Modern picture of the Intergalactic Magnetic Field search with very-high-energy gamma-ray observations

Ie. Vovk
ICRR, University of Tokyo, Japan

The extreme Universe viewed in very-high-energy gamma rays 2022,
07.02.2023, Kashiwa, Japan

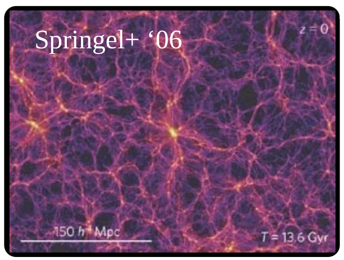
Intergalactic Magnetic Field: hidden window to the early Universe

ICRR
Institute for Cosmic Ray Research
University of Tokyo

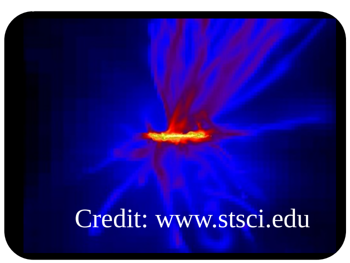
It is generally assumed, that the B-fields in modern galaxies result from amplification of some weaker field (Kronberg ‘94, Grasso & Rubinstein ‘01).

Seed B-field

Cosmological



Galactic



Dynamo amplification

Modern fields in galaxies and clusters

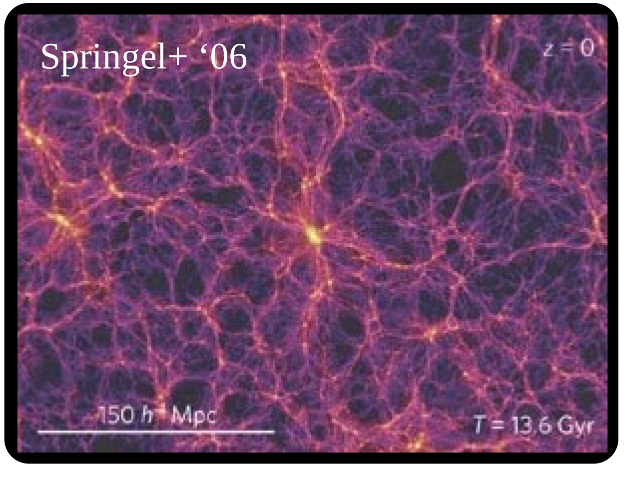
Though the nature of this “seed” field is uncertain (Widow ‘02, Kulsrud & Zweibel ‘08), its properties significantly affect the evolution of galaxies and the Universe as a whole (e.g. Dolag+ ’99).

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

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

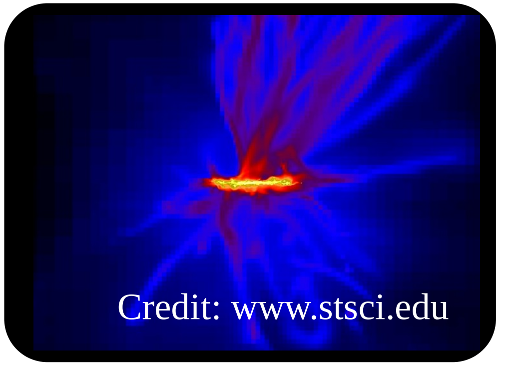
Origin of IGMF

“Cosmological”
Fills 100% of the Universe

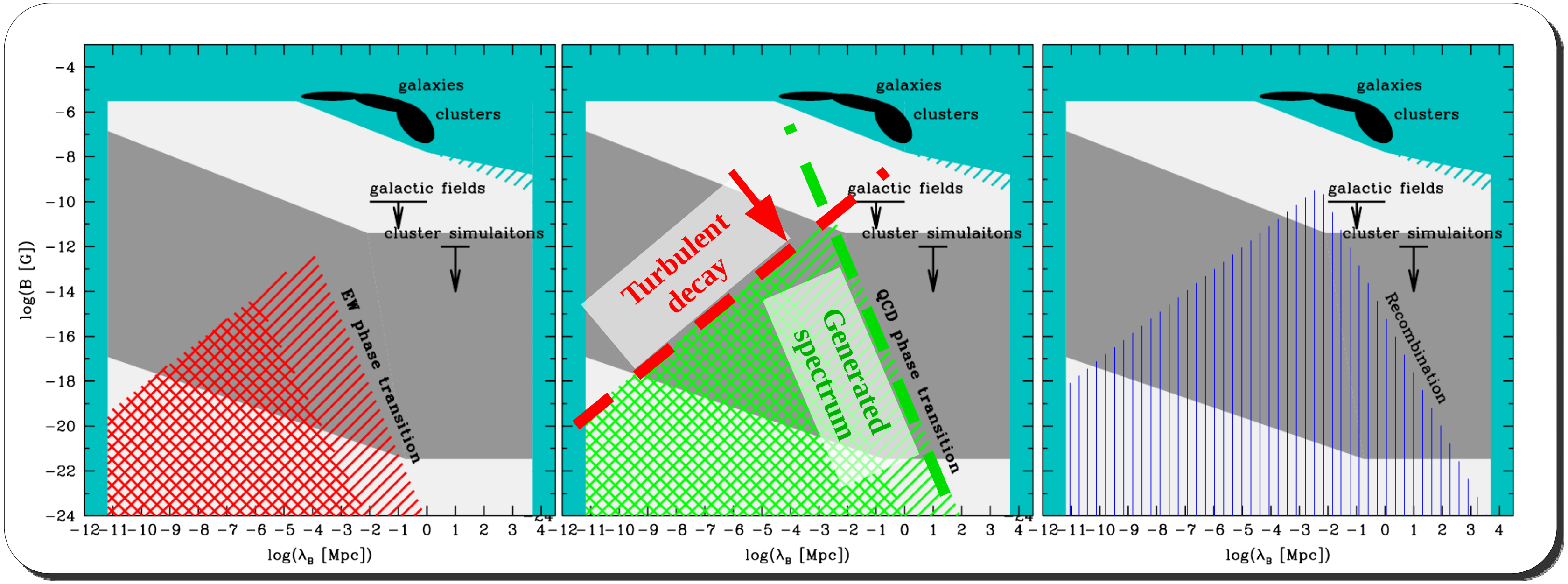


“Galactic”
(large z)
Filling factor: unknown

“Galactic”
(small z)
Filling factor: unknown



Cosmological IGMF



Neronov & Semikoz '09

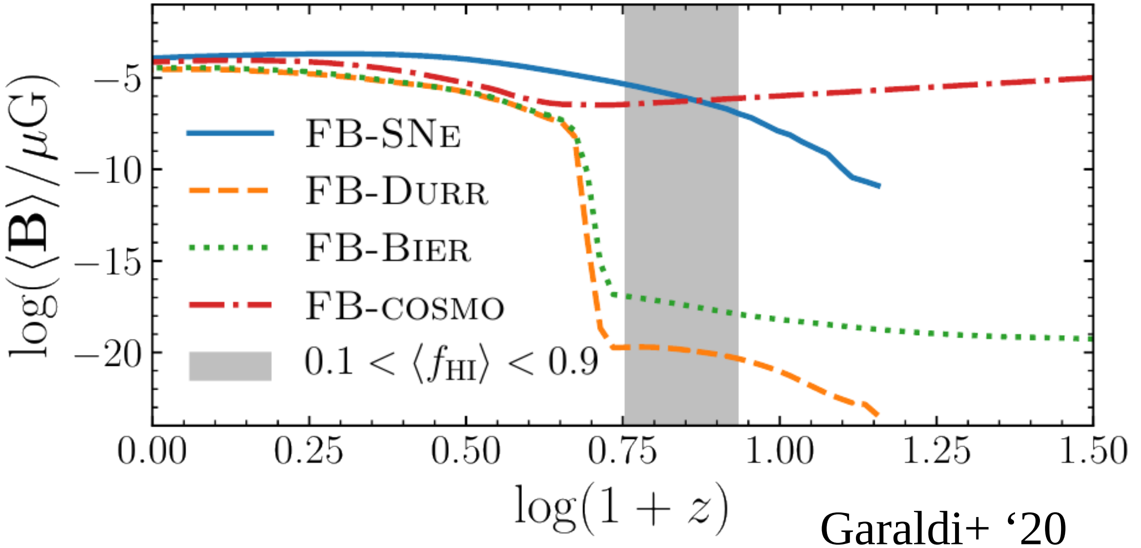
Generation:

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

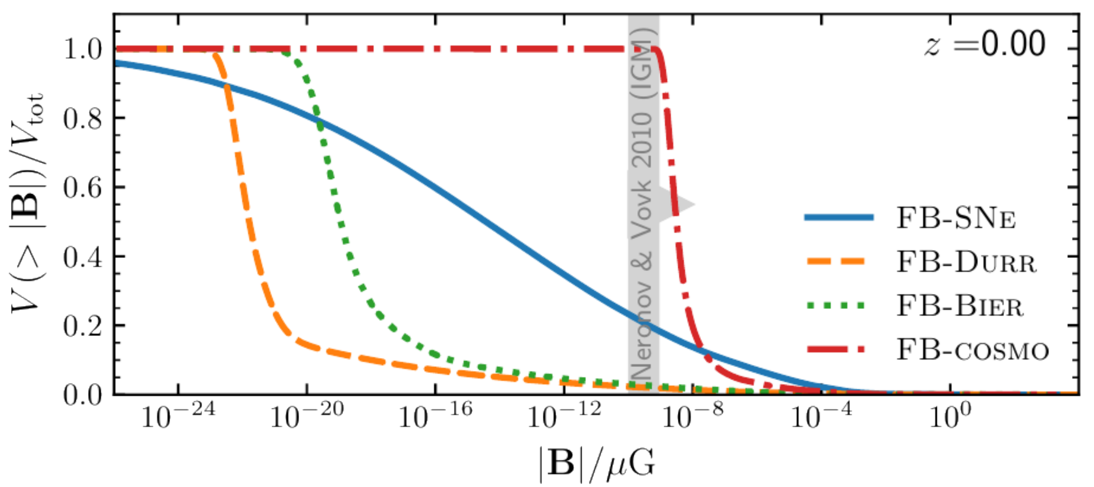
May explain:

- ✔ **Baryonic assymentry (BAU)**
  Transfer of hypermagnetic helicity to baryon number
  (e.g. Giovannini & Shaposhnikov 1998; Fujita & Kamada 2016; Kamada & Long 2016)
- ✔ **Hubble constant tension between CMB and BAO**
  Enhanced recombination rate due to IGMF-induced small-scale matter inhomogeneities (Jedamzik & Pogosian 2020)

Galactic non-AGN magnetization



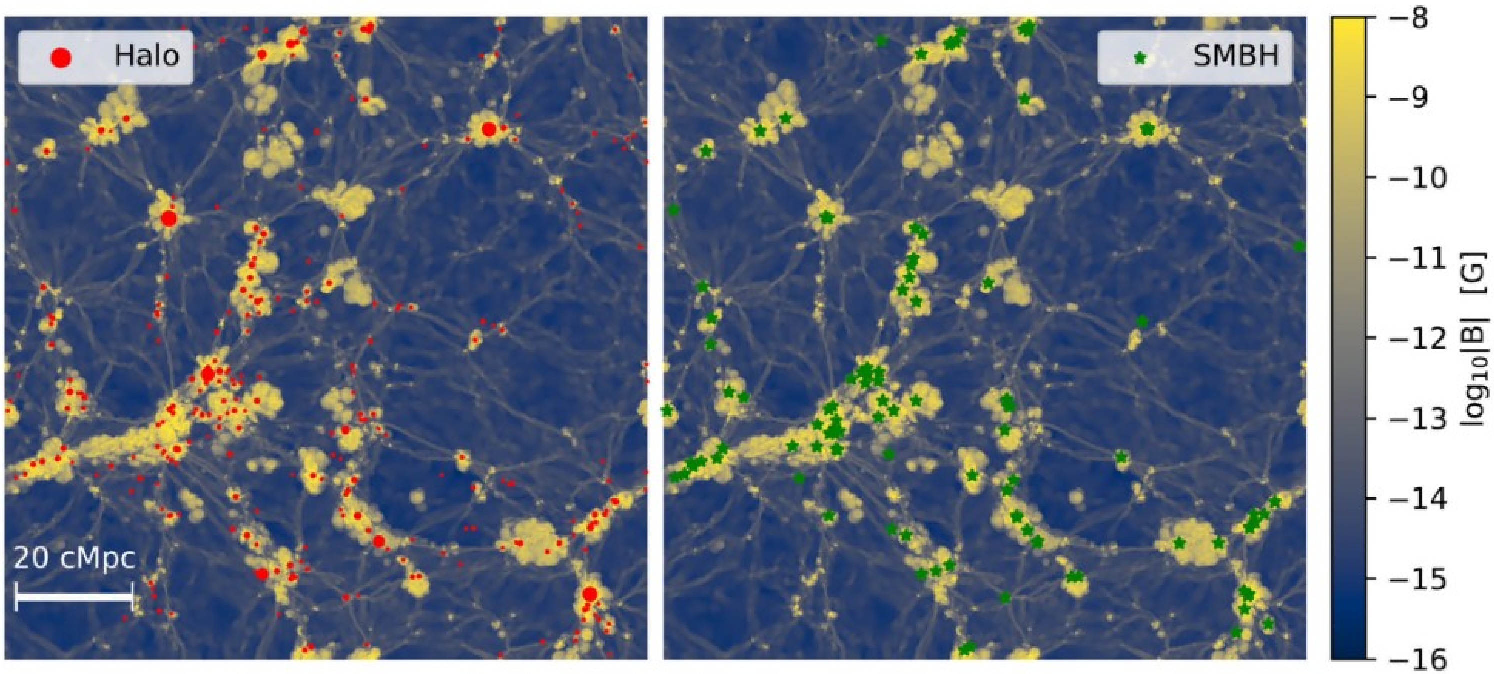
Garaldi+ '20



- Multi-resolution MHD simulations with radiation transfer with the 25-70 Mpc box.
- Galactic IGMF amplification at z~2
- Gradual build up of SNe-generated field
- Magnetization with "batteries" is subdominant compared to SNe
- Cosmological IGMF likely feels most of the volume at z~0

Galactic non-AGN magnetization

Aramburo-Garcıa+ ‘21



- Magnetized ($B>10^{-12}$ G) outflow-driven “bubbles” surrounding AGNs
- Large regions of unperturbed (cosmological) IGMF

Difficult to differentiate between the cosmological and galactic IGMF contributions

Why IGMF constraints are important now?

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

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)

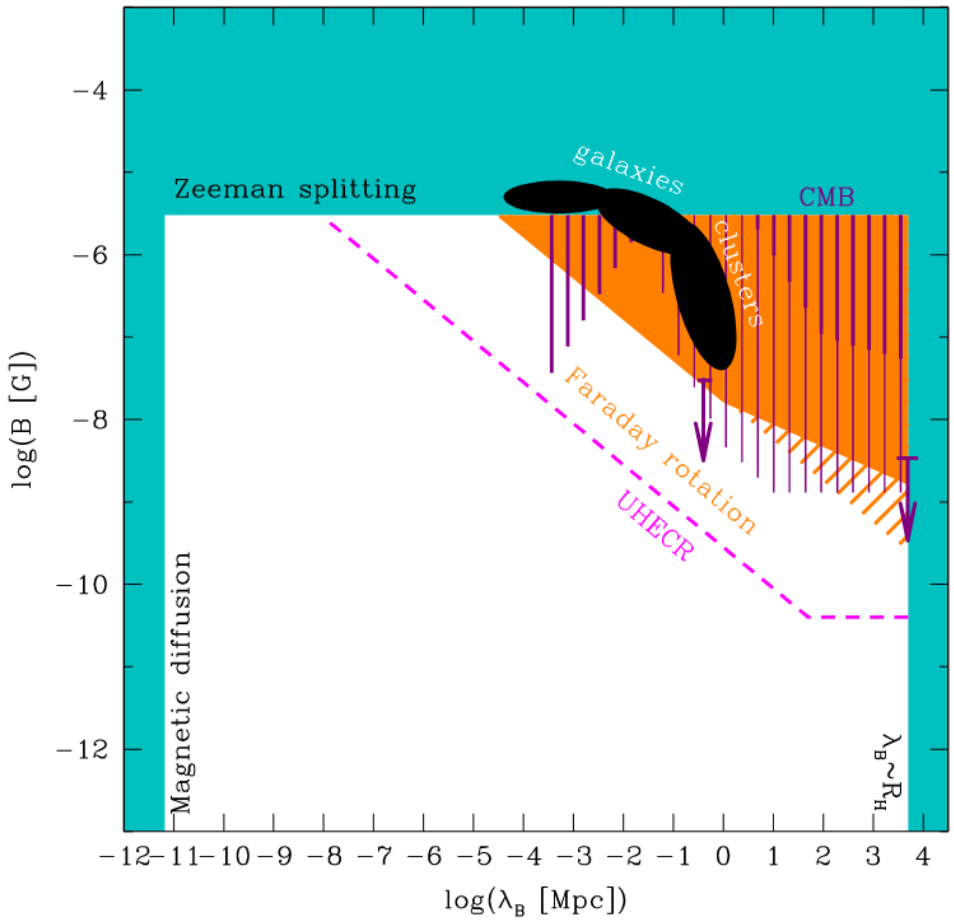
...and local propagation effects

3. Ultra high-energy cosmic rays anisotropy
Combination of the large-scale structure and magnetic horizon in CR propagation
(Globus+ 19)

IGMF measurement is desired

Towards IGMF measurement

Neronov & Semikoz ‘09



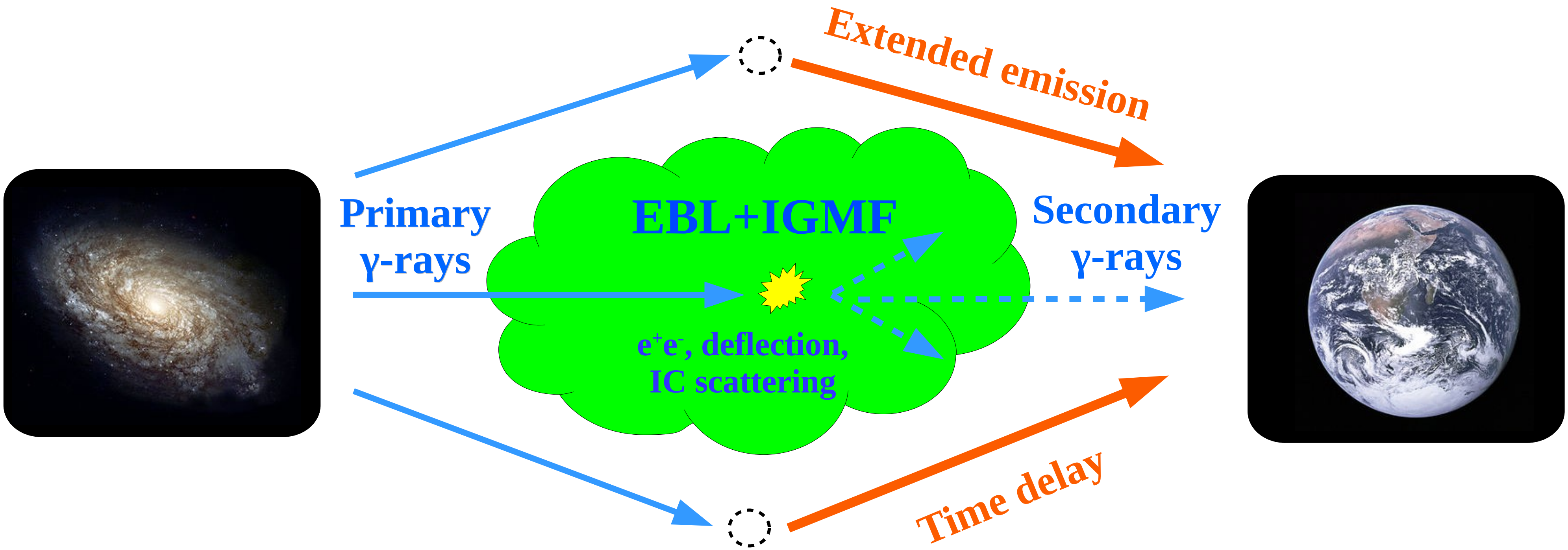
- No detection via Zeeman splitting and Faraday rotation in radio band.
- No imprint in CMB temperature fluctuations.
- No clear imprint in UHECR deflections (though the recently-detected anisotropy may be it)
- Weak ($B<10^{-12}$ G) IGMF required by galaxy formation simulations.

Alternative – measurements in the gamma-ray band

IGMF measurements through gamma-ray data

Institute for Cosmic Ray Research University of Tokyo

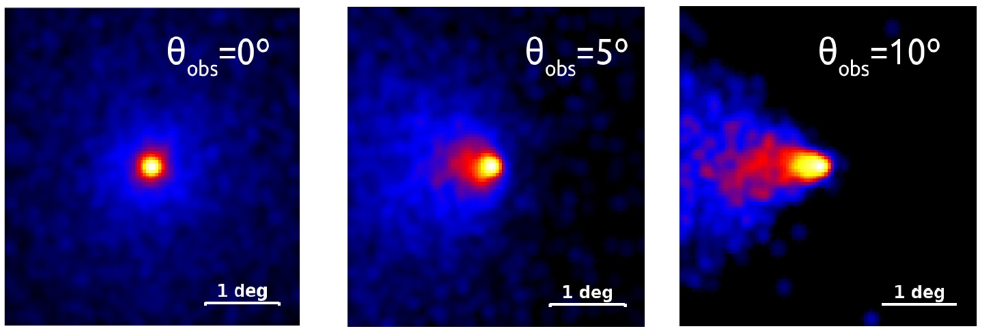
Extremely weak IGMF can be detected using a “long lever arm” of ~100 Mpc scale cascades, initiated by distant AGNs.



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

Institute for Cosmic Ray Research
University of Tokyo



“Smoking gun”: extended halo

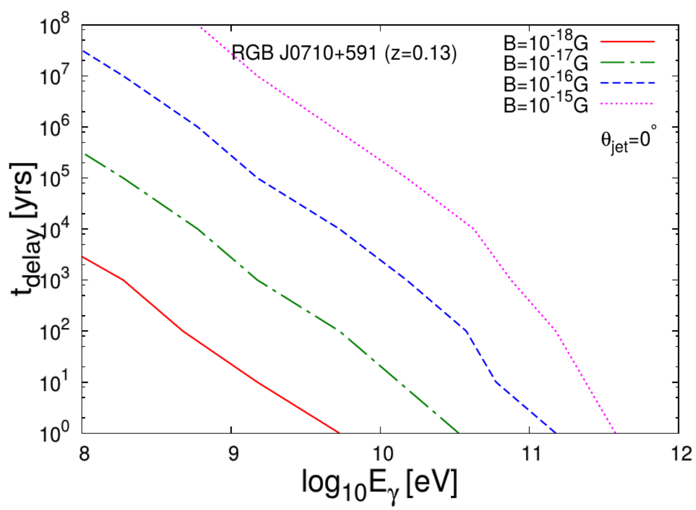
Size and shape depend on IGMF strength and source parameters (jet opening and orientation).

Delayed emission

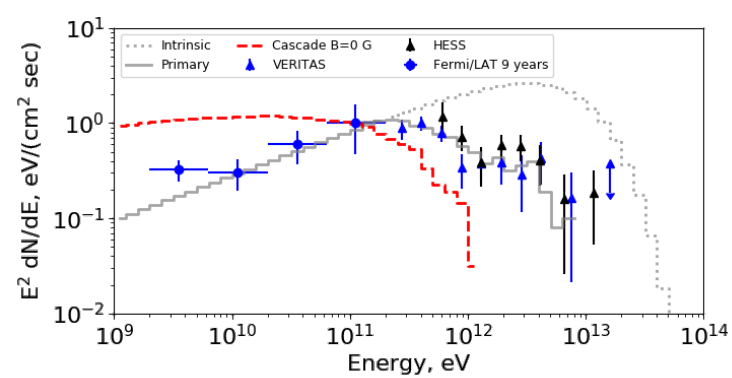
The delay is set by IGMF, but light curve shape may also depend on the jet parameters.

New spectral components

Depend on IGMF, source spectrum, jet orientation.



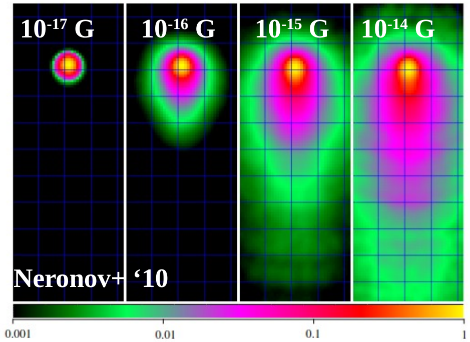
Taylor+ ‘11



IGMF searches: “halos” and “echos”

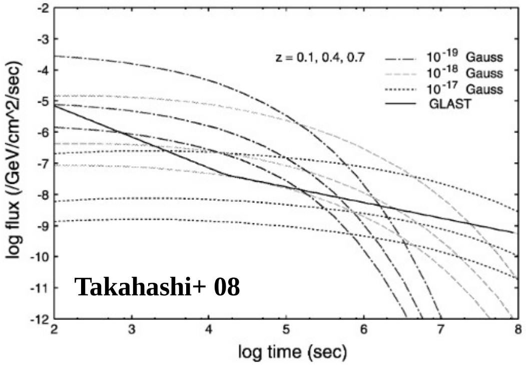
IGMF effect

Spatially-extended “halo”
(e.g. Aharonian+ ‘94, Plaga ‘95, Neronov & Semikoz ‘09, Neronov+ ‘10)



- “Smoking gun” for IGMF
- Sensitive to strong fields ($B>10^{-16}$ G)
- Time delay: $10^3 – 10^7$ yr (source variability?)
- Targets: AGNs (deep exposures)

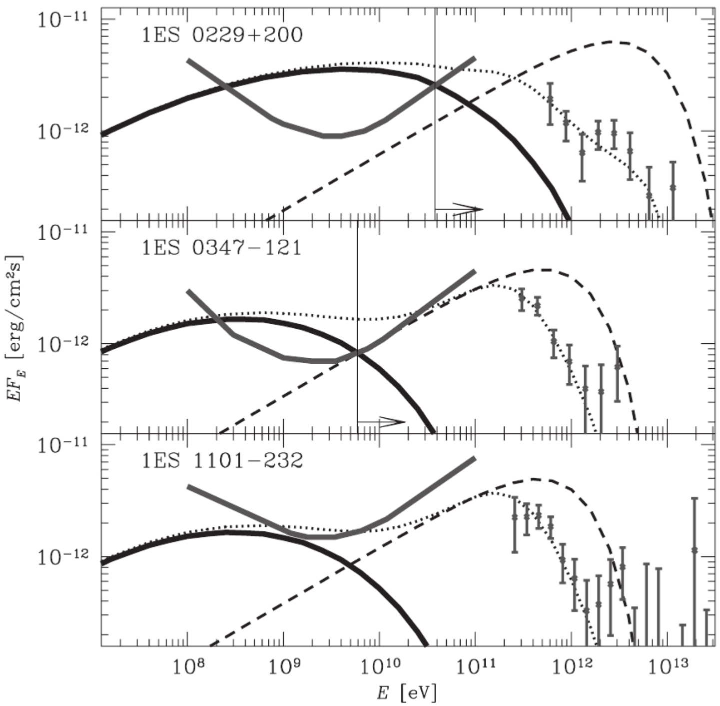
Time-delayed “echo”
(Razzaque+ ‘04, Ichiki+ ‘08, Murase+ ‘08, Takahashi+ 08, Neronov & Semikoz’ 09)



- Energy / time dependency is IGMF-specific
- Sensitive to IGMF $10^{-20} – 10^{-17}$ G
- Targets: GRBs (TeV emission?) and AGNs (long-term monitoring)

IGMF constraints from single blazar observations

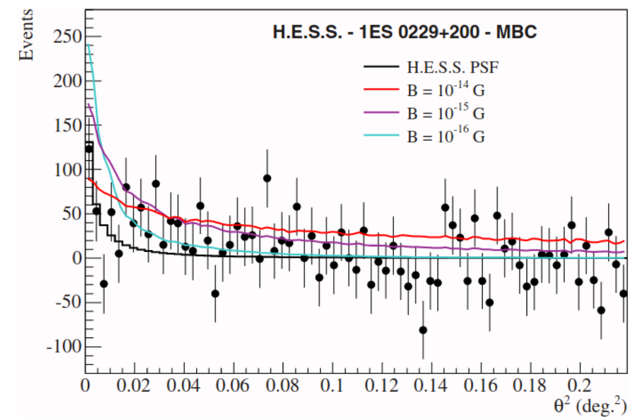
Abramowski+ ‘14



Neronov & Vovk ‘10

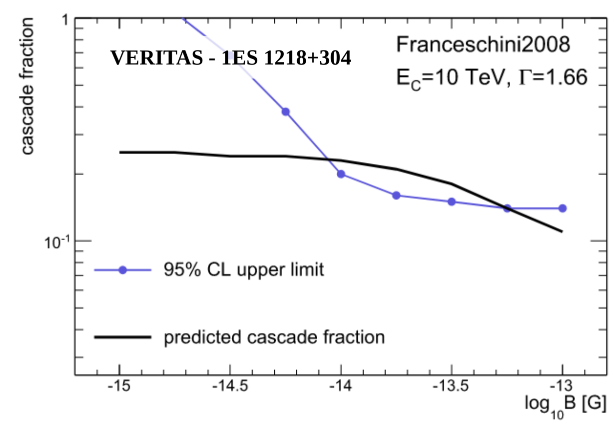
IGMF-induced suppression of the secondary emission from the source direction

→ IGMF > 10^{-16} G



Absence of “halos” larger than PSF and smaller than FoV

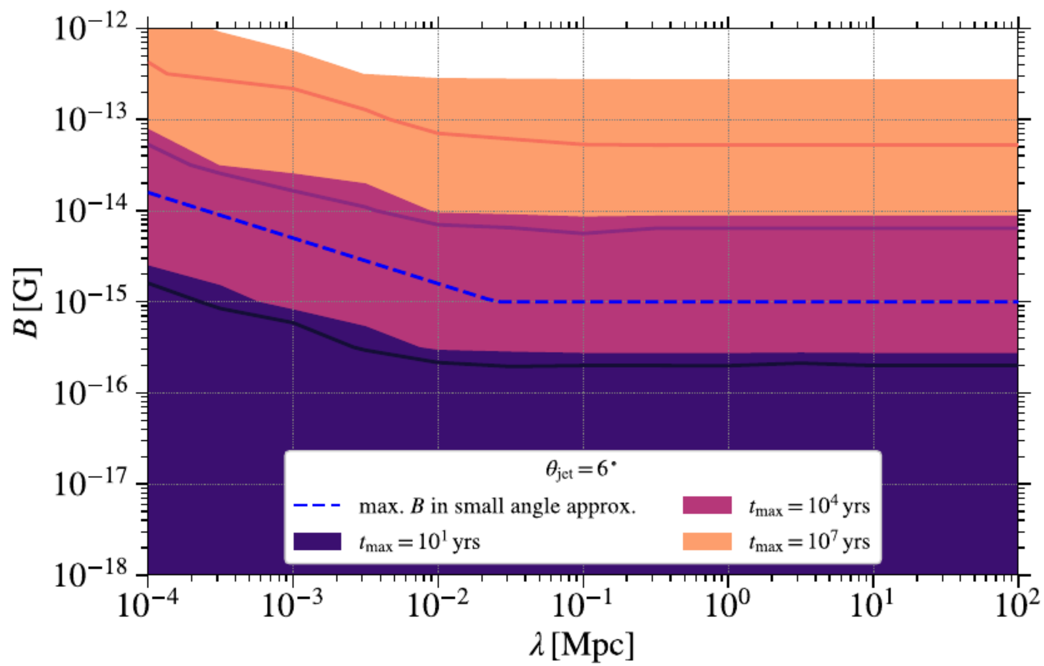
→ Narrow exclusion zones in the 10^{-16} G – 10^{-15} G range



Archambault+ ‘17

IGMF constraints from joint blazar fit

Ackermann+ '18



Combined fit of 6 blazars

- including (stationary) TeV measurements.
- joint fit of cascade and primary emission.
- several jet combinations probed

But...

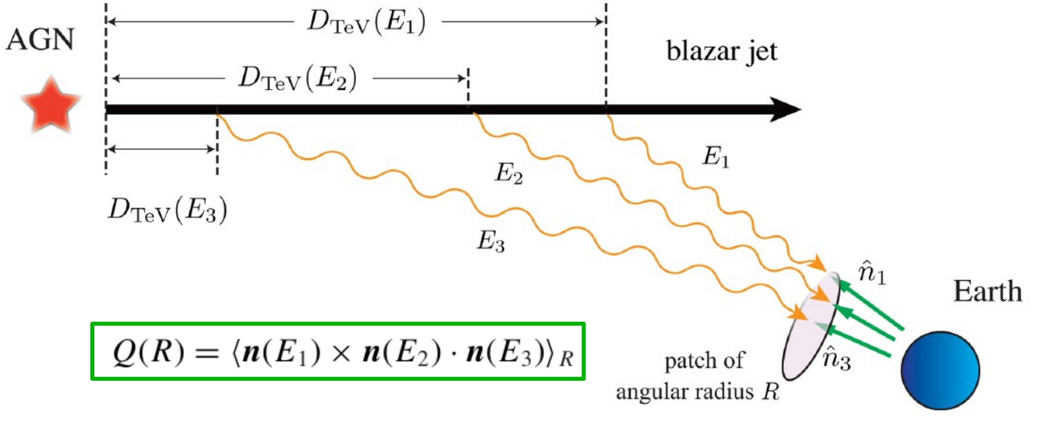
- Small angle approximation may not work for > 10^{-15} G.
- Variability at TeV energies is poorly (or not at all) constrained.

So...

IGMF constraint remains ~10^{-15} G

Helical IGMF searches

Photon arrival directions at different energies may be used to infer the IGMF helicity



From Tashiro & Vachaspati+ '15

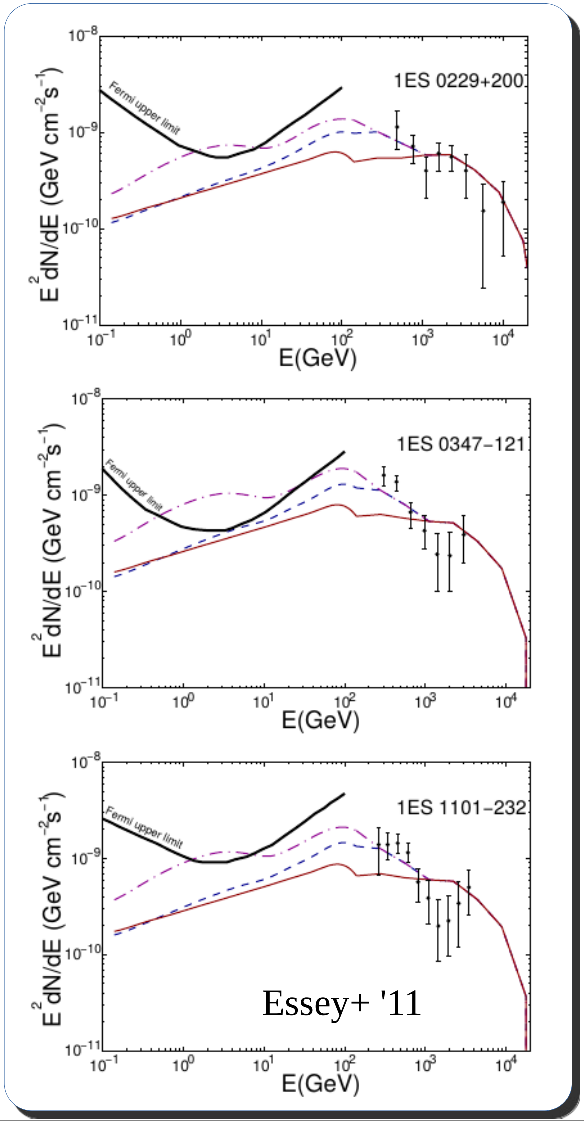
Positive signal in the early (~2.5 yrs) Fermi/LAT data (Tashiro+ '14, Tashiro & Vachaspati '15):

→ maximally helical IGMF with B~10^{-14} @ L=10 Mpc

Negative result with 11-yr long LAT event sample (Kachelriess & Martinez '20):

- sources with $\Theta_{obs} \sim \Theta_{jet}$ are preferred for such studies;
- helicity detection may be possible with CTA if stacking halos of tens of sources;
- more optimal estimators are desired.

UHECR-induced cascades and IGMF



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

A possible explanation: 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).

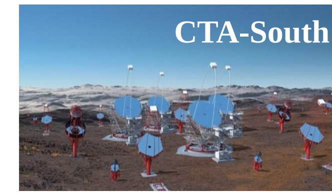
Though the mean free path of UHECRs is different from gamma-rays, the development of the cascade is sensitive to IGMF.
Too strong IGMF would isotropise the cascade and suppress the TeV emission.
Too low IGMF would cause the overprediction of the GeV fluxes.

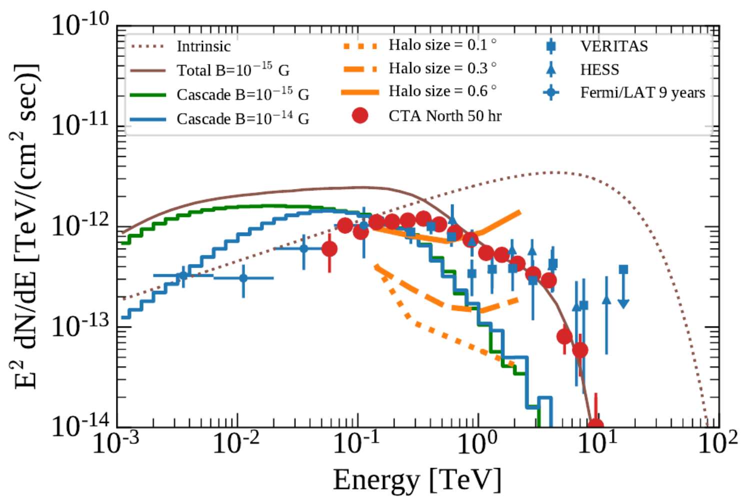
Under this assumption, the limits become (Essey+ '11):

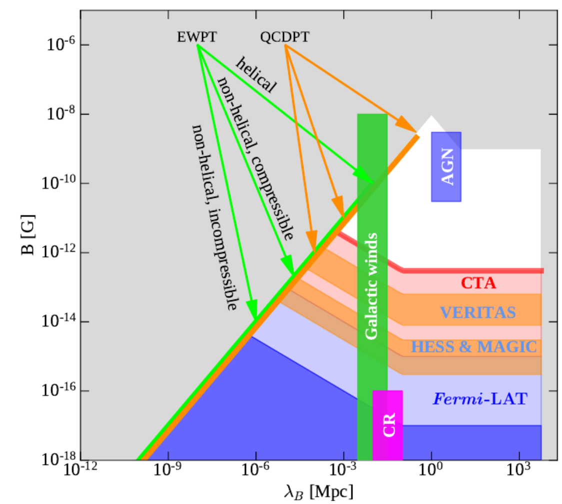
$$10^{-17}\ \mathrm{G} < B < 10^{-14}\ \mathrm{G}$$

IGMF searches in CTA era

Cherenkov Telescope Array (CTA) – next generation IACT observatory







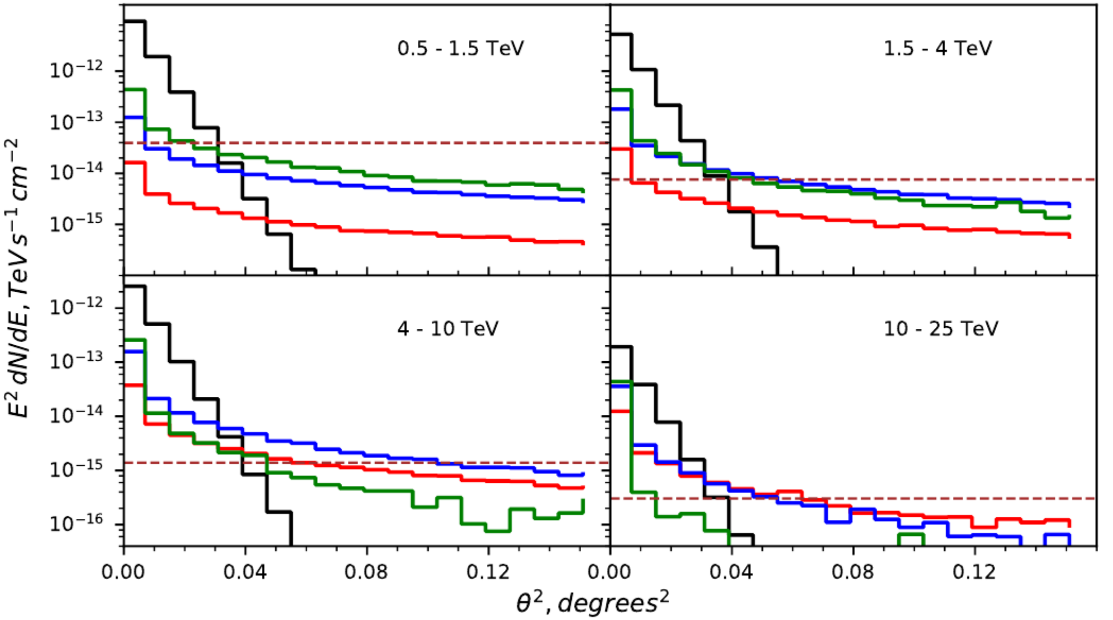
Abdalla+ '20

CTA may reach ~3x10^{-13} G IGMF using "halo" constraints.

More reliable time delay constraints would require dedicated (decade-long) observational campaigns.

IGMF searches in CTA era

Looking for stronger IGMF with nearby sources of ~100 TeV emission



10^{-12} G $3\text{x}10^{-12}$ G 10^{-11} G

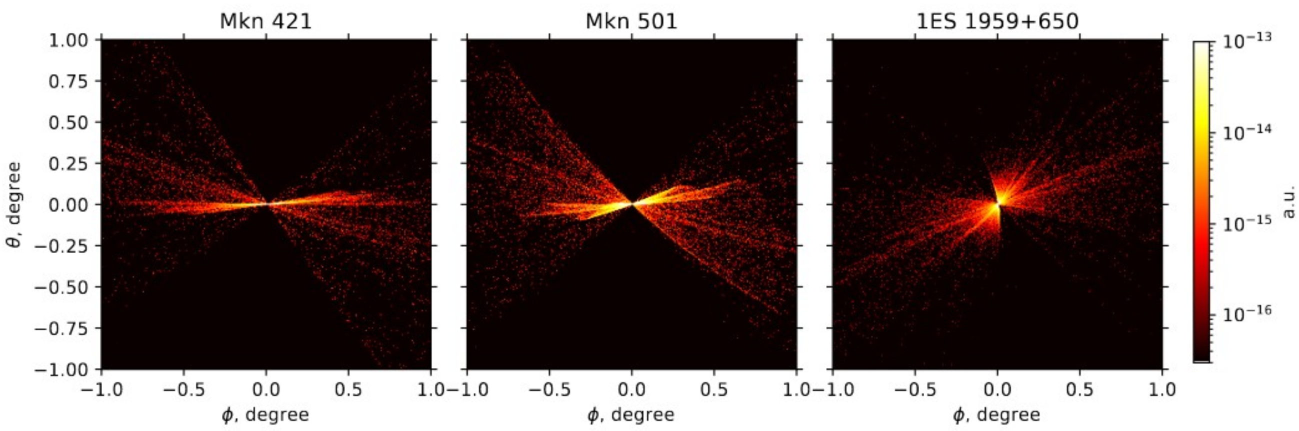
Korochkin + ‘20

- observable halos for up to ~10^{-11} G
- require next-generation instruments e.g. CTA
- require long (50-350 hr) exposures
- source activity needs to be known at ~10 kyr time scales (jet observations?)
- sensitive to MF in the <10 Mpc range from the source (i.e. galactic / cluster fields)

May be an interesting task for future observations of Mrk 501 and Mrk 421

IGMF searches in CTA era

Large-scale IGMF with λ_B > 10-100 Mpc induces asymmetric “halos”



Korochkin+ ‘22

Asymmetry may be detectable with CTA for 10^{-14} – 10^{-12} G IGMF.

Two-sided asymmetric halo is indicative of large λ_B (one-sided halo correlated with the jet orientation is expected otherwise).

Detection of such asymmetry may speak in favour of the cosmological (infaltionary) nature of IGMF.

Looking for the time-delayed “echo”?

1 **Except if “halo” is detected, limits from its non-detection depend on the assumed source flux in the past.**

E.g. time delay scaling with halo size at z ~0.14 is

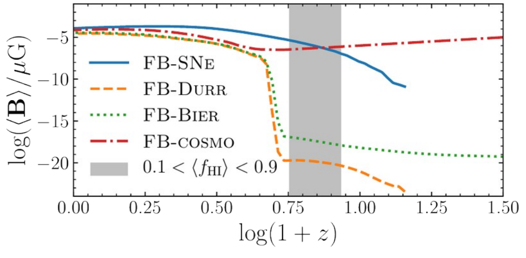
$$T_d \simeq \theta^2 D_A \simeq 1 (\theta / 10^{-3} deg)^2 \, yr$$

→ Reliable limits – knowledge of the variability history

2 **Next “important” IGMF constraints require z>1**

Not many persistent sources there – but some variable

Garaldi+ ‘20



↓

Disentangle galactic / extragalactic IGMF origin

GRBs / flaring AGNs to search for IGMF “echo”?

But:

- intrinsic time delay may be $\Delta t \sim 10^2$-10^4 s → strong suppression (GRB)
  (Razzaque+ ‘04, Ichiki+ ‘08, Takahashi+ ‘08, Murase+ ‘08/09)
- required accuracy $\varepsilon = c\Delta t/d \sim 10^{-17}$,
  while double-precision floating-point type has $\varepsilon \sim 10^{-16}$
  → modern simulation packages (CRPropa, CRBeam, ELMAG) may not be suitable

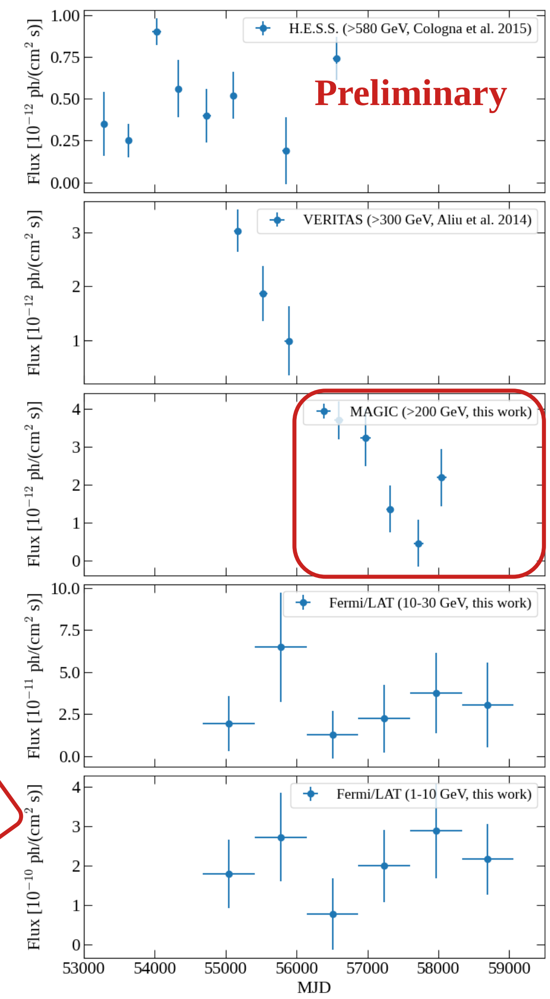
Robust IGMF limit from contemporaneous GeV-TeV variability

MAGIC collaboration, TeVPA ‘22

Primary source for IGMF constaints - 1ES 0229+200 - is found 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

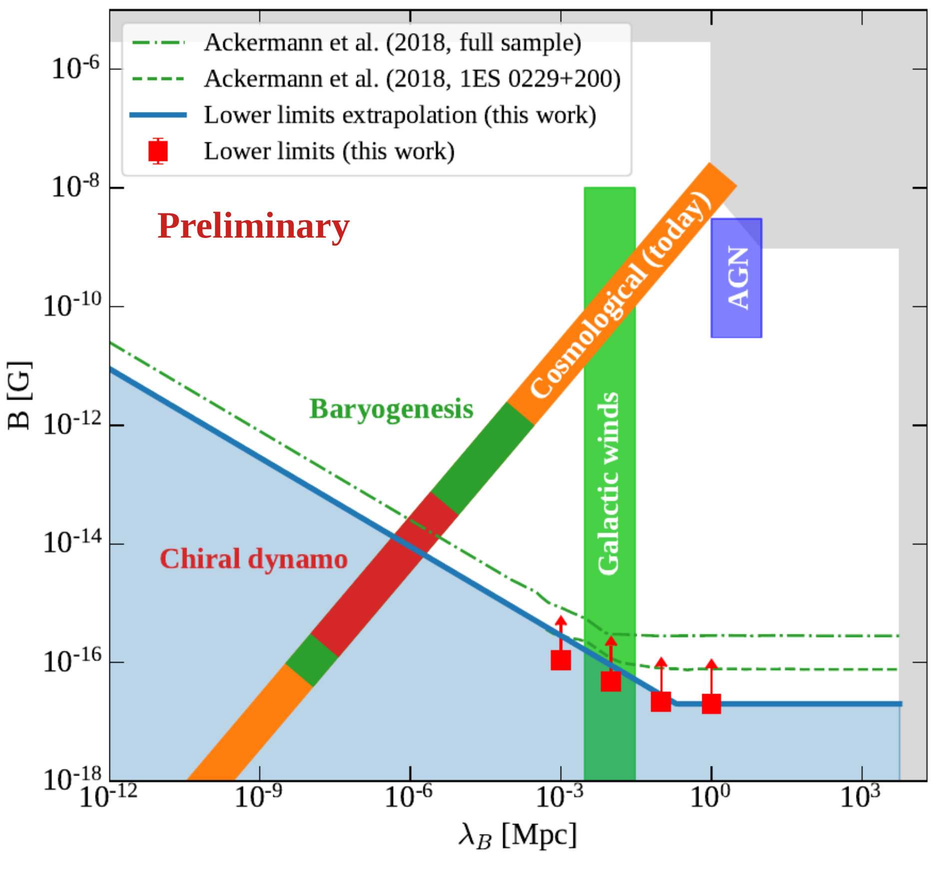
More reliable TeV-GeV comparison

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

Robust IGMF limit from contemporaneous GeV-TeV variability

MAGIC collaboration, TeVPA '22



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

MAGIC observations relax assumptions on the source flux (in)stability.

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

GRB190114C – unique opportunity for pair echo detection

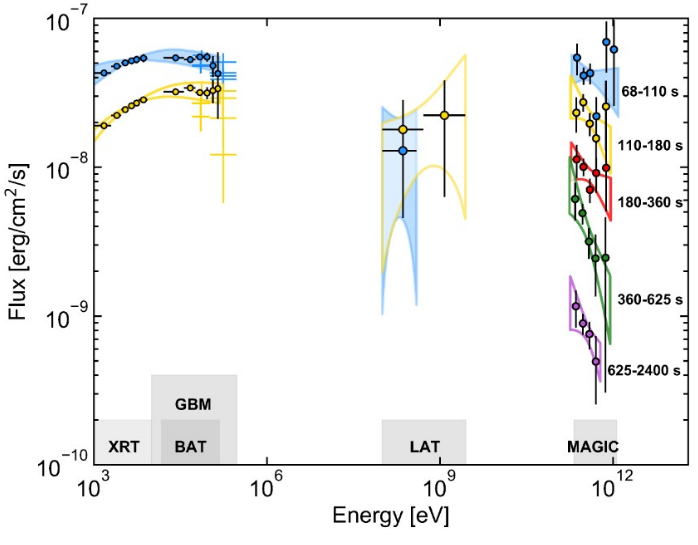
Bright TeV GRB with key properties, required for IGMF-induced "echo" searches

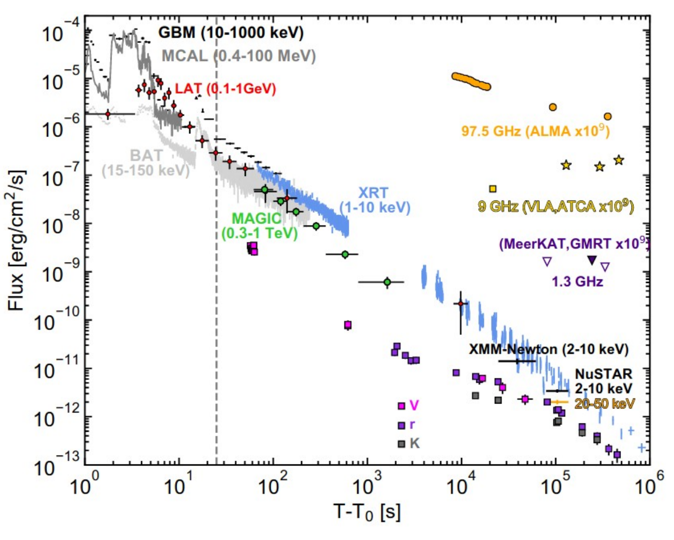
(MAGIC collaboration '19 a/b)

Contemporaneous HE (0.1-1 GeV) + VHE (0.3-1 TeV) detections

Larger redshift z=0.42

Long duration $\Delta t \sim 10^3$ s





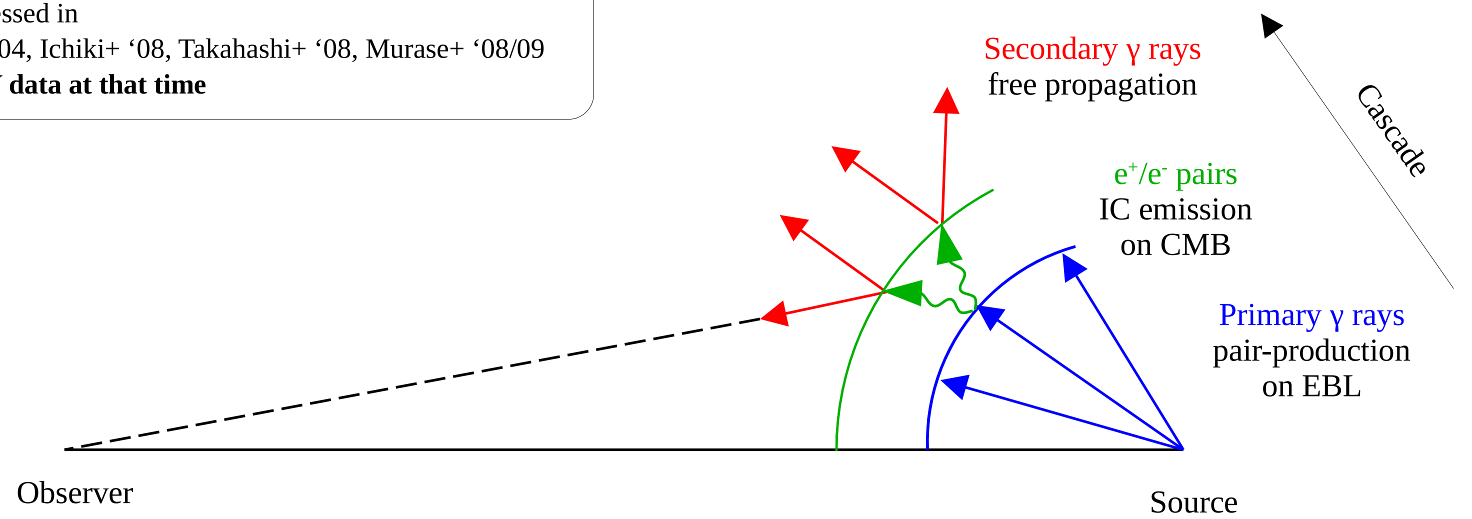
$\varepsilon = 1\,(E_\gamma/1\text{ TeV})^2$ GeV → energy bands well aligned

$K = T_{flare} / (T_{delay} + T_{flare})$ → smaller flux suppression

Intrinsic time delay of the electromagnetic cascade "echo"

Time delay = (primary+electron+secondary) travel time - direct light propagation time

Earlier addressed in
Razzaque+ '04, Ichiki+ '08, Takahashi+ '08, Murase+ '08/09
without TeV data at that time



Intrinsic angular spread of cascade

Slower than light
election motion

Pair production
angular dependency

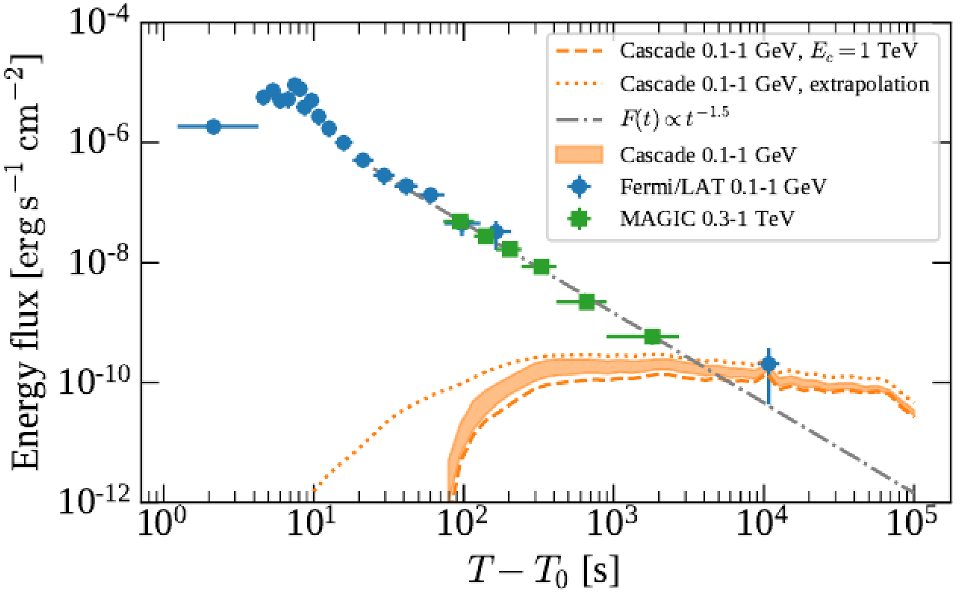
IC emission
angular profile

GRB190114C: "pair echo" prediction in the zero IGMF case

Vovk '23, accepted

- "Echo" calculated summing up the 6 MAGIC time bins, assuming a power law spectral shape.
- **If emission @ 10^4 s is the pair echo:**
  - prompt phase VHE flux can not exceed much the F(t) ~ $t^{-1.5}$ extrapolation.
  - IGMF < 10^{-21} G @ z ≈ 0.4 → Possible contradiction with constraints from blazars @ z ~ 0.1. Favors "galactic" IGMF origin. Inhomogeneous IGMF?
  - only sub-dominant role of the plasma instabilities
- **If emission @ 10^4 s is not the pair echo:**
  - IGMF > 10^{-21} G @ z ≈ 0.4, in agreement with constraints from blazars.

"Pair echo" for zero IGMF
is consistent with GRB190114C observations



→ IGMF measurements with TeV bright GRBs at z~1 are feasible

Final remarks

Strong evidences for non-zero IGMF at z~0.2 from non-detection of the expected secondary gamma-ray emission.

IGMF nature identification:

- from measured IGMF-induced “echo” / “halo”
- from redshift evolution (many sources)

→ A new page in the Early Universe studies (if IGMF is cosmological)

Spatial structure of IGMF (“bubbles” vs uniform field):

- from gamma-ray data
- from UHECR anisotropy

→ UHECR sources identification

Leap forward is expected from future CTA observations.

But **improvements are possible already** now:

- multi-year observational campaigns;
- target-of-opportunity observations (GRBs and AGNs).

Emerging population of TeV-bright GRBs may allow to probe IGMF @ z ~ 1 already in the following few years.