Intergalactic magnetic field lower limits up to the redshift $z \approx 3$

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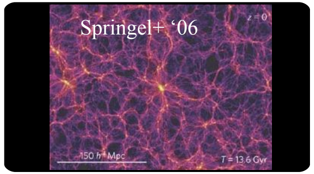
Present-day galactic field origin problem

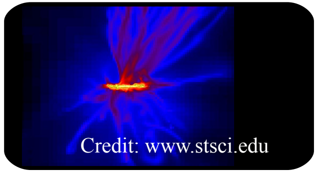
It is generally assumed, that the magnetic fields in modern galaxies result from amplification of some weaker “seed” field (Kronberg ‘94, Grasso & Rubinstein ‘01).

Seed B-field

Cosmological



Galactic



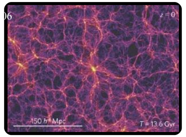
Dynamo amplification

Modern fields in galaxies and clusters

What is the nature of the “seed” field?

What is the “seed” field origin?

Why does it matter?



“Cosmological” origin

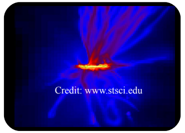
New window into the Early Universe

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” origin

Traces galaxy evolution and feedback



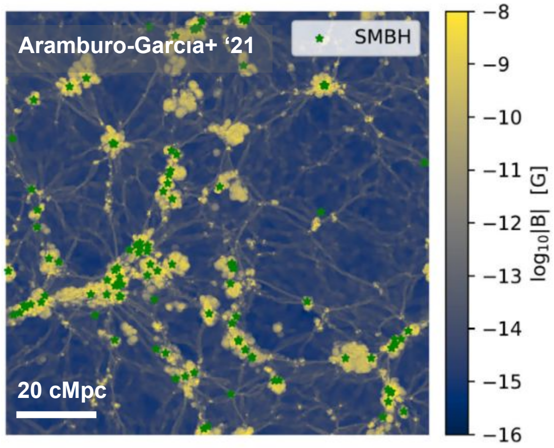
- protogalaxies (vorticity, Bierman battery)
- reionization (Durrive battery)
- stellar evolution feedback (SN, CR-driven currents)
- AGNs

Widrow ‘02, Miniati & Bell ‘11, Beck+ ‘13, Durrive & Langer 15, Garaldi+ ‘21, Vazza+ ‘25 …

IGMF measurements – an attempt to identify the “seed” field and understand the present-day IGM magnetisation

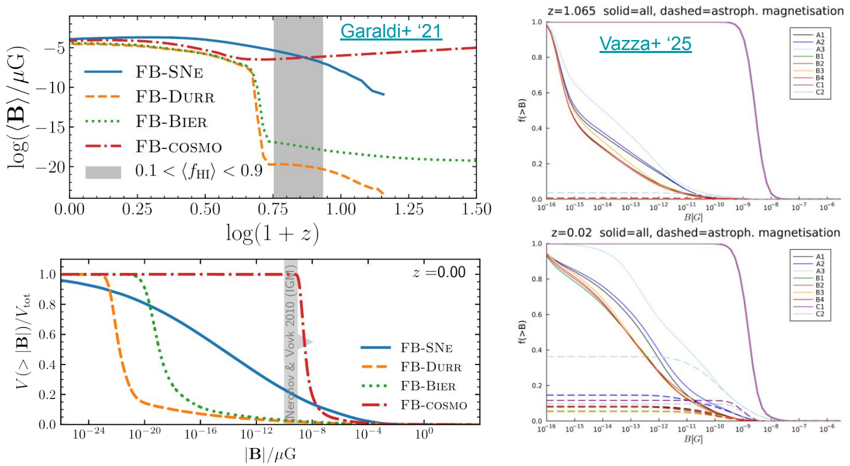
Modern picture of IGM magnetization

Complex structure



- Magnetized outflow-driven "bubbles" surrounding AGNs
- Large regions of unperturbed (cosmological) IGMF
- "Bubble" volume filling fraction strongly depends on the feedback model (e.g. the CAMELS project, Yueying+ '23)

Redshift dependency



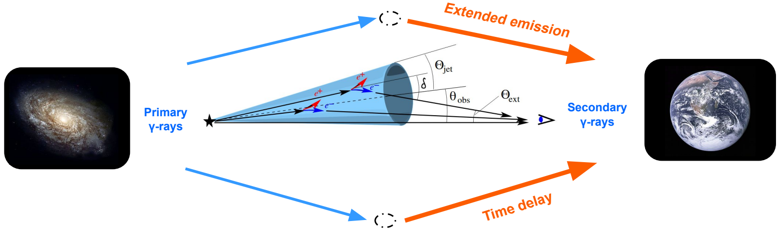
- **Magnetisation history is mechanism-specific**
- @ z = 0 both galactic and cosmological fields mix in non-negligible proportions

Present-day IGM may contain a mixture of cosmological and galactic magnetic fields

Measurements at different redshifts may be used to trace its origin

IGMF constraints with gamma-ray observations

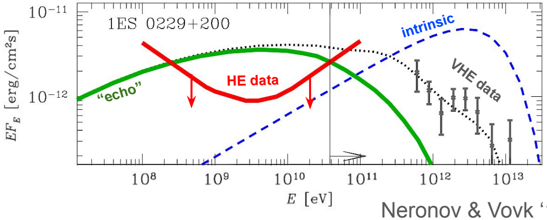
Idea: charged-particle cascades are sensitive to the large-scale (~100 Mpc) IGMF



Non-negligible IGMF – "halos" & "echos"
around distant sources
(Plaga '95, Neronov & Semikoz '09)

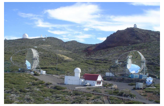
IGMF measurements: low- ("echo") and high- (intrinsic) energy emission balance

Fermi/LAT
all-sky, 0.1 – 300 GeV band



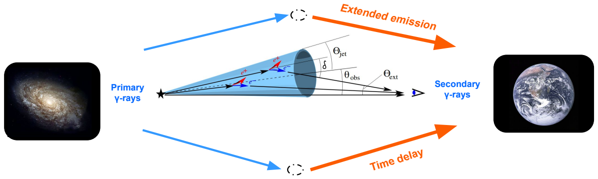
Neronov & Vovk '10

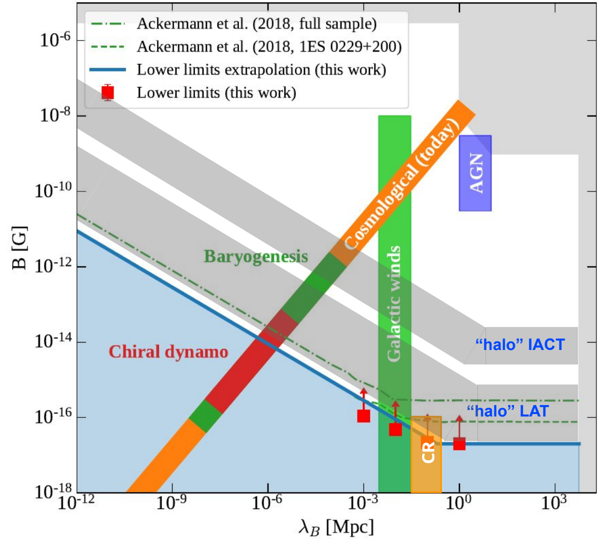
Ground-based IACTs
targeted observations > 100 GeV



IGMF lower limits up to z ≈ 3

Modern IGMF constraints





Adapted from MAGIC Collaboration '23 with the models of Miniati & Bell '11, Furlanetto & Loeb '01 and Bertone+ '06

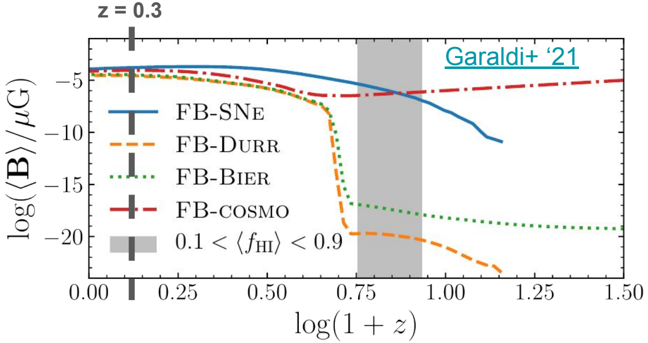
Fermi/LAT measurements

(Neronov & Vovk '10, Tavecchio+ '10, Dermer+ '11, Dolag+ '11, Taylor+ '11, Vovk+ '12, Finke+ '15, Ackermann+ '18, Huang+' 23, Dzhatdoev+ '24, Vovk+'24, Blunier+ '25)

are complemented by **IACTs**

(Aharonian+ '01, Aleksic+ '10, Abramowski+ '14, Archambault+ '17, Aharonian+ '23, MAGIC Collaboration '23).

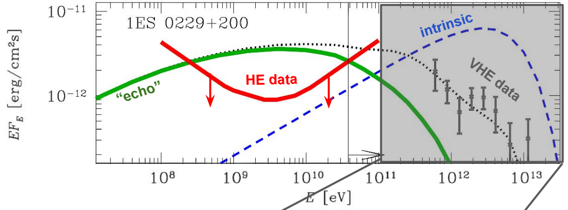
These limits derived at low redshifts z ~ 0.1 – 0.3



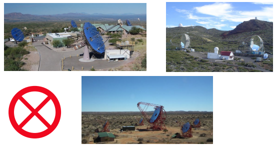
… So we know IGMF exists – but do not know its origin

High-redshift IGMF measurements challenge

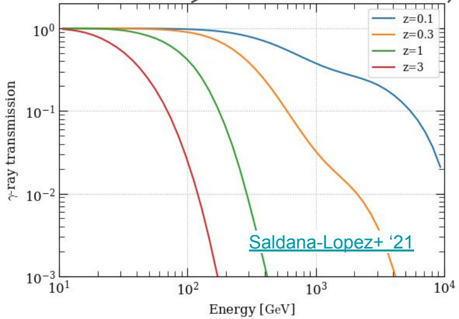
IGMF measurements: low- (“echo”) and high- (intrinsic) energy emission balance



Strong intrinsic VHE emission attenuation on EBL

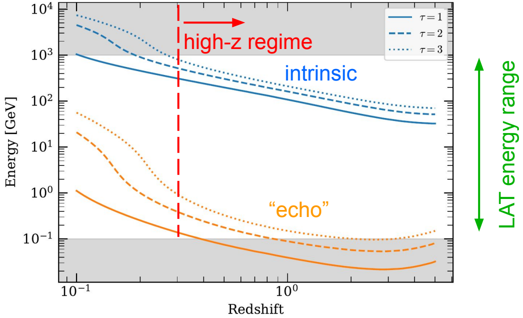


- only a handful reported TeV-band detections at $z > 0.5$
- sparse measurements → artificial assumptions on the source (non-)variability within the observational time window



17-yr long Fermi/LAT all-sky exposure

- dozen of AGN detections in VHE band (4FGL, Neronov+ ‘15, Neronov & Semikoz ‘25)
- fully contemporaneous HE – VHE measurements



High-redshift AGNs sample and analysis

Source sample: 20 sources with z = 0.5 - 3

- confident detections (4FGL TS>25): 4
- tentative detections (4FGL TS>9): 4
- bright @ 30-100 GeV: 5
- dedicated VHE searches (Neronov & Semikoz ‘25): 4
- bright 4LAC sources with SIMBAD redshifts: 3

Standard Fermi/LAT analysis

- wide energy range 0.1 GeV – 1 TeV
- 17-year long exposure
- SEDs with FermiPy
  (use “PSF classes” for higher sensitivity)
- light curves from aperture photometry

Conservative “echo” model

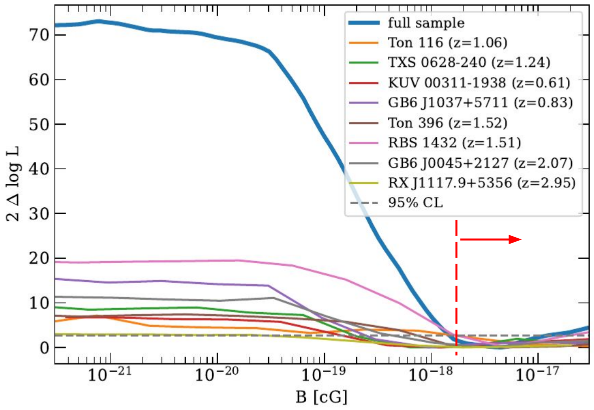
- CRBeam MC simulation (Kalashev+ ‘23)
- variable IGMF strength and volume filling factor
- conservative EBL model choice
- free high-energy cut-offs for all sources

Accurate data – model comparison

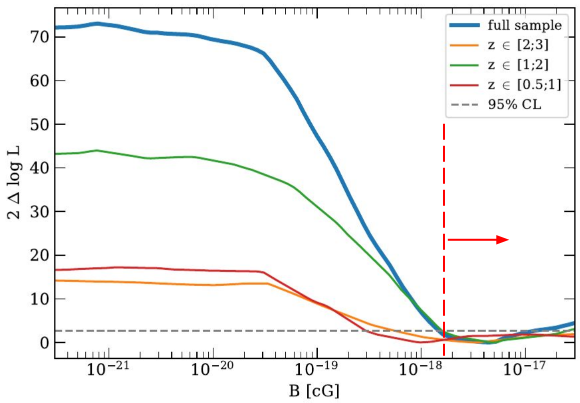
- use exact LAT energy and time bins
- “flux – likelihood” profiles pre-computed with FermiPy
- account for LAT collection area systematics

Results: collective high-redshift IGMF limit

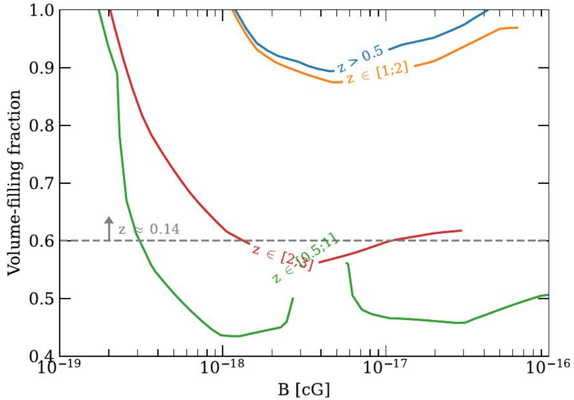
Total limit and individual sources



Binned by redshift



Volume-filling fraction constraints



$$B \gtrsim \begin{cases} 1 \times 10^{-18}\ \text{cG} & , \lambda_B \geq D_e \\ 1 \times 10^{-18}\,(\lambda_B/D_e)^{-1/2}\ \text{cG} & , \lambda_B < D_e \end{cases}$$

$$D_e(z) \approx 2(1+z)^{-3} \sqrt{\frac{0.1\ \text{GeV}}{E_\gamma}}\ \text{cMpc}$$

Zero-IGMF model rejection @ 8.6σ significance level

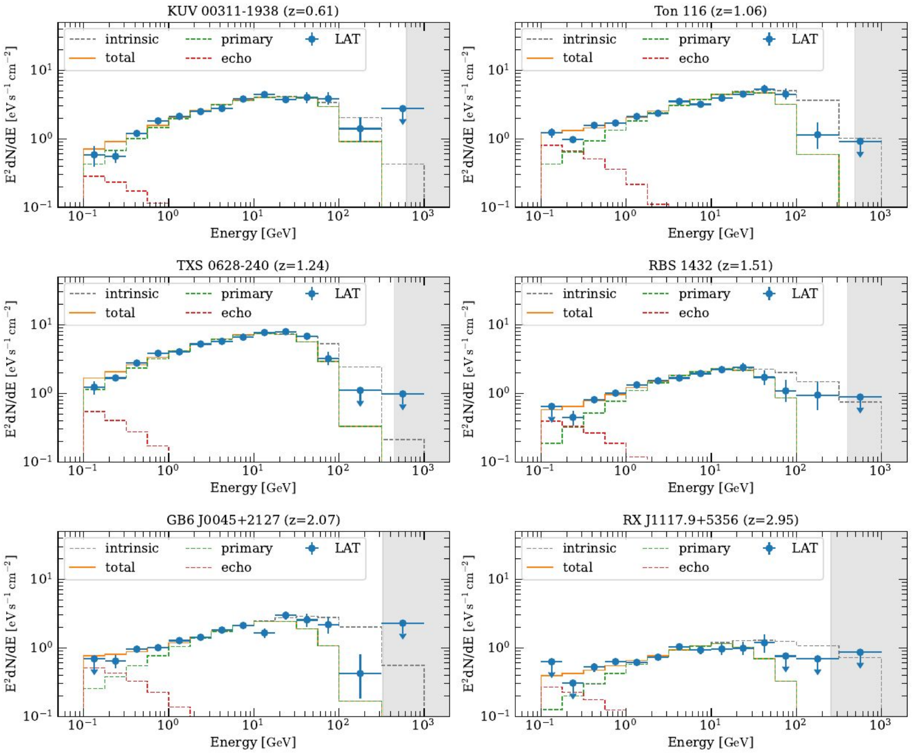
Large volume filling fraction: f > 0.5 – 0.9

Results: high-redshift IGMF limits from individual sources

Beyond a collective constraint

- IGMF limits also on source-by-source basis
- possible upper limit B < 10^{-17} cG (only 2.8σ significant)

Common name	z	$\sqrt{TS}_{100-300}$	S_{IGMF} [σ]	$\log(B_{95})$ [dex(cG)]	$\log(B)$ [dex(cG)]
GB6 J0045+2127	2.07	3.2	3.6	-17.4	-16.5 ± 0.5
GB6 J1037+5711	0.83	9.5	4.1	-18.1	-16.8 ± 0.9
GB6 J1424+3615	1.09	3.3	2.1	-18.5	–
KUV 00311-1938	0.61	6.3	2.8	-18.4	-17.5 ± 0.6
RBS 1432	1.51	5.9	4.5	-16.9	-16.5 ± 0.2
RX J1117.9+5356	2.95	2.0	2.0	-18.4	–
TXS 0628-240	1.24	2.7	3.3	-18.0	-16.8 ± 0.8
Ton 116	1.06	6.3	2.6	-17.1	–
Ton 396	1.52	4.9	2.9	-17.3	-16.3 ± 0.8



IGMF lower limit is not dominated by a single object

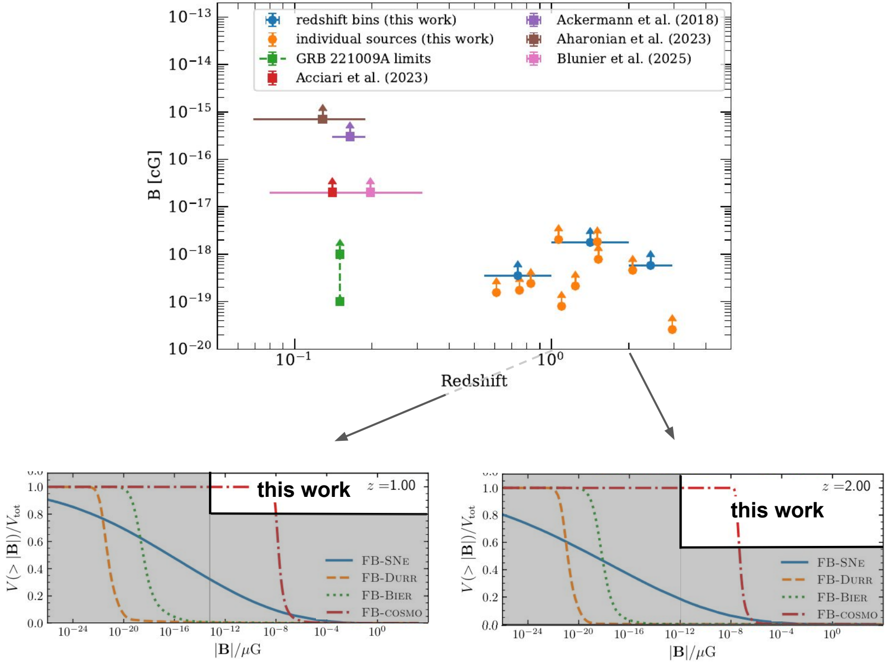
Results: redshift-resolved IGMF limits

Compared to earlier (stronger?) limits:

- **conservative** choice of the VHE attenuation model (deliberate): lower exclusion power, but robust against EBL uncertainties
- **first-ever limits @ z > 1**, enabling IGMF evolution tests

VHE photons mean free path λ_{mfp} > 100 Mpc @ z < 3
→ probe large-scale IGMF contribution
(and give volume-filling fraction f > 0.8)

For galactic IGMF with B > 10^{-18} cG, f < 40% @ z = 0
and quickly falls with redshift
(e.g. Garaldi+ '21, Vazza+ '25)

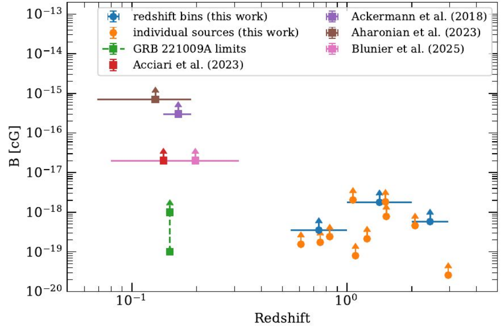


adapted from Garaldi+ '21

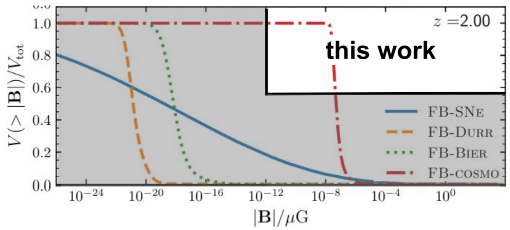
Obtained limits probe IGMF unaffected by the galactic feedback, pointing to its cosmological origin

Key findings

- first IGMF lower limits at redshifts above z = 1
- robust single-instrument constraints
- evidences for cosmological IGMF origin



Low- and high-z measurements may eventually separate the galactic / cosmological IGMF contributions



Backup

High-redshift AGNs suitable for IGMF constraints

Source sample

- firm 4FGL detections (TS>25)
- tentative 4FGL detections (TS>9)
- VHE detections from Neronov & Semikoz ‘25
- 4LAC sources with redshifts from SIMBAD

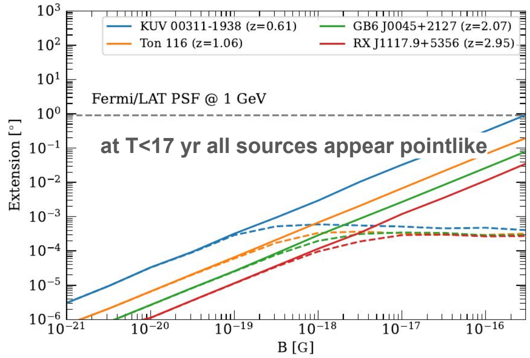
Fermi/LAT analysis

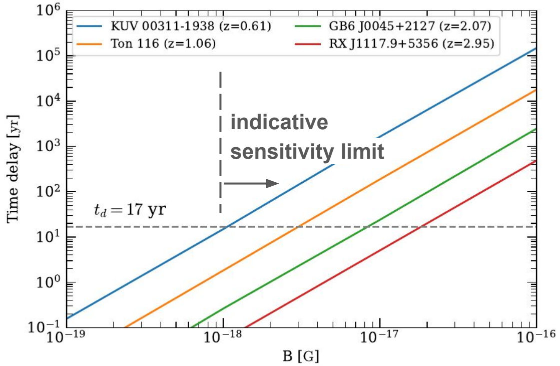
- wide energy range 0.1 GeV – 1 TeV
- SED extraction tuned for higher sensitivity (“PSF classes”)
- light curves from aperture photometry

	4FGL name	Common name	z	Spec.	Γ	νF_ν^{30-100}	$\sqrt{TS_{VHE}}$
Confident detections	4FGL J0033.5-1921	KUV 00311-1938	0.61	LP	1.75 ± 0.02	3.9 ± 0.5	6.6
	4FGL J1037.7+5711	GB6 J1037+5711	0.83	LP	1.89 ± 0.01	2.5 ± 0.4	10.1
	4FGL J1243.2+3627	Ton 116	1.07	LP	1.77 ± 0.02	4.0 ± 0.5	6.4
	4FGL J1427.0+2348	PKS 1424+240	0.604	LP	1.82 ± 0.01	12.5 ± 0.9	18.3
Bright @ 30-100 GeV	4FGL J0035.2+1514	RX J0035.2+1515	1.09	LP	1.83 ± 0.04	1.3 ± 0.3	2.0
	4FGL J0043.8+3425	GB6 J0043+3426	0.966	LP	1.94 ± 0.02	2.2 ± 0.4	3.2
	4FGL J0630.9-2406	TXS 0628-240	1.24	LP	1.81 ± 0.02	6.4 ± 0.7	1.7
	4FGL J1517.7+6525	1H 1515+660	0.702	LP	1.83 ± 0.03	1.4 ± 0.3	2.3
	4FGL J2357.4-1718	RBS 2066	0.85	PWL	1.72 ± 0.07	1.2 ± 0.3	2.3
Tentative detections	4FGL J0649.5-3139	NVSS J064933-313917	0.563	LP	1.68 ± 0.08	0.6 ± 0.2	3.9
	4FGL J1101.4+4108	RX J1101.3+4108	0.58	PWL	1.87 ± 0.08	0.5 ± 0.2	3.1
	4FGL J1309.4+4305	B3 1307+433	0.691	LP	1.91 ± 0.02	0.9 ± 0.2	4.5
	4FGL J1340.5+4409	RX J1340.4+4410	0.546	PWL	1.74 ± 0.12	0.3 ± 0.2	4.6
dedicated VHE search	4FGL J0045.3+2128	GB6 J0045+2127	2.07	LP	1.81 ± 0.03	2.4 ± 0.4	3.8
	4FGL J0915.9+2933	Ton 0396	1.52	LP	1.88 ± 0.02	2.0 ± 0.4	4.3
	4FGL J1425.0+3615	FBQS J142455.5+361536	1.09	LP	1.88 ± 0.05	0.8 ± 0.2	0.0
	4FGL J1448.0+3608	RBS 1432	1.51	LP	1.82 ± 0.02	1.7 ± 0.3	7.1
Bright w. SIMBAD redshifts	4FGL J0120.4-2701	PKS 0118-272	0.557	LP	1.92 ± 0.02	3.3 ± 0.5	6.5
	4FGL J1118.0+5356	RX J1117.9+5356	2.95	LP	1.88 ± 0.03	1.1 ± 0.2	2.4
	4FGL J1248.3+5820	PG 1246+586	0.847	LP	1.91 ± 0.01	5.4 ± 0.5	7.8

“echo” emission model

- **per-source “echo” model**
  - CRBeam MC simulation (shown to work up to z ~ 1 at least)
  - IGMF strength $B_{phys} = 10^{-21} - 10^{-16}$ G
  - conservative EBL model choice (miminal predicted “echo” flux)
  - allow volume filling factor f < 1 (mixing B and B_{min} models)
- **adjustment to the data**
  - spatial distribution: scatter over a 1 deg cone
    (not effect on the expected – negligible – extension)
  - temporal distribution: convolve with $\theta(t - t_{start}) \times \theta(t_{stop} - t)$
    (verified source variability affects the outcome by < 5-10%)
- **comparison with the data**
  - model evaluated exactly to the LAT energy and time bins
  - include free high-energy cut-offs for all sources
  - use “flux – likelihood” profiles pre-computed by FermiPy
  - account for LAT collection area systematics





Limitations of the used approach

1. single-instrument limits require that both “echo” and attenuated emission are within the range of the instrument
   → *works for LAT only @ z > 0.3*

$$E_\gamma \approx 0.08(1+z)^2 \left(\frac{E_{\gamma,0}}{0.3\ \mathrm{TeV}}\right)^2\ \mathrm{GeV}$$

2. field-strength probed is not volume-averaged: such constraints are weakly sensitive to fields above B_{iso} which isotropises the “echo”
   → *caution when comparing with cosmological simulations*

$$B_{iso} \approx 6\times 10^{-16}(1+z)^2 \frac{E_\gamma}{0.1\ \mathrm{GeV}} \mathrm{cG}$$

3. derived limits may be affected by plasma instabilities (e.g. Broderick+ ‘12). However, recent studies indicate the play only a marginal role in reduction of the cascade power (Perry & Lyubarsky ‘21, Alawashra+ ‘25)
   → *not considered here*

Intrinsic and “echo” photon energies