Intergalactic magnetic fields

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Overview

Propagation of very-high-energy gamma-rays and the role of intergalactic magnetic field (IGMF)

Lower bound on IGMF from existing gamma-ray data

Perspectives for the measurement of IGMF strength and correlation length with next generation gamma-ray telescopes

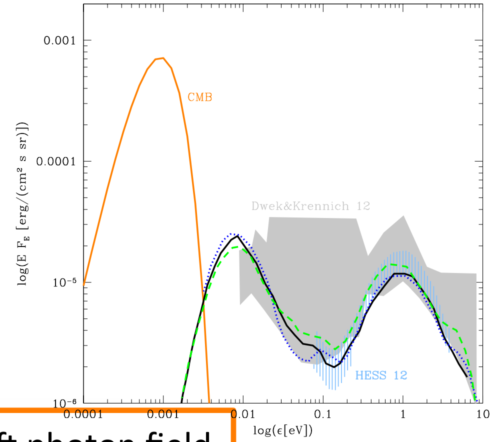
Physics of IGMF:

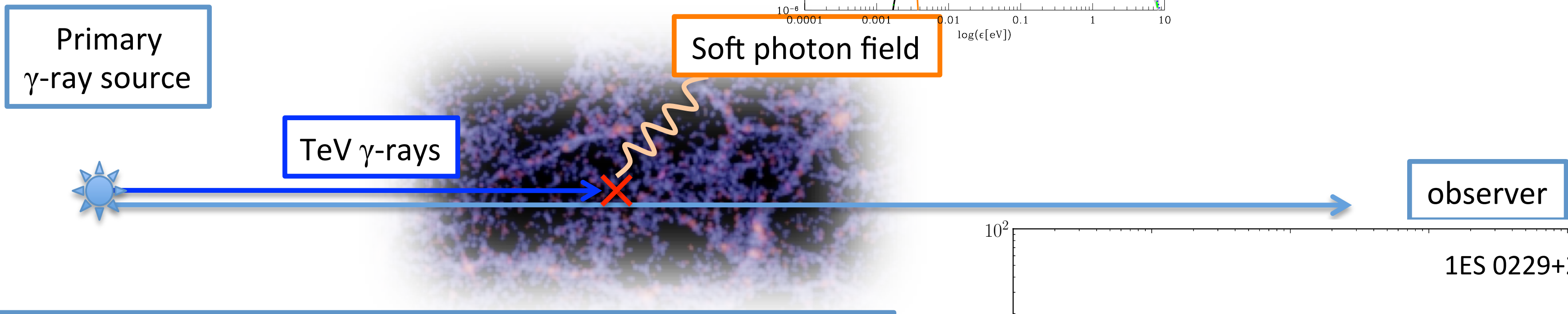
- Problem of the origin of cosmic magnetism
- Cosmological magnetic fields
- Magnetic fields from galactic winds

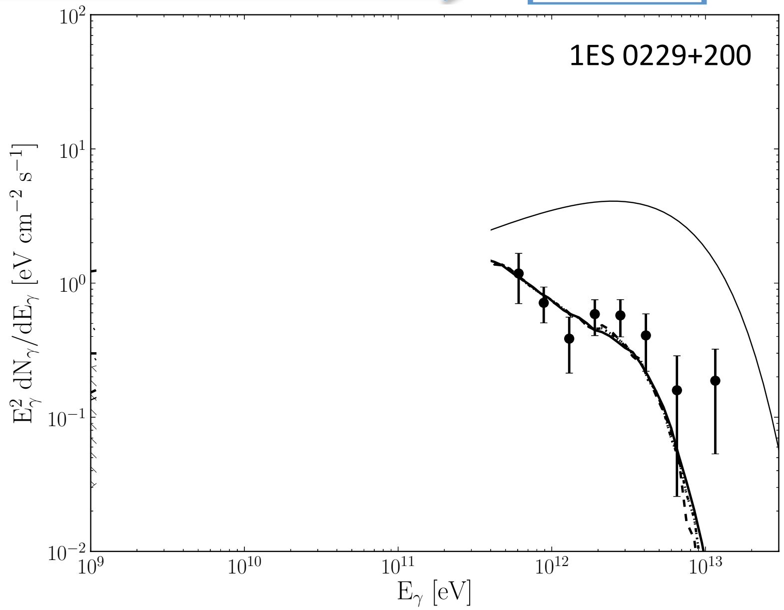
Complementary techniques for the measurement of magnetic fields

Summary

Propagation of VHE gamma-rays through IGM



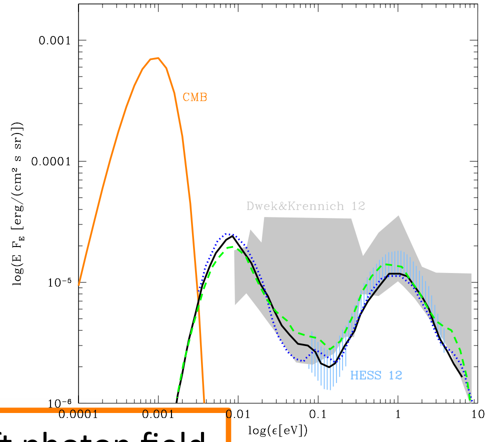


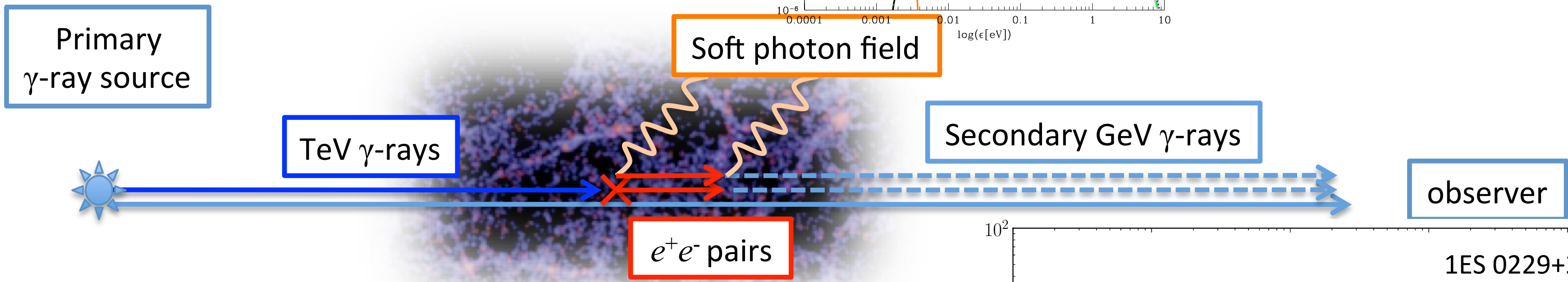


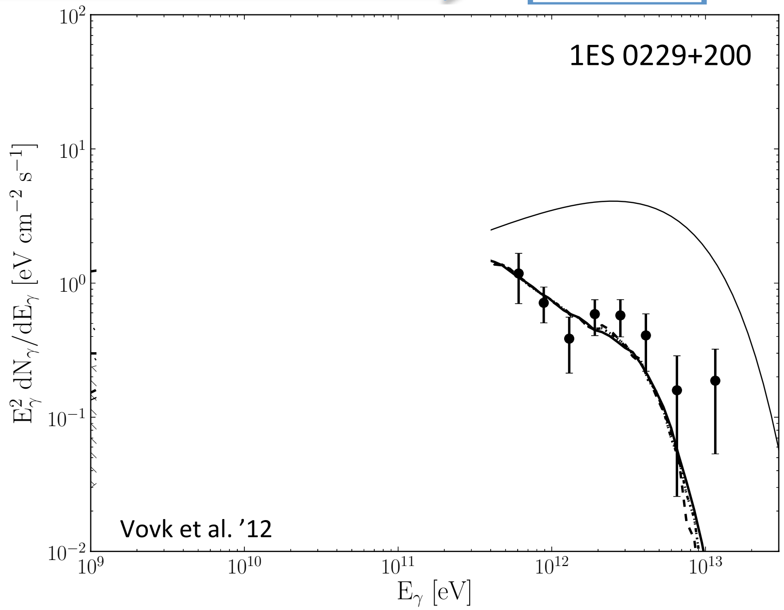
Gamma-rays with energies above 0.1 TeV are absorbed in interactions with the EBL photons during their propagation through the intergalactic medium (IGM).

This leads to the observed effect of suppression of the flux from extra-galactic sources in the very-high-energy (VHE) band.

Propagation of VHE gamma-rays through IGM





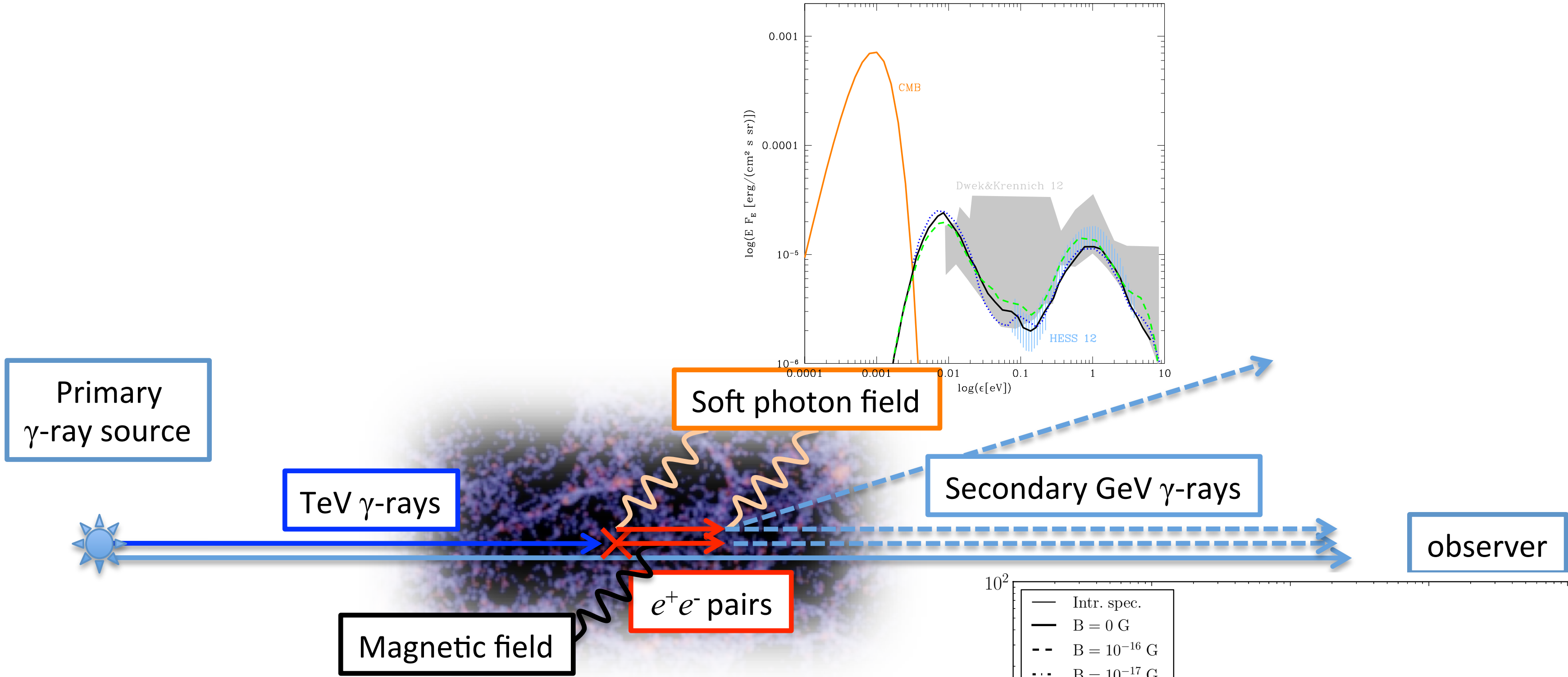


Absorption of VHE γ-rays leads to deposition of e^+e^- pairs in the IGM.

e^+e^- pairs loose energy via inverse Compton scattering of Cosmic Microwave background photons.

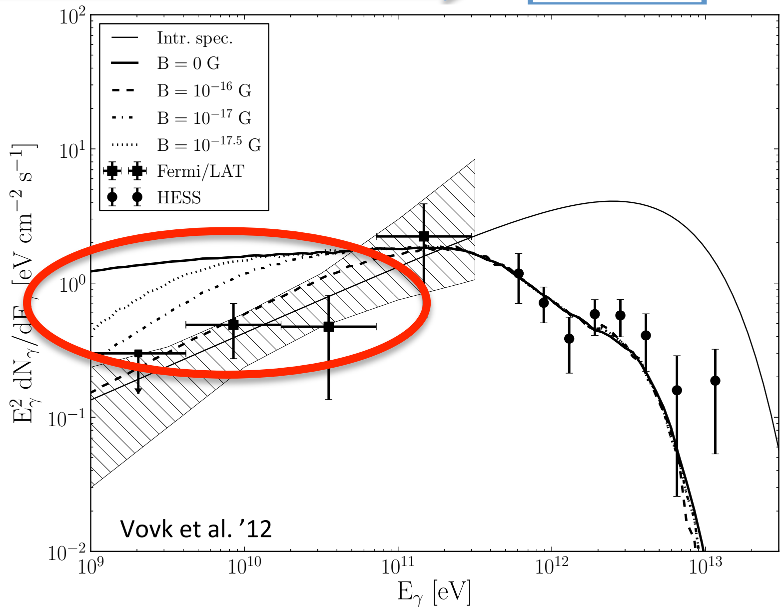
Secondary inverse Compton γ-rays should be detectable (almost) from the direction of the source if there are no magnetic fields which deflect electrons/positrons.

Propagation of VHE gamma-rays through IGM

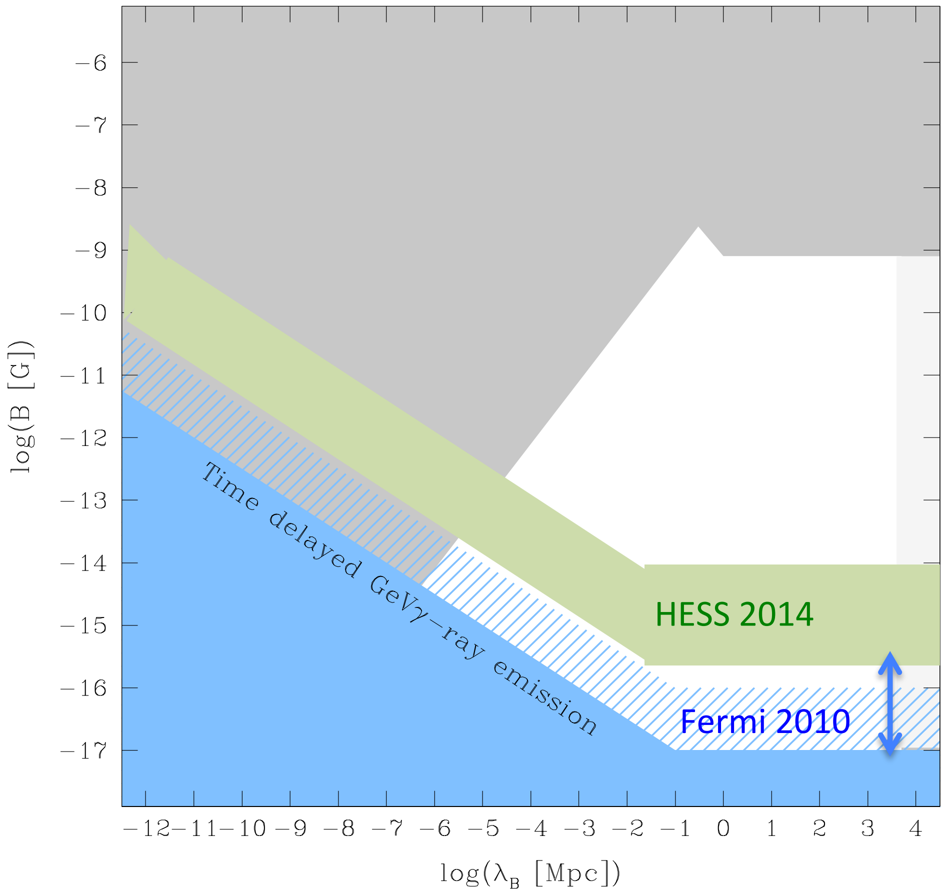


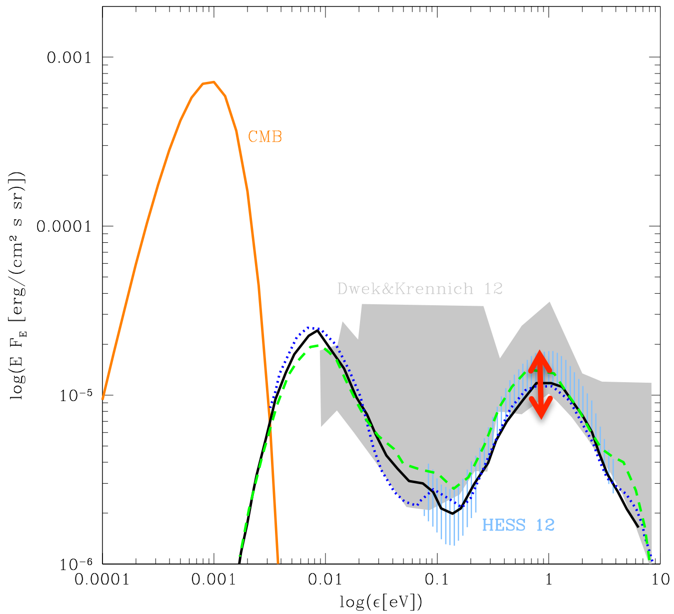
Strong enough magnetic field suppresses secondary inverse Compton signal from the direction of parent point source.

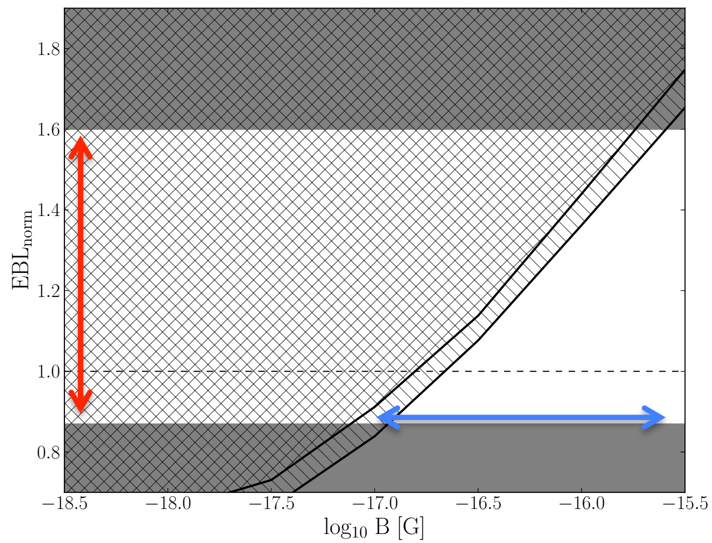
Non-detection of GeV-band secondary inverse Compton emission from a set of TeV γ-ray-loud blazars suggests the presence of non-zero magnetic field in the IGM.



Lower bound on IGMF





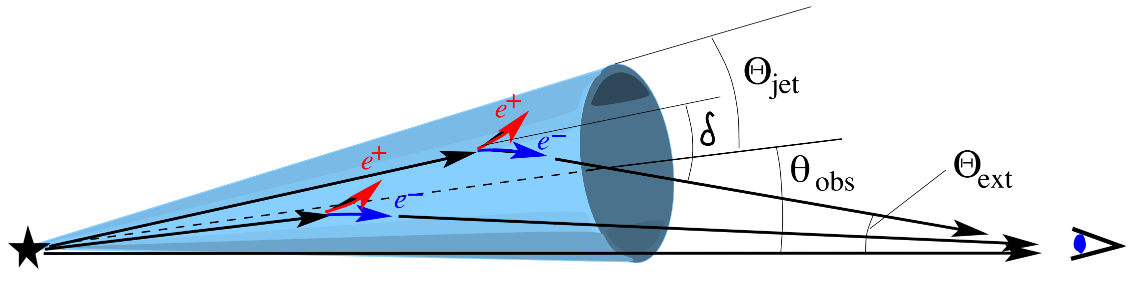


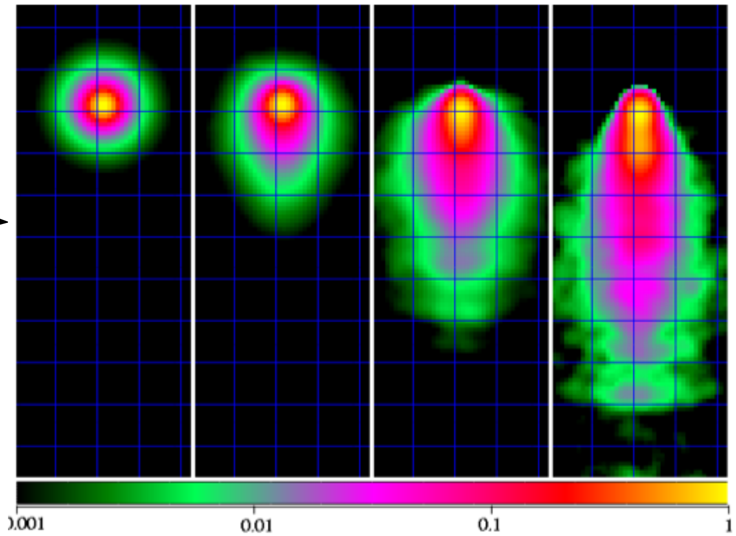
To suppress the secondary GeV emission, the intergalactic magnetic field (IGMF) should be at least 10^{-17} (10^{-14}) G

Uncertainty in normalization of EBL introduces an uncertainty in the level of the lower bound on IGMF strength.

Abramowski et al. '14; AN & Vovk '10; Taylor et al. '11; Dermer et al. '11; Tavecchio et al. '11; Vovk et al. '12

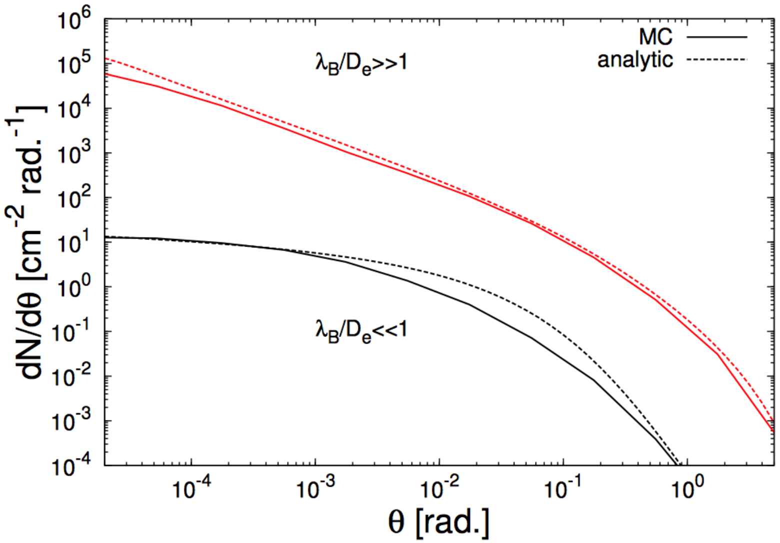
Extended emission around distant blazars





Secondary γ-rays travel along different path than direct γ-rays from the source.

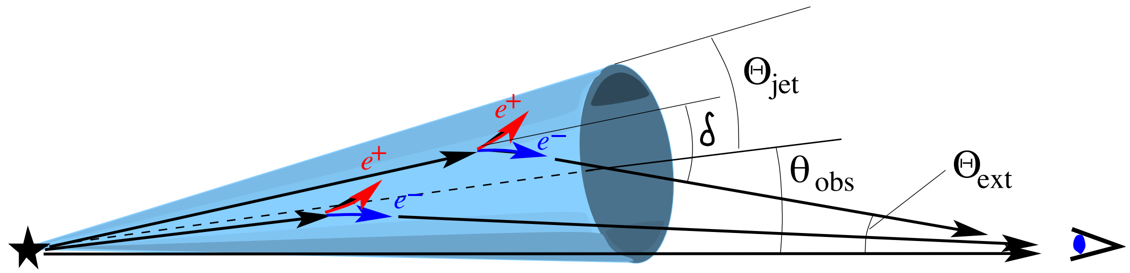
Secondary signal appears, in general, as extended emission around an initially point source.

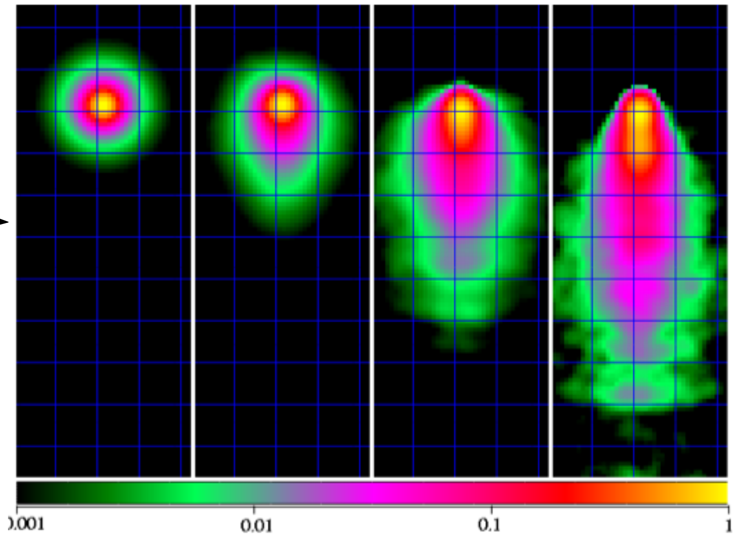


Size of the extended source grows with the increase of B. Measurement of the *size and brightness profile of extended source* provides a possibility to measure B and λ_B separately.

AN et al. '10, 13

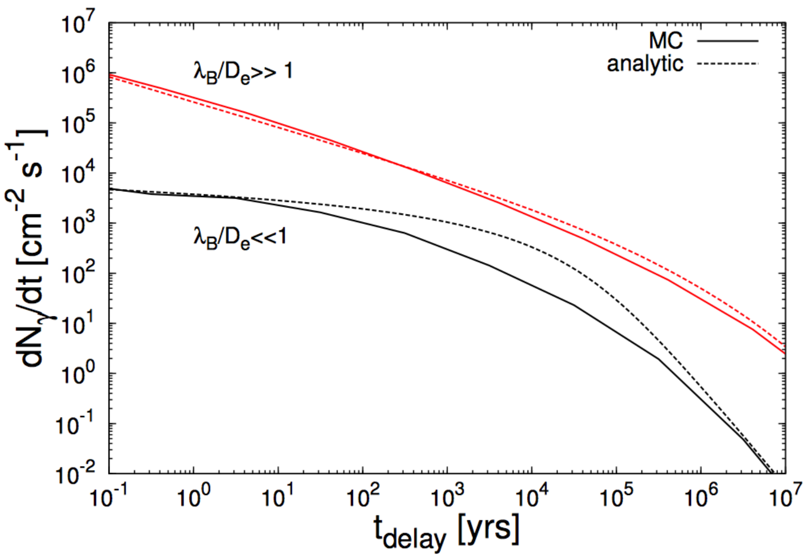
Delayed emission from blazar flares





Secondary γ-rays travel along different path than direct γ-rays from the source.

Secondary signal is delayed compared to the direct source signal.



Time delay of the secondary emission grows with the increase of B. Measurement of the *decay time and slope of lightcurve* of delayed emission provides a possibility to measure B and λ_B separately.

Plaga '95; Murase et al. '08; AN et al. '13

Toward detection of / improved limits on IGMF with CTA

Absorption of E_0~10 TeV γ-rays leads to generation of secondary extended / time delayed emission at E_1~0.1 TeV.

Precise knowledge to the **time-averaged** flux / spectrum of blazars in the **10 TeV** range is needed for a reliable prediction of the amount of secondary emission in the 100 GeV band.

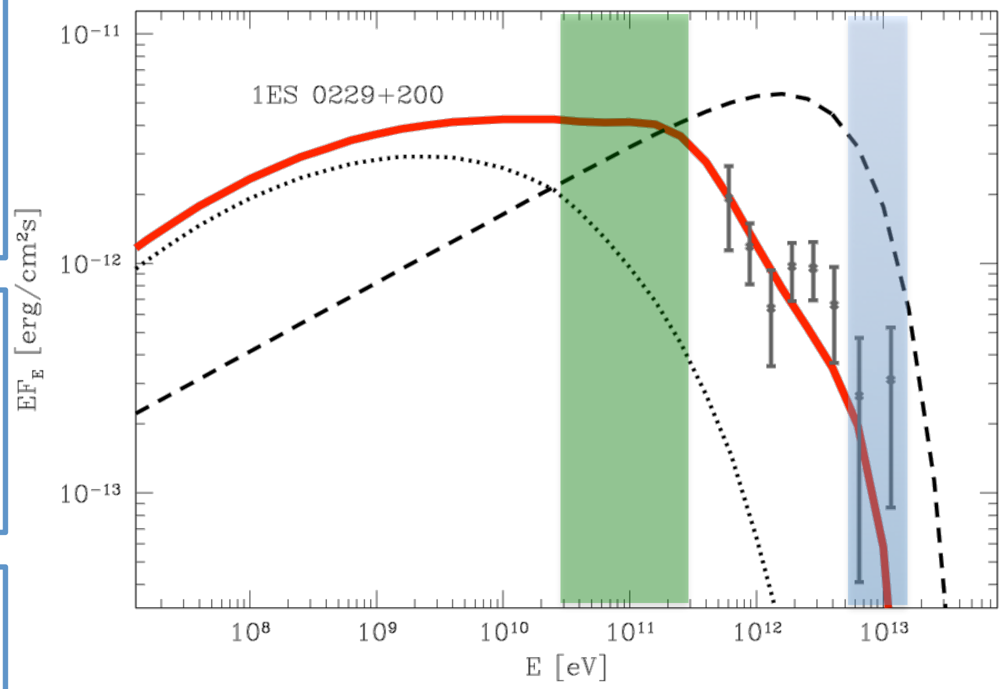
➔ *long term monitoring with CTA/SST, HAWC*

Precise characterisation of EBL is needed to remove the overall uncertainty of normalization of the secondary emission component.

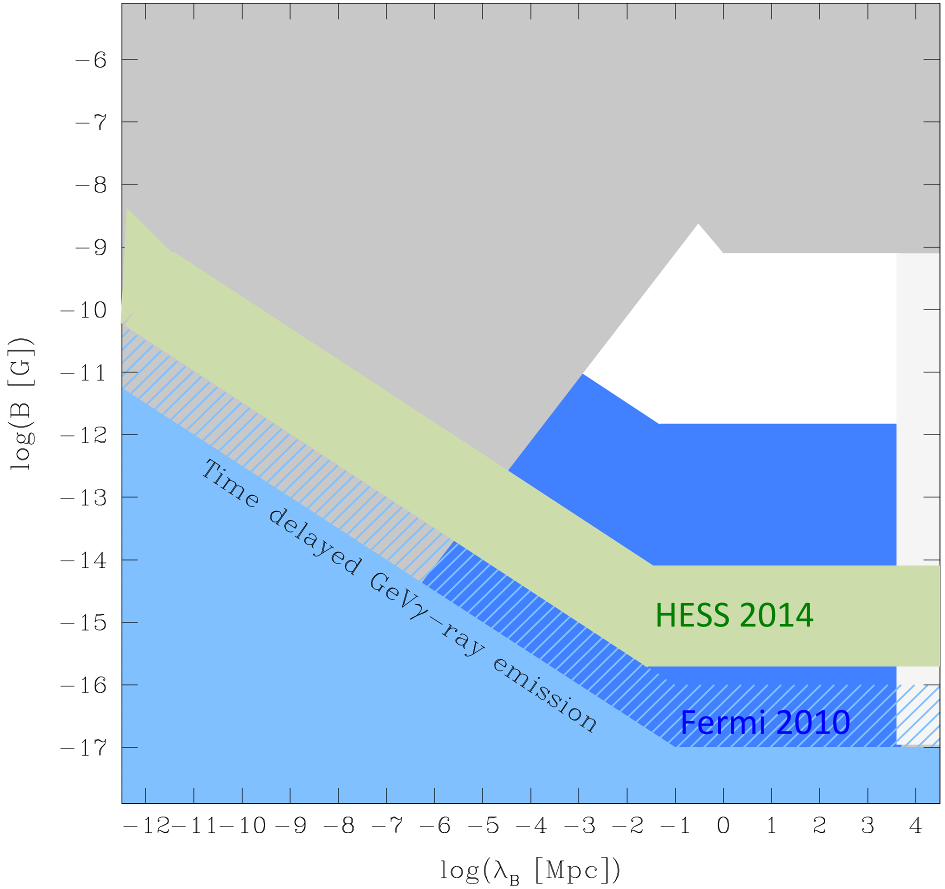
➔ *deep exposures with CTA/LST+MST+SST*

Narrow PSF and high sensitivity in the 10-100 GeV band are needed to detect sub-dominant extended / time delayed emission with strongly energy-dependent size / lightcurve.

➔ *deep exposures with CTA/LST and / or next-generation space telescopes (HERD?)*



Future perspectives with CTA



Next-generation telescopes, like CTA, could potentially provide not only bounds, but measurements of IGM magnetic fields, if their strength is below $\sim 10^{-12}$ G.

Detection of IGMF characteristics would provide new insights into

- origin of cosmic magnetic fields,
- physics of the Early Universe,
- baryonic feedback on structure formation

Problem of the origin of cosmic magnetic fields

All known types astronomical sources possess magnetic fields:

* Stars : $B \sim 1 - 10^3$ G (e.g. Sun)
  $B \sim 10^{12} - 10^{15}$ G (neutron stars)
* Planets : $B \sim 1$ G (e.g. Earth)
* Galaxies : $B \sim 10\ \mu$G (e.g. Milky Way)
* Galaxy clusters : $B \sim 1\ \mu$G

Ubiquity of cosmic magnetic fields is due to the common presence of charged particles forming high-conductivity plasma in astrophysical environments.

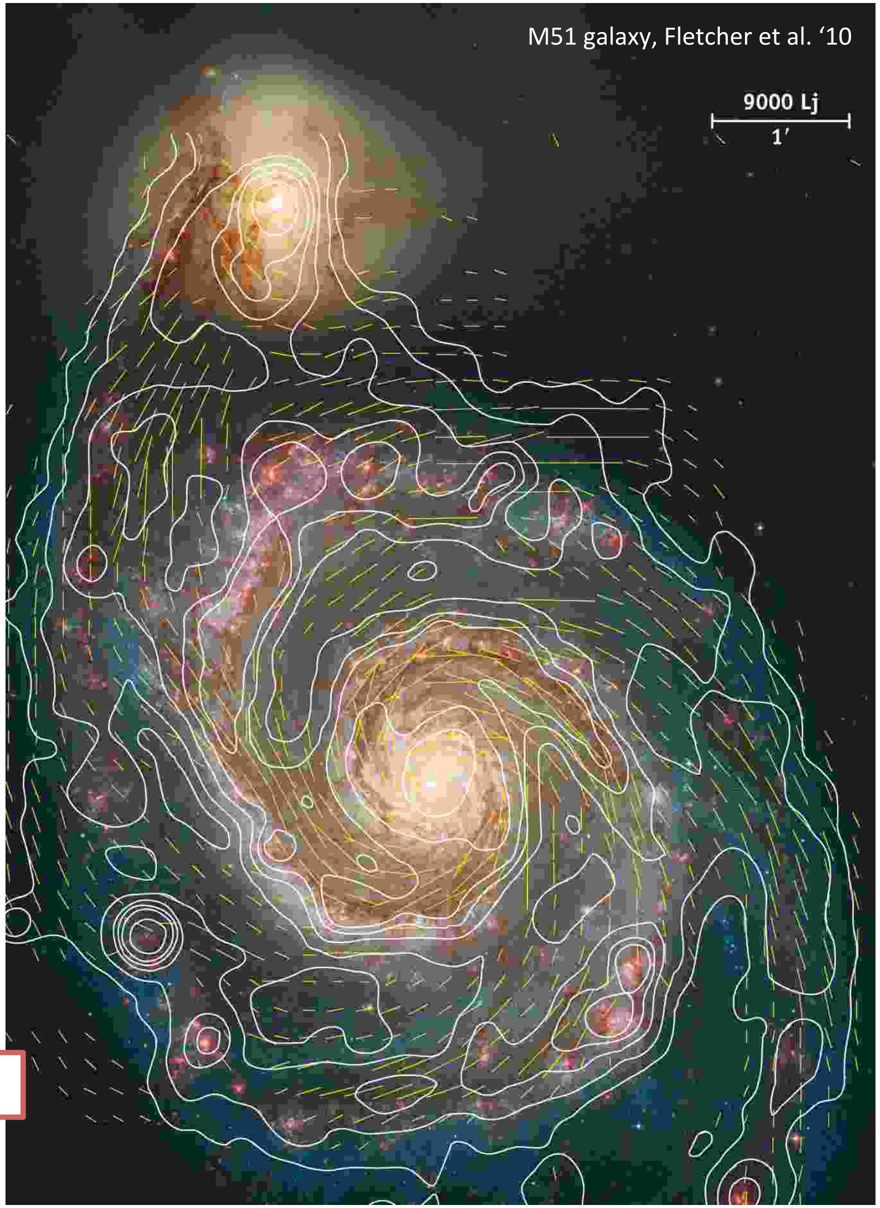
Magnetic field – charged plasma dynamics is typically governed by non-linear MHD equations:

Non-linearities / turbulence

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

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

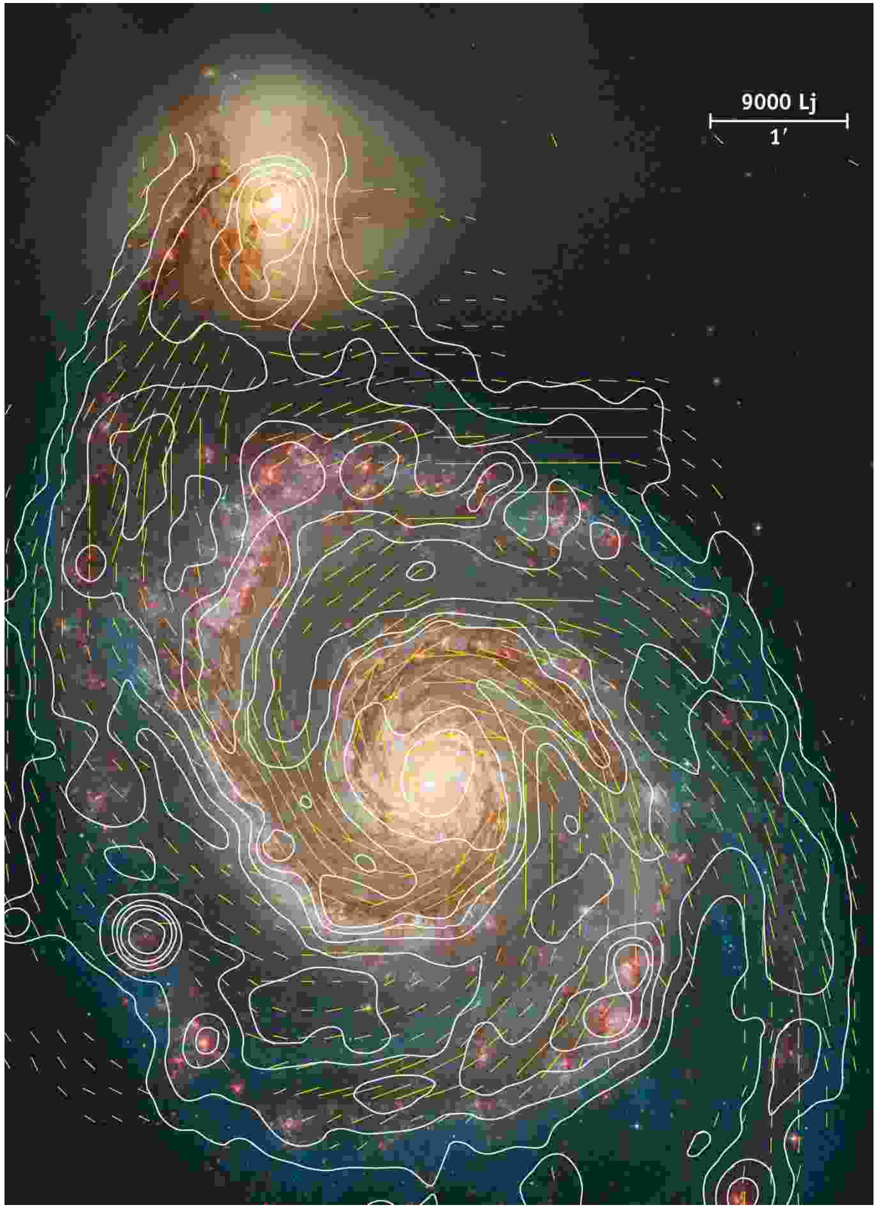
Small scale dumping



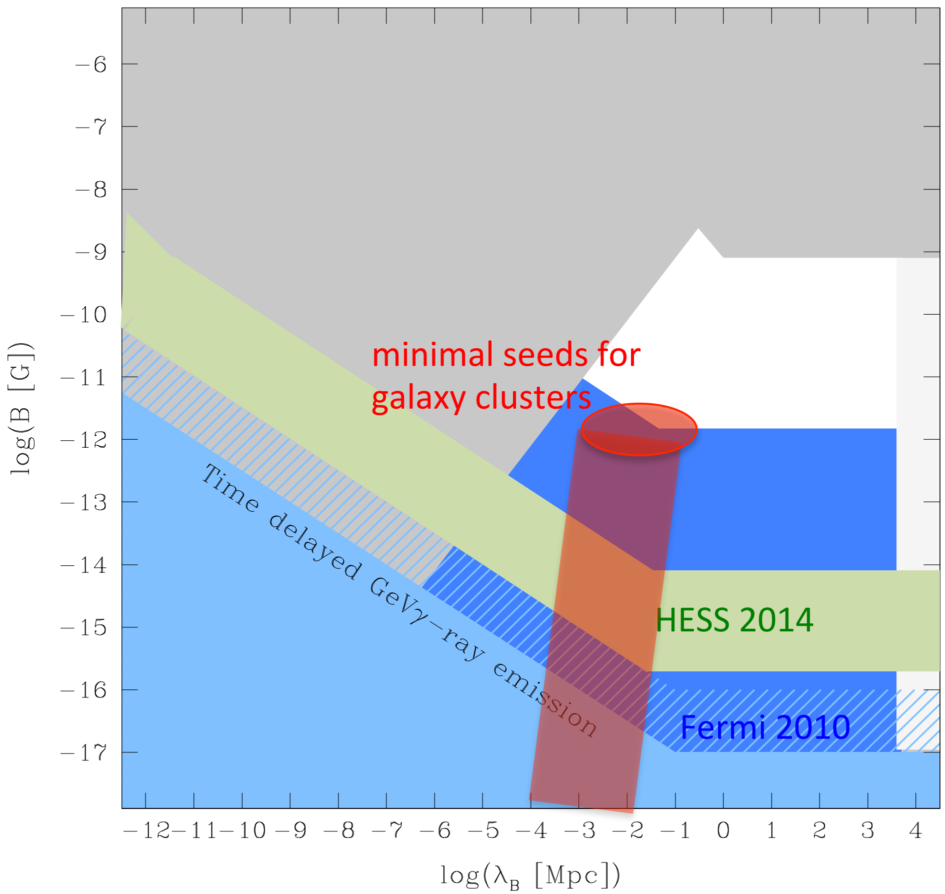
Problem of the origin of cosmic magnetic fields

Example: galactic magnetic fields.

- Gravitational collapse during structure formation leads to compression and amplification of weak field:
  $\Phi = BL^2 \sim const$
- Exponential amplification of magnetic field in the presence of plasma motions
- $$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{v} \times \vec{B})$$
  works on the eddy turnover time scale
  $$t \sim \frac{L}{v} \simeq 10^8 \left[\frac{L}{10\ \mathrm{kpc}}\right] \left[\frac{v}{10^2\ \mathrm{km/s}}\right]^{-1} \mathrm{yr}$$
  and is able to amplify galactic magnetic field from, e.g. **10^{-20} G** up to $10\ \mu$G in some 35 e-folding time, i.e. on several Gyr time scales.
- A different type of dynamo should operate on the scale of galaxy clusters, starting from initial field **$\sim 10^{-12}$ G**.



Seed fields for galactic and cluster dynamos



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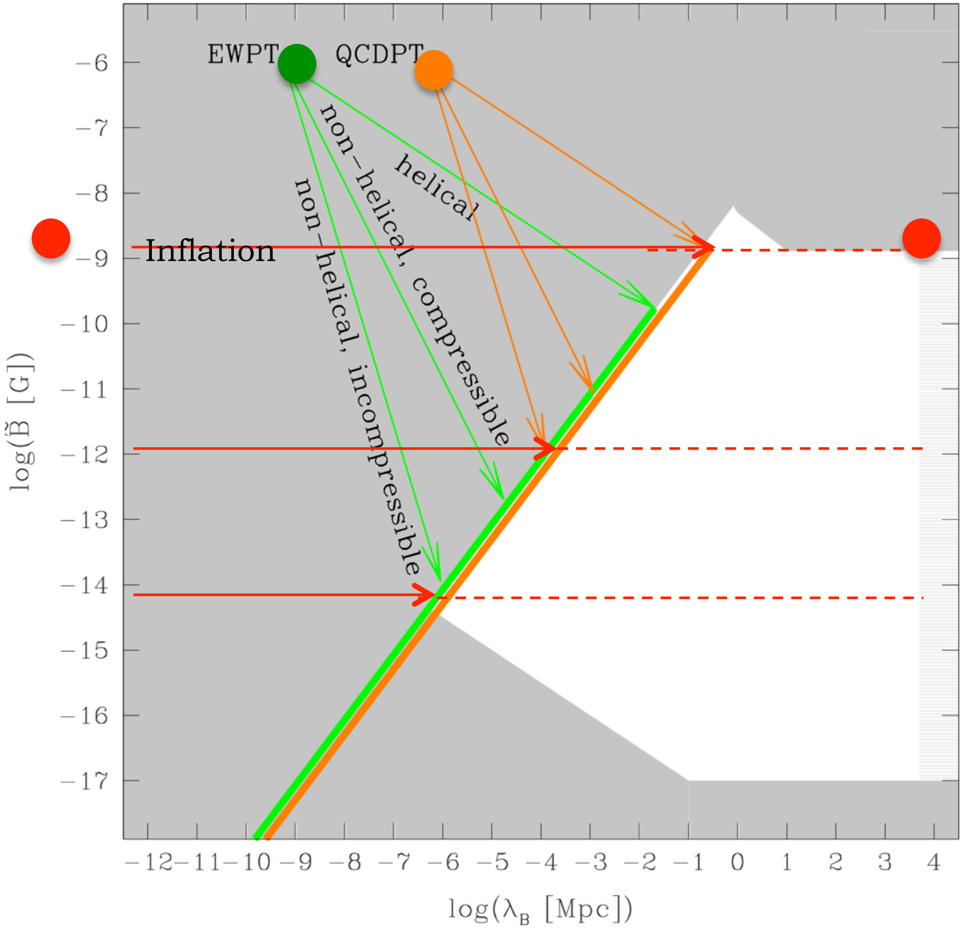
Relic fields from the Early Universe



Intergalactic magnetic fields might be relic magnetic fields left over from the Early Universe.

Magnetic fields in the Early Universe could me produced at the moments of phase transitions or during the epoch of Inflation.

Their initial correlation length is typically small, not larger than the size of horizon at the moment of production. Their initial energy density is at most of the order of the critical density of the Universe.

Example: ElectroWeak phase transition: maximal comoving correlation length

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

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

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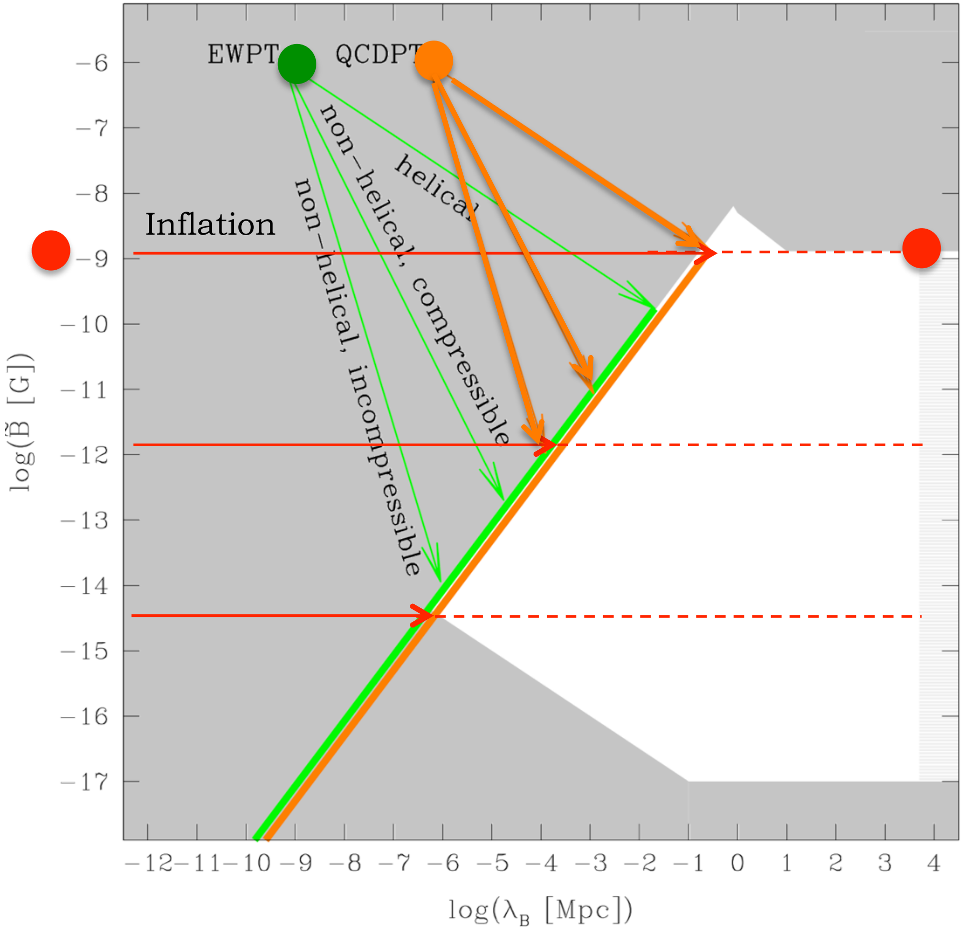

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Magnetic fields evolve by dissipating their energy into turbulent motions of plasma and finally into heat. As a result, their correlation length increases and their strength decreases.

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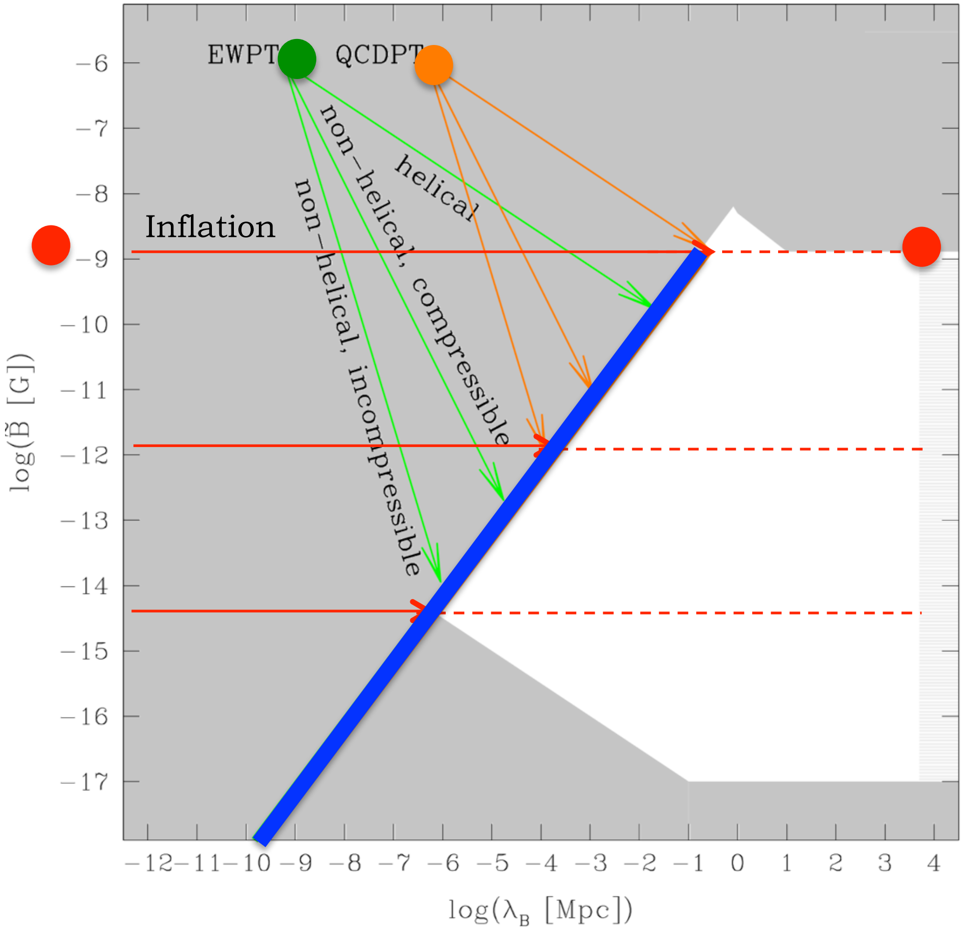

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Final correlation length and strength of the relic fields today satisfy the relation $B \approx 10^{-8}[\lambda_B/1\ \mathrm{Mpc}]$ G.

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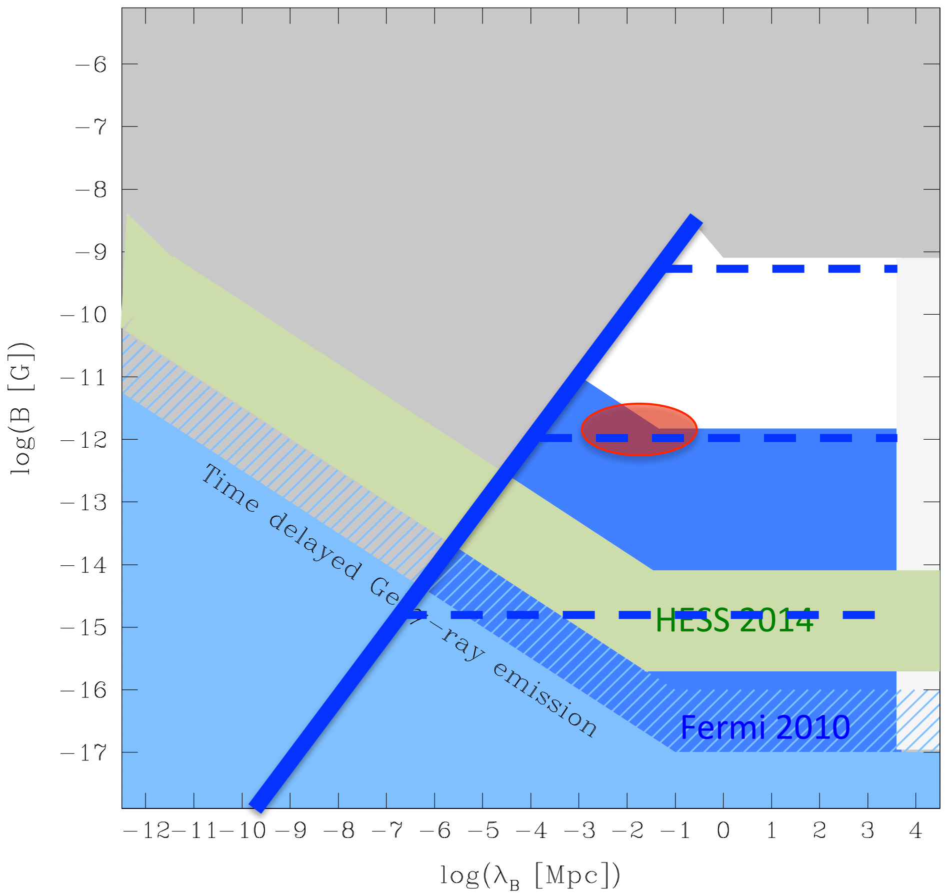

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Measurement of IGMF strength / correlation length satisfying relation $B \approx 10^{-8}[\lambda_B/1\ \mathrm{Mpc}]$ G or magnetic field with $\lambda_B \sim R_H$ would be a strong indication for the "relic" nature of such IGMF. Discovery of relic / primordial magnetic fields would provide a new type of cosmological data pre-dating the CMB and Big Bang Nucleosynthesis epochs (our earliest available cosmological data.

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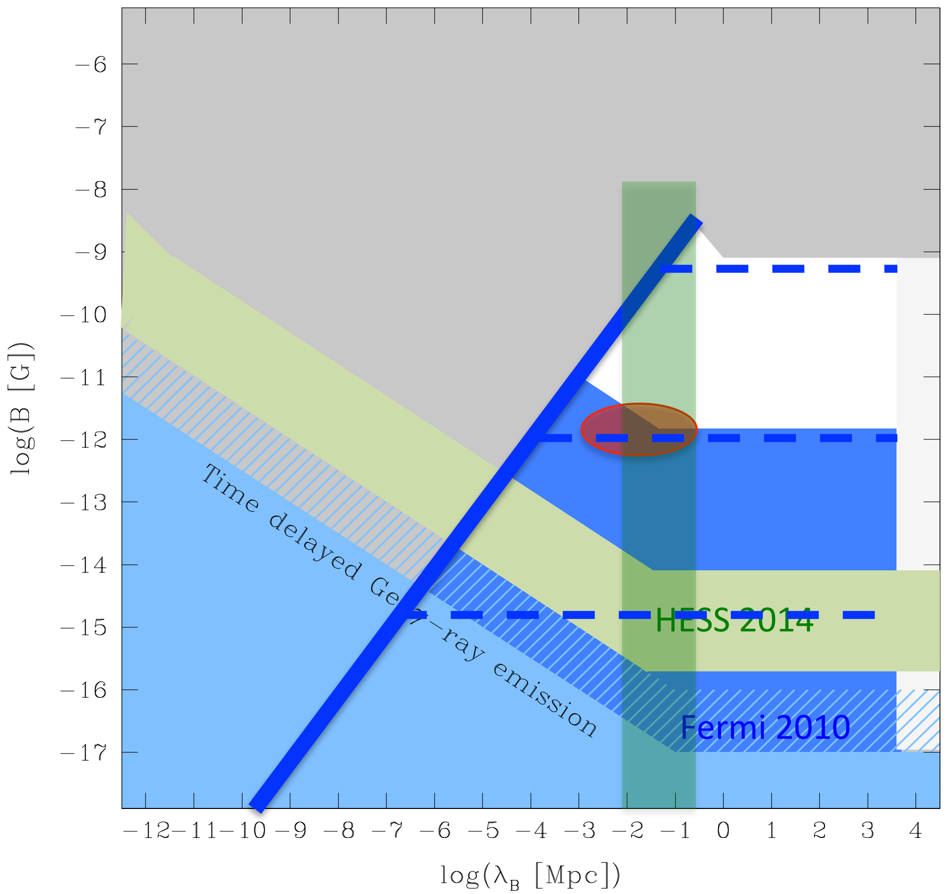

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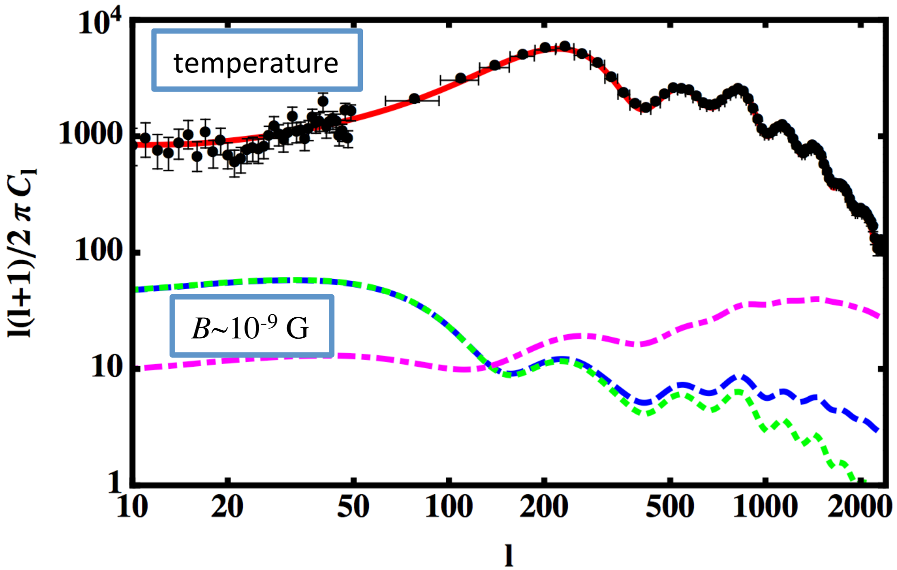
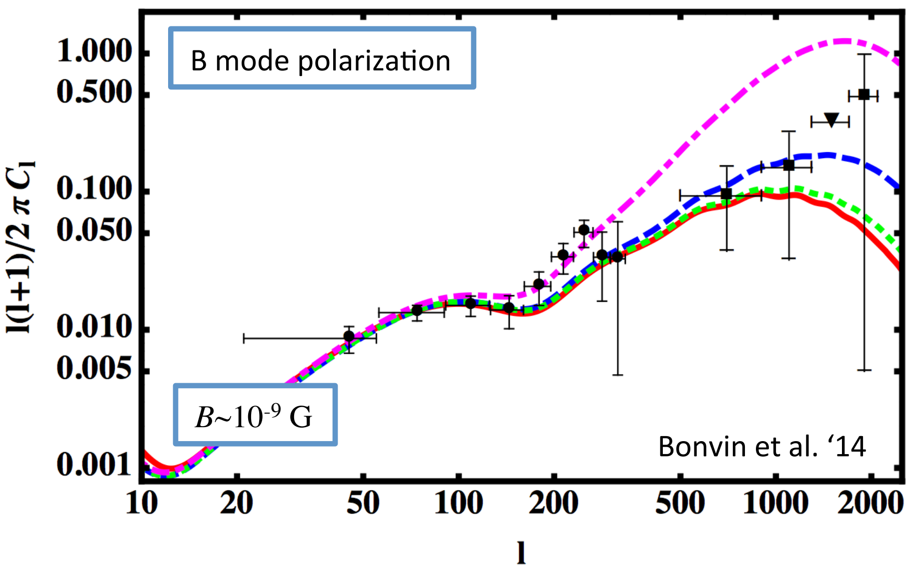
Galactic winds are responsible for the "wash out" of most of the baryonic content of galaxies in the course of structure formation.

Complementary probes: CMB





Presence of magnetic field affects CMB anisotropies and polarization in multiple ways: generation of vector and tensor perturbations, generation of magnetosonic waves, Faraday rotation of polarization, …

Magnetic field does not dominate the structure of CMB anisotropies: $\varrho_B<10^{-6}\varrho_{cr}\sim(3\times10^{-9}\text{ G})^2/8\pi$

Spectrum B polarization due to vector (dashed) and tensor (solid) modes generated by magnetic field with nearly scale-invariant spectrum n_s=-2.9 and strength $B=3\times10^{-9}$ G (Lewis '04), compared to the B-mode polarization spectrum measured by BICEP2.

* Somewhat stronger bound on B might arise from the non-gaussianity constraints.

Barrow et al '97, Seshadri & Subramanian '01, Lewis '04, Kahniashvili & Ratra '07, Durrer '07, Shaw & Lewis '10, '12, …

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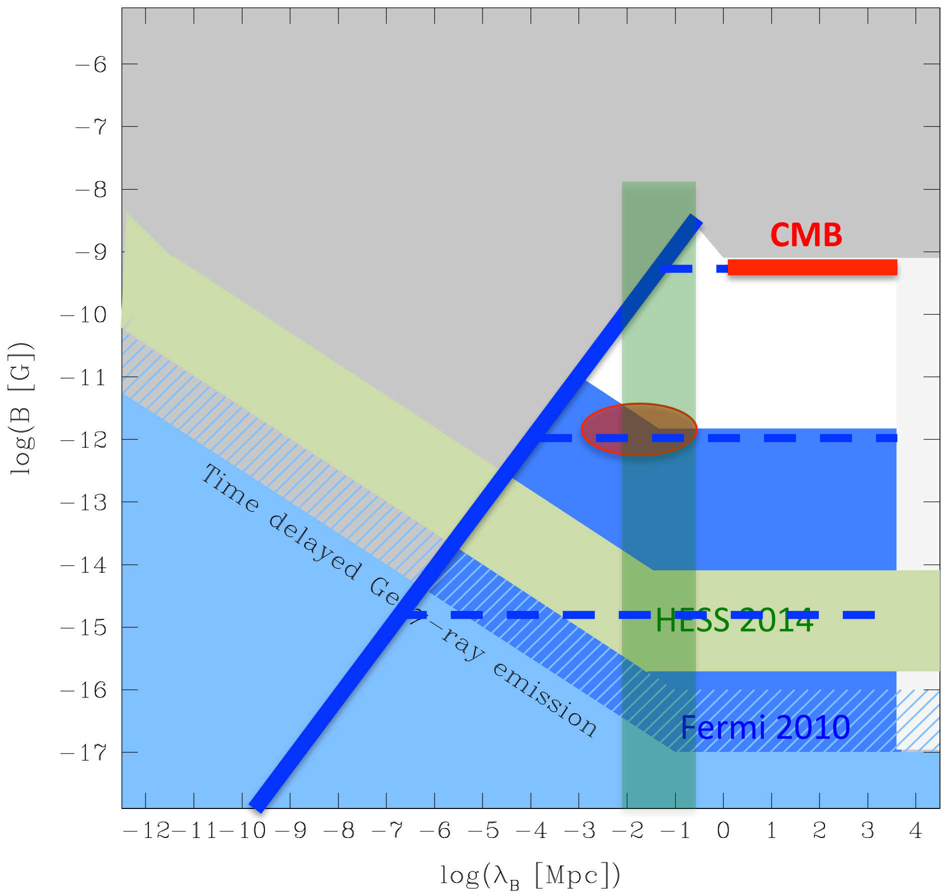

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Complementary probes: Faraday rotation

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

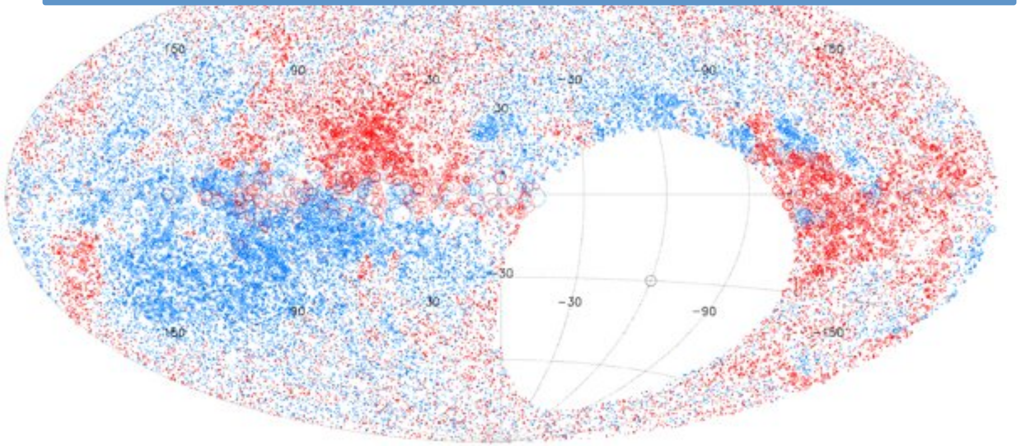
$$RM = RM_{Galactic} + RM_{IGM} + RM_{source}$$

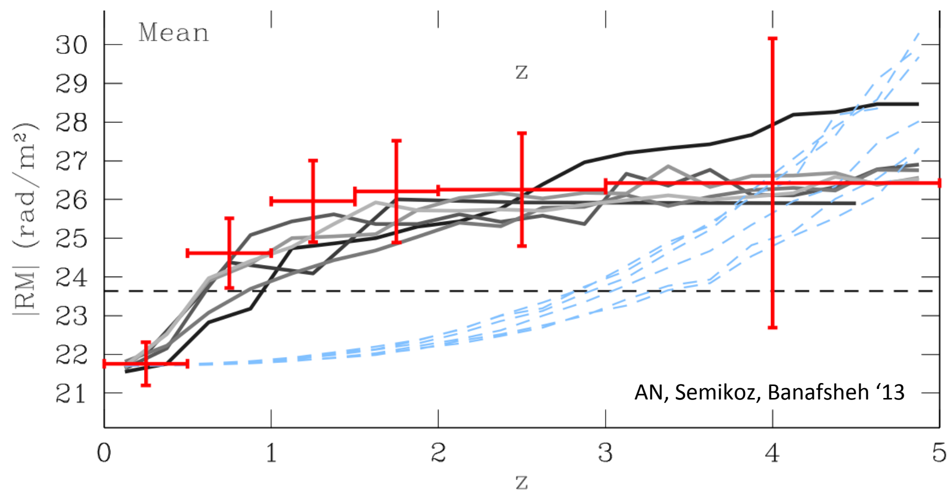
RM from the intergalactic medium is expected to depend on the distance to the source, i.e. to scale with the redshift z.

Such z dependence is detected at 3σ level in the largest RM data set from the NVSS sky survey and in other data sets.

It is not clear if the effect is due to cosmological fields. Alternative interpretations are e.g. fields at the far outskirts of galaxies.

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





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

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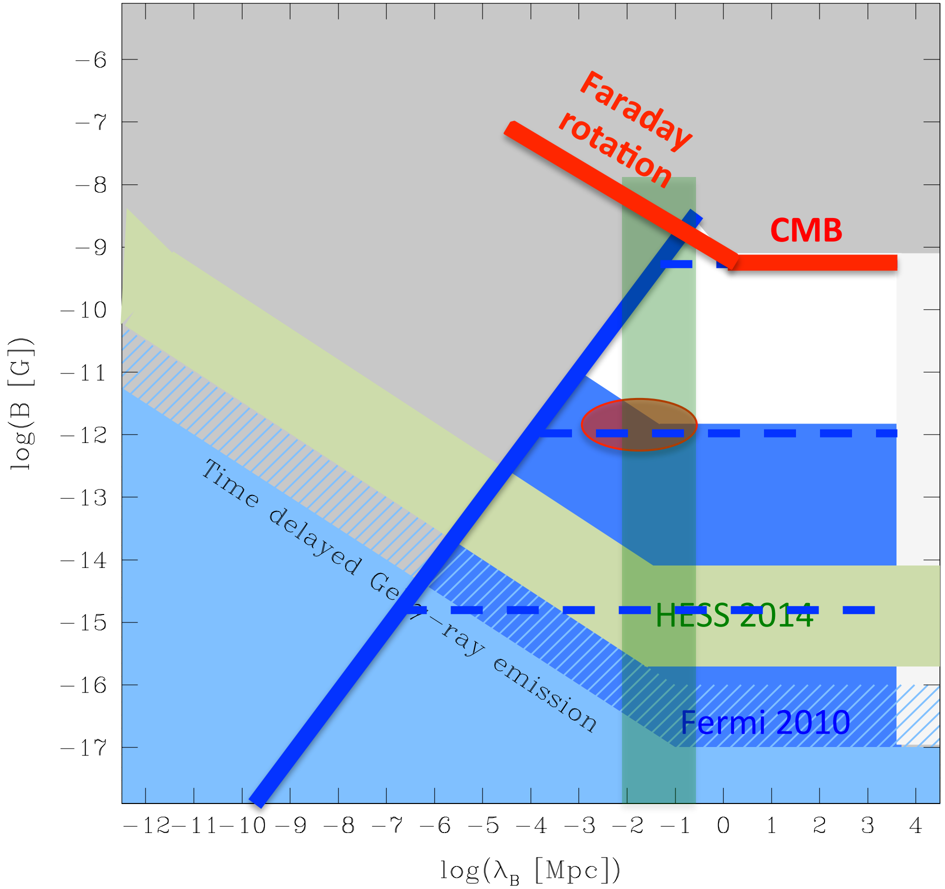

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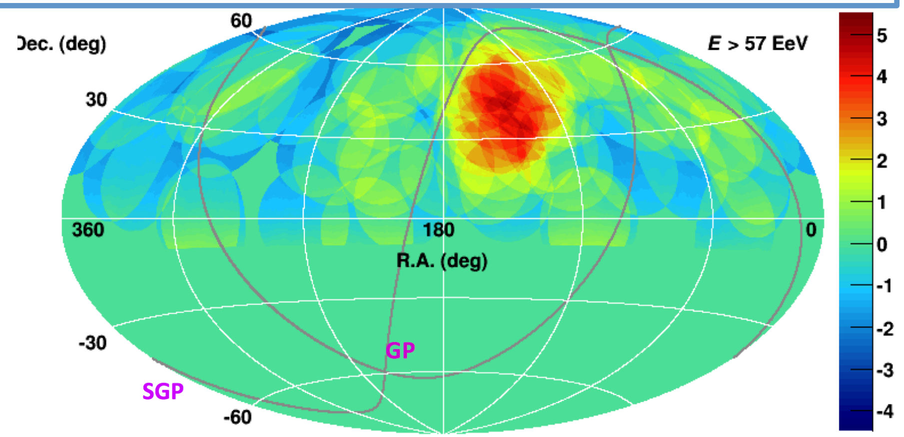
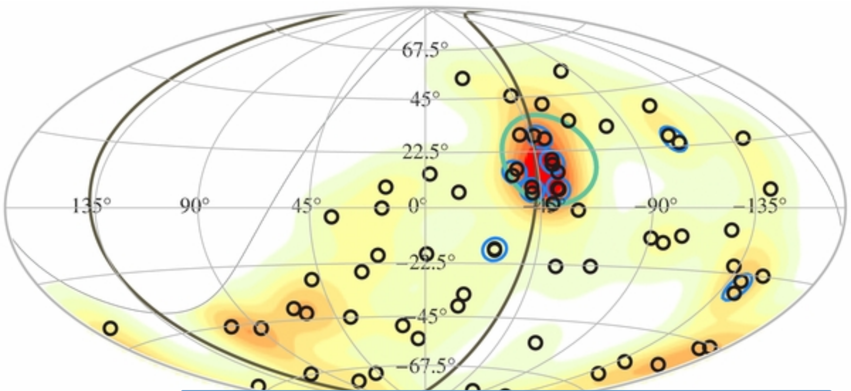
Complementary probes: UHECR

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





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

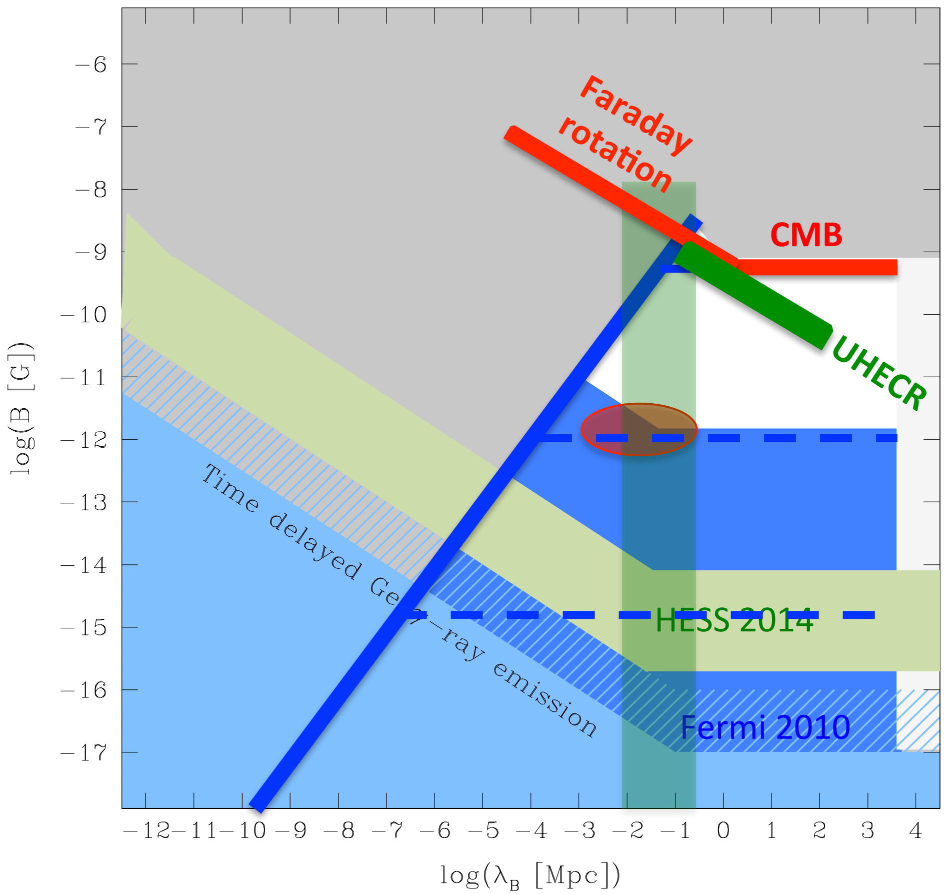
Trajectories of charged Ultra-High-Energy Cosmic Ray particles (UHECR) are deflected by Galactic and intergalactic magnetic fields. The deflection angle by intergalactic magnetic field with strength B and correlation length λ is

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

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.

Relic fields from the Early Universe



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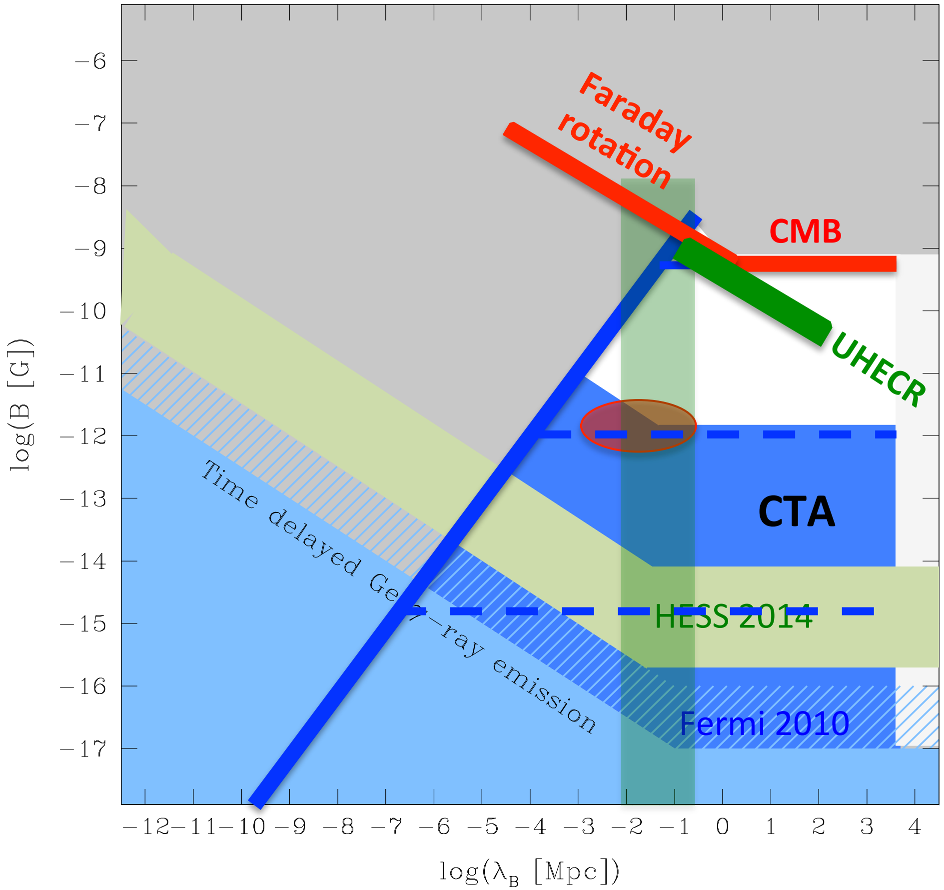
Summary

Gamma-ray telescopes (present and next generation) provide a tool for measurement of magnetic fields in the intergalactic medium, via observation of secondary inverse Compton emission from electron-positron pairs deposited in the IGM by interactions of VHE gamma-rays with EBL photons.

Measurement of IGMF strength and correlation length will provide an important step toward solution of the problem of the origin of cosmic magnetism.

If IGMF will prove to be of primordial origin, its discovery will provide cosmological data pre-dating the epochs of CMB and BBN.

If IGMF will prove to originate from magnetized galactic winds, its study will provide new insight into the Large Scale Structure formation.



Several complementary techniques are available for the study of IGMF, including CMB anisotropy and polarization, Faraday rotation measurements, and ultra-high-energy cosmic ray anisotropies.

Pair cascades and plasma instabilities

Long-term stability of blazars