Hunting For Magnetic Monopoles With The NOνA Detector

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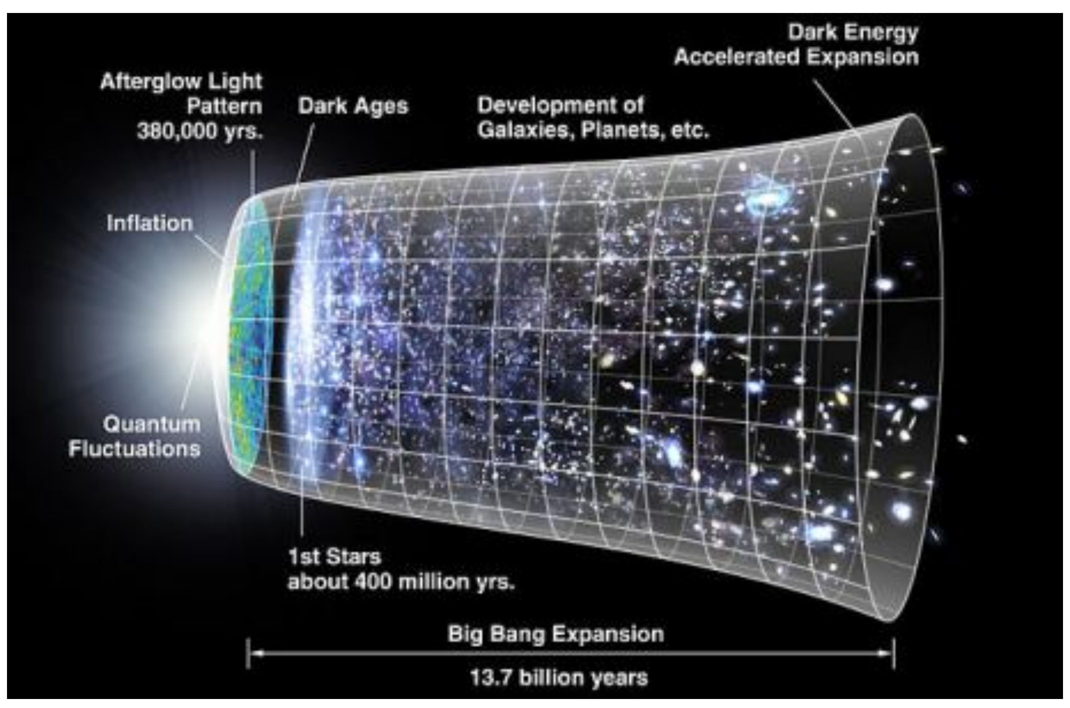
Introduction

Since Paul Dirac first put forward the idea of the magnetic monopole in 1931, there have been many experimental and theoretical efforts to find this elusive particle, but so far without any success. Our group is now taking on this challenge!

We are searching for magnetic monopoles generated in the early age of the universe (immediately after the Big Bang), which is predicted by many grand unified theories.



In this diagram (http://en.wikipedia.org/wiki/Universe) time increases from left to right, and one dimension of space is suppressed, so at any given time the Universe is represented by a disk-shaped "slice".

To accommodate magnetic monopoles in classical electromagnetism, the Maxwell Equations would also be more beautiful in the symmetric form:

$$\nabla \cdot \vec{D} = 4\pi\rho_e \qquad -\nabla \times \vec{E} = \frac{1}{c}\frac{\partial \vec{B}}{\partial t} + \frac{4\pi}{c}\vec{J}_m$$

$$\nabla \cdot \vec{B} = 4\pi\rho_m \qquad \nabla \times \vec{H} = \frac{1}{c}\frac{\partial \vec{D}}{\partial t} + \frac{4\pi}{c}\vec{J}_e$$

Given that magnetic charge (ρ_m) is a pseudoscalar (odd under time reversal), unlike electric charge (ρ_e) being even under time reversal, a particle carrying both electric and magnetic charge would naturally violate CP. This is the most elegant theoretical way to explain CP violation.

The NOνA Detector

The detector, located at Ash River, MN, will be the largest scintillator detector in the world after construction: as large as 15.6m x 15.6m x 66.9m.

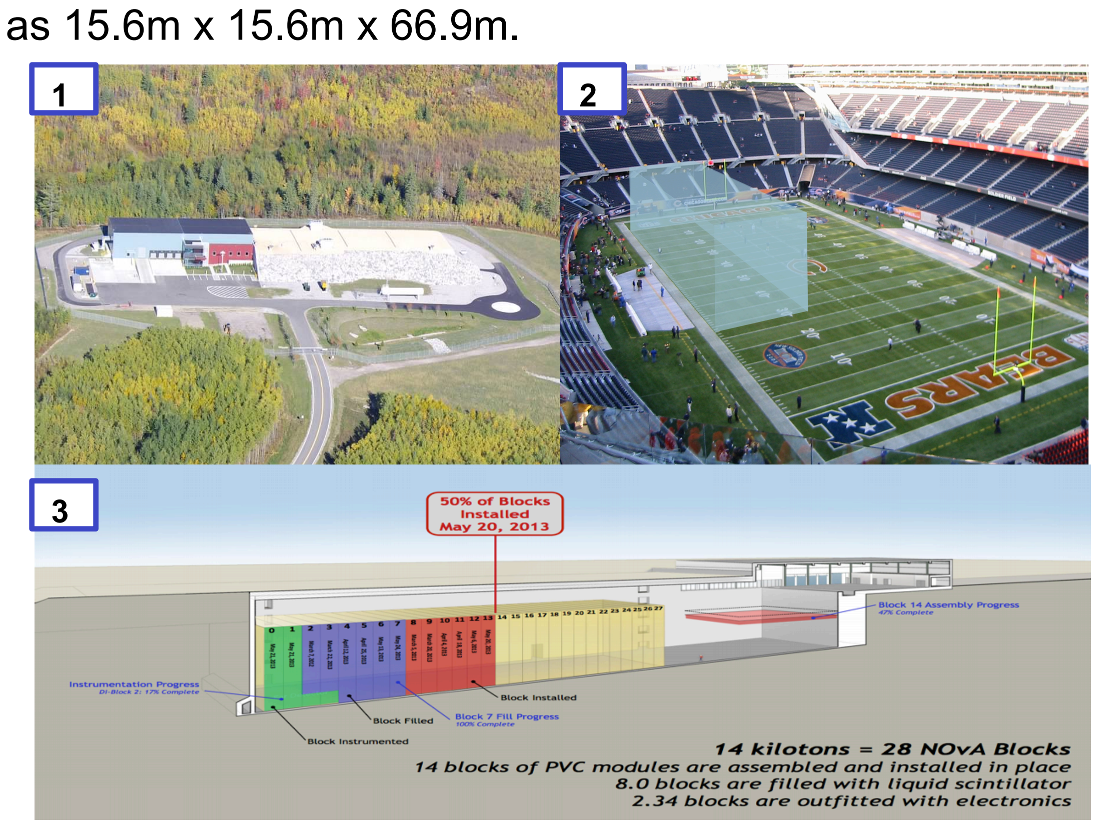
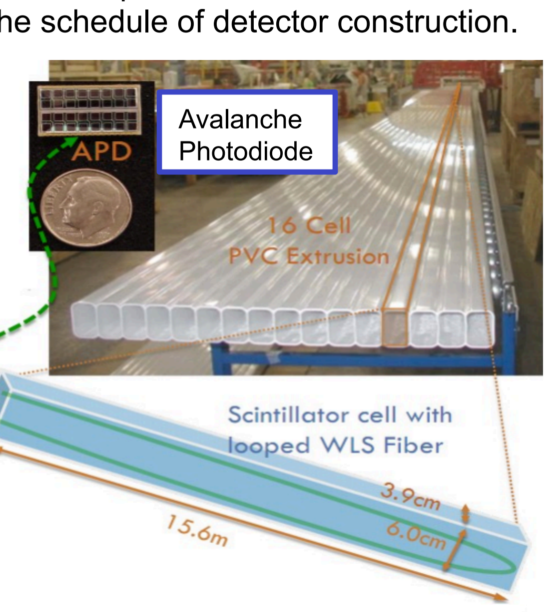
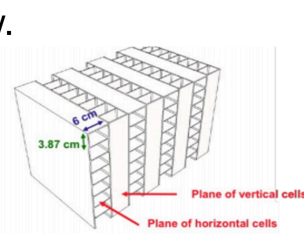


Figure 1 is the top view of the detector site at Ash River. Figure 2 is a scale of the entire effective region of the detector compared to a football stadium. Figure 3 shows the current status and the schedule of detector construction.

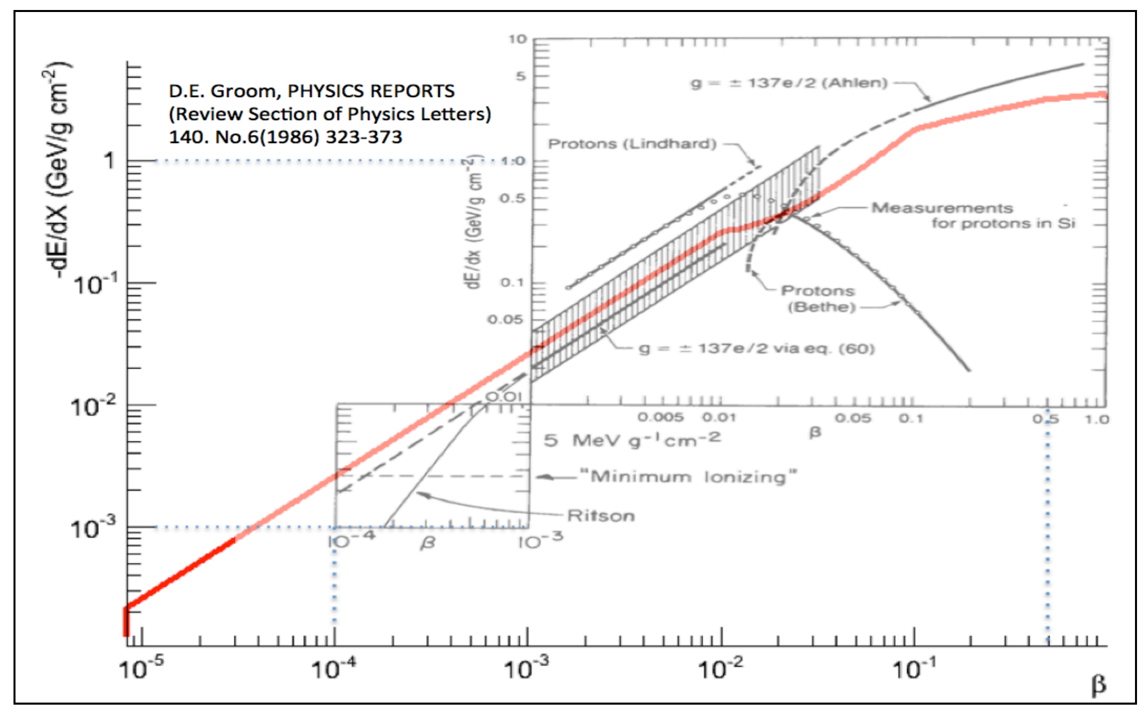
Each cell is 3.9 cm x 6.0 cm x 15.6 m large and filled with scintillator oil. The trajectory of a charged particle is determined as it passes through adjacent horizontal and vertical planes, as shown in the layout picture below.



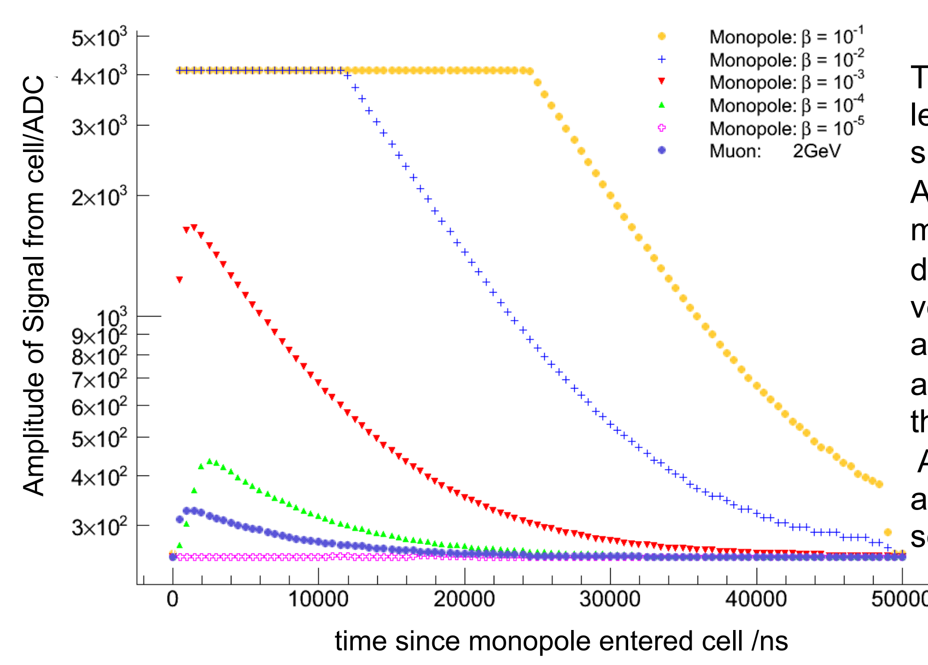


Magnetic Monopole Simulation

According to Dirac quantization condition, a magnetic monopole contains charge of at least 68.5*e*, which indicates it might be quite heavily ionizing, as can be seen in the plot below.



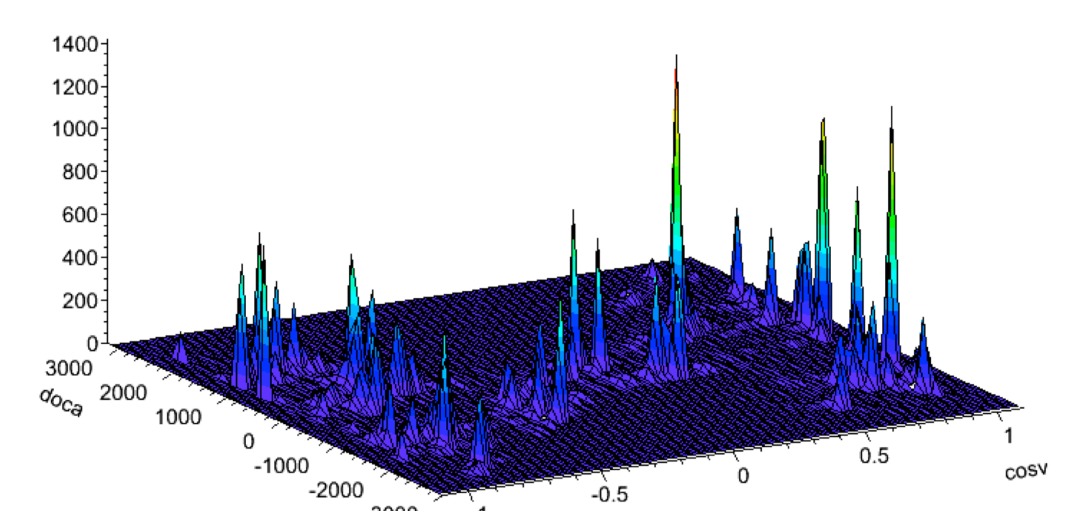
The plot above is a comparison between the latest Geant4 simulation (the red curve) and theoretical estimation of the stopping power of a magnetic monopole passing through silicon as a function of monopole velocity (β=v/c).



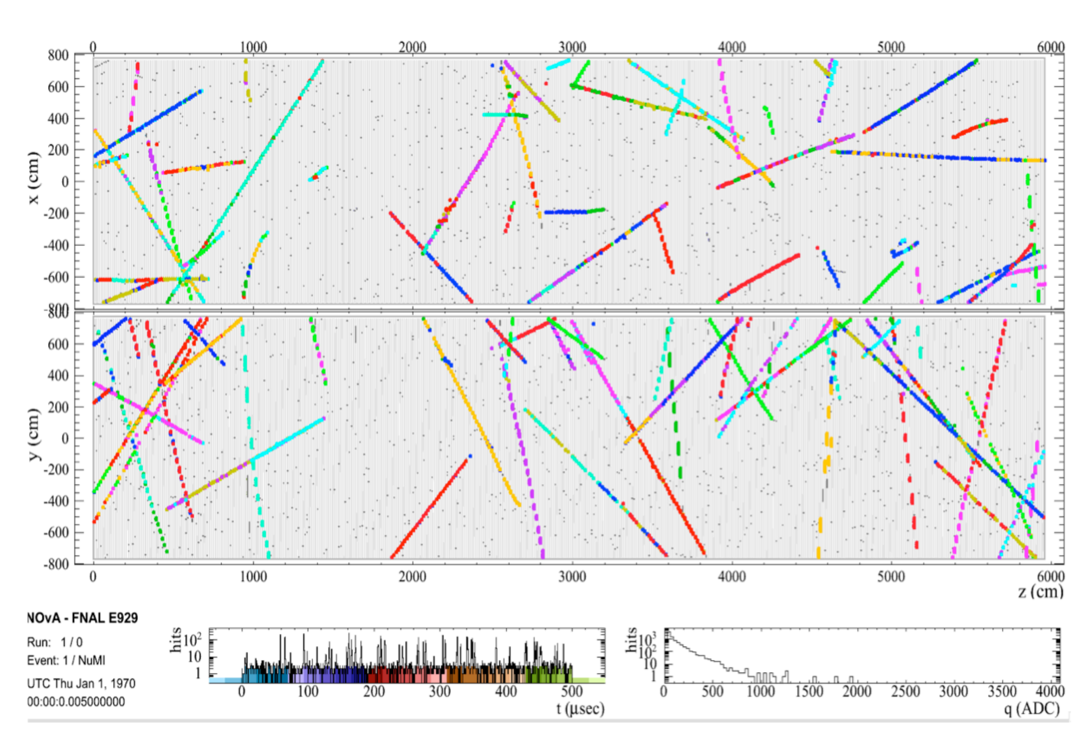
The plot on the left is the simulation of APD response to monopoles with different velocities assuming they are travelling through a cell. A 2GeV muon is also present for scale.

Magnetic Monopoles Reconstruction

Monopoles are supposed to be massive and leaving long straight tracks once they enter the detector. The track reconstruction is based on a modified Hough Transform algorithm, which can tell apart the monopole tracks from the other cosmic ray tracks and other backgrounds. This algorithm can also reconstruct any straight cosmic tracks as well.



The 2D histogram shown above illustrates how the algorithm identifies tracks: each peak corresponds to a track, the higher the peak, the longer the track is.



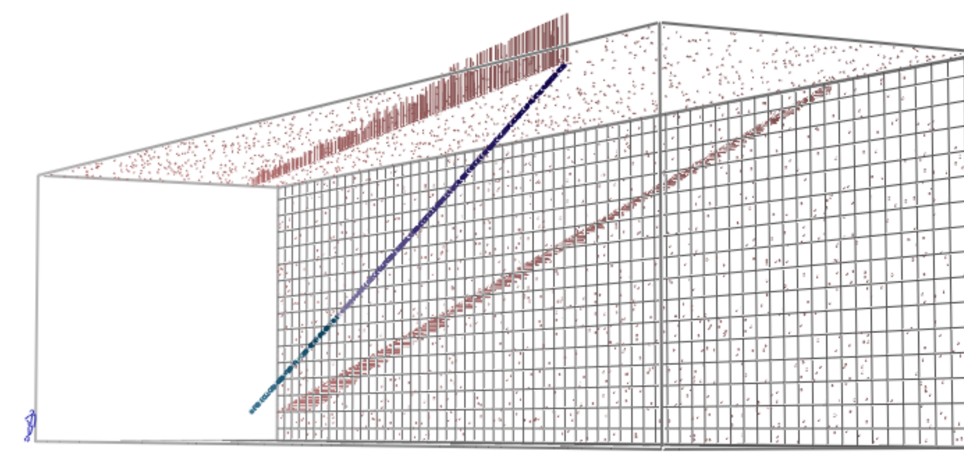
The event display shows the result of the algorithm applied to a window of 500 μs of cosmic simulation. All tracks travelling through at least 2 planes have been successfully reconstructed.

Magnetic Monopoles Hunting Strategy

Human knowledge is very limited about magnetic monopoles: the velocity and the mass of monopoles vary a lot based on different physics models.

We are trying to cover all the possibilities:

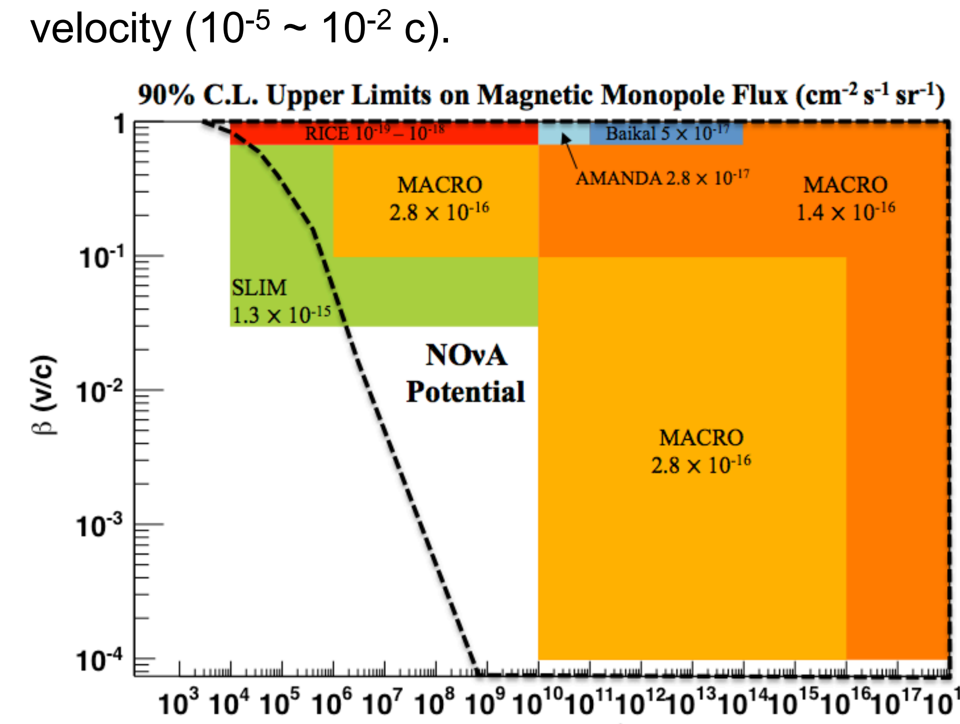
1. For slow (β<10^{-3}) magnetic monopoles, we are able to tell them apart from other long cosmic rays with our current timing resolution;
2. For fast (β>10^{-3}) magnetic monopoles, we would see a lot of saturated (reaching maximum ADC read out) hits along a track since they are heavily ionizing.



The plot above is a 3D event display of a simulated magnetic monopole with mass = 10^{16}GeV/c^2 and β = 10^{-3}, shooting from the top of the NOνA detector and leaving a long track behind. This monopole track has been successfully reconstructed with 2D information from both XZ and YZ views, despite the overlaid simulated noise hits.

Magnetic Monopoles Potential Reach

The advantage of NOνA, compared to many other experiments (MACRO, SLIM and etc.) with accumulation of years of cosmic data, is that we are sensitive to a intermediate mass region (10^5 ~10^{11} GeV/c^2) of monopoles with relatively low velocity (10^{-5} ~ 10^{-2} c).



This figure above demonstrates the advantage of the NOνA detector in search of magnetic monopole. We are sensitive to all the possible monopoles in the phase region of velocity *vs.* mass, especially the area not covered by previous experiments, on the right of the black curve.

Acknowledgments

Computing Division of Fermilab:

These "artists" contributed a lot in setting up the software framework in both offline and data driven trigger. They also helped a lot in improving the performance of the pattern recognition module, which is used in monopole triggering and reconstruction.

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As the coordinator of G4 EM working group, he provided me with useful advice in using the latest version (v4.9.6) of Geant4 to simulate monopoles.

Eric Katsavounidis (MIT):

Professor Katsavounidis, who used to search monopoles in MACRO when he was a graduate student, generously gave me his PHD thesis and provided me with precious experience on this topic.