Improved IGMF limits from Fermi and MAGIC observations of 1ES 0229+200

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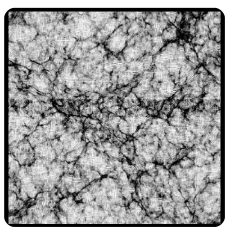
IGMF – a hidden window to the early Universe

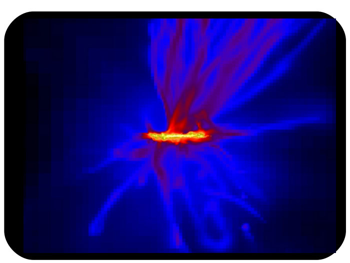
It is generally assumed, that the B-fields in modern galaxies result from amplification of some weaker field (Kronberg '94, Grasso & Rubinstein '01).

Seed B-field

Cosmological



Astrophysical



Dynamo amplification

Modern fields in galaxies and clusters

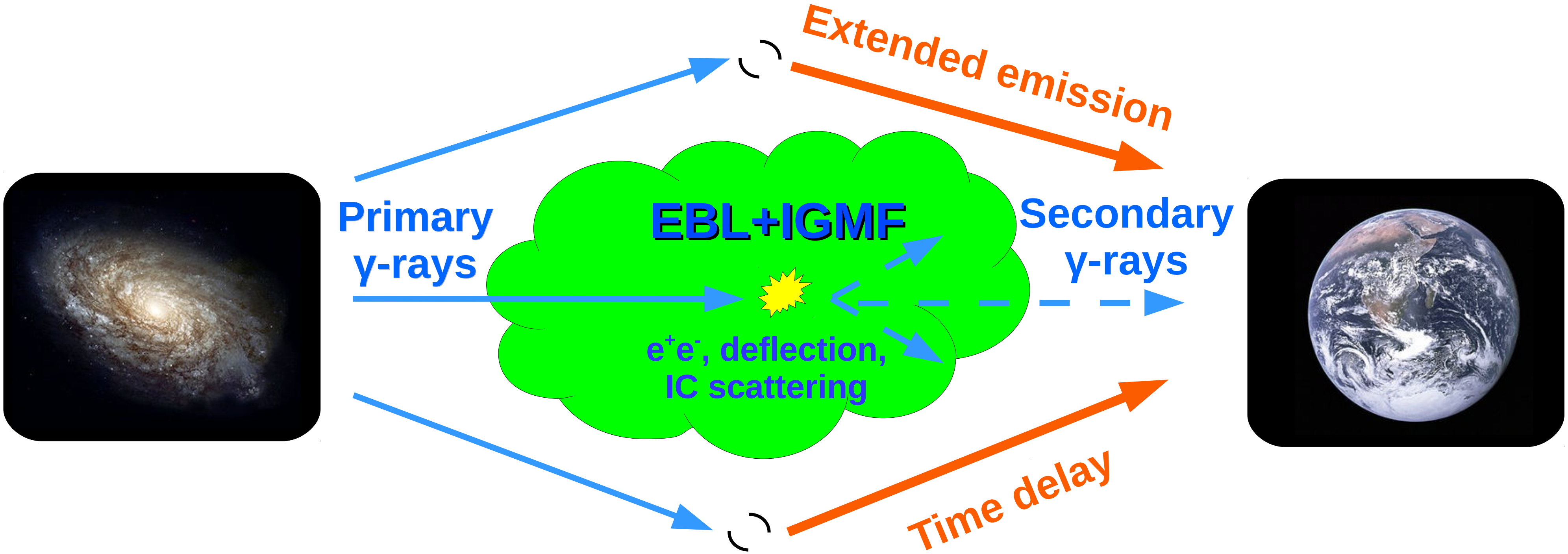
Though the nature of this "seed" field is uncertain (Widow '02, Kulsrud & Zweibel '08), its properties significantly affect the evolution of galaxies and the Universe as a whole (e.g. Dolag+ '99).

IGMF – a possible "seed" field for astrophysical dynamos, filling most of the Universe volume.

→ IGMF detection = unique data on the Universe's early days

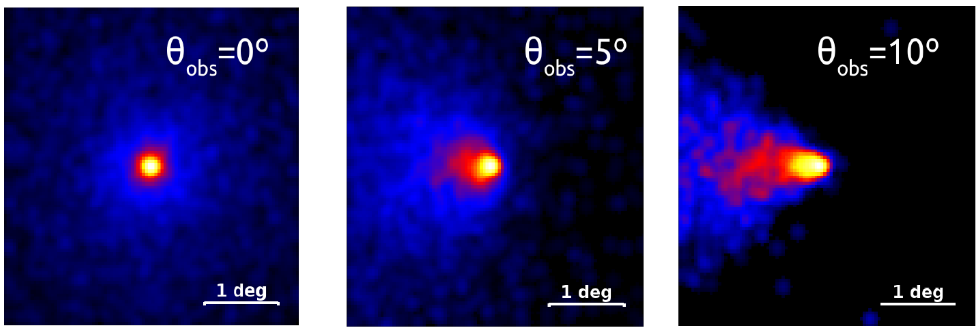
IGMF measurements through gamma-ray data

Extremely weak IGMF can be detected using a "long lever arm" of ~100 Mpc scale cascades, initiated by distant AGNs.



The presence of non-negligible IGMF leads to appearance of extended – and delayed – "halos".
(Plaga '95, Neronov & Semikoz '09)

Observational properties of the IGMF-modified cascades



"Smoking gun": extended halo

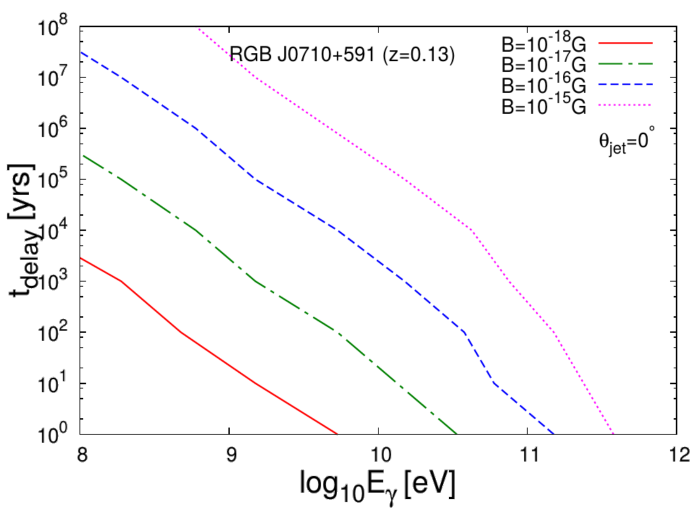
Size and shape depend on IGMF strength **and** source parameters (jet opening and orientation).

Delayed emission

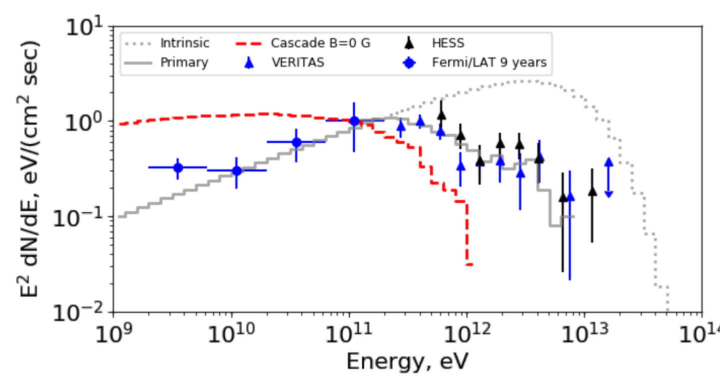
The delay is set by IGMF, but light curve shape may also depend on the jet parameters.

New spectral components

Depend on IGMF, source spectrum, jet orientation.



Taylor+ '11

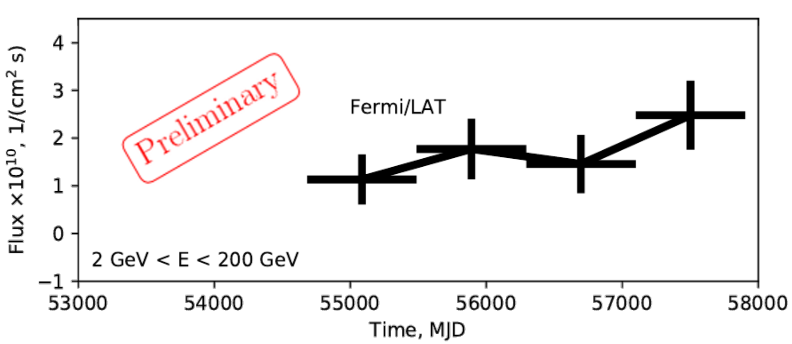


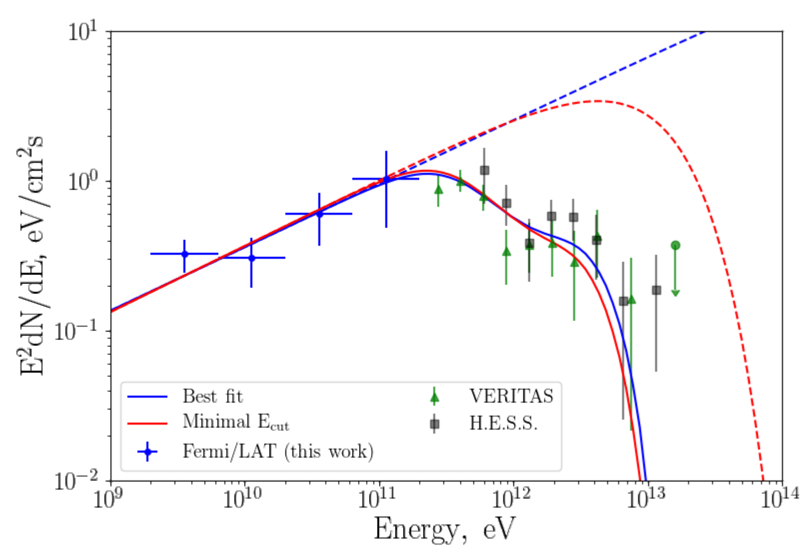
1ES 0229+200 – primary source for IGMF constraints

IGMF measurements with gamma-ray data require **hard spectrum** AGNs at large redshifts.
Low variability is prefered for halo searches.
One of the best sources with such characteristics – **1ES 0229+200**.

1ES 0229+200 in a nutshell

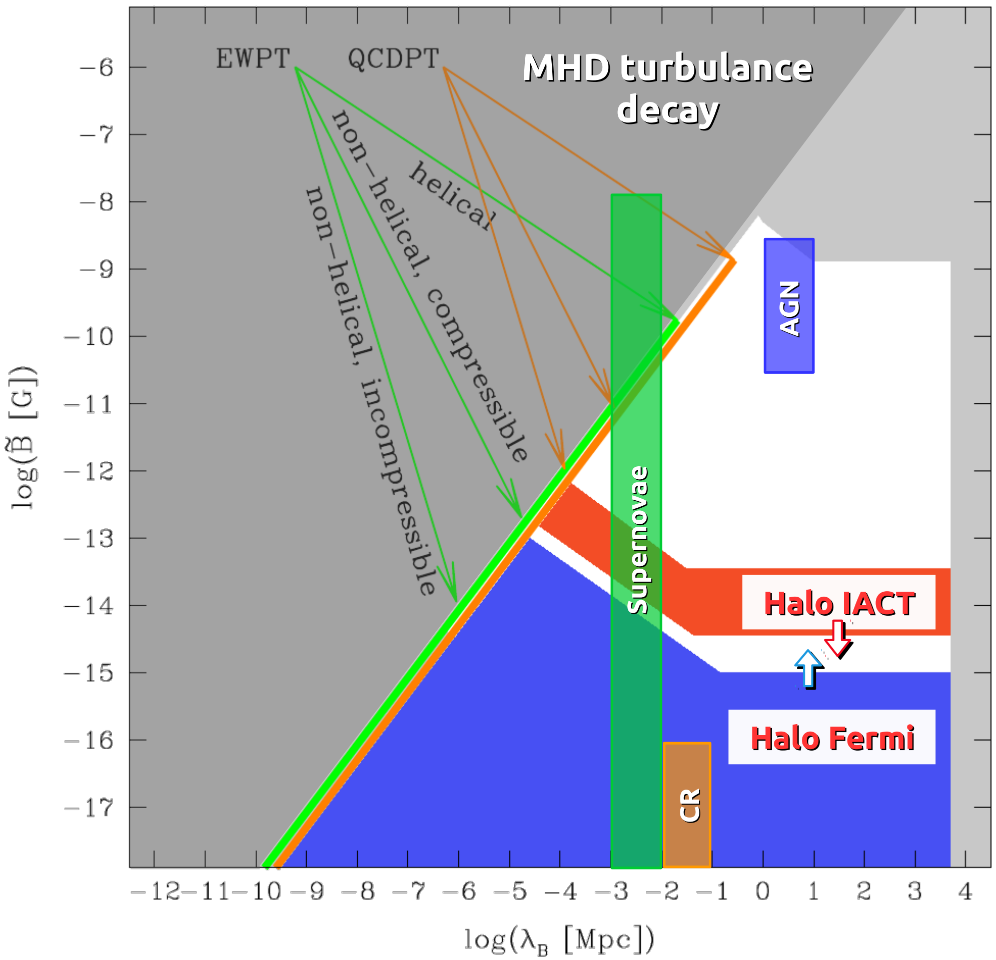
- redshift z=0.14
- hard Γ~1.5 intrinsic spectrum (Aharonian+ '07, Vovk+ '12)
- no evidence for cut-off
- low, but present flux variability (Aliu+ '14)





H.E.S.S. data from Aharonian+ '07,
VERITAS – Aliu+ '14
E_{cut} > 10 TeV is prefered by the data

Previous constraints on IGMF



Fermi/LAT measurements (Neronov & Vovk ‘10, Tavecchio+ '10, Dermer+ ;11, Dolag+ ‘11, Taylor+ ‘11, Vovk+ ‘12, Finke+ ‘15) are complemented by **IACTs** (Aharonian+ ‘01, Aleksic+ ‘10, Abramowski+ ‘14, Archambault+ ‘17).

These limits are based primarily on halo non-detection — a “smoking gun” of IGMF presence.

The gap between LAT and IACT measurements is slowly closing as more exposure is being accumulated.

Figure adapted from Durrer & Neronov ‘13 with the models of Miniati & Bell '11, Furlanetto & Loeb '01 and Bertone+ '06

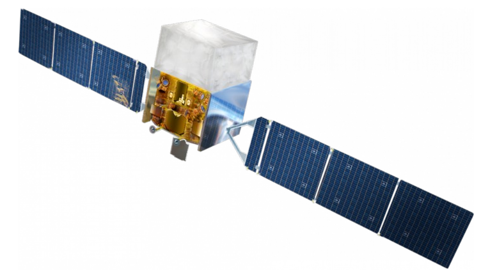
MAGIC and Fermi/LAT observations of 1ES 0229+200

MAGIC

Telescopes: two D=17m
Site: La Palma (Canary Islands)
Energy range: 40 GeV – above 50 TeV
Resolution: 0.07°-0.14° (0.1-1 TeV)
Sensitivity: 0.6% Crab units (integral)

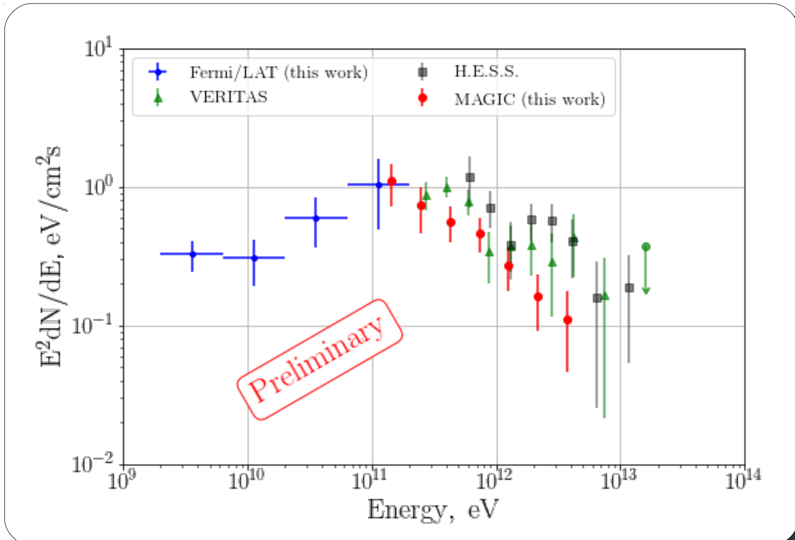
Observation period: 2013 - 2017
Exposure: ~120 hr
Energy range: 100 GeV – 10 TeV

Fermi/LAT



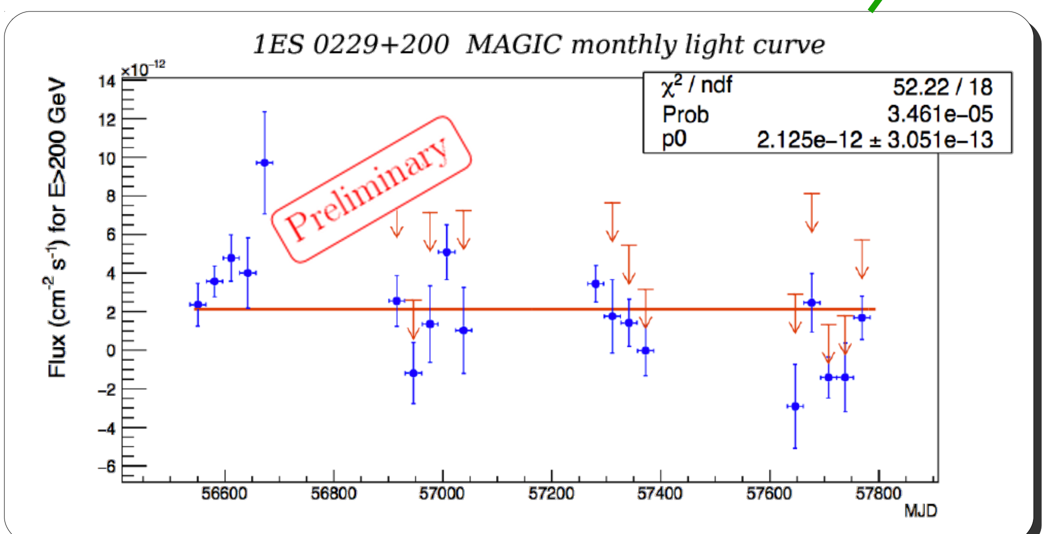
Observation period: 2008 - 2017
Exposure: ~9 years
Used E range: 1 – 100 GeV
Processing: Pass8 data
Notes: using both likelihood fits and aperture photometry for consistency.

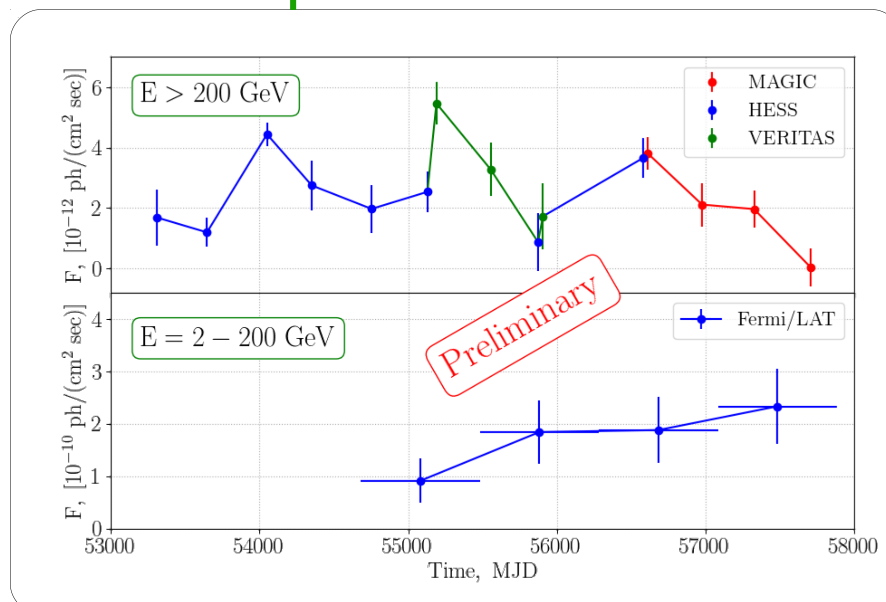
Measured spectrum and light curve



Measured Γ~2.5 spectrum is consistent in shape with that of VERITAS (Aliu+ '14) and HESS (Aharonian+ '07), however is ~40% lower.

Variability already on the ~0.5 year time scale. Comparison with HESS and VERITAS data (from Cologna+ '15), suggests persistent variability on yearly time scales.



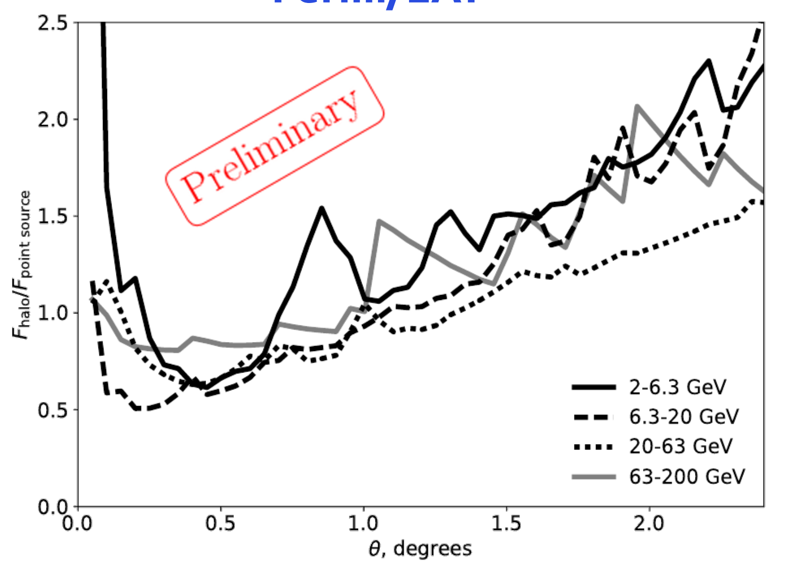


Search for extended emission

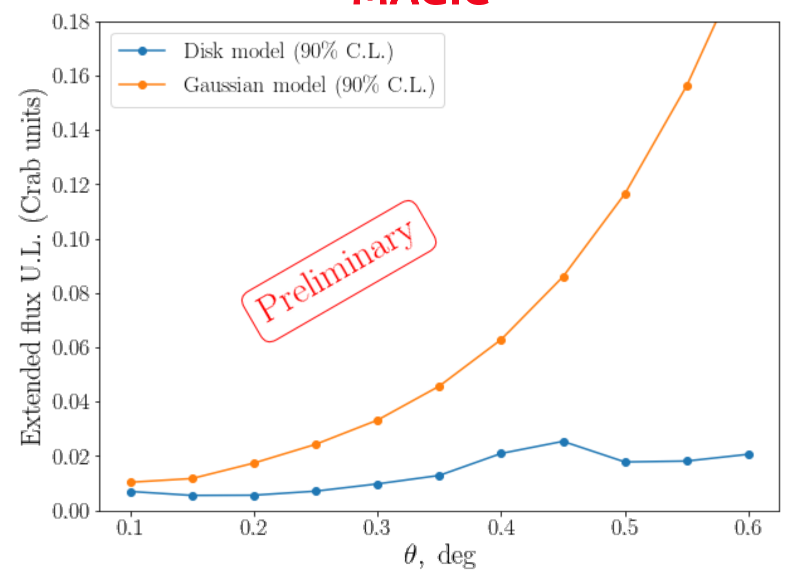
As the halo shape depends on a number of unkown parameters (θ_{jet}, θ_{obs}, λ_B etc), it is not possible to predict it for the specific case of 1ES 0229+200.

→ Simpler approach: scan for disk/gauss-like emission around it.

Fermi/LAT



MAGIC



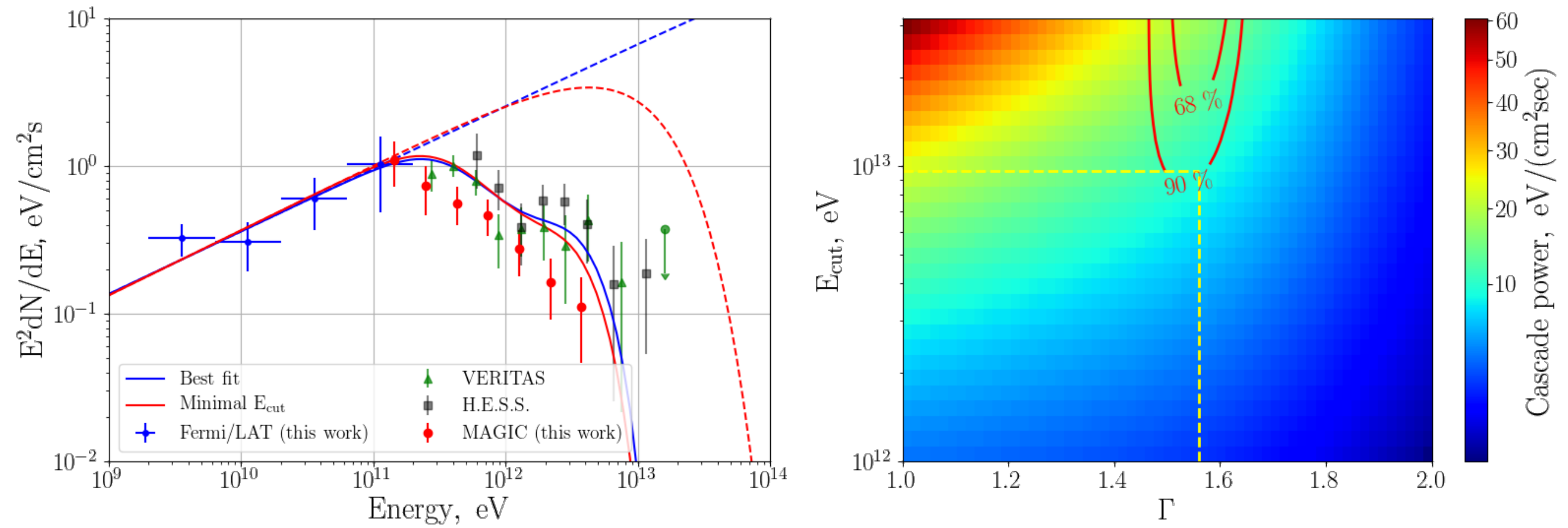
No halo is detected in the 2 GeV – 1 TeV energy range.

We also cross-check these results with the full likelihood fit.

Modelling the expected cascade contribution

To see how constraining the derived limits are we simulated the cascade for various IGMF strength, using the most conservative Γ-E_{cut} combination.

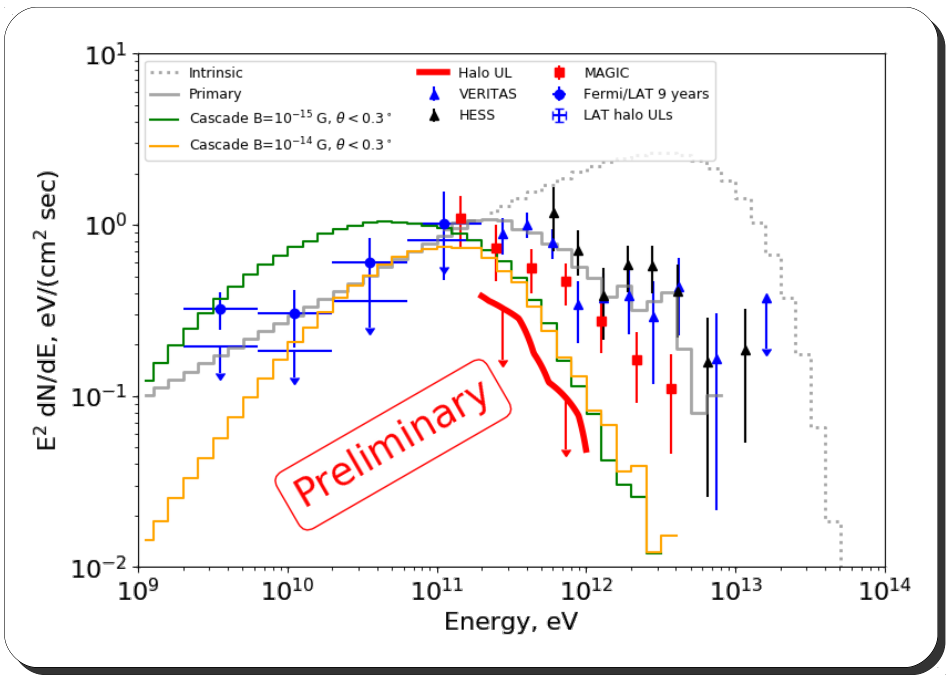
To define it, we scanned the Γ-E_{cut} parameter space and chose among the minimal Ecuts (at 90% C.L.) the one that gives the lowest cascade power.



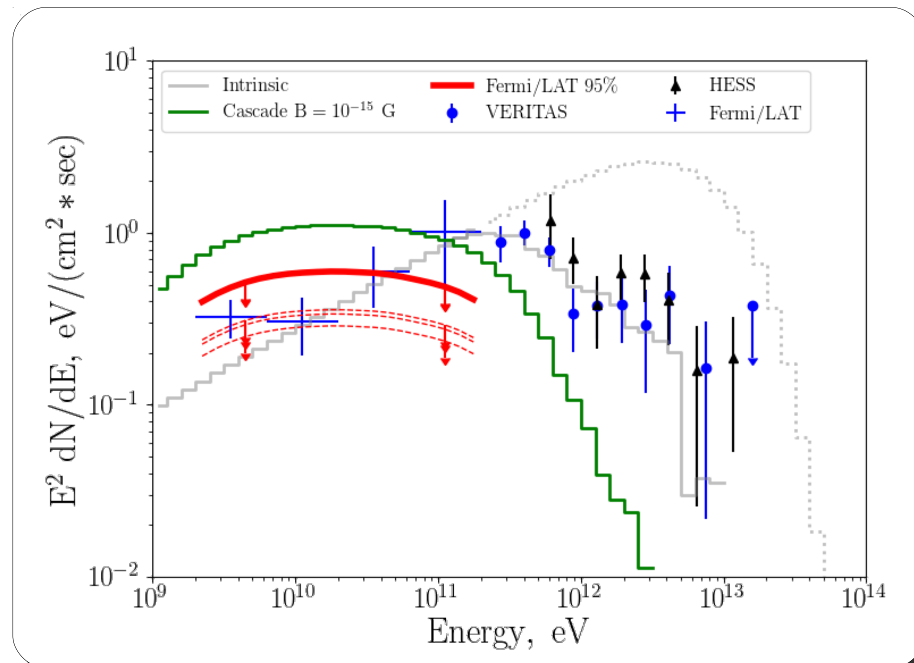
These correspond to Γ_{min}~1.6 and E_{cut}^{min} ~ 9.6 TeV (in observer's frame).

Updated limits on IGMF

Derived upper limits exclude IGMF in the
range $10^{-16} < B < 3 \times 10^{-14}$ G
Combined with the earlier LAT constraints (Taylor+ ‘11 and Vovk+ ‘12)
the entire range $B < 3 \times 10^{-14}$ G is excluded.

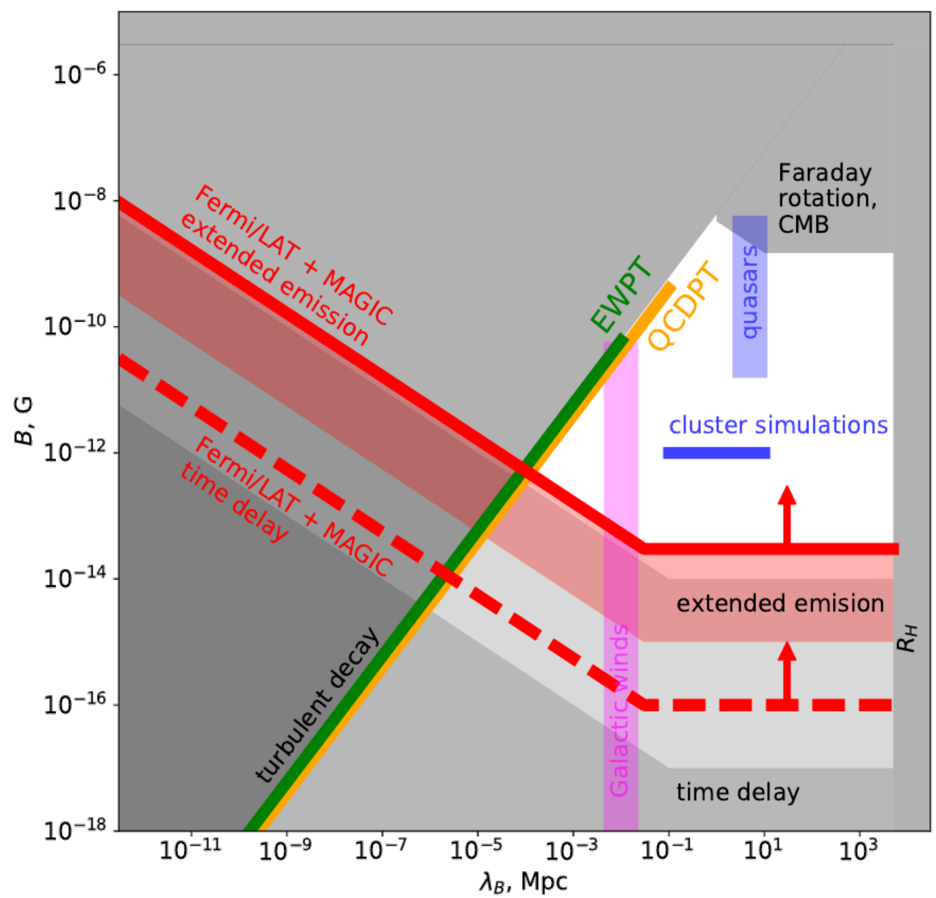


Obtained upper limits with minimal cascade models overplotted.



Cross-check: upper limit on 10^{-15} G IGMF assuming 10° aligned jet (solid line) and 5° inclined jet (dashed lines). Full likelihood fit.

Summary



Deep Fermi/LAT and MAGIC observations of 1ES 0229+200 confirm mild (no flares) secular variability of the source.

No spectral changes were detected in the TeV band.

Combining both the morphological and spectral information on the halo, Fermi/LAT+MAGIC data constrain IGMF to

$B > 3\times10^{-14}$ G ($\lambda_B > 0.03$-0.1 Mpc)

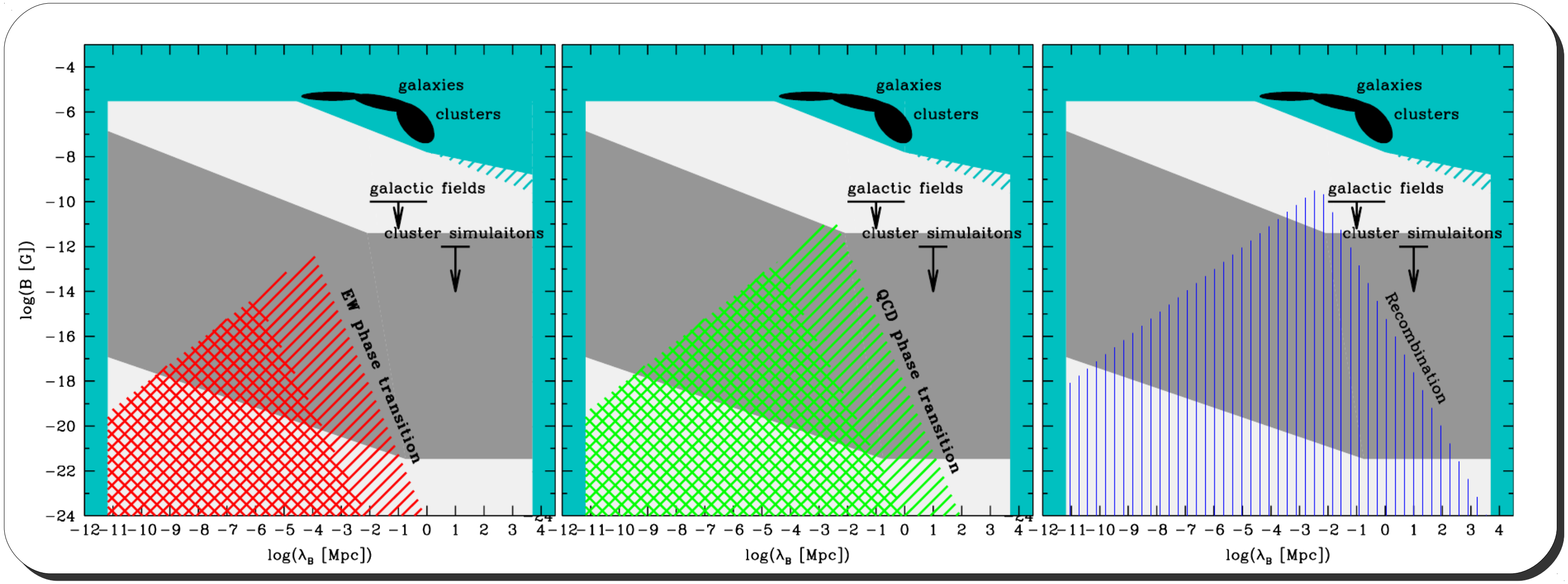
This limit already excludes cosmological IGMF, formed during the electroweak phase transition and is in tension with the QCD transition models.

Even stronger constraints can be derived, if $E_{cut} >> 10$ TeV – can be verified with deeper observations and CTA.

If the absence of a secondary radiation is due to plasma wave excitation (e.g. Broderick+ '12), we can infer a heating rate of ~10^{42} erg/s from our observations.

Backup

Cosmological IGMF



Neronov & Semikoz, '09

Magnetic fields produced during different epochs:

- ✔ QCD phase transitions: ~10^{-12}
- ✔ electroweak phase transitions: 10^{-11} G
- ✔ recombination: ~10^{-9} G

Astrophysical IGMF

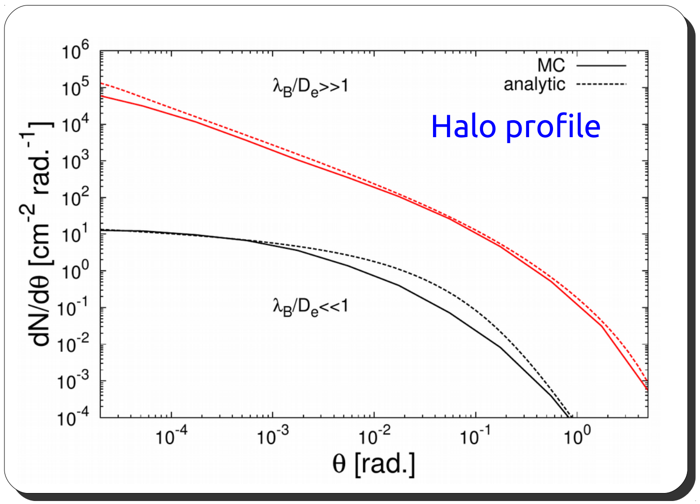
- Vorticity in protogalaxies during the radiation-dominated era can produce fields as strong as 10^{-19}G.
- Biermann battery effect operating in protogalaxies can also lead to the production of $\sim 10^{-17}$ G field on large (megaparsec) scales.
- Stellar evolution (with account for the Biermann battery effect) can also produce a B-field inside the young galaxy.
- AGN are also promising sites for the magnetic field to be born and amplified.

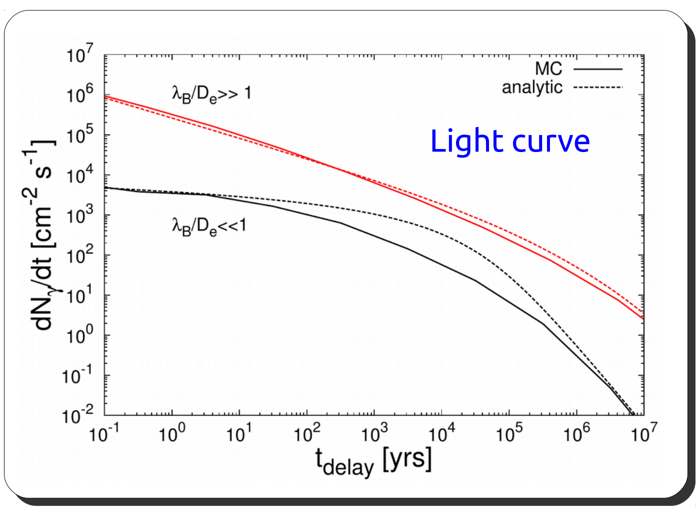
(L. M. Widrow, Rev. Mod. Phys. 74, 775 (2002))

- Cosmic-ray-driven currents in young galaxies can also be responsible for the creation of the magnetic fields.

(Miniati F. and Bell A., ApJ, v. 729, I. 1, id. 73 (2011))

Correlation length of IGMF





Neronov+ '13

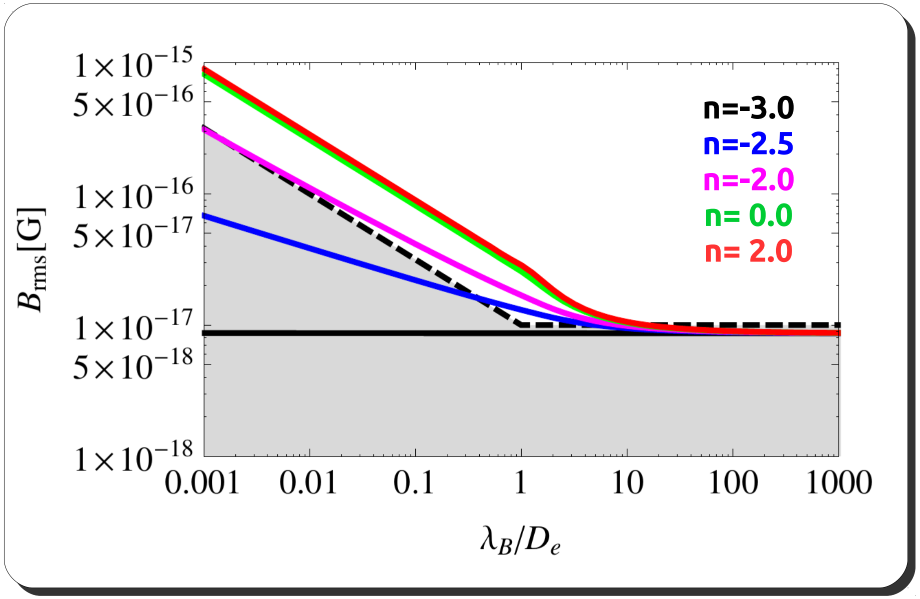
Correlation length is another key parameter of the IGMF, though more difficult to infer than its strength.

Correlation length of IGMF defines the deflection mode of particles (simple or diffusion in angle) and, thus, affects the shape of the produced halo.

The change of the deflection mode $\lambda>D_e$ to $\lambda<D_e$ with the energy would allow to estimate the correlation length.

Similar information can be infered from the light cuves, if the time delayed emission would be clearly identified.

IGMF power spectrum



Deflection angle:

$\delta = D_e/R_L$ $\quad \lambda \gg R_L$ $\quad$ homogeneous field

$\delta = \sqrt{D_e \lambda}/R_L$ $\quad \lambda \ll R_L$ $\quad$ diffusion in angle

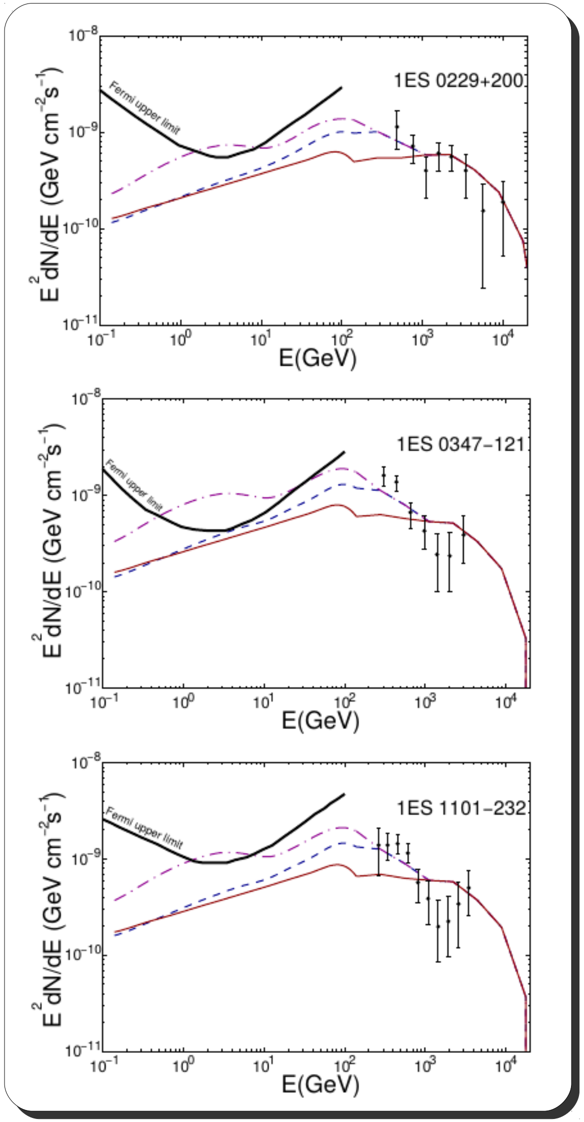
However, the particle does not necessarily make a random walk, if one takes into account the spectrum of the magnetic field

$$P_B(k) \sim k^n$$

This question was addressed by Caprini & Gabici '15, who pointed out that the limit on the IGMF depends on the its assumed spectrum. For n=-3 the constraint at $\lambda << D_e$ becomes as weak as for $\lambda >> D_e$.

This may be important for constraining the IGMF production mechanisms, predicting λ<0.1 Mpc.

UHECR-induced cascades and IGMF



Essey+ '11

Despite the fact that the flaring activity of AGNs can be used to detect the IGMF-associated time delay, certain VHE object demonstrate surprisingly low variability.

<u>A possible explanation:</u> their emission mechanisms are different from the other, flaring sources. For instance, the detected TeV emission can be an outcome of the electromagnetic cascade, initiated by the Ultra High Energy Cosmic Rays (UHECRs), produced in these sources (Essey+ '11, Essey & Kusenko '11).

Though the mean free path of UHECRs is different from gamma-rays, the development of the cascade is sensitive to IGMF.

Too strong IGMF would isotropise the cascade and suppress the TeV emission.

Too low IGMF would cause the overprediction of the GeV fluxes.

Under this assumption, the limits become (Essey+ '11):

$$10^{-17}\ \mathrm{G} < B < 10^{-14}\ \mathrm{G}$$

Plasma instabilities and the secondary cascade development

The discussed IGMF constraints stem from the non-detection of the expected secondary IC emission from the electromagnetic cascades.
An alternative possibility to explain these observations is to assume that the cascade power is dissipated differently then via IC emission in gamma rays.

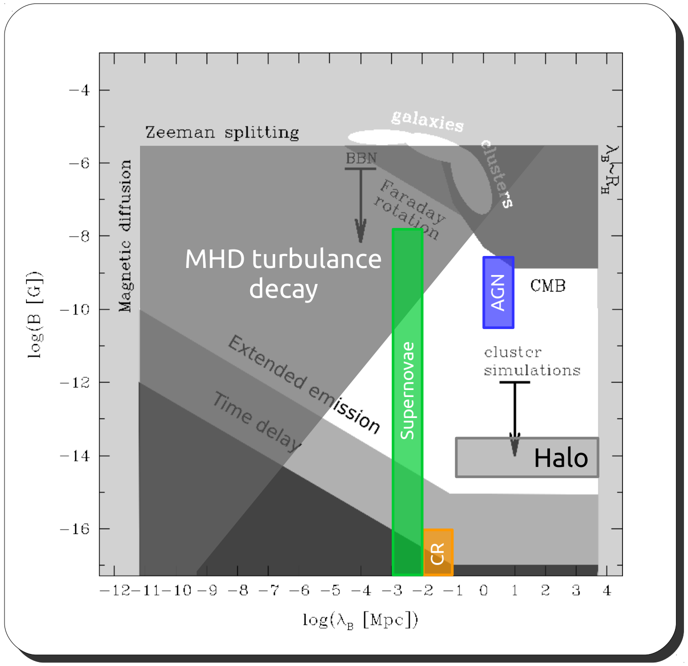
Chang+ '12 and Broderick+ '12 suggested that this power can be dissipated via the plasma instabilities during the cascade development, leading to a strong suppression of the gamma-ray emission.

Miniati & Elyiv '12 considered the back reaction of the beam perturbations on the instability growth rate and concluded that the non-linear Landau damping and large-scale plasma inhomogenieouties should stop the development of the instabilities.

Schlickeiser+ '12 also considered the non-linear case with the back reaction and concluded that for certain beam densities (similar to those expected for the "IGMF" blazars) half of the initial power is transferred to the turbulance.

Overall, the role of the instabilities in the cascade development is not completely clear. Further investiagations are clearly needed.

General picture and opened questions



Miniati & Bell '11
Furlanetto & Loeb '01
Bertone+ '06

IGMF can be produced by various mechanisms and gamma-ray measurements start to constrain some of them. This gives opens interesting possibilities for the studies of the history of the Universe.

Opened theoretical questions:
Gamma-ray or CR cascades?
Importance of the instabilities?

Observational issues:
For weak IGMF (< 10^{-16} G) a characteristic time delay can be deteceted. For stronger IGMF we should rather look for halos. Both are not detected so far.

Coherence length of IGMF?

IGMF at larger reshifts (z~1)?

The TeV duty cycles of the used AGNs are, perhaps, observationally, the most important question.