The MoEDAL-Experiment At the LHC

Searching for the Magnetic Monopole and other highly ionizing avatars of new physics

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"PATRAS:" Meeting CERN July 2014

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- *Introduction*
  - *A brief history of the magnetic monopole*
- *The Physics Program*
  - *Highly Ionizing Particles – Avatars of New Physics*
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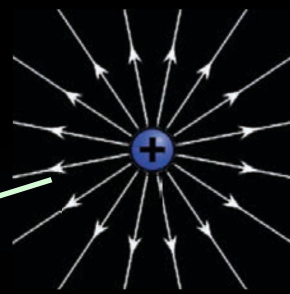
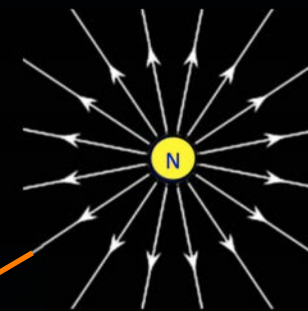
- *The MoEDAL Detector*
  - *The Collaboration*
  - *The 4 sub-detectors*
  - *Cosmic MoEDAL*
- *Last Words*

Seeking Magnetic Charge (6 scenarios)

$$\vec{\nabla}\cdot\vec{E} = \rho_{\mathrm{E}}$$
$$\vec{\nabla}\cdot\vec{B} = 0$$
$$\vec{\nabla}\times\vec{E} = -\frac{\partial\vec{B}}{\partial t}$$
$$\vec{\nabla}\times\vec{B} = \frac{\partial\vec{E}}{\partial t} + \vec{j}_{\mathrm{E}}$$

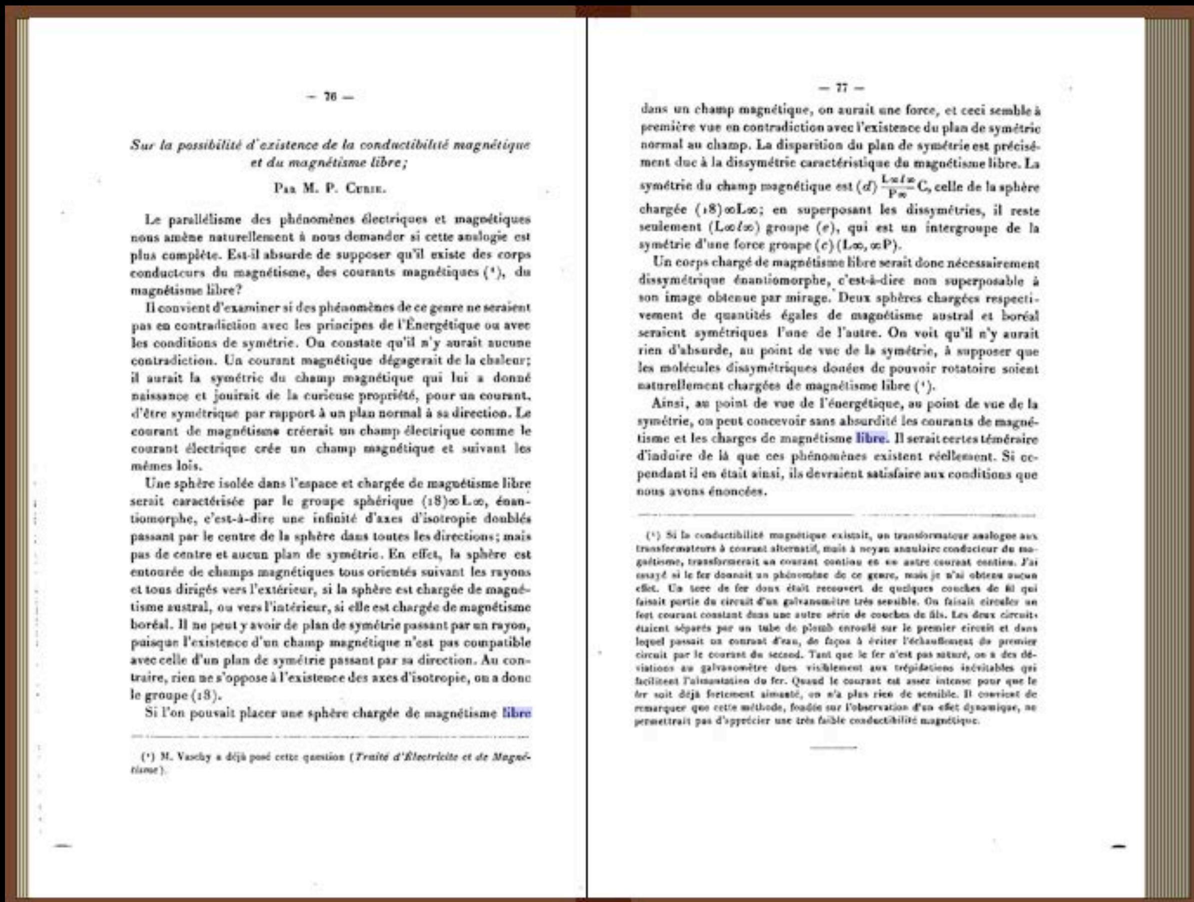


$$\vec{\nabla}\cdot\vec{E} = \rho_{\mathrm{E}}$$
$$\vec{\nabla}\cdot\vec{B} = \rho_{\mathrm{M}}$$
$$\vec{\nabla}\times\vec{E} = -\frac{\partial\vec{B}}{\partial t} - \vec{j}_{\mathrm{M}}$$
$$\vec{\nabla}\times\vec{B} = \frac{\partial\vec{E}}{\partial t} + \vec{j}_{\mathrm{E}}$$



- *Magnetic charge would symmetrize to Maxwell's Equation*
- *The symmetrized Maxwell's equations are invariant under rotations in the plane of the electric and magnetic field*
- *This symmetry is called Duality - the distinction between electric and magnetic charge is merely one of definition*

Maxwell's Asymmetric Equations



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Sur la possibilité d'existence de la conductibilité magnétique et du magnétisme libre;

Par M. P. Curie.

Le parallélisme des phénomènes électriques et magnétiques nous amène naturellement à nous demander si cette analogie est plus complète. Est-il absurde de supposer qu'il existe des corps conducteurs du magnétisme, des courants magnétiques (¹), du magnétisme libre?

Il convient d'examiner si des phénomènes de ce genre ne seraient pas en contradiction avec les principes de l'Énergétique ou avec les conditions de symétrie. On constate qu'il n'y aurait aucune contradiction. Un courant magnétique dégagerait de la chaleur; il aurait la symétrie du champ magnétique qui lui a donné naissance et jouirait de la curieuse propriété, pour un courant, d'être symétrique par rapport à un plan normal à sa direction. Le courant de magnétisme créerait un champ électrique comme le courant électrique crée un champ magnétique et suivant les mêmes lois.

Une sphère isolée dans l'espace et chargée de magnétisme libre serait caractérisée par le groupe sphérique (18)∞L∞, énantiomorphe, c'est-à-dire une infinité d'axes d'isotropie doublés passant par le centre de la sphère dans toutes les directions; mais pas de centre et aucun plan de symétrie. En effet, la sphère est entourée de champs magnétiques tous orientés suivant les rayons et tous dirigés vers l'extérieur, si la sphère est chargée de magnétisme austral, ou vers l'intérieur, si elle est chargée de magnétisme boréal. Il ne peut y avoir de plan de symétrie passant par un rayon, puisque l'existence d'un champ magnétique n'est pas compatible avec celle d'un plan de symétrie passant par sa direction. Au contraire, rien ne s'oppose à l'existence des axes d'isotropie, on a donc le groupe (18).

Si l'on pouvait placer une sphère chargée de magnétisme libre

(¹) M. Vaschy a déjà posé cette question (*Traité d'Électricité et de Magnétisme*).

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dans un champ magnétique, on aurait une force, et ceci semble à première vue en contradiction avec l'existence du plan de symétrie normal au champ. La disparition du plan de symétrie est précisément due à la dissymétrie caractéristique du magnétisme libre. La symétrie du champ magnétique est (d) $\frac{L\infty l\infty}{P\infty}C$, celle de la sphère chargée (18)∞L∞; en superposant les dissymétries, il reste seulement (L∞l∞) groupe (e), qui est un intergroupe de la symétrie d'une force groupe (c)(L∞, ∞P).

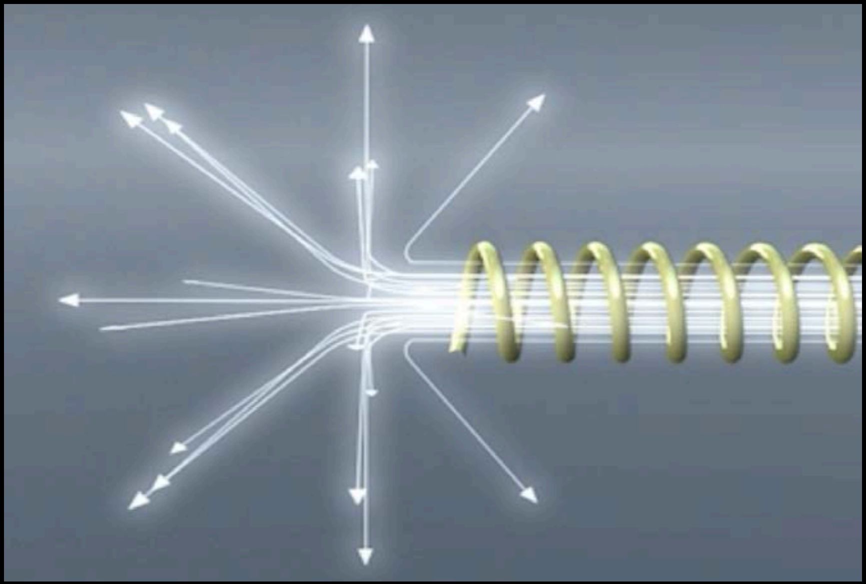
Un corps chargé de magnétisme libre serait donc nécessairement dissymétrique énantiomorphe, c'est-à-dire non superposable à son image obtenue par mirage. Deux sphères chargées respectivement de quantités égales de magnétisme austral et boréal seraient symétriques l'une de l'autre. On voit qu'il n'y aurait rien d'absurde, au point de vue de la symétrie, à supposer que les molécules dissymétriques douées de pouvoir rotatoire soient naturellement chargées de magnétisme libre (¹).

Ainsi, au point de vue de l'énergétique, au point de vue de la symétrie, on peut concevoir sans absurdité les courants de magnétisme et les charges de magnétisme libre. Il serait certes téméraire d'induire de là que ces phénomènes existent réellement. Si cependant il en était ainsi, ils devraient satisfaire aux conditions que nous avons énoncées.

(¹) Si la conductibilité magnétique existait, un transformateur analogue aux transformateurs à courant alternatif, mais à noyau annulaire conducteur du magnétisme, transformerait un courant continu en un autre courant continu. J'ai essayé si le fer donnait un phénomène de ce genre, mais je n'ai obtenu aucun effet. Un tore de fer doux était recouvert de quelques couches de fil qui faisait partie du circuit d'un galvanomètre très sensible. On faisait circuler un fort courant constant dans une autre série de couches de fils. Les deux circuits étaient séparés par un tube de plomb enroulé sur le premier circuit et dans lequel passait un courant d'eau, de façon à éviter l'échauffement du premier circuit par le courant du second. Tant que le fer n'est pas saturé, on a des déviations au galvanomètre dues visiblement aux trépidations inévitables qui facilitent l'aimantation du fer. Quand le courant est assez intense pour que le fer soit déjà fortement aimanté, on n'a plus rien de sensible. Il convient de remarquer que cette méthode, fondée sur l'observation d'un effet dynamique, ne permettrait pas d'apprécier une très faible conductibilité magnétique.

- *Pierre Curie was the first to suggest that Magnetic Monopoles could exist (Seances, Société Française de Physique, 1894)*
- *We are now at the 120th anniversary of the monopole search!*

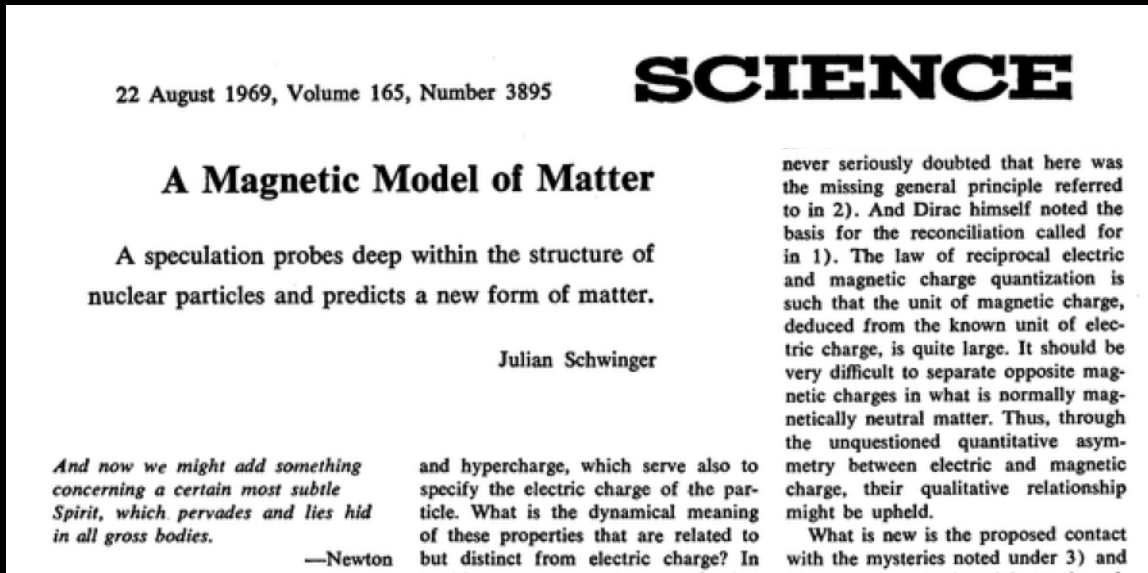
Dirac's Monopole



- *In 1931 Dirac hypothesized that the Monopole exists as the end of an infinitely long and thin solenoid - the "Dirac String"*
- *Requiring that the string is not seen gives us the Dirac Quantization Condition & explains the quantization of charge!*

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

Schwinger's Dyon


22 August 1969, Volume 165, Number 3895 **SCIENCE**

A Magnetic Model of Matter

A speculation probes deep within the structure of nuclear particles and predicts a new form of matter.

Julian Schwinger

And now we might add something concerning a certain most subtle Spirit, which pervades and lies hid in all gross bodies.
—Newton

and hypercharge, which serve also to specify the electric charge of the particle. What is the dynamical meaning of these properties that are related to but distinct from electric charge? In

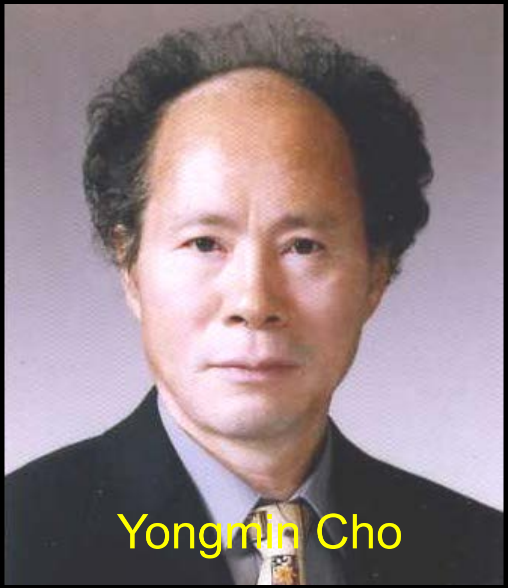
never seriously doubted that here was the missing general principle referred to in 2). And Dirac himself noted the basis for the reconciliation called for in 1). The law of reciprocal electric and magnetic charge quantization is such that the unit of magnetic charge, deduced from the known unit of electric charge, is quite large. It should be very difficult to separate opposite magnetic charges in what is normally magnetically neutral matter. Thus, through the unquestioned quantitative asymmetry between electric and magnetic charge, their qualitative relationship might be upheld.
What is new is the proposed contact with the mysteries noted under 3) and

- *Postulated a "dyon" that carries electric & magnetic charge*
- *Quantisation of angular momentum with two dyons (q_{e1},q_{m1}) and (q_{e2},q_{m2}) yields*
- $$(q_{e1}, q_{m1}) - (q_{e2}, q_{m2}) = 2nh/m_0 \quad (\text{ n is an integer})$$
- *Fundamental magnetic charge is now $2g_D$*
  - *If the fundamental charge is 1/3 (d-quark) as the fundamental electric charge then the fundamental magnetic charge becomes $6g_D$*

The ‘t Hooft-Polyakov Monopole

- *In 1974 ‘t Hooft and Polyakov showed that monopoles exist with the framework of Grand Unified Theories*
  - *Such monopoles are topological solitons (stable, non dissipative, finite energy solutions) with a topological charge*
  - *The topology of the soliton’s field configuration gives stability EG a knot in a rope fixed at the ends (boundary conditions)*

The Cho-Maison Magnetic Monopole



- *Yongmin Cho's pioneering paper in 1986 envisioned a spherically symmetric Electroweak Monopole, with:*
  - *Magnetic charge $2g_D$ & mass estimated to be 4→7 GeV/c^2*
- *The Cho monopole is a non-trivial hybrid between the abelian Dirac monopole & the non-abelian 't Hooft-Polyakov monopole*
- *The Cho-Maison monopole would be detectable by MoEDAL*

The Ways to get High Ionization

- ***Electric charge*** *- ionization increases with increasing charge and falling velocity β (β=v/c):*

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

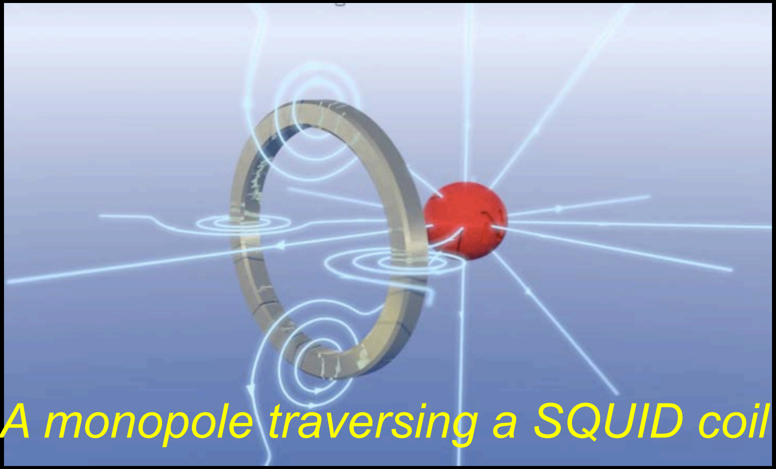
- ***Magnetic charge*** *- ionization increases with magnetic charge and decreases with velocity β – a unique signature*

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

  - *The velocity dependence of the Lorentz force cancels $1/\beta^2$ term*

- *The ionization of a relativistic monopole is $(ng)^2$ times that of a relativistic proton i.e $4700n^2$!! (n=1,2,3…)*

Induction Experiments - Evidence?



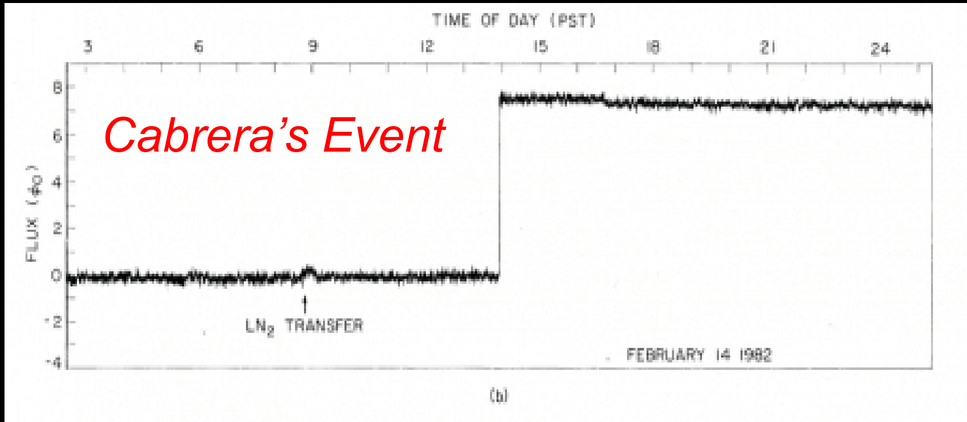
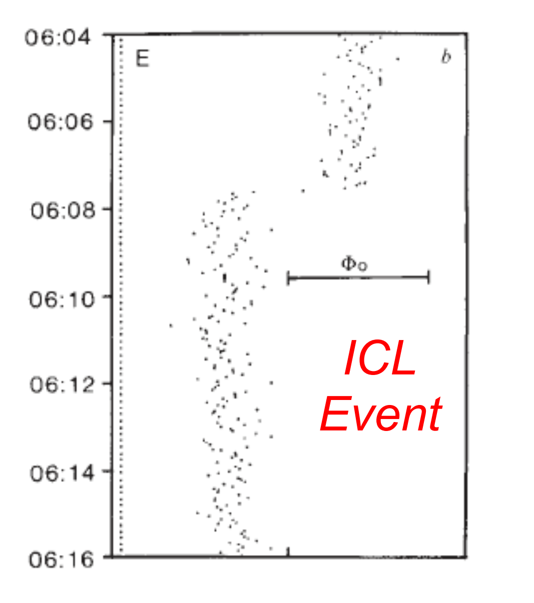


FIG. 2. Data records showing (a) typical stability and (b) the candidate monopole event.

- *Data from Cabrera's apparatus taken on St Valentine's day in 1982 (A=20 cm^2).*
  - *The trace shows a jump – just before 2pm - by 8 units that one would expect from a monopole traversing the coil.*
- *In August 1985 a groups at ICL reported the:"observation of an unexplained event" compatible with a monopole traversing the detector (A= 0.18 m^2*



Magnetic Monopole Properties

Magnetic charge
= ng = n68.5e
(if e→1/3e; g→3g)
HIGHLY IONIZING

Coupling constant =
g/ħc ~ 34. Spin ½?

Energy acquired in
a magnetic field
=2.06MeV/gauss.m
= 2TeV in a 10m,
10T LHC magnet

GUT monopoles ~10^{17} GeV
IMM monopoles mass as
low as 10^{7} GeV
4-7 TeV EW monopole

Physics Program (34 Scenarios)

Cornell University Library

arXiv.org > hep-ph > arXiv:1405.7662

High Energy Physics – Phenomenology

The Physics Programme Of The MoEDAL Experiment At The LHC

B. Acharya, J. Alexandre, J. Bernabéu, M. Campbell, S. Cecchini, J. Chwastowski, M. De Montigny, D. Derendarz, A. De Roeck, J. R. Ellis, M. Fairbairn, D. Felea, M. Frank, D. Frekers, C. Garcia, G. Giacomelli, M. Giorgini, D. HaŞegan, T. Hott, J. Jak\rubek, A. Katre, D-W Kim, M.G.L. King, K. Kinoshita, D. Lacarrere, S. C. Lee, C. Leroy, A. Margiotta, N. Mauri, N. E. Mavromatos, P. Mermod, V. A. Mitsou, R. Orava, L. Pasqualini, L. Patrizii, G. E. P\uav\ualaş, J. L. Pinfold, M. Platkev\vc, V. Popa, M. Pozzato, S. Pospisil, A. Rajantie, Z. Sahnoun, M. Sakellariadou, S. Sarkar, G. Semenoff, G. Sirri, K. Sliwa, R. Soluk, M. Spurio, Y.N. Srivastava, R. Staszewski, J. Swain, M. Tenti, V. Togo, M. Trzebinski, J. A. Tuszyński, V. Vento, O. Vives, Z. Vykydal, A. Widom, J. H. Yoon

(Submitted on 29 May 2014)

To be published in IJMPA

Dedicated to the memory of Giorgio Giacomelli who passed away in January 2014

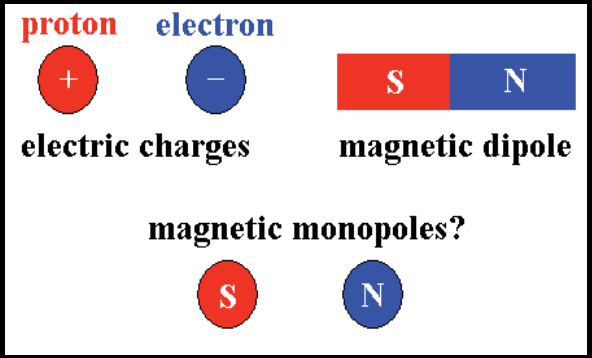
- *Magnetic Charge: 6 scenarios, EW Monopole, D particles, etc.*
- *SUSY: 9 scenarios, metastable stop quarks and sleptons, etc*
- *Extra Dimensions: 5 scenarios: eg BH remnants, KK particles etc.*
- *"Other Scenarios" involving singly electrically charged particles: 6 scenarios: long lived massive quarks, 4th generation fermions, etc*
- *Multiply charged particles: 8 scenarios: doubly charged Higgs, doubly charged leptons, Q-balls, strangelets, quirks, etc*

MoEDAL Addresses Fundamental Questions:

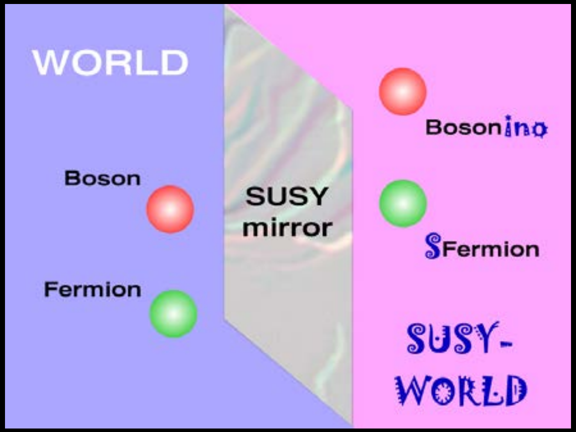
Are there extra dimensions?

What is the nature of Dark matter?

What happened just after the big bang?



Does magnetic charge exist?



Are there new symmetries of nature?

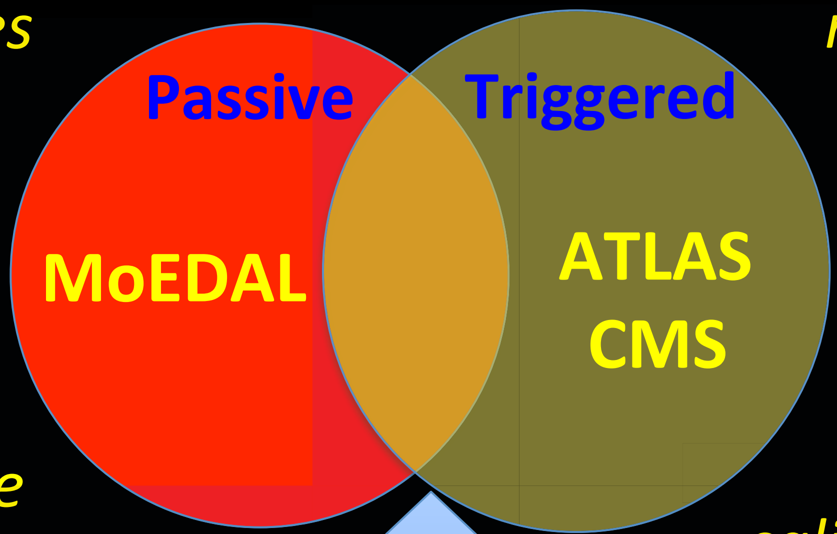
MoEDAL's Complementarity

Optimized for highly ionizing particles

Insensitive to SM particles

Can directly detect & trap magnetic charge

Calibrated by heavy-ions



Optimized for SM relativistic MIPs & photons

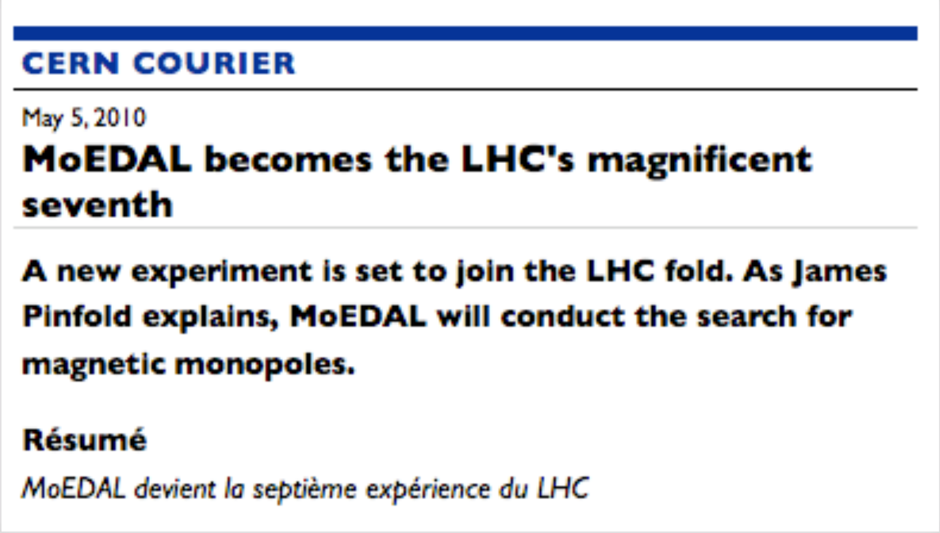
Cannot directly detect magnetic charge

Cannot be directly calibrated for highly ionizing particles

The totally different systematics amd mode of detection of MoEDAL compared to the ATLAS/CMS experiments will yield important validation of and insights into a joint observation of new physics that we hope to see starting in 2015

MoEDAL the 7th LHC Experiment

AIM: The search for the highly ionizing particle avatars of New Physics with magnetic and/or electric charge



CERN COURIER

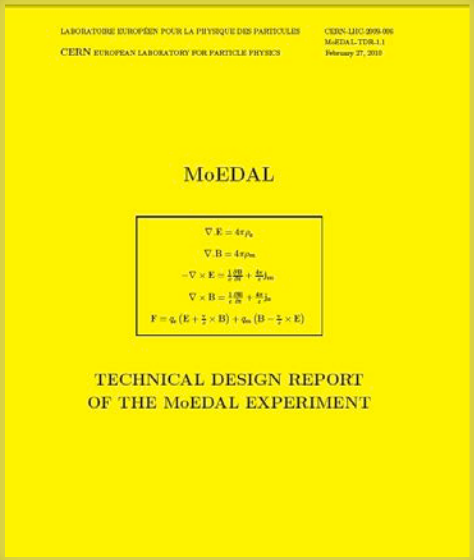
May 5, 2010

MoEDAL becomes the LHC's magnificent seventh

A new experiment is set to join the LHC fold. As James Pinfold explains, MoEDAL will conduct the search for magnetic monopoles.

Résumé

MoEDAL devient la septième expérience du LHC



LABORATOIRE EUROPÉEN POUR LA PHYSIQUE DES PARTICULES
CERN EUROPEAN LABORATORY FOR PARTICLE PHYSICS

CERN-LHC-2009-006
MoEDAL-TDR-1.1
February 27, 2010

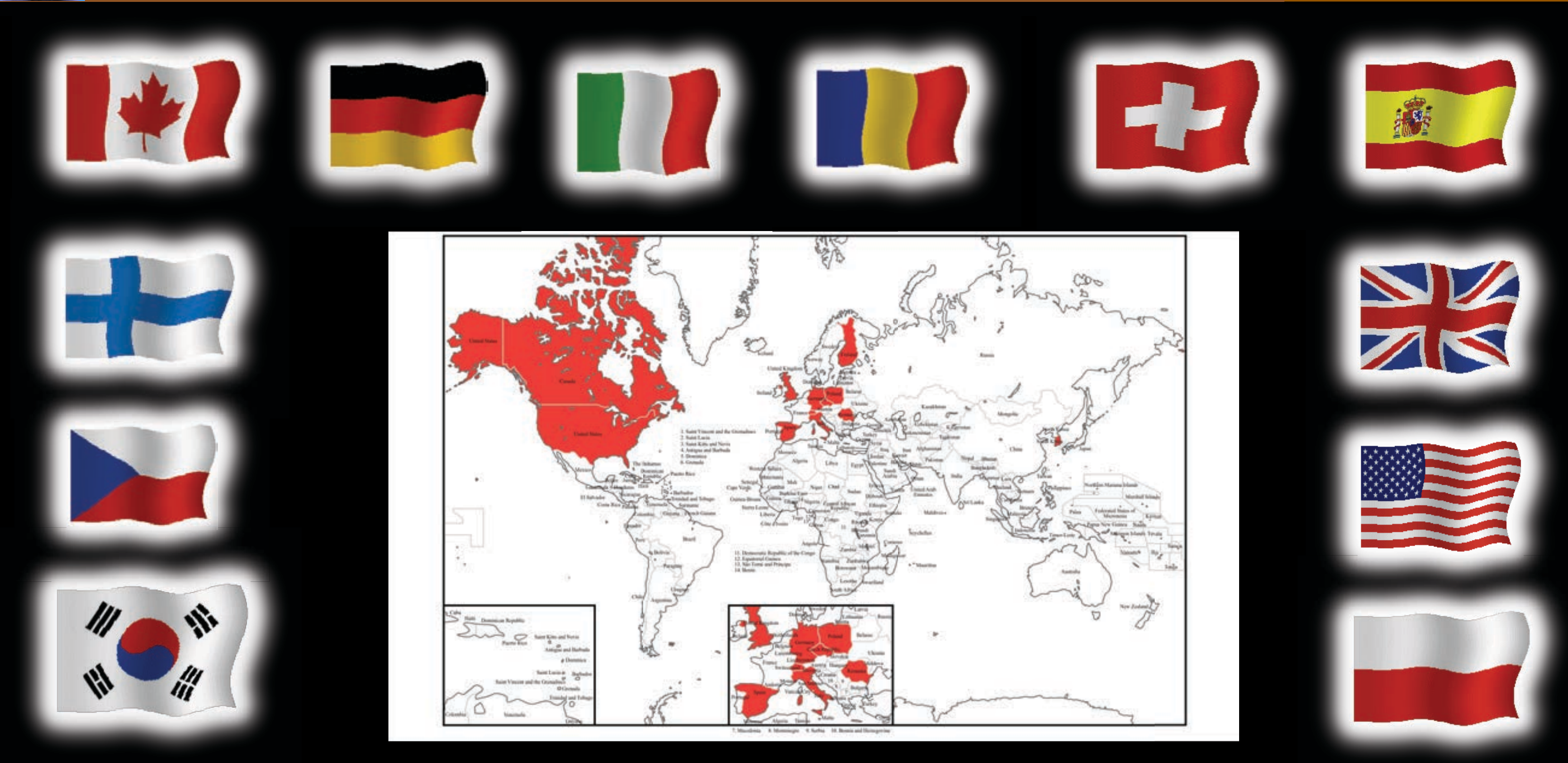
MoEDAL

$$\nabla \cdot \mathbf{E} = 4\pi\rho_e$$
$$\nabla \cdot \mathbf{B} = 4\pi\rho_m$$
$$-\nabla \times \mathbf{E} = \frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} + \frac{4\pi}{c}\mathbf{j}_m$$
$$\nabla \times \mathbf{B} = \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi}{c}\mathbf{j}_e$$
$$\mathbf{F} = q_e\left(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B}\right) + q_m\left(\mathbf{B} - \frac{\mathbf{v}}{c} \times \mathbf{E}\right)$$

TECHNICAL DESIGN REPORT
OF THE MoEDAL EXPERIMENT

- *In September 2009 he Large Hadron Collider Committee (LHCC), accepted the MoEDAL Technical Design Report.*
  - *The CERN Research Board (CRB) unanimously approved the MoEDAL during their 190th meeting on December 3rd 2009. Official data taking starts in the Spring of 2015. Test data has already been taken.*

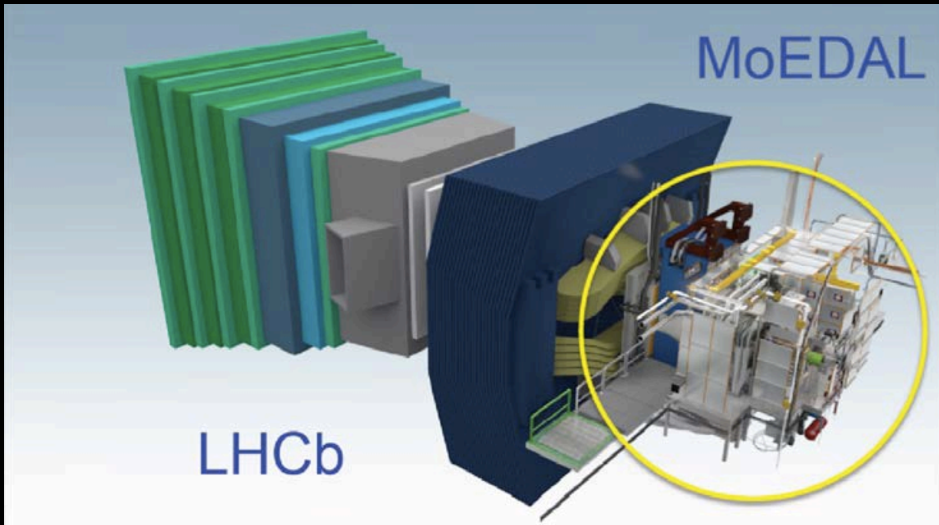
The Collaboration



- *Now 64 physicists from 12 countries and 23 institutions:*

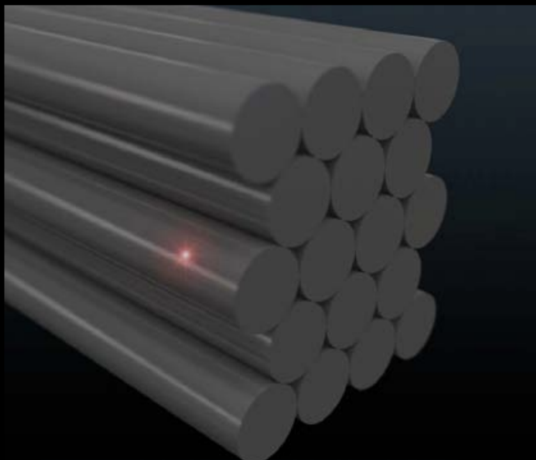
U. Alberta, UBC, INFN Bologna, U. Bologna, U. Cincinatti, Concordia U., CSIC Valencia, DESY, Gangneung-Wonju Nat. U., U. Geneva, U. Helsinki, ICTP Trieste, IEAP/CTU Prague, IFIC Valencia, Imperial College London, INP/PAS Cracow, ISS Bucharest, King's College London, Konkuk U., Muenster U., Northeastern U., Simon Langton School UK, Tuft's.

The MoEDAL Experiment



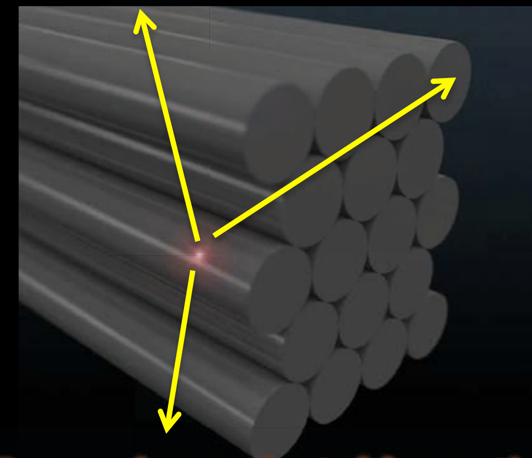
- *The MoEDAL detector design consists of 4 subdetectors, the:*
  - *Low Threshold (≥ 5xMIP) Nuclear Track Detector (LT-NTD) system*
  - *High Charge Catcher (HCC) NTD array (≥ 50 xMIP)*
  - *Magnetic Monopole/Exotics Trapper (MMT) Al trapping volumes*
  - *TimePix pixel device (TMPX) array online radiation monitoring system*

The Trapping Detector System



Trapped monopole

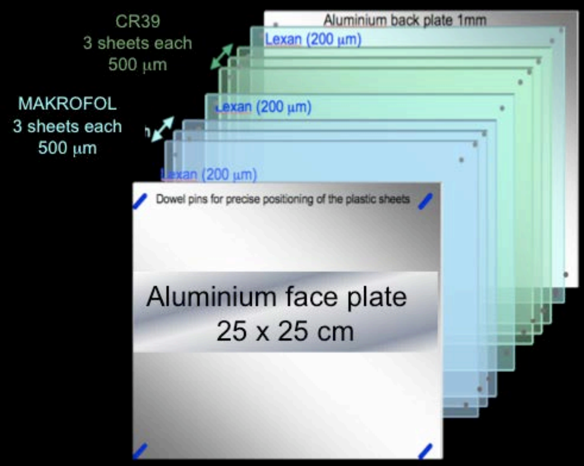
SQUID magnetometer (ETH Zurich)

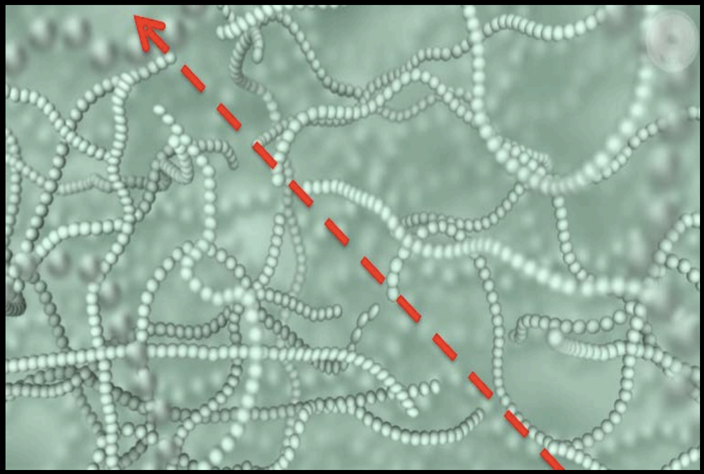


Trapped pseudostable particle decaying to charged particles

- *We will deploy trapping volumes (~1 tonne) in the MoEDAL/ VELO Cavern to trap highly ionizing particles*
  - *The binding energies of monopoles in nuclei with finite magnetic dipole moments are estimated to be hundreds of keV*
- *After exposure the traps are removed and sent to:*
  - *The SQUID magnetometer at ETH Zurich for Monopole detection*
  - *Underground lab to detect decays of MSPs*

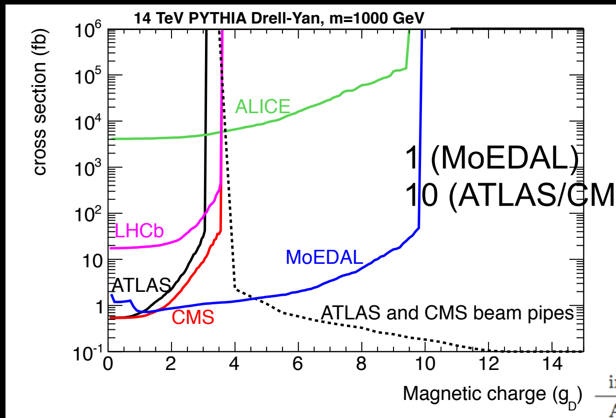
The Nuclear Track Detector System

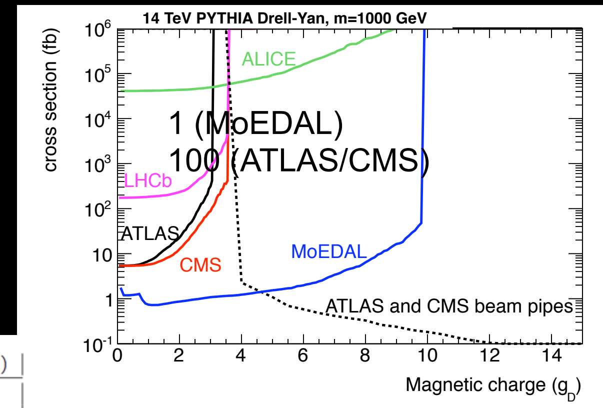




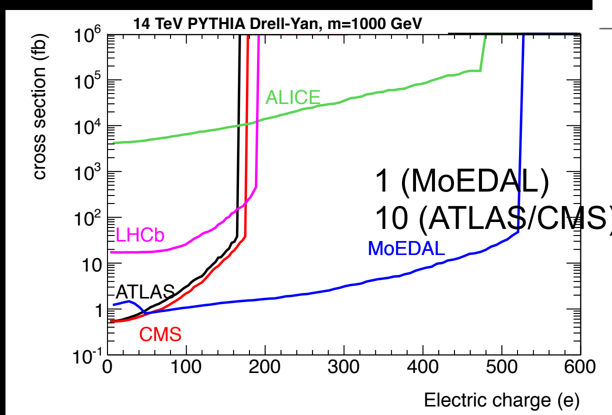
- *Largest array (150 m^2 of NTDs every deployed at an accelerator*
  - *Plastic BTD stacks consist of CR39 (threshold 5 MiPs) and Makrofol (50 MiPs) – that are "damaged" by the highly ionizing particle*
  - *The damage is revealed by controlled etching in a hot Sodium Hydroxide solution – etch pits are formed*
  - *Charge resolution is ~0.1|e|, where |e|is the electron charge*
- *NTD system acts like a giant camera that is only sensitive to new physics - no known SM backgrounds*

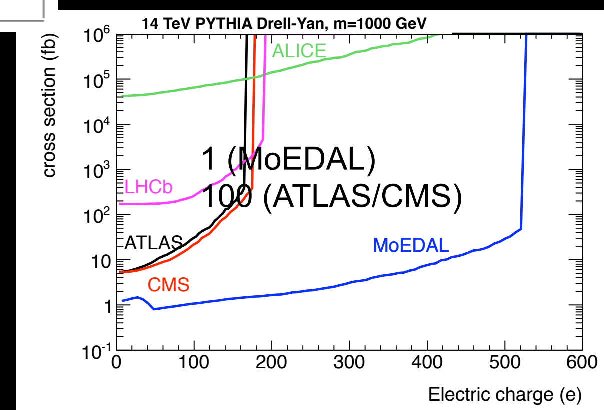
Sensitivity to Highly Ionizing Particles





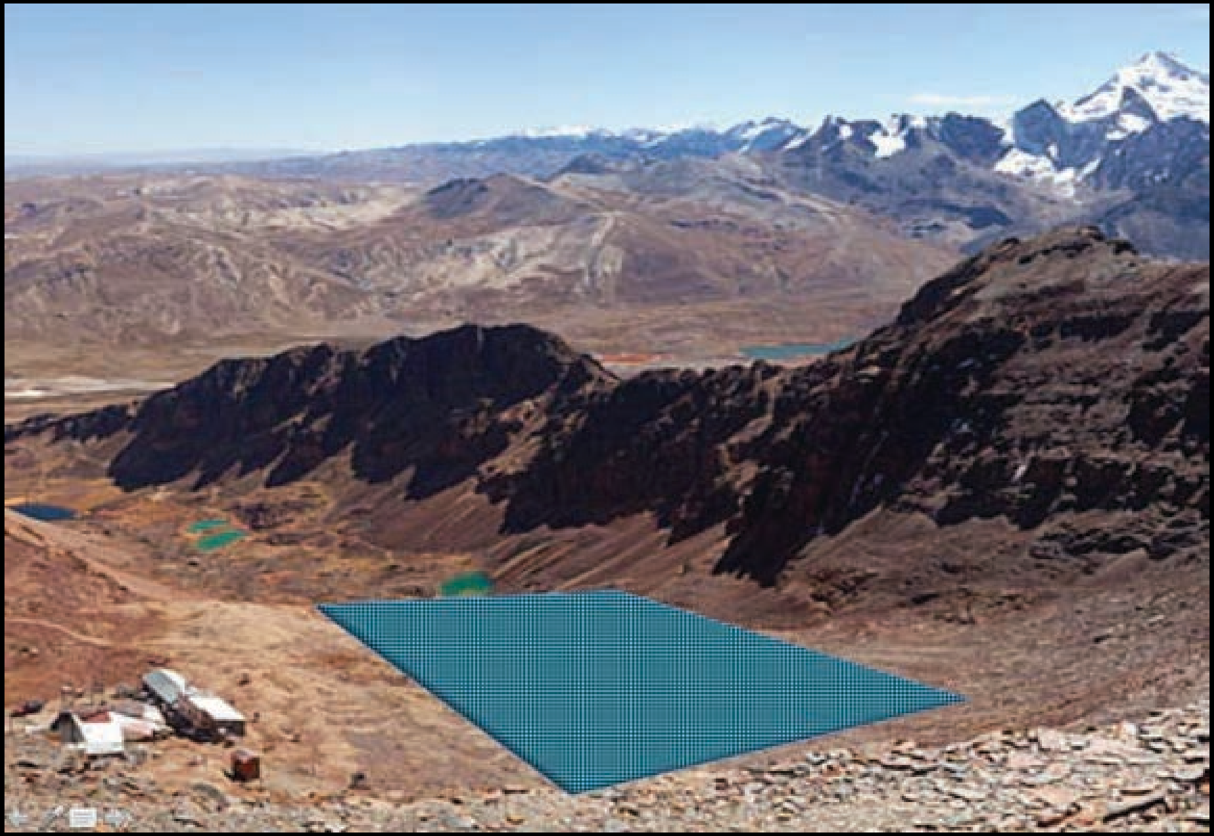
interaction point	L (cm^{-2}s^{-1})	$\int Ldt$ (fb^{-1})
ATLAS	$5 \cdot 10^{33}$	20
CMS	$5 \cdot 10^{33}$	20
LHCb/MoEDAL	$5 \cdot 10^{32}$	2
ALICE	10^{30}	0.004





- *Cross-section limits for magnetic (LEFT) and electric charge (RIGHT) (from* ***arXiv:1112.2999V2*** *[hep-ph]) assuming:*
  - *Only one MoEDAL event is required for discovery and 10 (left) – 100 (right) events in the other (active) LHC detector*

The Future – Cosmic-MoEDAL



- *Cosmic-MoEDAL would deploy 10K-50K m^2 of NTDs at Mount Chacaltaya (5385m) - 50/100 times larger than MACRO/SLIM*
  - *To detect monopoles from late phase transition & GUT scenarios with mass from ~$10^5 \rightarrow 10^{18}$ GeV with fluxes below the Parker Bound*

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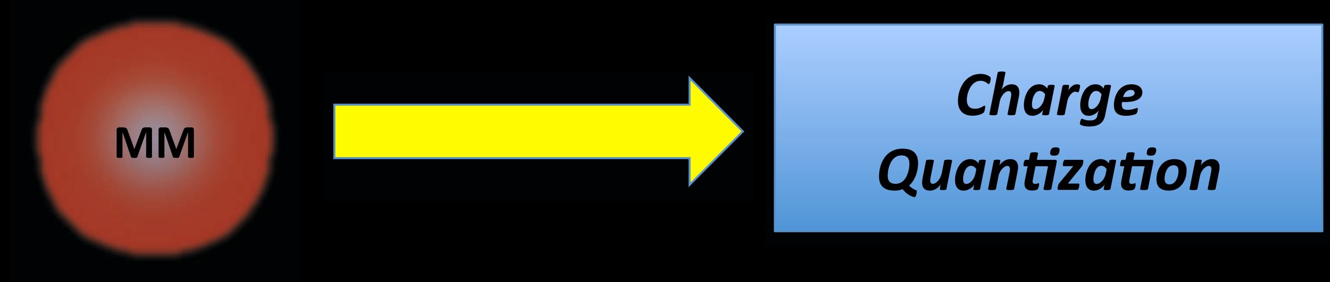
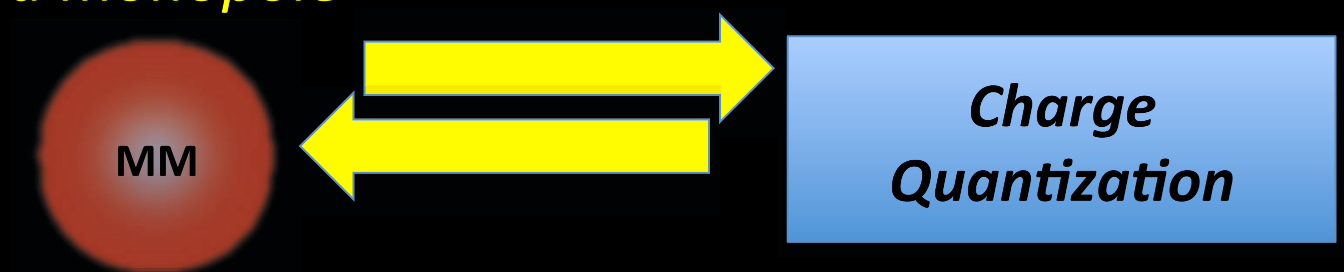
The Polchinski Conjecture

- *Dirac showed that the existence of at least one magnetic monopole would explain charge quantization*



- *Thus, the leading string theorist Joseph Polchinski conjectured, any theory requiring charge quantization must have a monopole*



- *He also maintains that in any fully unified theory, for every gauge field there will exist electric and magnetic sources.*

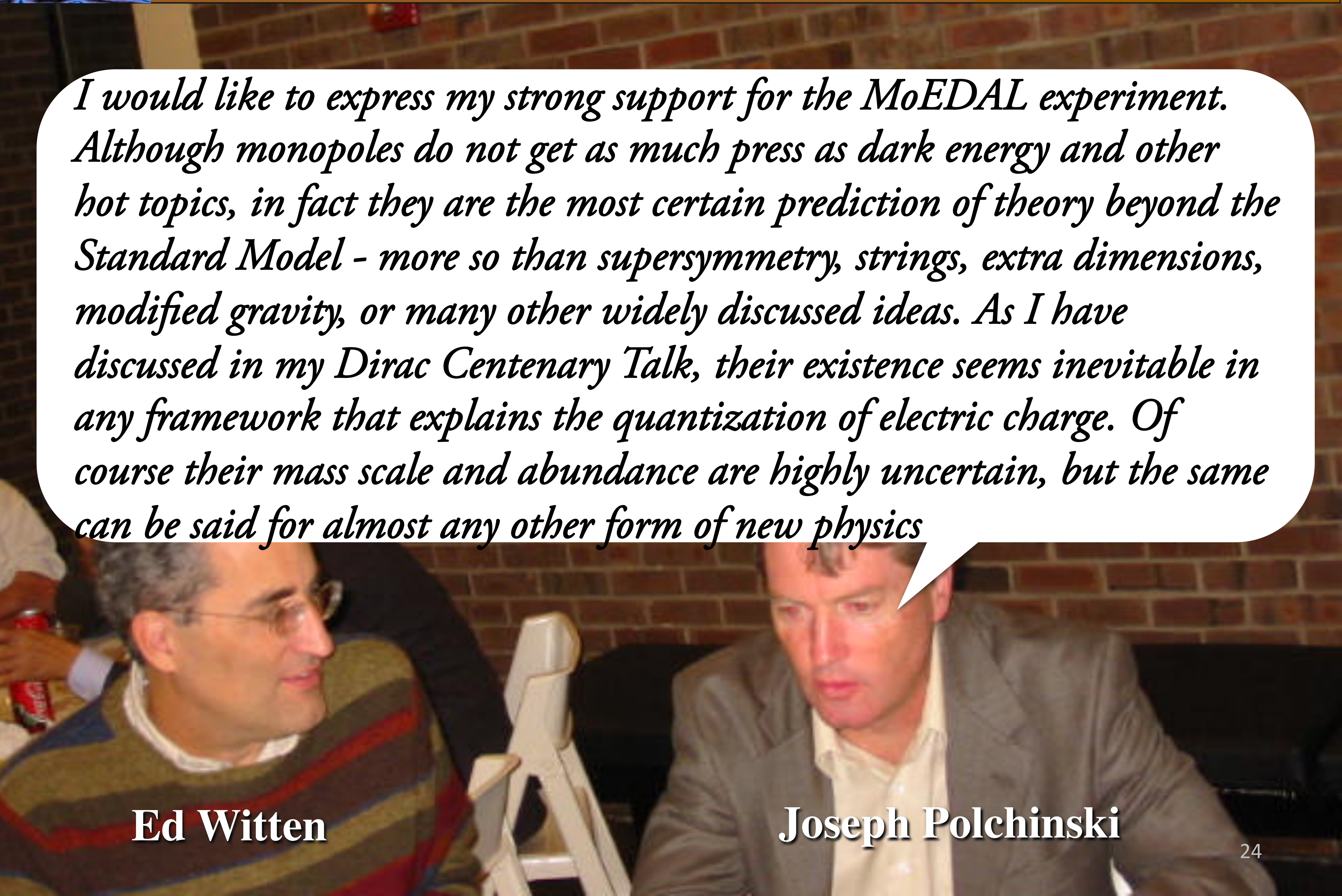
On the Existence of the Monopole

- *The existence of magnetic monopoles is suggested by Electromagnetic theory. But, Grand unified and superstring theories, predict the existence of the monopole.*

- ***Dirac** felt that he "would be surprised if Nature had made no use of it". It, being the Magnetic Monopole.*

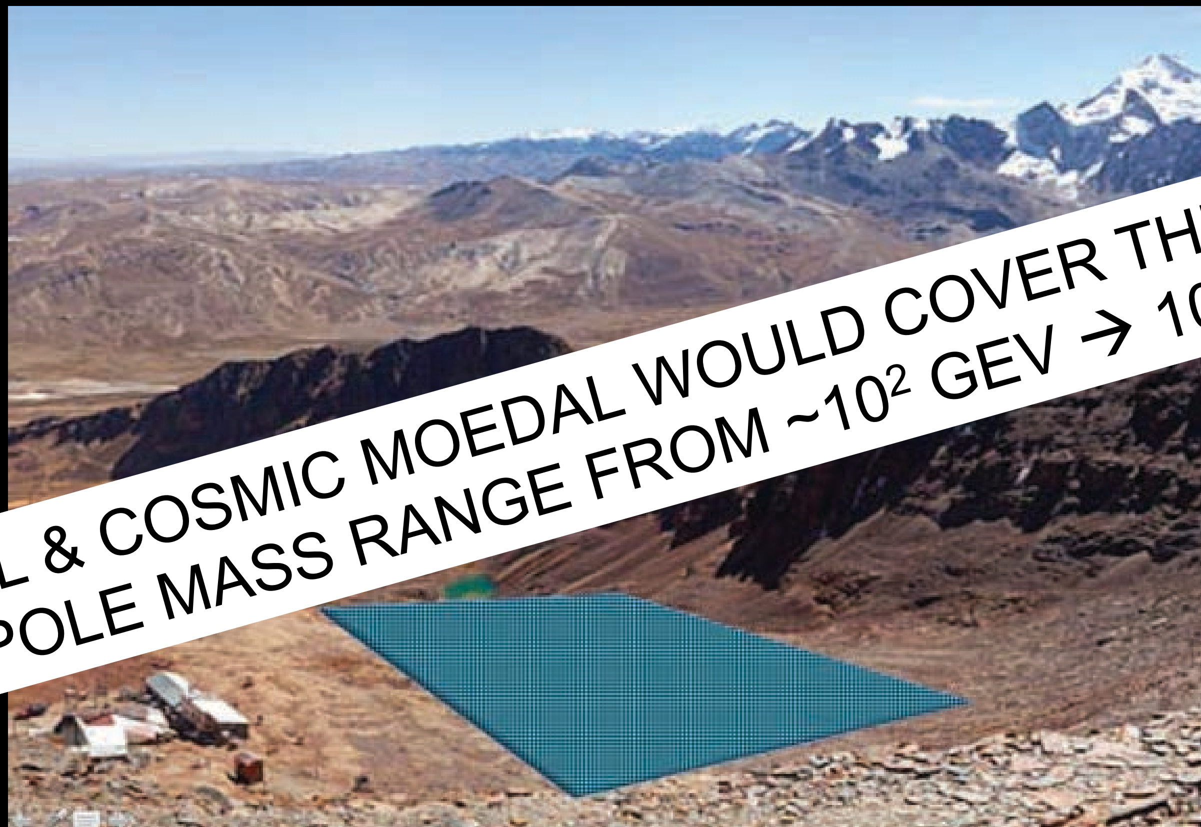
- ***Ed Witten** once asserted in his Loeb Lecture at Harvard, "almost all theoretical physicists believe in the existence of magnetic monopoles, or at least hope that there is one."*

Closing Remarks



EXTRA SLIDES

The Future – Cosmic-MoEDAL



- *Cosmic-MoEDAL would deploy 10K-50K m^2 of NTDs at Mount Chacaltaya (5385m) - 50/100 times larger than MACRO/SLIM*
  - *To detect monopoles from late phase transition & GUT scenarios with mass from ~10^5 → 10^{18} GeV with fluxes below the Parker Bound*

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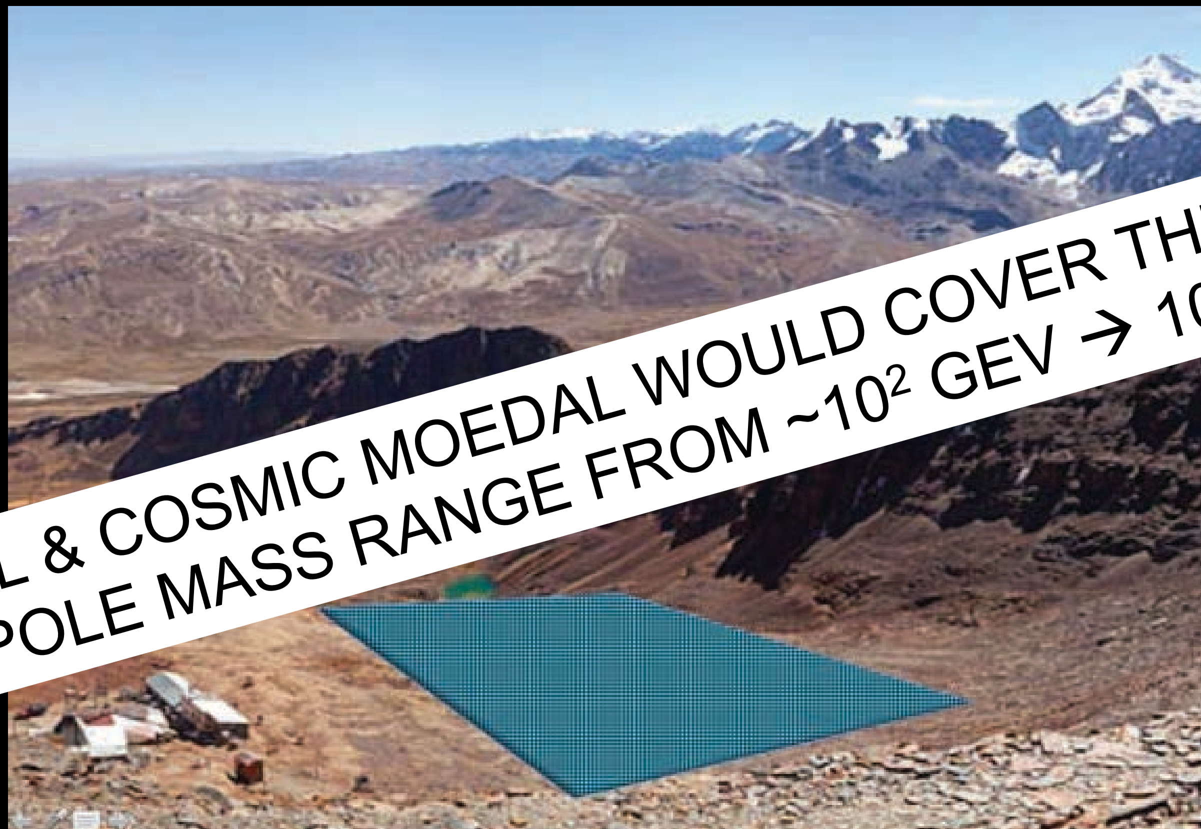
The Future – Cosmic-MoEDAL



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  - *To detect monopoles from late phase transition & GUT scenarios with mass from ~10^5 → 10^{18} GeV with fluxes below the Parker Bound*

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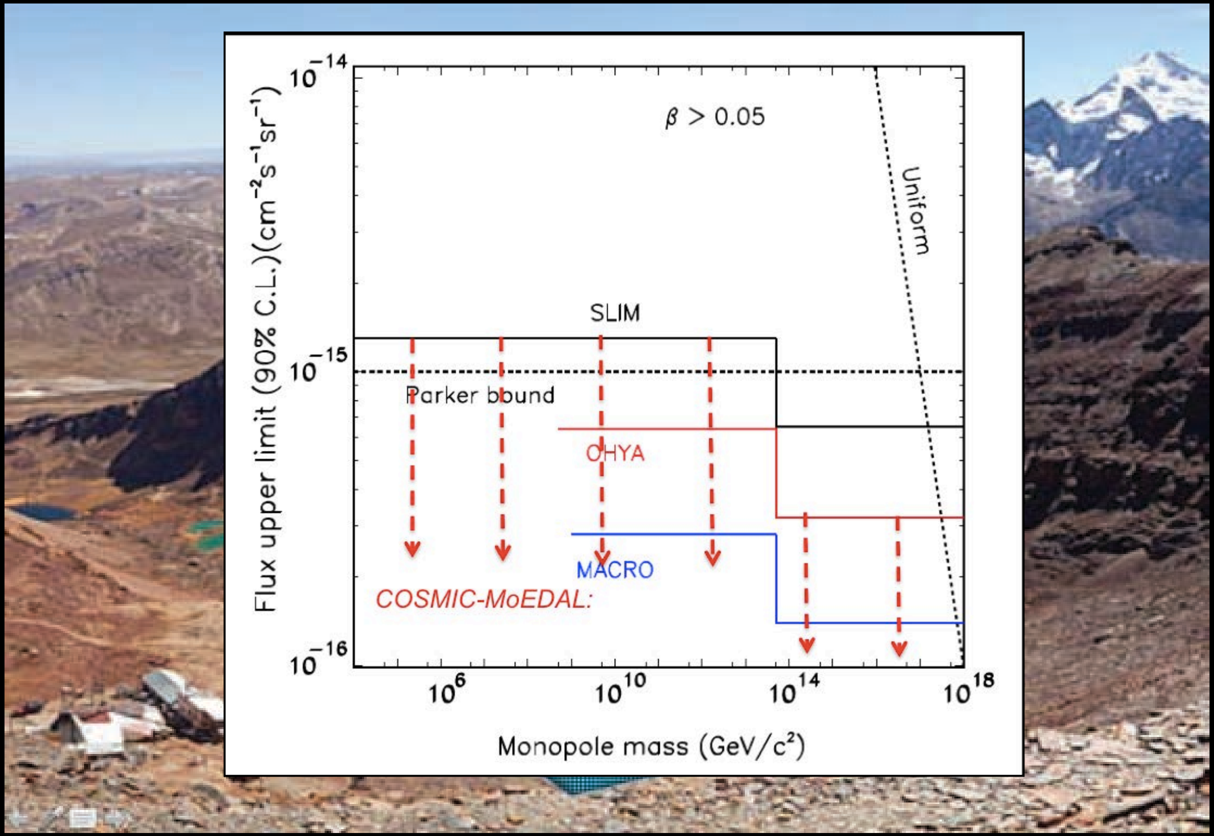
Cosmic-MoEDAL –Pushing the Limits



- *Cosmic-MoEDAL would deploy 10K-50K m^2 of NTDs at Mount Chacaltaya (5385m) - 50/100 times larger than MACRO/SLIM*
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