Nuclear Track Detectors

Search for Magnetic Monopoles

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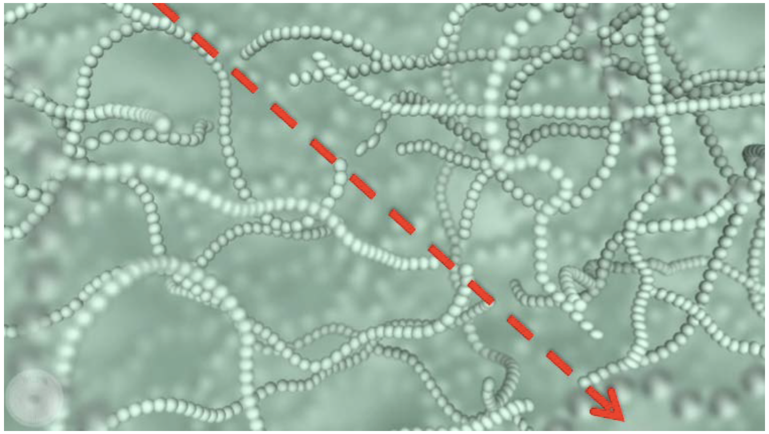
Nuclear Track Detectors (NTDs)

- **Insulating solid materials, e.g. plastics (CR39, Makrofol, Lexan,..) glasses, minerals …**



- **The passage of a charged particle cause the break of chemical bonds** **("latent track")**

- **The level of damage depends on the Restricted Energy Loss (*REL*) of the passing particle**

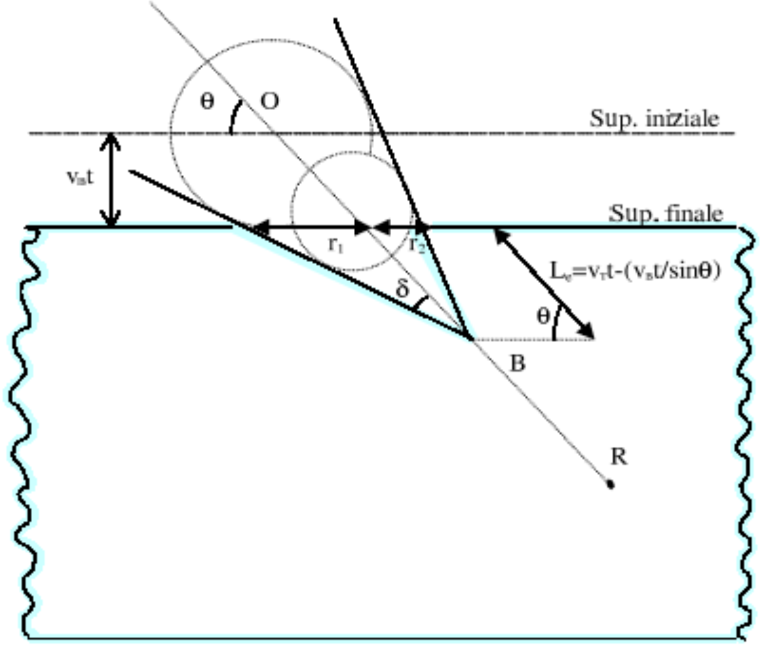
$$REL = \left(-\frac{dE}{dx}\right)_{E<T_{max}} = K\frac{z^2}{\beta^2}\frac{Z}{A}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]$$

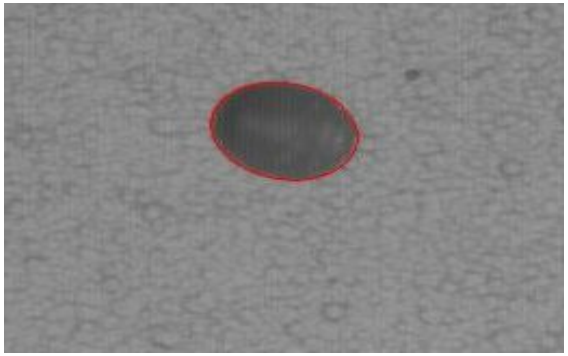
T_{max}=200 eV for CR39 , = 350 eV for Makrofol, Lexan

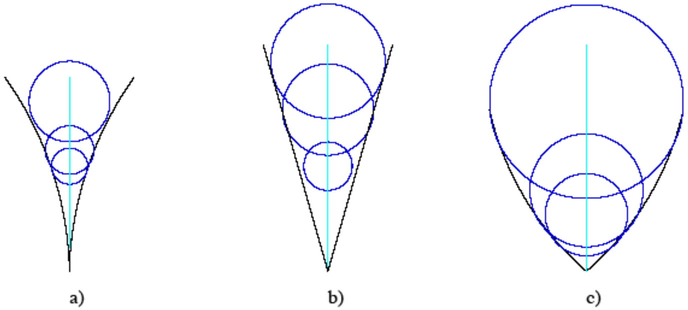
- **The "latent" track can be made visible to an optical microscope through an appropriate chemical etching**

The chemical etching

a water solution of (f.e.) NaoH, or KOH or others, at high concentration (4-7 N), and temperature (40-80 °C)

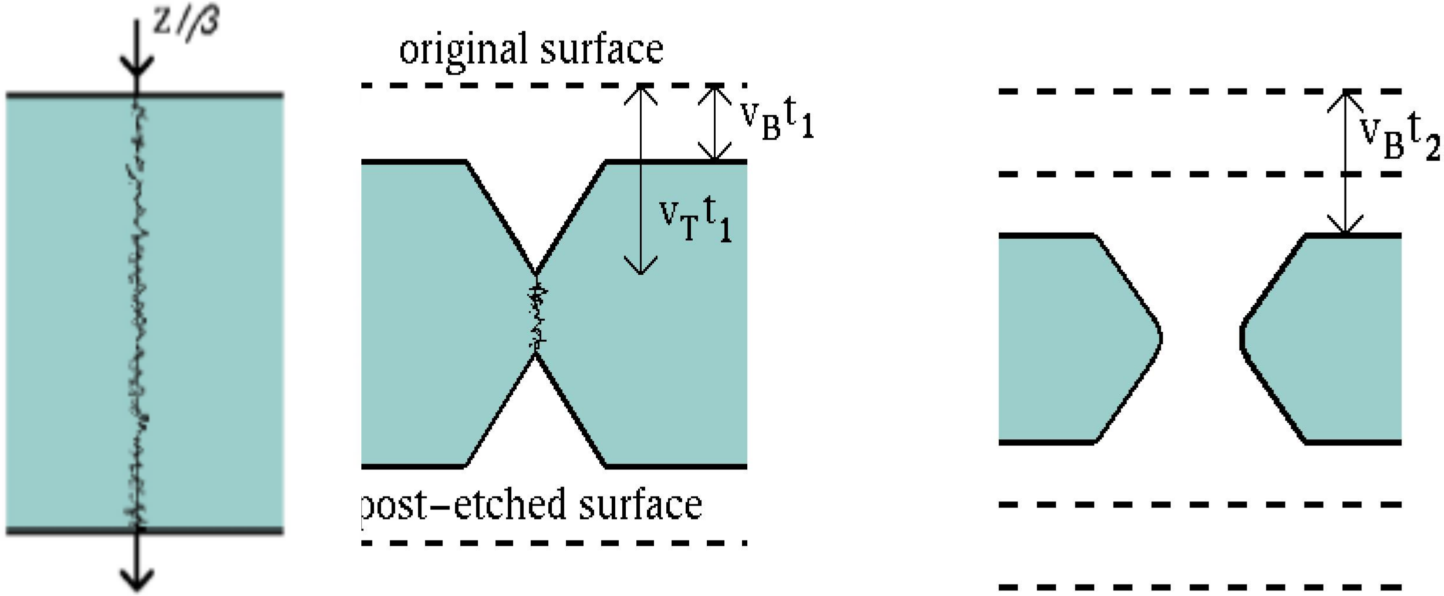




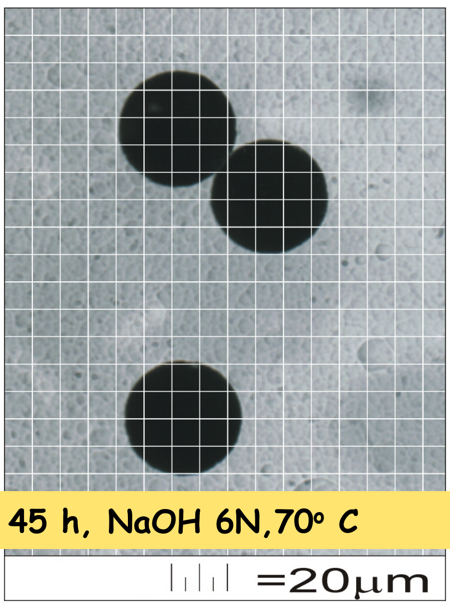


particle velocity

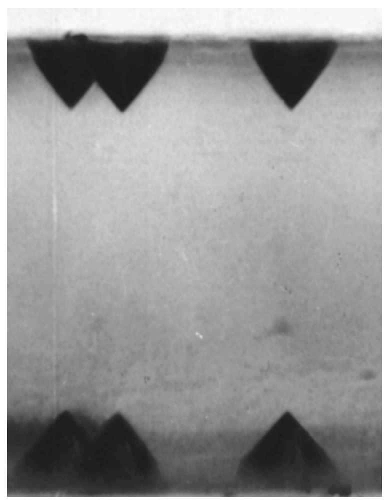
decreasing constant increasing

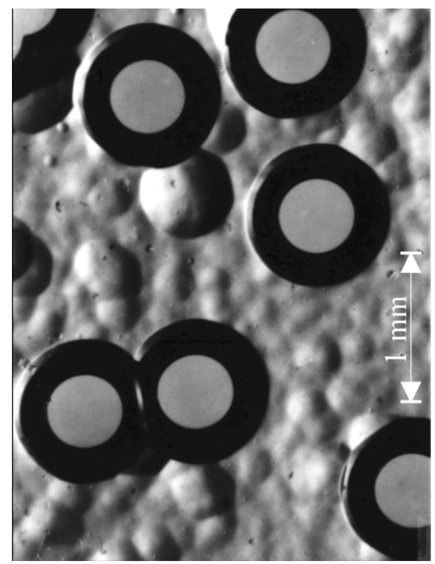


S^{16+} 200 GeV/nucleon



45 h, NaOH 6N,70° C





120 h, NaOH 8N, 80° C

$$v_T = v_{Track}\,(N,\ T,\ REL,\ldots)$$

$$v_B = v_{Bulk}\,(N,\ T,\ldots)$$

N = solution concentration e.g. 6N NaOH, 7N KOH, etc.

T = solution temperature, e.g. 50°C, 70°C, etc.

$p = v_T / v_B \approx f(REL,..)$ is usuallly used the detector response

From the geometry of etch-pits

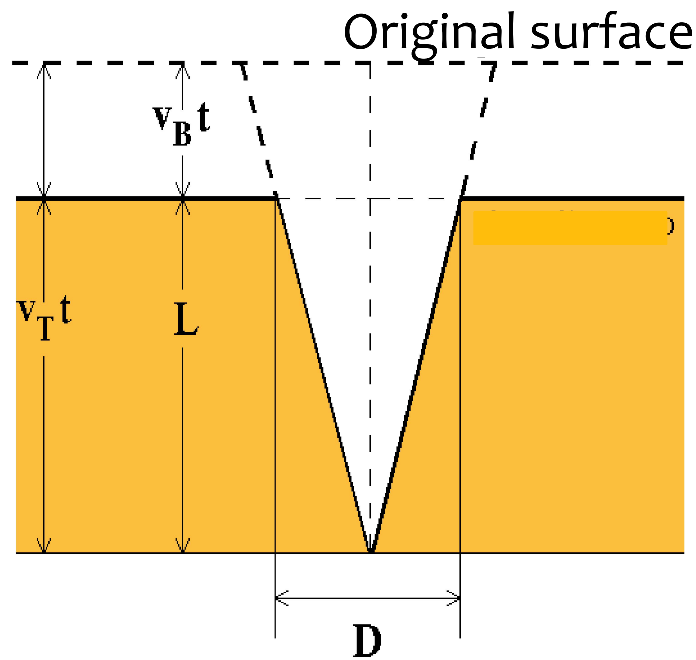
For normal incidence:

Base cone diameter

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

Cone length:

$$L_e = (p-1)\, v_B\, t$$



Similar relations hold at different angles of incidence

ETCHING PROCEDURE STEPS

1- THICKNESS MEASUREMENT (1 µm accuracy)

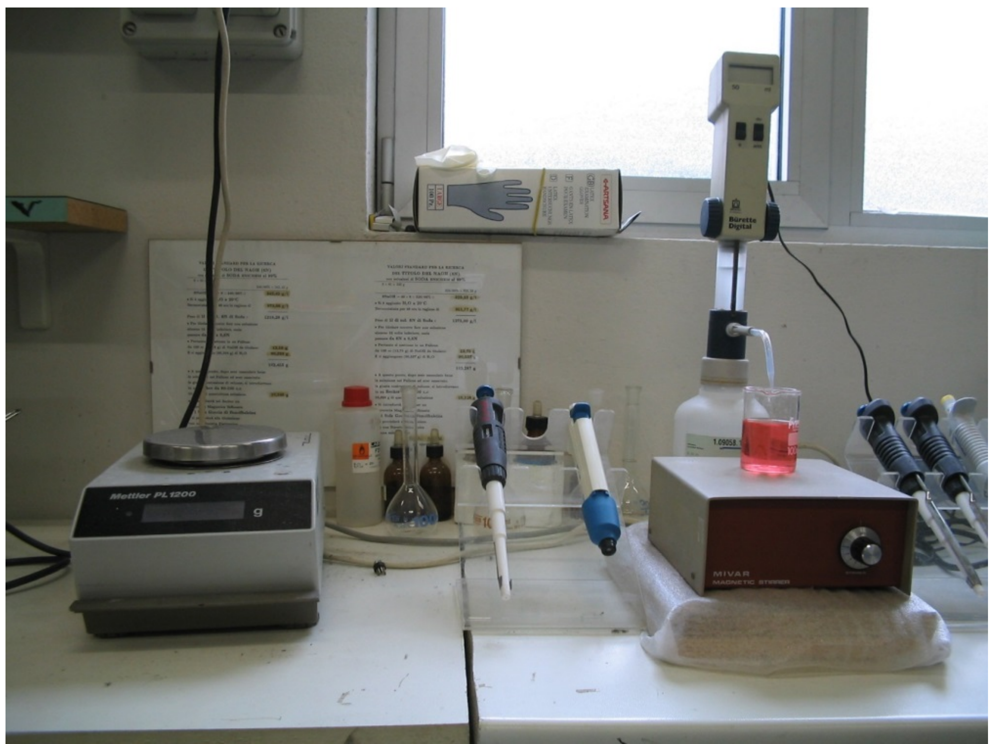
2- PREPARATION OF THE NaOH or KOH WATER SOLUTIONS

Demineralized water

NaOH pearls

Stirring System

Titration



Etching under controlled temperature (± 0.1 °C)

Constant stirring of the solution

Very tight tank covers in to avoid evaporation

RINSING in water + CH_3COOH in order to stop the etching process and clean the etch pits.

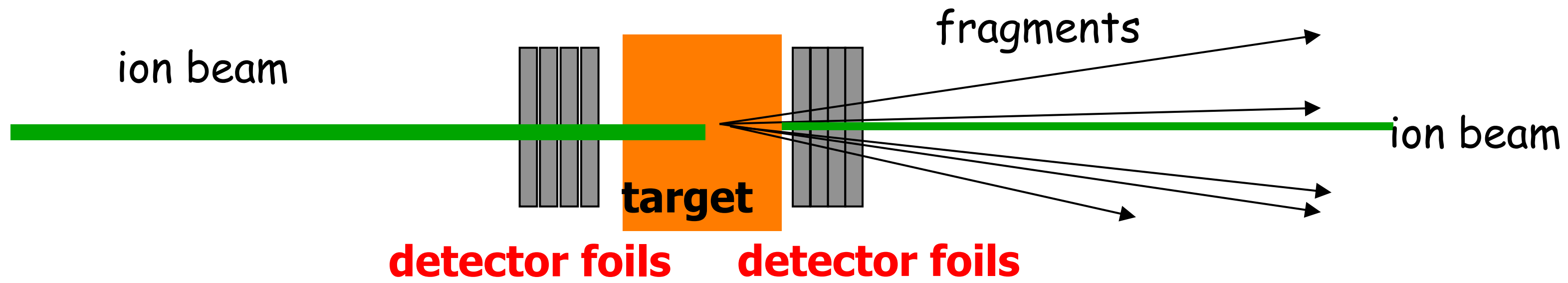
Drying in open air → Thickness Measurements

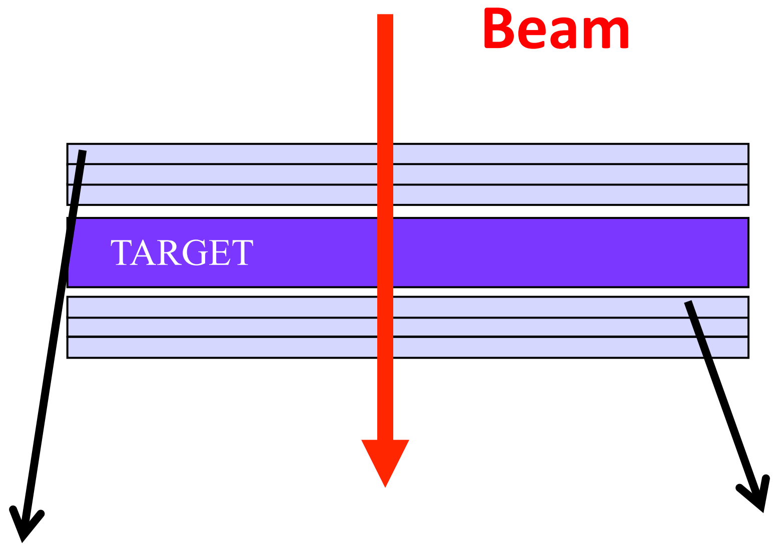
$$V_B = (S1 - S2)/2 \times t\_etch$$

CALIBRATION OF (CR39) NUCLEAR TRACK DETECTOR with fast heavy ions

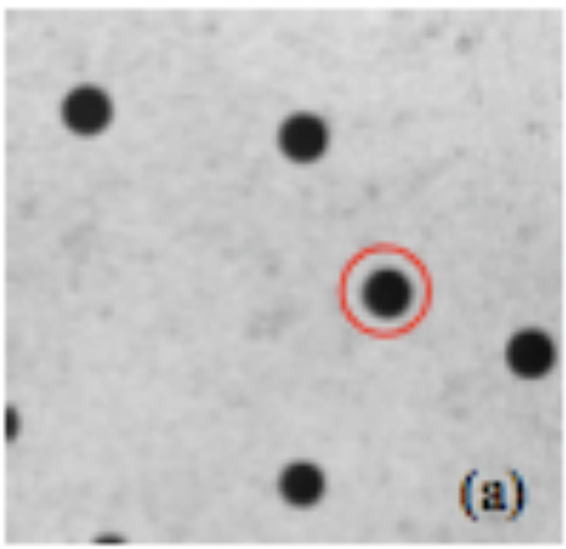
Accelerator	Ion	Energy /nucleon
SPS-CERN	Pb^{82+}	158
	In^{49+}	130
AGS –BNL (USA)	Fe^{26+}	1-10
	Si^{14+}	1-5
NSRL (BNL-USA)	Fe^{26+}	1
HIMAC (Japan)	Fe^{26+}	0.1 - 0.4
	C^{6+}	0.3

Exposure to relativistic ion beams: the set up



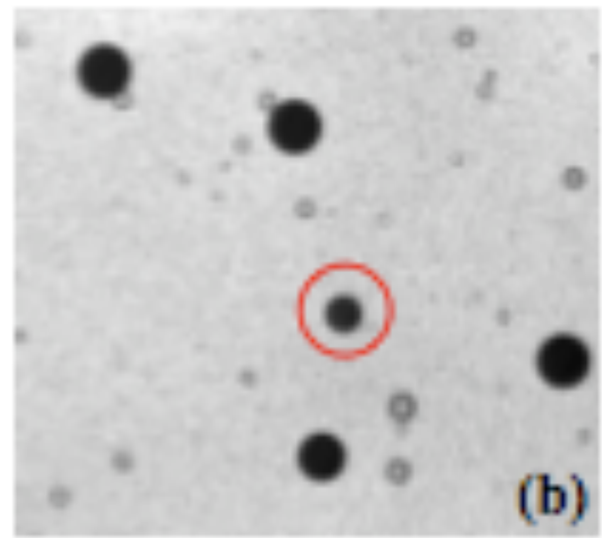


Top detector foil

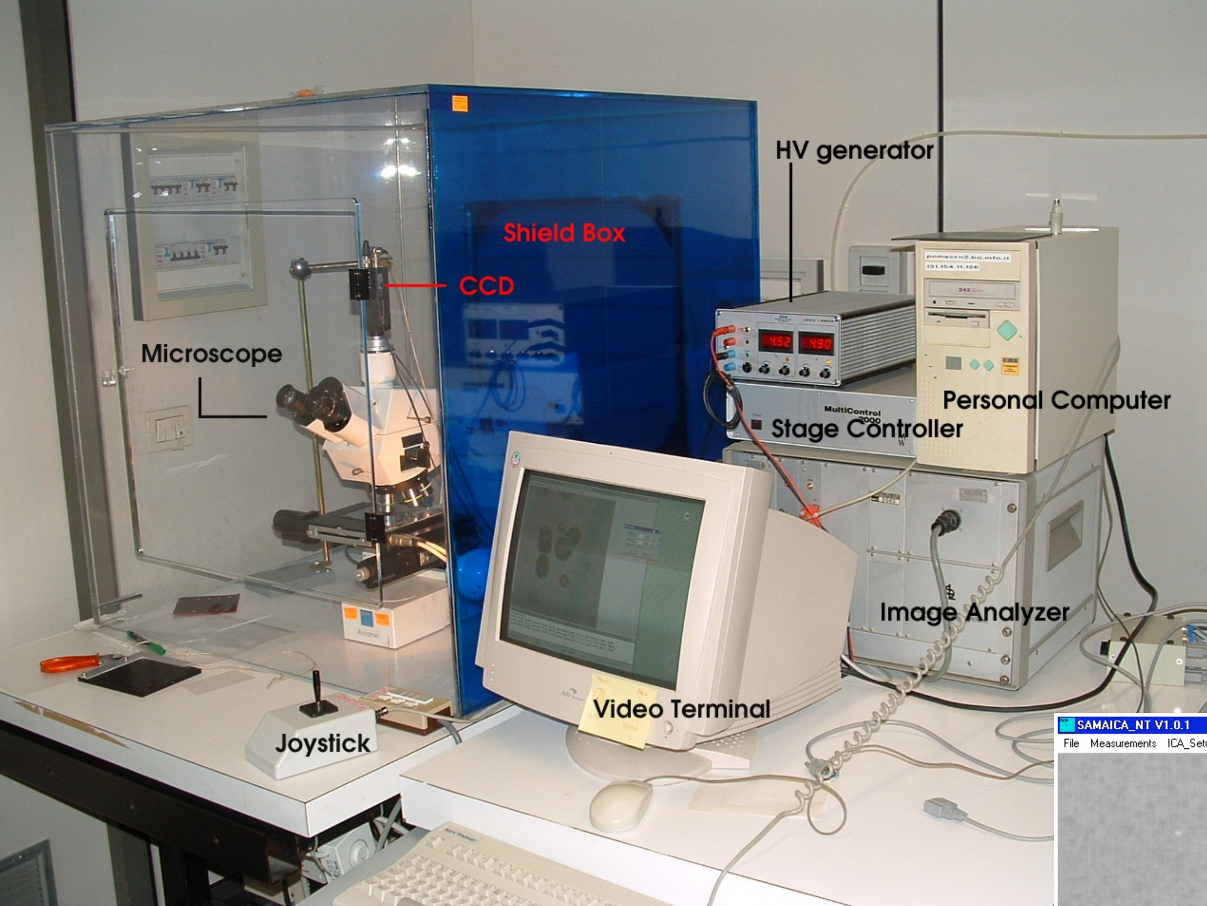


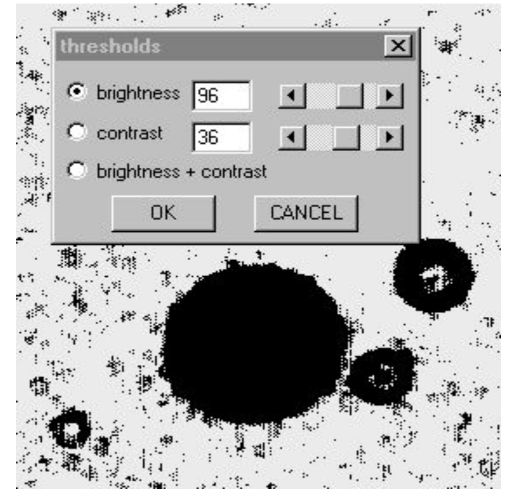
Beam tracks

detector foil after the target

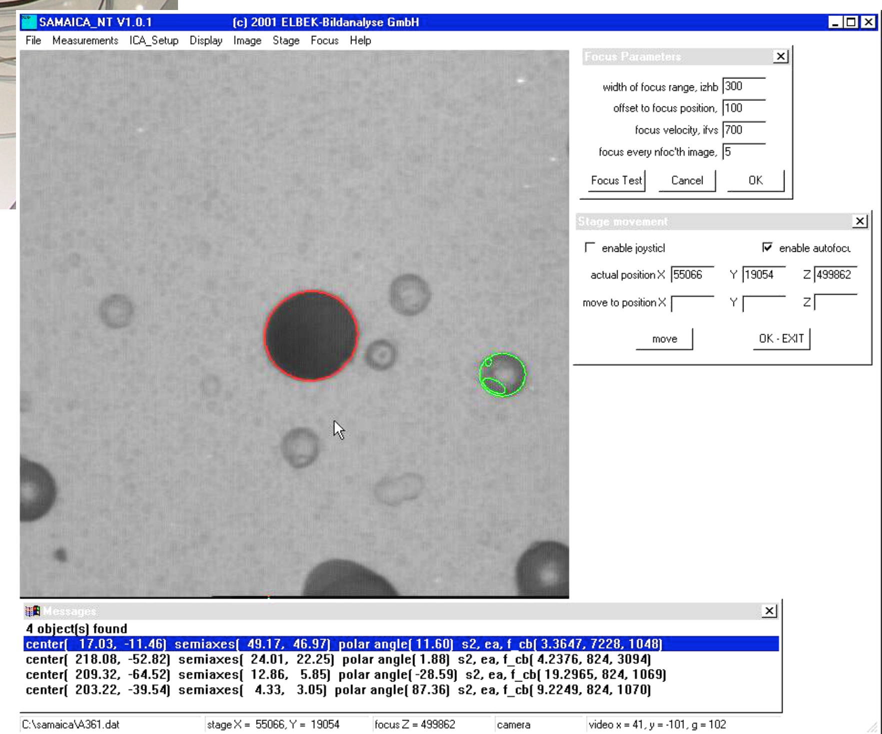


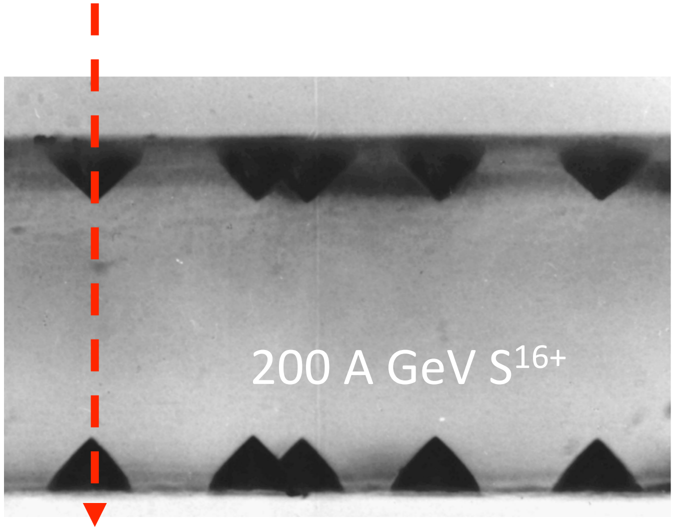
Beam and fragment tracks

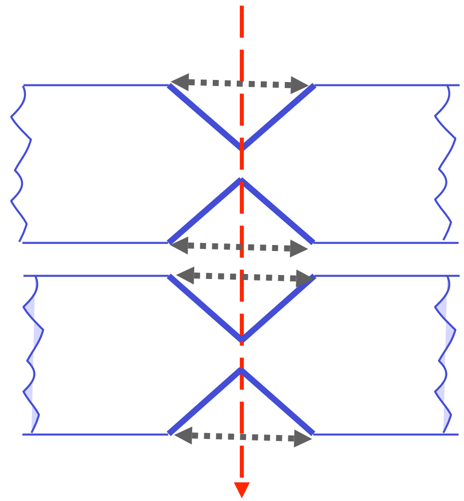


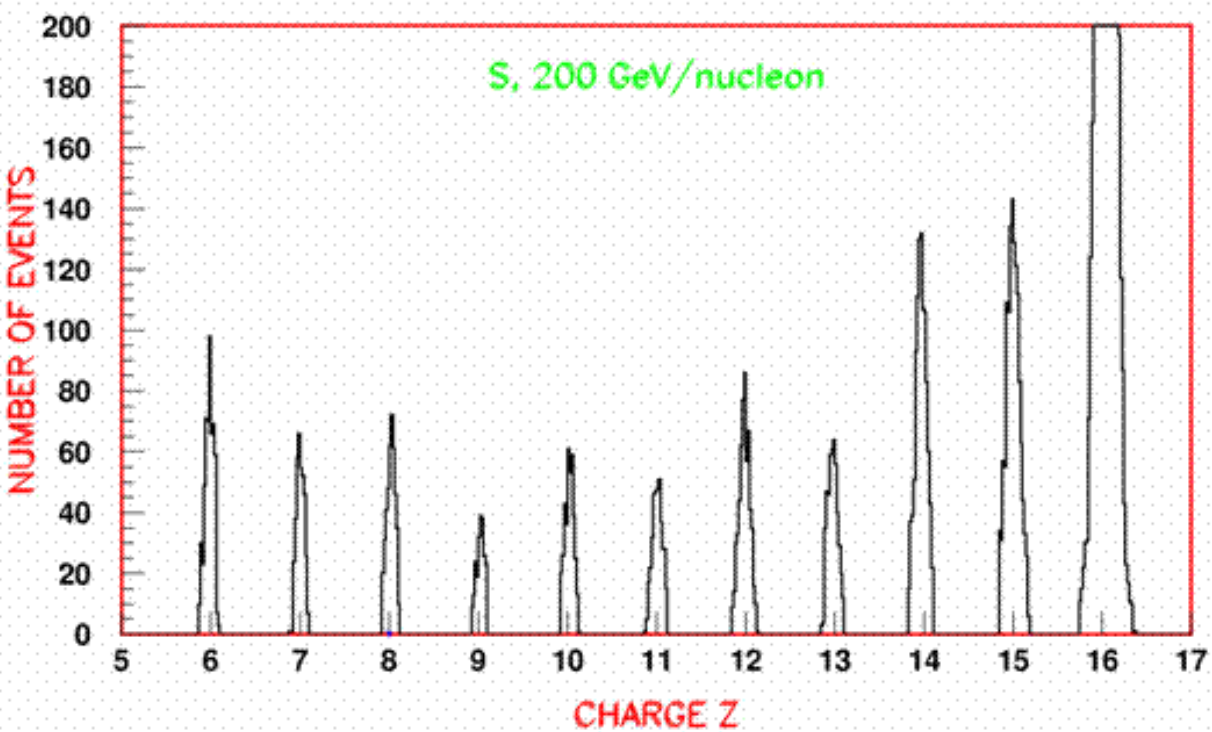


Automatic Scanning System









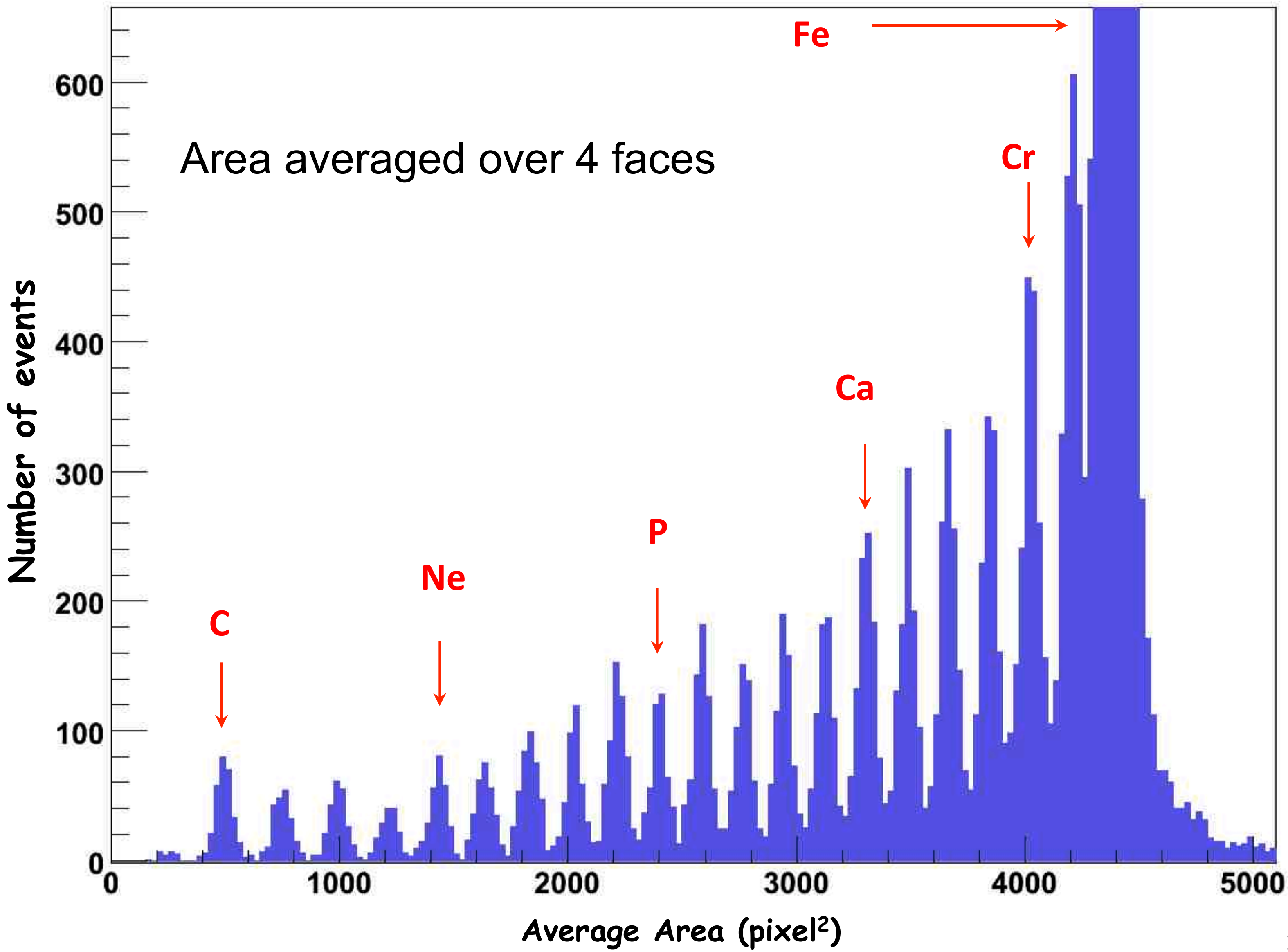
$$\sigma_z = \frac{\sigma_1}{\sqrt{n}}$$

n = number of independent measurements

in CR39 σ_1 ~ 0.2e

σ_z~0.05e , n=12

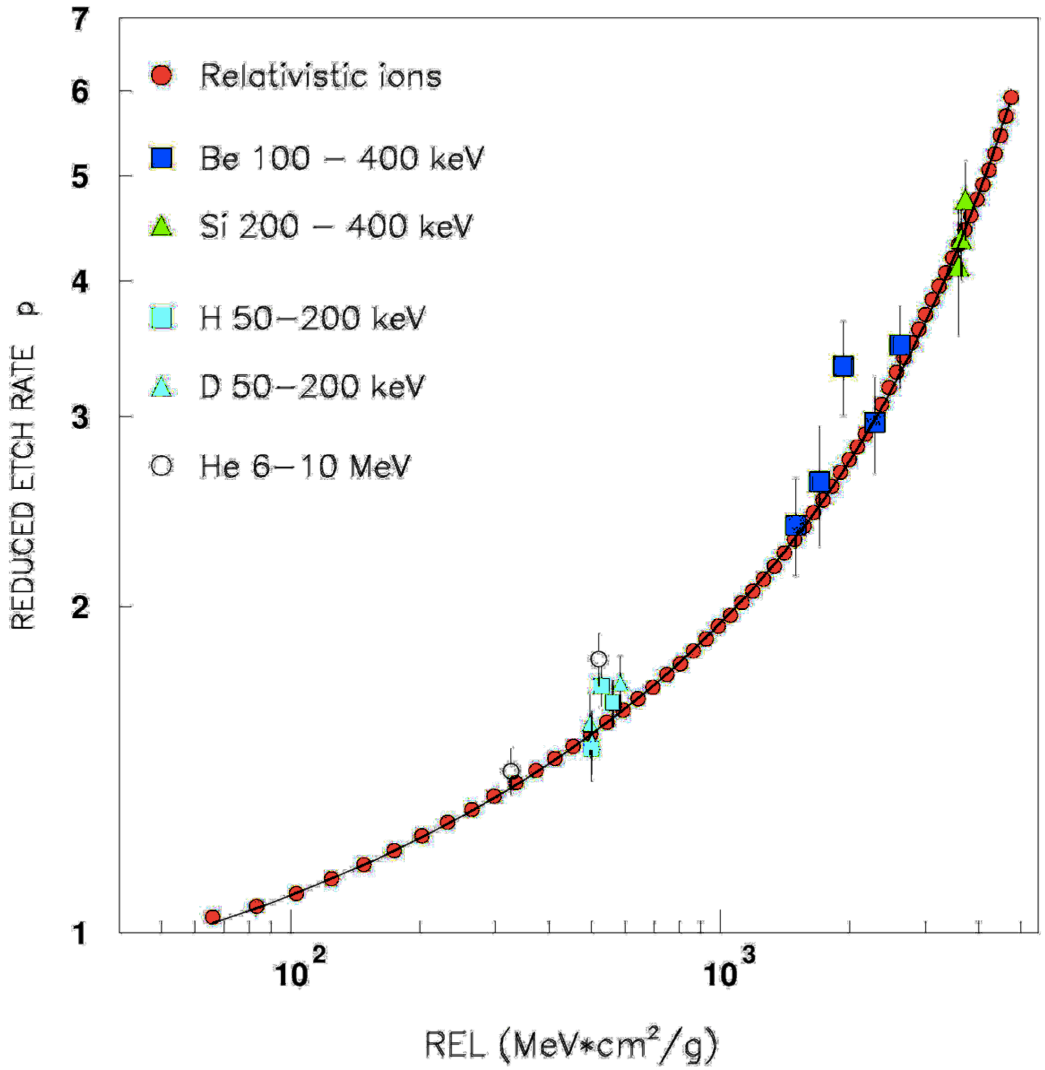
DISTRIBUTION OF ETCHED CONE BASE AREAS – AFTER TARGET **1 A GeV Fe^{26+}**



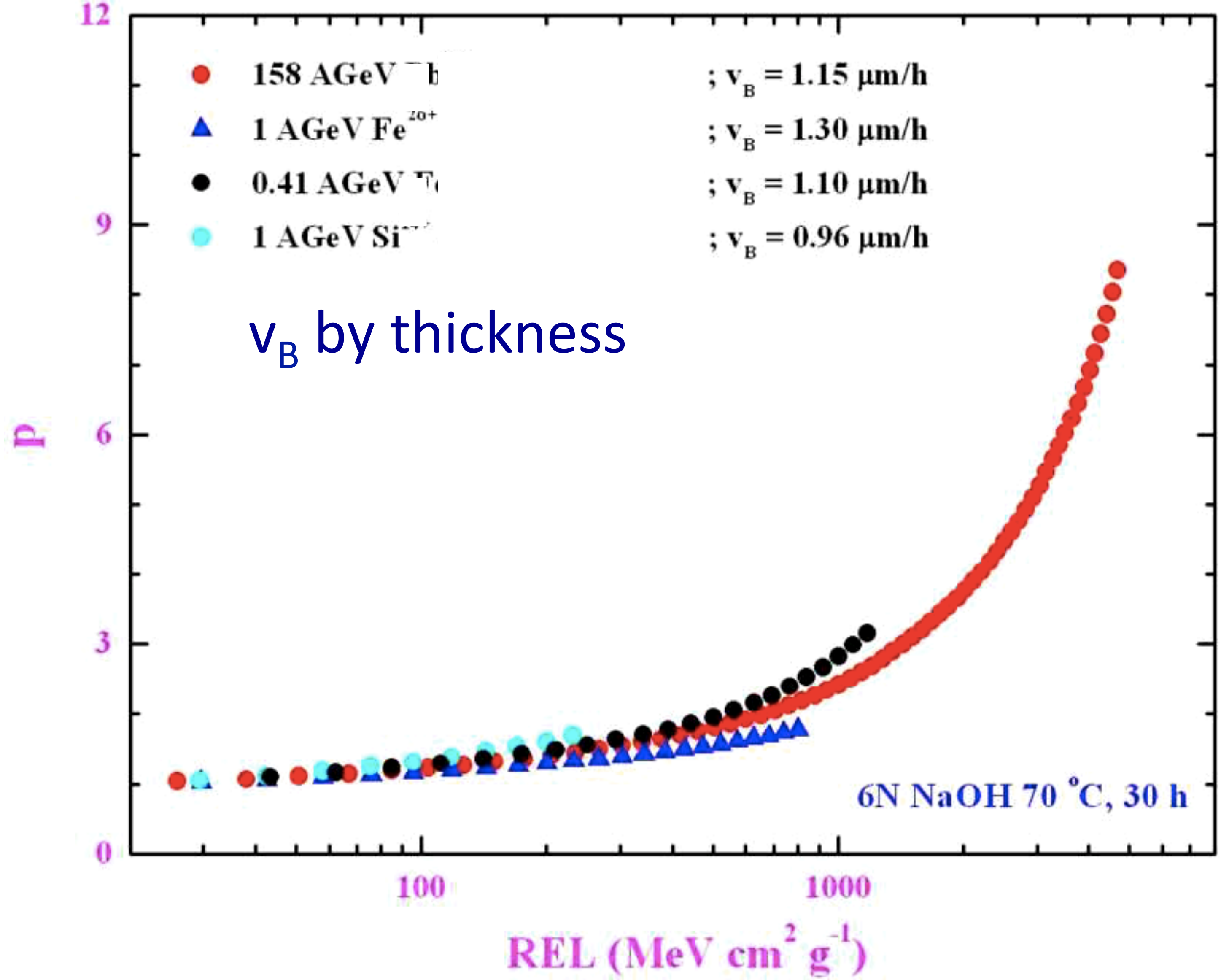
From the Surface Area (diameter..) & v_B → v_T/v_B

From Z, Energy of ions → Restricted Energy Loss (Z/beta…)

→ $p=v_T/v_B$ vs REL

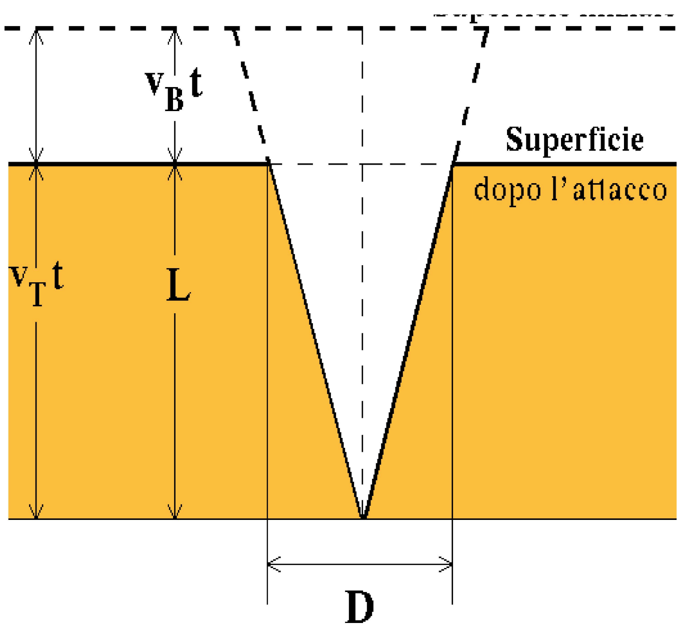


Dependence of the response on the bulk etching rate

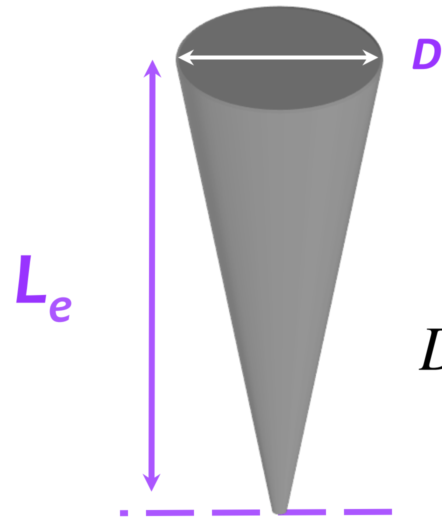


Bulk Etch Rate Measurements

By Thickness



By D-L_e measurements

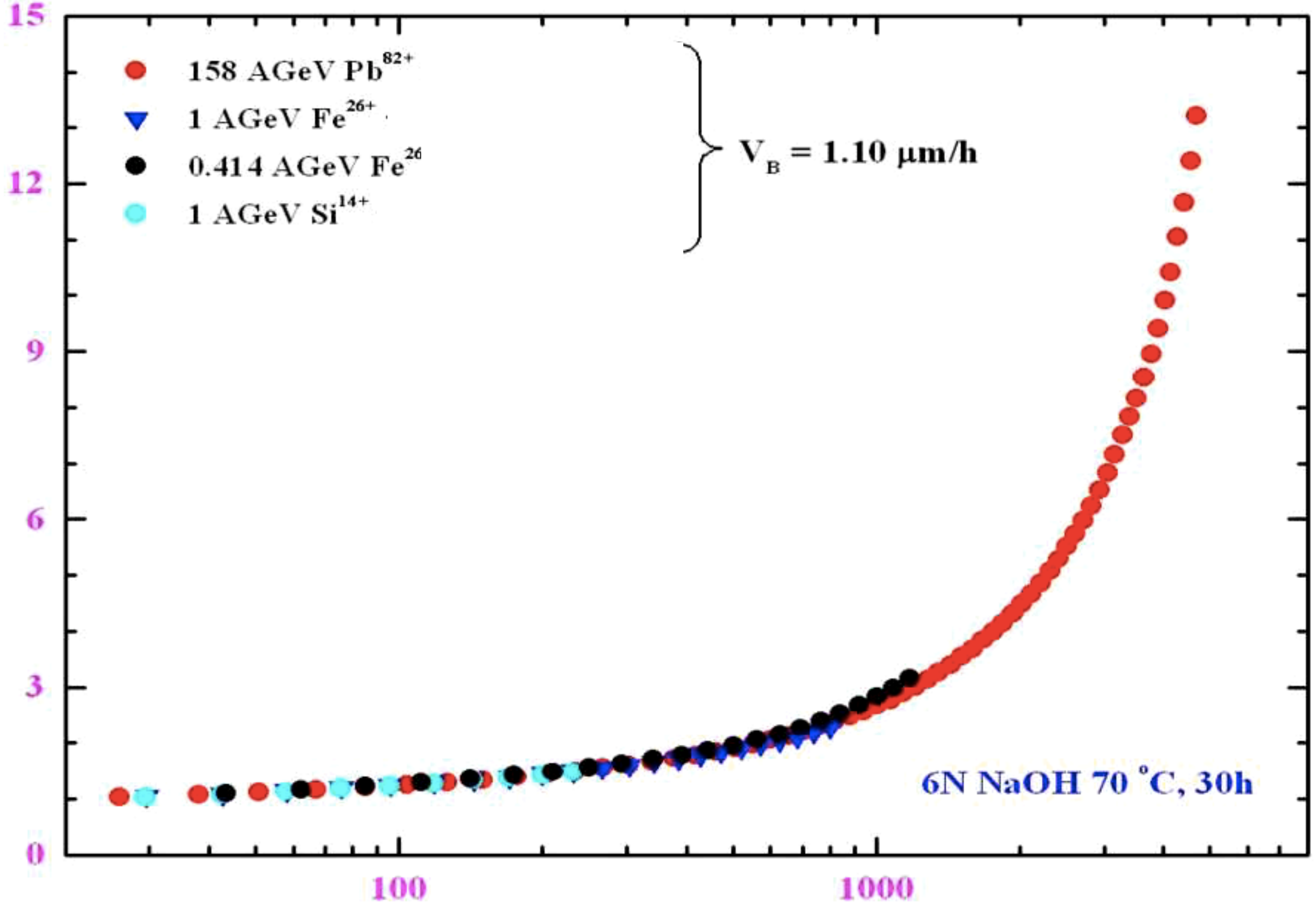


$$L_e = (v_T - v_B)t$$

$$D = 2v_B t\sqrt{\frac{(v_T - v_B)}{(v_T + v_B)}}$$

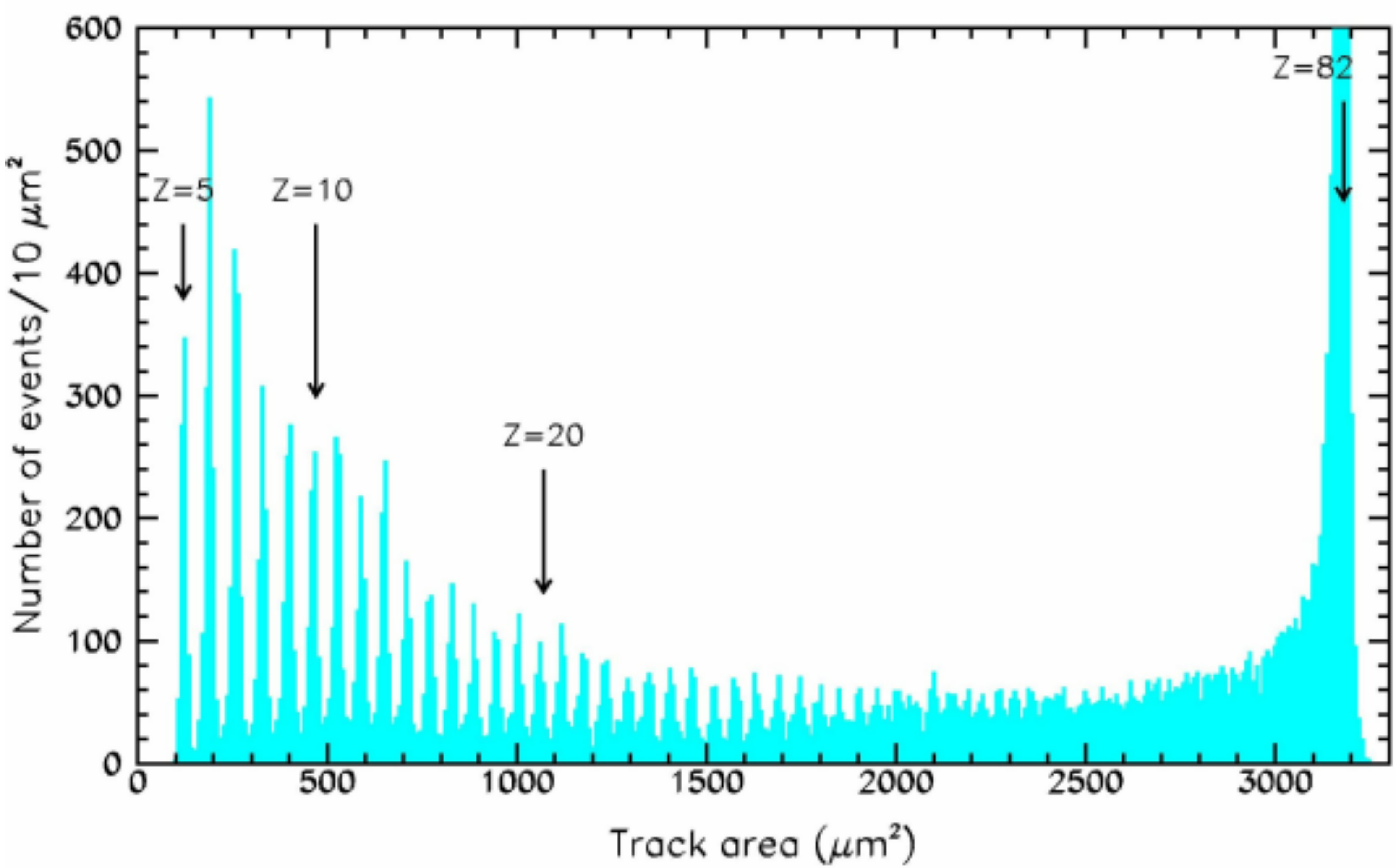
$$v_B = \frac{D^2}{4tL_e}\left[1 + \sqrt{\left(1 + \frac{4L_e{}^2}{D^2}\right)}\right]$$

p

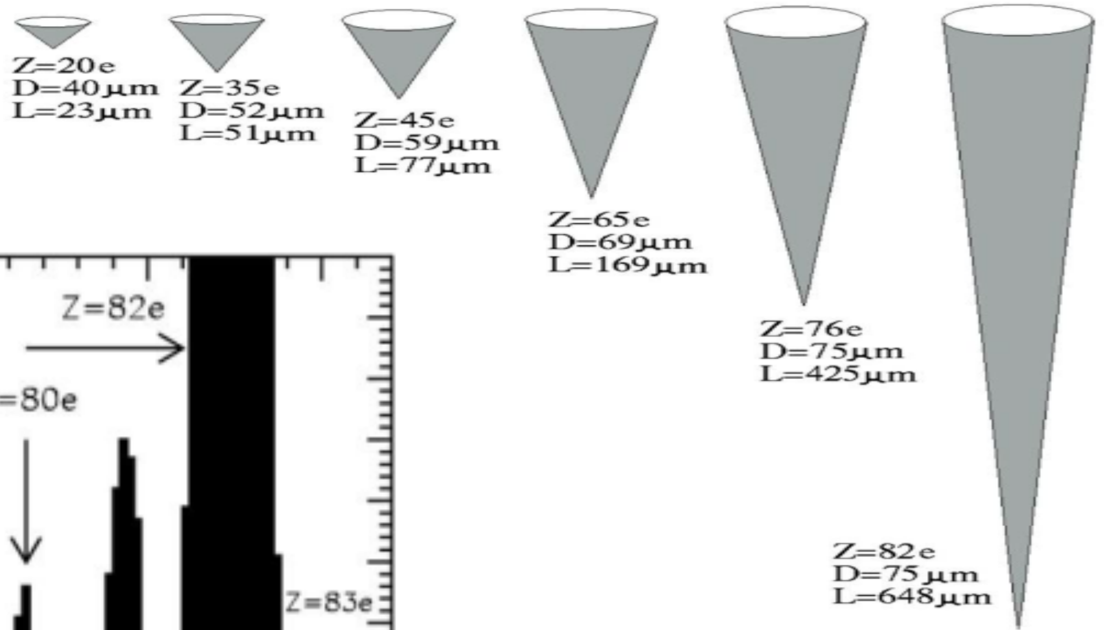


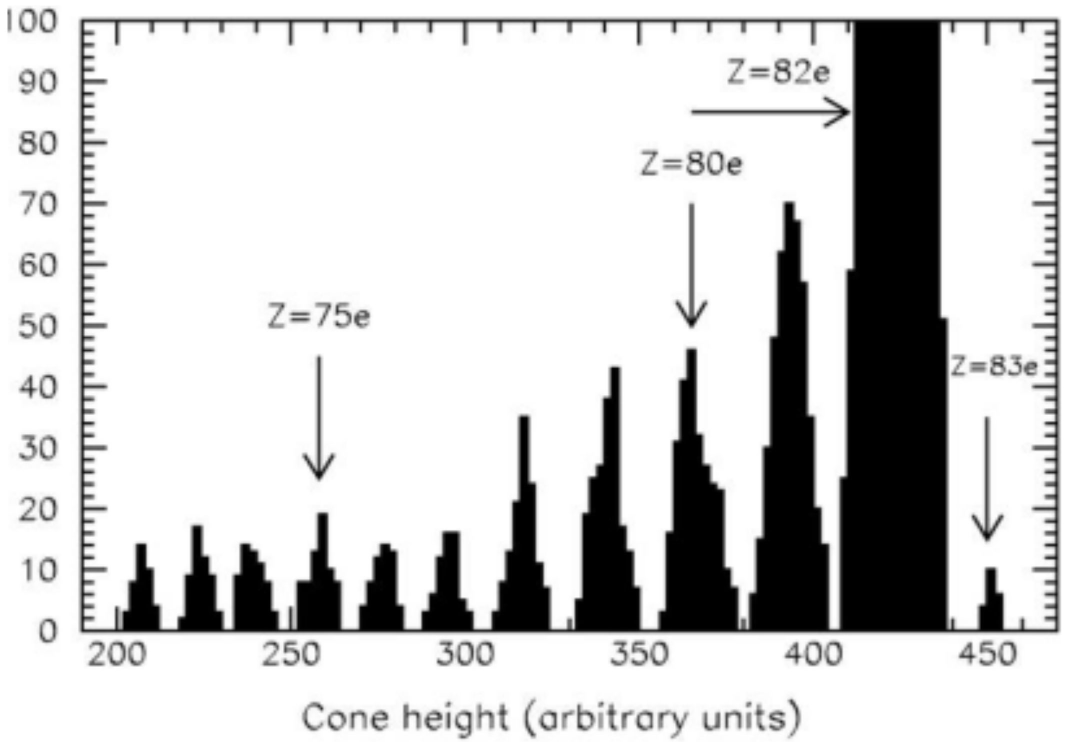
REL ($MeV/g/\ cm^2$)

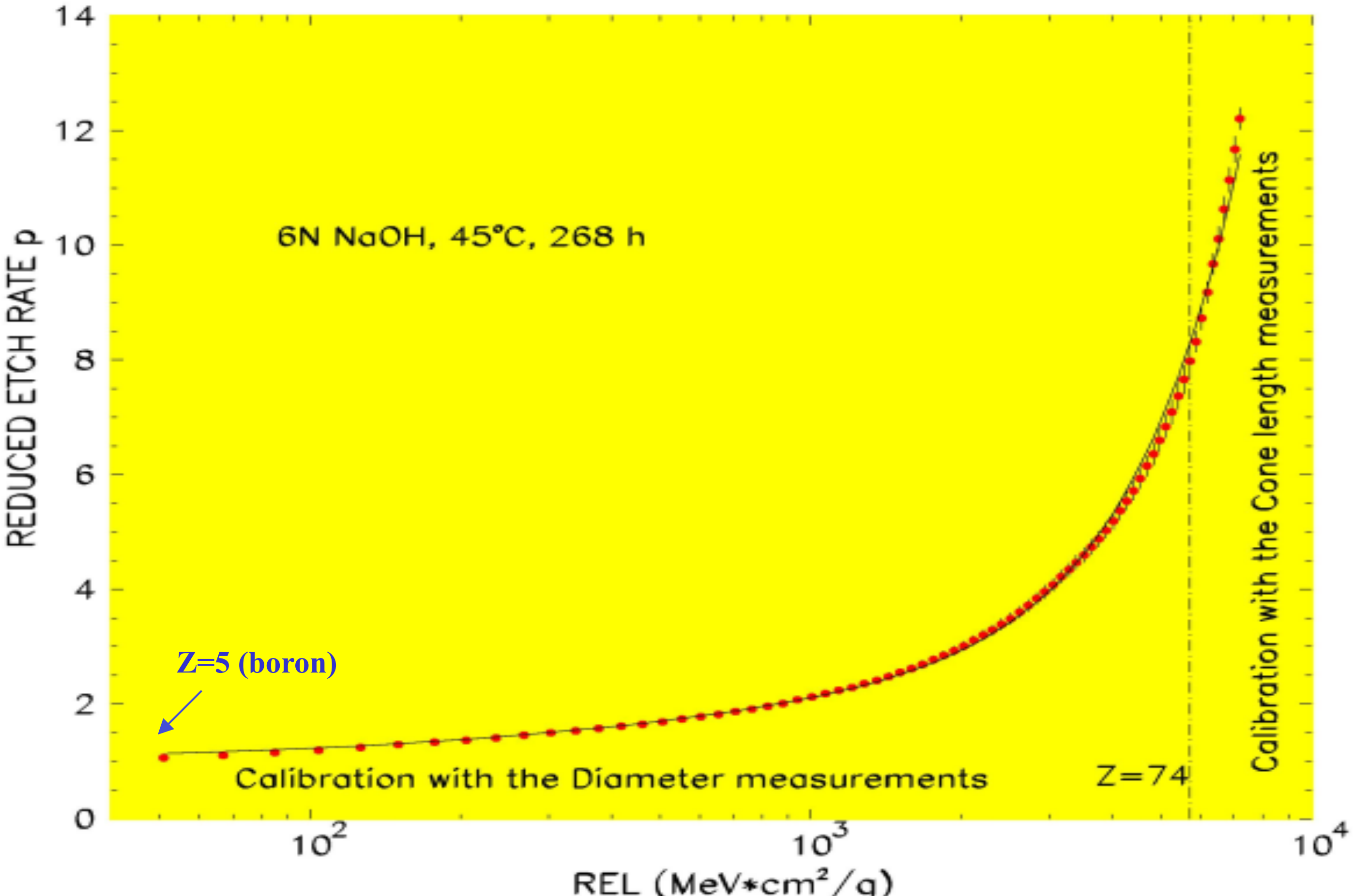
$\mathbf{D = 2v_B t\sqrt{[(p-1)/p+1)]}}$ for $p \gg 1$ $D \sim 2v_B\, t$



Diameters and heights for "relativistic" cones of increasing charge



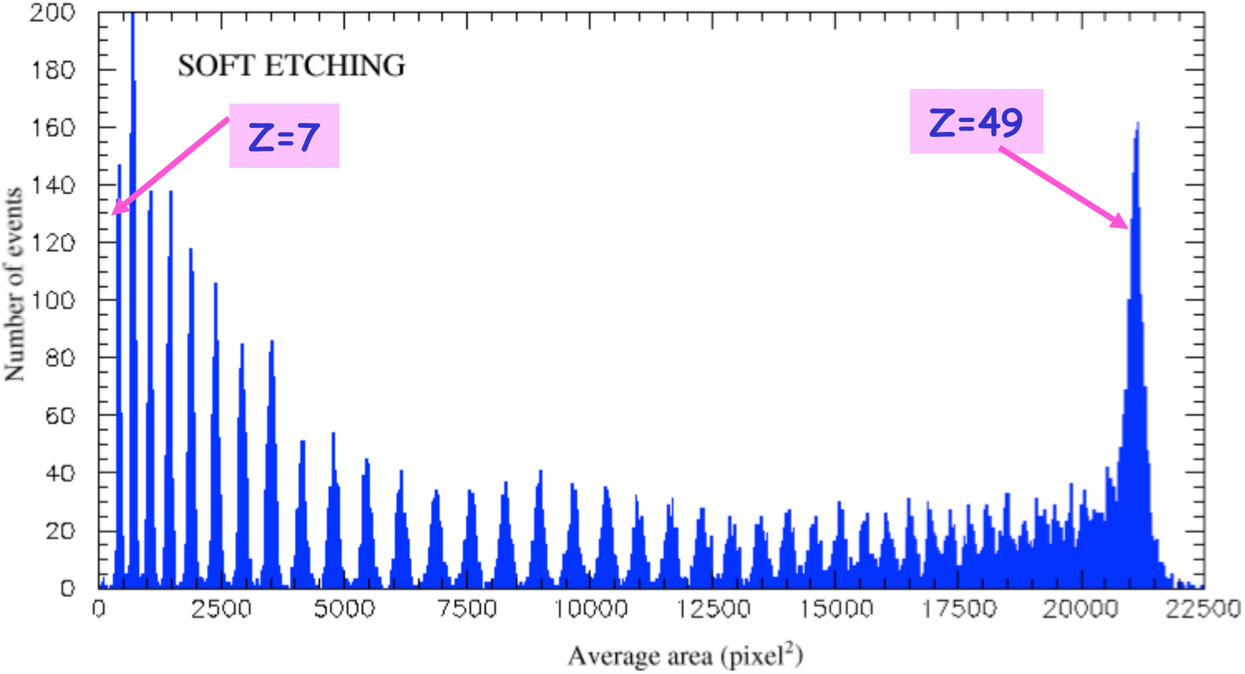




Detector threshold if $v_T=v_B$, $p = 1$ → REL_{thr}

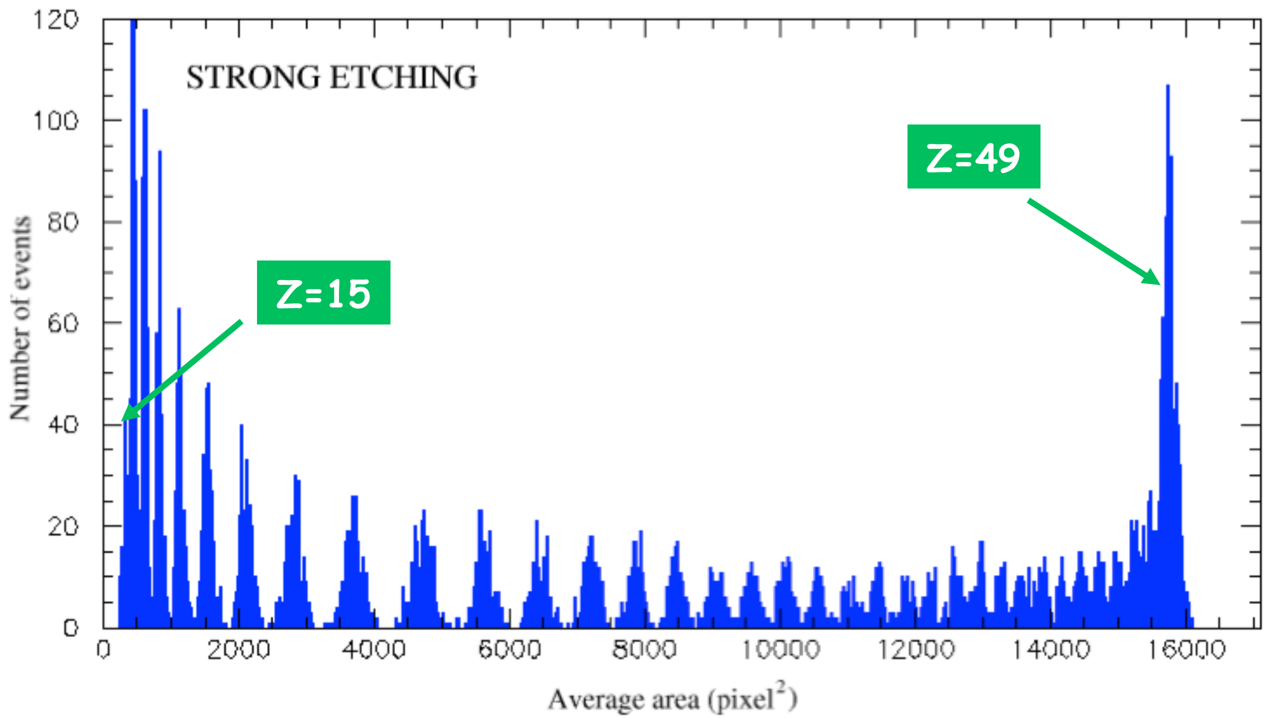
It depends on the etching conditions

Minimum for CR39 : REL_{thr}~ 25 $MeVcm^2g^{-1}$ $(Z/\beta)_{thr}$ <5



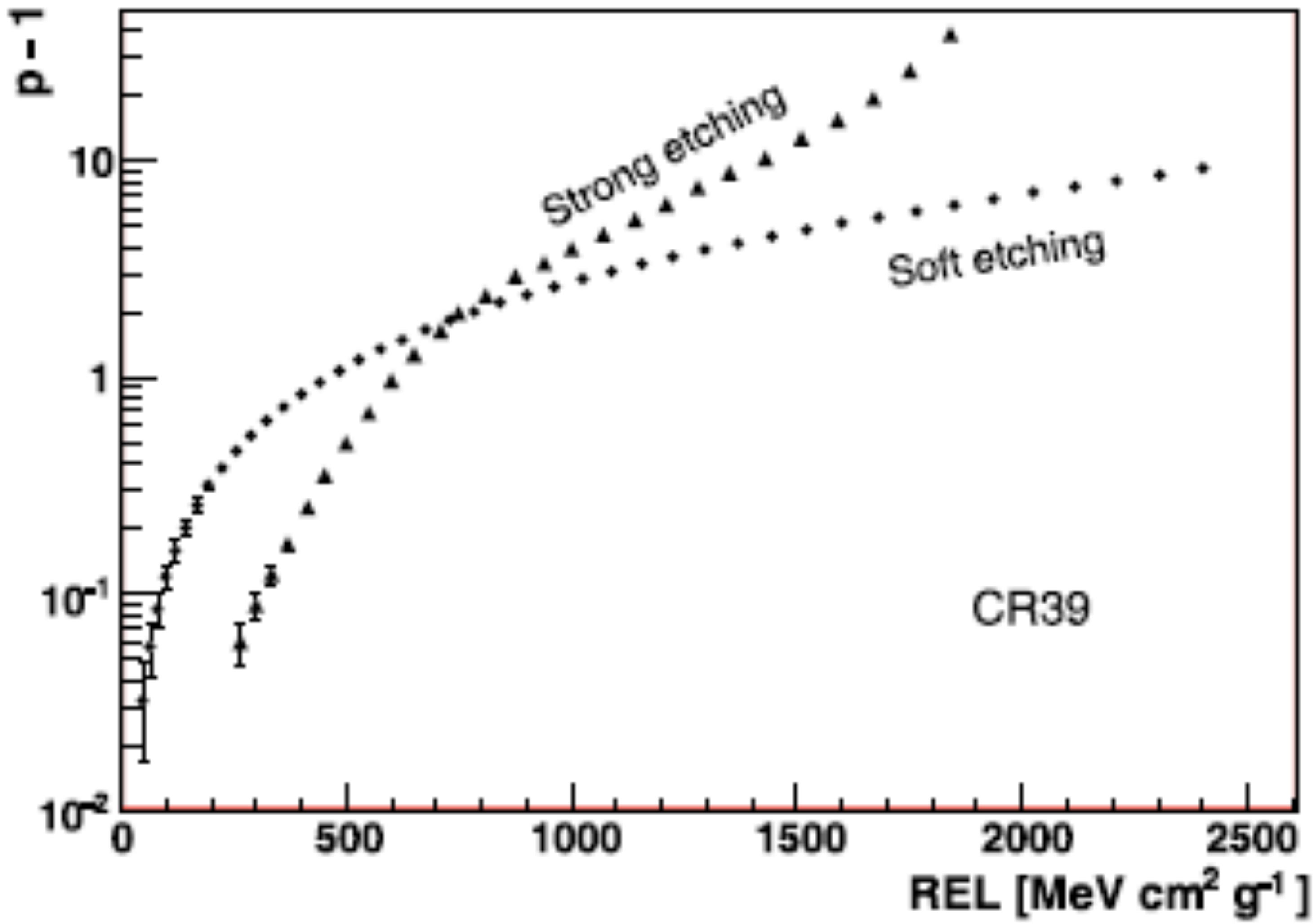
160 A GeV In $^{49+}$ fragments (2 faces)

6N NaOH + alcohol 1%, 70 °C, 40h

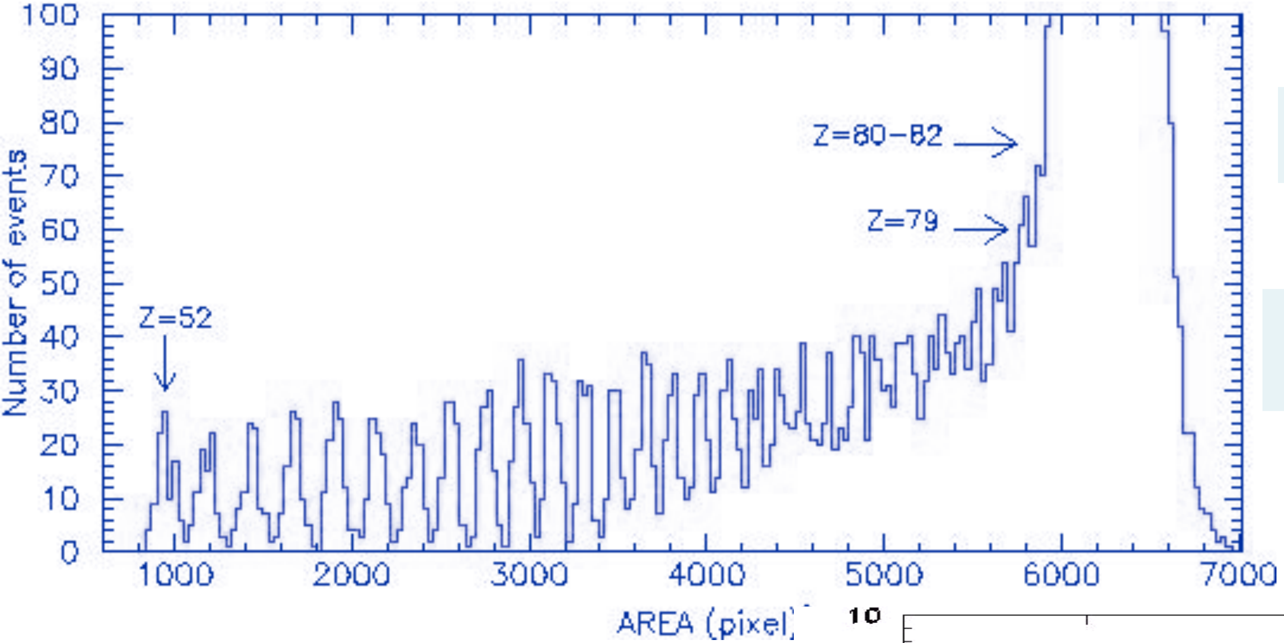


7N KOH + alcohol 1.25%, 77°C, 6h

Calibrations



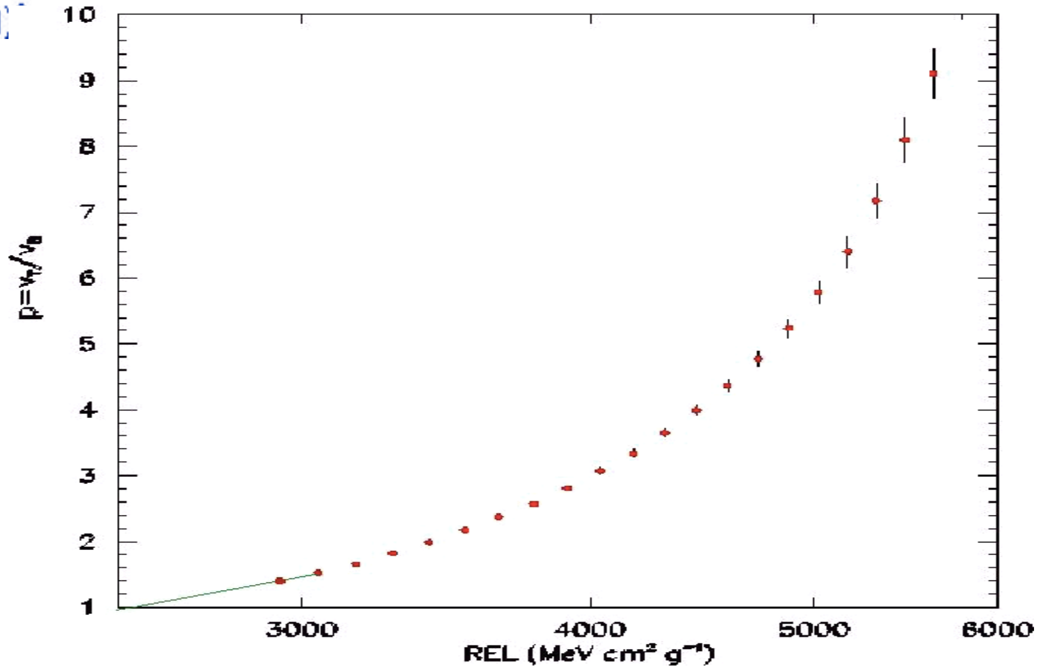
The Makrofol nuclear track detector



Pb^{82+} + fragments (2 faces)

6N KOH + alcohol 20%, 50 ^{o}C, 8 h

Threshold: ~ 2500 MeV·cm^2·g^{-1} (Z/β ~50)



Nuclear track detectors : some applications

- **Searches Magnetic monopoles searches at accelerators**

- Searches for penetrating massive particles
MM, Nuclearites, Strangelets, Q-balls.. in the Cosmic Radiation

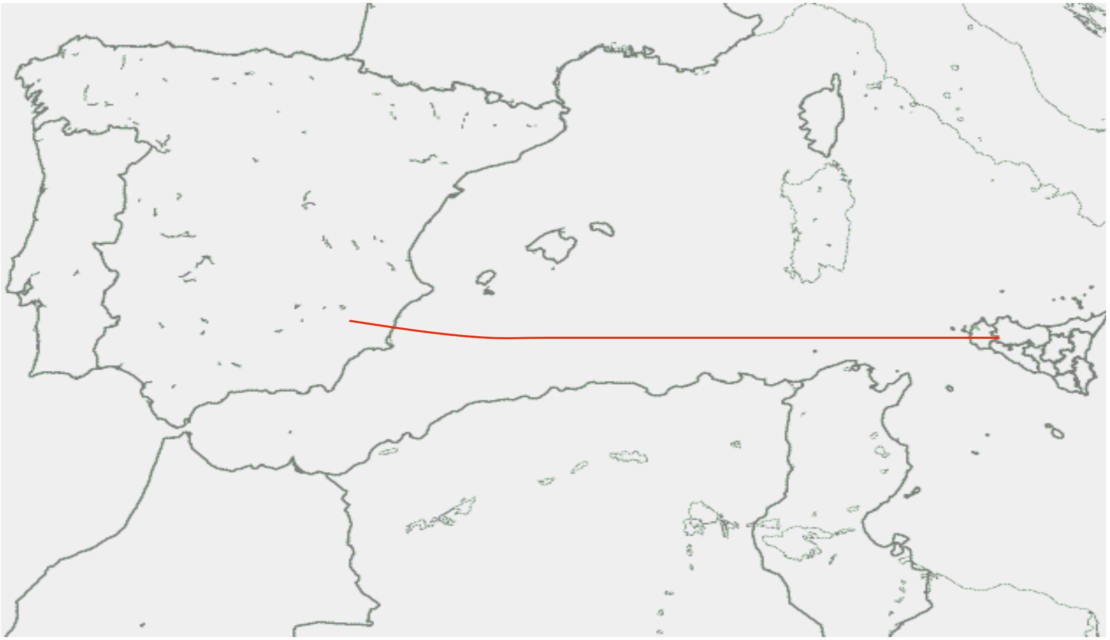
- Cosmic ray elemental composition

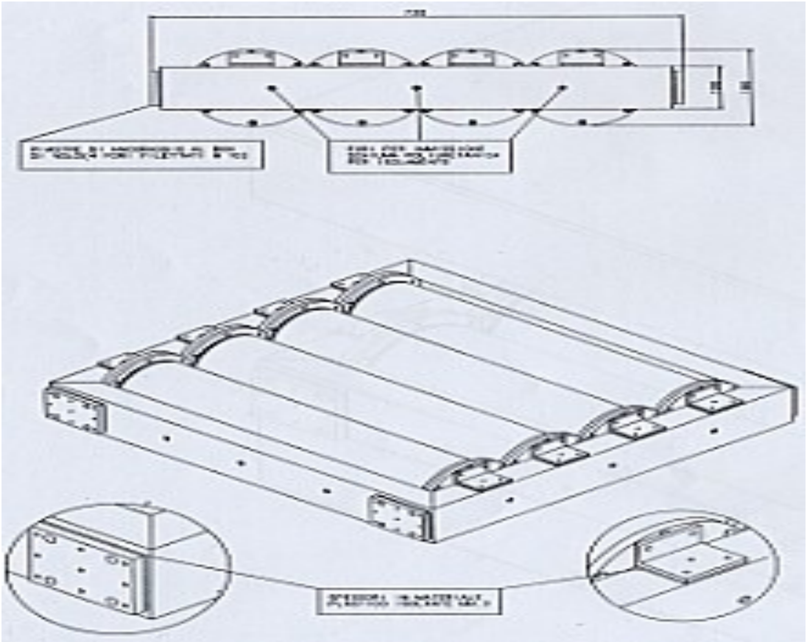
- Measurements of Charge Changing Cross sections
(Relevant for cosmic ray propagation)

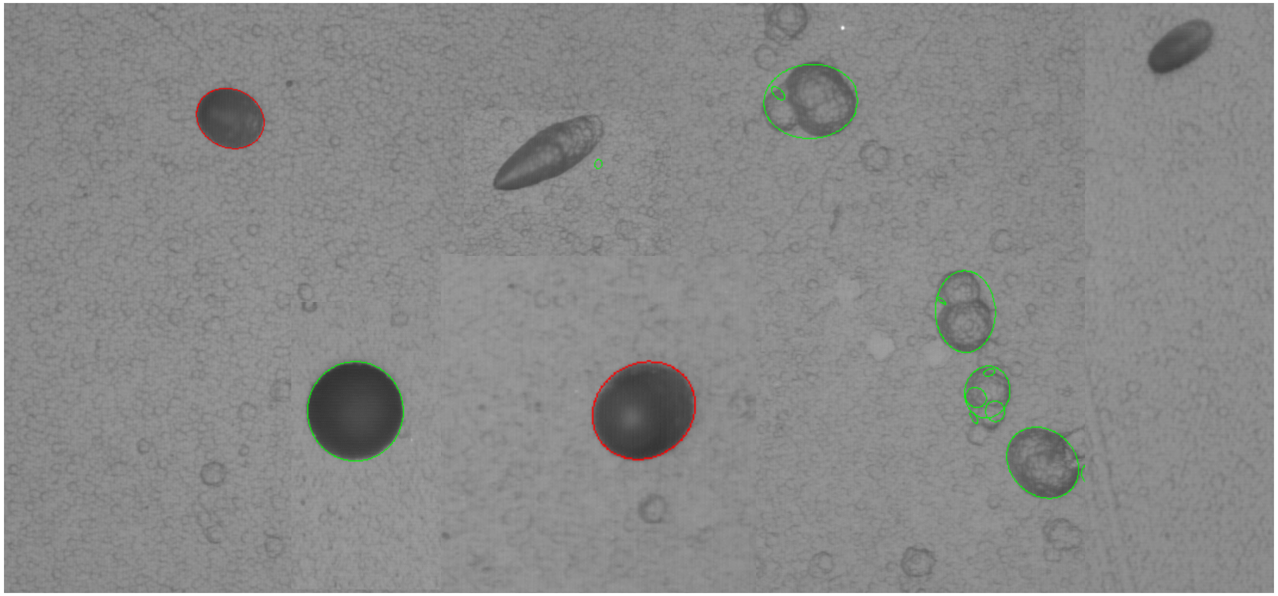
- Radon Concentration, Neutron dosimetry

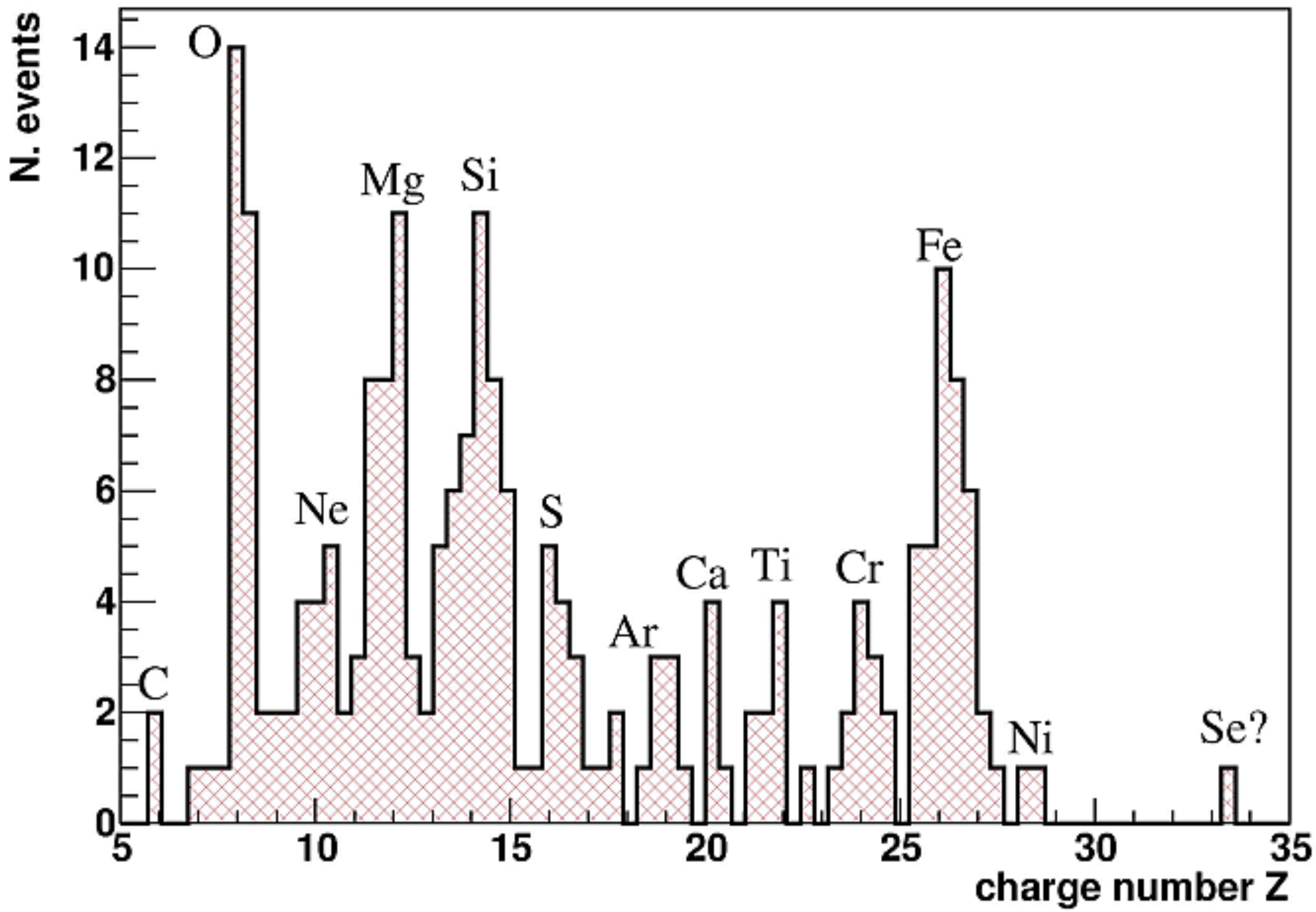
Comic ray elemental composition

The CAKE experiment (INAF, ASI - Italy)





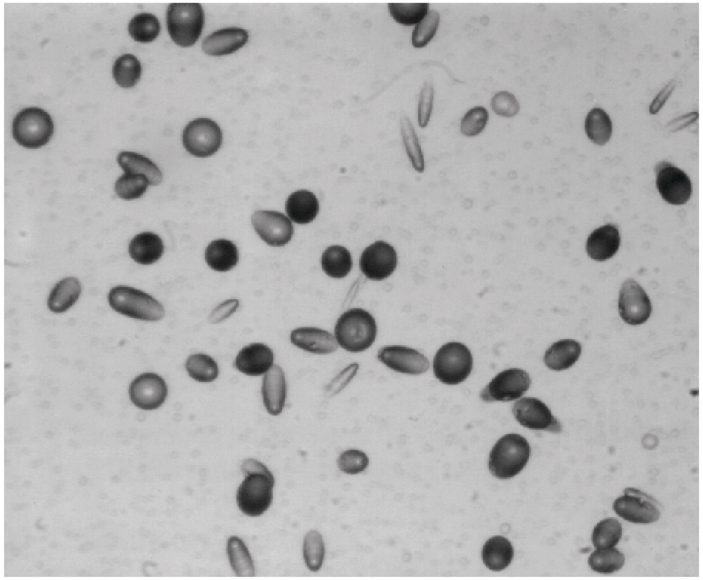




N. events
charge number Z
O
Mg
Si
Fe
Ne
S
Ca
Ti
Cr
Ar
C
Ni
Se?

RADON MEASUREMENTS WITH THE CR39 NUCLEAR TRACK DETECTOR

The CR39 nuclear track detector can be used for measurements of radon concentrations via the detection of 5.5 MeV α particles from the radon decay ($^{222}\mathrm{Rn} \longrightarrow {}^{218}\mathrm{Po} + \alpha$). The exposure time is of the order of some months. After chemical etching, α-tracks are observed and counted with an optical microscope.

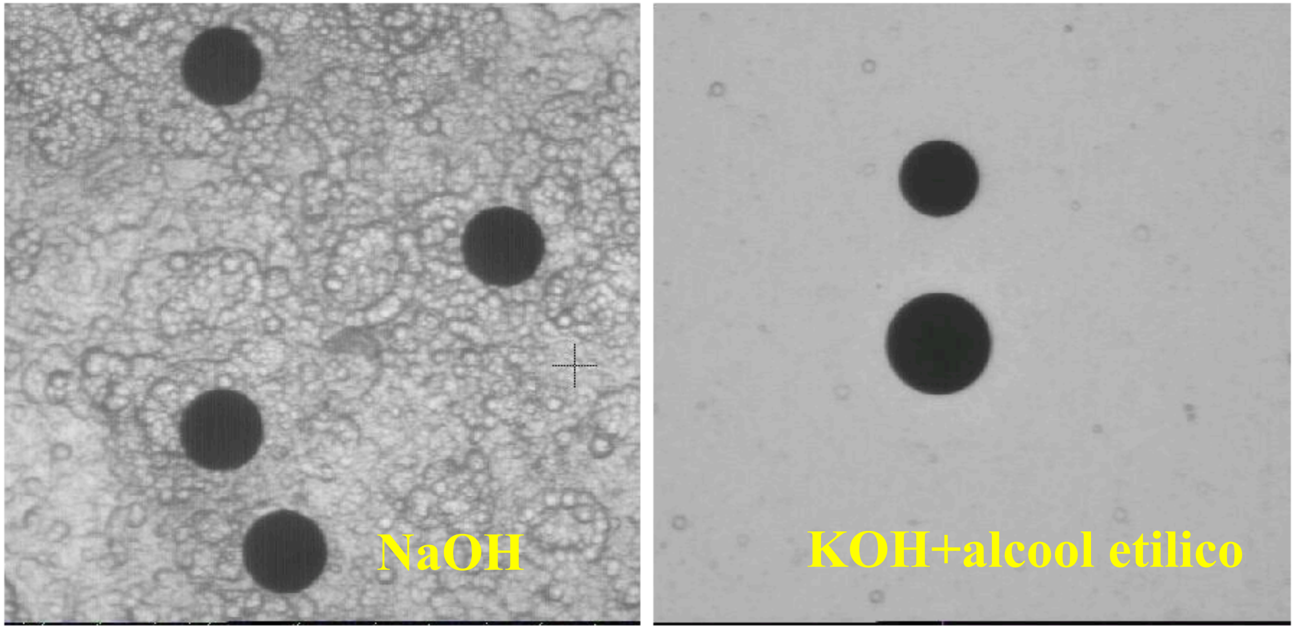


Microphotograph of α particle tracks in CR39 from ^{222}Rn decay. The CR39 sheet was etched for 8 hours in 6N NaOH at 70 °C.

New results

- New (very delicate!) etching procedure → higher signal/noise ratio

OLD



NEW

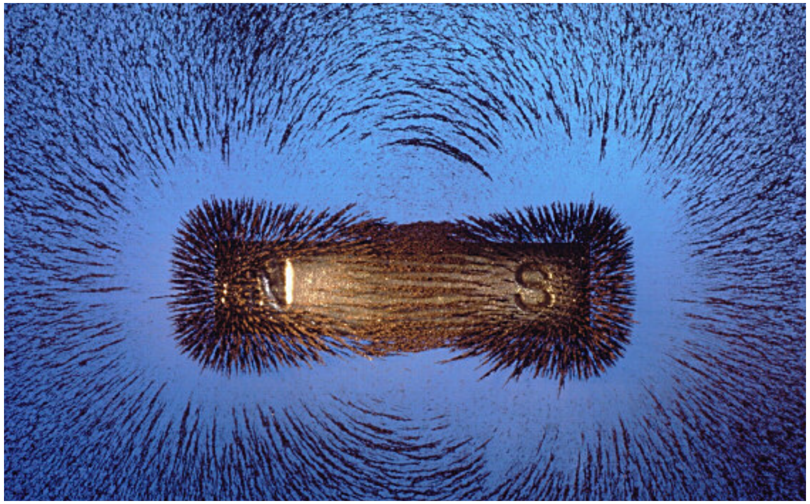
Magnetic Monopoles ?

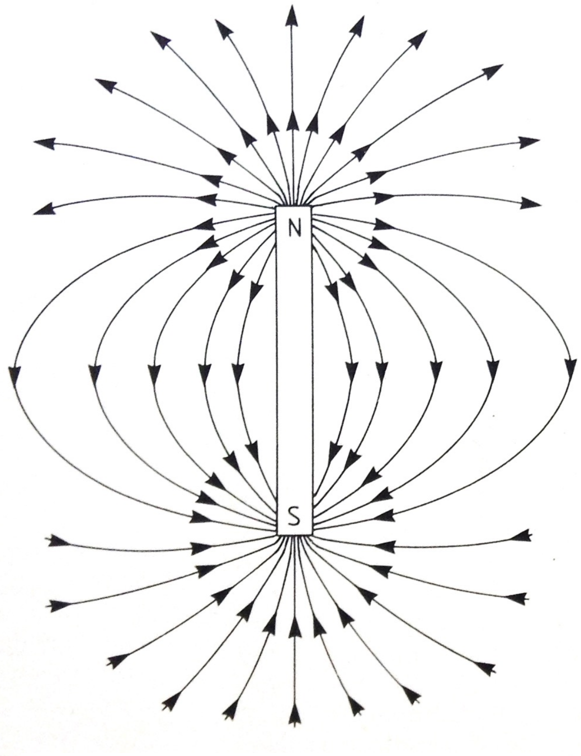
Magnets in Nature 1269

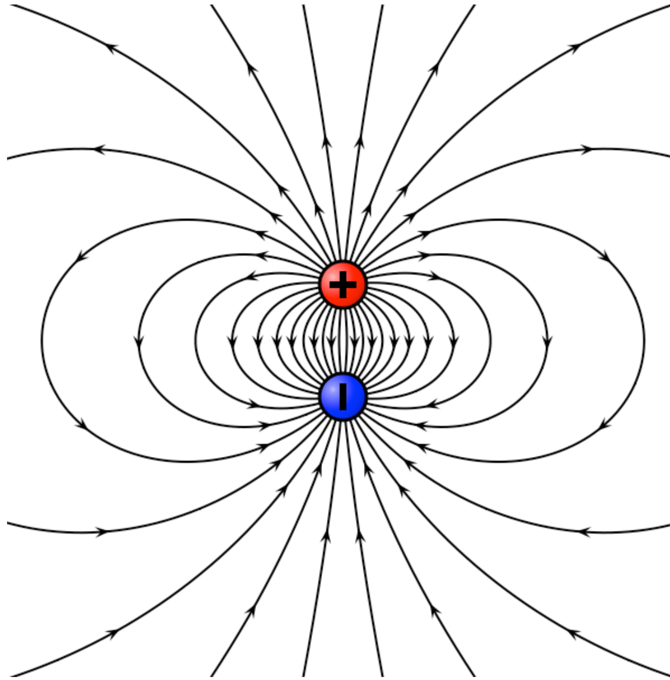
first scientific account

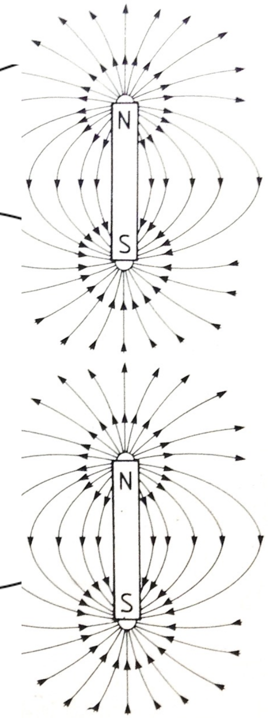
"… In this stone you should thoroughly comprehend there are two points of which one is called the North, the remaining one the South."

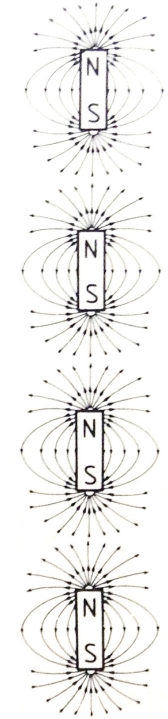
Petrus Peregrinus (De Magnete; *Actum in castris in obsidione Luceriæ anno domini 1269*) During the siege of the town of Lucera, South Italy by Charles of Anjou, king of France











magnetic dipole

electric dipole

magnetic monopoles

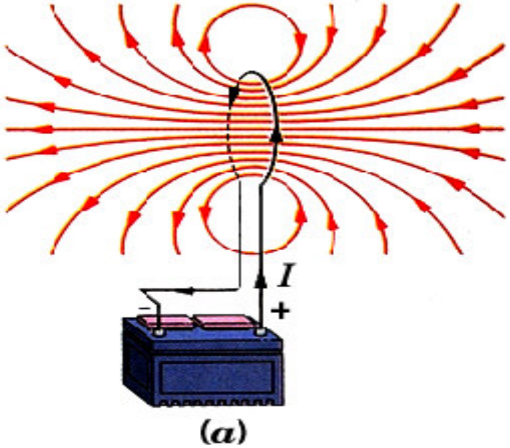
proton electron

electric charges

1820 

Ampère : all magnetism is due to electric currents

(and invents microscopic currents)



1873 

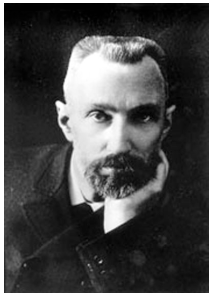
Maxwell Equations

$$\nabla \cdot \mathbf{E} = 4\pi\rho_e$$

$$\nabla \cdot \mathbf{B} = \boxed{4\pi\rho_b}$$

$$-\nabla \times \mathbf{E} = \frac{\partial \mathbf{B}}{\partial t} \boxed{+ 4\pi\mathbf{j}_b}$$

$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + 4\pi\mathbf{j}_e$$

1894 

Pierre Curie: Magnetic Monopoles could exist

1931 Paul Dirac: Quantization of electric charge

Proc. R. Soc. London 133 (1931) 60

Electric charge always comes in discrete values multiple of the charge of the electron

$$Q = n \times q_e = n \times 1.6 \cdot 10^{-19}\ coulombs$$

Dirac made the connection of isolated poles and quantization of electric charge

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

Dirac relation

$$\boxed{\mathrm{g_D} = \frac{\hbar \mathrm{c}}{2\mathrm{e}} = \frac{137}{2}\mathrm{e}}$$

$$\boxed{\mathrm{g} = \mathrm{n}\ \mathrm{g_D}}$$

The first strong **scientific** motivation for magnetic monopoles

It inspired a large variety of possible experiments.

MM's Properties

- Magnetic Charge

  If n = 1 and e = electron charge

  $g_D = \hbar c\ /2e = e/2\alpha = 68.5\ e = 3.3 \times 10^{-8}$ esu

- Electric charge $= 0$ MM , $\neq 0$ Dyon

- Coupling constant $\alpha_M = g^2{}_D/\hbar c = 34.25$

- Energy gain in a magnetic field $W = n\ g_D\ B\ L = n\ 2.06$ MeV/G m

- Mass : Not predicted. Estimate:

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

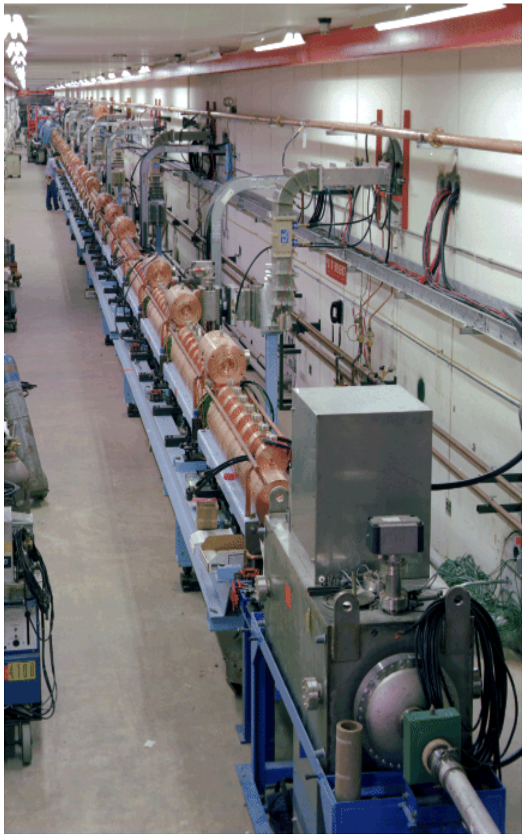
- Large Energy Loss : $\beta \sim 1$ MMs ionize 4700 x m.i.p.

  $\beta \sim 10^{-3}$ $10 \div 100$ x m.i.p.

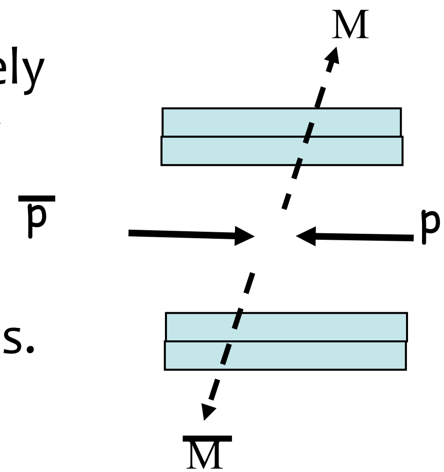
Since 1950s searches for Dirac magnetic monopoles at every new accelerator ...

Searches for classical MMs

$$e^+e^- \to M\overline{M},\ \overline{p}p \to M\overline{M}\ ,\quad pp \to ppM\overline{M}$$

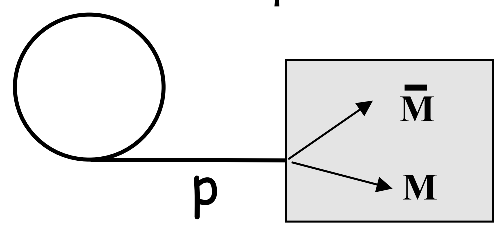


- **direct detection** (immediately after production in high-energy collisions)
  - (ex.) thin plastic sheets surround interaction regions.

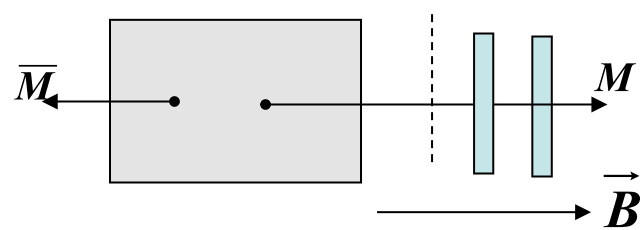


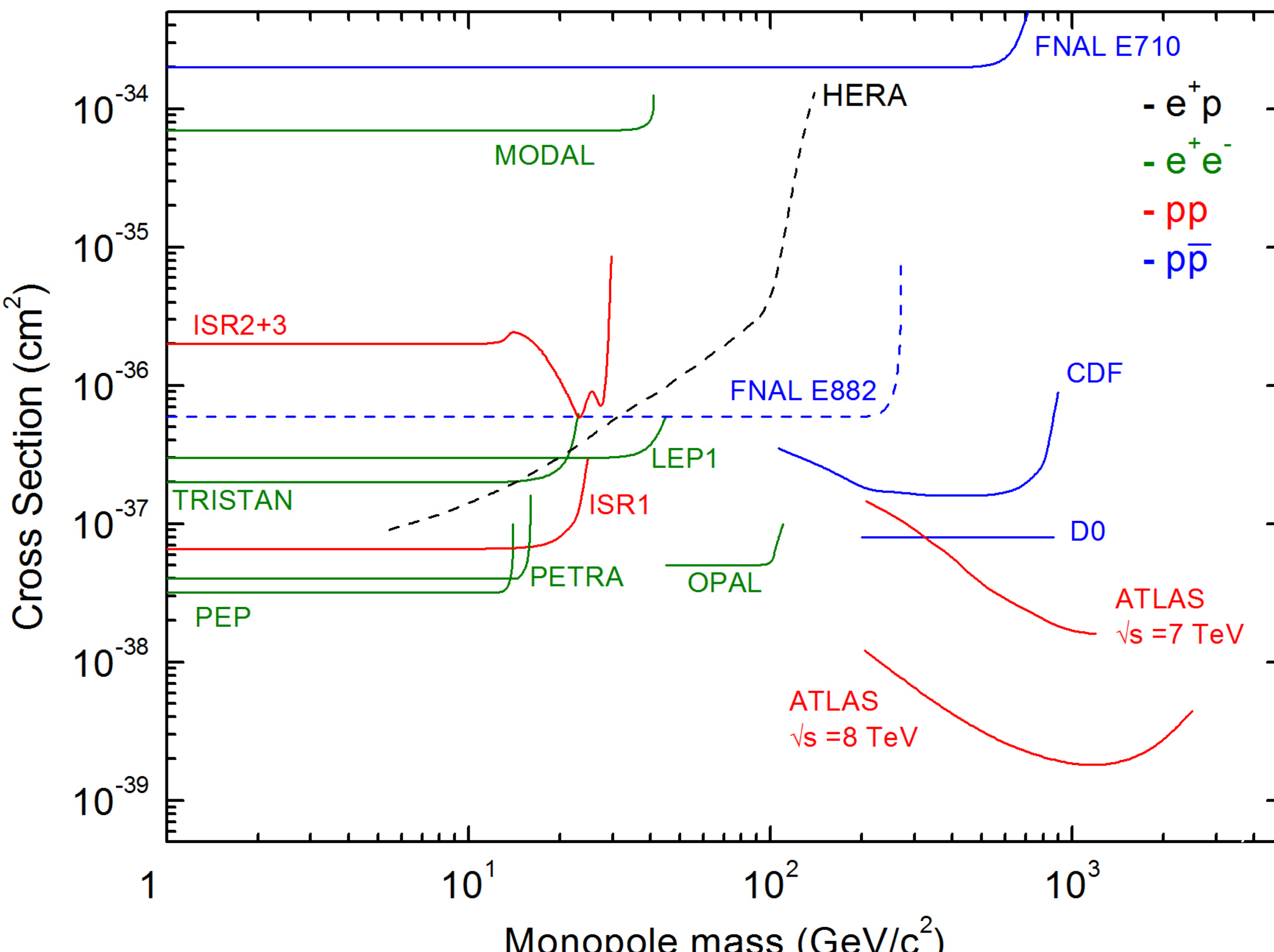
- **indirect searches**: (where monopoles are searched for a long time after their production)

MMs { Produced, Stopped, Trapped }



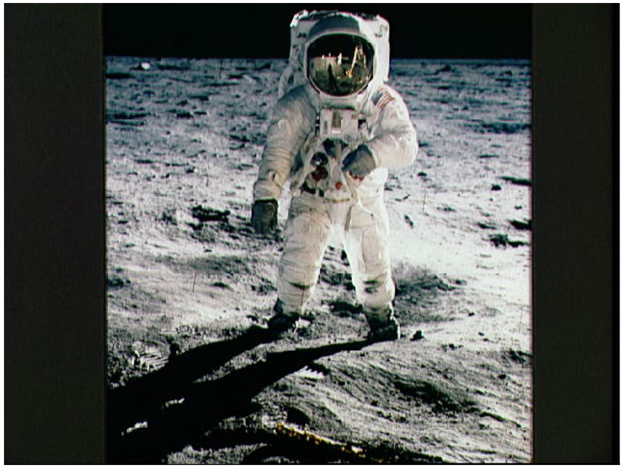
Later { Extracted, Accelerated, Detected }





FNAL E710
HERA
- e⁺p
- e⁺e⁻
- pp
- pp̄
MODAL
ISR2+3
FNAL E882
CDF
LEP1
TRISTAN
ISR1
D0
PETRA
OPAL
PEP
ATLAS
√s =7 TeV
ATLAS
√s =8 TeV
Cross Section (cm²)
Monopole mass (GeV/c²)
10⁻³⁴
10⁻³⁵
10⁻³⁶
10⁻³⁷
10⁻³⁸
10⁻³⁹
1
10¹
10²
10³

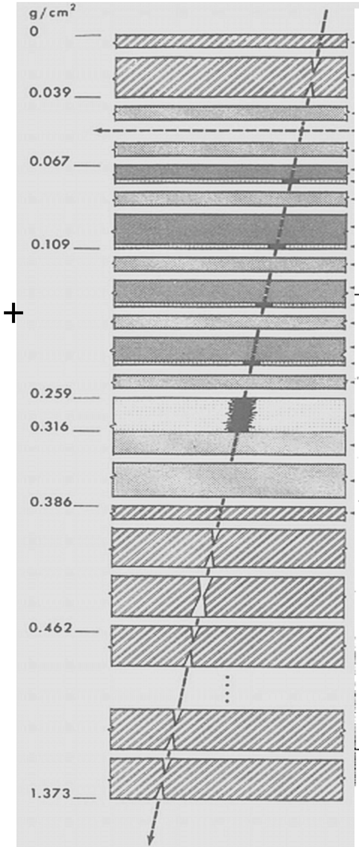
- **Searches in bulk matter**
- Terrestrial magnetic materials
- Meteorites
- Moon rocks: *One of the first scientific experiments with moon rocks was to search for a concentration of magnetic monopoles*



- **Searches in Cosmic Rays**
- with counters
- passive detectors

The " Price Event"
balloon flight
10 m² plastic detectors + emulsions + Č films.

PRL 35 (1975) 0486




The New York Times

Bronfman Asks Abductors For More Proof Son Lives

Mujib Reported Overthrown and Killed In a Coup by the Bangladesh Military

Basic Unit of Magnetism Believed to Be Detected

Lisbon Resumes Control Of Angola Administration

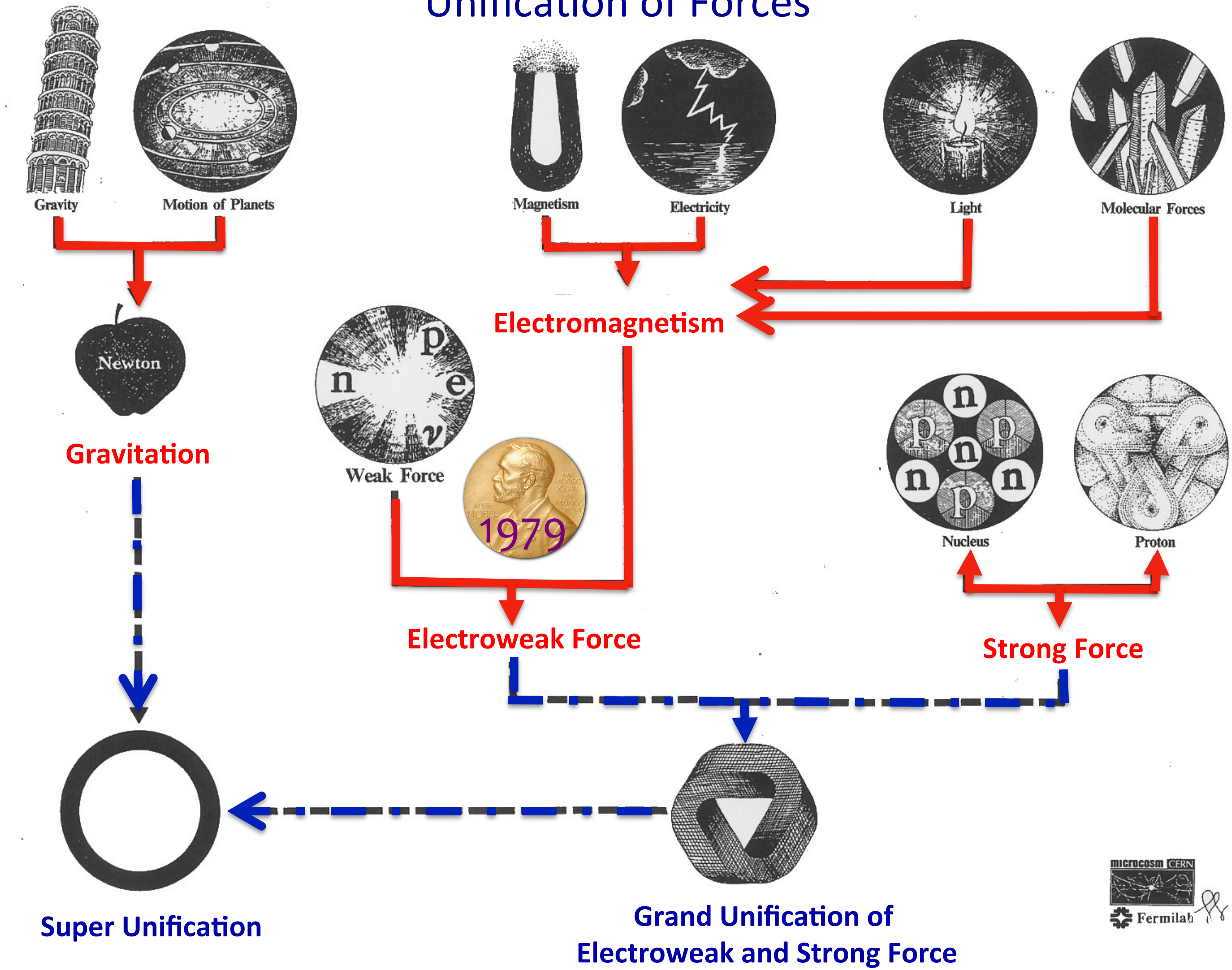
Death of 2 Doctors Poses a Fitness Issue

Physicists Believe They Have Detected the Basic Unit of Magnetism

August 1975

Price monopole

Unification of Forces



4. GUT Monopoles (Gauge, Cosmic,..) 1974

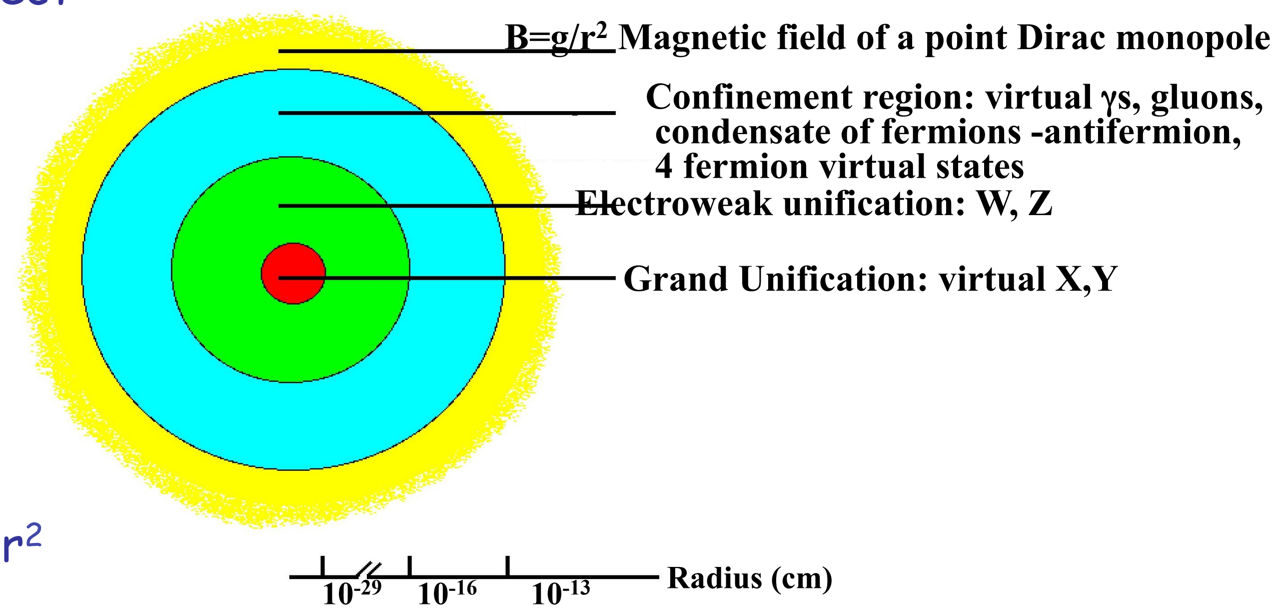
Gauge theories of unified interactions predict MMs

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

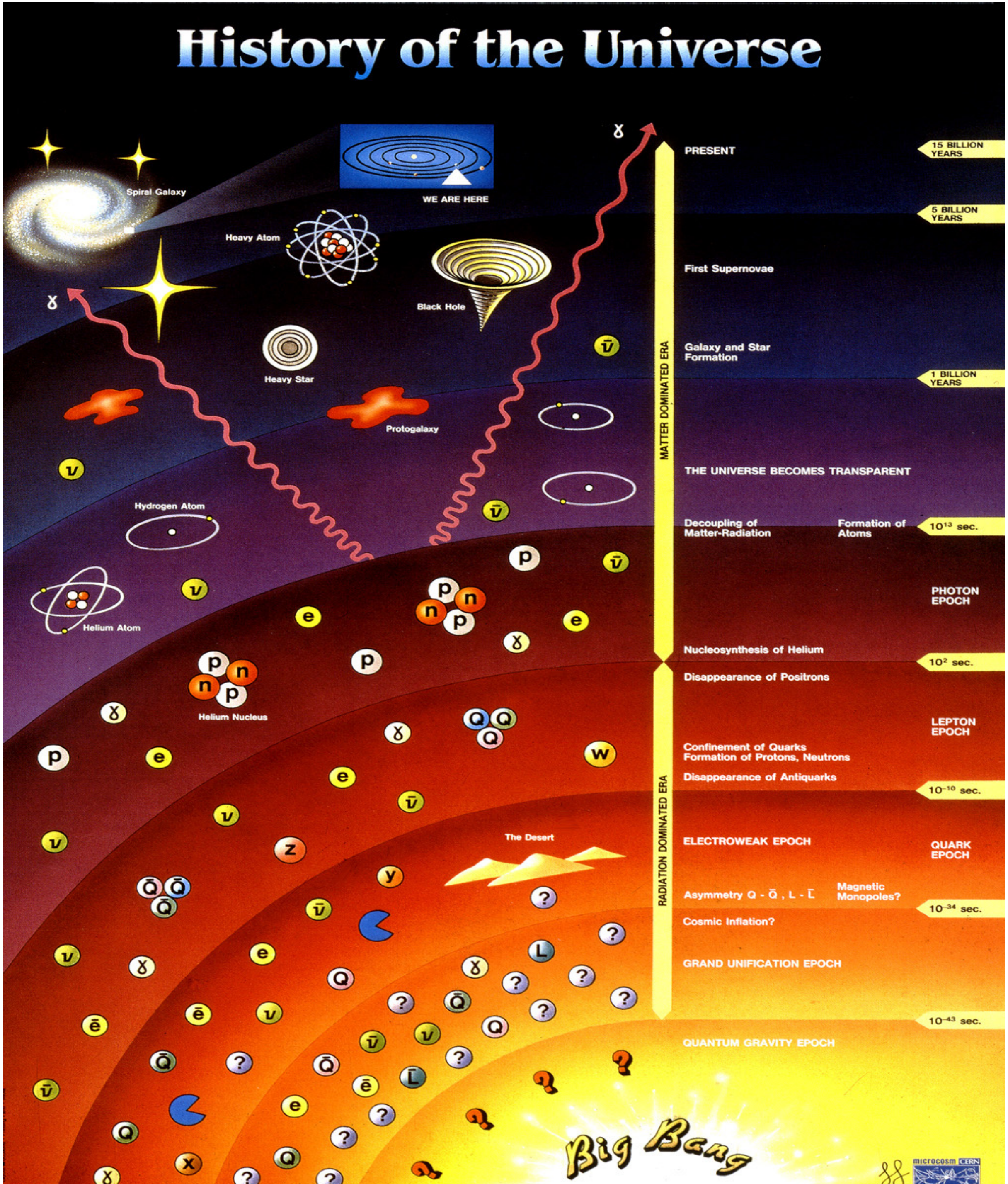
* Mass $m_M \geq m_X/G > 10^{16}$ GeV ~ 0.02 μg → 10^{17} GeV

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

* Size: extended object



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



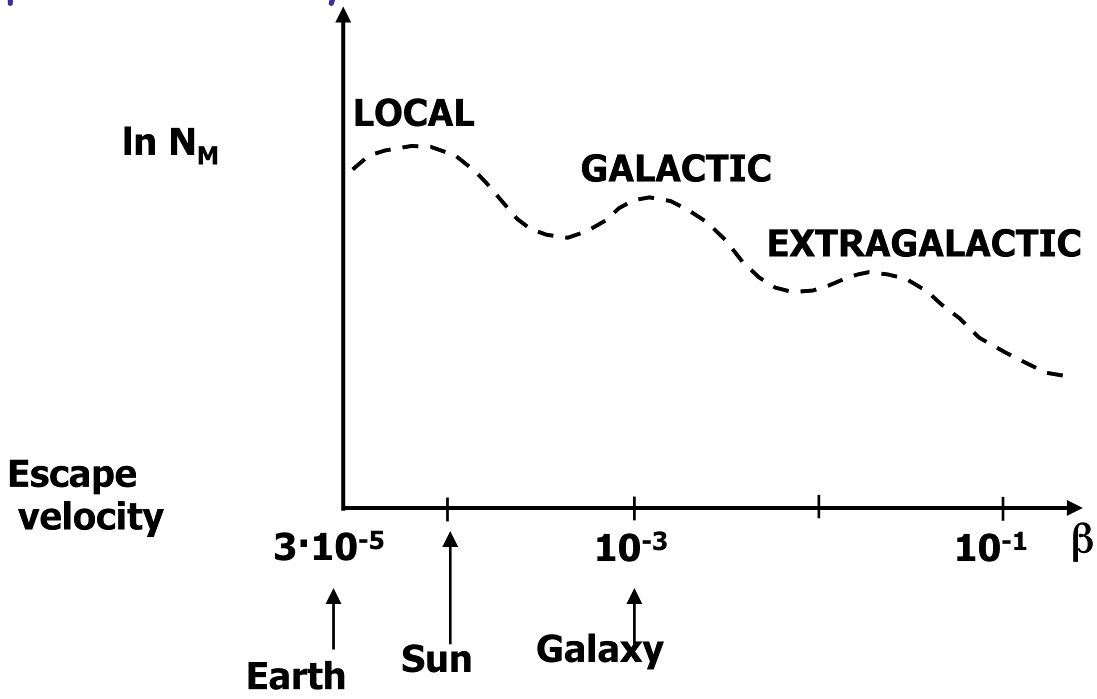
Magnetic Monopoles?

10^{-34} s

Grand Unification Epoch

GUT MMs

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

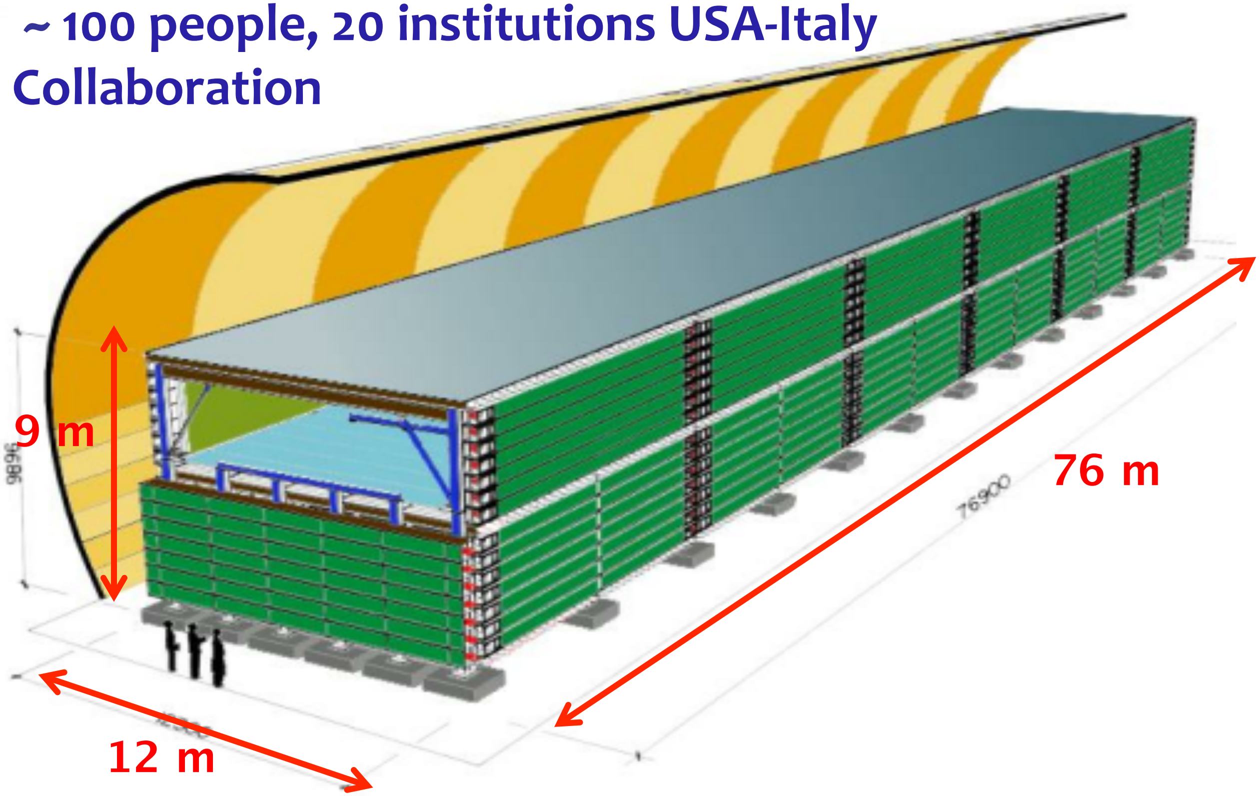


Cosmological limits on MM flux : ~5 $10^{-12}\,\beta$ $cm^{-2}s^{-1}sr^{-1}$

Astrophysical limits on MM flux : ~ 10^{-15} "

Monopole Astrophysics and Cosmic Ray Observatory
The MACRO experiment @ Gran Sasso

~ 100 people, 20 institutions USA-Italy Collaboration



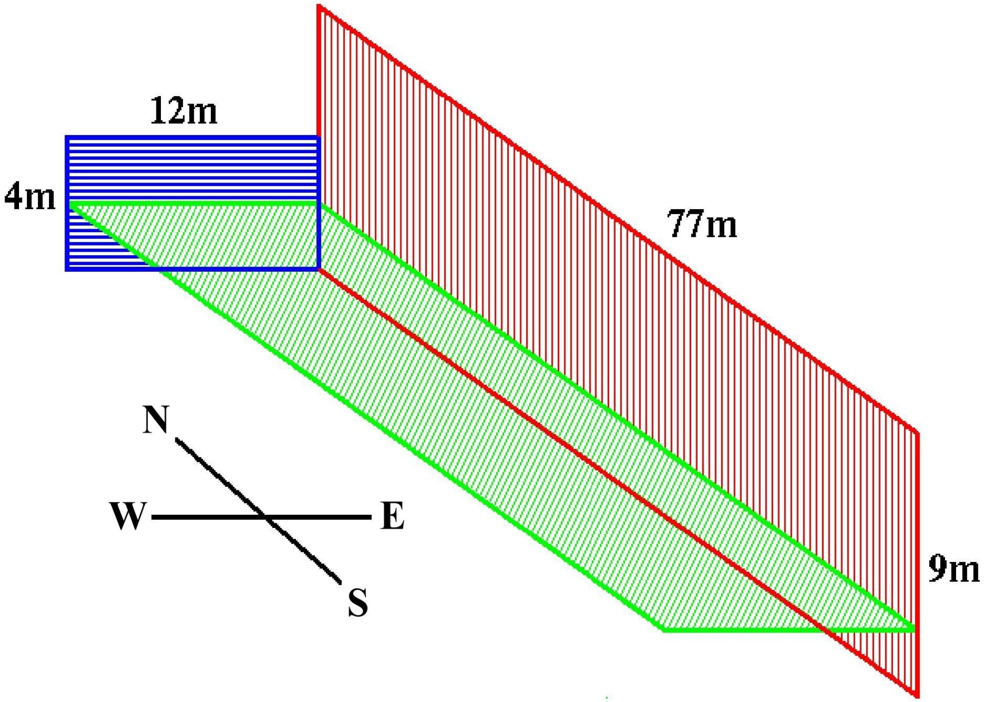
From 1989 to 2000

3 Subdetectors:
- Scintillators
- Limited Streamer tubes
- Nuclear track detectors

$S\Omega$ ~10,000 m^2sr

Redundany & Complementarity

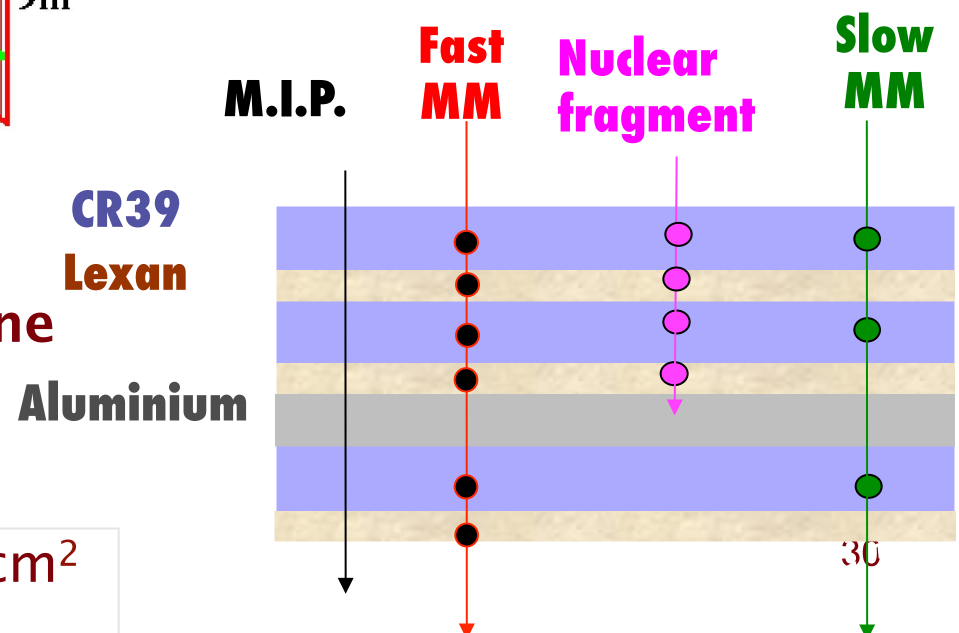
The MACRO track-etch subdetector



Total surface : ~ 1263 m^2

$S\Omega_{\text{fast MM}}$ ~ 7100 m^2 sr

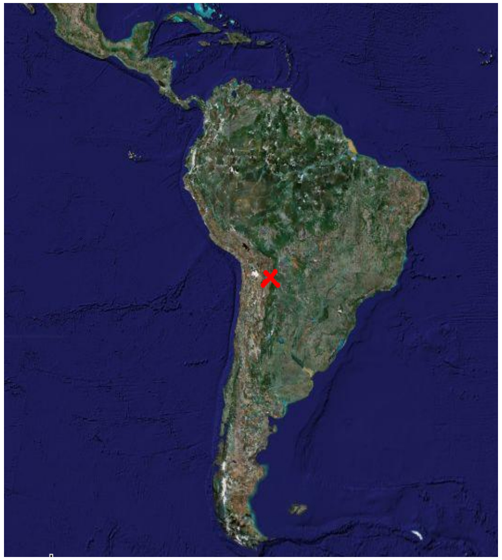
T_exposure ~ 10 years



Used in triggered and stand-alone mode

modules 24.5 x 24.5 cm^2

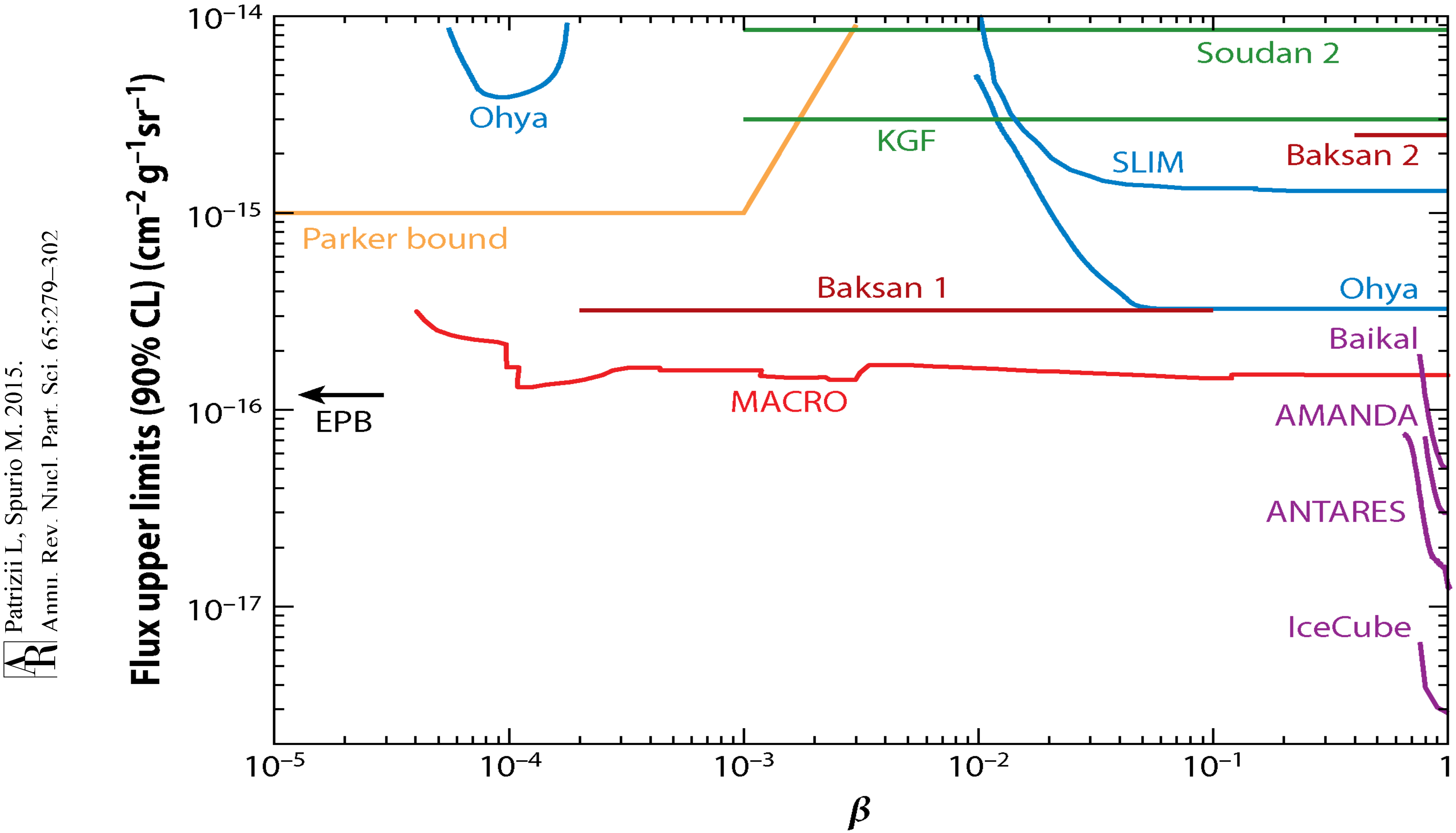
Search for Light Monopoles @ Chacaltaya, Bolivia, 5230 m asl



Bolivia: Lab. Fisica Cosmica , UMSA, LaPaz
Canada: CSR, Univ. Alberta, Edmonton
Italy: INFN and Phys Depts, Bologna, Torino
Pakistan: PINSTECH, Islamabad

430 m² array of NTDs

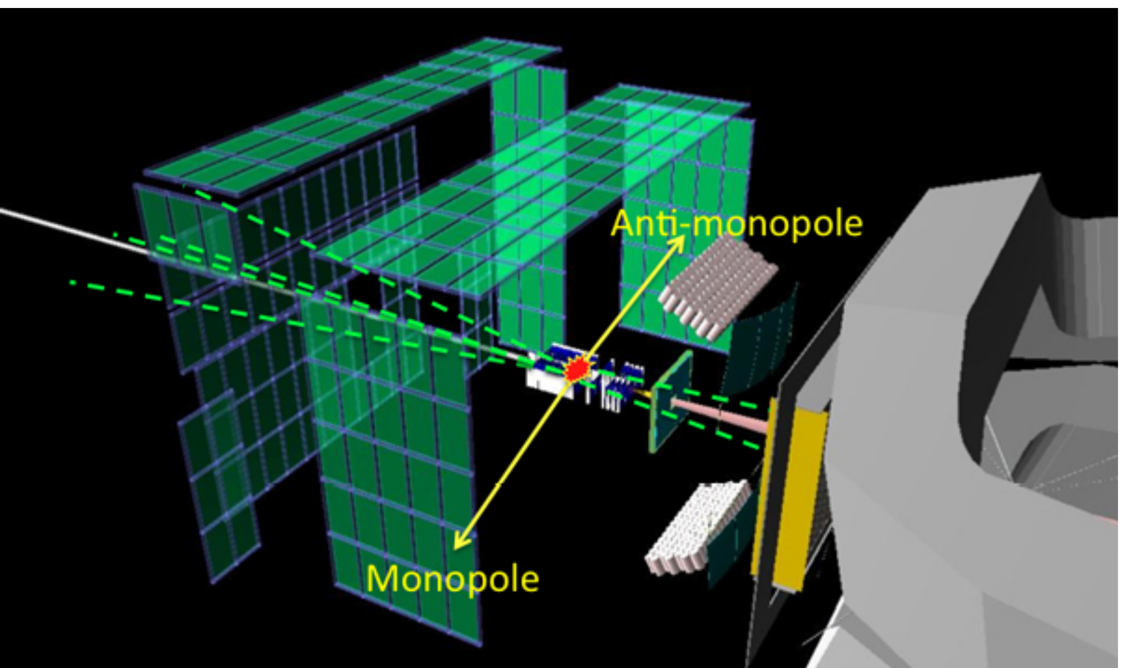
GUT Cosmic Monopoles



tracking calorimeter **scintillators** **NTDs** **ν-telescopes**

Pursuing the Quest for Monopoles at the LHC with the MoEDAL Experiment

International collaboration
65 physicists from
21 participating institutions

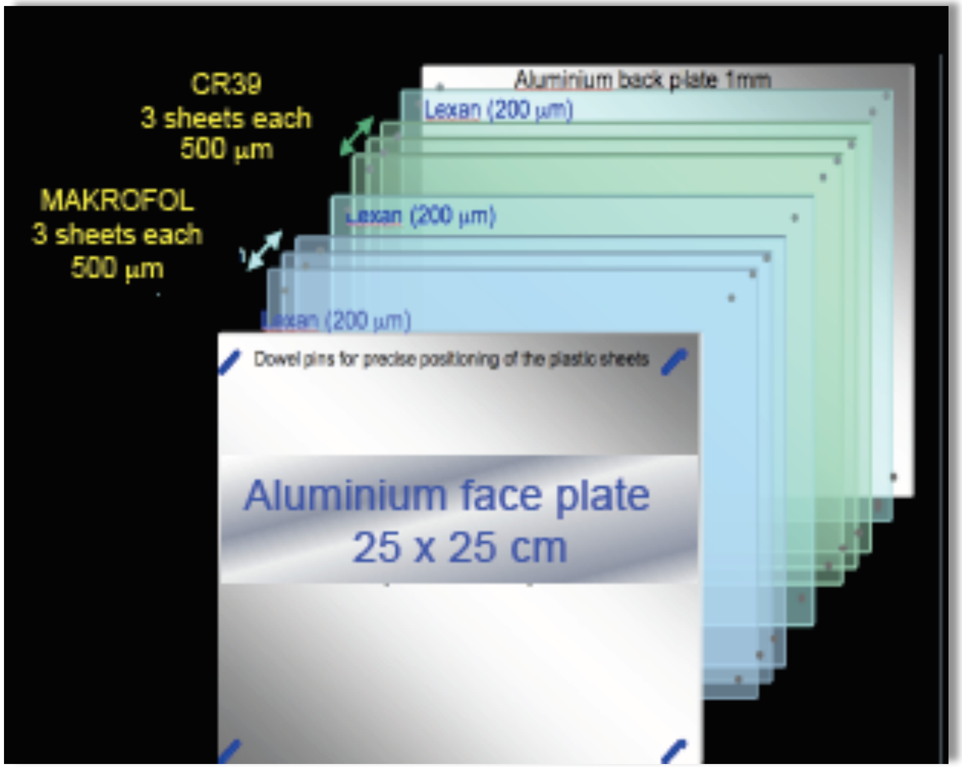


Housed in the LHCb VELO cavern

DETECTOR SYSTEMS

- Low threshold Nuclear Track Detectors array : $Z/\beta > 5$
- High threshold NTD array $Z/\beta >$ ~50
- Monopole Trapping detector (1 ton)

The MoEDAL Nuclear Track Detector

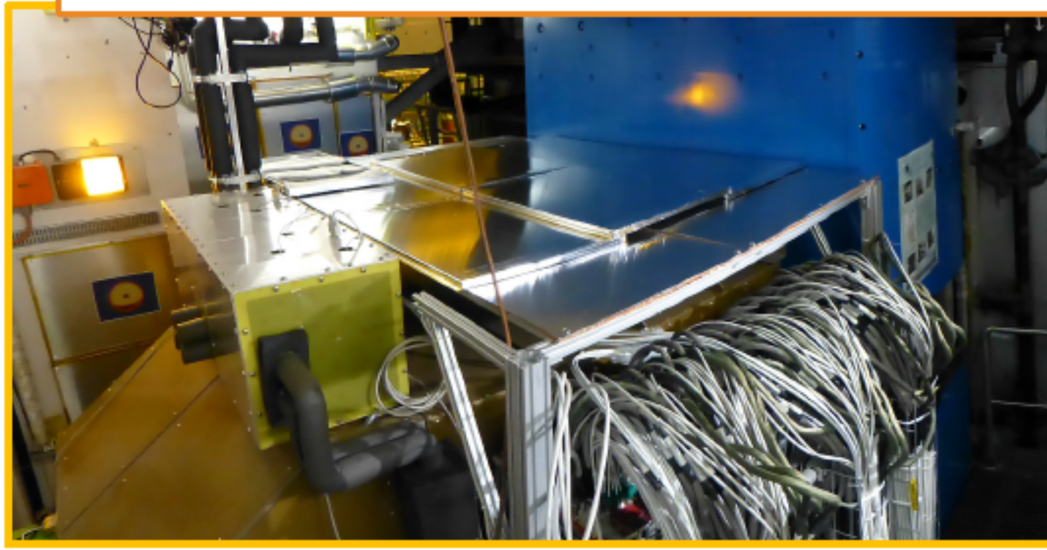


BASIC UNIT
- 3 layers of Makrofol (each 500 mm thick)
- 3 layers CR39 (each 500 mm thick)
- 3 layers of Lexan (each 200 mm thick)
- Sheet size 25 x 25 cm

NTDs deployment

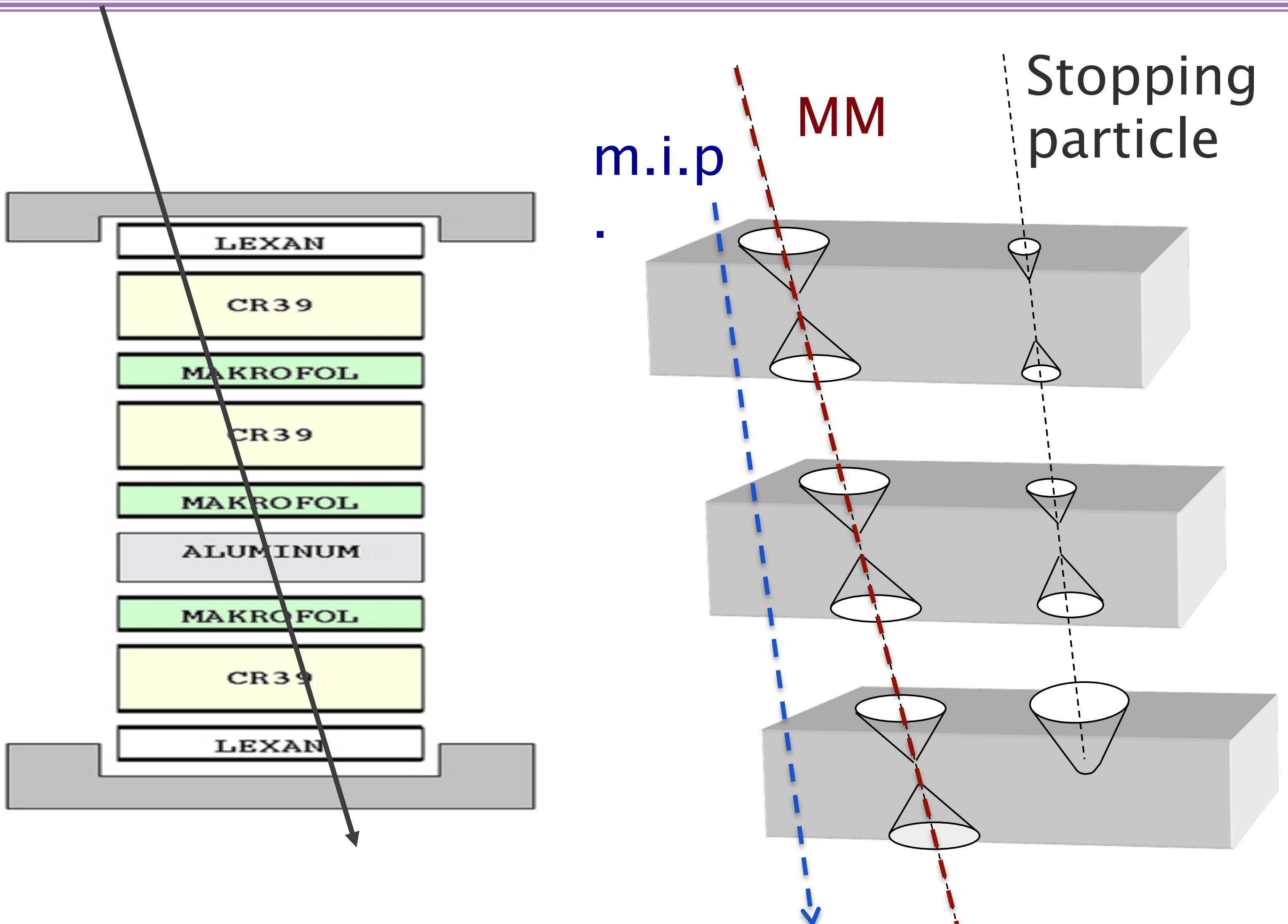
2012: LT-NTD
NTDs sheets kept in boxes mounted onto LHCb VELO cavern walls

2015: LT-NTD
Top of VELO cover – closest possible location to IP



2015: HCC-NTD
Installed in LHCb acceptance between RICH1 and TT

The search technique



Fast MM signal: collinear etch pits && constant dE/dx

Conclusions

If MM discovered → breakthrough in the understanding of electromagnetism, in Astrophysics and in Cosmology

Joseph Polchinski, theoretical physicist at the 2002 Dirac Centennial Symposium

"*the existence of magnetic monopoles is one of the safest bets that one can make about physics not yet seen*"

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http://arjournals.annualreviews.org/eprint/fS7npepcwV54KYGS4MPF/full/10.1146/annurev-nucl-102014-022137