Can strangelets solve the muon puzzle ?

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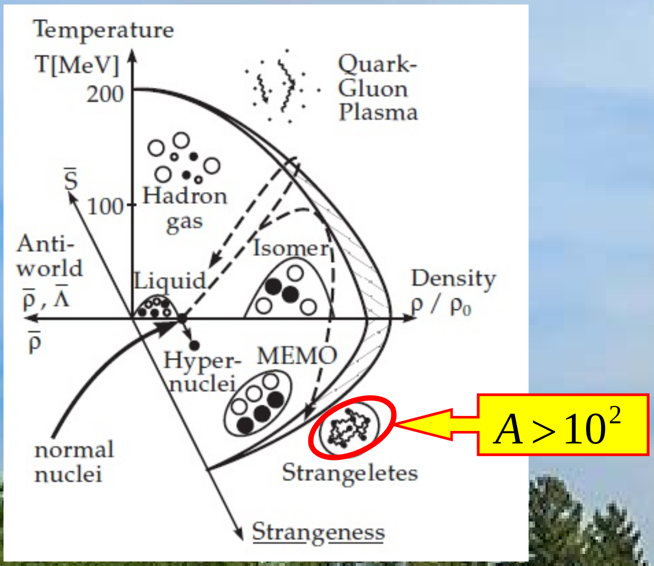
Outline

- stable strange quark matter
- imprints in astrophysics
- SQM in CR
- abundance and mass spectrum
- muon bundles
- muon excess in EAS

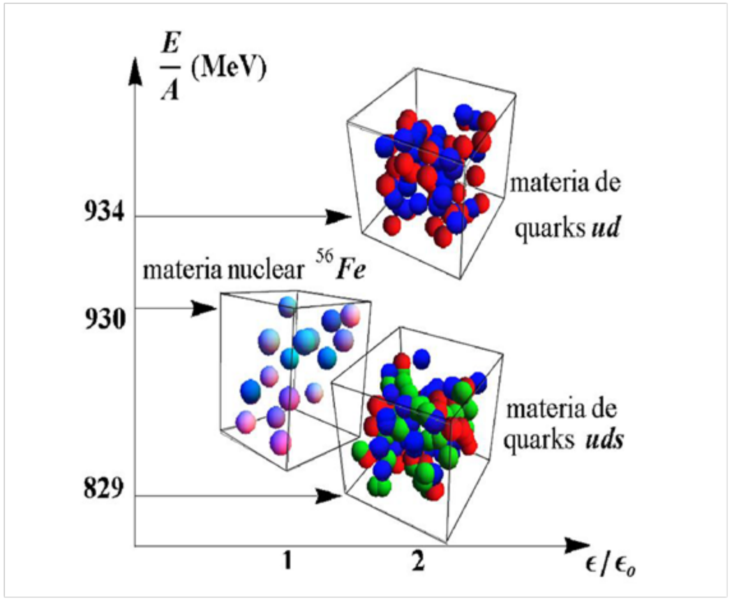


20th ISVHECRI, Nagoya, 21-26 May 2018

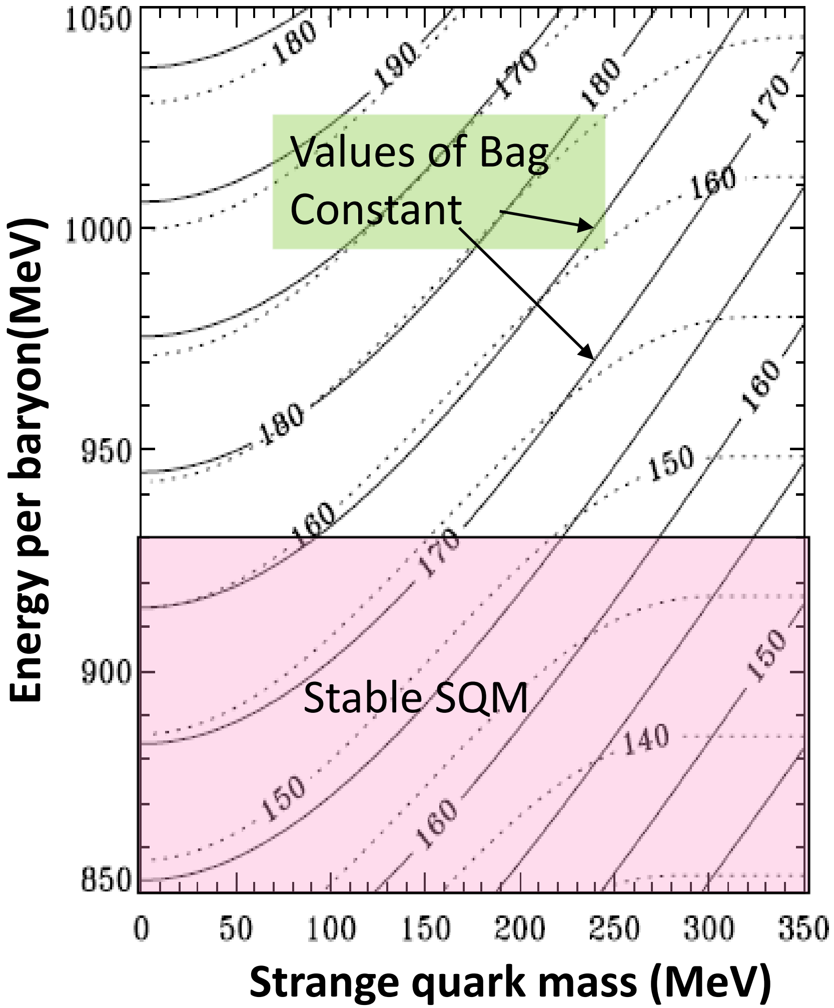
Strange quark matter

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.

Ground state of nuclear matter?



J. Madsen, PRL 87 (2001) 172003

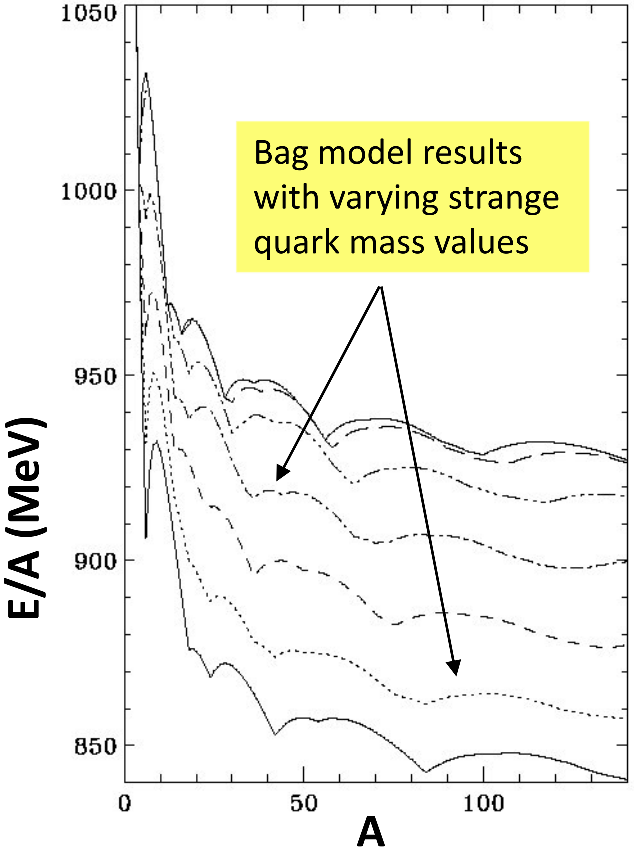


Stability can not be calculated in QCD, but is addressed in phenomenological models (MIT Bag Model, Color Flavor Locking…).

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

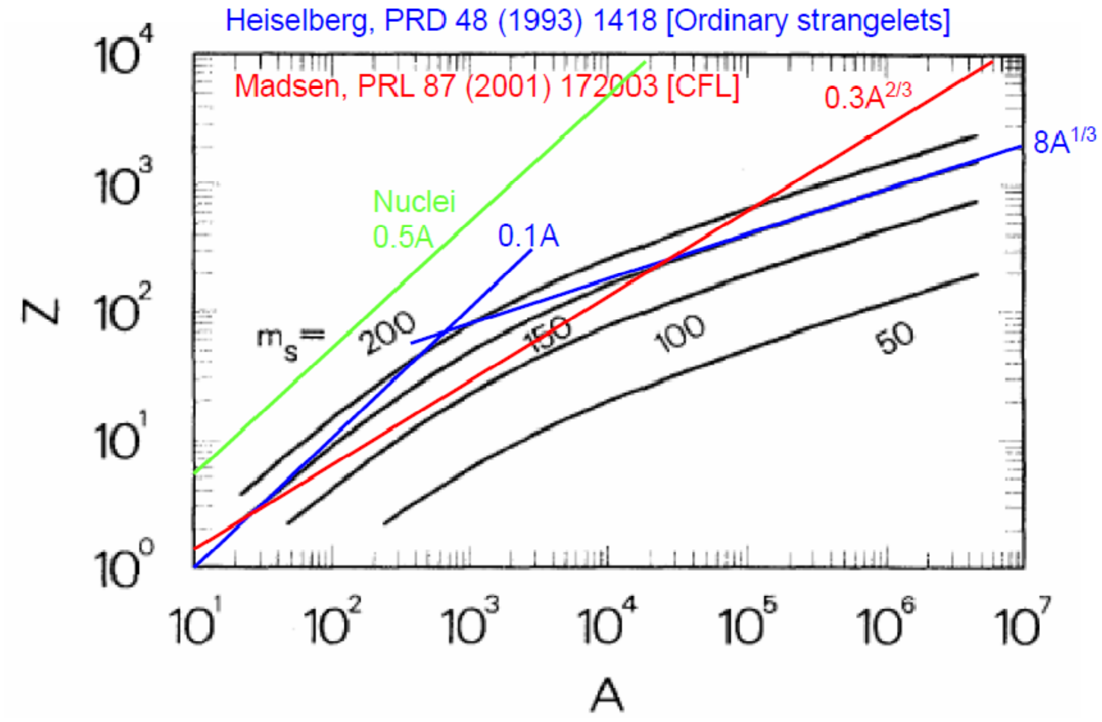
Strange quark matter

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


Bag model results with varying strange quark mass values

SQM is less stable
for lower baryon number (A < ~100)

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

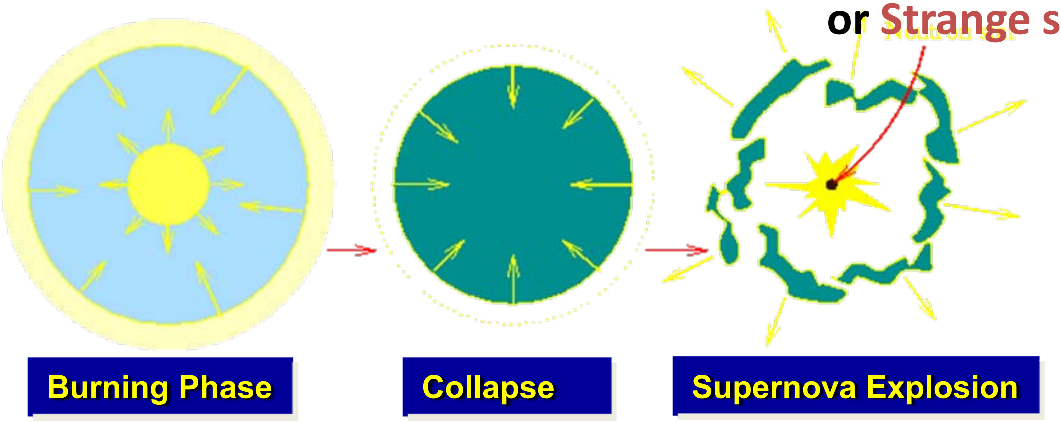

Heiselberg, PRD 48 (1993) 1418 [Ordinary strangelets]

Madsen, PRL 87 (2001) 172003 [CFL]

Strange Quark Matter have low Z/A

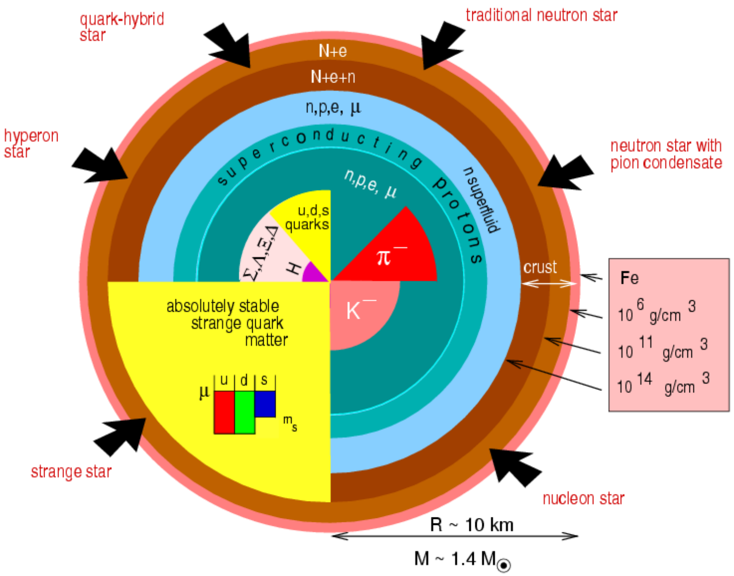
Strange stars

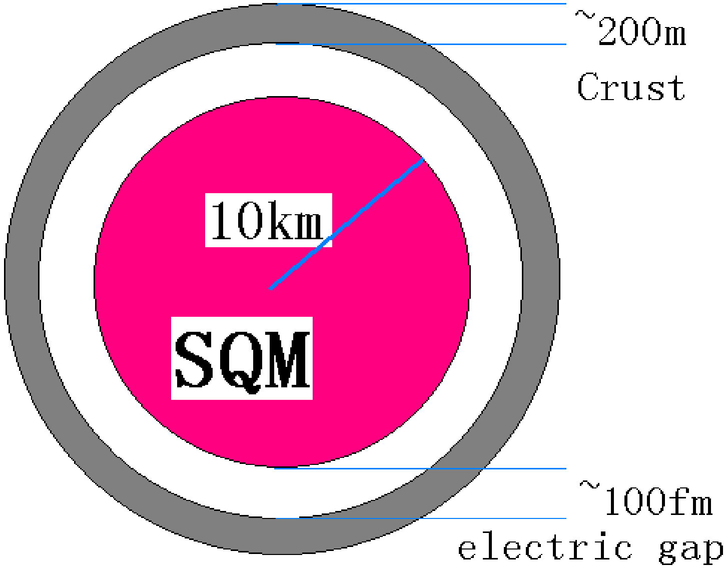
Neutron Stars
or **Strange stars?**



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

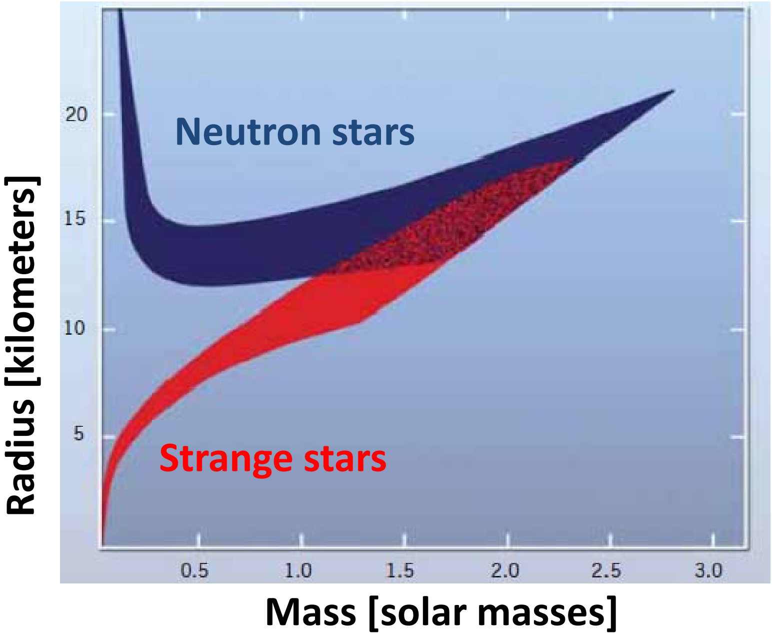
Strange stars: Structures





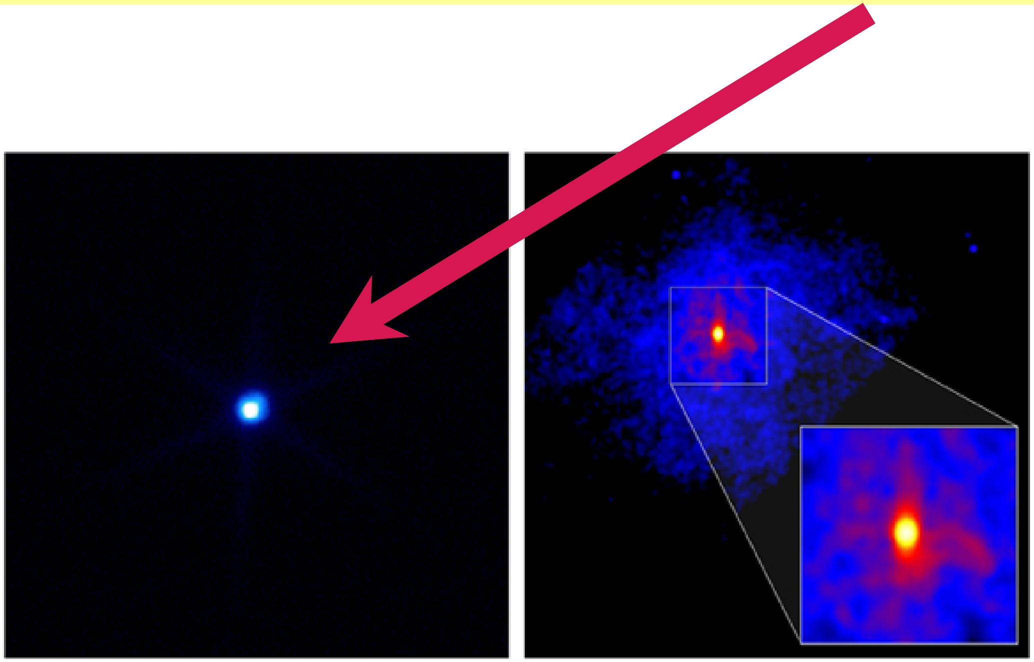
Bare Strange stars: Observed?

Strange stars: a curiosity



Strange stars may be much smaller than neutron stars.

NASA News release (2002/4/10): RX J1856 a strange star?



Drake et al. (2002, ApJ, 572, 996):

Reasons for RX J1856 being a strange star ?

1. Small radius ~ 6 km with no X-ray pulsation !
2. Featureless X-ray spectrum

Chart of nuclides

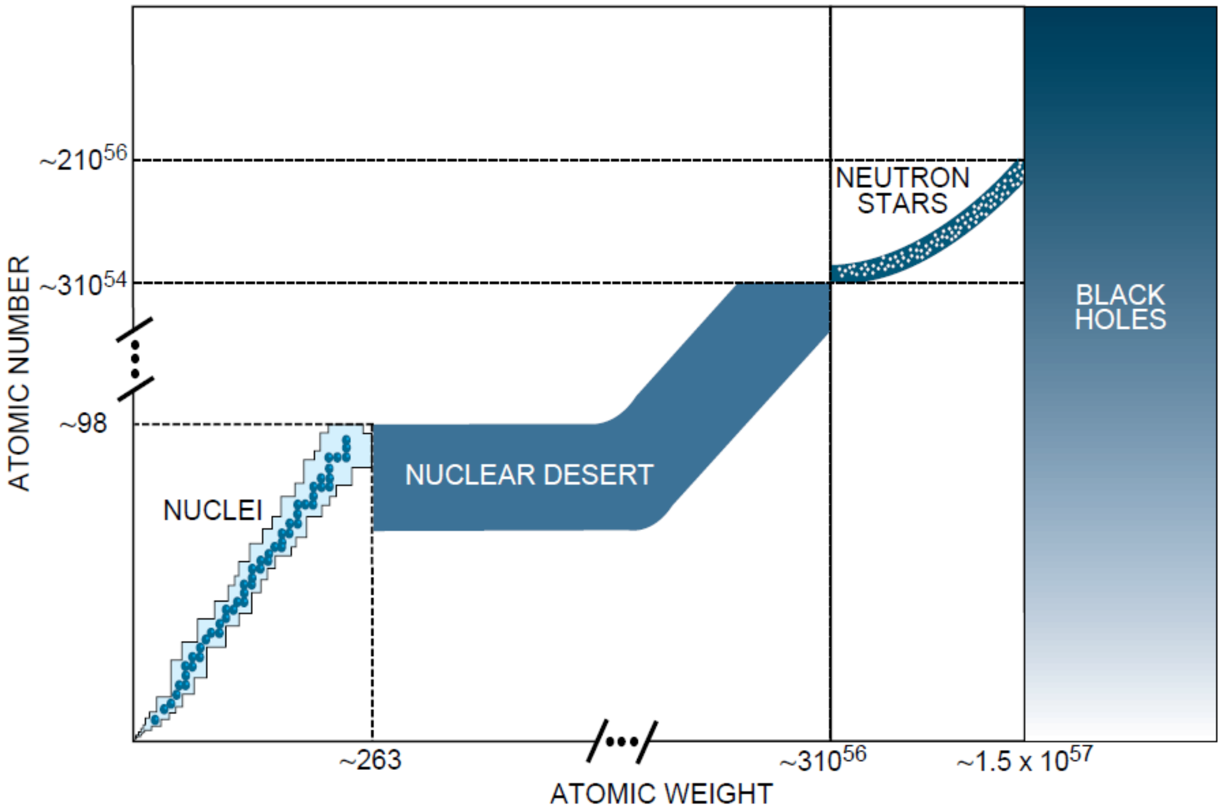
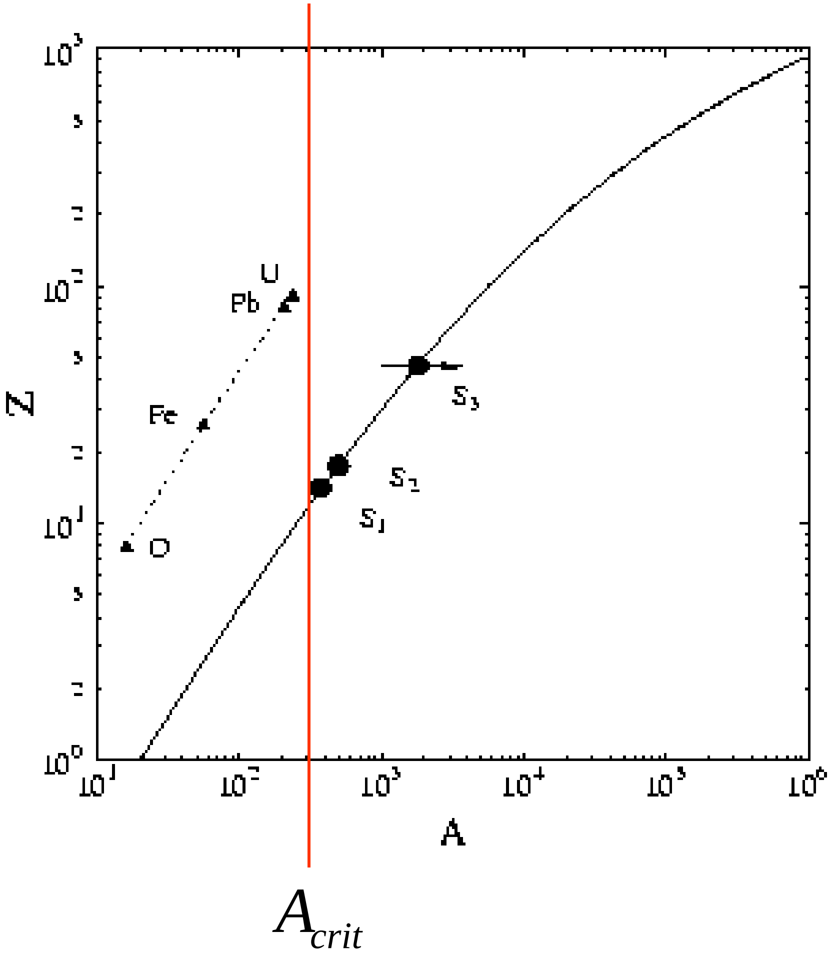


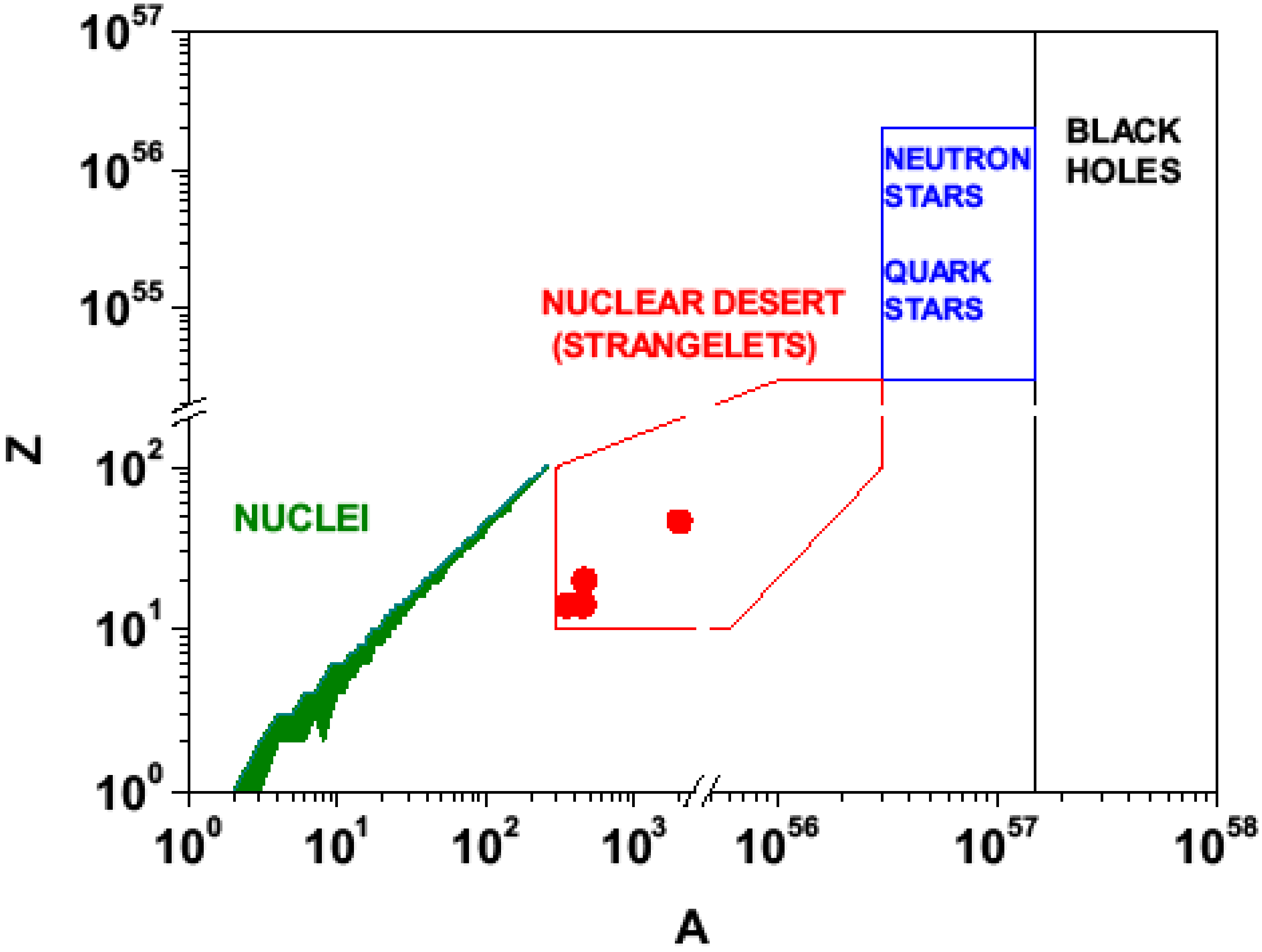
CHART OF NUCLIDES shows all known forms of stable matter. Between the heaviest atomic elements and neutron stars, which are giant nuclei, lies a vast, unpopulated nuclear desert. This void may actually be filled with strange quark matter.

Have Strangelets been Already Observed in Cosmic Rays ?

- In counter experiment (Saito) two anomalous events have been observed with values of charge Z~14 and of mass number A~350 and ~450
- The Prices’s event with Z~46 and A>1000, turned out to be fully consistant with the Z/A ratio characteristic for SQM
- The so called Exotic Tract (projectile traversid ~200 g/sq.cm of atmosphere with Z~20 and A~460 has been reported by Ichimura



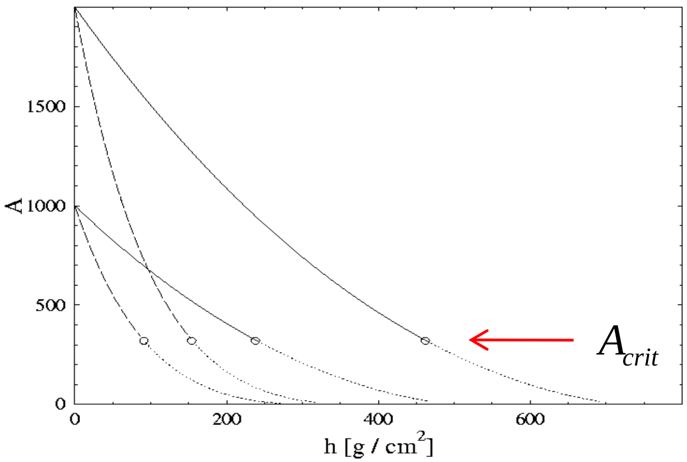
Nuclear desert may be filled with strangelets

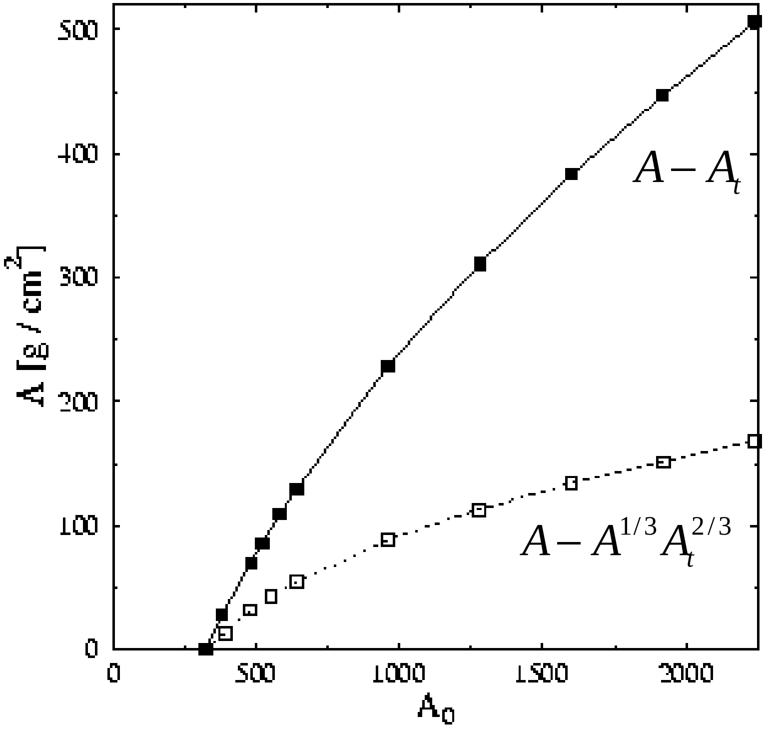


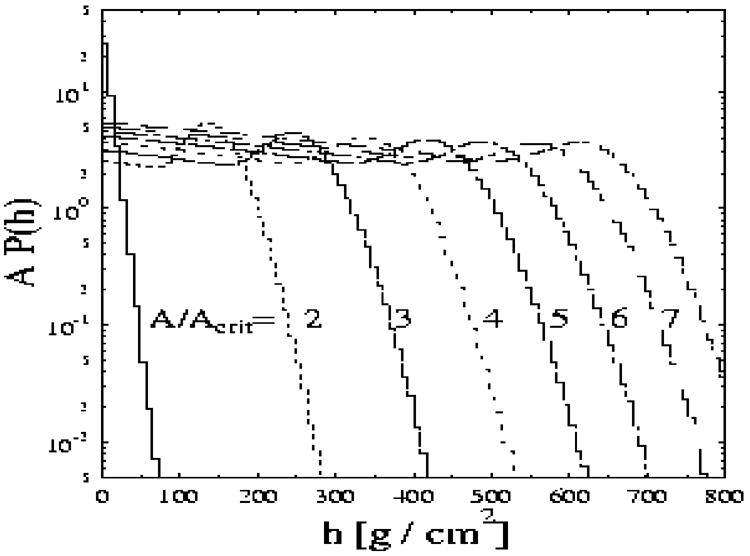
Propagation of strangelets in the atmosphere

each quark from target interacts with only one quark from strangelet, i.e., the mass number is diminished to the value $A_k = A_0 - kA_t$ for $A \geq A_{crit} \cong 320$

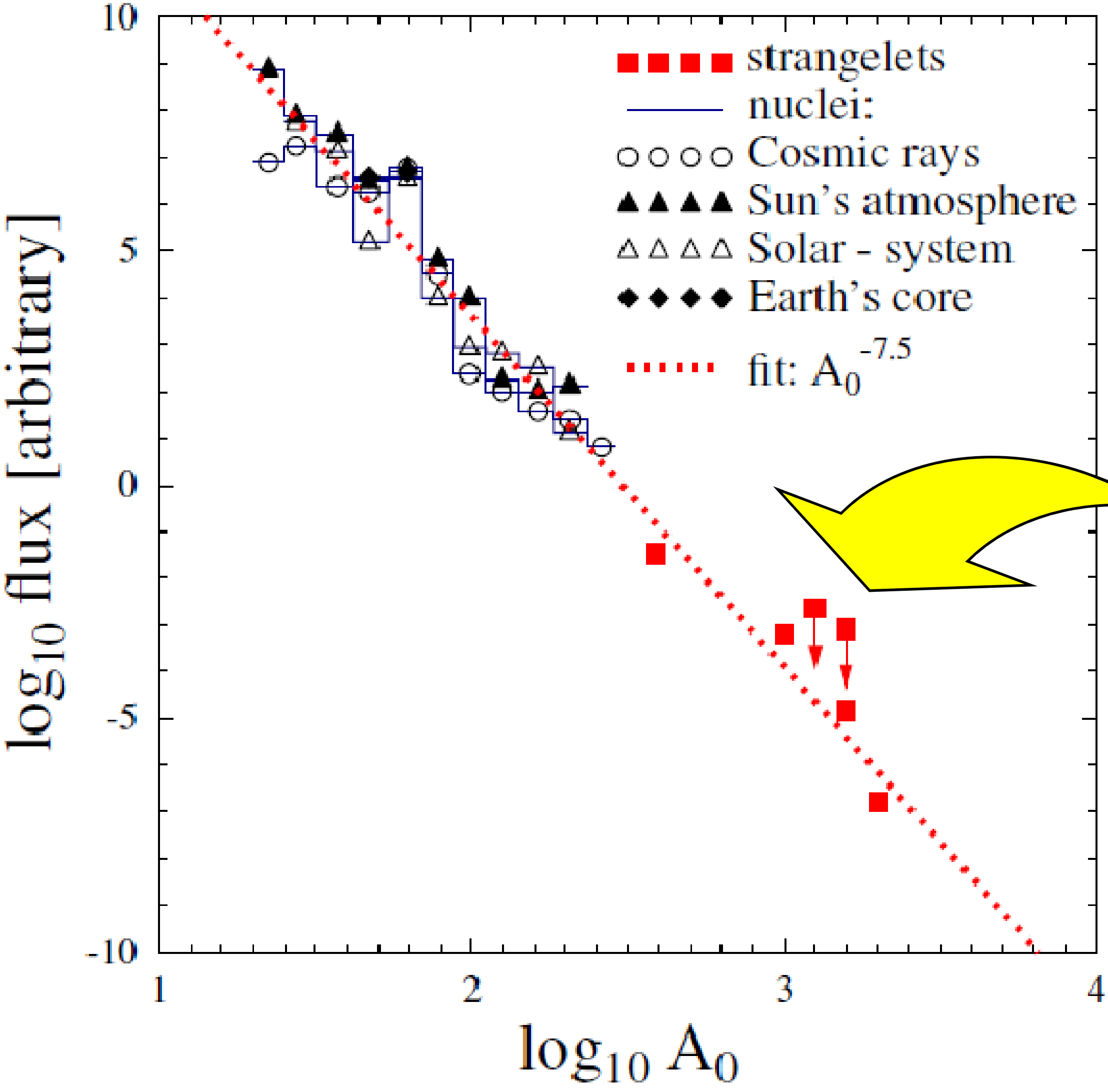
$$\Lambda = \frac{1}{3}\lambda_{NA_t}\left(\frac{A_0}{A_t}\right)^{1/3}\left(1-\frac{A_{crit}}{A_0}\right)^{2}\left(4-\frac{A_{crit}}{A_0}\right)$$







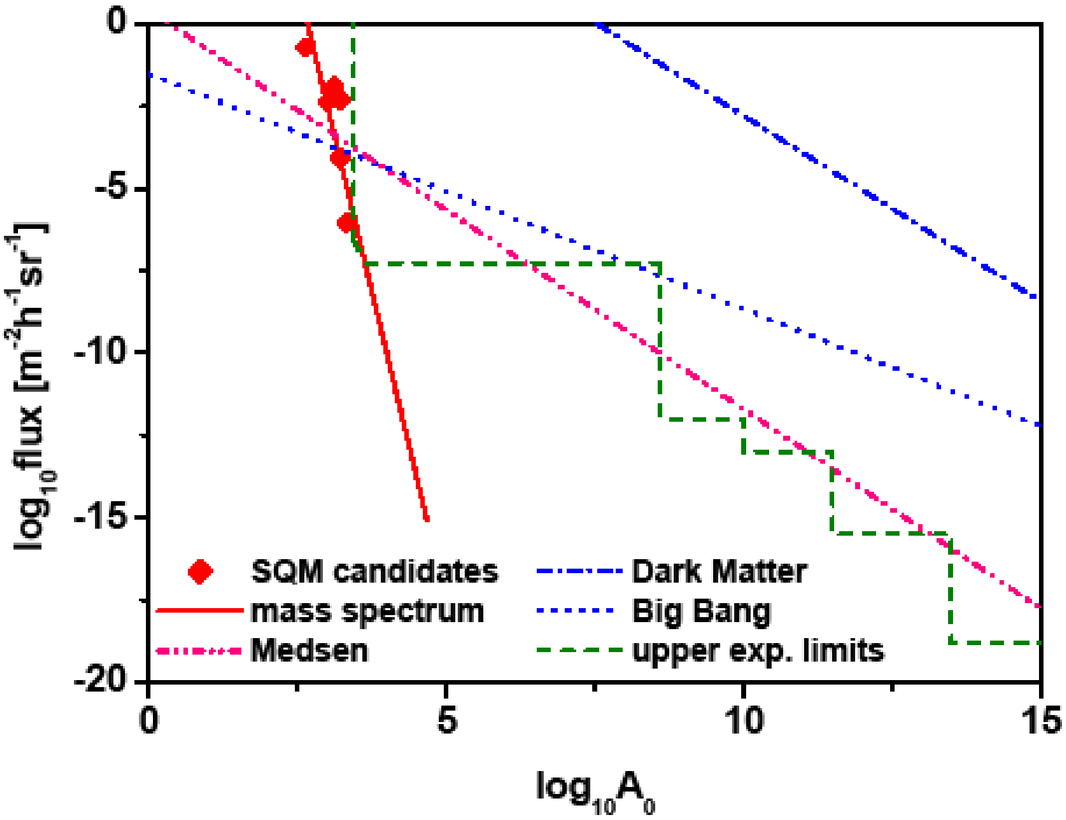
Abundances of elements in the Universe



strangelets

$$N(A_0) \propto A_0^{-7.5}$$

expected flux of SQM in comparision with astrophysical limits



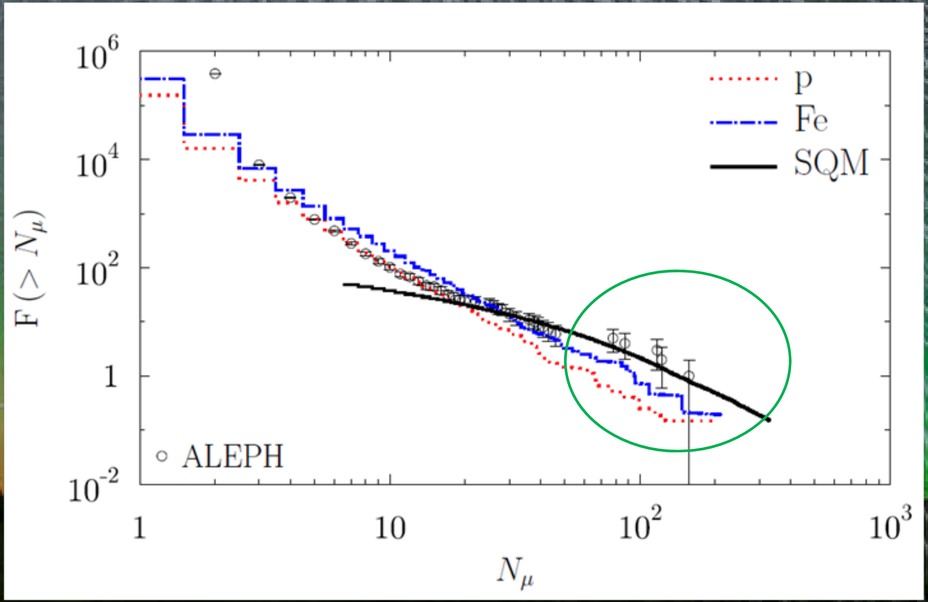
$$\boxed{F_S / F_{tot} \cong 2.4 \cdot 10^{-5}}$$

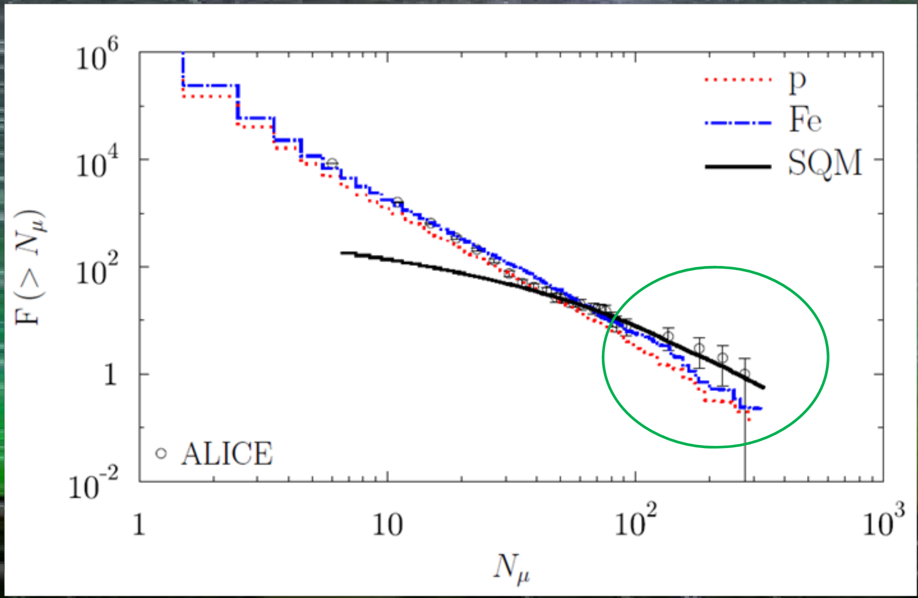
at 10 GeV per particle

Flux upper limits for strangelets set by SLIM (Search for Light magnetic Monopoles experiment operated at Chacaltaya) and experiments onboard balloons and satelites.

Note that there is a well-known equality between the energy density of CRs, ρ_{CR} , the magnetic fields, the motion of gas clouds, and starlight. The estimated value of ρ_{CR} ~ 0.8 eV cm^{-3} is comparable with the energy density of the cosmic microwave background, ρ_{CMB} ~ 0.3 eV cm^{-3} . On the other hand, the energy density of strangelets, ρ_{SQM} ~ $2 \cdot 10^{-6}$ eV cm^{-3} , are apparently of the same order as that of the fluctuations in the CMB.

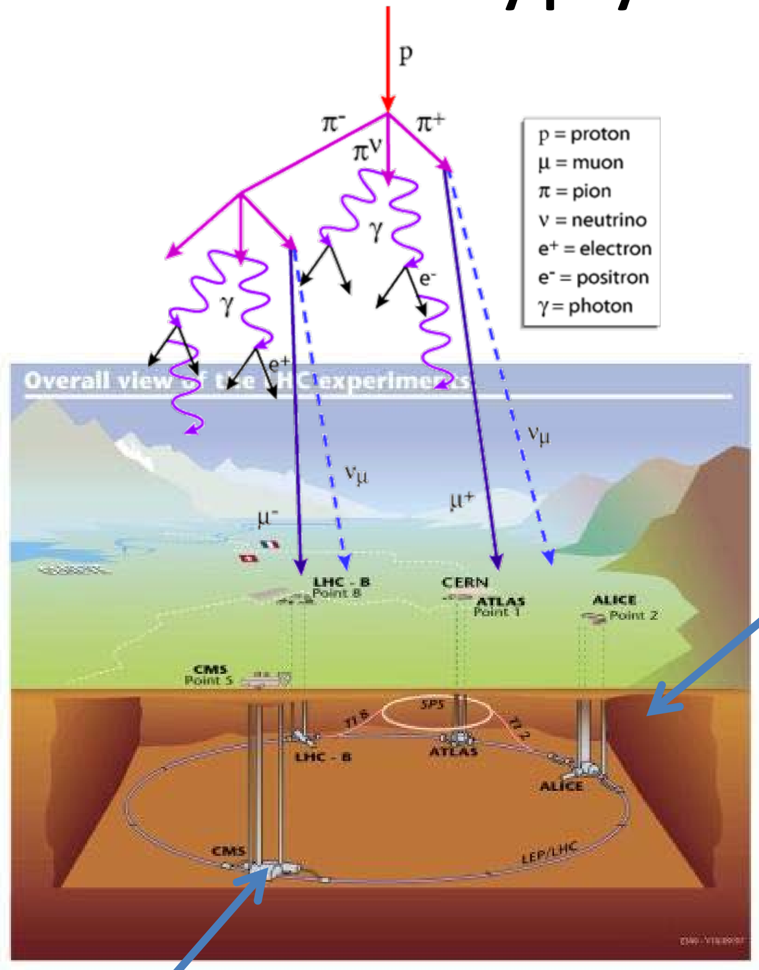
High multiplicity muon bundles from strangelets

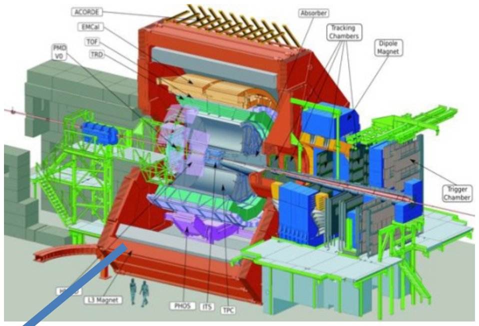




P. Kankiewicz, M. Rybczyński, G. Wilk, and Z. Włodarczyk, **ApJ 839 (2017) 31** [arXiv:1612.04749]

Cosmic ray physics with CERN experiments

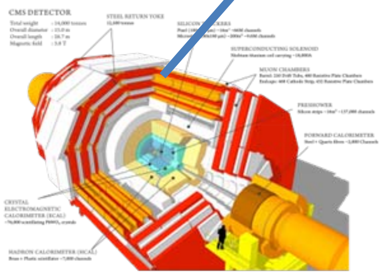




Detection of CR by the LHC ALICE experiment

ALICE is located 52 m undergrounds
(28 m of overbunden rock)

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

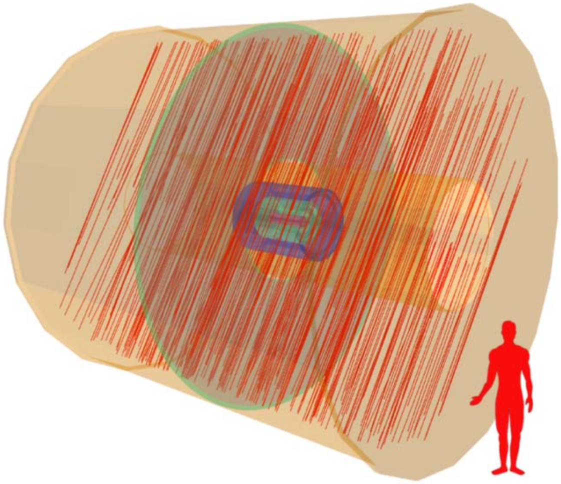


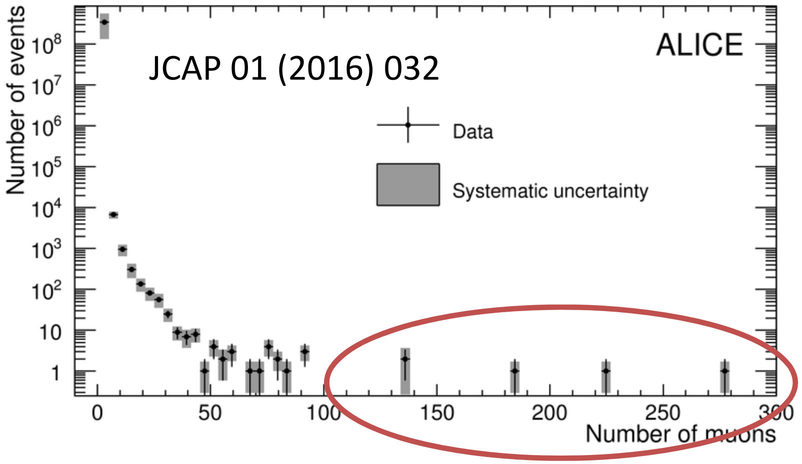
These detectors are not designed to cosmic ray physics!

Advantages:
- Detectors with very high performance
- Presence of magnetic field

Detection of CR by the LHC ALICE experiment

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

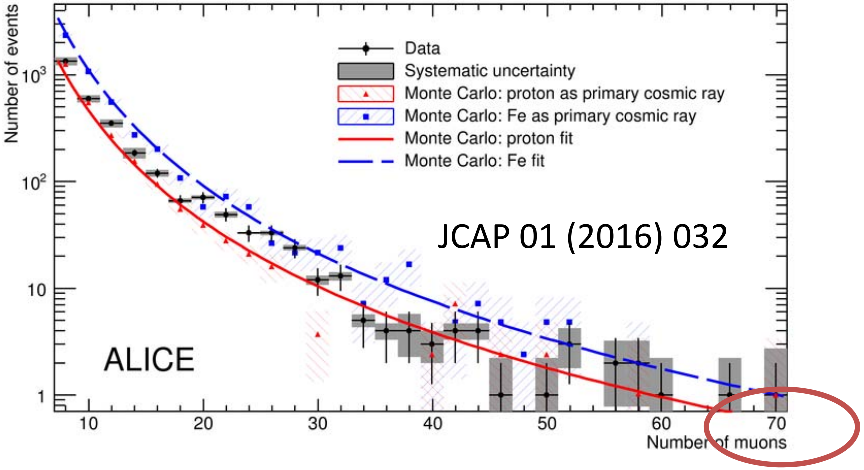




$$0^\circ < \Theta < 50^\circ$$

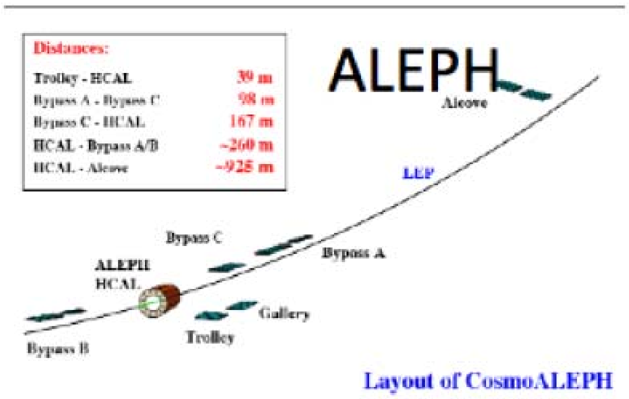
$$E_\mu > 16\ \mathrm{GeV}/\cos\Theta$$

Total time of data taking: 30.8 days
Effective area: 17 m^2



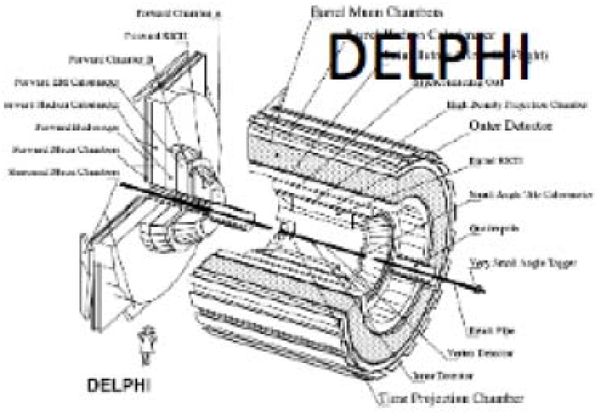
ALICE experiment registered the presence of large groups of muons produced in EAS by cosmic ray interactions in the upper atmosphere.

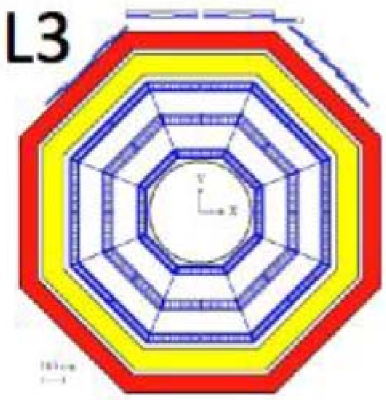
Detection of CR by CERN LEP experiments



Distances:	
Trolley - HCAL	39 m
Bypass A - Bypass C	98 m
Bypass C - HCAL	167 m
HCAL - Bypass A/B	~260 m
HCAL - Alcove	~925 m

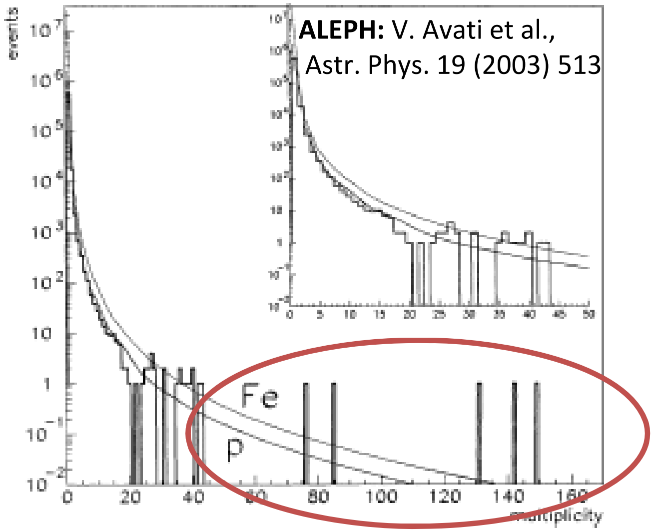
Layout of CosmoALEPH





- ✧ **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.

LEP results: muon multiplicity spectra

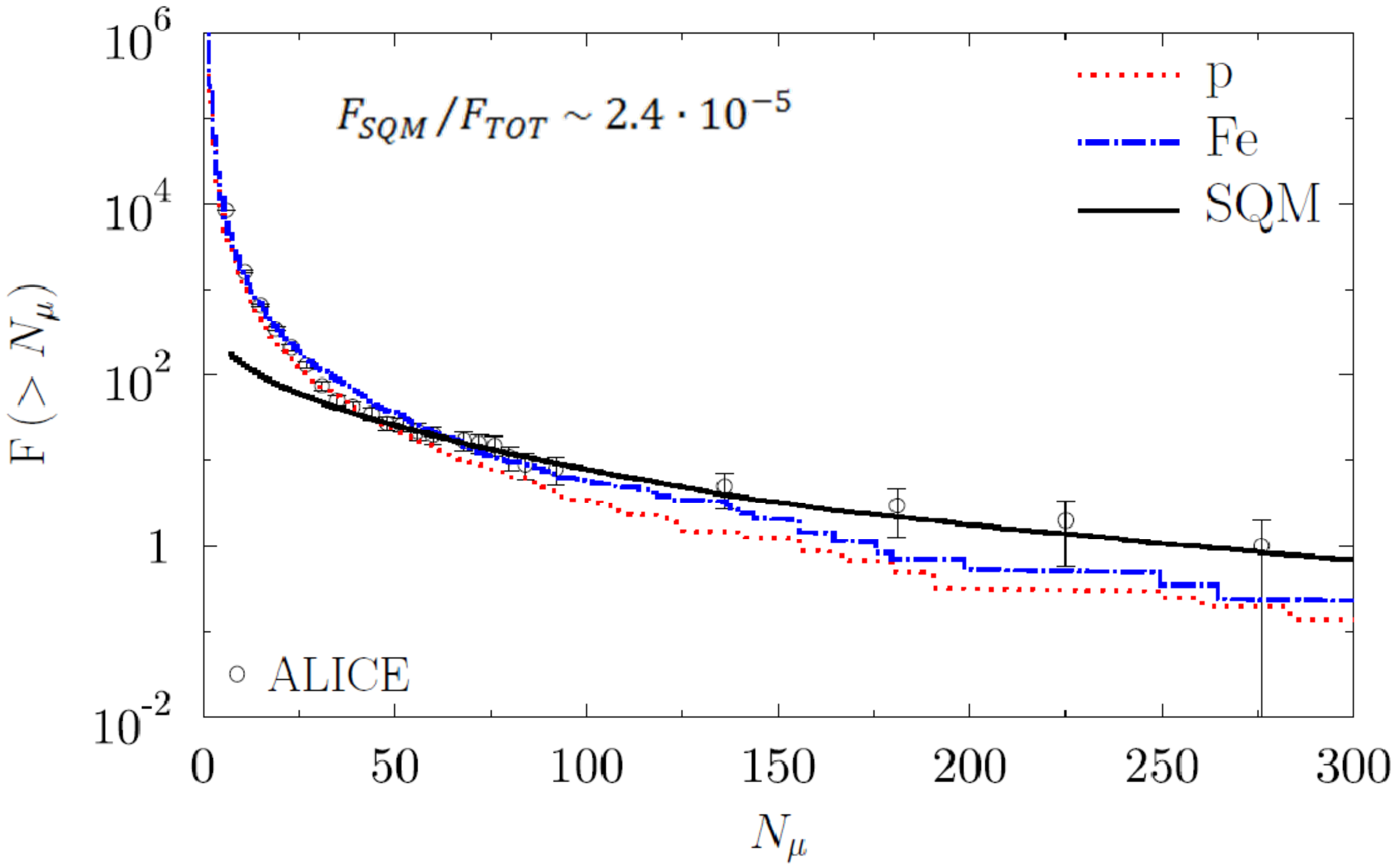


ALEPH: V. Avati et al., Astr. Phys. 19 (2003) 513

- ✔ 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

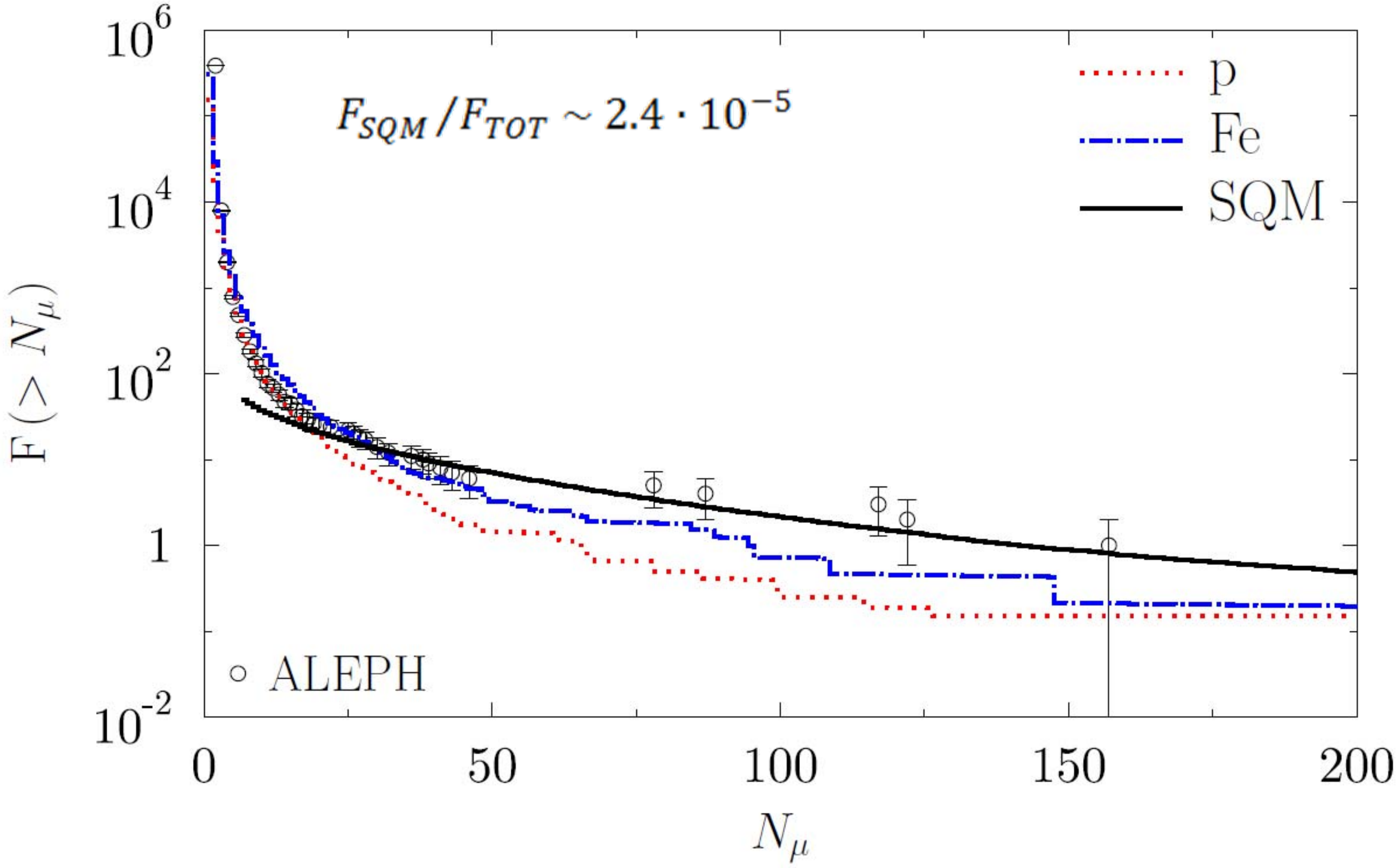
The only LEP result not consistent with the standard hadronic interaction models was the observation of the 'anomalous' number of high multiplicity muon bundles.

High multiplicity muon bundles from strange quark matter



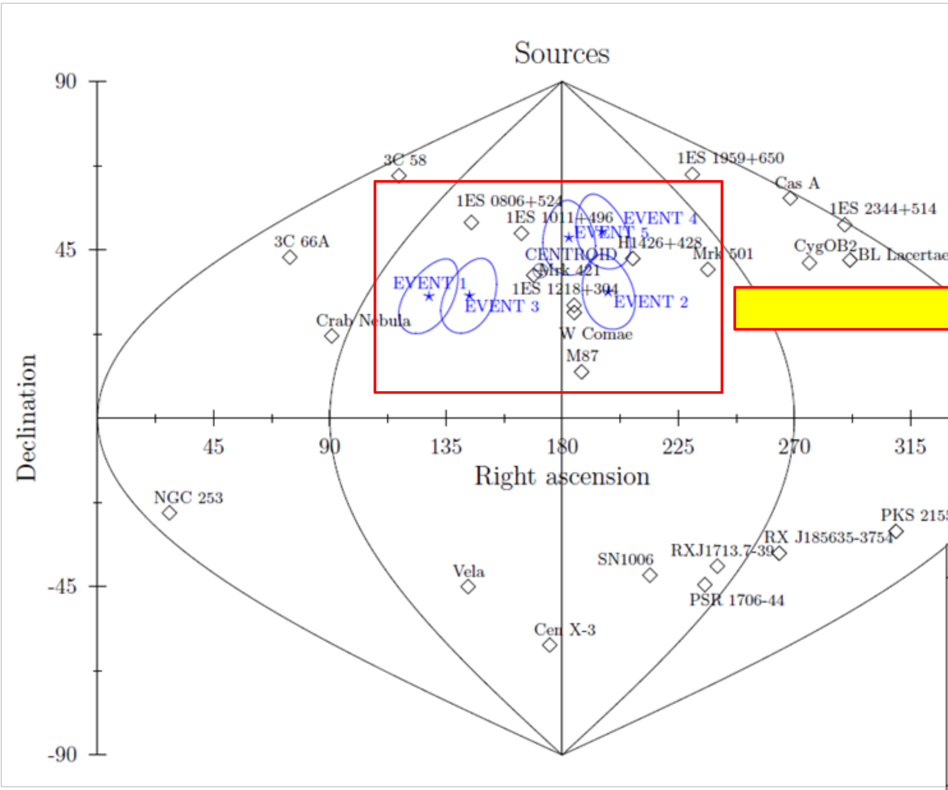
Integral multiplicity distribution of muons for the ALICE data (circles) published in JCAP 01 (2016) 032. Monte Carlo simulations for primary protons (dotted line); iron nuclei (dashed dot line) and primary strangelets with mass A taken from the $A^{-7.5}$ distribution (full line) with abundance of the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

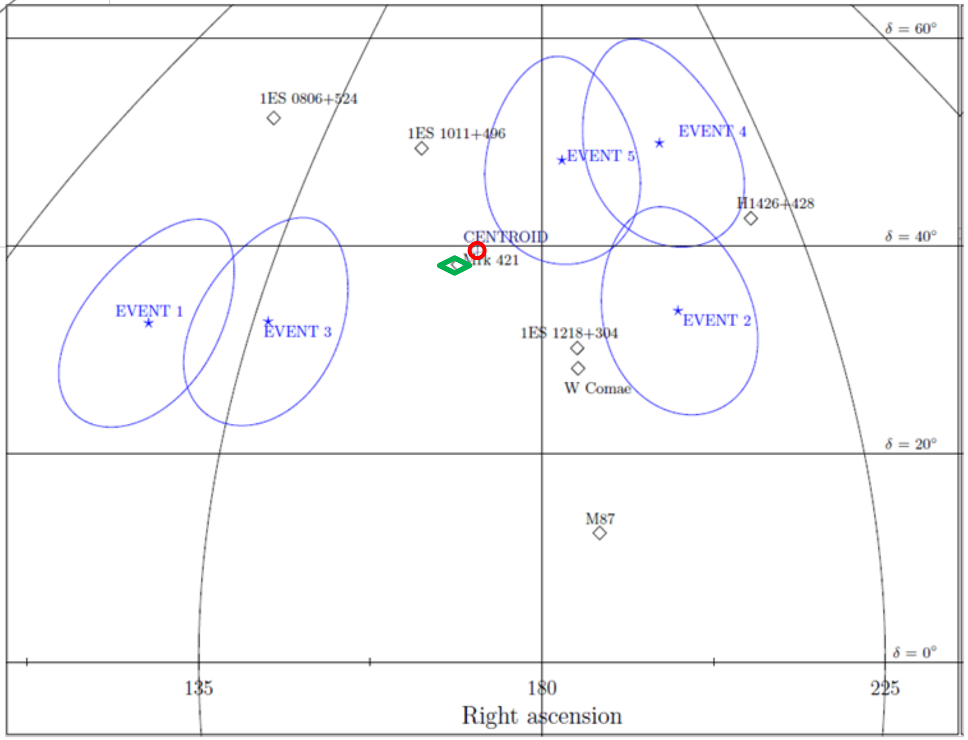
High multiplicity muon bundles from strange quark matter



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 at 10 GeV.

Anisotropy of arrival directions

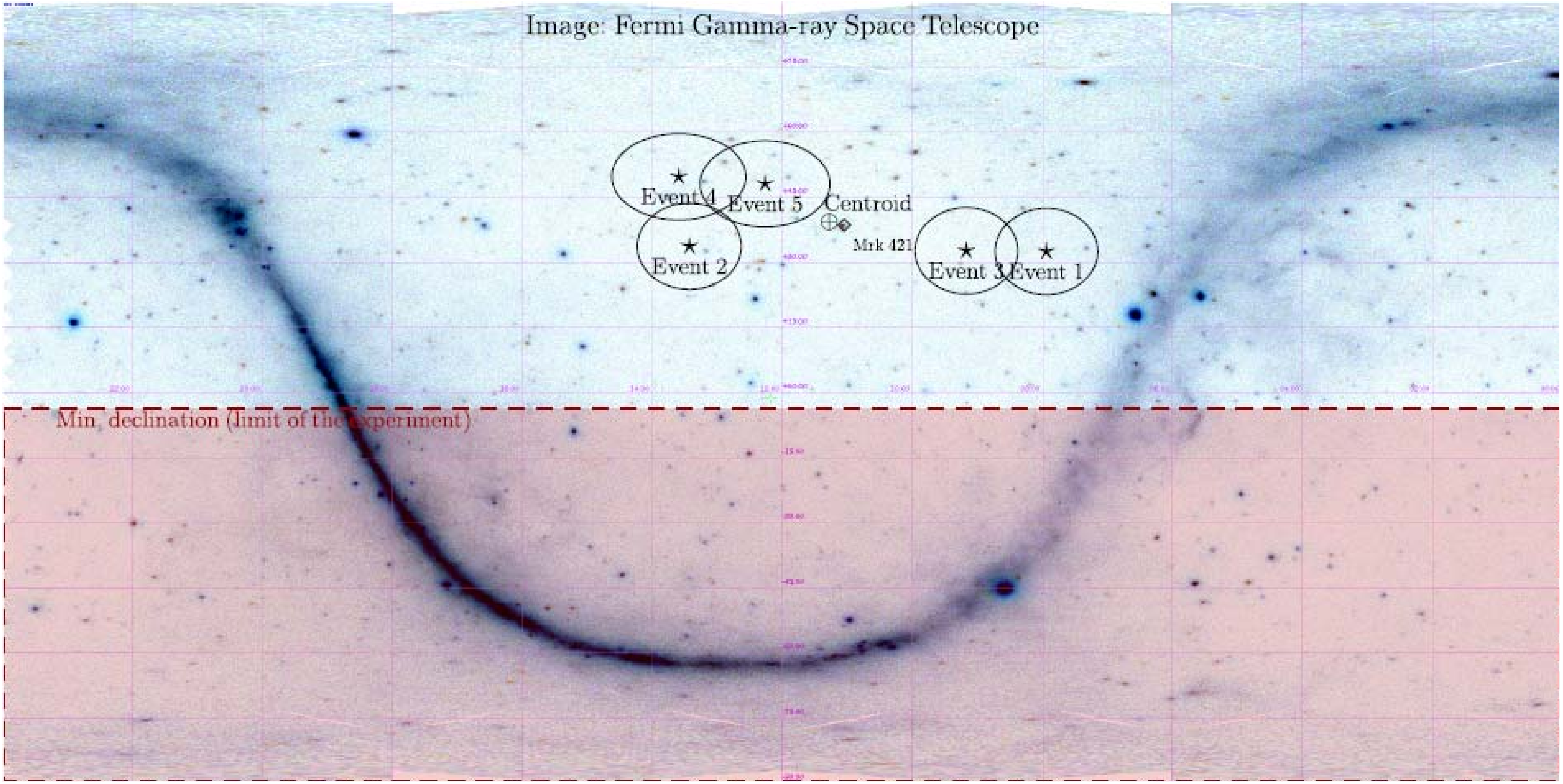




Five high-multiplicity muon events in the equatorial reference frame (α, δ).

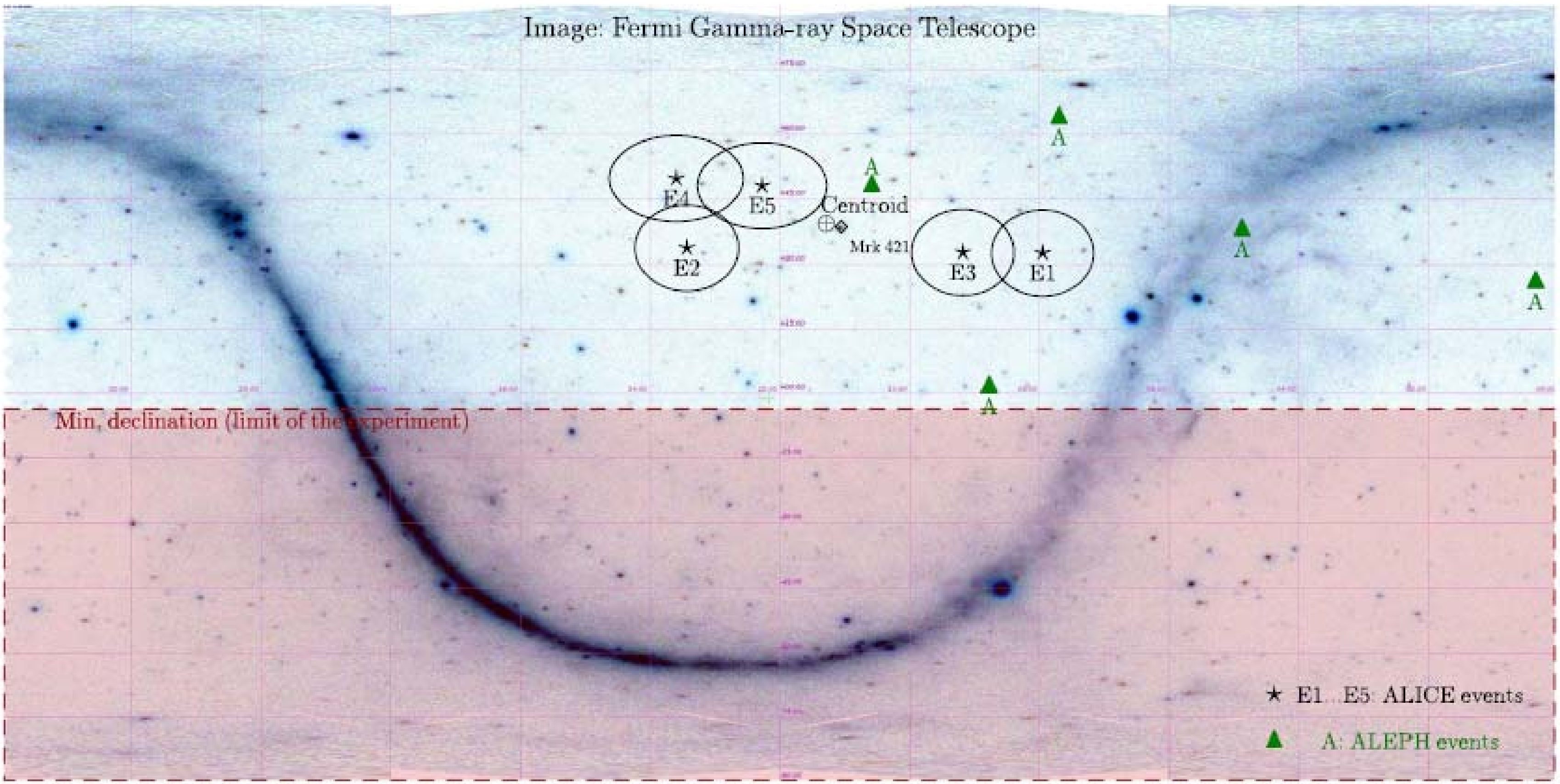
Most known extragalactic TeV Sources (blazars, SNRs, radio galaxies) in the sky [Horan and Weekes, New Astr. Rev. 48 (2004) 527], [Turley et al., arXiv:1608.08983] are also shown (note that **the Mrk 421 blazar** is the source located very close to the **centroid** of the five considered events).

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



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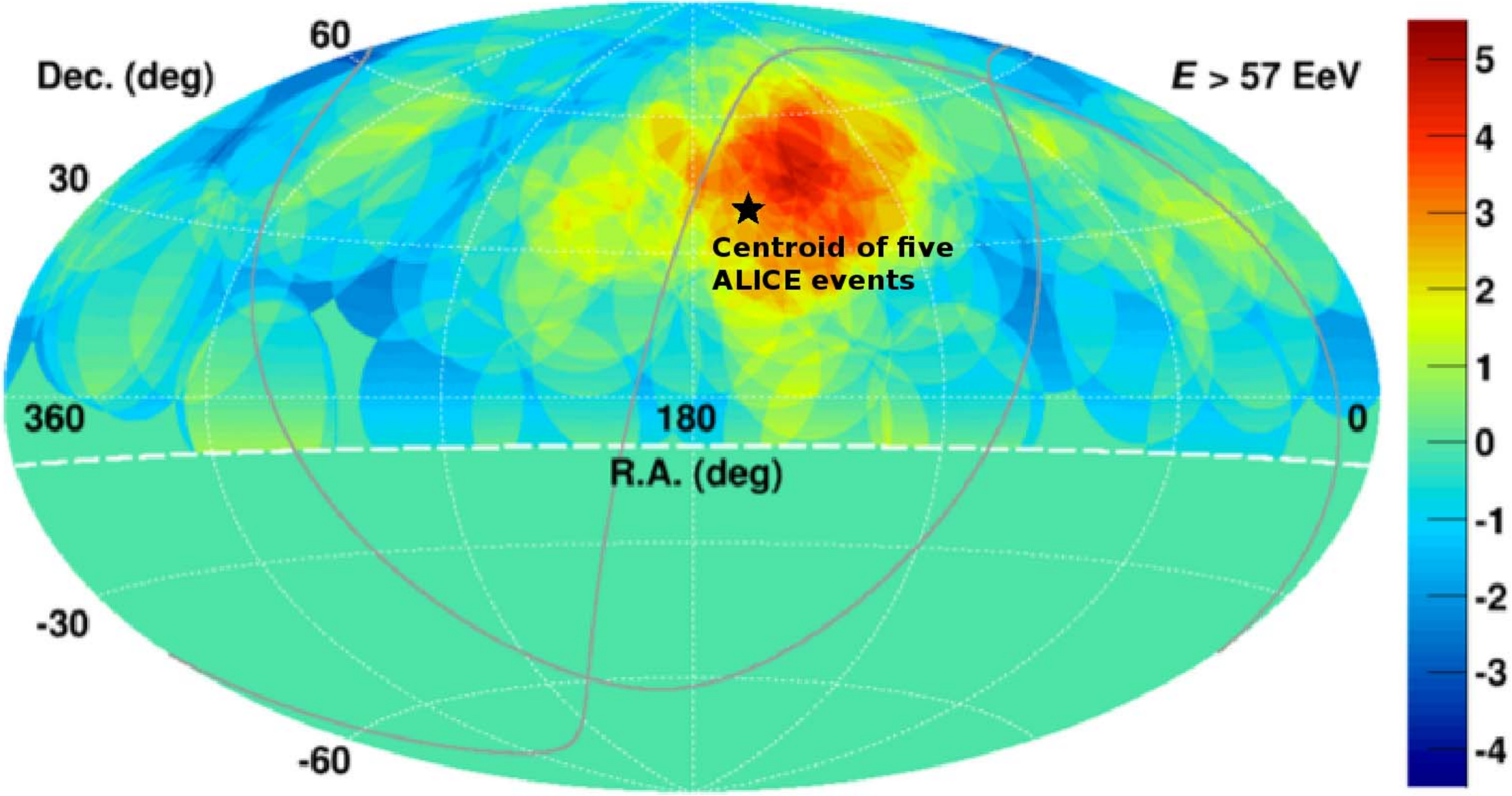
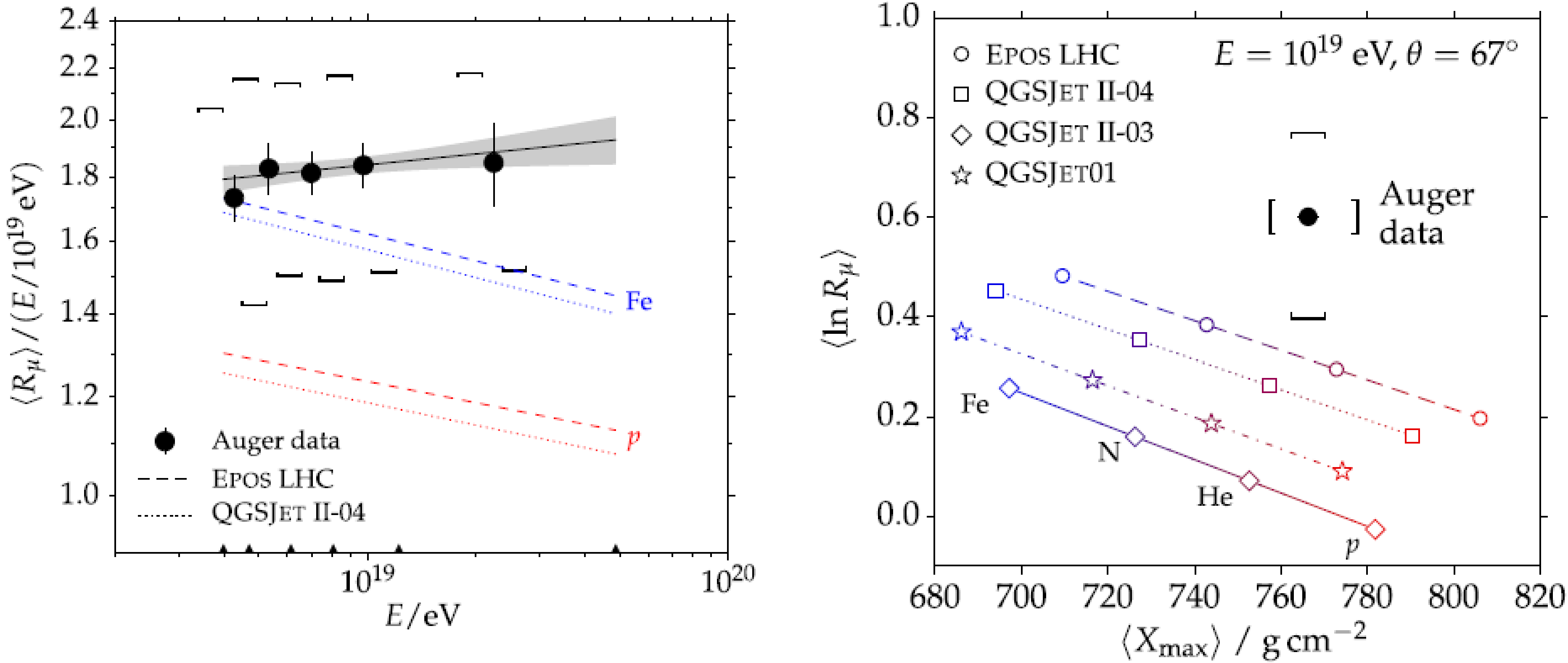


Aitoff projection of the UHECR map in equatorial coordinates taken from Telescope Array Collaboration data **[The Astrophysical Journal Letters 790 (2014) L21]**

muon excess in EAS



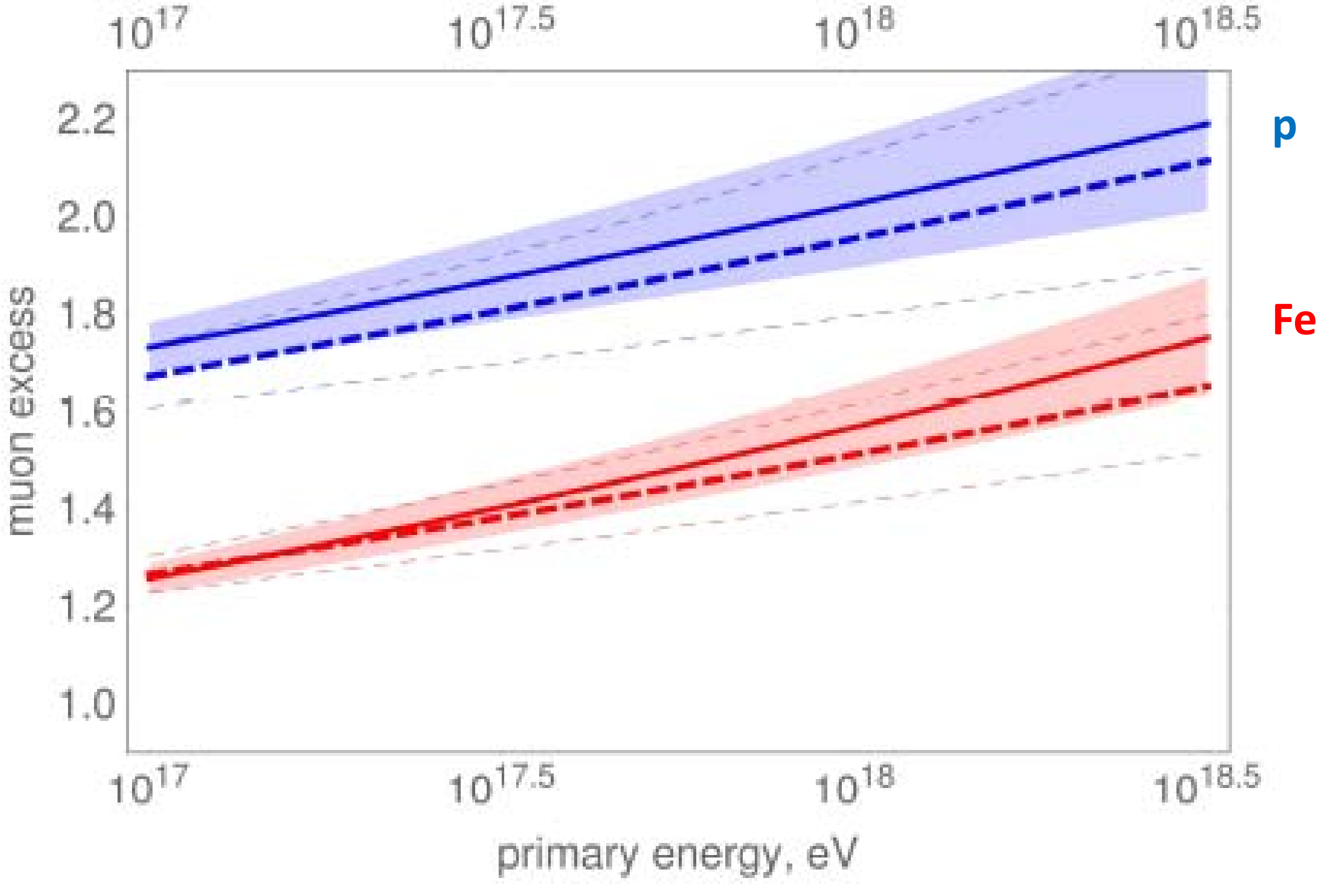
Aab A et al. [Pierre Auger Collaboration] 2015 Phys. Rev. D 91 032003 Erratum: [2015 Phys.Rev. D 91 059901]

$$R_\mu = N_\mu / N_{\mu,19}$$

At zenith angle $\Theta = 67^0$ the muon content

$R_\mu = 1$ corresponds to $N_\mu = 1.455 \cdot 10^7$ muons at the ground with energies above 0.3 GeV

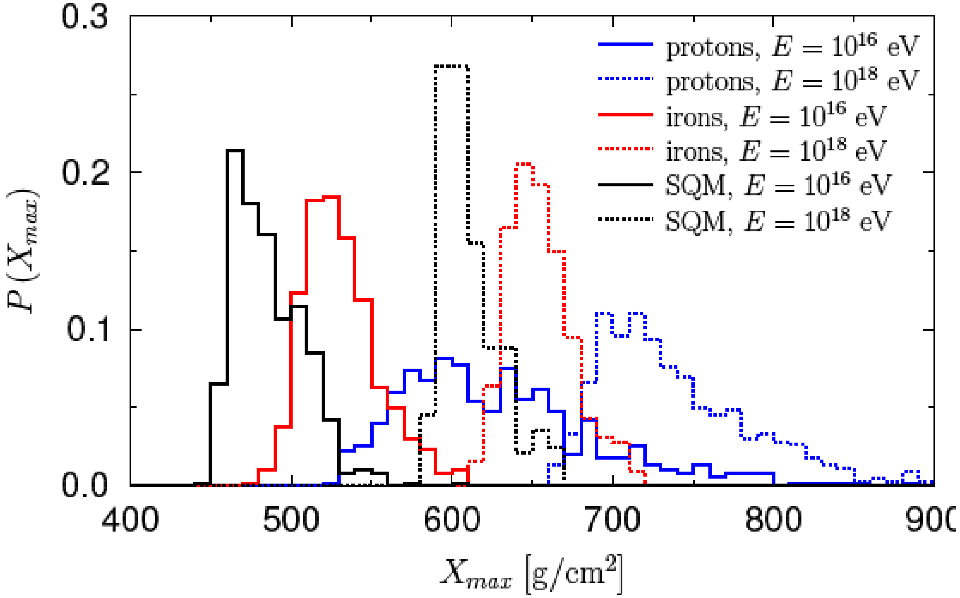
muon excess in EAS

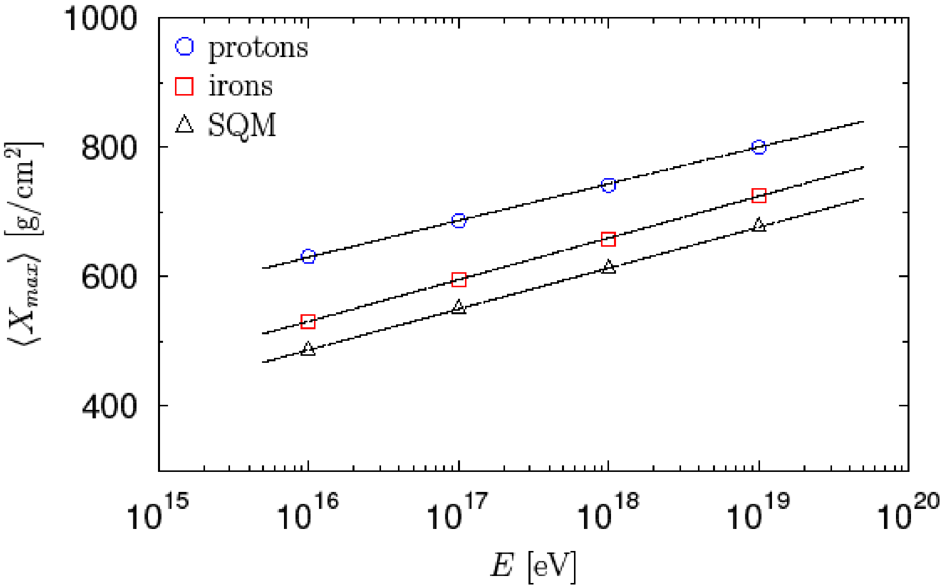


The empirically determined number of muons with energies above 0.75 GeV exceeds the simulated one.

The Sydney University Giant Air-shower Recorder (**SUGAR**) [arXiv:1803.08662]

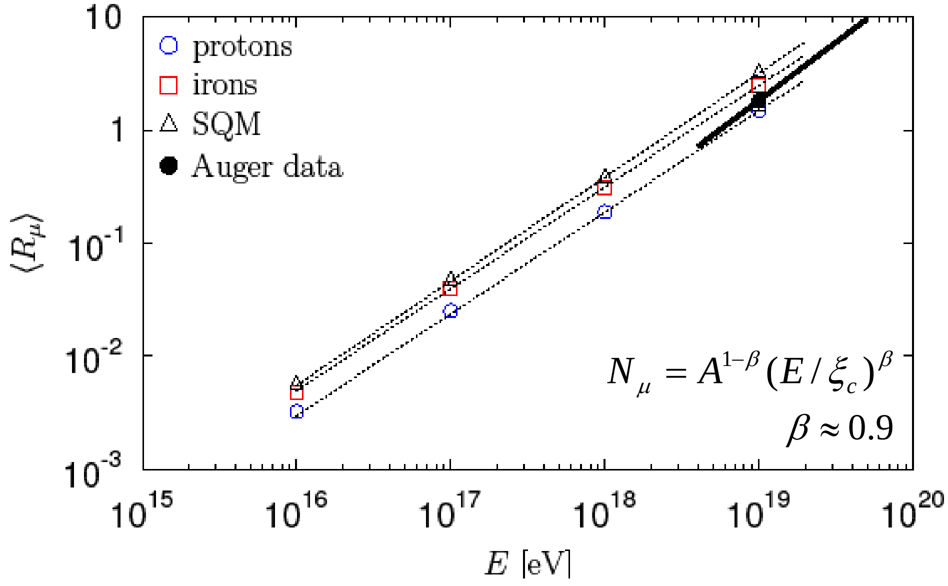
EAS from SQM

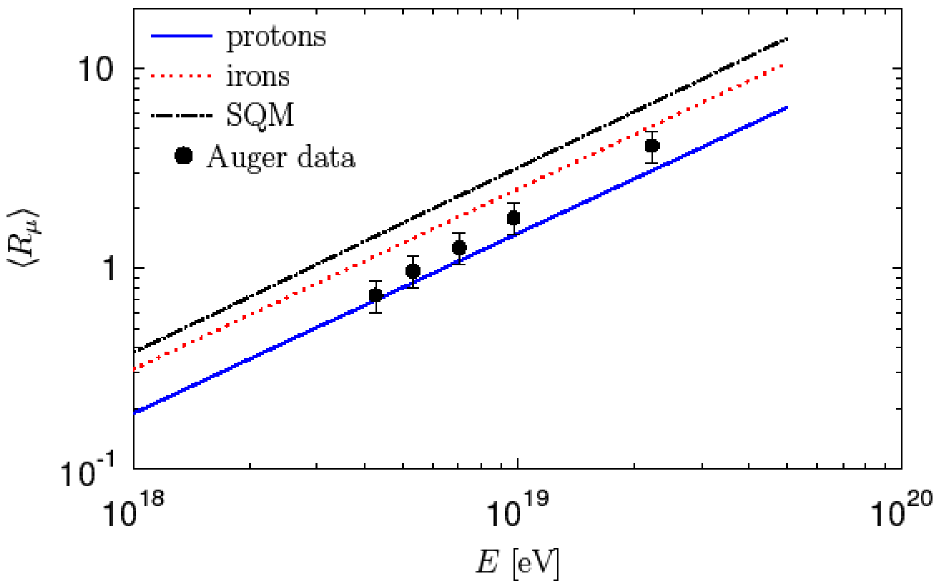


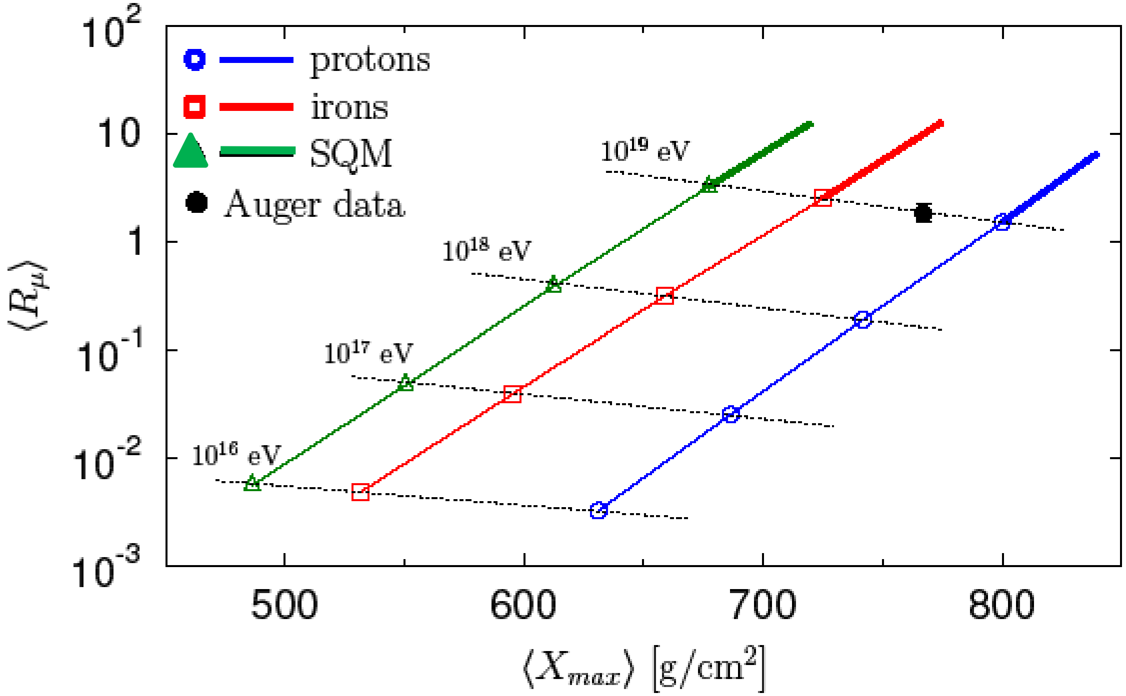


we have used FOO model (from SHOWERSIM modelar software)

muon content in EAS







a rough agreement between the simulations and the data for ordinary nuclei without any contribution of strangelets in primary flux of cosmic rays

$$< R_\mu >= 1.82 \pm 0.38$$

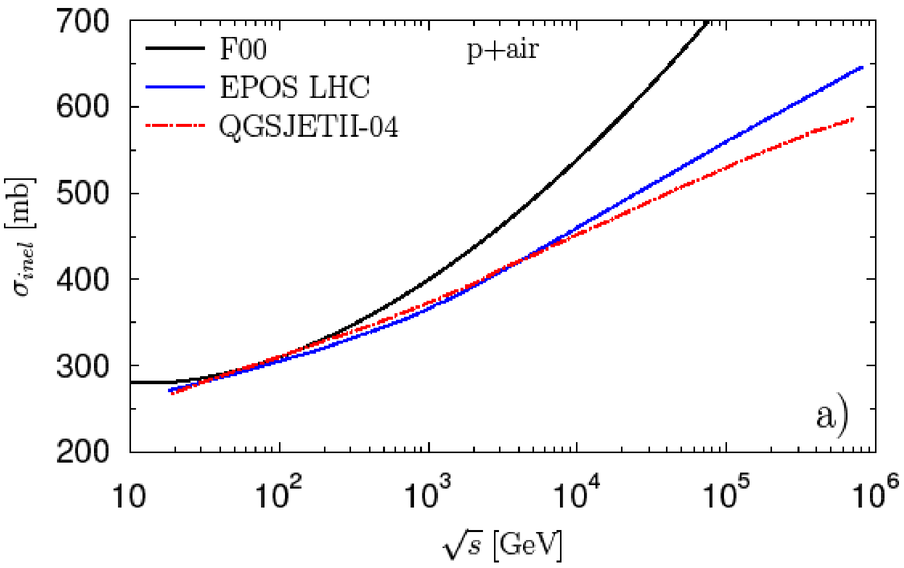
$$\omega = \sigma(R_\mu) / < R_\mu >= 0.20 \pm 0.01$$

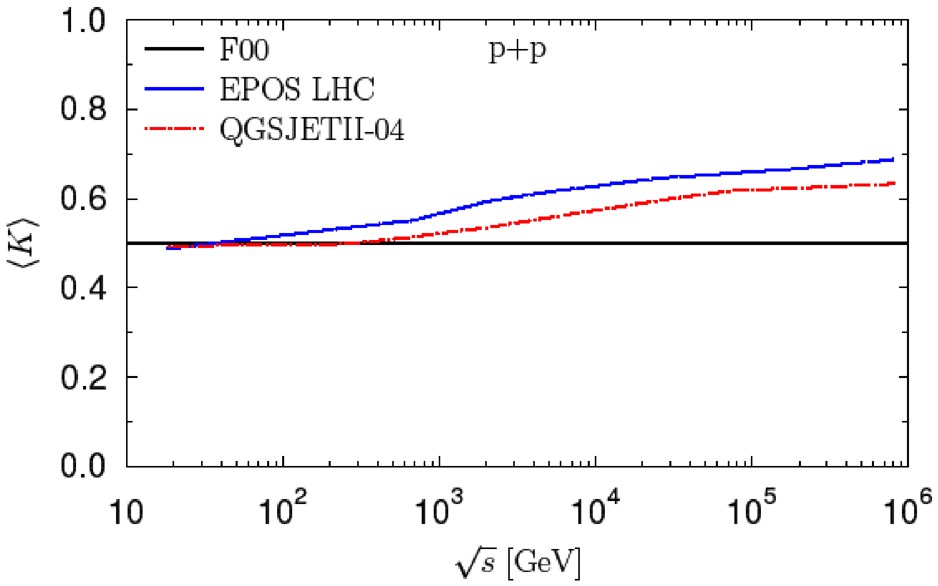
for single component $\omega = \begin{cases} 0.04 & Fe \\ 0.13 & p \end{cases}$

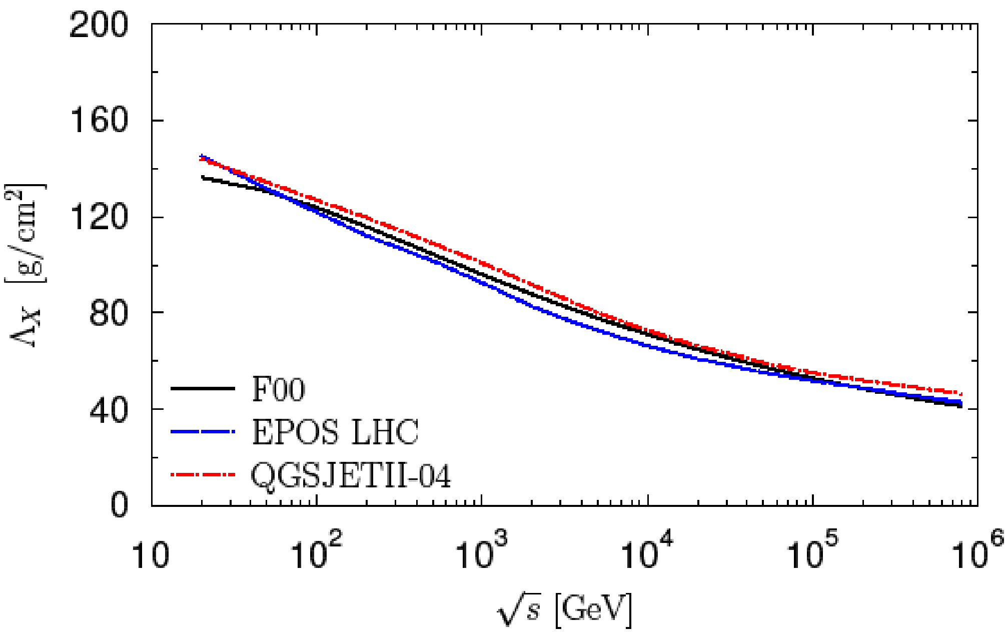
best description :
40% p, 20% He, 35% CNO, 5% Fe

at $4 \cdot 10^{18}$ eV: $< \ln A >= 1.4$

$\sigma(\ln A) = 1.3$





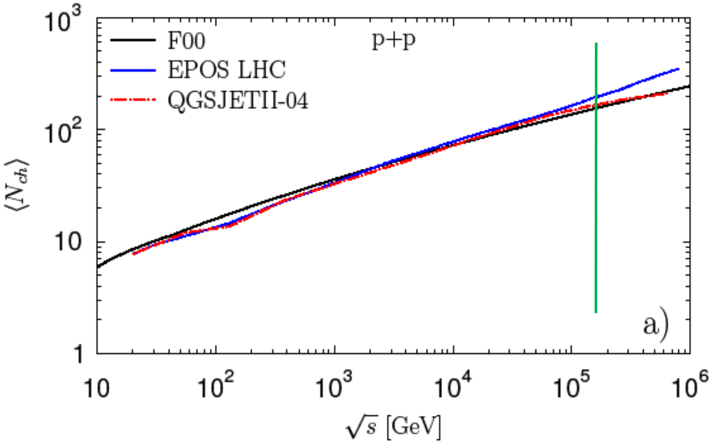


The deep tail of maximum distribution

$$\frac{dN}{dX_{\max}} \propto \exp\left(-\frac{X_{\max}}{\Lambda_X}\right)$$

depends on
shower maxima attenuation length

$$\Lambda_X \cong 0.8\frac{2.4\cdot10^4\, g/cm^2}{<K>\sigma_{inel}}$$


F00
EPOS LHC
QGSJETII-04
p+p
a)
$\langle N_{ch} \rangle$
$\sqrt{s}$ [GeV]
1
10
10^2
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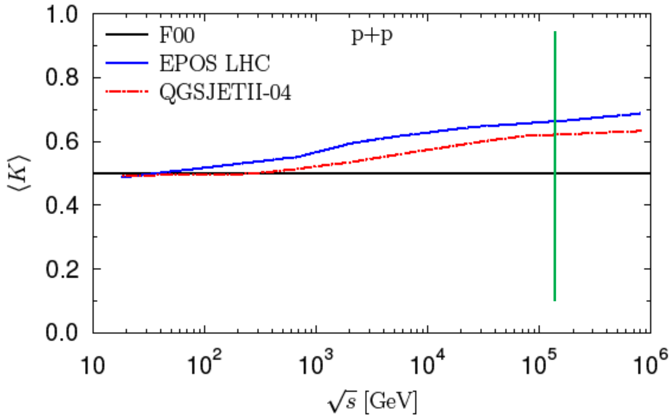
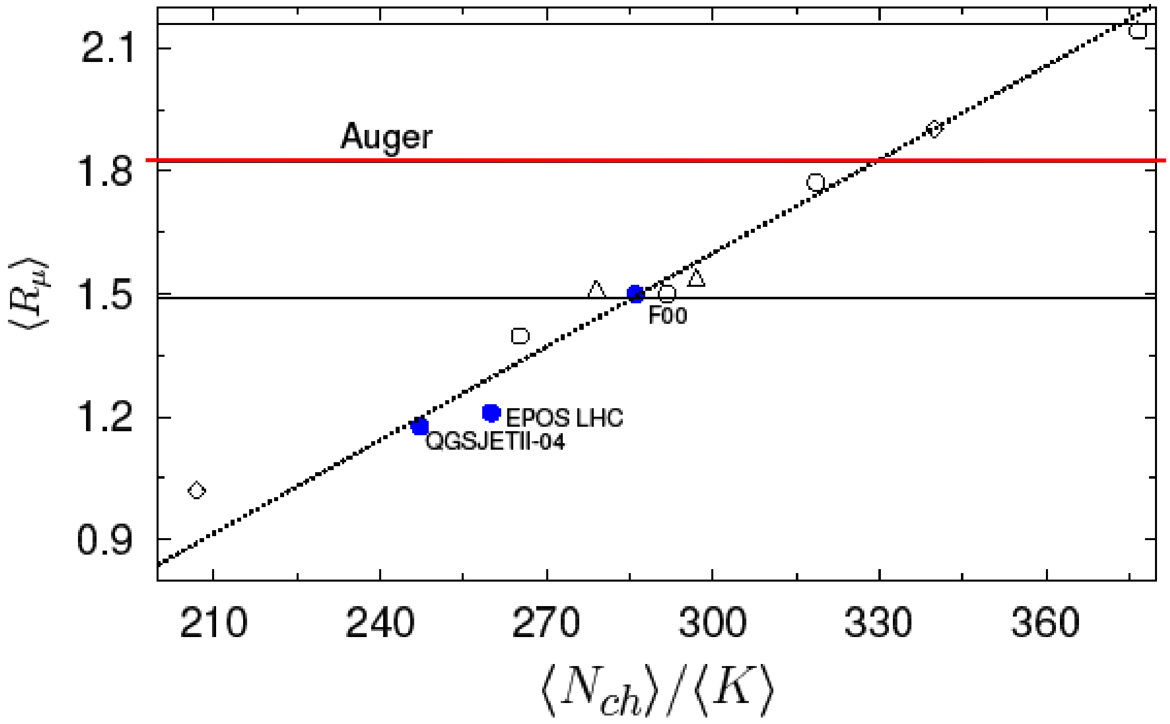
10^2
10^3
10^4
10^5
10^6


F00
EPOS LHC
QGSJETII-04
p+p
$\langle K \rangle$
$\sqrt{s}$ [GeV]
0.0
0.2
0.4
0.6
0.8
1.0
10
10^2
10^3
10^4
10^5
10^6


Auger
F00
EPOS LHC
QGSJETII-04
$\langle R_\mu \rangle$
$\langle N_{ch} \rangle / \langle K \rangle$
0.9
1.2
1.5
1.8
2.1
210
240
270
300
330
360

Concluding Remarks

- Accelerator apparata can be suitable for cosmic-ray physics. Recently CERN ALICE experiment, in its dedicated cosmic ray run, observed muon bundles of very high multiplicities confirming therefore similar findings from the LEP era at CERN (in the Cosmo-LEP program: ALEPH, DELPHI and L3)

- 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. SQM allows to reproduce the high muon multiplicity groups.

- The arrival directions of the observed high muon multiplicity groups suggest their extragalactic origin.

- Ordinary nuclei, without any contribution from strange quark matter in the primary flux of cosmic rays, can describe muon content in EAS. Even if the strangelets contribute with a small amount in the primary flux and generate high multiplicity muon bundles, their influence on the average muon content $< R_\mu >$ in EAS is negligible.

FASCINATING SEARCHES (both experimental and theoretical)

FOR STABLE STRANGE MATTER (has many faces, sometimes leading to different conclusions)

WOULD HAVE NUMEROUS IMPLICATIONS FOR PHYSICS AND ASTROPHYSICS.

THIS IS A VALID INTEREST IN FUTURE SEARCH OF STRANGE QUARK MATTER.

Further reading:
P. Kankiewicz, M. Rybczyński, G. Wilk, and Z. Włodarczyk, Muon Bundles as a Sign of Strangelets from the Universe,
ApJ 839 (2017) 31 [arXiv:1612.04749]

Thank you
for you attention