Detection of cosmological magnetic fields with gamma-ray cascades in CTA era

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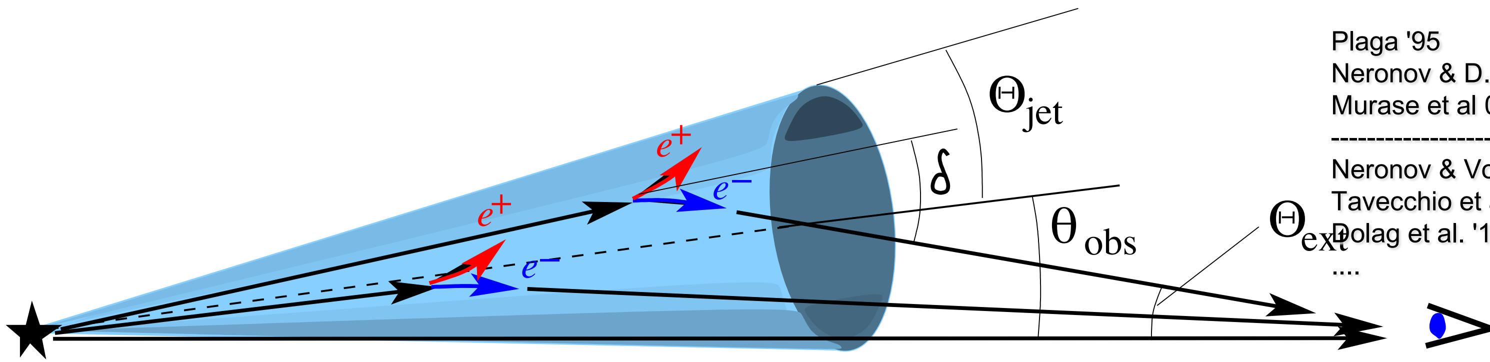
2007.14331 2009.14174 2106.02690 2111.10311 2112.08202 2201.05630.   2306.07672

Plan:

- *IGMF detection with gamma-rays*
  - *Standard case*
  - *AGN feedback and influence on cascade*
  - *3D cascade simulations: systematics*
  - *How we can detect cosmologically important IGMF B = 1-10pG*
  - *Detection of IGMF from inflation*
  - *Experimental results by Cherenkov telescopes and from BOAT GRB*
- *Conclusions*

Inter-Galactic Magnetic Field detection with gamma-rays

IGMF measurement with gamma-ray telescopes



Plaga '95
Neronov & D.S. '07, '09
Murase et al 08

Neronov & Vovk '10
Tavecchio et al. '10
Dolag et al. '10
....

γ-rays with energies above ~0.1 TeV are absorbed by the pair production on the way from the source to the Earth.

$$D_{\gamma_0} = \frac{1}{n_{\rm IR}\sigma_{PP}} \propto 150 \text{ Mpc} \frac{4 \text{ TeV}}{\text{E}} \frac{10nW/(m^2 sr)}{(\nu F(\nu))_{IR}}$$

$$E_{\gamma 0} = 2E_e \qquad \lambda_e = \frac{1}{n_{\rm CMB}\sigma_{ICS}} \sim 1 \text{ kpc}$$

e^+e^- pairs re-emit γ-rays via inverse Compton scattering of CMB photons.

Inverse Compton γ-rays could be detected at lower energies.

$$E_\gamma = 12 \text{ GeV} \left(\frac{E_e}{2\text{TeV}}\right)^2$$

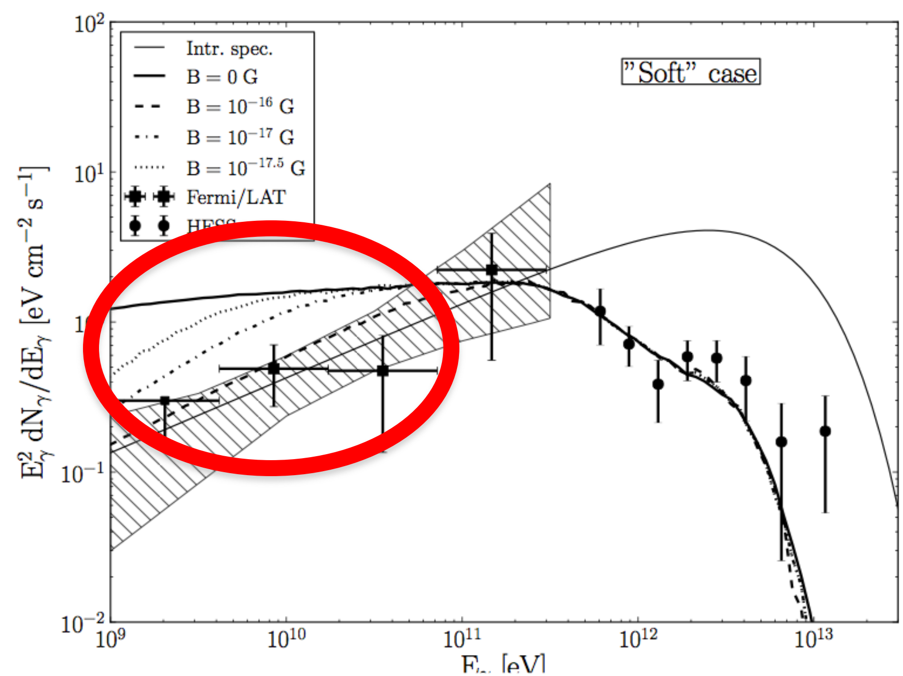
The hardest VHE blazar 1ES 0229+200

Blazar 1ES 0229+200 is considered to be the best candidate for the search of the cascade emission because it has very hard VHE spectrum extending into the ~10 TeV energy band, where γ-ray emission is strongly attenuated by the pair production effect.

Most of the primary γ-ray beam power is removed and transferred to the cascade emission which should appear in the GeV energy band.

The source is extremely weak in the Fermi energy band. It is detected only in the 3-year long exposure.

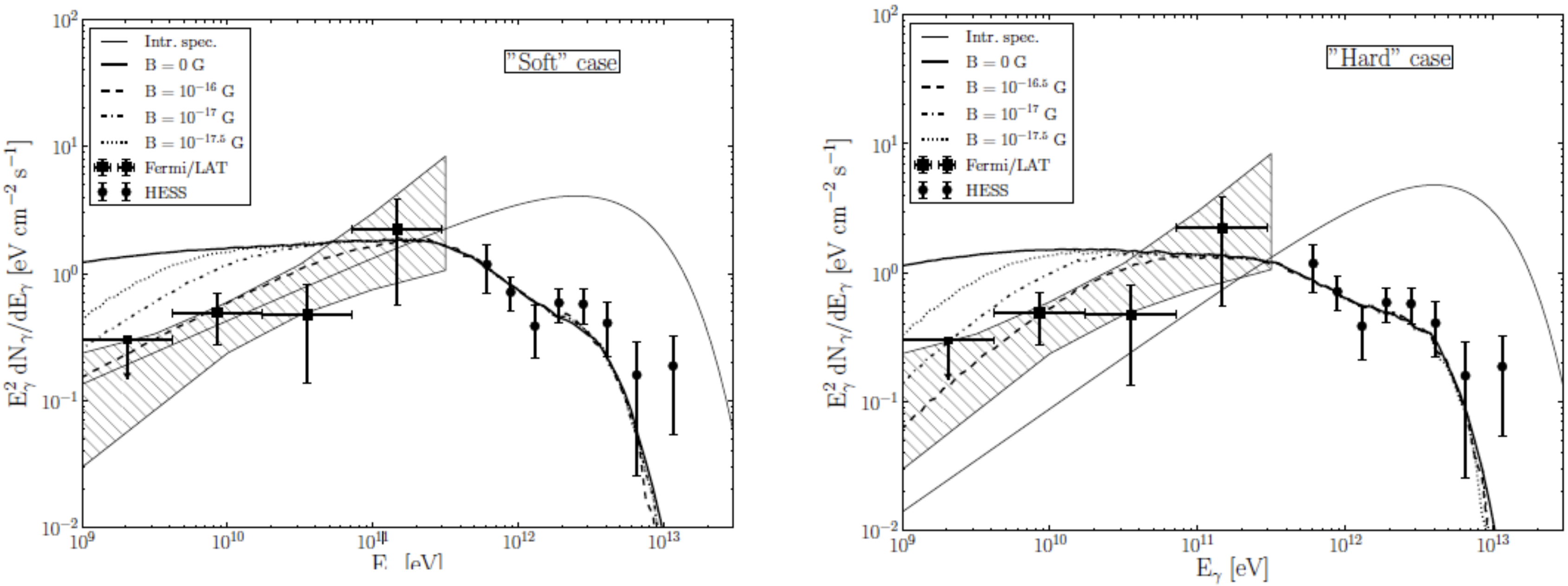
The source is stable in the VHE band: no variability is found between observations made over ~5 yr time span.



$$\Gamma = 1.36 \pm 0.25$$

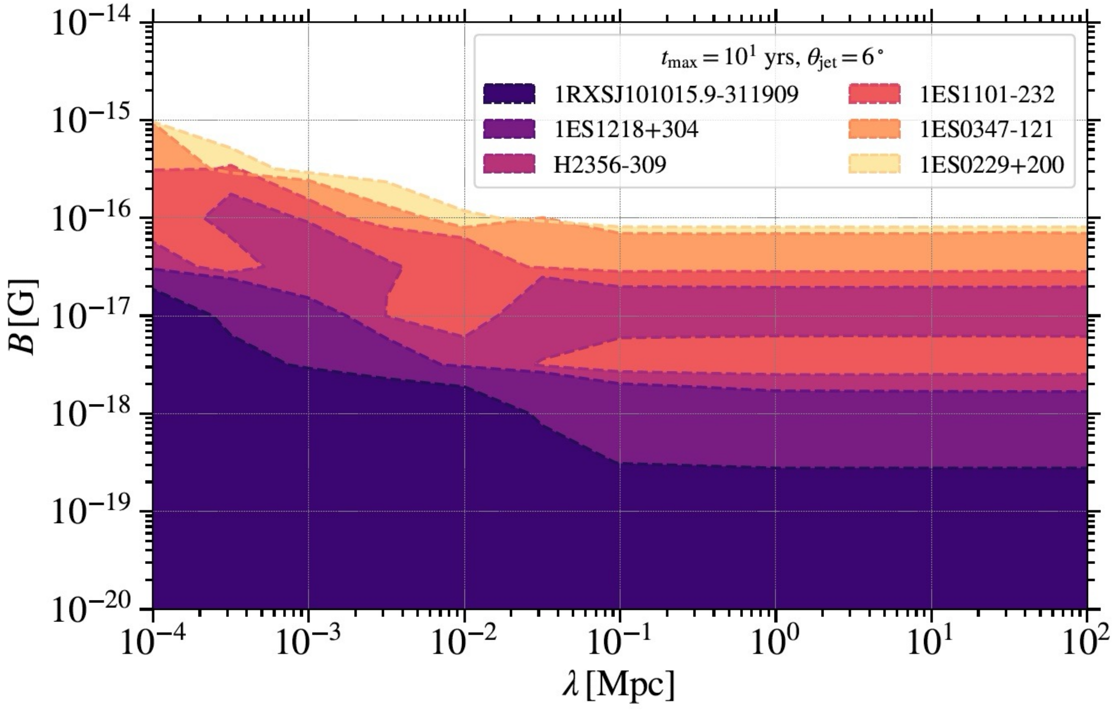
Vovk, Taylor, Neronov, and DS 1112.2534

EGMF from spectrum of 1ES 0229+200



From Ye.Vovk, A.Taylor, A.Neronov, and DS 1112.2534

Constraints on IGMF



J.Biteau et al, Fermi-LAT ApJS 237 (Aug, 2018) 32, [1804.08035].

Cascade component

- Fraction of electron energy in secondary photons in direction of observer

$$\alpha = \frac{\sum E_\gamma}{E_e}$$

- Fraction of voids on the way of primary photon

$$D_{void} = \Delta D_{\gamma_0}$$

- Ratio of point source flux at E_γ and $E_{\gamma 0}$

$$R = F(E_{\gamma_0}) / F(E_\gamma)$$

$$\mathrm{F_{ext}} = \alpha \cdot \mathrm{R} \cdot \Delta \cdot \mathrm{e}^{-\tau(\mathrm{E}_\gamma, \mathrm{z})} \left\langle F_{PS}(E_\gamma) \right\rangle$$

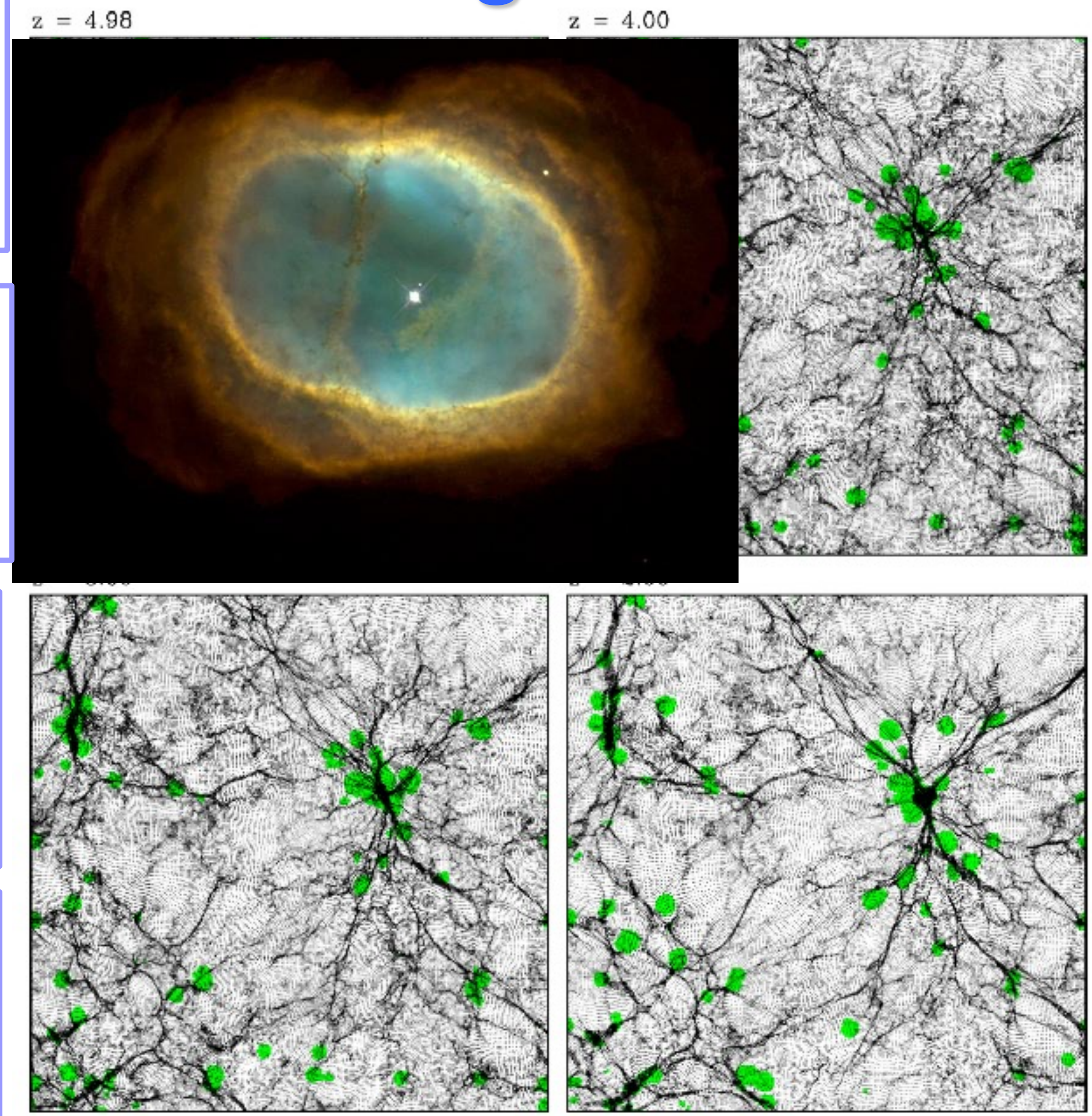
IGMF from galactic winds?

Galactic winds expanding into the intergalactic medium form "bubbles" around galaxies, similar to the stellar wind bubbles blown by massive stars in the interstellar medium.

Bubbles are able to expand up to $\sim$100 kpc distances around small galaxies (up to 10^{10} M_{Sun}) and up to $\sim$1 Mpc distances in the case of Milky Way like galaxies.

Bubbles are blown as long as star formation or AGN activity in the galaxy is strong enough. They might contract after the end of the star formation activity.

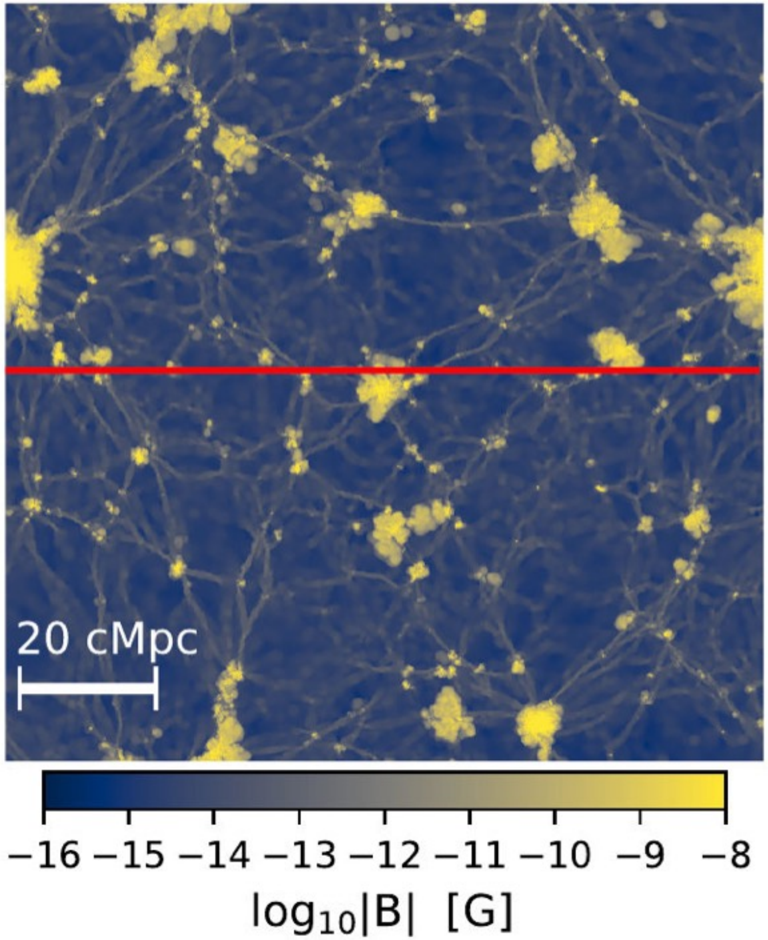
Volume filling factor of these galactic wind blown bubbles is uncertain. State-of-art simulations are not able to model the bubble evolution "from the first principles".



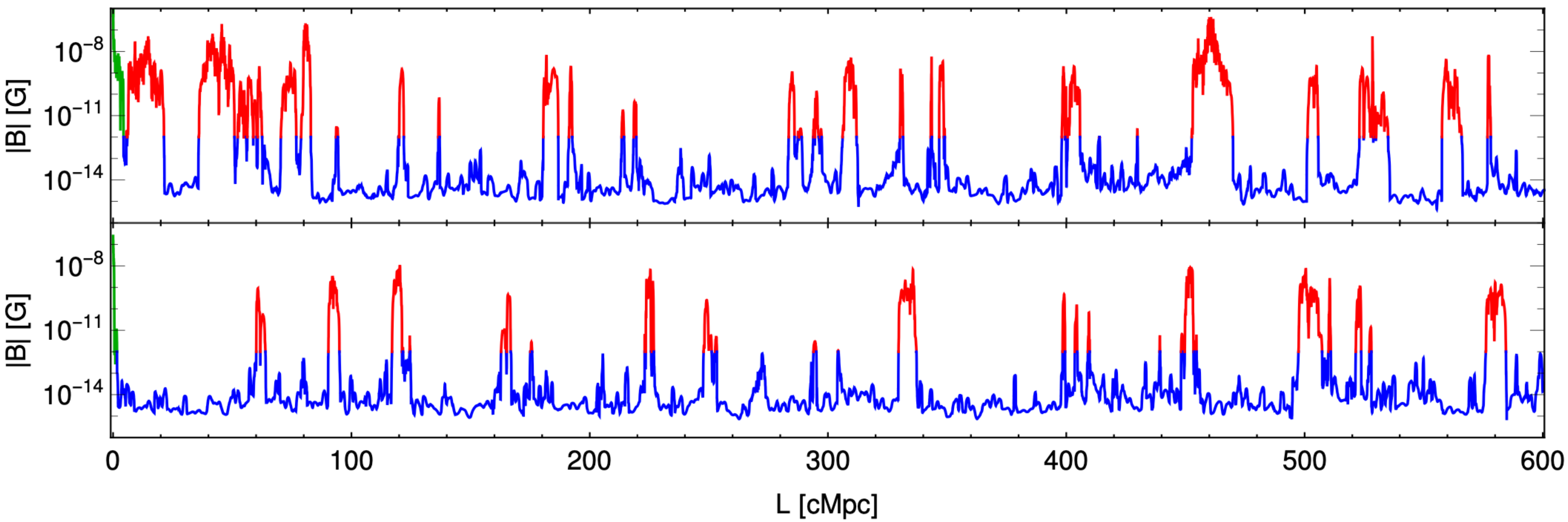
Pinsonneault et al. '10

Inter-Galactic Magnetic Field and AGN feedback

3D magnetic field in ILLUSTRIS-TNG

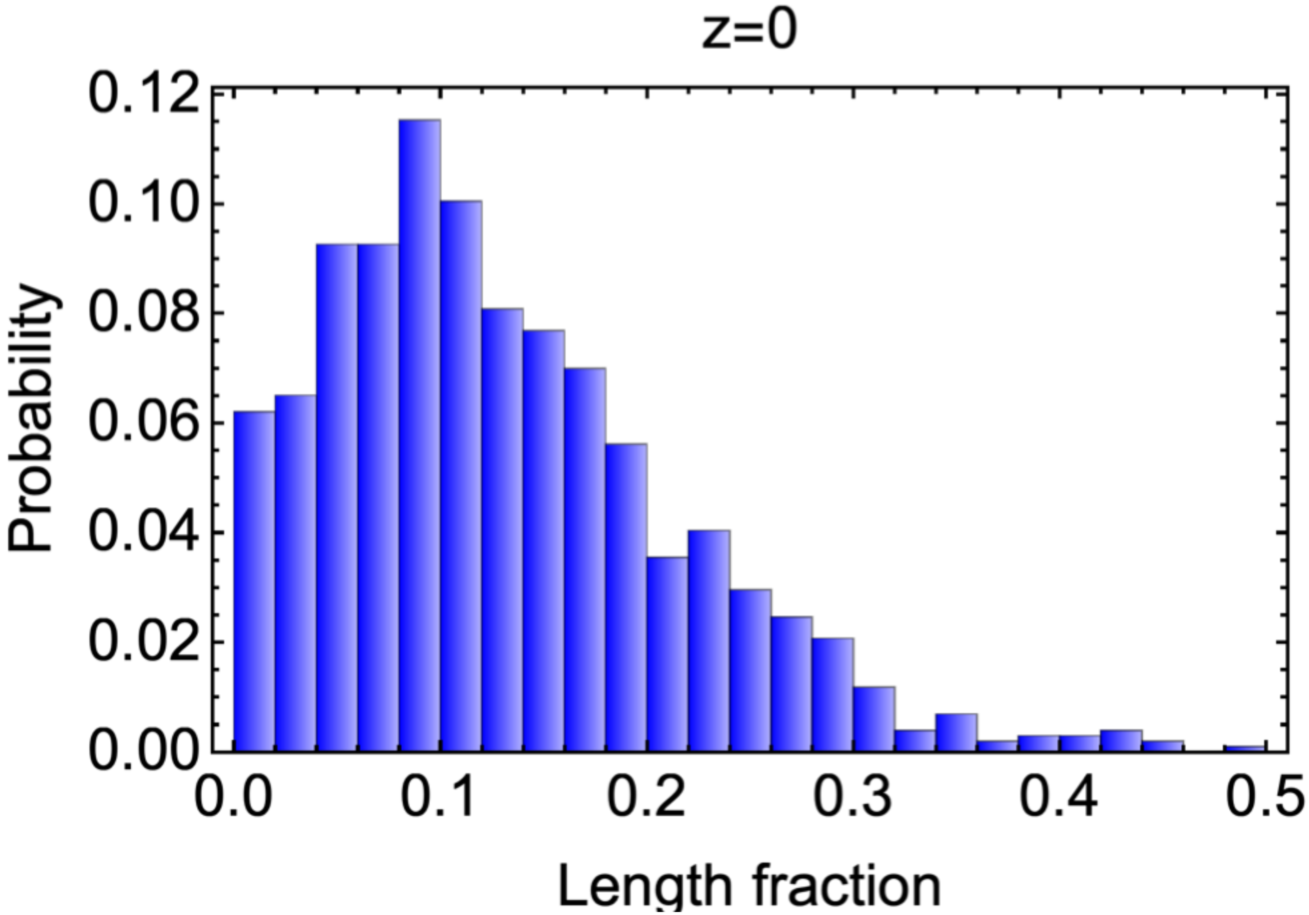


IGMF on LOS and magnetic bubbles



K.Bondarenko et al, 2106.02690

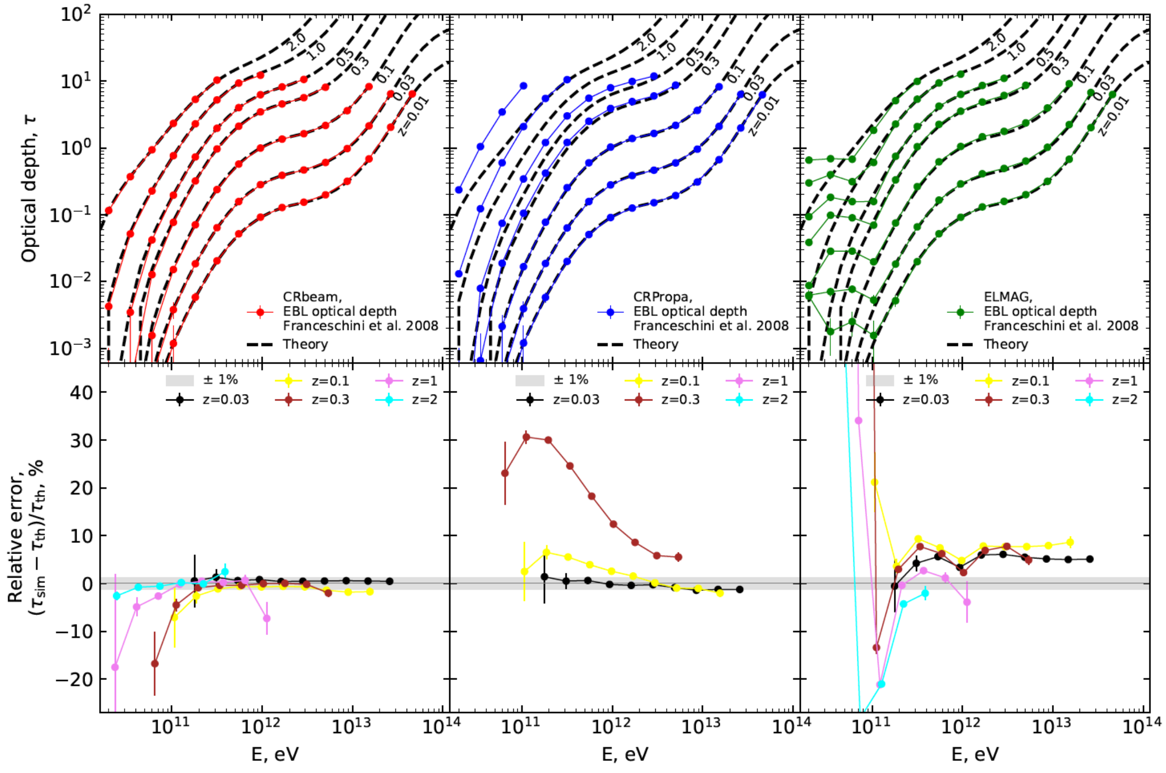
Probability to have strong MF on LOS



K.Bondarenko et al, 2106.02690

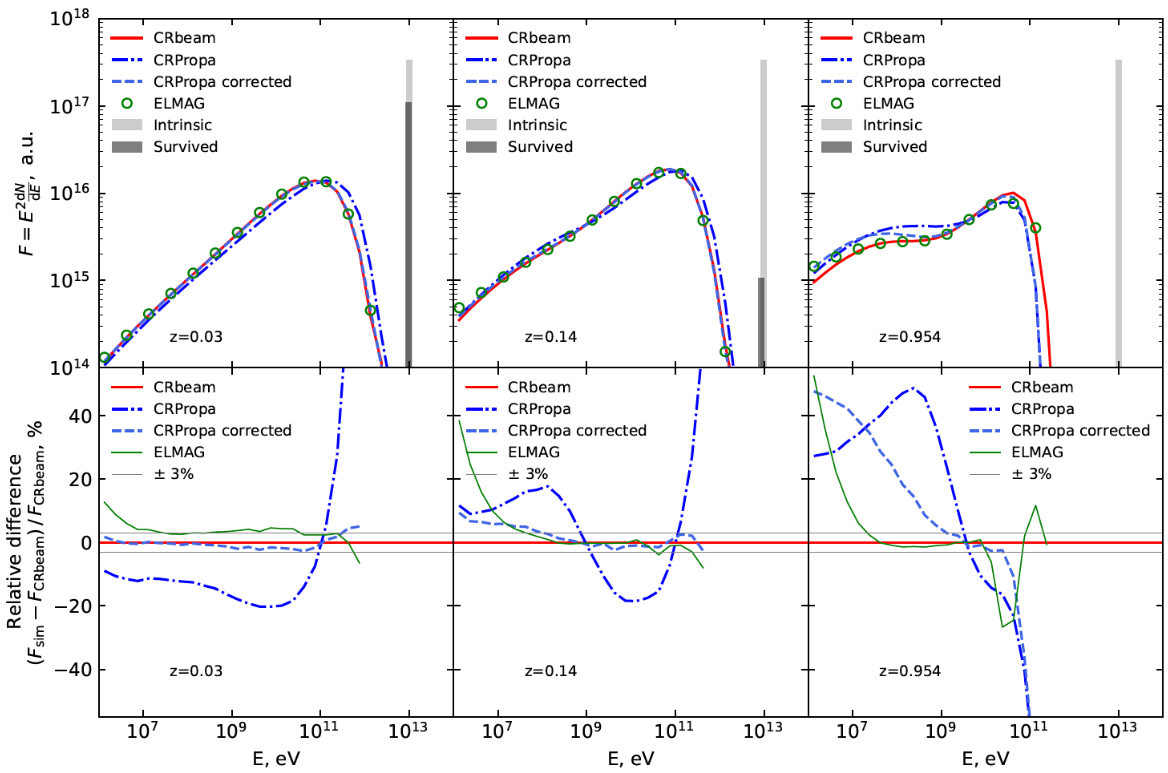
3D cascade codes in CTA era

Optical depth of gamma-rays on EBL+CMB



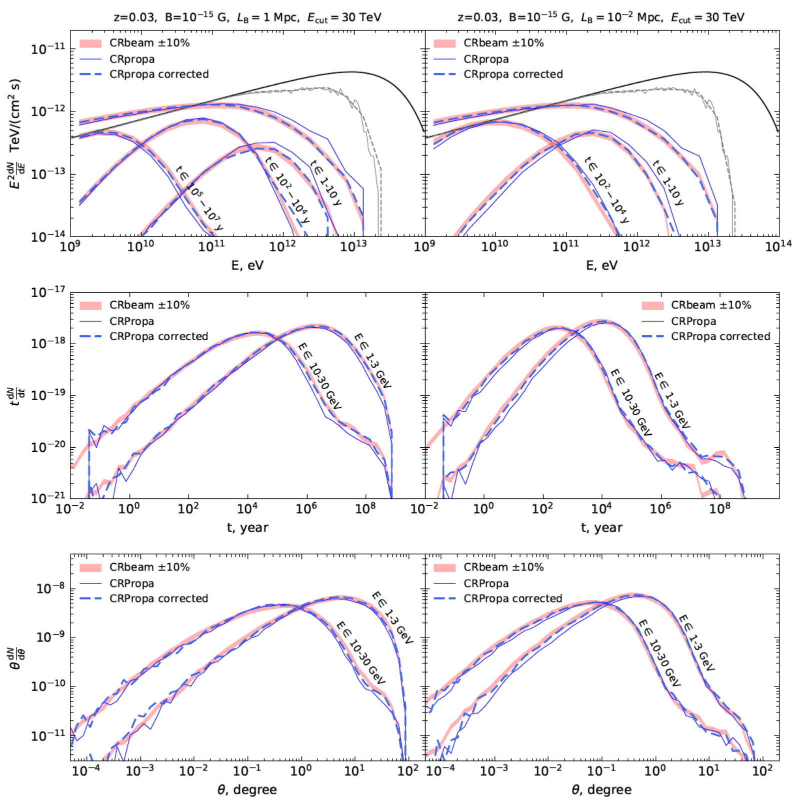
From A.Korochkin, A.Neronov, and DS, arXiv 2201.03996

Secondary gamma-ray spectrum



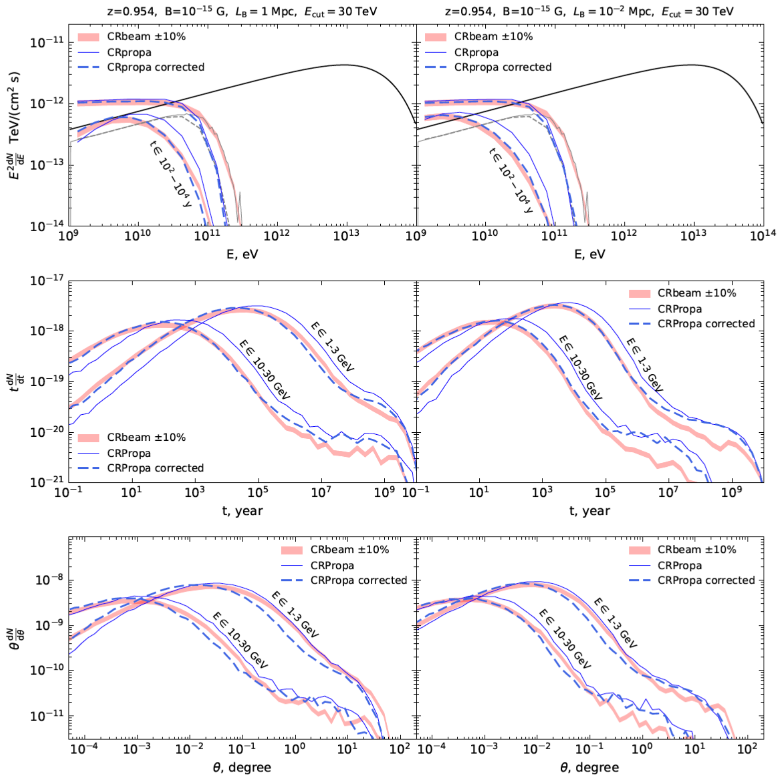
From A.Korochkin, A.Neronov, and DS, arXiv 2201.03996

3D cascade at z=0.03



From A.Korochkin, A.Neronov, and DS, arXiv 2201.03996

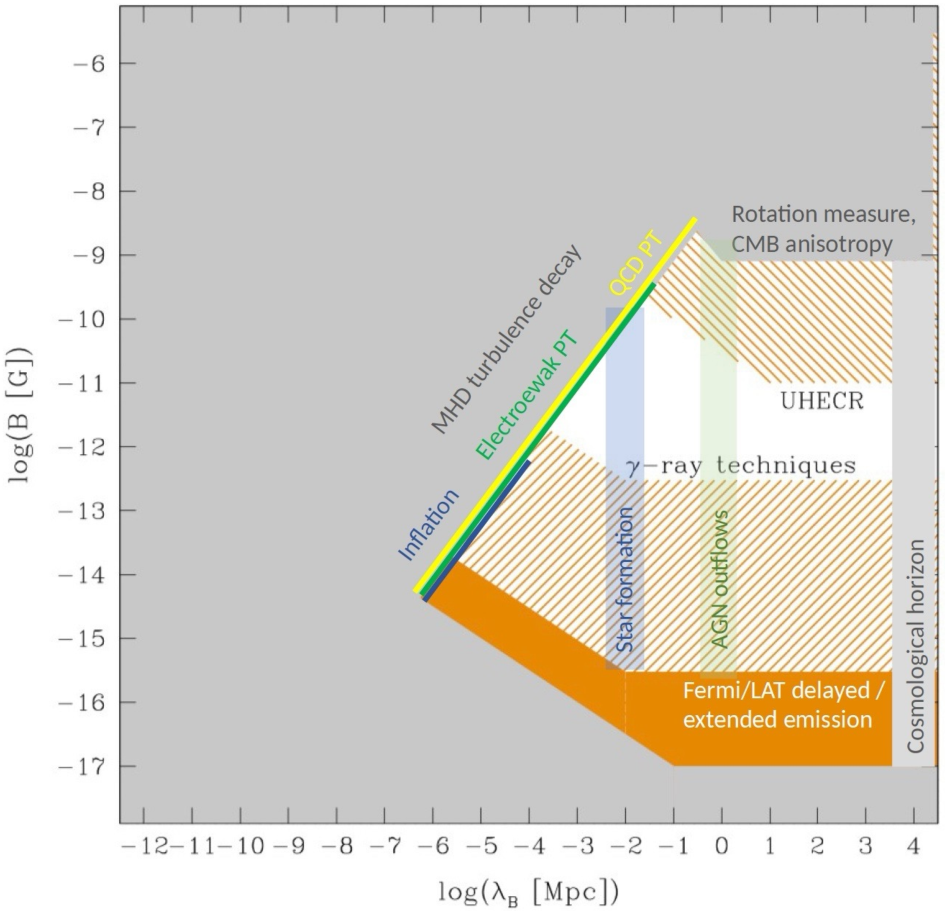
3D cascade at z=0.954



From A.Korochkin, A.Neronov, and DS, arXiv 2201.03996

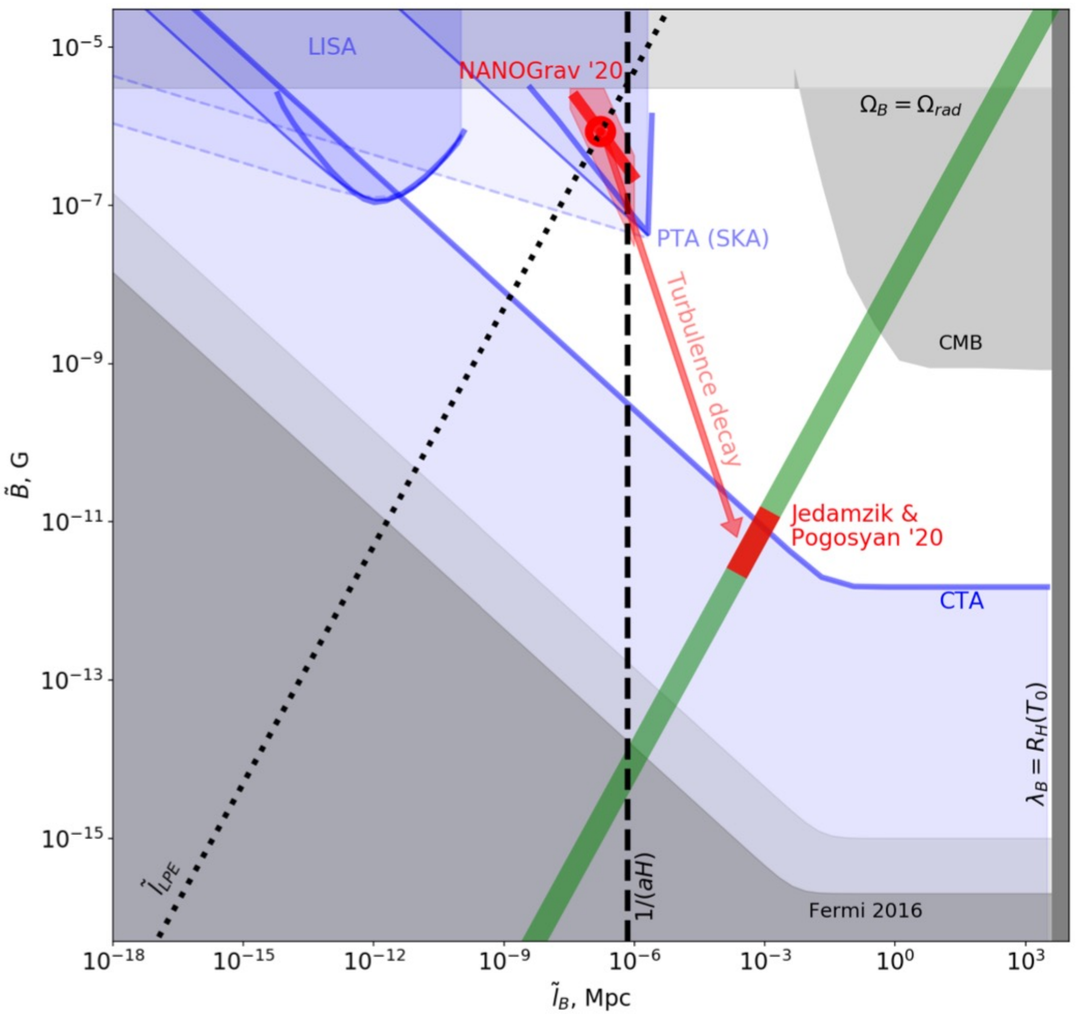
Can gamma-telescopes detect 10 pG IGMF (one which can help with H0 problem)?

Detection of IGMF



R.Durrer and A.Neronov, A&A Rev. 21 62, [1303.7121].

IGMF from QCD phase transition



A. Neronov et al., 2009.14174

Detection of 10 pG IGMF

Cosmological IGMF

$$B \sim 10^{-11} \left[\frac{\lambda_B}{1\ \mathrm{kpc}}\right]\ \mathrm{G}$$

Primary photon optical depth distance

$$\lambda_{\gamma 0} \simeq 2.5 \left[\frac{E_{\gamma 0}}{100\ \mathrm{TeV}}\right]^{-1.6}\ \mathrm{Mpc}$$

Electron travel energy loss distance

$$D_e \simeq 7 \left[\frac{E_e}{50\ \mathrm{TeV}}\right]^{-1}\ \mathrm{kpc}$$

Secondary photon energy

$$E_\gamma \simeq 8 \left[\frac{E_e}{50\ \mathrm{TeV}}\right]^{2}\ \mathrm{TeV}$$

Kalashev et al, 2007.14331

Conditions to detect 10 pG IGMF

Probe of the strongest fields $B \lesssim 10^{-11}$ G requires

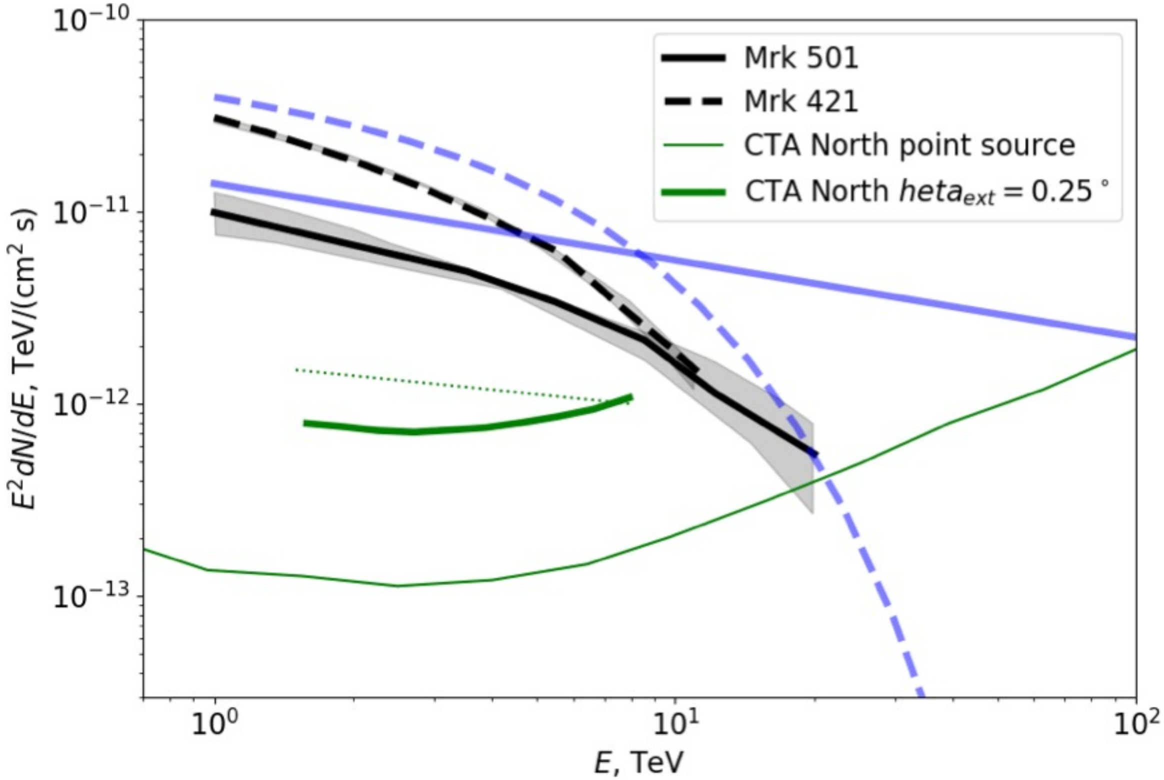
(a) large primary point-source power in the 100 TeV energy range,

(b) detectability of extended emission in multi-TeV energy range, and

(c) presence of primordial IGMF in the several Mpc region around the source.

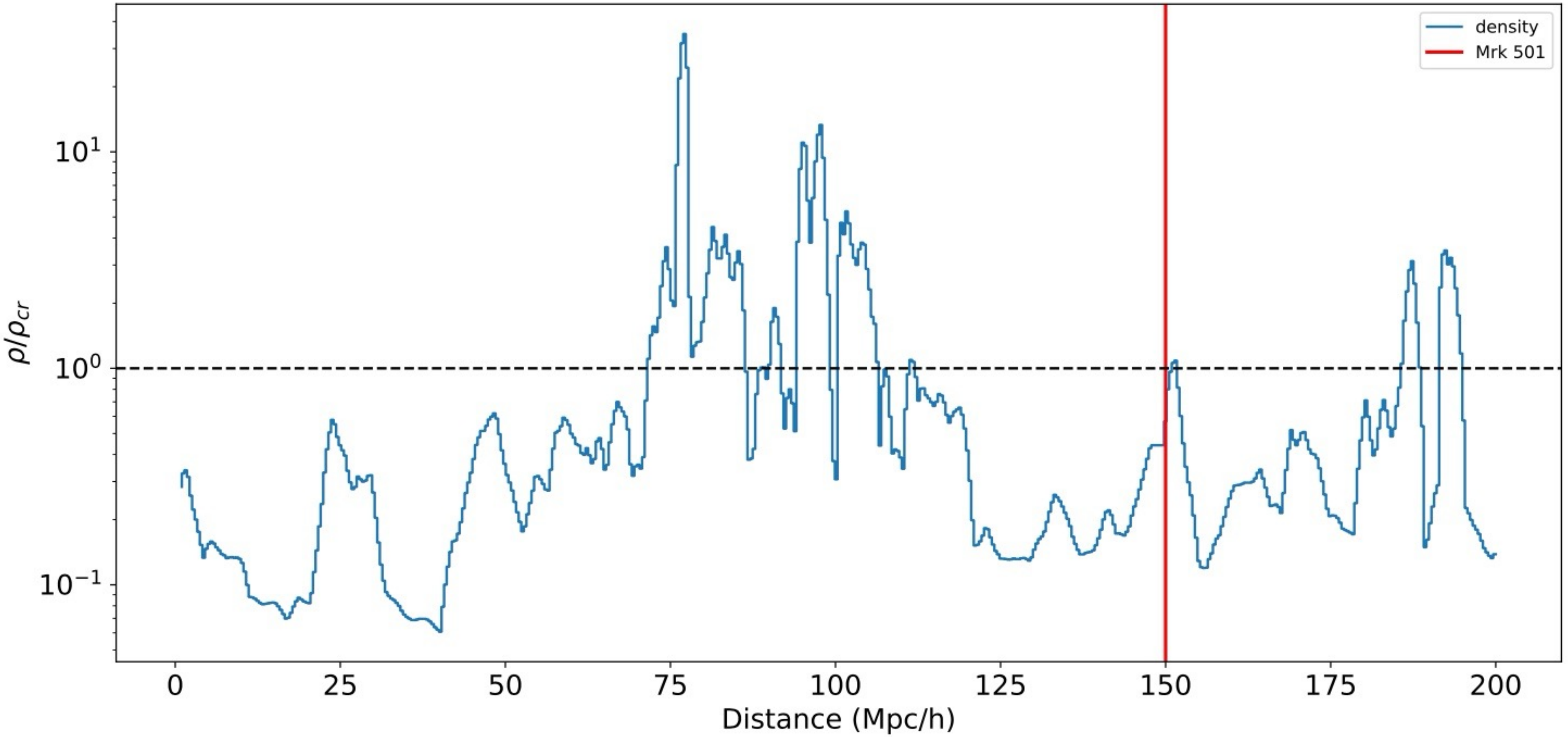
Kalashev et al, 2007.14331

Spectrum Mkn 421 and Mkn 501



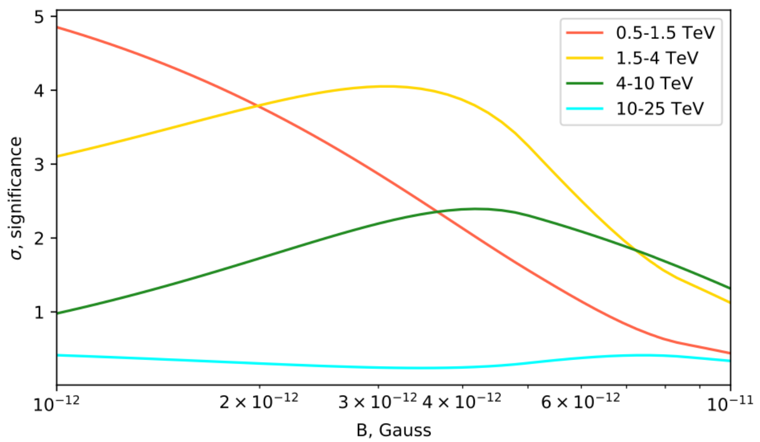
Kalashev et al, 2007.14331

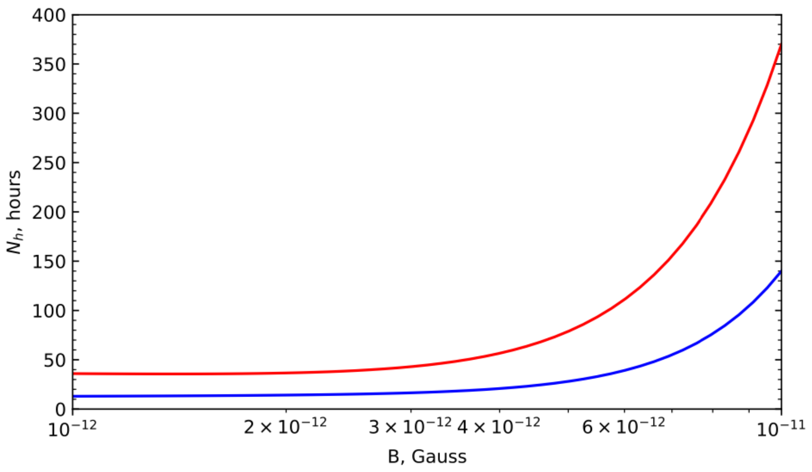
IGMF on LOS to Mkn 501



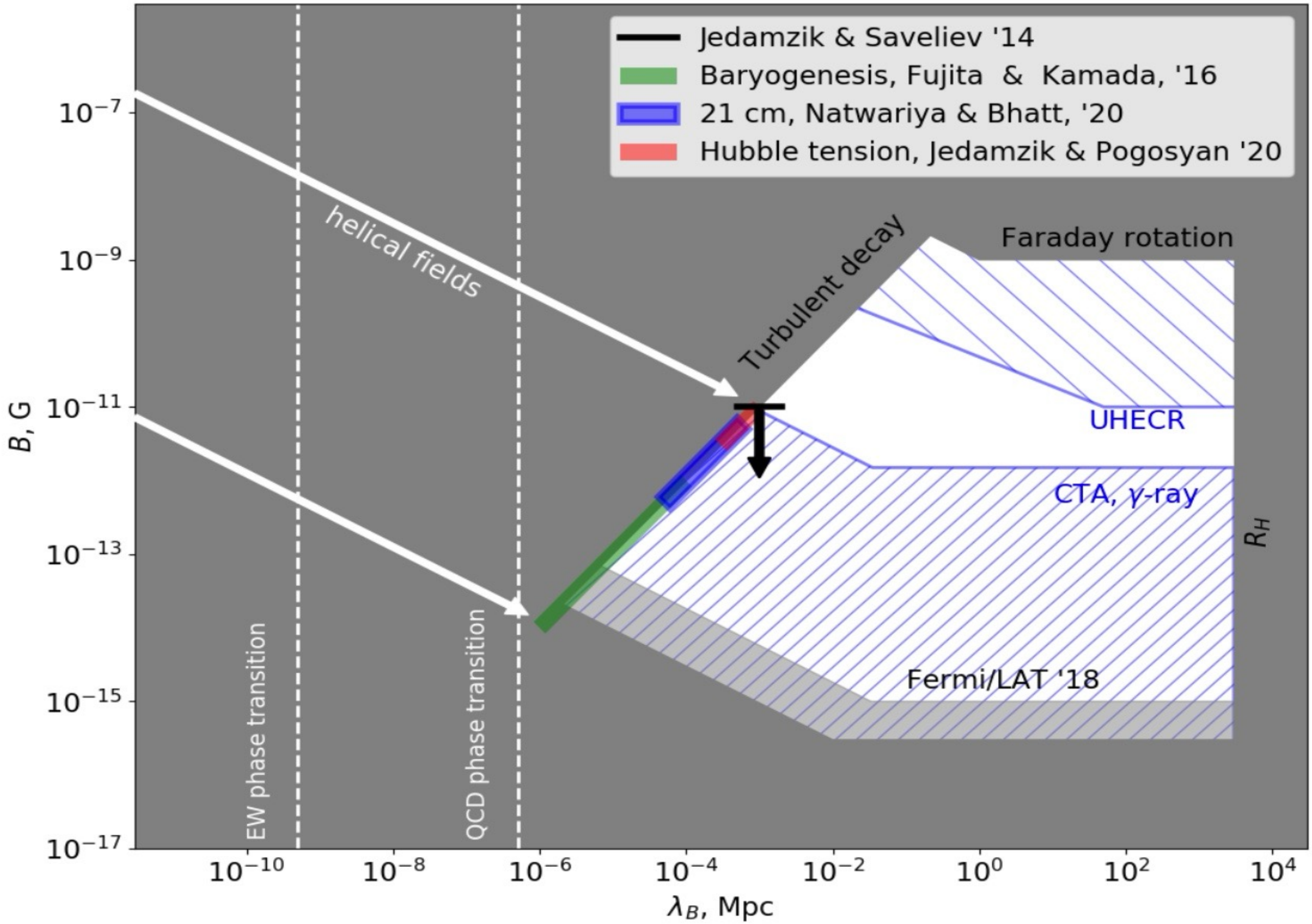
Kalashev et al, 2007.14331

Detection of extended emission around Mkn 501 by CTA North for 1-10 pG IGMF





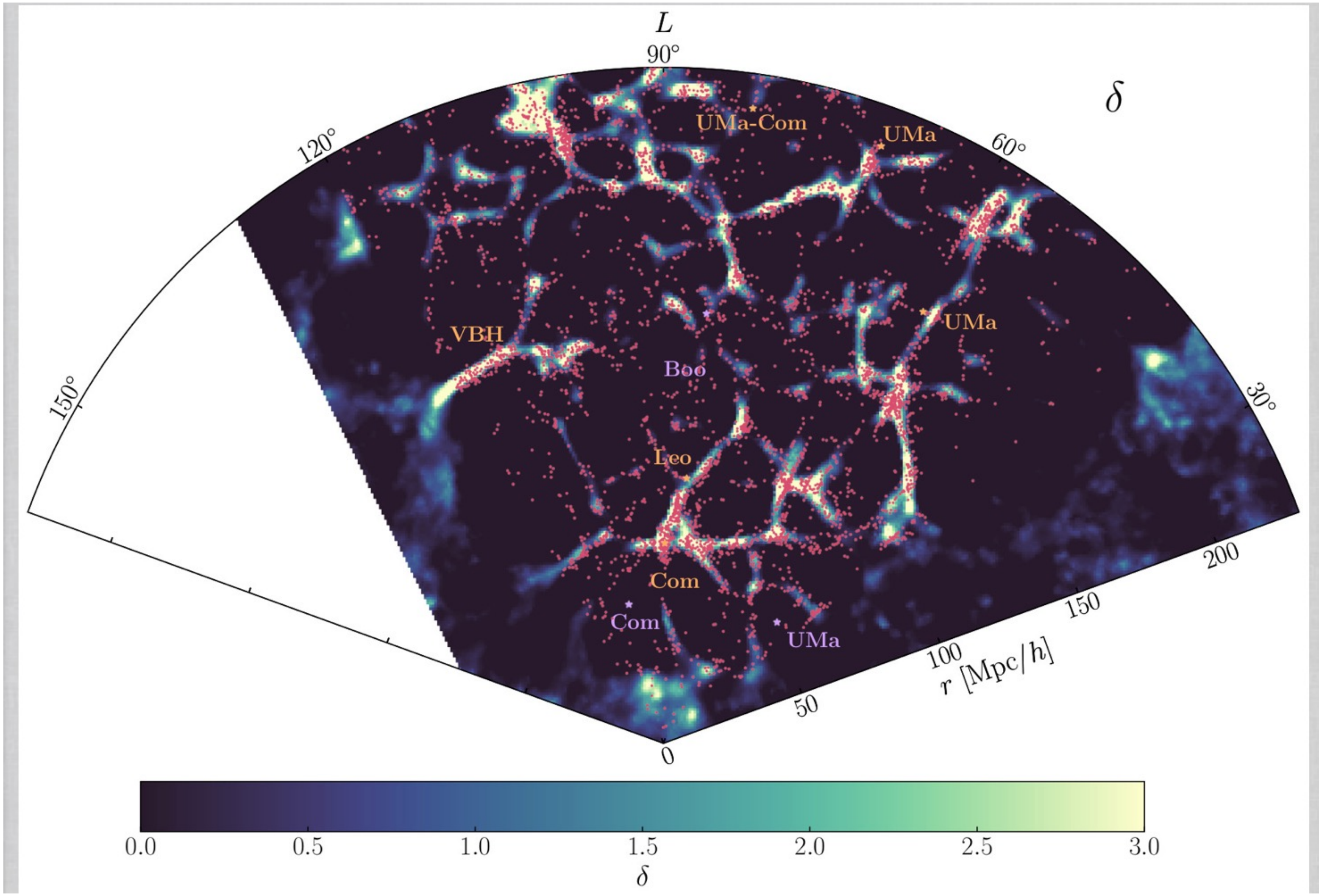
Kalashev et al, 2007.14331



Kalashev et al, 2007.14331

Detection of Inter-Galactic Magnetic Field from inflation

BORG LSS and RAMSES MHD



TeV blazars within 250 Mpc

Name	RA	Dec	z	$F_{1\mathrm{TeV}}$, TeV cm^{-2} s^{-1}
Mkn 421	166.11	38.21	0.031	2×10^{-11}
Mkn 501	253.47	39.76	0.033	1×10^{-11}
QSO B2344+514	356.77	51.7	0.044	4×10^{-12}
Mkn 180	174.11	70.16	0.046	8×10^{-13}
1ES 1959+650	299.99	65.15	0.047	6×10^{-12}
AP Librae	229.42	-24.37	0.04903	4×10^{-13}
TXS 0210+515	33.57	51.75	0.04913	2×10^{-13}

A.Korochkin et al, 2111.10311.

IGMF from inflation

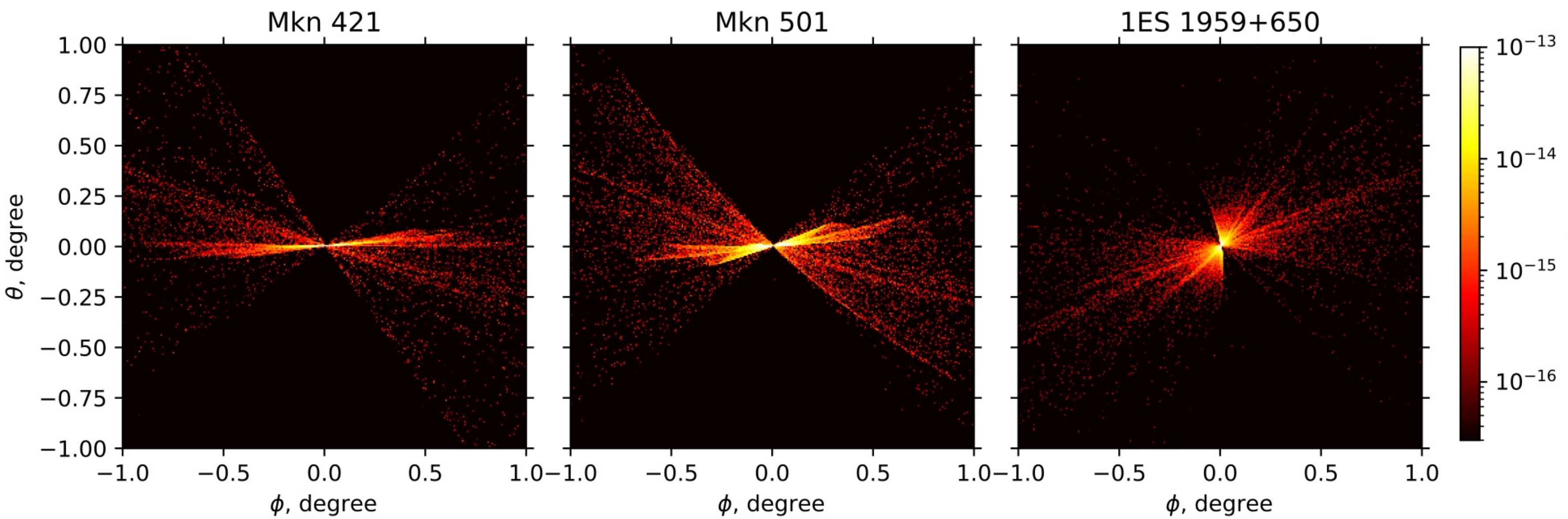
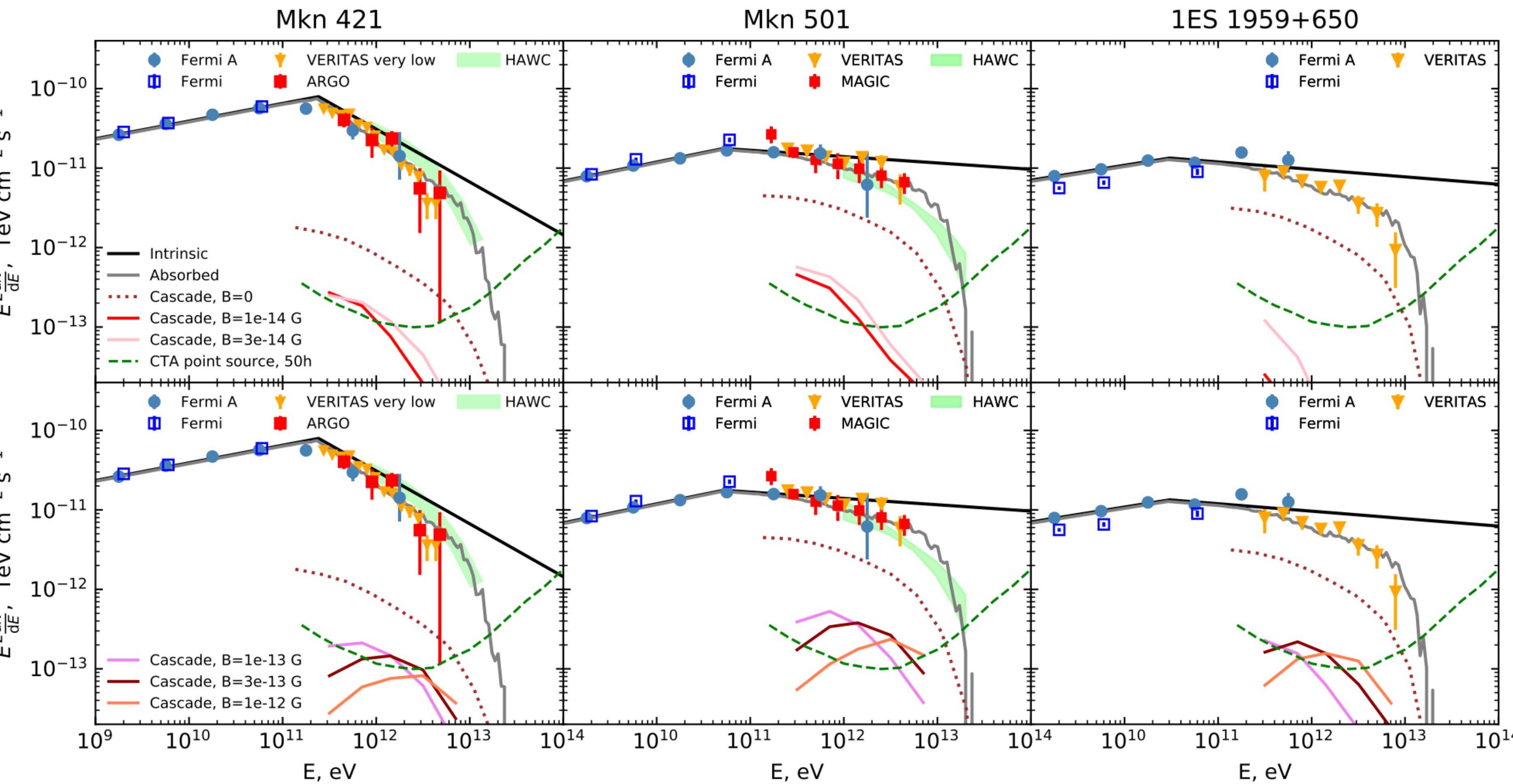


FIG. 4: Images of the extended emission signal in the energy range 200 GeV - 2 TeV for the three brightest sources in our sample. The assumed initial cosmological magnetic field strength is $B = 10^{-13}$ G. The direction of the jet axis coincides with the direction from the source to the observer and the jet opening angle is 5°.

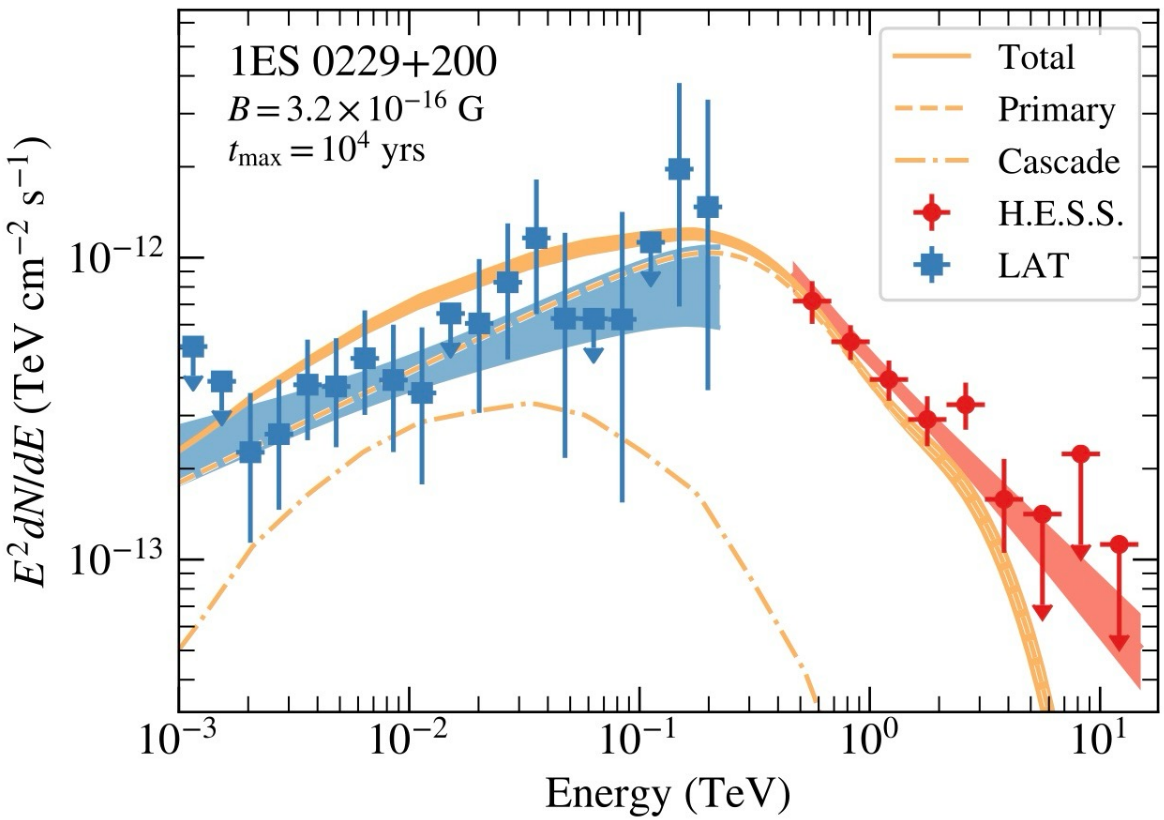
A.Korochkin et al, 2111.10311.



A.Korochkin et al, 2111.10311.

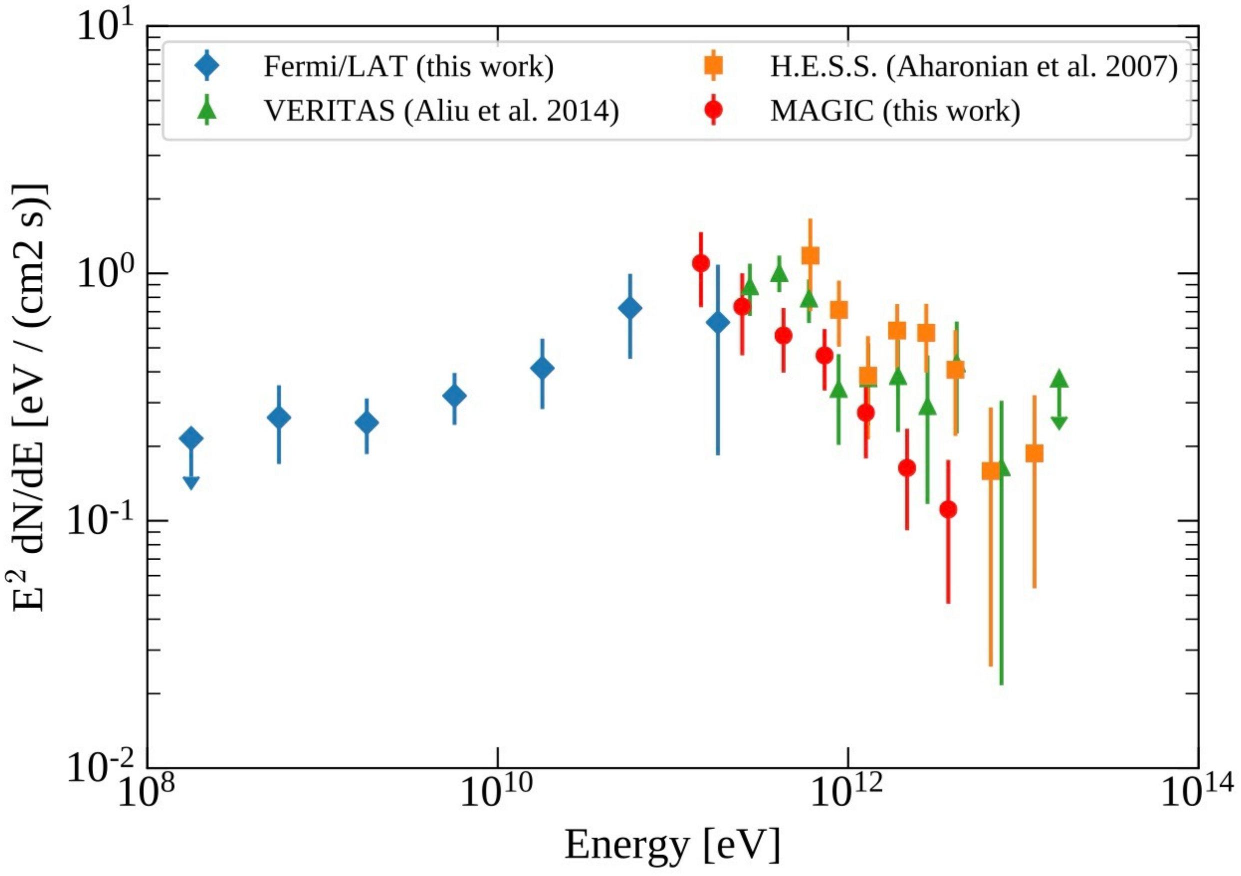
Inter-Galactic Magnetic Field by MAGIC

Cosmological magnetic field from 1ES 0229+200 measurements



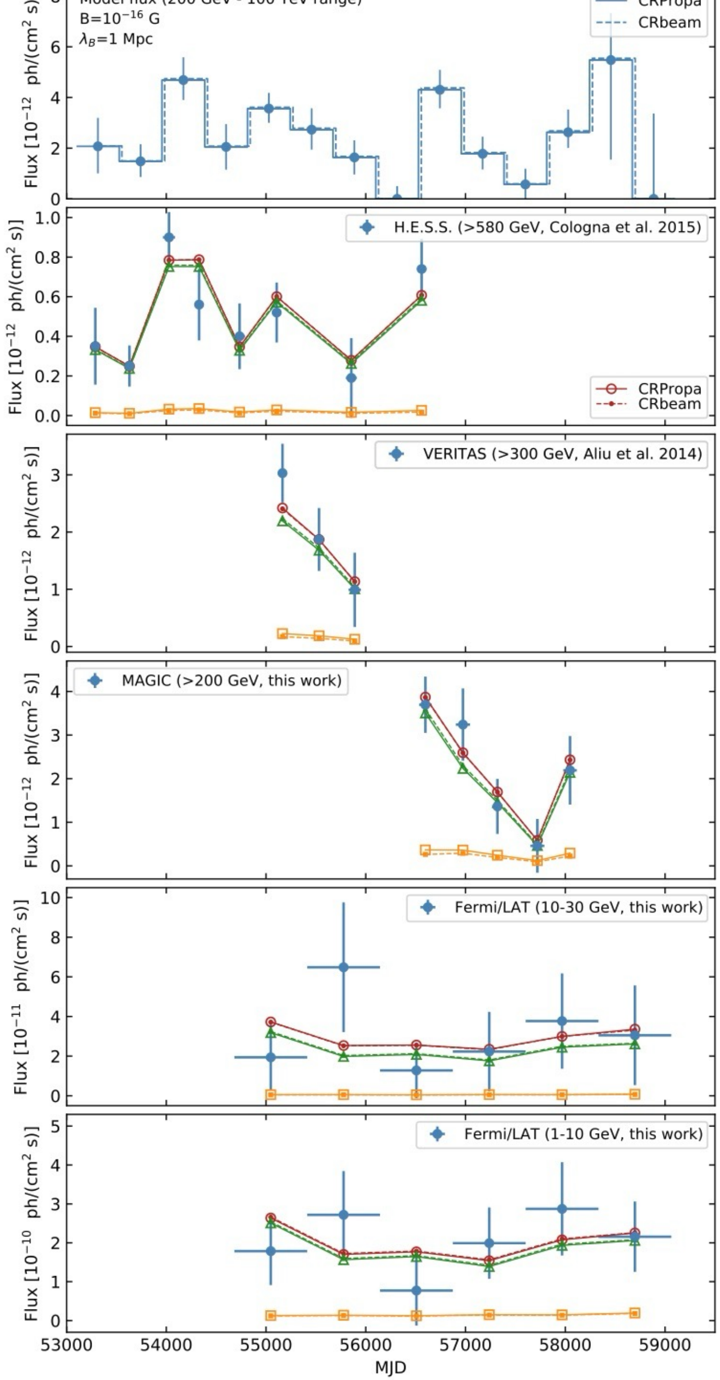
Fermi and HESS collab 2306.05132

Cosmological magnetic field from 1ES 0229+200 measurements



MAGIC collab 2210.03321

Flux of 1ES 0229+200 in gamma-rays



Flux of 1ES 0229+200 in gamma-rays

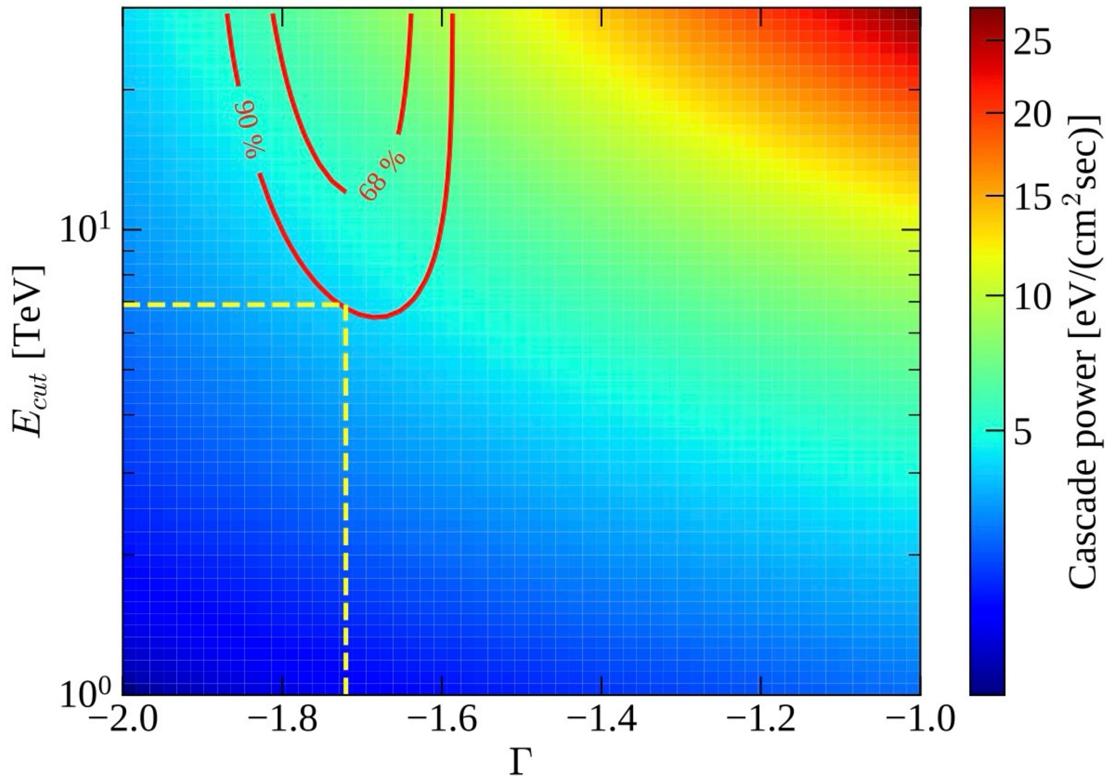
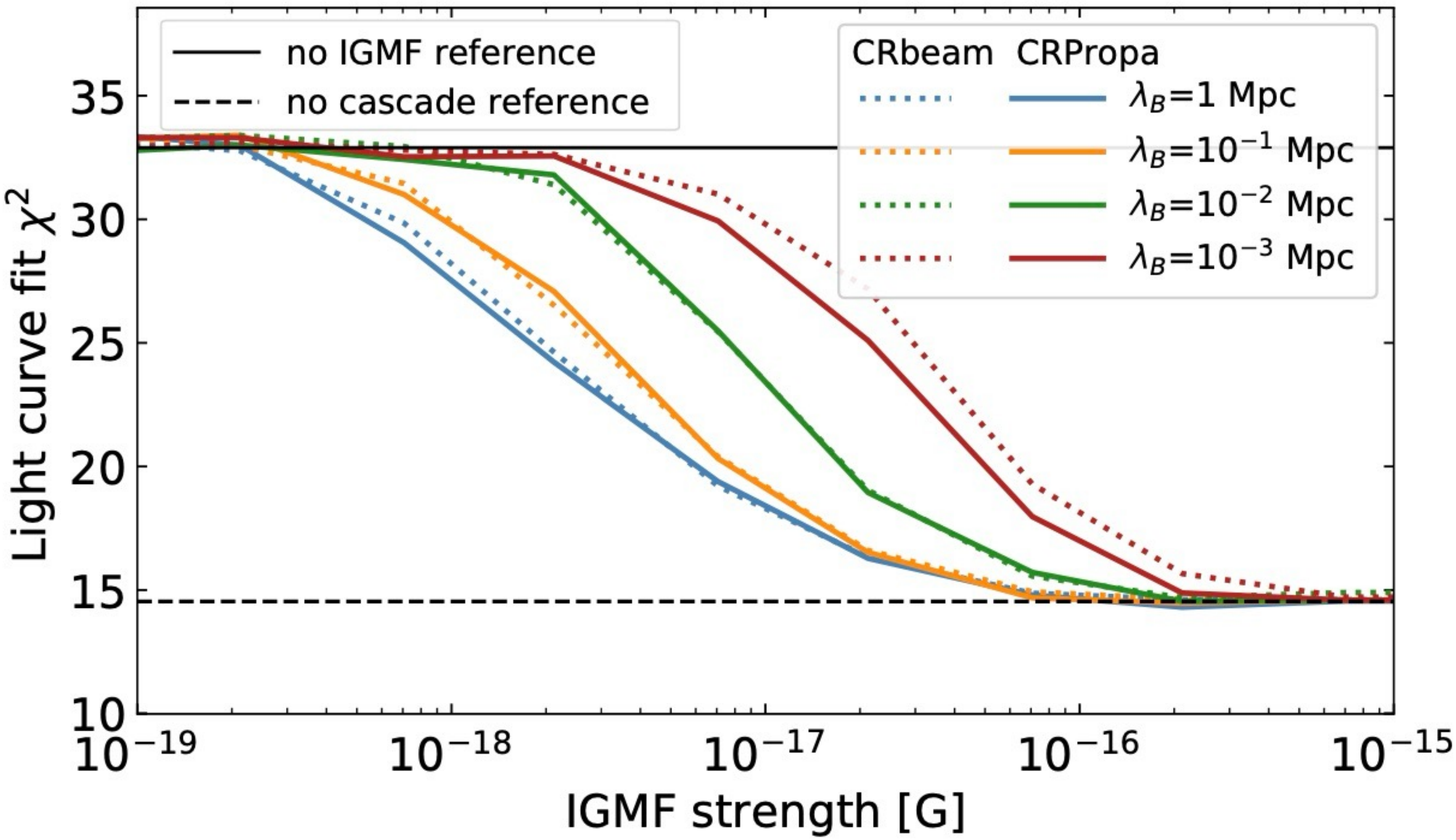
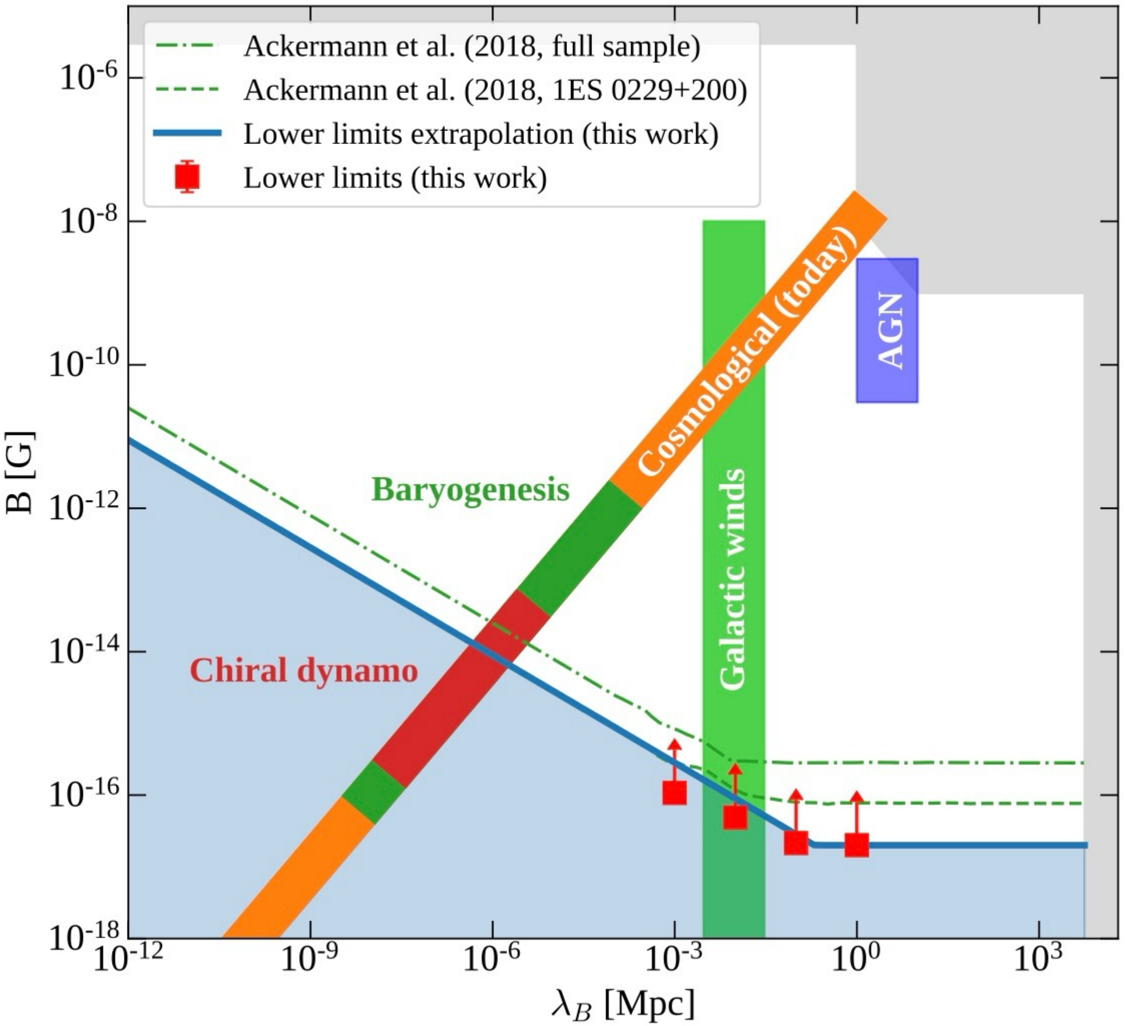


Fig. 3. The scan of the cascade power in the $\Gamma - E_{cut}$ parameter space along with the 68% and 90% confidence contours from the χ^2 fit. At 90% confidence level the minimal cascade, marked with the yellow dashed lines, corresponds to $\Gamma \approx 1.72$ and $E_{cut} \approx 6.9$ TeV.

Flux of 1ES 0229+200 in gamma-rays



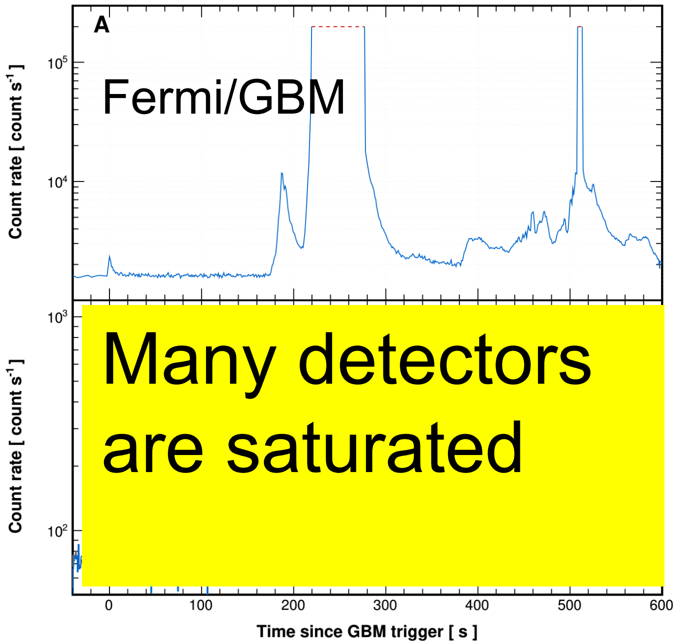
Magnetic field from 1ES 0229+200

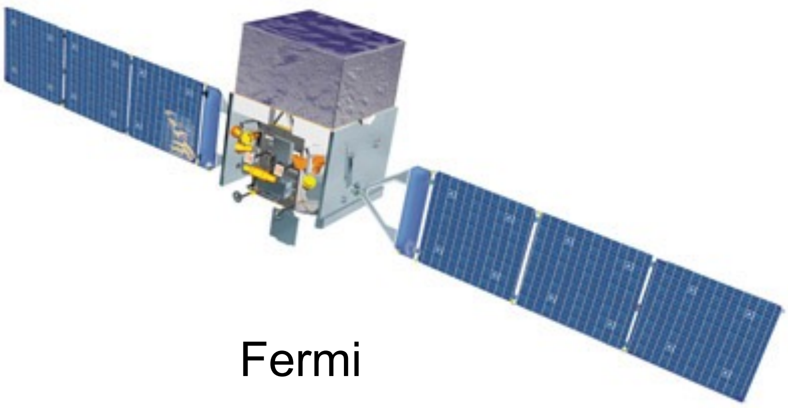


Inter-Galactic Magnetic Field from BOAT GRB

GRB 221009A: brightest-of-all-time (BOAT) GRB

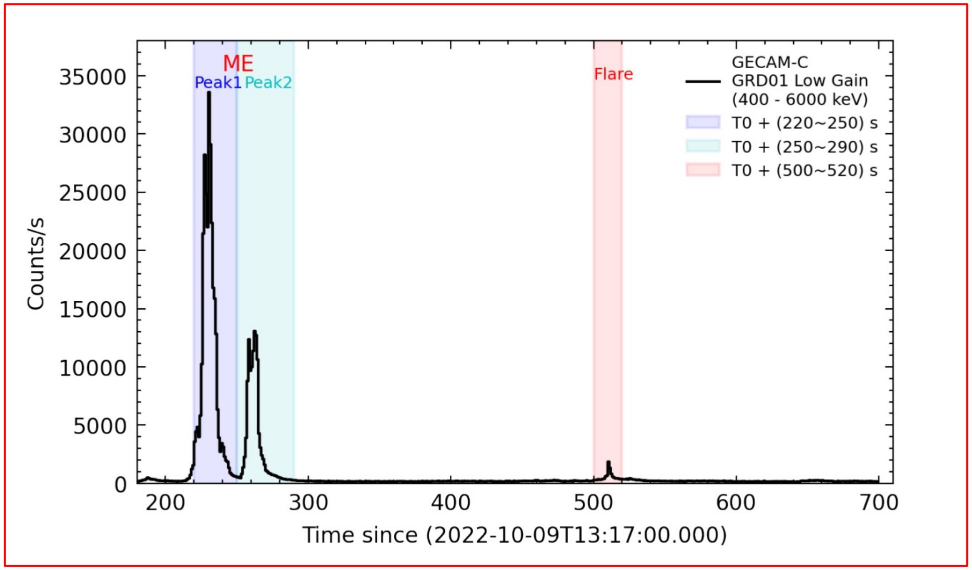
- Triggered on a weak precursor
- Fluence: >5e-2 erg/cm^2， low redshift (z=0.151)
- deriving an enormous energy $E_{\gamma,iso}$~10^{55} erg

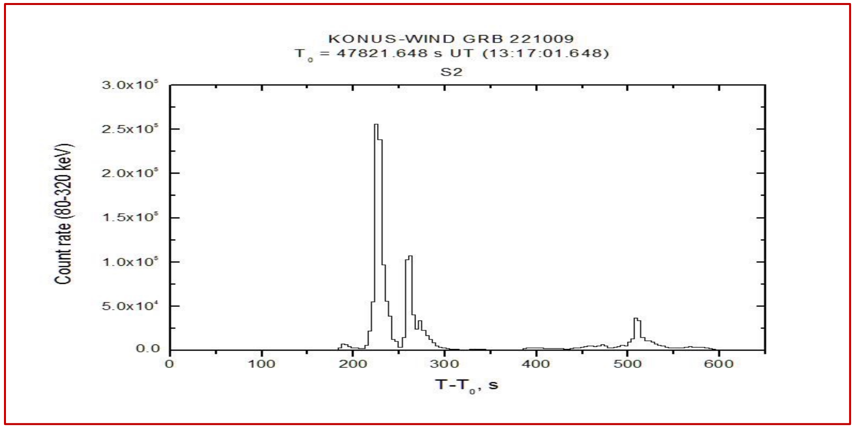




Fermi

GECAM/Konus-Wind Observations of GRB 221009A

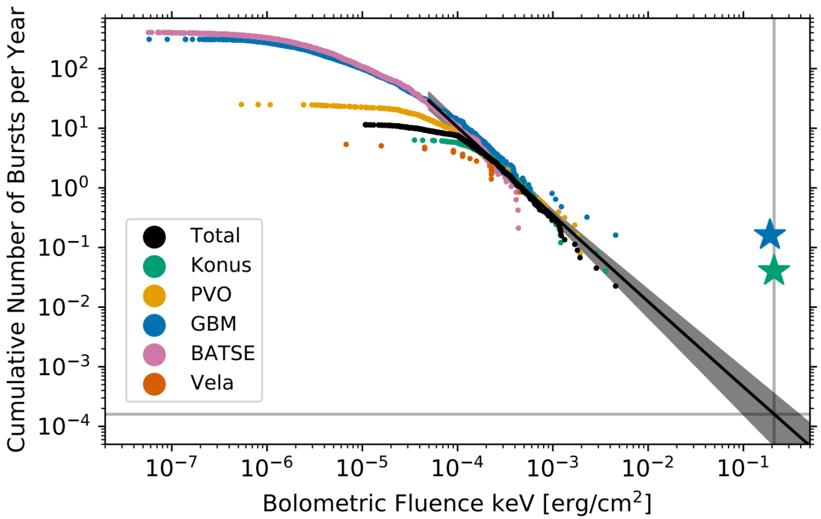


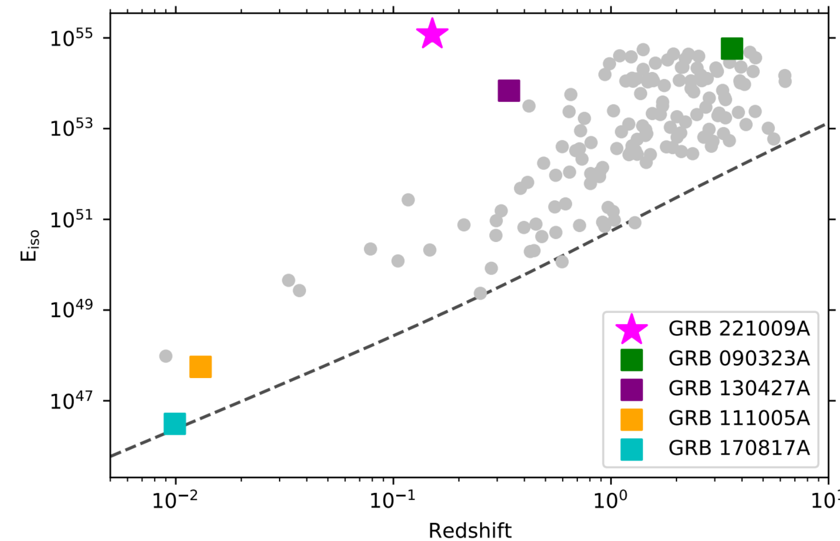


E_iso~ 1.5 × 10^55 erg

Mian peak 1 lasts ~10 s

GRB 221009A: A very rare event





Fluence: >5 × 10 $^{-2}$ erg/cm^2

R_GRB≤ 6.1 × 10^{-4} Gpc^{-3} yr^{-1}

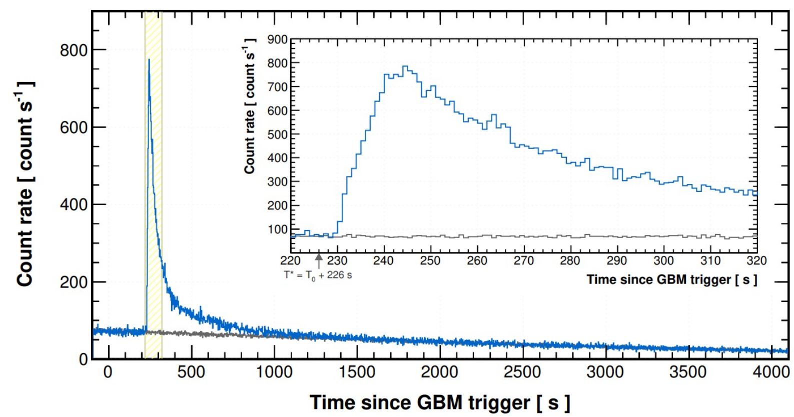
z=0.151 volume ~ 1 Gpc^3

R<10^-3 yr

Buns et al. 2023

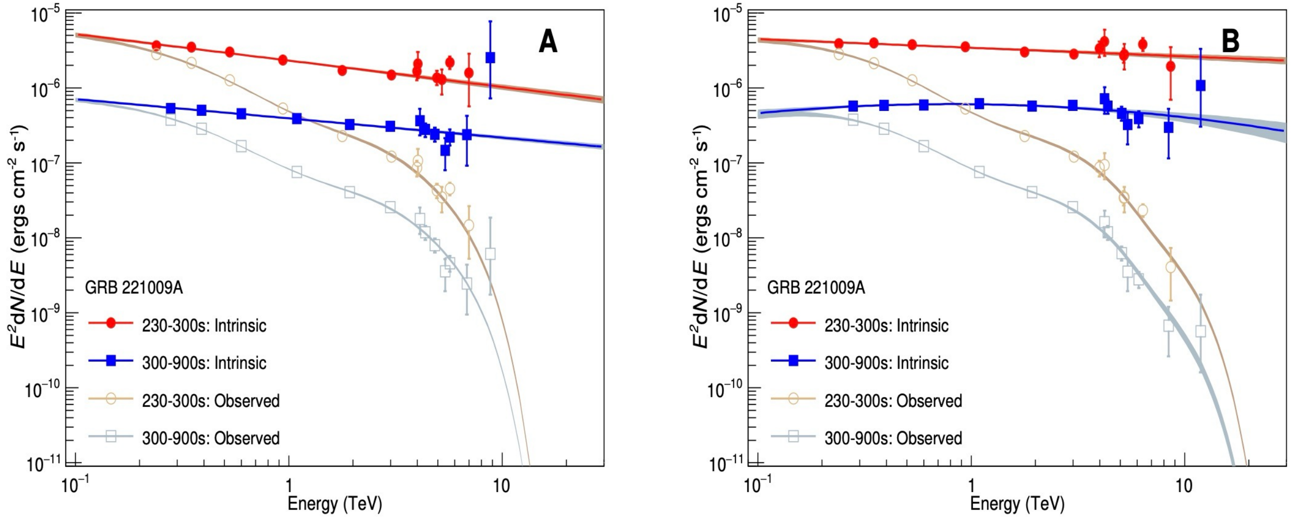
LHAASO GRB221009A

- LHAASO detection of GRB 221009A: first GRB seen by a extensive air shower detector
- High statistics: >60,000 photons above 0.2TeV (LHAASO-WCDA)
- TeV count rate light curve: Smooth temporal profile – **external shock origin**

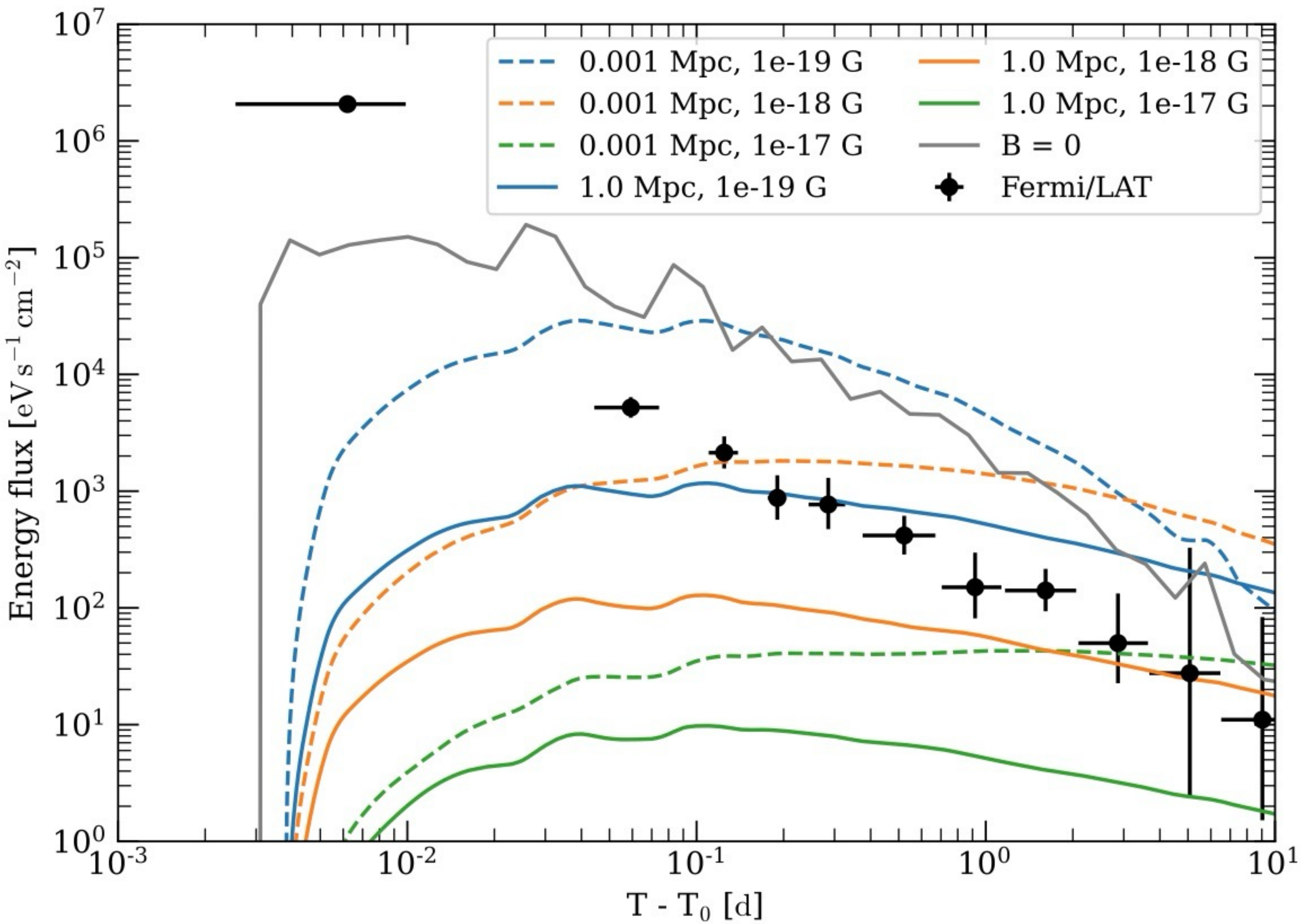


First time detection of the TeV afterglow onset !

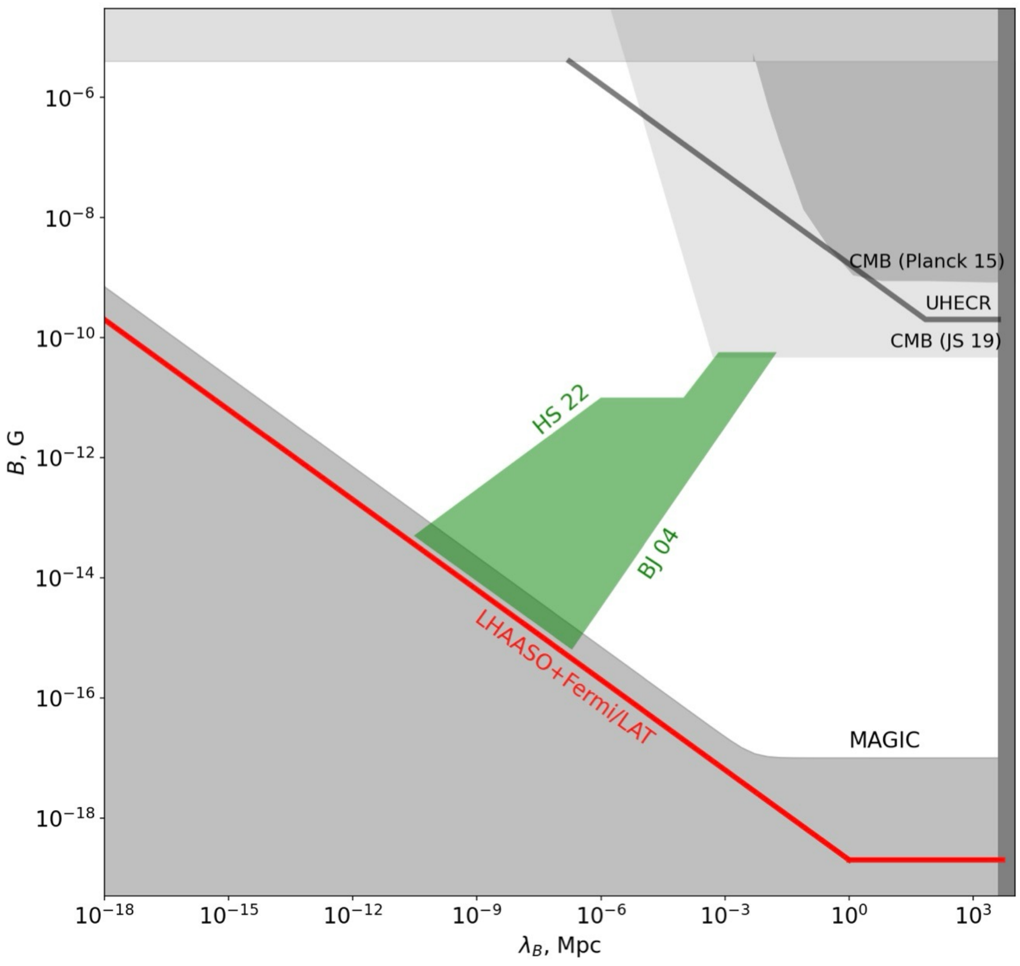
Flux from BOAT GRB in in LHAASO



Flux from BOAT GRB in Fermi and cascade contribution



Constraint on IGMF from BOAT GRB



Summary

- *One has to be careful in choice of cascade models, CRpropa does not work at high redshifts, use CRbeam or ELMAG*
- *Inter-Galactic Magnetic Fields in the voids of LSS with strength up to 10 pG can be found from high precision blazar spectra/time delay/ extended emission measurements by CTA*
- *Astrophysical MF can affect measurements on 10%-20% level, which depends on LOS to source*
- *Primordial MF from inflation can be found by measurement of extended emission with network of blazars*

Summary

- *Low limit on Inter-Galactic Magnetic Field was found from long term measurements of 1ES 0229+200*
- *Low limit on IGMF was found from BOAT GRB*