Magnetic Monopoles at the LHC and in the Cosmos

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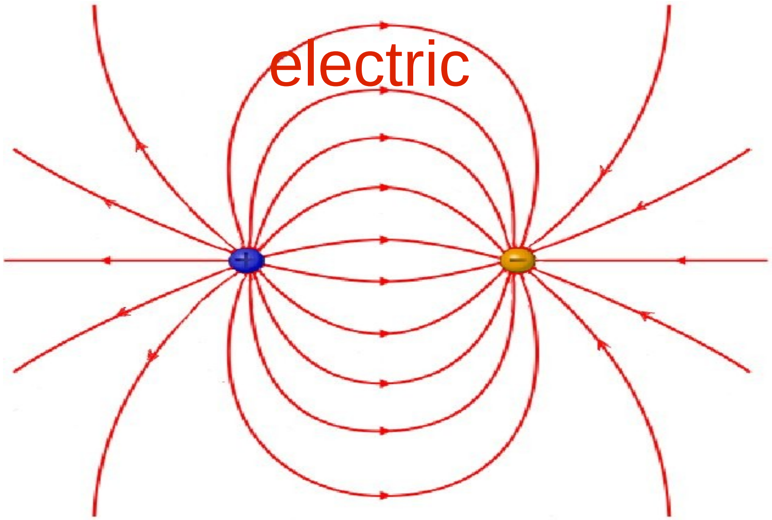
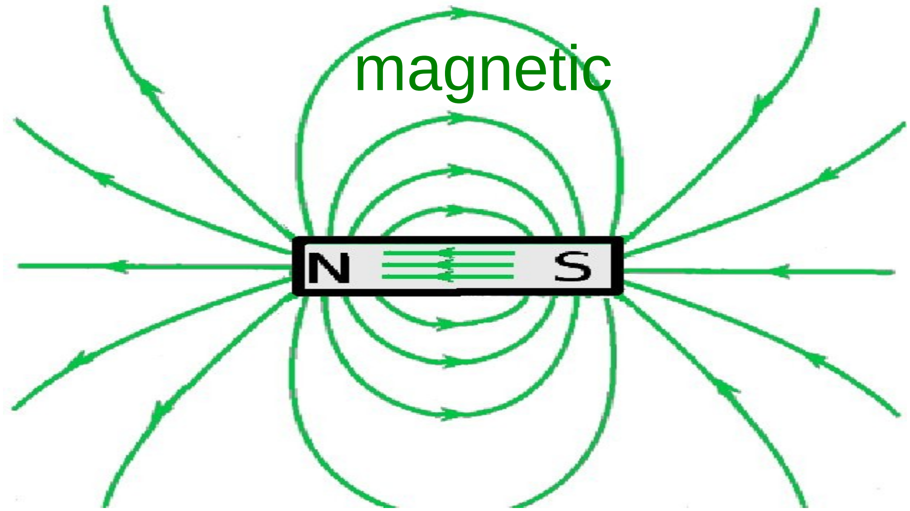
particle physics seminar

University College London

16 May 2014

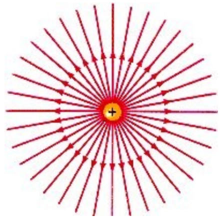
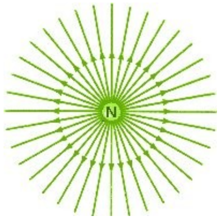
MONOPOLE – THE BASICS

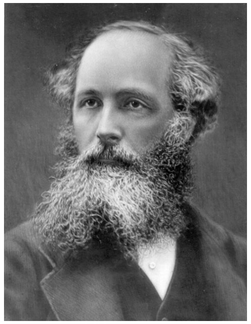




Sources of electric field exist (electrons, protons...)

- Are there magnetic equivalents?

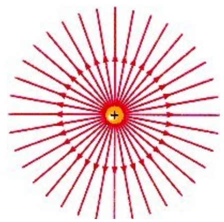
proton  magnetic monopole 



MAXWELL
(1862)

Without monopoles

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



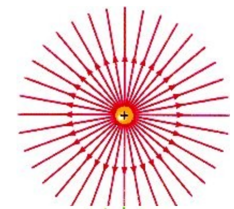
$$\nabla \cdot \mathbf{B} = 0$$

$$-\nabla \times \mathbf{E} = \frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi}{c}\mathbf{j_e}$$

With monopoles

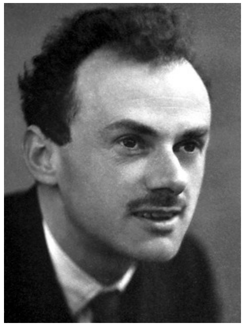
$$\nabla \cdot \mathbf{E} = 4\pi\rho_e$$



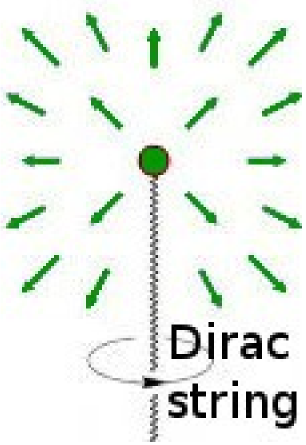
$$\nabla \cdot \mathbf{B} = 4\pi\rho_m$$

$$-\nabla \times \mathbf{E} = \frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} + \frac{4\pi}{c}\mathbf{j_m}$$

$$\nabla \times \mathbf{B} = \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi}{c}\mathbf{j_e}$$



DIRAC
(1931)



Proc. Roy. Soc. A 133, 60 (1931)

Valid quantum-field theory formulation

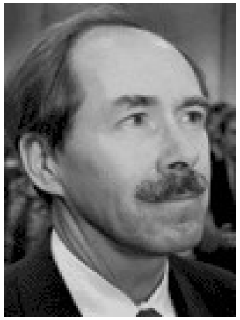
Side result: $$q_e q_m = n\frac{h}{\mu_0} \quad (n \text{ integer number})$$

- explains quantisation of electric charge!
- Fundamental magnetic charge g_D = 68.5 (with $q_m = gec$ and n = 1)
- Very high ionisation energy loss

PR 144, 1087 (1966)

Schwinger generalised Dirac's relation to dyons

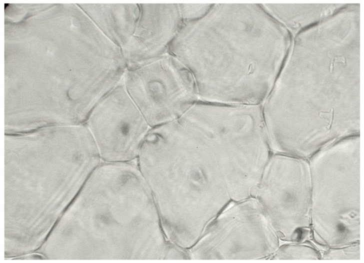
$$q_{e1}q_{m2} - q_{e2}q_{m1} = 2n\frac{h}{\mu_0} \quad (n \text{ integer number})$$



't HOOFT AND POLYAKOV
(1974)

Nucl. Phys. B 79, 276 (1974); JETP Lett. 20, 194 (1974)

U(1) group of electromagnetism is a subgroup of a broken gauge symmetry



- Topological solutions of the field equations.
  Very general result!
- Minimum magnetic charge g_D or $2g_D$ (depending on model)
- Mass ~ 10^{16} GeV (unification scale)

Cho and Maison demonstrated that monopole solutions are allowed in the electroweak theory itself

- Charge $2g_D$
- Mass ~ few TeV

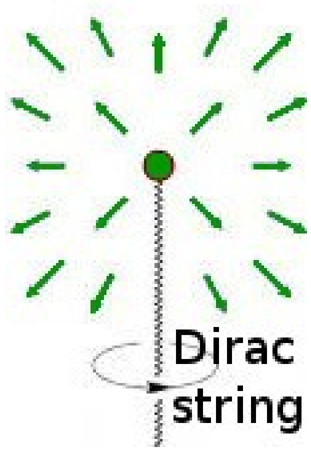
PLB 391, 360 (1997), arXiv:hep-th/9601028

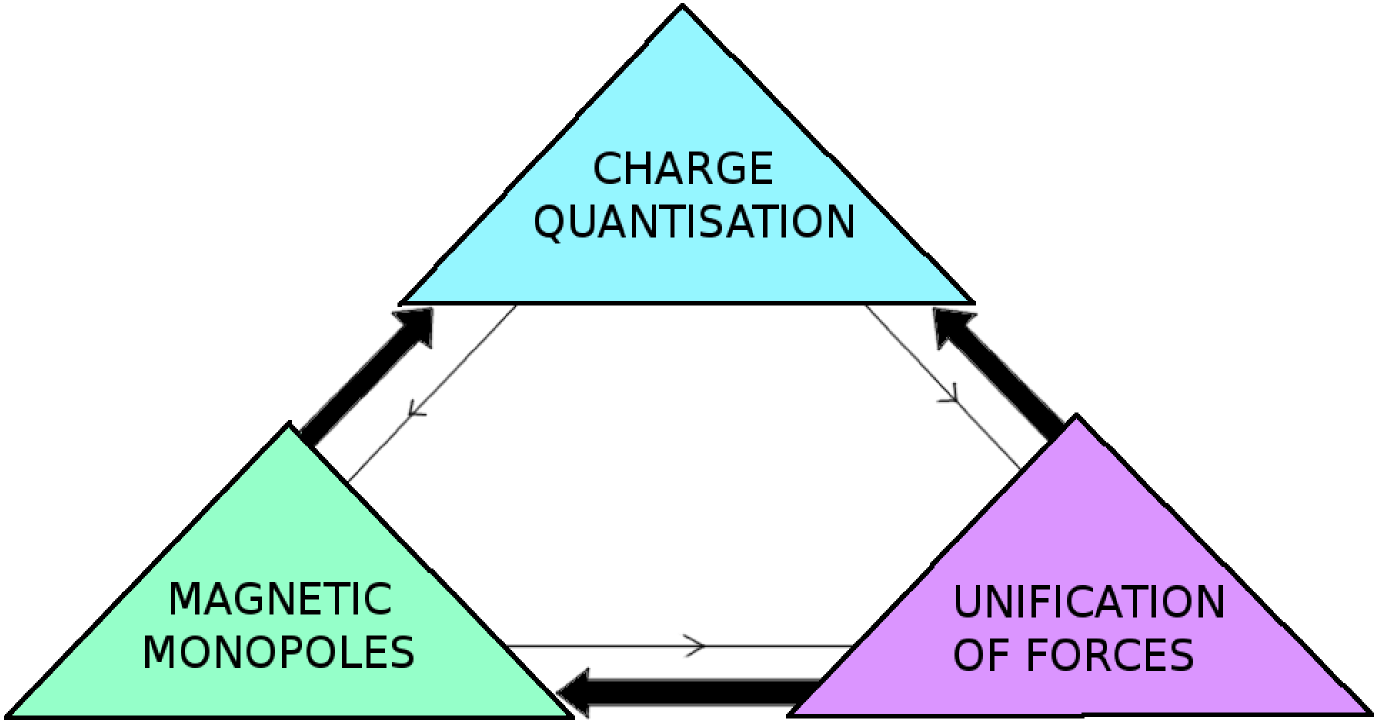
“MONOPOLES” IN CONDENSED-MATTER SYSTEMS

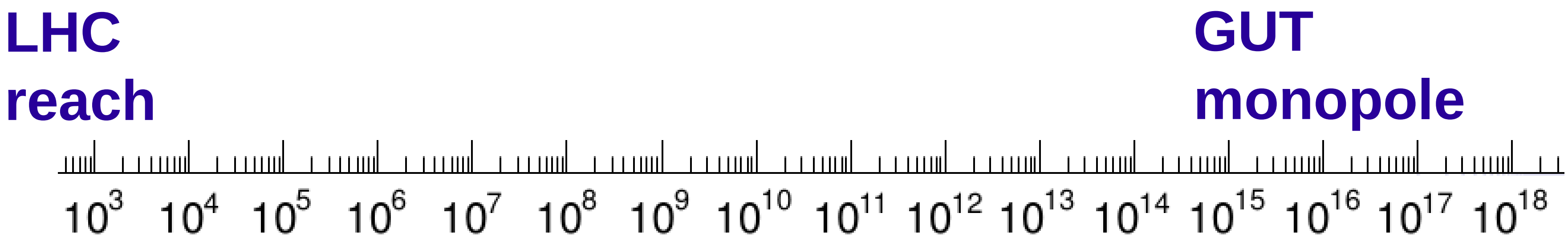
Spin ice: quasi-particles resembling monopoles
(but N cannot be separated from S)

Superfluids: B* field mathematically analogous to magnetic field

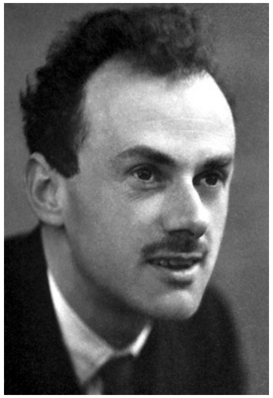
- Observation of B*-pole → example of quantum-field representation of monopole

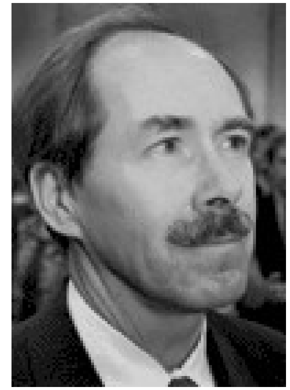
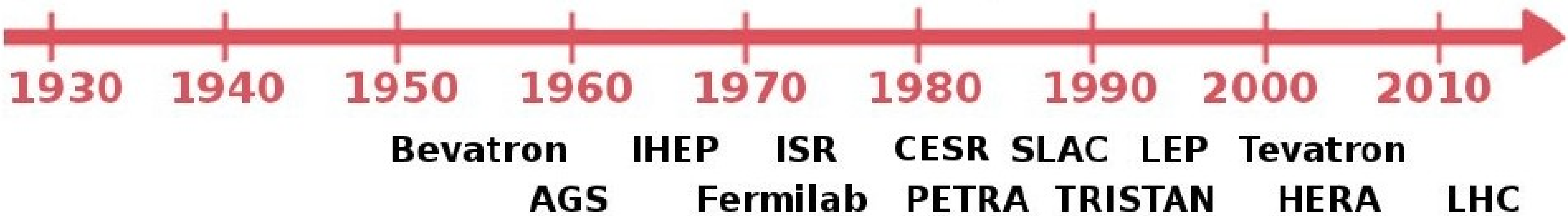


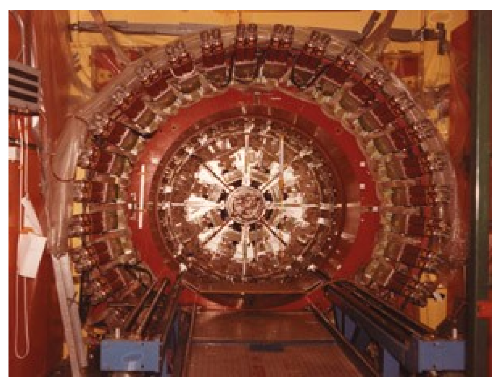




Possible monopole mass range (GeV)

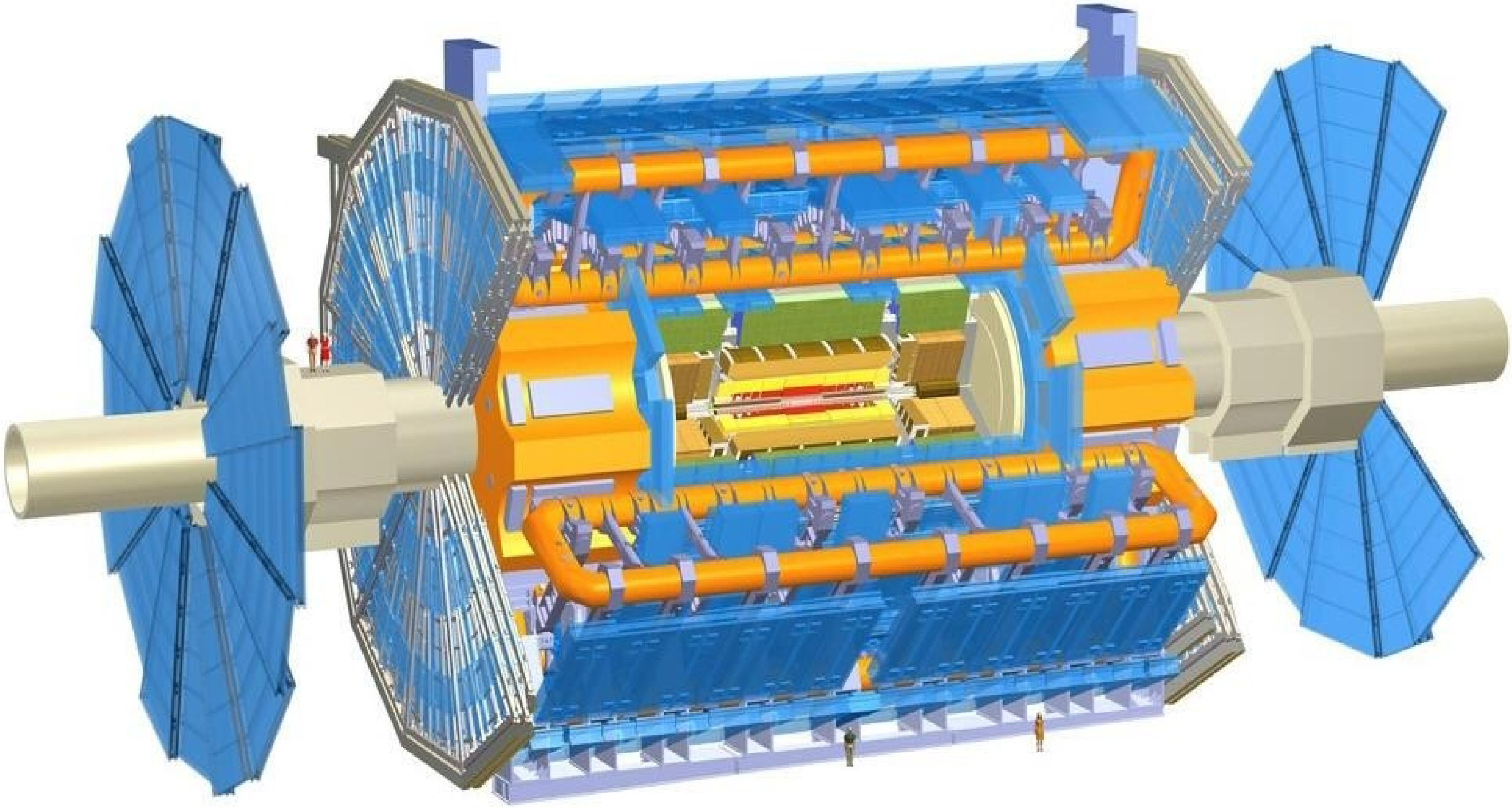




1930
1940
1950
1960
1970
1980
1990
2000
2010
Bevatron
AGS
IHEP
ISR
Fermilab
CESR
PETRA
SLAC
TRISTAN
LEP
Tevatron
HERA
LHC

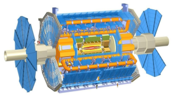


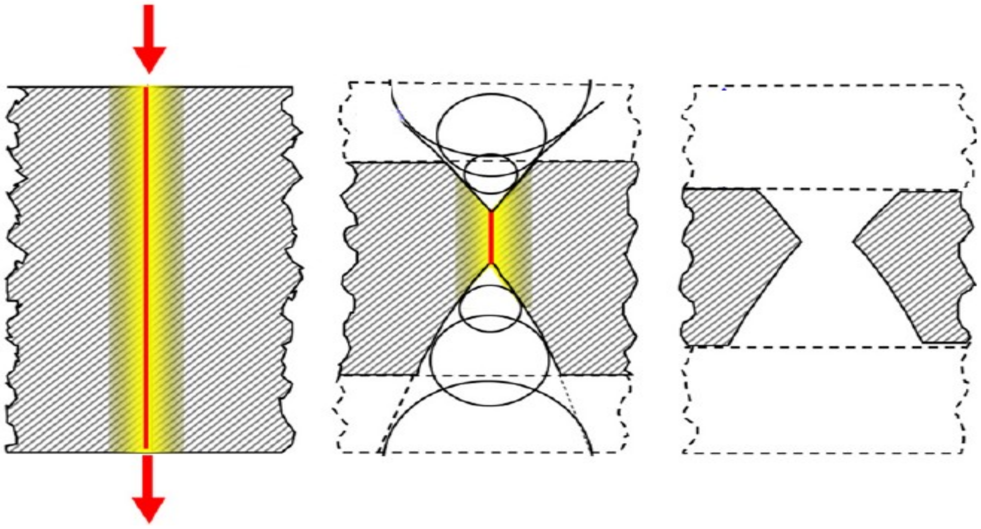

COLLIDER SEARCH TECHNIQUES FOR DIRECT DETECTION

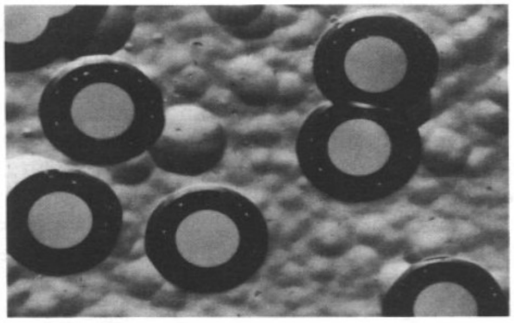
- General-purpose detectors



COLLIDER SEARCH TECHNIQUES FOR DIRECT DETECTION

- General-purpose detectors 
- Nuclear-track detectors





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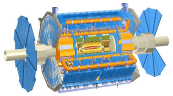
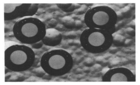
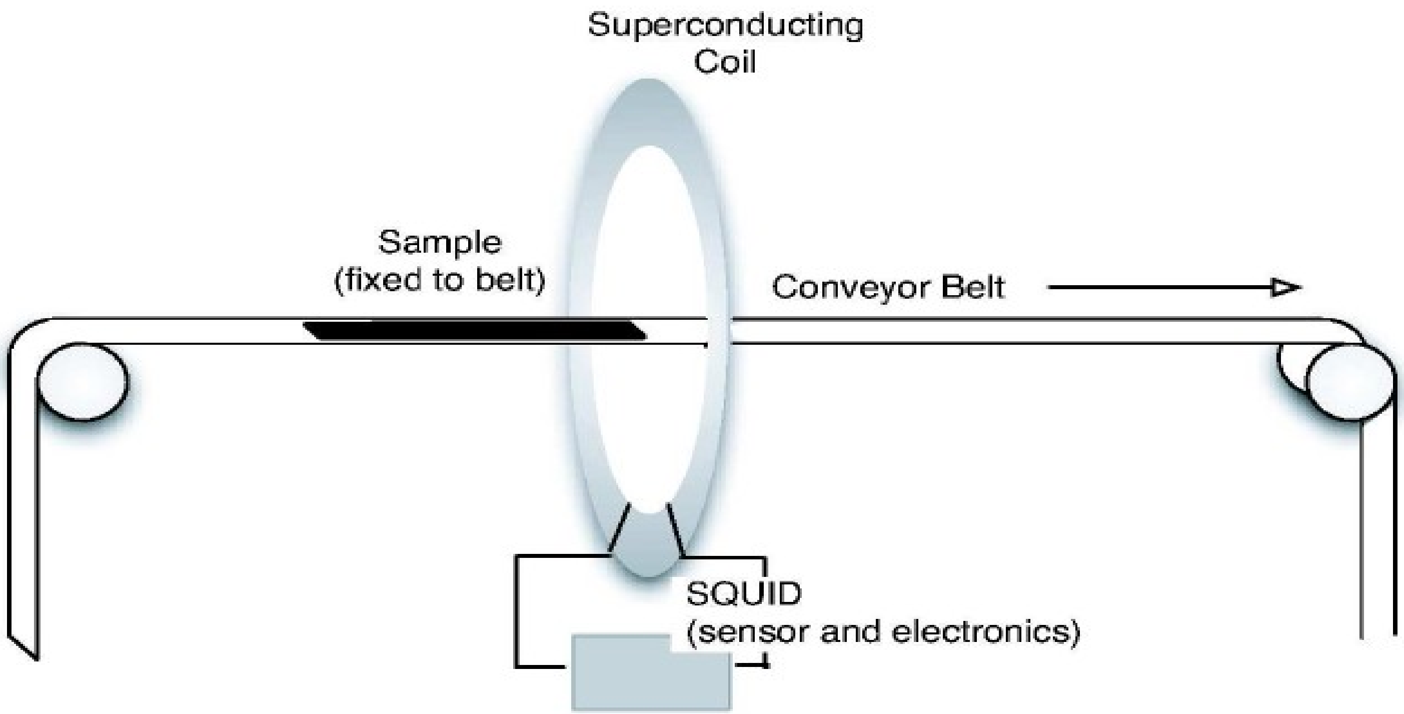
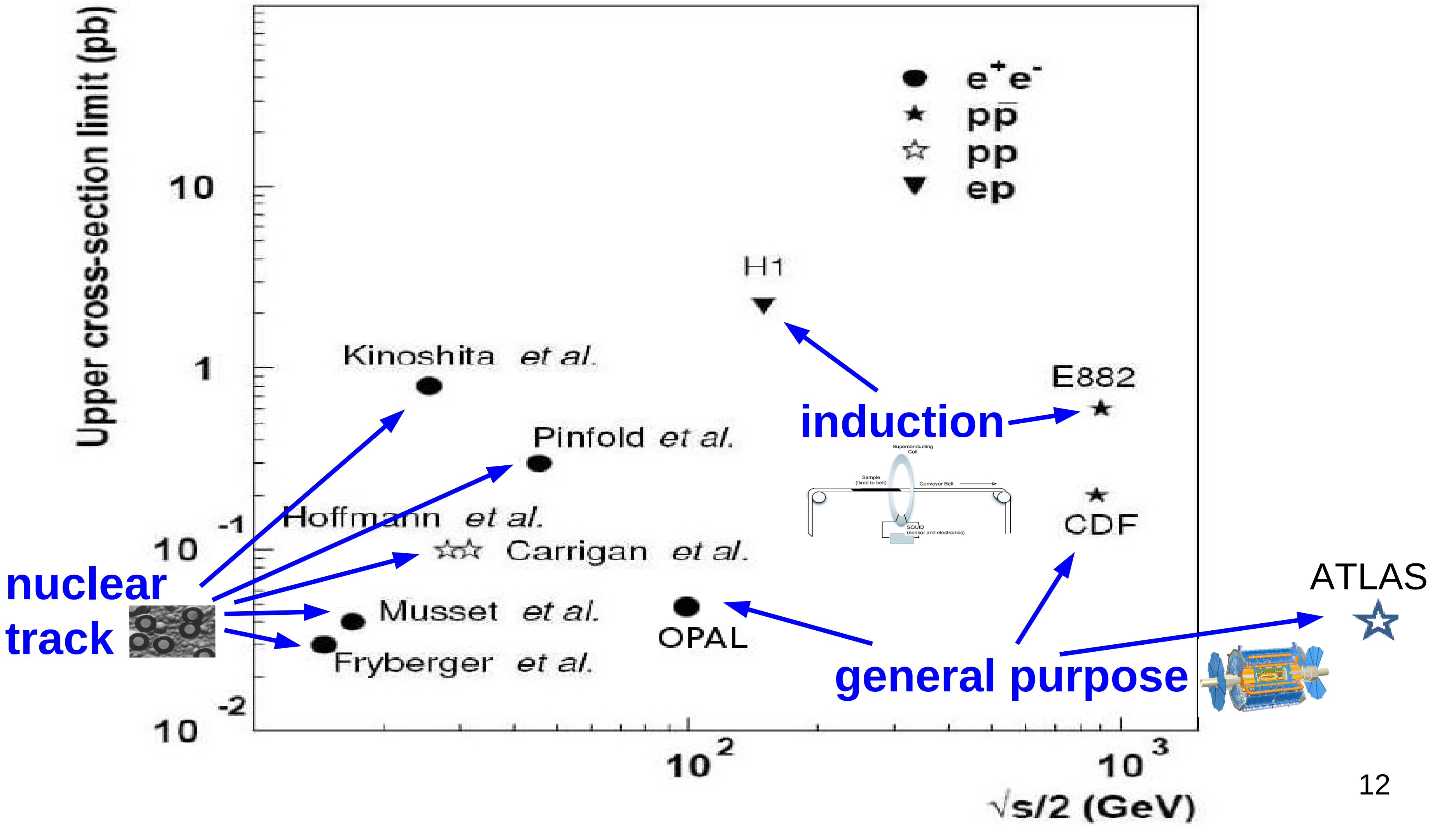
- General-purpose detectors 
- Nuclear-track detectors 
- Induction technique



DIRECT COLLIDER SEARCHES – CURRENT LIMITS

Phys. Rept. 438, 1 (2007), arXiv:hep-ph/0611040

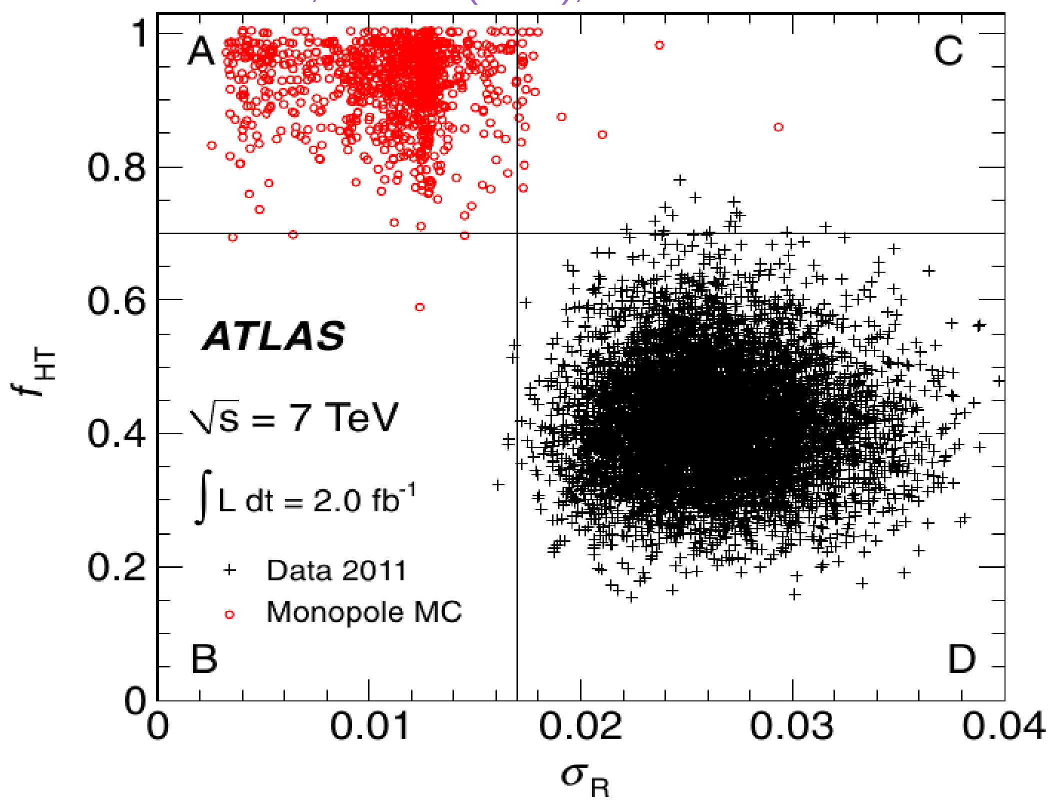


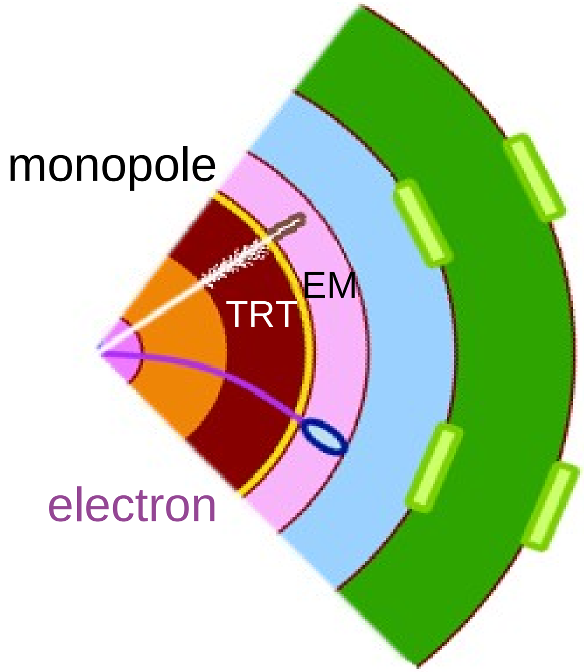
ATLAS SEARCH

First monopole constraints at the LHC

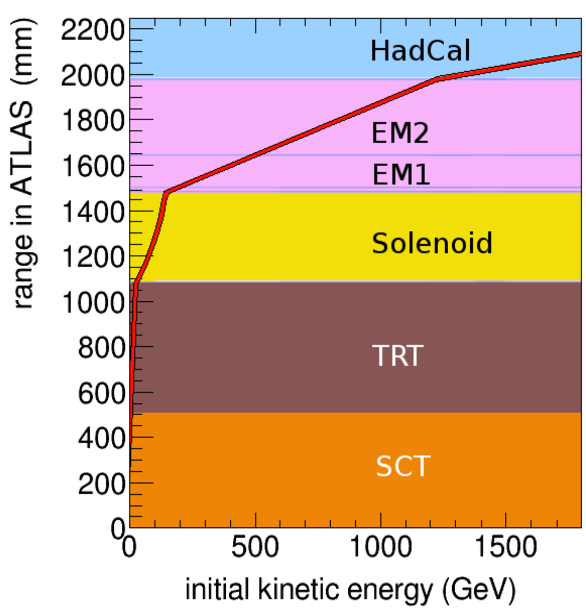
- 7 TeV *pp* collision data
- Interpreted for $g = g_D$ and $200 < M < 1500$ GeV

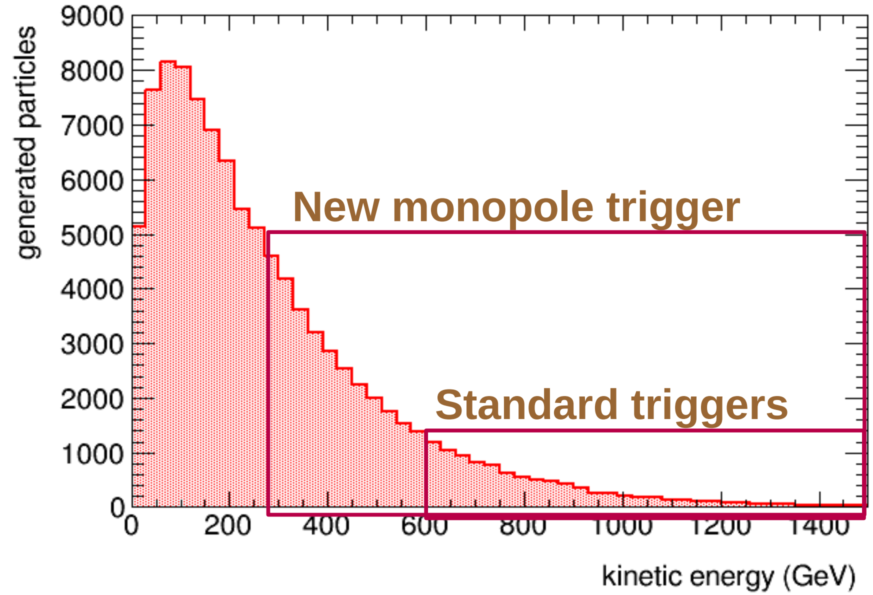
PRL 109, 261803 (2012), arXiv:1207.6411





NEW ATLAS SEARCHES

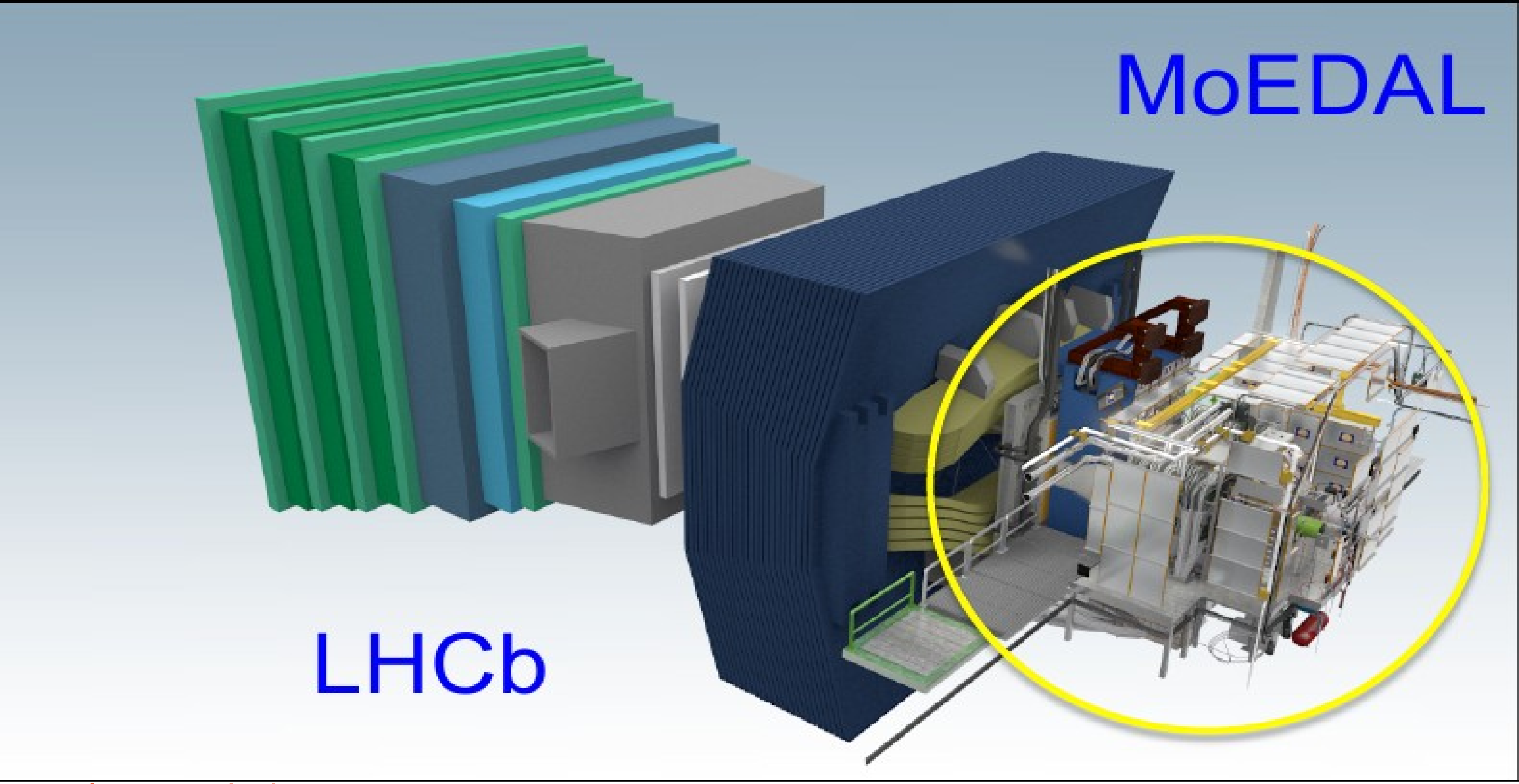




8 TeV data at final stage of analysis

- Much better sensitivity thanks to new trigger
- Can probe $g = 2g_D$

Preparations for 14 TeV collisions

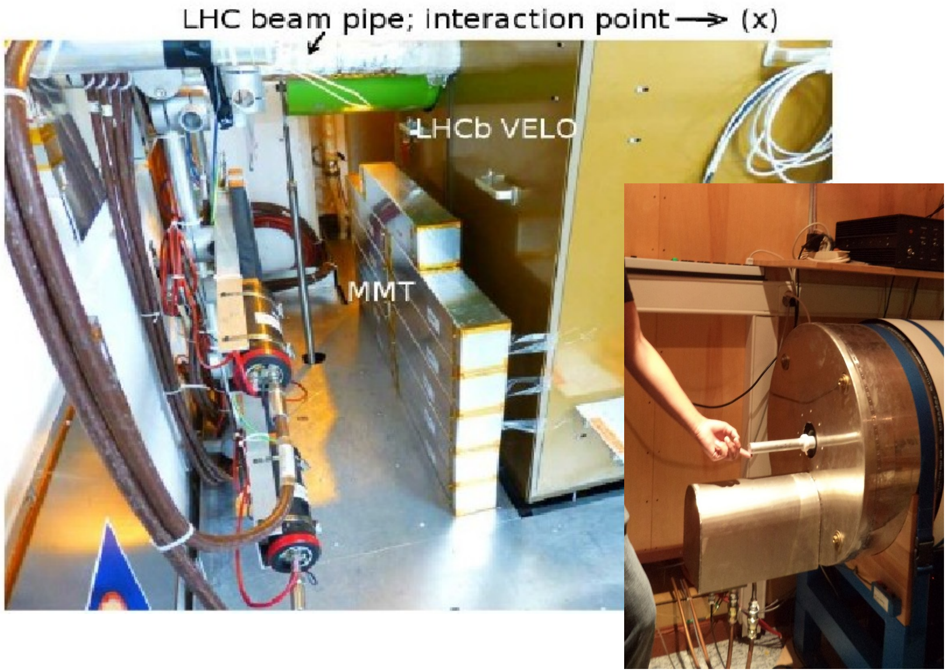


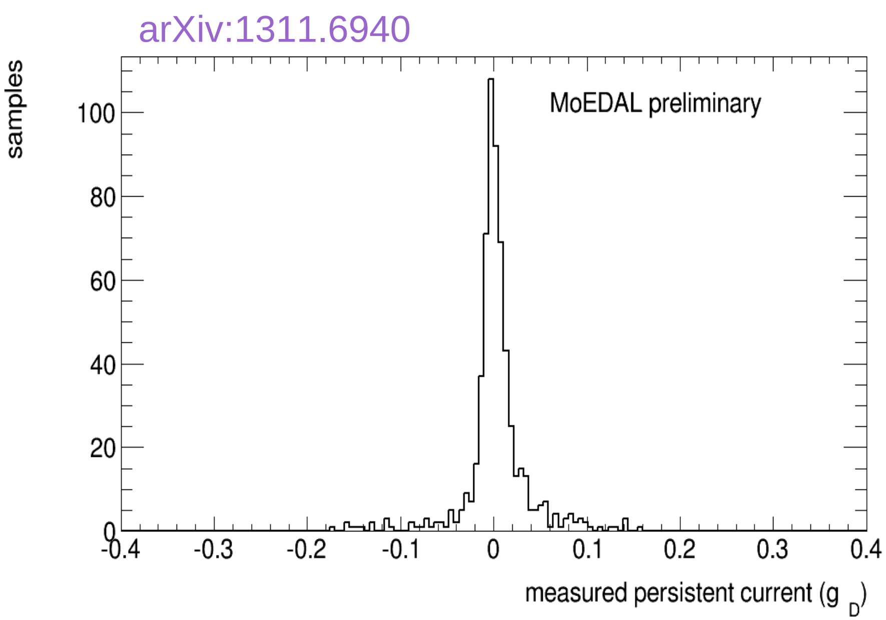
Nuclear-track detectors

- Passive exposure
- Robust methods
- Low material budget

Magnetic-monopole trapper

MAGNETIC MONOPOLE TRAPPER (MMT)





Aluminium test array

- Exposed to 8 TeV collisions
- 606 samples scanned with superconducting magnetometer

LHC BEAM PIPES

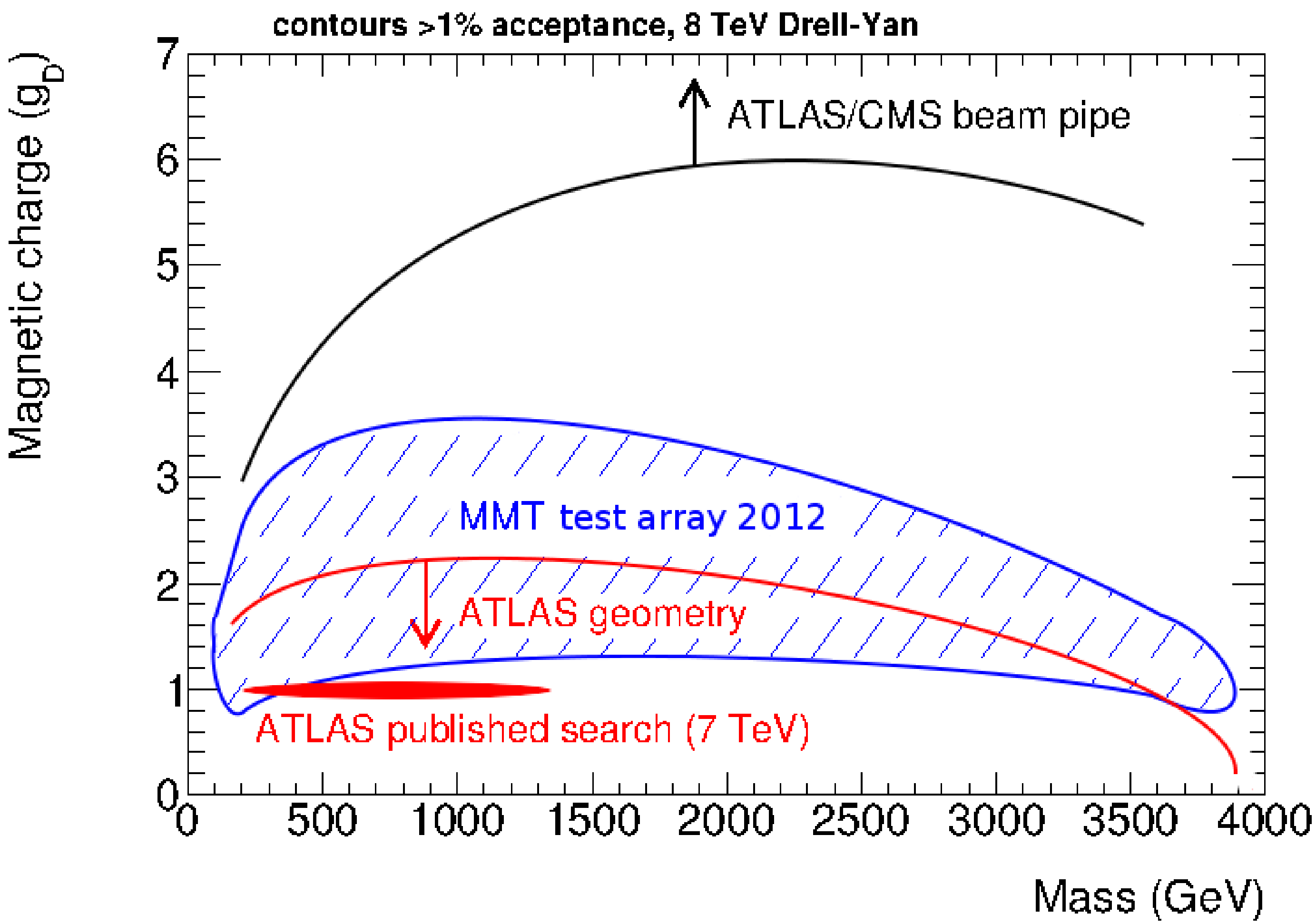
ATLAS and CMS beryllium pipes replaced after 8 TeV runs

- Available for analysis ~2017
- Cut and scan with magnetometer

Only way to detect very-high-charge monopoles

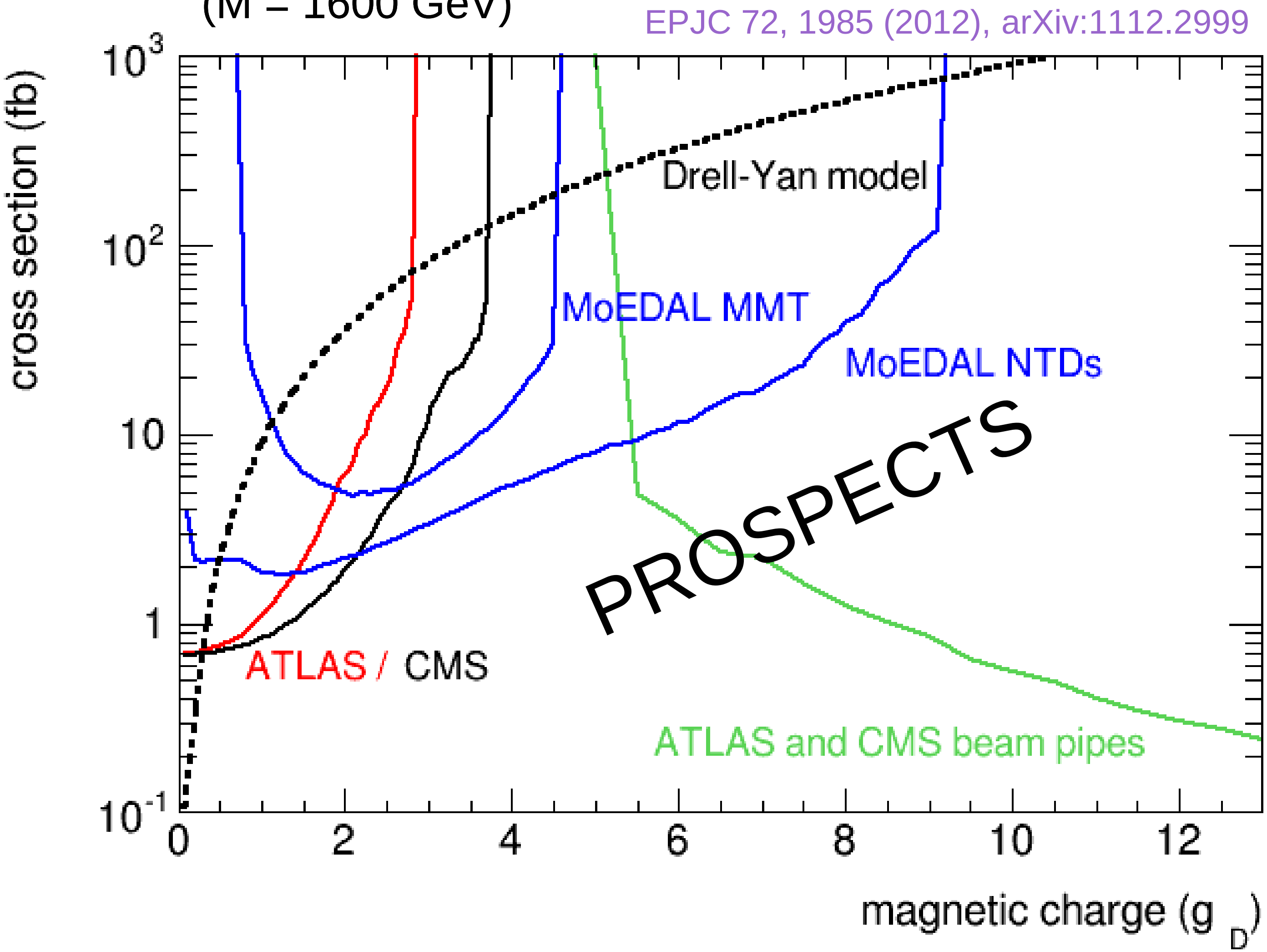
EPJC 72, 2212 (2012), arXiv:1206.6793
EPJC 72, 1985 (2012), arXiv:1112.2999

LHC 8 TeV COVERAGE



LHC 14 TeV PROSPECTS
(after 2015)

(M = 1600 GeV)

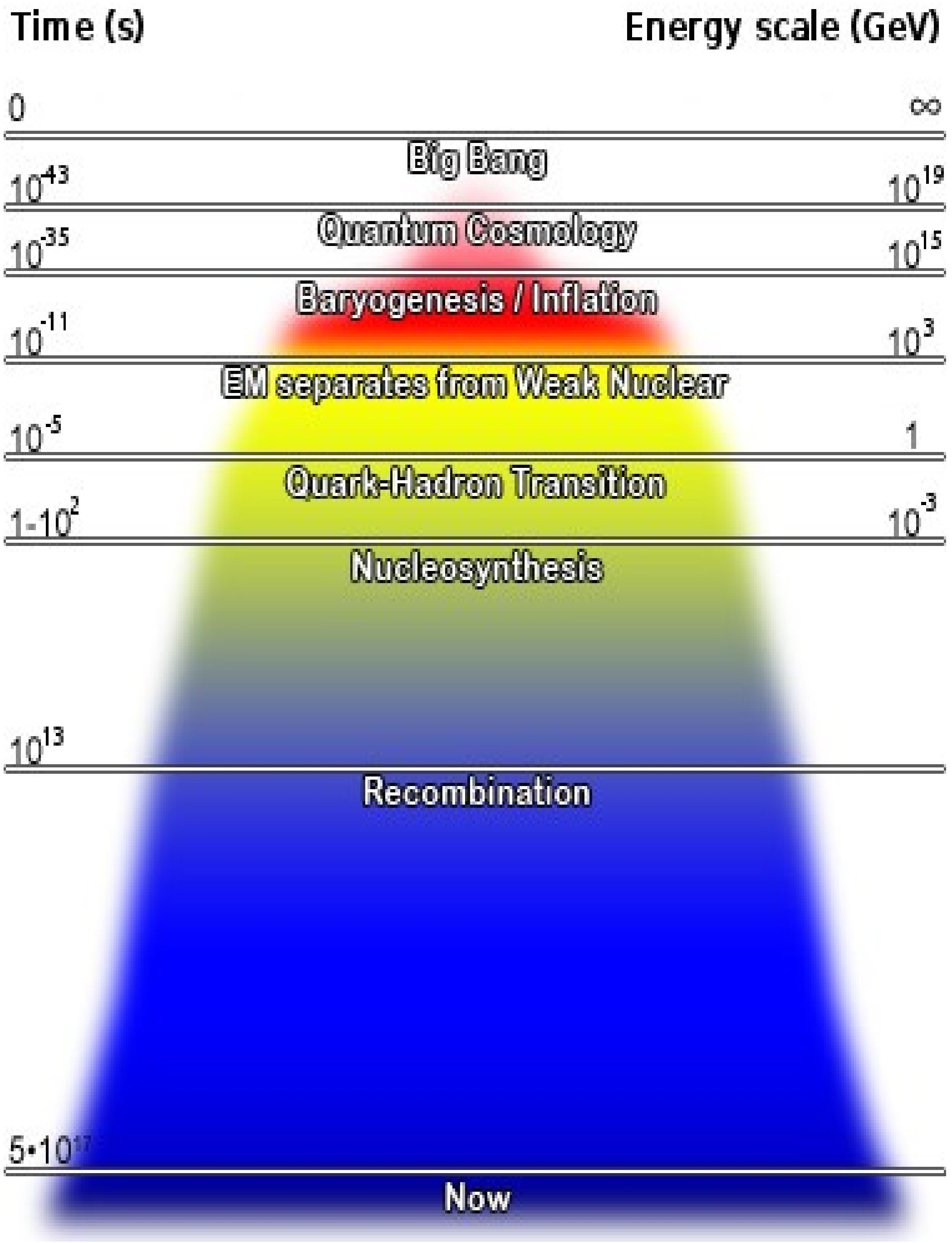


PRIMORDIAL MONOPOLES

Would naively expect enormous monopole density

Inflation theory solves this problem

Large uncertainty on relic monopole abundances



MONOPOLES IN THE GALAXY

Could be bound to matter, trapped inside stars and dust...

Could be free, accelerated to very high velocities by magnetic fields...

Field still exists

→ $F < 10^{-15}\ cm^{-2}s^{-1}sr^{-1}$

PRD 26, 1296 (1982)

MONOPOLES ON EARTH

THE FAMOUS “CABRERA EVENT”

(induction detector, 1982)

Sudden flux jump with magnitude g_D

– monopole passage...

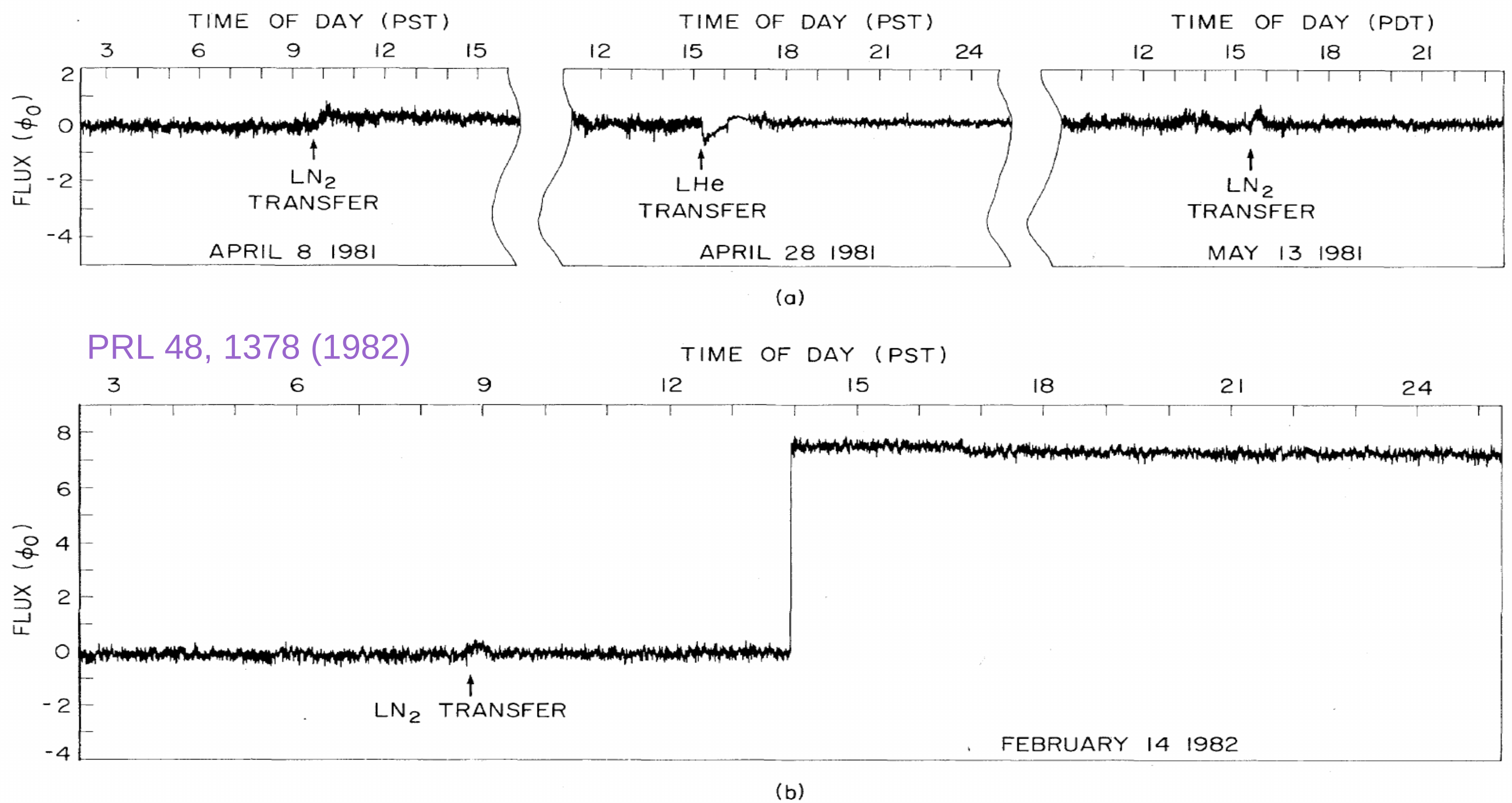
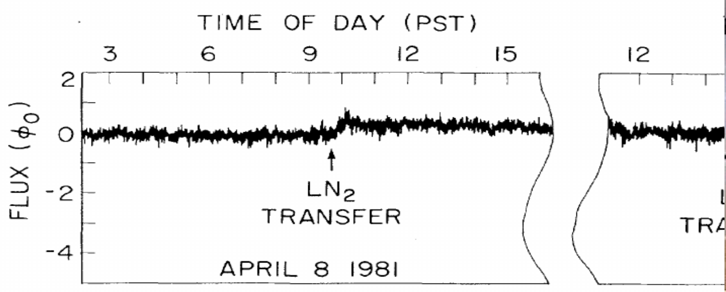


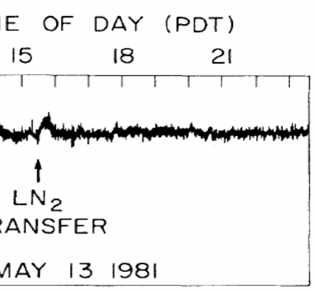
FIG. 2. Data records showing (a) typical stability and (b) the candidate monopole event.

THE FAMOUS "CABRERA EVENT"
(induction detector, 1982)

Sudden flux jump with magnitude g_D

– monopole passage... or spurious offset?





PRL 48, 1378 (1982)

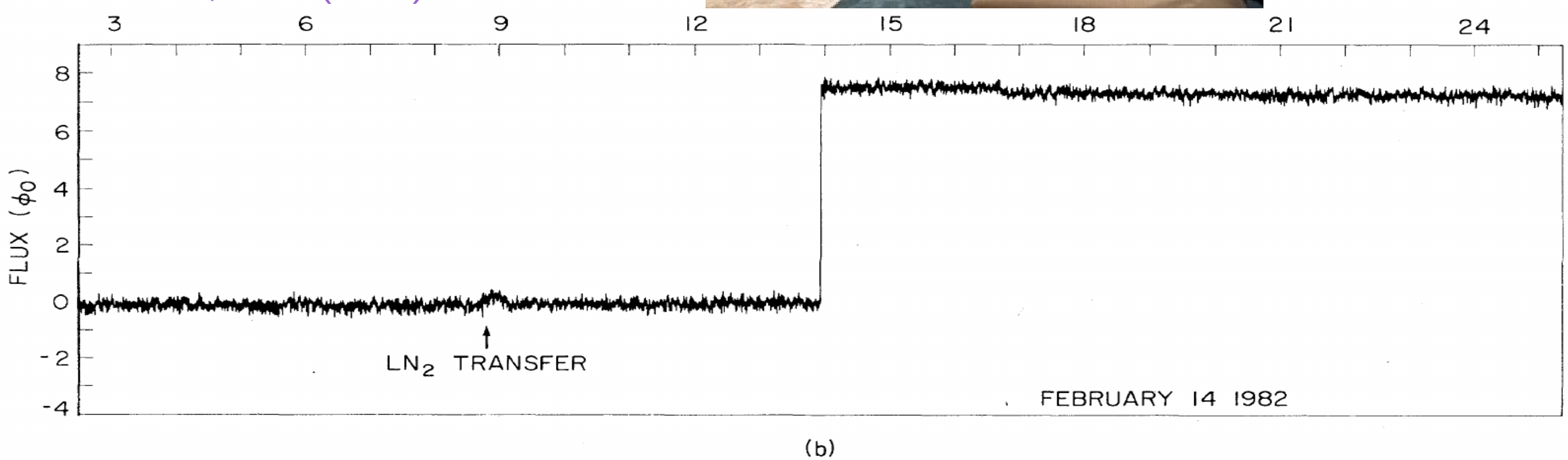
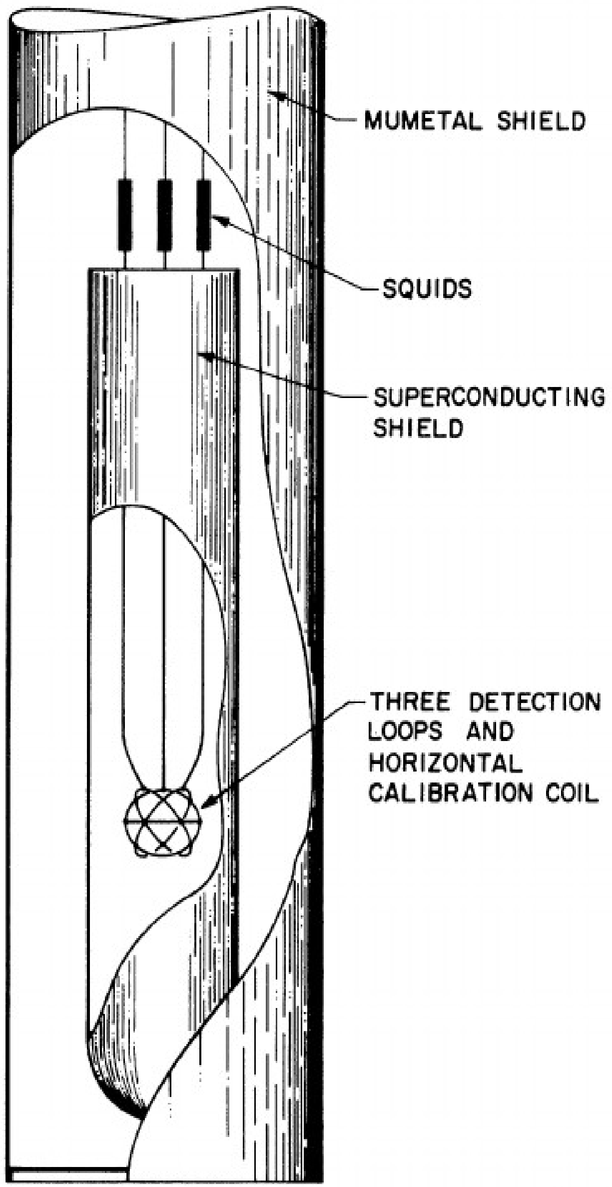


FIG. 2. Data records showing (a) typical stability and (b) the candidate monopole event.

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)



IONISATION DETECTORS – MACRO (2002)

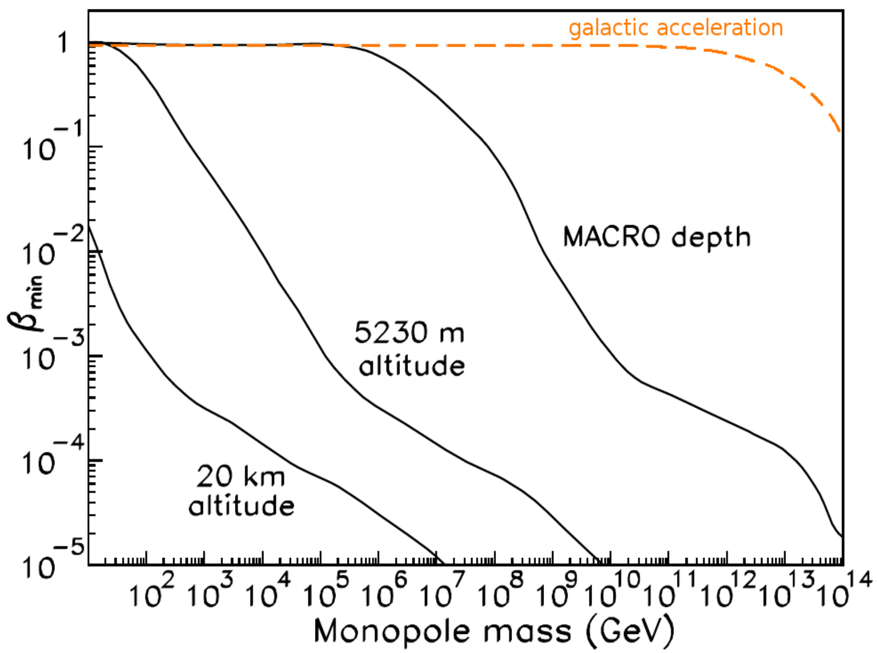
- 1400 m underground
- 1000 m^2, 10 m height
- 5 years exposure
- Various detection techniques:
  - Scintillator (time-of-flight): $0.0001 < \beta < 0.01$
  - Scintillator (dE/dx): $0.001 < \beta < 0.1$
  - Streamer tubes: $0.0001 < \beta < 0.01$
  - Nuclear track: $0.001 < \beta < 1$
- $F < 10^{-16}\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

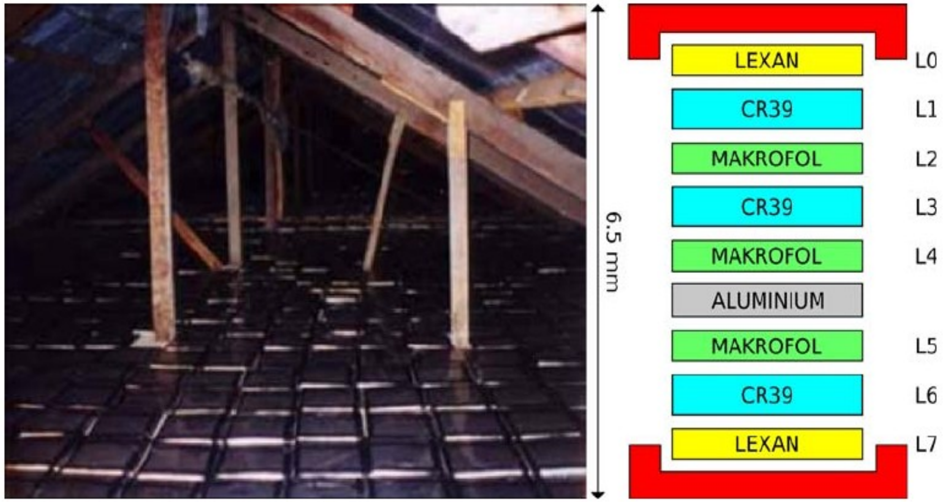
EPJC 25, 511 (2002), arXiv:hep-ex/0207020

IONISATION DETECTORS – 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), arXiv:0801.4913





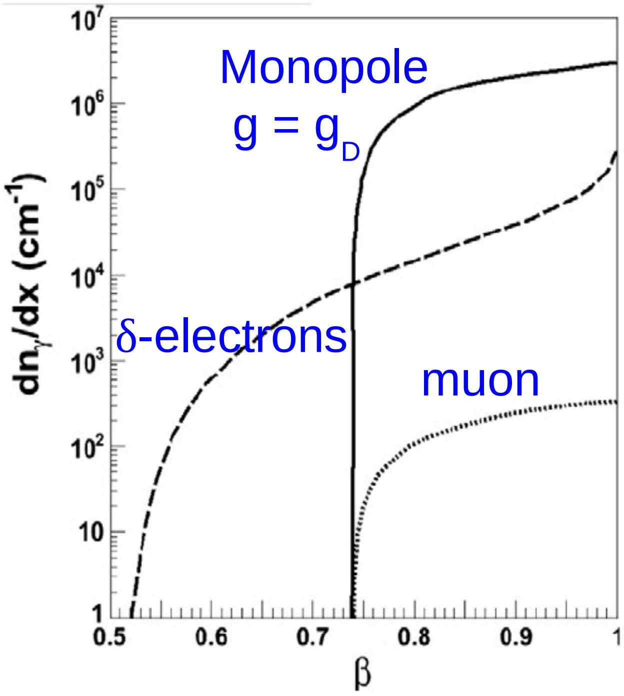
NEUTRINO OBSERVATORIES
(2008 – 2013)

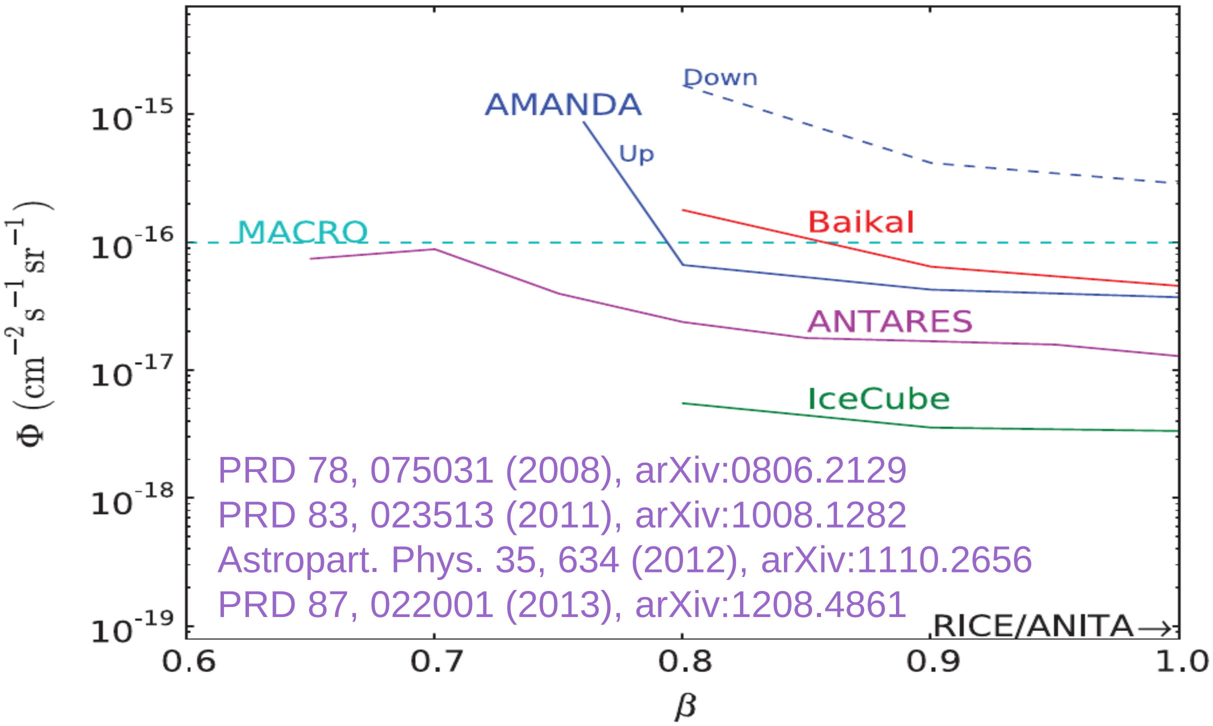
Relativistic monopoles

→ 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

ANCIENT MICA
(1969 – 1990)

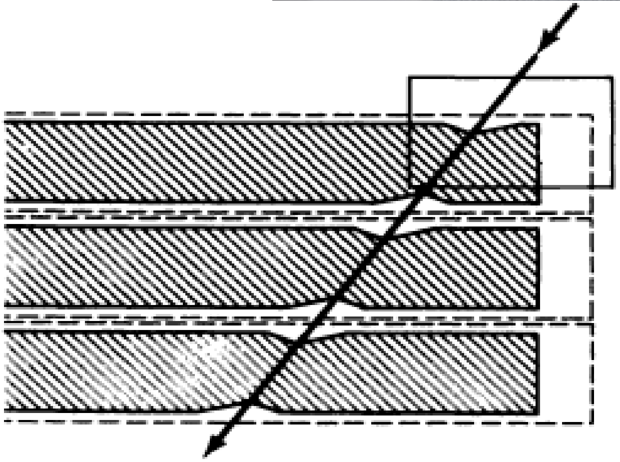
> 500 millions years exposure time!

Track formed if:

- $g \geq 2\, g_D$
- Or, low-velocity ($\beta \sim 10^{-3}$) monopole captured a nucleus on its way through the rock

Given one of the above:

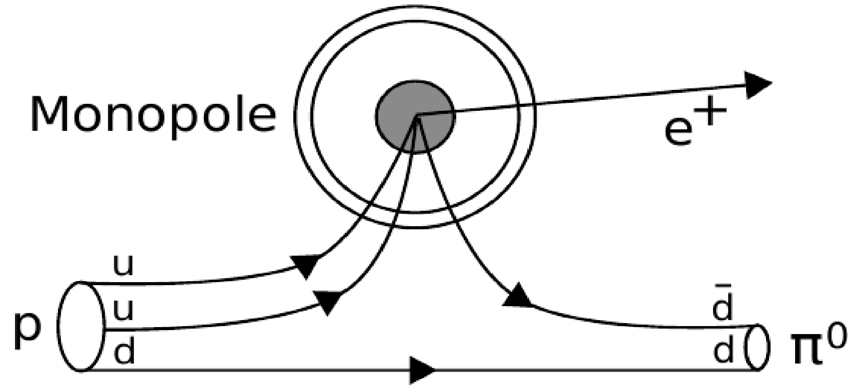
$F < 5 \cdot 10^{-20}\ \mathrm{cm^{-2} s^{-1} sr^{-1}}$



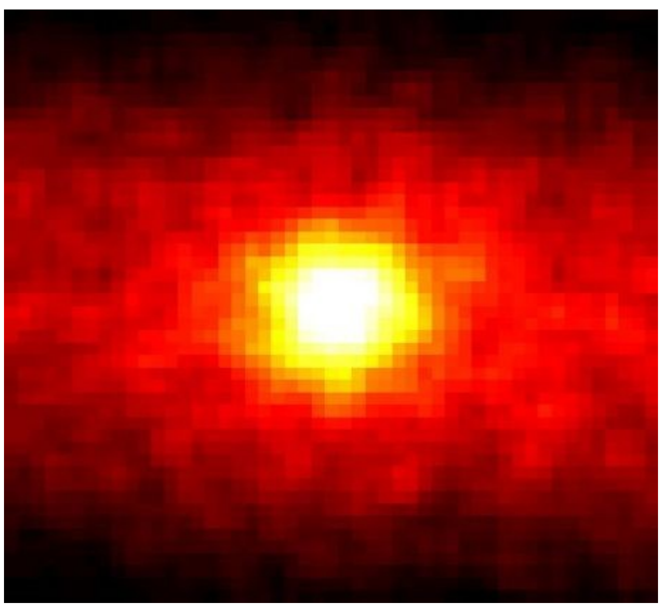
PR 184, 1398 (1969)
PRL 52, 1265 (1984)
PRL 56, 1226 (1986)
EPL 12, 25 (1990)

CATALYSIS OF PROTON DECAY

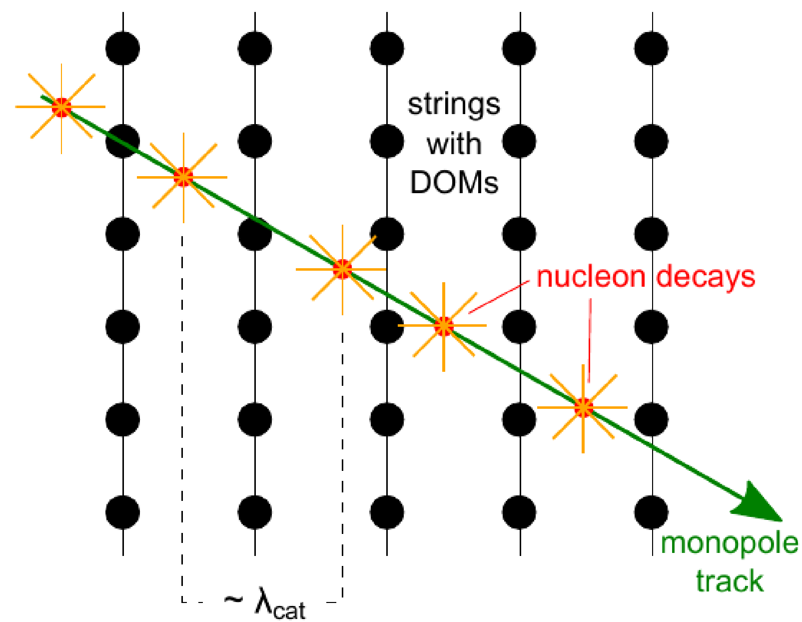
- GUT monopoles
- $\beta \sim 10^{-3}$
- $\sigma \sim 100$ mb



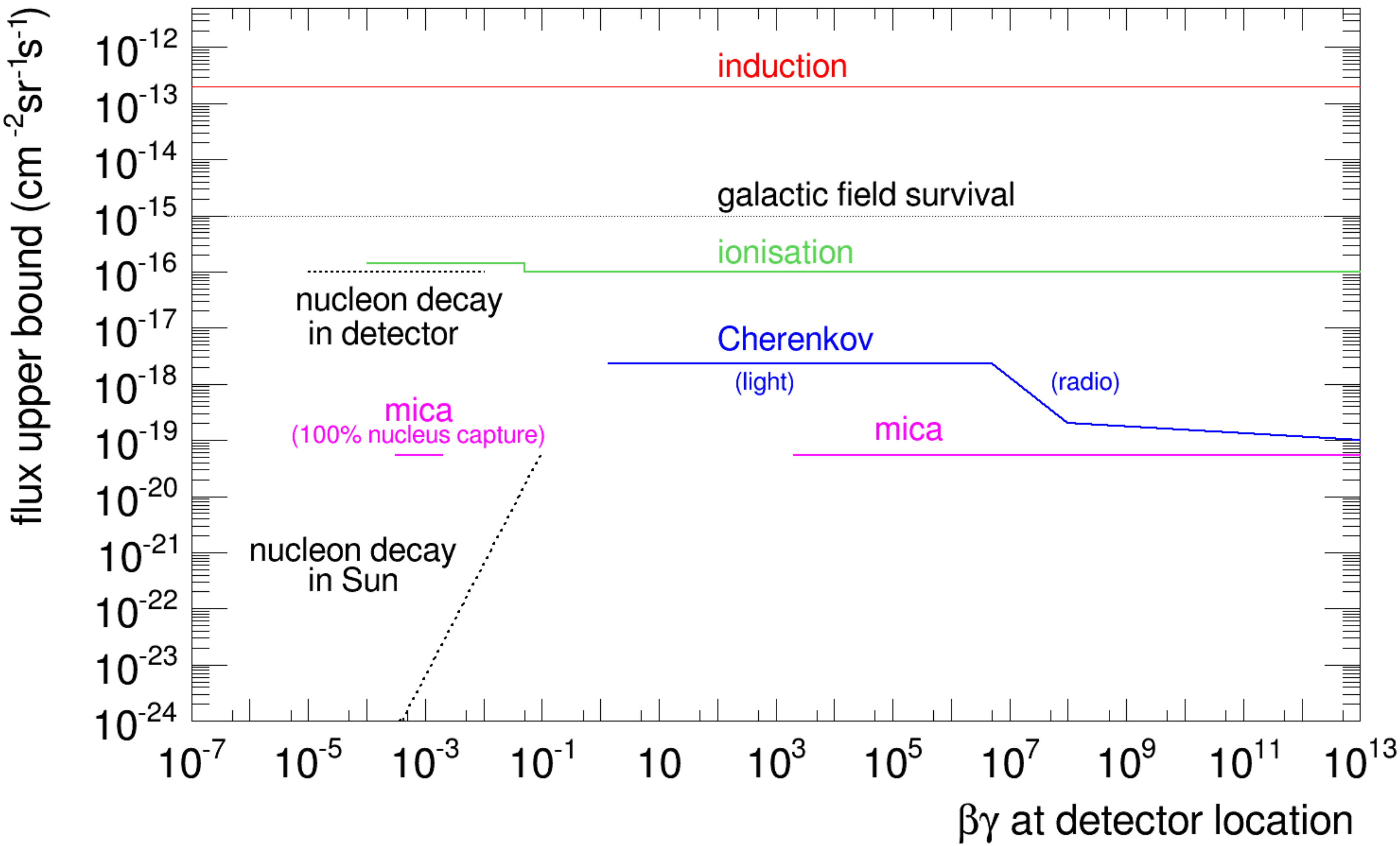
Superkamiokande (2012)



IceCube (2014)

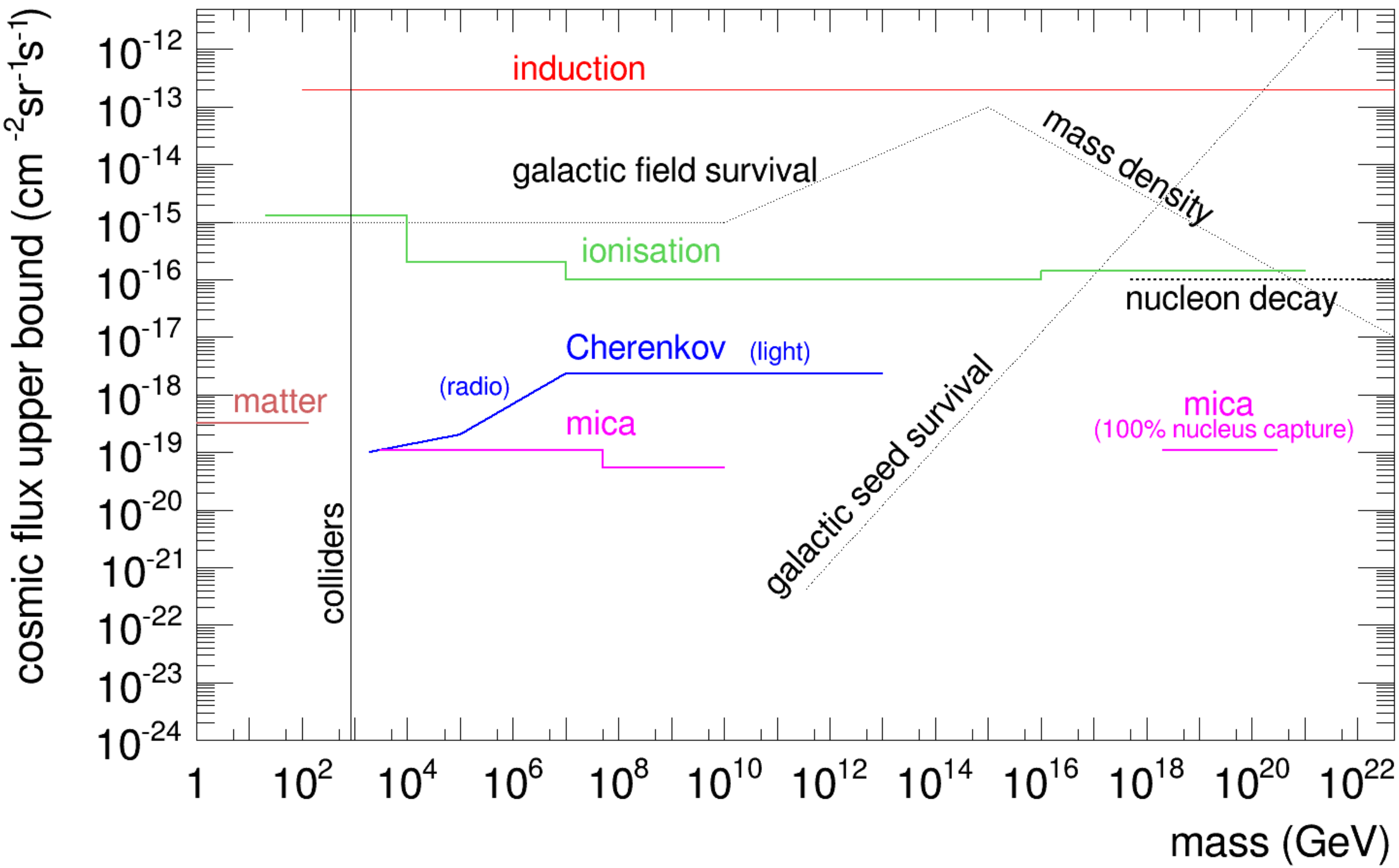


COSMIC FLUX LIMITS – SUMMARY 1

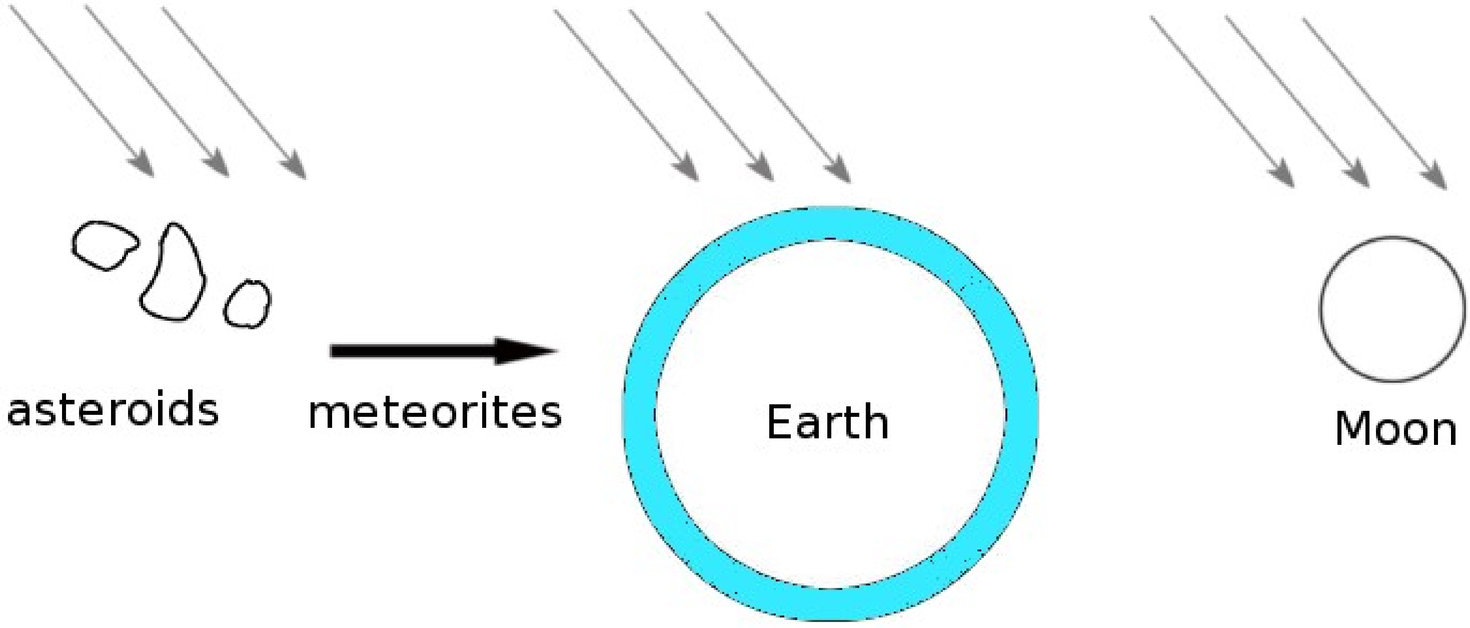


COSMIC FLUX LIMITS – SUMMARY 2

(assuming E_{kin} = 10^{13} GeV)

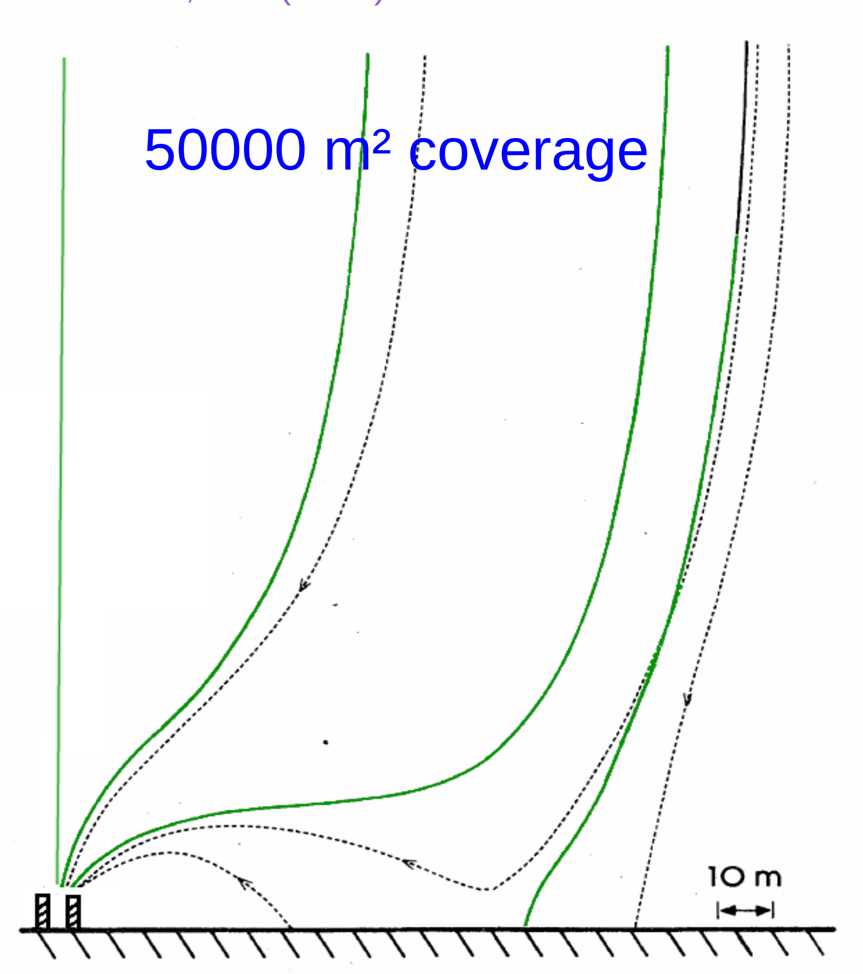


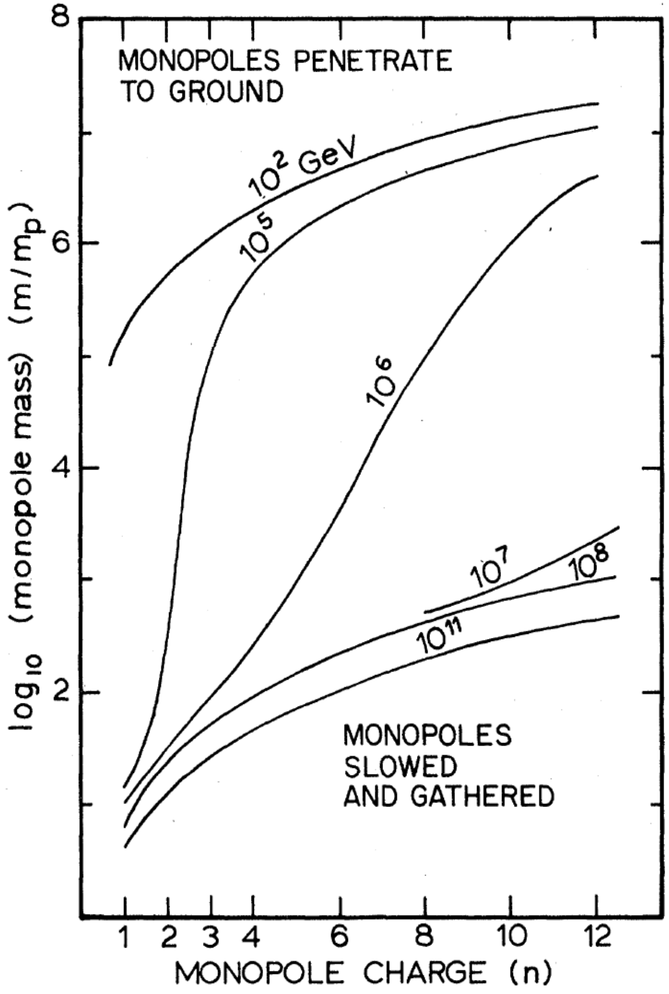
MATTER SEARCHES



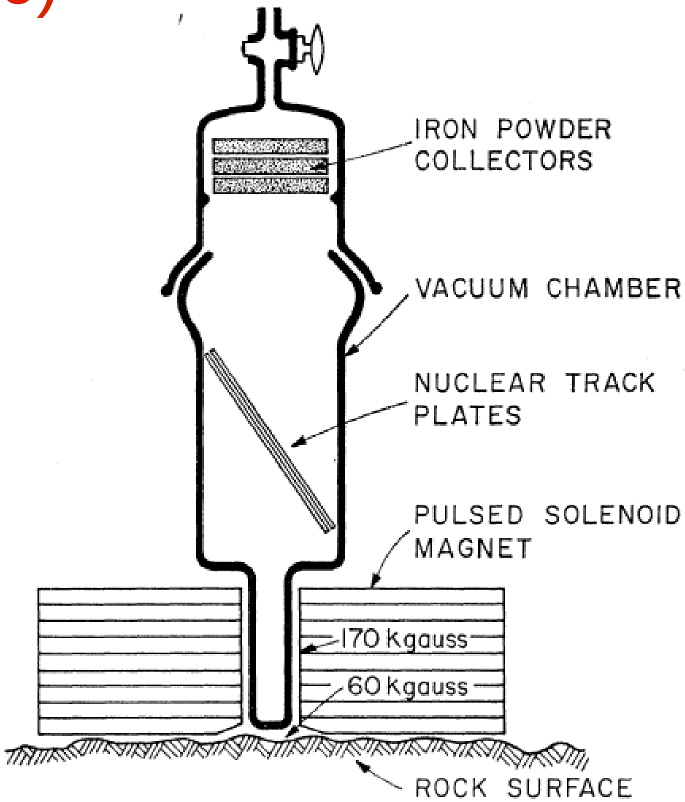
COLLECTION FROM ATMOSPHERE
(1951 – 1981)

PR 83, 899 (1951)
PR 149, 1070 (1966)
PRD 24, 612 (1981)





EXTRACTION TECHNIQUE
(1963 – 1976)



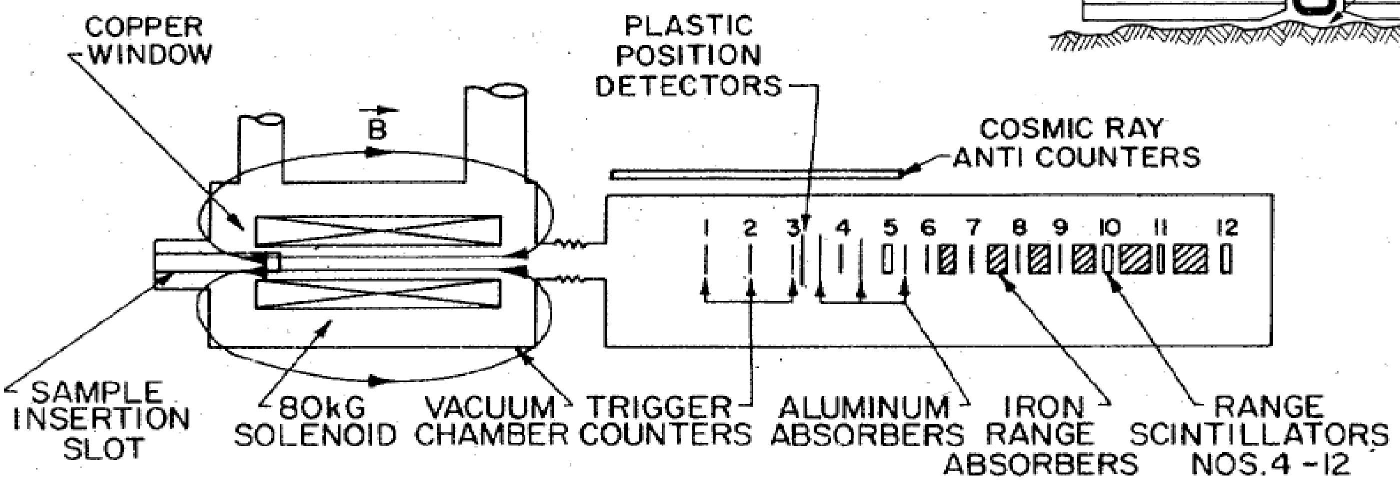
Meteorite fragments
Nucl. Phys. 49, 87 (1963)

Magnetite
Phys. Rev. 132, 387 (1963)

Deep-sea manganese nodules
Phys. Rev. 177, 2029 (1969)

Deep-sea sediments
Phys. Rev. D 4, 1285 (1971)

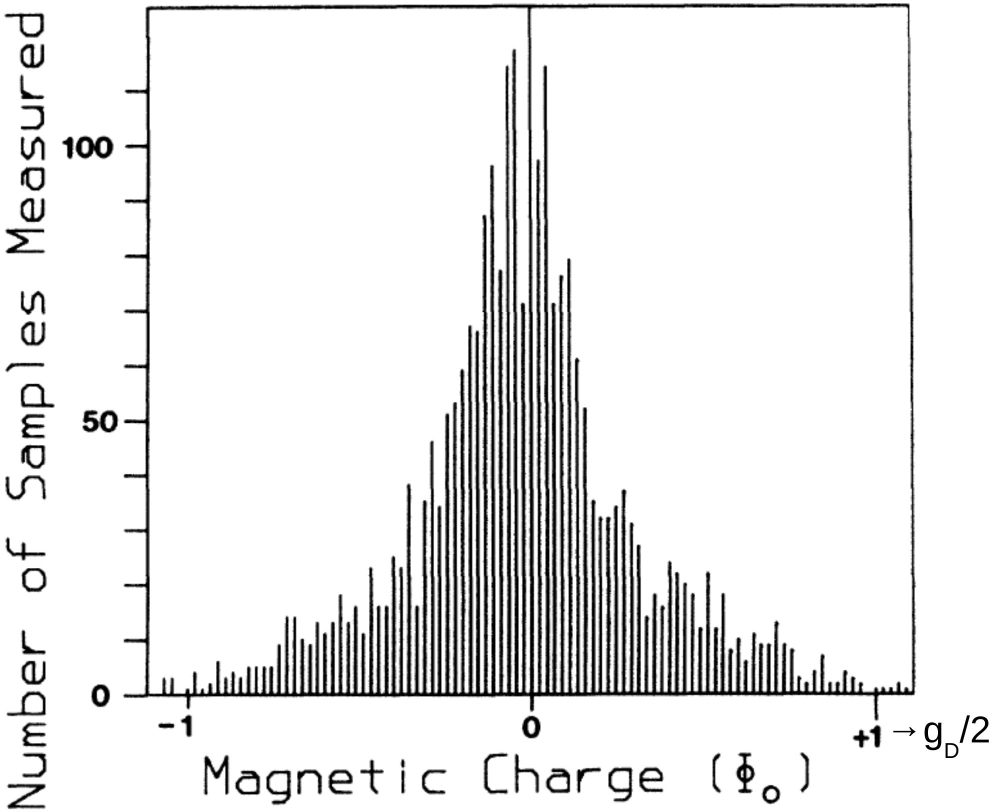
Air and sea water
Phys. Rev. D 13, 1823 (1976)



LARGE-SCALE INDUCTION SEARCH
(1986)

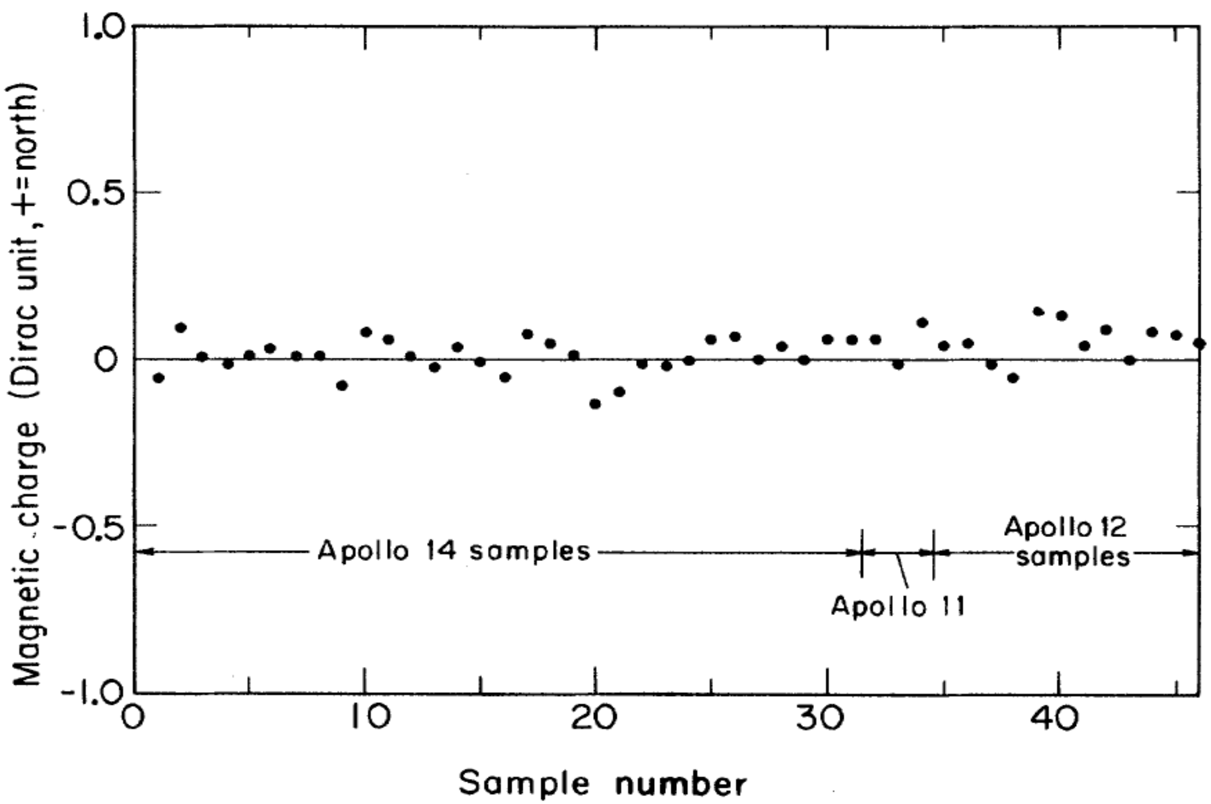
- 180 kg sea water
- 145 kg manganese nodules
- 498 kg deep schist at 25 km depth
- 20 times more material than all previous searches together
- Robust technique

PRA 33, 1183 (1986)



MOON ROCKS (1973)

- 48 kg returned from Apollo missions
- 4 billions years exposure
- No atmosphere, no magnetic field
  → remains there (few meters depth)

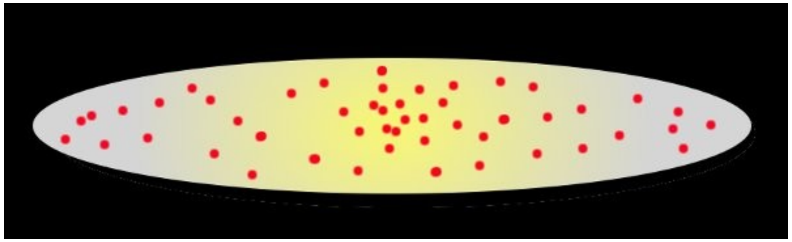


$F < 6 \cdot 10^{-19}\ cm^{-2}s^{-1}sr^{-1}$
(low mass / low energy)

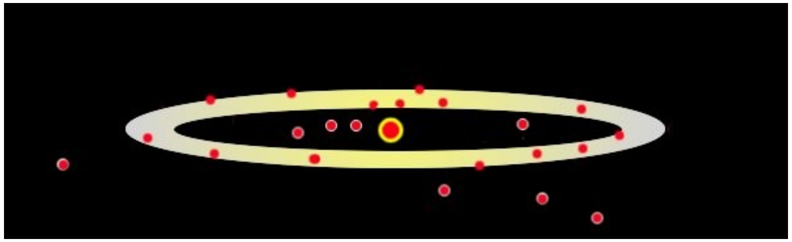
PRD 4, 3260 (1971)
PRD 8, 698 (1973)

STELLAR MONOPOLES

Cloud

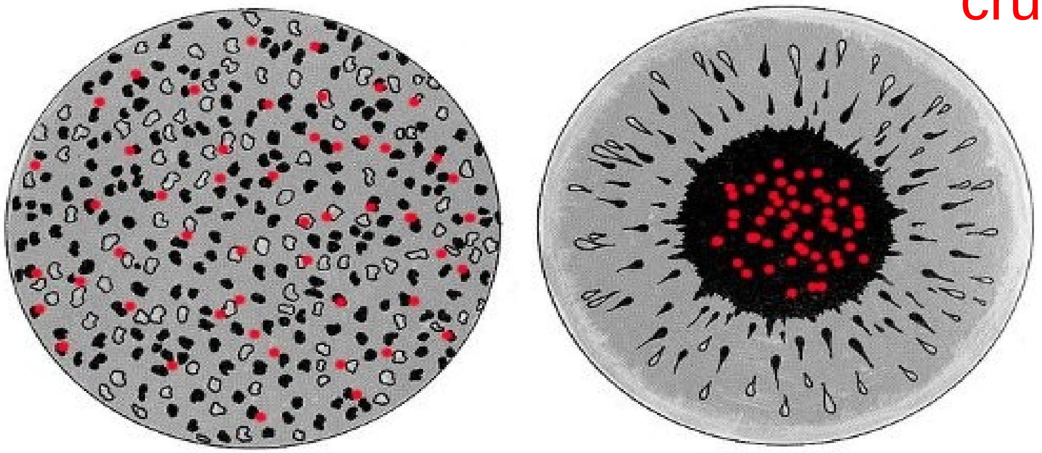


Planetary System



Heavier than the heaviest nuclei → absent from crust

Planetary differentiation



EARTH HEAT
(1980)

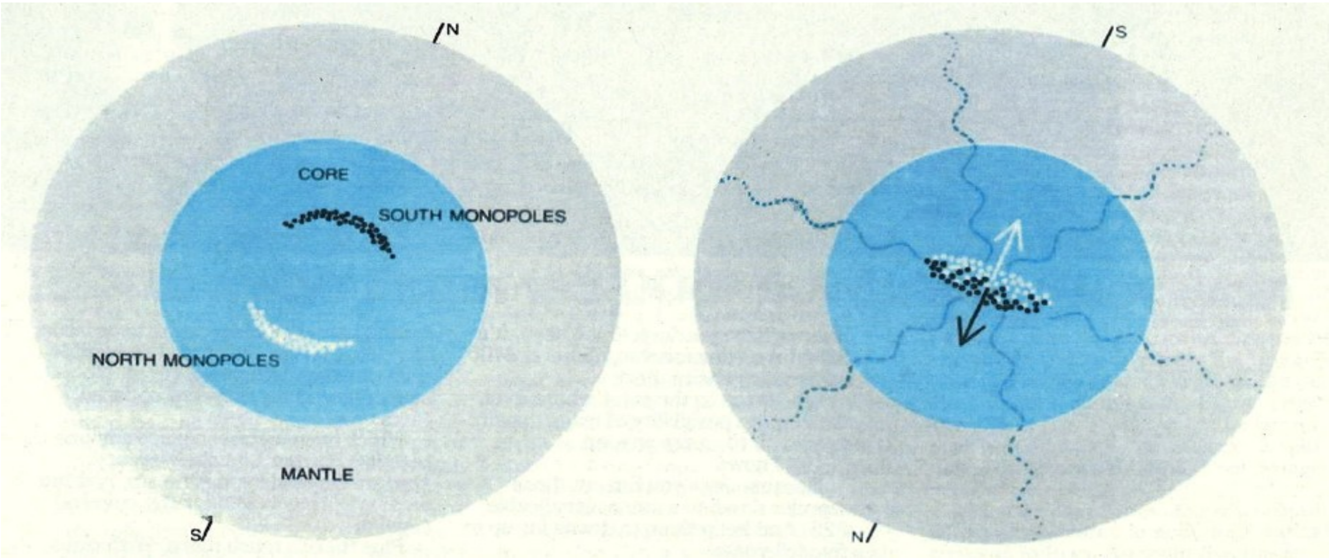
Nature 288, 348 (1980)

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



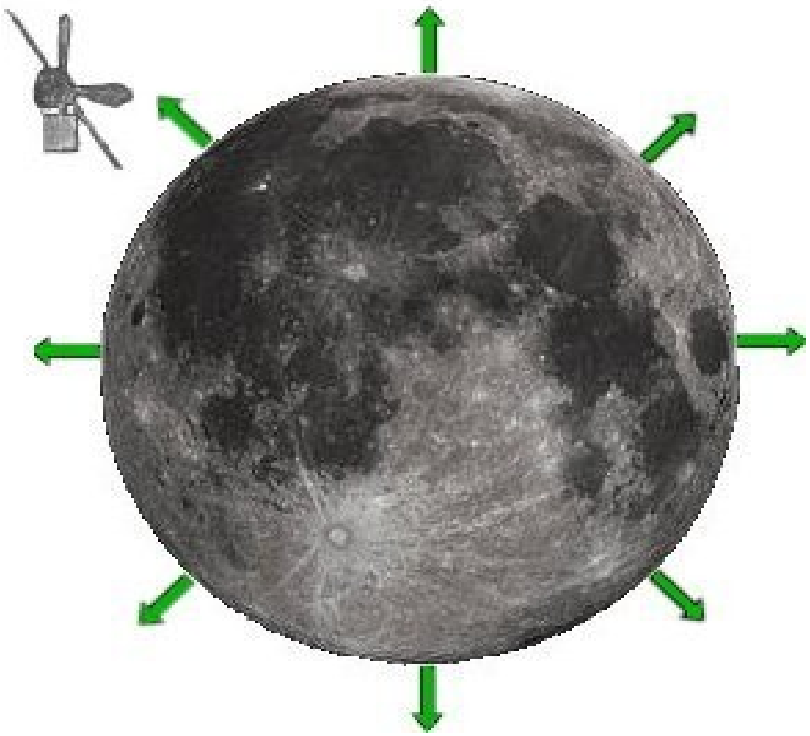
MOON FIELD
(1983)

PRD 27, 1525 (1983)

Magnetometer observations aboard Explorer 35 orbiting the Moon: no radial component

→ limit $\rho < 4 \cdot 10^{-9}$ mon./g

Must assume monopoles predominantly of one sign



METEORITE INDUCTION SEARCH (1995)

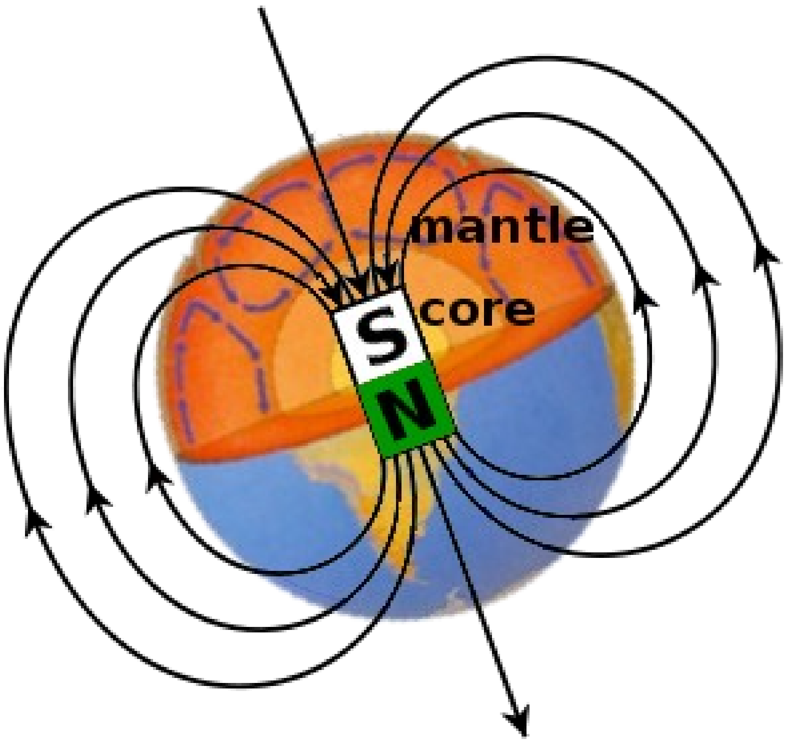
PRL 75, 1443 (1995)

331 kg rocks (meteorites, ferromanganese nodules, iron ores, blueschists, sediments, kimberlites, chromates)

112 kg meteorites

- ~100 kg chondrites → stellar monopoles!
- Not dislodged by meteor impact → $M < 10^{17}$ GeV

POLAR VOLCANIC ROCKS
(2013)

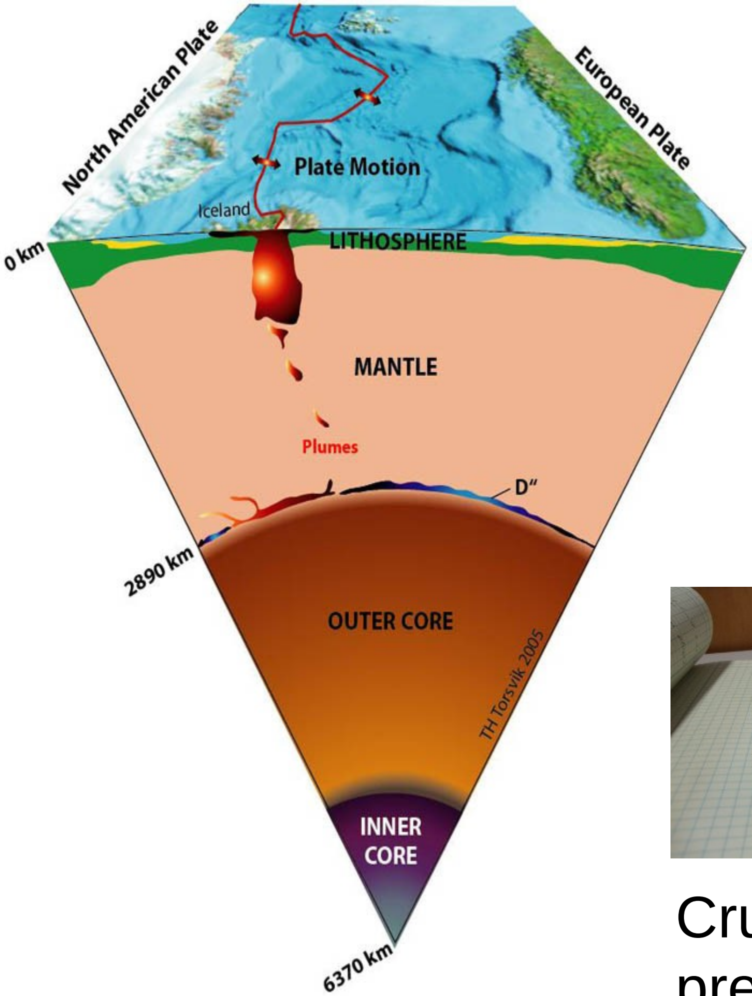


Magnetic force exceeds gravitational force ($g = g_D$):

$M < 4 \cdot 10^{14}$ GeV

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

POLAR ROCKS – SAMPLES



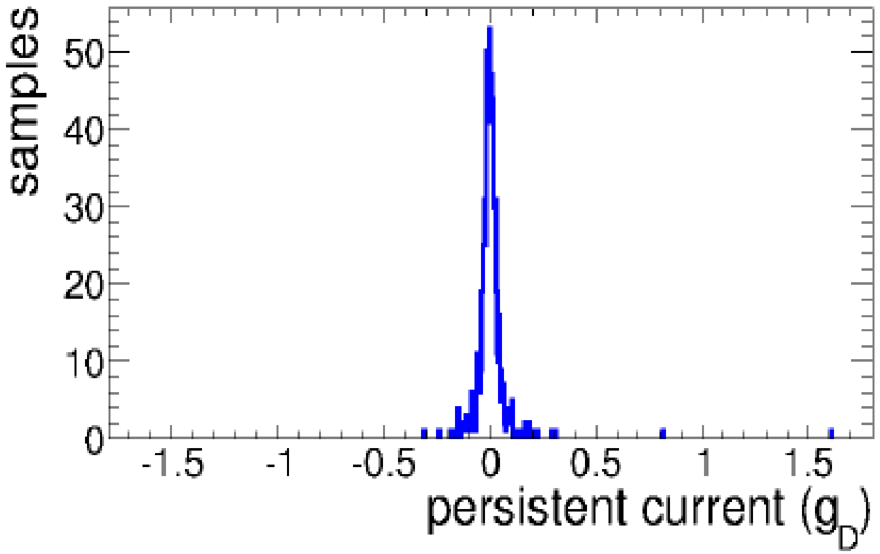
High latitude, mantle derived

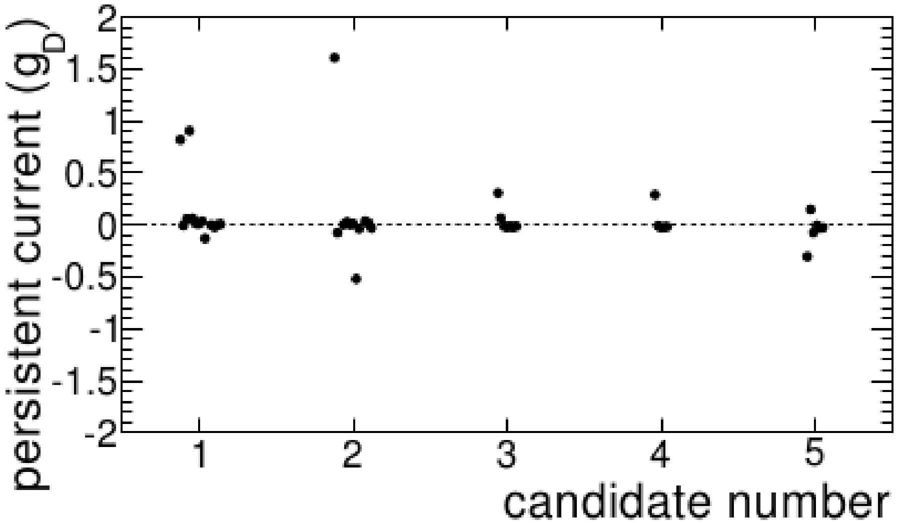
- Hotspots
- Mid-ocean ridges
- Large igneous provinces
- Isotopic content indicating deep origins

Crushed to reduce magnetisation for precise magnetometer measurement

POLAR ROCKS – RESULTS

PRL 110, 121803 (2013), arXiv:1301.6530

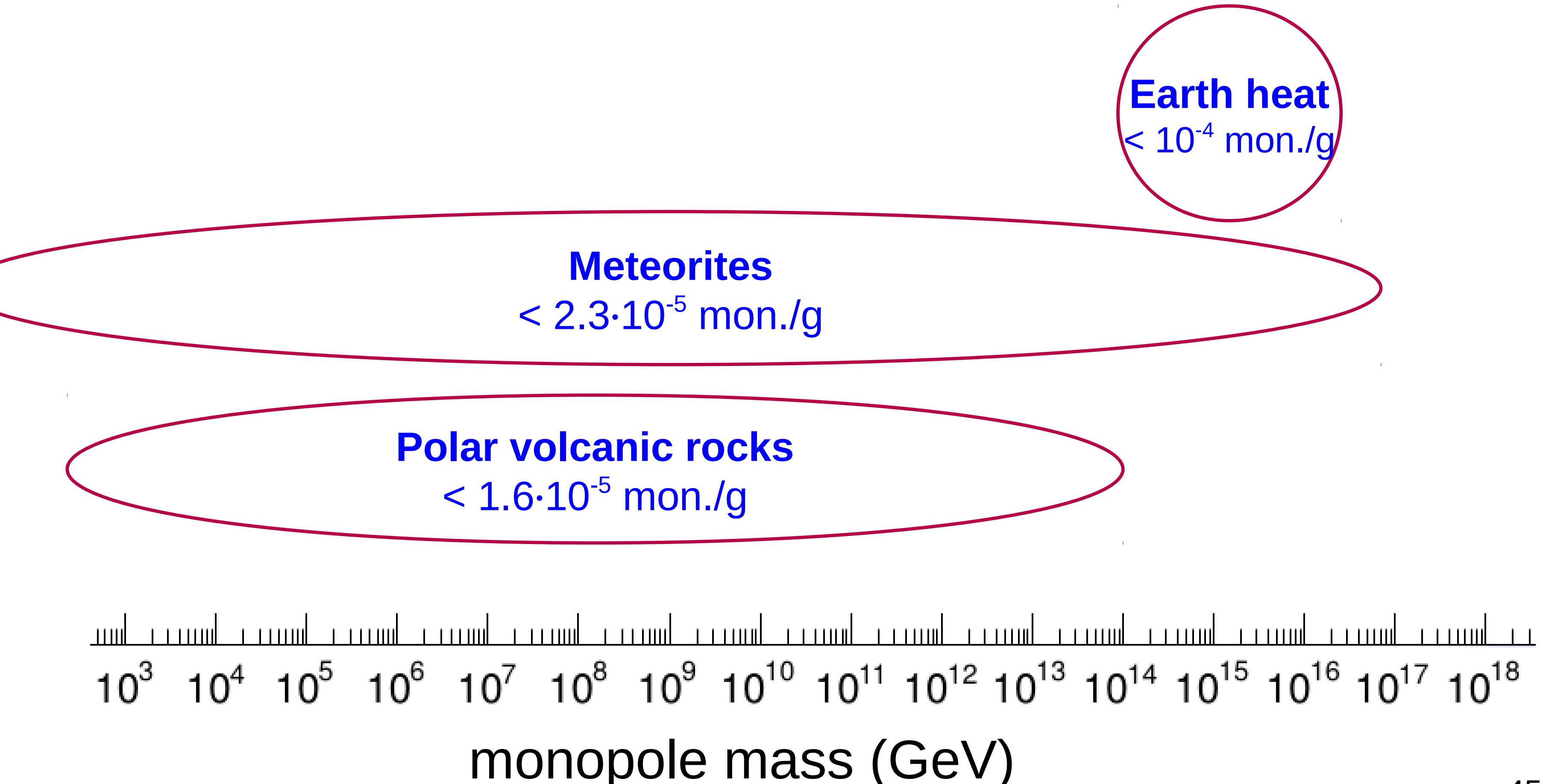




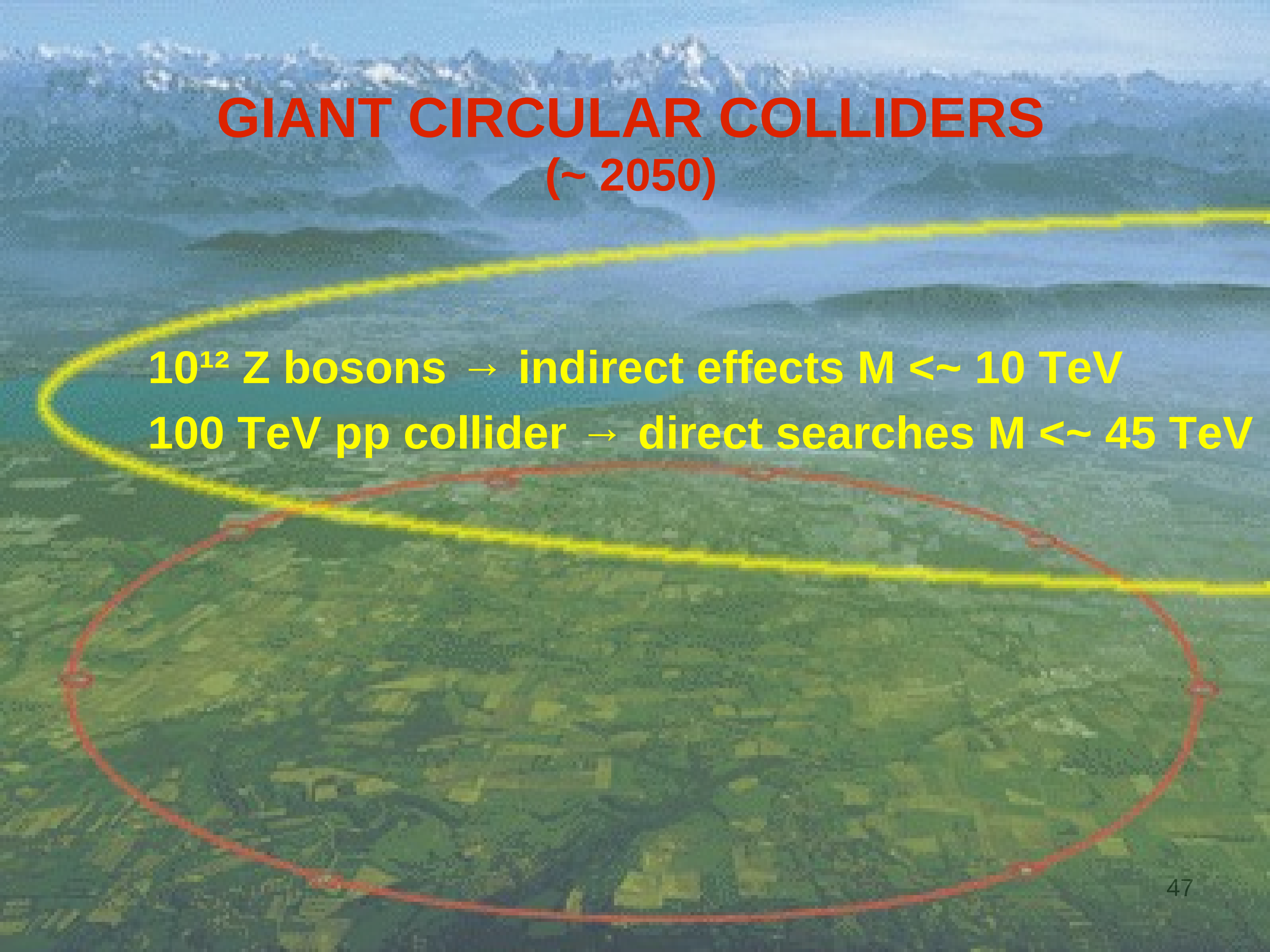
No monopoles found in 24 kg of polar volcanic rocks

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

LIMITS ON STELLAR MONOPOLE DENSITY IN THE SOLAR SYSTEM



CAN WE DO BETTER?



GIANT CIRCULAR COLLIDERS
(~ 2050)

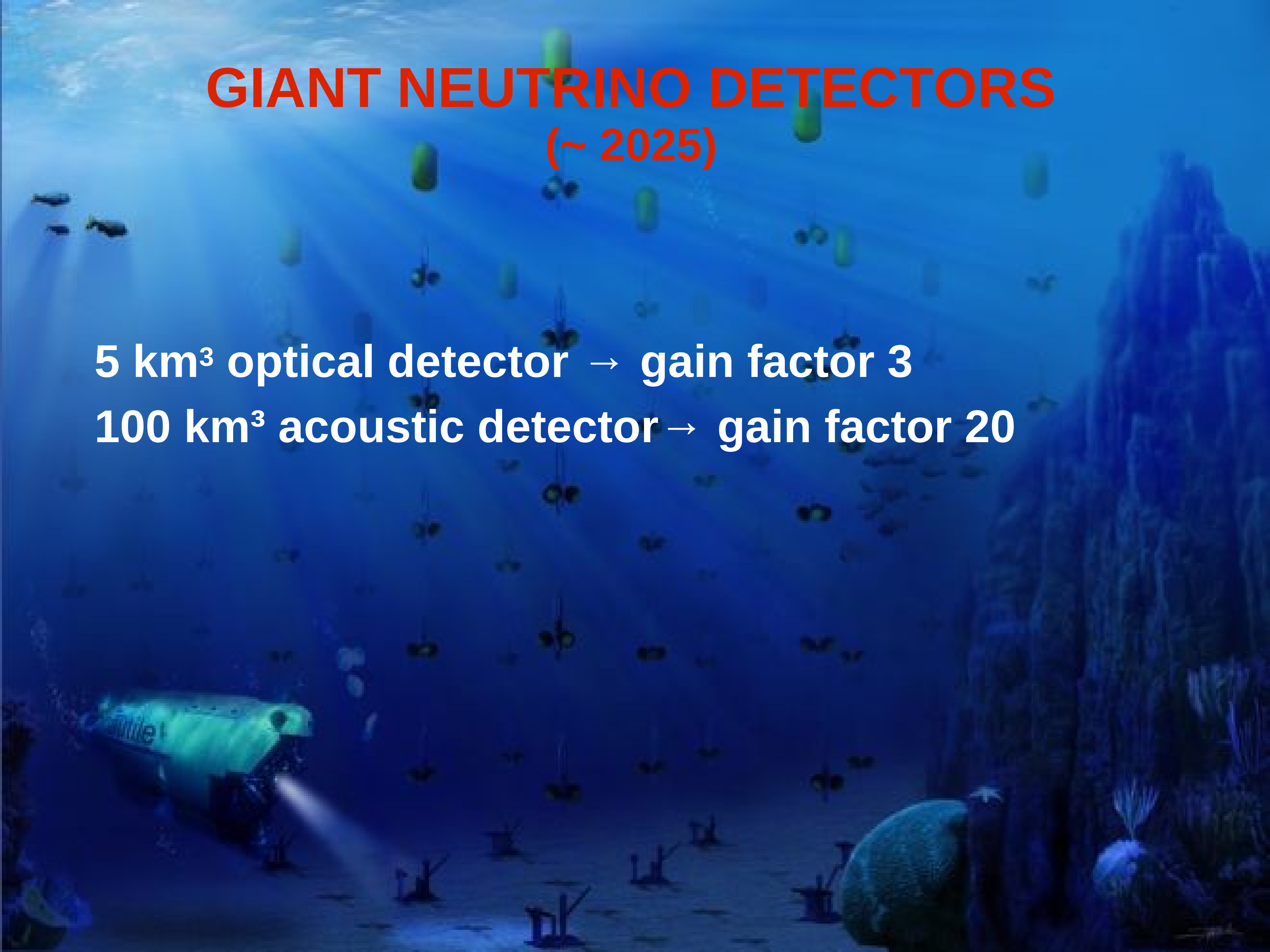
10^{12} Z bosons → indirect effects M <~ 10 TeV

100 TeV pp collider → direct searches M <~ 45 TeV

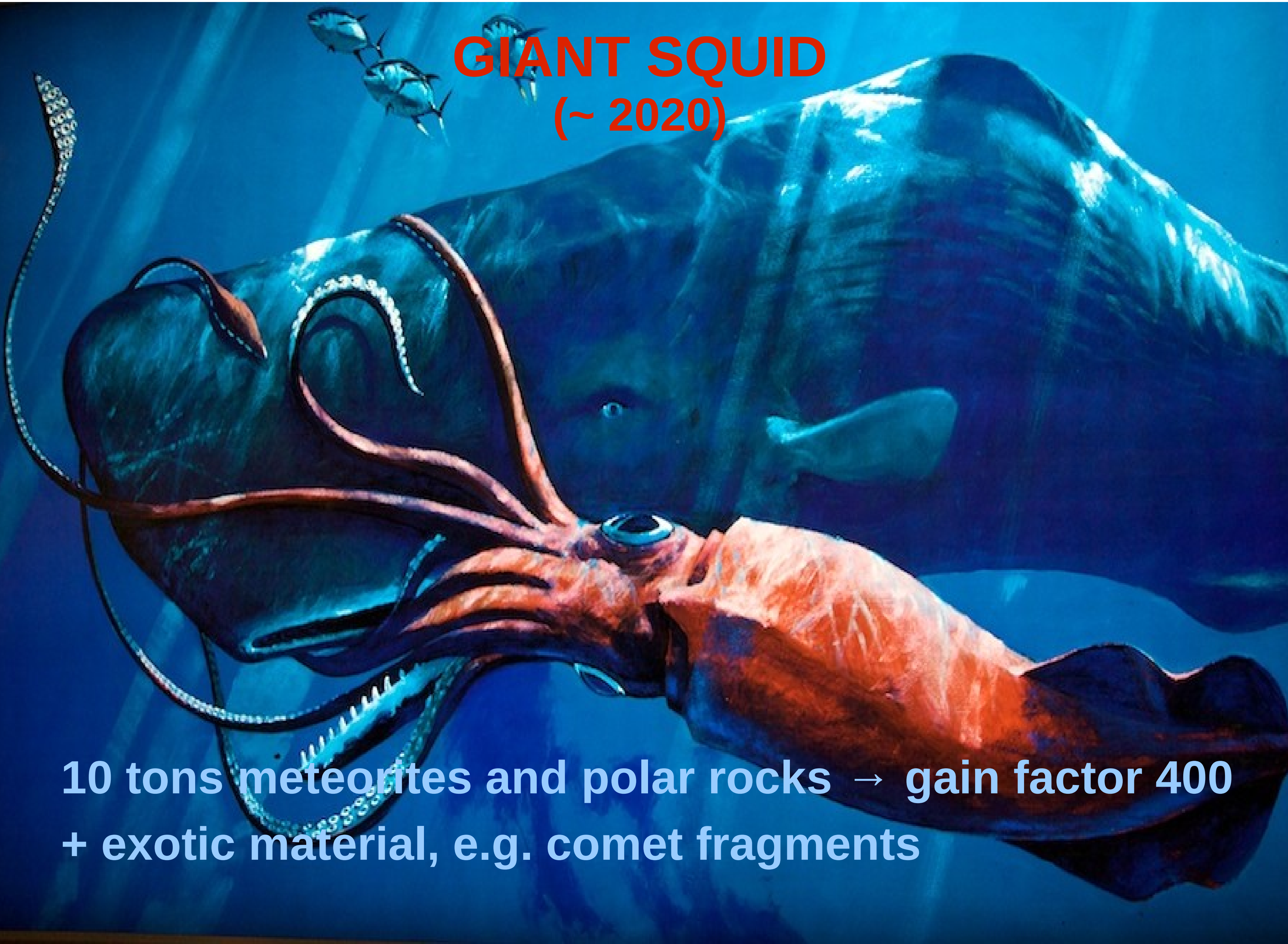
GIANT NEUTRINO DETECTORS
(~ 2025)

5 km^3 optical detector → gain factor 3

100 km^3 acoustic detector → gain factor 20



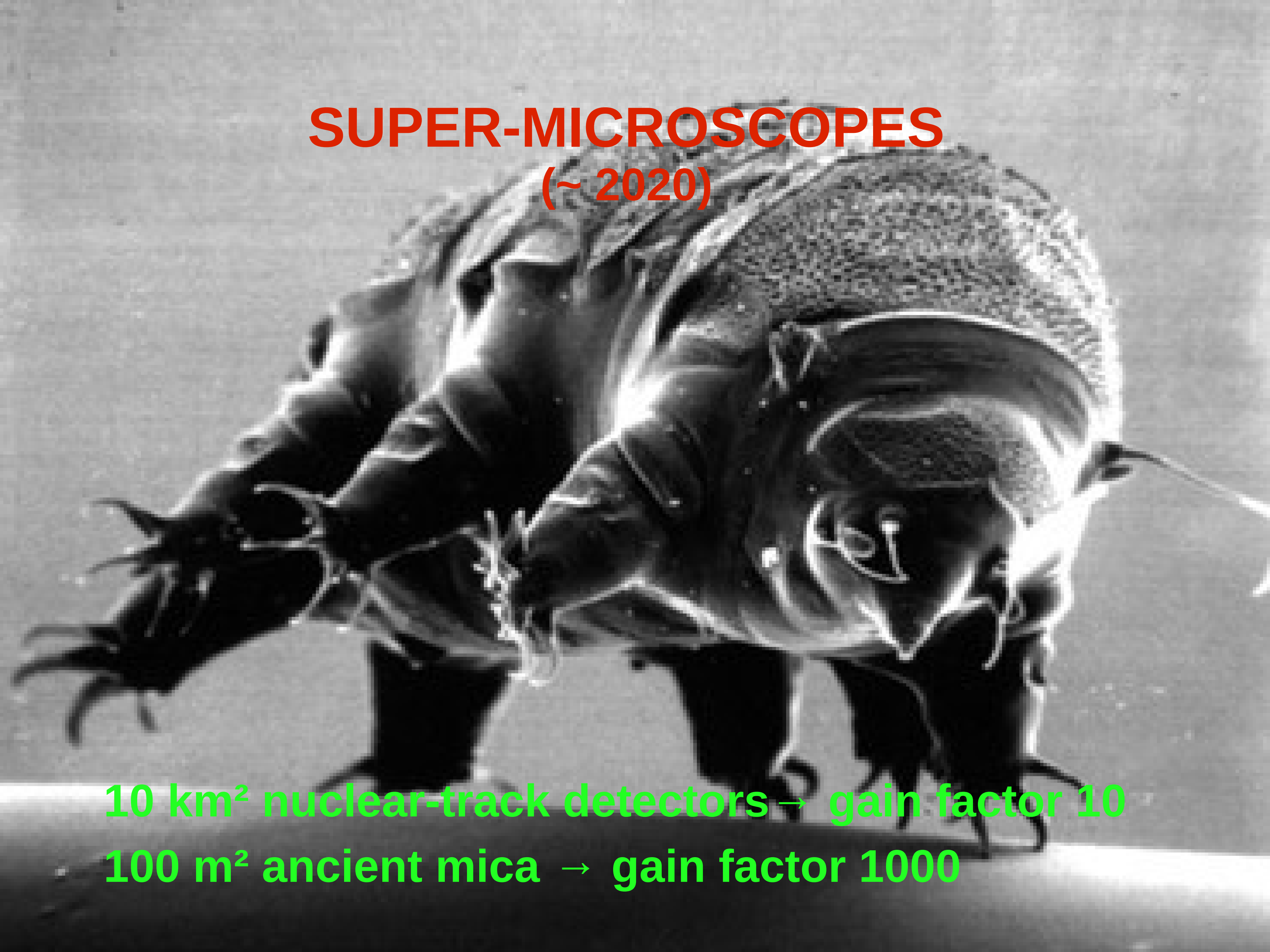
GIANT SQUID
(~ 2020)



10 tons meteorites and polar rocks → gain factor 400

+ exotic material, e.g. comet fragments

SUPER-MICROSCOPES
(~ 2020)



10 km² nuclear-track detectors → gain factor 10

100 m² ancient mica → gain factor 1000

Extra material

Monopole ionisation energy loss

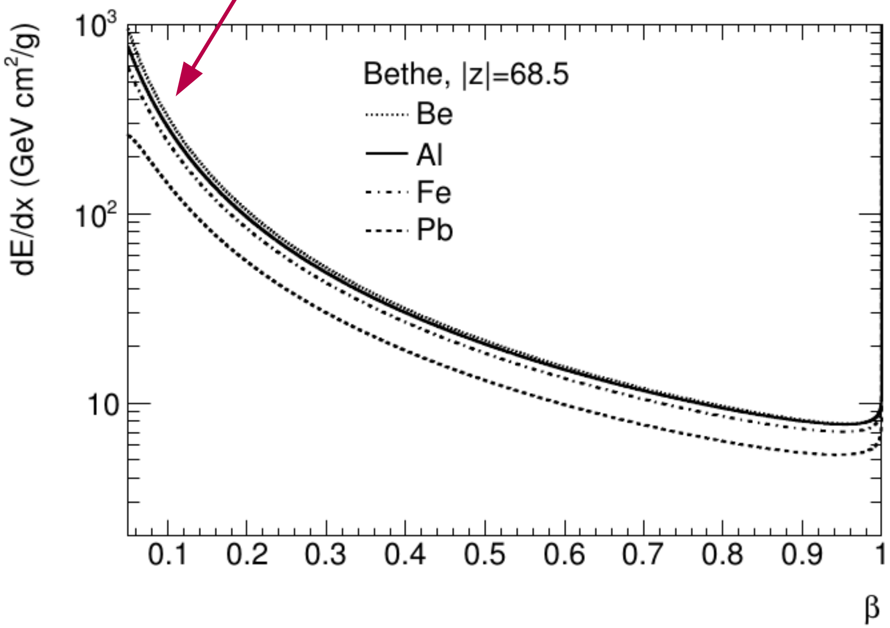
Electric

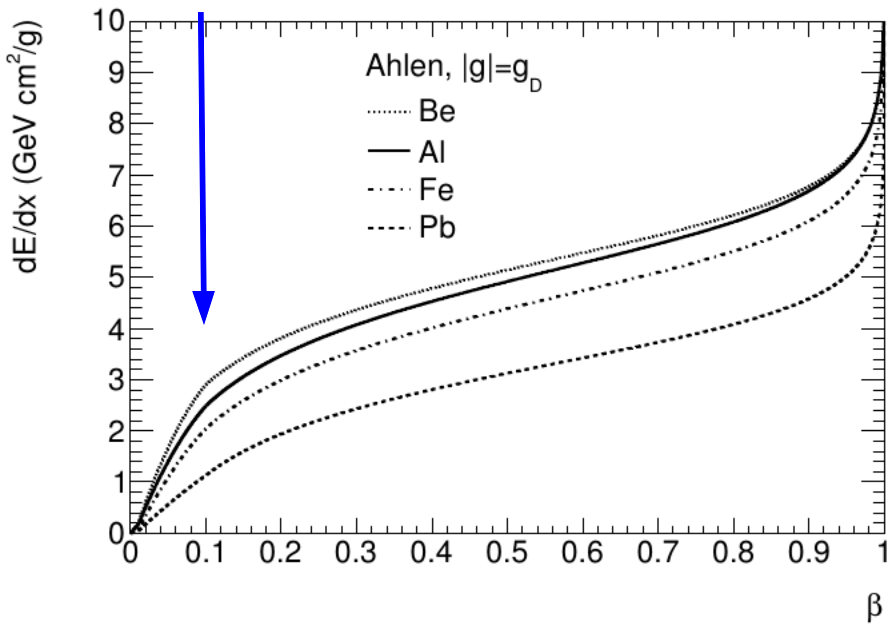
$$-\frac{\mathrm{d}E}{\mathrm{d}x} = K\frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\frac{2m_ec^2\beta^2\gamma^2}{I} - \beta^2\right]$$

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!





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

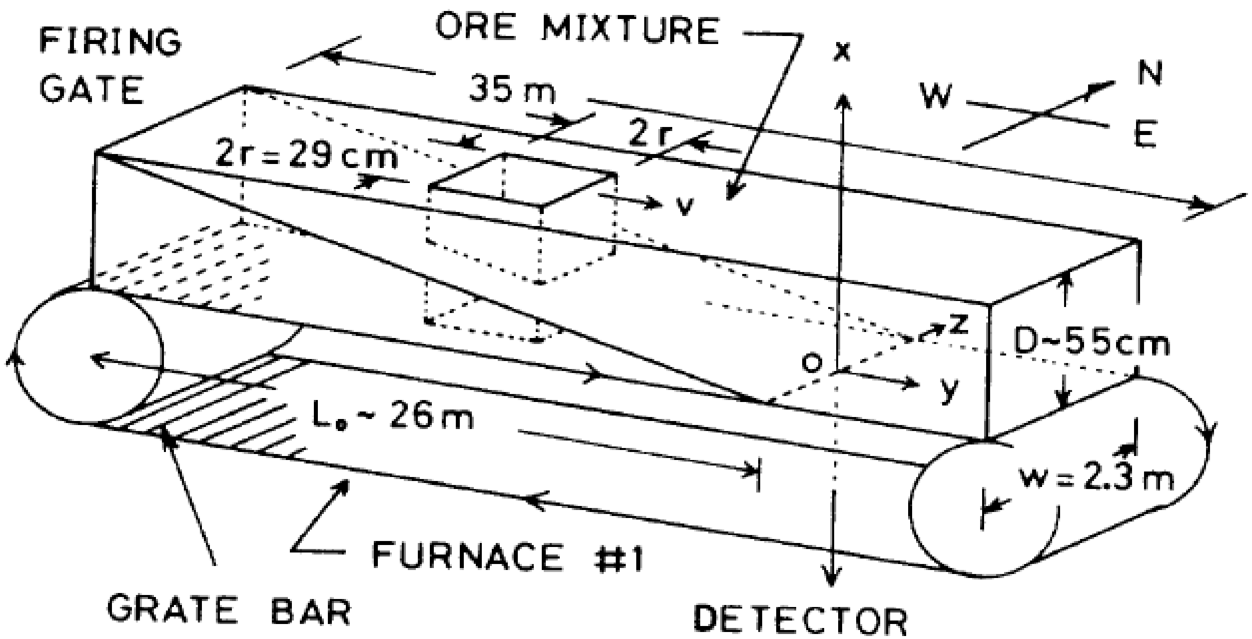
Iron ore (induction)

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

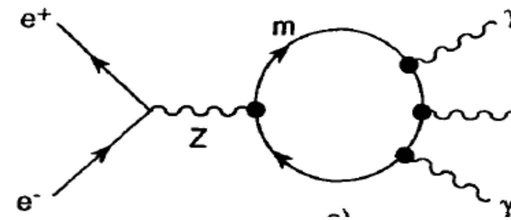
- Large amounts (>100 tons) of material
- Assume ferromagnetic binding

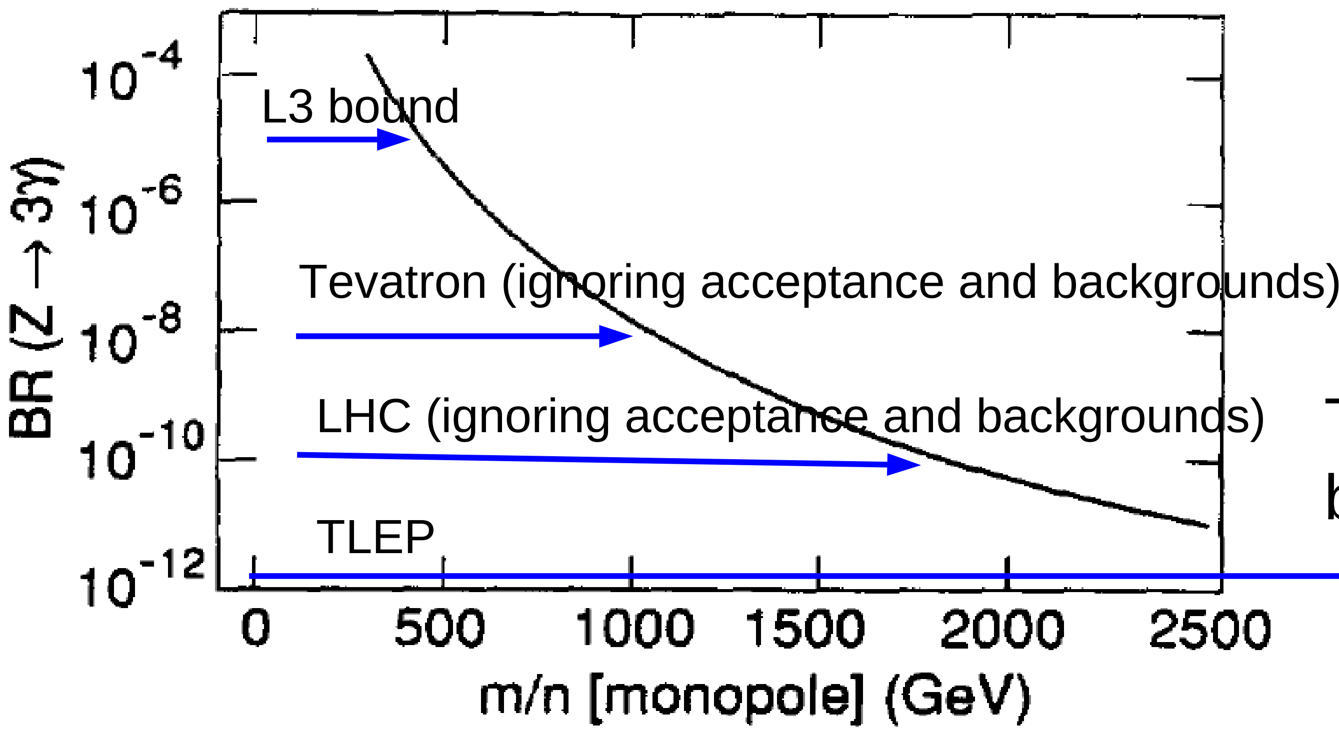
Must also assume no binding to nuclei!

PRD 36, 3359 (1987)



Z decay to three photons





TLEP would be awesome!

Monopoles in 100 TeV pp collisions

Contours with >5% acceptance