

# Strange Quark Matter Status and Prospects

2004 NASA/JPL Workshop

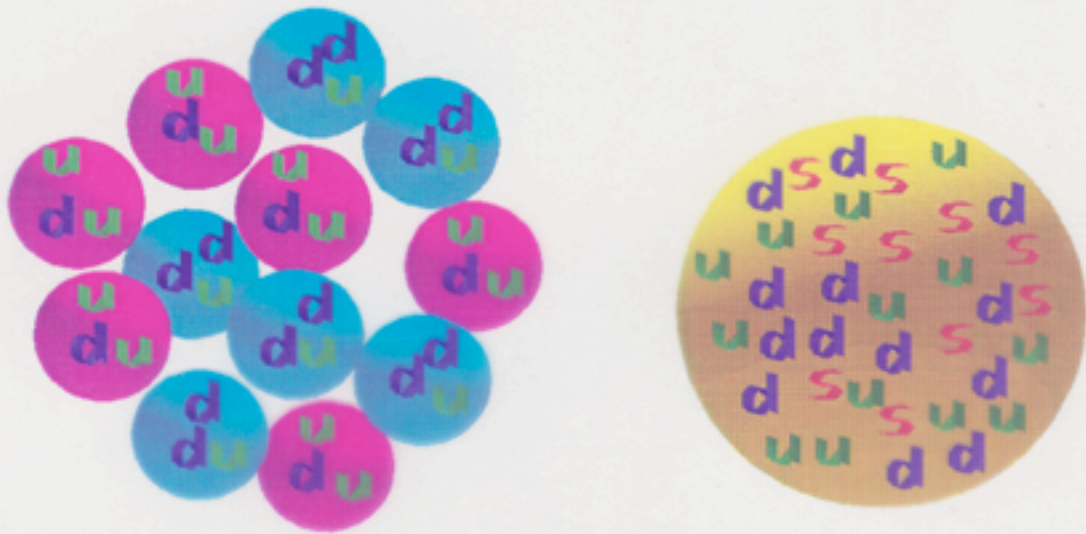
On

Physics for planetary Exploration

J. Sandweiss April 21, 2004

# Strange Quark Matter

Stable or metastable massive multi-quark states containing  $u, d$  and  $s$  quarks.



*"Artist's Interpretation"*

Nuclear Matter

(Carbon)

$$Z=6$$

$$A=12$$

$$Z/A=1/2$$

Strange Matter

(Strangelet)

$$Z=1$$

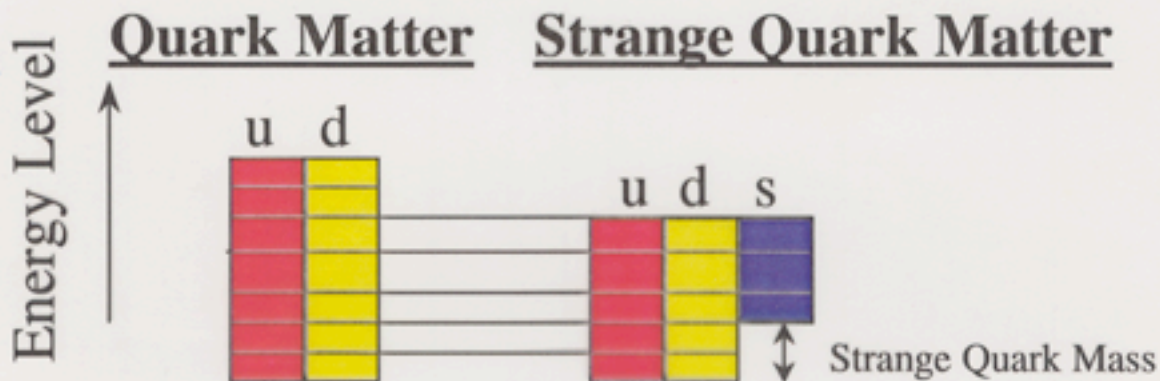
$$A=12 \text{ (36 quarks)}$$

$$Z/A=0.083$$

$$N_S=10, f_S=N_S/A=0.83$$

# Strange Quark Matter

The existence of quark states with more than three quarks is allowed in QCD. The stability of such quark matter states has been studied with lattice QCD and phenomenological bag models, but is not well constrained by theory.



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  $Z / A$** .

From Farhi and Jaffe

From E. Farhi and R. L. Jaffe, Phys. Rev. D 30, 2379-90 (1984).

MIT Bag Model Calculation

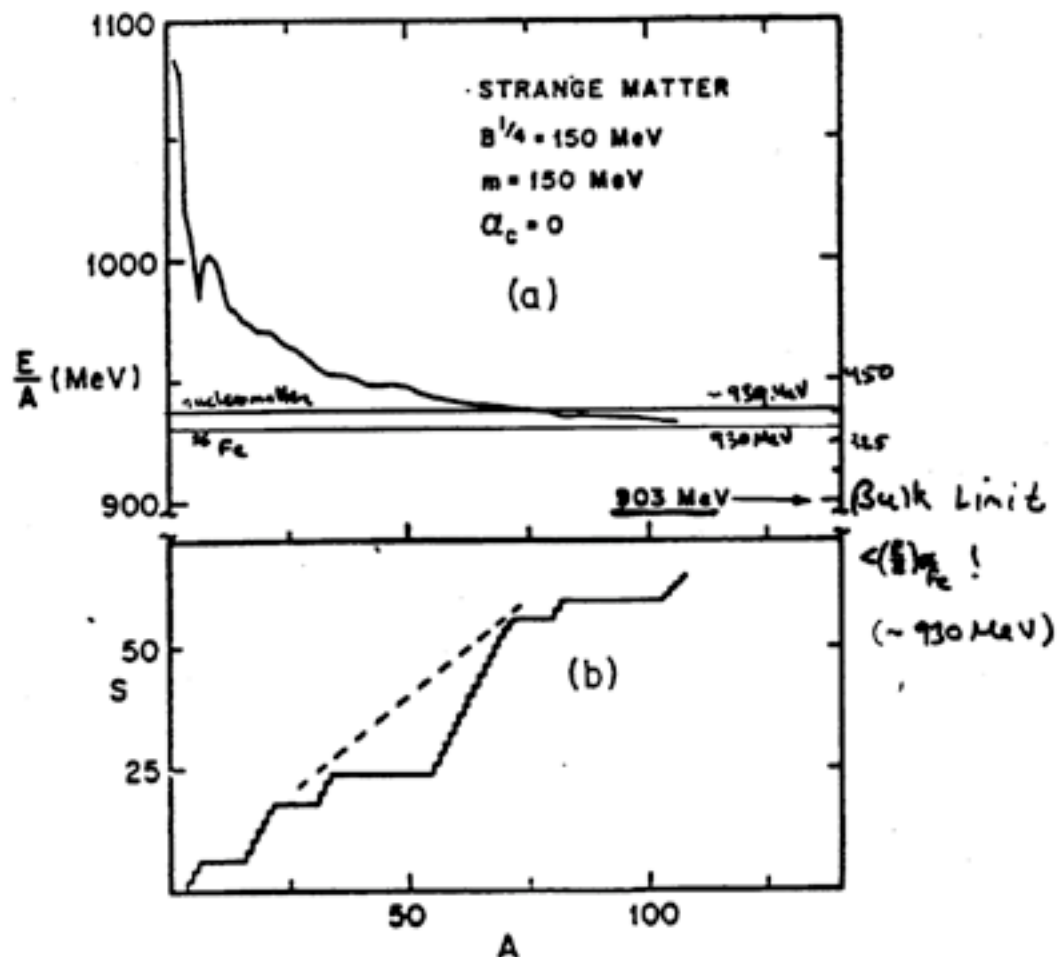


FIG. 4. (a)  $E/A$  versus  $A$  in the hadronic bag model for  $u$ ,  $d$ , and  $s$  quarks. Parameters are such that  $E/A$  in bulk is 903 MeV. (b)  $S$  versus  $A$  in the hadronic bag model for  $u$ ,  $d$ , and  $s$  quarks. Parameters are such that  $E/A$  in bulk is 903 MeV.

- Most stable when  $\frac{S}{A} \sim 0.8$
- Becomes more stable with higher  $A$

EXPERIMENTAL QUESTION

# Color-flavor locked strangelets

Jes Madsen

*Institute of Physics and Astronomy, University of Aarhus, DK-8000 Århus C, Denmark  
(August 3, 2001)*

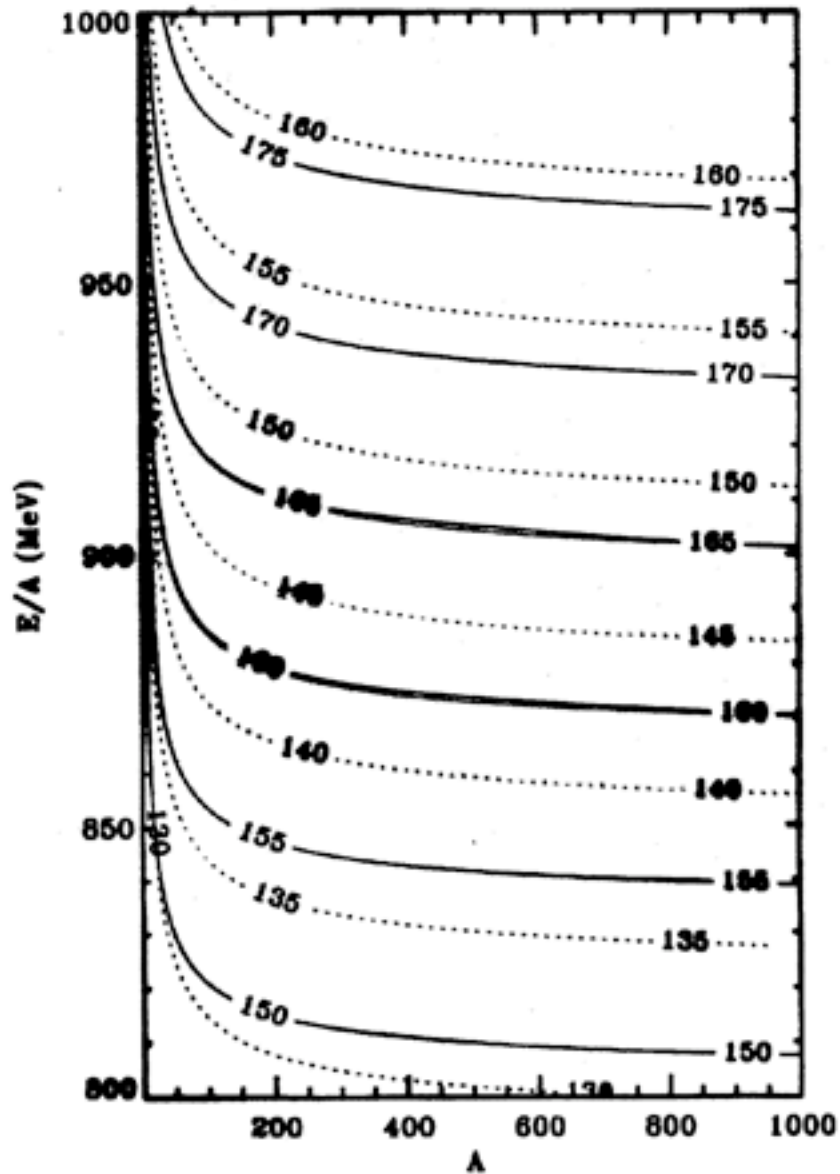


FIG. 2. Energy per baryon in MeV as a function of  $A$  for CFL-strangelets (full curves) and ordinary strangelets (dashed curves) with  $B^{1/4}$  in MeV as indicated,  $\Delta = 100\text{MeV}$  and  $m_s = 150\text{MeV}$ .

## CFL Charge/Mass Relation for Strangelets:

$$Z \sim 0.3 A^{2/3}$$

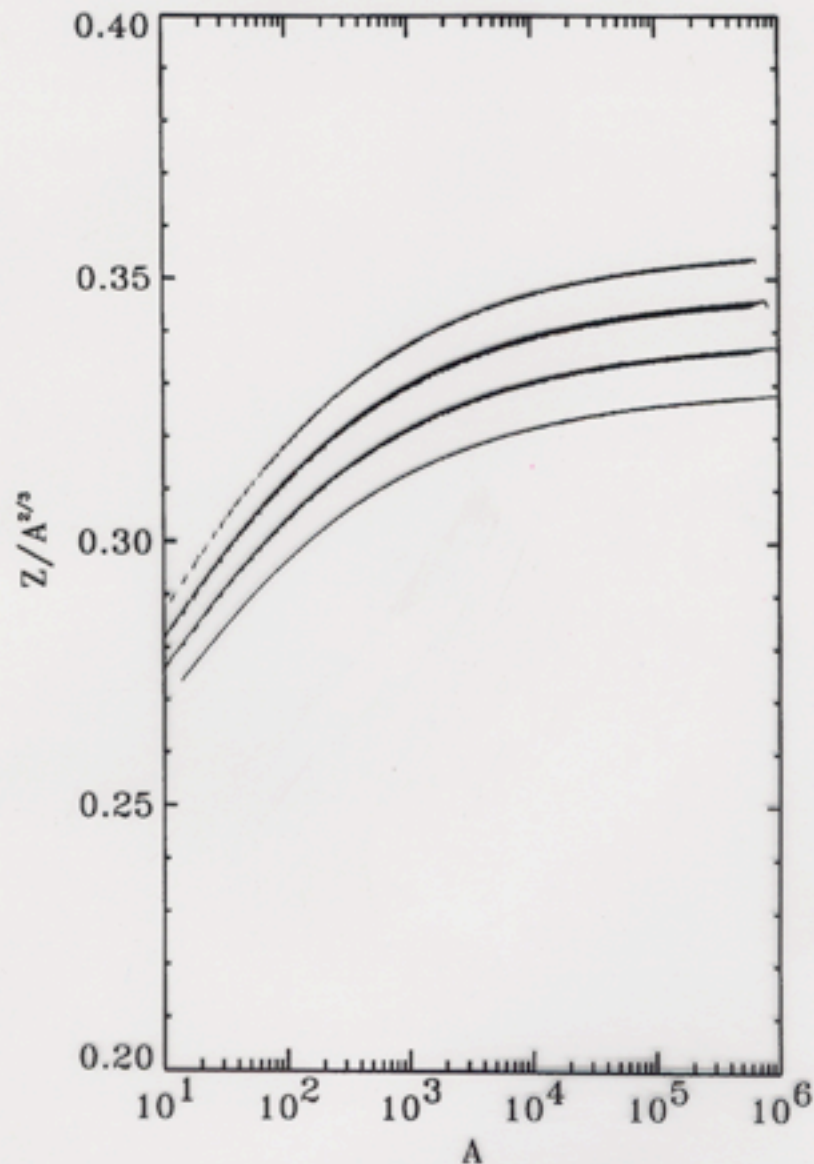


FIG. 3. Charge divided by  $A^{2/3}$  as a function of  $A$  for CFL-strangelets with  $B^{1/4} = 150, 160, 170,$  and  $180$  MeV (top to bottom),  $\Delta = 100$  MeV and  $m_s = 150$  MeV.

## Properties of Strangelets

The size of a strangelet is unlimited (for  $A > A_{\min}$ )

Since strangelets have low  $Z/A$ , Coulomb energy is not important - *no fission*.

Strangelets can grow by absorbing neutrons - this is an exothermic reaction ( $\sim 20\text{MeV}$  photon emission)

*New Energy Source*

Shaw, Shin, Dalitz, Desai, *Nature*, 337, (1989), 436.

Strangelets with  $A > 10^{17}$  ( $R > 5$  angstroms) cannot be supported on the surface of the earth ( $\text{mg} \sim 1$  eV/angstrom)

"Strangelets" with  $M > 2 * M_{\text{SUN}}$  will collapse into a black hole.

Strange quark systems with  $M < 2 * M_{\text{SUN}}$  would be similar to neutron stars ("strange stars").

SQM is the true ground state of hadronic, baryonic matter.

# Properties of Strangelets (Continued)

Atomic  $Z$  up to 1000

Because of the low charge density inside a strangelet the total charge can exist up to  $Z=1000$  before Spontaneous pair creation shields the nuclear charge.

A new chemistry becomes available

Production of VERY dense matter



## Conclusions from Accelerator Searches

- It is not possible to make strangelets with  $A > 8$  by coalescence at accelerators

- In a region where there is evidence for making QGP, no strangelets are seen

- No Light Metastable Strangelets Exist  
( $A < 100$ ,  $\tau > 100\text{ns}$ )

- OR -

- No QGP

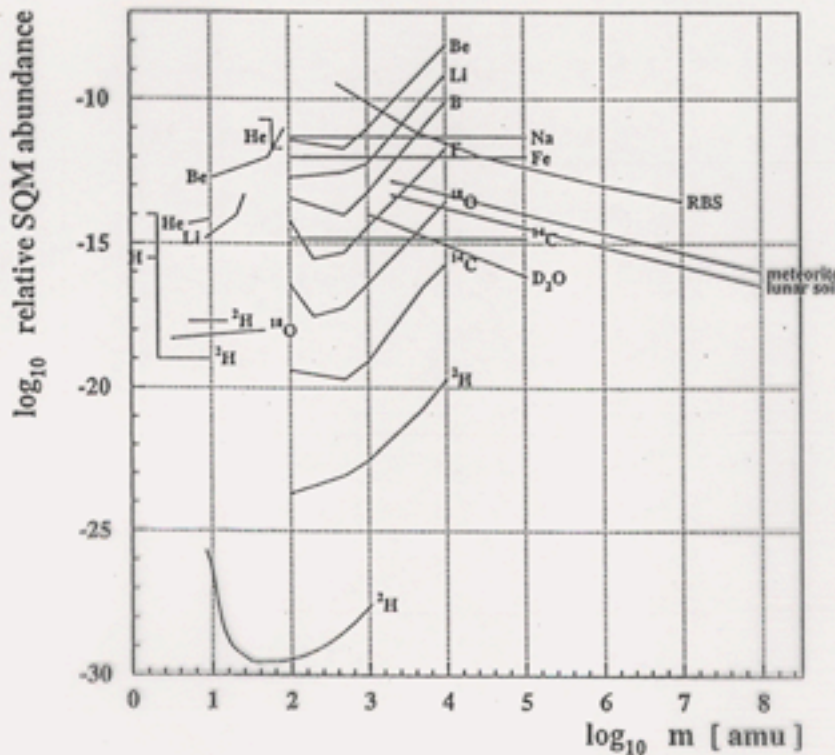
- OR -

- No distillation mechanism

Further work at accelerators will not answer the question of the existence of stable SQM at zero pressure

beam of 450 MeV which is below the Coulomb barrier of normal matter. Gamma multiplicities and gamma total energies have been measured. If these probes would contain a substantial fraction of strange quark matter one expects either a high gamma multiplicity or a high total gamma energy. None of it was observed leading to an upper limit of strangelet concentration in these material in the order of  $10^{-13}$  to  $10^{-16}$  per ordinary nucleon for strangelet masses between  $10^3$  and  $10^8$  amu. These limits are about a factor 100 better compared to earlier measurements mentioned above which use the technique of Rutherford backscattering (Brügger *et al* 1989).

A compilation of achieved limits on the concentration relative SQM abundance is shown in figure 3 Data has been taken from the compilation by (Blackman and Jaffe 1989) and the measurements by Brügger *et al* (1989), Hemmick *et al* (1990), Vandegriff *et al* (1996) and Perillo Isaac *et al* (1998).

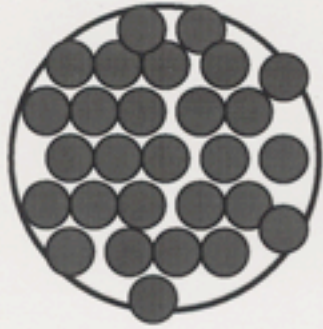


R. Klingenberg  
 J. Physics G-25,  
 R 273, (1999)

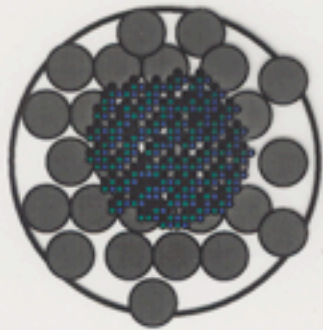
R. Klingenberg, J. Physics  
 G - Nuclear and Particle  
 Physics 25, R273 (1999)

Figure 3. Upper limits on the abundance of stable strange quark matter as heavy isotopes determined in various probes as discussed in the text.

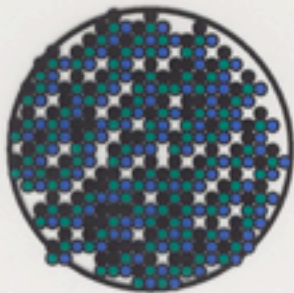
The concentration limits as found by the experimental investigation allows to set limits on the flux of SQM as nuclearites. It is based on the general assumption that galactic cosmic radiation containing stable strange quark matter is absorbed and deposited in



**No stable strange  
matter - *Neutron  
Stars***



**Strange matter  
stable under  
pressure - *Hybrid  
Stars***



**Strange matter stable  
at zero pressure -  
*Strange Stars***

IF Strange Quark Matter is  
Stable at Zero External  
Pressure, All Compact  
Stars are Strange Stars  
not Neutron Stars!

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National Aeronautics and  
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## Cosmic X-rays reveal evidence for new form of matter

NASA's Chandra X-ray Observatory has found two stars - one too small, one too cold - that reveal cracks in our understanding of the structure of matter. These discoveries open a new window on nuclear physics, offering a link between the vast cosmos and its tiniest constituents.

Chandra's observations of RXJ1856.5-3754 and 3C58 suggest that the matter in these stars is even denser than nuclear matter found on Earth. This raises the possibility these stars are composed of pure quarks or contain crystals of sub-nuclear particles that normally have only a fleeting existence following high-energy collisions.

By combining Chandra and Hubble Space Telescope data, astronomers found that RXJ 1856 radiates like a solid body with a temperature of 1.2 million degrees Fahrenheit (700,000 degrees Celsius) and has a diameter of about 7 miles (11.3 kilometers). This size is too small to reconcile with standard models for neutron stars - until now the most extreme form of matter known.

“Taken at face value, the combined observational evidence points to a star composed not of neutrons, but of quarks in a form known as strange quark matter,” said Jeremy Drake of the Harvard-Smithsonian Center for Astrophysics (CfA) in Cambridge, Mass., and lead author of a paper on RXJ1856 to appear in June 20, 2002 issue of The Astrophysical Journal. “Quarks, thought to be the fundamental constituents of nuclear particles, have never been seen outside a nucleus in Earth-bound laboratories.”

Observations by Chandra of 3C58 also yielded startling results. A team composed of Patrick Slane and Steven Murray, also of CfA, and David Helfand of Columbia University, New York, failed to detect the expected X-radiation from the hot surface of 3C58, a neutron star believed to have been created in an explosion witnessed by

## The Web



The newly discovered star RXJ 1856 is too small for standard models. (NASA et al.)

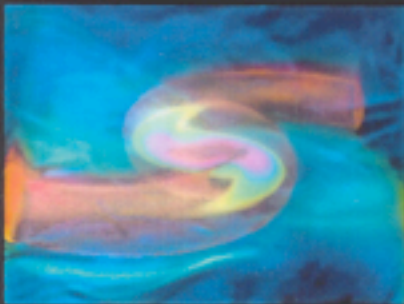
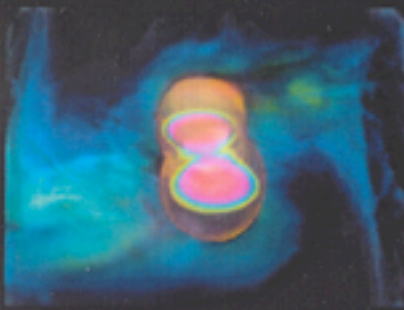
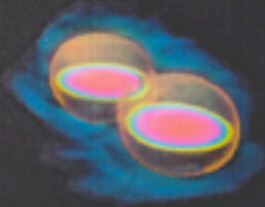
## Fact sheet

## E-mail

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judy.pettus@msfc.nasa.gov

## Other news releases

## SQM Fragments from Colliding Strange Stars (Inspirals)



- Tidal Formation of fragments: size -  $A \sim 10^{38}$
- Fragments Spend time in *figure 8* orbits,  $v \sim 0.1c$
- Interactions split fragments into smaller fragments and provide a mechanism to inject fragments into galaxy
- As much as  $0.1 M_{\text{SUN}}$  can be ejected.

11/020507

*one*  
Two Seismic Events with the  
Properties for the Passage of Strange Quark Matter Through the Earth

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## I. INTRODUCTION

In this paper we present very strong evidence for the detection of two 1993 seismic events with epiliner sources. We are aware of only one model that predicts seismic line events with frequency of one or two a year, namely the passage of "nuggets" of strange quark matter (SQM) through the earth.

In 1984, Witten [1] pointed out that, while matter made of up and down quarks is not stable, because ups and downs condense to form protons and neutrons, matter made of up, down, and strange quarks, SQM, may well be stable. This is because of the roughly 10% decrease in kinetic energy from having three Fermi seas with which to satisfy the Pauli principle instead of just two. Witten also suggested a scenario for early universe SQM nugget production, variations of which are still under debate [2], as well as the possibility of strange quark nuggets (SQN's) as dark matter candidates [3].

SQN's would not be limited in total baryon number [4] as is ordinary matter. Thus very large nuggets of SQM are possible. They would have nuclear densities ( $\sim 10^{14}$  gm/cm<sup>3</sup>). Because of the larger mass of the strange quark, an SQN with 3A quarks would have an excess of positively charged quarks over strange (negatively charged) quarks, and hence a net positive charge from "nuclear particles" which would be balanced by an electron cloud. For  $M > 10^9$  gram, the cloud would be mostly inside the nuclear part of the SQN. The SQN would be nearly neutral and, with high mass and low abundance, would not interact with electromagnetic energy, hence it's suitability as a dark matter candidate. Finally, Witten [1] suggested looking for seismic signals from SQN's passing through the earth, an idea considered, among others, by deRujula and Glashow [5] in more detail.

This possibility motivated our work, but our detection of two epiliner source events could reflect other possible unknown phenomena. Two of us [ETH and VLT] examined detection of SQN seismic signals via a Monte Carlo calculation [6]. Briefly, a ton sized SQN would have dimensions of about 20 microns, the size of a blood cell. As it passed through the earth it would break inter and intra-molecular bonds, like a stone dropped in water, producing a seismic signal. The rate of seismic energy [E] production would be given by

$$dE/dt = f \alpha \rho V^3$$

where  $\alpha$  is the SQN cross section,  $\rho$  is the nominal earth density,  $V$  is the SQN speed (a few hundred km/sec, the galactical viral velocity [6]), and  $f$  is the fraction of SQN energy loss that results in seismic waves rather than heat. Underground nuclear explosions have  $f$  of about 0.01, chemical ones about 0.02. The small size of SQN, which enhances coherence and depresses random motion and yields a high ratio of surface area to energy generating volume, implies that  $f$  might be larger for the SQN case.



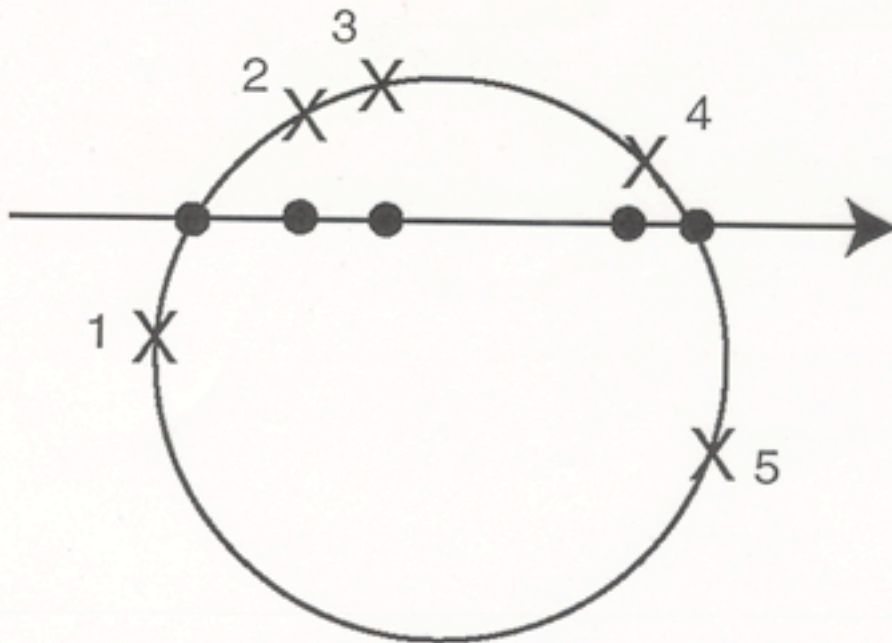


Figure 1. Difference between point and line events. Xs represent seismic stations and dots are the corresponding points of closest approach.

An earthquake at the entry point would generate signals with the first arrival at station 1, then stations 2,3,4, and 5. A nuclearite passage would have the first arrival at station 4, near the exit, then stations 2, 1, 3, and 5.

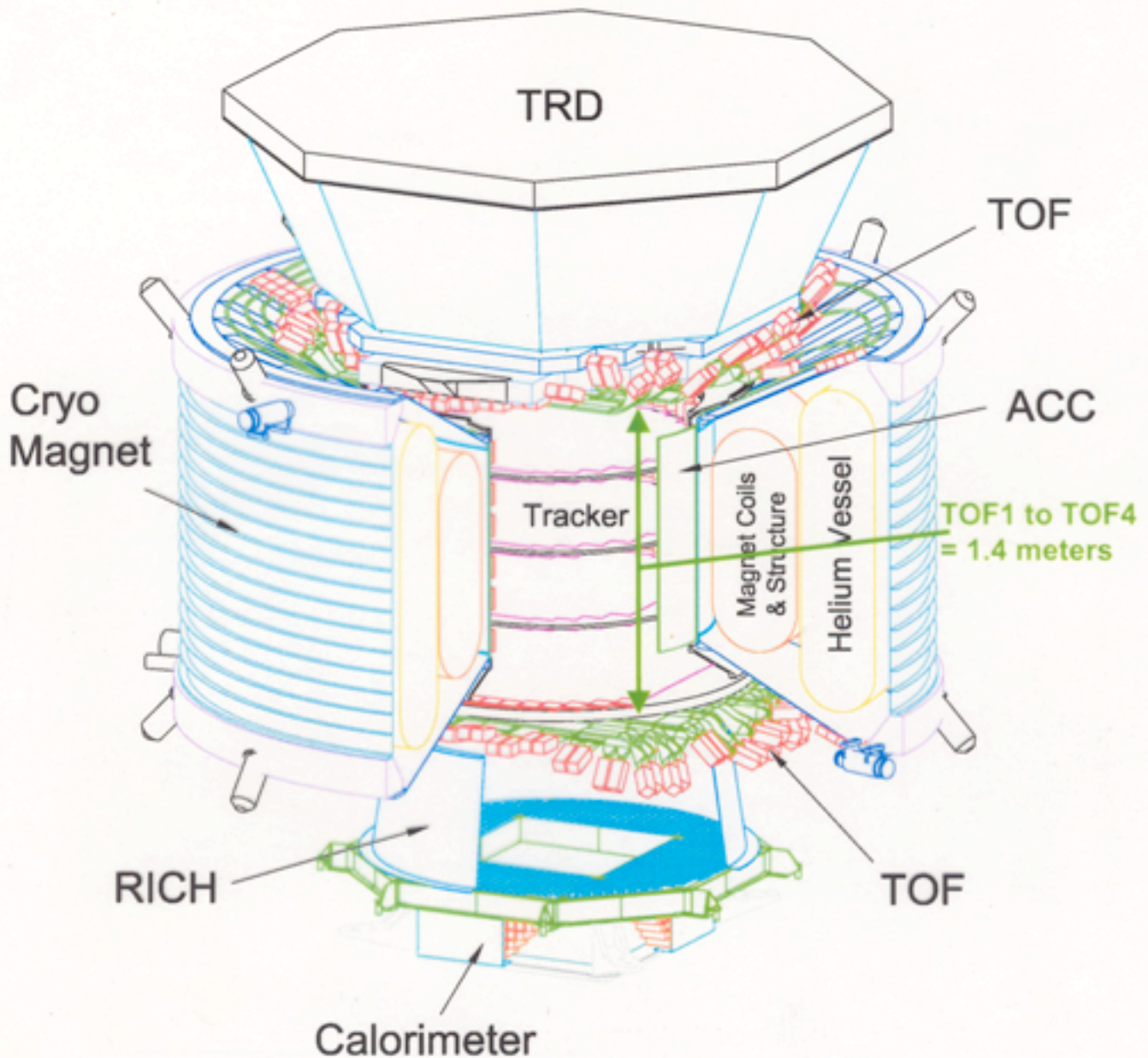
#### B. Travel Times

Seismic signal travel times through the earth are well known (IASPEI [7]) and calibrated down to point source depths of 700 kilometers. For this study one of us (I. Tibuleac) generated additional travel times tables by ray tracing through the standard earth model [7] to a depth of 2880 kilometers: the core-mantle boundary. Signals that travel through the core are quite complex due to reflections and refractions at the boundaries, and hence were not considered in this study. The fact that the core is roughly half an earth radius implies that roughly 75% of random strikes will not enter the core.

The travel time tables generated were compared to published data [7] down to 700 kilometers and were calibrated with signals reflected from the core-mantle interface, and are in good agreement with both.

## Strangelet Search with AMS

Signal is low  $Z/A$ : not consistent with any normal nucleus



AMS can measure rigidity, velocity, and charge ( $Z$ ) over a certain region and thus can measure a mass and  $Z/A$

Over a larger region, where the charge measurement is saturated, and/or the rigidity is above some maximum, one can still tell that a track is *not* a normal nucleus.

## **Propagation of Strangelets in the Galaxy**

- **Bound to Magnetic Field**
- **Undergo Interactions**
- **Accelerated in Super Nova Shock Waves**

**Expected to Behave Like Cosmic Ray Nuclei:**

$$dN(E)dE \propto E^{-2.5}$$

**Confinement time  $\sim 10^7$  y**

# Strangelet Flux at AMS

(near Earth) *J. Madsen*

Geomagnetic cutoff means only part of spectrum is visible near earth

Assume:  $dN(E)dE \propto E^{-2.5}$  ( $E = \text{K.E.} / \text{Baryon}$ )

Lowest velocity  $> 0.01c$   
(Supernova Shock wave)

$$R_{\min} = 6 \text{ GeV}/c$$

$$\text{CFL Relation: } Z=0.3 A^{2/3}$$

Then:

$$F = 5 \times 10^5 \text{ m}^{-2} \text{ y}^{-1} \text{ sterad}^{-1}$$

x Rate of Strange Star Collisions / ( $10^{-4}/\text{y}$ )

x Mass Ejected per Collision / ( $0.01M_{\text{SUN}}$ )

x Galactic Volume / ( $100\text{kpc}^3$ )

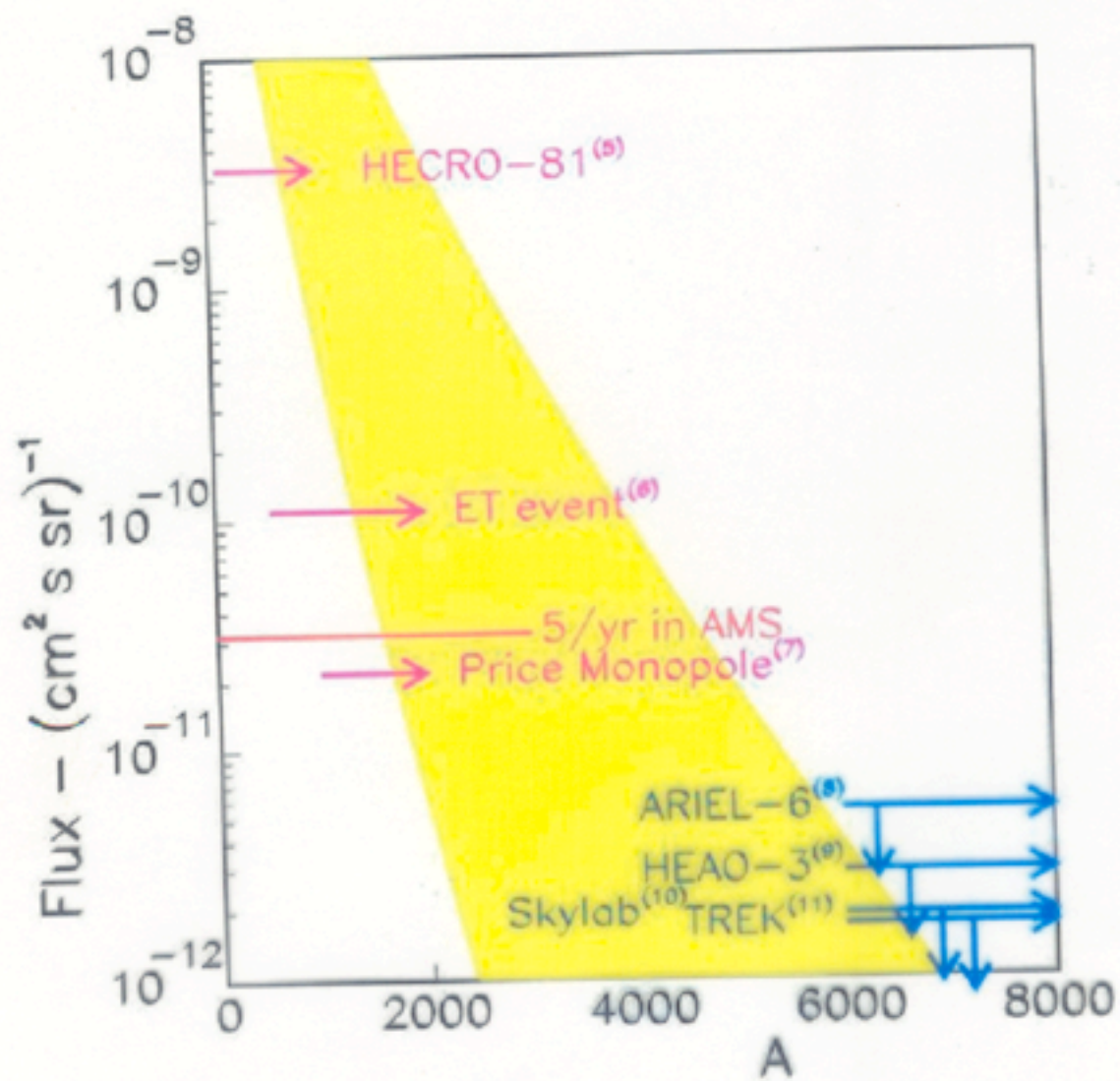
x Confinement Time / ( $10^7 \text{ y}$ )

*Estimate does not include absorption  
or loss of strangelets on "way" to earth.*

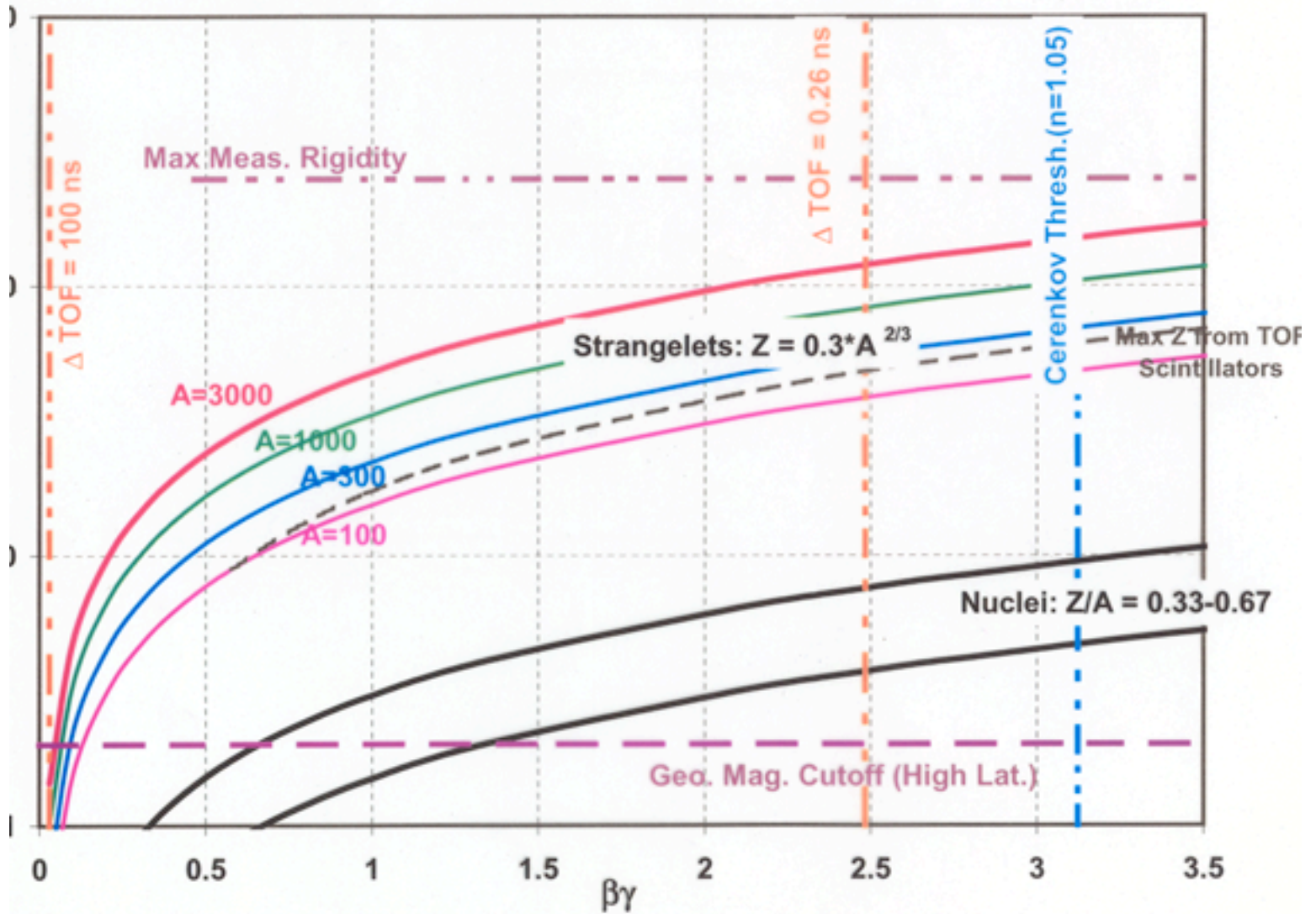
$$F = 5 \times 10^5 \text{ m}^{-2} \text{ y}^{-1} \text{ sterad}^{-1}$$

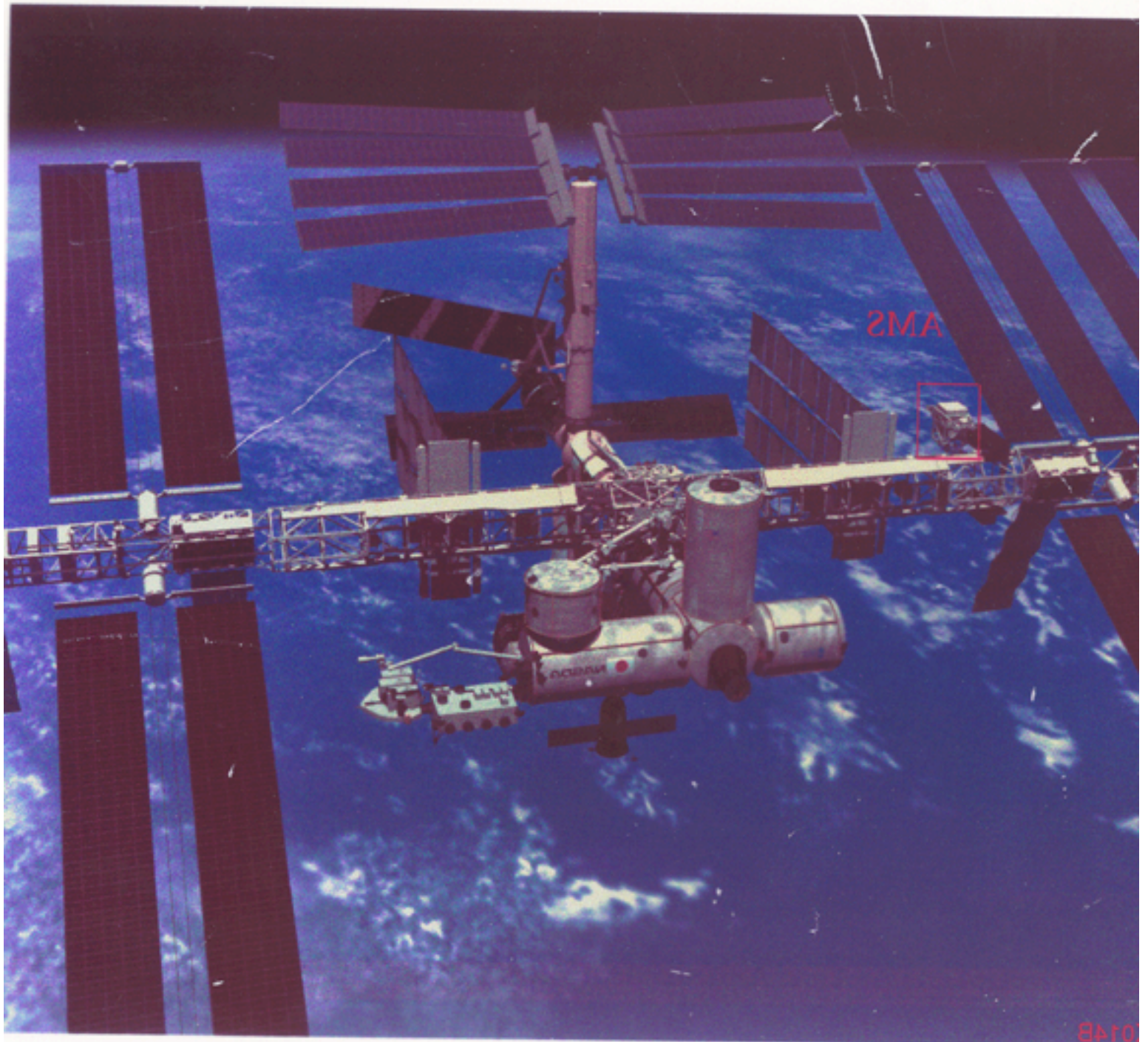
*This is a large flux!*

- AMS ~ 0.5 m<sup>2</sup> sterad
- Plenty of “wiggle room” for assumptions
- If nothing is seen in the 2-3 years that AMS will run there is little hope that stable SQM at zero pressure exists.



# Regions Accessible to AMS







February 20, 2002

Laura Feiveson  
Report

First I will use the upper and lower bounds of the absorbance coefficients to get a more accurate estimate of the number of strangelets hitting the surface.

The upper and the lower limits are:  $e^{-(A^{2/3}) \cdot 0.04}$  and  $e^{-(A^{2/3}) \cdot 0.08}$

I need to multiply these numbers by the estimated densities that have already been calculated in the previous report. Then using the estimate that earth is silicon which has a density of  $5 \cdot 10^{22}$  atoms per cubic centimeter and that water has a density of about  $3.3 \cdot 10^{22}$  molecules per cubic centimeter, I will also find the lower and upper bounds of the number of strangelets per each atom of silicon (or molecule of water in the ocean).

The result:

**The density of strangelets in the earth's crust**

Baryon Value	number/cm3		number/silicon atom	
	Lower Limit	Upper Limit	Lower	Upper
50	1.99E+03	3.42E+03	3.98E-20	6.84E-20
100	4.10E+02	9.72E+02	8.22E-21	1.95E-20
1000	3.06E-02	1.67E+00	6.13E-25	3.35E-23
2000	1.03E-04	5.87E-02	2.05E-27	1.18E-24
3000	1.13E-06	4.63E-03	2.26E-29	9.27E-26
4000	2.20E-08	5.24E-04	4.40E-31	1.05E-26
5000	6.24E-10	7.49E-05	1.25E-32	1.50E-27

**The density of strangelets in the ocean**

Baryon Value	number/cm3		number/molecule of water	
	Lower Limit	Upper Limit	Lower	Upper
50	1.37E+07	2.36E+07	4.11E-16	7.07E-16
100	7.23E+06	1.71E+07	2.16E-16	5.12E-16
1000	1.35E+04	7.38E+05	4.04E-19	2.21E-17
2000	1.23E+02	7.04E+04	3.68E-21	2.11E-18
3000	2.39E+00	9.81E+03	7.15E-23	2.93E-19
4000	7.09E-02	1.69E+03	2.12E-24	5.05E-20
5000	2.79E-03	3.36E+02	8.35E-26	1.00E-20

# Number of Strangelets Expected on the Surface of the Moon

Baryon Value	Stopping Line	Volume of Moon to Stopping Line
50	138	5.01 E 19
100	52	1.89 E 19
1000	1.8	6.53 E 17
2000	0.63	2.29 E 17
3000	0.35	1.27 E 17
4000	0.23	8.35 E 16
5000	0.17	6.17 E 16
	7	6.17 E 16

**Use the biggest one from the table above: 136 cm**

Density in the top 138 cm (no./cc)

Baryon Value	Lower	Upper
50	3.68 E 14	6.35 E 1
100	9.75 E 13	2.31 E 14
1000	1.83 E 10	1.00 E 14
2000	8.34 E 07	4.77 E 12
3000	1.08 E 06	4.43 E 09
4000	2.40 E 04	5.73 E 08
5000	7.58 E 02	9.10 E 07

Density per silicon (no./atom)

Lower	Upper
7.39 E-09	1.27 E-08
1.95 E-09	4.62 E-09
3.67 E-13	2.00 E-11
1.67 E-15	9.56 E-13
2.16 E-17	8.88 E-14
4.81 E-19	1.15 E-14
1.52 E-20	1.82 E-15