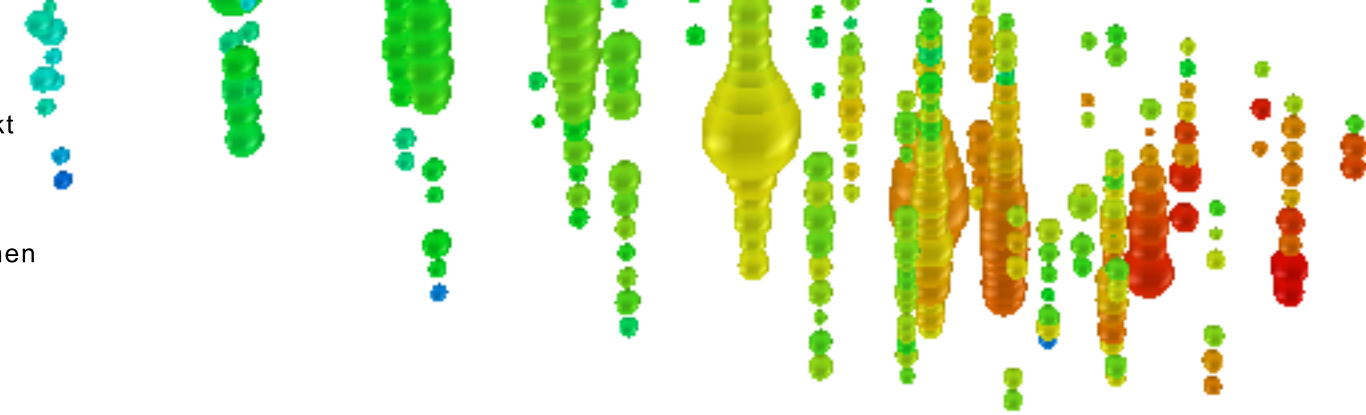




BERGISCHE  
UNIVERSITÄT  
WUPPERTAL



bmb+f - Förderschwerpunkt  
Astroteilchenphysik  
Großgeräte der physikalischen  
Grundlagenforschung

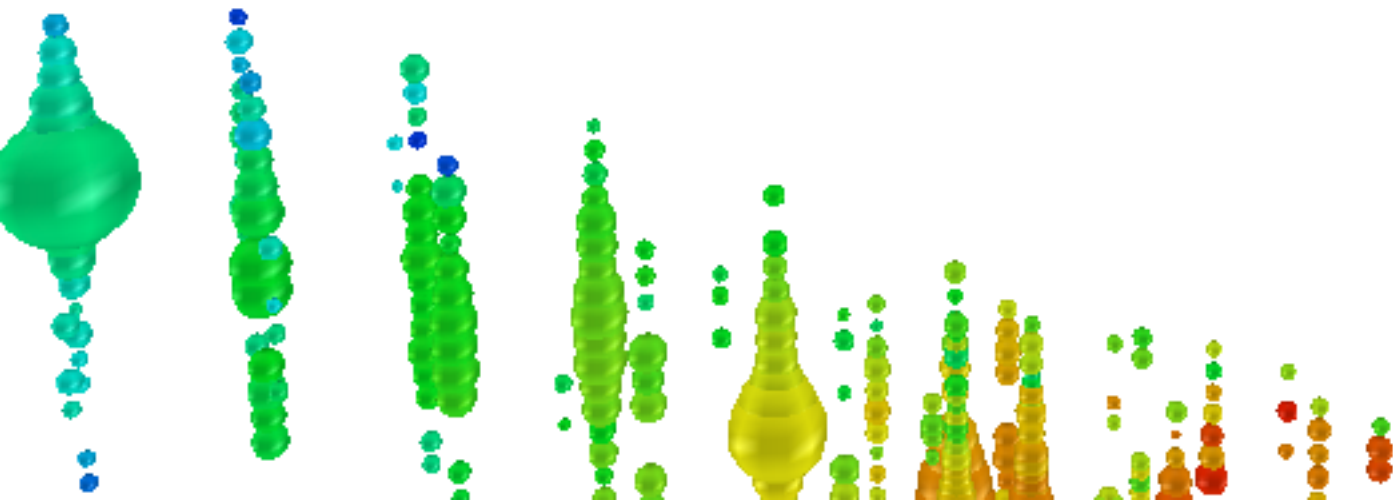


# Luminescence

of water or ice as a new detection method for

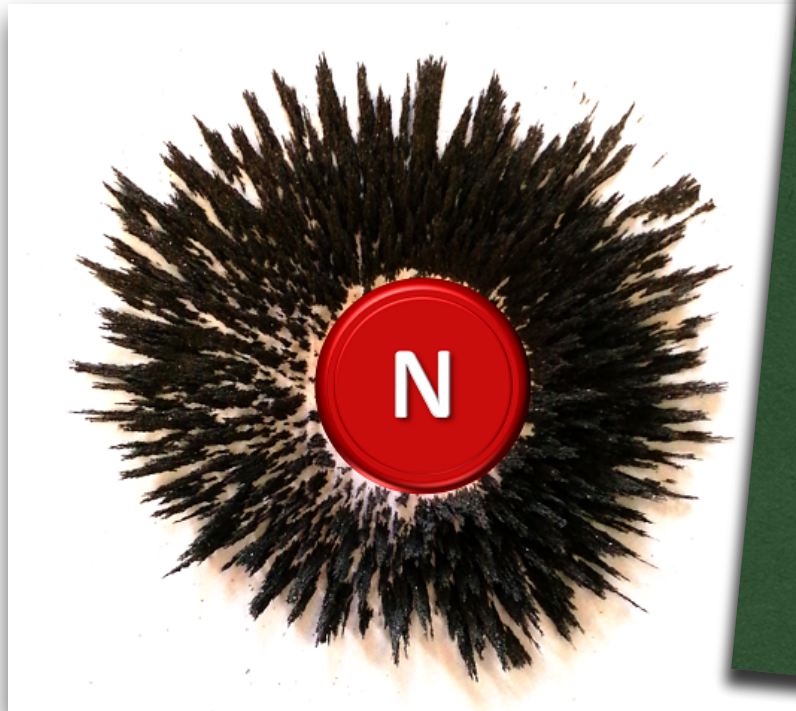
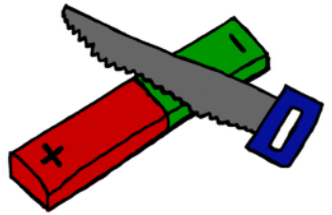
# Magnetic Monopoles

Anna Pollmann  
for the IceCube Collaboration



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# Magnetic Monopoles



1864

$$\nabla \cdot D = 4\pi\rho_e$$

~~$$\nabla \cdot B = 4\pi\rho_m$$~~

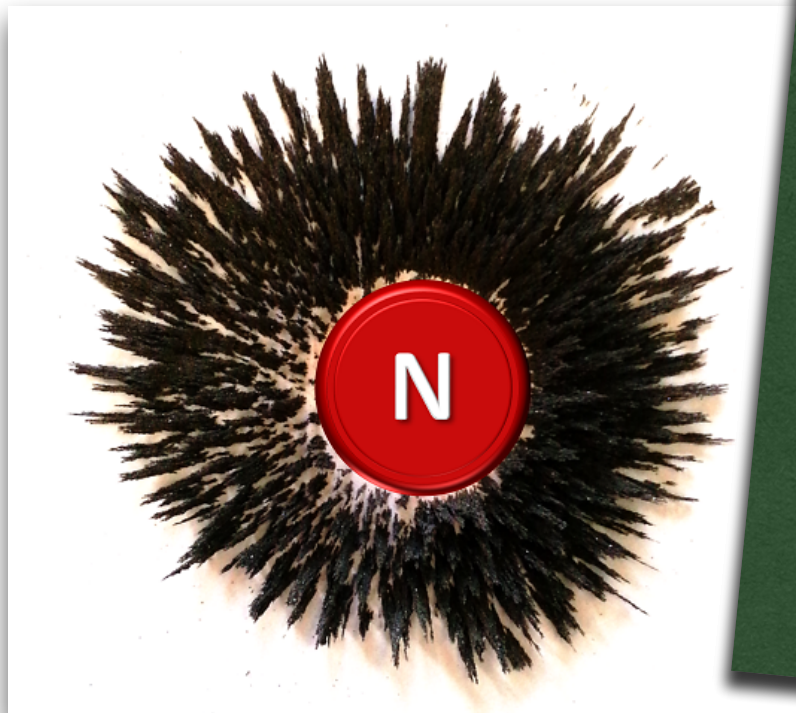
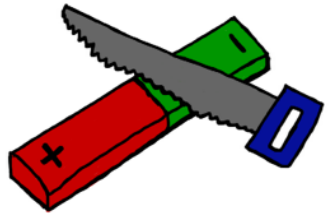
~~$$\nabla \times E - c^{-1} \dot{B} = 4\pi c^{-1} j_m$$~~

~~$$\nabla \times H - c^{-1} \dot{D} = 4\pi c^{-1} j_e$$~~

*James Clerk Maxwell*



# Magnetic Monopoles



1864

$$\nabla \cdot \mathbf{D} = 4\pi\rho_e$$

$$\nabla \cdot \mathbf{B} = 4\pi\rho_m$$

$$\nabla \times \mathbf{E} - c^{-1} \dot{\mathbf{B}} = 4\pi c^{-1} \mathbf{j}_m$$

$$\nabla \times \mathbf{H} - c^{-1} \dot{\mathbf{D}} = 4\pi c^{-1} \mathbf{j}_e$$

James Clerk Maxwell

1931

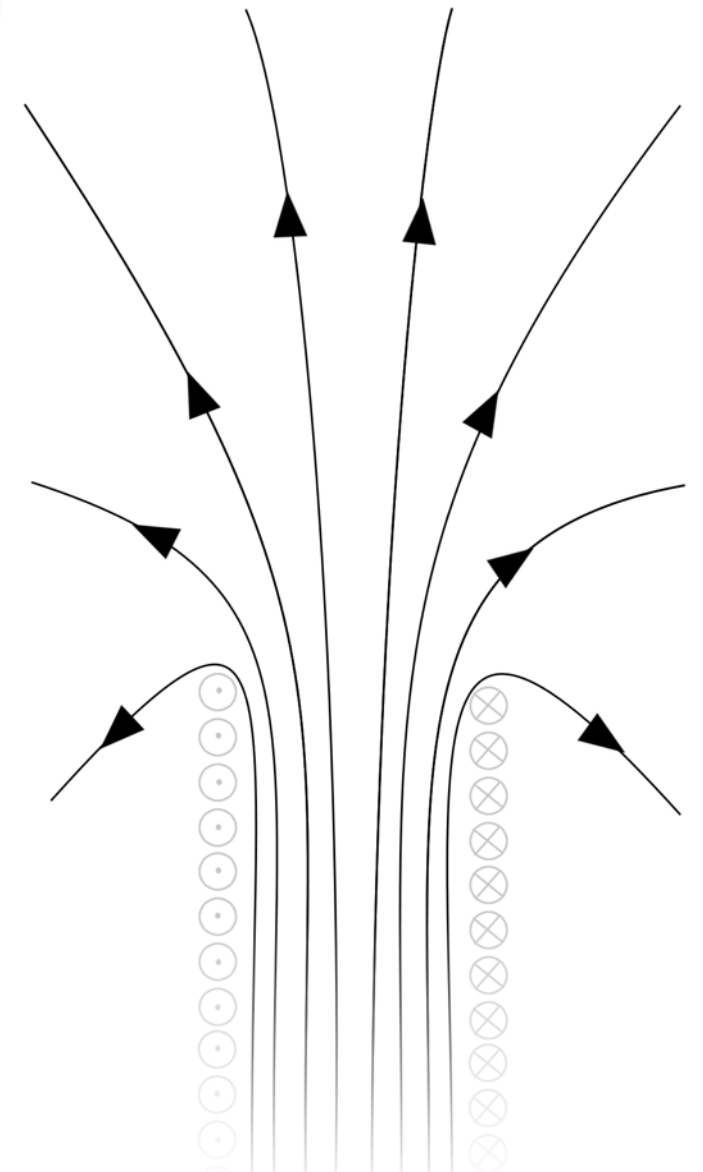
Search: Quantisation of electric charge  $e$

$$e = \sqrt{\hbar c \alpha}$$

Result: Dependence of a magnetic charge  $g$

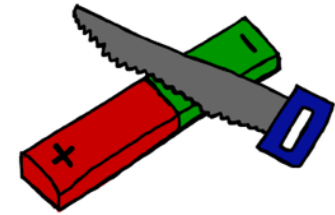
$$g = k \frac{e}{2\alpha}$$

Paul Dirac



Field of a magnetic monopole  
(analogous to the end of a solenoid)

# Magnetic Monopoles



- elemental magnetic charge

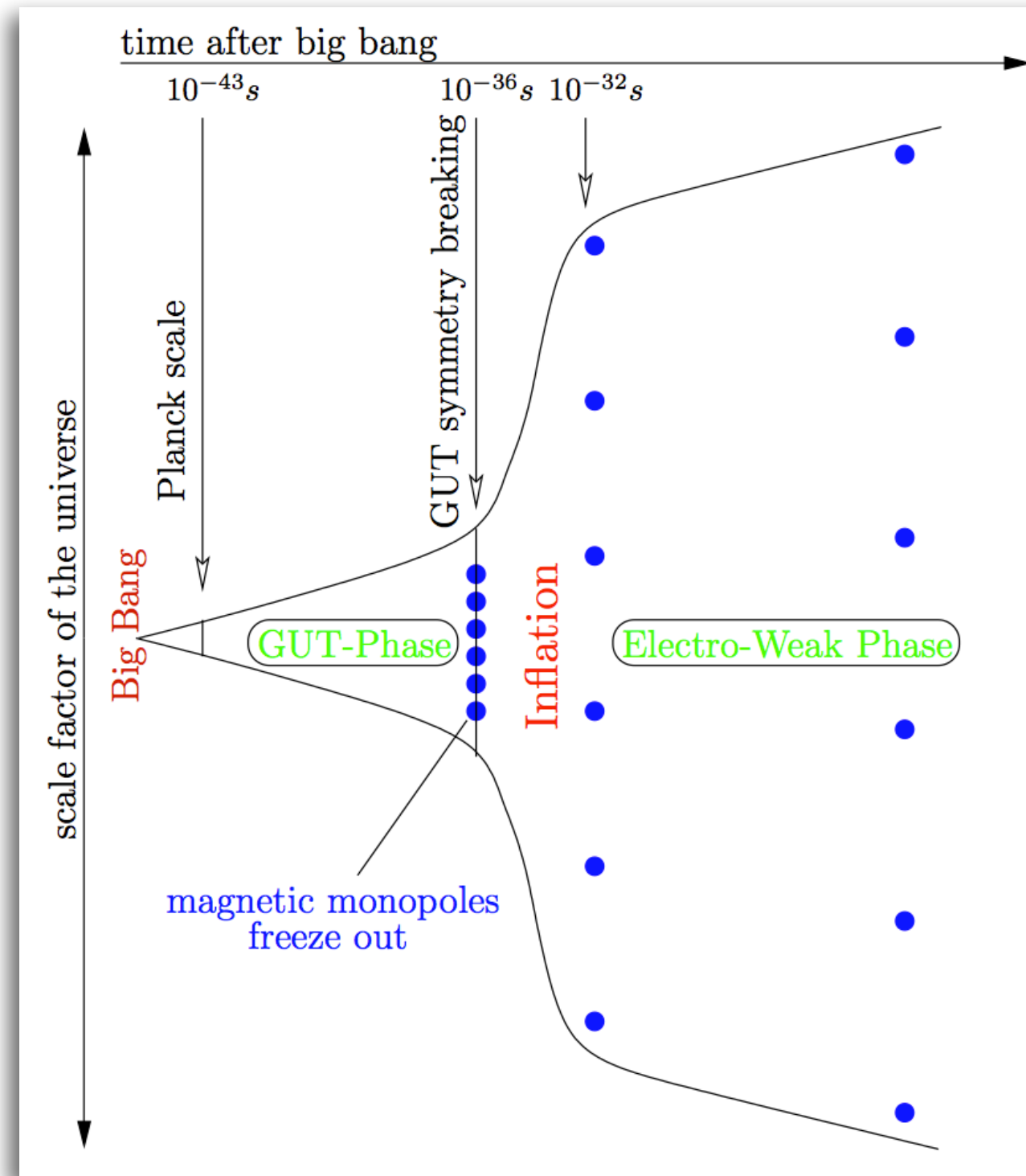
$$g_D = \frac{1}{2} \frac{e}{\alpha} \approx 68.5 \cdot e$$

- topological defects with huge mass created shortly after the Big Bang

$$10^{10} \text{ GeV} \leq M_{\text{GUT}} \leq 10^{17} \text{ GeV}$$

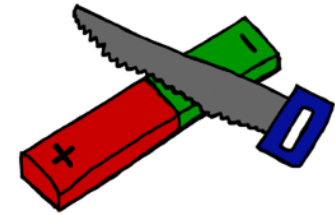
- acceleration in magnetic fields

$$E_{\text{kin}} \leq 10^{14} \text{ GeV}$$





# Magnetic Monopoles



## Monopole Problem

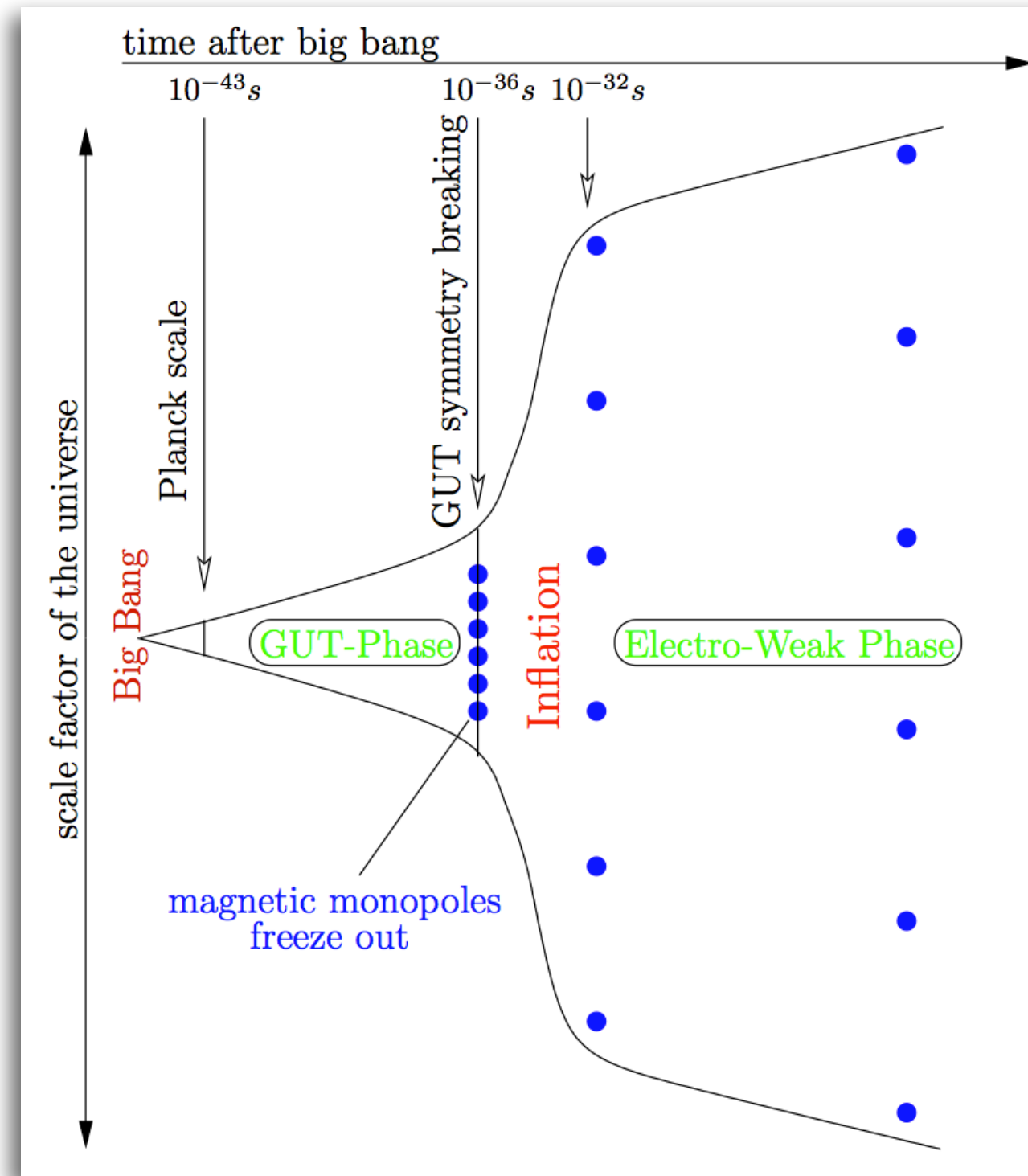
- Kibble mechanism (one monopole per domain)

vs

- mass density of the universe
- Parker bound: dissipation of magnetic fields

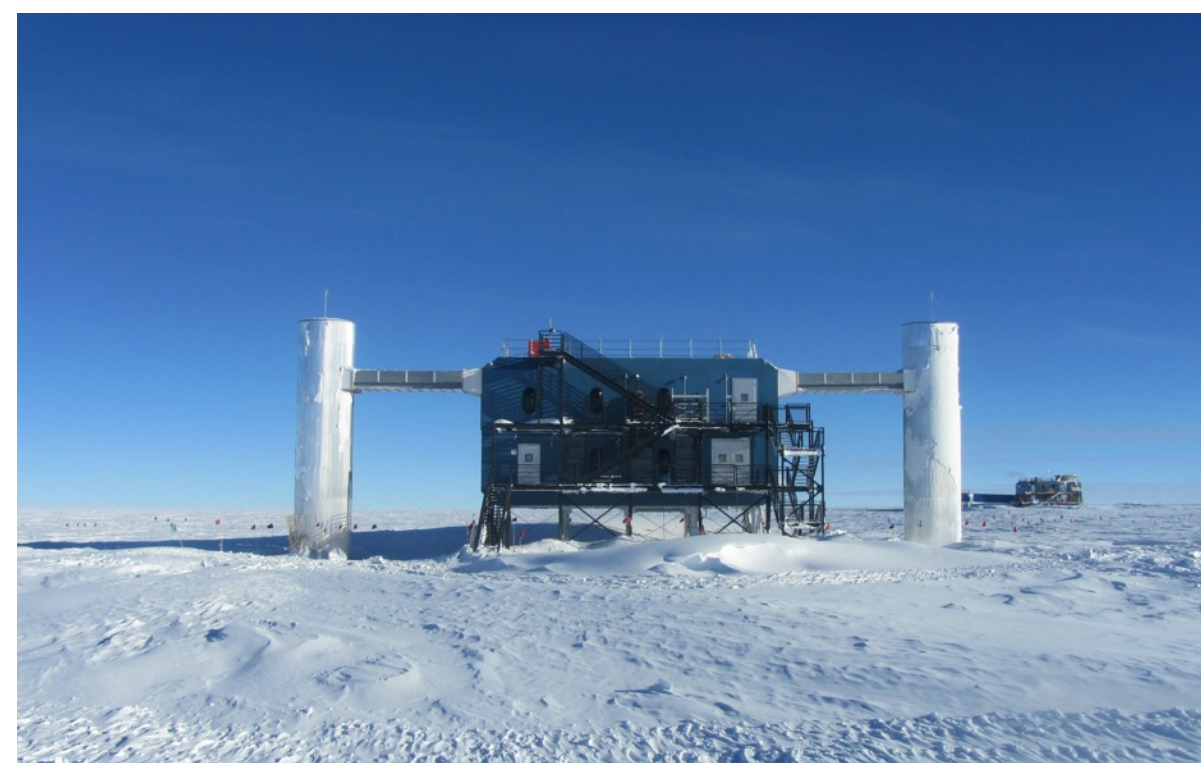
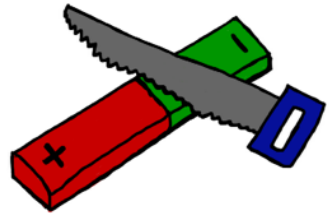
## New Models

- inflationary phase of the universe
  - ➔ dilution of monopoles
- (later) symmetry breaking through intermediate steps
  - ➔ smaller monopole masses
  - ➔ large mass range



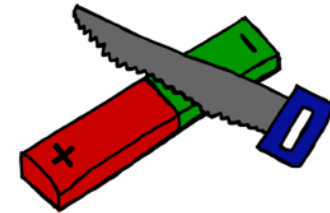
Gluesenkamp '10

# IceCube





# IceCube



## IceTop array

81 stations

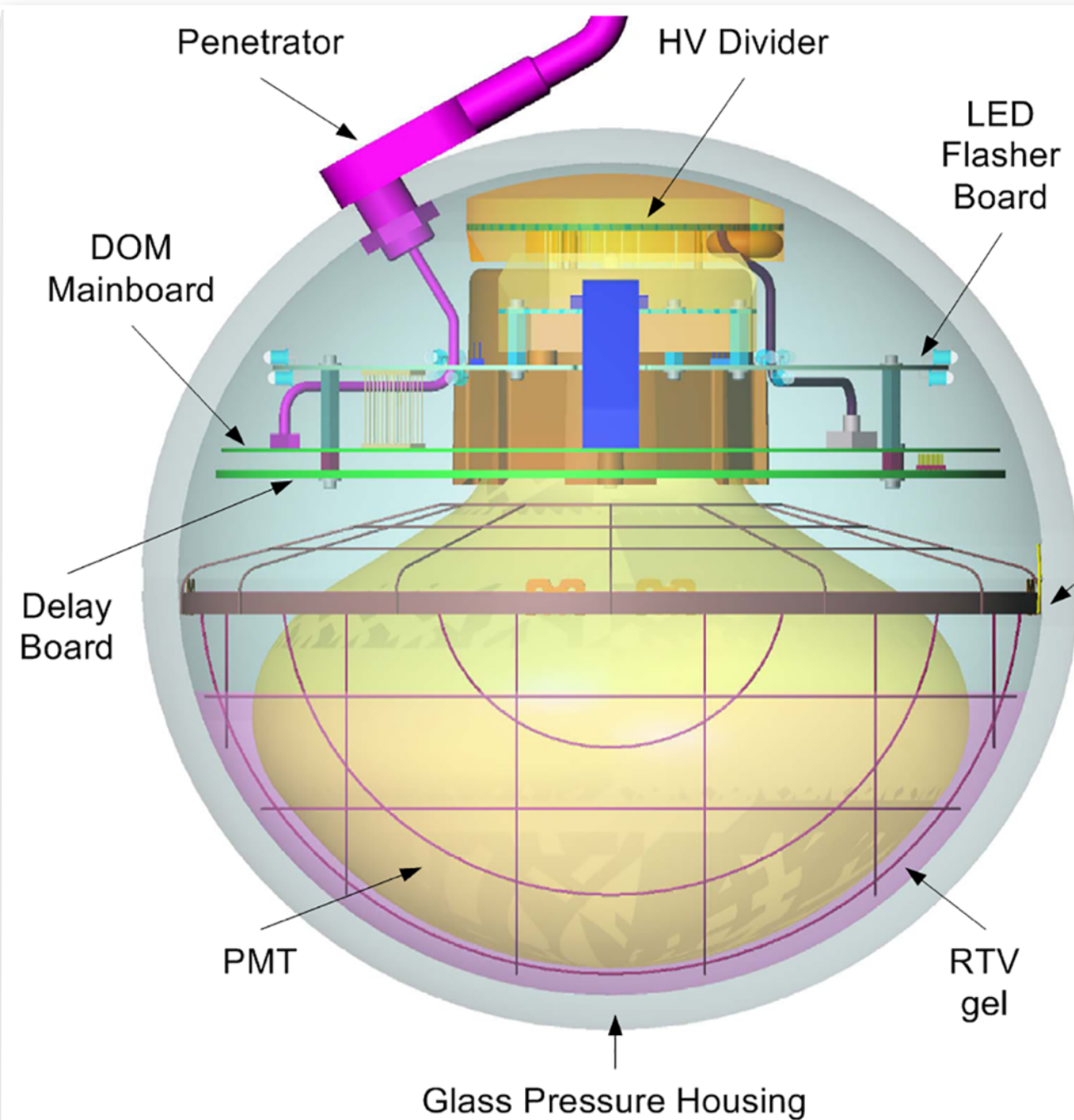
## IceCube array

86 strings, each with  
60 optical sensors

1450m

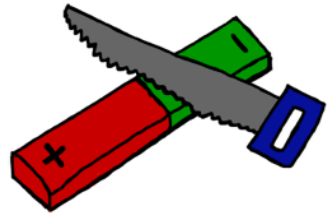
2450m

## Digital Optical Modules (DOMs)



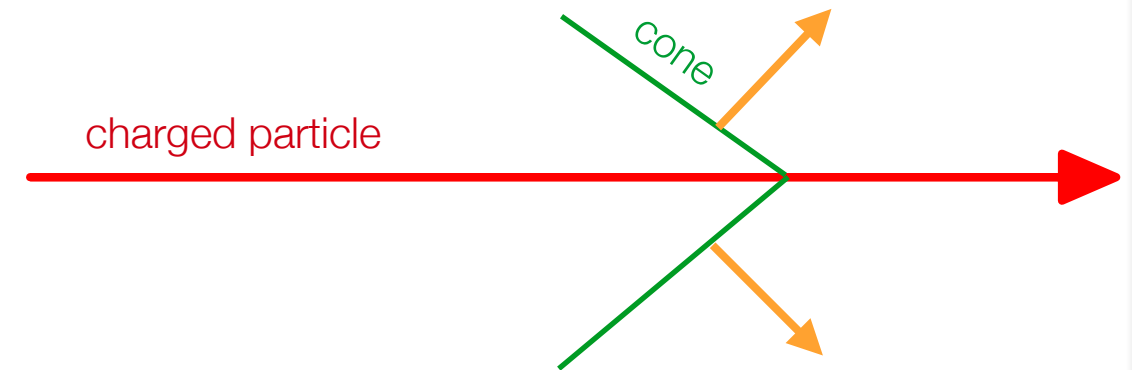


# Detection Signatures (for Monopoles)

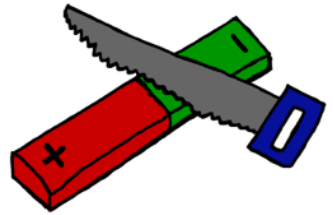


## Direct Cherenkov light

- a charge with velocity  $> 0.76 c$
- Cherenkov light originates from a cone

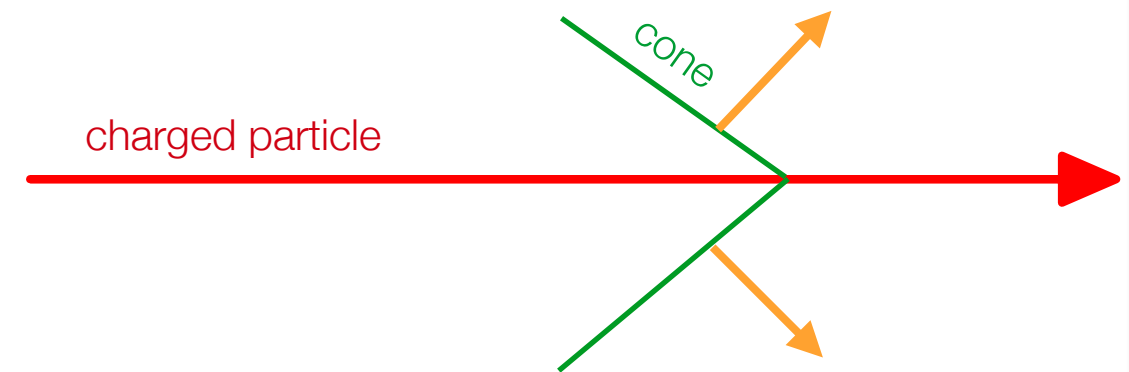


# Detection Signatures (for Monopoles)



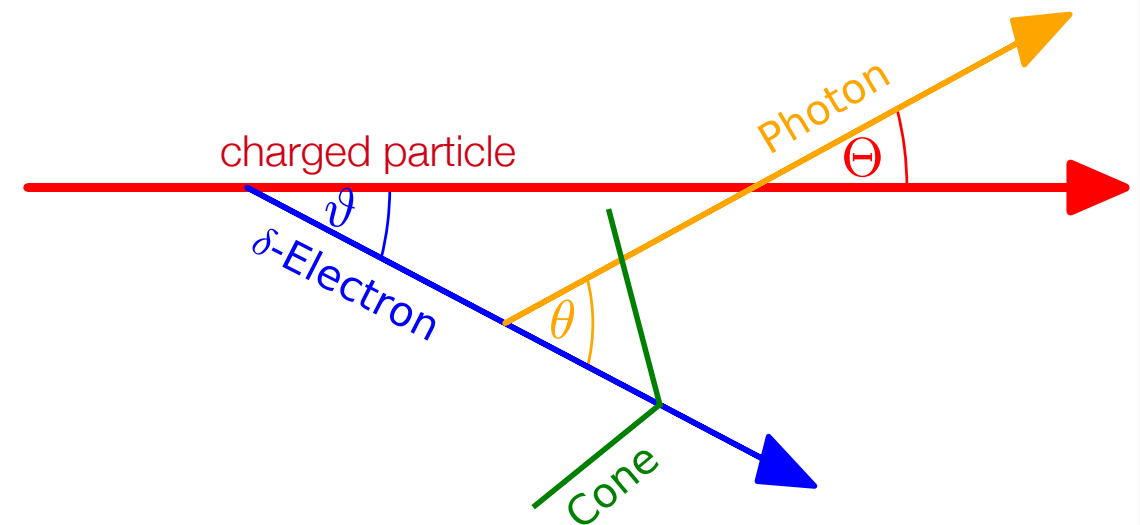
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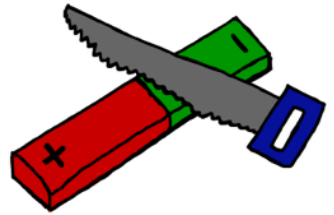


## Indirect Cherenkov light

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

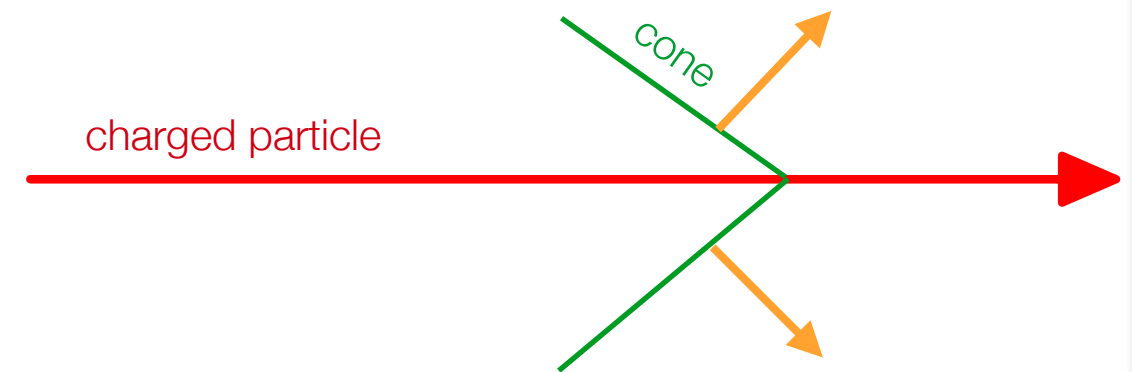


# Detection Signatures (for Monopoles)



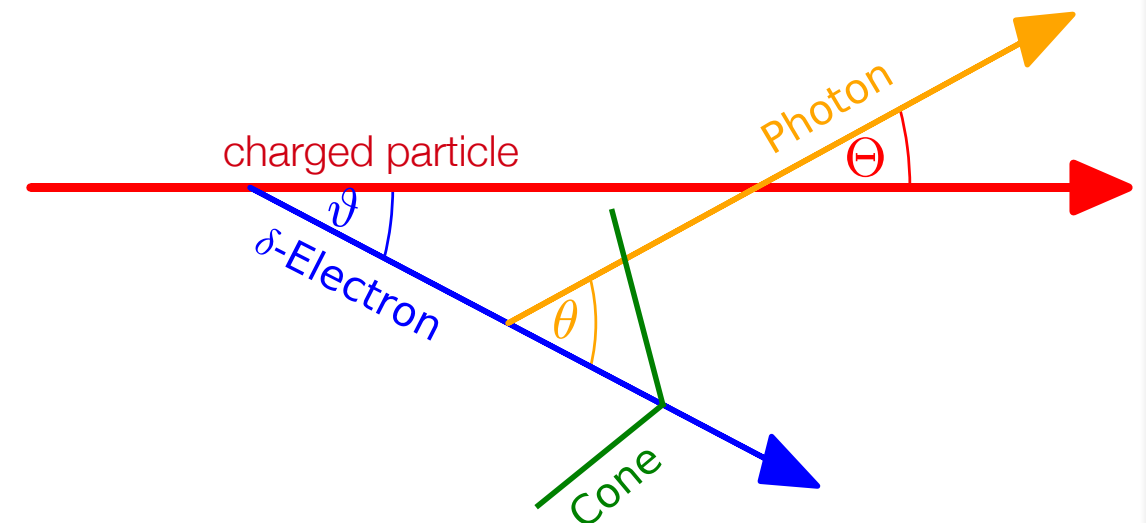
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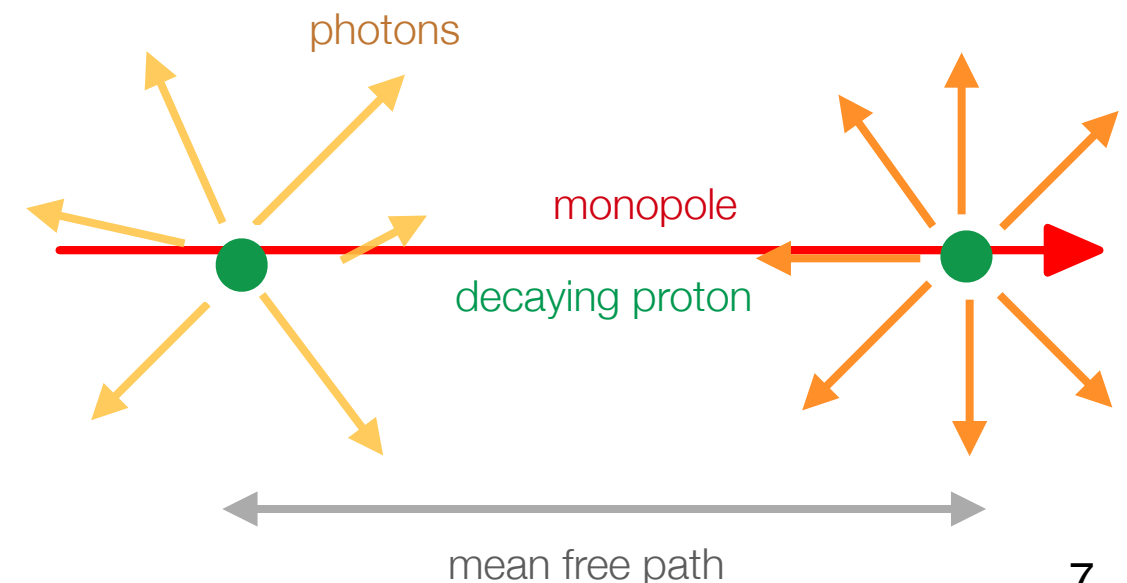
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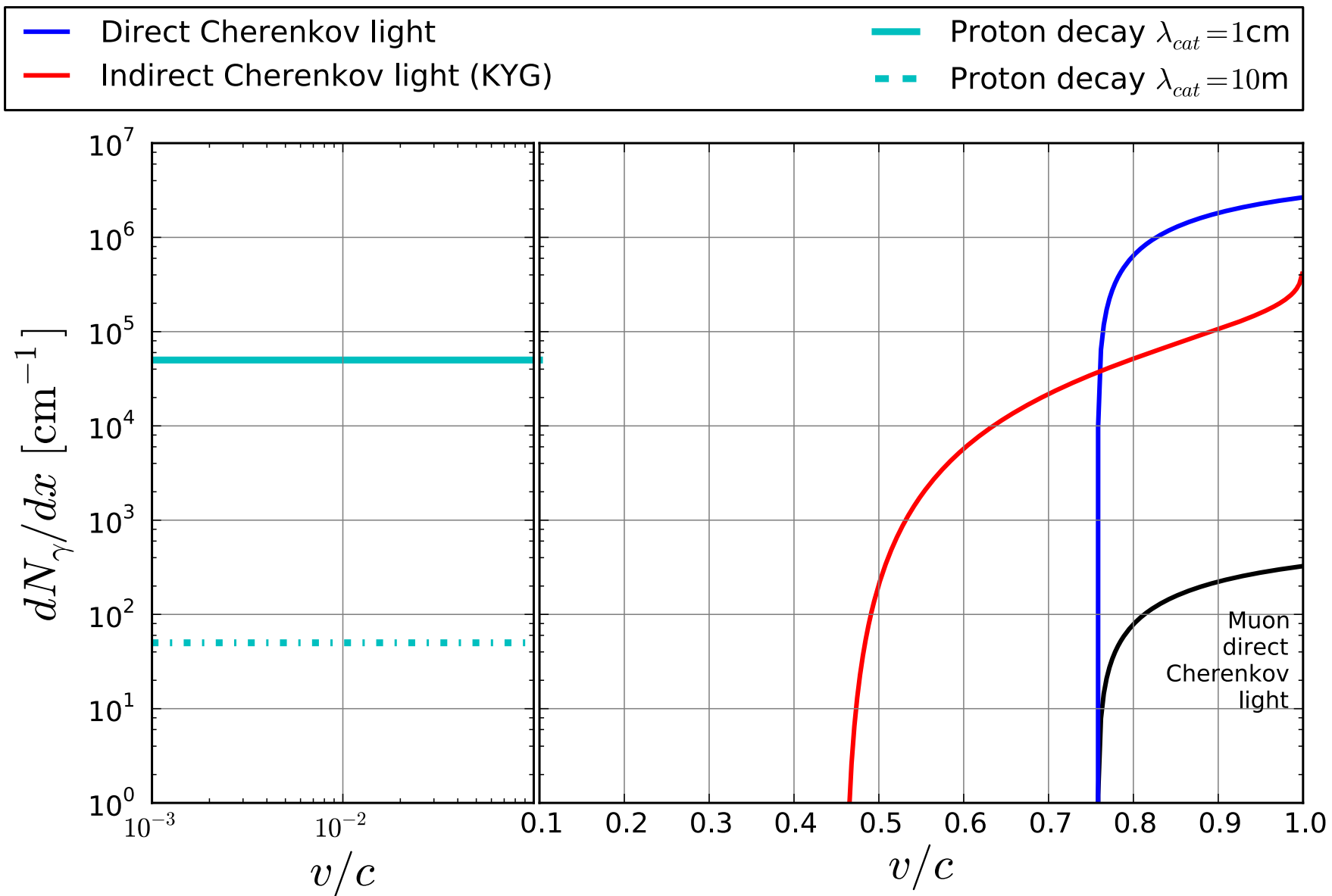
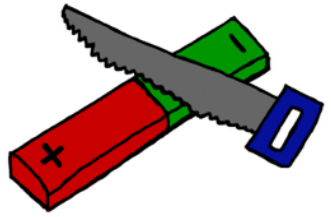
## Catalysis of proton decay

- proposed in some GUT theories
- broken symmetry in the monopole core enables  $M + p \rightarrow M + e^+ + \pi^0$
- pion decay produces cascade
- dominates for  $v < 0.1 c$

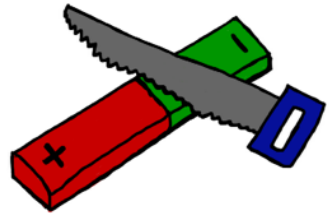




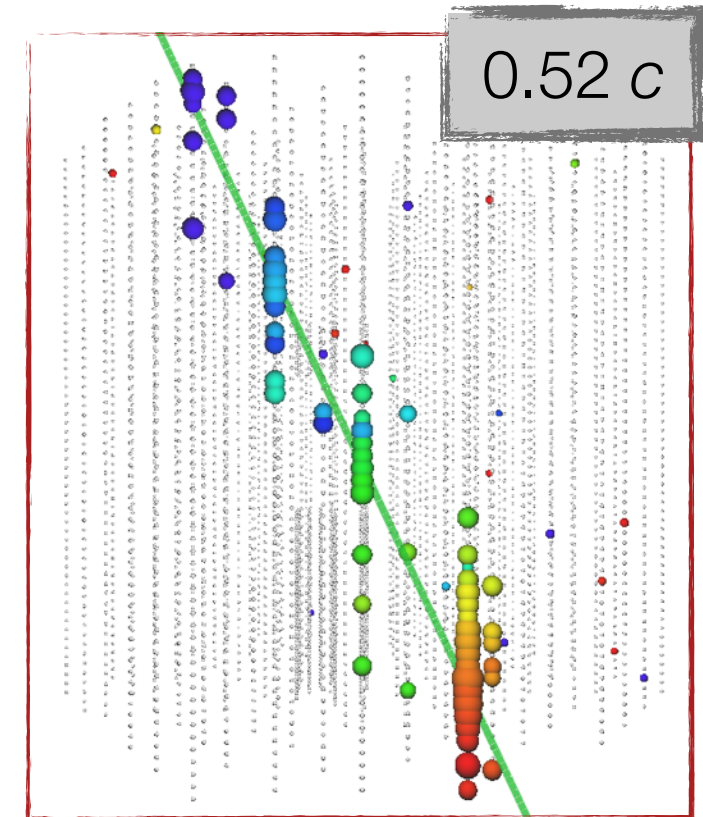
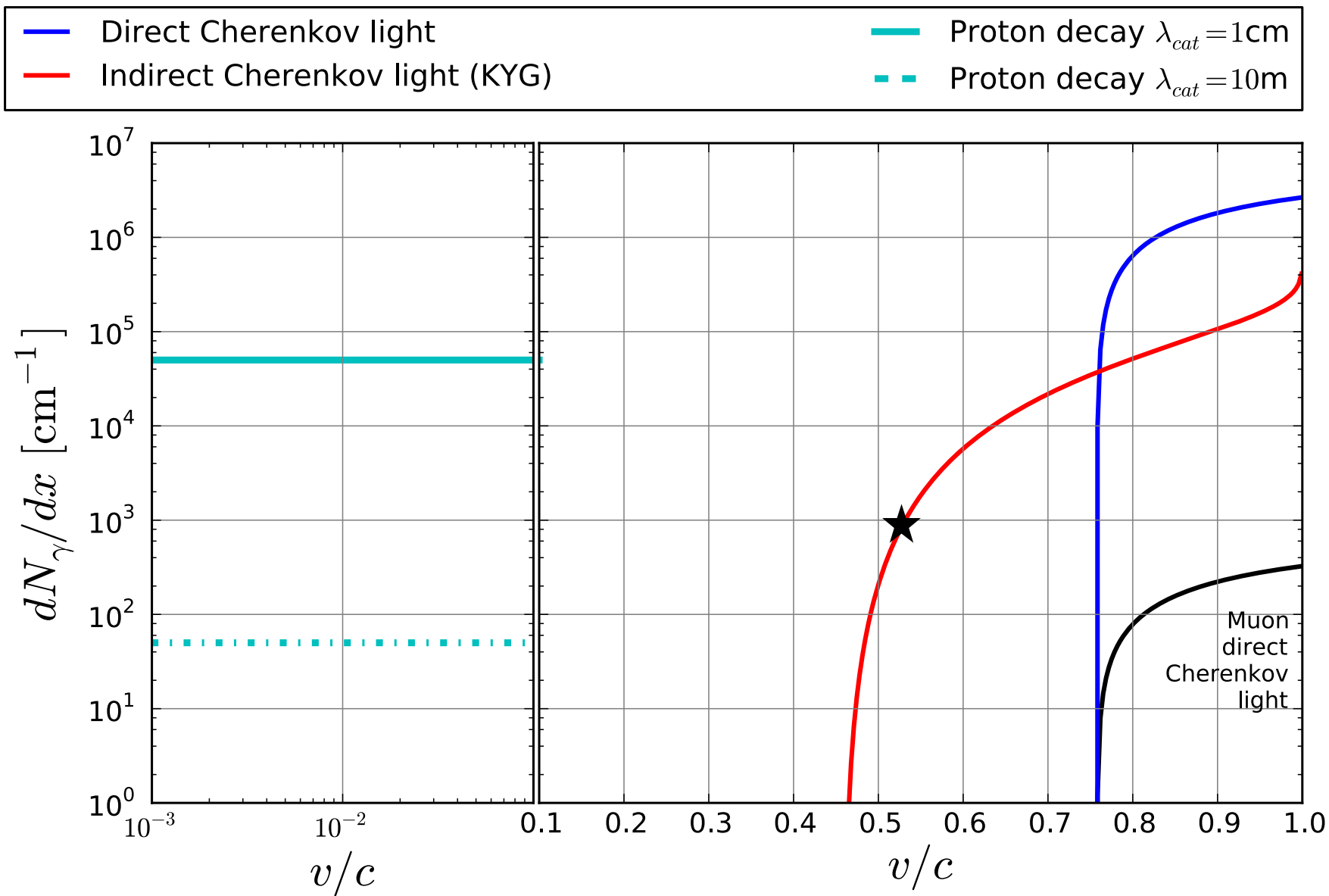
# Light Yield of Monopoles



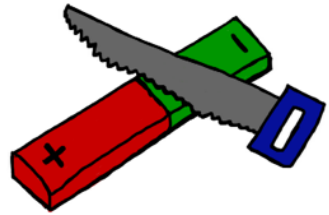
# Light Yield of Monopoles



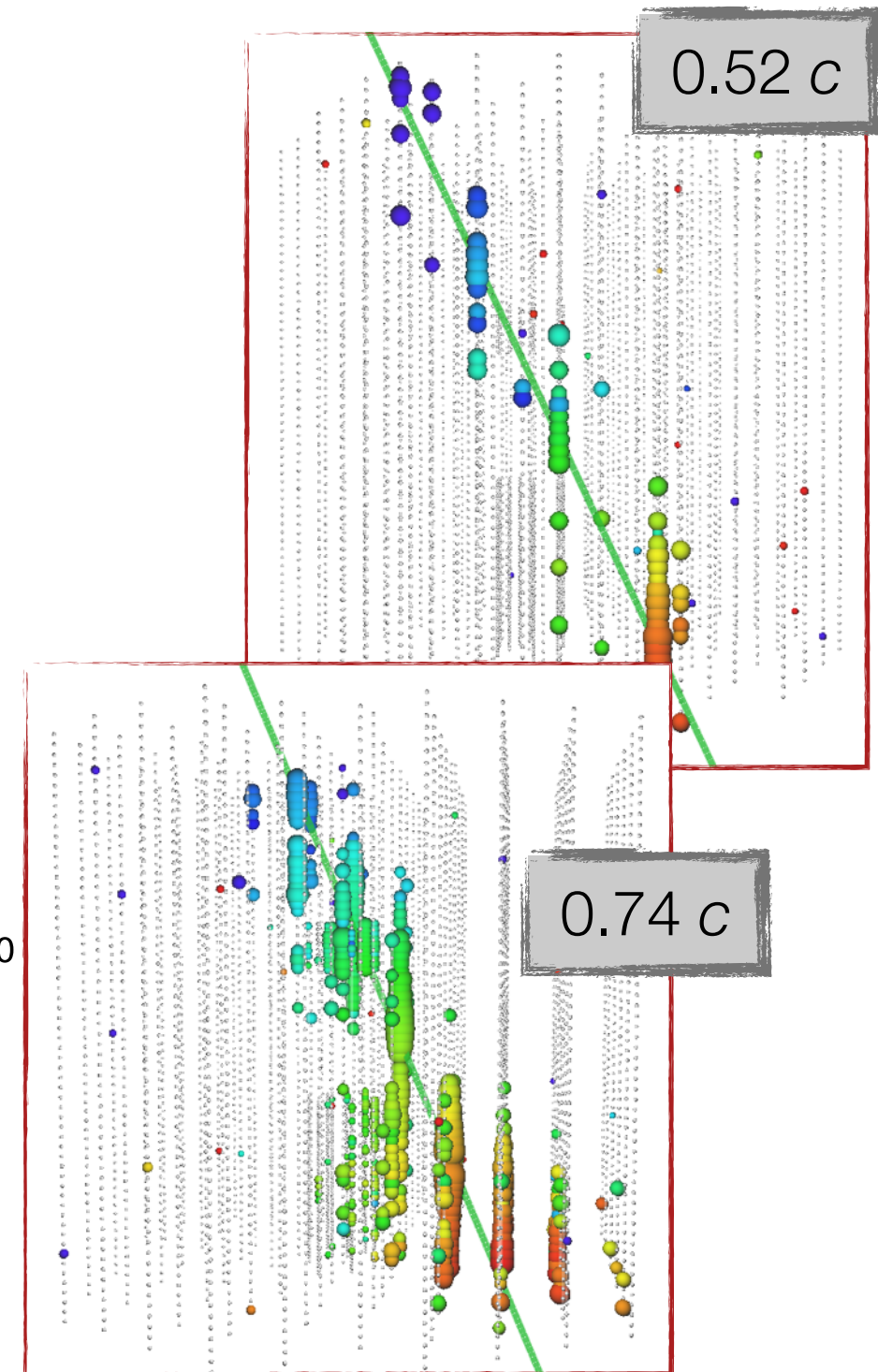
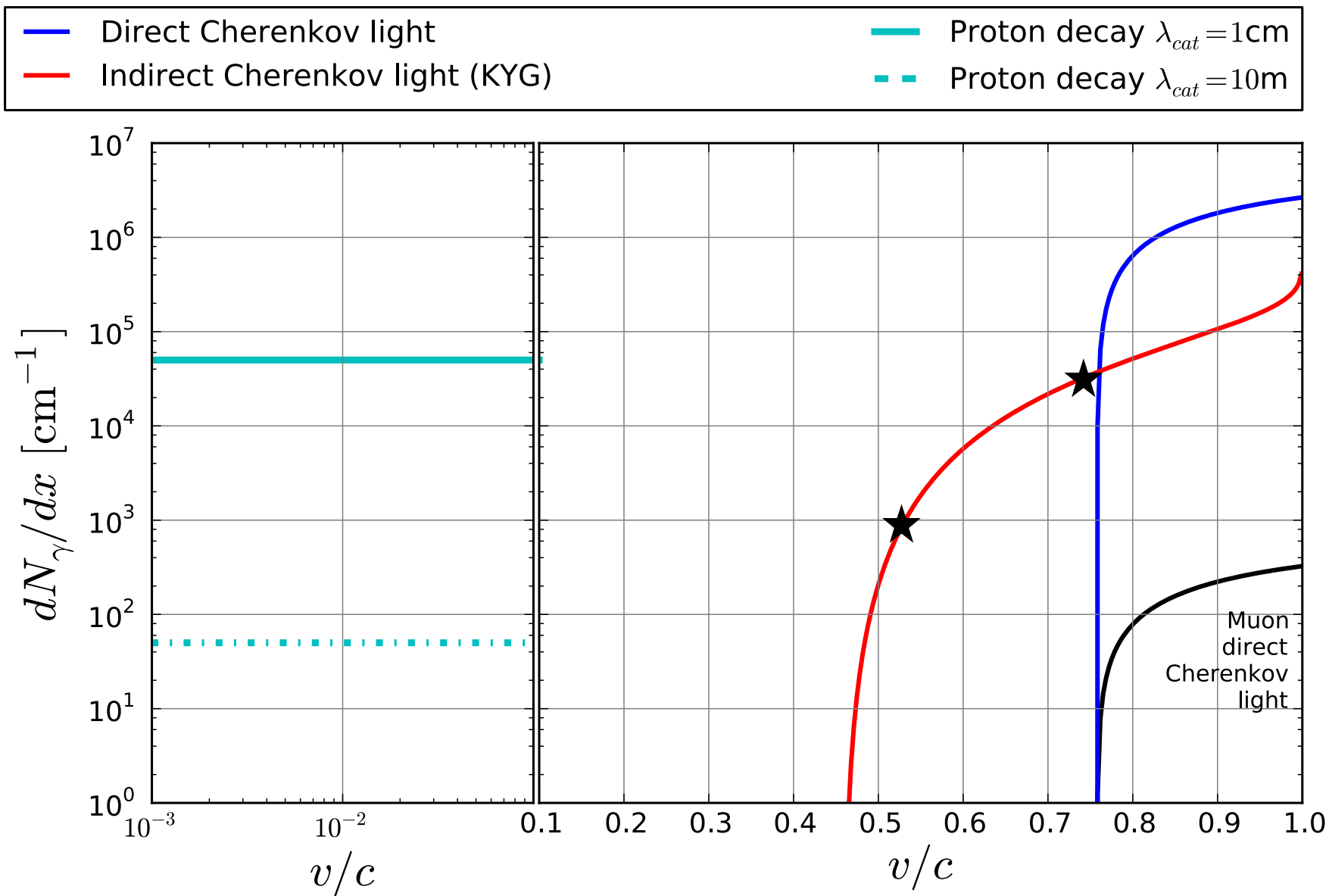
## Monopole Signatures in IceCube



# Light Yield of Monopoles

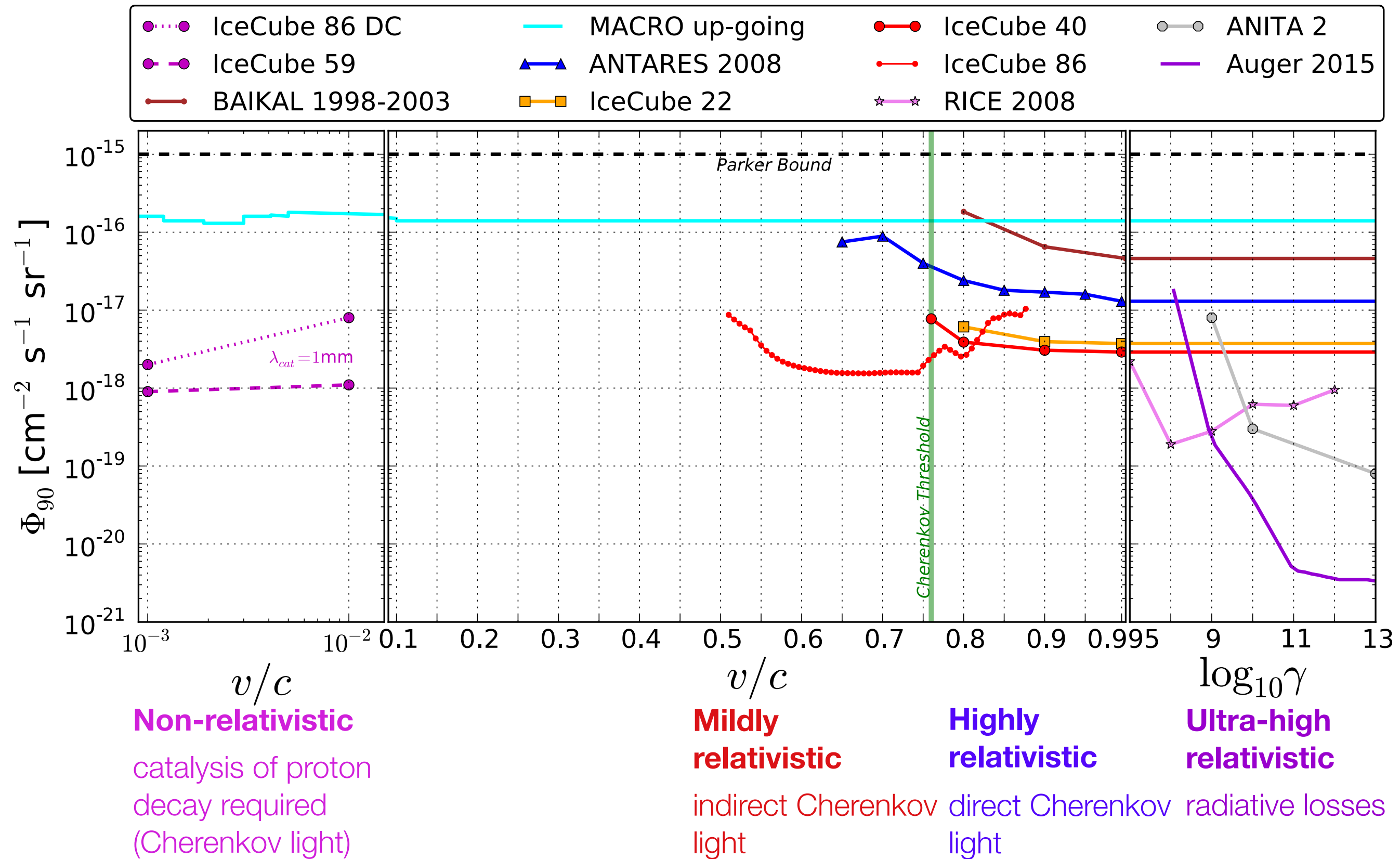
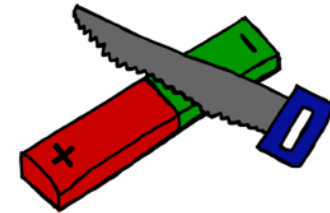


## Monopole Signatures in IceCube

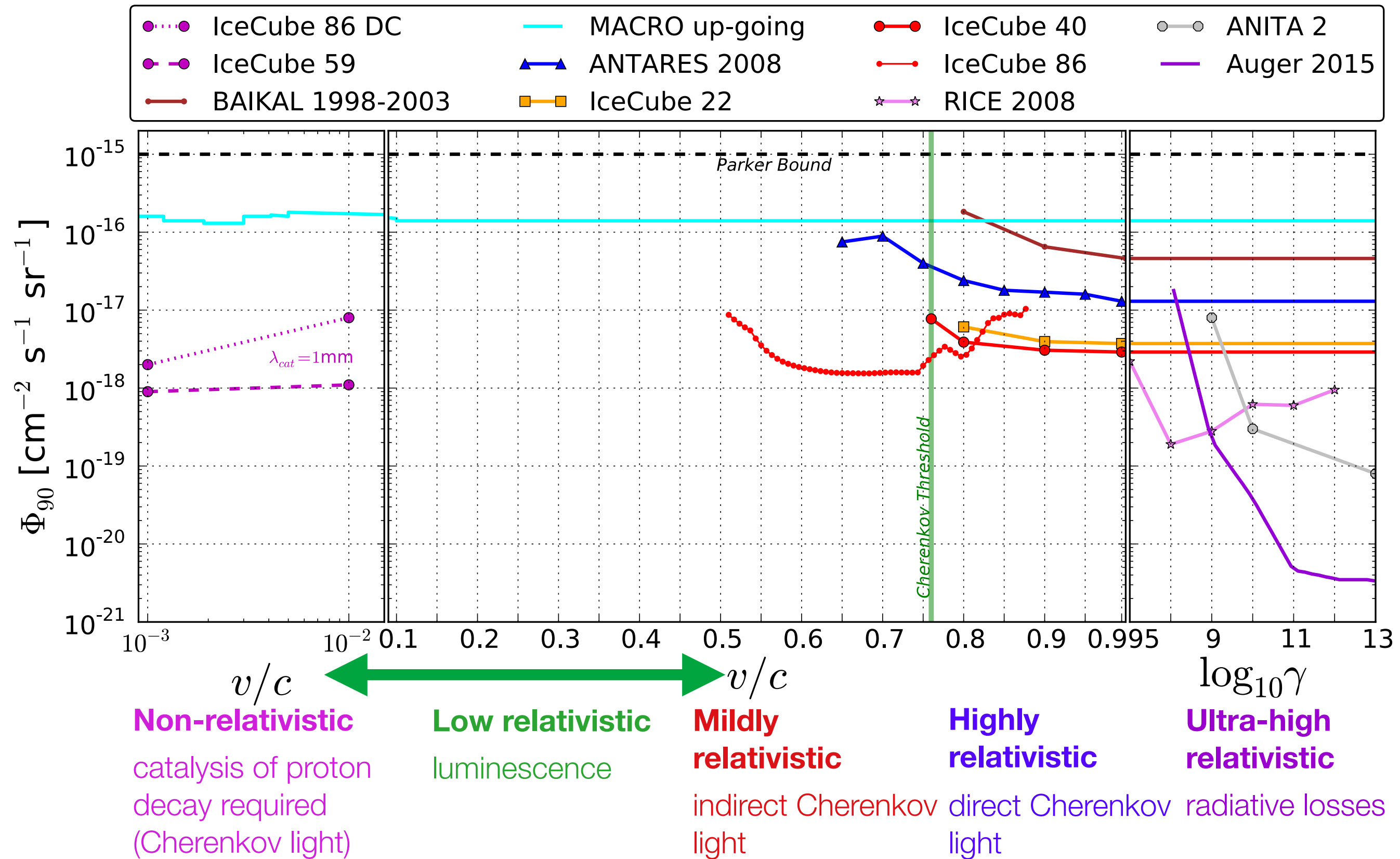
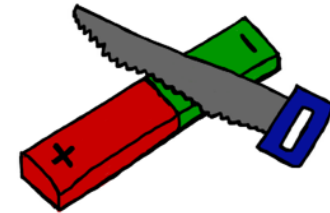




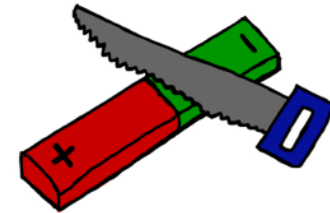
# Monopole - Searches / Interaction



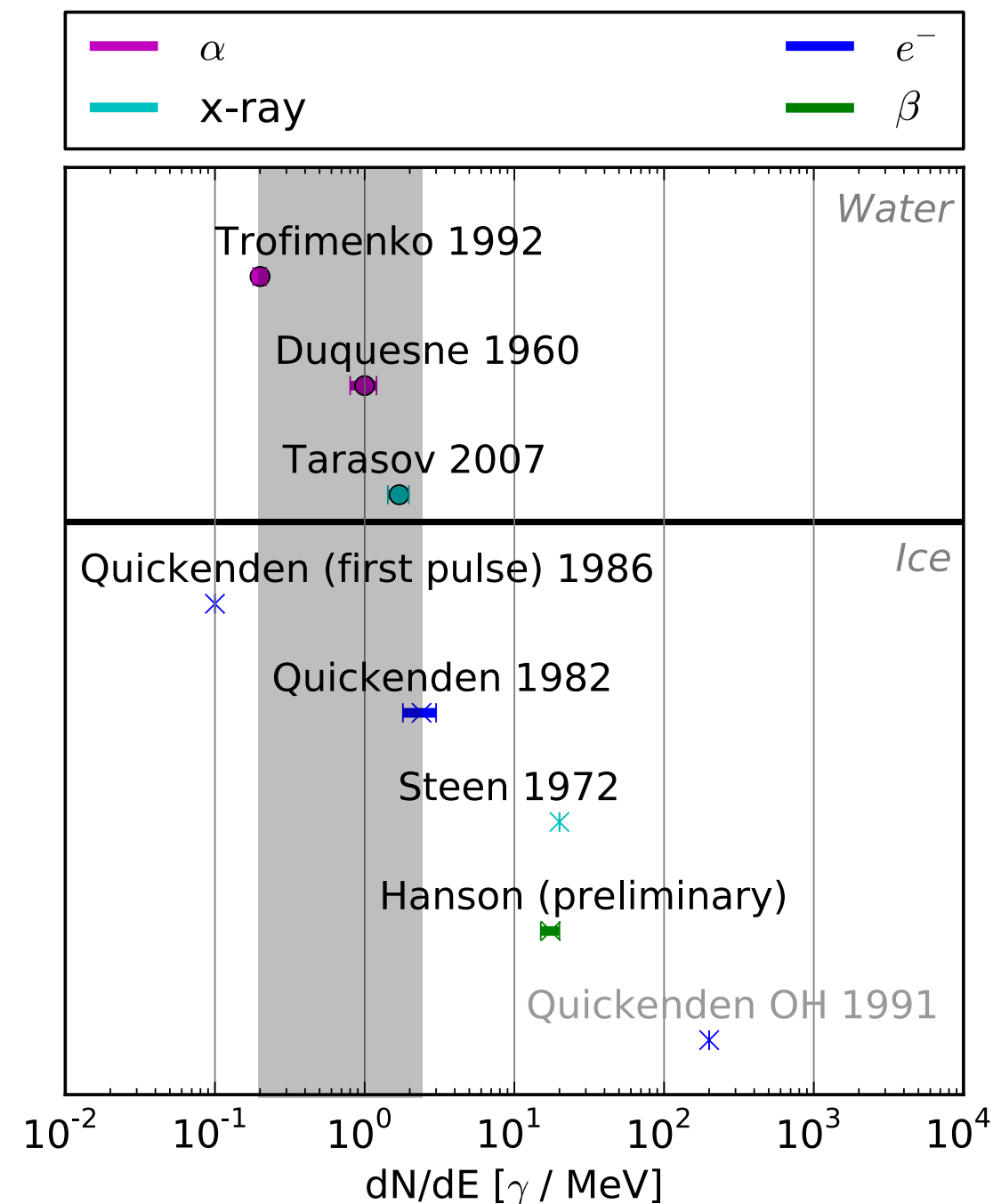
# Monopole - Searches / Interaction



# Luminescence

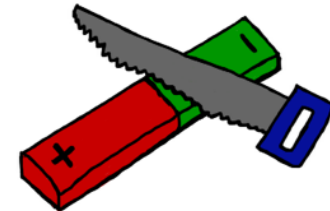


- excitation of transparent media by ionizing radiation giving light subsequently
- efficiency measurements:  
*Baikal* 0.2  $\gamma$  / MeV  
*Quickenden* 2.4  $\gamma$  / MeV
- decay time
  1. excitation level:  $\sim 300$  ns
  3. excitation level:  $\sim 2000$  ns
- emission spectrum lines:
  - $\sim 290$  nm
  - $\sim 380$  nm
  - $\sim 550$  nm
- temperature dependence



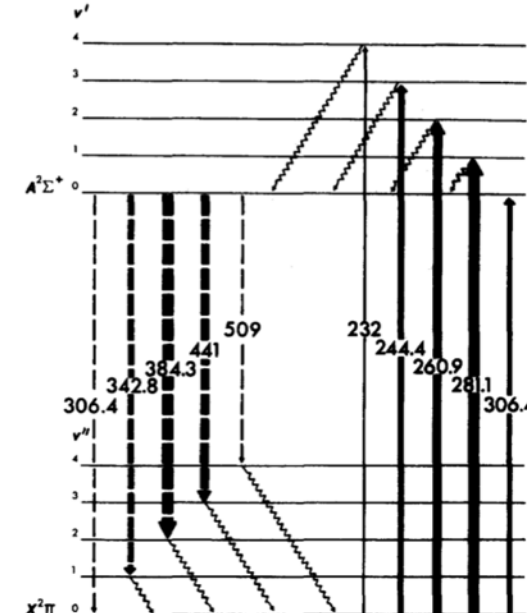


# Luminescence

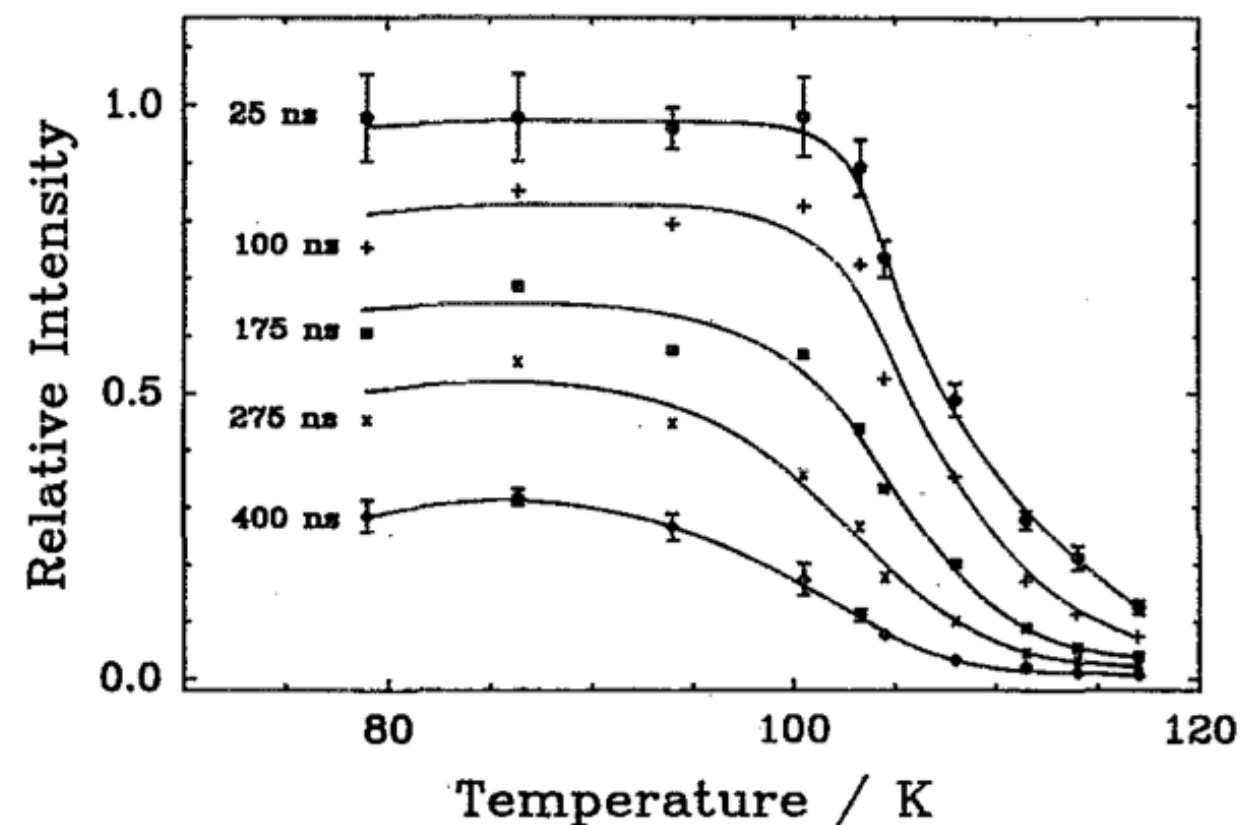


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 $\sim 290$  nm  
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 $\sim 550$  nm
- temperature dependence

OH vibrational states

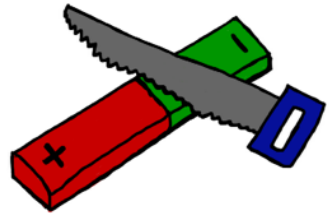


Quickenden '86

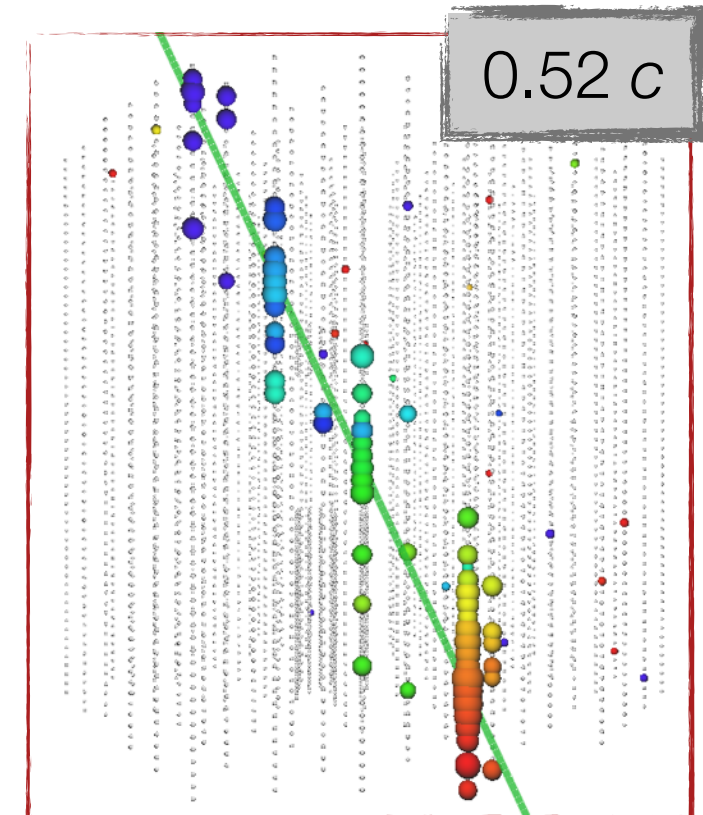
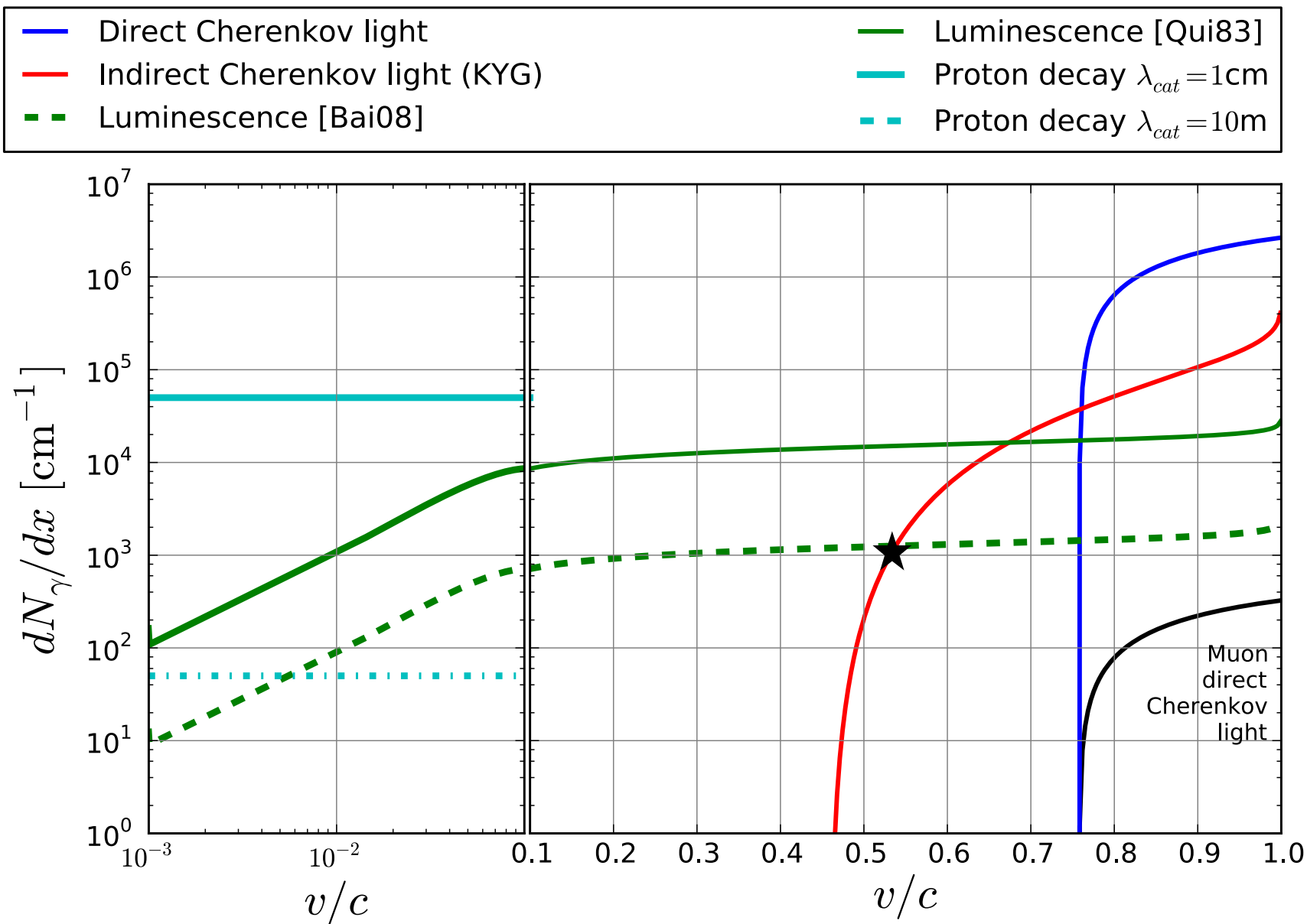


Quickenden '86

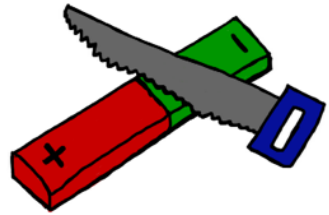
# Light Yield of Monopoles



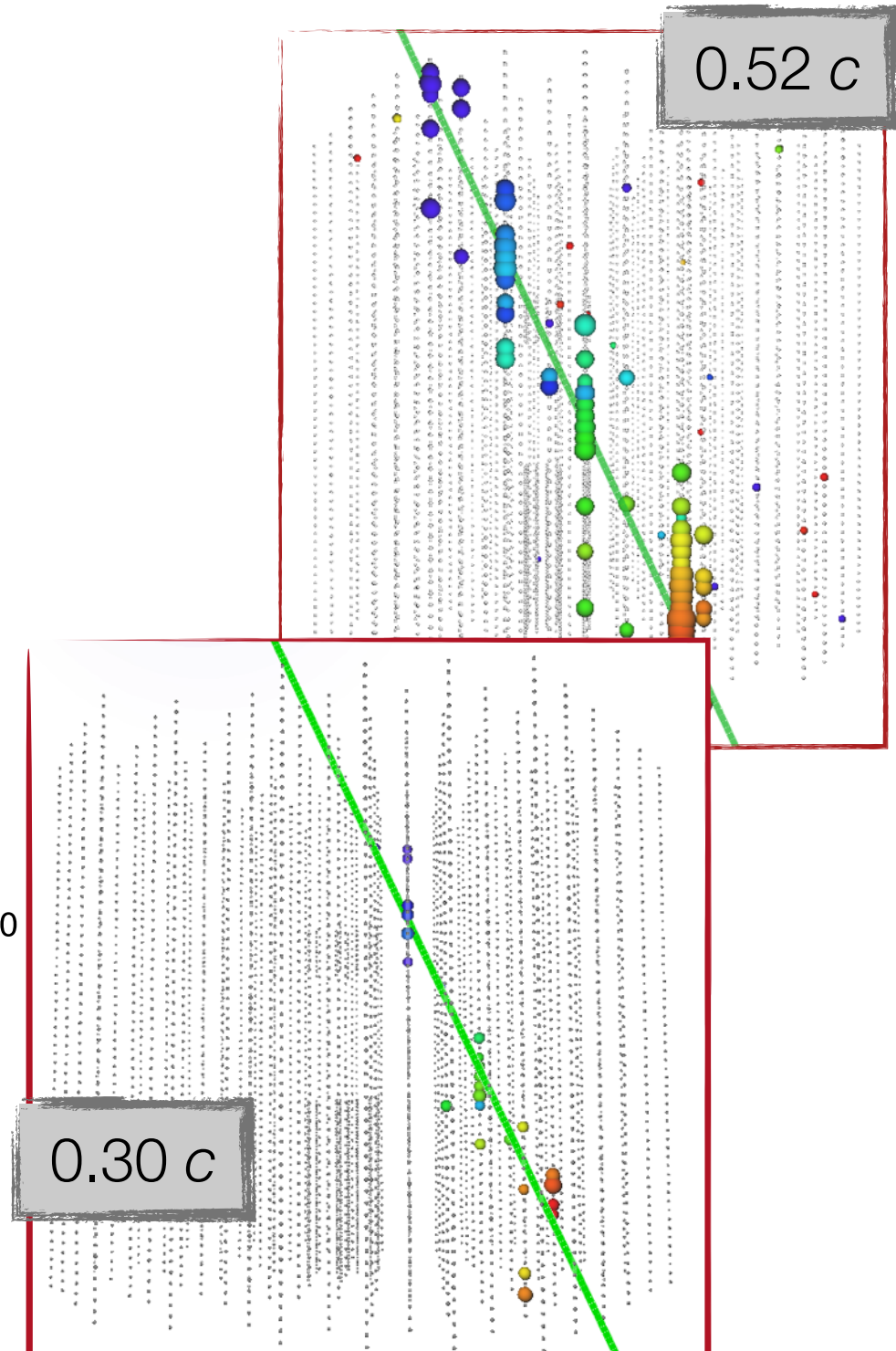
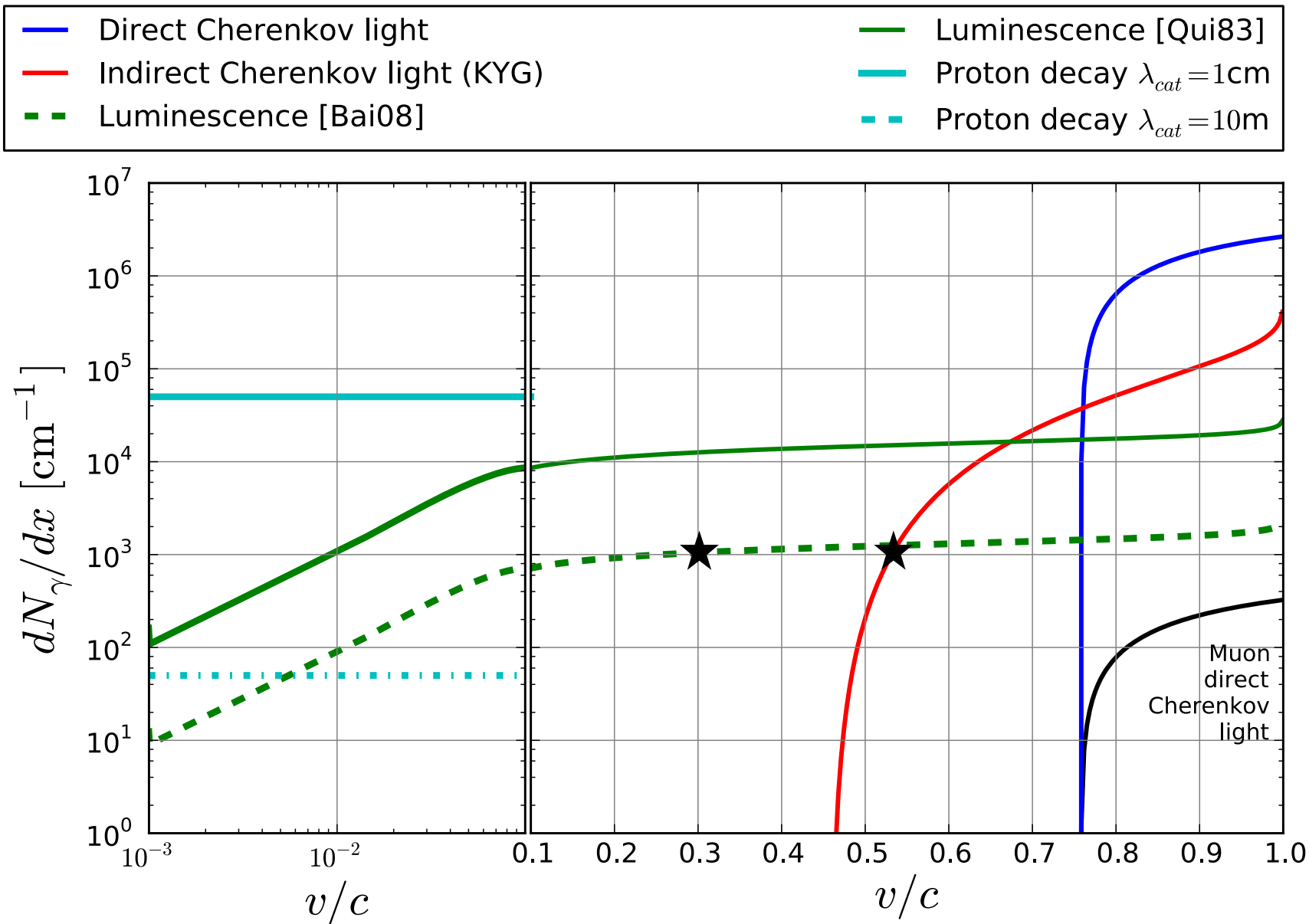
## Monopole Signatures in IceCube



# Light Yield of Monopoles

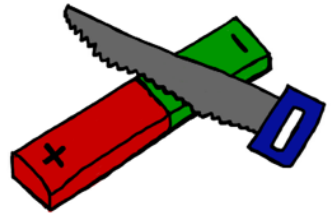


## Monopole Signatures in IceCube



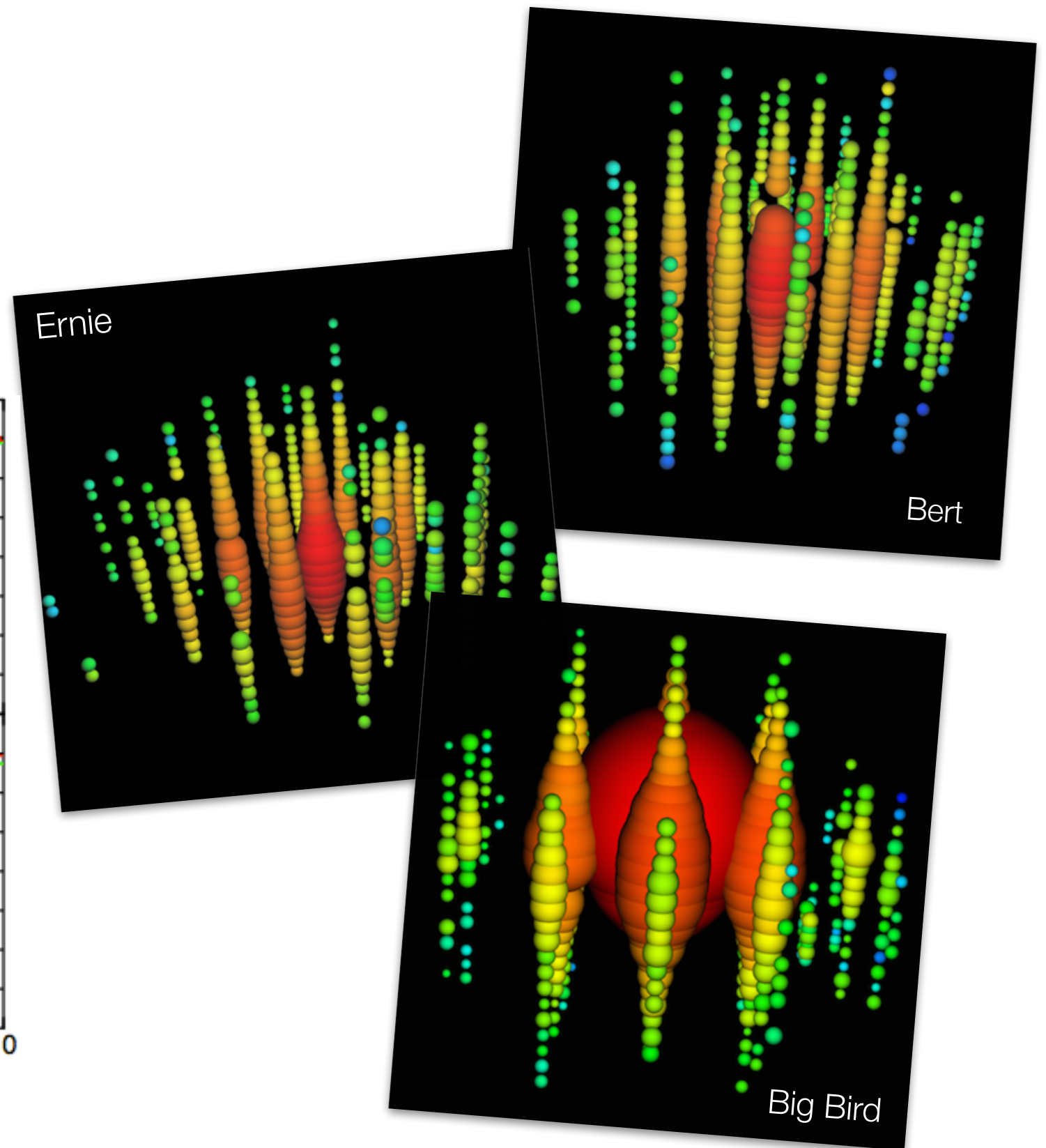
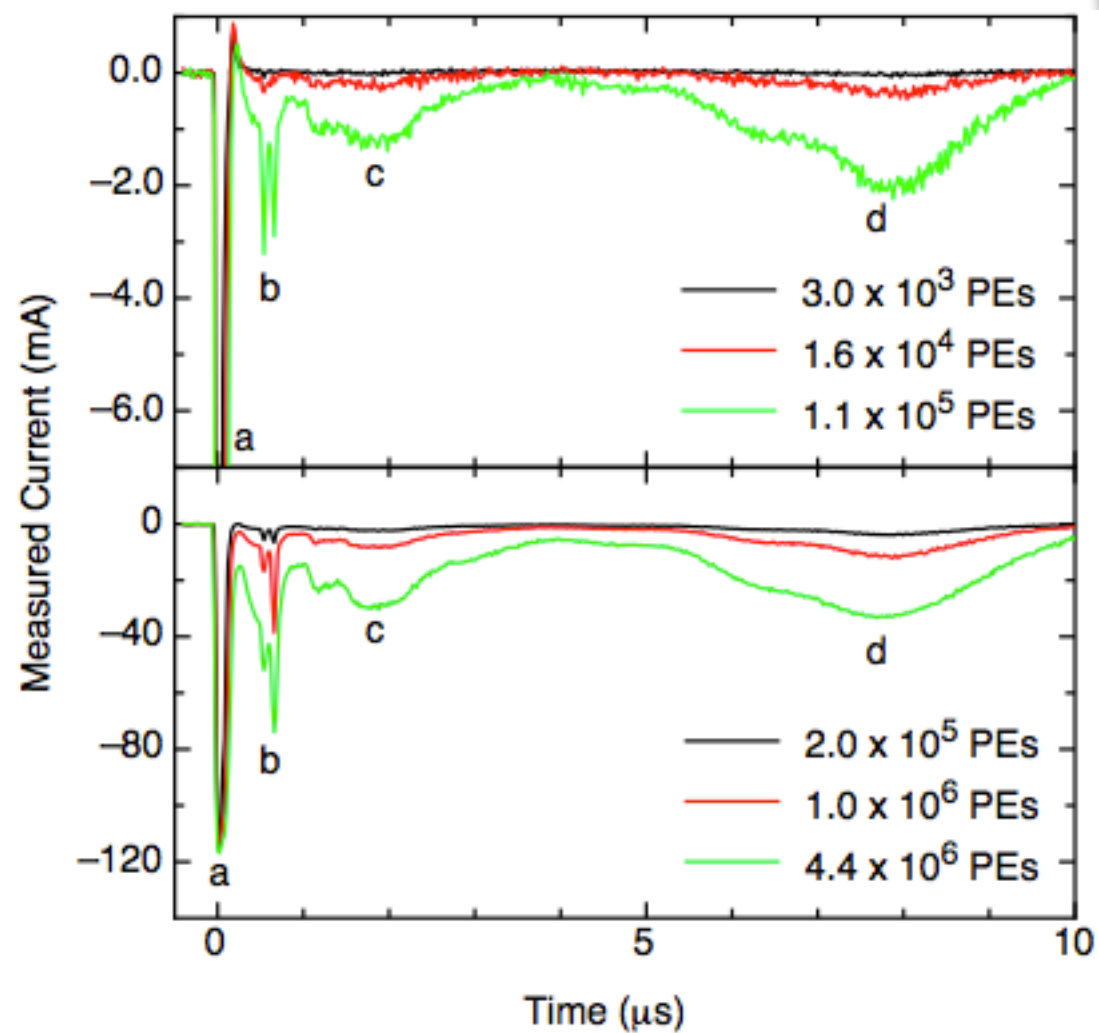


# Luminescence Measurements

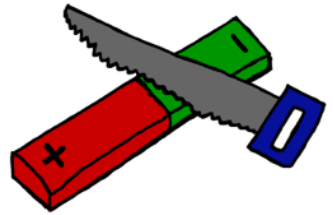


## In situ measurement

- high energetic astrophysical neutrino events

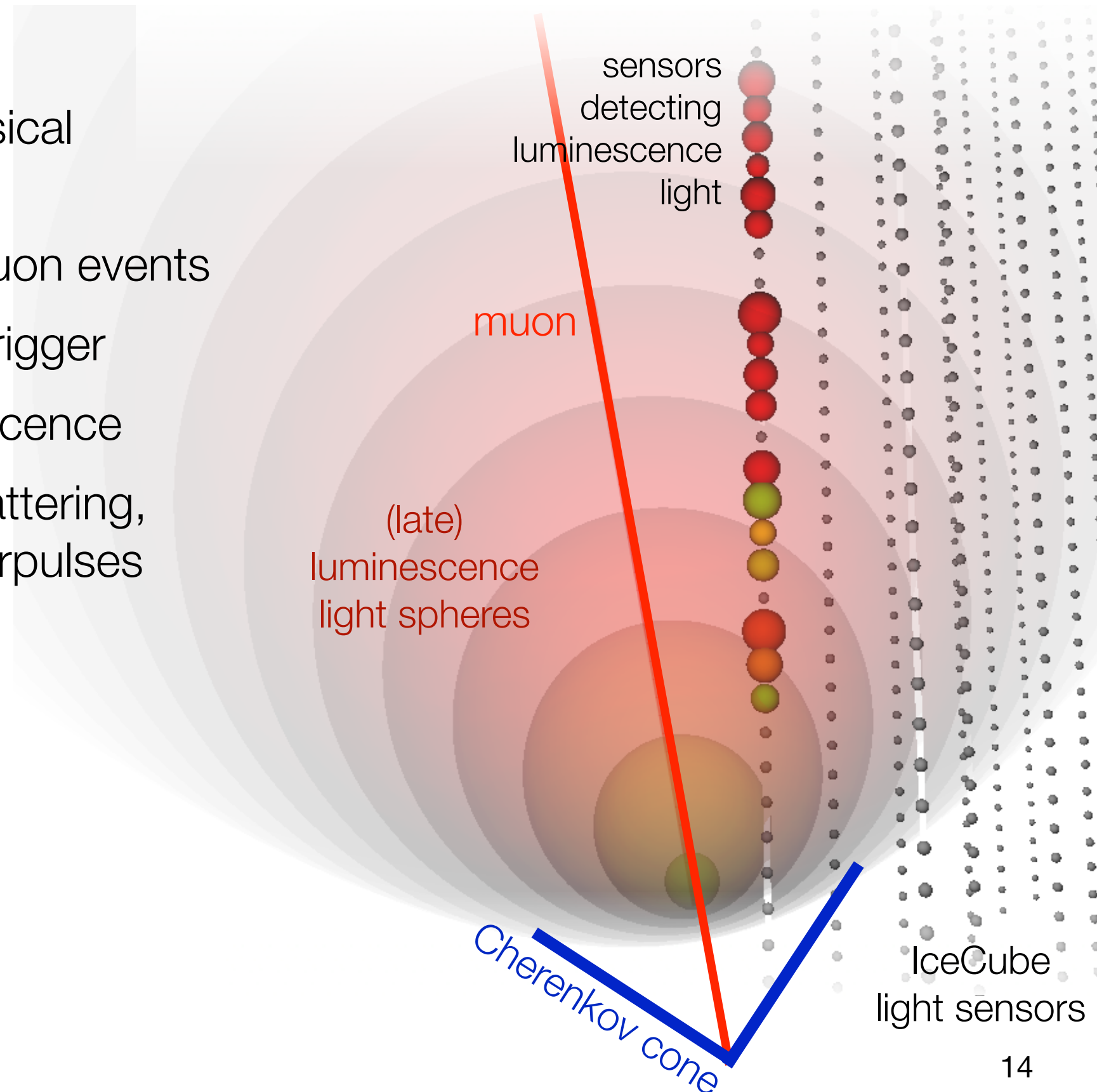


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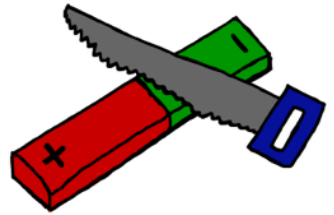


## In situ measurement

- high energetic astrophysical neutrino events
- low energetic vertical muon events
  - Cherenkov cone as trigger
  - late hits from luminescence
  - background from scattering, PMT noise, PMT afterpulses



# Luminescence Measurements

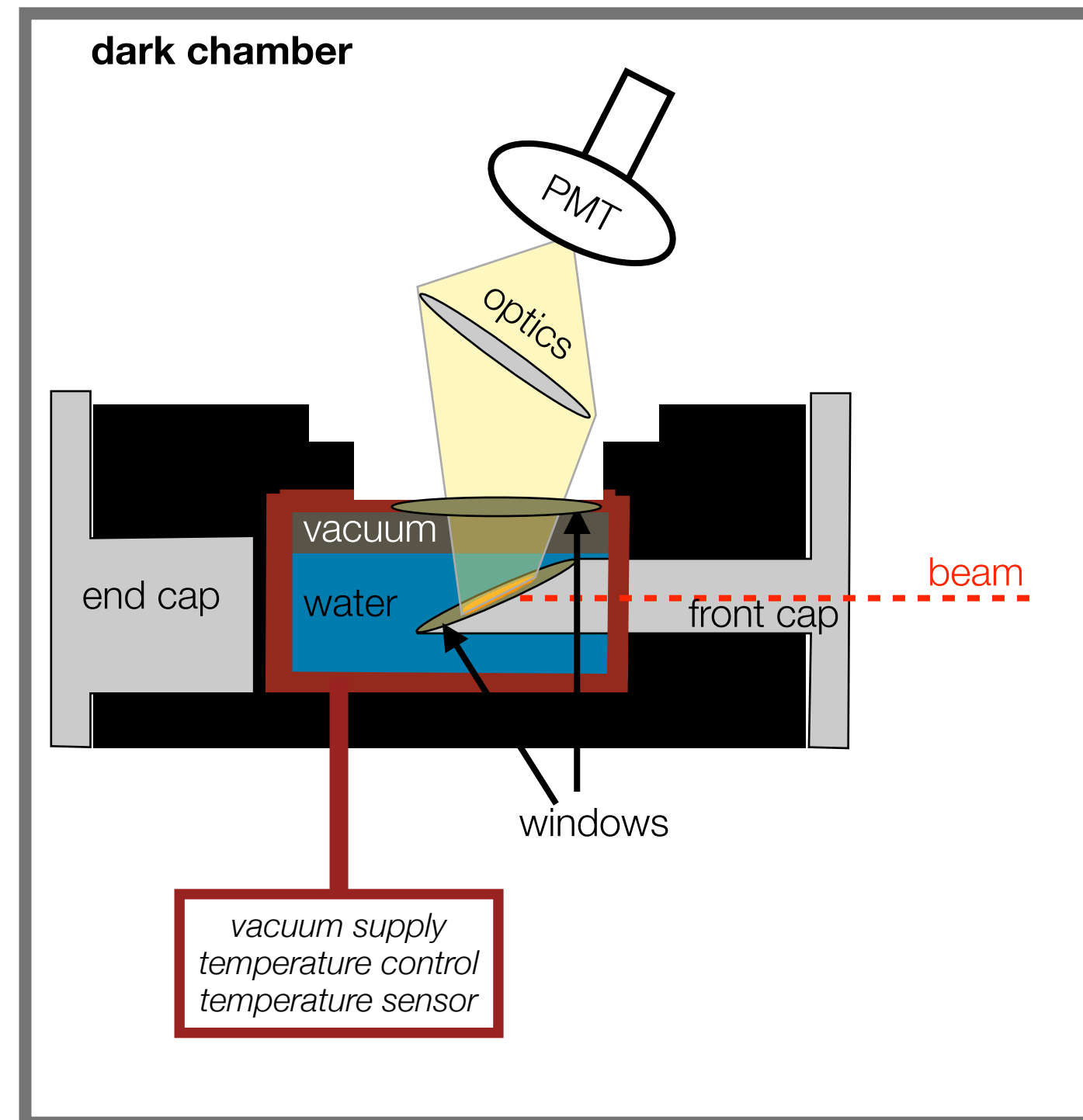


## Setup

- using ultra pure water
- materials allowed contact with water:
  - copper
  - polypropylene
  - borosilicate glass
- optics customized for the given conditions

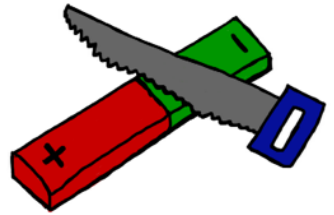
## Procedure

1. calibration using known scintillator together with a source / e<sup>-</sup>-gun
2. sample of ultra pure water / ice irradiated by different ions / energies
3. sample of South Pole ice



*Inspired by Hofmann '12*

# Luminescence Measurements

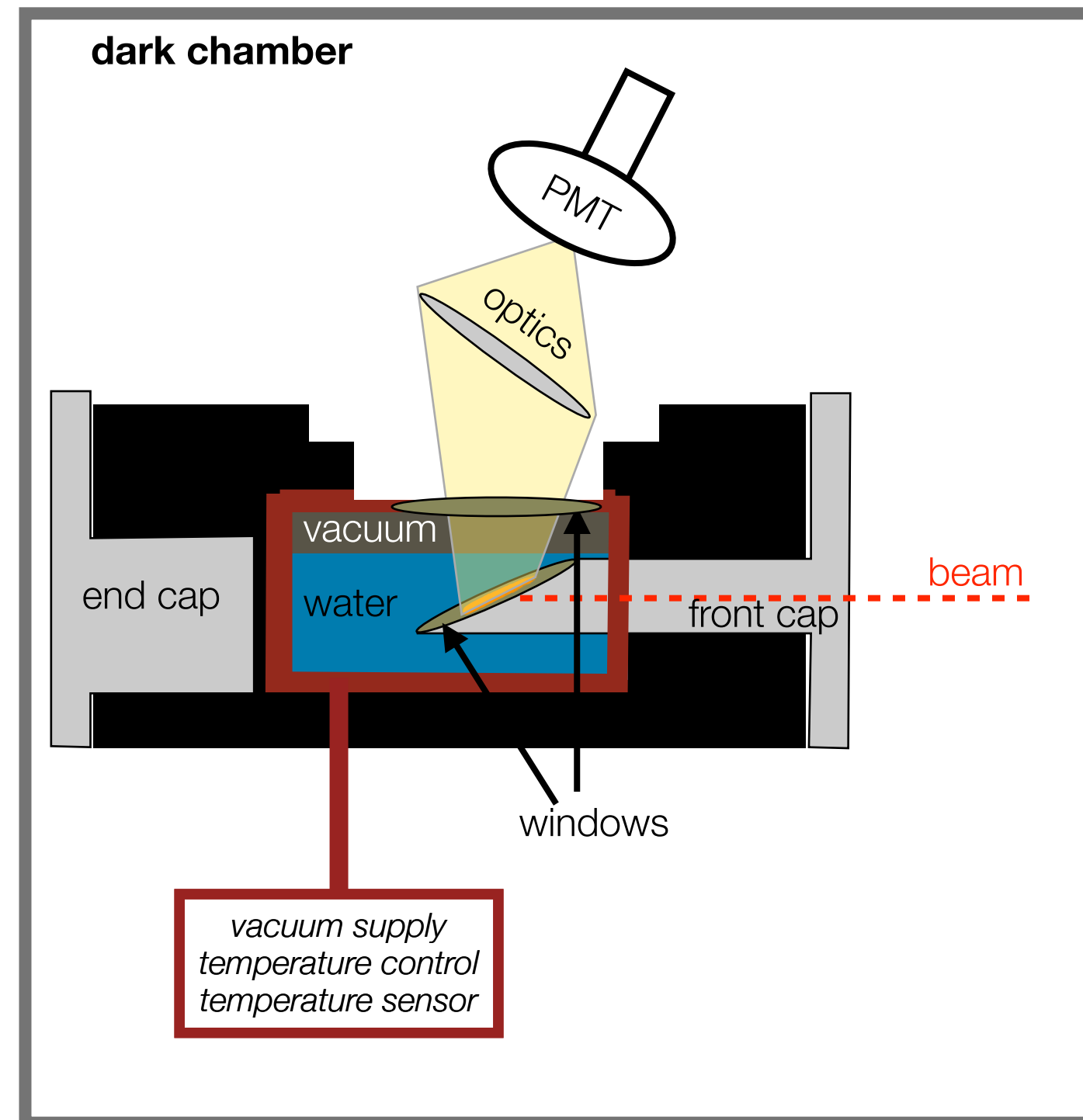


## Measurements

- $dN_\gamma/dE_{\text{dep}}$ : luminescence efficiency
- $\tau$ : life times of excited states
- $\lambda$ : wavelength spectrum

## Dependencies

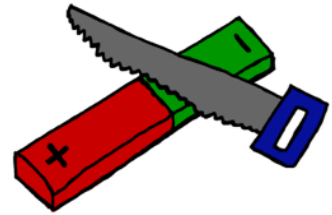
- temperature -50 - +20°C
- radiation type ( $e^-$ , ions, UV)
- impurities (air, surrounding materials)



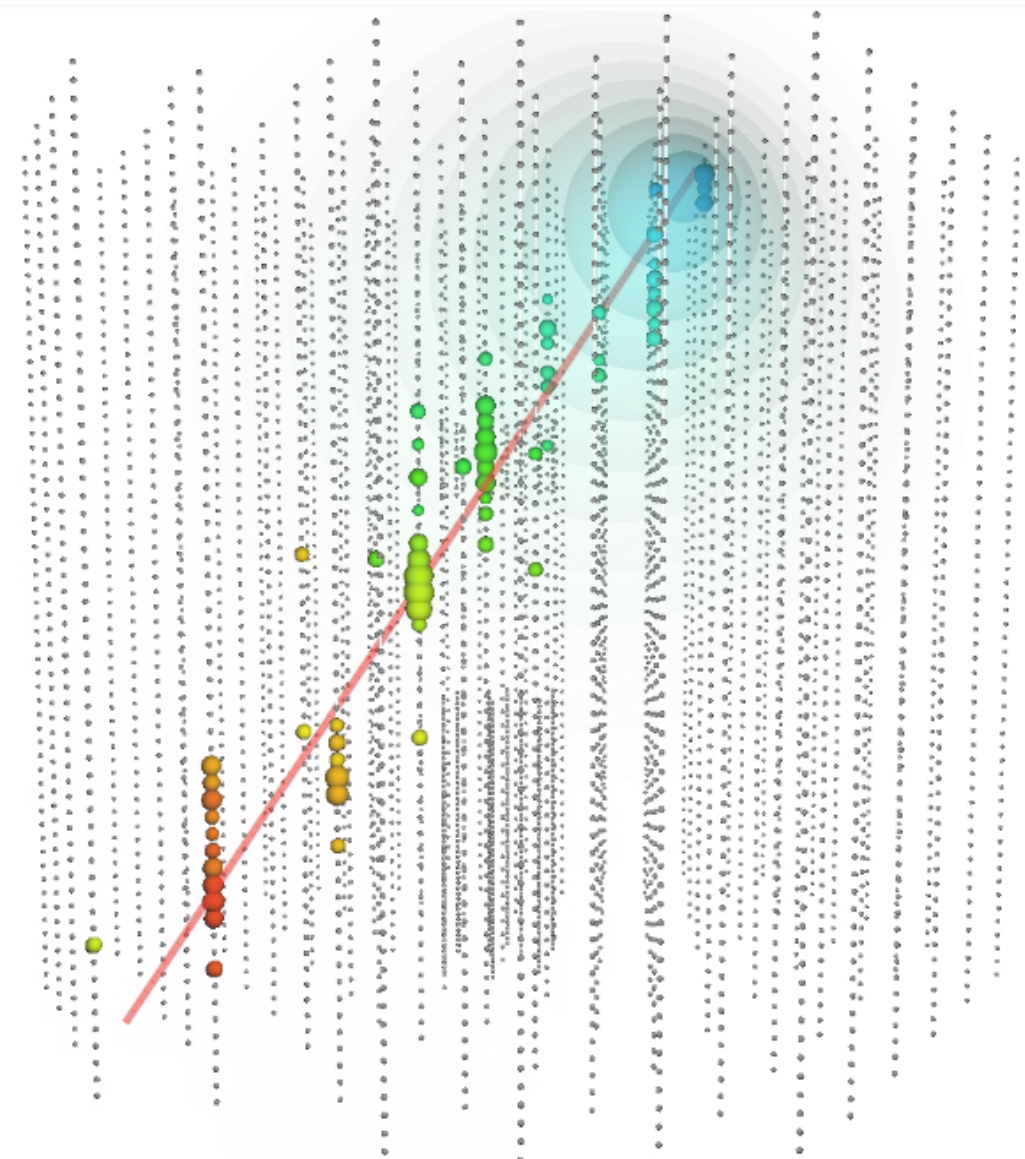
*Inspired by Hofmann '12*



# Summary / Outlook

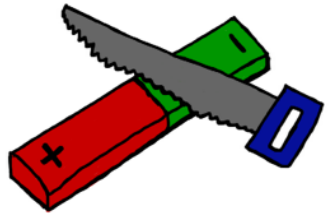


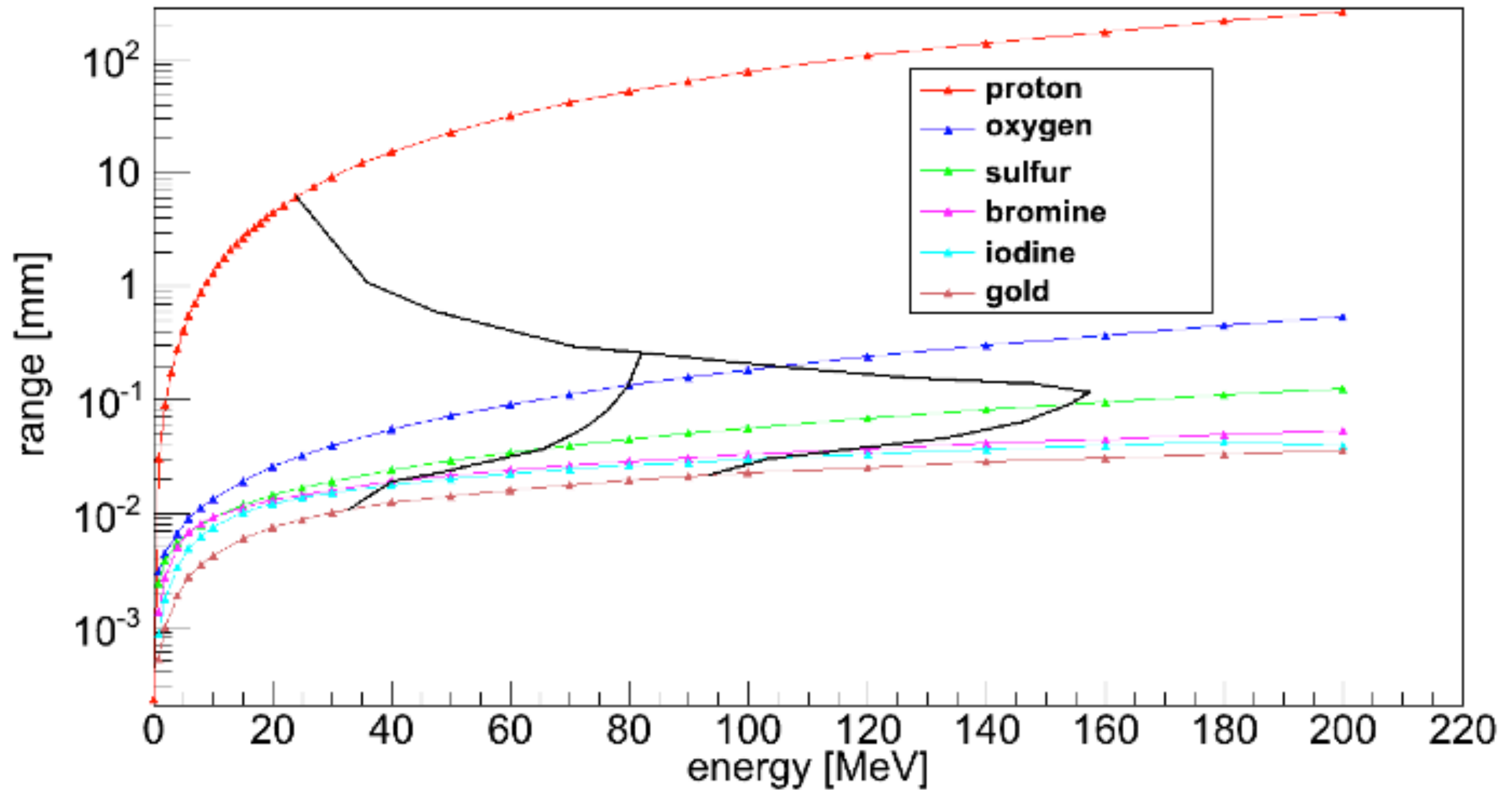
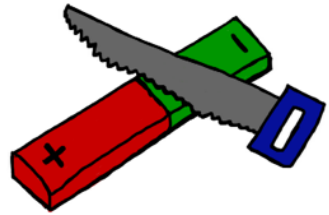
- magnetic monopoles are promising candidates for physics beyond the standard model
- experimental limits supersede theoretical upper bounds
- no recent measurement at low relativistic monopole speeds
- luminescence of pure water could be a new detection signature in water Cherenkov neutrino telescopes
- lab measurement of luminescence is in preparation



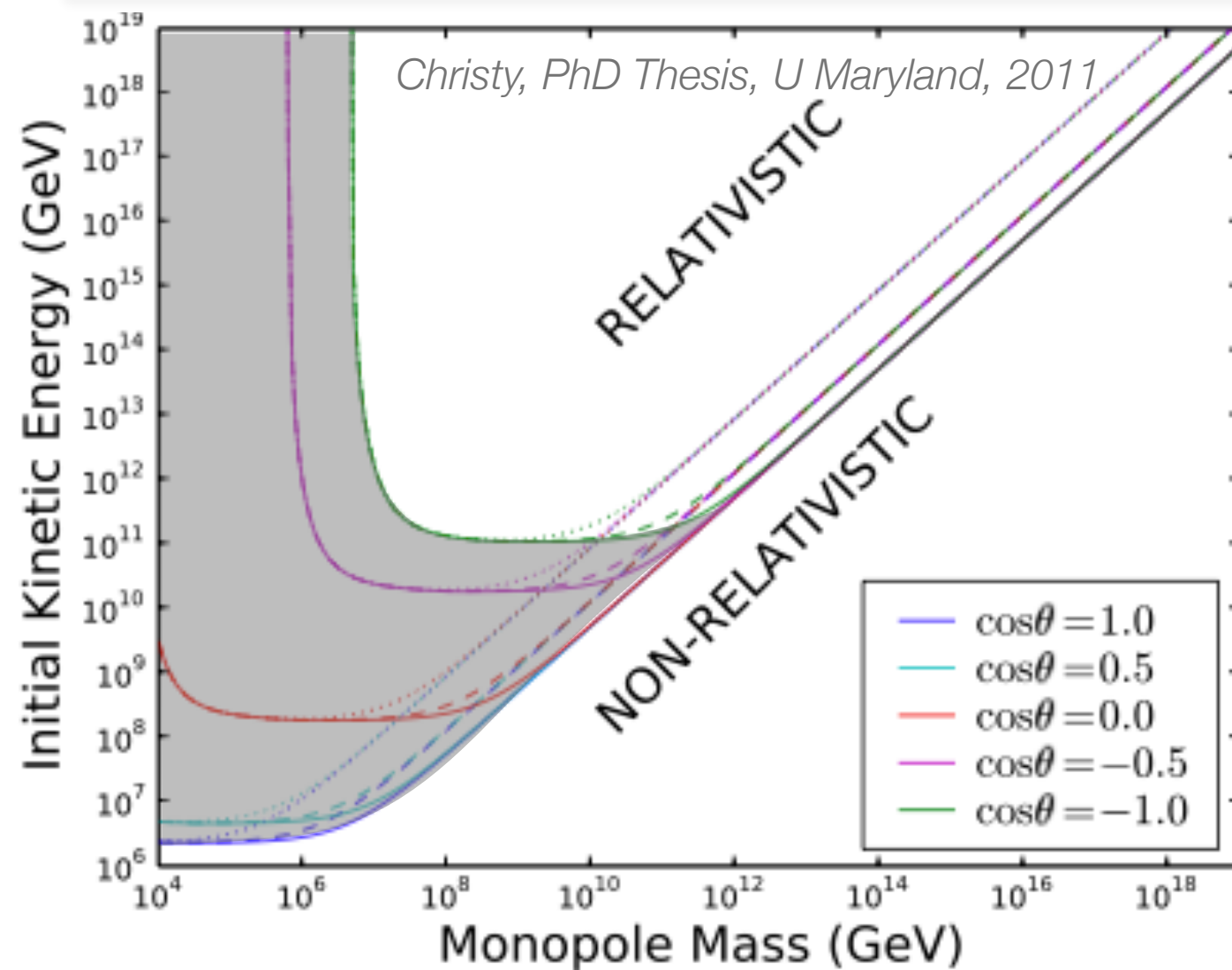
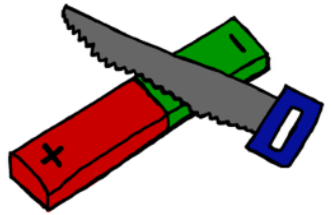
# Backup

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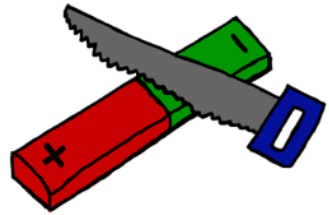
# Parameter space



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

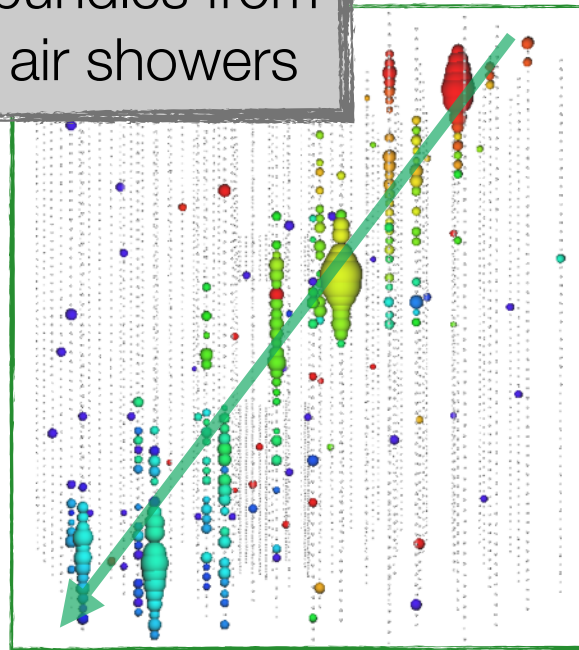


# Monopole vs Background

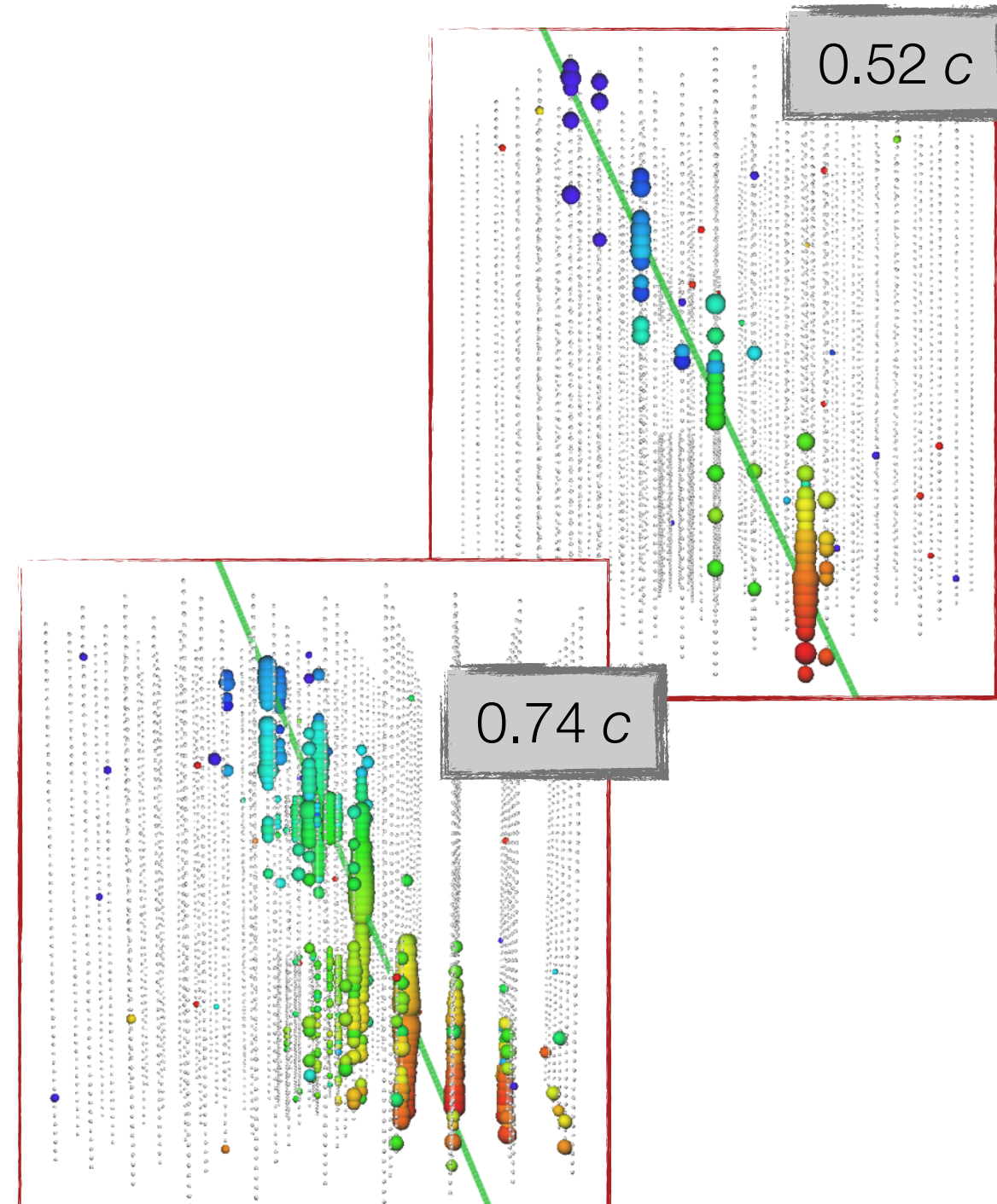


## Background

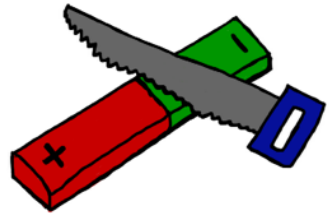
muon  
bundles from  
air showers



## Monopoles

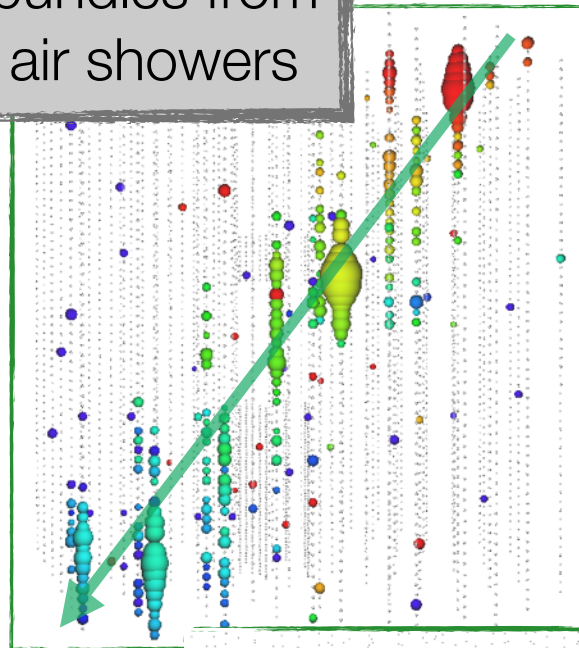


# Monopole vs Background

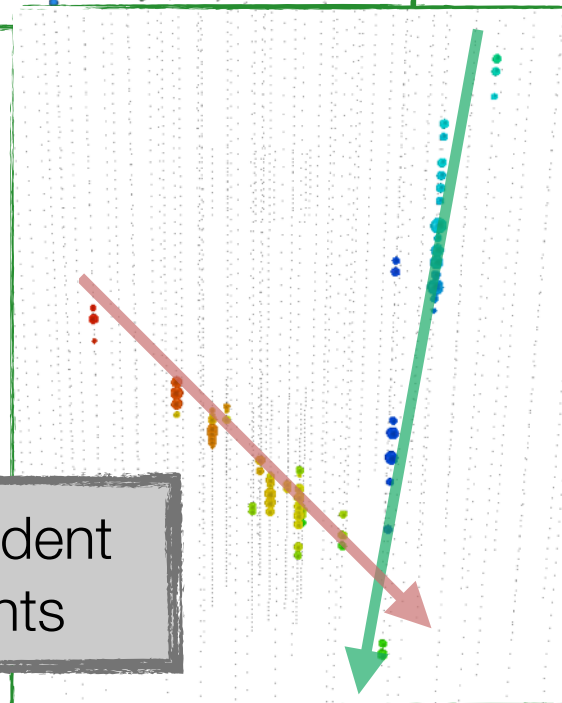


## Background

muon  
bundles from  
air showers

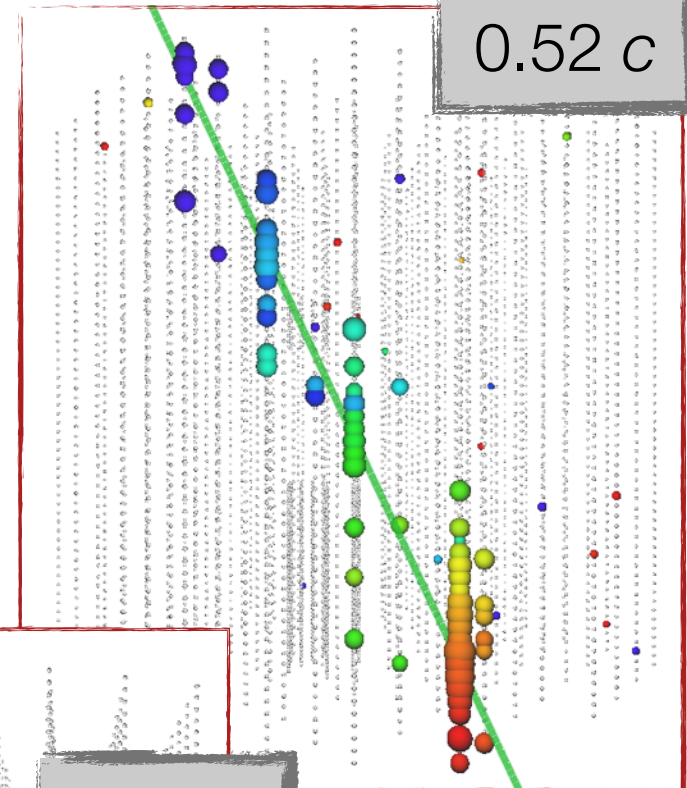


coincident  
events

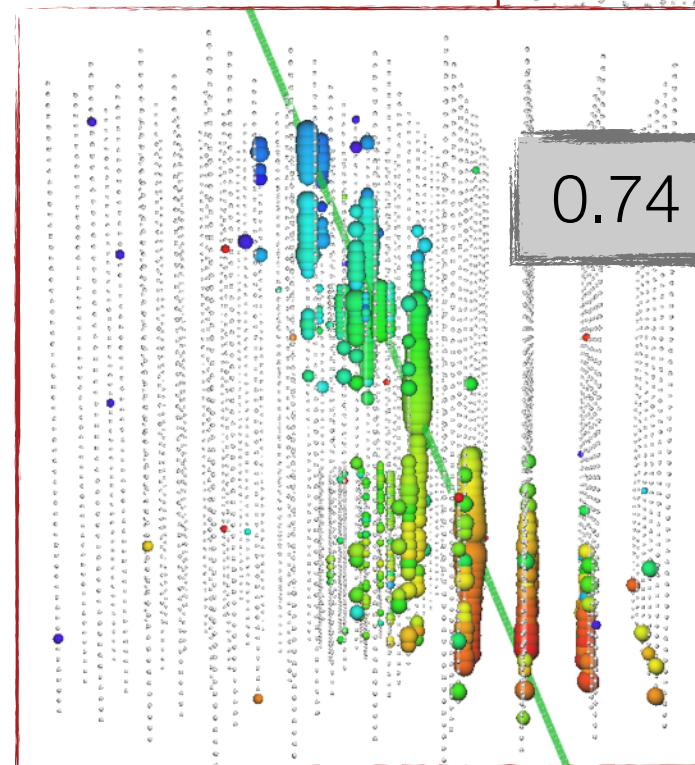


## Monopoles

0.52 c

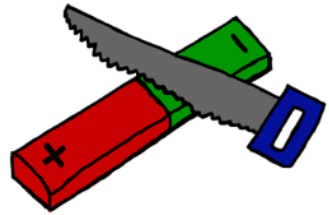


0.74 c





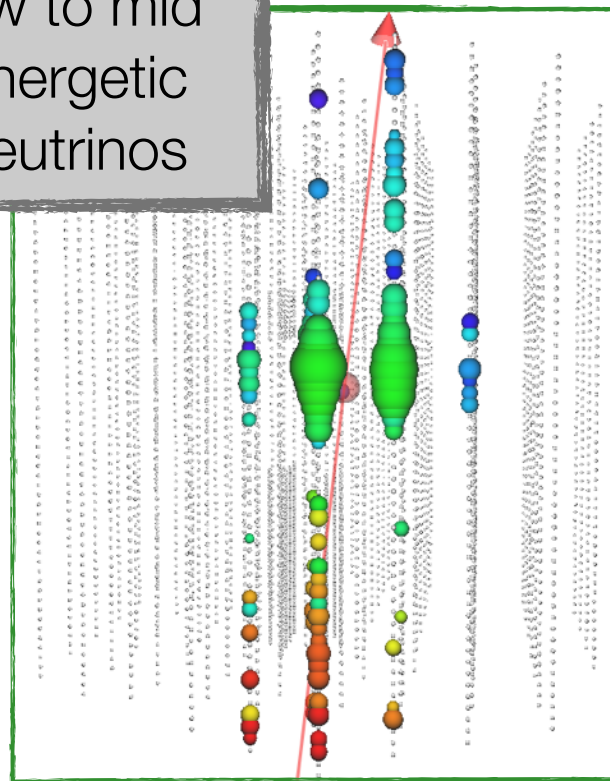
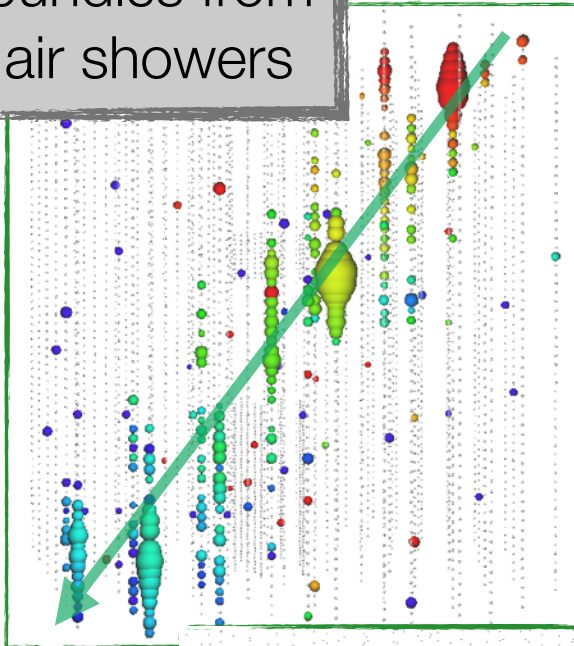
# Monopole vs Background



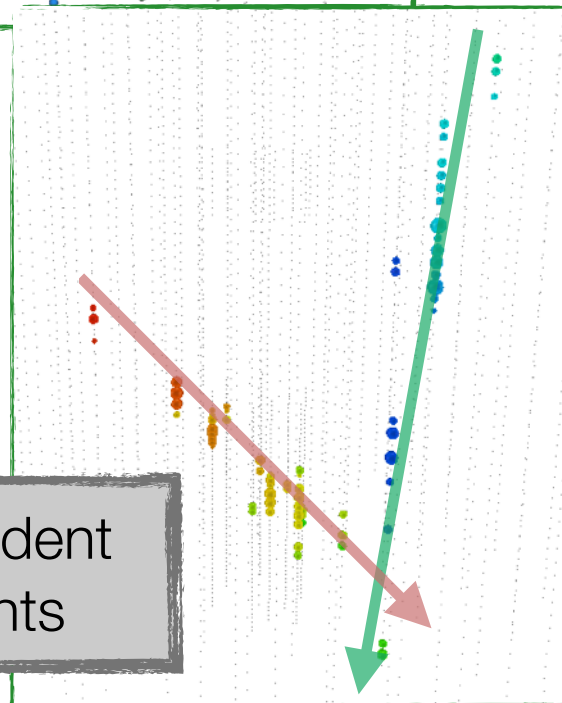
## Background

muon  
bundles from  
air showers

low to mid  
energetic  
neutrinos

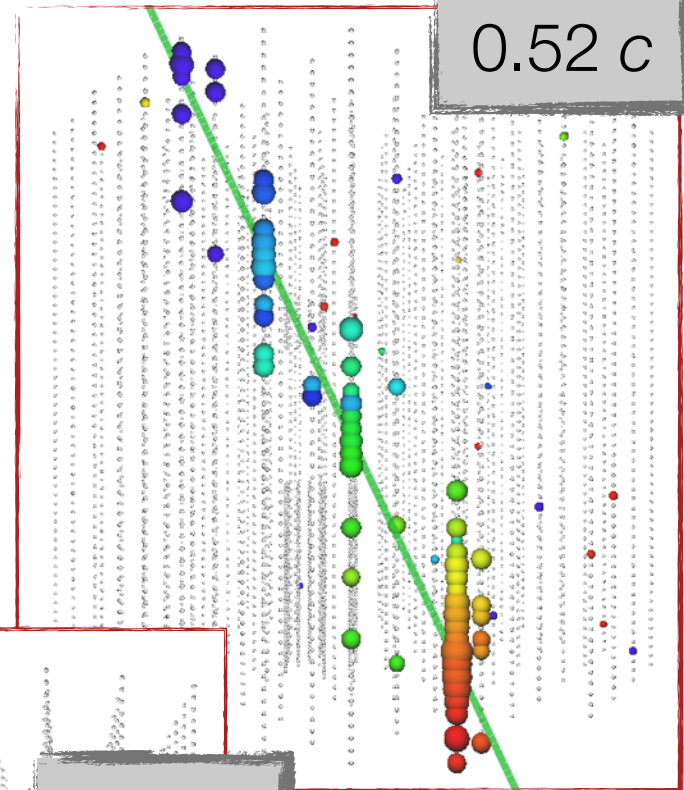


coincident  
events

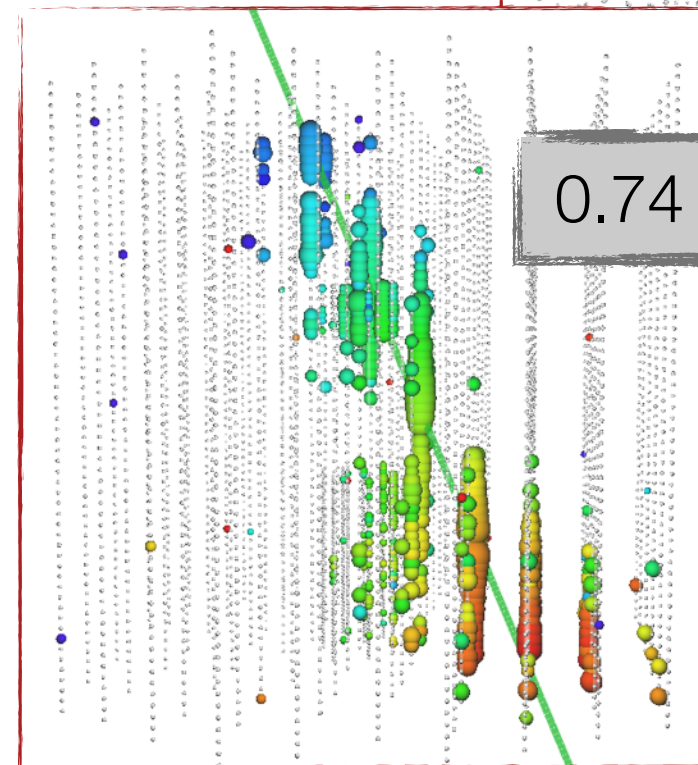


## Monopoles

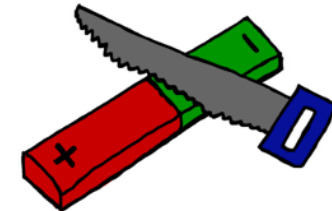
0.52 c



0.74 c

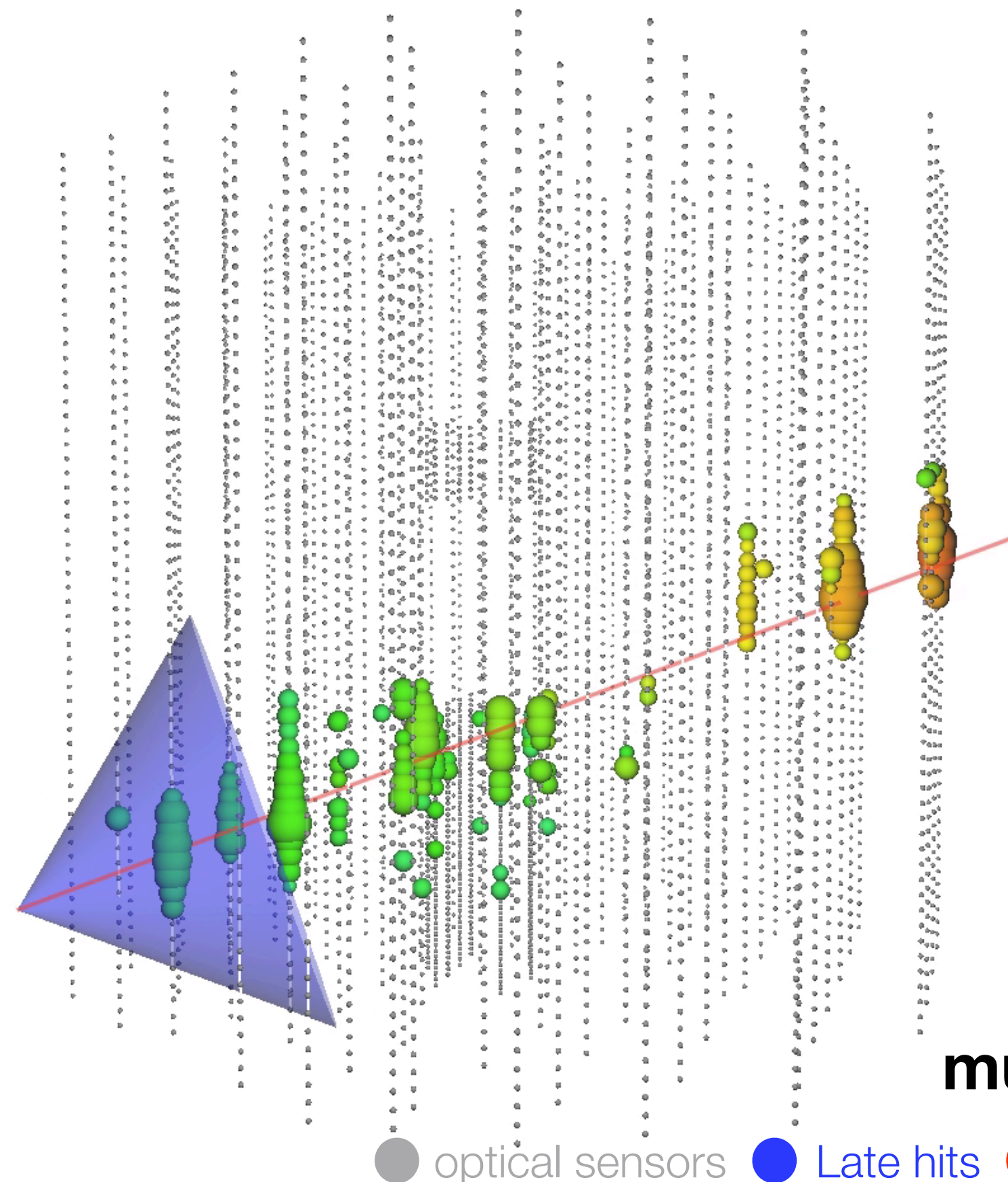


# Event Selection



## Selection variables

- number of sensors recording a hit
- speed
- direction
- gap within the hits
- COG separation length
- . . . . .

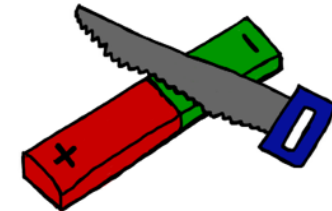


**muon (neutrino)**

● optical sensors ● Late hits ● Early hits — Track

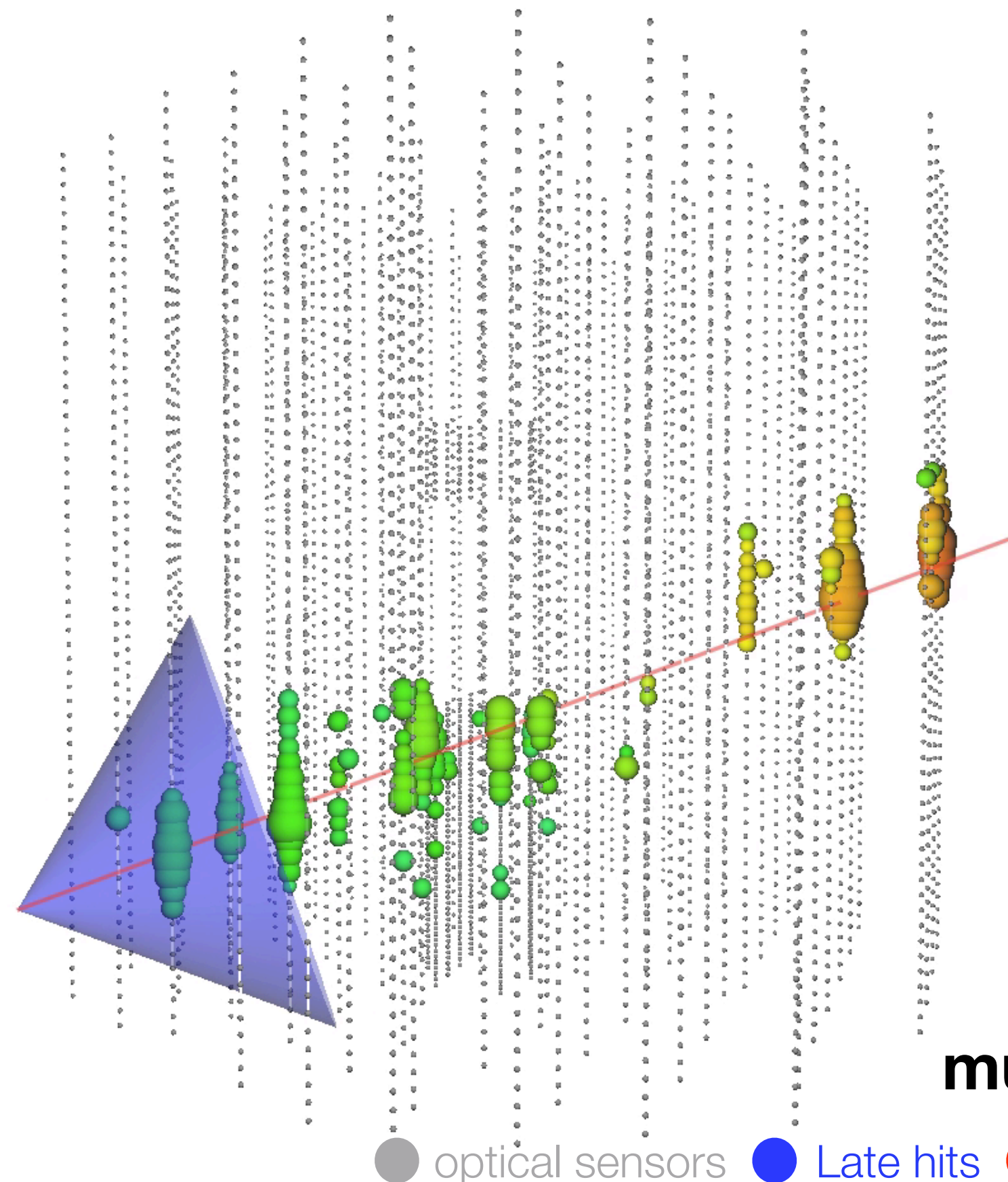


# Event Selection



## Selection variables

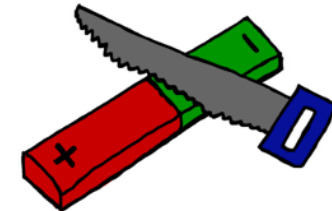
- number of sensors recording a hit
- speed
- direction
- gap within the hits
- COG separation length
- . . . . .



**muon (neutrino)**

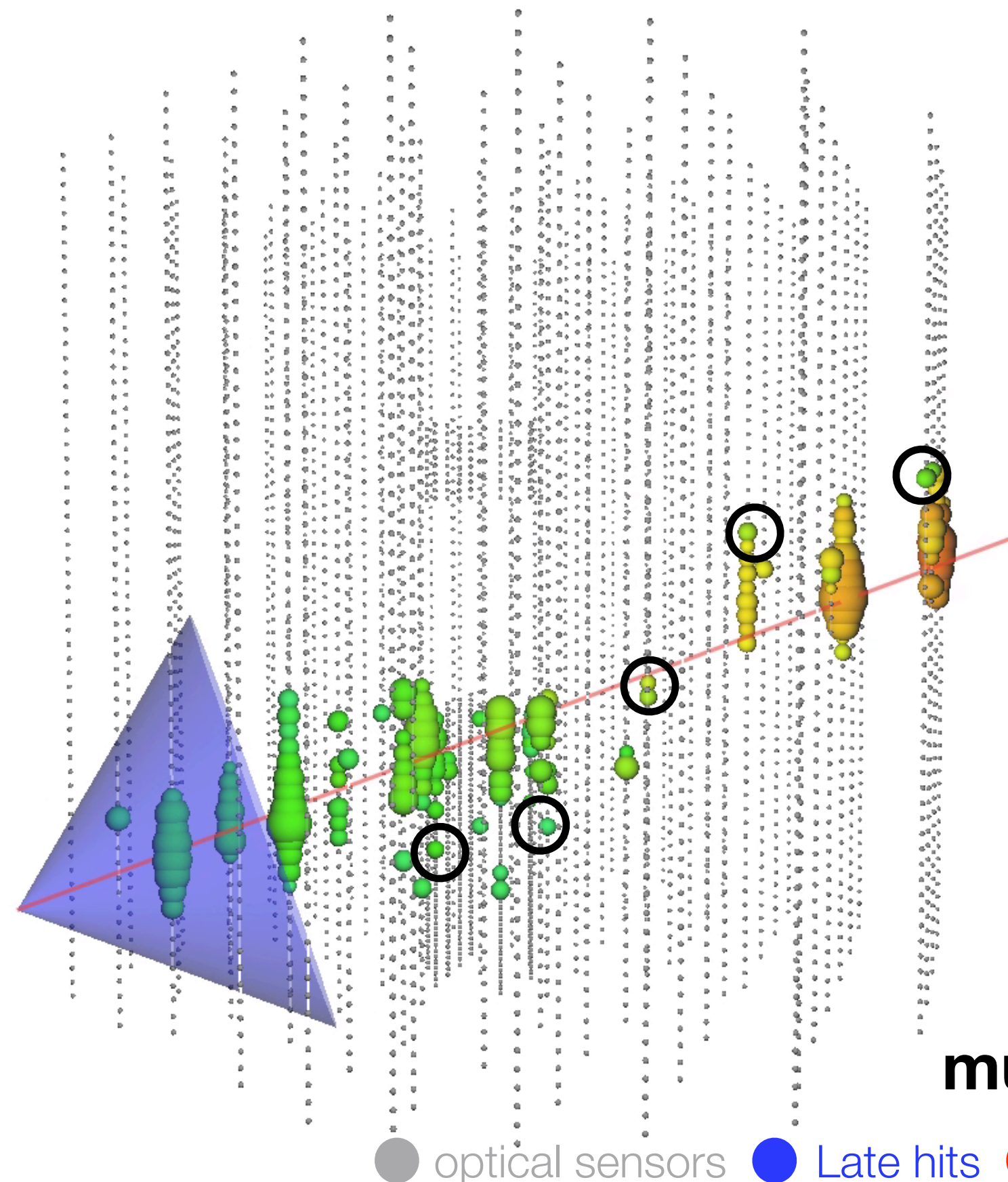
● optical sensors ● Late hits ● Early hits — Track

# Event Selection



## Selection variables

- number of sensors recording a hit
- speed
- direction
- gap within the hits
- COG separation length
- .....

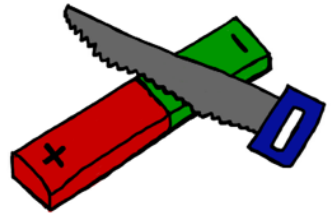


muon (neutrino)

● optical sensors ● Late hits ● Early hits — Track

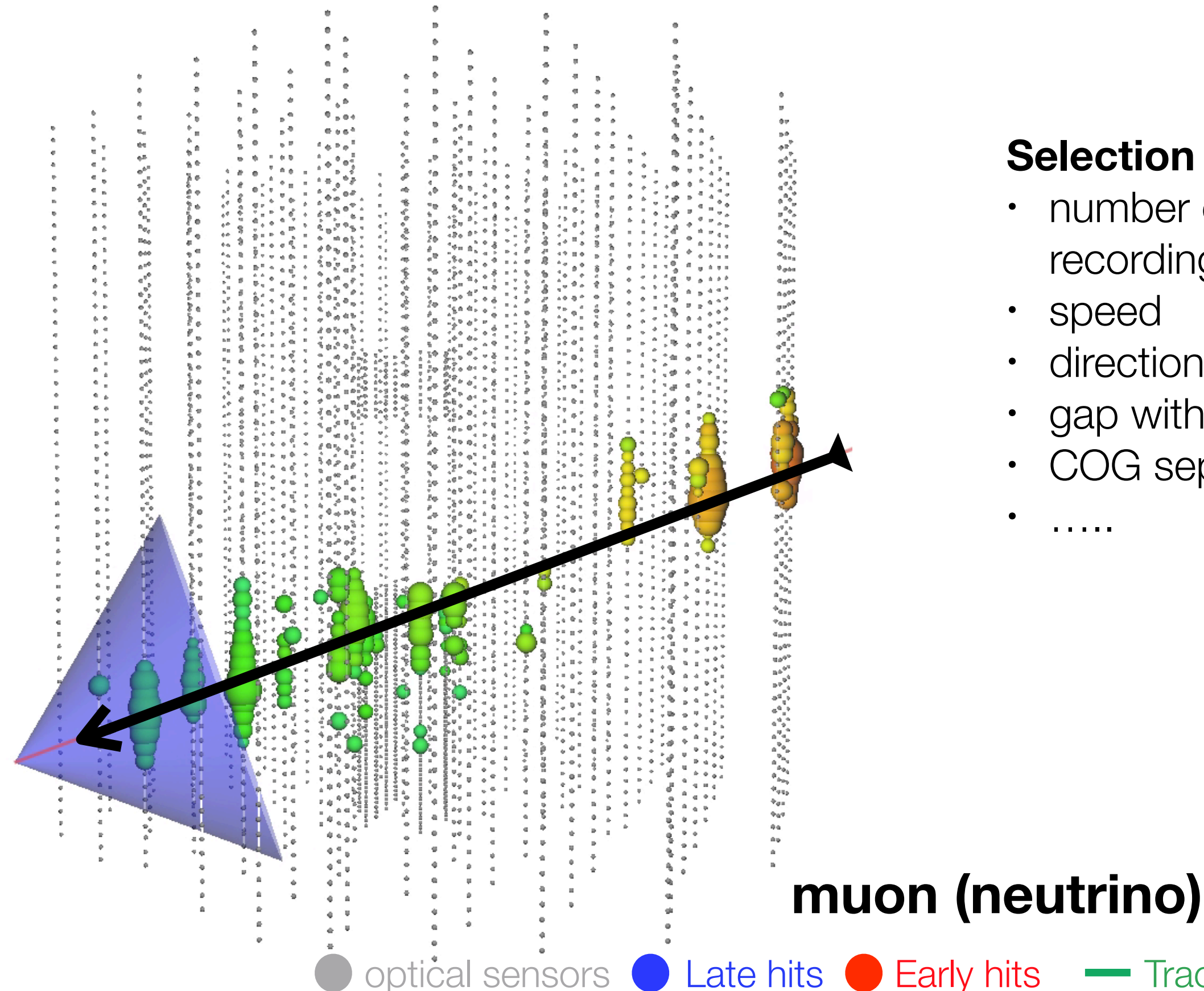


# Event Selection

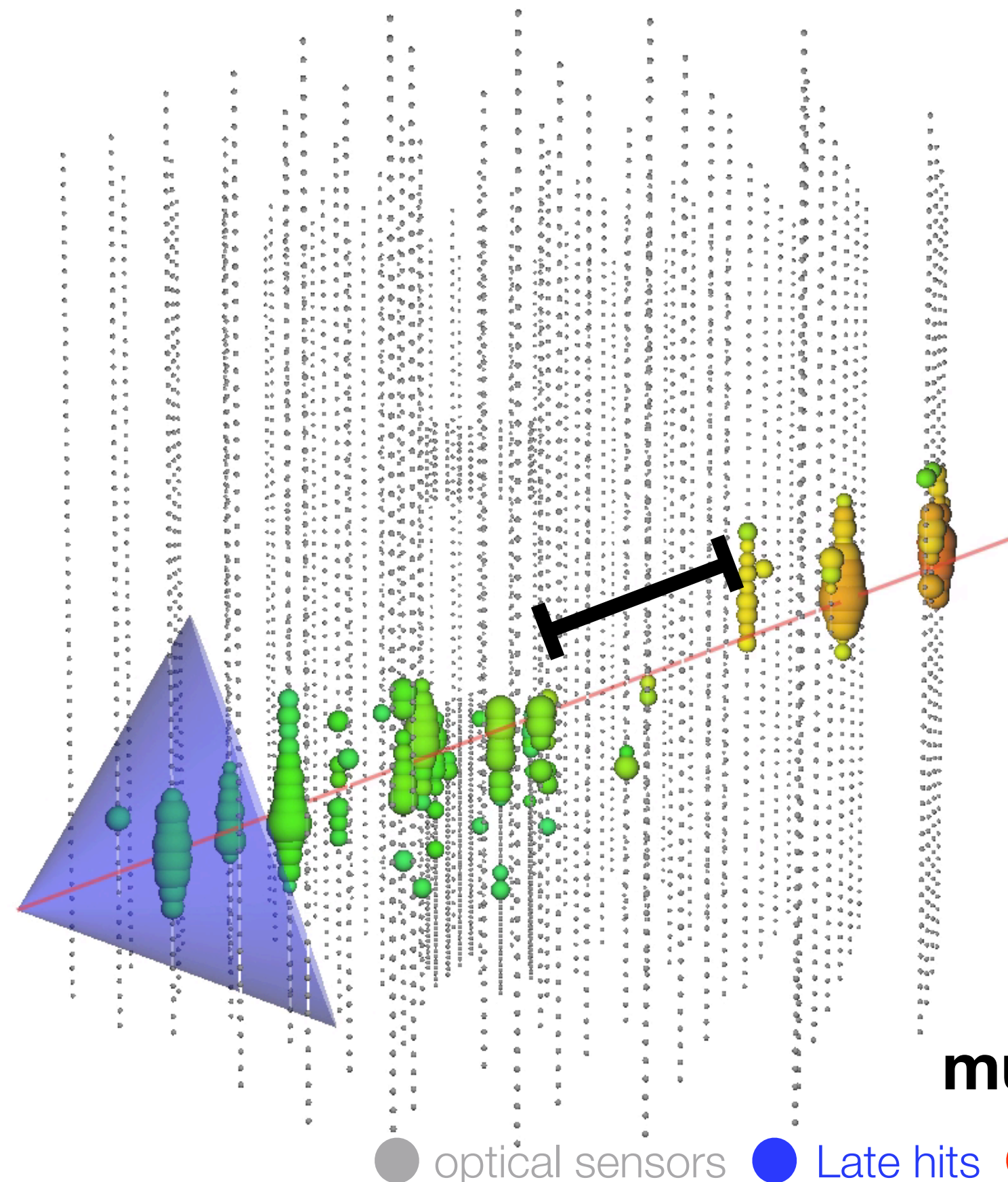
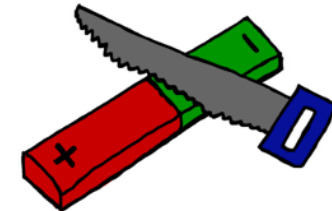


## Selection variables

- number of sensors recording a hit
- speed
- direction
- gap within the hits
- COG separation length
- . . . . .



# Event Selection



## Selection variables

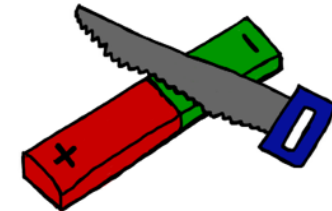
- number of sensors recording a hit
- speed
- direction
- gap within the hits
- COG separation length
- . . . . .

**muon (neutrino)**

● optical sensors    ● Late hits    ● Early hits    — Track

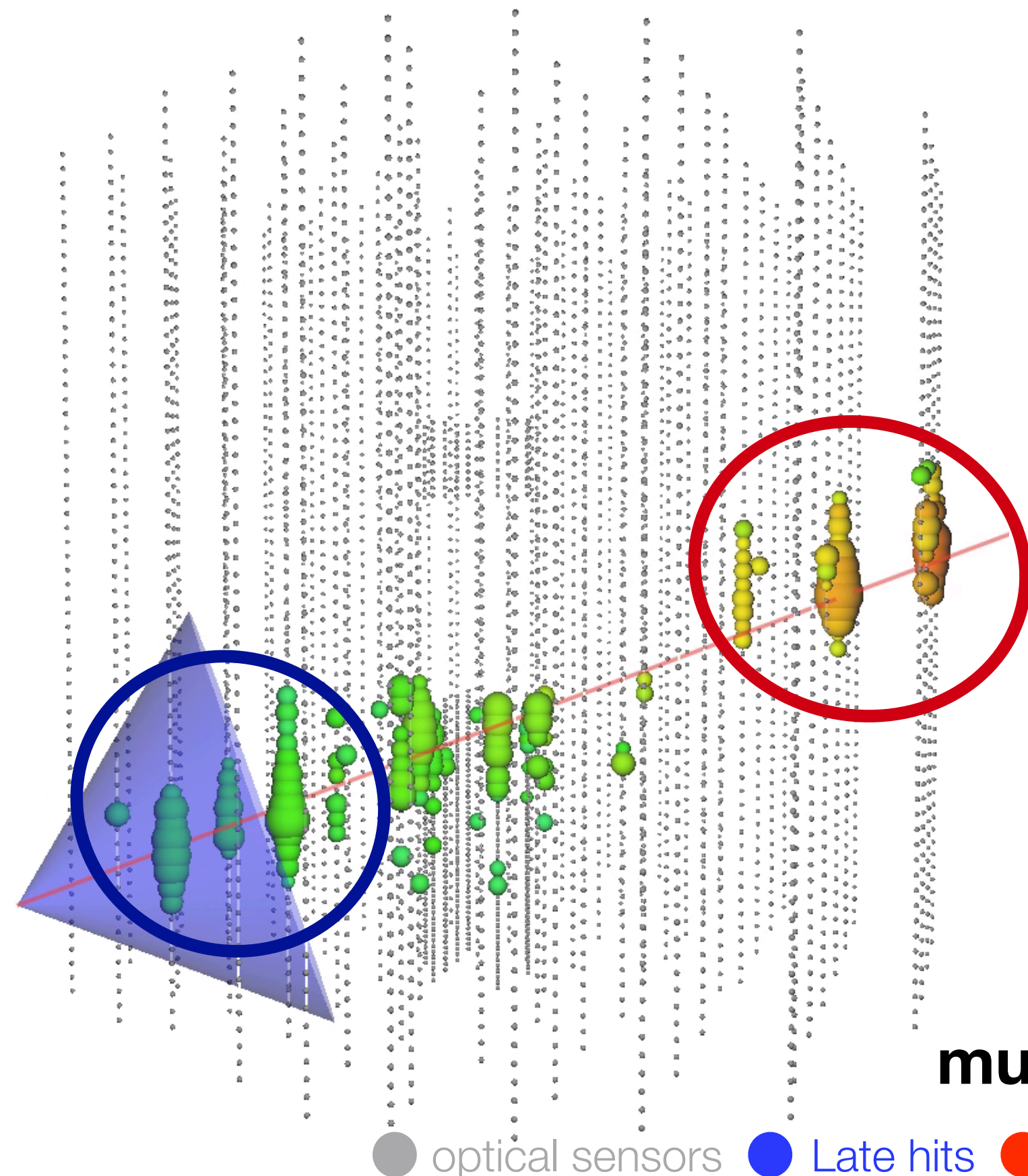


# Event Selection



## Selection variables

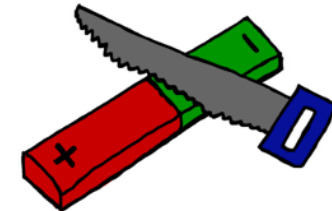
- number of sensors recording a hit
- speed
- direction
- gap within the hits
- COG separation length
- . . . . .



**muon (neutrino)**

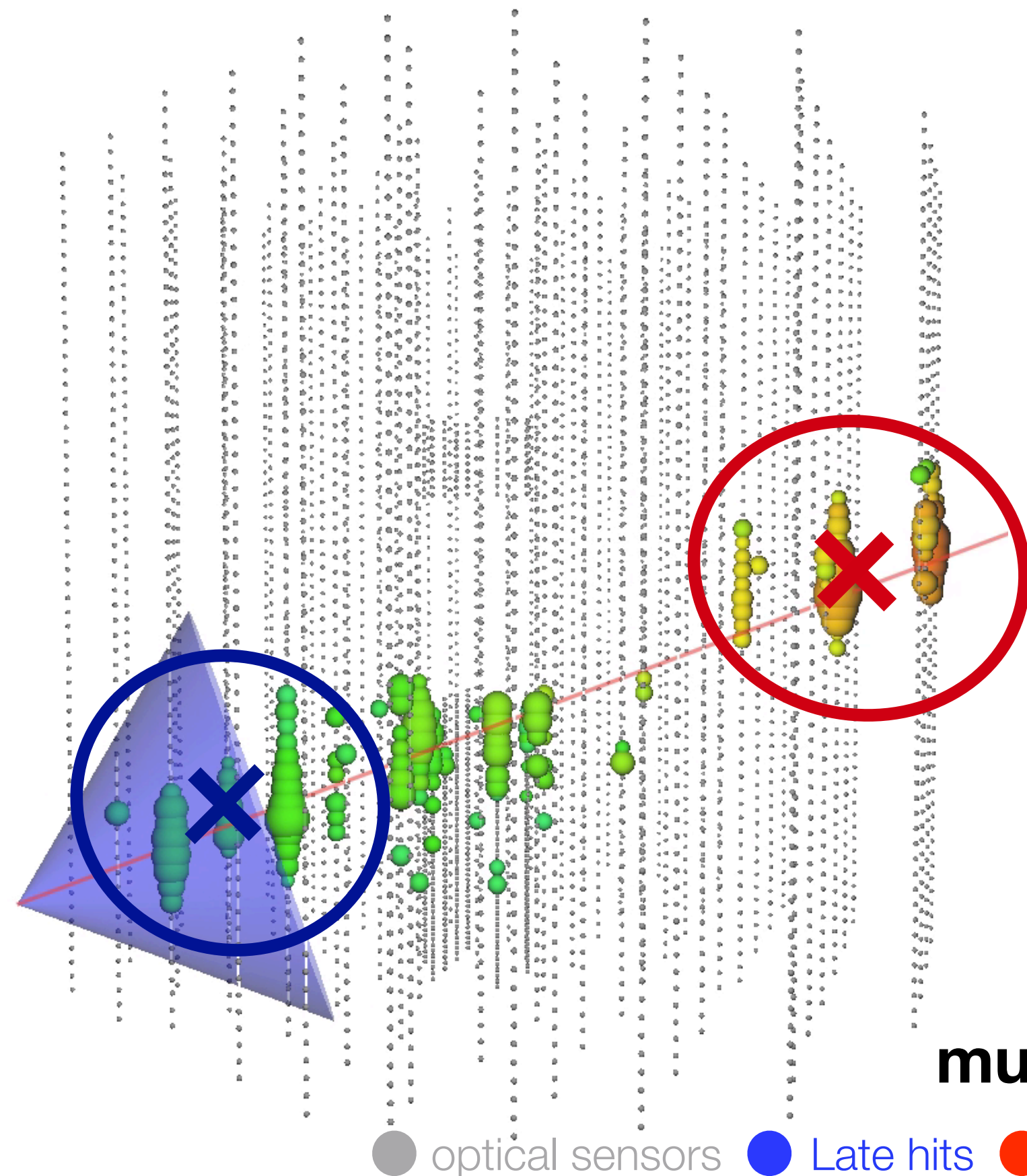
● optical sensors ● Late hits ● Early hits — Track

# Event Selection



## Selection variables

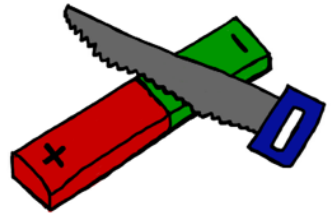
- number of sensors recording a hit
- speed
- direction
- gap within the hits
- COG separation length
- . . . . .



muon (neutrino)

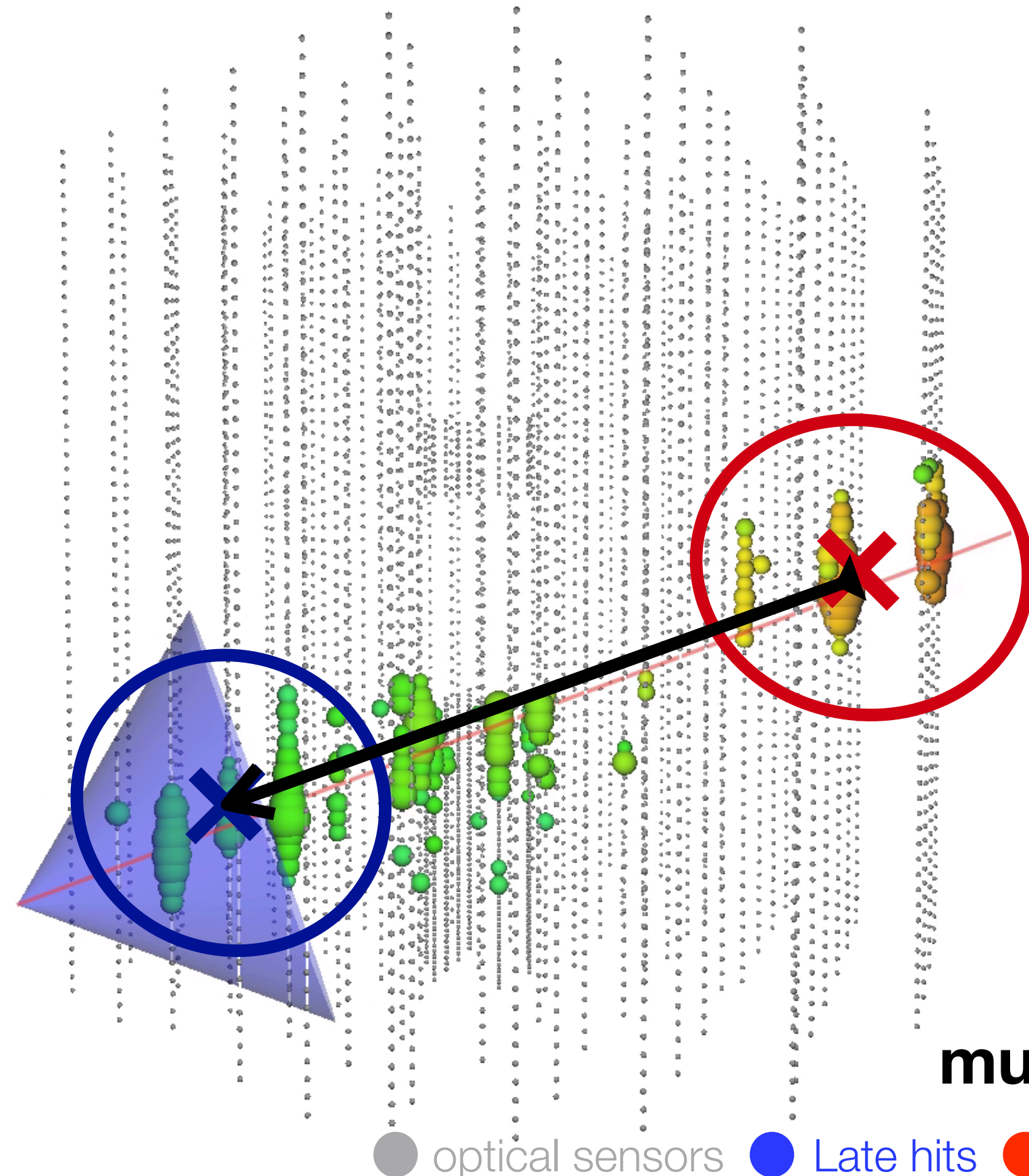


# Event Selection



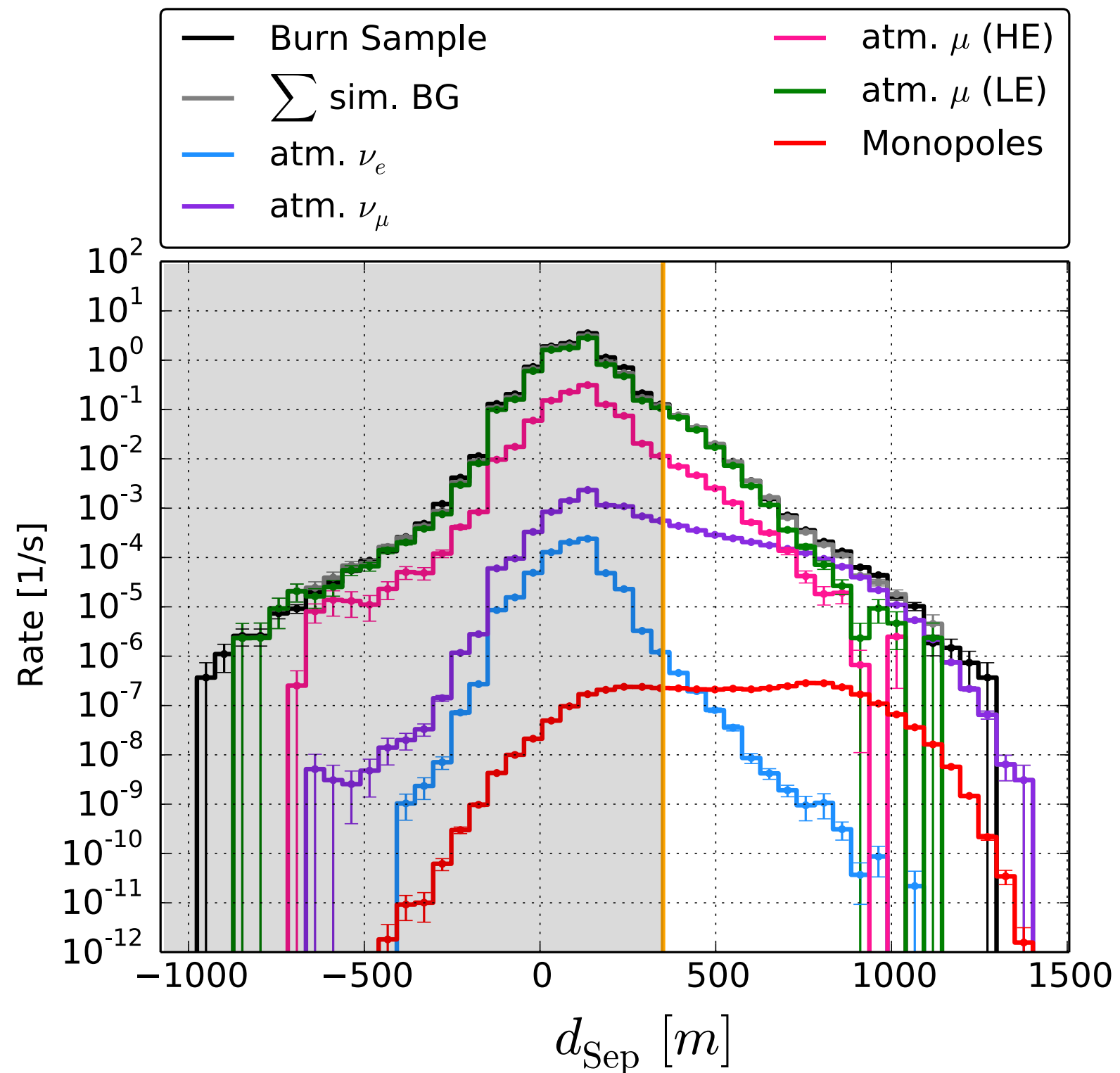
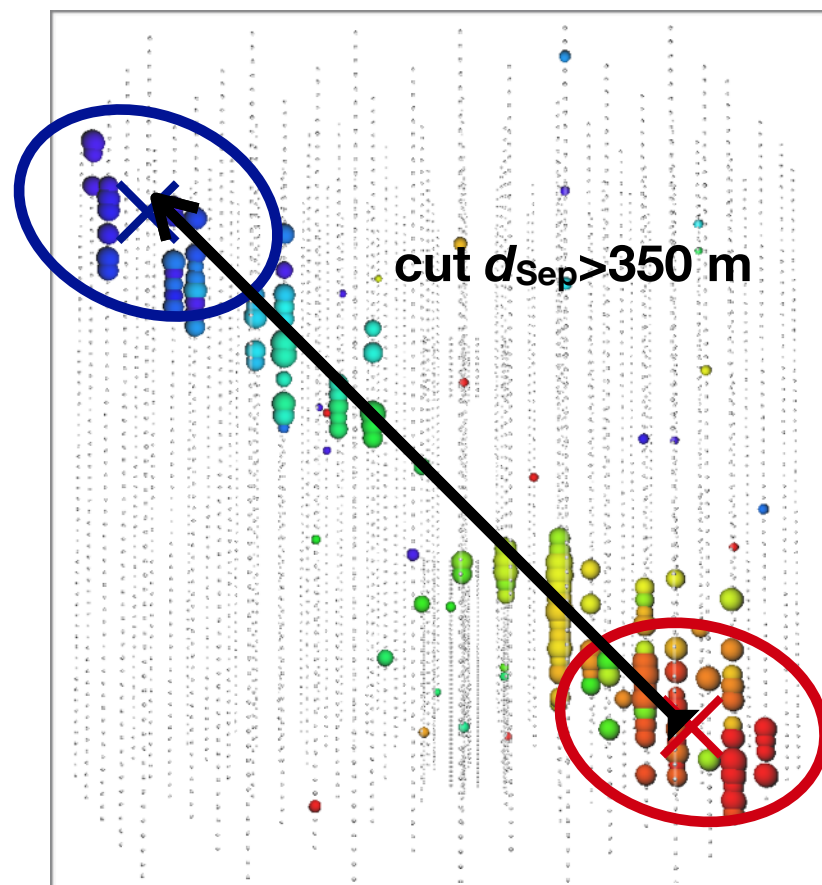
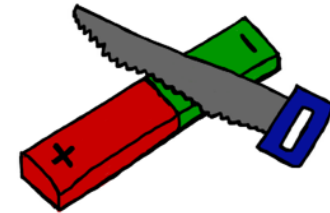
## Selection variables

- number of sensors recording a hit
- speed
- direction
- gap within the hits
- COG separation length
- . . . . .



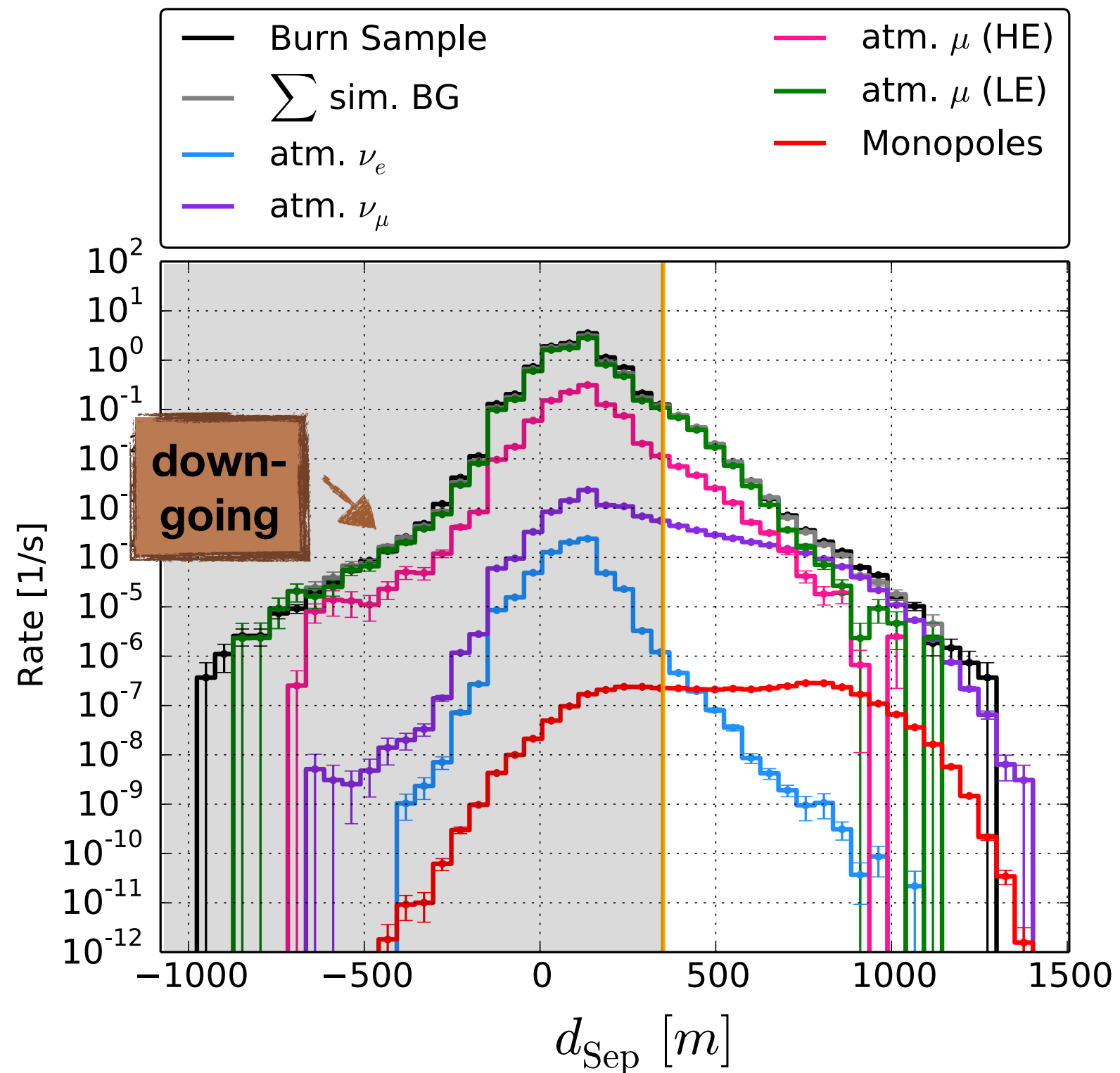
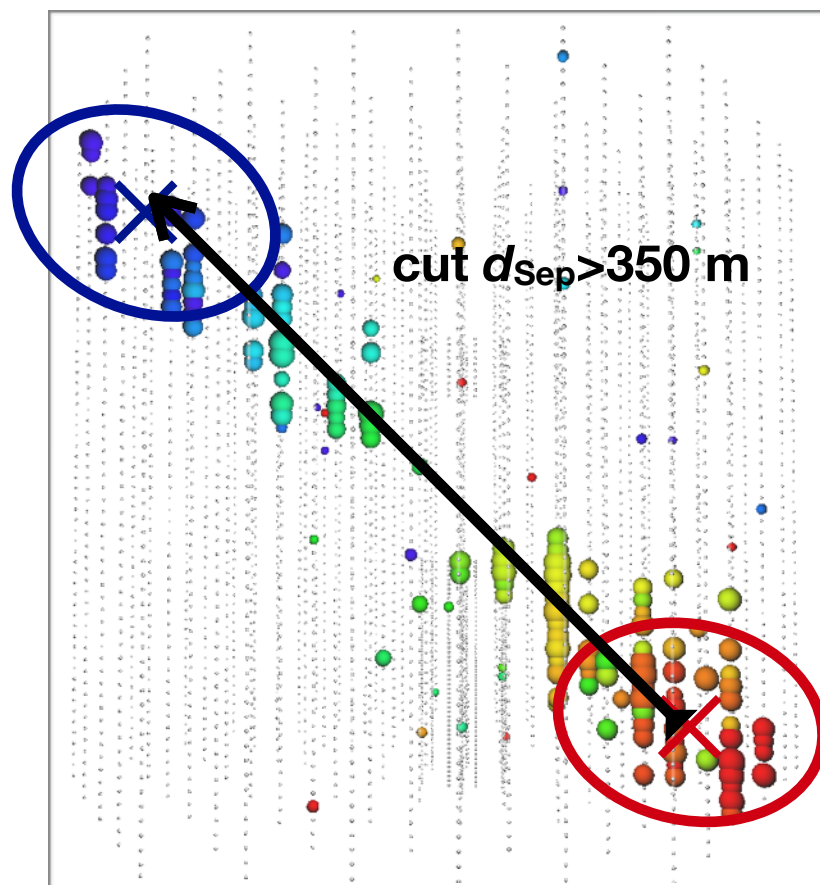
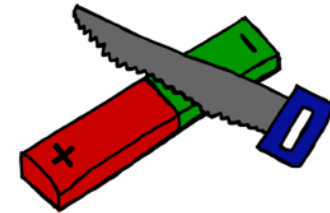
muon (neutrino)

# Event Selection - separation of COGs

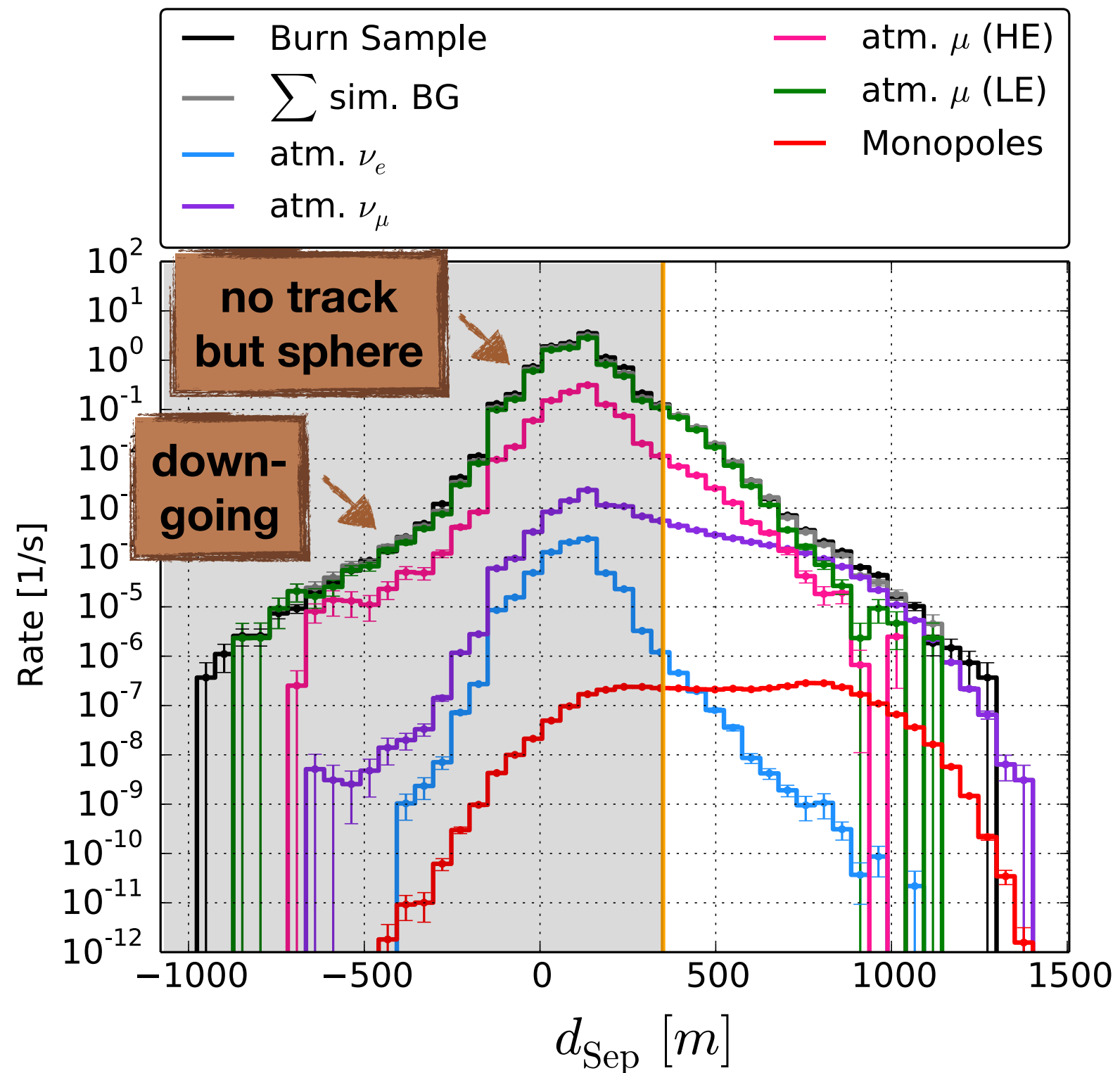
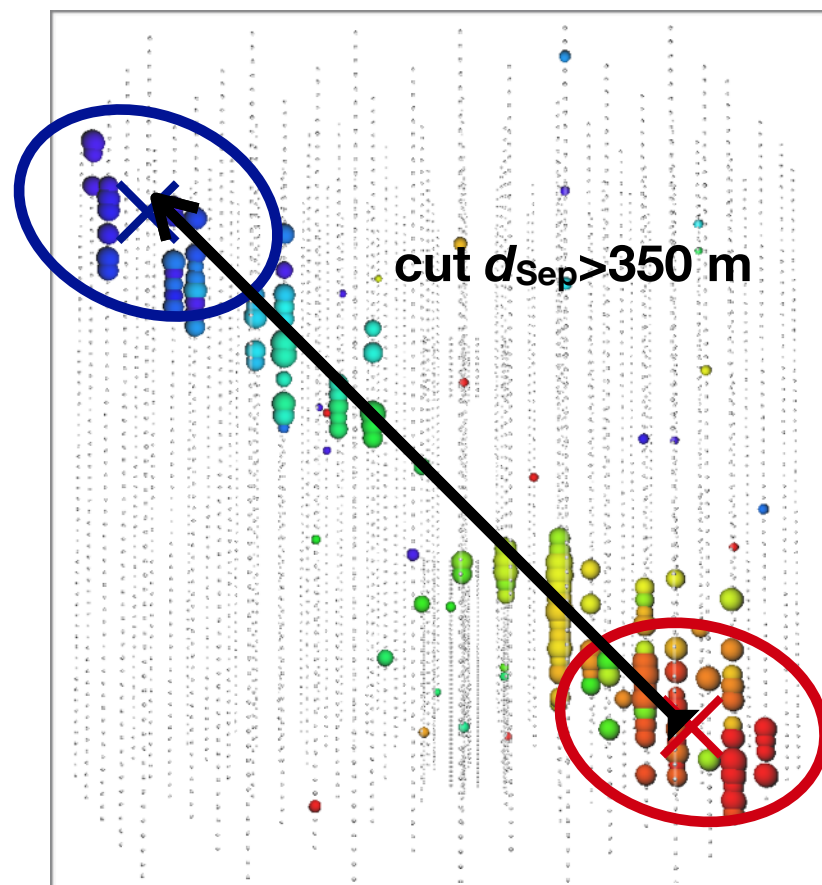
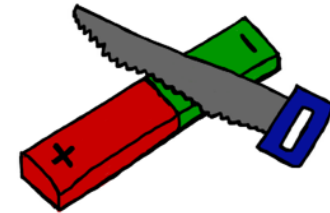




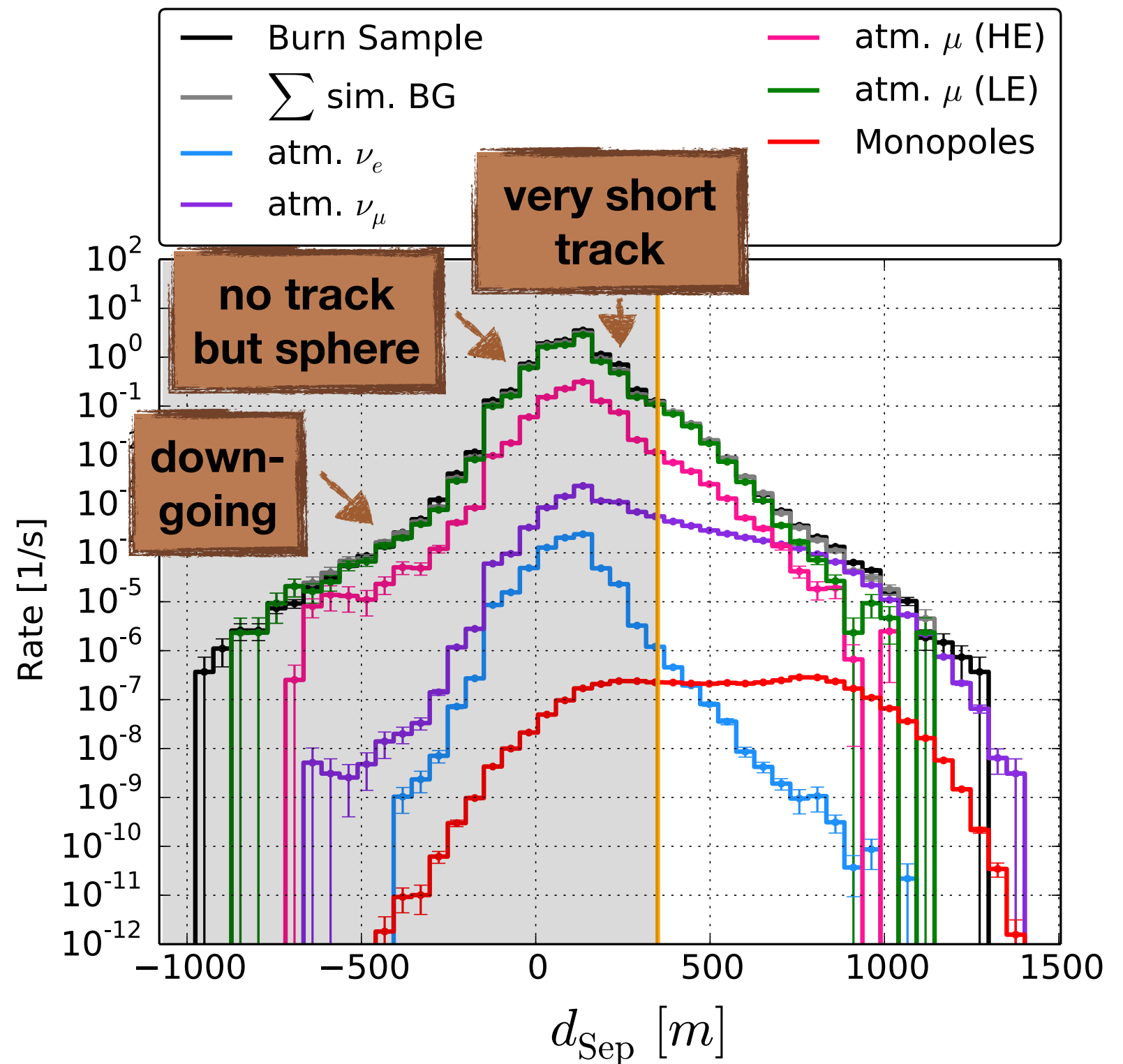
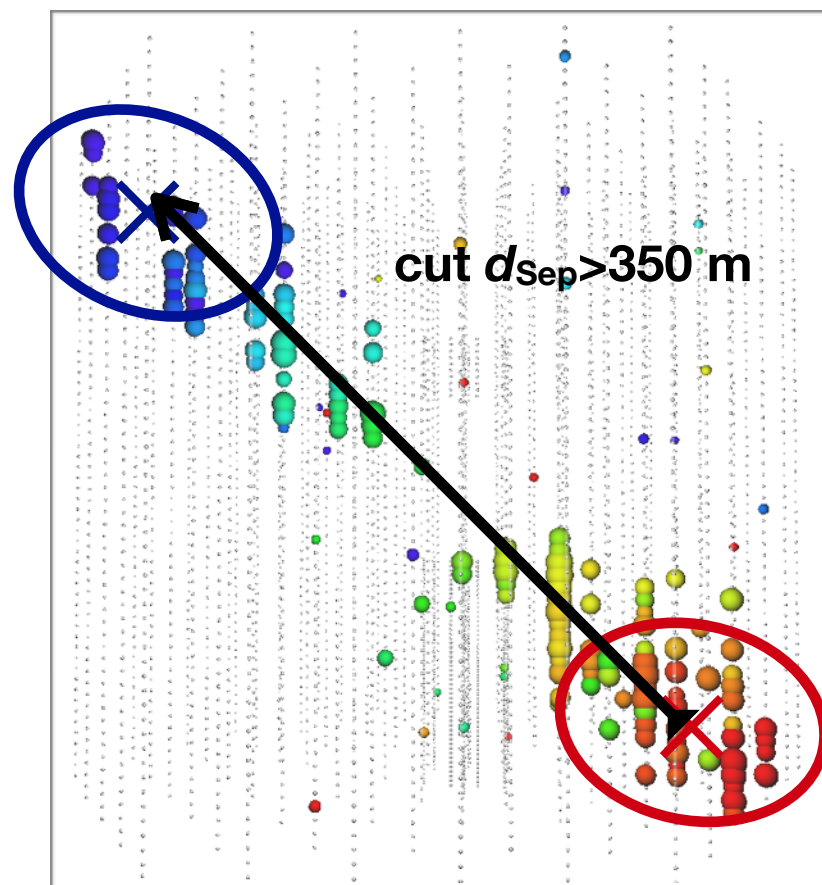
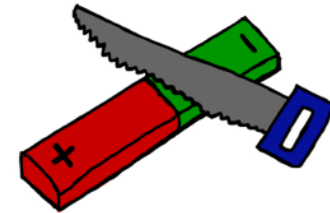
# Event Selection - separation of COGs



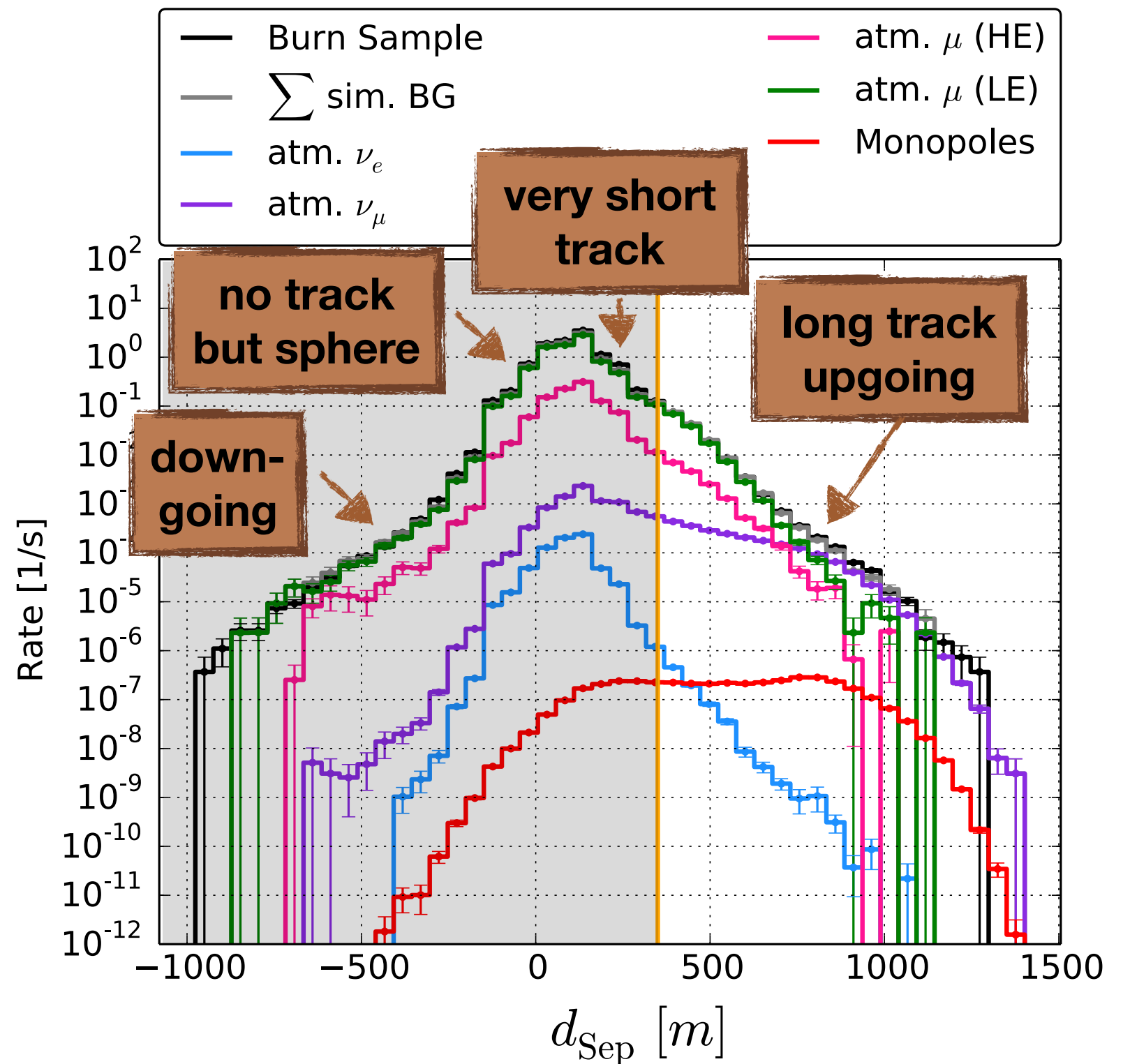
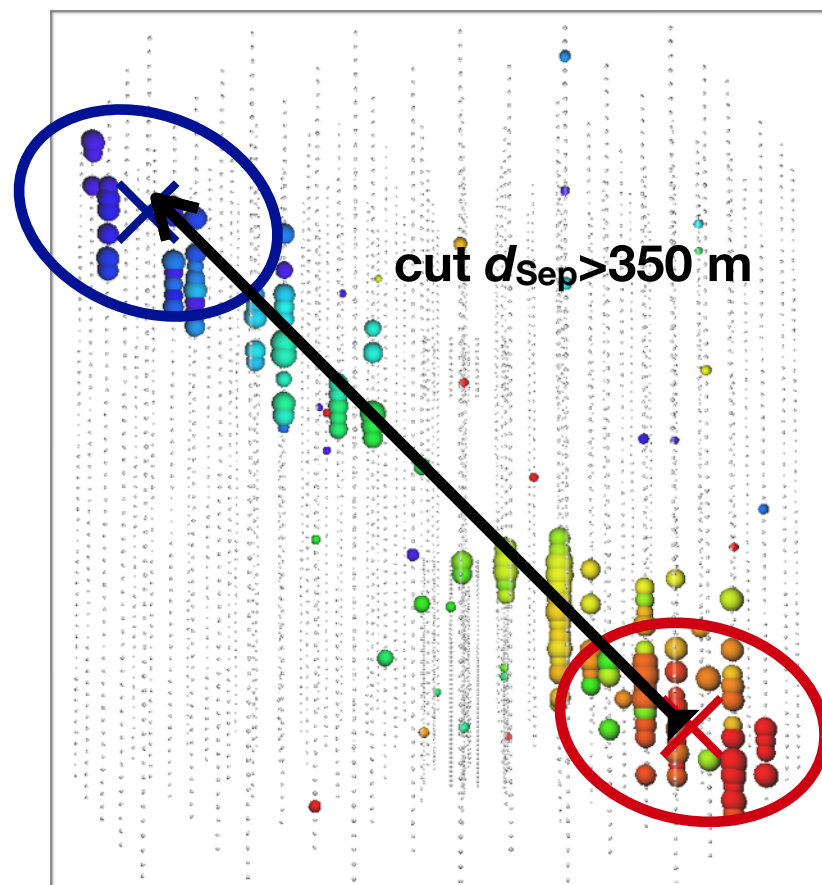
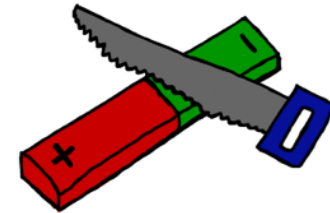
# Event Selection - separation of COGs



# Event Selection - separation of COGs



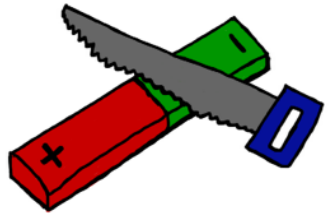
# Event Selection - separation of COGs





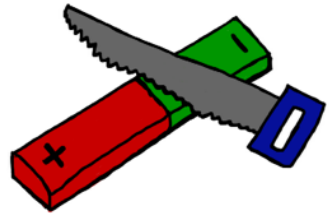
# Unblinding Result

---

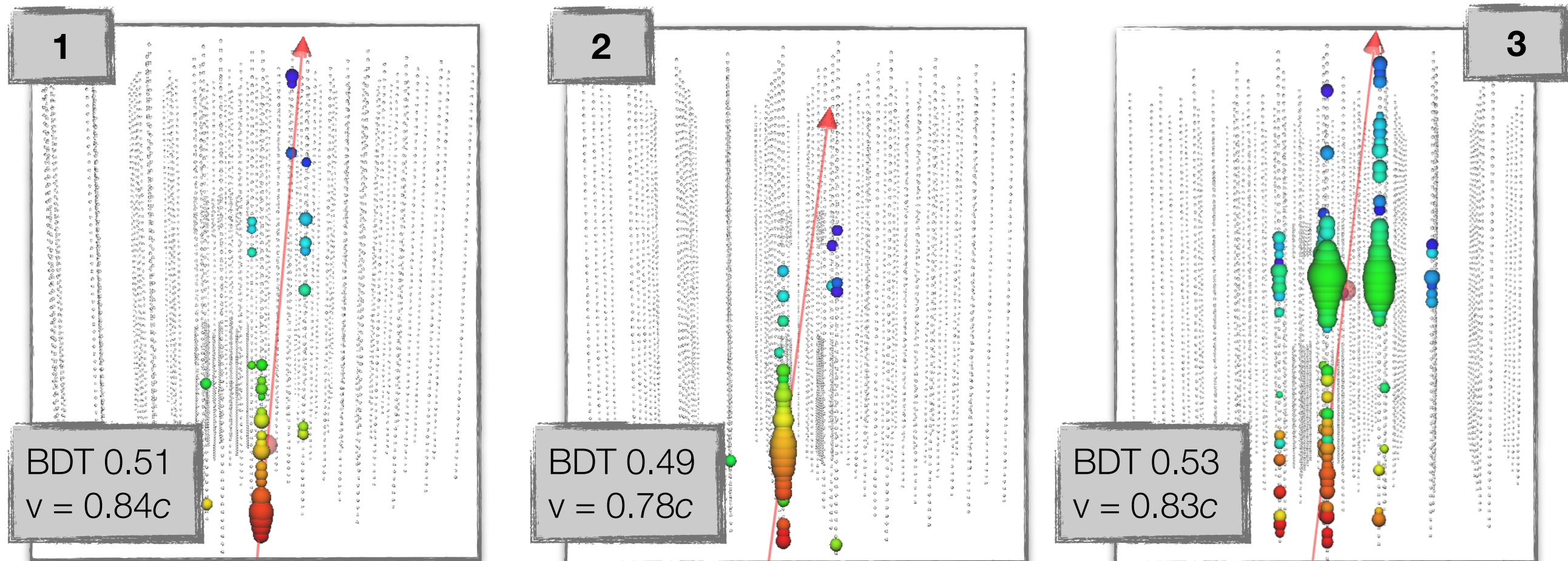


**Background estimation < 3.6 events / year**

# Unblinding Result

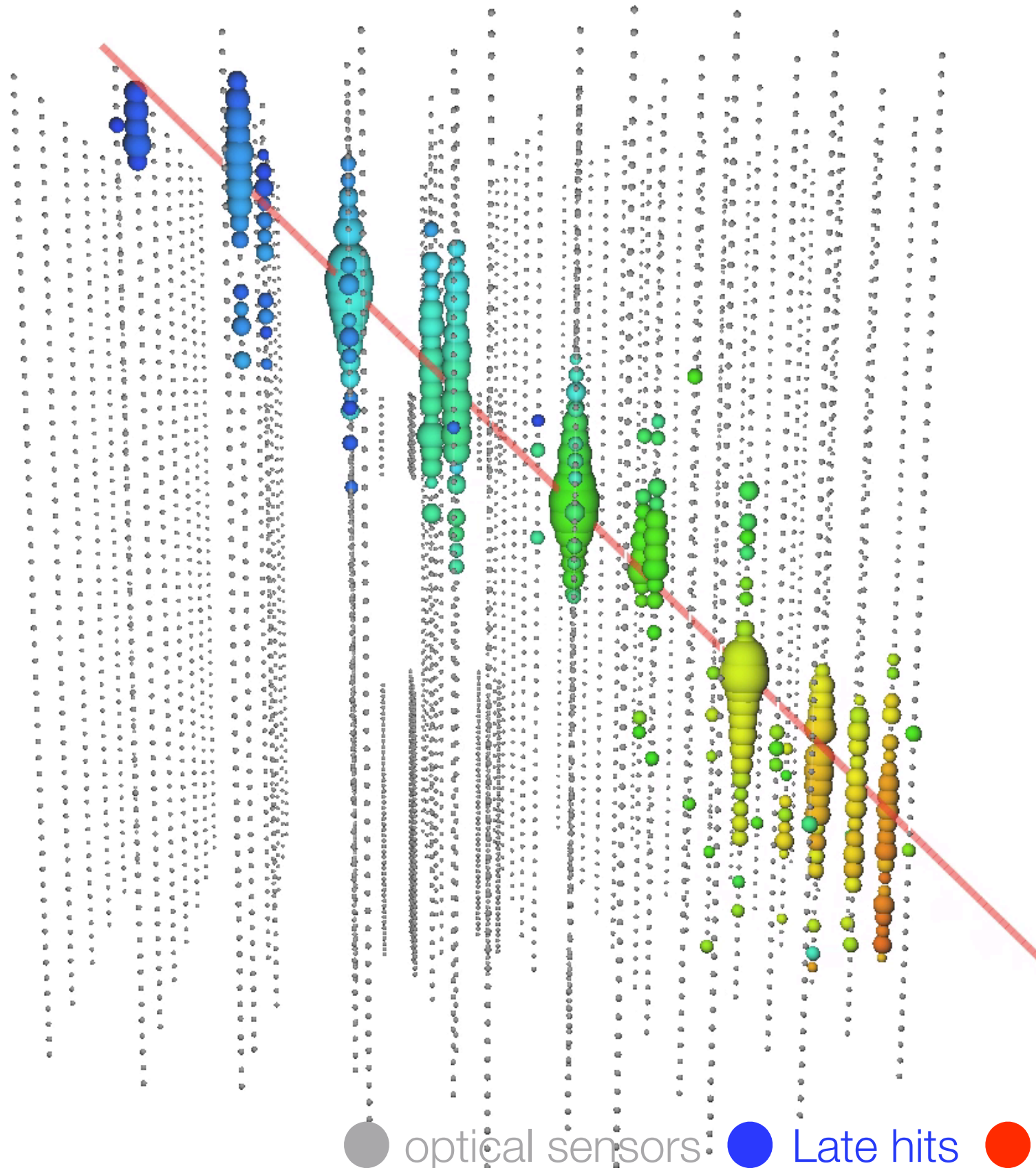
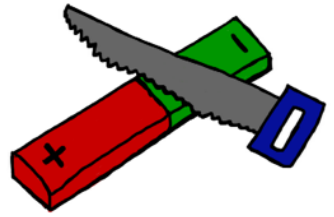


Background estimation < 3.6 events / year



- **All:** highly relativistic -> direct Cherenkov light
- **1 & 2:** obvious background shape -> likely low energetic atmospheric neutrino
- **3:** simulations done -> not bright enough for a monopole

# Signature of a simulated monopole



## Event characteristics:

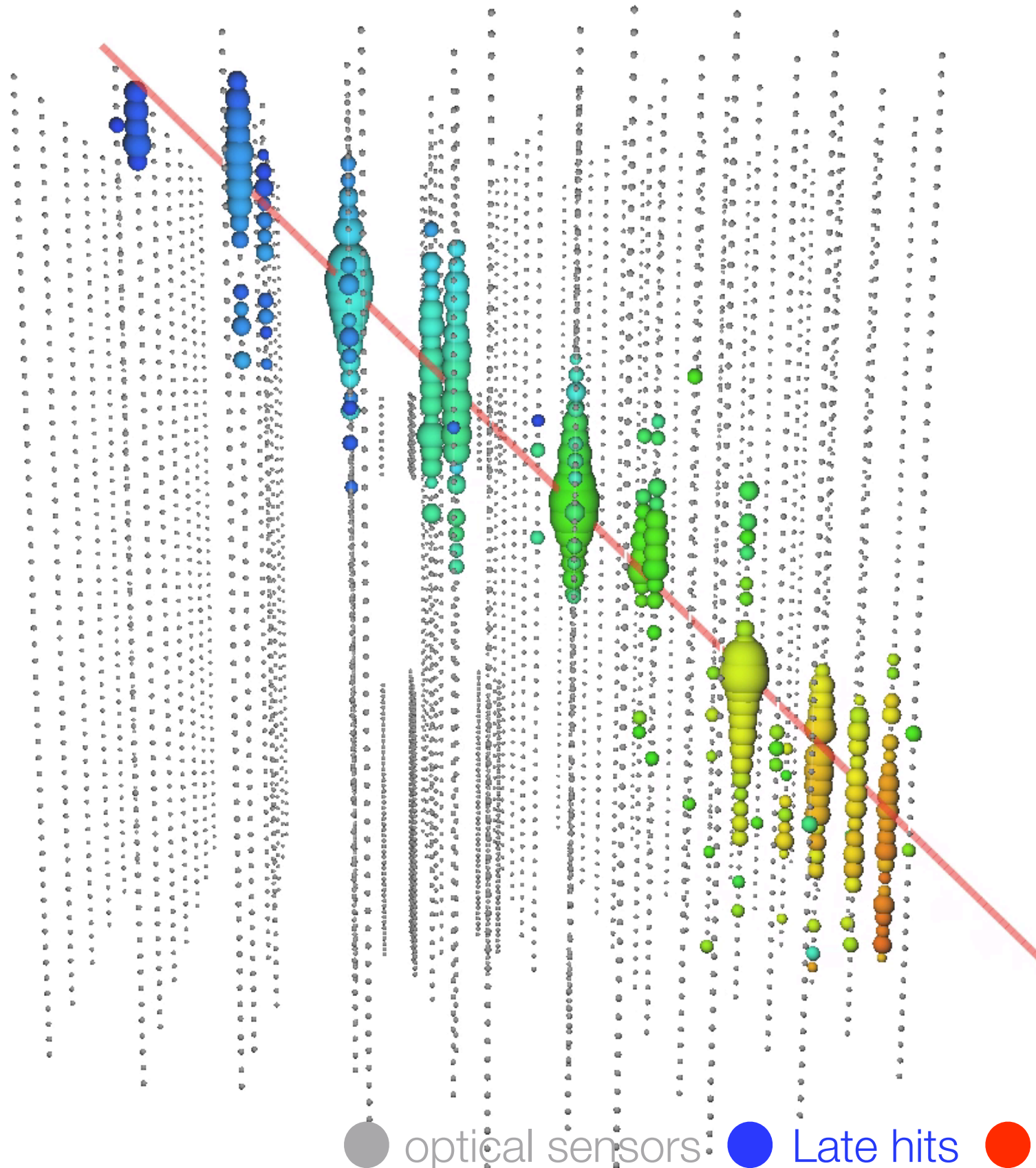
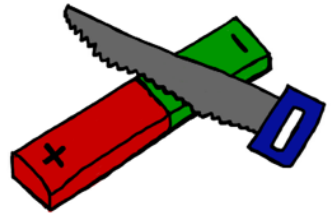
- through-going
- homogenous brightness
- homogenous velocity

$v=0.73 c$

● optical sensors ● Late hits ● Early hits — Track



# Signature of a simulated monopole



## Event characteristics:

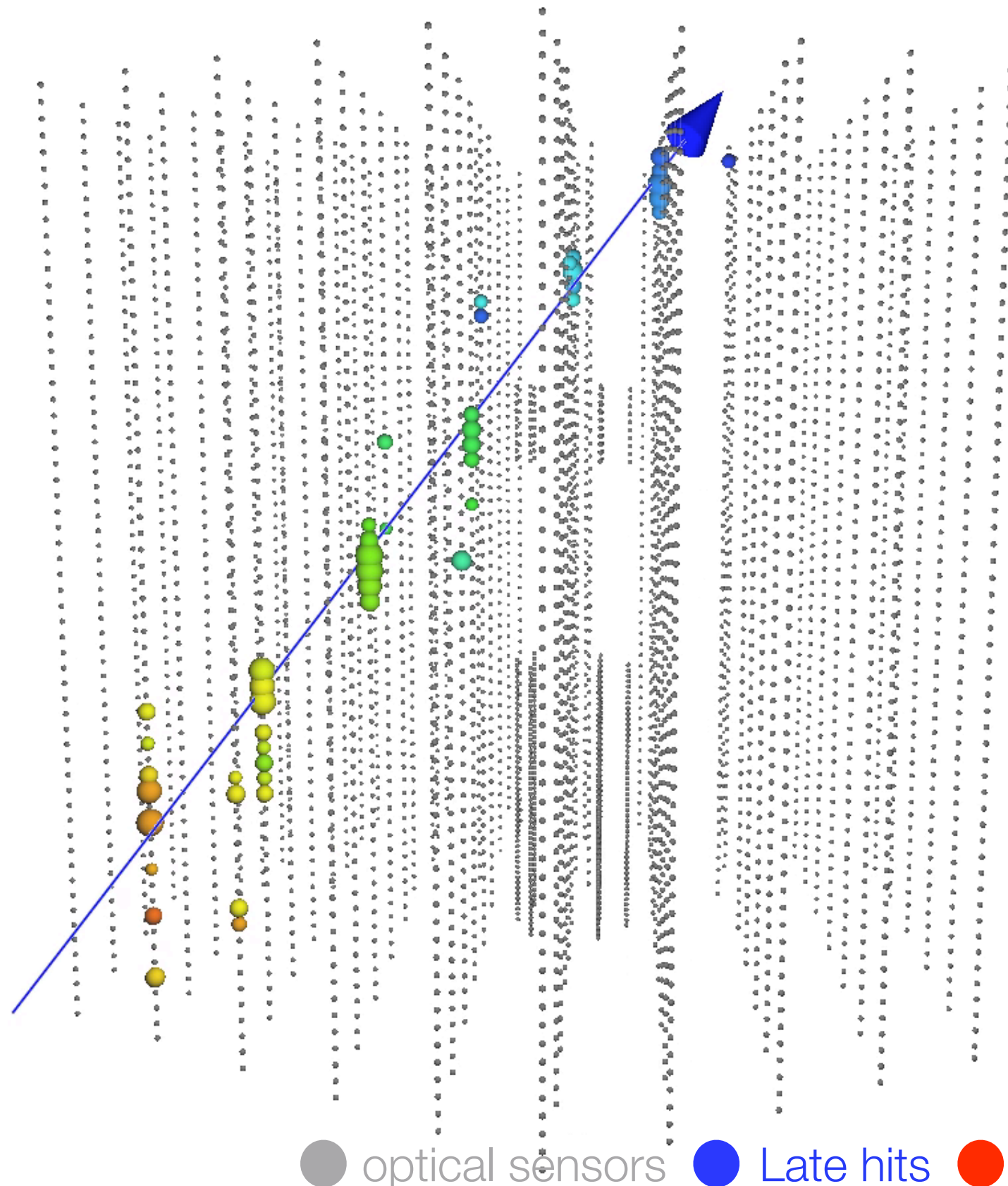
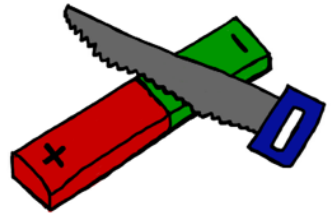
- through-going
- homogenous brightness
- homogenous velocity

$v=0.73 c$

● optical sensors ● Late hits ● Early hits — Track



# Signature of a simulated monopole



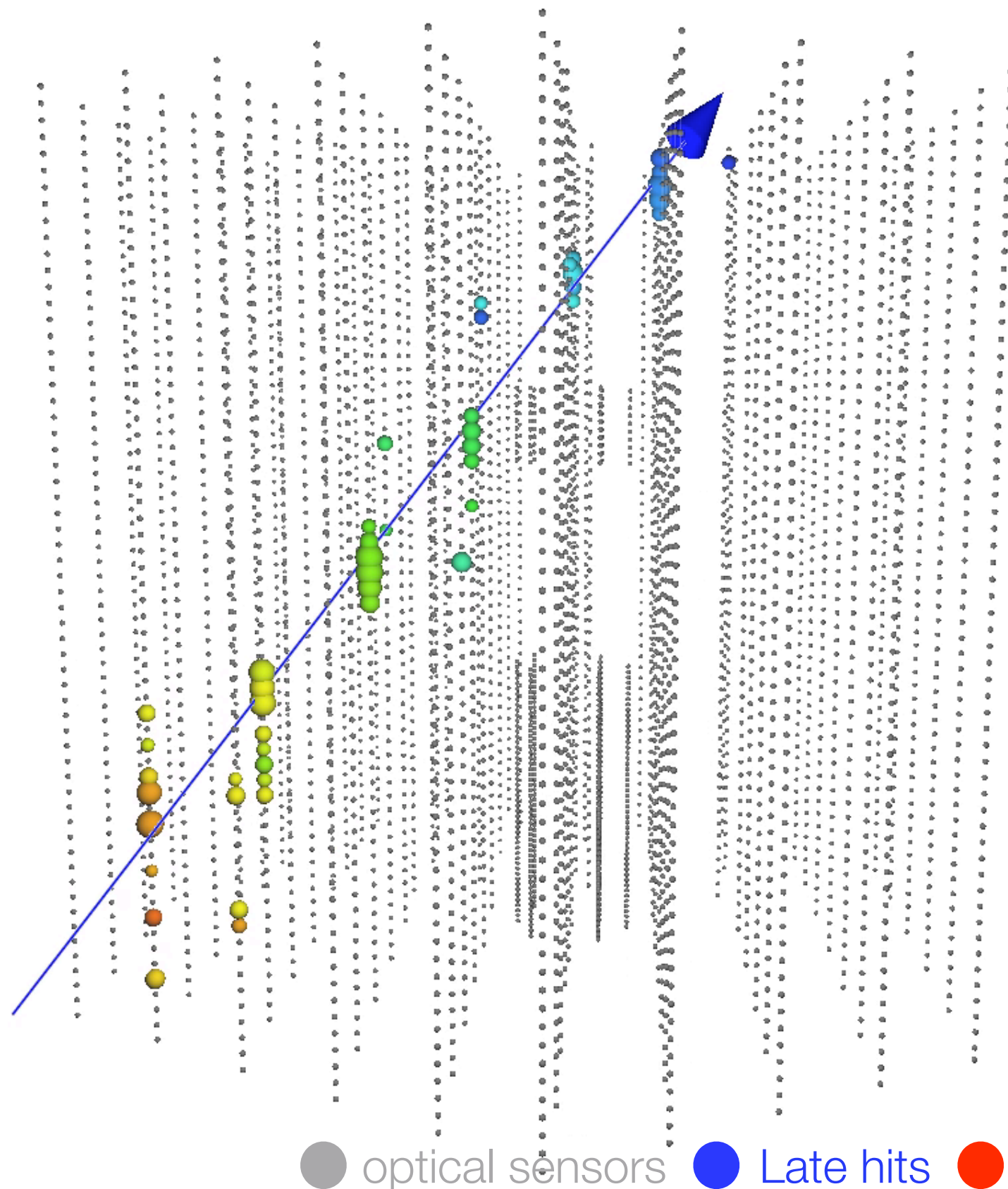
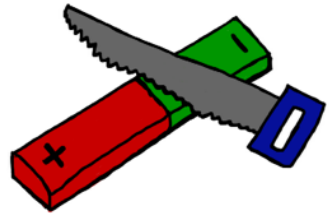
## Event characteristics:

- through-going
- homogenous brightness
- homogenous velocity

$v=0.54 c$

● optical sensors ● Late hits ● Early hits — Track

# Signature of a simulated monopole



## Event characteristics:

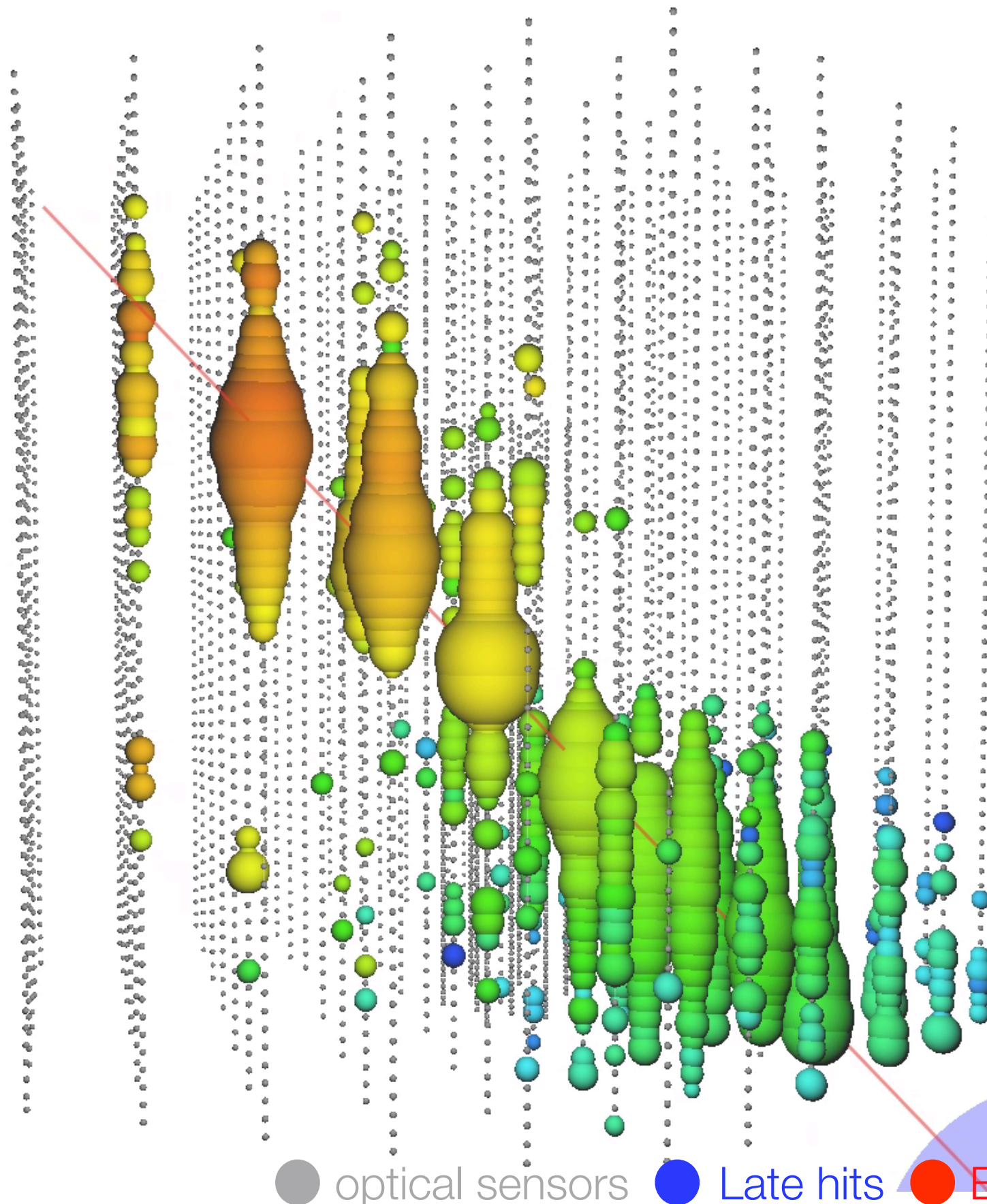
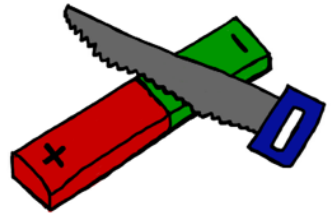
- through-going
- homogenous brightness
- homogenous velocity

$v=0.54 c$

● optical sensors ● Late hits ● Early hits — Track



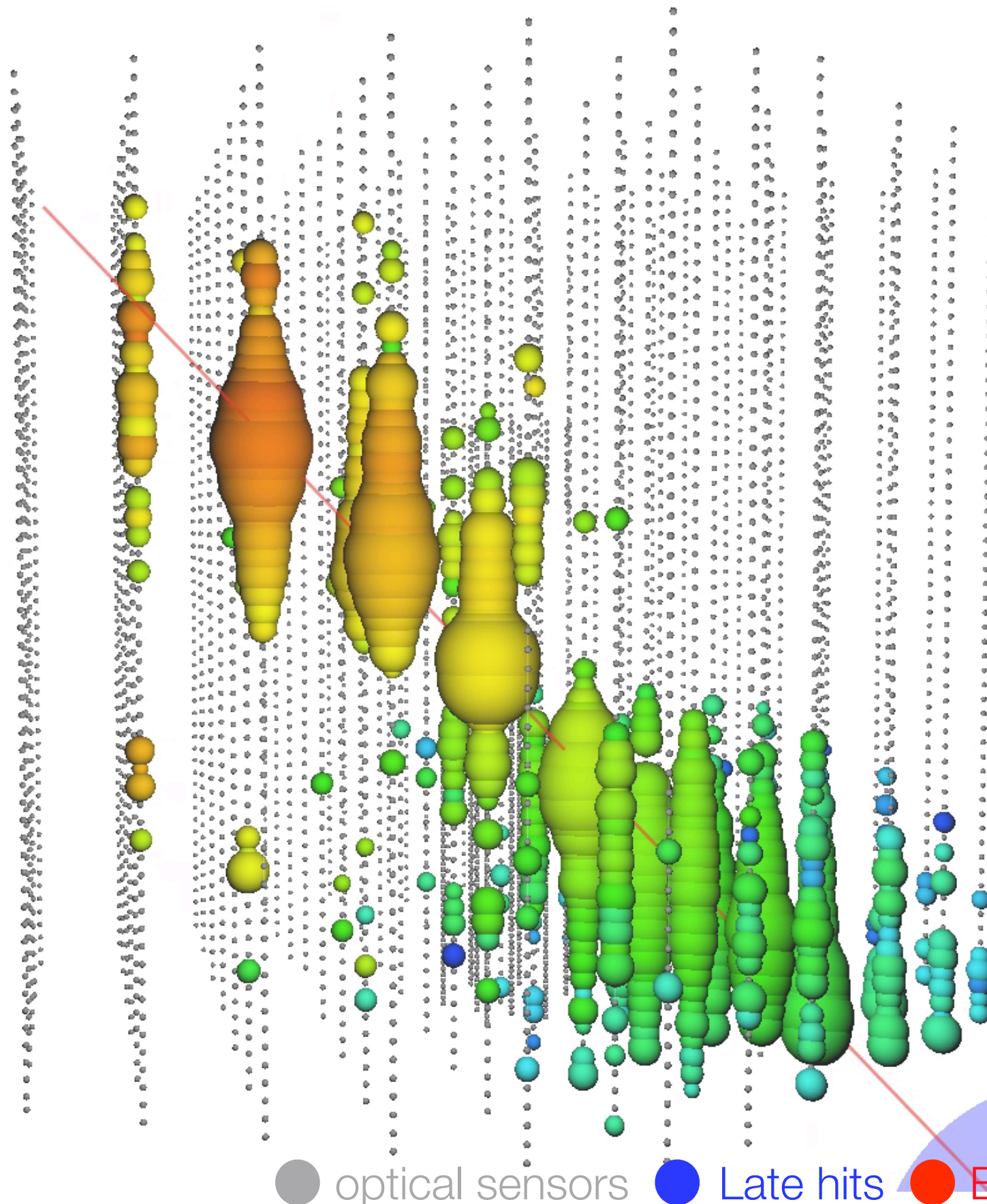
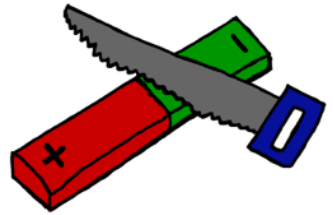
# Background: Air shower from cosmic rays



## Event characteristics:

- muon produced in an air shower
- non-homogenous brightness
- speed =  $c$
- downgoing
- often: several showers at once

# Background: Air shower from cosmic rays

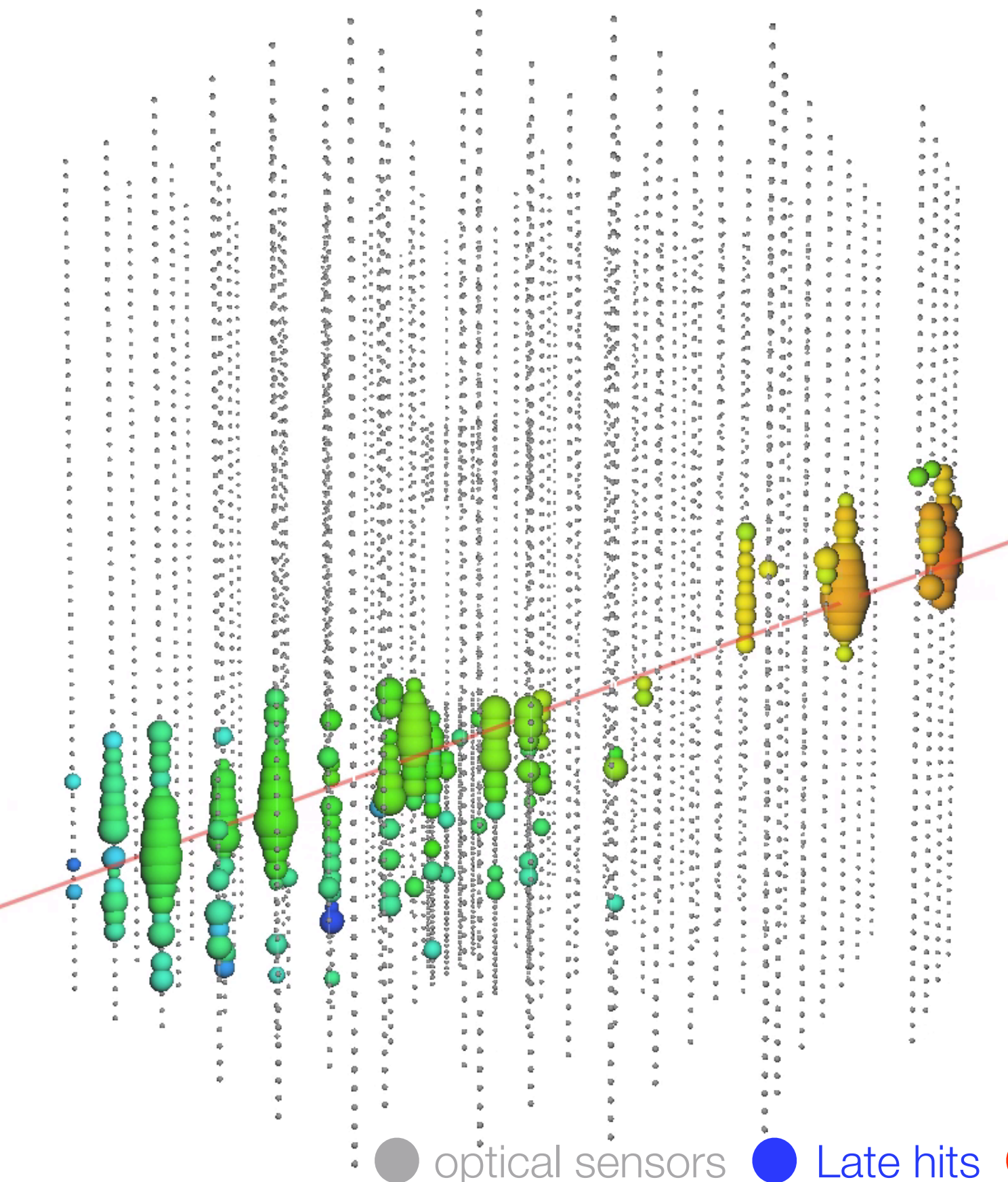
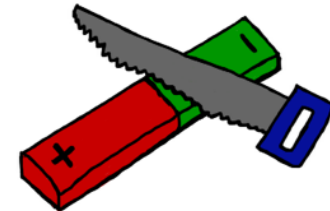


## Event characteristics:

- muon produced in an air shower
- non-homogenous brightness
- speed =  $c$
- downgoing
- often: several showers at once



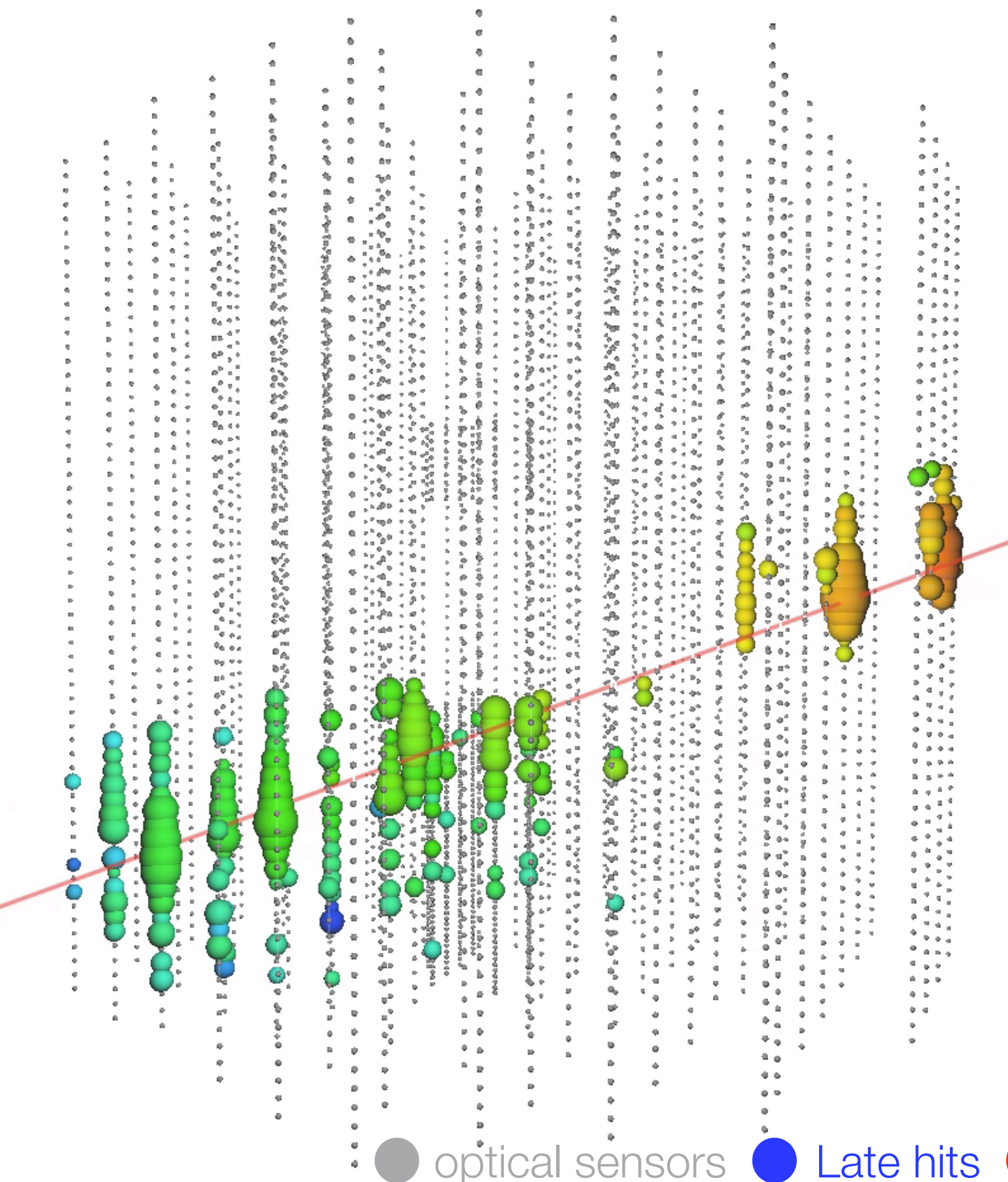
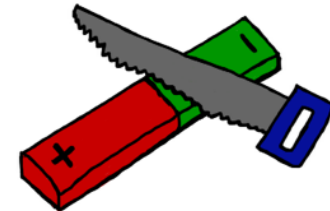
# Background: Neutrino



## Event characteristics:

- neutrino produced in an air shower
- muon-neutrino interaction  $\rightarrow$  muon
- non-homogenous brightness
- speed =  $c$
- isotropic direction

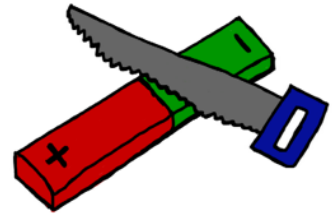
# Background: Neutrino



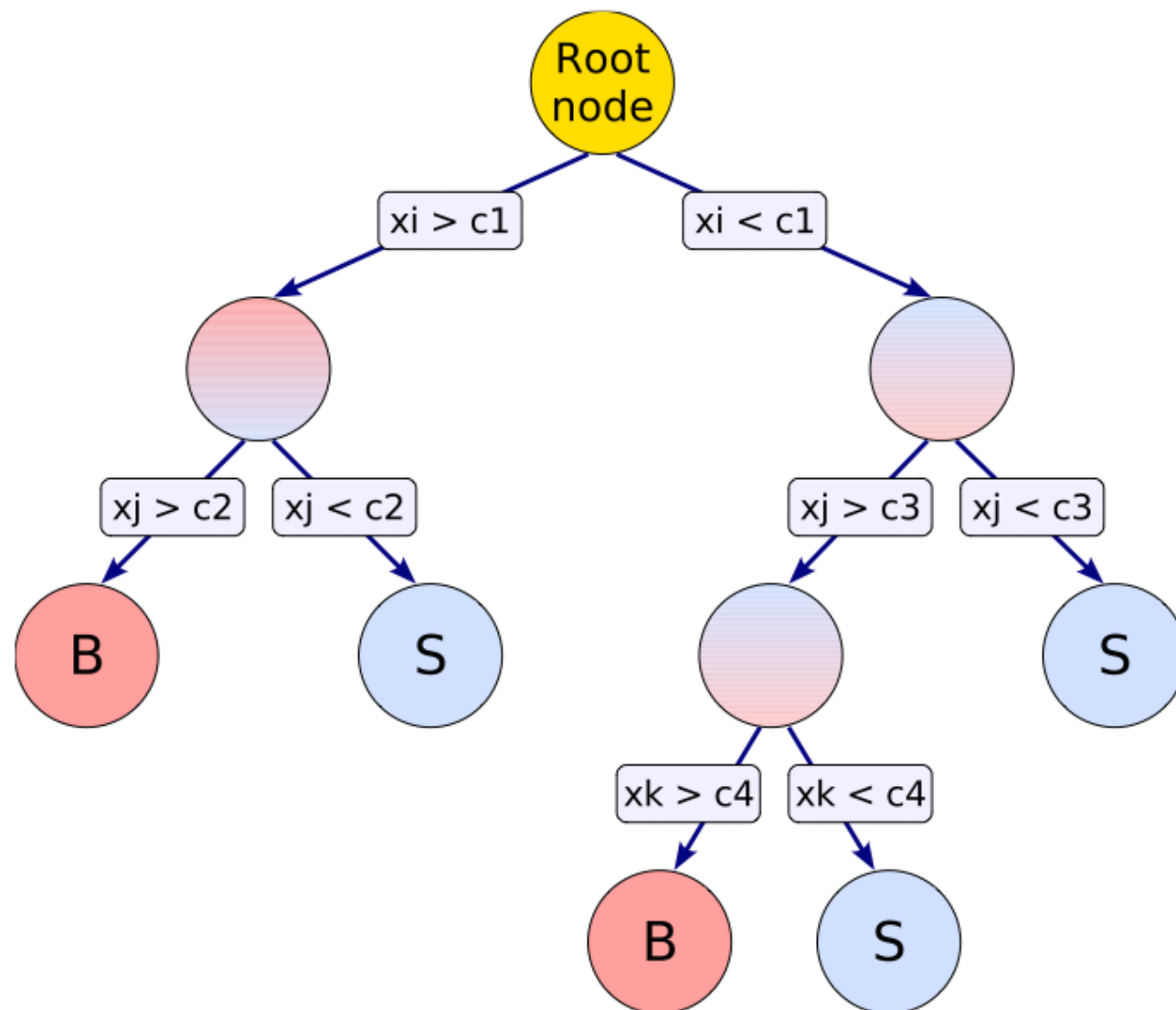
## Event characteristics:

- neutrino produced in an air shower
- muon-neutrino interaction  $\rightarrow$  muon
- non-homogenous brightness
- speed =  $c$
- isotropic direction

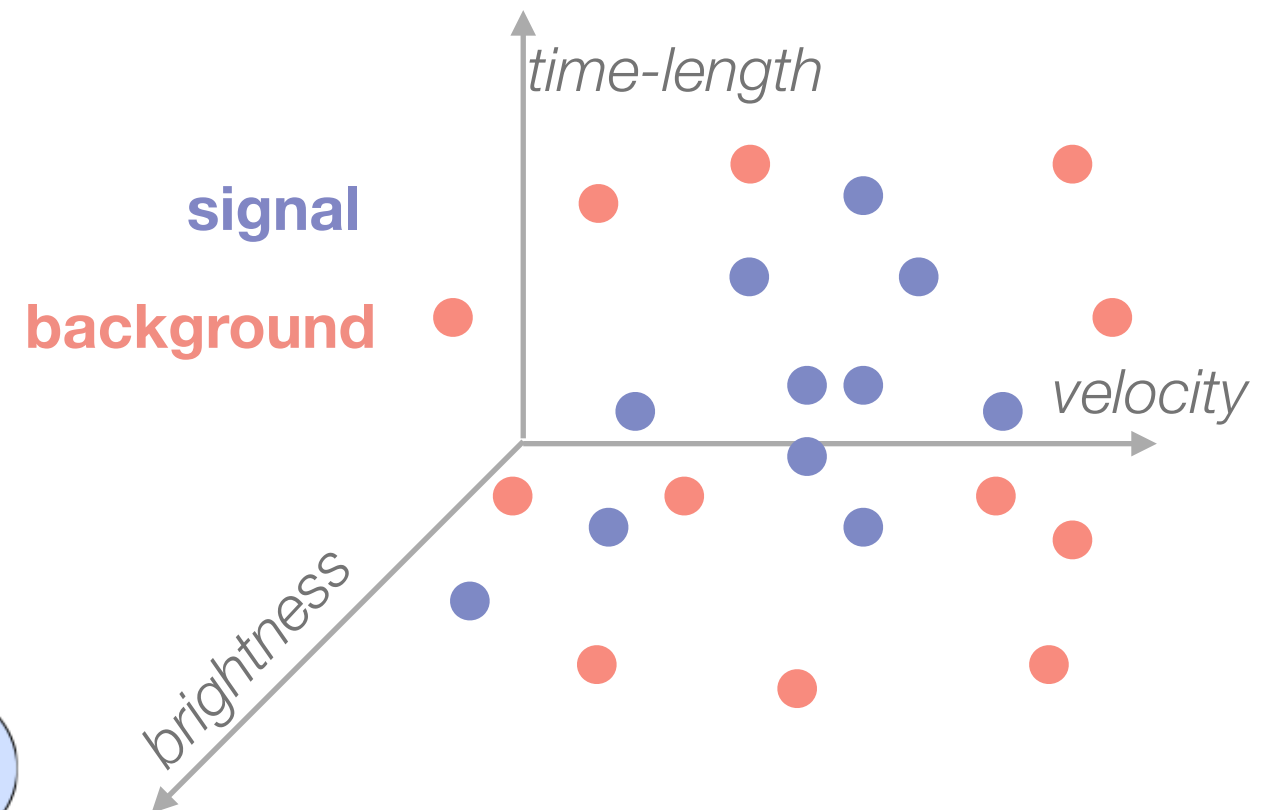
# Event Selection - Boosted decision tree



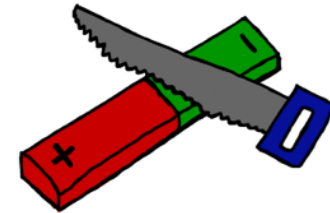
## Decision tree



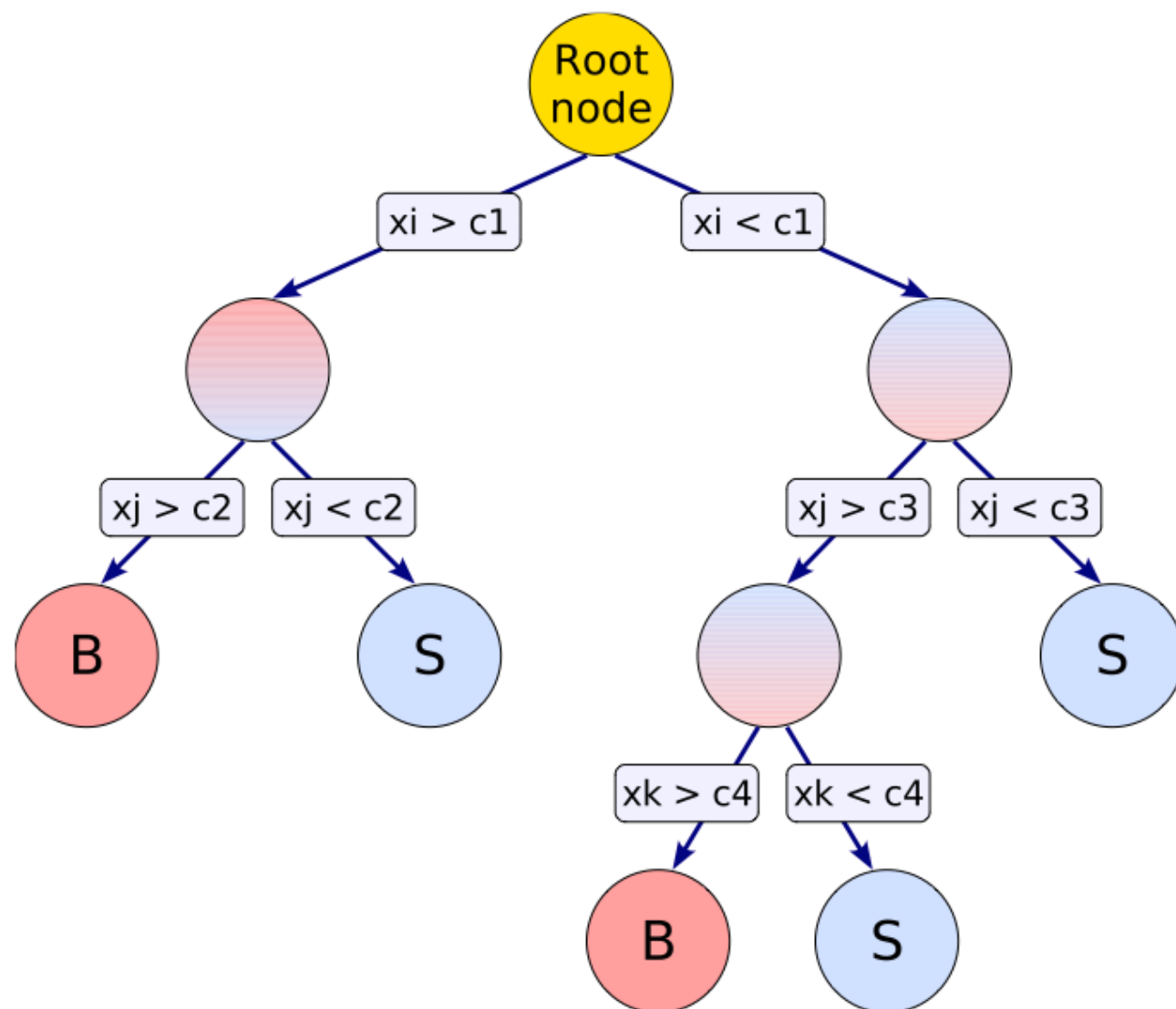
## 3-dimensional example



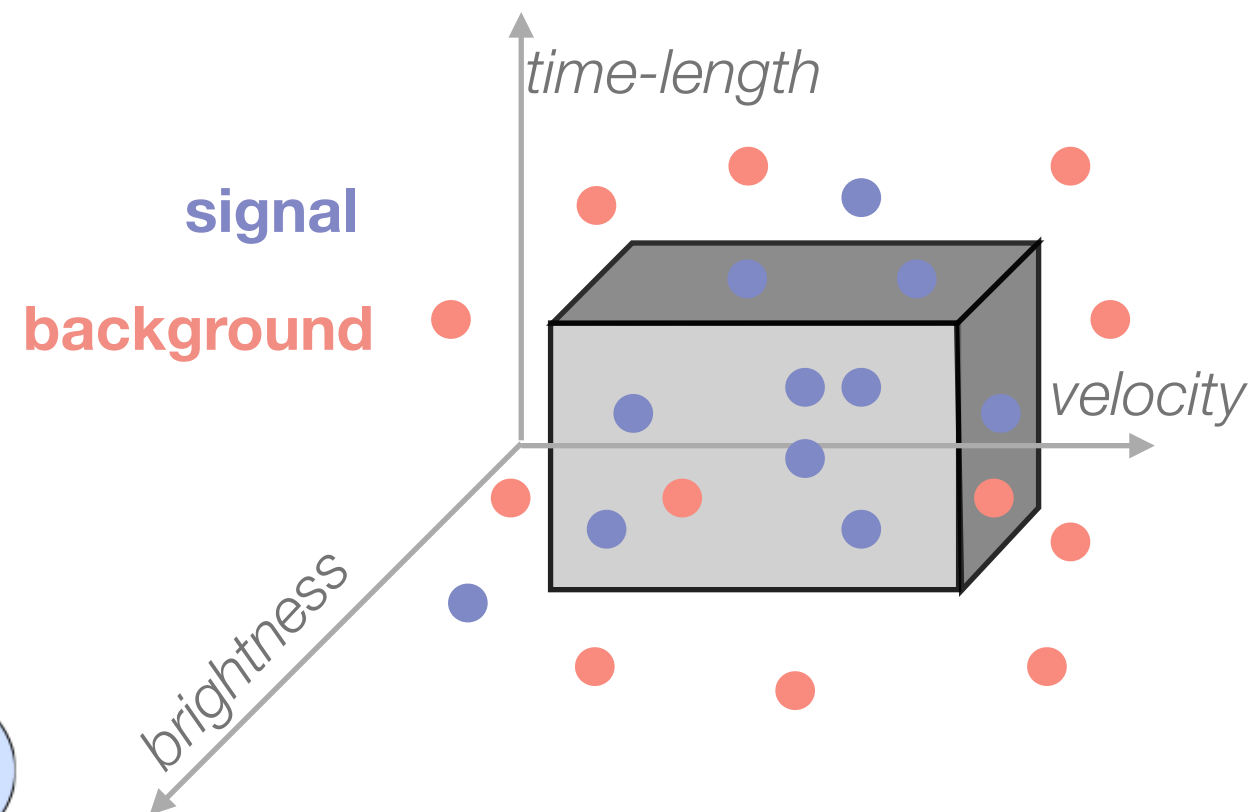
# Event Selection - Boosted decision tree



## Decision tree

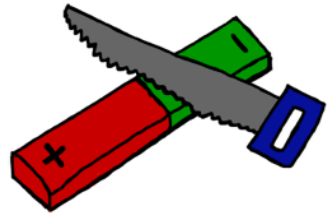


## 3-dimensional example

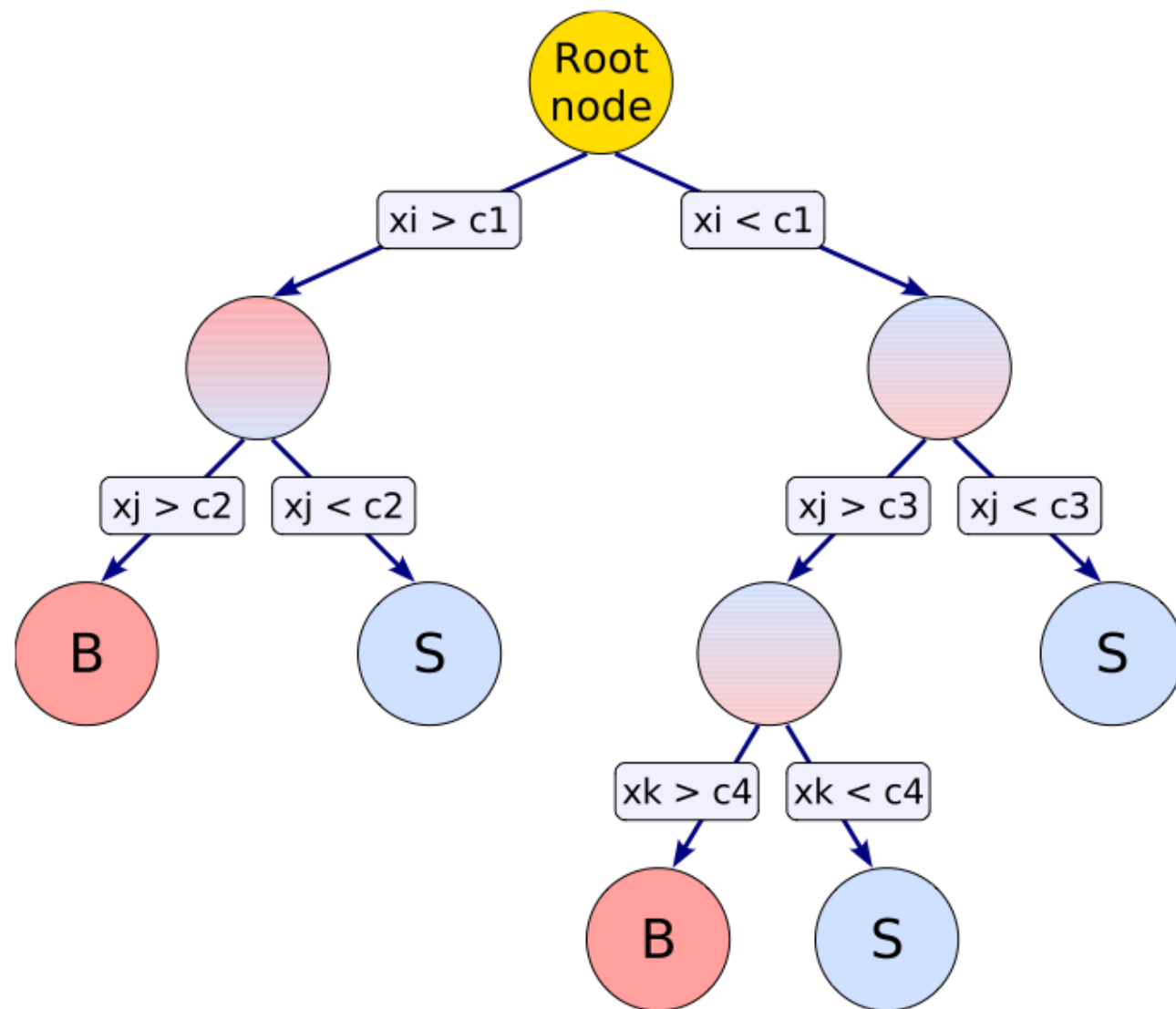




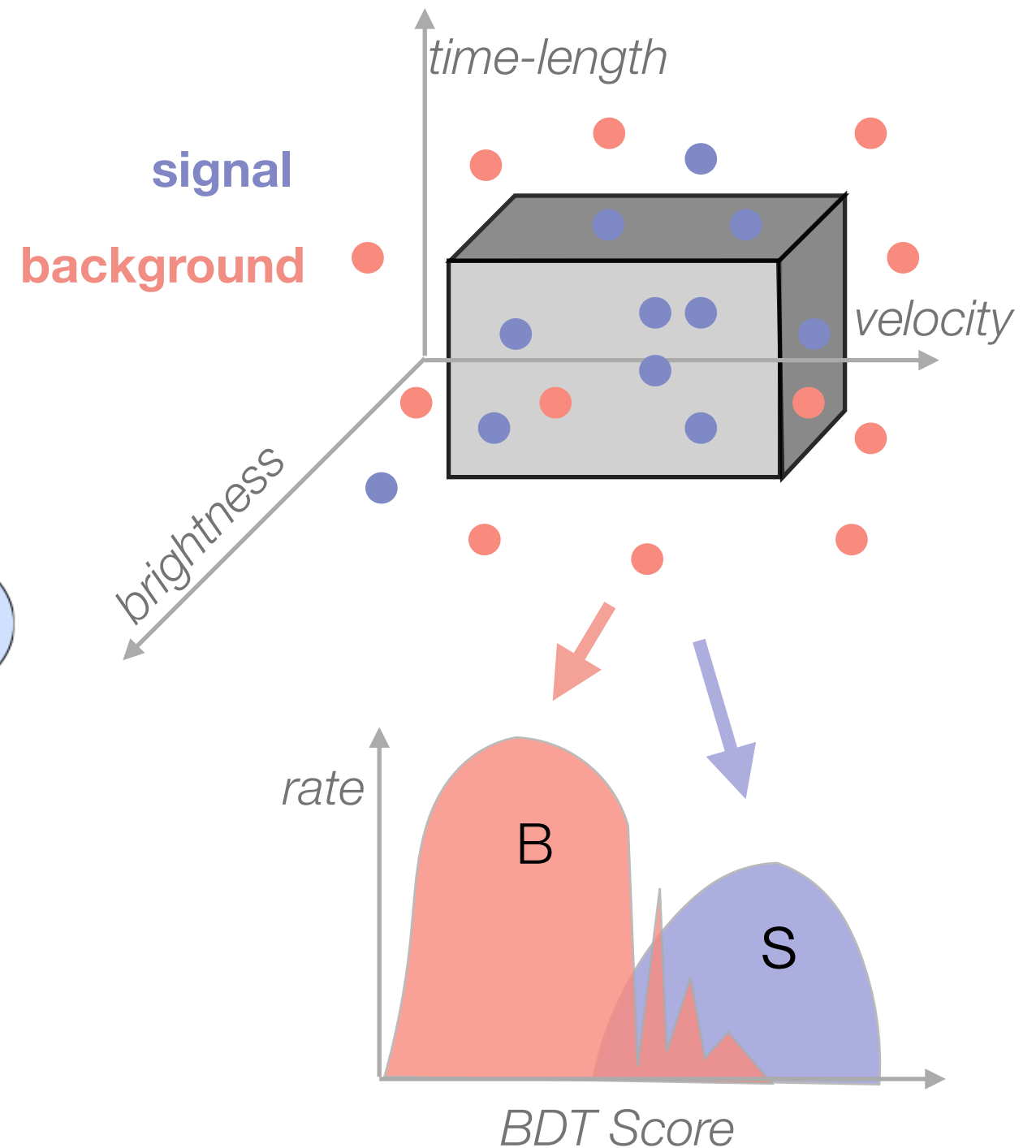
# Event Selection - Boosted decision tree



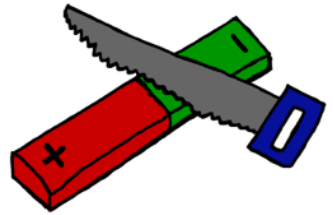
## Decision tree



## 3-dimensional example



# Event Selection - Pull-validation



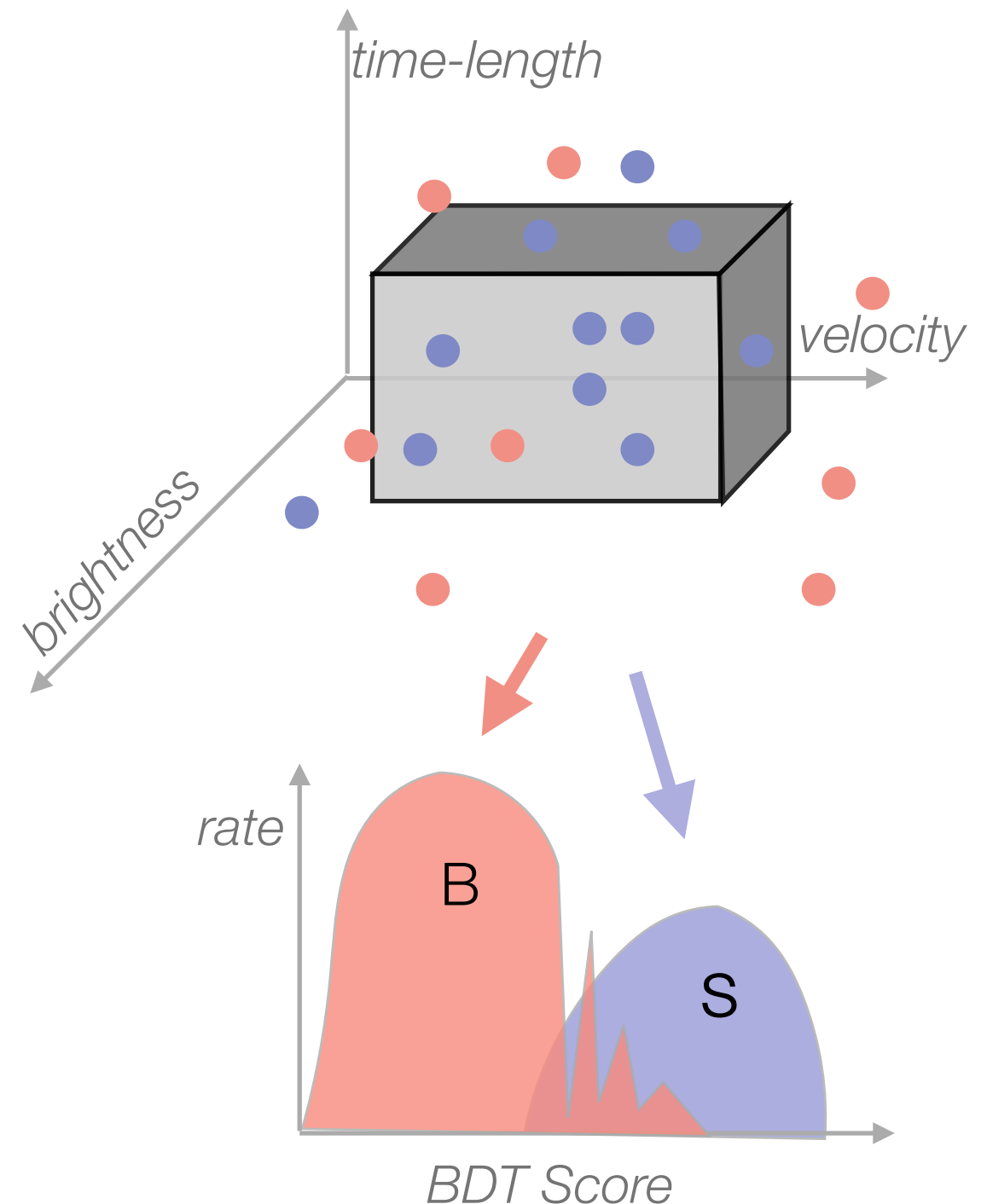
## Re-sampling

- smaller training sample -> larger fluctuation when testing
- train on hundred of samples
- smoother population of space

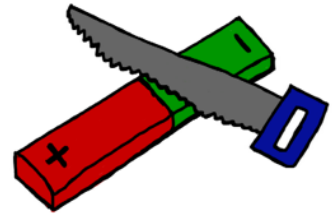
## Pull-validation

- train BDT on 10% sub-sample
- apply on disjunct 90% rest
- interpret the fluctuation between sub-samples as statistical uncertainty of the whole sample

## 3-dimensional example



# Event Selection - Pull-validation



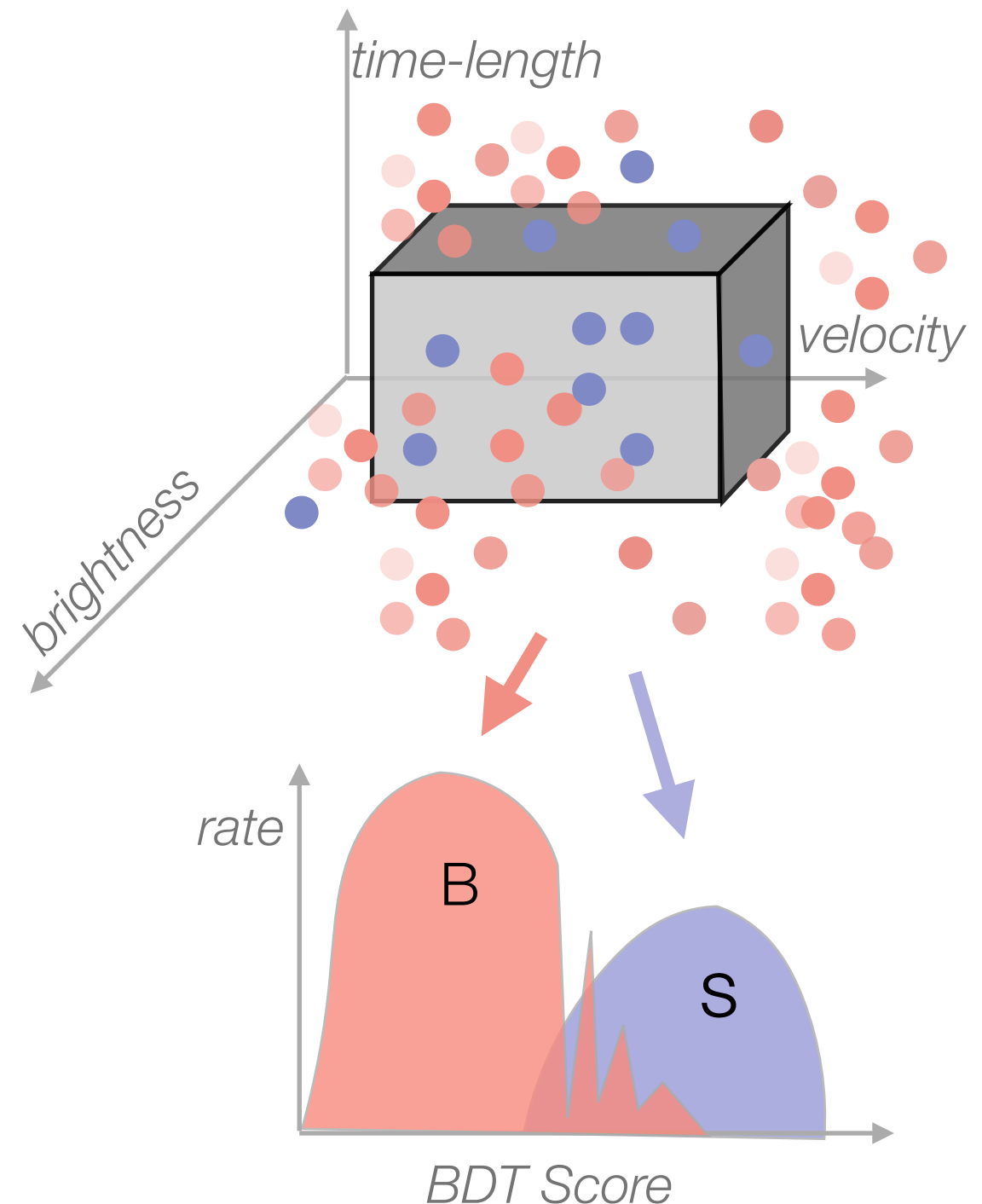
## Re-sampling

- smaller training sample -> larger fluctuation when testing
- train on hundred of samples
- smoother population of space

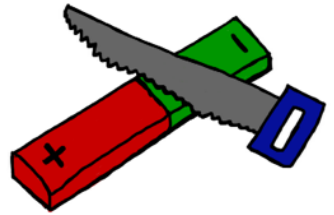
## Pull-validation

- train BDT on 10% sub-sample
- apply on disjunct 90% rest
- interpret the fluctuation between sub-samples as statistical uncertainty of the whole sample

## 3-dimensional example



# Event Selection - Pull-validation



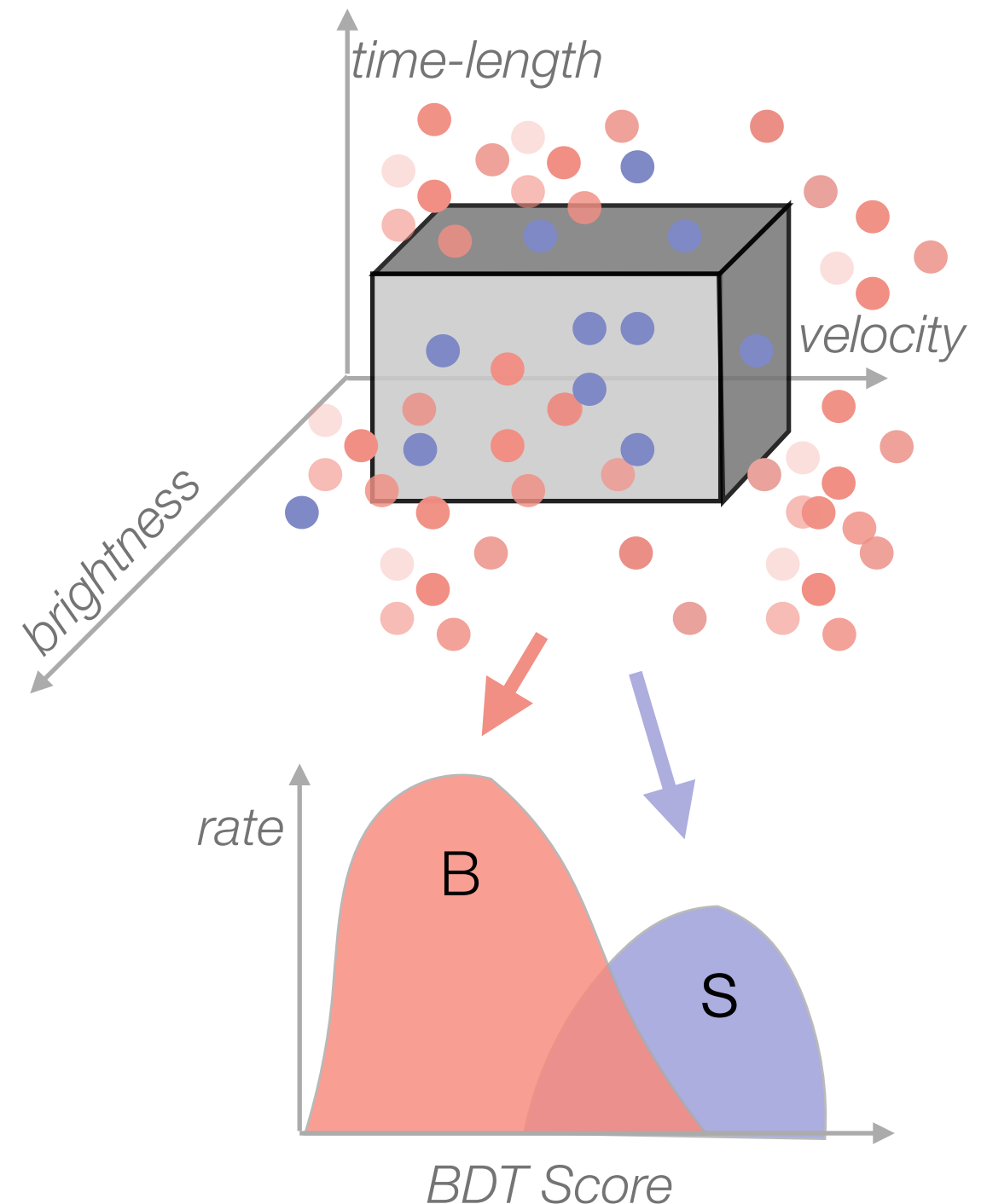
## Re-sampling

- smaller training sample -> larger fluctuation when testing
- train on hundred of samples
- smoother population of space

## Pull-validation

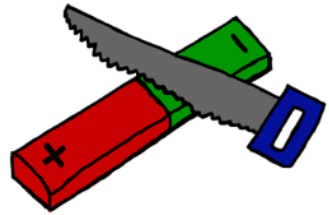
- train BDT on 10% sub-sample
- apply on disjunct 90% rest
- interpret the fluctuation between sub-samples as statistical uncertainty of the whole sample

## 3-dimensional example



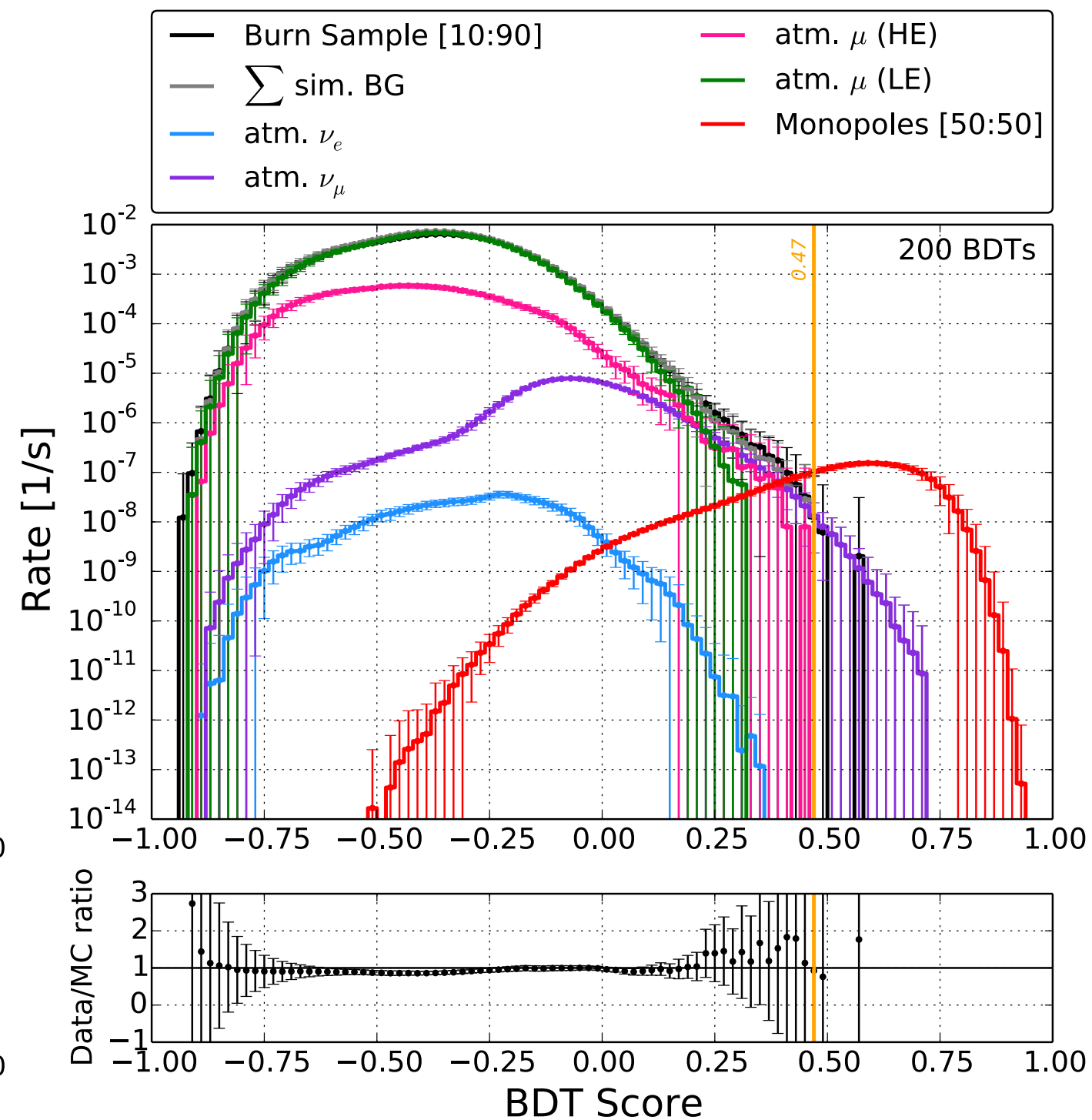
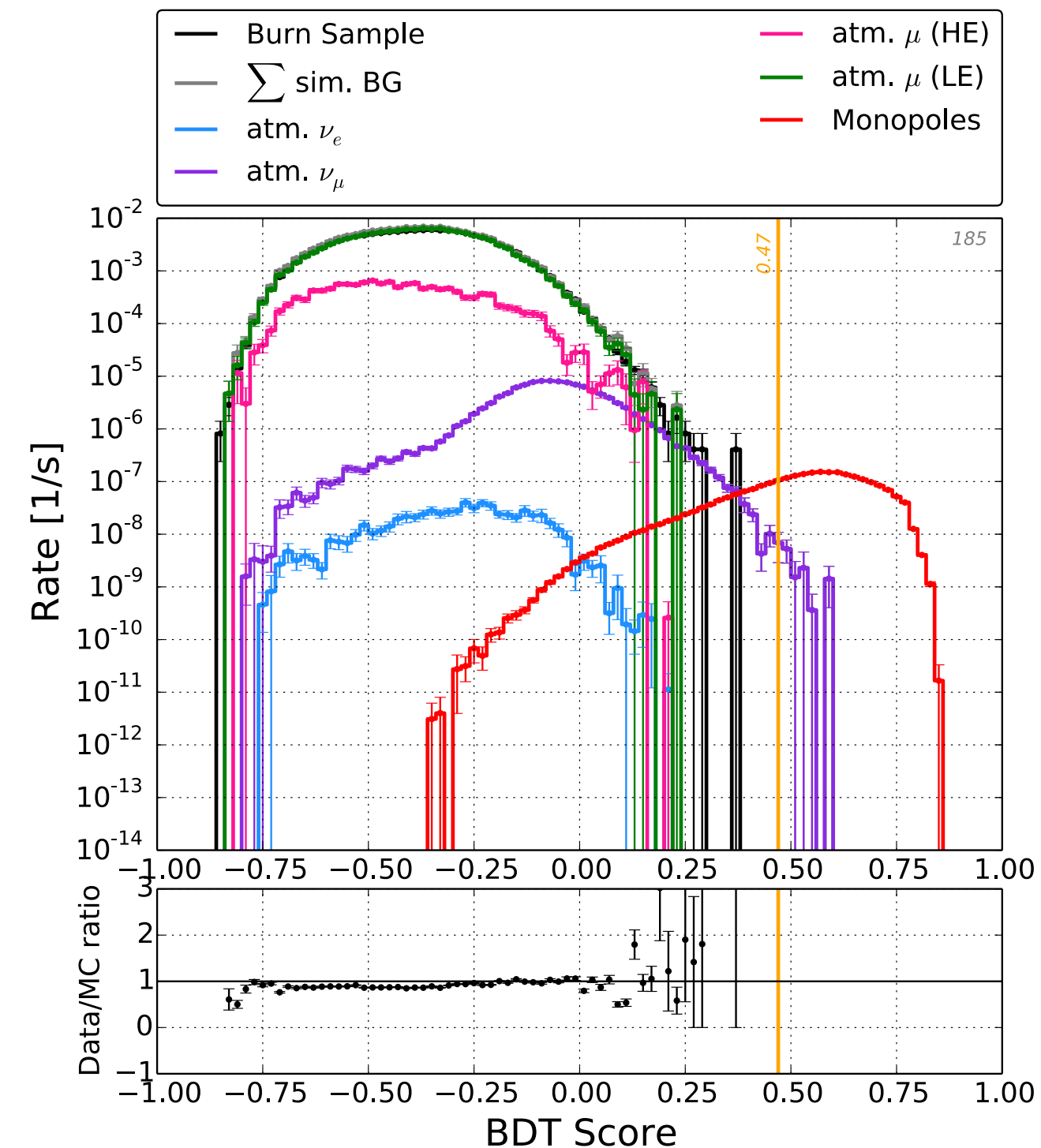


# Event Selection - Pull-validation



## Single BDT

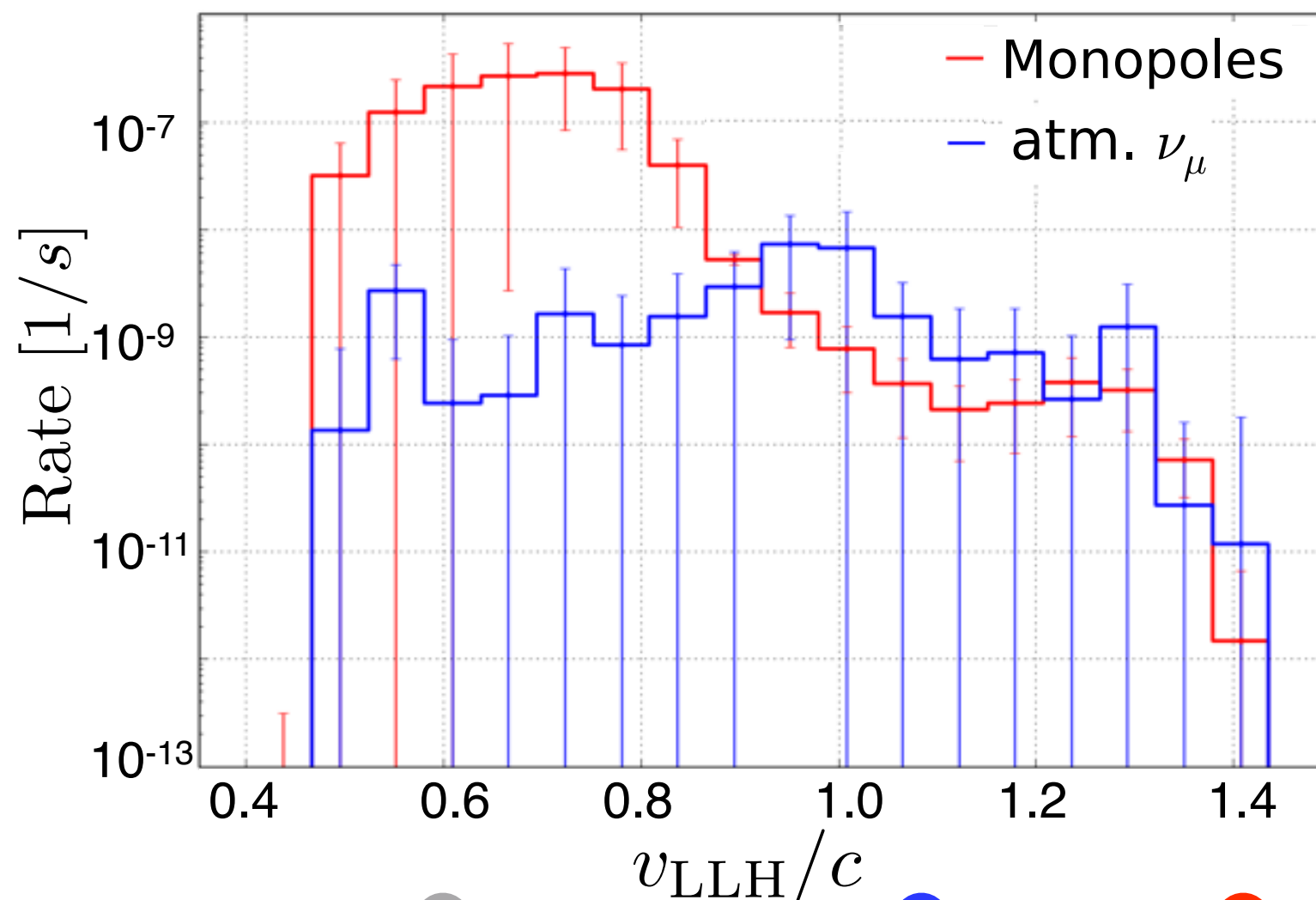
## 200 BDTs averaged



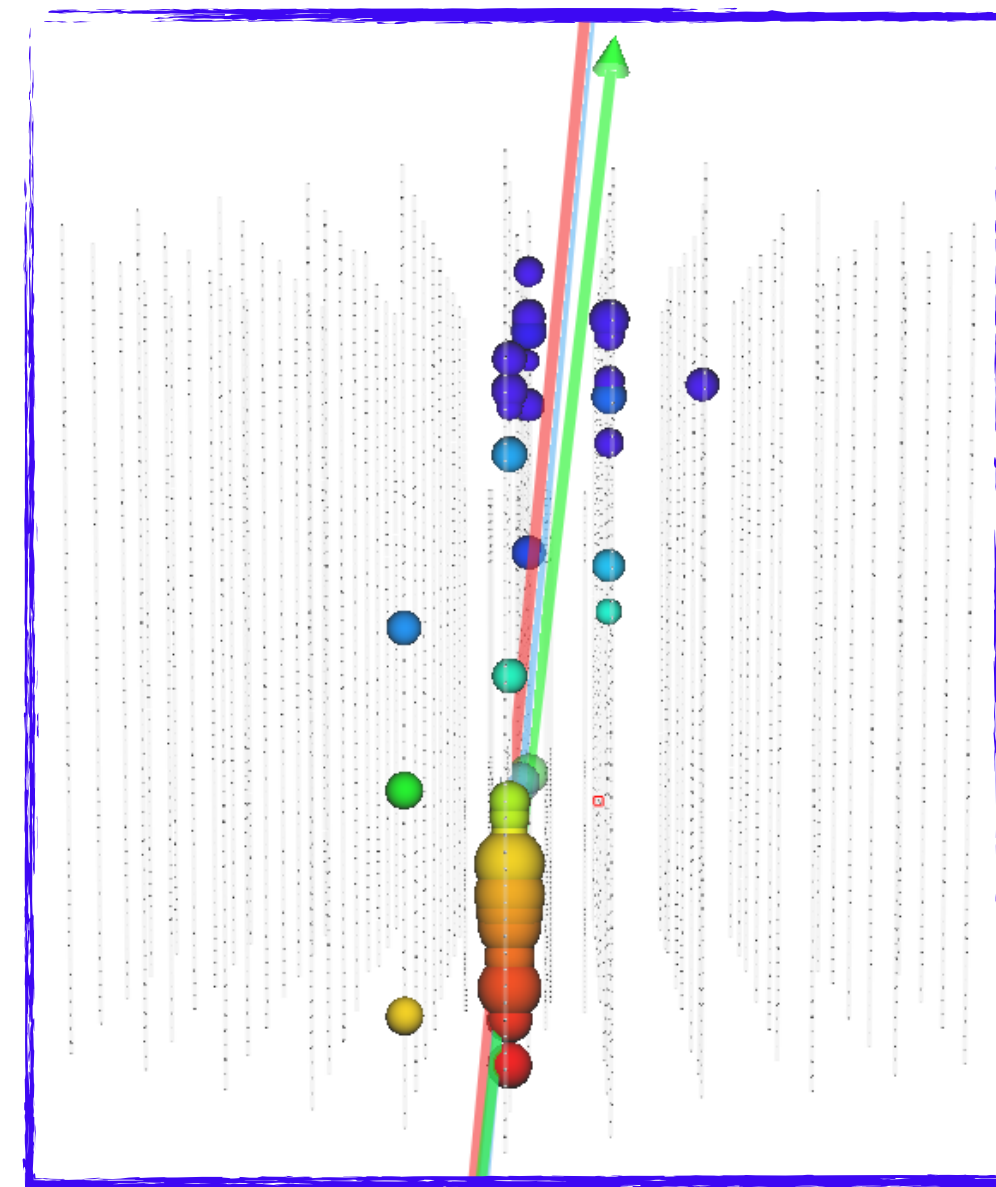
# Event Selection - Checks

Pull-validation method  
published on  
**ArXiv:1510.05226**

- bin height fluctuation due to pull-validation
- relative contribution of each event to background rate
- distribution of other variables
- and many more checks done

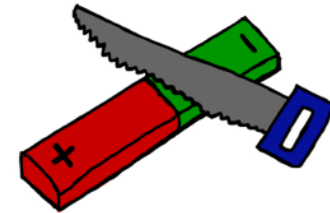


## Expected background event shape

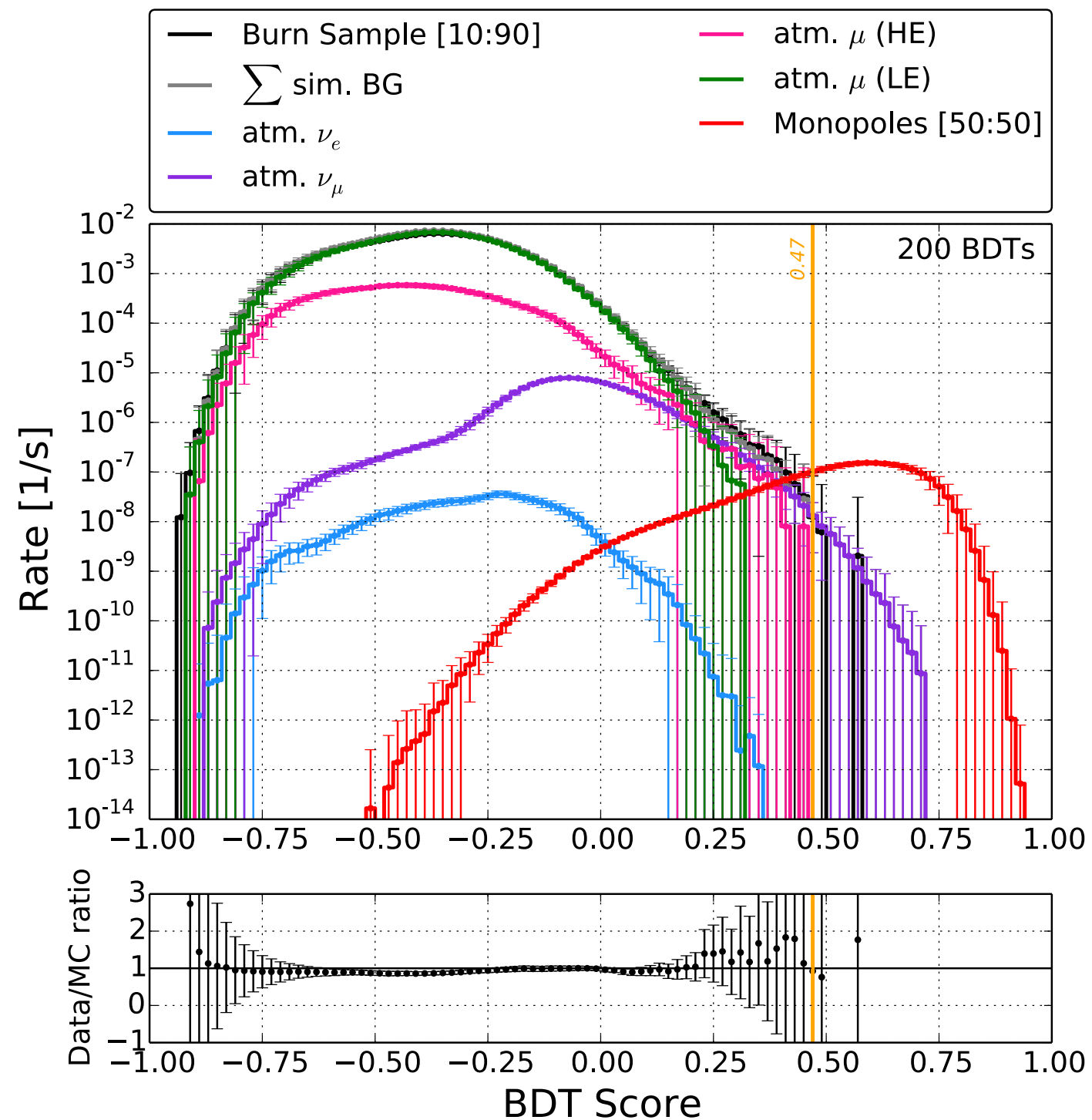
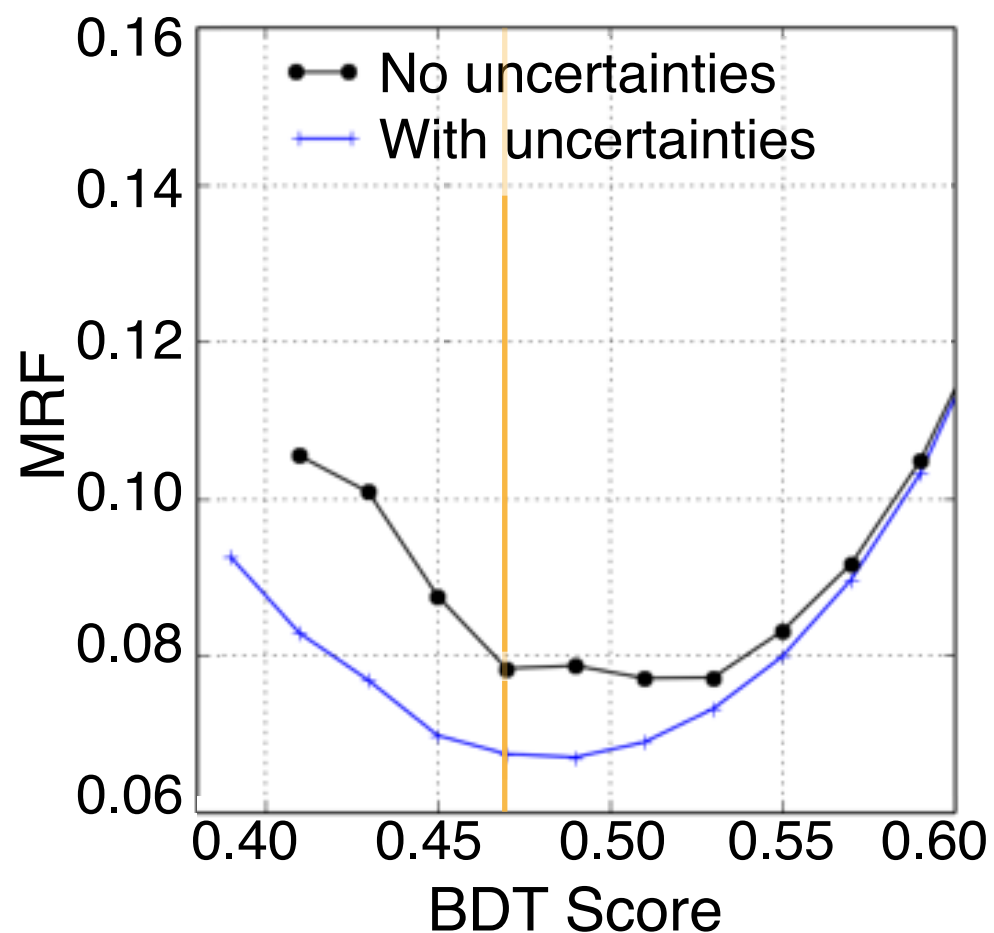


● optical sensors ● Late hits ● Early hits — Track

# Event Selection - Sensitivity optimisation

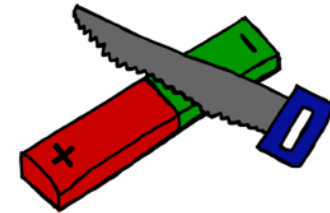


- Feldman Cousins with uncertainties
- cut at BDT score 0.47 to gain statistics and stability

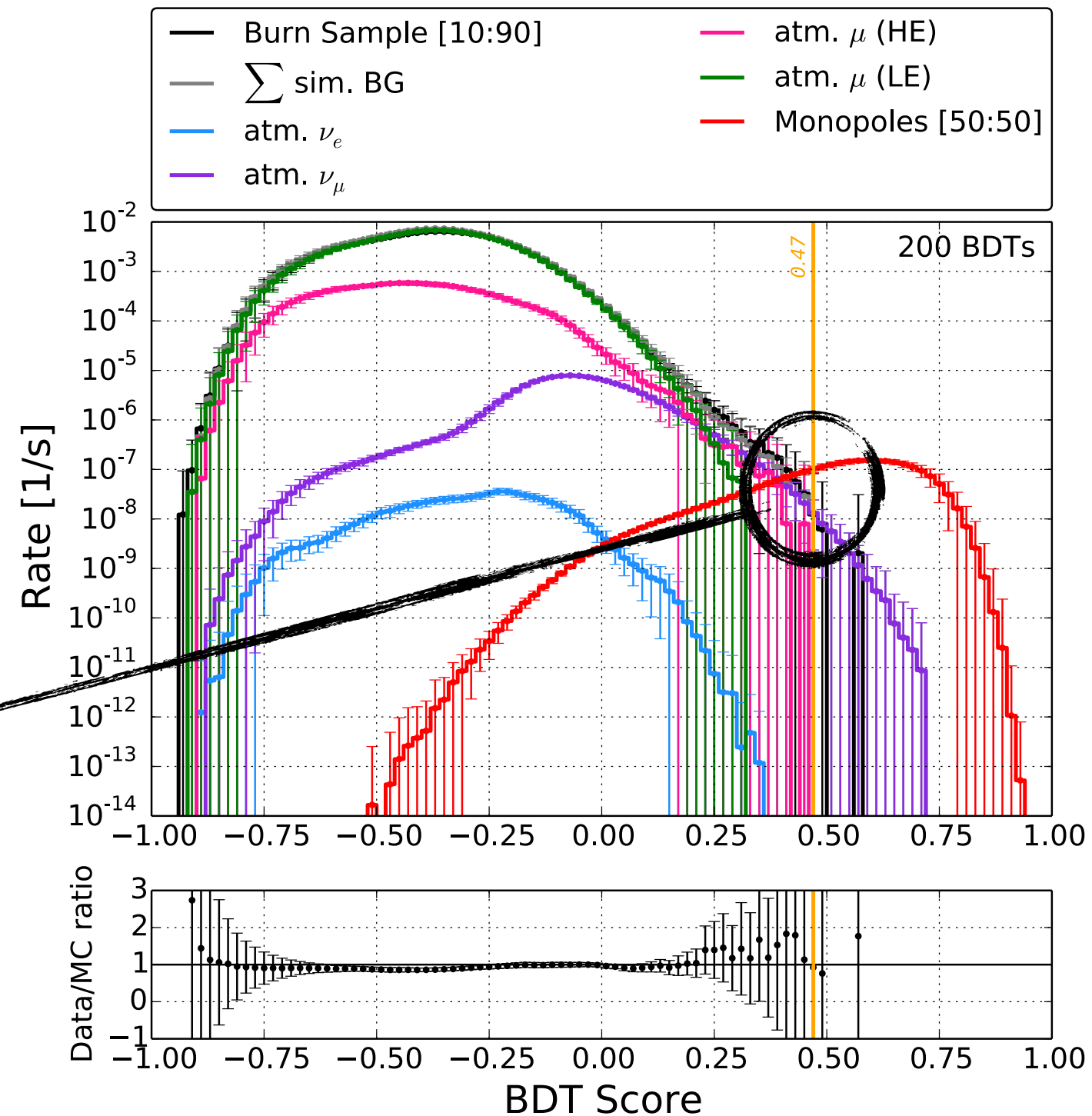
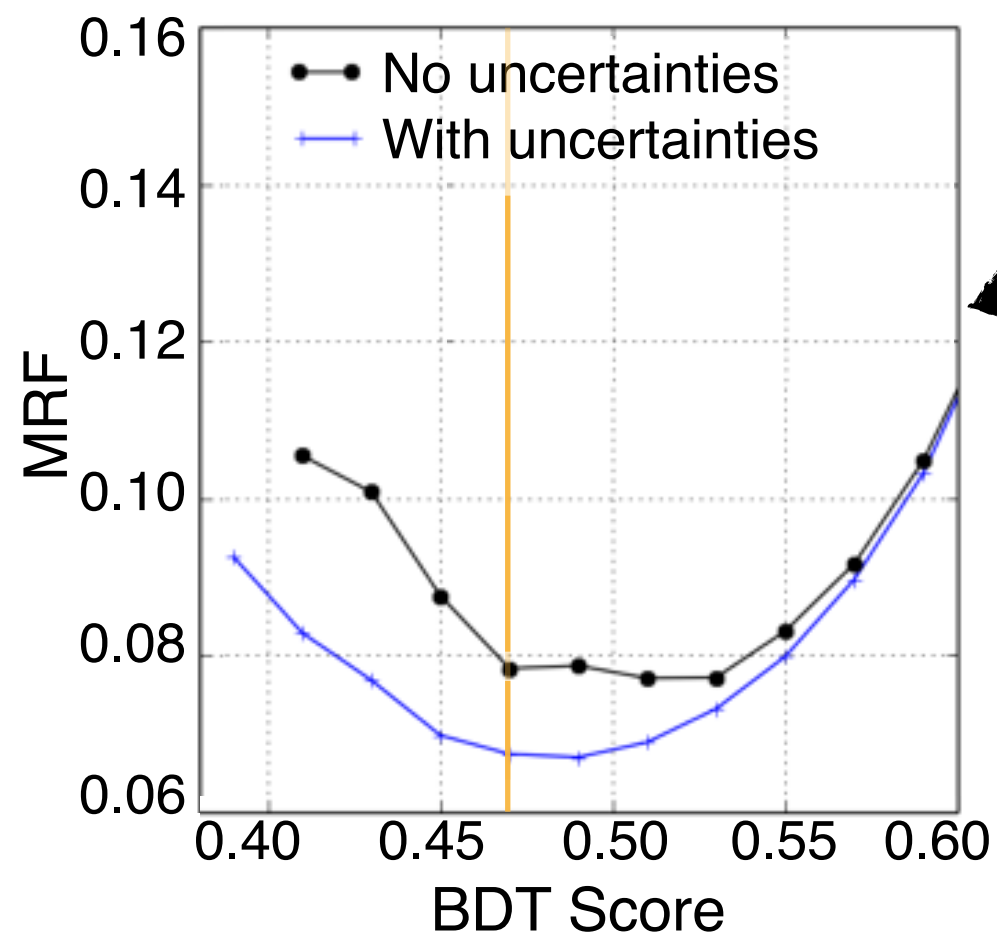




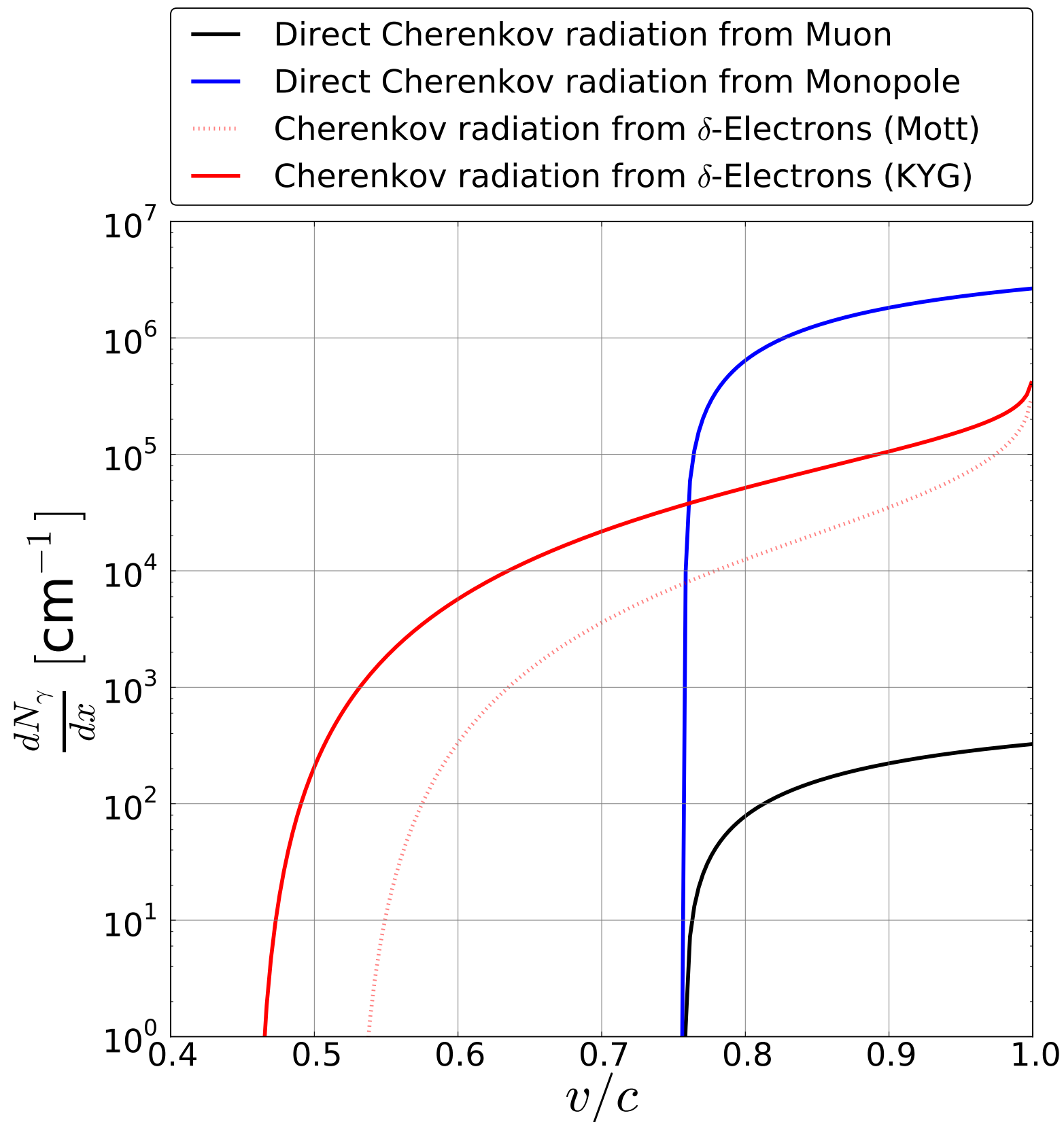
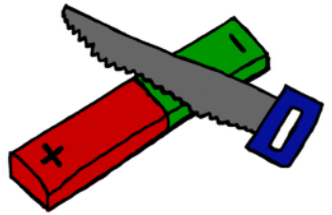
# Event Selection - Sensitivity optimisation



- Feldman Cousins with uncertainties
- cut at BDT score 0.47 to gain statistics and stability



# Monopole - Electron Cross Section



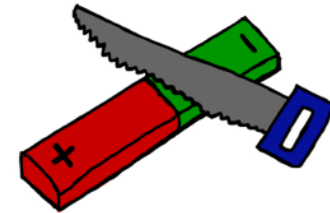
## Mott

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

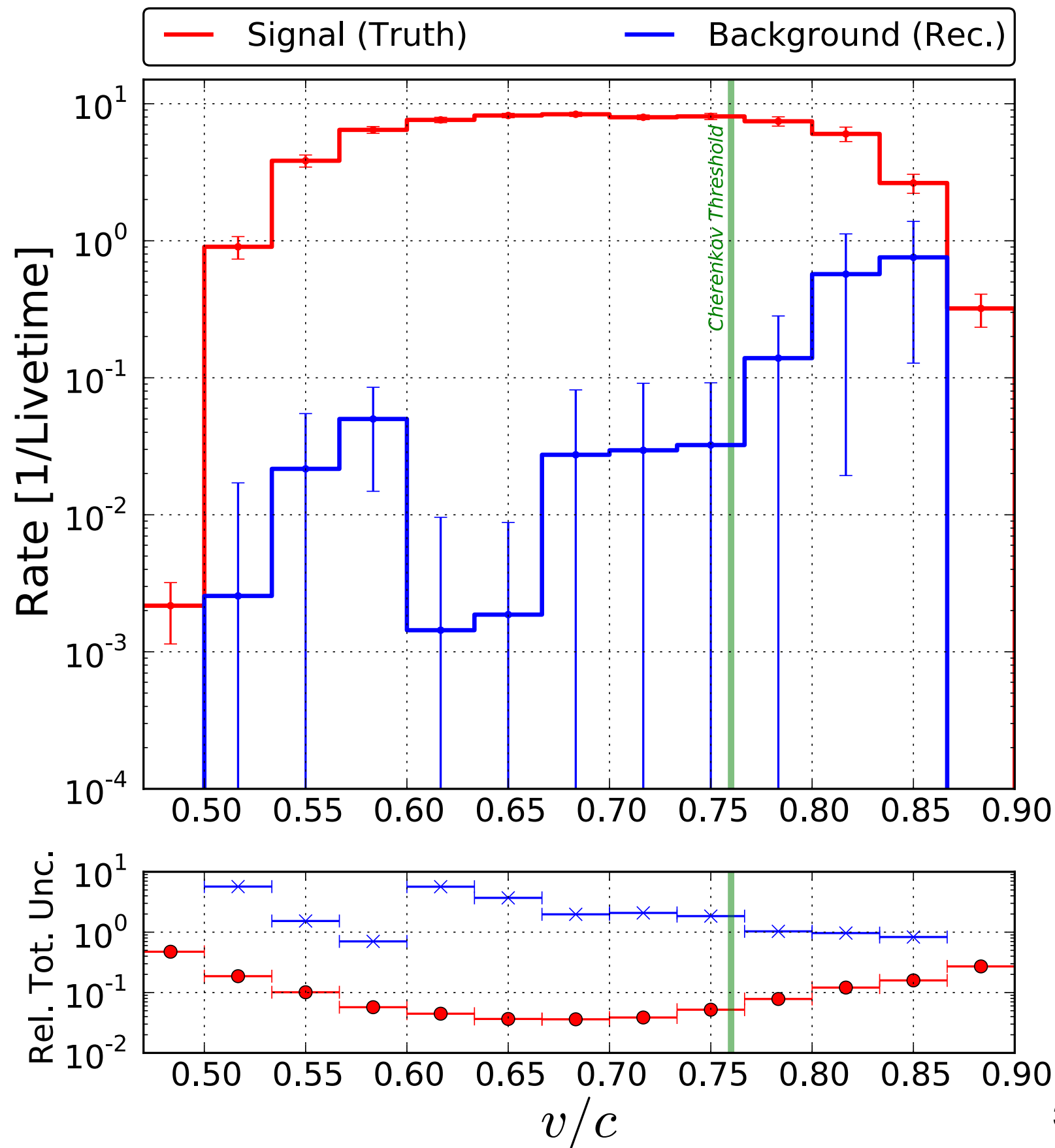
## KYG

- electrodynamic
- quantum field theory

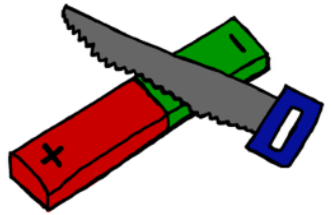
# Event Selection - Velocity dependence



- Feldman Cousins with uncertainties
- cut at BDT score 0.47 to gain statistics and stability
- normalize and smooth bins

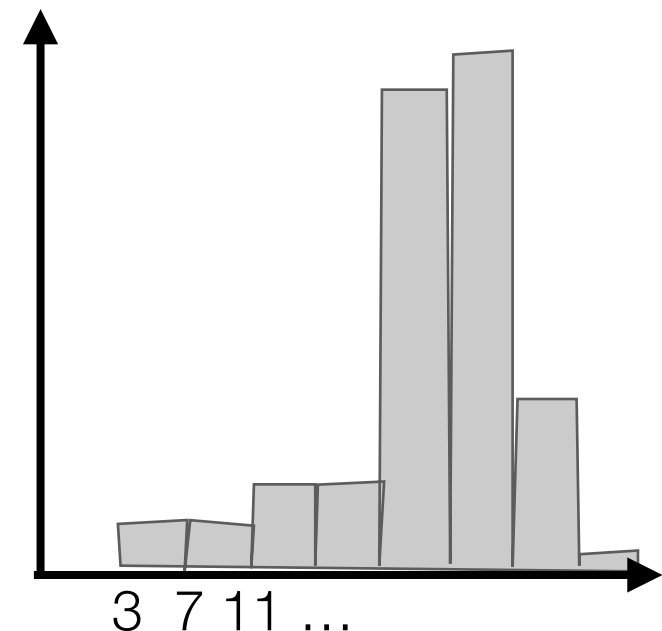
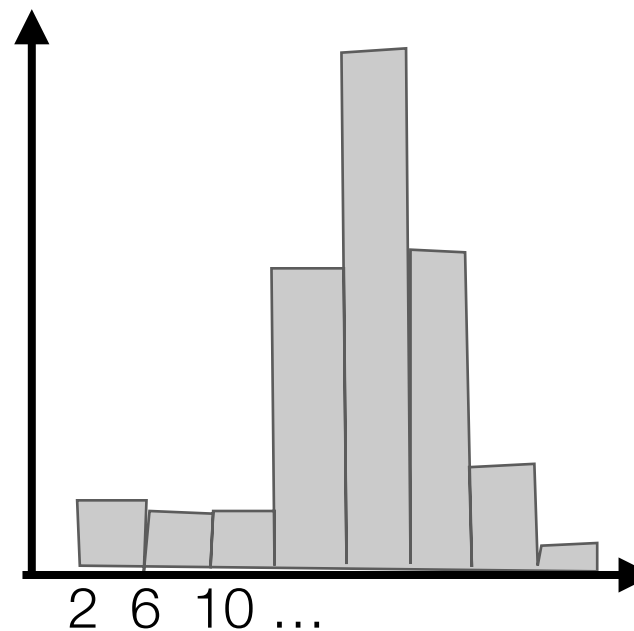
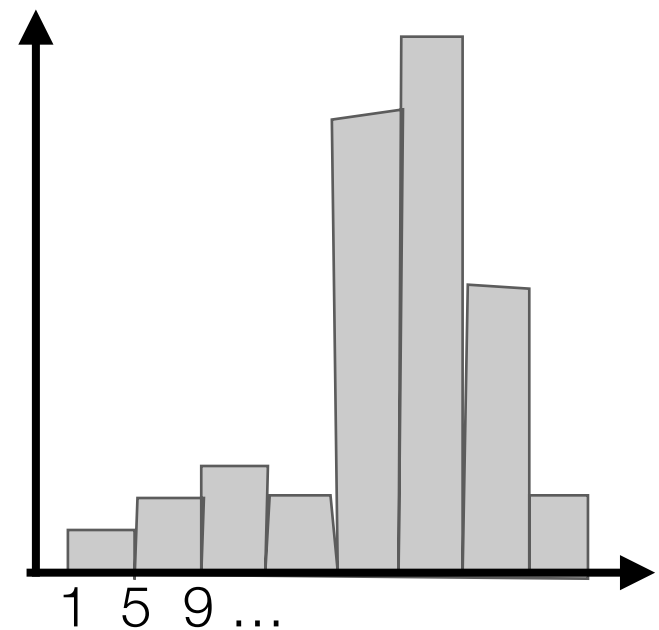
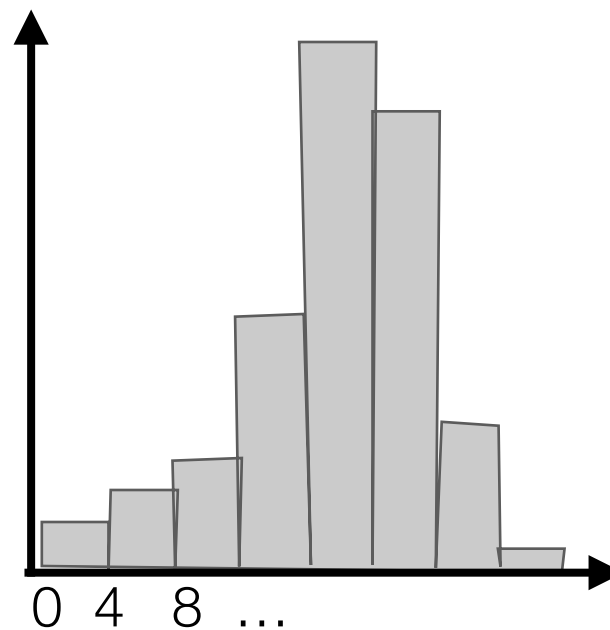


# Event Selection - Velocity dependence



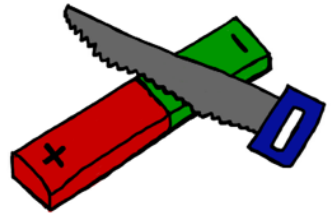
- Feldman Cousins with uncertainties
- cut at BDT score 0.47 to gain statistics and stability
- normalize and smooth bins

## Effect of different histogram origins



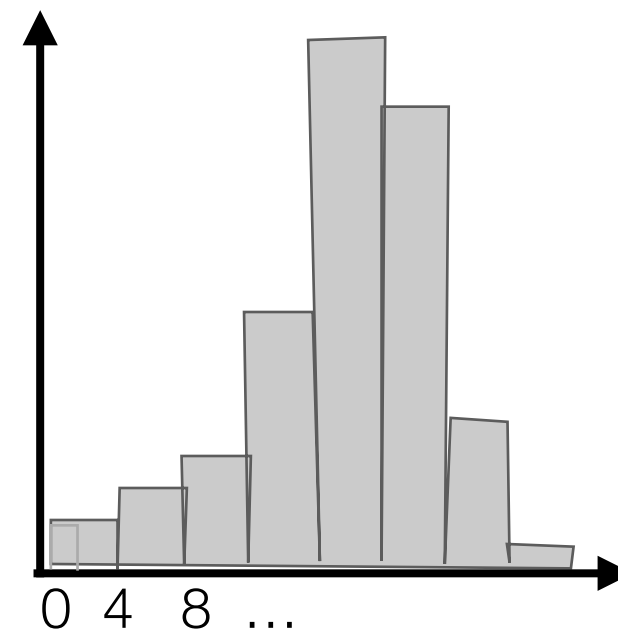


# Event Selection - Velocity dependence

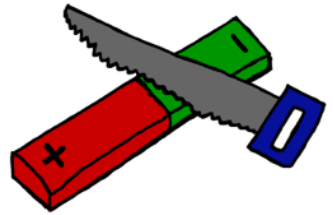


- Feldman Cousins with uncertainties
- cut at BDT score 0.47 to gain statistics and stability
- normalize and smooth bins:
  - averaged 5 histograms
  - width: reconstruction uncertainty

## Effect of different histogram origins

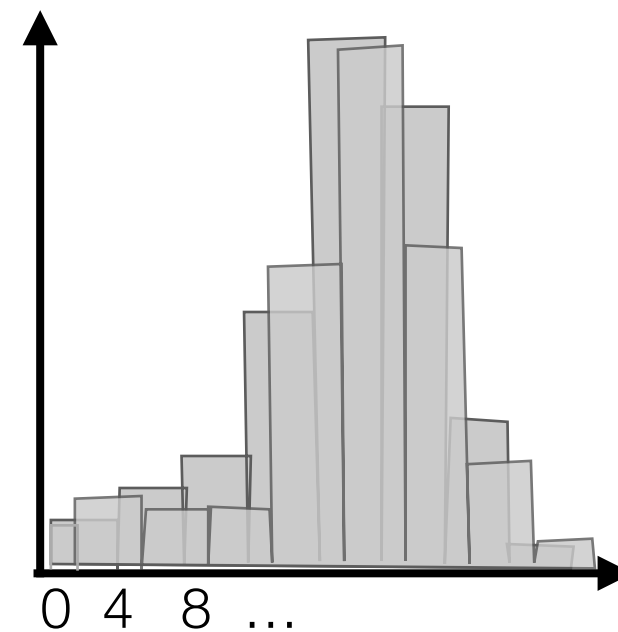


# Event Selection - Velocity dependence

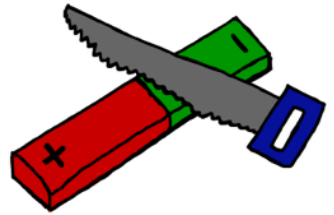


- Feldman Cousins with uncertainties
- cut at BDT score 0.47 to gain statistics and stability
- normalize and smooth bins:
  - averaged 5 histograms
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## Effect of different histogram origins

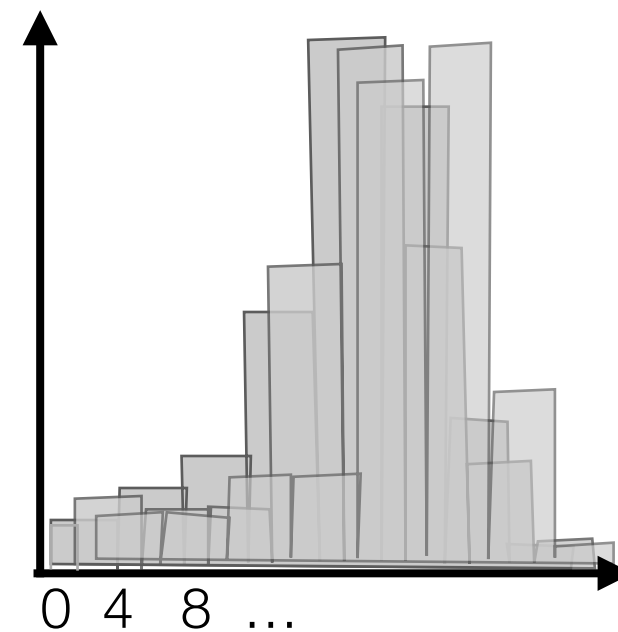


# Event Selection - Velocity dependence

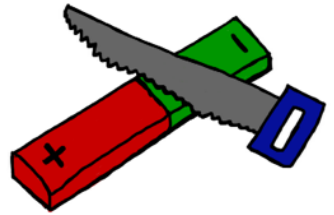


- Feldman Cousins with uncertainties
- cut at BDT score 0.47 to gain statistics and stability
- normalize and smooth bins:
  - averaged 5 histograms
  - width: reconstruction uncertainty

## Effect of different histogram origins

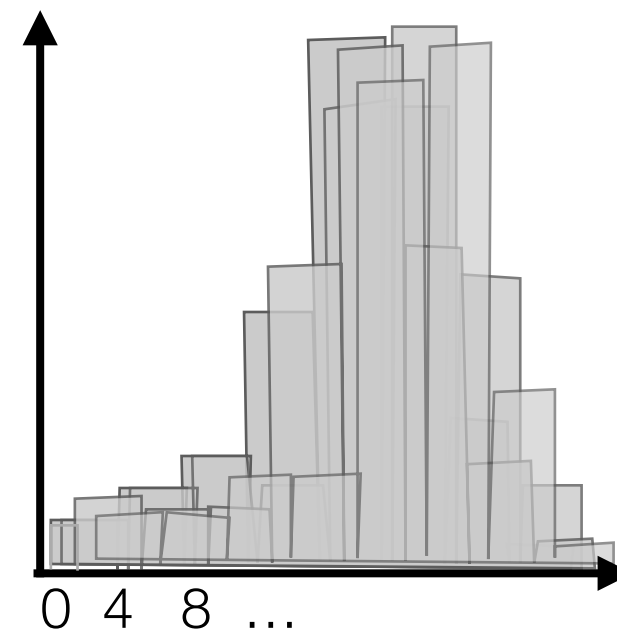


# Event Selection - Velocity dependence



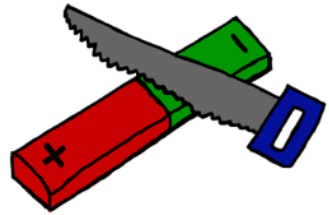
- Feldman Cousins with uncertainties
- cut at BDT score 0.47 to gain statistics and stability
- normalize and smooth bins:
  - averaged 5 histograms
  - width: reconstruction uncertainty

## Effect of different histogram origins



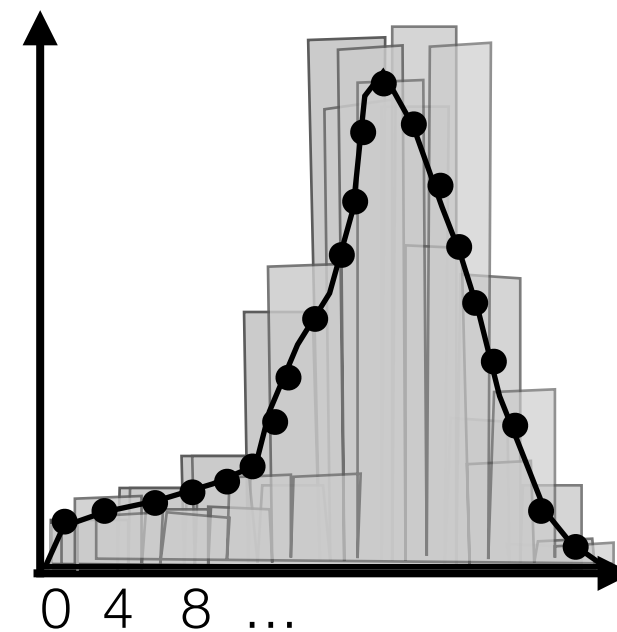


# Event Selection - Velocity dependence

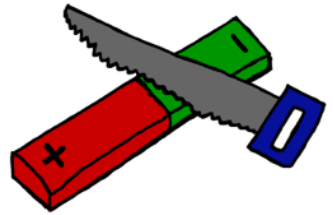


- Feldman Cousins with uncertainties
- cut at BDT score 0.47 to gain statistics and stability
- normalize and smooth bins:
  - averaged 5 histograms
  - width: reconstruction uncertainty

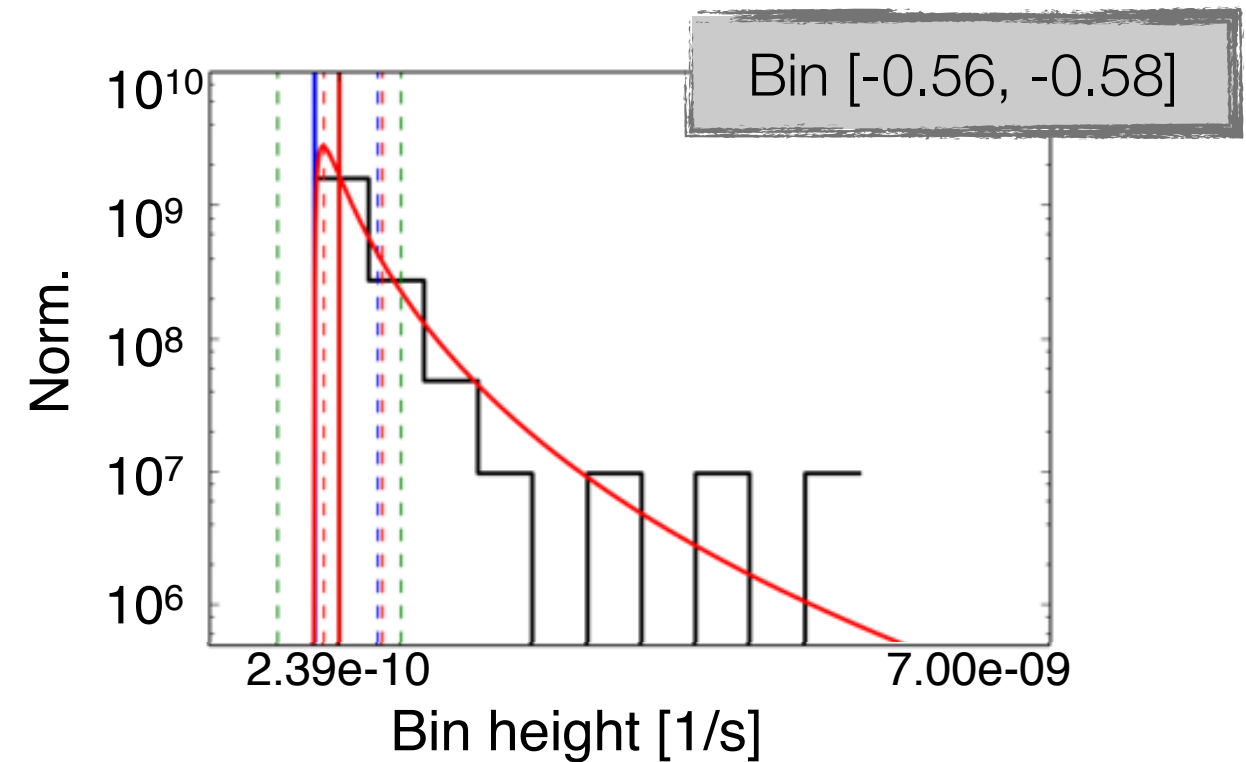
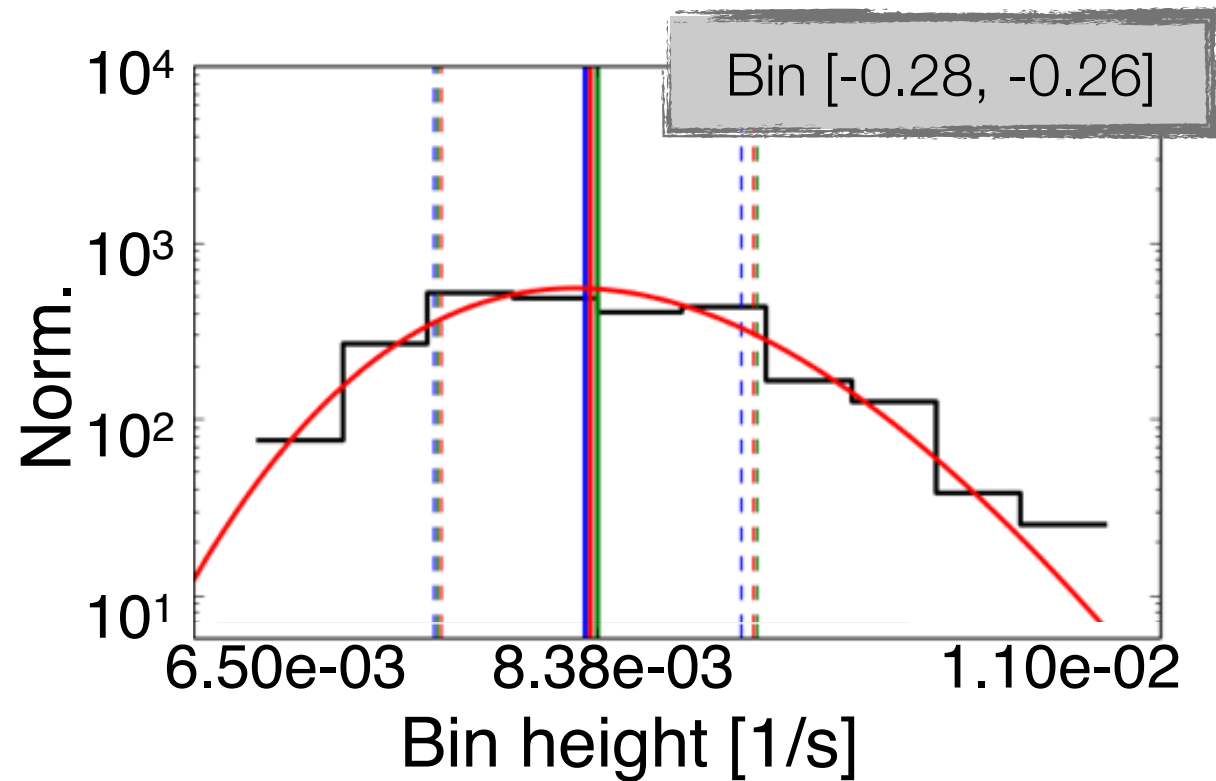
## Effect of different histogram origins



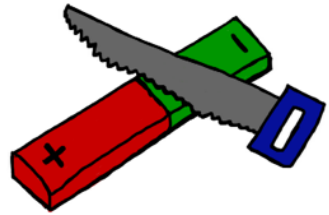
# Event Selection - Checks



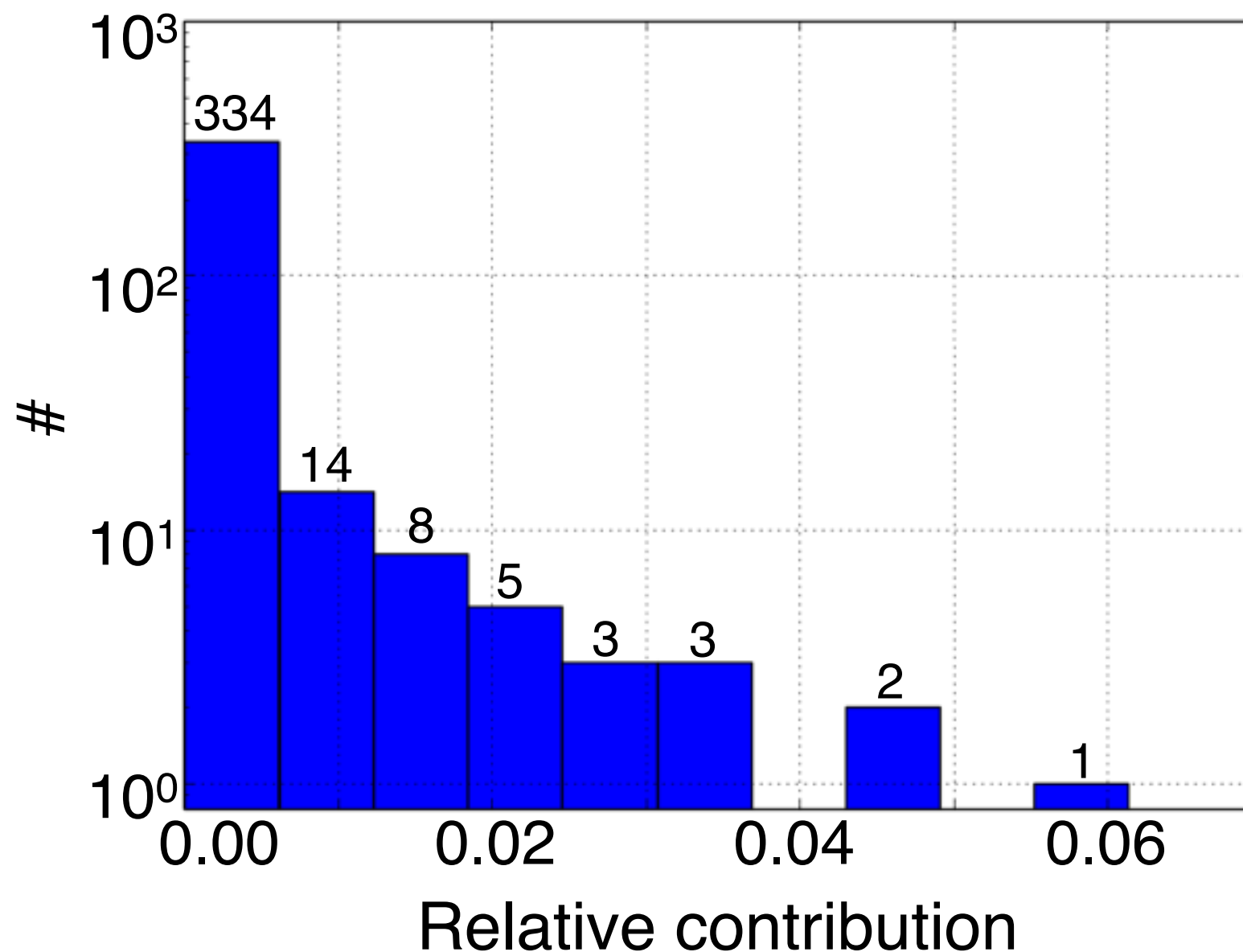
- bin height fluctuation due to pull-validation

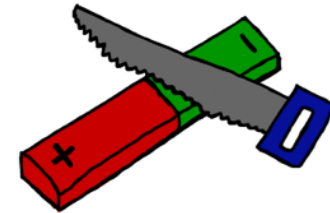


# Event Selection - Checks

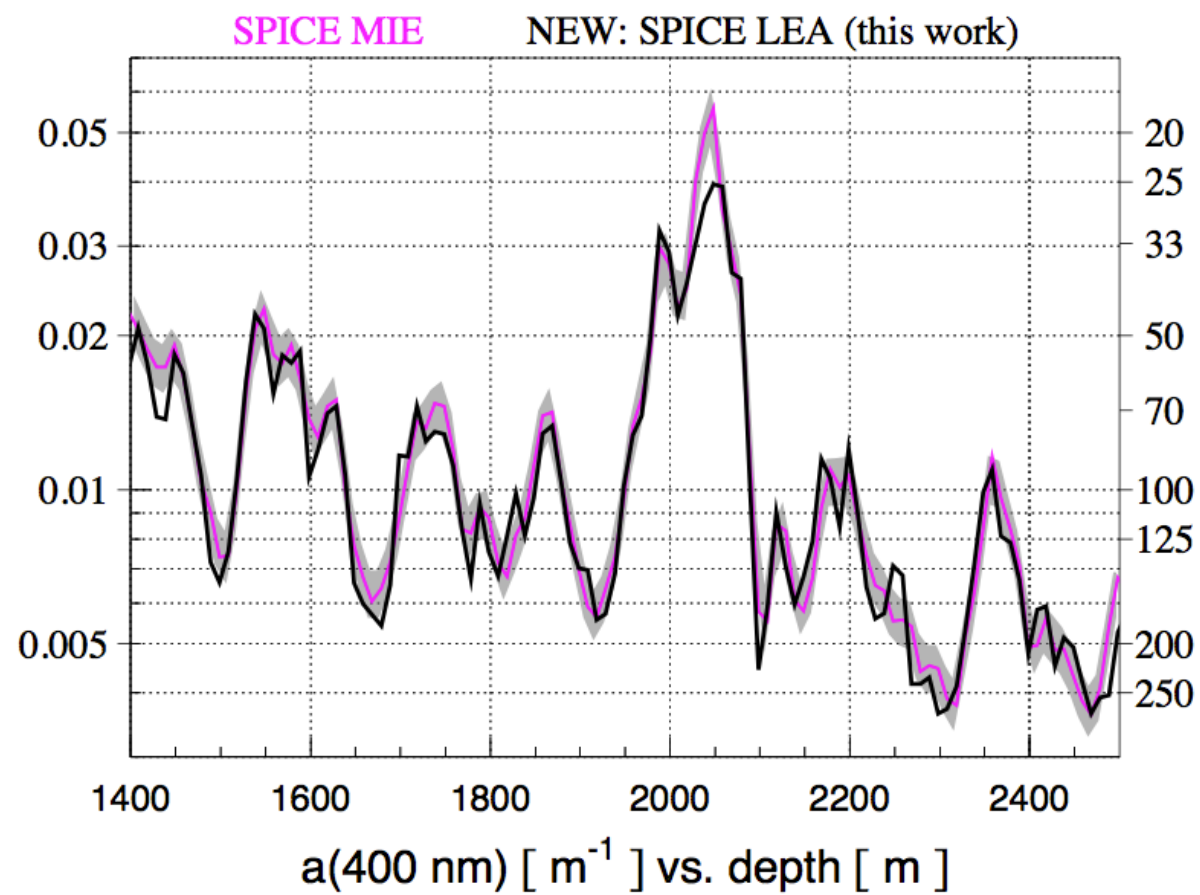


- bin height fluctuation due to pull-validation
- relative contribution of each event to background rate

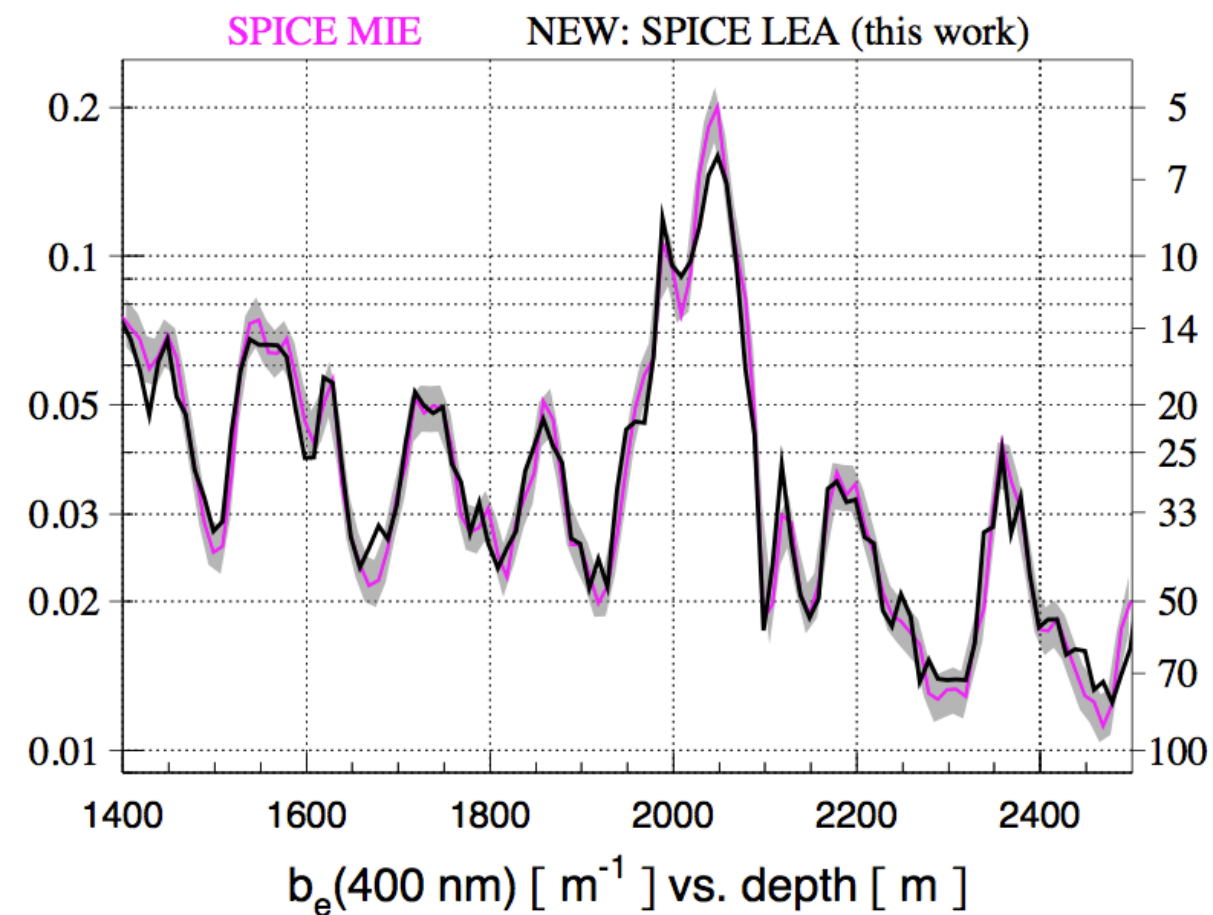




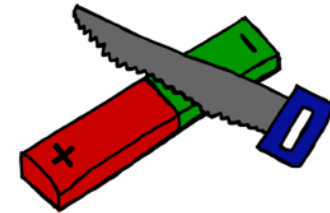
## Absorption



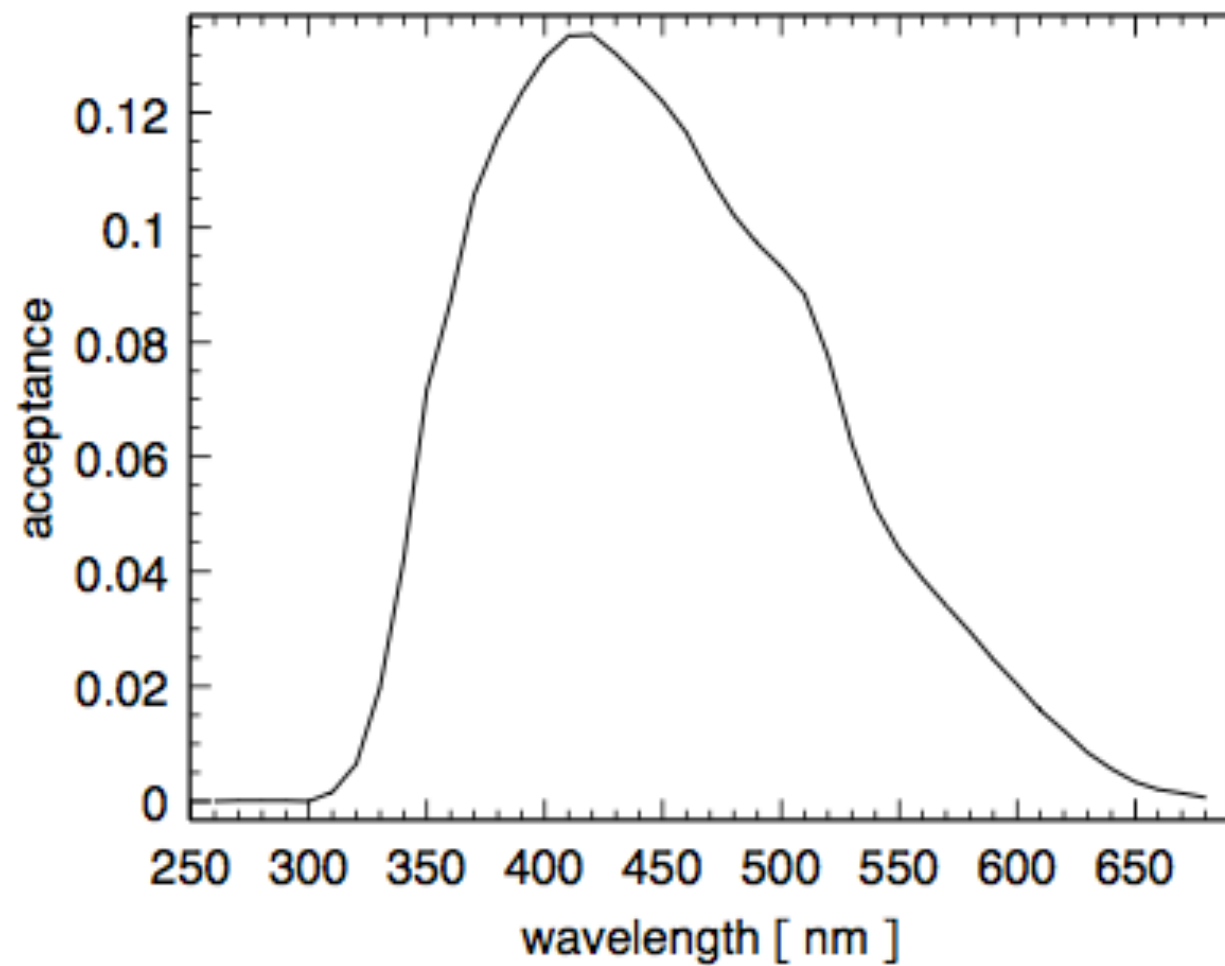
## Scattering



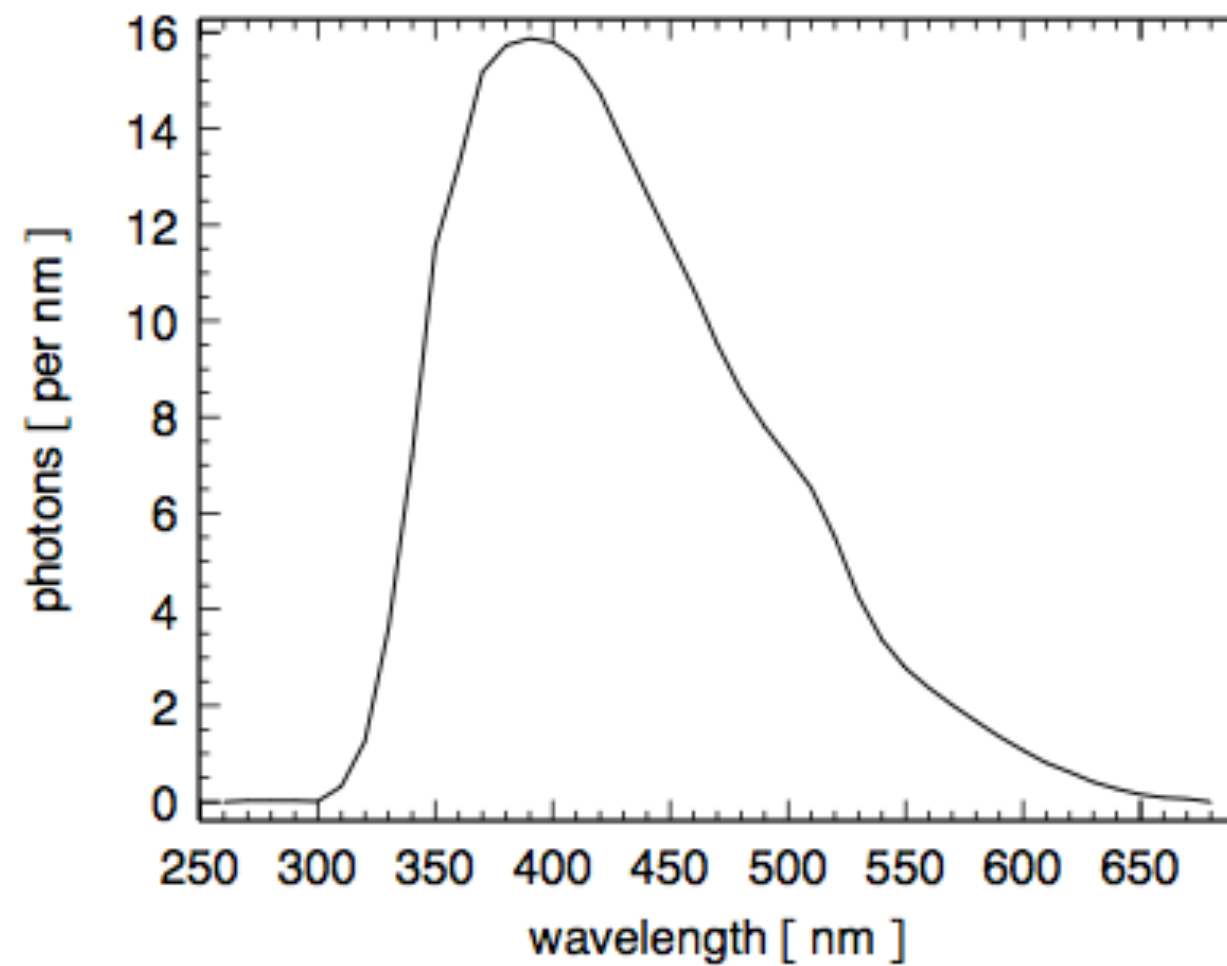


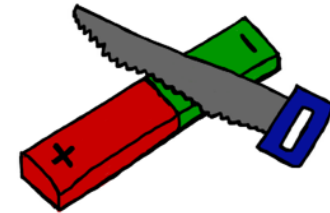


## DOM acceptance

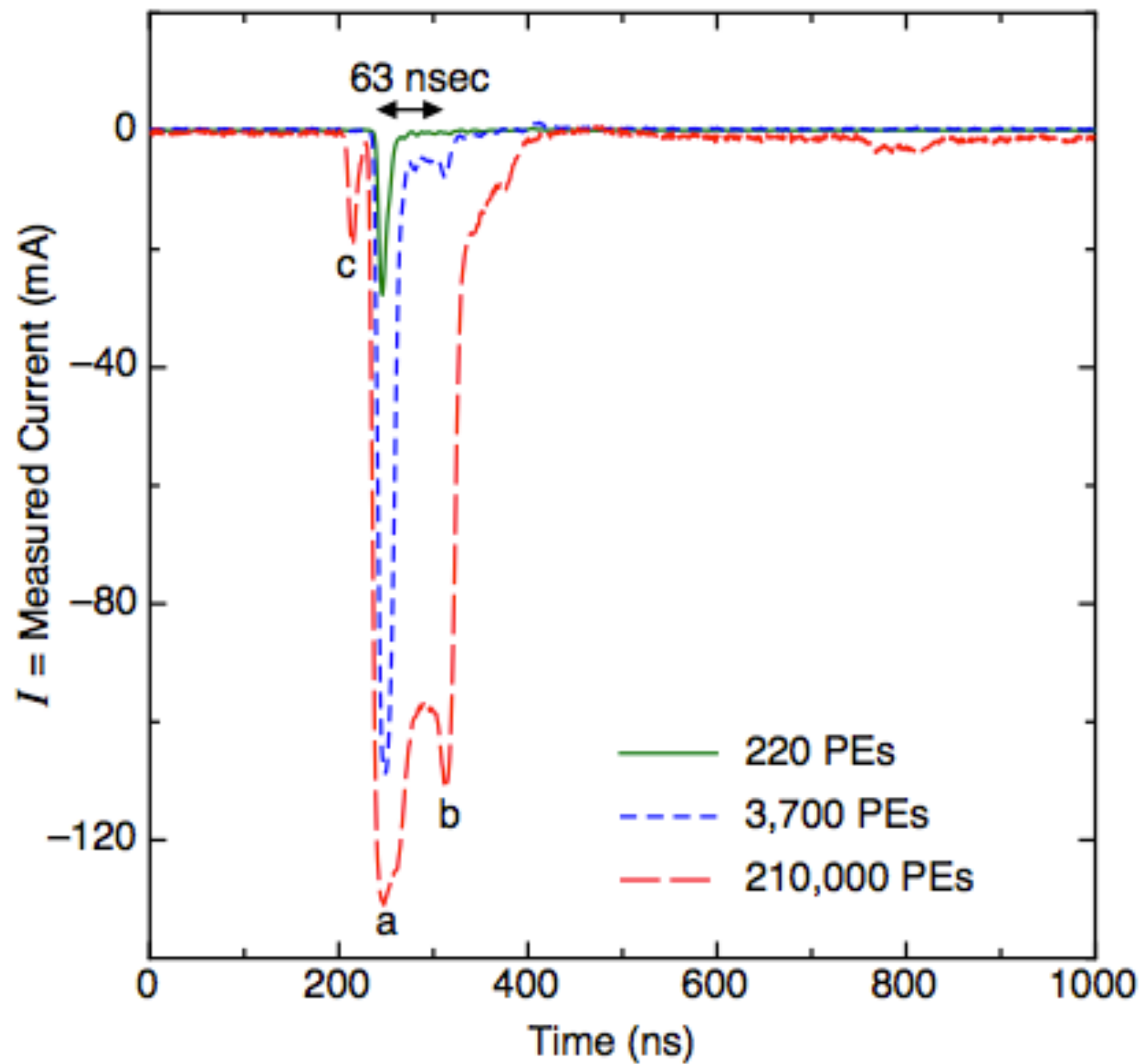


## Photon number

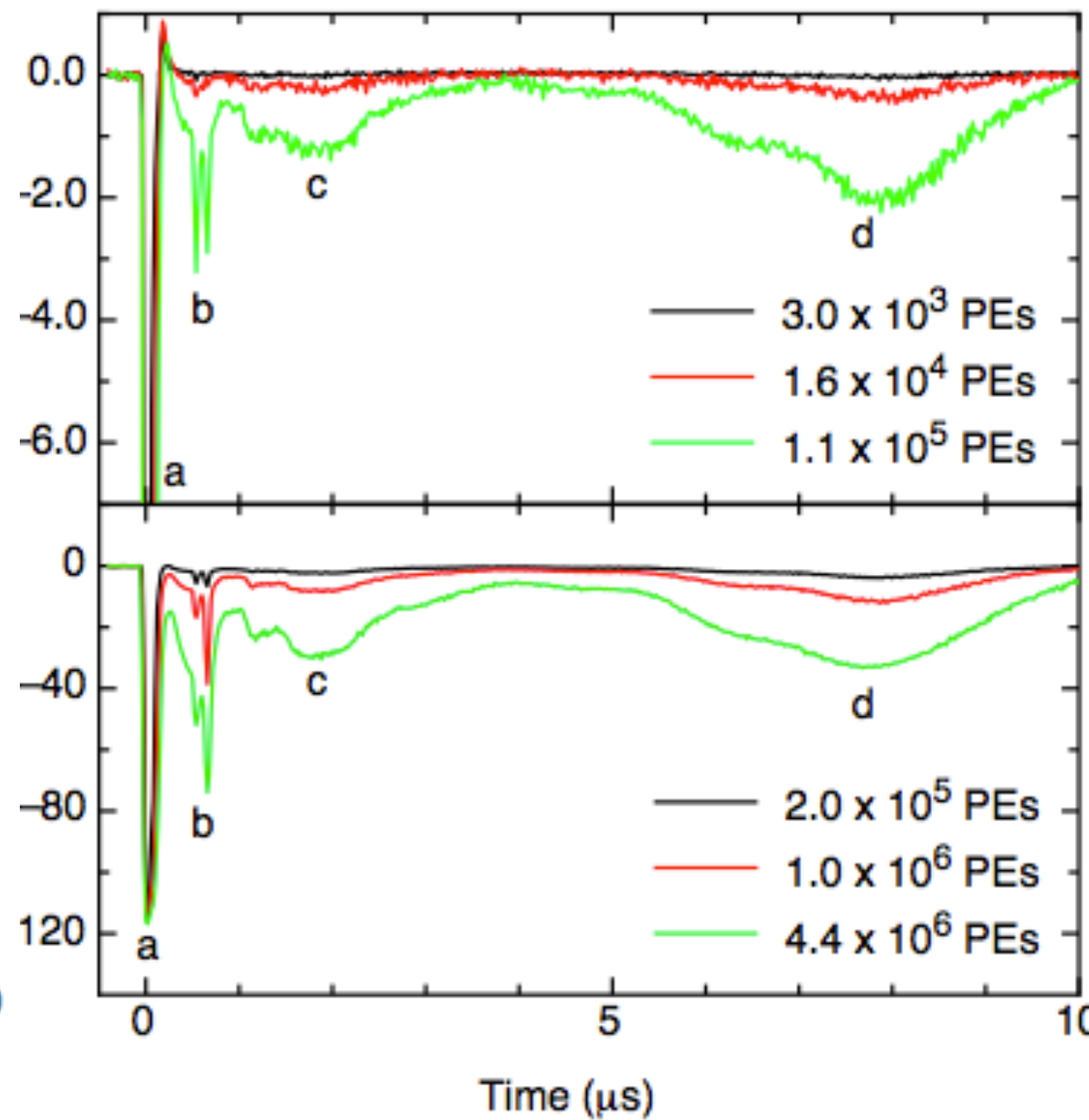




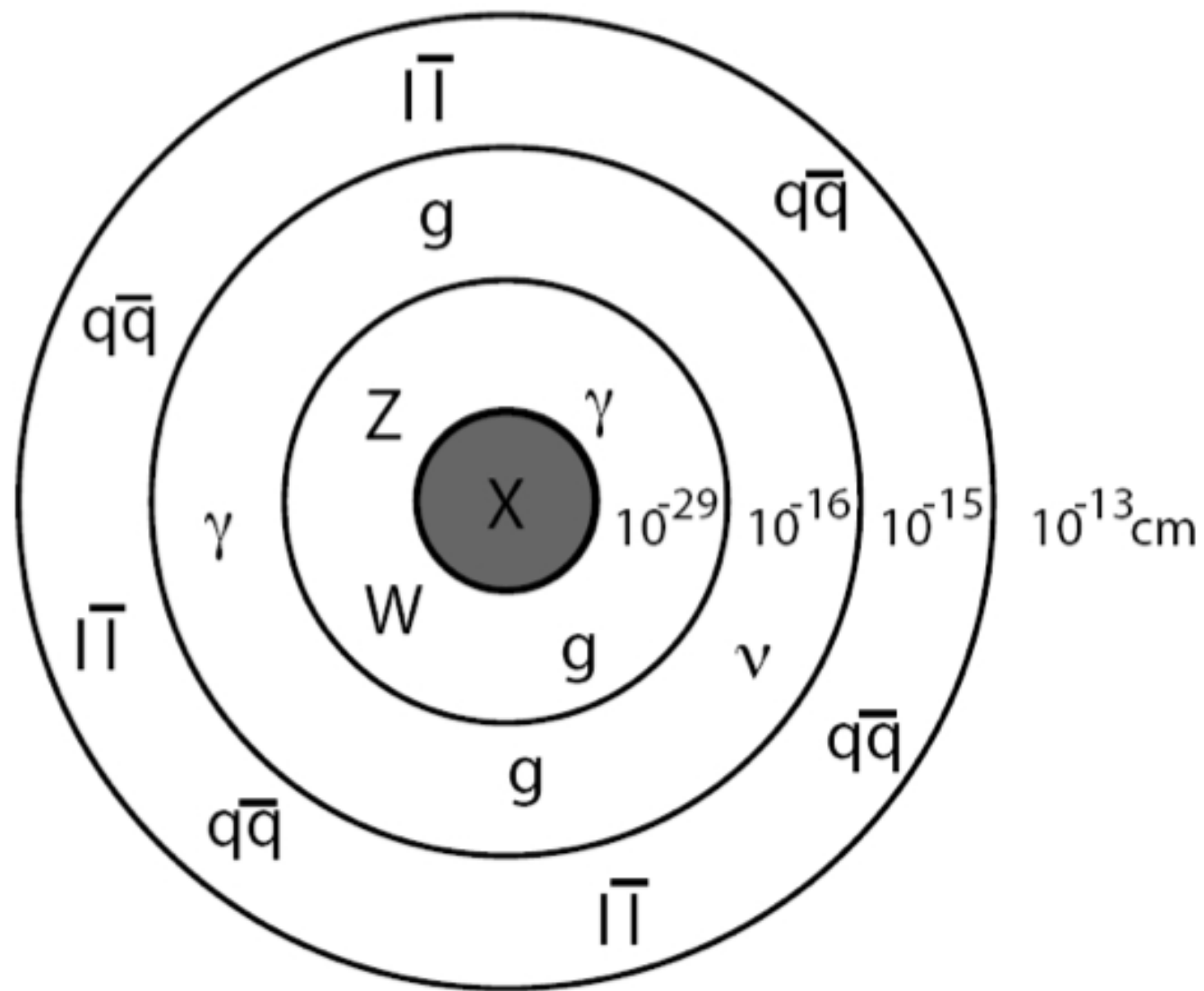
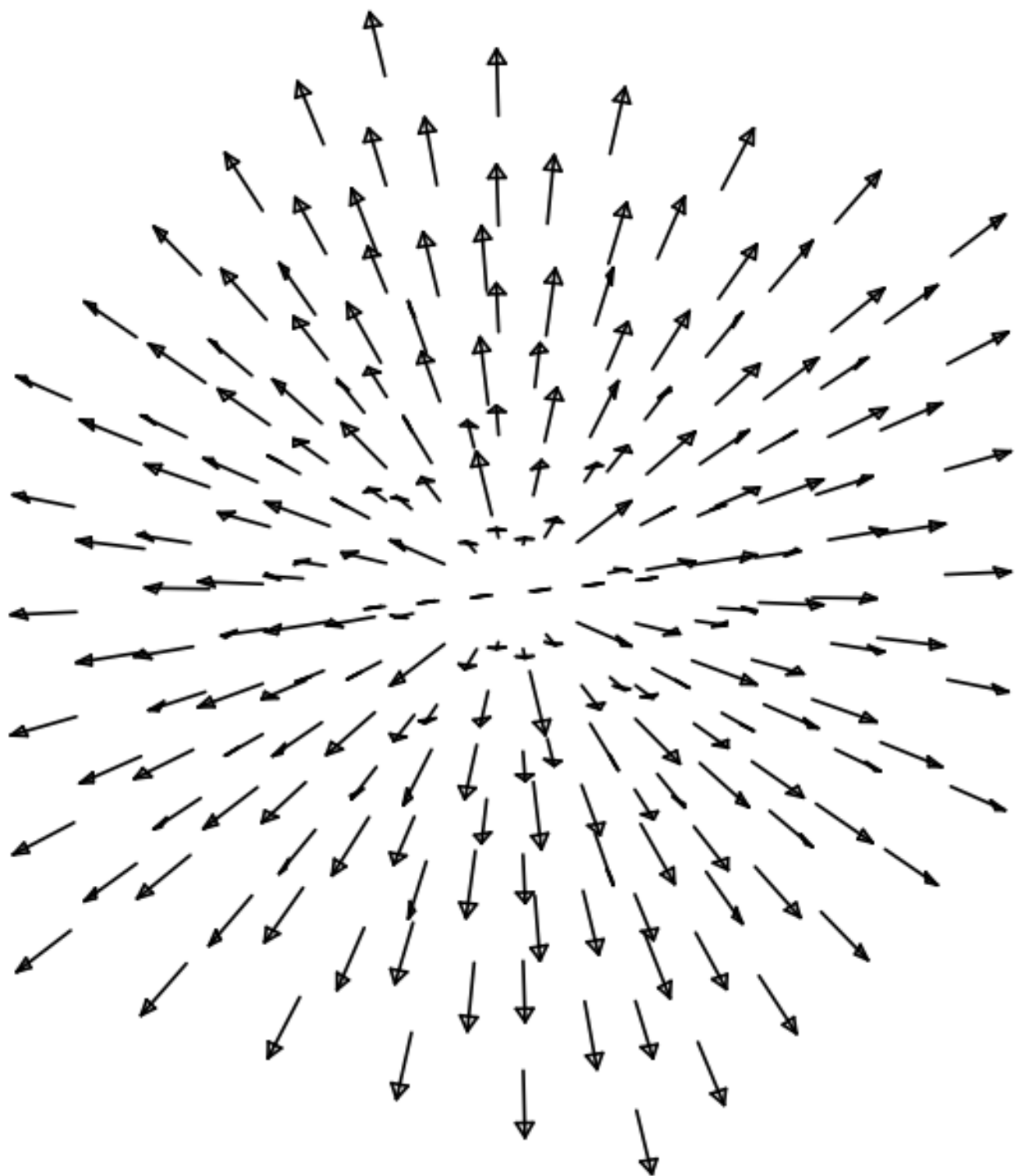
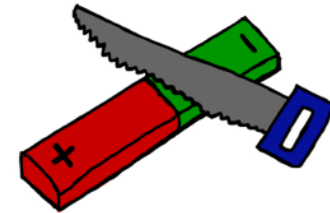
Low energy



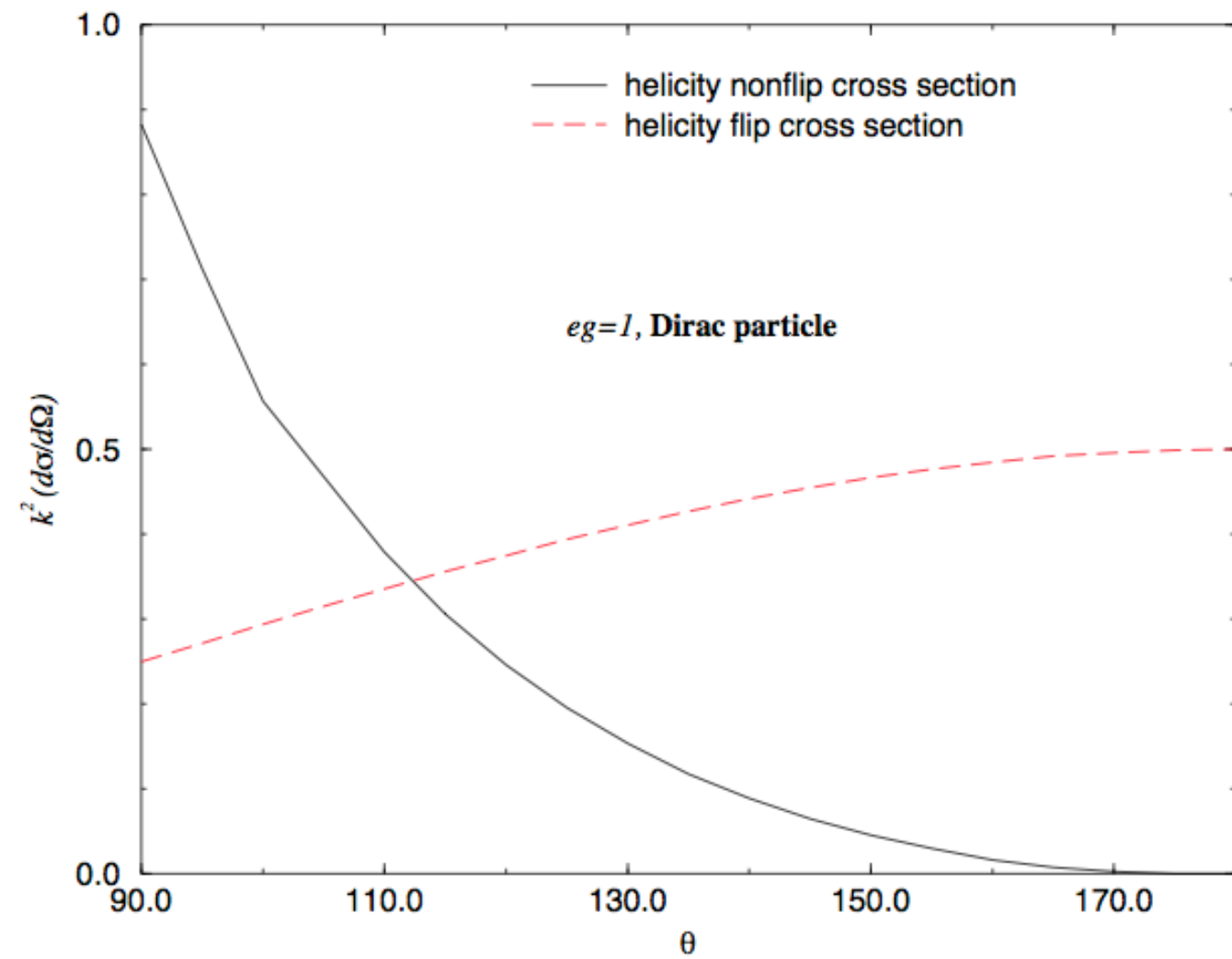
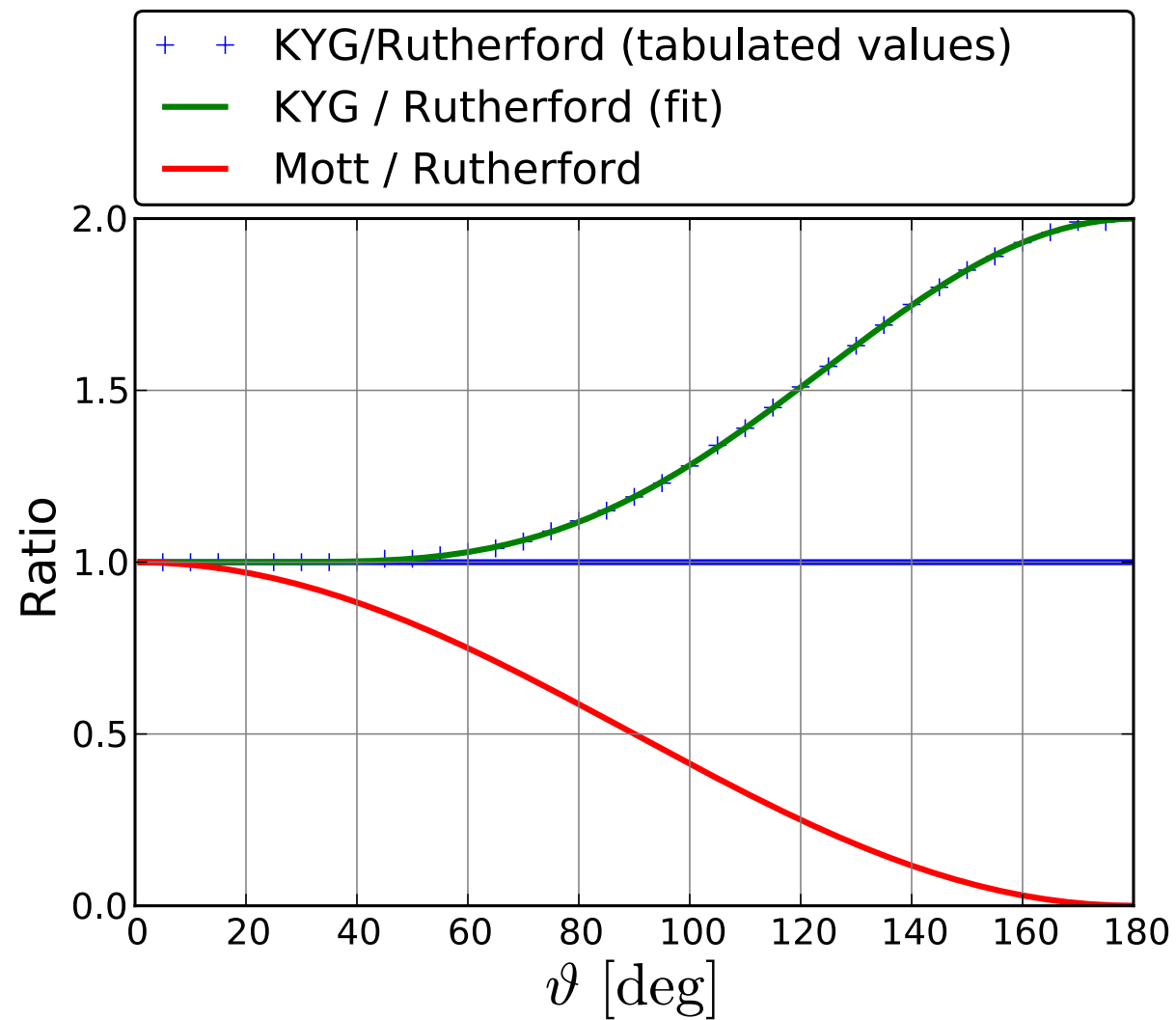
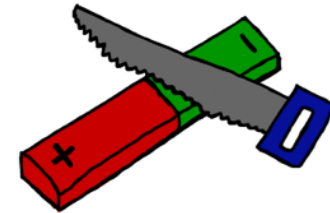
High energy



# Monopoles

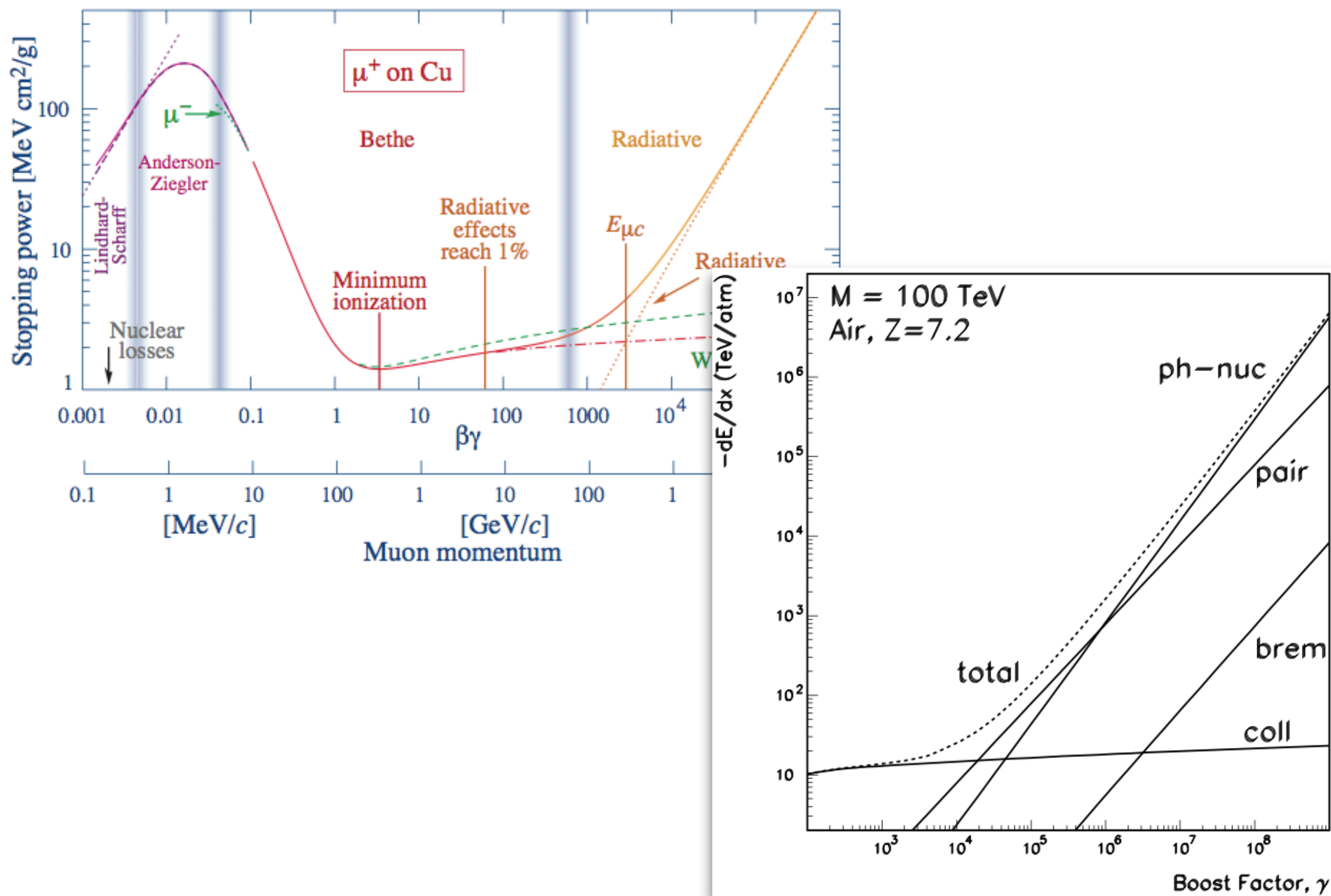
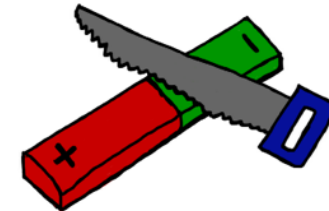


# Interaction - KYG

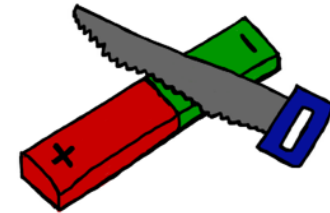




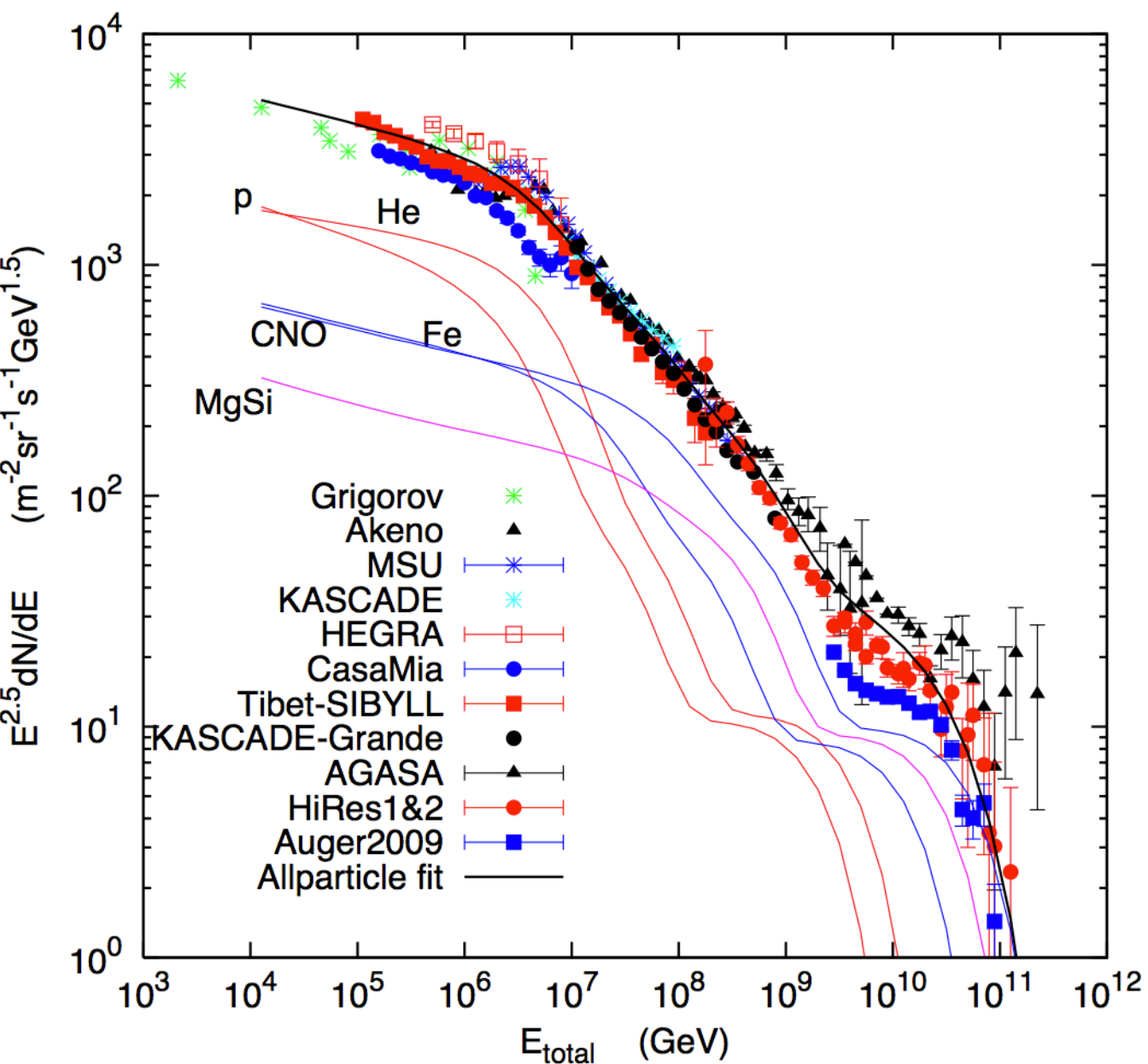
# Interaction - Energy loss



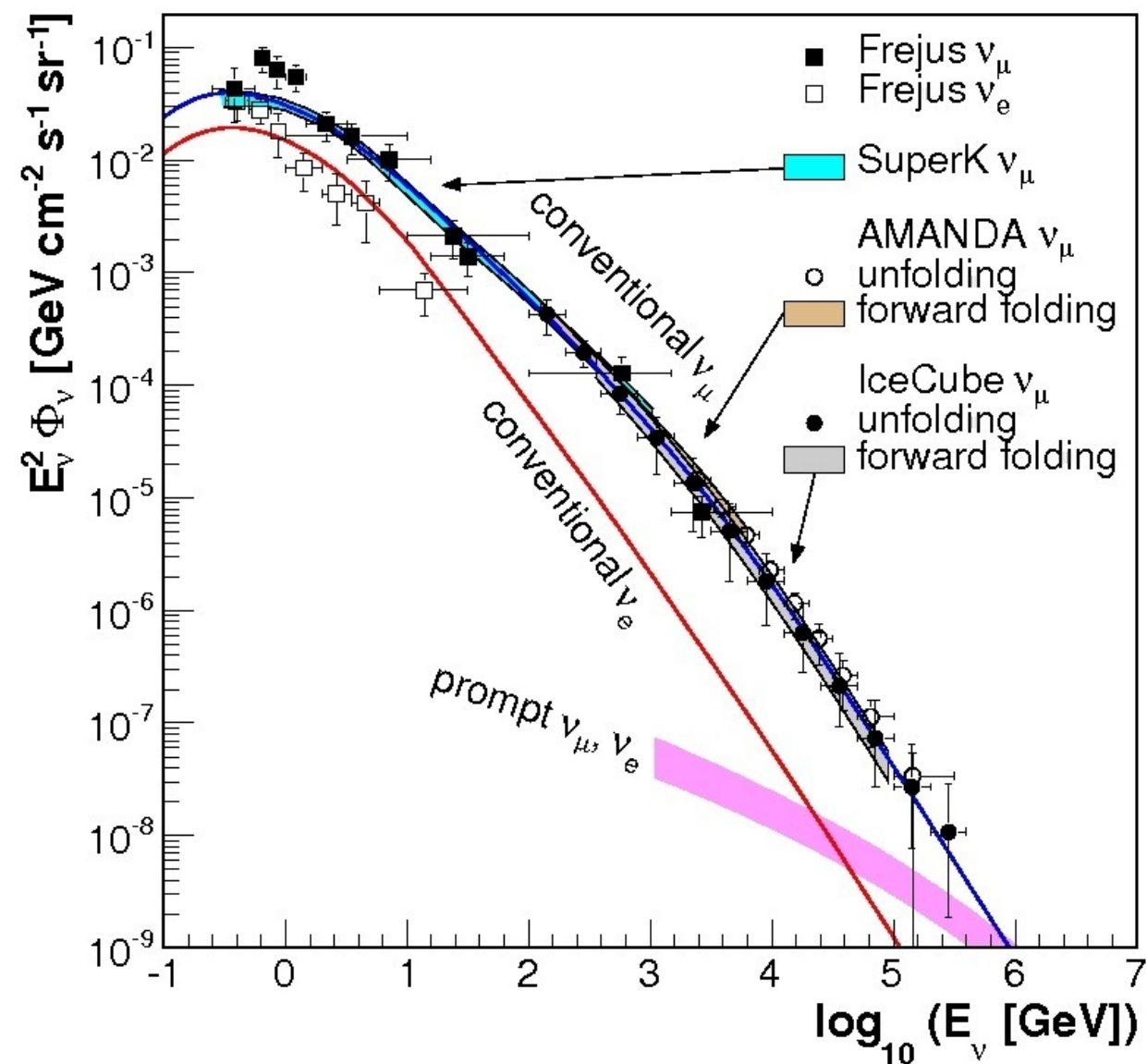
# Simulation - Spectra



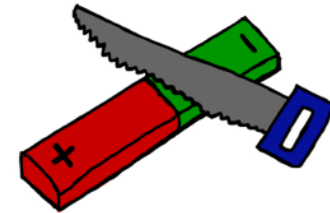
## Cosmic ray



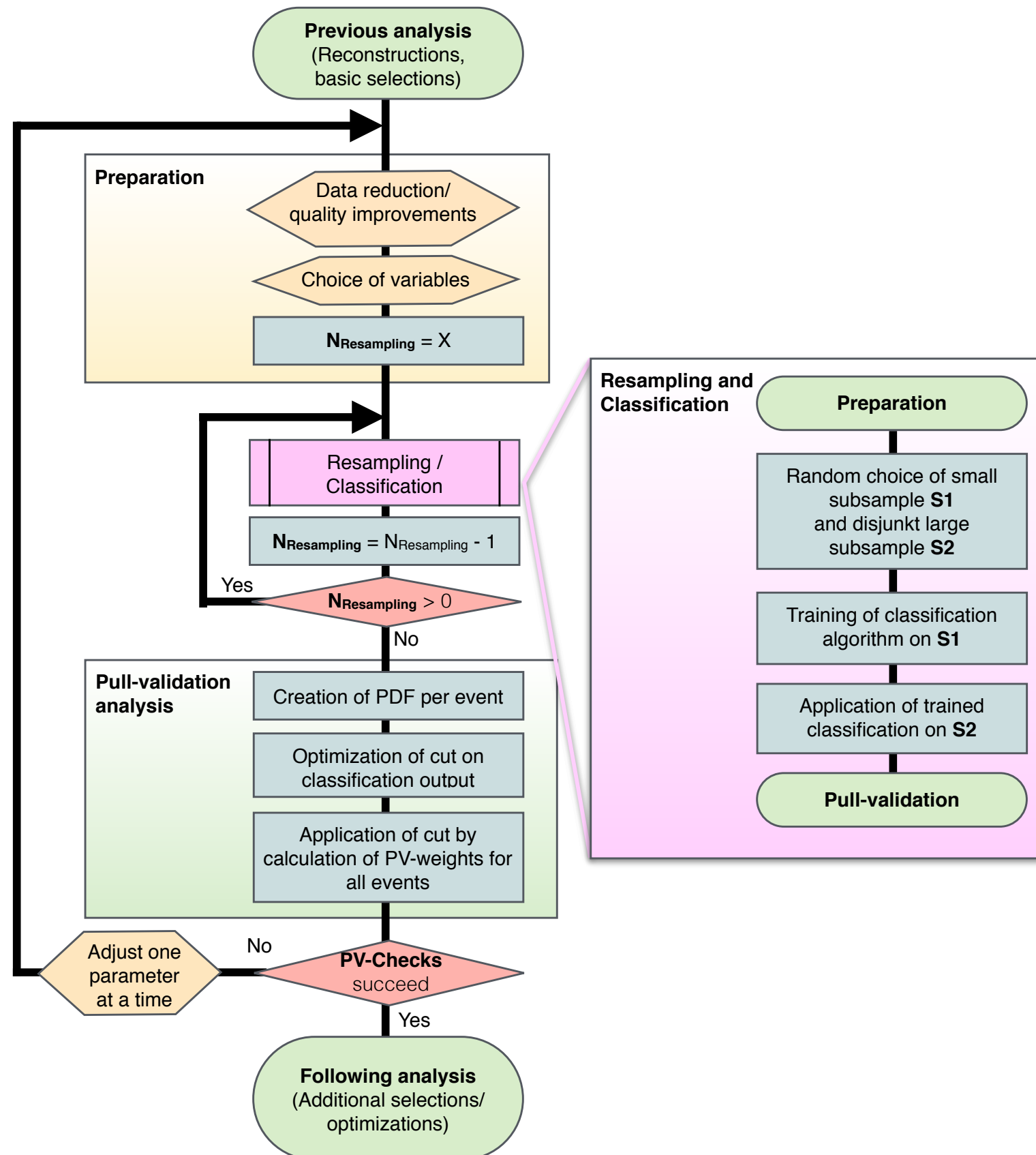
## Neutrinos



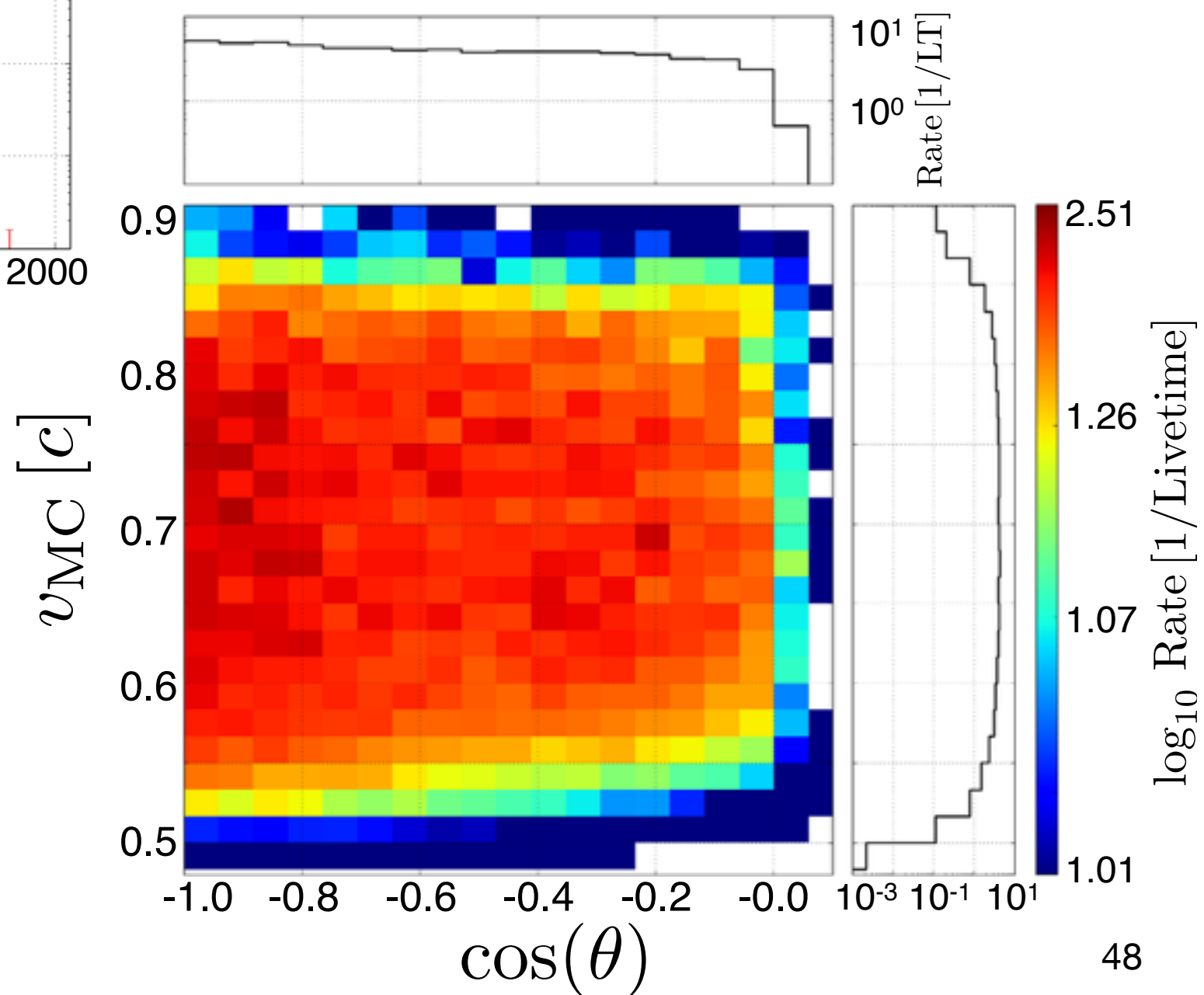
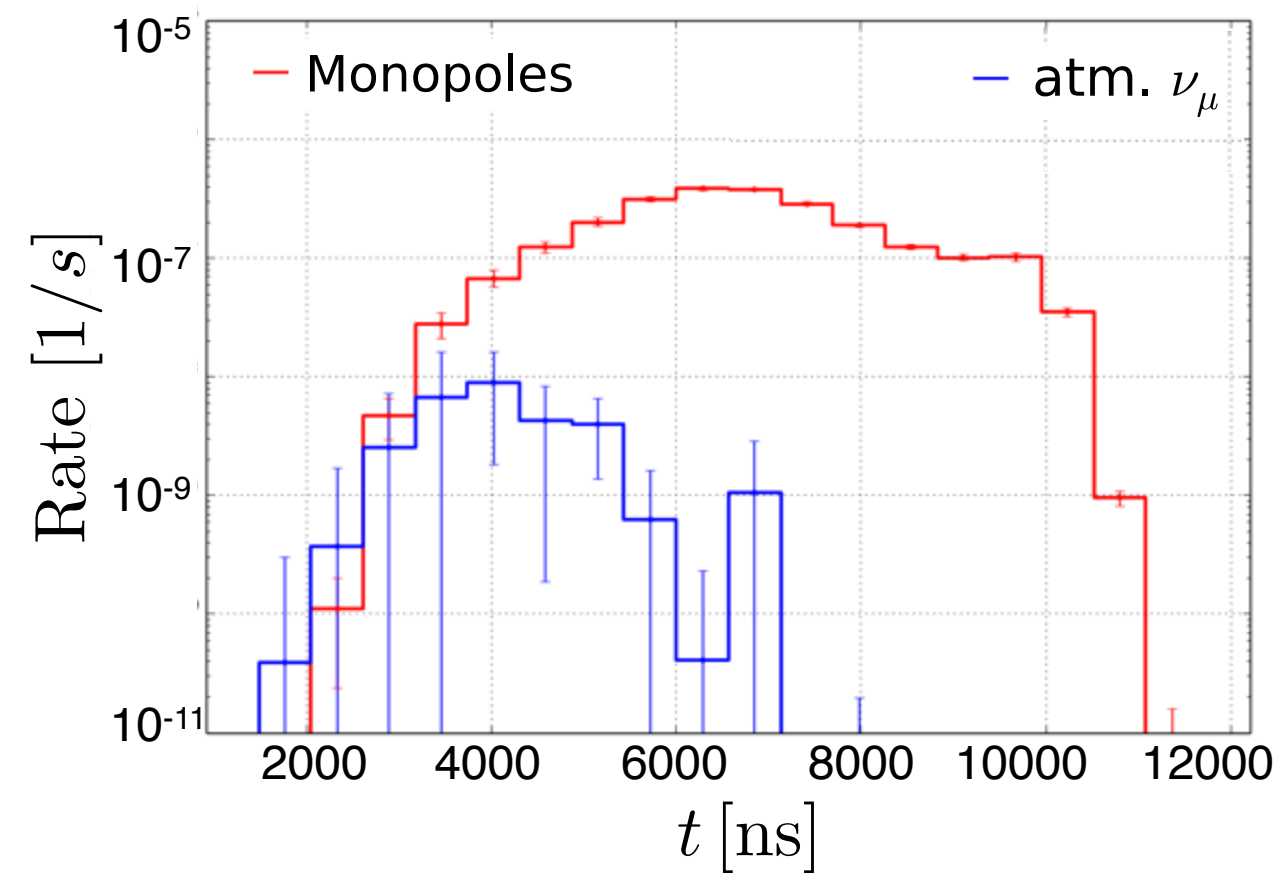
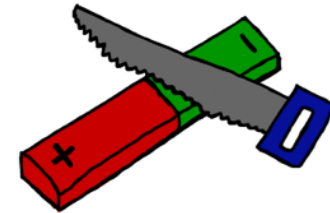
# Event Selection



## The Pull-validation process

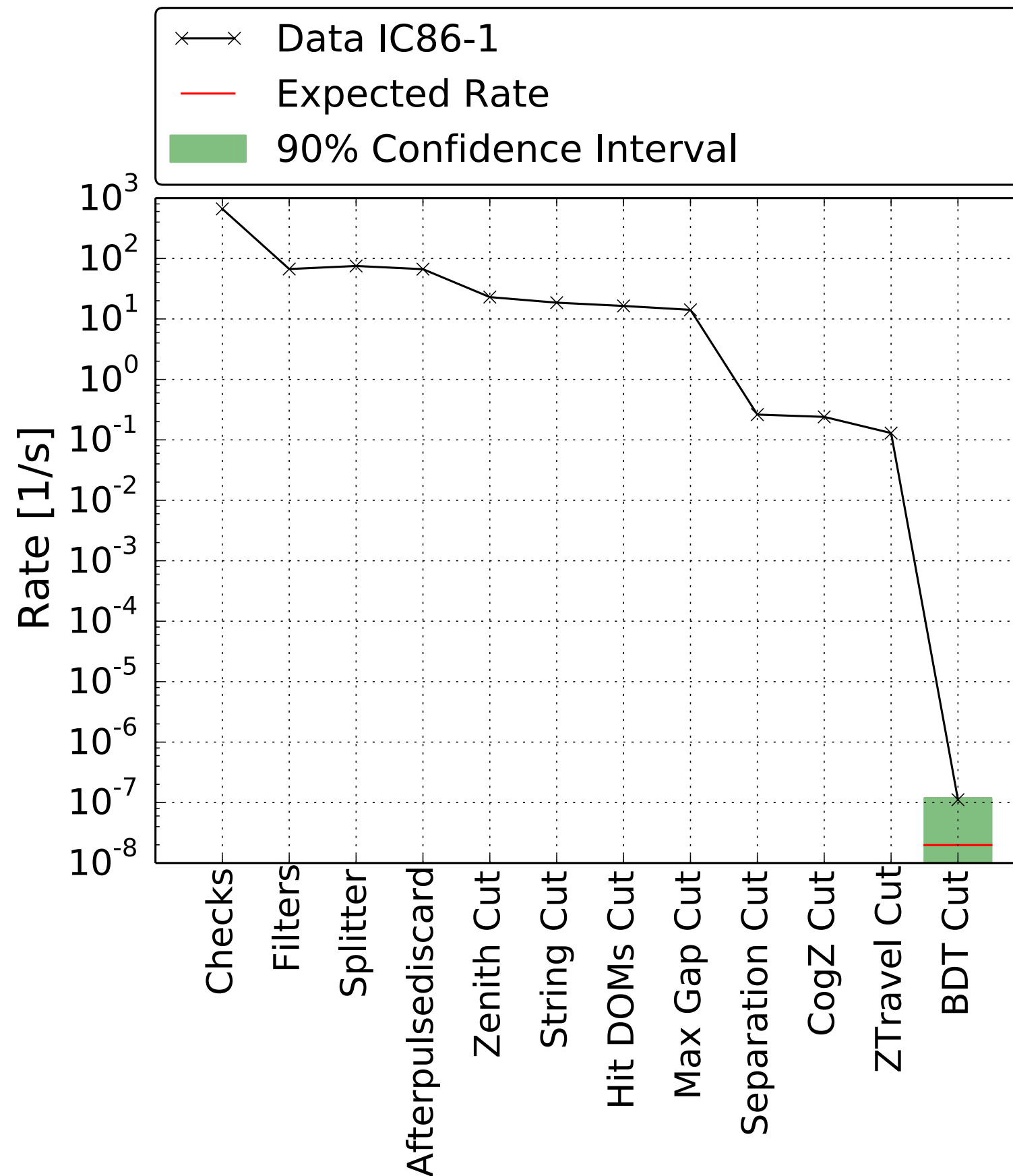
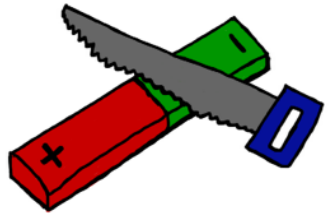


# Event Selection - After Pull-Validation

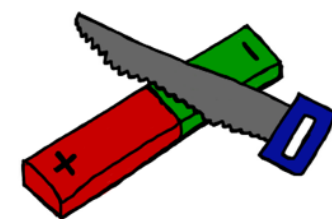




# Results



# Results



	Event 1	Event 2	Event 3
Run	118191	118704	119352
Event	41572632	70730573	32762119
Filter	(SDST) Muon	(SDST) Muon SDST LowUp	(SDST) Muon
Split	1	1	2 (after-pulse)
BDT score	0.507	0.491	0.536
$n_{\text{DOM}_{100}}$	33	28	77
$\bar{s}$ [m]	47.5	37.5	85.3
$t_{\text{Gap}}$ [ns]	418	468	290
$d_{\text{Gap}_{100}}$ [m]	163.9	101.2	67.5
$d_{\text{Sep}}$ [m]	746.8	447.4	623.6
$\bar{s}_{\text{NPE}}$ [m]	19.9	9.5	63.8
$n_{\text{DOM}_{50}}^*$	16	26	18
$z_{\text{travel}}$ [m]	289.8	201.5	327.2
$z_{\text{pattern}}$	16	14	11
$n_{\text{DOM}_{50}}$	21	23	32
$n_{\text{DOM}_{100}}$	33	28	77
$v_{\text{proxy}}/c$	0.84	0.78	0.83
$k_{100}$	0.29	0.16	0.14
$t_w$ [ns]	106.4	44.2	24.2
$t$ [ns]	3921	3086	3953
$\bar{z}_{\text{DOM}}$ [m]	-157.8	-219.9	-39.8
$z_{\text{COG}}$ [m]	-324.1	-291.3	30.8
$v_{\text{LLH}}^M/c$	1.01	1.00	0.94
$r_{\text{LLH}}^M$	7.37	7.17	7.35
$r_{\text{LLH}}^\mu$	6.97	6.92	7.33
$\theta_{\text{ILF}}$ [rad/degrees]	2.94 / 168.4	3.01 / 172.4	3.01 / 172.5
$\theta_{\text{LLH}}$	2.95 / 168.9	2.99 / 171.1	2.99 / 171.2
$n_{\text{String}}$	5	5	8
$n_{\text{DOM}}$	35	31	110
$n_{\text{NPE}}$	84.4	132.9	594.9

# Proton Decay

