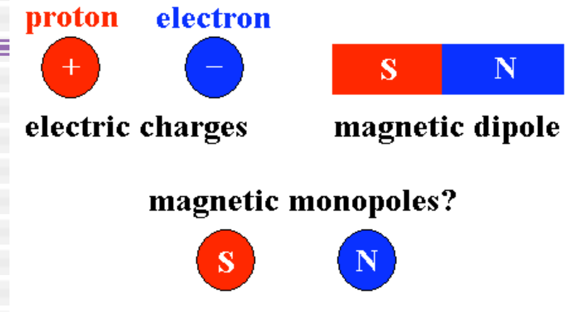
Searches for Exotica

- Introduction
- Classical Dirac MMs
- Searches for classical MMs
- GUT MMs
- Searches for GUT MMs
- Intermediate mass MMs
- Nuclearites and Q-balls
- Conclusions

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

1990s: Intermediate Mass Magnetic Monopoles

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

  $g_D = \hbar c\, /2e = e/2\alpha = 68.5\, e = 3.3\text{x}\, 10^{-8}$ 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** $\alpha_M = g^2_D/\hbar c = 34.25$

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

$\beta > 0.04$ $(dE/dx)_{MM,C} \cong 0.72(9.0 + \ln \beta^2)$ GeV g^{-1} cm^2

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

$(dE/dx)_{MM,Al} \cong (20 + 130)\ \beta$ GeVg^{-1}cm^2

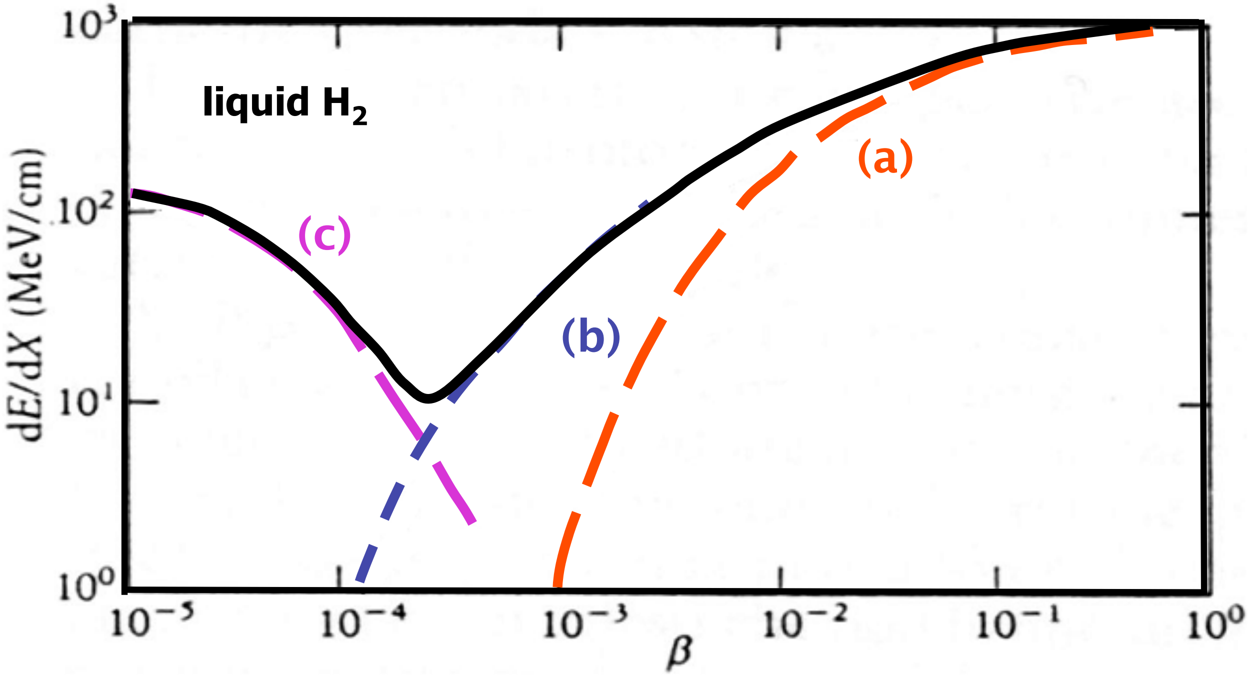
$10^{-4} < \beta < 10^{-3}$ Drell effect $M + He \rightarrow M + He^*$

+ 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)



Seeking Monopoles at Accelerators

$$e^+e^- \to MM\,,\ \ \bar{p}p \to M\bar{M}\,,\ \ pp \to ppM\bar{M}$$

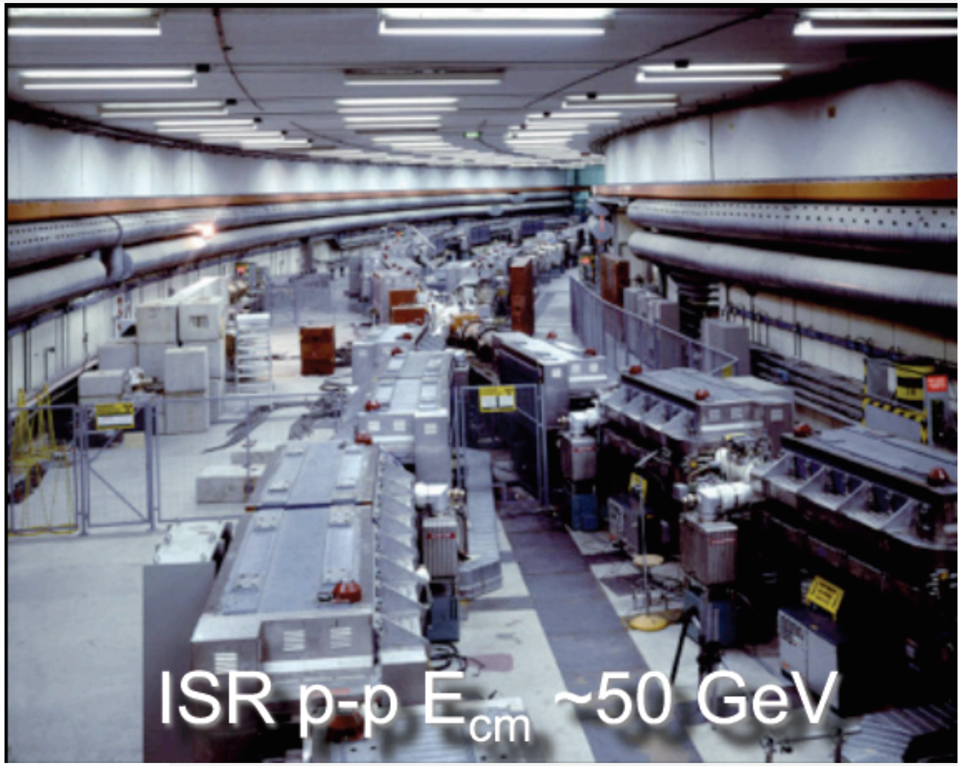
- **DIRECT Experiments** –

 Poles produced and detected immediately

Searches with:

  - Scintillation counters & Wire chambers
  - Plastic Nuclear Track Detectors

- **INDIRECT Experiments** – monopoles are:
  - Produced, stopped and trapped in matter – (eg beam pipe)
  - Later they are extracted, accelerated & detected.



Accelerator based searches

Accele-Rator	Reaction	Beam Energy Gev	√s GeV	Mass limit GeV	Cross Section cm^2	MM Charge	TECN	Year	Ref.
LBL	pA	6.2	3.76	<1	1.e-40	1	EMUL	1959	14
CERN	pA	28.0	7.6	<3	1.e-35	<4	CNTR	1961	15a
AGS	pA	30.0	7.86	<3	2.e-40	<2	CNTR	1963	15
CERN	pA	28.0	7.6	<3	1.e-40	<2	EMUL	1963	15b
IHEP	pA	70.0	11.9	<5	1.e-41		EMUL	1972	16
FNAL	pA	400	28.3	<13	5.e-42	<24	CNTR	1974	17a
ISR	pp	60	60	<30	1.e-36	<3	PLAS	1975	25
FNAL	pA	400	28.3	<12	5.e-43	<10	INDU	1975	17
FNAL	pA	300	24.5		2.e-30		OSPK	1975	17b
IHEP	pA	70	11.9	<5	1.e-40	<2	CNTR	1976	17c
CERN	pp	56	56	<30	1.e-37	<3	PLAS	1978	26
CERN	pp	63	63	<20	1.e-37	<24	CNTR	1978	17d
SLAC	e+e-	29	29	<30	4.e-38	<3	PLAS	1982	27
CERN	pp	52	52	<20	8.e-36		CNTR	1982	24
CERN	e+e-	34	34	10	4.e-38	<6	PLAS	1983	29
CERN	pp	540	540		1.e-31	1,3	PLAS	1983	18
SLAC	e+e-	29	29		3.e-38	<3	PLAS	1984	28
FNAL	pap	1800	1800	<800	3.e-38	>=1	PLAS	1987	18a
CLEO	e+e-	10.6	10.6	<4	9.e-37	<0.15	CLEO	1987	18b
CERN	e+e-	50-52	50-52	<24	8.e-37	1	PLAS	1988	18c
DESY	e+e-	35	35	<17	1.e-38	<1	CNTR	1988	30
KEK	e+e-	50-61	50-61	<29	1.e-37	1	PLAS	1989	31
FNAL	pp	1800	1800	<850	2.e-34	>=0.5	PLAS	1990	23
CERN	e+e-	88-94	88-94	<45	3.e-37	1	PLAS	1992	32
CERN	e+e-	88-94	88-94				PLAS	1993	33
CERN	PbA	160A	17.9	<8.1	1.9e-33	>=2	PLAS	1997	18d
AGS	AuAu	11A	4.87	<3.3	0.65e-33	>=2	PLAS	1997	18d
FNAL	pap	1800	1800	260-420	7.8e-36	2-6	INDU	2000	19
FNAL	pap	1800	1800	265-410	0.2e-36	1-6	INDU	2004	20
HERA	e+p	300	300		0.5e-37	1-6	INDU	2005	22
FNAL	pap	1800	1800	369	0.2e-36	>=1	CNTR	2006	34

32 searches

14 using plastic NTDs

3 using emulsions

3 using induction

12 using counters

Direct limit from LEP2

Phys. Lett. B663, 37. (2008)

Search for pair produced MMs with the OPAL jet chamber

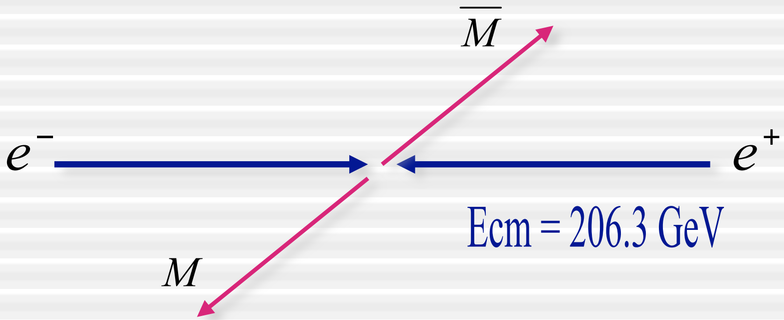
$$e^+e^- \longrightarrow \gamma^* \longrightarrow M\,\bar{M}$$

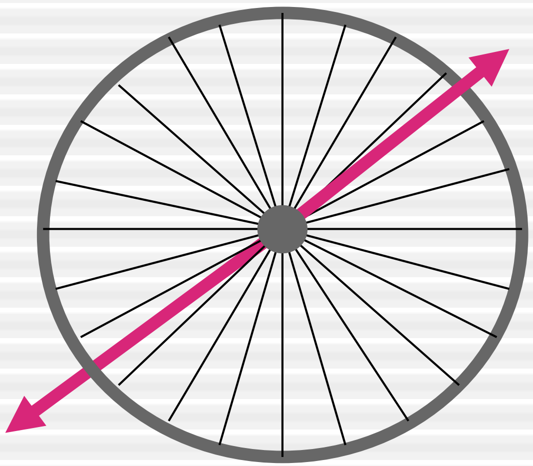
Monte Carlo simulations assuming $\alpha_{MM} >> \alpha$ for 45 GeV $< m_M <$ 104 GeV,

Uniform azimuthal distribution and $(1 + \cos^2\theta)$ polar angle distribution

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

Search for back to back tracks → 2 opposite CJ sectors with high energy release

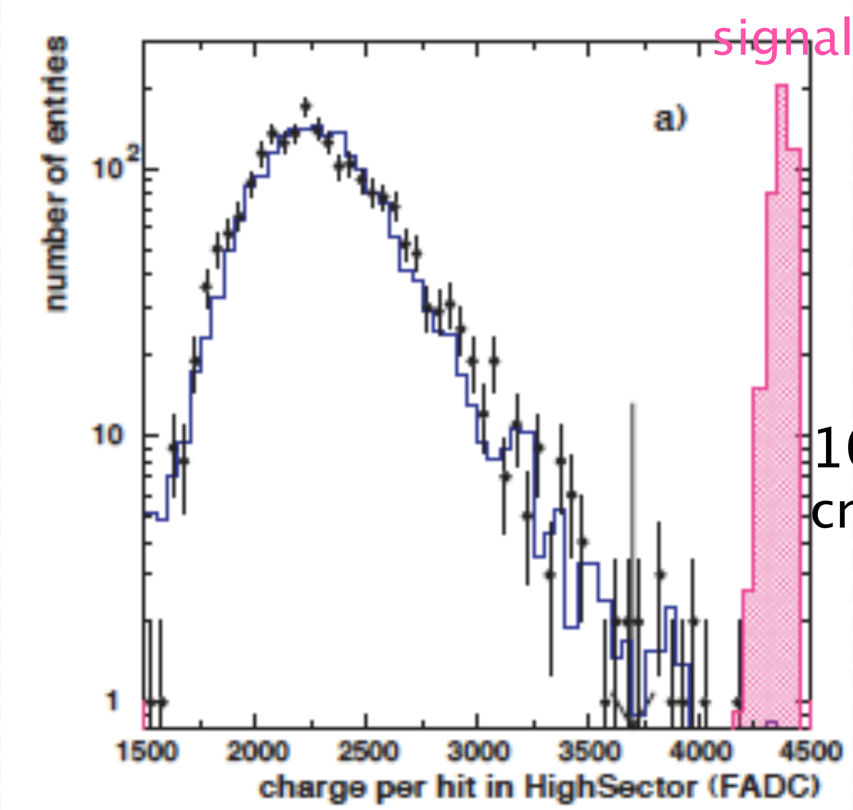




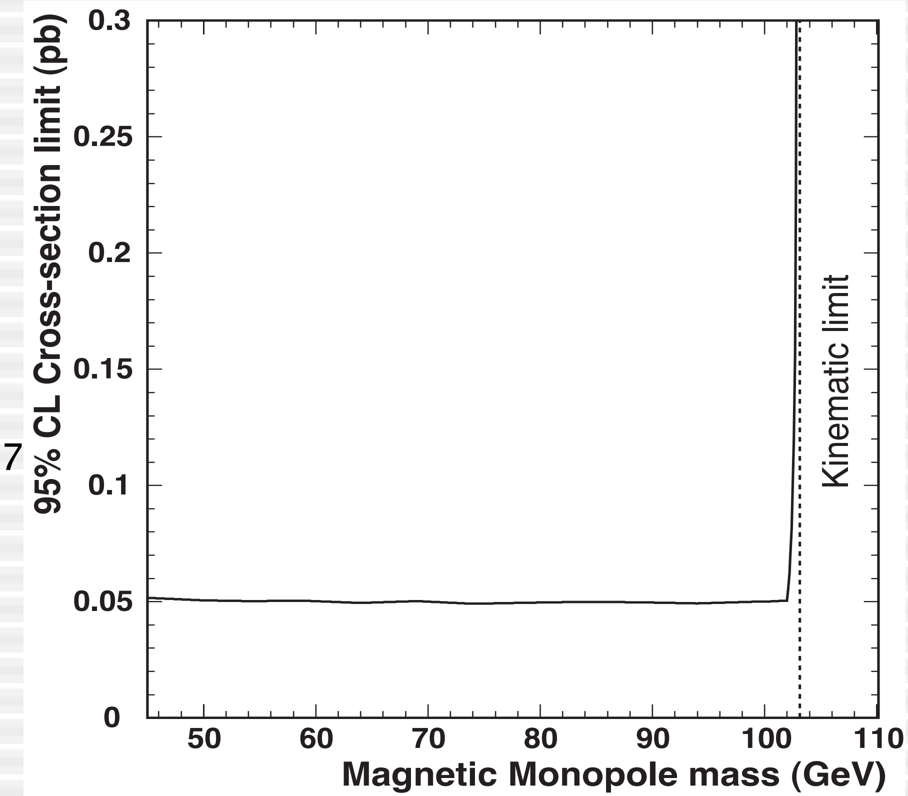
New direct limit from a LEP2 experiment

MonteCarlo

MM signal



10^{-37} cm^2



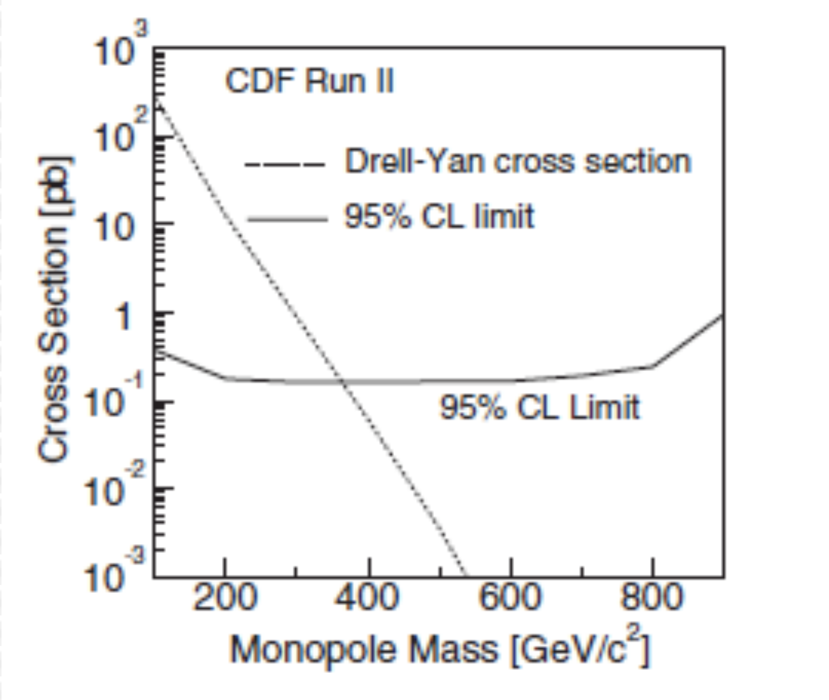
MM search at the Tevatron

(PRL 96, 201801 (2006))

CDF: Direct Search in $p\bar{p}$ Collisions

35.7 pb^{-1} sample of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV collected by CDF in 2003
Central Outer Tracker and TOF detectors
1.5 T magnetic field parallel to the beam direction

MM pair production excluded (95% CL) for cross sections greater than 0.2 pb for $200 < M_M < 700$ GeV/c^2



MMs search at HERA (H1 Coll.)

Two models:

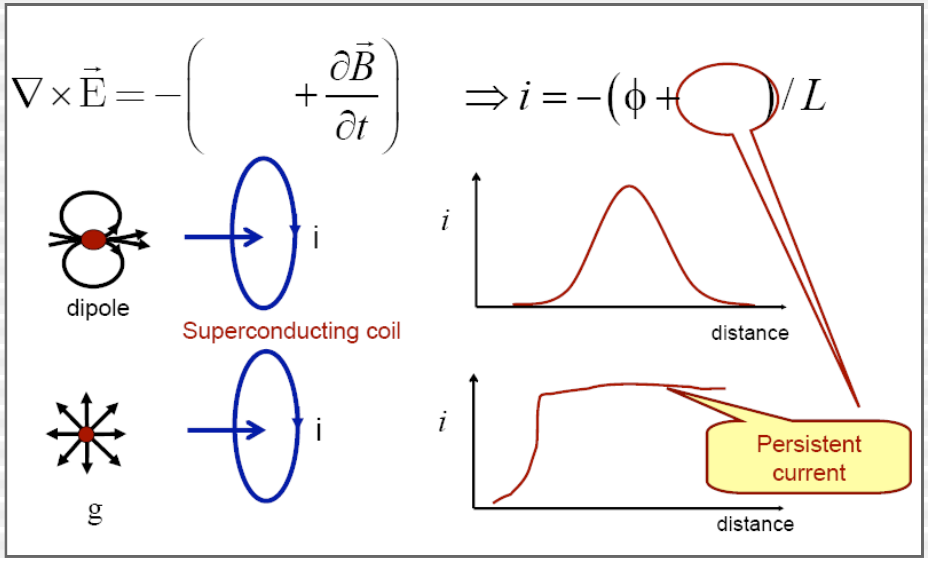
$$e^+p \rightarrow M\overline{M}\, e^+p$$

$$e^+p \rightarrow M\overline{M}\, e^+X$$

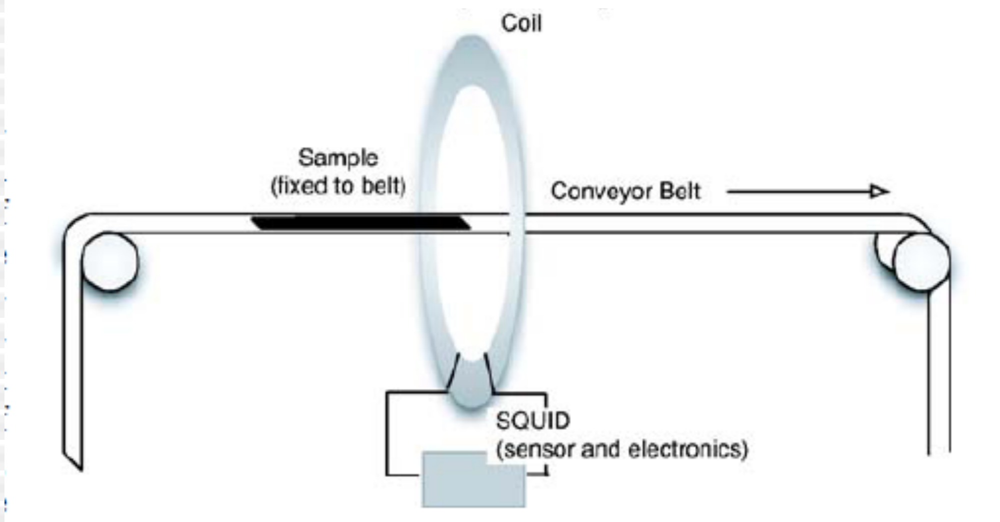
Luminosity = 62 ± 1 pb^{-1} $\sqrt{s} = 300$ GeV

MMs:
- Produced in : 1995 – 1997
- Stopped in the beam pipe
- Trapped

Later:
- Beam pipe cut into long strips
- MM in supercond.coil+SQUID

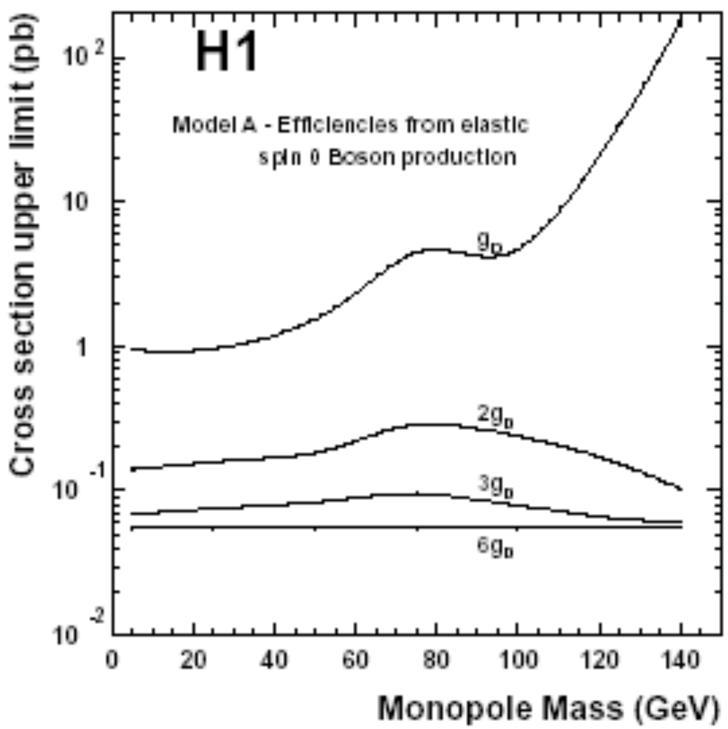


Superconducting coil

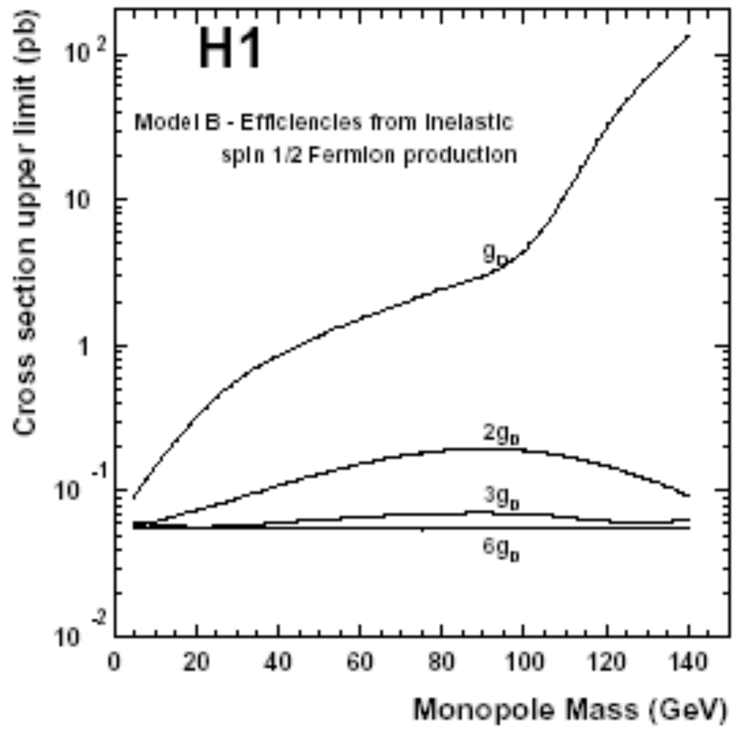


Model dependent upper limits on cross section

MM as a Boson



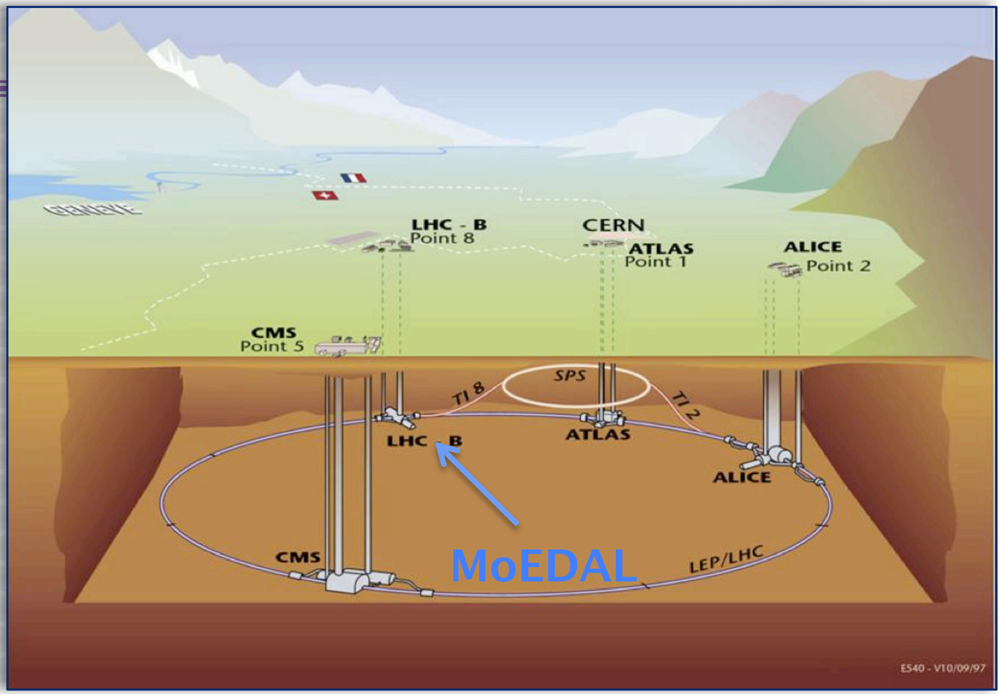
MM as a Fermion

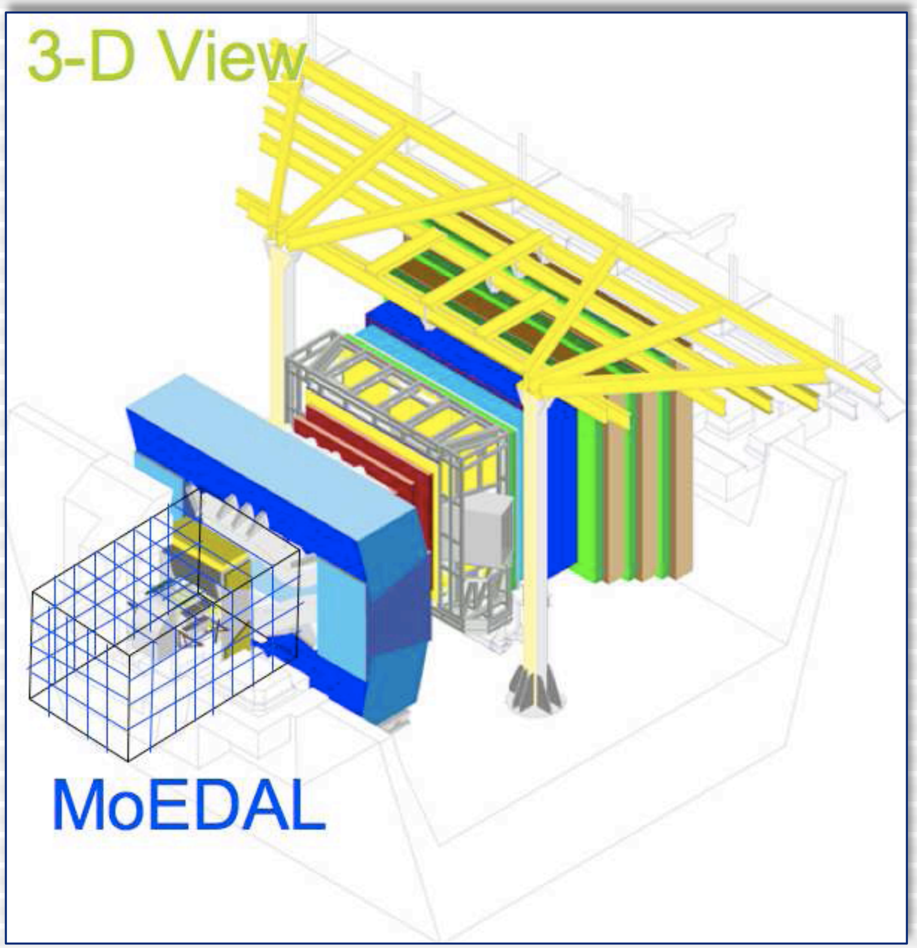


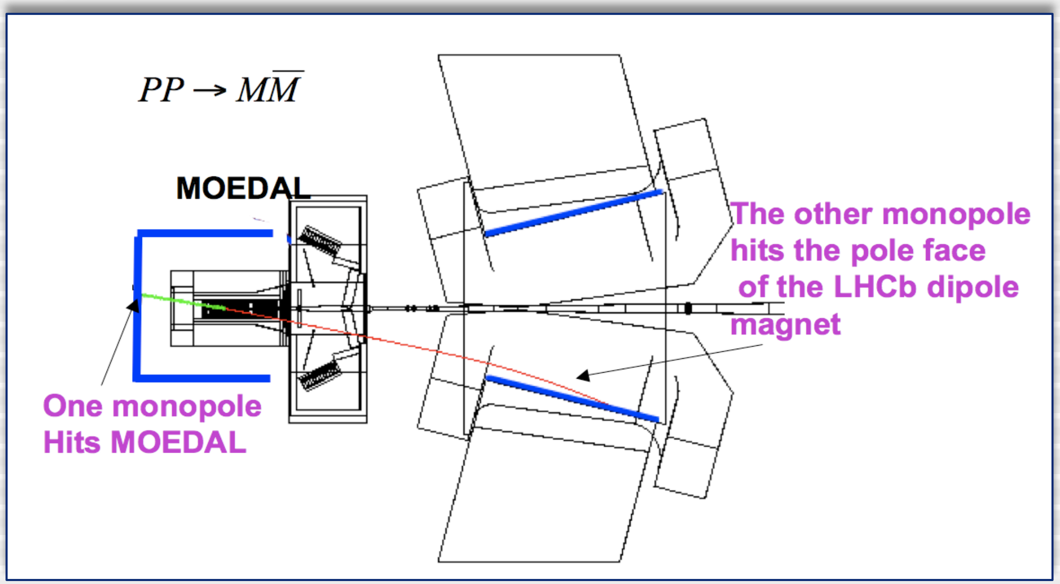
Eur. Phys. J. C 41, 133-141 (2005)

MoEDAL : Monopole Search at LHC

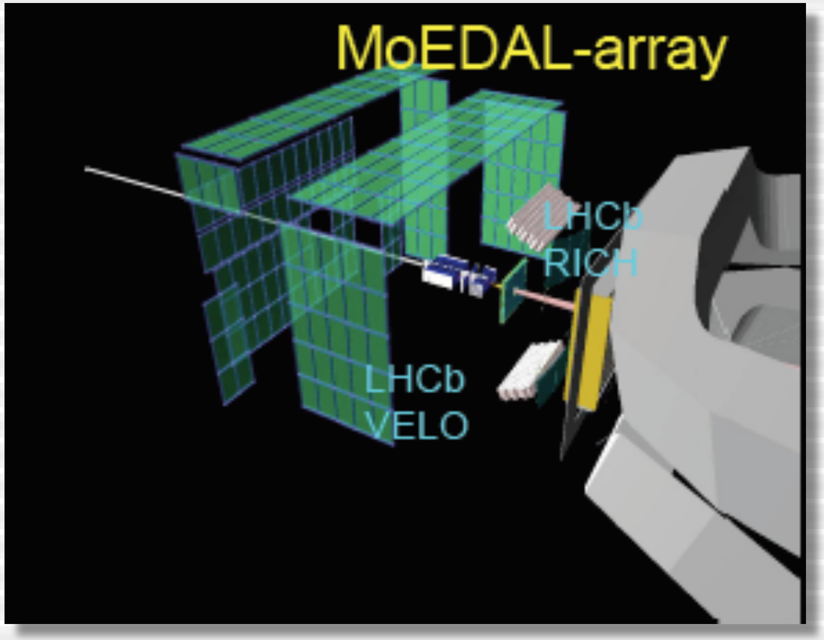
MoEDAL will be housed in the VELO Cavern of the LHCb Detector

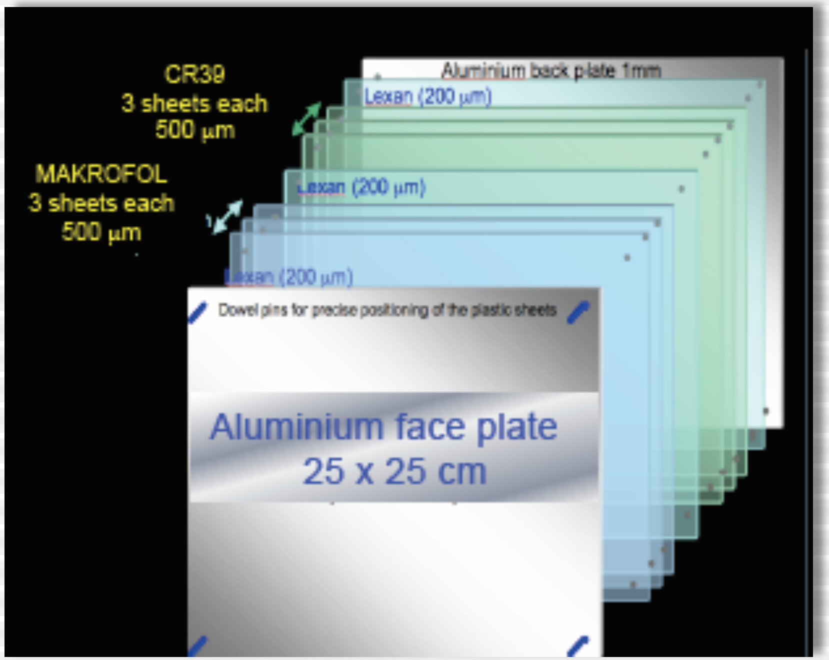






The MoEDAL Detector at LHC



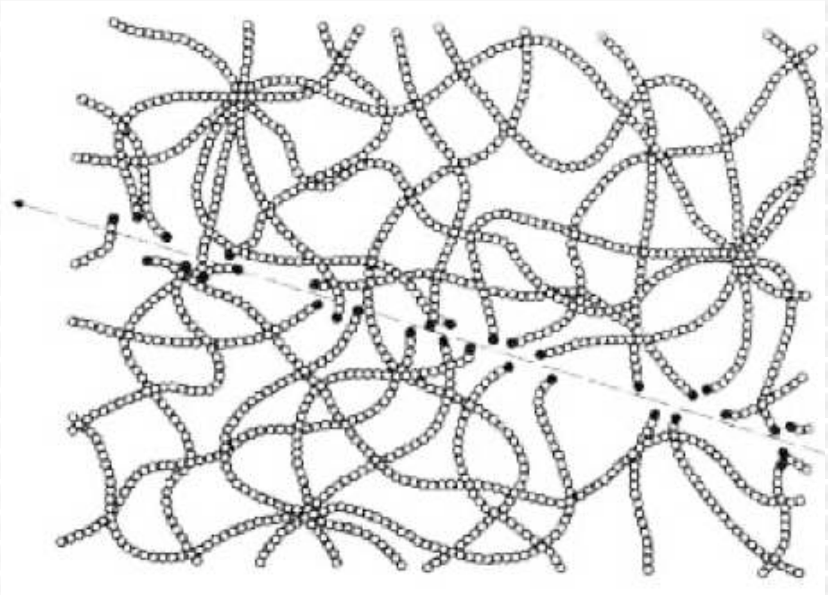


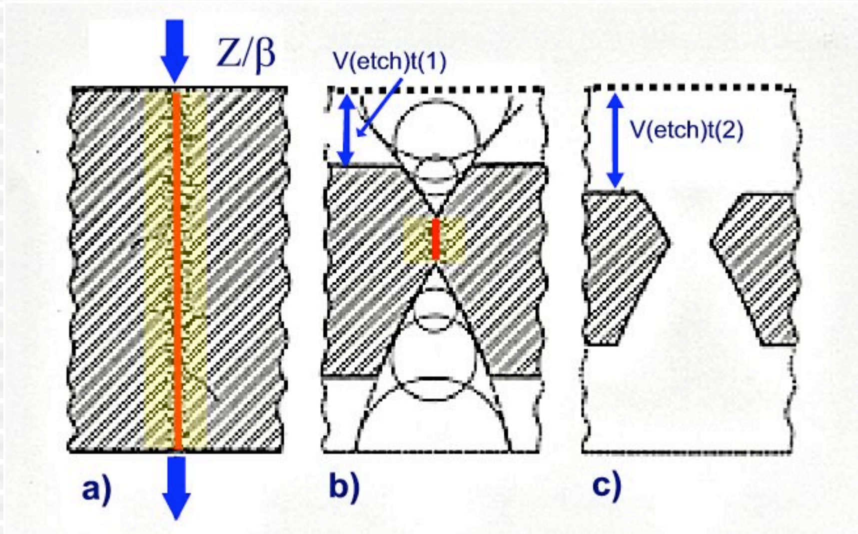
- dedicated to the search for highly ionizing exotic particles, using plastic track-etch detectors
- MoEDAL will run with p-p collisions at a luminosity of 10^{32} cm^{-2} s^{-1} and in heavy-ion running
- It can detect up to a 7 TeV mass monopole with charge up to ~3g

BASIC UNIT
- 3 layers of Makrofol (each 500 mm thick)
- 3 layers CR39 (each 500 mm thick)
- 3 layers of Lexan (each 200 mm thick)
- Sheet size 25 x 25 cm

◆Test deployment in 2009
full deployment of detectors in 2010

Track Etch Detectors





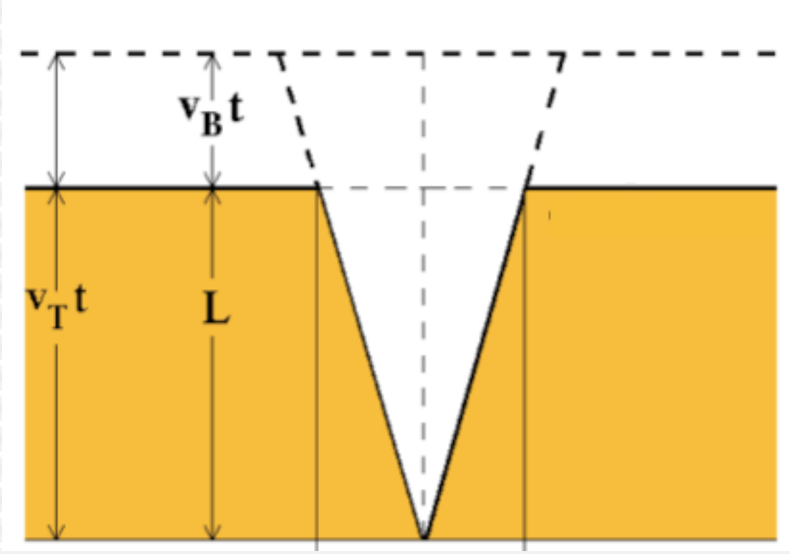
- The passage of a highly ionizing particle through the plastic track-etch detector (eg CR39) is marked by an invisible damage zone (“latent track”) along the trajectory.

- Under a proper chemical etching a “μ”-cone shaped etch-pit is formed :

$v_T = v_{Track}$ (etchant, Restricted Energy Loss,...

$v_B = v_{Bulk}$ (etchant,..) $v_T > v_B$

$\mathbf{p} = v_T / v_B \approx f$ (REL..)



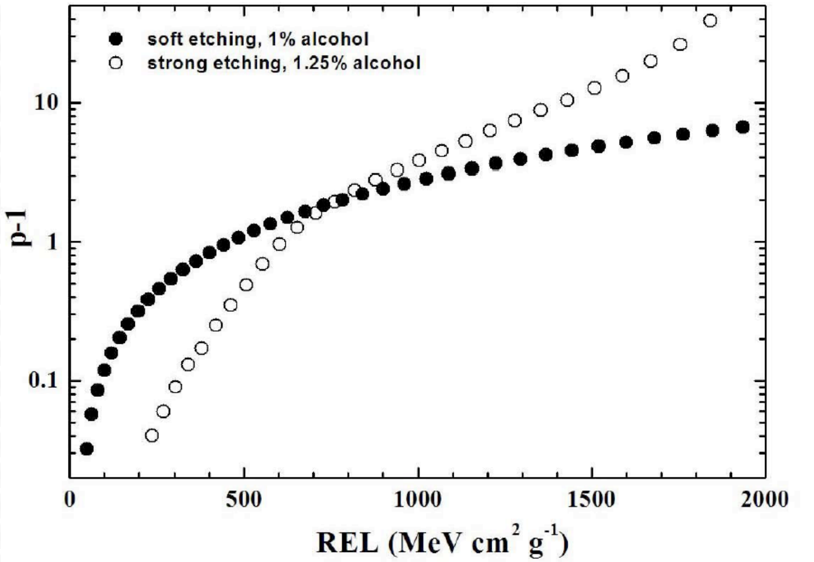
Base cone diameter

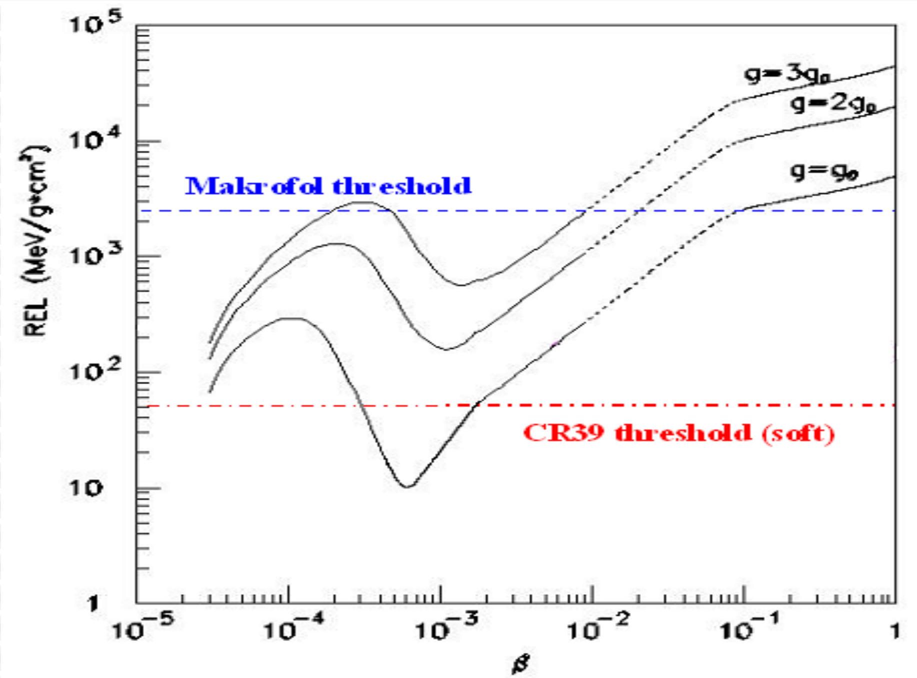
$$\mathbf{D} = 2 v_B t \sqrt{[(\mathbf{p}-1)/\mathbf{p}+1)]}$$

Cone length:

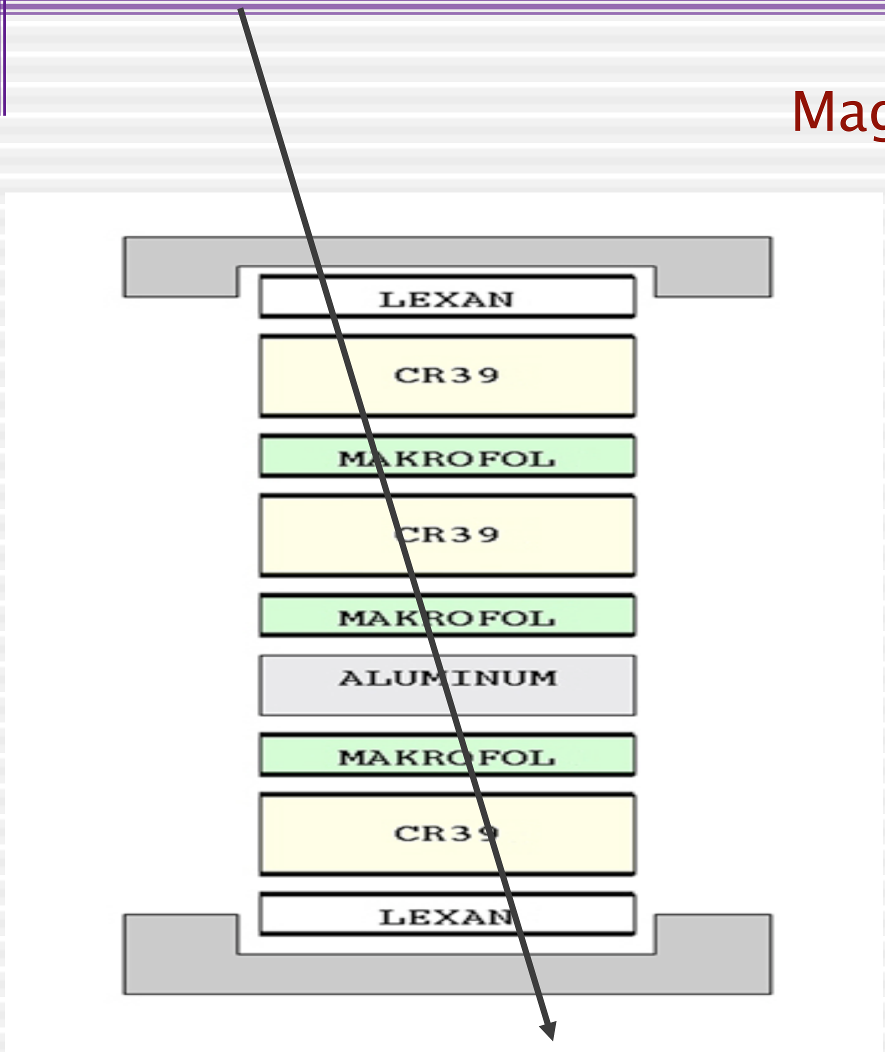
$$\mathbf{L} = (\mathbf{p}-1)\, v_B\, t$$

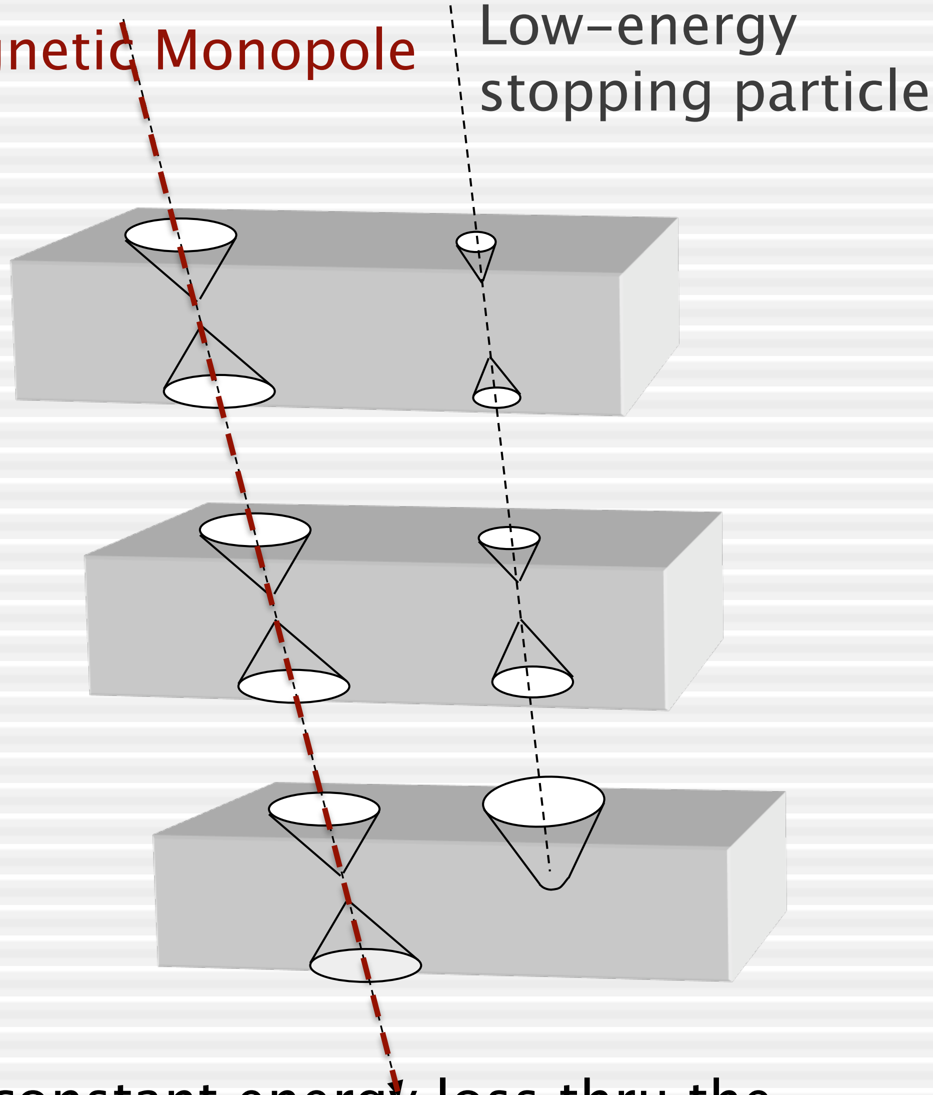
By calibration with heavy ion beams





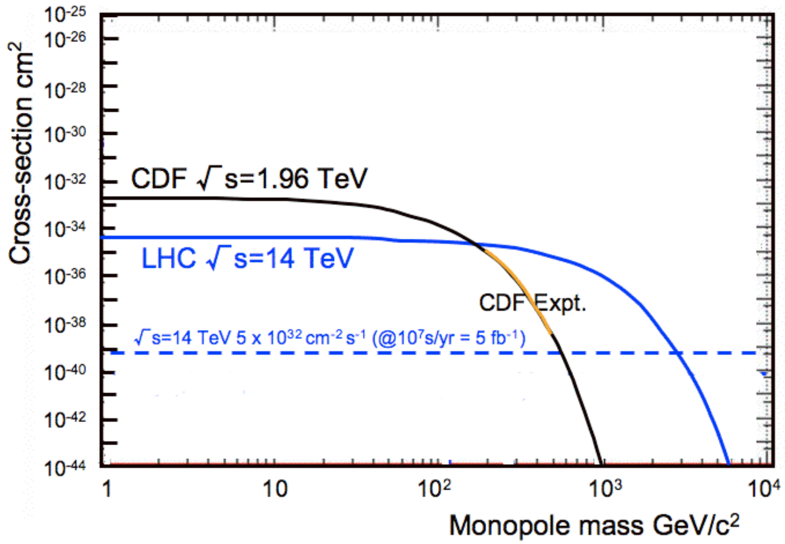
The search technique

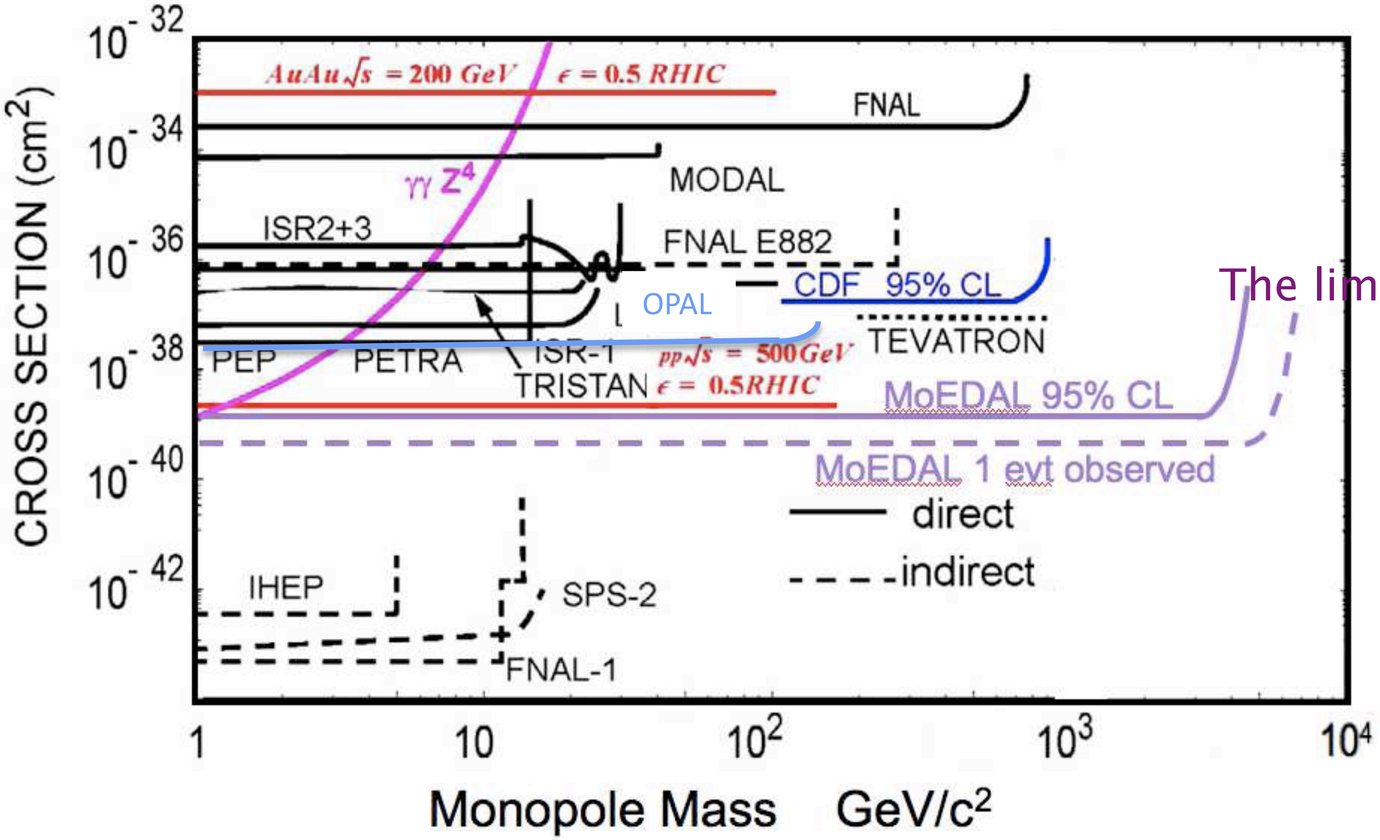




The signal: collinear etch pits + constant energy loss thru the detector foils

Physics Reach for MM





The limit curve for 10fb^{-1}

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

Gauge theories of unified interactions predict MMs

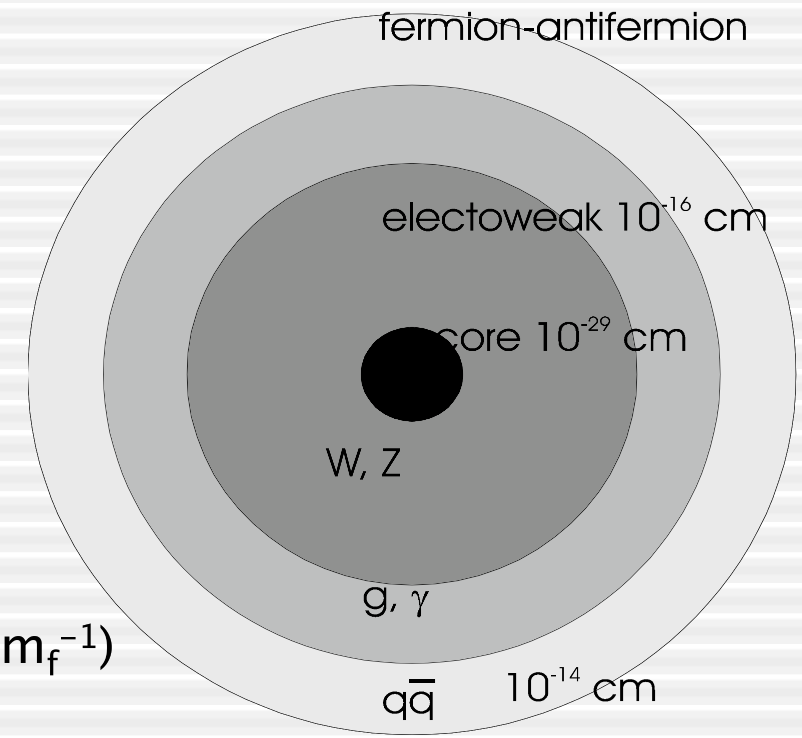
$$SU(5) \xrightarrow[10^{-35}\,s]{10^{15}\,GeV} SU(3)_C \times [SU(2)_L \times U(1)_y] \xrightarrow[10^{-9}\,s]{10^{2}\,GeV} SU(3)_C \times U(1)_{EM}$$

✱**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)

✱**MM Structure**

- grand unification core
  - virtual X–bosons (10^{-29} cm)
- electroweak unification
  - virtual W, Z, γ, g (10^{-16} cm)
- confinement region
  - g, γ (10^{-13} cm)
- condensate
  - fermion–antifermion pairs ($r \sim m_f^{-1}$)
- **r > few fm B ~ g/r^2**



GUT MMs

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

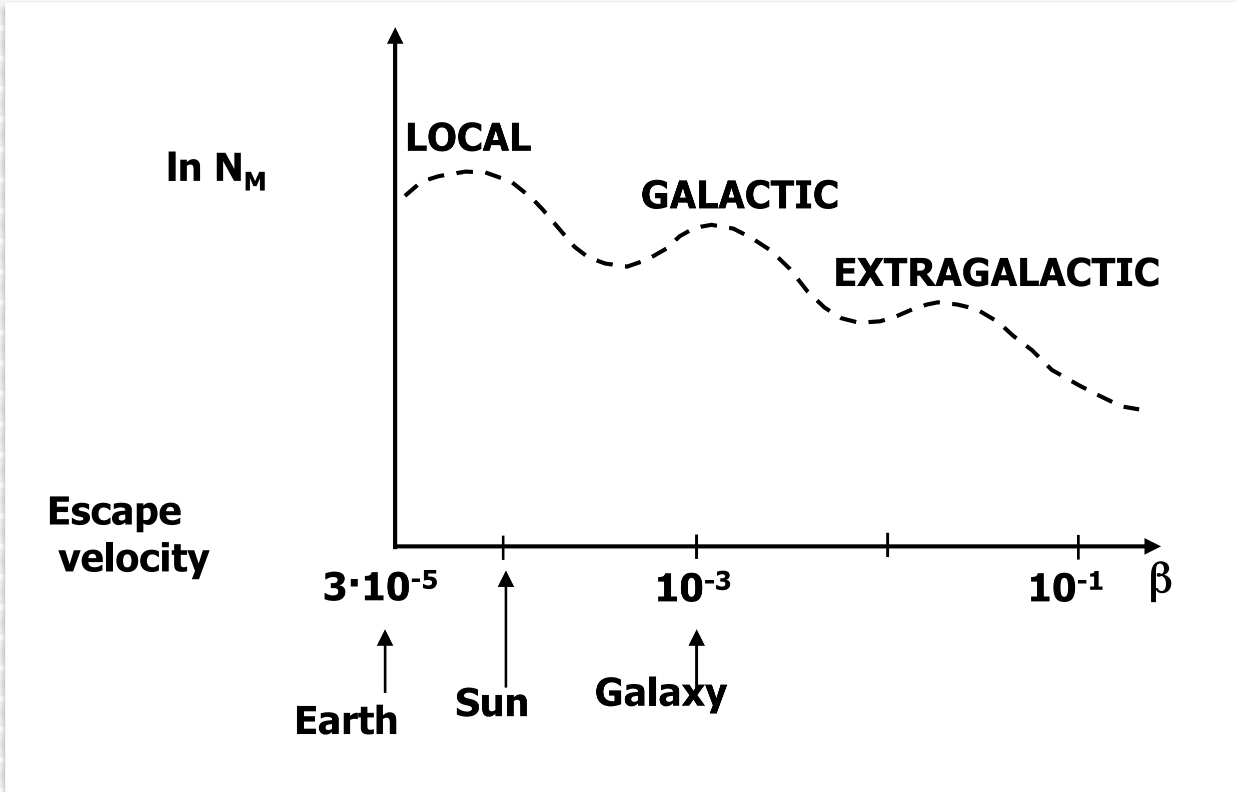
- ✱Production: In the Early Universe at G.U.T. phase transition
  - – as topological defects G→U (1) x … ($t \sim 10^{-35}$ s)
  - – in high energy collisions ($t \sim 10^{-34}$ s)

$$e^+ e^- \rightarrow M \overline{M}$$
$$q \overline{q} \rightarrow M \overline{M}$$

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

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

Expected MM velocities are related to the escape velocity of the system in which they are confined



Bounds on MM flux

- **Survival of galactic magnetic fields**
  "Parker Bound" (TPB)

$\Phi_{TPB} < 10^{-15}\ cm^{-2}\ s^{-1}\ sr^{-1}$ for $\beta < 3\ 10^{-3}$

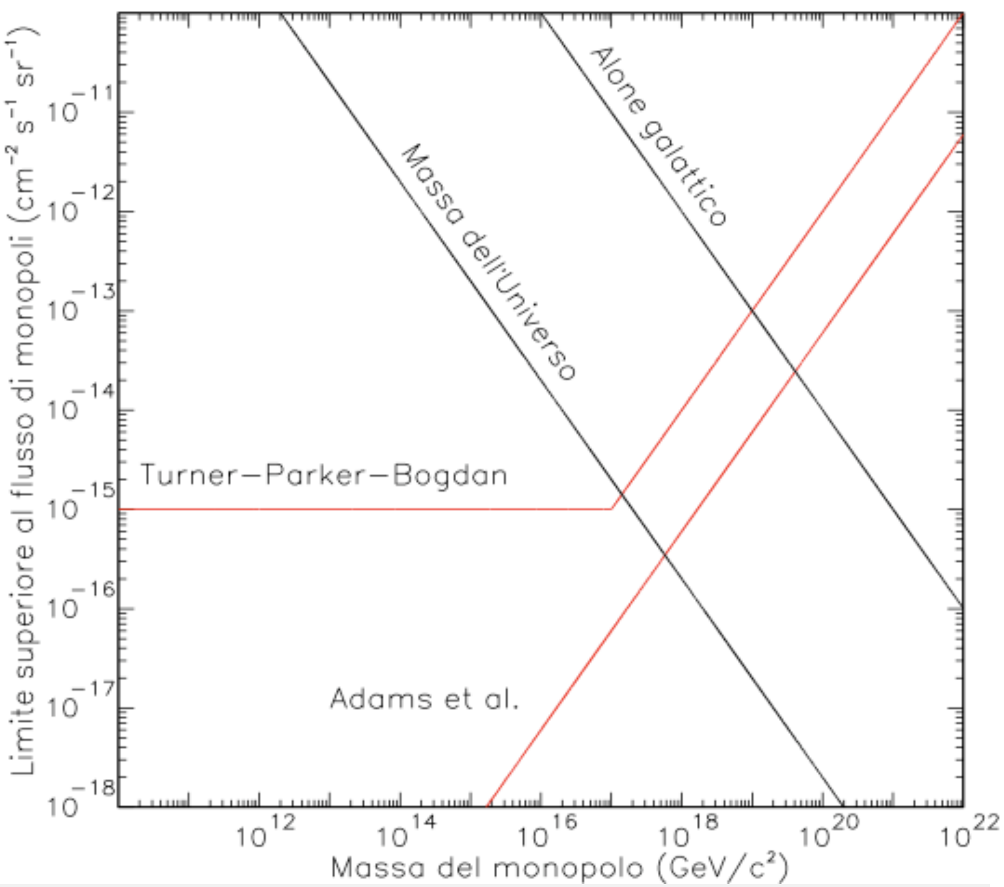
$\Phi_{TPB} < 10^{-9}\ \beta^2\ m_{17}\ cm^{-2}\ s^{-1}\ sr^{-1}$ for $\beta > 3\ 10^{-3}$

- **Survival of early seed of galactical magnetic field**
  "Extended Parker Bound" (EPB)

$\Phi_{EPB} < m_{17}\ 10^{-16}\ cm^{-2}\ s^{-1}\ sr^{-1}$

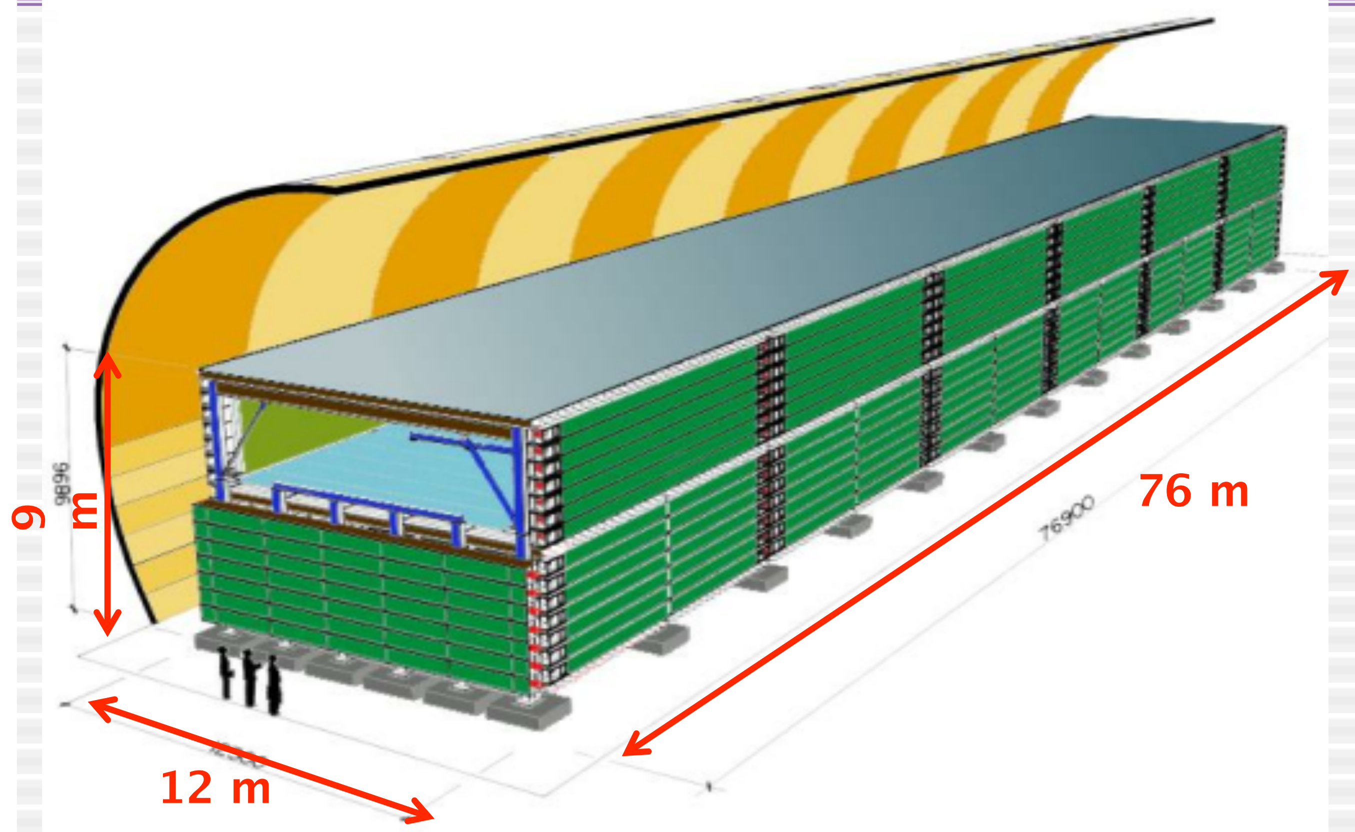
$m_{17} = m_M / 10^{17}\ GeV/c^2$

- **Limits from Universe mass density**
  "uniform" or "clumped"



The MACRO experiment @ Gran Sasso

From early 1989 to December 2000



3 Subdetectors:

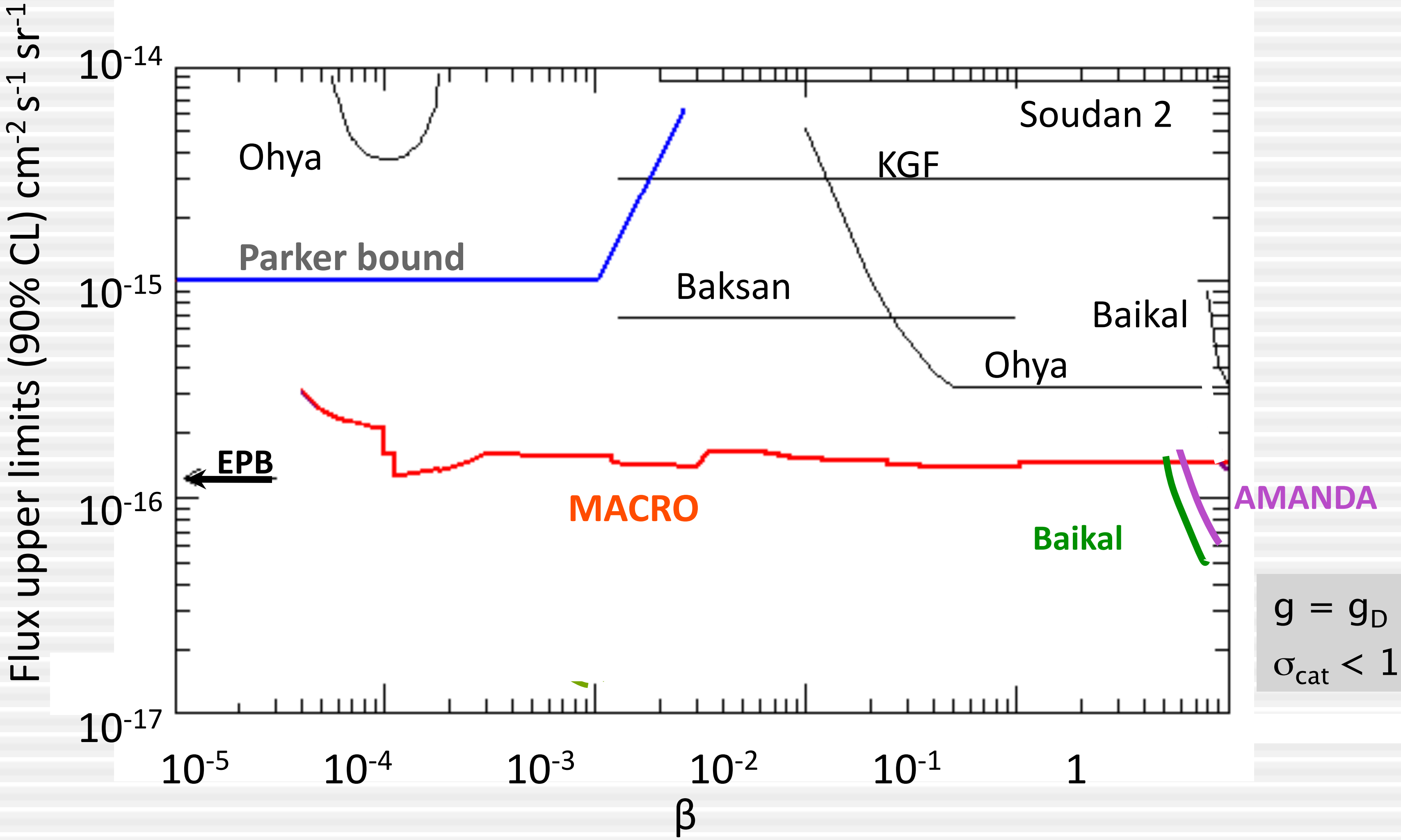
- Scintillators
- Limited Streamer tubes
- Nuclear track detectors

$S\Omega \sim 10{,}000\ m^2 sr$

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

→ **Redundancy & Complementarity**

Status of GUT MM searches



$g = g_D$

$\sigma_{cat} < 1$ mb

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

ex. (Shafi) **$M \sim 10^{10}$ GeV , $g = 2\, g_D$,**

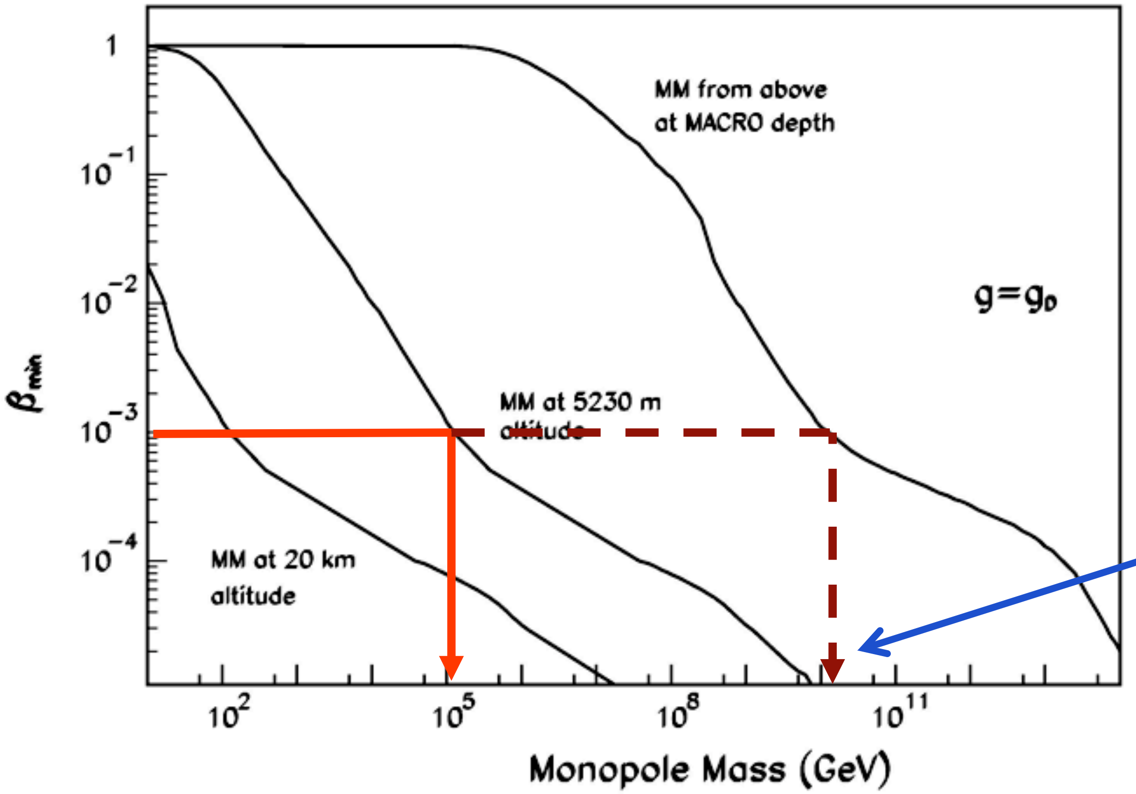
$$SO(10) \xrightarrow[10^{-35}\ \mathrm{s}]{10^{15}\ \mathrm{GeV}} SU(4) \times SU(2) \times SU(2) \xrightarrow[10^{-23}\ \mathrm{s}]{10^{9}\ \mathrm{GeV}} SU(3) \times SU(2) \times U(1)$$

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$)$ $(L/300$pc$)$

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

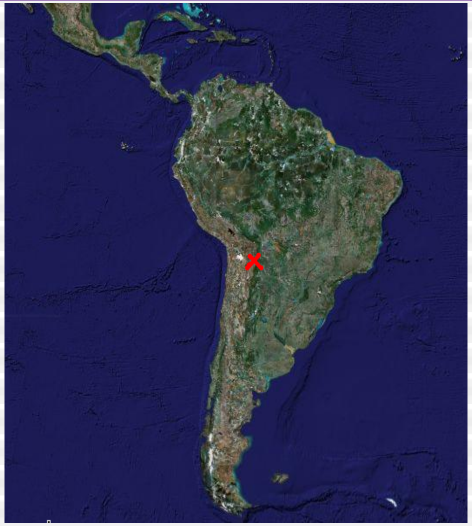
For “light” MMs, acceptance ≠ 4π: they could slow down, go under threshold and/or be trapped in the Earth



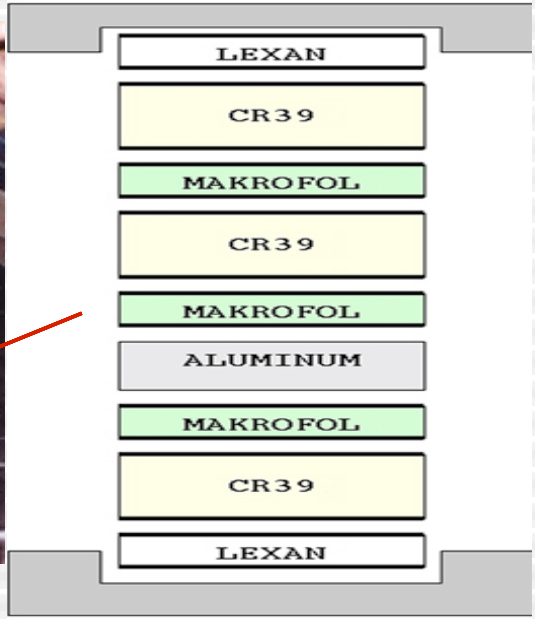
Minimum MM mass detectable @ LNGS for $\beta \sim 10^{-3}$

Accessible regions in the plane (mass, β) for MMs from above

SLIM @ Chacaltaya, 5230 m asl



SLIM Module (24x24 cm^2)



Array of nuclear track detectors ~ 430 m^2

Construction 2000–'01
Exposure time: 4y
Analysis completed 2007

IMM searches: Under-ice, Underwater experiments

AMANDA, Lake Baikal, ANTARES,

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

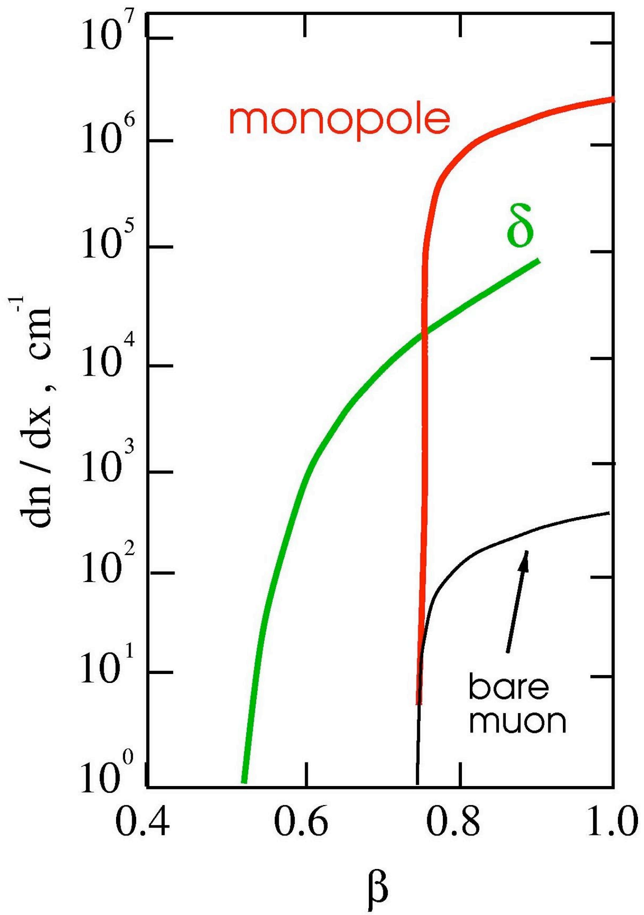
δ-rays Č light $\beta_{MM} > 0.6$

$$\frac{d^2 N_\gamma}{d\lambda\, dx} = \frac{2\pi\alpha}{\lambda^2}(g_D n)^2\left(1 - \frac{1}{\beta_{Mon.}^2 n^2}\right)$$

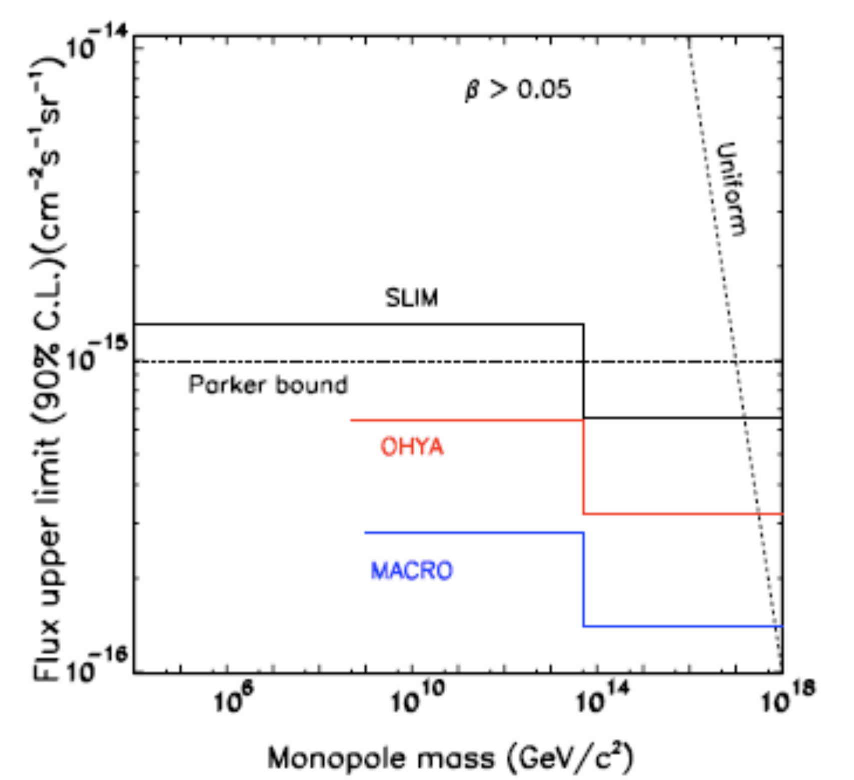
Cherenkov emission enhanced by a factor ~ 8500 compared with the μ yield

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

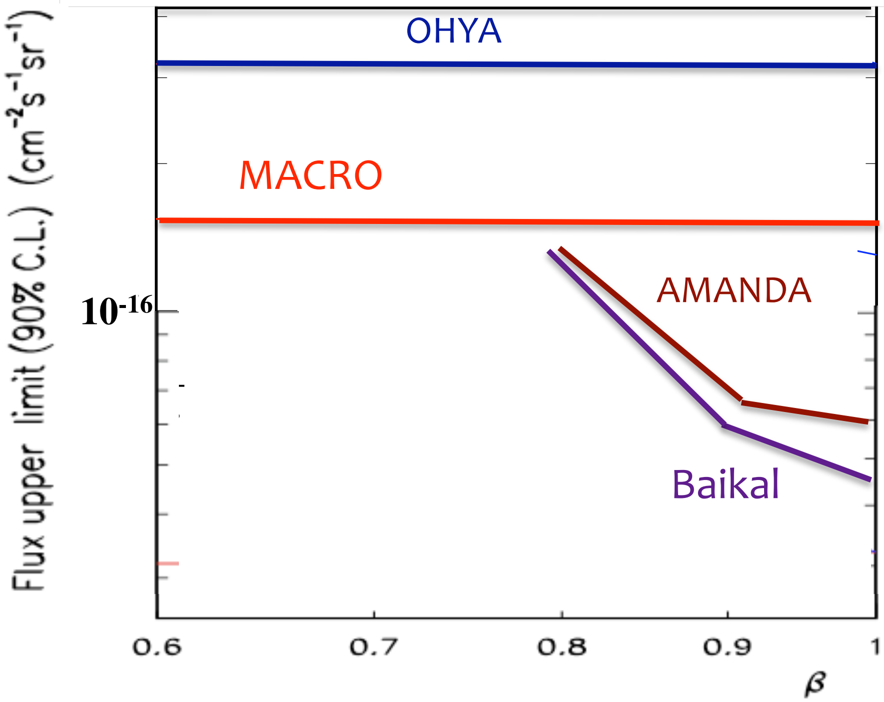
(M > 10^{6-9} GeV from above)



IMM : Flux Upper Limits



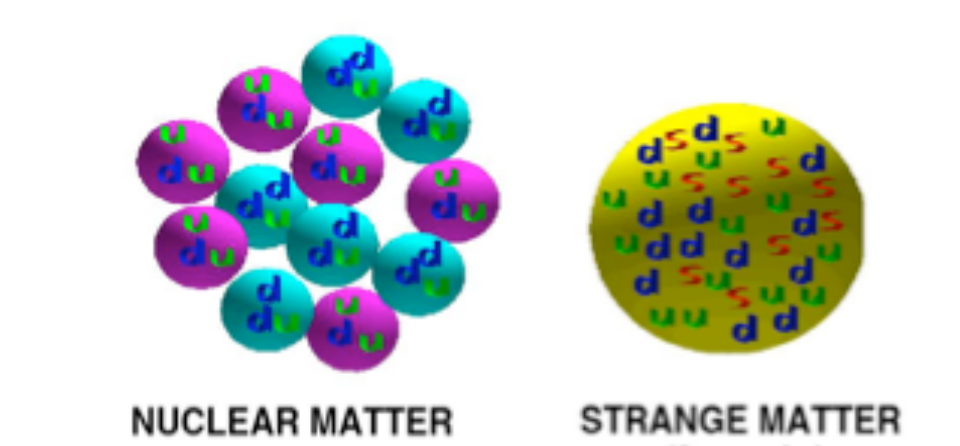
M> 10¹¹ GeV



Strange Quark Matter

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

- Aggregates of u, d, s quarks of approx. equal number + electrons
- Ground state of QCD
- Stable for $\sim 300 < A < 10^{57}$



$\rho_{SQM} \sim 3.5 \times 10^{14}$ g cm^{-3}

$\rho_{nuclei} \sim 10^{14}$ g cm^{-3}

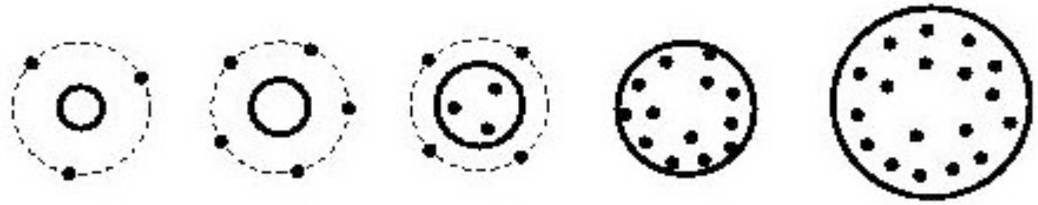
Produced in: the Early Universe → Cold DM candidates

: Neutron Star collisions → Quark stars

SQM : alias Nuclearites, Strangelets

Nuclearite : large neutral Thomson- atom like constituted by an SQM bag core + electrons

Strangelet : small, Bohr-atom like constituted by an SQM bag core surrounded by electrons



R (fm)	10^2	10^3	10^4	10^5	10^6
M (GeV)	10^6	10^9	10^{12}	10^{15}	10^{18}

Nuclearites – basics

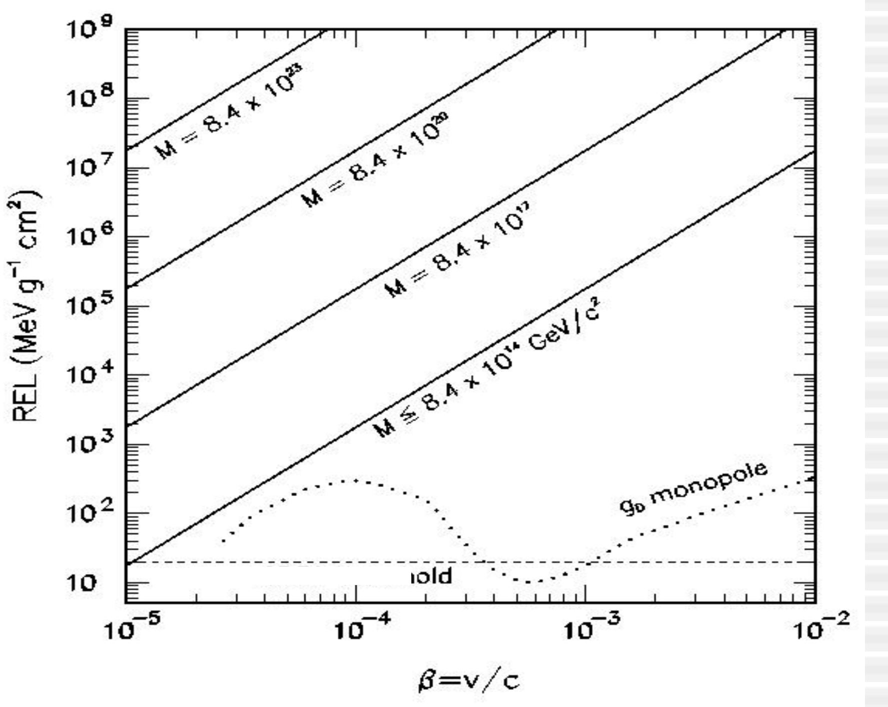
A. De Rújula and S.L. Glashow, Nature **312** (1984) 734

- Typical galactic velocities $\beta \approx 10^{-3}$
- Dominant interaction: elastic collisions with atoms in the medium
- Large energy loss

$$dE/dx = -\sigma \rho_{medium} v^2_N$$

$\sigma \sim \pi\, 10^{-16}\ cm^2$ $R_N < 10^{-8}$ cm e^- inside

$\sigma \sim \pi \times R^2_N$ $R_N > 10^{-8}$ cm e^- cloud



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

Nuclearites: status of the search

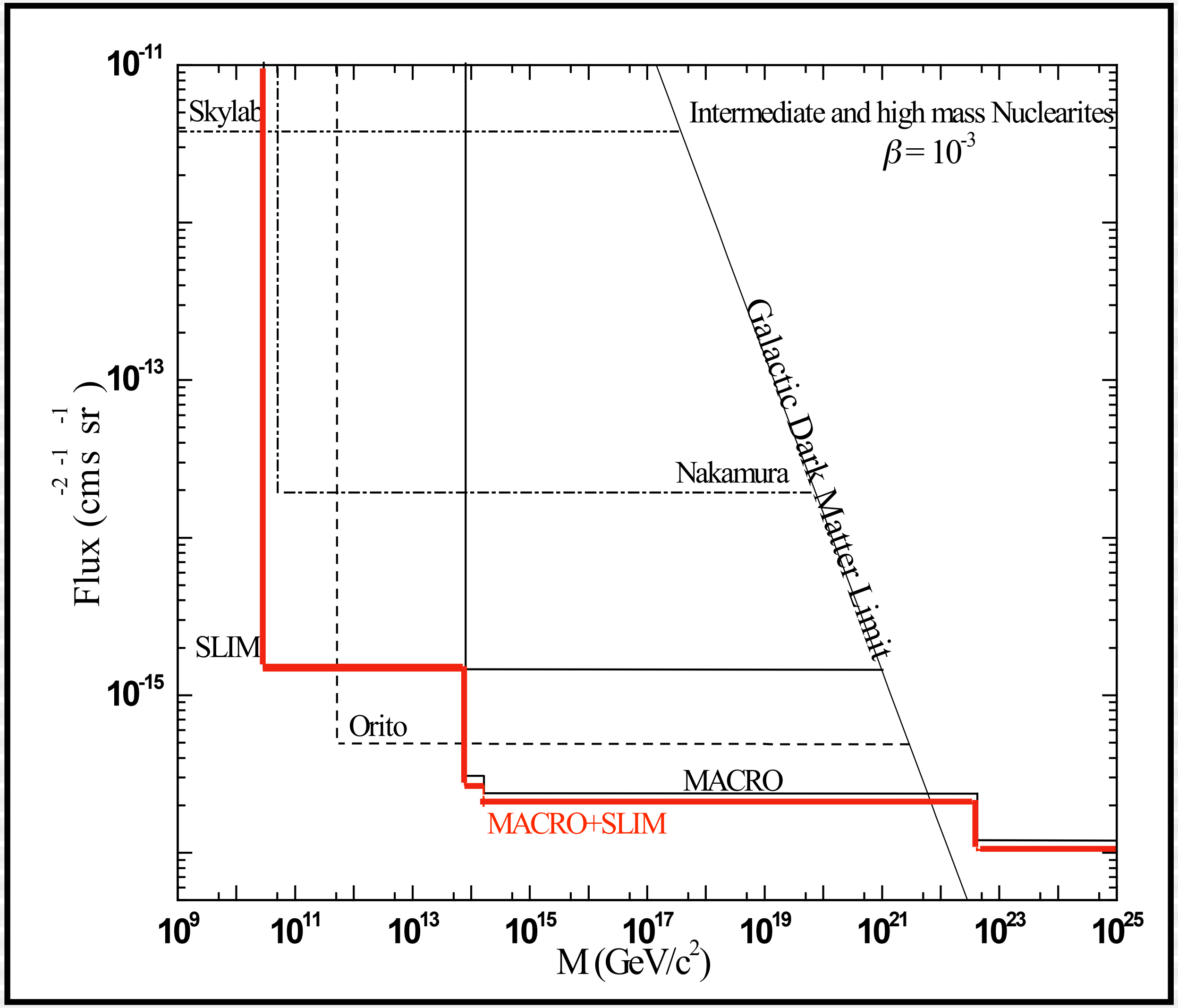
SLIM : 5300 m

Mt. Norikura: 2000 m

Ohya : 100 hg/cm^2

MACRO : 3700 hg/cm^2

In the future: Neutrino Telescopes

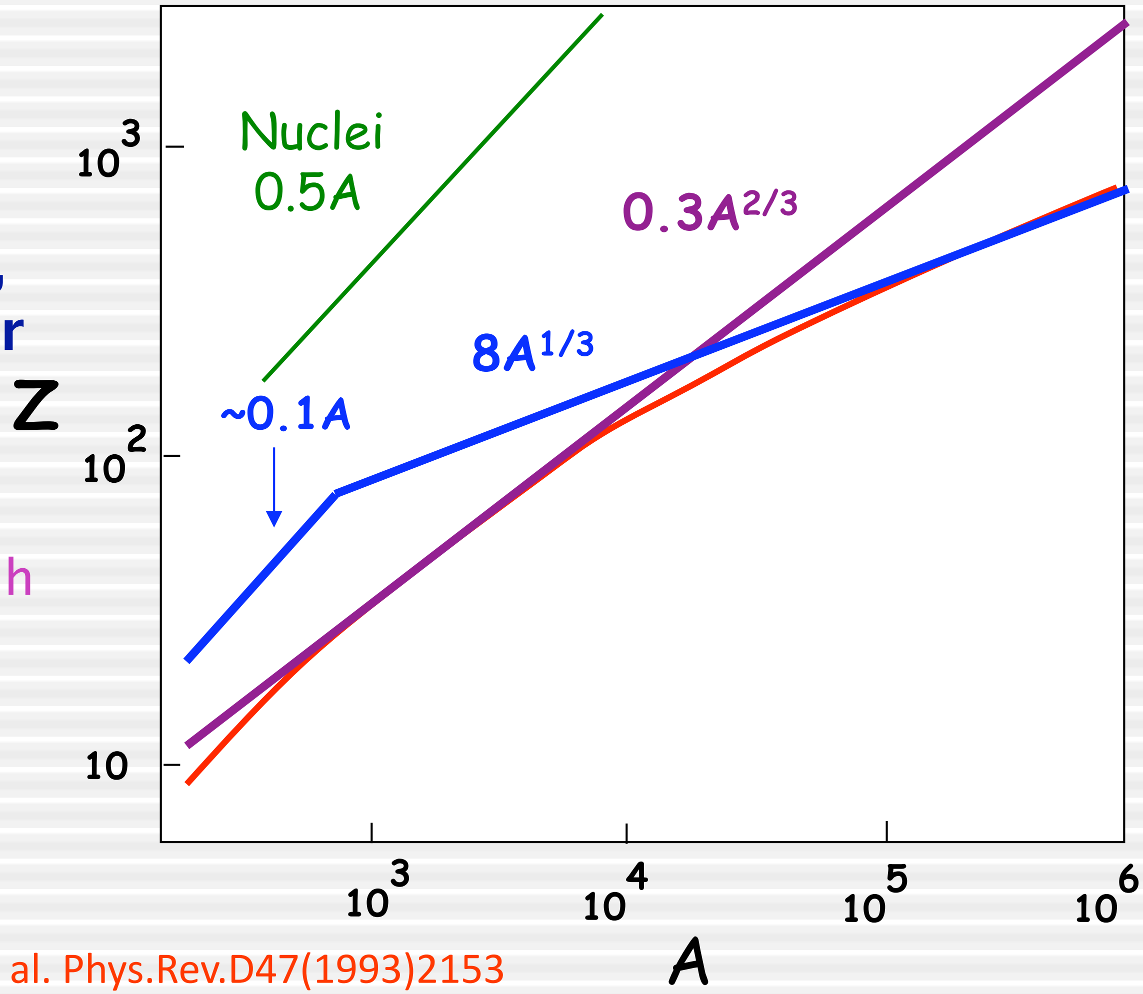


Strangelets– Basics

- **Positively charged ; a very low charge to mass (Z/A) ratio (their signature)**
- **A ≤ 10^6**
- **Produced in neutron stars, pulsars, accelerated in super novae, …**

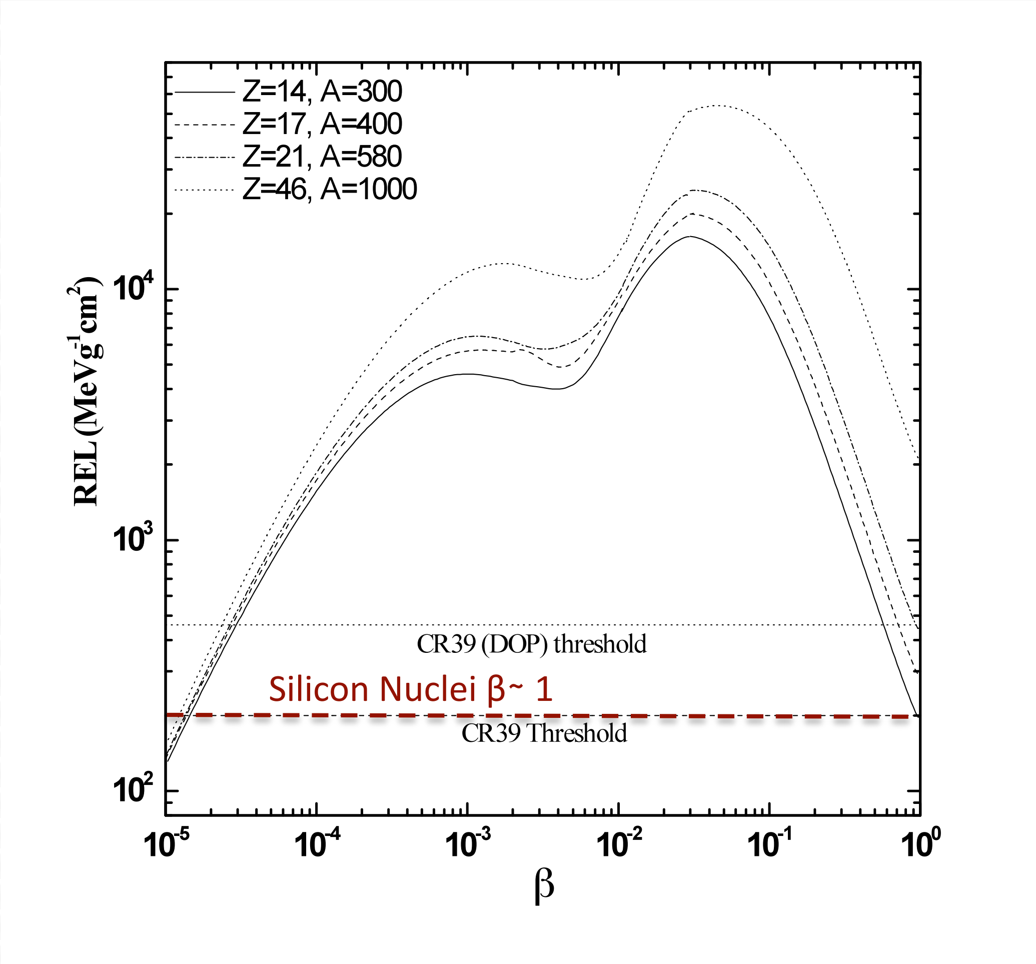
⇒ A cosmic ray component ?

⇒ May be accelerated to very high energies



M. Kasuya et al. Phys.Rev.D47(1993)2153
H.Heiselberg, Phys. Rev.D48(1993)1418
J. Madsen Phys. Rev.Lett.87(2001)172003

- Behave like ordinary nuclei
- Same acceleration processes and Energy Loss



Restricted energy loss in nuclear track detectors

Flux Predictions

Two proposed fluxes

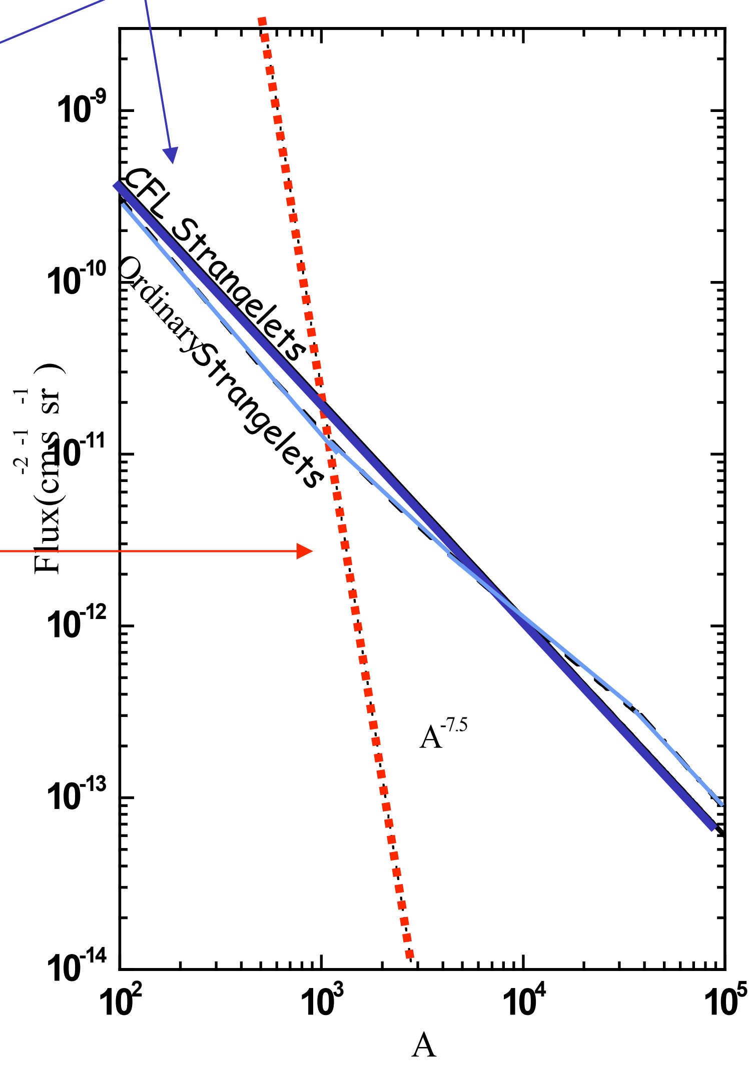
→Strange star binary collision + propagation in the galaxy:

$F \propto A^{-0.467} Z^{-1.2} \max[R_{SM}, R_{GC}]^{-1.2}$

→ Candidate events + relative abundance of elements in the Universe: $F \propto A^{-7.5}$

Rybczynski M. et al. Nucl. Phys. B 151 (2006) 341

*J. Madsen, Phys. Rev. D**71** (2005) 014026*



Expected at Chacaltaya (1sr):

- Madsen: ~ 300 events/100 m^2 / year.
- Wilk:~ 6 events/100 m^2 / year.
- Banerjee : ~ 5-10 events/100 m^2 / year.

Propagation in Atmosphere

Two models:

1- Strangelets losing mass by colliding with air nuclei:

- *Wilk,G. et al. J. Phys. G 22 (1996) L105.*
- *Wu, F. et al., J. Phys. G 34 (2007) 597*

2- Strangelets increasing mass and charge by accreting neutrons and protons

- *Banerjee S., et al., J. Phys. G 25 (1999) L15.*

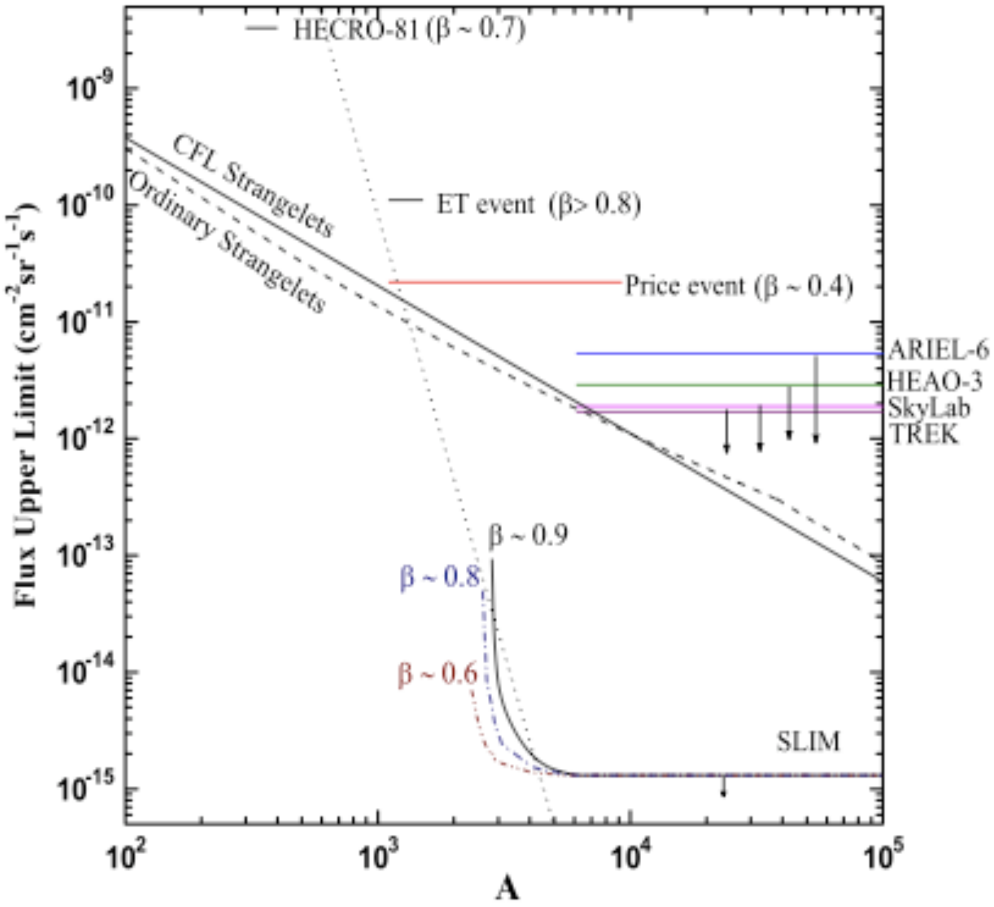
Strangelets: status of the search

Most recent result from SLIM at Chacaltaya, Bolivia

**No event detected ->
flux upper limit set**

Constrains in propagation models in atmosphere.

More with the future AMS2 experiment



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

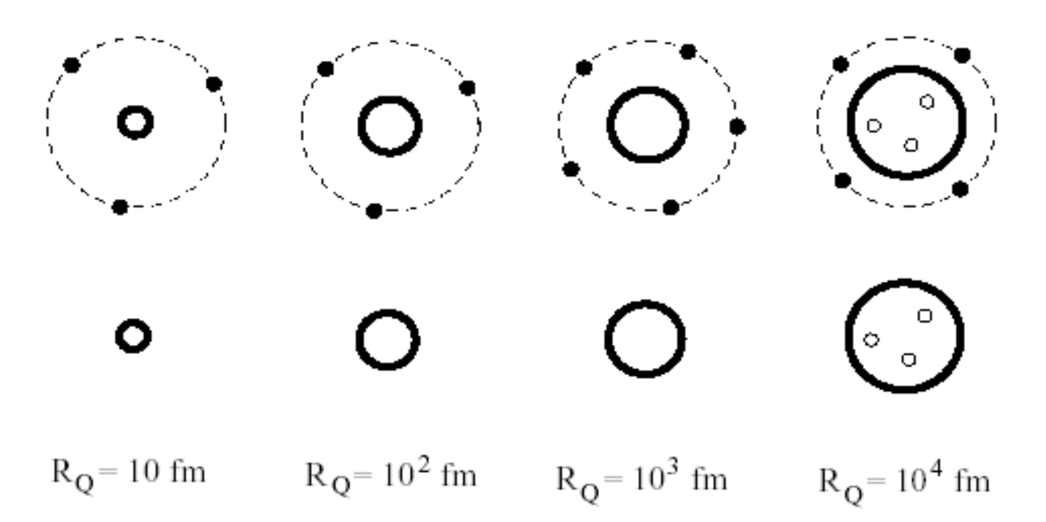
Produced in the Early Universe ; possible components of Cold Dark Matter

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

A qualitative picture

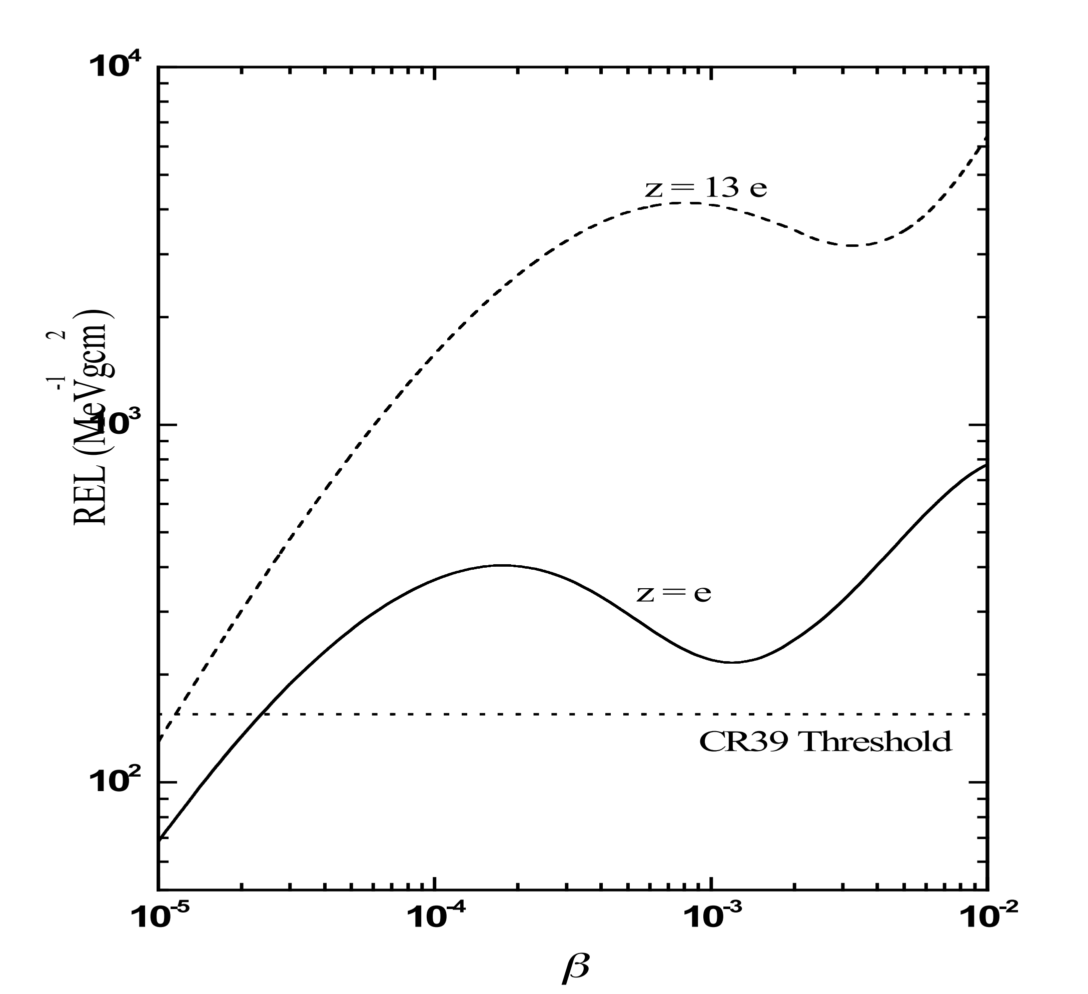
Charged Q-balls
similar to strangelets :

Neutral Q-balls
similar to nuclearites

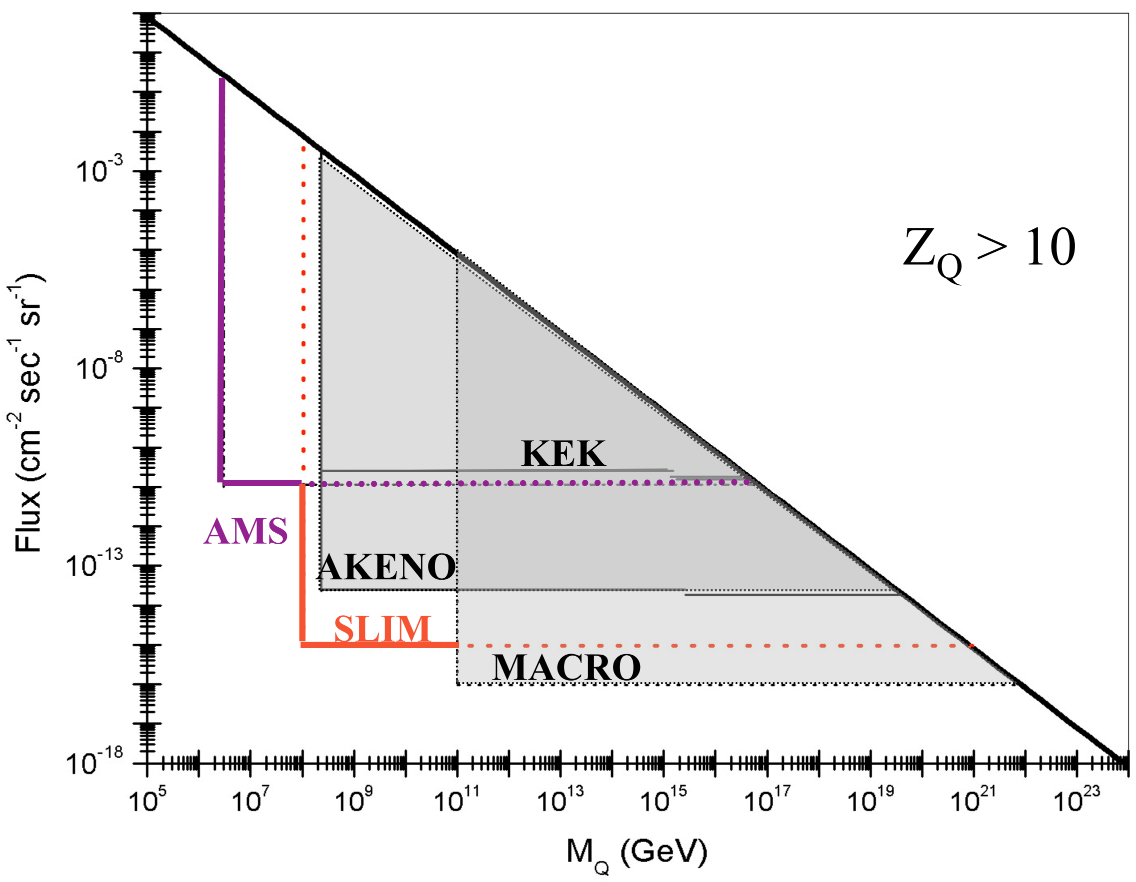


R_Q : dimension of the Q-ball core;
the black points indicate electrons, open circles indicate s-electrons.

Restricted Energy Loss for charged Q-balls



Charged Q- balls: search status



AKENO, KEK : ground level

MACRO : 3700 hg/cm^2 undg.

AMS2: Space Station

SLIM: 540 g/cm^2 atm depth

Conclusions

- Dirac MMs at accelerators $m_M > 0.9$ TeV

  In the future : at RHIC probe ?

  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 $4x\ 10^{-5} < \beta < 1$

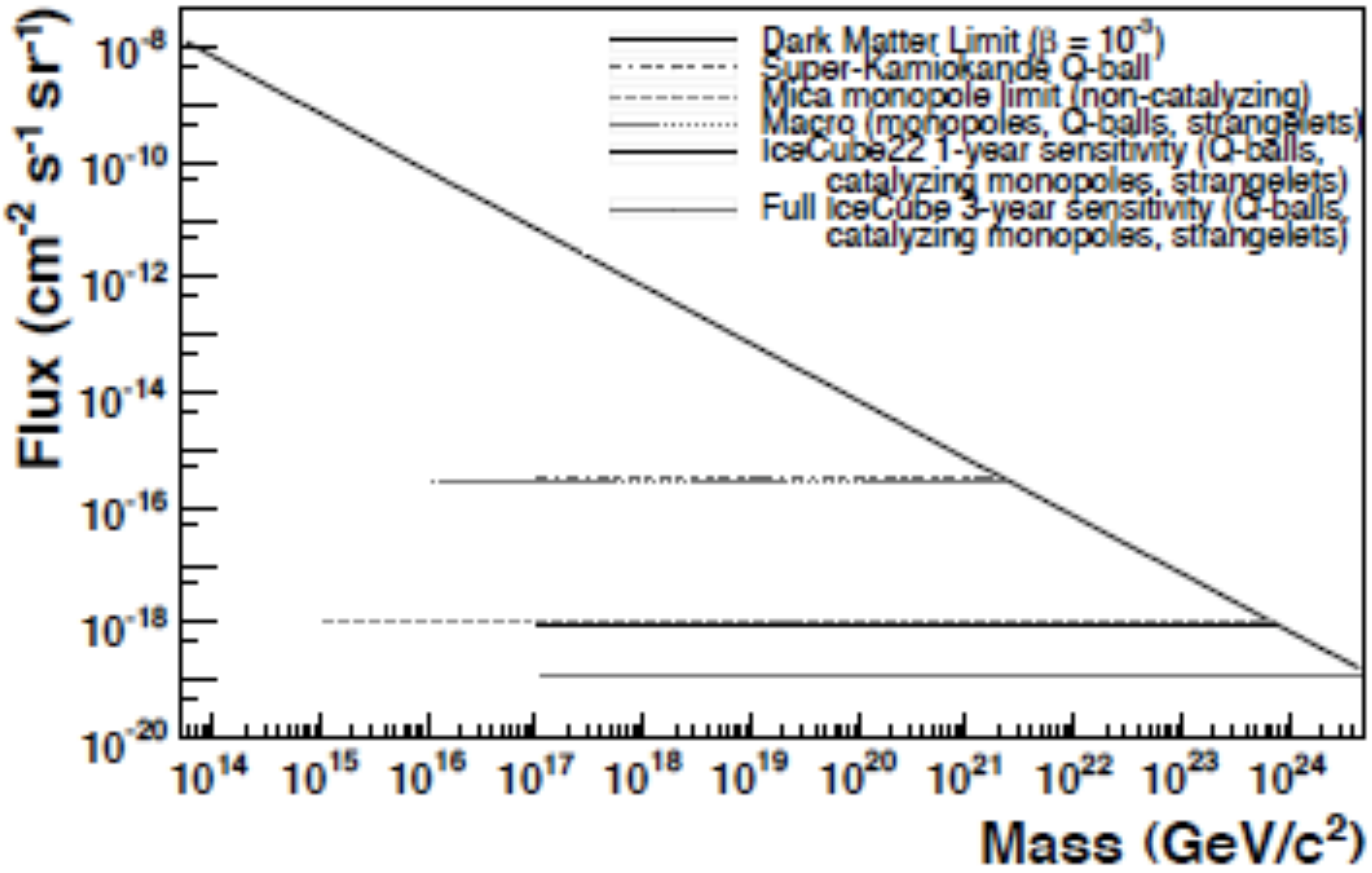
  For the future: need new detectors with much larger surfaces

- IMMs: Experiments at mountain : $\Phi < 1.5\ 10^{-15}\ cm^{-2} s^{-1} sr^{-1}$ from above

  For the future: need much larger detectors

  Experiments with neutrino telescopes for $\beta > 0.6$

- Nuclearites, Q- Balls: None found; limits ~ as for fast GUT MMs



"Ultimately the question of whether such exotic particles exist [...] rests an experimental issue... "

(Madsen, astro-ph/0512512)