# 磁单极子、分数电荷探测
# - 关于深空实验的初步讨论

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# 一页简介

- **<u>磁单极子</u>**、**<u>稳定分数电荷粒子</u>**等一般被认为可能与基础物理的核心问题相关
  - 与标准模型电荷量子化相关
  - 与宇宙起源早期演化相关（起源、暴涨）
  - 可以由部分新物理理论预言，例如大统一理论，弦论
- 通常认为这些粒子
  - 极其稀有（实验寻找结果限制、宇宙学限制等）
  - 稳定（只带有电磁荷，参与电磁相互作用）

# 关于磁单极子探测的几页PPT

# Where to Find Monopoles

*Lightest Monopoles are Stable and pair production (magnetic charge conservation)*

- ***Primordial "cosmic" monopole***
  - Moving freely through outer space
  - Accelerated to relativistic speeds by galactic magnetic fields if m < $10^{15}$ GeV
- ***Primordial "stellar" monopole***
  - Bound in matter before star formation: earth, moon, comet, meteorite
- ***Secondary production***
  - Inside high-energy cosmic ray
  - With high-energy collisions at accelerators

⇩

From theory, masses and rates uncertain

Experiments to look for monopoles:

**Cosmic rays**
=> limitation: detector size and time of exposure

**Bulk matter**
=> limitation: sample size

**Accelerators**
=> limitation: center-of-mass energy

# Property and Detection

## Ionization energy loss

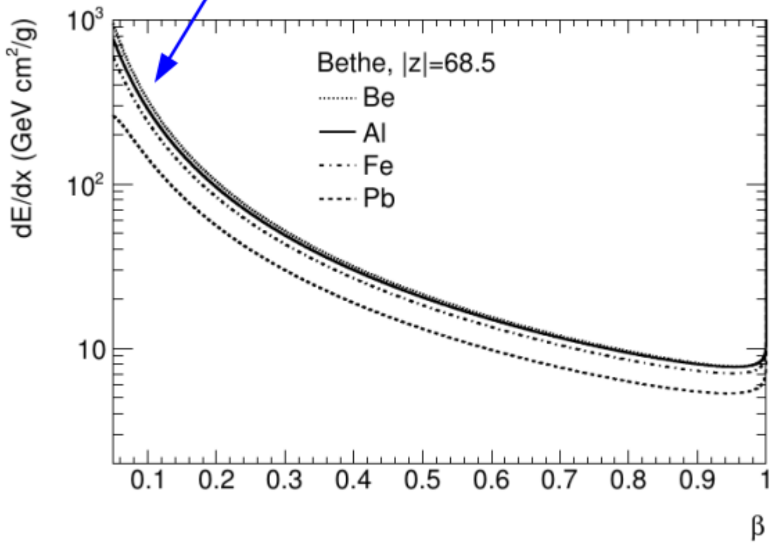
**Electric**

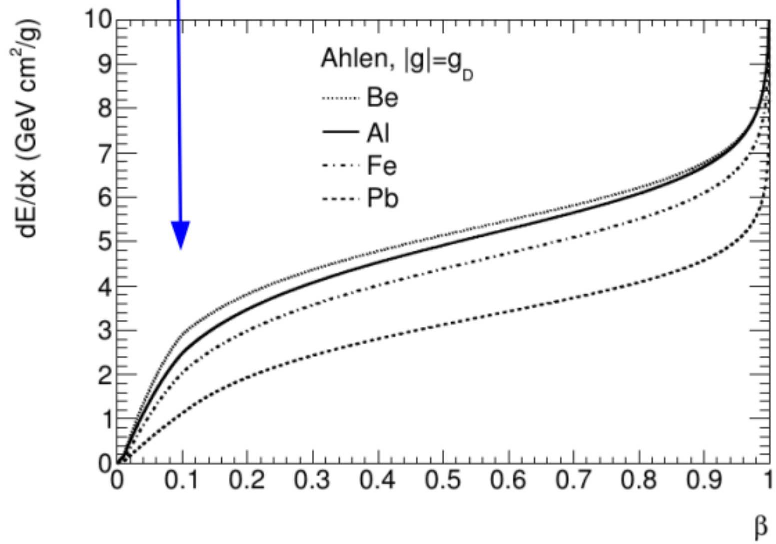
$$-\frac{\mathrm{d}E}{\mathrm{d}x} = K\frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\frac{2m_ec^2\beta^2\gamma^2}{I} - \beta^2\right]$$

**Magnetic**

$$-\frac{\mathrm{d}E}{\mathrm{d}x} = K\frac{Z}{A}g^2\left[\ln\frac{2m_ec^2\beta^2\gamma^2}{I_m} + \frac{K(|g|)}{2} - \frac{1}{2} - B(|g|)\right]$$

No Bragg peak!




*Highly ionizing in detector!*

For Dirac monopole with g = $g_D$, yield ~1000 larger dE/dx than a MIP with z = 1

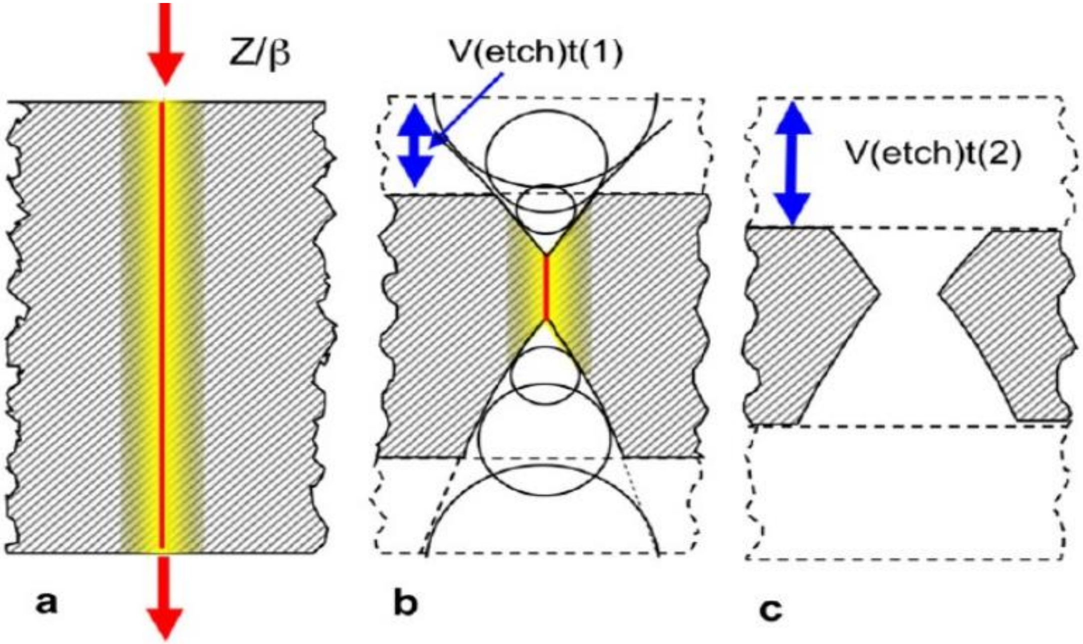
# Property and Detection

Detection: track-etch technique

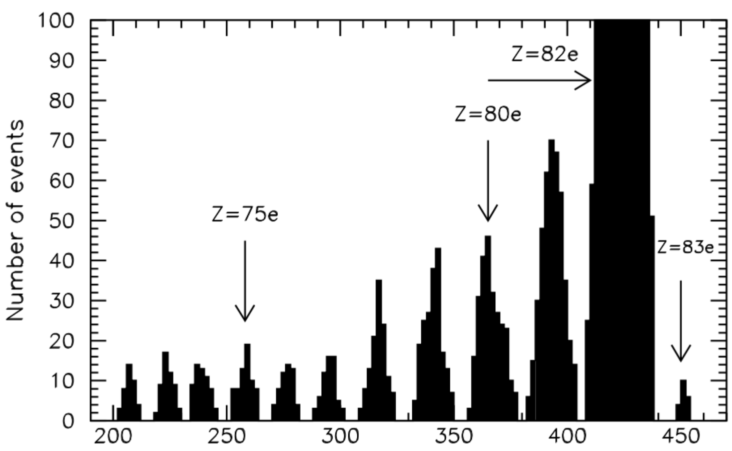
*Passage of highly ionizing particle causes permanent damage in plastic foils*

$\Rightarrow$ *Etching reveals the etch-pit cones, area and height of cones depends on restricted energy loss of the incident particles and of charge Z*

$\Rightarrow$ *Can be calibrated with ion beams*




*Example of cone-height v.s. Z*

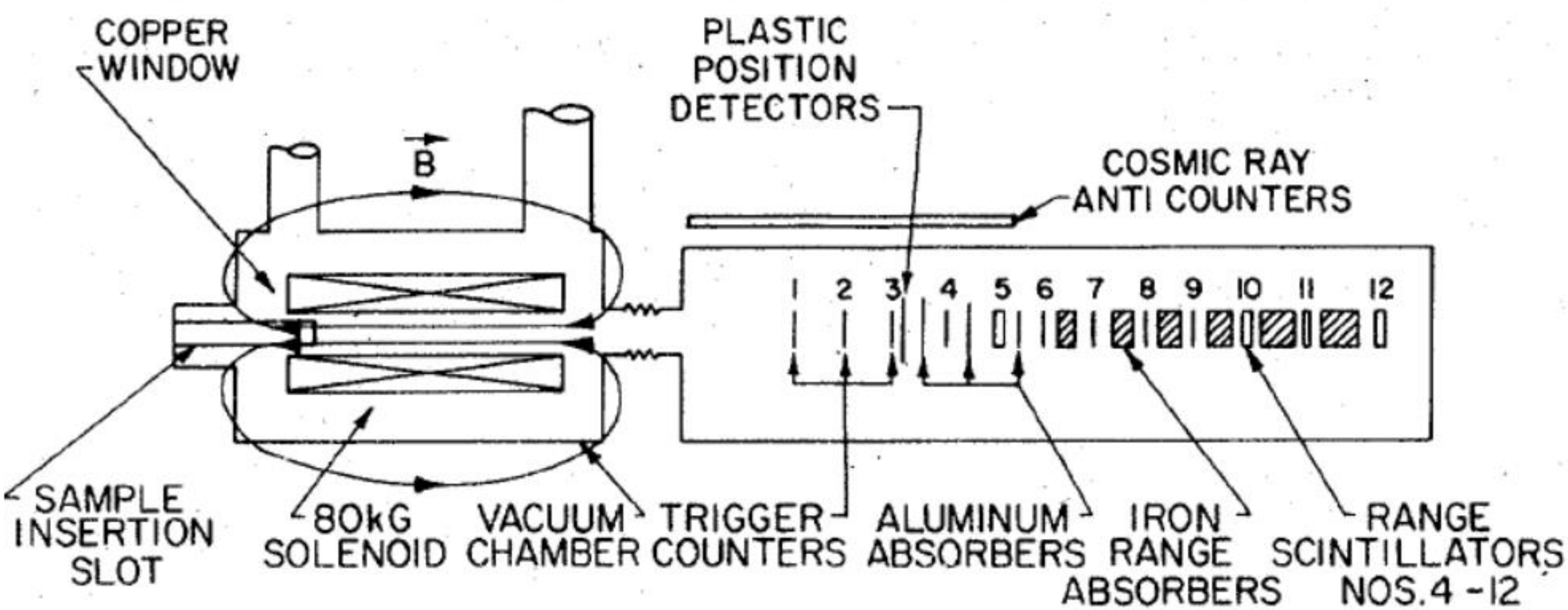


# Property and Detection

Detection: extraction method

*Strong magnetic field (> 50k G) applied to extract and accelerate monopoles trapped in matter*

$\Rightarrow$ *Detector telescope measures dE/dx and range*

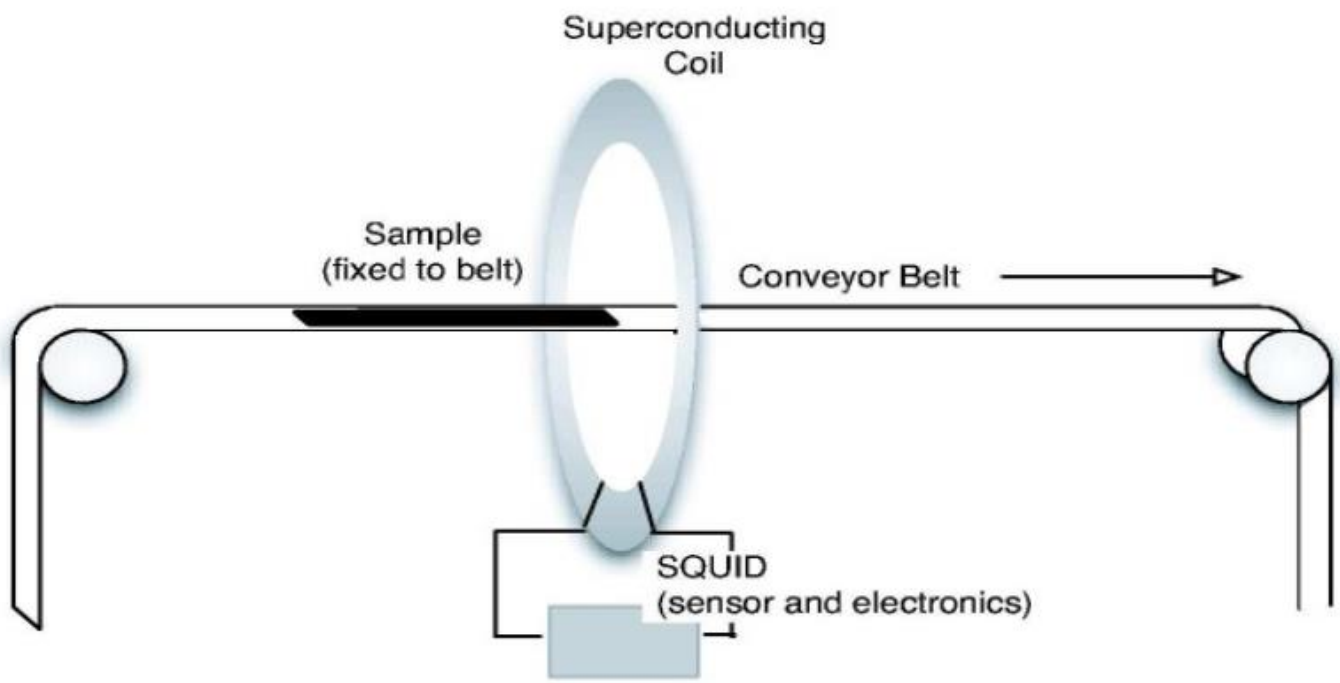


# Property and Detection

Detection: induction technique

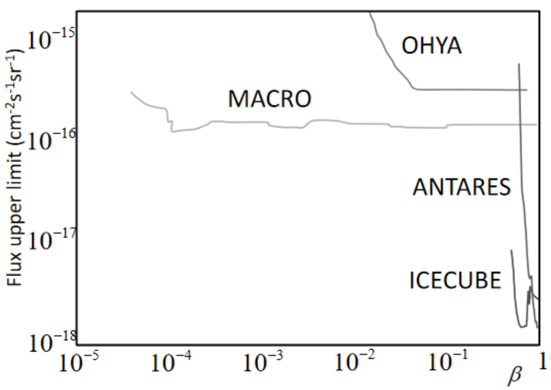
*Moving magnetic charge induces electric field*

⇒ *In combination with a superconducting coil, tiny permanent current occurs and measured*



# 小结

- 磁单极子仍未被发现
  - 除了以上述方法，还有利用核子衰变来探测（GUT MM可以催化稳定核子如质子衰变）
  - 前面略去了在大型加速器实验上的寻找（和本讨论相关度不太，且质心能量仅 TeV）
  - 亦有宇宙学限制，如Parker Bound等
  - 各类综述文献均有实验限制的总结，例如PDG2018



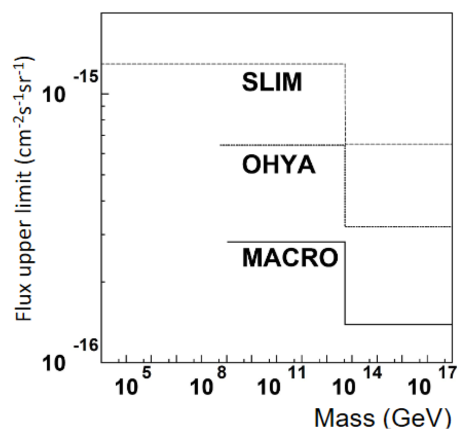




Figure 117.1: Upper flux limits for (left) GUT monopoles as a function of $\beta$ (right) Monopoles as a function of mass for $\beta > 0.05$.

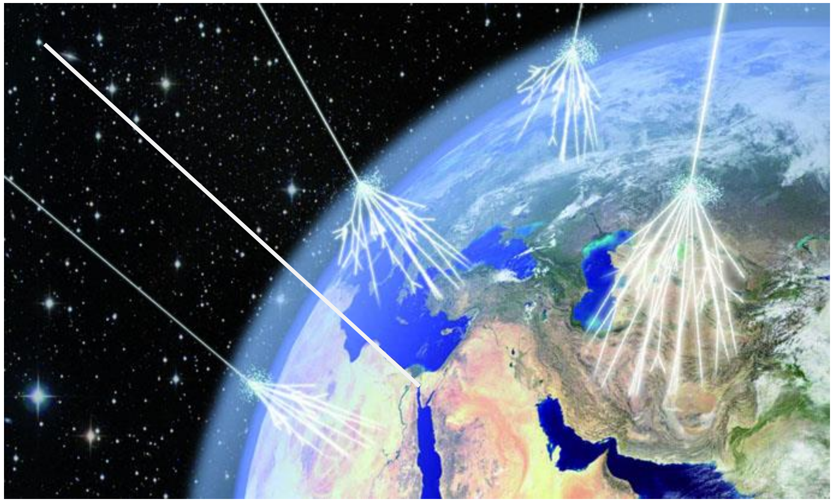
相对而言MM的寻找还有很大空间

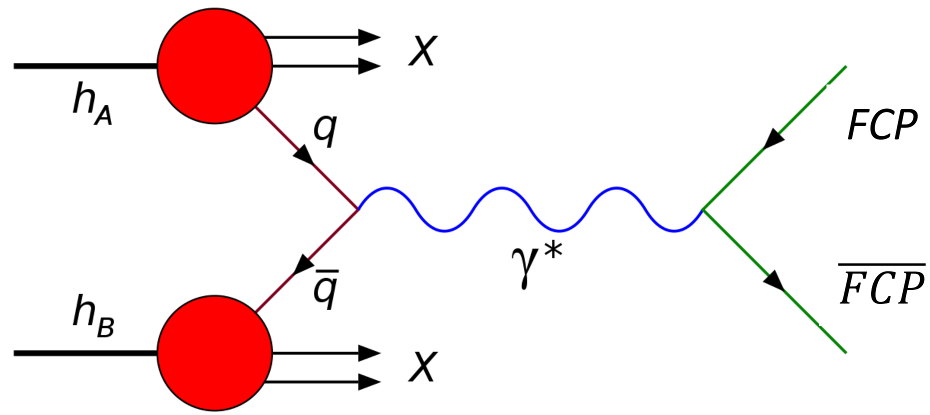
MM的信号有特点一般信噪比好，因而**接受度**是核心

对于深空探测而言，优势可能还是月壤就地取材探测？

# 关于分数电荷的几页PPT

# Potential Sources of FCP






- ***From outside the earth***
  - ✓ Produced in early universe, lightest ones likely stable, and concentrated on bulk matter
  - ✓ Or produced in present universe, travel to earth as cosmic rays
  - ✓ Or produced as cosmic rays interact with atmosphere

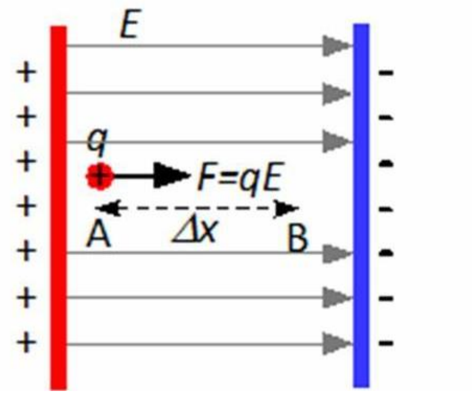
- ***Produced with Accelerator***
  - ✓ Pair production of FCPs, e.g. Drell-Yan process
  - ✓ Probing mass range limited by C.M.E.
  - ✓ Can be searched for with fix-target, $e^+e^-$ and hadron colliders

# Experimental Probes

***Particles or bulk-matter samples to be examined***

**Measure Charges**

via classic motion measurement (F = qE); Camera, Laser/CCD (bulk matter)




via ionization energy loss in the detectors (accelerator, cosmic rays)

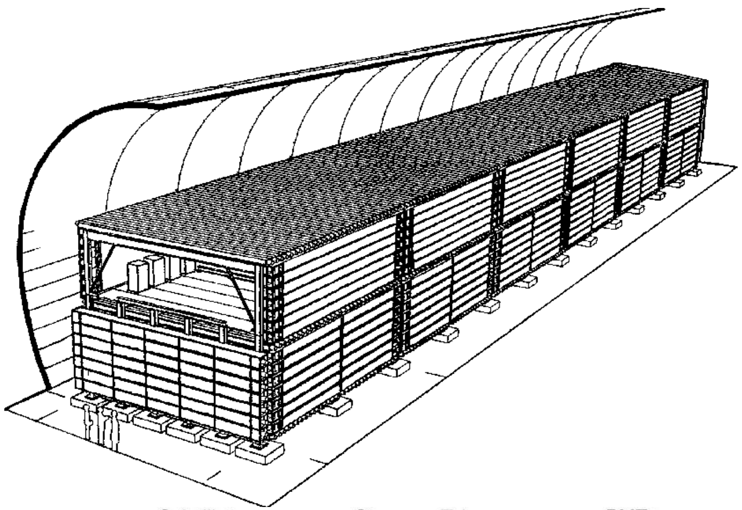
***For both cases, tricky to probe small charges***

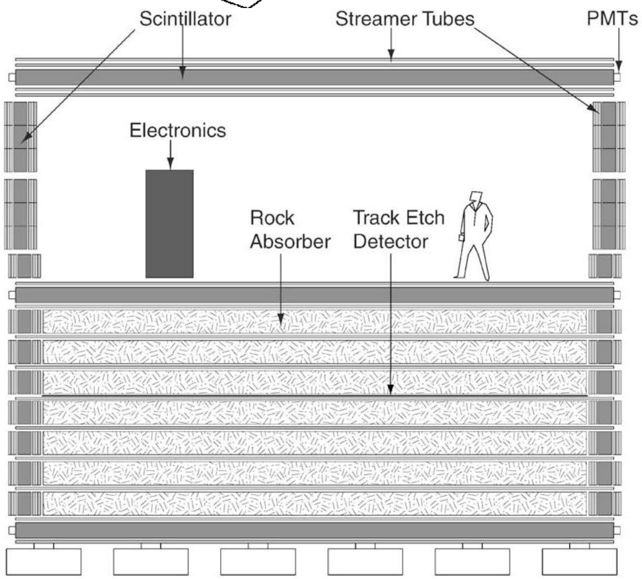
$$\frac{-dE}{dX} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} [\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta}{2} - \frac{C}{Z}]$$

# Experimental Results

## MACRO Experiment

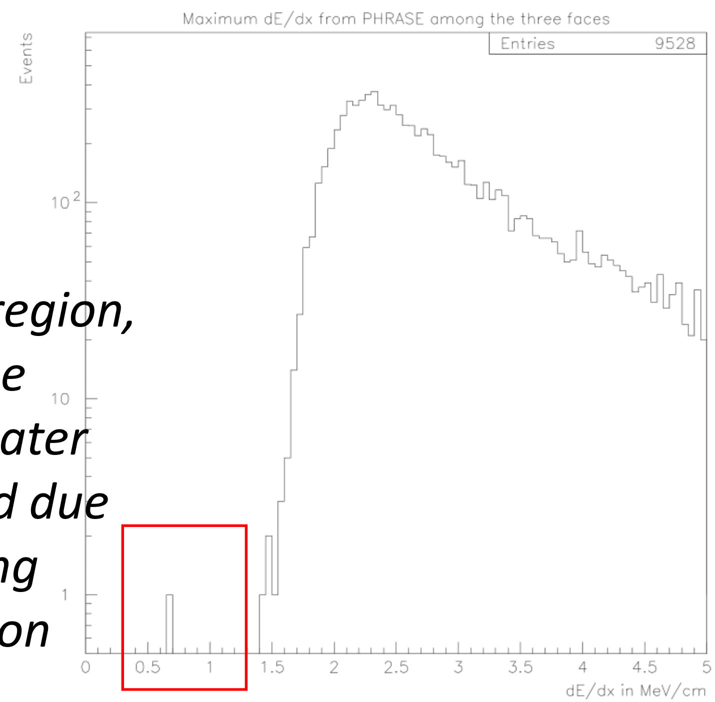
arXiv:hep-ex/0402006v1






- FCPs were searched for as lightly ionizing particles, for total run time (1989 – 2000)

- Streamer tube tracker + Liquid scintillator for FCP searches



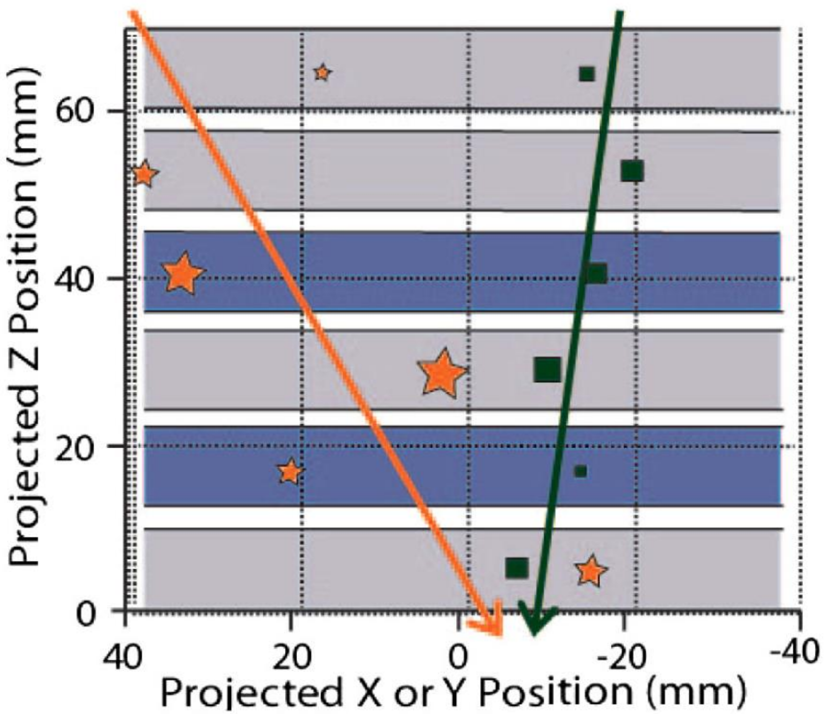

*Signal region, only one event, later rejected due to timing confusion*

Y.

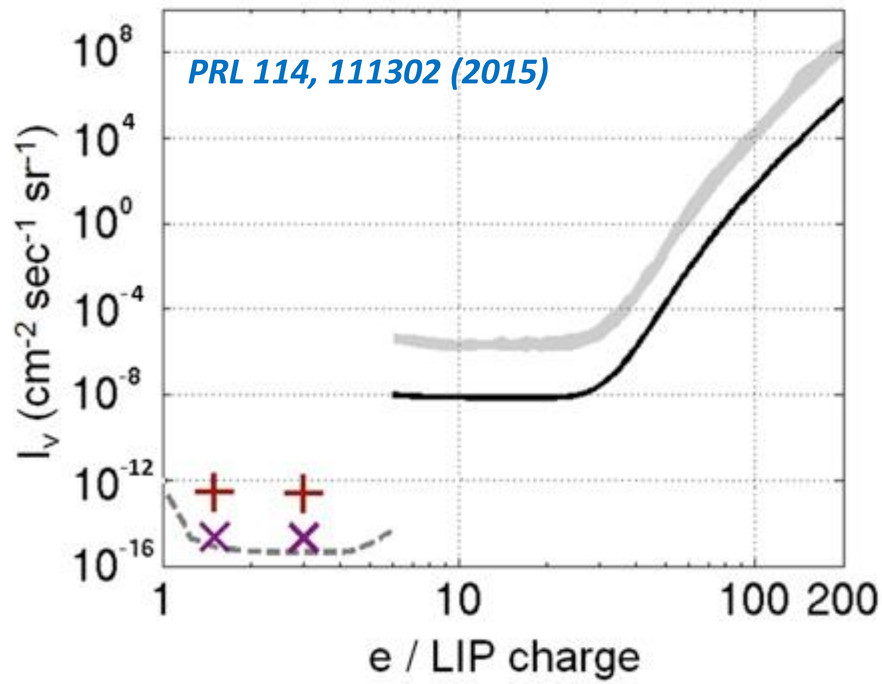
# Experimental Results

More recent: CDMS-II

*Underground, Soudan mine in Minnesota, U.S.*




*Main focus was for WIMP*




Low-threshold solid-state detectors in an array to detect very lightly ionizing particles from cosmic rays,

➔Sensitive to $1/200 < q < 1/6e$

➔No positive results

➔Upgrade ongoing to SuperCDMS

# Bulk Matter in a Nutshell

| Method | Material | Sample (mg) | Nucleons |
|---|---|---|---|
| Ferromagnetic levitometer | Steel | 3.7 | $2.4 \times 10^{21}$ |
| Ferromagnetic levitometer | Tungsten | 3.0 | $1.4 \times 10^{21}$ |
| Ferromagnetic levitometer | Niobium | 6.5 | $4.2 \times 10^{21}$ |
| Ferromagnetic levitometer | Meteorite | 2.8 | $1.8 \times 10^{21}$ |
| Ferromagnetic levitometer | Seawater solutes | See Reference 39 | See Reference 39 |
| Superconducting levitometer | Niobium | 1.1 | $7 \times 10^{20}$ |
| Liquid drop | Seawater | 0.05 | $3.2 \times 10^{19}$ |
| Liquid drop | Mercury | 2.0 | $1.3 \times 10^{21}$ |
| Liquid drop | Silicon oil | 17.4 | $1.1 \times 10^{22}$ |
| Liquid drop | Silicon oil | 70.1 | $4.5 \times 10^{22}$ |
| Liquid drop | Mineral oil | 259 | $1.7 \times 10^{23}$ |
| Liquid drop | Meteorite | 3.9 | $2.51 \times 10^{21}$ |

→100mg

- Two main classes of experiments: Liquid drop; Levitometer
- Both cases need special care of samples, and need high precision system
- Limitation is the sample size / throughput

*"One drop in the sea"*

# Searches in Bulk Matter

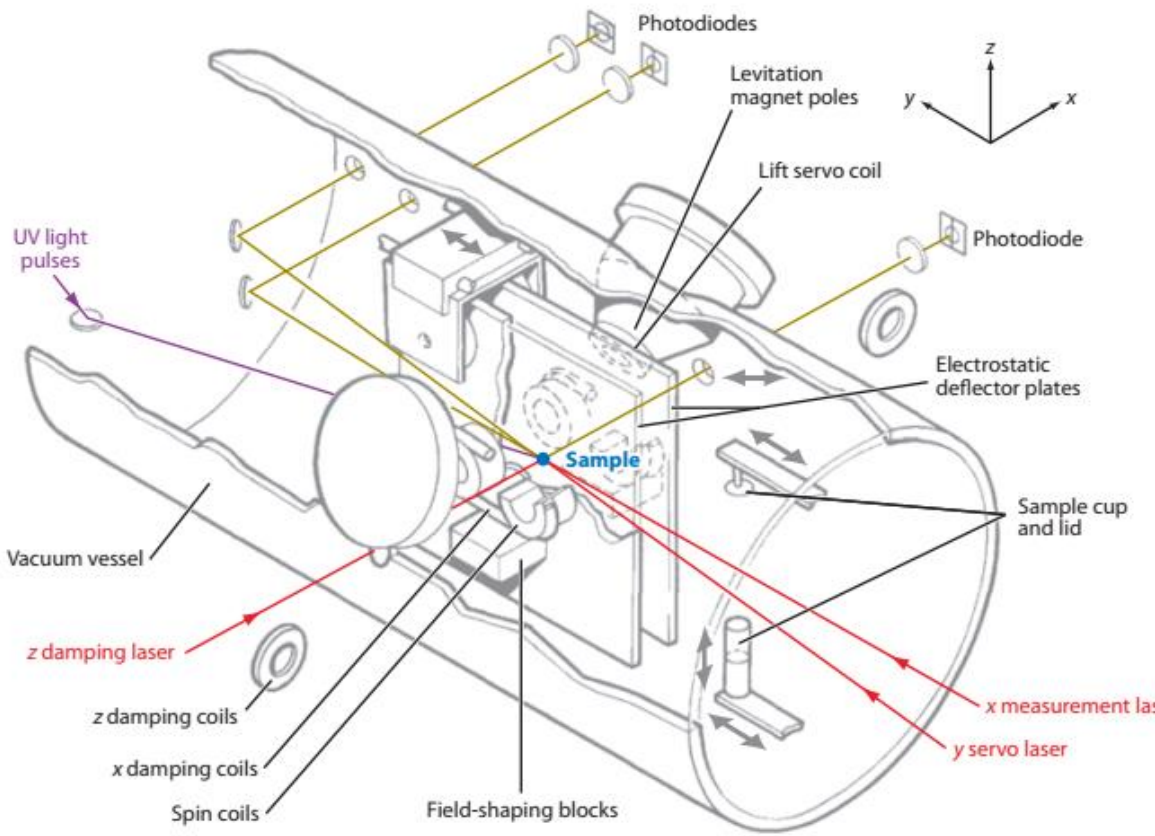
- ***Materials often chosen for ease of use w.r.t. experiments:***
  - Chemical features of FCP+nuclei system unclear
  - Used: **sea water**, **silicone oil**, **mercury**, **iron**, **niobium**, **meteorite**






  - Might be interesting to do in the future: rocks from comet and Moon, plus many others to be explore ?

# Searches in Bulk Matter




Some used diamagnetic levitation on a sample consisting of superconducting niobium ball – disadvantage of very limited sample choice;

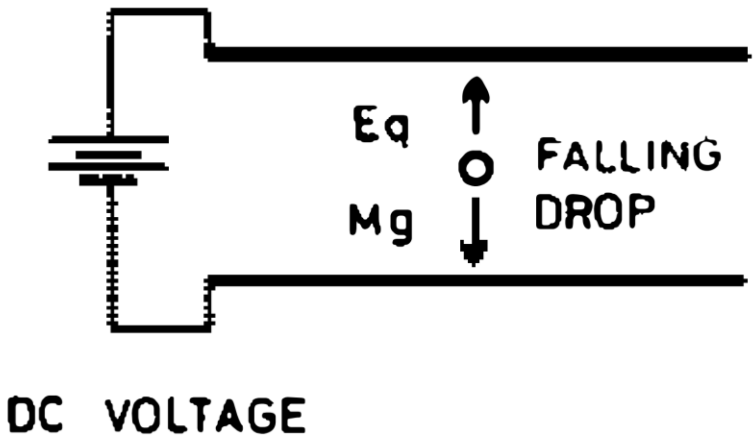
***Ferromagnetic Levitometer***

- Magnetic field to levitate the sample of O(0.1mm) diameter
- Oscillating electric field with laser and photodiodes to measure charge
- Sample coated with iron, or iron ball coated with sample
- UV light to remove electrons one-by-one from the sample

# Searches in Bulk Matter

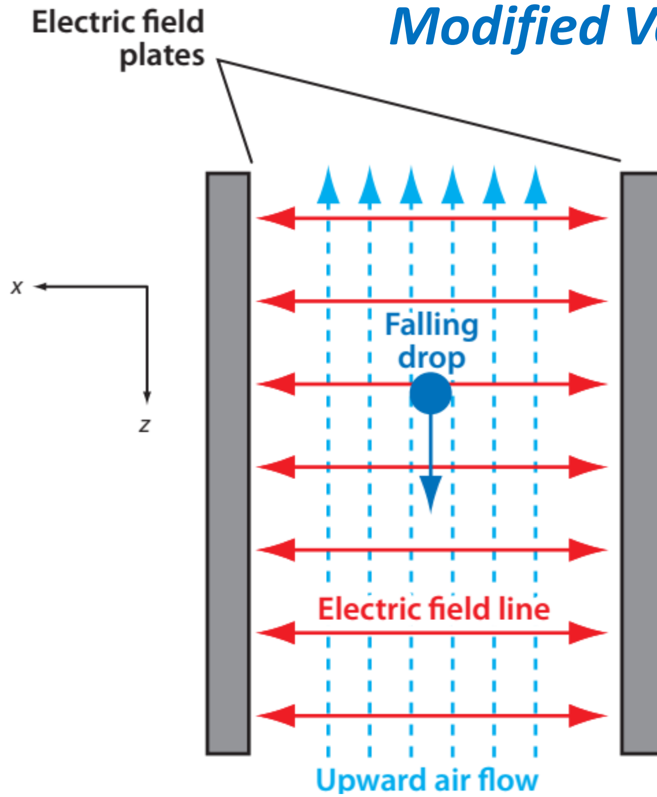
**Liquid drop experiments**

*Millikan Oil experiment*




Traditional method need to suspend the old drop and therefore limit the throughput to <<mg

*Modified Version*




Stokes' Law

$$v_{\text{vert-term}} = \frac{mg}{6\pi\eta r}$$

$$m = \frac{4}{3}\pi\rho r^3$$

$$v_{\text{horiz-term}} = \frac{EQ}{6\pi\eta r}$$

} Q

# 小结

- 分数电荷粒子仍未被发现
  - 前面略去了在大型加速器实验上的寻找（和本讨论相关度不太，且质心能量仅 TeV）

整体情况与MM类似
困难在于低电荷量的探测精度
对于深空探测而言，优势可能还是月壤就地取材探测？

# 总结

- **磁单极子**、**稳定分数电荷粒子**的探测已有不少结果，特别是宇宙线，以及bulk matter样品方式，但可以探索的空间仍很大

- 下一代实验要超过现有精度，例如更大接受度，或更新技术

- 深空探测一个明显可能性在于Bulk matter实验，或许就地取材，利用小型探测器可以长期运行？

- 其它：
  - 例如对MM/FCP在大气中的电磁shower过程研究，是否可以利用先用大阵列宇宙线观测站，例如LHASSO等来探测。