Magnetic Monopoles

IceCube Searches for Magnetic Monopoles — Covering the Full β Spectrum (Almost)

A. Burgman

Division of High Energy Physics
Uppsala University

2018–10–16

UPPSALA UNIVERSITET ICECUBE

Magnetic Monopole Basics

Magnetic Charge

- ▷ Free north or south pole

Quantum Formulation

- ▷ Dirac, 1931
- ▷ $g_n = n\frac{1}{2\alpha}e$
- ▷ $g_1 =\sim 68.5e$
  - ▷ Dirac charge, g_D

Magnetic Monopole Mass

- ▷ $m_{MM} \in [10^4; 10^{17}]$ GeV

Lower m_{MM}

- ▷ Collider seaches

Higher m_{MM}

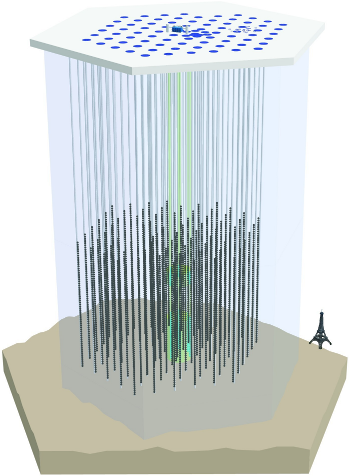
- ▷ Primordial flux seaches

Magnetic Monopole Energy

- ▷ $E_{kin} \lesssim 10^{15}$ GeV

Primordial population accelerated by extra-galactic magnetic fields

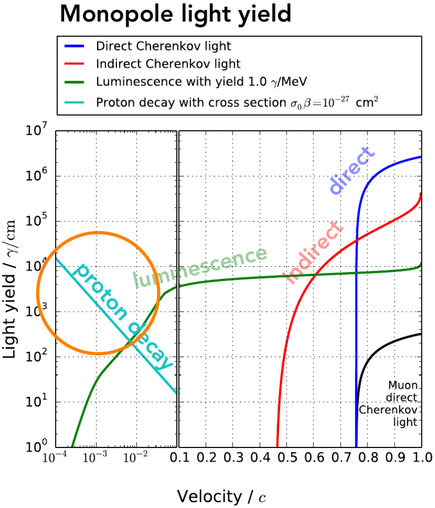
IceCube Basics



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

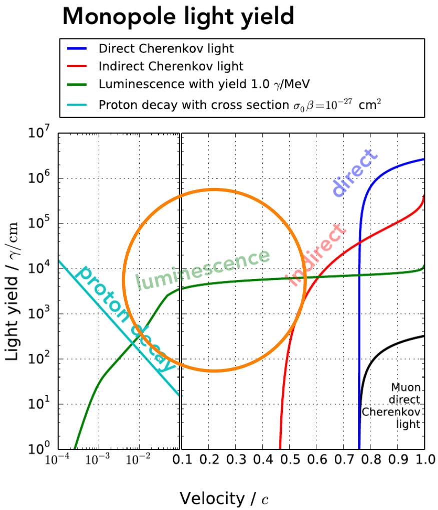
Event types
▷ Cascades $(\nu_{e,\tau})$
▷ Tracks (μ, ν_μ)
▷ Starting/stopping
▷ Through-going

Magnetic Monopole Light Production Channels



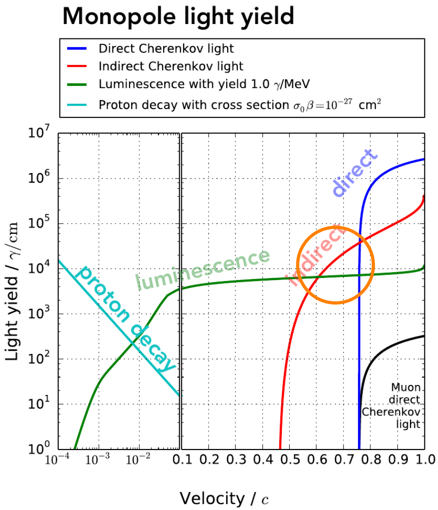
Non-relativistic
$\beta \lesssim 0.01$
▷ Particle cascades from induced proton decay in medium

Magnetic Monopole Light Production Channels



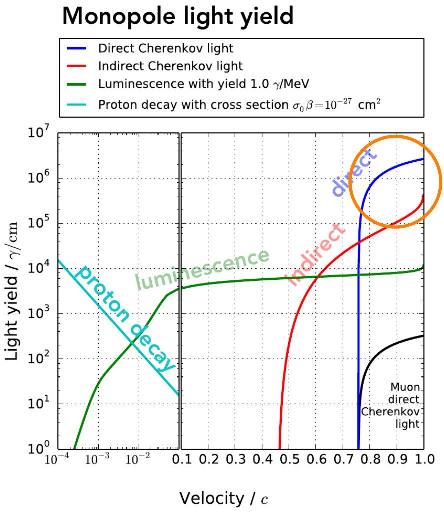
Low relativistic
$0.01 \lesssim \beta \lesssim 0.5$
▷ Luminescence light from excitation and subsequent deexcitation of medium

Magnetic Monopole Light Production Channels



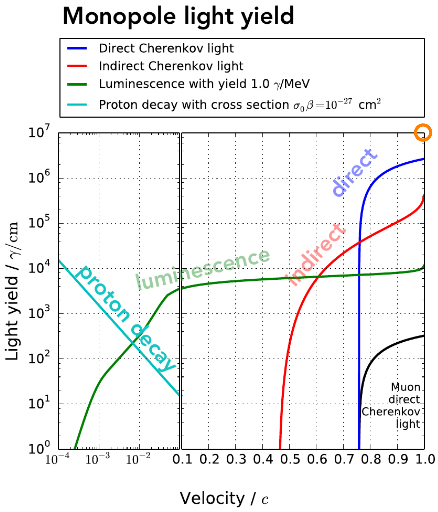
Mildly relativistic
$0.5 \lesssim \beta \lesssim 0.75$
▷ Indirect Cherenkov light from ionization of medium

Magnetic Monopole Light Production Channels



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

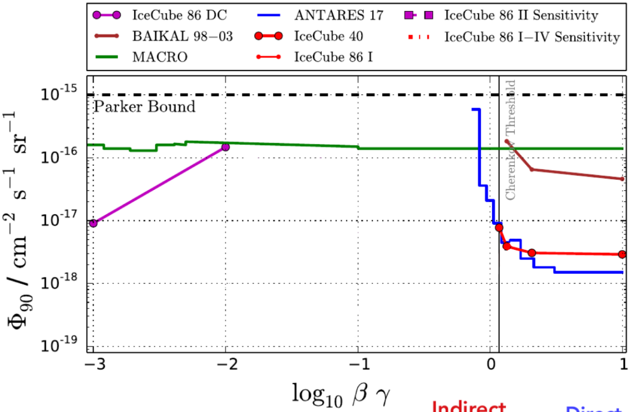
Magnetic Monopole Light Production Channels



Ultra-relativistic
$0.999\,95 \lesssim \beta$ $100 \lesssim \gamma$
▷ Stochastic nuclear interactions, direct Cherenkov light

Monopole Flux Landscape

◁ … sans current Icecube ▷



Catalysis of proton decay

Luminescence

Indirect Cherenkov radiation

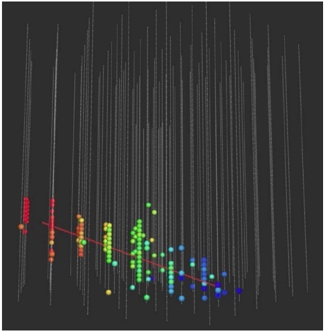
Direct Cherenkov radiation

Non-Relativistic Monopoles

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

Analysis Steps

1. Slow track hypothesis
   ⇒ discern **long** events
2. Apply cleaning
   - Hits far from track
   - Fitted fast tracks
3. Apply BDT to remove remaining background events



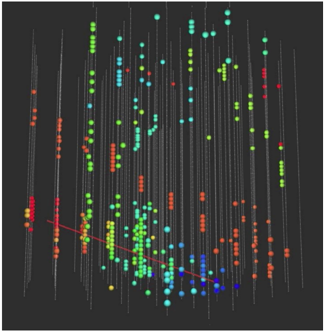
Main Challenge Removing non-related hits from event

Non-Relativistic Monopoles

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

Analysis Steps

1. Slow track hypothesis
   ⇒ discern **long** events
2. Apply cleaning
   - Hits far from track
   - Fitted fast tracks
3. Apply BDT to remove remaining background events



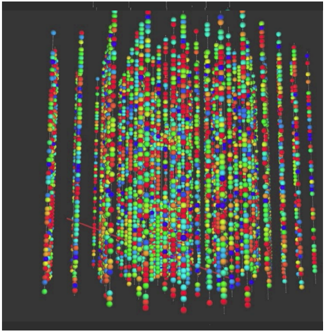
Main Challenge	Removing non-related hits from event → Coincident muon tracks

Non-Relativistic Monopoles

Analyzer	E. Jacobi
β Range	10^{-3} – 10^{-2}
Light Production	Induced proton decay
Event Characteristics	Extremely slow, dim track

Analysis Steps

1. Slow track hypothesis
   ⇒ discern **long** events
2. Apply cleaning
   - Hits far from track
   - Fitted fast tracks
3. Apply BDT to remove remaining background events

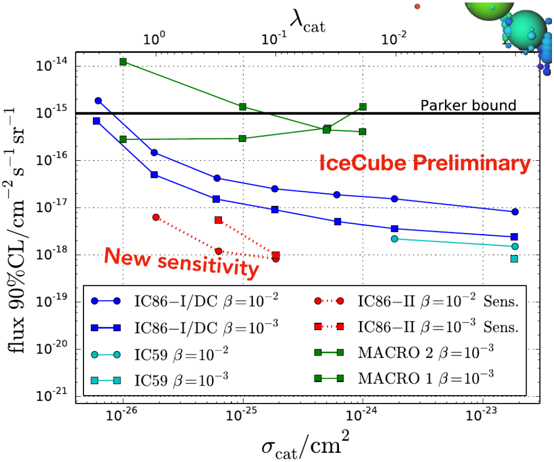


Main Challenge	Removing non-related hits from event → Coincident muon tracks → PMT noise etc.

Non-Relativistic Monopoles

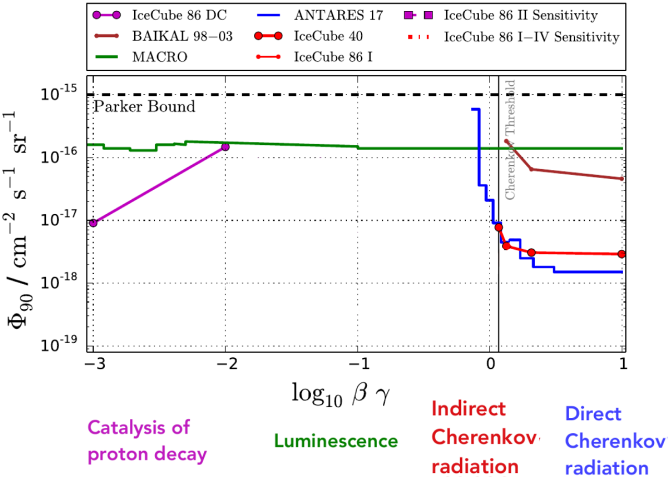
Sensitivity

Sensitivity on monopole flux
over proton decay catalysis cross section, σ_{cat}



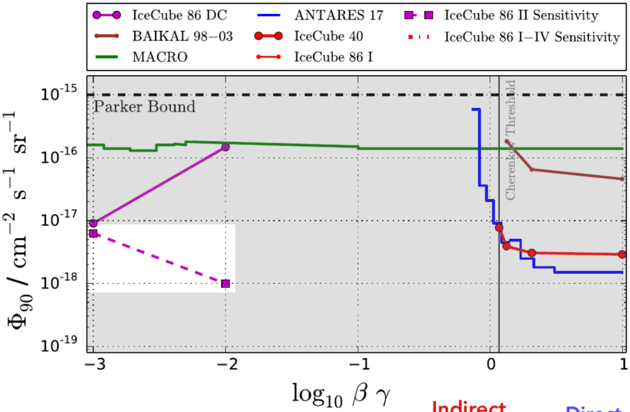
Monopole Flux Landscape

◁ Final sensitivity ▷



Monopole Flux Landscape

◁ Final sensitivity ▷



Catalysis of proton decay

Luminescence

Indirect Cherenkov radiation

Direct Cherenkov radiation

Low Relativistic Monopoles

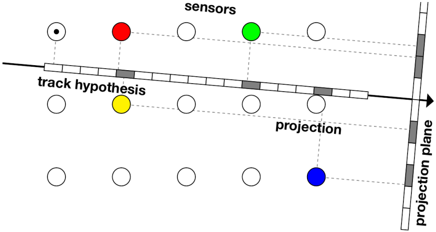
Analyzer	F. Lauber
β Range	0.1 – 0.5
Light Production	Luminescence light
Event Characteristics	Slow, smooth, fairly dim track

Analysis Steps

1. Quality cuts (central track, through-going)
2. Neural network to quantify the smoothness of the track
3. BDT to remove final remaining background

Into neural network:
Hits projected onto...

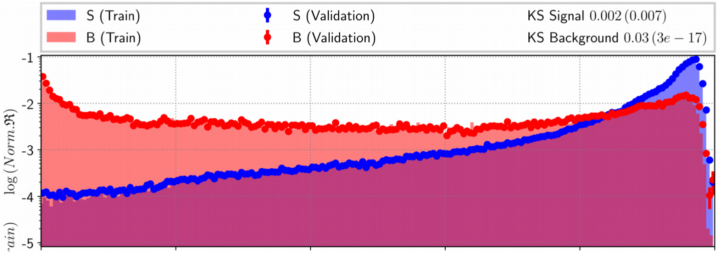
- ▷ line along track
- ▷ plane orthogonal to track



Low Relativistic Monopoles

Toy BDT score distributions

Good separation between SG and BG



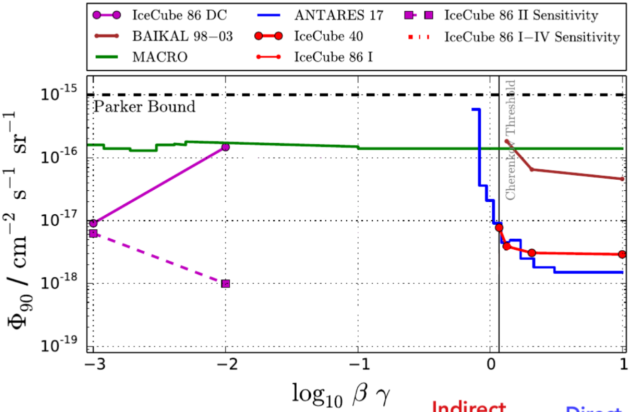
Current BG reduction: 5 OoM

Required BG reduction: another 3 OoM

Preliminary Results Timeline: ∼ summer 2019

Monopole Flux Landscape

◁ Sensitivity to come ▷



Catalysis of proton decay

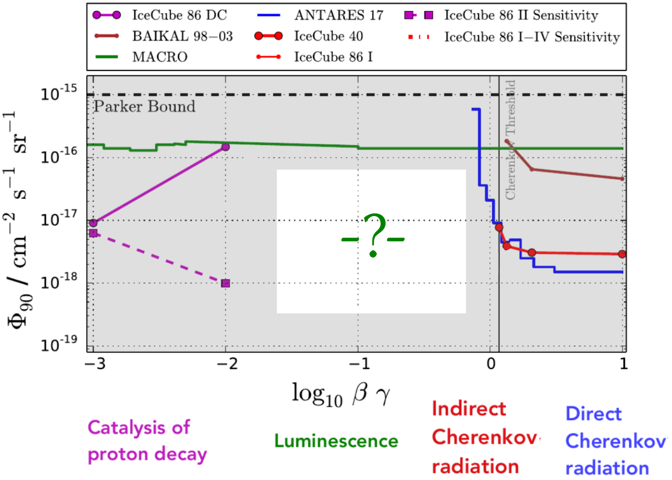
Luminescence

Indirect Cherenkov radiation

Direct Cherenkov radiation

Monopole Flux Landscape

◁ Sensitivity to come ▷



Mildly Relativistic Monopoles

Analyzer	A. Pollmann
β Range	0.5 – 0.75
Light Production	Indirect Cherenkov light (beta-electrons)
Event Characteristics	Moderately fast, bright, smooth track

Analysis Steps

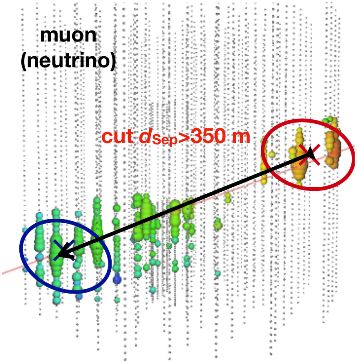
1. Loose quality cuts (number of hit strings, DOMs)
2. Loose BG reduction cuts (track length, hit distribution, direction)
3. BDT to remove final remaining background

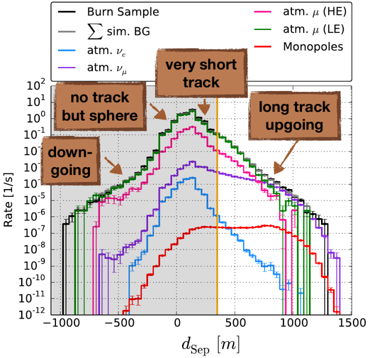
Mildly Relativistic Monopoles

d_{Sep} — a powerful selection variable

Gives distance from center of first quartile of hits to center of last quartile of hits

→ shows the type of track





Mildly Relativistic Monopoles

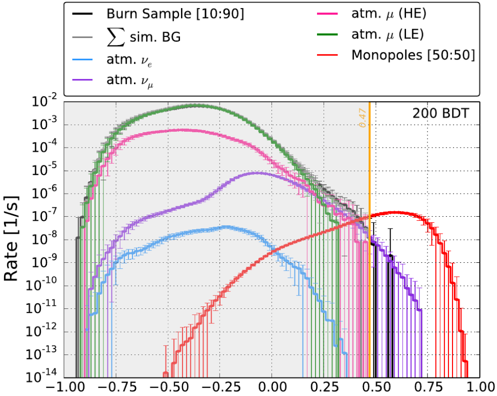
BDT score at final level

Good separation between SG and BG at final level

→ cut at BDT score 0.47

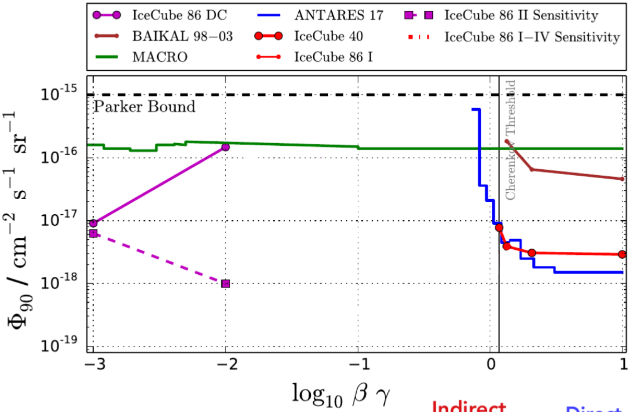
Three events remaining in data at final level

→ expected and background-like



Monopole Flux Landscape

◁ Published limit ▷



Catalysis of proton decay

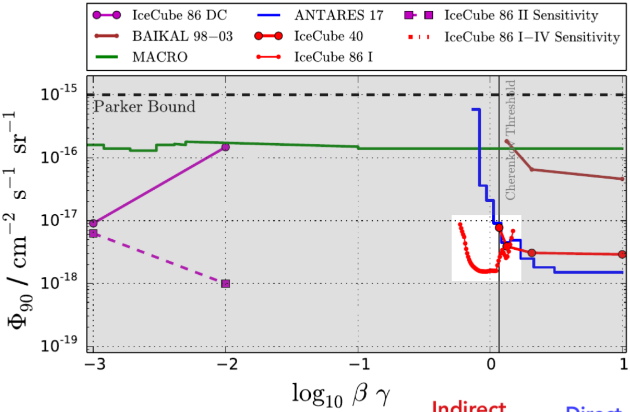
Luminescence

Indirect Cherenkov radiation

Direct Cherenkov radiation

Monopole Flux Landscape

◁ Published limit ▷



Catalysis of proton decay

Luminescence

Indirect Cherenkov radiation

Direct Cherenkov radiation

Relativistic Monopoles

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

Analysis Steps

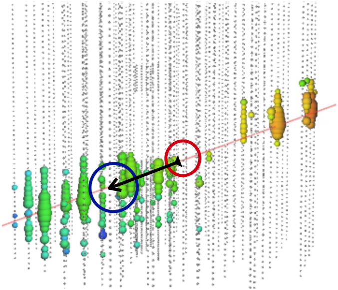
1. Using cuts from EHE analysis (a search for high energy neutrinos) $\Rightarrow$ sample with...
   - Bright events
   - Low atm. event rate
2. BDT to remove remaining neutrino events (EHE analysis signal events)

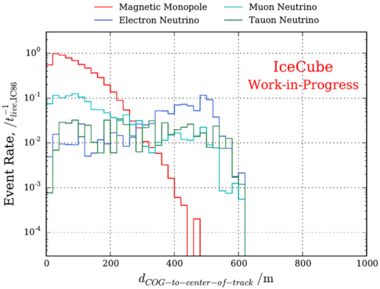
Relativistic Monopoles

$d_{COG\text{-}offset}$ — a powerful selection variable

Gives distance from center-of-gravity of hits to center of track

→ shows large concentrations of light



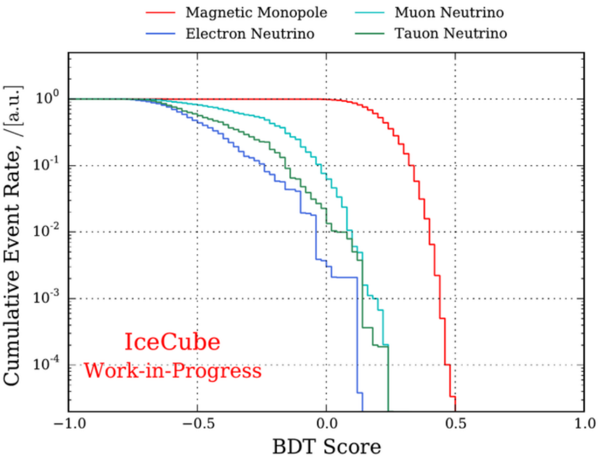


Relativistic Monopoles

Projected BDT score at final level

Possible BG reduction of 2 OoM while keeping $\sim 90\,\%$ of signal

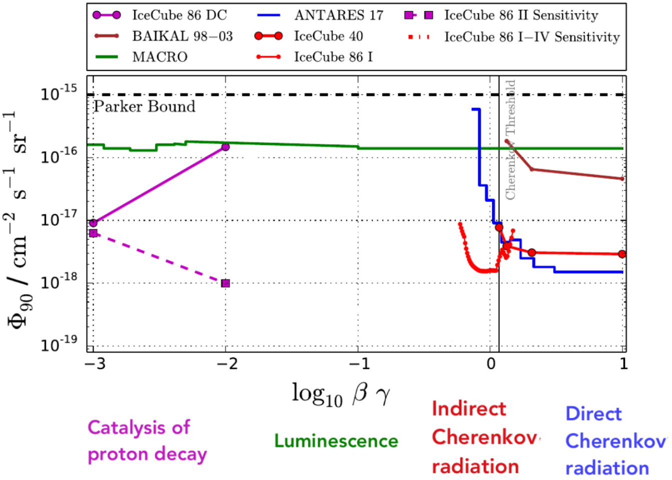
$\rightarrow$ cut at BDT score 0.087



Preliminary Results Timeline: $\sim$ summer 2019

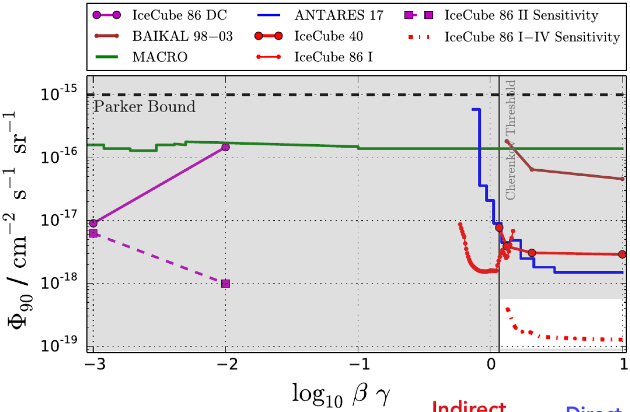
Monopole Flux Landscape

◁ Projected sensitivity (to be updated!) ▷



Monopole Flux Landscape

◁ Projected sensitivity (to be updated!) ▷



Catalysis of proton decay

Luminescence

Indirect Cherenkov radiation

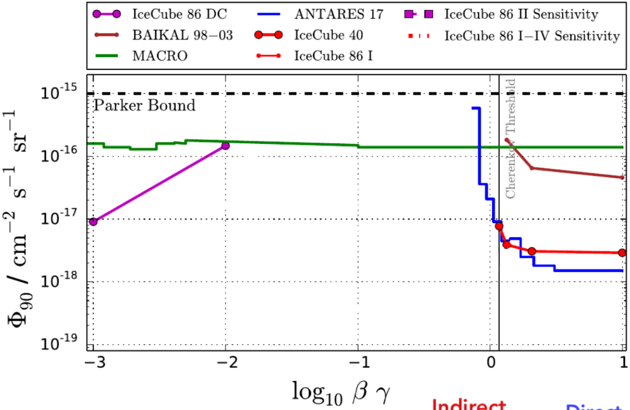
Direct Cherenkov radiation

Concluding Remarks

◁ (Expected) world leading IceCube-results over most of β-range ▷

Concluding Remarks

◁ (Expected) world leading IceCube-results over most of β-range ▷



Catalysis of proton decay

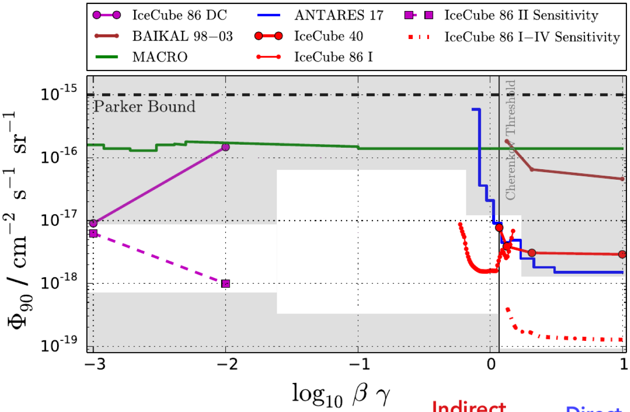
Luminescence

Indirect Cherenkov radiation

Direct Cherenkov radiation

Concluding Remarks

◁ (Expected) world leading IceCube-results over most of β-range ▷



Catalysis of proton decay

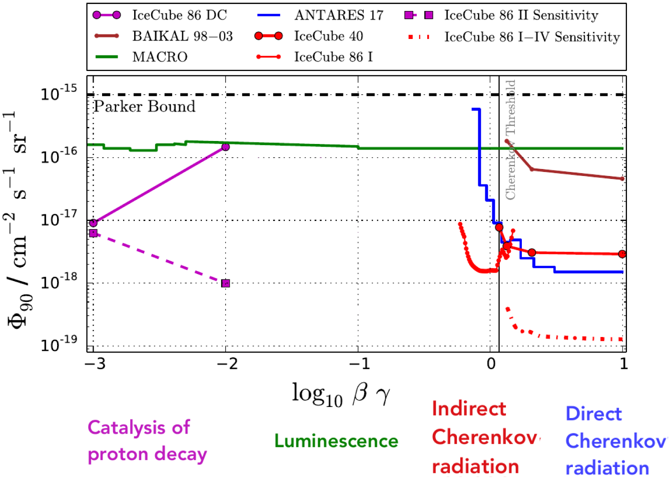
Luminescence

Indirect Cherenkov radiation

Direct Cherenkov radiation

Concluding Remarks

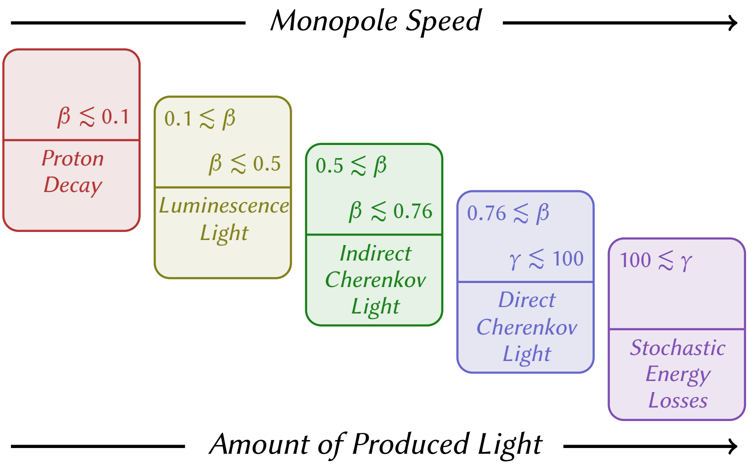
◁ (Expected) world leading IceCube-results over most of β-range ▷



Thank you

Backups

Backup I — Magnetic Monopoles in Ice



Backup II — Monopole Mass Predictions

Model	**Mass** /GeV
$\Lambda_{MM} \sim \Lambda_{EW}$	4.0×10^4
$SU(15)$	10^8
$SO(10)$	$10^{10} - 10^{16}$
$SU(5)$	10^{17}

Backup III

Accelerator	Magnetic Field /µG	Coherence Length /Mpc	Kinetic Energy per passing /GeV
Normal Galaxies	3 – 10	10^{-2}	$(0.3 - 1)\times 10^{12}$
Starburst Galaxies	10 – 50	10^{-3}	$(1.7 - 8)\times 10^{11}$
AGN jets	~ 100	$10^{-4} - 10^{-2}$	$1.7\times(10^{11} - 10^{13})$
Galaxy Clusters	5 – 30	$10^{-4} - 1$	$3 \times 10^{9} - 5 \times 10^{14}$
Extragalactic Sheets	0.1 – 1	1 – 30	$1.7 \times 10^{13} - 5 \times 10^{14}$

- A monopole interacting only with one accelerator type:
  - Broad energy distribution centered on $E_{kin} \times \sqrt{n}$
  - n is the expected number of passings
- A primordial monopole arriving at Earth today
  - Passed ~ 100 extragalactic sheet domains
  - Energy distribution centered at $\sim 10^{15}$ GeV

Backup IV — EHE Analysis Cuts

Cuts from the EHE Analysis

Level 2 — *Analysis Cut:* Cuts on n_{pe}, n_{ch} and the χ^2_{red} of the EHE ILF to get extremely bright events

Level 3 — *Atmospheric ν_e Cut:* Cut on $\log\left(n_{pe}\right)$ depending on χ^2_{red} to demand more light for more cascade like events than track like events

Level 4 — *Atmospheric μ Cut:* Cut on $\log\left(n_{pe}\right)$ depending on zenith direction to demand more light for downgoing events

Level 5 — *IceTop Veto:* Remove events with one or more IceTop hits within a certain time window