A robust lower bound on intergalactic magnetic fields (IGMF) from Fermi/LAT and MAGIC observations of 1ES 0229+200

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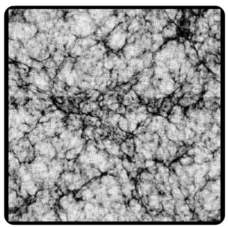
IGMF – a hidden window to the early Universe

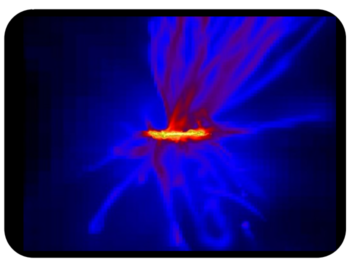
It is generally assumed, that the B-fields in modern galaxies result from amplification of some weaker field (Kronberg '94, Grasso & Rubinstein '01).

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

Why IGMF constraints are important now?

Intergalactic magnetic field (IGMF) – a hidden window to the early Universe

Cosmological IGMF explains:

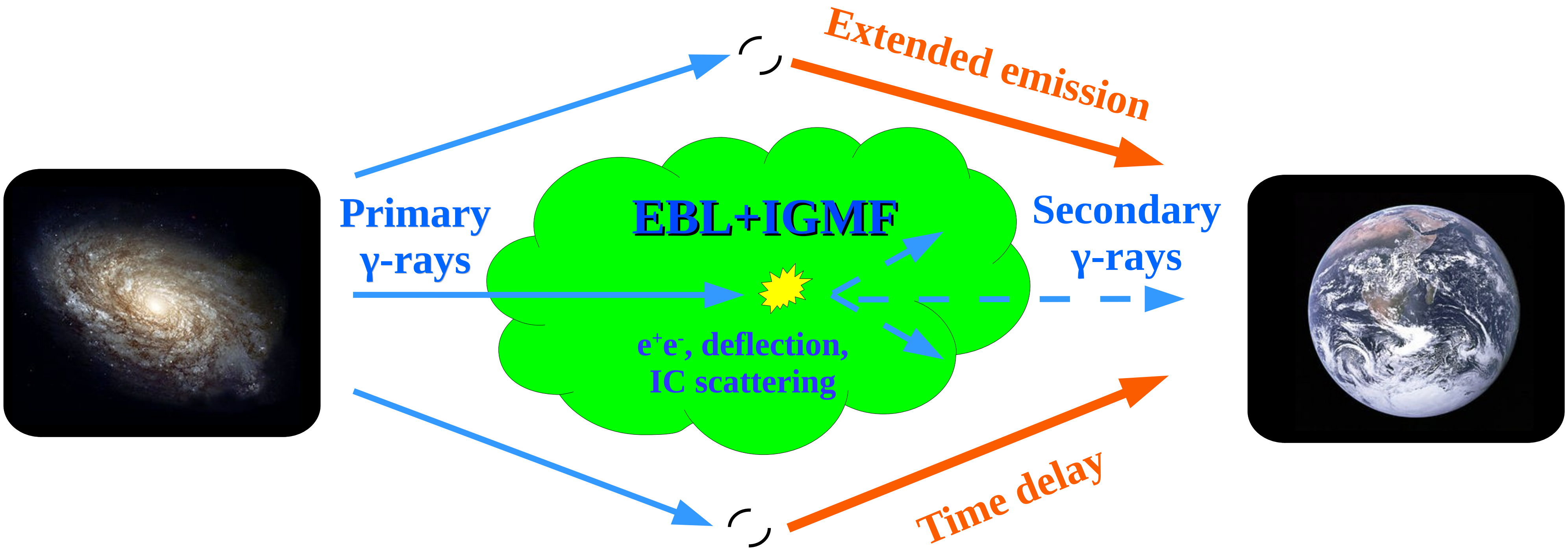
1. Baryonic assymetry of the Universe (BAU)
Transfer of hypermagnetic helicity to baryon number
(e.g. Giovannini & Shaposhnikov 1998; Fujita & Kamada 2016; Kamada & Long 2016)

2. Hubble constant tension between CMB and BAO
Enhanced recombination rate due to IGMF-induced small-scale matter inhomogeneities
(Jedamzik & Pogosian 2020)

IGMF measurement is desired

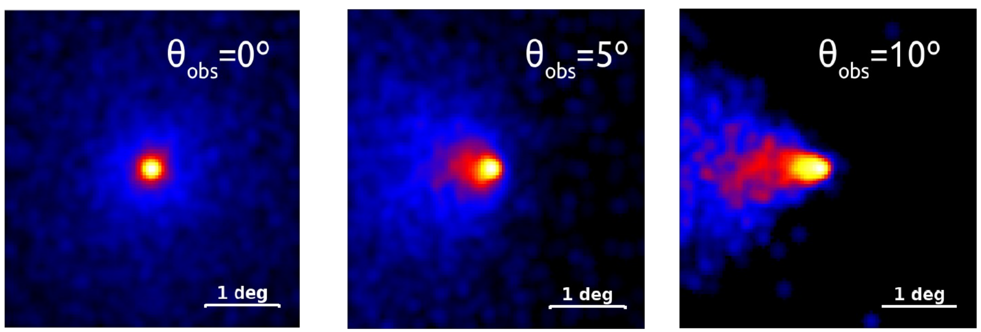
IGMF measurements through gamma-ray data

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



The presence of non-negligible IGMF leads to appearance of extended – and delayed – gamma-ray “halos”.
(Plaga ‘95, Neronov & Semikoz ‘09)

Observational properties of the IGMF-modified cascades



“Smoking gun”: extended halo

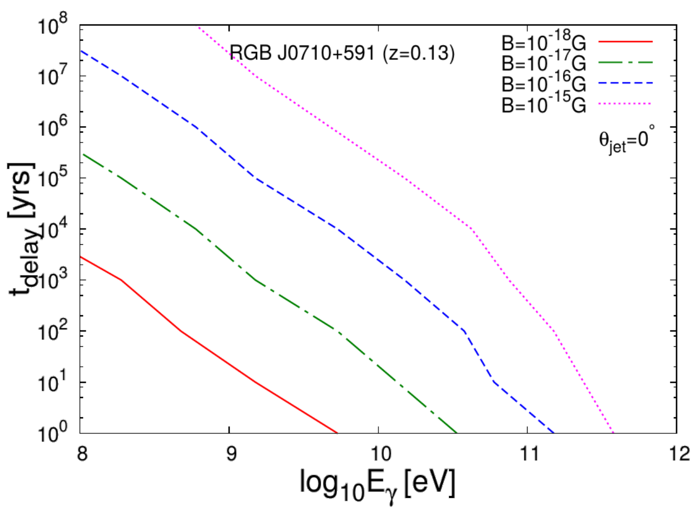
Size and shape depend on IGMF strength **and** source parameters (jet opening and orientation).

Delayed emission

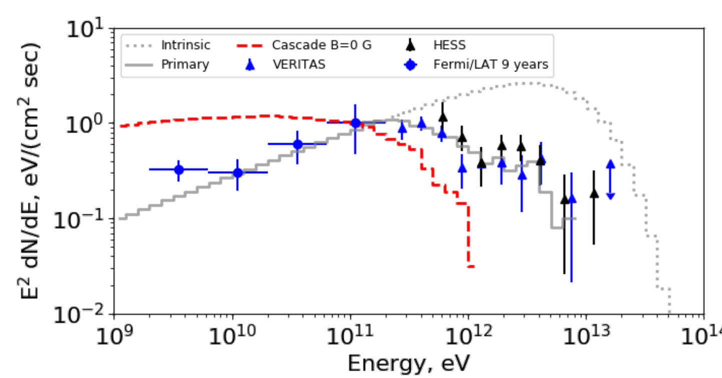
The delay is set by IGMF, but light curve shape may also depend on the jet parameters.

New spectral components

Depend on IGMF, source spectrum, jet orientation.



Taylor+ ‘11



Complicated story of IGMF constraints

	Assumptions	Code	Sources	IGMF limit
2010	No variability on ~10^5 yr time scales + linear emission (Neronov & Vovk ‘10)	private	3	>10^{-16} G
	No variability on ~10^5 yr time scales + conical jet (Tavecchio+ ‘10)	private	1	>10^{-16} G
	No variability on >10 yr time scales + conical jet (Dermer+ ‘11)	private	1	>10^{-17} G
2018	No variability on >10 yr time scales + conical jet + small angle approximation (Ackermann+ ‘18)	public	6	>10^{-16} - 10^{-13} G

2022 Can we do better?..

How may MAGIC help?

Strongest IGMF constraints come from a single source – **1ES 0229+200**
And MAGIC has spent **~150 hr** on it.

(a) One may search for the extended (“halo”) emission

Complex analysis with many assumptions on:

- jet opening / orientation
- source (non)variability
- “halo” angular profile

Proper analysis requires marginalization over all of these…
Costly computationally…

(b) One may search for the delayed (“echo”) emission

\+ almost assumption-free
\- *need to know the source variability*

How may MAGIC help?

1ES 0229+200 is variable in TeV energy band

Indications already in the older H.E.S.S. and VERITAS data.

However, no significant spectral variability in the VHE band.

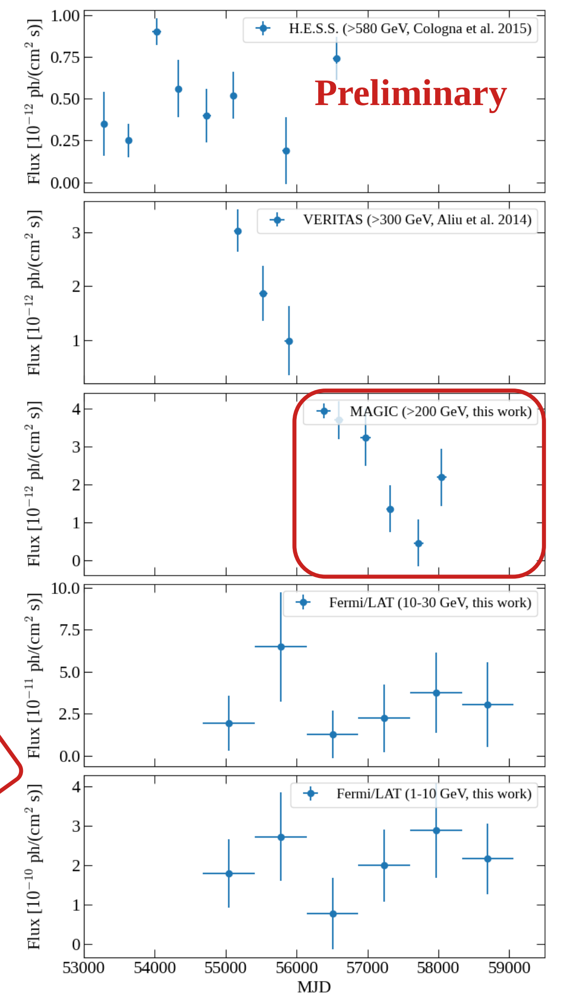
MAGIC has contemporaneous measurements with Fermi/LAT

Variability even in MAGIC data themselves

More reliable TeV-GeV comparison

As TeV data are mostly “halo-free”, we can relax the “no variability” assumption and predict the GeV cascade exactly matching the source flux in TeV band.

For the first time



Predicting the "echo"

Delayed emission can be predicted based on the known variability pattern:

$$F_c(E_\gamma, t) = \int_0^\infty \int_{E_\gamma}^\infty \underbrace{G(E_{\gamma,0}, E\gamma, t-\tau, \tau)}_{} \underbrace{F_s(E_{\gamma,0}, t-\tau)}_{} dE_{\gamma,0} d\tau$$

Cascade Green's function — Variability pattern

CRPropa3 + Berezinsky & Kalashev (2016) codes used to compute the Green's functions for different energy bands

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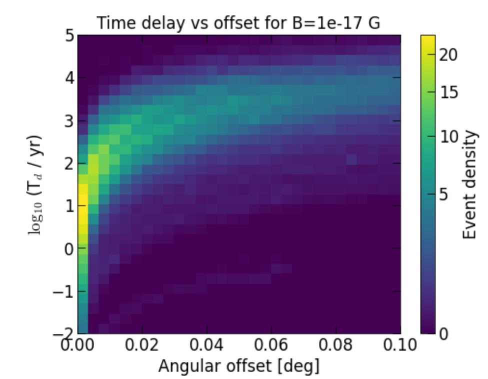
Expected time delay depends on the angular offset

$$T_d \simeq \theta^2 D_A \simeq 1(\theta /10^{-3} deg)^2 yr$$

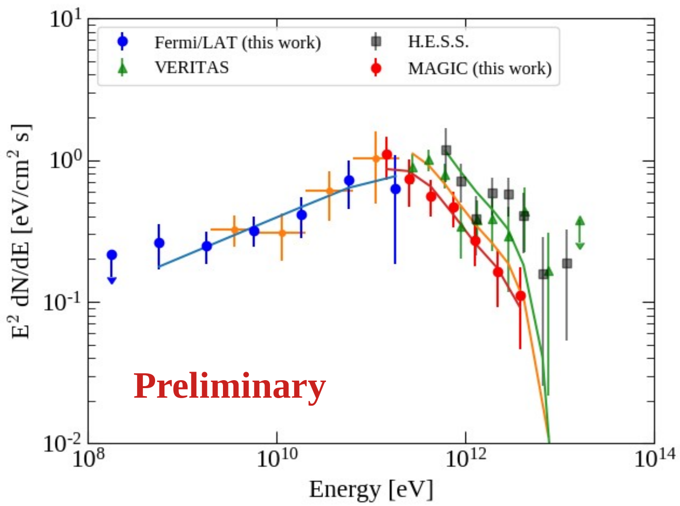
⬇

For time delays of ~10 yr these calculations are insensitive to instrument PSF / source jet properties



→ The only big question is the source spectrum

Source spectrum and minimal cascade



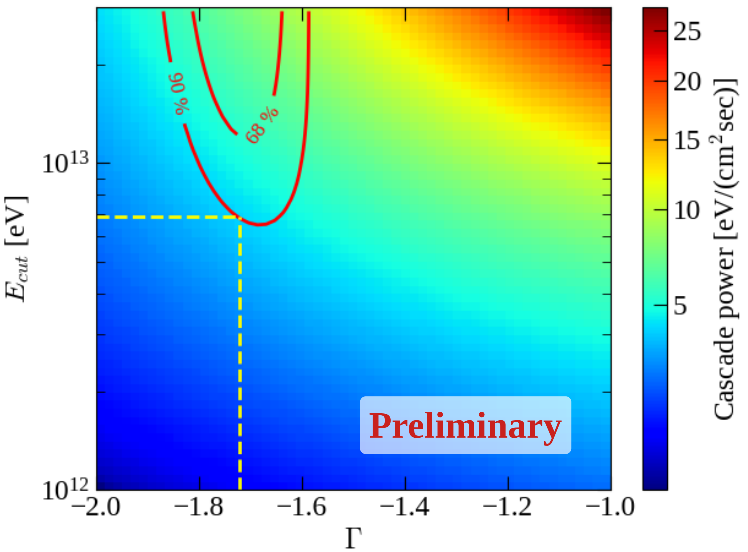
We've updated Fermi/LAT data and allowed for variability in the fit. Spectrum is consistent with the power law with a cut-off model

Γ=1.74±0.07, E_{cut} > 10 TeV, *(χ^2 = 14 over 22 d.o.f.)*

Conservative approach to IGMF limits - minimize the cascade power:

Γ_{min}≈1.72, E_{cut} ≈ 6.9 TeV

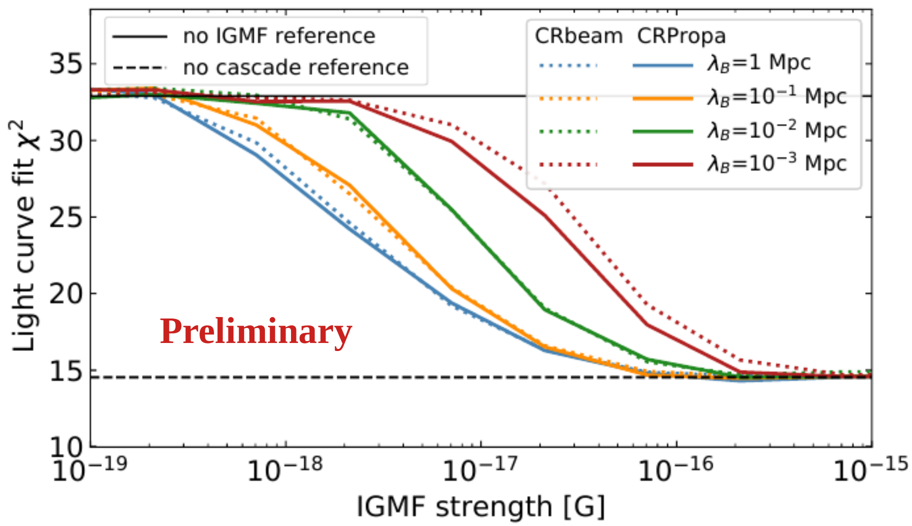
This actually reduced the cascade power compared to our earlier estimates.

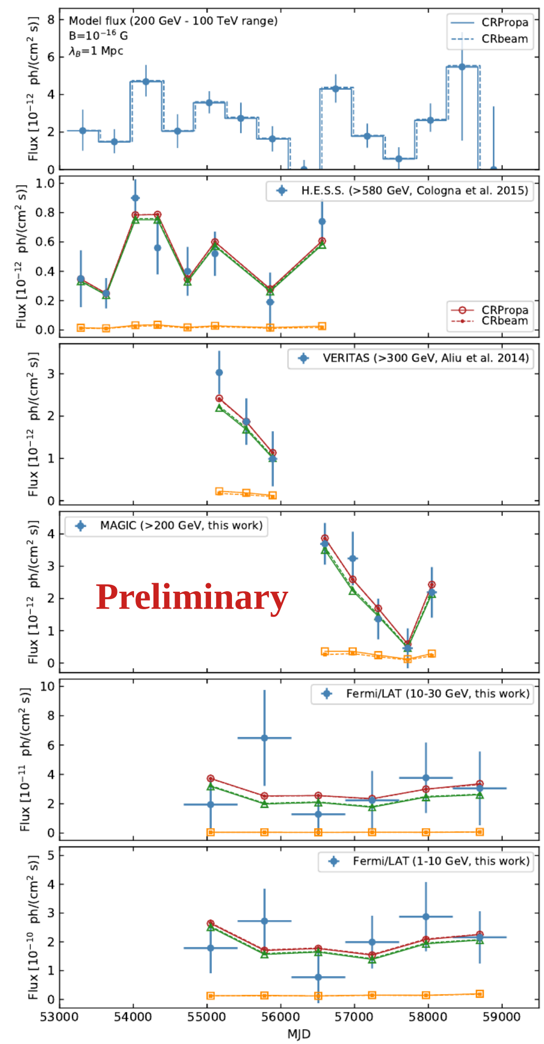


Fitting light curves and excluding “echo”

Advanced light curve fit: predicting fluxes in
exact time bins and exact energy ranges used in the data

Under the hood:
MC simulations on IGMF B-λ grid (no analytical approximations)

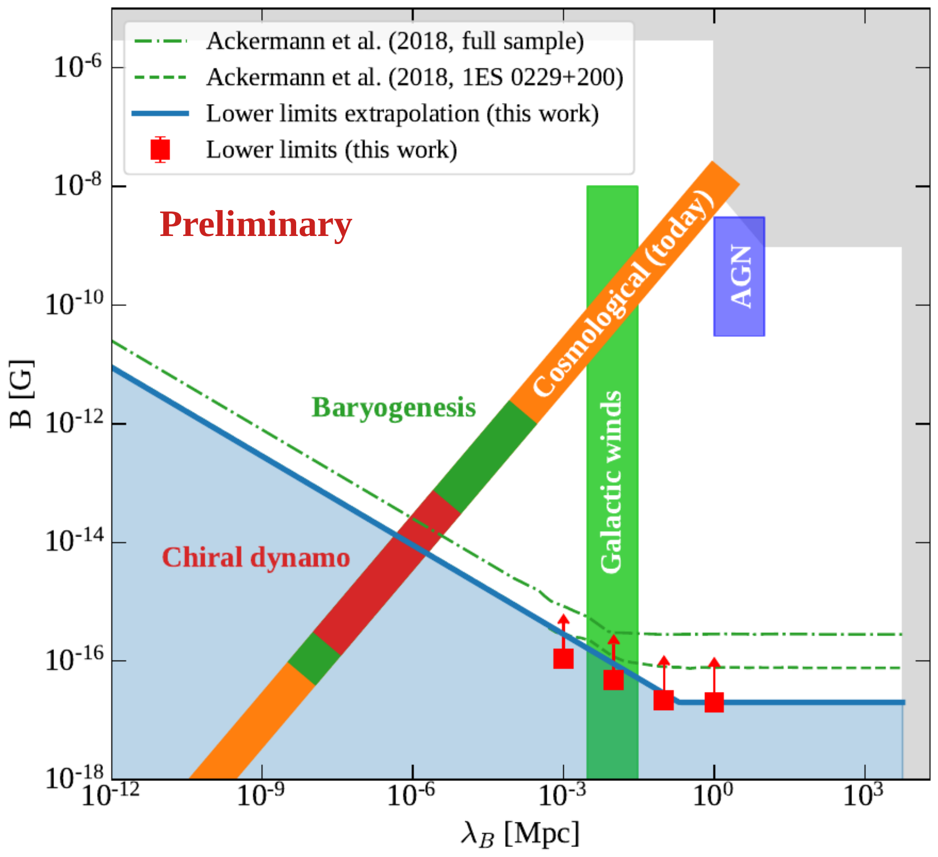




Example for B=10^{-16} G and λ=1 Mpc

Result:
IGMF constraints in virtually assumption-free way

Robust, assumption-free IGMF limit



All of previous studies were based on strong assumptions on the source TeV flux.

For the first time we use contemporaneous Fermi, MAGIC, H.E.S.S. and VERITAS data to relax these.

Strong constraint on models of cosmological magnetogenesis – e.g. IGMF that may have been responsible for baryon assymetry of the Universe.

Example that relevant IGMF can be measured via a detection of delayed “echo” on ~10 yr time scales. Challenging, but feasible task for Fermi/LAT and CTA.

Thank you for your attention!