Cosmic voids of the Universe Large Scale Structure: finding, population, active galactic nuclei and magnetic fields

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Void finders

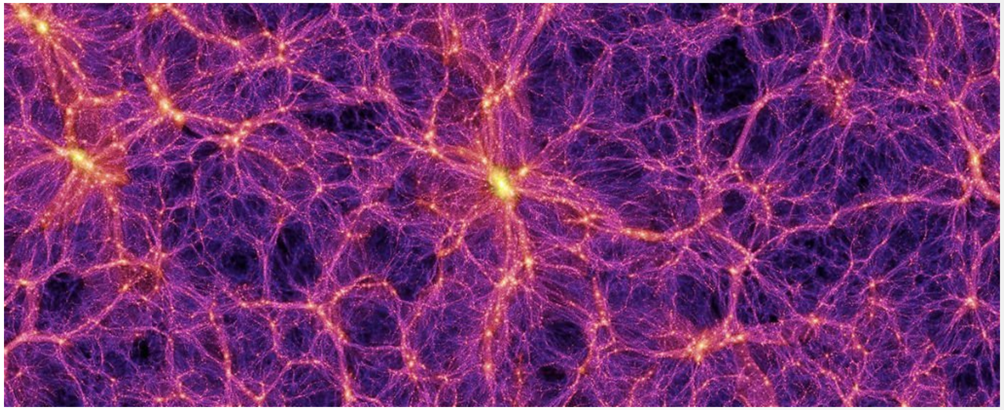
Cosmic voids are regions in the Universe with small concentration of matter.

Main three classes of void finders:

1. It's based on a **density criterion** and defines voids as regions empty of galaxies or with density well below the mean. (Colberg et al. 2005; Brunino et al. 2007; Elyiv et al. 2013)

2. It uses **geometry criteria** and identifies voids as geometrical structures like spherical cells, polyedra, etc. (Platen et al. 2007; Neyrinck 2008, ZOBOV; Leclercq et al. 2014)

3. It's based on **dynamical criteria** in which galaxies are considered as test particles of the cosmic velocity field. (Hahn et al. 2007; Lavaux & Wandelt 2010)



The disadvantages of the first and second void finder classes:

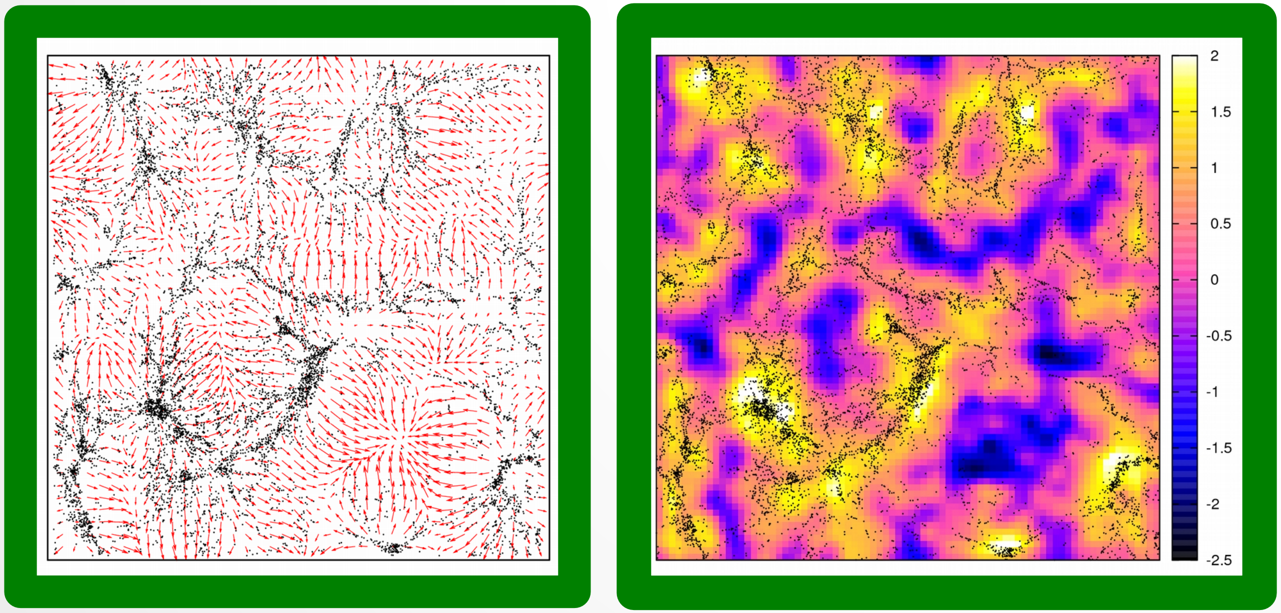
1. Galaxies are used as mass tracers and some biasing prescription has to be adopted to specify the relation between the galaxy and the mass density field.
2. By definition, voids are the low-density regions. Any method that uses galaxies to identify voids is then prone to shot noise error.

Main advantage of void finders of the third class is that they can be defined in Lagrangian coordinates, which greatly alleviates the shot noise problem and eases the theoretical interpretation of the results.

Dynamical and uncorelated void finders

In work by *Elyiv, A., Marulli, F., Pollina, G., et al. 2015, MNRAS, 448, 642* we proposed two void finders that are based on dynamical criterion to select voids in Lagrangian coordinates and minimize the impact of sparse sampling.

1. **Uncorrelated Void Finder** (UVF) uses the observed galaxy - galaxy correlation function to relax the objects' spatial distribution to homogeneity and isotropy.
2. **Lagrangian Zeldovich Void Finder** (LZVF) exploits the Zel'dovich approximation to trace back in time the orbits of galaxies located in voids and their surroundings.



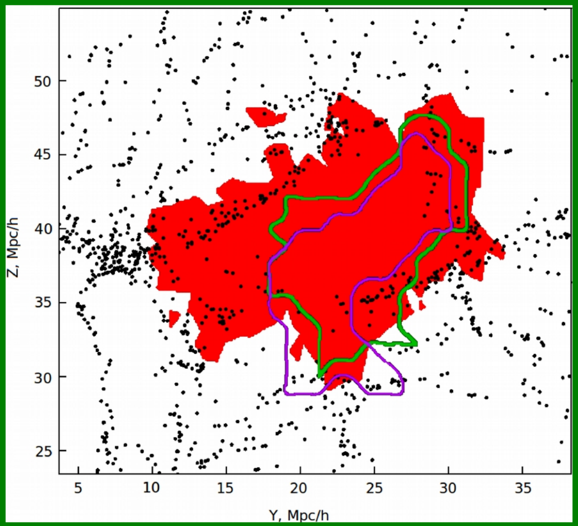
The reconstructed displacement field (left panel) and its divergence (right panel), obtained with the UVF finder.

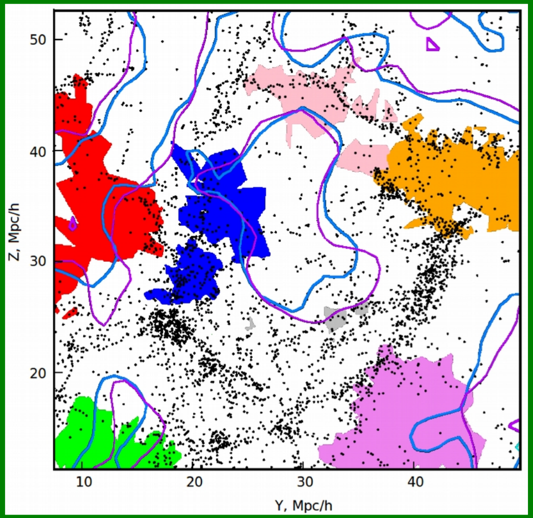
Dynamical and uncorrelated void finders

In our approach voids are defined as regions of the negative velocity divergence, which can be regarded as sinks of the back-in-time streamlines of the mass tracers.

The significance of the divergence signal in the central part of voids obtained from both our finders is 60% higher than for overdensity profiles in the modern ZOBOV finder.

The ellipticity of the stacked void measured in the divergence field is closer to unity, as expected, than what is found when using halo positions.





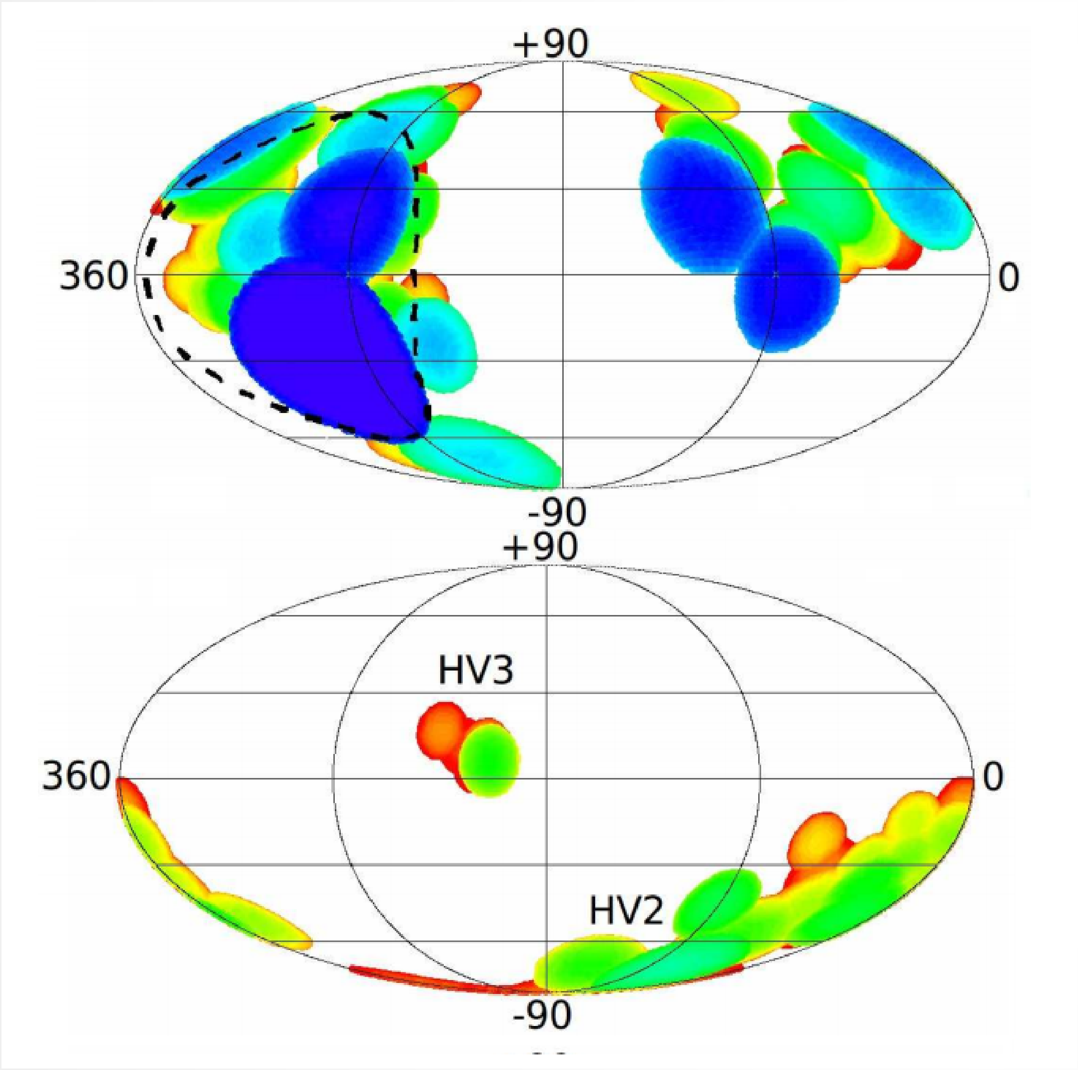
Zoom of two regions of the slice. Thick and thin lines show the shapes of voids selected by UVF and LZVF finders, respectively. Filled colored areas show the voids found by ZOBOV. The underdense regions selected by UVF and LZVF appear always similar.

Voids of Local Universe

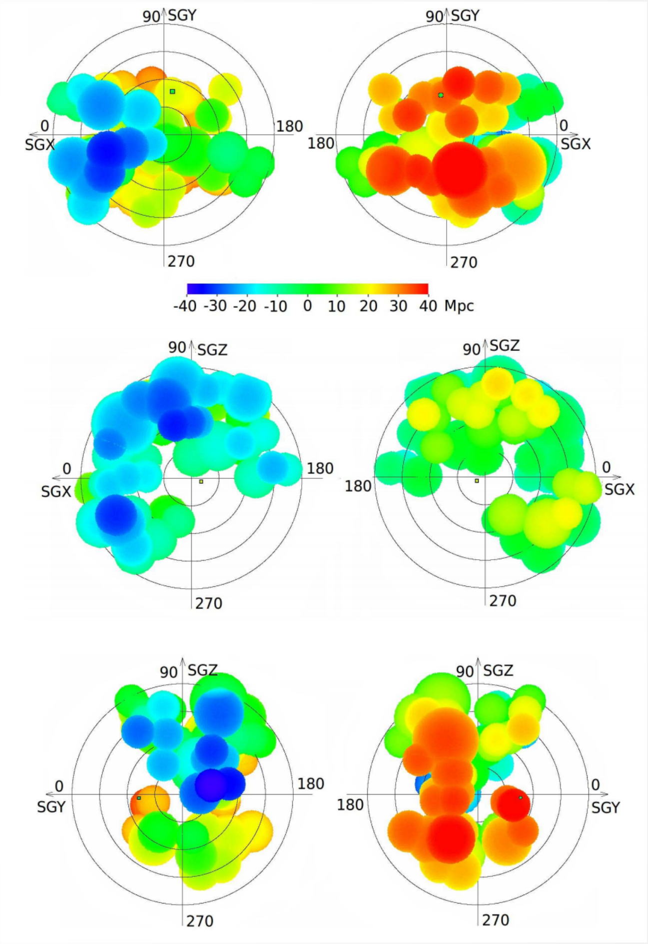
- Within a distance of 40 Mpc from us, 89 spherical cosmic voids were discovered with the diameters of 24 to 12 Mpc, containing no galaxies with absolute magnitudes brighter than the Magellanic Clouds, $M_K < -18.4$.
- We found that 93% of spherical voids overlap, forming three more extended percolated voids, called hypervoids.
- The largest of them, HV1, has 56 initial spherical cells and extends in a horseshoe shape, enveloping the Local Volume and the Virgo cluster.
- The total volume of these voids incorporates about 30% of the Local Universe.
- Among 2906 dwarf galaxies excluded from the original sample (n = 10502) in the search for spherical volumes, only 68 are located in the voids we have discovered.
- The dwarf population of the voids shows a certain tendency to sit shallow near the surfaces of cosmic voids.

Elyiv A., Karachentsev I., Karachentseva V., Melnyk O., Makarov D., 2013, Astrophysical Bulletin, 68, 1

Voids and hypervoids in Local Universe

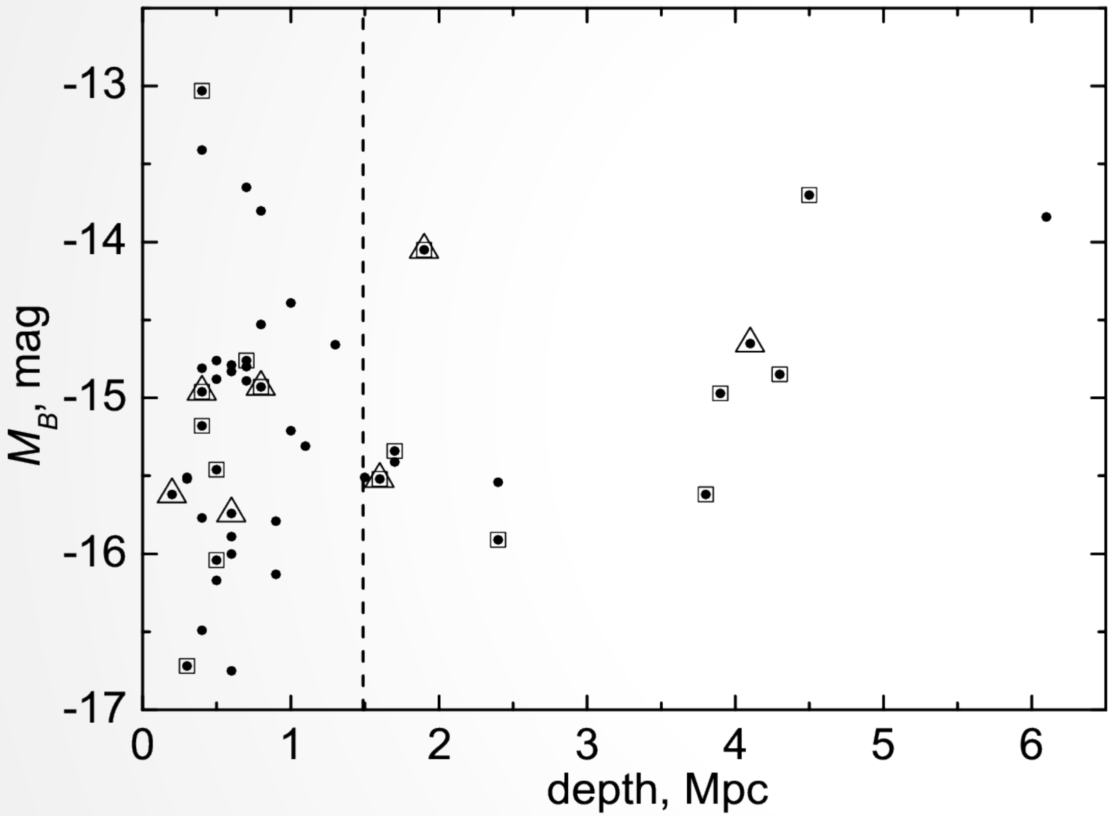


Distribution of voids projected on the sky in the equatorial coordinate system: the HV1 hypervoid (the top panel), the HV2 and HV3 hypervoids (the upper panel). The sizes of the circles correspond to the actual angular scales of voids. Colors show the distances to the surface of voids.



Projection of the HV1 hypervoid on the supergalactic SGX–SGY plane (the top panel), SGX–SGZ (the middle panel), SGY–SGZ (the bottom panel). The view from the negative (left) and positive (right) directions of the Z, Y, X axes is shown in three panels, respectively. Colors show the distances to the supergalactic plane.

Void population



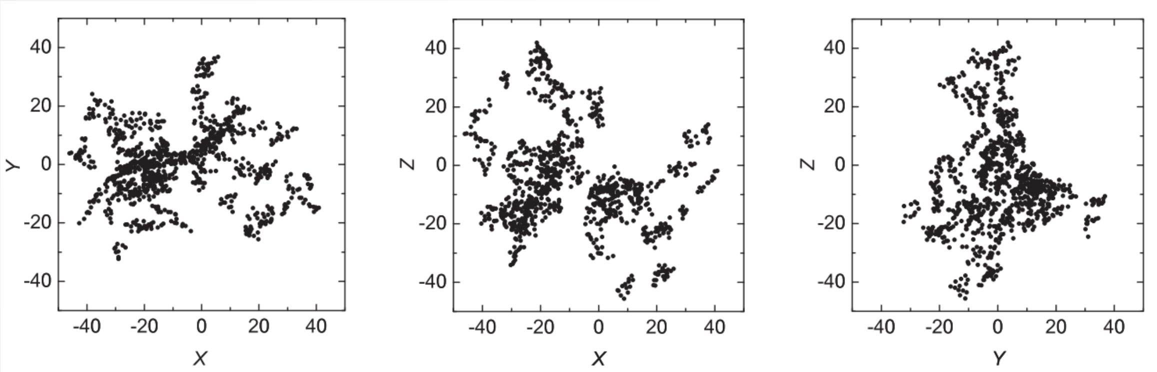
Distribution of 48 dwarf galaxies in the nearby (D < 40 Mpc) voids by absolute magnitude MB and the bedding depth under the surface of hypervoid.

- majority of void galaxies located under void surface <1.5 Mpc;
- only 40% are also isolated;
- 85% are Ir, Im, BCG, Sm;
- gas reserves per luminosity unit in 2-3 times larger $M_{HI}/L_B = 2.1\ M_\odot/L_\odot$ for the same types from other environments
- The galaxies in voids are bluer and fainter than those in denser environments.

Galaxy agglomerates

- Above 42% of Local Universe do not belong to pairs, groups or clusters.
- We applied percolation clustering and found 226 diffuse agglomerates with more 4 members.
- These non-virialized agglomerates are characterized by a median dispersion of radial velocities ~ 170 km/s, the linear size ~ 6 Mpc, integral K-band luminosity of 3×10^{11} L⊙, and a formal virial-mass-to-luminosity ratio of about 700 M⊙/L⊙.
- The mean density contrast for the considered agglomerates is only ∼ 5, and their crossing time is about 30 - 40 Gyr.

Karachentsev I., Karachentseva V., Melnyk O., Elyiv A., Makarov D., 2012, Astrophysical Bulletin, 67, 353



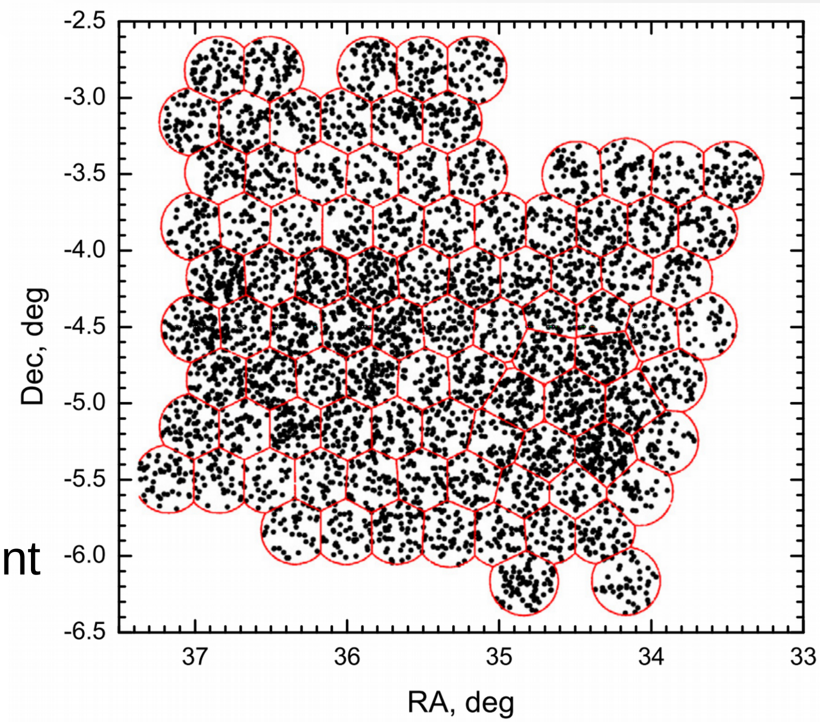
The spatial distribution of members of the low density agglomerates with n ≥ 10 presented in three planes of equatorial Cartesian coordinates (in Mpc).

Active Galaxy Nuclei and Large Scale structure

X-ray surveys constitute an important part of LSS surveys due to the weak absorption at such high energies.

More than 95% of all detected objects in X-ray surveys away from the galactic plane are Active Galactic Nuclei (AGN).

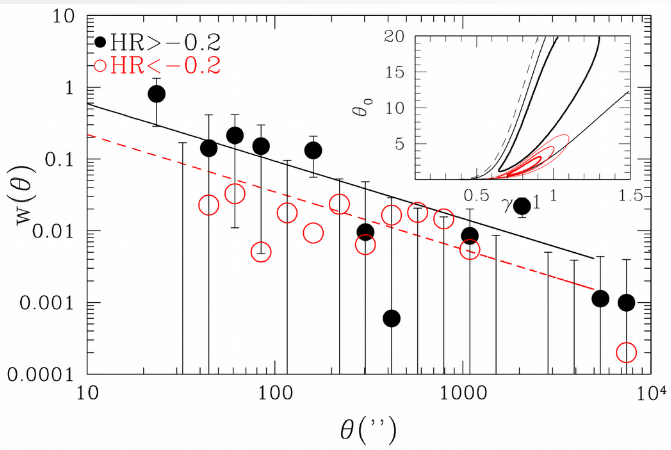
Owing to their high X-ray luminosity, AGN can be detected over a wide range of redshifts in contrast to normal galaxies, till z=4. These objects are excellent tracers of the cosmic web and voids.



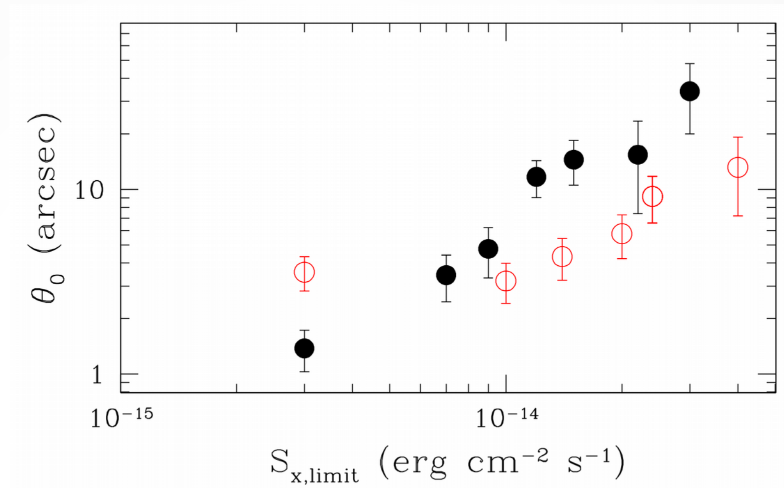
In work *Elyiv A., Clerc N., Plionis M., et al. 2012, A&A, 537, A131* we studied the large-scale structure of different types of AGN using the medium-deep XMM-LSS survey.

We measured the two-point angular correlation function of ∼ 5700 and 2500 X-ray point-like sources over the ∼ 11 sq. deg. field in the soft (0.5-2 keV) and hard (2-10 keV) bands.

Active Galaxy Nuclei and Large Scale structure

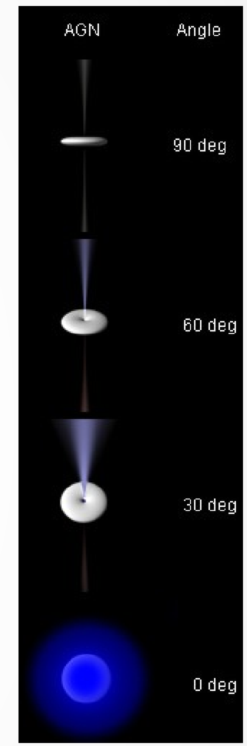


Amplitude of angular correlation function for the XMM-LSS sample in the soft band for sources with HR > −0.2 (filled circles, hard-spectrum AGN), and for sources with HR < −0.2 (open circles; soft-spectrum AGN).



Best-fit correlation length θ_0 vs the flux limit of AGN sample in the soft (filled circles) and the hard bands (open circles).

AGN types



type 2, obscured, hard-spectrum

type 1, unobscured, Soft-spectrum

Blazar

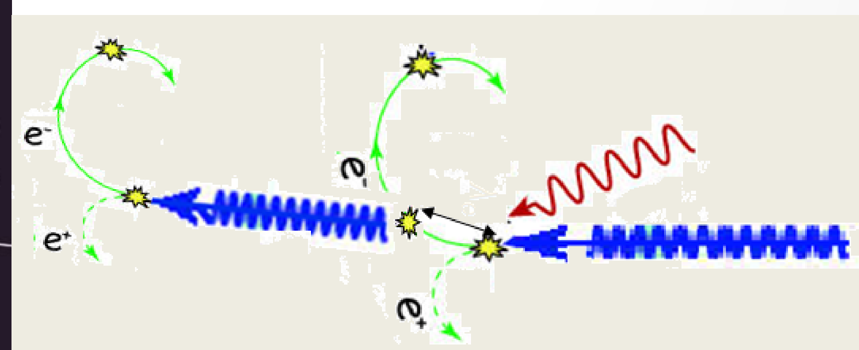
- We confirm that the clustering strength θ_0 grows with the flux limit of the sample, a trend which is also present in the amplitude of the spatial correlation function, but only for the soft band. It means that faint AGN prefer reside in less dense regions.
- Our analysis of AGN subsamples with different hardness ratios shows that the sources with a hard-spectrum are more clustered than soft-spectrum ones. This result may be a hint that the two main types of AGN populate different environments. AGN with soft spectrum are located more closer to void borders than with hard spectrum.

High energetic processes in voids.

Depending on the model, the predictions of the typical strength of the magnetic field in the cosmic voids range from 10^{-20} G up to 10^{-9} G, from the limit on rotation measure of emission from distant quasars, from the analysis of anisotropies of the cosmic microwave background.

Gamma-ray observations could, in principle, be used to constrain properties of the MF using the imaging and/or timing of the γ-ray signal.

Electro-magnetic cascade: γ-rays from **Blazar** (class of energetic AGN which emit a relativistic jet that is pointing toward observer) interact with the infrared/optical background photon producing secondary electrons and positrons. Which deflect in weak cosmic void magnetic field and emit secondary rays via inverse Compton scattering of CMB photons. Some of them with $E_\gamma > 1$ MeV produce e^+e^- and so on.



Cosmic void: magnetic field, CMB, infrared background

Blazar:
TeV photons

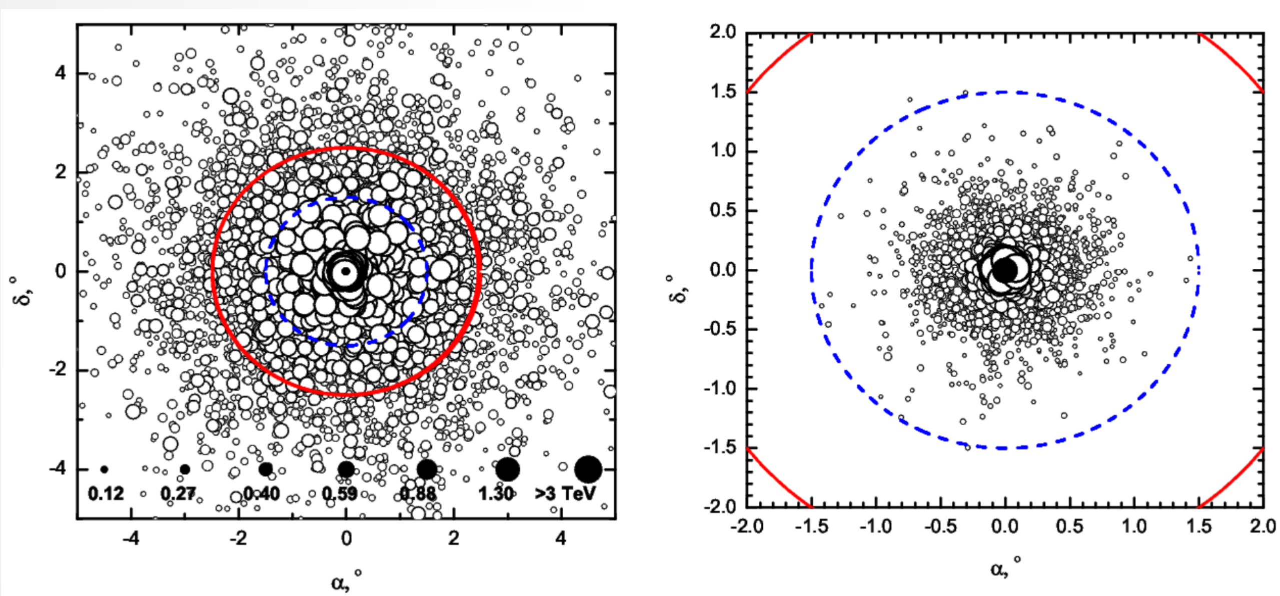
Elyiv A., Neronov A., & Semikoz D. 2009, Phys.Rev.D., 80, 023010

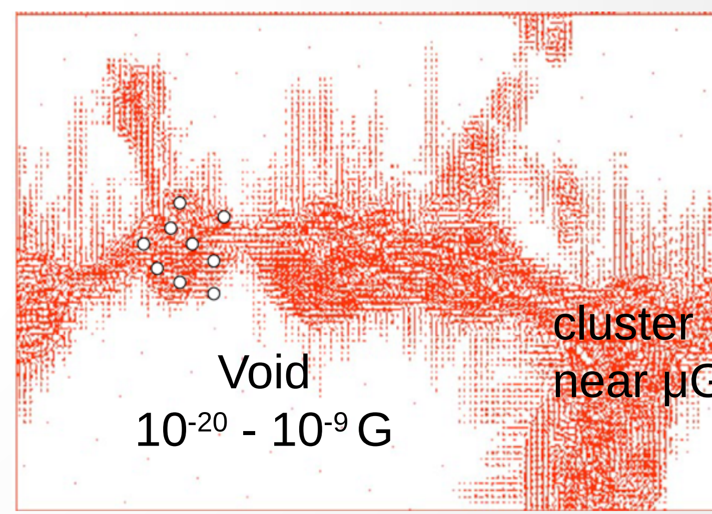
Electro-magnetic cascades from blazar and measurement magnetic field in voids.

The stronger magnetic field, the more deflection of e+e-, the more extended observed halo in TeV energies. Strong magnetic field in galaxy clusters (a few μG) scatters e+e- pairs and destroys electro-magnetic cascade.

Therefore weak magnetic fields in voids and its volume filling factor matter.

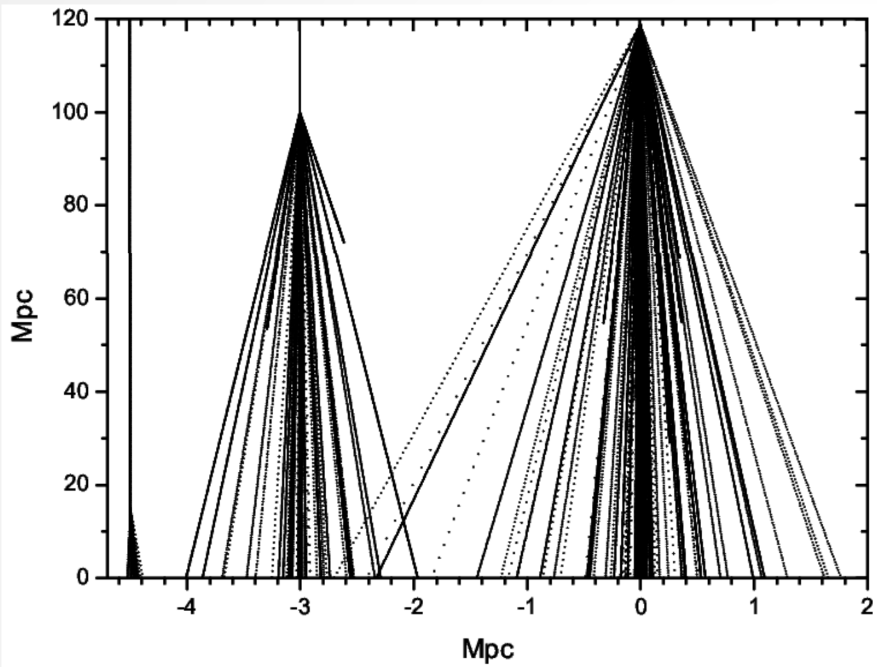
Reconstruction of cosmic void magnetic filed on the base of the halos observations around TeV-blazars, surface brightness profile, spectrum, morphology is possible.



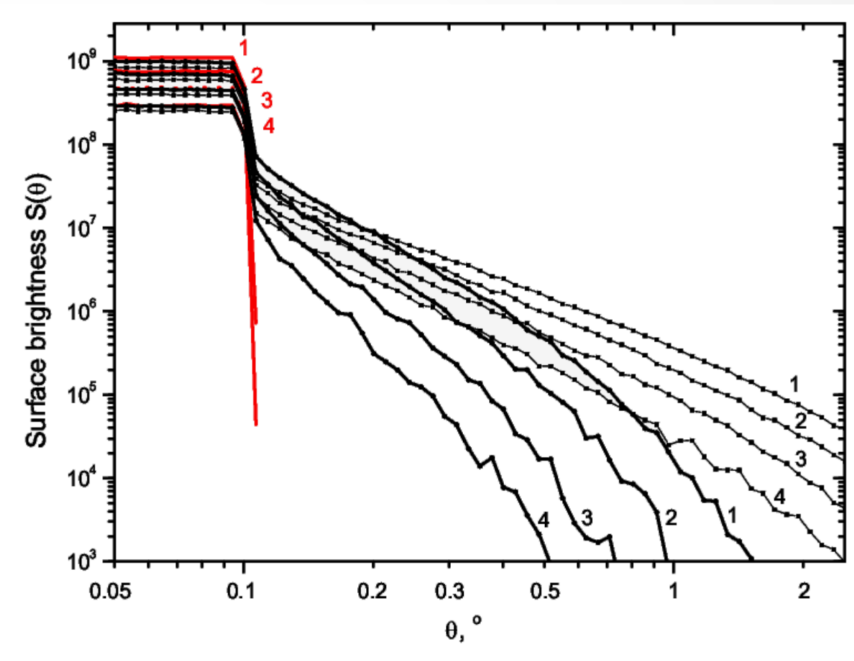


The arrival directions of the primary and secondary cascade γ-rays (circles) from a blazar at a distance D = 120 Mpc. The MF strength is 10^{-14} G (left panrl) and 10^{-15} G (right panel). The sizes of the circles representing each photon are proportional to the photon energies. The blue dashed circle has radius 1.5°, equal to the radius of the FoV or MAGIC telescope. The radius of the blue solid circle is 2.5°, which corresponds to the size of the FoV of HESS telescope.

Electro-magnetic cascades from blazar and measurement magnetic field in voids.

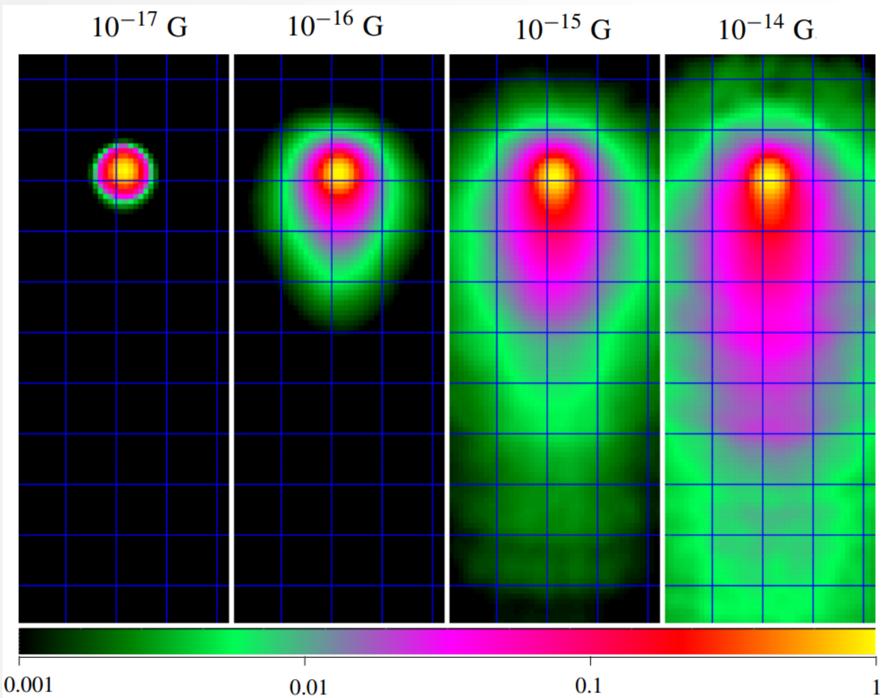


Examples of showers from γ-photons with different primary energies 10 (left), 30 (middle) and 100 TeV (right) in EGMF 10^{-15} G.



Surface brightness profiles of emission in different energy bands (1 – 0.10-0.12 TeV, 2 – 0.12-0.18 TeV, 3 – 0.18-0.27 TeV, 4 – 0.27-0.40 TeV) produced by the cascades in MF of the strength 10^{-14}G (thin lines) and 10^{-15}G (thick lines) and without magnetic field (red lines)

Electro-magnetic cascades from blazar and measurement magnetic field in voids.



E > 1 GeV band images of the sky region around TeV blazars with jet opening angle 3° and sight of light offset 3°. From left to right, void magnetic filed: 10^{-17}, 10^{-16}, 10^{-15}, 10^{-14} G.

- The brightness profile of degree-scale observed halo can be used to infer the lightcurve of the primary TeV γ-ray source over the past 10^7 yr, comparable to the life-time of the parent AGN. This implies that the degree-scale jet-like GeV emission could be detected also from “TeV blazar remnants”.
- The brightness profile of the GeV “jets” depends on the strength and the structure of the magnetic filed of cosmic voids on the light of sight, their observation provides additionally information about the MF.

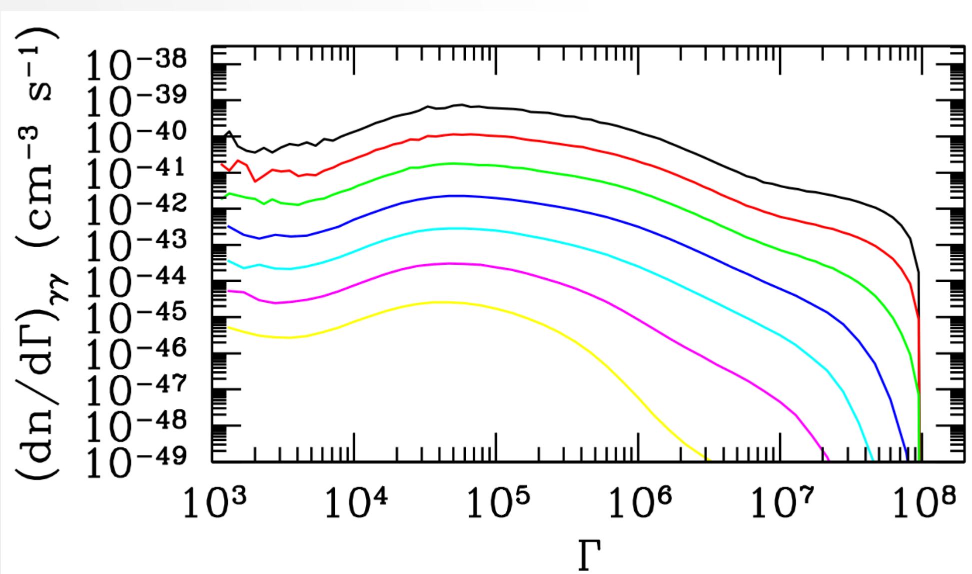
Neronov A., Semikoz D., Kachelriess M., Ostapchenko S., Elyiv A. 2010, The Astrophysical Journal Letters,, 719, L130

Properties and stability of electro-magnetic cascade in voids.

- In work *Miniati F., Elyiv A., 2013, ApJ, 770, 54* we analyzed the stability properties of a low density ultra relativistic pair beam as part of electro-magnetic cascade produced by multi-TeV gamma-ray photons from blazars.

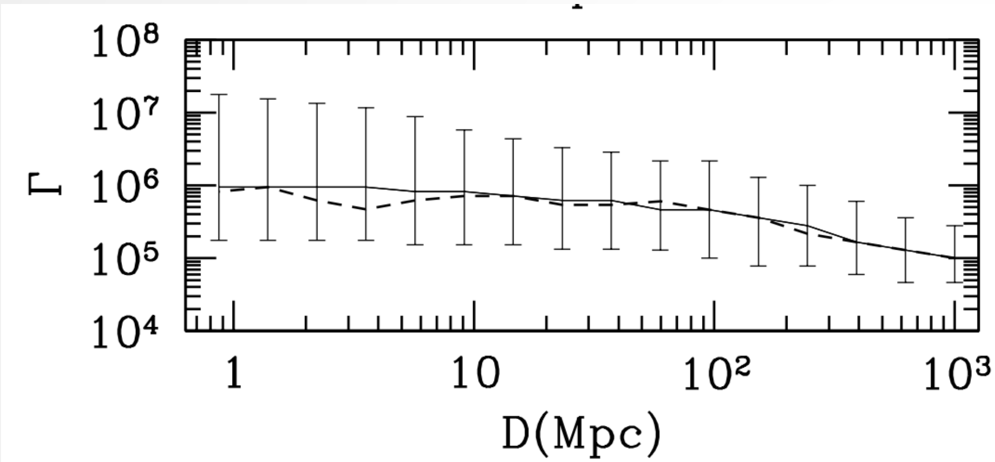
- Dissipation of such beams could affect considerably the thermal history of intergalactic medium. The problem is important for probes of magnetic field in cosmic voids through gamma-ray observations.

- We use a Monte Carlo method to quantify the properties of the blazar induced electromagnetic shower, in particular the bulk Lorentz factor and the angular spread of the pair beam generated by the cascade, as a function of distance from the blazar itself.

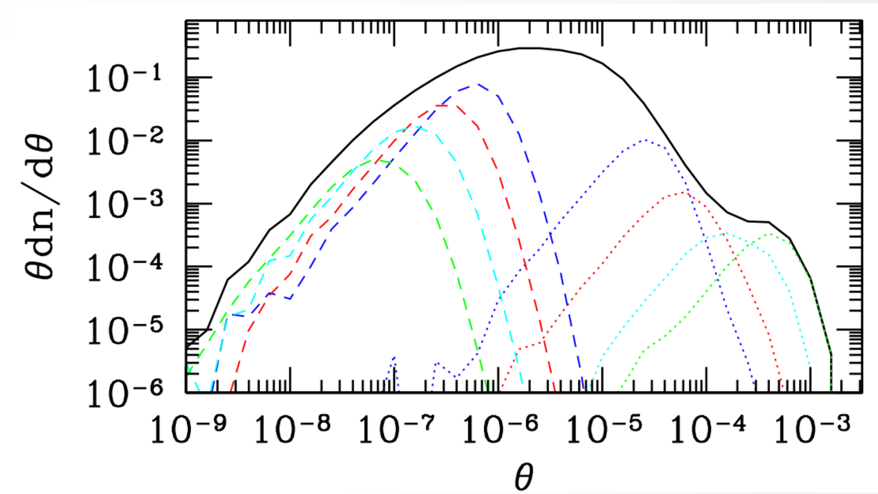


Energy distribution of the beam pairs generated at distances, from top to bottom, of 3.5 (black), 9.1 (red), 23.3 (green), 60 (blue), 153 (cyan), 390 (magenta), and 1000 (yellow) Mpc from a blazar with equivalent isotropic gamma-ray luminosity of 10^{45} erg s^{-1}.

Properties and stability of electro-magnetic cascade in voids.



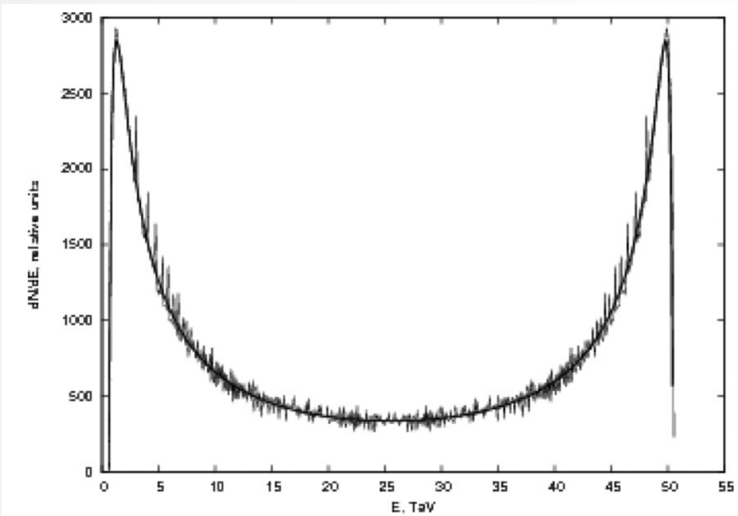
Peak (dash) and mean (solid) pair beam energy as a function of distance from the blazar. Vertical bars correspond to 68% percentile of the energy spread about the median.

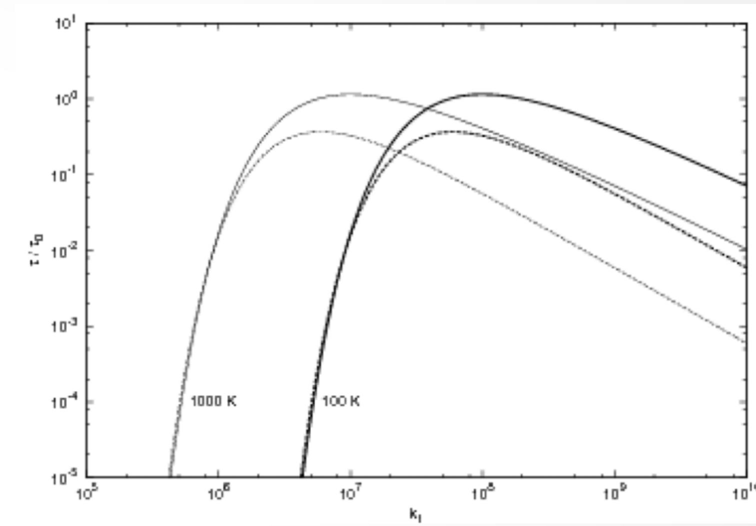


Angular distribution of beam pairs generated at 244 Mpc (solid), from the blazar. The colored curves indicate the contribution to the angular distribution from pairs in the energy range: from 1000 (dot green) to $2.15\times10^8\ m_e c^2$(dash green).

- Due to the effect of non-linear Landau damping, which suppresses the growth of plasma oscillations, the beam relaxation timescale is found significantly longer than the inverse Compton loss time.
- Density inhomogeneities associated with cosmic structure induce loss of resonance between the beam particles and plasma oscillations, strongly inhibiting their growth.
- We conclude that relativistic pair beams produced by blazars in the intergalactic medium are stable on timescales long compared to the electromagnetic cascade's.
- There are not significant effects of pair-beams on the intergalactic and especially cosmic voids medium.

Properties and stability of electro-magnetic cascade in voids.





Probability of a single gamma ray of energy 10^8 (51.1 TeV) being absorbed when interacting with monoenergetic isotropically distributed soft photons 2×10^{-7} (0.1 eV) of EBL. The analytical result from this work (thick line) agrees perfectly with the result from the numerical simulations (thin line) from Elyiv et al. 2009

Comparison of the analytical approximation of the optical depth (dashed lines) with the numerically calculated one (solid lines) for a Wien-type soft photon distribution with q = 2 and two temperatures TW = 100 and 1000 K

- In work *Schlickeiser R., Elyiv A., Ibscher D., Miniati F., 2012, ApJ, 758, 101* using limit that primary photons from Blazar in orders more energetic that background photons we analytically demonstrated that the angular distribution of the generated pairs from the double photon collision processes in the lab frame is highly beamed in the direction of the initial gamma-ray photons.

- We also analytically calculated a new the energy spectrum of the generated pairs from a monoenergetic beamed gamma ray interacting with a monoenergetic, gyrotropically and isotropically distributed soft photon distribution. It agrees perfectly with the earlier derived production spectrum of Aharonian et al. (1983) and with the numerically computed energy spectrum.

Main conclusions

- Two new void finders are created: dynamical LZVF based on Lagrangian Zeldovich approximation, and uncorrelated UVF based on the two-point correlation function properties. Both finders show more reliable results than contemporary ones.

- We extracted voids in the Local Universe and found that dwarf galaxies in voids reside not profound under surface (< 1.5 Mpc) and avoid its central regions.

- We found differences in environment type 2 and 1 AGN. The softer spectrum and fainter AGN, the closer is located to the void border.

- Analytical and numerical studies of high energetic processes in voids show that by gamma-ray halo observations around distant Blazars is possible to estimate magnetic field properties in voids, volume filling factor of voids and emission properties of Blazars.

- The stability properties of a low-density ultrarelativistic pair beam produced in the voids by multi-TeV gamma-ray photons from Blazars is proofed. There appears to be almost no effect of pair beams on the thermal history of intergalactic medium.

Publications: 22 articles.
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