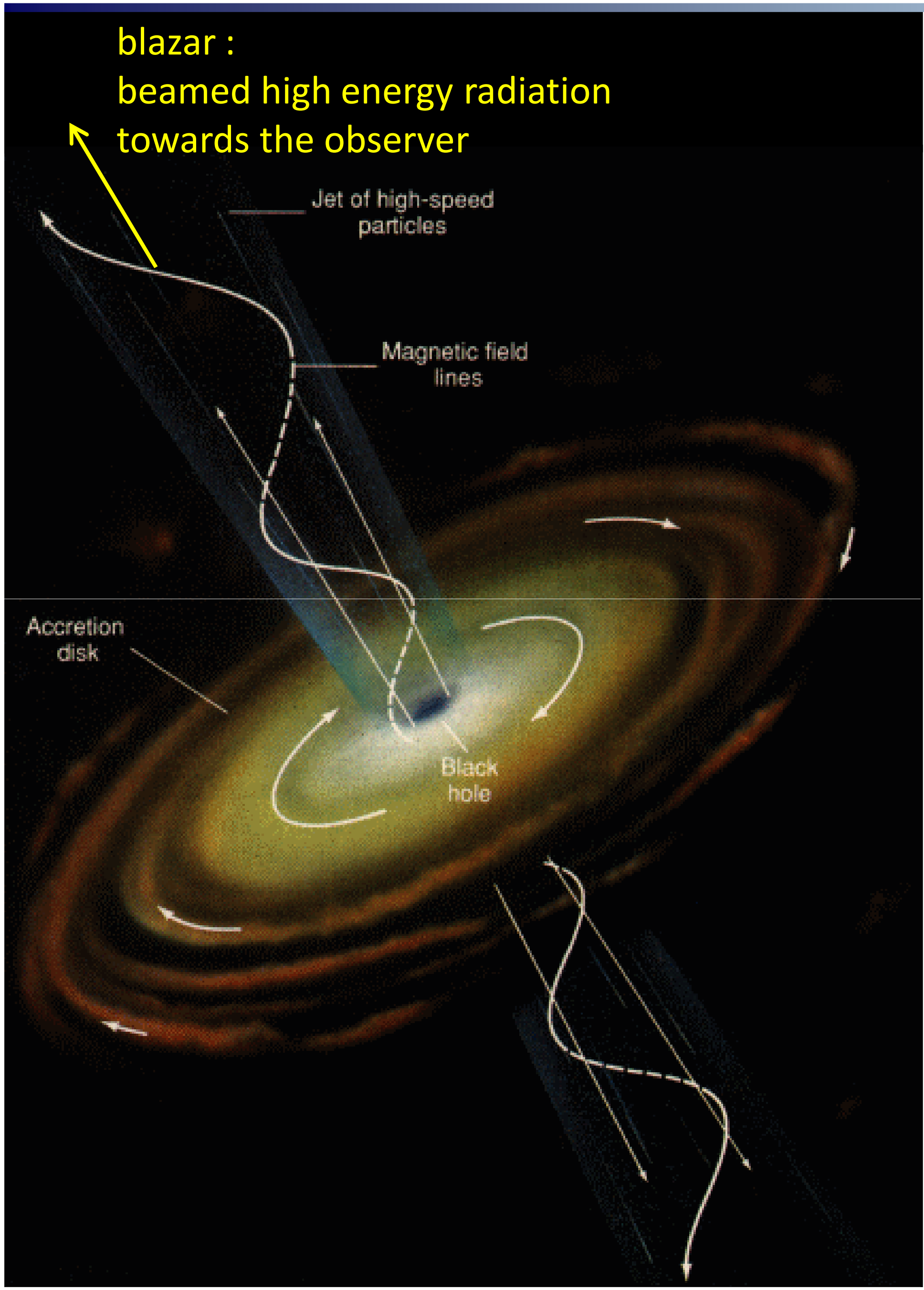
$$E_\gamma \simeq \frac{4}{3}k_B T_{\mathrm{cmb}}\,(E_e/m_e c^2)^2 \simeq 80\,\mathrm{GeV}\,(E_{\gamma,0}/10\,\mathrm{TeV})^2$$



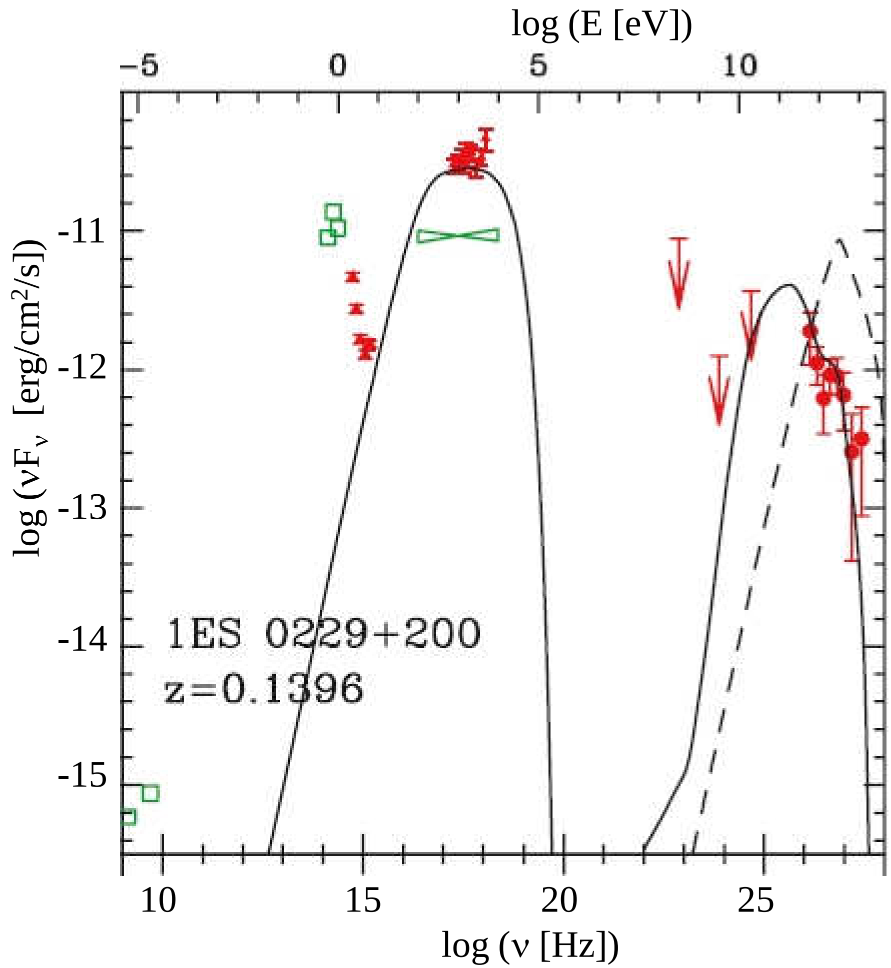
⇒ overall: all >TeV energy of far away sources is redeposited in the 1-100 GeV range through an electromagnetic cascade...

- **deflection of e^+e^- in intervening magnetic fields leads to angular deflection (halos) and time delay (echos) of impulsive point-like energy injection** (Aharonian et al. 94)

Constraints - blazar sources



Spectrum: typical double hump shape



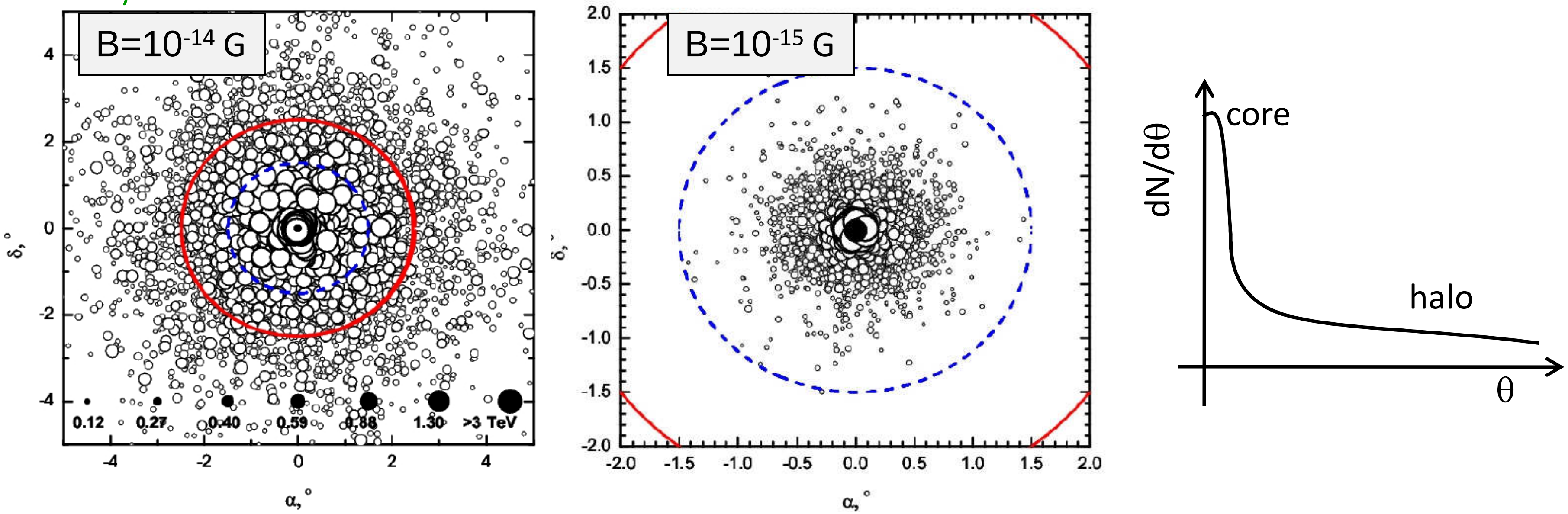
Constraints - magnetic halos and echos of blazars

➤ deflection angle during cascading: $\delta\theta \approx \frac{\lambda_e}{r_L} \approx 10^{-3}\left(\frac{B}{10^{-16}\,\mathrm{G}}\right)\left(\frac{E_{\gamma,0}}{10\,\mathrm{TeV}}\right)^{-2}$

➤ time delay wrt straight line propagation: $\delta t \approx 2\,10^2\,\mathrm{yr}\left(\frac{B}{10^{-16}\,\mathrm{G}}\right)^2\left(\frac{E_{\gamma,0}}{10\,\mathrm{TeV}}\right)^{-5}$

$\Rightarrow$ time delay on day scale can probe tiny magnetic fields $<10^{-18}$G
(Plaga 95, Murase et al. 08, Takahashi et al. 11)

Elyiv et al. 09



➤ halo extension: $\Theta \approx \frac{\lambda_\gamma}{D}\delta\theta \approx 10^{-4}\left(\frac{B}{10^{-16}\,\mathrm{G}}\right)\left(\frac{E_{\gamma,0}}{10\,\mathrm{TeV}}\right)^{-3}\left(\frac{D}{1\,\mathrm{Gpc}}\right)^{-1}$

➤ detection with Fermi (?): Ando & Kusenko (10) claim detection of halo around 170 stacked Fermi AGN at >10GeV, disputed by Neronov & Semikoz (10)

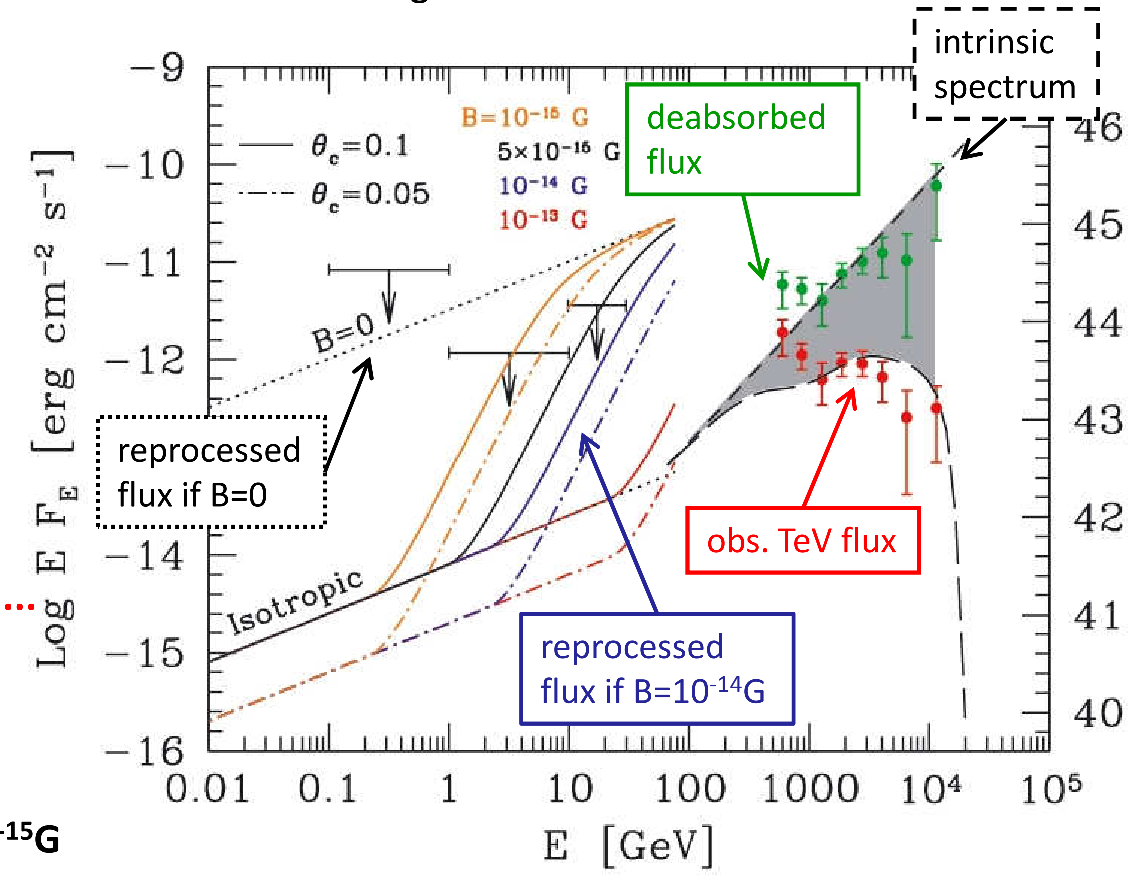
Constraints - spectral echos of blazars

➢Neronov & Vovk (10), Tavecchio et al. (10): energy of >TeV photons is reprocessed in the multi-GeV range... upper limits on multi-GeV flux allows to put a lower limit on intergalactic B

→ data points at GeV
count energy in PSF of Fermi

→ reprocessed component
is deflected by $\delta\theta$, spread over halo
of extension Θ :

if $\delta\theta$ exceeds the beaming angle of the source θ_c, or if Θ exceeds the PSF extension, reprocessed flux is depleted... at low energy / high B



⇒ **assuming homogeneous B, B > 10^{-15}G**

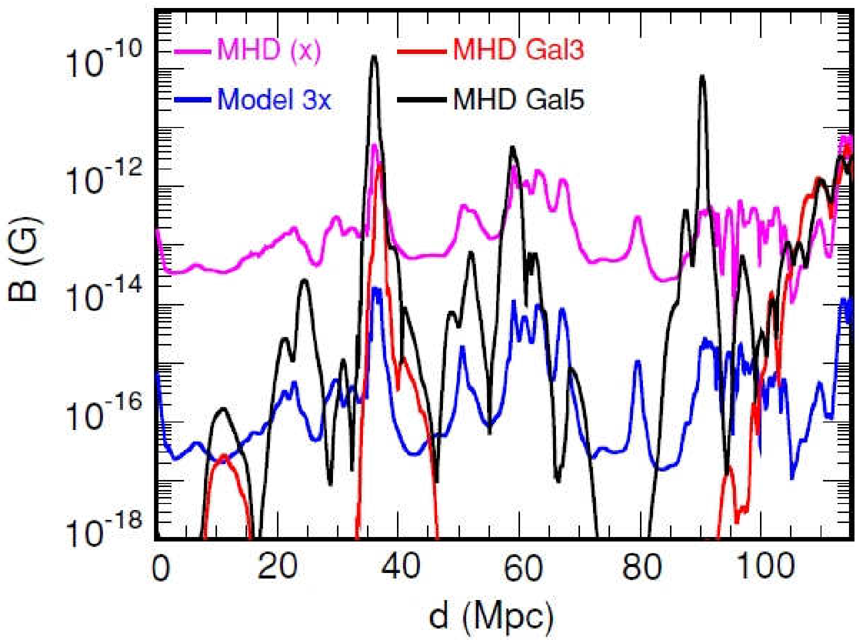
➢ Note: constraint assumes steady source, if limited activity timescale T_s, $\delta t < T_s$ implies a weaker limit B > 10^{-17}G... (Dermer et al. 11, Taylor et al. 11)

Constraints - blazar observations and the filling factor

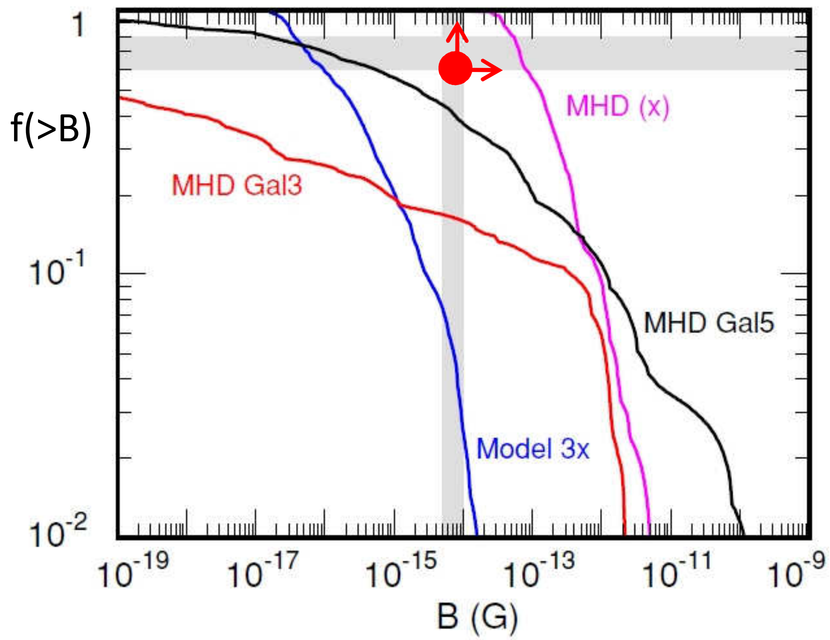
- Dolag et al. 11: constraint can be translated in a constraint on the filling factor of IGM fields

(assuming B=0 in a fraction 1-f of the volume, B homogeneous in the rest)

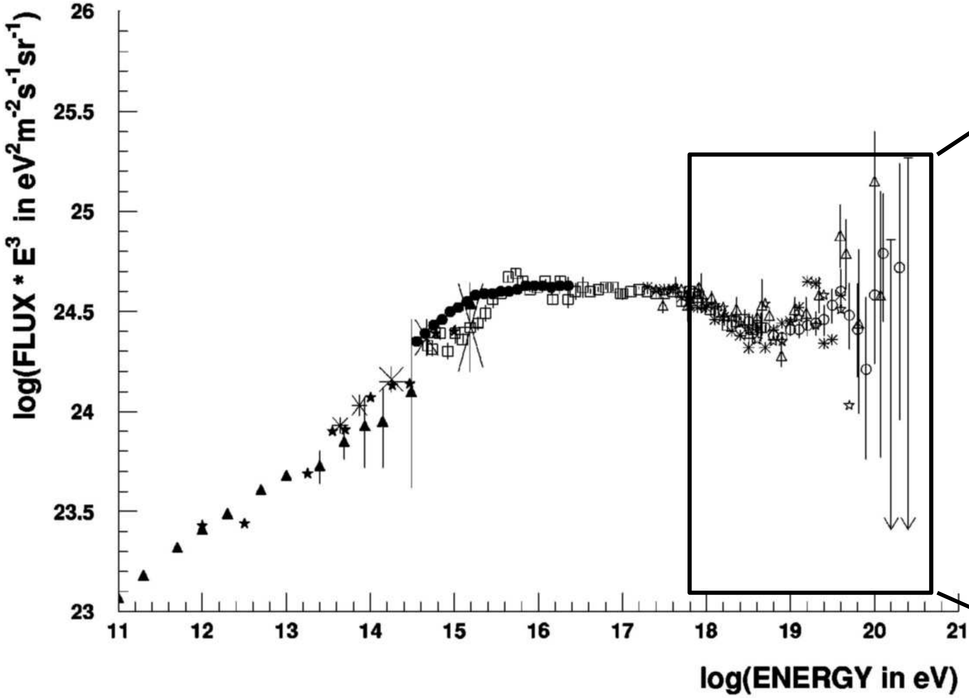
MHD simulations of large scale structures



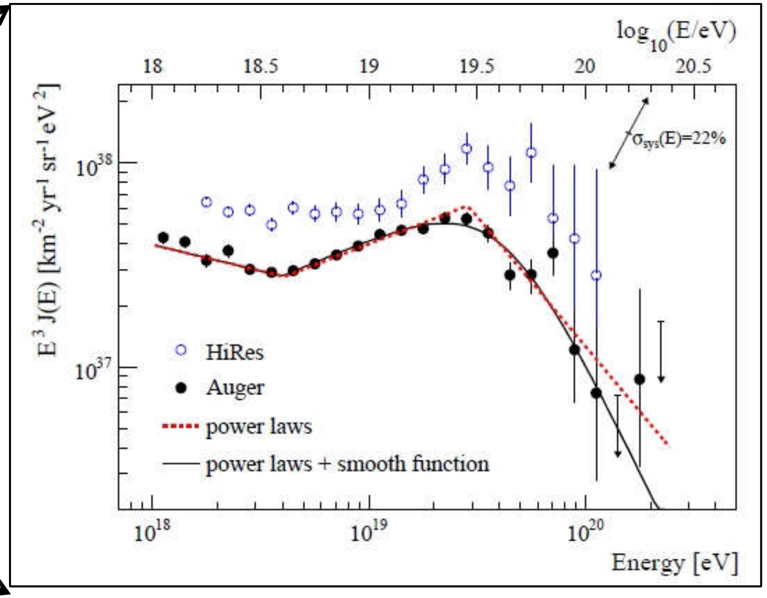
volume filling factor of magnetic fields



Constraints - UHE cosmic ray propagation



Ultra-high energy cosmic ray spectrum



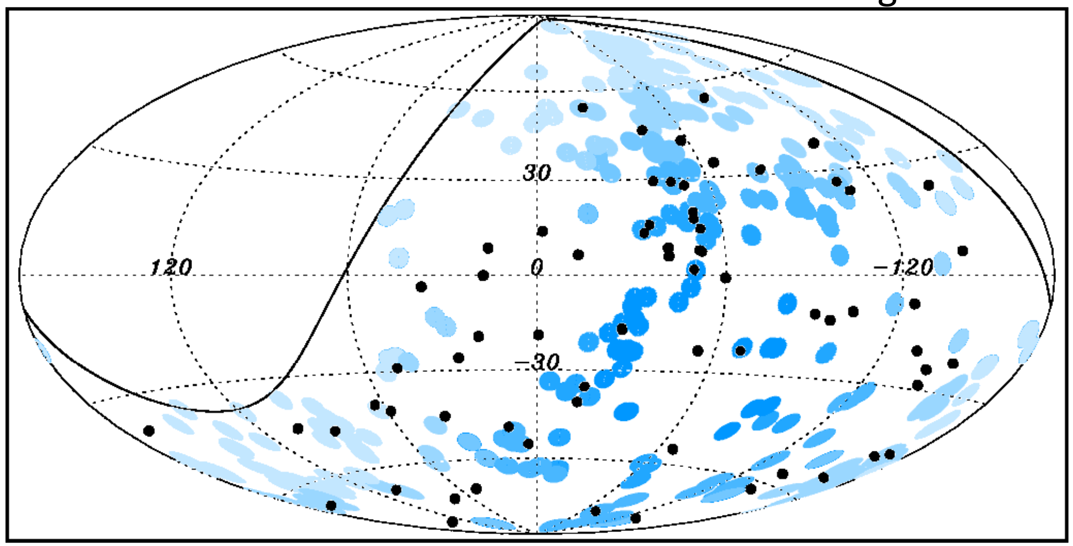
Ultra-high energy cosmic rays are:

→ extra-galactic
→ weakly sensitive to B,

$$r_L \simeq 100\,\mathrm{Mpc}\,Z^{-1}\left(\frac{E}{10^{20}\,\mathrm{eV}}\right)\left(\frac{B}{10^{-9}\,\mathrm{G}}\right)^{-1}$$

⇒ **may probe IGM fields of moderate strength**

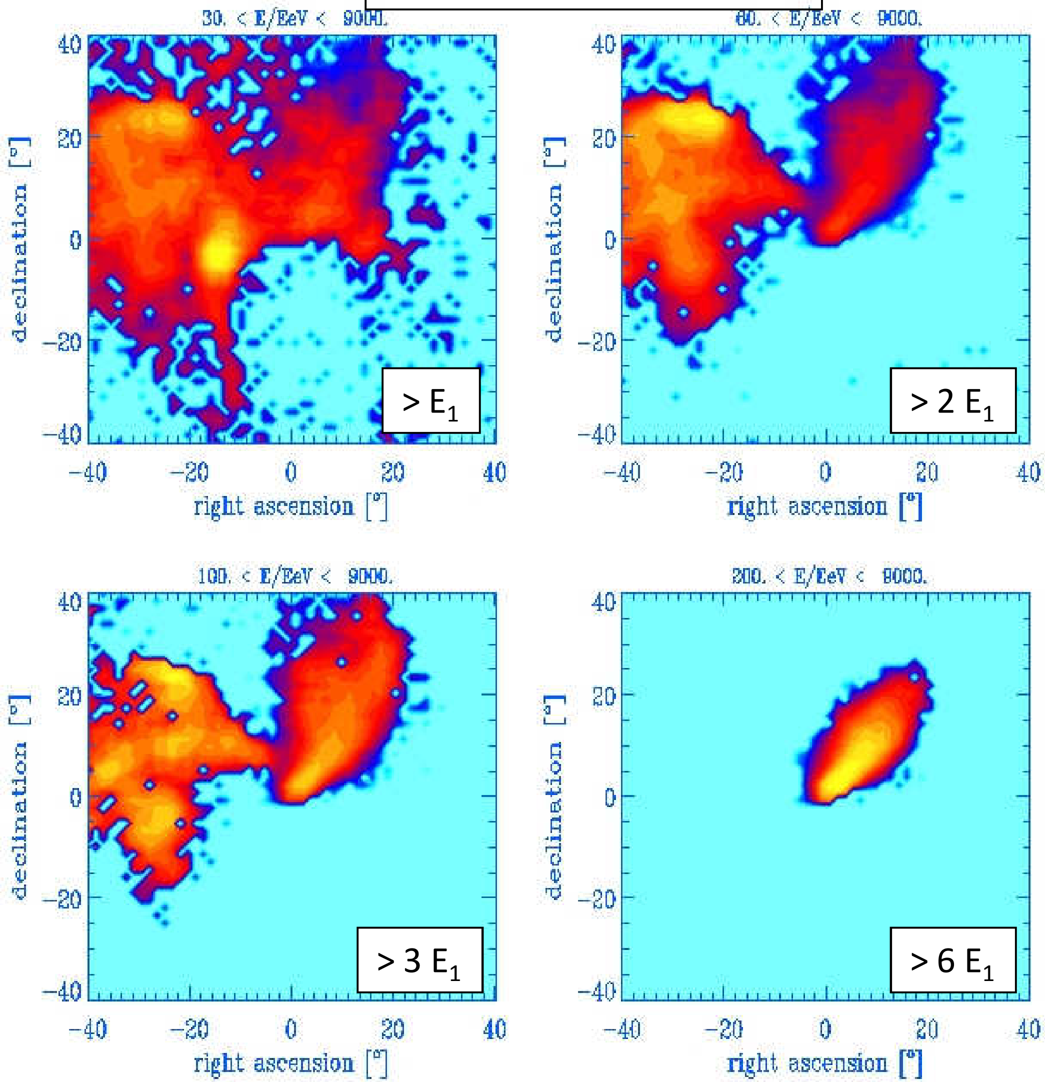
Arrival directions > 6 10^{19} eV for Auger



Constraints - UHE cosmic ray lensing

➢ one example: if clusters of events are seen around a given direction, image reconstruction can lead to constraints on magnetic field/coherence length etc...

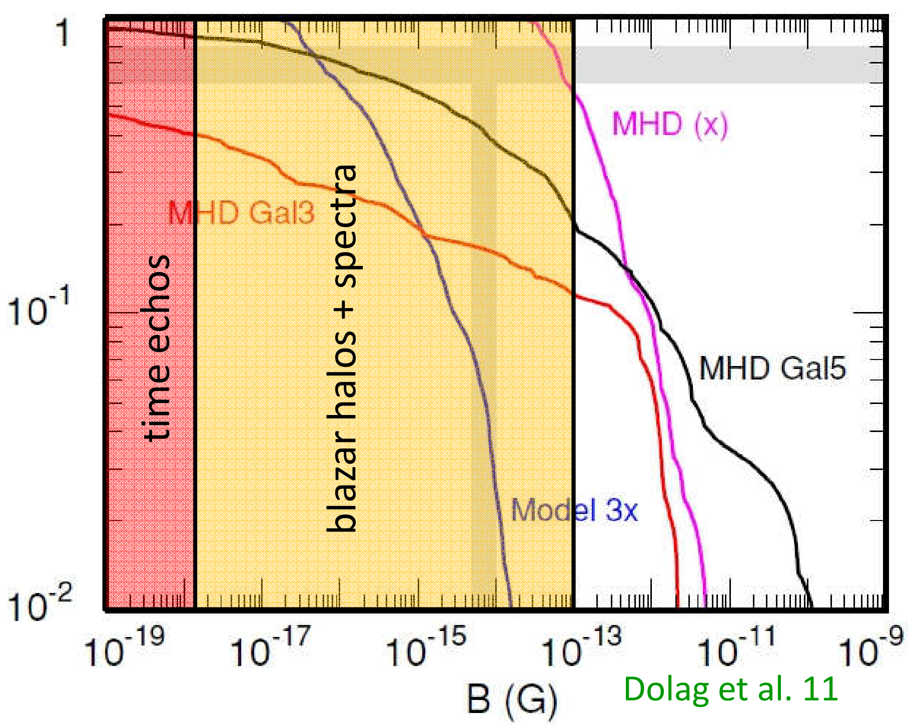
Magnetic strong lensing



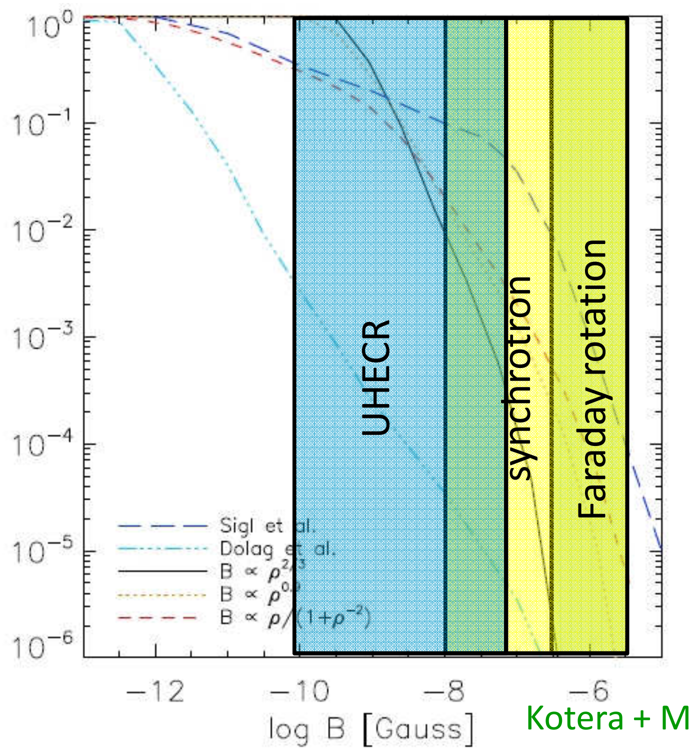
Miralda-Escude & Waxman 96
Sigl, M.L., Biermann 99
M.L., Sigl, Biermann 99
Harari,et al. 02

Summary & outlook

- the distribution and the origin of magnetic fields on > galaxy scales remains an open problem...
- it is a wide field of research, with connections to many other areas of research...
- many possible seeds, various stages of seeding, complex evolution during structure formation...
- recent (simultaneous) GeV - TeV observations of extreme blazars allow to constrain the intergalactic field B > 10^{-16} G... consequences for astrophysical models of B origin?



Dolag et al. 11



Kotera + ML 08

→ radio surveys: LOFAR (ongoing), SKA (projected 2020)