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Searches for magnetic monopoles: A review

Vasiliki A. Mitsou

Mini-workshop on Highly Ionising Avatars of New Physics

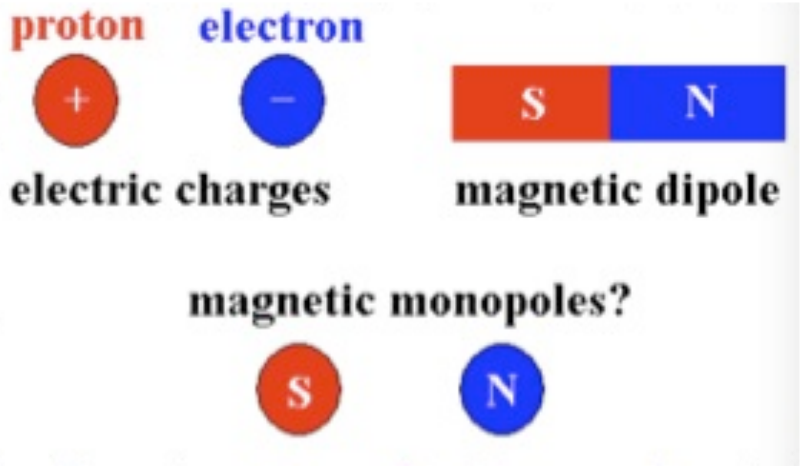
ICNFP 2018

7th International Conference on New Frontiers in Physics

4 – 12 July 2018, Kolymbari, Crete, Greece

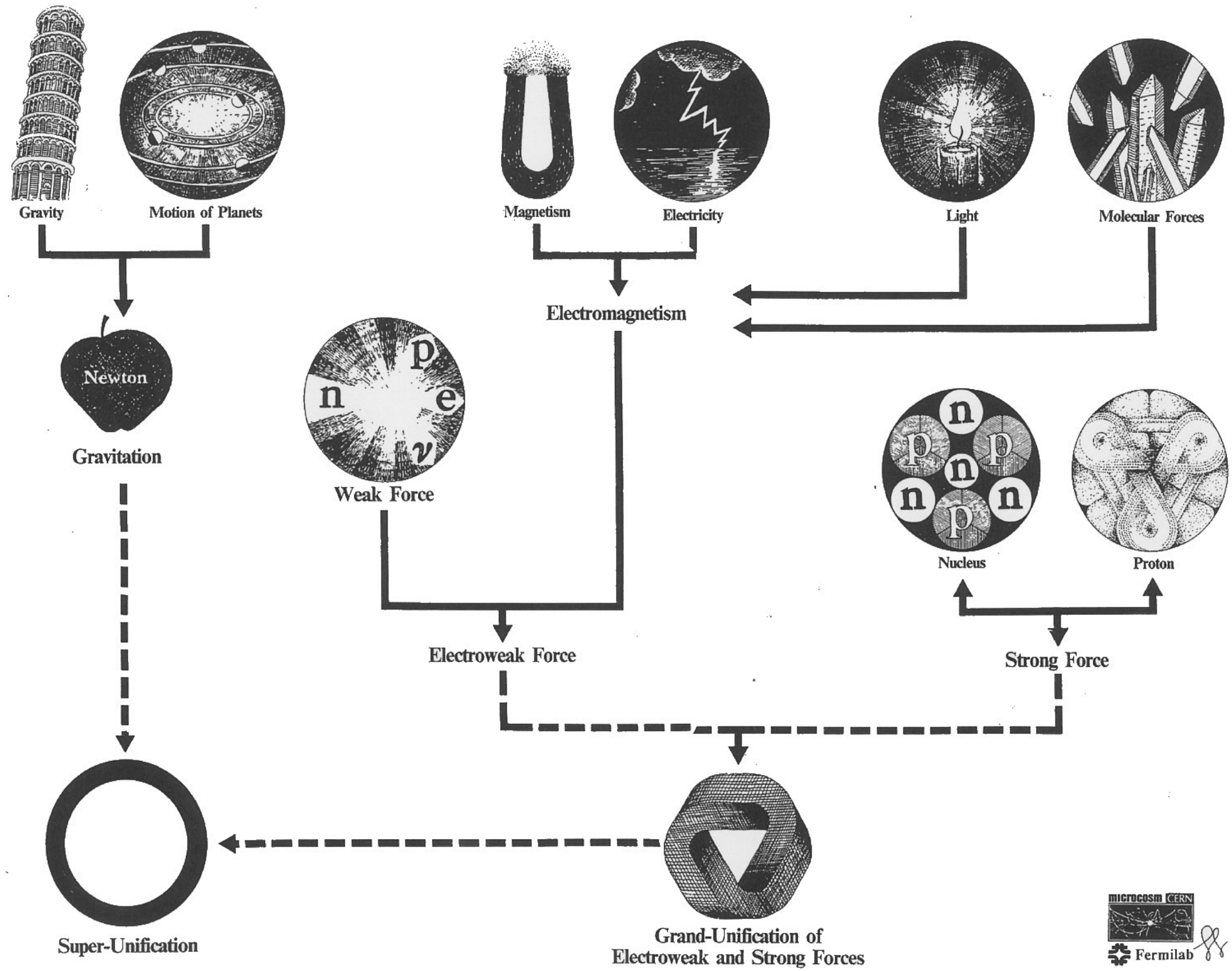
Magnetic monopoles

- Motivation
- (Some) theoretical proposals

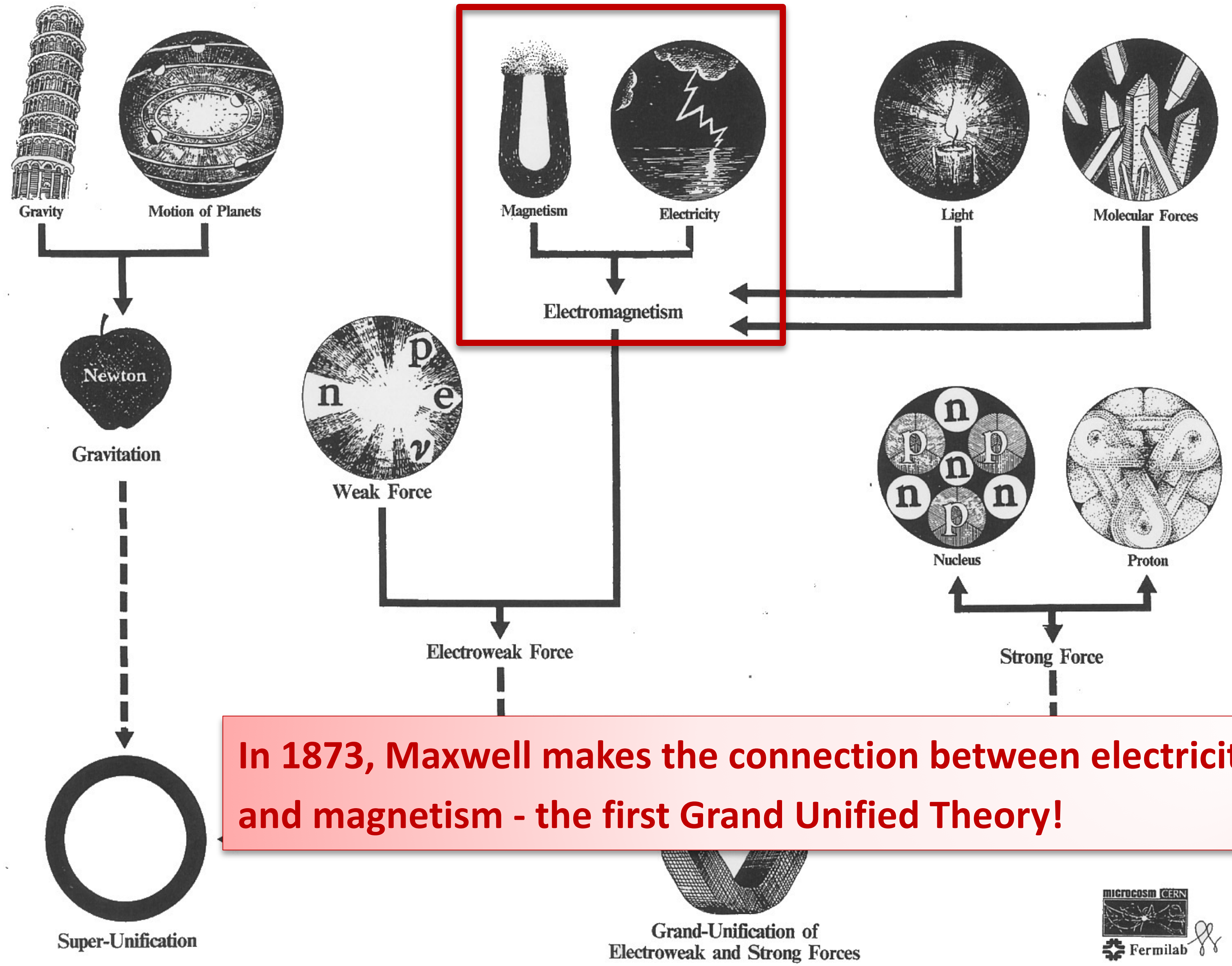


☞ talk by Sarben Sarkar in "Avatars" workshop

Unification of Forces



Unification of Forces



In 1873, Maxwell makes the connection between electricity and magnetism - the first Grand Unified Theory!

Magnetic monopoles: symmetrising Maxwell

- As no magnetic monopole had ever been seen, Maxwell kept isolated magnetic charges out from his equations – making them *asymmetric*
- A magnetic monopole restores the symmetry to Maxwell's equations

Name	Without Magnetic Monopoles	With Magnetic Monopoles
Gauss's law:	$\vec{\nabla} \cdot \vec{E} = 4\pi\rho_e$	$\vec{\nabla} \cdot \vec{E} = 4\pi\rho_e$
Gauss' law for magnetism:	$\vec{\nabla} \cdot \vec{B} = 0$	$\vec{\nabla} \cdot \vec{B} = 4\pi\rho_m$
Faraday's law of induction:	$-\vec{\nabla} \times \vec{E} = \frac{\partial \vec{B}}{\partial t}$	$-\vec{\nabla} \times \vec{E} = \frac{\partial \vec{B}}{\partial t} + 4\pi\vec{J}_m$
Ampère's law (with Maxwell's extension):	$\vec{\nabla} \times \vec{B} = \frac{\partial \vec{E}}{\partial t} + 4\pi\vec{J}_e$	$\vec{\nabla} \times \vec{B} = \frac{\partial \vec{E}}{\partial t} + 4\pi\vec{J}_e$

- Symmetrised Maxwell's equations invariant under rotations in (**E**, **B**) plane of the electric and magnetic field
- Duality ➤ distinction between electric and magnetic charge is only a matter of definition

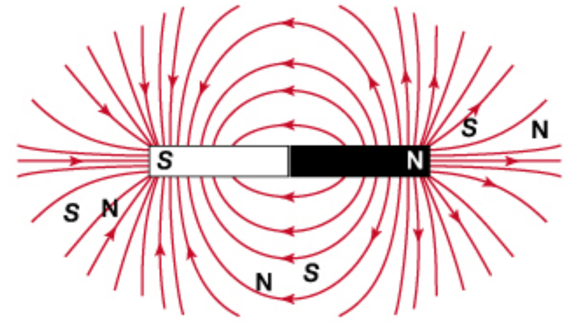
Dirac's monopole

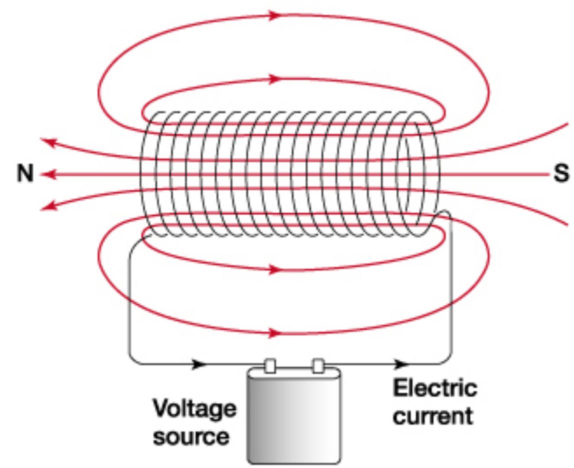
- Paul Dirac in 1931 hypothesised that the magnetic monopole exists
- In his conception the monopole was the end of an infinitely long and infinitely thin solenoid
- Dirac's quantisation condition:

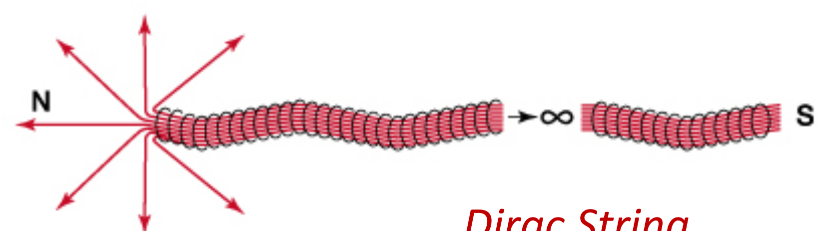
$$ge = \left[\frac{\hbar c}{2}\right]n \quad OR \quad g = \frac{n}{2\alpha}e \quad \left(from \quad \frac{4\pi eg}{\hbar c} = 2\pi n \quad n = 1,2,3..\right)$$

  - where **g** is the **magnetic charge** and α is the fine structure constant 1/137
- This means that **g = 68.5e** (when n=1)!
- If magnetic monopole exists then charge is quantised:

$$e = \left[\frac{\hbar c}{2g}\right]n$$





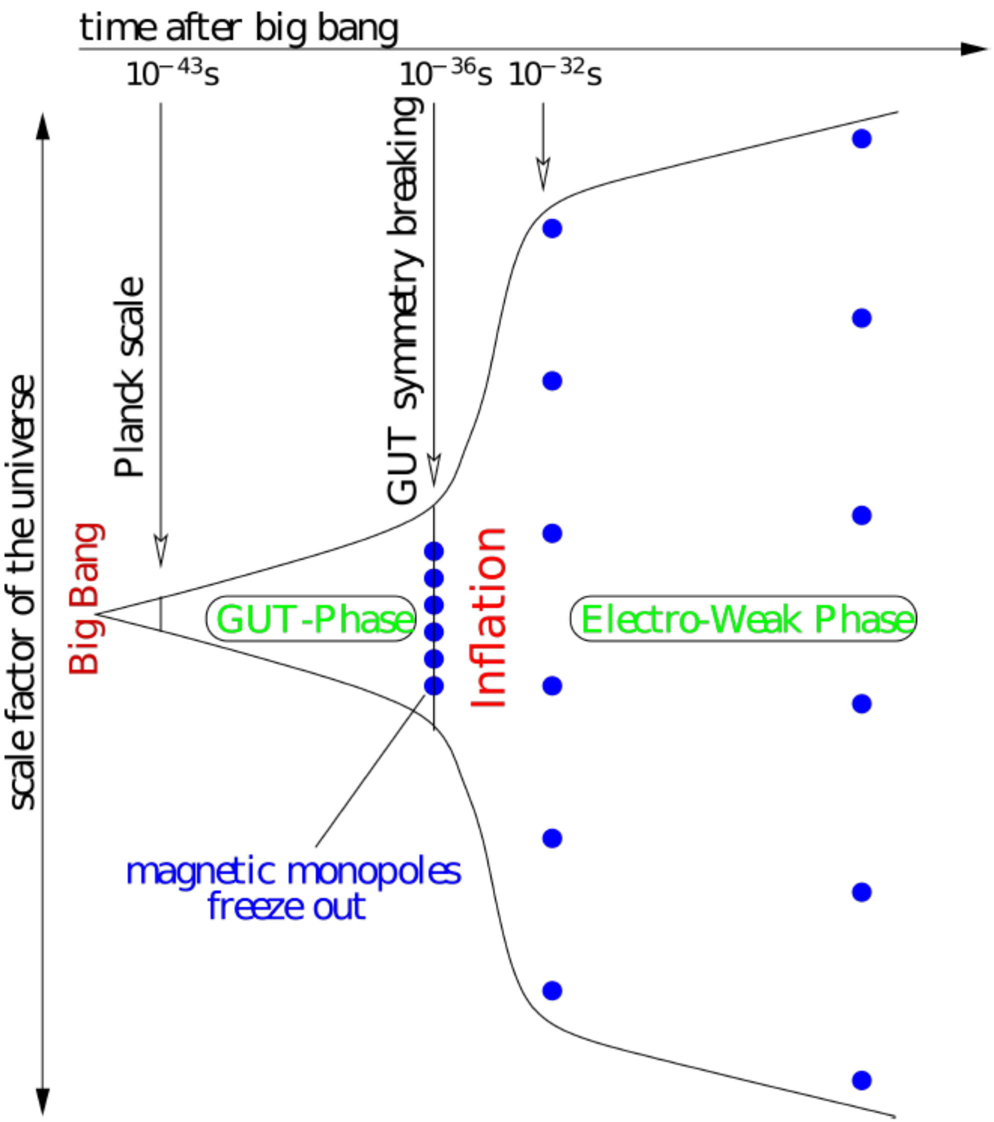


Dirac String

GUT monopoles

- 't Hooft and Polyakov (1974) showed that monopoles are fundamental solutions to non-Abelian gauge grand unification theories (GUTs)
- **Topological solitons**: stable, non-dissipative, finite-energy solutions
- Mass:
  - **10^{13} GeV < M < 10^{19} GeV**
  - in intermediate stages of symmetry breaking: **10^{7} GeV < M < 10^{13} GeV**

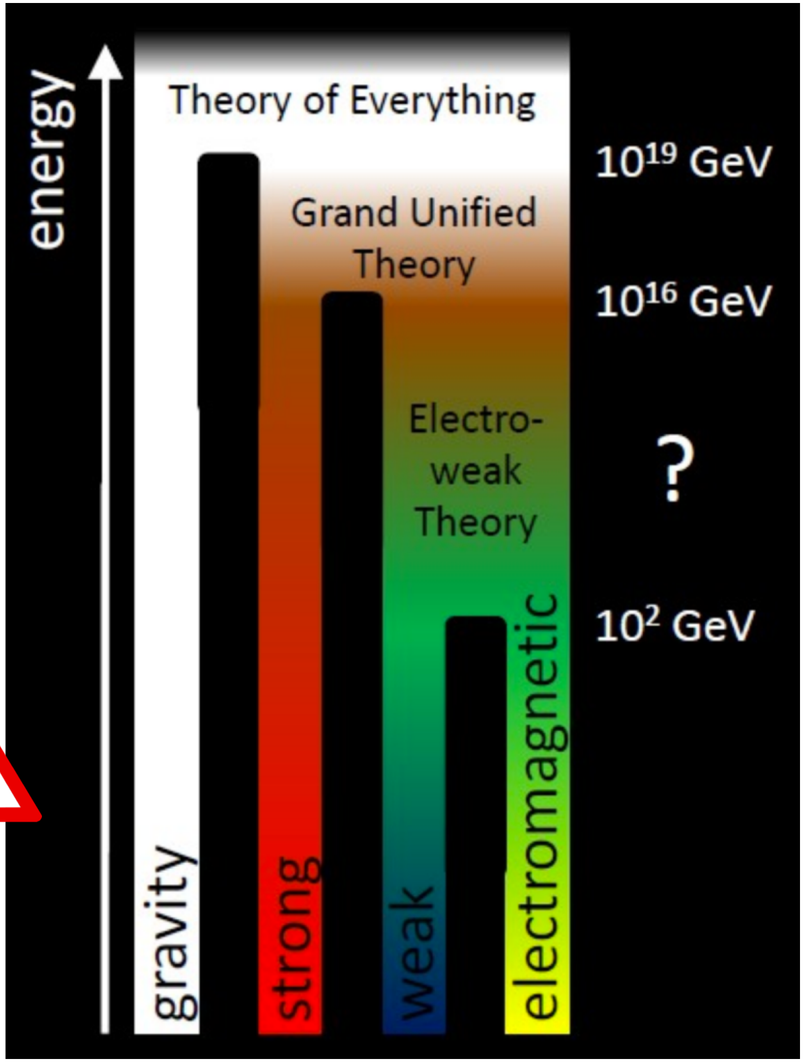
  → cannot be produced in accelerators
- Size: **extended object**
  - radius > few femtometers



T. Glüsenkamp 10

Electroweak monopole

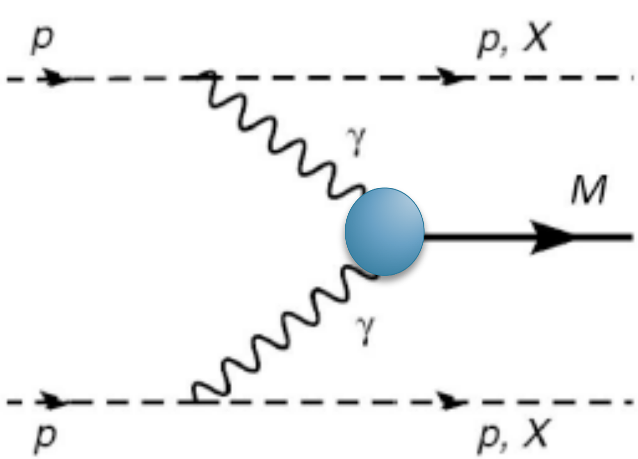
- In 1986 Cho & Maison [Phys.Lett. B391 (1997) 360], envisioned a spherically-symmetric electroweak (EW) monopole arising from the framework of the Weinberg-Salam model
- Non-trivial hybrid between the Dirac and the ‘t Hooft & Polyakov monopole
- Properties
  - charge $2g_D$
  - mass predicted to be ~4 ÷10 TeV ➜ accessible to LHC !
- *“The Price of an Electroweak Monopole”* Point-singularity makes estimate of mass classically impossible ➜ finite-energy solution needed [Ellis, Mavromatos, You, Phys.Lett. B756 (2016) 29]

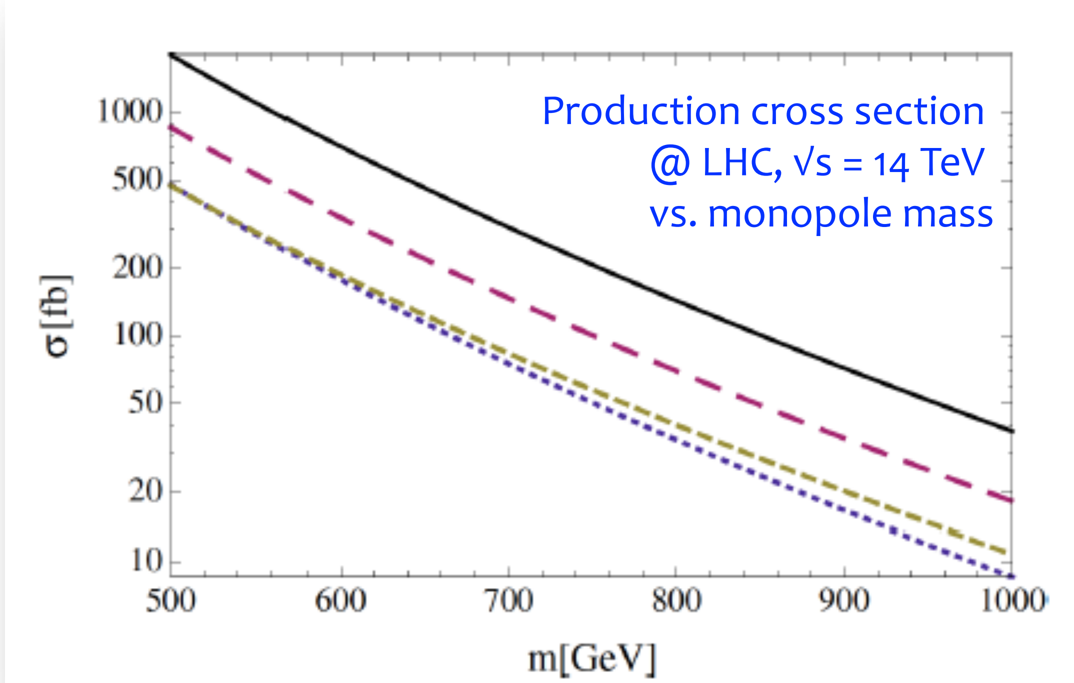


A. Rajantie

Monopolium

Dirac or other monopoles may not be free states but bound states
→ **monopolium** (MM)





$$\sigma(2\gamma \to M) = \frac{4\pi}{E^2} \frac{M^2\,\Gamma(E)\,\Gamma_M}{(E^2 - M^2)^2 + M^2\,\Gamma_M^2}$$

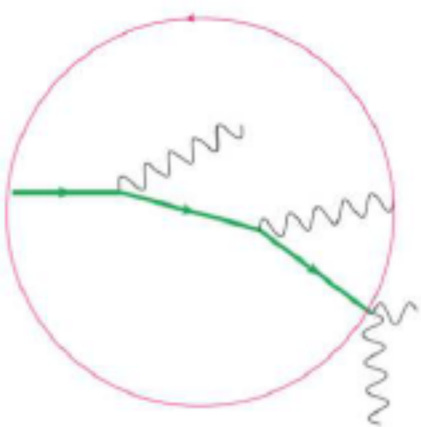
Binding energy fixed = 2m/15 , e.g.
for m=750 GeV, binding energy = 100 GeV
→ monopolium mass M = 1400 GeV

Epele, Fanchiotti, Garcia-Canal, VAM, Vento, EPJ Plus 127 (2012) 60 [arXiv:1205.6120 [hep-ph]]

Monopolium detection

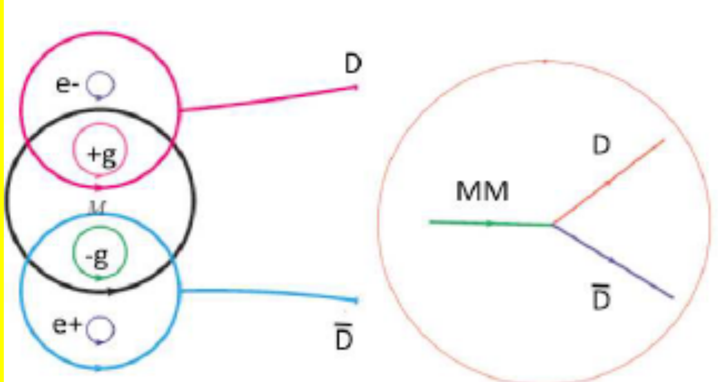
- Via its decay to **two photons** [Epele, Fanchiotti, Garcia-Canal, VAM, Vento, arXiv:1607.05592]
- Monopolium is neutral in its ground state thus, if produced in such a state, it is difficult to detect it directly
- However… it may be produced in an excited state, which could be a magnetic multiple ➜ highly ionising

☞ talk by Vicente Vento in "Avatars" workshop



Its decay via photon emission would produce a **peculiar trajectory** in the medium, if the decaying states are also magnetic multipoles

Monopolium might break up into highly-ionising **Dyons**



In presence of magnetic fields ➤ huge polarisability $d \sim r_M^3 B \sim (\alpha E_{binding})^{-3} B$

V. Vento, in MoEDAL Physics Review, Int.J.Mod.Phys. A29 (2014) 1430050

Magnetic monopole properties in a nutshell

- Single magnetic charge (Dirac charge): $g_D = 68.5e$
  - higher charges are integer multiples of Dirac charge: $g = ng_D$, $n = 1, 2, \ldots$
  - if carries electric charge as well, is called Dyon
- Large coupling constant: $g/\hbar c \sim 34$
- Monopoles would *accelerate* along field lines – and *not curve* as electrical charges in a magnetic field – according to the Lorentz equation

$$\vec{F} = g\left(\vec{B} - \vec{v} \times \vec{E}\right)$$

- Dirac monopole is a point-like particle; GUT monopoles are extended objects
- Monopole spin is not determined by theory → free parameter
- Monopole mass not predicted within Dirac's theory; other theories predict masses from $\mathcal{O}$(TeV) (electroweak) to $\gtrsim 10^{17}$ GeV (GUT) → free parameter
- Monopole interaction with matter: high ionisation, Cherenkov radiation, transition radiation and multiple scattering

Searches for magnetic monopoles

- Detection techniques
- Past results
- Currently operating experiments

☞ talk by Laura Patrizii on July 7th

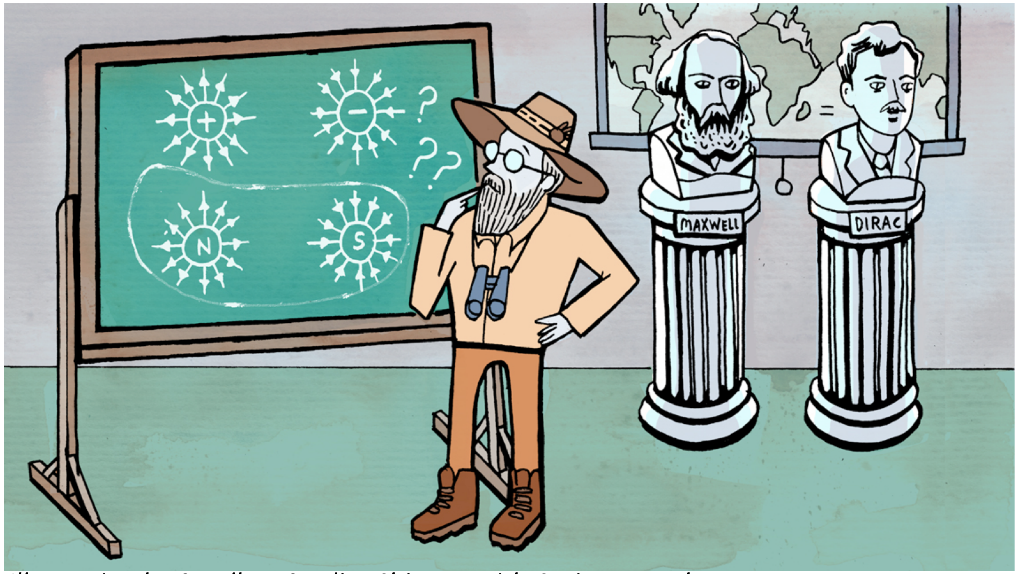
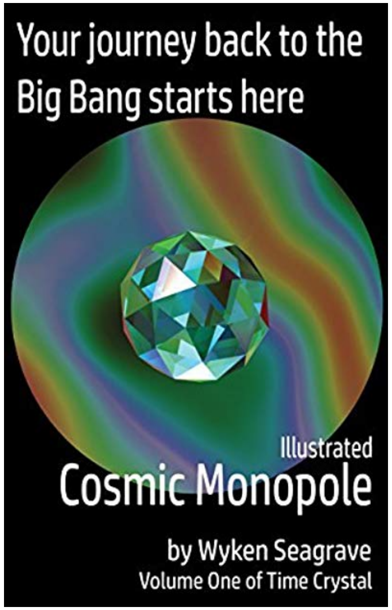
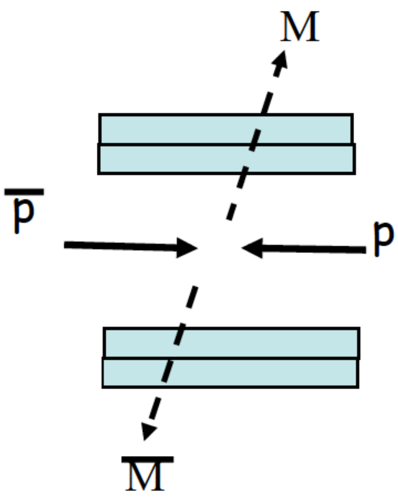


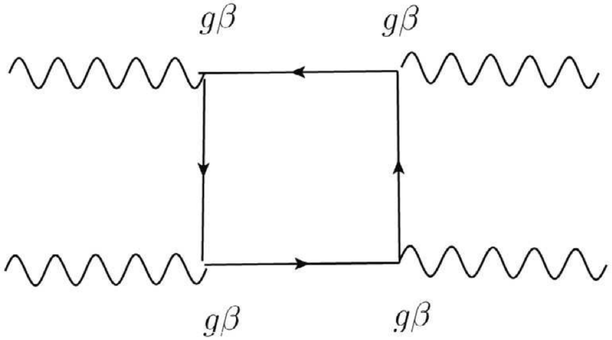
Illustration by Sandbox Studio, Chicago with Corinne Mucha

Monopole origin

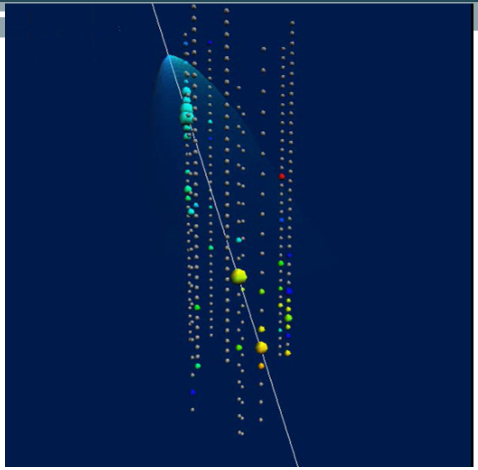
- Cosmic monopoles
  - only way to probe GUT-scale monopoles
- Monopoles produced in high-energy collisions
  - only ≲ TeV masses accessible
  - plus: indirect detection of virtual monopoles yielding multi-photon events
- Various detection techniques can be (have been) deployed to detect both cosmic and collider monopoles
  - certain limitations apply





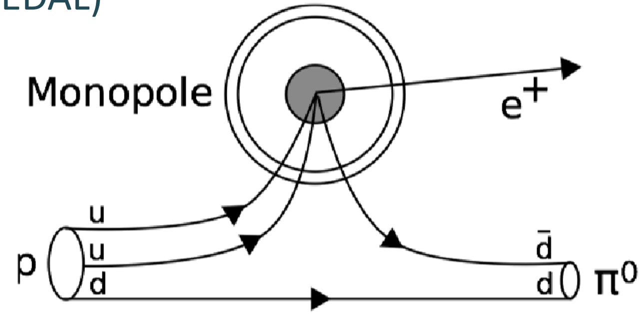


Detection techniques



- High ionisation in gaseous detectors – transition radiation
  - MACRO, ATLAS, …
- Induction technique in superconductive coils (SQUID)
  - initially for cosmic monopoles; not competitive with other techniques nowadays
  - for monopoles trapped in material: rocks, beam pipes, …
- Cherenkov light in scintillators
  - cosmic monopoles
  - balloon-borne experiments
  - deep-sea/ice experiments: ANTARES, IceCube

- Energy loss in nuclear track detectors
  - cosmic (SLIM, …)
  - colliders: PETRA, Tevatron (D0), LEP (MODAL, OPAL), LHC (MoEDAL)
- Catalysis of nucleon decay
  - GUT monopoles may catalyse B-number violating decays via the Callan-Rubakov mechanism
  - Soudan, MACRO, IMB
  - ν-telescopes: IceCube, Super-Kamiokande



Energy loss

$$\frac{\text{charge}}{\text{velocity: } \beta = v/c} = z/\beta$$

$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]$$

Electric charge

Bethe-Bloch formula

High ionisation (HI) possible when:

- multiple electric charge (H^{++}, Q-balls, etc.) = n × e
- very low velocity & electric charge
- magnetic charge (monopoles, dyons) = ng_D = n × 68.5 × e
  - a singly charged relativistic monopole has ionisation ~4700 times MIP!!
- any combination of the above

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

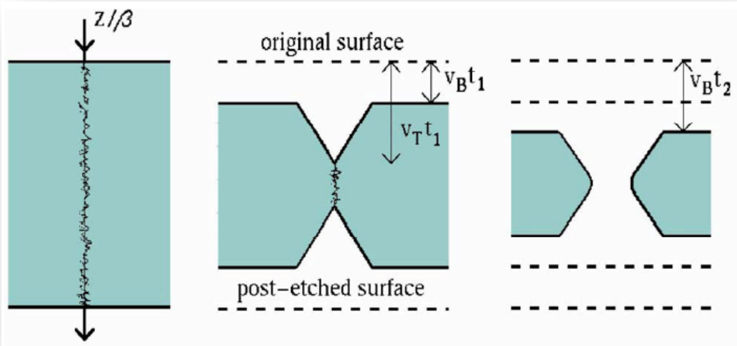
Magnetic charge

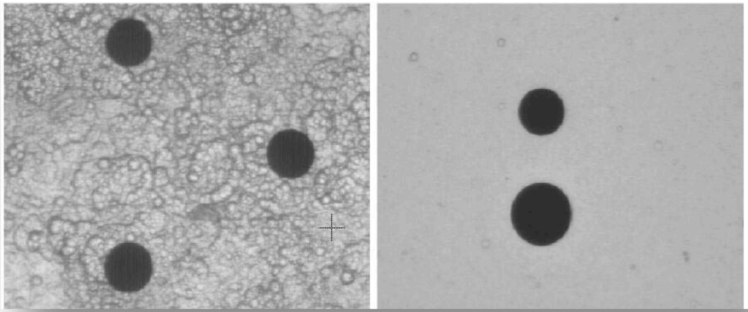
Ahlen formula

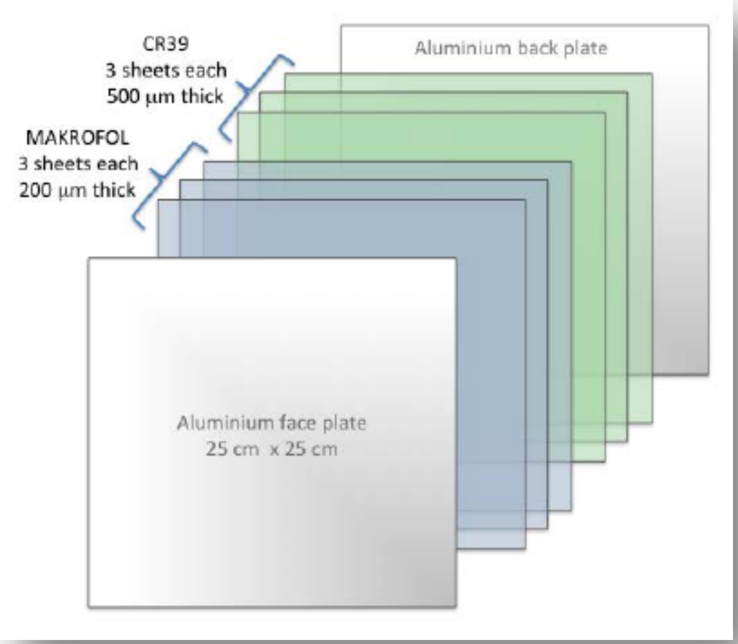
☞ talks by Igor Ostrovskiy & by Stanislav Pospisil in "Avatars" workshop

Nuclear Track Detectors (NTDs)

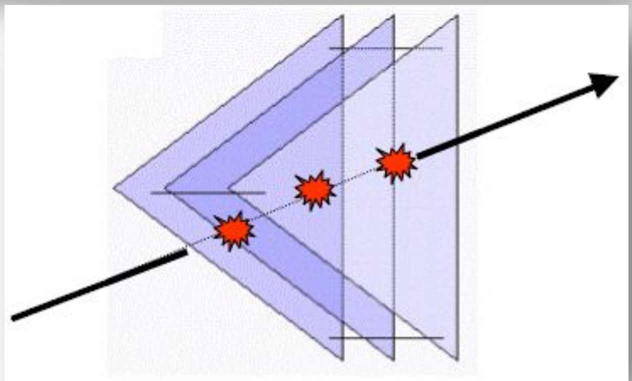
- Passage of a highly ionising particle through the plastic NTD marked by an invisible damage zone (**"latent track"**) along the trajectory
- The damage zone is revealed as a **cone-shaped etch-pit** when the plastic sheet is chemically **etched**
- Plastic sheets are later **scanned** to detect etch-pits



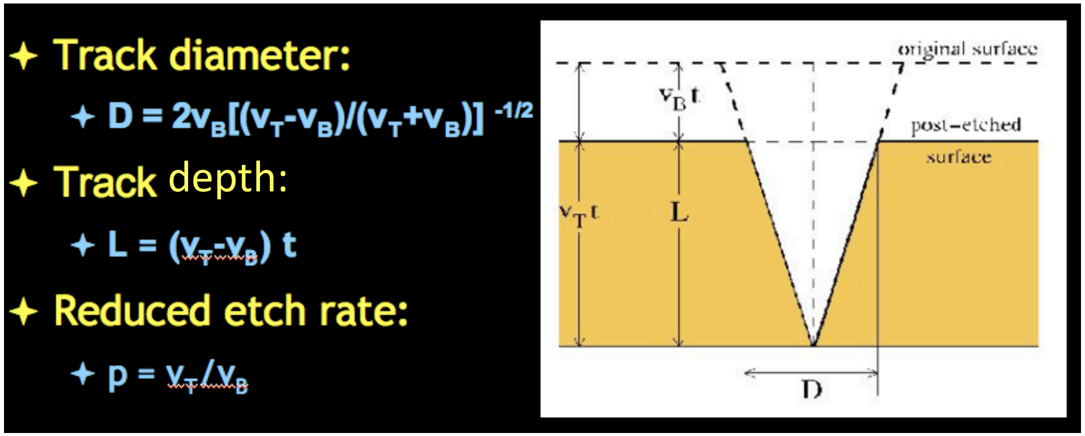


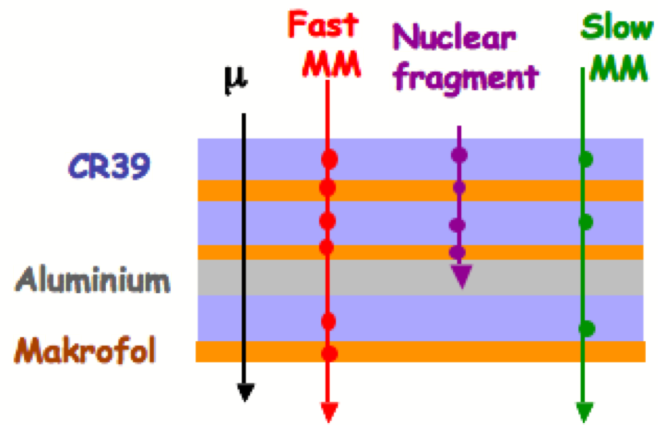


Looking for aligned etch pits in multiple sheets



NTD analysis procedure



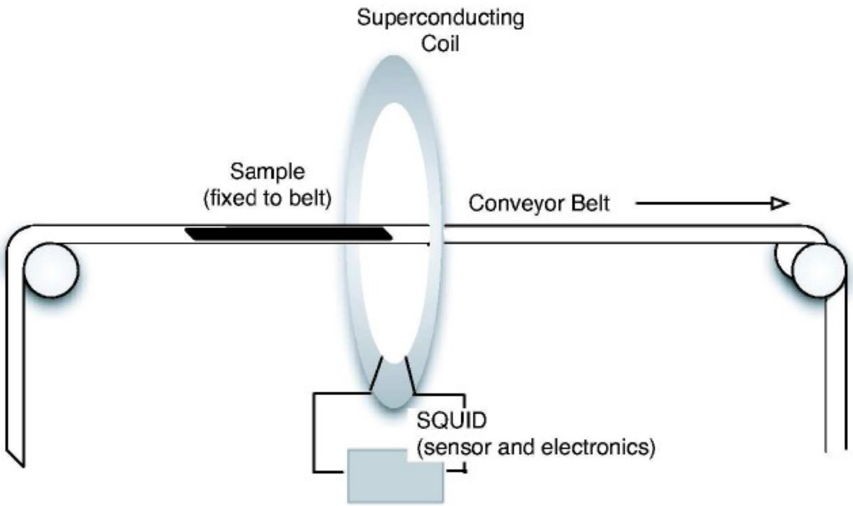


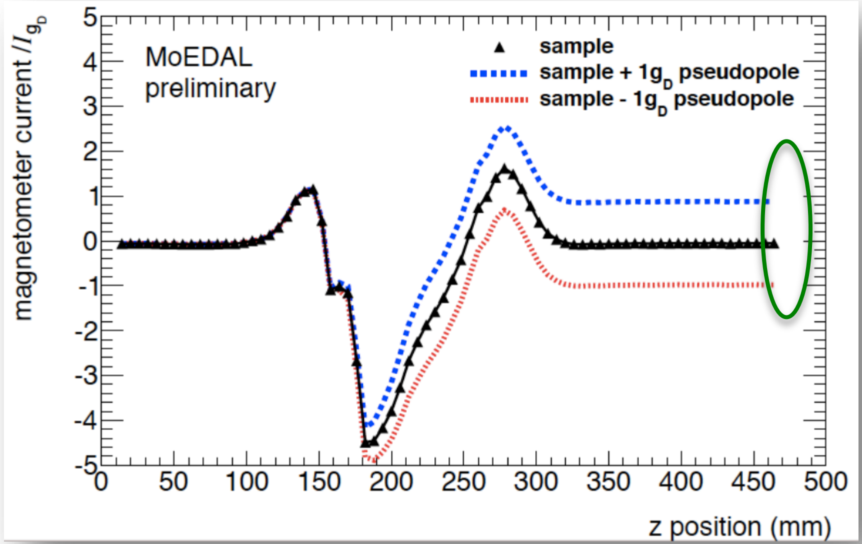
- Electrically-charged particle: $dE/dx \sim \beta^{-2}$ ➔ slows down appreciably within NTD ➔ opening angle of etch-pit cone becomes **smaller**
- Magnetic monopole: $dE/dx \sim \ln\beta$
  - slow MM: slows down within an NTD stack ➔ its ionisation falls ➔ opening angle of the etch pits would become **larger**
  - relativistic MM: dE/dx essentially constant ➔ trail of equal diameter etch-pit pairs
- The reduced etch rate is simply related to the *restricted energy loss* $REL = (dE/dx)_{\text{10nm from track}}$

see, e.g. Cecchini, Patrizii, Sahnoun, Sirri, Togo, arXiv:1606.01220

Induction technique

- Binding energy of monopoles in nuclei with finite magnetic dipole moments → $\mathcal{O}$(100 keV)
- Monopole trapping volumes analysed with superconducting quantum interference device (SQUID)
- **Persistent current:** difference between resulting current after and before
  - first subtract current measurement for empty holder
  - if other than zero → *monopole signature*

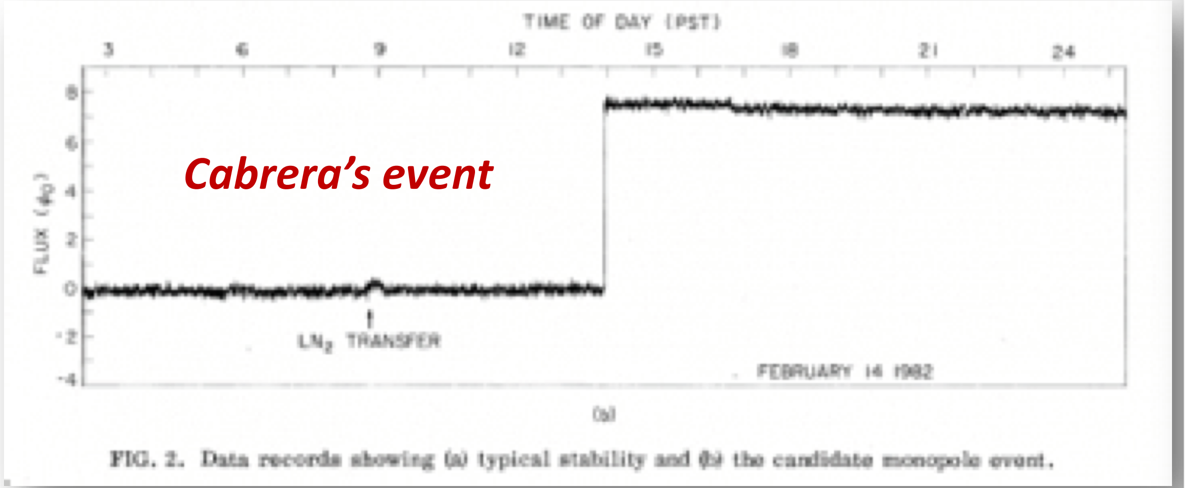




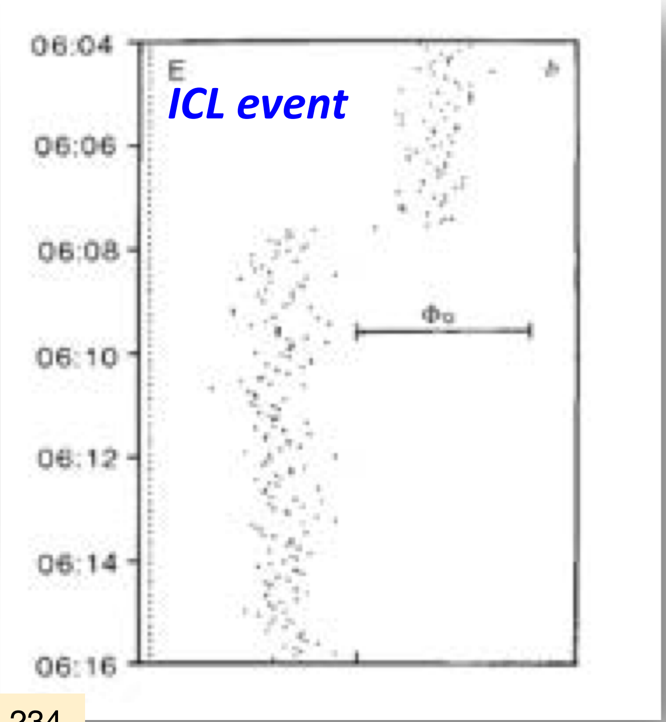
Typical sample & pseudo-monopole curves

Induction – evidence?

- Data from Cabrera's apparatus taken on St. Valentine's day in 1982
  - the trace shows a jump consistent with a monopole traversing the coil
- In August 1985 a group at Imperial College London reported the "observation of an unexpected event" also compatible with a monopole traversing the detector
  - however their analysis conclude that *"it is increasingly likely that Cabrera's original candidate event was spurious"*

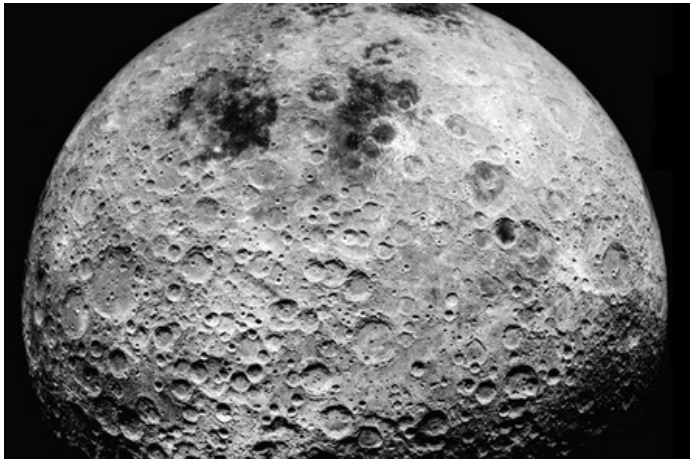


Phys.Rev.Lett. 48 (1982) 1378

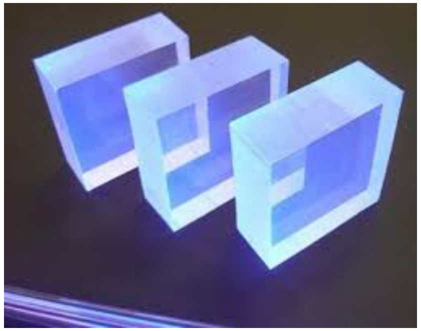


Nature 317 (1985) 234

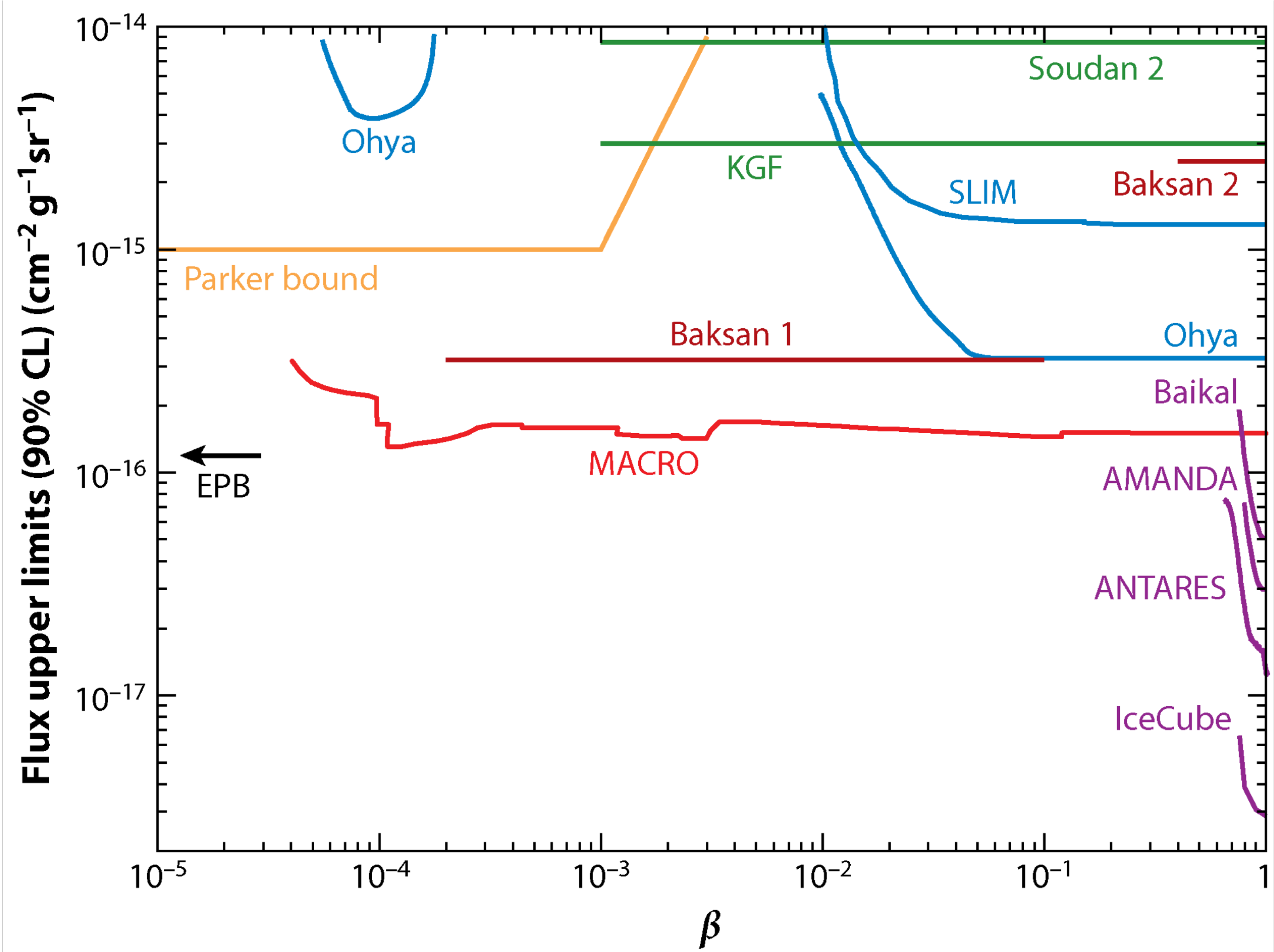
Monopoles of cosmic origin



- Searches in bulk matter
  - terrestrial magnetic materials
  - meteorites
  - moon rocks: One of the first scientific experiments with moon rocks was to search for a concentration of magnetic monopoles
- Searches in cosmic rays
  - passive detectors, e.g. NTDs
  - Cherenkov detectors
  - scintillators
  - streamer tubes
  - nucleon-decay catalysis
- Galactic magnetic field implies that monopole flux has to respect an upper limit
  → Parker bound



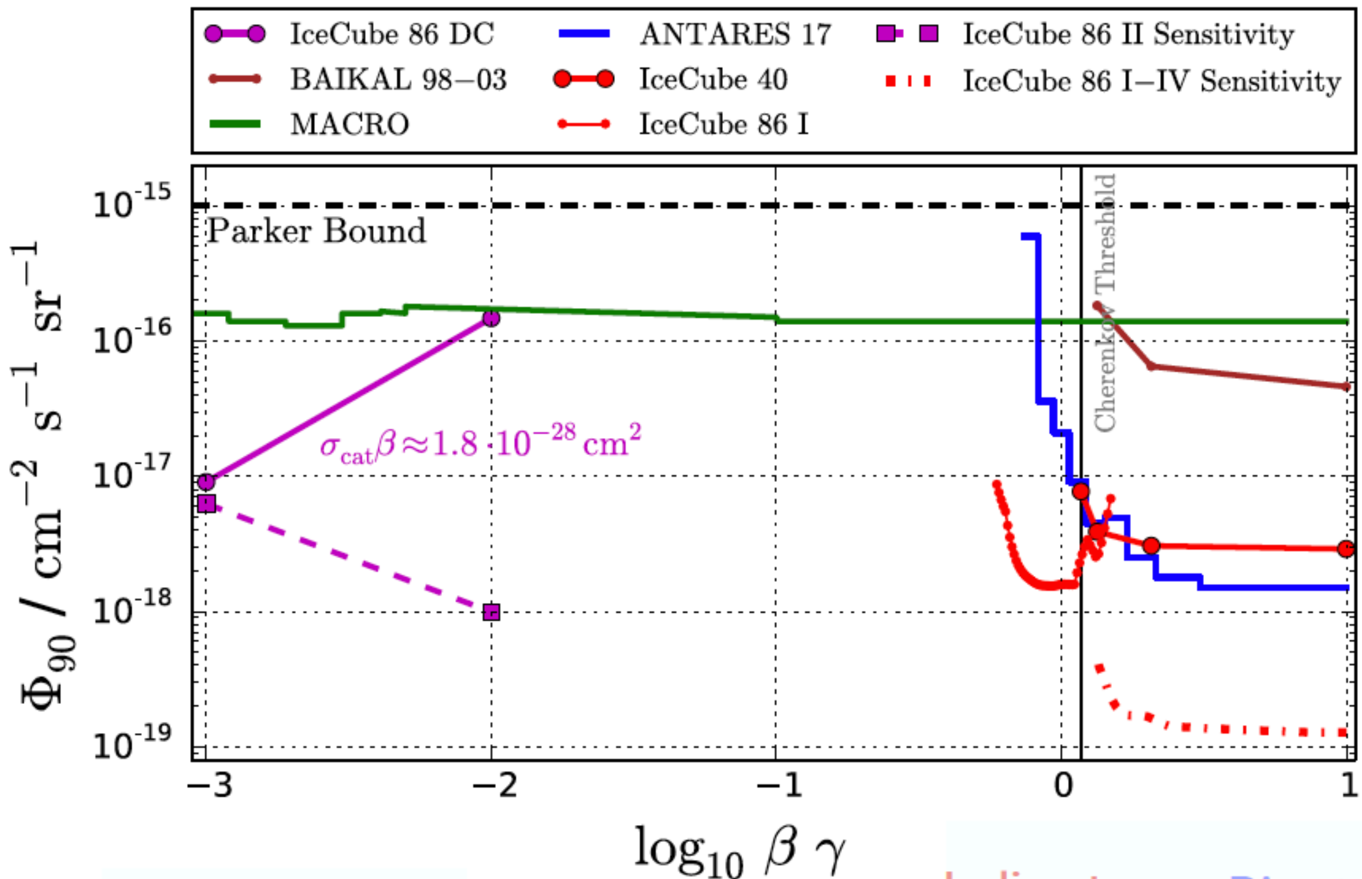
Cosmic monopole searches



Patrizii L, Spurio M. 2015.
Annu. Rev. Nucl. Part. Sci. 65:279–302

tracking calorimeter | scintillators | NTDs | ν-telescopes

Focus on "fast" (β>0.1) monopoles



Catalysis of proton decay

Luminescence

Indirect Cherenkov radiation

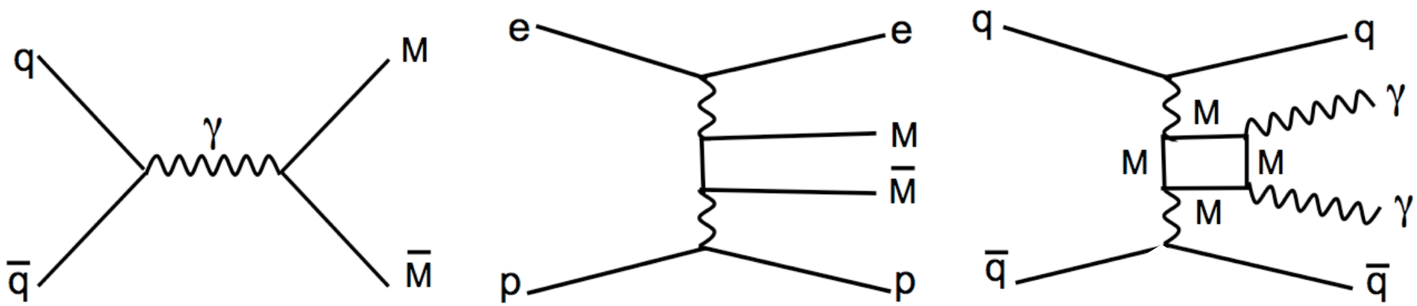
Direct Cherenkov radiation

☞ talk by Anna Pollmann in "Avatars" workshop

arXiv:1610.06397

Monopole production at colliders

Production mechanisms in colliders



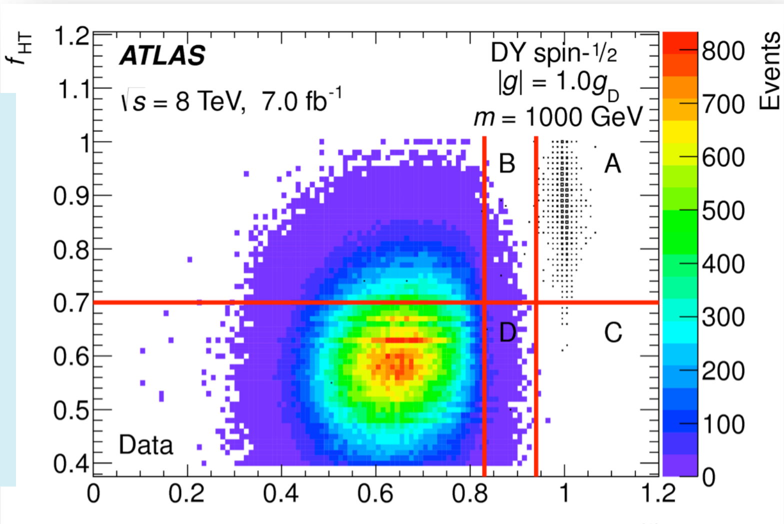
Drell Yan mechanism | Photon fusion | Box diagram

- Various high ionisation techniques (including NTDs) and induction (D0, CDF, HERA) have been used to search for monopoles at colliders
- Dirac monopole production with $\sigma > 0.05$ pb at **LEP** was excluded by OPAL for $45 <$ mass < 102 GeV [Phys.Lett. B663 (2008) 37]
- CDF @ **Tevatron** excluded MM pair production at the 95% CL for cross-section < 0.2 pb and monopole masses $200 < m_M < 700$ GeV [Phys.Rev.Lett. 96 (2006) 201801]

ATLAS @ LHC

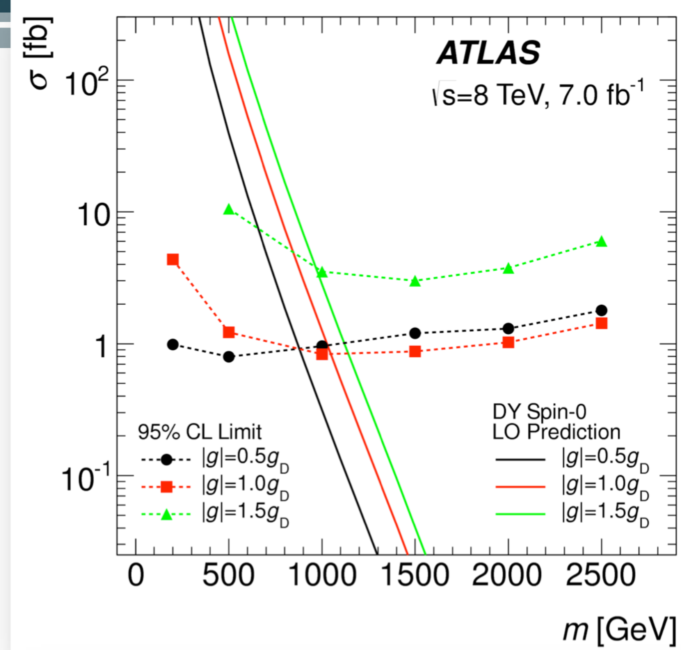
- Distinct signals in Transition Radiation Tracker (high-threshold hit) and EM calorimeter (large localised energy deposit)
- Upper cross-section limits set for Dirac monopoles of mass of 200 – 2500 GeV
- Magnetic charges probed: $0.5 < |g| < 2.0\ g_D$

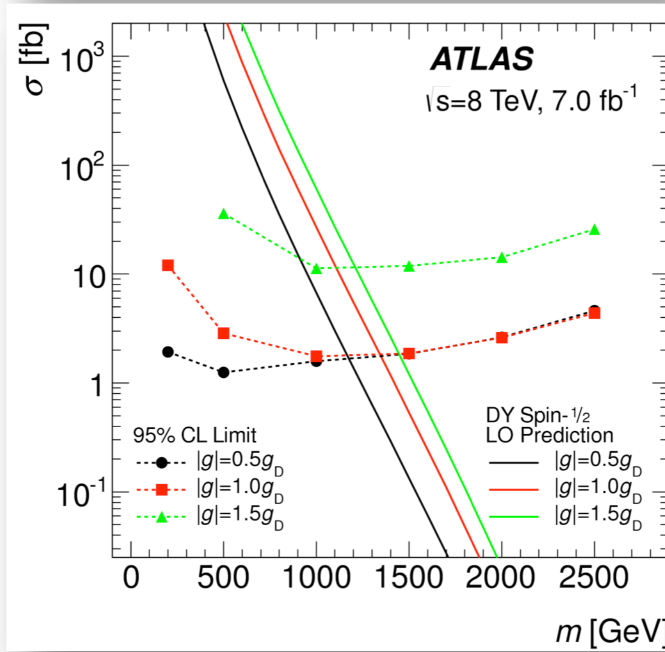
fraction of HT TRT hits



energy-dispersion variable in EM calorimeter

PRD 93, 052009 (2016)

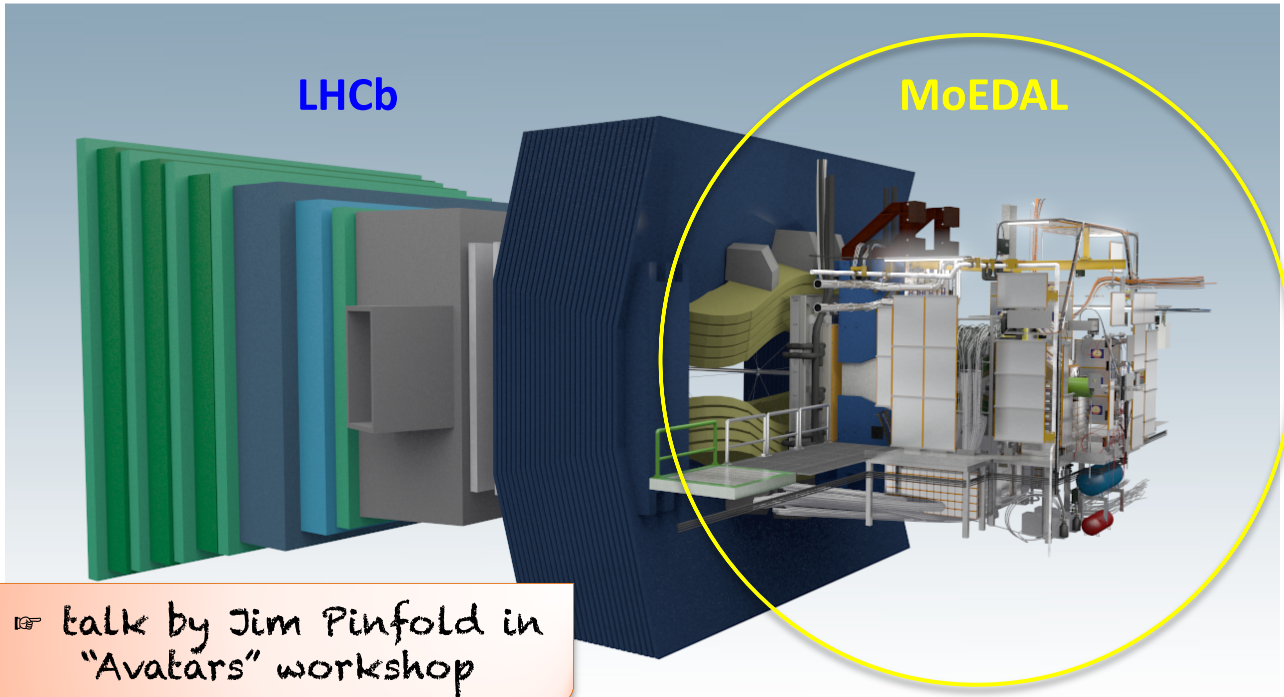




☞ talk by Judita Mamuzic in "Avatars" workshop

Monopole & Exotics Detector At LHC

MoEDAL



☞ talk by Jim Pinfold in "Avatars" workshop

MoEDAL is unlike any other LHC experiment:

- mostly **passive detectors**; no trigger; no readout
- the largest deployment of passive **Nuclear Track Detectors (NTDs)** at an accelerator
- the 1st time **trapping detectors** are deployed as a detector

DETECTOR SYSTEMS

① Low-threshold NTD (**LT-NTD**) array
  - $z/\beta >$ ~5 – 10

② Very High Charge Catcher NTD (**HCC-NTD**) array
  - $z/\beta >$ ~50

③ Monopole Trapping detector (**MMT**)

④ TimePix radiation background monitor

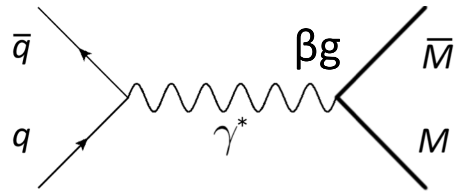
MoEDAL physics program
Int. J. Mod. Phys. A29 (2014) 1430050
[arXiv:1405.7662]

Latest MoEDAL results

- More exposure **(× 5.7)** including 2016
- New interpretations w.r.t. previous analyses
  - **spin-1 monopoles**
  - **β-dependent $\gamma M\bar{M}$ coupling**

DY lower mass limits [GeV]		Magnetic charge |g|				
		g_D	$2g_D$	$3g_D$	$4g_D$	$5g_D$
MoEDAL 13 TeV 2015+2016 exp.	spin 0	600	1000	1080	950	690
	spin ½	1100	1540	1600	1400	—
	spin 1	1100	1640	1790	1710	1570
	spin 0, β-dep.	490	880	960	890	690
	spin ½, β-dep.	850	1300	1380	1250	1070
	spin 1, β-dep.	930	1450	1620	1600	1460
MoEDAL 13 TeV 2015 exp.	spin 0	460	760	800	650	—
	spin ½	890	1250	1260	1100	—
MoEDAL 8 TeV	spin 0	420	600	560	—	—
	spin ½	700	920	840	—	—
ATLAS 8 TeV	spin 0	1050	—	—	—	—
	spin ½	1340	—	—	—	—

Detector: **222 kg** of Al bars
Exposure: **2.11 fb^{-1}** of *pp* collisions

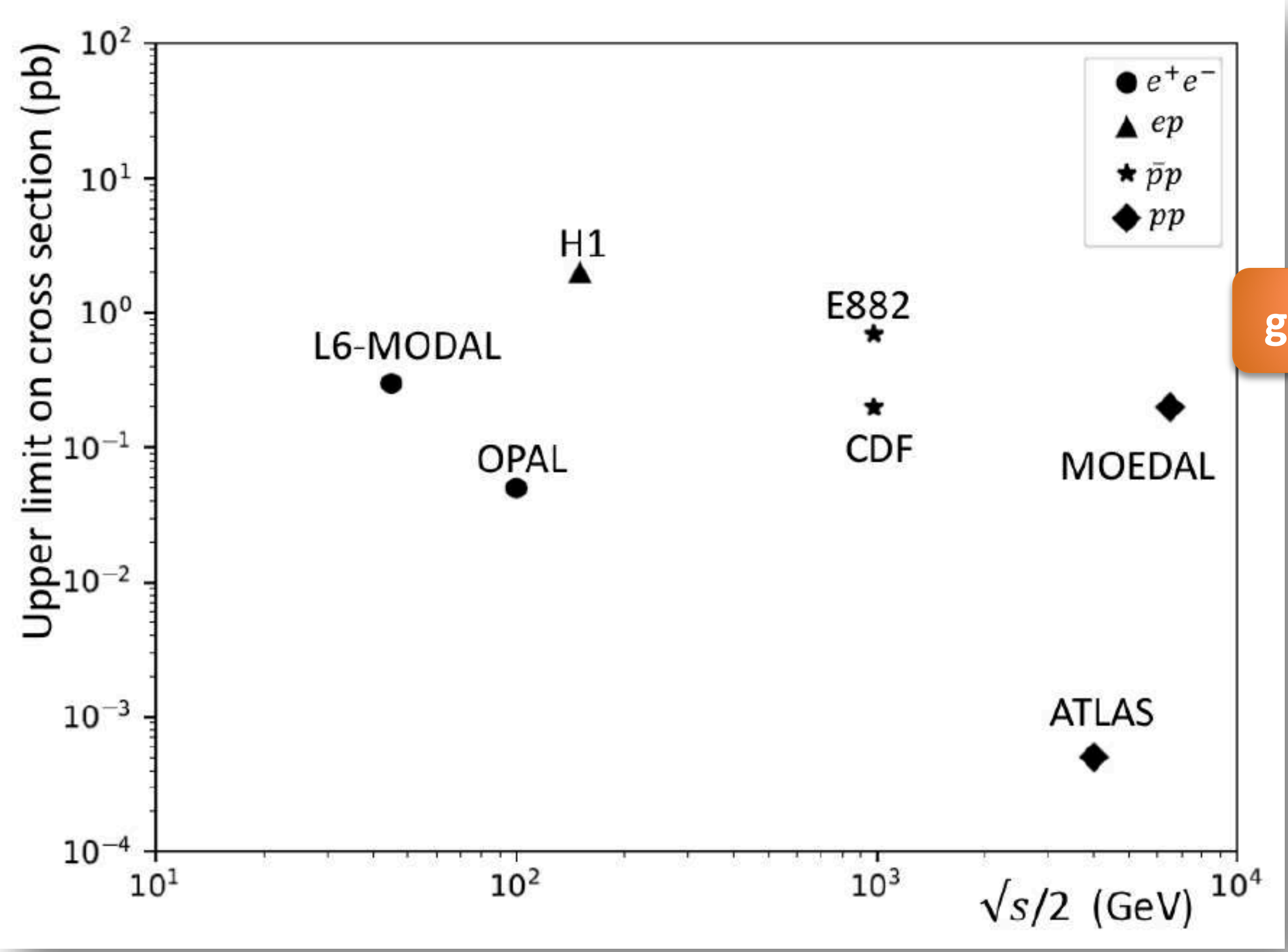


- Mass limits are *highly model-dependent*
  - Drell-Yan production does *not* take into account non-perturbative nature of the large monopole-photon coupling
- World-best collider limits for **|g| ≥ 2 g_D**

PLB 782 (2018) 510 [arXiv:1712.09849]

for γ-fusion ☞ talks by Stephanie Baines & Arka Santra in "Avatars" workshop

Collider searches summary (as of August 2017)



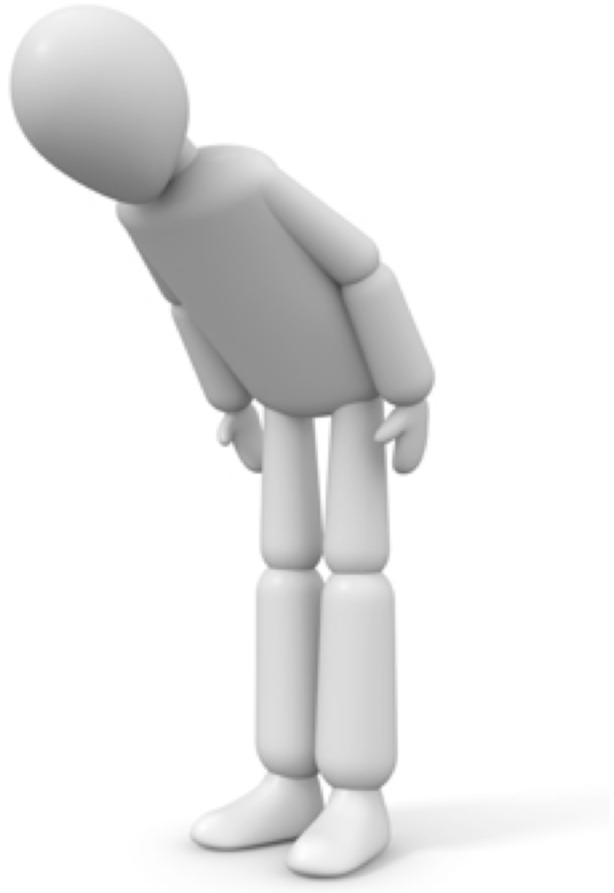
$g = g_D$

RPP, Chin.Phys. C40 (2016) 100001

Outlook

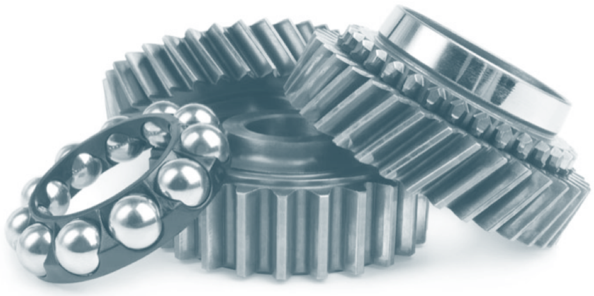
- Monopoles continue to excite interest and have been the subject of numerous experimental searches
- There are several strong arguments to expect that magnetic monopoles exist
- The MoEDAL experiment at the LHC is one of the key players in this quest
- **Stay tuned for upcoming results !**

Thank you for your attention!



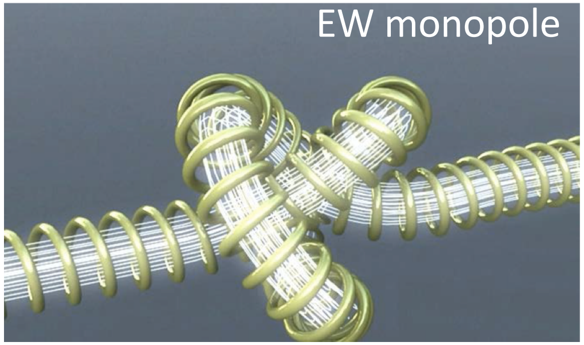
Project supported by a 2017 Leonardo Grant for Researchers and Cultural Creators, BBVA Foundation

Spares



Magnetic monopole mass

- No real prediction for classical Dirac monopole mass
  - if monopole radius ~ electron radius ⇒ $m_{monopole} \approx n \times (2.4\ \text{GeV})$
- There are other models where monopoles could appear in a mass range accessible to the LHC. e.g.:
  - the electroweak Cho-Maison monopole [PLB 391 (1997) 360]
  - the Troost-Vinciarelli monopole had a matter field: 50-100 GeV [PLB 63 (1976) 453]



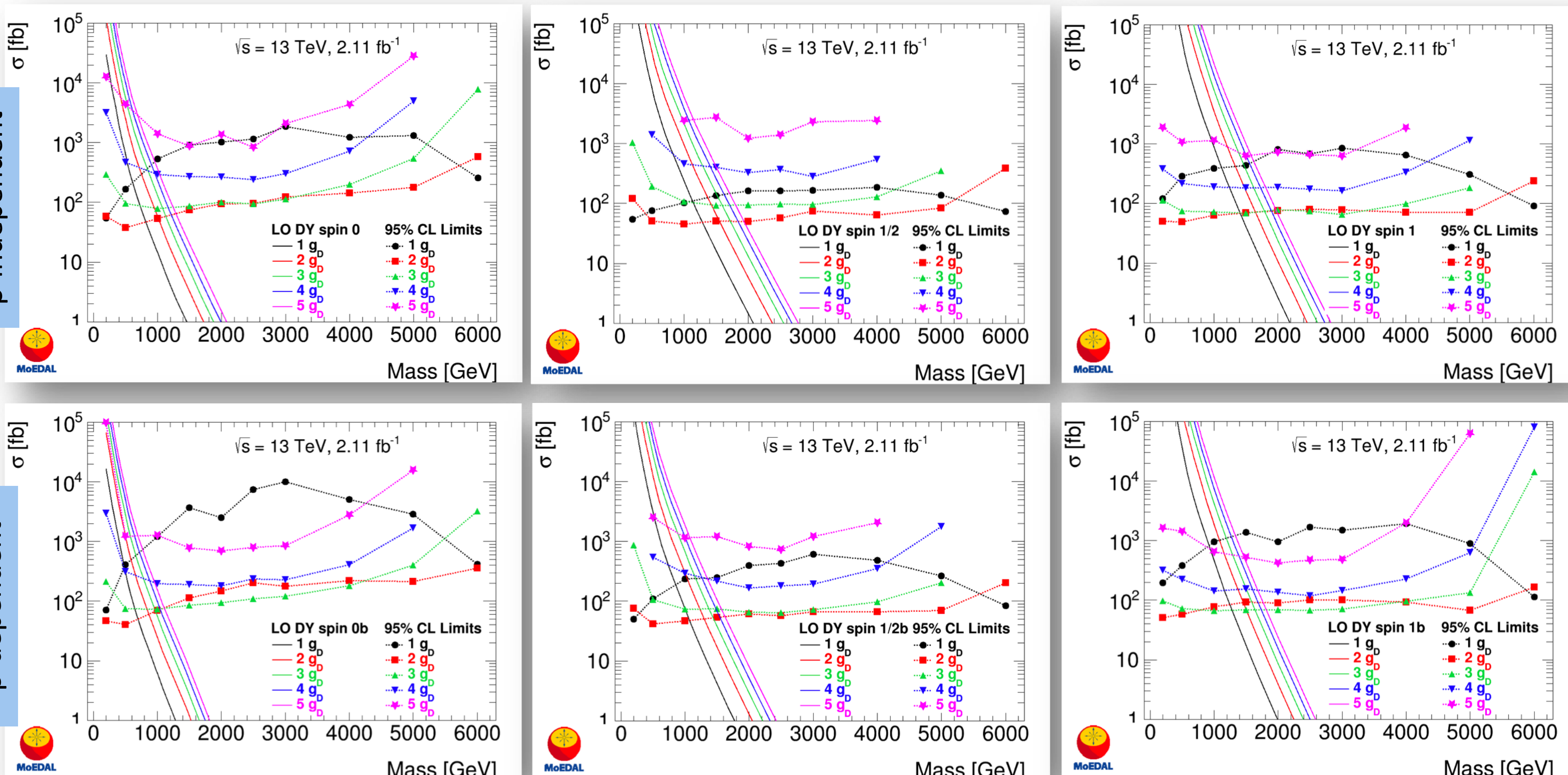
- GUT monopoles
  - 't Hooft and Polyakov (1974) showed that monopoles are fundamental solutions to non-Abelian gauge "GUT" theories – in any theory with an unbroken U(1) factor embedded
  - $m(M_{GUT}) \geq m_X/G > 10^{16}$ GeV □ 10^{17} GeV ~ 0.02 □g - not producible by particle accelerators
- We consider the magnetic monopole mass a free parameter

MMT 2015-2016 results

Detector: prototype of **222 kg** of Al bars
Exposure: **2.11 fb^{-1}** of **13 TeV** *pp* collisions 2015&2016

β-independent

β-dependent



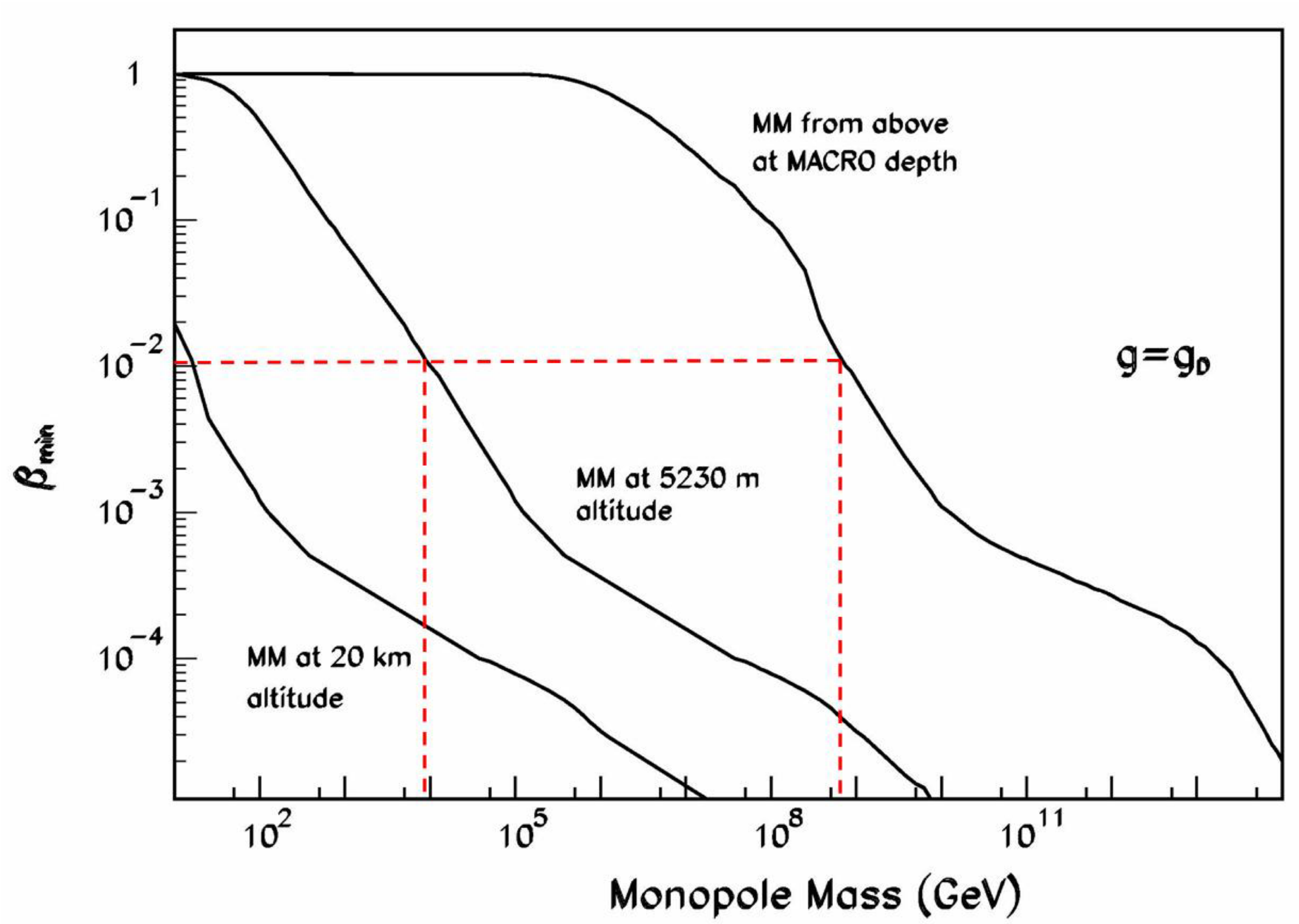
DY spin-0

DY spin-½

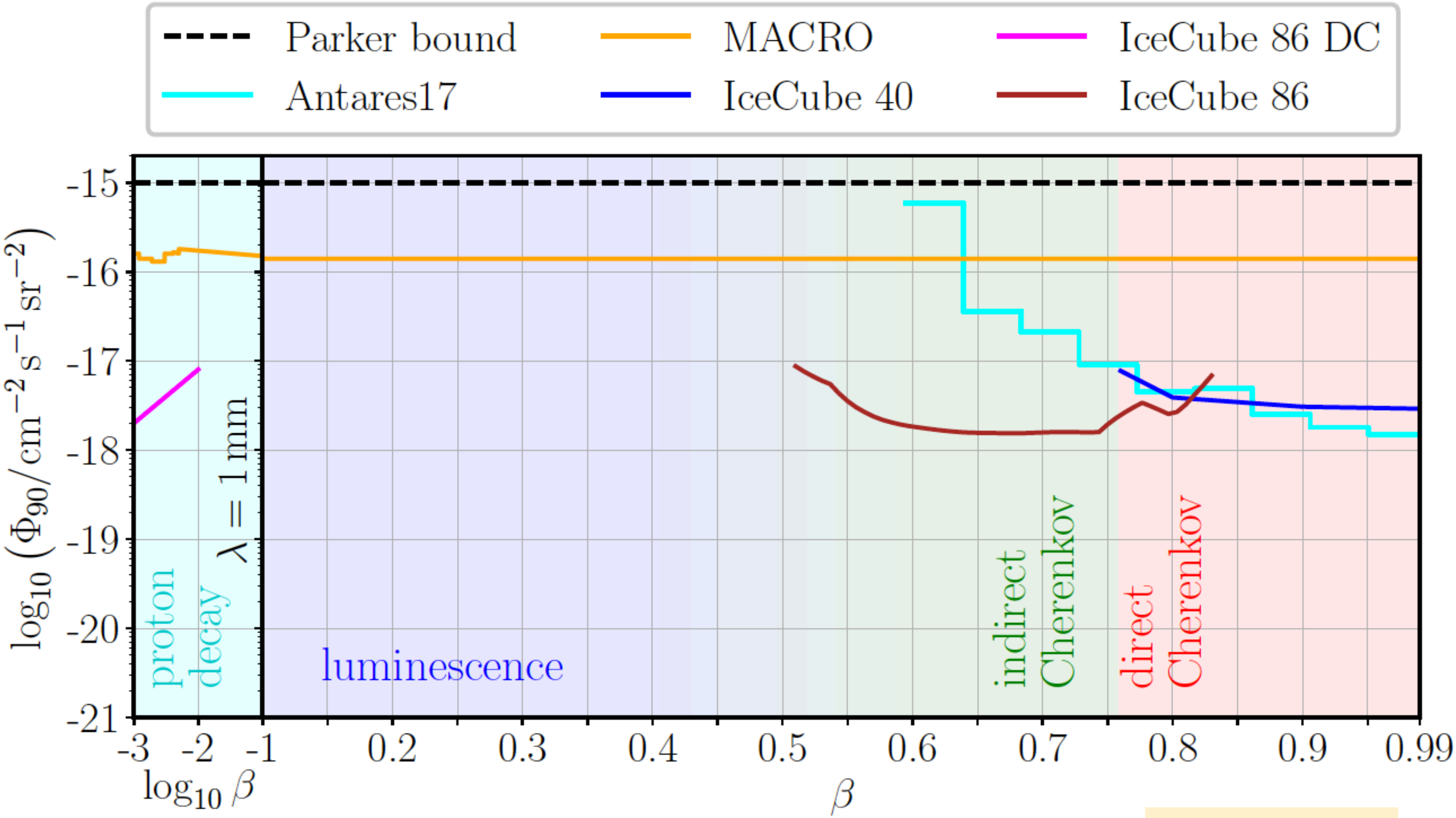
DY spin-1

PLB 782 (2018) 510 [arXiv:1712.09849]

Cosmic monopoles



SLIM Collab, Eur.Phys.J. C55 (2008) 57



F. Lauber, ICNFP2017