# POTENTIAL FOR MONOPOLE SEARCHES USING ICE CORE SAMPLES

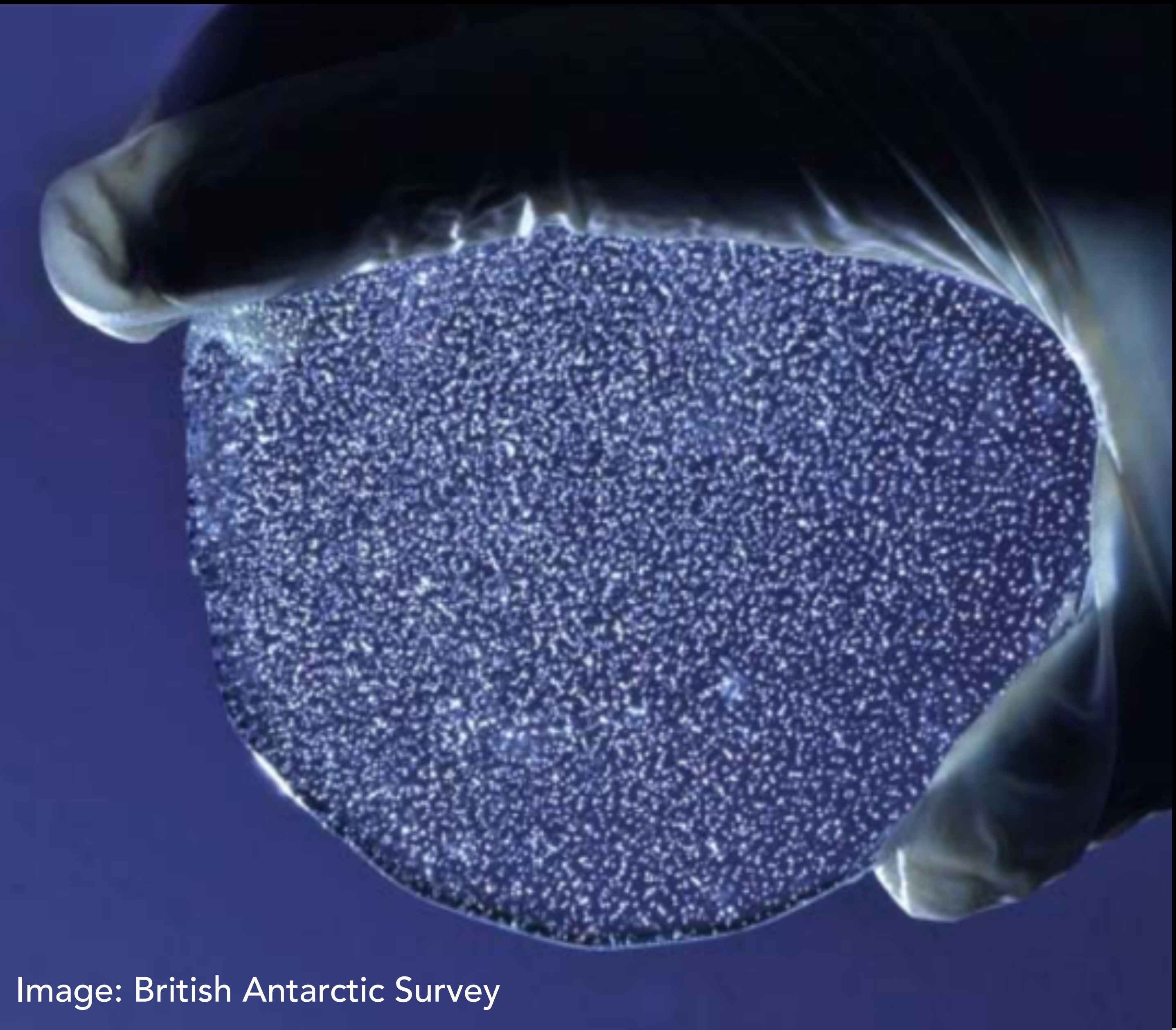

Image: British Antarctic Survey

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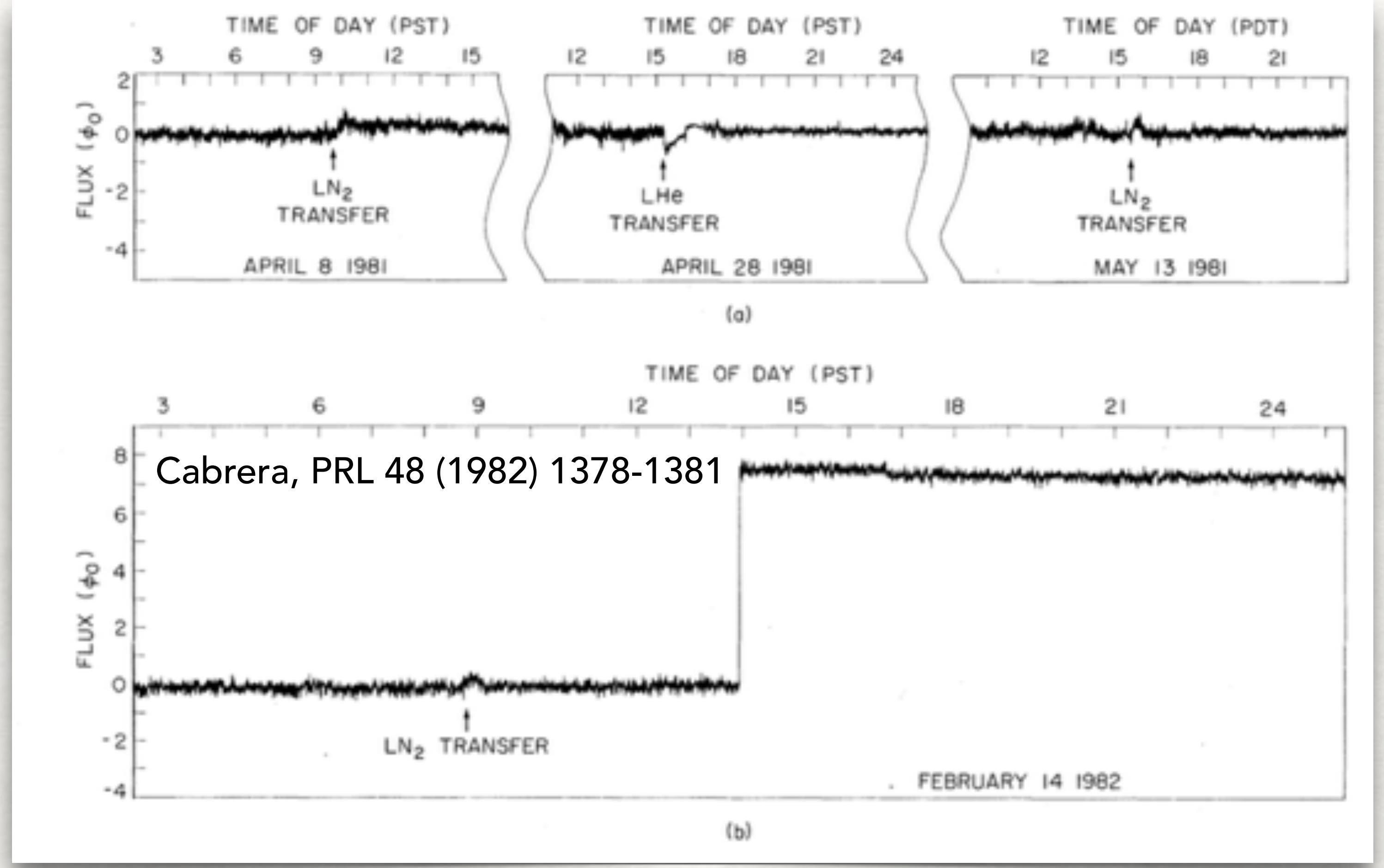
# OUTLINE

- Sources of monopoles
- Measurement method
- Previous searches in material
- The potential for using ice cores
  - Northern hemisphere drill sites
  - Southern hemisphere drill sites
- Practical issues
- Performing a competitive search
- Summary

# SOURCE OF MONOPOLES

- Motivation:
  - Monopoles are theoretically convenient… and could explain deep concepts like charge quantisation.
  - In 1982 there was an *interesting* event found by Cabrera that has not been repeated or refuted since …




  - The LHC is currently our best shot for finding new physics, but has found nothing radically new since the Higgs.

# SOURCE OF MONOPOLES

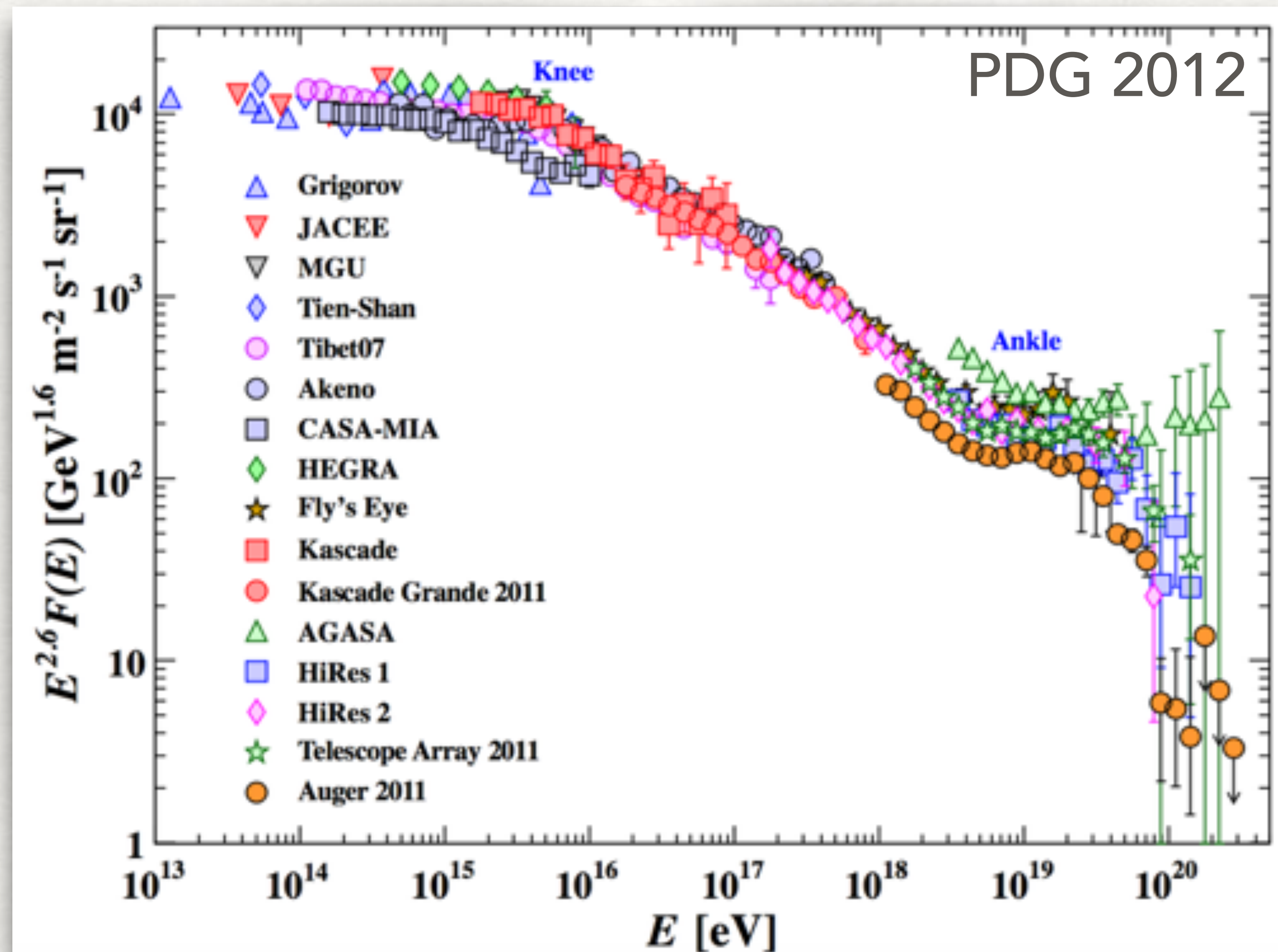
- GUT Scale relics of the Big Bang:
  - 't Hooft and Polyakov's monopoles required for some GUTs.
  - Would exist in matter with a given relative abundance - so just look for them in material.

- Electroweak monopoles could be created in ultra high energy cosmic ray (UHECR) collisions with the atmosphere:
  - Spectrum of type and energies of cosmic ray primaries with matter in the upper atmosphere.
    - LHC energy is 14 TeV;
    - UHECR energies exceed $10^{20}$ eV ($10^{8}$ TeV).
  - Air showers well known from experiments such as Auger and its predecessors.

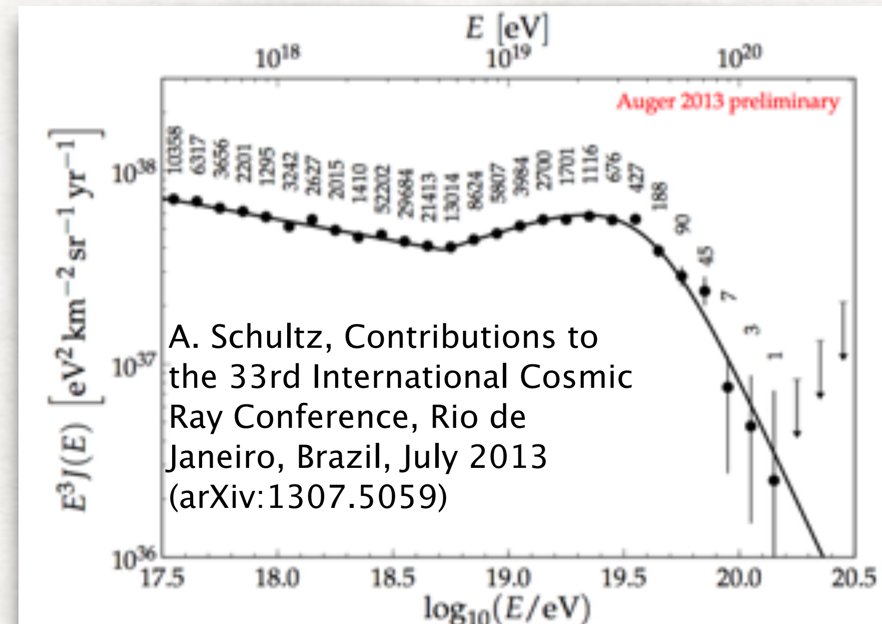
- Highly ionising stable particles with magnetic charge can get trapped in material.

# SOURCE OF MONOPOLES

- Flux multiplied by $E^{2.6\ (\text{or } 3)}$ to accentuate features of the knee and ankle on a single plot.




Precise measurement of the UHE CR flux has been provided by Auger, along with a model to describe the flux near the ankle.



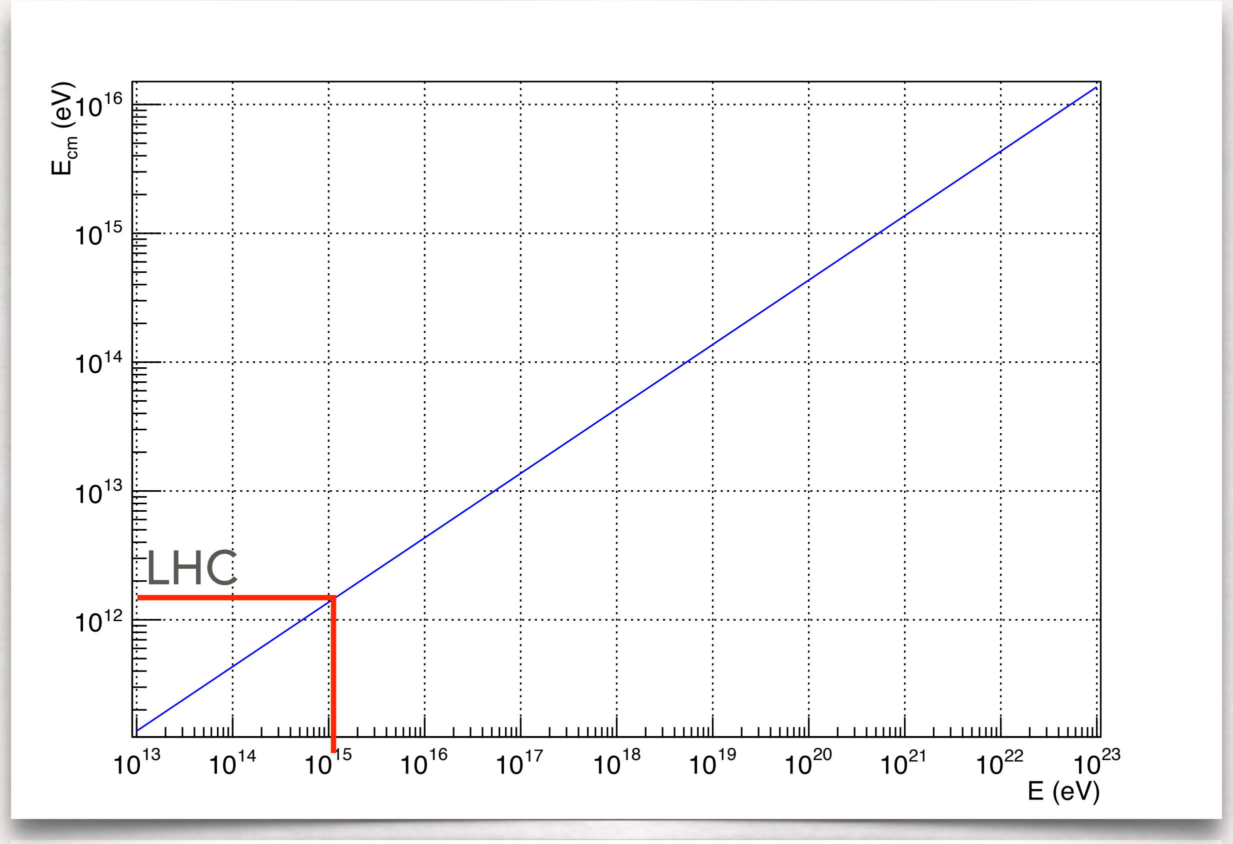

$$J(E; E > E_a) \propto E^{-\gamma_2}\left[1 + \exp\left(\frac{\log_{10} E - \log_{10} E_{1/2}}{\log_{10} W_c}\right)\right]^{-1}$$

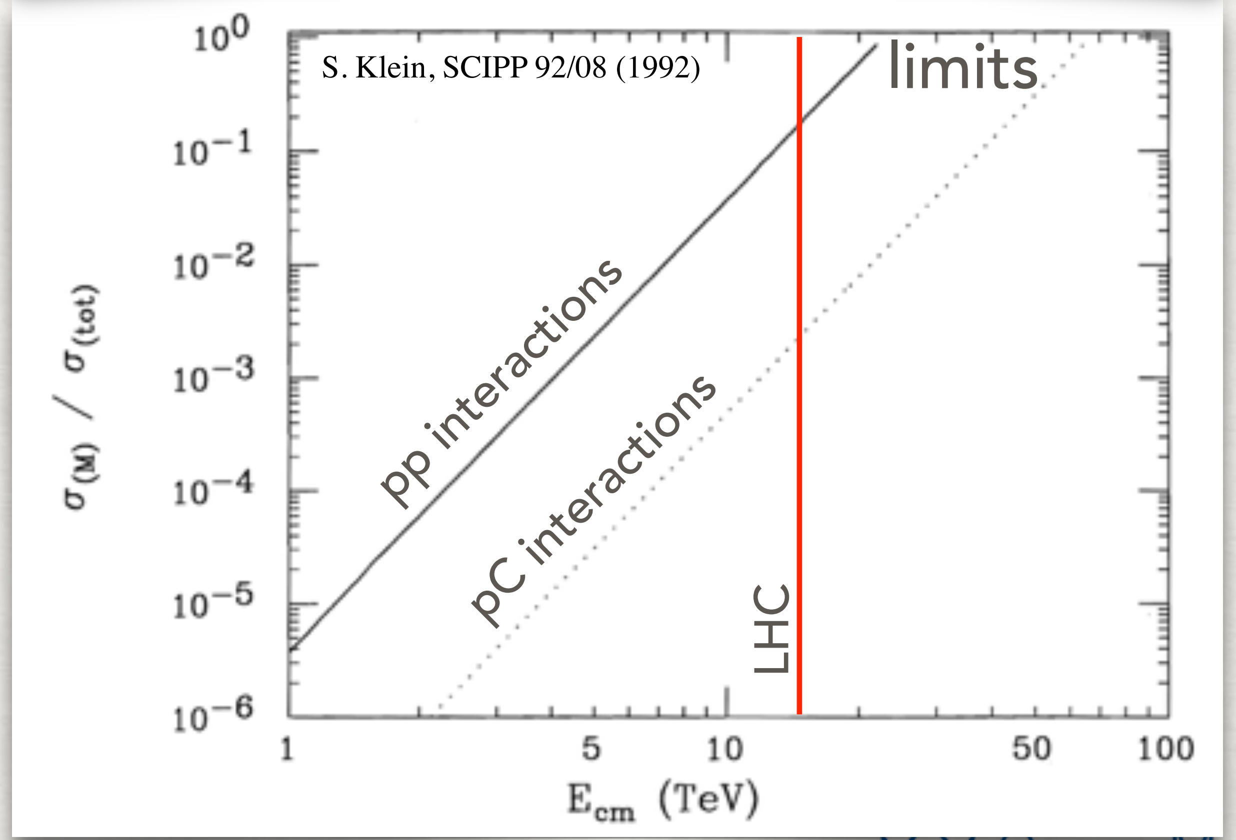
| Parameter | Result ($\pm\sigma_{\text{stat}} \pm \sigma_{\text{sys}}$) |
|---|---|
| $\log_{10}(E_a/\text{eV})$ | $18.72 \pm 0.01 \pm 0.02$ |
| $\gamma_1$ | $3.23 \pm 0.01 \pm 0.07$ |
| $\gamma_2$ | $2.63 \pm 0.02 \pm 0.04$ |
| $\log_{10}(E_{1/2}/\text{eV})$ | $19.63 \pm 0.01 \pm 0.01$ |
| $\log_{10} W_c$ | $0.15 \pm 0.01 \pm 0.02$ |

Discussion of the composition of UHECR's can be found in 1604.07584.

# SOURCE OF MONOPOLES

- The atmosphere becomes a fixed target experiment.
- LHC collision energy corresponds to $E_{cm}$ ~13TeV; equivalent to E~ $10^{15}$.
- UHECR provide access to TeV, EeV ranges and beyond; limited only by flux of primary interactions with the atmosphere and integrated solid angle of stopping target.



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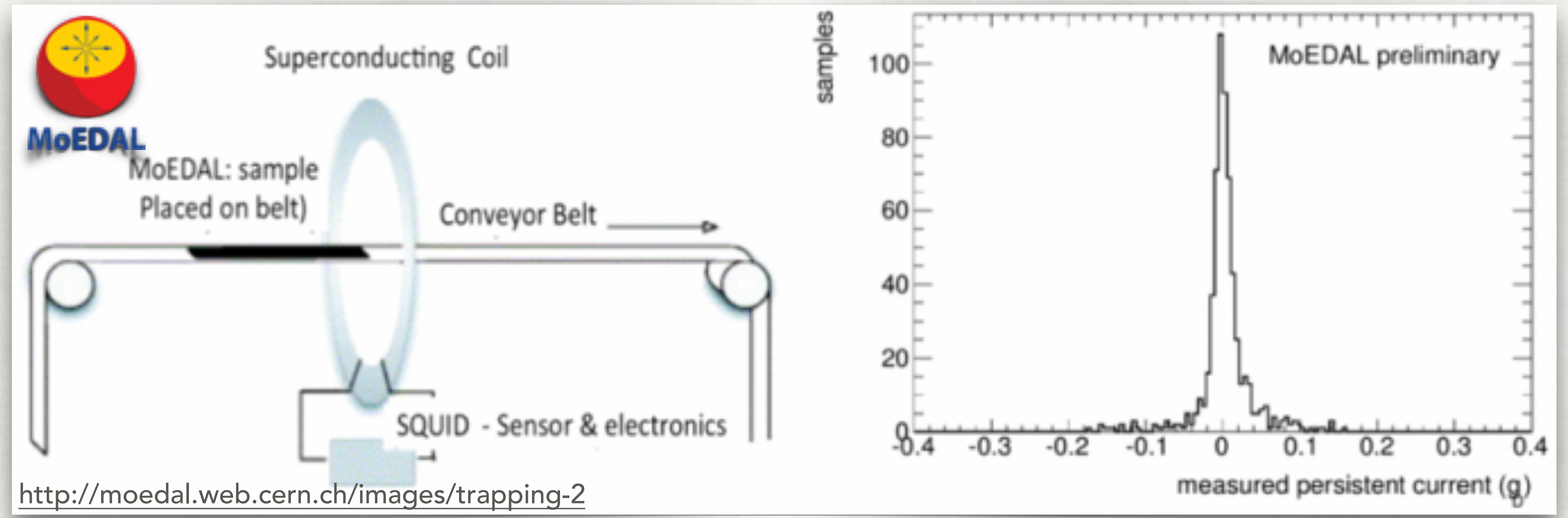
# MEASUREMENT METHOD

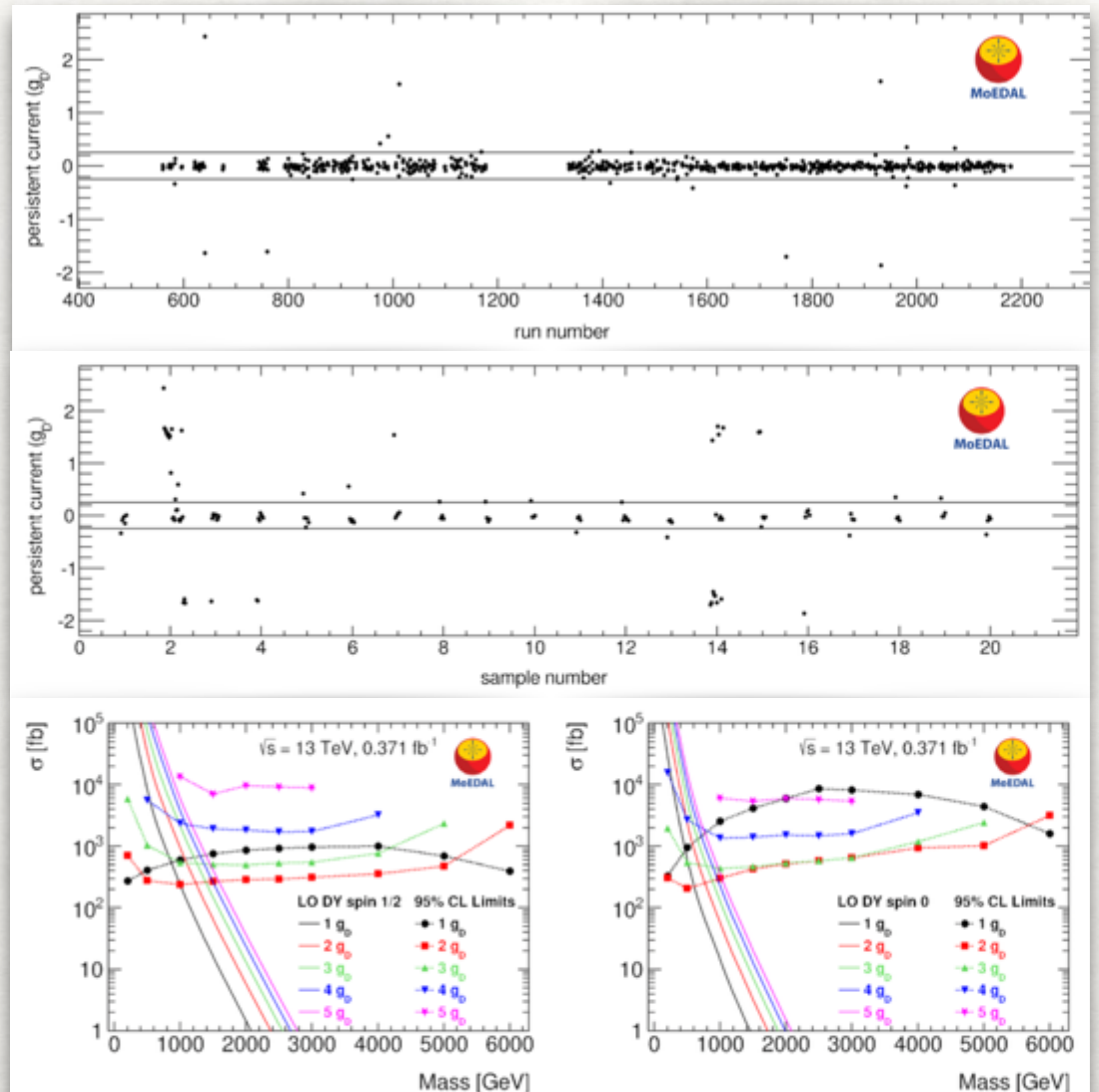
- Analogous to the trapping detector measurement method of MoEDAL:
    - Pass material through a SQUID and look for a reproducible change in current.




- Pro:
    - MoEDAL provides experience in terms of how to handle material and sensitivity of magnetometer to monopoles.
    - This experience is improving with time as MoEDAL analyse trapping detector material during the LHC Run cycle.
    - Beam pipe studies and any inner detector decommissioning material studies will just add to this expertise.

# MEASUREMENT METHOD

- Example: MoEDAL 13TeV LHC data trapping detector result




- $g_D$: Dirac magnetic charge
- Trapping detector material used to place model independent and model dependent limits on the production of monopoles in pp collisions at the LHC.
- Drell-Yan background (solid) falls of rapidly with mass.
- Signal limits are reasonably flat across the mass range probed.
- For UHECR's the centre of mass energy is not known for a collision.

# PREVIOUS SEARCHES IN MATERIAL

- Kovalik and Kirschvink, Phys Rev A (1986) 1183-1187.

TABLE I. Summary of previous experimental searches for monopoles trapped in matter.

| Samples | Type of detector | Amount of material | References |
|---|---|---|---|
| Meteorite | Emulsion | 0.56 kg | 16 |
| Meteorite | Particle detector | 0.060 kg | 17 |
| Deep-sea nodules | Plastic | 113 $cm^3$ | 10 |
| Ferromanganese pavement | Plastic | 7.73 kg | 11 |
| Ocean-floor sediment | Particle detector | $1.6\times10^6$ $cm^3$ | 18 |
| Seawater | Particle detector | $1.63\times10^6$ $cm^3$ (i.e. 1630 l) | 12 |
| Air | Particle detector | $6.84\times10^7$ $cm^3$ | 12 |
| | Induction | Total mass examined (kg) | |
| Ti, Cu, Al brass, Teflon | SQUID | 0.001 72 | 19 |
| Au, Cu, W | SQUID | 0.030 06 | 3 |
| Moon rocks | non-SQUID | 47.8 | 6–8 |
| Seawater | SQUID | 180 | This study |
| Mn nodules | SQUID | 145 | This study |
| South Fork Mt. schist | SQUID | 56.7 | This study |
| Rand Mt. schist | SQUID | 441.3 | This study |



[12]Carrigan et al, PRD **13** 1823 - 1825 (1076)

# PREVIOUS SEARCHES IN MATERIAL

- Kovalik and Kirschvink, Phys Rev A (1986) 1183-1187.

The number of monopoles in bulk matter is small with none found in 643 kg of stable, highly magnetic material measured in this experiment and an additional 180 kg of seawater. This total of 823 kg of matter is roughly 20 times larger than the total amount of material directly searched for magnetic charge by all previous searches as shown in Table I, and is over 25 000 times more than all previous experiments using SQUID-based techniques. This suggests that the cosmic flux of monopoles has remained small over the past 150 million years or that matter does not easily stop monopoles even after a passage of 25 km through the Earth's crust. Current experimental and theoretical limits on the monopole flux[27] seem adequate to explain the results obtained.

Thus, the data obtained in this experiment actually represent the number of tightly bound monopoles and not all the possible bound-monopole configurations. Since it only places a lower constraint on the number of bound monopoles, further experiments must attempt to include not only materials with different properties and geologic histories, but also a means to catch those displaced during processing.

The authors (Kovalik and Kirschvink) proposed looking for monopoles in the dust/ice of comets; this is not very practical - but the Rosetta mission brought this possibility one step closer.

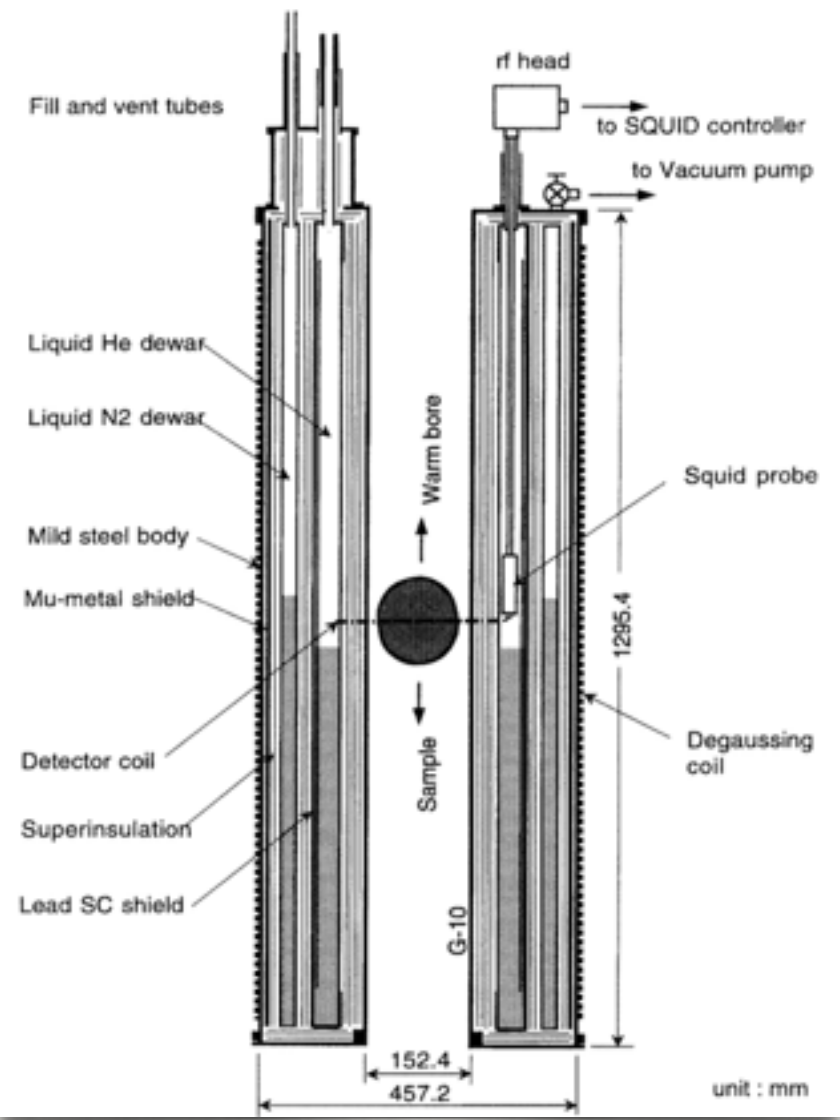
823kg sets the limit on the amount of matter studied in a SQUID based search for monopoles.

# PREVIOUS SEARCHES IN MATERIAL

- Limit on monopoles / nucleon is <~$10^{-29}$; obtained not from comets, but meteorite fragments and other samples.

Jeon and Longo, Phys.Rev.Lett.75:1443-1446,1995; Erratum-ibid.76:159,1996

| Samples[a] | Mass | Number | Age | Notes |
|---|---|---|---|---|
| Perry collection meteorites[b] | 32.7 kg | 65 pcs | $> 10^9$ years | 2 |
| Antarctic meteorites | 81.0 kg | 99 pcs | $> 10^9$ years | 2 |
| Ferromanganese nodules[c] | 5.0 kg | 31 pcs | $10^2 - 10^7$ years | 3 |
| Iron ores-magnetite[d] | 20.4 kg | 39 pcs | $\sim 10^9$ years | 4 |
| Iron ores-hematite | 5.0 kg | 8 pcs | $\sim 10^9$ years | 4 |
| Blueschists[e] | 66.2 kg | 77 pcs | $\sim 10^9$ years | 5 |
| Sedimentary rock cores[f] | 112.5 kg | $\approx$ 400 pcs | $\sim 10^9$ years | 6 |
| Kimberlites[g] | 3.7 kg | 4 pcs | | 7 |
| Chromates | 4.9 kg | 10 pcs | | |
| Garnets[h] | <1 gm | > 10 pcs | $\sim 10^9$ years | 8 |
| Total | 331.4 kg | >743 pcs | | |





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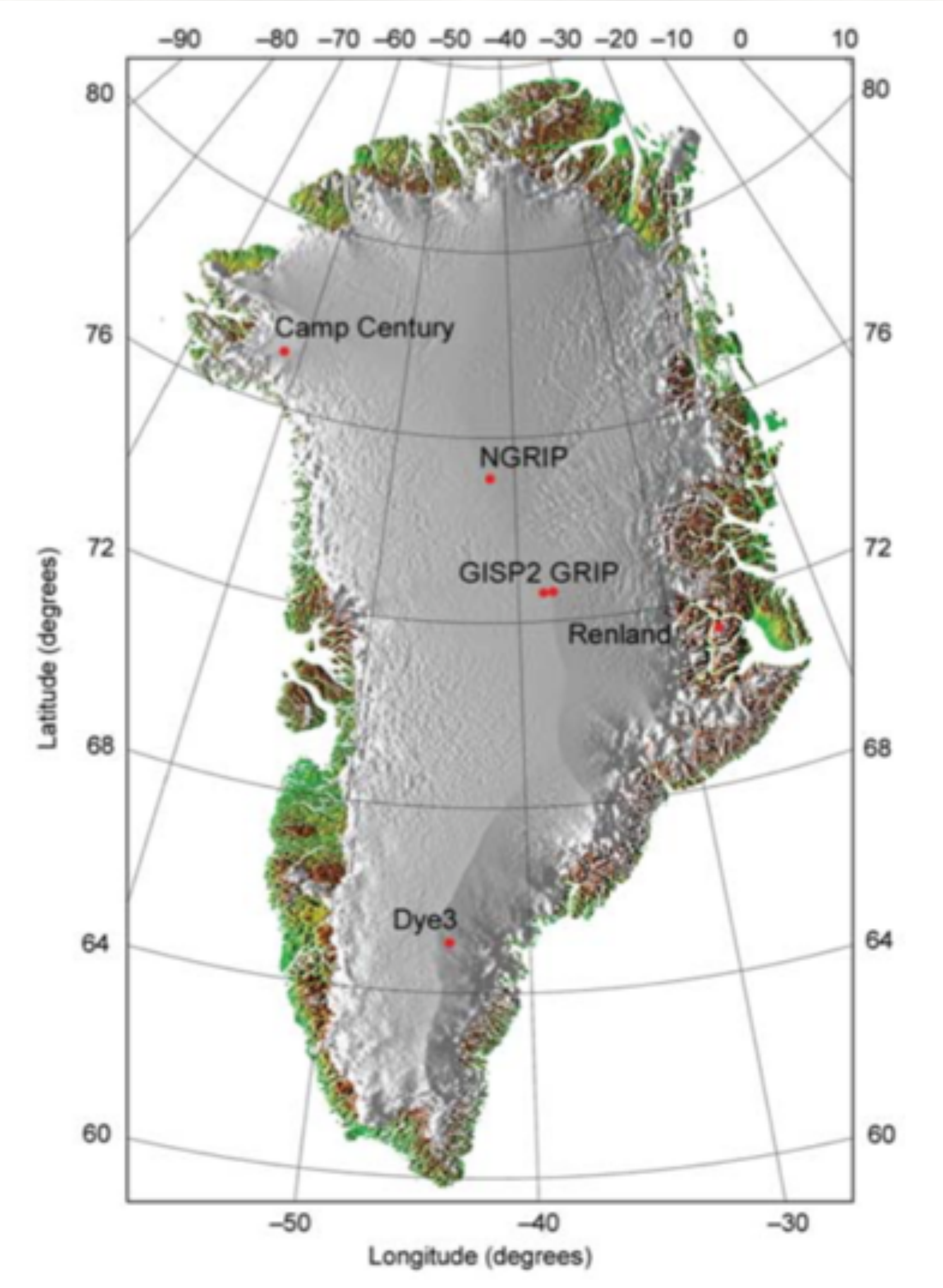
# THE POTENTIAL FOR USING ICE CORES

- Stringent limits exist on primordial monopoles from previous studies;
  - More than 826kg of material would need to be examined to match the mass of previous studies.
  - Ice is geologically young compared with the mineral samples studied previously.
  - Unlikely to shed new light on the primordial monopole search issue.

- What if monopoles are created in high energy interactions by cosmic rays?
  - Will stop in material (c.f. MoEDAL acceptance as a function of energy).
  - Depending on energy of the monopole created, it could penetrate far into the target material.
  - Flux is low, so integrating over a long time is desirable.

# NORTHERN HEMISPHERE DRILL SITES

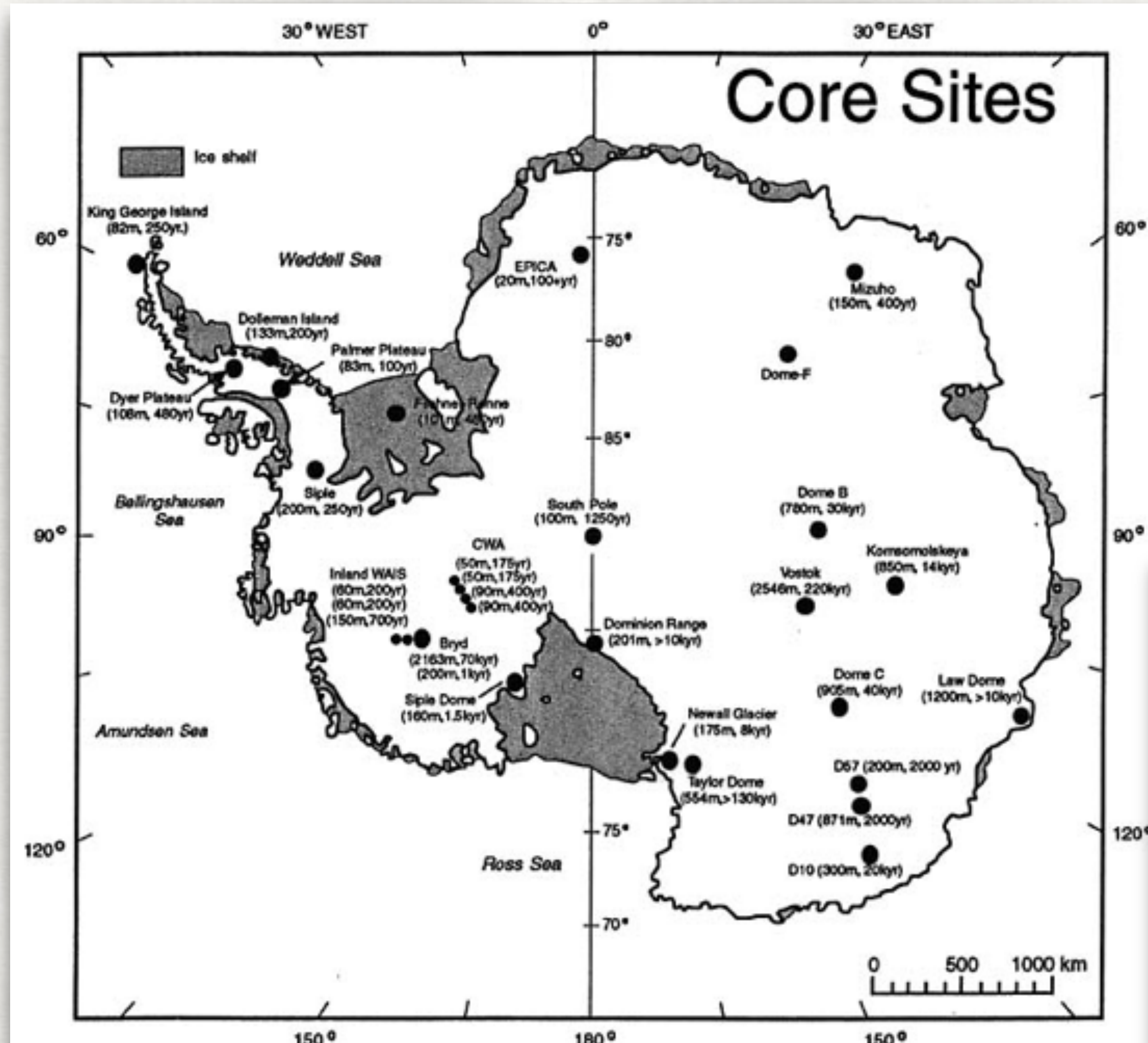
- As an illustration we can consider existing samples drilled in Greenland:
  - Camp Century (>1350m)
  - NGRIP (3085m)
  - GRISP2 (3053m)
  - GRIP (3027m)
  - Renland (325m)
  - Dye3 (>2000m)



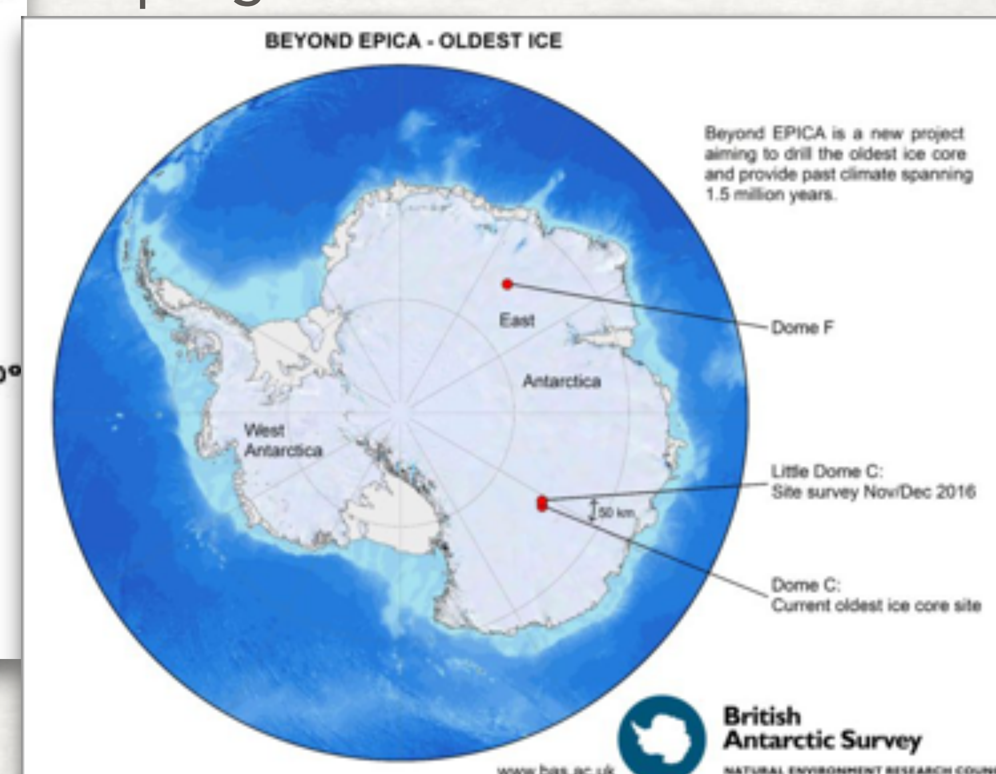

Anderson et al., Nature **431** (2004) 147-151; Johnsen et al., J. Quaternary Sci (2001) 16 (4) 299–307.

# SOUTHERN HEMISPHERE DRILL SITES

- Active drilling projects being planned/ongoing.




- Core depths up to 3661m.
- e.g. climatologists are drilling at Dome C as part of the Beyond Epica - Oldest Ice project.
- Potential to link particle physics into a climate science programme.




http://www.antarcticglaciers.org/

# PRACTICAL ISSUES

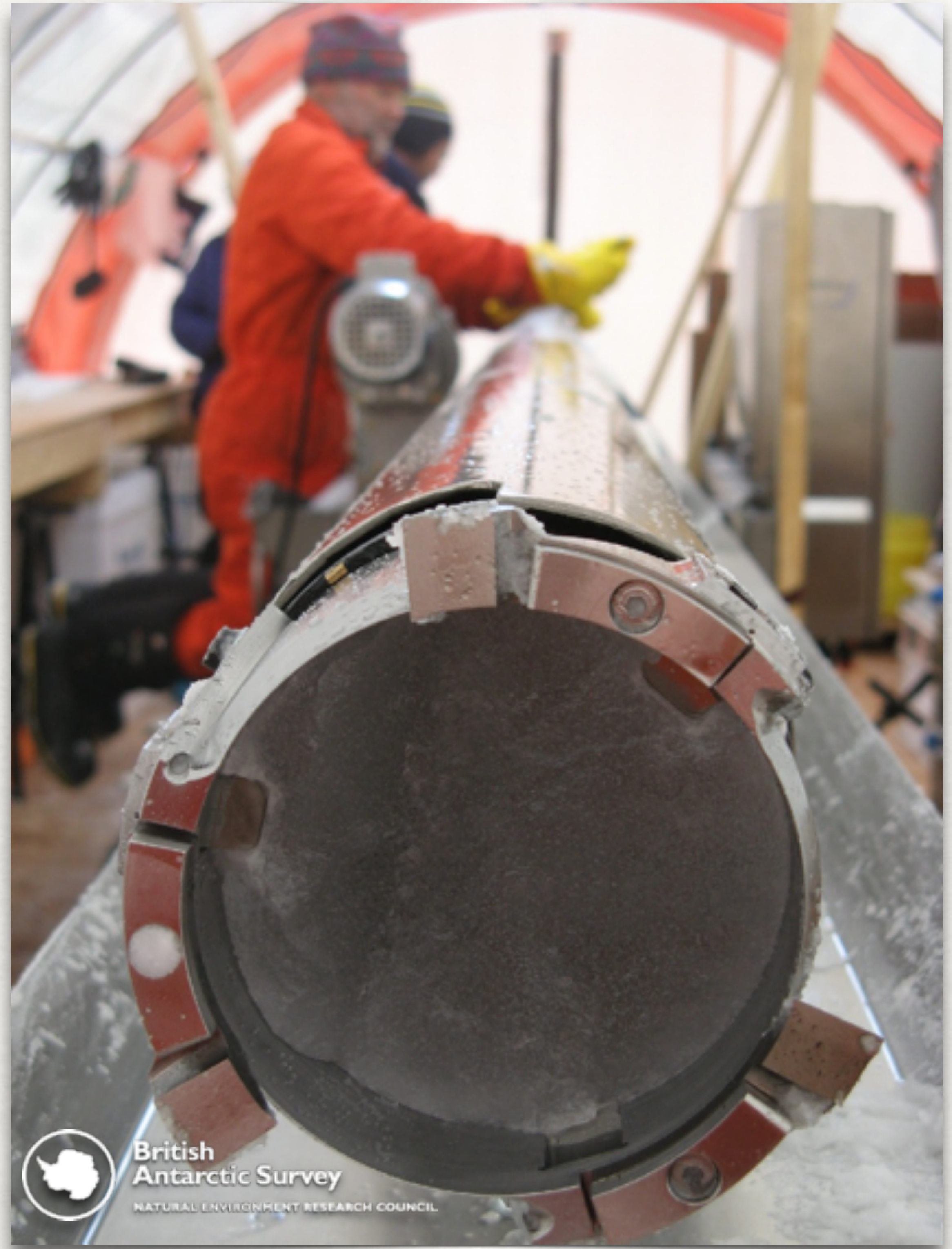
- There are two ways forward to analysing the material in ice cores:

1. **Simplest method is to obtain a rock magnetometer with large bore and pass cores through this.**
    - Sensitivity limited by bore size.
    - Standard large-bore magnetometers are too small to take the cores; so this would be a non-standard piece of equipment.
    - Core measurements would be best done at existing storage sites; logistical issues exist in relocating and setting up the measurement (including handling samples).
    - Need to gain access to such material and possibly drill a sample.
        - Started exploring access options to understand constraints.

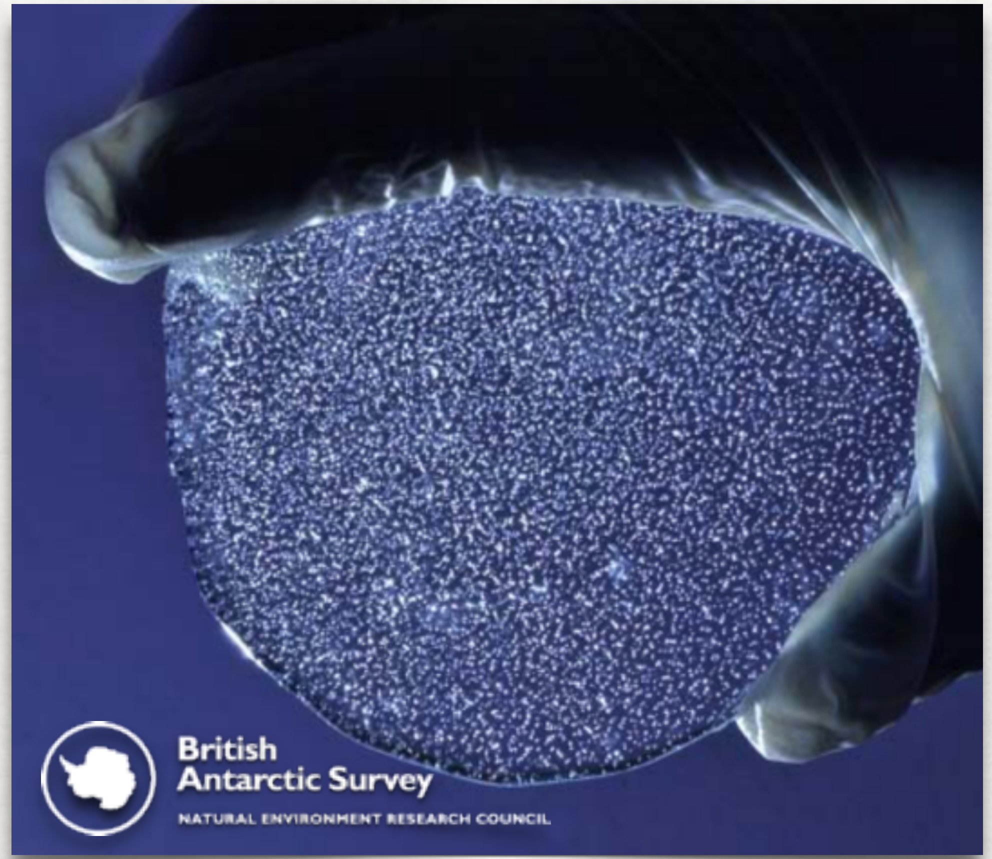
- There are two ways forward to analysing the material in ice cores:

2. **Melt the cores, and bottle up.**
    - Geologists/climatologists would not share material for a destructive study like this.
    - Requires a dedicated drilling expedition for such an experiment.
    - Advantage is that small bore magnetometers could be used to retain sensitivity to monopoles while being able to use relatively cheap equipment.
    - Disadvantage would be potential loss in other scientific output from any given sample (only used for particle physics).
    - Can consider multiple measurement stations (depending on how small the transverse dimensions of a sample is) … as an ice monopole search needs mass, not a continuous timeline.
    - **Expensive endeavour with additional logistical issues to be explored.**

# ICE CORES




- Core sample lengths: from 1 to 6m in length
- Diameter 50-132mm
- Various measurements made (gas analysis, conductivity, …) on core samples to understand climate evolution.



# PERFORMING A COMPETITIVE SEARCH

- Require a SQUID magnetometer with an appropriate bore to take samples.
- Arrange access to sample(s) or identify collaborators to work with in order to obtain core samples.
- Previous studies of material have searched in an integral of 823+331kg of material [1154kg] for GUT scale monopoles; using different material samples and a SQUID based detector.
  - Includes 180kg of seawater.
- 1630 litres of seawater has been studied using a particle detector approach.
  - equivalent to 1670kg.
- Sensible targets:
  - Feasibility study with a small sample of material to explore practicalities.
  - Exceed 180kg of ice for a first measurement, with a long term goal of analysing several tonnes of material.

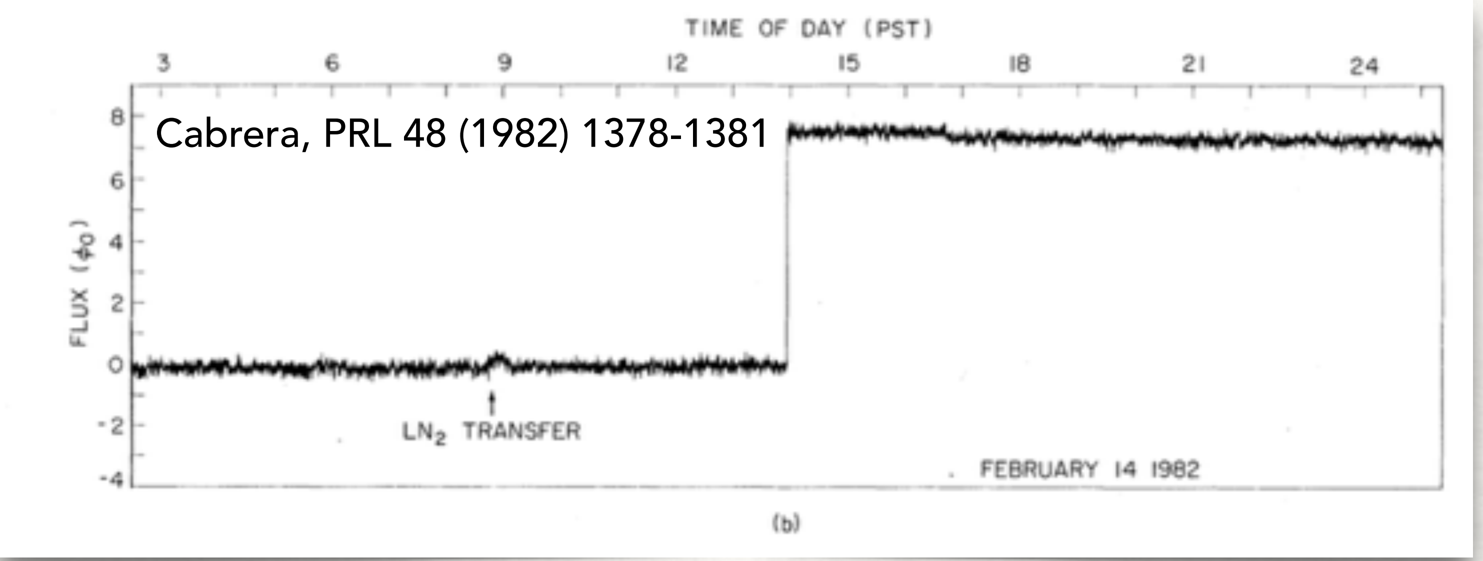
# PERFORMING A COMPETITIVE SEARCH

| Core Depth (m) | Bore Size (cm) | Volume ($\ell^3$) | Mass (kg) |
|---|---|---|---|
| 1 | 7.6 | 4.5 | 4.2 |
| 500 | 7.6 | 2268 | 2080 |
| 1000 | 7.6 | 4536 | 4160 |
| 2000 | 7.6 | 9072 | 8320 |
| 1 | 10 | 7.9 | 7.2 |
| 500 | 10 | 3926 | 3601 |
| 1000 | 10 | 7854 | 7202 |
| 2000 | 10 | 15708 | 14402 |

- Analyse 25-43 m of core samples to reach the 180kg mark.
- Analyse 160-274 m of core samples to reach the 1154kg mark.
- 2km core has a mass 7-12.5 times more material than studied with SQUIDs previously.
- Corresponds to a cumulative exposure of up to 800,000 years (depending on sample length/drill location).
- Complementary to the Cosmic MoEDAL approach.

# OTHER FACTORS

- What if this is a real monopole event?




- Detection by a SQUID experiment would indicate that while rare, these events are do happen.
- Ice cores have the benefit of temporal records (can be used to determine exposure time for parts of the sample);
  - Deep core samples are better than surface ones.
  - Use sediment cores (a la Jeon and Longo) as an alternative source of material to search for these particles.

# SAMPLE CALIBRATION

- Looking for a signal where measurements are expected to be normally null raises several important questions:
  - Dead time?
  - Sensitivity variation with time?
  - Linearity of response?

- Use long thin dipole magnets (c.f. MoEDAL calibration method) to check performance (pseudo-pole approach). Spin ice samples could also be used to periodically calibrate the SQUID magnetometer operation.
  - Validate the performance of measuring a non-null signal throughout the experiment.
  - Important calibration point in case a signal is found.

# SUMMARY

- Presented a concept for a next generation trapping detector search for monopoles.

- Complements LHC programme, would extend previous searches in material and the proposed cosmic ray detector programme (Cosmic MoEDAL).

- Many details still to be worked out; but this concept has potential and is worth exploring further.

- People are welcome to join me in the scoping study for an ice core based search for monopoles.

# RELATIVE TRAPPING STRENGTHS FOR MATERIAL

- See Milton (arXiv:hep-ex/0602040) for details

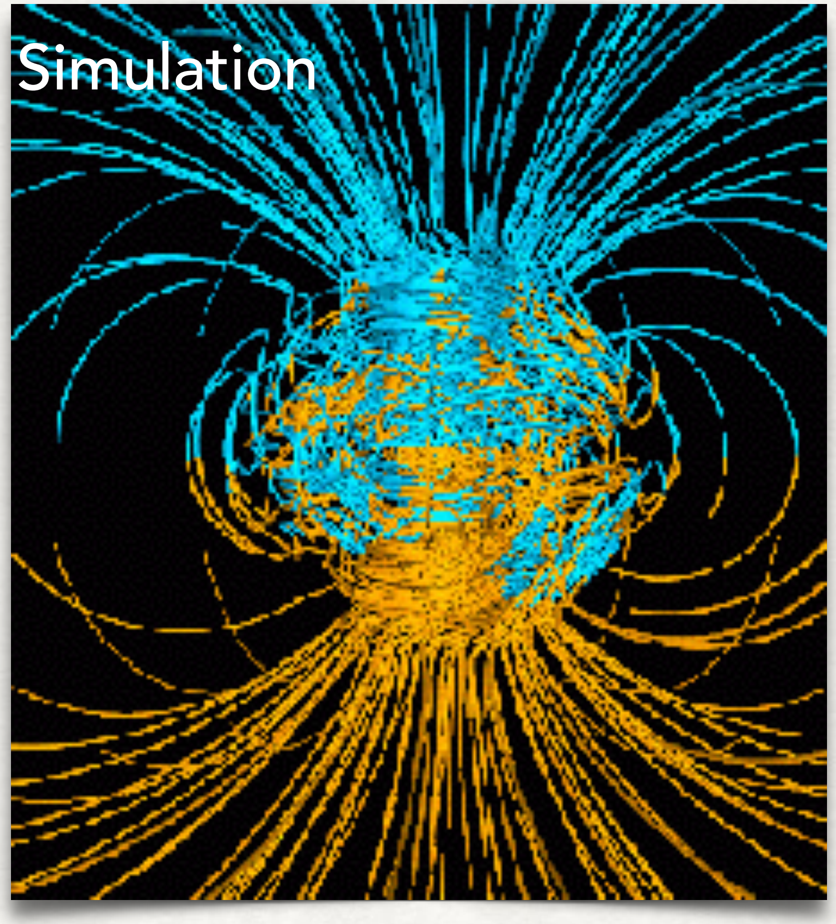
| Nucleus | Spin | $\gamma$ | $\hat{\gamma}$ | $J$ | $E_b$ | Notes | Ref |
|---|---|---|---|---|---|---|---|
| $n$ | $\frac{1}{2}$ | $-1.91$ | | $\frac{1}{2}$ | 350 keV | NR,hc | [146] |
| $^1_1$H | $\frac{1}{2}$ | 2.79 | 2.79 | $l-\frac{1}{2}=0$ | 15.1 keV | NR,hc | [142] |
| | | | | | 320 keV | NR,hc | [146] |
| | | | | | 50–1000 keV | NR,FF | [147] |
| | | | | | 263 keV | R | [148, 149] |
| $^2_1$H | 1 | 0.857 | 1.71 | $l-1=0$ $(\lvert m'\rvert=1)$ | $\frac{130}{\lambda}$ keV | R,IM | [151, 152] |
| $^3_2$He | $\frac{1}{2}$ | $-2.13$ | $-3.20$ | $l+\frac{1}{2}=\frac{3}{2}$ | 13.4 keV | NR,hc | [142] |
| $^{27}_{13}$Al | $\frac{5}{2}$ | 3.63 | 7.56 | $l-\frac{5}{2}=4$ | 2.6 MeV | NR,FF | [148, 149] |
| $^{27}_{13}$Al | $\frac{5}{2}$ | 3.63 | 7.56 | $l-\frac{5}{2}=4$ | 560 keV | NR,hc | [153] |
| $^{113}_{48}$Cd | $\frac{1}{2}$ | $-0.62$ | $-1.46$ | $l+\frac{1}{2}=\frac{49}{2}$ | 6.3 keV | NR,hc | [142] |

- Computation of binding energies leads to the conclusion that monopoles can be bound in almost any material; as the magnetic field of M distorts the field of the the nuclei it gets bound to.

- Composition of an ice core sample is $H_2O$; binding energy is 263 keV; accompanied with a photon emission.

# EARTH'S MAGNETIC FIELD

- The Earth's magnetic field is expected to flip from time to time and monopoles created in the atmosphere will travel to the surface to be trapped in material (if not trapped in the atmosphere).




Glatzmaier and Roberts (1995). *Nature*. **377** (6546): 203–209.
https://websites.pmc.ucsc.edu/~glatz/geodynamo.html

Godynamo simulation of the Earth's magnetic field in a stable configuration.

Surface field strength is weak: varies from 25-65μT.

No significant curvature of particle trajectory for a PeV/EeV particle from point of creation to point of impact on the surface.