CREDO in the multimessenger context (a simple cosmologist's perspective)

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Ultra-high energy cosmic rays (UHECRs) are extremely energetic subatomic particles (mostly protons, but also some heavier atomic nuclei)

CREDO aims at UHECR with extreme energies
> 10^20 eV – extremely rare and extremely difficult to be found by other methods

Possible physical sources of UHECR

- Do UHECRs exist at all? If not, this also carries a very meaningful physical information
  - Zevatrons: ultra-high energy cosmic accelerators; required: small size and strong magnetic field
- Non-acceleration models (physics outside of the standard model?)

While the source of UHECRs remains a mystery, so does the exact mechanism to accelerate particles to these high energies.

However, as UHECRs seem to have enough energy to escape the typical magnetic field of a spiral galaxy (i.e. our Mikly Way), it is mostly believed that UHECRs are of extragalactic origin.

Still, they MAY be of local origin (Solar System, Milky Way)… we never know.

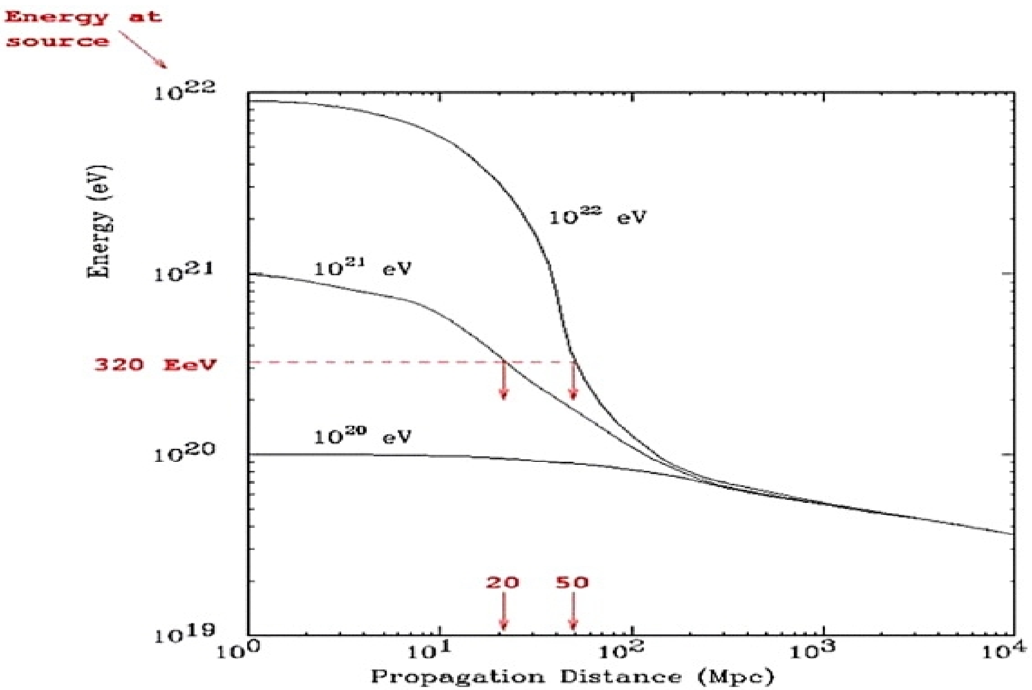
Greisen-Zatsepin-Kuzmin (GZK) limit

But if UHECRs are created in extreme extragalactic environments, a problem appears: how are we able to detect them at such high energies?

Above 5×10^{19} eV, cosmic rays should interact with the radiation of the cosmic microwave background, which should reduce the cosmic ray's energy and limit the free path of such UHECR to ~100 Mpc. This theoretical upper limit to the energy of a cosmic ray is called the Greisen-Zatsepin-Kuzmin limit (GZK limit).

Then, either it is not true, or cosmic rays arrive from distances closer than ~100 Mpc.

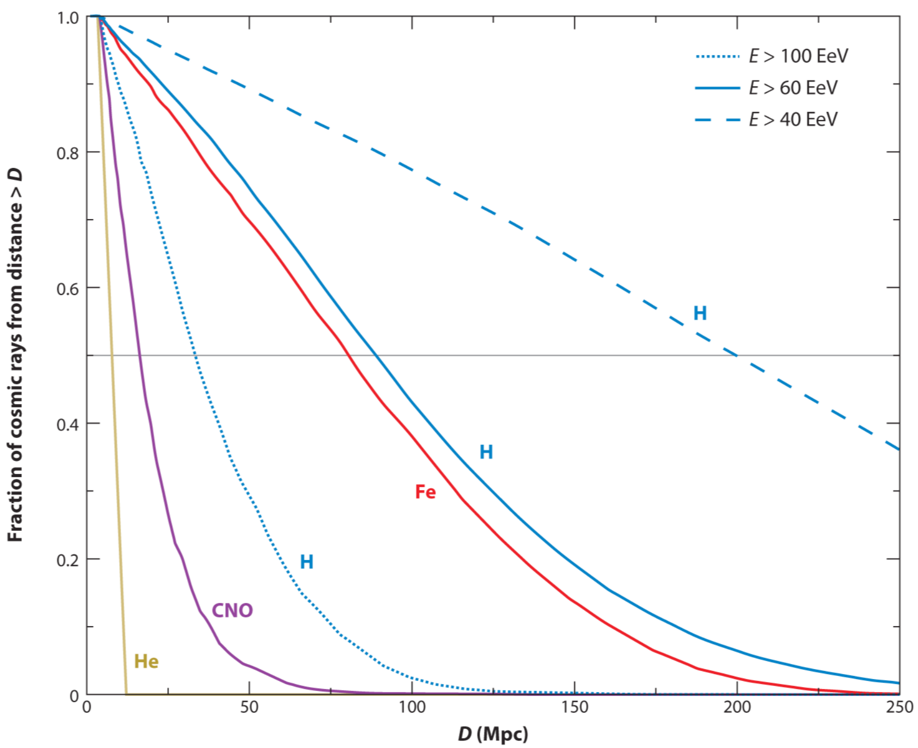
GZK limit: interactions with CMB will limit detectability of of UHECR to <100 Mpc



For high energy protons, the propagation distance does not exceed ~100 Mpc, and the exact value depends on its energy

Figure 3 from The cosmic ray energy spectrum as measured using the Pierre Auger Observatory
Giorgio Matthiae 2010 New J. Phys. 12 075009 doi:10.1088/1367-2630/12/7/075009

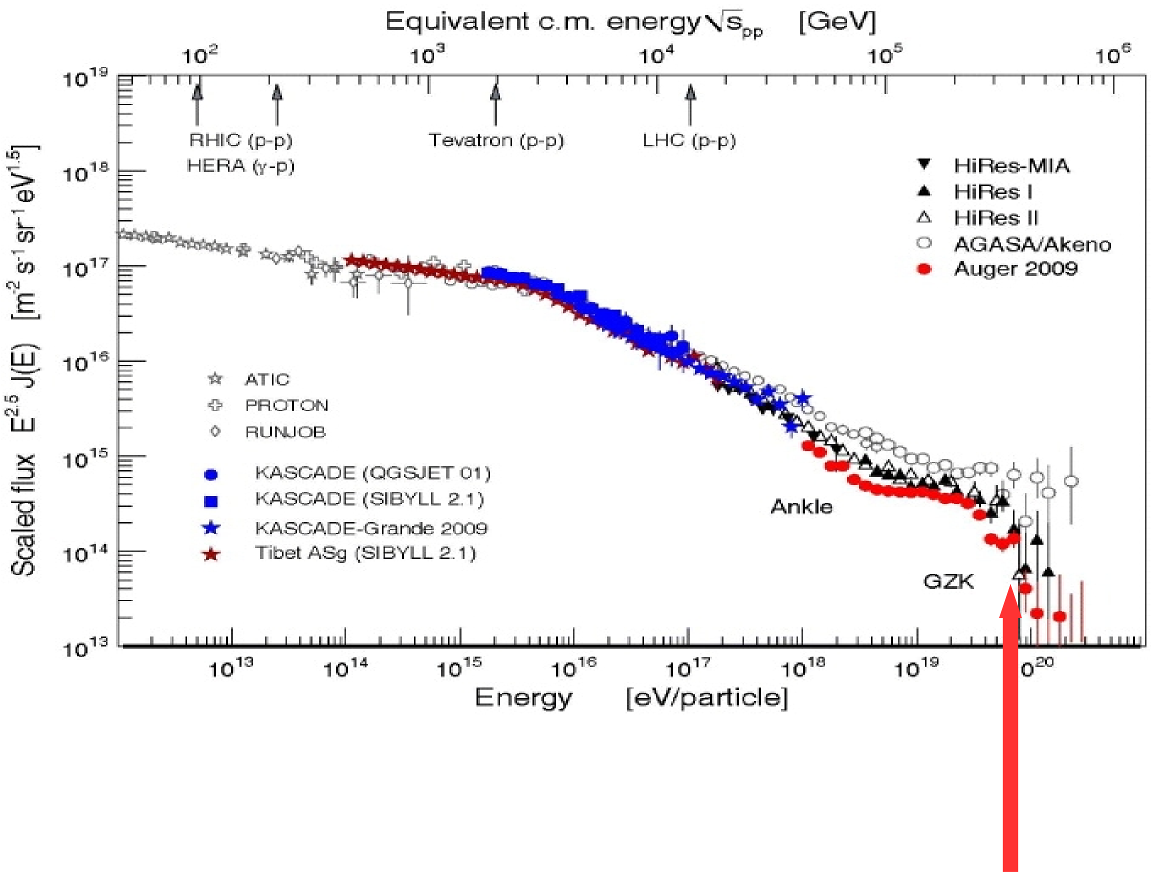
GZK limit for heavier nuclei is even more restrictive



Kotera K, Olinto AV. 2011.
Annu. Rev. Astron. Astrophys. 49:119–53

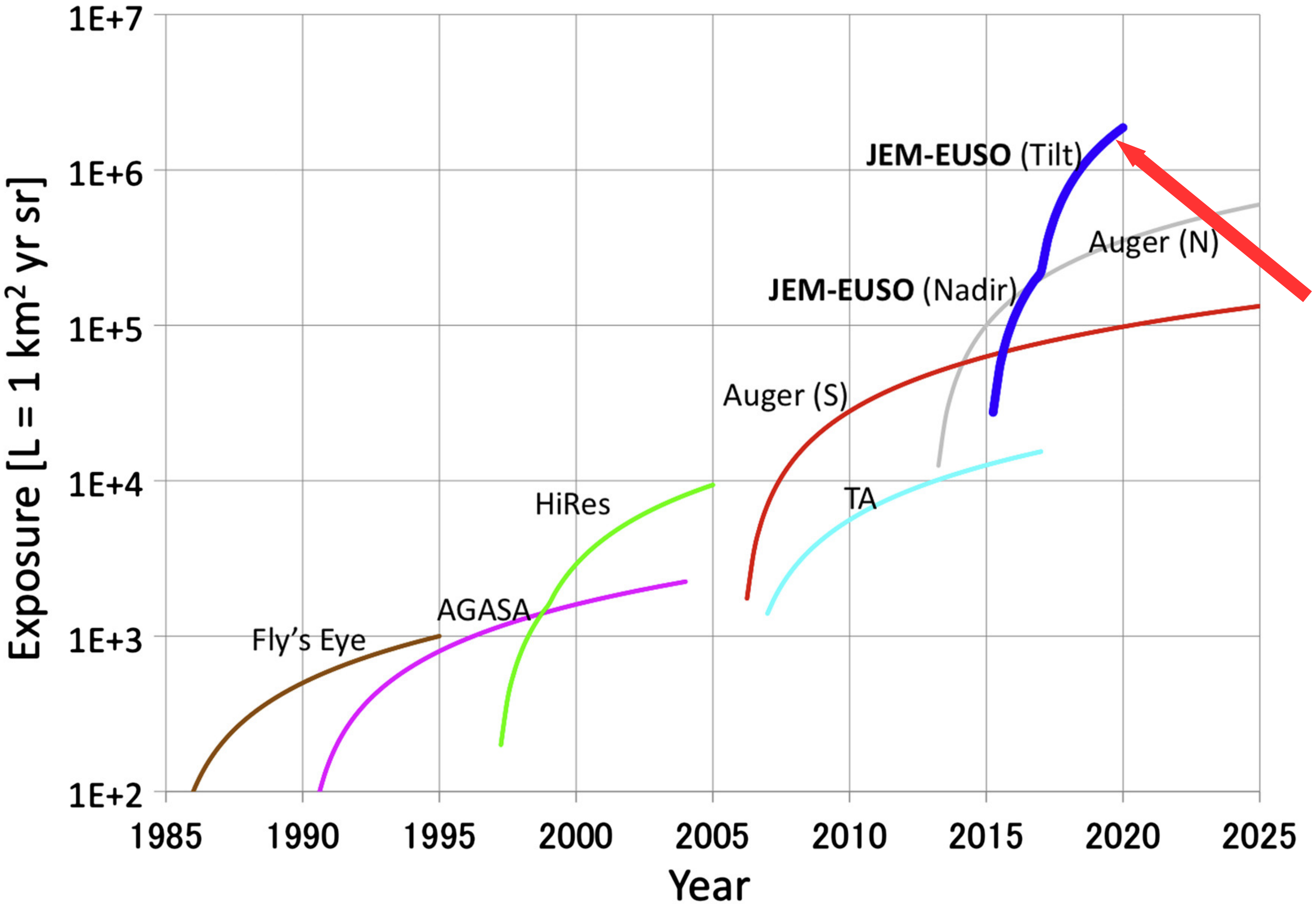
Fraction of heavier nuclei that survives propagation over a distance > D, for protons above 40, 60, and 100 EeV and for He, CNO, and Fe above 60 EeV. The gray solid line shows where 50% of a given species can originate for a given atomic mass and energy.

At trans-GZK energies (E ~60 EeV), only protons and iron survive the propagation over D ~50 Mpc.



Observationally, GZK limit was first seen by HiRes experiments, and confirmed by Pierre Auger Observatory

Figure 2 from The cosmic ray energy spectrum as measured using the Pierre Auger Observatory
Giorgio Matthiae 2010 New J. Phys. 12 075009 doi:10.1088/1367-2630/12/7/075009



To observe such high-energy cosmic rays one needs a very large exposure:

CREDO

JEM-EUSO (will use all Earth's atmosphere as a telescope)

Kajino (2010)

EUSO – Extreme Universe Space Observatory

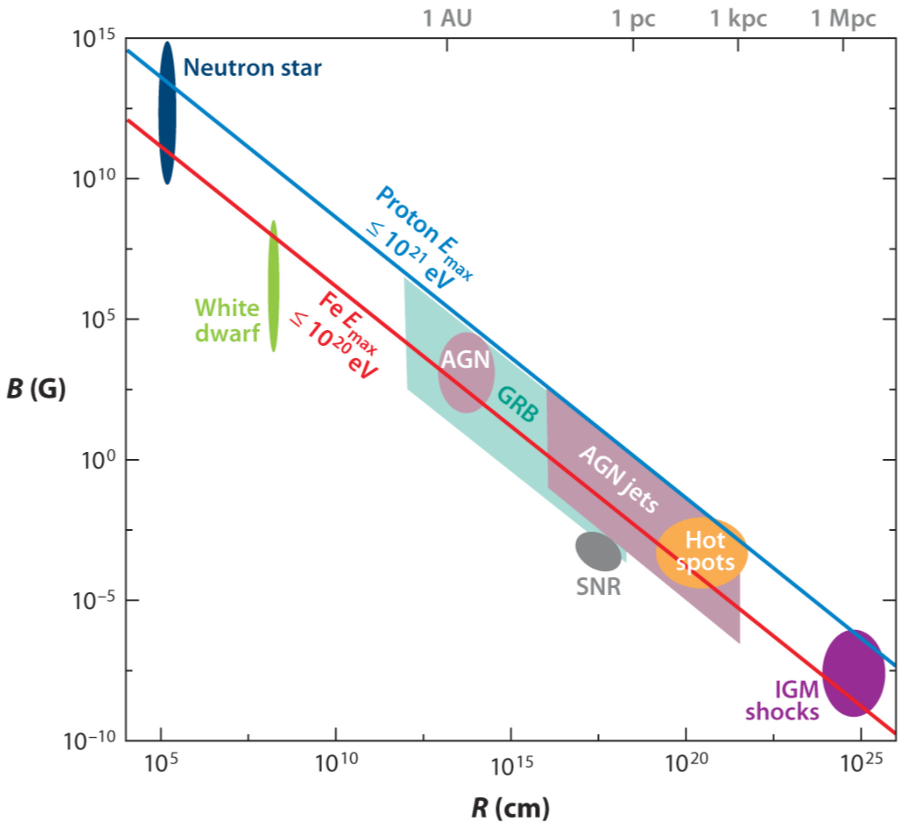
- UV telescope directed to the atmosphere from space (International Space Stations; now a series of balloon experiments).
- Observations during nights (UV filter to avoid human lights).
- Fresnel lenses (with this large dimensions they are used in space for the first time).
- MAPMT – multianode photomultipliers (1” x 1” - 256 pixels in 4 MAMPTs).
- Ultra fast camera (400kHz, 2.5 μs per frame).
- Very fast switches (<5 μs) to reduce 100 times PMT collection efficiency) (design and made in Łódź).
- Fast trigger (FPGA).

- The main target is to measure Extensive Air Shower (EAS) development in the atmosphere (atmosphere is a target for cosmic ray particles); Typical EAS lasts about 30 μs.
- Atmospheric studies: initial state of lightnings and TLEs (the fastest camera), daily variation of atmosphere UV emission and albedo.
- Meteor observations and studies.

Physical sources of UHECR and their multimessenger context

- Zevatrons: ultra-high energy cosmic accelerators; required: small size and strong magnetic field
- A necessary condition for the acceleration of UHECRs in an astrophysical source is the so called Hillas criterion (Hillas 1984).
- It defines a relation between a magnetic field B of an accelerator and its radius R necessary to make it possible to speed up a particle magnetically to a sufficiently high energy.

Source candidates according to Hillas criterion



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Updated Hillas (1984) diagram.

Above the dark blue lines, protons can be confined to energies above E_max = 10^21 eV. Above the red line, iron nuclei can be confined to energies above E_max = 10^20 eV. The most powerful candidate sources are shown with the uncertainties in their parameters.

AGN = active galactic nuclei

GRB = gamma-ray bursts

IGM = intergalactic medium

SNR = supernova remnants

Therefore, the strongest candidate sites for UHECR acceleration are

- active galactic nuclei (AGN),
- gamma ray bursts (GRBs)
- neutron stars
- shocks in the intergalactic medium

Less plausible candidates are

- supernova remnants (SNR)
- white dwarfs

even if they are very likely contributors to lower energy cosmic rays

Active Galactic Nuclei (AGNs) are central regions of galaxies characterized by:

- High absolute luminosities
- Nonthermal Spectra that do not look like the sum of many stellar spectra,
- Most of the luminosity is in a region of the spectrum other than optical (e.g., radio, UV, Infrared, X),
- bright, star-like nucleus,
- strong emission lines (in most cases) ,
- rapid variability,
- (sometimes) radio jets

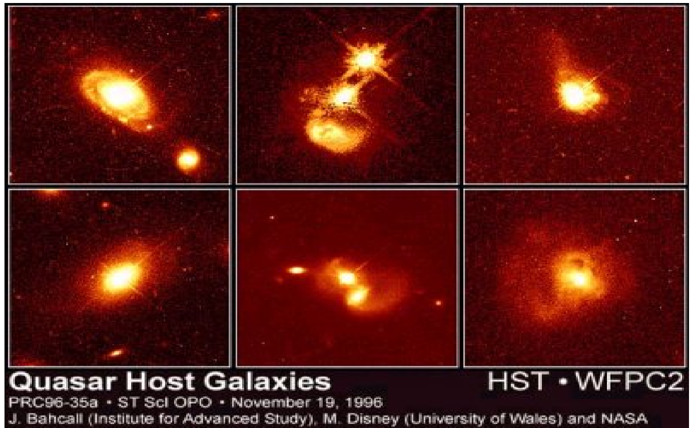
AGN variaties

- Quasars
- BL Lacertae objects (lacertides, blazars)
- Seyfert galaxies
- LINERs

… depending on the adopted criteria, almost every big galaxy can be identified as AGN (as practically all big galaxies host supermassive black holes in their centers with some residual activity

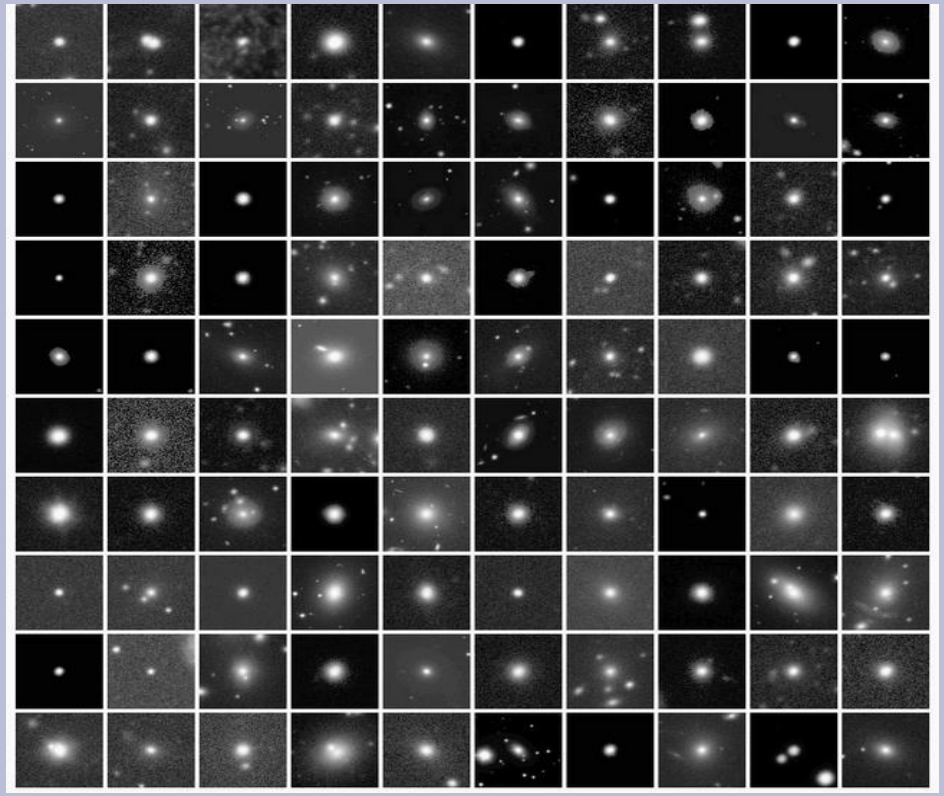
AGN activity

According to our present understanding of quasars/AGNs they are relatively short-time (~ mln of years) phenomena. They activate when matter is fed to supermassive black hole engines at the centers of galaxies, and turned off when the matter is consumed/pushed away by galactic winds associated with these events.



“Special” types of AGNs: BL Lac objects

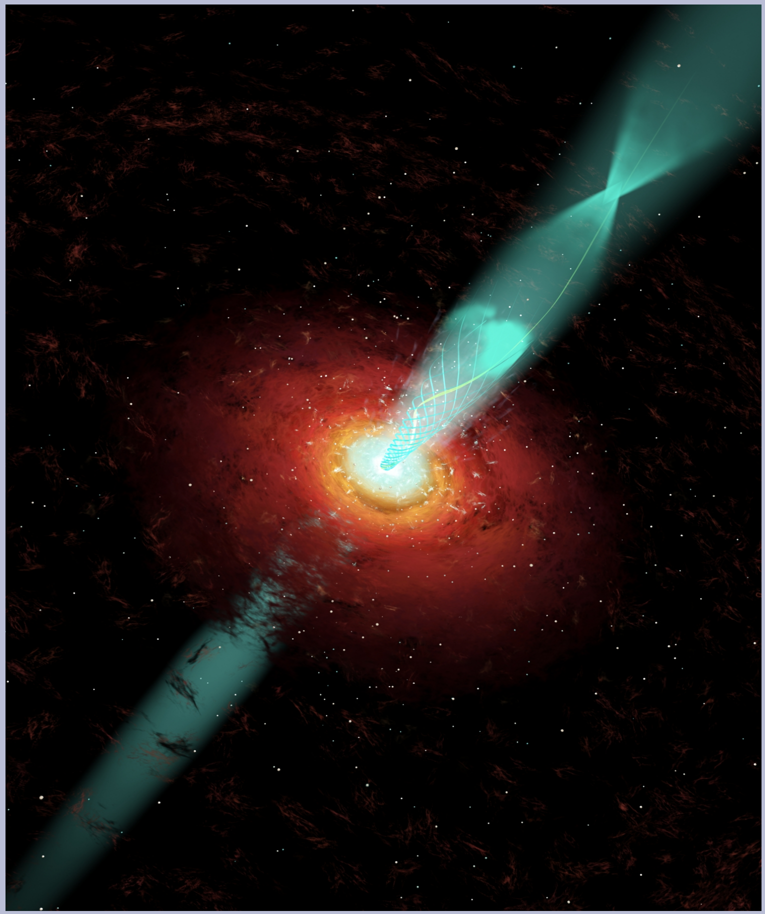
- star-like point objects
- “strange” spectra: no emission lines
- a strong continuum from radio to X
- with a strong variability in all wavelengths



Nilsson et al. 2003, at the Nordic Optical Telescope.

“Special” types of AGNs: BL Lac objects

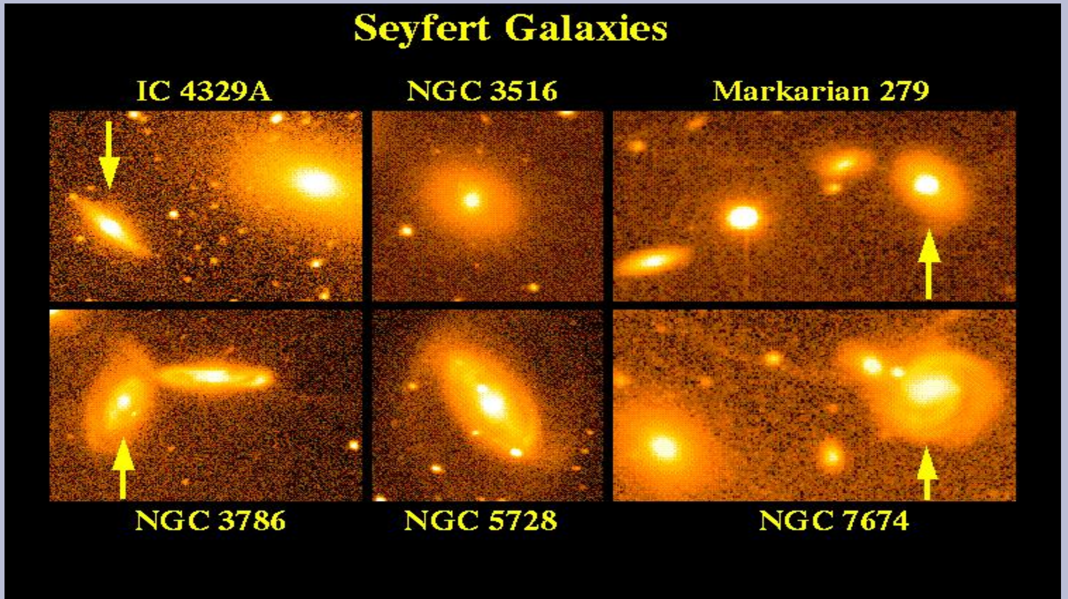
- The prototype of this class of AGNs has been originally classified as a variable star in our own galaxy and named BL Lacertae.
- Now they are believed to be active galaxies at which we look directly in the jet.



- Credit: Cosmovision, a group led by Dr. Wolfgang Steffen of the Instituto de Astronomia, UNAM, Ensenada, Mexico

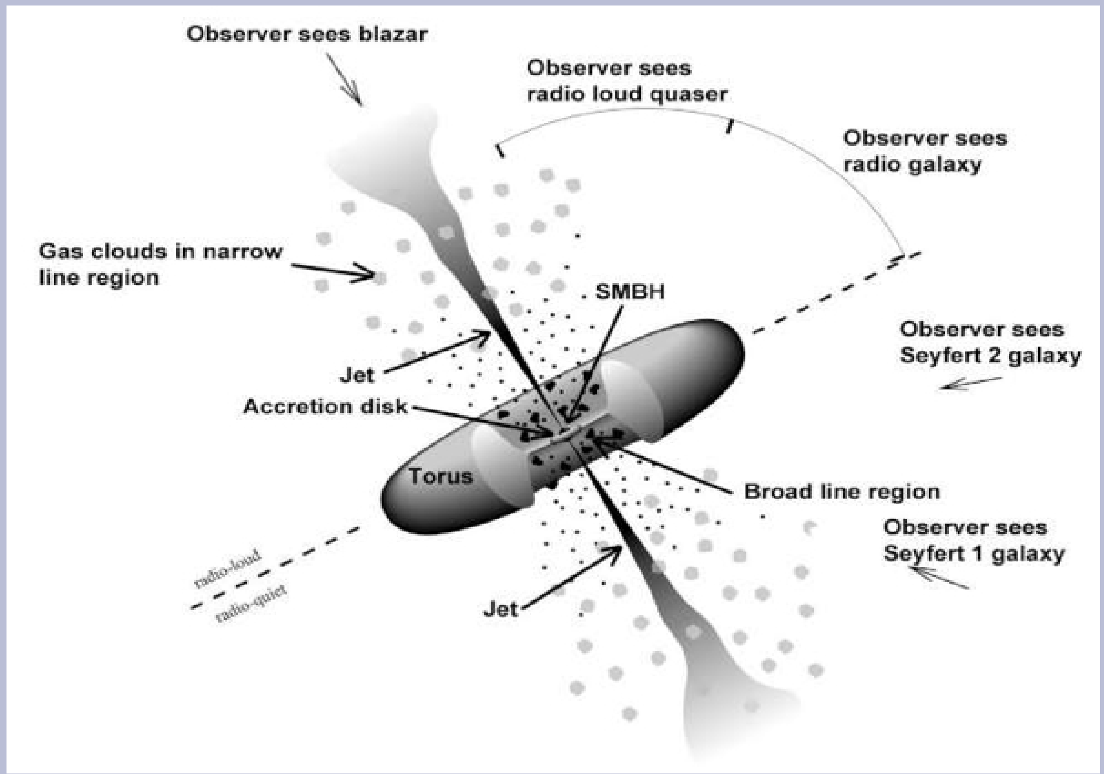
“Special” types of AGNs: Seyfert galaxies

- 20% of spirals, and 10% of all galaxies are Seyfert galaxies
- Seyfert galaxies are lower-luminosity active galactic nuclei, with MB > -21.51 + 5 log h_0 for the active nucleus (Schmidt & Green 1983), for distinguishing Seyfert galaxies from quasars. A Seyfert galaxy has a quasar-like nucleus, but the host galaxy is clearly detectable.



AGNs: a unification scenario

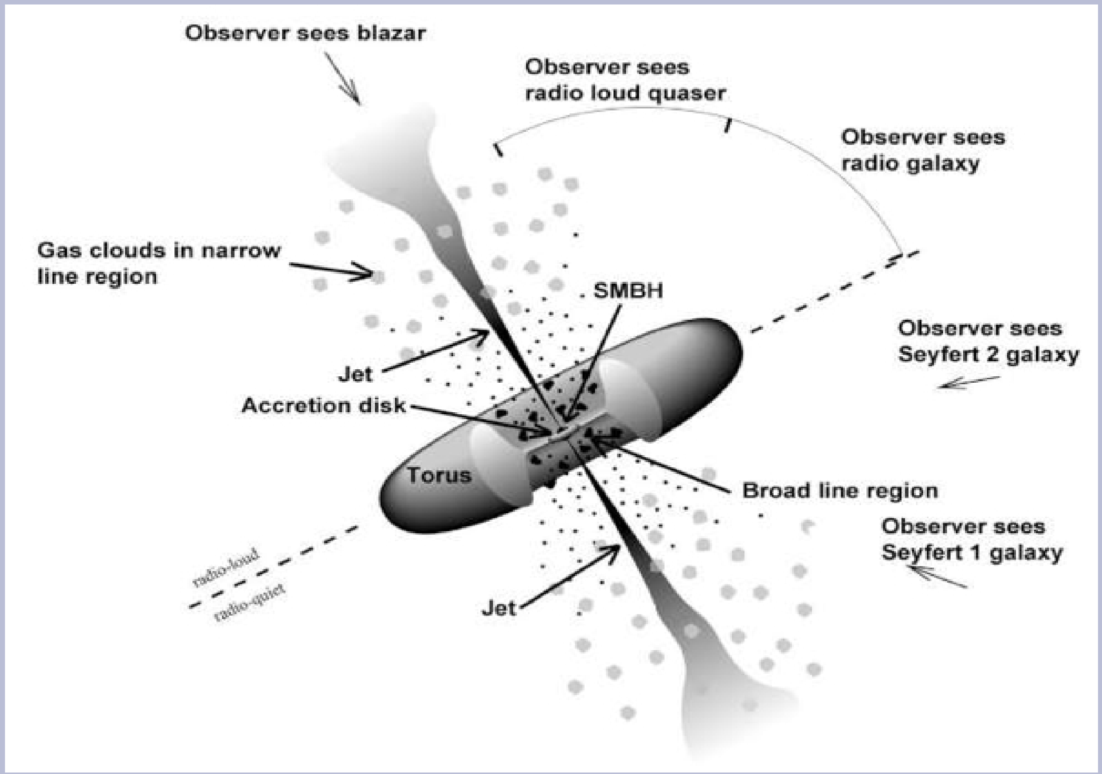
- It was proposed that all AGNs are the same objects placed differently in space with respect to us: Seyferts – more edge-on, type depending on the angle of view; quasars – seen from above, BL Lac objects – directing the jet towards us.
- However, the quasars and BL Lac objects are typically much more distant than the Seyfert galaxies
- Recently, there are some indications that AGNs may change a type… but this is a different story



(Urry and Padovani, 1995)

AGNs as UHECR sources

- In central engines (but with high energy loses – less likely)
- In jets (of radio-loud AGNs), lobes or hot spots
- In transient events (flares) → blazars



Neutrino from a blazar TXS 0506+056

A high-energy neutrino event detected by IceCube on 22 September 2017 was coincident in direction and time with a gamma-ray flare from the blazar TXS 0506+056.

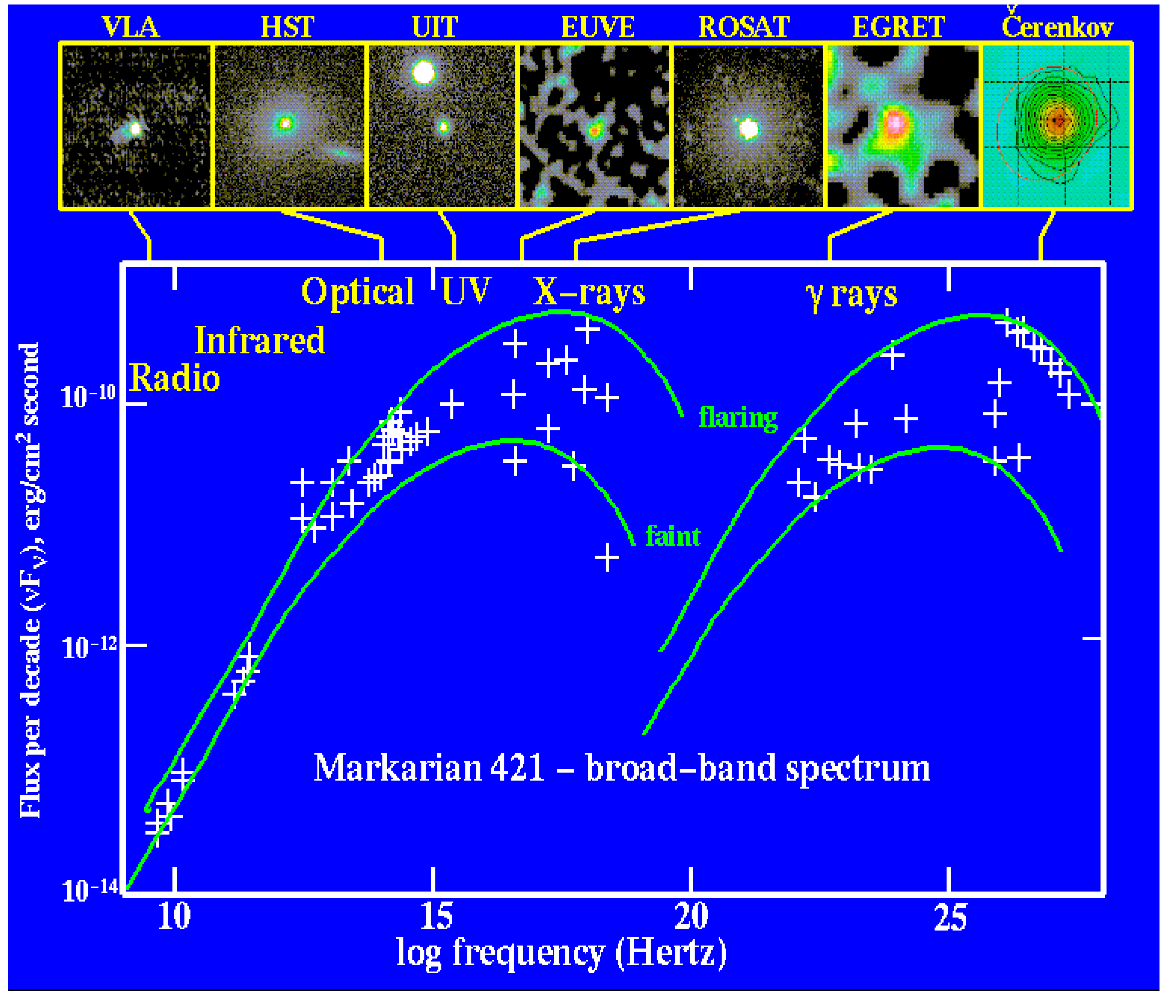
Investigation of 9.5 years of IceCube neutrino observations revealed an excess of high-energy neutrino events, with respect to atmospheric backgrounds, at the position of TXS 0506+056 between September 2014 and March 2015.

→ 3.5σ evidence for neutrino emission from the direction of TXS 0506+056, independent of and prior to the 2017 flaring episode.

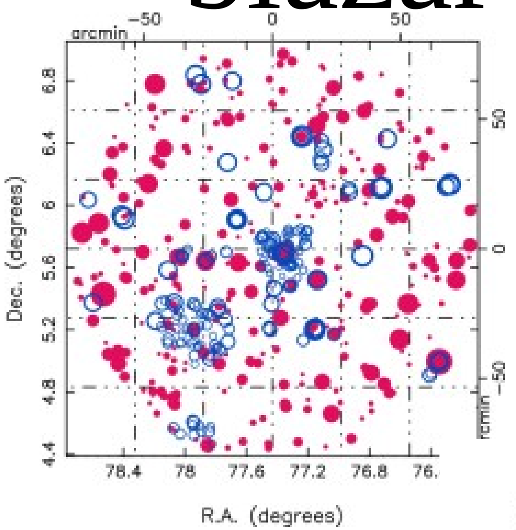
This suggests that blazars are identifiable sources of the high-energy astrophysical neutrino flux.

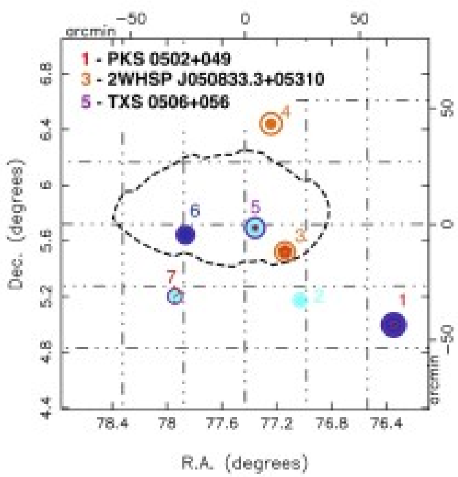
Which is, actually, a very good news for CREDO

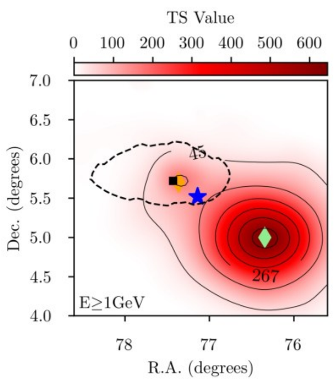
- Blazars are perfect for multimessenger studies as they are visible in practically all range of electromagnetic spectrum
- They are variable objects (flares) → time domain aspect



Multimessenger context: blazar TXS 0506+056 or sth. else?





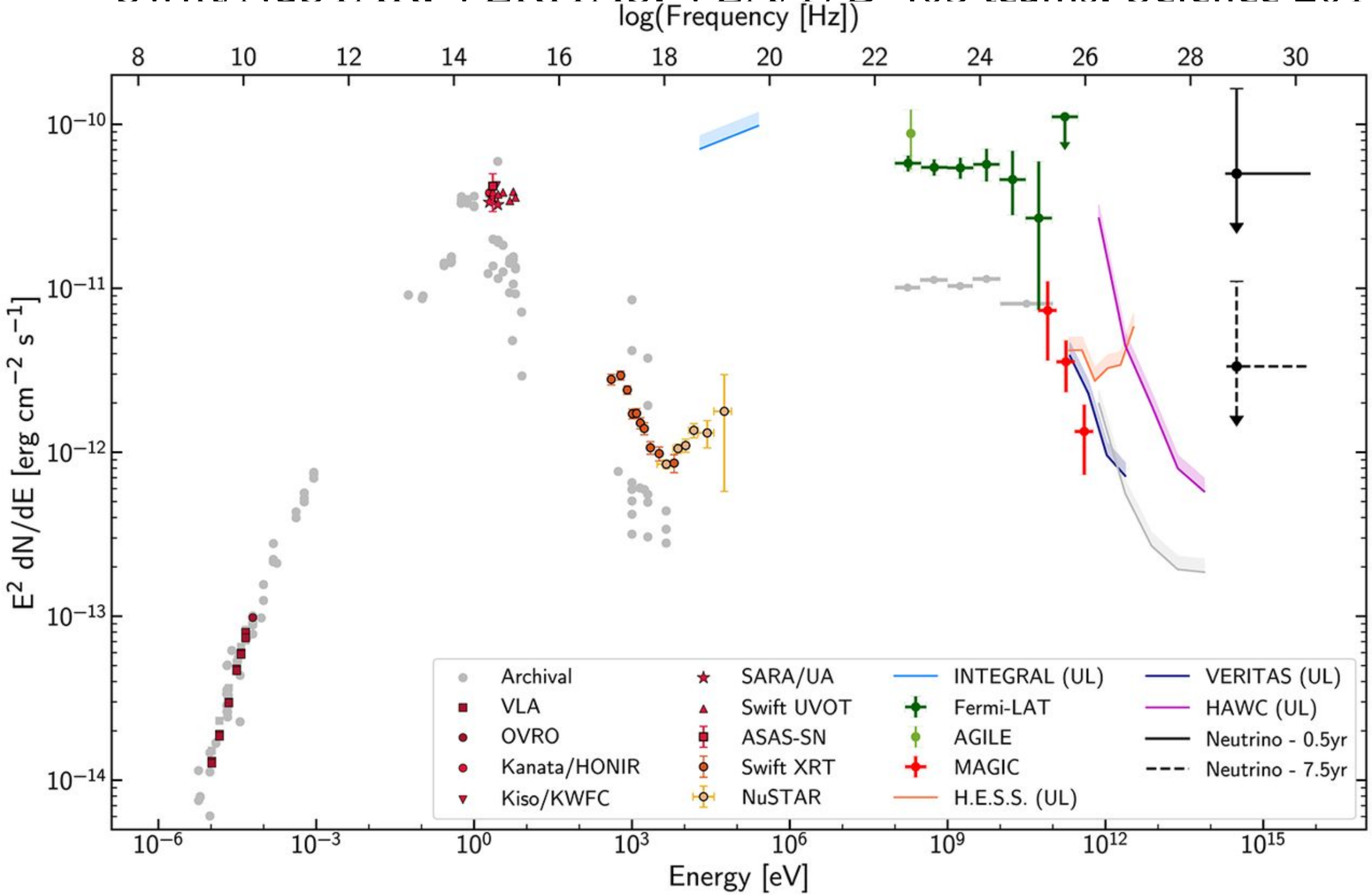


The region around the IceCube-170922A neutrino alert. neighbouring bright γ-ray source, the blazar PKS 0502+049. PKS 0502+049 contaminates the γ-ray emission region at low energies but TXS 0506+056 dominates the sky above a few GeV.

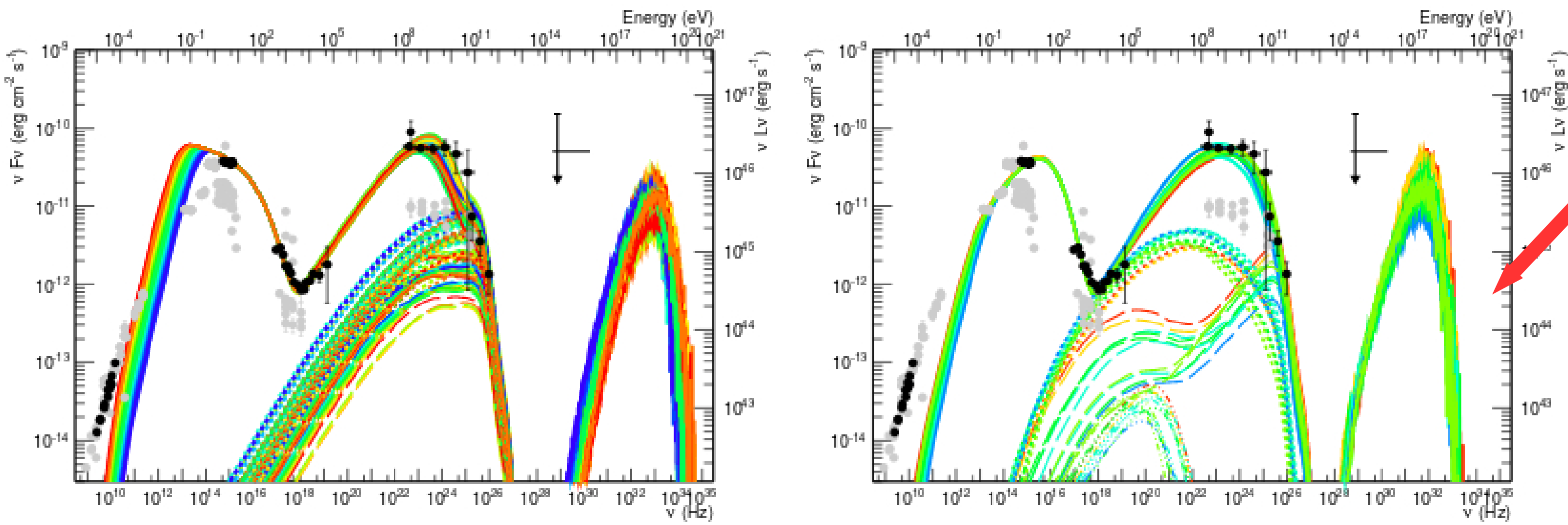
(Padovani et al 2018)

TXS 0506+056 Spectral Energy Distribution - data

(The IceCube Collaboration, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S., INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, Swift/NuSTAR, VERITAS, VLA/17B-403 teams: Science 2018)



TXS 0506+056 Spectral Energy Distribution - models



(a) Proton synchrotron modeling of TXS 0506+056   (b) Lepto-hadronic modeling of TXS 0506+056

Figure 1. Modeling of TXS 0506+056 for the proton synchrotron (1a) and lepto-hadronic (1b) scenarios. Black dots represent data from Ice Cube Collaboration et al. (2018), while gray points are archival data. For each model, bold lines represent the total emission in photons (below 100 TeV) and neutrinos (above 100 TeV); dashed lines the emission from pion cascades; dotted lines the emission from Bethe-Heitler cascades; dotted-dashed lines the proton synchrotron emission. Colours from red to blue represent increasing values of R.

AGNs as UHECRs sources

- GZK limit → 100 Mpx → z < 0.025
-
- NED: 3600 objects classified as QSOs or X-ray sources
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- But: mostly Sayfert galaxies, no strong quasars in this range
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- Will it suffice?

UHECR-AGN/local galaxy field correlation remains inconclusive…

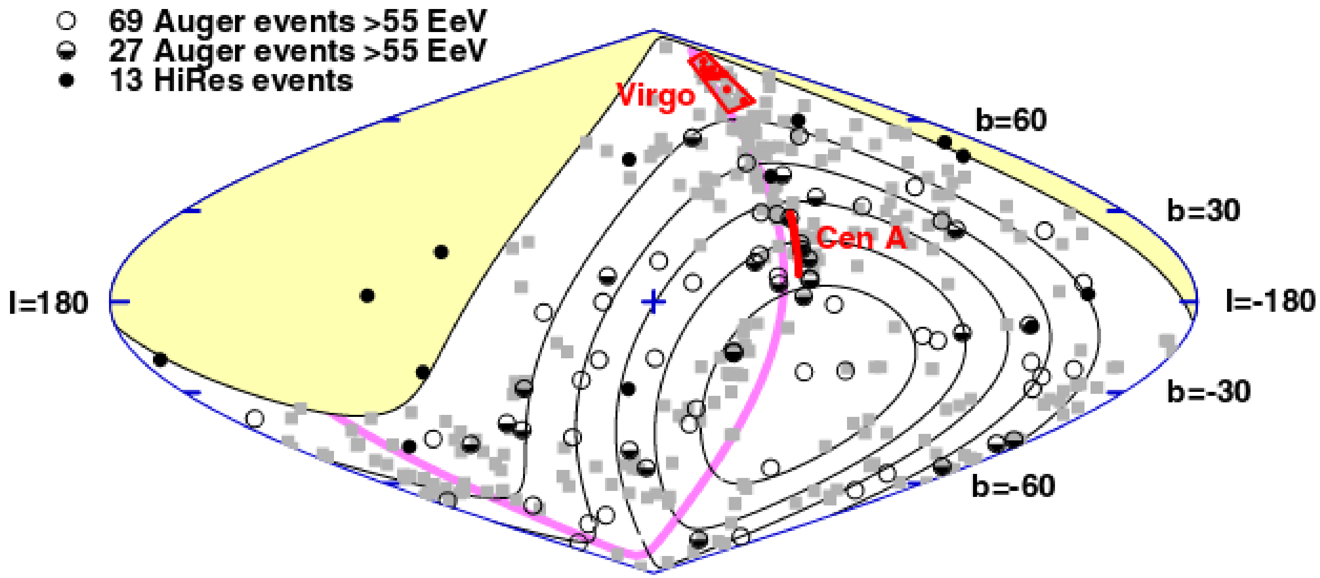
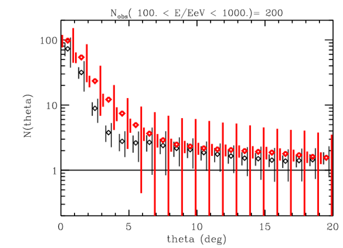


FIG. 22 (color online). Correlation of the arrival directions of UHECR with AGN from the VCV catalog. The shaded part of the sky is not visible by Auger. The gray squares are the AGN within z less than 0.018. The Auger events are shown as circles. The first 27 events are half-filled. The 13 HiRes events are shown with black dots. The thin lines show the six regions of the sky to which Auger has equal exposure. The wide gray line is the supergalactic plane.



Siegl et al. 2004

Gamma-ray bursts

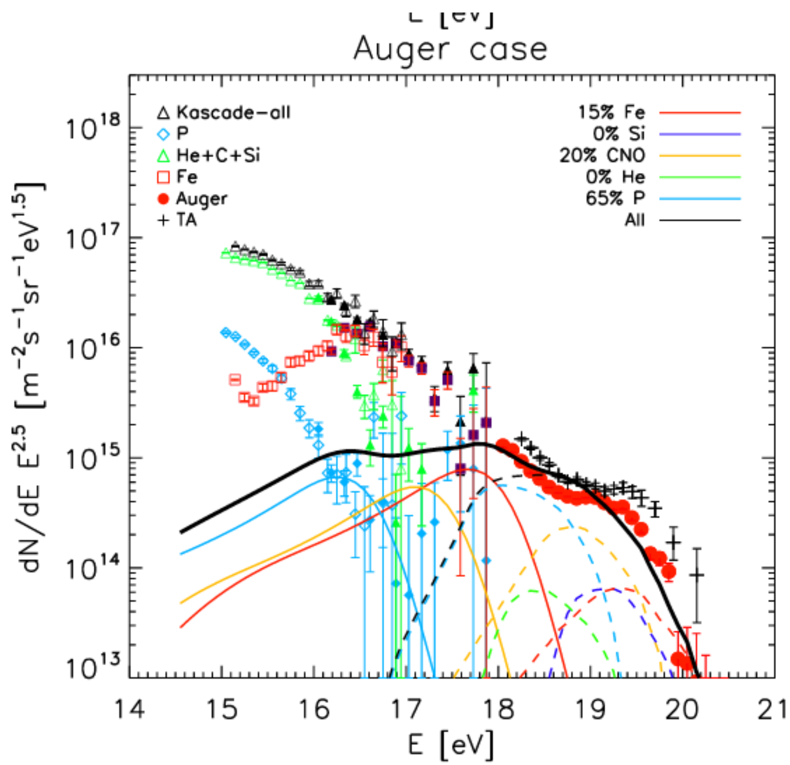
One of the appealing features of GRBs as UHECR sources is that because of their transient nature, neutrinos, which will inevitably be produced by interactions of UHECRs near the source, should be detectable in approximate coincidence with the gamma-ray signal (± few days). However, charged UHECRs are significantly delayed in magnetic fields and not expected to come in coincidence...

Pulsars (NS)

It has been shown that an extragalactic pulsar population can reproduce the Auger spectrum and composition measurements (Fang et al. 2012, 2013).

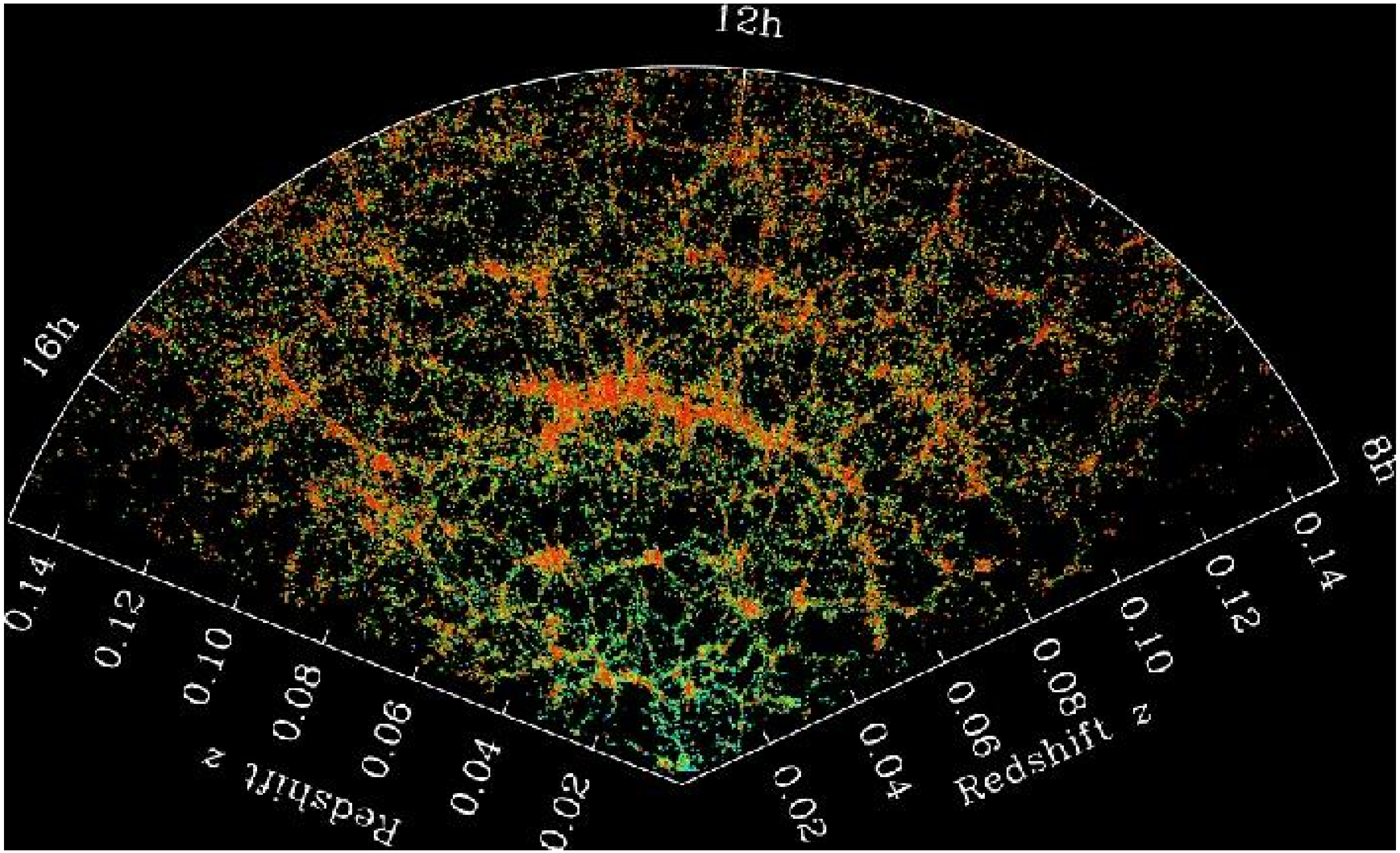
If this is really the case, the diffuse neutrino counterparts associated with pulsar UHECR sources are expected.

Then, can CREDO + 5-10 years of IceCube confirm or rule out this scenario?



(Fang et al. 2012, 2013).

Shocks in the intergalactic medium – large scale structure of the Universe



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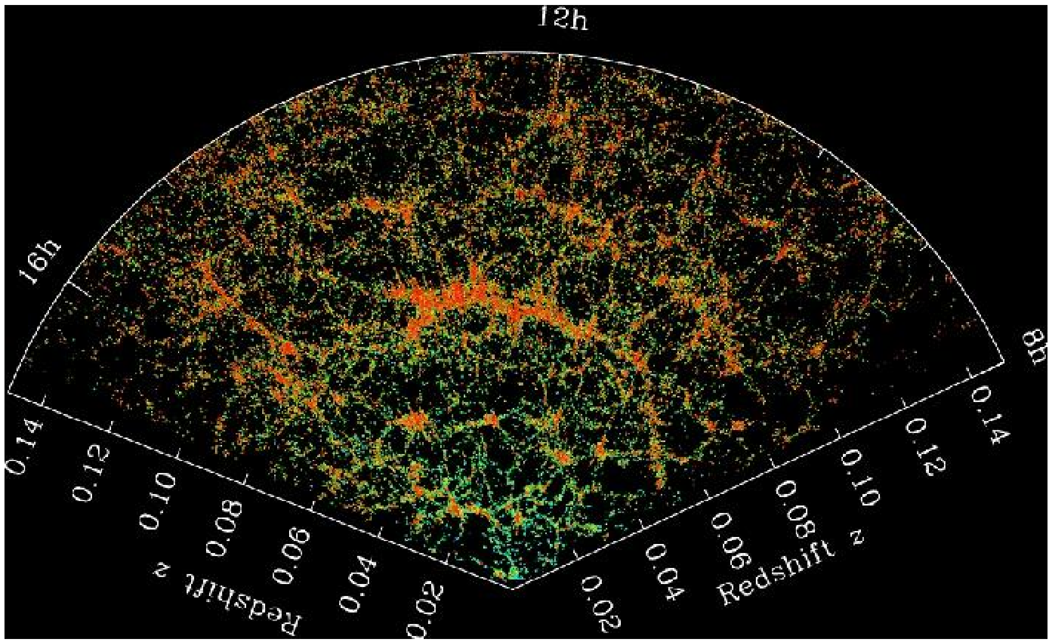

"Cosmic Web":

- Clusters
- Filaments
- Voids

Made of Dark Matter
and only traced by baryonic matter
(in a biased way).

Shocks in the intergalactic medium

In the large scale structure of the universe, filaments and galaxy clusters, the accretion of gas produces shocks.

In particular in galaxy clusters, magnetic fields $B \sim 1-10 \mu G$ have been measured. Similar fields could be present in 1 Mpc scales.

In filaments falling into the nodes, the lower energy particles originated from "traditional" accelerators can be further accelerated...

Non-acceleration origin of UHECRs

Other models of particle physics beyond the Standard Model have also been proposed for the origin of UHECRs (so called top − down models.

In these models, UHECRs are the products of the decay of heavy relic particles, left from the very early universe (or, even more exotically, topological defects).

Summary: CREDO in the multimessenger context

- cross-correlation with existing large surveys at all wavelengths
    - to find correlation with local galaxy distribution
    - to find correlation with local AGN distribution
    - to find correlation with local filaments and clusters

Space domain

- cross-correlation with transient events of different kinds (GW events; GRBs; neutrino detections; nearby blazar flares)
- cross-correlation with (mostly future, but near future!) big time-domain surveys: LSST (optical); SKA (radio)
- cross correlation with all types of small time-domain projects

Time domain

Future prospects: LSST

- The Large Synoptic Survey Telescope
- To produce the deepest and widest sky survey with an additional **time domain** capability
- 8.4-m mirror; 3200 megapixel camera
- **37 billion** stars and galaxies
- 10 year survey of the sky
- 10 million alerts, 1000 pairs of exposures, 15-30 Terabytes of data (i.e. a whole SDSS) every night
- 200 petabyte set of images and data products