

And the very exotic Particles ?

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Beyond the Standard Model
Bologna 2/10/2006

1. Introduction

2. Magnetic Monopoles

Dirac, GUT, Intermediate mass

3. Dark matter

Nuclearites, Q-balls,

4. Conclusions. Outlook

1. Introduction


MMs

-Symmetry of Maxwell Equations

$$\begin{aligned}\nabla \cdot \vec{E} &= 4\pi\rho_e & \nabla \times \vec{B} &= \frac{4\pi}{c}\vec{J}_e + \frac{1}{c}\frac{\partial\vec{E}}{\partial t} \\ \nabla \cdot \vec{B} &= 4\pi\rho_m & \nabla \times \vec{E} &= \frac{4\pi}{c}\vec{J}_m - \frac{1}{c}\frac{\partial\vec{B}}{\partial t}\end{aligned}\quad (\text{cgs units})$$

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

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


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

-1974 GUT of Strong and Electroweak interactions

-1990s Intermediate Mass Magnetic Monopoles

Dark Matter components

Nuclearites, Q-balls,

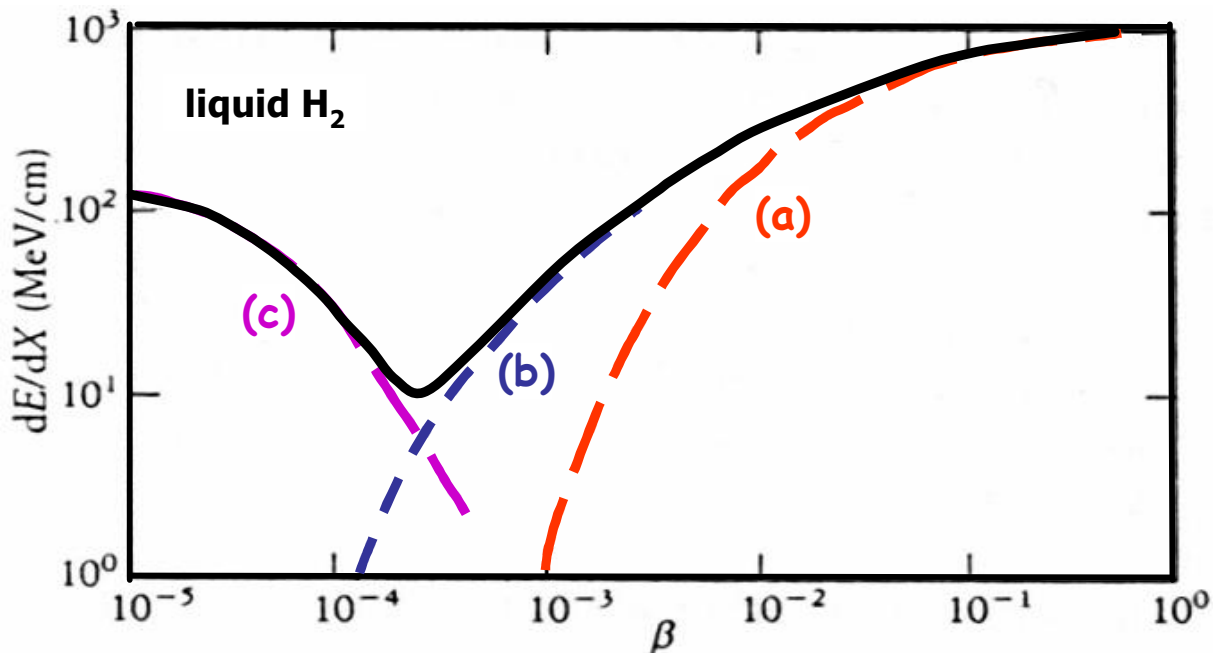
2. MM Energy Losses

$\beta > 10^{-2}$ **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)



Searches for classical MMs at accelerators

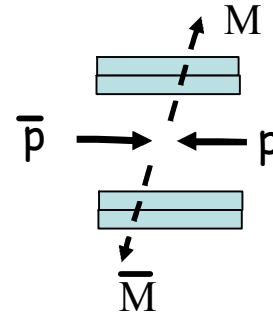
$$e^+e^- \rightarrow M M, \quad \bar{p}p \rightarrow M \bar{M}, \quad pp \rightarrow pp M \bar{M}$$

• Direct experiments

poles produced - detected immediately (large dE/dx)

Searches with

scintillation counters
nuclear track detectors



Limits (95 % CL)

$$\sigma(e^+e^-) < \sim 10^{-37} \text{ cm}^2$$

$$m_M < 104 \text{ GeV}$$

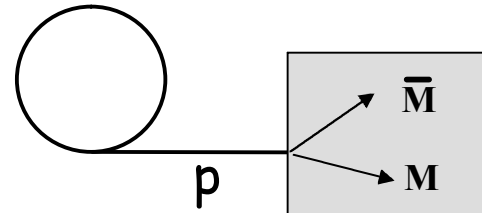
$$\sigma(\bar{p}p) < 2 \times 10^{-34} \text{ cm}^2$$

$$m_M < 850 \text{ GeV}$$

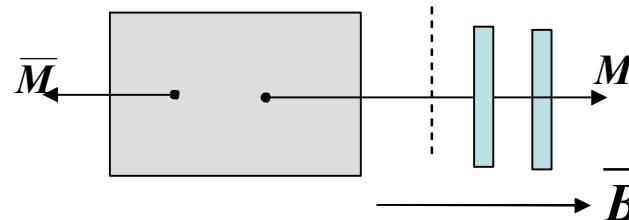
$e p$

• Indirect expts

MMs { Produced
Stopped
Trapped



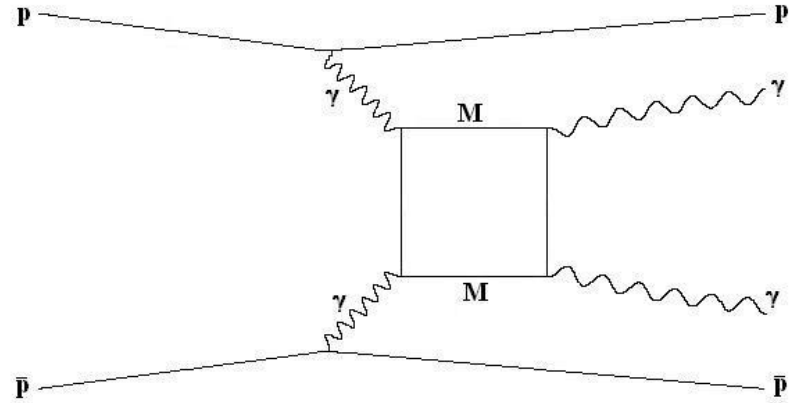
Later { Extracted
Accelerated
Detected



Others

New indirect (direct) experiments at Fermilab

- Search for $\gamma\gamma$ production

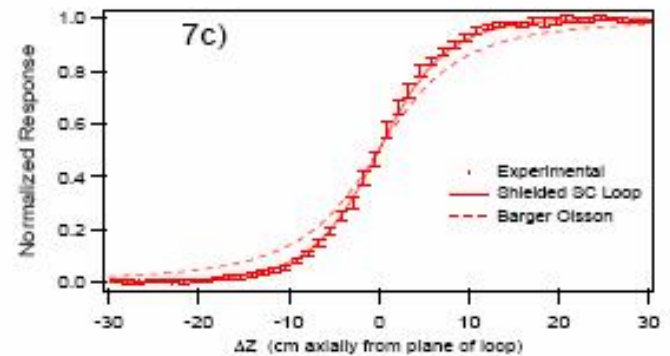
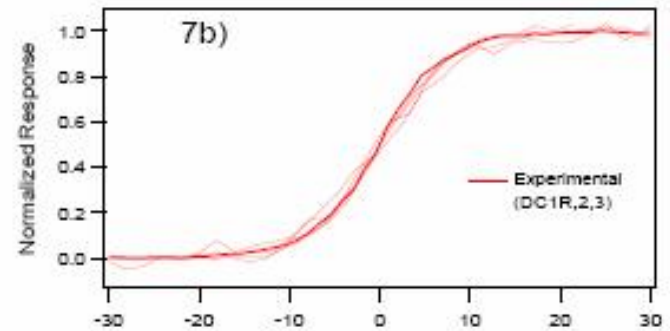
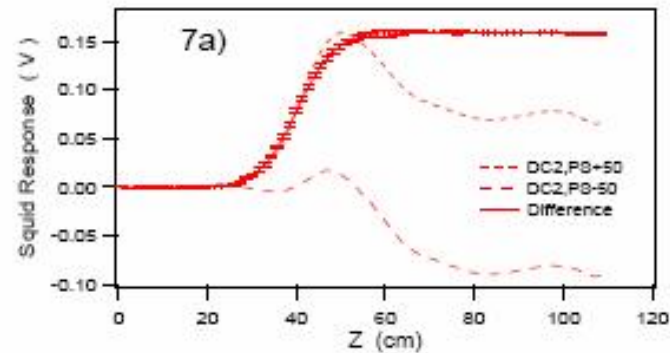
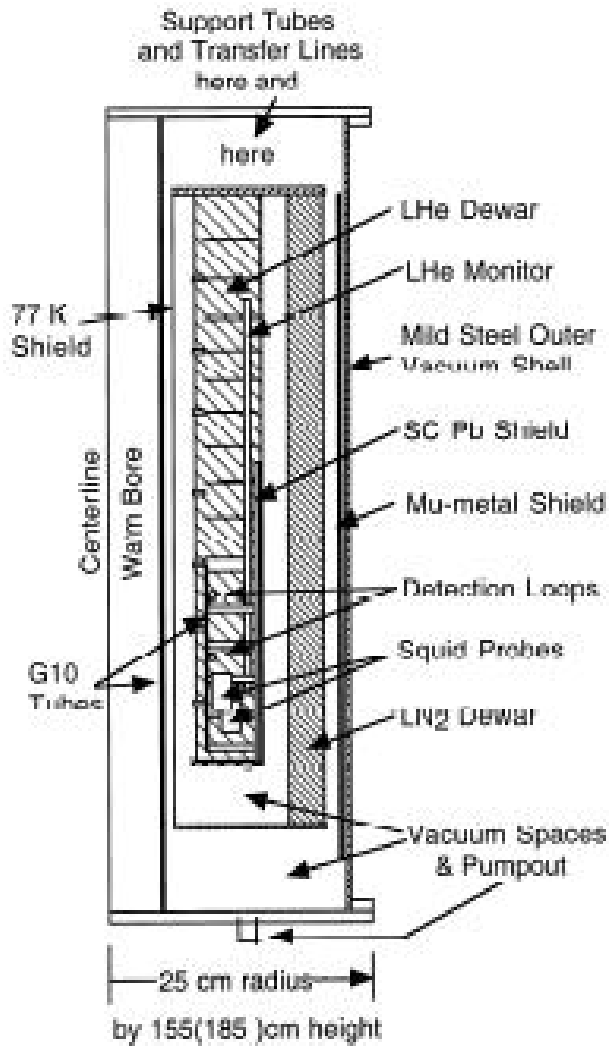


Feynman diagram for $\gamma\gamma$ production in p-antip collisions at the 2 TeV Tevatron collider via a virtual monopole loop.

The cross section at energies below the monopole production threshold would be enhanced by the strong coupling of virtual MMs to photons.

- Beam pipe+parts cut and analyzed with strong SC magnet

660 samples of Be, Pb and Al from the old CDF and D0 detectors were analyzed over a period of 7 years; most samples were run more than once



Superconducting coil + Squid

Expected steps: DO Al, CDF Pb and Al

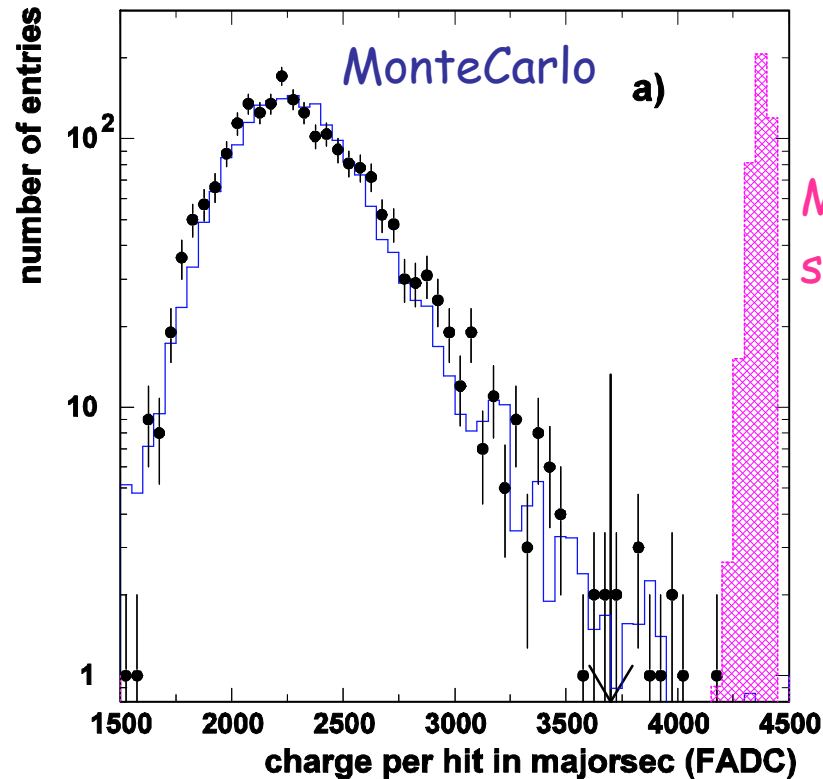
New direct limit from a LEP2 experiment

Search for pair produced MMs with the OPAL jet chamber as tracking device

Monte Carlo simulations assuming $\alpha_{MM} \gg \alpha$ for $45 \text{ GeV} < m_M < 104 \text{ GeV}$,
1+costeta polar distribution and uniform azimuthal distribution

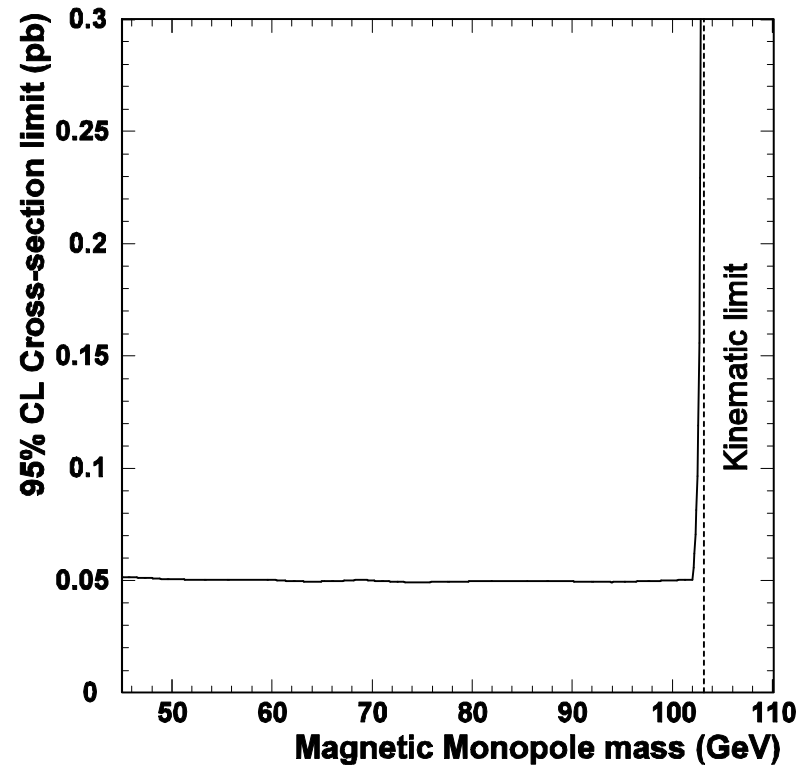
Data at $s^{1/2} = 206.3 \text{ GeV}$, $L = 63 \text{ pb}^{-1}$

Search for Back to Back tracks \rightarrow 2 opposite CJ sectors with high energy release



MM
signal

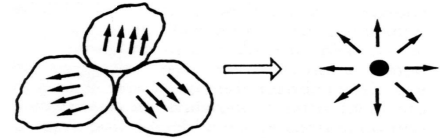
10^{-37}



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

-Gauge theories of unified interactions predict MMs [$m_M \sim 10^{17}$ GeV]

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



-**Production:** In the Early Universe

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

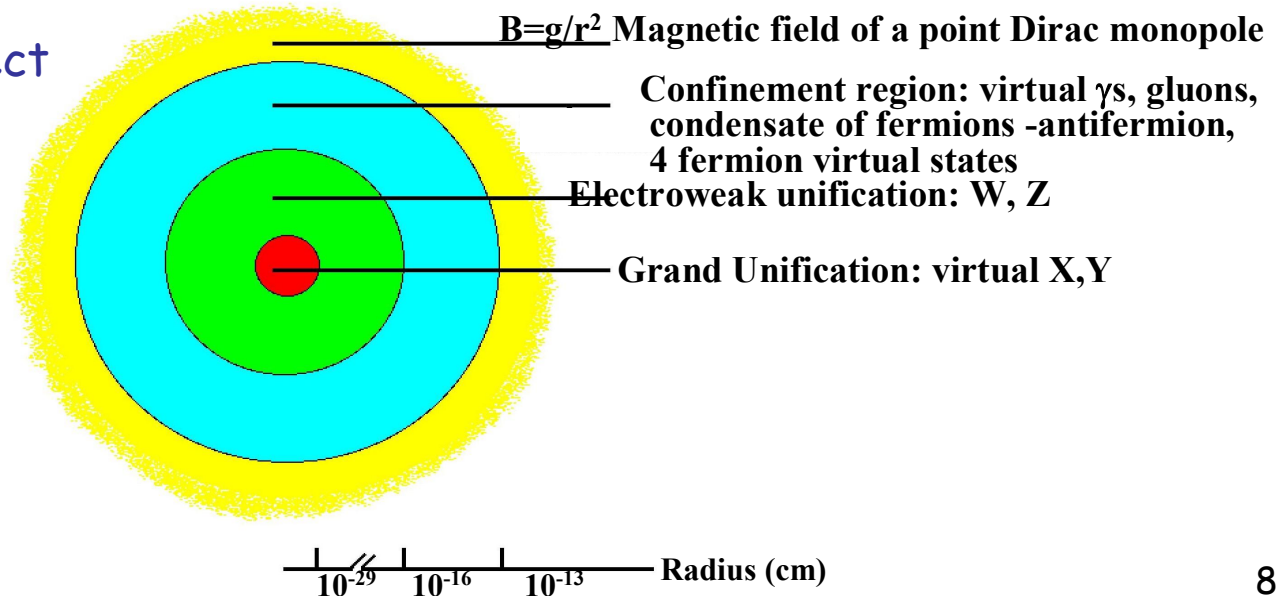
-in high energy collisions ($t \sim 10^{-34}$ s) ($e+e^- \rightarrow MM$, $qq \rightarrow MM$)

-Follow Universe "history" \Rightarrow slowed down \Rightarrow galaxy formation

\Rightarrow magnetic fields \Rightarrow poles accelerated

-MMs may be present today in the Cosmic Radiation as "relic" particles

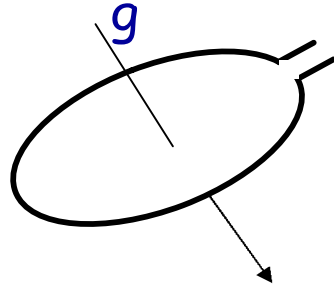
* Size: extended object



Searches for GUT Magnetic Monopoles

• Induction devices

Method depends only on long range E.M. interaction



Superconducting solenoid

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

=twice the quantum change of superconductivity

Early experiments :

1 loop, 10 cm², no coincidence arrangements

Stanford, 1982: the "Cabrera" event

Later detectors:

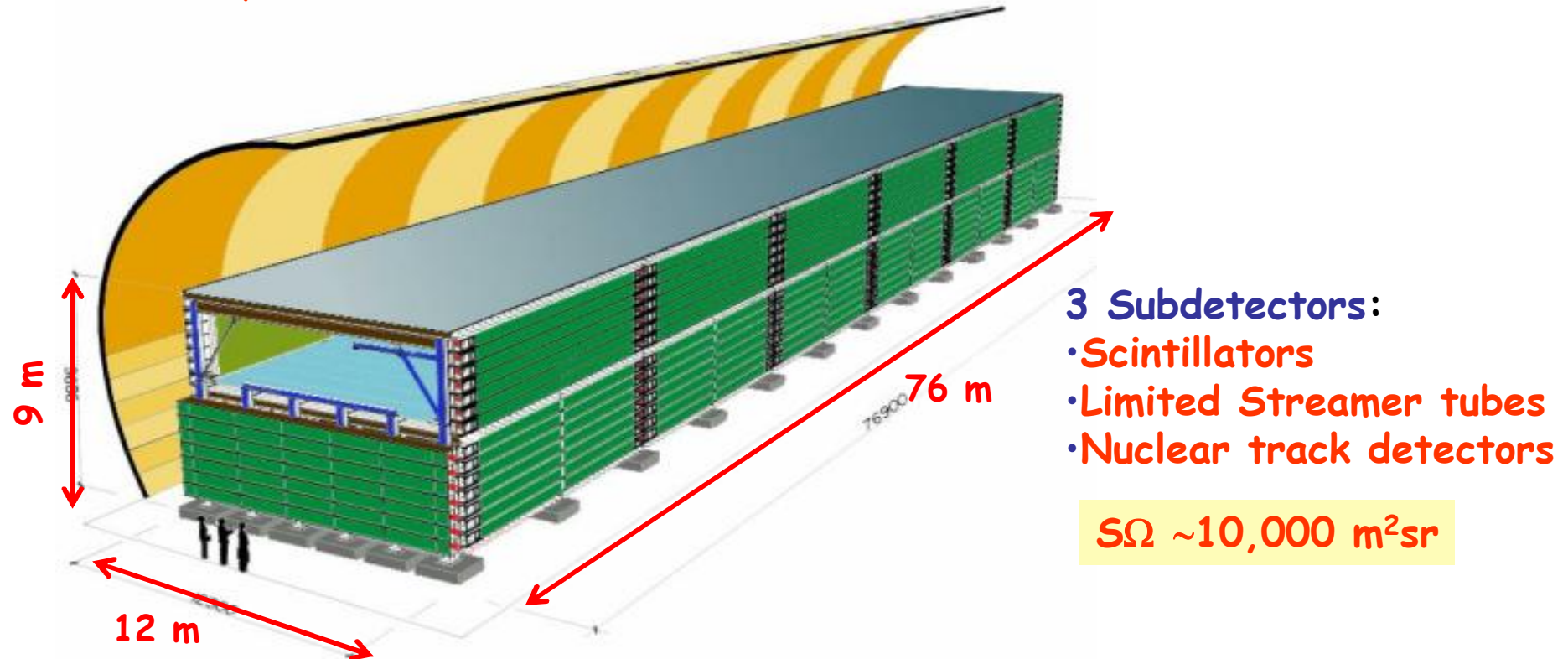
coincidence arrangements+accelerometers, cosmic ray and R.F. monitors

Present combined limit:

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

The MACRO experiment @ Gran Sasso

From early 1989 to December 2000



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

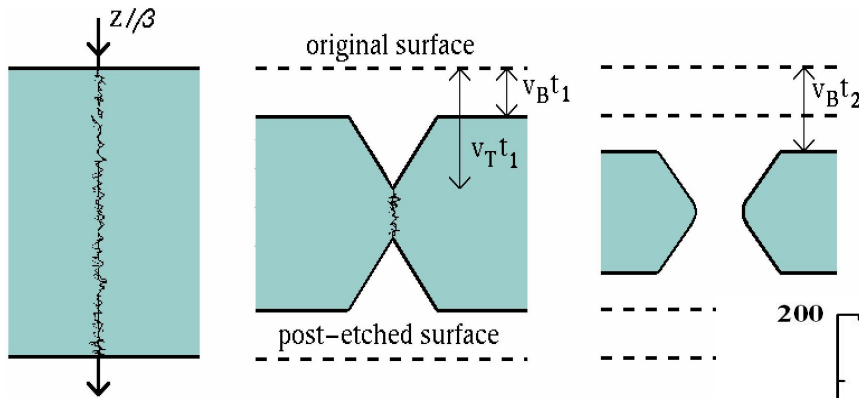


Redundancy & Complementarity

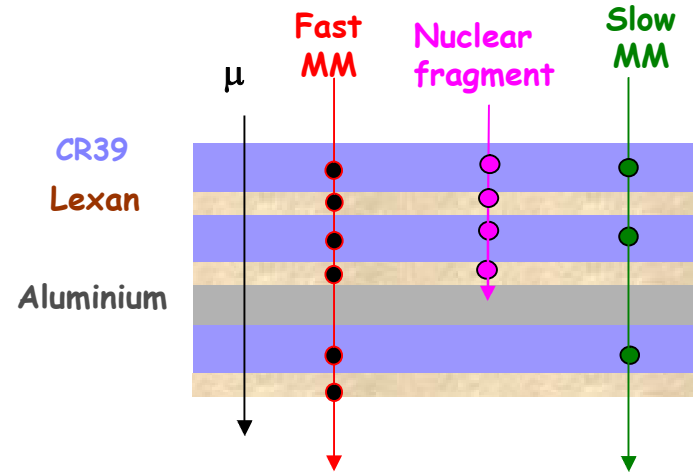
Nuclear Track Detectors

Total surface : $\sim 1263 \text{ m}^2$ ($S\Omega \sim 7100 \text{ m}^2 \text{ sr}$)

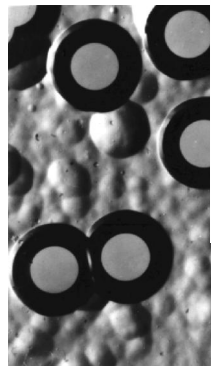
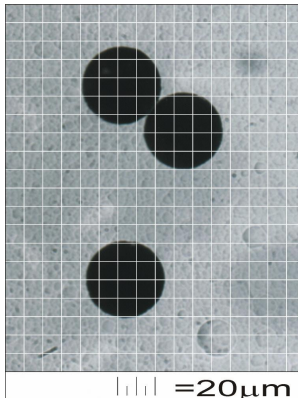
modules $24.5 \times 24.5 \text{ cm}^2$



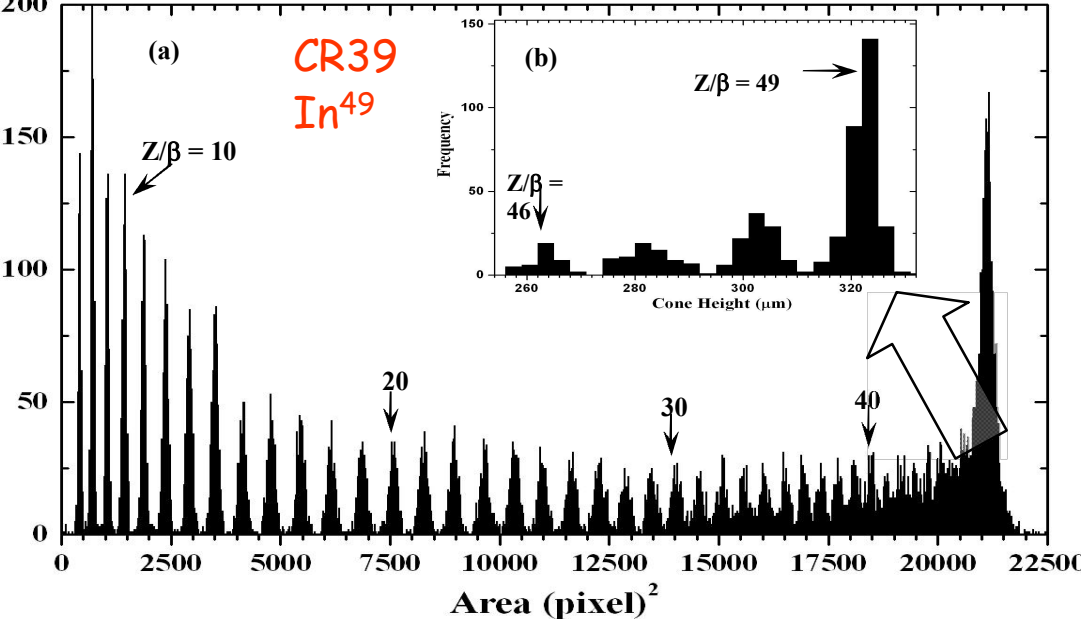
The track-etch technique



S^{16} ions
In CR39

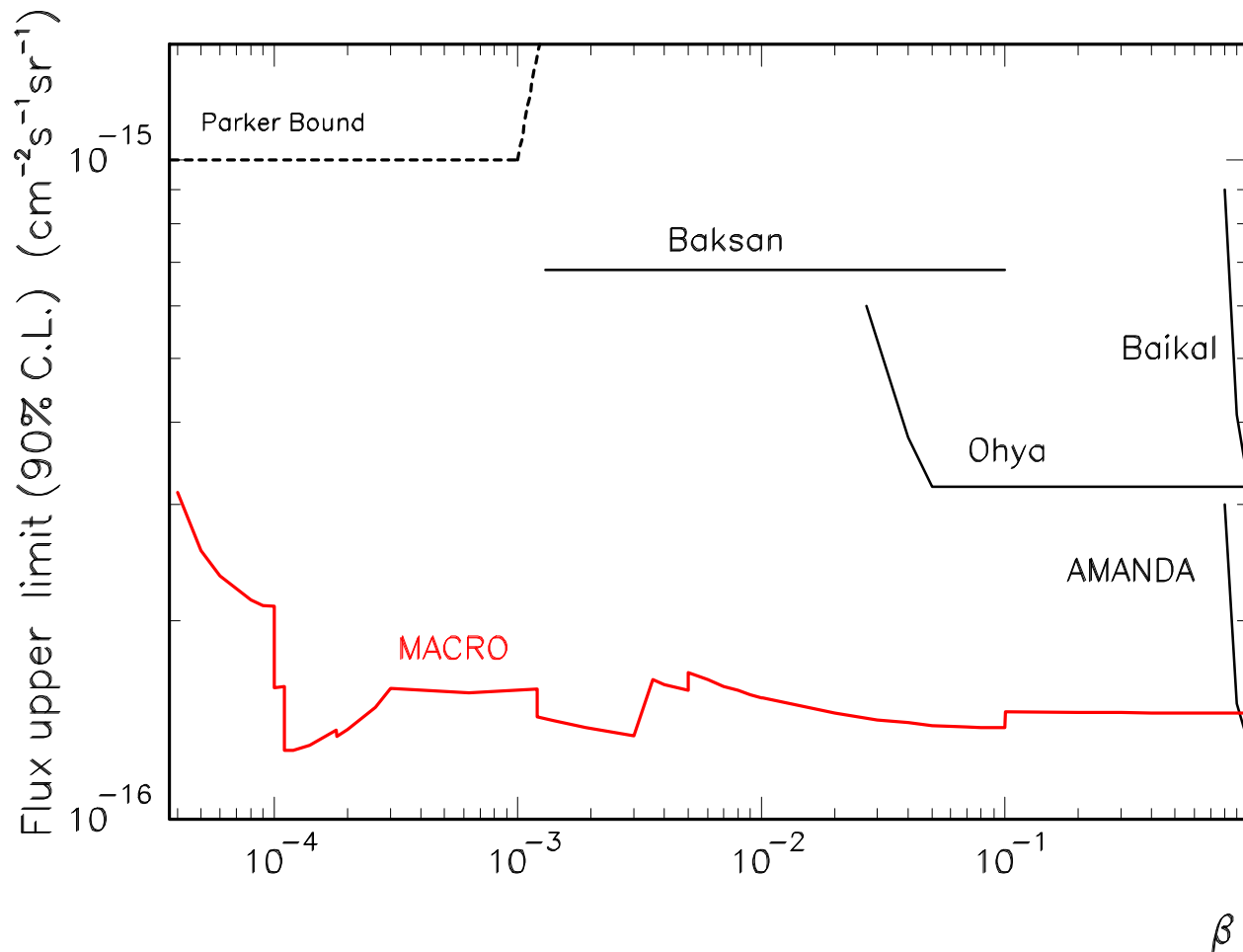


Number of events



Flux upper limits for GUT MMs

EPJ C25 (2002) 511



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

Catalysis of proton decay

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



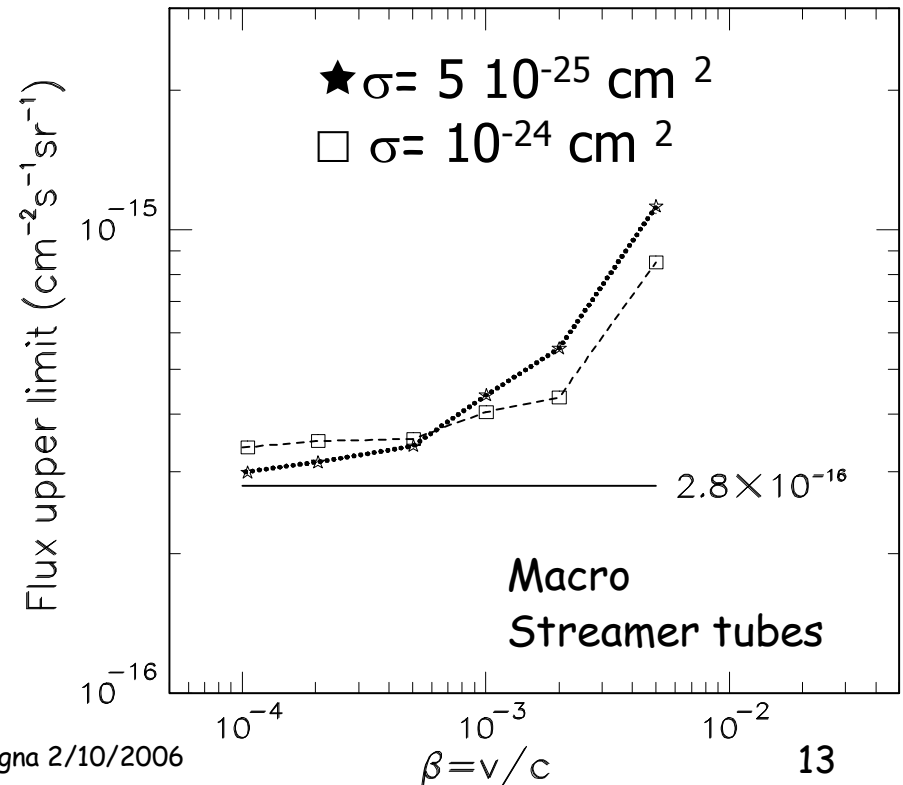
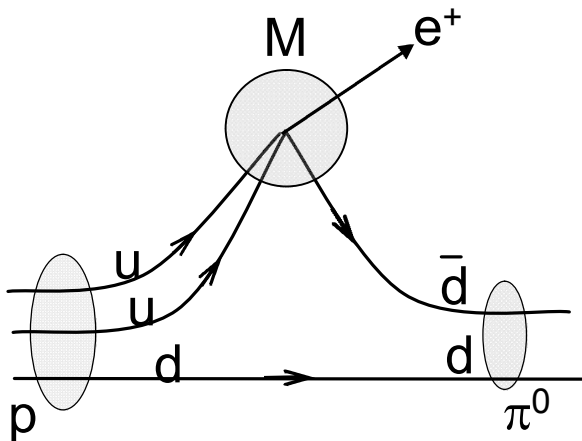
If $\sigma_{\Delta B \neq 0} \sim \sigma_{\text{core}} \sim 10^{-56} \text{ cm}^2 \sim \text{negligible}$

Rubakov-Callan mechanism

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

could see a string of p decays along MM trajectory

Illustration. Effect of the presence in the p of a $\Delta B \neq 0$, 4fermion condensate $e+d\bar{u}\bar{u}$



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

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

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

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

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

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

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

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

IMM searches at high altitudes

SLIM

Chacaltaya, Bolivia 5290 m asl →

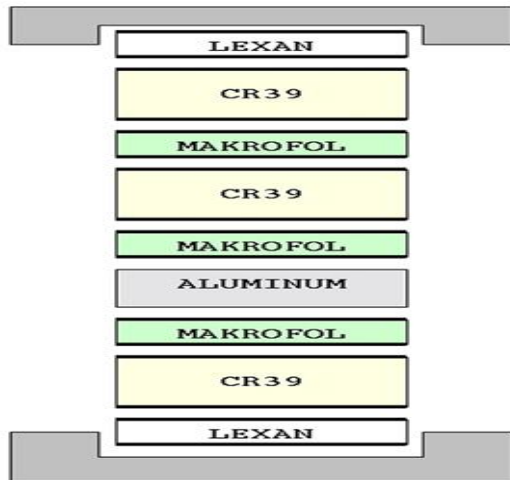
440 m² of nuclear track detectors

Koksil, Himalaya, 4275 m asl

100 m² of nuclear track detectors



Modules 24 x 24 cm²

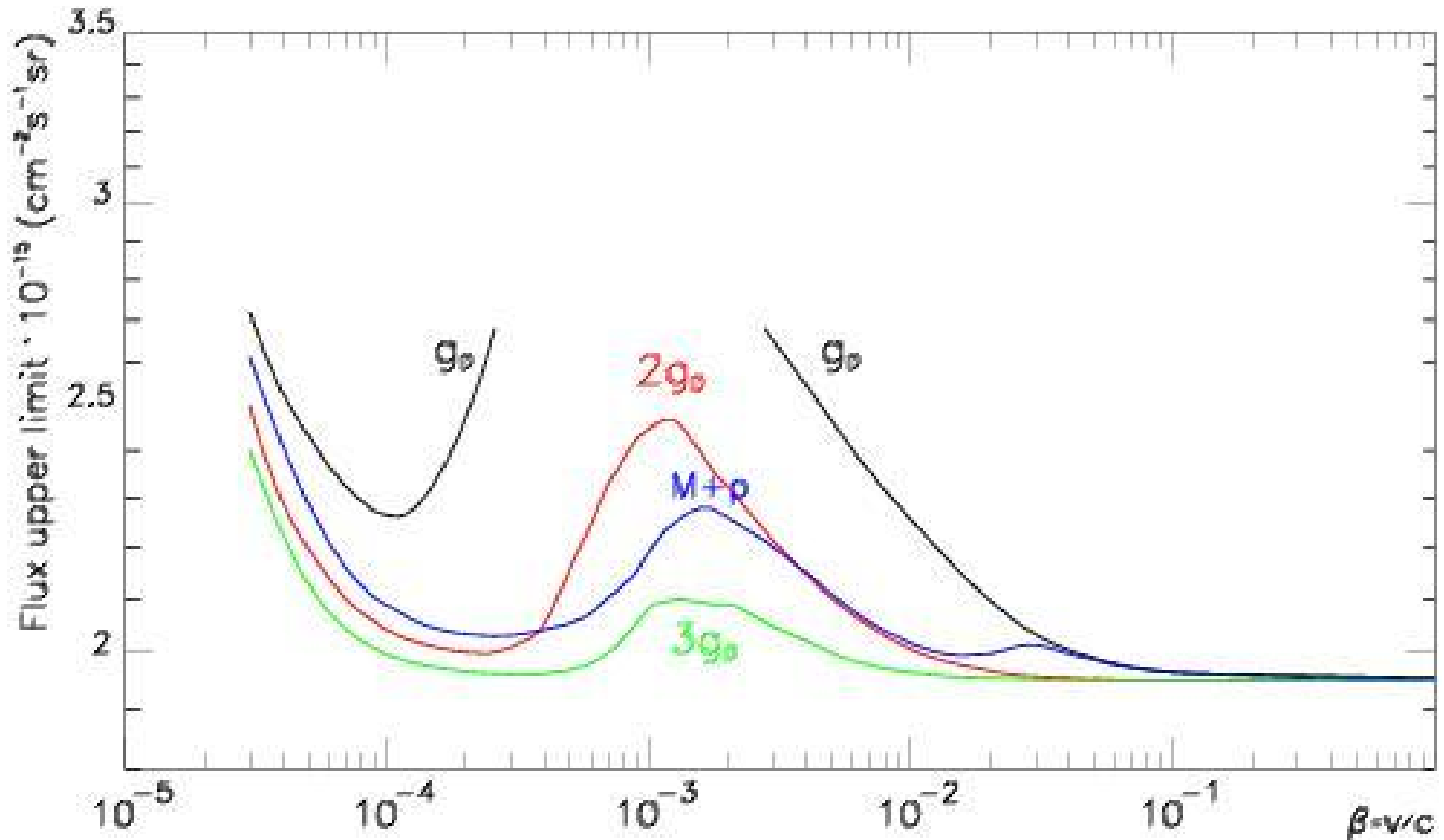


Present limit from the SLIM experiment

Analyzed area 308 m²; Exposure 3.9 y ;

905 CL limit $_{\text{at } \beta=1} = 1.9 \cdot 10^{-15} \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$

IMMs
from
above

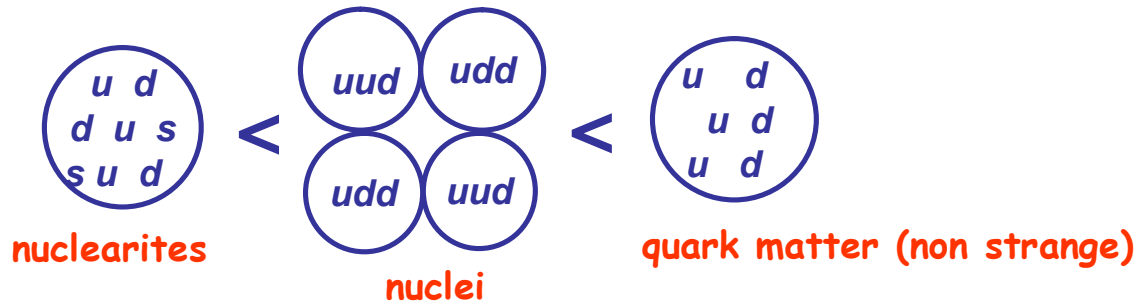


3. DM : Nuclearites

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

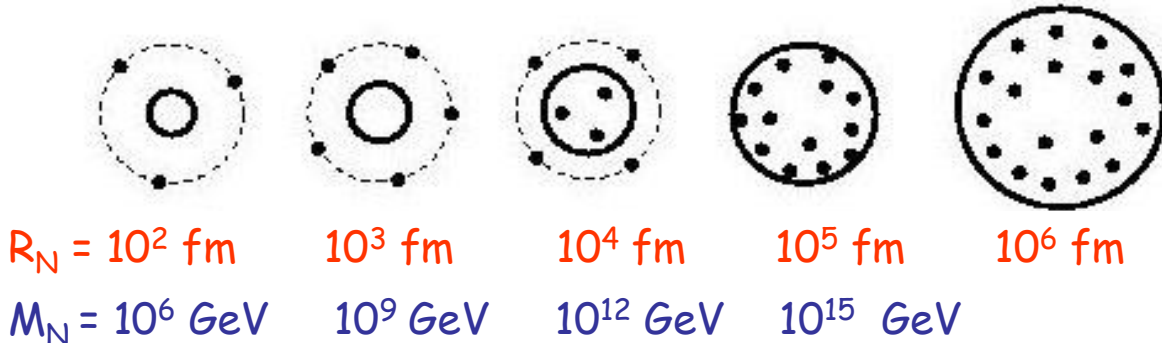
A. De Rujula, S. L. Glashow, Nature 312 (1984) 734

- 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 **baryon number A** : $\sim 300 < A < 10^{57}$
- $Z \sim A^{1/3} ? , \sim A^{2/3} ? ; Z/A \ll 1 , \rho_N \sim 3.5 \times 10^{14} \text{ g cm}^{-3}$ ($\rho_{\text{nuclei}} \sim 10^{14} \text{ g cm}^{-3}$)



Produced in Early Universe: **candidates** for cold **Dark Matter**
 Searched for in CR reaching the Earth
 Large energy losses in matter

Structure



black points
are electrons

Low mass nuclearites. Some predictions

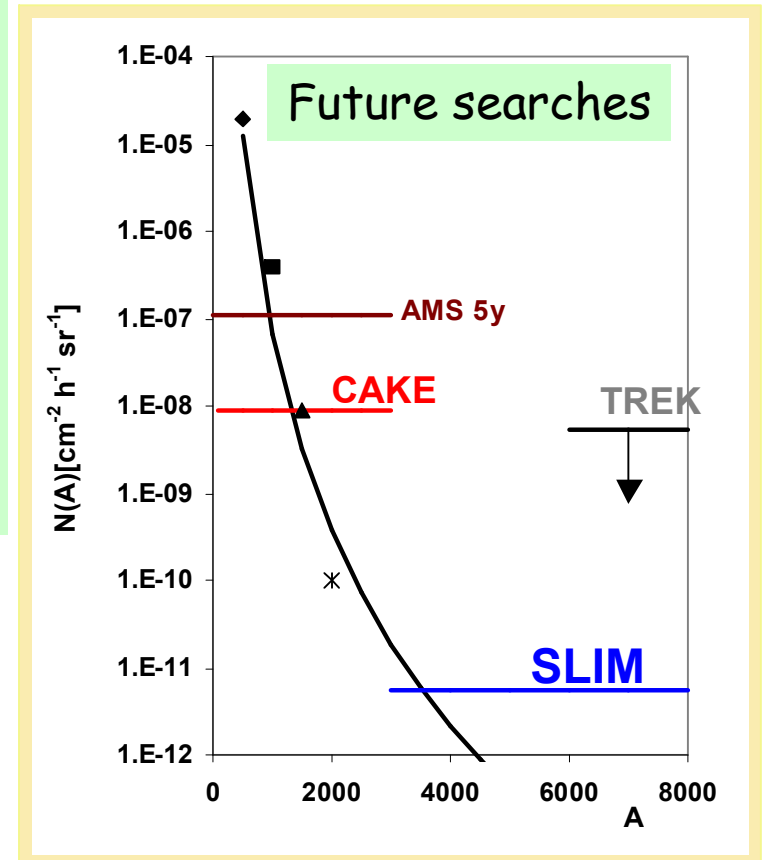
Flux of light nuclearites may increase strongly with decreasing mass

Flux could 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 : $7 \times 10^{-6} \text{ m}^{-2} \text{ h}^{-1} \text{ sr}^{-1}$ for $m_N > 3 \times 10^3$

SLIM: ~ 100 events in 4 y

present experimental limit: same as for fast MMs

Supersymmetric Q-balls

- S. Coleman, *Nucl. Phys. B*262 (1985), 263

- A. Kusenko et al., *Phys. Lett. B* 404 (1997) 285; *Phys. Lett. B* 405 (1997) 108;

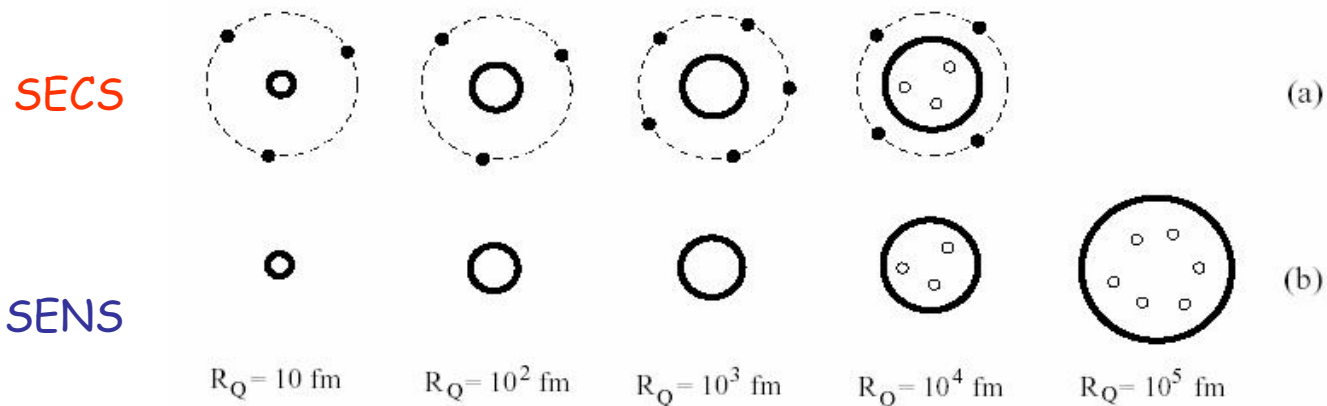
Q-balls : coherent states of **squarks**, **sleptons** and **Higgs fields**

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

- 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;

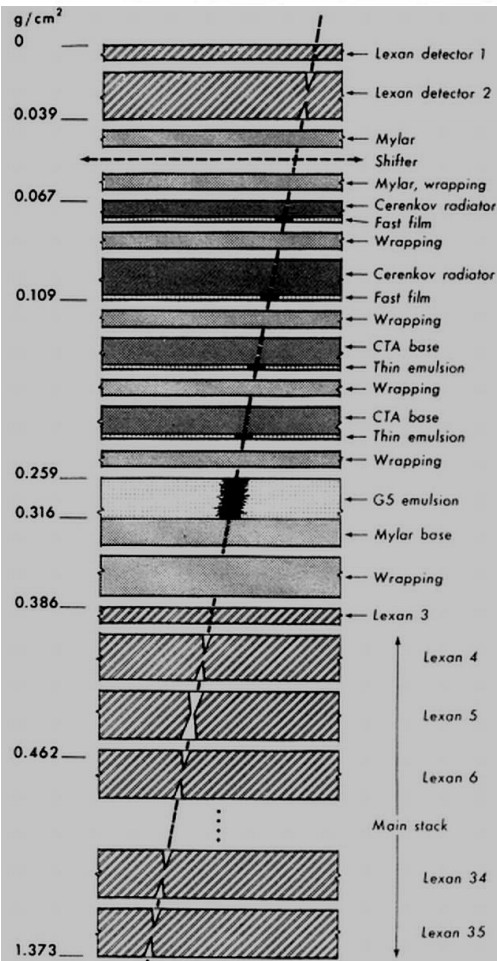
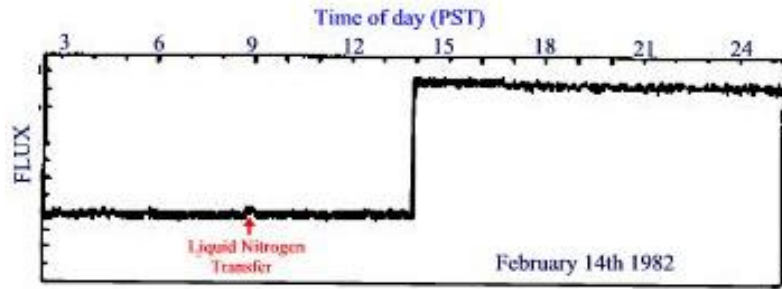
the black points indicate electrons, open circles indicate s-electrons.

4. Conclusions - Outlook

Several "exotic"(unexplained)events from CR experiments

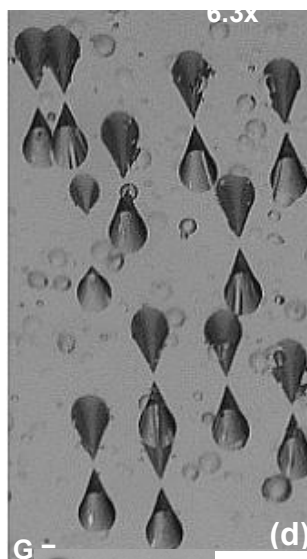
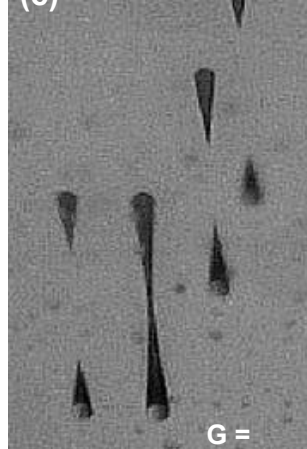
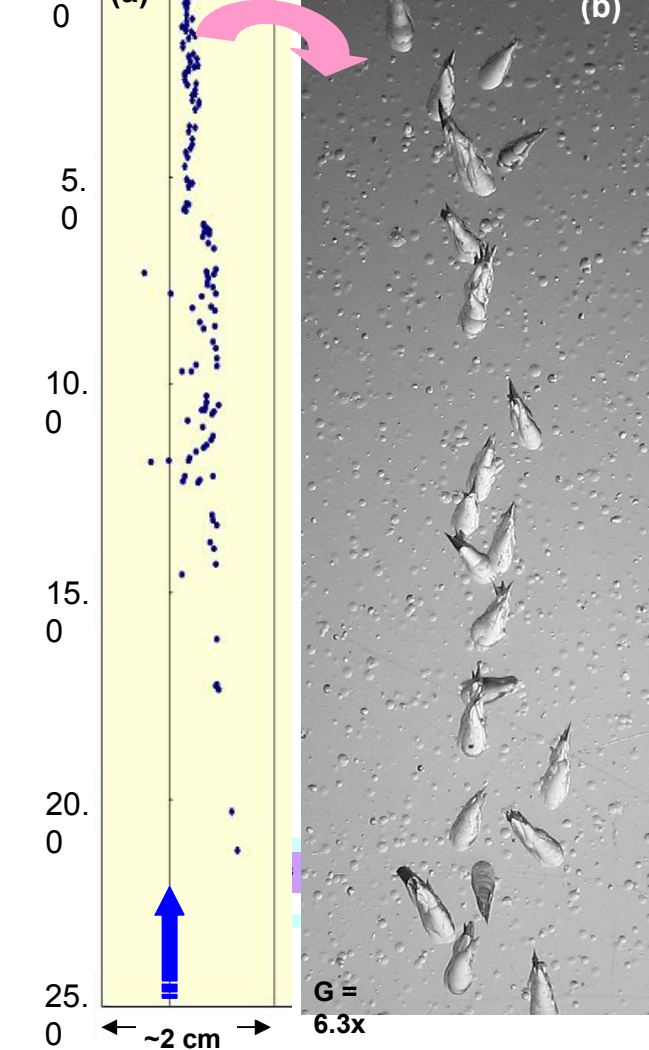
- Dirac MMs at accelerators $m_M > 0.9 \text{ TeV}$
In the future : at LHC probe $0.9 < m_M < 7 \text{ TeV}$
- Flux of GUT MMs in the cosmic radiation:
MACRO : $\Phi < 1.4 \cdot 10^{-16} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ for $4 \times 10^{-5} < \beta < 1$
Future: need new refined detectors with much larger surfaces
- IMMs:
Experiments at mountain altitudes $\Phi < 1.9 \cdot 10^{-15} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ from above
Future: need much larger detectors
Experiments with neutrino telescopes for $\beta > 0.6$
- Nuclearites: None found; limits ~ as for fast GUT MMs
- Q-balls " "

Some particles were thought to have been discovered



The "Price Event":
 PRL 35 (1975) 0486
 Balloon flight-10 m²
 NTDs+emulsions+Č films.





Strong etching

Probably an extremely rare manufacturing defect involving 1 m² of CR39.

Soft+strong etching

| | | | | | | |
|------|------|----------------|------------------------|----------------|-------------|------|
| 7247 | 7248 | 7249 | 7250 | 7251 | 7252 | 7253 |
| 7313 | 7314 | 7315 | 7316 | 7317 | 7318 | 7319 |
| 7339 | 7340 | 7341 (6.93) | 7342 (6.80) | 7343 (6.90) | 7344 | 7345 |
| 7405 | 7406 | 7407 (7.35) | 7408 (7.33) | 7409 (7.09) | 7410 | 7411 |
| 7431 | 7432 | 7433 (7.18) | 7434 (6.78) | 7435 (7.24) | 7436 | 7437 |
| 7457 | 7458 | 7459 | 7460 | 7501 | 7502 | 7503 |
| 7523 | 7524 | 7525 | 7526 | 7527 | 7528 | 7529 |

