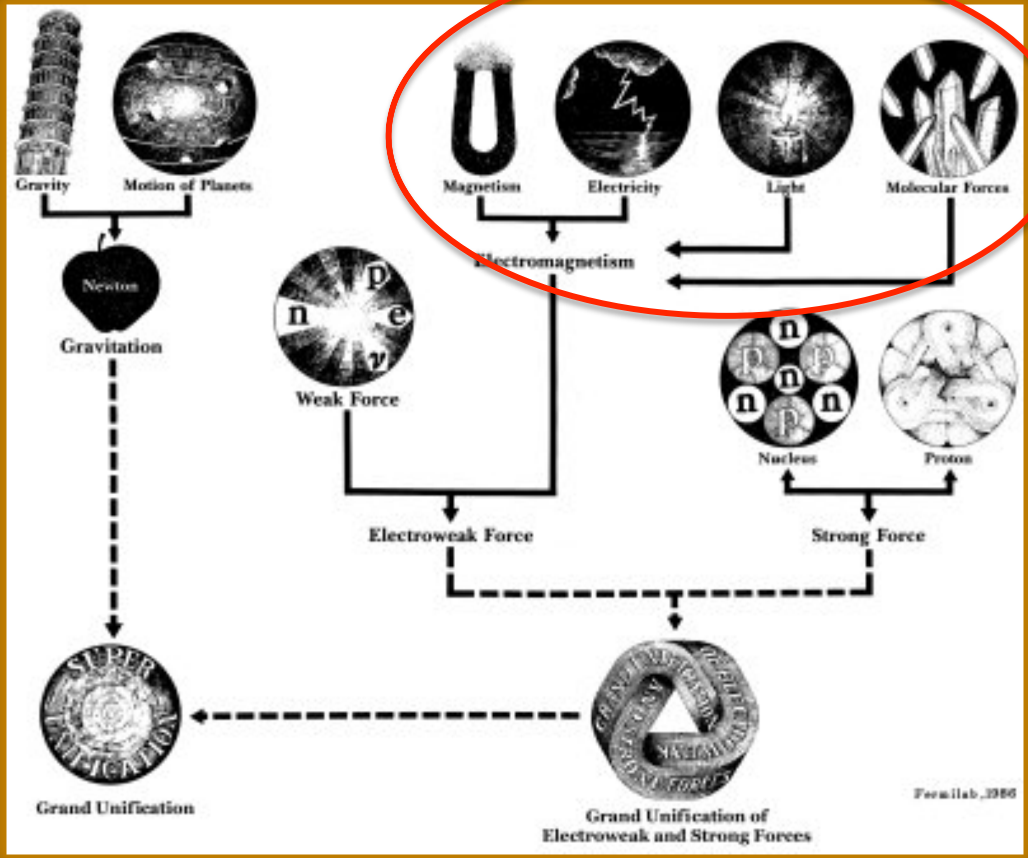
Searching for Monopoles and Other Exotica at Colliders and in Cosmic Rays

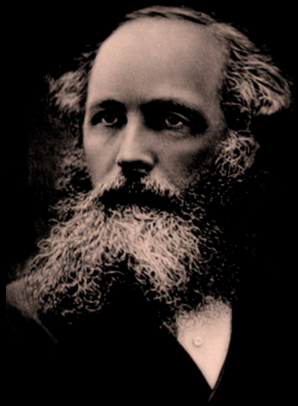
James L Pinfold, University of Alberta

Highly Ionizing Particles from the Cosmos

- Topological Solitons:
  - a) GUT & Intermediate Mass Monopoles
  - b) EW Monopoles
- Q-balls - Non-topological Solitons
- Strange Quark Matter
  - 1) Low mass nuclearites (up to multi TeV masses
  - 2) Intermediate mass nuclearites with masses ~$10^8 < M < 10^{22}$ GeV
  - 3) Macroscopic nuclearites with masses $M > 10^{22}$ GeV
- Primordial Black Holes & Remnants
- Highly Ionizing Particles in high energy cosmic ray showers

Maxwell's Grand Unification

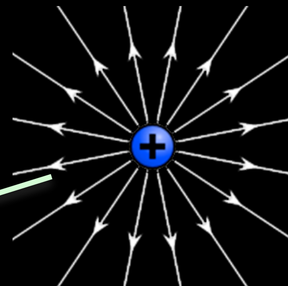




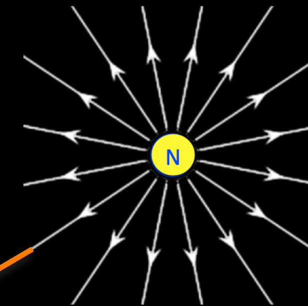
- *Maxwell, in 1873, makes the connection between electricity & magnetism – the Victorian Grand Unified Theory!*

Monopoles Symmetrize Maxwell's Eqns

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



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



- *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*

Pierre Curie's Challenge

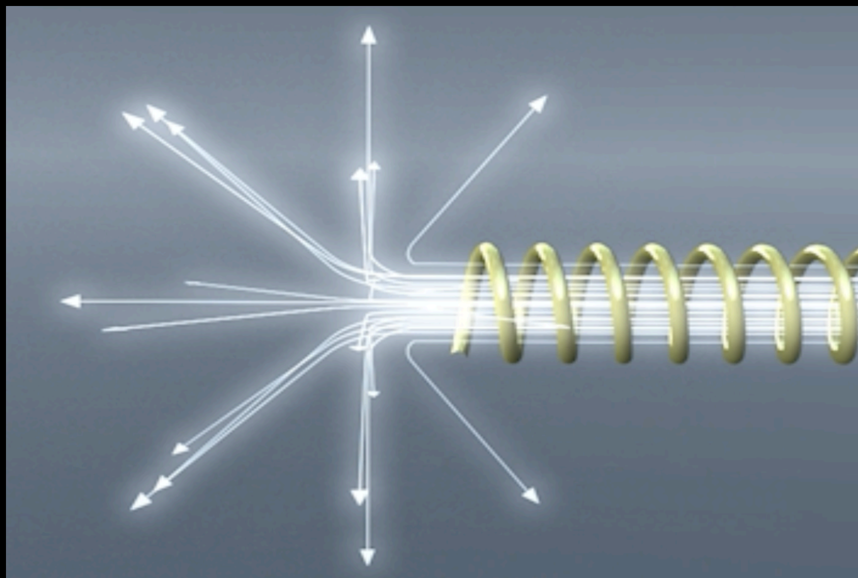
Sur la possibilité d'existence de la conductibilité magnétique et du magnétisme libre;

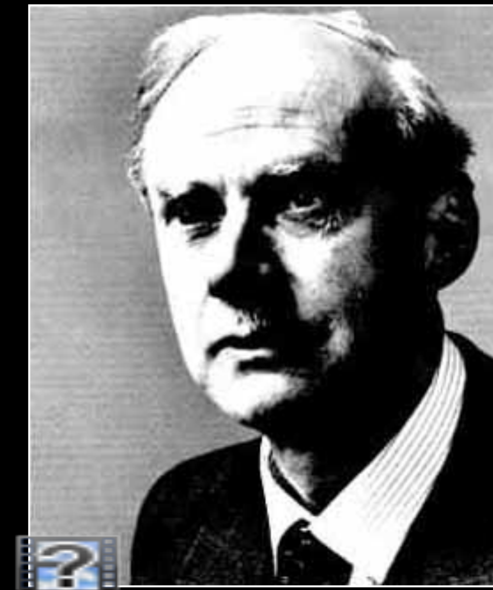
Par M. P. Curie.

- *Pierre Curie was the first to suggest that Magnetic Monopoles could exist (Seances, Société Française de Physique, 1894*

The 123rd Birthday of the Monopole Quest

Dirac's Monopole





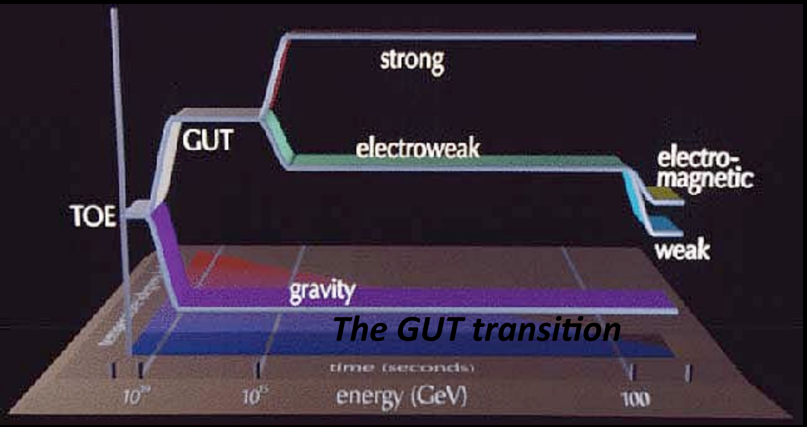
- *In 1931 Dirac hypothesized that the Monopole exists as the end of an infinitely long and thin solenoid - the "Dirac String"*
- *Requiring that the string is not seen gives us the Dirac Quantization Condition & explains the quantization of charge!*

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

The ‘t Hooft-Polyakov Monopole

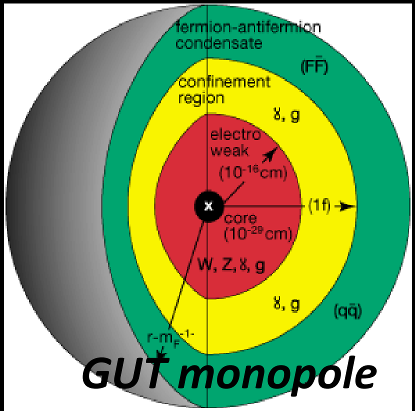
- *In 1974 ‘t Hooft and Polyakov showed that monopoles exist with the framework of Grand Unified Theories*
  - *Such monopoles are topological solitons (stable, non dissipative, finite energy solutions) with a topological charge*
  - *The topology of the soliton’s field configuration gives stability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

The GUT Monopole



The GUT transition


Water freezing to ice



GUT monopole

- *A symmetry-breaking phase transition caused the creation of topological defects as the universe froze out at the GUT trans.*
  - *The GUM is a tiny replica of the Big Bang with mass ~ 0.2 μg (10^{17} GeV.*
- *Lighter "Intermediate Mass Monopoles" can be produced at later Phase Transitions – mass $10^5 \rightarrow 10^{12}$ GeV or lower, eg:*

10^{15} GeV   **10^9 GeV**

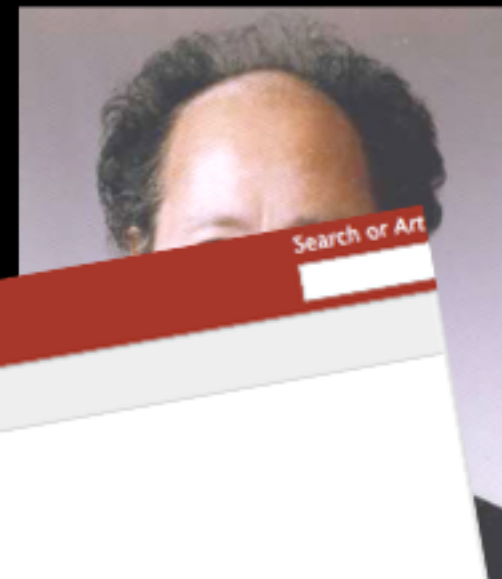
SO(10) → SU(4) x SU(2) x SU(2) → SU(3) x SU(2) x U1

10^{-35} s   **10^{-23} s**

The Cho-Maison Monopole

- *Yongmin Cho's pioneering paper in 1986 envisioned a spherically symmetric EW (Cho-Maison) monopole arising from the framework of the Weinberg-Salam model*
- *The Cho-Maison monopole is a non-trivial hybrid between the Dirac monopoles & the 'tHooft-Polyakov monopole*
  - *Magnetic charge 2gd & mass estimated to be ~4 → ~10 TeV*
- *If the Cho-Maison monopole is not detected at the LHC it can be detected in Cosmic-MoEDAL*

The Cho-Maison Monopole



arXiv.org > hep-ph > arXiv:1602.01745

Search or Art

High Energy Physics – Phenomenology

The Price of an Electroweak Monopole

John Ellis, Nick E. Mavromatos, Tevong You

(Submitted on 4 Feb 2016 (v1), last revised 10 Feb 2016 (this version, v2))

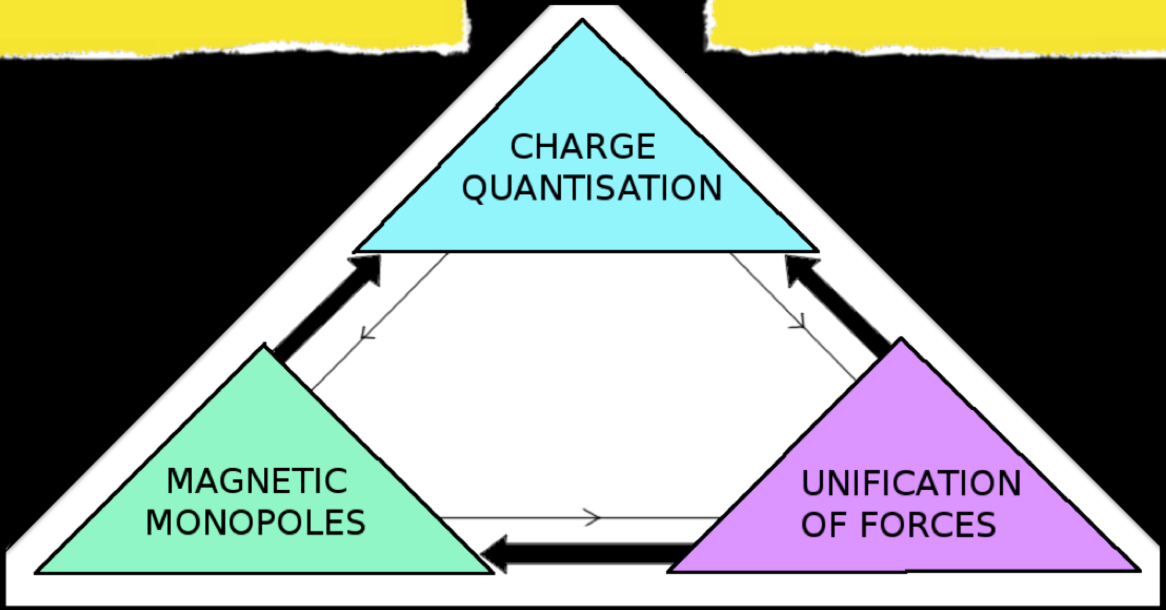
In a recent paper, Cho, Kim and Yoon (CKY) have proposed a version of the SU(2) × U(1) Standard Model with finite-energy monopole and dyon solutions. The CKY model postulates that the effective U(1) gauge coupling → ∞ very rapidly as the Englert-Brout-Higgs vacuum expectation value → 0, but in a way that is incompatible with LHC measurements of the Higgs boson $H \to \gamma\gamma$ decay rate. We construct generalizations of the CKY model that are compatible with the $H \to \gamma\gamma$ constraint, and calculate the corresponding values of the monopole and dyon masses. We find that the monopole mass could be < 5.5 TeV, so that it could be pair-produced at the LHC and accessible to the MoEDAL experiment.

- ... Dirac
- ... opole
- ... the Standard Model (Weinberg-Salam)
- T...-Maison monopole could be detectable by MoEDAL

The Importance of the Monopole

They restore symmetry to Maxwell's Equations

They explain electric charge quantization



GUT & EW monopoles are excitations of the Higgs field

They are required by GUTs string theory & M-theory

Properties of the Magnetic Monopole

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 solenidal field

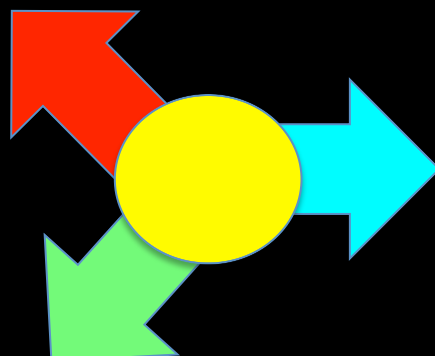
The monopole mass is
not predicted within
the Dirac's theory, ~
4-7 TeV EW monopole

Highly Ionizing Particles, Avatars of New Physics

ELECTRIC CHARGE (e)

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

VERY HIGH IONIZATION
Z↑ β(=v/c)↓



MINI-ELE… CHARGE (n…

$$\sim Kz^2\frac{Z}{A}\frac{1}{\beta^2}$$

…NIZA…
Z(<<1) β(~1)

VERY HIGH IONIZATION
g= n68.5e (n=1,2..)

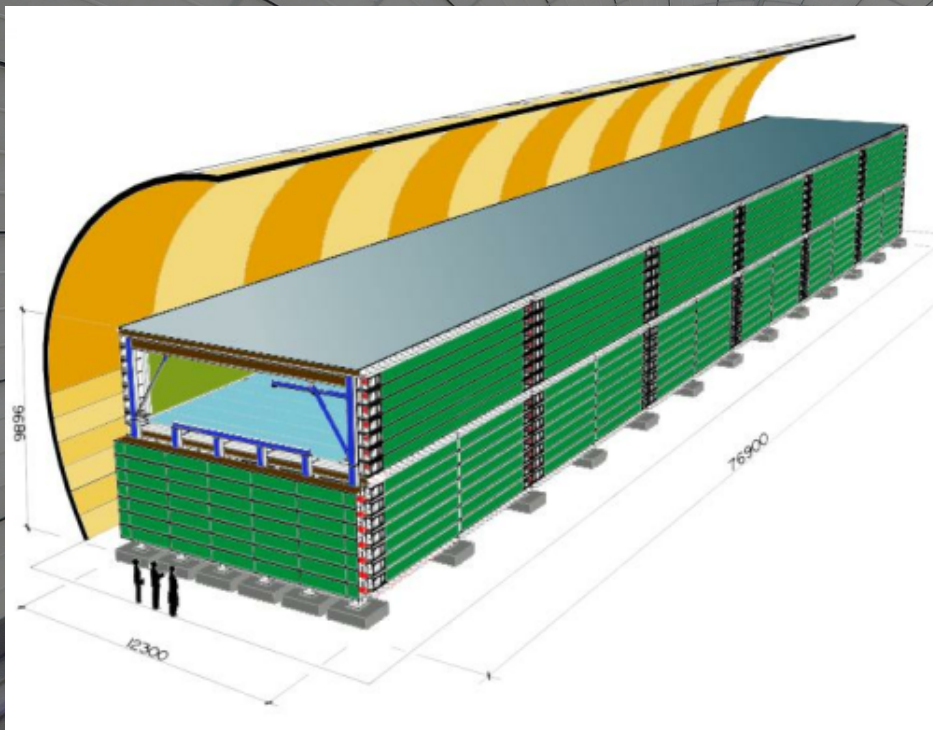
MAGNETIC CHARGE (g)

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

The velocity dep. of the Lorentz force cancels $1/\beta^2$ term

Astroparticle Experiments

MACRO Observatory Grand Sasso (1989-2000)

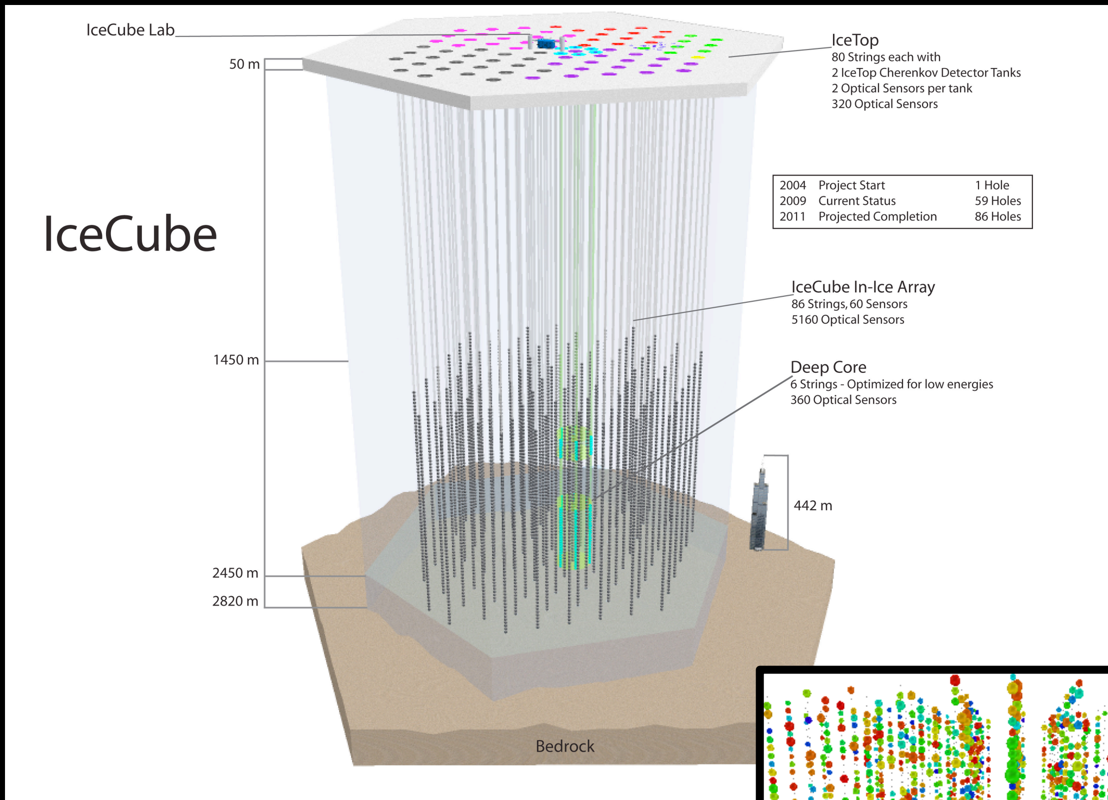


- *NTD surface : ~ 1300m^2*
- *$\Sigma\Omega_{fast\ MM}$ ~ 7100 m^2 sr*

- *3 Subdetectors:*
  - *Scintillators*
  - *Limited Streamer Tubes*
  - *Nuclear Track Detectors*

MACRO Limits on GUT Cosmic MMs still the best (on the PDG since 2000)

The IceCube Search for Monopoles

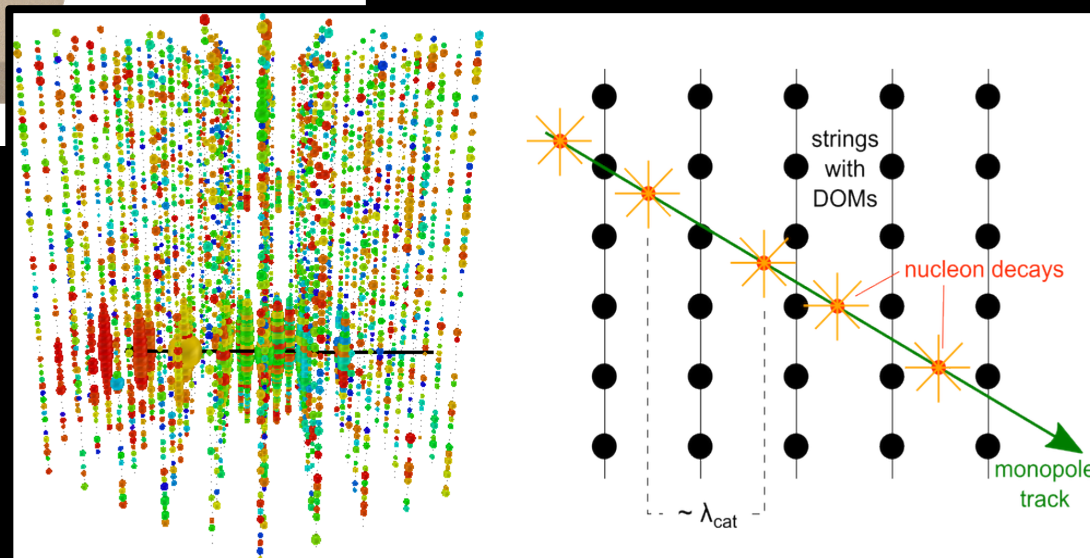


SEARCH 1

Upward coming relativistic GUT monopoles

SEARCH 2

Upward coming non-relativistic GUT Monopoles using catalysis of proton Decay



Limits on Intermediate Mass Monopoles

- *Intermediate monopoles with mass in the range 10^5 GeV → 10^{12} GeV*
- *IMMs can be accelerated in the galactic B field to relativistic velocities*

$$W = g_D\, B\, L \sim 6 \times 10^{19}\ \mathrm{eV}\ (B/3\times10^{-6}\ \mathrm{G})\ (L/300\mathrm{pc})$$

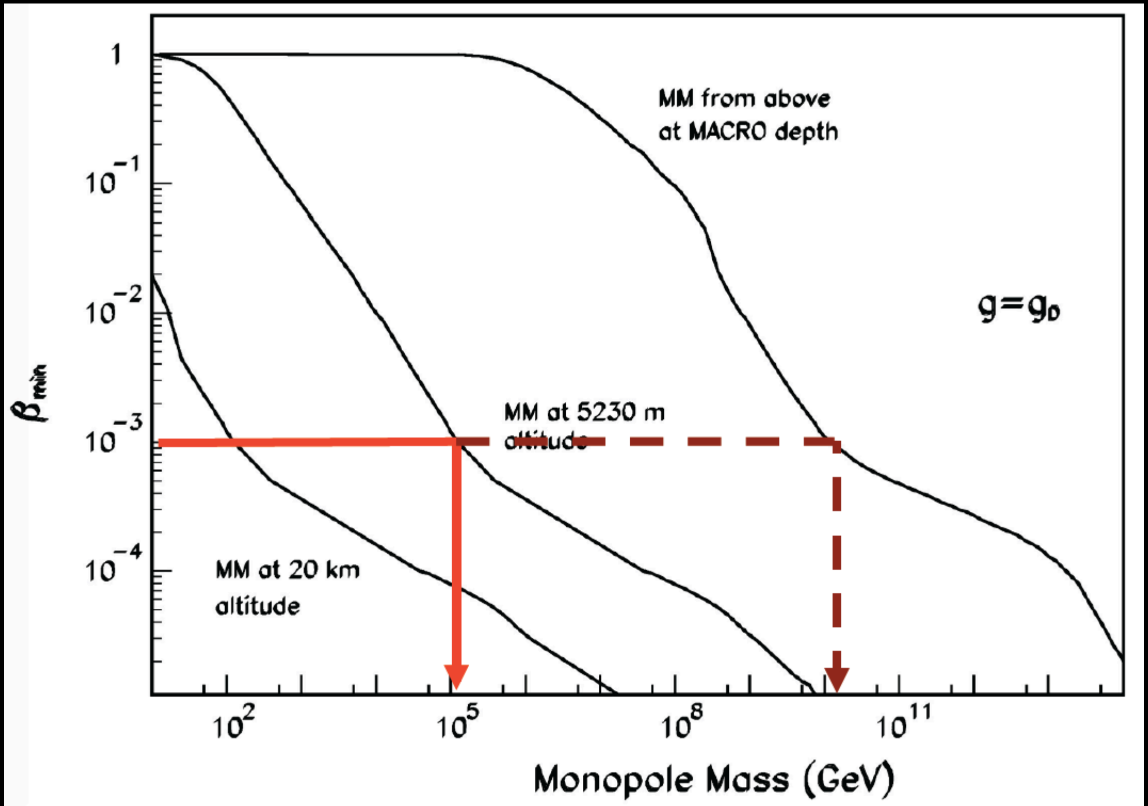
Galaxy W ~ 6 x 10^{19} eV

Neutron stars W ~ 10^{20} - 10^{24} eV

AGN W ~ 10^{23} - 10^{24} eV

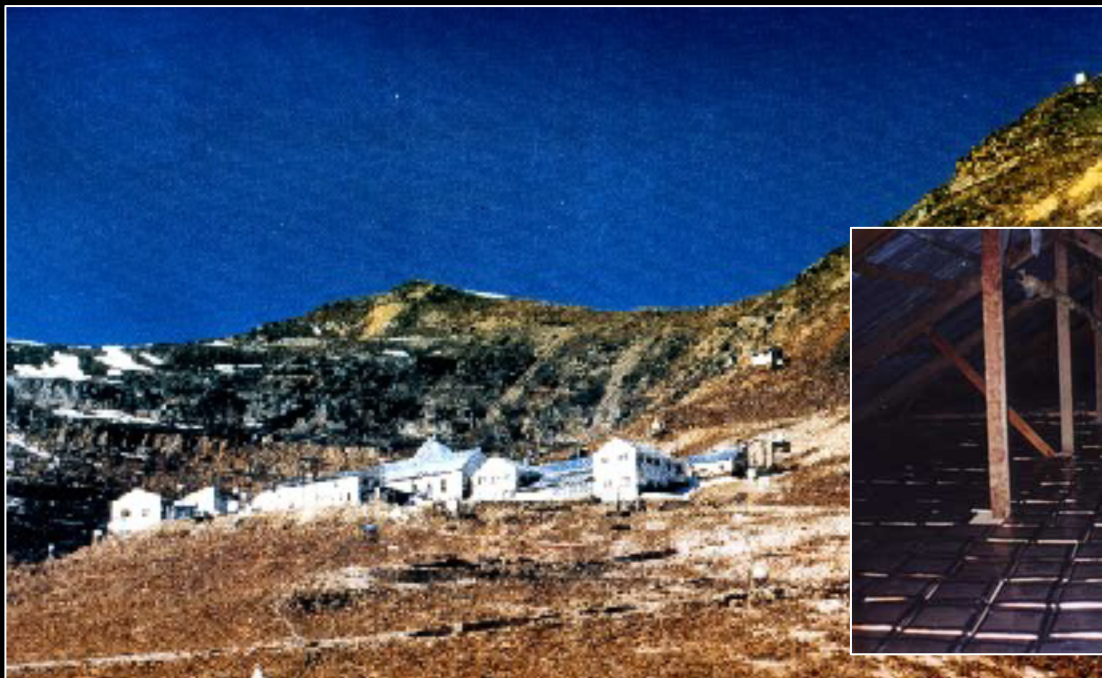
- *If monopole mass is less than ~ 10^{13} GeV it will not penetrate the Earth to reach underground/underwater/under-ice detectors*

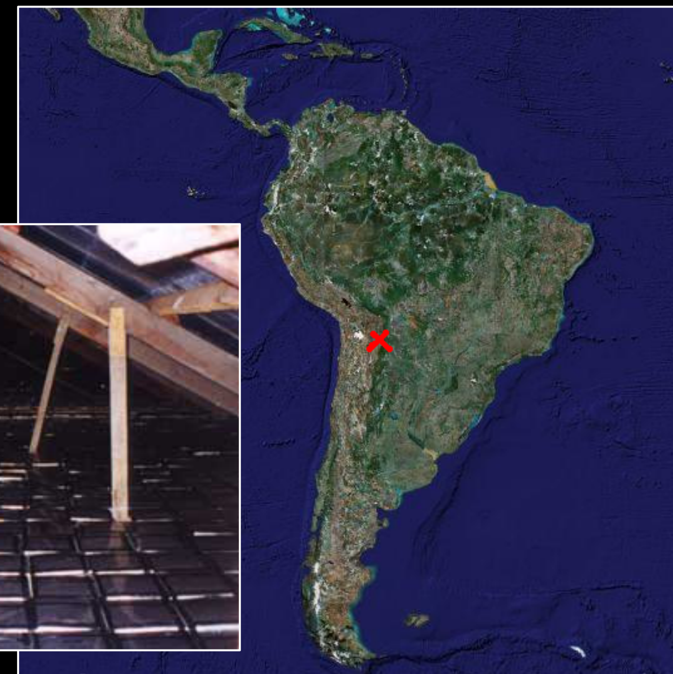
How to Efficiently Detect IM Monopoles



- *IMMs will often be ranged out in the Earth or the atmosphere. and they can only be detected from above.*
- *One needs large areas to push down below the Parker Bound*
- *Thus, the solution is to deploy a IMM detector at High Altitude*

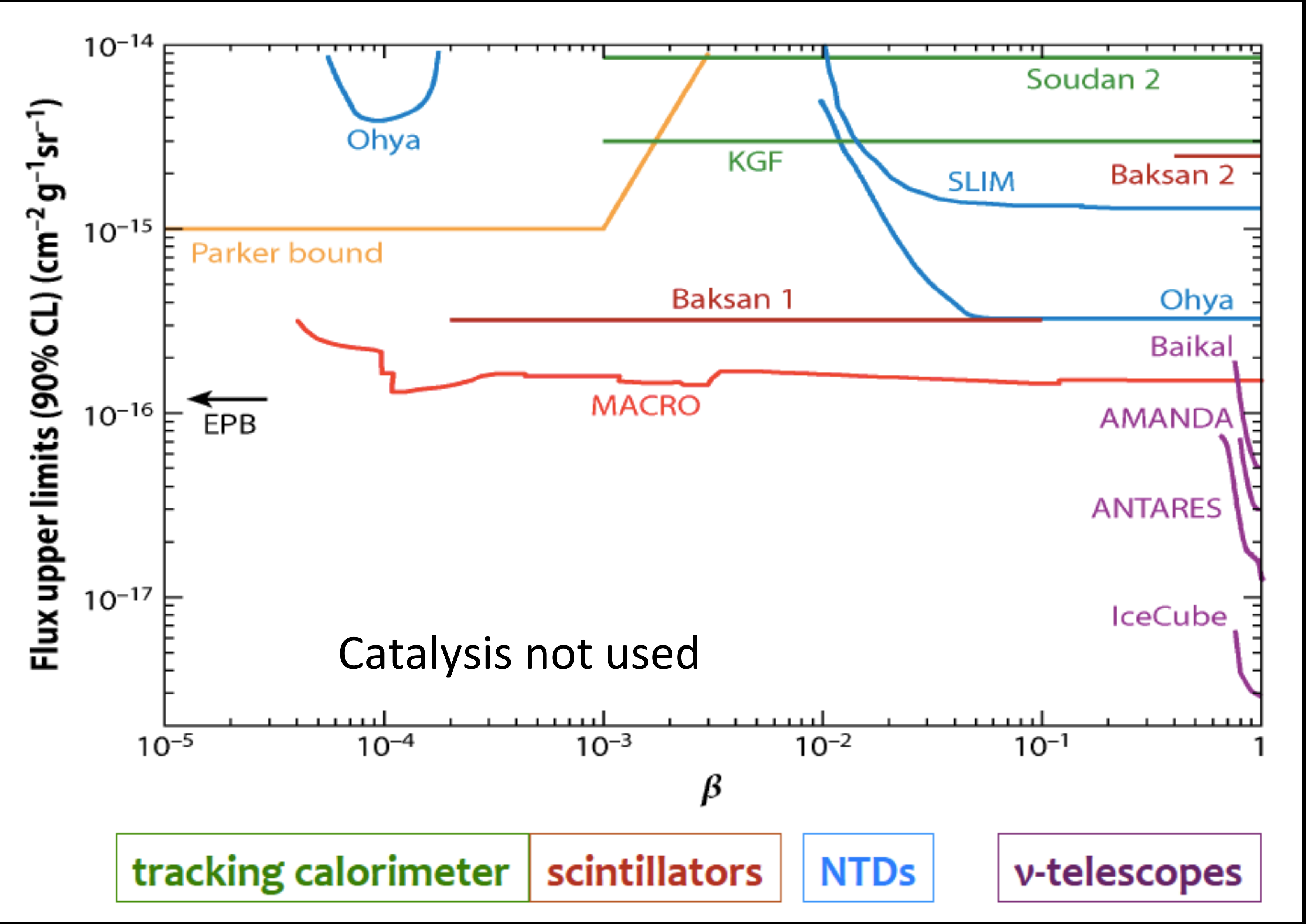
The SLIM Experiment



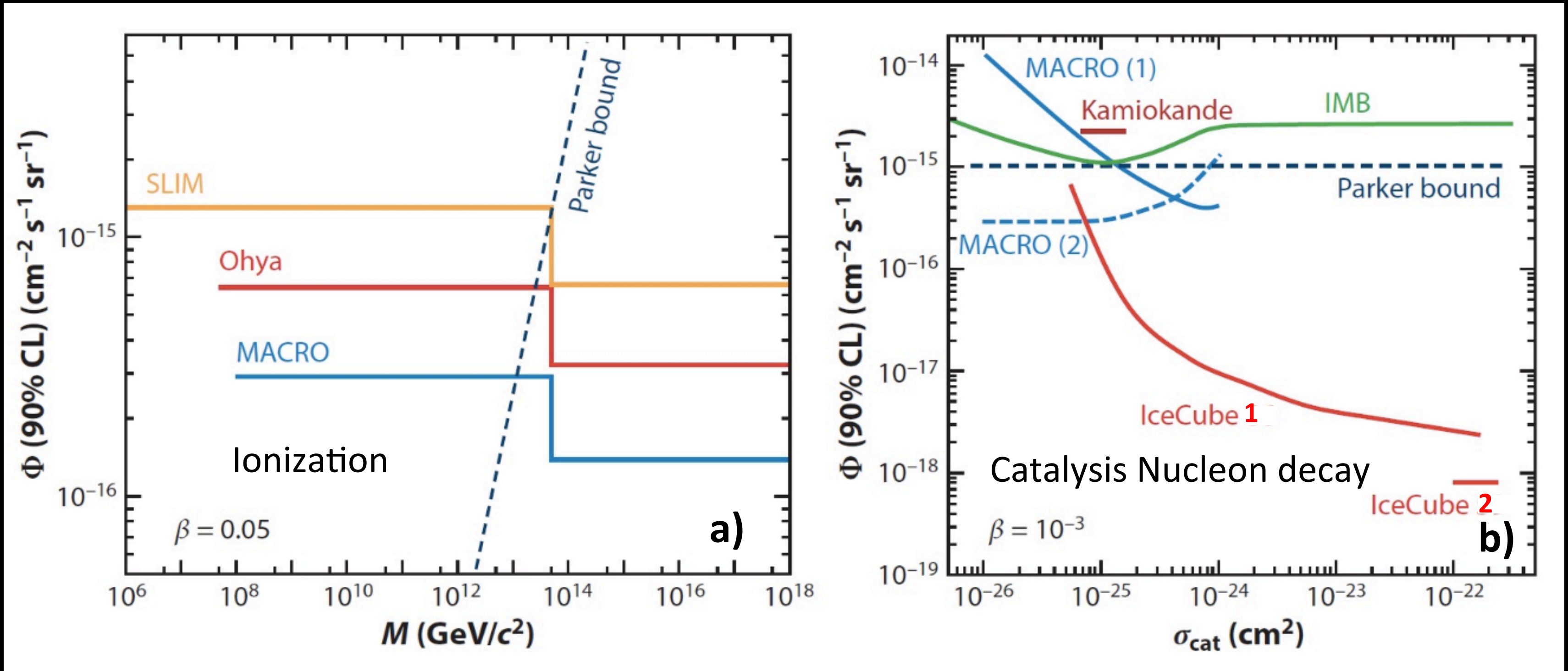


- *Search for Light and IM Monopole (SLIM), Chacaltaya, Bolivia, 5230 m asl using an array on Nuclear Track Detector (NTD) modules*
    - *Duration of experiment 1999-2006*
    - *Surface area of Nuclear Track Detector Modules ~ 410 m^2*

Limits on GUMs from Cosmic Detectors (1)



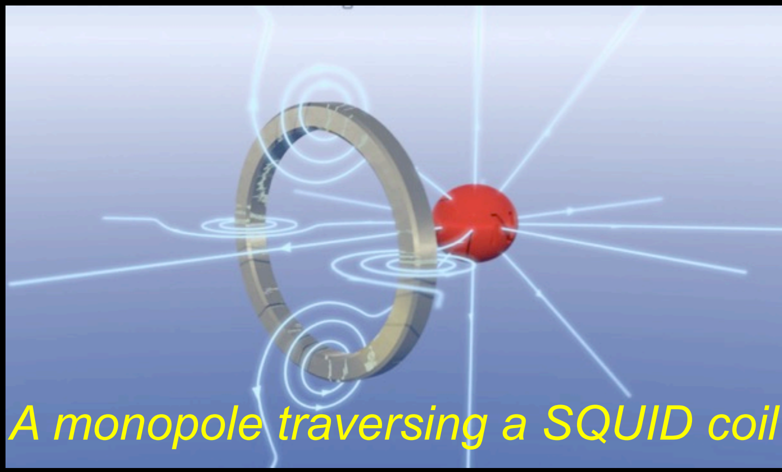
Limits on GUMs from Cosmic Detectors (2)



a) Upper flux limits for GUT Monopoles (GUMs)'s as a function of their mass M for $\beta = 0.05$ as set by MACRO, Ohya, & SLIM.

b) Upper limits on the flux of $\beta = 10^{-3}$ M as a function of the catalysis cross section σ_{Cat} for 2 IceCube analyses, 2 MACRO analyses, IMB, & Kamiokande .

Induction Experiments - Evidence?



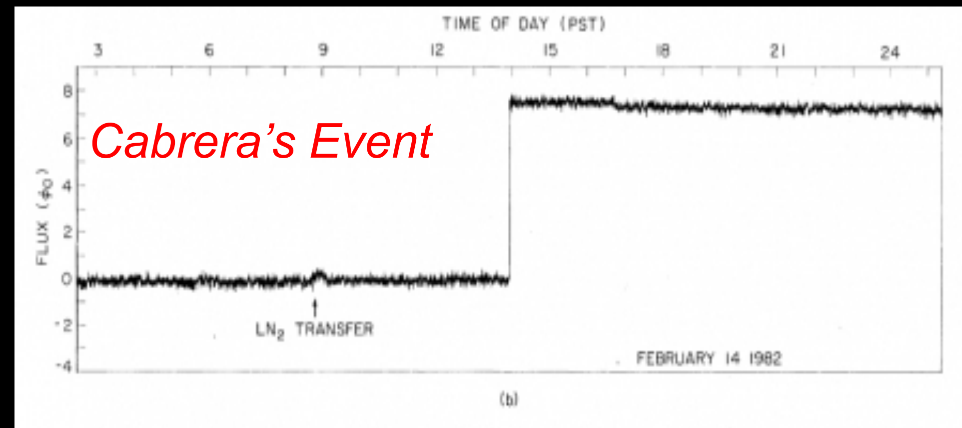
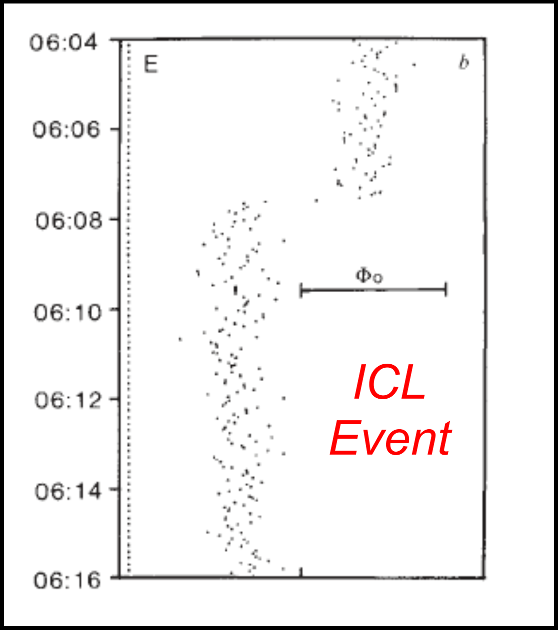


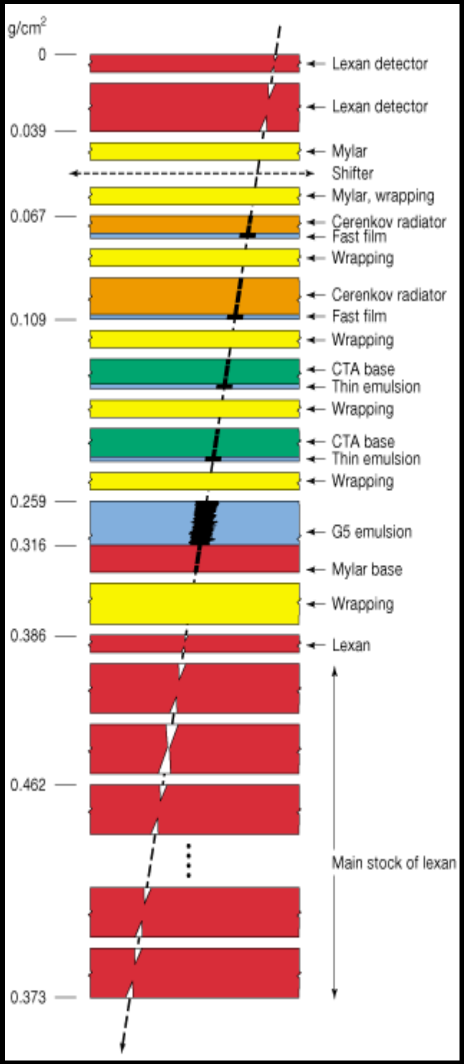
FIG. 2. Data records showing (a) typical stability and (b) the candidate monopole event.

- *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 - 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*
- *SAME TECHNOLOGY IS UTILIZED BY MoEDAL*



Buford Price's Strange Event

- *In 1975, researchers from Berkeley and the University of Houston claimed to have seen a monopole.*
- *Price and colleagues were studying cosmic ray interactions in stacks of emulsions and plastic track-etch detectors lifted to high altitude by a balloon (130K ft) over Sioux City, Iowa.*
  - *The characteristics of the`monopole event' ,said the researchers, "strongly favour the identification of the particle as a magnetic monopole with a charge of 137 and a mass greater than 200 times that of a proton, travelling at a velocity half the speed of light". (TIME Aug. 25th 1975)*
- *Alvarez offered an alternative explanation - the cosmic ray magnetic monopole could be a platinum nucleus fragmenting to osmium and then to tantalum.*
- *There are some questions but the GUT monopole explanation is not ruled out*



Accelerator Experiments

The Beginning

IL NUOVO CIMENTO Vol. XXII, N. 3 1° Novembre 1961

Search for Magnetic Monopoles.

M. Fidecaro, G. Finocchiaro (*) and G. Giacomelli (**)
CERN - Geneva

(ricevuto il 30 Settembre 1961)

@ CERN -PS

IL NUOVO CIMENTO Vol. 28 A, N. 1 1 Luglio 1975

Search for Magnetic Monopoles at the CERN-ISR with Plastic Detectors.

G. Giacomelli, A. M. Rossi and G. Vannini
Istituto di Fisica dell'Università - Bologna
Istituto Nazionale di Fisica Nucleare - Sezione di Bologna

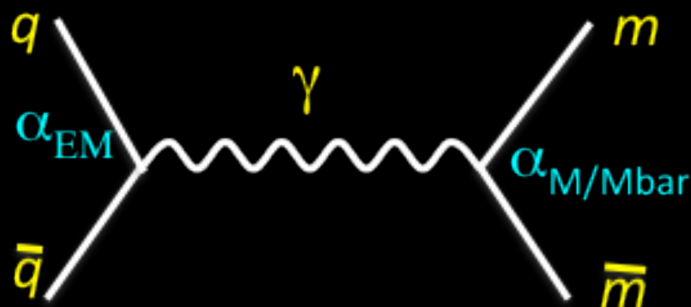
A. Bussière
CERN - Geneva
DPhN/HE - Saclay

G. Baroni, S. Di Liberto, S. Petrera and G. Romano
Istituto di Fisica dell'Università - Roma
Istituto Nazionale di Fisica Nucleare - Sezione di Roma

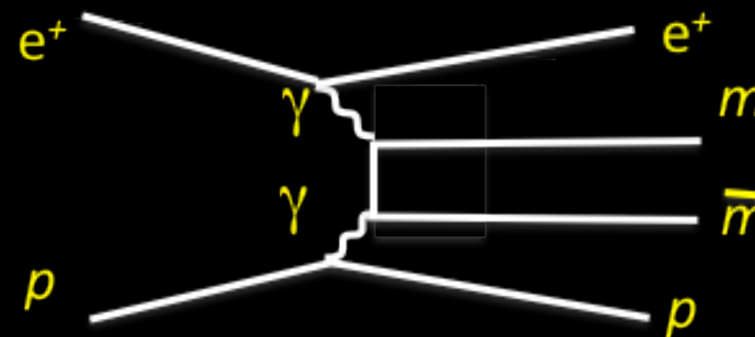
@ CERN – ISR

Monopole Production at Colliders

$e^+e^- \rightarrow M\bar{M}$, $pp \rightarrow M\bar{M}$, $e^+p \rightarrow e^+pM\bar{M}$, etc,

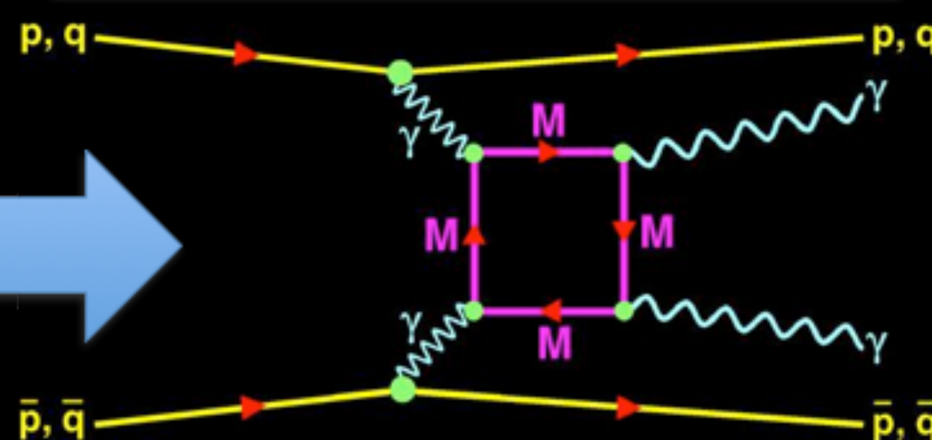


Drell-Yan Production



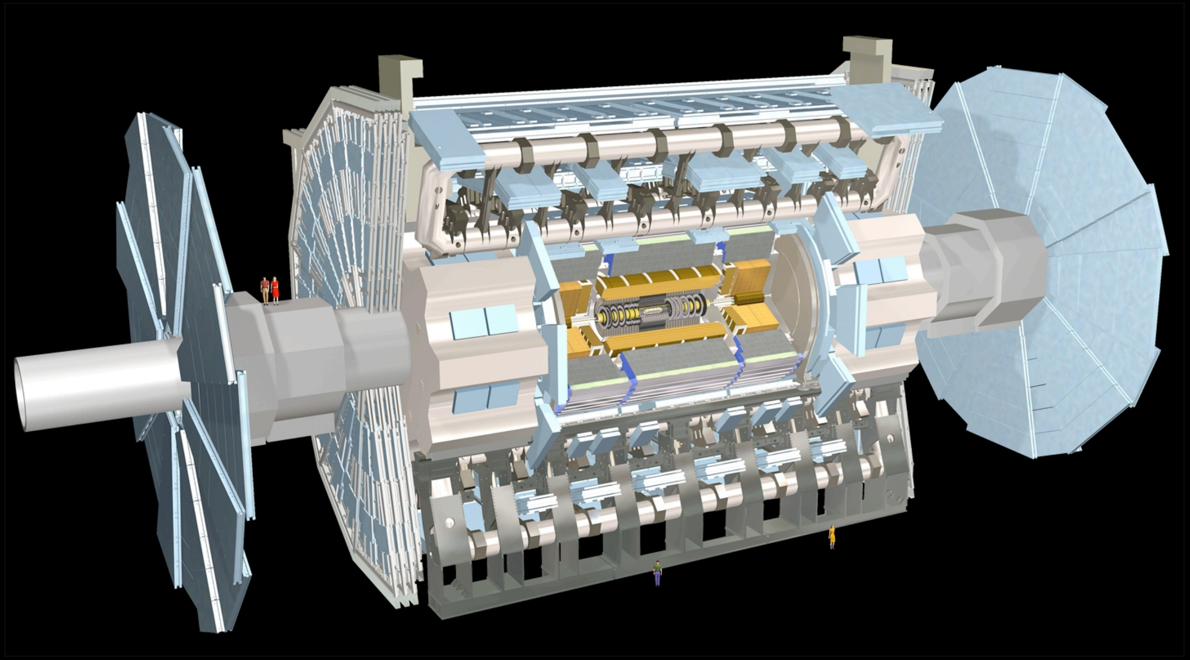
Two-photon production

Indirect search using virtual monopole box diagrams allow – observable two high energy gammas.



Results from ATLAS (1)

ATLAS Detector   7000 tonnes & 46m x 25m

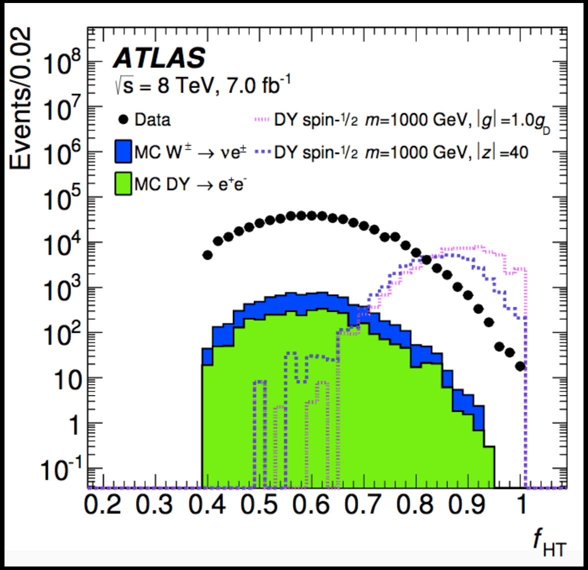


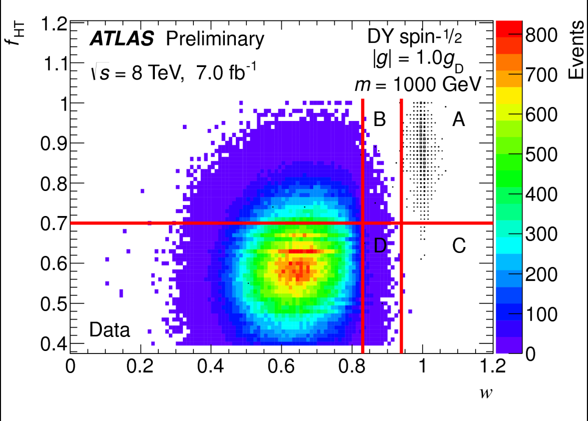
- *The two general purpose LHC detectors ATLAS and CMS*
  - *Standard collider electronic detectors with magnetic field comprised of: Inner Tracker; EM calorimeter, Hadronic Calorimeter and Muon detectors*
  - *Multi level trigger is required.*

Results from ATLAS (2)

The ATLAS Search for Monopoles & Stable Highly Charged Particles (Phys Rev. D 93 052009 2016)

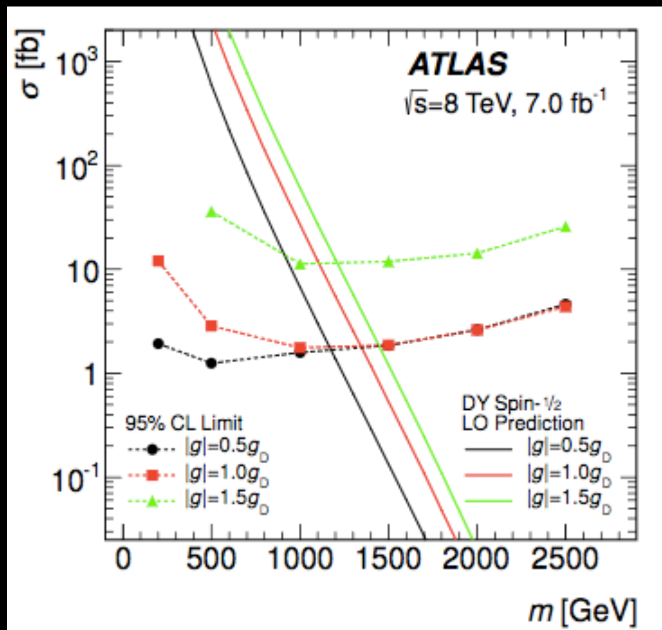
- *ATLAS event selection*
  - *Level-1: Hardware triggers select events with **ET** > 18 → 20 GeV in the EM calo (ECAL) and **ET** < 1 GeV in hadronic calo*
  - *Level-2: ECAL associated hits in a wedge of = ±0.015 rad in ϕ;*
  - *Discriminants: fraction & # HT TRT hits ($N^{trig}_{HT} > 20$ & $f^{trig}_{HT} > 0.37$)*
  - *EM energy deposit dispersion (fraction of EM energy contained in most energetic cells, w)*
  - *Background determined from data using ABCD regions*

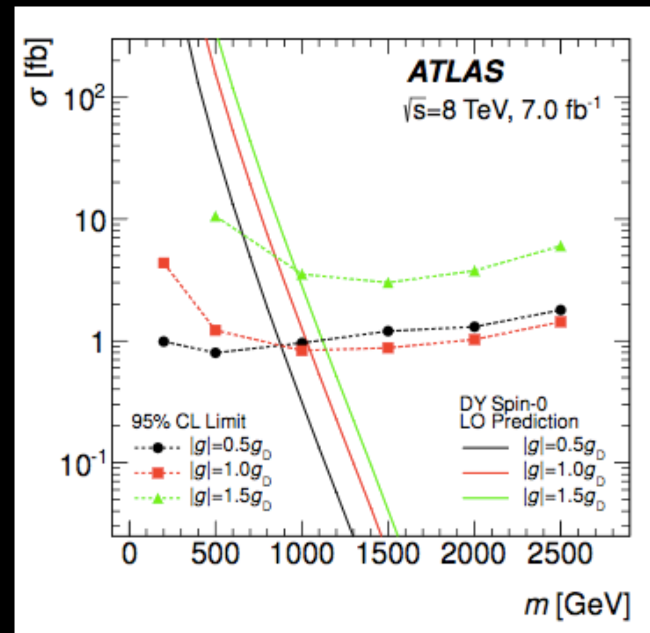




Results from ATLAS (3)

The ATLAS √s =8TeV Monopole Search Results





Drell-Yan Lower Mass Limits (GeV)

	$\lvert g\rvert = 0.5g_D$	$\lvert g\rvert = 1.0g_D$	$\lvert g\rvert = 1.5g_D$
spin-1/2	1180	1340	1210
spin-0	890	1050	970

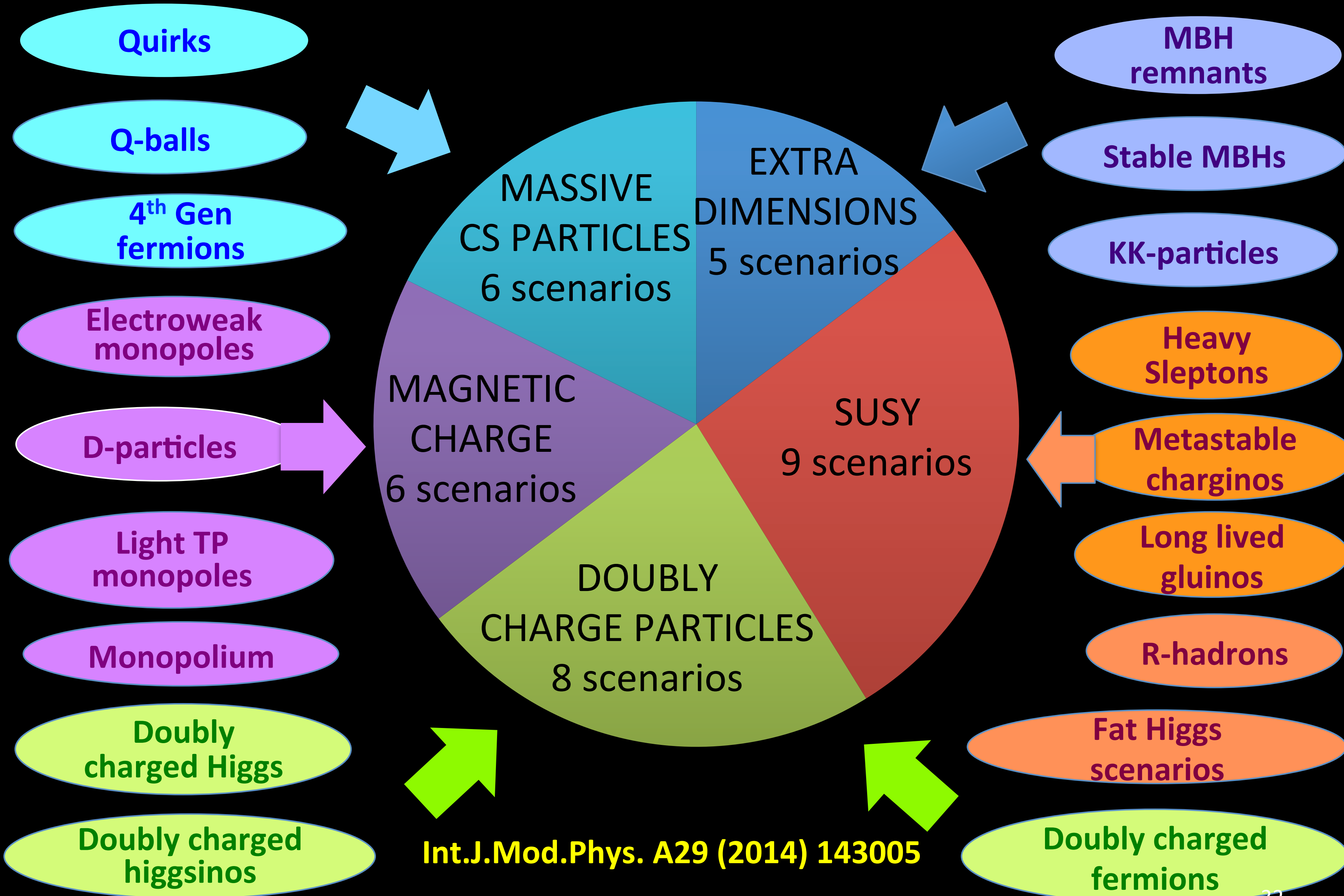
- *Limits on integer magnetic charge g_D=1*

The MoEDAL Experiment & Collaboration

66 physicists from 14 countries & 26 institutes. on 4 continents:

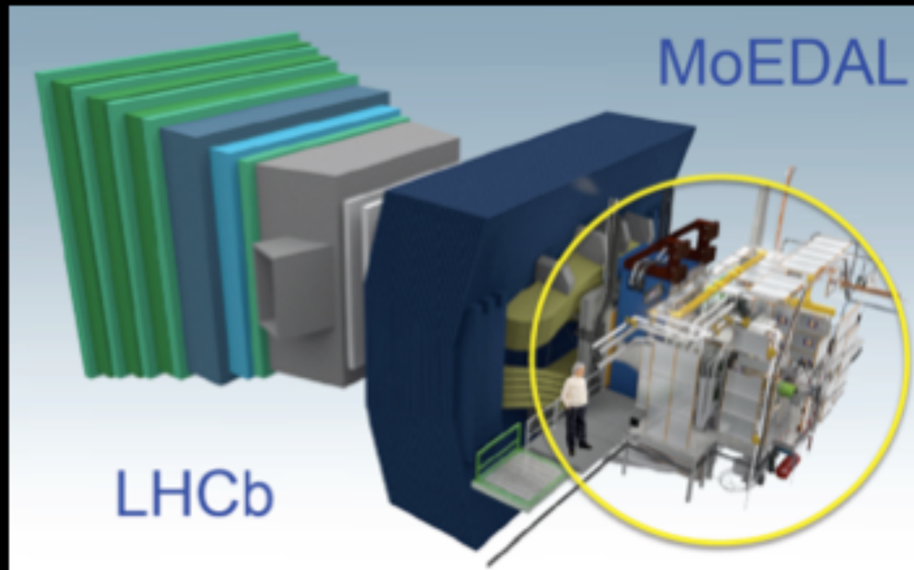
1) U. Alberta, 2) U. Alabama,3) UBC, 4) INFN Bologna, 5) U. Bologna,6) CAAG-Algeria, 7) U. Cincinatti, 8) Concordia U., 9) CSIC Valencia,10) Gangneung-Wonju Nat. U.,11) 12) U. Geneva, 13) U. Helsinki, 14) IEAP/CTU Prague, 15) IFIC Valencia, 16) Imperial College London, 17) ISS Bucharest,18) King's College London, 19) Konkuk U., 20) U. Montréal,21) MISiS Moscow, 22) Muenster U., 23) National Inst. Tec. (india), 24) Northeastern U., 25) Queen Mary College UK, 25) IRIS/Simon Langton School UK, 26) Tuft's.

MoEDAL – Physics Scenarios (34+)



The MoEDAL Detector

Permanent Physical record of new physics



No Standard Model Physics Backgrnds

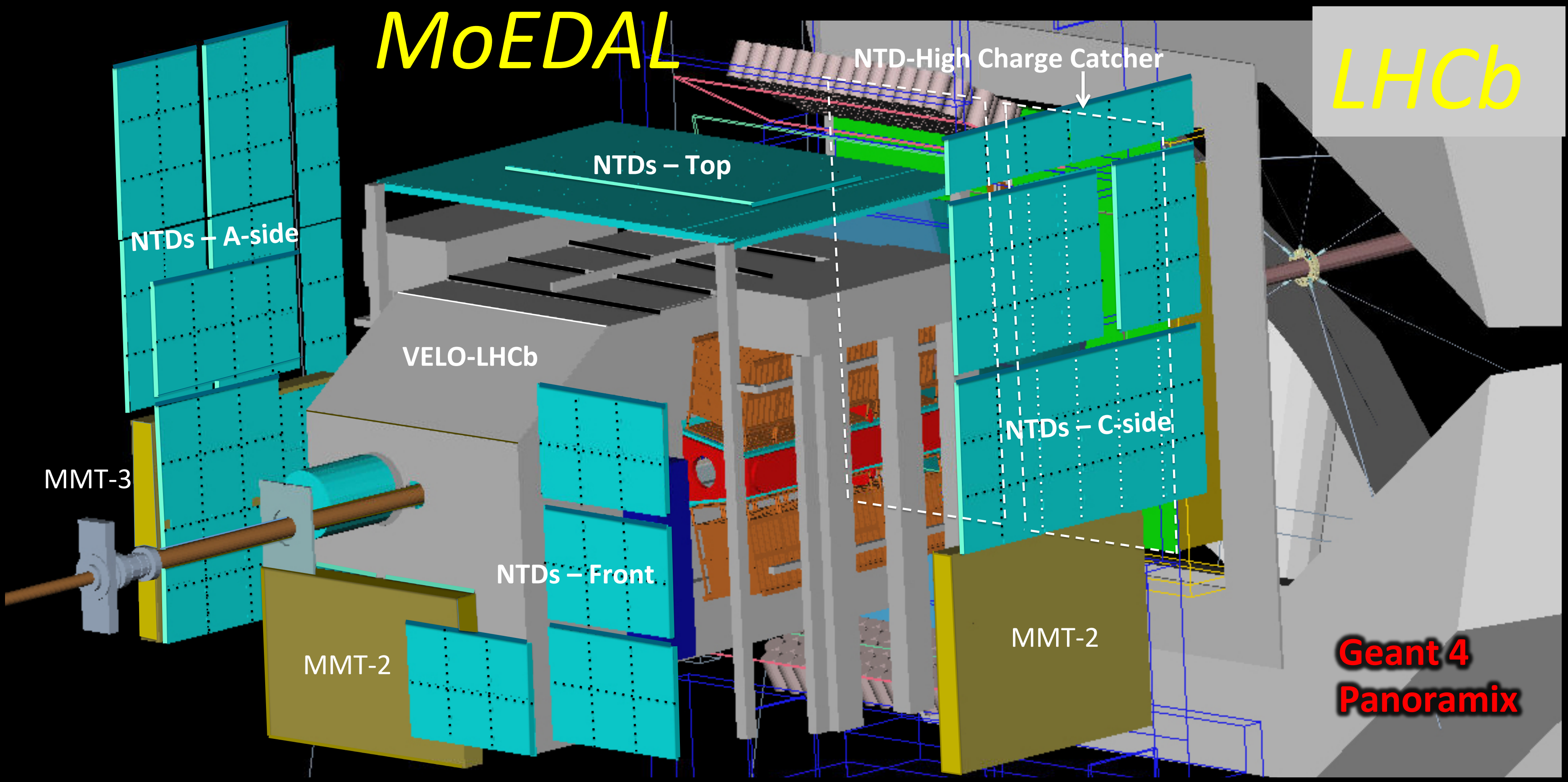
MoEDAL is largely passive and made up of three detector systems

NUCLEAR TRACK DETECTOR Plastic array (~200 sqm) – Like a Giant Camera

TRAPPING DETECTOR ARRAY A tonne of Al to trap Highly Ionizing Particles for analysis

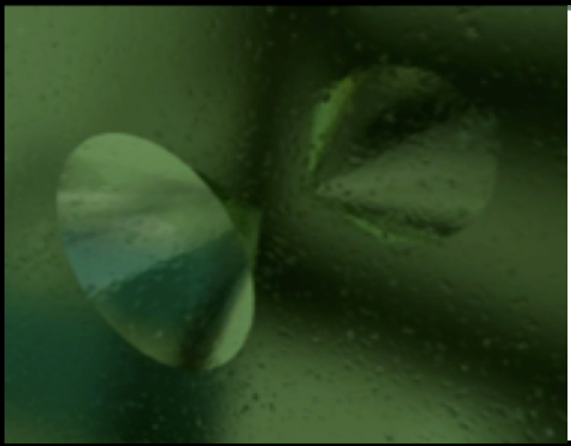
TIMEPIX Array a digital Camera for real time radiation monitoring

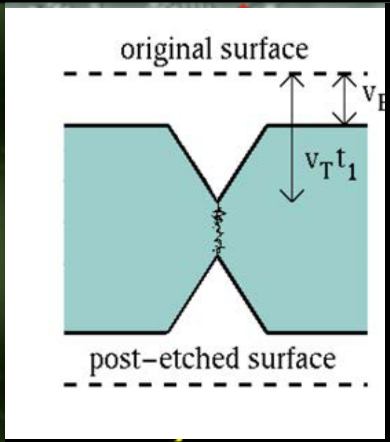
Full MoEDAL Deployment 2014-2015

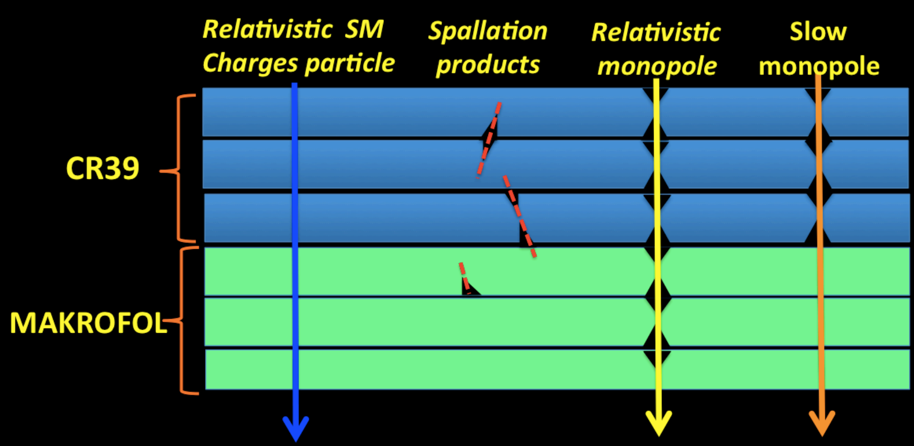


- *Acceptance for at least one monopole from monopole pair production to hit NTDs ~70% (over 150 m^2 of plastic)*

The Signal in the NTDS

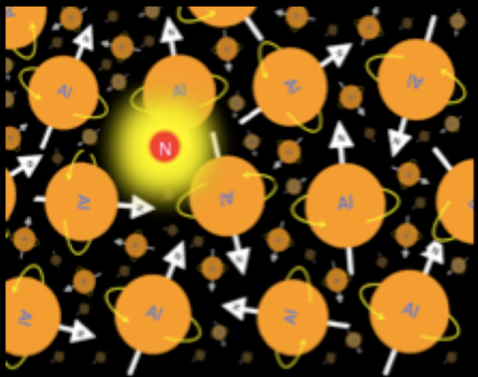






- *Largest NTD array (**150m²** tot) ever deployed at an accelerator*
  - *NTD tacks consist of CR39 (Thr. 5 mip) & Makrofol (Thr. 50 mip)*
  - *Damage revealed by controlled etching - etch pits are formed*
  - *Charge resolution is ~|0.1|e, where |e| is the electron charge*
  - *Precision of each etcha pit measurement ~20-50 microns*
- *NTDs are calibrated at heavy-ion beams at NSRL & NA61*
- *ATLAS and CMS cannot calibrate for highly ionizing plastic*

Signal in Squid MMT Detectors



Monopole trapped by aluminium nuclei

The MoEDAL trapping detectors at IP8

THE Zurich DC-SQUID magnetometer

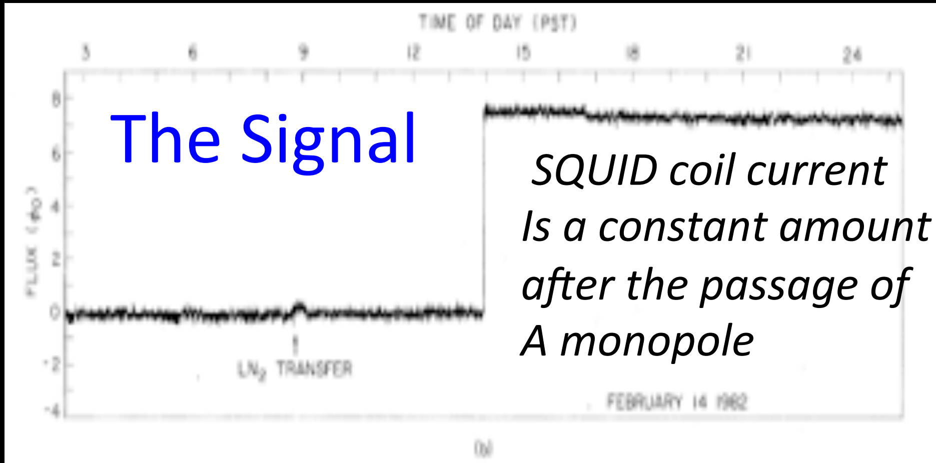
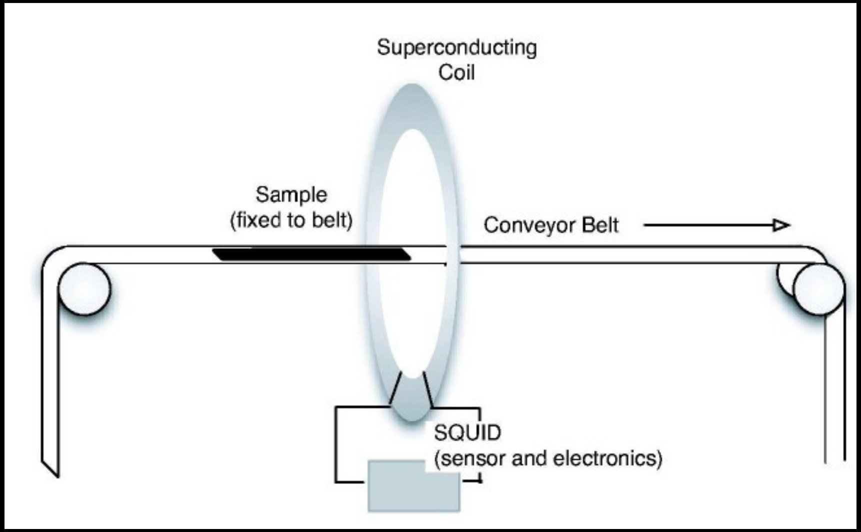
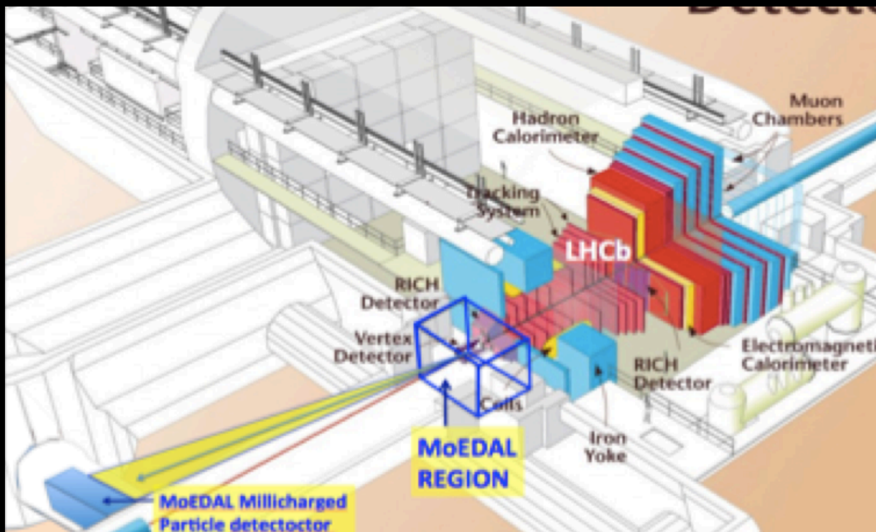
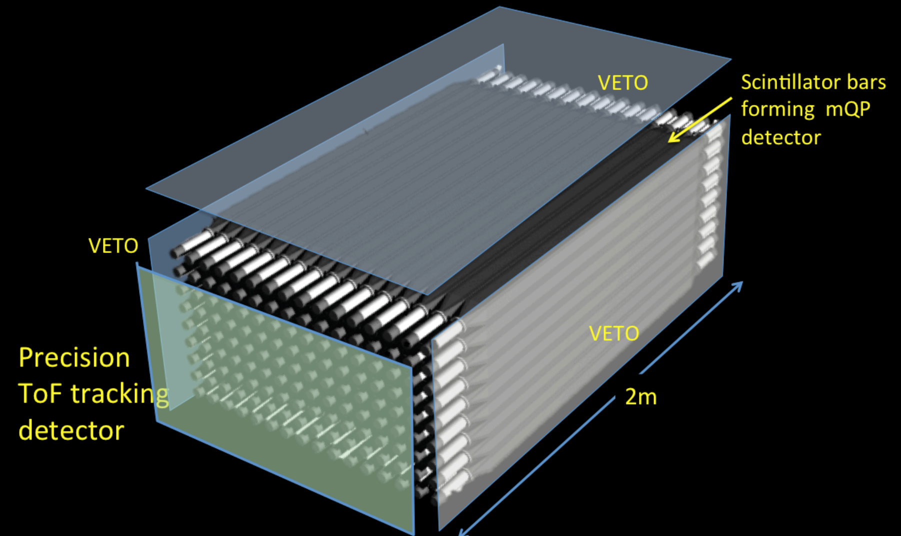


FIG. 2. Data records showing (a) typical stability and (b) the candidate monopole event.



MoEDAL Apparatus for Penetrating Particles (MAPP)

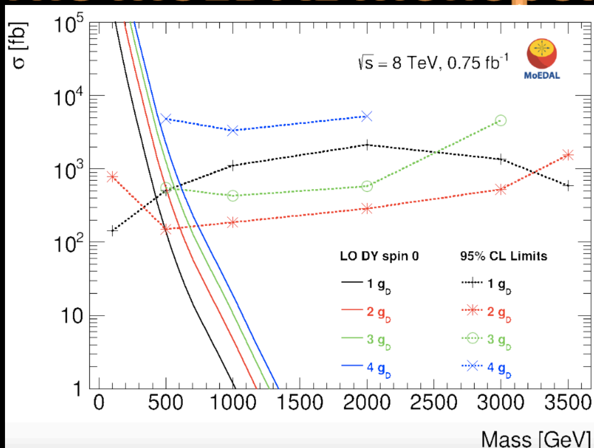


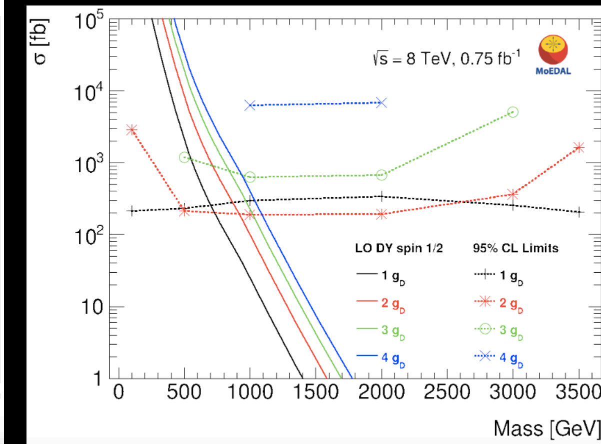


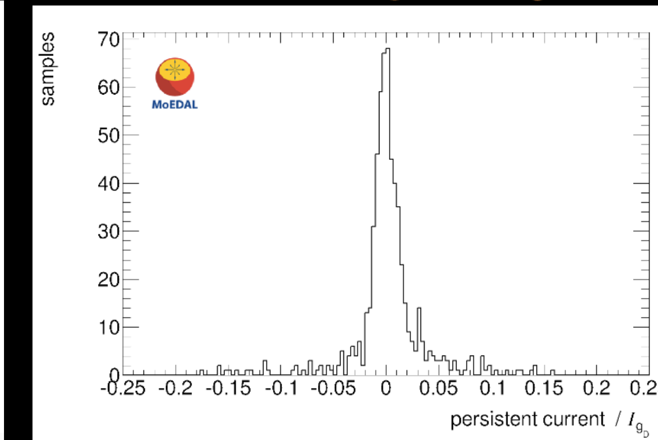
- *MAPP will be able to take data in p-p, p-A,A-A and also fixed target interactions using SMOG (an internal gas target in LHCb)*
- *MAPP has three motivations*
  - *To search for particles with charges <<1e (ATLAS & CMS limited to searches with particles of charge e ≥ 1/3)*
  - *To search for new pseudo-stable neutrals with long lifetime and anomalously penetrating particles*

First MoEDAL Results

The MoEDAL Monopole Search at s = √8 TeV - JHEP 1608 (2016) 067







DY Lower Mass Limits [GeV]	$\lvert g\rvert = g_D$	$\lvert g\rvert = 2g_D$	$\lvert g\rvert = 3g_D$
spin-1/2	700	920	840
spin-0	420	600	560

MoEDAL

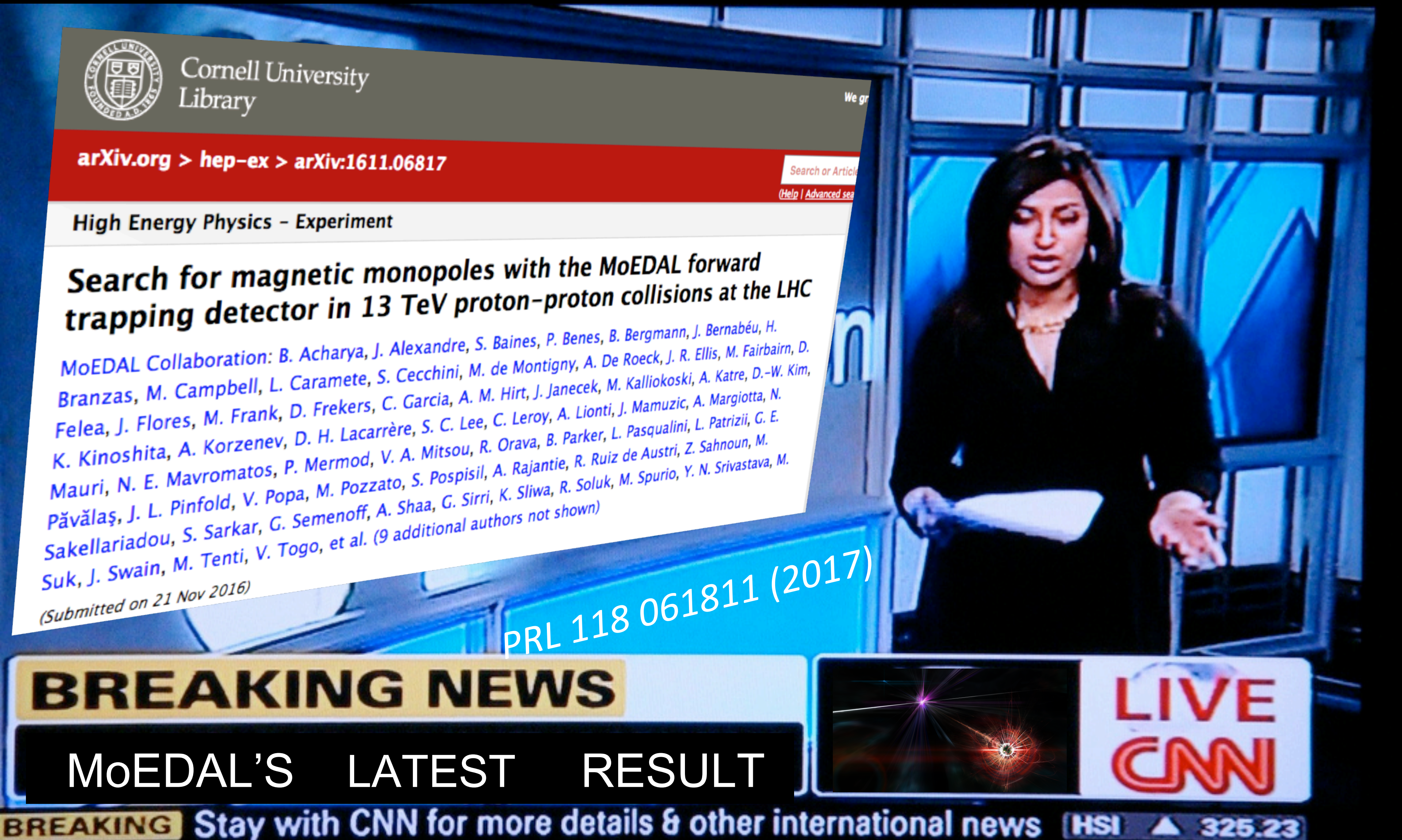
$\lvert g\rvert = g_D$
1340
1050

ATLAS

World best limits for $|g| > g_D$

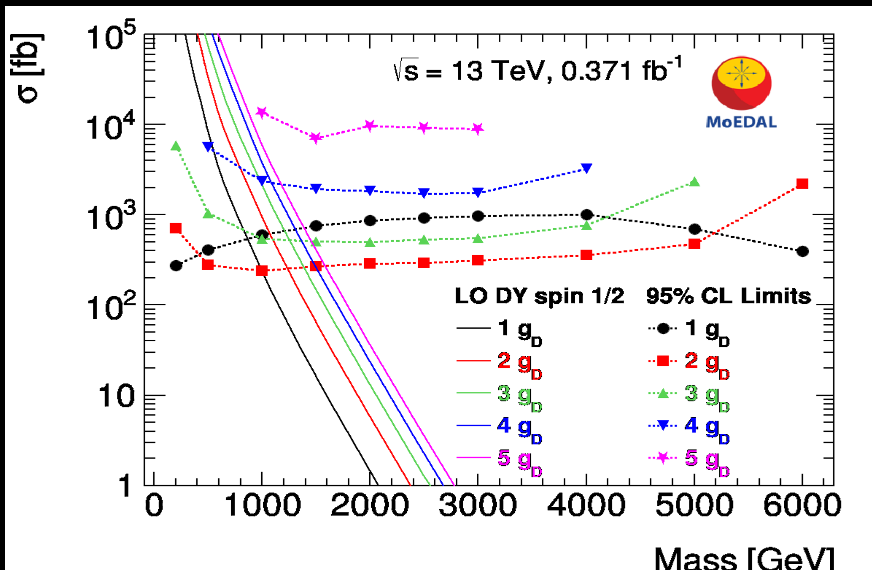
(previously ~400 GeV at the Tevatron)

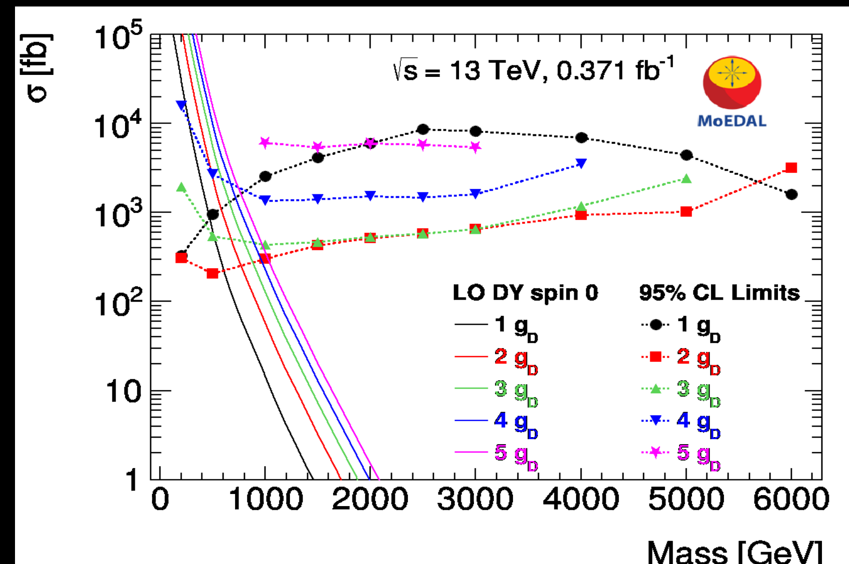
LHC's First 13 TeV Result on Monopoles



Latest MoEDAL Results

Latest MoEDAL Results at $\sqrt{s}$ =13 TeV - PRL 118 061811 (2017)



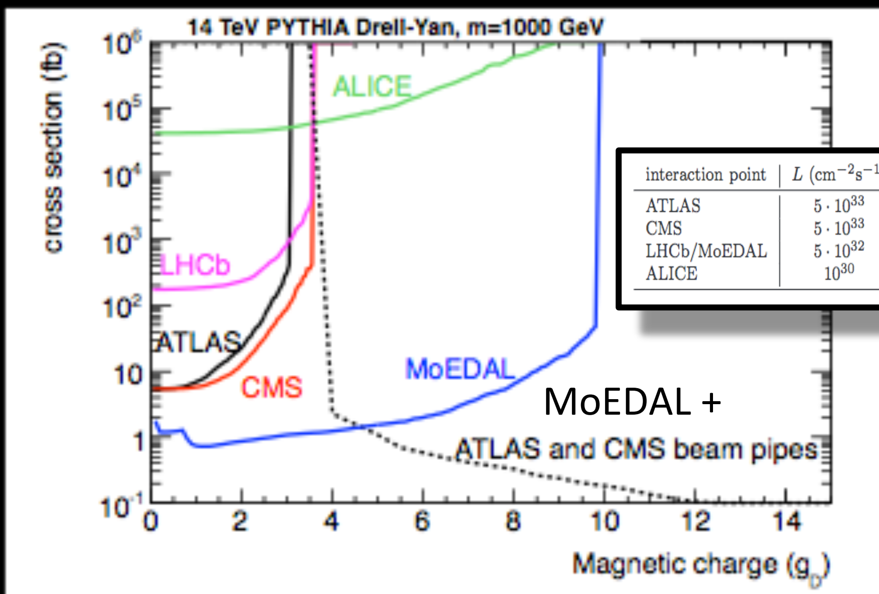


- *First monopole constraints in 13 TeV pp collisions*
  - *Probe TeV masses for up to $5g_D$ for the 1st time at the LHC*
  - *Exclude monopole with $|g|=4g_D$ for the 1st time at the LHC*

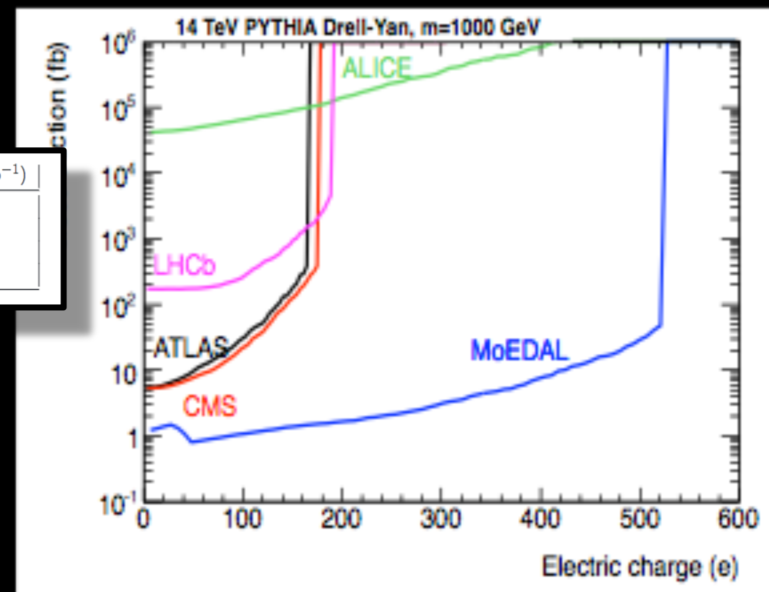
mass limits [GeV]	$1g_D$	$2g_D$	$3g_D$	$4g_D$
MoEDAL 13 TeV (this result)				
DY spin-1/2	890	1250	1260	1100
DY spin-0	460	760	800	650
MoEDAL 8 TeV				
DY spin-1/2	700	920	840	–
DY spin-0	420	600	560	–
ATLAS 8 TeV				
DY spin-1/2	1340	–	–	–
DY spin-0	1050	–	–	–

MoEDAL's Sensitivity

detector	energy threshold	angular coverage	luminosity	robust against timing	robust efficiency
ATLAS	medium	central	high	no	no
CMS	relatively low	central	high	no	no
ALICE	very low	very central	low	yes	no
LHCb	medium	forward	medium	no	no
MoEDAL	low ✔	full ✔	medium ✔	yes ✔	yes ✔



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])*
- *MoEDAL COMPLEMENTS the physics reach of the existing LHC experiments*

MoEDAL's Complementarity

Designed & Optimized for highly ionizing particles

Insensitive to SM particles

Mass ~ 1 ton

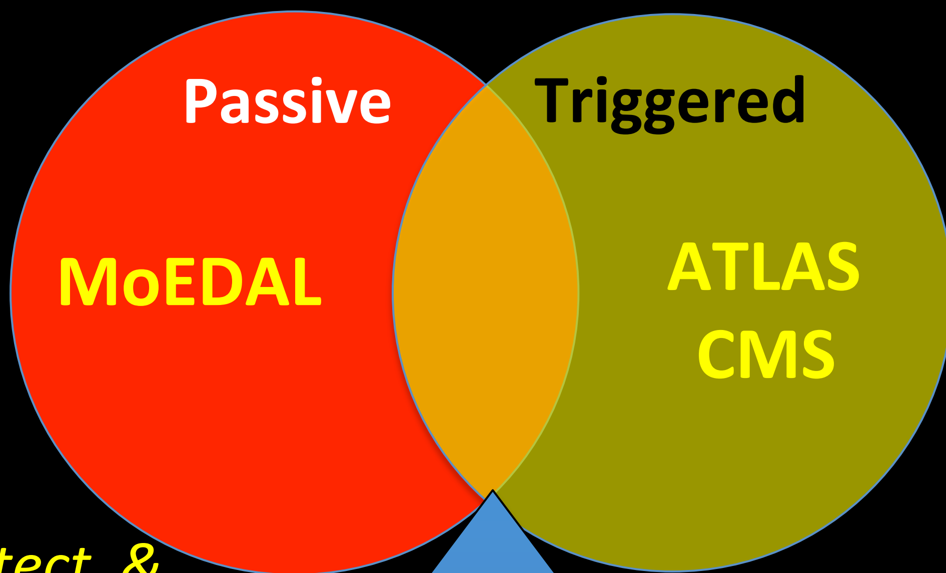
Size ~ 5m³

Thickness in RL ~ 0.02 X_0

Can directly detect & trap magnetic charge

Calibrated by heavy-ions

Soon able to detect ~ 0.01e



Designed & optimized for SM rel. charged particles & photons

Mass ~10K tons

Size ~ 25m diam. x 46 m length

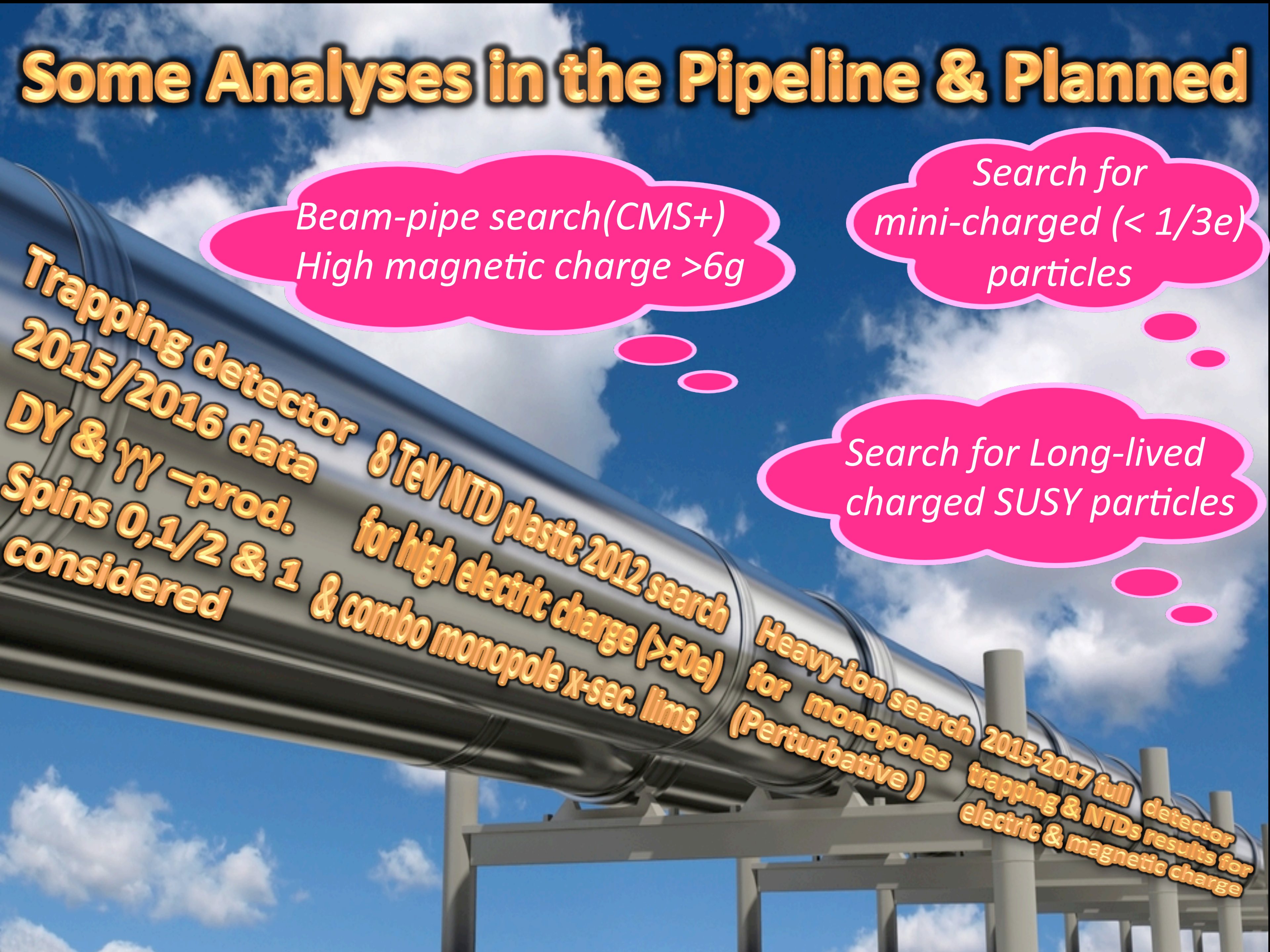
~ 25 X_0 RLs thick

Cannot detect magnetic charge

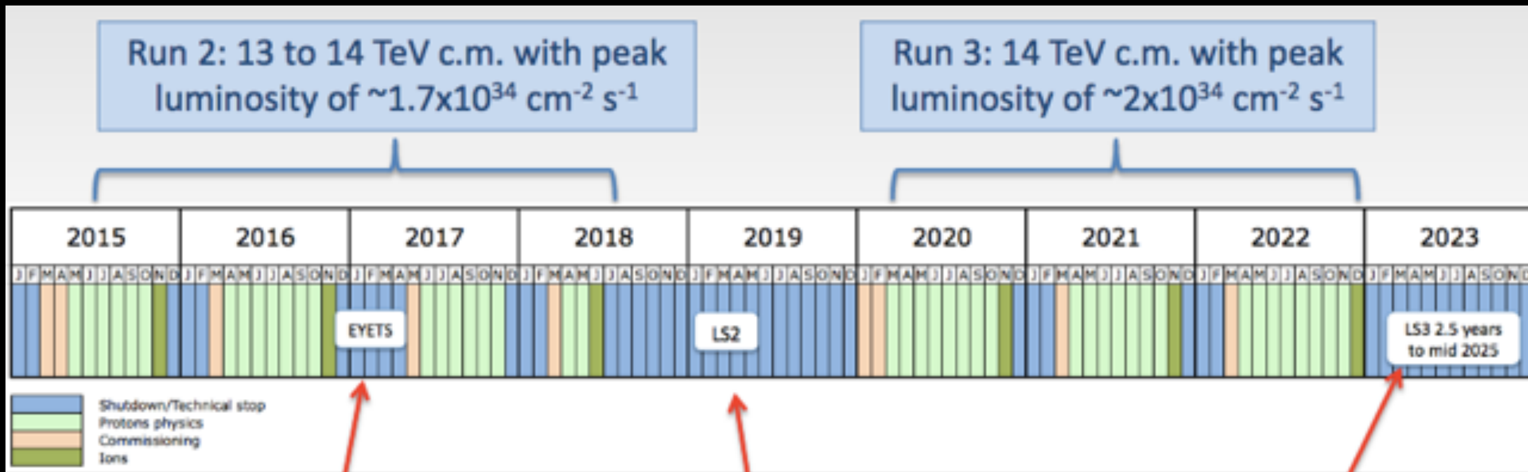
Cannot be calibrated for highly ionizing particles

Can only detect charge > ~0.3e

The different systematics and mode of detection of MoEDAL allow important validation of joint LHC observations


Some Analyses in the Pipeline & Planned
Beam-pipe search(CMS+)
High magnetic charge >6g
Search for
mini-charged (< 1/3e)
particles
Search for Long-lived
charged SUSY particles
Trapping detector
2015/2016 data
DY & γγ –prod.
Spins 0,1/2 & 1
considered
8 TeV NTD plastic 2012 search
for high electric charge (>50e)
& combo monopole x-sec. lims
Heavy-ion search 2015-2017 full detector
for monopoles trapping & NTDs results for
(Perturbative) electric & magnetic charge

More Luminosity and Higher Energy



- *Luminosity acquired by MoEDAL before the end of RUN-2 is likely to be ~6 fb^{-1}. Our request was for 10 fb^{-1}*
- *We will be requesting an additional 20-30 fb^{-1} of data in RUN-3 to Run 1t the increased E_{cm} of 14 TeV*
  - *Continue the search for magnetic charge to higher energy & luminosity*
  - *A higher luminosity is necessary to push the search for electrically charged massive(pseudo)-stable particles from, e.g., SUSY scenarios.*
  - *Start the search in earnest for mini-charged particles and long-lived secondaries using MAPP*

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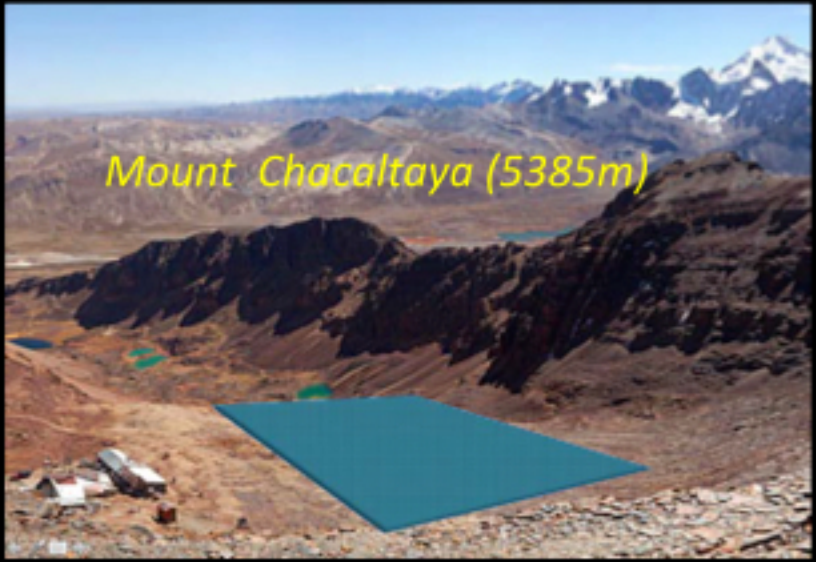
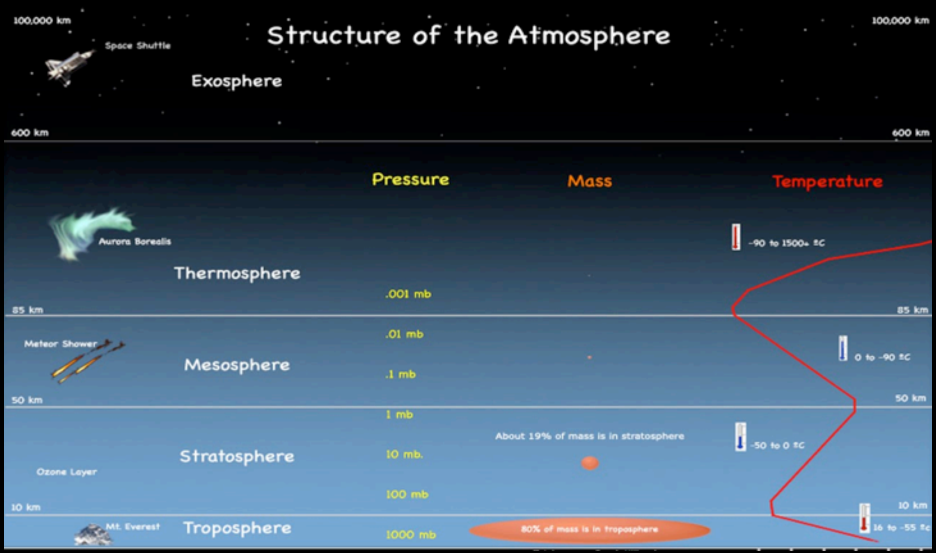
The Future?

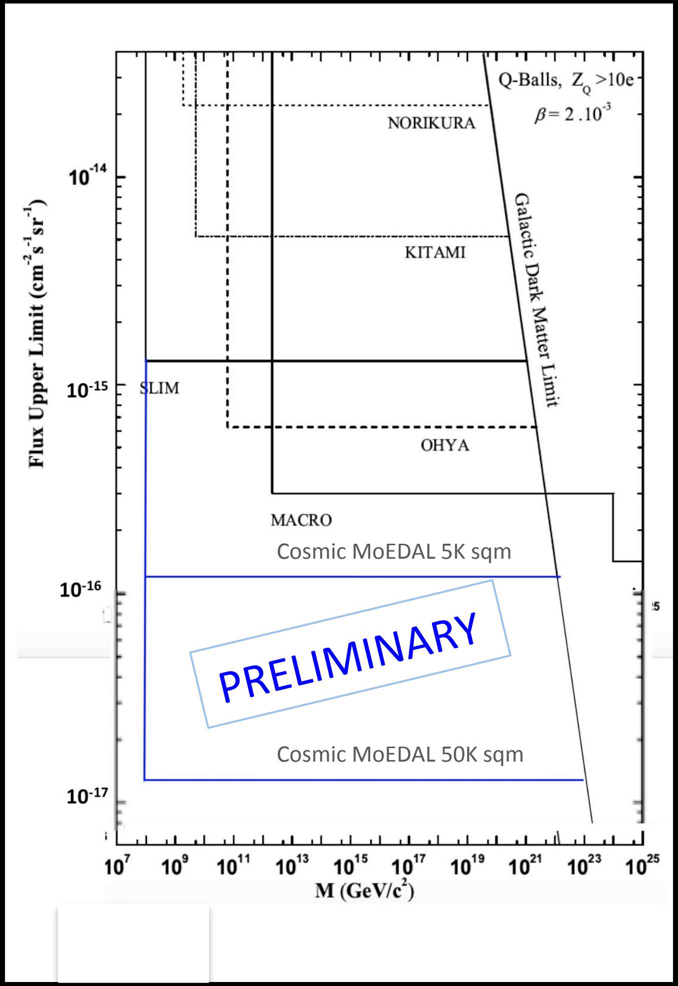
The Future - Cosmic-MoEDAL?



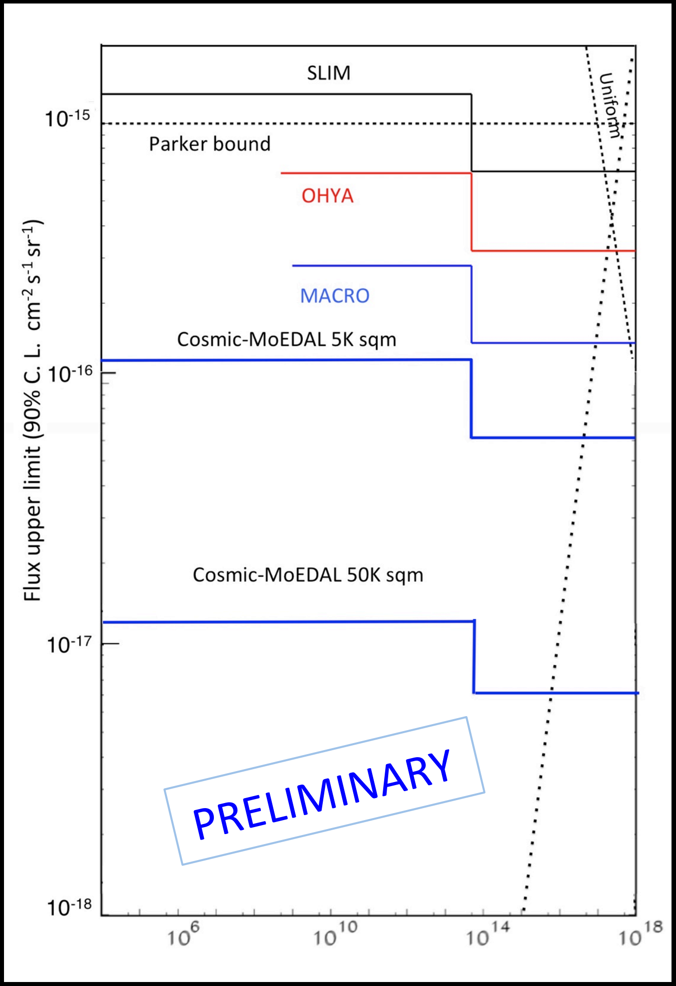


- Cosmic-MoEDAL envisage deployment of 5K-50K m^2 NTDs at high altitude - > 5/50 times larger than MACRO/SLIM
  - To detect remnants from the early universe: EW monopoles and monopoles from late phase transition & GUT scenarios with mass from ~10^4 to 10^{18} GeV, as well as strangelets, nuclearites, etc
  - We can also look for monopoles and massive (pseudo)-stable charged particles particles produced in very high energy air showers.
- Sites under consideration: Chacaltaya (5km); Tenerife -Tiede (3km); IceCube (3km); Jeju Island (2km)

Cosmic-MoEDAL Flux Limits



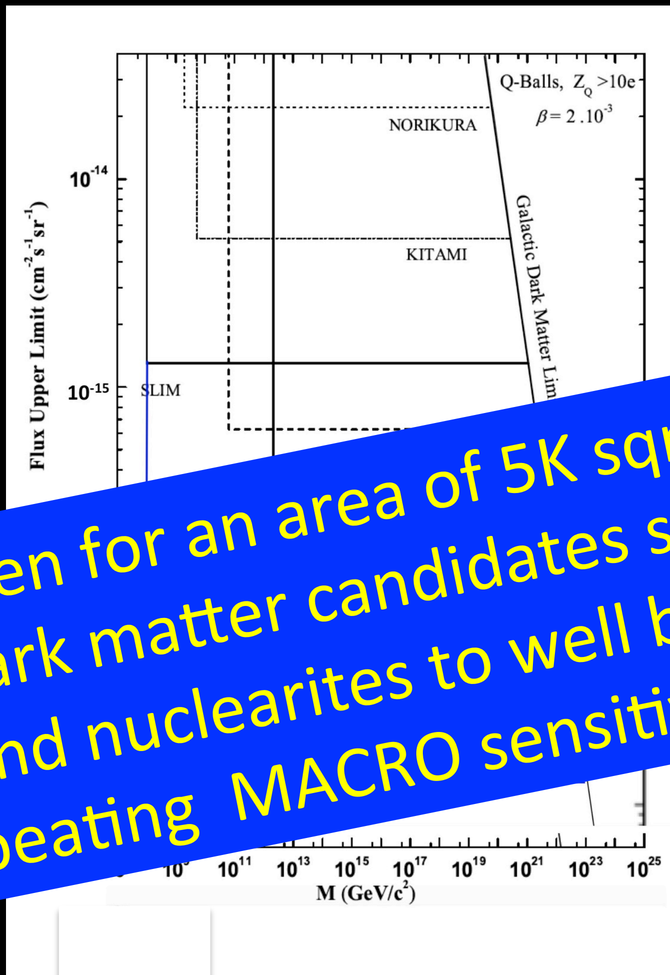
Monopoles



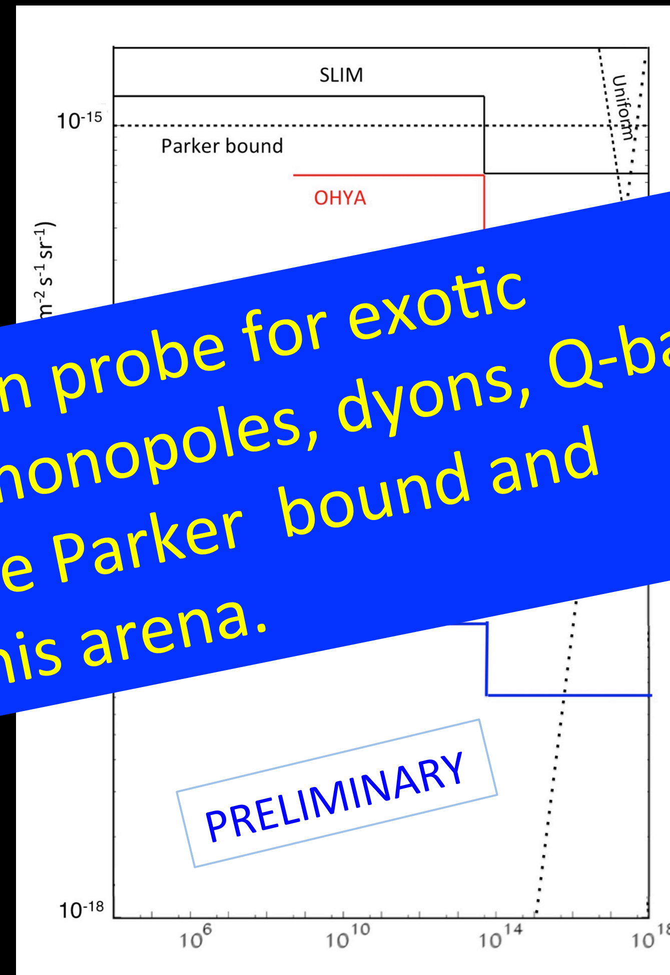
Nuclearites

- *Assume area of detector is 5- 50,000 m^2, is exposed for 4 years on Mt Chacaltaya and for monopoles a charge of $1g_d$ (Dirac charge)*

Cosmic-MoEDAL Flux Limits



Monopoles



Nuclearites

Even for an area of 5K sqm we can probe for exotic dark matter candidates such as monopoles, dyons, Q-balls and nuclearites to well below the Parker bound and beating MACRO sensitivity in this arena.

- *Assume area of detector is 5- 50,000 m^2, is exposed for 4 years on Mt Chacaltaya and for monopoles a charge of 1g_d (Dirac charge)*

Capability of Cosmic MoEDAL

- *A ≥ 5K→50K sqm Cosmic-MoEDAL array will take enable us to pursue the search for light/IMM and GUT monopoles to well below the Parker Bound.*
  - *There continues to higher energy the search for magnetic monopoles at the LHC.*
- *This array will also enable us to to pursue search for Monopoles/Nuclearites/Qballs to fluxes of $10^{-16} cm^{-2} s^{-1} sr^{-1}$ or less with greater sensitivity than MACRO.*
- *Great payoff in the search for exotic dark matter and with great discovery potential*
- *No show stoppers arising from technology, experience, cost. The cost for the (5000 sqm) detector estimated at between 3-4M Euros is relatively modest*

Conclusion

The synergy between Collider and Cosmic Ray Physics is well illustrated by the Search or the magnetic monopole – MoEDAL can take the search from the LHC TeV scale up to the GUT-scale with Cosmic-MoEDAL using the same detector technique.