Probing quark matter in compact stars with cosmic rays

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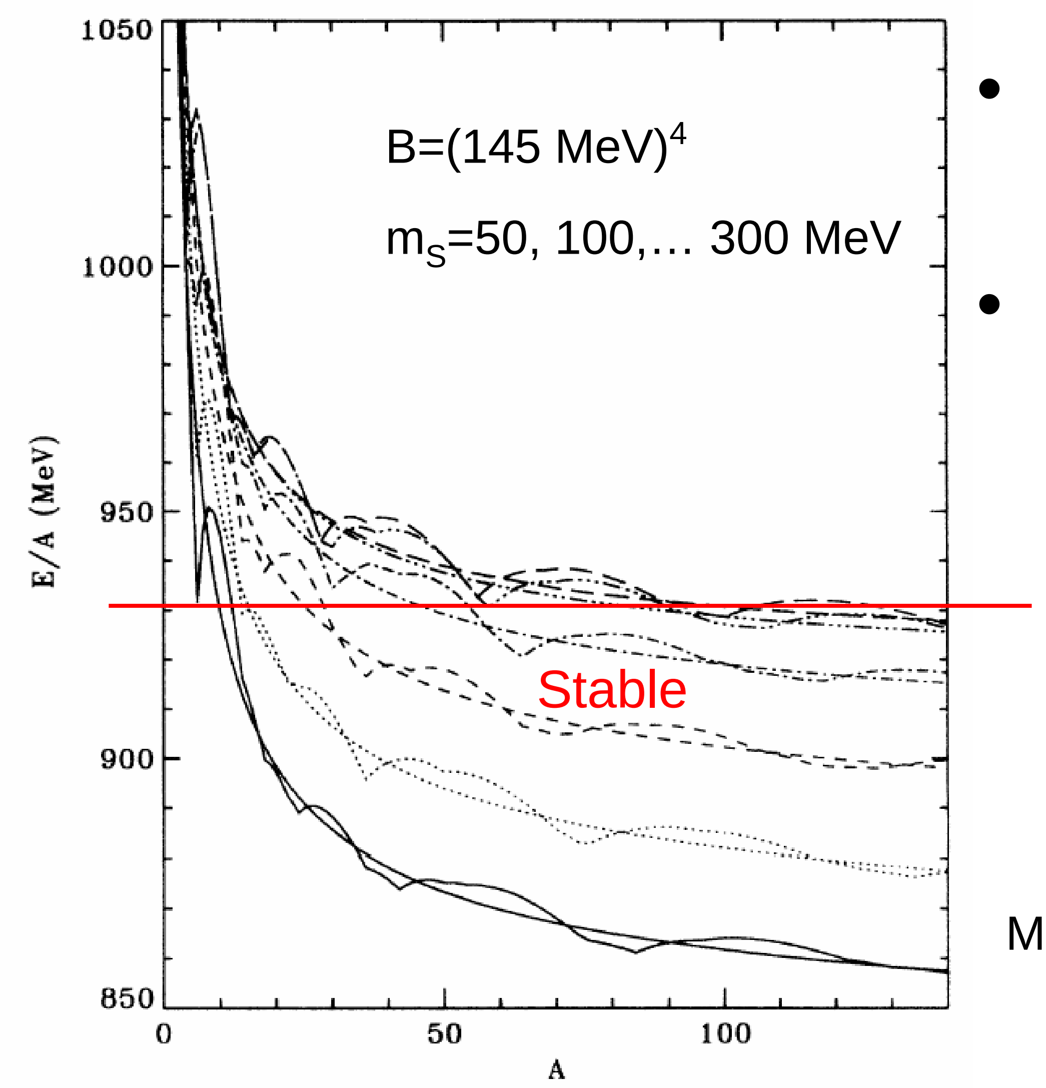
Strangelets in cosmic rays?

- What are strangelets ?
- Ways to detect a cosmic ray strangelet flux
- A strangelet search with AMS-02 on the International Space Station
- A lunar soil strangelet search
- Strangelets beyond the GZK-cutoff ?

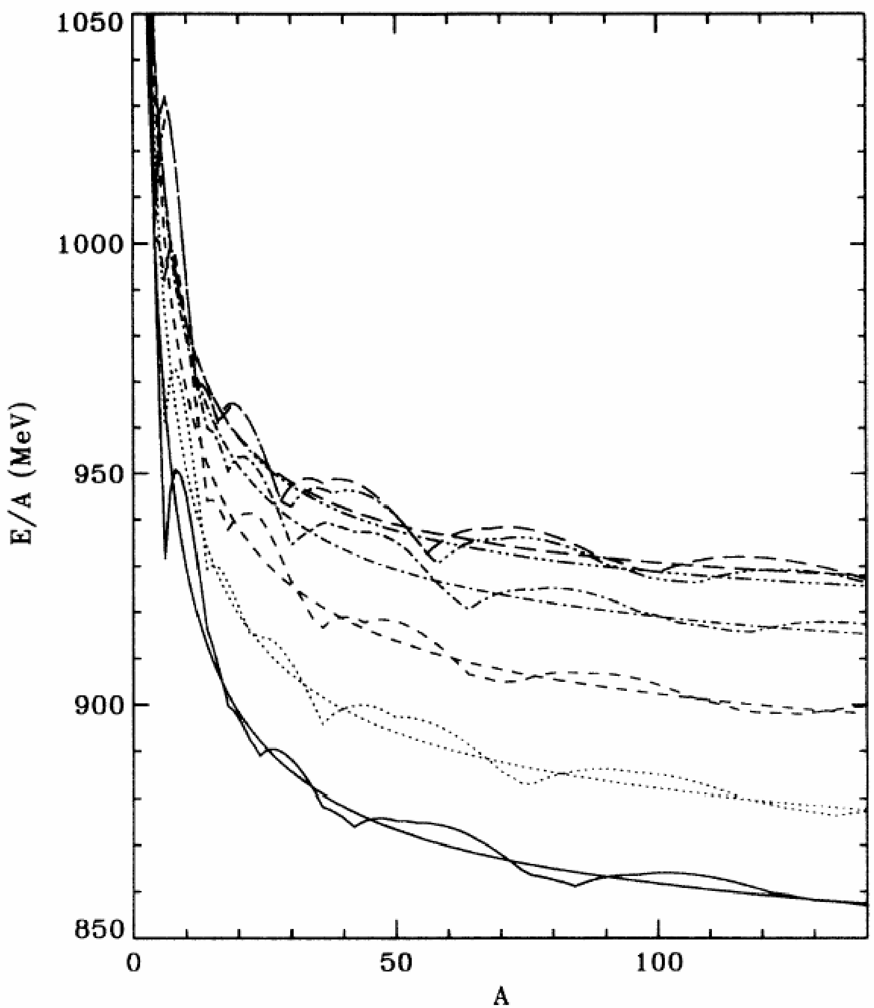
"Ordinary" strangelets

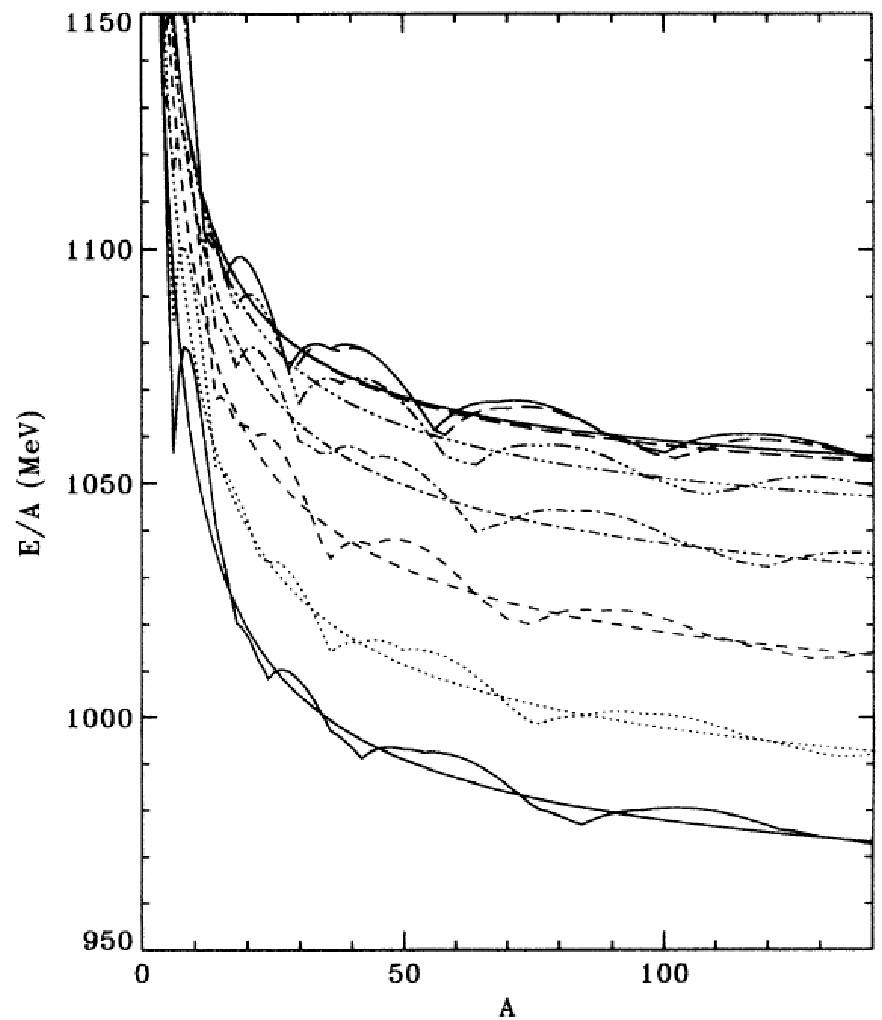


- Witten; Farhi & Jaffe…
- Shell-model vs. liquid drop model
  - Bulk $E \sim A$
  - Surface tension $E \sim A^{2/3}$
  - Curvature $E \sim A^{1/3}$

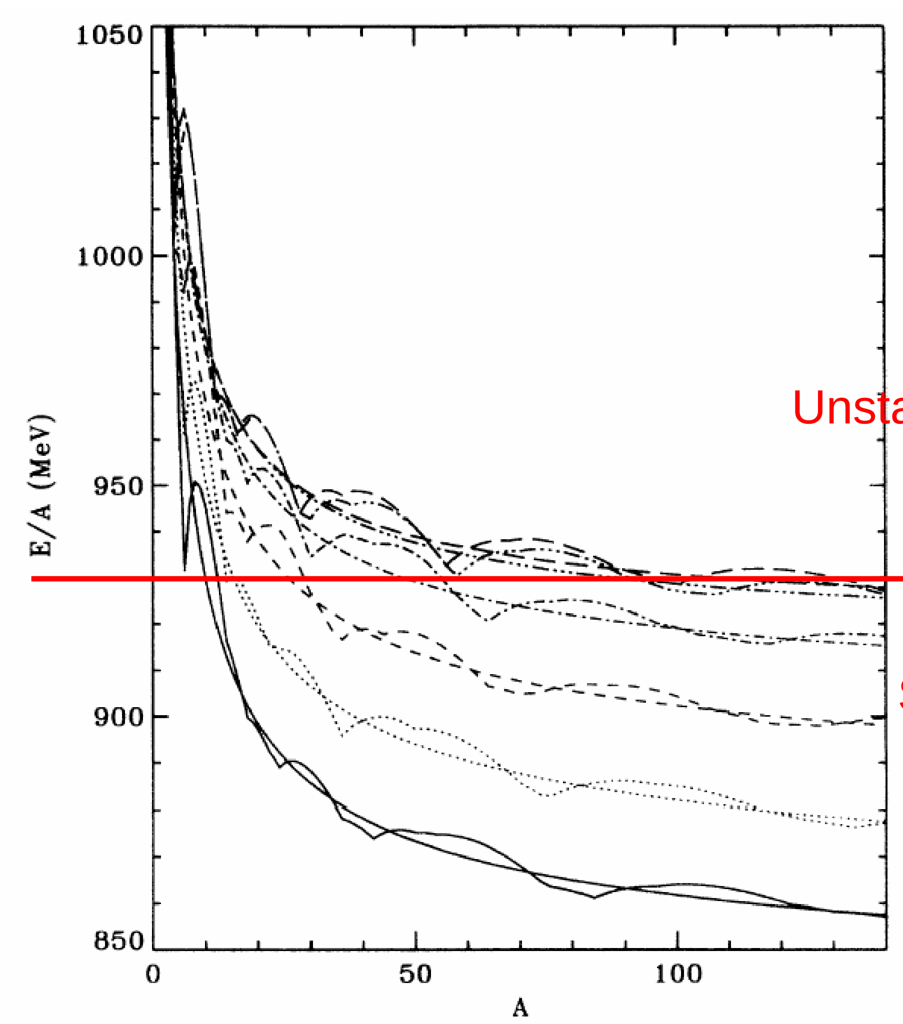
Madsen, PRD 50 (1994) 3328

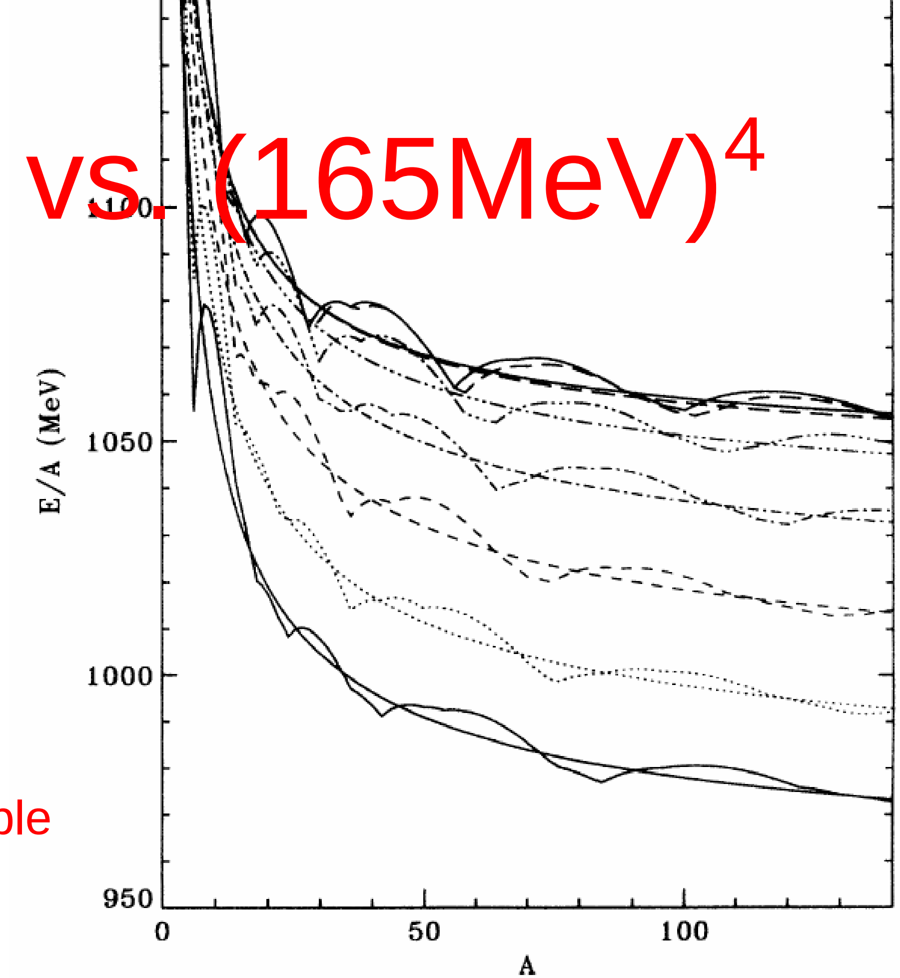
$B = (145\text{MeV})^4$ vs. $(165\text{MeV})^4$





B = (145MeV)^4 vs. (165MeV)^4

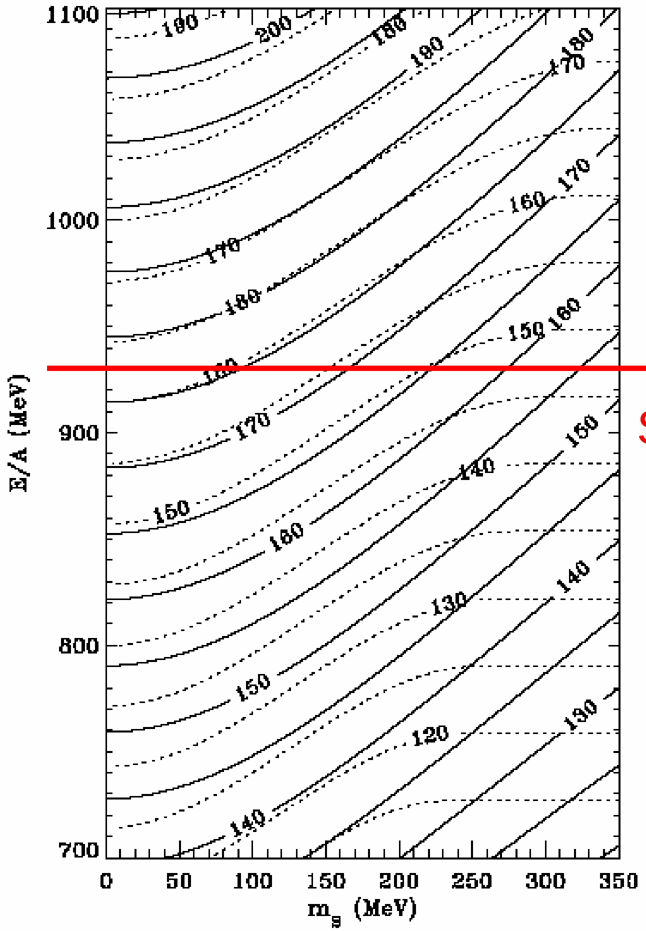




Unstable

Stable

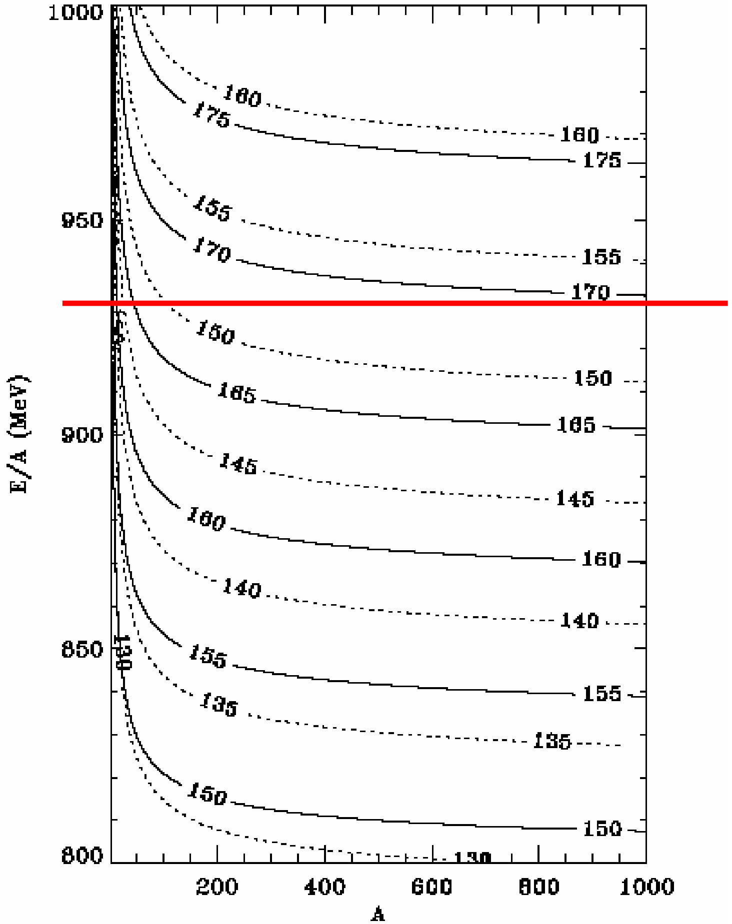
Color-Flavor Locking



Stable

BULK

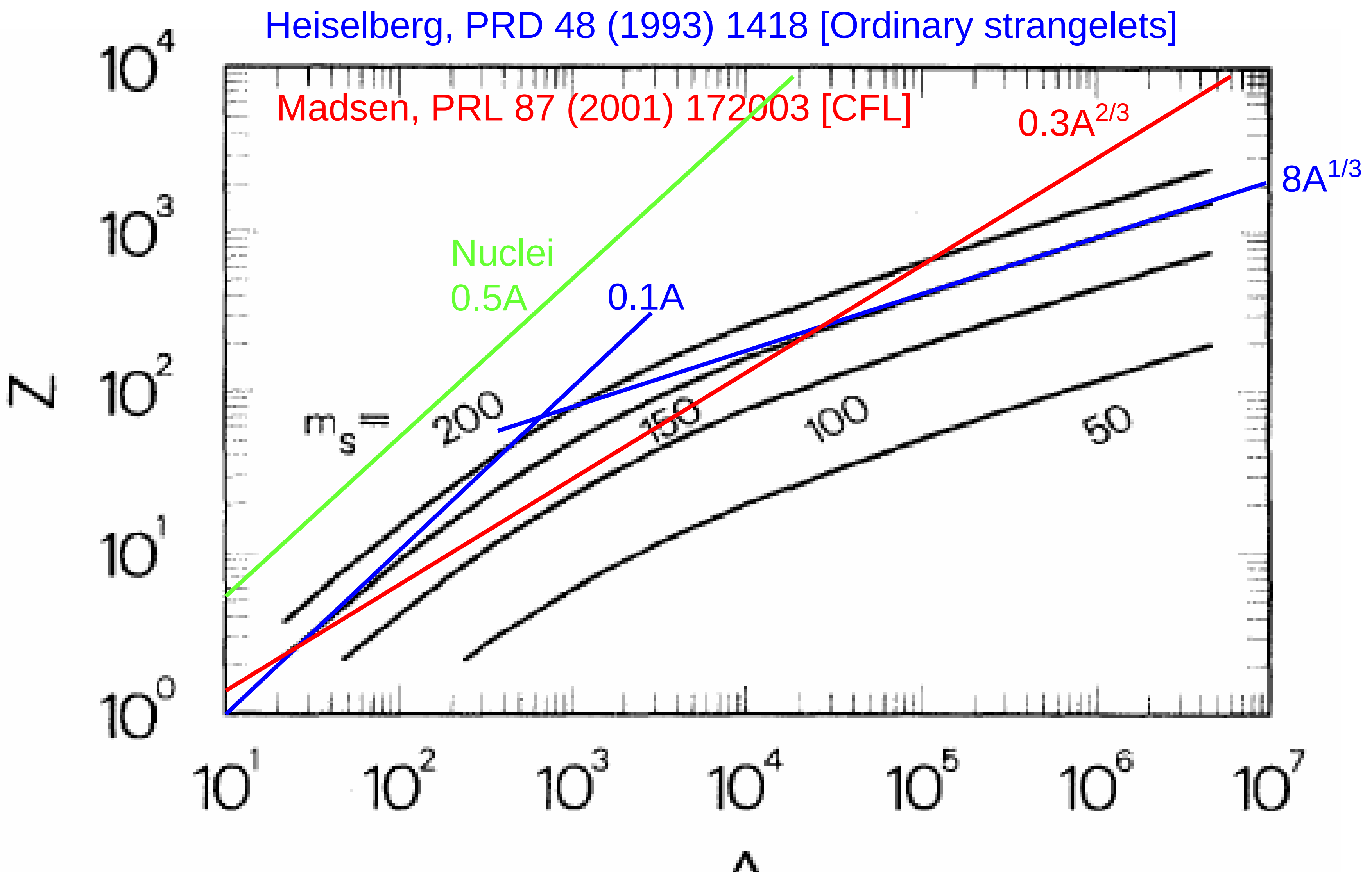
$\Delta = 100\text{MeV}$



STRANGELETS

Madsen, PRL 87 (2001) 172003

Strangelets have low Z/A



Periodic Table of Strangelets

1 H 10 5																	2 He 20 17
3 Li 30 31	4 Be 40 48			Z El bag CFL	Element strangelet mass (amu) for MIT bag model and CFL model							5 B 50 68	6 C 60 89	7 N 70 110	8 O 80 130	9 F 90 160	10 Ne 100 190
11 Na 110 220	12 Mg 120 250											13 Al 130 280	14 Si 140 310	15 P 150 350	16 S 160 380	17 Cl 170 420	18 Ar 180 460
19 K 190 500	20 Ca 200 540	21 Sc 210 580	22 Ti 220 620	23 V 230 670	24 Cr 240 710	25 Mn 250 760	26 Fe 260 800	27 Co 270 850	28 Ni 280 900	29 Cu 290 950	30 Zn 300 1000	31 Ga 310 1000	32 Ge 320 1100	33 As 330 1100	34 Se 340 1200	35 Br 350 1200	36 Kr 360 1300
37 Rb 370 1300	38 Sr 380 1400	39 Y 390 1400	40 Zr 400 1500	41 Nb 410 1500	42 Mo 420 1600	43 Tc 430 1700	44 Ru 440 1700	45 Rh 450 1800	46 Pd 460 1800	47 Ag 470 1900	48 Cd 480 2000	49 In 490 2000	50 Sn 500 2100	51 Sb 510 2200	52 Te 520 2200	53 I 530 2300	54 Xe 540 2400
55 Cs 550 2400	56 Ba 560 2500		72 Hf 720 3700	73 Ta 750 3700	74 W 790 3800	75 Re 820 3900	76 Os 850 4000	77 Ir 890 4100	78 Pt 920 4100	79 Au 960 4200	80 Hg 1000 4300	81 Tl 1000 4400	82 Pb 1000 4500	83 Bi 1100 4600	84 Po 1100 4600	85 At 1100 4700	86 Rn 1200 4800
87 Fr 1200 4900	88 Ra 1300 5000		104 Rf 2100 6400	105 Db 2200 6500	106 Sg 2300 6600	107 Bh 2300 6700	108 Hs 2400 6800	109 Mt 2500 6900	110 —— 2500 7000	111 —— 2600 7100	112 —— 2700 7200	113 —— 2800 7300	114 —— 2800 7400	115 —— 2900 7500	116 —— 3000 7600	117 —— 3100 7700	118 —— 3200 7800

57 La 570 2600	58 Ce 580 2600	59 Pr 590 2700	60 Nd 600 2800	61 Pm 610 2800	62 Sm 620 2900	63 Eu 630 3000	64 Gd 640 3100	65 Tb 650 3100	66 Dy 660 3200	67 Ho 670 3300	68 Er 680 3400	69 Tm 690 3400	70 Yb 700 3500	71 Lu 710 3600
89 Ac 1300 5100	90 Th 1400 5100	91 Pa 1400 5200	92 U 1500 5300	93 Np 1500 5400	94 Pu 1600 5500	95 Am 1600 5600	96 Cm 1700 5700	97 Bk 1700 5800	98 Cf 1800 5900	99 Es 1800 5900	100 Fm 1900 6000	101 Md 2000 6100	102 No 2000 6200	103 Lr 2100 6300

FIG. 2: The Periodic Table for strange quark matter, showing the predicted mass range. Noble gases are shown in yellow, "volatiles" are in green. The remainder are considered "metallic" in terms of their atmospheric behavior. The strangelet masses are calculated both for the CFL charge-mass relation $Z = 0.3A^{2/3}$ and the MIT bag model relation $0.1A \leq Z \leq 8A^{1/3}$

From: B. Monreal (nucl-ex/0506012)

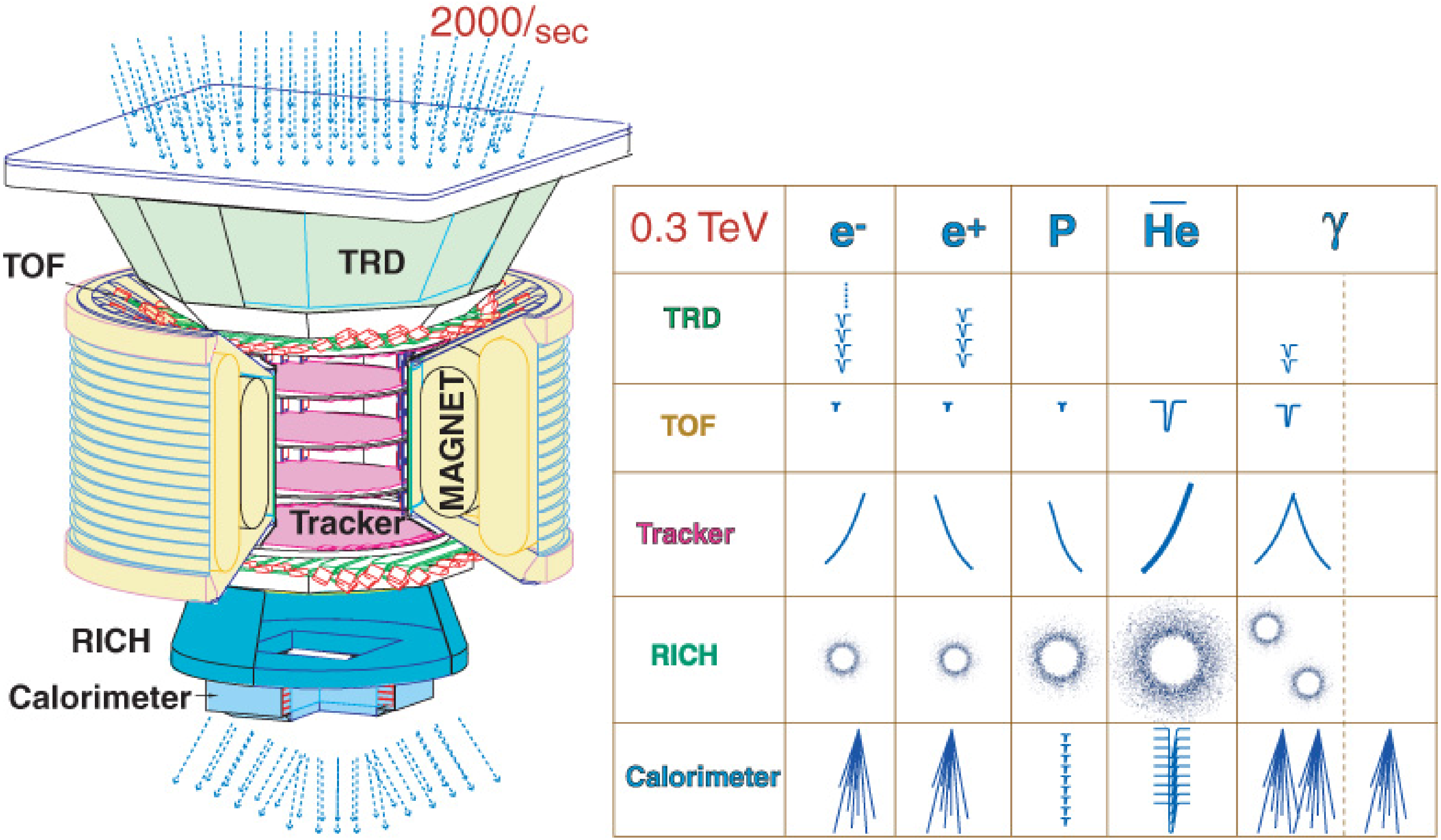
Detecting strangelets at 1-1000 GV

Find low Z/A cosmic rays with high precision equipment in space

=>

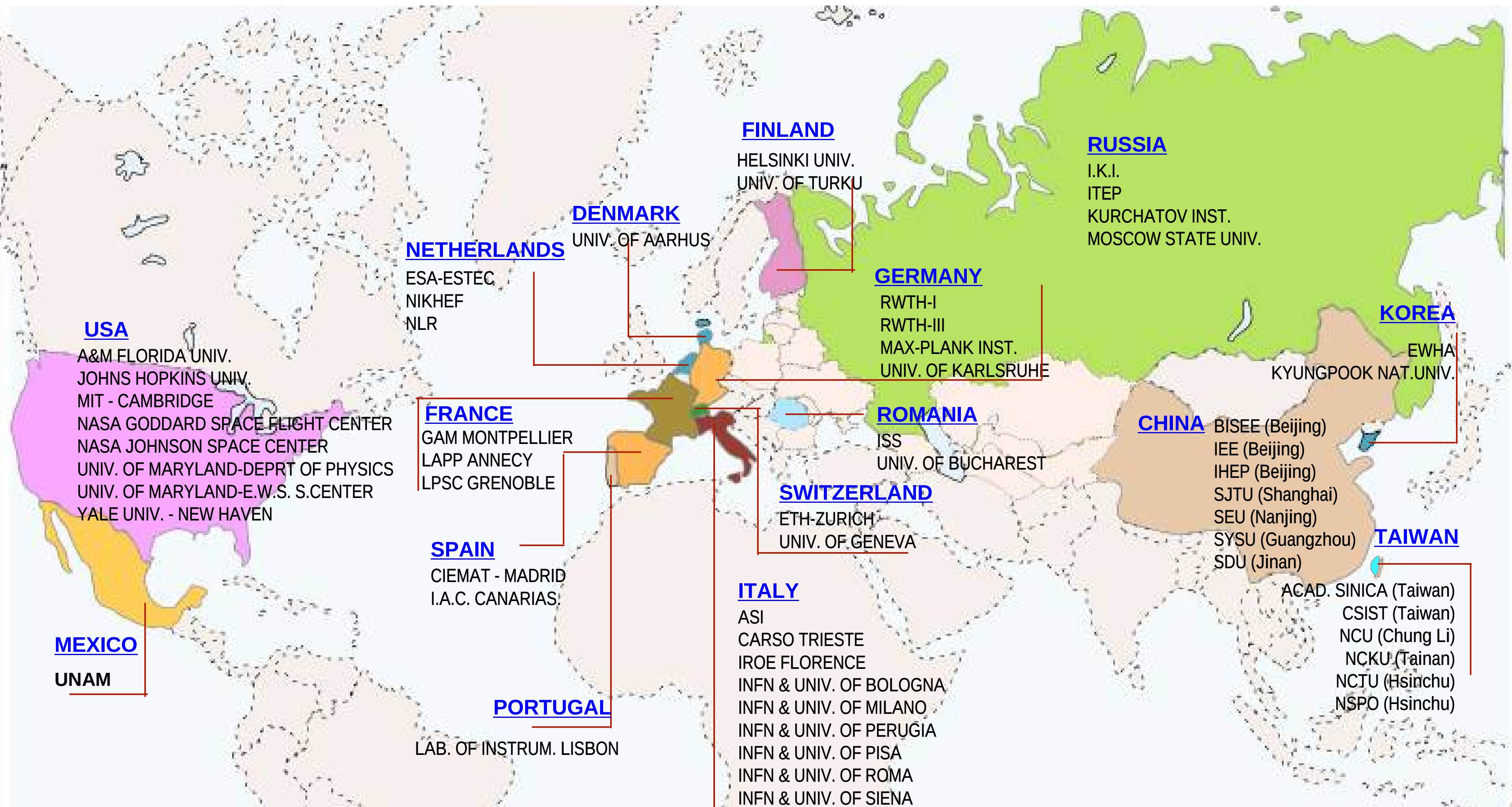
AMS-02

AMS: A TeV Magnetic Spectrometer in Space



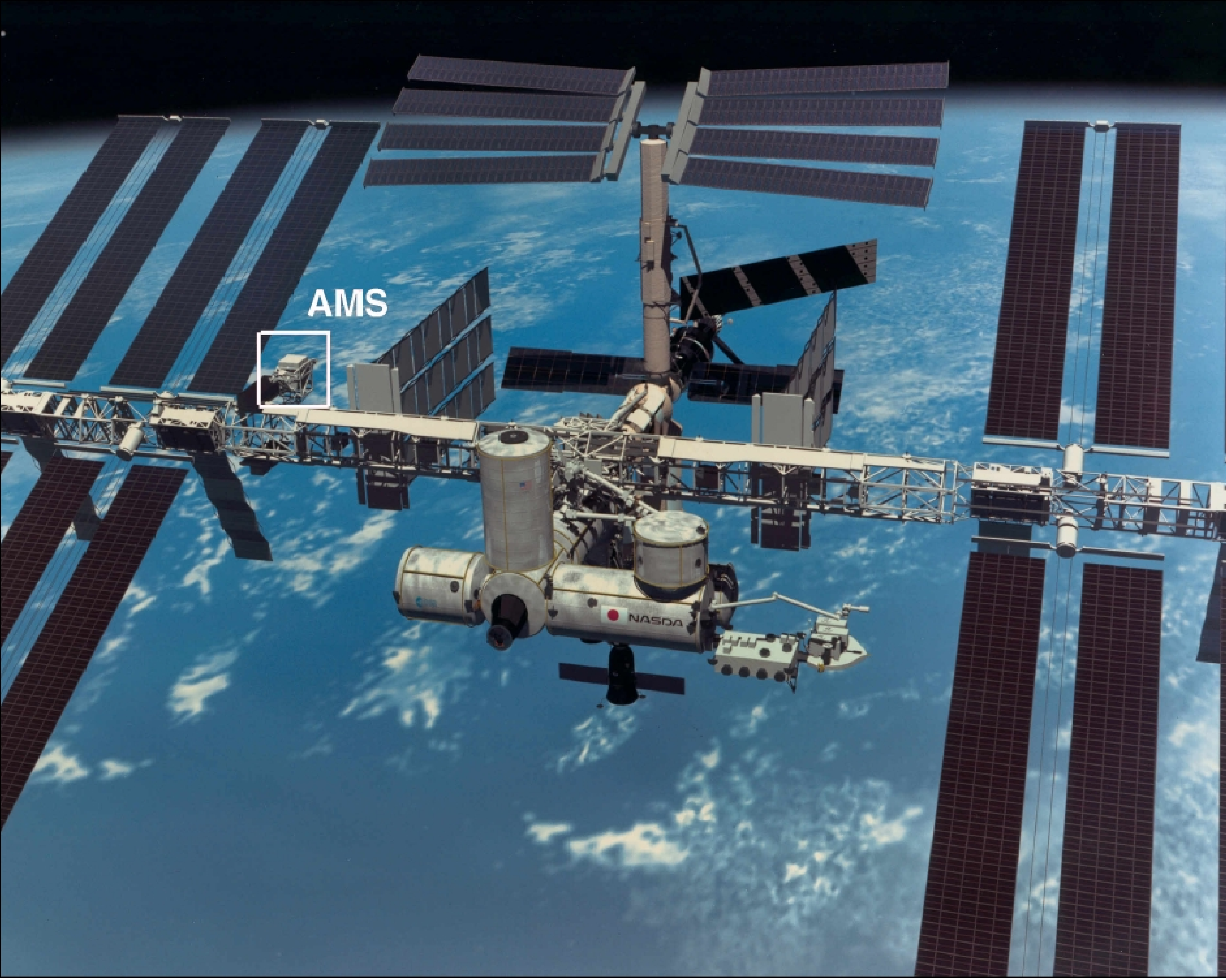
y2K025 _5 Gamma

AMS-02 Collaboration



16 Countries, 56 Institutes, 500 Physicists

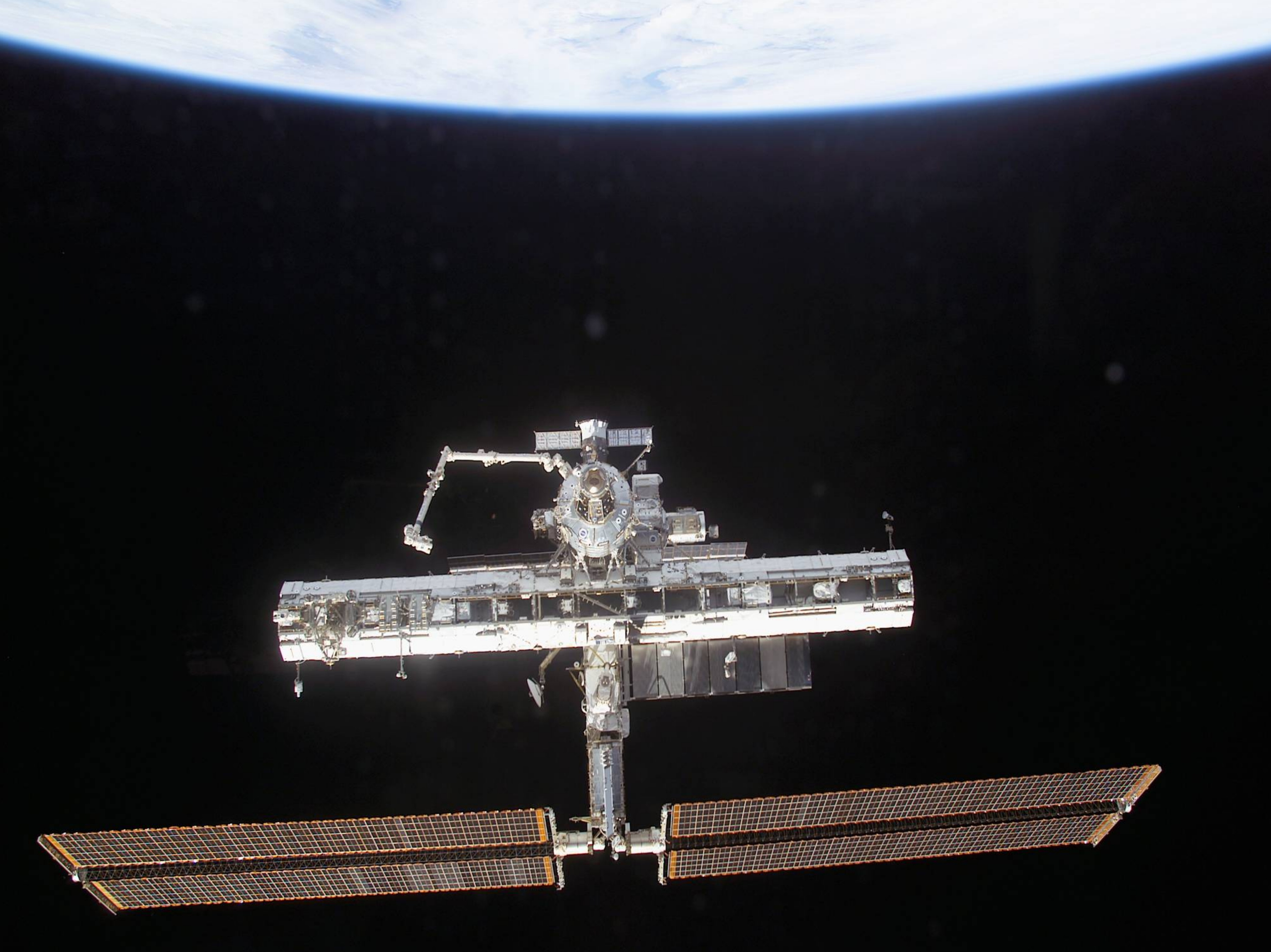
~ 95% of AMS is constructed in Europe and Asia



National Aeronautics and Space Administration

S98-11010

Lyndon B. Johnson Space Center
Houston Texas 77058

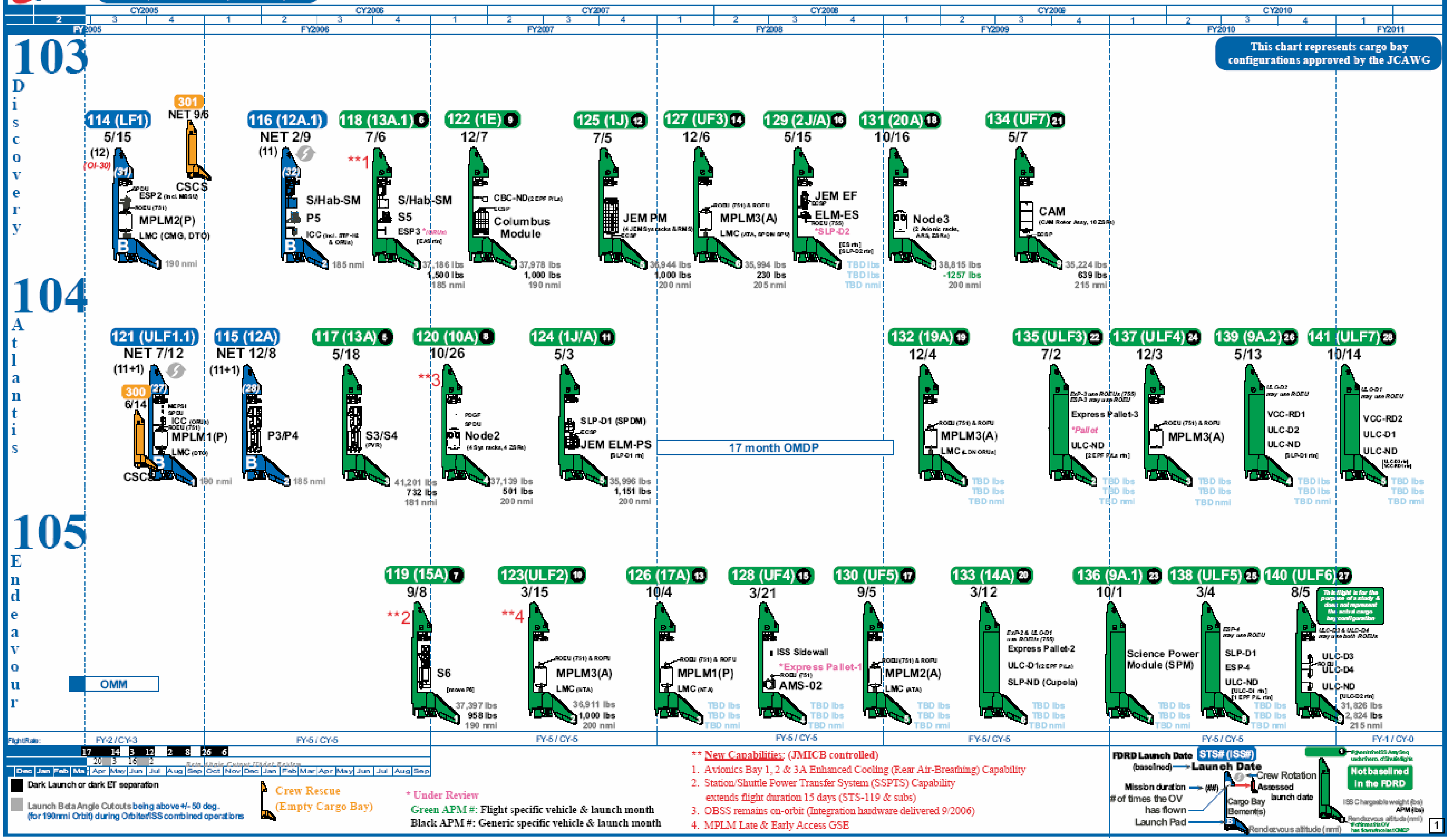


Space Shuttle Program

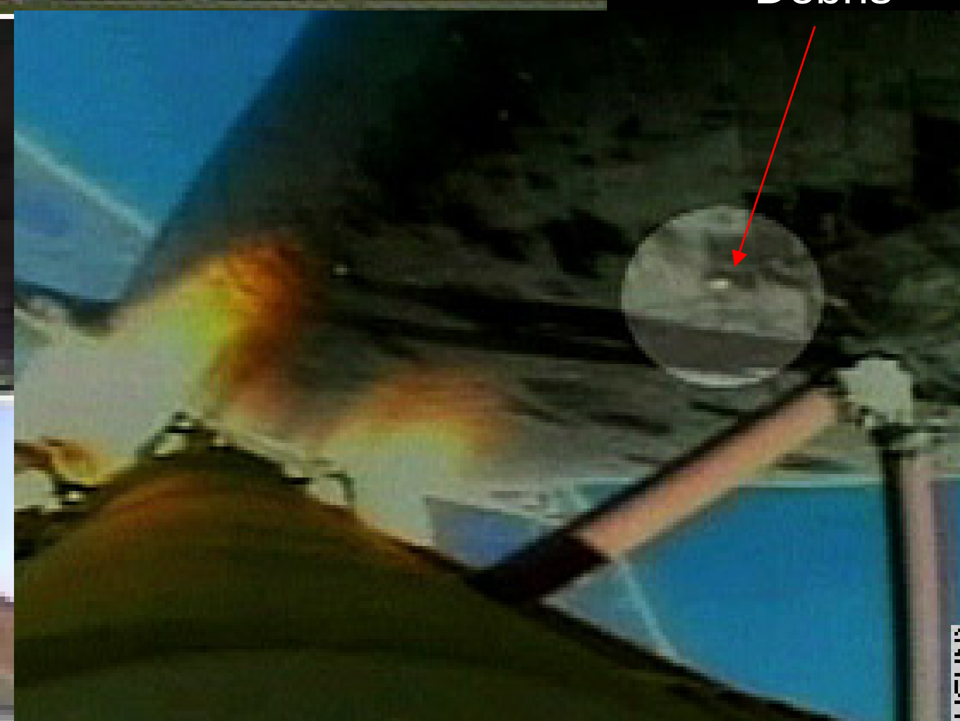
This manifest is based on Preliminary Manifest Option 05A-13B & ISS Assembly Sequence Rev. G (CR 8937A)

Flight Assignment Working Group (FAWG) Planning Manifest

USH-700C/Manifest & Schedules
Prepared by: Barton K. Gibson
Chart updated: 24-March-05

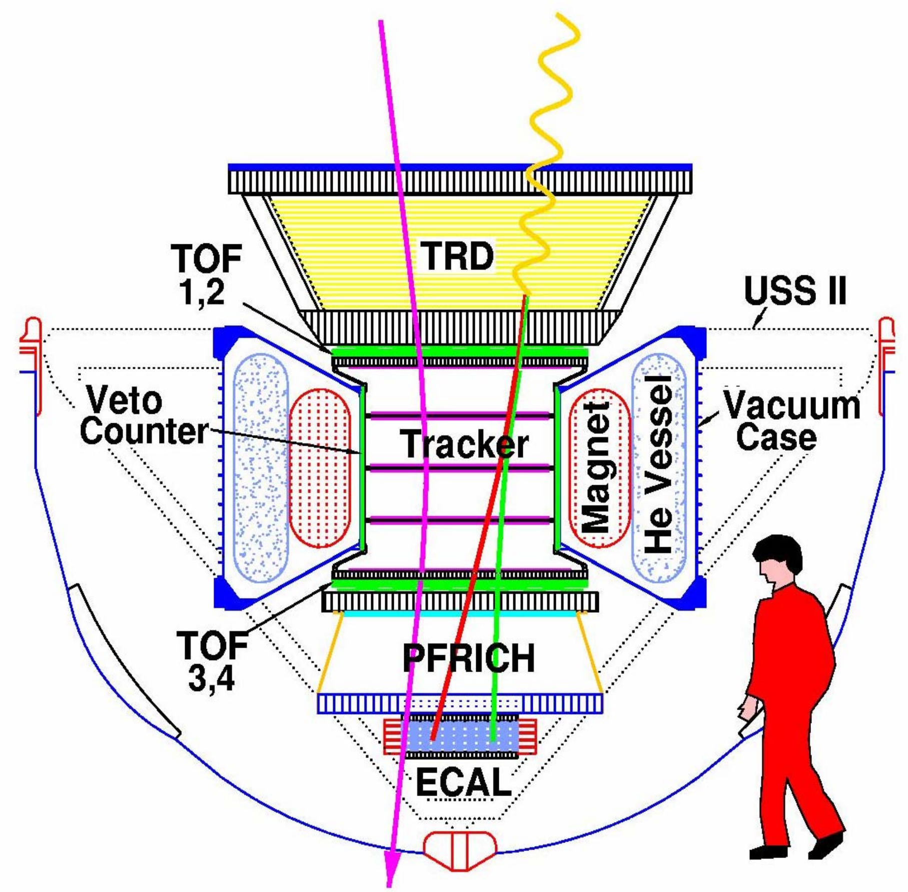



Debris


Debris

Alpha Magnetic Spectrometer

AMS-02

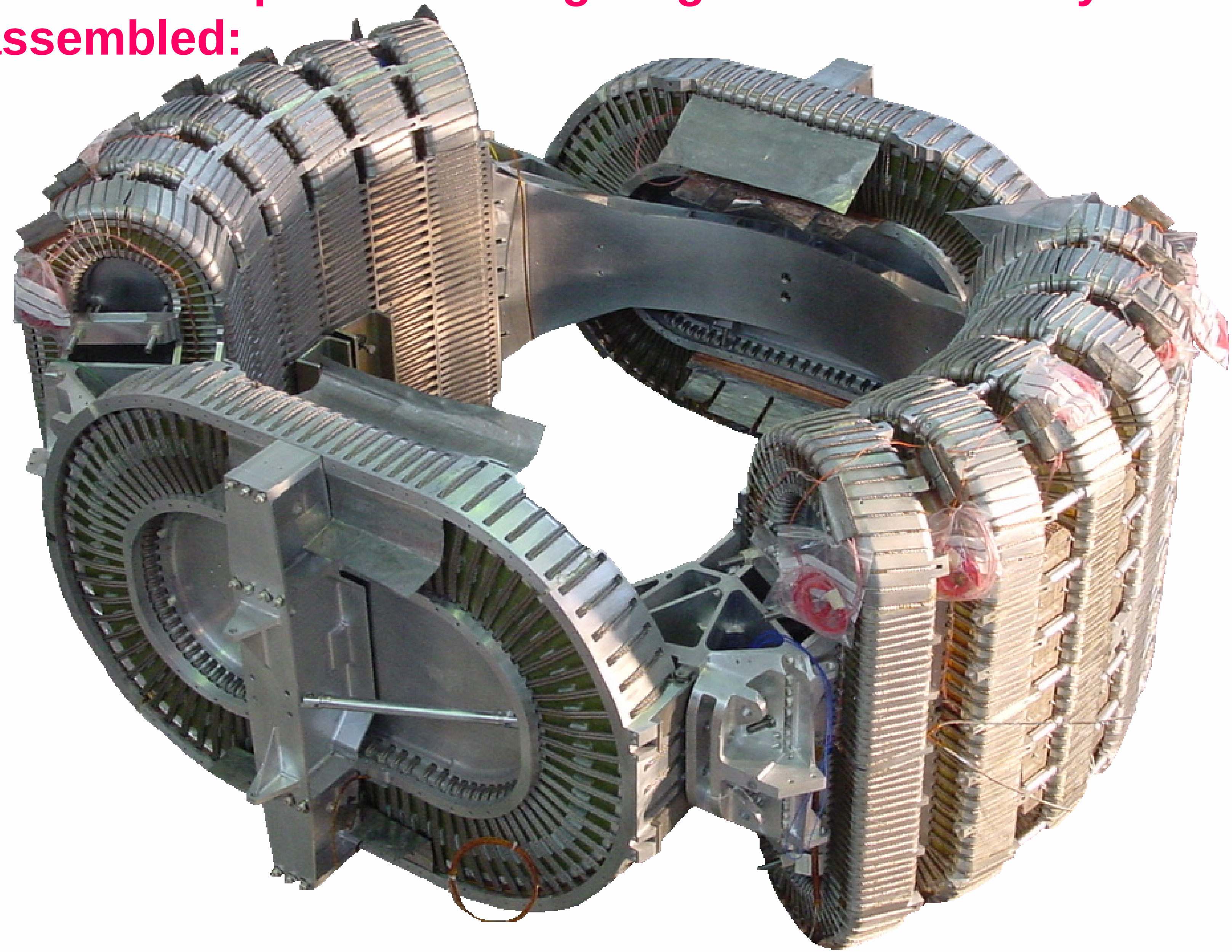


International Space Station
2008 - 2011 (or longer)

PURPOSE

- Cosmic rays
- Antimatter (anti-He)
- Dark matter
- Strangelets
- Superconducting magnet technology

The AMS superconducting magnet coils are fully assembled:

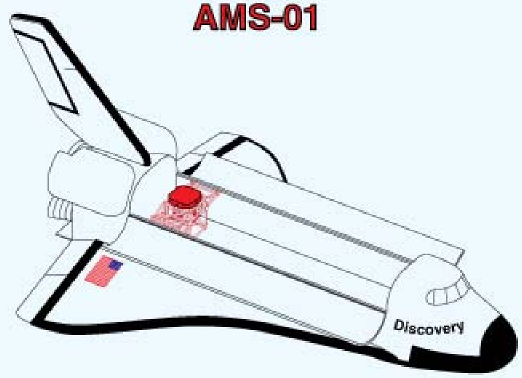


Volume 35 cu. ft., Field 8,600 Gauss, Weight 2 tons

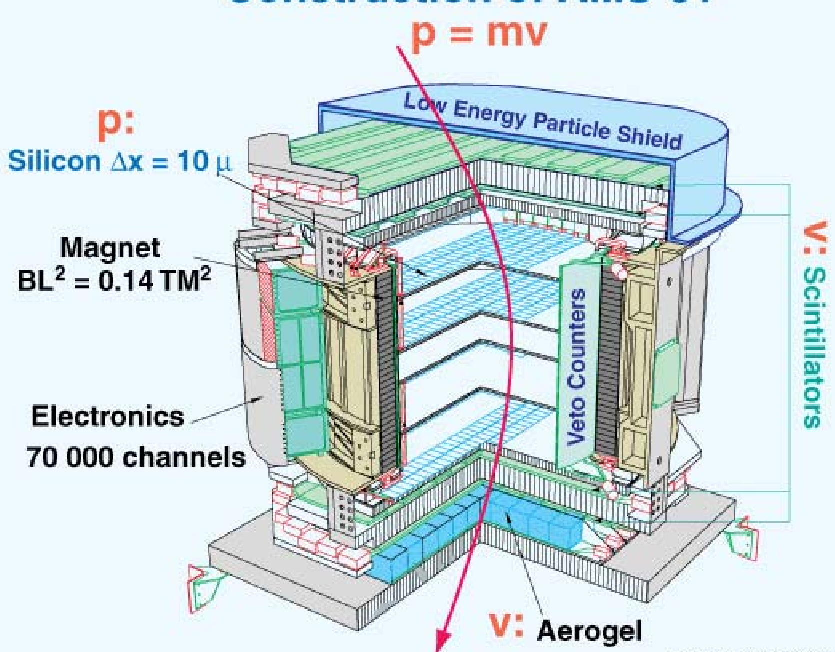
Alpha Magnetic Spectrometer

First flight, STS-91, 2 June 1998 (10 days)

AMS-01



Construction of AMS-01

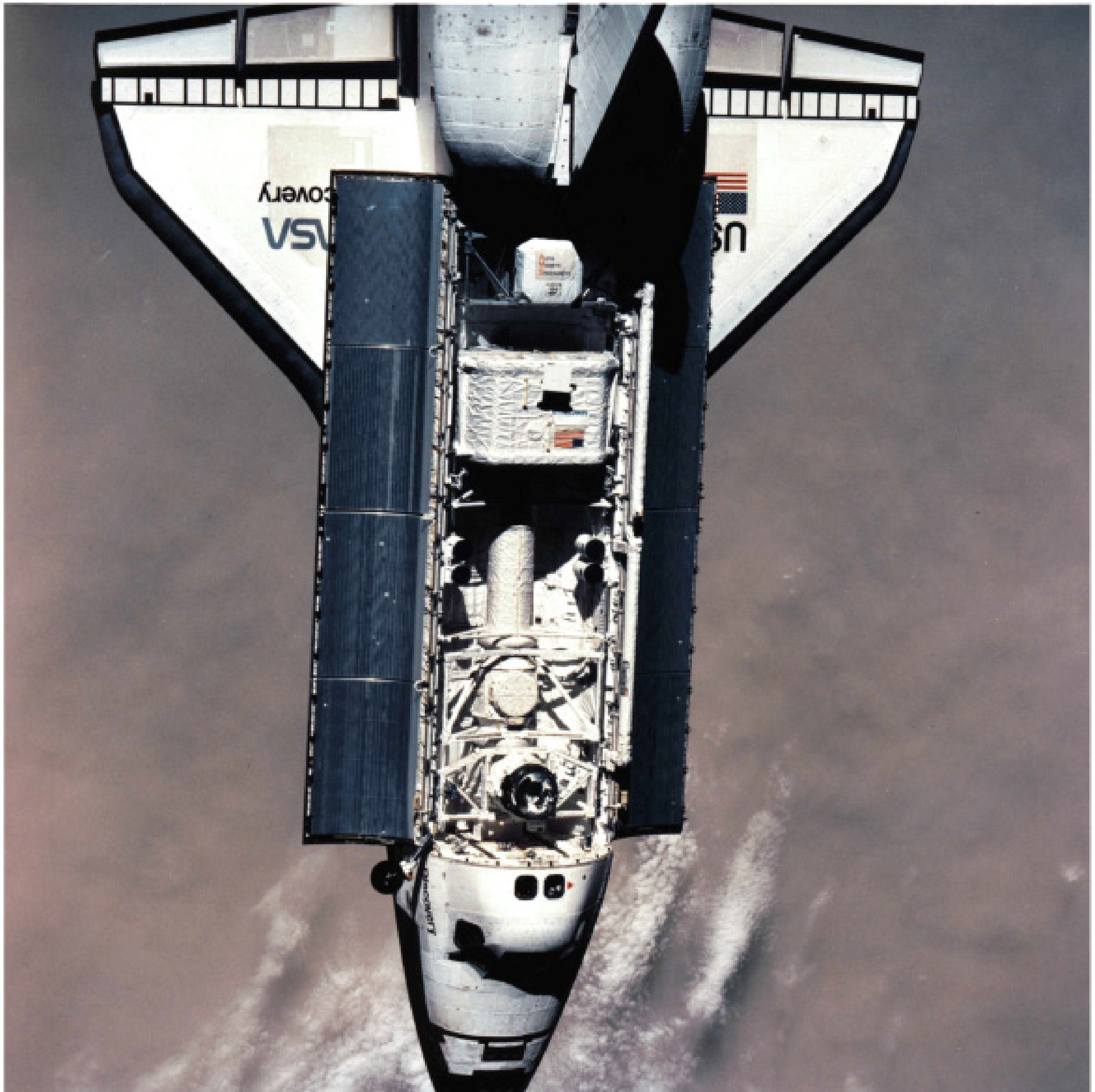


y99163_1AmsSts91Detect

National Aeronautics and
Space Administration

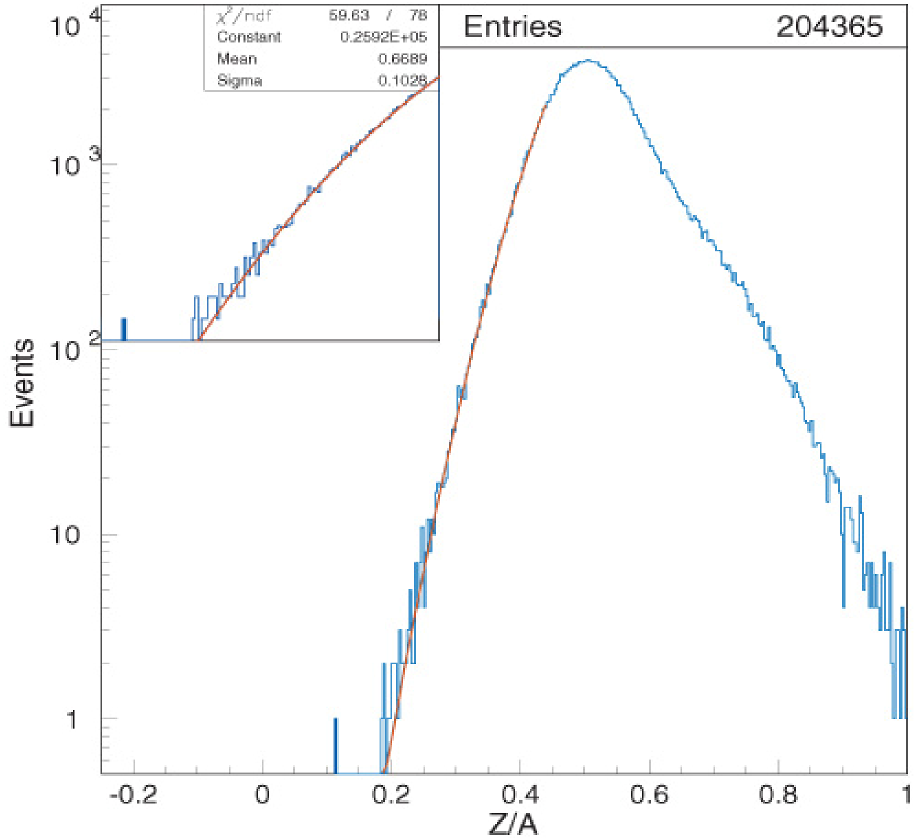
NASA7-726-068

Lyndon B. Johnson Space Center
Houston, Texas 77058



y98235

AMS-01 Anomalous Cosmic Rays



Choutko (MIT)

One Candidate with Z=2, Z/A=0.114
Color Locked Strangelet (Z=2, Z/A=0.116)
(see J. Madsen PRL 87, 172003 (2001) Found
or
$^{2}O^{16}$

y02K244aChoutko

Strangelets from strange star binary collisions

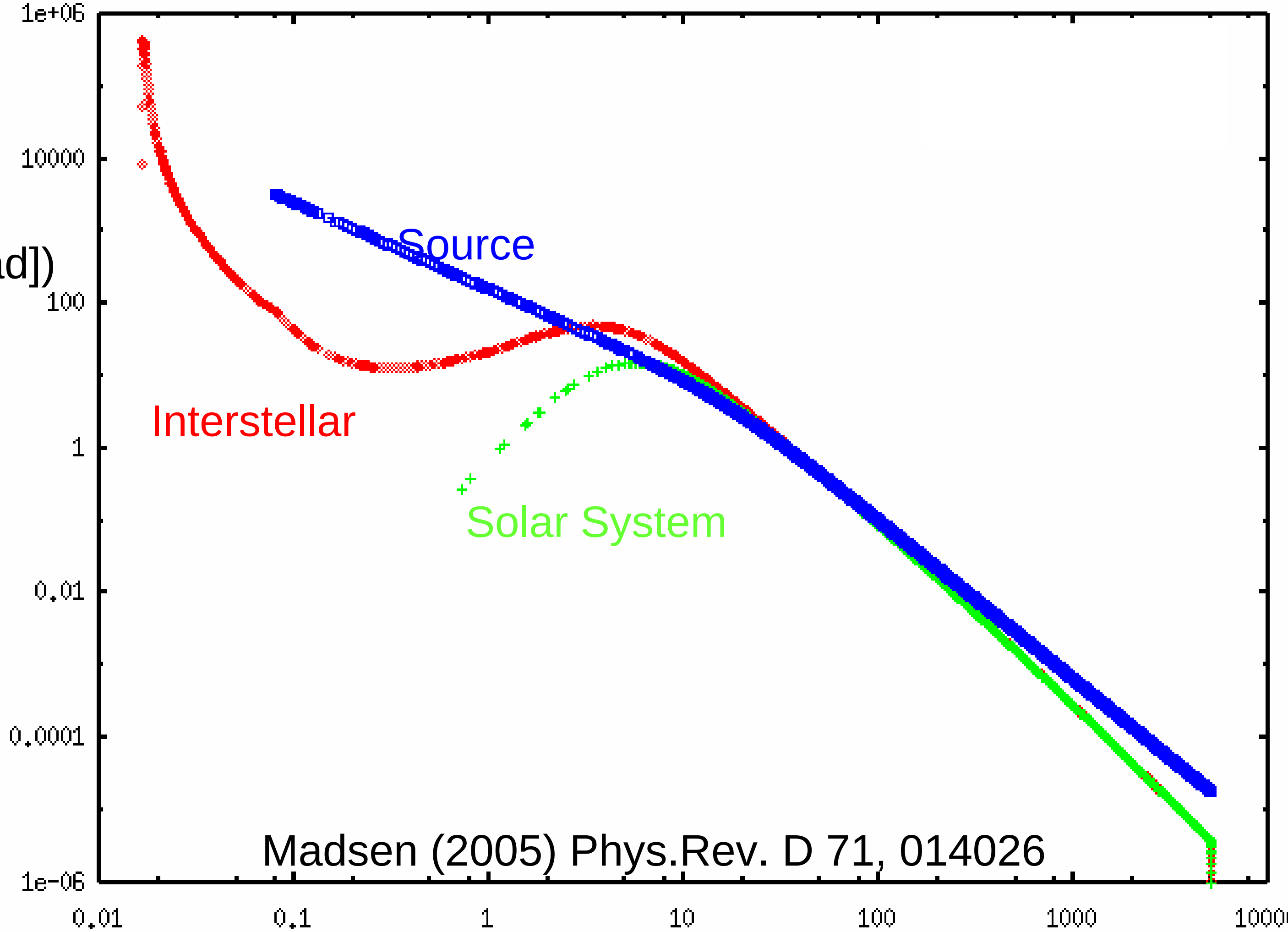
- 1 binary ”neutron star” collision per 10,000 years in our Galaxy
- Release of 10^{-6} solar masses per collision
- Basic assumptions:
  - SQM absolutely stable!
  - All mass released as strangelets with mass A (fluxes for mass A give lower limit of flux if mass spectrum of masses below A)

Strangelet propagation

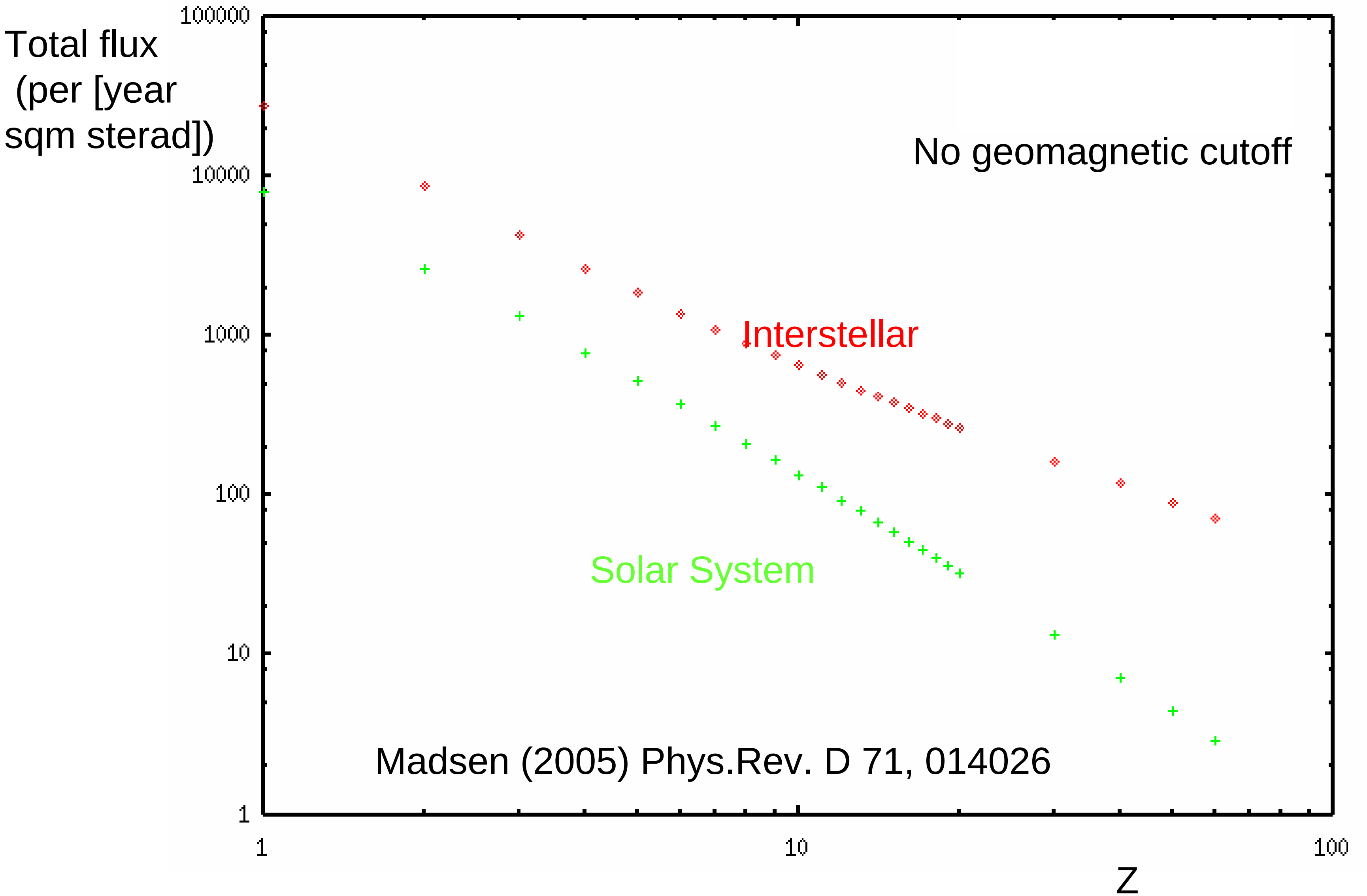
- Acceleration in supernova shocks etc
  - Source-flux powerlaw in rigidity
- Diffusion in galactic magnetic field
- Energy loss from ionization of interstellar medium and pion production
- Spallation from collision with nuclei
- Escape from galaxy
- Reacceleration from passing shocks

Cosmic strangelet flux

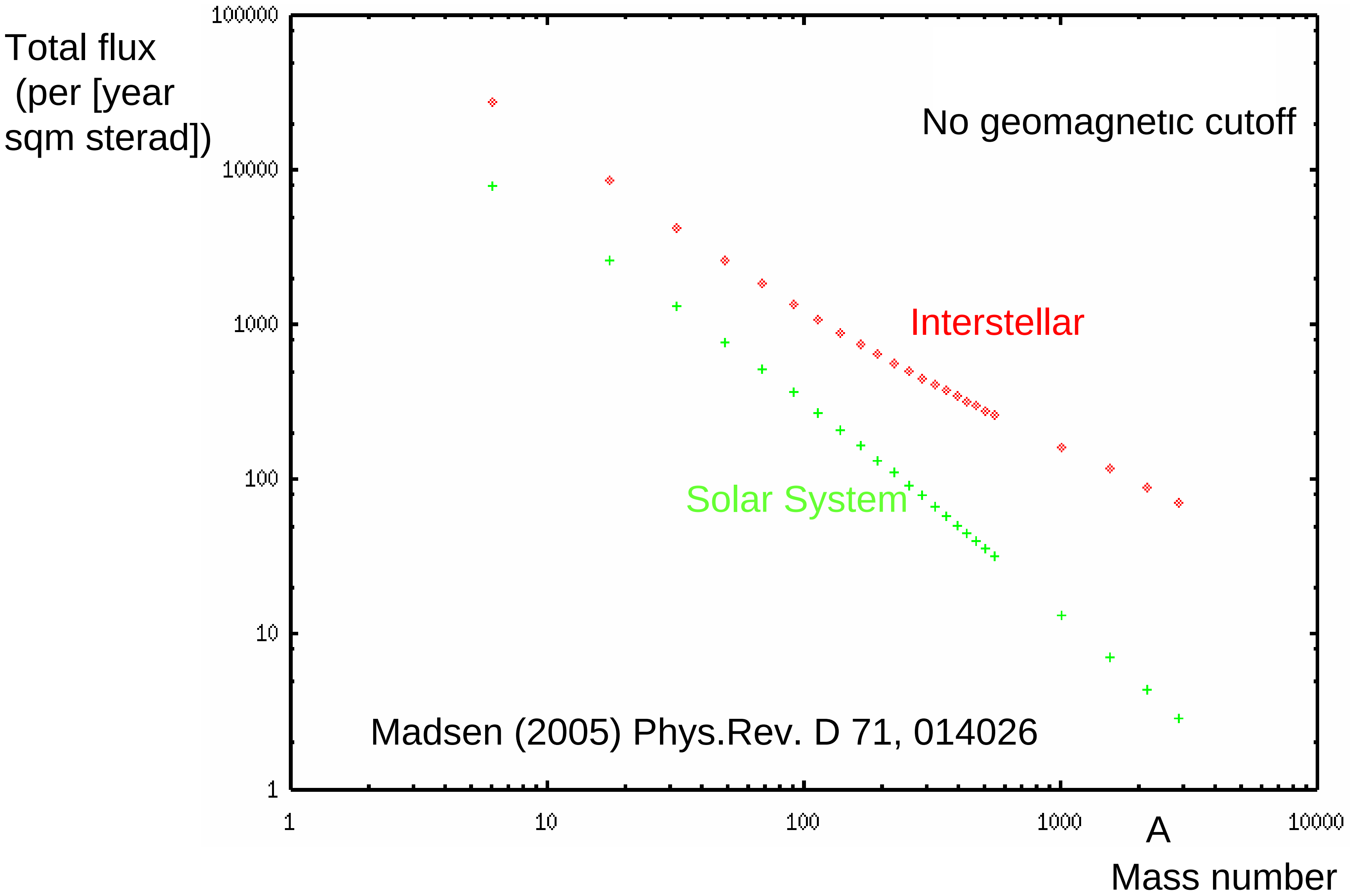
Z=8. A=138 [CFL]



Total CFL-strangelet flux



Total CFL-strangelet flux



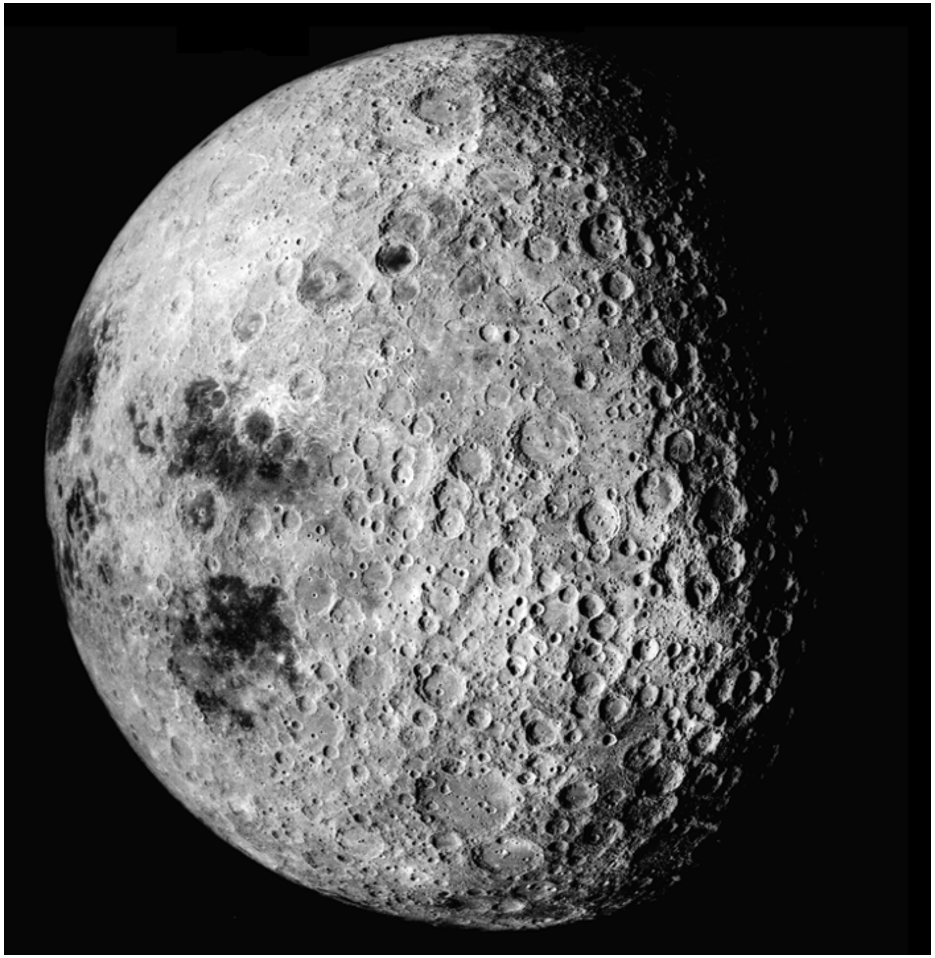
Detecting strangelets at 100 MeV

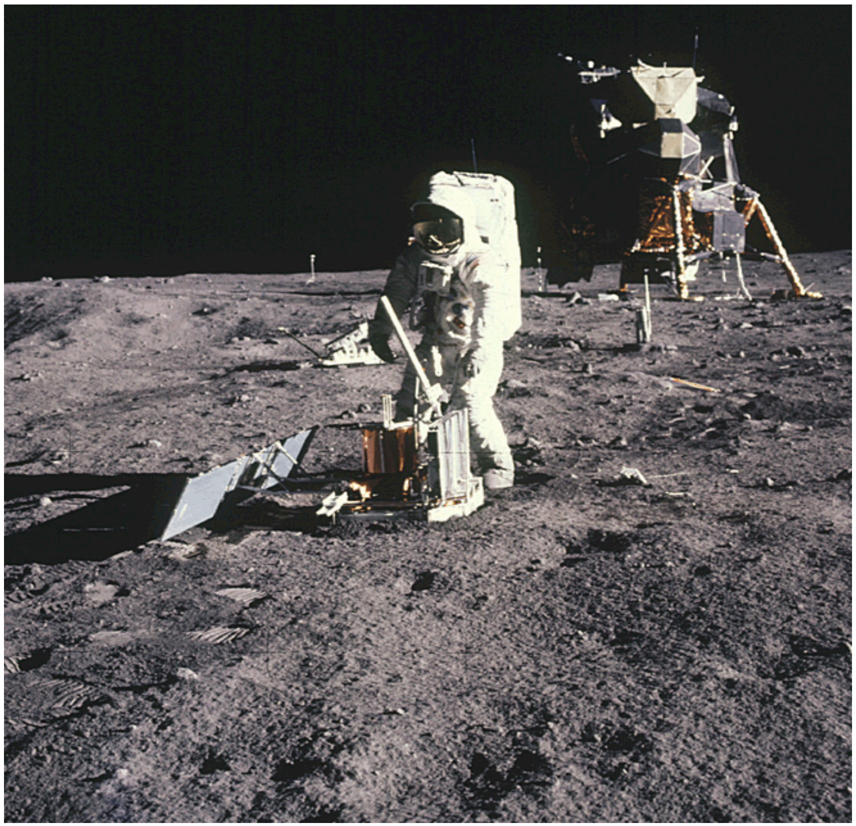
Find low Z/A ”nuclei” in lunar dust with high precision accelerator mass spectrometer

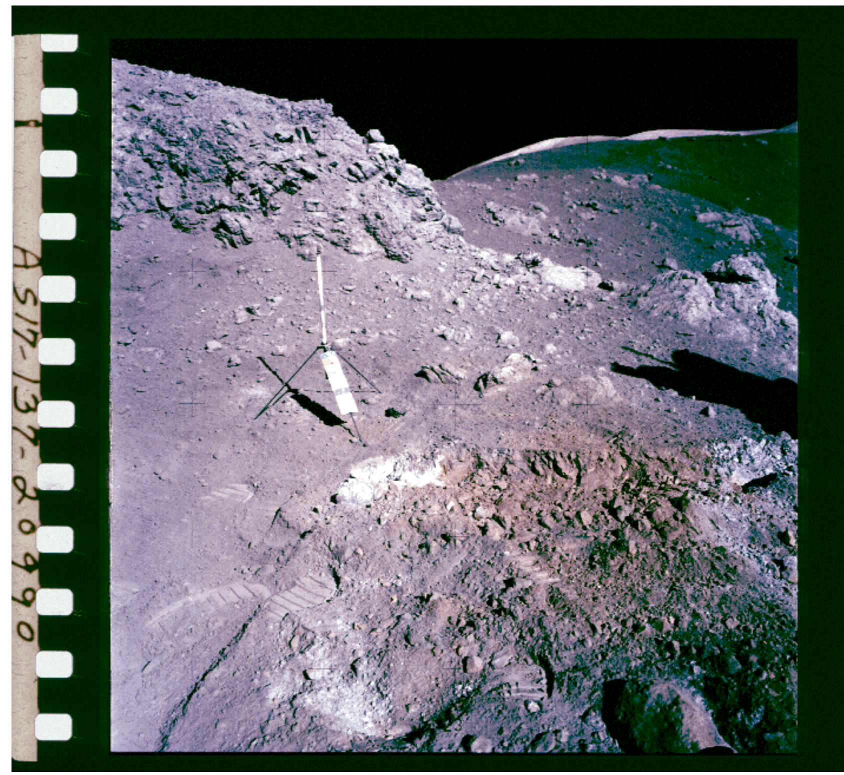
=>

Lunar Soil Strangelet Search

The Moon as a strangelet detector



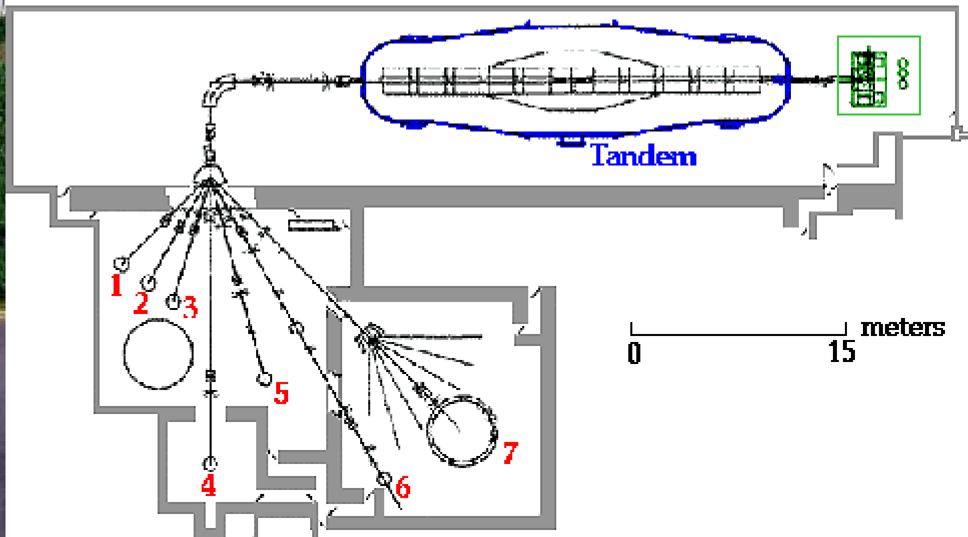



AS17-137-20990

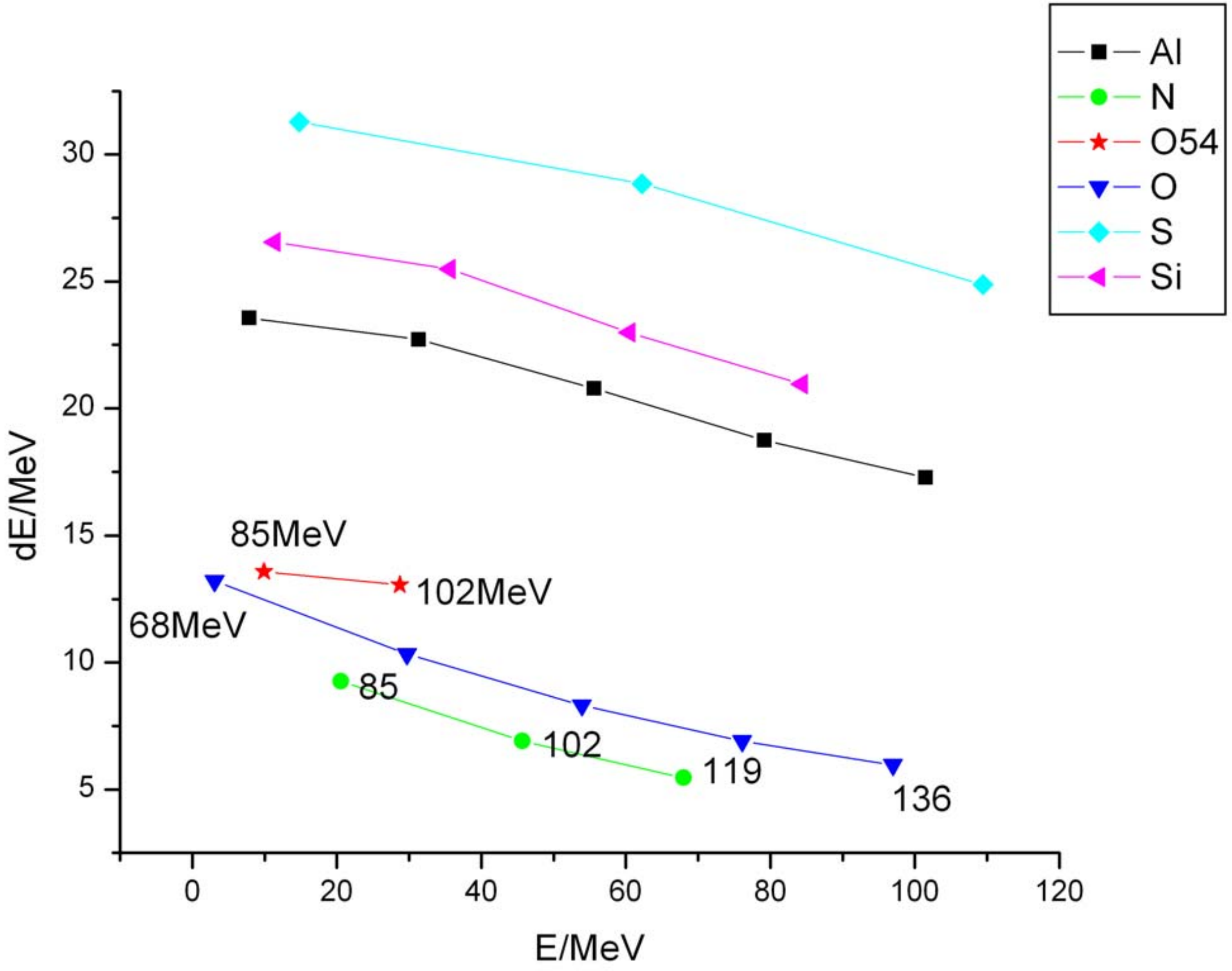
Wright Nuclear Structure Lab
Yale

LSSS-collaboration:

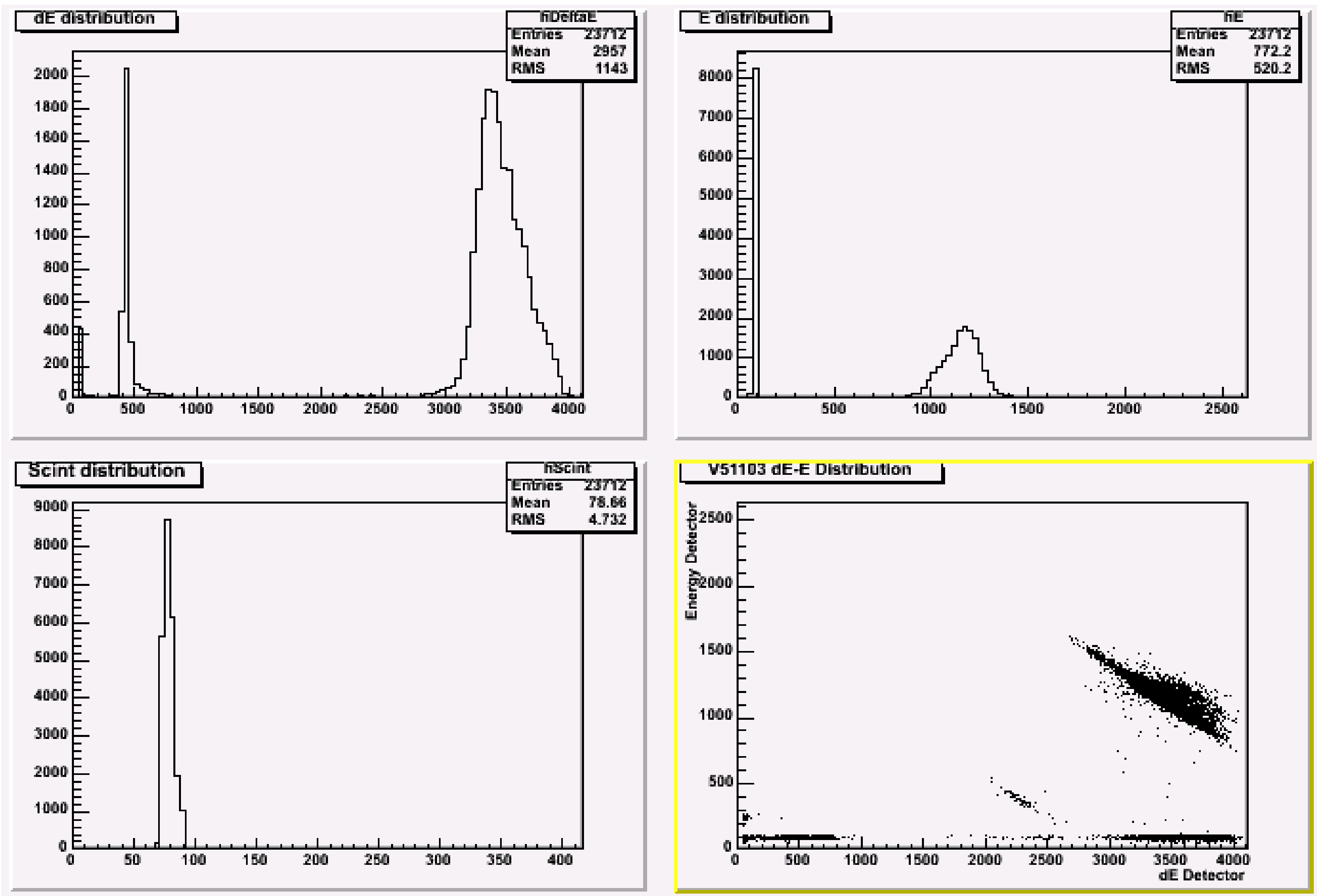
Sandweiss, Majka, Finch, Ashenfelter,
Beausang, Casten, Chikanian, Han,
Heinz, Parker, Emmet, Baris (Yale)
Fisher, Monreal (MIT)
Madsen (Århus)

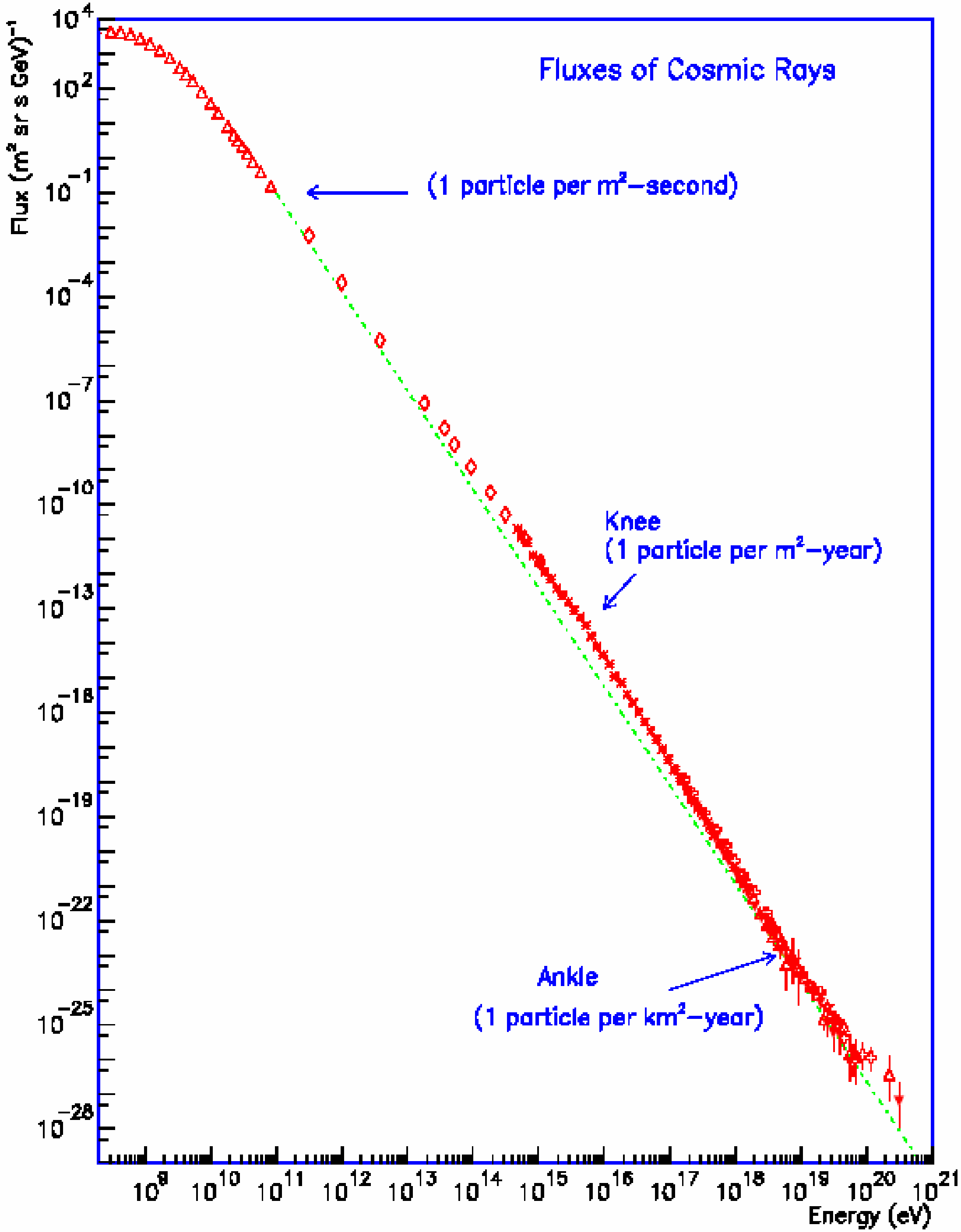


Background Ions in E-dE



First run March 2005





Cronin, Gaisser & Swordy (1997)

Strangelets could also explain Ultra-High Energy Cosmic Rays

Madsen & Larsen, PRL 90 (2003) 121102

1. Avoids the acceleration problem of ordinary UHECR candidates (HIGH Z)
2. Avoids the GZK cut-off from interaction with 2.7K cosmic microwave background (HIGH A)

Eliminating the GZK-cutoff

a) Photo-pion production cut-off at $\gamma_\pi \approx m_\pi / E_{2.7K}$

$$E_{\text{photo-pion}} \approx \gamma_\pi A m_p \approx 10^{20}\,\text{eV}A$$

b) Photo-disintegration at $\gamma_{\text{dis}} \approx 10\text{MeV} / E_{2.7K}$

$$E_{\text{photo-dis}} \approx \gamma_{\text{dis}} A m_p \approx 10^{19}\,\text{eV}A$$

c) Photo-pair-production above $\gamma_{\text{pair}} \approx 2m_e / E_{2.7K}$

$$E_{\text{photo-pair}} \approx \gamma_{\text{pair}} A m_p \approx 10^{18}\,\text{eV}A$$

$$-dE/dt \propto Z^2 A^{-1} \text{ small for low } Z/A$$

Conclusions

- Strangelets have low Z/A
- CFL and non-CFL strangelets differ wrt. Z
- Experimental verification/falsification of
  - Strangelet existence
    - Realistic from AMS-02 [2008-?]
    - Possible from lunar soil search [2005]
  - (A,Z)-relation (CFL or ordinary)
    - Optimistic, but not impossible from AMS-02 or lunar soil search
- Possible explanation of UHECR's