Stable massive particle searches in cosmic rays and in matter

Philippe Mermod

SWAPS Workshop

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Non-WIMP, non-decaying particles

- Assume mass > TeV, beyond collider reach
- Can be elementary or composite
- Production in early Universe
- Possibly constitute dark matter
- Possibly bind to matter

	considered mass range	main detection principle in cosmic rays	main detection principle in matter	dark matter candidate
X^+, X^{++}	$< 10^{22}$ GeV	time-of-flight	mass spectrometry	no
X^-, X^{--}	$< 10^{22}$ GeV	time-of-flight	mass spectrometry	$X^- p$, $X^{--}\alpha$
X^0	$< 10^{22}$ GeV	nuclear recoil	mass spectrometry	yes
monopole	$< 10^{22}$ GeV	time-of-flight high ionisation Cerenkov nucleon decay	induction	monopolium
Q-ball	$< 10^{22}$ GeV	high ionisation nucleon decay	—	yes
quark matter	< 1000 kg	high ionisation	mass spectrometry	yes

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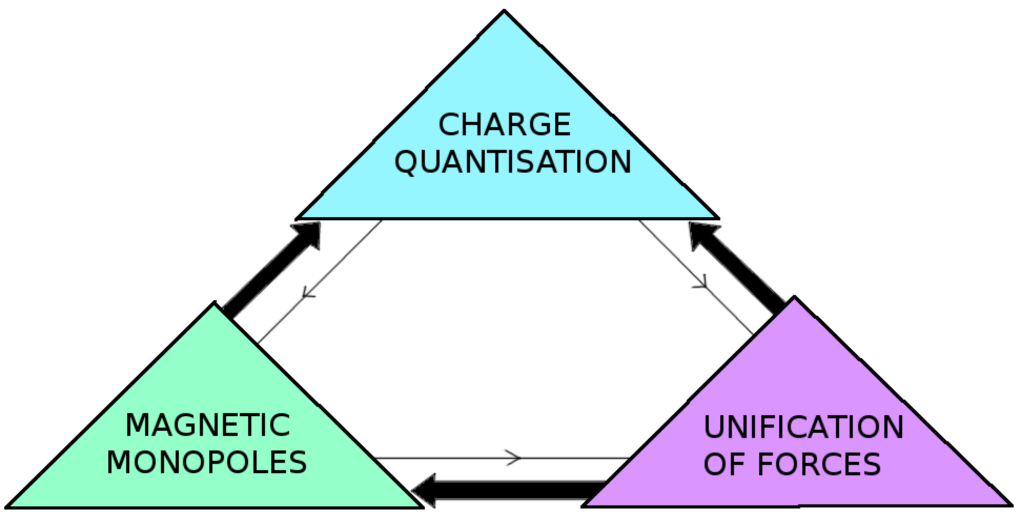
Present focus & Swiss involvement

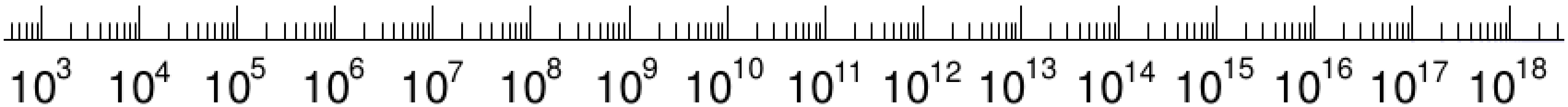
Magnetic monopoles

- Symmetrise Maxwell's equations
- Explain quantisation of electric charge (Dirac 1931)
  - Magnetic charge g_D equivalent to 68.5 electron charges
- Prediction of grand-unification theories ('Hooft 1974)



LHC reach

GUT monopole



Possible monopole mass range (GeV)

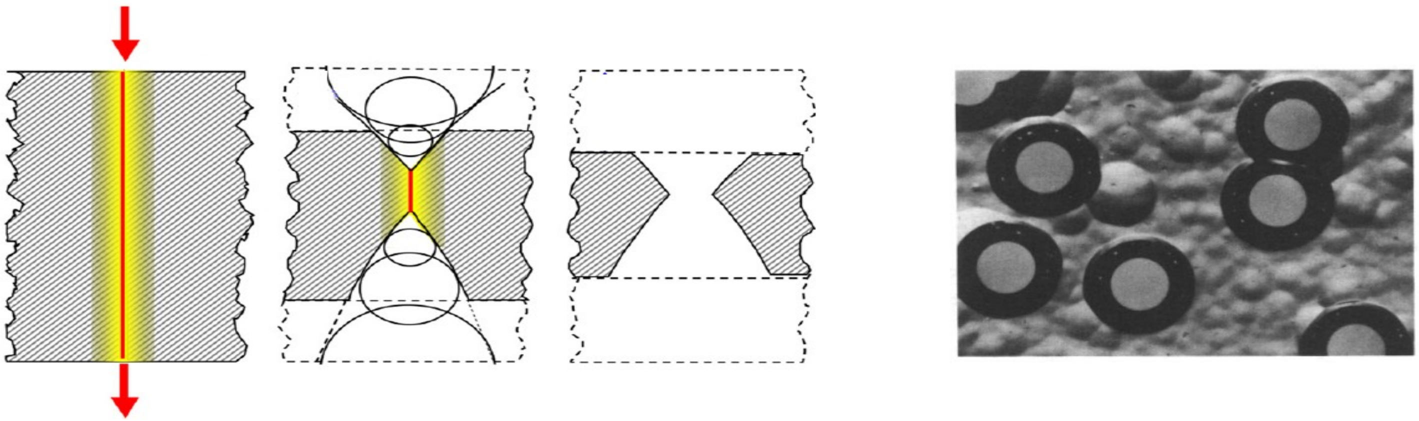
Strange quark matter

Aggregates of up, down and strange quarks could be more stable than ordinary matter

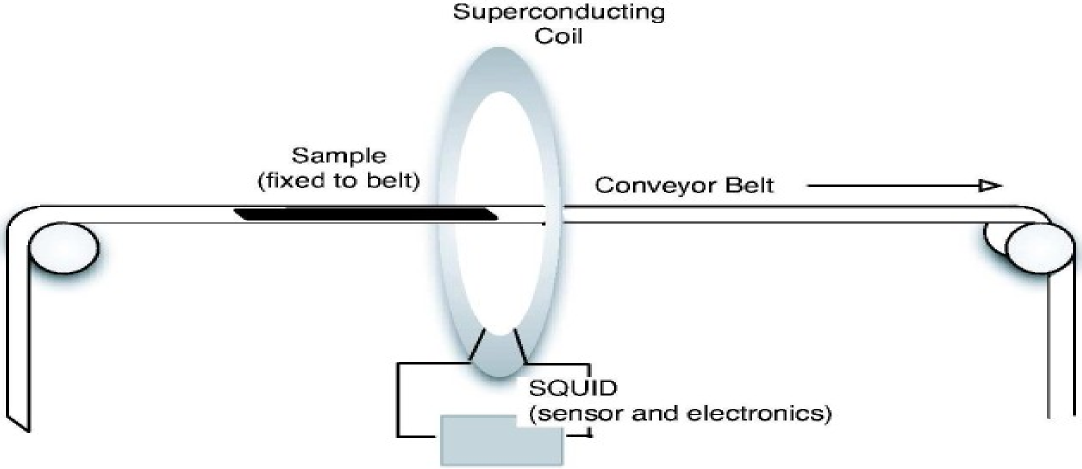
- Strangelets / quark nuggets / nuclearites (of nuclear density)
- Compact objects → dark matter without BSM physics
- Anti-quark nuggets possible
- Huge possible mass range, from GeV to solar mass
  → need variety of experimental approaches
- Electric charge $Z \simeq 0.3A^{2/3}$ (compensated by electrons)
- Atomic displacement along path for mass > 10^{-10} g

Relevant detection techniques

- Nuclear-track detectors (highly-ionising particles)



- Induction (monopoles)



Relevant detection techniques

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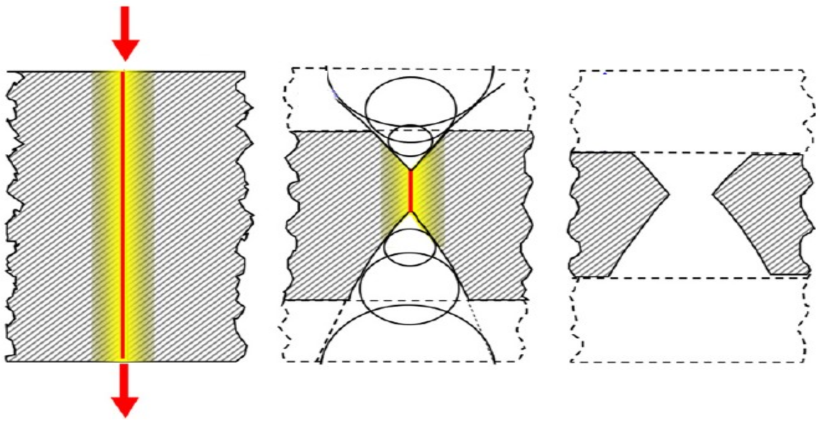
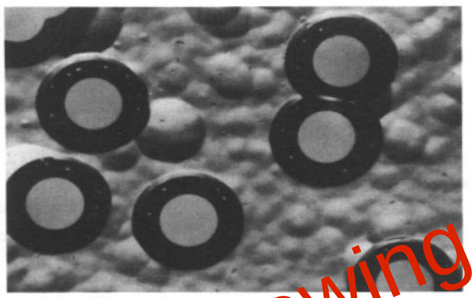
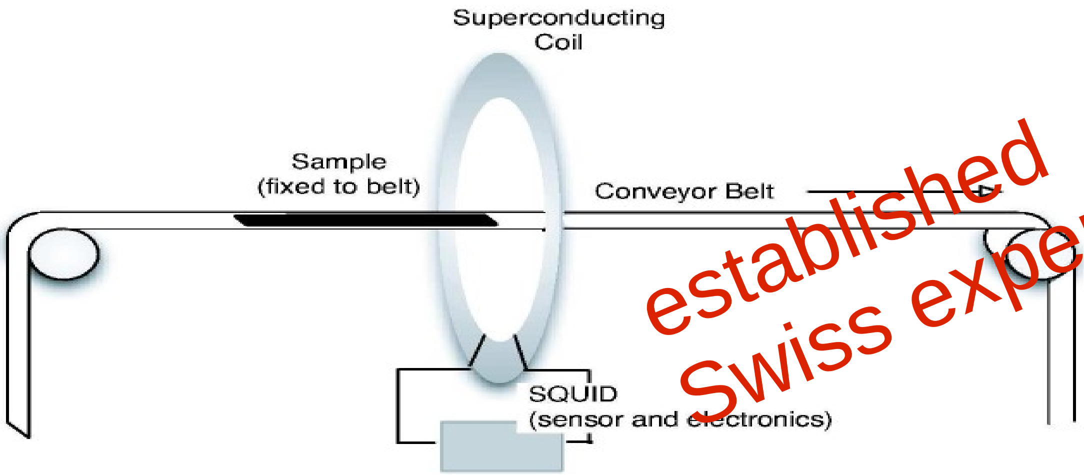




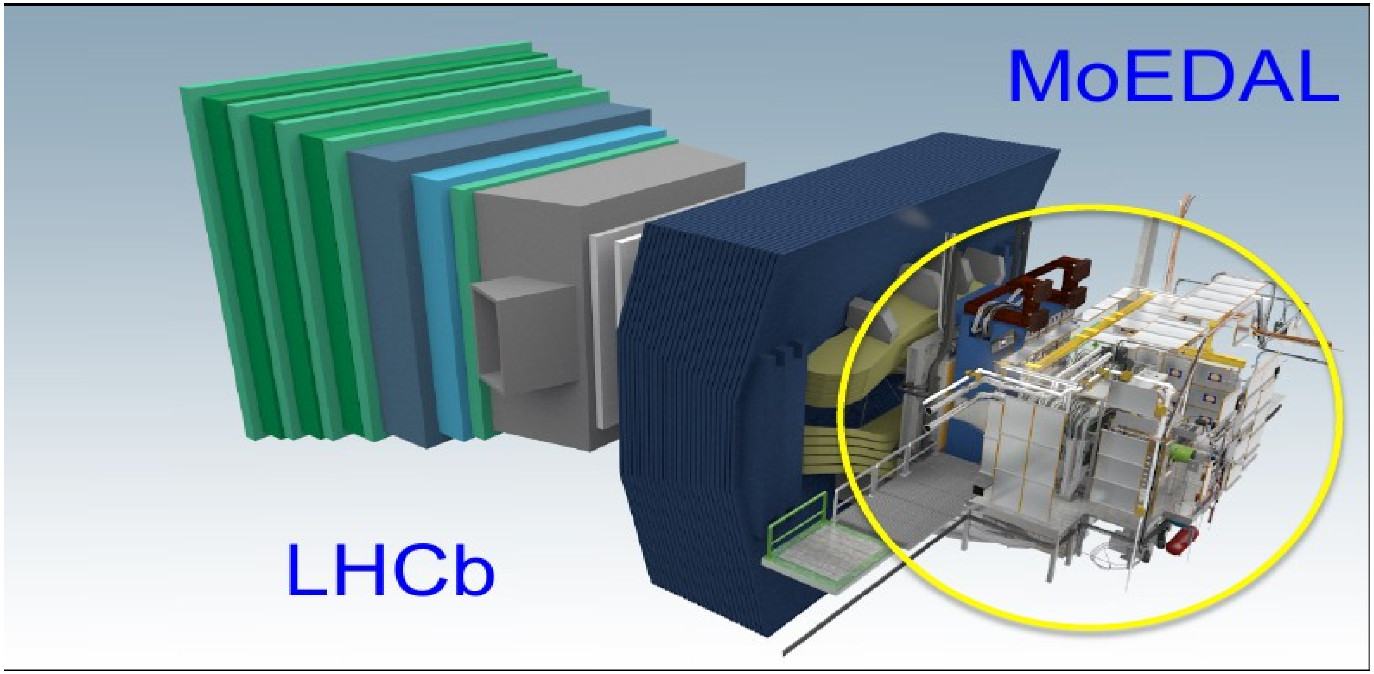
growing
Swiss expertise

- Induction (monopoles)



established
Swiss expertise

Highly-ionising particle searches at the LHC

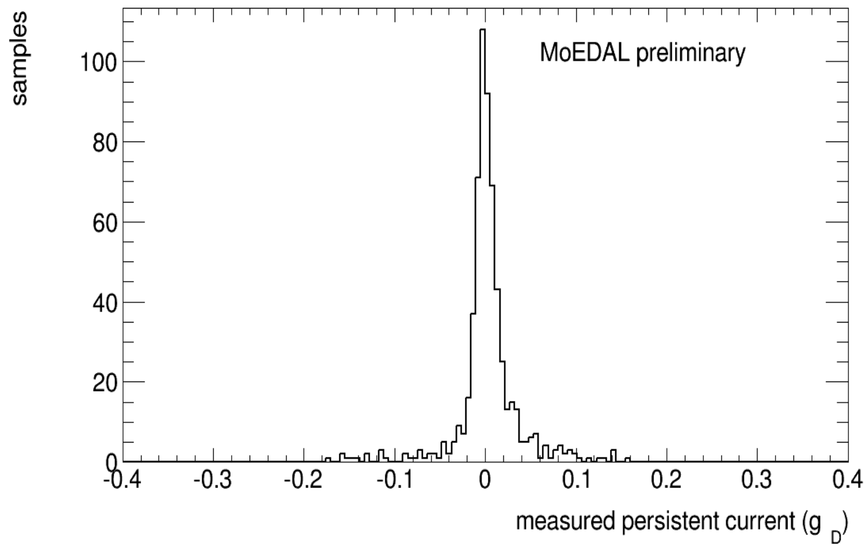


Nuclear-track detectors

Magnetic-monopole trapper

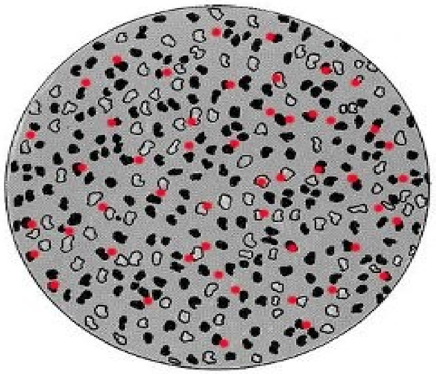
Trapped monopoles at the LHC
(work led by University of Geneva)

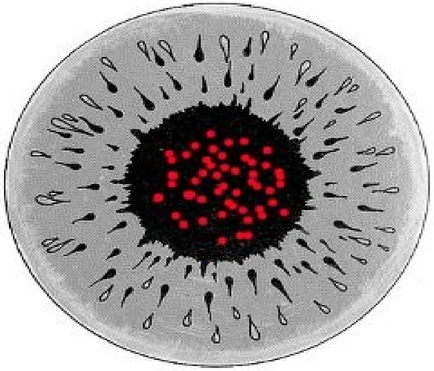
- Material exposed to 8 TeV collisions
  - Dedicated MoEDAL absorbing array
  - Beam pipes
- Superconducting magnetometer at Laboratory for Natural Magnetism (ETH Zürich)
  - Tests, calibrations, methods, physics measurements: done



EPJC 72, 2212 (2012)
arXiv:1311.6940 (2013)

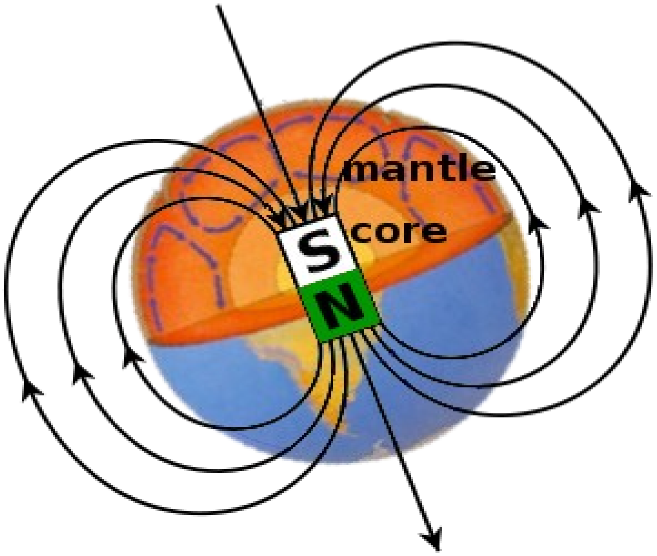
Trapped monopoles in polar rocks
(work led by University of Geneva)





Differentiation:

Monopoles heavier than the heaviest nuclei
→ absent from crust if present before the planet formed



Magnetic force exceeds gravitational force for

$M < 4 \cdot 10^{14}$ GeV (for $g = g_D$)

Over geologic time, accumulation in the mantle beneath the geomagnetic poles

Search for Magnetic Monopoles in Polar Volcanic Rocks

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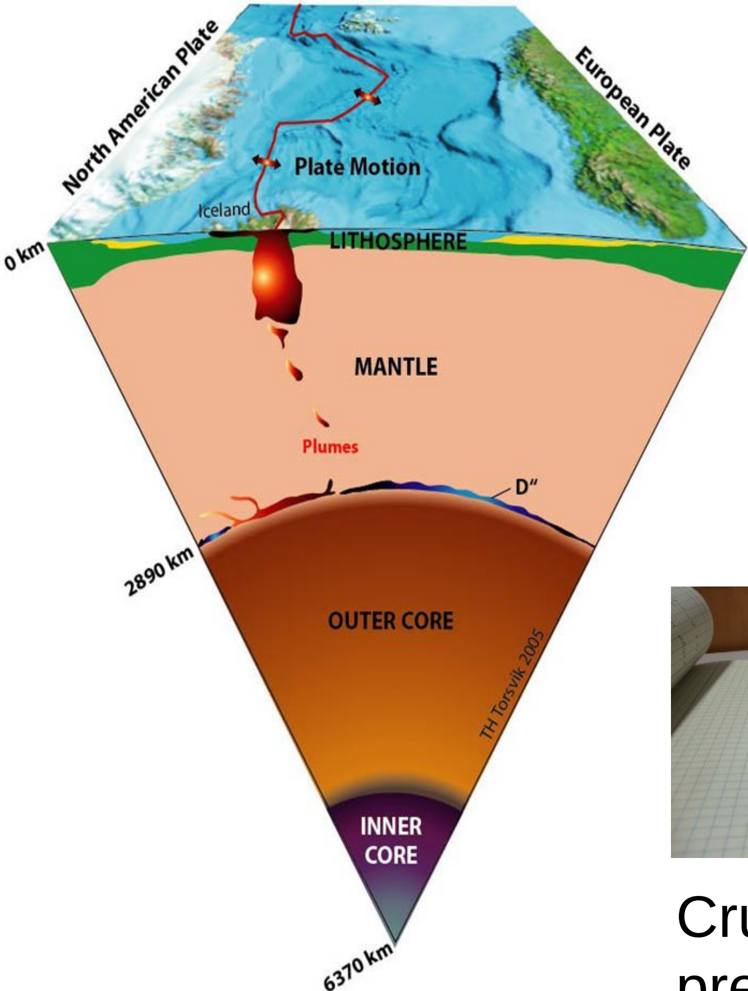
S. B. Thorarinsson
Nordic Volcanological Center, Institute of Earth Sciences, University of Iceland, 101 Reykjavik, Iceland
(Received 28 January 2013; published 22 March 2013)

For a broad range of values of magnetic monopole mass and charge, the abundance of monopoles trapped inside Earth would be expected to be enhanced in the mantle beneath the geomagnetic poles. A search for magnetic monopoles was conducted using the signature of an induced persistent current following the passage of igneous rock samples through a SQUID-based magnetometer. A total of 24.6 kg of rocks from various selected sites, among which 23.4 kg are mantle-derived rocks from the Arctic and Antarctic areas, was analyzed. No monopoles were found, and a 90% confidence level upper limit of 9.8×10^{-5}/g is set on the monopole density in the search samples.

DOI: 10.1103/PhysRevLett.110.121803 PACS numbers: 14.80.Hv, 91.25.−r, 91.35.Gf, 93.30.Li

Polar rock samples



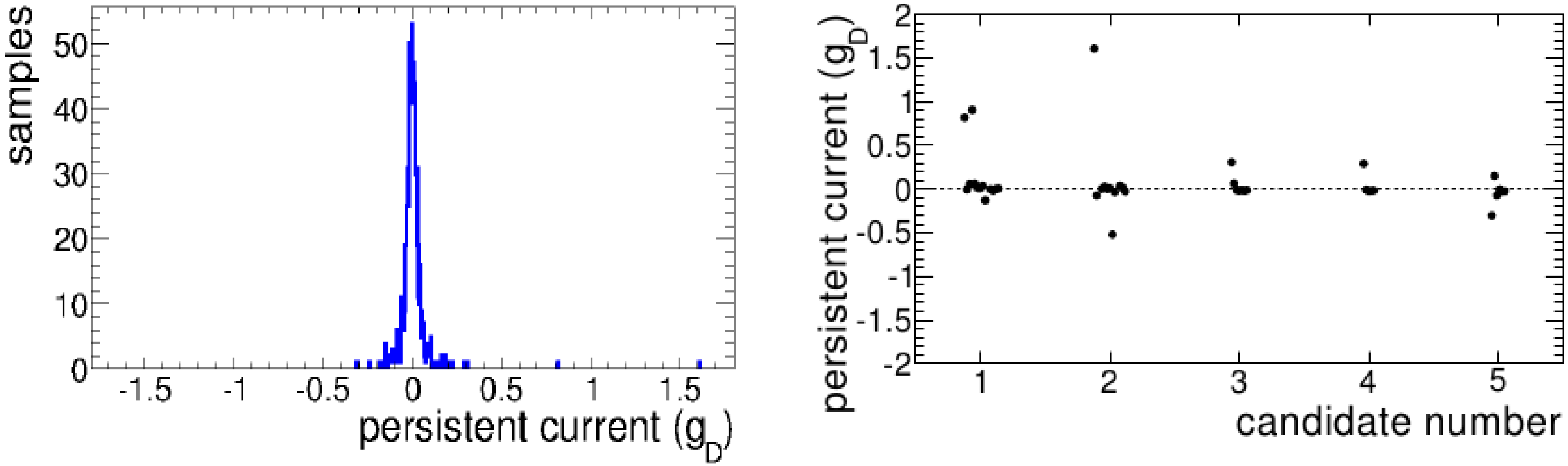
High latitude, mantle derived

- Hotspots
- Mid-ocean ridges
- Large igneous provinces
- Isotopic content indicating deep origins

Crushed to reduce magnetisation for precise magnetometer measurement

Polar rock results

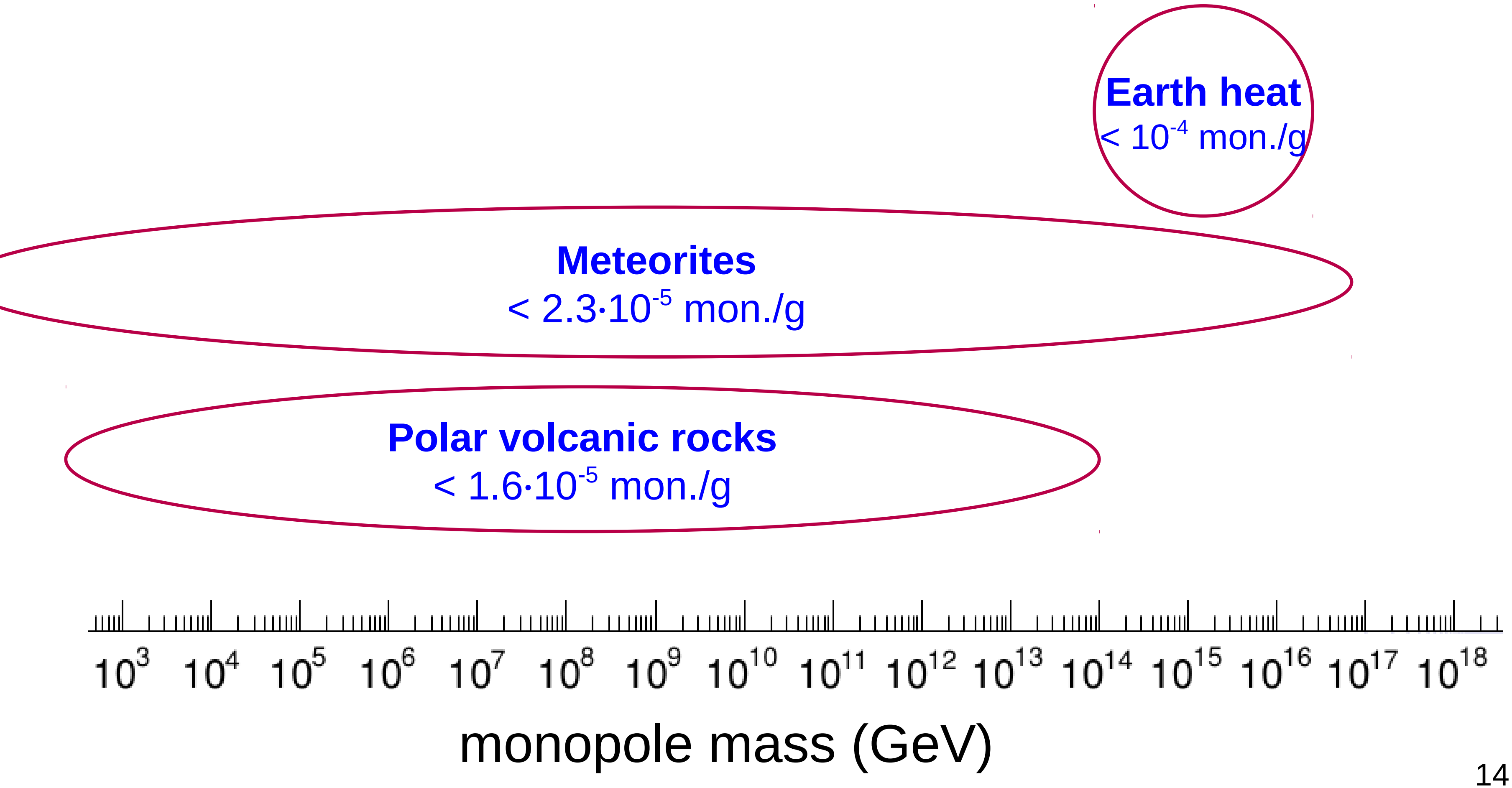
PRL 110, 121803 (2013), arXiv:1301.6530



No monopole found in 24 kg of polar volcanic rocks

– In simple model, translates into limit of less than 1.6 monopole per 100 kg in the Solar System

Limits on monopole density in the Solar System



Sort-term plans with induction technique

- New magnetometer to be installed in Zürich next year
  - Conveyor belt – even better for monopole searches
  - Tests and calibrations to be performed, automatic procedures to be developed
- Primordial monopole search aims
  - Improve sensitivity by factor 5-10
    - >100 kg of polar rocks
    - >100 kg of meteorites
  - Feasibility will depend on performance of new instrument

Cosmic monopoles and nuclearites: MACRO (2002)

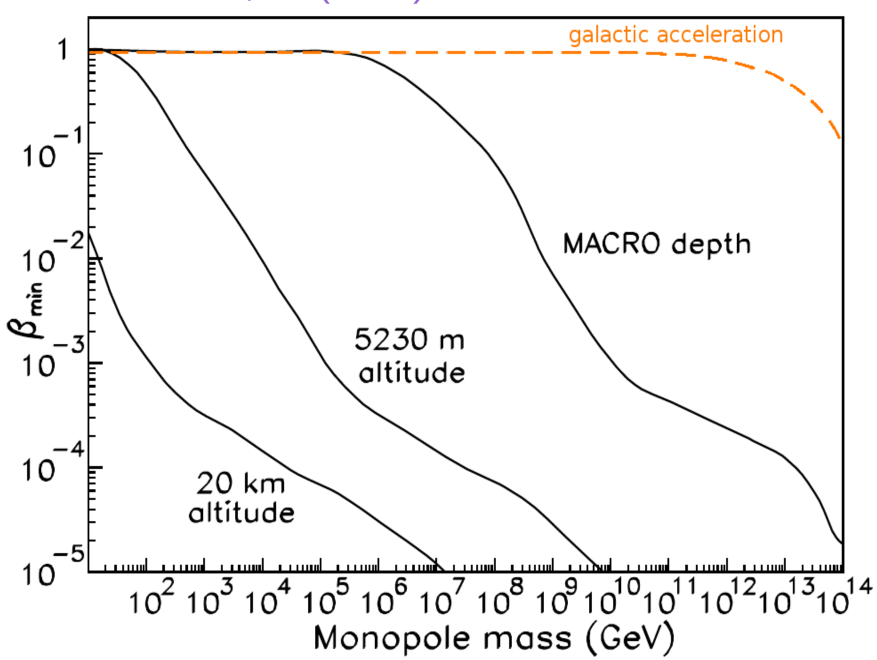
- 1400 m underground
- 1000 m^2, 10 m height
- 5 years exposure
- Various detection techniques:
  - Scintillator (time-of-flight): $0.0001 < \beta < 0.01$
  - Scintillator (dE/dx): $0.001 < \beta < 0.1$
  - Streamer tubes: $0.0001 < \beta < 0.01$
  - Nuclear track: $0.001 < \beta < 1$
- $F < 10^{-16}\ cm^{-2}s^{-1}sr^{-1}$

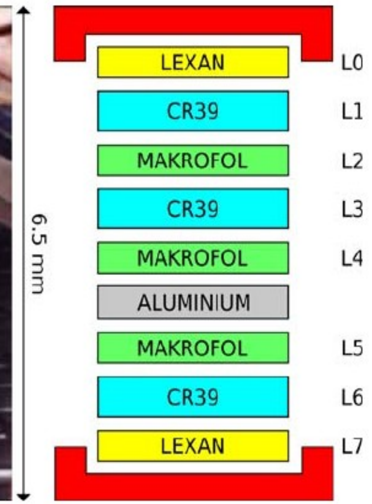
EPJC 25, 511 (2002)

Cosmic monopoles and nuclearites: SLIM (2008)

- 5230 m altitude
  (Chacaltaya observatory)
- 400 m^2
- 4 years exposure
- F < 10^{-15} cm^{-2}s^{-1}sr^{-1}

EPJC 55, 57 (2008)





Ancient mica
(1969 – 1990)

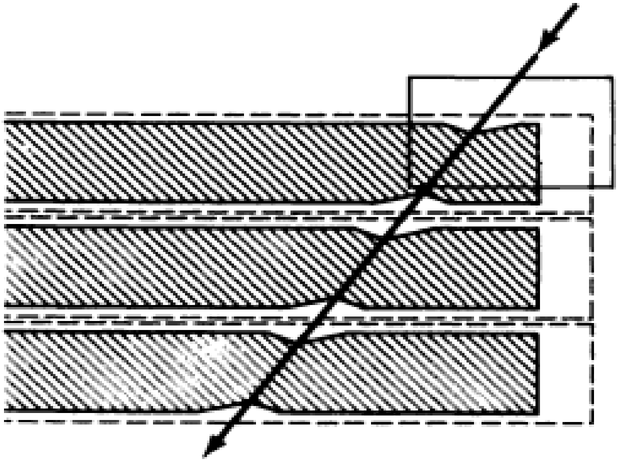
> 500 millions years exposure time!

Track guaranteed if:

- Nuclearite mass > 10^{-10} g
- Monopole $\beta > 0.9$ and $g \geq 2g_D$
- Monopole $\beta \sim 10^{-3}$ captured a nucleus on its way through the rock

Analysed total of ~40x40 cm^2 of very old crystals

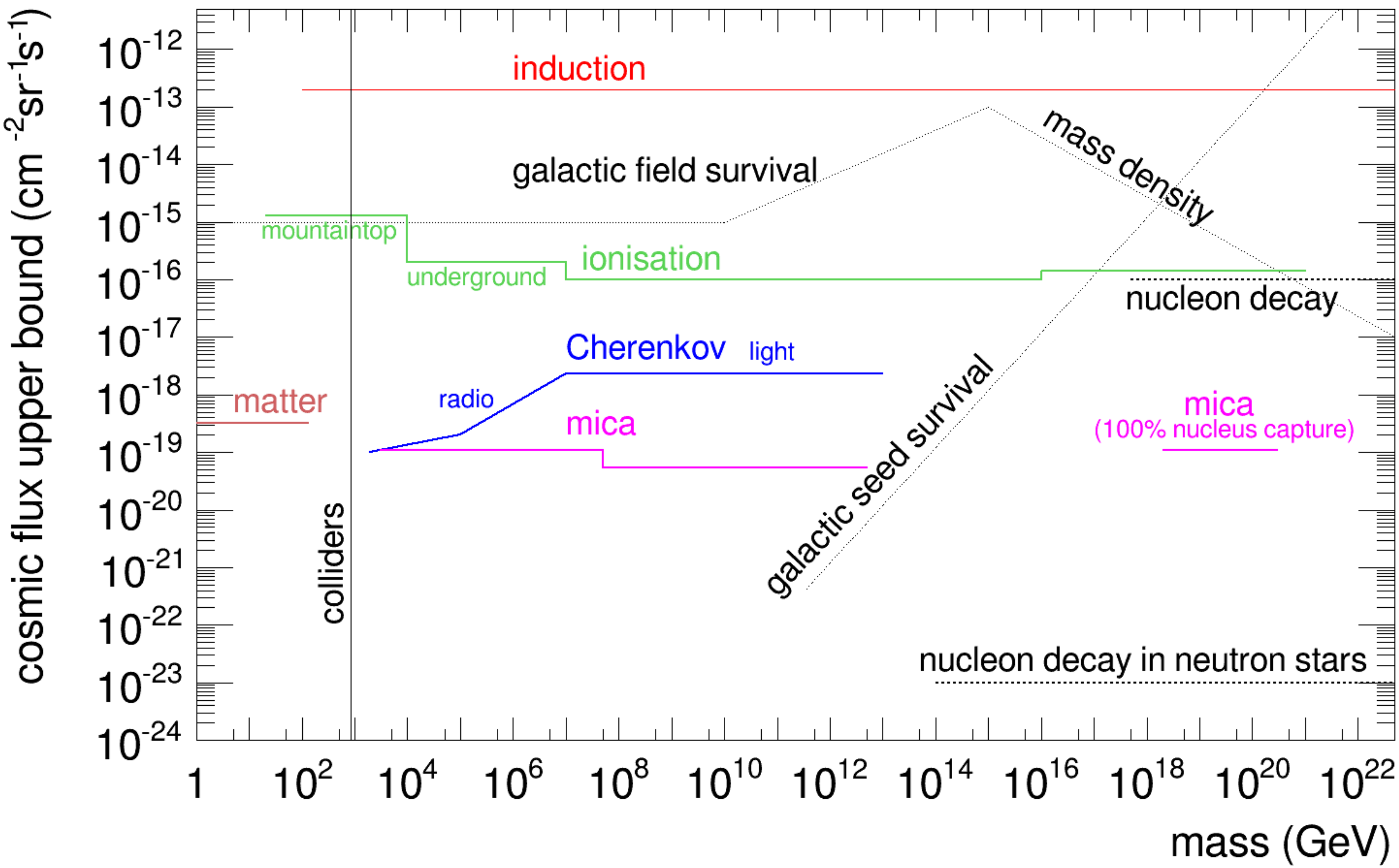
$F < 5 \cdot 10^{-20}\ cm^{-2}s^{-1}sr^{-1}$



PR 184, 1398 (1969)
PRL 52, 1265 (1984)
PRL 56, 1226 (1986)
PRD 38, 3813 (1988)
EPL 12, 25 (1990)

Cosmic flux limits – monopoles

assuming $E_{kin} = 10^{13}$ GeV, expected from acceleration in galactic magnetic fields



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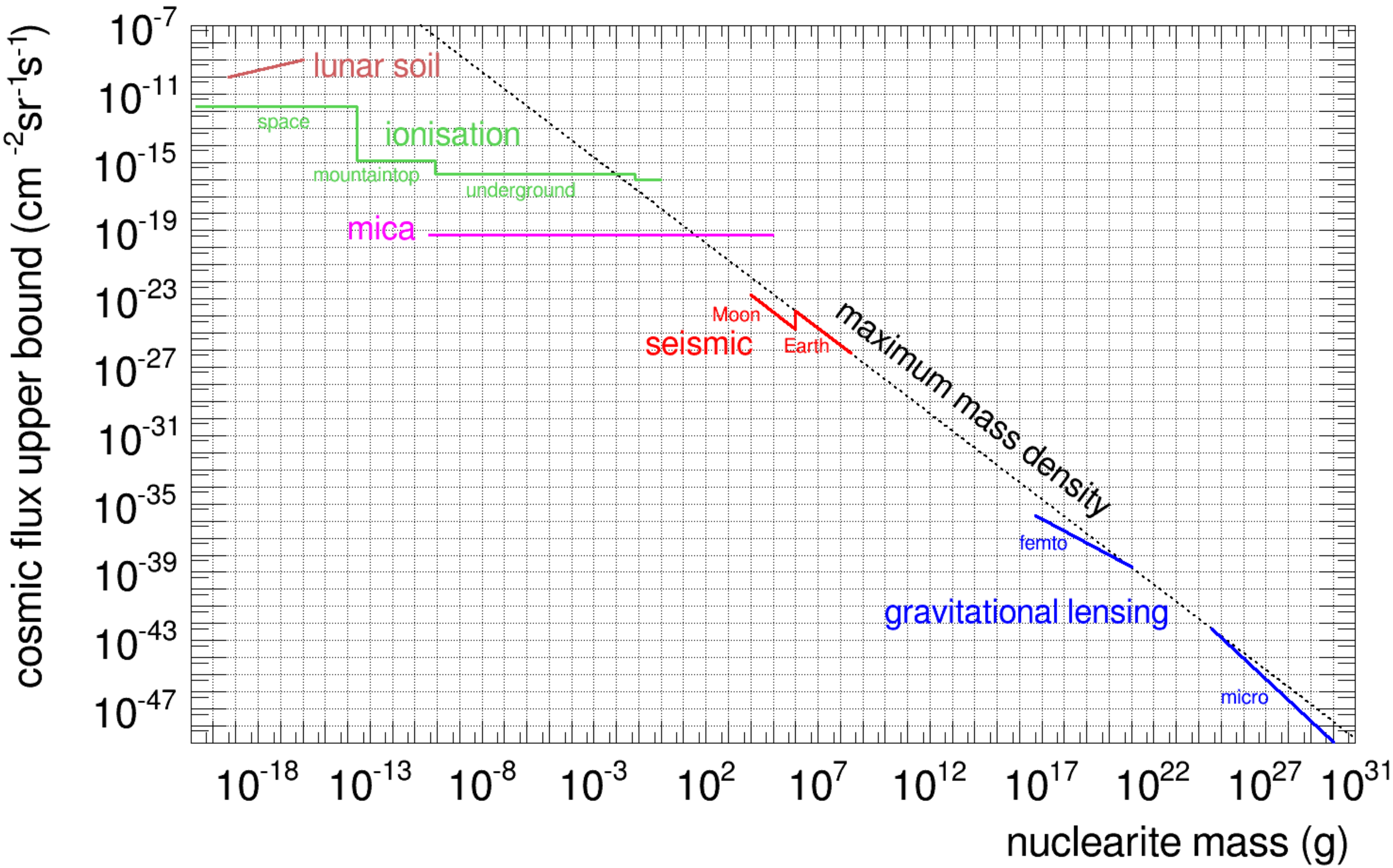


Sort-term plans with nuclear-track detectors

- MoEDAL will acquire ~10 high-performance modern scanning microscopes
  - Sub-micron precision at > 100 cm² / hour
  - Even faster in low-resolution mode with automatic pattern-recognition procedure
  - Other advantages of machine vision: high contrast, triangulation-based 3D imaging, digital data storage
  - All this was not available in the 1980s!
- Heavy-ion beam calibrations
  - Brookaven NSRL beamline
  - GANIL beams provide the right ionisation to test mica response → establish sensitivity to relativistic $g = g_D$
- Possible new cosmic-ray searches:

  10 km² array → gain factor 10

  150 m² ancient mica → gain factor 1000

WIMP dark matter with ancient mica

- Nuclear recoils from WIMP interactions would leave detectable ~ 1 μm tracks in mica
  - Advantages: unique target nuclei (Al, K), very long exposure time, potentially probe structure of dark-matter halo
  - Disadvantages: need very good depth resolution, backgrounds from alpha and neutron-induced recoils
- Analysis of 0.1 mm^2 with atomic force microscopy set limit 10^{-31} cm^2 on WIMP cross section (PRL 74, 4133 (1995))
  - 150 m^2 mica → bring down the sensitivity to ~10^{-40} cm^2 (region of DAMA/CoGeNT/CRESST)
  - ➔ Can this possibly be done with an optical microscope using the power of modern machine vision?

Summary

- Monopoles, *Q*-balls, strange quark matter
  - Motivated by fundamental arguments and can potentially explain dark matter
- Searches in polar rocks using superconducting magnetometers in Zürich
  - Best constraints on monopole density in material that formed the Solar System
- Proposed future search with 12x12 m^2 of ancient mica using modern scanners
  - Improve monopole limits by factor 1000 and establish sensitivity to relativistic singly-charged monopoles
  - Probe nuclearites in mass range 0.1-100 kg for the first time (dark-matter candidate!)
  - Possibility of completely new and independent WIMP investigation

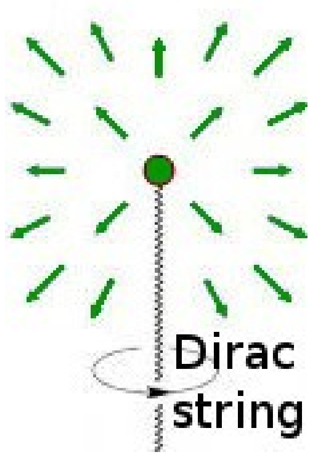
Extra material

“MONOPOLES” IN CONDENSED-MATTER SYSTEMS

Spin ice: quasi-particles resembling monopoles
(but N cannot be separated from S)

Superfluids: B* field mathematically analogous to magnetic field

- Observation of B*-pole → example of quantum-field representation of monopole



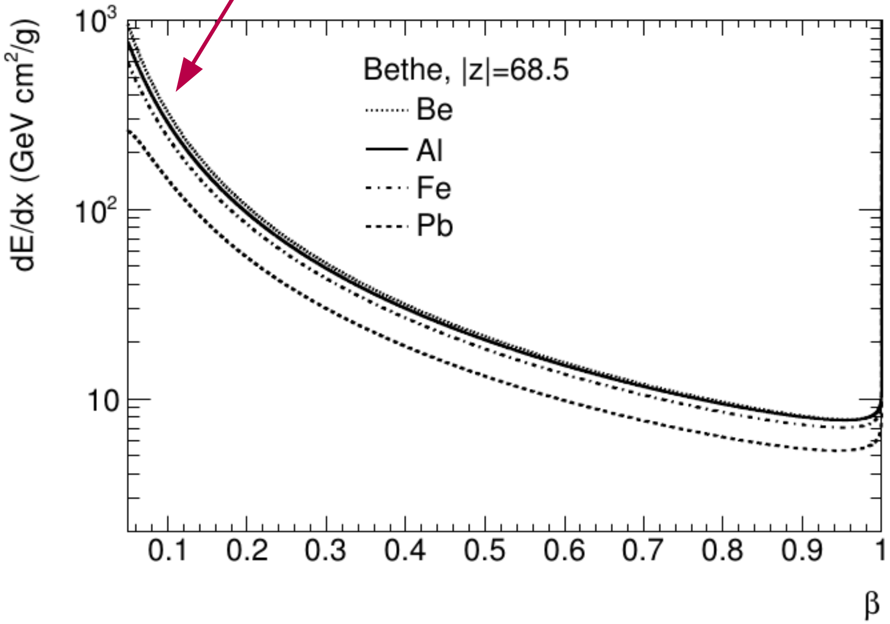
Monopole ionisation energy loss

Electric

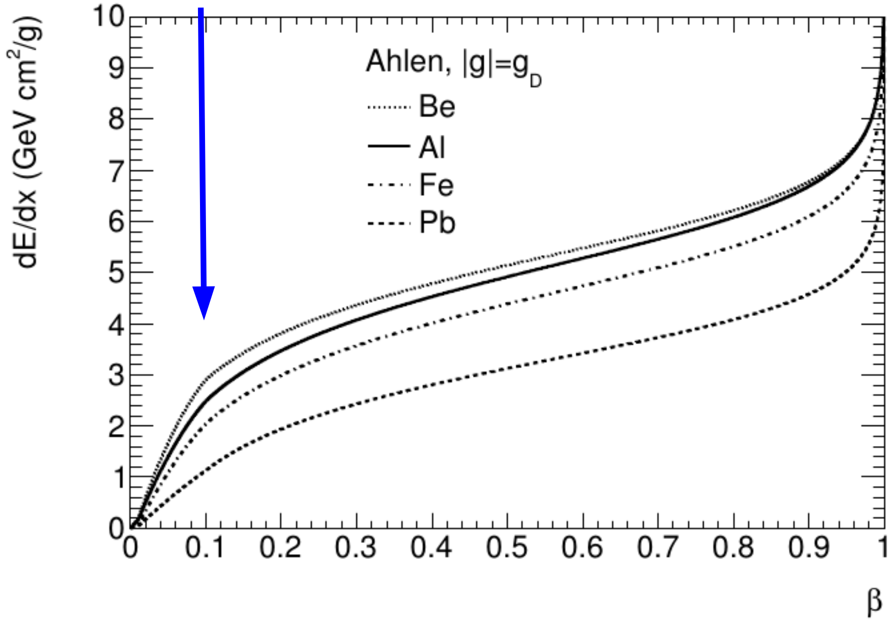
$$-\frac{\mathrm{d}E}{\mathrm{d}x} = K\frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\frac{2m_ec^2\beta^2\gamma^2}{I} - \beta^2\right]$$

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!

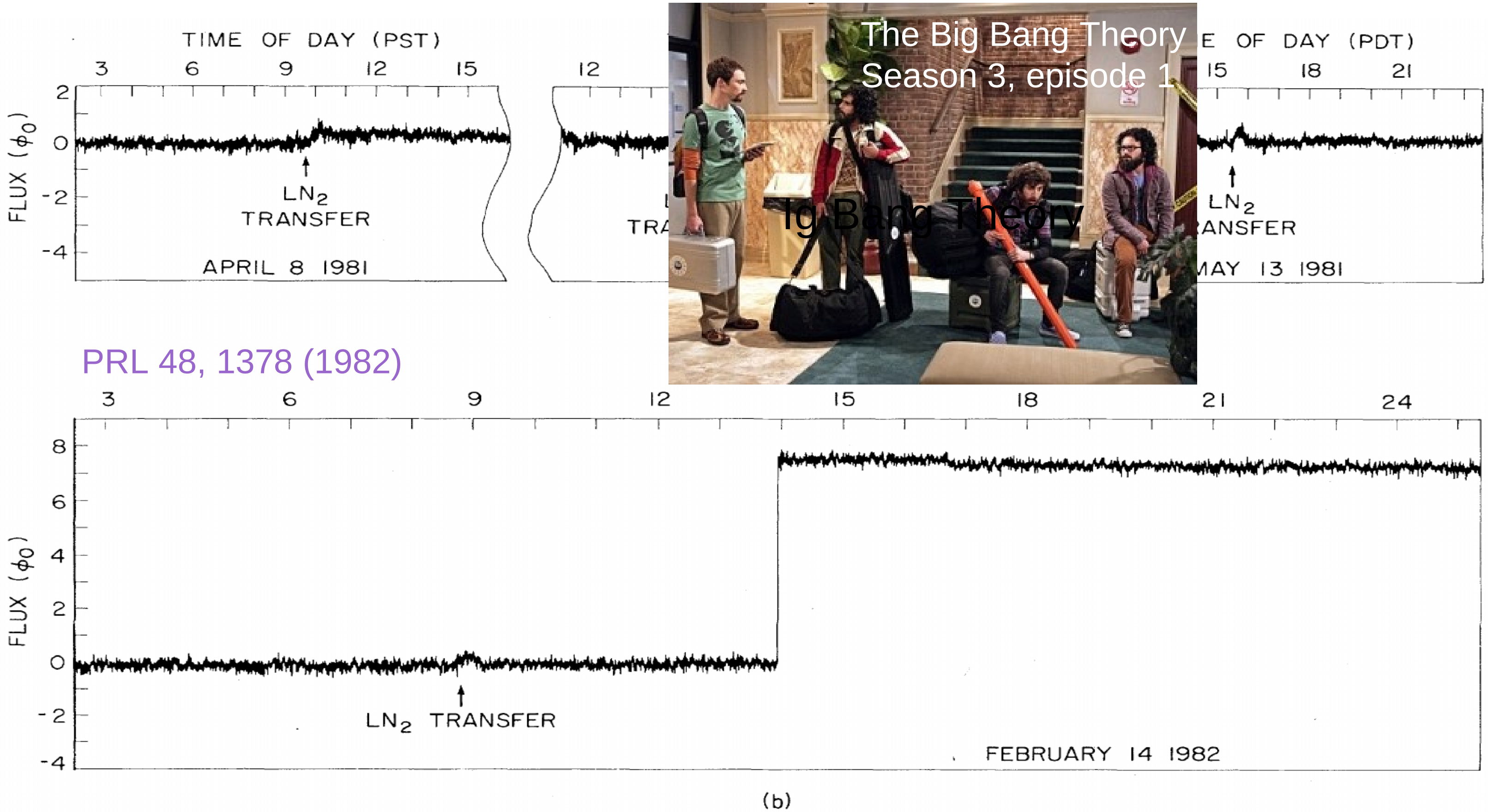


Dirac monopole: $|g_D| = 68.5$ → several thousand times greater d*E*/d*x* than a minimum-ionising |z|=1 particle

THE FAMOUS “CABRERA EVENT”
(induction detector, 1982)

Sudden flux jump with magnitude g_D

– monopole passage... or spurious offset?



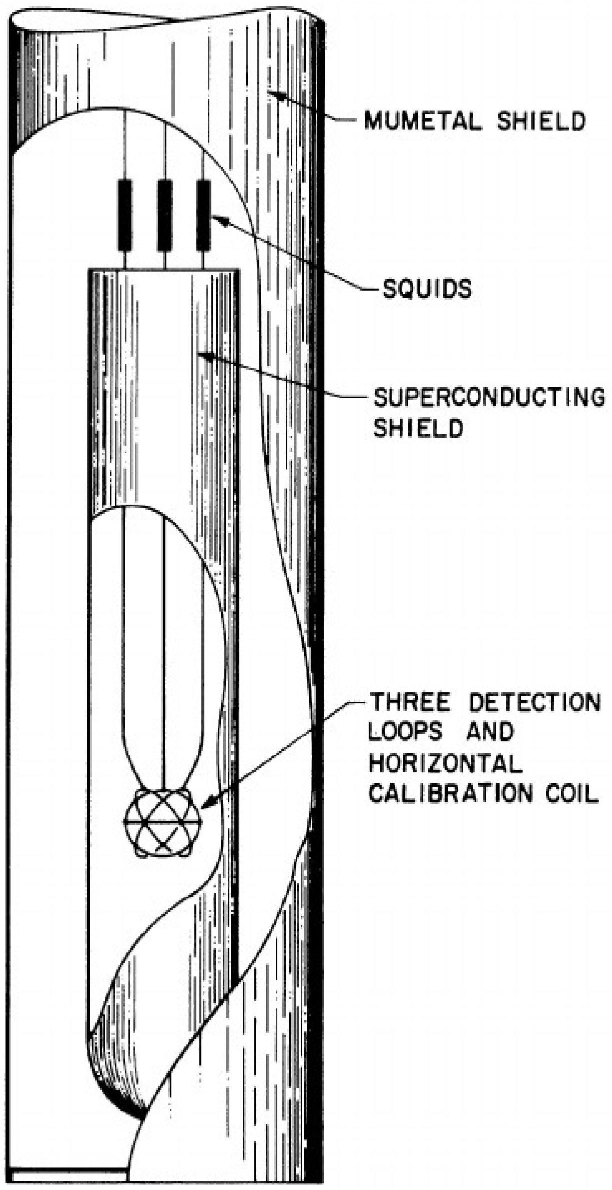
PRL 48, 1378 (1982)

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

INDUCTION DETECTORS
(1982 – 1991)

- Response depends only on magnetic charge → can probe very low velocities / high masses
- ~ 1 year exposure
- Limited to ~ 1 m^2 area
- Need multiple loops in coincidence
  (initial Cabrera apparatus had only 1 loop)
- $F < 2 \cdot 10^{-13}\ cm^{-2} s^{-1} sr^{-1}$

PRL 64, 835 (1990)
PRL 64, 839 (1990)
PRD 44, 622 (1991)
PRD 44, 636 (1991)



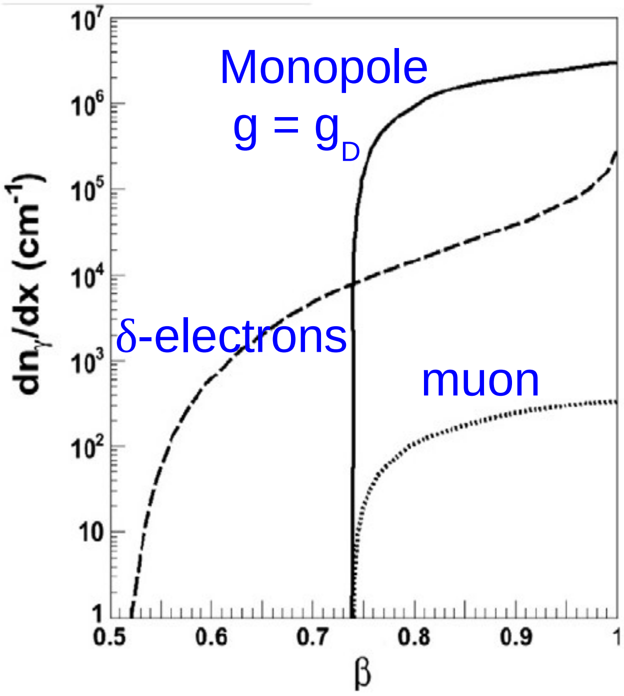
NEUTRINO OBSERVATORIES
(2008 – 2013)

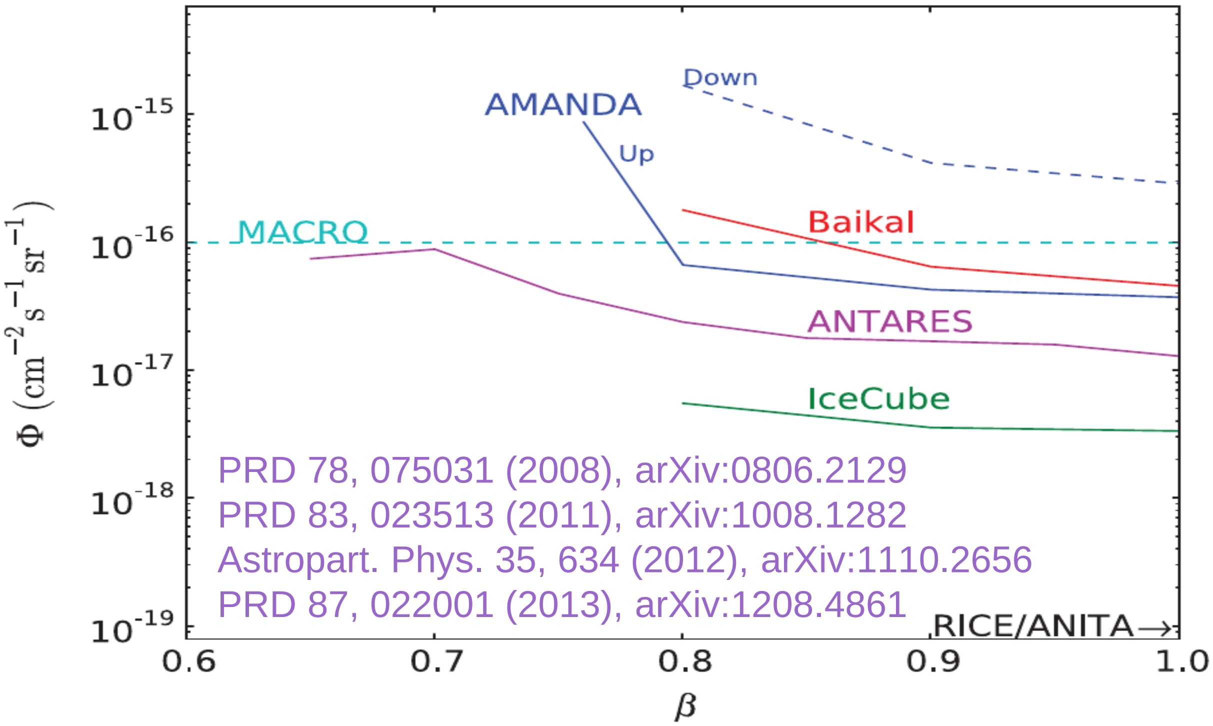
Relativistic monopoles

→ copious Cherenkov radiation

Sensitivity to upward signals

→ extreme energies

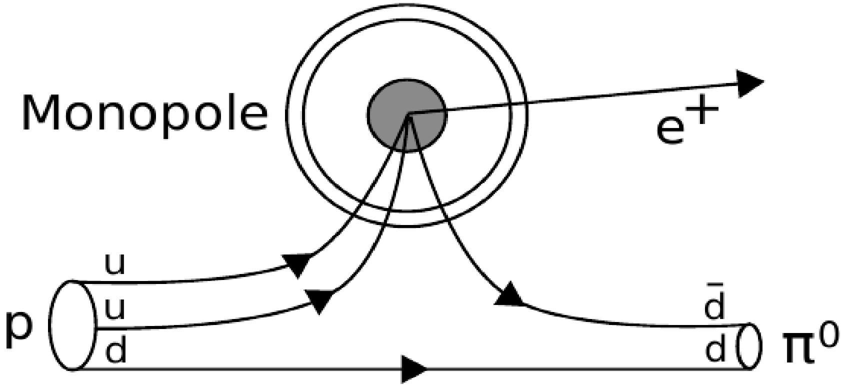




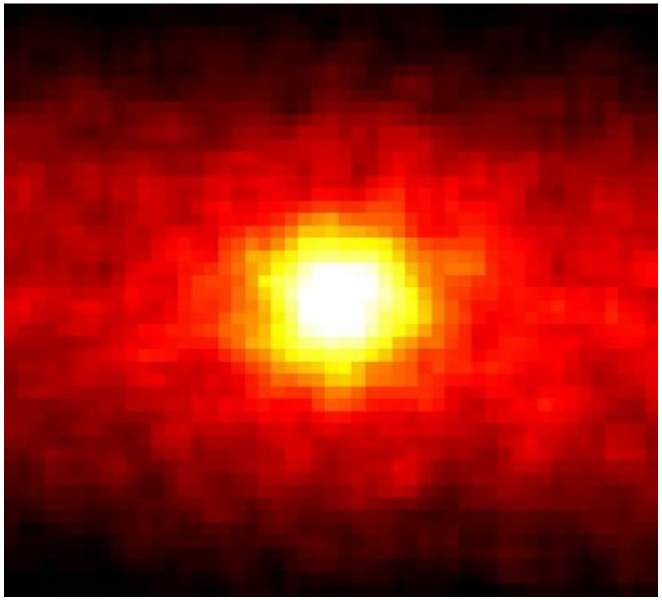
PRD 78, 075031 (2008), arXiv:0806.2129
PRD 83, 023513 (2011), arXiv:1008.1282
Astropart. Phys. 35, 634 (2012), arXiv:1110.2656
PRD 87, 022001 (2013), arXiv:1208.4861

CATALYSIS OF PROTON DECAY

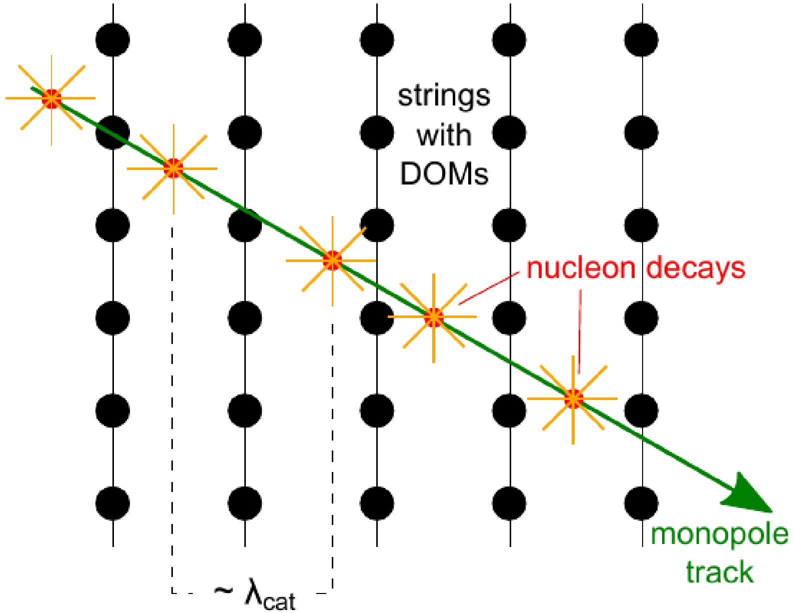
- GUT monopoles
- $\beta \sim 10^{-3}$
- $\sigma \sim 100$ mb



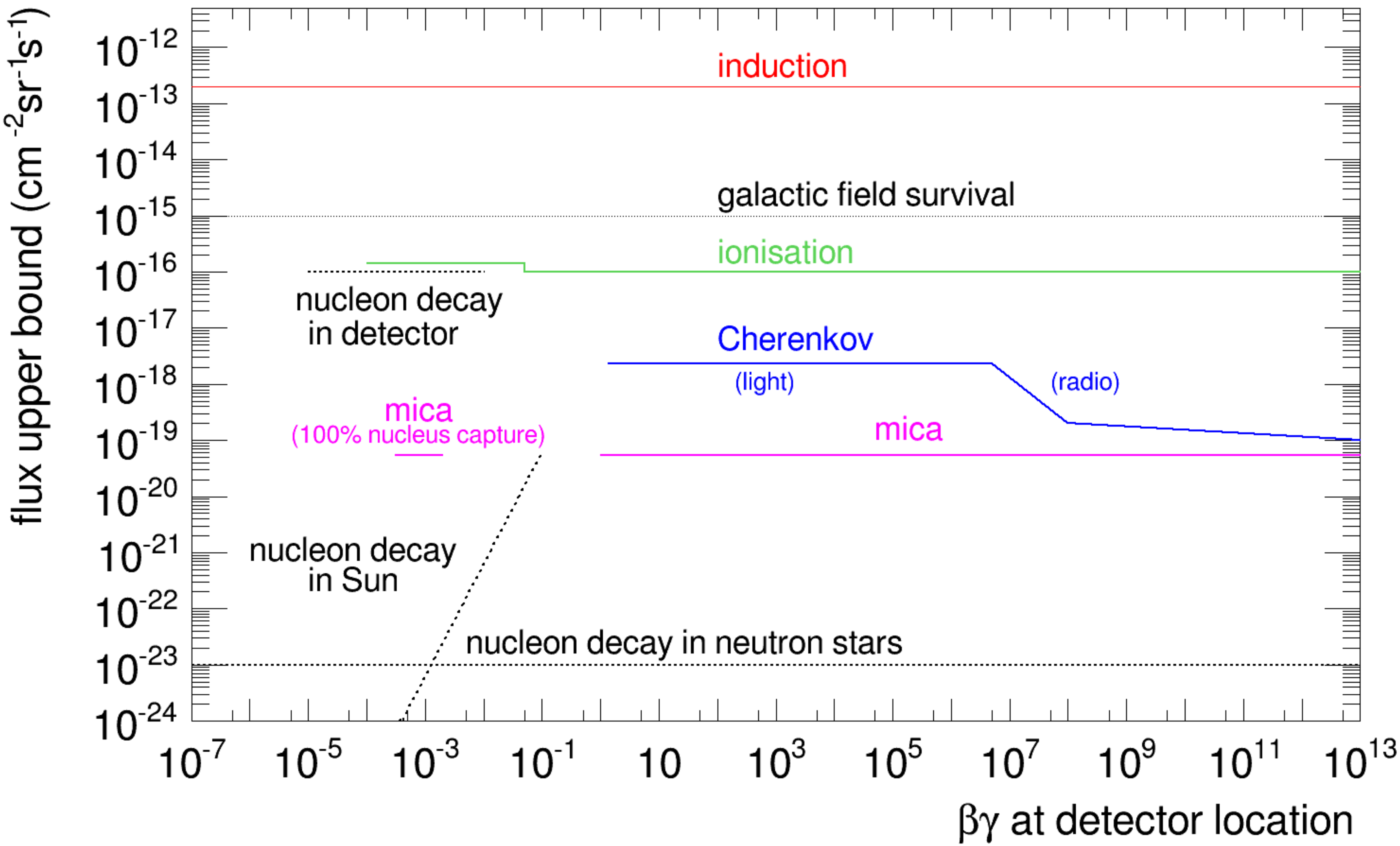
Superkamiokande (2012)



IceCube (2014)



COSMIC FLUX LIMITS – SUMMARY 1



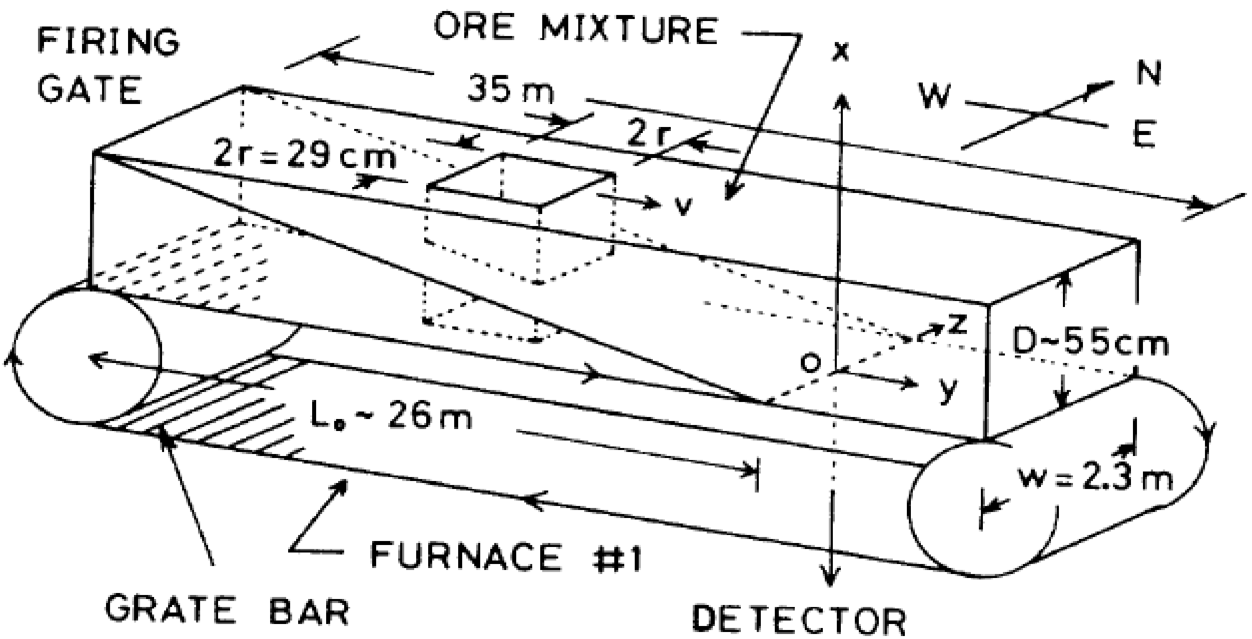
Iron ore (induction)

Superconducting coil placed under a furnace where iron ore Is heated to 1300 ^{o}C

- Large amounts (>100 tons) of material
- Assume ferromagnetic binding

Must also assume no binding to nuclei!

PRD 36, 3359 (1987)



EARTH HEAT
(1980)

Nature 288, 348 (1980)

Heat from monopole-antimonopole annihilations during geomagnetic reversals

→ limit $\rho < 10^{-4}$ mon./g

Must assume mass ~10^{16} GeV and:

- Stable dipole magnetic field when no reversal
- Monopoles and anti-monopoles both present