Muon bundles from the Universe*

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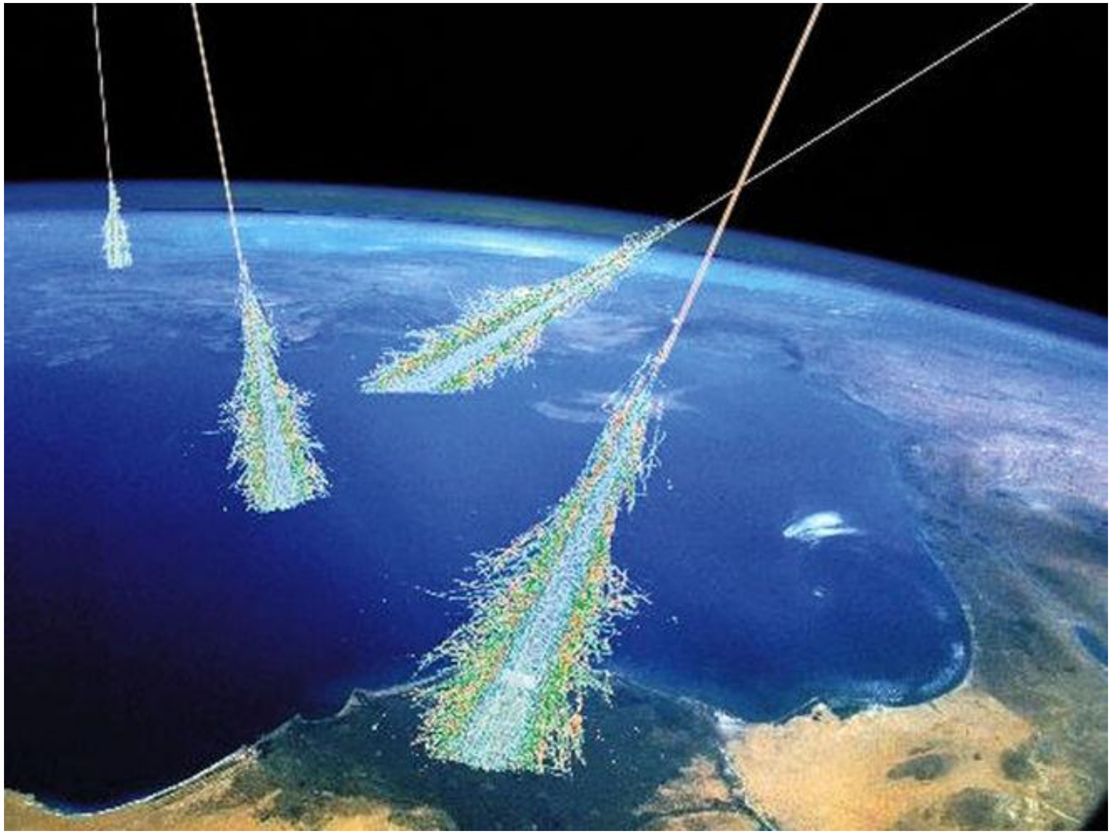
*based on P. Kankiewicz, MR, G. Wilk, and Z. Włodarczyk, **ApJ 839 (2017) 31** [arXiv:1612.04749]

Introduction

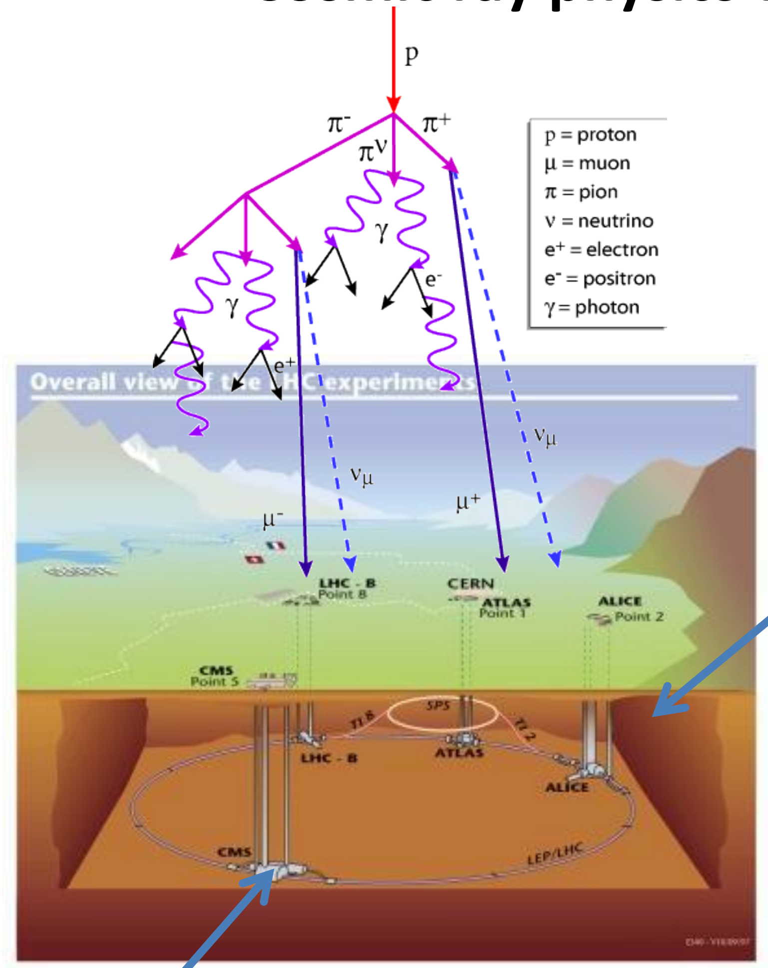
- ✓ Cosmic rays (CR) are particles coming from the Galaxy or outside the Galaxy reaching the Earth's atmosphere.
- ✓ 90% protons, 9% He nuclei, 1% heavier nuclei
- ✓ Gammas, neutrinos
- ✓ Rate ~1000 particles hits the atmosphere per m^2s

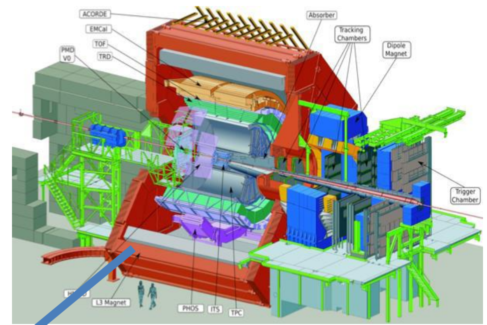
CR are characterized by:

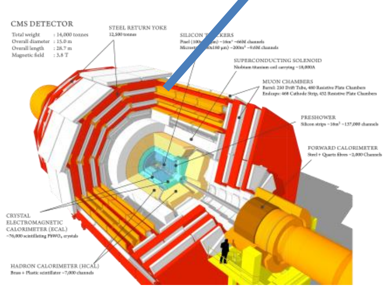
- ✓ Identity of the particle
- ✓ Energy ($10^9 – 10^{20}$ eV)
- ✓ All arrival directions



Cosmic ray physics with CERN experiments







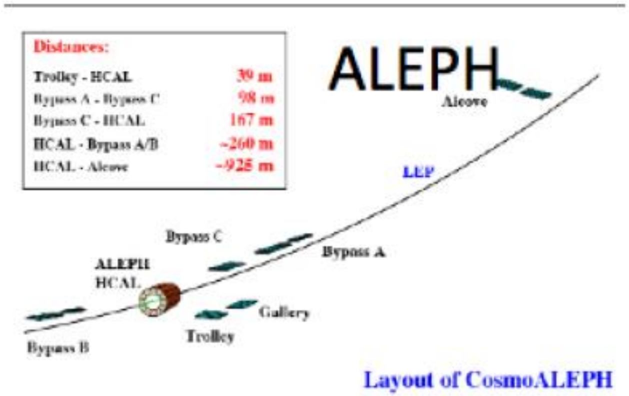
- ✓ Small detectors with respect to EAS experimets
- ✓ Low underground
- ✓ Detection of muons (only!) crossing the rock
- ✓ Short time of data taking

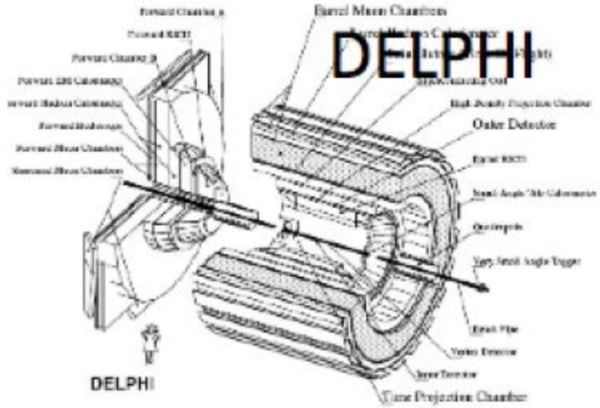
These detectors are not designed to cosmic ray physics!

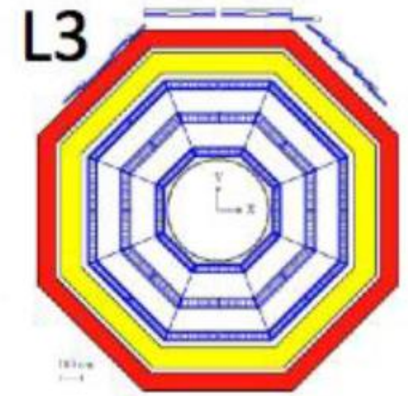
Advantages:

- Detectors with very high performance
- Presence of magnetic field

Detection of CR by CERN LEP experiments







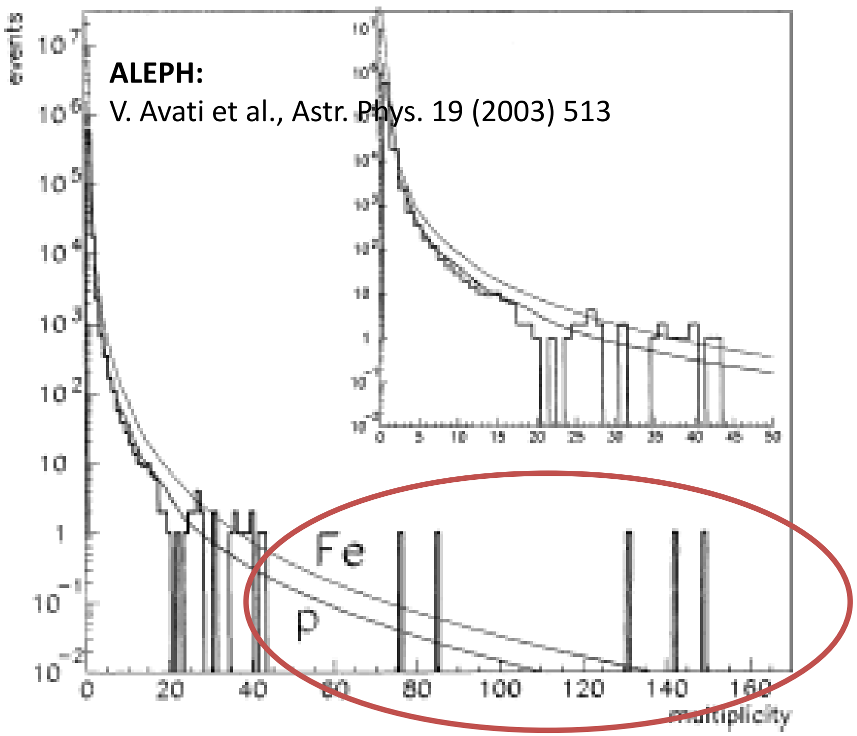
- **ALEPH: 130 m of rock, momentum muon threshold p > 70/cosθ**
  - ✓ underground scintillators, HCAL (horizontal area ~ 50 m^2), TPC projected area ~ 16 m^2

- **DELPHI: 100 m of rock, momentum muon threshold p > 52/cosθ**
  - ✓ Hadron calorimeter (horizontal area ~ 75 m^2), muon barrel, TPC, ToF and outer detectors

- **L3+C: 30 m of rock, momentum muon threshold p > 20/cosθ + surface array**
  - ✓ Scintillator surface array (200 m^2), trigger, muon barrel (100 m^2), hadron calorimeter, etc.

COSMIC RAY ENERGY COVERAGE FROM $10^{14} – 10^{18}$ eV

LEP results: muon multiplicity spectra



✓ These muon bundles are not well described (more than an order of magnitude above the simulation)

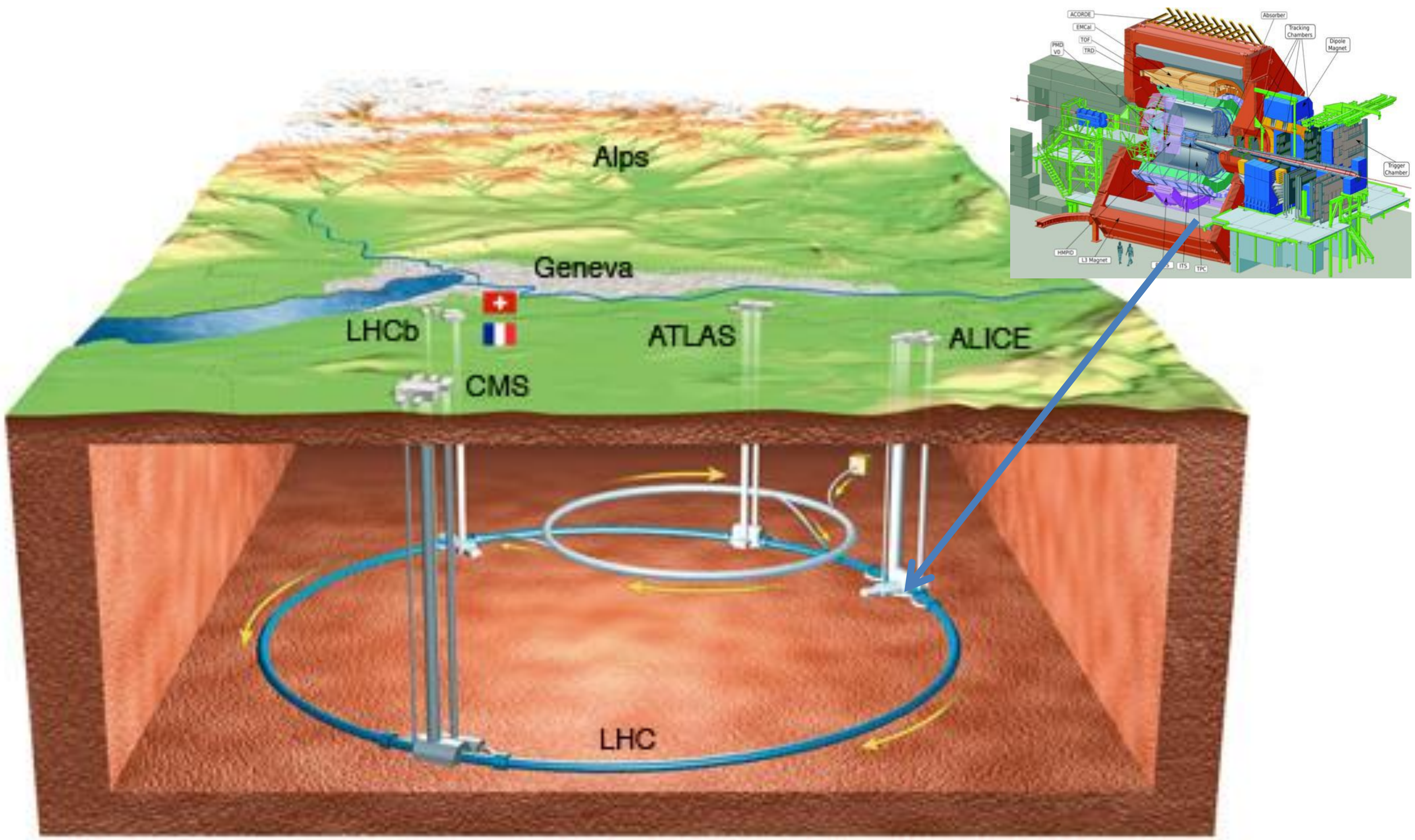
✓ Data indicates that heavier component is needed to explain higher multiplicity muon bundles

✓ Even the combination of extreme assumptions of highest measured flux value and pure iron spectrum, fails to describe the abundance of high multiplicity events.

✓ The conclusions of DELPHI and L3+C are similar to ALEPH

The only LEP result not consistent with the standard hadronic interaction models was the observation of the 'anomalous' number of high multiplicity muon bundles.

Detection of CR by the LHC ALICE experiment

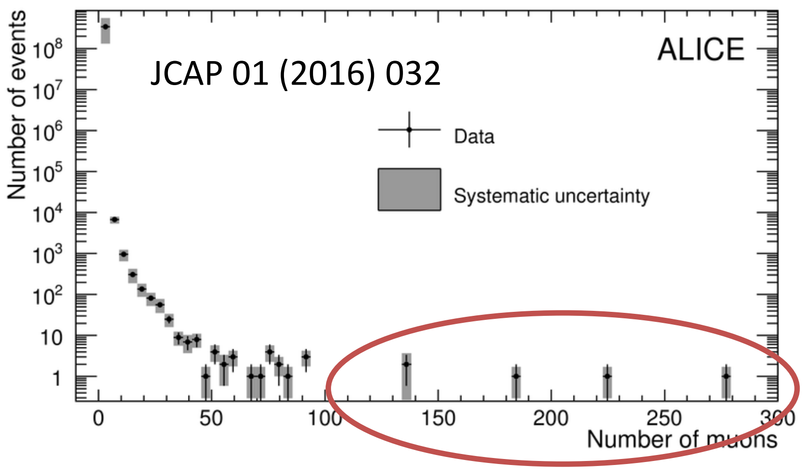


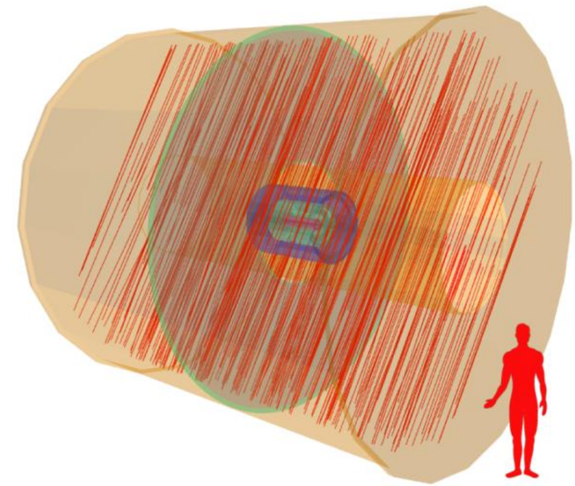
ALICE is located 40 m underground

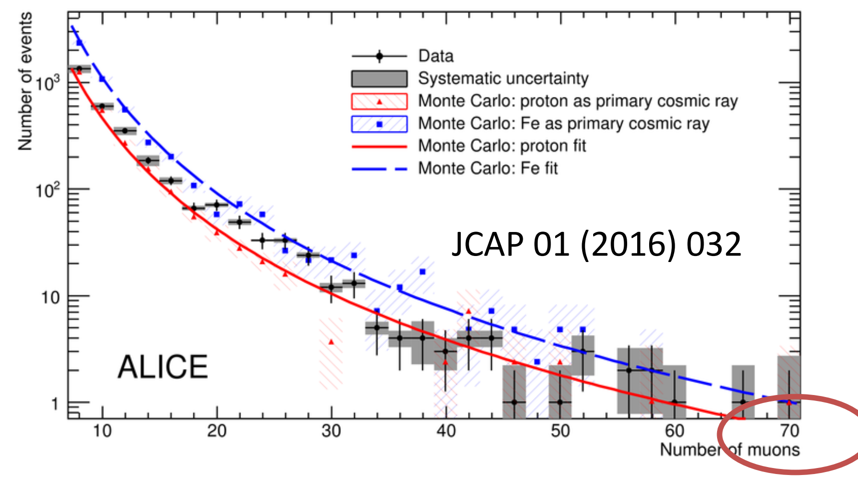
- ✓ **30 m of rock (molasse)**
- ✓ **10 m of air**

Detection of CR by the LHC ALICE experiment

Recently the ALICE experiment has been used to perform studies that are of relevance to astro-particle physics.







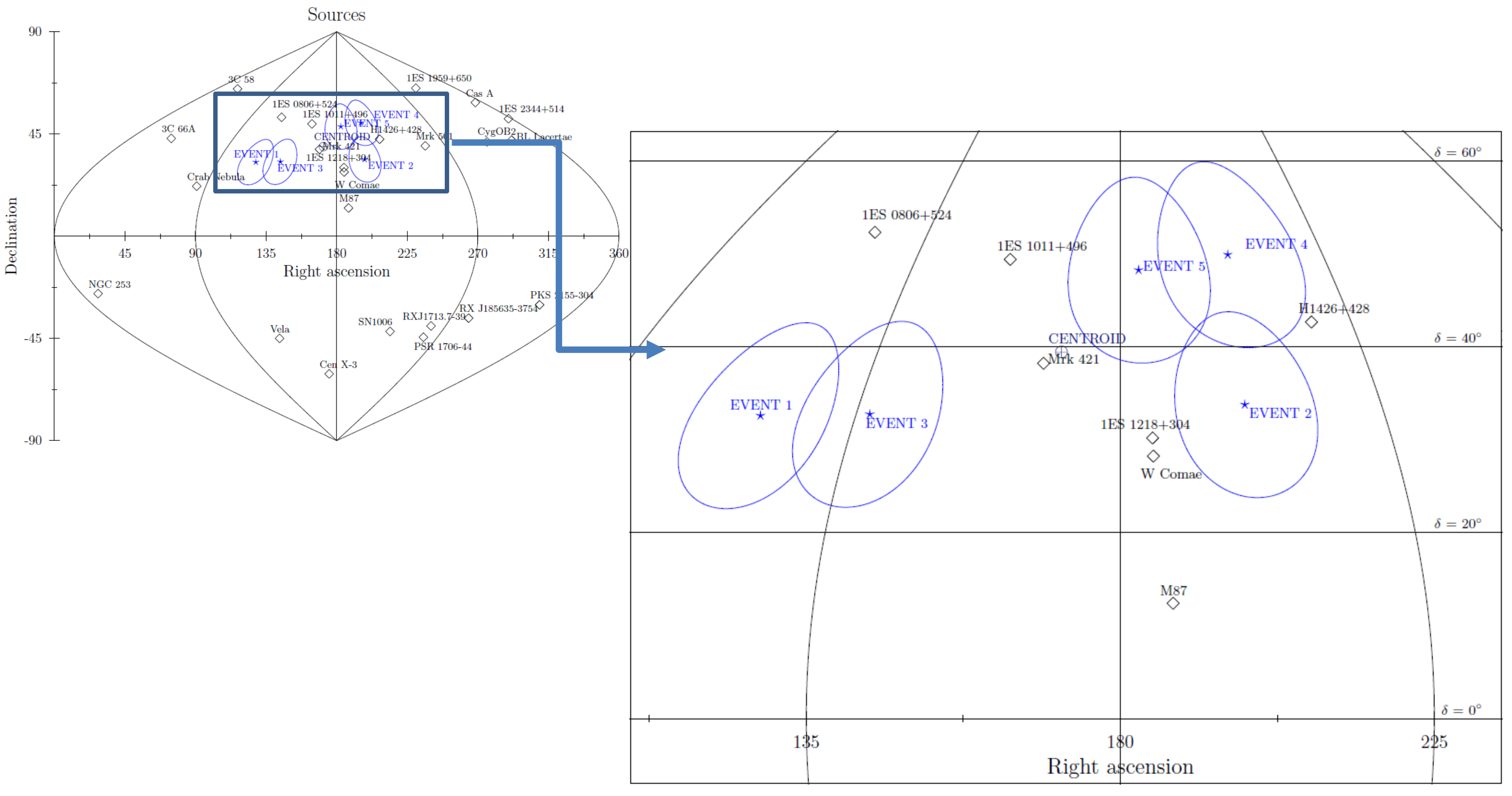
$0° < \Theta < 50°$

$E_{\mu} > 16\ \mathrm{GeV}/\cos\Theta$

Total time of data taking: 30.8 days

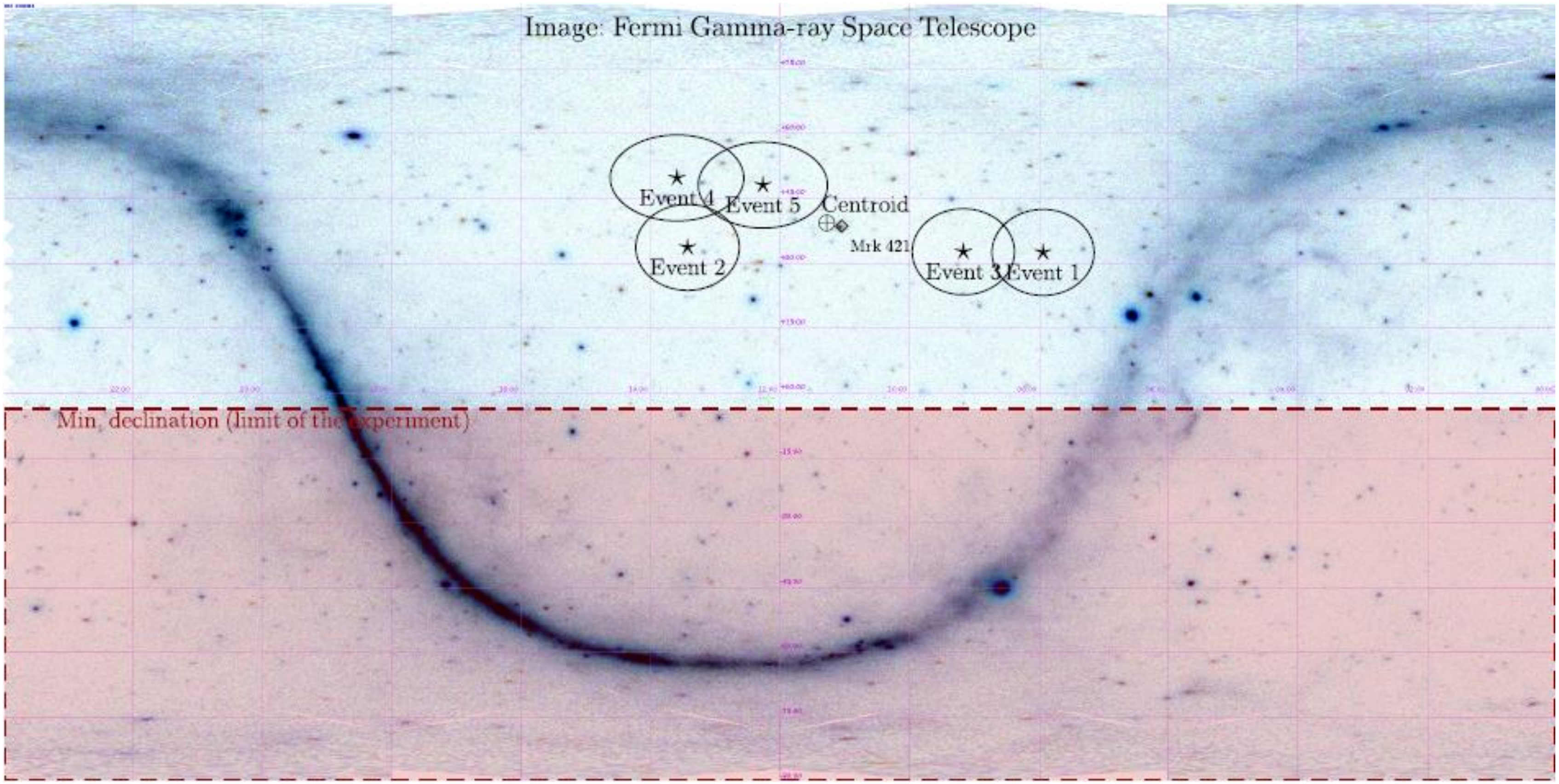
ALICE experiment registered the presence of large groups of muons produced in EAS by cosmic ray interactions in the upper atmosphere.

Anisotropy of arrival directions



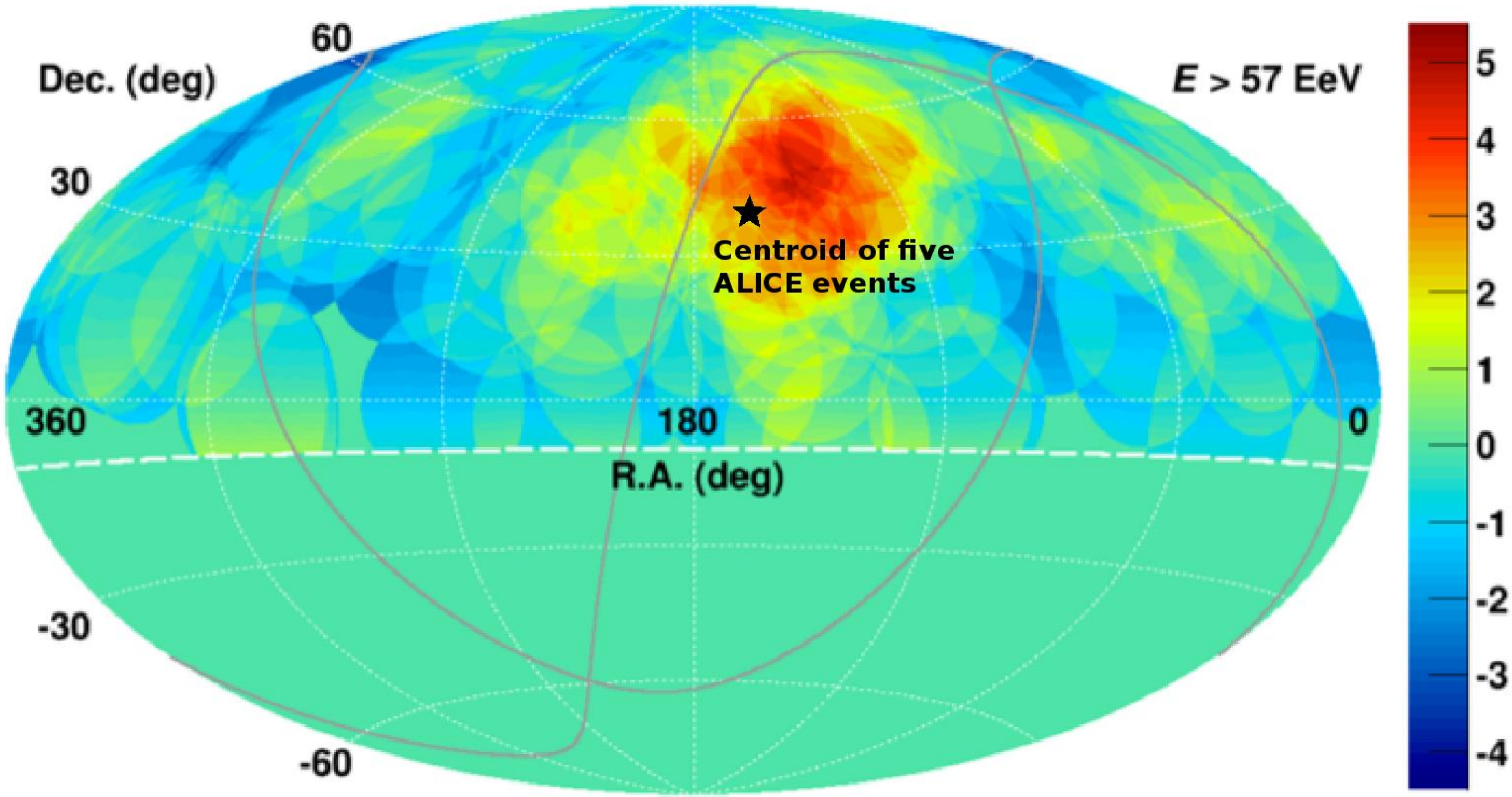
Five high-multiplicity muon events in the equatorial reference frame (α, δ).
Most known extragalactic TeV Sources (blazars, SNRs, radio galaxies) in the sky [Horan and Weekes, New Astr. Rev. 48 (2004) 527], [Turley et al., arXiv:1608.08983] are also shown (note that **the Mrk 421 blazar** is the source located very close to the centroid of the five considered events).

Anisotropy of arrival directions



Five high-multiplicity muon events. All events are located close to the galactic pole (far from the galactic plane). Background: Inverted (negative) image of the Fermi telescope mosaic. The minimum declination limit (due to the restricted zenith angle in the experiment) is marked by a horizontal line. The area in the southern sky not covered by the experiment is marked by a rectangle (filled).

Anisotropy of arrival directions



Aitoff projection of the UHECR map in equatorial coordinates taken from Telescope Array Collaboration data **[The Astrophysical Journal Letters 790 (2014) L21]**

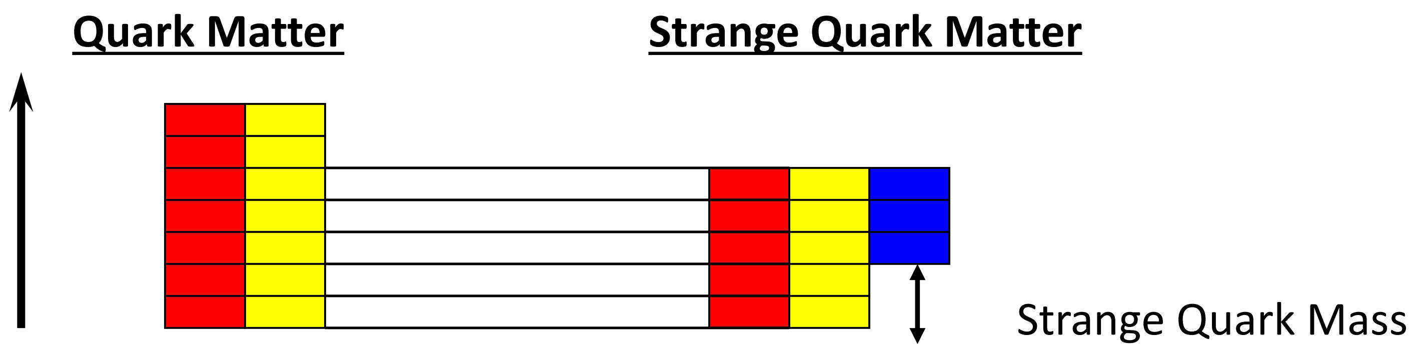
The possible source
of high multiplicity muon groups

What is strange quark matter?

Strange quark matter (SQM) composed of up, down and strange quarks may be meta-stable or even stable in bulk.

States have a reduced Fermi energy, reduced Coulomb, no fission.
Thus SQM states could range in size from A=2 to A > 10^6.

Witten [PRD 30 (1984) 272] proposed that SQM could even be the ground state of nuclear matter and could exist in bulk as remnants of the Big Bang.

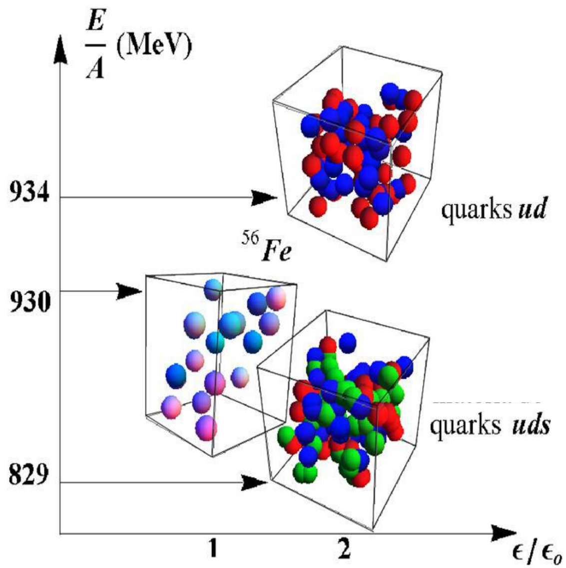


The addition of strange quarks to the system allows the quarks to be in lower energy states despite the additional mass penalty.

There is additional stability from reduced Coulomb repulsion. SQM is expected to have low Z/A

Strange quark matter

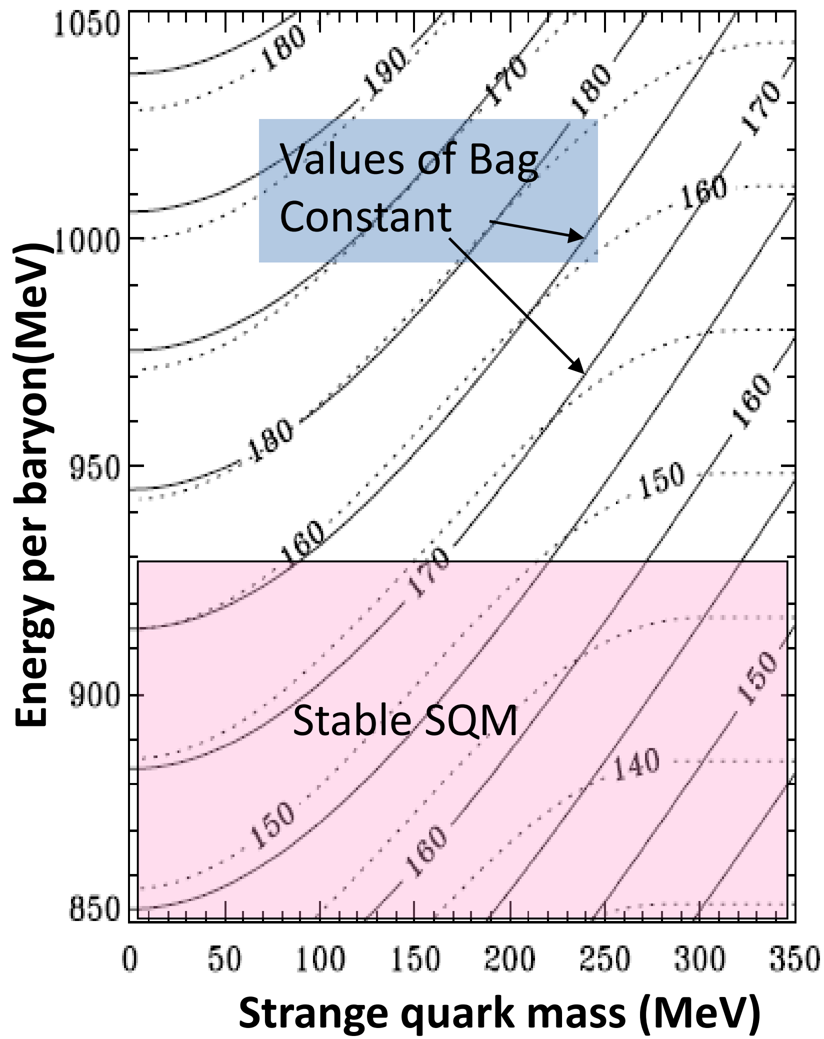
Ground state of nuclear matter?



Stability can not be calculated in QCD, but is addressed in phenomenological models (MIT Bag Model, Color Flavor Locking…).

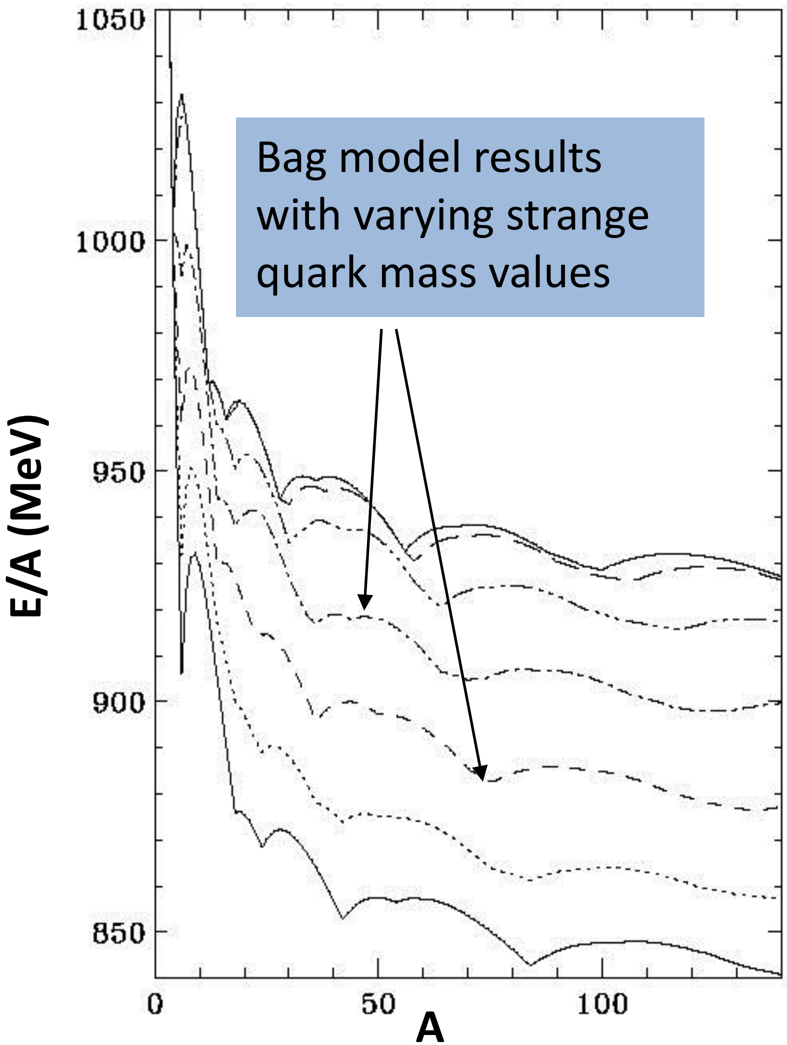
For a large part (~half) of available parameter space, these models predict that SQM is absolutely stable in bulk

J. Madsen, PRL 87 (2001) 172003



Strange quark matter

Roughly equal numbers of u, d, s quarks in a single ‘bag’ of cold hadronic matter.

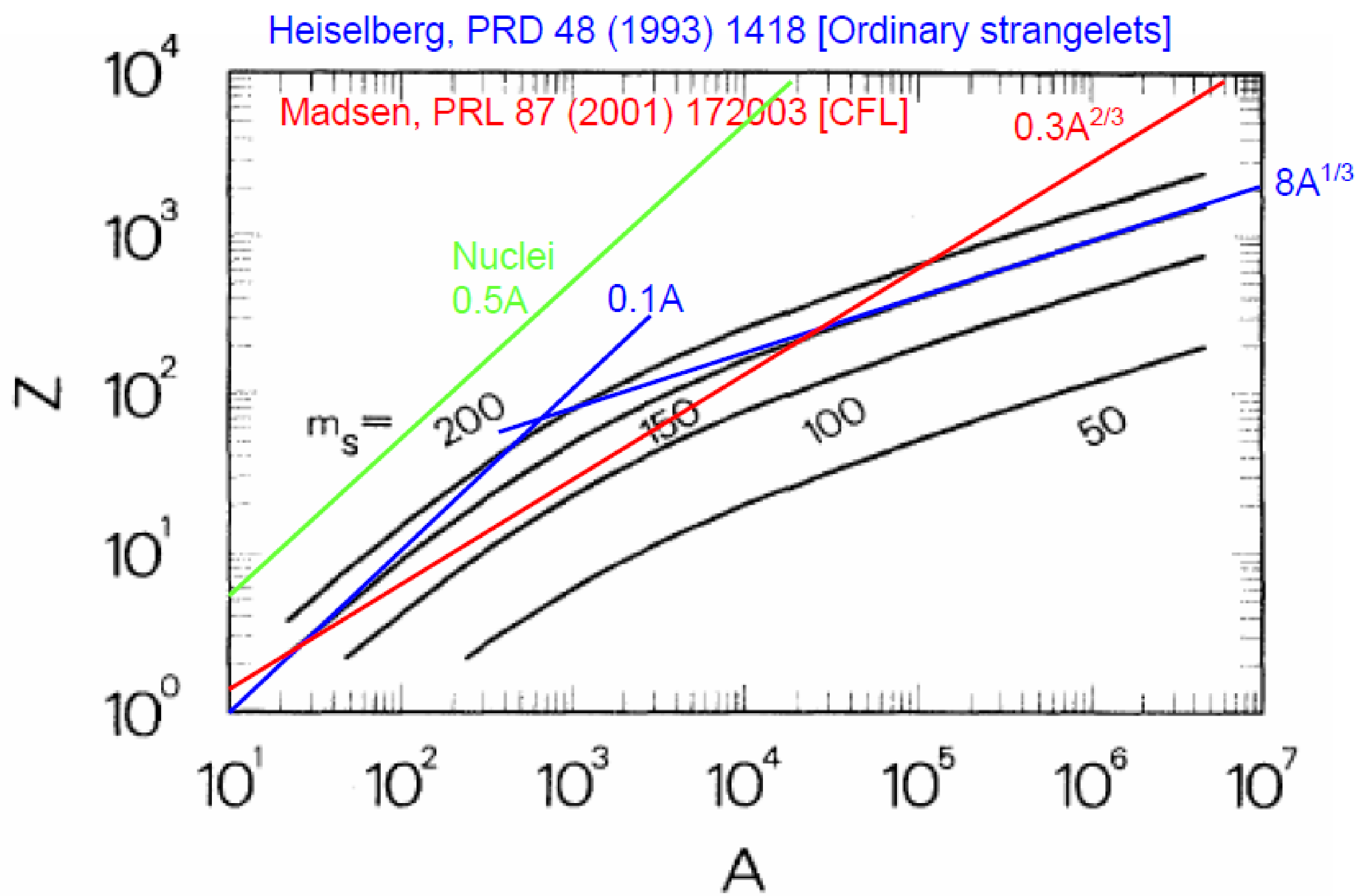


SQM is less stable
for lower baryon number (A < ~1000)

[E. Farhi, R.L. Jaffe, Phys. Rev. D 30 (1984) 2379]
[C. Alcock and E. Farhi, Phys. Rev. D 32 (1985) 1273]

Strange quark matter

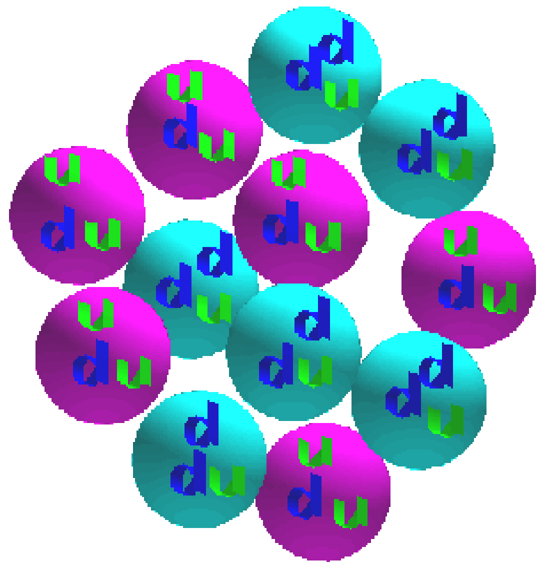
Roughly equal numbers of u, d, s quarks in a single ‘bag’ of cold hadronic matter.



Strange Quark Matter have low Z/A

Strange quark matter

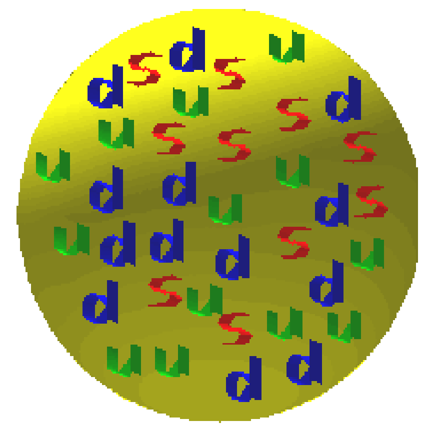
Roughly equal numbers of u, d, s quarks in a single 'bag' of cold hadronic matter.



Nucleus (^{12}C)

Z=6, A=12

Z/A = 0.5



Strangelet*

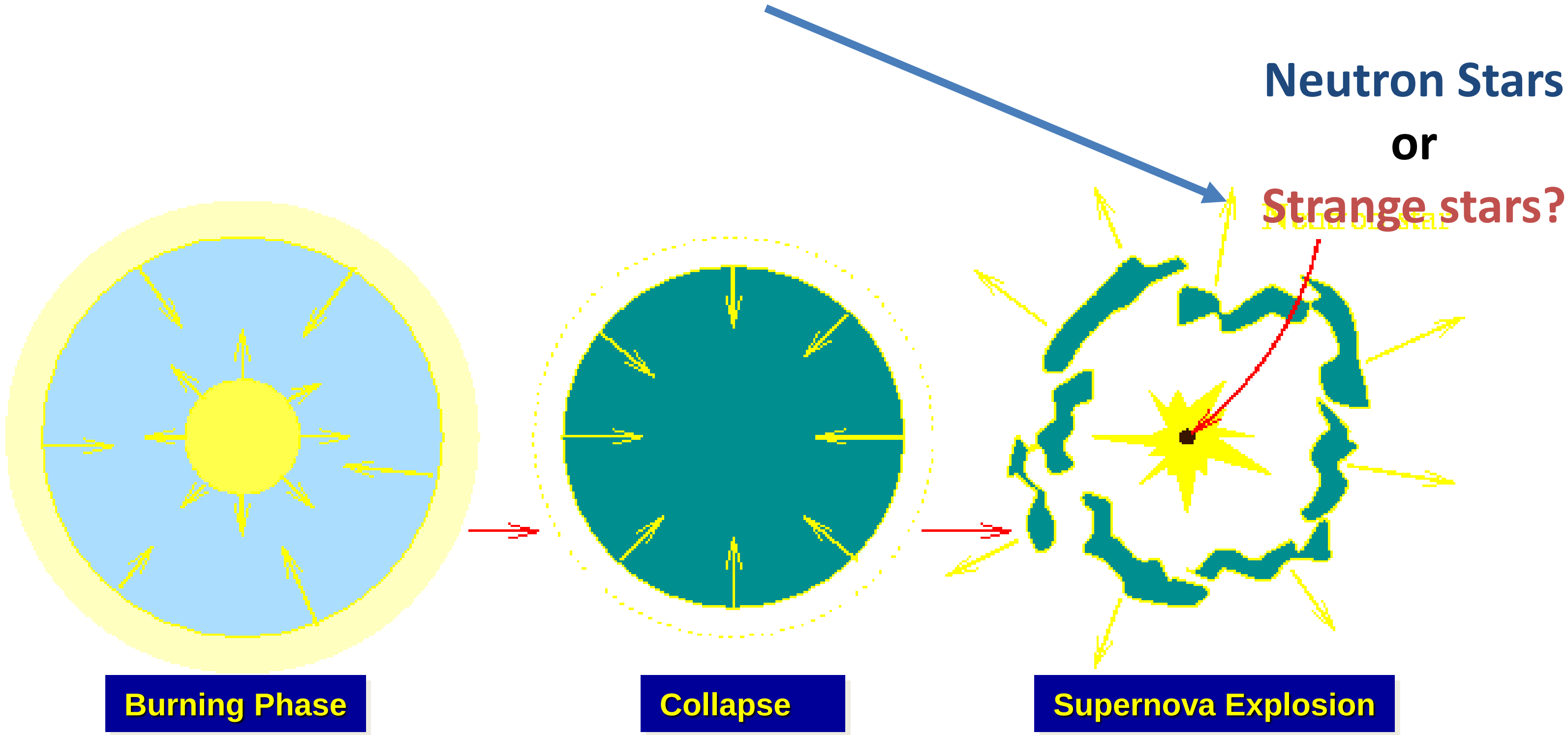
A=12 (36 quarks)

Z/A = 0.083

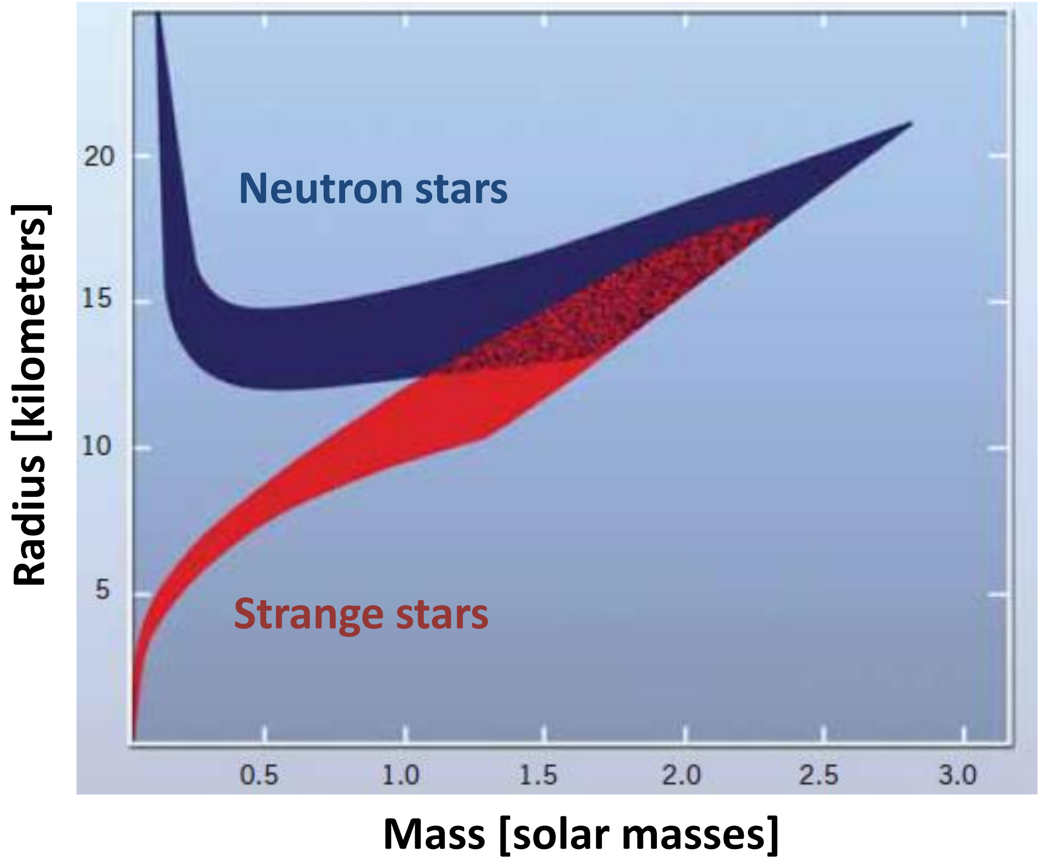
*small lump of Strange Quark Matter

Strange stars

Witten, PRD 30 (1984) 272
Haensel et al., A&A 160 (1986) 121
Alcock et al., ApJ 310 (1986) 261



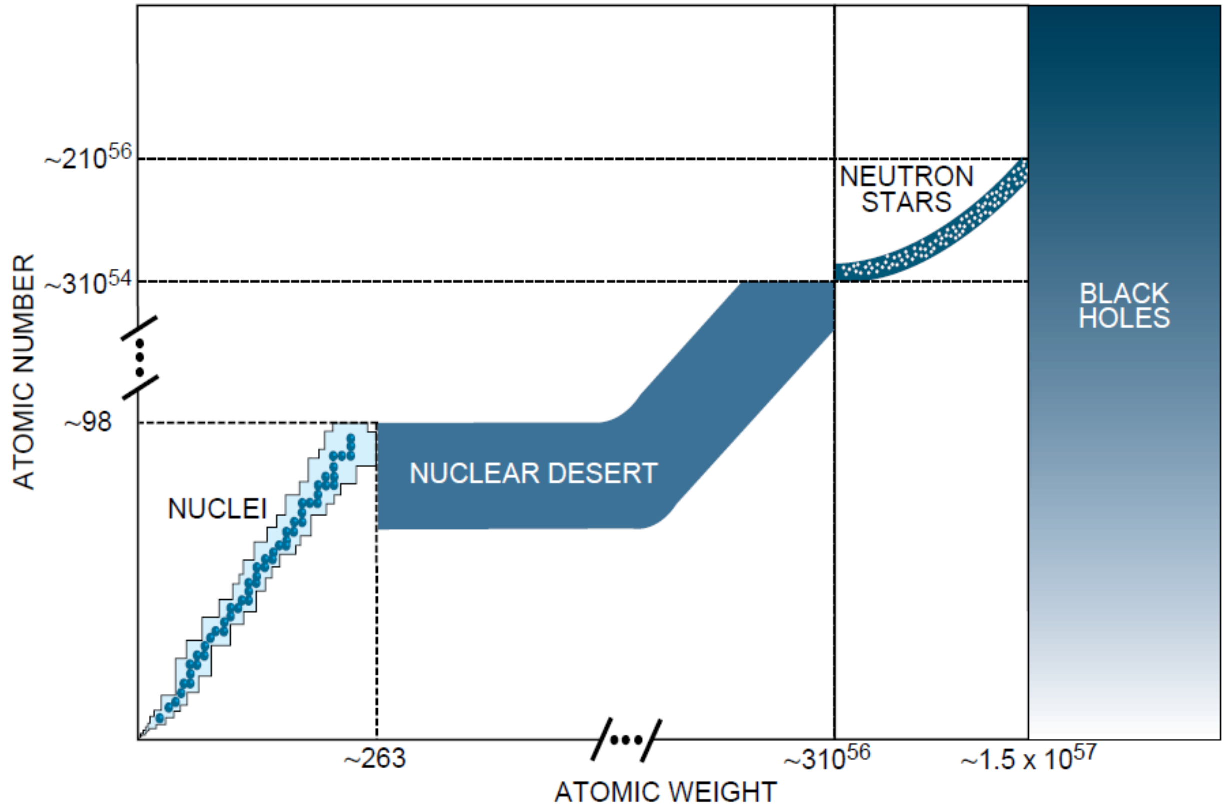
Strange stars: a curiosity



Plot from P. Haensel, Świat Nauki, March 2005

Strange stars may be much smaller than neutron stars.

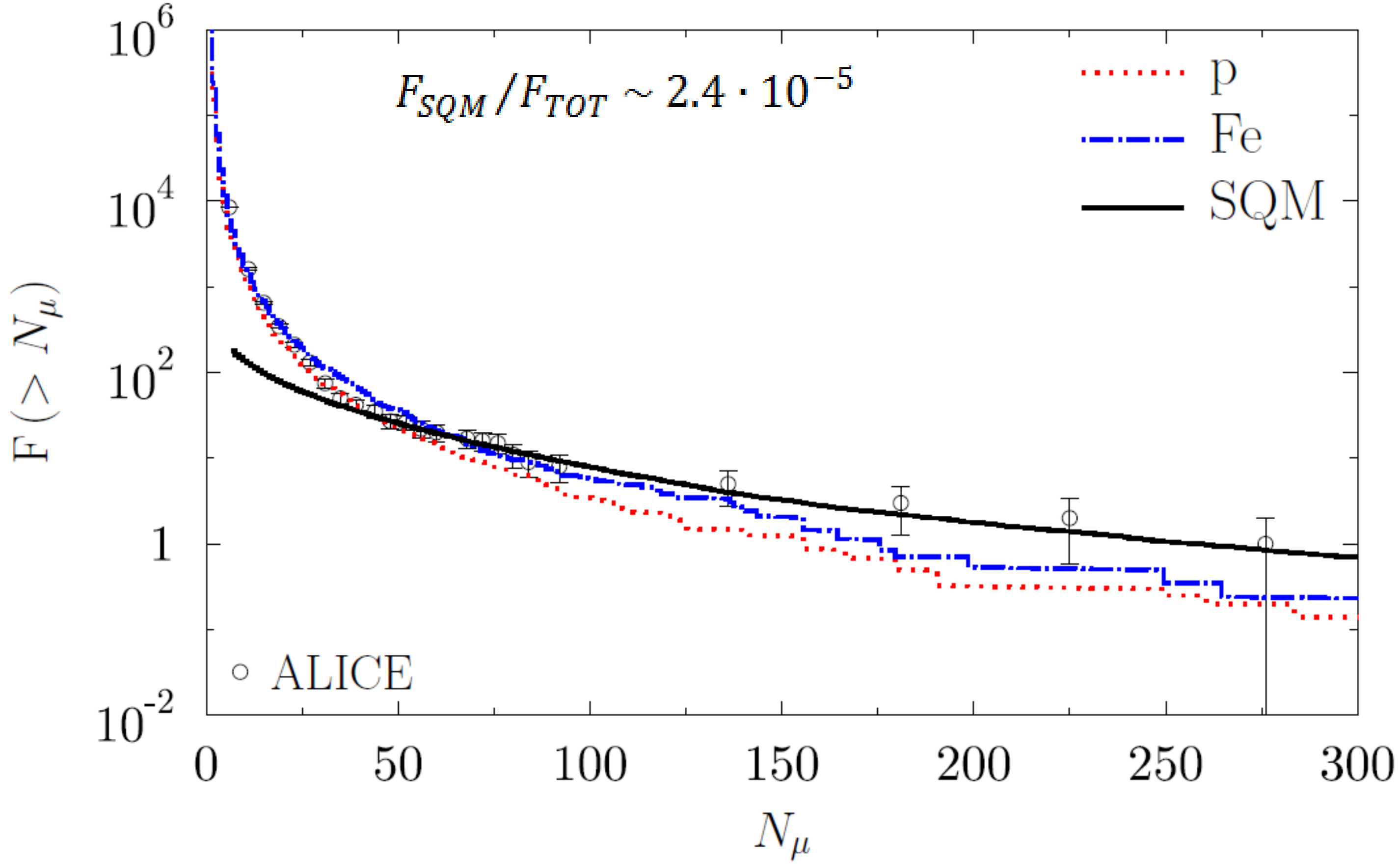
Chart of nuclides



Plot from Sci. Am. 270 (1994) 58

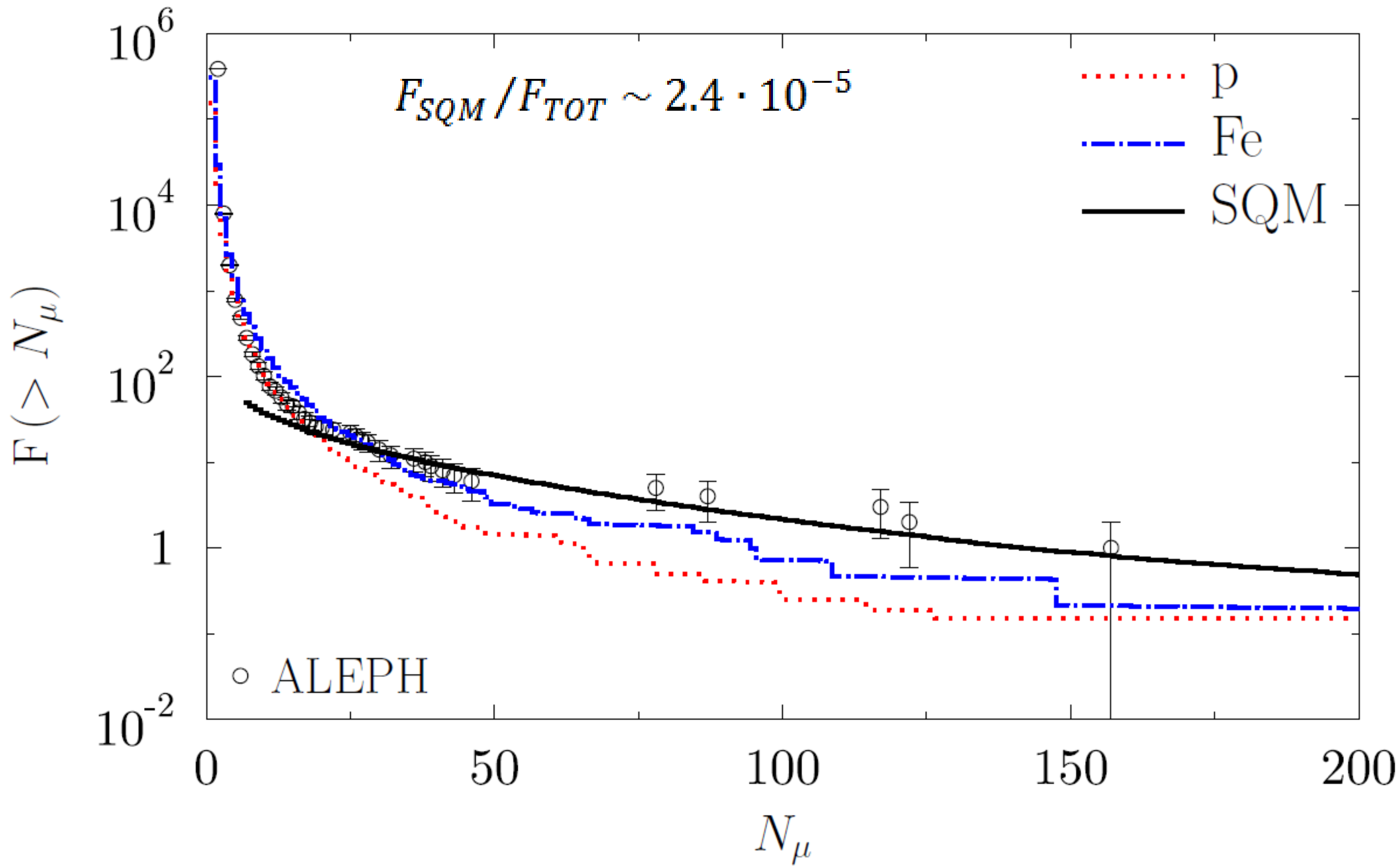
CHART OF NUCLIDES shows all known forms of stable matter. Between the heaviest atomic elements and neutron stars, which are giant nuclei, lies a vast, unpopulated nuclear desert. This void may actually be filled with strange quark matter.

High multiplicity muon bundles from strange quark matter



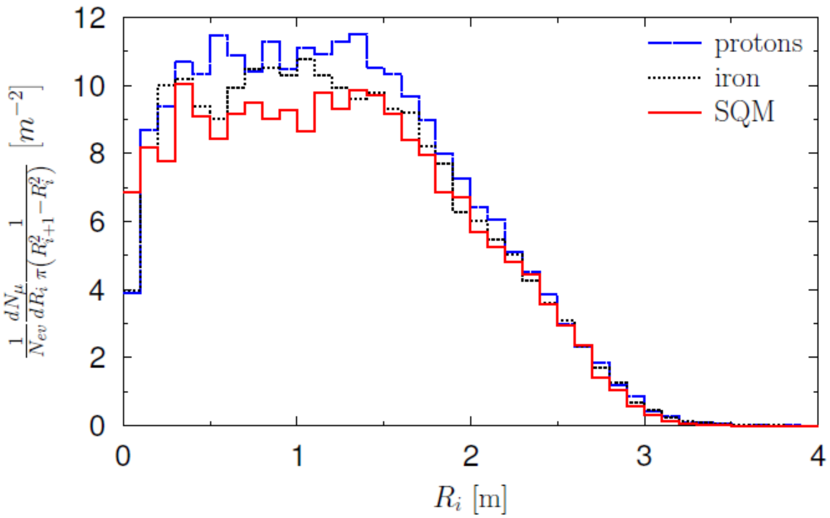
Integral multiplicity distribution of muons for the ALICE data (circles) published in JCAP 01 (2016) 032. Monte Carlo simulations for primary protons (dotted line); iron nuclei (dashed dot line) and primary strangelets with mass A taken from the $A^{-7.5}$ distribution (full line) with abundance of the order of $2 \cdot 10^{-5}$ of the total primary flux.

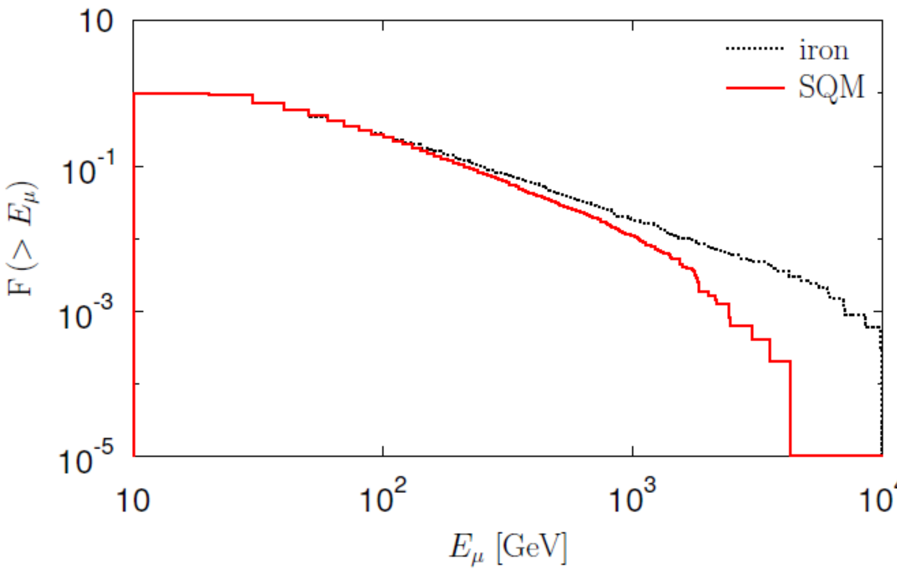
High multiplicity muon bundles from strange quark matter



Integral multiplicity distribution of muons the ALEPH data (circles) published in Astr. Phys. 19 (2003) 513. Monte Carlo simulations for primary protons (dotted line); iron nuclei (dashed dot line) and primary strangelets with mass A taken from the $A^{-7.5}$ distribution (full line) with abundance of the order of $2 \cdot 10^{-5}$ of the total primary flux.

How to distinguish different primaries in ALICE?





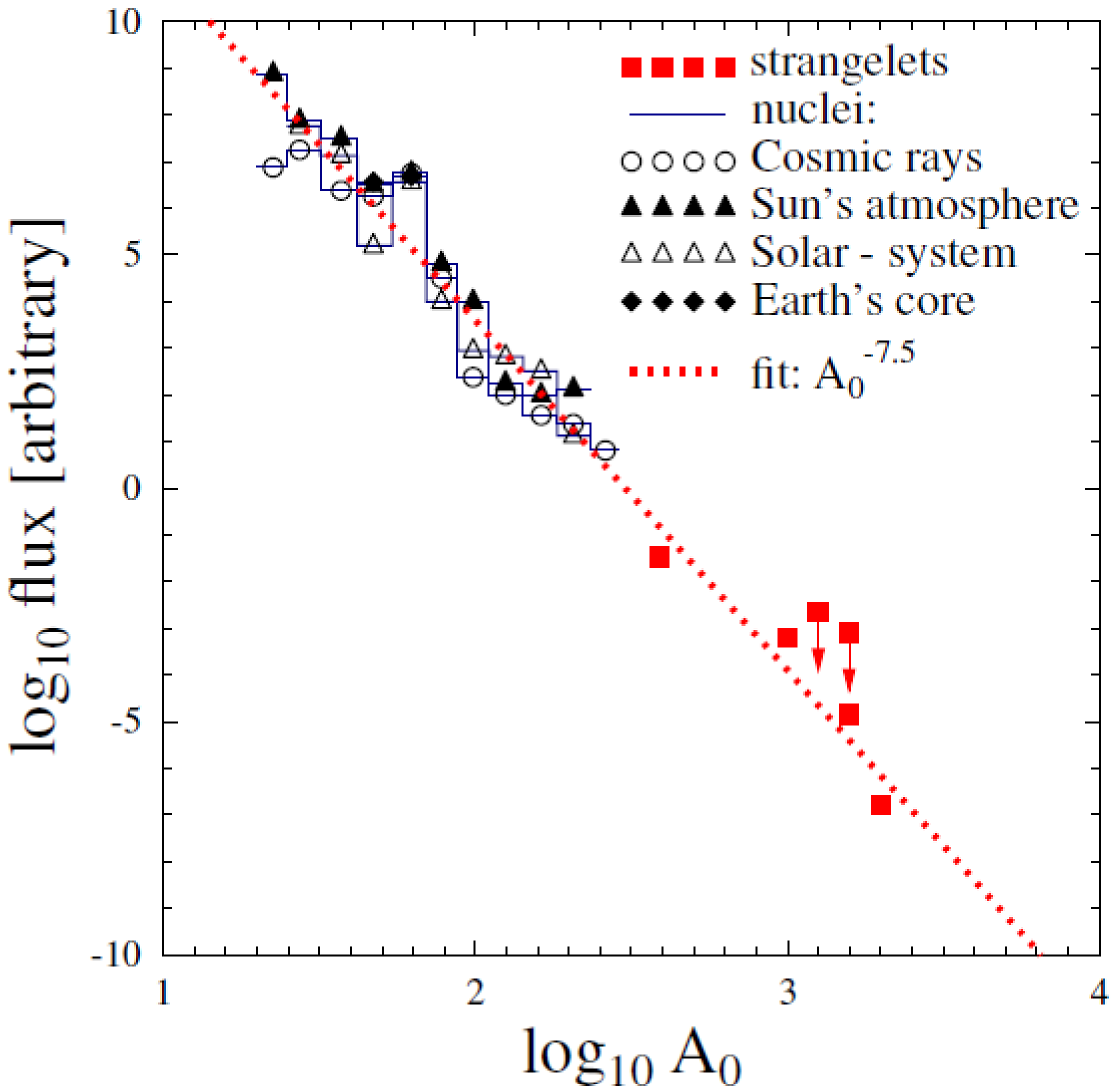
Muons from events with $N_\mu > 100$

Conclusions

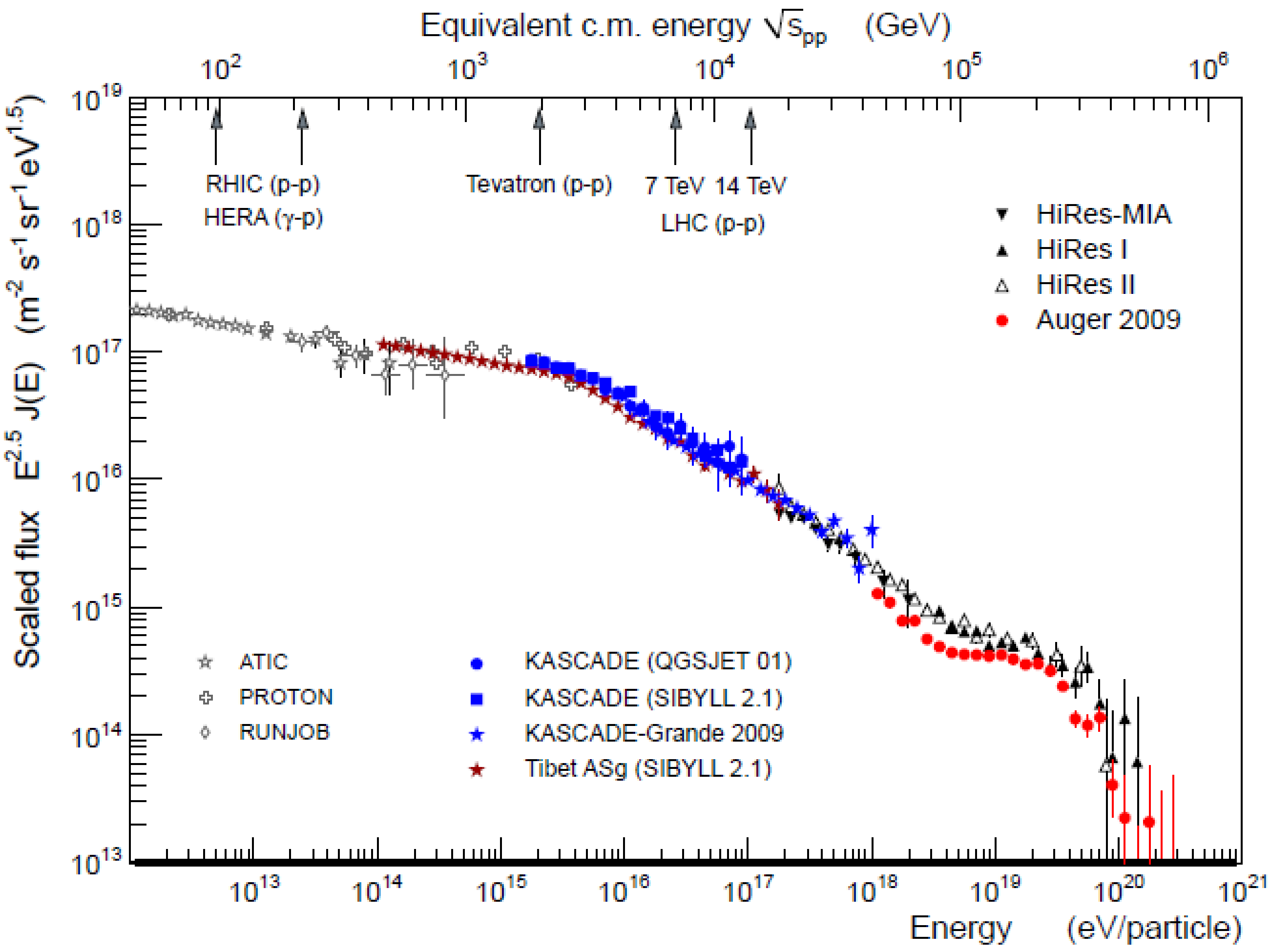
- ✓Accelerator apparata can be suitable for cosmic-ray physics.
- ✓ The measured by the CERN ALICE experiment low multiplicities of muon groups favor light nuclei as primaries, medium multiplicities show tend to heavier primaries.
- ✓ At high multiplicities of muon groups the common interaction models fail to describe muon bundles.
- ✓ A relatively small (of the order of 10^{-5} of total primary flux) admixture of SQM of the same total energy allows to reproduce the high muon multiplicity groups.
- ✓ The arrival directions of the observed high muon multiplicity groups suggest their extragalactic origin

Additional slides

Abundances of elements in the Universe

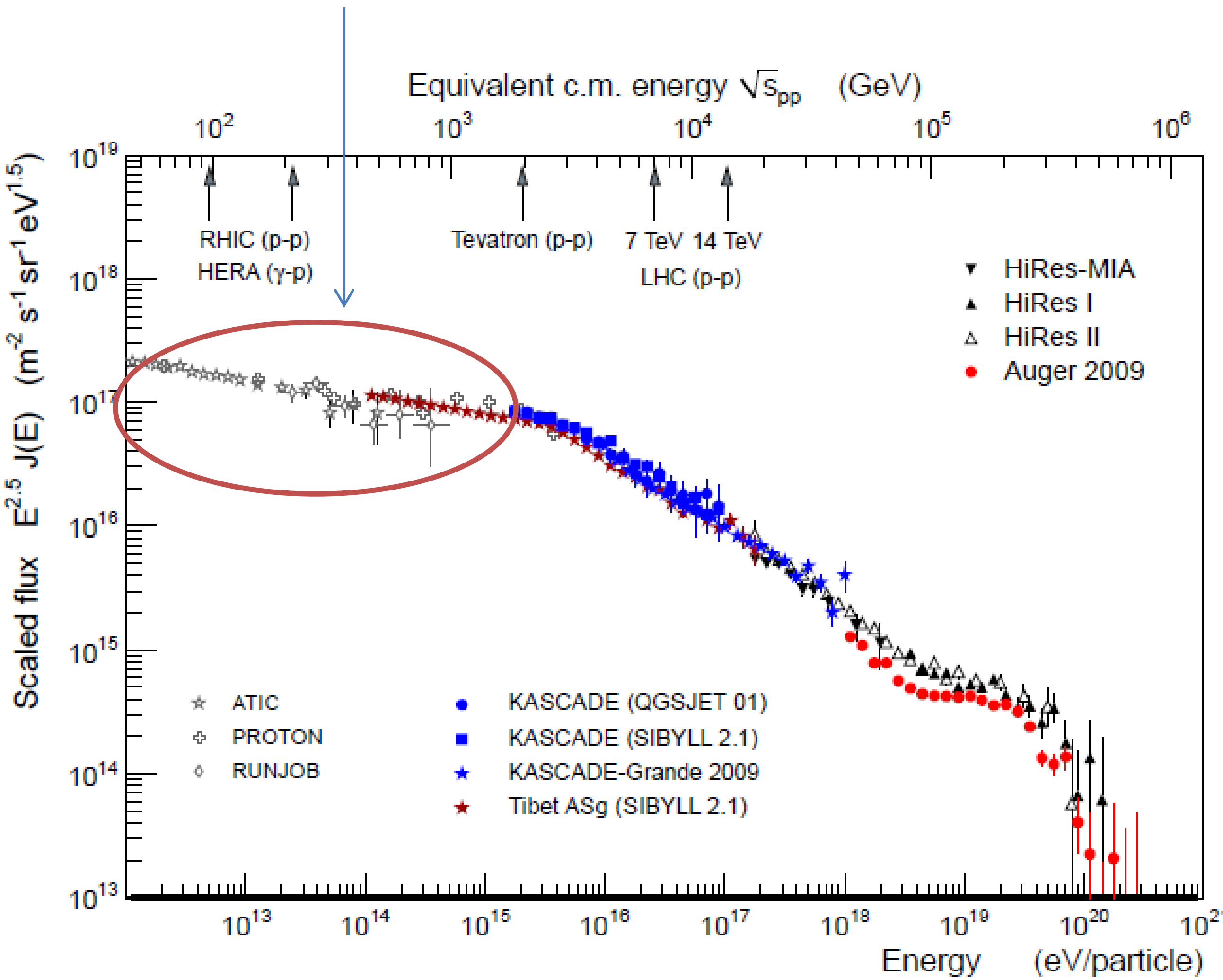


Cosmic ray energy spectrum



Cosmic ray energy spectrum

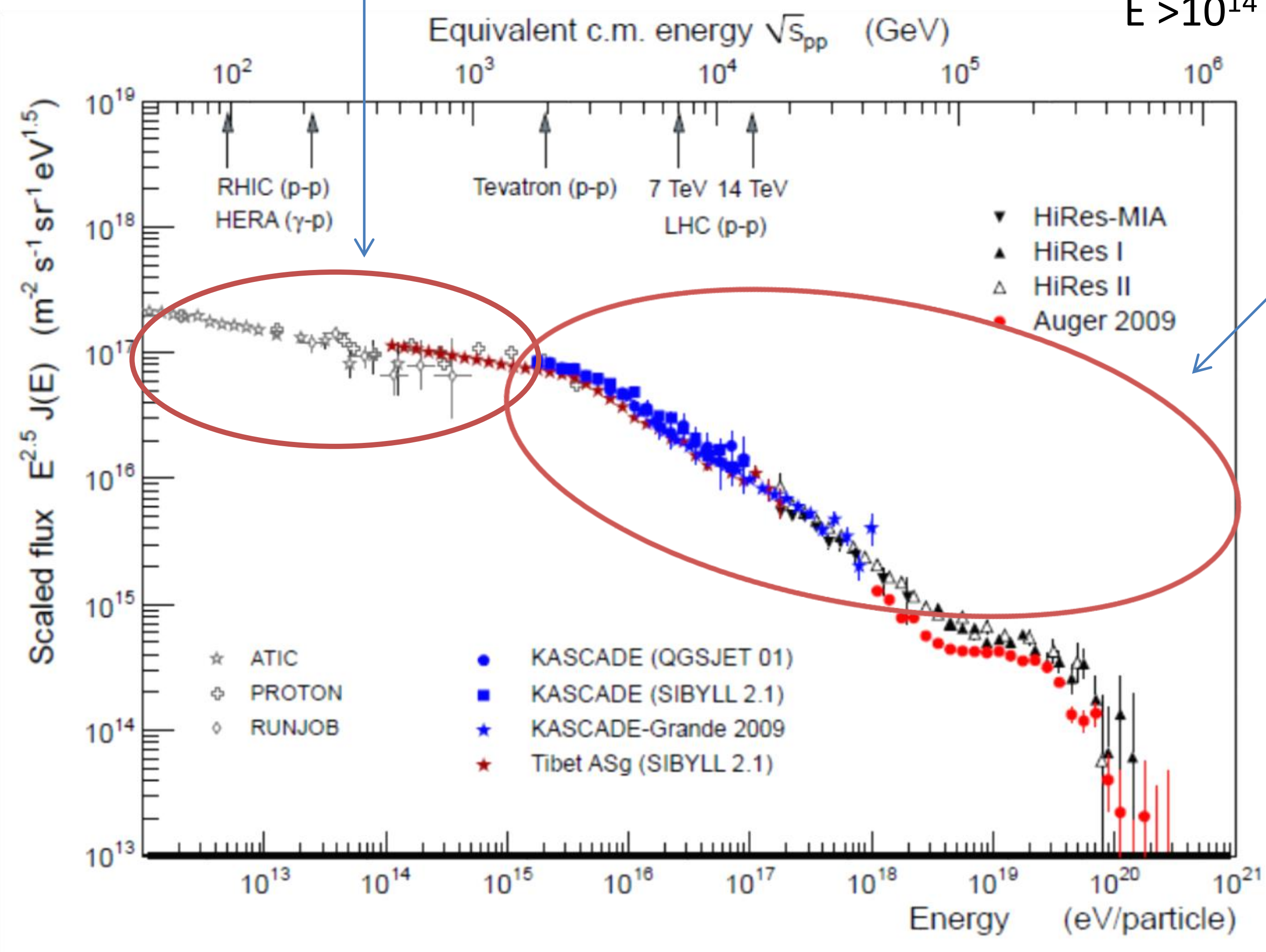
Direct measurements (baloons, satellities)
up to E ~10^{14} eV → Primary particles



Cosmic ray energy spectrum

Direct measurements (baloons, satellities)
up to E ~10^{14} eV → Primary particles

Indirect measurements
([under]ground experiments)
E >10^{14} eV → Secondary particles

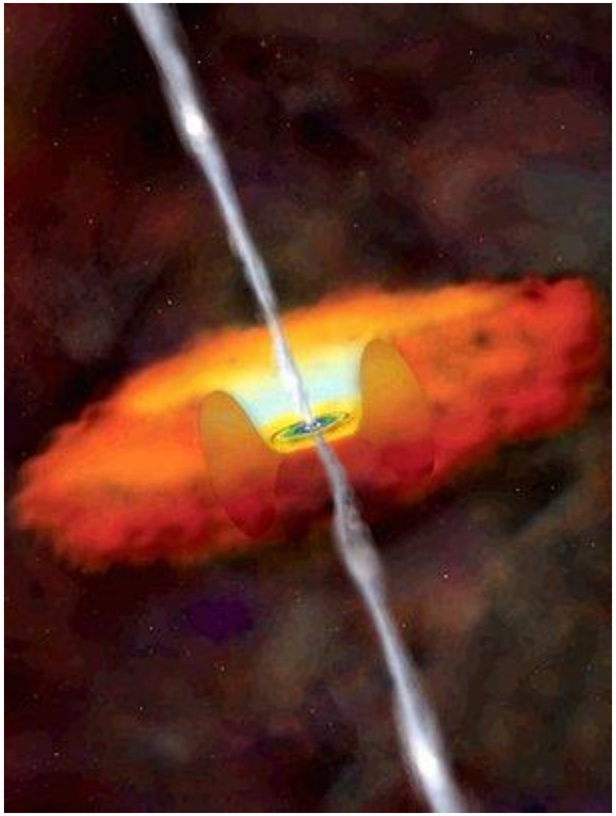


The Mrk 421 blazar

Blazars are a subgroup of a very bright active galaxies (called Active Galactic Nuclei, AGN). Radiation emitted by blazars extends across the entire range of the electromagnetic spectrum, from radio frequency up to high-energy gamma radiation.

Specifically, to be classified as a blazar an AGN must be observed with one of the following properties:

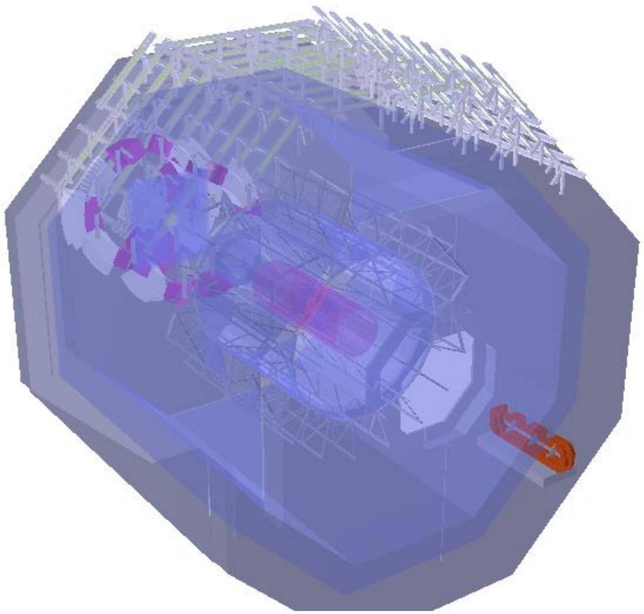
- ✓ high radio-brightness accompanied by flatness of the radio spectrum
- ✓ high optical polarization,
- ✓ strong optical variability on very short timescales (less than few days).

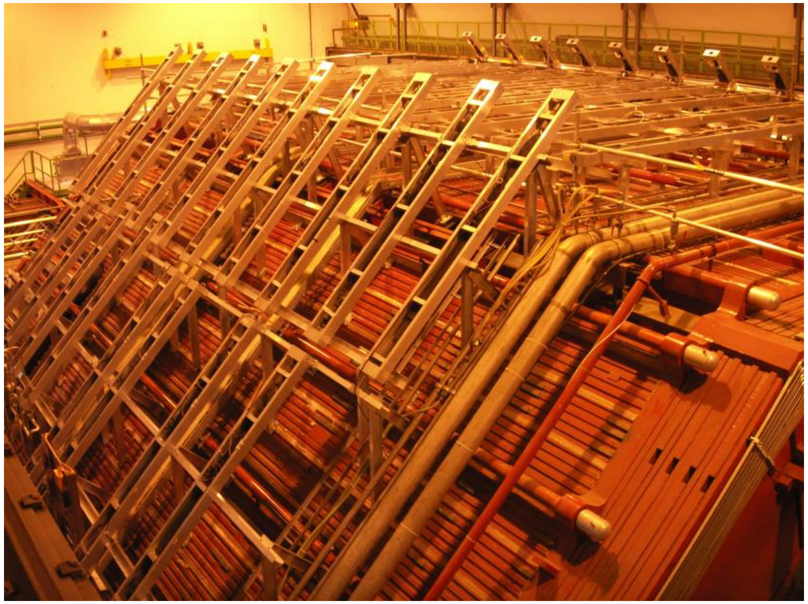


Artistic vision of active galaxy with central black hole and streams of relativistic plasma drawn from its center.

Markarian 421 (Mrk 421) is located in the constellation Ursa Major at redshift z = 0.03 (roughly equivalent to 115 Mpc or 370 million light-years).
It is one of the brightest objects in its class, thus often monitored by different instruments.

Detection of CR by the LHC ALICE experiment





ALICE configuration for cosmic ray physics:

- ✓ Cylindrical multi-gap resistive-plate chamber array
- ✓ TOF covers a cylindrical surface of polar acceptance in the theta range 45 ≤ Θ ≤ 135
- ✓ Modular structure: 18 sectors in azimuthal angle
- ✓ Time resolution less than 100 ps
- ✓ Efficiency around 95%

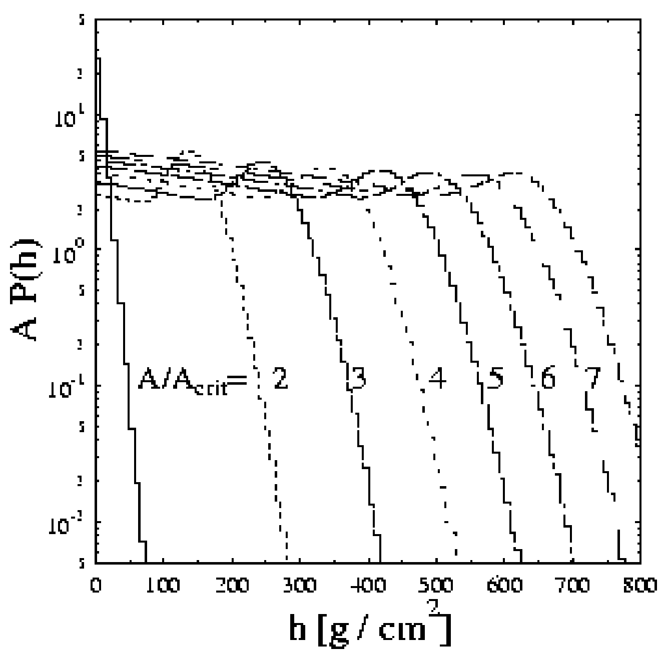
Propagation of strange quark matter in the atmosphere

All quarks from the air nucleus target of mass number A_t which are located in the geometrical intersection of the two colliding projectiles are involved and each quark from the target interacts with only one quark from strangelet.

During the interaction up to $3A_t$ quarks from the strangelet could be used up and its mass could drop to a value of $A - A_t$, at most, for $A \geq A_{crit} \cong 320$.

The total penetration length of strangelet:

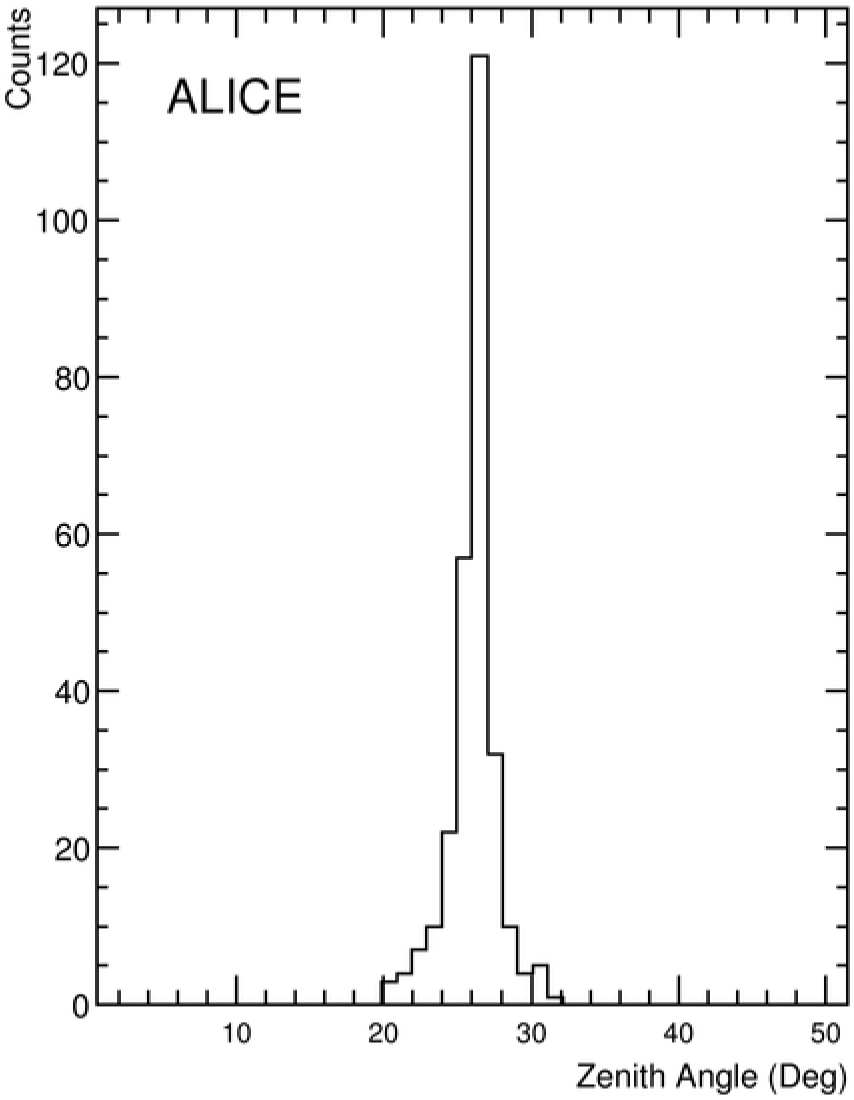
$$\Lambda = \frac{1}{3}\lambda_{NA_t}\left(\frac{A_0}{A_t}\right)^{1/3}\left(1 - \frac{A_{crit}}{A_0}\right)^2\left(4 - \frac{A_{crit}}{A_0}\right)$$

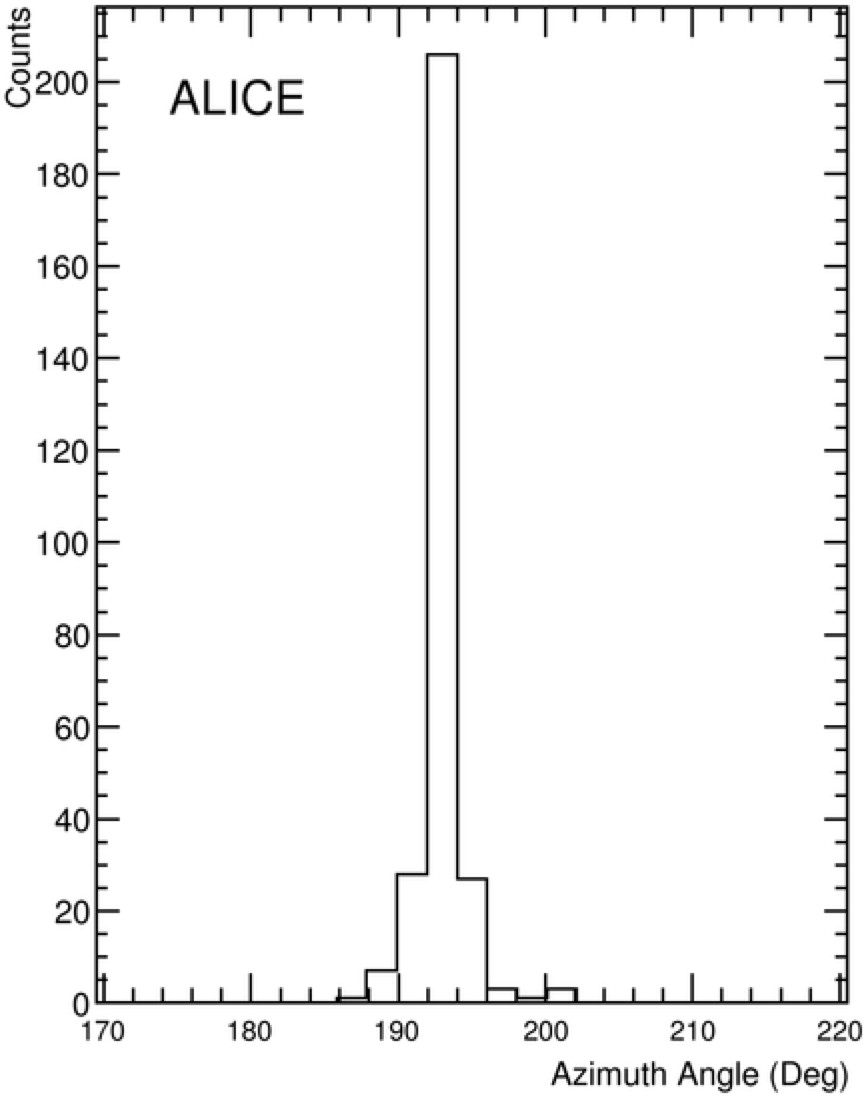


[G. Wilk and Z. Włodarczyk, Acta Phys. Hung. 4 (1996) 395 [hep-ph/9606401]]
[G. Wilk and Z. Włodarczyk, J. Phys. G 23 (1997) 2057]

ALICE result: highest multiplicity reconstructed

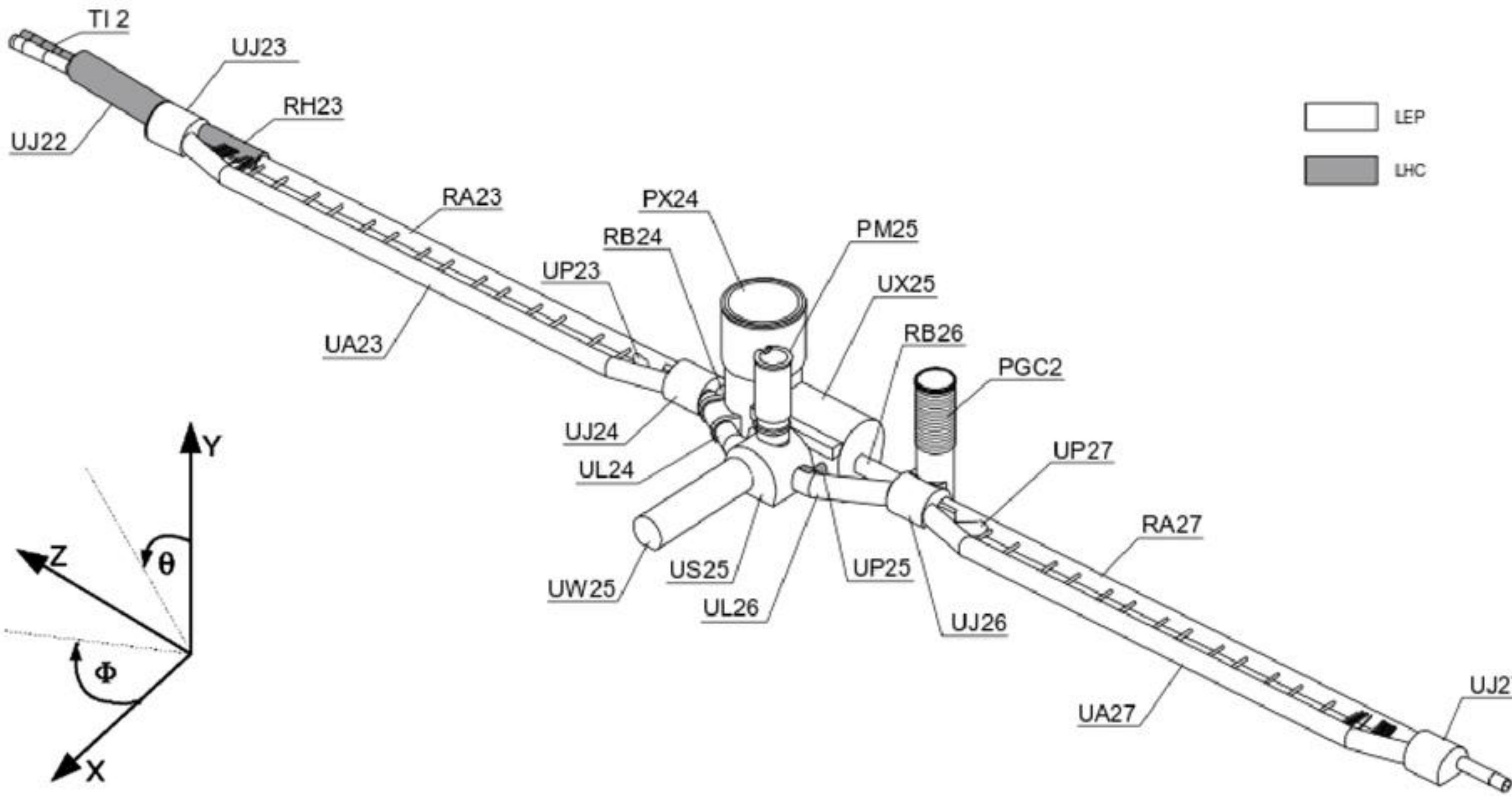
Event with 276 atmospheric muons



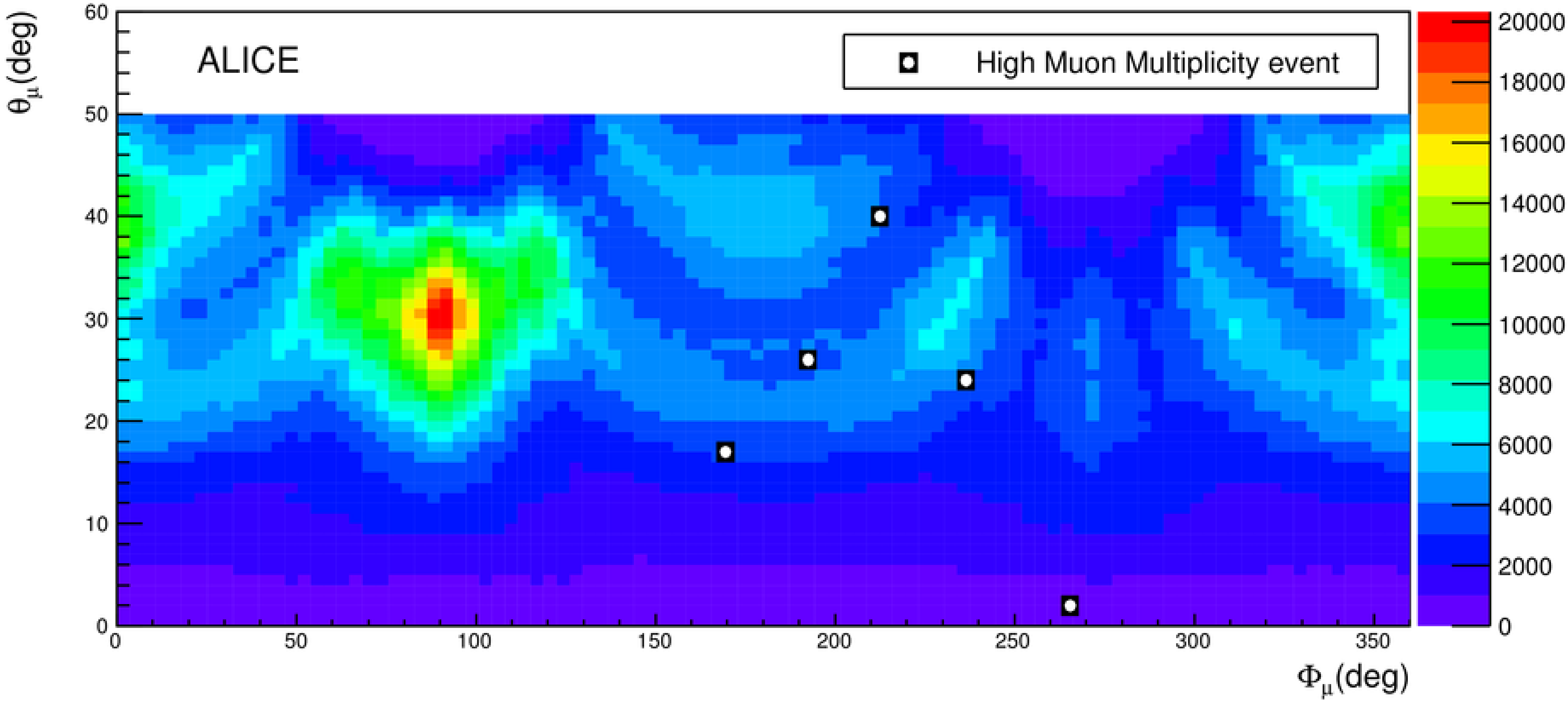


Anisotropy of Arrival Directions

Event	N_μ	Φ [°]	θ [°]	Date (JD)	Az [°]	h [°]	α_{2000}	δ_{2000}
1	181	212.4	40.4	2455247.53666	268.5	49.6	7 h 54 m	32° 36′
2	136	170.2	16.6	2455256.64166	226.3	73.4	13 h 25 m	33° 49′
3	276	192.9	26.0	2455708.26792	249.0	64.0	9 h 08 m	32° 45′
4	225	235.7	23.5	2456044.54870	291.8	66.5	13 h 35 m	49° 57′
5	136	264.8	2.6	2456052.38119	320.9	87.4	12 h 14 m	48° 18′



Layout of Point 2 at underground level.



Zenith vs Azimuth angle distribution of the muons in ALICE with superimposed the location of the five high muon multiplicity events (white circle on a black square).