Intergalactic magnetic fields

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Overview

Introduciton / motivations

Characterization of IGMF

Sources of IGMF

Observational constraints on IGMF

Summary

Motivation

Galactic vs. intergalactic magnetic fields

Magnetic fields in galaxies are generated via MHD dynamo mechanism.

The MHD equations for the dynamo action do not explicitly include source term:

Plasma motions develop turbulence

Viscosity dumps motions on small scales

$$\rho\left(\frac{\partial\vec{v}}{\partial t}+(\vec{v}\nabla)\vec{v}\right)+\vec{B}\times(\nabla\times\vec{B})=-\nabla\vec{P}+\rho\vec{g}+\kappa\nabla^{2}v$$

Magnetic fields produce back-reaction on plasma motions

$$\frac{\partial\vec{B}}{\partial t}=\nabla\times(\vec{v}\times\vec{B})+\frac{1}{\sigma}\nabla^{2}B$$

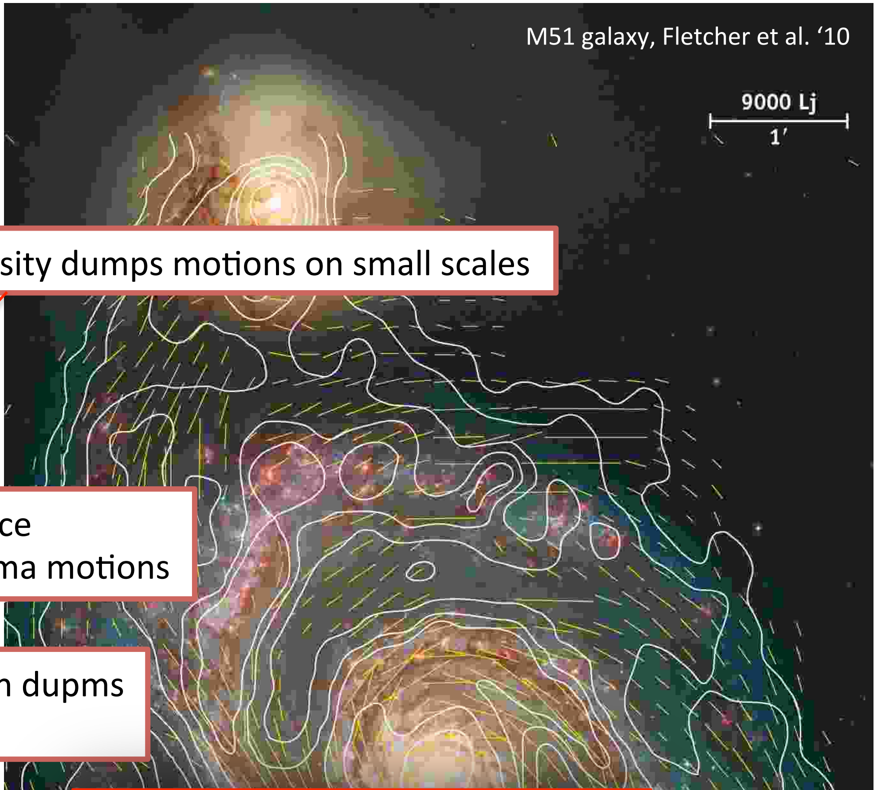
Ohmic dissipaiton dupms B on small scales

Plasma motions amplify pre-existing weak magnetic fields

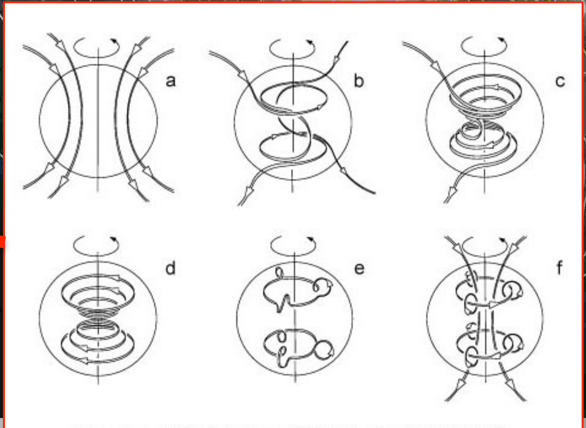
Exponential amplification of magnetic field in the presence of plasma motions works on the eddy turnover time scale

$$t\sim\frac{L}{v}\simeq 10^{8}\left[\frac{L}{10\ \text{kpc}}\right]\left[\frac{v}{10^{2}\ \text{km/s}}\right]^{-1}\text{yr}$$

and is able to amplify galactic magnetic field from, e.g. 10^{-20} G up to 10 μG in some 35 e-folding time, i.e. on several Gyr time scales .



M51 galaxy, Fletcher et al. ‘10



Love, J. J., 1999. Astronomy & Geophysics, 40, 6.14-6.19.

Galactic vs. intergalactic magnetic fields

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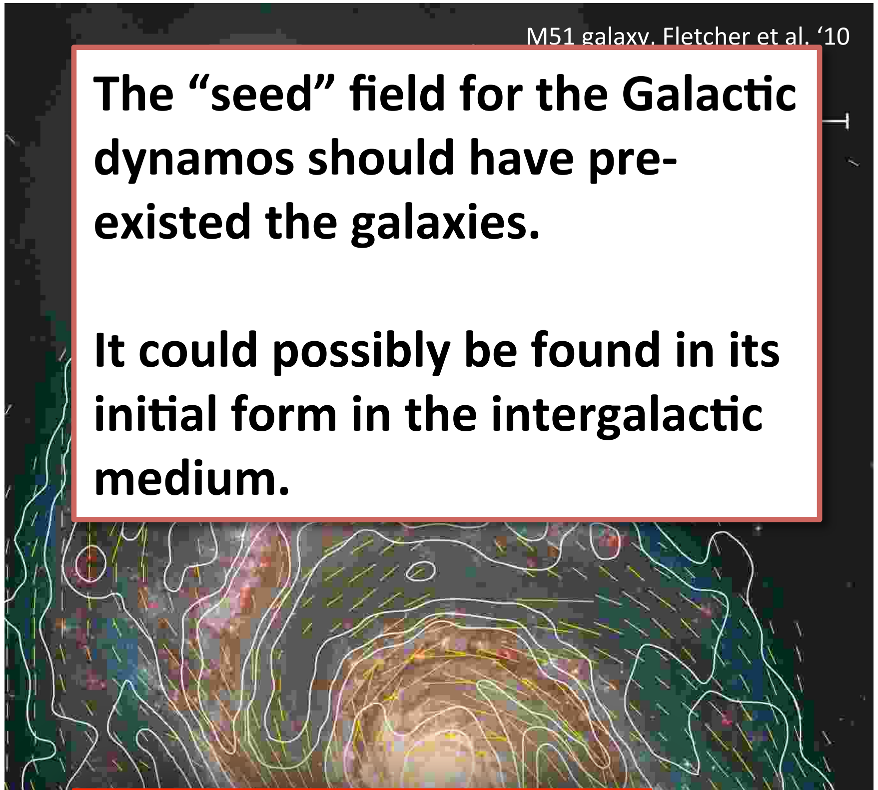
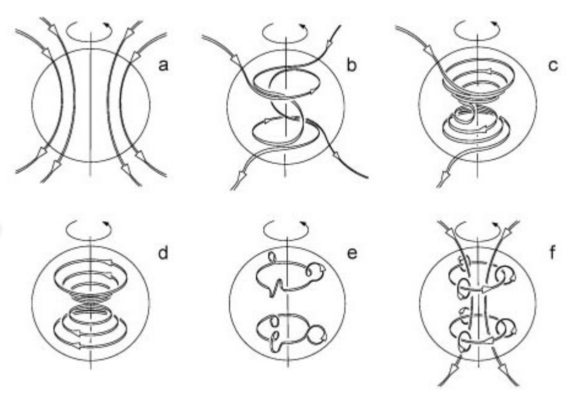


M51 galaxy, Fletcher et al. '10

The "seed" field for the Galactic dynamos should have pre-existed the galaxies.

It could possibly be found in its initial form in the intergalactic medium.



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Magnetic fields in the Early Universe?

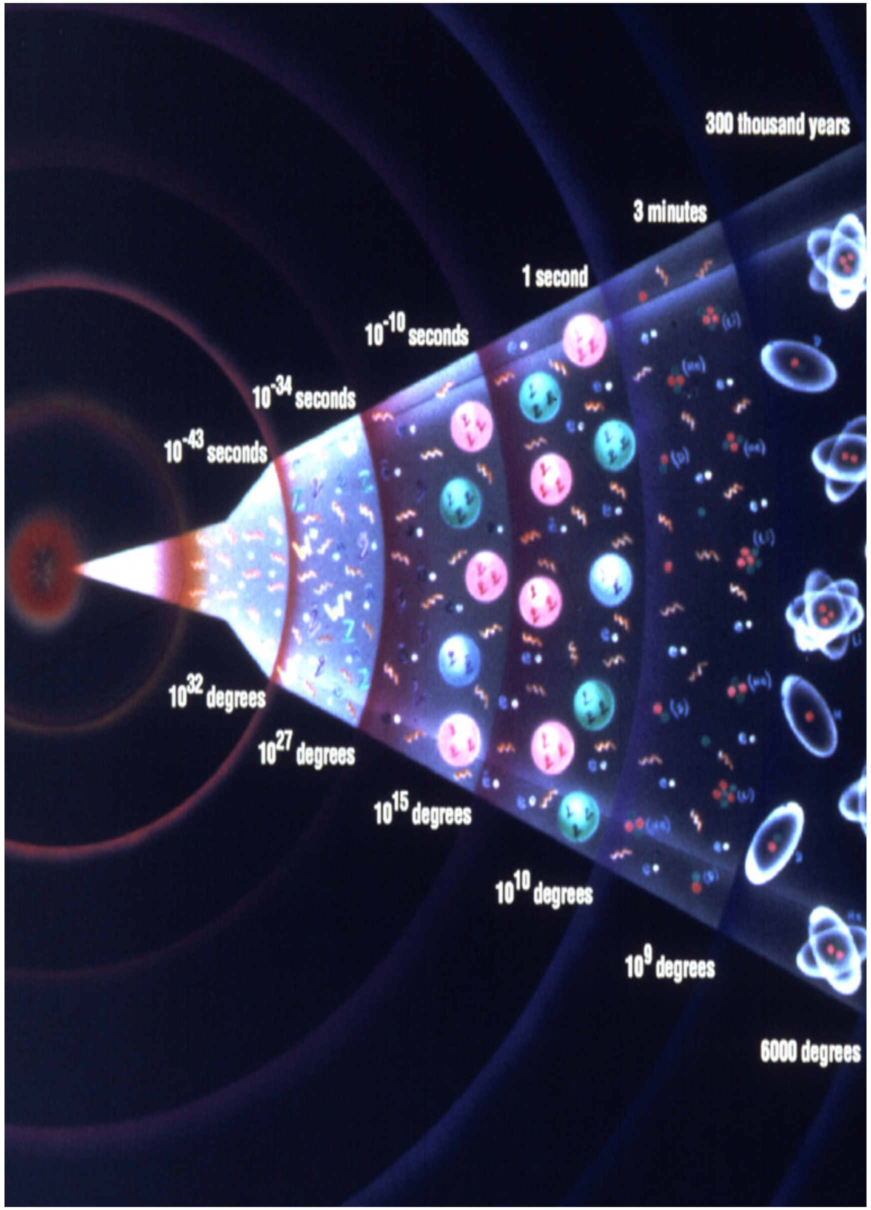
Early Universe was also filled with high conductivity charged plasma. It might have also possessed magnetic field which was in a dynamical co-evolution with expanding matter.

Was magnetic field generated in the Early Universe? How?

If yes, did it play a significant role in physical processes (e.g. expanding plasma dynamics)?

Are there any observable consequences of the presence of magnetic field in the Early Universe?

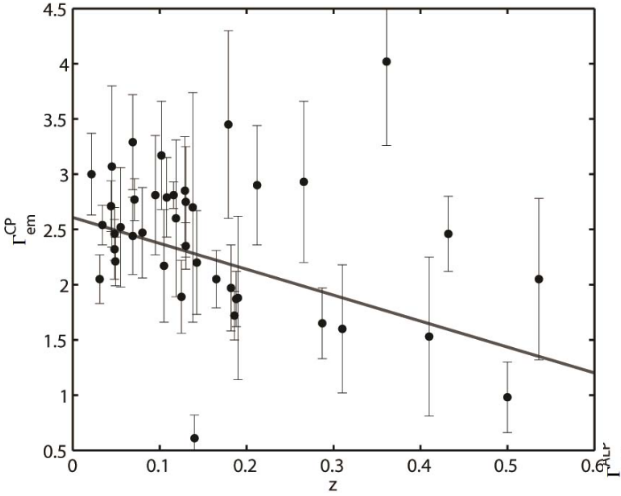
Are they related to the observed magnetic fields in astronomical objects?

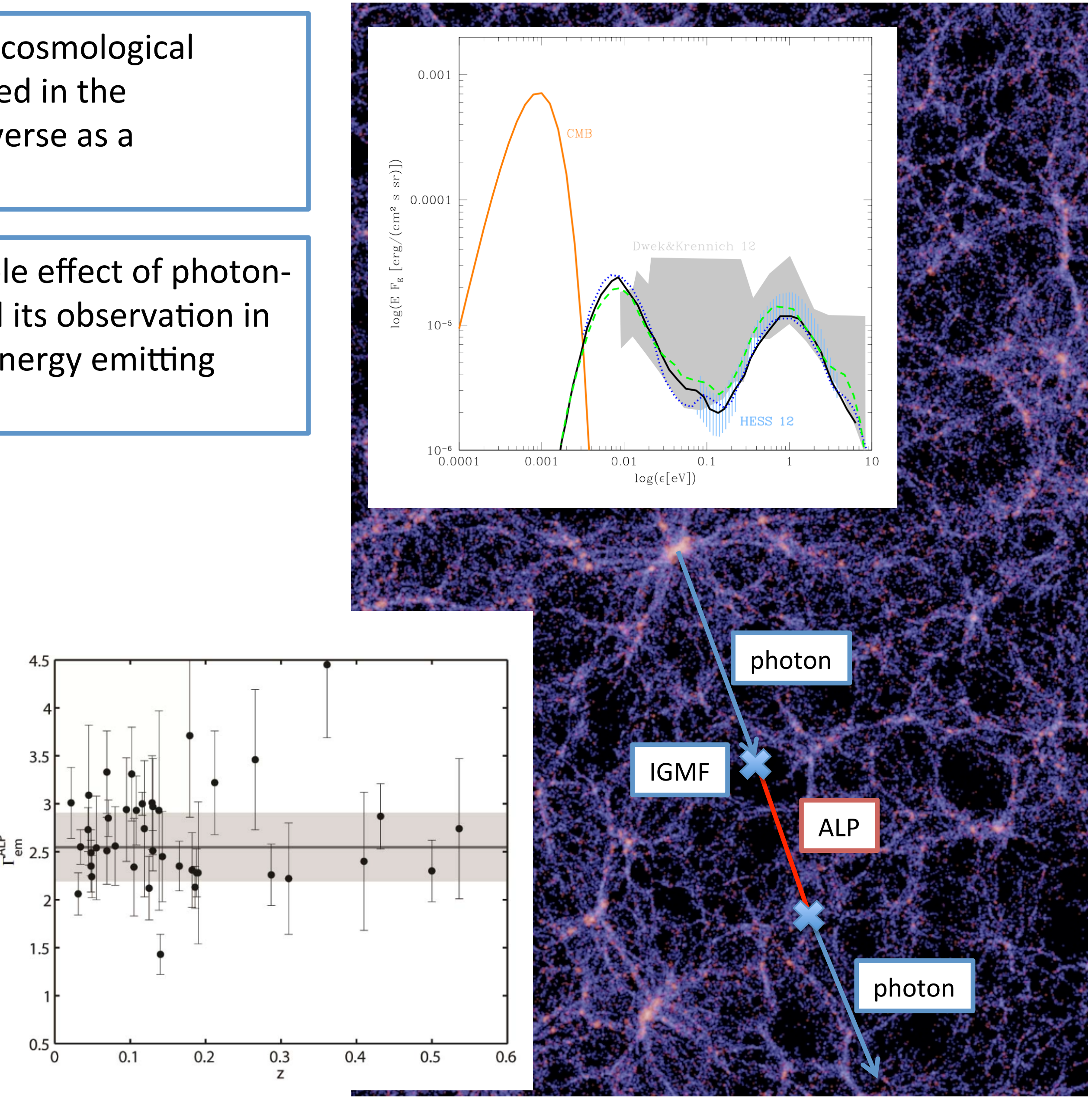


Fundamental physics probe(s)

Non-negligible IGMF spread over cosmological distance scales could be considered in the framework of the use of the Universe as a fundamental physics laboratory.

An example is given by the possible effect of photon-axion-like-particle conversion and its observation in the spectra of distant very-high-energy emitting blazars.





photon

IGMF

ALP

photon

e.g. Roncadelli, de Angelis, Bignami arXiv:1503.0443

(G)astrophysical probe(s)

The process of “return” of magnetic fields with baryon loaded plasma into intergalactic medium is a part of more general process of baryonic feedback during structure formation.

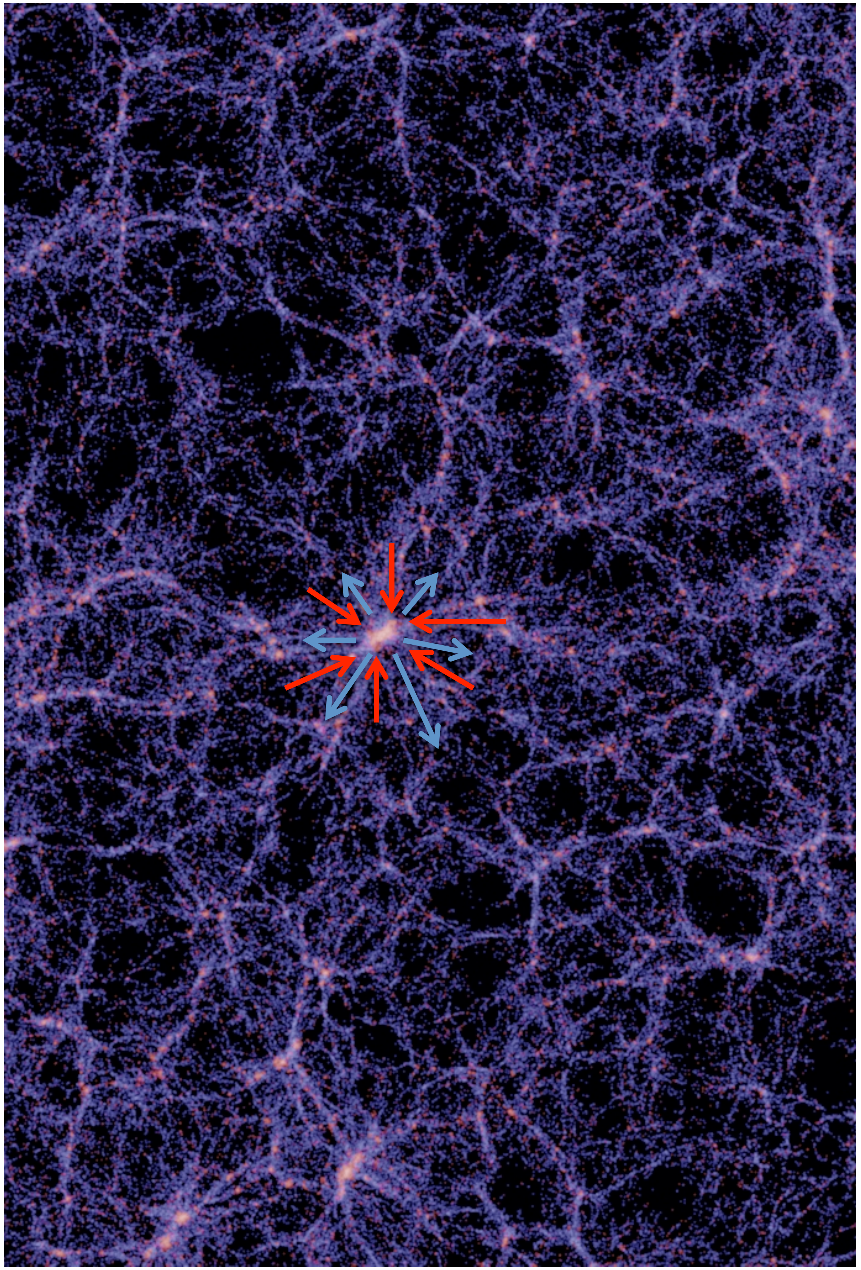
Measurement of IGMF properties (strength, distance scales) could provide useful constraints on the feedback.

Turbulence / dynamo in galaxies drives magnetic field energy density in equipartition with the energy density of turbulent motions

$$U_B \sim U_{turb} \simeq \frac{m_p n v^2}{2} \simeq 0.3 \left[\frac{n}{1\ \mathrm{cm}^{-3}}\right]\left[\frac{v}{10\ \mathrm{km/s}}\right]^2 \frac{\mathrm{eV}}{\mathrm{cm}^3}$$

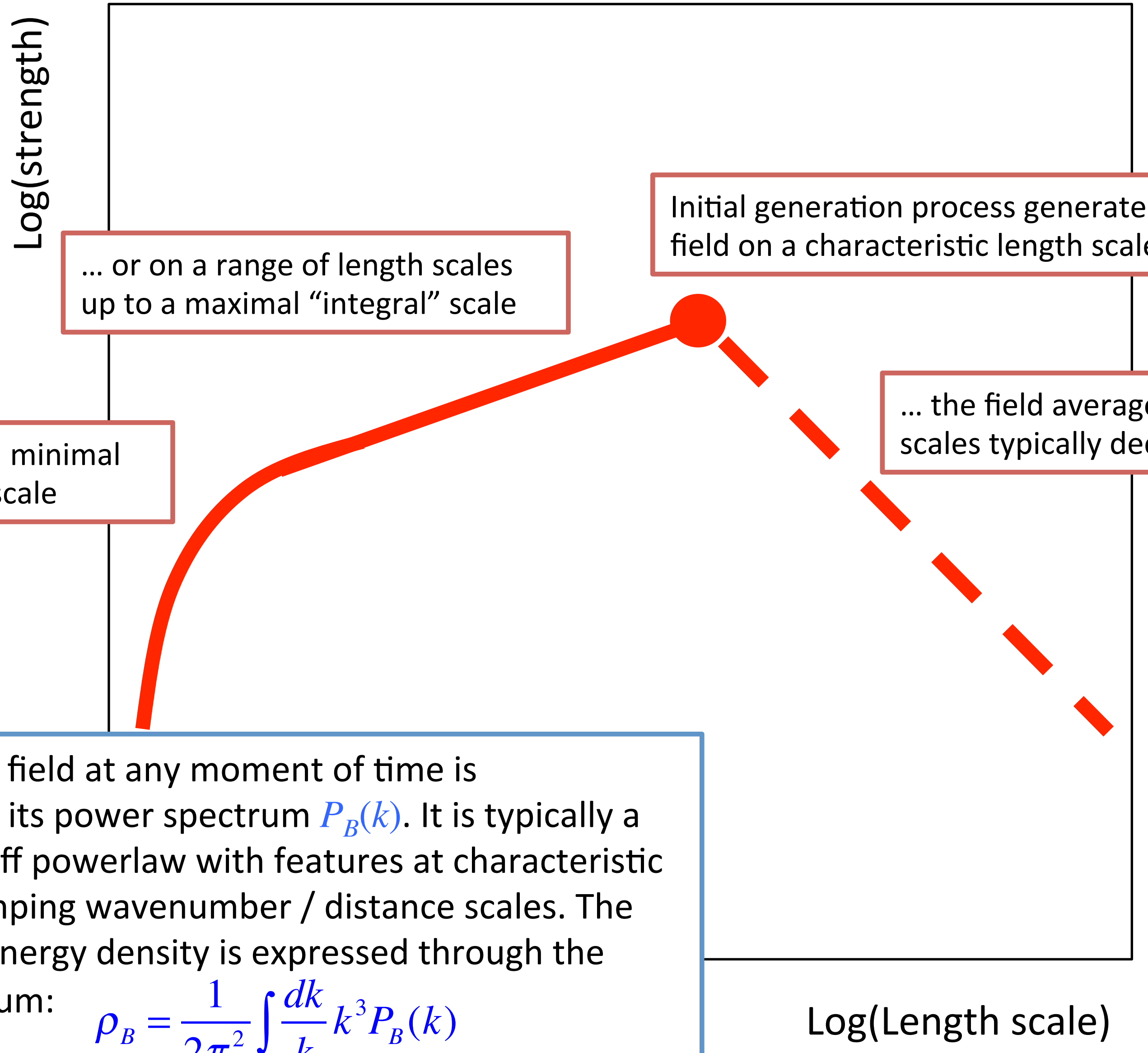
Supernova (AGN) driven turbulence also results in production of galactic winds which return baryons into the intergalactic medium.

Tracing the IGMF spread by galactic winds provides a possibility to trace the baryonic feedback on structure formation.



IGMF characteristics

IGMF characteristics



Initial generation process generates magnetic field on a characteristic length scale

… or on a range of length scales up to a maximal “integral” scale

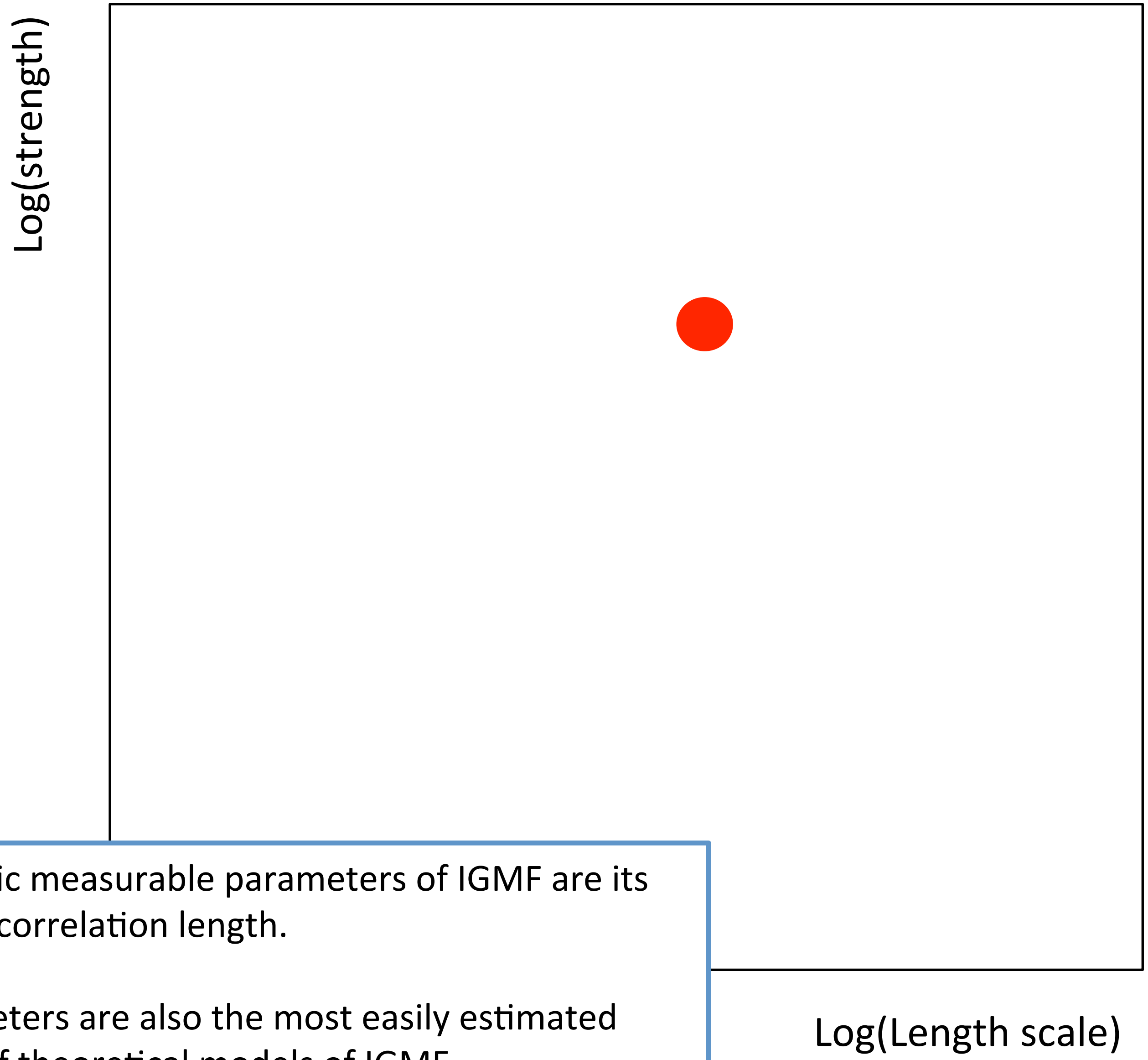
… down to a minimal “damping” scale

… the field averaged over larger scales typically decreases

The magnetic field at any moment of time is characterized its power spectrum $P_B(k)$. It is typically a broken / cutoff powerlaw with features at characteristic integral / damping wavenumber / distance scales. The overall field energy density is expressed through the power spectrum:

$$\rho_B = \frac{1}{2\pi^2}\int \frac{dk}{k} k^3 P_B(k)$$

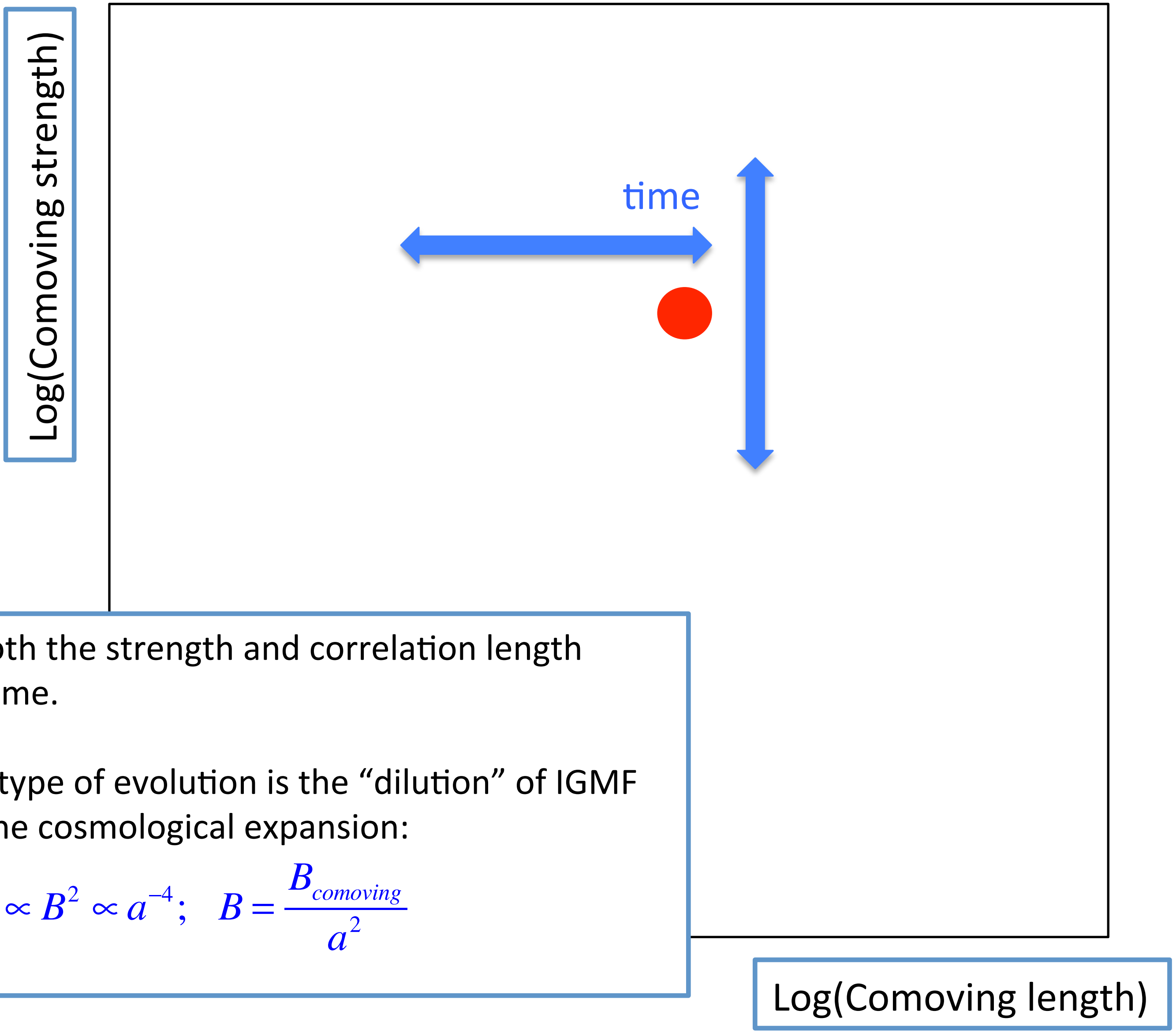
IGMF characteristics



The most basic measurable parameters of IGMF are its strength and correlation length.

These parameters are also the most easily estimated parameters of theoretical models of IGMF.

IGMF characteristics



In general, both the strength and correlation length evolve with time.

The simplest type of evolution is the “dilution” of IGMF strength by the cosmological expansion:

$$\rho_B \propto B^2 \propto a^{-4}; \quad B = \frac{B_{comoving}}{a^2}$$

Co-evolution of magnetic fields and plasma

Nonlinear “mode coupling” term(s)

$$\rho\left(\frac{\partial\vec{v}}{\partial t}+(\vec{v}\nabla)\vec{v}\right)+\vec{B}\times(\nabla\times\vec{B})=-\nabla\vec{P}+\rho\vec{g}+\kappa\left(\nabla^2\vec{v}+\frac{1}{3}\nabla(\nabla\vec{v})\right)$$

$$\frac{\partial\vec{B}}{\partial t}=\nabla\times(\vec{v}\times\vec{B})+\frac{1}{\sigma}\nabla^2\vec{B}$$

Comoving magnetic field $B{\sim}a^2B_{phys}$ is conserved in the linear regime on the scales much larger than the Ohmic dissipation scale. Linear approximation is not valid at the distance scales shorter or comparable to the “largest processed eddy” scale, $L{\sim}vt$.

Nonlinear terms are responsible for the transfer of power from larger to smaller scales and for development of turbulence:

$$v\sim\sin(kx)$$

$$v\nabla v\sim k\sin(kx)\cos(kx)\sim k/2\sin(2kx)$$

* Valid for “comoving” fields

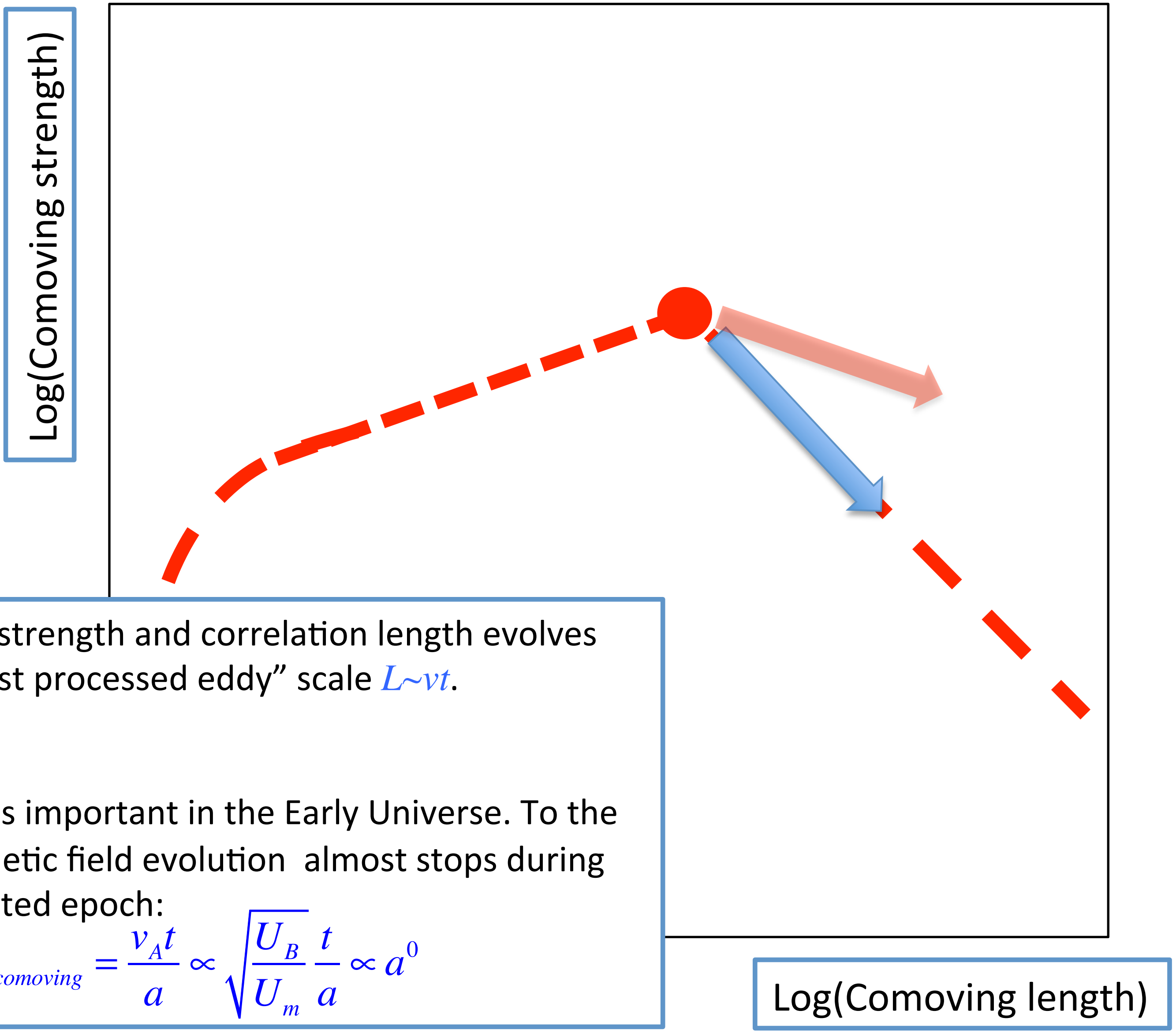
Nonlinear terms dominate on the distance scales $l>\frac{\kappa}{v}$, $l>\frac{1}{\sigma v}$, i.e. as long as the kinetic and magnetic Reynolds numbers are

$$R_k=\frac{lv}{\kappa}\sim\frac{lv}{\lambda_{mfp}}\gg 1,\qquad R_m=lv\sigma\gg 1$$

As soon as $R_k{\sim}1$ at the integral scale, turbulence development stops. Viscous term dominates and plasma motions are suppressed, $v\rightarrow 0$. If R_m is still large, magnetic field stops evolving, $B{\sim}const$.

Example: neutrino decoupling: $\kappa{\sim}\lambda_{mfp,\nu}$. or photon decoupling, $\kappa{\sim}\lambda_{mfp,\gamma}$.

IGMF characteristics



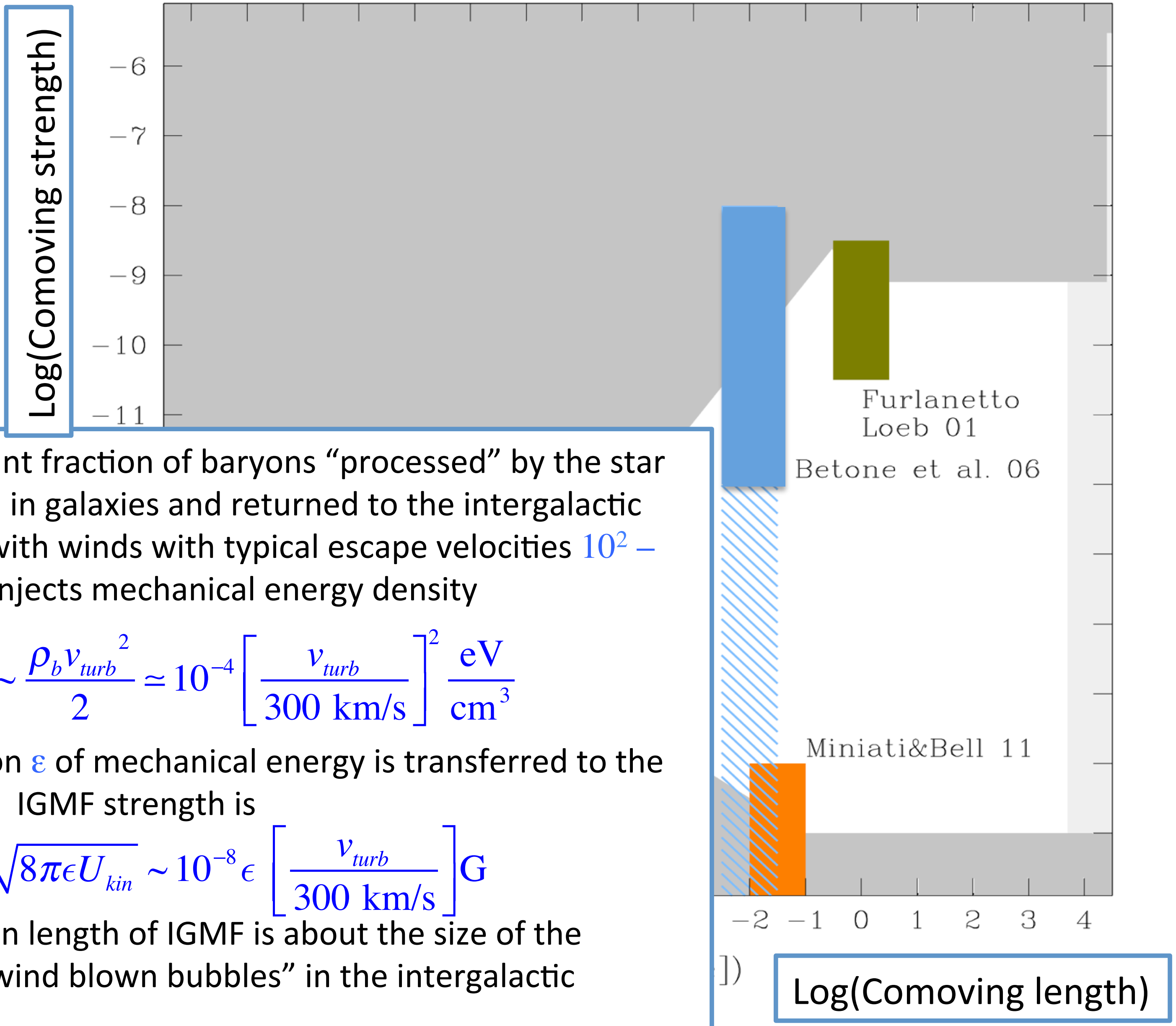
Magnetic field strength and correlation length evolves with the “largest processed eddy” scale $L \sim vt$.

This evolution is important in the Early Universe. To the contrary, magnetic field evolution almost stops during matter-dominated epoch:

$$L_{comoving} = \frac{v_A t}{a} \propto \sqrt{\frac{U_B}{U_m}}\,\frac{t}{a} \propto a^0$$

Sources of IGMF

… galactic winds



A significant fraction of baryons "processed" by the star formation in galaxies and returned to the intergalactic medium with winds with typical escape velocities $10^2 - 10^3$ cm/s injects mechanical energy density

$$U_{kin} \sim \frac{\rho_b v_{turb}^2}{2} \simeq 10^{-4}\left[\frac{v_{turb}}{300\ \text{km/s}}\right]^2 \frac{\text{eV}}{\text{cm}^3}$$

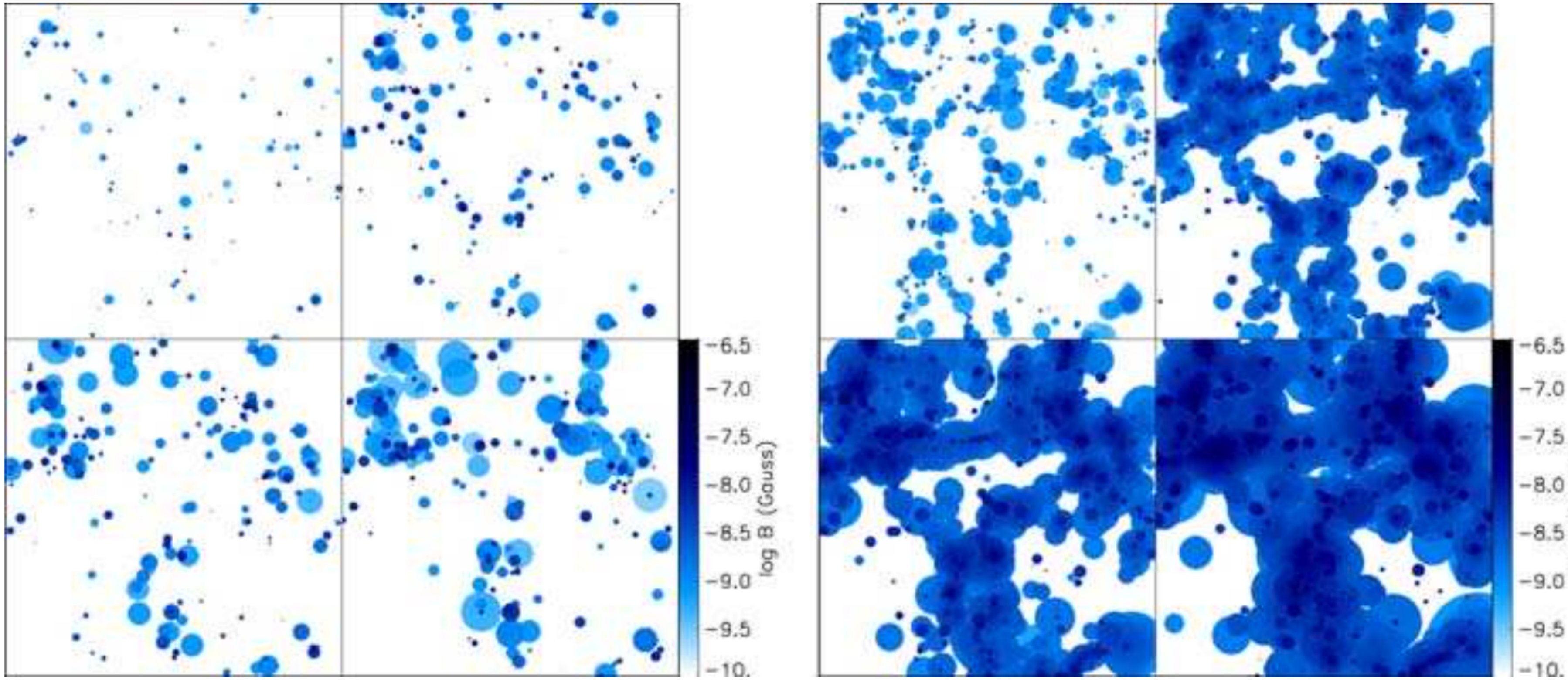
If a fraction ε of mechanical energy is transferred to the IGMF, the IGMF strength is

$$B \sim \sqrt{8\pi\epsilon U_{kin}} \sim 10^{-8}\epsilon\left[\frac{v_{turb}}{300\ \text{km/s}}\right]\text{G}$$

Correlation length of IGMF is about the size of the "galactic wind blown bubbles" in the intergalactic medium.

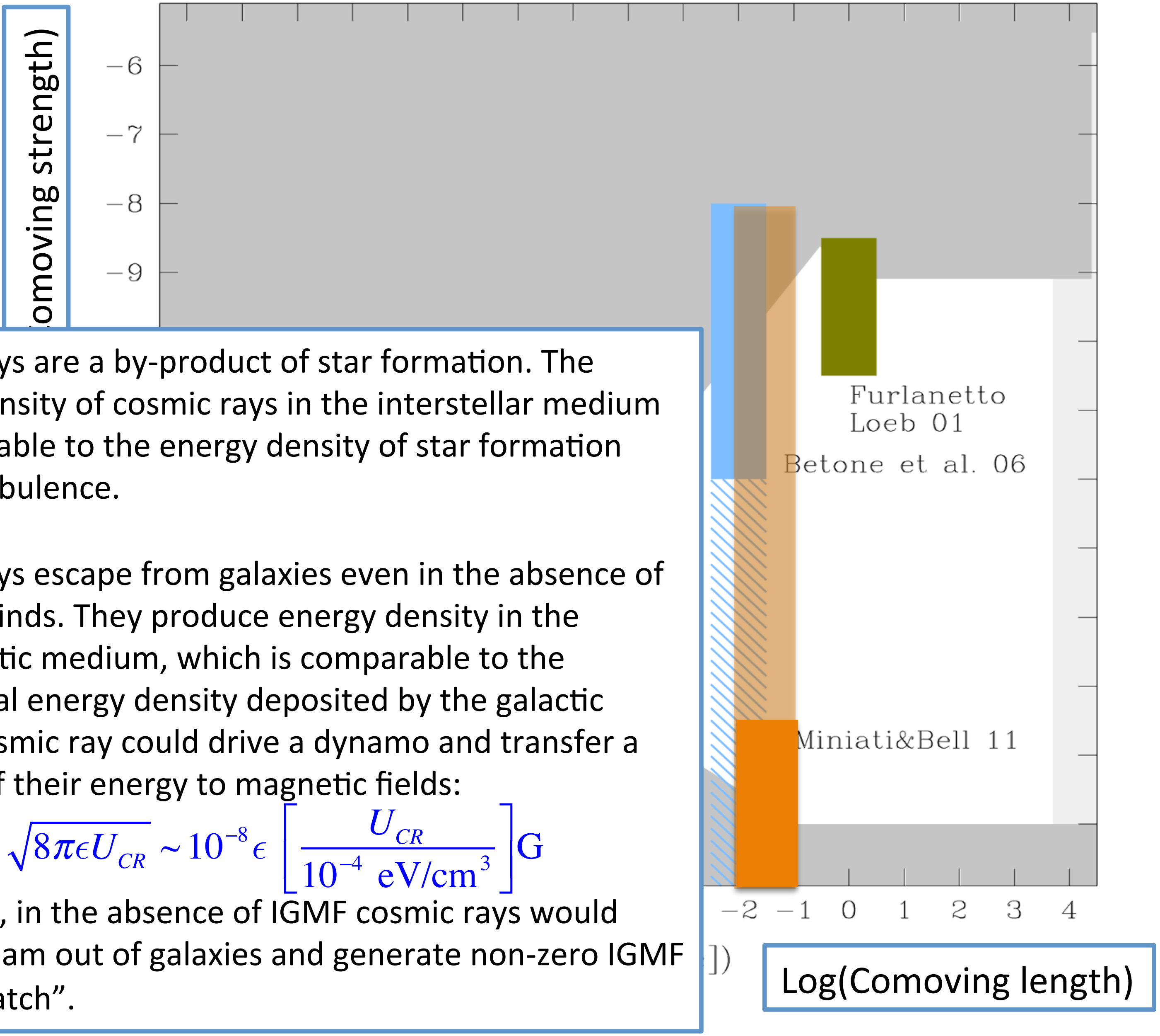
Kronberg '99, Bertone, Vogt, Ensslin '06; Donnert et al. '09

… galactic winds



Kronberg '99, Bertone, Vogt, Ensslin '06; Donnert et al. '09

… cosmic rays



Cosmic rays are a by-product of star formation. The energy density of cosmic rays in the interstellar medium is comparable to the energy density of star formation driven turbulence.

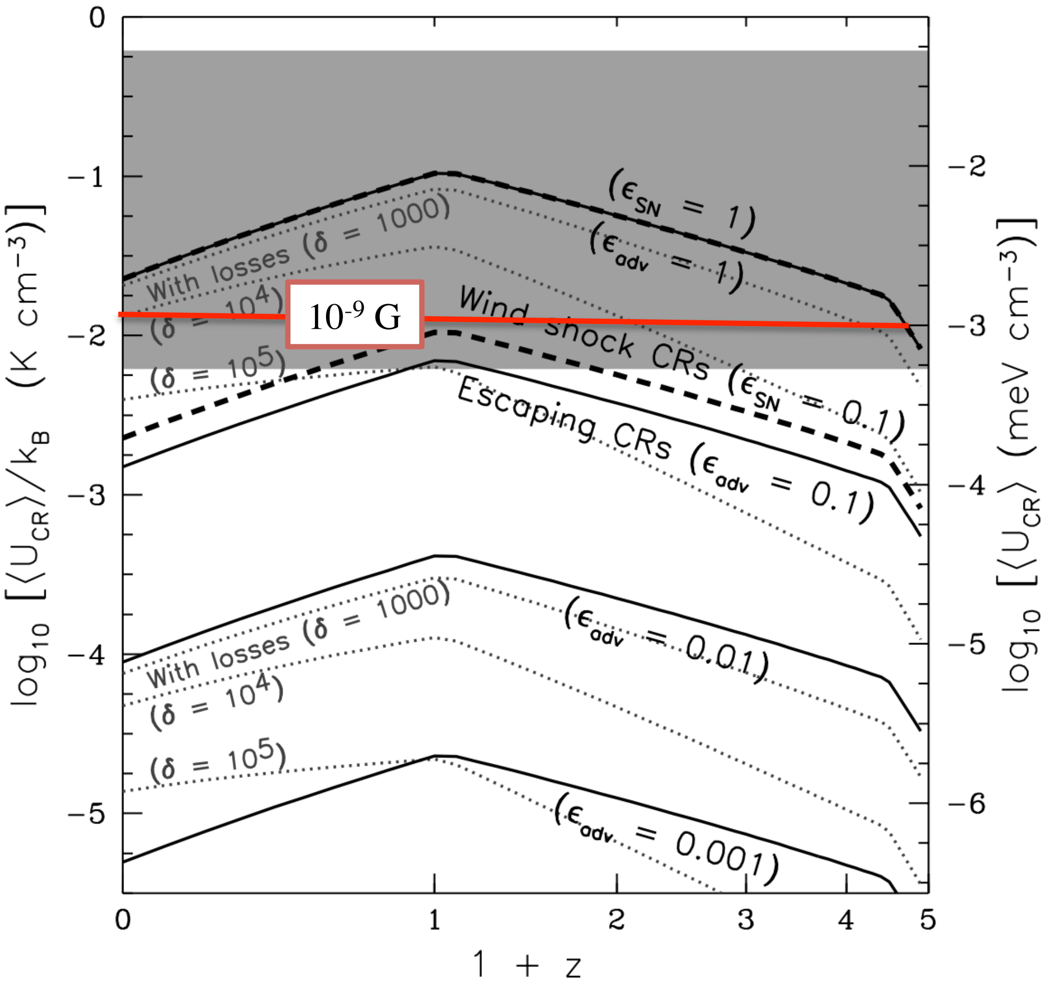
Cosmic rays escape from galaxies even in the absence of galactic winds. They produce energy density in the intergalactic medium, which is comparable to the mechanical energy density deposited by the galactic winds. Cosmic ray could drive a dynamo and transfer a fraction of their energy to magnetic fields:

$$B \sim \sqrt{8\pi\epsilon U_{CR}} \sim 10^{-8}\epsilon\left[\frac{U_{CR}}{10^{-4}\ \mathrm{eV/cm^3}}\right]\mathrm{G}$$

Moreover, in the absence of IGMF cosmic rays would freely stream out of galaxies and generate non-zero IGMF “from scratch”.

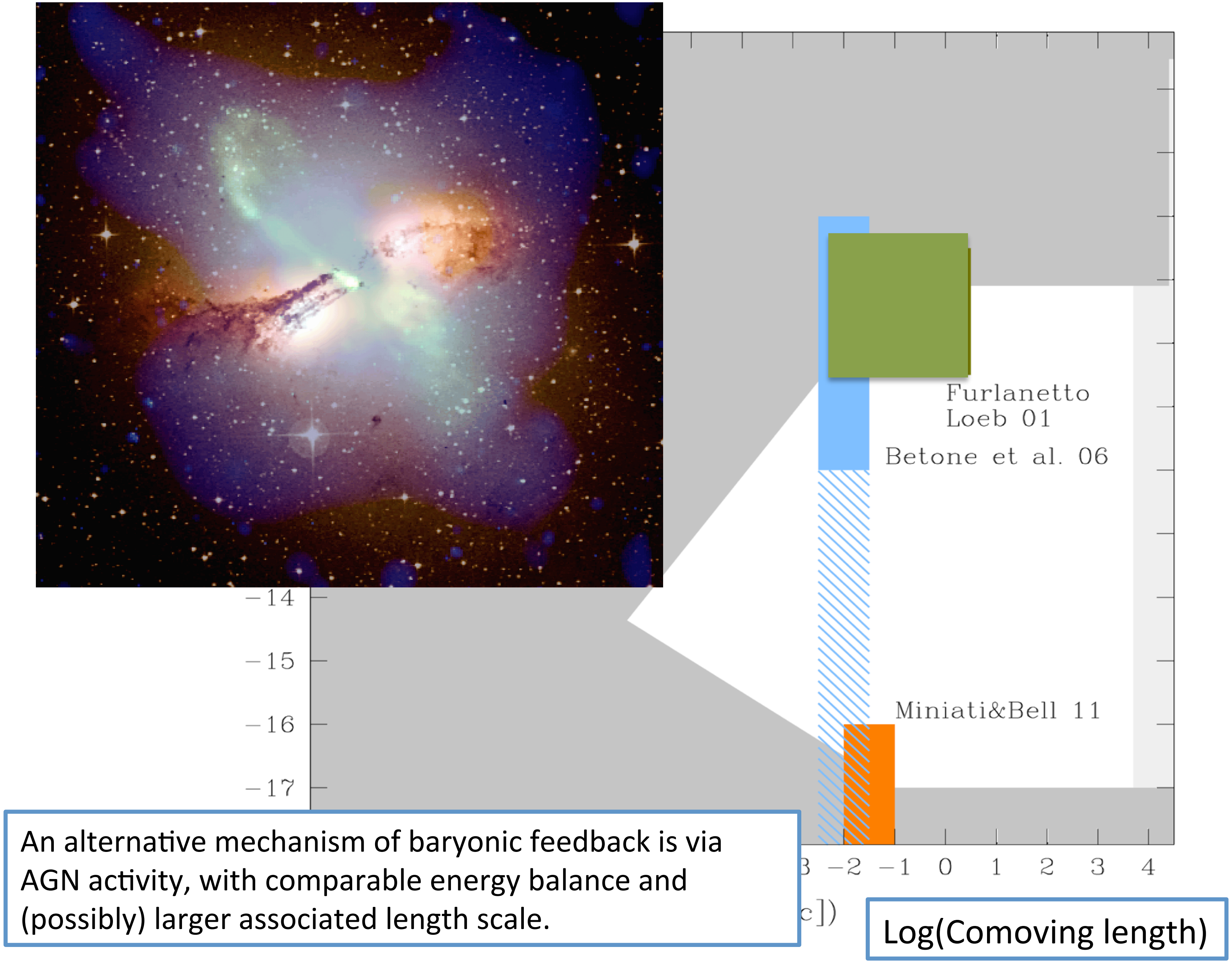
Miniati & Bell ‘01

… cosmic rays



Lacki '15

… AGN



An alternative mechanism of baryonic feedback is via AGN activity, with comparable energy balance and (possibly) larger associated length scale.

Rees ‘87, Daly&Loeb ’90, Furnaletto&Loeb ’01

… primordial magnetic fields

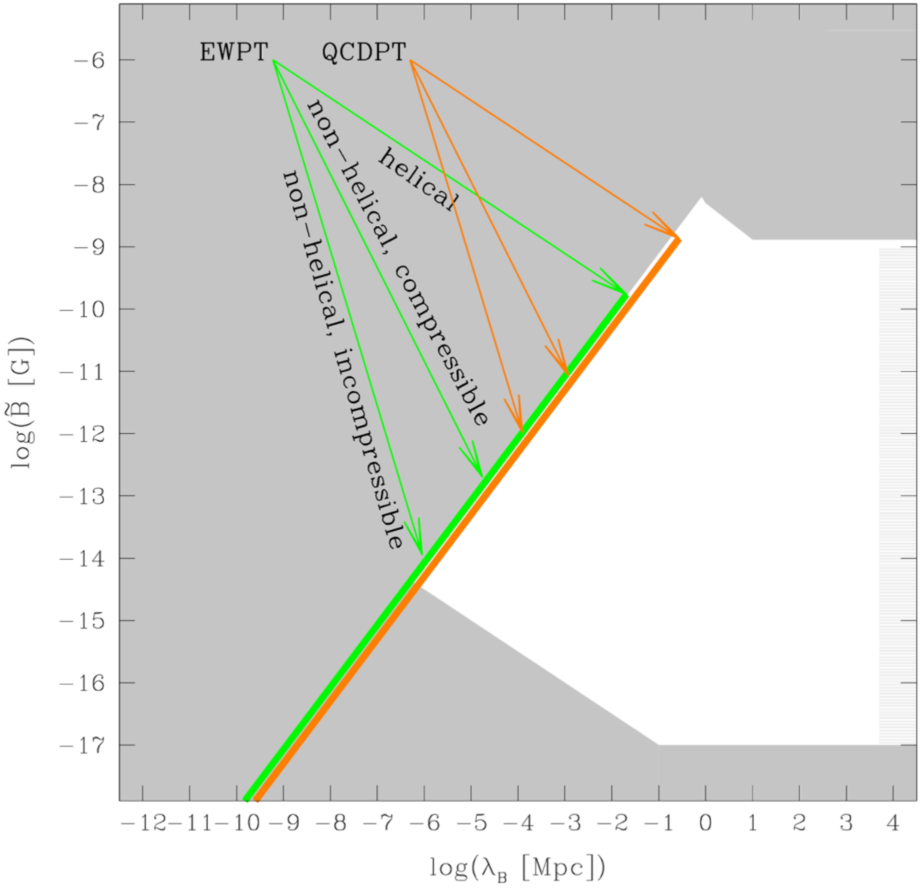
Generation of magnetic fields in cosmological conditions is possible only during phase transitions or during Inflation, when out-of-equilibrium processes lead to charge separation.

Amplification / decay of magnetic fields happens throughout the radiation dominated epoch, via transfer of energy between plasma and magnetic field.

The turbulent co-evolution of magnetic field and plasma naturally stops at the epoch of recombination / matter-radiation equality.
At this moment of time, the integral scale is

$$l \sim v t_{rec} \sim \sqrt{\frac{\rho_B}{\rho}}\, t_{rec} \sim 1 \left[\frac{B}{10^{-8}\ \mathrm{G}}\right] \mathrm{Mpc}$$

Relic magnetic fields are characterized by specific relation between their strength and correlation length. This could be used to distinguish them from the IGMF spread by galactic winds / AGN / cosmic rays.



Jedamzik & Sigl ‘12, Kahniashvili et al ‘13, Durrer & AN ‘13, …

Observational constraints on IGMF

Faraday rotation of signal from distant quasars

Polarization angle of electromagnetic wave Propagating though magnetized plasma rotates by an angle

$$\Psi = RM\,\lambda^2, \quad RM = \frac{e^3}{2\pi m_e^2}\int_{los}\frac{n_e B_{\|}}{(1+z)^2}dx$$

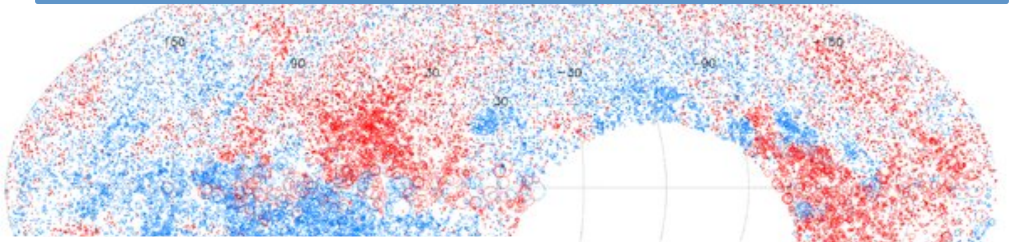
Knowing the distribution of electrons in the intergalactic medium (?) and measuring the RM one could measure $B_{\|}$.
The total RM is

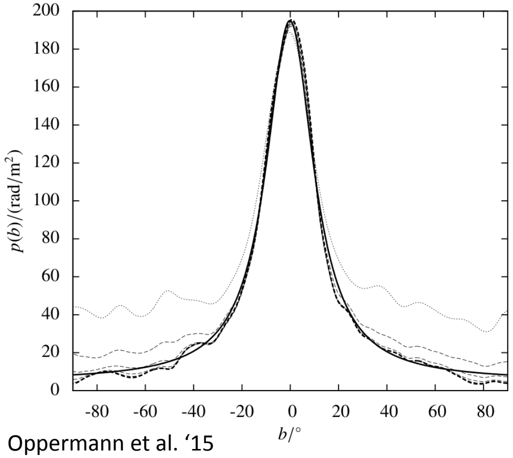
$$RM = RM_{Galactic} + RM_{IGM} + RM_{source}$$

RM from the intergalactic medium is a minor contribution to the overall RM.

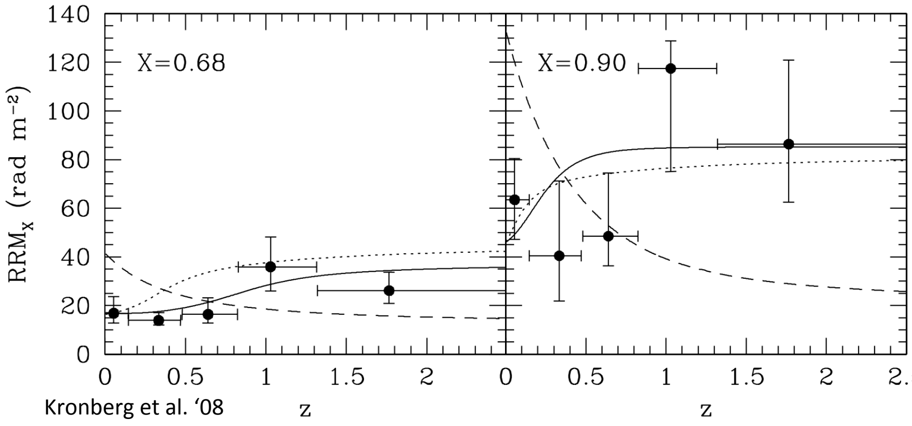
A possibility to single out the extragalactic RM on top of a much stronger Galactic RM would be to find a redshift dependence of the RM.

37000 RM measurements from NVSS survey, Taylor et al. '09



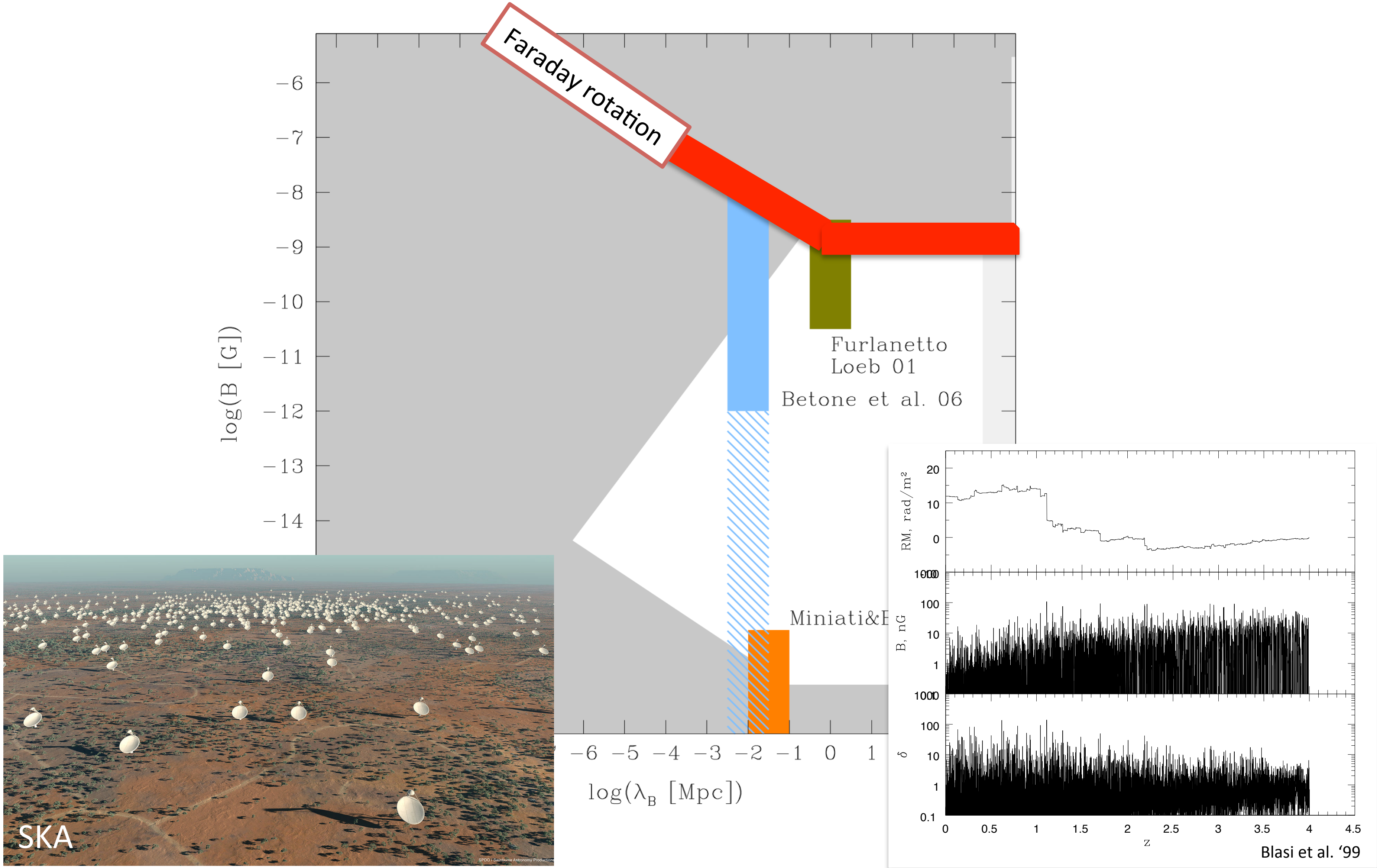


Oppermann et al. '15



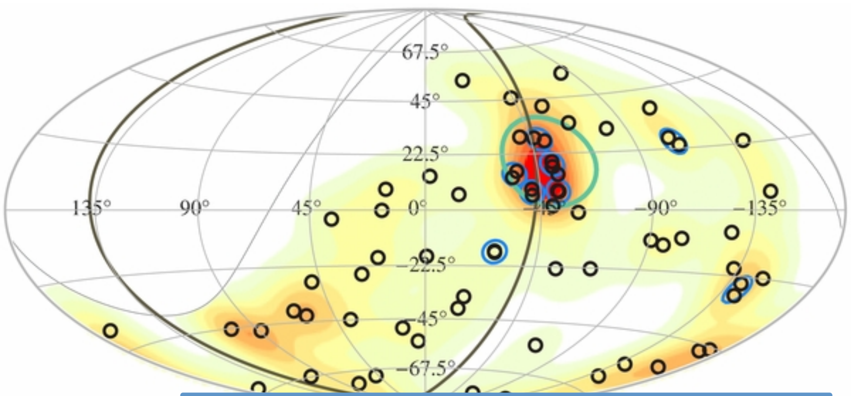
Kronberg et al. '08

Kronberg & Perry '84, Kronberg '94, Blasi et al. '99, Bernet et al., '10, …



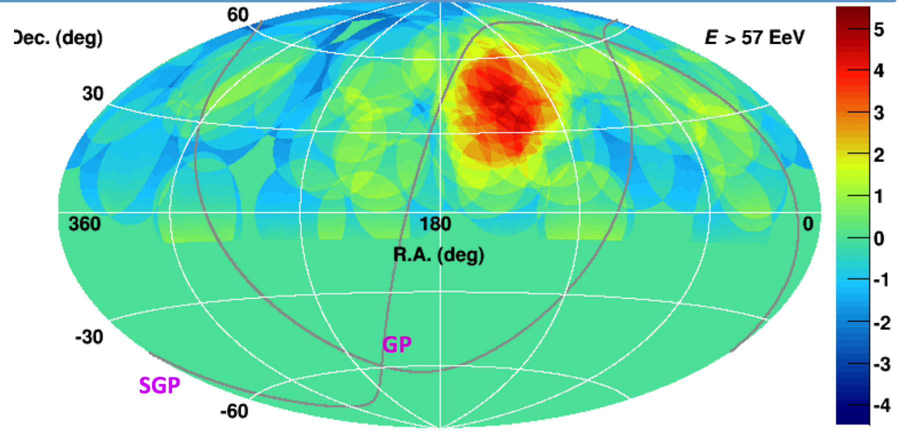
Blasi et al. ‘99

Deflections of UHECR



Pierre Auger Observatory
“hot spot” at 20° angular scale in the direction around Centaurus A, Abraham et al. ‘08

Telescope Array “hot spot” at 20° angular scale, Fukushima et al. ‘13



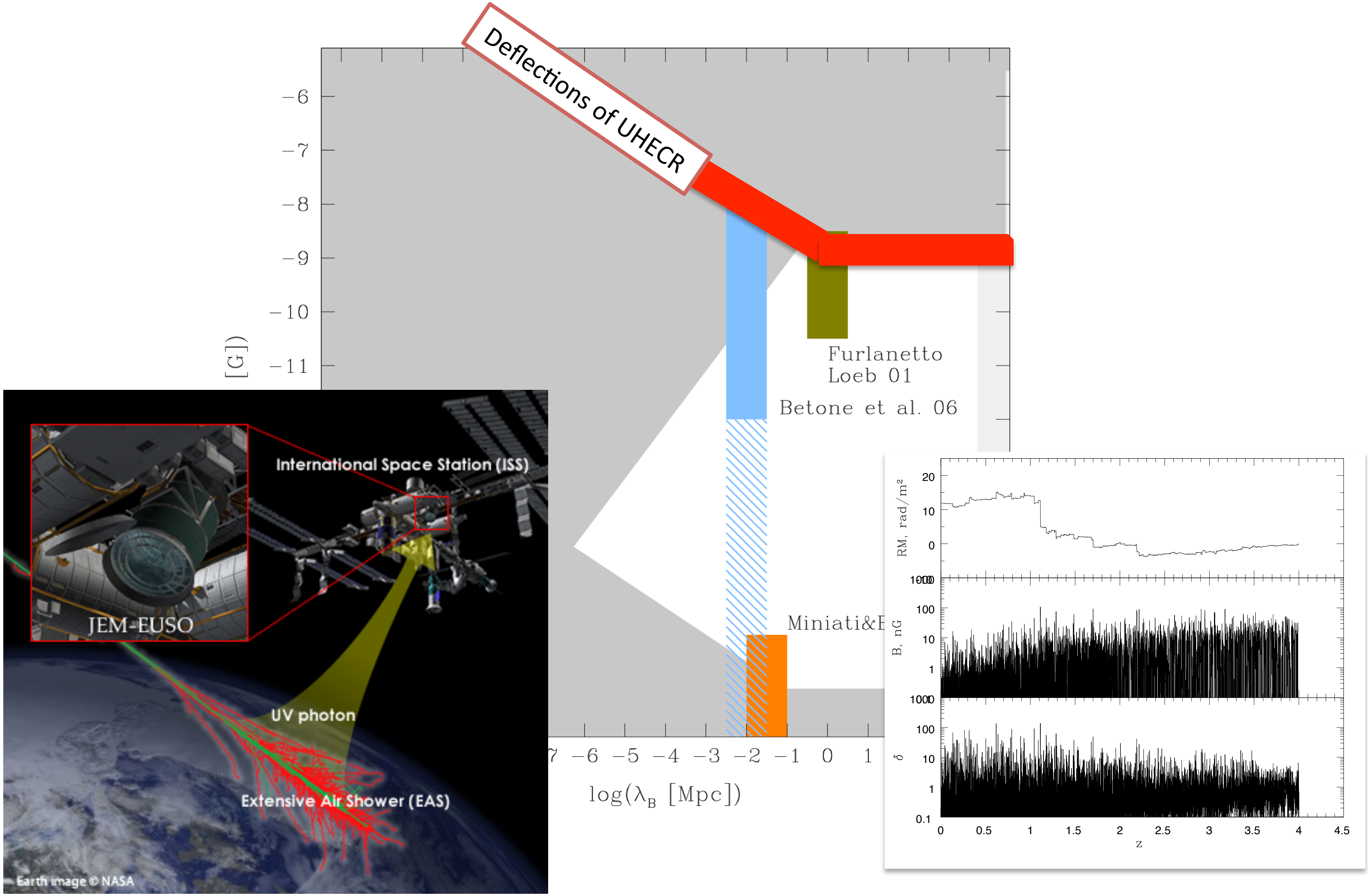
Trajectories of charged Ultra-High-Energy Cosmic Ray particles (UHECR) are deflected by Galactic and intergalactic magnetic fields. The deflection angle by intergalactic magnetic field with strength B and correlation length λ is

$$\theta = \frac{ZeB\sqrt{D\lambda}}{E_{UHECR}} \simeq 4^{o} Z \left[\frac{E_{UHECR}}{10^{20}\ \mathrm{eV}}\right]^{-1} \left[\frac{B}{10^{-9}\ \mathrm{G}}\right] \left[\frac{D}{50\ \mathrm{Mpc}}\right]^{1/2} \left[\frac{\lambda}{1\ \mathrm{Mpc}}\right]^{1/2}$$

Strong intergalactic magnetic field broadens angular distribution of UHECR around the direction of the source.

Measurement of the energy-dependent angular spread of UHECR around the source would provide a measurement of intergalactic magnetic field.

Deflections of UHECR

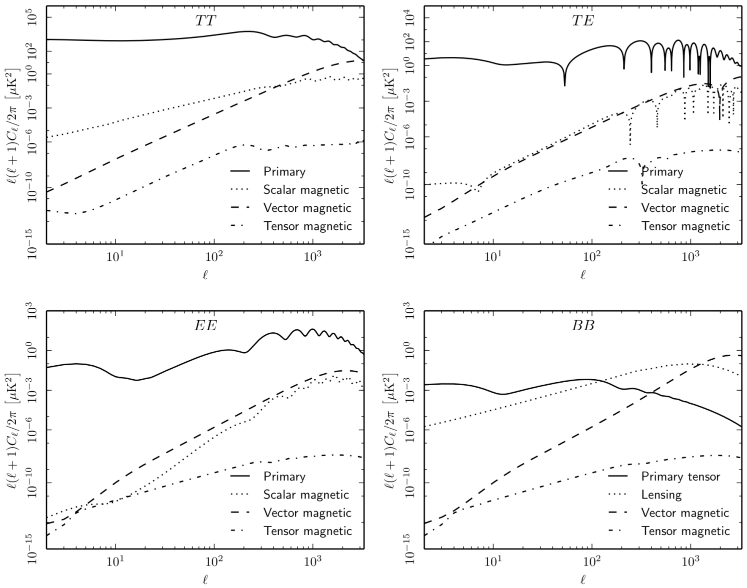


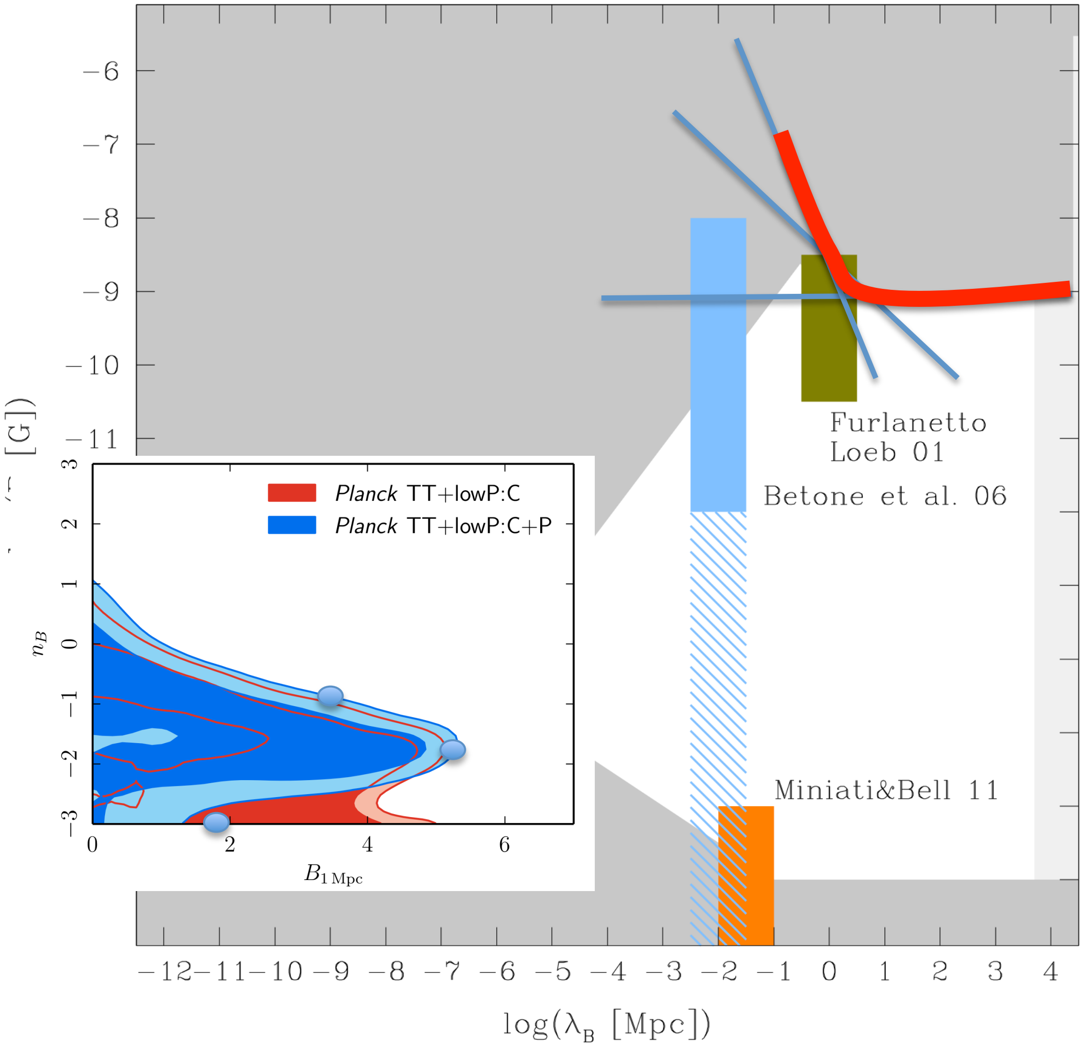
CMB

The energy density of magnetic field is

$$U_B \simeq 10^{-5} U_{CMB}\left[\frac{B}{10^{-8}\ \mathrm{G}}\right]^2$$

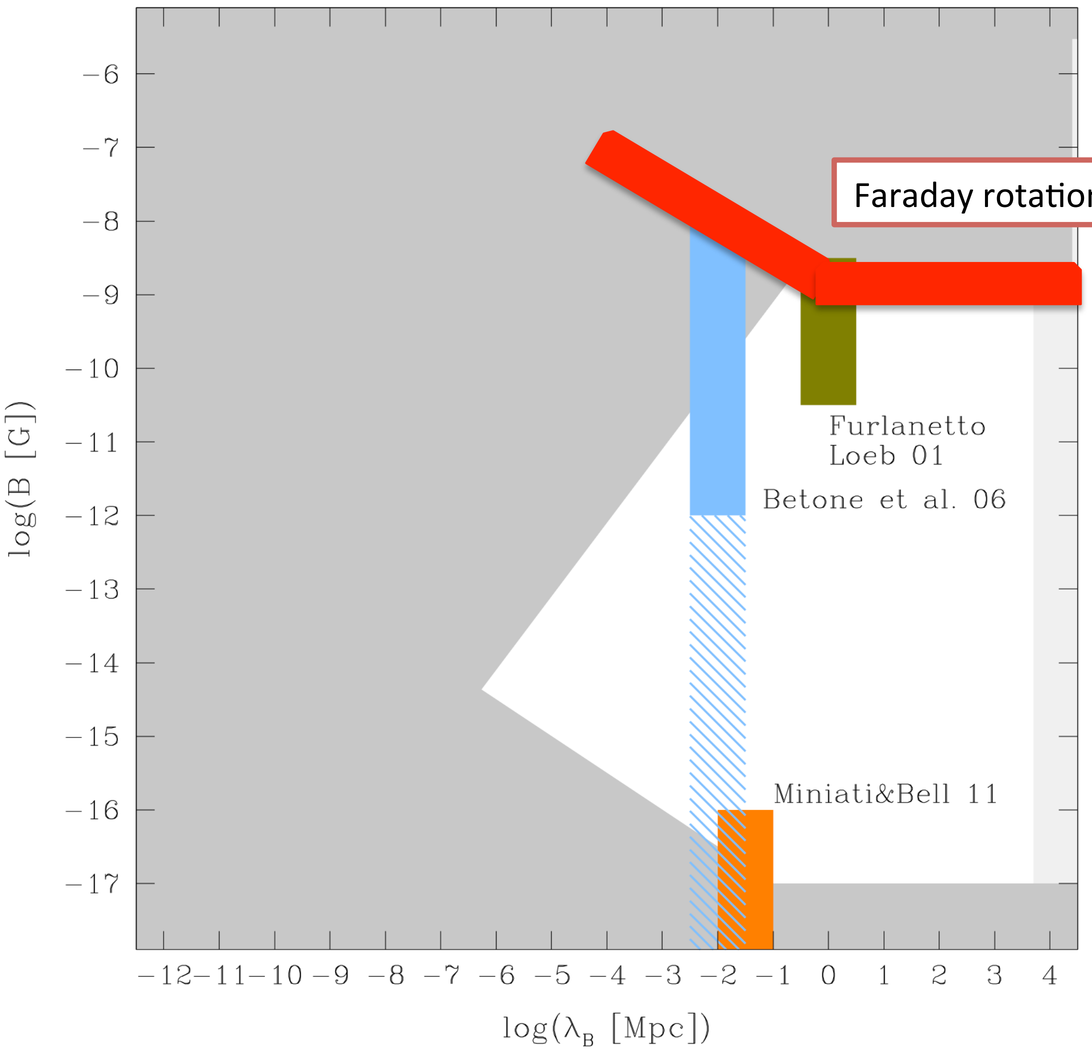
Strong enough cosmological magnetic field produces density / pressure perturbations produce strong enough scalar / vector / tensor perturbations which contribute to the CMB anisotropy.





Planck 2015 results, XIX

Summary of upper bounds



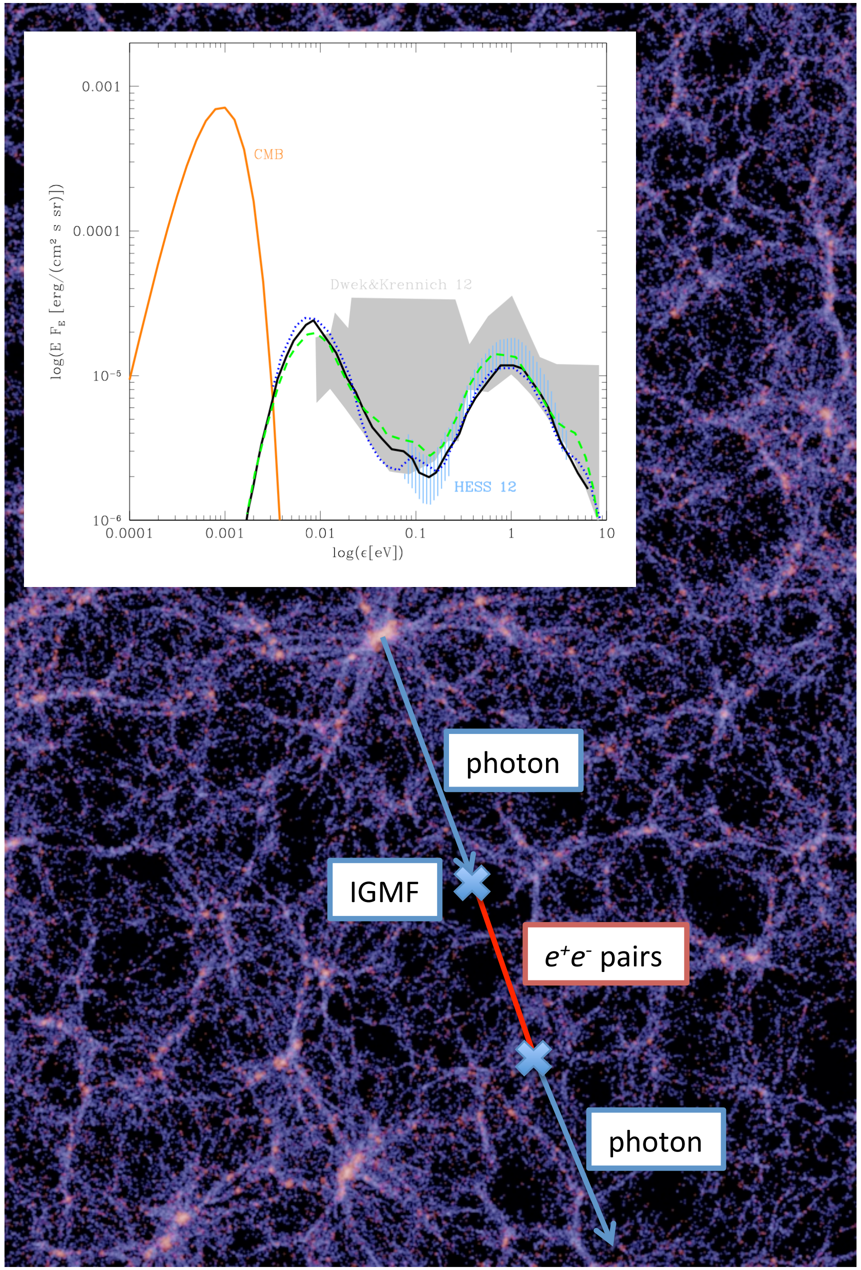
Faraday rotation, UHECR deflections, CMB

Lower bound from gamma-ray observations

High-energy gamma-rays from distant sources interact in the intergalactic medium producing electron positron pairs.

These pairs loose energy on secondary "cascade" gamma-ray emission, after being deviated by the intergalactic magnetic field.

Measurement of the spectral and timing characteristics of the secondary cascade emission provides information on intergalactic magnetic field strength.



Plaga '95, AN & Vovk '10, Tavecchio et al. '10, Dermer et al. '11 , ….

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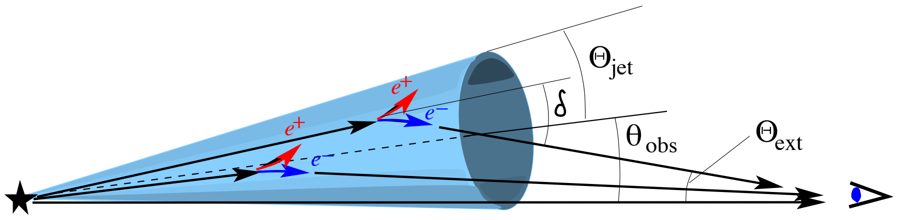
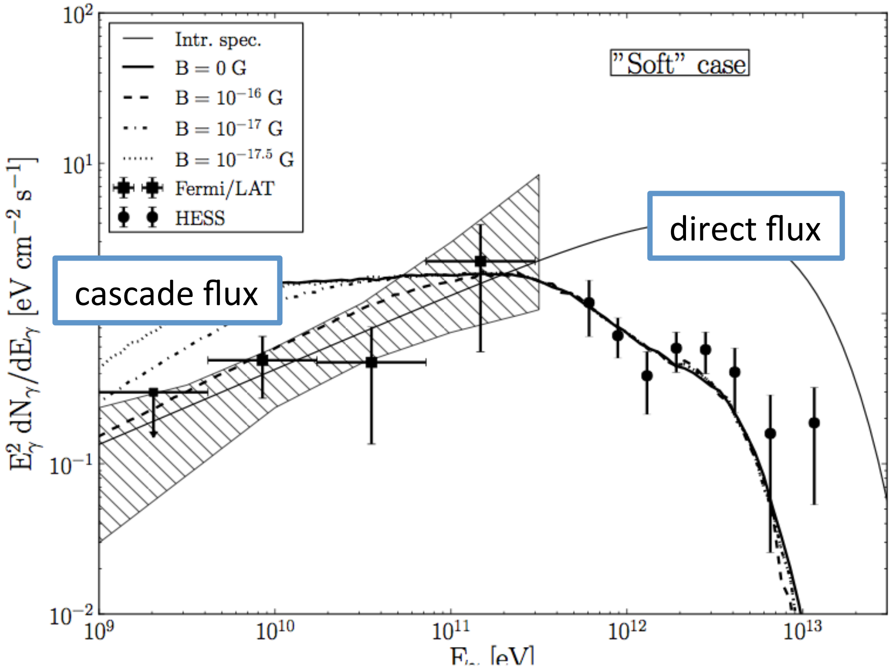
Non-observation of the cascade emission in the GeV band initiated by the pair production by TeV gamma-rays imposes a lower bound on the intergalactic magnetic field at the level of 10^{-17} G – 10^{-16} G.





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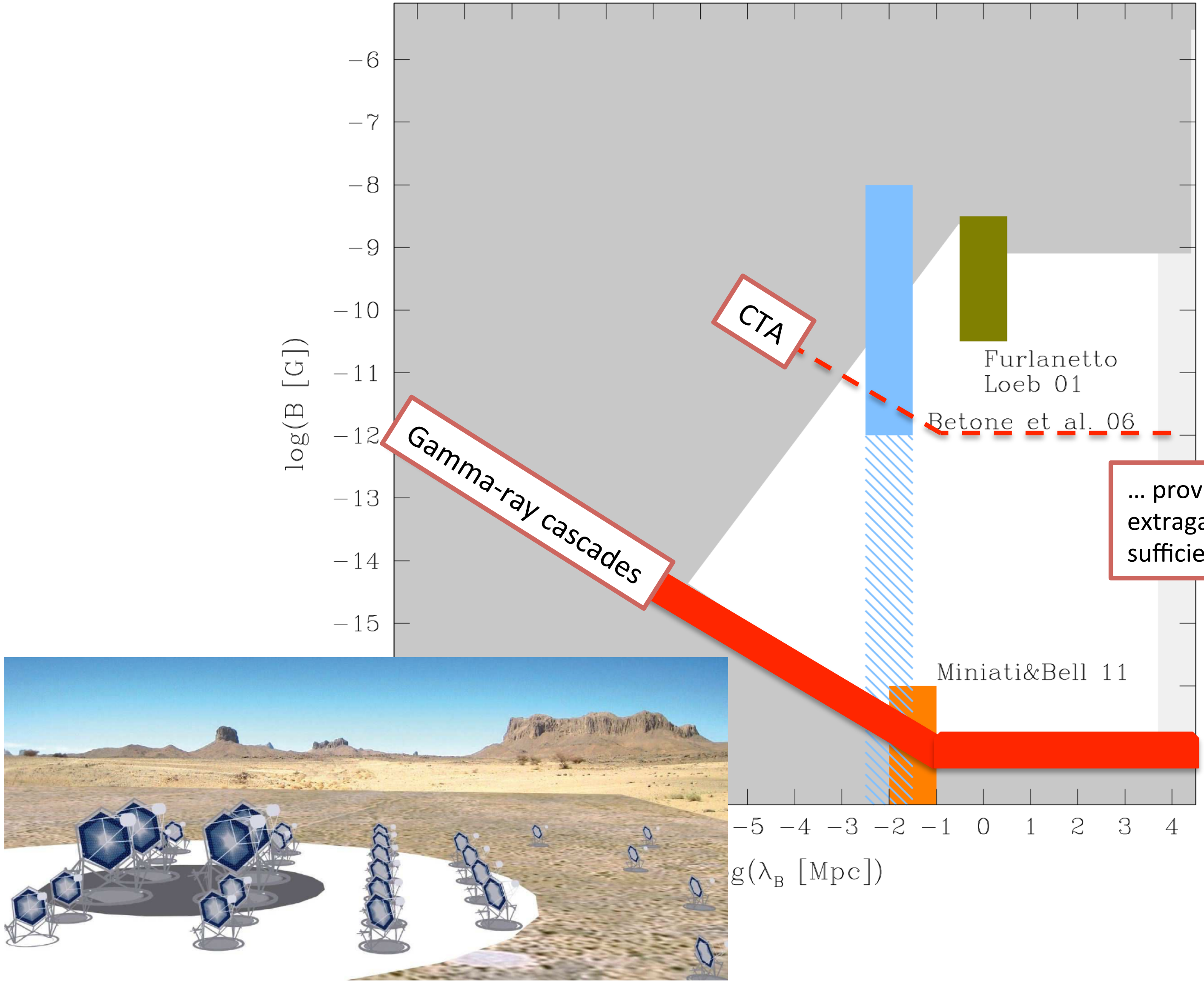


… provided that spectra of at least some extragalactic sources extend to sufficiently high energies….

Summary

Measurement of intergalactic magnetic field is important in the context of the problem of the origin of cosmic magnetic fields.

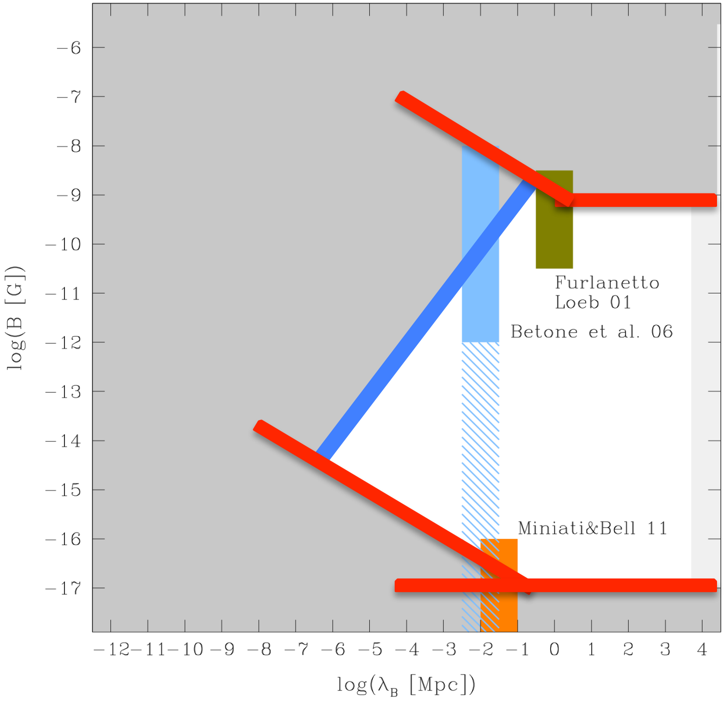
The properties of IGMF are determined either by the physical processes in the Early Universe or by the details of the process of galaxy feedback on the intergalactic medium.

Basic properties of intergalactic magnetic fields: correlation length and strength are constrained by observations in radio-to-gamma-ray bands.

IGMF of cosmological origin could be identified via a characteristic relation between its strength and correlation length, $B \approx 10^{-8} (\lambda/1\ \mathrm{Mpc})\ \mathrm{G}$.

IGMF spread by galactic winds, AGN and/or cosmic rays could span a wide range of strengths. It is expected to have correlation length in the 10 kpc – Mpc range.

Measurement of IGMF should be possible (but challenging) with the next generation gamma-ray and /or radio and/or microwave telescopes and/or detectors of UHECR.



Magnetic fields from Inflation

Generation (rather than *amplification*) of magnetic fields in cosmological conditions is possible only during phase transitions or during Inflation, when out-of-equilibrium processes lead to charge separation.

Inflation could, in principle, generate a scale-invariant field with

$$P_B(k) \sim k^{n_s}, \quad n_s = -3$$

However, there is no self-consistent model up to now, which results in such a field.

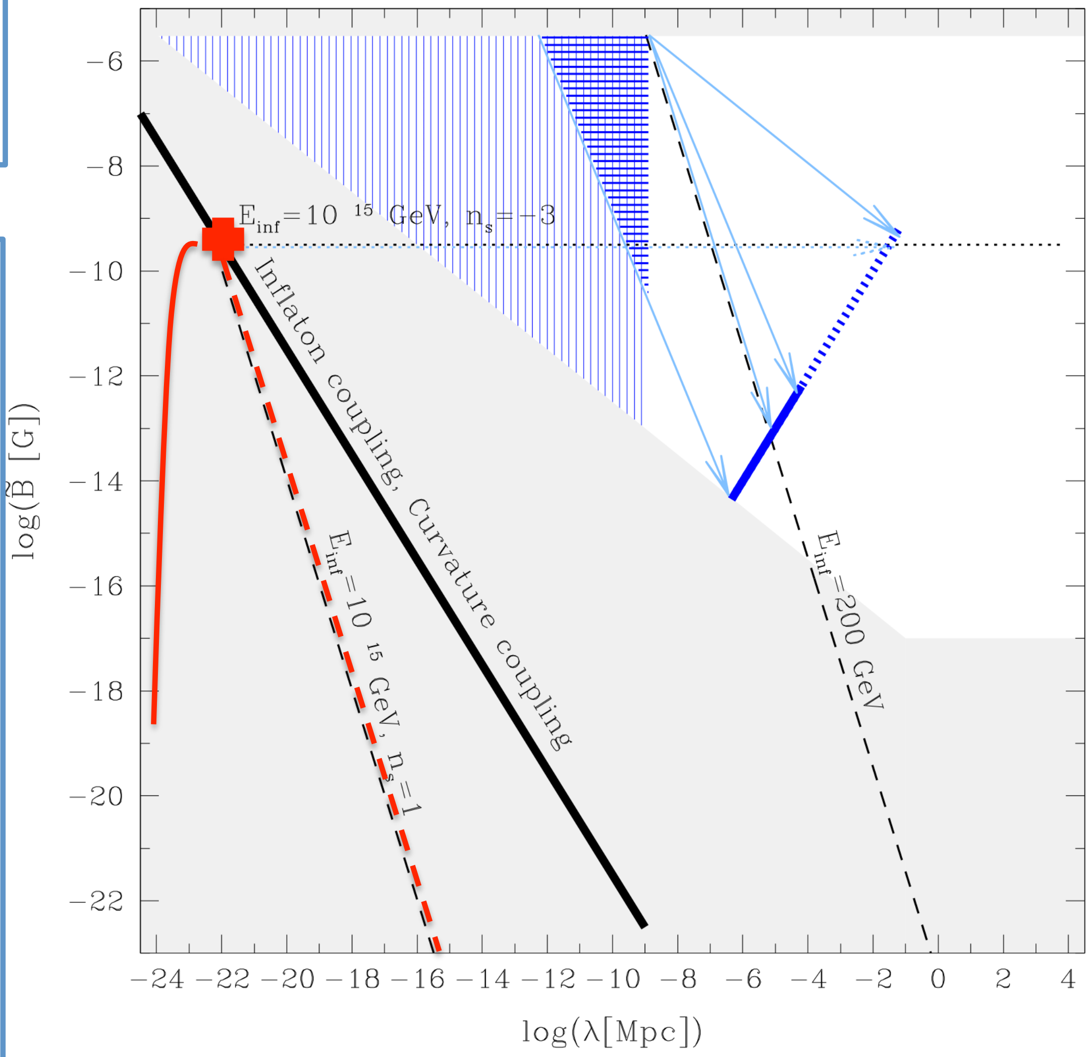
Most of the self-consistent models predict soft power spectrum with $n_s \geq 1$, peaking at a the comoving length scale

$$\lambda_B \sim t_{Inflation} \simeq 10^4 \left[\frac{H_{Inflation}}{10^{14}\ \mathrm{GeV}}\right]^{-1} \mathrm{cm}$$

and reaching the (comoving) field strength at this scale up to

$$B \sim 3\left[\frac{\rho_B}{\rho_{rad}}\right]^{1/2} \mu\mathrm{G} \sim 10^{-9}\left[\frac{H_{Inflation}}{10^{-3} M_{Pl}}\right] \mathrm{G}$$

At this scale.



Turner & Widrow '88, Ratra '92, Subramanian '10, Kunze '10, ……

Magnetic fields from phase transitions

Generation (rather than *amplification*) of magnetic fields in cosmological conditions is possible only during phase transitions or during Inflation, when out-of-equilibrium processes lead to charge separation.

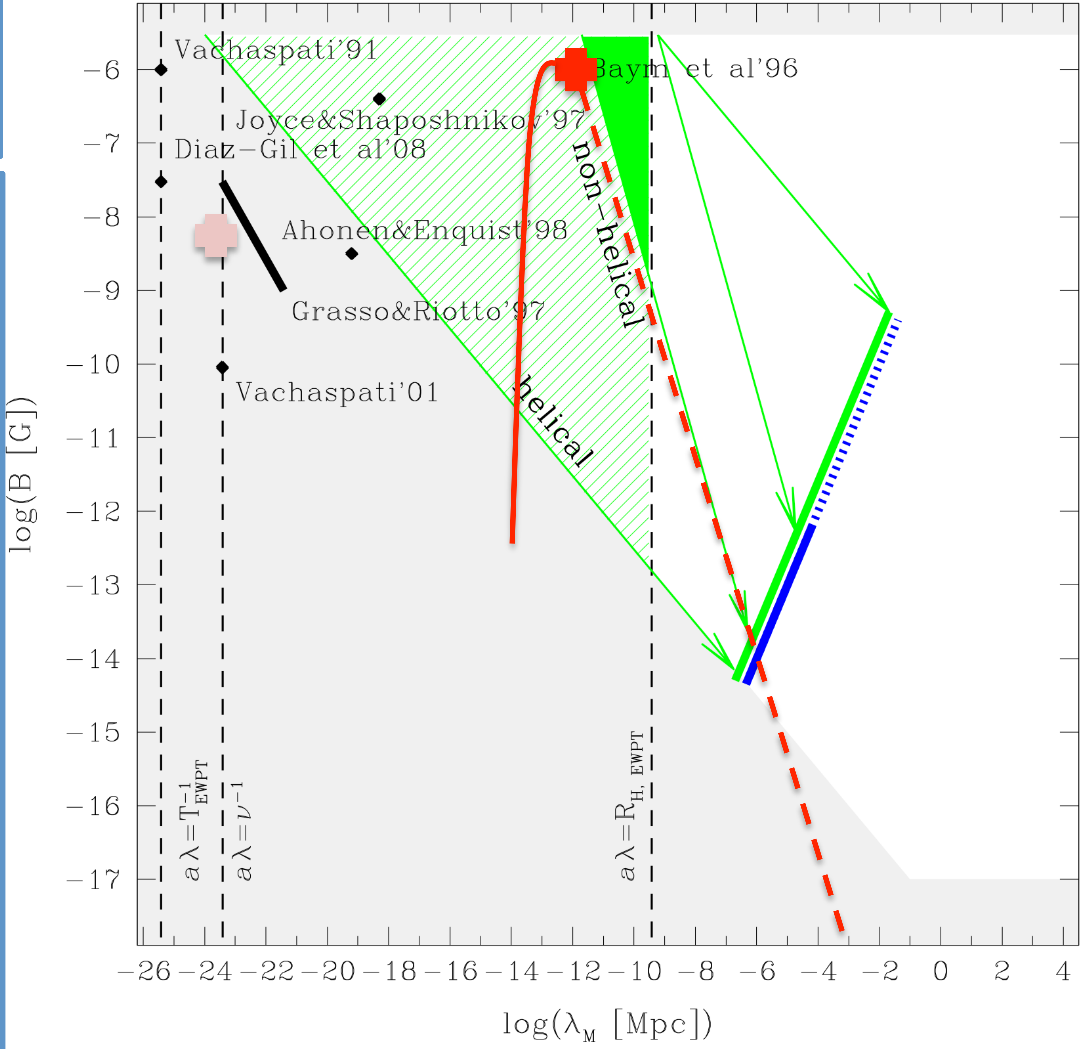
First order phase transitions are expected to proceed via bubble nucleation. Magnetic fields generated at the typical distance scale of the bubbles, which are a fraction of horizon size:

$$\lambda_B \sim \varepsilon t_{EW} \simeq 10^{14}\left[\frac{\varepsilon}{10^{-2}}\right]\left[\frac{E_{EW}}{10^2\ \mathrm{GeV}}\right]^{-1}\ \mathrm{cm}$$

Alternatively, a second-order phase transition or a cross-over would generate magnetic field on much shorter distance scale, $\lambda_B \sim T^{-1}$. Such field is quickly damped by Ohmic dissipation. Models resulting in the field strength up to the equipartition with radiation at this scale

$$B \sim 3\left[\frac{\rho_B}{\rho_{rad}}\right]^{1/2}\ \mu\mathrm{G}$$

Were proposed. Causality requirements limit the slope of the power spectrum to be $n_s \geq 2$.



Vachaspati '91, Enquist & Olesen '93, Kamionkowski et al. '94, Joyce & Shaposhnikov '97, Durrer & Caprini '03, ……

Magnetic fields from phase transitions

Generation (rather than *amplification*) of magnetic fields in cosmological conditions is possible only during phase transitions or during Inflation, when out-of-equilibrium processes lead to charge separation.

First order phase transitions are expected to proceed via bubble nucleation. Magnetic fields generated at the typical distance scale of the bubbles, which are a fraction of horizon size:

$$\lambda_B \sim \varepsilon t_{QCD} \simeq 10^{17}\left[\frac{\varepsilon}{10^{-2}}\right]\left[\frac{E_{QCD}}{10^2\ \mathrm{MeV}}\right]^{-1}\ \mathrm{cm}$$

Alternatively, a second-order phase transition or a cross-over would generate magnetic field on much shorter distance scale, $\lambda_B \sim T^{-1}$. Such field is quickly damped by Ohmic dissipation. Models resulting in the field strength up to the equipartition with radiation at this scale

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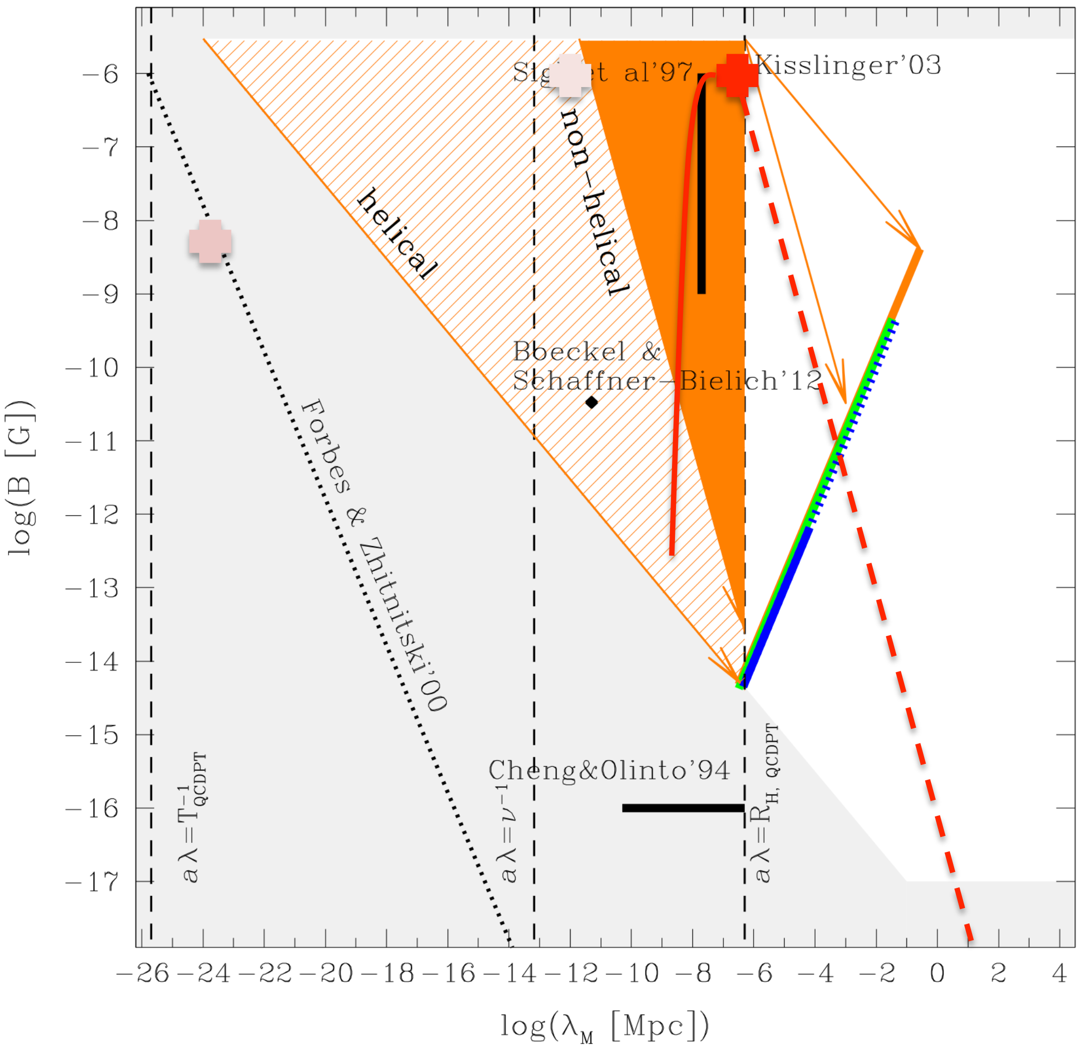
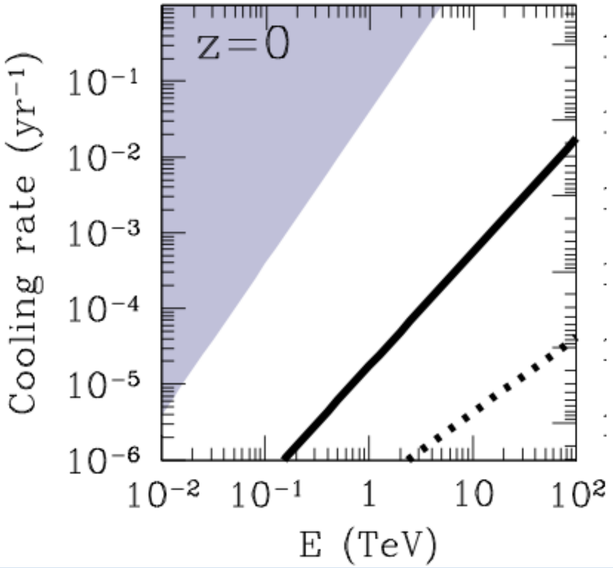


Vachaspati '91, Enquist & Olesen '93, Kamionkowski et al. '94, Joyce & Shaposhnikov '97, Durrer & Caprini '03, ……

Pair cascades and plasma instabilities



Directed flow of e^+e^- forms a beam which is potentially subject to an instability. Energy of e^+e^- could be dissipated via generation of Langmuir waves, rather than into inverse Compton emission.

In the linear approximation, the rate of growth of plasma instability is faster than the rate of the IC cooling

$$\frac{dW_{Langmuir}}{dt} = \gamma_{linear} W; \; \gamma_{linear} > \frac{1}{t_{ICS}}$$

Broderick et al. '11

The density of the e⁺e⁻ beam is very low, $n_{\rm beam} \sim 10^{-25}$ cm^{-3}. This is much lower than the density of the ionized non-relativistic intergalactic medium, $n_{\rm IGM} \sim 10^{-6}$ cm^{-3}, or of the ambient relativistic particles in the IGM, $n_{\rm CR} \sim 10^{-14}$ cm^{-3}. It is not clear if the analytical estimates of collective “plasma” effects are applicable in such regime.

Even if plasma physics calculations are applicable, the analytical estimates in linear regime of the instability growth have to make a number of simplifying assumptions, such as e.g. that of monoenergetic distribution of electrons in the beam, a particular shape of the angular distribution of particles etc. These assumptions are, strictly speaking, not valid. Controversial results are reported in different cases when one of the assumptions is relaxed.

Linear growth rate of the instability is not applicable in regime when the instabilities are supposed to remove energy from the beam. The behaviour of instabilities in the non-linear regime is not known.

Tsytovich & Shapiro '65; Miniati & Elyiv '12; Schlickeiser et al. '12

A way to avoid simplifying analytical parametrizations is to go to PIC simulations. A first attempt in this direction shows that there are quasi-linear relaxation effects which suppress the growth rate of instability by orders of magnitude making it energetically insignificant.

Sironi & Giannos ‘13