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H4.SMR/1574-31

"VII School on Non-Accelerator Astroparticle Physics"

26 July - 6 August 2004

Magnetic Monopole Searches

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Magnetic Monopole Searches

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7th School, ICTP, Trieste, 26/7– 6/8, 04

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3. Searches for classical MMs
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5. Searches for GUT MMs
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7. Intermediate mass MMs
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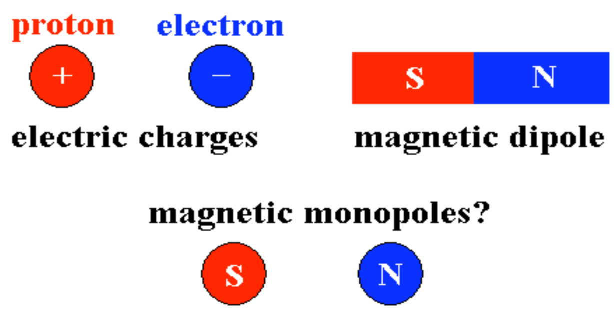
1. Introduction

An idea of long time ago…



Symmetry of Maxwell Equations

$$\nabla \cdot \vec{E} = 4\pi\rho_e \qquad \nabla \times \vec{B} = \frac{4\pi}{c}\vec{J}_e + \frac{1}{c}\frac{\partial \vec{E}}{\partial t}$$

$$\nabla \cdot \vec{B} = 4\pi\rho_m \qquad \nabla \times \vec{E} = \frac{4\pi}{c}\vec{J}_m - \frac{1}{c}\frac{\partial \vec{B}}{\partial t}$$

(cgs units)

1931 Dirac: Quantization of electric charge Proc. R. Soc. London, 133 (1931) 60

$$eg = n\frac{\hbar c}{2}, \quad n = 1, 2, 3, \ldots$$ Dirac relation

$$g_D = \frac{\hbar c}{2e} = \frac{137}{2}e \quad , \quad g = n\,g_D$$

1974 GUT of Strong and Electroweak interactions

2. Classical ("Dirac") MMs

- Mass : No prediction. Estimate:

  if $R_M = R_e$ $m_M \sim g_D^2\, m_e/e^2 \sim 4700\, m_e \sim 2.4$ GeV

- Magnetic Charge

  If n = 1 and e = electron charge

  $g_D = \_c\ /2e = e/2\alpha = 68.5\ e = 3.3\text{x}\ 10^{-8}$ esu

  If $|e|=1/3 \rightarrow 3\ g_D$

- Electric charge = 0 MM , ≠ 0 Dyon

  Systems M-p, M-Al^{27} (Monopole-Dipole Interaction)

- Coupling constant

  $\alpha_M = g^2{}_D/\_c = 34.25$

- Energy gain in a magnetic field

  $W = n\ g_D\ B\ L = n\ 20.5$ keV/G cm

  If L= 1 kpc and B = 3 μG → $W \cong 1.8\ \text{x}10^{11}$ GeV

MM Energy Losses

$\beta > 10^{-2}$ Ionization *(à la Bethe-Bloch)* $(Ze_{eq})^2 = (g\beta)^2$ (a)

for $\beta = 1$: $(dE/dx)_{MM} = 4700\ (dE/dx)_{m.i.p.}$

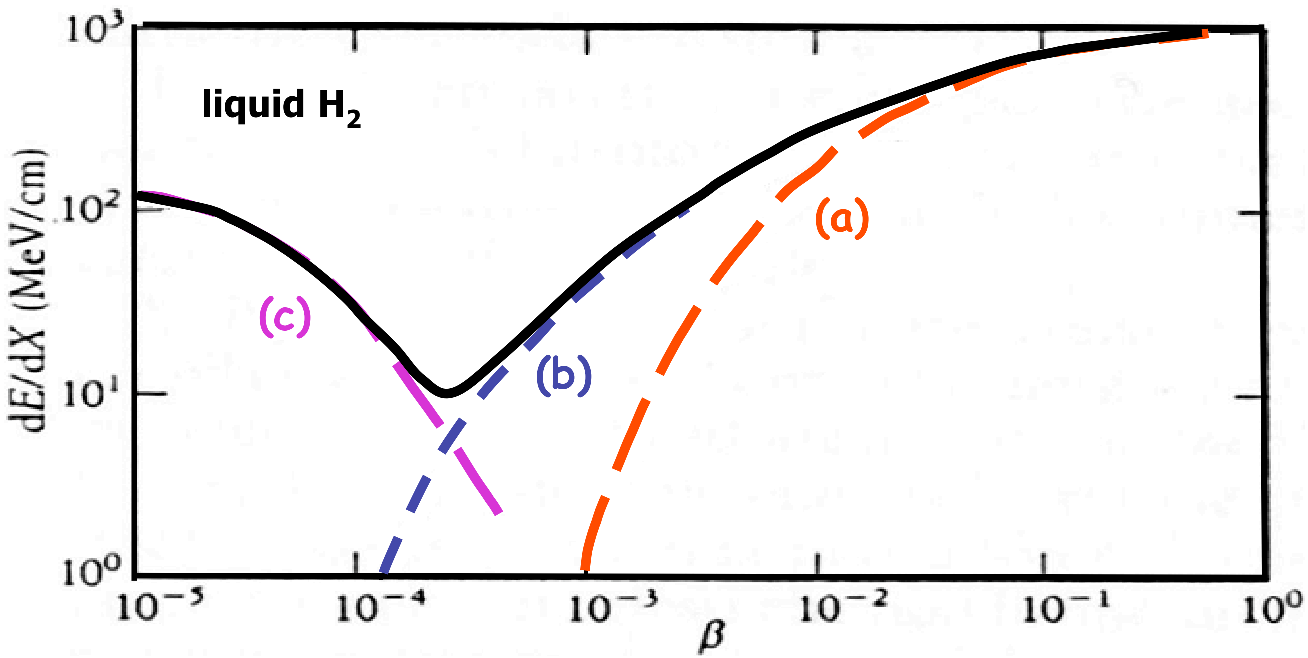
$10^{-4} < \beta < 10^{-2}$ Excitation Medium as Fermi gas (b)

$10^{-4} < \beta < 10^{-3}$ Drell effect $M + He \rightarrow M + He^*$

+ Penning effect $He^* + CH_4 \rightarrow He + CH_4 + e^-$

$\beta < 10^{-4}$ Elastic collisions (c)

(coupling of the atom magnetic moment with the MM magnetic charge)

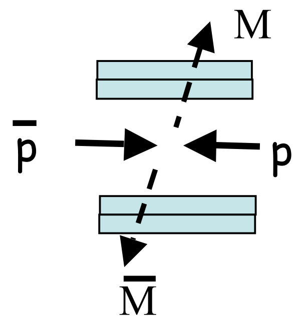


3. Searches for classical MMs at accelerators /1

$$e^+e^- \rightarrow M\overline{M}, \quad \bar{p}p \rightarrow M\overline{M}, \quad pp \rightarrow pp\,M\overline{M}$$

•Direct experiments:

poles produced - detected immediately (large dE/dx)



Searches with

scintillation counters

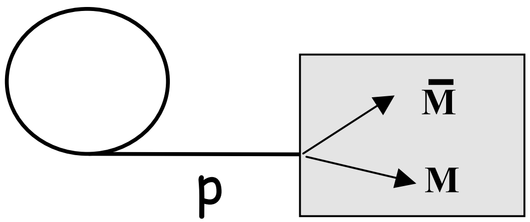
nuclear track detectors

Limits (95 % CL) $\sigma(e^+e^-) < 5\times10^{-37}\ cm^2$ $\quad m_M < 102\ GeV$

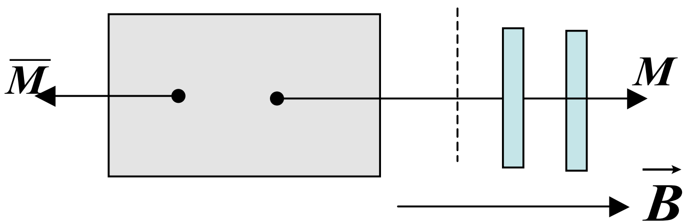
$\sigma(p\bar{p}) < 2\times10^{-34}\ cm^2$ $\quad m_M < 850\ GeV$

•Indirect expts:

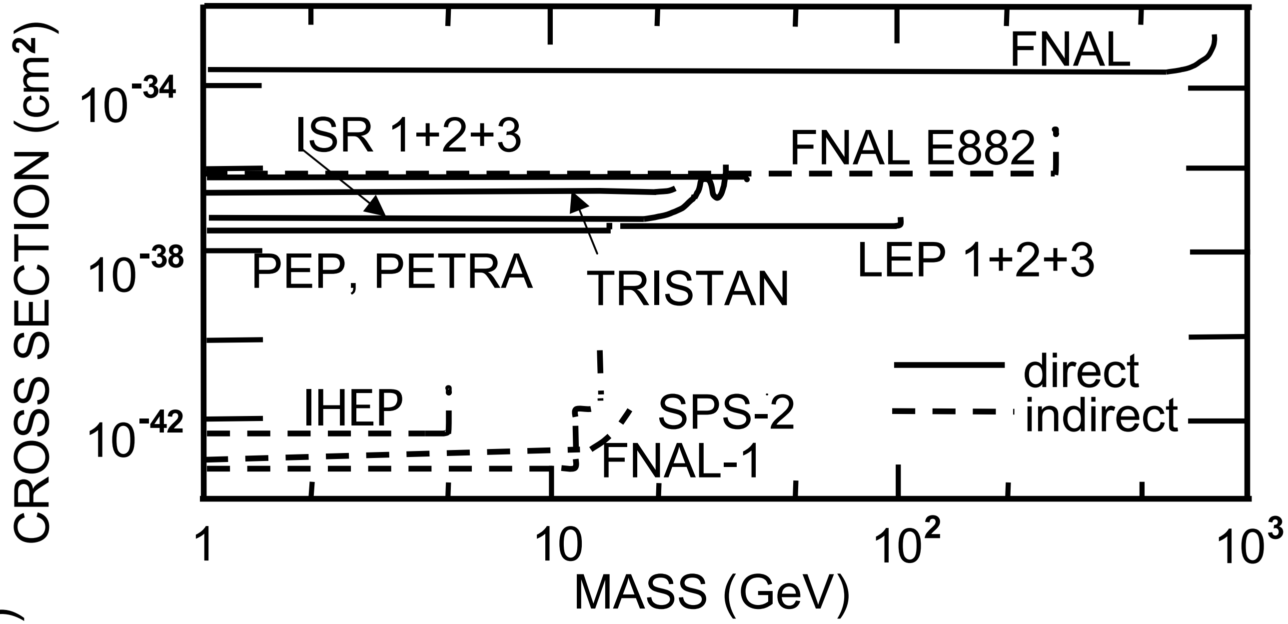
MMs { Produced / Stopped / Trapped



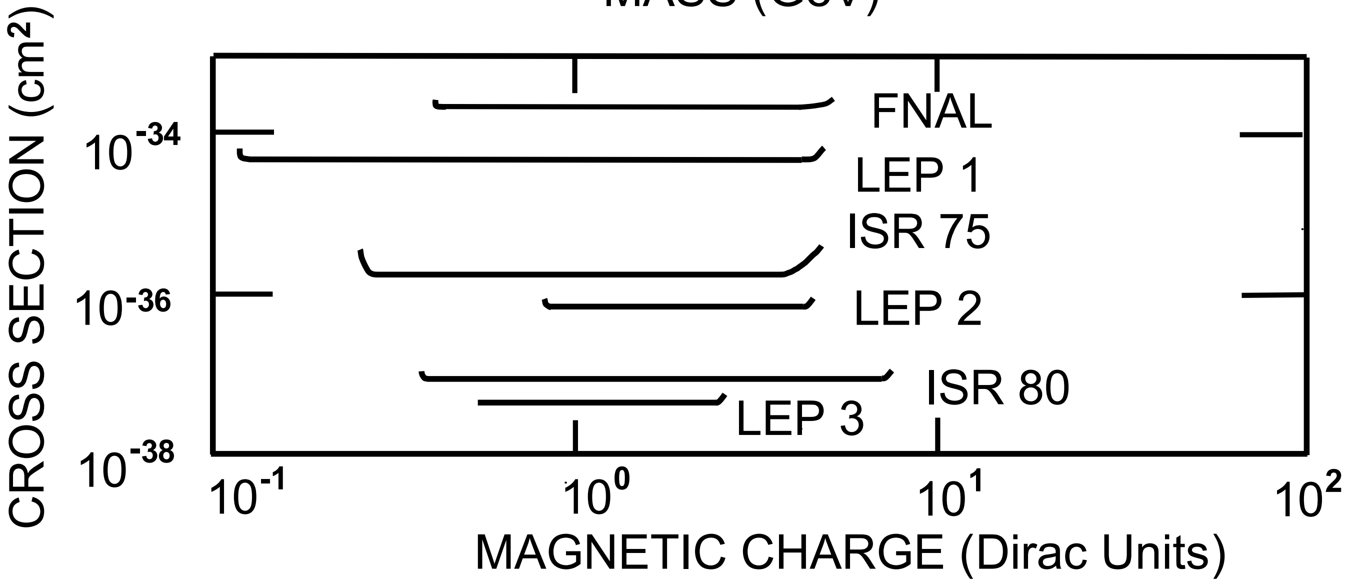
Later { Extracted / Accelerated / Detected



Limits for classical MMs at accelerators



Upper limits vs mass



Upper limits vs charge

Searches for classical MMs at accelerators /2

- Multi-γ events
  - -At ISR pp→multi-γ at $\sqrt{s}$ = 53 GeV $\sigma < 2\times10^{-37}$ cm^2
  - -At Fermilab (D0 Coll.) search for γ-pairs of high transverse energies in pp collisions M> 870 GeV for spin 1/2 Dirac MMs (95 % CL)
  - -At LEP (L3 Coll.) search for Z →$\gamma\gamma\gamma$ events M>510 GeV (95 % CL)

- Searches in bulk matter
  - -Moon rocks
  - -Meteorites
  - -Terrestrial magnetic materials

  } Superconducting loop +SQUID

- Searches in the cosmic radiation
  - -with counters
  - -with emulsions + Lexan
  - -*fossil tracks in mica*

→ the "Price event" (1975)

4. GUT Monopoles (Gauge, Cosmic,..)

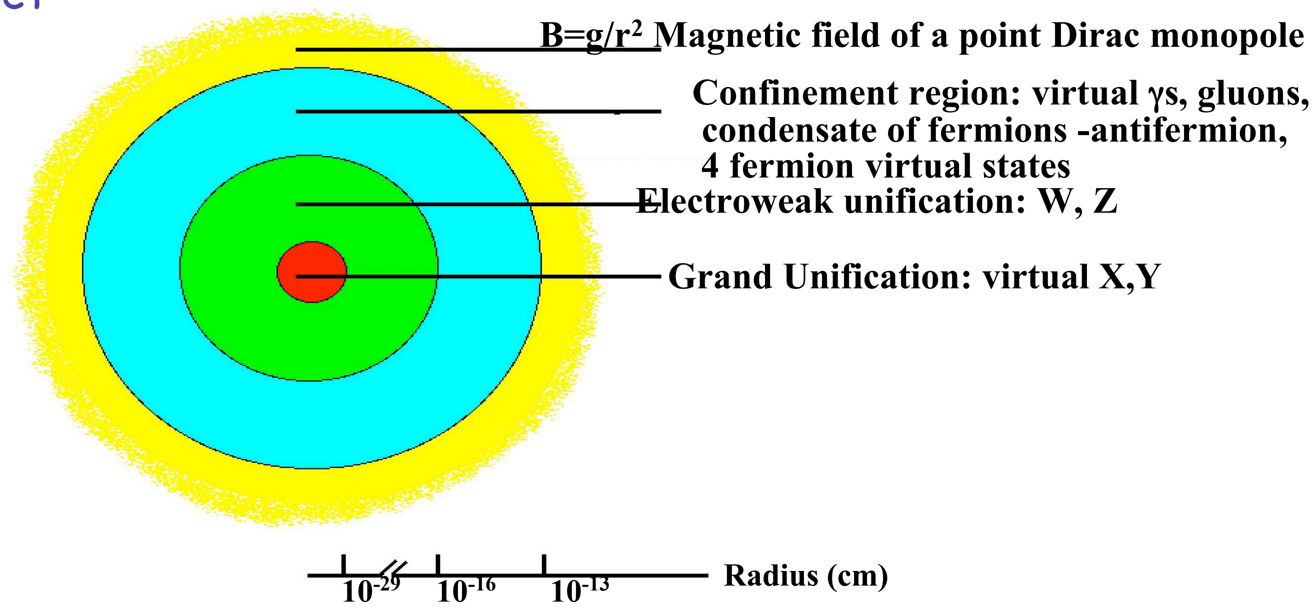
Gauge theories of unified interactions predict MMs

$$SU(5) \xrightarrow[10^{-35}\ s]{10^{15}\ GeV} SU(3)_C \times [SU(2)_L \times U(1)_Y] \xrightarrow[10^{-9}\ s]{10^{2}\ GeV} SU(3)_C \times U(1)_{EM}$$

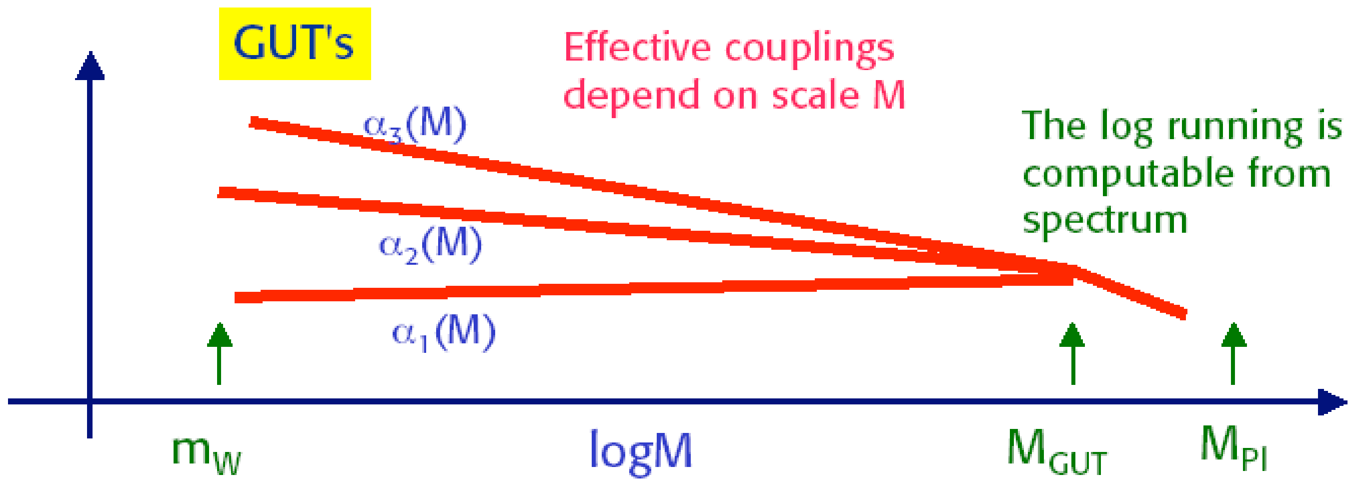
✱ Mass $m_M \geq m_X/G > 10^{16}$ GeV ~ 0.02 μg → 10^{17} GeV

(Kaluza –Klein poles → $> 10^{19}$ GeV , SUSY → > 10^{17} GeV)

✱ Size: extended object



r > few fm $B \sim g/r^2$



The large scale structure of particle physics:

- SU(3) ⊗ SU(2) ⊗ U(1) unify at M_{GUT}
- at M_{Pl}: quantum gravity

$$G_{Newton} = \frac{\hbar c}{M_{Pl}^2}$$

r ~ 10^{-33} cm

Superstring theory:
a 10-dimensional non-local, unified theory of all interact's

G. Altarelli

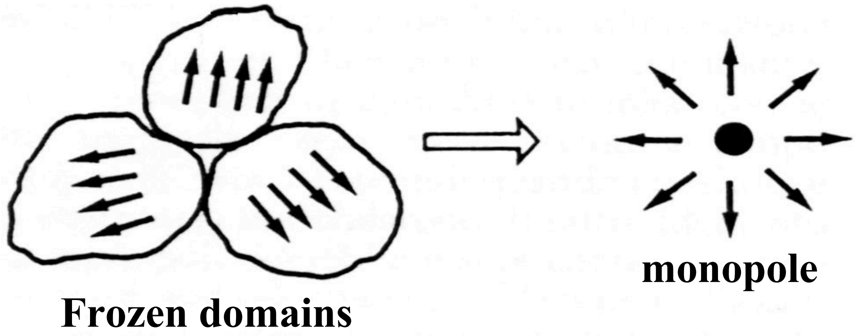
The really fundamental level

GUT MMs

✱ Magnetic charge $g = n\, g_D$ several models predict n>1 (2,3)

✱ Production: In the Early Universe at G.U.T. phase transition

- as topological defects $G \to U(1) \times \ldots$ ($t \sim 10^{-35}$ s)



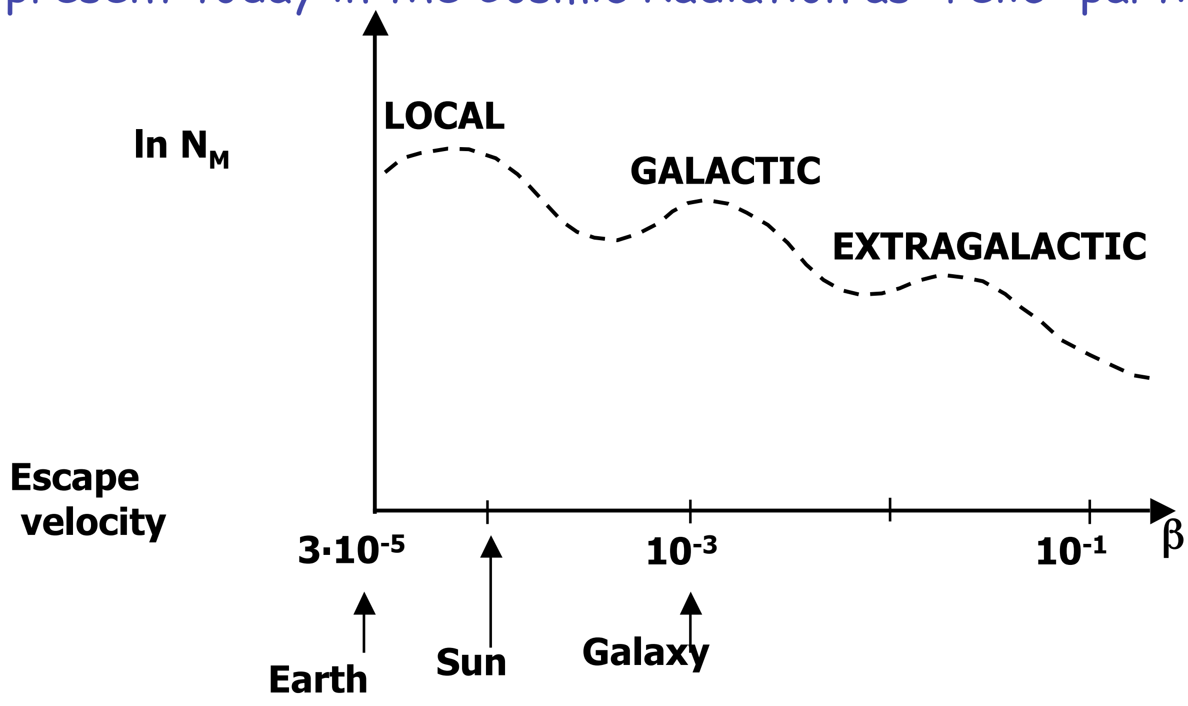
$e^+ e^- \to M \bar{M}$
$\bar{q} q \to M \bar{M}$

- in high energy collisions ($t \sim 10^{-34}$ s)

MMs follow "history" of the Universe ⇨ slowed down ⇨ formation of galaxies ⇨ magnetic fields ⇨ poles accelerated

GUT MMs

May be present today in the Cosmic Radiation as "relic" particles



Cosmological limits on MM flux

$\rho_M < \rho_c$ — Uniform → $F < 5 \times 10^{-12}\ \beta\ (cm^{-2}\ s^{-1}\ sr^{-1})$

Clumped → $\times 10^{5}$

Astrophysical limits on the GUT MM flux

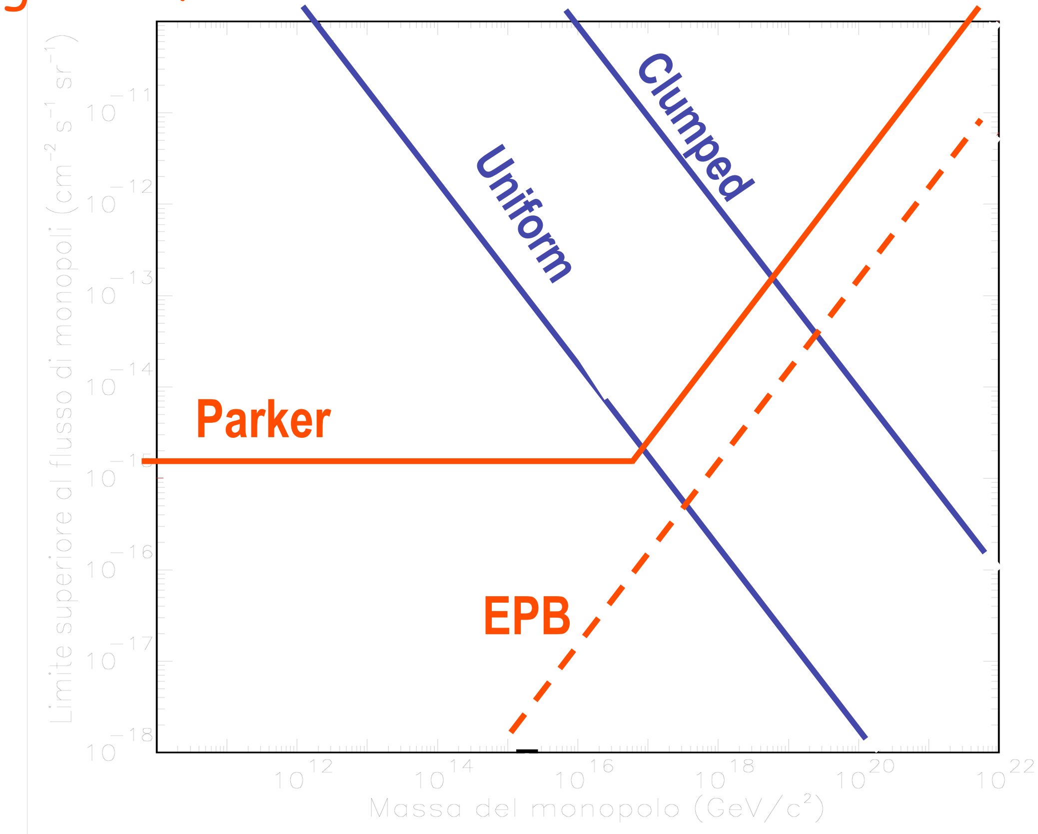
Survival of galactic magnetic fields ⇨ the Parker bound

F< 10^{-15} cm^{-2} s^{-1} sr^{-1} for β<3 10^{-3}

F< 10^{-15} (β/3 10^{-3}) cm^{-2} s^{-1} sr^{-1} for β >3 10^{-3}

Survival of early seed magnetic field ⇨ Extended Parker Bound

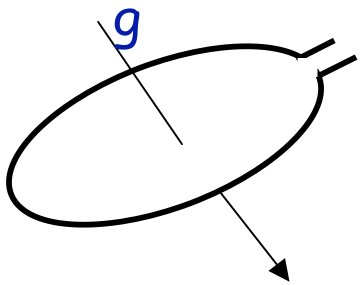
F< 1.2 10^{-16} cm^{-2} s^{-1} sr^{-1}



5. Searches for GUT Magnetic Monopoles

Induction devices

Method depends only on long range E.M. interaction



Superconducting solenoid

$$\Delta i = \frac{4\pi N}{L} g_D = 2\Delta i_0$$

Early experiments :
1 loop, 10 cm^2, no coincidence arrangements
Stanford, 1982: the "Cabrera" event

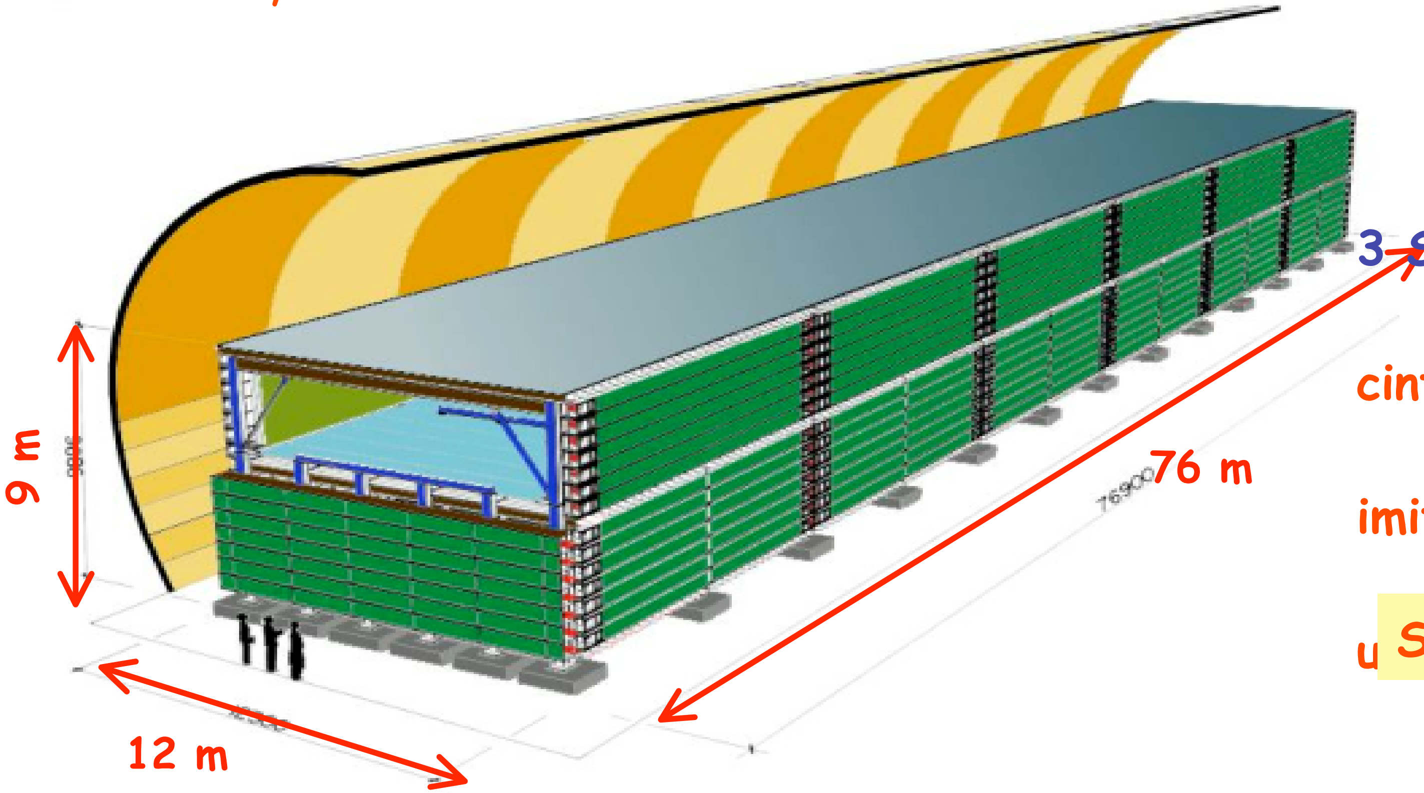
Later detectors:
coincidence arrangements+accelerometers, cosmic ray and R.F. monitors

Present combined limit:

$F < 2 \times 10^{-13}\ cm^{-2} s^{-1} sr^{-1}$ (90 % CL)

The MACRO experiment @ Gran Sasso

from early 1989 to December 2000



3 Subdetectors:

cintillators

imited Streamer tubes

u ... rs

SΩ ~10,000 m²sr

Different analysis techniques were used for various β regions, by using the three subdetectors

Redundancy & Complementarity

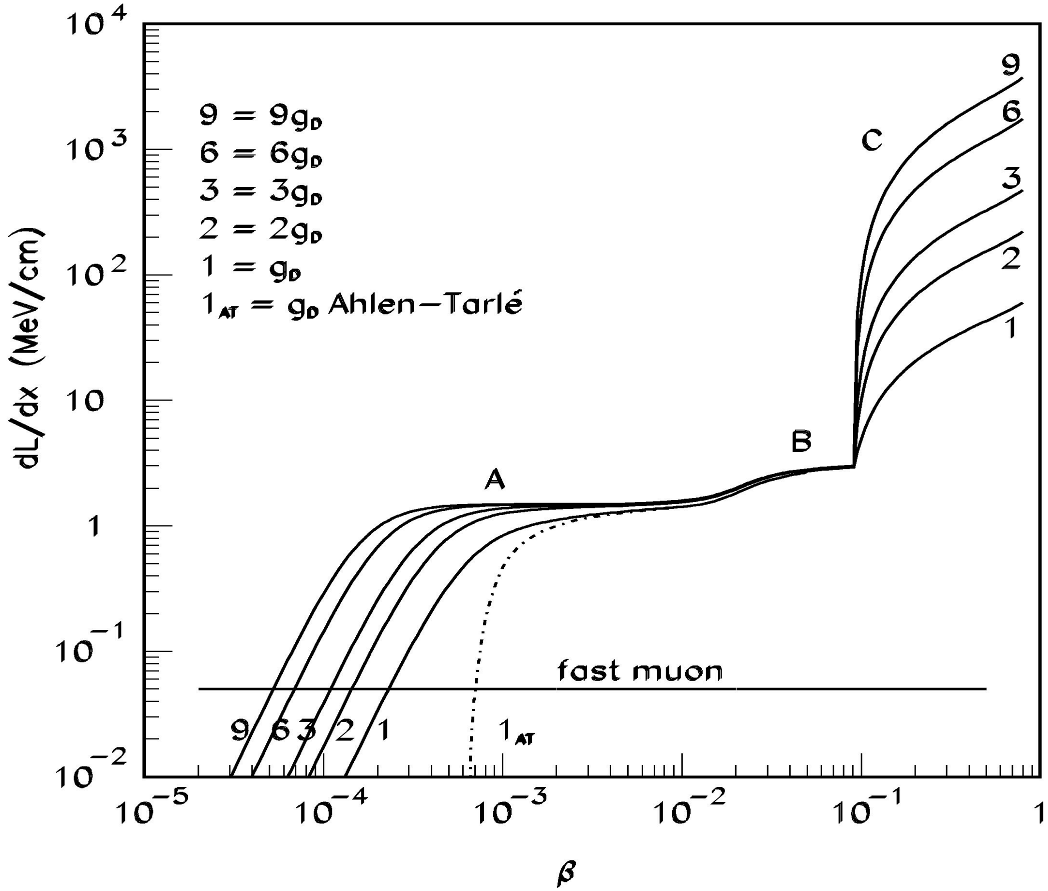
MACRO: Scintillation counters

Liquid scintillator:

mineral oil+pseudocumene +wls

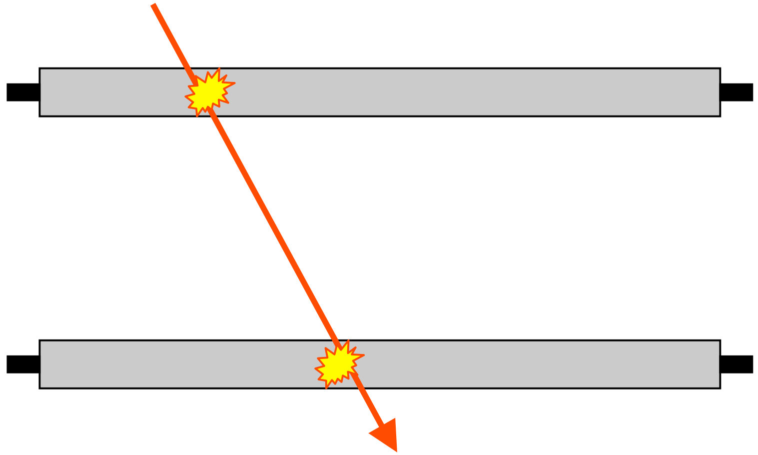
Total mass : 600 t

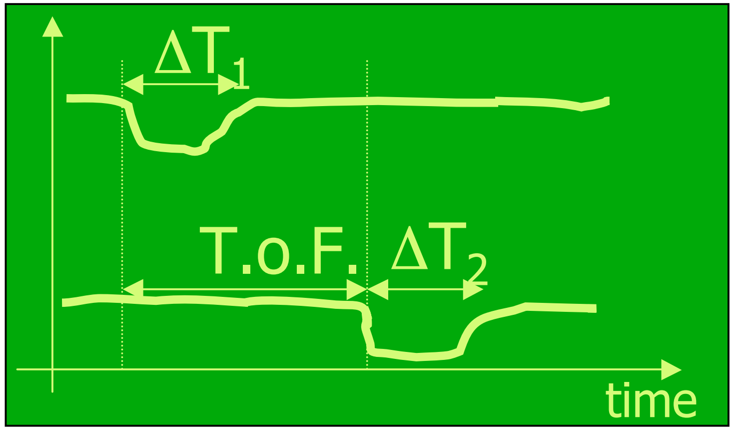
Time resolution: ~500 ps



Calibration tools: cosmic muons, LED's, UV laser

MACRO: MM Searches with scintillators





✓ Study of the PMT pulse

✓ Measurement of the light yield

✓ Consistency check between the box crossing time and the ToF across MACRO

For slow monopoles : the PMT pulse might reduce to a train of single photoelectrons

For fast monopoles : look for large energy deposits

Dedicated hardware: 200 MHz WFD + ADC/TDC system + independent triggers

MACRO: Streamer Tubes

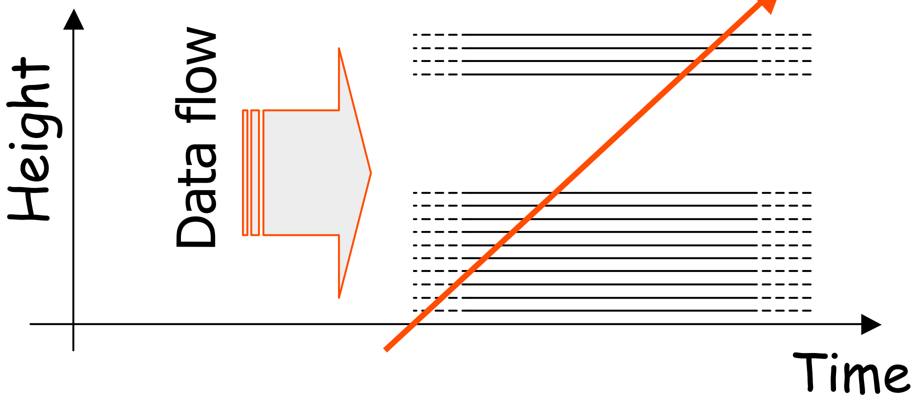
3 cm x 3 cm x 12 m cell with 100 mm Cu-Be wire

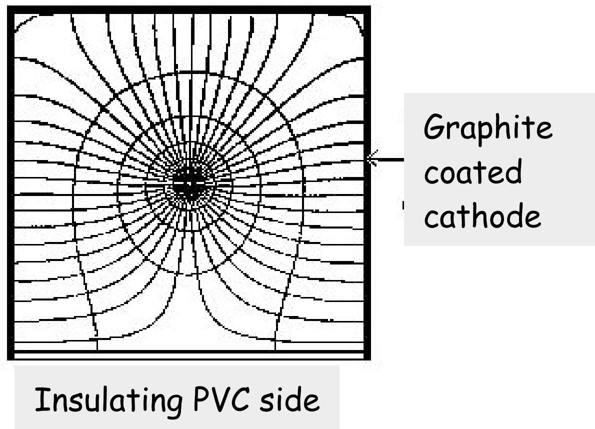
Gas mixture: He (73%) + n-pentane (27%)

Total surface : ~ 19000 m^2

Pick-up strips for stereo track reconstruction

Angular resolution: ~ 0.5°





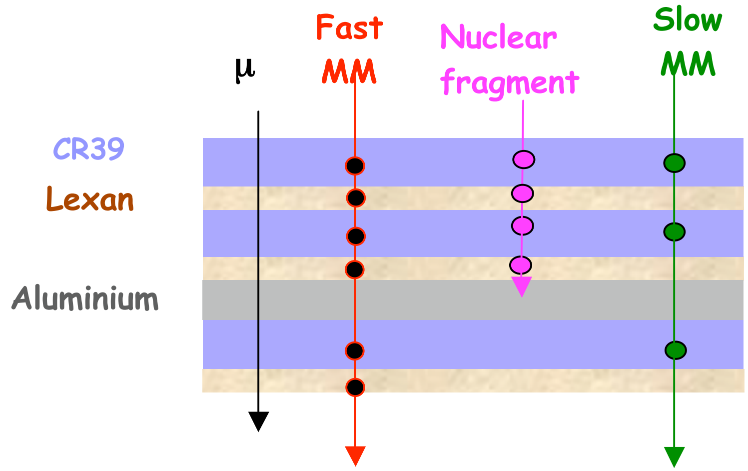
Look for time alignments in a ~ 500 ms window with 150 ns resolution

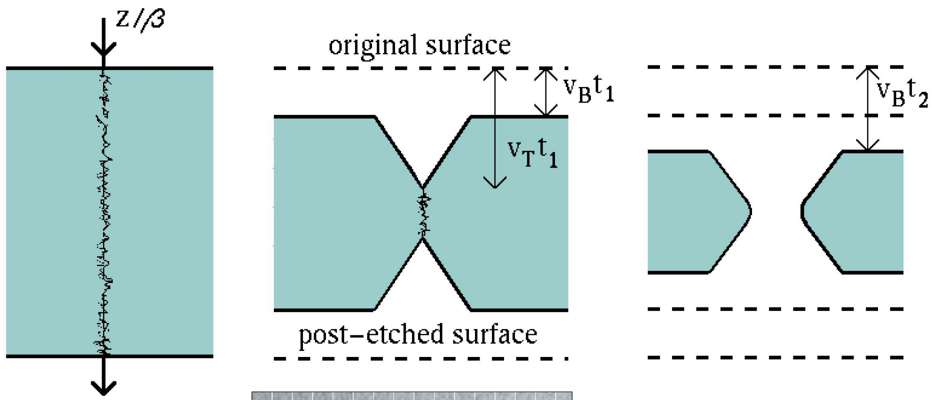
Require single track in wire, strip and time view

MACRO: The Nuclear Track Subdetector

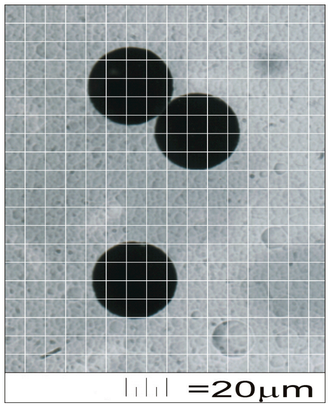
Total surface : ~ 1263 m^2 (SΩ~ 7100 m^2 sr)

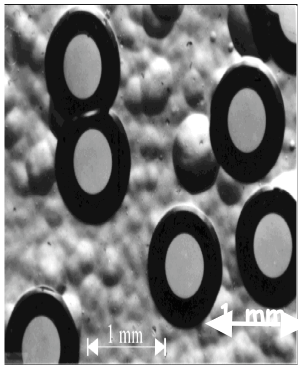
modules 24.5 x 24.5 cm^2





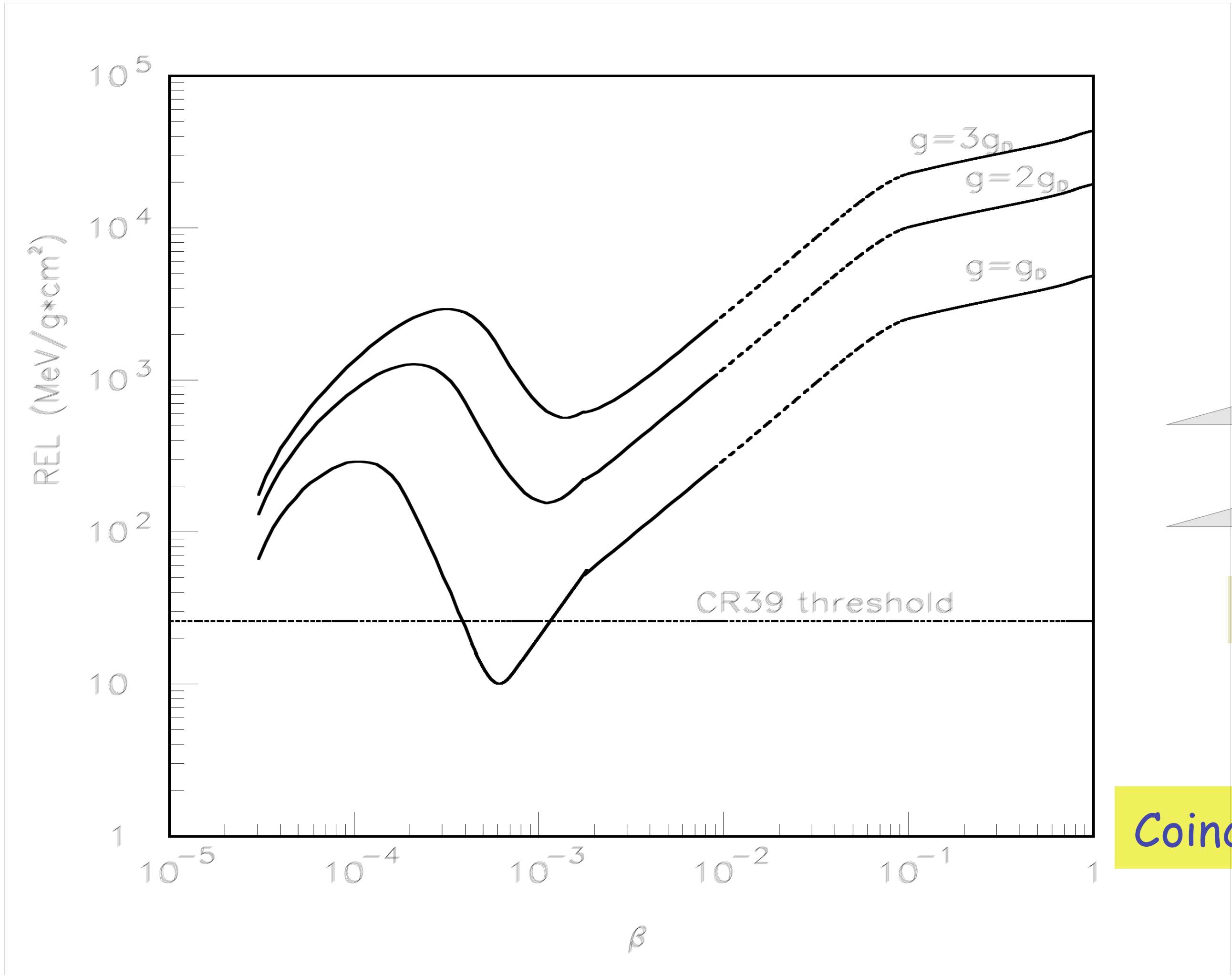
The track-etch technique



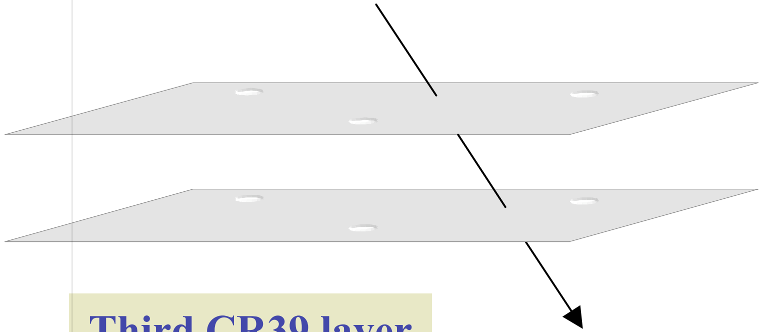


Relativistic S^{16} ion tracks in CR39

Restricted Energy Loss vs β for MMs in CR39



First CR39 layer



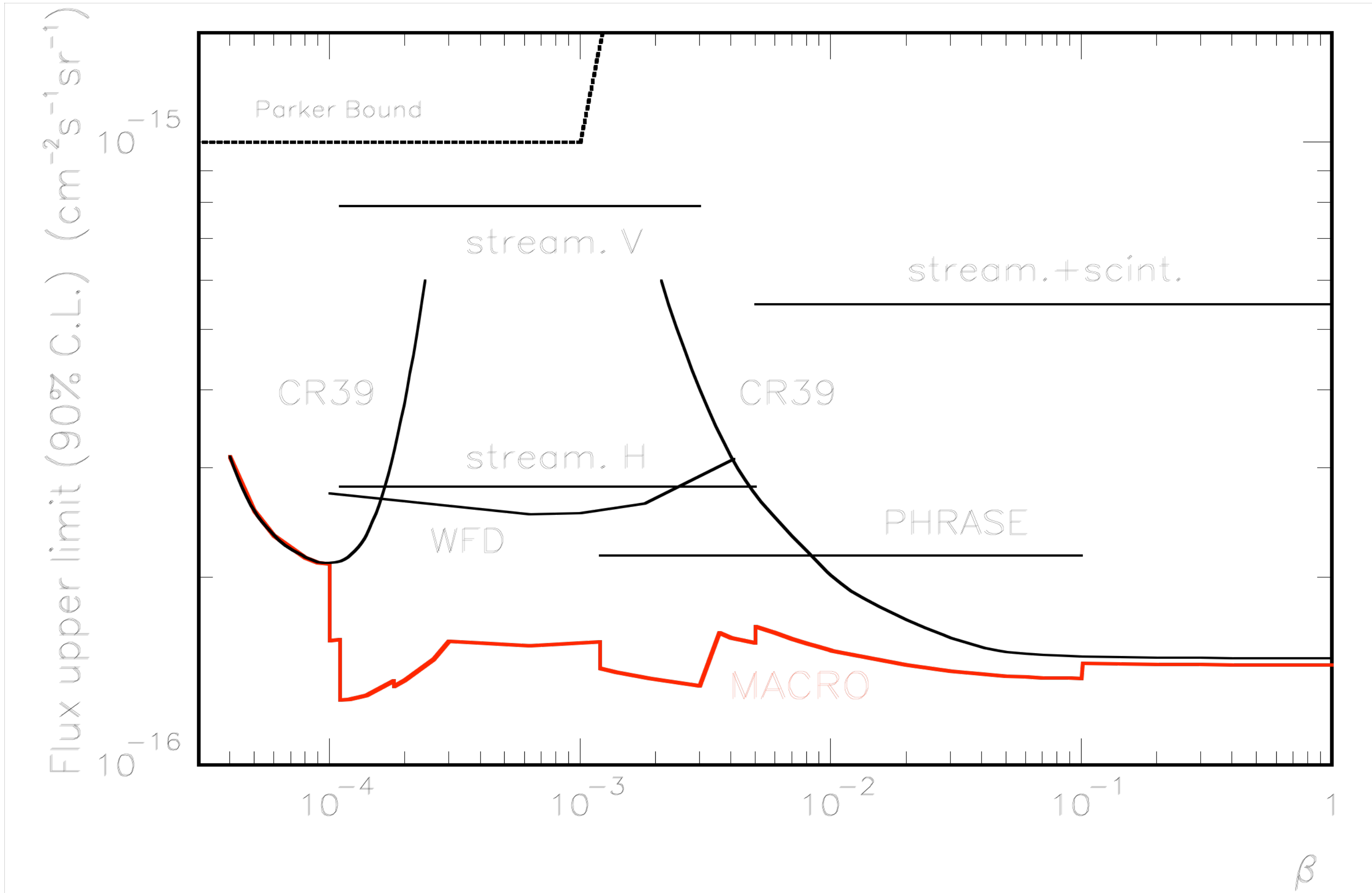
Third CR39 layer

MM

Coincidence in position, angle, REL

MACRO final results

EPJ C25 (2002) 511

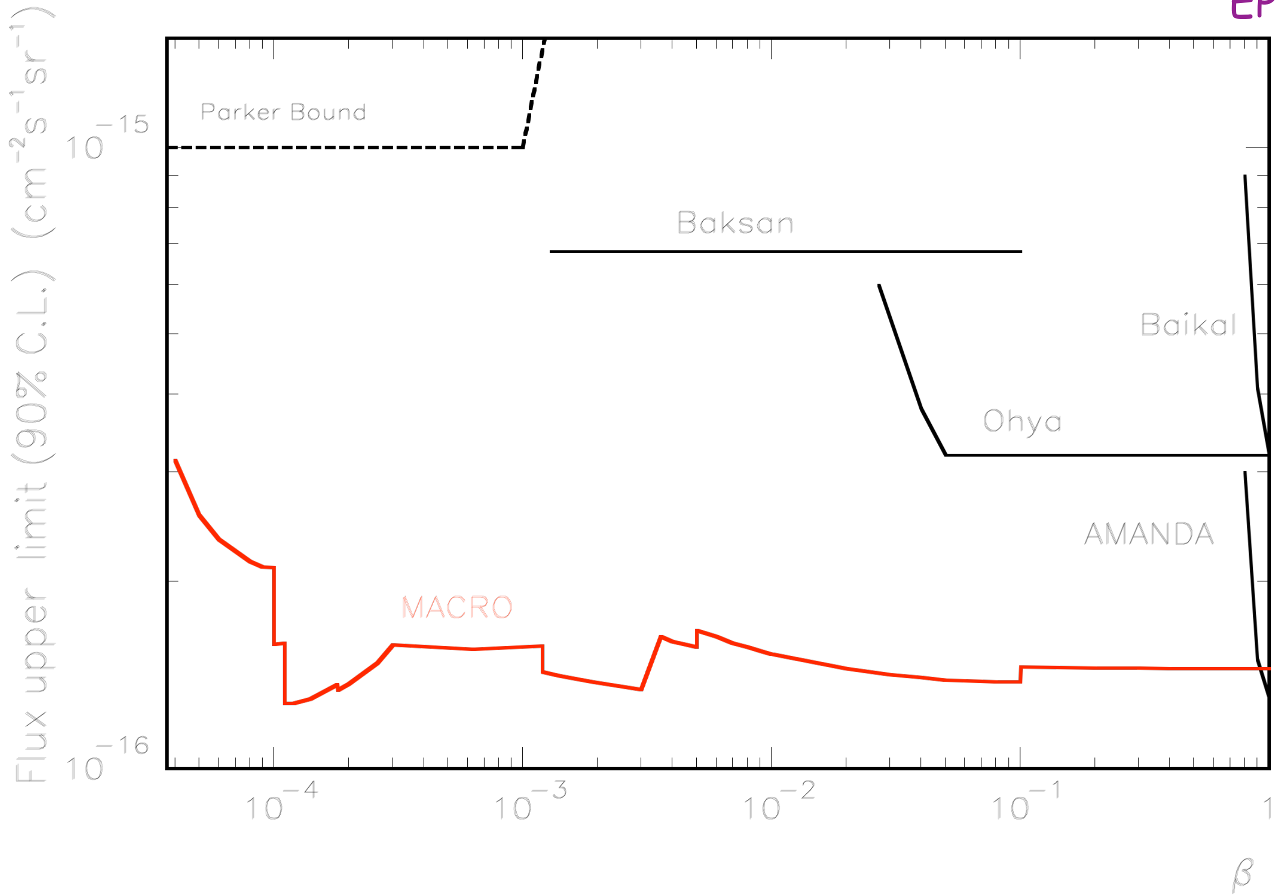


$g = g_D$

$\sigma_{cat} < 1$ mb

Flux upper limits for GUT MMs

EPJ C25 (2002) 511



Direct searches , $g = g_D$, isotropic flux , $\sigma_{cat} < 1$ mb

6. Catalysis of proton decay

GUT MM – p interaction may violate baryon and lepton number conservation

$$M + p \longrightarrow M + e^{+} + \pi^{0}$$

If $\sigma_{\Delta B \neq 0} \sim \sigma_{core} \sim 10^{-56}$ cm^2 ~ negligible

Rubakov-Callan mechanism

If $\sigma_{\Delta B \neq 0} \sim \sigma_{strong}$ could see a string of p decays along MM trajectory

$\sigma_{\Delta B \neq 0} \sim \sigma_0/\beta$ (or σ_0/β^2)

p-decay detectors

IMB	$\Phi < 1 \div 3 \; 10^{-15}$ cm^{-2} sr^{-1} s^{-1}	$10^{-5} < \beta < 10^{-1}$
Kamiokande		$5 \; 10^{-5} < \beta < 10^{-3}$

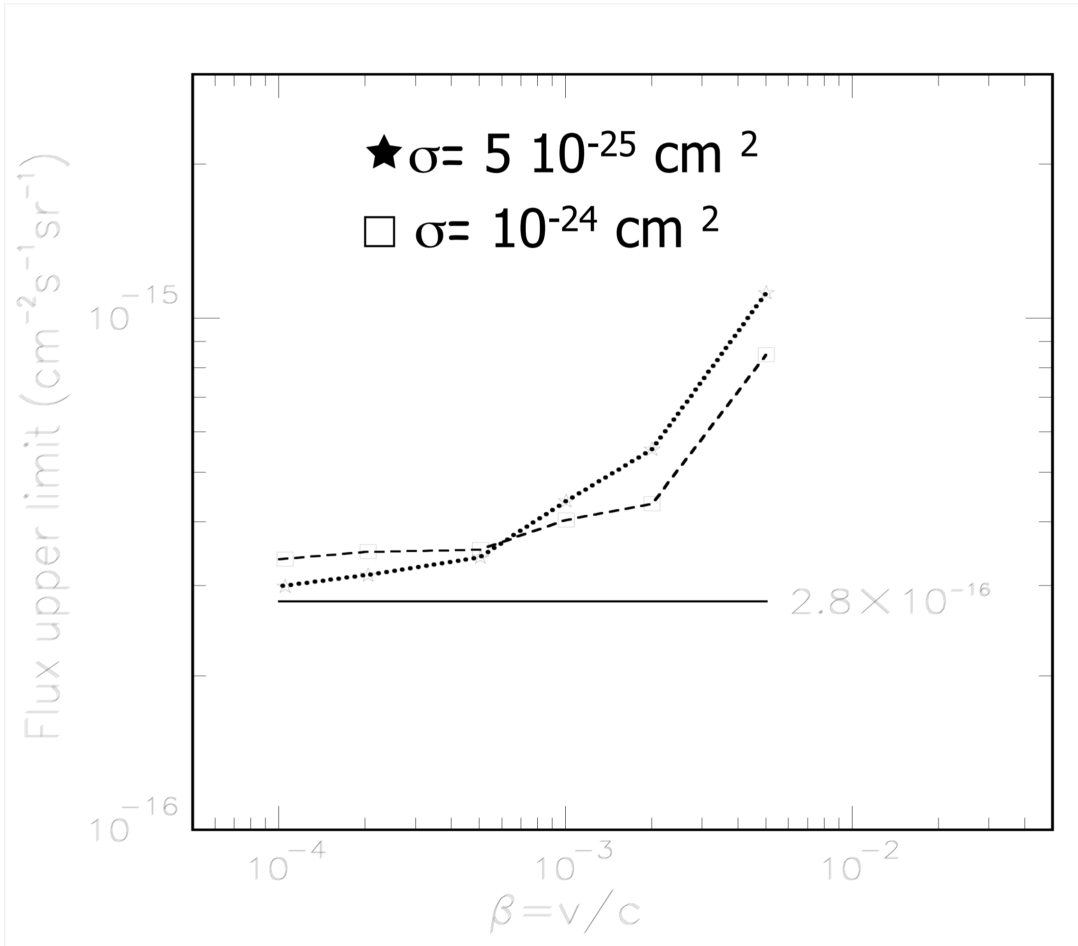
ν-telescopes

Lake Baikal	$\Phi < 6 \; 10^{-17}$ cm^{-2} sr^{-1} s^{-1}	$\beta \sim 10^{-5}$

MACRO: dedicated search for MM induced p decay

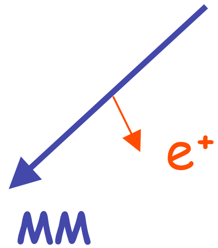
using the streamer tube system

$S\Omega$ = 4250 m^2sr , t = 70,000 hours



Look for

- Slow MM track
- Fast e^+ track



EPJ C26 (2002) 163

7. Intermediate mass MMs
(10^5 - 10^{12} GeV)

1994 De Rujula CERN-TH 7273/94
E. Huguet & P. Peter hep-ph/ 901370
Shafi – Talk at the Neutrino Workshop, Venice, 2001
Wick et al. Astropart. Phys. 18, 663 (2003)

Produced in the Early Universe in later phase transitions

$$SO(10) \xrightarrow[10^{-35}\ s]{10^{15}\ GeV} SU(4) \times SU(2) \times SU(2) \xrightarrow[10^{-23}\ s]{10^{9}\ GeV} SU(3) \times SU(2) \times U(1)$$

ex. (Shafi) $M \sim 10^{10}$ GeV , $g = 2\, g_D$, no p-decay catalysis

IMMs can be accelerated in the galactic B field to relativistic velocities

$W = g_D\, B\, L \sim 6 \times 10^{19}$ eV $(B/3\times10^{-6}\ G)\ (L/300pc)$

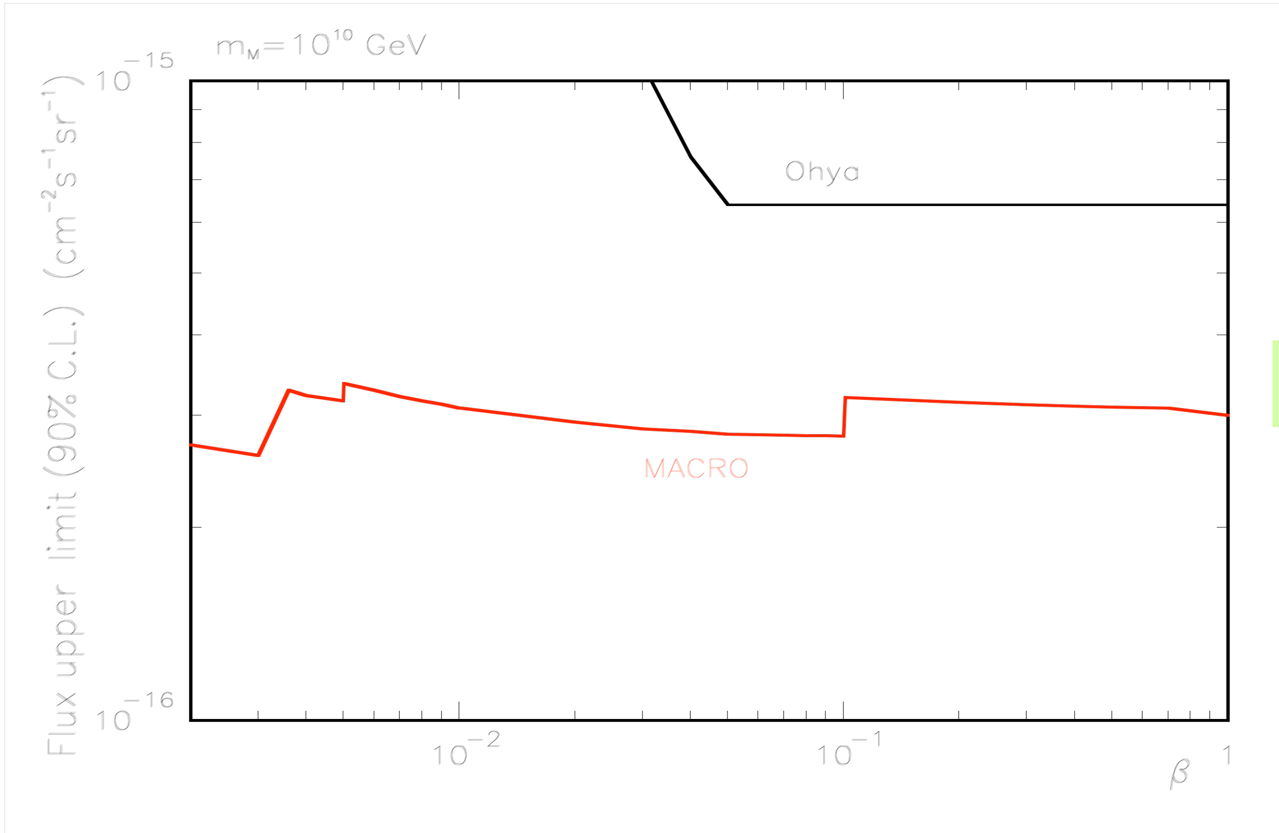
Galaxy $W \sim 6 \times 10^{19}$ eV

Neutron stars $W \sim 10^{20} - 10^{24}$ eV

AGN $W \sim 10^{23} - 10^{24}$ eV

Could they produce highest energy cosmic ray showers $E > 10^{20}$ eV ?

IMM searches in the cosmic radiation : the present situation



M = 10^{10} GeV

IMM searches at high altitudes

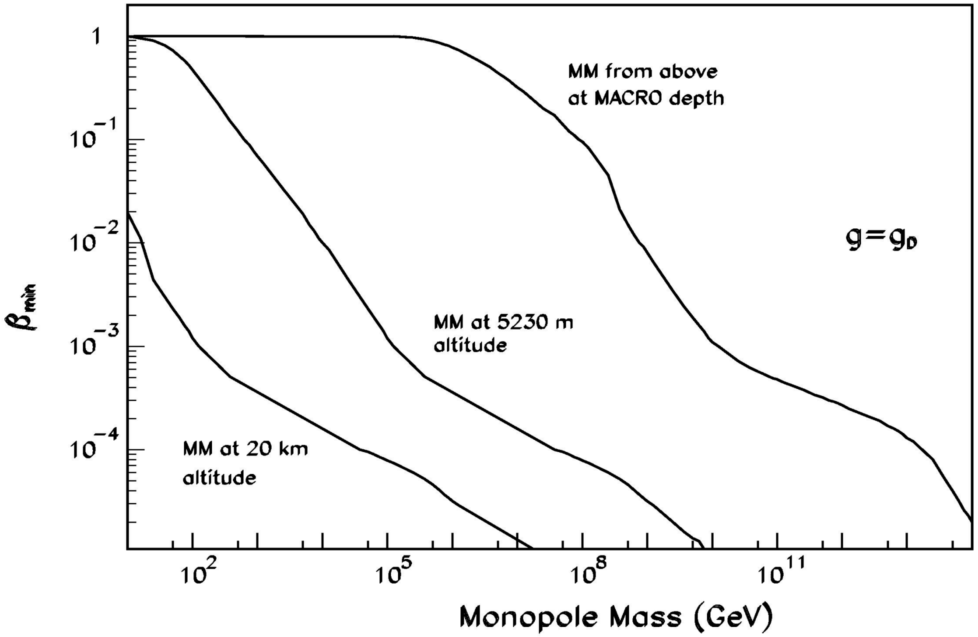
SLIM

Chacaltaya, Bolivia 5290 m asl

440 m^2 of nuclear track detectors

Koksil, Himalaya, 4275 m asl

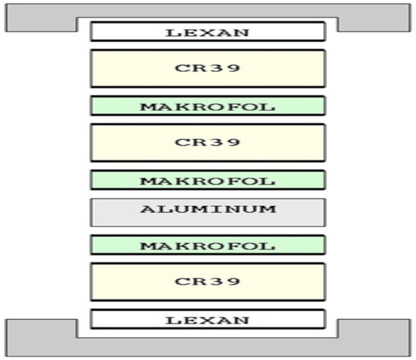
100 m^2 of nuclear track detectors



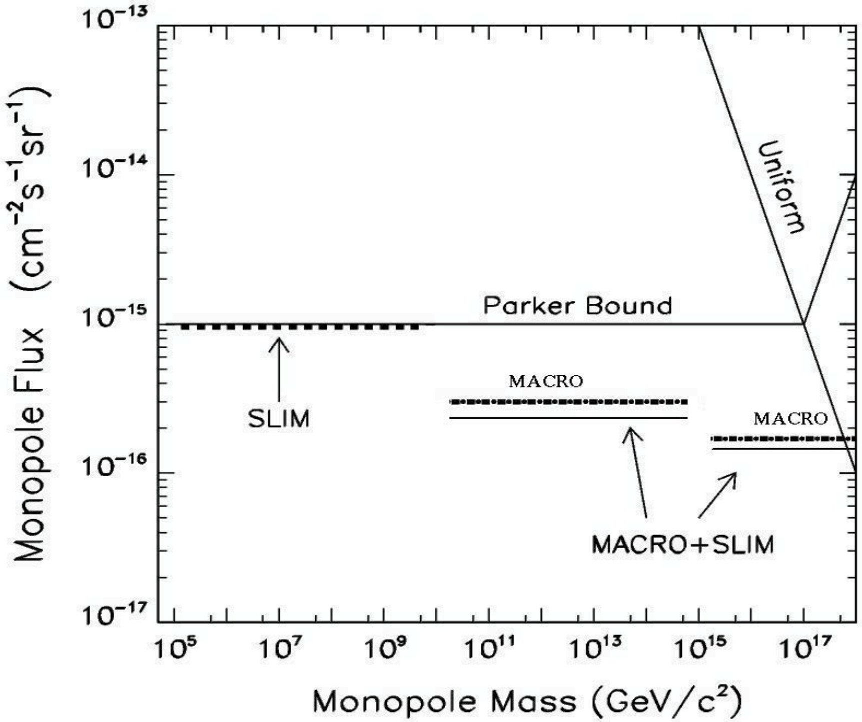
Accessible regions in the plane (mass, β) for MMs coming from above for an experiment at high altitudes and underground.

The SLIM detector layout @ Chacaltaya

Modules 24 x 24 cm^2



90 % C.L. flux upper limits vs MM mass for SLIM (expected, in absence of candidates) and MACRO



IMM searches: Under-ice, Underwater experiments

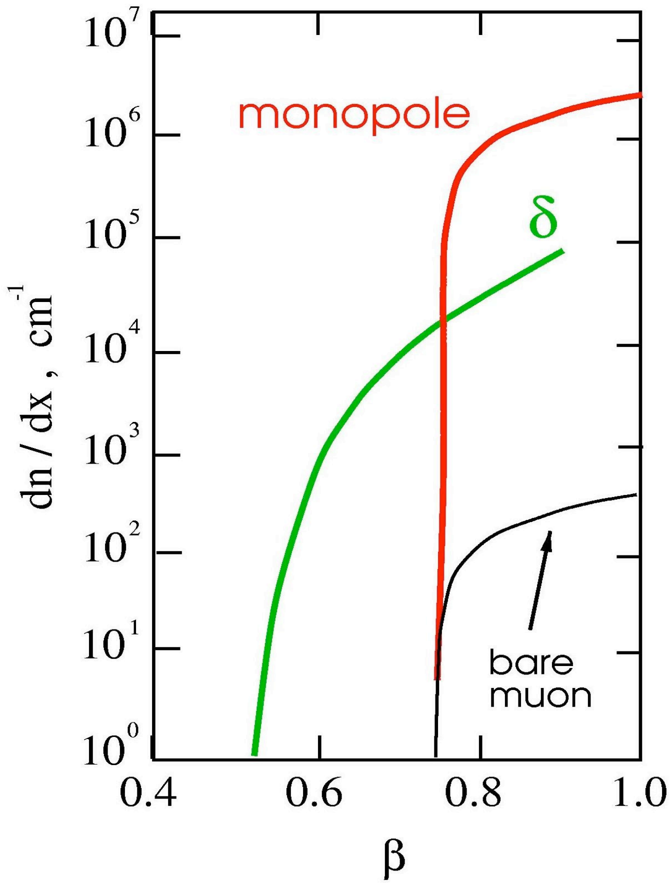
AMANDA, Lake Baikal, ANTARES

Direct _ light $\beta_{MM} > 1/n \sim 0.75$

δ-rays _ light $\beta_{MM} > 0.6$

M > 10^{10-11} GeV from below

(M > 10^{6-9} GeV from above)

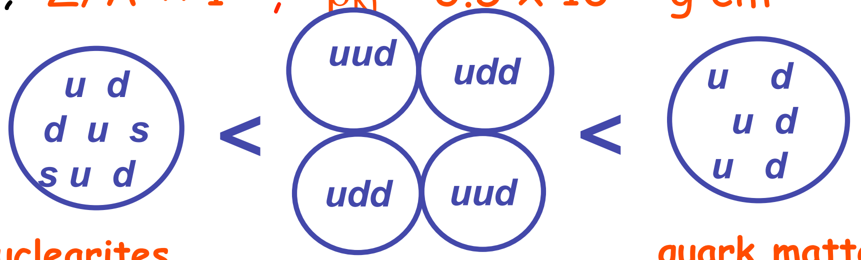


8. NUCLEARITES

E. Witten, Phys. Rev. D30 (1984) 272

A. De Rujula, S. L. Glashow, Nature 312 (1984) 734

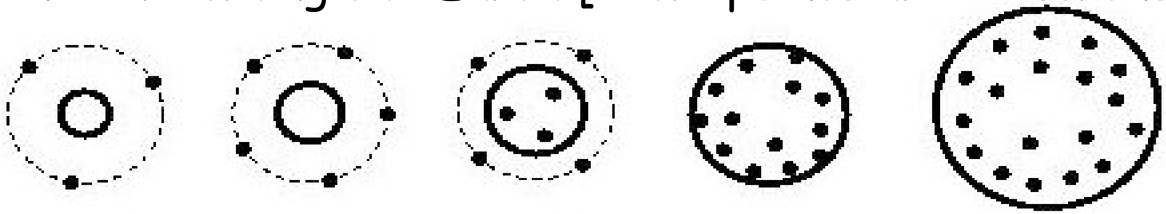
- Aggregates of u, d, s quarks + electrons , $n_e = 2/3\ n_u - 1/3\ n_d - 1/3\ n_s$
- Ground state of nuclear matter; stable for any barion number A : $\sim 300 < A < 10^{57}$
- $Z \sim A^{1/3}$? , $\sim A^{2/3}$? ; $Z/A \ll 1$, $\rho_N \sim 3.5 \times 10^{14}$ g cm^{-3} ($\rho_{nuclei} \sim 10^{14}$ g cm^{-3})



nuclearites | nuclei | quark matter (non strange)

Produced in Early Universe: candidates for cold Dark Matter

Searched for in CR reaching the Earth [black points are electrons]



$R_N = 10^2$ fm | 10^3 fm | 10^4 fm | 10^5 fm | 10^6 fm

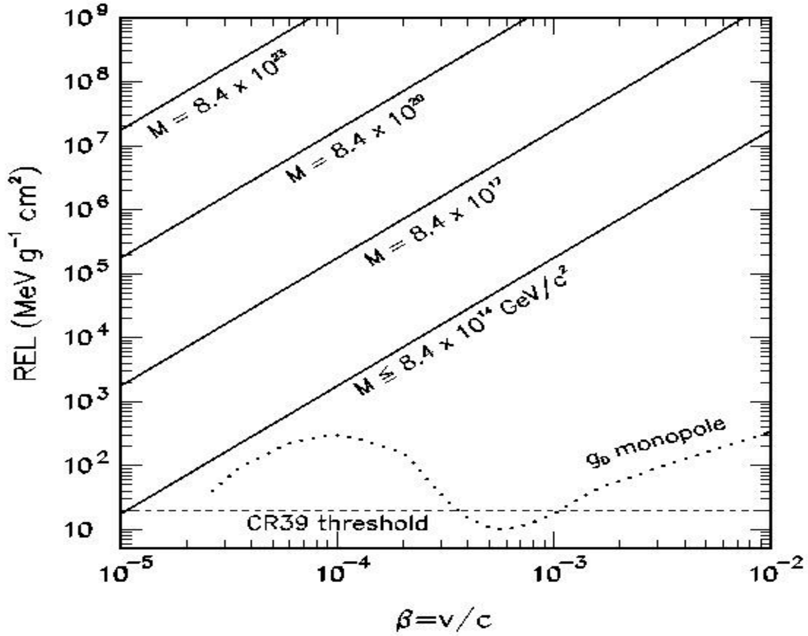
$M_N = 10^6$ GeV | 10^9 GeV | 10^{12} GeV | 10^{15} GeV

Nuclearites: Interaction with matter

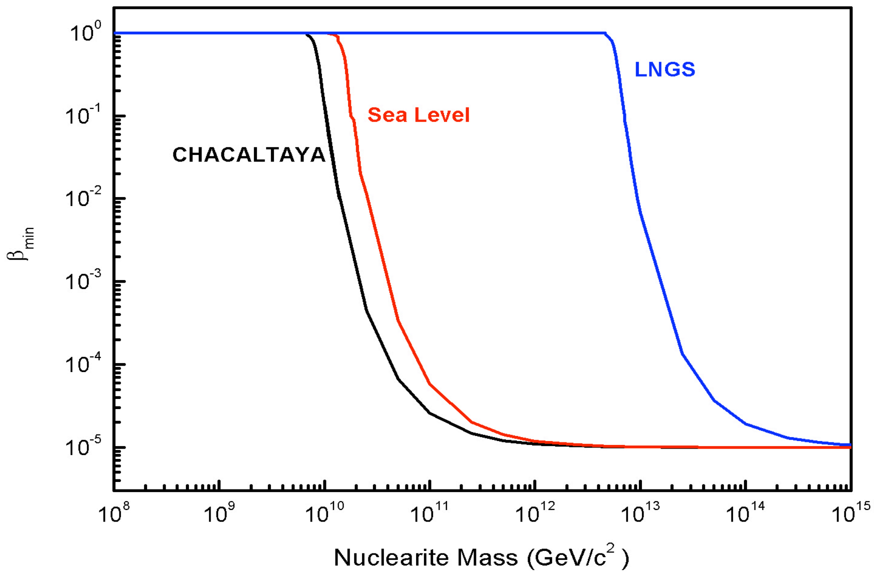
Main energy loss mechanism for nuclearites with $\beta \sim 10^{-3}$ is by atomic collisions

$$dE/dx = -\sigma \rho_{medium} v^2_N \qquad \sigma \sim \begin{cases} \pi\, 10^{-16}\ cm^2 & R_N < 1Å \\ \pi \times R^2_N & R_N > 1Å \end{cases}$$

In scintillators and track-etch detectors:
signal similar to that of a MM

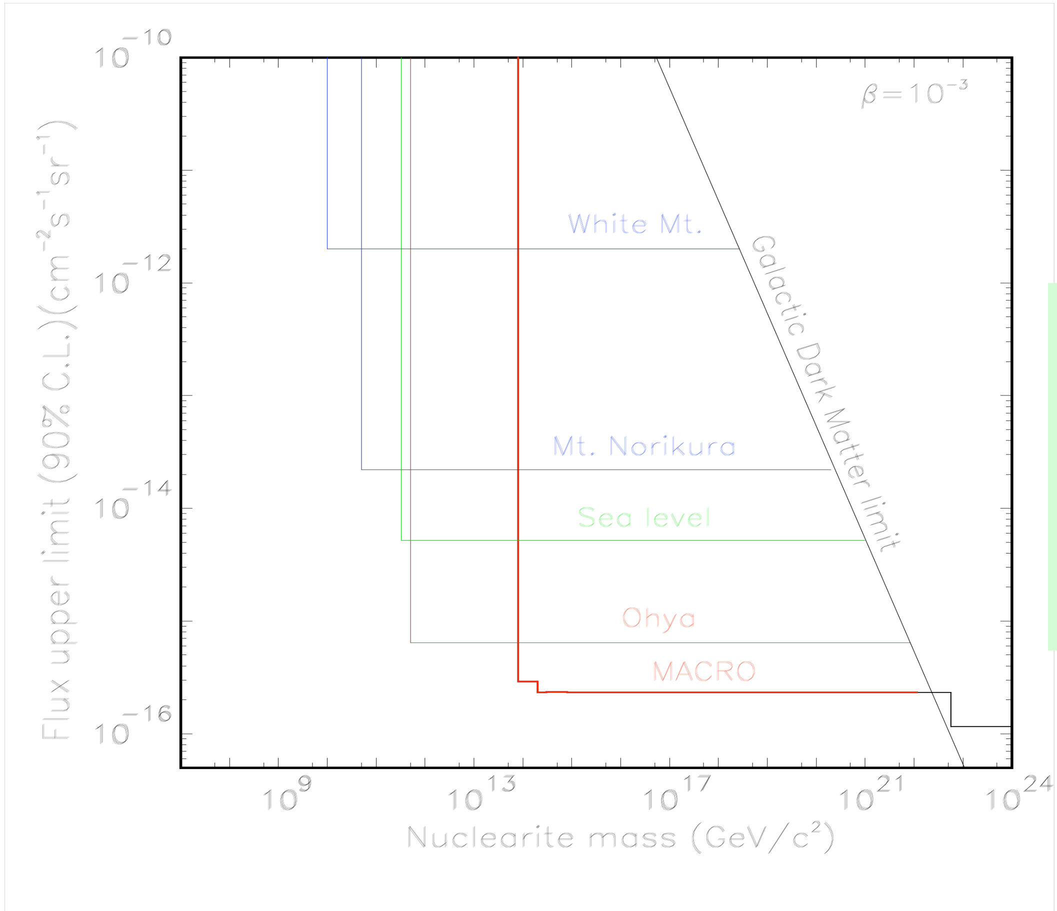


In water: part of the lost energy is radiated as visible light



Accessible regions in the plane (mass, β) for nuclearites coming from above for an experiment at high altitudes and underground.

High Mass Nuclearites: present situation:



White Mountain 4800 m a.s.l.

Mt. Norikura 2000 m a.s.l.

Ohya : 100 hg/cm^2 undergr.

MACRO : 3700 hg/cm^2 undergr.

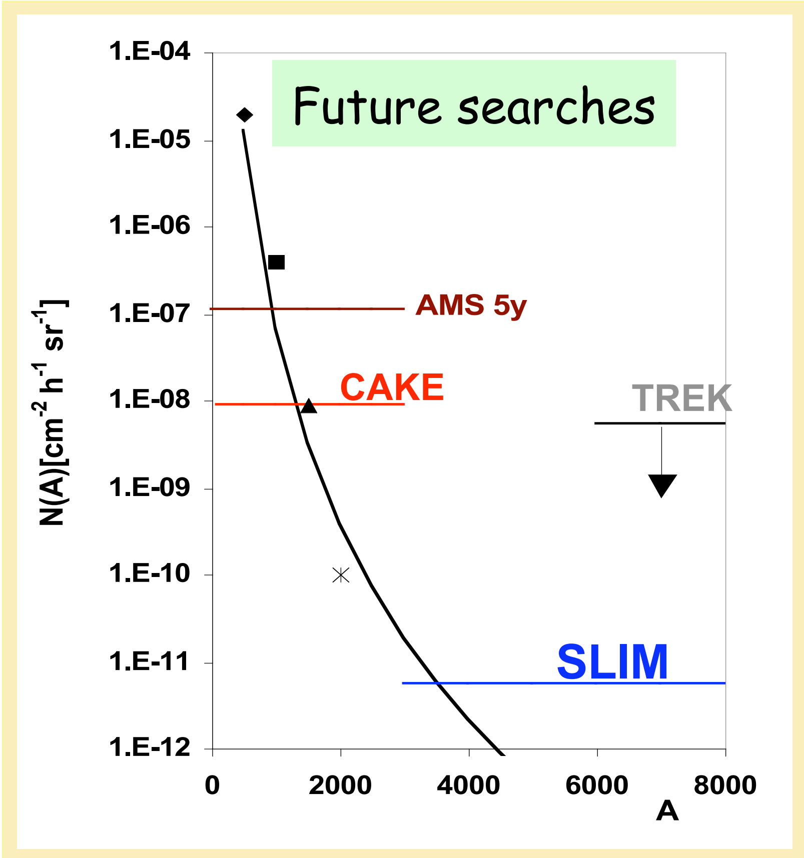
Low mass nuclearites

Flux of light nuclearites may increase strongly with decreasing mass

Flux may become almost equal to flux of ordinary nuclei

Light nuclearites may be accelerated to relativistic velocities

G. Wilk et al. hep-ph/0009164;
I. Madsen et al PRL 90(2003)121102



Predicted Flux @ Chacaltaya : 7×10^{-6} m^{-2} h^{-1} sr^{-1} for $m_N > 3 \times 10^3$

SLIM: ~ 100 events in 4 y

8. 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;

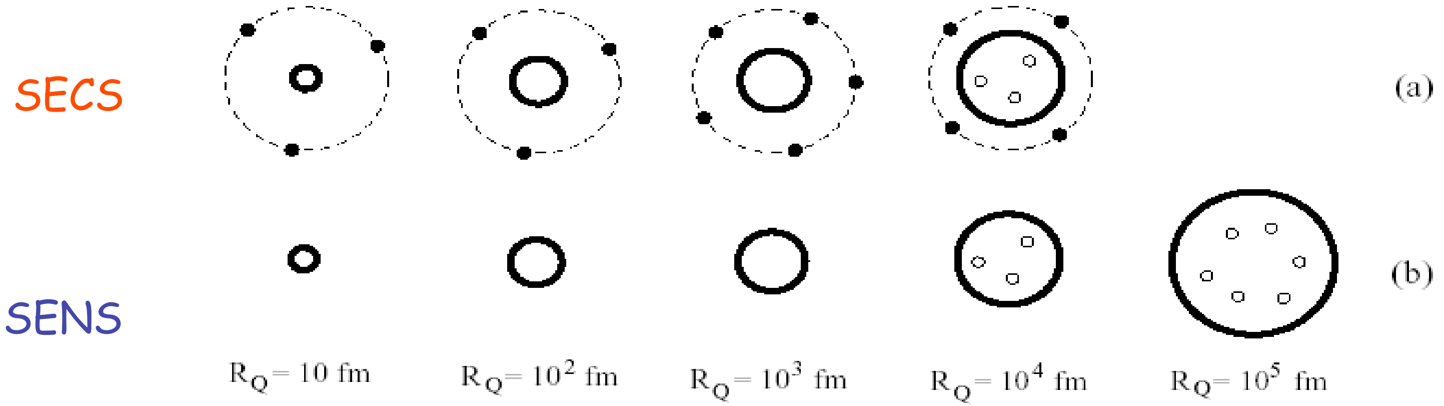
Q-balls : coherent states of squarks, sleptons and Higgs fields

$Q \leq 10^{30}$ $\quad 10^{8} < M_Q < 10^{25}$ GeV

- Produced in the Early Universe
- Candidates for Cold Dark Matter , concentrated in the galactic halos, $\beta \sim 10^{-3}$

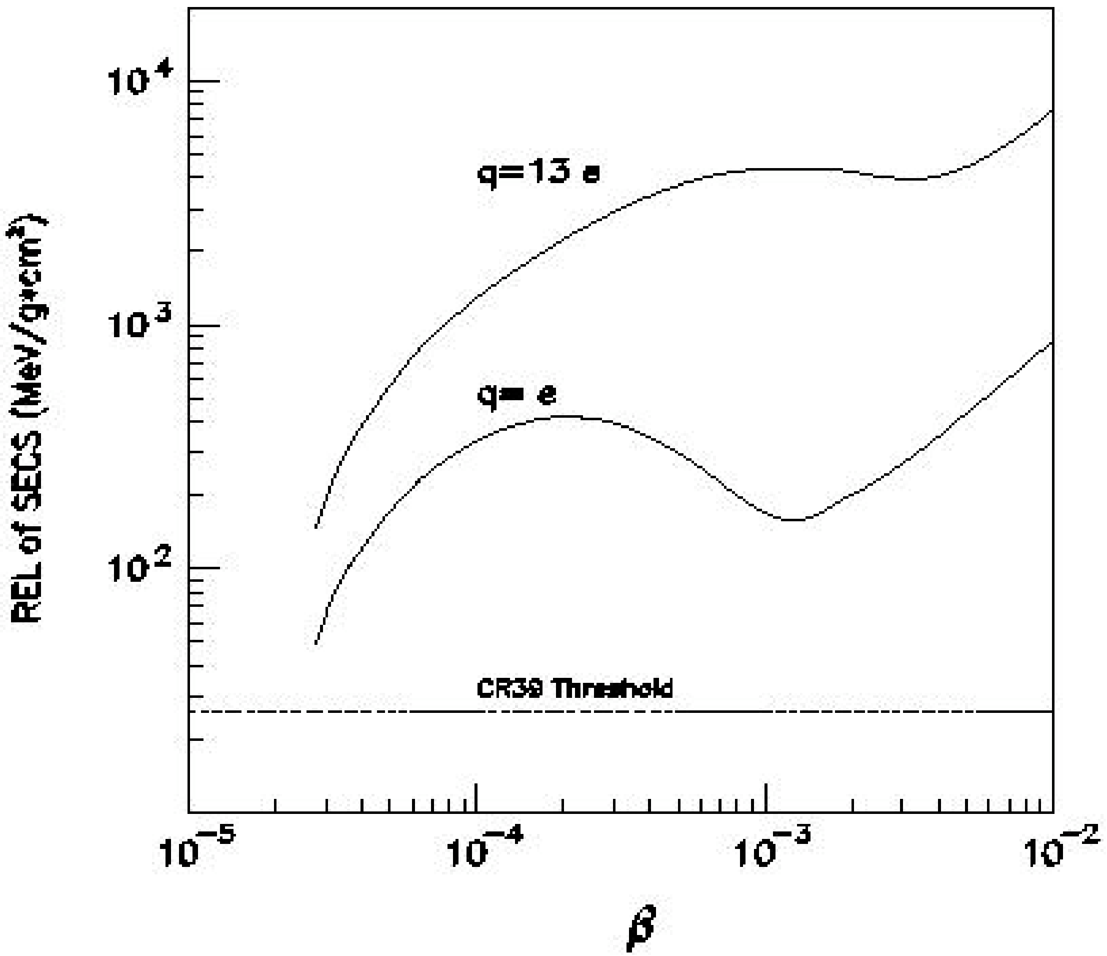
SECS : Supersym. Electrically Charged Solitons

SENS : Supersym. Electrically Neutral Solitons

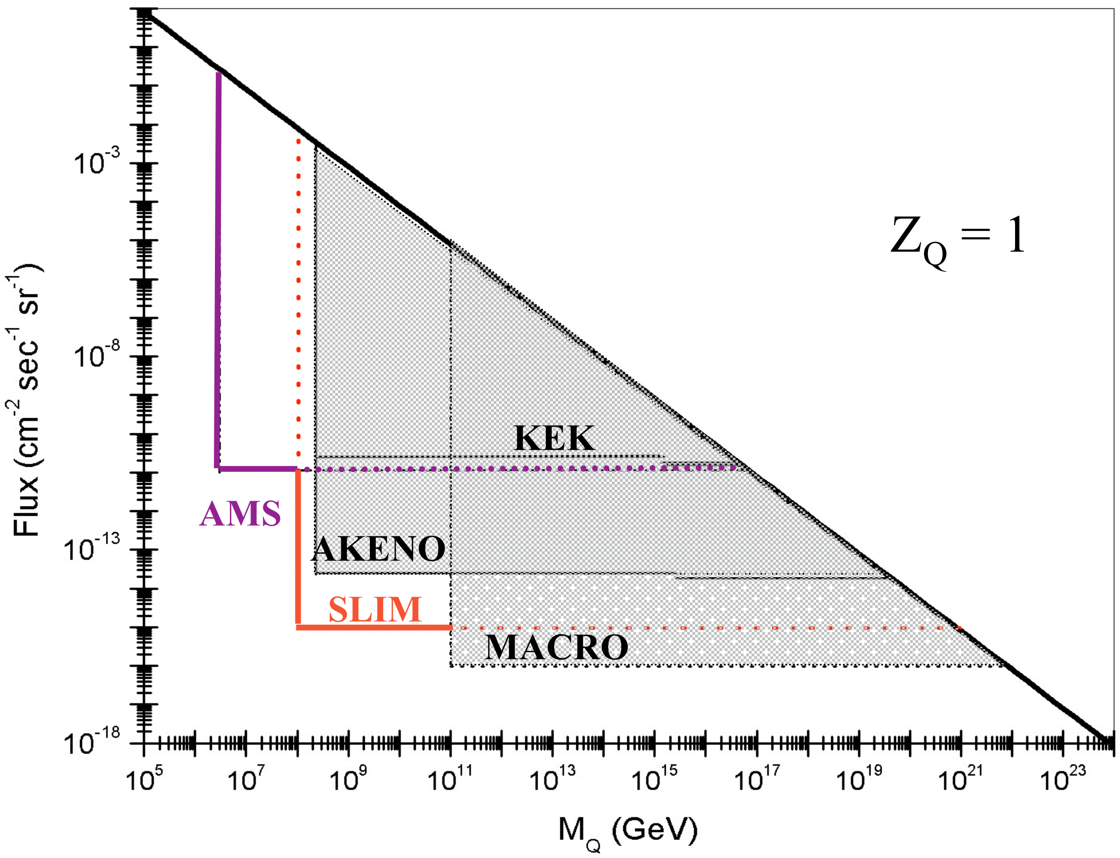


R_Q : dimension of the Q-ball core;
the black points indicate electrons, open circles indicate s-electrons.

Supersymmetric electrically charged solitons (SECS) should essentially behave in detectors like nuclearites



Charged Q- balls: current /near future situation



AKENO, KEK : ground level

MACRO : 3700 hg/cm² undg.

AMS: Space Station

SLIM: 500 g/cm² atm depth

9. Conclusions - Outlook

- Dirac MMs at accelerators $m_M > 0.9$ TeV

  In the future : at LHC probe $0.9 < m_M < 7$ TeV

- Flux of GUT MMs in the cosmic radiation:

  MACRO : $\Phi < 1.4\ 10^{-16}$ cm^{-2} s^{-1} sr^{-1} for $4\text{x}\ 10^{-5} < \beta < 1$

  For the future: one would need new detectors with much larger surfaces

- IMMs:

  Experiments at mountain altitudes $\Phi < 10^{-15}$ cm^{-2} s^{-1} sr^{-1}

  For the future: need much larger detectors

  Experiments with neutrino telescopes for $\beta > 0.6$ from below

  For the future: need measurements from above

- Nuclearites: None found, limits ~ as for GUT MMs

- Q-balls " "