POWER-LIKE ABUNDANCE OF ELEMENTS IN UNIVERSE

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- Between the heaviest atomic elements and neutron stars lies a vast unpopulated "nuclear desert".
- We argue that this void may actually be filled with strange quark matter (strangelets).
- The fluxes of candidates for strangelets measured in cosmic ray experiments on different depths of atmosphere are investigated.
- The flux of strangelets reaching the Earth atmosphere as a function of mass is estimated and compared with astrophysical limit. It turnes out that its expected power-like mass spectrum continue the observed abundance distribution of normal nuclei in the Universe.
- We discuss the possible growth mechanism of strangelets in sources of production, which results in such power-law distribution.

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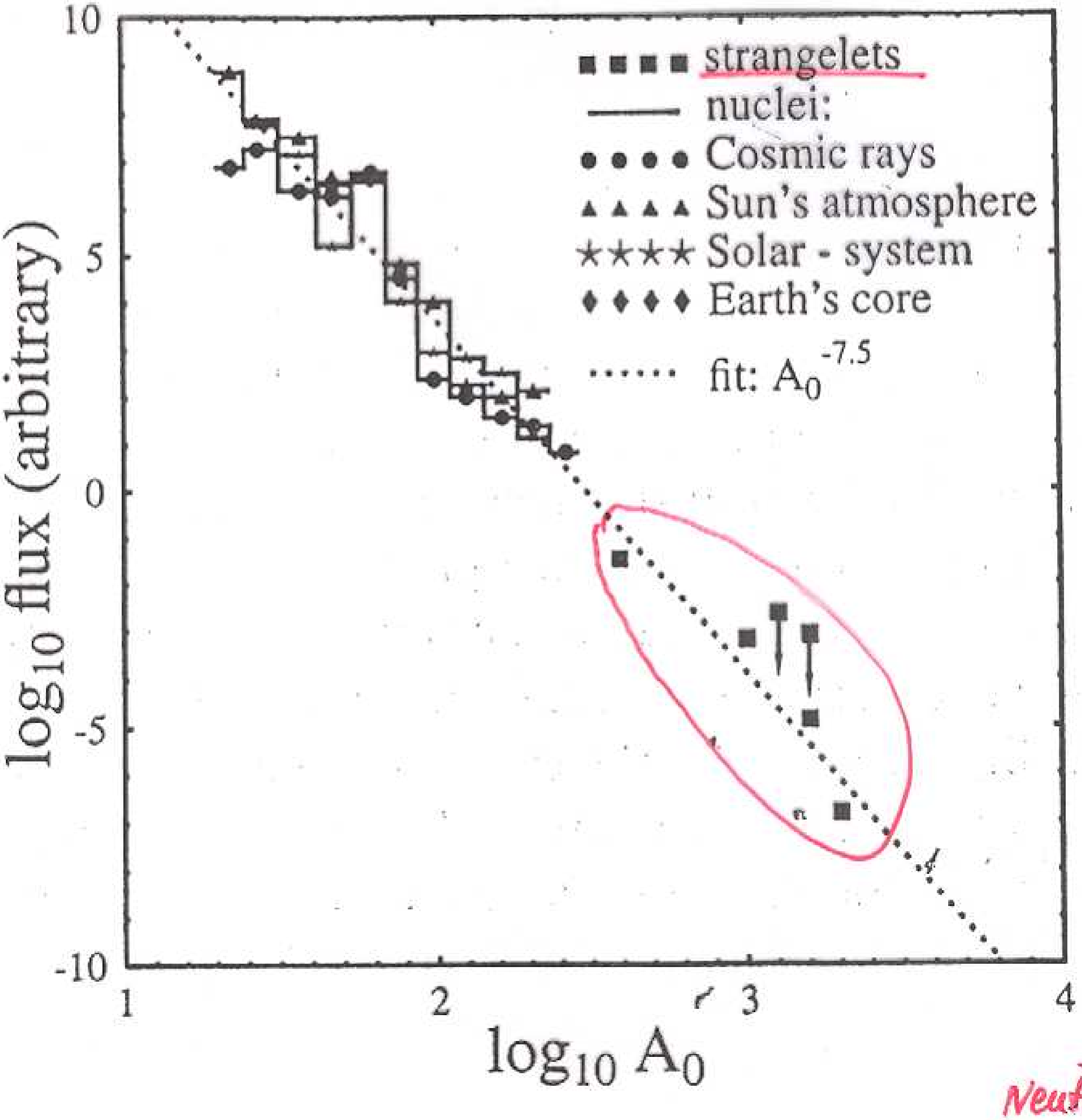

→
Neutron
(quark)
stars

- What it is Strange Quark Matter ?

  $\Longrightarrow$ true ground state of QCD [1] consisting of roughly equal number of up (u), down (d) and strange (s) quarks: (u,d,s)

- It is absolutely stable at high mass numbers A ($A > A_{crit} = 300 \div 400$). For small A it decays rapidly by evaporating neutrons.

- SQM formed at very early stage of the Universe would, however, evaporated (*because of weak decays*) long time ago

- but it is probably continuously produced in neutron stars with a superdense quark surface and in quark stars with a thin nucleon envelope

  $\Longrightarrow$

  collisions of such objects could therefore produce small lumps of SQM called STRANGELETS, with $10^2 < A < 10^6$, permeating the Galaxy and possibly reaching Earth.

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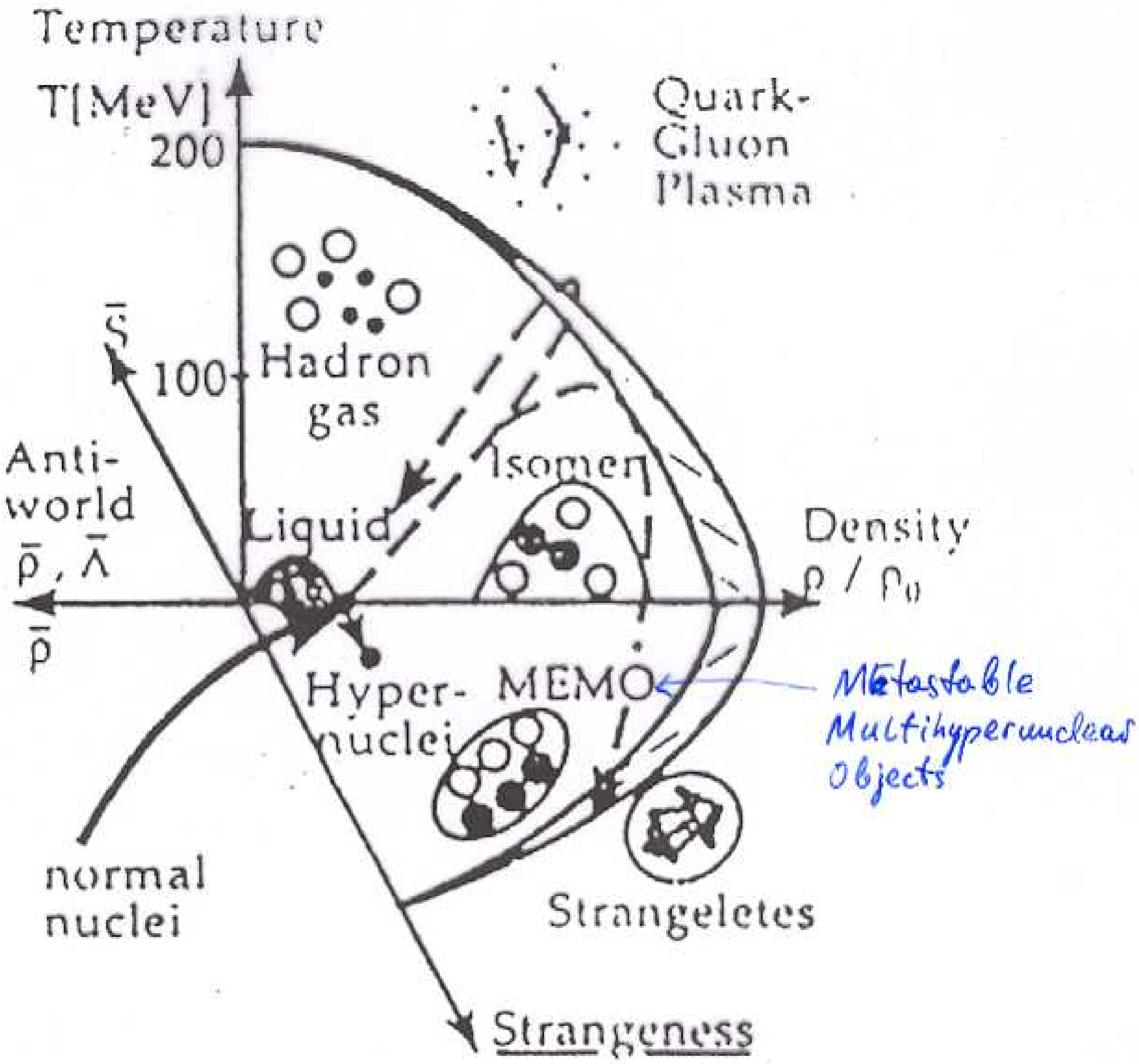
[1] E.Witten, PRD30 (1984) 272.



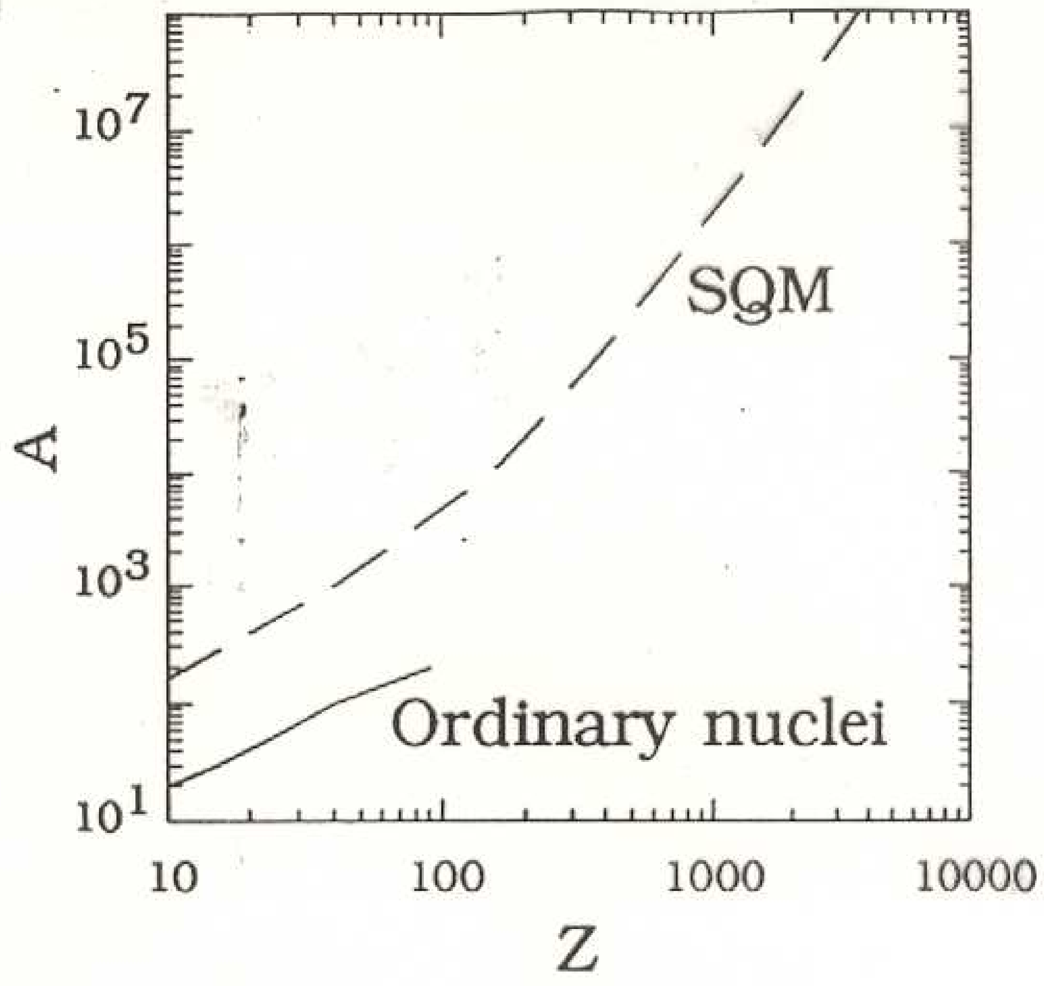
In heavy ion collisions **strange objects** can be created:

(1) either via clustering of hyperons (solely in the hadronic sector)

(2) or via strangeness separation out of QGP with possible distillation of strangelets

$$\text{QGP:} \begin{pmatrix} u + u\bar{u} \\ d + d\bar{d} \\ \bar{s}s \end{pmatrix} \rightarrow \begin{pmatrix} K^+ \\ K^0 \end{pmatrix} + \begin{pmatrix} u \\ d \\ s \end{pmatrix}$$

↳ taking away $\bar{s}$ quarks



SQM is distinguished from ordinary nuclei by very hig values of A/Z and its stability for $Z > 92$

- NOTICE: strangelet is NOT a nucleus but rather a BAG of (u,s,d) quarks with geometrical radii

$$R = r_0 \cdot A^{1/3}$$

comparable to those of ordinary nuclei of the corresponding mass number A:

$$r_0 = \left\{ \frac{3\pi}{2\left(1 - \frac{2\alpha_c}{\pi}\right)\left[\mu^3 + \left(\mu^2 - m^2\right)^{3/2}\right]} \right\}^{1/3}$$

where:

μ is s-quark chemical potential

m is s-quark mass

$\Longrightarrow$

- PROBLEM: how they can reach deep into atmosphere (*and form known candidates for strangelets*)?

Simple estimation:

- the mean free path of strangelets with mass A in the atmosphere ($A_{air} = 14.5$) is

$$\lambda_{Sair} = \frac{A_{air} m_N}{\pi \left(1.12 A_{air}^{1/3} + r_0 A^{1/3}\right)^2}$$

  and is equal to: 16, 5 and 1.4 g/cm^2 for A $= 10^2$, 10^3 and 10^4 (for m= 150 Mev and μ=300 MeV)

$\Longrightarrow$ almost typical nuclear values $\Longrightarrow$

- PROBLEM:

  how they can reach deep into atmosphere

  (*and form known candidates for strangelets*)?

Cosmic nuclearities

There are several reports suggesting direct candidates for SQM. In particular, the following anomalous massive particles, which can be interpreted as strangelets, have been apparently observed in Cosmic Ray (CR) experiments:

- (*i*) In counter experiment devoted to study primary CR nuclei two anomalous events have been observed (*Saito*) [10] with values of charge $Z \cong 14$ and of mass numbers $A \cong 350$ and $A \cong 450$, respectively.
- (*ii*) The so called Price's event [11] with $Z \cong 46$ and $A > 1000$, regarded previously as possible candidate for magnetic monopole.
- (*iii*) The so called Exotic Track (ET) event with $Z \cong 20$ and $A \cong 460$ has been reported in [12]. The name comes from the fact that the projectile causing that event has apparently traversed $\approx 200\ \mathrm{g/cm^2}$ of atmosphere.

It is remarkable that all possible candidates for SQM have mass numbers near or slightly exceeding A_{crit} (it is also argued that *Centauro* [13] event, regarded to be possible candidate for strangelet, contains probably ≈ 200 baryons [14]). Also the values of Z and A mentioned above are fully consistent with the existing theoretical estimations for Z/A ratio, which is characteristic for the SQM [15], *cf.* Fig. 4.

[10] T. Saito et al., Phys. Rev. Lett. 65 (1990) 2094

[11] P. B. Price et al., Phys. Rev. D18 (1978) 1382

[12] M. Ichimura et al., Nuovo Cim. A106 (1993) 843

[13] C.M.G. Lattes et al., Phys. Rep. 65 (1980) 151

To resolve contradiction:

"normal size" vs "strong penetrability"

$$\Longrightarrow$$

propositions:

strangelets reaching deeply into atmosphere are formed in many successive interactions with air nuclei according to one of the scenarios:

- initially small strangelet picks up mass from the collision
- initiall very large strangelet ($A \sim 10^3$) decreases due to the subsequent collisions until $A = A_{crit}$ at which point it disintegrates[3]

Hint: strangelet of $A \sim 10^3$ is much more stable than air nuclei

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[2] S.Banerjee et al. PRL 85 (2000) 1384.

[3] G.Wilk and Z.Włodarczyk, JPG22 (1996) L105, NPB (PS) B52 (1997) 215.

Proposition: Strangelets reaching deeply into the atmosphere are formed in many successive interactions with air nuclei of much heavier lumps of SQM entering our atmosphere

(1) SM ("Standard model"): all quarks of A_t which are located in the geometrical intersection of the two colliding projectiles are involved but it is assumed that each q from the target (air nucleus) interacts with only one quark from the strangelet

=> each interaction eliminates $3A_t$ q's from strangelet (at most) → $A \to A' = A - A_t$

=> total penetration depth of the strangelet can be estimated here as:

$$\Lambda \simeq \frac{4}{3}\lambda_{NA_t}\left(A_0/A_t\right)^{1/3}$$

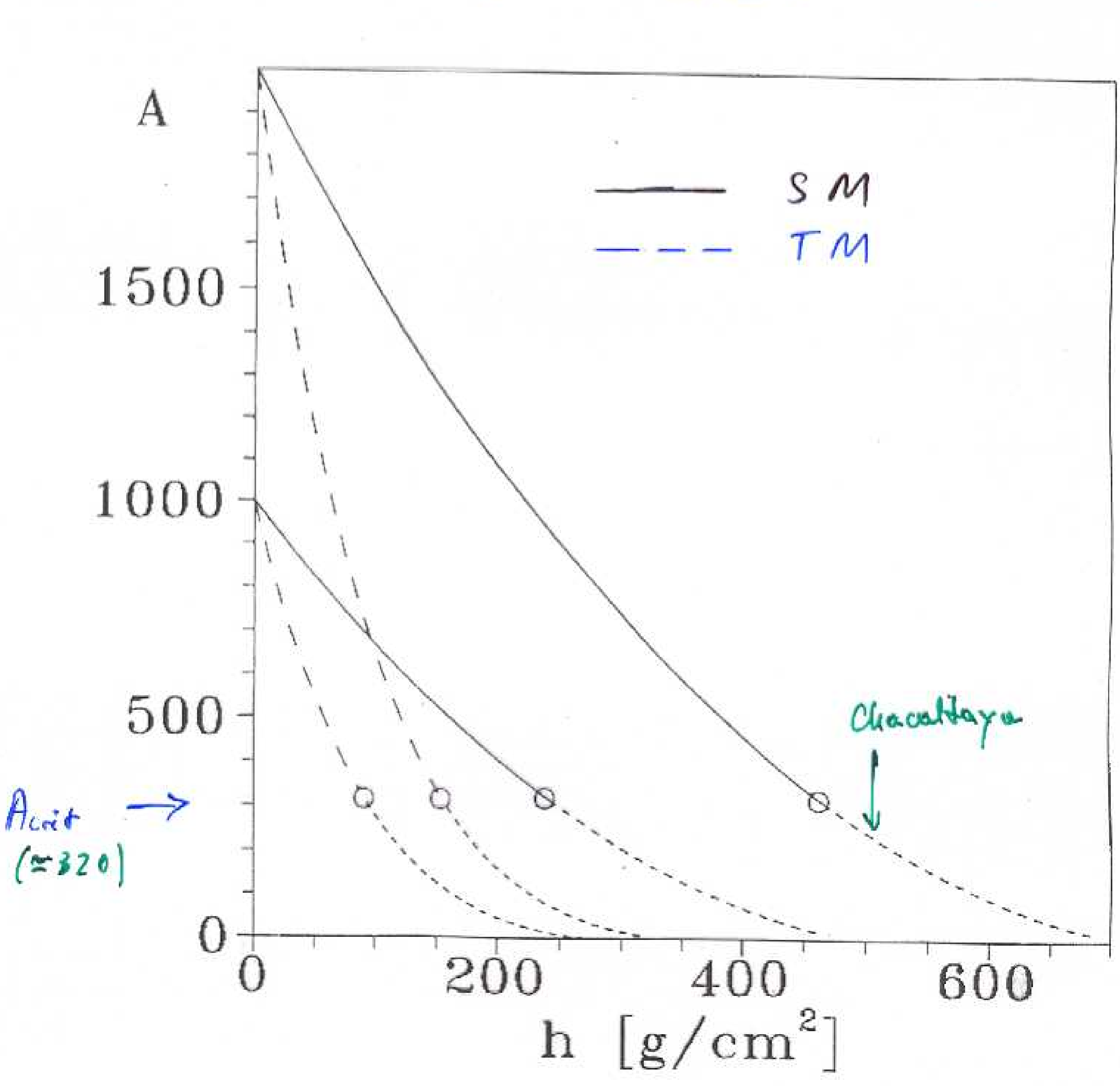
λ_{NA_t} for N(Air) collision

A_0 – initial mass number of strangelet

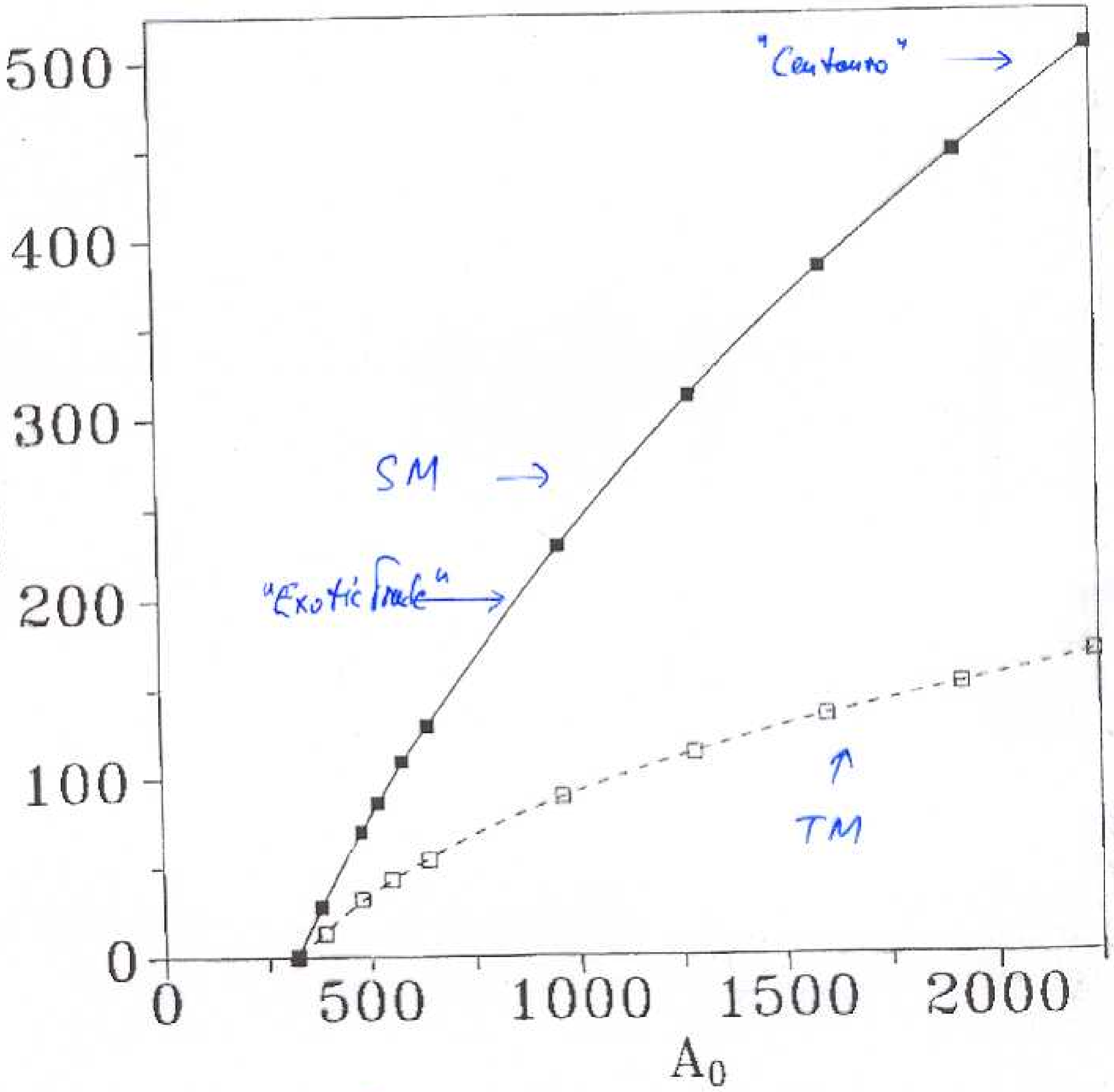
(2) TM ("Tube Model") – all quarks from both air and part of S pushed by it are used – after collision $A \to A' = A - A^{1/3} \cdot A_t^{2/3}$

$A_t = 14.5$ in practice.

An example of the predicted decrease of the
actual size of strangelet A
with depth of the atmosphere $h\,[g/cm^2]$ traversed



o - - - - -   in both SM and TM
corresponds to $A < A_{crit}$
(here strangelets practically
dissolve into baryons)



Atmospheric length Λ [g/cm^2] after which initial strangelet reaches its critical dimension: $A = A_{crit}$, as a function of its initial size: A_0. Here $A_{crit} = 320$

Squares: multiple of A_{crit} (for $A_{crit} \neq 320$; $A_0 > 600$)
results simply scale in A_{crit}/A_0
=> read new A_0)

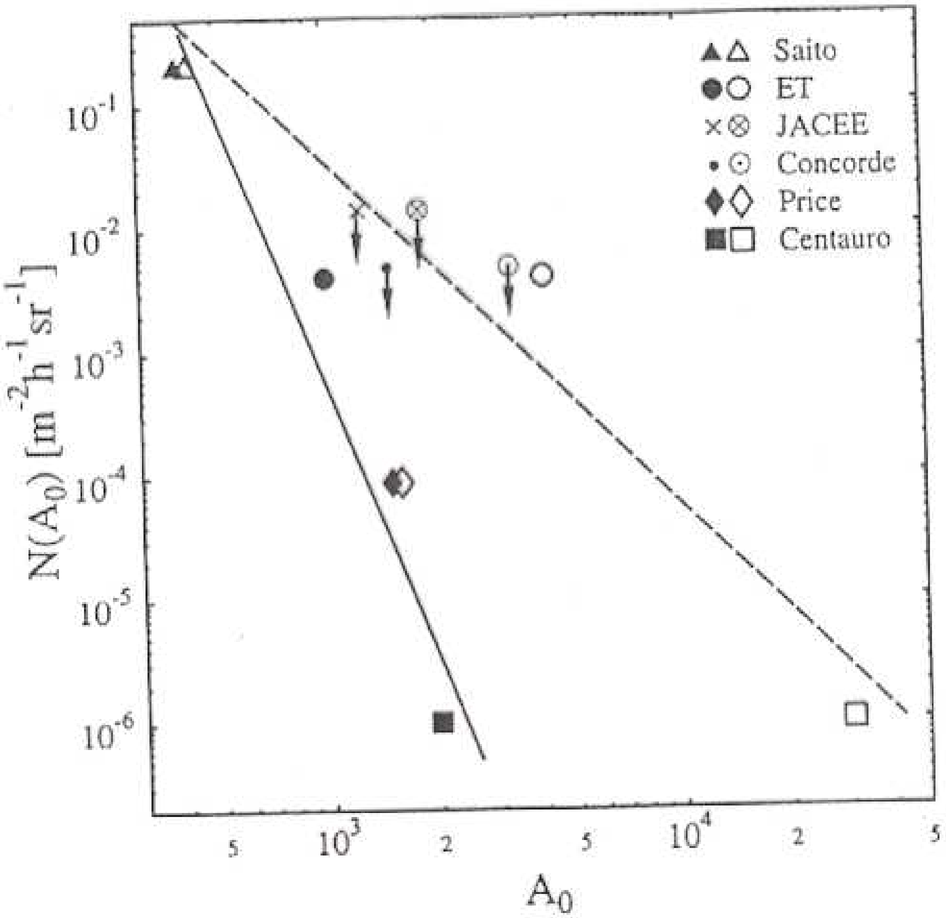


Fig. 3. The estimation of the expected flux of strangelets on the border of atmosphere, $N(A_0)$, as a function of their mass number as obtained from SM (full symbols; solid line for power fits) and TM (empty symbols; dashed line). See [3,9] for further details.

SM model prefered $\Rightarrow$ $N(A_0) \sim A_0^{-7.5}$

data archives from the ALEPH COSMO-LEP program

☐ more than 3.7 10^5 muon events have been recorded in the effective run time 10^6 seconds

☐ multi-muon events observed in the 16 m^2 TPC with momentum cut-off 70 GeV have been analysed and good agreement with MC simulations obtained for multiplicities N_μ between 2 and 40

☐ there are 5 events
with unexpectedly large multiplicities N_μ (up to 150)
which rate cannot be explained,
even assuming pure iron primaries

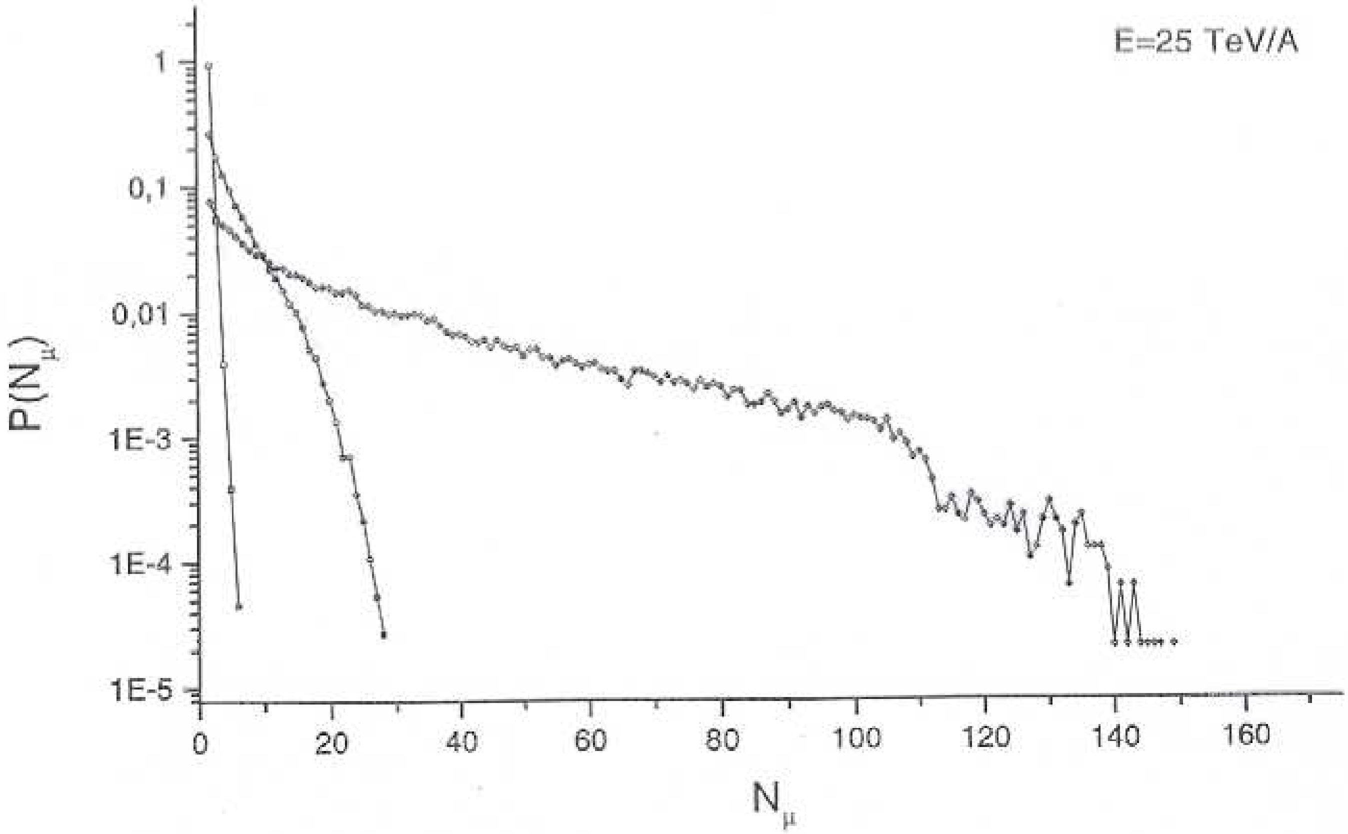
notice that the high multiplicity events discussed here
(with $N_\mu \cong 110$ recorded on 16 m^2) correspond to
~ 5600 muons in total ($E_\mu \geq 70$ GeV) or
~ 1000 muons with energies above 220 GeV

Baksan Valley experiment ($E_\mu \geq 220$ GeV) observed

7 events with more than 3000 muons

Monte Carlo simulation

- ☐ primaries were sampled from $P(E) \sim E^{-2.7}$ with energies above 10 TeV/A
- ☐ 'normal' chemical composition (40% p, 20% He, 20% C-N-O, 10% Ne-S and 10% Fe)
- ☐ strangelets with A=400



the relative flux of strangelets

$F_s / F_{tot} \simeq 2.4 \cdot 10^{-5}$ (at the same energy per particle)

⟷ the same as obtained above

Muon bundles from CosmoLEP

We would like to bring ones attention to the data from the cosmic-ray run of the ALEPH detector at the CosmoLEP experiment. Data archives from the ALEPH runs have revealed a substantial collection of cosmic ray muon events [23]. More than 3.7×10^5 muon events have been recorded in the effective run time 10^6 seconds. Multi-muon events observed in the 16 m^2 time projection chamber with momentum cut-off 70 GeV have been analysed and good agreement with the Monte Carlo simulations obtained for multiplicities N_μ between 2 and 40. However, there are 5 events with unexpectedly large multiplicities N_μ (up to 150) which cannot be explained, even assuming pure iron primaries.

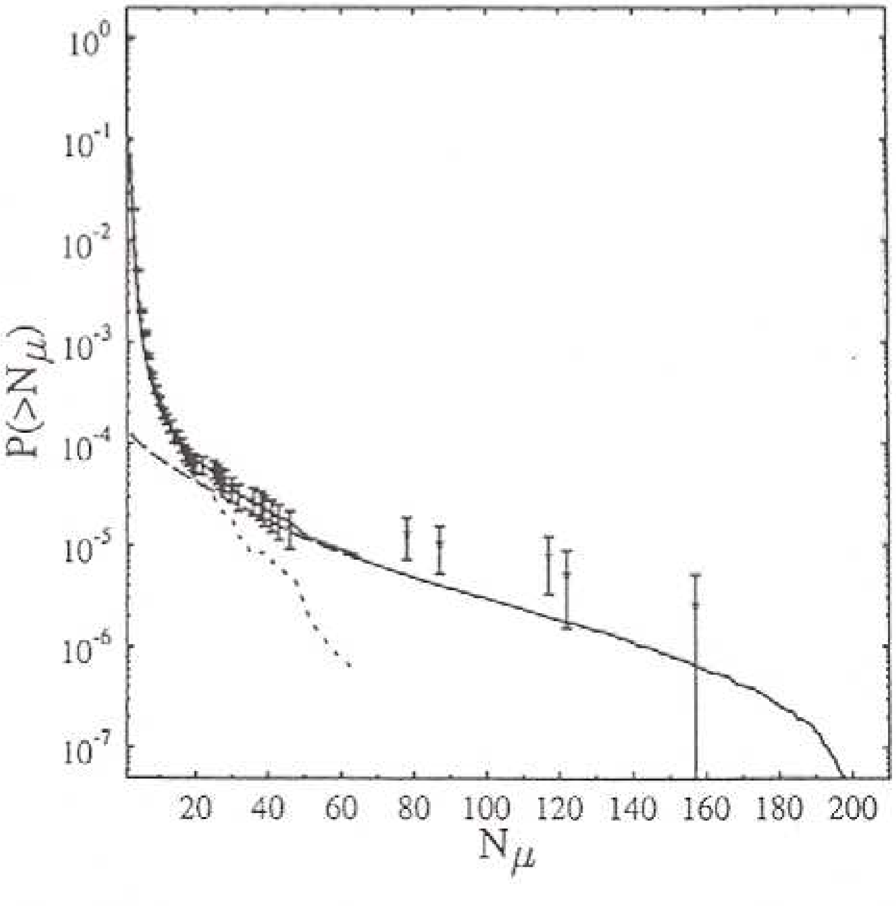


Fig. 9. Integral multiplicity distribution of muons for the CosmoLEP data [24] (stars). Monte Carlo simulations for primary nuclei with "normal" composition (dotted line) and for primary strangelets with $A = 400$ (dashed line). Full line shows the summary (calculated) distribution.

to describe the observed rate of high multiplicity events
one needs the relative flux of strangelets

$$\mathbf{F_S/F_{total} \cong 2.4\ 10^{-5}}$$

(at the same energy per particle)

☐ this is pecisely the flux we have estimated when interpreting direct candidates for strangelets and

☐ is fully consistent with exising experimental estimations

☐ it accomodates also roughly the observed flux of Centauro events

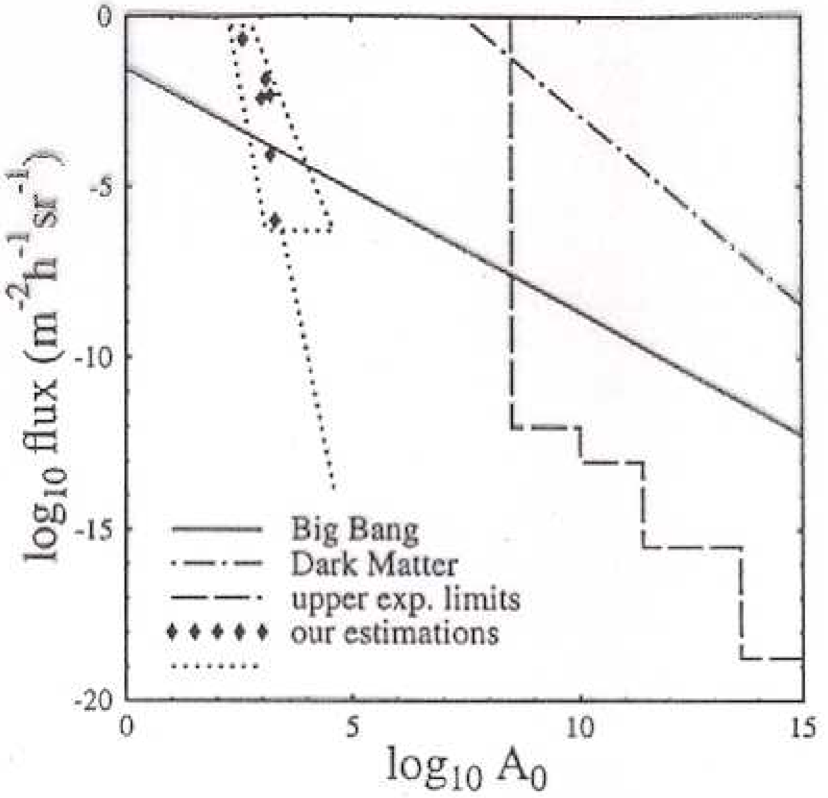


Fig. 13. The expected flux (our results) of strangelets compared with the upper experimental limits, compiled by Price [33], and predicted astrophysical limits: Big Bang estimation comes from nucleosynthesis with quark nuggets formation; Dark Matter one comes from local flux assuming that galactic halo density is given solely by quark nuggets.

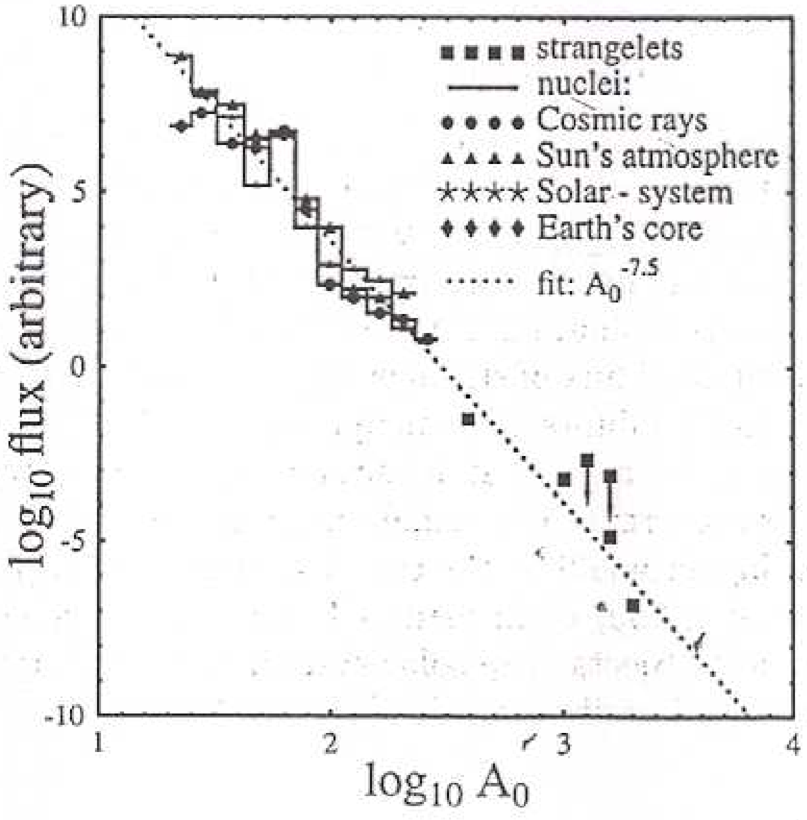
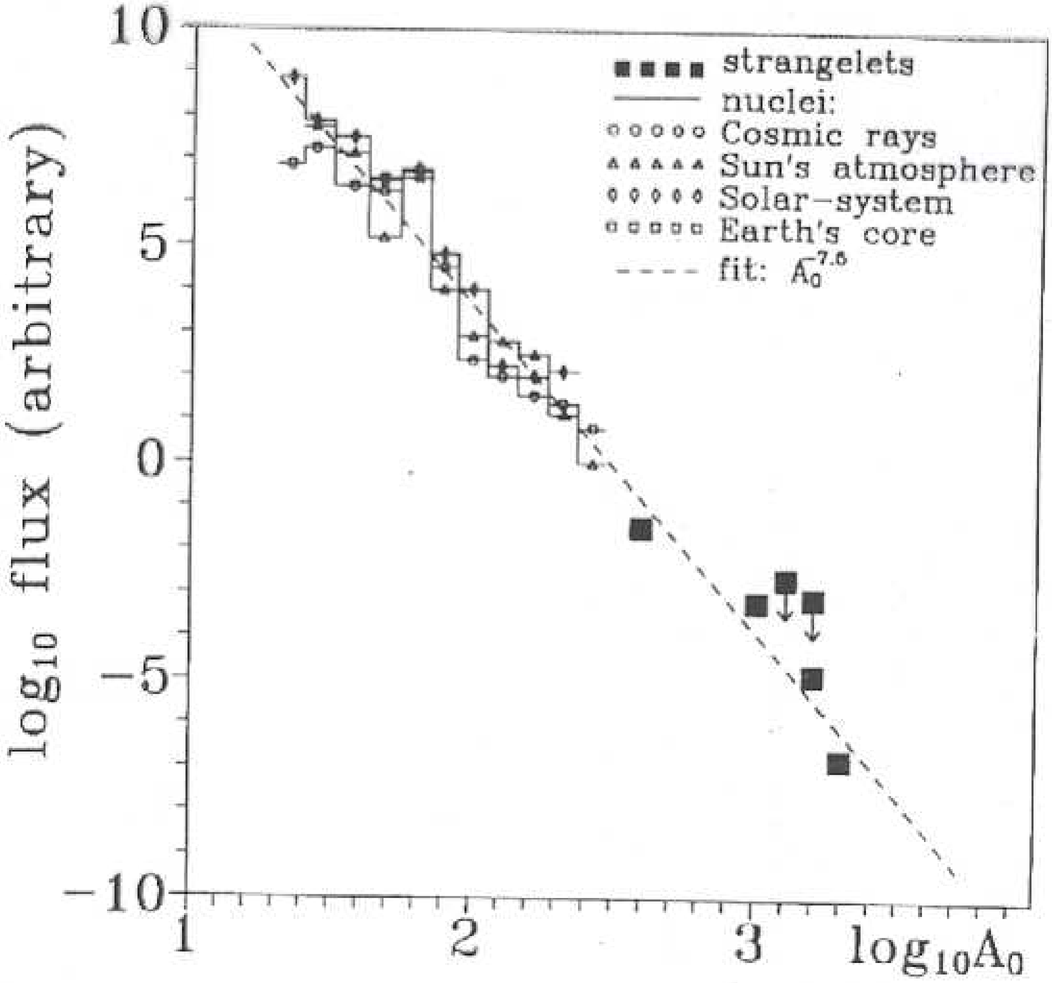


Fig. 14. Comparison of the estimated mass spectrum $N(A_0)$ for strangelets with the known abundance of elements in the Universe [34].



Summary of existing data on chemical composition of cosmic rays (relativistic velocities) and the material of various astrophysical objects:

- Sun's atmospher
- Solar-system matter
- Earth's core

compared with our estimations of strangelets intensity and our fit: $A_0^{-7.5}$

Consecutive steps of histogram denote the following nuclei:

Ne (Mg, Si) S (K, Ca) Fe (Cu, Zn)

(Kr, Sr, Zr) (Te, Xe, Ba) (Rare earths) (Os, Ir, Pt, Pb)

- Seed with mass $m = A_i(t_i)$ appears in time t_i with the uniform probability $P(t_i) = \frac{1}{t}$

- This seed absorbs neutrons increasing its mass according to the growth equation

$$\frac{\partial A_i}{\partial t} = \frac{\alpha}{A_i}$$

where $\alpha = nA_iL\sigma$ (in time t our object traverses distance L absorbing neutrons, which density is n, with the cross section σ)

$$\Longrightarrow$$

- The resulting mass spectrum has power-like form:

$$P(A) = \frac{m^{\frac{1}{\alpha}}}{1+\frac{1}{\alpha}} \cdot A^{\left(1+\frac{1}{\alpha}\right)}$$

- $\Rightarrow$ universal scanario leading to power-like abundance of ALL elements (including strangelets) ?