Bright Needles in a Haystack

Searching for Magnetic Monopoles with the IceCube Detector

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Final Ph.D. Seminar
2020–10–30

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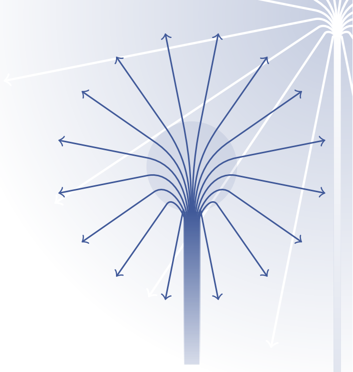
IceCube

Overview

- Magnetic monopoles and IceCube
  - Magnetic monopoles
  - IceCube
  - Magnetic monopole detection with IceCube
- Analysis strategy
  - Including MC samples
- Event selection
  - Step I
  - Step II
- Result
  - Effective area
  - Sensitivity
  - Signal uncertainty
  - Background uncertainty
  - Final result
    - Discovery or upper limit?

Magnetic Monopoles

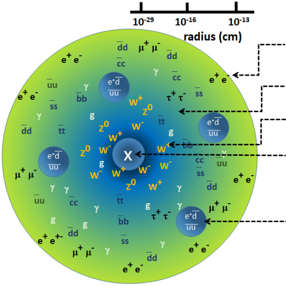


Dirac: Monopole allowed as one end of semi-infinite, infinitesimally thin, solenoid

- ▷ Dirac's quantization condition for electric **and** magnetic charges
- ▷ Dirac charge, $\boldsymbol{g_D} \approx \frac{1}{2\alpha} e$

't Hooft & Polyakov: Monopole allowed as topological defect between domains of differently directed Higgs field

- ▷ Non-vacuum state of Higgs field in monopole center, requires local energy lump
- ▷ Size of energy lump (**mass**) depends on energy scale of symmetry-break → **unknown**
  - If GUT symmetry breaks directly into EM: $m_{MM} \sim 10^{14}$ GeV to 10^{17} GeV
  - If intermediate symmetry breaks into EM: $m_{MM} \sim 10^{5}$ GeV to 10^{13} GeV



Current Magnetic Monopole Population

Magnetic monopoles ('t Hooft-Polyakov) would form during the symmetry-break that yields the electromagnetic $U(1)$ gauge group

Formation between symmetry-break domains $\Rightarrow$ Far between adjacent monopoles $\Rightarrow$ Few annihilations, large fraction still abundant

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Precise time of symmetry-break depends on energy scale of break $\Rightarrow$ Unknown current abundance

Large spatial expansion around this time $\Rightarrow$ Unknown current abundance

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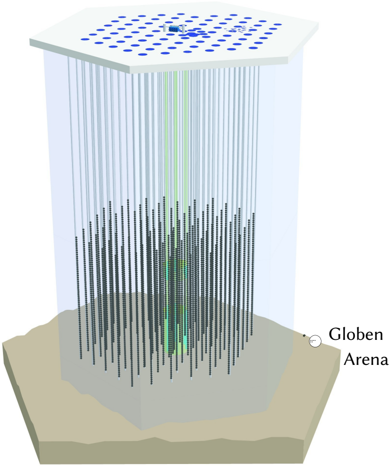
Extraterrestrial magnetic fields accelerate monopoles to $\lesssim 10^{16}$ GeV

$\Rightarrow$ Large portion of mass range allowed to be relativistic, even ultrarelativistic

IceCube

General purpose neutrino detector

- Neutrino astronomy
- Neutrino oscillations
- Dark matter (direct/indirect)
- Exotics (NSI, sterile, monopoles)



Constituent Arrays

- main in-ice array
- DeepCore
  - denser instrumentation
  - lowers E-threshold
- IceTop
  - surface array
  - cosmic ray detector

Instrumentation — DOMs
(Digital Optical Modules)

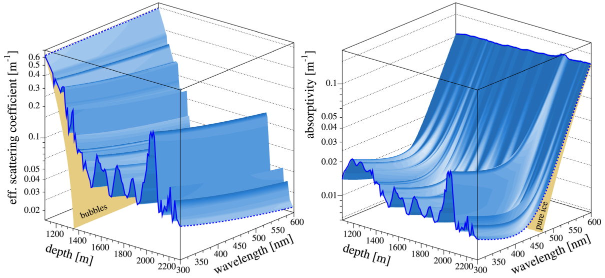
- 5160 in-ice DOMs (main array + DeepCore)
- 324 surface DOMs (IceTop)

IceCube Ice-Model

Ice-Model Governs photon from production to detection (or absorption)

DOM efficiency The probability that a photon hitting the DOM surface is detected by the DOM

DOM angular acceptance The relative sensitivity of a DOM depending on the incident zenith angle of the photon

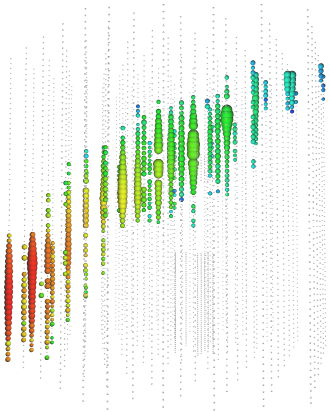


Scattering and absorption The characteristic scattering and absorption lengths of optical light in the ice

IceCube — Typical Events

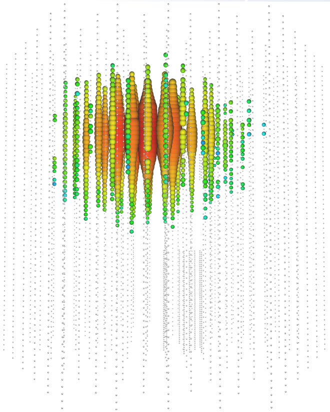
Track:

- μ
- ν_μ CC

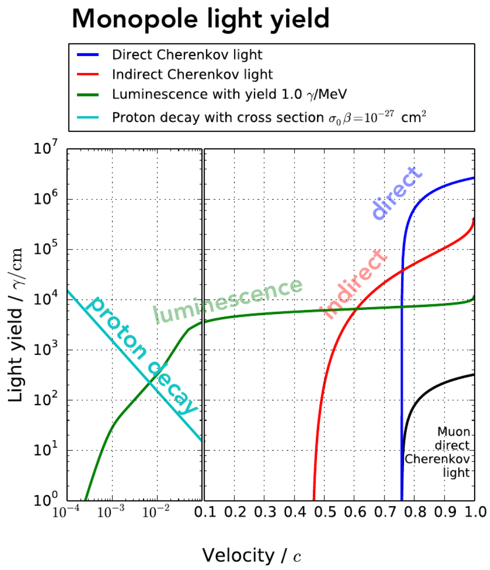


Cascade:

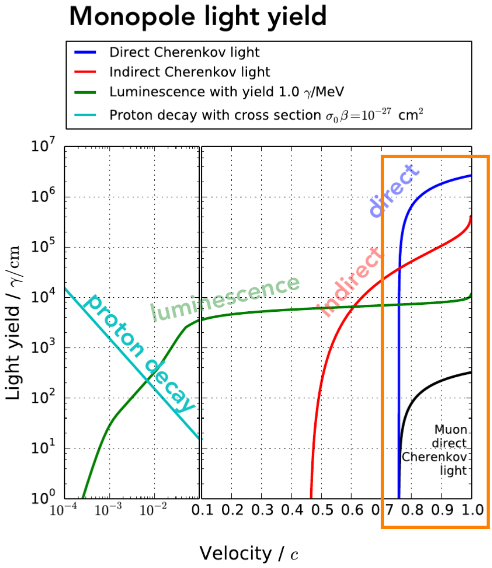
- $\nu_{e,\tau}$ CC
- ν_{all} NC



Magnetic Monopole Light Production



Magnetic Monopole Light Production



Cherenkov Light

Speed above Cherenkov Threshold, β_{CT}

$$\beta_{CT} = \frac{1}{n_\lambda}$$

for $n_\lambda = 1.34$:

$$\beta_{CT} \approx 0.746$$

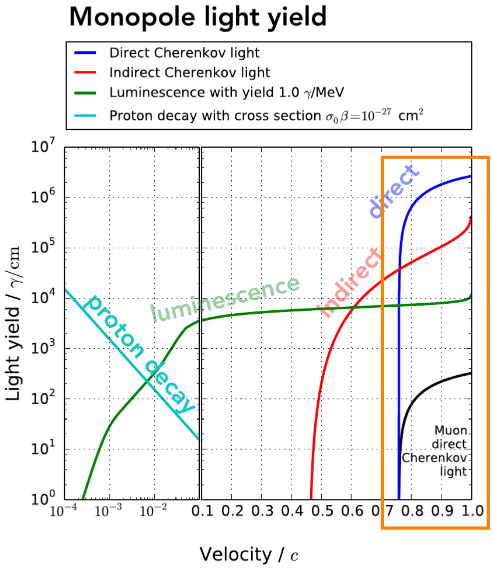
Produced in semi-forward direction, with angle θ_C

$$\cos(\theta_C) = \frac{1}{n_\lambda \beta}$$

for $n_\lambda = 1.34$, $\beta = 1$

$$\theta_C \approx 41.7^\circ$$

Magnetic Monopole Light Production



Frank-Tamm equation for monopoles

$$\frac{d^2N_\gamma}{d\lambda dx} = \frac{2\pi\alpha}{\lambda^2}\left(\frac{gn_\lambda}{e}\right)^2 \times \left(1 - \frac{1}{(\beta n_\lambda)^2}\right)$$

- increasing with β
- homogeneous
- larger than for electric charges by factor

$$\left(\frac{gn_\lambda}{e}\right)^2$$

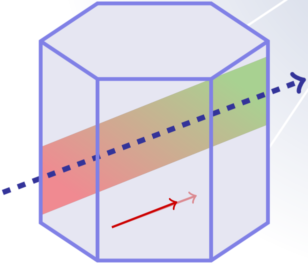
for $g = g_D$, $n_\lambda = 1.34$

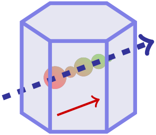
$$\left(\frac{gn_\lambda}{e}\right)^2 \approx 8430$$

Monopole Signatures

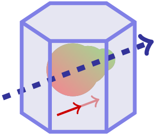
Relativistic Monopole Event Characteristics

- ▷ Bright
- ▷ Subluminal speed
- ▷ Track-like
- ▷ Non-starting/-stopping
- ▷ Non-stochastic

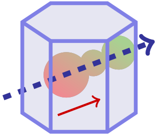




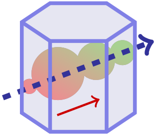
Dim



Cascade

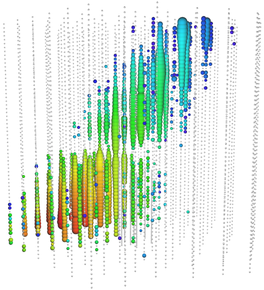


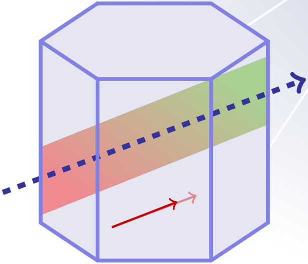
Starting

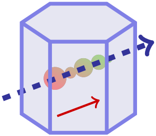


Stochastic

Monopole Signatures







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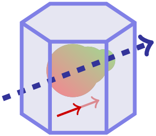
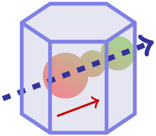


Cascade



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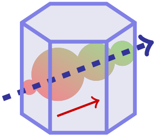
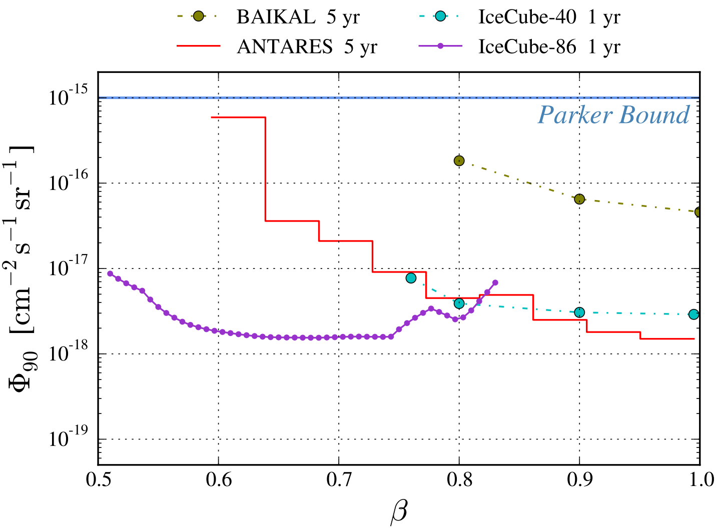


Stochastic

Monopole Flux Upper Limit Landscape



Analysis Strategy

Step I — Apply EHE Analysis Selection

- IceCube analysis
  - Searching for GZK neutrinos
  - Similar event characteristics
- Objectives
  - Accept bright events
  - Reject atmospheric events

Step II — Custom Selection via BDT

- Train BDT
  - Variables based on monopole event signatures
- Objective
  - Reject Remaining Neutrinos

Livetime 8 yr of collected data

Monte Carlo Data

Background

IceCube central MC production

Energy range	ν_e	$[10^5, 10^8]$ GeV
	ν_μ	$[10^5, 10^9]$ GeV
	ν_τ	$[10^5, 10^9]$ GeV

Assumed Flux

Diffuse muon neutrino analysis, 2017

- Single power law
  - $\phi_\nu = 1.01^{+0.26}_{-0.23}$
  - $\gamma_\nu = -2.19 \pm 0.10$

$$\Phi_\nu = \phi_\nu \times \left(\frac{E_\nu}{100\,\text{TeV}} \right)^{-\gamma_\nu}$$

Signal

Private MC production

β range $[0.750, 0.995]$

Assumed flux

Best upper limit

- Uniform over β
- $\Phi_{MM} = 3.46 \times 10^{-18}\ \text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$

Event Selection

Triggers and Filters

- ▷ Trigger the detector to commence data collection
- ▷ Quick data sorting based on fast reconstruction

Step I

- ▷ Apply EHE Analysis Selection
  - Accept bright events
  - Reject atmospheric events

Step II

- ▷ Custom Selection via BDT
  - Variables based on monopole event signatures
  - Reject Remaining Neutrinos

Triggers and Filters

Triggers and Filters Accept events from...

- any trigger
- the *online EHE filter*, where $n_{PE} \geq 10^3$

Step I

- Apply EHE Analysis Selection
  - Accept bright events
  - Reject atmospheric events

Step II

- Custom Selection via BDT
  - Variables based on monopole event signatures
  - Reject Remaining Neutrinos

Step I

Triggers and Filters Accept events from...

- any trigger
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Step I

- Apply EHE Analysis Selection
  - Accept bright events
  - Reject atmospheric events

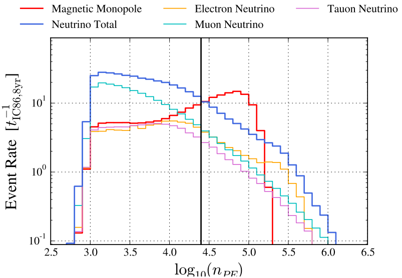
Step II

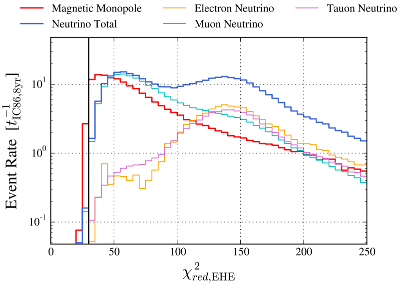
- Custom Selection via BDT
  - Variables based on monopole event signatures
  - Reject Remaining Neutrinos

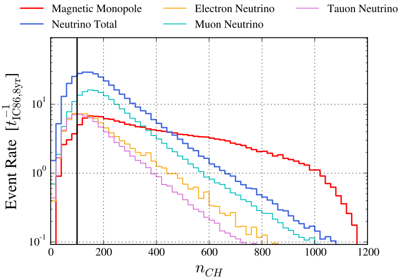
Step I — The Offline EHE Cut

Quick cuts to reduce data volume

- Track quality:
  $\chi^2_{red,\mathrm{EHE}} \leq 30$
- Num. photo-electrons:
  $n_{PE} \leq 20\,000$
- Num. channels:
  $n_{CH} \leq 100$





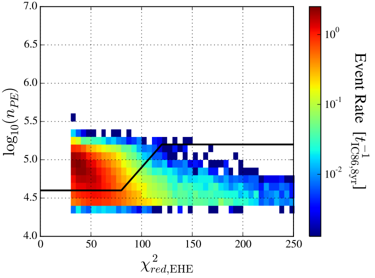


Step I — The Track Quality Cut

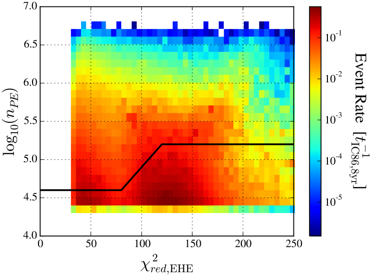
Cut on brightness, based on track-likeness

$$\log_{10}(n_{PE}) \geq \begin{cases} 4.6 & \text{if} \quad \chi^2_{red,\mathrm{EHE}} < 80 \\ 4.6 + 0.015 \times \left(\chi^2_{red,\mathrm{EHE}} - 80\right) & \text{if} \quad 80 \leq \chi^2_{red,\mathrm{EHE}} < 120 \\ 5.2 & \text{if} \quad 120 \leq \chi^2_{red,\mathrm{EHE}} \end{cases}$$

Monopoles:



Neutrinos:

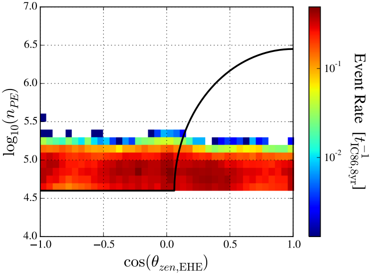


Step I — The Muon Bundle Cut

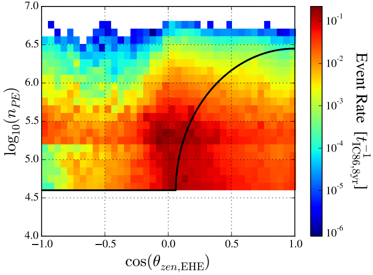
Cut on brightness, based on zenith direction

$$\log_{10}(n_{PE}) \geq \begin{cases} 4.6 & \text{if} \quad \cos(\theta_{zen,\text{EHE}}) < 0.06 \\ 4.6 + 1.85 \times \sqrt{1 - \left(\frac{\cos(\theta_{zen,\text{EHE}}) - 1}{0.94}\right)^2} & \text{if} \quad 0.06 \leq \cos(\theta_{zen,\text{EHE}}) \end{cases}$$

Monopoles:



Neutrinos:



Step I — The Surface Veto

Downgoing events should not be detectable at the surface

If $\cos\left(\theta_{zen,\mathrm{EHE}}\right) < 85^{\circ}$:

- $N_{IT-pulse}\left(\Delta t\right) \leq 1$
  - $\Delta t = [t_{ca} - 1000\,\mathrm{ns}; t_{ca} + 1500\,\mathrm{ns}]$
  - t_{ca} is the in-ice track closest approach time to IceTop

Applied as a 10.6 % rate decrease for the $\cos\left(\theta_{zen,\mathrm{EHE}}\right) < 85^{\circ}$ region to account for random IceTop coincident events.

Step I

Triggers and Filters Accept events from...

- any trigger
- the *online EHE filter*, where $n_{PE} \geq 10^3$

Step I

- Apply EHE Analysis Selection
  - $\gtrsim 40\,000$ registered photo-electrons required
  - < 0.1 atmospheric events accepted per analysis livetime

Step II

- Custom Selection via BDT
  - Variables based on monopole event signatures
  - Reject Remaining Neutrinos

Step II

Triggers and Filters Accept events from...

- any trigger
- the *online EHE filter*, where $n_{PE} \geq 10^3$

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- Apply EHE Analysis Selection
  - $\gtrsim 40\,000$ registered photo-electrons required
  - < 0.1 atmospheric events accepted per analysis livetime

Step II

- Custom Selection via BDT
  - Variables based on monopole event signatures
  - Reject Remaining Neutrinos

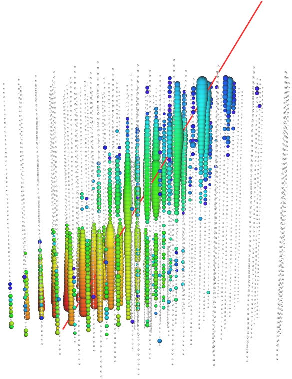
Step II — BrightestMedian Reconstruction

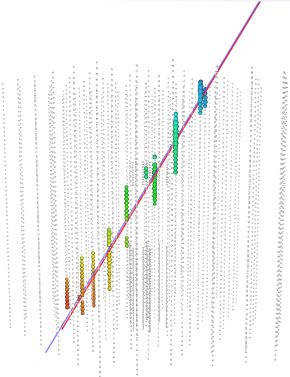
1. Clean pulse-map

- ▷ Select 10 % brightest DOMs
- ▷ Select median position pulses in each selected DOM
- ▷ Reject all other DOMs/pulses

2. LineFit (standard IceCube)

- ▷ Treats each pulse as an individual measurement of particle position
- ▷ Leaves speed as free parameter





Step II — BrightestMedian Reconstruction

1. **Clean pulse-map**
   - ▷ Select 10 % brightest DOMs
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   - ▷ Treats each pulse as an individual measurement of particle position
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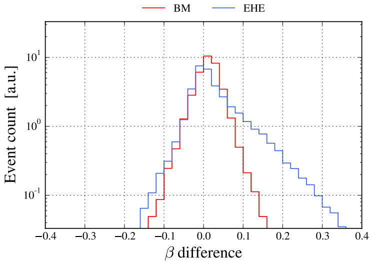
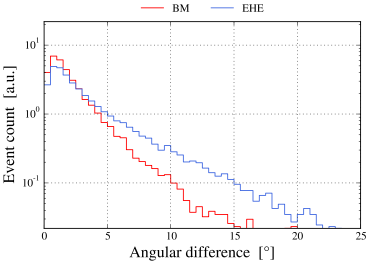
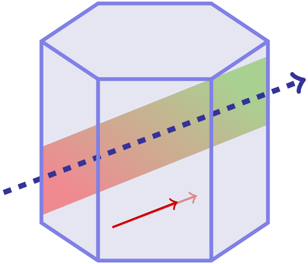




Step II — Monopole Signatures

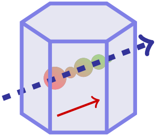
Reject remaining neutrinos

- ▷ Variables based on monopole event signatures



Relativistic Monopole
Event Characteristics

- ▷ Bright
- ▷ Subluminal speed
- ▷ Track-like
- ▷ Non-starting/-stopping
- ▷ Non-stochastic



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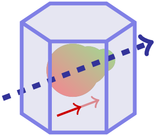
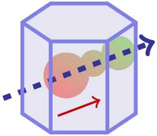
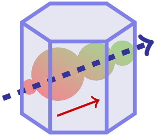


Cascade



Starting



Stochastic

Step II — BDT Variables

Signature variables — 6

Brightness

- ***Signature in Step I***

Non-stochastic

- Charge-weighted distance between hit and track
- Relative standard deviation of partial energy losses along track

Subluminal speed

- Reco. speed
- FWHM of hit time distribution

Track-like + Non-starting/-stopping

- Hit length-fill-ratio along track
- Relative offset of hit-CoG from track mid-point

Helper variables — 3

Brightness

- $\log_{10}(n_{PE})$

Zenith direction

- $\cos(\theta_{zen,\mathrm{BM}})$

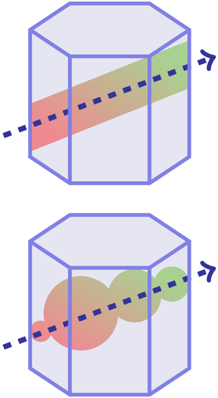
Centrality

- $d_{C,\mathrm{BM}}$

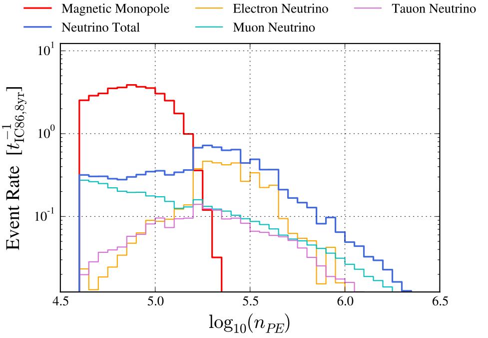
Step II — BDT Variables

Helper variables — Brightness

- $\log_{10}(n_{PE})$



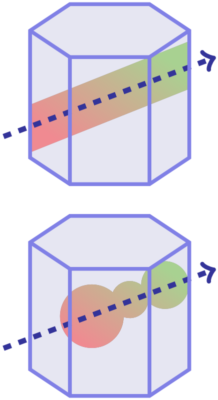
Neutrinos brighter than monopoles!



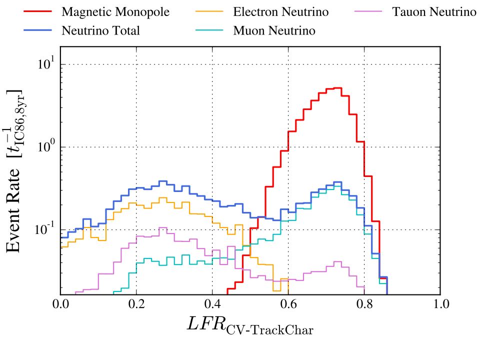
Step II — BDT Variables

Signature variables — Track-like + Non-starting/-stopping

- Hit length-fill-ratio along track



$$LFR = \frac{[\text{LengthDetectedLight}]}{[\text{GeometricLength}]}$$



Step II — Boosted Decision Tree

Mulitvariate data classification tool

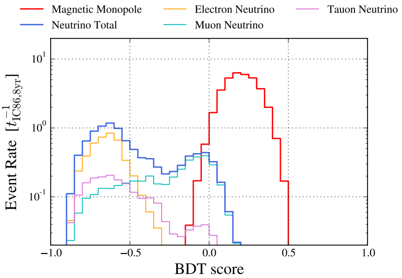
- ▷ Series of decision trees
  - Trained in sequence
  - Known SG & BG events
- ▷ Event boost between trees
  - Misclassified events are boosted before next tree in sequence
- ▷ Validation, KS-test
  - Known SG & BG events in validation sample

Overtraining KS test *p*-value

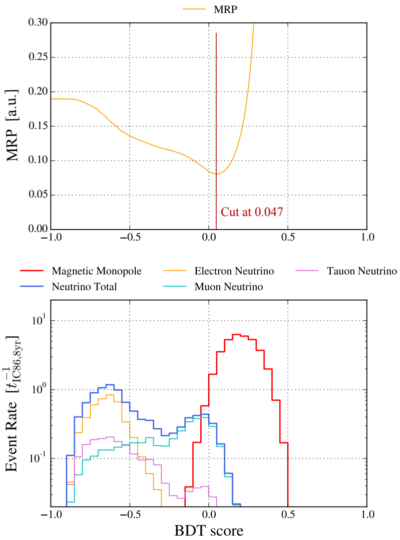
Signal	0.38
Background	0.84

Common IceCube hyper-parameters

```
--num-trees 300
--depth 3
--beta .7
--prune-strength 35
--frac-random-events=0.5
```



Step II — Setting BDT Score Cut



Model Rejection Potential

$$\mathrm{MRP} = \frac{\Phi_{90,sens}}{n_{SG}}$$

Minimal MRP

⇒

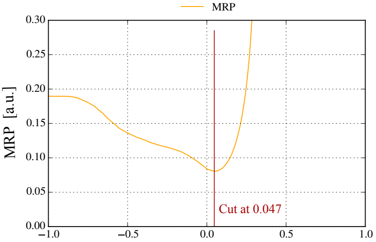
best sensitivity per expected signal event

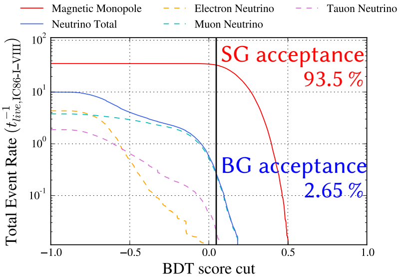
“

The best value ~~for money~~ per signal event

”

Step II — Setting BDT Score Cut





Model Rejection Potential

$$\mathrm{MRP} = \frac{\Phi_{90,sens}}{n_{SG}}$$

Minimal MRP

$\Rightarrow$

best sensitivity per expected signal event

“

The best value ~~for money~~ per signal event

”

Step II

Triggers and Filters Accept events from...

- any trigger
- the *online EHE filter*, where $n_{PE} \geq 10^3$

Step I

- Apply EHE Analysis Selection
  - $\gtrsim 40\,000$ registered photo-electrons required
  - < 0.1 atmospheric events accepted per analysis livetime

Step II

- Custom Selection via BDT
  - SG acceptance 93.5 %
  - BG acceptance 2.65 %

Remaining Flux

Analysis level		n_{SG}	n_{BG}	n_{ν_e}	n_{ν_μ}	n_{ν_τ}
Trigger		244	838	146	548	144
EHE filter		178	371	90.1	202	78.2
Step I	Offline EHE	89.9	57.2	23.4	20.0	13.8
	Track quality	64.1	20.4	6.77	9.91	3.72
	Muon bundle	35.5	10.1	4.39	3.83	1.90
	Surface veto	35.5	9.99	4.33	3.78	1.88
Step II		33.2	0.265	0.003 02	0.241	0.0209

Reminder — Flux assumptions

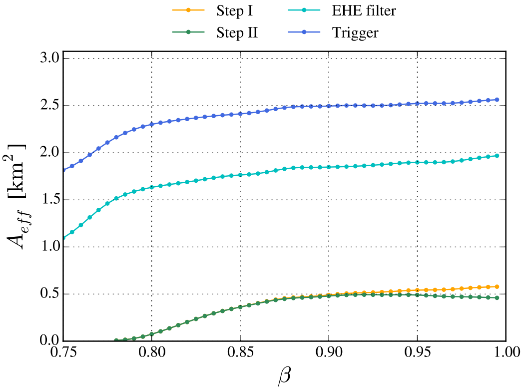
SG Assumed as best upper limit in range

BG Assumed as diffuse muon neutrino flux result
Truncated energy, $E_\nu > 10^5$ GeV

Effective Area

The event selection efficiency quantified as the area of an ideal detector recording with 100 % efficiency.

$$A_{eff}^{LV} = A_{gen} \times \frac{N_{LV}}{N_{gen}}$$



Analysis level	(Average) Effective area [km^2]
Trigger	2.39
EHE Filter	1.74
Step I	0.348
Step II	0.326

Sensitivity

Upper Limit

$$\Phi_{90}^{MM} = \Phi_{0}^{MM} \times \frac{\mu_{90}\left(n_{BG}, n_{OB}\right)}{n_{SG}}$$

$\mu_{90}\left(n_{BG}, n_{OB}\right)$ is the numerical upper limit, from Feldman & Cousins

Sensitivity

The average upper limit that can be expected to be set assuming a given background rate, n_{BG}

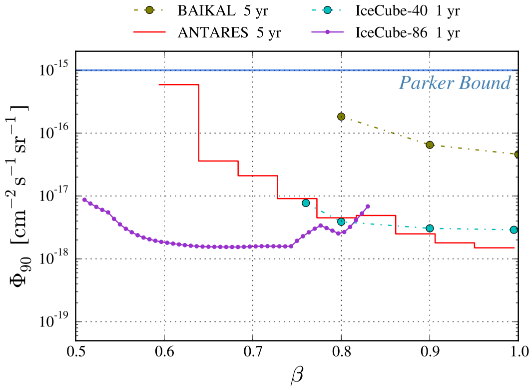
$$\overline{\Phi}_{90}^{MM} = \Phi_{0}^{MM} \times \frac{\bar{\mu}_{90}\left(n_{BG}\right)}{n_{SG}}$$

$$\bar{\mu}_{90}\left(n_{BG}\right) = \sum_{n_{OB}=0}^{\infty} \left(\mu_{90}\left(n_{OB}, n_{BG}\right) \times \frac{e^{-n_{BG}}\left(n_{BG}\right)^{n_{OB}}}{n_{OB}!} \right)$$

Sensitivity

The average upper limit that can be expected to be set assuming a given background rate, n_{BG}

$$\overline{\Phi}_{90}^{MM} = \Phi_0^{MM} \times \frac{\bar{\mu}_{90}\left(n_{BG}\right)}{n_{SG}} \quad , \quad \bar{\mu}_{90}\left(n_{BG}\right) = \sum_{n_{OB}=0}^{\infty} \left(\mu_{90}\left(n_{OB}, n_{BG}\right) \times \frac{e^{-n_{BG}}\left(n_{BG}\right)^{n_{OB}}}{n_{OB}!} \right)$$



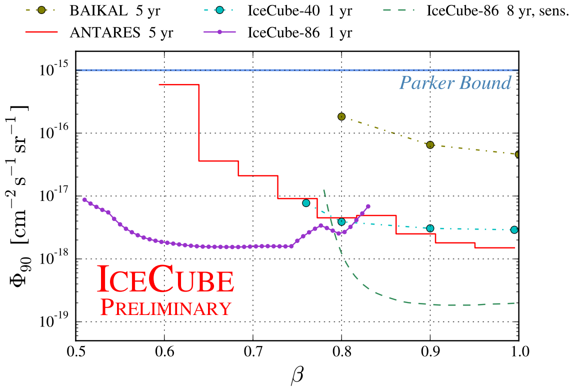
Expected BG rate

$$n_{BG} = 0.265$$

Sensitivity

The average upper limit that can be expected to be set assuming a given background rate, n_{BG}

$$\bar{\Phi}_{90}^{MM} = \Phi_0^{MM} \times \frac{\bar{\mu}_{90}(n_{BG})}{n_{SG}} \quad , \quad \bar{\mu}_{90}(n_{BG}) = \sum_{n_{OB}=0}^{\infty} \left(\mu_{90}(n_{OB}, n_{BG}) \times \frac{e^{-n_{BG}} (n_{BG})^{n_{OB}}}{n_{OB}!} \right)$$



Expected BG rate

$$n_{BG} = 0.265$$

Sensitivity

$$\bar{\Phi}_{90}^{MM} = 2.78 \times 10^{-19} \text{ cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$$

SG Efficiency Uncertainty — Systematics Studies

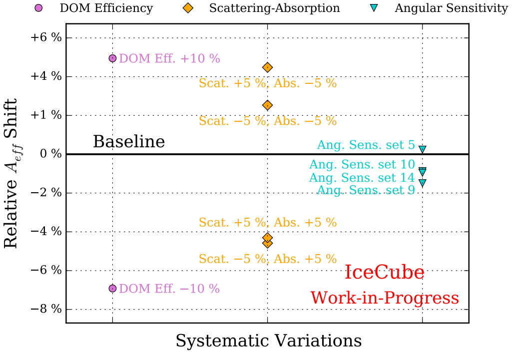
Baseline 4×10^5 MC signal events

Systematics 1×10^5 MC signal events for each set

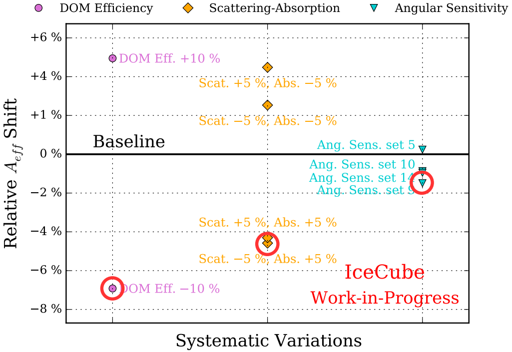
Ice-model variations:

- **DOM Efficiency**
  - DOM Efficiency +10 %
  - DOM Efficiency −10 %
- **Scattering & Absorption**
  - Scattering +5 %, Absorption +5 %
  - Scattering +5 %, Absorption −5 %
  - Scattering −5 %, Absorption +5 %
  - Scattering −5 %, Absorption −5 %
- **DOM Angular Sensitivity**
  - 49 (p_0,p_1) sets available for systematics studies
  - Choosing sets 5, 9, 10, 14 (framing distribution)

SG Efficiency Uncertainty — Systematics Studies

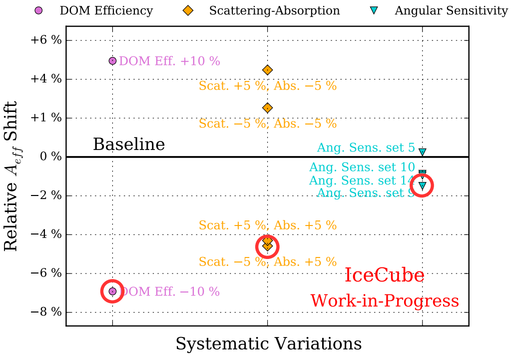


SG Efficiency Uncertainty — Systematics Studies



- Picking largest A_{eff} diff. as the uncertainty in each category
- Syst. uncertainty quadratic sum: 8.4 %

SG Efficiency Uncertainty — Systematics Studies



- Picking largest A_{eff} diff. as the uncertainty in each category
- Syst. uncertainty quadratic sum: 8.4 %

Statistical uncertainty ∼ 0.5 % ← negligible

BG Uncertainty and Alternative Astrophysical Fluxes

Assumed Flux

Diffuse muon neutrino analysis, 2017

- $\phi = 1.01^{+0.26}_{-0.23}$
- $\gamma = -2.19 \pm 0.10$

Large uncertainty from error bands

Alternative Fluxes

Diffuse muon neutrino analysis, 2019

- $\phi = 1.44^{+0.25}_{-0.24}$
- $\gamma = -2.28^{+0.09}_{-0.08}$

High energy starting events analysis, 2019

- $\phi = 2.15^{+0.49}_{-0.15}$
- $\gamma = -2.89^{+0.19}_{-0.20}$

Flux	$n_{\text{Step I}}$	$n_{\text{Step II}}$
$\Phi^{2017}_{\text{DIF-}\nu_\mu}$	$9.99^{+10.3}_{-5.13}$	$0.265^{+0.265}_{-0.135}$
$\Phi^{2019}_{\text{DIF-}\nu_\mu}$	$9.41^{+7.32}_{-3.93}$	$0.251^{+0.192}_{-0.105}$
$\Phi^{2019}_{\text{HESE}}$	$1.14^{+1.74}_{-0.618}$	$0.0288^{+0.0463}_{-0.0158}$

Experimental Event Rates

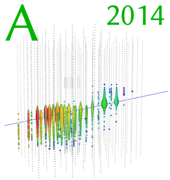
Analysis level		n_{OB}	n_{SG}	n_{BG}
EHE filter		1.63×10^8	178	371
Step I	Online EHE	3.16×10^4	89.9	57.2
	Track quality	8.46×10^3	64.1	20.4
	Muon bundle	3	35.5	10.1
	Surface veto	3	35.5	9.99
Step II		0	33.2	0.265

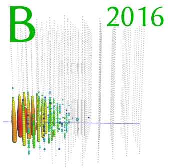
Reminder — Flux assumptions

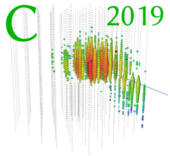
SG Assumed as best upper limit in range

BG Assumed as diffuse muon neutrino flux result
Truncated energy, $E_\nu > 10^5$ GeV

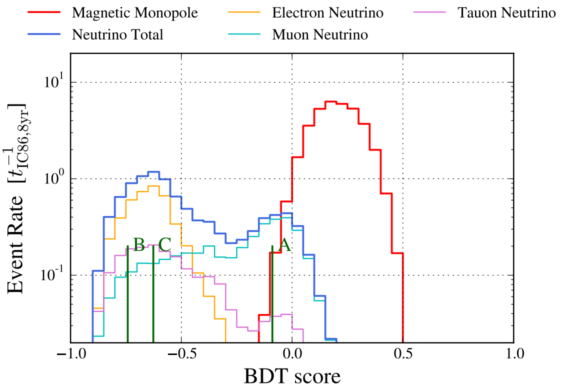
Experimental Events — Accepted at Step I







$$n_{OB}(\text{Step I}) = 3$$



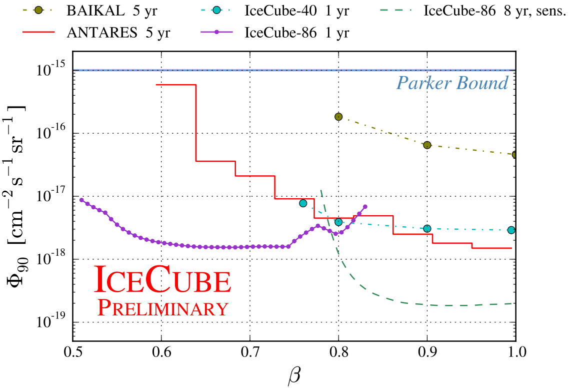
Experimental Events — Accepted at Step II

n_{OB}(Step II) = 0

Upper Limit

$$\Phi_{90}^{MM} = \Phi_{0}^{MM} \times \frac{\mu_{90}\left(n_{BG}, n_{OB}\right)}{n_{SG}}$$

n_{BG} compatible with zero,
using $n_{BG} = 0$ gives most conservative result



Sensitivity

$$\overline{\Phi}_{90}^{MM} = 2.78 \times 10^{-19}\ \text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$$

Upper Limit

$$\Phi_{90}^{MM} = \Phi_0^{MM} \times \frac{\mu_{90}(n_{BG}, n_{OB})}{n_{SG}}$$

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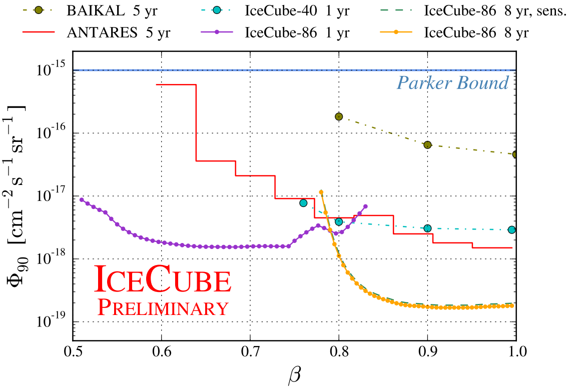


Sensitivity

$$\overline{\Phi}_{90}^{MM} = 2.78 \times 10^{-19} \text{ cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$$

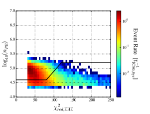
Upper Limit

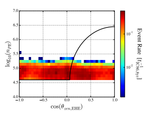
$$\Phi_{90}^{MM} = 2.54 \times 10^{-19} \text{ cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$$

Summary

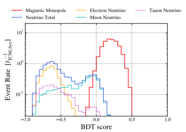
Objective — Discover magnetic monopoles

Step I — EHE event selection

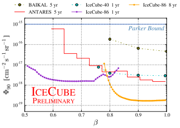




Step II — 5 monopole signatures ⇒ 9 BDT variables ⇒



Result — No monopole discovery — Competitive upper limit



Thank you