Multimessenger Astroparticle Physics

Alessandro De Angelis
Univ. PD, INFN/INAF Padova & LIP/IST Lisboa

7. More Experimental Results. The Final Exam.

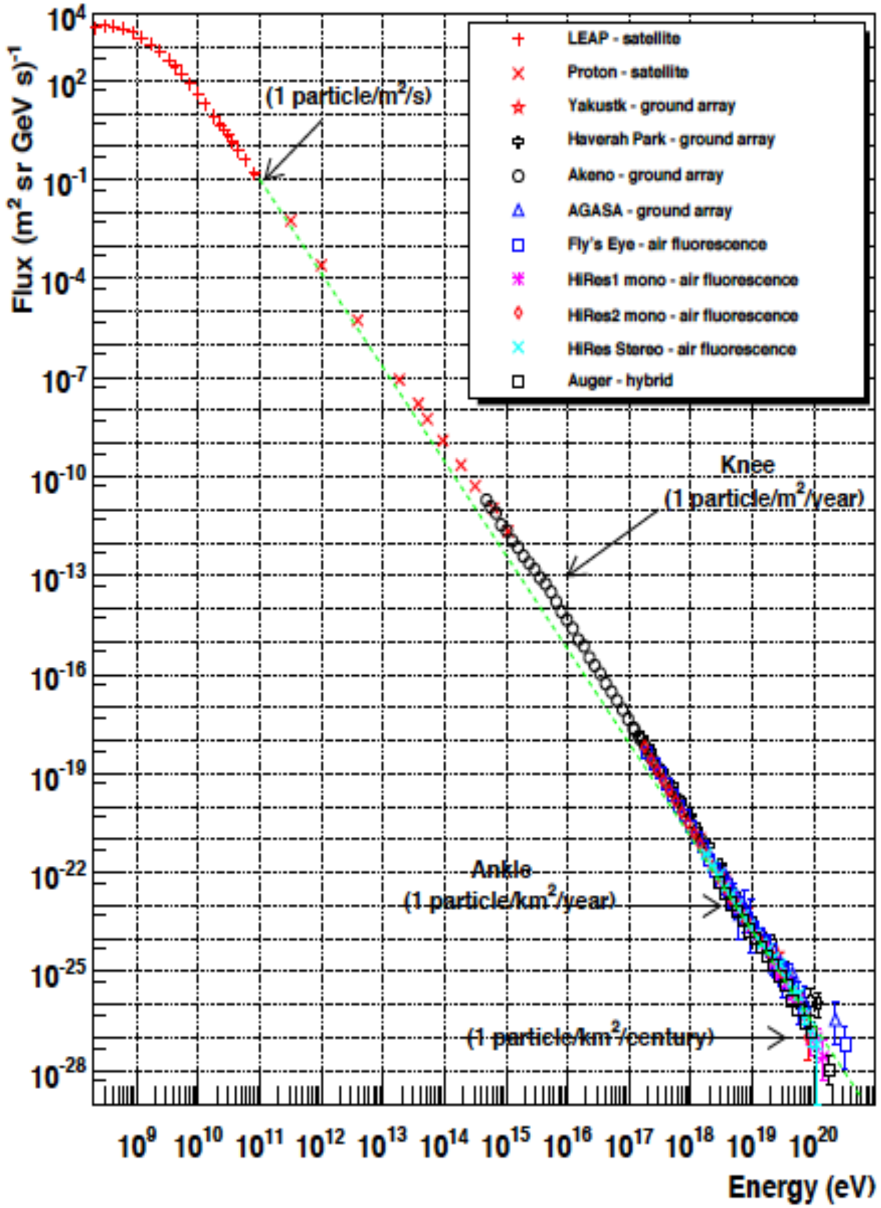
CHARGED COSMIC RAYS

Composition, energy dependence

- Charged CR arrive to the Solar System after deflection from the galactic B (~1 μG) and possibly by extragalactic B
- Close to the Earth they start interacting with B up to O (1G). Fluxes of charged particles at energies <1-2 GeV, can thus be influenced, e.g., by the solar cycle.
- Cosmic rays are basically protons (~90 %) and heavier nuclei. The e- flux at the top of the atmosphere is small (a few per mil) but extremely interesting as it may indicate unknown astrophysical or DM sources
- e+ fluxes are even smaller (about 4 orders of magnitude) and so far compatible with secondary production by hadronic interactions of primary CR with the interstellar medium. Up to now there is no evidence for the existence of heavier anti-nuclei (in particular anti-deuterium and anti-helium)

Energy spectrum

- At E~1 GeV, 1000s of particles/m^2/s) while strong cutoff at E ~ $10^{19.5}$ eV. At the highest, E ~ 10^{11} GeV, < 1 particle/km2/century.
- At the end of the known spectrum CR have energies >> the highest beam energies attained in any human-made accelerator and their interactions on the top of the Earth atmosphere have cm energies ~ few hundred TeV
- Low fluxes at VHE energies: one can study the energies up to the ~ 1 PeV with satellites, while above rely on ground-based detectors.



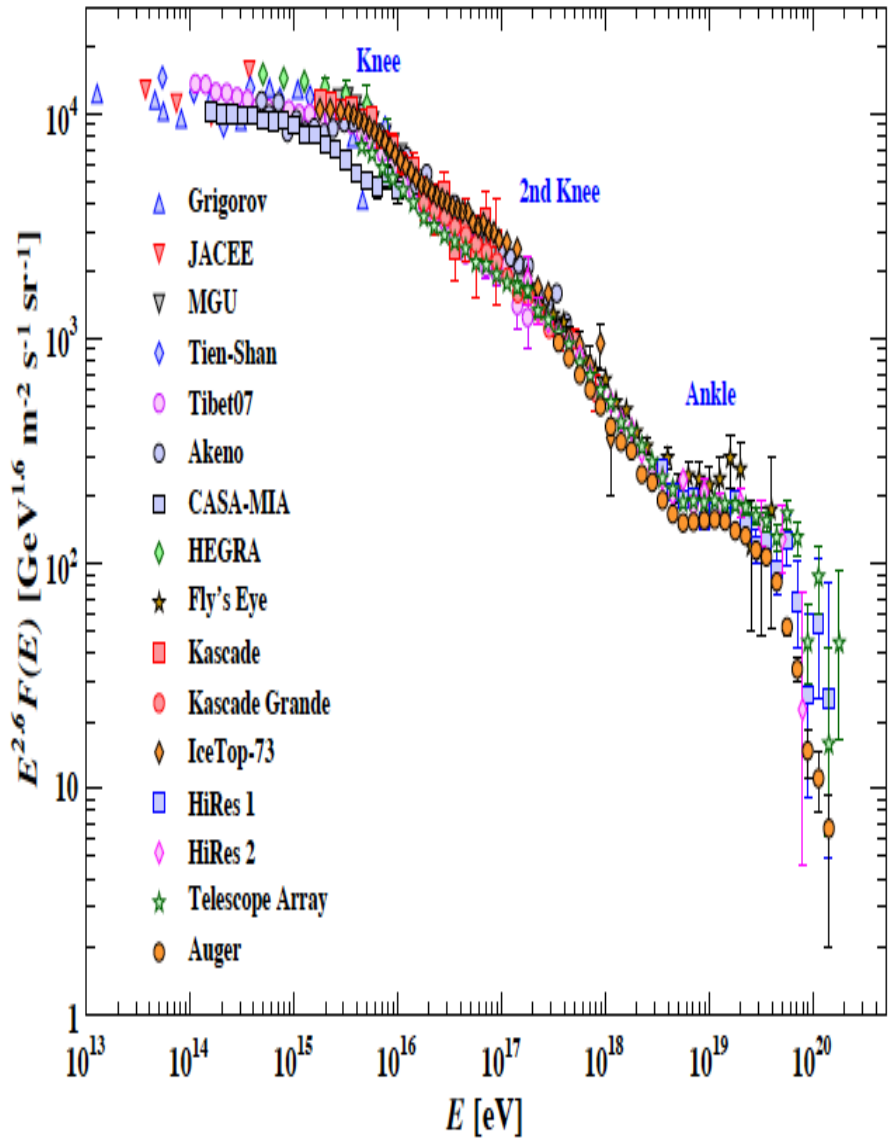
Energy spectrum

- Above a few GeV the CR flux follows a power law,

  $I(E) \cong k\, E^{-p}$

  p between 2.7 and 3.3.
- Below a few GeV, flux modulated by the solar activity and in particular by solar B
  - Effects variable in time
- The small changes in p can be visualized multiplying the flux by some power of the energy. Anthropomorphic representation: 2 clear features corresponding to changes in the spectral index
  - The knee around E ~ 5 PeV, associated to the transition from galactic to EG cosmic rays; it corresponds to a steepening from p~2.7 to p~3.1
    - Second knee at E~ 400 PeV?
  - The ankle around E~ 5 EeV and its nature is still controversial
- From ~10 GeV to >> 100 TeV

$$\frac{dN}{dE} \simeq 1.8 \times 10^4 E^{-2.7} \frac{\text{nucleons}}{\text{m}^2\,\text{s}\,\text{sr}\,\text{GeV}}$$

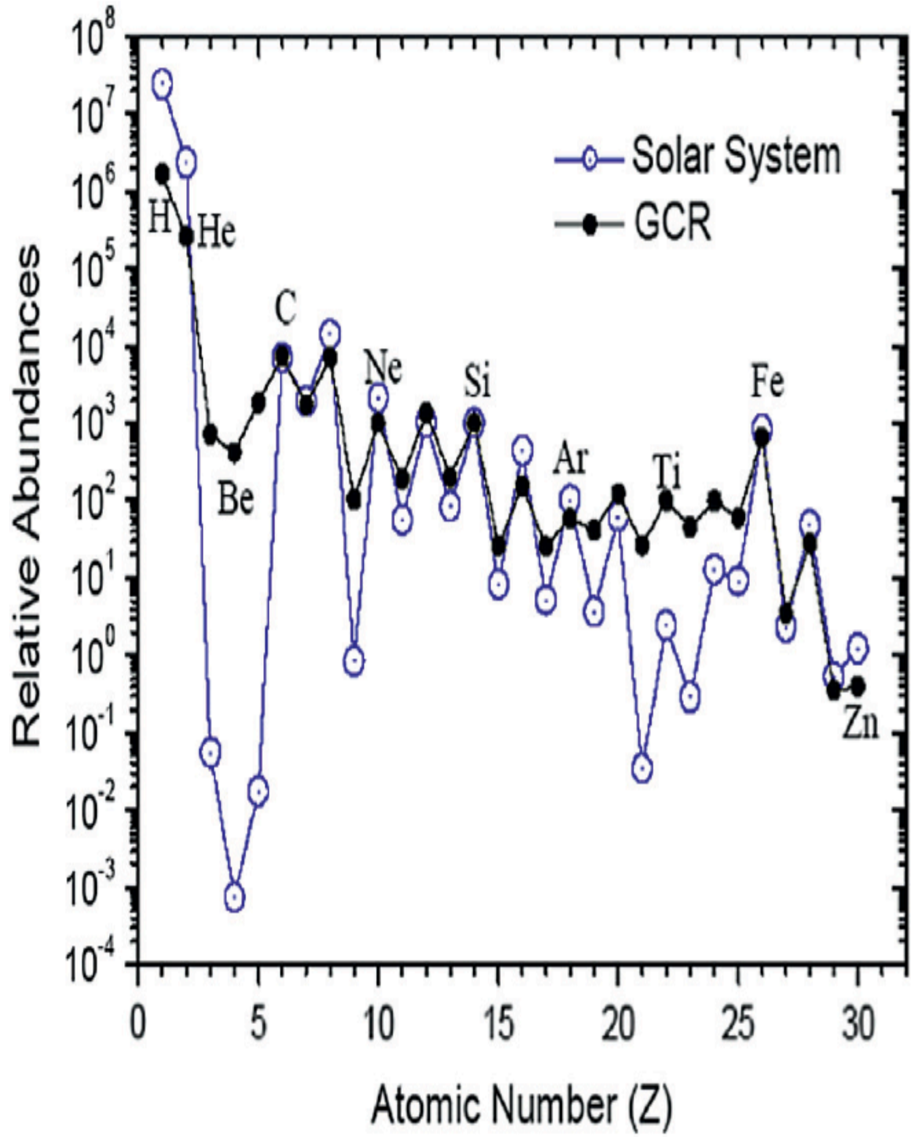


Composition

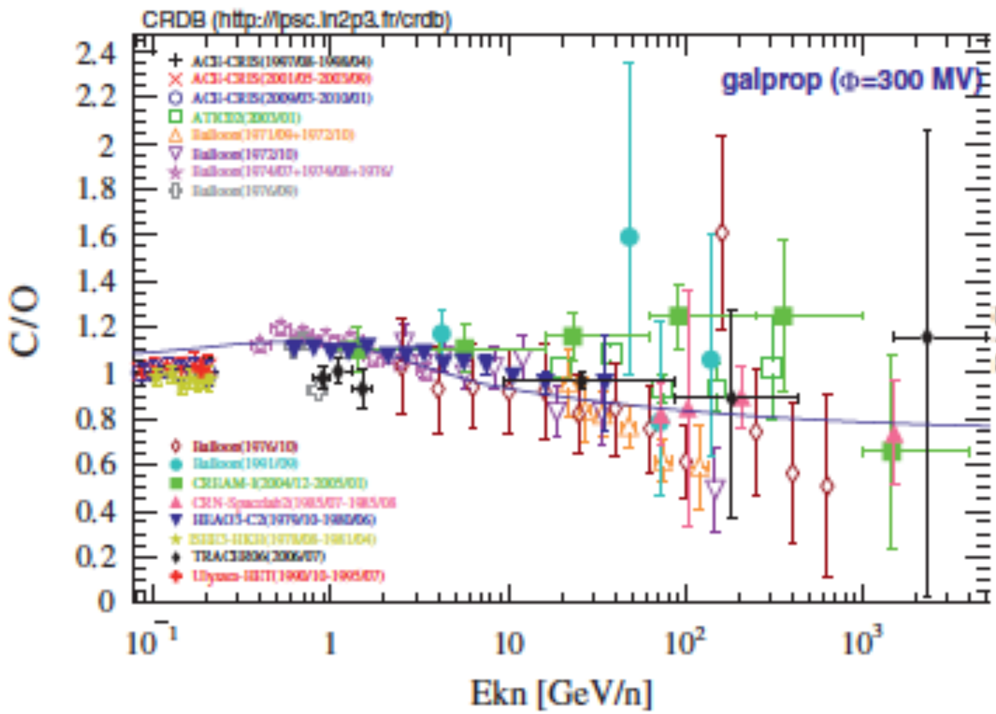
- Not a well-defined problem: it depends on where experiments are performed. One could try a schematic separation between “primary" cosmic rays as produced by astrophysical sources and “secondaries”, i.e., produced in interactions of the primaries with ISM or with nuclei in the atmosphere.
- Li, Be and Bo, for example, are very rare products in stellar nucleosynthesis, and thus are secondary particles, as well as antiprotons and positrons-if some antimatter is primary is a question of primary interest
- The interaction with the Earth's atmosphere is particularly important since it changes drastically the composition of cosmic rays. In the cases in which the flux of cosmic rays has to be measured at ground one needs nontrivial unfolding operations to understand the primary composition
- What one observes is a cascade shower generated by a particle interacting with the atmosphere, and the unfolding of the fundamental properties (nature and energy of the showering particle) requires the knowledge of the physics of the interaction at energies never studied at accelerators: experimental data are thus less clear
- Accessing the composition of cosmic rays can be done, in the region below a few TeV, at the top or above the Earth atmosphere by detectors placed in balloons or satellites able, for example, of combining the momentum measurement with the information from Cherenkov detectors, or transition radiation detectors.

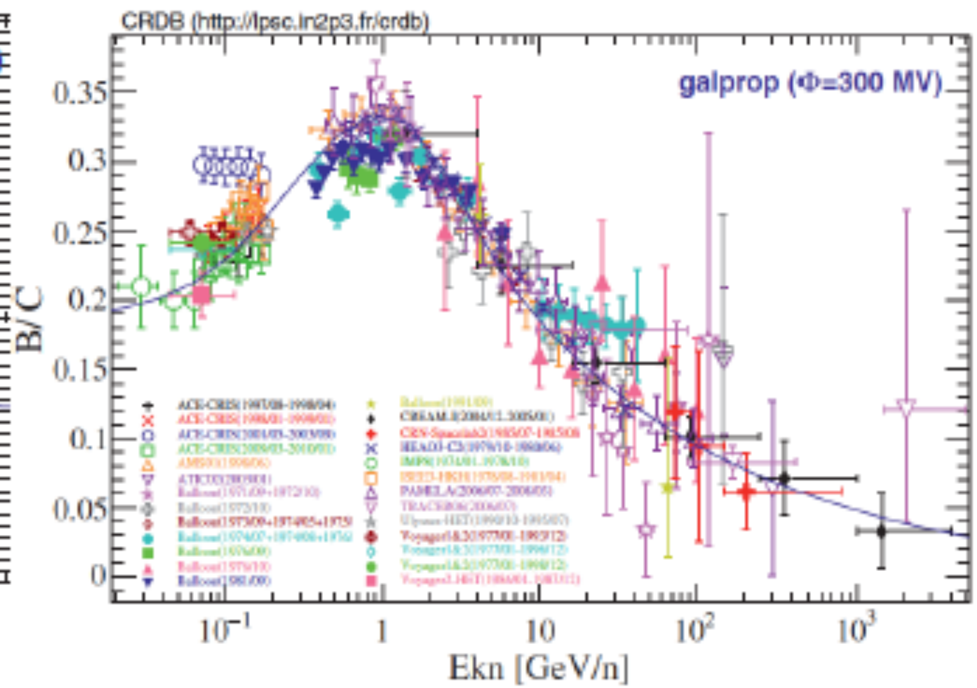
Composition

- Nucleons with even number of nucleons are more stable, having higher binding energy because of pairing effects.
- On top of this, primary CR are produced in stellar end-products, being the “valley" elements mainly secondaries produced in the interaction of the primaries with the ISM (“spallation").
- Direct composition measurements are not possible above a few hundred GeV. For EAS detectors, effective at higher energies, being able to distinguish between a shower generated by a proton or by a heavier particle is difficult
  - the muonic contents of the air shower;
  - depth of the maximum of the shower, X_{max}
- Experimental evidence that the chemical composition of cosmic rays changes after the knee with an increasing fraction of heavy nuclei at higher energy, at least up to about 1 EeV



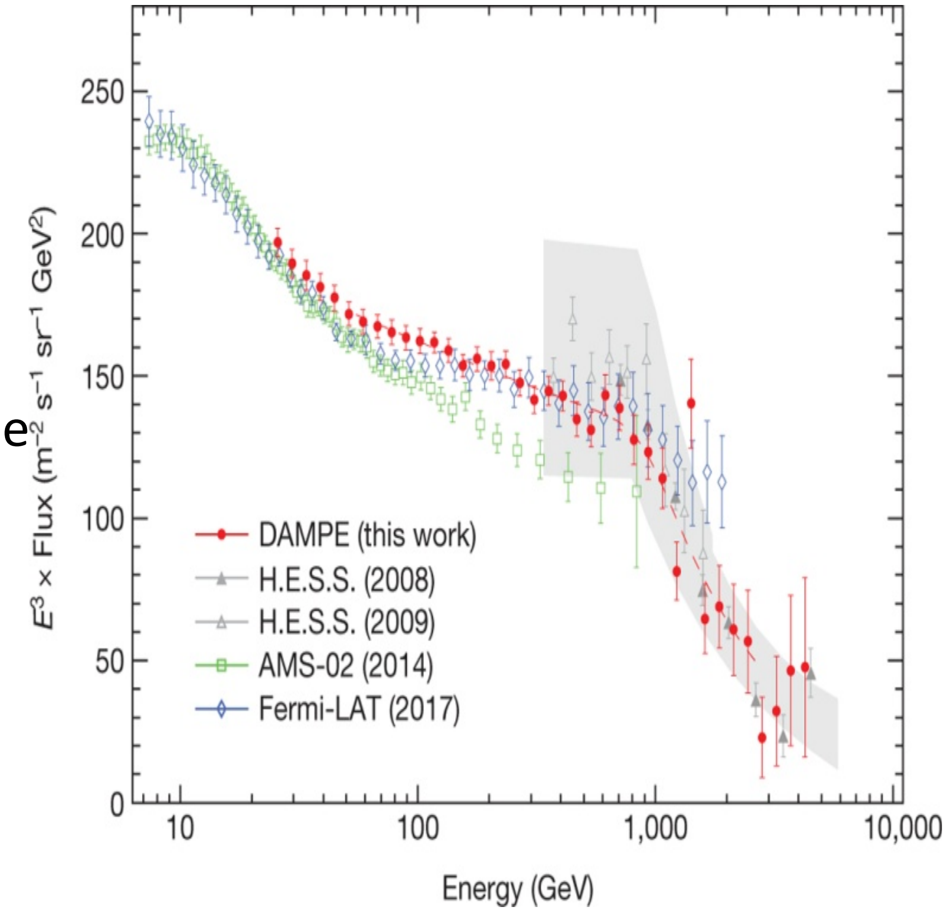
Primaries and secondaries





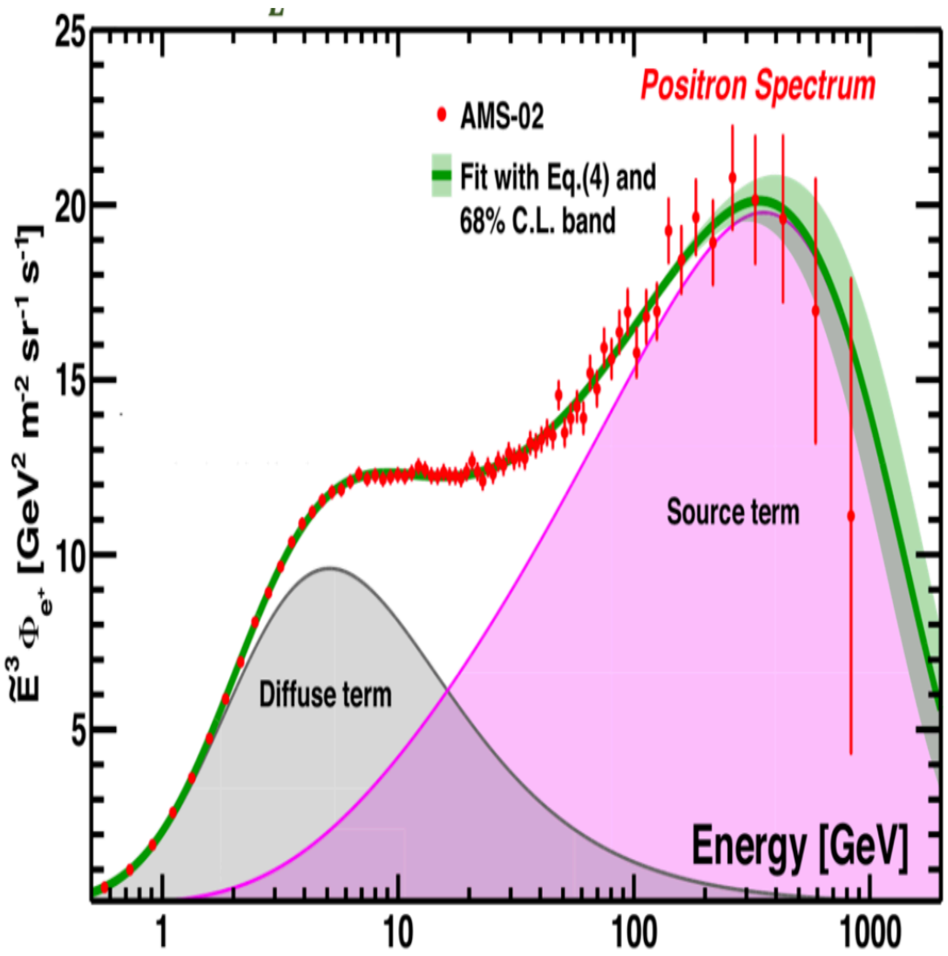
Electrons and Positrons

- HE e+ and e- have short propagation distances (~100 pc) as they lose energy through synchrotron and IC while propagating through the Galaxy.
- Their spectra are therefore dominated by local e accelerators or by the decay/interactions of heavier particles nearby. Positrons in particular could be the signature of the decay of DM particles.
- The experimental data on the flux of e- plus e+ suggested in a recent past the possible evidence a bump-like structure (ATIC balloon experiment results) at energies between 250 and 700 GeV.
- These early results were not confirmed by later and more accurate instruments like the Fermi LAT, AMS-02, DAMPE

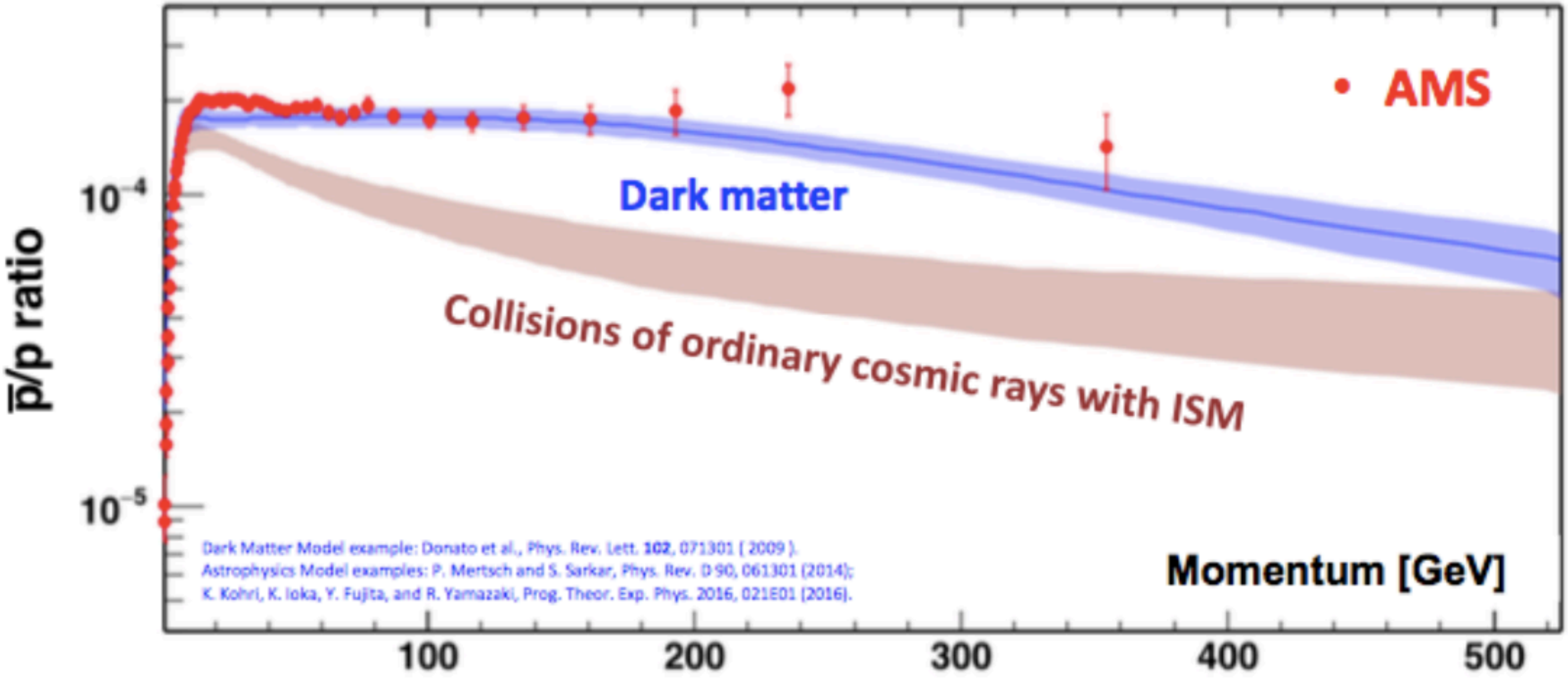


Positrons

- Excess in the HE e+ flux with respect to standard sources (pulsars) and interactions of CR with the ISM, first observed by PAMELA and thus called the PAMELA effect, was clearly confirmed by AMS-02
- In a matter-dominated Universe, one would expect this ratio to decrease with E, unless specific sources of positrons are present nearby.
  - If these sources are heavy particles decaying to final states involving e+, one could expect the ratio to increase, and then steeply drop after reaching half of the mass of the particle.
  - If an astrophysical source of HE positrons is present, a smooth spectrum is expected instead.
- The present data favors nearby sources, but is compatible with a hypothetical DM particle with a mass of ~800 GeV.. The most recent data on the abundance of high-energy pulsars nearby might justify an astrophysical explanation of this excess but not the results in antiproton.



Antiprotons



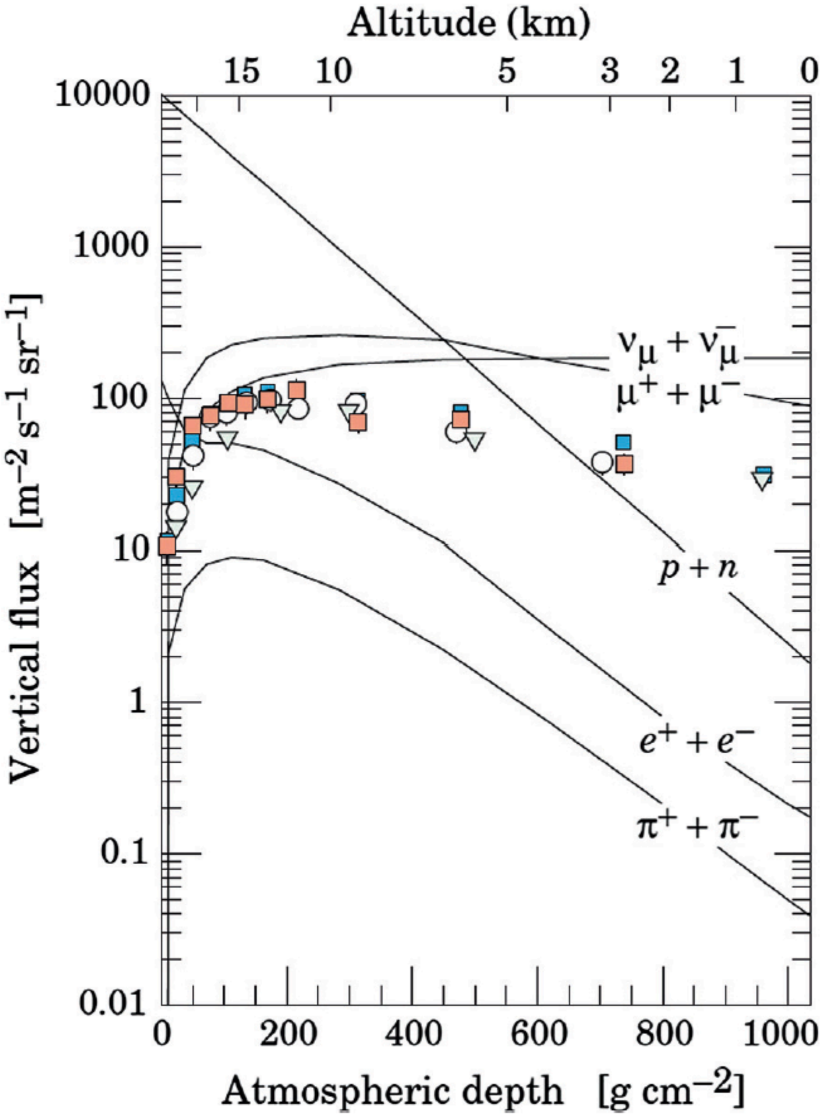
Muons

Astrophysical muons can hardly reach the Earth's atmosphere due to their lifetime ($\tau \sim 2\,\mu$s); this lifetime is however large enough, that secondary muons produced in the atmosphere can reach the Earth's surface, offering a wonderful example of time dilation: the space crossed in average by such particles is $L \simeq c\gamma\tau$, and already for $\gamma \sim 50$ (i.e., an energy of about 5 GeV) they can travel 20, 30 km, which roughly corresponds to the atmospheric depth. Muons lose some 2 GeV by ionization when crossing the atmosphere.

Charged particles at sea level are mostly muons (see Fig. 10.36), with a mean energy of about 4 GeV.

The flux of muons from above 1 GeV at sea level is about 60 $\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$. A horizontal detector sees roughly one muon per square centimeter per minute. The zenith angular distribution for muons of $E \sim 3$ GeV is $\propto \cos^2\theta$, being steeper at lower energies and flatter at higher energies: low energy muons at large angles decay before reaching the surface. The ratio between μ^+ and μ^- is due to the fact that there are more π^+ than π^- in the proton-initiated showers; there are about 30 % more μ^+ than μ^- at momenta above 1 GeV/c.

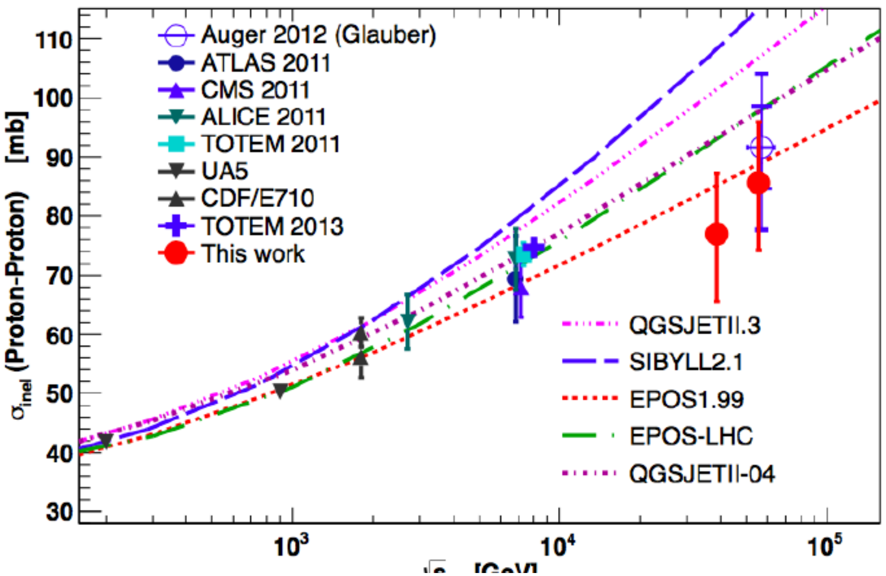
A fortiori, among known particles only muons and neutrinos reach significant depths underground. The muon flux reaches $10^{-2}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$ under 1 km of water equivalent (corresponding to about 400 m of average rock) and becomes about $10^{-8}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$ at 10 km of water equivalent.

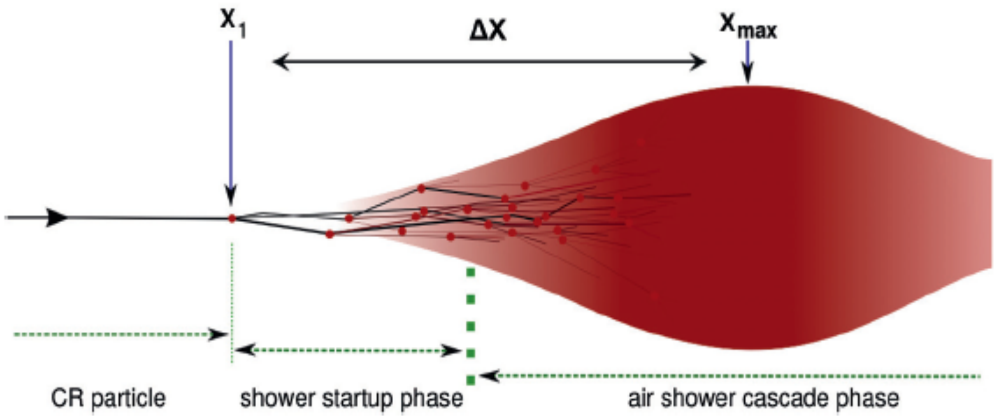


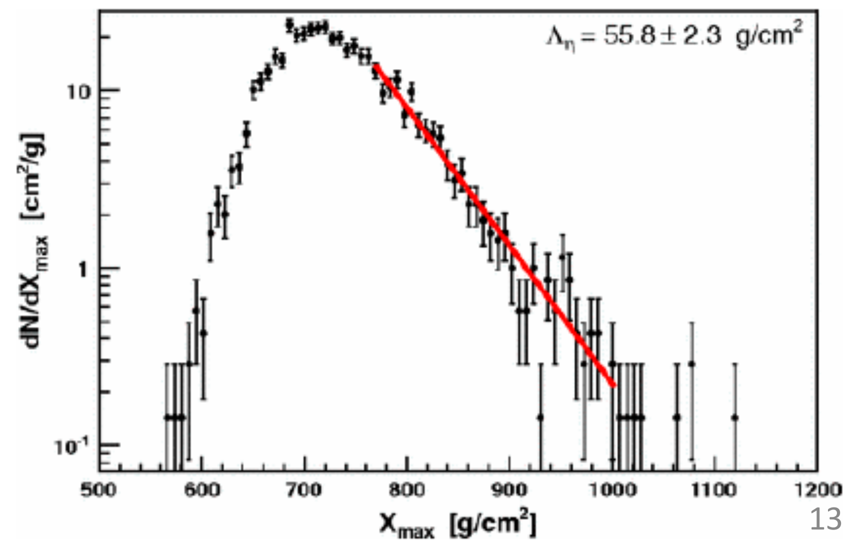
UHECR: Composition

The depth of the maximum number of particles in the shower, X_{max}, schematically represented in Fig. 10.38), is sensitive to the cross-section of the primary cosmic ray interaction in the air. Thus it can be used either to measure the cross-section, if the composition is known, or, once the cross section for a nucleus grows with its atomic number, to determine the composition, if the nuclei-air interaction cross-sections at these energies are assumed to be described correctly by the model extrapolations of the cross-sections measured at lower energies in the accelerators. Indeed, X_{max} may be defined as the sum of the depth of the first interaction X_1 and a shower development length ΔX (see Fig. 10.38):

$$X_{max} = X_1 + \Delta X \, .$$







UHECR: EHE

Ultra-High-Energy Cosmic Rays (UHECR) are messengers from the extreme Universe and a unique opportunity to study particle physics at energies well above those reachable at the LHC. However, their limited flux and their indirect detection have not yet allowed to answer to the basic, and always present, questions: Where are they coming from? What is their nature? How do they interact?

The energy spectrum of the UHECR is nowadays well measured up to 10^{20}eV (see Fig. 10.37). The strong GZK-like suppression at the highest energies may be interpreted assuming different CR composition and sources scenarios. Indeed, both pure proton and mixed composition scenarios are able to describe the observed features. In the case of a pure proton scenario, the ankle would be described by the opening, at that energy, of the pair production channel in the interaction of the incoming protons with the CMB photons ($p\,\gamma_{CMB} \to p\,e^+e^-$) (this is called the "dip model"), while the suppression at the highest energies would be described in terms of the predicted GZK effect. In the case of mixed composition scenarios such features may be described playing with different sources distributions and injection spectra, assuming that the maximum energy that each nucleus may attain, scales with its atomic number Z.

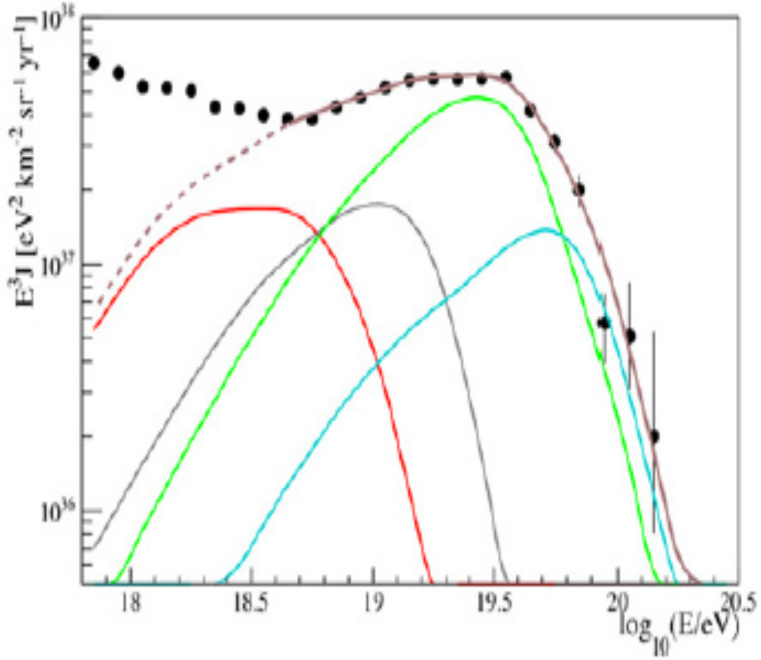
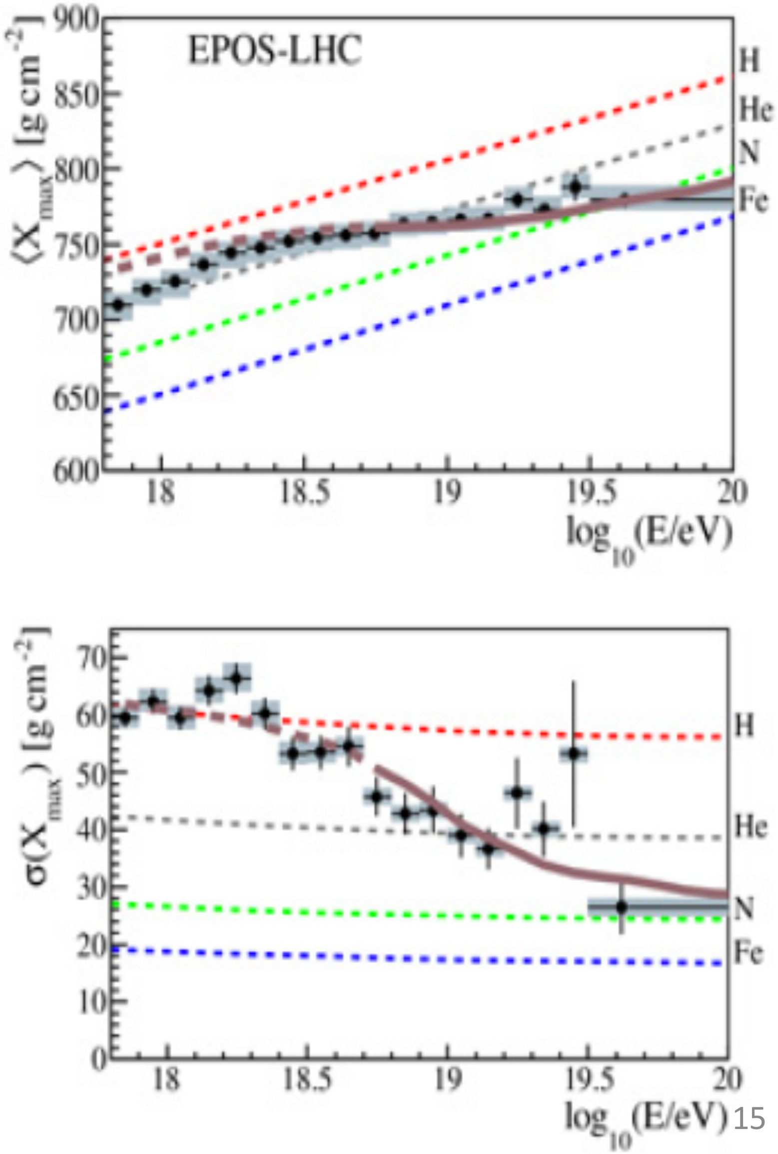


Fig. 10.37 UHECR Energy spectrum measured by the Pierre Auger Observatory (closed circles); the spectrum has been multiplied by E^3. Superposed is a fit to the sum of different components at the top of the atmosphere. The partial spectra are grouped as according to the mass number as follows: Hydrogen (red), Helium-like (grey), Carbon, Nitrogen,Oxygen (green), Aluminum-like (cyan), Iron-like (blue), total (brown). Image credit: Pierre Auger Collaboration

UHECR: Composition

The study of the first two momenta of the X_{max} ($\langle X_{max} \rangle$ itself and the RMS of $\langle X_{max} \rangle$) distributions is nowadays the main tool to constrain hadronic interactions models and hopefully access the cosmic ray composition. The mean and the RMS of the X_{max} distributions measured by the Pierre Auger collaboration as a function of the energy are shown in Fig. 10.42 and compared to the prediction for pure p, He, N and Fe. A fit to extract the fractions of each of these components as a function of the energy was then performed assuming several different hadronic interaction models. The results indicate evidence of a change of the cosmic ray composition from light elements (with a large fraction of protons) at lower energies to heavier elements (He or N depending on the hadronic model) but basically a null abundance of Fe at least until $10^{19.4}$ eV. However, none of the present simulations models is able to reproduce well the observed data. Combining the X_{max} results with variables related with the muonic contents of these extreme high energy EAS the tension between the measurements and the model predictions becomes even more evident.



UHECR: Sources

When integrating over all energies, say, above a few GeV, the arrival direction of charged cosmic rays is basically isotropic—a fact which can find explanation in the effect of the galactic magnetic field smearing the directions–the Compton-Getting effect, a dipole anisotropy of about 0.6% resulting from the proper motion of Earth in the rest frame of cosmic ray sources, has to be subtracted. However, Milagro, IceCube, HAWC, ARGO and the Tibet air shower array have observed additional small large-scale anisotropies (at the level of 10^{-3}), and small small-scale anisotropies (at the level of about 10^{-4}–10^{-5}) in an energy range from a few tens of GeV to a few hundreds of TeV (see Fig. 10.43). Its origin is still under debate; the disentangling of its probable multiple causes is not easy. There is no simple correlation of anisotropies with known astrophysical objects.

At extremely high energies, instead, statistically significant anisotropies have been found – and their interpretation is straightforward.

To accelerate particles up to the ultra-high-energy region above the EeV, 10^{18} eV, one needs conditions that are present in astrophysical objects such as the surroundings of SMBHs in AGN, or transient high-energy events such as the ones generating gamma ray bursts. Galactic objects are not likely to be acceleration sites for particles of such energy, and coherently we do not observe a concentration of UHECRs in the galactic plane; in addition, the galactic magnetic field cannot confine UHECRs above 10^{18} eV within our galaxy.

UHECR Sources

- Due to the GZK horizon and to EG B (1 nG - 1 fG), the number of sources is relatively small => some anisotropy could be found studying the arrival directions of UHECR
- Indication for intermediate-scale anisotropy, correlated to nearby AGN reported by Auger
- In ~30 000 CR with E>8 EeV recorded in 12 years, corresponding to a total exposure of 76,800 km2 sr yr, Auger has seen at > 5.2σ a dipole anisotropy of about 6.5%
- After correcting for B, the direction is consistent with the flux-weighted dipole from nearby AGN

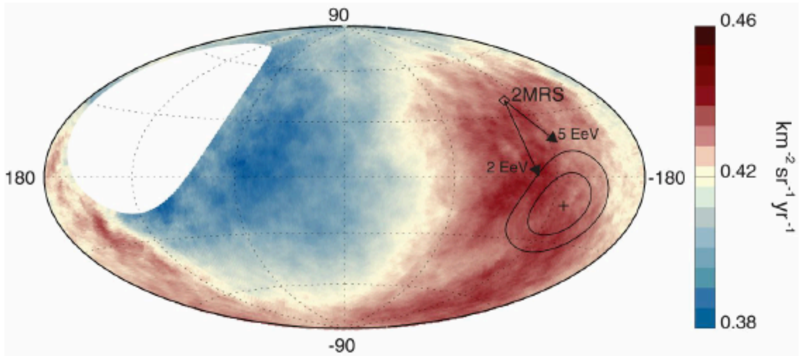
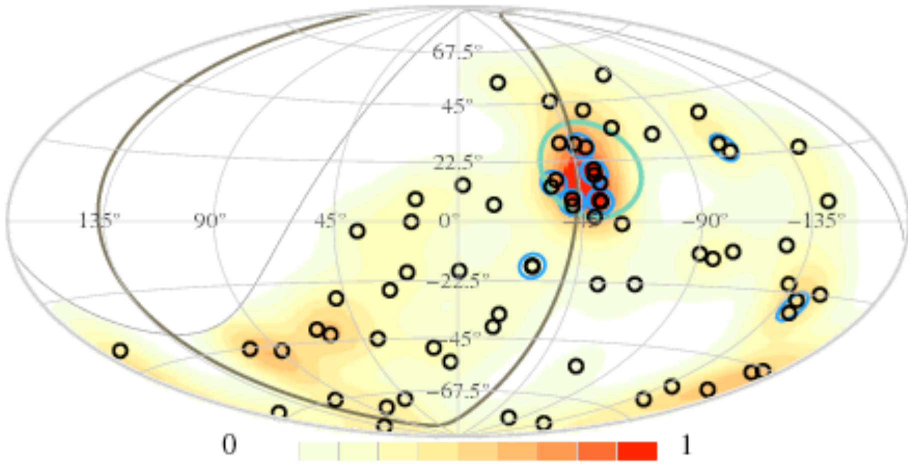
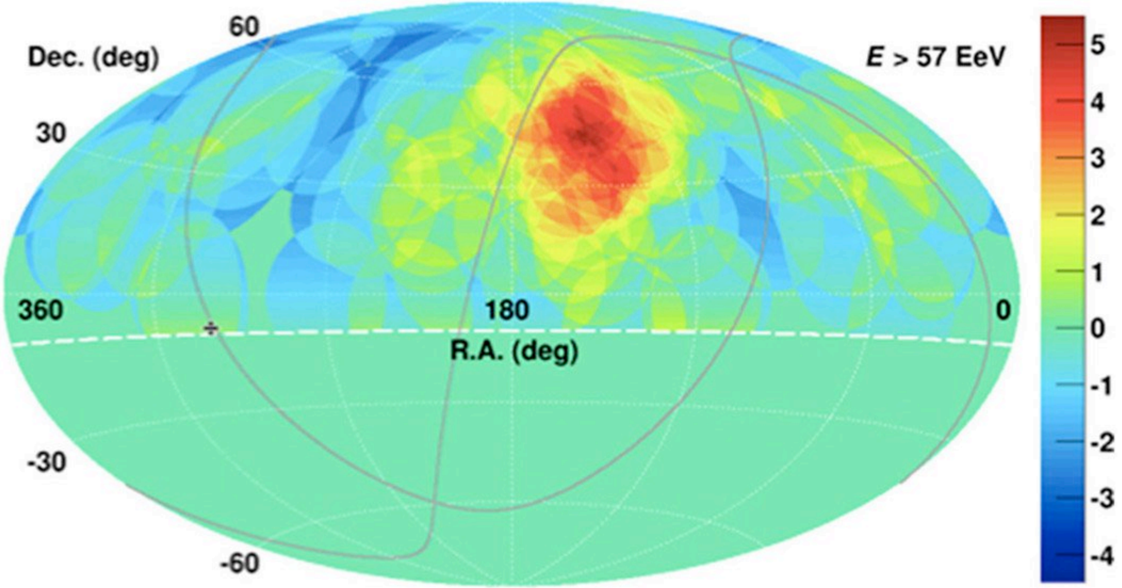


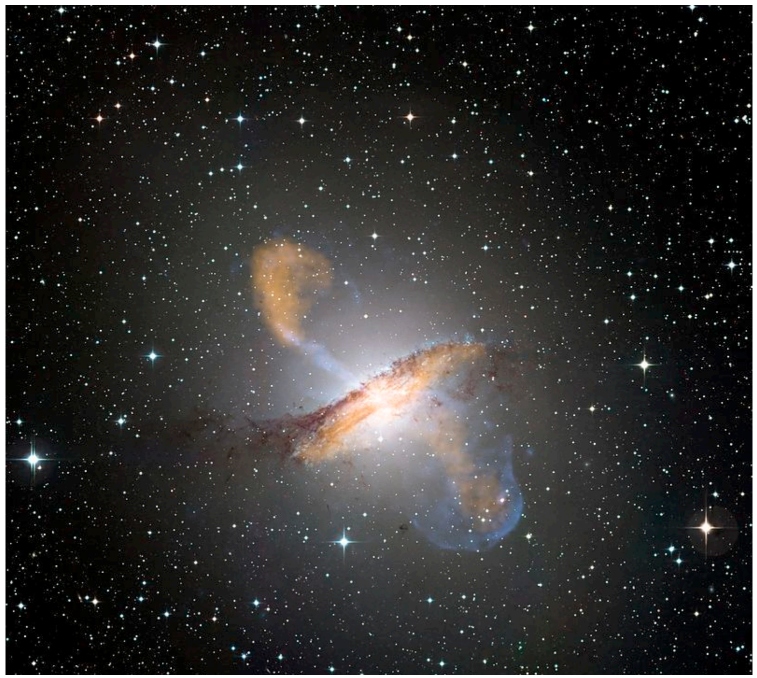
Fig. 10.44 Sky map in galactic coordinates showing the cosmic-ray flux for $E > 8$ EeV. The cross indicates the measured dipole direction; the contours denote the 68% and 95% confidence level regions. The dipole in the 2MRS galaxy distribution is indicated. Arrows show the deflections expected due to the galactic magnetic field on particles with $E/Z = 5$ and 2 EeV. Image credit: Pierre Auger collaboration

UHECR individual sources?

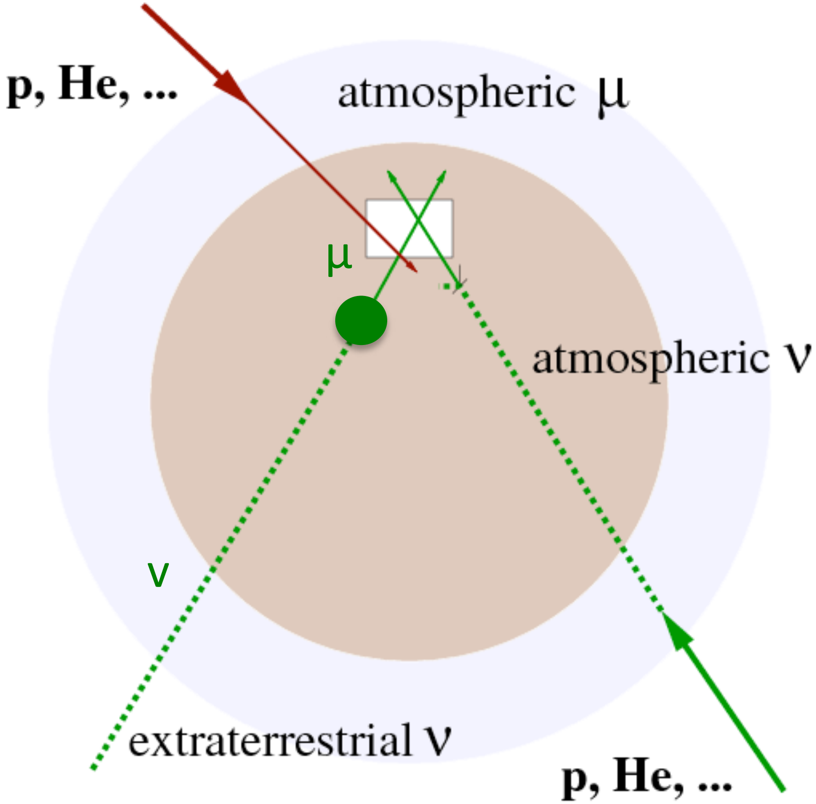
- In 2007 the Pierre Auger collaboration claimed with a signicance >3σ a hot spot near the Centaurus A AGN, at a distance of about 4 Mpc. Cen A is also a VHE gamma-ray emitter.
- However, the data collected after 2007 have not increased the signicance of the detection.
- The Telescope Array Project observes at energies above 57 EeV a hot spot, with best circle radius 25 degrees, near the region of the Ursa Major constellation.

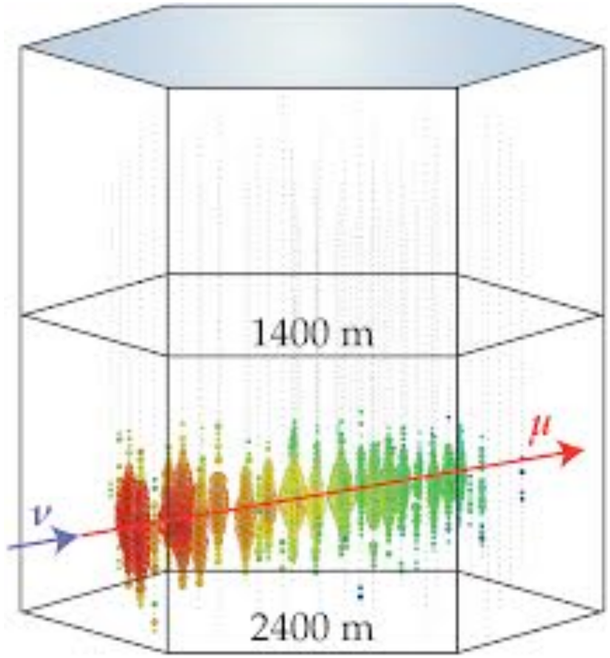






TXS 0506 +056: The IceCube neutrino





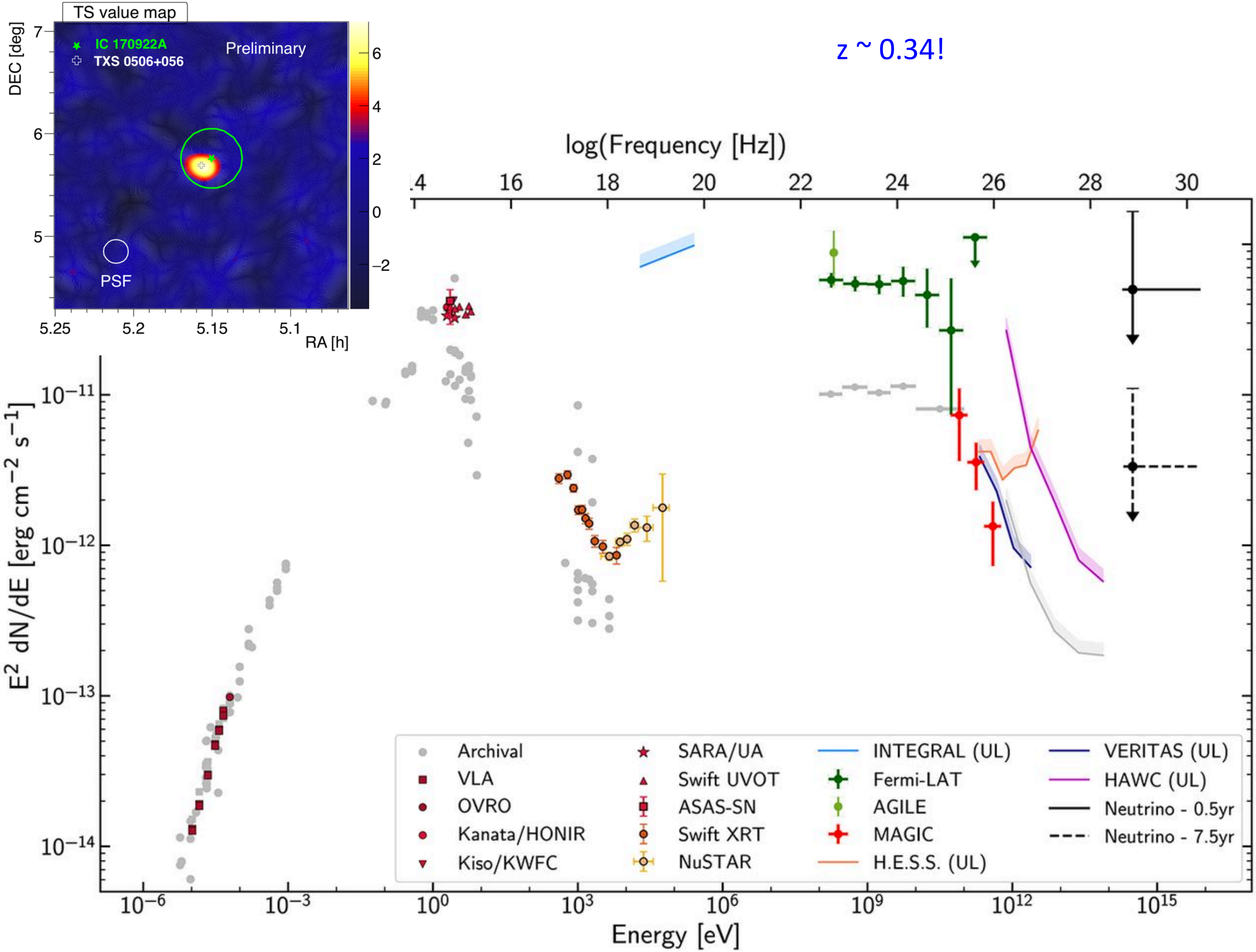
EXP

$E_{\mu,seen} \sim 20$ TeV
$E_\nu \sim 300$ TeV
$E_p \sim 6$ PeV – 10 PeV

TH

$E_p \sim 10$ PeV – 20 PeV

z ~ 0.34!

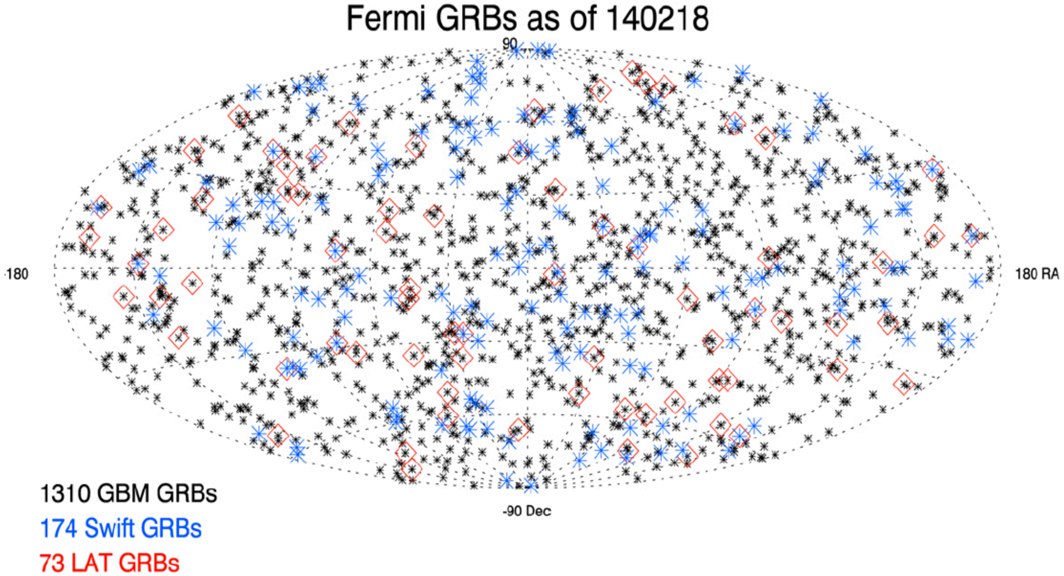

TS value map
IC 170922A
TXS 0506+056
Preliminary
PSF
DEC [deg]
RA [h]
log(Frequency [Hz])
E^2 dN/dE [erg cm^{-2} s^{-1}]
Energy [eV]
Archival
VLA
OVRO
Kanata/HONIR
Kiso/KWFC
SARA/UA
Swift UVOT
ASAS-SN
Swift XRT
NuSTAR
INTEGRAL (UL)
Fermi-LAT
AGILE
MAGIC
H.E.S.S. (UL)
VERITAS (UL)
HAWC (UL)
Neutrino - 0.5yr
Neutrino - 7.5yr

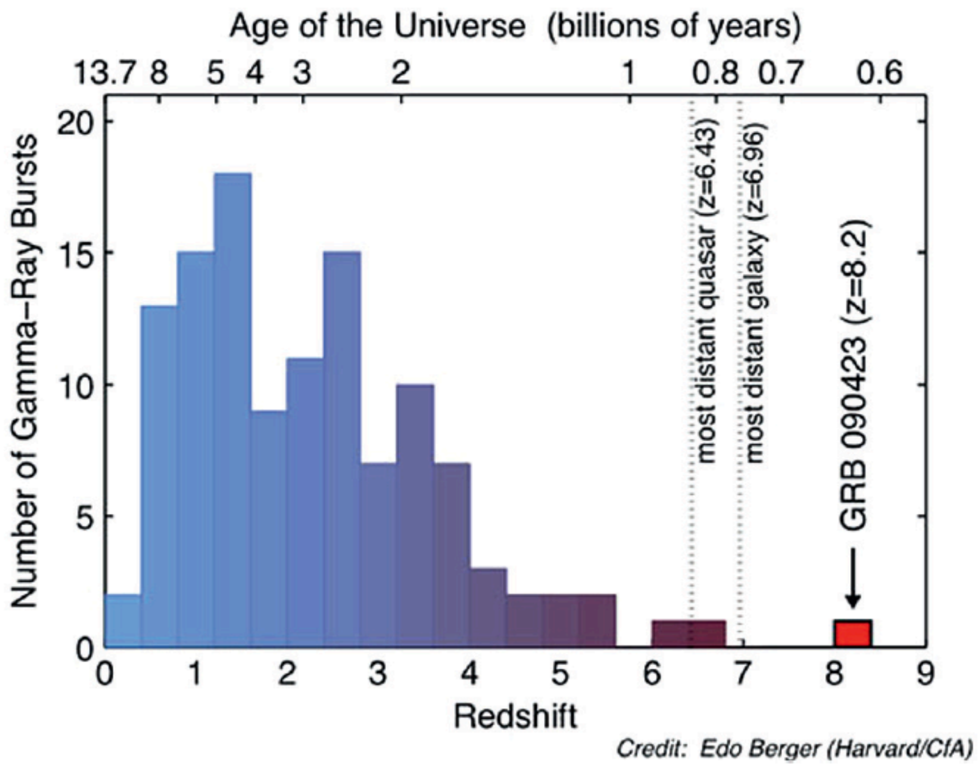
IceCube: Ep ~ 10 PeV

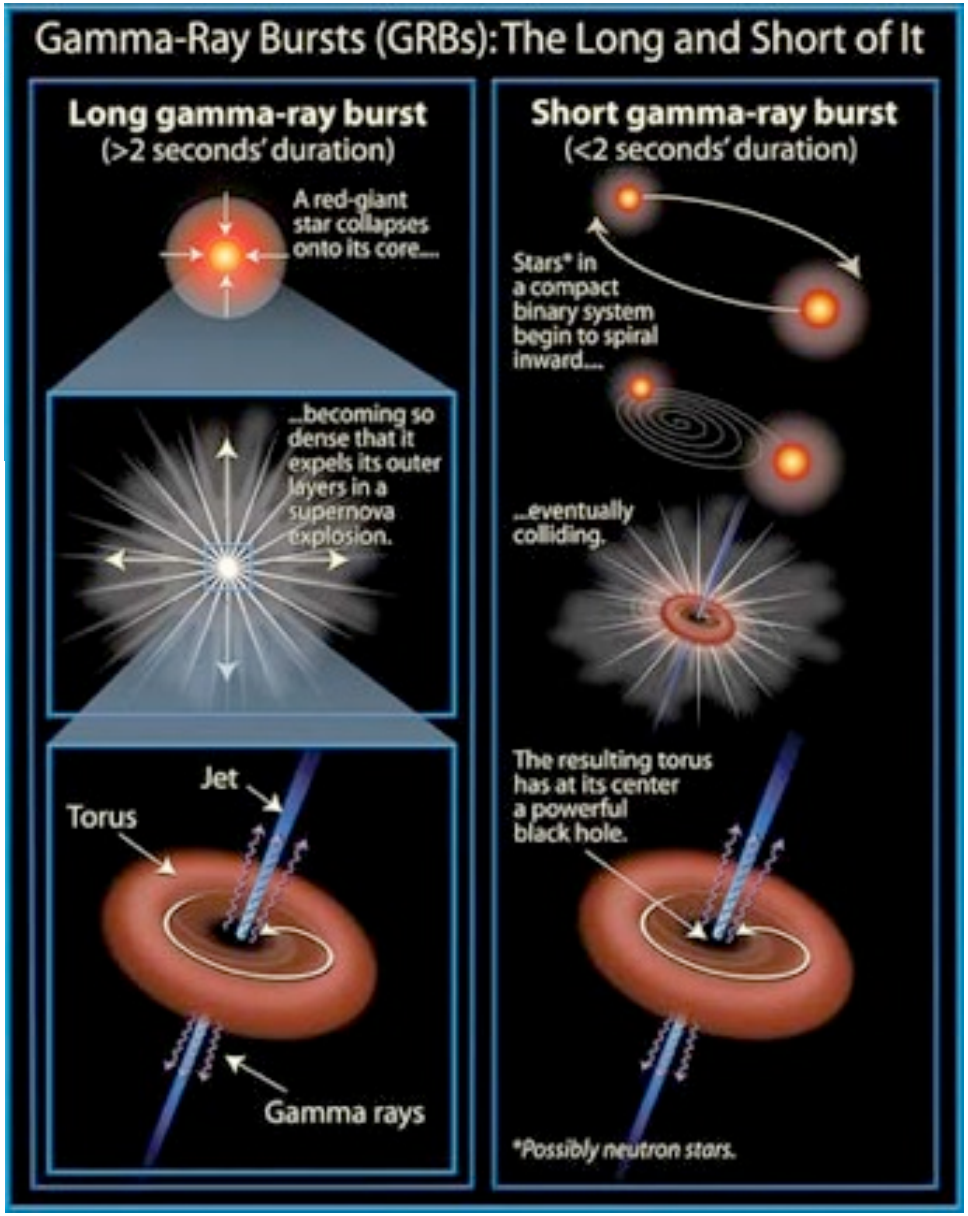
- Background probability extremely low

- Independent informations:
  - Neutrino flux (column density, cutoff energy for protons)
  - Gamma SED (column density, shape of the proton yield)
  - MW SED quiet/in flare: e/p ratio
  - Degradation of energy between gamma and neutrino: column density

GRBs


Fermi GRBs as of 140218
90
-180
180 RA
-90 Dec
1310 GBM GRBs
174 Swift GRBs
73 LAT GRBs


Age of the Universe (billions of years)
13.7 8 5 4 3 2 1 0.8 0.7 0.6
Number of Gamma−Ray Bursts
most distant quasar (z=6.43)
most distant galaxy (z=6.96)
GRB 090423 (z=8.2)
Redshift
Credit: Edo Berger (Harvard/CfA)


Gamma-Ray Bursts (GRBs): The Long and Short of It
Long gamma-ray burst
(>2 seconds' duration)
A red-giant star collapses onto its core...
...becoming so dense that it expels its outer layers in a supernova explosion.
Torus
Jet
Gamma rays
Short gamma-ray burst
(<2 seconds' duration)
Stars* in a compact binary system begin to spiral inward...
...eventually colliding.
The resulting torus has at its center a powerful black hole.
*Possibly neutron stars.

ABOUT THE EXAM…

About the exam: examples of articles

Some scientific articles/subjects you might choose for the final exam (of course you can propose your own, and I'll answer you if it's OK for me)

- WIMP mass limit from LHC
- DM searches from ASTROGAM (science with e-ASTROGAM, A. De Angelis et al.)
- Search for spectral irregularities due to photon-axionlike particle oscillations with the Fermi Large Area Telescope. By Fermi-LAT Collaboration (M. Ajello et al.). Phys. Rev. Lett. 116 (2016) 161101.
- Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A. The IceCube Collaboration et al. Science 12 Jul 2018: eaat1378.
- A gamma-ray determination of the Universe's star formation history. By Fermi-LAT Collaboration (M. Ajello et al.). Science 362 (2018) 1031.
- Observation of Gravitational Waves from a Binary Black Hole Merger. By LIGO and Virgo Collaborations (B. Abbott et al.). Phys. Rev. Lett. 116 (2016) 061102.
- …

- Or: analysis of Fermi data from a source (if done)