BERGISCHE UNIVERSITÄT WUPPERTAL

ICECUBE

bmb+f - Förderschwerpunkt
Astroteilchenphysik
Großgeräte der physikalischen Grundlagenforschung

Searches for

Magnetic Monopoles with IceCube

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for the IceCube Collaboration
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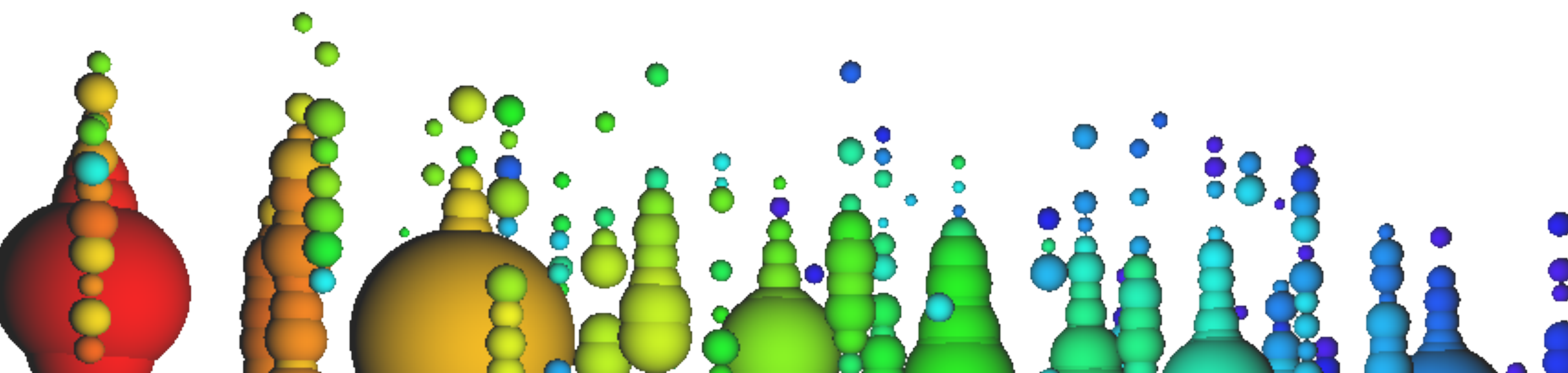
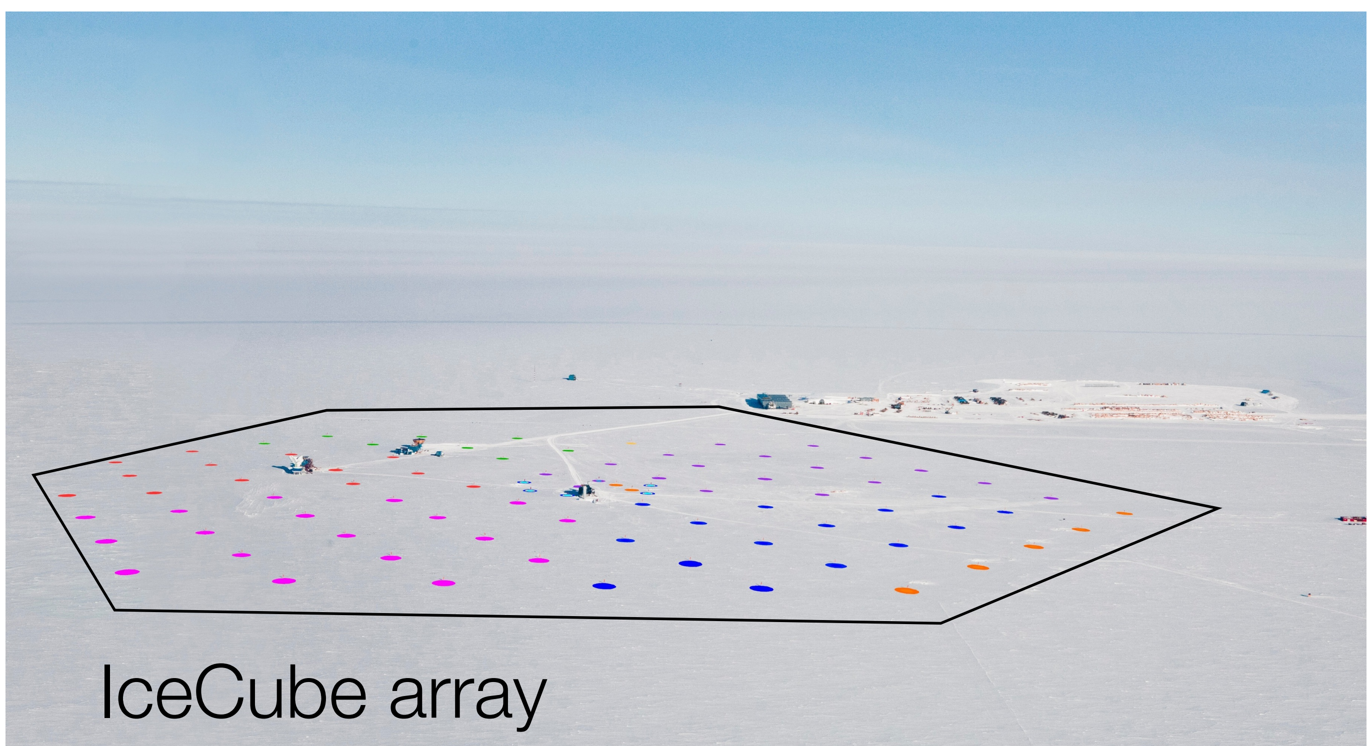
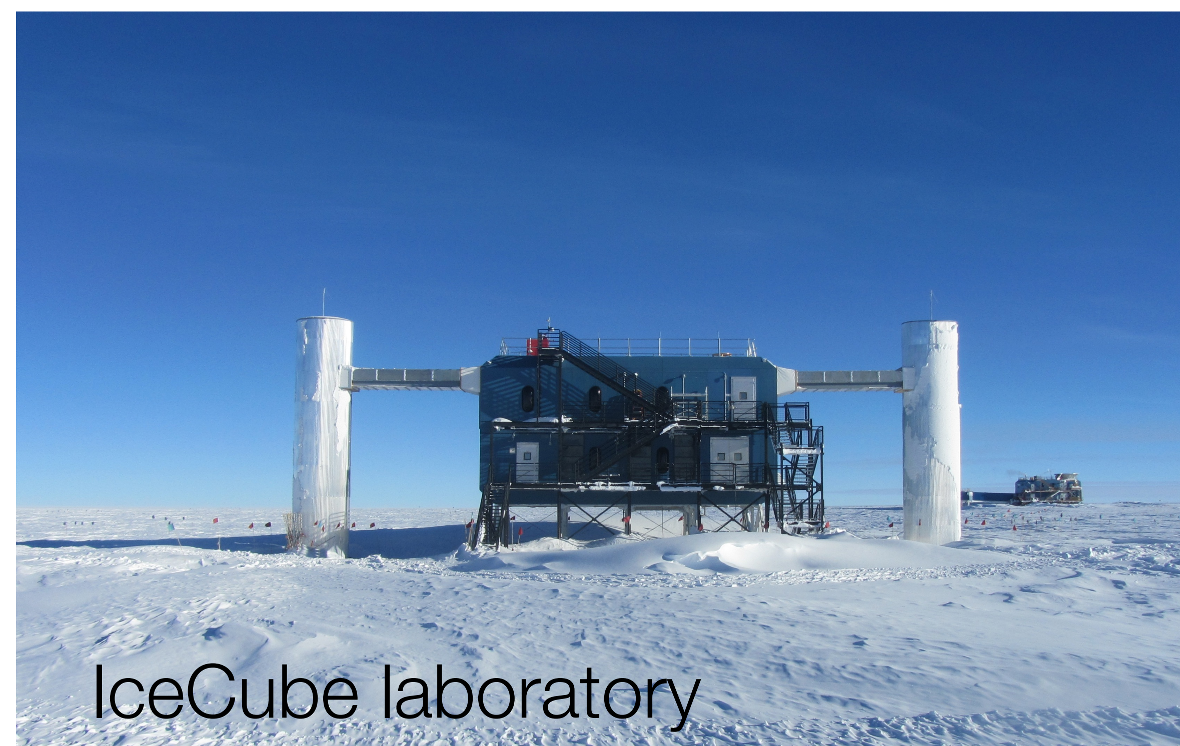


IceCube neutrino telescope





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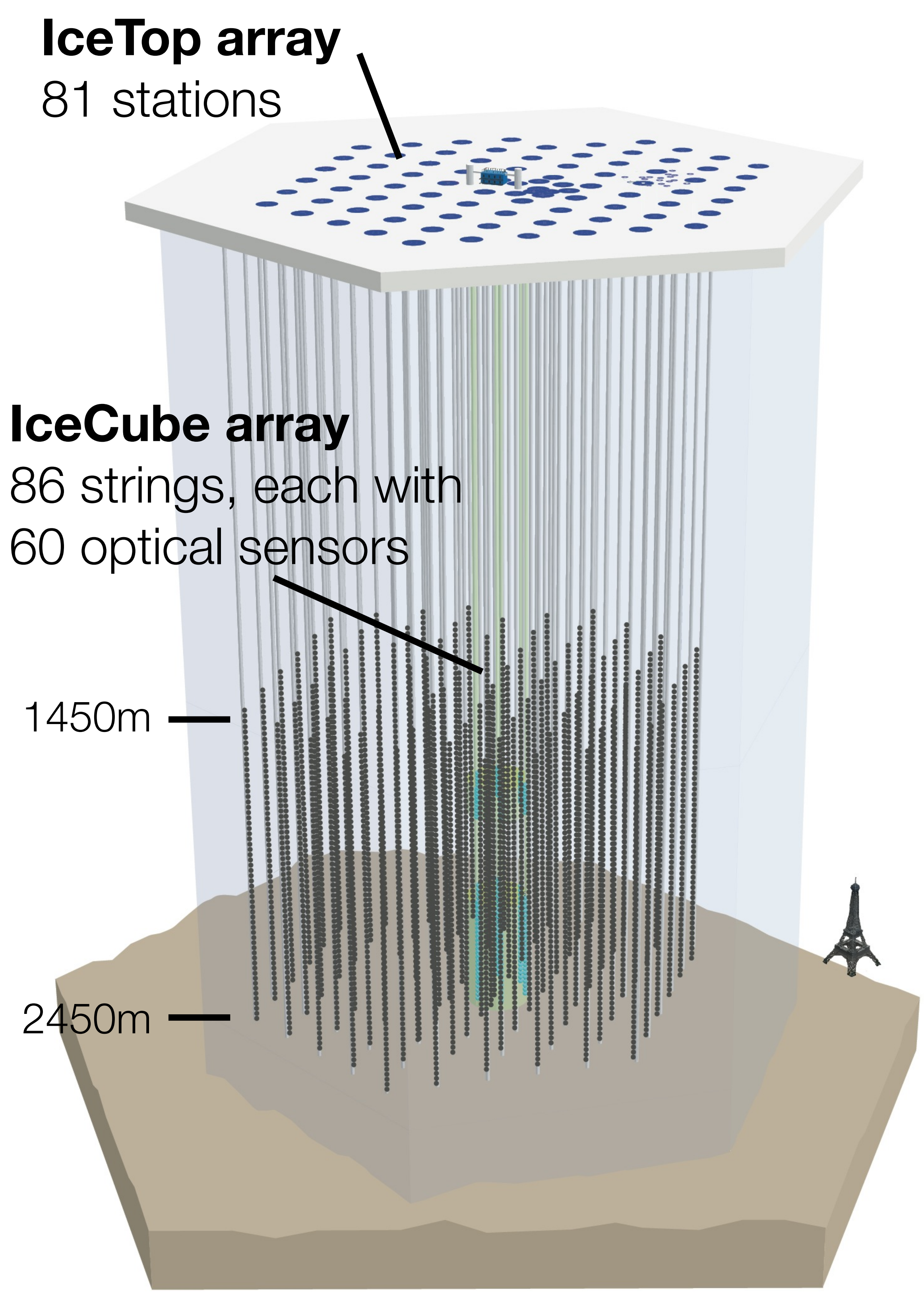

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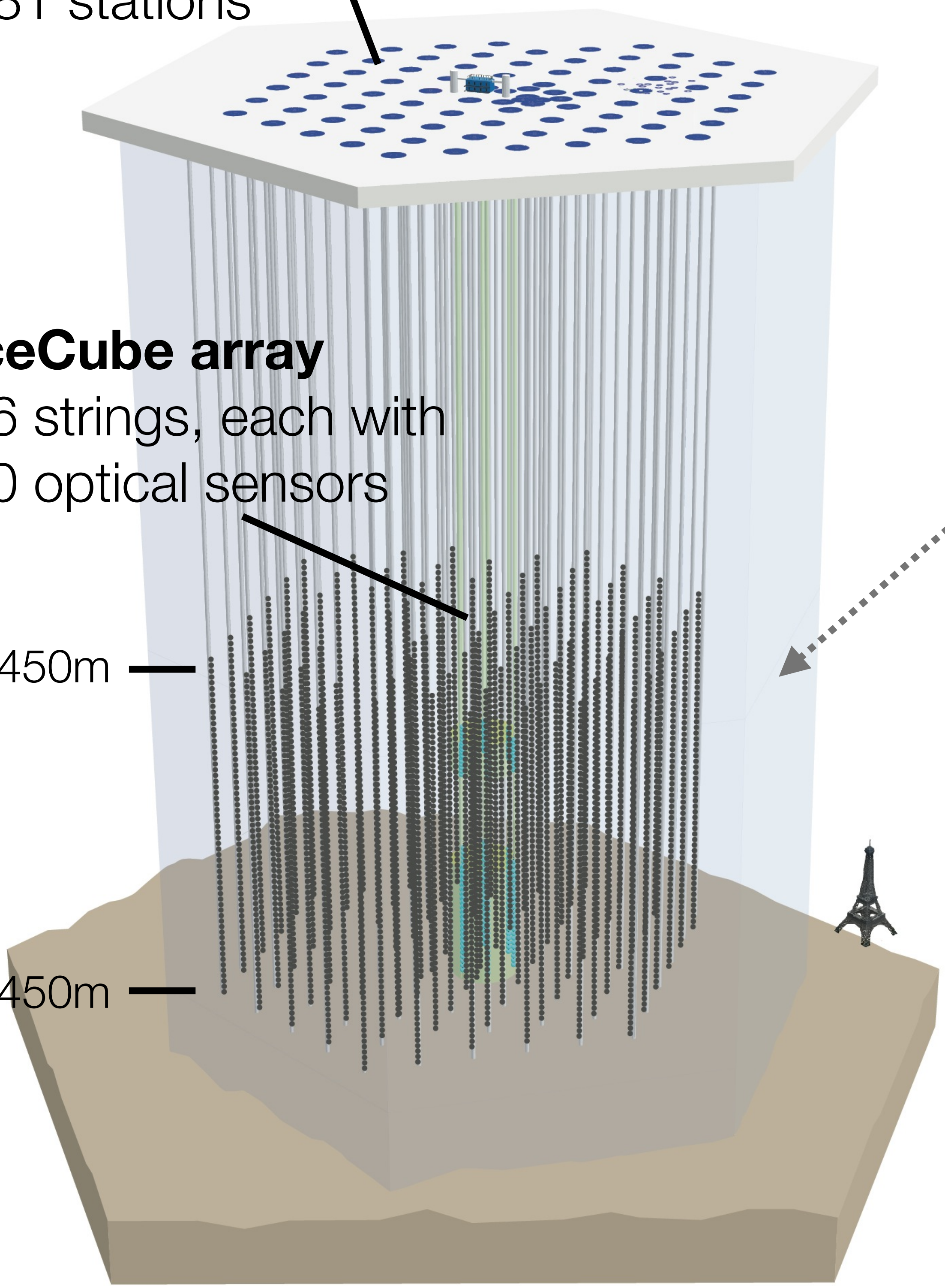
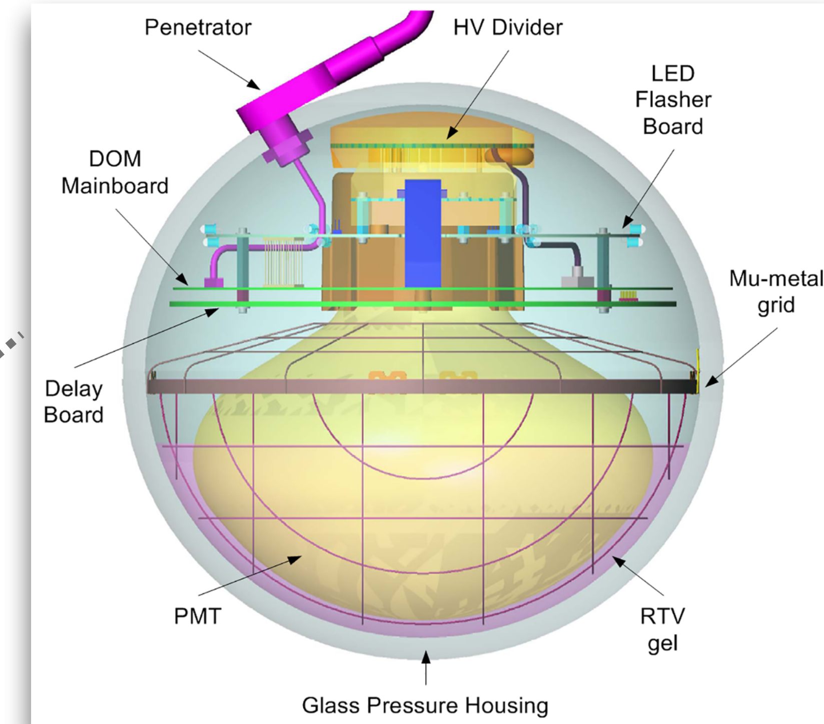
IceCube neutrino telescope

IceTop array
81 stations

IceCube array
86 strings, each with
60 optical sensors



Digital Optical Modules (DOMs)



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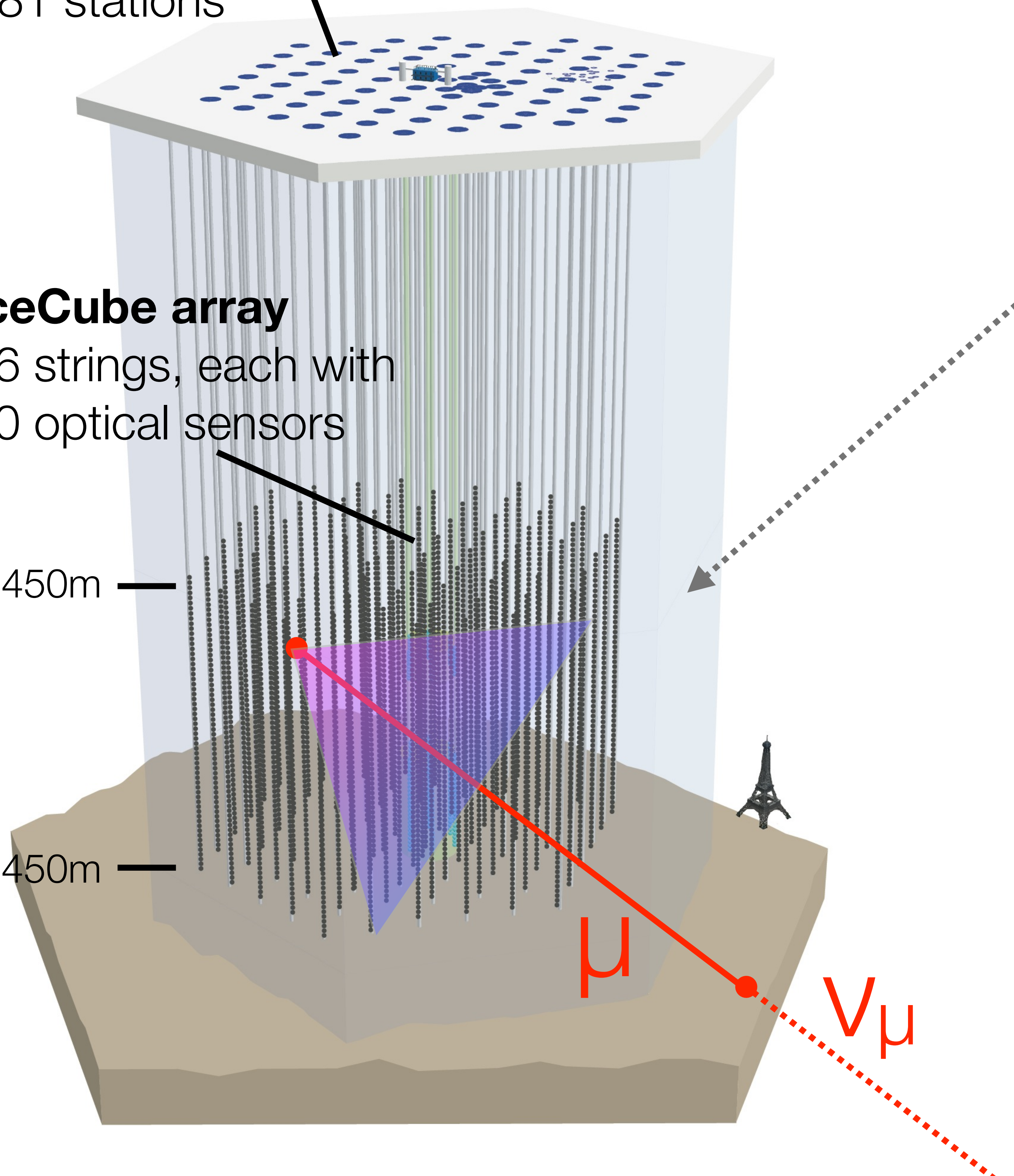

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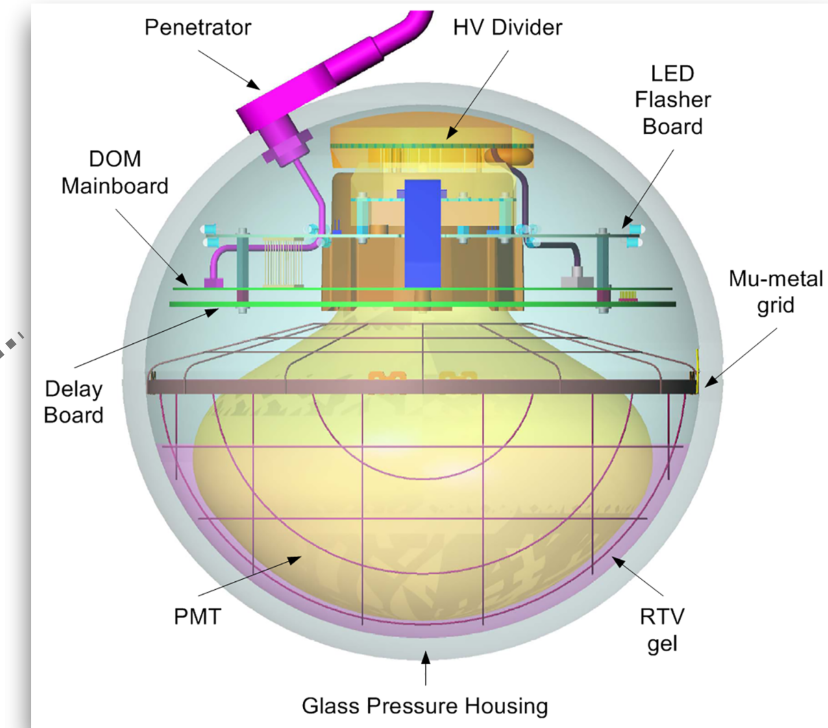

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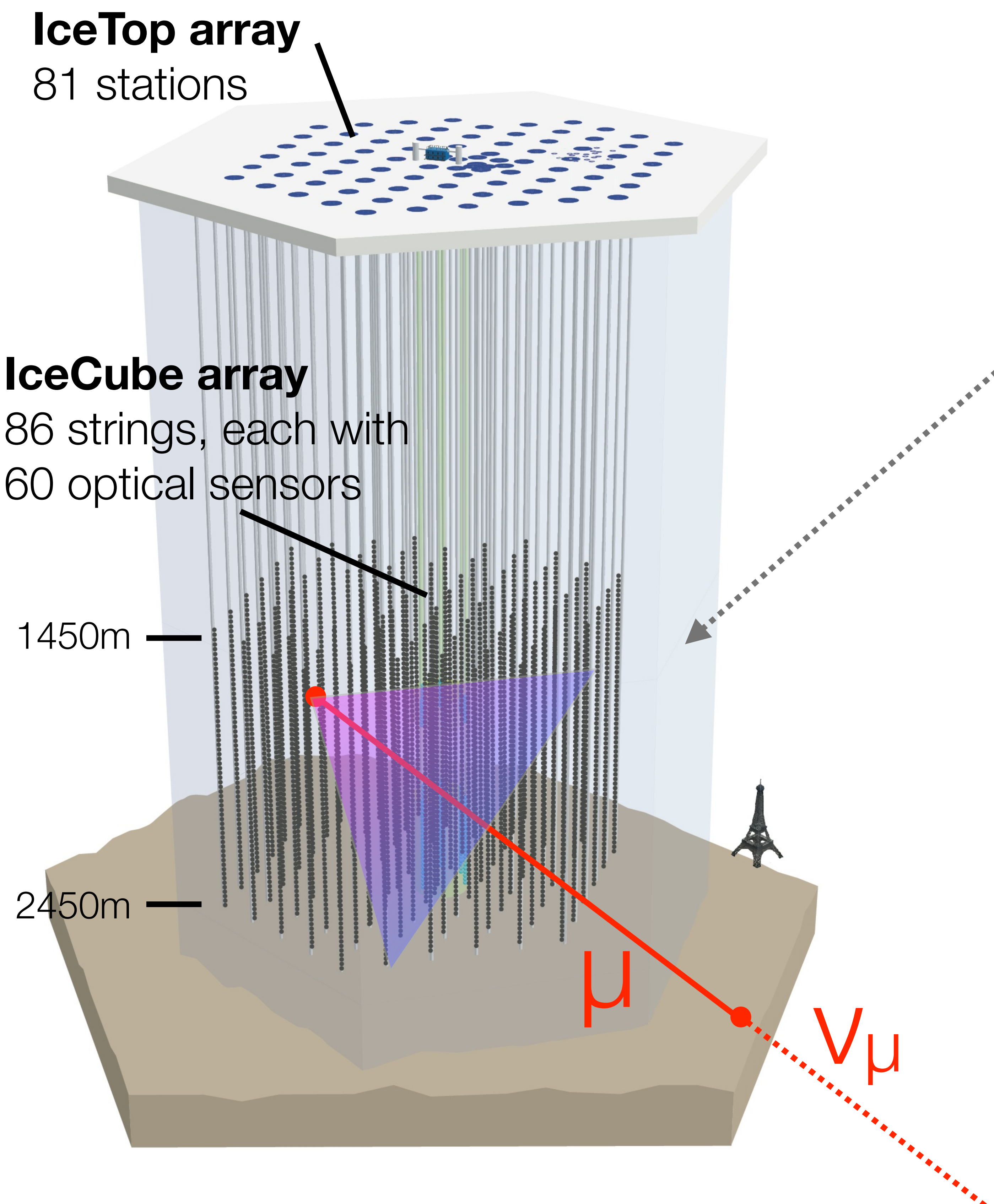

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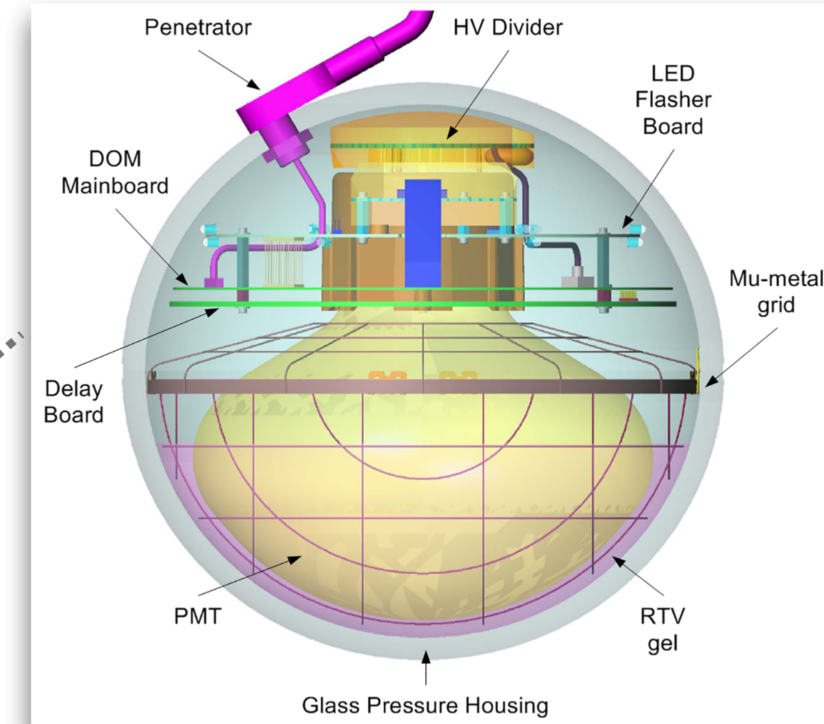
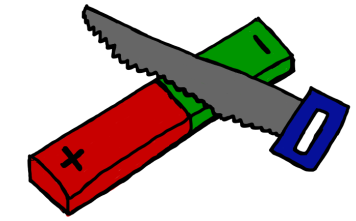


Physics World:

Breakthrough of the Year 2013

Discovery of astrophysical neutrinos

Magnetic Monopoles



- elemental magnetic charge (Dirac)

  $g_D = e / 2\,\alpha \approx 68.5\,e$

- with huge mass created
  - shortly after the Big Bang (GUT)

    10^{13} GeV ≦ M_{MM} ≦ 10^{19} GeV

  - in intermediate stages of symmetry breaking (IMM)

    10^{7} GeV ≦ M_{MM} ≦ 10^{13} GeV

  - at accelerators (electroweak and other)

    M_{MM} ~ TeV, $\Phi \sim 10^{-22}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$

- ionization power

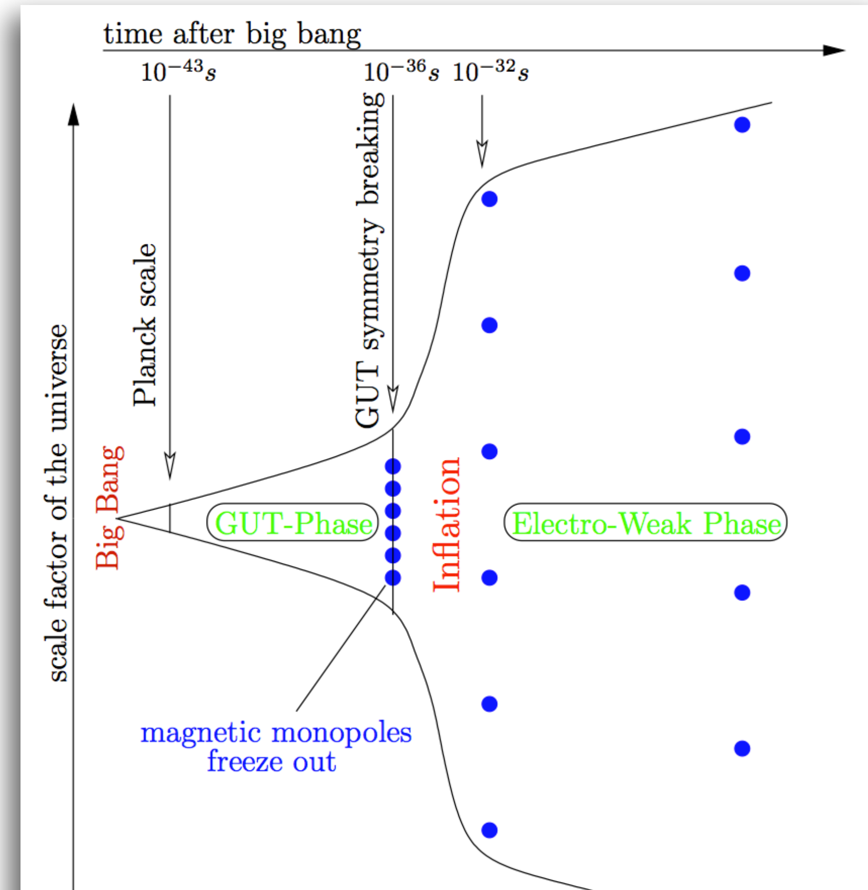
  $E_{dep} \sim g^2$ (Muons: $\sim Z^2 / \beta^2$)

- acceleration in magnetic fields for

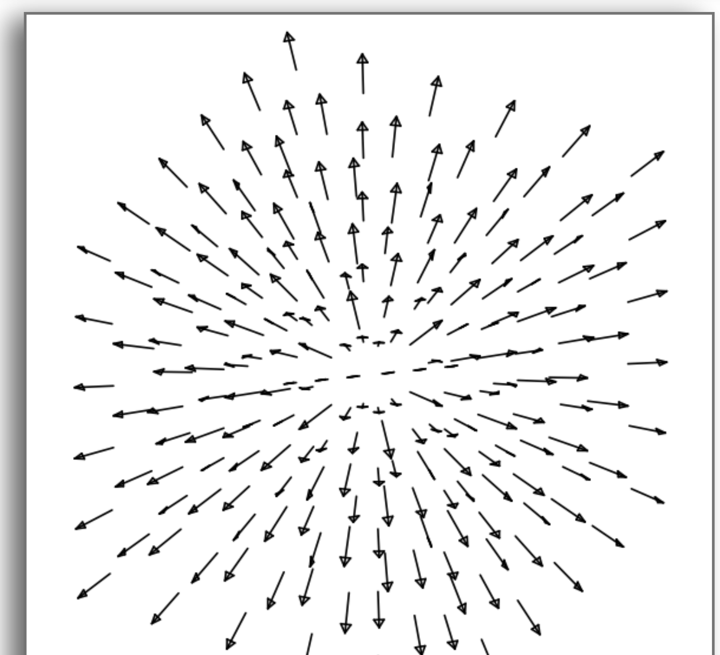
  M_{MM} ≦ 10^{14} GeV to E_{kin} ≦ 10^{15} GeV

  - trapping around galaxy, sun, Earth

    $v \sim 10^{-3}$ / 10^{-4} / 10^{-5} c



Gluesenkamp ´10

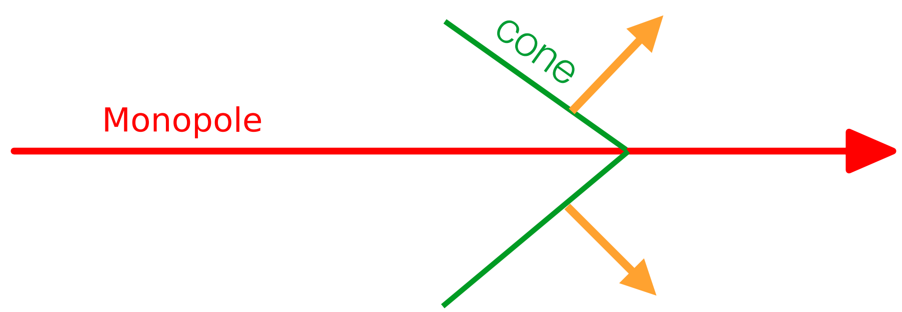

Rajantje, Contemp. Phys., 53(3) 2012

Monopole detection at relativistic speeds

Cherenkov radiation

Direct

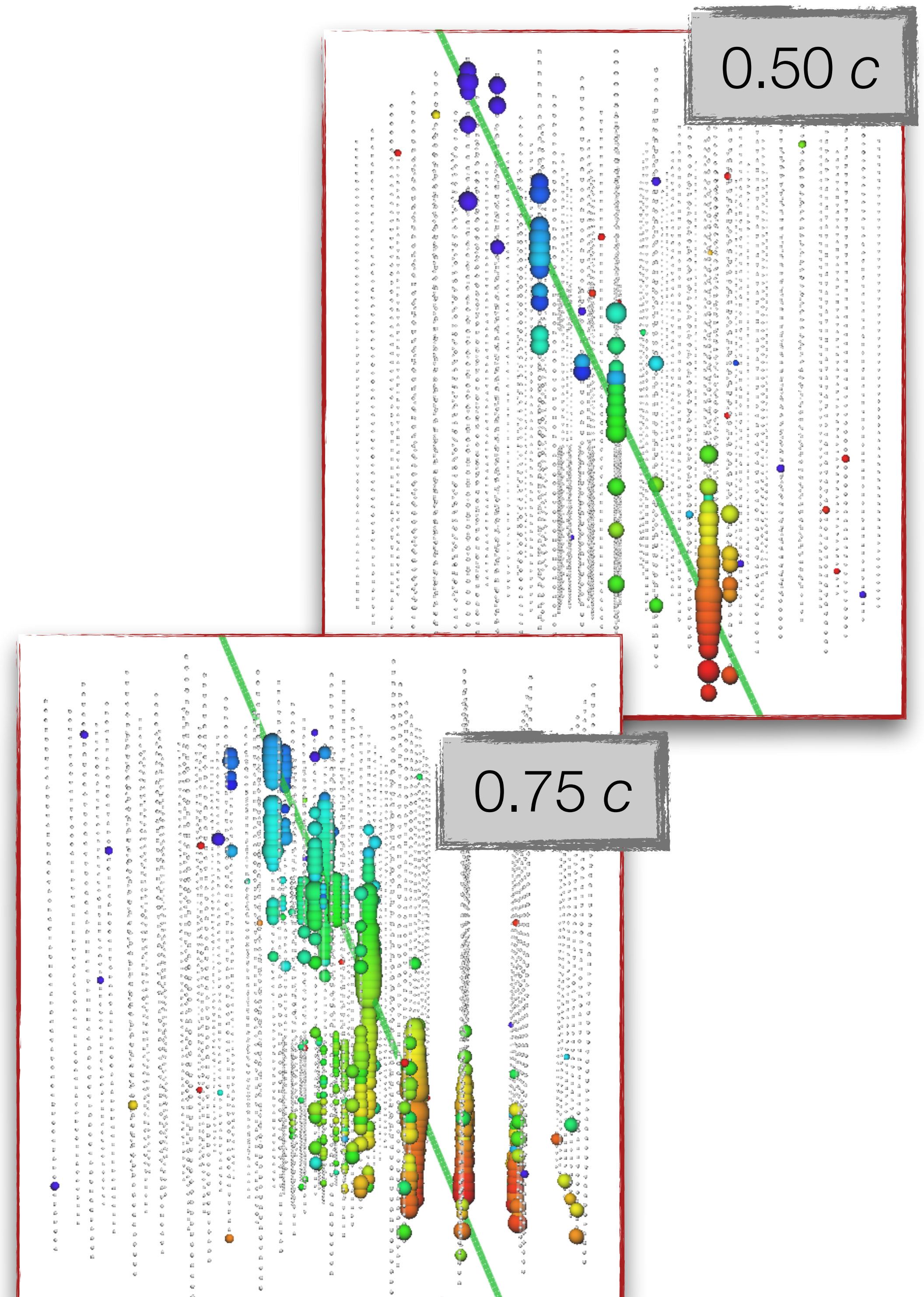
- a charge with velocity > 0.75 *c*
- Cherenkov light originates from a cone



Indirect

- a charge knocks electrons off their atoms
- electrons are energetic enough to emit Cherenkov light
- diffuse Cherenkov light around track

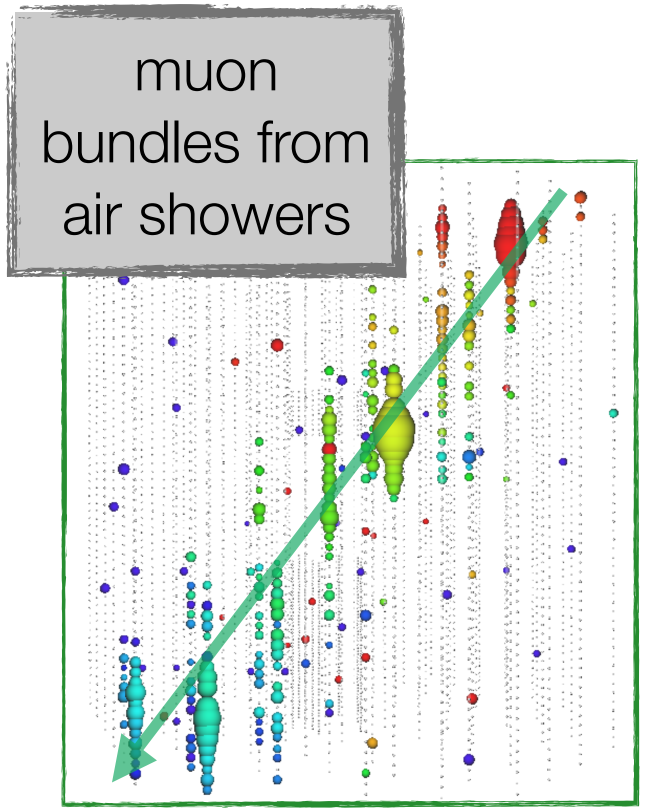
Monopole Signatures in IceCube



Event signatures in IceCube

EPJ C76 (2016) 133

Background



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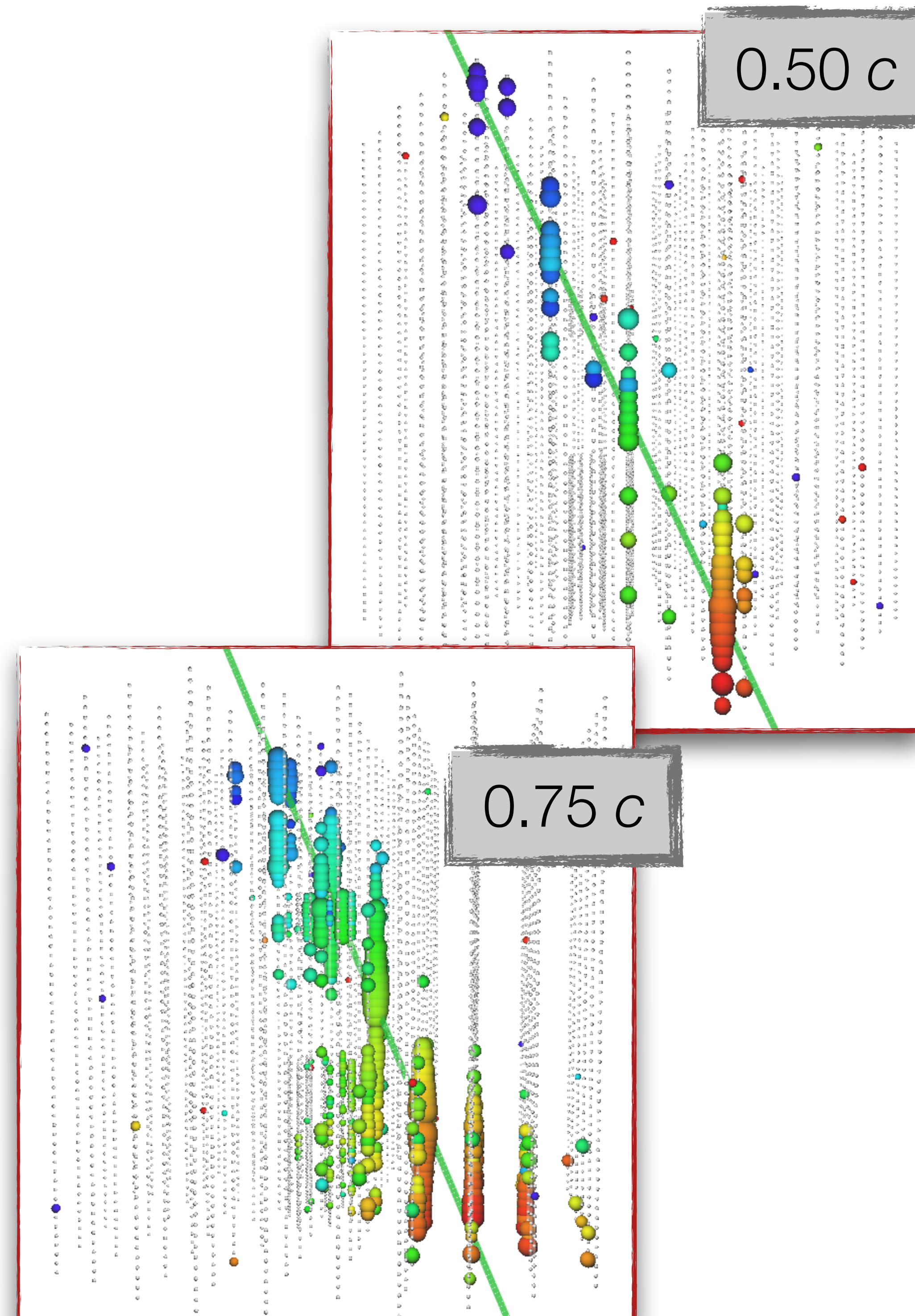
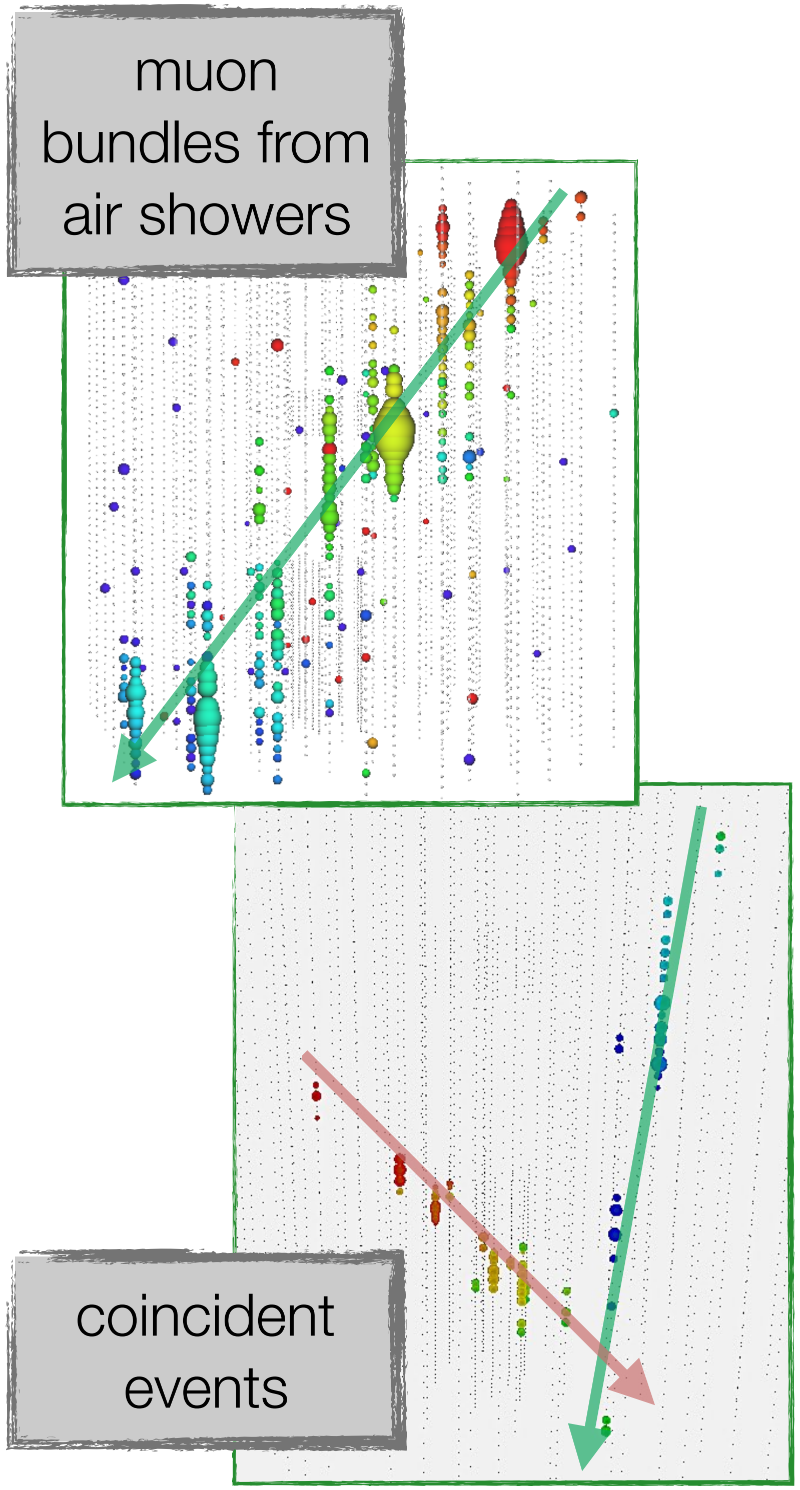


Event signatures in IceCube

EPJ C76 (2016) 133

Background



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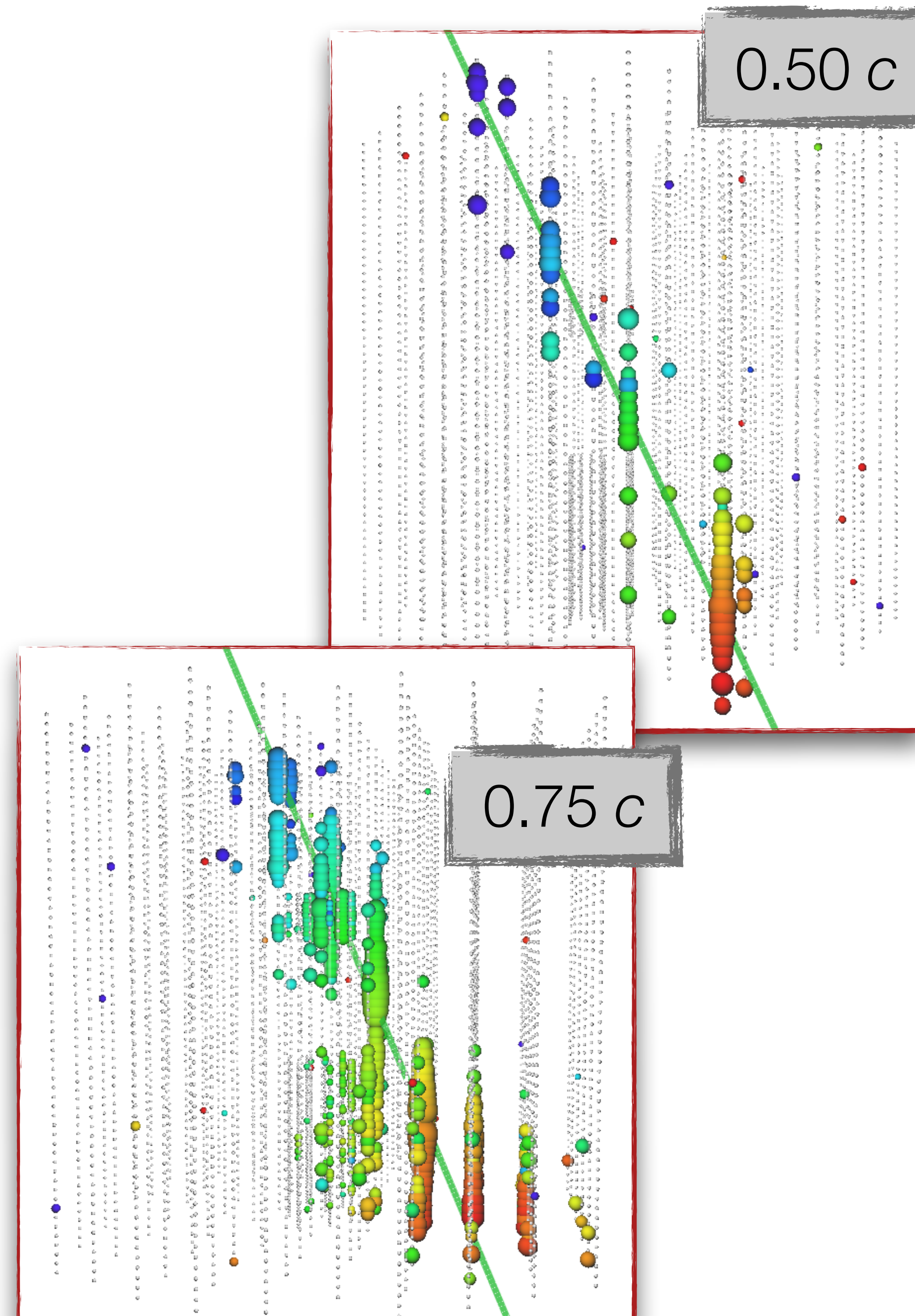
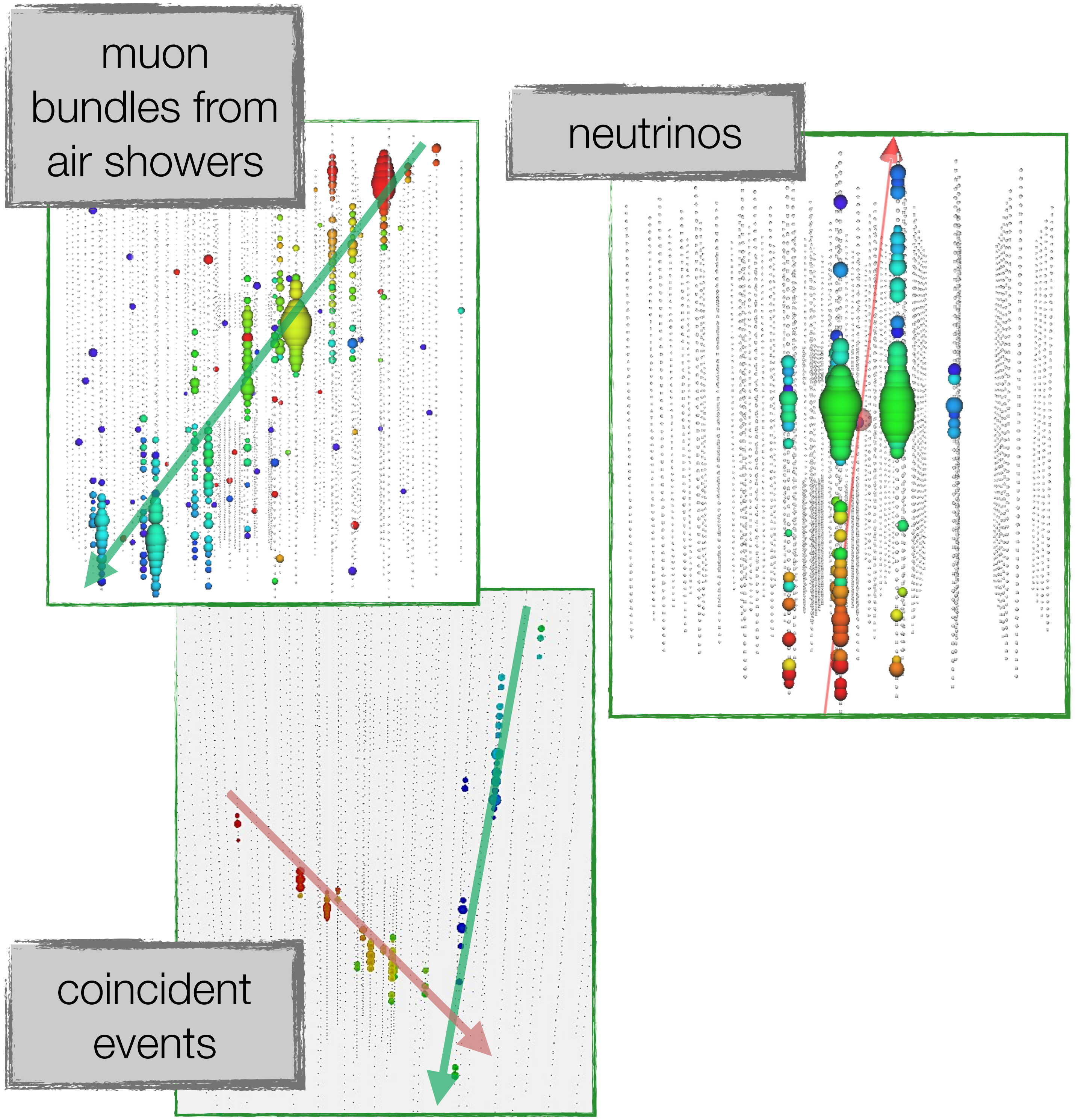


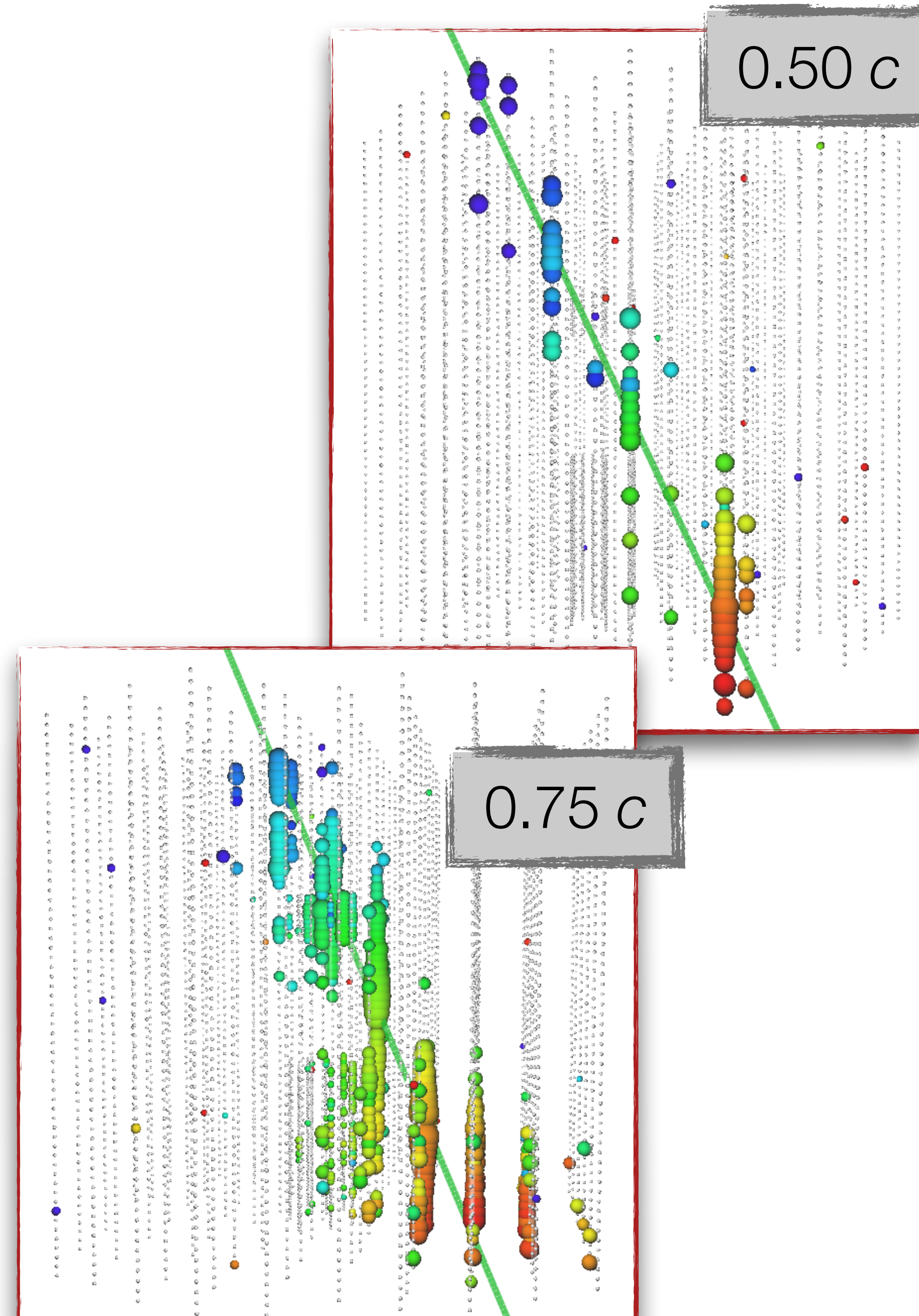
Event signatures in IceCube

EPJ C76 (2016) 133

Background

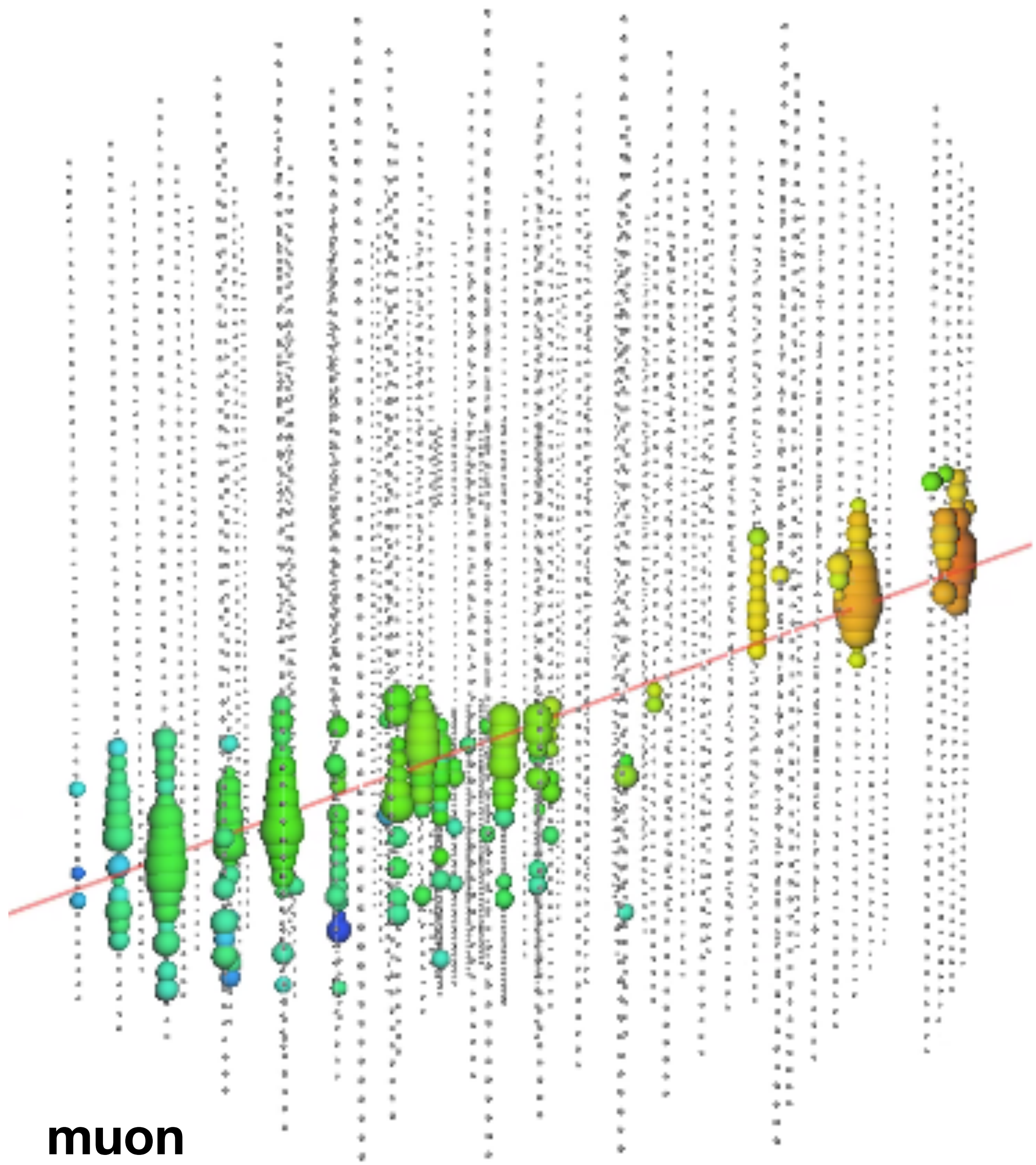


Monopole Signatures in IceCube



Event selection

EPJ C76 (2016) 133



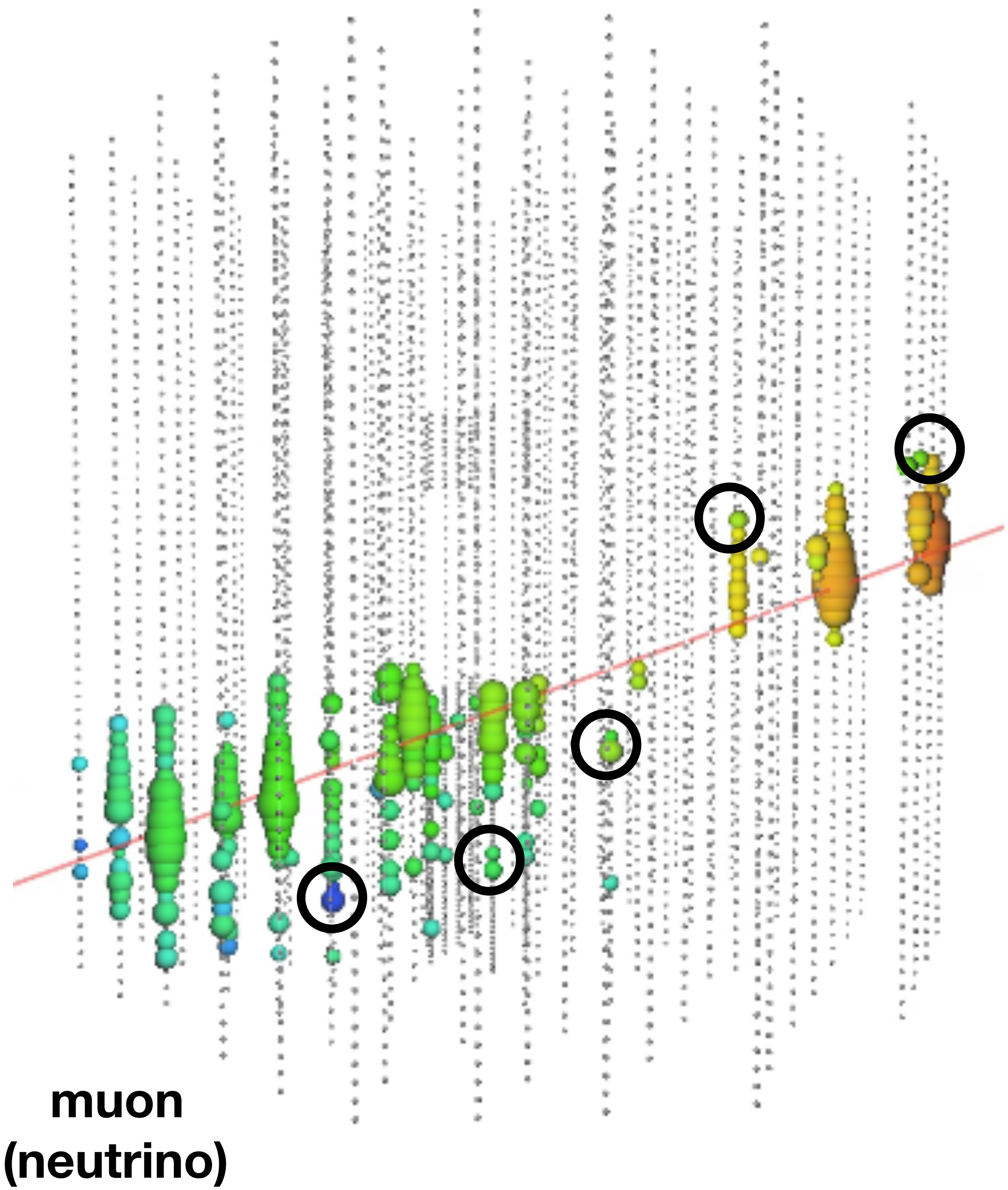
muon (neutrino)

Selection variables

- number of sensors recording a hit
- speed
- direction
- gap within the hits
- …..

Event selection

EPJ C76 (2016) 133



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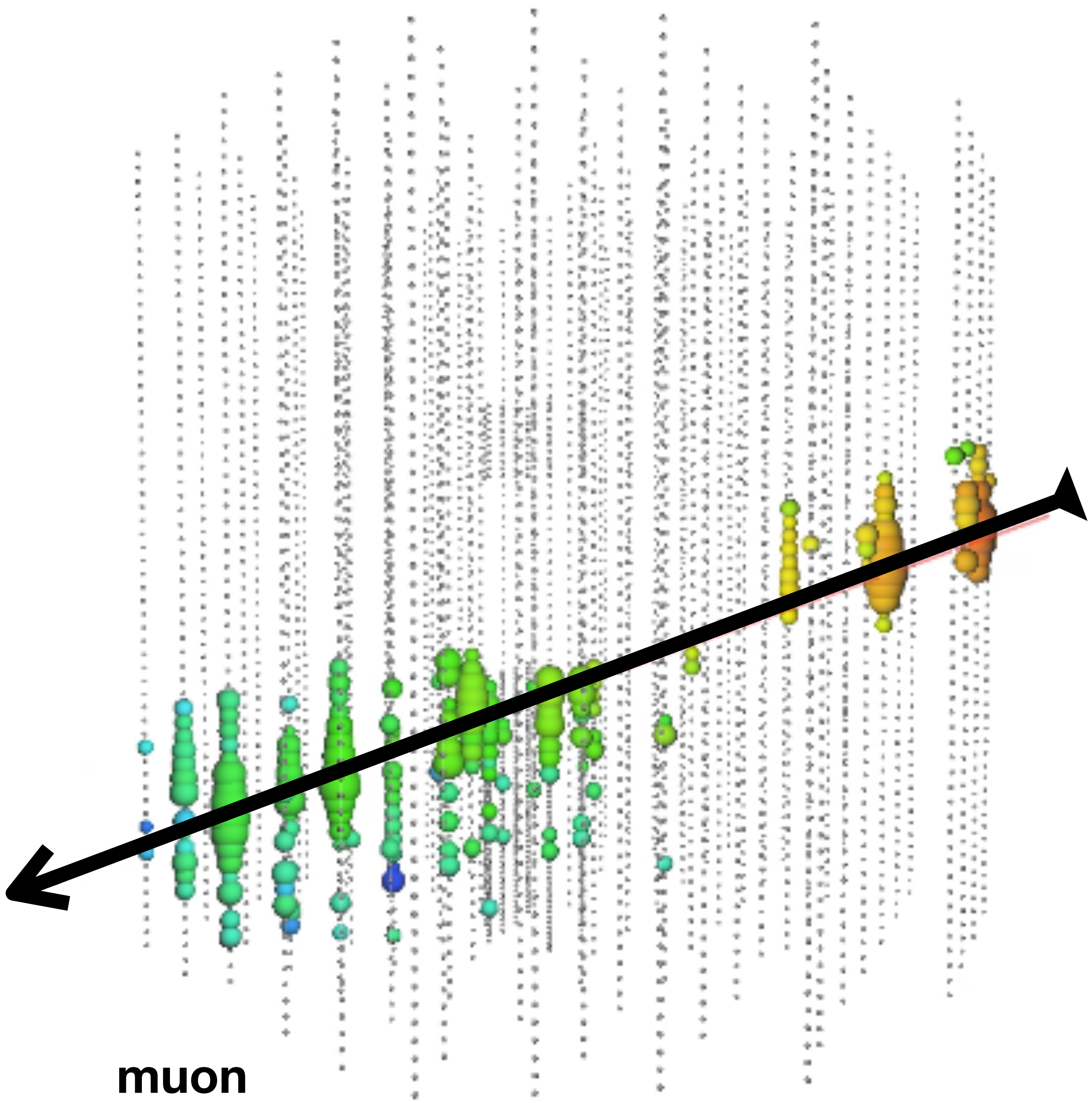
EPJ C76 (2016) 133



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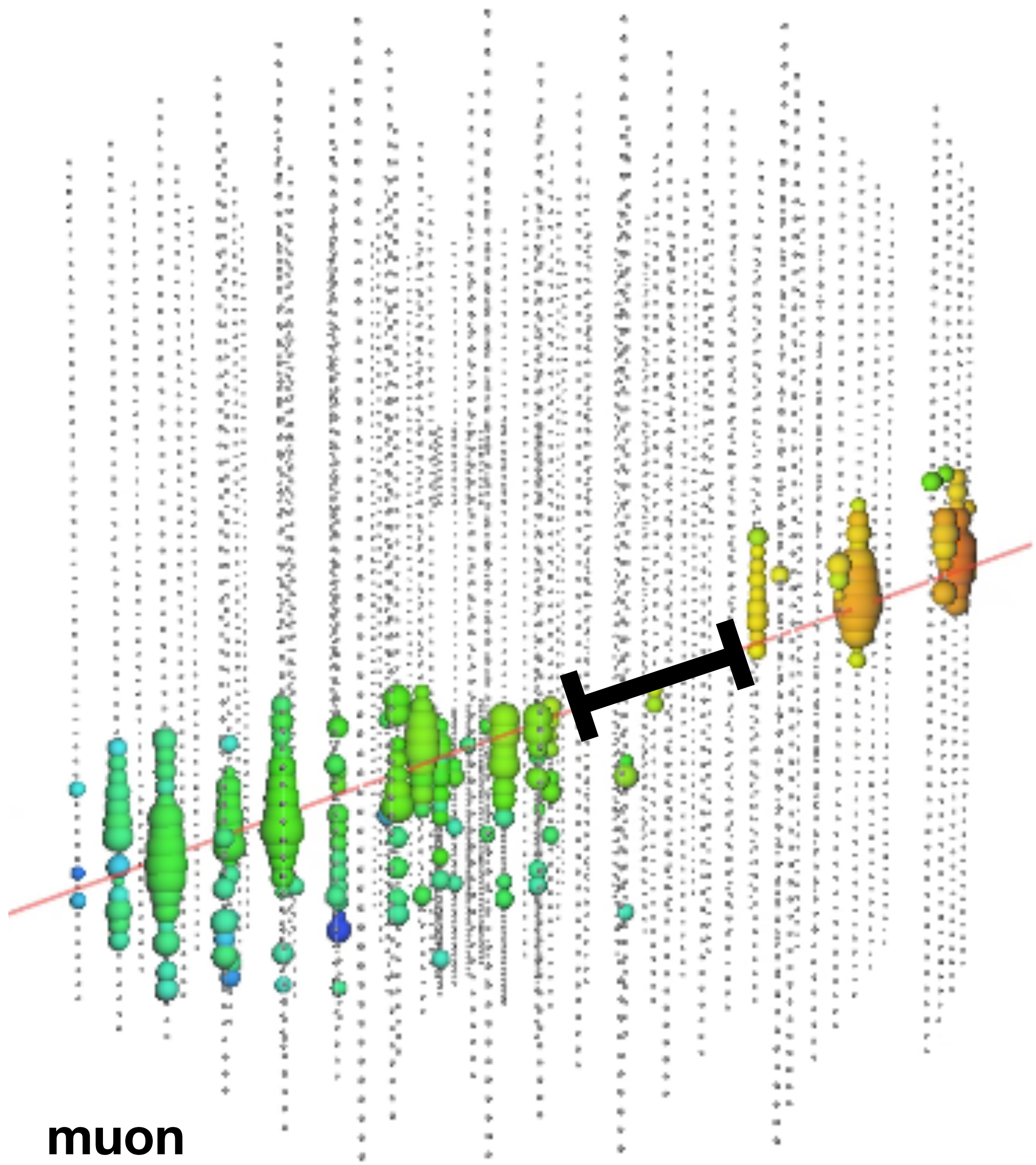
EPJ C76 (2016) 133



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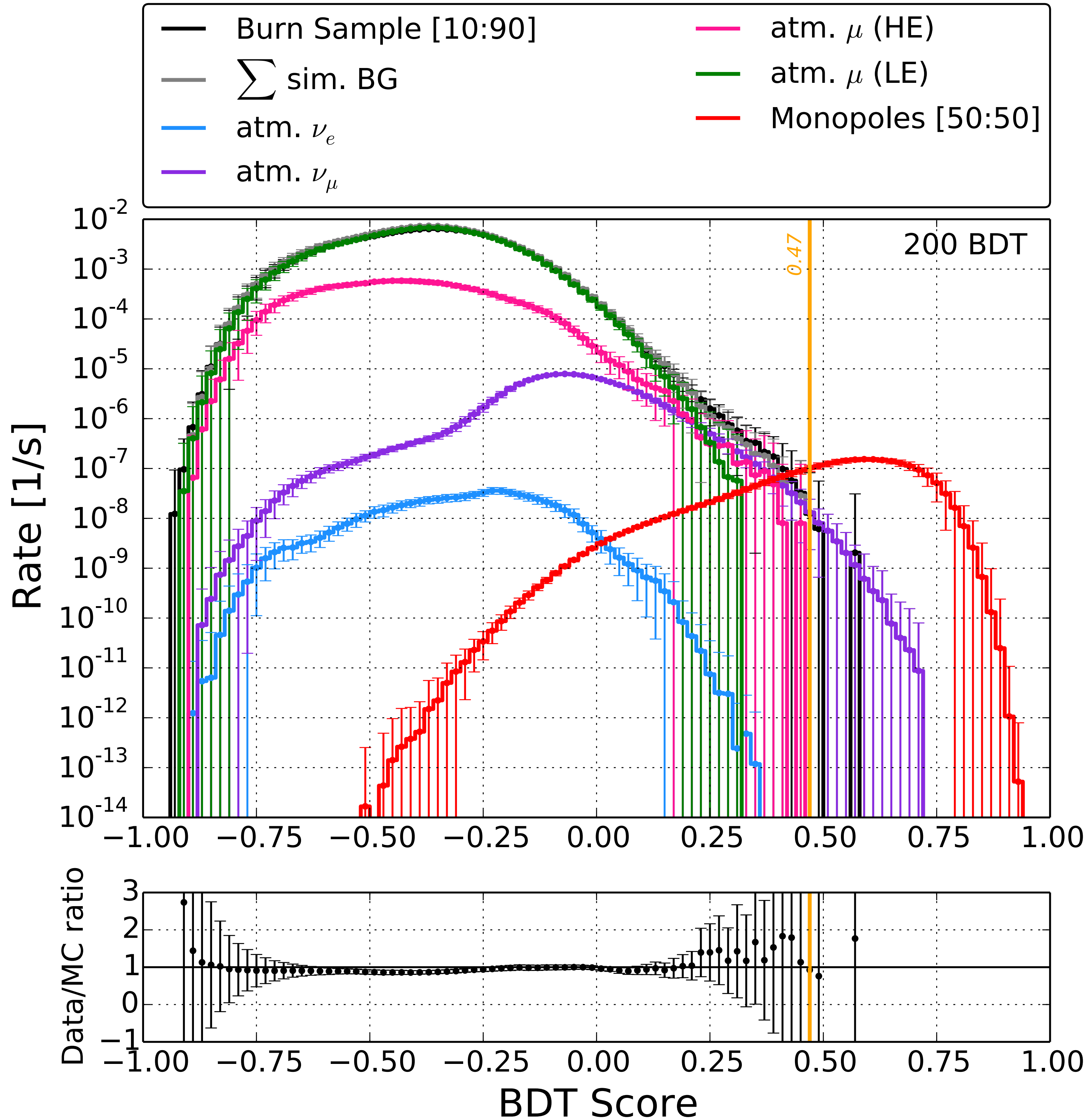
Analysis scheme

EPJ C76 (2016) 133

- simple selection criteria, followed by machine learning
- blind analysis based on background and signal simulation
- background rate of ≤ 3 events / year predicted



Analysis scheme

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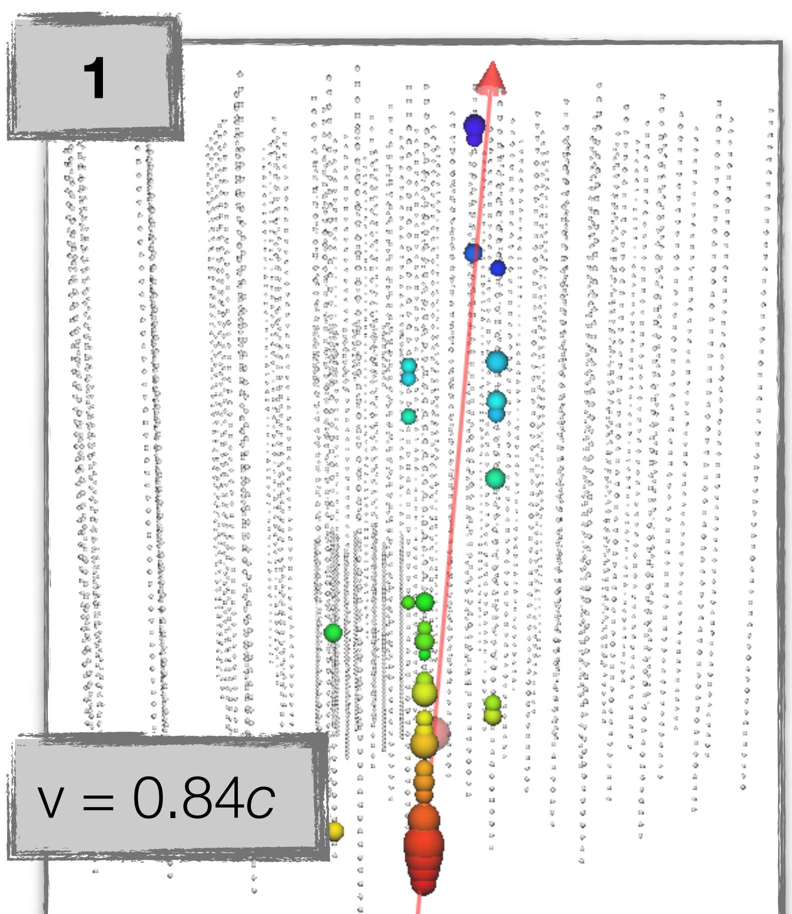
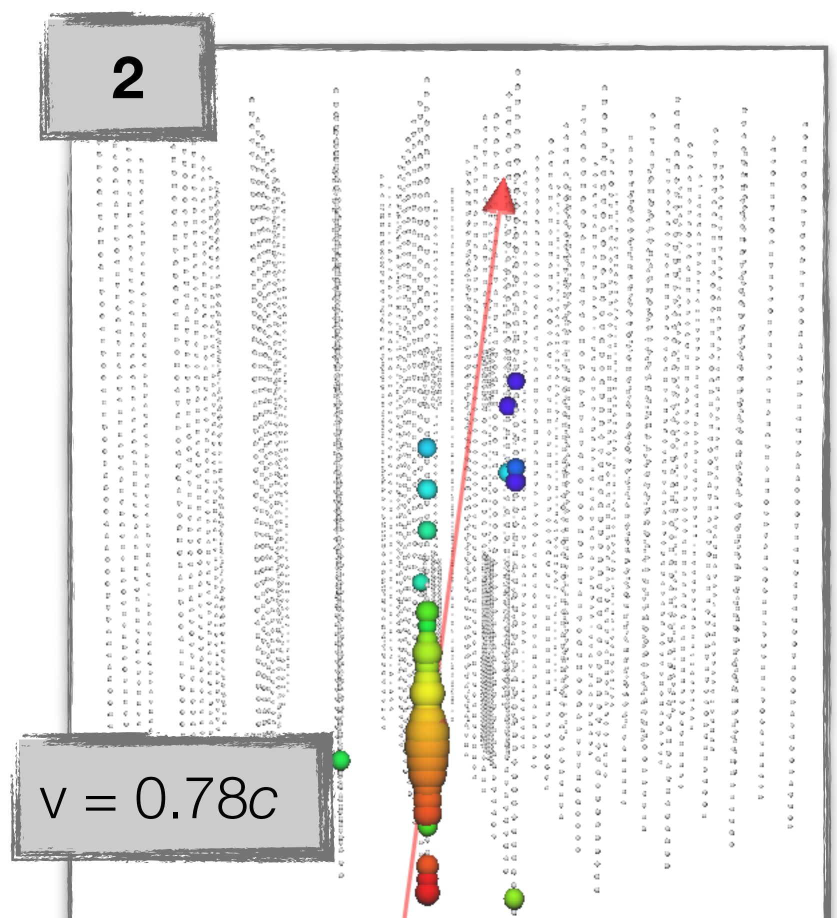
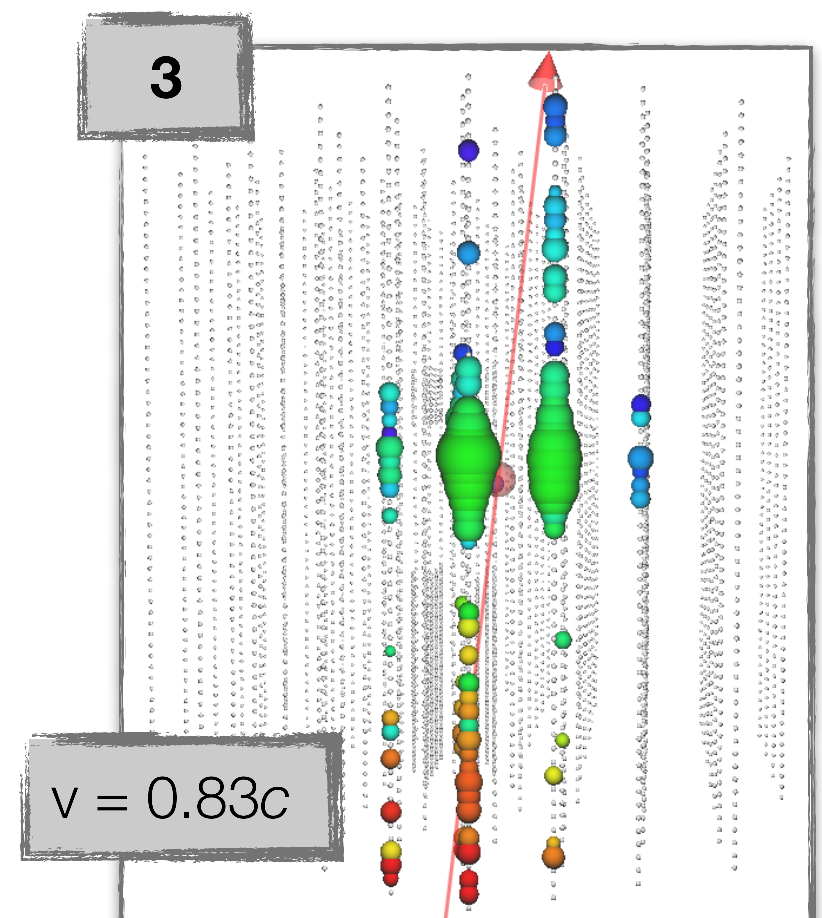
- 1 & 2: obvious background shape -> muon (neutrino)
- 3: too dim







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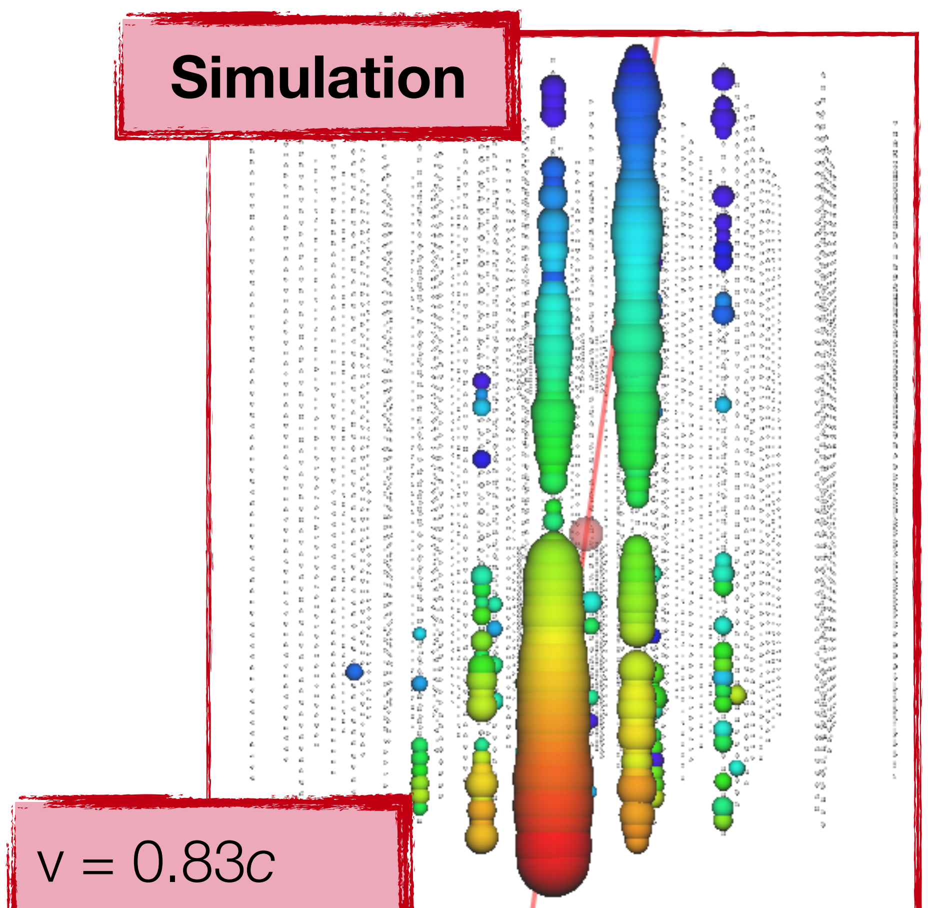
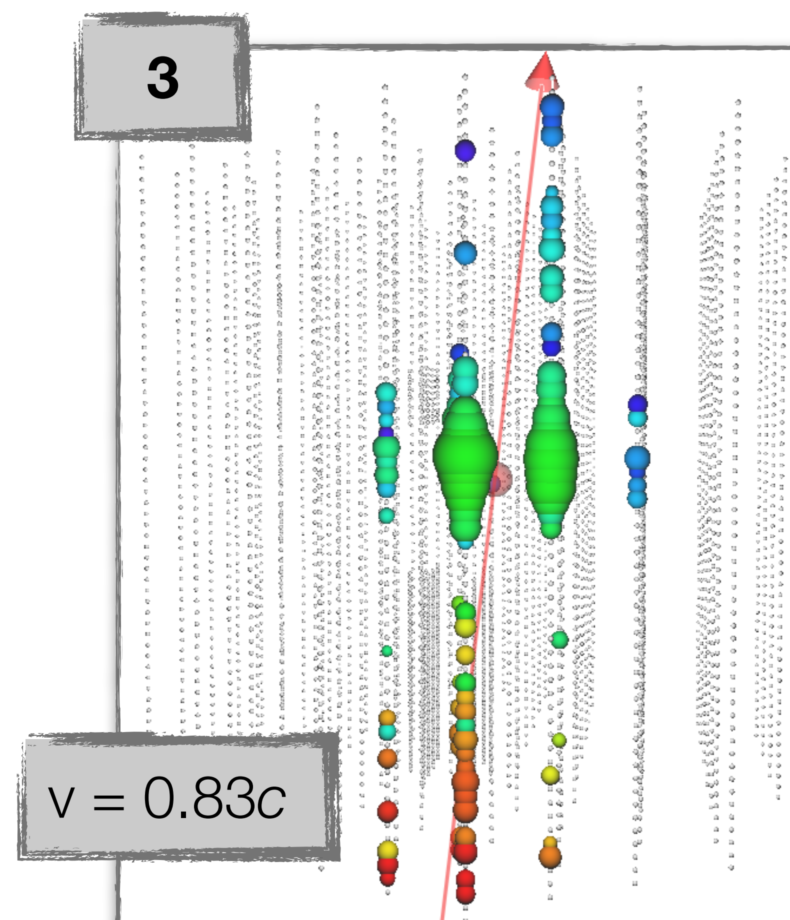
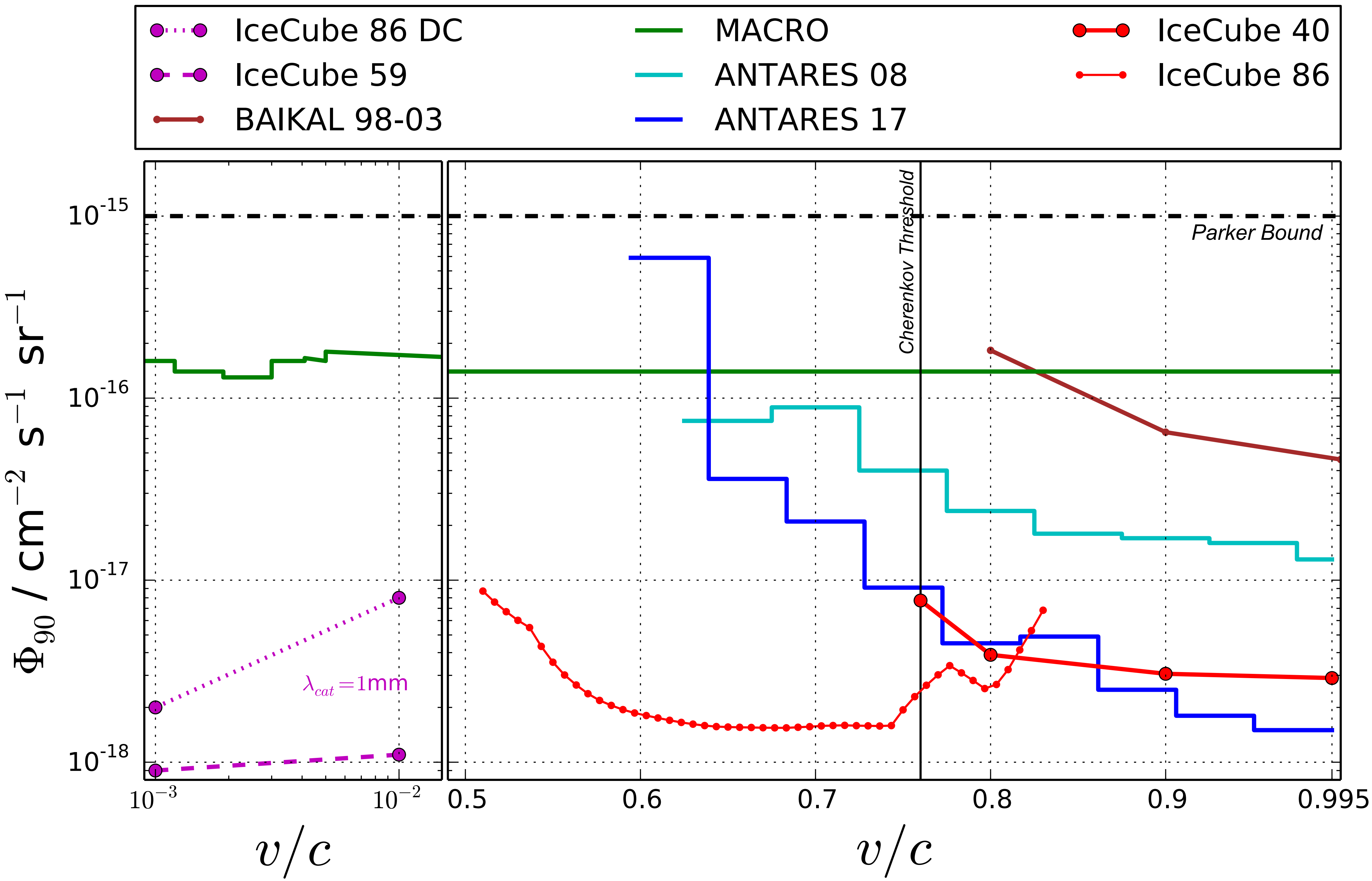




Limits

EPJ C76 (2016) 133



Catalysis of proton decay

Indirect Cherenkov radiation

Direct Cherenkov radiation

Slow monopole interaction

EPJ C74 (2014) 2938

- decay of proton -> electromagnetic cascade
- depends on the gauge group, only for massive MM
- speed dependent cross section

  $\sigma_{CAT} = \sigma_0 / \beta$

  theoretical estimation

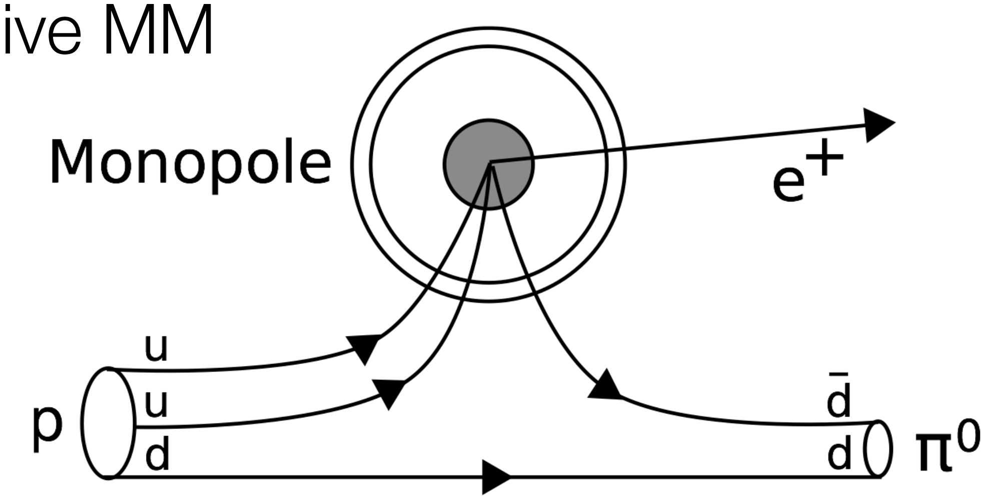
  $10^{-21}\,\mathrm{cm}^2 \leqq \sigma_{CAT} \leqq 10^{-27}\,\mathrm{cm}^2$

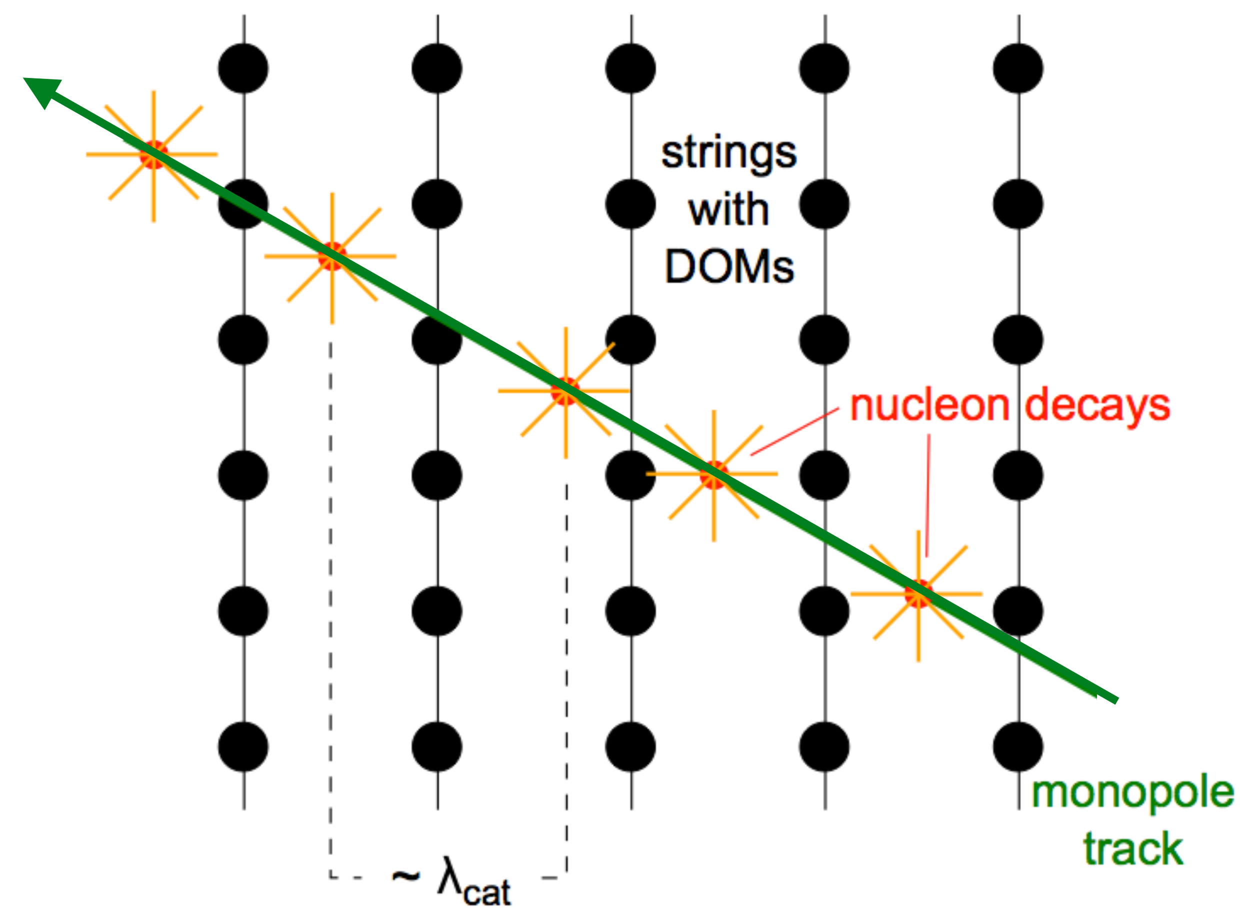
- free mean path $\lambda = 1 / \sigma_{CAT}$
- IceCube: $10^{-3} \leqq \beta \leqq 10^{-2}$
- typical event length

  ~ milli seconds

- PMT noise and muons

  as background





Slow monopole signature

EPJ C74 (2014) 2938

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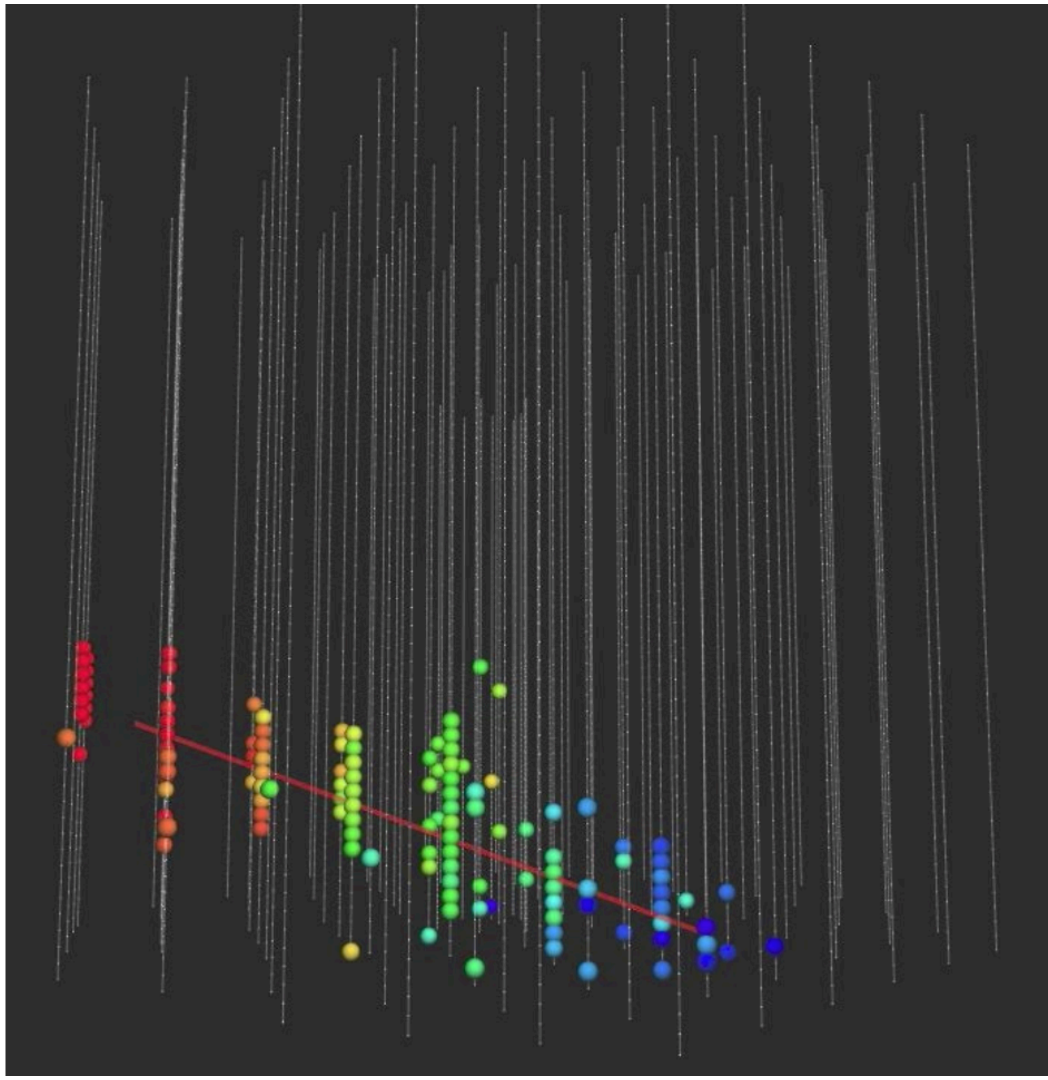
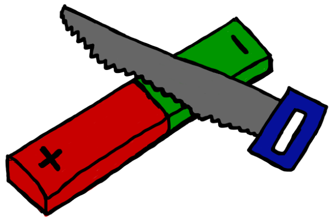
Monopole signal



Slow monopole signature

EPJ C74 (2014) 2938



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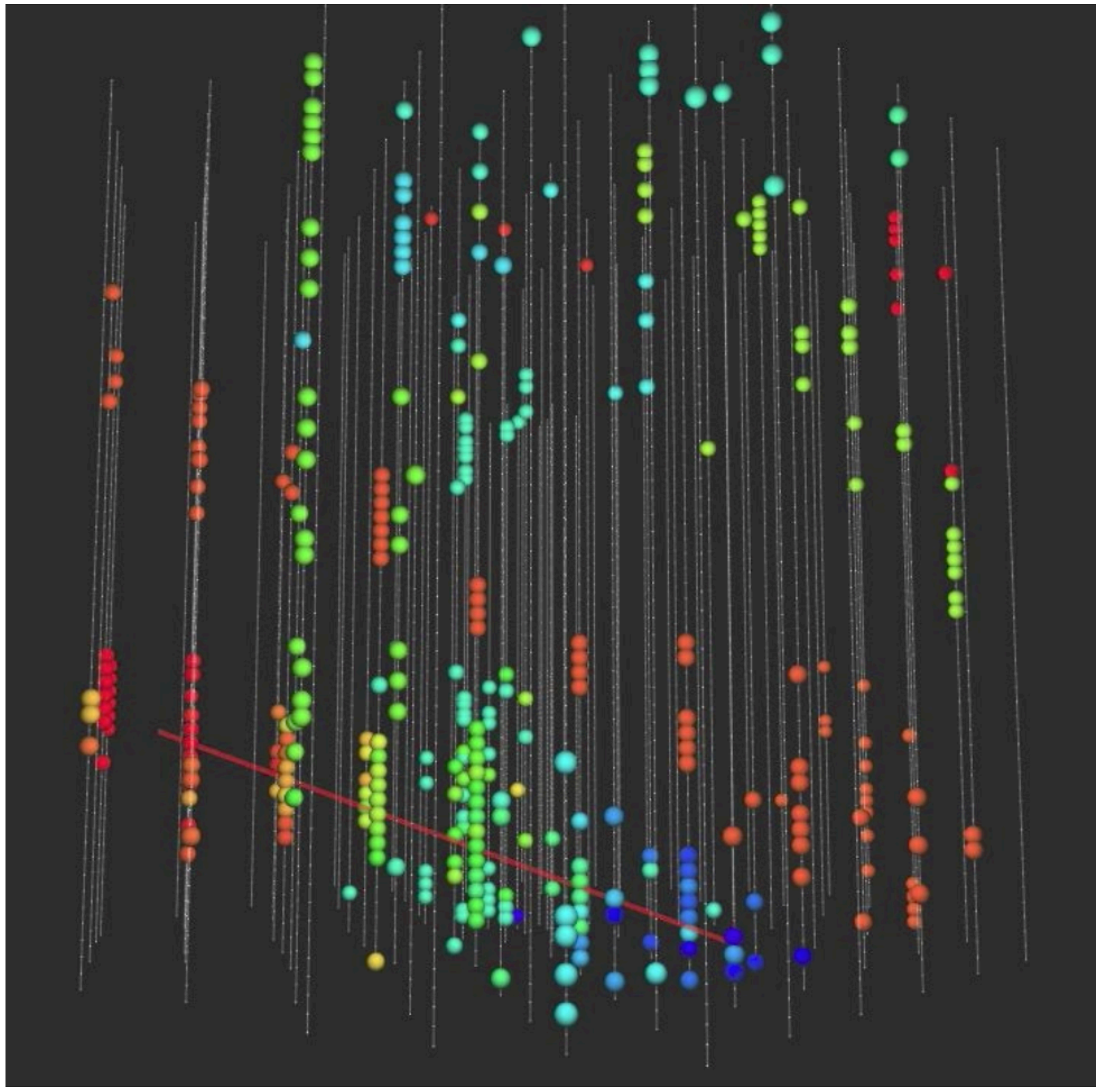
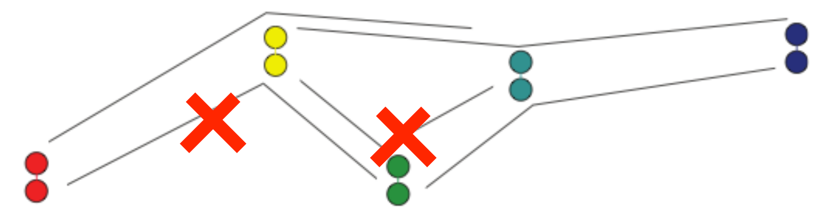
Monopole signal +
Air shower



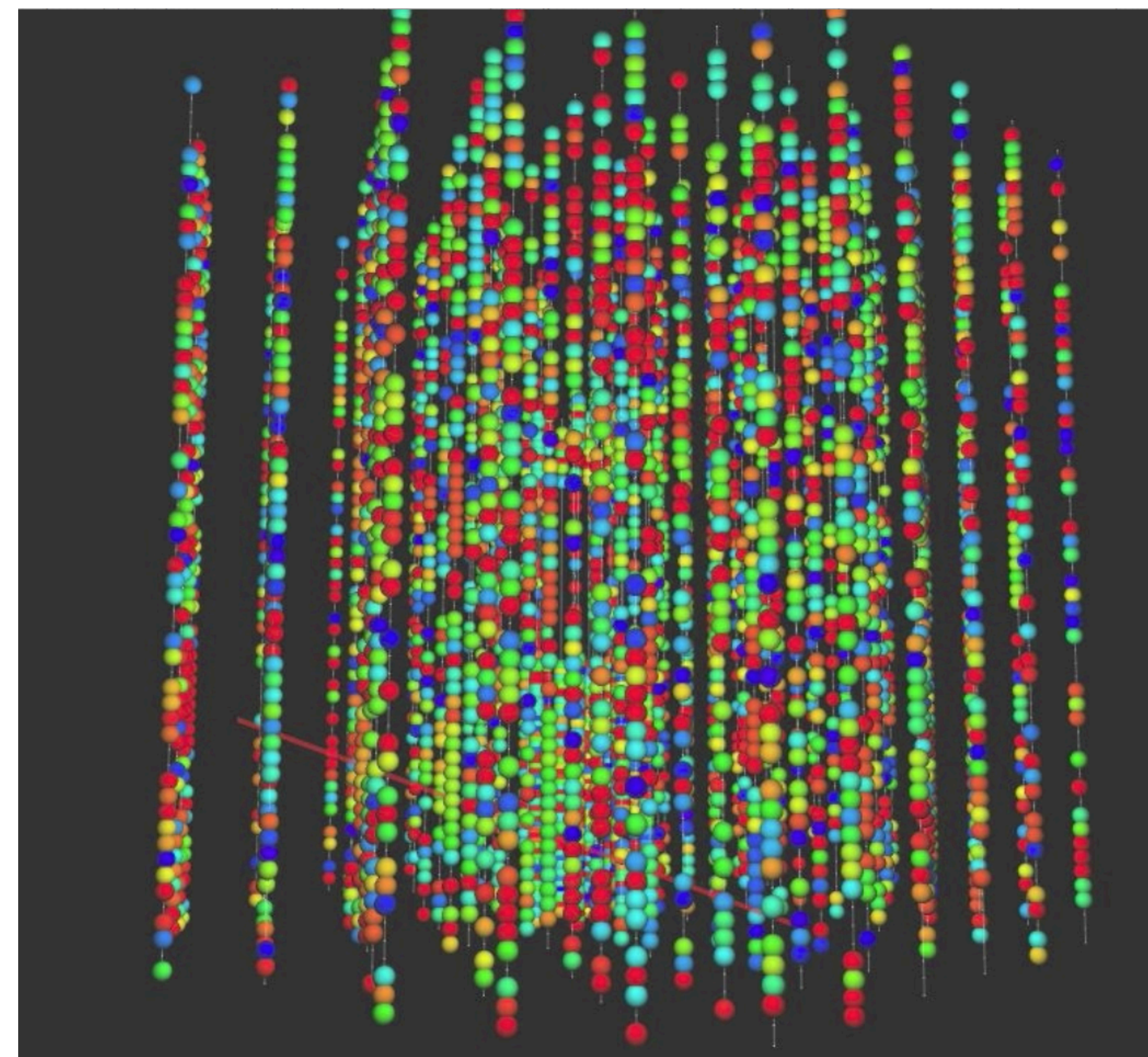
Slow monopole signature

EPJ C74 (2014) 2938

- reconstruction: search for independent local coincidences
- triplets are 3 pairs of hits fulfilling certain conditions
  - duration
  - angle
  - speed
- event selection: triplets should be consistent with a straight particle track



Monopole signal +
Air shower + Noise



Slow monopole signature

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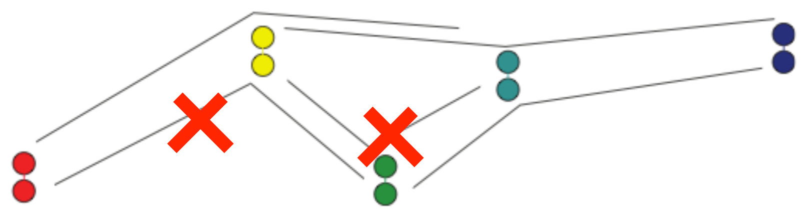
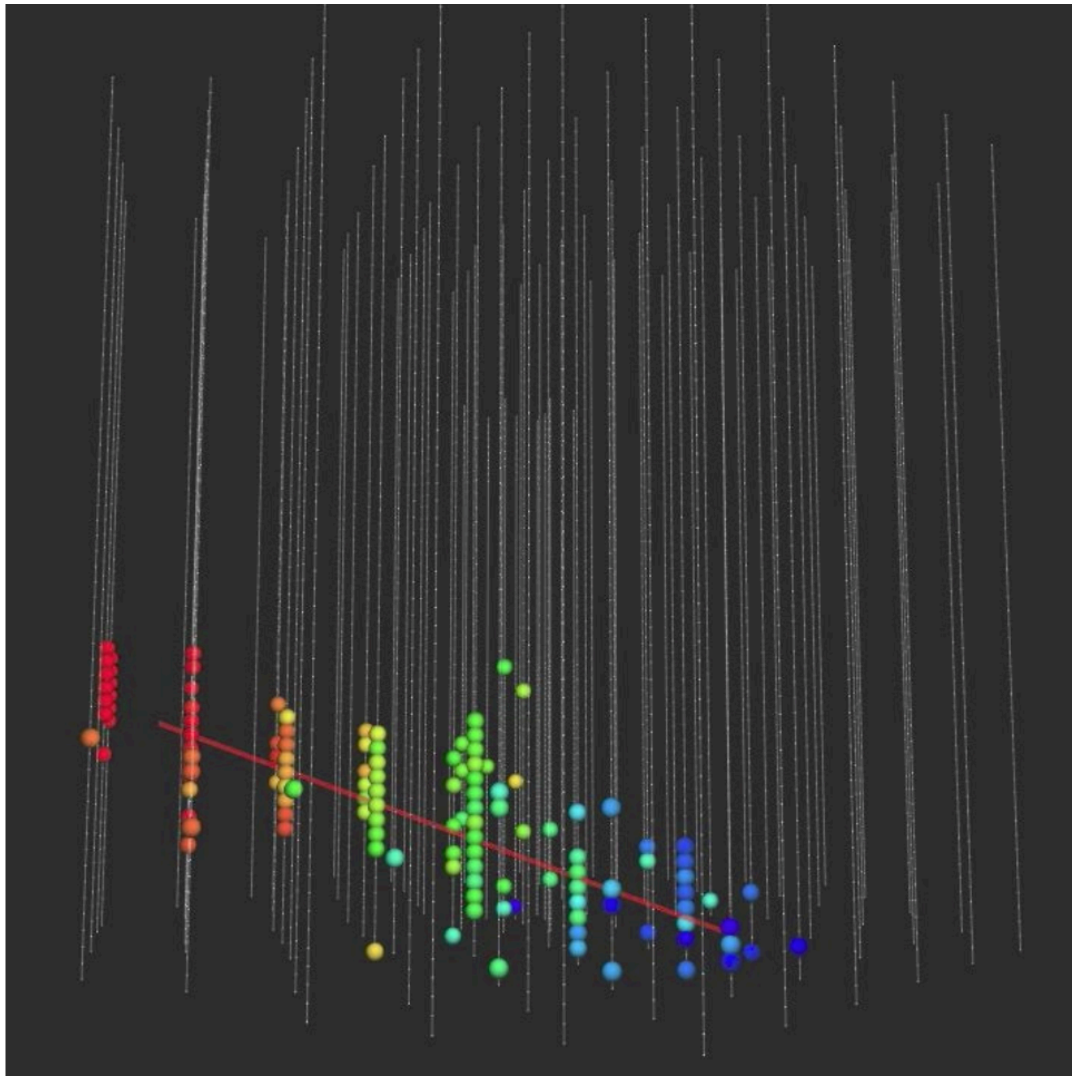


Reconstructed monopole signal



Slow monopole signature

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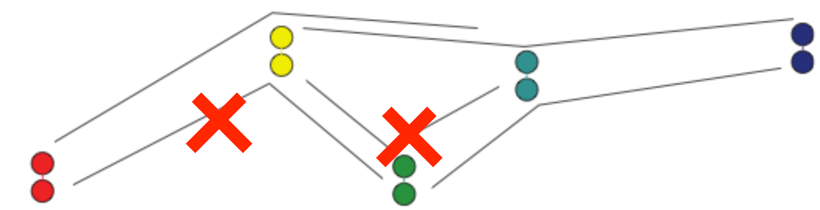
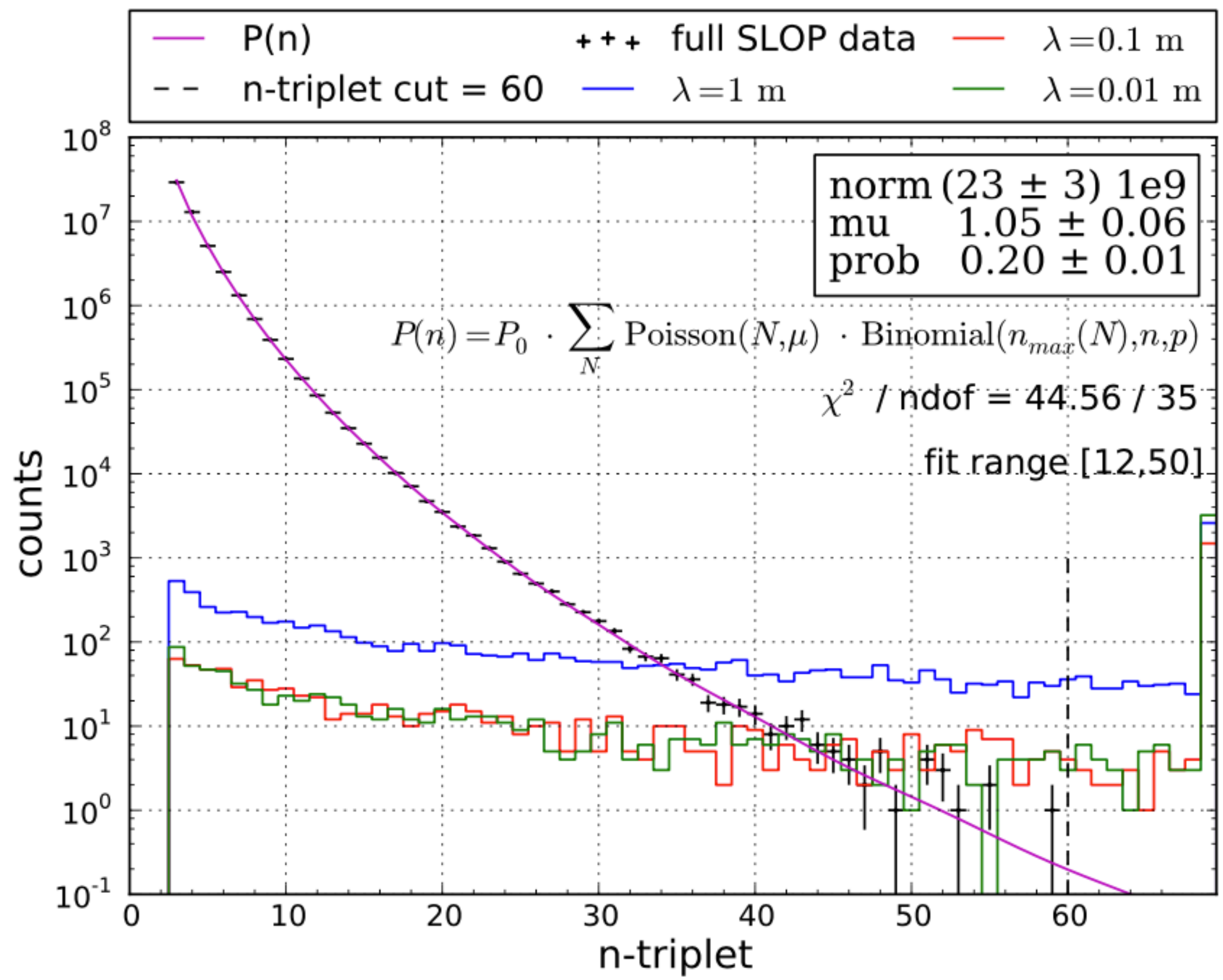
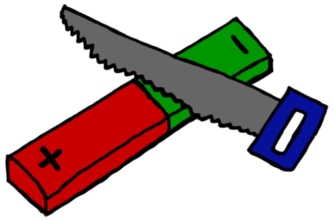




Slow monopole signature

ArXiv: 1309:7007



- reconstruction: search for independent local coincidences
- triplets are 3 pairs of hits fulfilling certain conditions
    - duration
    - angle
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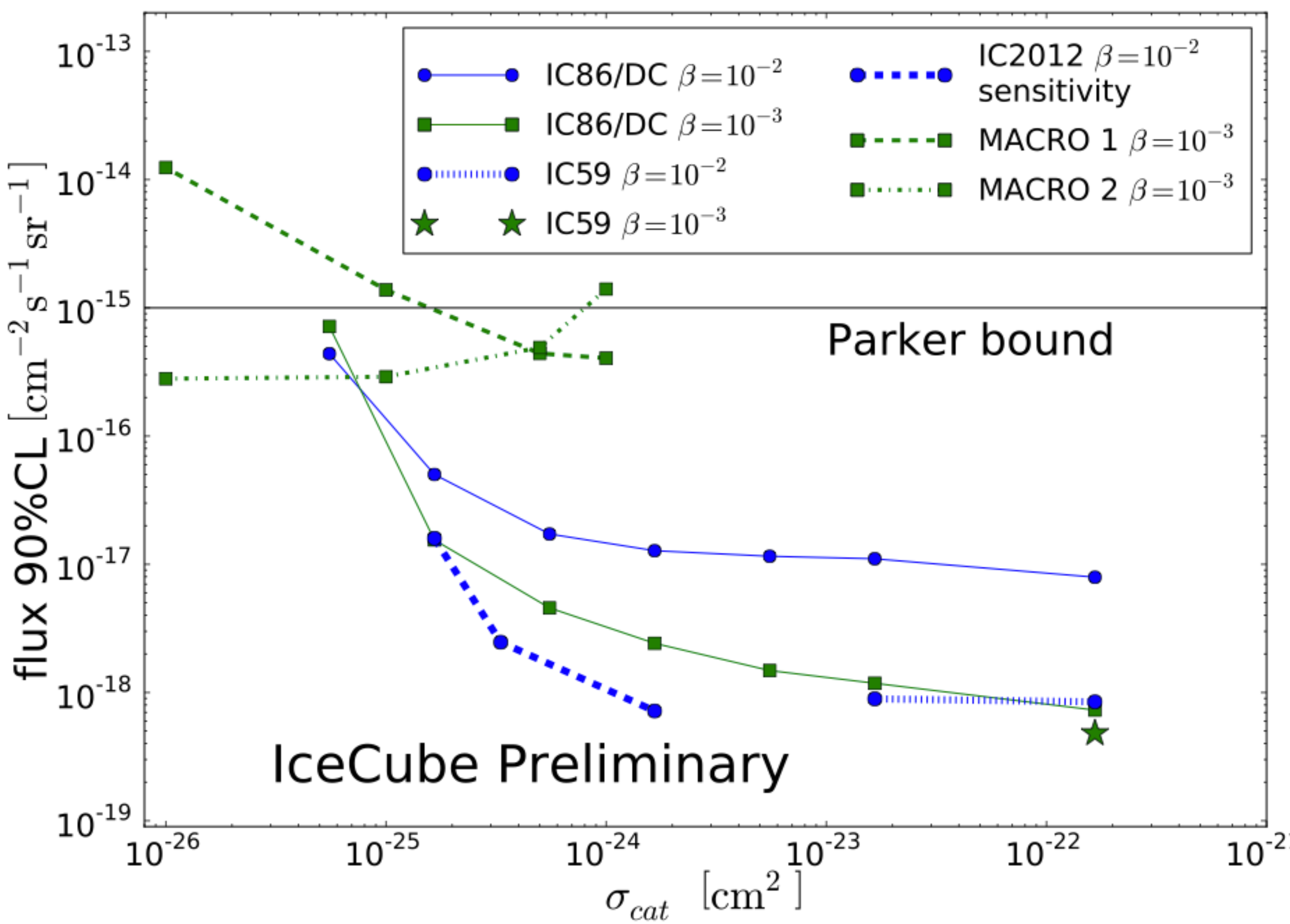
- event selection: triplets should be consistent with a straight particle track

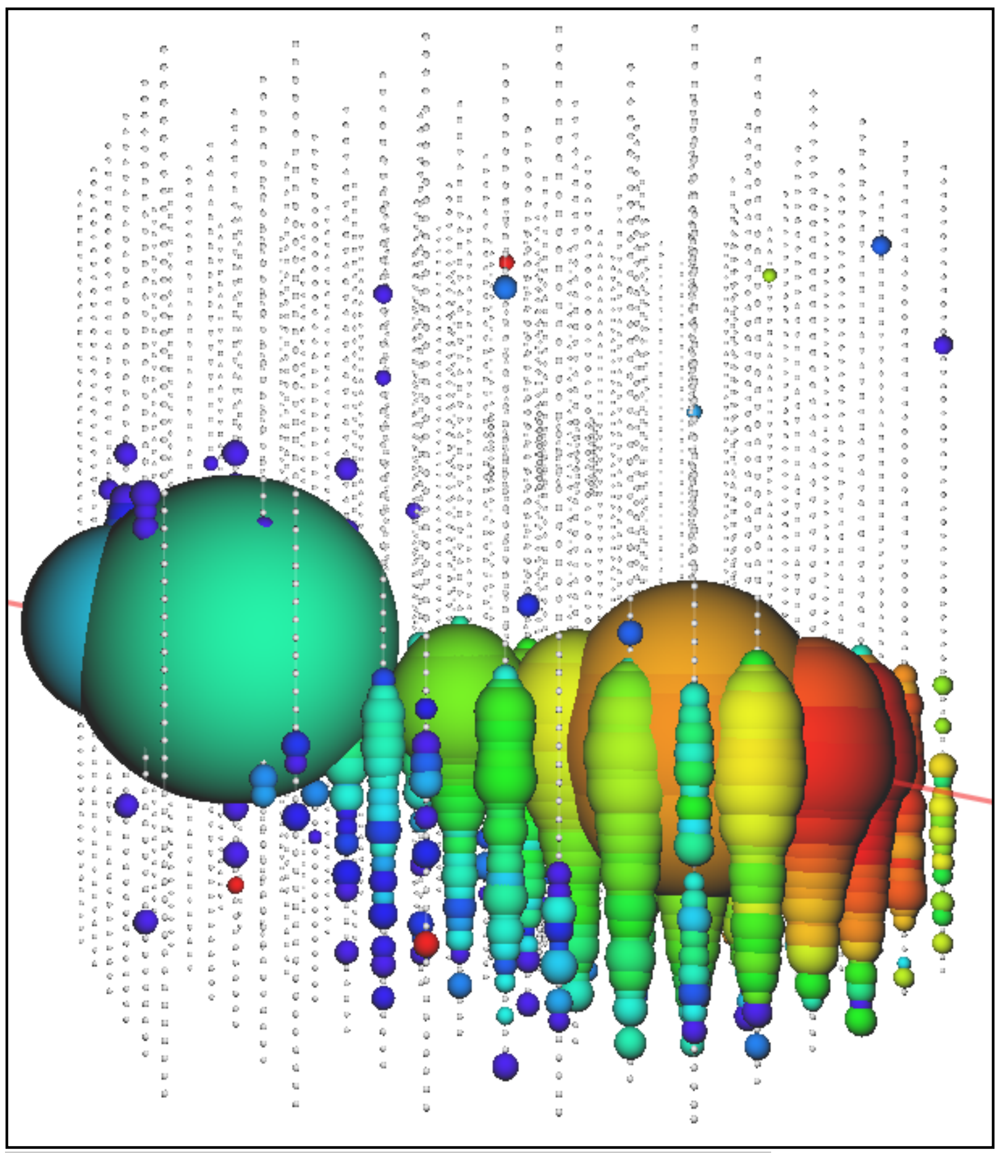
- 1 year of data: 2012/2013
- 5 years available



New search at high speeds

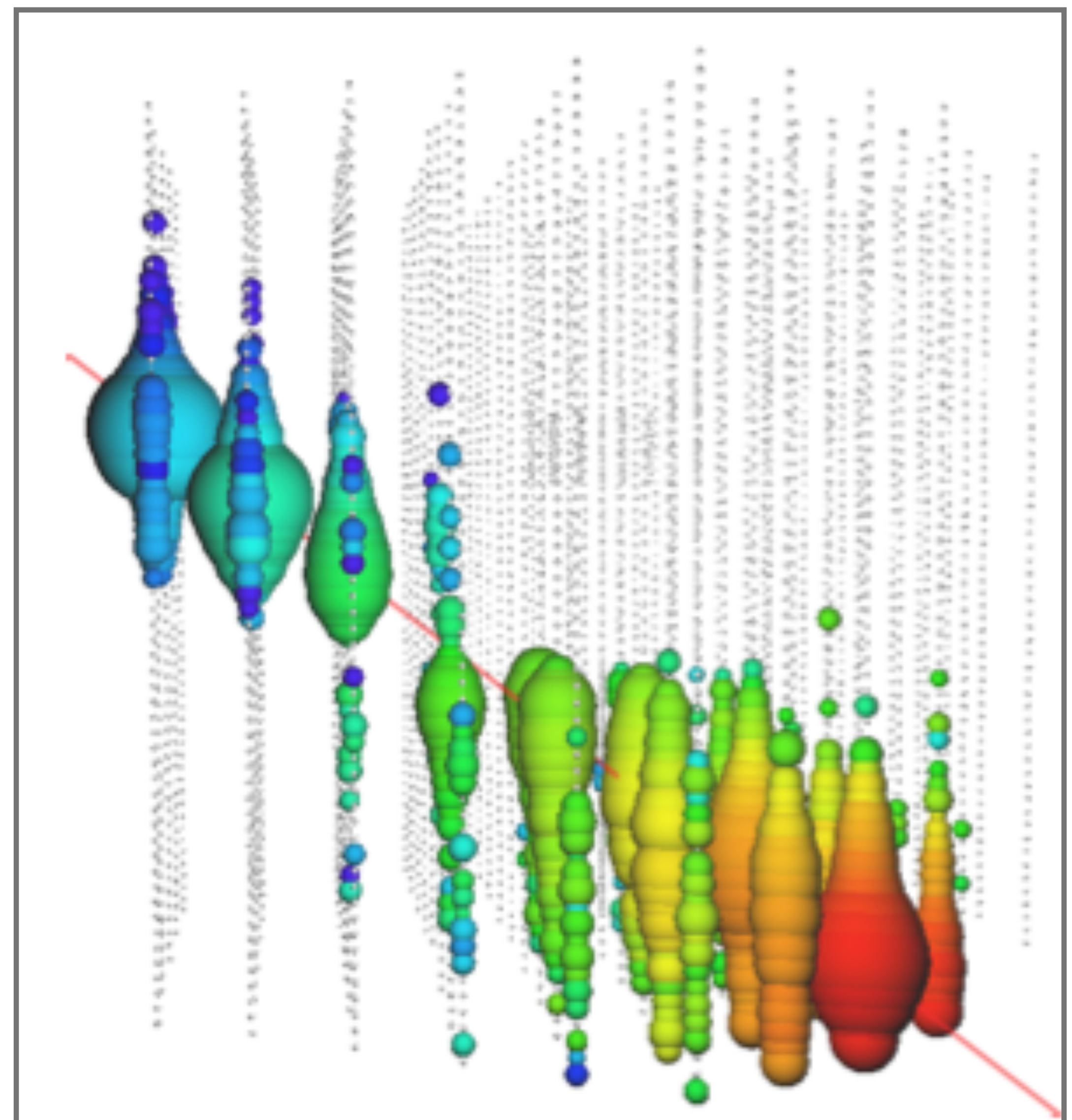
New challenge: distinguish fast monopoles from astrophysical neutrinos

μ-neutrino
2.6 ± 0.3 PeV



Astrophys.J. 833 (2016) 1

Simulation of a monopole
with 0.99 *c*

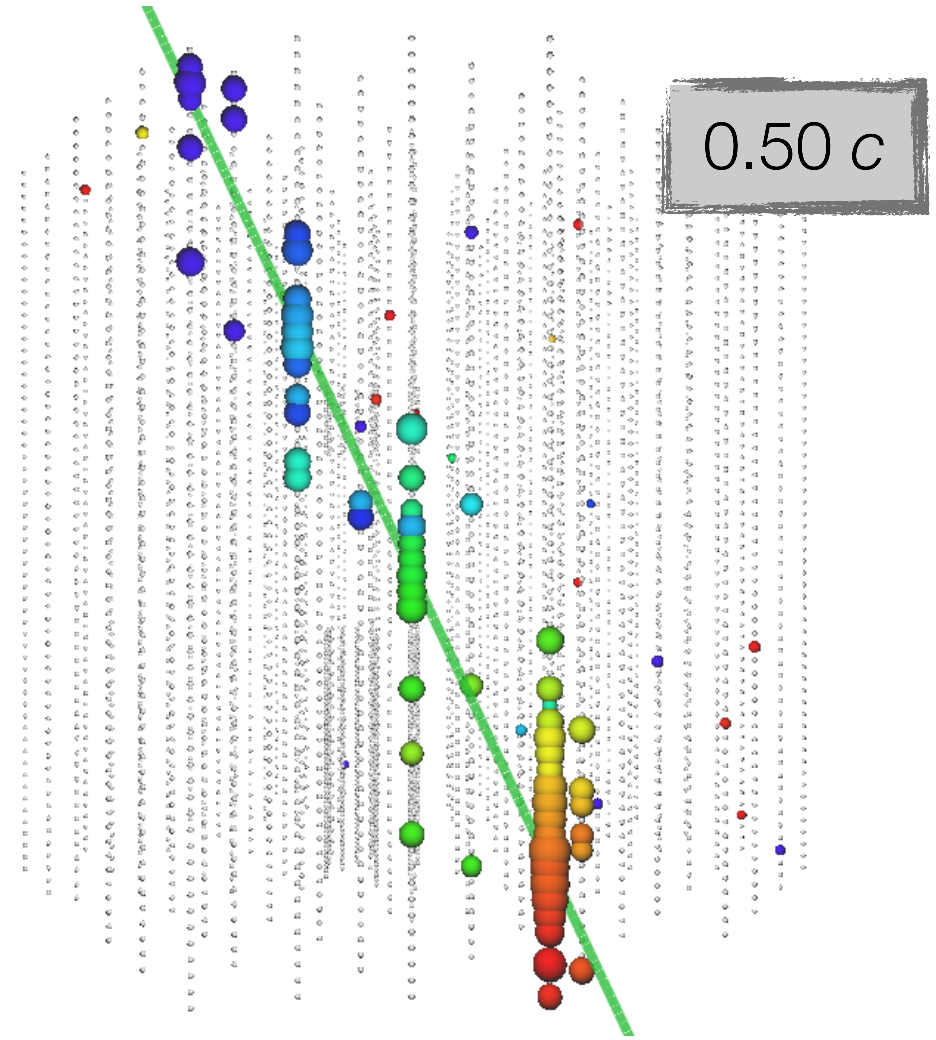


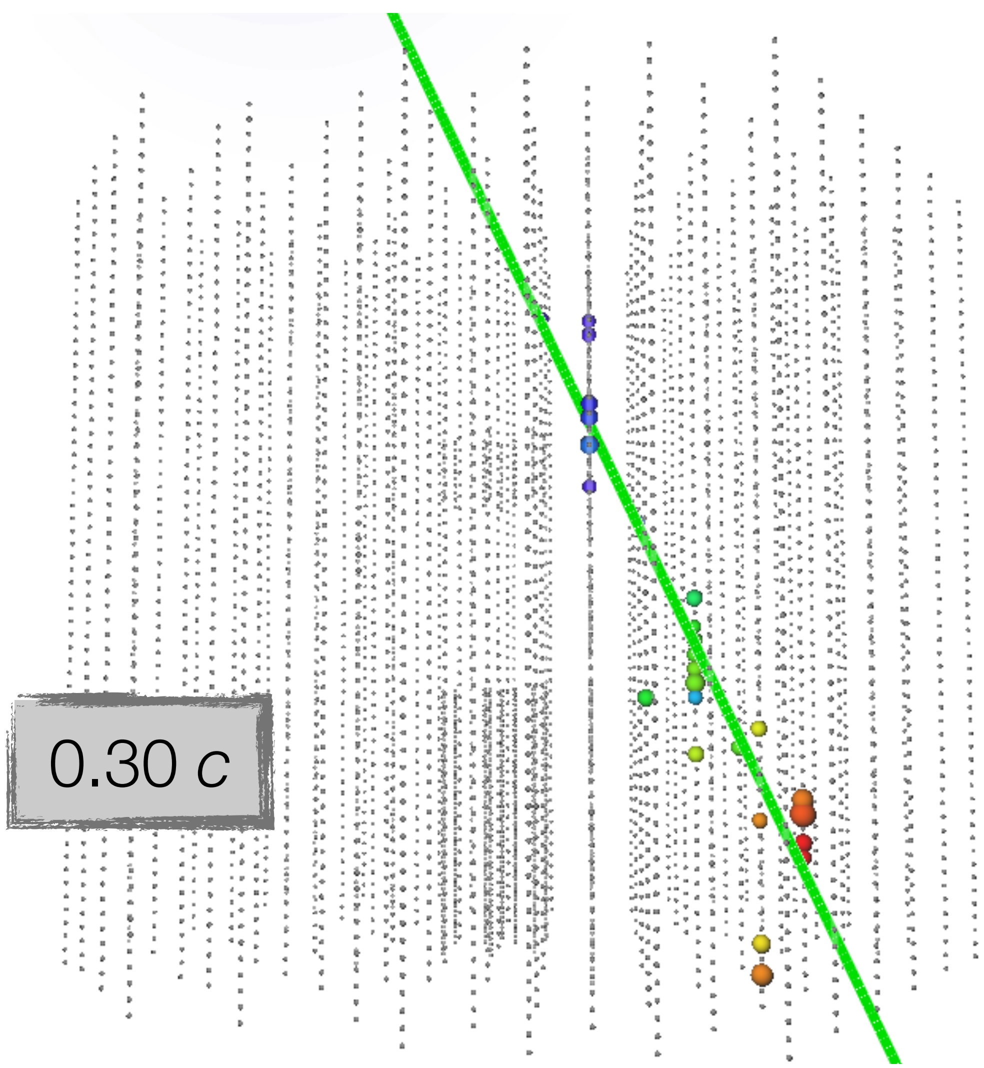
New search at low speeds

Arxiv:1610:06397

Luminescence as new detection method:

- isotropic light emission after electronic excitation
- experimental measurement of light yield





- data taking > 1 year
- enabling new monopole parameter space < 0.5 *c*

Summary

- IceCube's large volume provides best sensitivities to intermediate / high mass magnetic monopoles

- non-relativisitic searches
  10^{13} GeV $\leqq M_{MM} \leqq 10^{19}$ GeV

- relativistic searches
  10^{8} GeV $\leqq M_{MM} \leqq 10^{14}$ GeV

- new searches extending to lower masses

- ongoing analyses at all channels

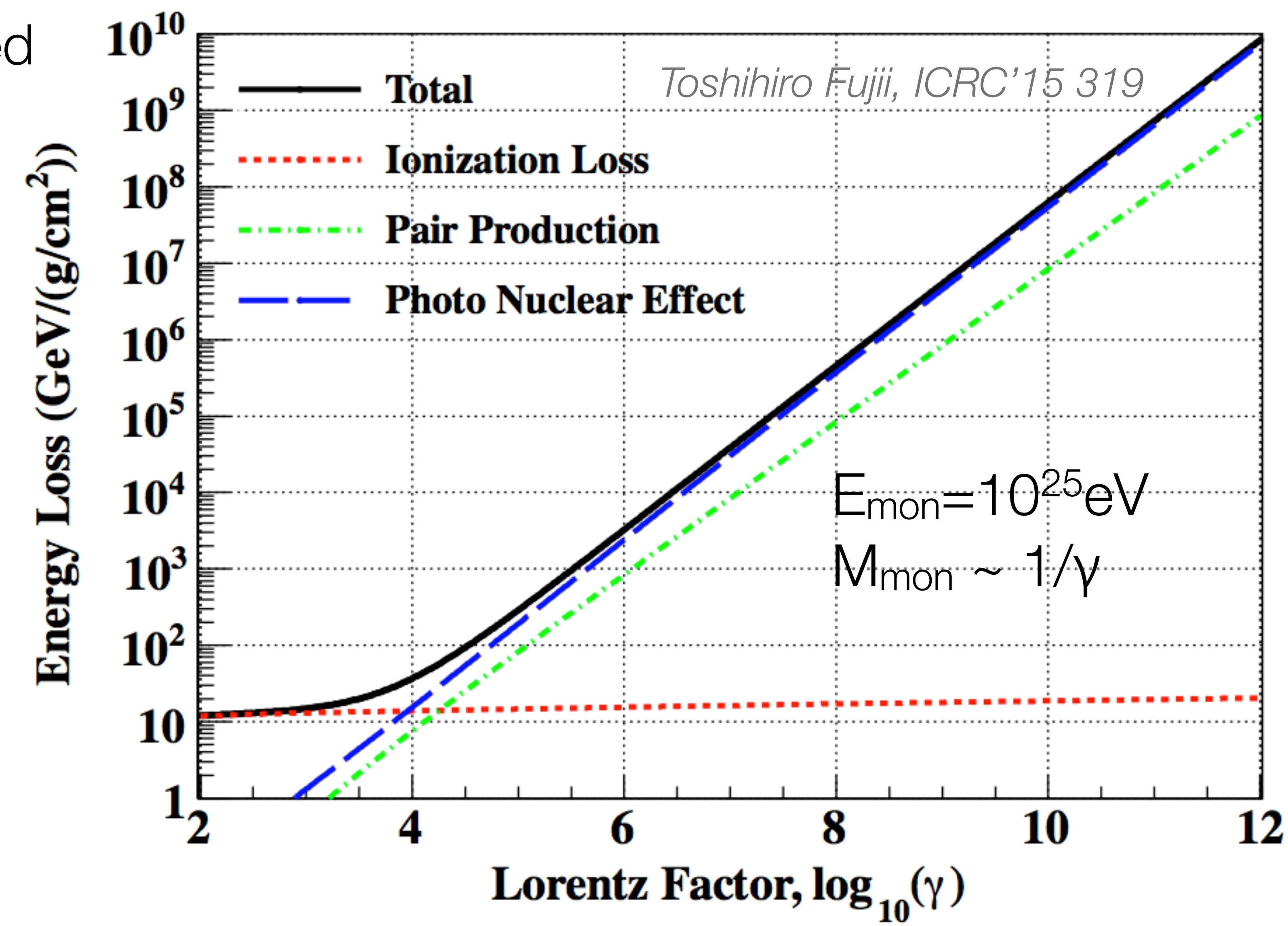
Backup

IceCube - Highly relativistic

- speed distribution instead of distinct speeds
- indirect Cherenkov light included
- challenge: separation from astrophysical neutrinos
- later: ultra relativistic speeds incl. radiative losses from monopoles
- explicit limits for

  $g = n \cdot g_D$

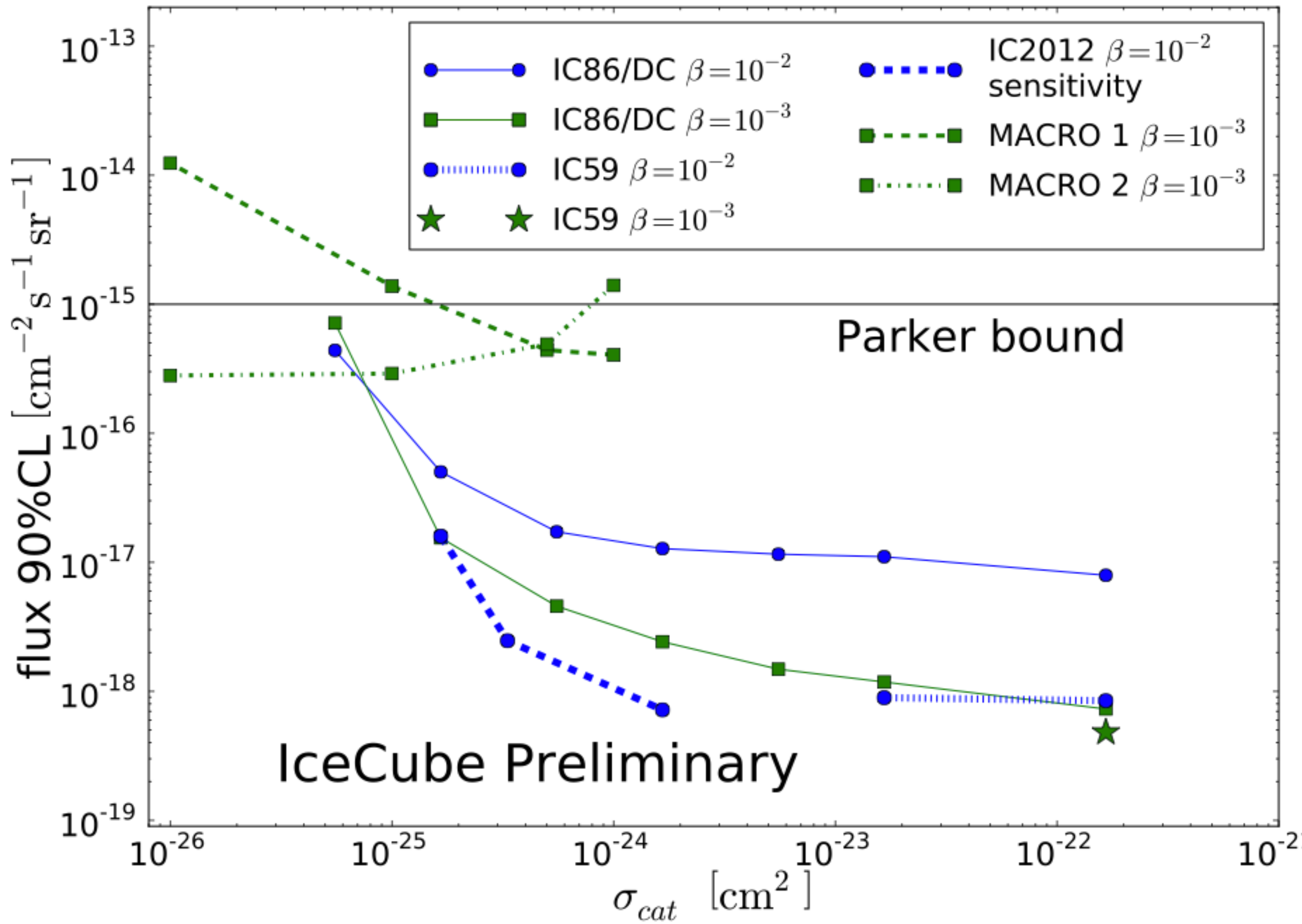
  with
  - $n = 1$: Dirac charge
  - $n = 2$: many GUTs
  - $n = 3$: d instead of e^- as elemental electric charge
  - $n = 6$: Dyons have $2g_D$ (Schwinger)



Sensitivity

ArXiv: 1309:7007

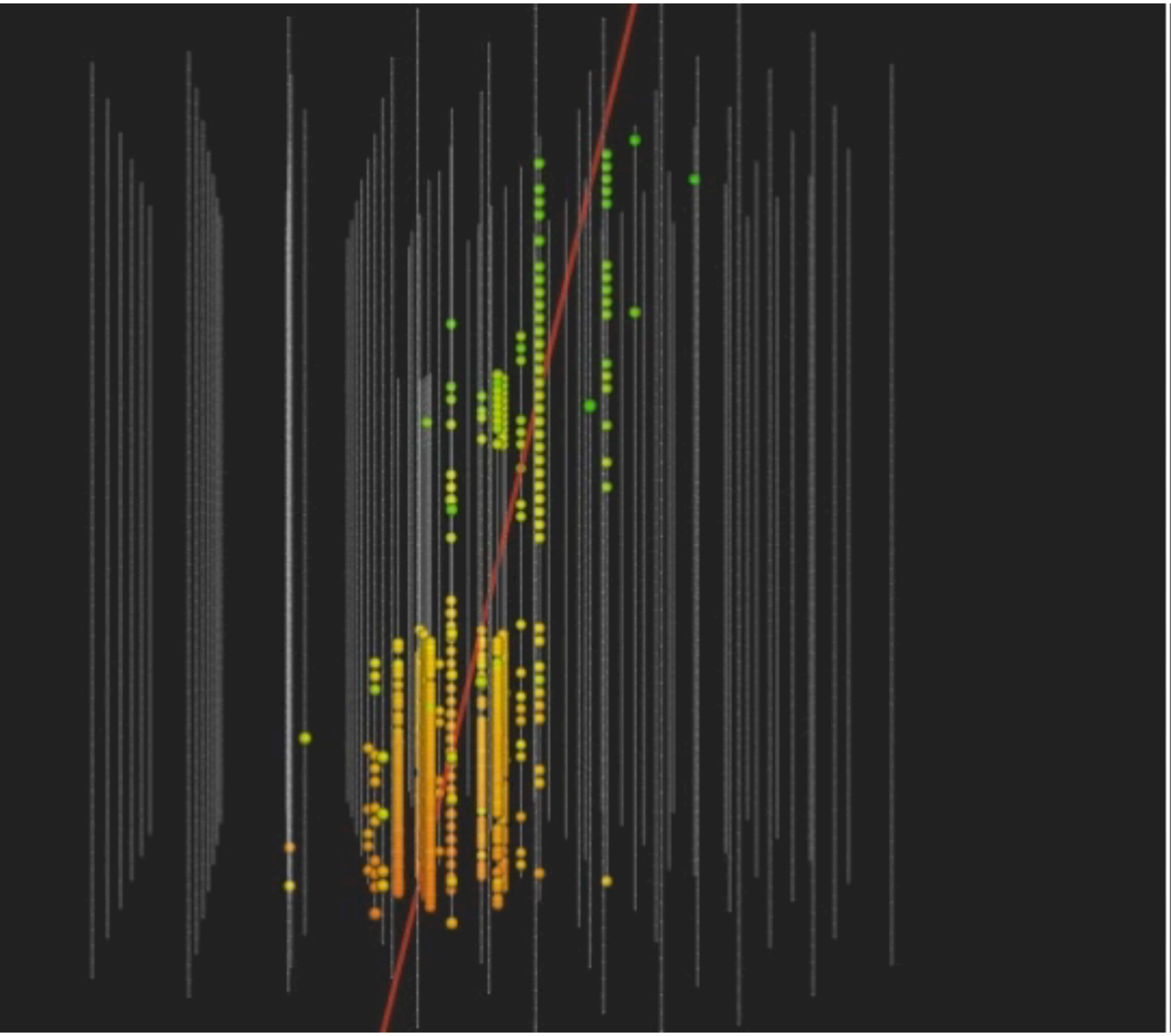
- 1 year of data: 2012/2013
- 4 years available

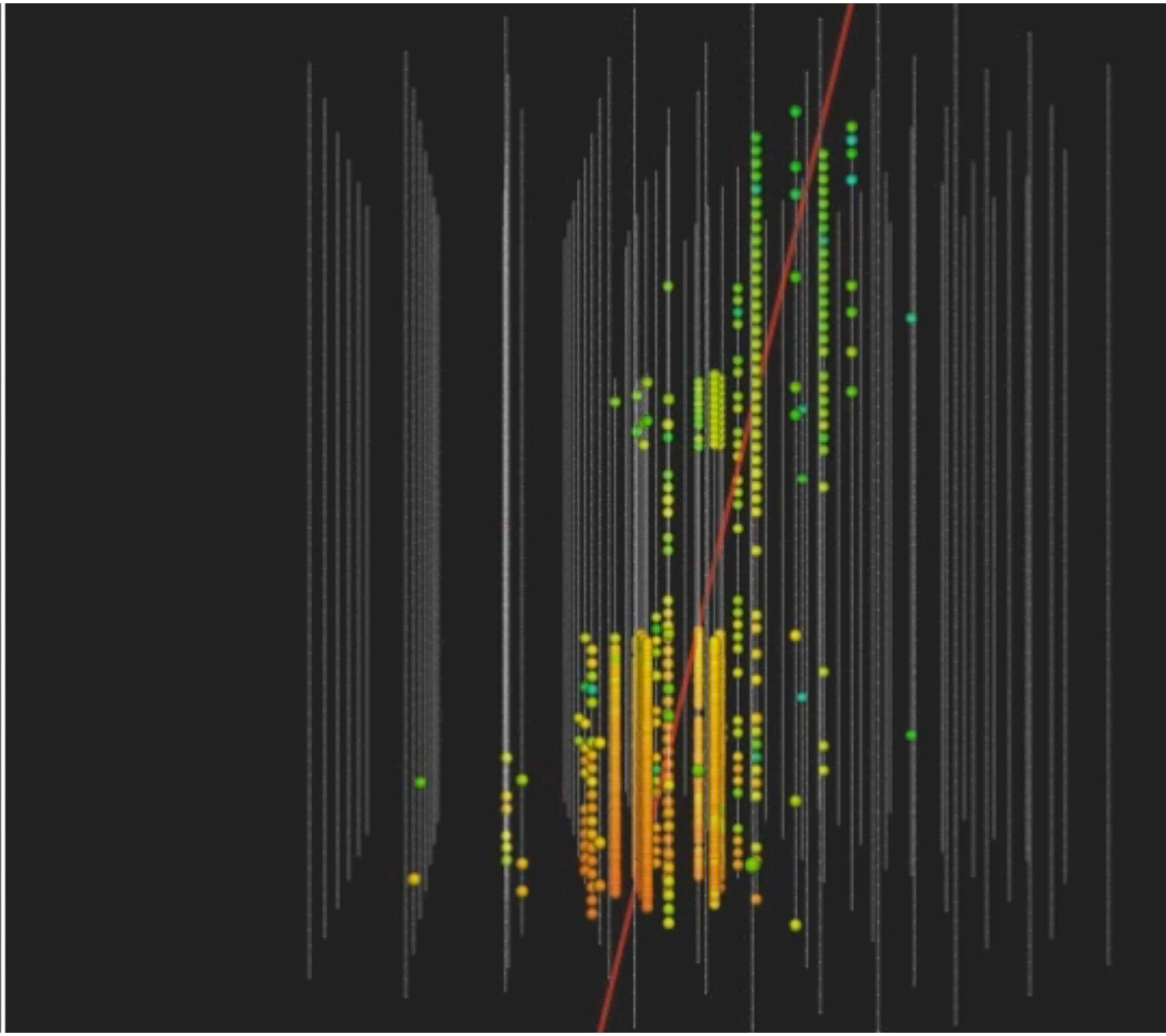


optical sensors Late hits Early hits Track

Light Yield of Monopoles

$v = 0.6\,c$
$dN/dE = 2\ \gamma/\mathrm{MeV}$
$\tau = 5000\ \mathrm{ns}$





Indirect Cherenkov Light

Indirect Cherenkov Light
+
Luminescence

Light Yield of Monopoles

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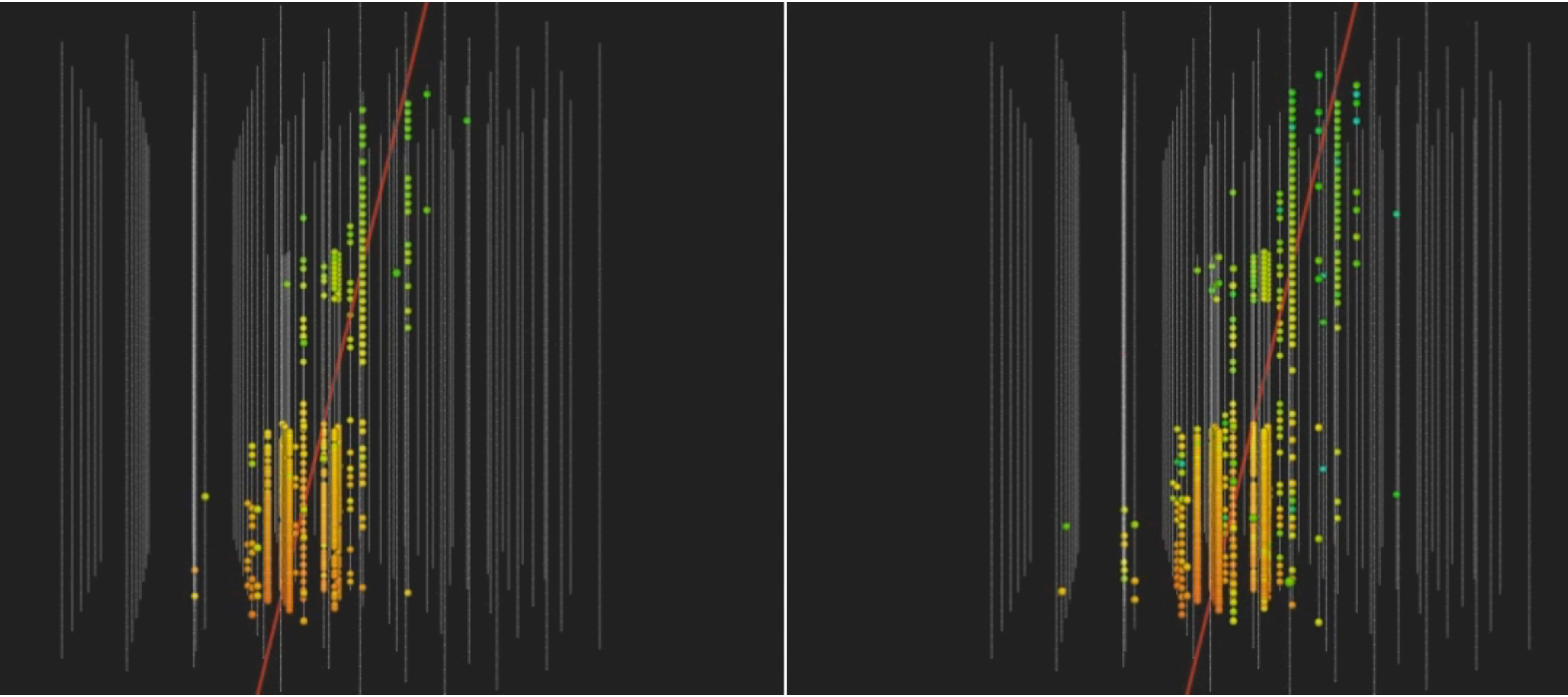
$dN/dE = 2\ \gamma/\mathrm{MeV}$

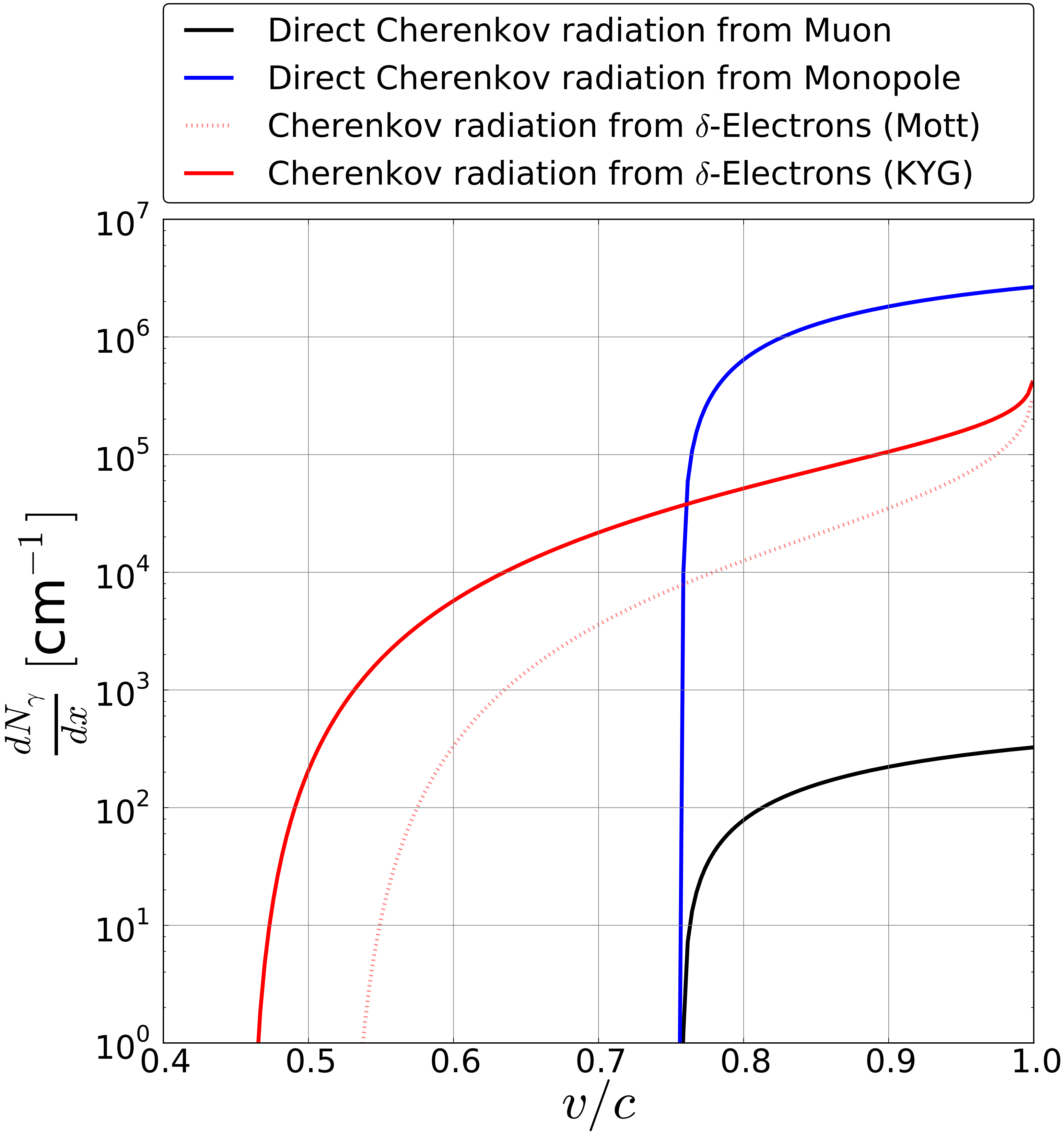
$\tau = 5000\ \mathrm{ns}$



Indirect Cherenkov Light

Indirect Cherenkov Light
+
Luminescence

Monopole - Electron Cross Section



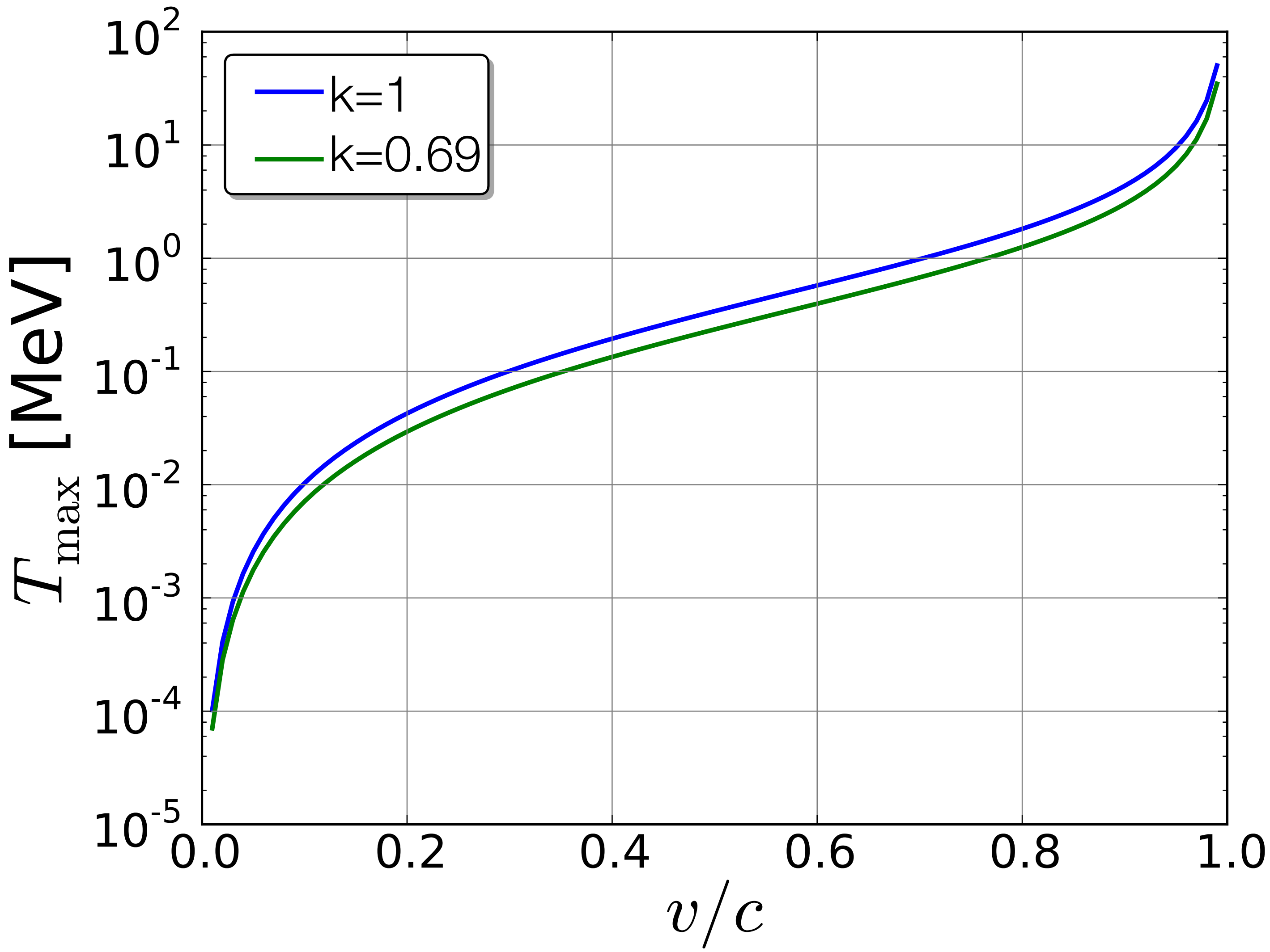
Mott

- Rutherford for monopoles
- quantum mechanical correction
- magneto-static
- semi-classical

KYG

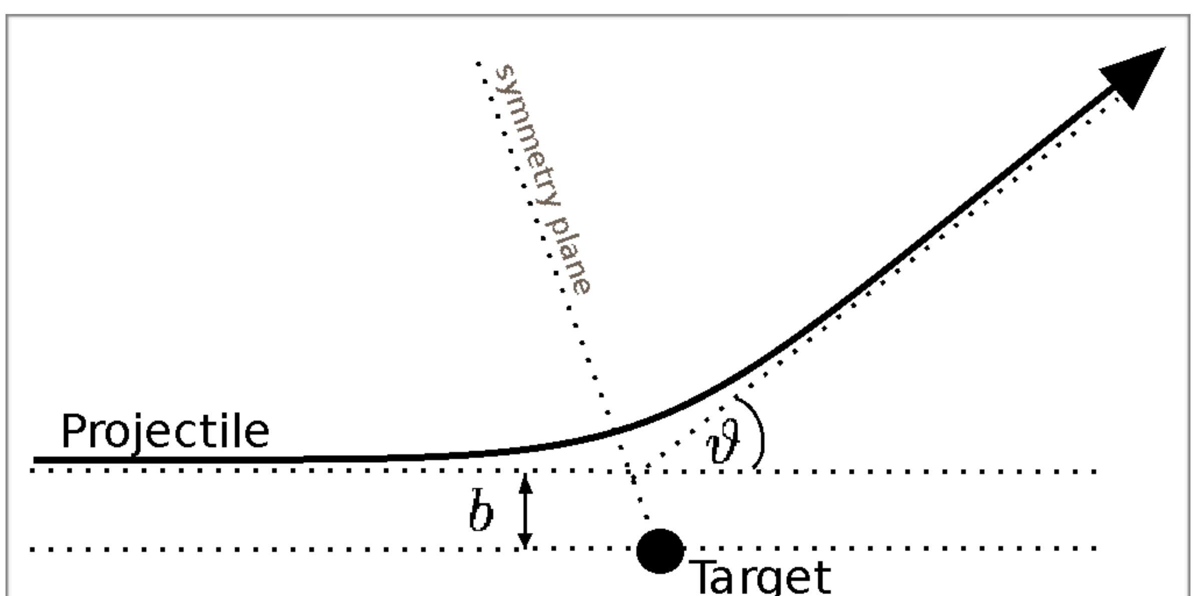
- electrodynamic
- quantum field theory

Interaction - The k factor



$$\sin^2\frac{\vartheta}{2} \approx \frac{T}{T_{\max}}$$

$$T_{\max} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + \frac{2\gamma m_e}{M} + \left(\frac{m_e}{M}\right)^2}$$



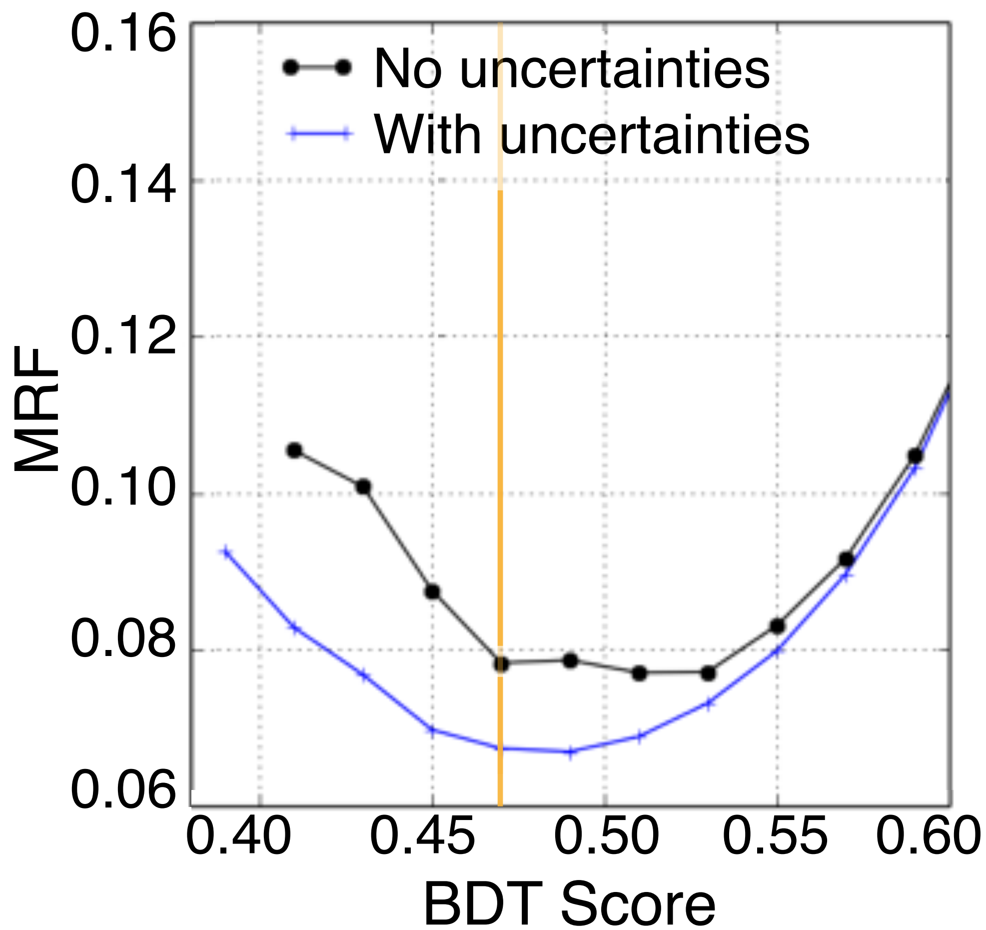
$$T(b) \propto \frac{1}{b_{\min}^2 + b^2}$$

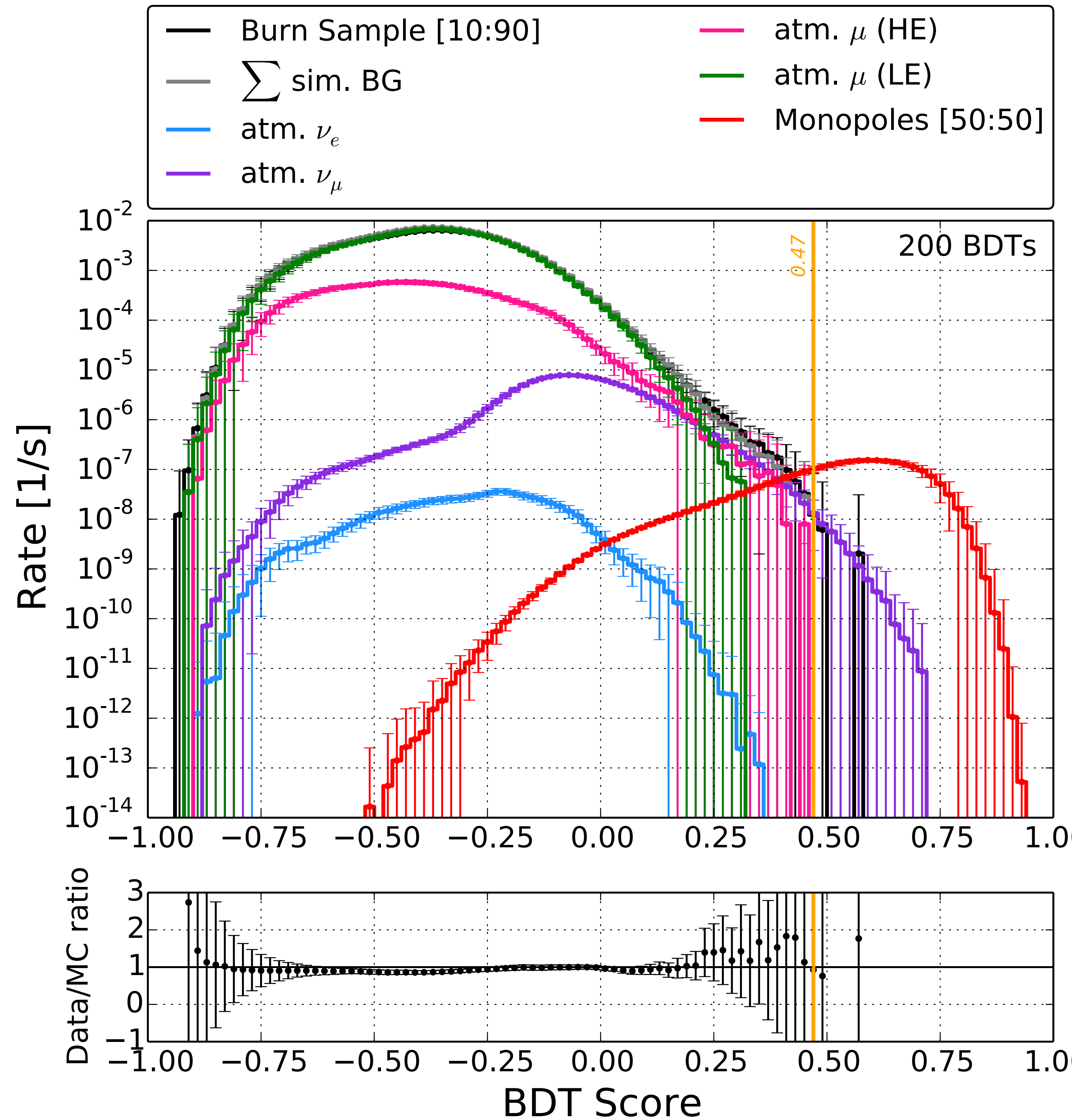
$$T_m = k \cdot T_{\max} \text{ with } k = 0.69$$

Event Selection - Sensitivity optimisation

- Feldman Cousins with uncertainties

- cut at BDT score 0.47 to gain statistics and stability





Event Selection - Sensitivity optimisation

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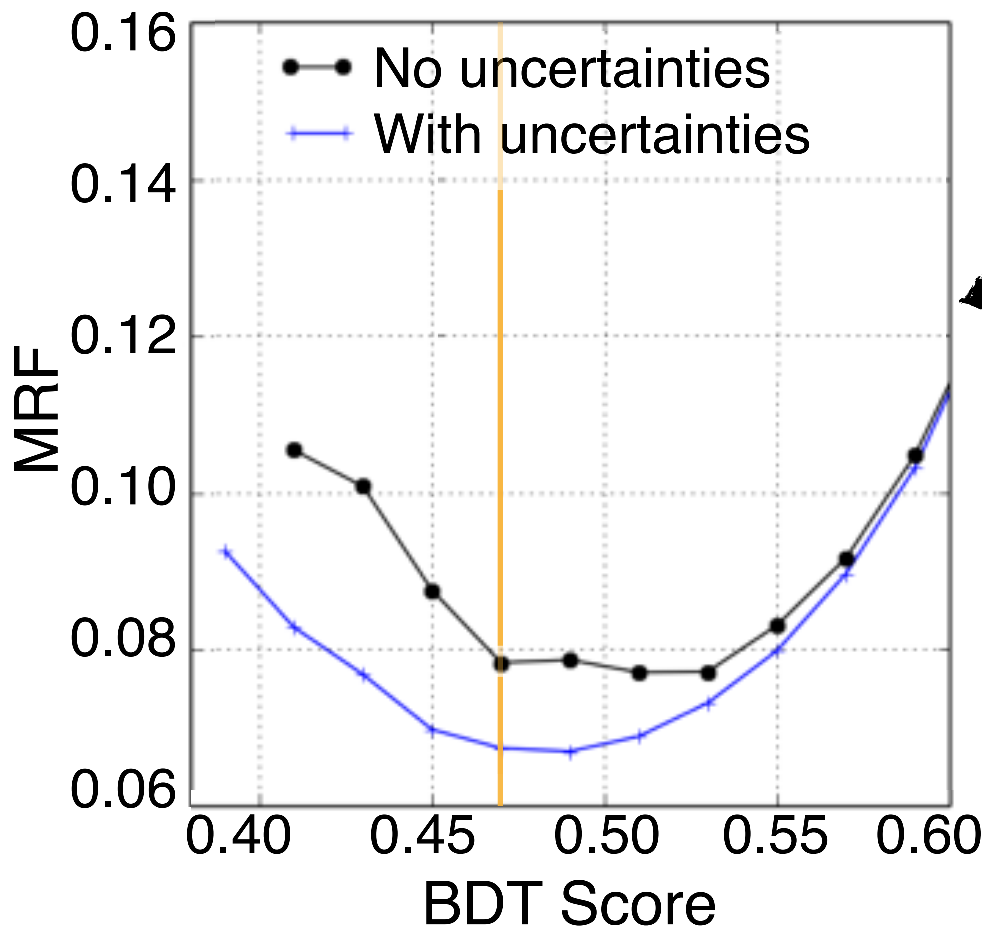
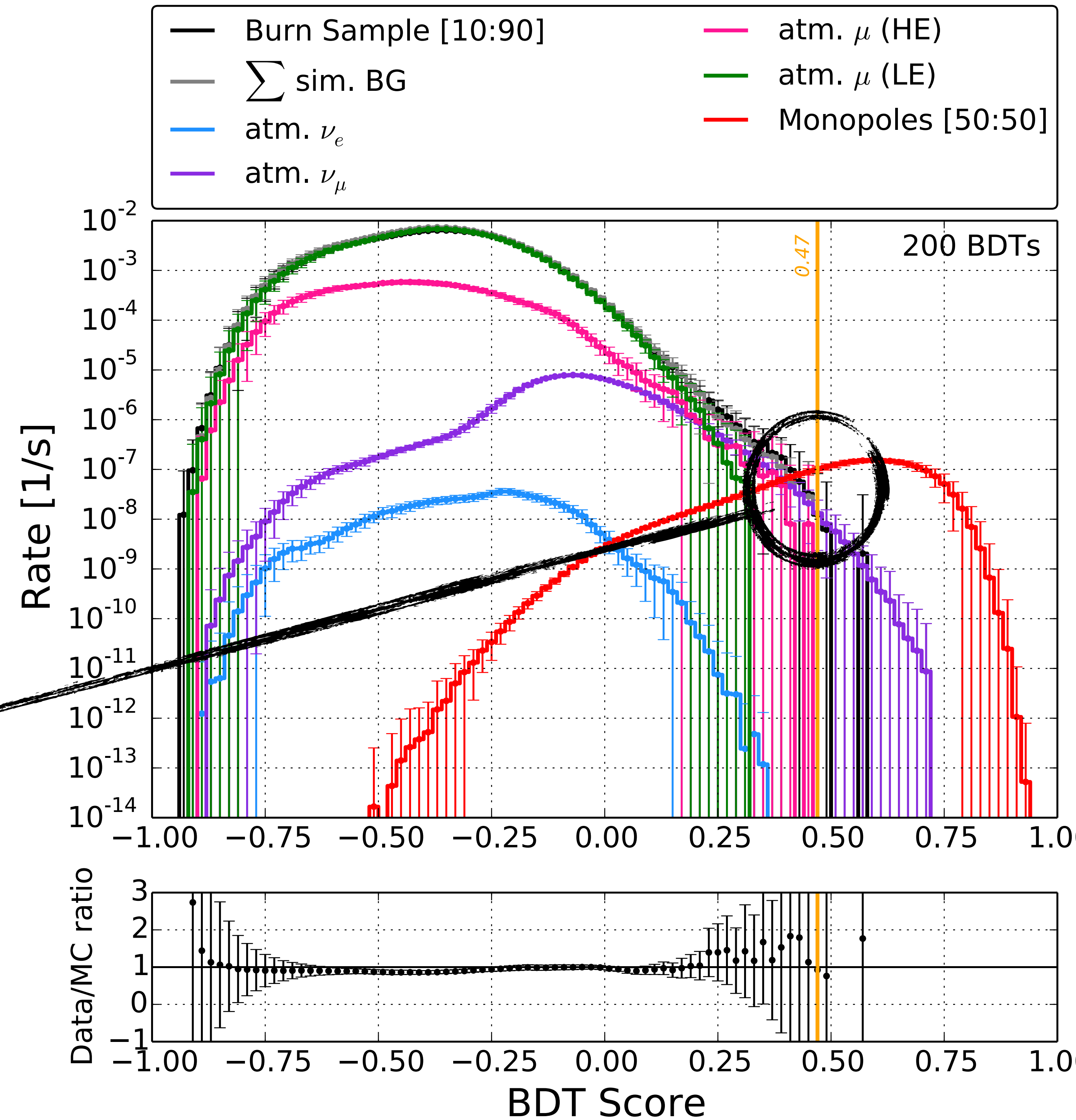
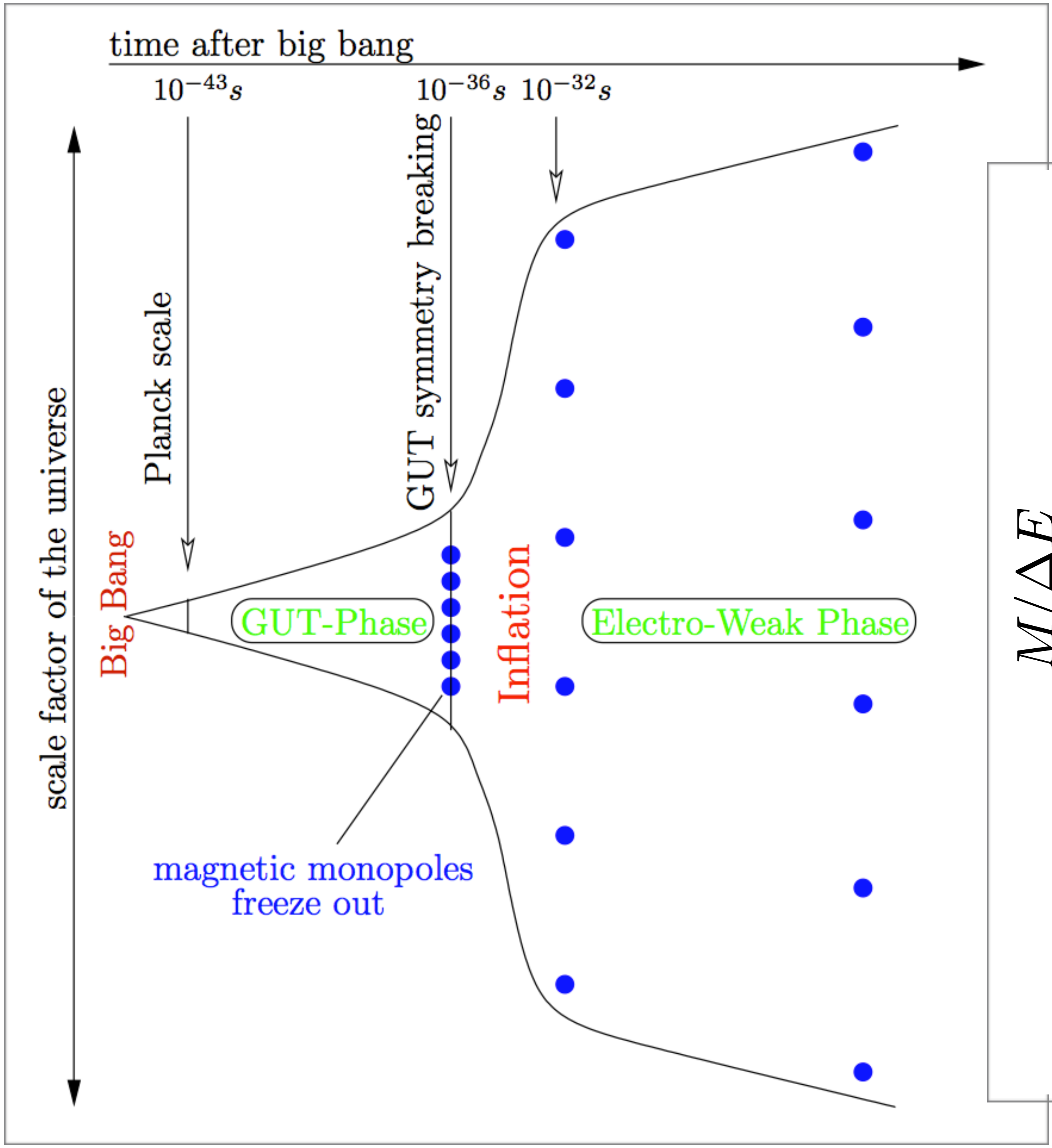
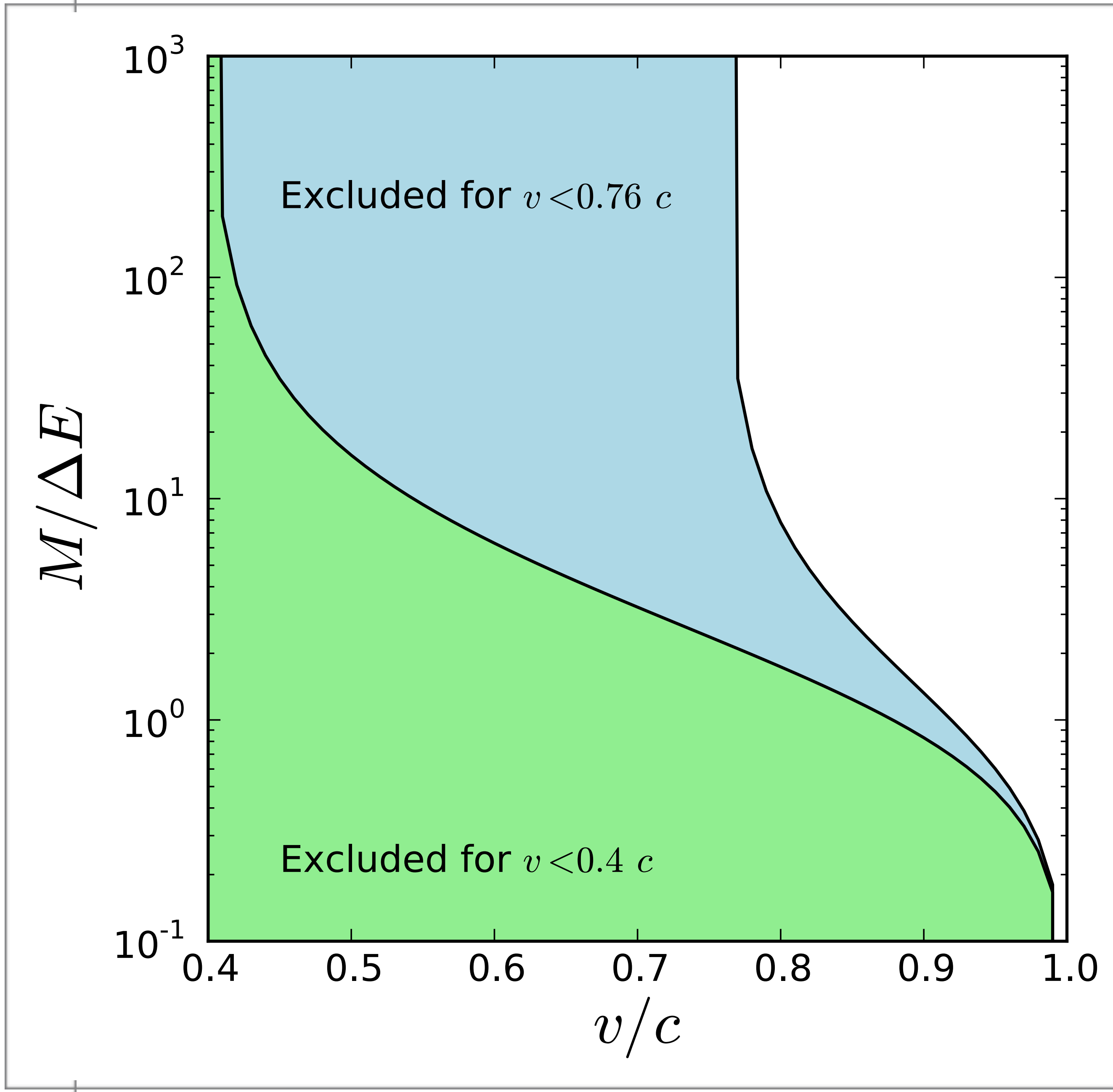




Monopoles

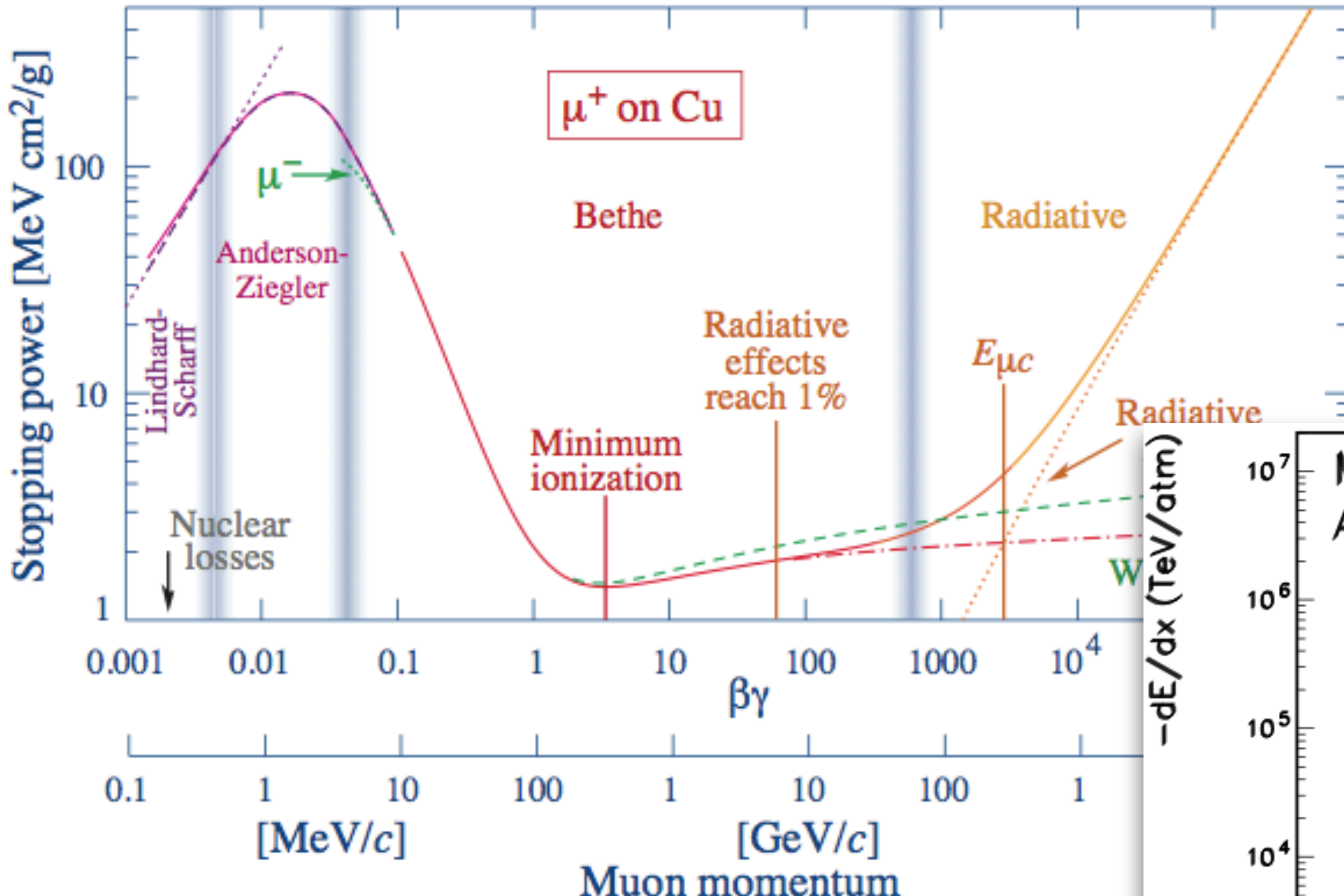


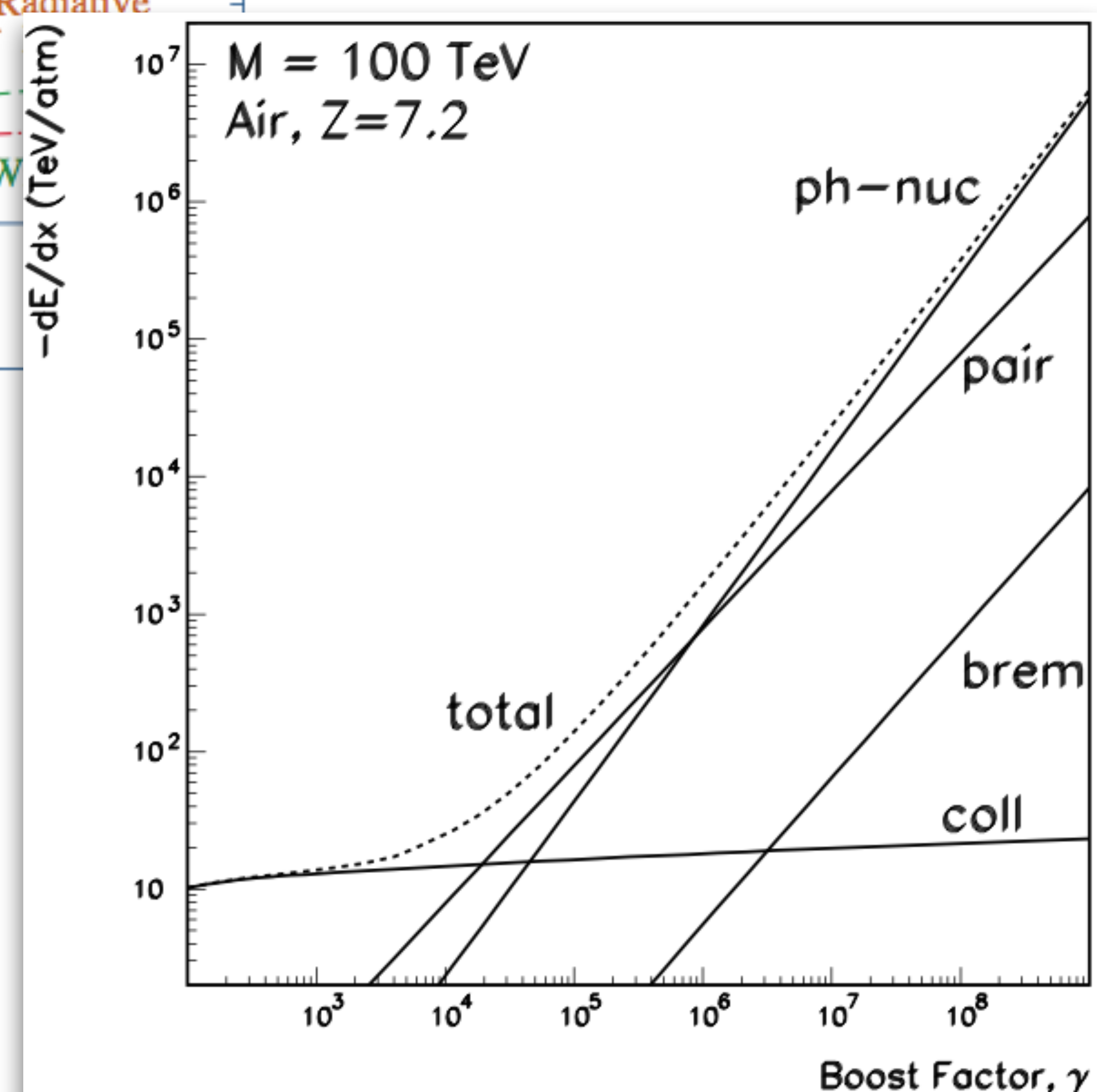
time after big bang
$10^{-43}s$
$10^{-36}s$
$10^{-32}s$
Planck scale
GUT symmetry breaking
scale factor of the universe
Big Bang
GUT-Phase
Inflation
Electro-Weak Phase
magnetic monopoles
freeze out



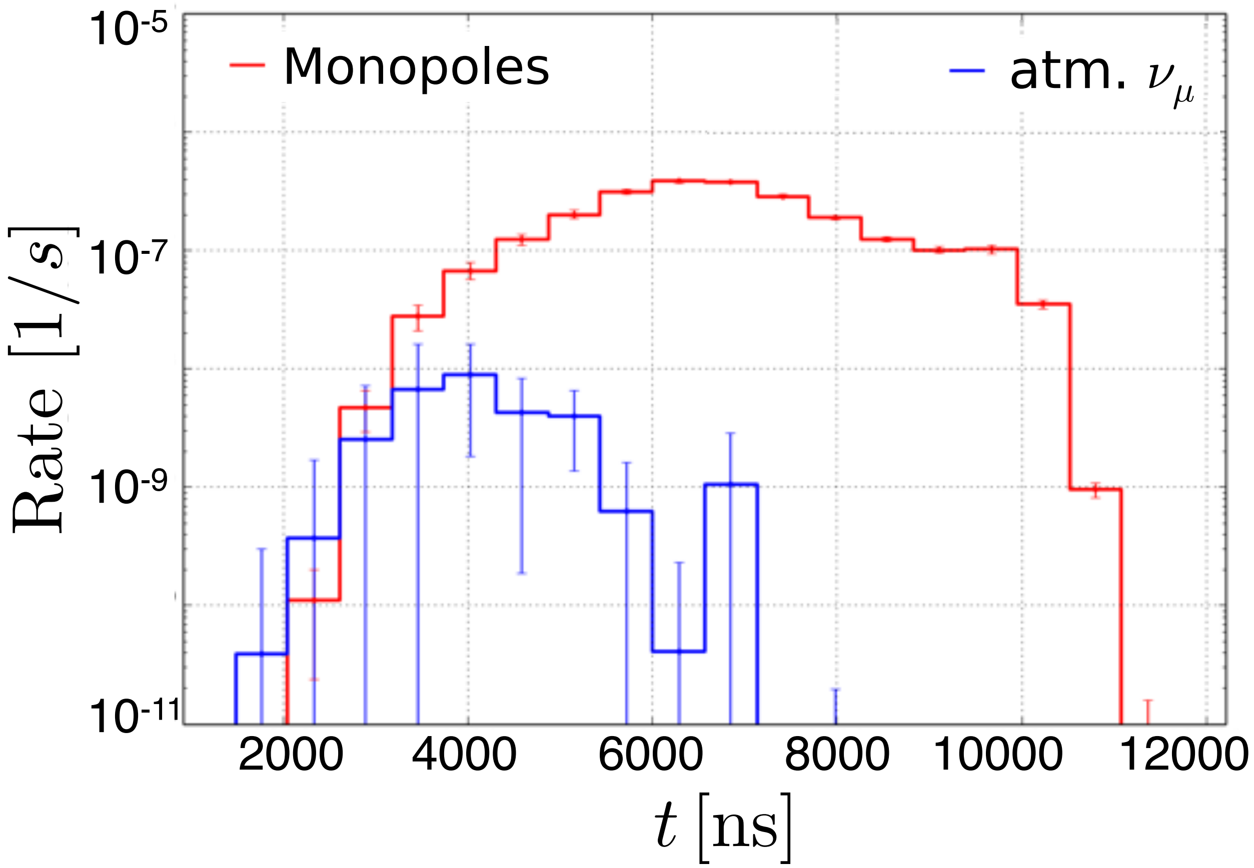
Excluded for $v < 0.76\ c$
Excluded for $v < 0.4\ c$
$M/\Delta E$
v/c
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
0.4
0.5
0.6
0.7
0.8
0.9
1.0

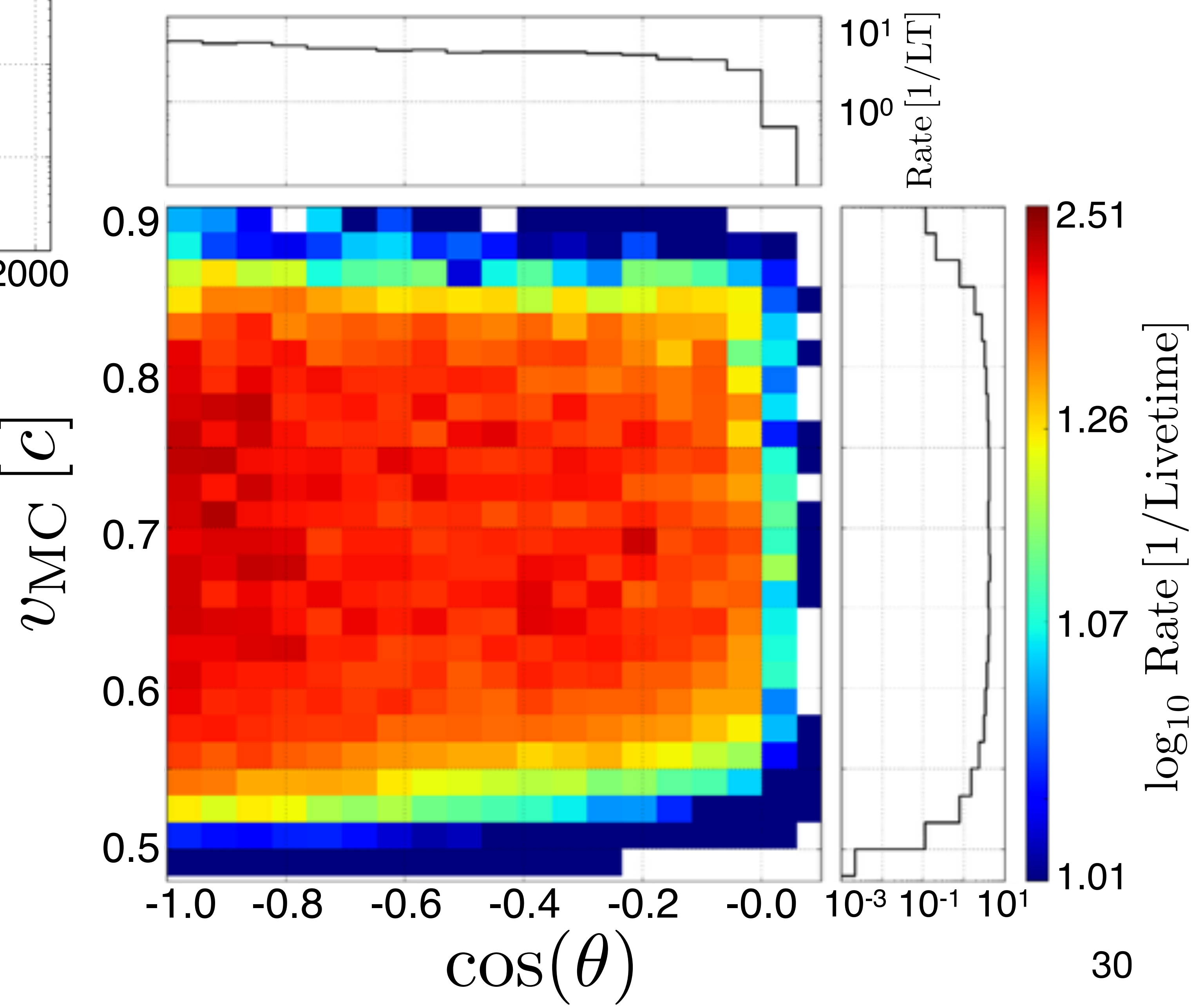
Interaction - Energy loss



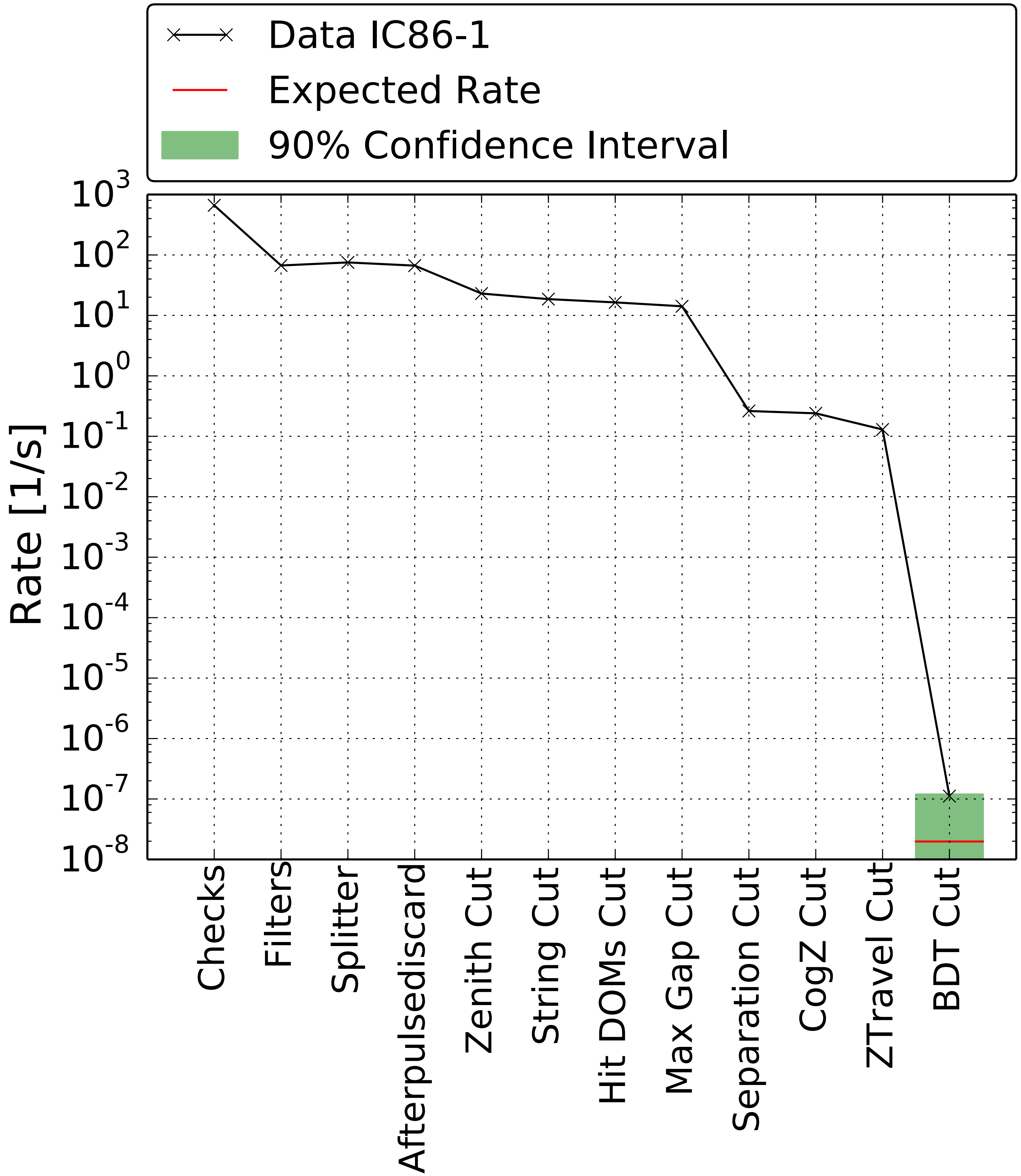


Event Selection - After Pull-Validation



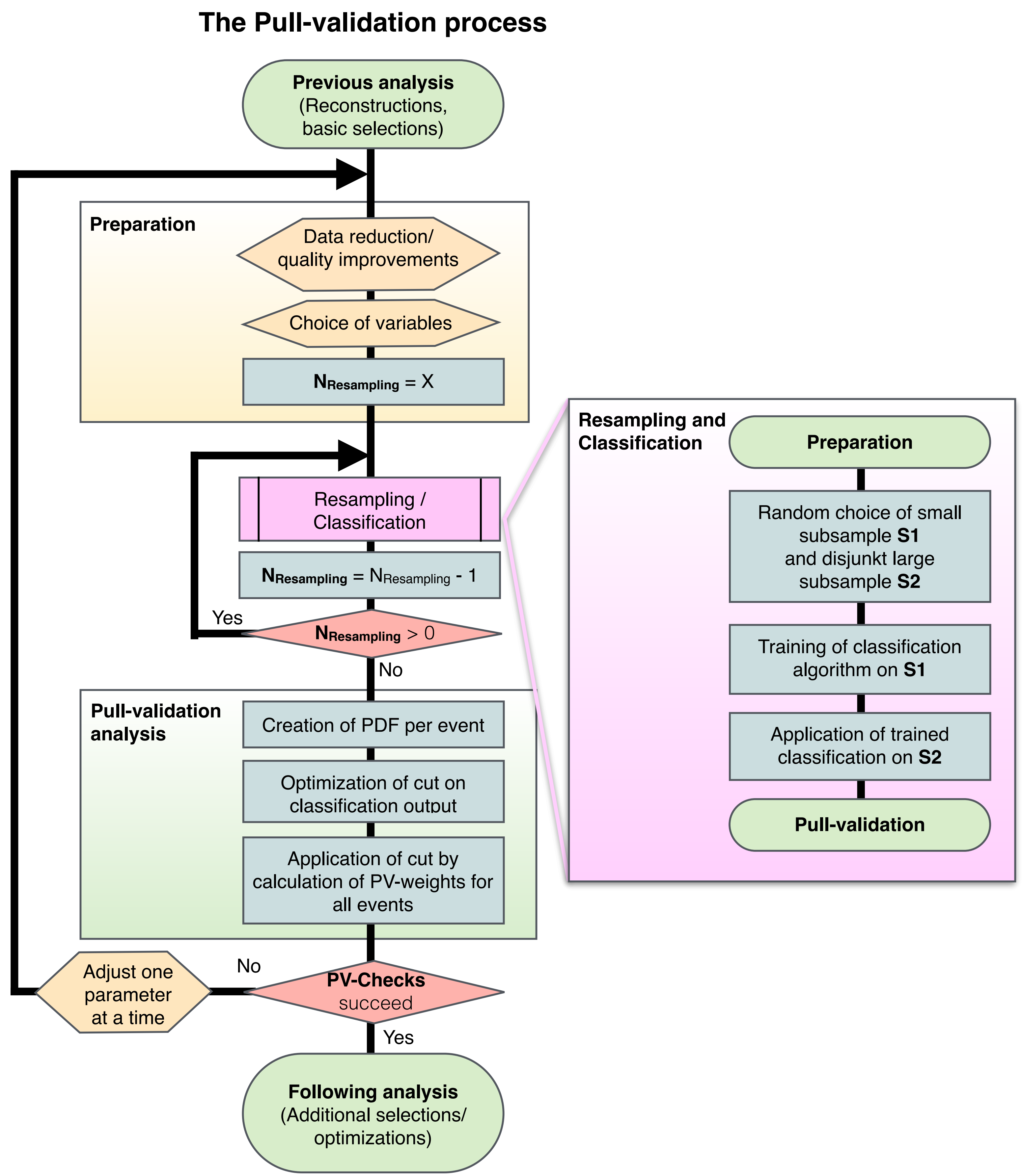


Results



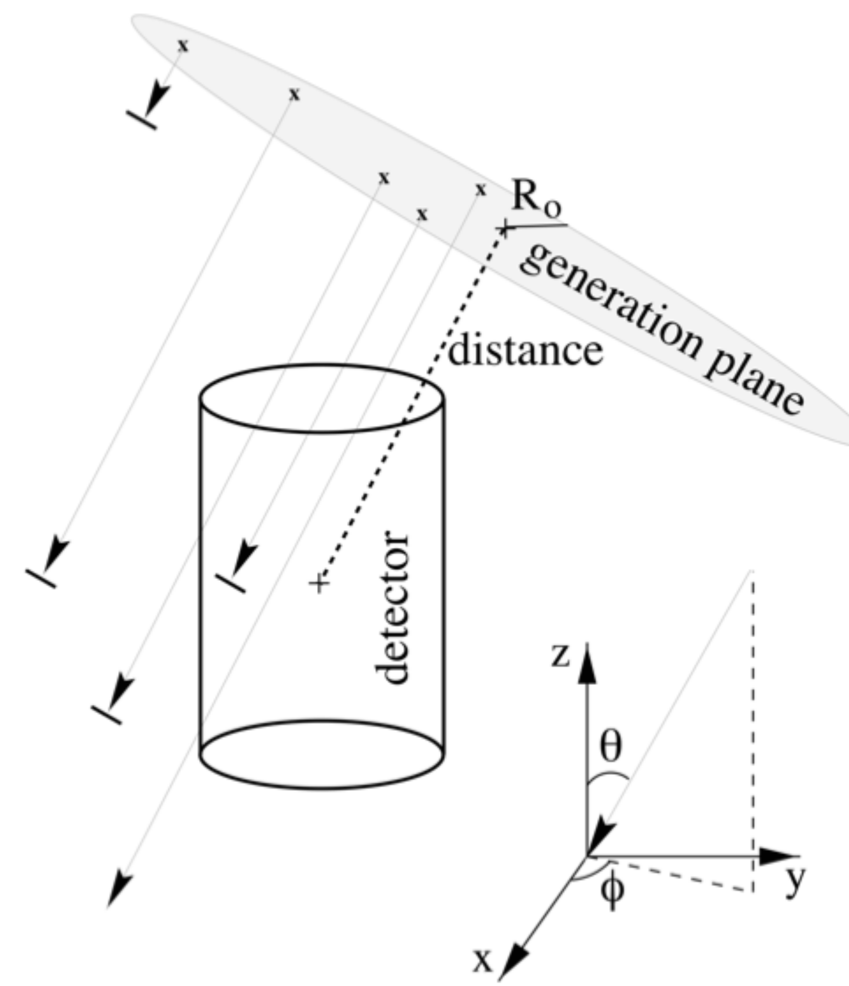
Data IC86-1
Expected Rate
90% Confidence Interval
Rate [1/s]
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
Checks
Filters
Splitter
Afterpulsediscard
Zenith Cut
String Cut
Hit DOMs Cut
Max Gap Cut
Separation Cut
CogZ Cut
ZTravel Cut
BDT Cut

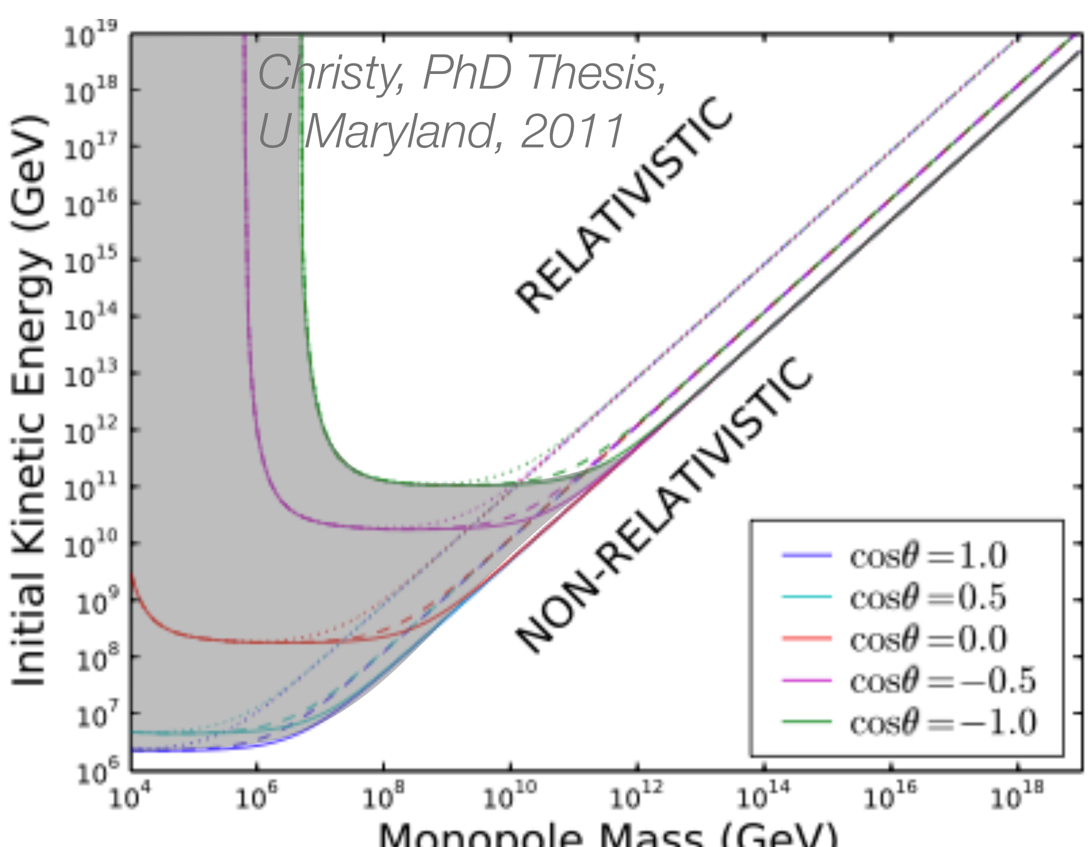
Event Selection



Principle of monopole searches at ν-Telescopes

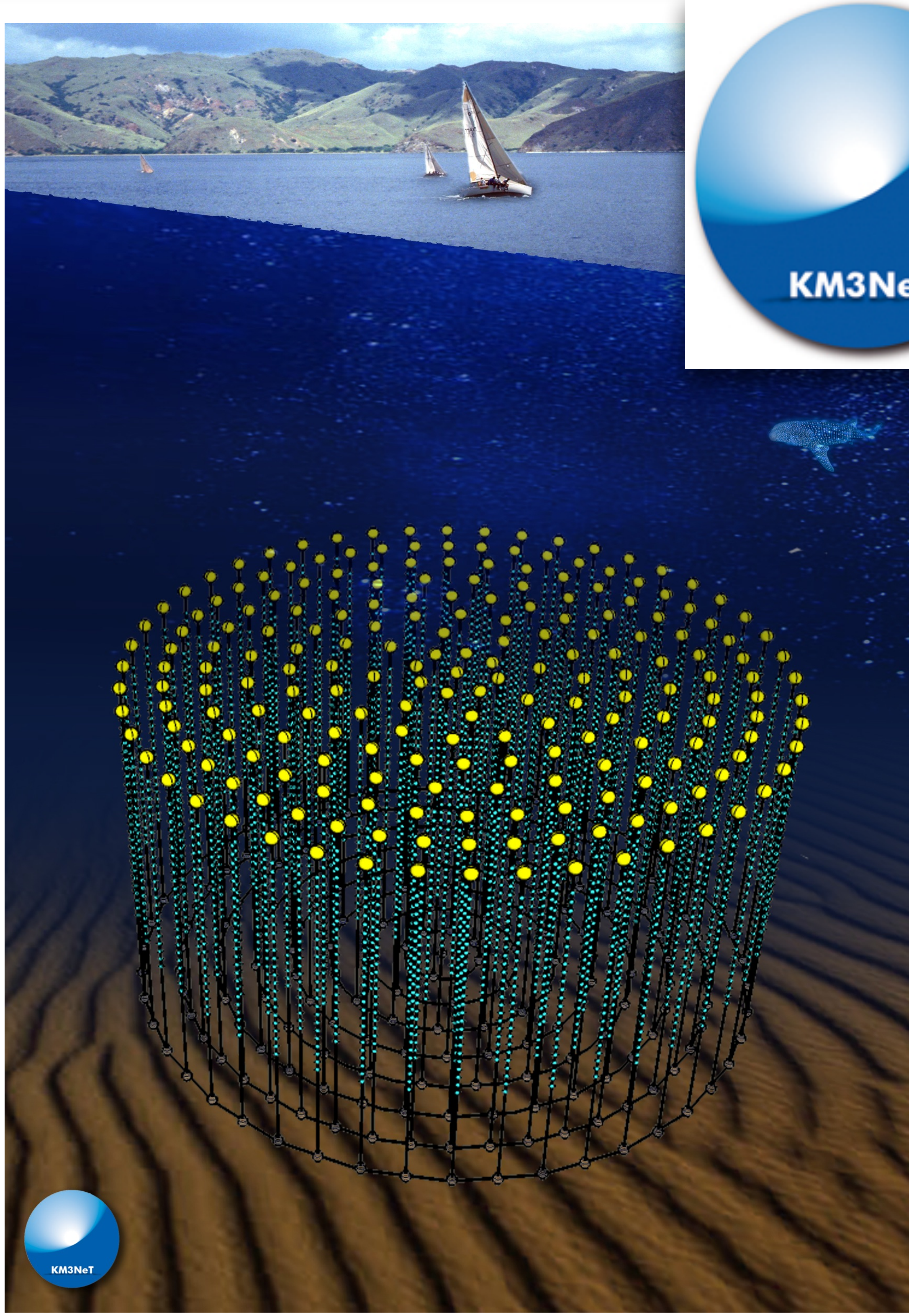
- simulation of monopoles according to theories
  - Dirac charge
  - arbitrary mass / no propagation through Earth
- light production
- discrimination from background
  - speed
  - light yield
  - angular distribution

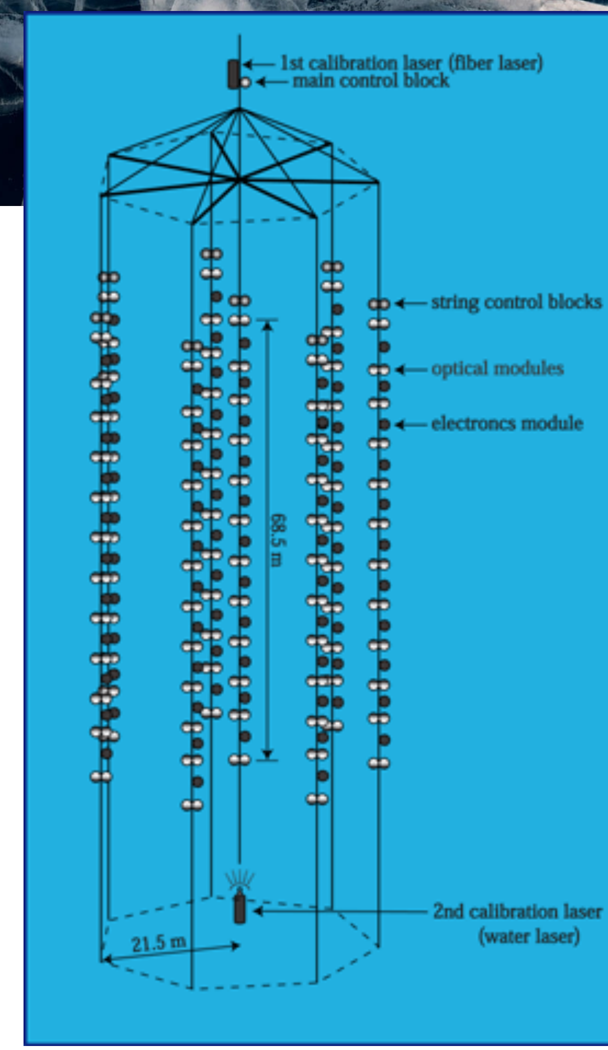




- *down-going monopole*
  vertically from north to south
- *up-going monopole*
  vertically from south to north
- *solid: v/c = 0.76*
- *dotted: γ = 10*

KM3NeT and BAIKAL





Baikal

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