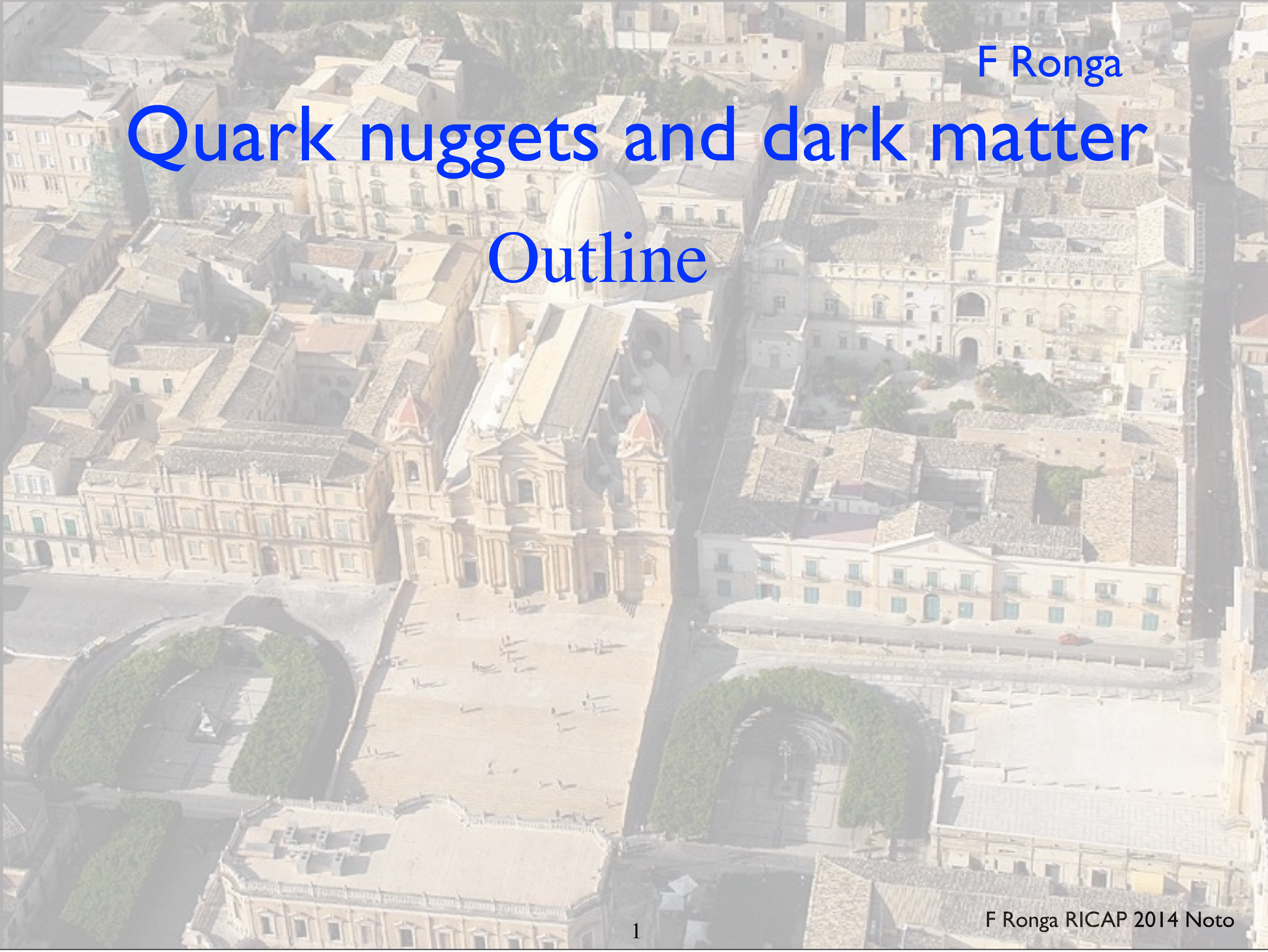

F Ronga

Quark nuggets and dark matter

Outline

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- quark and antiquark nuggets (nuclearites as particular example)

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usual WIMPS detectors of a few square meter are not sensitive to high mass particles..M~4 10^{-3} gr. ==> Φ~1 ev/year/m^2

D.M. and Quark nuggets examples

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- for recent updates:

Kyle Lawson ISVHECRI 2014 CERN,
Labun,L.,Birrell,J.,Rafelski,J Compact Ultradense Matter Impactors. Phys.Rev.Lett.**110**,111102 (2013)

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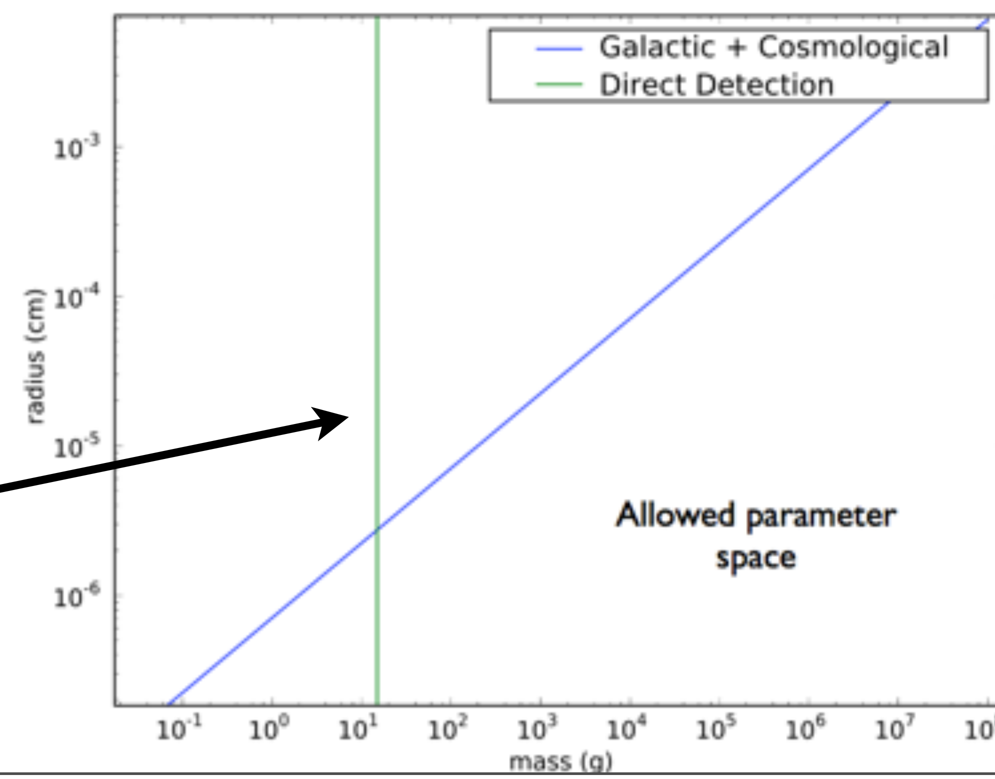
•current limits on anti-quark nuggets ~40 gr. (Anita Ice-cube ecc.)

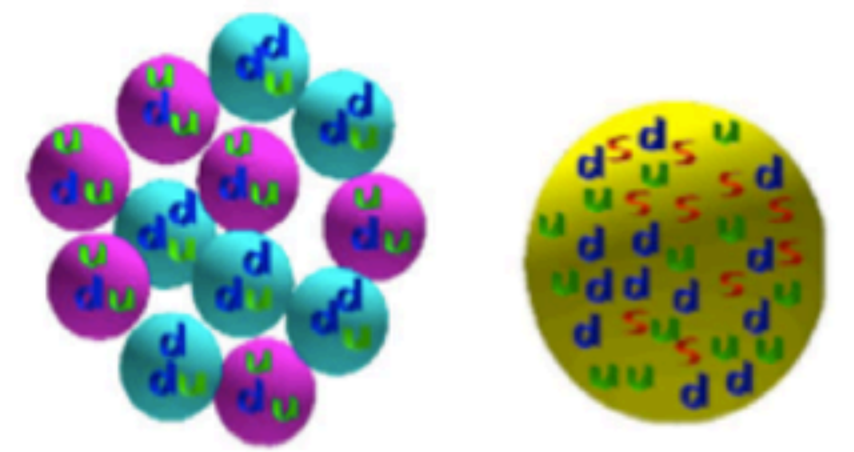


Nuclearite : a neutral quark nugget with strange quarks

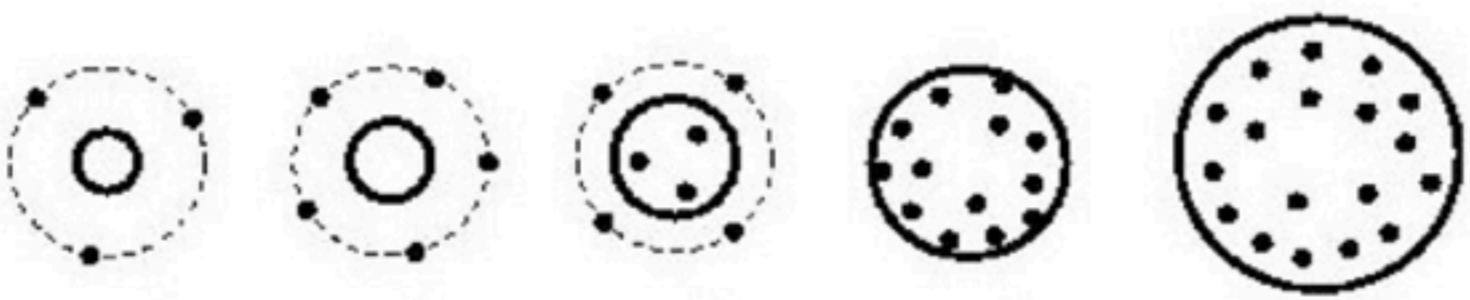
Strange Quark Matter (nuclearites, strangelets)

E. Witten, Phys. Rev. D30 (1984) 272A. De Rujula, L. Glashow, Nature 312 (1984) 734

- Aggregates of u, d, s quarks + electrons of ~ equal number, density: 3.5×10^{14} g cm^{-3}.
- Ground state of nuclear matter (E/A < 930 MeV).
- Stable for any baryon number A (few < A< 10^{57}).



..a qualitative picture...



(black dots are electrons)

M (GeV) 10^{6} 10^{9} 10^{12} 10^{15} 10^{18}

- ➢ Nuclearites : core + electrons , neutral, A > 10^6 — CDM candidate
- ➢ Strangelets : positively charged, A < 10^6 — Cosmic ray component

Nuclearite : energy loss

- Nuclearite :energy loss by elastic collision

$$\frac{\mathrm{d}E}{\mathrm{d}x} = -A\rho v^2 \qquad (1)$$

where ρ is the density of the traversed medium, v the nuclearite velocity and A is its effective cross-sectional area. The effective area can be obtained by the nuclearite density ρ_N. For a small nuclearite of mass less than 1.5 ng, the cross-sectional area A is controlled by its electronic atmosphere which is never smaller than 10^{-8} cm:

$$A = \begin{cases} \pi \cdot 10^{-16}\,\mathrm{cm}^2 & \text{for } m < 1.5\,\mathrm{ng} \\ \pi\left(\dfrac{3m}{4\pi\rho_N}\right)^{2/3} & \text{for } m > 1.5\,\mathrm{ng} \end{cases} \qquad (2)$$

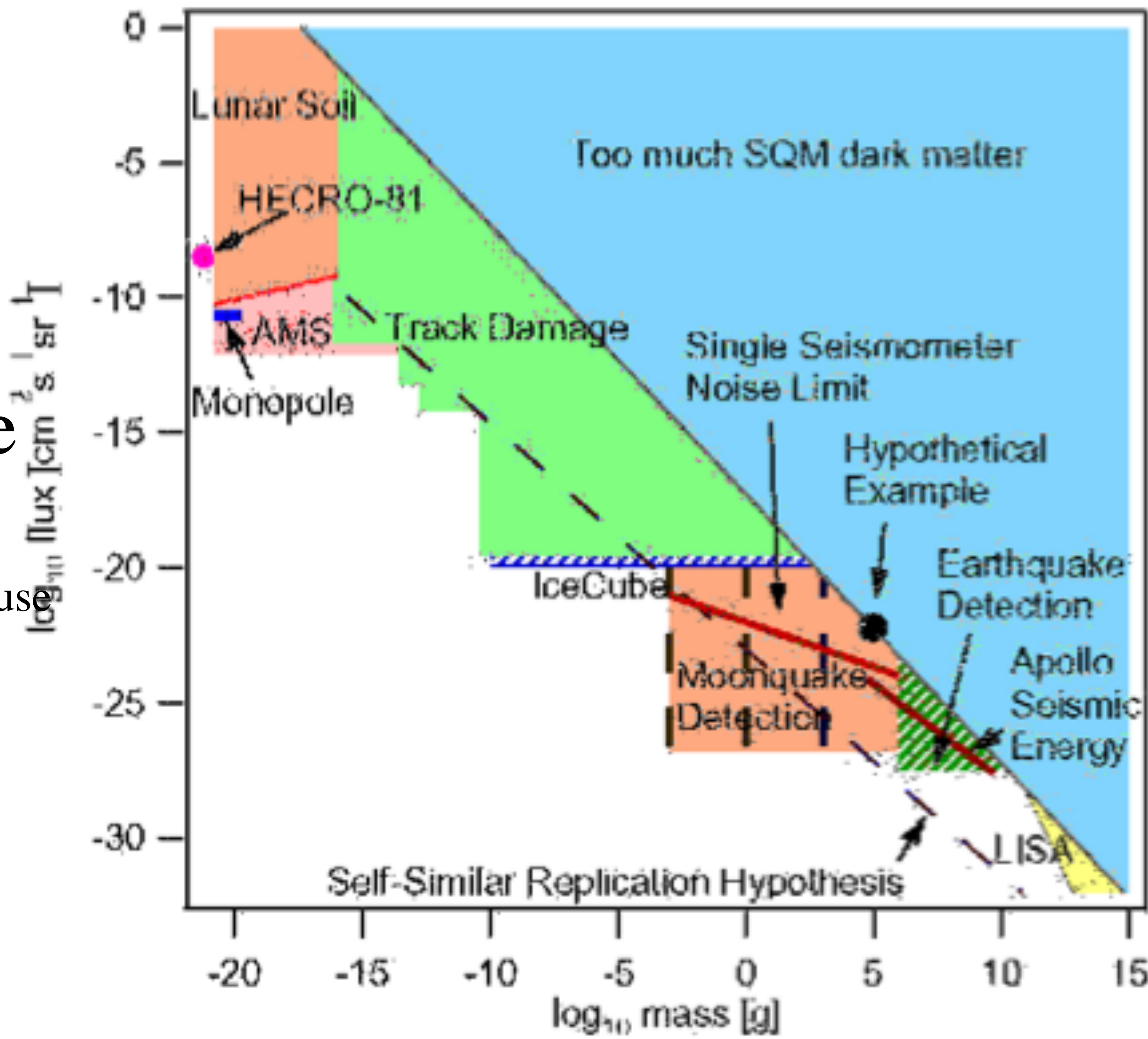
where $\rho_N = 3.6 \cdot 10^{14}\,\mathrm{g/cm^3}$ is the nuclearite density and m its mass.

- Other quark nuggets (charged or with anti-quark) will have energy loss >> than nuclearite (additional energy loss by ionization or annihilation)

Search for quark or anti-quark nuggets with earthquakes (moon or earth)

- The moon is more quiet than the Earth : limit by the total seismic energy
- Moon search with the Apollo seismic network. 28 shallow moonquakes events. But 23/28 are when the moon faces RA 12h

Frohlich, C., Y. Nakamura. Possible extra-Solar-System cause for certain lunar seismic events, Icarus 185, 21-28, 2006.



from Banerdt et al Nucl. Phys B 166 (2007)

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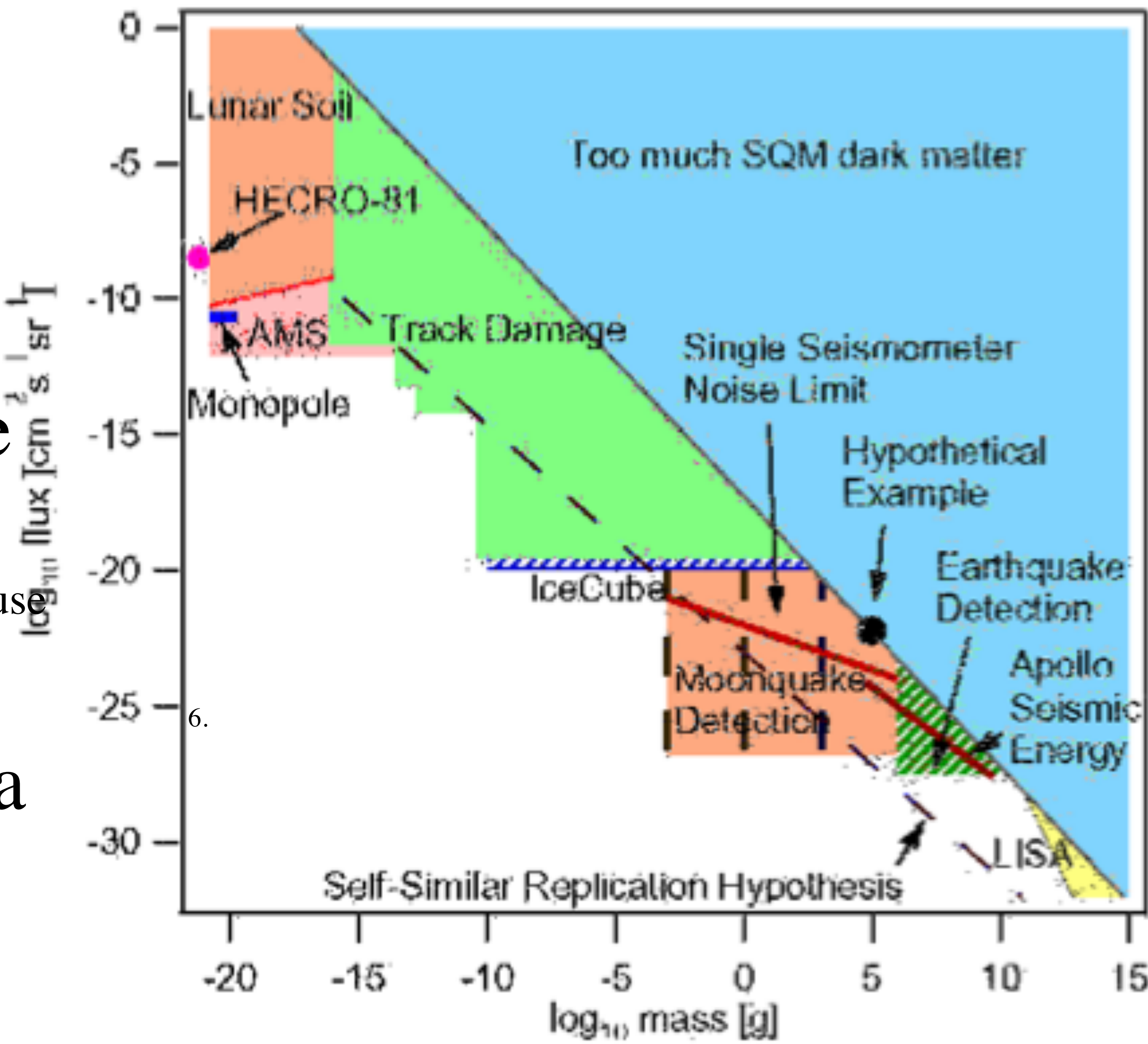


from Banerdt et al Nucl. Phys B 166 (2007)

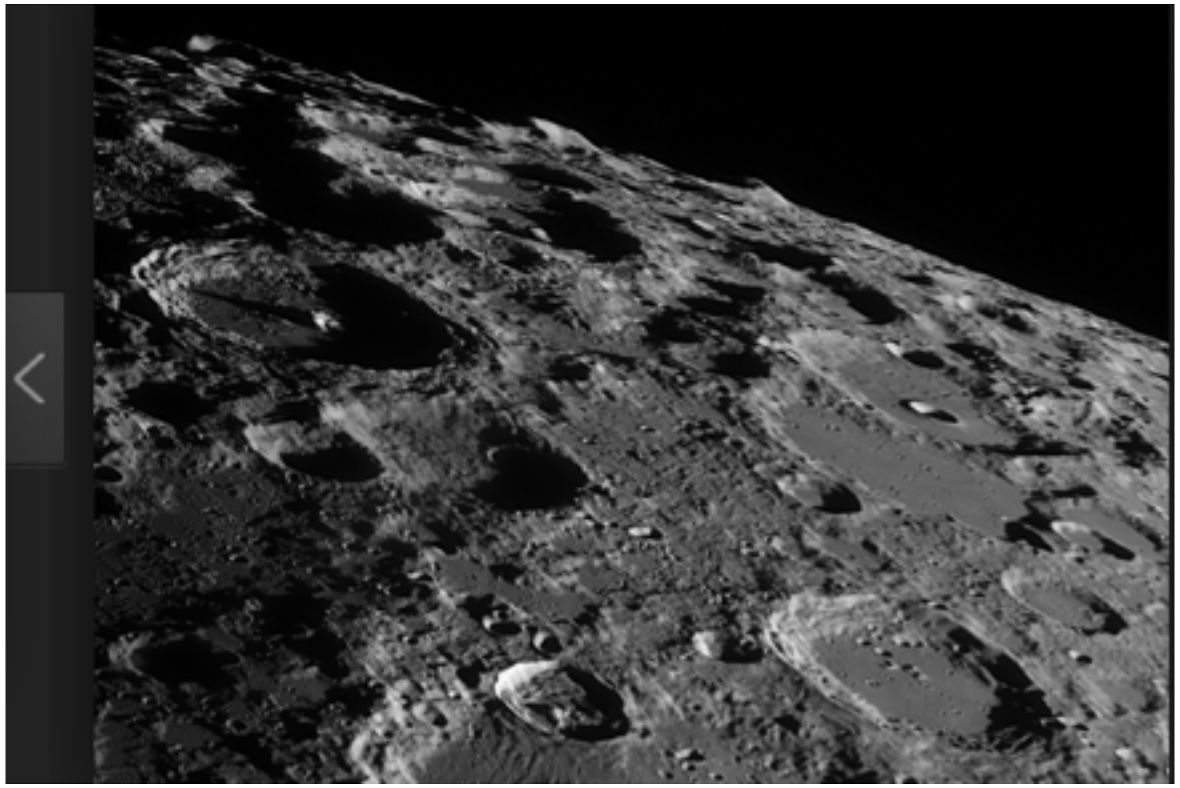
• Earth search : in 2002 there was a claim of a nuclearite candidates. Later, problems in the timing discovered==> No candidates in 4 years

• Seismic search for strange quark nuggets

Eugene T. Herrin, Doris C. Rosenbaum (Southern Methodist U.), Vigdor L. Teplitz (NASA, Goddard). Phys.Rev. D73 (2006) 043511

Tunguska event: antiquark nugget?

- Meteors produces an explosion and a crater at the surface
- Dense antiquark balls should penetrate in the Earth and produces several small craters from materials coming out from the deep



Meteor craters on the Moon

Tunguska Dark Matter Ball

C.D. Froggatt (Glasgow U.) , H.B. Nielsen (Bohr Inst.)

Mar 27, 2014 - 61 pages

1

e-Print: arXiv:1403.7177 [hep-ph] | PDF

Abstract (arXiv)
It is suggested that the Tunguska event in June 1908 cm-large was due to a cm-large ball of a condensate of bound states of 6 top and 6 anti-top quarks containing highly compressed ordinary matter. Such balls are supposed to make up the dark matter as we earlier proposed. The expected rate of impact of this kind of dark matter ball with the earth seems to crudely match a time scale of 200 years between the impacts. **The main explosion of the Tunguska event is explained in our picture as material coming out from deep within the earth, where it has been heated and compressed by the ball penetrating to a depth of several thousand km.** Thus the effect has some similarity with volcanic activity as suggested by Kundt. We discuss the possible identification of kimberlite pipes with earlier Tunguska-like events. A discussion of how the dark matter balls may have formed in the early universe is also given.

Outline

• quark and antiquark nuggets (nuclearites as particular example)

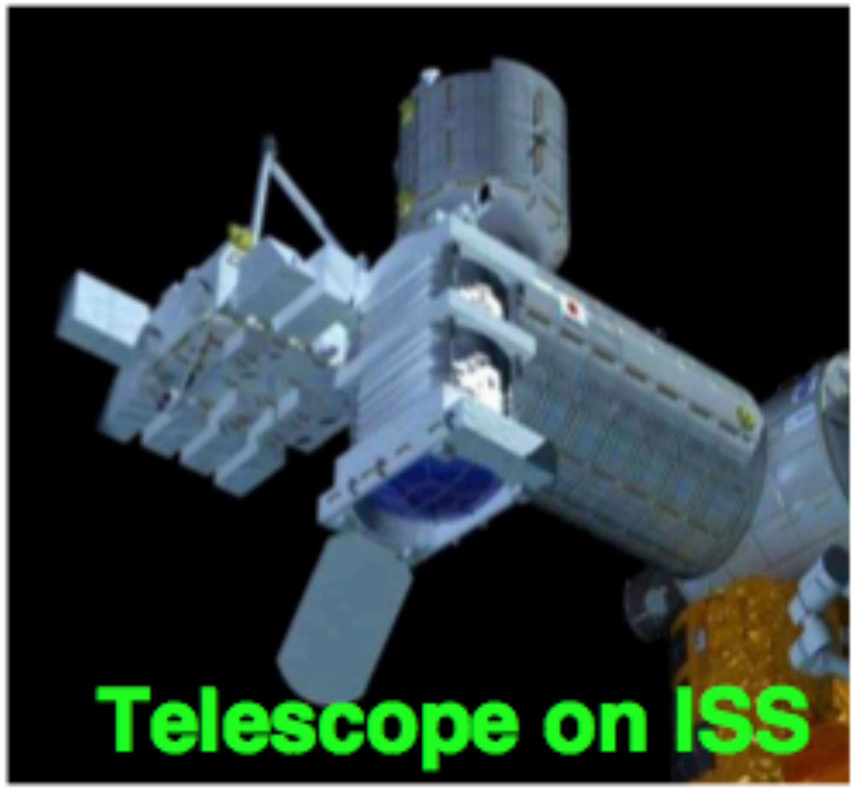
• meteors, the Tunguska event (Siberia 1908)

• meteors from space (JEM-EUSO)

• upper limits of a nuclearite search in resonant gravitational wave bar detectors (Nautilus Explorer ~ 11 years useful livetime)

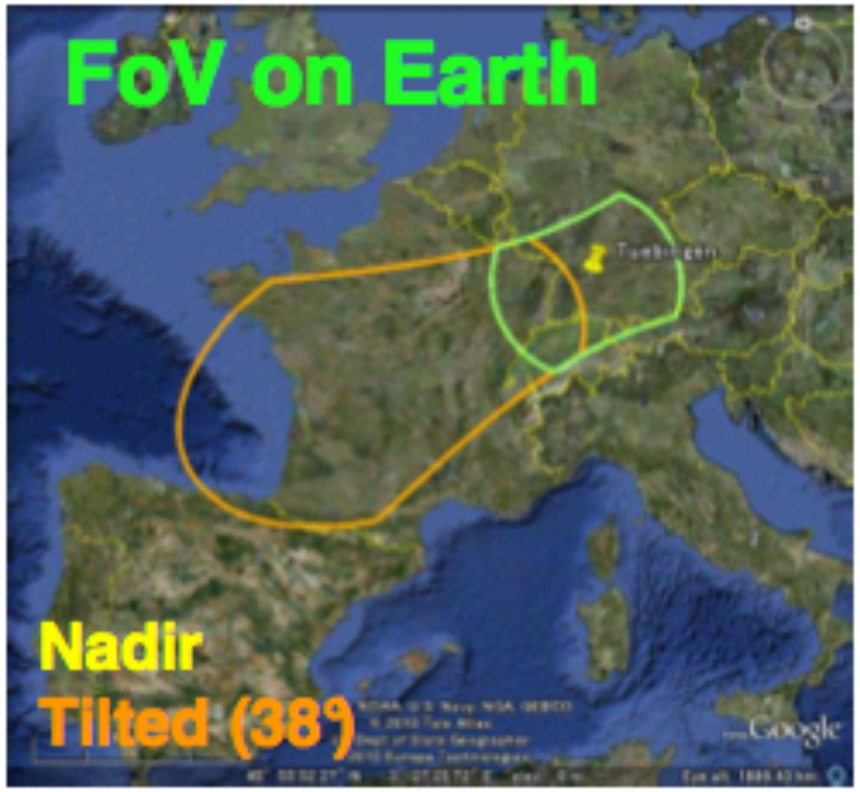
Meteors and Nuclearites in JEM-EUSO(Japan) =>> K EUSO (Russia)

M. Bertaina A..Cellino,F.Ronga JEM-EUSO Meteor and nuclearite observations Exp Astronomy DOI 10.1007/s10686-014-9375-4



MISSION PARAMETERS

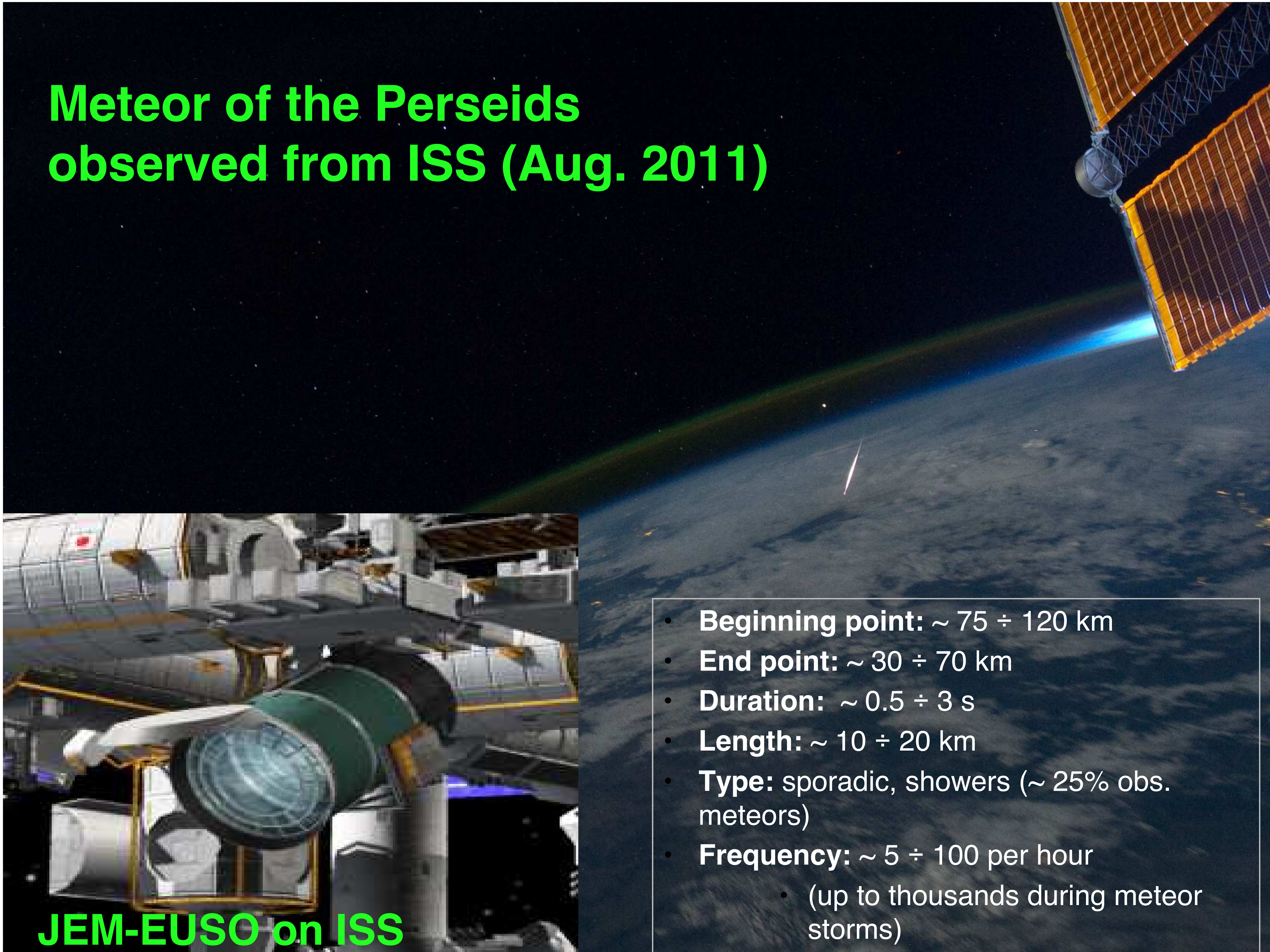
- **Site to Attach:** Japanese Experimental Module/Exposure Facility #2
- **Height of the Orbit:** ~ 400 km
- **Inclination of the Orbit:** 51,64 °
- **Latitude & longitude:** 51.6°N – 51.6°S (for all longitudes)
- **Period of the Orbit:** 90 mins



INSTRUMENT PARAMETERS

- **Field of view:** ± 30°
- **Aperture diameter:** 2.5 m
- **Optical bandwidth:** 330 – 400 nm
- **Angular resolution:** 0.07°
- **Pixel size:** 2.9 mm
- **Number of pixels:** ~ 3 × 10^5
- **Pixel size at ground:** 560 m
- **Event time sampling:** 2.5 μs = 1 GTU
- **Observational area:** > 1.9 × 10^5 km^2 (depending on the pointing angle)
- **PMT Gain:** 10^6 (0.16 pC / phe)
- **Detector efficiency:** 0.1
- **KI partition:** rectangular (4 x 2 pixels)

Meteors and Nuclearites in JEM-EUSO



Meteor of the Perseids observed from ISS (Aug. 2011)

JEM-EUSO on ISS

- **Beginning point:** ~ 75 ÷ 120 km
- **End point:** ~ 30 ÷ 70 km
- **Duration:** ~ 0.5 ÷ 3 s
- **Length:** ~ 10 ÷ 20 km
- **Type:** sporadic, showers (~ 25% obs. meteors)
- **Frequency:** ~ 5 ÷ 100 per hour
  - (up to thousands during meteor storms)

Nuclearites in JEM-EUSO

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- special acquisition for slow events, limitations from the data rate

- Nuclearites produce light in the atmosphere by thermal radiation. No mass ablation==>>The light emission is constant

- Light emission starts at h : 24 -60 km

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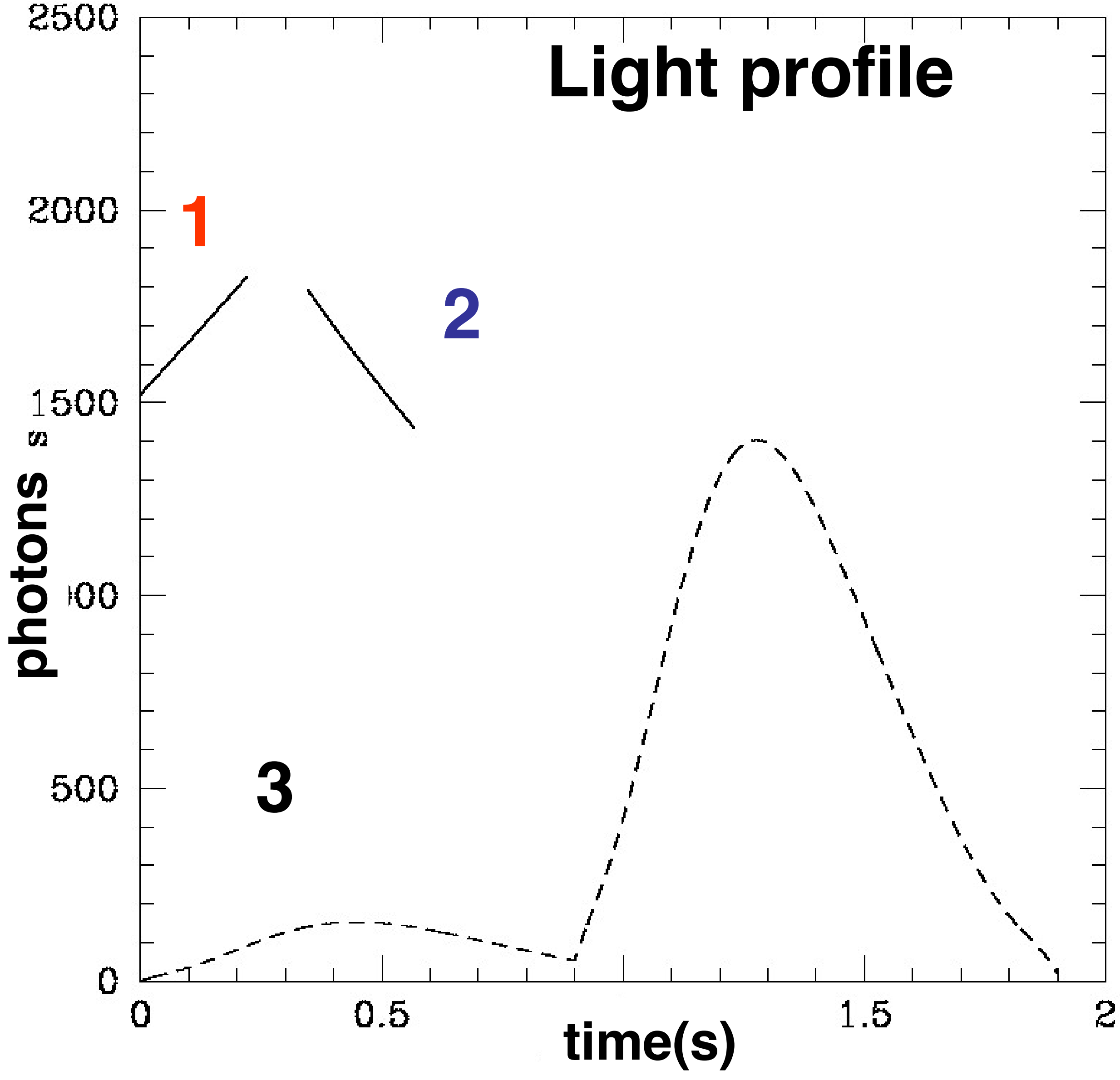
Criteria to identify nuclearites:

- speed : meteors up to 70 km/sec nuclearites ~300 km/sec
- light profile and light starting point, most of the meteors doesn't reach earth (due to the mass ablation)
- nuclearites of mass > 0.1 gr. could cross the Earth , upward-going events

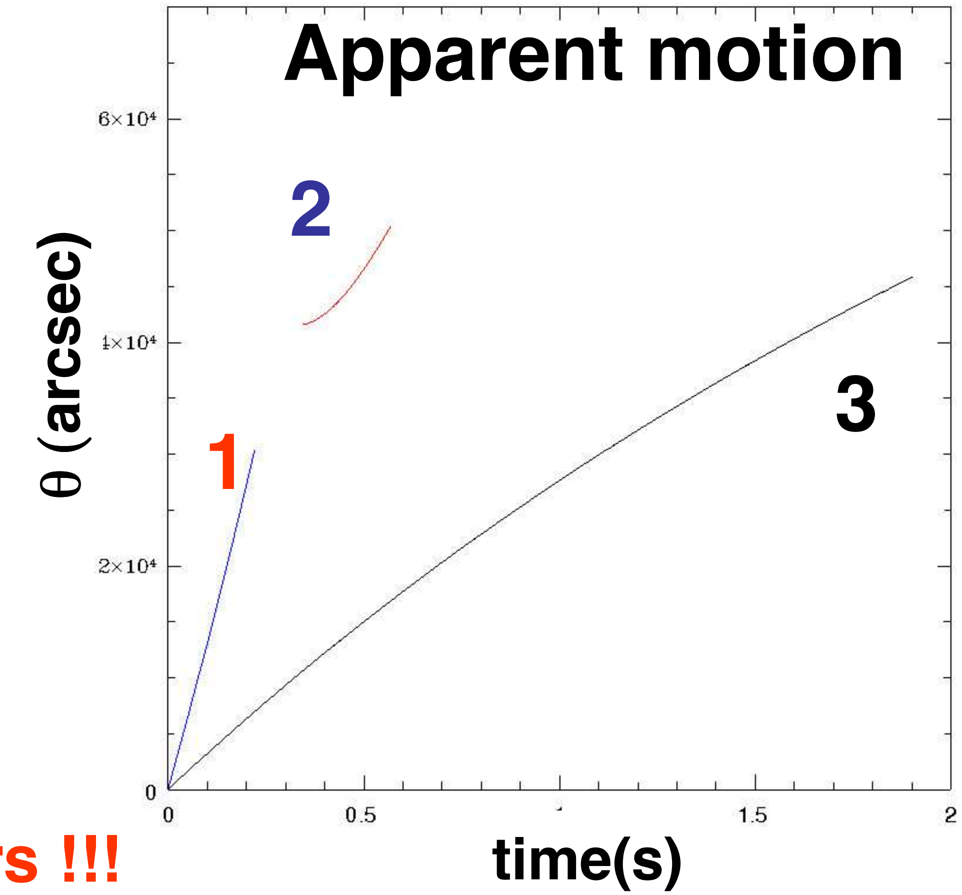
Nuclearite and meteor simulations in JEM-EUSO



1) up-ward going nuclearite
m = 20 g , v = 250 km/s, θ = 45°

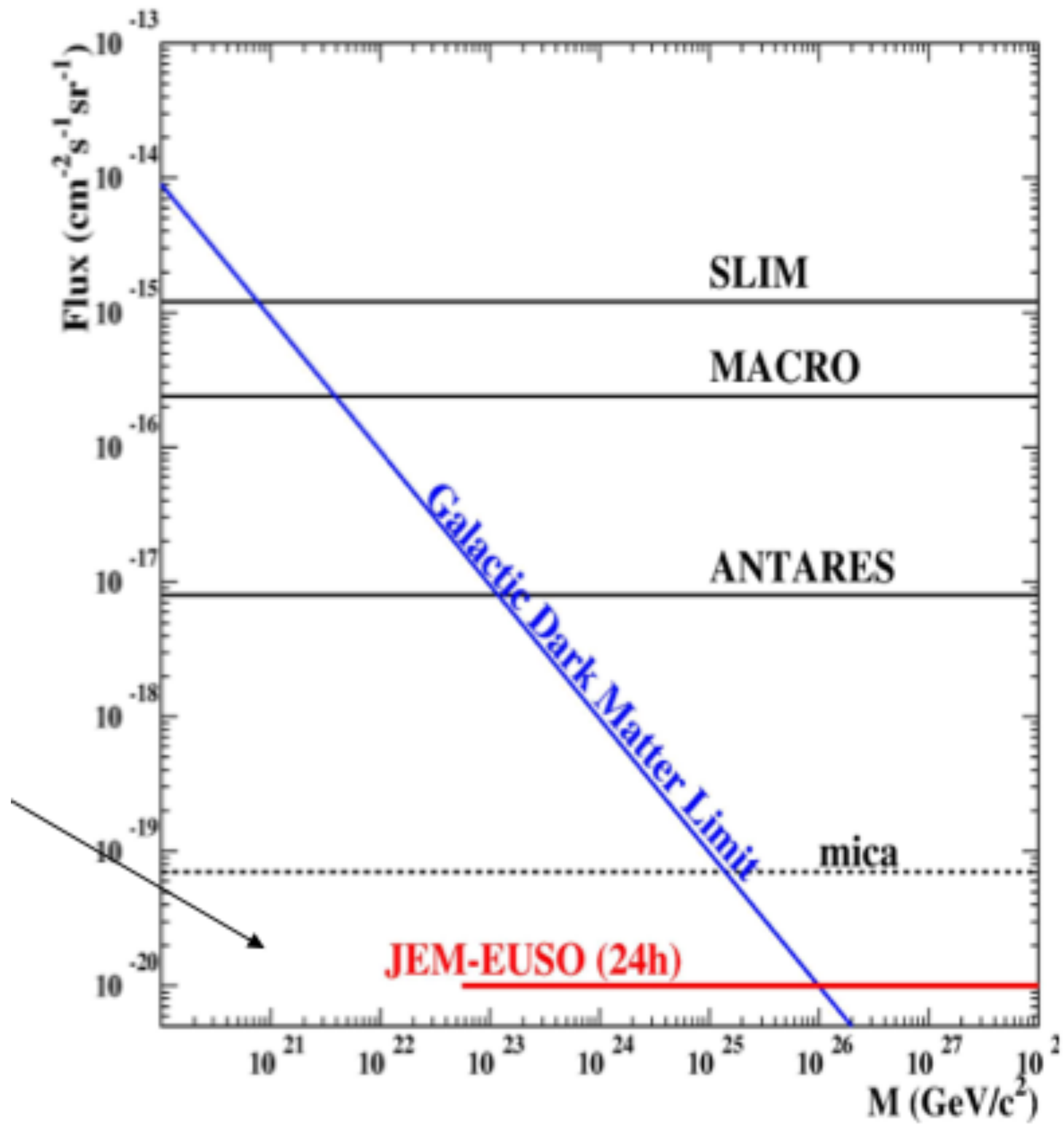
2) down-ward going nuclearite
m = 20 g , v = 250 km/s, θ = 45°

3) Meteor
M = -1 v = 70 km/s , θ = 45°



Nuclearites are much faster than meteors !!!

Nuclearites Upper Limits in in JEM-EUSO (24h live-time)



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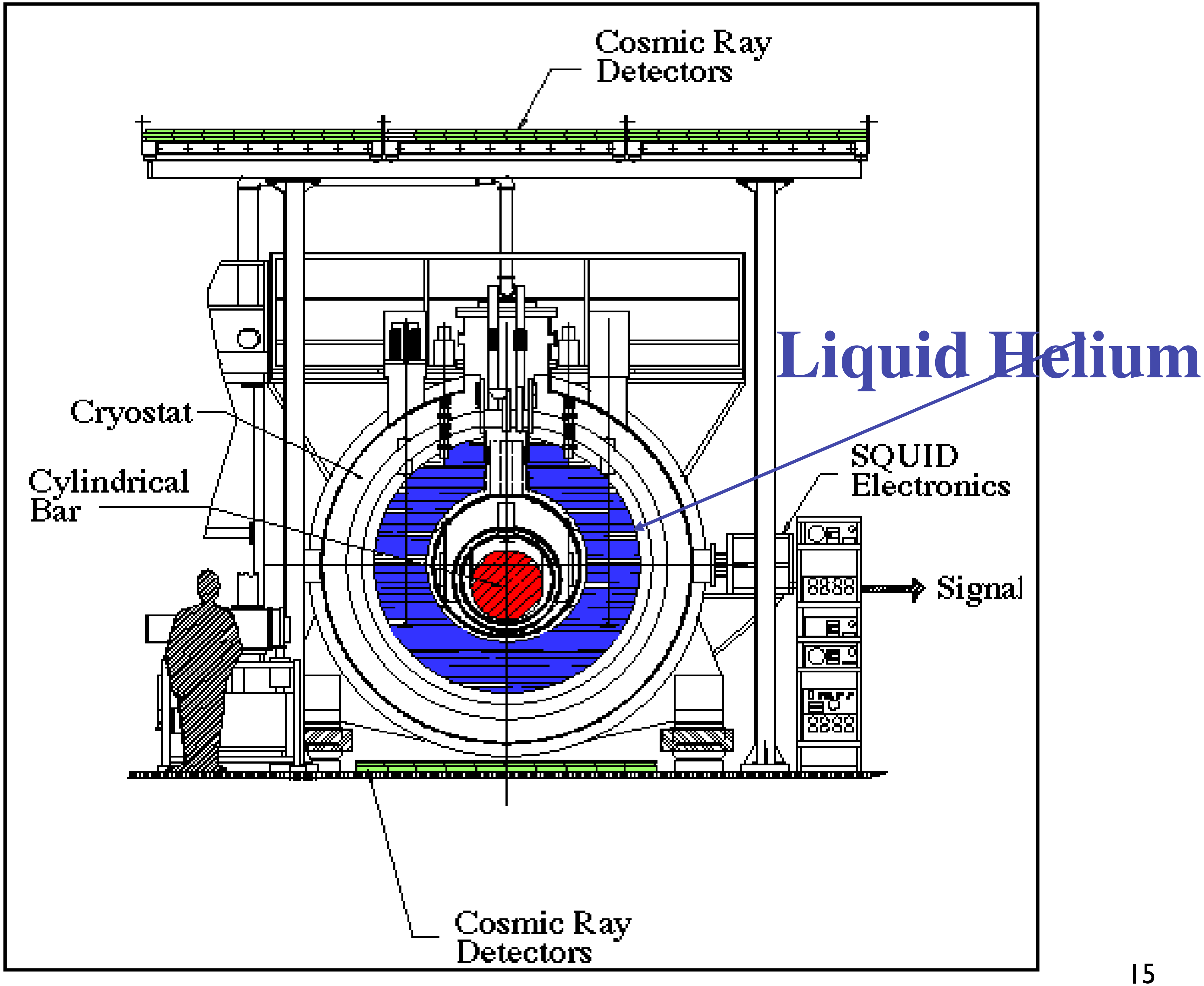
Cylindrical resonant Gravitational Waves detector: Nautilus (in continuos run from 2003)



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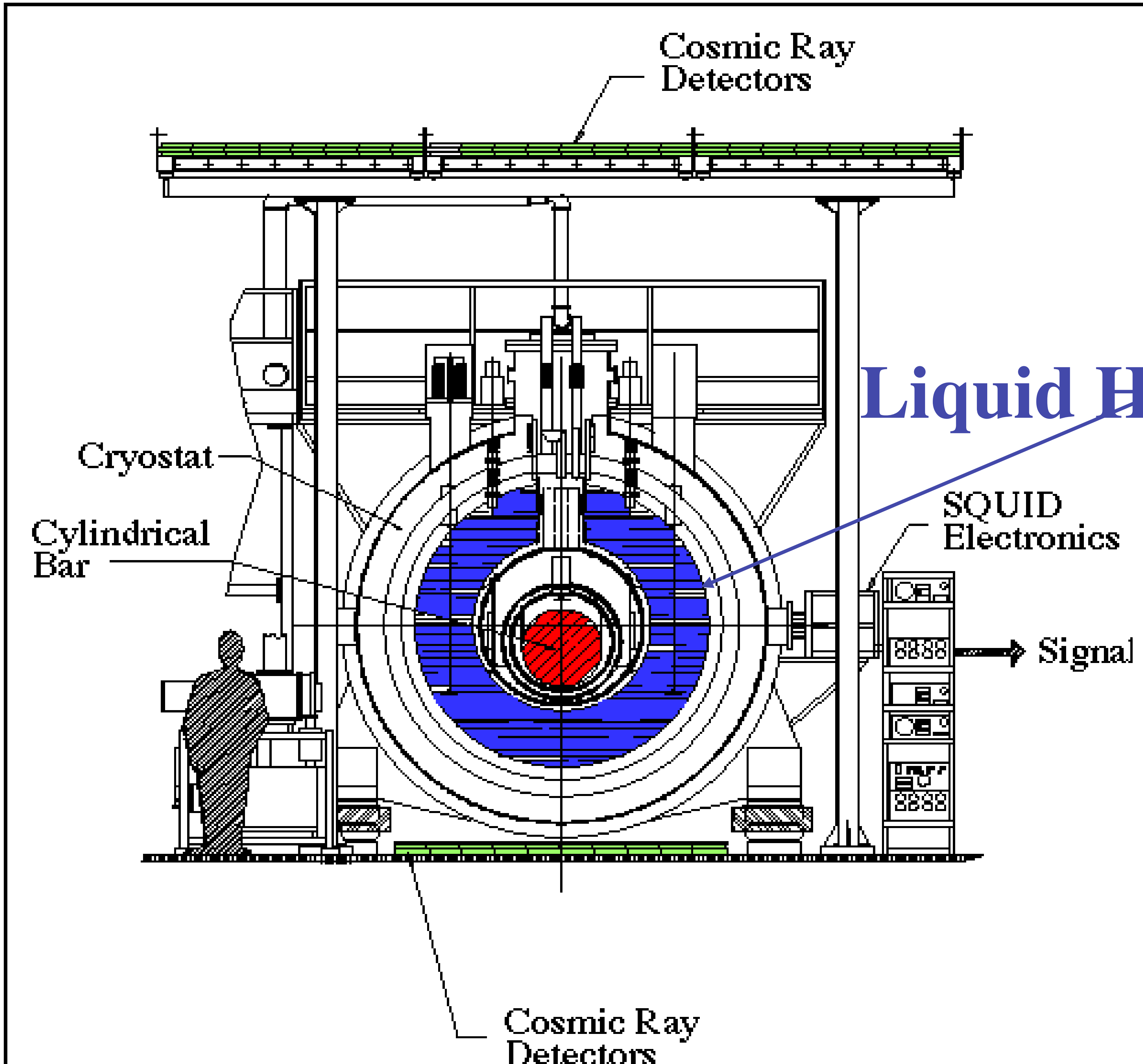
Al 2036 bar 2300 Kg
L=3 m r=0.3m



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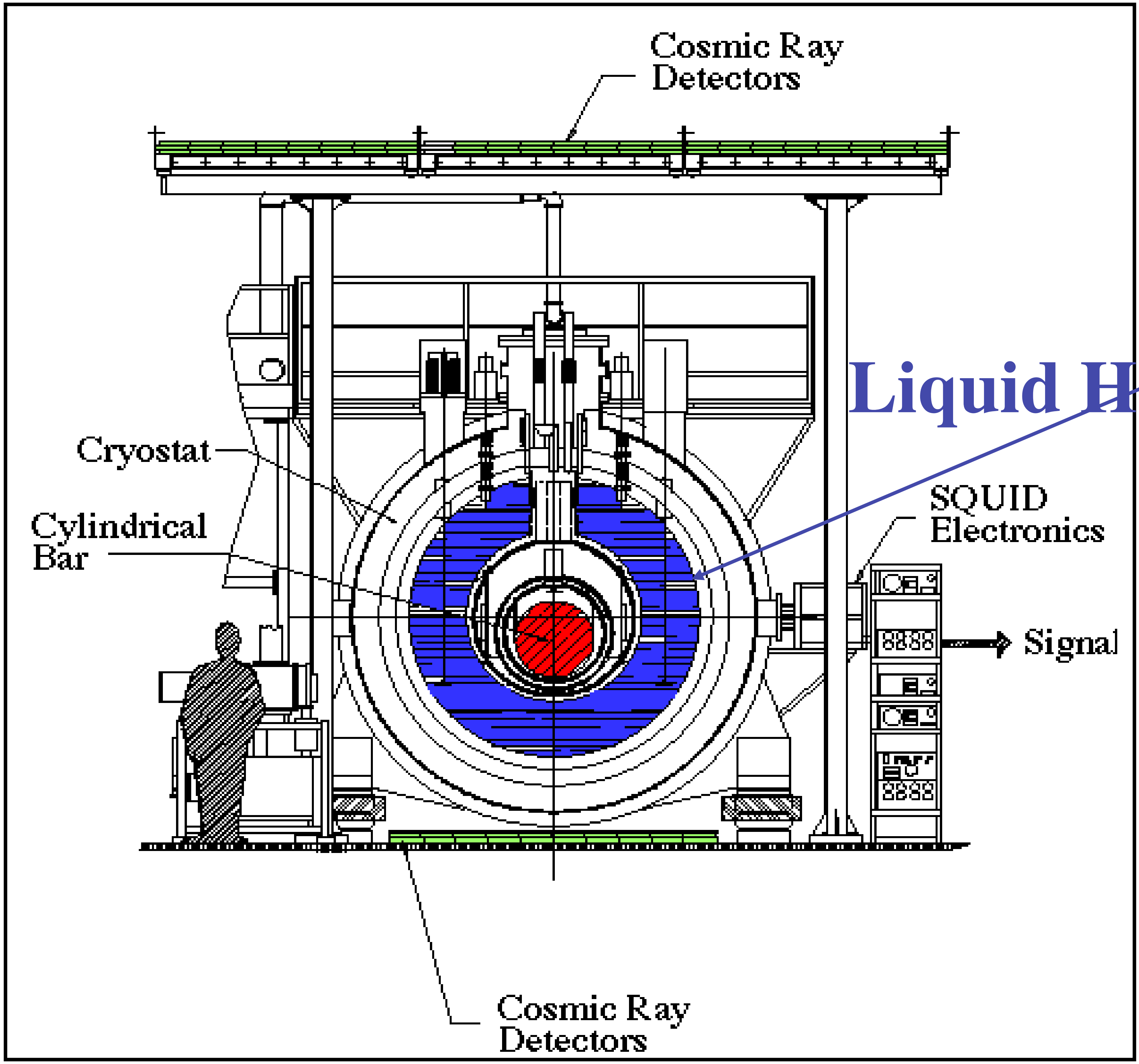

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Cross section : 2 aluminum shields, container for helium **2000 liters**

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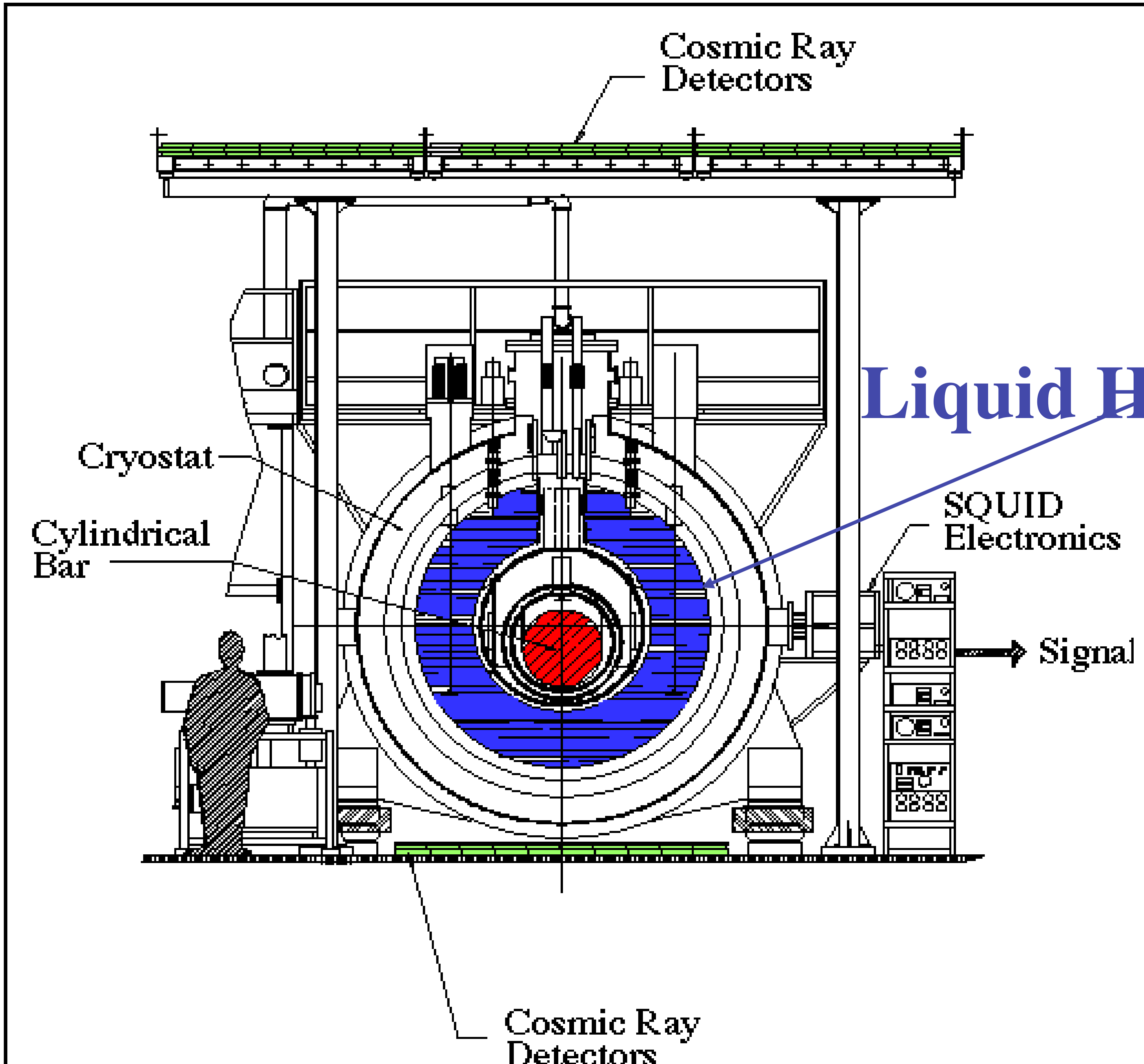

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Mechanical suspension: shields are suspended in a chains and copper wire around the bar
260 db @ 1 kHz

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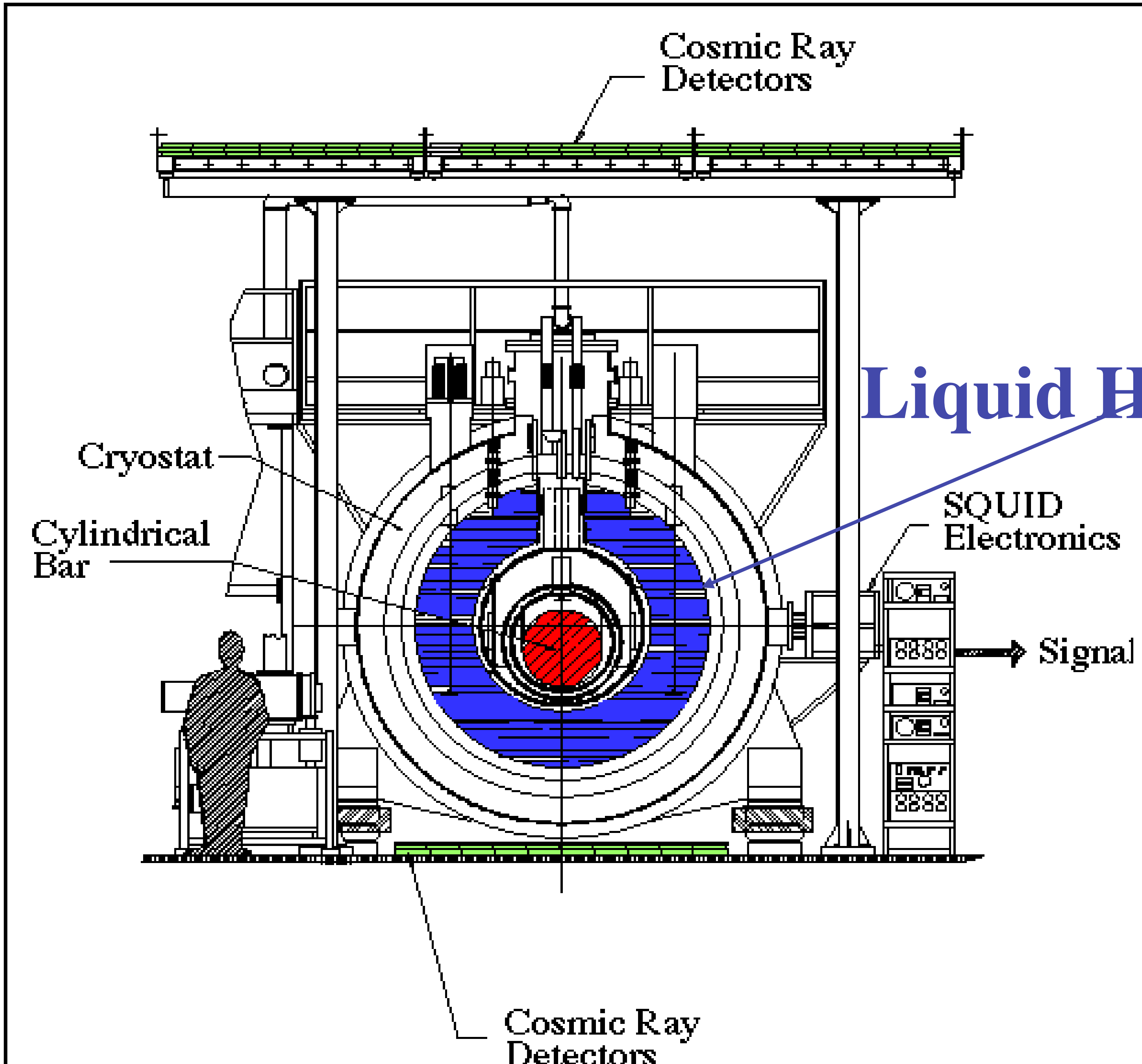

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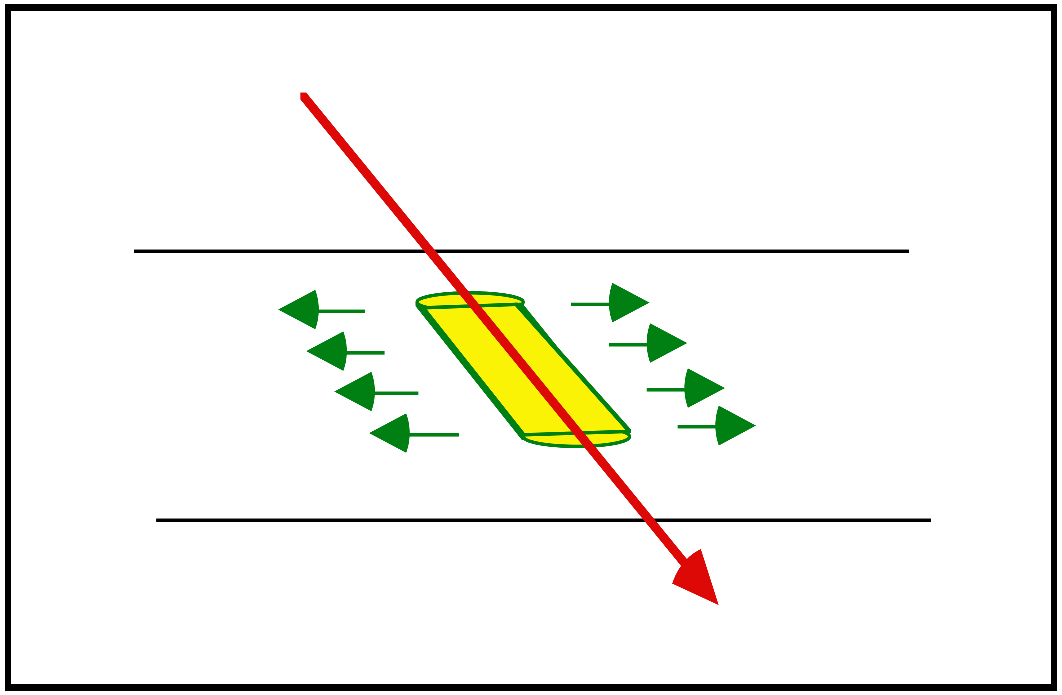
Readout : capacitive transducer with SQUID and 5kHz ADC

Nuclearite detection by thermo-acoustic effect in the bar

Interaction of a nuclearite with a bar: energy lost is converted in thermal heating and therefore pressure wave



$$\delta T = \frac{\delta E}{\rho C V_0}$$

$$\delta p = \gamma \frac{\delta E}{V_0} \qquad \gamma = \frac{3\alpha}{\rho\, k C_v}$$

$$k = 3*(1-2*pois)/Y$$

γ Grunesein parameter Y = Young module, C= specific heat, α linear thermal expansion coefficient, pois=Poisson module

Verified with a dedicated experiment on a particle beam (RAP)

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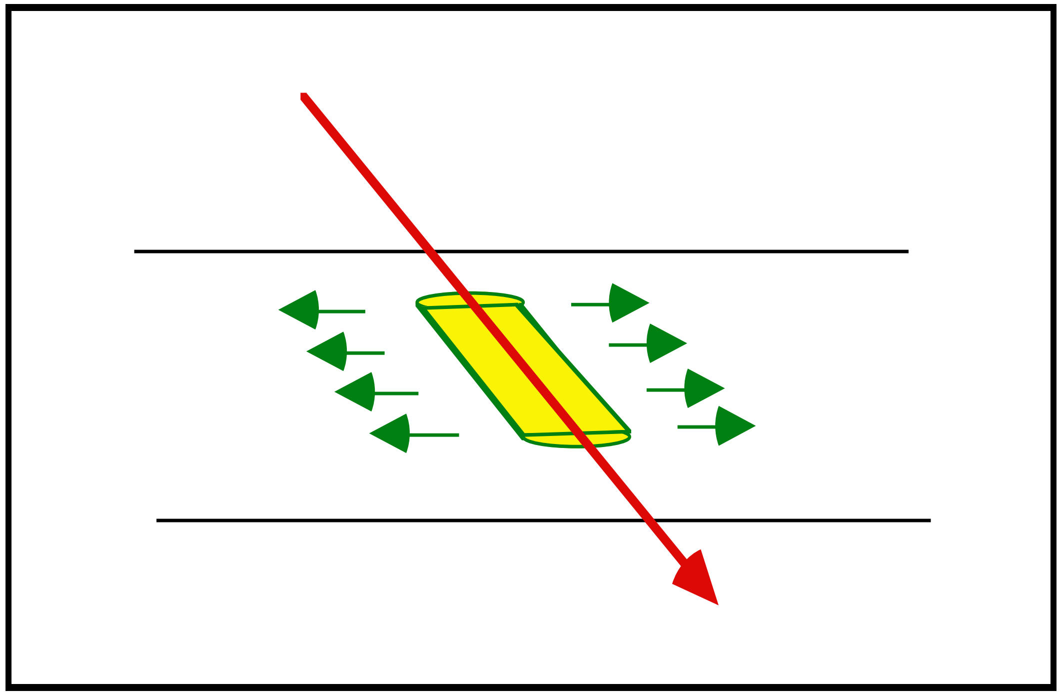

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Bar is like a 2.3 Ton bolometer; detection mechanism simpler than the one based on the light emission or on track etch

Data analysis

• data from : EXPLORER (CERN)   2003 - 2010, NAUTILUS (2003-2013), similar acquisitions and data analysis.
• two different analysis (from different peoples)

Analysis presented here :

• selection of data with Enoise < 2.0 mKelvin, good SQUID calibration, run length>10 h
• focus on the Nautilus 2011 2012 2013 data, due to the higher quality of the data. Results for E< 4 Kelvin are for Nautilus 2011 2012 2013 only. At higher energies all data are used
• for Nautilus 2011 -2012 -2013 further event cleaning removing

a) burst of events
b) event shapes based on the ADC signal and the output of the optimal filter (possible only for high energy events
c) events with big seismic activity

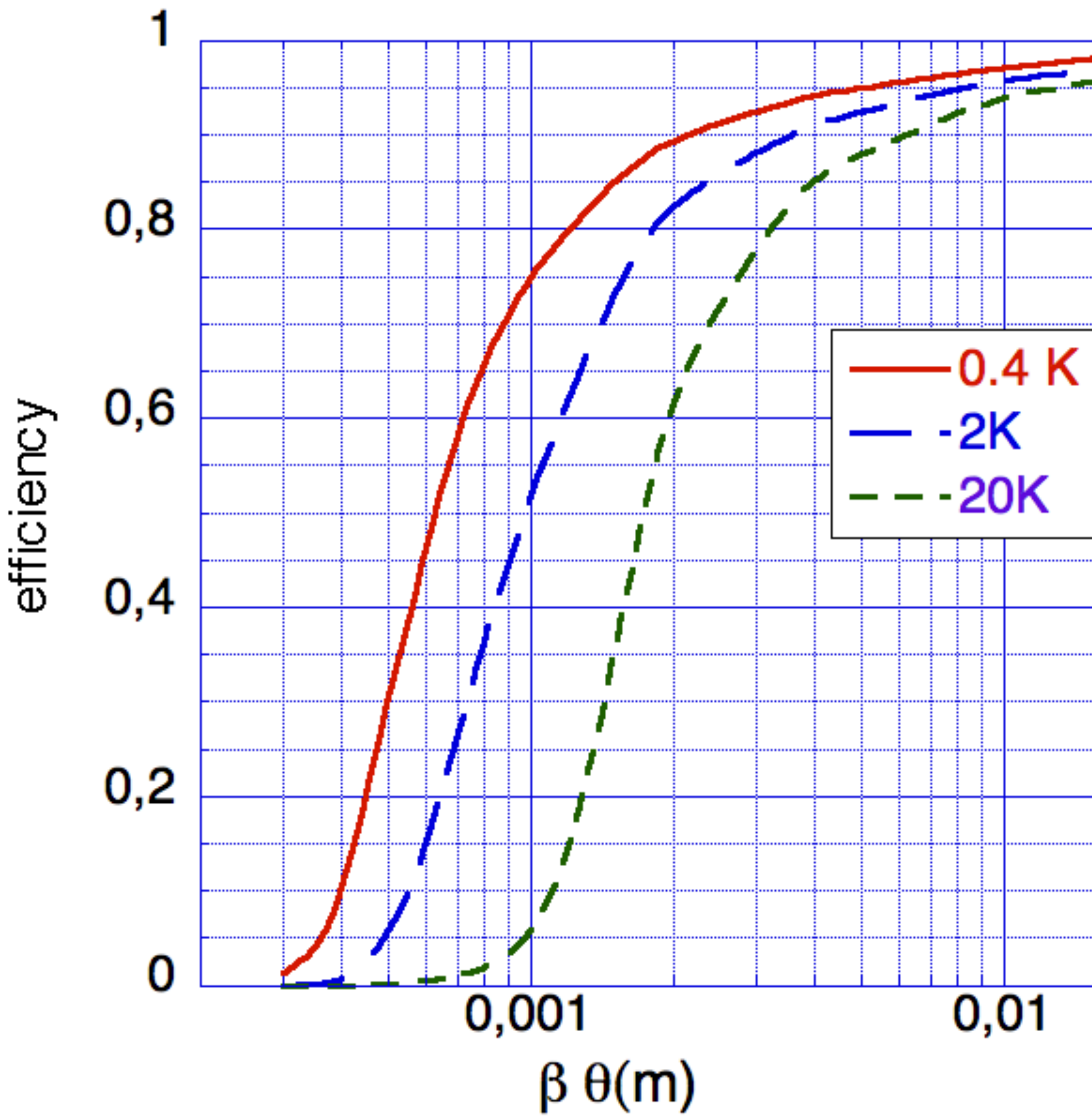
Nuclearite efficiencies and simulation

$$\frac{dE}{dx} = 480 \frac{\text{GeV}}{\text{cm}} \left[\frac{\beta\theta(m)}{10^{-3}} \right]^2 ,$$

where the mass dependence is

$$\theta(m) = 1 \quad \text{if } m \leq 1.5 \text{ ng} ,$$

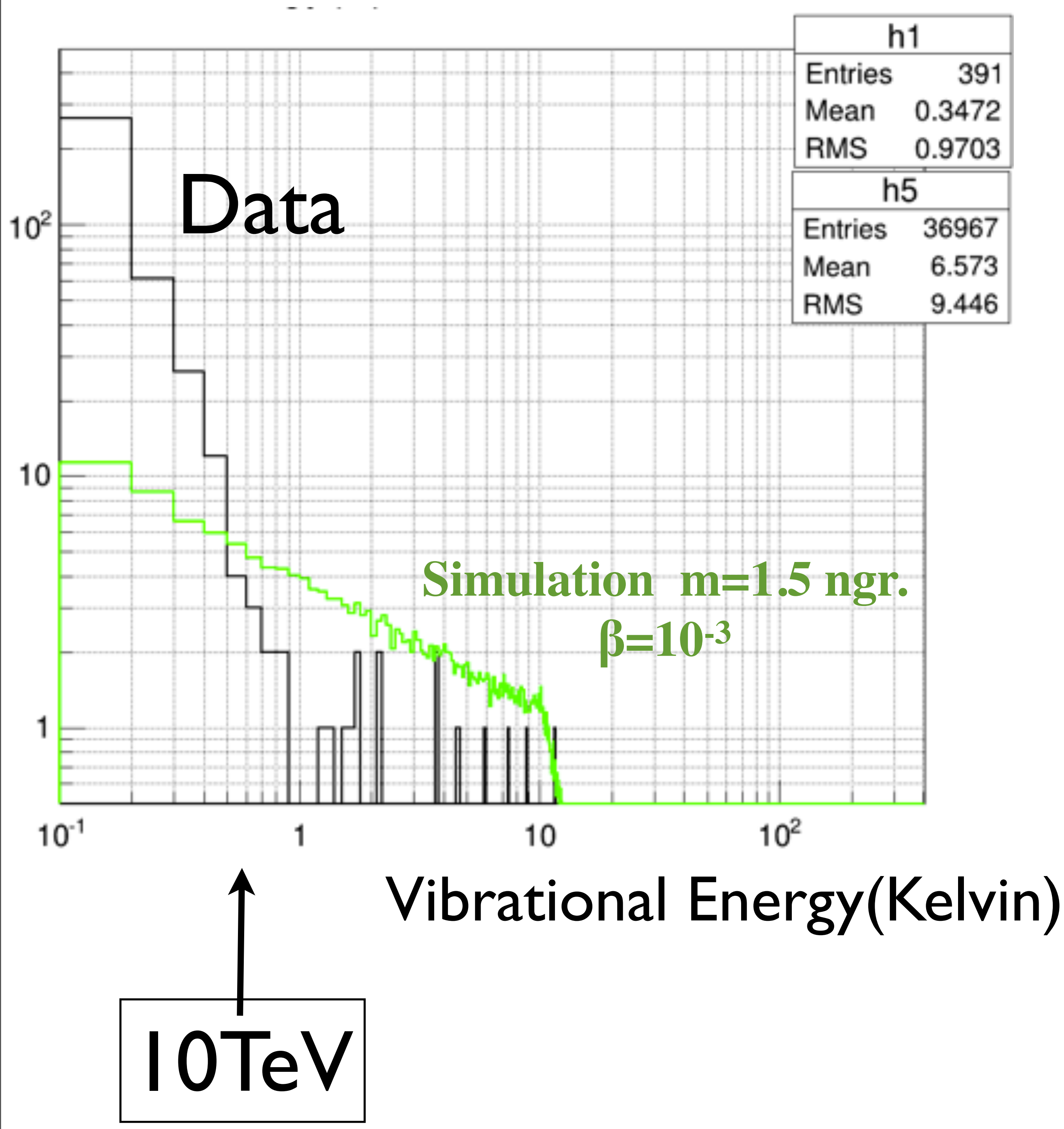
$$\theta(m) = \left[\frac{m}{1.5 \text{ ng}} \right]^{1/3} \quad \text{if } m \geq 1.5 \text{ ng} .$$



Note that there is no intrinsic detector limitation in beta

Results

Nautilus 2011-2013: 391 events
E>0.1 (Kelvin) in 878.5 days



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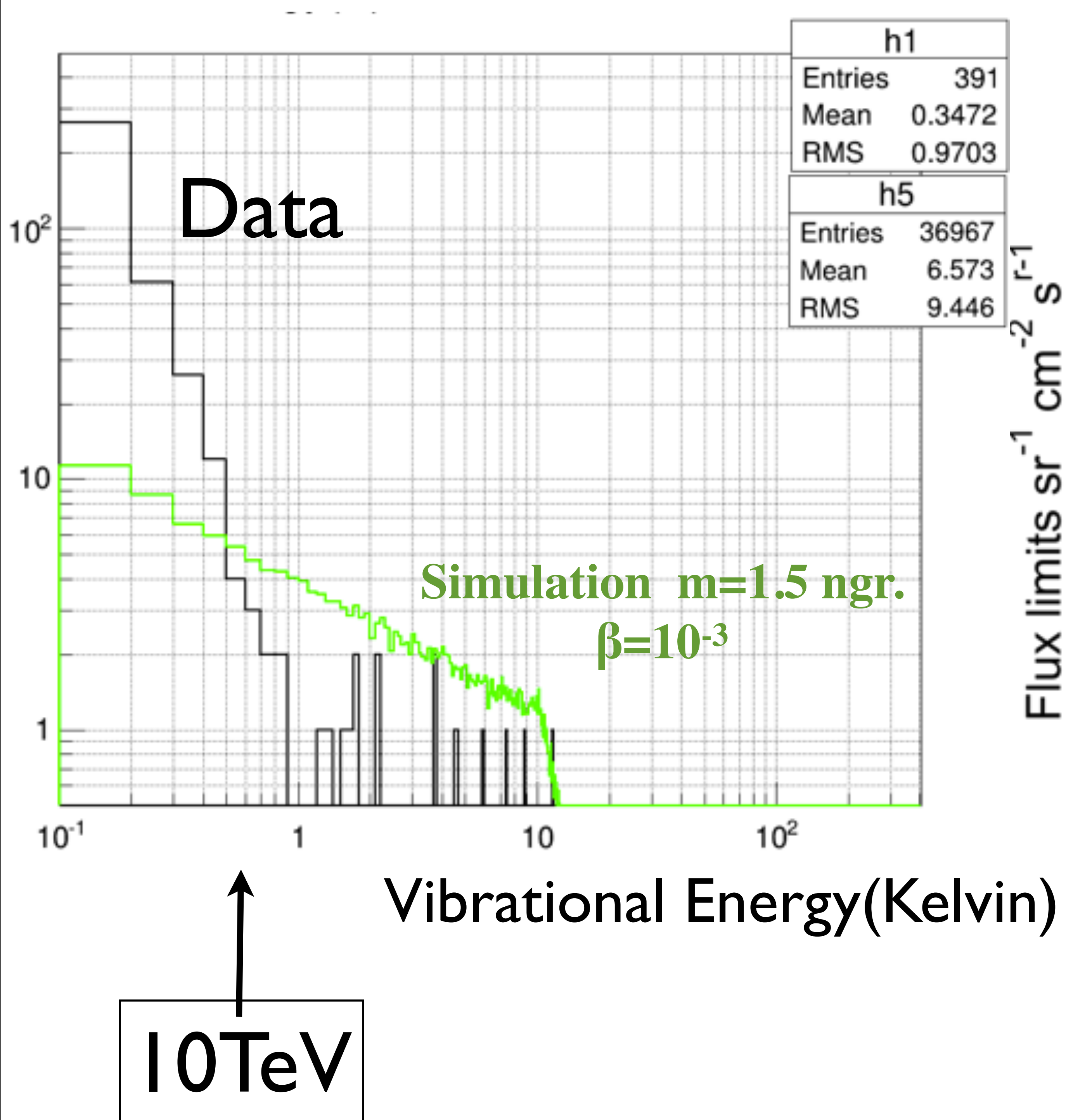
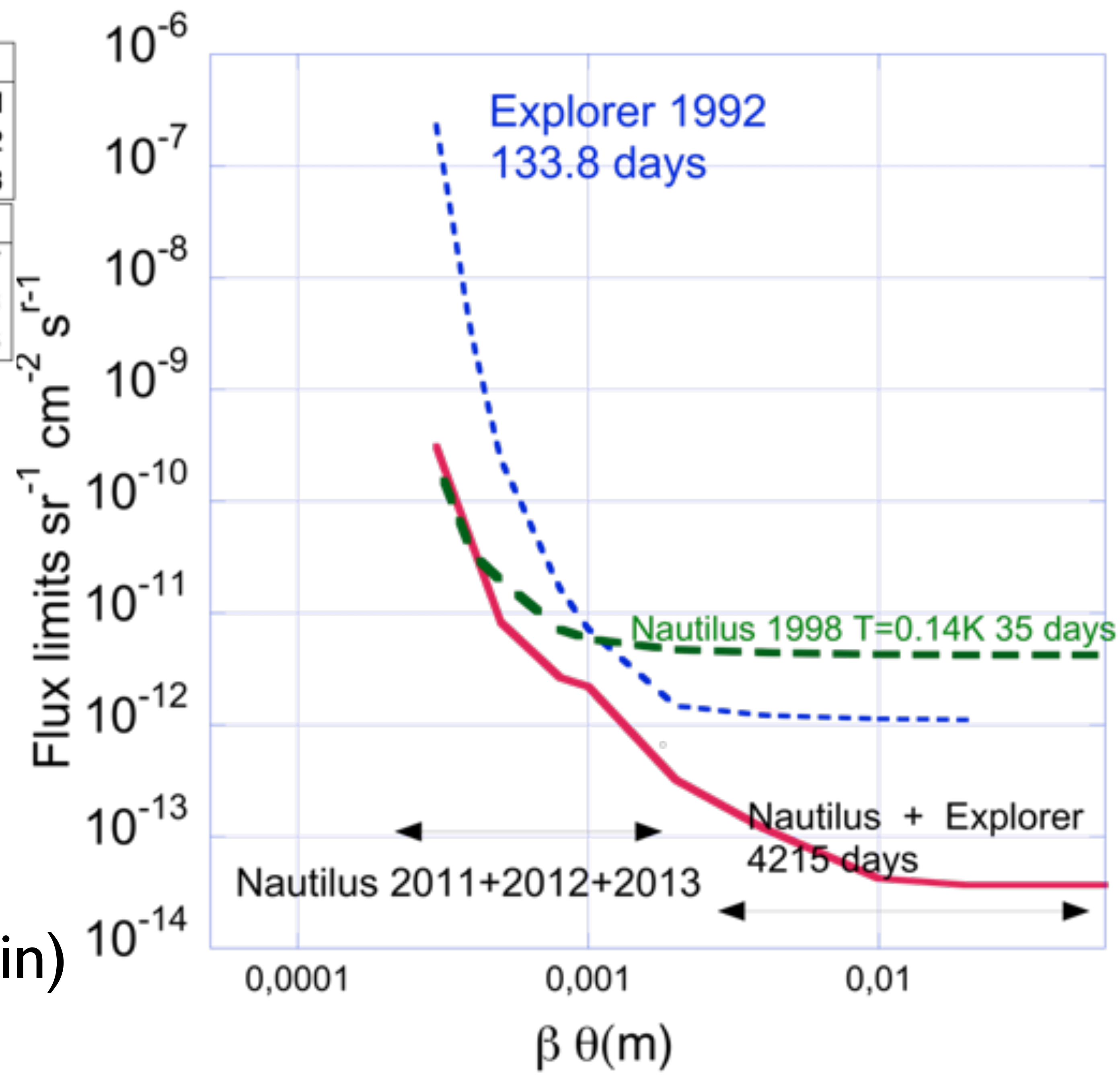
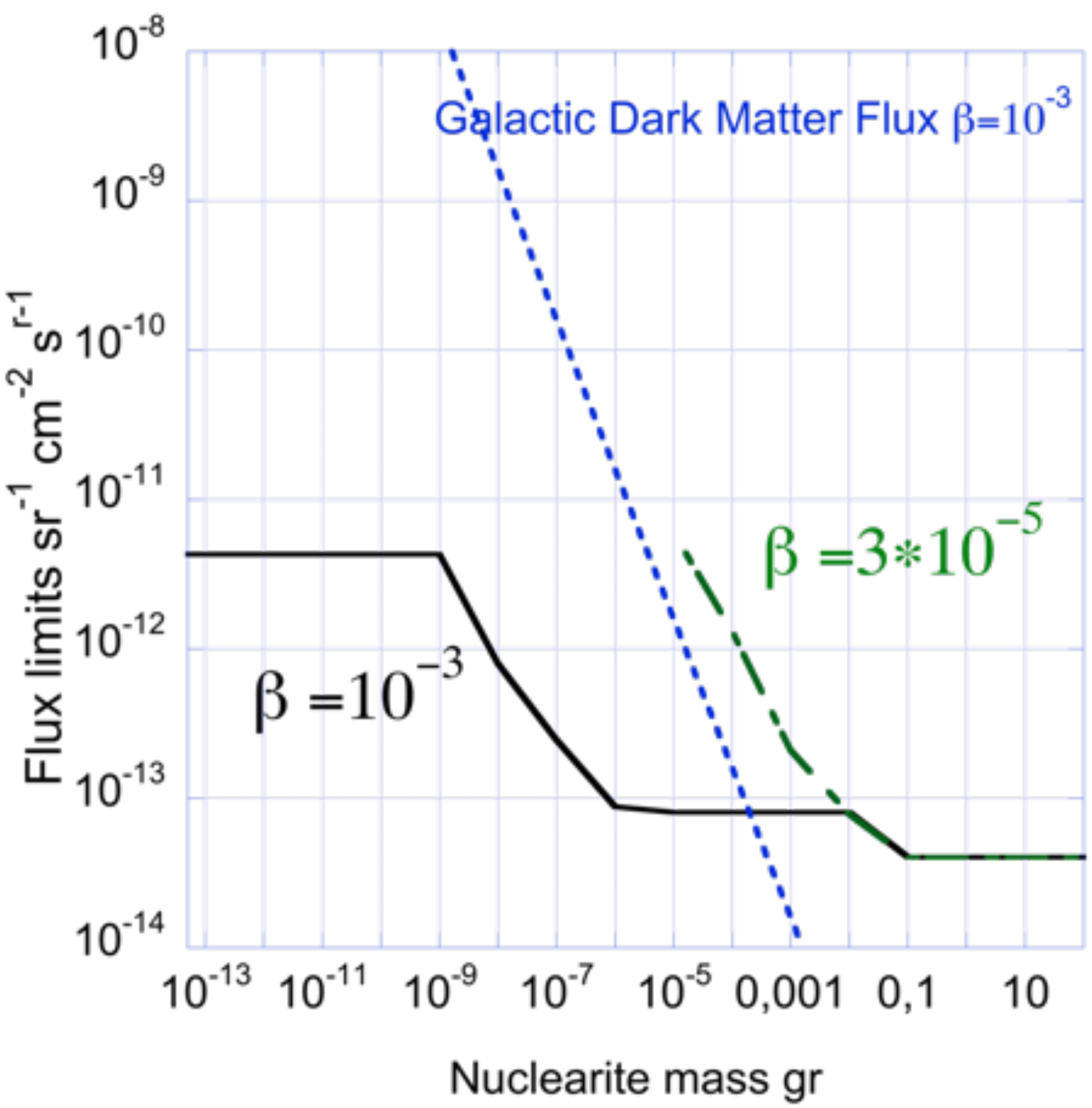


Flux limits (90%)
(optimum interval method)



Nautilus and Explorer Nuclearite upper limits



- Other experiments above sea level using track etch detectors have obtained lower limits.
- The interest in this search is the "more robust" calorimetric technique (calibrated on a beam)

Summary

• very heavy quark and antiquark nuggets could be DM constituents

• the study of meteor is interesting for this search.

In the Space : is an interesting by-product of detectors developed for high energy cosmic rays
On the Earth : the development of cheap and fast video-camera open interesting opportunity.
On the Moon : with future missions and with the current observations of flashes due to meteor impacts (NASA program)

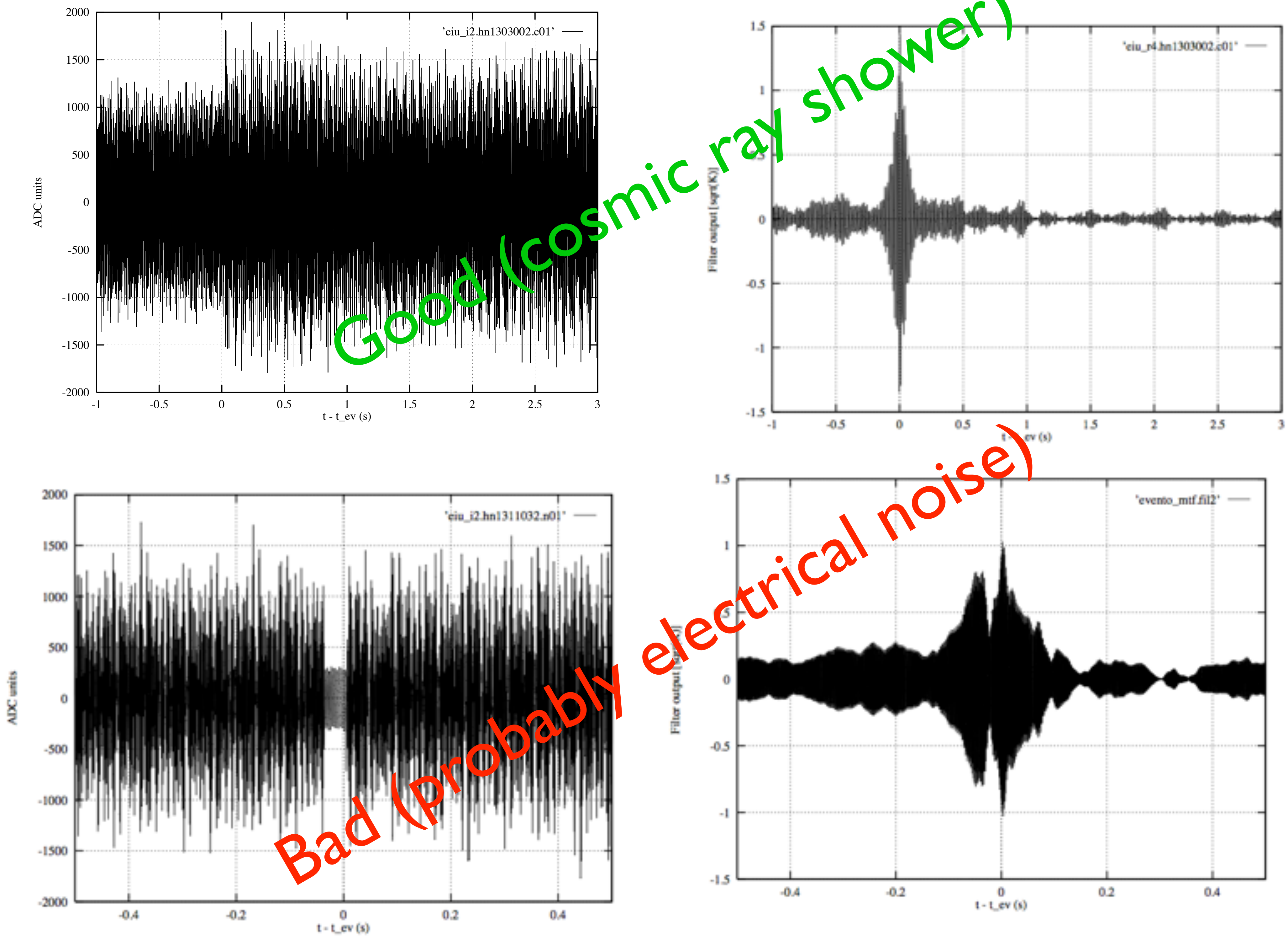
• Resonant GW bar detectors at sea level excludes nuclearites as main component of the Galactic Dark matter for mass between 10^{-13} and 10^{-4} gr. Calibrated calorimetric technique.

Backup

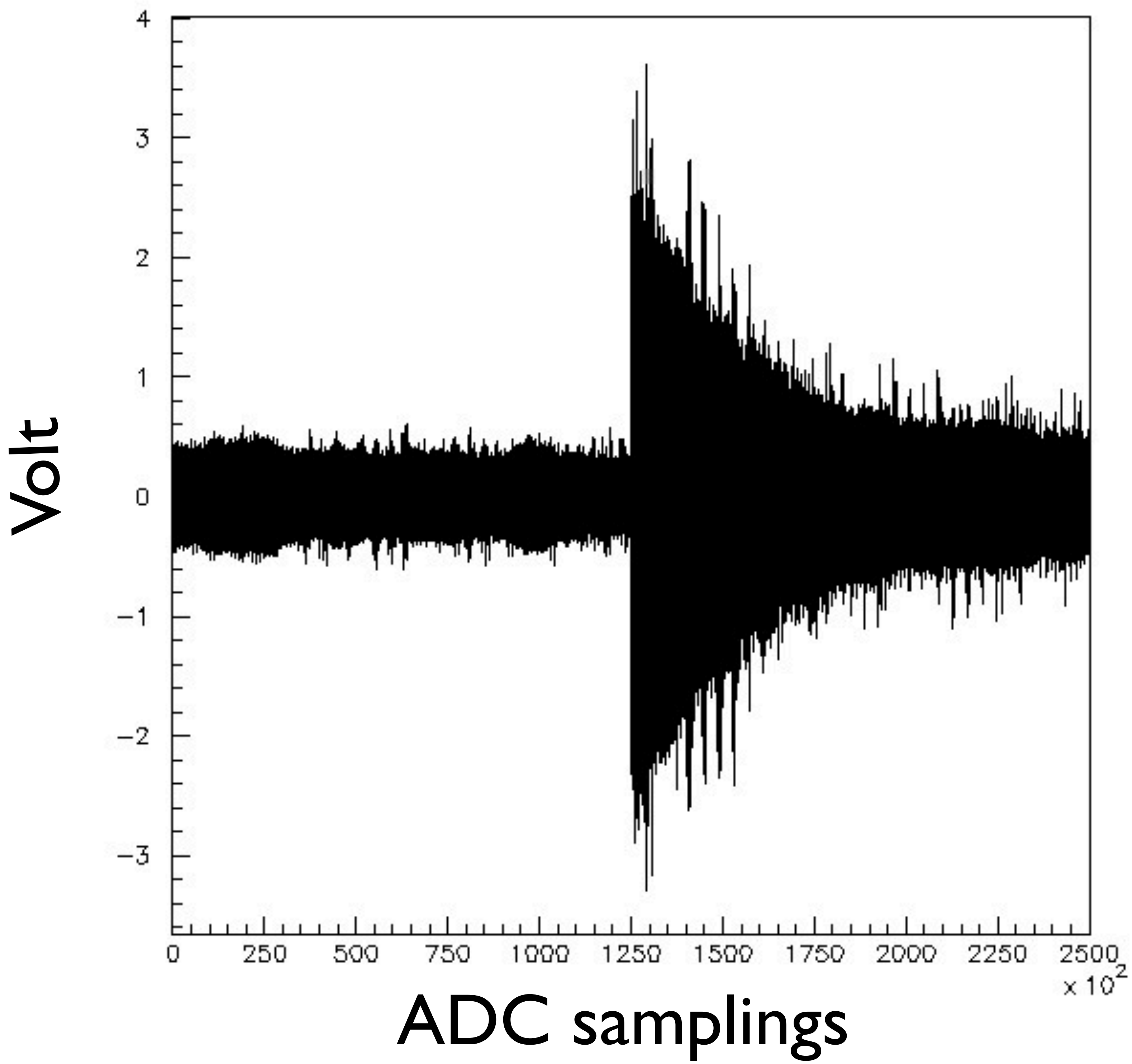
Event shape example (NAUTILUS)

A good event should be a mechanical excitation of the bar, with a decay time of a ~300 sec on the ADC

ADC   Optimum filter



The largest event (June 2013)



Anti-quark nuggets search using optical flashes on the Moon

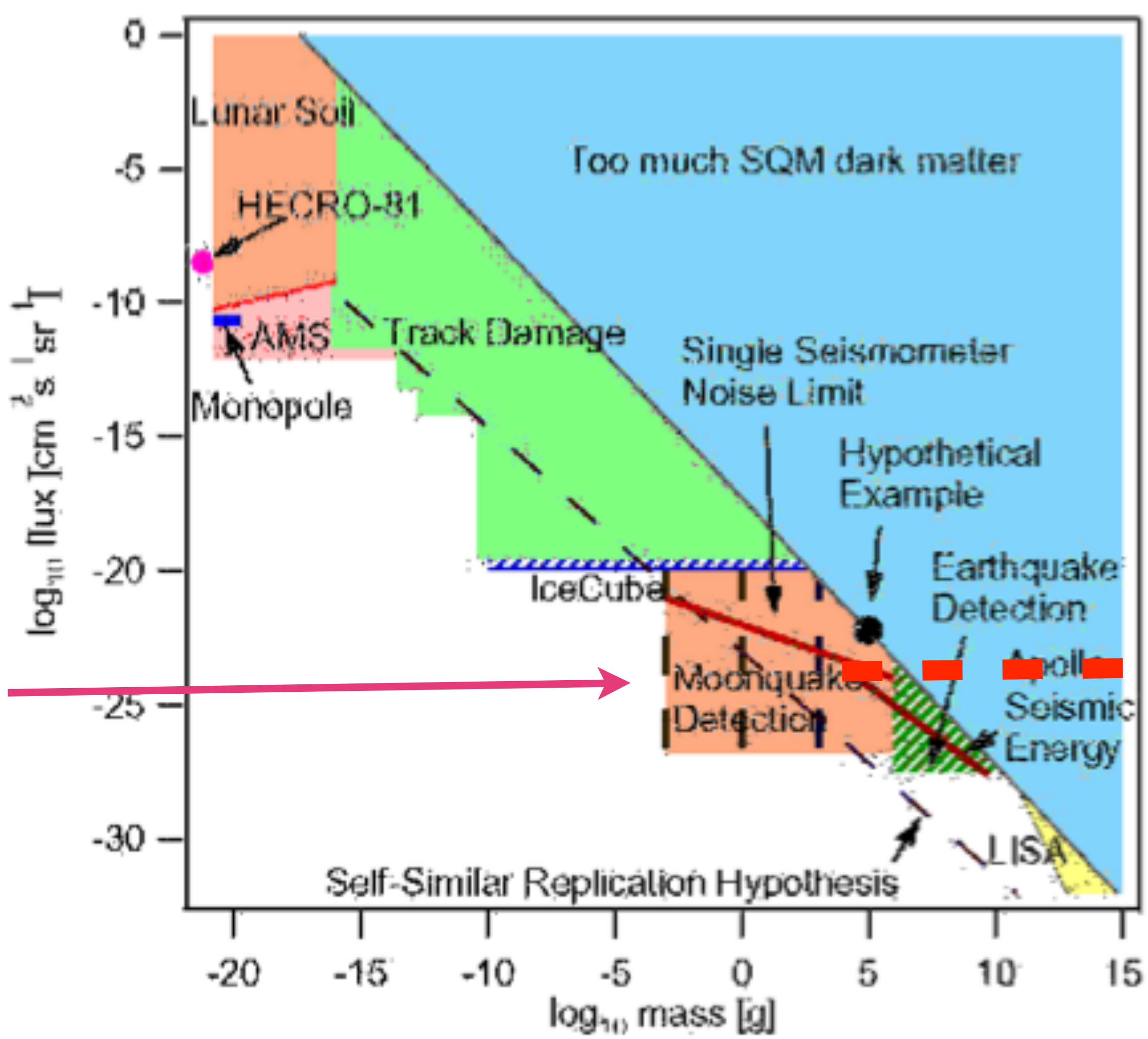
- Nasa program to observe Lunar flashes due to meteors impact with terrestrial optical telescope

http://www.nasa.gov/centers/marshall/news/lunar/publications.html#.VBrFN-dD-kK

- Public data are in http://www.nasa.gov/centers/marshall/pdf/155422main_ALAMO_lunar_impact_observations301.pdf

- An anti-quark nugget of mass ~> 10kg should cross the Moon and should give ~ coincident flashes
- Looked to the data (60 sec window) found 6 double flashes all belonging to known meteor showers (5 to the Gemini)

Current limit will improve with time



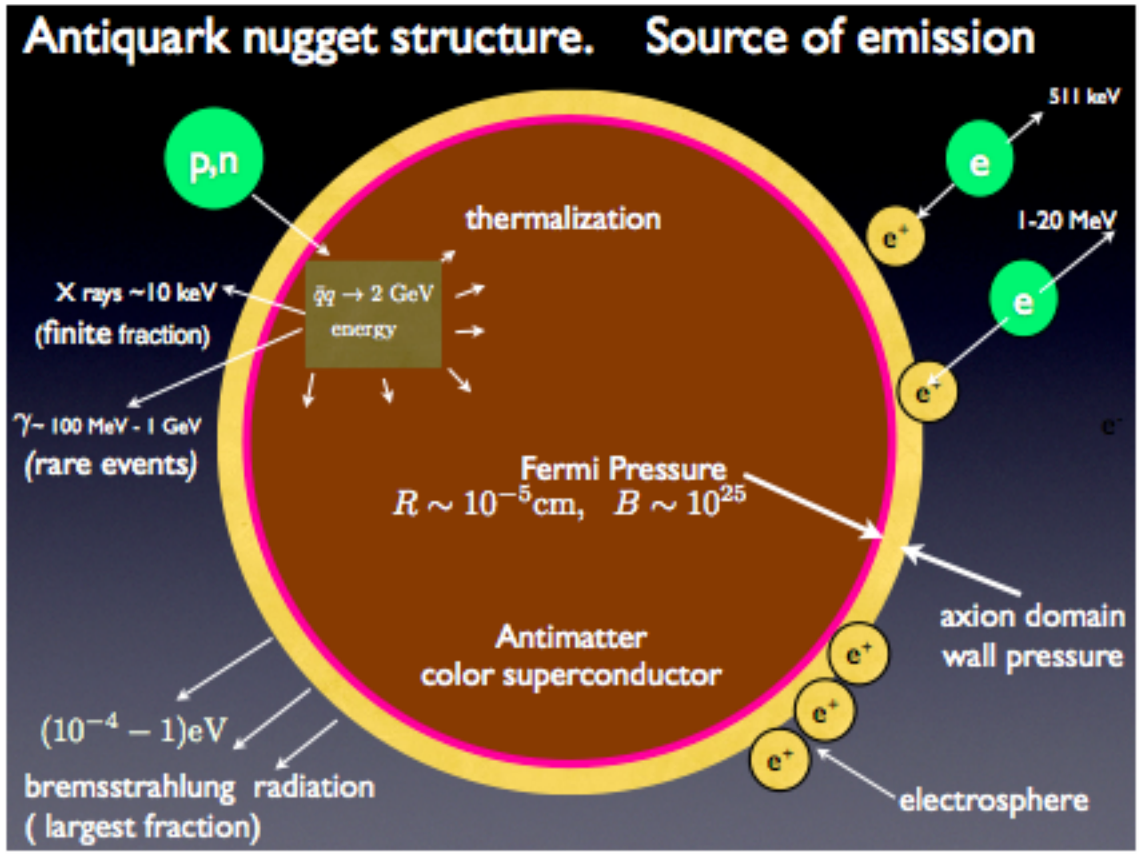


FIG. 2. (Anti)nugget internal structure and sources of emission from the core of the galaxy.

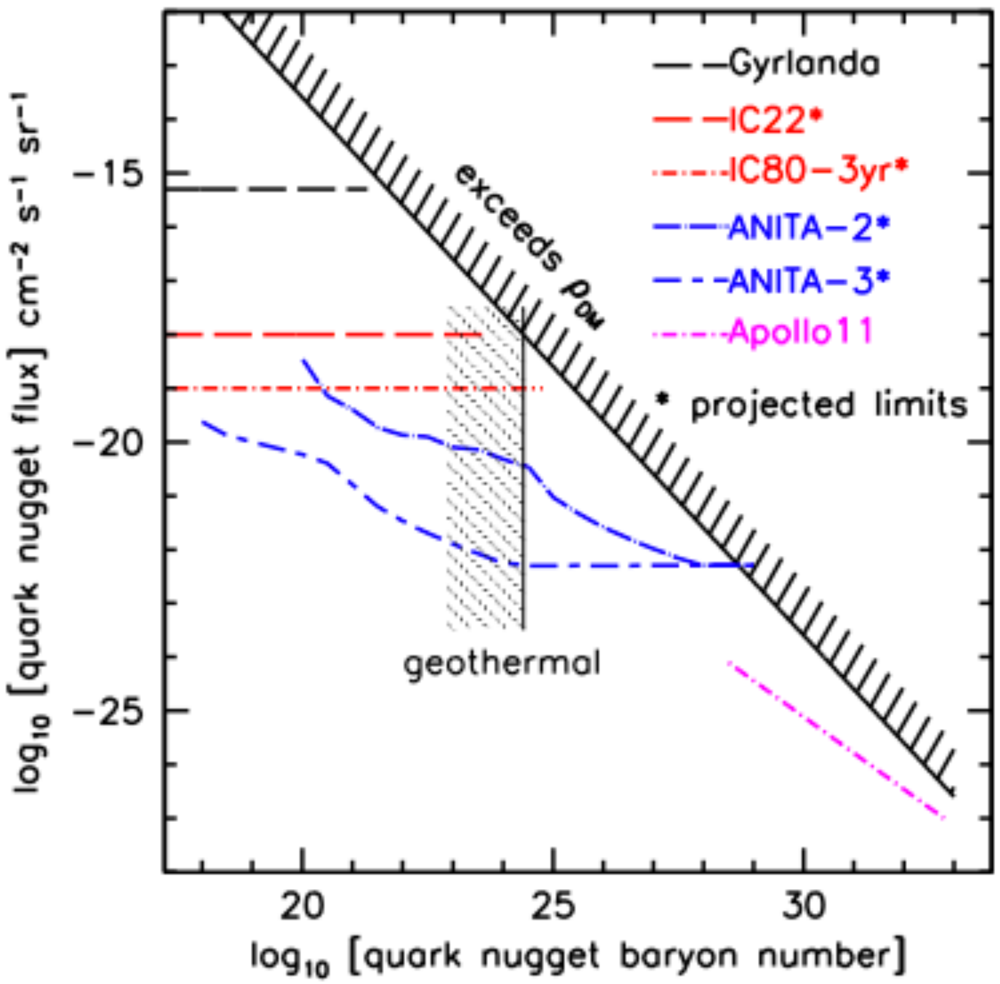
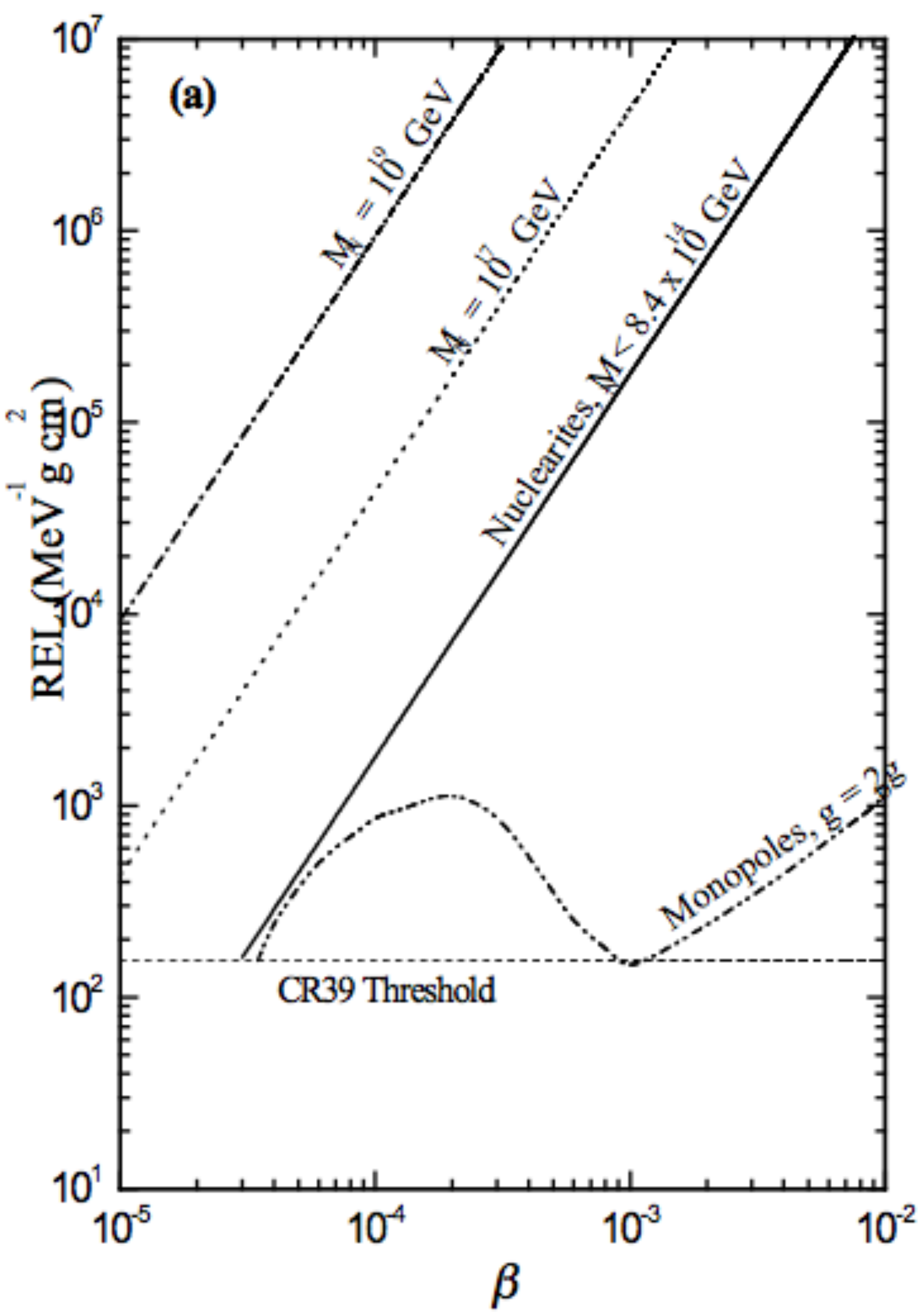


FIG. 5. Limits on quark nugget mass and density based on current constraints and ANITA data currently under analysis. Taken from [22].

Nuclearites, i.e. SQM "meteorites": ~neutral, $\beta \sim 10^{-3}$



Elastic collisions with atoms and molecules.

$$\frac{dE}{dx} = -a\rho\, v^2 \qquad \rho: \text{target density}$$

$$a = \begin{cases} \pi A^2 & \text{for } R \le 1\,A^\circ \quad (M \le 8.4\times 10^{14}\, GeV) \\ \pi\left(\dfrac{3M}{4\pi\rho_N}\right)^{2/3} & \text{for } R \ge 1\,A^\circ \quad (M \ge 8.4\times 10^{14}\, GeV) \end{cases}$$

The Restricted Energy Loss in CR39 vs beta for Nuclearites of various masses and for Magnetic Monopoles with $g=2g_D$.

REL=fraction of energy deposited near track. When the incoming particle has a velocity ßc < 10^{-2} c the REL coincides with the total energy loss in the medium. For particles with ßc > 10^{-2}c, the REL is a fraction of the electronic energy loss, leading to δ rays with energies lower than E_{max}, with E_{max}= 200 eV for CR39® and 350 eV for Lexan, respectively.

Supersymmetric Q-balls

- *S. Coleman, Nucl. Phys. B262 (1985), 263*
- *A. Kusenko et al., Phys. Lett. B 404 (1997) 285; Phys. Lett. B 405 (1997) 108;*

Q-balls : coherent states of squarks, sleptons and Higgs fields

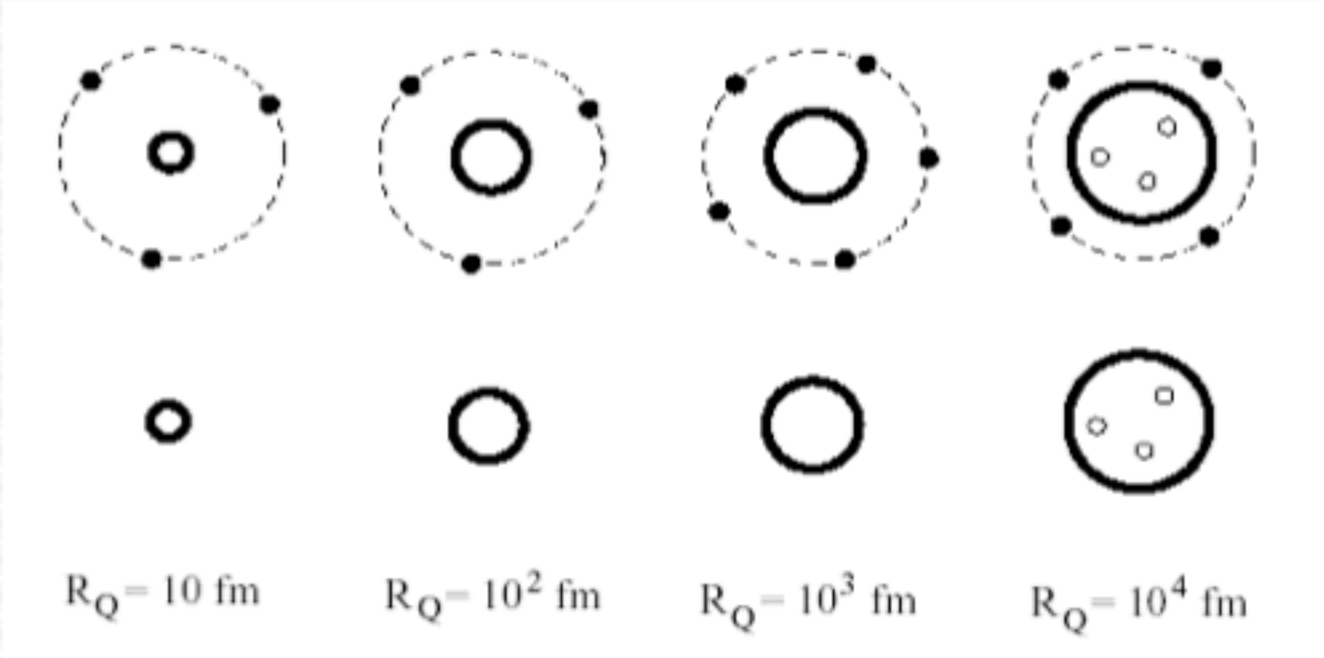
$10^{8} < M_Q < 10^{25}$ GeV

Produced in the Early Universe ; possible components of Cold Dark Matter

Concentrated in the galactic halos, $\beta \sim 10^{-3}$

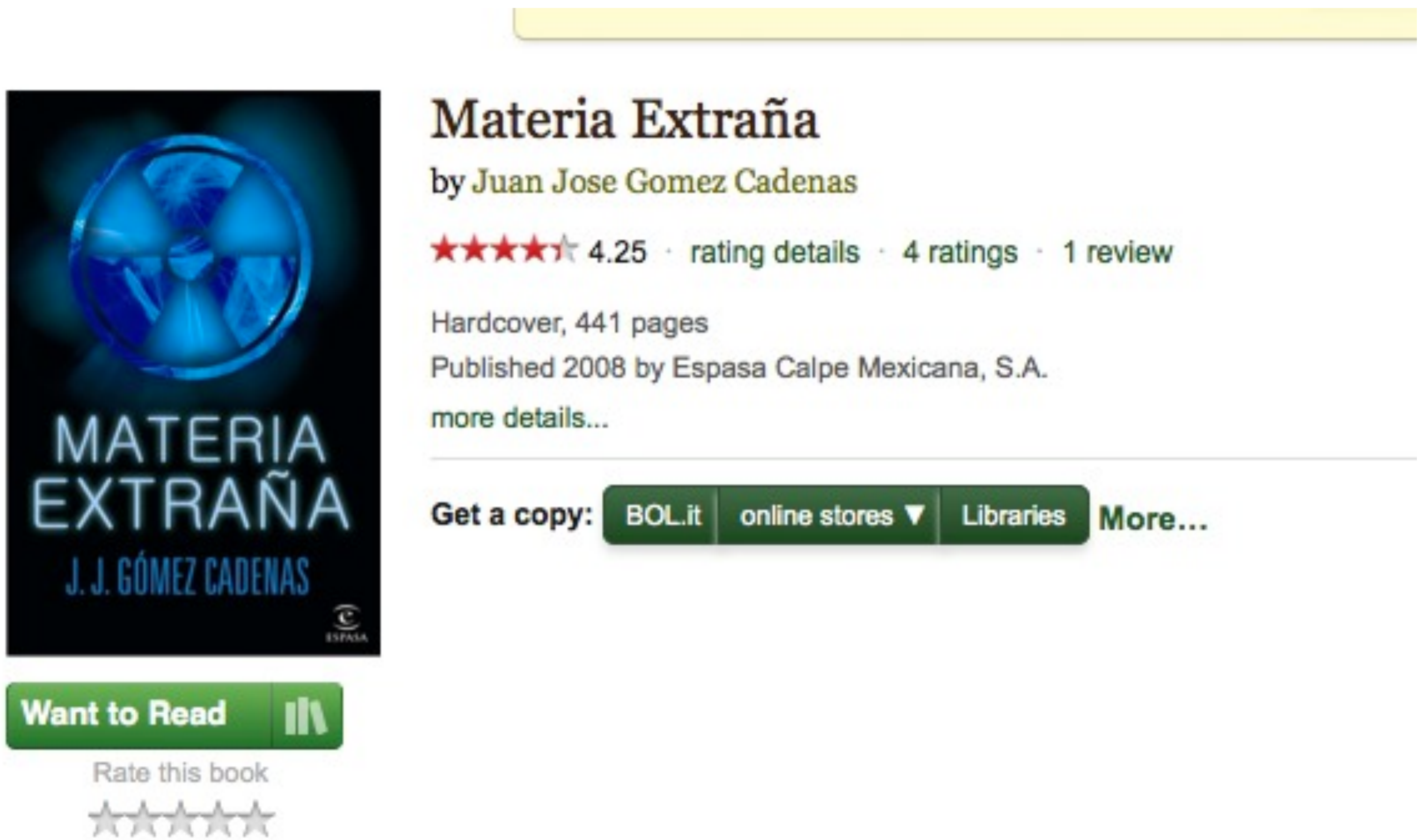
Charged Q-balls
similar to strangelets :

Neutral Q-balls
similar to nuclearites



R_Q : dimension of the Q-ball core;
the black points indicate electrons, open circles indicate s-electrons.

A fundamental book on strange quark matter!!



A strange particle produced in LHC could “eat” the Earth !!!

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

STUDY OF POTENTIALLY DANGEROUS EVENTS DURING HEAVY-ION COLLISIONS AT THE LHC: REPORT OF THE LHC SAFETY STUDY GROUP

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