Magnetic Monopoles in IceCube

IceCube Searches for Magnetic Monopoles — Covering a Large β Range

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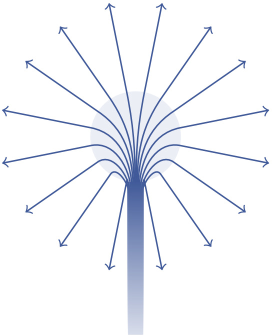
Magnetic Monopole Basics

Free magnetic north or south pole

- ▷ **Dirac, 1931**
- ▷ **t' Hooft, 1974**
  Polyakov, 1974



Charge, g_{MM}

- ▷ $g_{MM} = n\frac{1}{2\alpha}q_e$
- ▷ $n = 1 \Rightarrow g_{MM} \approx 68.5q_e$
  - ▷ Dirac charge, g_D

Mass, m_{MM}

- ▷ $m_{MM} \in [10^4; 10^{17}]$ GeV

Kinetic Energy, $E_{kin,MM}$

- ▷ $E_{kin,MM} \lesssim 10^{15}$ GeV

Searches

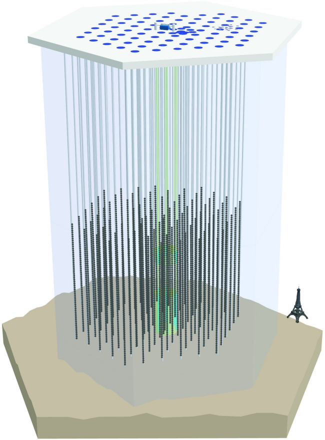
Collider production

- ▷ Lower mass monopoles

Primordial flux

- ▷ Higher mass monopoles

IceCube Basics



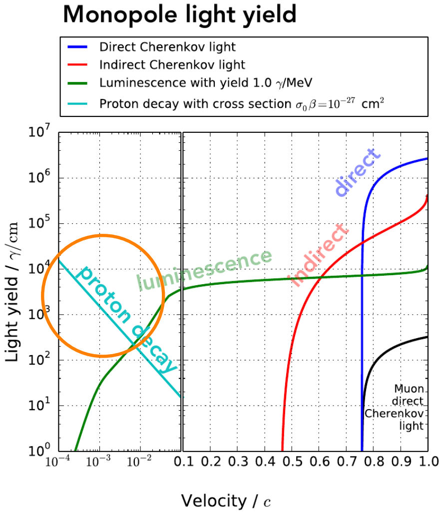
Detector

5160 DOMs (*Digital Optical Modules*) detecting light produced by in-ice particles

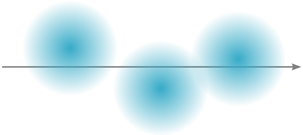
Event types

- ▷ Cascades ($\nu_{e,\tau}$)
- ▷ Tracks (ν_μ, μ)
  - ▷ Contained
  - ▷ Semi-contained
  - ▷ Through-going

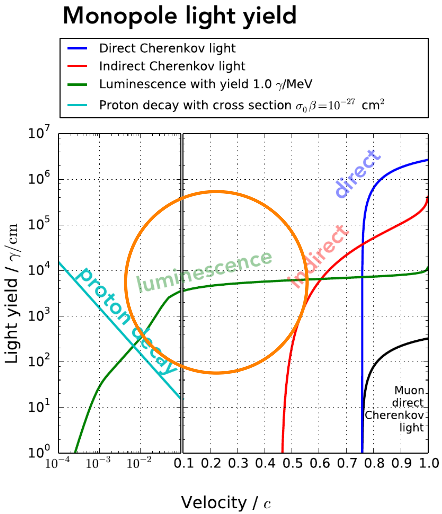
Magnetic Monopole Light Production Channels



Non-relativistic
$\beta \lesssim 0.01$
▷ Particle cascades from induced proton decay in medium

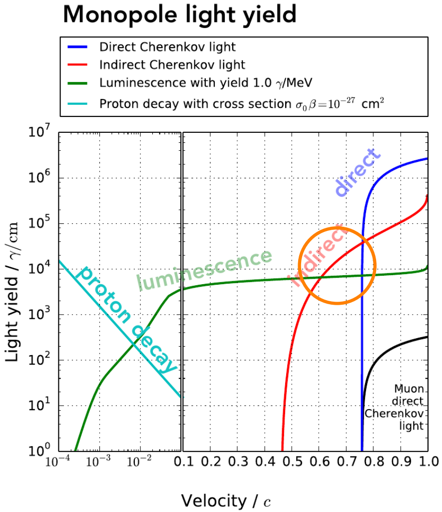


Magnetic Monopole Light Production Channels



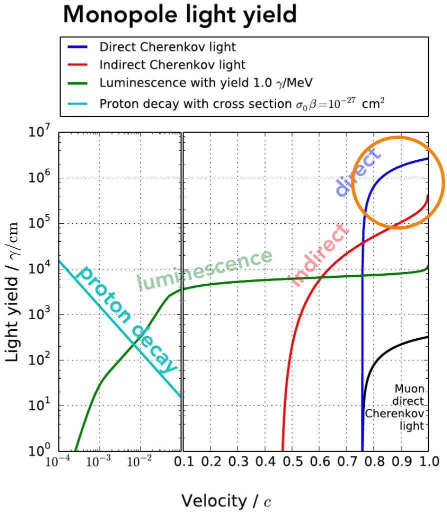
Low relativistic
$0.01 \lesssim \beta \lesssim 0.5$
▷ Luminescence light from deexcitation (post excitation) of medium

Magnetic Monopole Light Production Channels



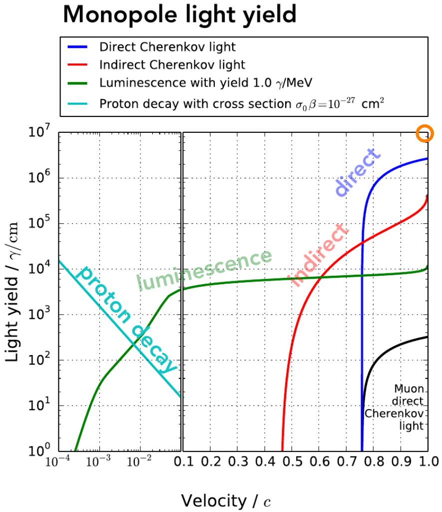
Mildly relativistic
$0.5 \lesssim \beta \lesssim 0.75$
▷ Indirect Cherenkov light from ionization of medium

Magnetic Monopole Light Production Channels

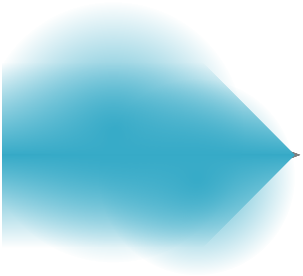


Relativistic
$0.75 \lesssim \beta \lesssim 0.999\,95$
▷ Direct Cherenkov light

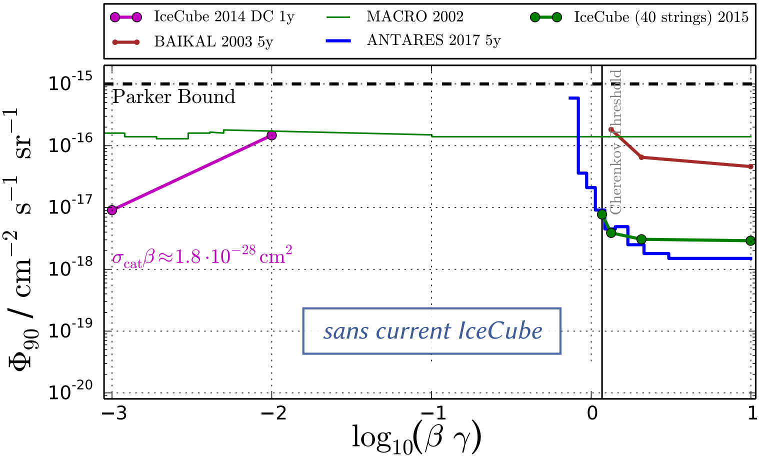
Magnetic Monopole Light Production Channels



Ultra-relativistic
$0.99995 \lesssim \beta$ $100 \lesssim \gamma$
▷ Stochastic nuclear interactions, direct Cherenkov light



Monopole Flux Landscape

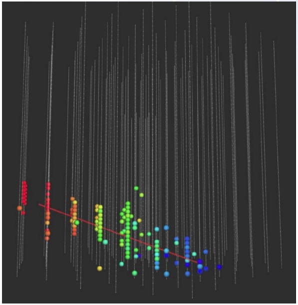


Non-Relativistic Monopoles

β Range	$10^{-3} - 10^{-2}$
Light Production	Induced proton decay
Event Characteristics	Extremely slow, dim track

Analysis Steps

1. Dedicated trigger for subrelativistic track-like topologies (ms scale)
   - Includes cleaning of likely muon tracks (hits close in time)
2. BDT to remove noise hits and sub-threshold muons
   - Dedicated variables to check for particle cascades along the monopole track



Main Challenge	Removing non-related hits from event

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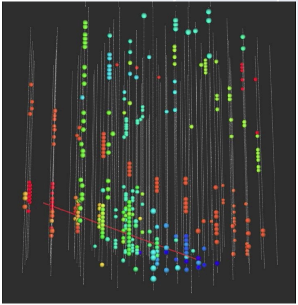

Main Challenge	Removing non-related hits from event → Coincident muon tracks

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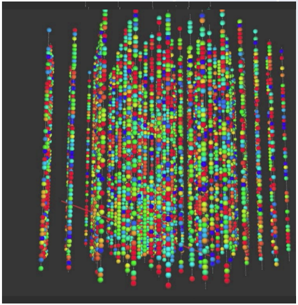
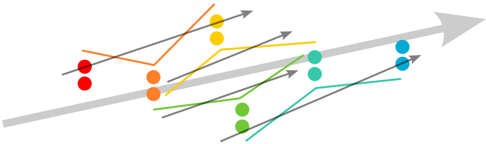


Main Challenge	Removing non-related hits from event → Coincident muon tracks → PMT noise etc.

A Selection Variable — Relative Angle

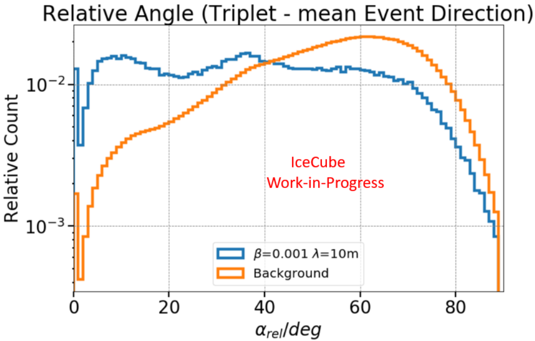
- A **slow track** is a collection of triplets



- A **triplet** consists of three hit-pairs
  - close in time (not too)
  - large internal angle
  - small internal speed differences

Relative Angle =

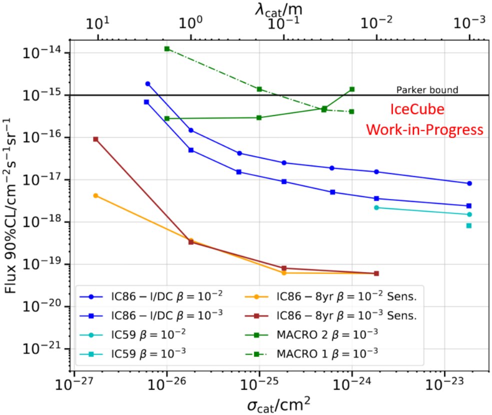
average(| direction(*triplet*) − direction(*full event*) |)



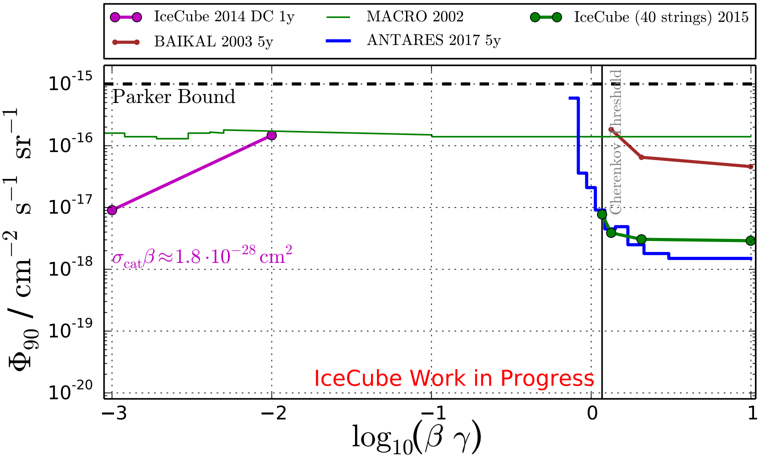
In-progress Sensitivity over σ_{cat}

Monopole flux sensitivity over proton decay catalysis cross-section

- **10–100 times lower** than previous limits
- Extends to **3 times lower** cross-section



Monopole Flux Landscape



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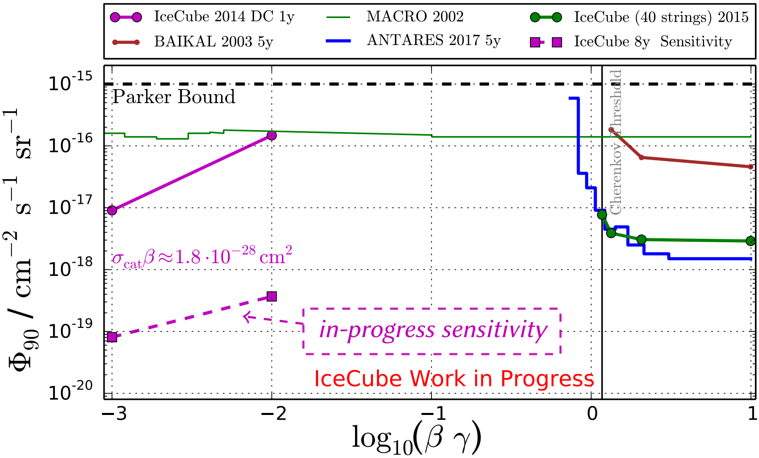
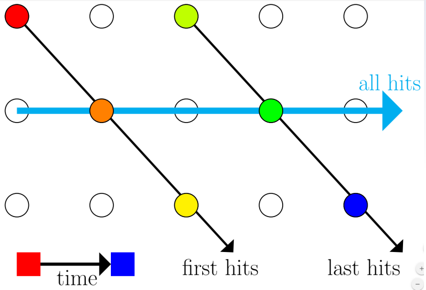


Low Relativistic Monopoles

β Range	0.1 – 0.5
Light Production	Luminescence light
Event Characteristics	Slow, smooth, fairly dim track

Analysis Steps

1. Quality cuts (central track, through-going)
2. BDT pull validation
   - 32 variables
   - 200 BDTs
   - 10 % of data for each BDT



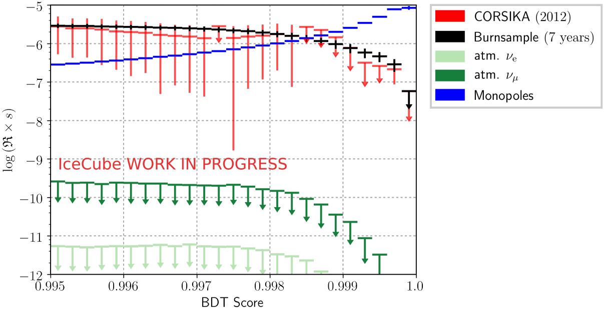
A BDT variable: Divide track in the middle, compare

- reco speed of first half *with* reco speed of second half
  - identifies events with coincident muon tracks

BDT score distribution

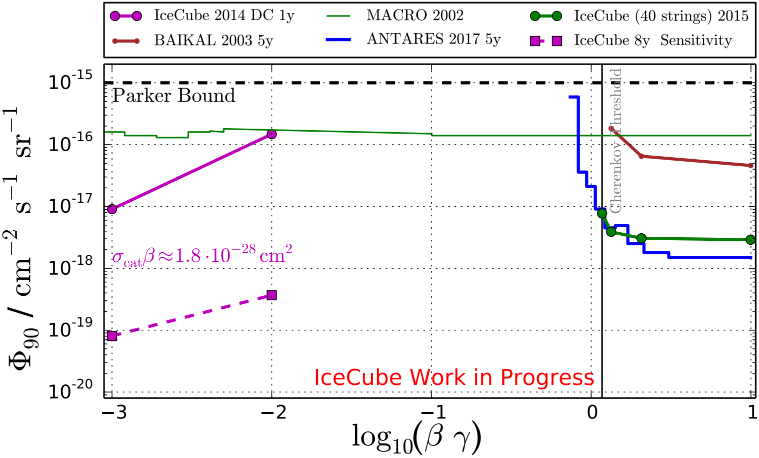
BDT Pull Validation "Collective result of many BDTs"

- ▷ Train 200 BDTs, each using 10 % of data (random selection)
  - Each event is used for training on average 20 times
- ▷ Yield each event on average 180 (= 200 − 20) scores
  - ⇒ Smoother score distributions
  - ⇒ Better handle on low-statistics tail



Clear separation between signal and background samples

Monopole Flux Landscape



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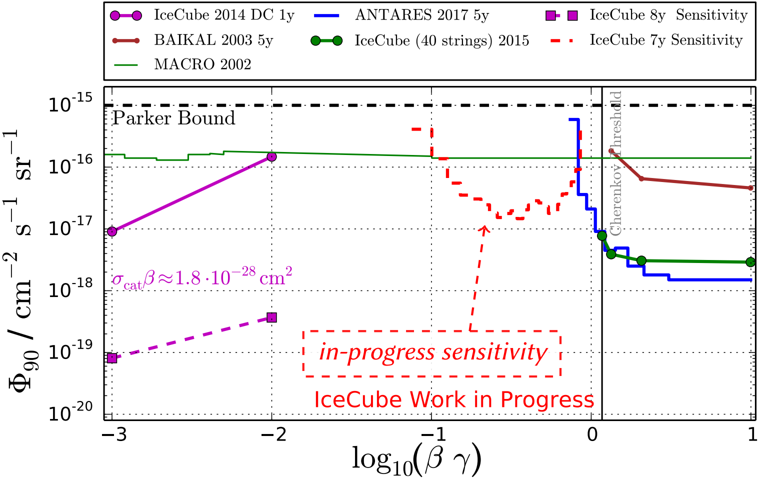


Mildly Relativistic Monopoles

β Range	0.5 – 0.75
Light Production	Indirect Cherenkov light (delta-electrons)
Event Characteristics	Moderately fast, bright, smooth track

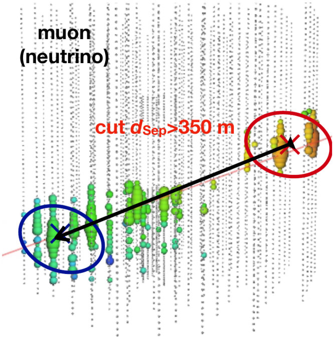
Analysis Steps

1. Quality cuts (e.g. number of hit strings, number of hit DOMs)
2. BG reduction cuts (e.g. track length, hit time distribution, direction)
3. BDT for final event classification, pull validation for remaining background estimation

A Selection Variable — Separation Distance

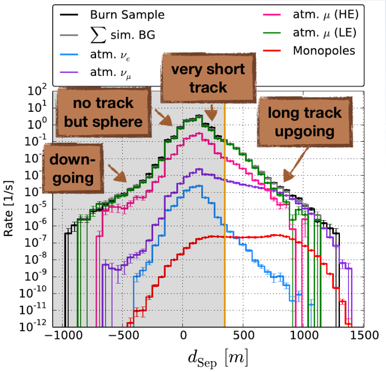
→ Divide track in quartiles in time

→ Find CoG of first and last quartile



→ Calculate distance between first and last CoG, take sign from *z*-difference

- '+' means up-going



▷ Identifies short and down-going tracks

BDT score at final level

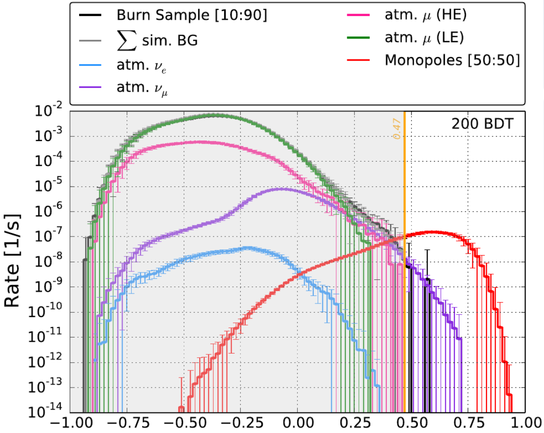
Clear **signal/background separation**

- ▷ cut at BDT score 0.47

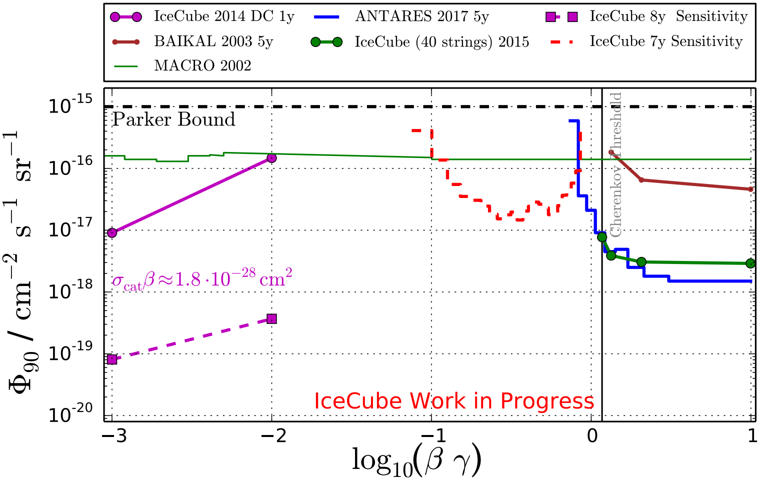
≲3 background events expected after all cuts

3 events observed in final level data

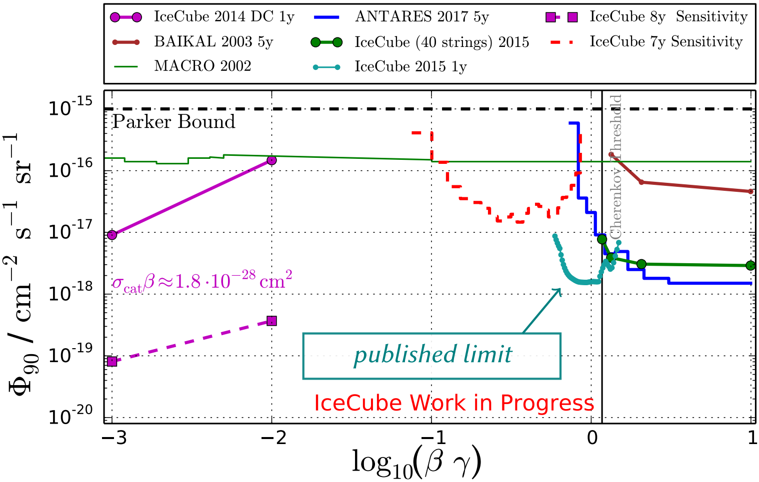
- ▷ Correspond to known background event signatures



Monopole Flux Landscape



Monopole Flux Landscape



Relativistic Monopoles

β Range	0.75 – 0.995
Light Production	Direct Cherenkov light
Event Characteristics	Extremely bright, smooth track

Analysis Steps

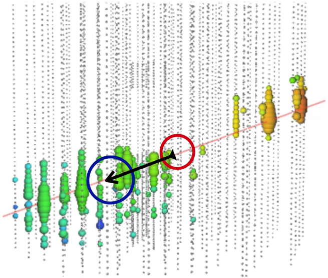
1. Cuts from EHE analysis
   - IceCube search for high energy ν

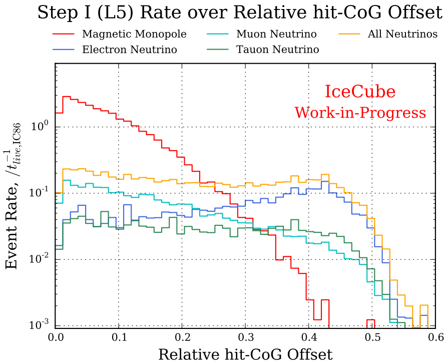
   ⇒ Sample with...
     - Bright events
     - Low atm. event rate
2. Dedicated BDT to remove remaining neutrino events

Main Background	Rare ultra high energy astrophysical neutrinos

A Selection Variable — Relative hit-CoG offset

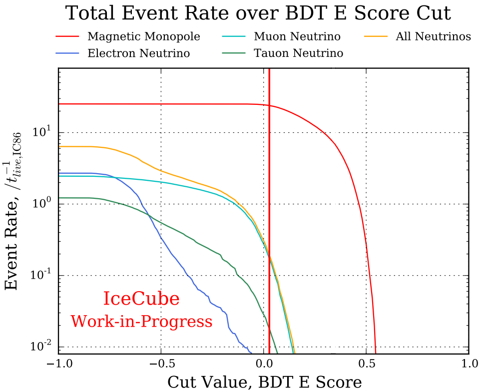
- → Find CoG of hits
- → Find geometric center of track, geometric track-length
- → Calculate distance between center-of-track and CoG relative to track-length





▷ Identifies events with large concentrations of light

BDT score at final level



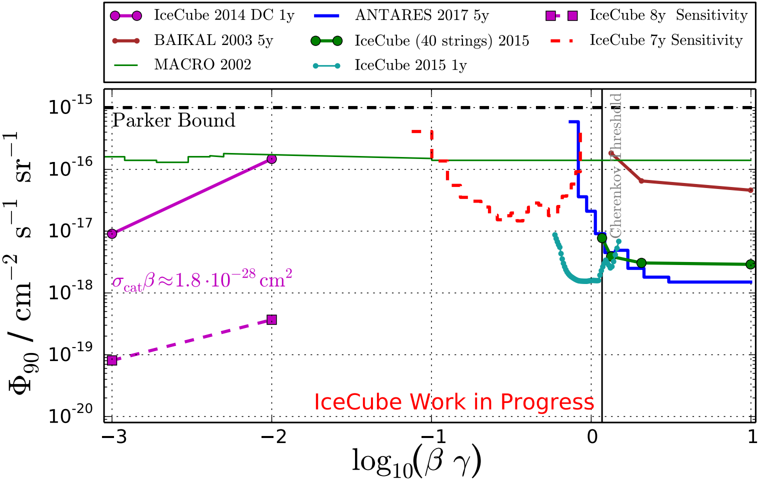
Cut decided by **optimal Model Rejection Factor**

- ▷ cut at BDT score 0.028

Background expectation reduced to **<0.2 events** per 6 yr of data

Signal expectation kept at **∼24 events** per 6 yr of data

Monopole Flux Landscape



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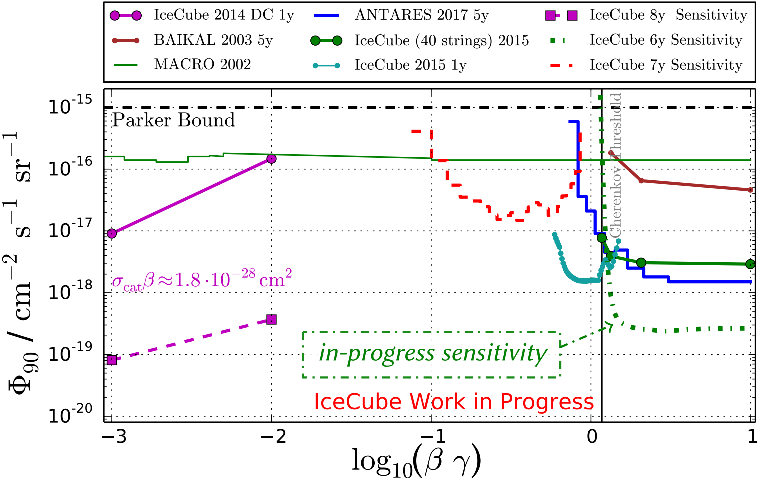


Summary

Magnetic Monopoles

- Free magnetic pole
- So far non-observed
- Wide allowed speed range of relic flux

IceCube Searches

Non-relativistic $0.001 \leq \beta \leq 0.01$ $\longrightarrow$ *sensitivity*

- Looooong events, dedicated triggers

Low relativistic $0.10 \leq \beta \leq 0.50$ $\longrightarrow$ *sensitivity*

- Dim and delayed events, many-BDT pull validation

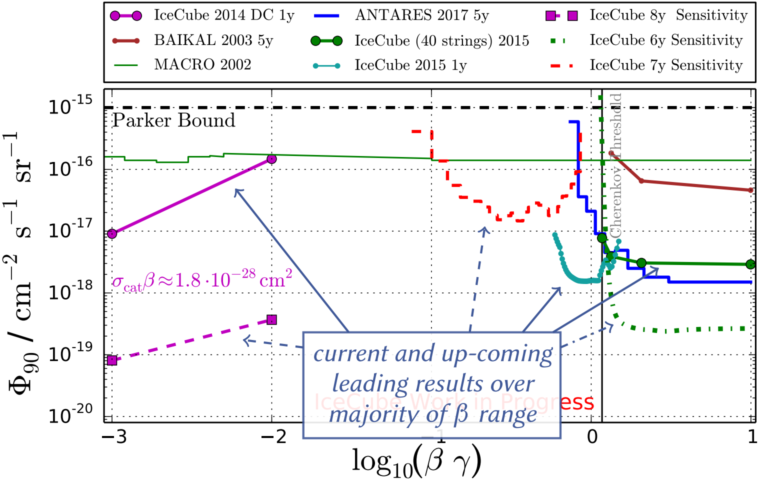
Mildly relativistic $0.50 \leq \beta \leq 0.75$ $\longrightarrow$ *upper limit*

- Smooth tracks, many-BDT pull validation

Relativistic $0.75 \leq \beta \leq 0.995$ $\longrightarrow$ *sensitivity*

- Extremely bright events, UHE neutrino background

Concluding Remarks



Thank you