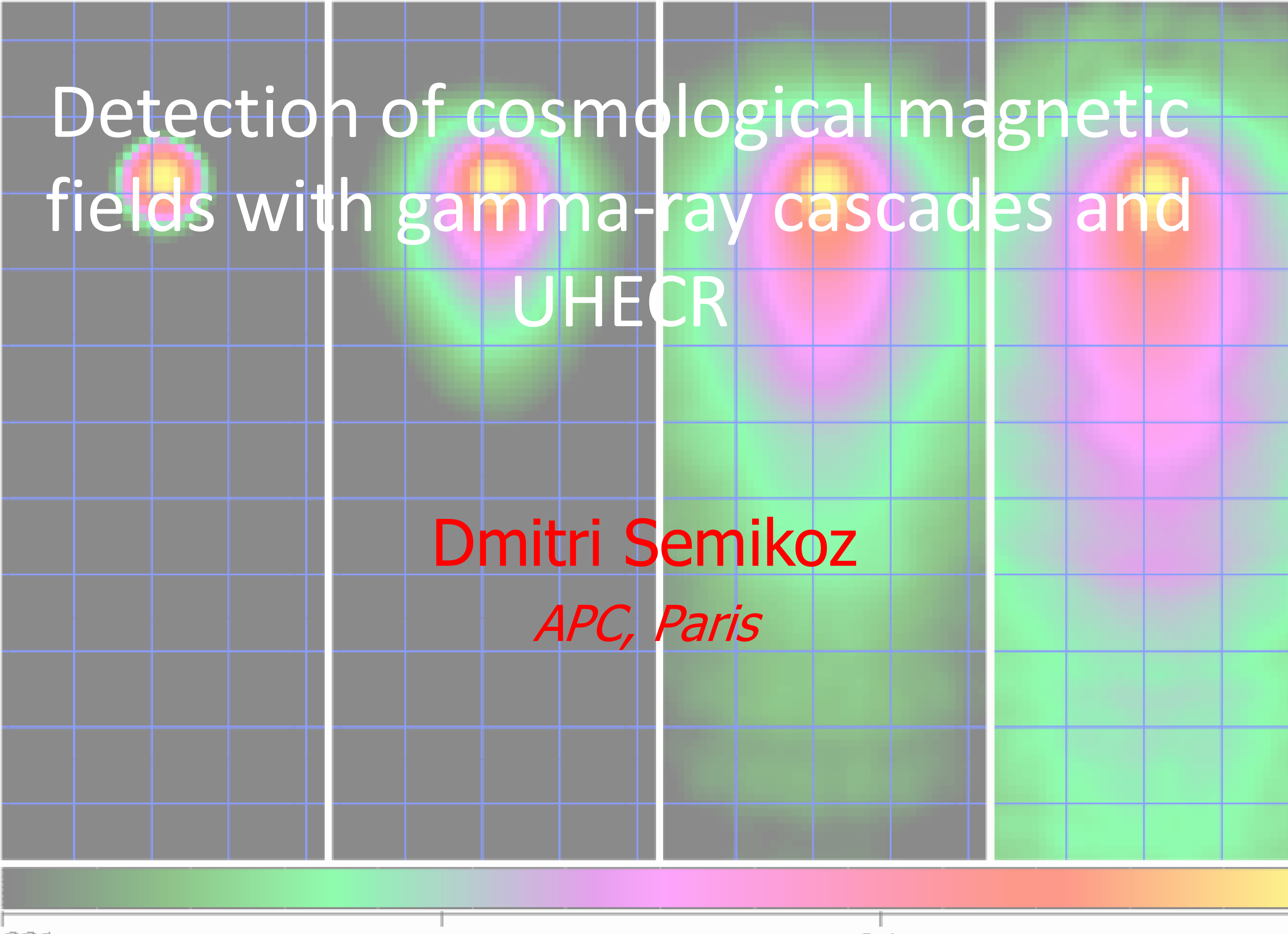
Detection of cosmological magnetic fields with gamma-ray cascades and UHECR

Dmitri Semikoz

APC, Paris



Plan:

- *IGMF and GW*
- *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 for 0229+200 MAGIC*
  - *IGMF from BOAT GRB*
- *UHECR from sources, Galactic MF and IGMF*
- *Conclusions*

Introduce Yourself:

- *PhD Moscow University & Fermilab 1993-1997 with V.Rubakov, I.Tkachev and A.Dolgov*
- *UHECR group of V.Kuzmin 1997-1999*
- *MPI fur Physik, Munich with G.Raffelt 1999-2002*
- *UCLA 2003-2005 astroparticle physics*
- *CNRS, APC, Paris from 2005 astroparticle physics*
- *Auger 2003-2010*
- *CTA from 2014 // IGMF*
- *LHAASO from 2023*

APC team

APC team IGMF subjects:

- *IGMF detection with gamma-rays*
  - *Andrii Neronov, Dmitri Semikoz*
  - *Jeffrey Blunier, PhD Dec 2024: CRBeam development and study of cascades*
- *LHAASO experiment: gamma-rays from Blazars*
  - *Dmitri Semikoz, Andrii Neronov*
  - *Denys Savchenko, Postdoc Oct 2022*
- *CTA experiment: gamma-rays from Blazars*
  - *Andrii Neronov, Dmitri Semikoz*

APC team IGMF subjects:

- *Cosmological MF production in the Early Universe*
  - *Andrii Neronov, Ch.Caprini, D.Semikoz*
  - *A. Roper Pol Postdoc 2019-2020, Teo Boyer, PhD Oct 2022*
- *IGMF detection with UHECR, GMF models*
  - *Dmitri Semikoz*

APC team other subjects:

- *Galactic cosmic ray model and secondary gamma-rays and neutrinos*
- *Galactic magnetic field model*
- *Astrophysical neutrinos: Seyferts models*
- *Astrophysical neutrinos and gamma-rays: galactic sources models*
- *Astrophysical neutrinos: experiments*
- *LHAASO sources, data-analysis and models*
- *UHECR propagation, transition galactic-extragalactic, acceleration*

Cosmological Magnetic Field and GW

Idea: use pulsars as clocks

Opportunities for detecting ultralong gravitational waves

M. V. Sazhin

Shternberg Astronomical Institute, Moscow

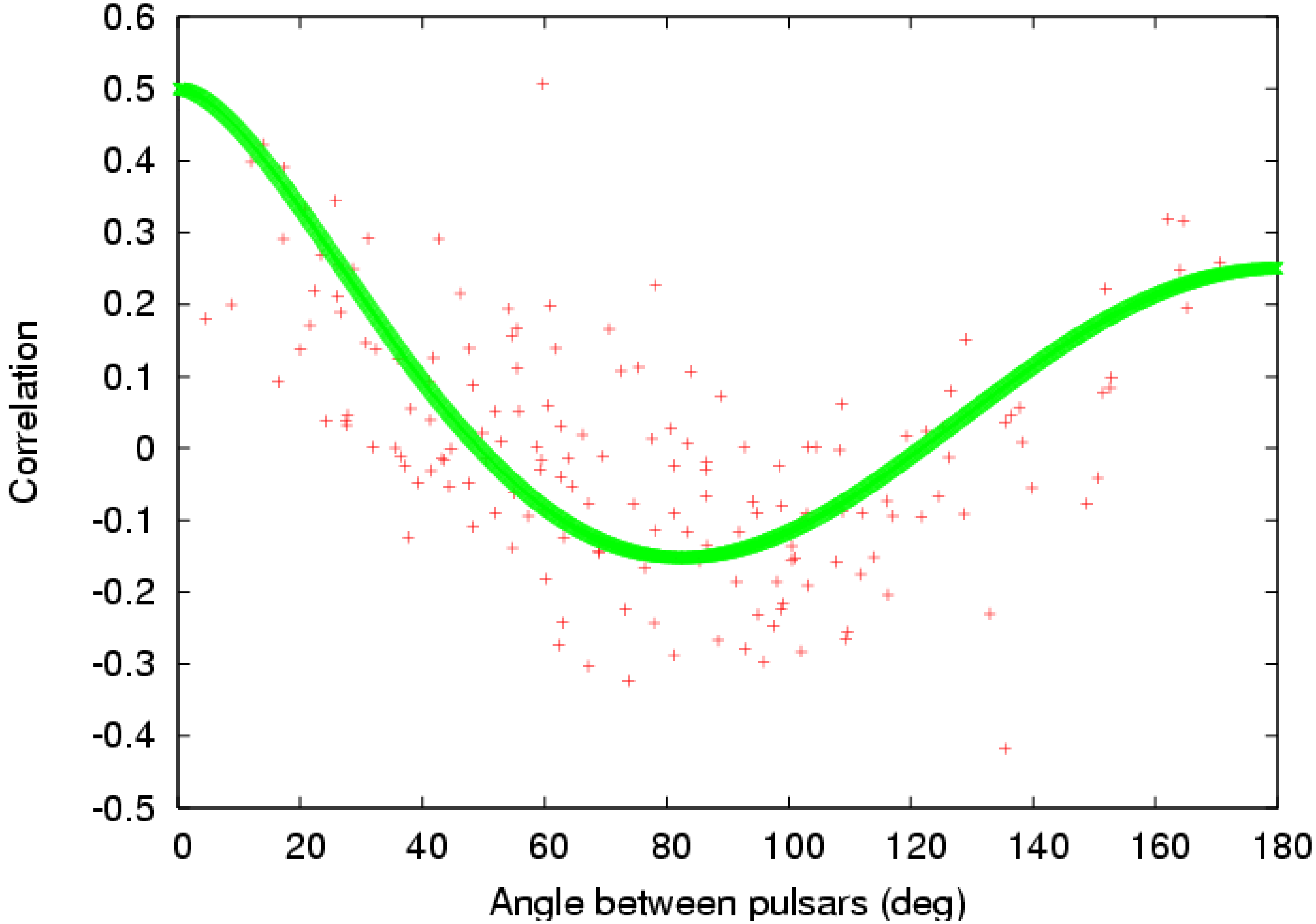
(Submitted June 14, 1977)

Astron. Zh. **55**, 65–68 (January–February 1978)

The influence of ultralong gravitational waves on the propagation of electromagnetic pulses is examined. Conditions are set forth whereby it might be possible to detect gravitational waves arriving from binary stars. There are some prospects for detecting gravitational radiation from double superstars with masses $\mathfrak{M}_1 \approx \mathfrak{M}_2 \approx 10^{10} \mathfrak{M}_\odot$.

PACS numbers: 97.80.—d, 97.60.Gb, 95.30.Gv

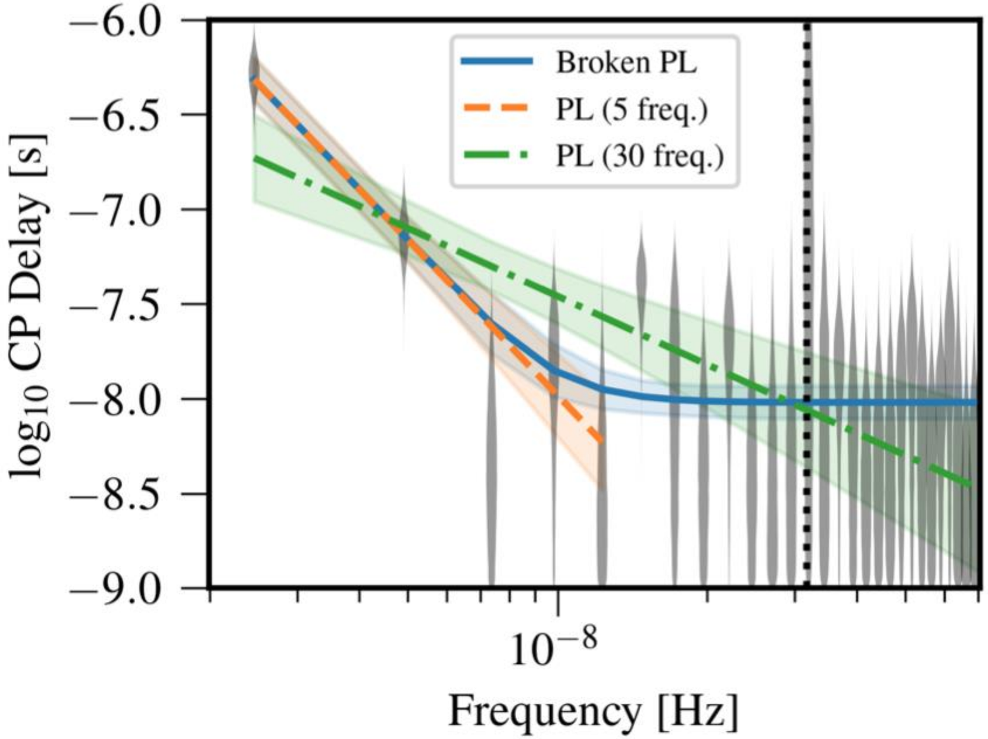
Detecting a Stochastic GW Background



Simulation using Parkes Pulsar Timing Array (PPTA) pulsars with GW background from binary black holes in galaxies

(Rick Jenet, George Hobbs)

NANOGrav



$$S(f) = \frac{A_{\rm CP}^2}{12\pi^2}\left(\frac{f}{f_{\rm yr}}\right)^{-\gamma} f_{\rm yr}^{-3},$$

$$S(f) = \frac{A_{\rm CP}^2}{12\pi^2}\left(\frac{f}{f_{\rm yr}}\right)^{-\gamma}\left(1+\left(\frac{f}{f_{\rm bend}}\right)^{1/\kappa}\right)^{\kappa(\gamma-\delta)} f_{\rm yr}^{-3},$$

NANOGrav Collaboration, 2009.04496

Pulsar timing arrays

$$S(f) = \frac{A_{\rm CP}^2}{12\pi^2}\left(\frac{f}{f_{\rm yr}}\right)^{-\gamma} f_{\rm yr}^{-3},$$

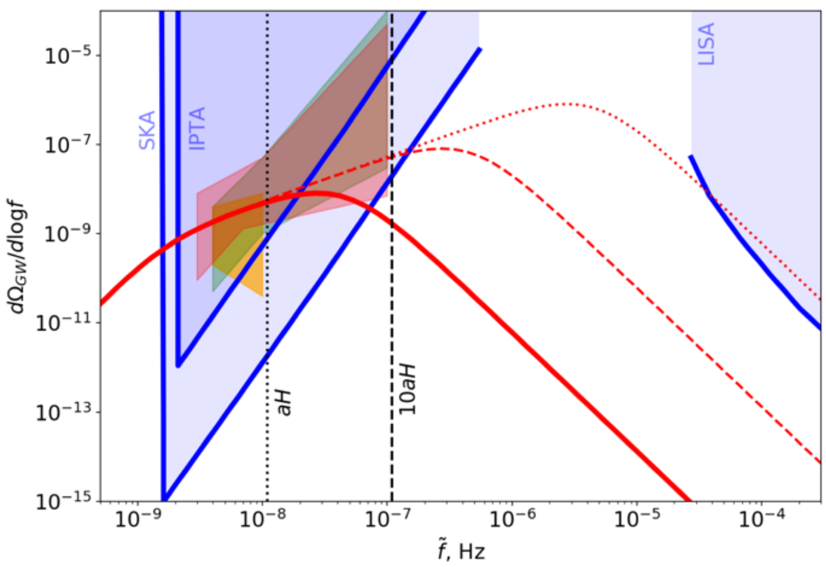
$$h_{\rm c}(f) = \sqrt{12\pi^2 S(f) f^3} = A_{\rm CP}\left(\frac{f}{f_{\rm yr}}\right)^{\frac{3-\gamma}{2}}$$

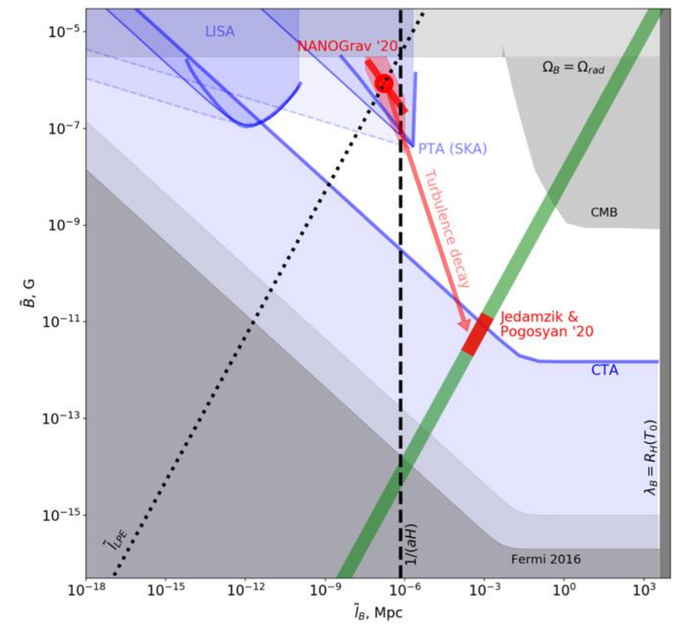
$$\Omega_{\rm GW}^0(f) = \Omega_{\rm yr}\left(\frac{f}{f_{\rm yr}}\right)^{\beta},$$

$$\Omega_{\rm yr} = \frac{2\pi^2}{3H_0^2} f_{\rm yr}^2 A_{\rm CP}^2, \quad \beta = 5 - \gamma.$$

A. Roper Pol et al., 2201.05630

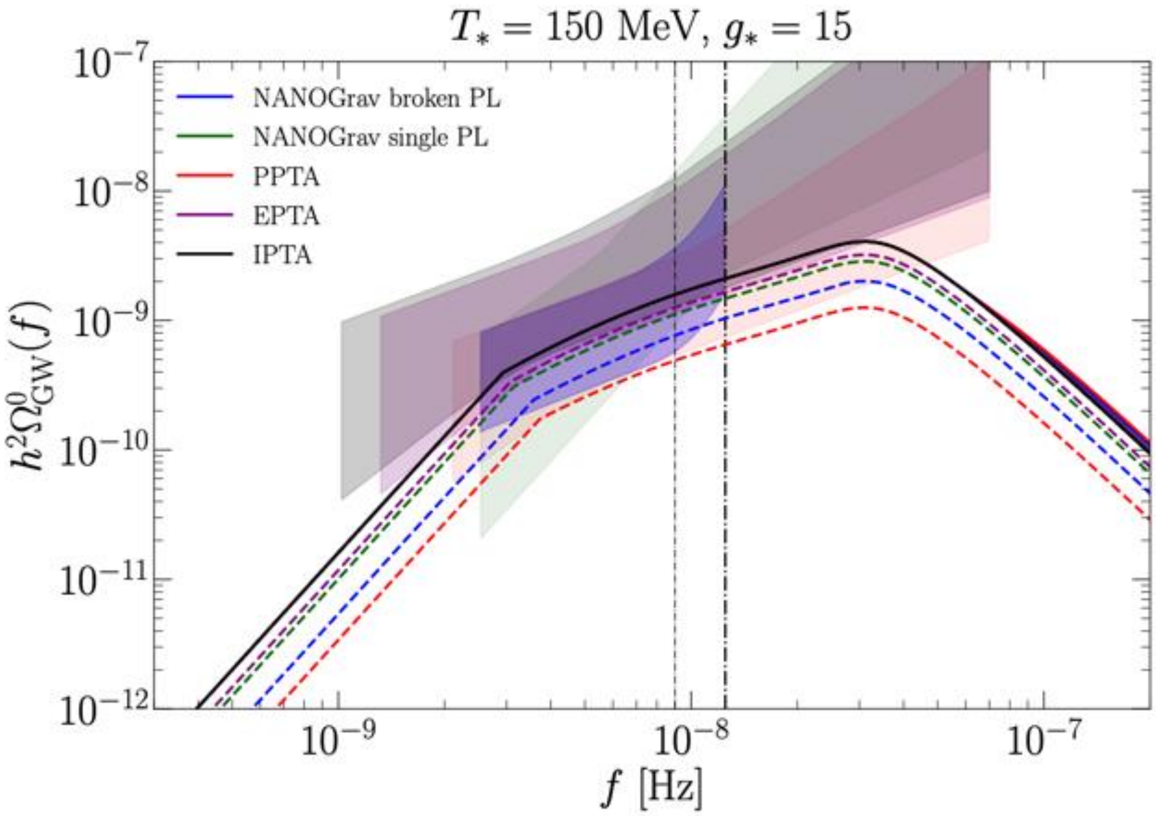
GW signal from QCD phase transition epoch





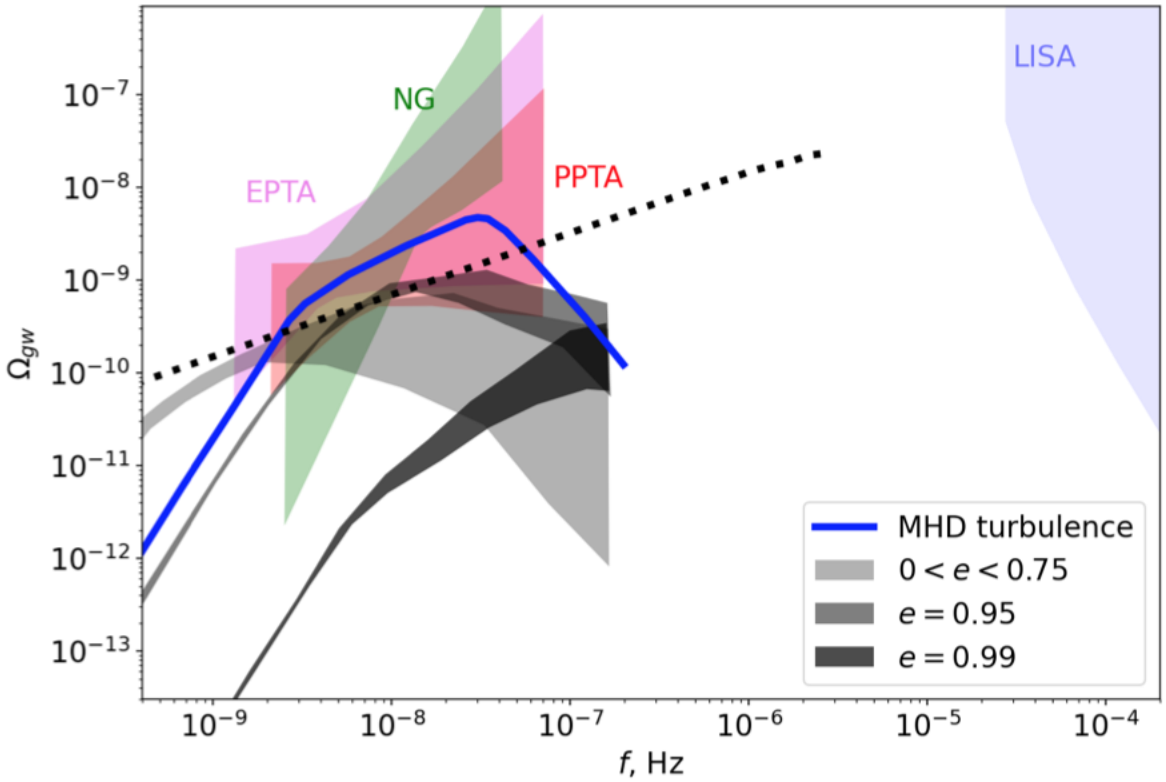
A. Roper Pol, Ch.Caprini, A.Neronov and D.S., 2009.14174

GW from QCD phase transition



A. Roper Pol et al., 2201.05630

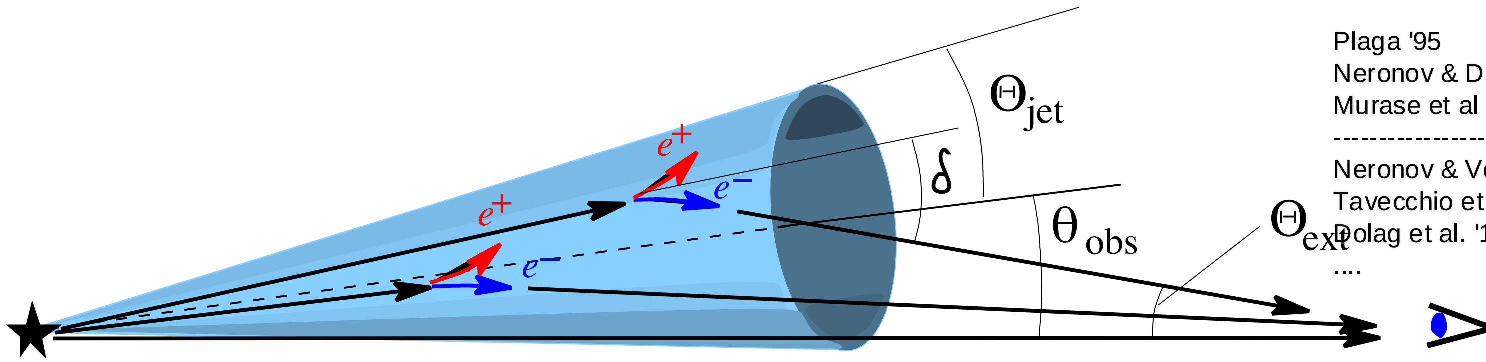
SGWB from SMBH binaries



A. Roper Pol et al., 2201.05630

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.

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

$$E_{\gamma_0} = 2E_e \qquad \lambda_e = \frac{1}{n_{CMB}\sigma_{ICS}} \sim 1\ \mathrm{kpc}$$

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

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

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

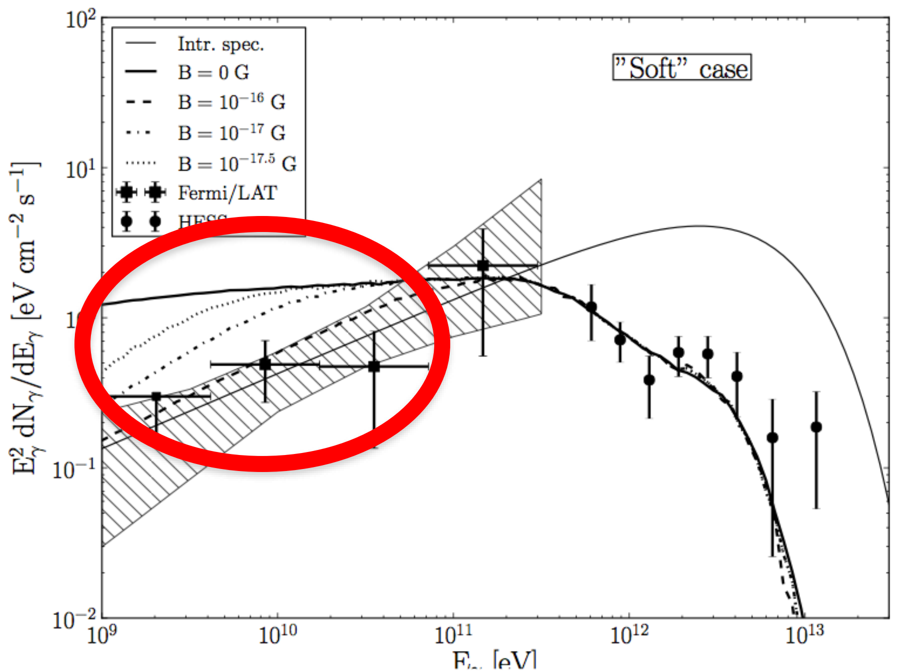
The hardest VHE blazar 1ES 0229+200

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.

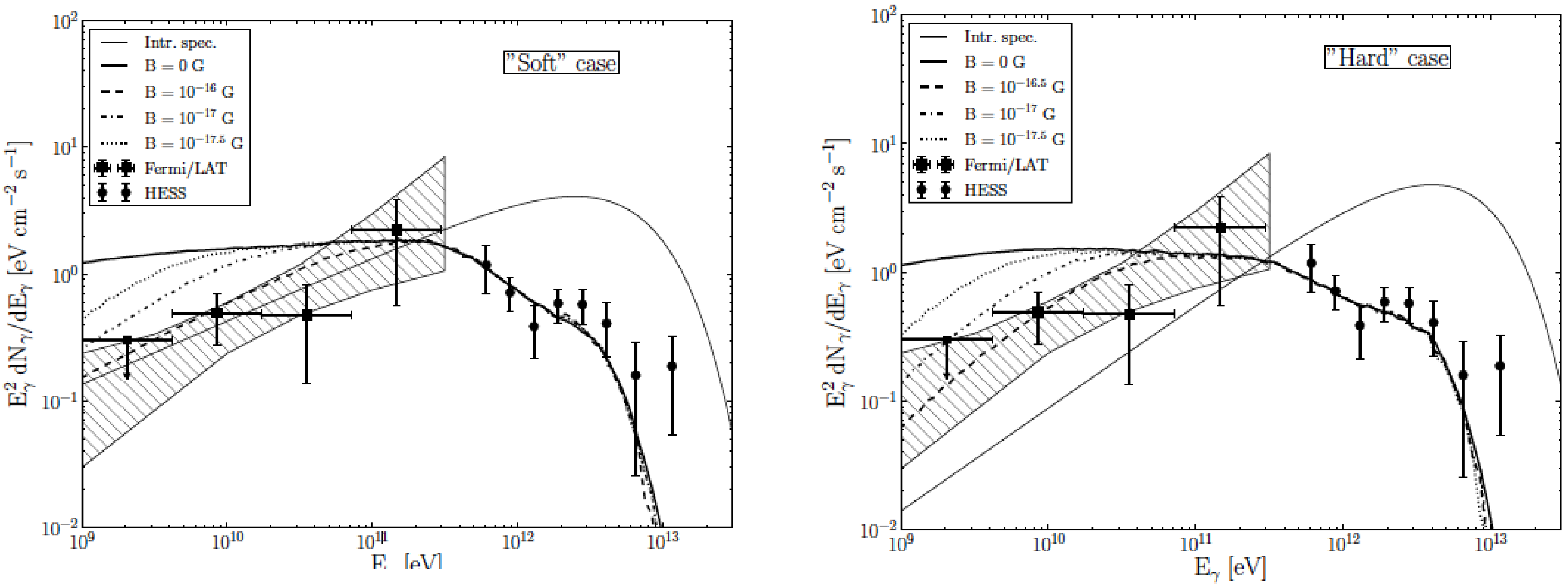
The source is stable in the VHE band: no variability is found between observations made over ~5 yr time span.



$G = 1.36 \pm 0.25$

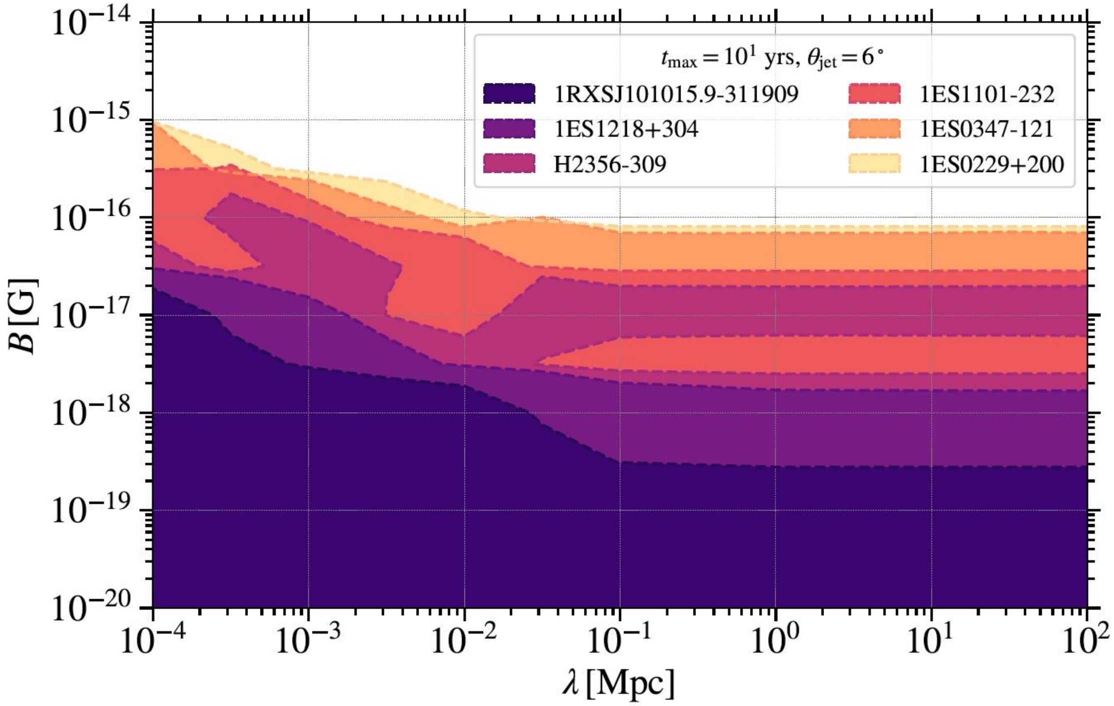
Vovk, Taylor, Neronov, and DS 1112.2534

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
- Fraction of voids on the way of primary photon
- Ratio of point source flux at E_γ and $E_{\gamma 0}$

$$a = \frac{\mathring{a}\, E_g}{E_e}$$

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

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

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

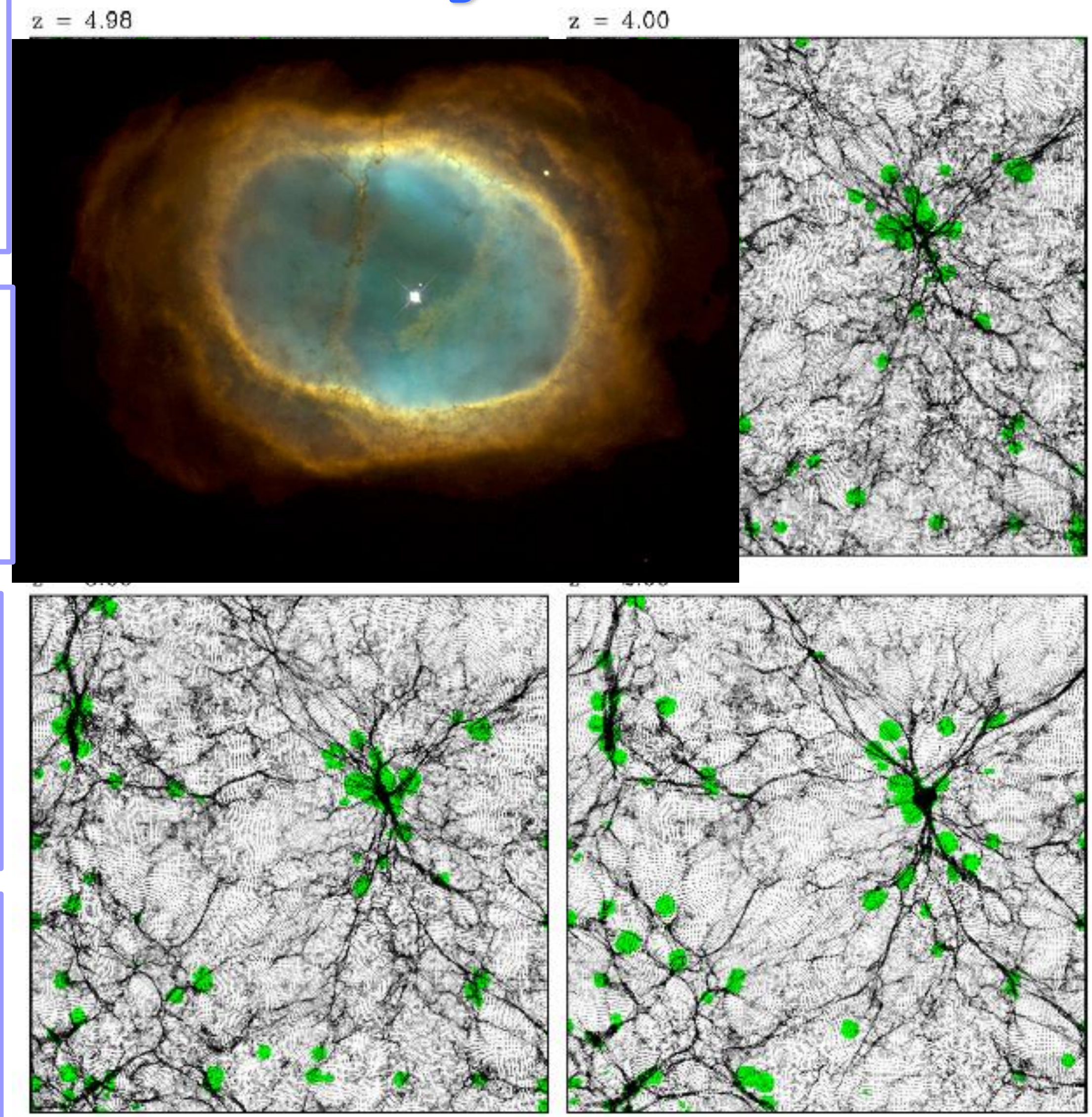
IGMF from galactic winds?

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 ~100 kpc distances around small galaxies (up to 10^{10} M_{Sun}) and up to ~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.

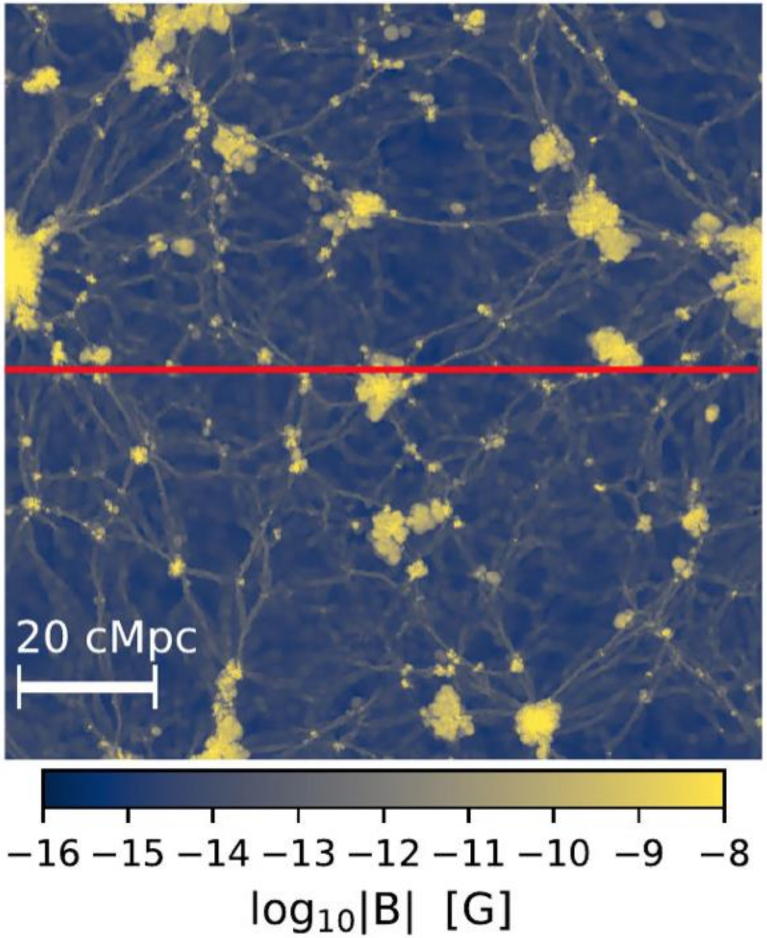
Volume filling factor of these galactic wind blown bubbles is uncertain. State-of-art simulations are not able to model the bubble evolution "from the first principles".



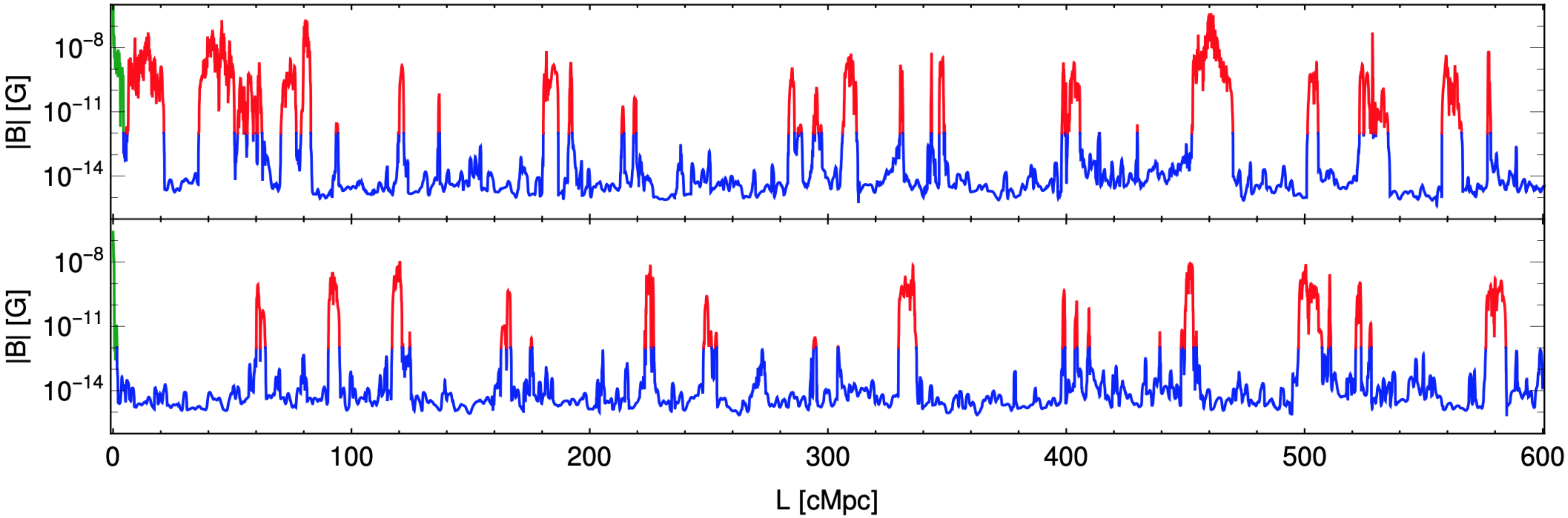
Pinsonneault et al. '10

Inter-Galactic Magnetic Field and AGN feedback

3D magnetic field in ILLUSTRIS-TNG

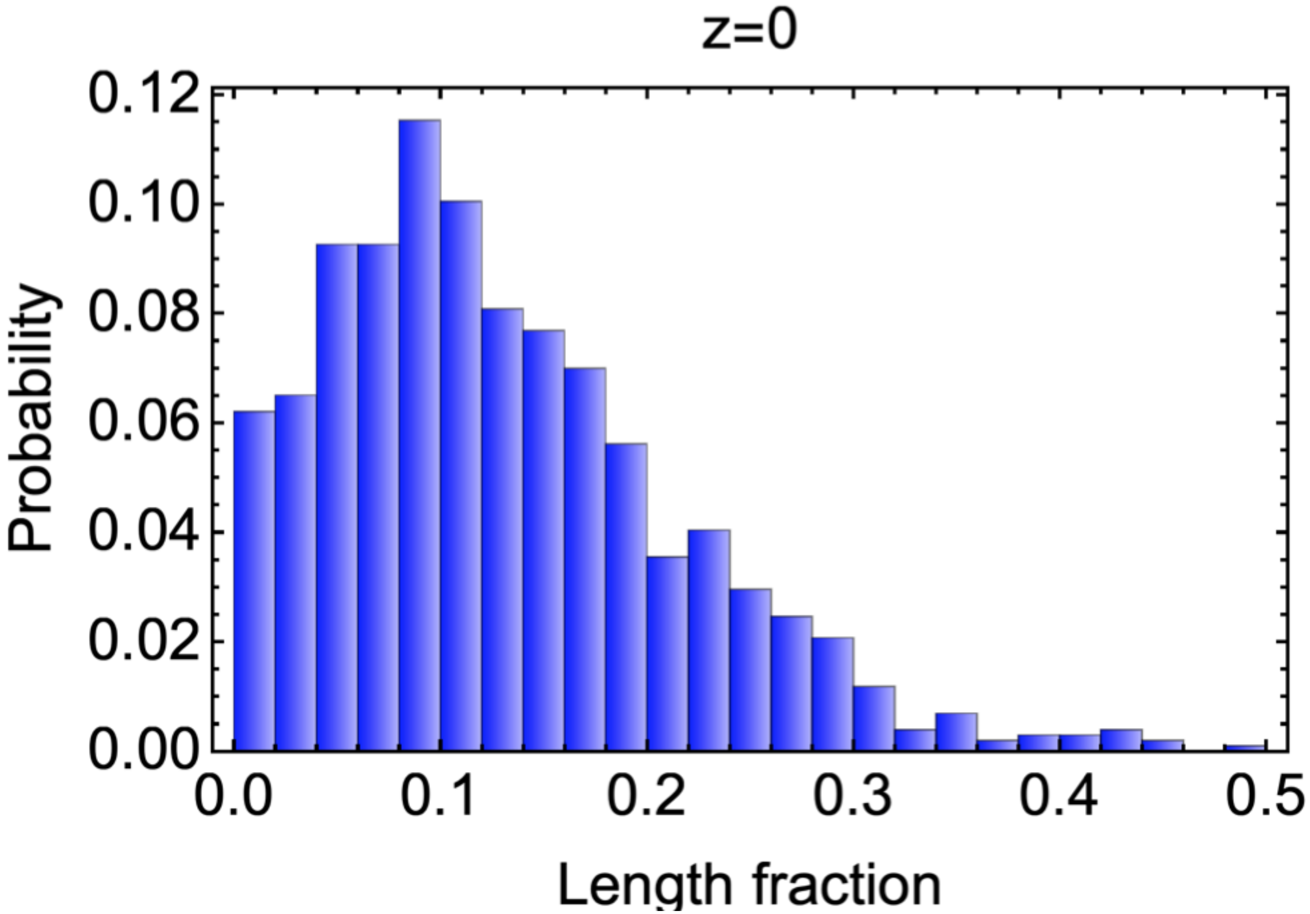


IGMF on LOS and magnetic bubbles



K.Bondarenko et al, 2106.02690

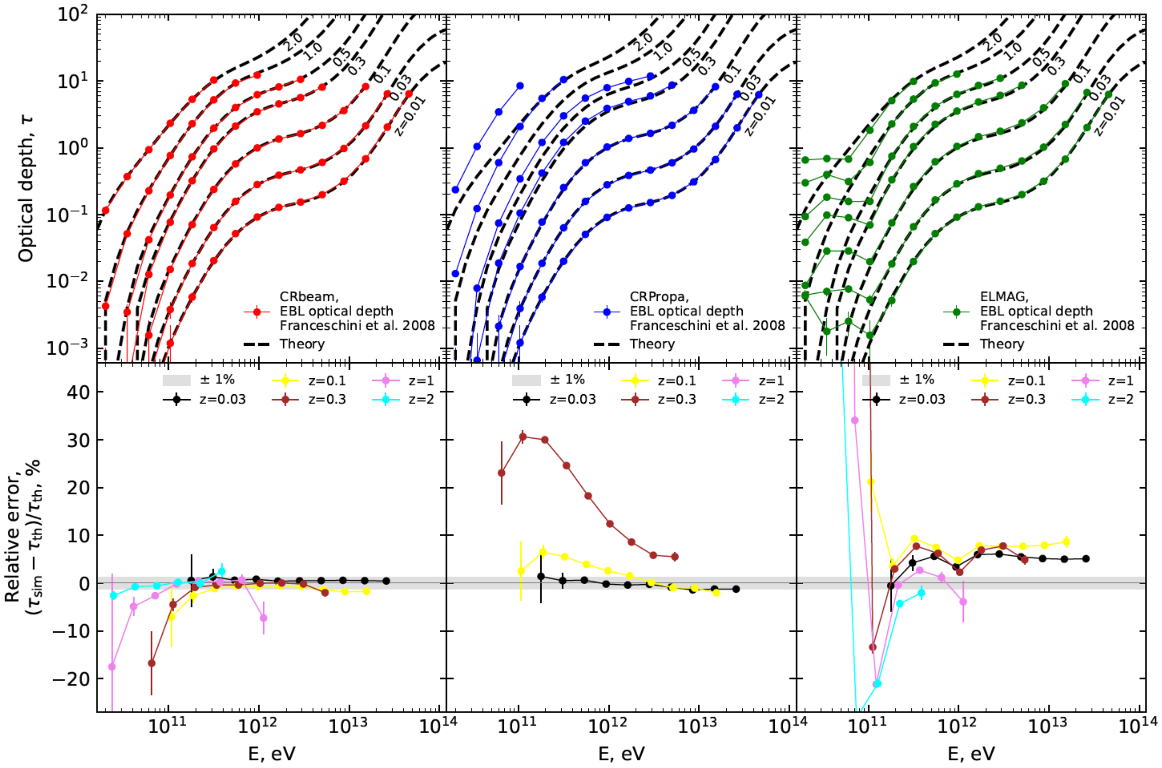
Probability to have strong MF on LOS



K.Bondarenko et al, 2106.02690

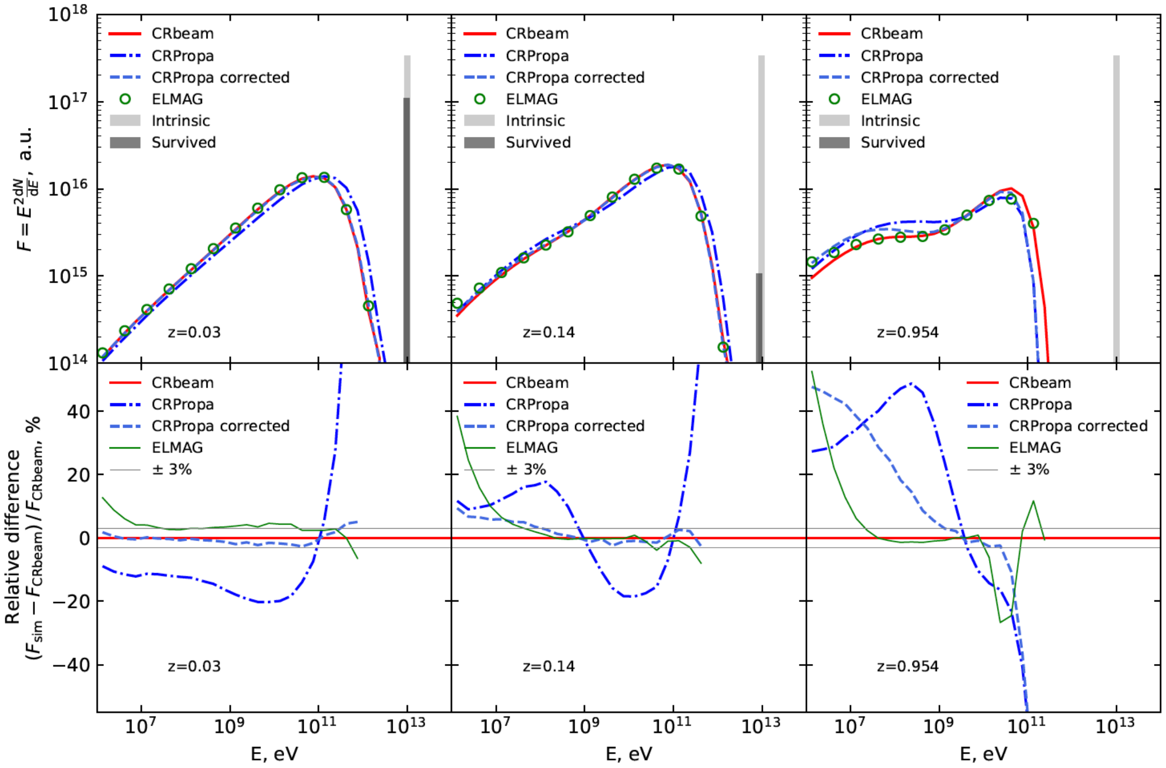
3D cascade codes in CTA era

Optical depth of gamma-rays on EBL+CMB



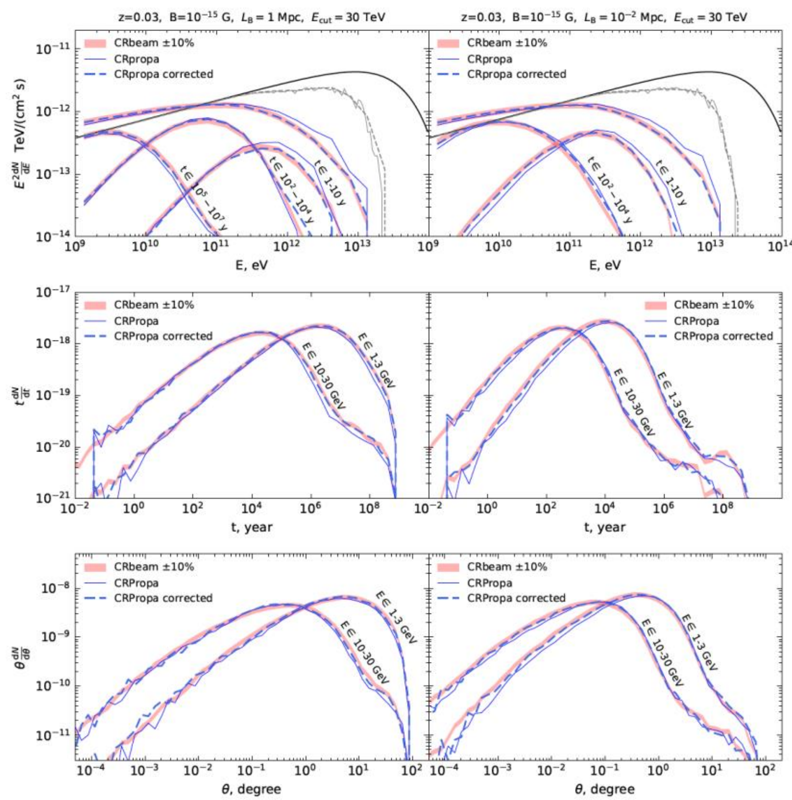
From A.Korochkin, A.Neronov, and DS, arXiv 2201.03996

Secondary gamma-ray spectrum



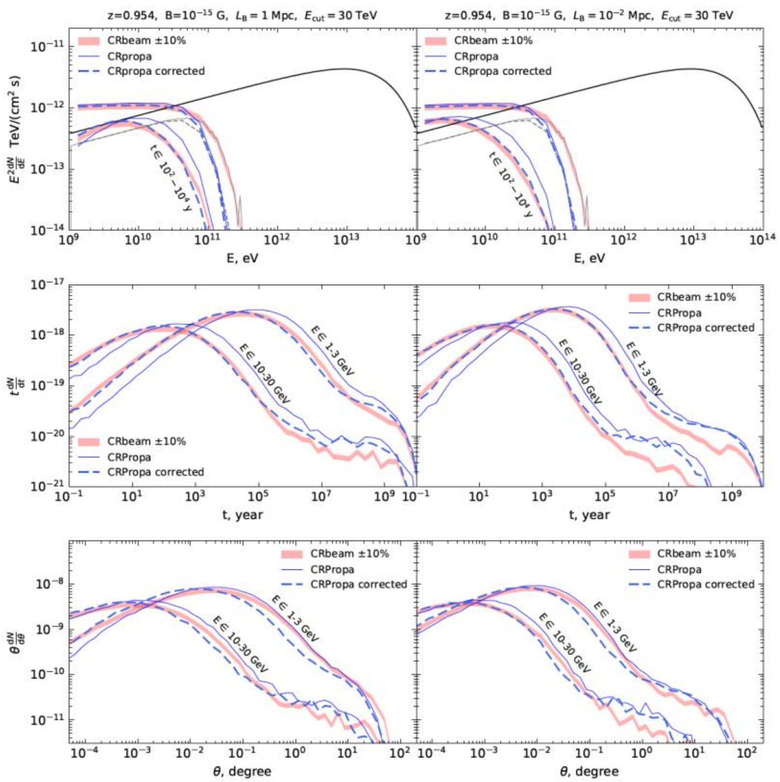
From A.Korochkin, A.Neronov, and DS, arXiv 2201.03996

3D cascade at z=0.03



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

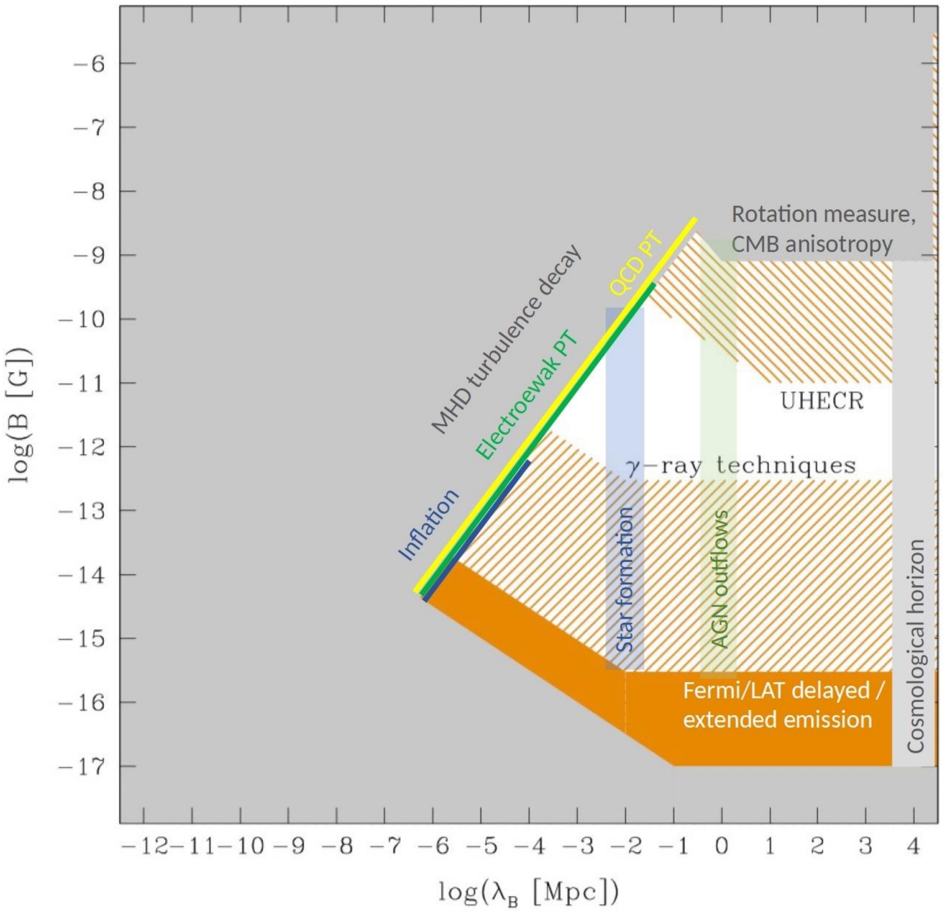
3D cascade at z=0.954



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

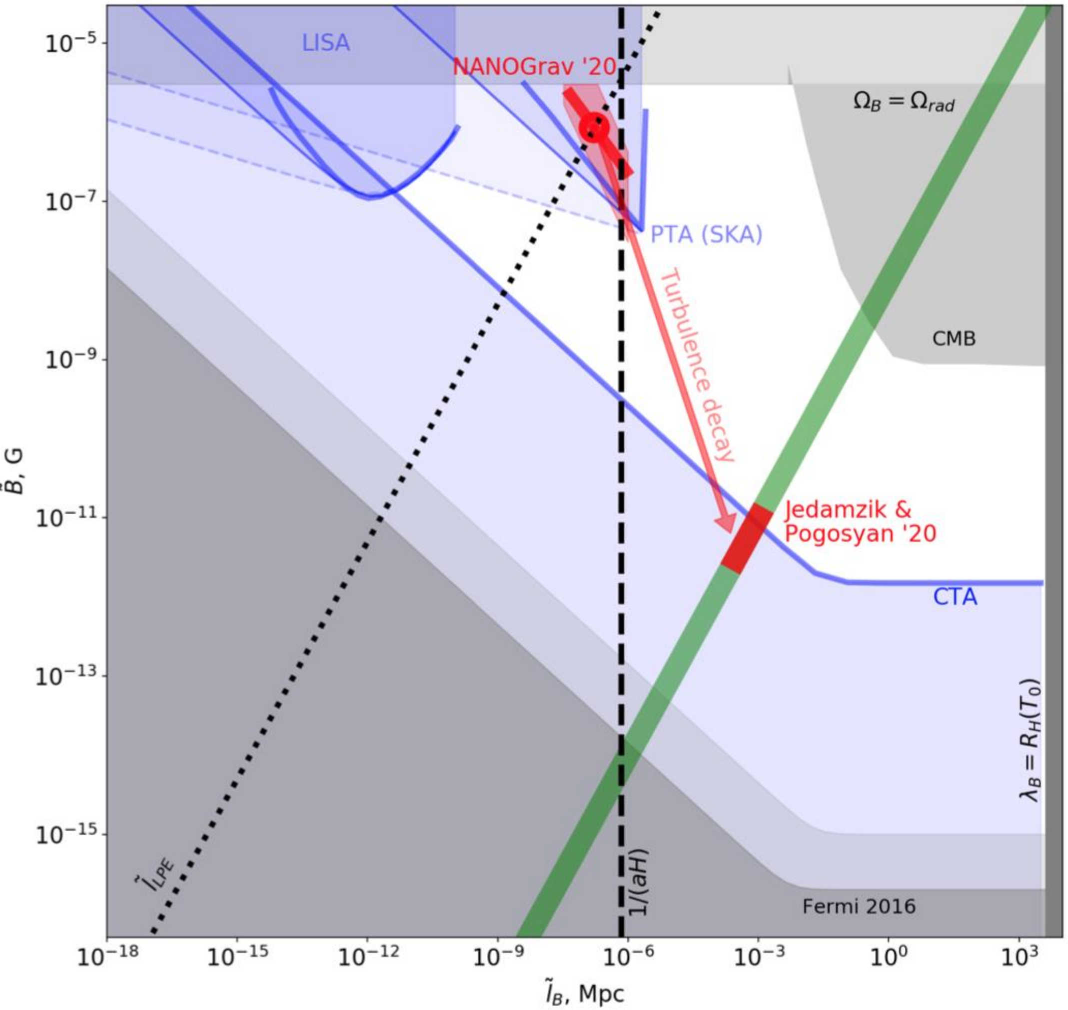
Can gamma-telescopes detect 10 pG IGMF (one which can help with H0 problem)?

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

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

Primary photon optical depth distance

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

Electron travel energy loss distance

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

Secondary photon energy

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

Kalashev et al, 2007.14331

Conditions to detect 10 pG IGMF

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

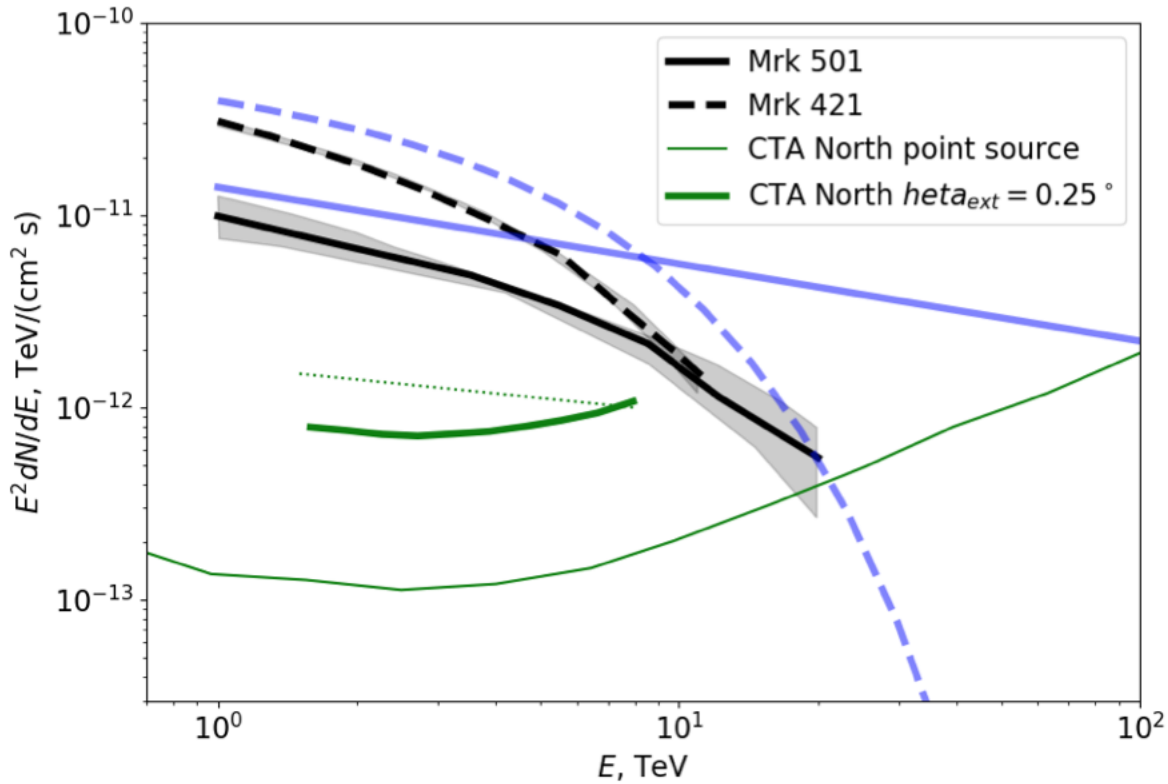
(a) large primary point-source power in the 100 TeV energy range,

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

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

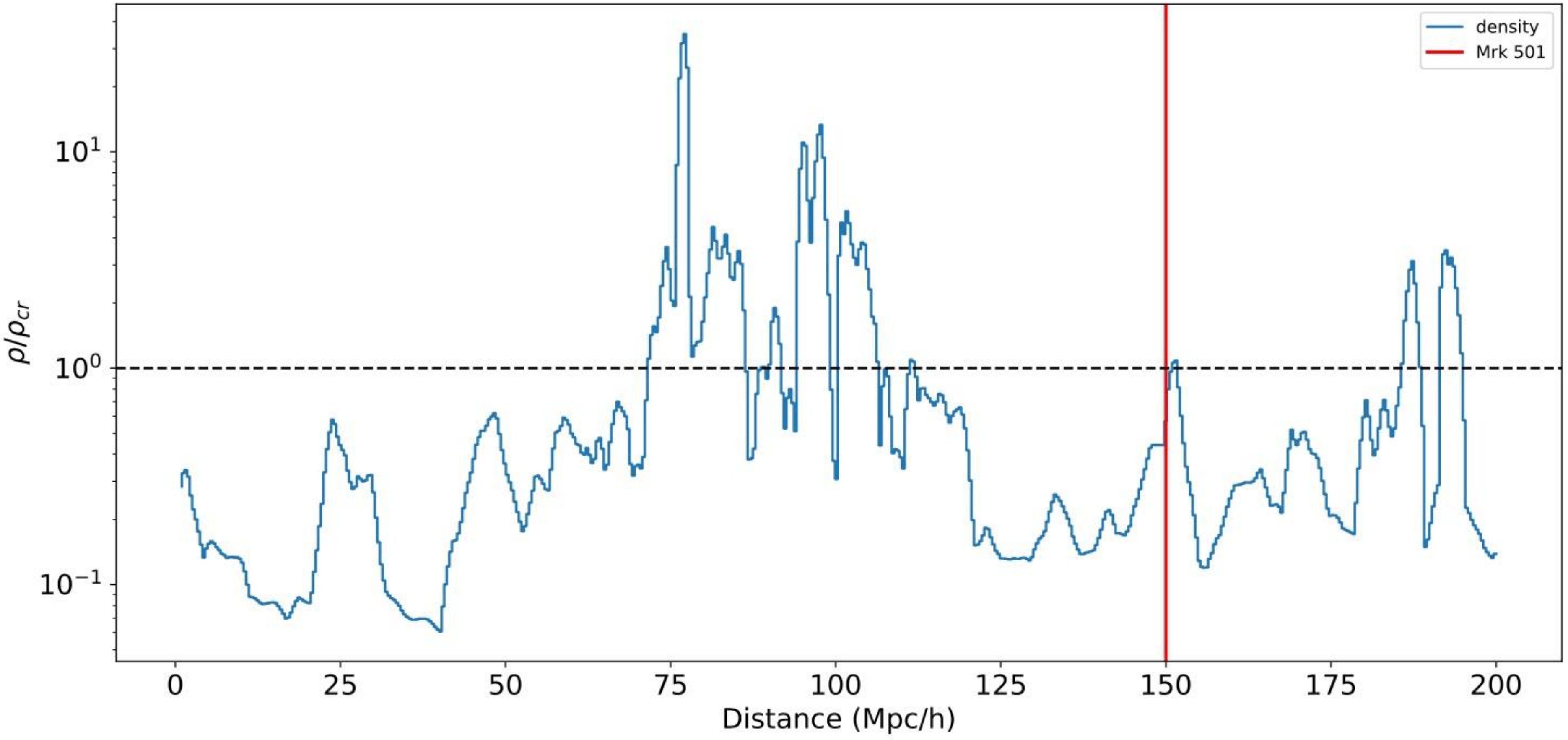
Kalashev et al, 2007.14331

Spectrum Mkn 421 and Mkn 501



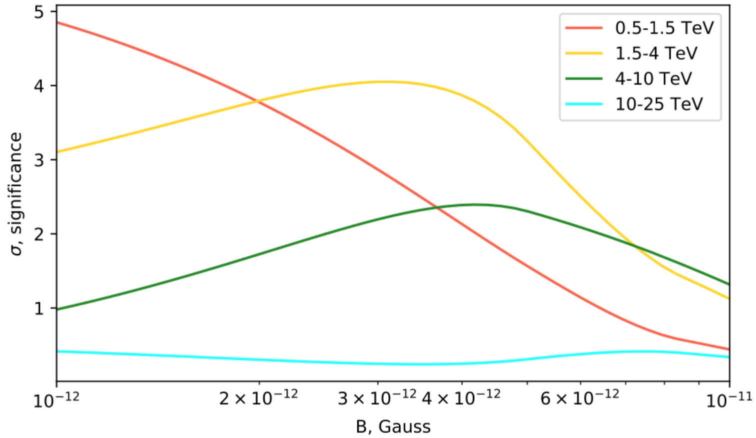
Kalashev et al, 2007.14331

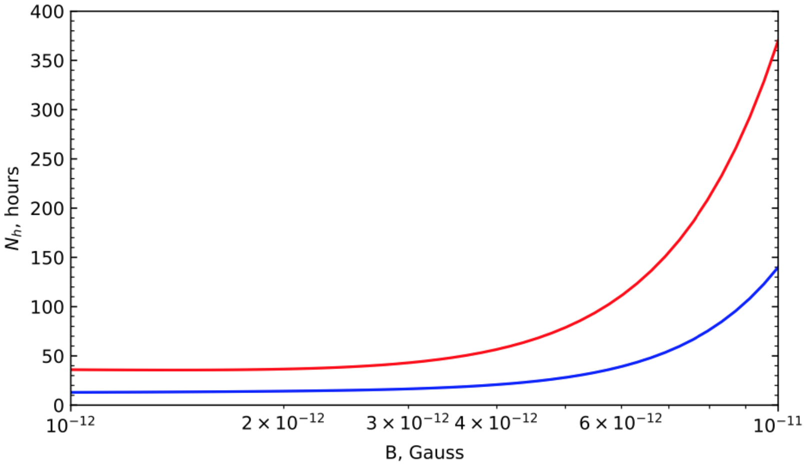
IGMF on LOS to Mkn 501



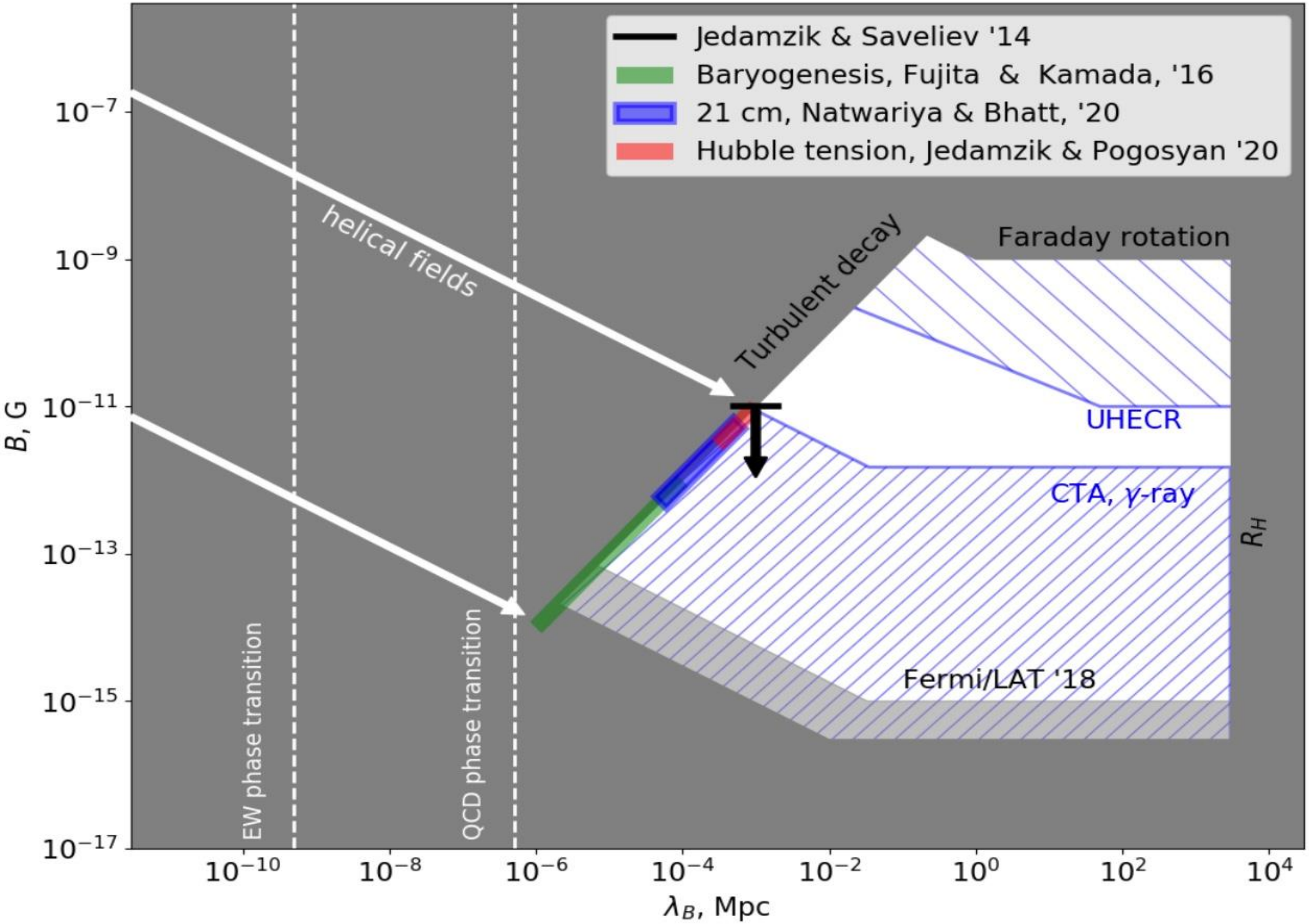
Kalashev et al, 2007.14331

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





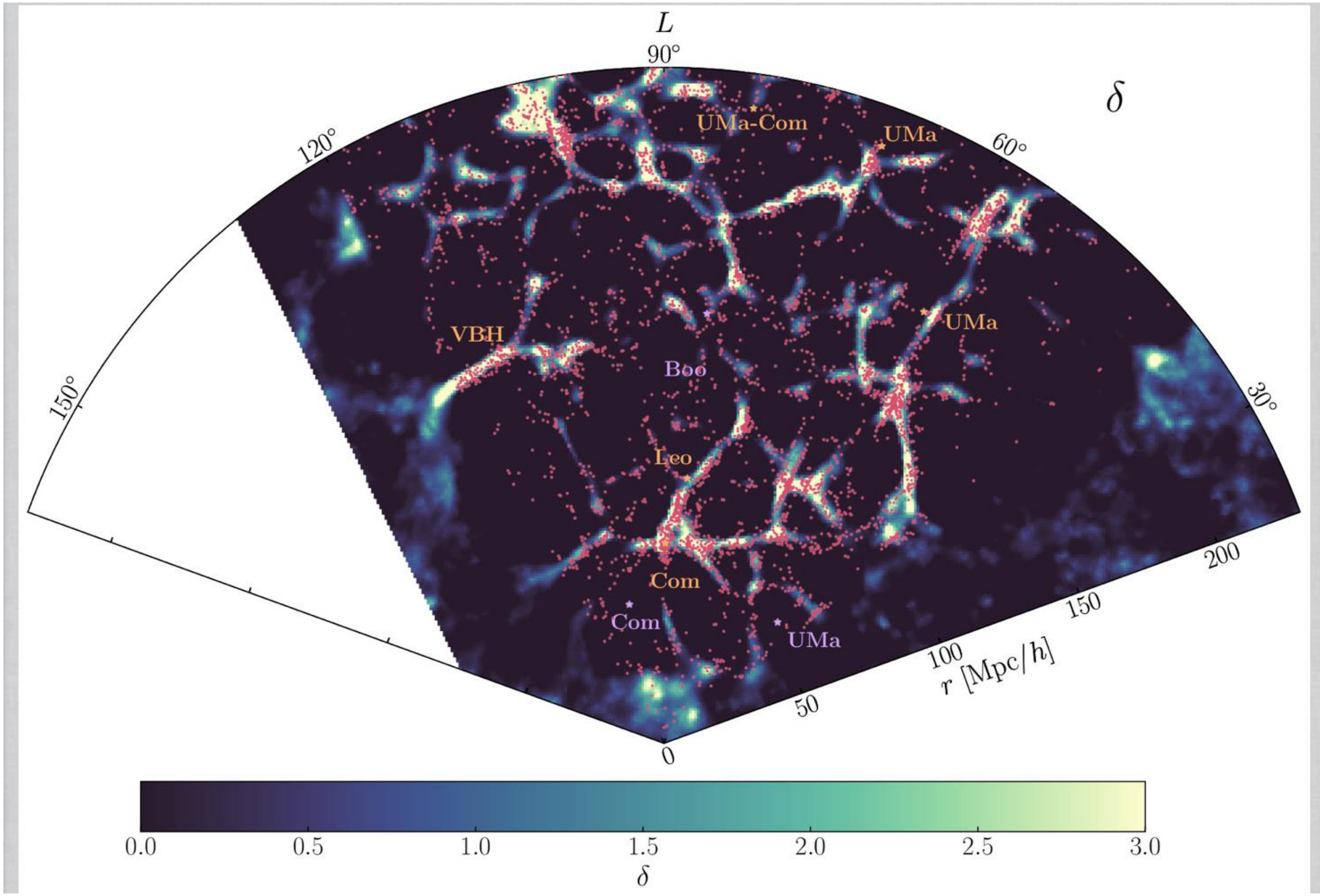
Kalashev et al, 2007.14331



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

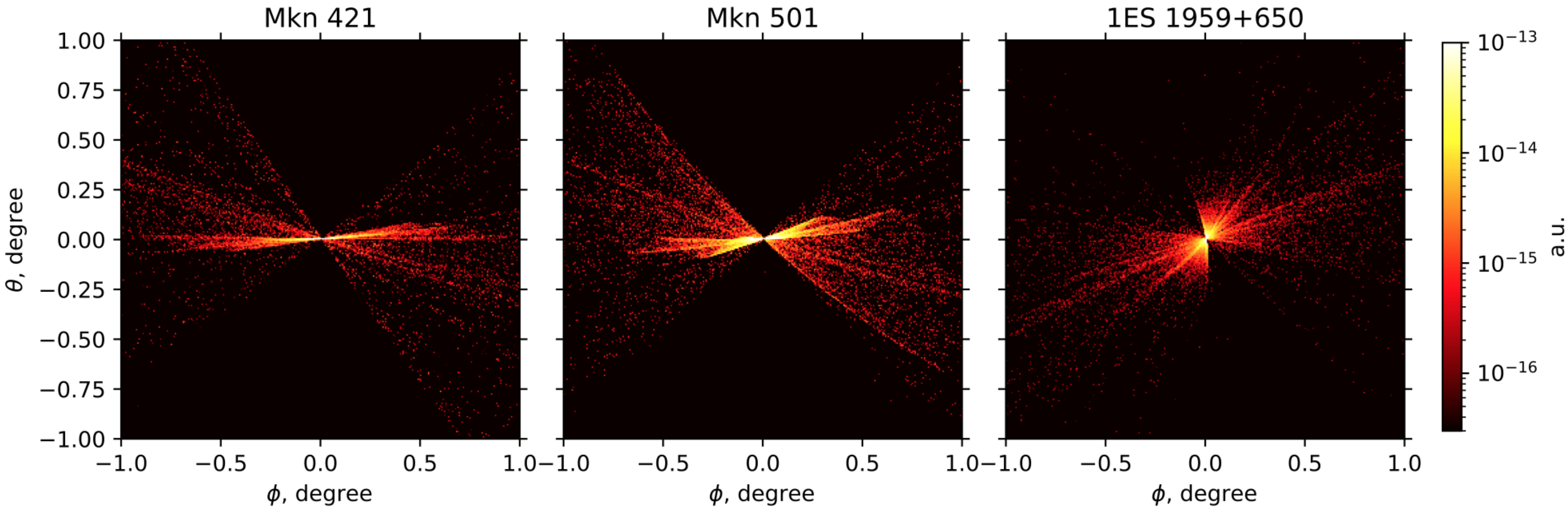
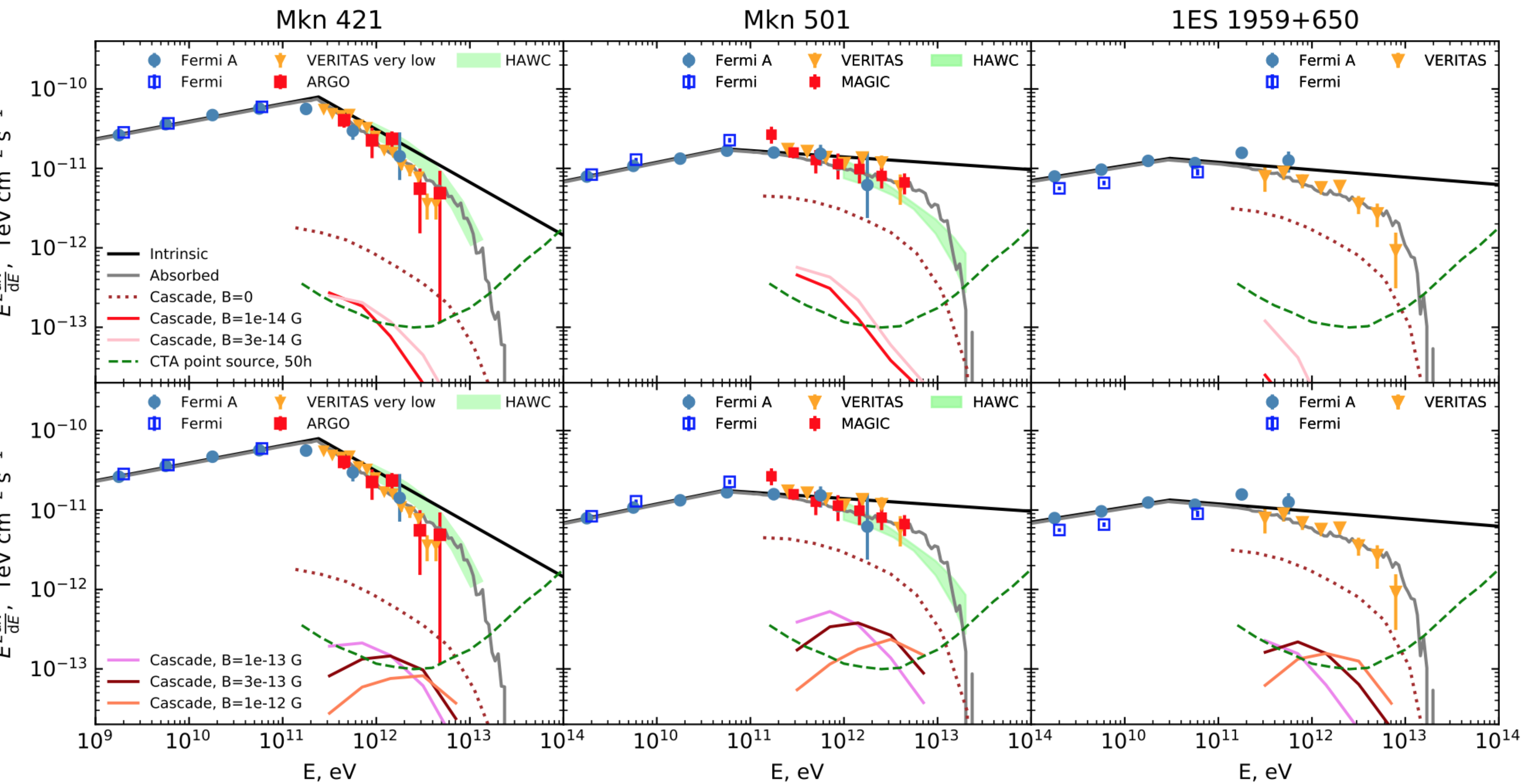


FIG. 4: Images of the extended emission signal in the energy range 200 GeV - 2 TeV for the three brightest sources in our sample. The assumed initial cosmological magnetic field strength is $B = 10^{-13}$ G. The direction of the jet axis coincides with the direction from the source to the observer and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

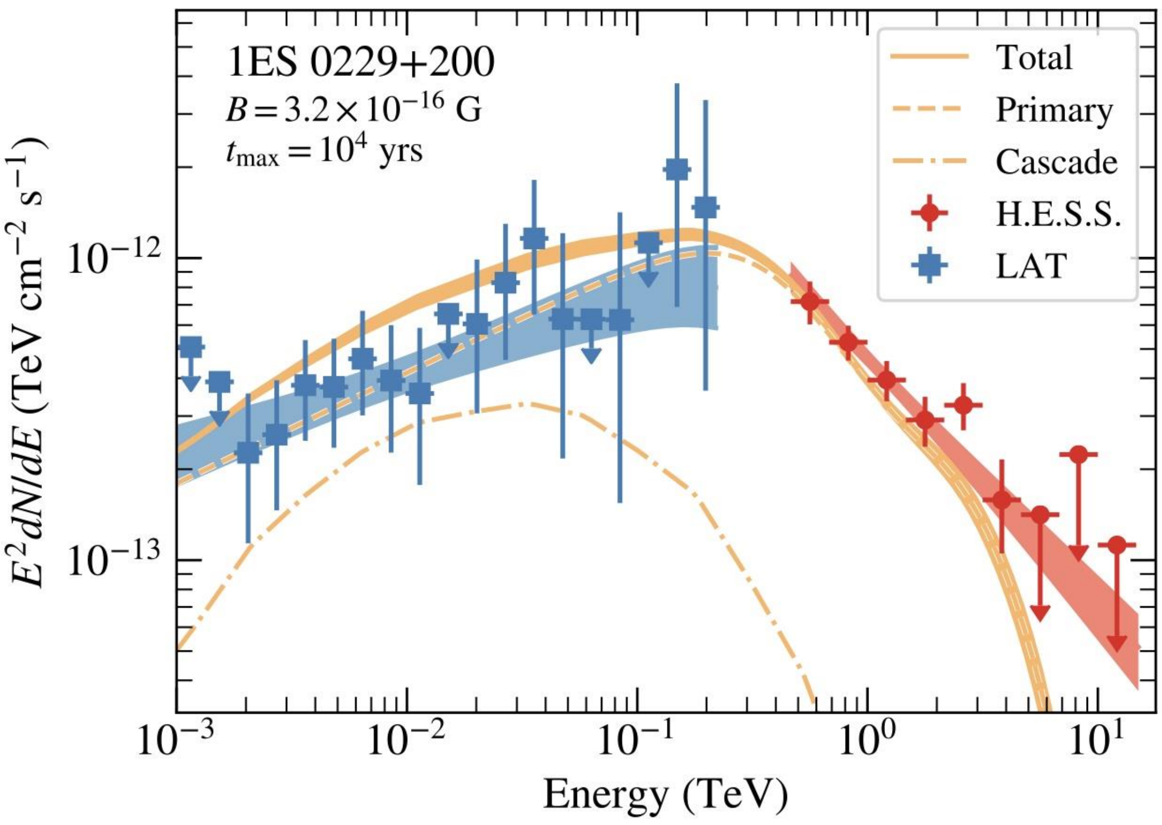
A.Korochkin et al, 2111.10311.



A.Korochkin et al, 2111.10311.

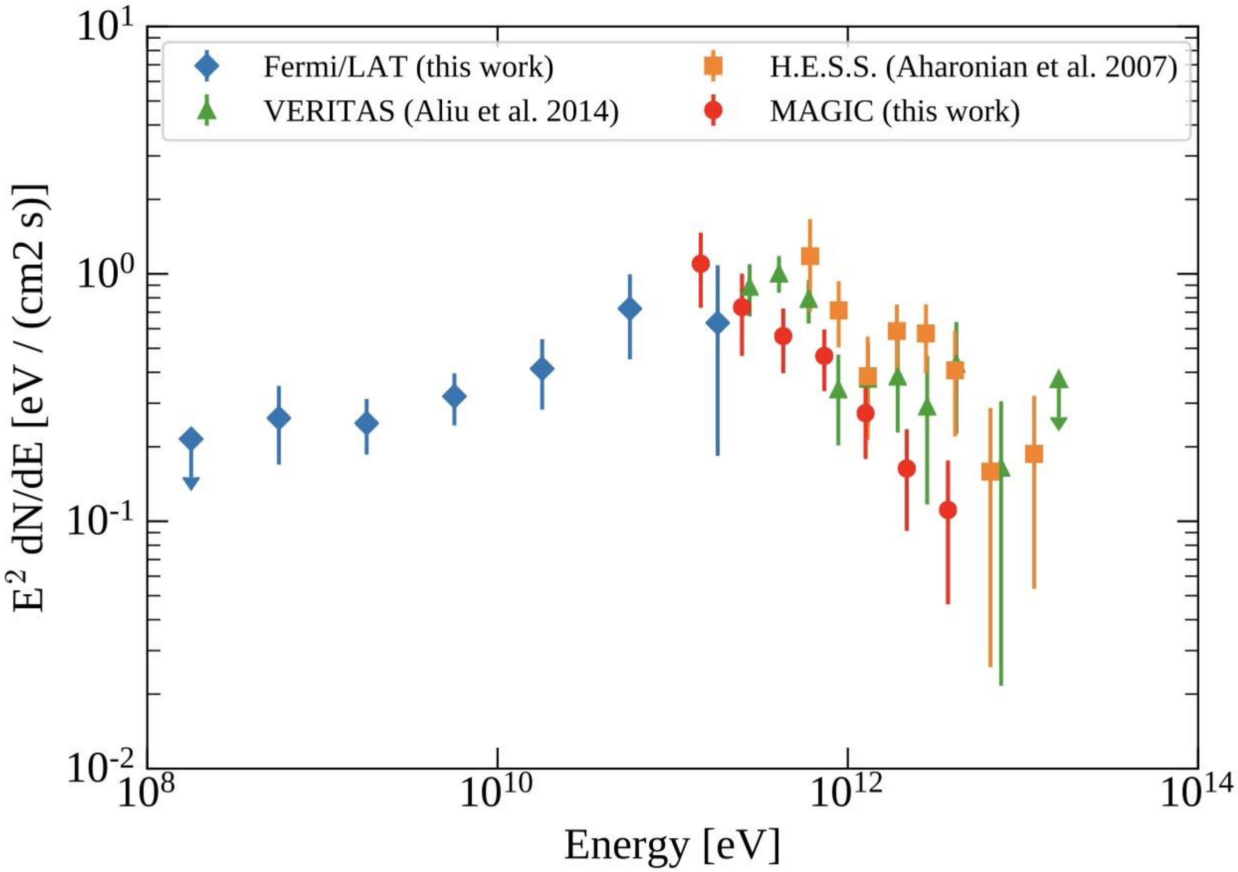
Inter-Galactic Magnetic Field by MAGIC

Cosmological magnetic field from 1ES 0229+200 measurements



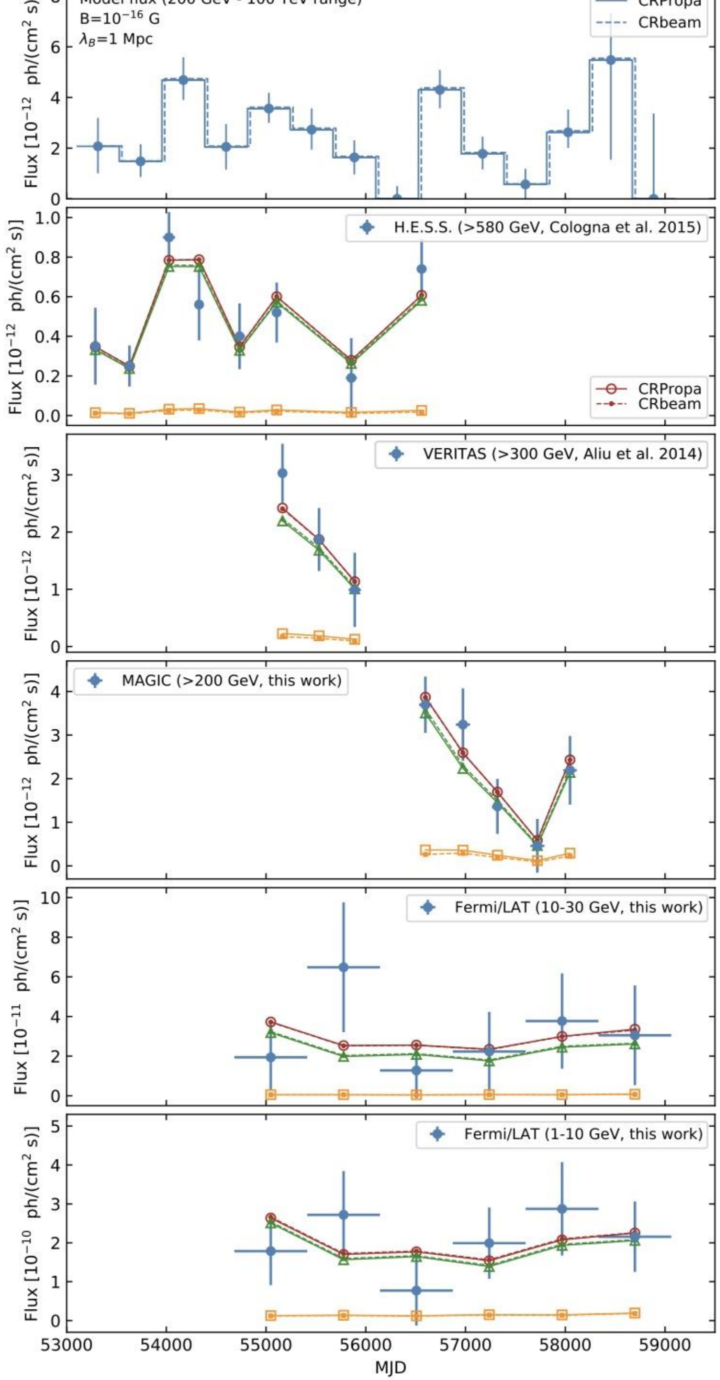
Fermi and HESS collab 2306.05132

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

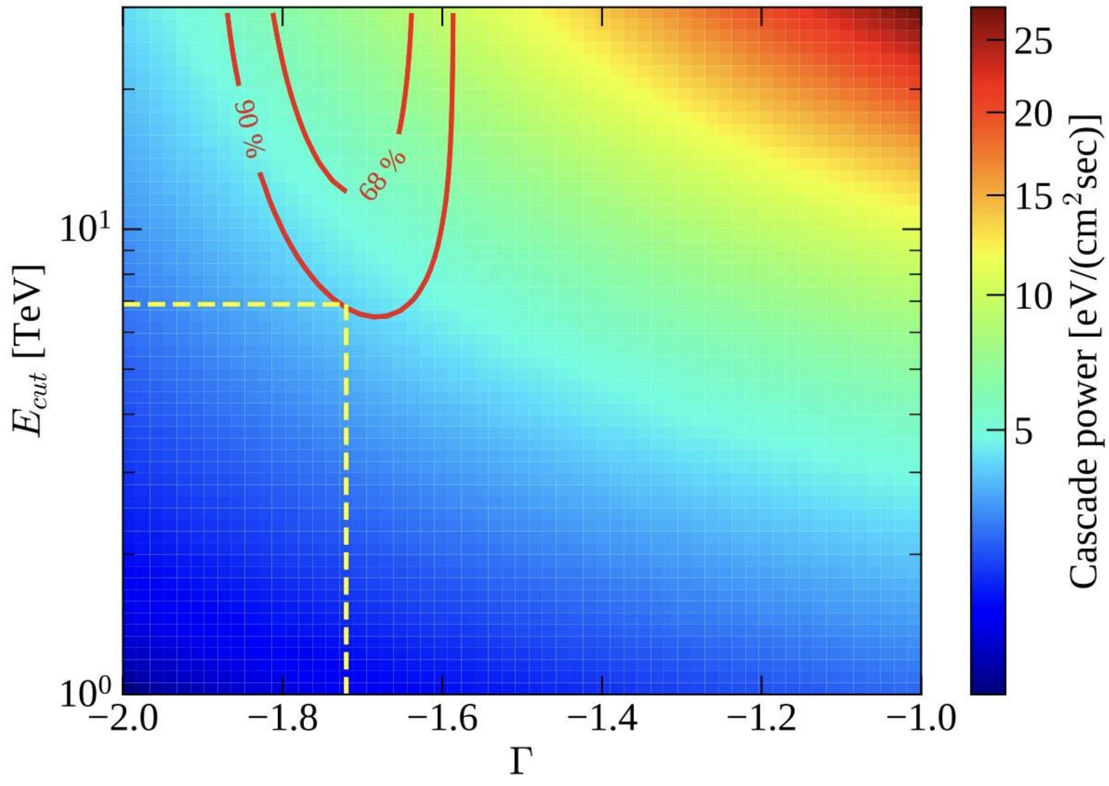
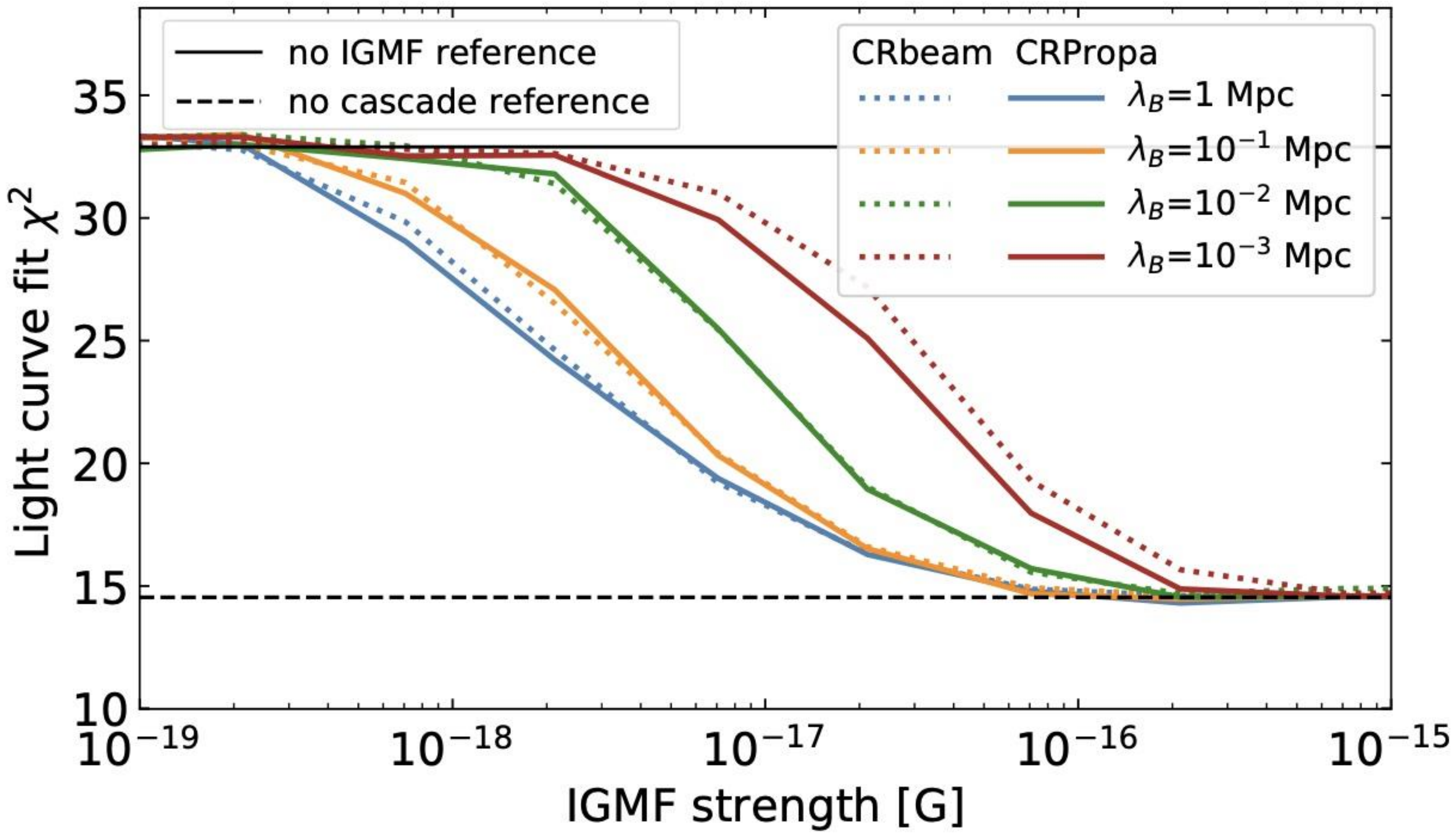
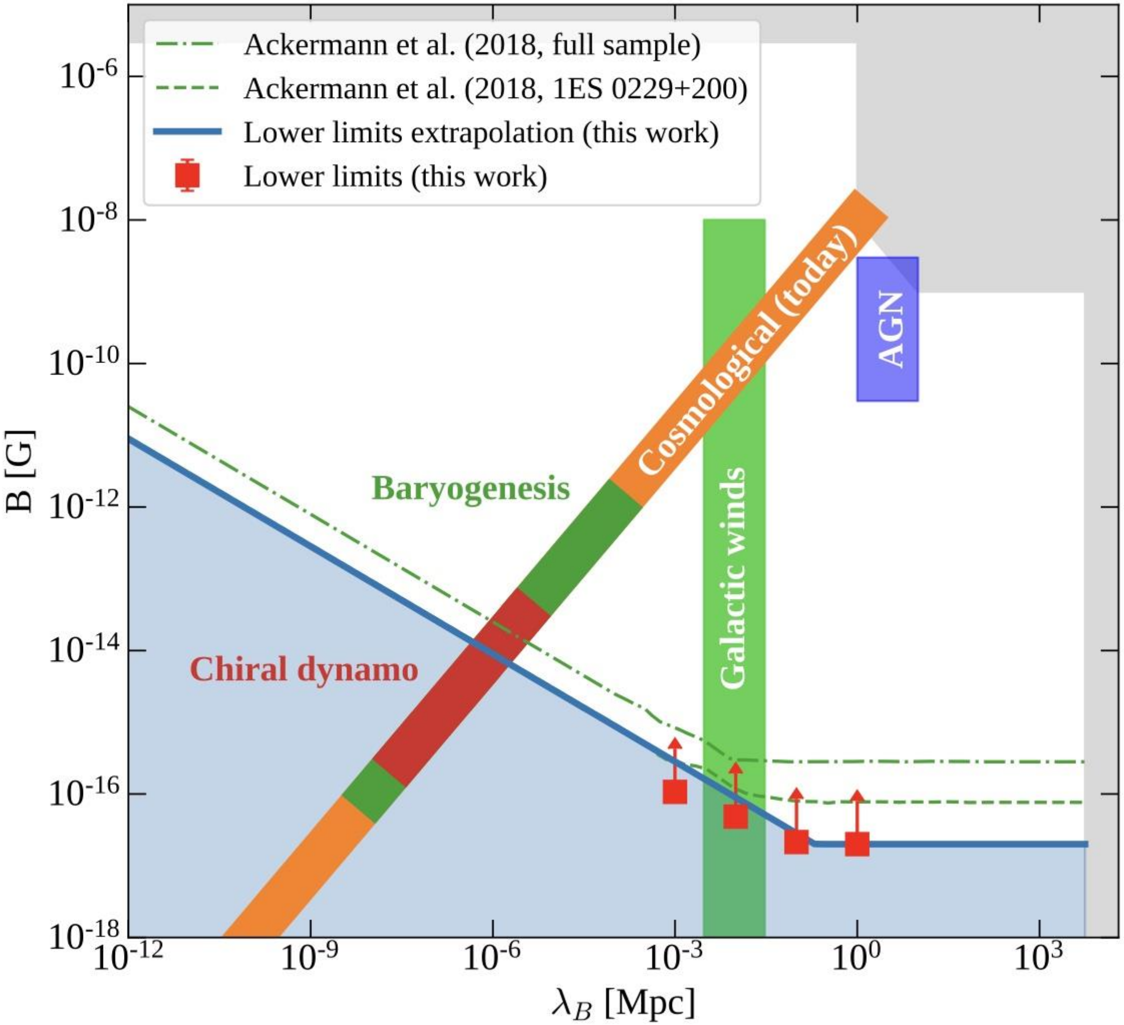


Fig. 3. The scan of the cascade power in the $\Gamma - E_{cut}$ parameter space along with the 68% and 90% confidence contours from the χ^2 fit. At 90% confidence level the minimal cascade, marked with the yellow dashed lines, corresponds to $\Gamma \approx 1.72$ and $E_{cut} \approx 6.9$ TeV.

Flux of 1ES 0229+200 in gamma-rays



Magnetic field from 1ES 0229+200

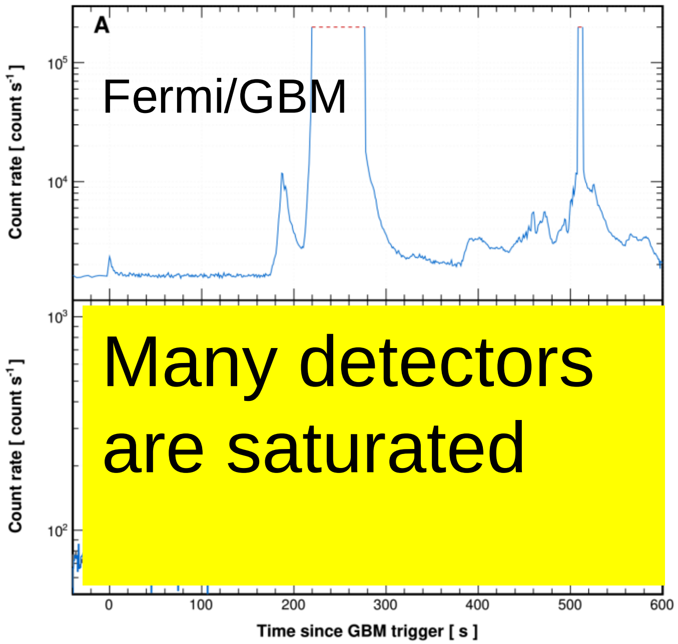


MAGIC collab 2210.03321

Inter-Galactic Magnetic Field from BOAT GRB

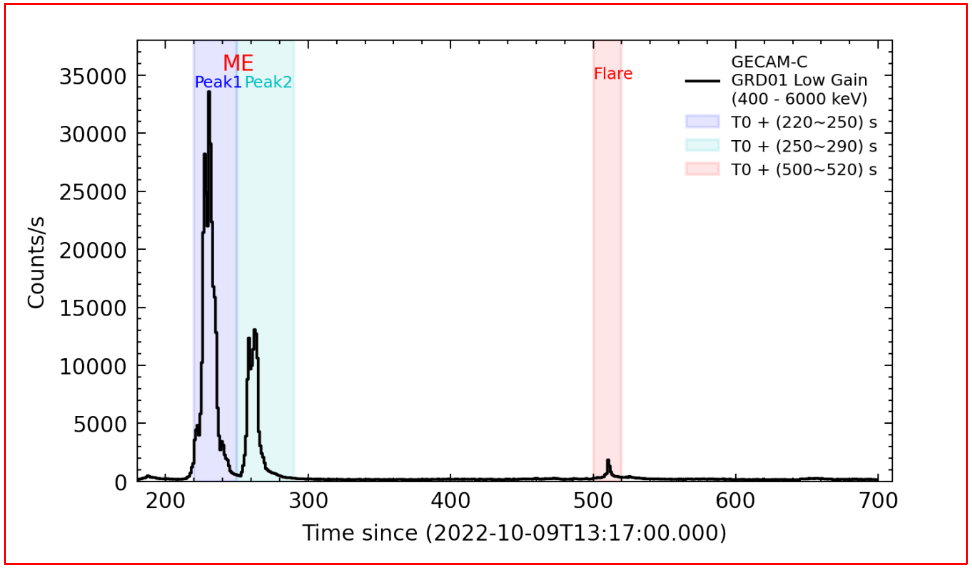
GRB 221009A: brightest-of-all-time (BOAT) GRB

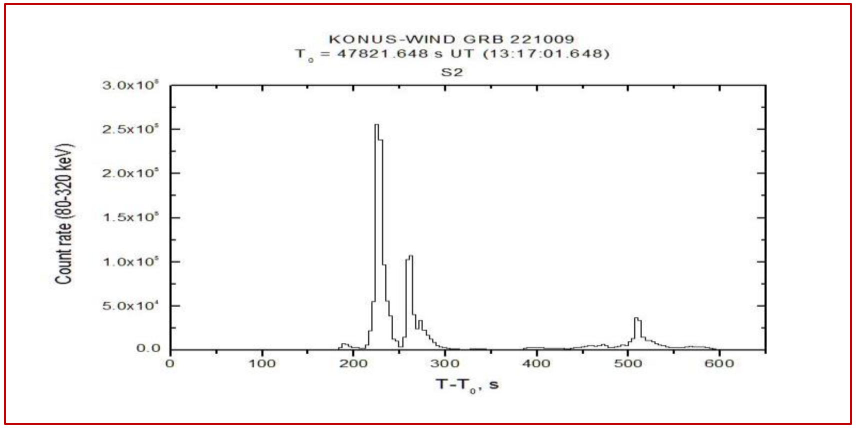
- Triggered on a weak precursor
- Fluence: >5e-2 erg/cm^2， low redshift (z=0.151)
- deriving an enormous energy $E_{\gamma,iso}$~$\mathbf{10^{55}}$ erg



Fermi

GECAM/Konus-Wind Observations of GRB 221009A

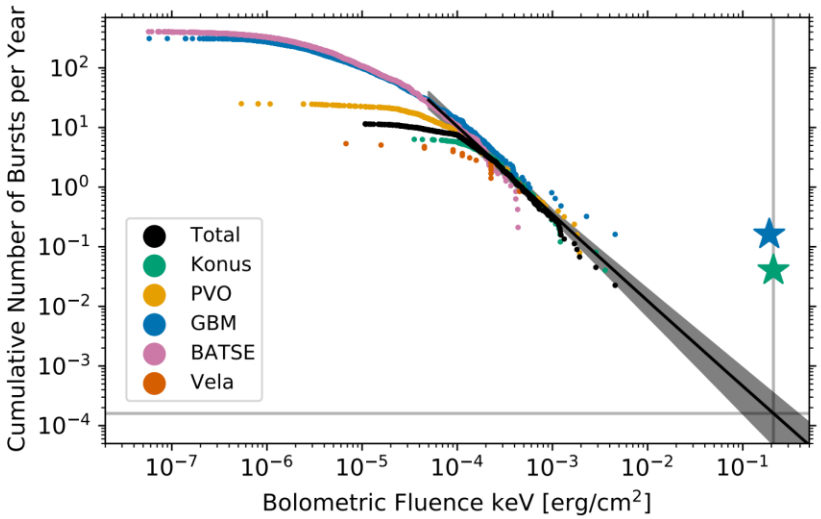


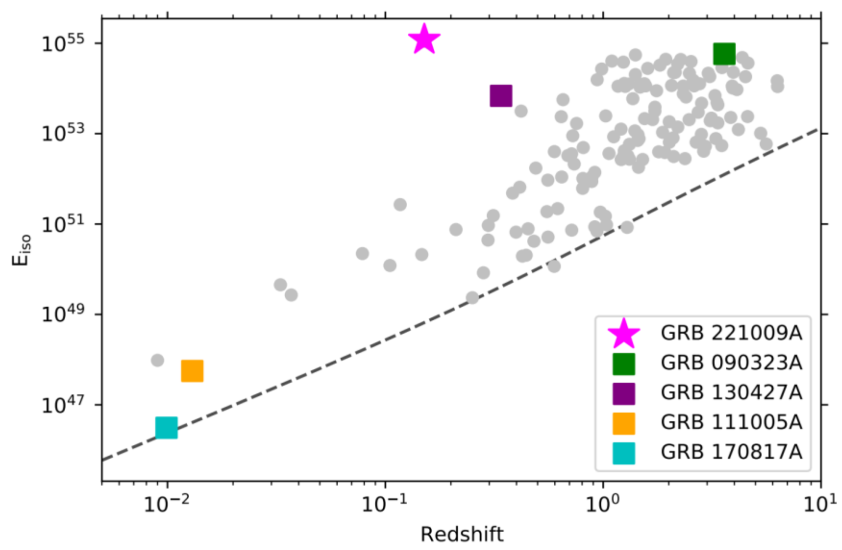


E_iso~ 1.5 × 10^55 erg

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}

R<10^-3 yr

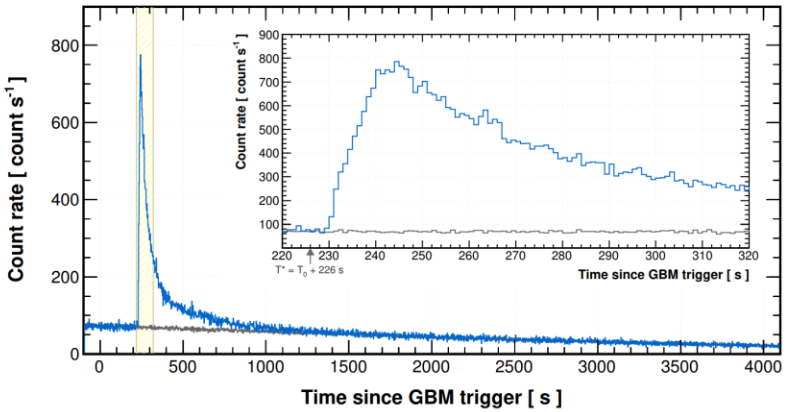
Buns et al. 2023

z=0.151 volume ~ 1 Gpc^3

LHAASO GRB221009A

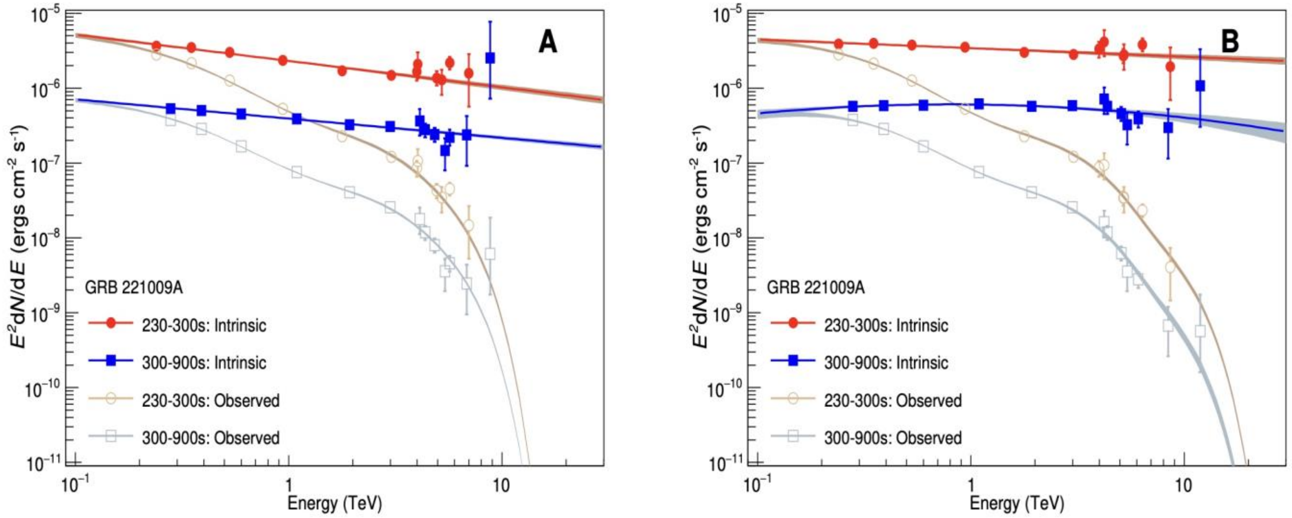
- LHAASO detection of GRB 221009A: first GRB seen by a extensive air shower detector

- High statistics: >60,000 photons above 0.2TeV (LHAASO-WCDA)
- TeV count rate light curve: Smooth temporal profile – **external shock origin**

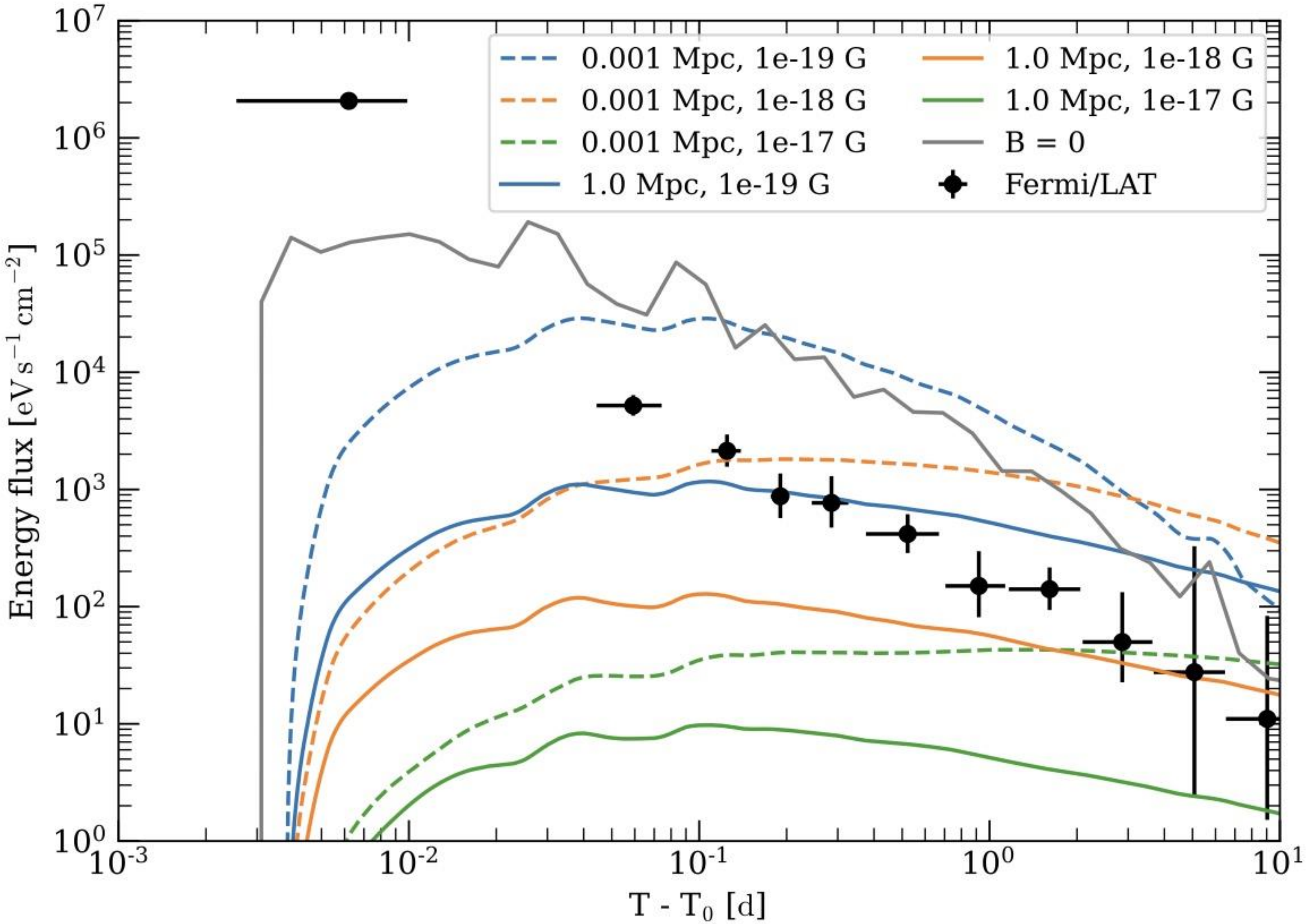


First time detection of the TeV afterglow onset !

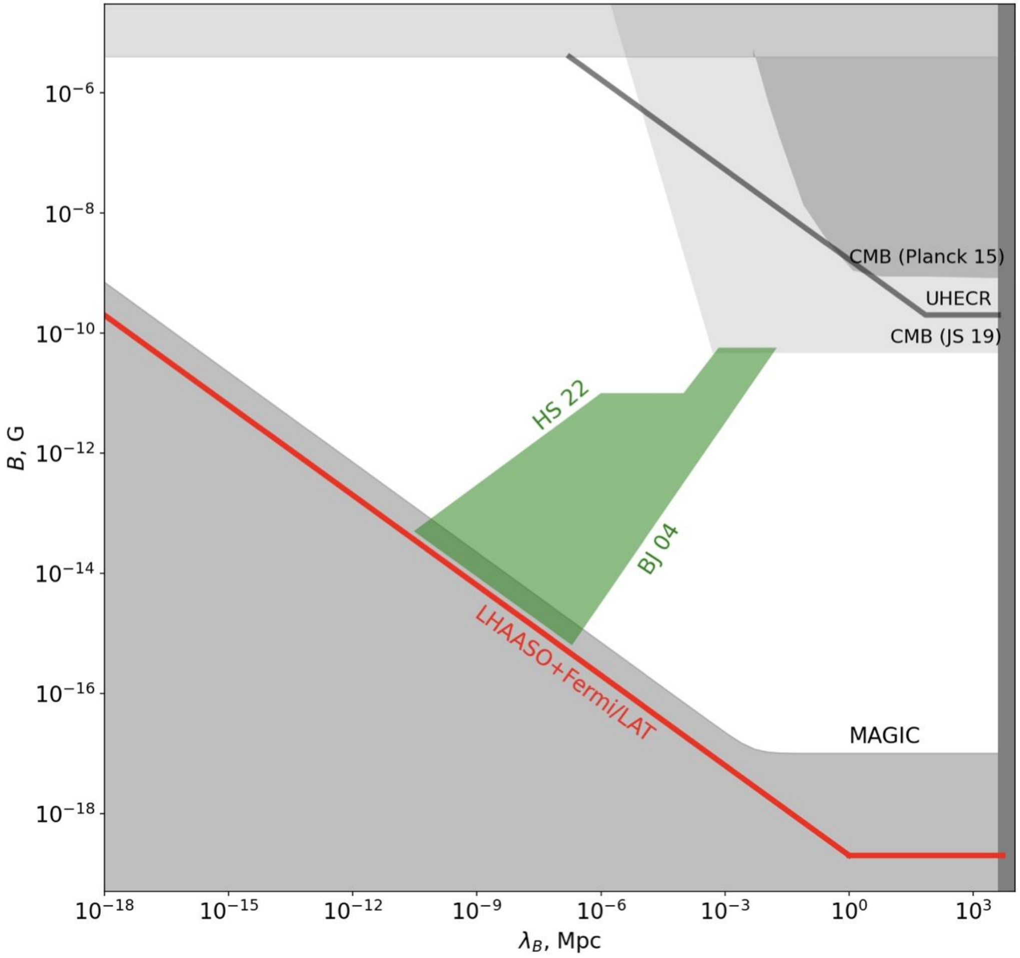
Flux from BOAT GRB in in LHAASO



Flux from BOAT GRB in Fermi and cascade contribution

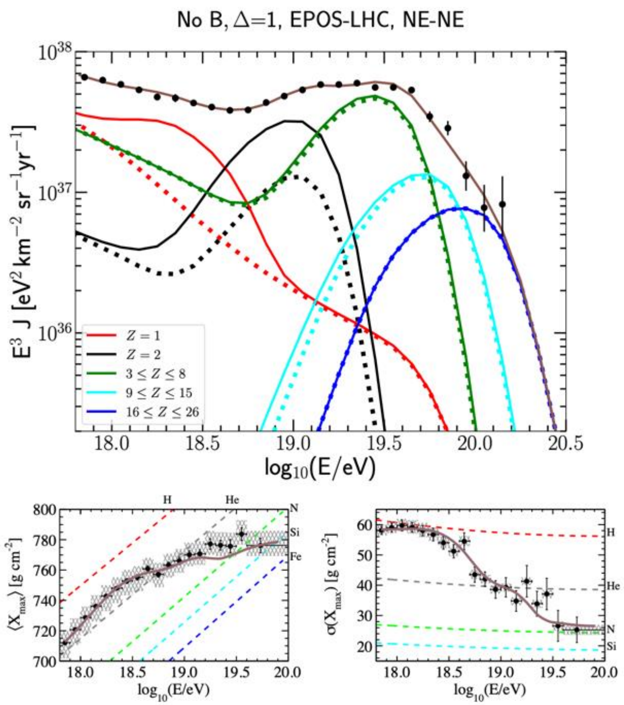


Constraint on IGMF from BOAT GRB

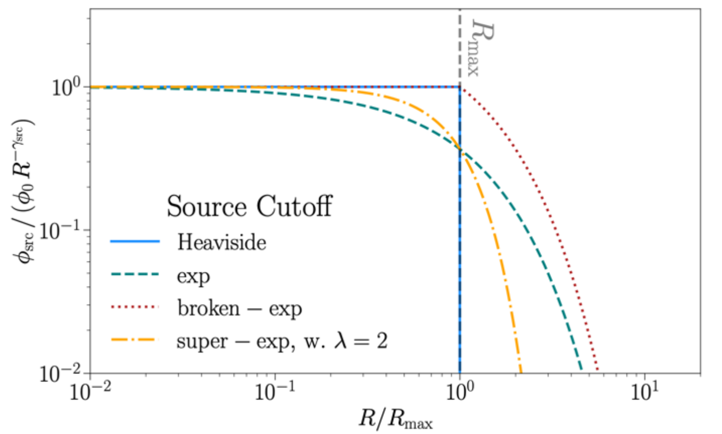


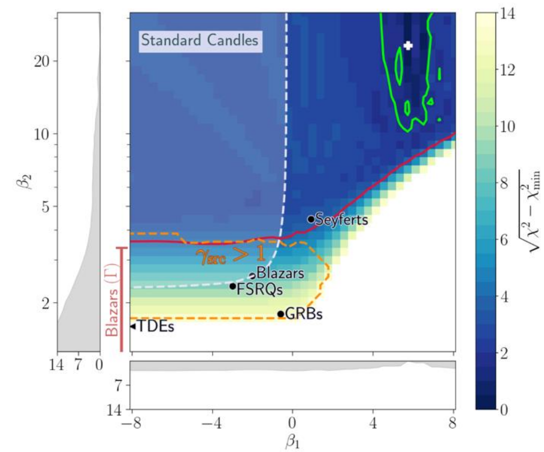
UHECR spectrum, composition and anisotropy

Auger spectrum and Emax



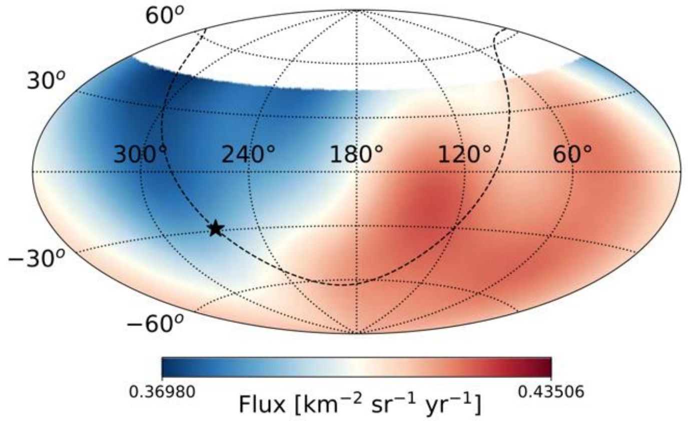
Pierre Auger Collaboration, 2404.03533

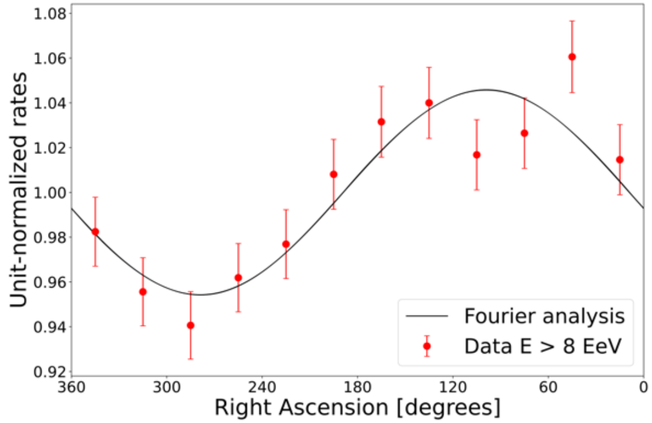


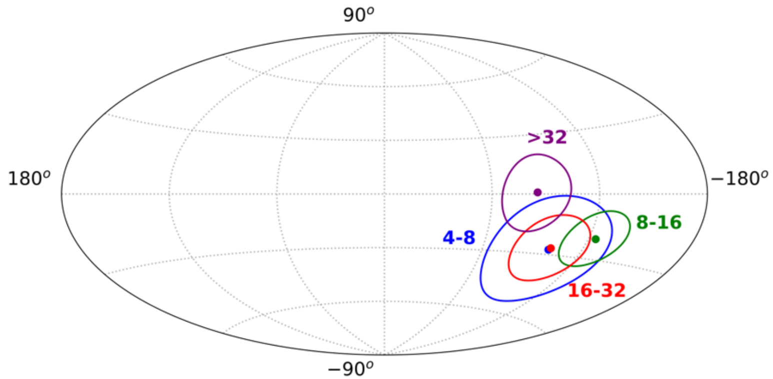


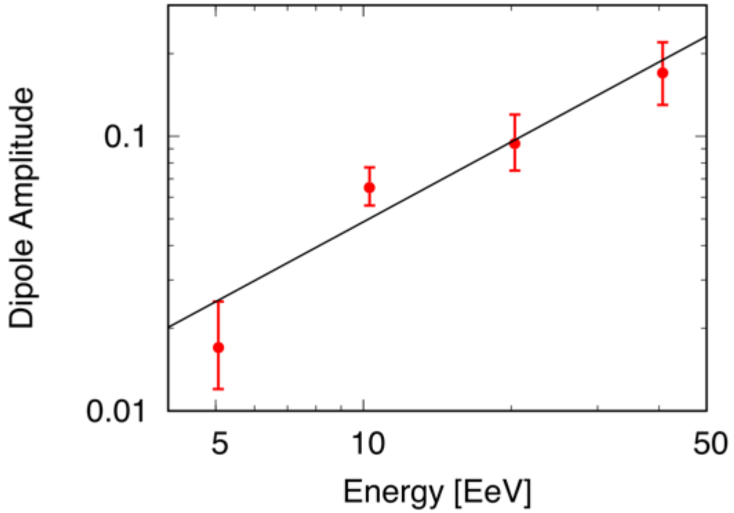
D. Ehlert , F. Oikonomou
and M.Unger 2207.10691

Auger dipole 6 sigma



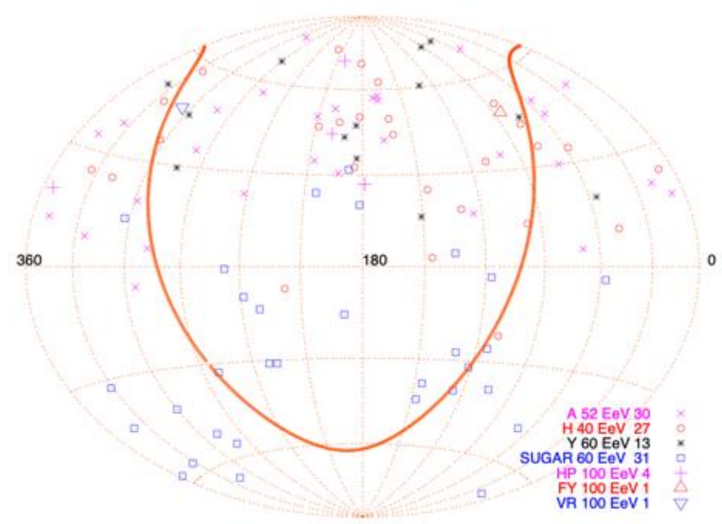


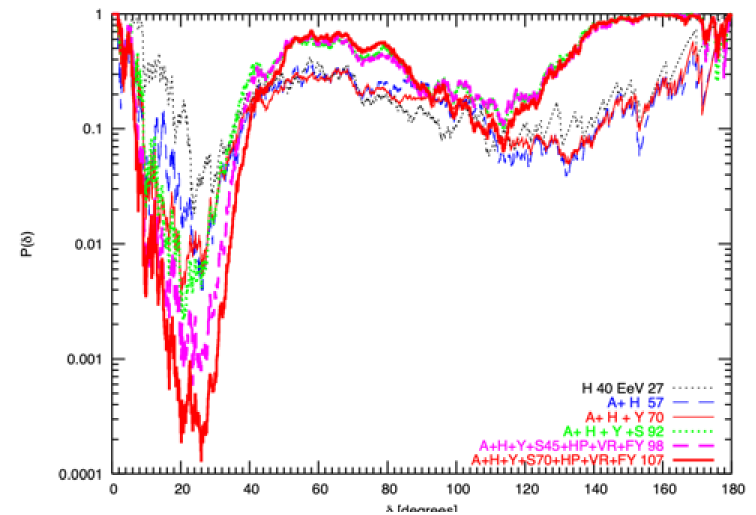




Pierre Auger Collaboration, 2408.05292

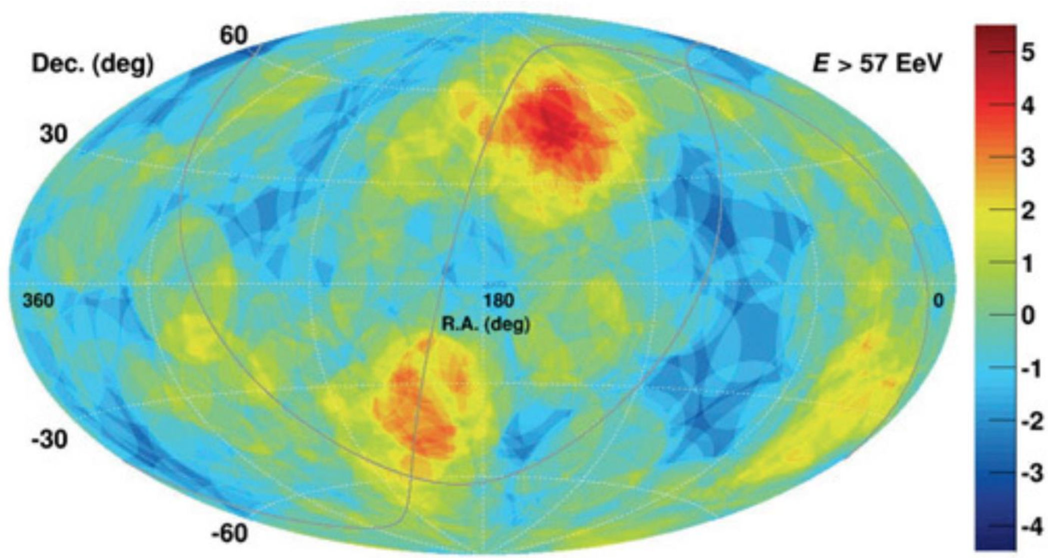
20-deg scale anisotropy in UHECR arrival directions





M.Kachelriess and D.S. arXiv:0512498

Auger-TA sky map E>57 EeV

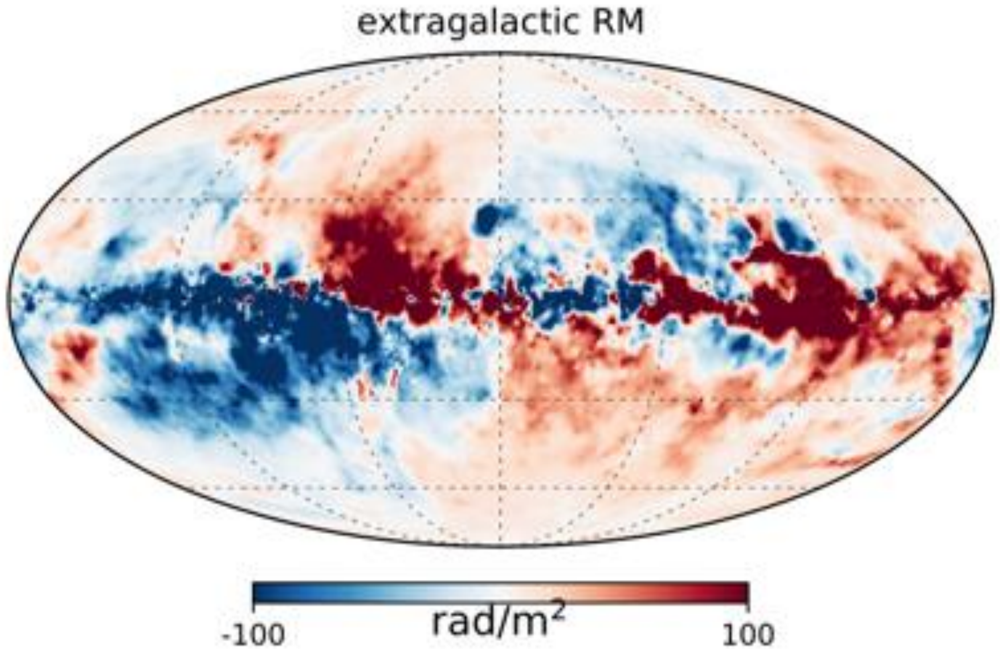


Full sky map combining the Telescope Array and Pierre Auger data events with E > 5.7×10 19 eV. The events have oversampling with a 20 @BULLET radius circle. The Telescope Array data set includes 109 events, representing the first 7 years of data collection. The Auger data set includes 157 events, representing 10 years of data. No correction was made for the energy scale difference between the Telescope Array and Pierre Auger data sets.

Auger & TA collaboration

UHECR and Galactic magnetic field

ROTATION MEASURE

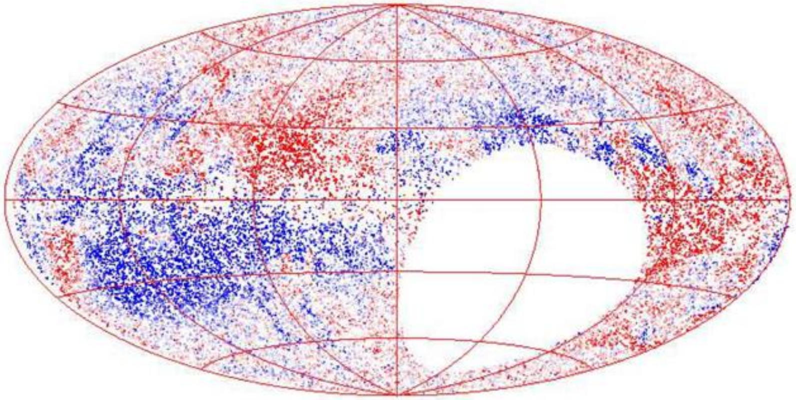


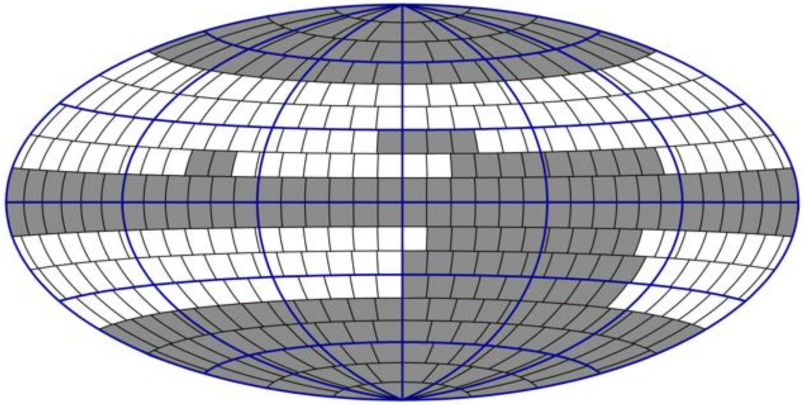
60000 extragalactic objects

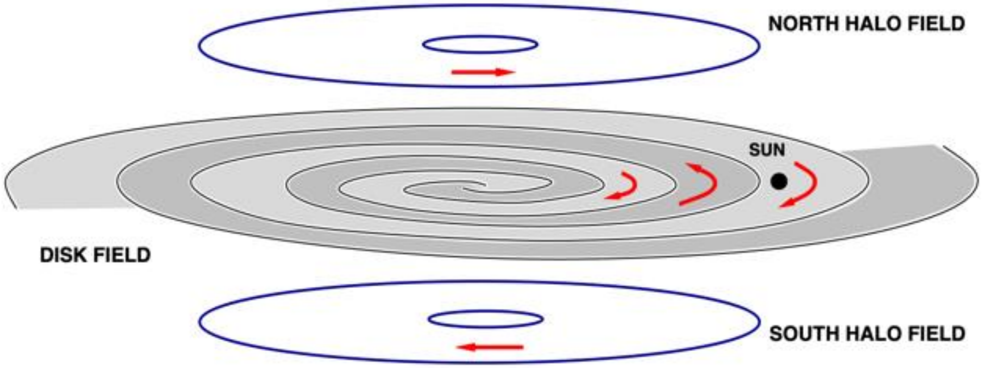
$$\mathrm{RM} \approx 0.812 \int_0^l \left[\frac{n_e(s)}{\mathrm{cm}^{-3}}\right]\left[\frac{B_\parallel(s)}{10^{-6}\,\mathrm{G}}\right]\left[\frac{\mathrm{d}s}{\mathrm{pc}}\right] \ \mathrm{rad/m}^2.$$

Pshirkov,Tinyakov, Kronberg and Newton-McGee

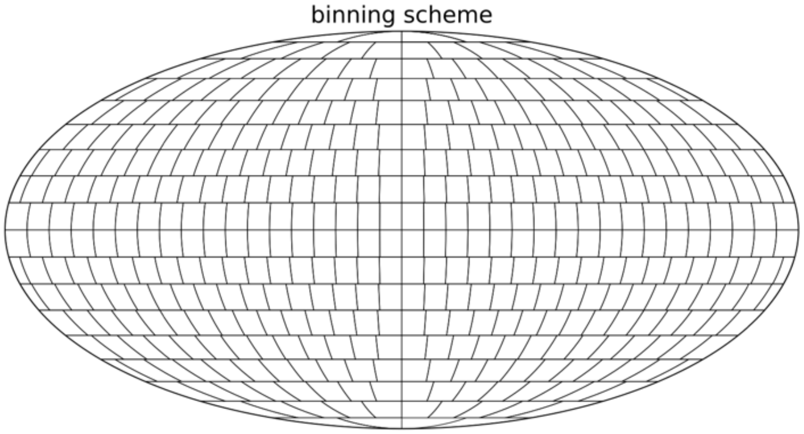
model 2011



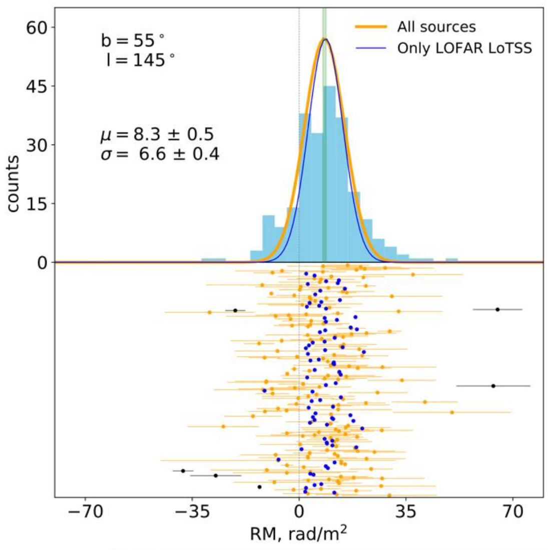


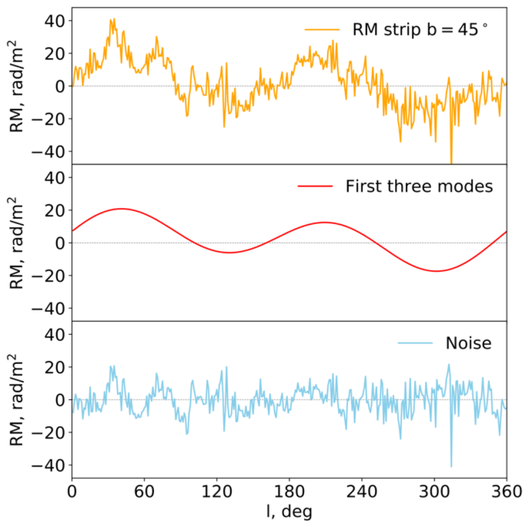


Model RM



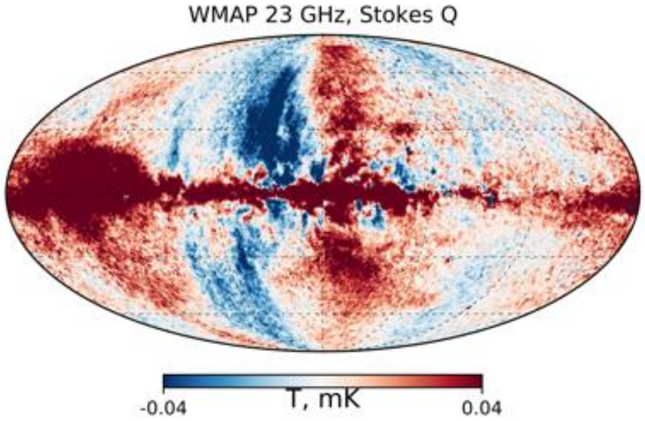
	χ^2	χ^2/ndf	ndf	χ^2_{var}	χ^2_{var}/ndf
RM	544	**1.92**	283	145	0.51
Q	385	**1.11**	348	238	0.68
U	482	**1.38**	348	251	0.72
total	1411	**1.36**	1037	634	0.61

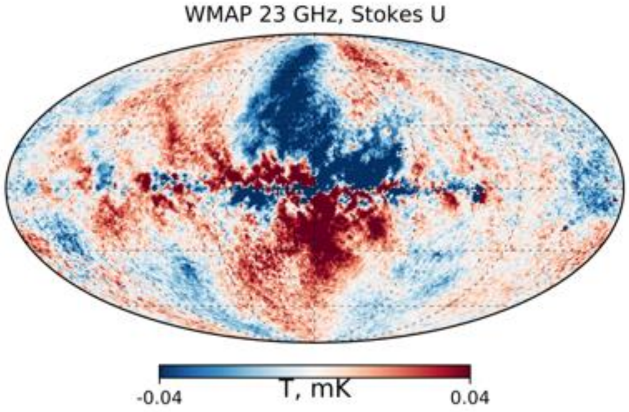




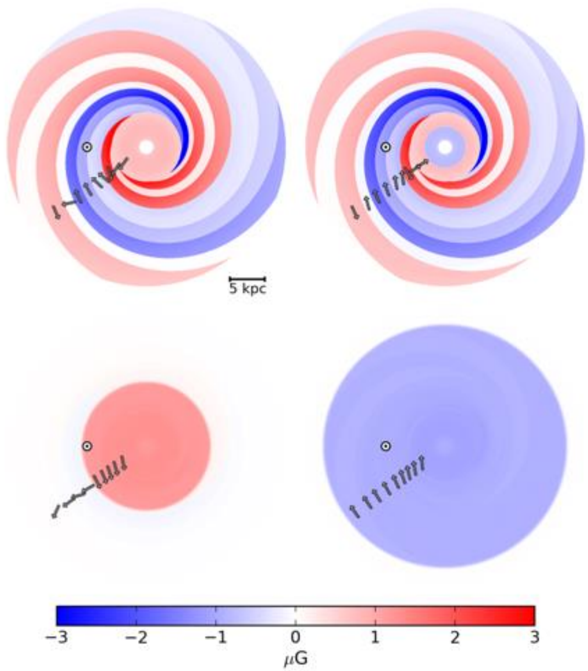
Synchrotron measure

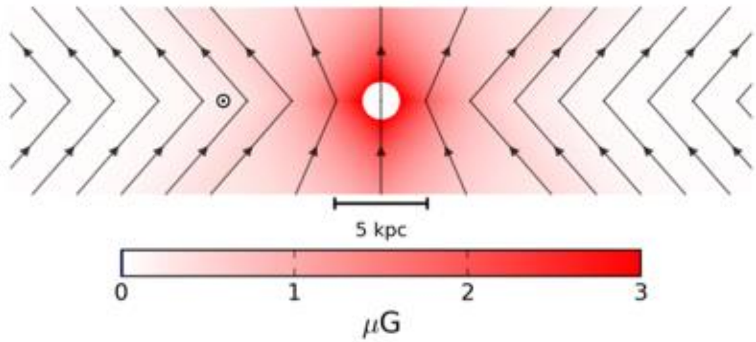
$$\nu_c \approx 1.6 \left[\frac{B_\perp}{10^{-6}\,\mathrm{G}}\right]\left[\frac{E}{10\,\mathrm{GeV}}\right]^2 \ \mathrm{GHz}.$$





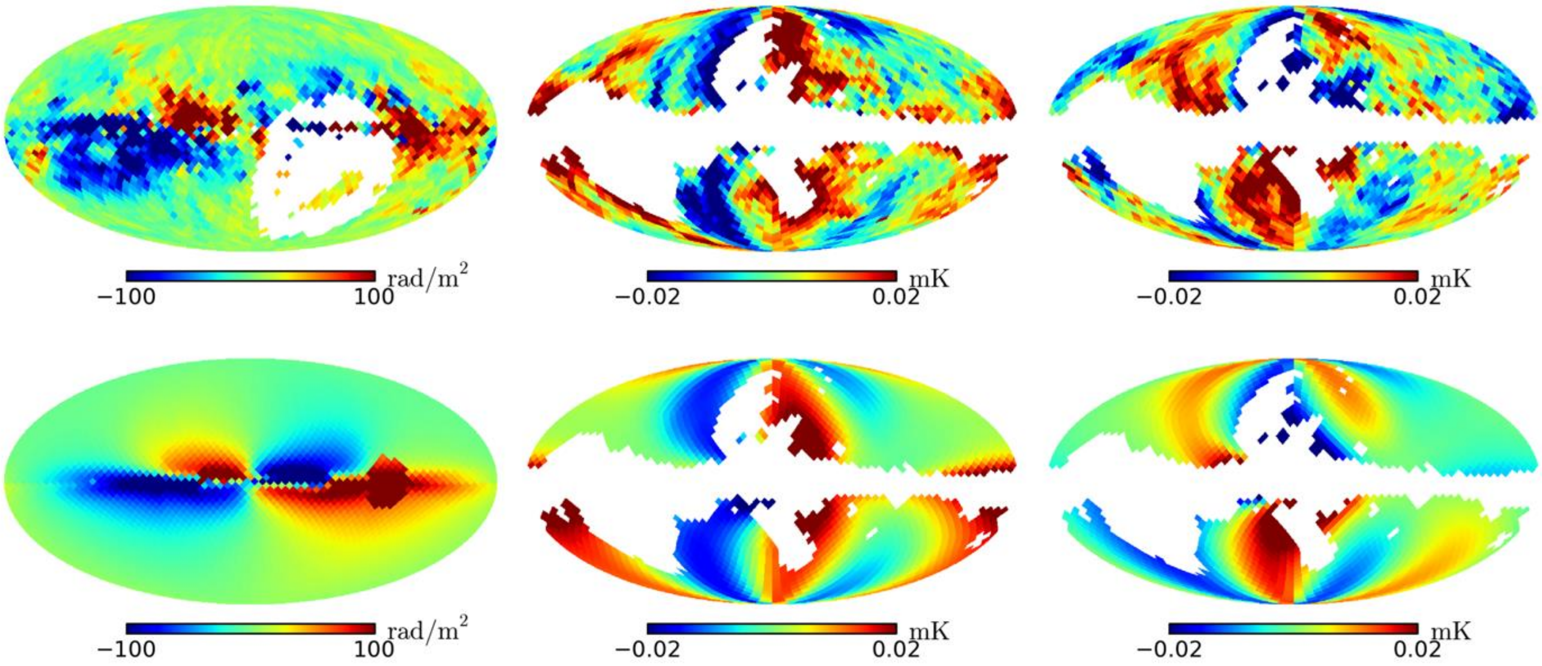
Jansson-Farrar 2012 model



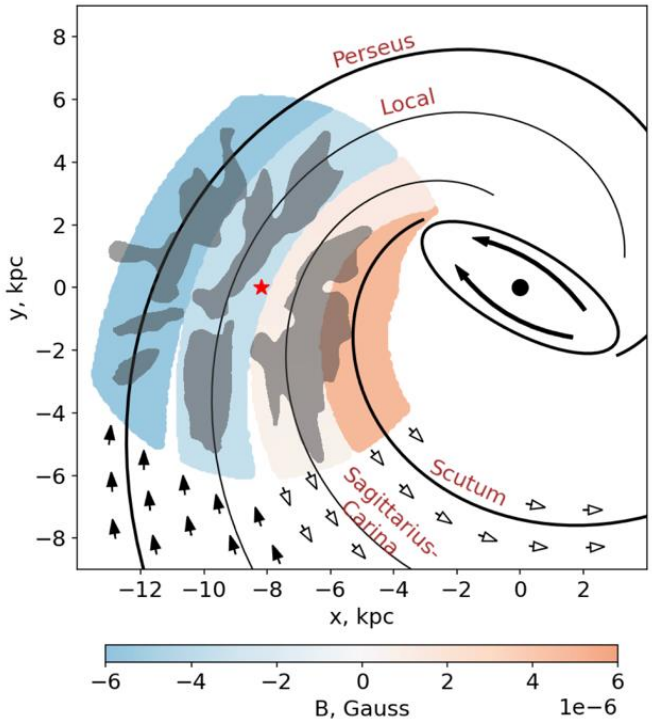


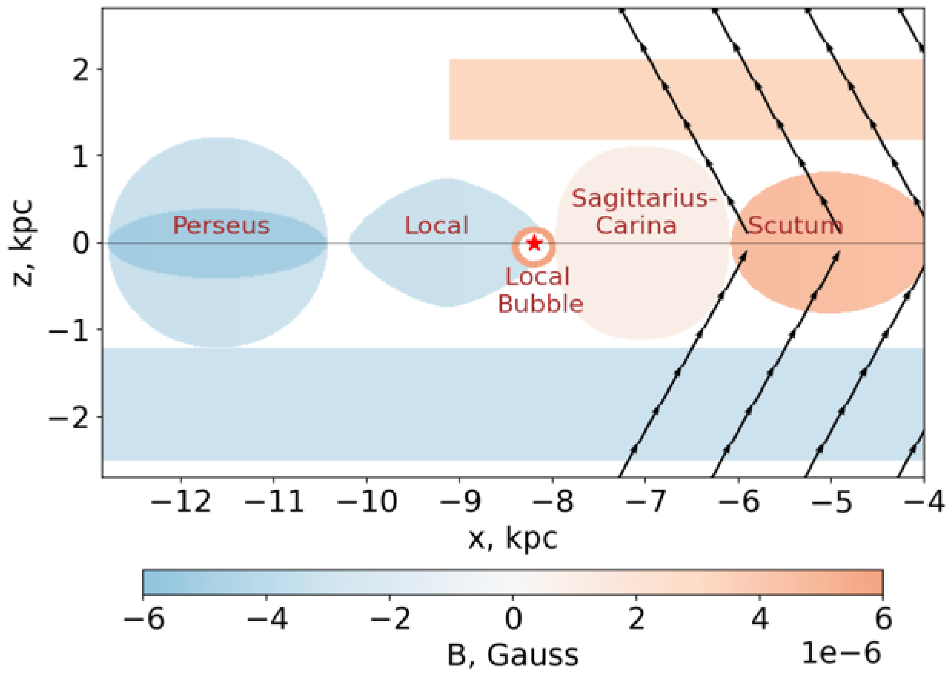
Jansson and Farrar, 1204.3662

Jansson-Farrar 2012 model



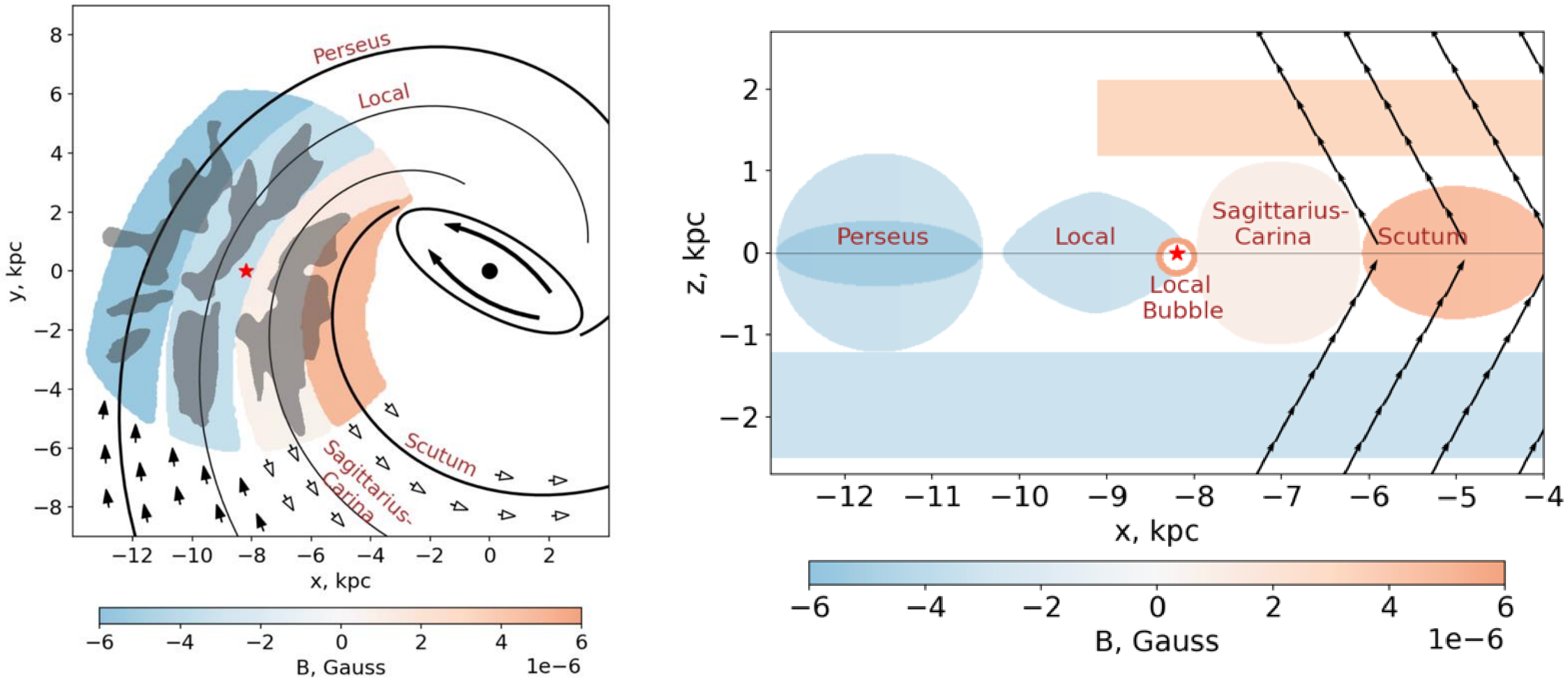
New model 2024





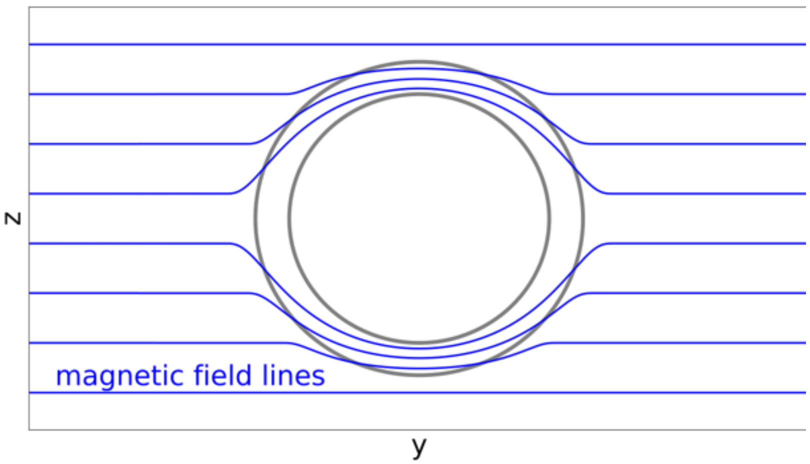
A.Korochkin, D.S. and P.Tinyakov, 2407.02148

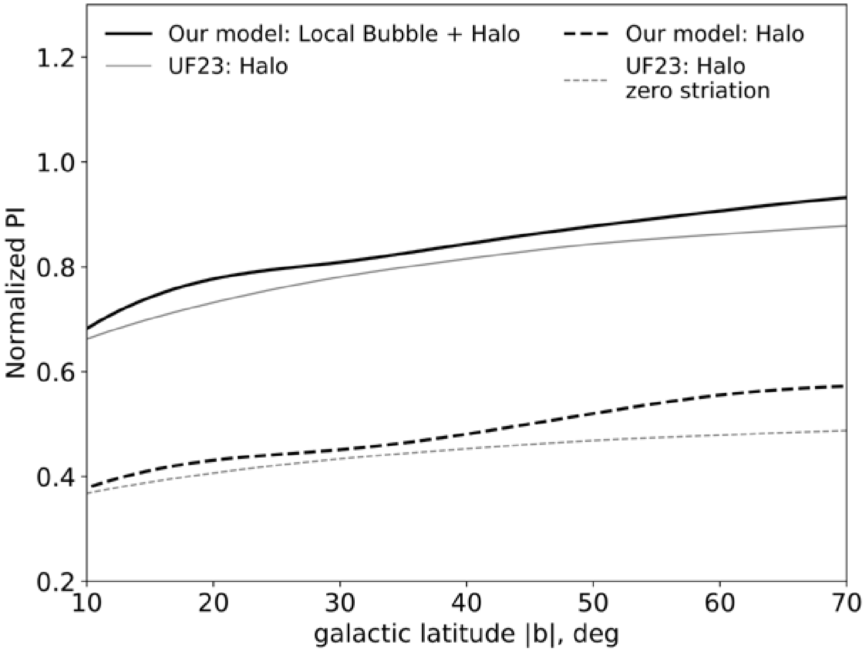
New model



A.Korochkin, D.S. and P.Tinyakov, 2407.02148

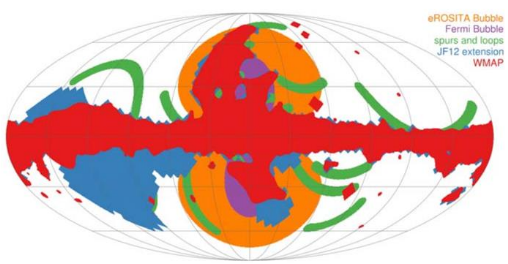
Local Bubble solved discrepansy between RM and synchrotron



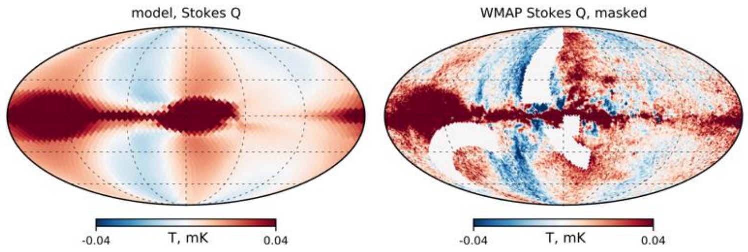


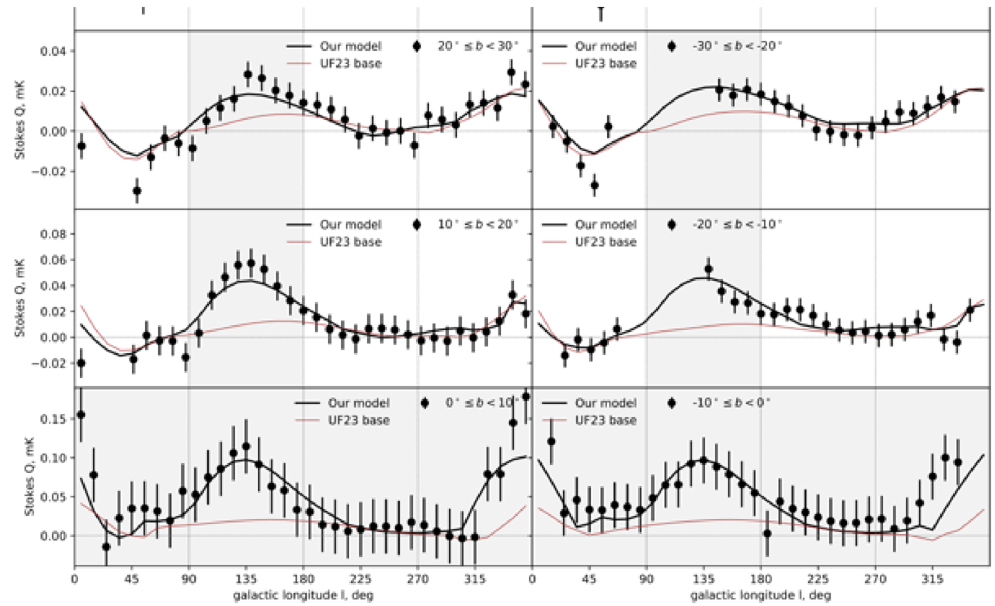
A.Korochkin, D.S. and P.Tinyakov, 2407.02148

FAN REGION: KEY TO UHECR DIPOLE



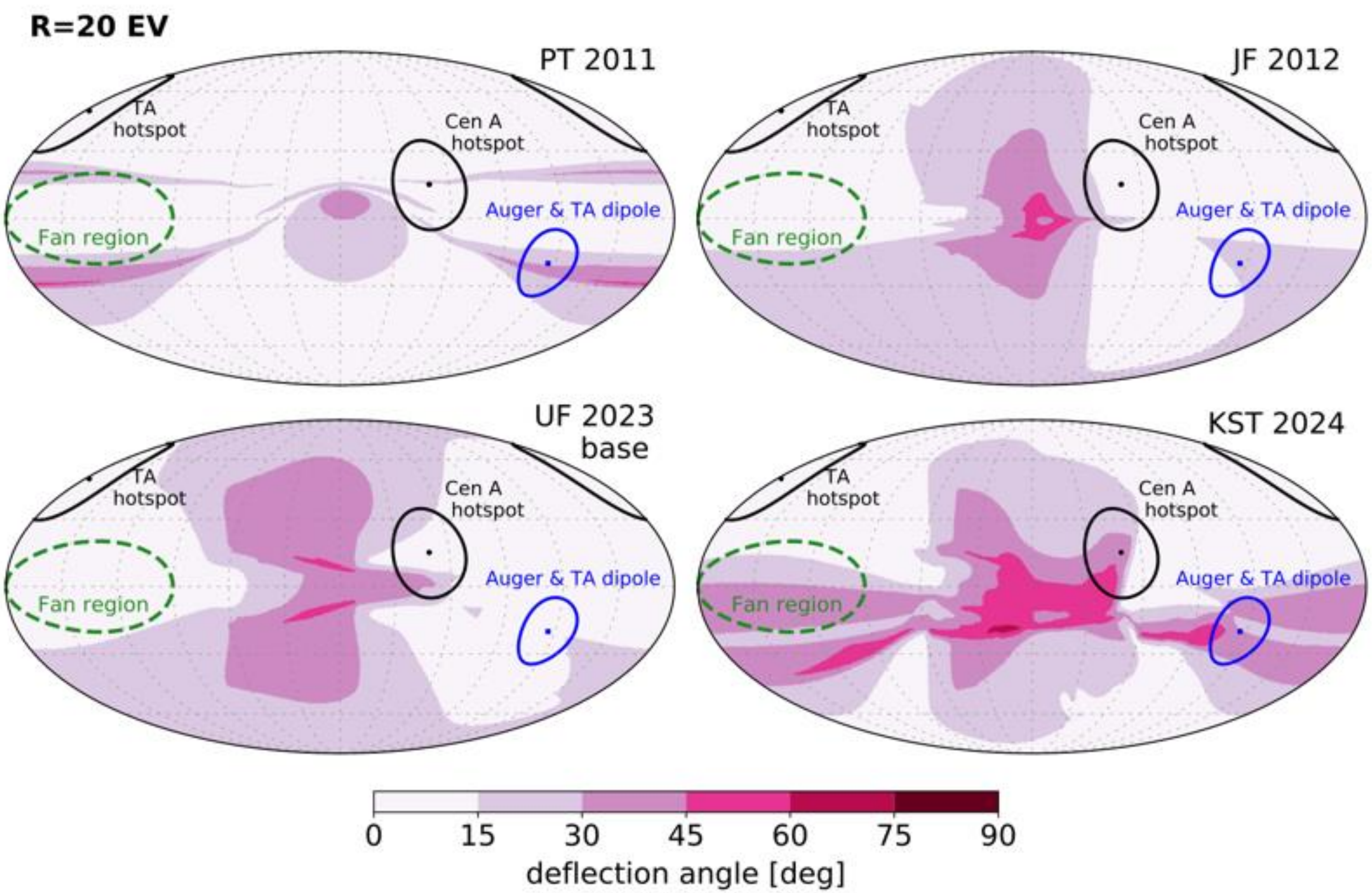
UF 2023





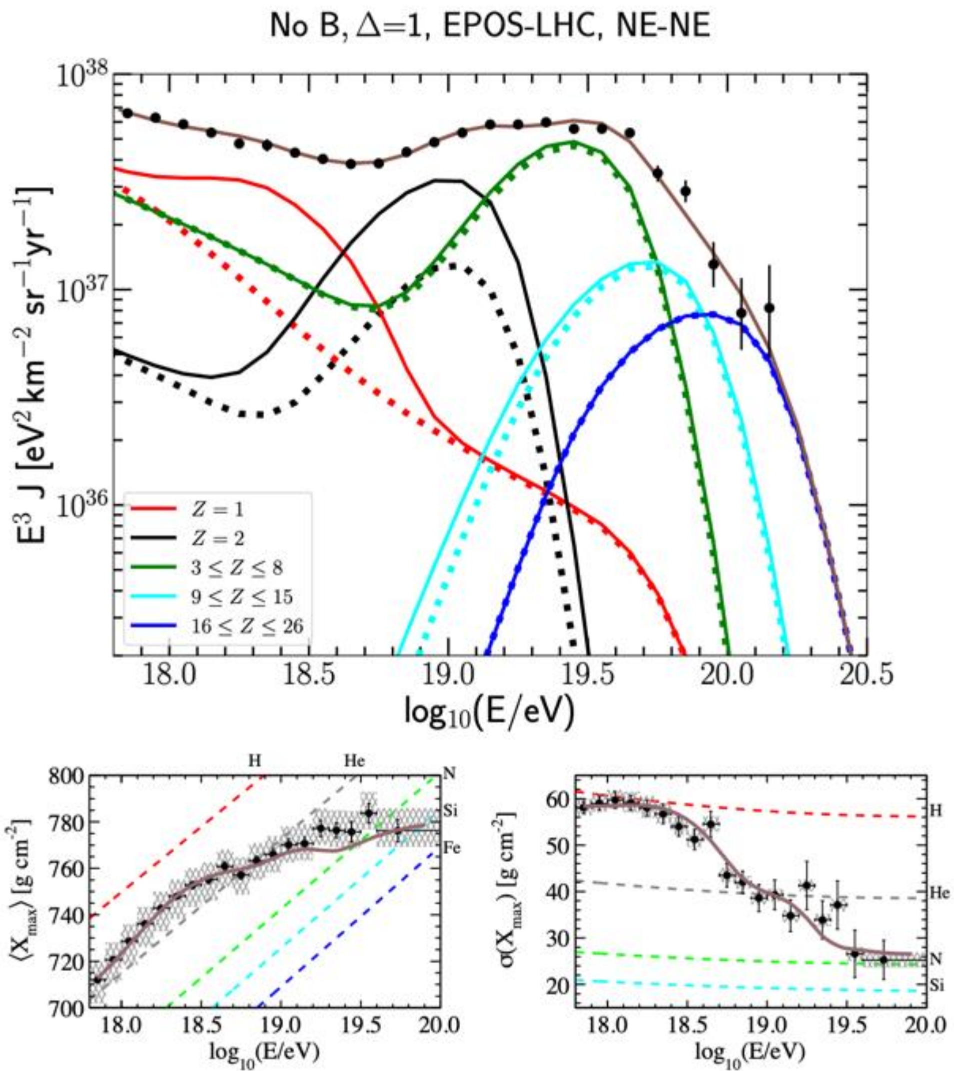
A.Korochkin, D.S. and P.Tinyakov, 2407.02148

UHECR R=20 EV



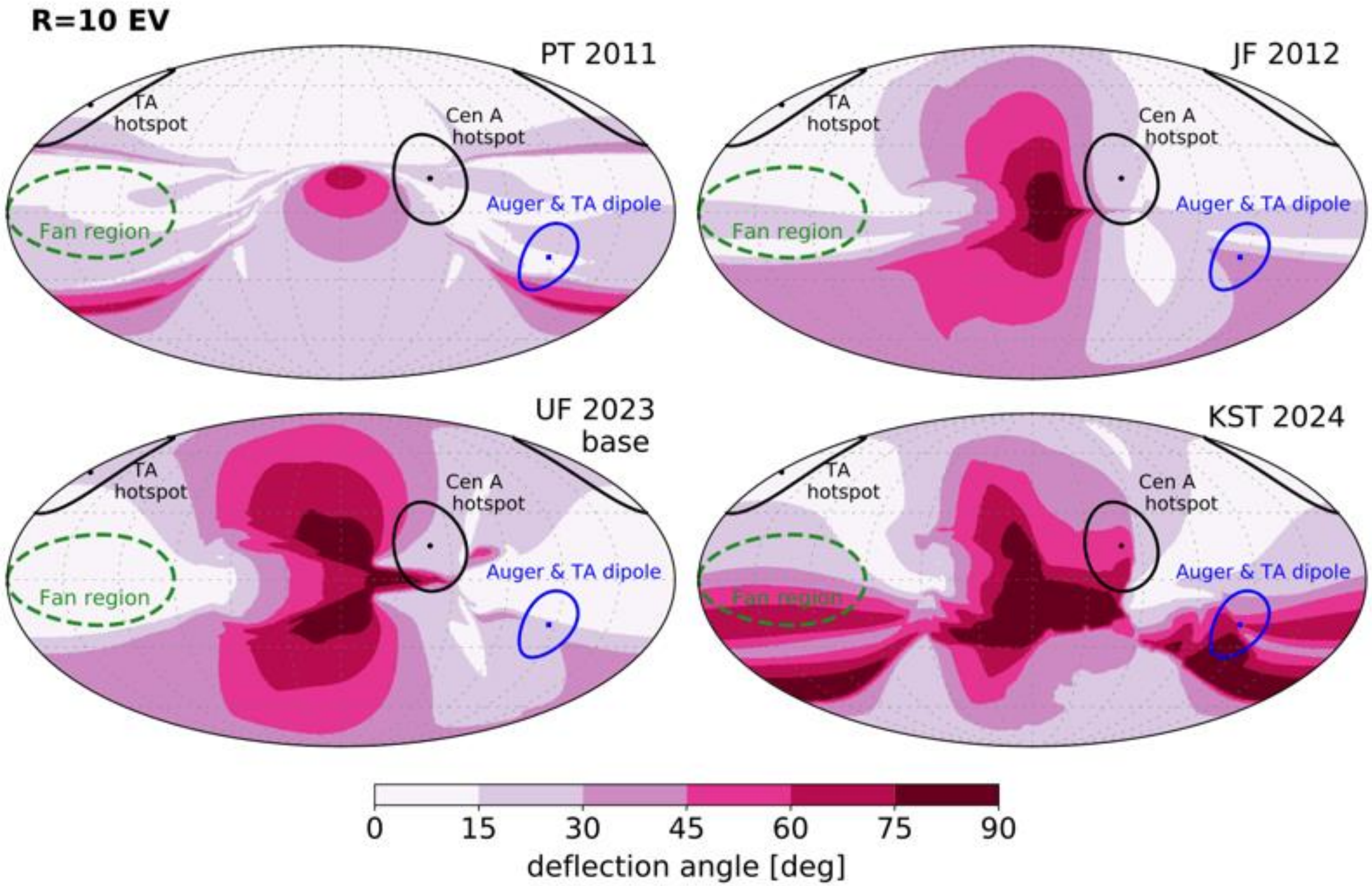
A. Korochkin, D.S. and P.Tinyakov 2501.16158

Auger spectrum and composition



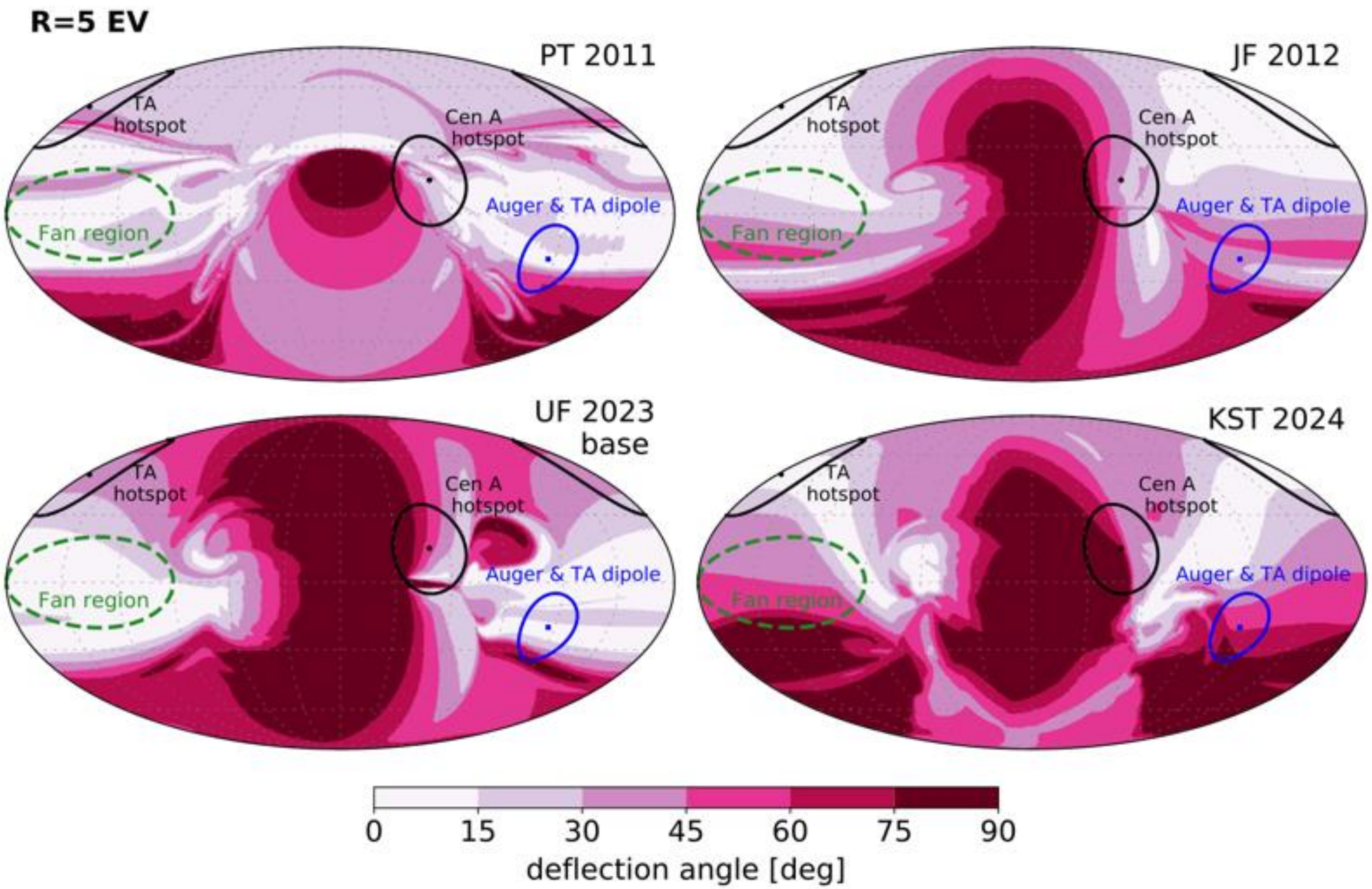
Pierre Auger Collaboration, 2404.03533

UHECR R=10 EV



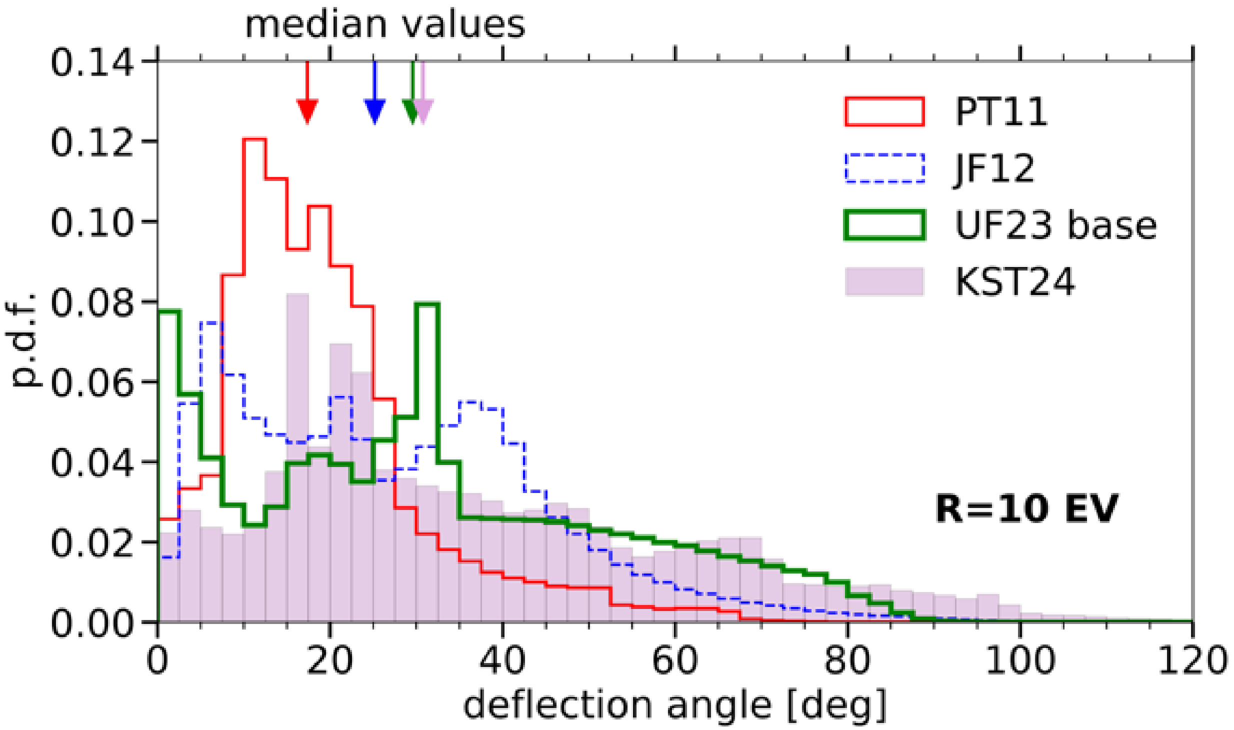
A. Korochkin, D.S. and P.Tinyakov 2501.16158

UHECR R=5 EV



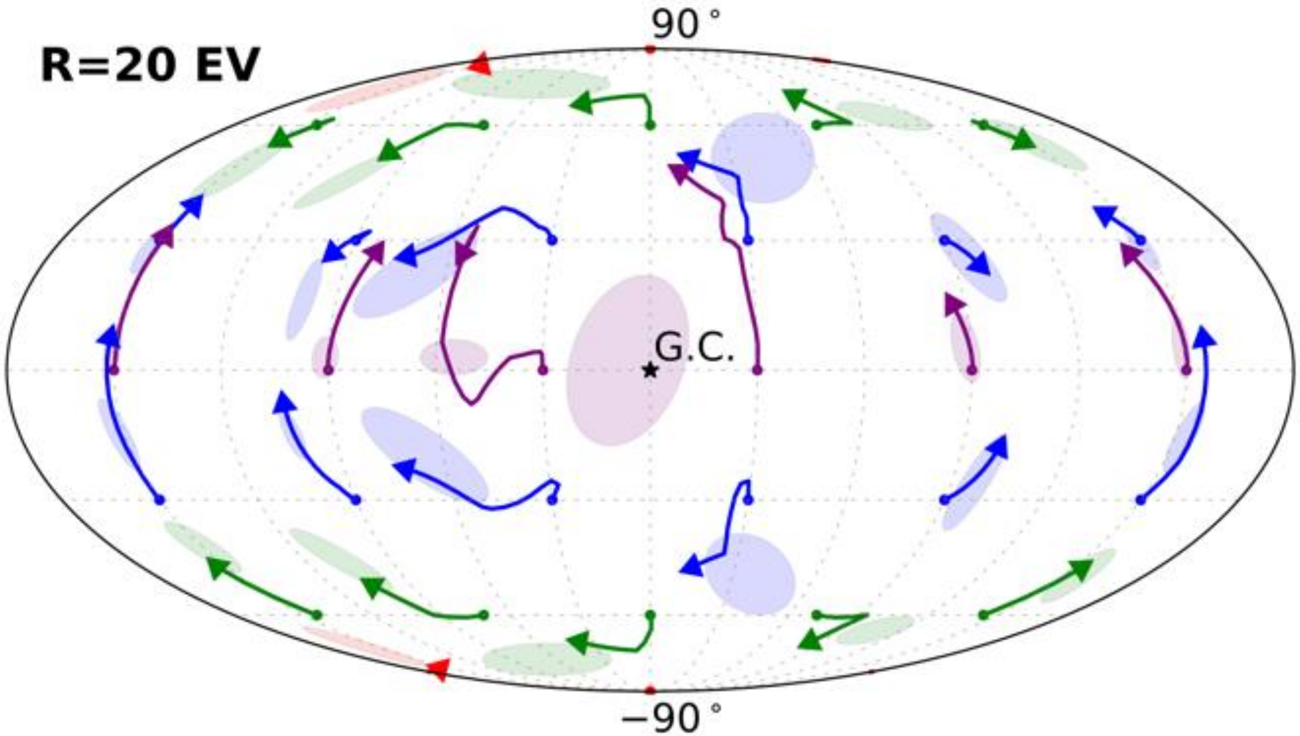
A. Korochkin, D.S. and P.Tinyakov 2501.16158

UHECR deflections R=10 EV



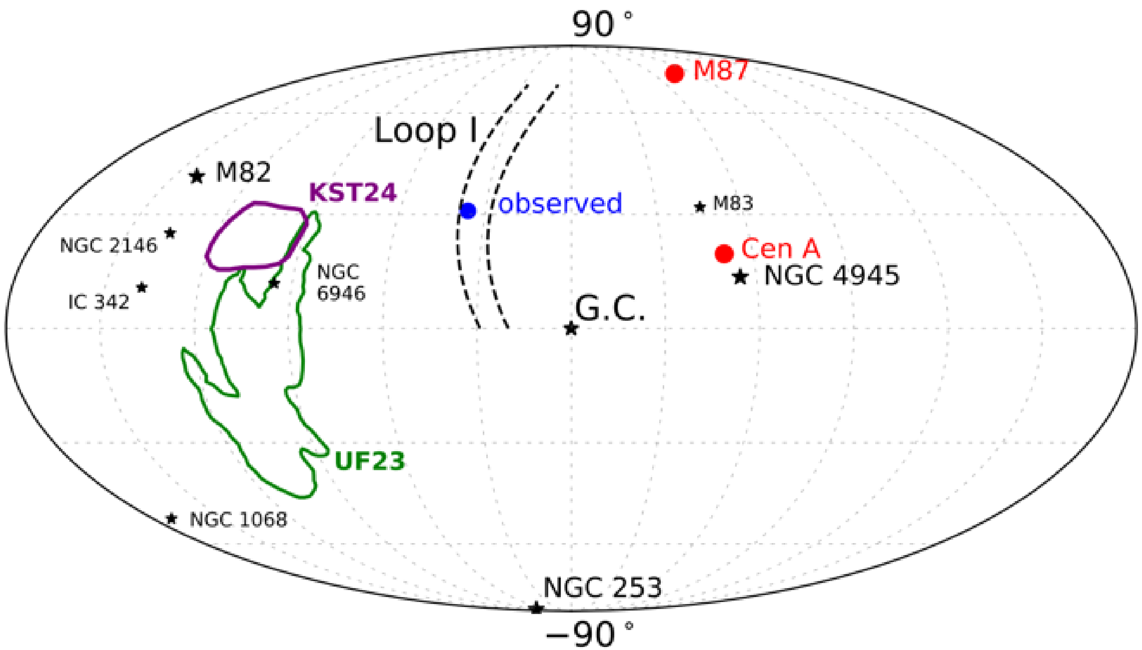
A. Korochkin, D.S. and P.Tinyakov 2501.16158

GMF UHECR deflection model-variartition



A. Korochkin, D.S. and P.Tinyakov 2501.16158

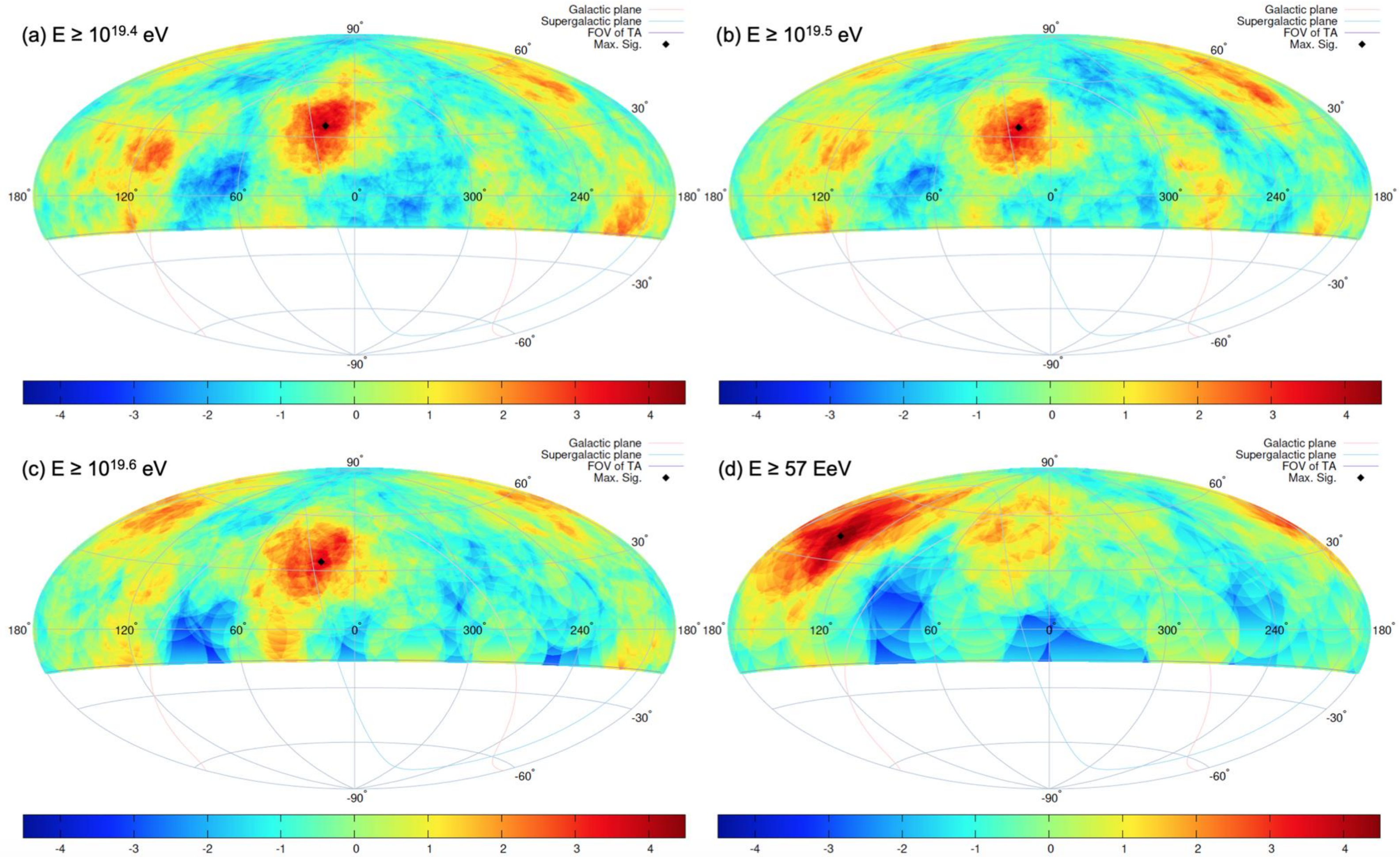
Amaterasu particle E=220 EeV for Fe or R=8 EV



A. Korochkin, D.S. and P.Tinyakov 2501.16158

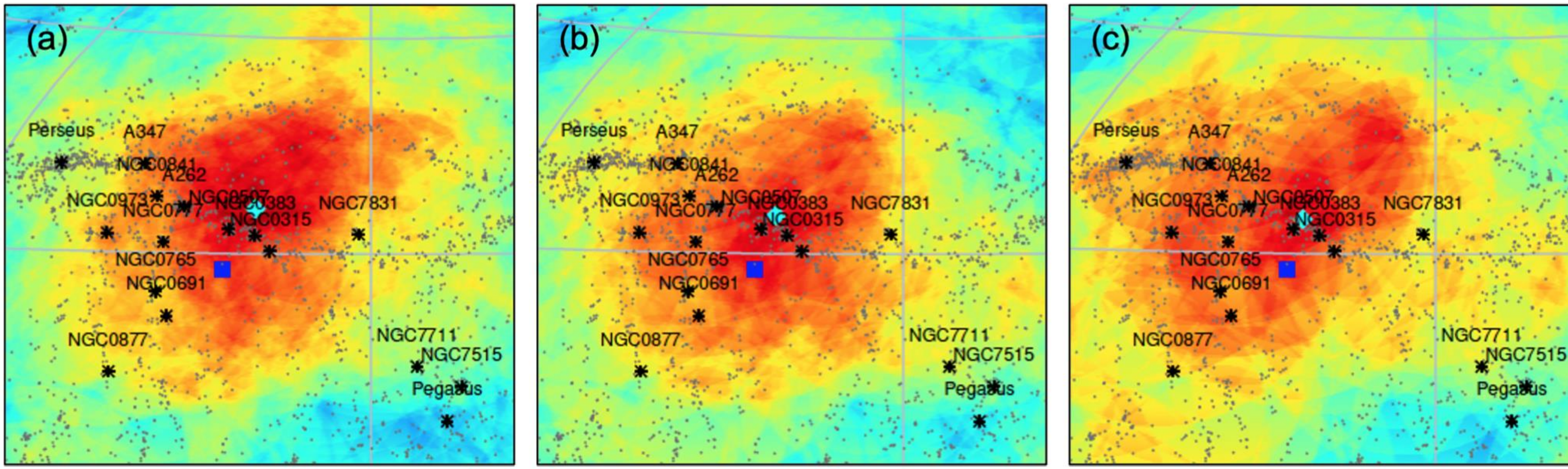
Inter-Galactic Magnetic Field detection with UHECR

TA sky map



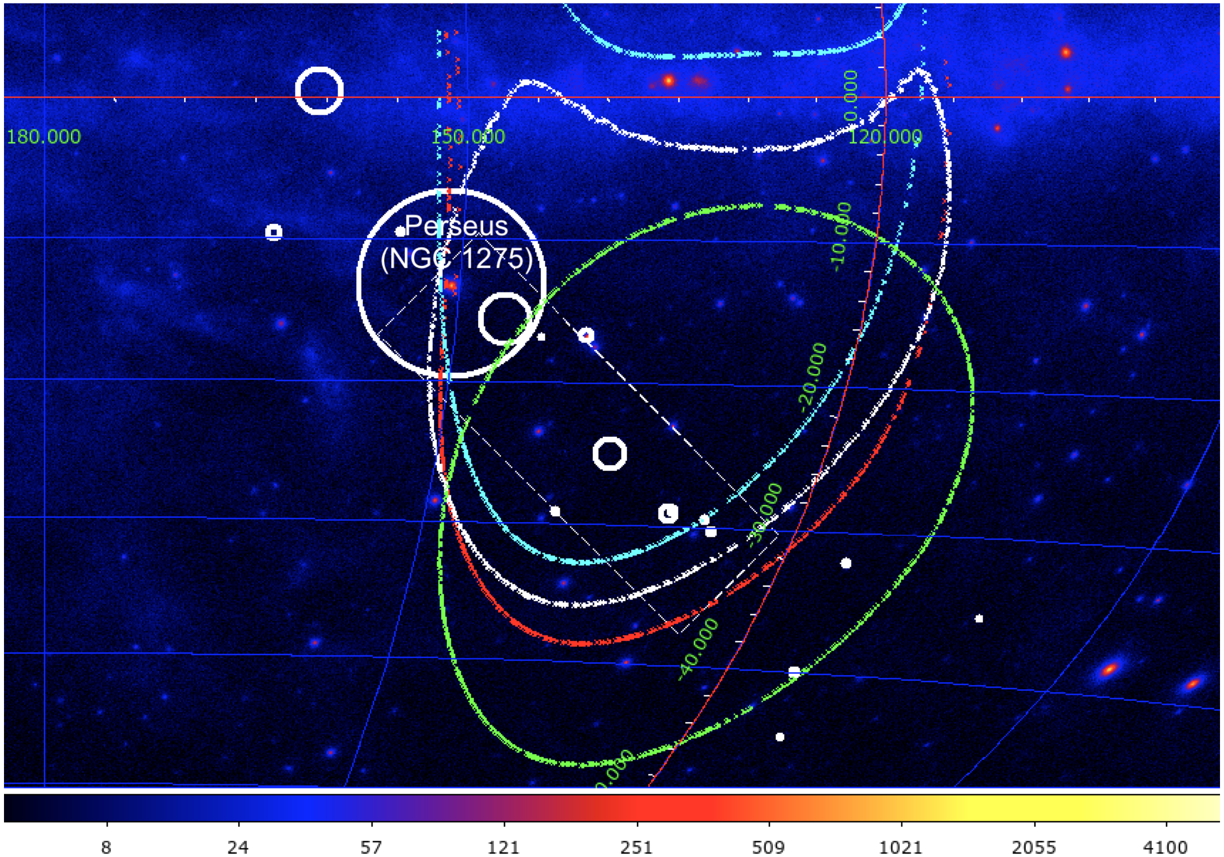
TA collaboration, 2110.14827

TA sky map of Perseus-Pisces SC



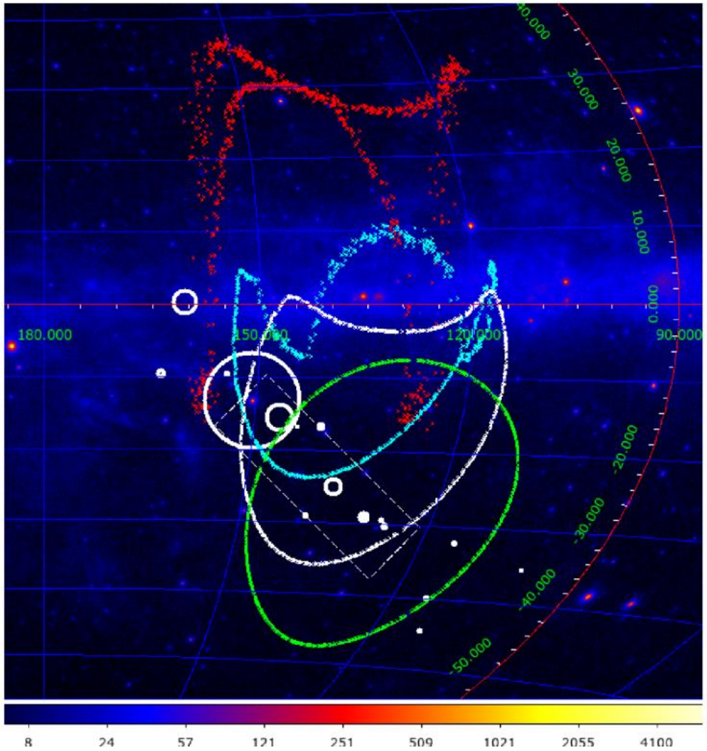
TA collaboration, 2110.14827

Deflection of UHECR protons with 25 EeV energy by several GMF models



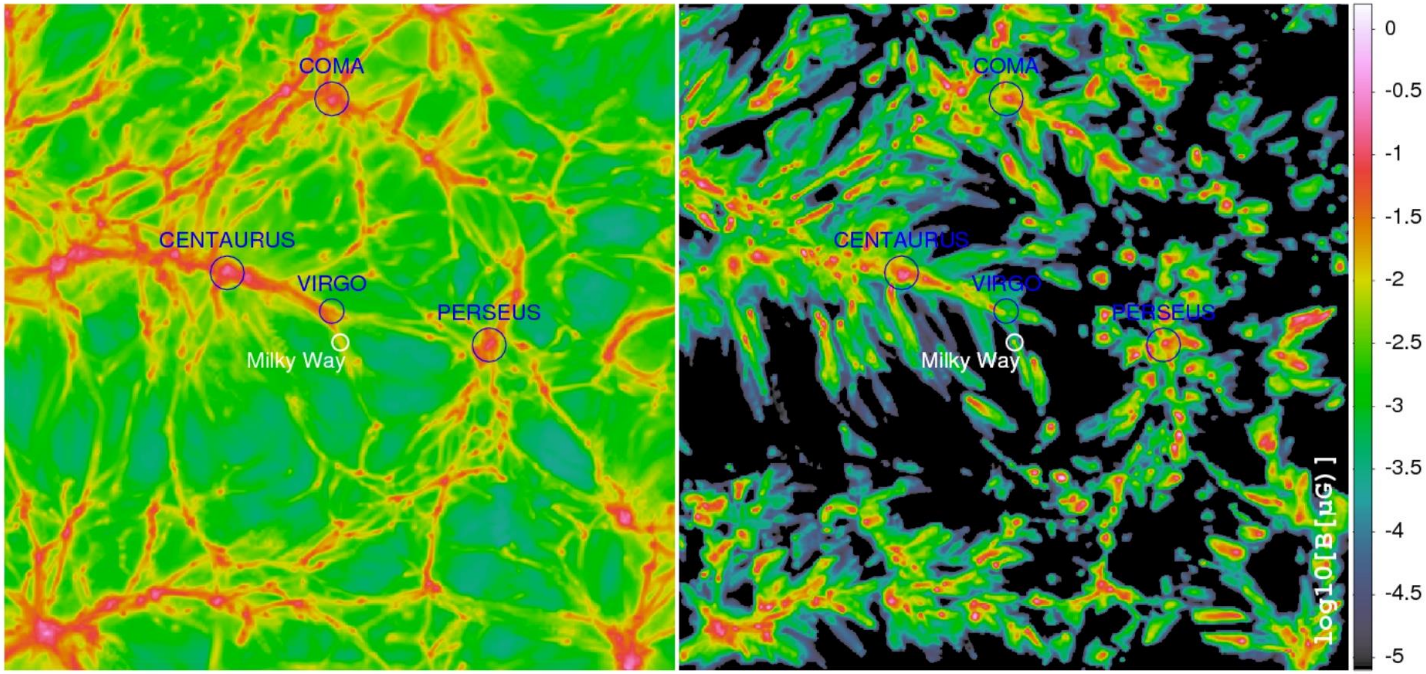
A.Neronov, D.S. and O.Kalashev, 2112.08202

Deflection of UHECR C, He and p with 25 EeV energy by JF12 GMF



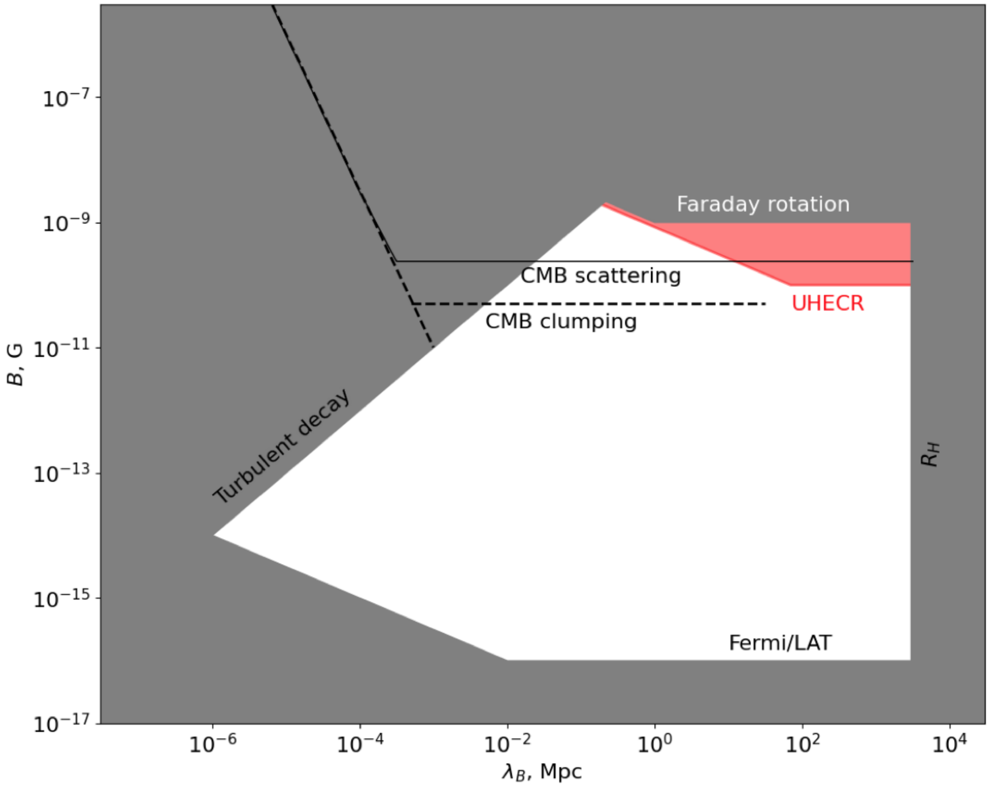
A.Neronov, D.S. and O.Kalashev, 2112.08202

Primordial IGMF and MF from astrophysical processes



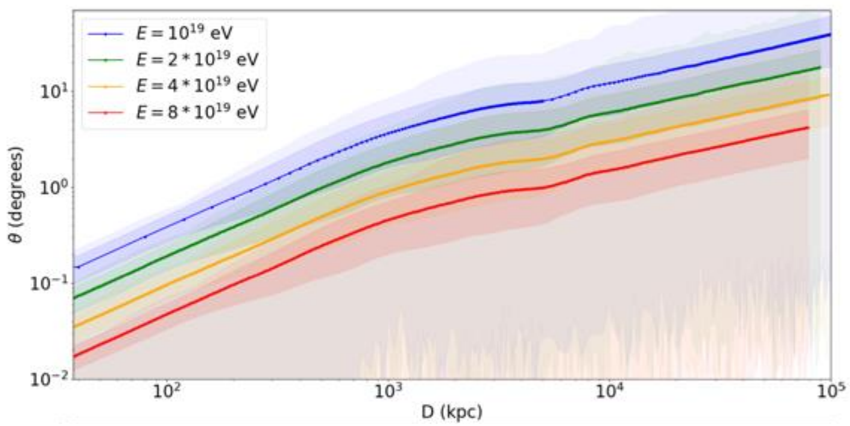
S. Hackstein et al, **MNRAS (2017) 1-11**, [1710.01353].

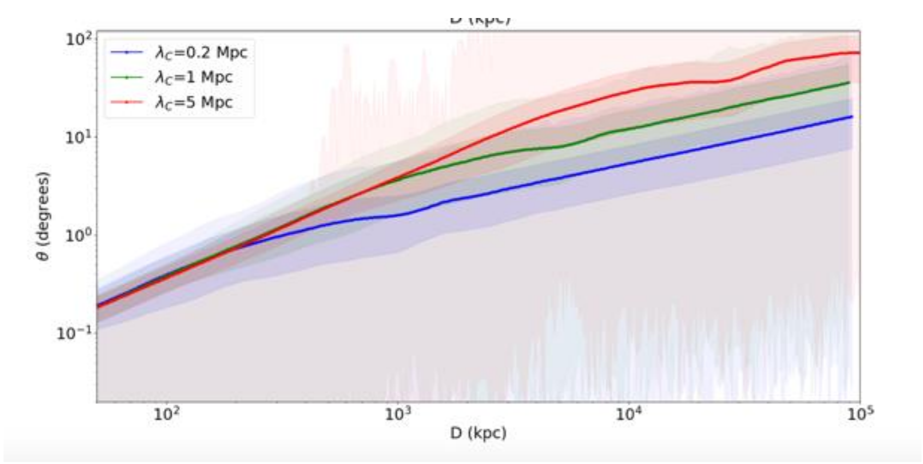
Limit on IGMF in Taurus void from UHECR observations



A.Neronov, D.S. and O.Kalashev, 2112.08202

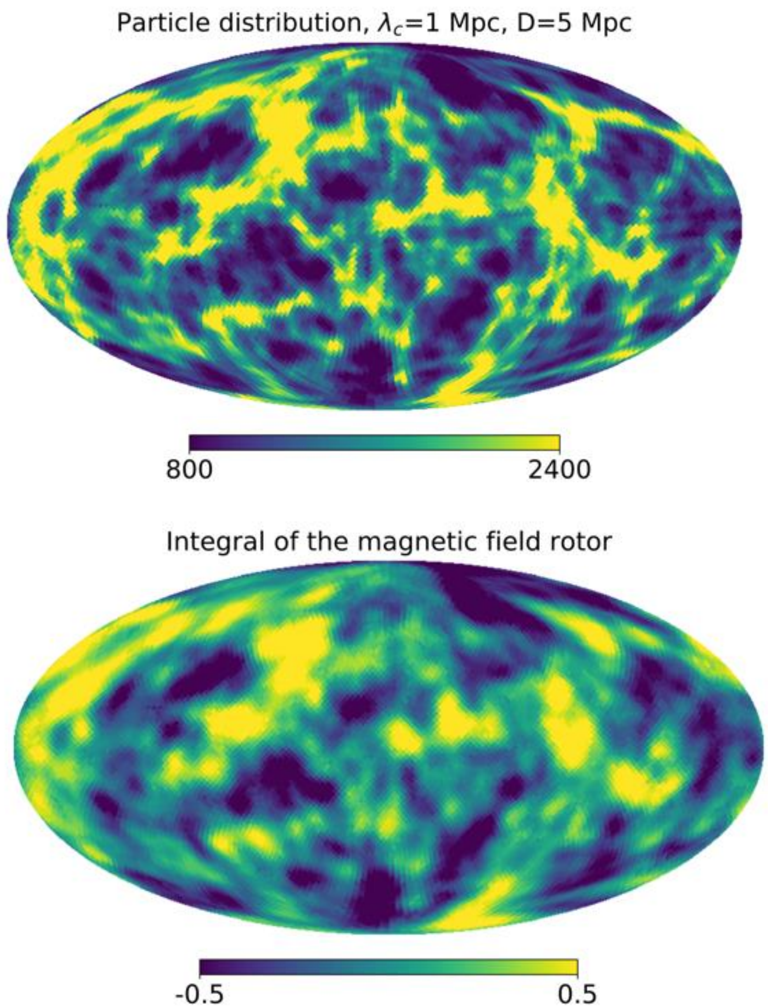
UHECR propagation in IGMF





$$\theta \sim 4^\circ \, Z \frac{B}{\mathrm{nG}} \, \frac{10 \ \mathrm{EeV}}{E} \sqrt{\frac{D}{\mathrm{Mpc}}} \sqrt{\frac{\lambda_C}{\mathrm{Mpc}}}$$

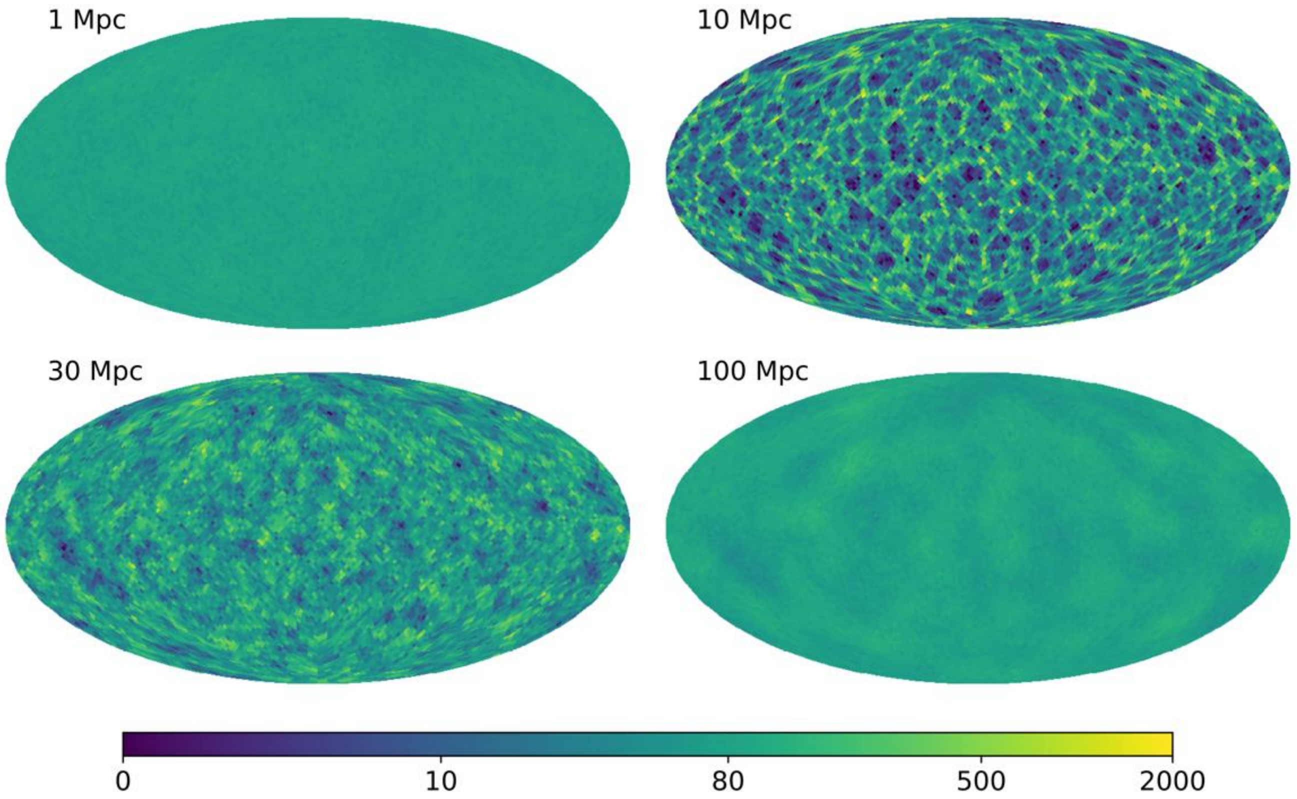
UHECR propagation in IGMF: caustics



$$A(D) = A_0 \left(1 - \frac{Ze}{E} \int_0^D (D - s) \, (\mathrm{rot}\vec{B} \cdot \mathrm{d}\vec{s}) \right) \quad ($$

A.Dolgikh, A.Korochkin, G.Rubtsov, D.S. and I.Tkachev, 2212.01494

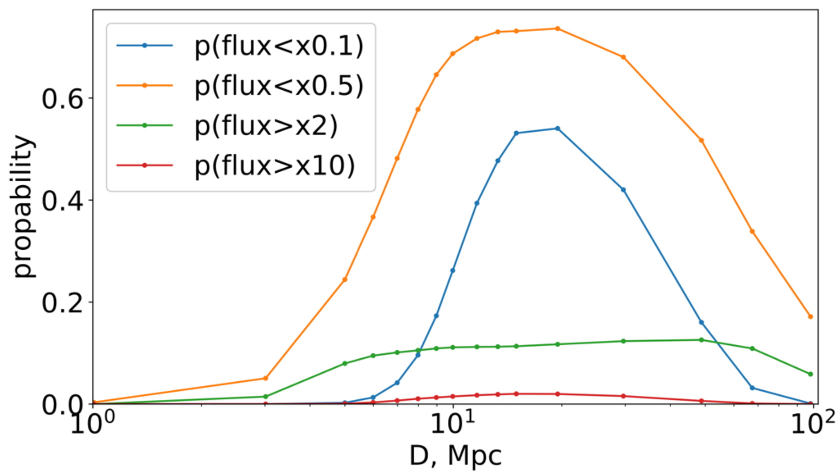
UHECR propagation in IGMF: caustics



Lambda=0.3 Mpc R=10 EV

A.Dolgikh, A.Korochkin, G.Rubtsov, D.S. and I.Tkachev, 2212.01494

UHECR propagation in IGMF: caustics



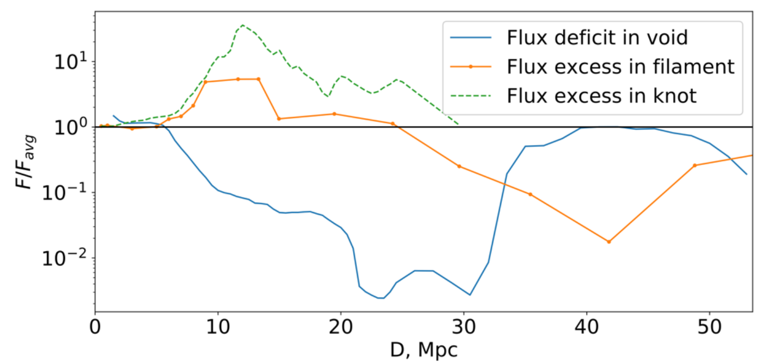
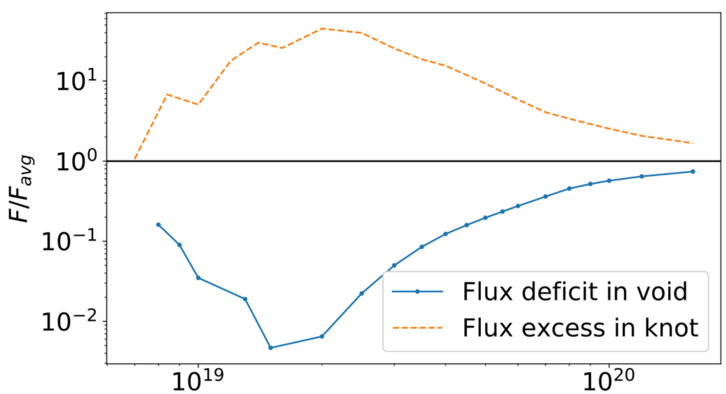
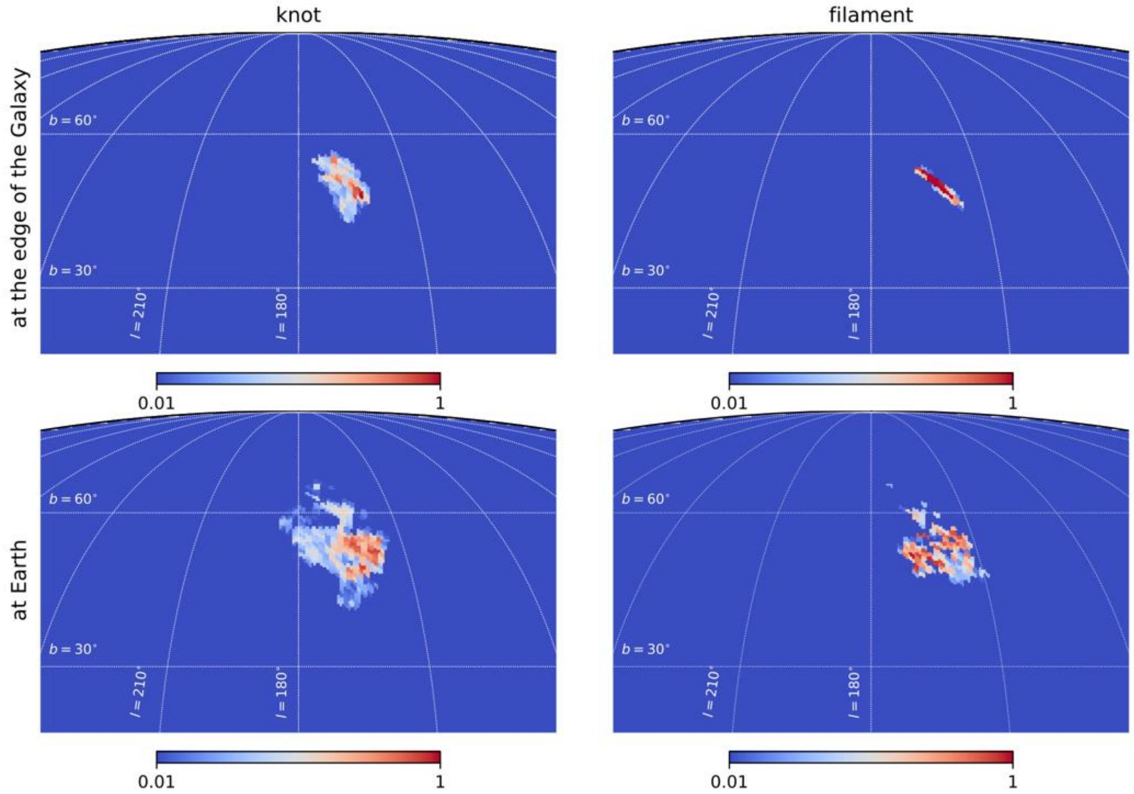


Fig. 2. Example of the relative flux excess and deficit as function of the distance to the source for the particles with the rigidity of $E = 10$ EV. For this figure we define magnetic void, filament and knot at the distance of 10 Mpc.



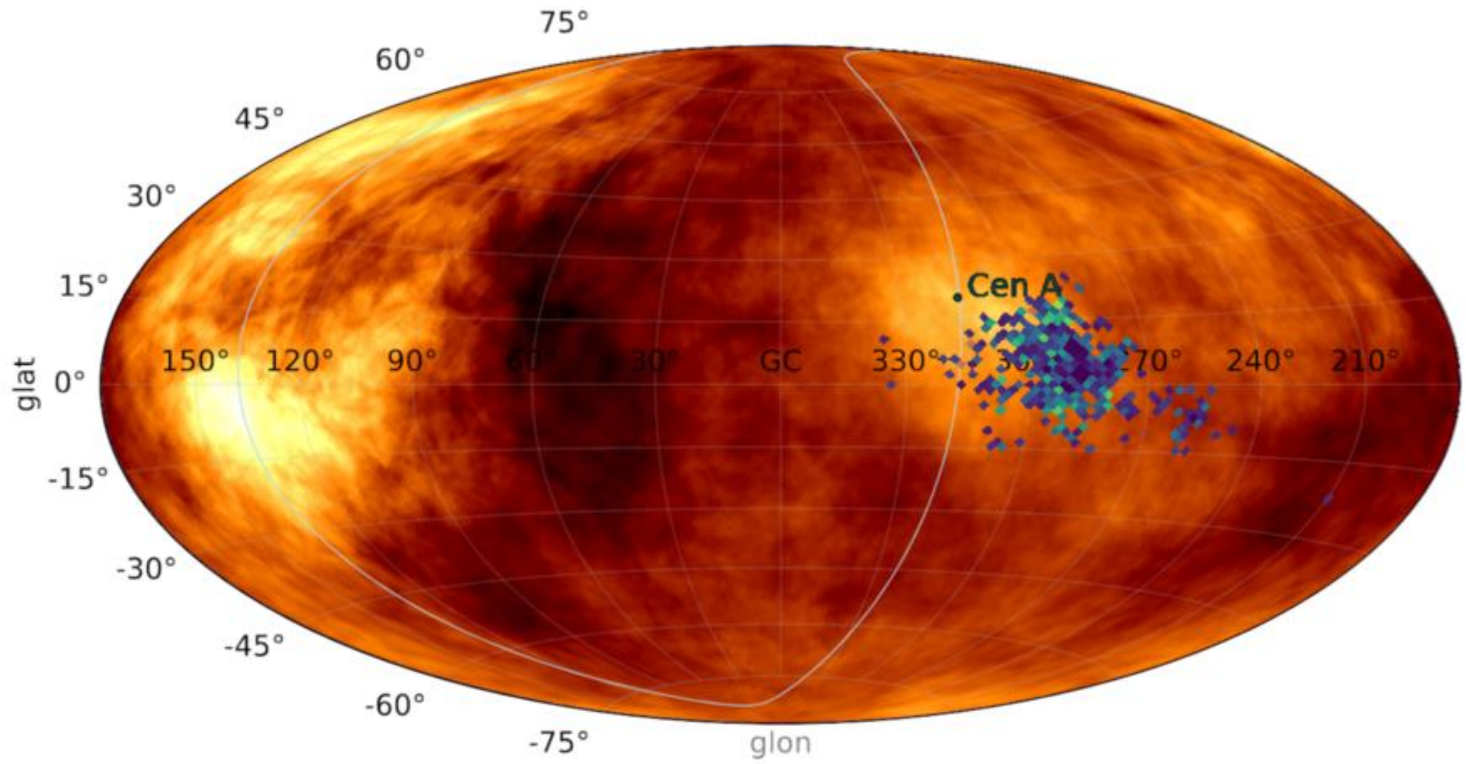
A.Dolgikh, A.Korochkin, G.Rubtsov, D.S. and I.Tkachev, 2312.06391

UHECR source in TA hot spot



A.Dolgikh, A.Korochkin, G.Rubtsov, D.S. and I.Tkachev, 2312.06391

Cen A flux is shifted in JF12 model



K.Dolgih, A.Korochkin, G.Rubtsov, D.S. and I.Tkachev, to appear arXiv:2502…

M83 is of for JF model

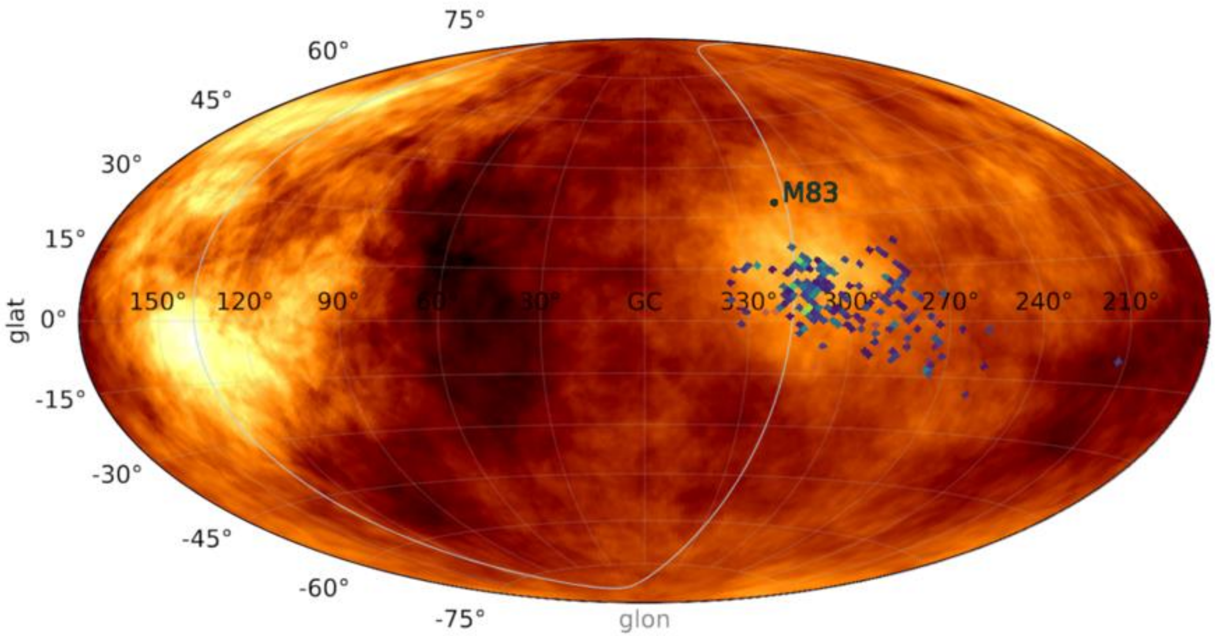
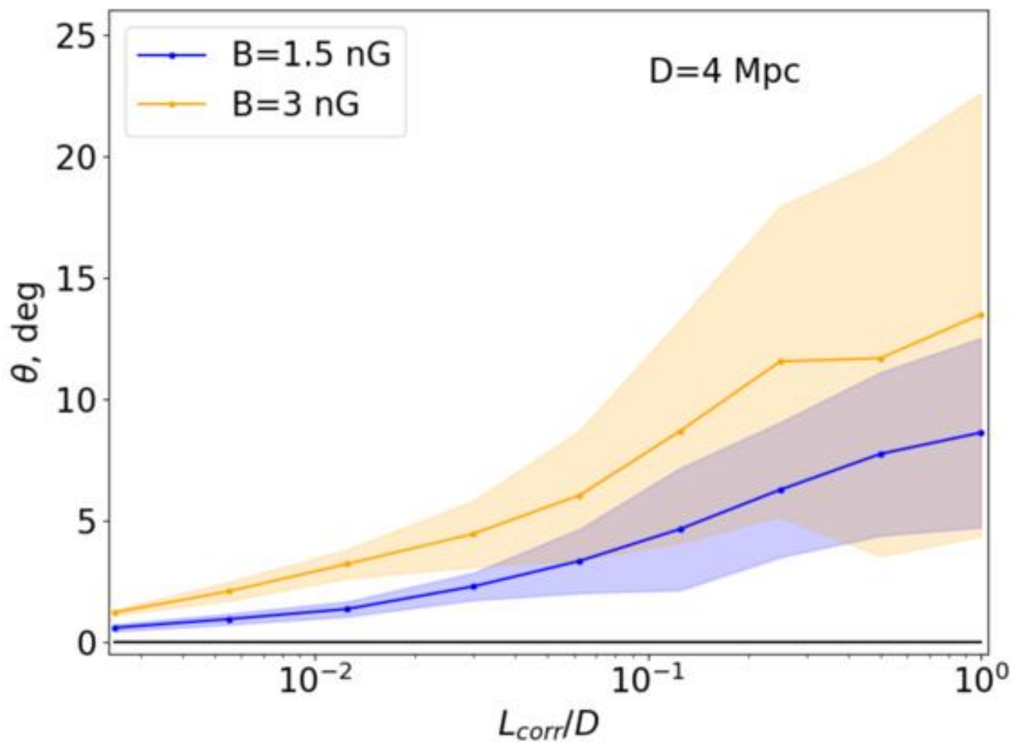


FIG. 3. Arrival directions of the carbon nuclei with $E = 60$ EeV from M 83 for the same magnetic fields and as Fig. 2.

K.Dolgih, A.Korochkin, G.Rubtsov, D.S. and I.Tkachev, to appear arXiv:2502…

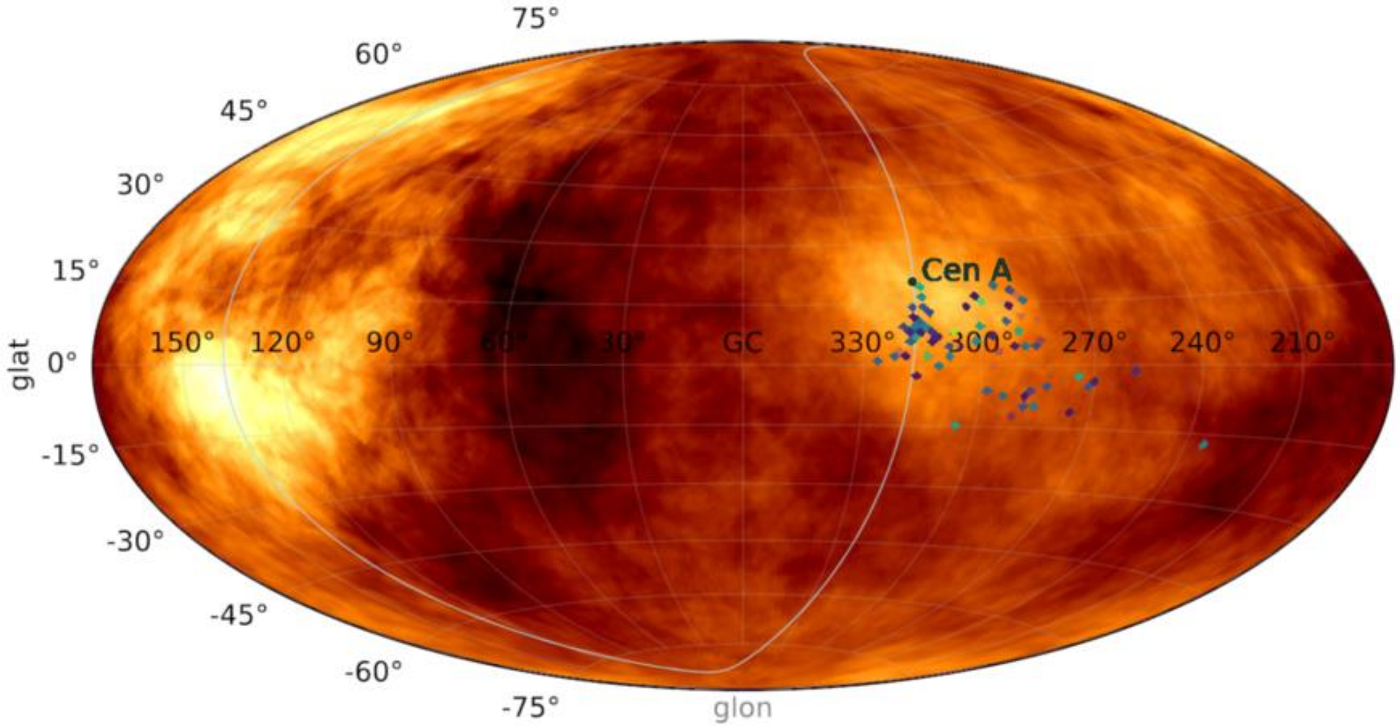
Cen A source: Cen A and IGMF with tiny coherence length

R=10 EV



K.Dolgih, A.Korochkin, G.Rubtsov, D.S. and I.Tkachev, to appear arXiv:2502…

Cen A back to place due to IGMF



K.Dolgih, A.Korochkin, G.Rubtsov, D.S. and I.Tkachev, to appear arXiv:2502…

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*
- *UHECR deflections are strongly GMF-dependent*
- *UHECR source observations are affected by caustics for R<100 Mpc in case Lambda = 1 Mpc*
- *We need more efforts both on GMF and IGMF studies to find out UHECR sources*