

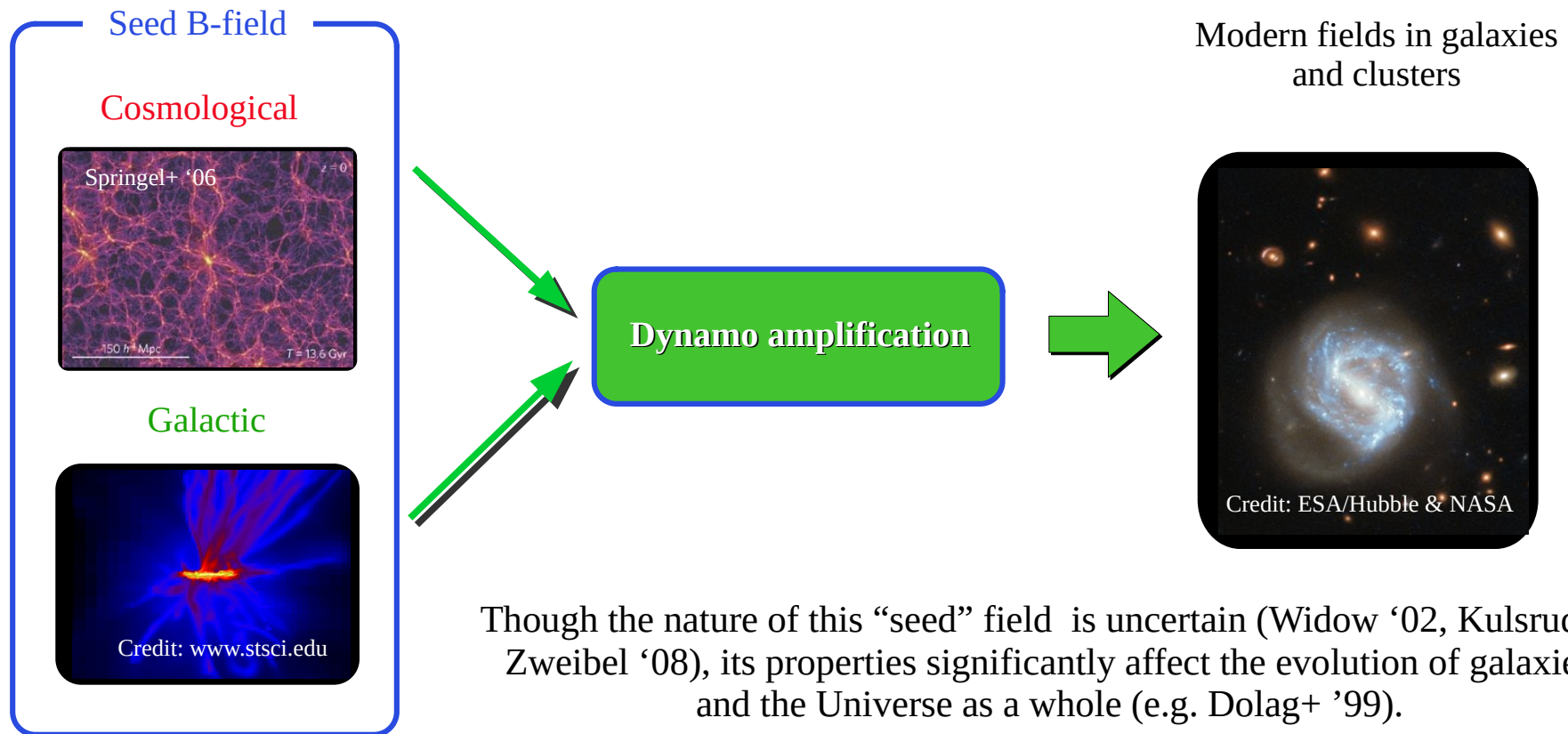
# **Intergalactic magnetic field constraints with VHE-bright GRBs**

Ie. Vovk  
ICRR, University of Tokyo, Japan

The extreme Universe viewed  
in very-high-energy gamma rays 2023,  
19.02.2024, Kashiwa

# Intergalactic Magnetic Field: 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).



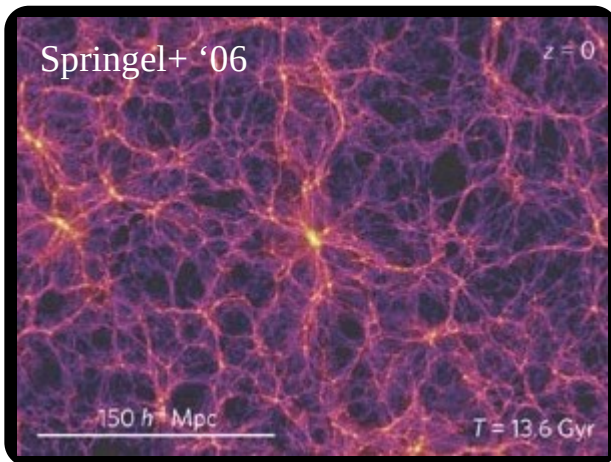
IGMF – a possible “seed” field for astrophysical dynamos, filling most of the Universe volume.



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

# Origin of IGMF

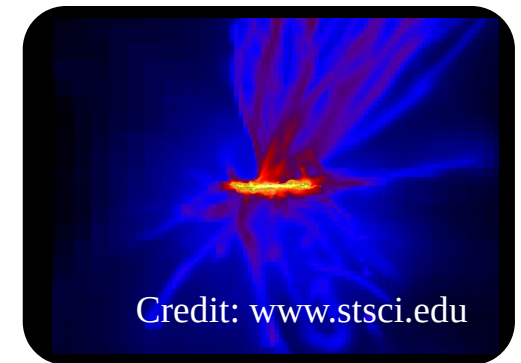
“Cosmological”  
Fills 100% of the Universe



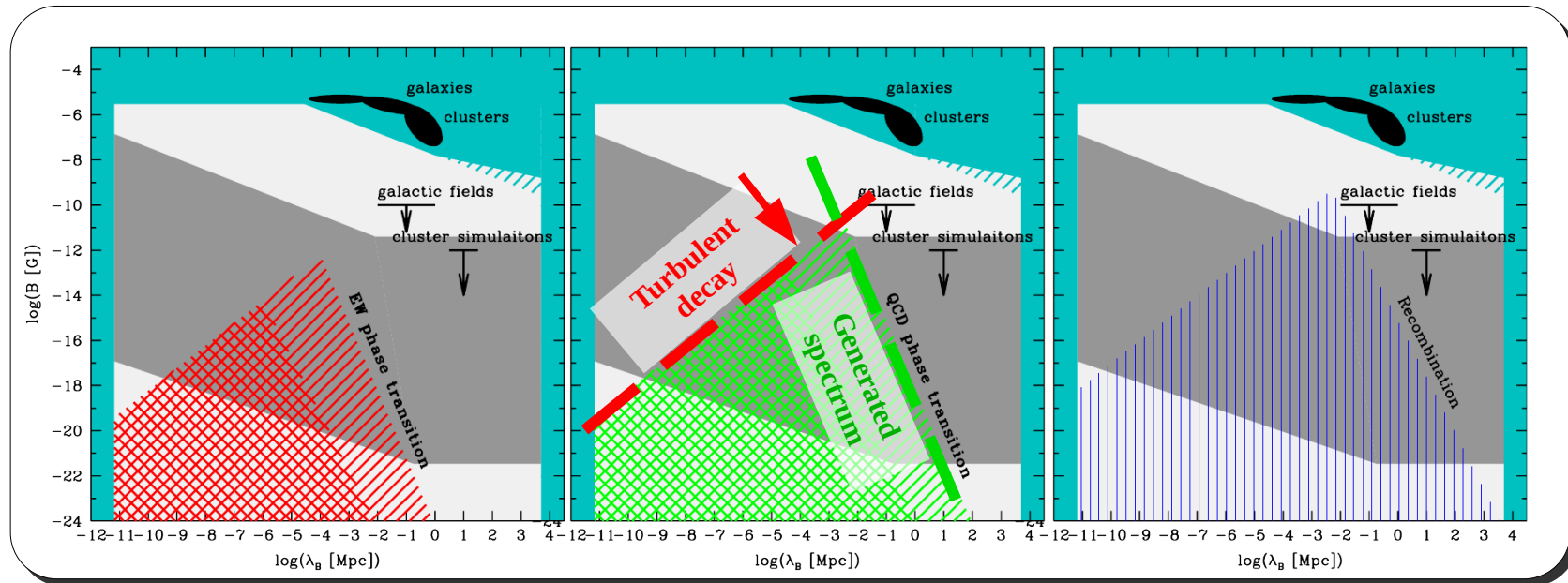
“Galactic”  
(large  $z$ )  
Filling factor: unknown



“Galactic”  
(small  $z$ )  
Filling factor: unknown



# Cosmological IGMF



Neronov & Semikoz '09

## Generation:

- ✓ QCD phase transitions:  $\sim 10^{-12}$  G
- ✓ electroweak phase transitions:  $10^{-11}$  G
- ✓ recombination:  $\sim 10^{-9}$  G

## May explain:

- ✓ **Baryonic asymmetry (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 IGMF

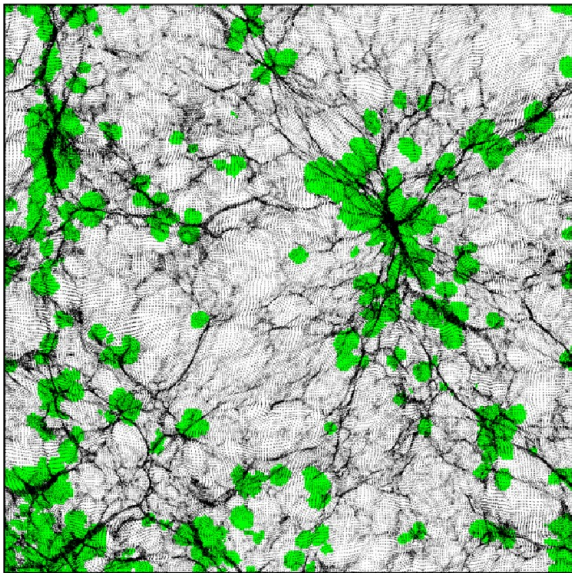


- Vorticity in protogalaxies during the radiation-dominated era can produce fields as strong as  $10^{-19}$  G.
- Biermann battery effect operating in protogalaxies can also lead to the production of  $\sim 10^{-17}$  G field on large (megaparsec) scales.
- Durrive battery may generate  $\sim 10^{-19}$  G field on sub-Mpc scales during the epoch of reionization
- 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.
- Cosmic-ray-driven currents in young galaxies can also be responsible for the creation of the magnetic fields.

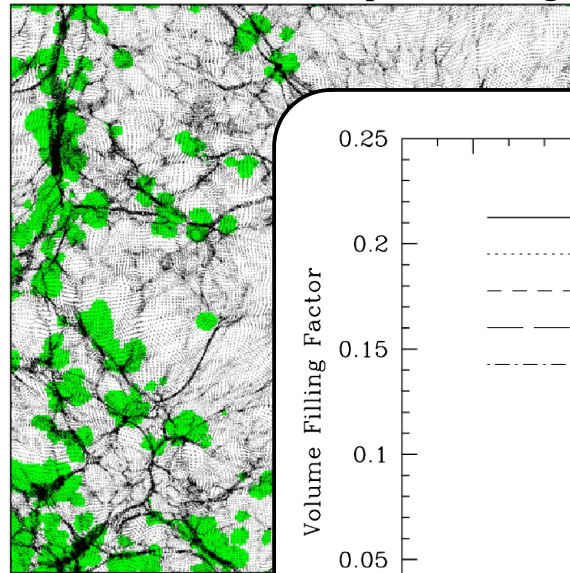
Widrow '02, Miniati & Bell '11, Garaldi+ '20

# Supernovae-driven outflows

$z = 3.00$

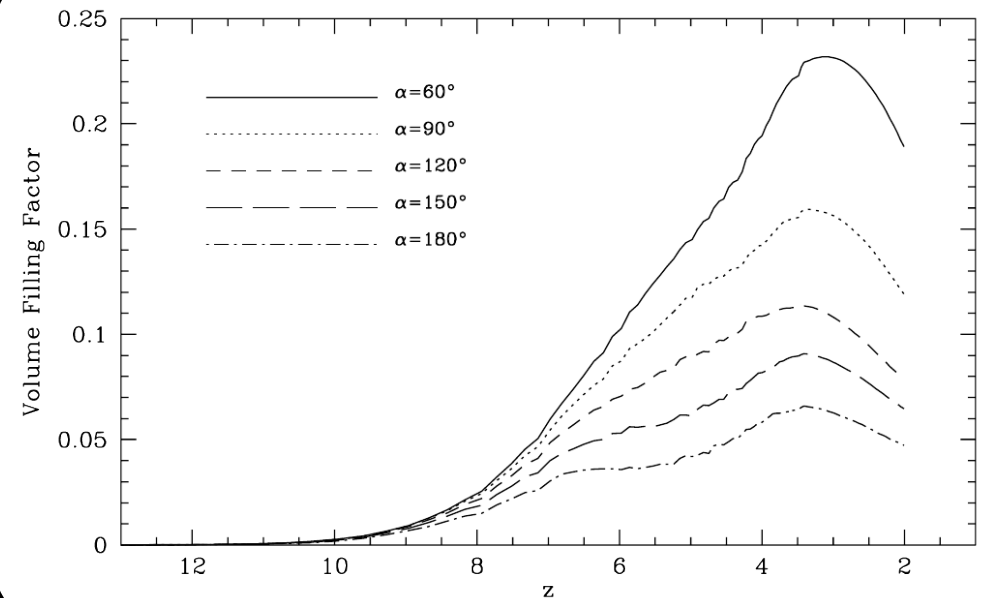


$z = 2.00$



15x15x0.1 Mpc comoving

Pinsonneault+'10

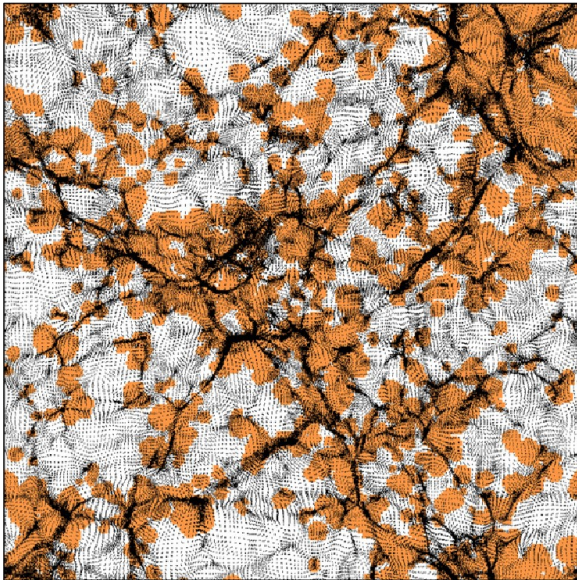


**Up to  $\sim 20\%$  of the space could be magnetized by outflows at  $z=3$**

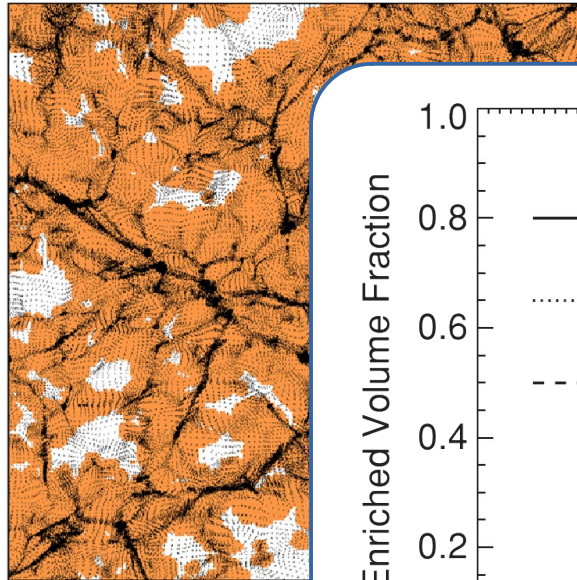
Cosmic rays may also generate  $10^{-17}$  G IGMF on kpc scales with large volume filling factor (Miniati & Bell '11)

# AGN-driven outflows

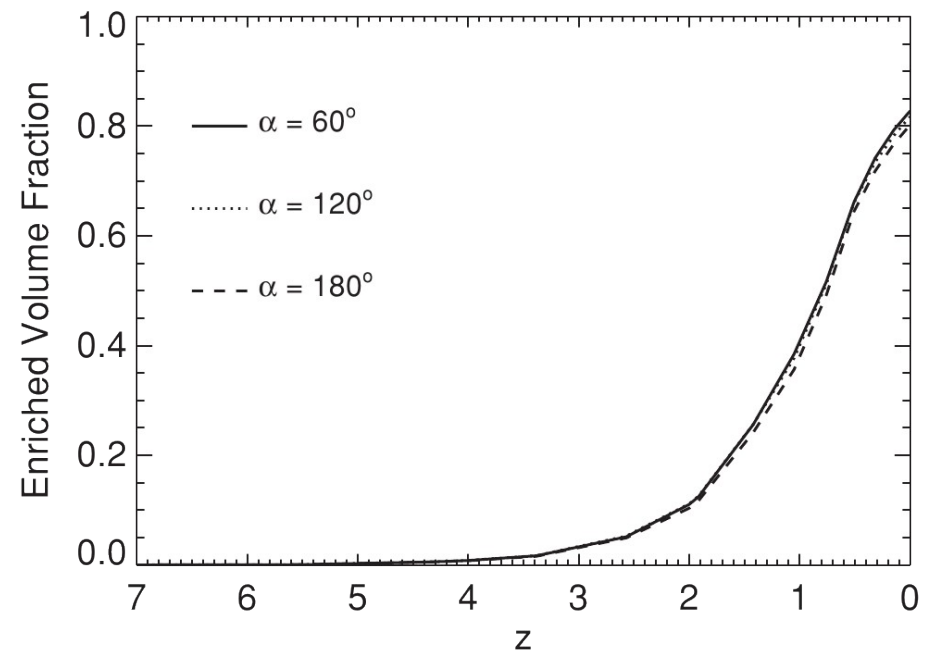
$z = 1.05$



$z = 0.00$  128x128x2  $h^{-1}$  Mpc comoving



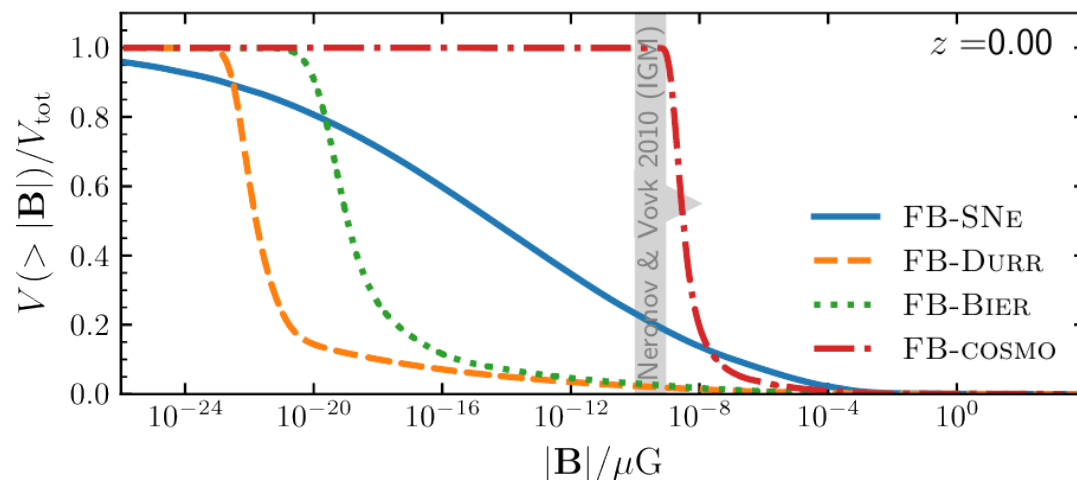
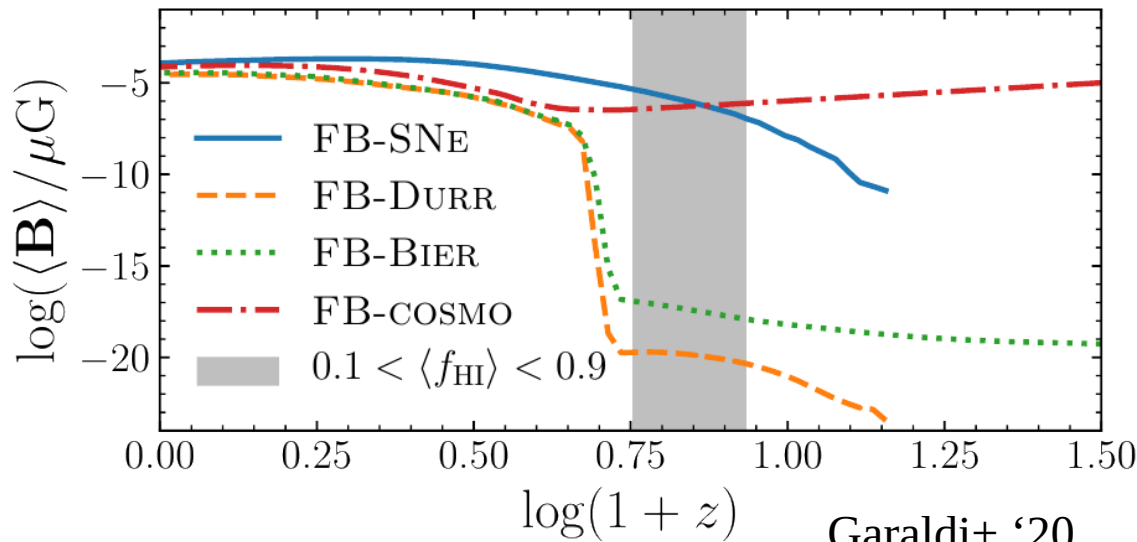
Germai+ '09



**$\sim 80\%$  of the space could be magnetized by outflows**

Other models suggest  $10^{-10}$  G IGMF on Mpc scales with  $\sim 20\%$  volume filling factor (Furlanetto & Loeb '01)

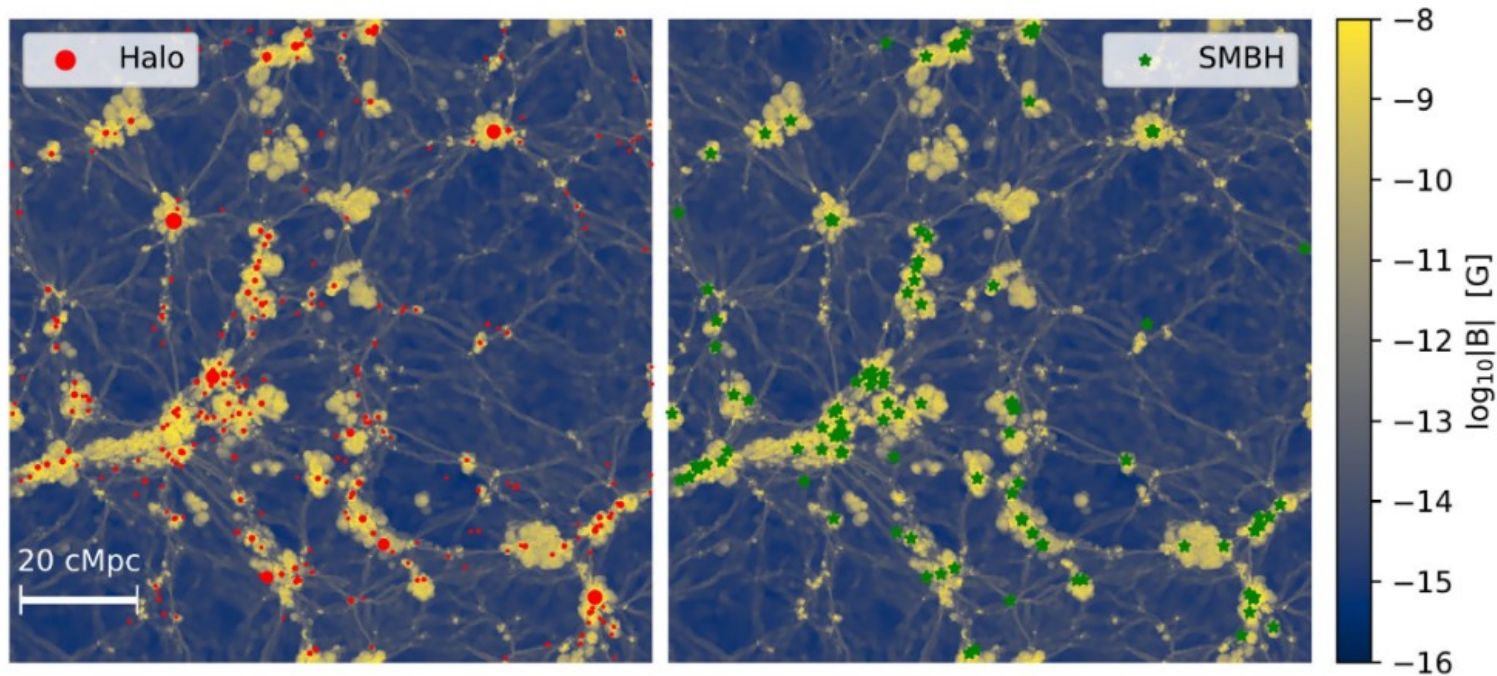
# IGM magnetization: modern view



- Multi-resolution MHD simulations with radiation transfer with the 25-70 Mpc box.
- Galactic IGMF amplification at  $z \sim 4$
- Gradual build up of SNe-generated field
- Magnetization with “batteries” is subdominant compared to SNe

# IGM magnetization: modern view

Aramburo-Garcia+ '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?



## 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

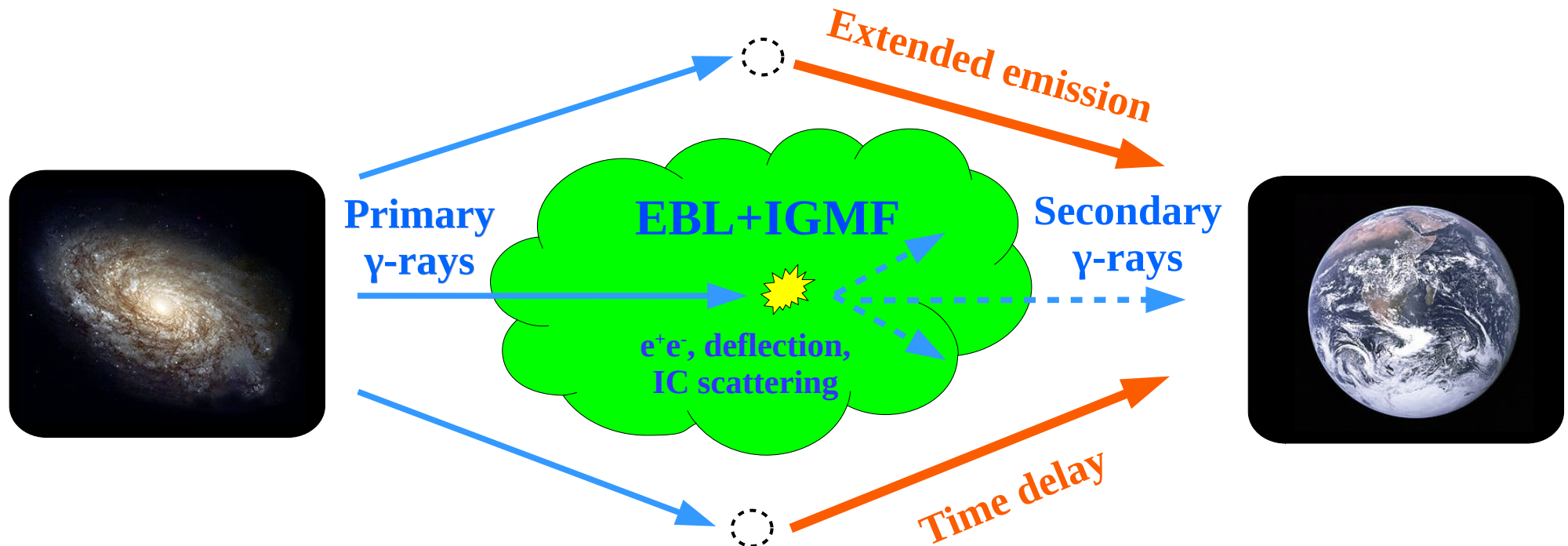
### 3. Ultra high-energy cosmic rays anisotropy

Combination of the large-scale structure and magnetic horizon in CR propagation  
(Globus+ 19)

**However, IGMF origin / properties remain uncertain**

# IGMF measurements through gamma-ray data

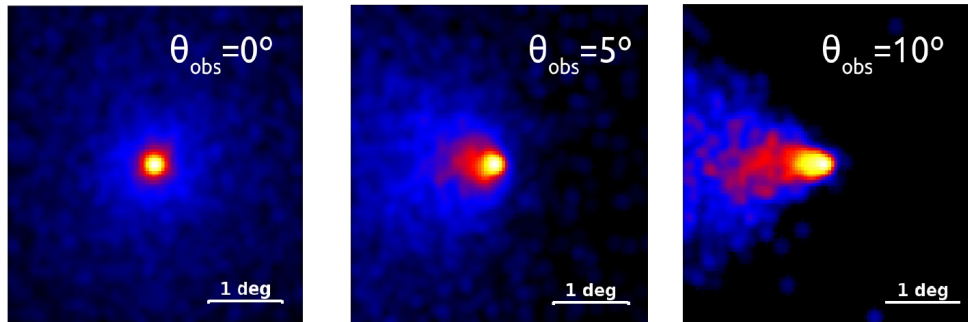
VHE  $\gamma$  rays from cosmological distances are subject to partial absorption and cascading, converting multi-TeV photons into a secondary  $\gamma$ -ray “pair echo”



The presence of non-negligible IGMF leads to appearance of extended – and delayed – “echo” / “halo”.

(Plaga ‘95, Neronov & Semikoz ‘09)

# Observational properties of the IGMF-modified cascades



## “Smoking gun”: extended halo

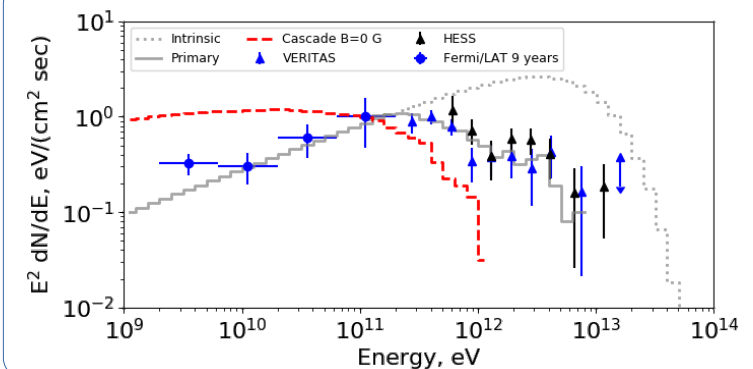
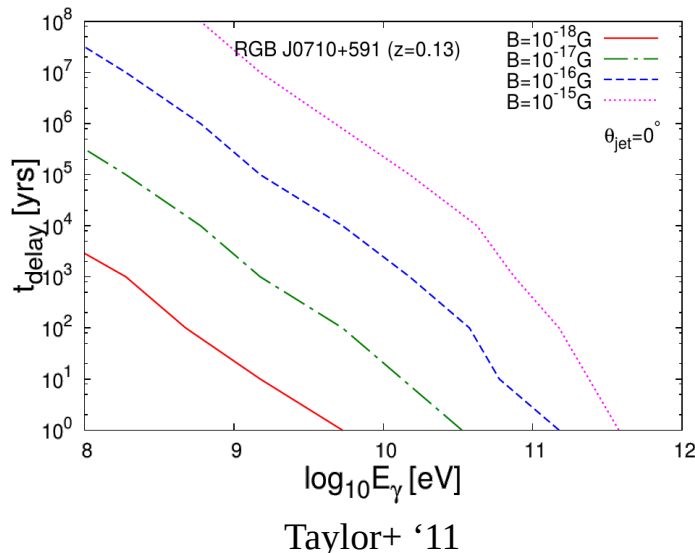
Size and shape depend on IGMF strength and source parameters (jet opening and orientation).

## 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.

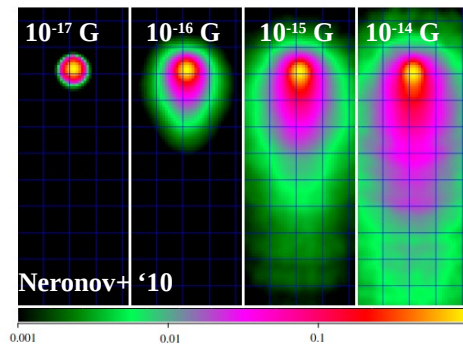


# IGMF searches: “halos” and “echos”

## IGMF effect

### Spatially-extended “halo”

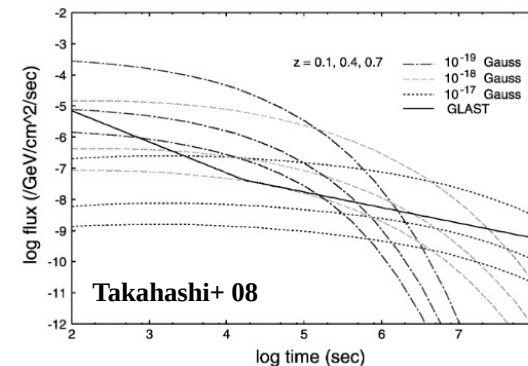
(e.g. Aharonian+ '94, Plaga '95, Neronov & Semikoz '09, Neronov+ '10)



- “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)

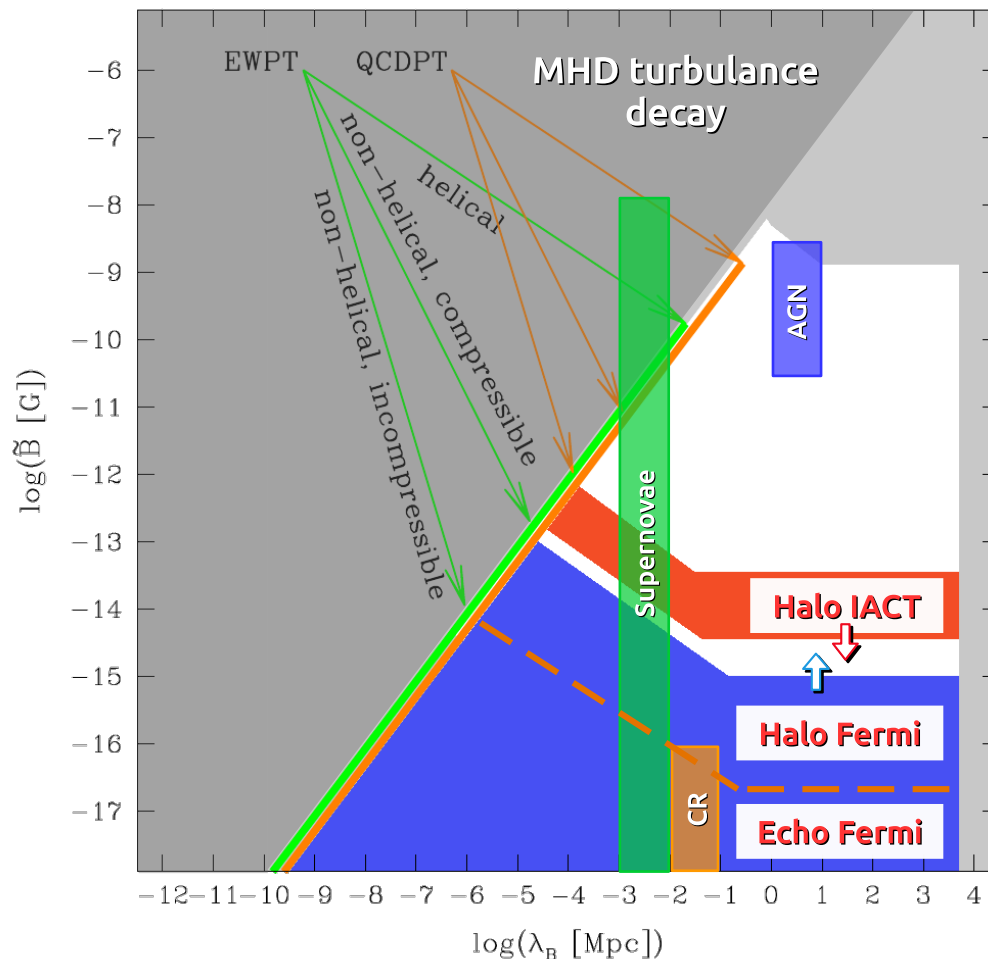
### Time-delayed “echo”

(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-bright) and AGNs (long-term monitoring)

# IGMF constraints from blazar observations



## Fermi/LAT measurements

(Neronov & Vovk '10, Tavecchio+ '10, Dermer+ '11, Dolag+ '11, Taylor+ '11, Vovk+ '12, Finke+ '15, Acciari+ '23)

are complemented by **IACs**

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

**These are IGMF constraints at  $z \sim 0.1$**

These limits are based primarily on halo non-detection (“smoking gun”).

Accumulated time series on AGNs and TeV GRB detections now enable also time-delayed “echo” searches.

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

# Looking for the time-delayed “echo”?

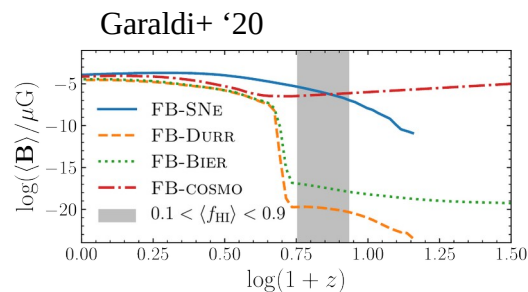
- 1 Except if “halo” is detected, limits from its non-detection depend on the assumed source flux in the past.

E.g. time delay scaling with halo size at  $z \sim 0.14$  is

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

→ Reliable limits – knowledge of the variability history

- 2 Next “important” IGMF constraints require  $z > 1$   
BUT: strong EBL absorption → limited number of the detectable persistent emitters



Disentangle galactic / extragalactic IGMF origin

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

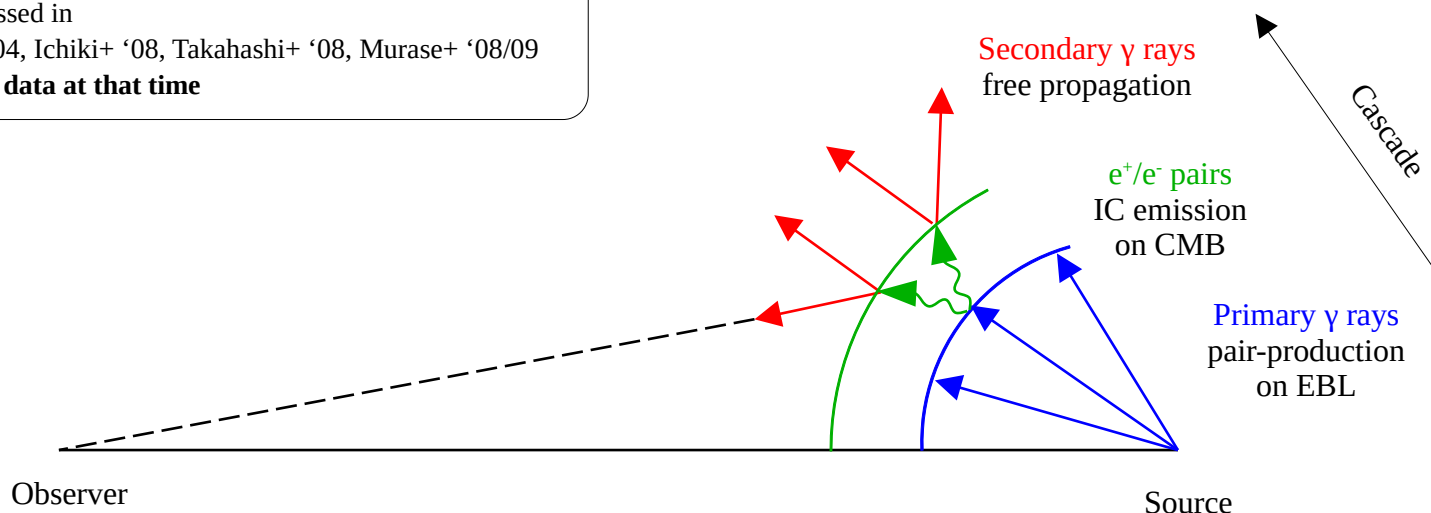
But:

- intrinsic time delay may be  $\Delta t \sim 10^2 - 10^4 \text{ s}$  → 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

# 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  
electron motion

Pair production  
angular dependency

IC emission  
angular profile

# Variability of the “main” IGMF blazar – 1ES 0229+200

Decade-long observational campaign with HESS, VERITAS, MAGIC and Fermi/LAT allow to properly probe for the “echo” signal with AGNs

**Primary source for IGMF constraints - 1ES 0229+200 - is found  
variable in TeV energy band**

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

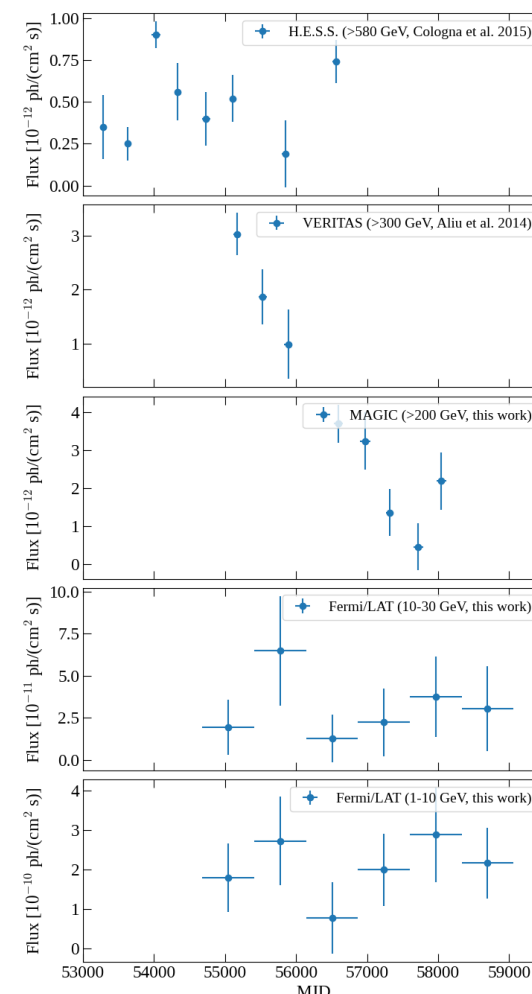
However, no significant spectral variability in the VHE band.

**MAGIC has contemporaneous measurements with Fermi/LAT**

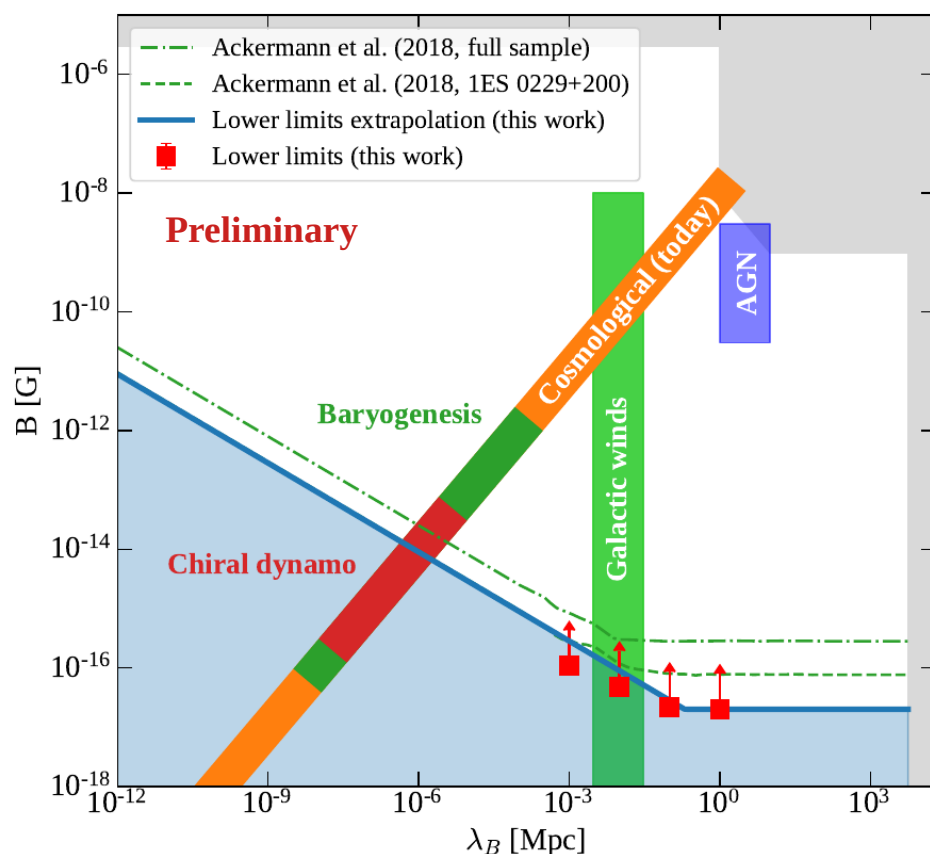
Variability even in MAGIC data themselves

More reliable TeV-GeV comparison

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



# Robust (?) IGMF limit from contemporaneous GeV-TeV variability



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  $\sim 10$  yr time scales. Challenging, but feasible task for Fermi/LAT and CTA.

**How robust is this limit?**

# IGMF constraints and plasma instabilities

**IGMF constraints cornerstone:** beam power is dissipated via IC cooling (expected secondary emission)

**An alternative:** beam power is dissipated differently and IC cooling is subdominant.

**Chang+ '12 and Broderick+ '12:** dissipation via the plasma instabilities (strong suppression of the secondary gamma-ray emission).

**Schlickeiser+ '12:** comparable energy loss on instabilities and IC (for certain beam densities half of the initial power is transferred to the turbulence).

**Vafin+ '18,19:** strongly condition-dependent beam energy damping on plasma instabilities

**Alawashra '22:** suppression of instabilities in tangled magnetic fields

➤ **Miniati & Elyiv '12:** negligible beam energy loss on instabilities (non-linear Landau damping and large-scale plasma inhomogeneities should stop the development of the instabilities).

➤ **Shalaby+ '18:** limited effect of IGM inhomogeneities on instability growth rate

➤ **Perry & Lyubarsky '21:** negligible instabilities contribution due to the loss of plasma wave resonance on IGM inhomogeneities in narrow relativistic beams

➤ **Alawashra '24:** beam broadening on instability without energy loss

To be continued...

# GRBs and role of plasma instabilities

**IGMF constraints cornerstone:** beam power is dissipated via IC cooling (expected secondary emission)

**An alternative:** beam power is dissipated differently and IC cooling is subdominant.

**But instabilities need time to grow**

Maximal instability growth rate:  $\omega_{i,\max} \sim 10^{-11} - 10^{-7} \text{ s}^{-1}$  (Broderick+ '12, Alawashra+ '24)

Maximum duration for which IC dominates the cooling (Broderick+ '12):

$$\Delta t \lesssim 5.3 (1 + \delta)^{1/2} \left( \frac{1+z}{2} \right)^{(11-6\zeta)/2} \times \left( \frac{EL_E}{10^{45} \text{ erg s}^{-1}} \right)^{-1} \left( \frac{E}{\text{TeV}} \right)^{-2} \text{ yr}$$

For typical blazars it corresponds to  $\Delta t \sim 300 \text{ yr}$ .

Short-lived sources lasting for  $\Delta t \ll \Delta t_{\max} = 1 / \omega_{i,\max} \sim 1 - 100 \text{ yr}$   
may be free from instabilities by definition.

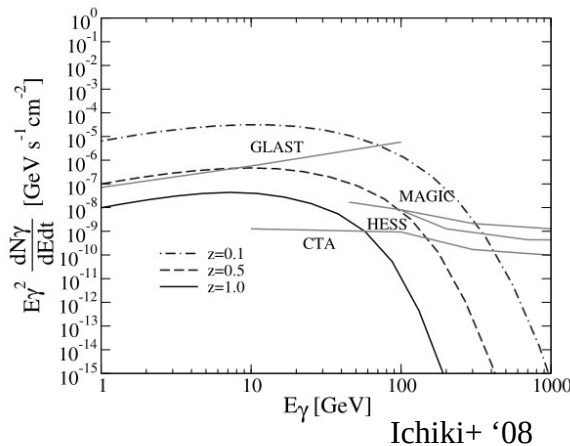
For GRBs  $\Delta t \sim 10^{-9} - 10^{-4} \Delta t_{\max}$

**As such GRBs are the cleanest sources to extract IGMF limits from**

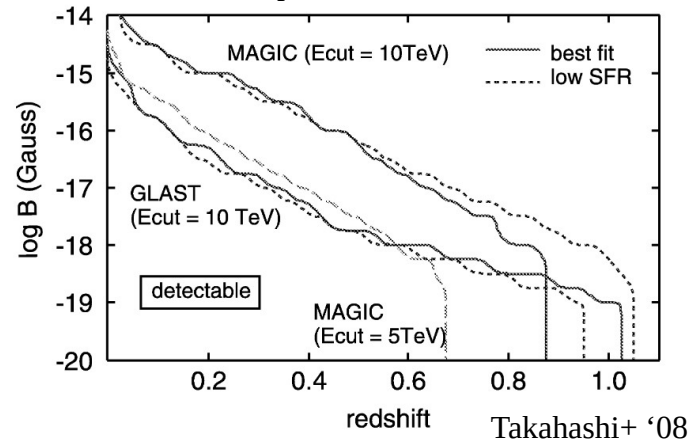
# Early GRBs “echo” searches

Early calculations were based on semi-analytical codes with approximate treatment of intrinsic and IGMF-induced beam broadening

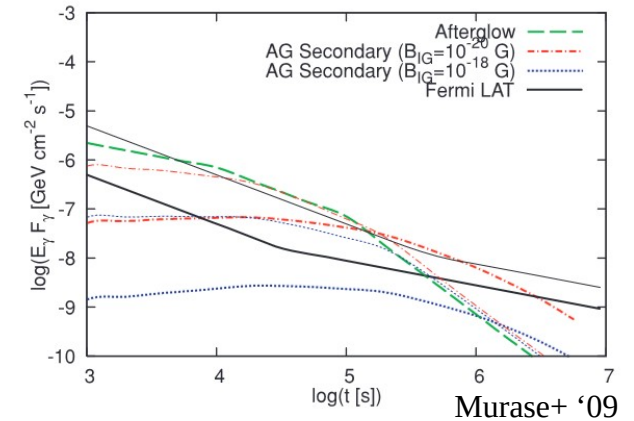
Fudicial GRB echo spectra for IGMF =  $10^{-18}$  G



IGMF vs redshift region expected to be probed with GRBs



Expected GRB “echo” @ 1 (thick) and 10 GeV (thin) energies



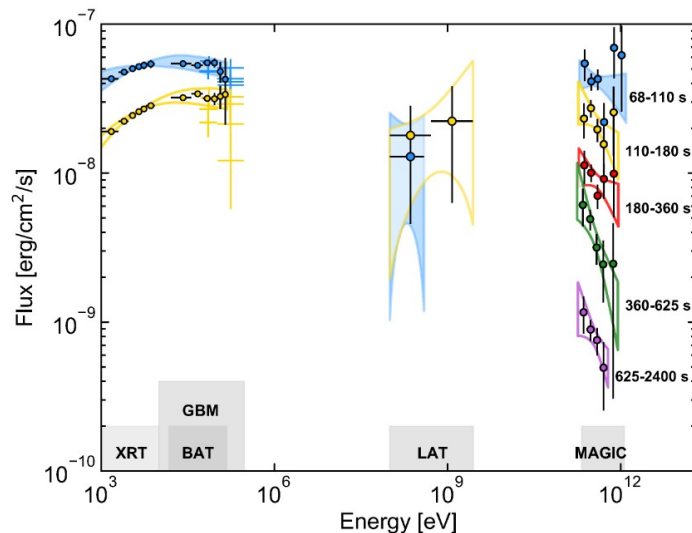
They concluded IGMF  $> 10^{-21}$  G should be detectable with GRB “echo”

**However, there we simply no TeV-bright GRBs known then**

# GRB190114C – first opportunity for pair echo detection

## Bright GRB with key properties (MAGIC collaboration '19 a/b)

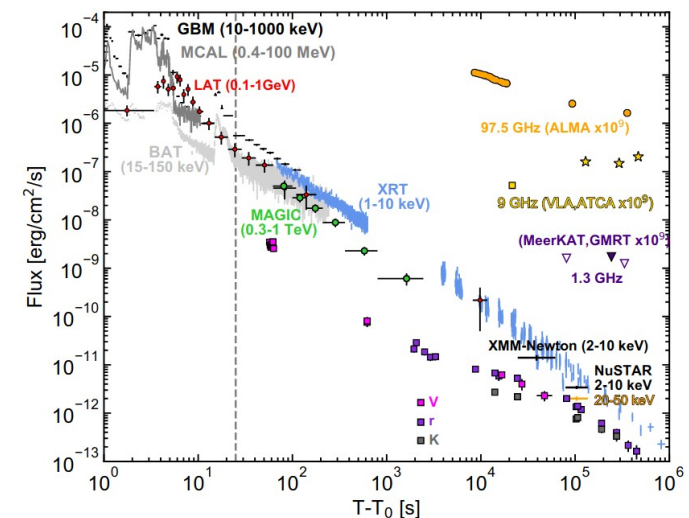
Contemporaneous  
HE (0.1-1 GeV) + VHE (0.3-1 TeV) detections



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

Larger redshift  
 $z=0.42$

Long duration  
 $\Delta t \sim 10^3 \text{ s}$



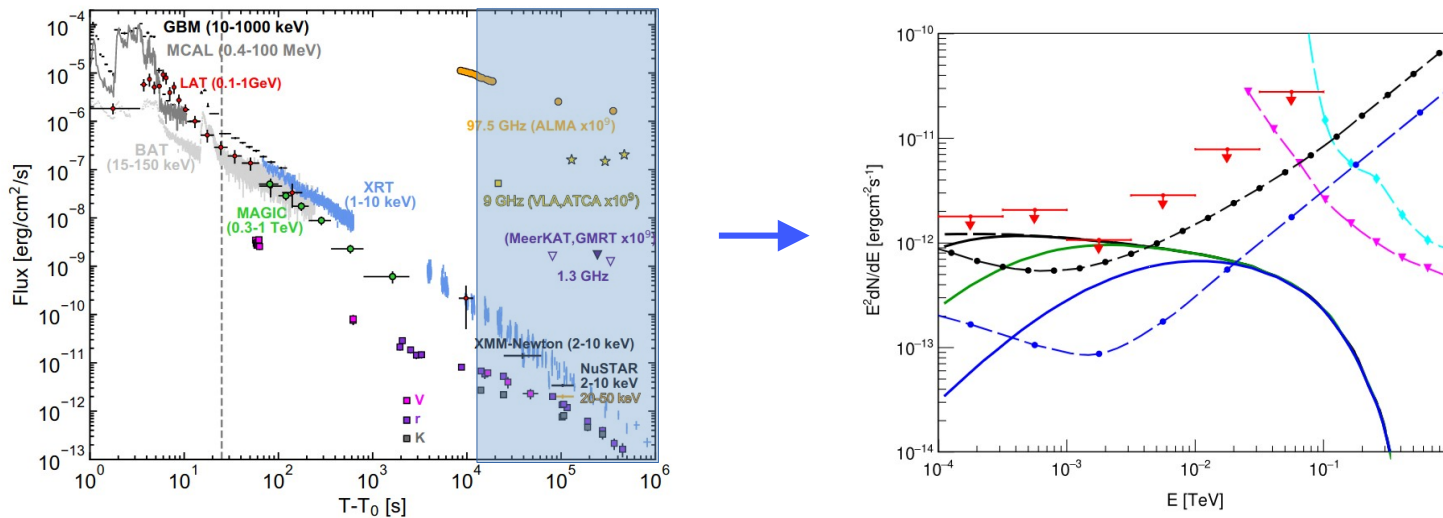
$K = T_{\text{flare}} / (T_{\text{delay}} + T_{\text{flare}})$   
→ smaller flux suppression

VHE light curve of GRB190114C → HE “echo” prediction → comparison to LAT

# GRB190114C: “pair echo” search at late times

Dzhatdоеv+ ‘20

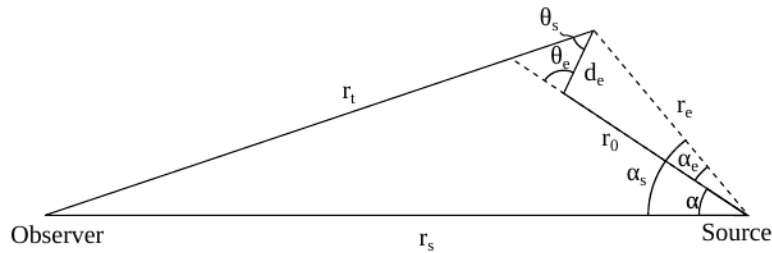
First GRB190114C “echo” search employed a simplified treatment of the intrinsic beam broadening and focused at late time  $T - T_0 > 2 \times 10^4$  sec emission



No “echo” signal was found, upper limits were consistent with zero IGMF case

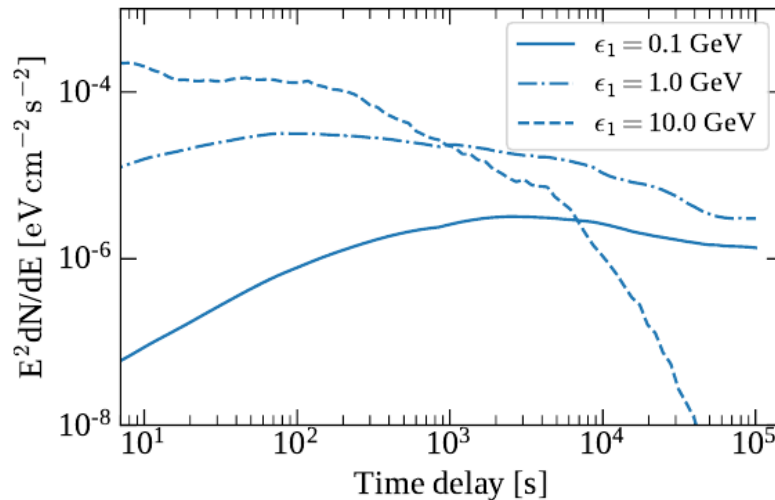
“Echo” search within the  $T - T_0 < 2 \times 10^4$  sec window required detailed calculation of the intrinsic time delay.

# Calculating the intrinsic “echo” time delay

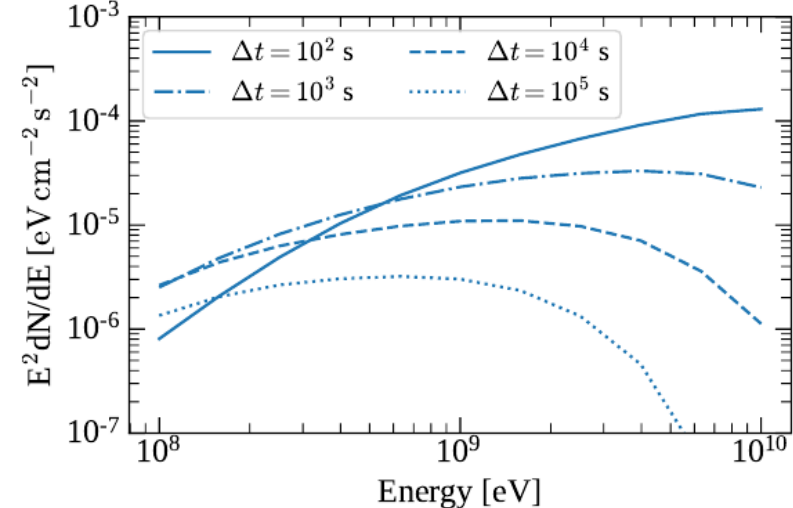


$$\Delta t \approx (1+z) \left[ t_e - \frac{d_e}{c} \left( 1 - \frac{r_0}{d_e + r_0} \frac{\theta_e^2}{2} \right) + \frac{1}{c} \frac{r_s r_e}{r_s - r_e} \frac{\alpha_s^2}{2} \right]$$

“Echo” kernel light curve



“Echo” kernel spectrum

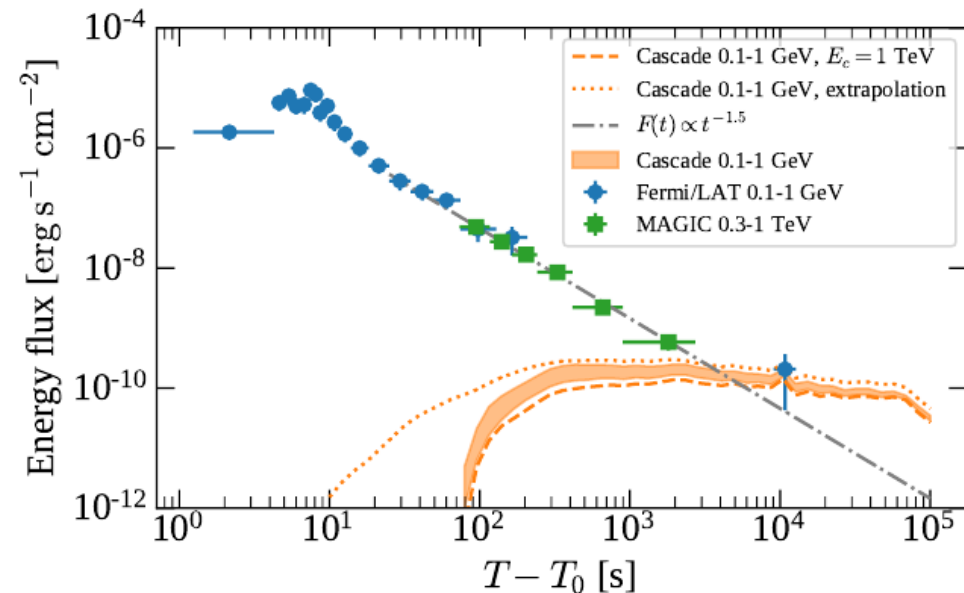


In general “echo” follows the source light curve  $F(t)$

$$F_{echo}(\epsilon_1, t) = \int_{-inf}^t F(E_\gamma, t') K(\epsilon_1, E_\gamma, t - t') dt'$$

# GRB190114C: “pair echo” prediction in the zero IGMF case

- Conservative “echo” estimate based MAGIC data from  $T - T_0 > 68$  s
  - power law injection spectrum following the measured index / slope evolution
  - exponential cut off @ 1 TeV (maximal energy MAGIC has detected). → Sub-dominant contribution of  $E > 1$  TeV emission in the 0.1-1 GeV range of Fermi/LAT measurements.
  - extrapolation to prompt phase down to  $T - T_0 = 5$  s. → Early-time “echo” still consistent with measurements (if spectrum is the same).
- HE detection @  $T - T_0 = 10^4$  s may be in slight tension with the  $F(t) \sim t^{-1.5}$  extrapolation identified in MAGIC collaboration ‘19 a/b



“Pair echo” prediction for zero IGMF case is consistent with the data

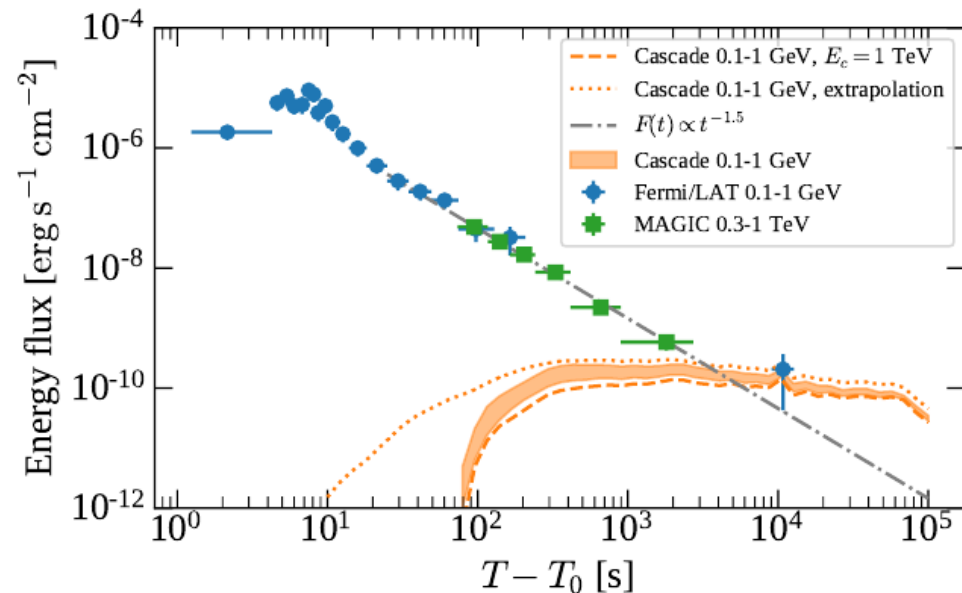
# GRB190114C: “pair echo” detection?

## 1. Emission @ $10^4$ s is an “echo”?

- prompt phase VHE flux can not exceed much the  $F(t) \sim t^{-1.5}$  extrapolation.
- IGMF  $< 10^{-21}$  G @  $z \approx 0.4 \rightarrow$  Possible contradiction with constraints from blazars @  $z \sim 0.1$ . Favours “galactic” IGMF origin. Inhomogenous IGMF?
- only sub-dominant role of the plasma instabilities

## 2. Emission @ $10^4$ s intrinsic to GRB?

- structured jets or multiple emission may result in time-delayed components (e.g. SSC peak shift as in MAGIC collaboration ‘19)
- if  $>80\%$  of it is intrinsic  $\rightarrow$  IGMF  $> 10^{-21}$  G @  $z \approx 0.4$ , in agreement with constraints from blazars.



IGMF measurements with TeV bright GRBs at  $z \sim 1$  are feasible

# IGMF with GRB221009A – the brightest GRB to date

GRB221009A: the brightest GRB to date (nearly with  $z=0.15$ ).

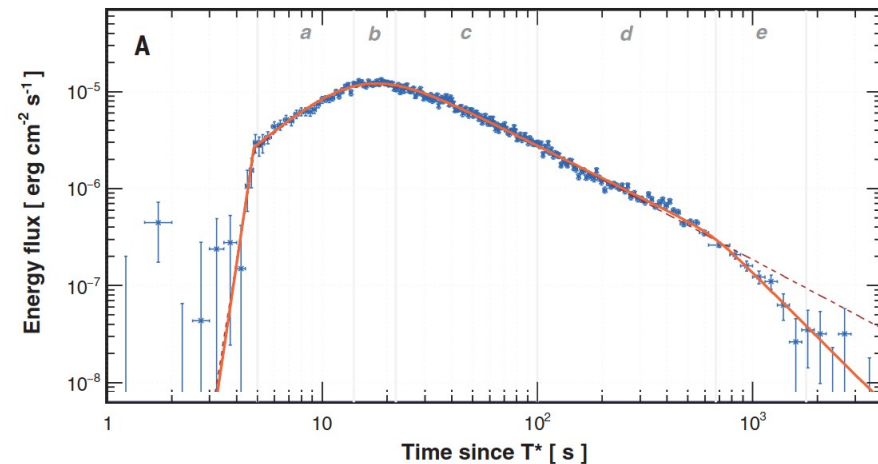
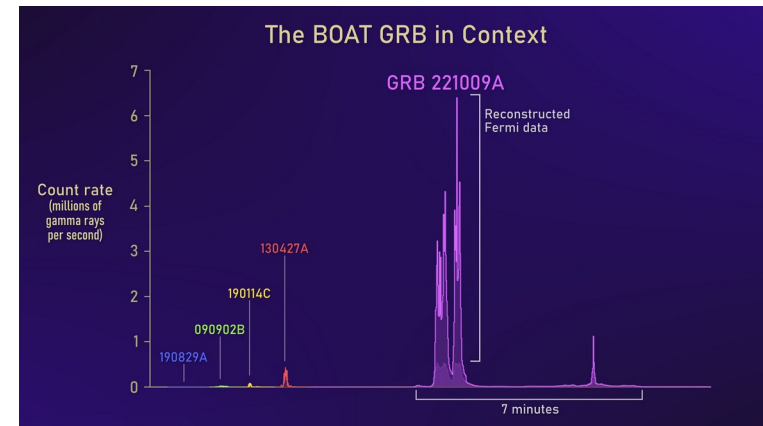
So bright it has saturated Fermi LAT/GBM  
<https://fermi.gsfc.nasa.gov/ssc/data/analysis/grb221009a.html>

Apparently missed by all major IACTs due to full Moon

Emission up to  $\sim 10$  TeV lasting for  $\sim 2$  ksec registered with LHAASO

- First GRB with detectable “echo”
- x-check to AGN-based IGMF constraints from similar redshift

Credit: NASA's Goddard Space Flight Center and Adam Goldstein (USRA)



# IGMF with GRB221009A – the brightest GRB to date

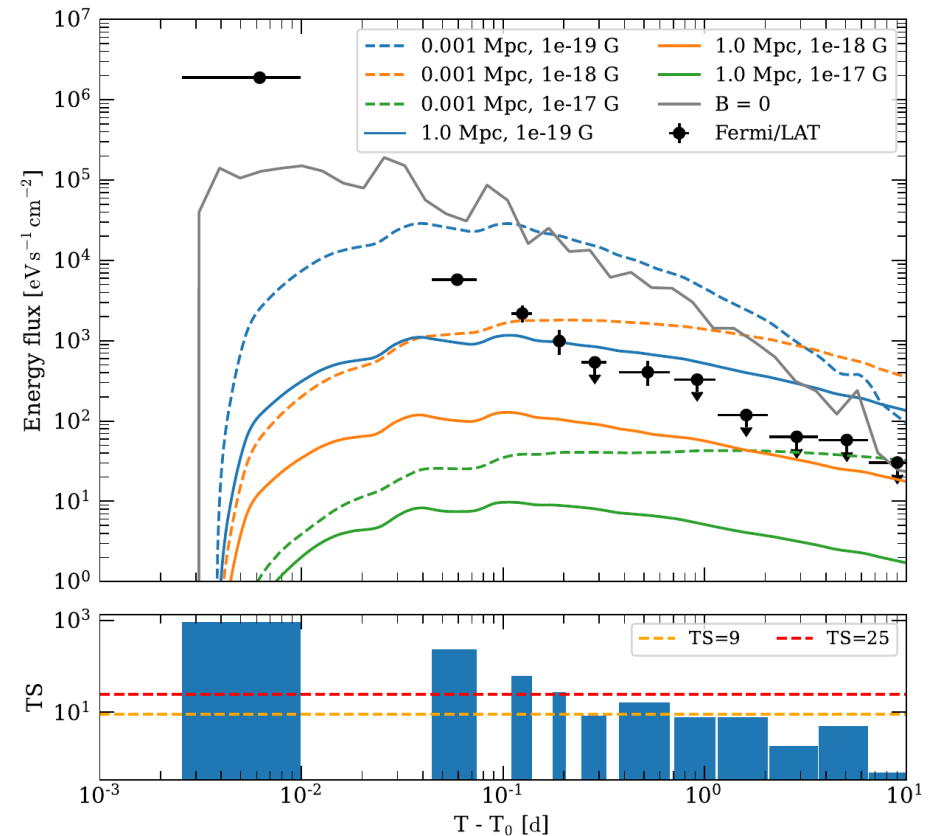
Total “echo” flux is set by the LHAASO multi-TeV light curve / spectra

Prediction based on the intrinsic cascade scatter only clearly overshoots the Fermi/LAT measurements (no saturation after  $T-T_0 \sim 300$  sec)

No clear indication for the IGMF-modified “echo” onset (like the one suggested for GRB190114C)

**IGMF with  $B > 10^{-19}$  G** is consistent with the data (convolution of the intrinsic cascade with the “echo” shape obtained from CRPropa)

Similar constrains also found by Dzhatdоеv+ ‘23 and Huang+ ‘23, neglecting the intrinsic “echo” spread.



**Independent verification of blazar-based IGMF constraints.**

# IGMF with GRB221009A – the brightest GRB to date

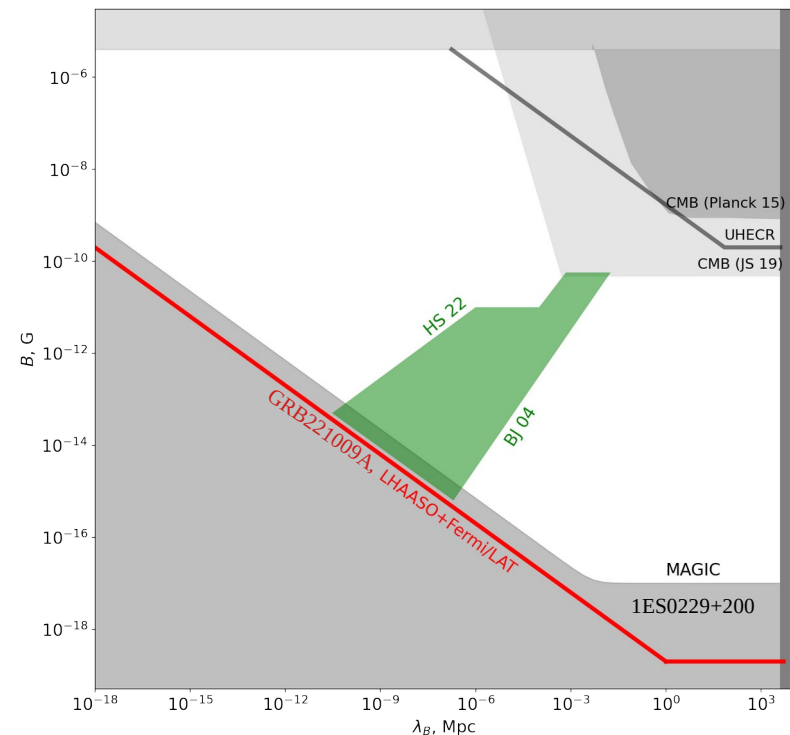
Galactic outflows may have a limited volume filling factor (Marinacci+ '18)

→ IGMF in voids is likely cosmological.

Turbulent decay of cosmological IGMF produced in EW or QCD transitions in Early Universe is  $\lambda_B \sim 10^{-5}$ - $10^{-1}$  pc (Banarjee+Jedamzik '04, Hoskin+Schekochihin '22)  $\ll D_e \sim 0.1$  Mpc

GRB221009A limit @ small  $\lambda_B$  is comparable to that from blazars.

GRB IGMF limit may be also less influenced by possible plasma instabilities (due to a short duration / narrow emission shell)



**GRB221009A confirms strong constraints on cosmological IGMF**

# Final remarks



**GRB “echo” signal** search – a viable tool to cross-check the IGMF constraints from blazars.

**IGMF constraints with GRBs are opportunistic:** we do not know where / when next bright burst will happen – example of GRB2201009A highlights the importance of ground-based instruments able to operate at “extreme” conditions.

**GRBs constrain weaker IGMF** compared to blazars – unless we get a second GRB2201009A event or the one with much harder spectrum – **but** they may **extend the redshift range** of IGMF constraints ( $z=1.1$  GRB201216C detected with MAGIC)

**GRB** constrains seem **insensitive to plasma instabilities**. While on-going theoretical studies may eventually demonstrate the same for blazars, recent GRB observations **support the existence of strong IGMF**.