The search for magnetic monopoles

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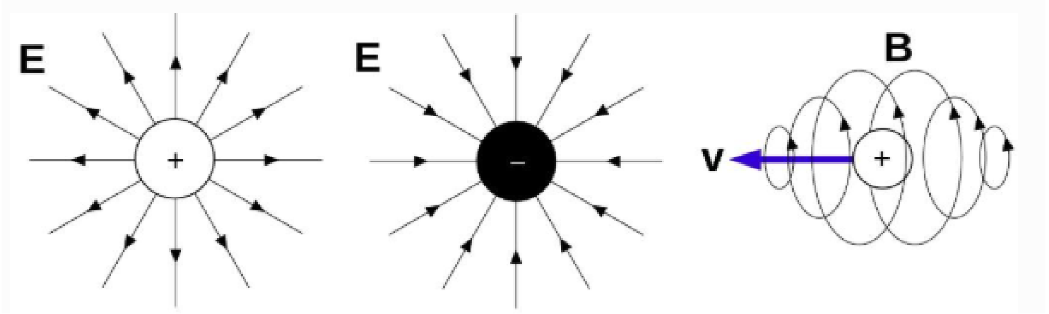
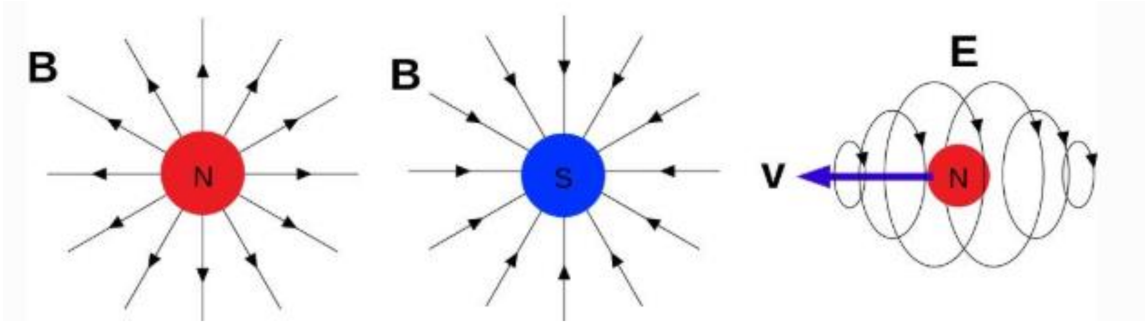
- What is a magnetic monopole ?
- Why magnetic monopoles ?
- How to look for magnetic monopoles.
- Outlook

What is a magnetic monopole ?

- Analagous to electric monopole



- B-field source
- Moving magnetic monopole produces E-field



Electromagnetism with and without magnetic monopoles

Without

$$\nabla \cdot E = \frac{\rho_e}{\varepsilon}$$

$$\nabla \cdot B = 0$$

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$\nabla \times B = \frac{1}{c^2}\frac{\partial E}{\partial t} + \mu_0 j_e$$

$$F = qE + q(v \times B)$$

With

$$\nabla \cdot E = \frac{\rho_e}{\varepsilon}$$

$$\nabla \cdot B = \mu_0 \rho_m$$

$$\nabla \times E = -\frac{\partial B}{\partial t} - \mu_0 j_m$$

$$\nabla \times B = \frac{1}{c^2}\frac{\partial E}{\partial t} + \mu_0 j_e$$

$$F = q(E + v \times B) + g\left(B - \frac{1}{c^2} v \times E\right)$$

Magnetic monoples symmetrise the Maxwell equations ?

Do monopoles really symmetrise the Mawell equations ?

Charges and currents	Fields
$\begin{pmatrix} \rho_\mathrm{e} \\ \rho_\mathrm{m} \end{pmatrix} = \begin{pmatrix} \cos\xi & -\sin\xi \\ \sin\xi & \cos\xi \end{pmatrix} \begin{pmatrix} \rho'_\mathrm{e} \\ \rho'_\mathrm{m} \end{pmatrix}$	$\begin{pmatrix} \mathbf{E} \\ \mathbf{H} \end{pmatrix} = \begin{pmatrix} \cos\xi & -\sin\xi \\ \sin\xi & \cos\xi \end{pmatrix} \begin{pmatrix} \mathbf{E}' \\ \mathbf{H}' \end{pmatrix}$
$\begin{pmatrix} \mathbf{J}_\mathrm{e} \\ \mathbf{J}_\mathrm{m} \end{pmatrix} = \begin{pmatrix} \cos\xi & -\sin\xi \\ \sin\xi & \cos\xi \end{pmatrix} \begin{pmatrix} \mathbf{J}'_\mathrm{e} \\ \mathbf{J}'_\mathrm{m} \end{pmatrix}$	$\begin{pmatrix} \mathbf{D} \\ \mathbf{B} \end{pmatrix} = \begin{pmatrix} \cos\xi & -\sin\xi \\ \sin\xi & \cos\xi \end{pmatrix} \begin{pmatrix} \mathbf{D}' \\ \mathbf{B}' \end{pmatrix}$

- Duality transformation
- Pure convention that we write the Maxwell equations with no magnetic monopoles
- **By convention** : $\frac{\rho_m}{\rho_e} = 0$
- *A magnetic monopole is a particle with a different magnetic to electric charge ratio than those particles already observed.*
- $\left(\frac{\rho_m}{\rho_e}\right)_{monopole} \neq \left(\frac{\rho_m}{\rho_e}\right)_{electron}$

Why monopoles ?

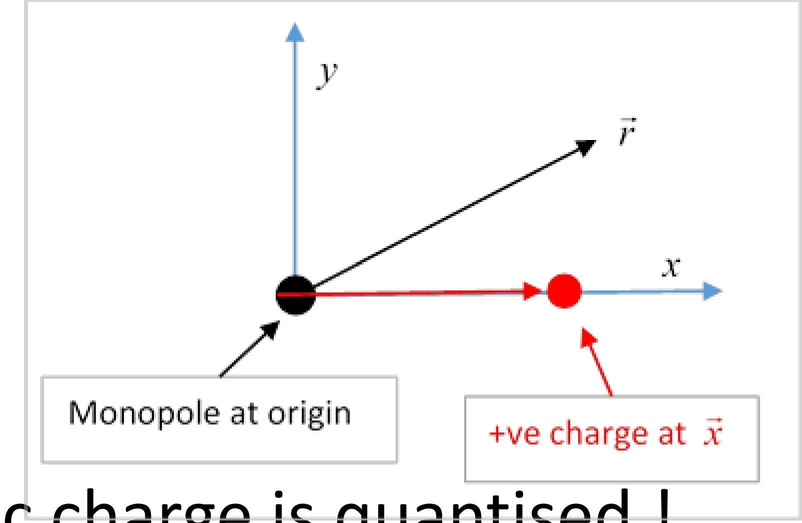
Whenever a new collision energy is reached or previously unchecked material becomes available, monopoles are sought.

Why ?

Why monopoles ? Dirac’s argument

- Angular momentum in field from monopole g and electric charge q
- $|\bar{L}| = \left|\int \bar{r} \times (\bar{E} \times \bar{B})\right| = kqg$
- But angular momentum is quantised
- $L = kqg = n\pi$

$$\rightarrow q = \frac{n\pi}{kg}$$



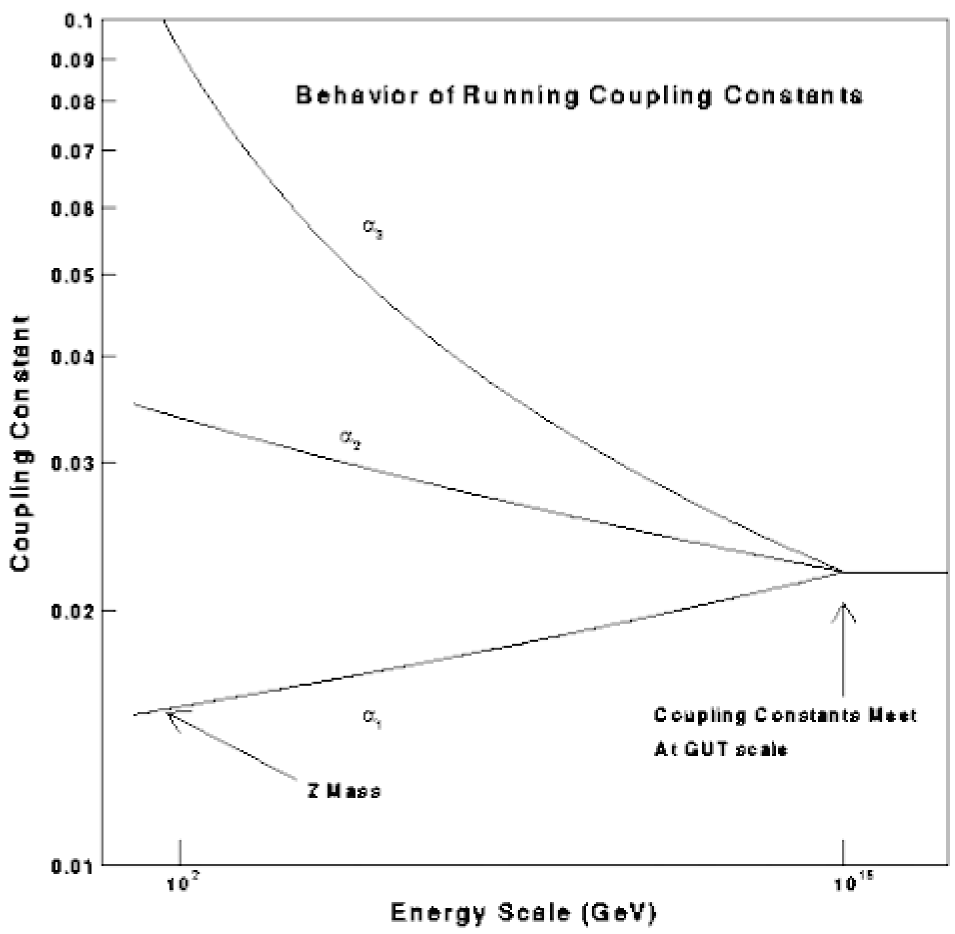
- One type of monopole implies that electric charge is quantised !
- Electric charge quantisation understood within quantum mechanics.
- $q = e \;\rightarrow g_D = \frac{n\pi}{ke}$
- Dirac charge – elementary magnetic charge.

Why monopoles ? Unification theories

- Magnetic monopoles naturally emerge in non-Abelian gauge theories
- Grand unified theory of strong and electroweak forces
- Monopoles expected
- String theory
- High mass 10^{15} GeV

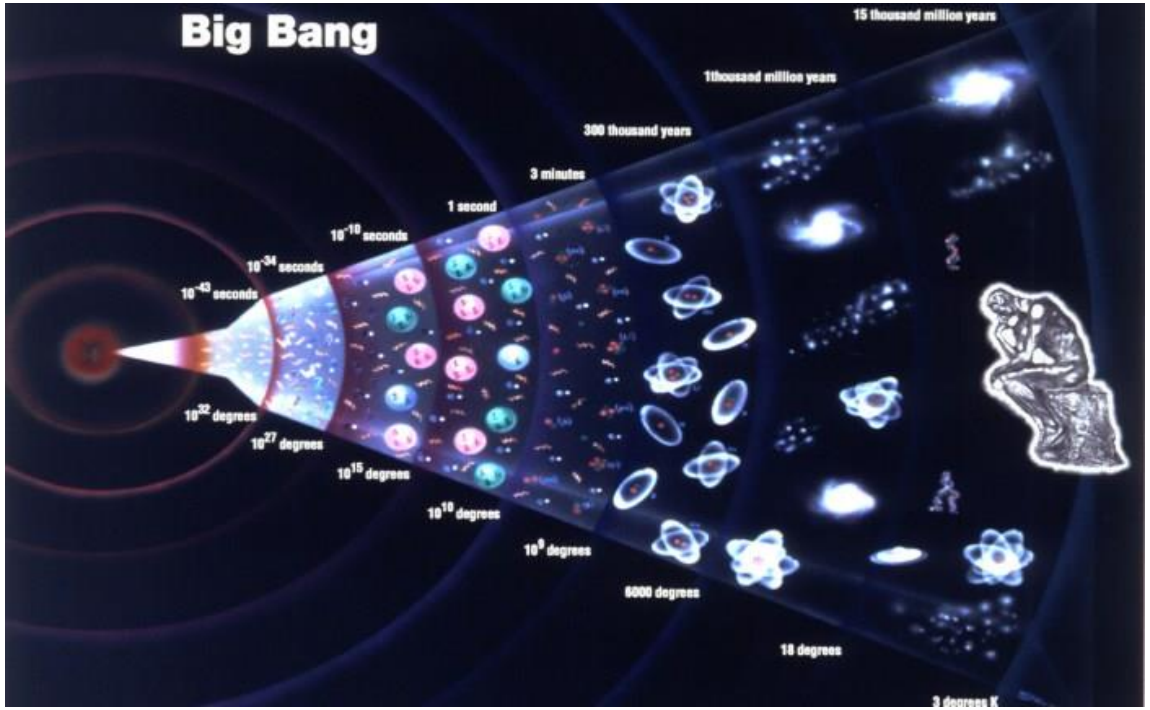
$$SU(5) \quad \underset{10^{-35}s}{\overset{10^{15}\ GeV}{\longrightarrow}} \quad SU(3)_C \times [SU(2)_L \times U(1)_Y]$$

- Lower masses for specific theories



Monopoles in the early universe

- Primordial monopoles
- Production from early universe
- Expect large flux (up to 1 monopole/m^3)
- Monopoles dominate mass density
- Slow down cosmic expansion



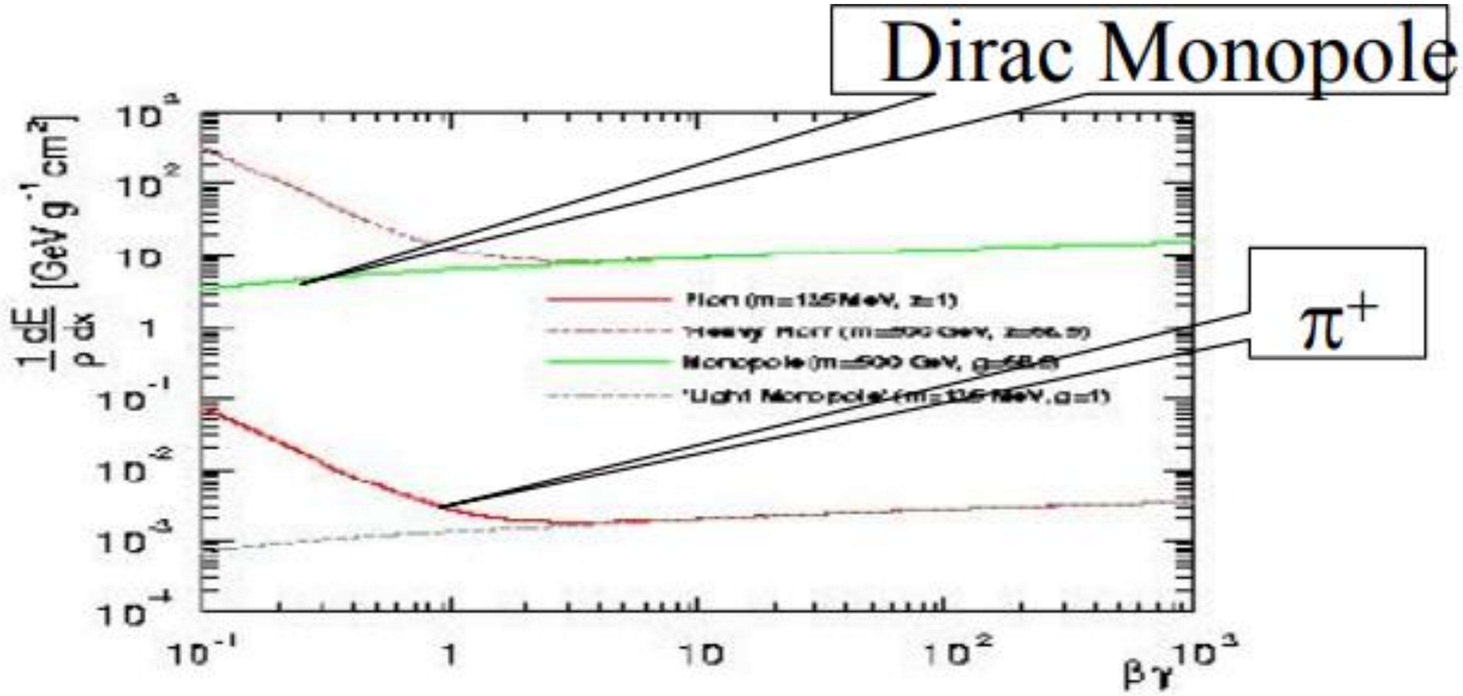
- Resolution
  - Cosmic inflation
  - Exponential expansion to dilute monopole density

Consequences and signatures of monopole monopoles

- Ionisation
- Induction
- Proton decay
- Acceleration in a B-field

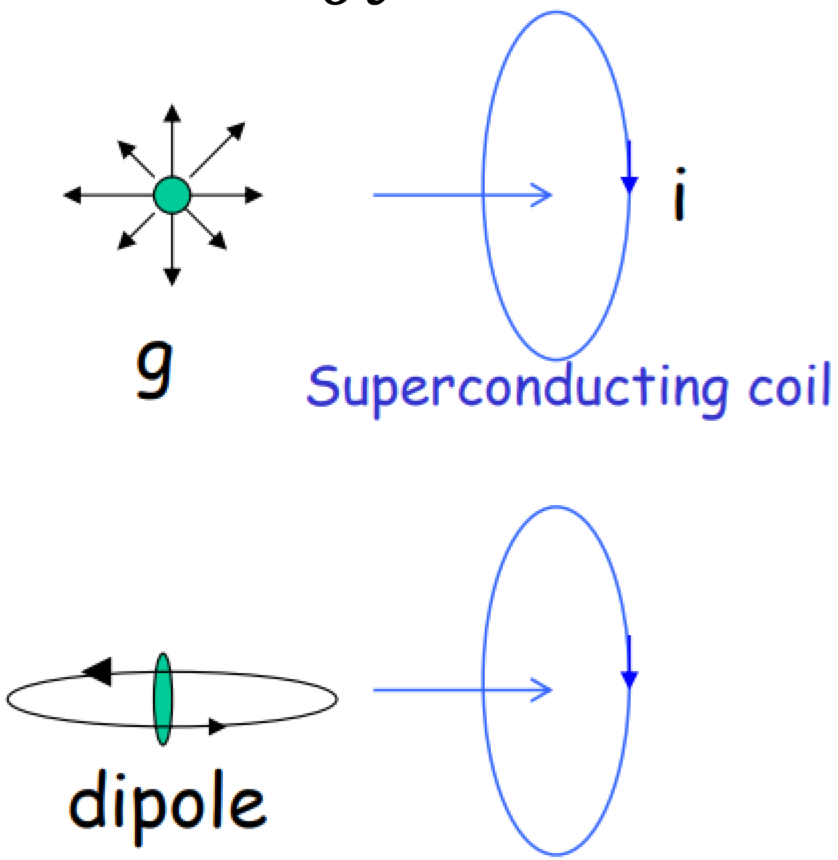
Ionisation

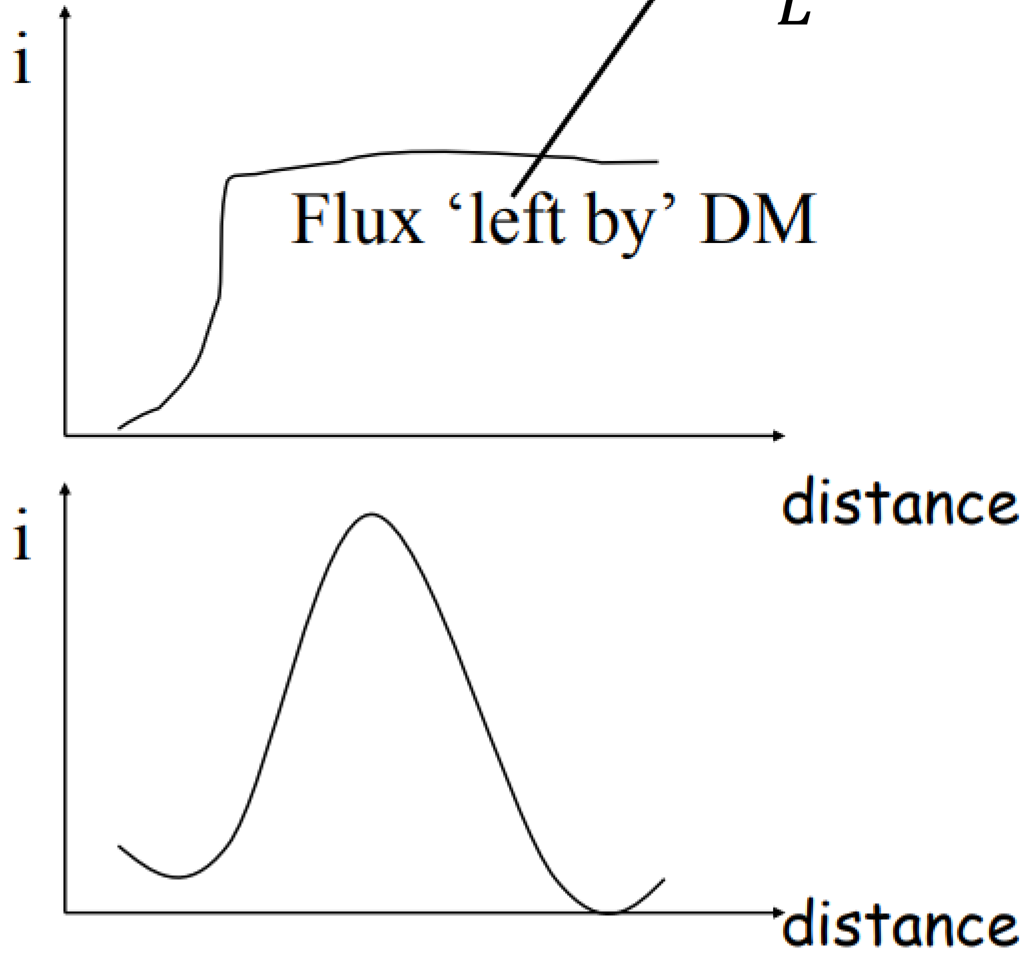
- Adapted Bethe-Bloch formula
- $\frac{dE}{dx}(DM) \sim \left(\frac{137}{2}\right)^2 \frac{dE}{dx}(e)$
  - Non-perturbative calculations
- Large ionisation
- No rise at low β



Induction properties

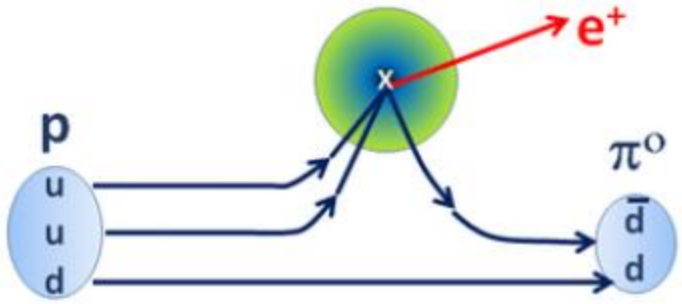
- $\nabla \times E = -\frac{\partial B}{\partial t} - \mu_0 j_m \quad \Rightarrow \quad i = -\frac{(\mu_0 g + \phi)}{L}$

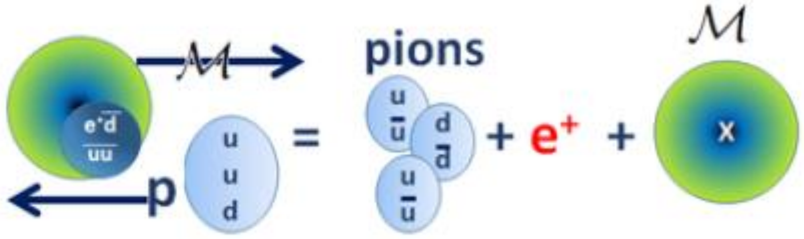




GUT monopoles – proton decay

- Rubakov and Callan: GUT monopoles catalyse proton decay
- Baryon number violating condensate near to massive monopole





Looking for monopoles : Cosmic rays

Parker limit.

- Galactic field $B \sim 3\ \mu$G sustained by dynamo mechanism
- Monopoles would accelerate in a galactic B-field, dissipating the field.
- Parker limit
  - Flux $F \leq\ 10^{-15}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\mathrm{sr}^{-1}$
- Baseline constraint

Cabrera event - 1982

Induction method

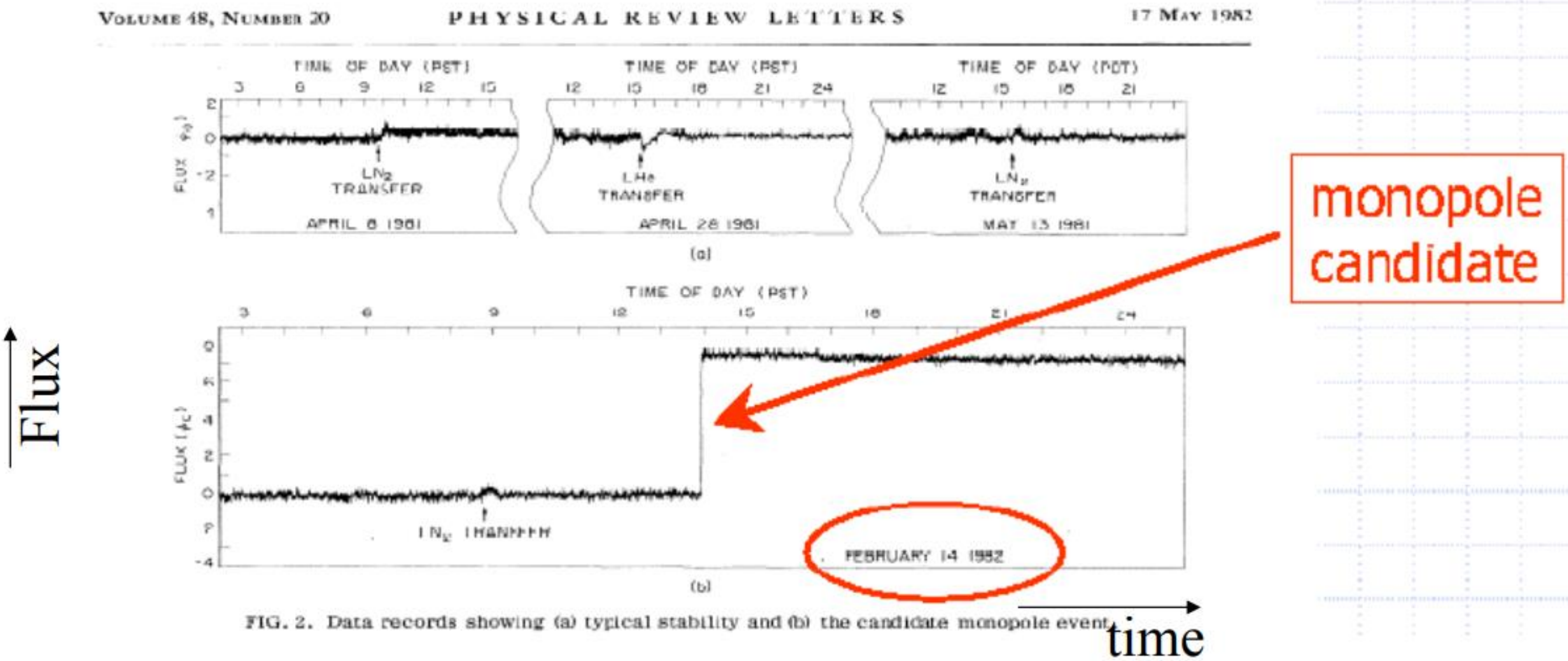
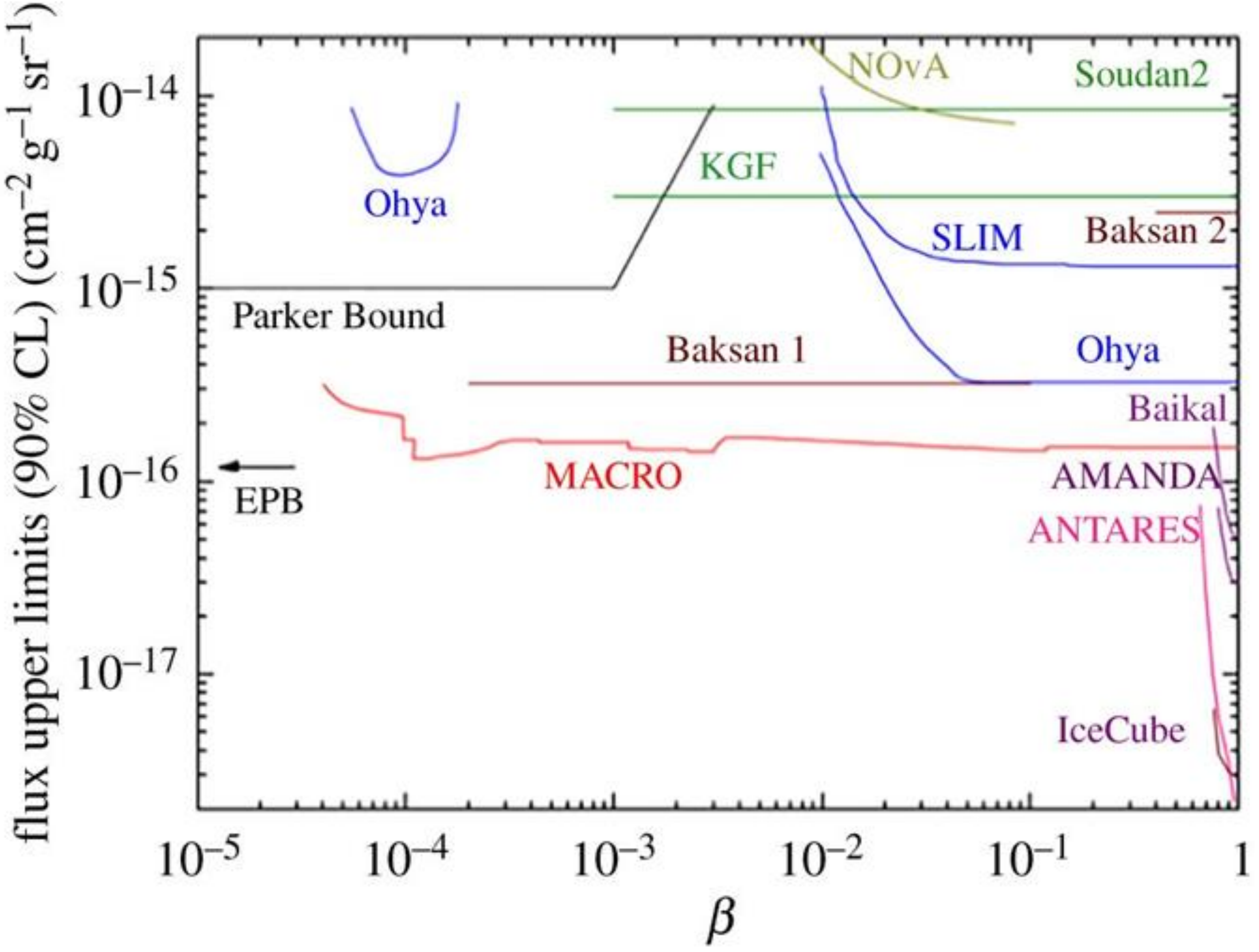


FIG. 2. Data records showing (a) typical stability and (b) the candidate monopole event.

Flux limits



flux upper limits (90% CL) (cm^{-2} g^{-1} sr^{-1})
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
β
NOvA
Soudan2
KGF
Ohya
SLIM
Baksan 2
Parker Bound
Baksan 1
Ohya
Baikal
MACRO
AMANDA
EPB
ANTARES
IceCube

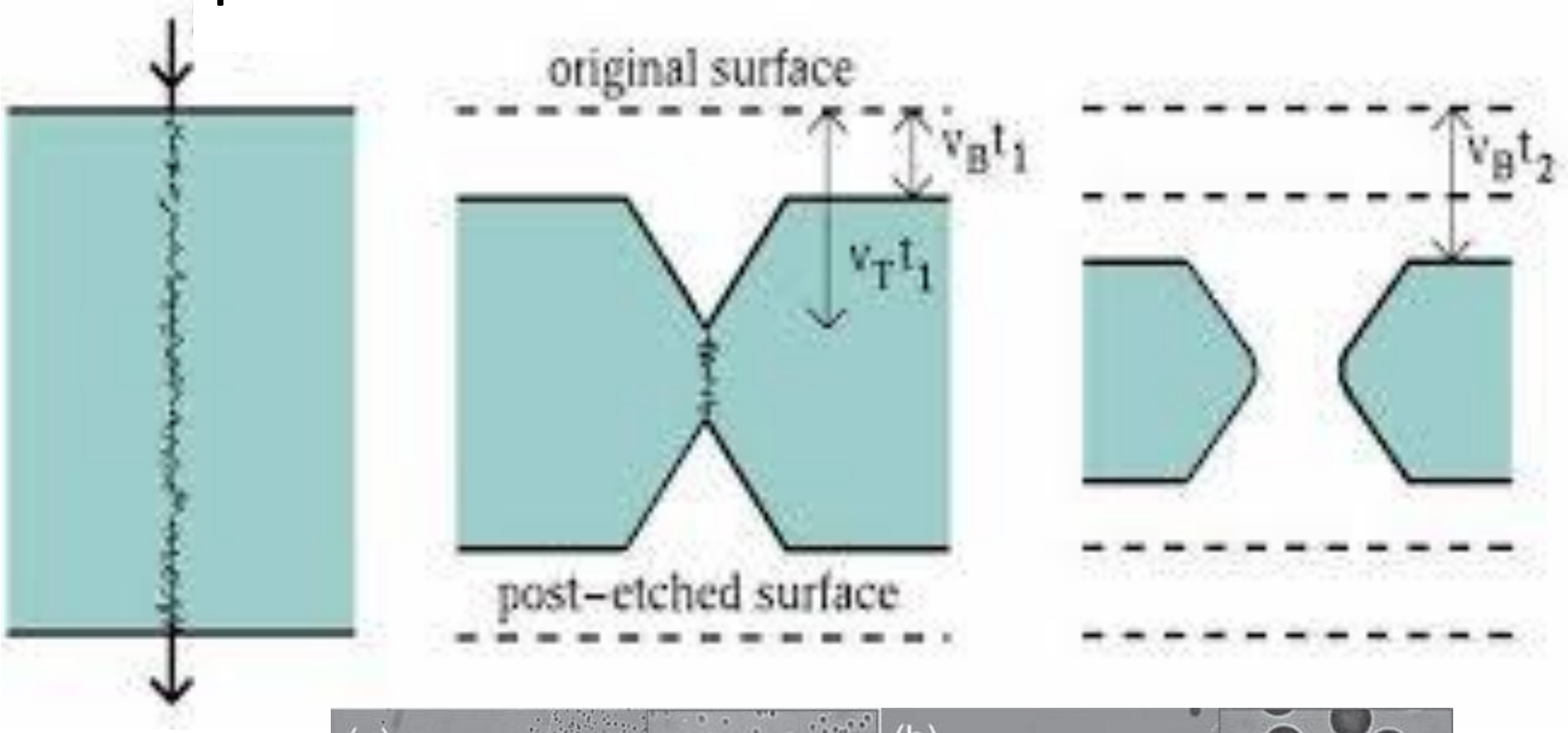
Macro

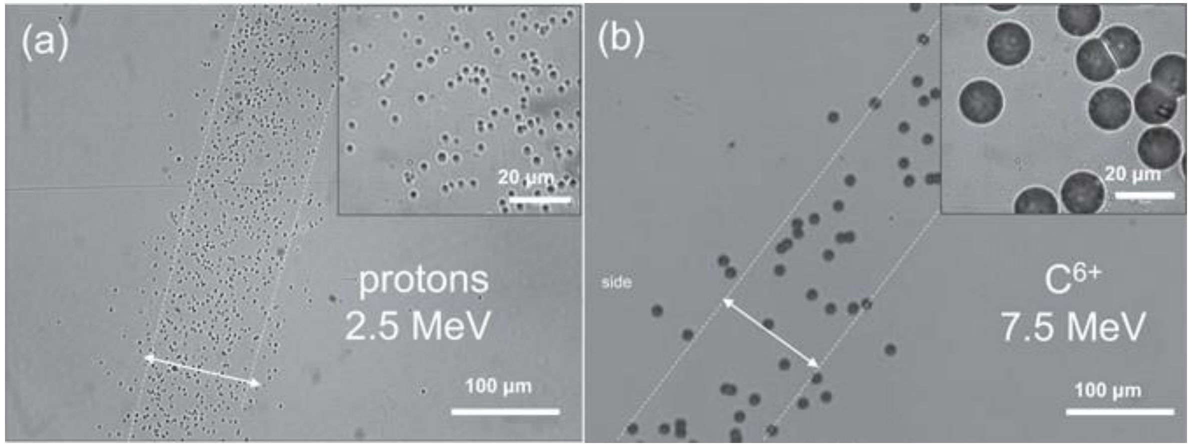
Gran Sasso
1988-2000
Liquid scintillators, streamer tubes, plastic track detectors over 76 x 12 x 9 m 3

Nuclear track detectors

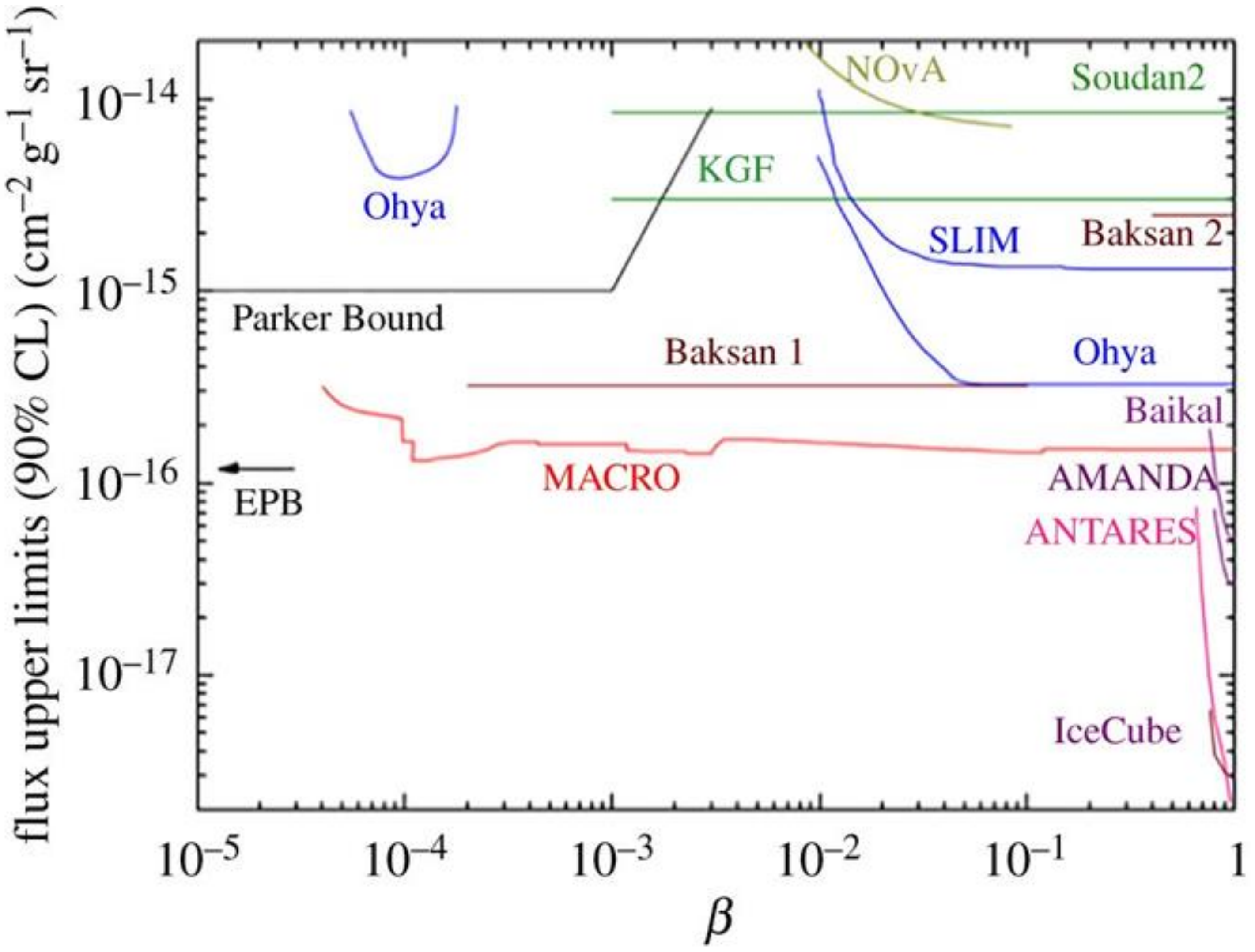
- CR-39
- Latent track
- Chemical etching

Monopole





Flux limits



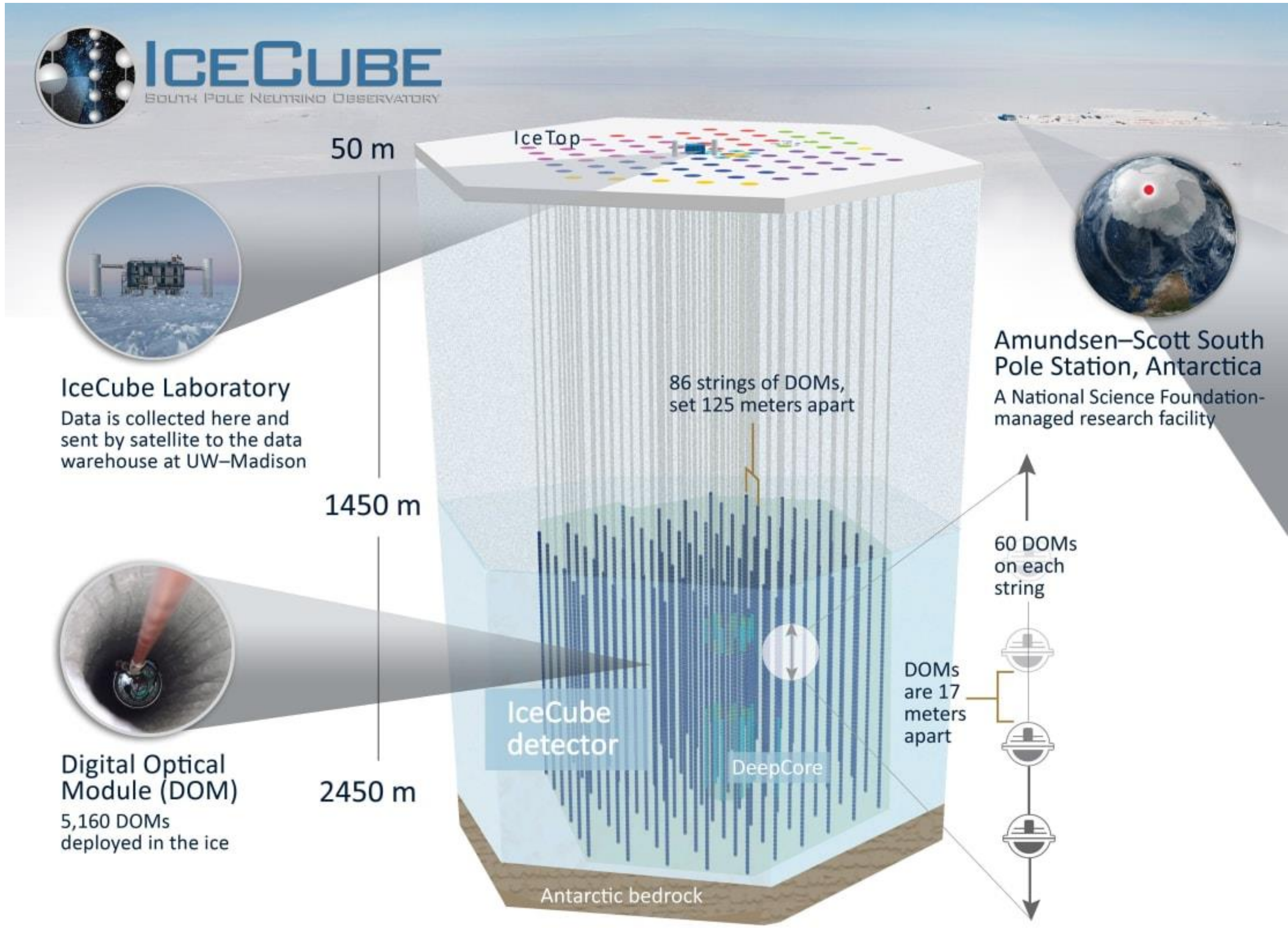
flux upper limits (90% CL) (cm^{-2} g^{-1} sr^{-1})
10^{-14}
10^{-15}
10^{-16}
10^{-17}
NOvA
Soudan2
KGF
Ohya
SLIM
Baksan 2
Parker Bound
Baksan 1
Ohya
Baikal
MACRO
AMANDA
EPB
ANTARES
IceCube
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
β

IceCube

Km^3 array at the South Pole

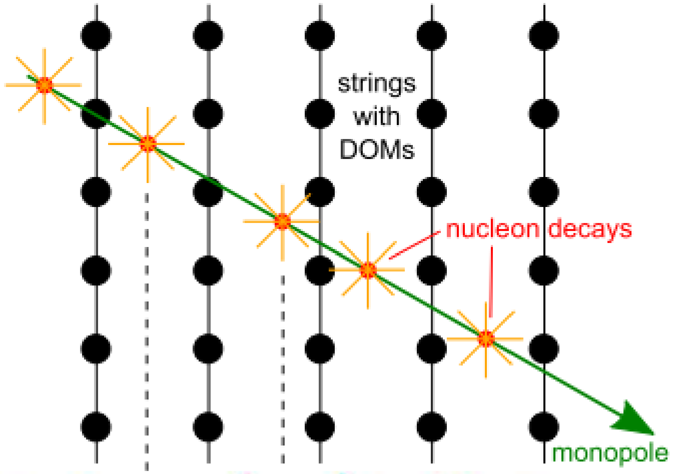
DOMs in 86 strings up to 2.5km below the surface

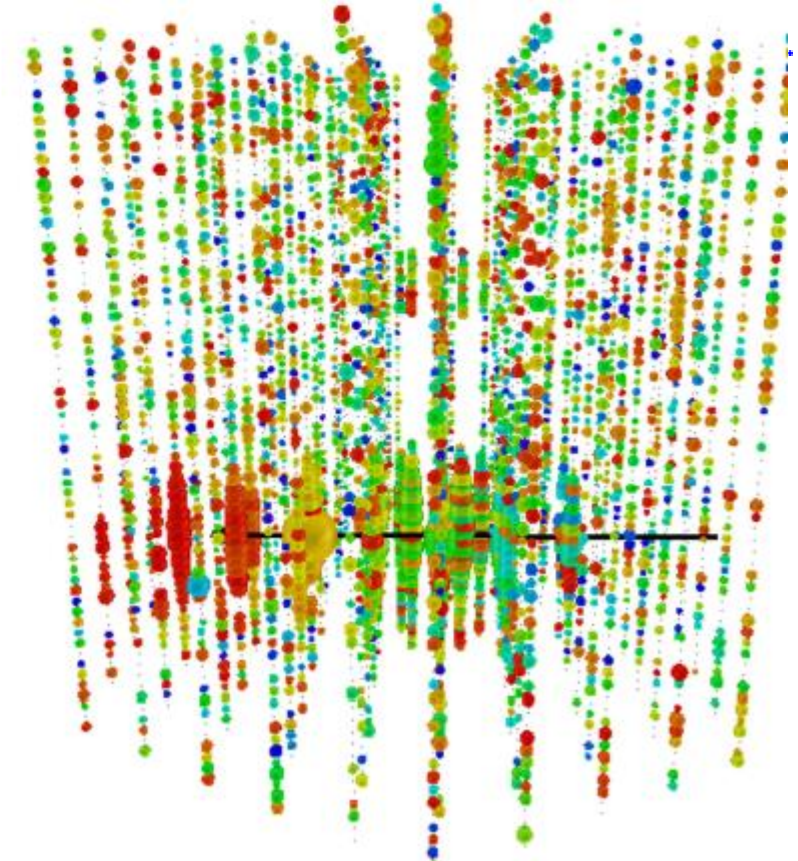
Cerenkov effect for the ultra-relativistic monopoles



IceCube – proton decay

- Rubakov-Callan
- $\sigma \sim 10^{-27} - 10^{-21}$ cm²
- Non-relativistic

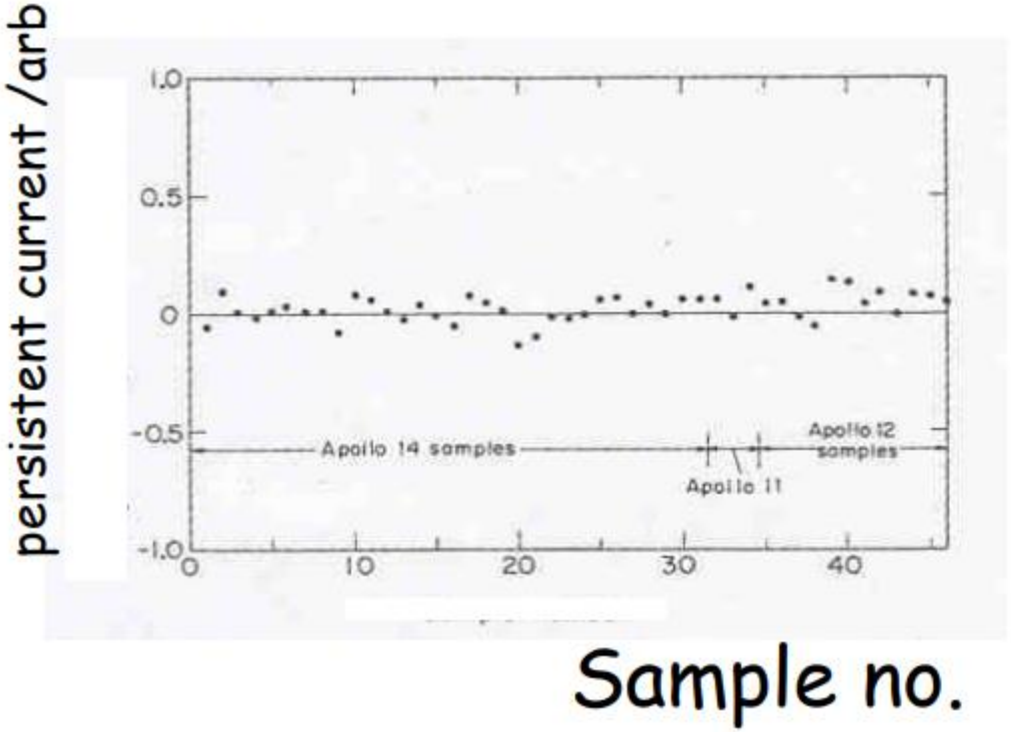


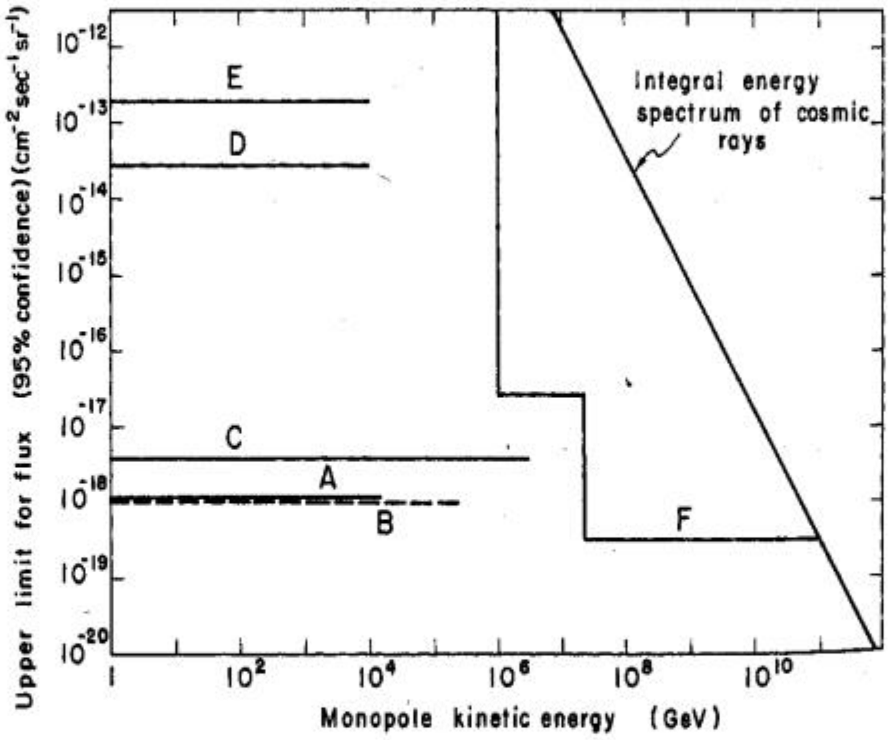


Monopoles trapped in matter ?

Monopoles trapped in matter

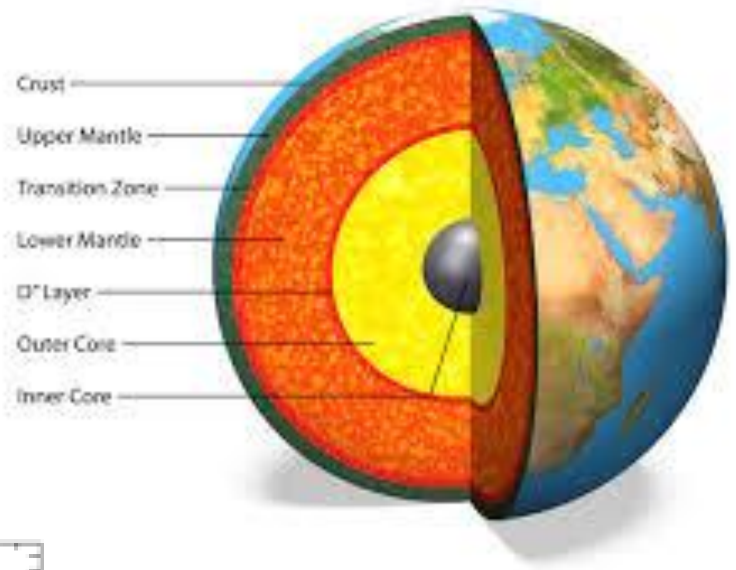
- Lunar searches
- 500 Myears of sampling
- Apollo 11, 12, and 14
- Induction method

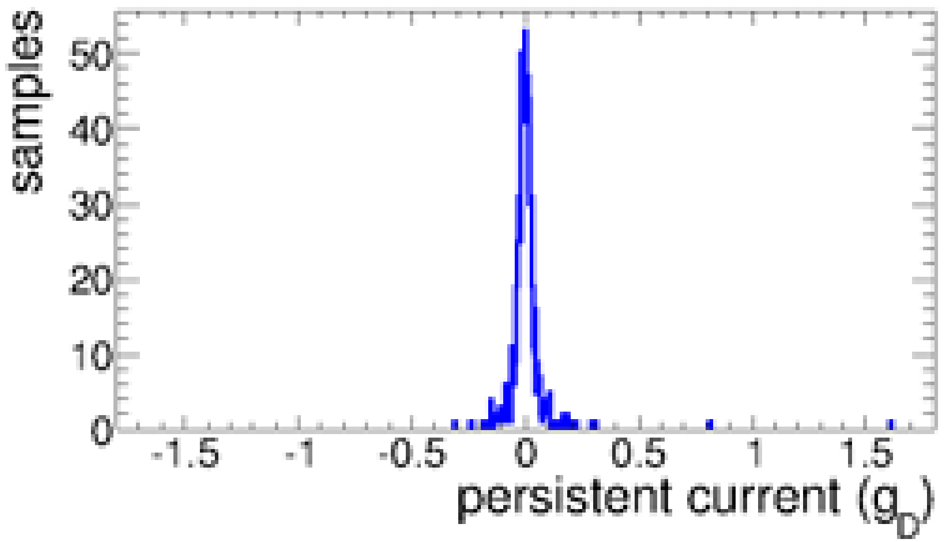




Monopoles in polar volcanic rock

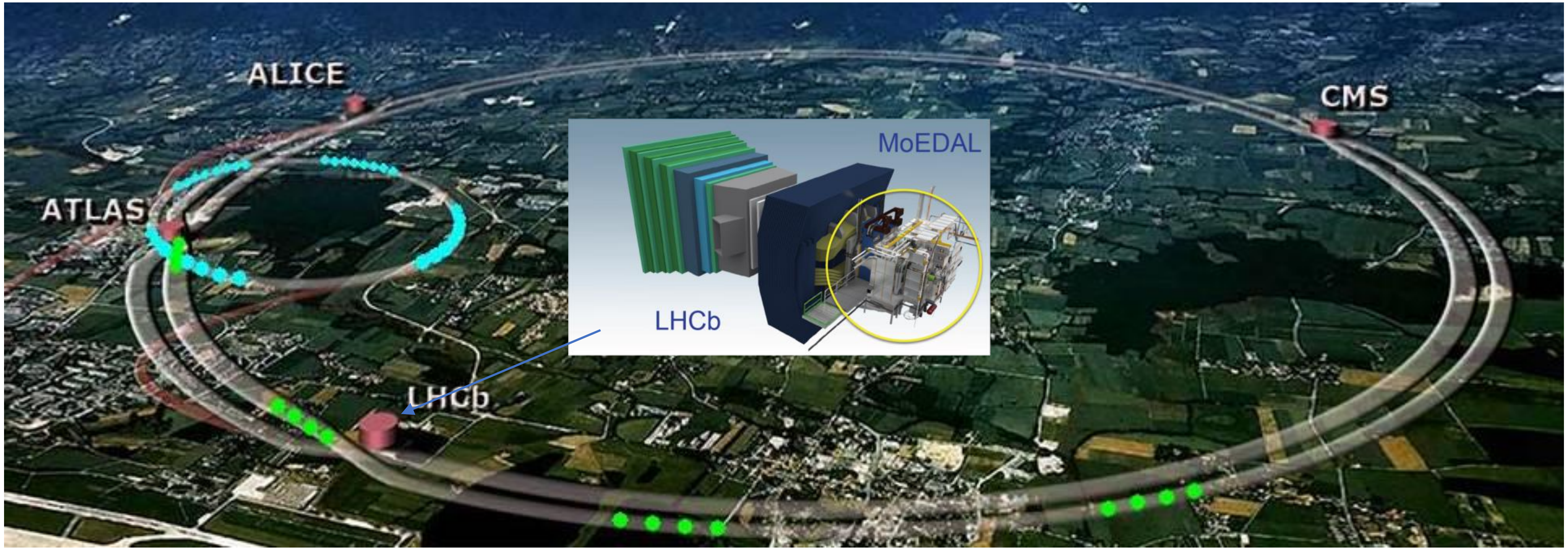
- Expected enhancement of monopole abundance in the mantle below the poles.
- 25kg of mantle-derived rocks from Arctic/Antarctic.
- Induction method





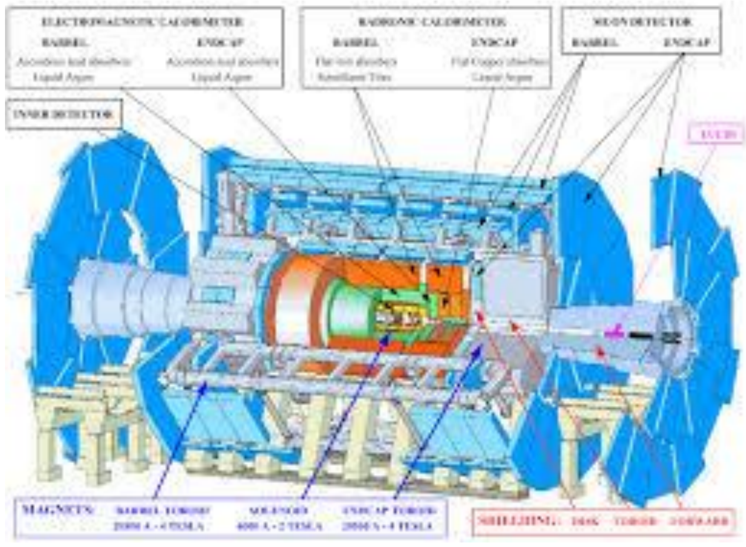
Monopoles at colliders

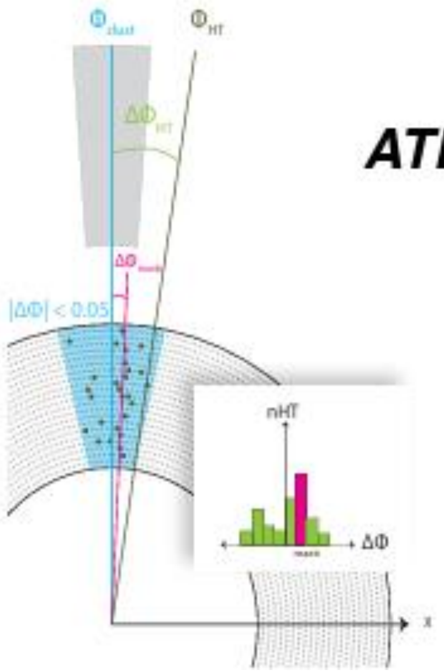
- 13 TeV pp c.o.m. energy
- General purpose experiments (ATLAS, CMS)
- Dedicated monopole search experiment (Moedal)

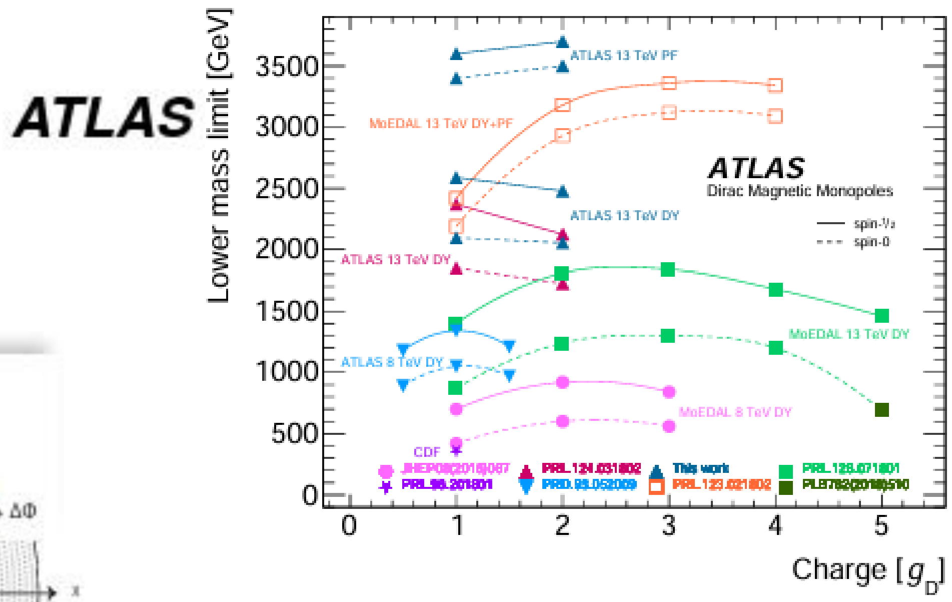


High ionizing signature - ATLAS

- Transition radiation tracker hits
- Align with narrow cluster in EM calo

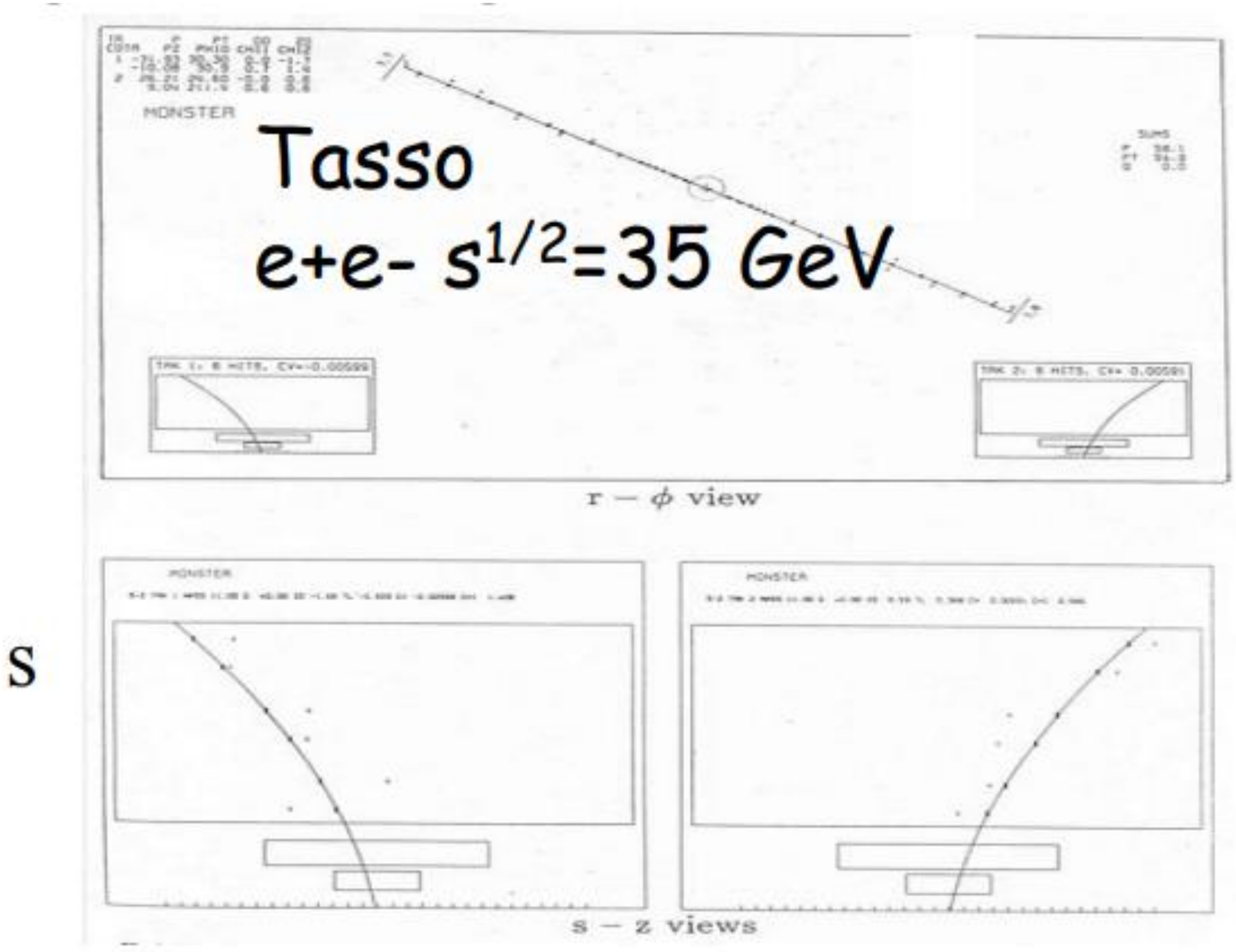






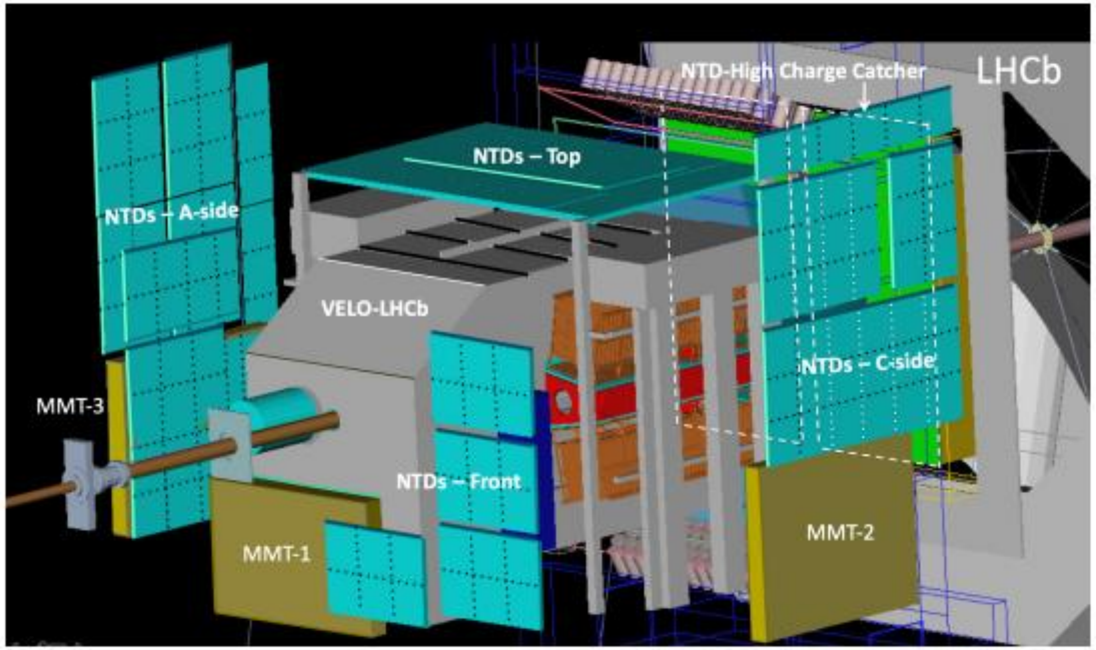
Parabolic trajectory

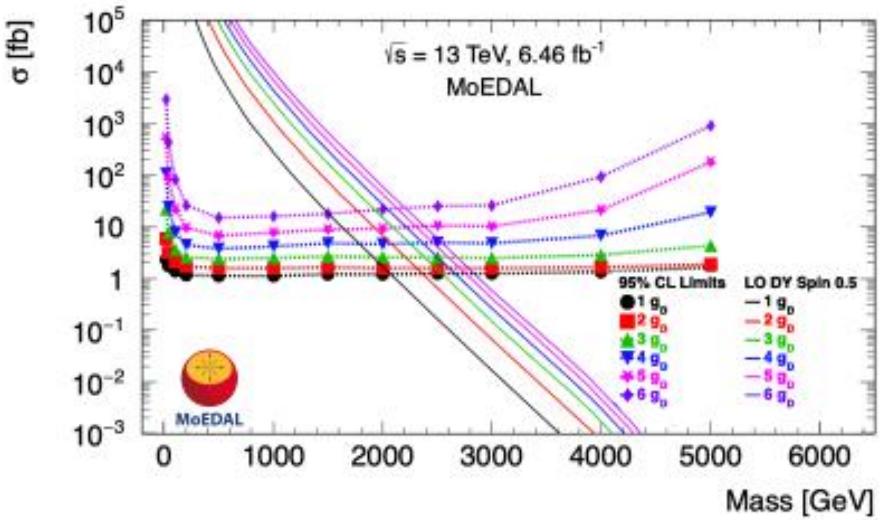
- Electric charge
  - $z = z_0 + s\tan\theta$
- Magnetic charge
  - $z = z_0 + s\tan\theta + s^2 C$



Moedal

- MoEDAL (the Monopole and Exotics Detector at the LHC)
- At LHC-B experiment
- Makrofol NTDs (10.7 m2)
- Monopole stoppers





Monopoles at HERA

- e(27 GeV) p (820 GeV) collisions
- Examine beampipe for trapped monopoles

- BBC documentary
- http://www.vega.org.uk/video/programme/56

Where to next ?

- Keep going to higher energies (e.g. FCC)
- Improved flux sensitivities (e.g. IceCube upgrade)
- Inventive choice of materials in which to look for monopoles.

Summary

- Magnetic monopoles are among the oldest exotic particle sought in particle physics
- Dirac showed that they explain electric charge quantisation
- They appear in unification theories beyond the Standard Model
- They turn up everywhere except in experiment.

- A personal note:
  - The community has invested heavily in searches for supersymmetry, extra dimensions.
  - Monopoles have as great if not greater motivation.
  - Important to follow the science more than the fashion.