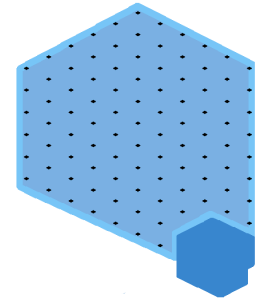


BEYOND-ICECUBE – ICECUBE+

+

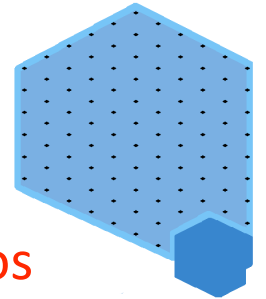


Simulation of a large optical extension of IceCube
for future neutrino-astronomy in the TeV-PeV
range with a detector on the DecaCube-scale

David Altmann and Christopher Wiebusch



Motivation

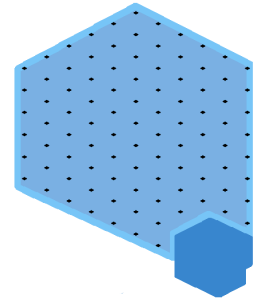


- Primary goal of IceCube is to discover TeV/PeV sources of high energy extra-terrestrial neutrinos
- Current proposals for upgrades are great ideas but can not sustain this core science for the future
 - Radio and acoustic detection: 10-100 km³ but focuses on E>>100 PeV GZK neutrinos
 - DeepCore, BeyondDC phase1 : extending but not replacing the science
 - BeyondDC phase 2, DM-ice completely different science goal
- A possible scenario after 3 year operation of IceCube is the observation of a 6 σ excess in the diffuse flux and a 4 σ point-source
 - Who would not want to understand these observations ?
 - A substantial increase of signal statistics is needed !
- IceCube technology just works
- Can we scale the optical IceCube detection method to the DecaCube scale with acceptable effort?

Yes, we can



Assumptions




1. Inter-string spacing in IceCube is not optimum

- optimized for $\sim 30\text{TeV}$, current limits prefer higher energy
- original optimum value $\sim 150\text{m}$ was reduced to $\sim 120\text{m}$ because of inter-string calibration
- with more channels we can afford a courser spacing

↳ strongly increase inter-string spacing

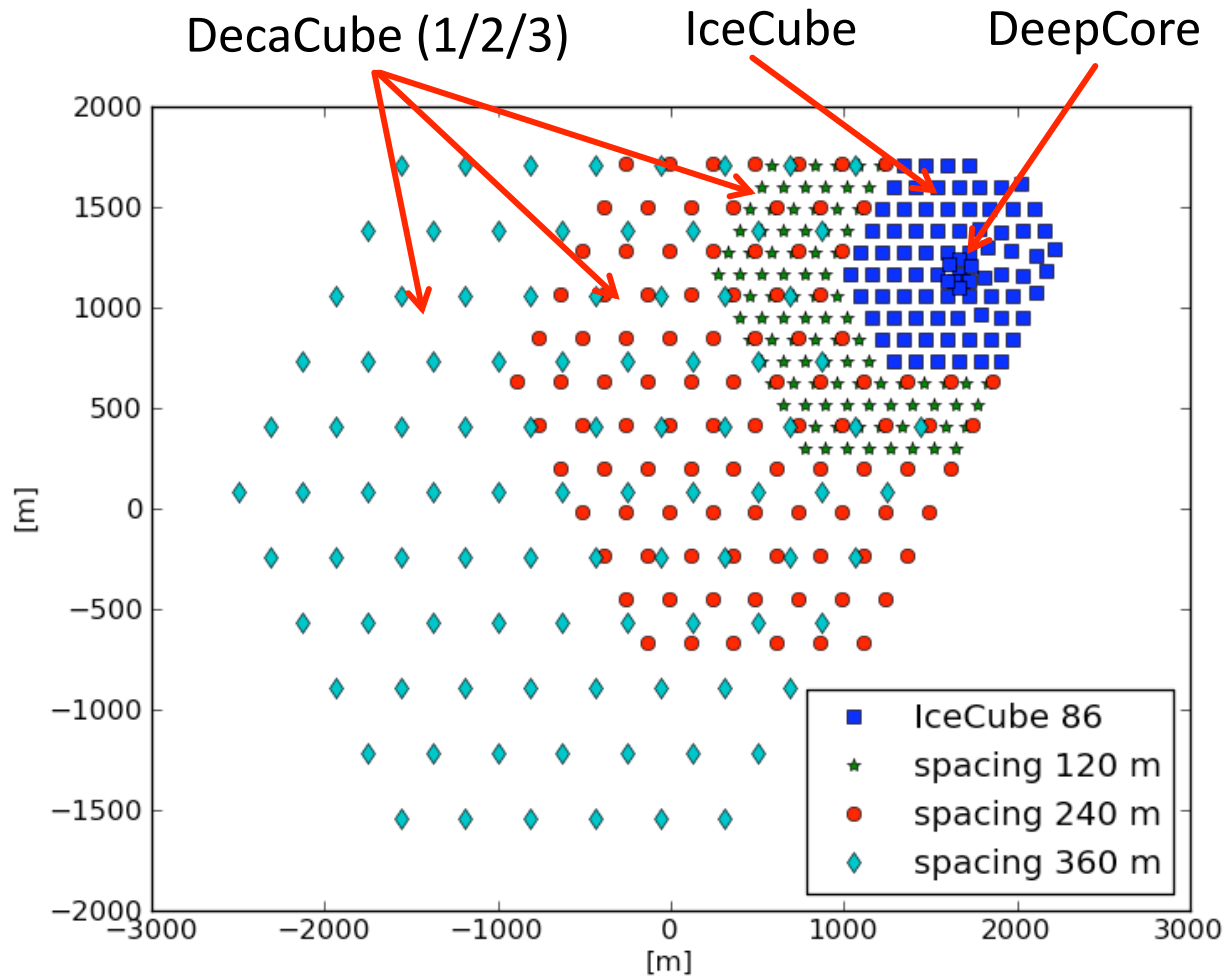
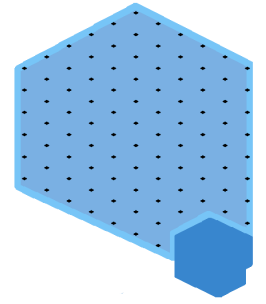
2. Scale of the project is set by

- costs of IceCube (80M\$ investment, 270M\$ total)
- deployment (20 strings/season, max 5 years)
- proposal by KM3NeT (~ 250 strings):
220M€ (investment only  1G\$ in IceCube counting)



100 strings, similar investment as IceCube

Studied geometries

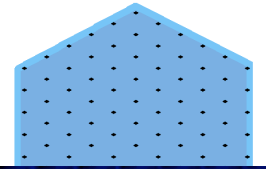


Spacing 1 (120m):
IceCube (1 km³)
+ 98 strings (1,3 km³)
= 2,3 km³

Spacing 2 (240m):
IceCube (1 km³)
+ 99 strings (5,3 km³)
= 6,3 km³

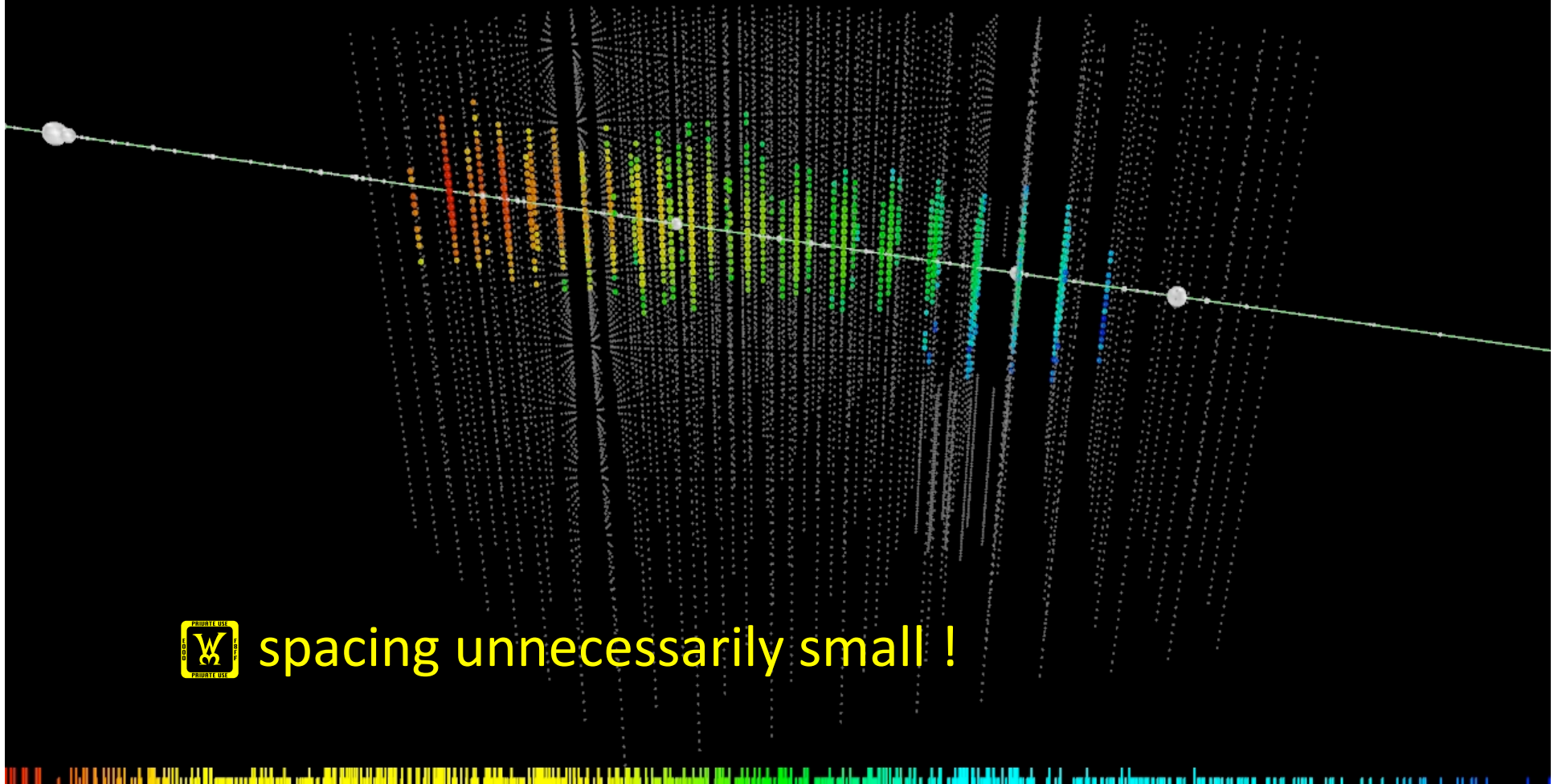
Spacing 3 (360m):
IceCube (1 km³)
+ 95 strings (11,6 km³)
= 12,6 km³

Spacing 1 – 120m



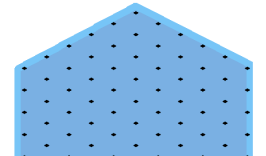
Type: NuMu
E(GeV): 7.99e+06
Zen: 80.85 deg
Azi: 232.33 deg
NTrack: 11/11 shown, min E(GeV) == 12.27
NCasc: 100/2847 shown, min E(GeV) == 6.27

  8 PeV

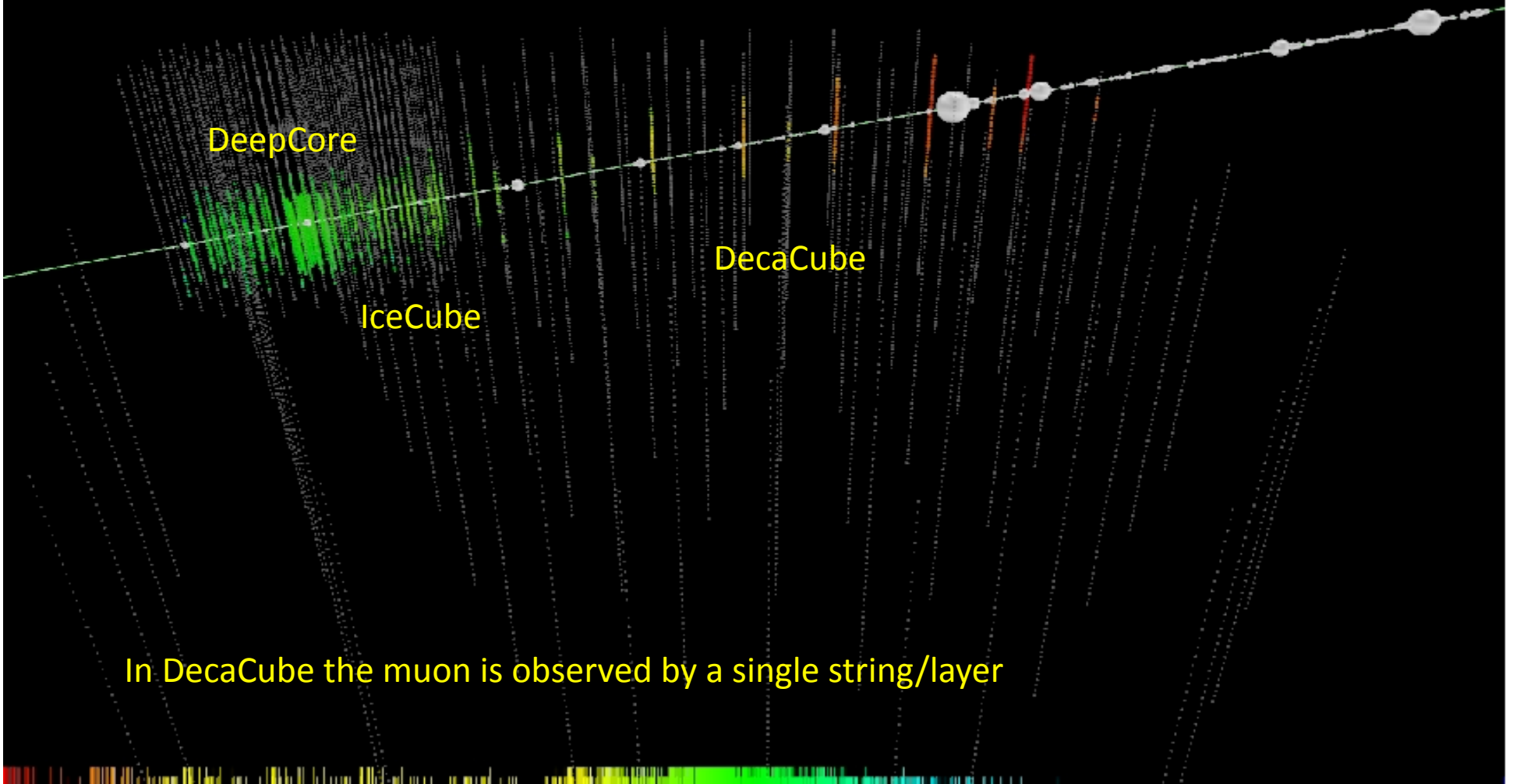


spacing unnecessarily small !

Spacing 3: 360m

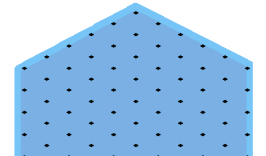


```
Type: NuMu  
E(GeV): 3.89e+08 start-energy  
Zen: 78.01 deg  
Azi: 151.75 deg  
NTrack: 11/11 shown, min E(GeV) == 22.21  
NCasc: 100/3772 shown, min E(GeV) == 5.54
```

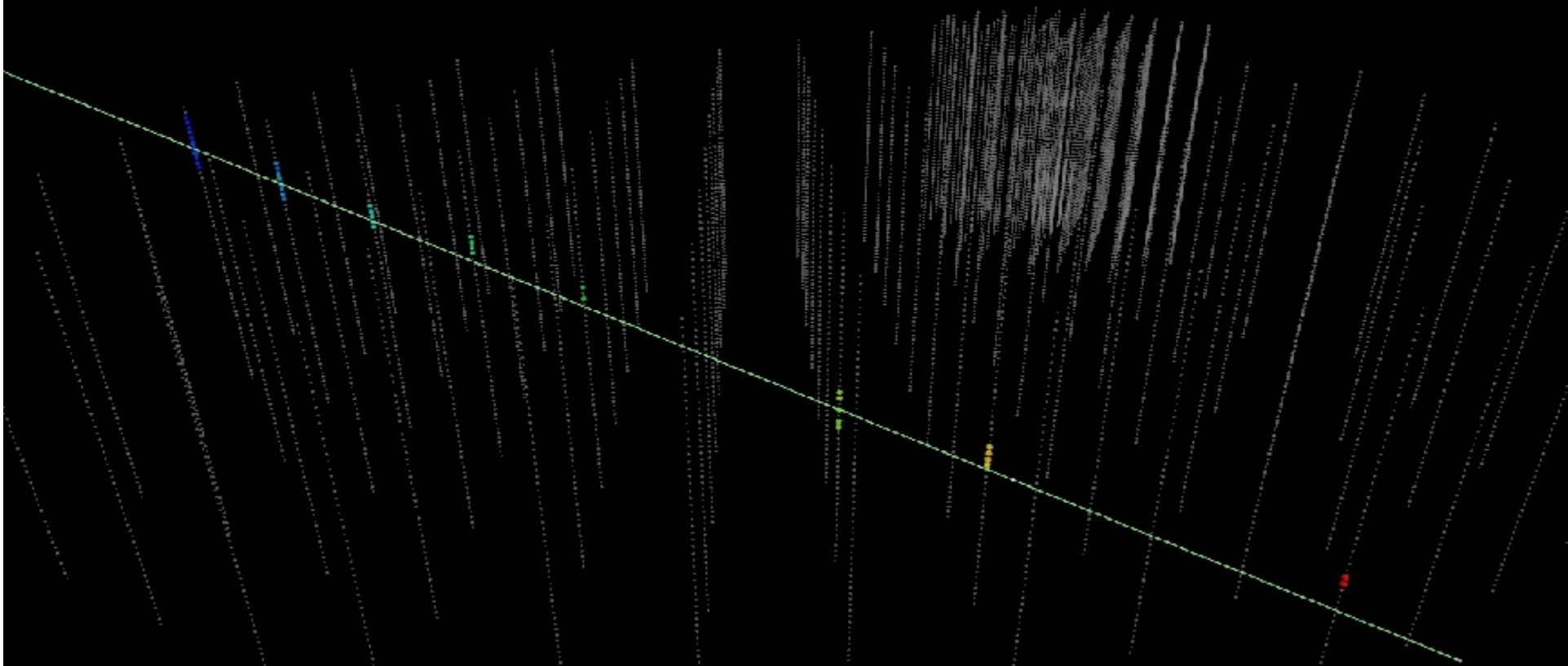


In DecaCube the muon is observed by a single string/layer

Spacing 3: 360m

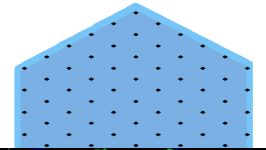


```
Type: NuMuBar          ~ 18 TeV
E(GeV) 1.87e+04
Zen: 99.36 deg
Azi: 209.08 deg
NTrack: 1/1 shown, min E(GeV) -- 16282.32
NCasc: 100/611 shown, min E(GeV) -- 1.35
```



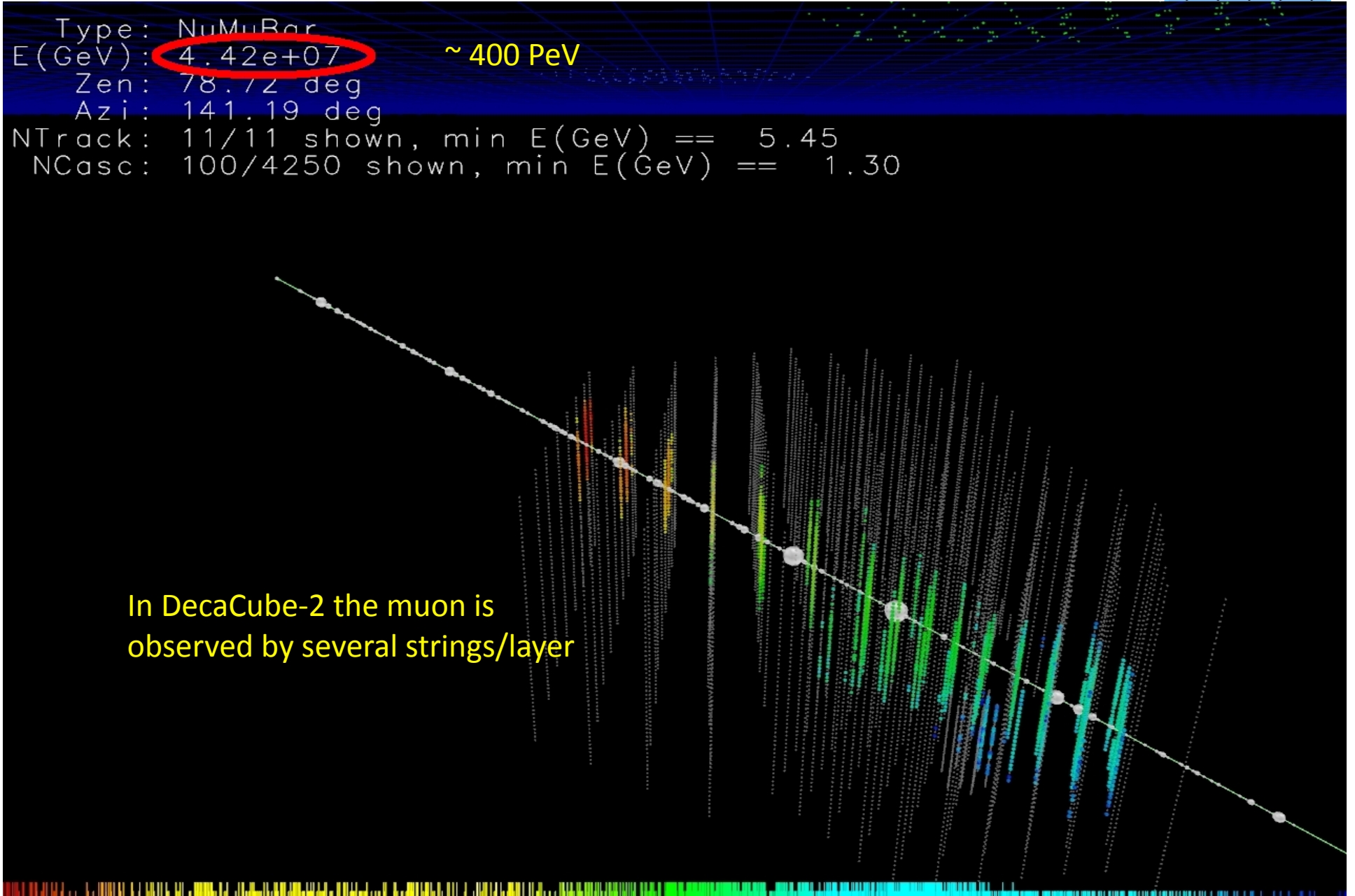
The threshold of Deca-Cube will be of the order of 10 TeV

Spacing 2

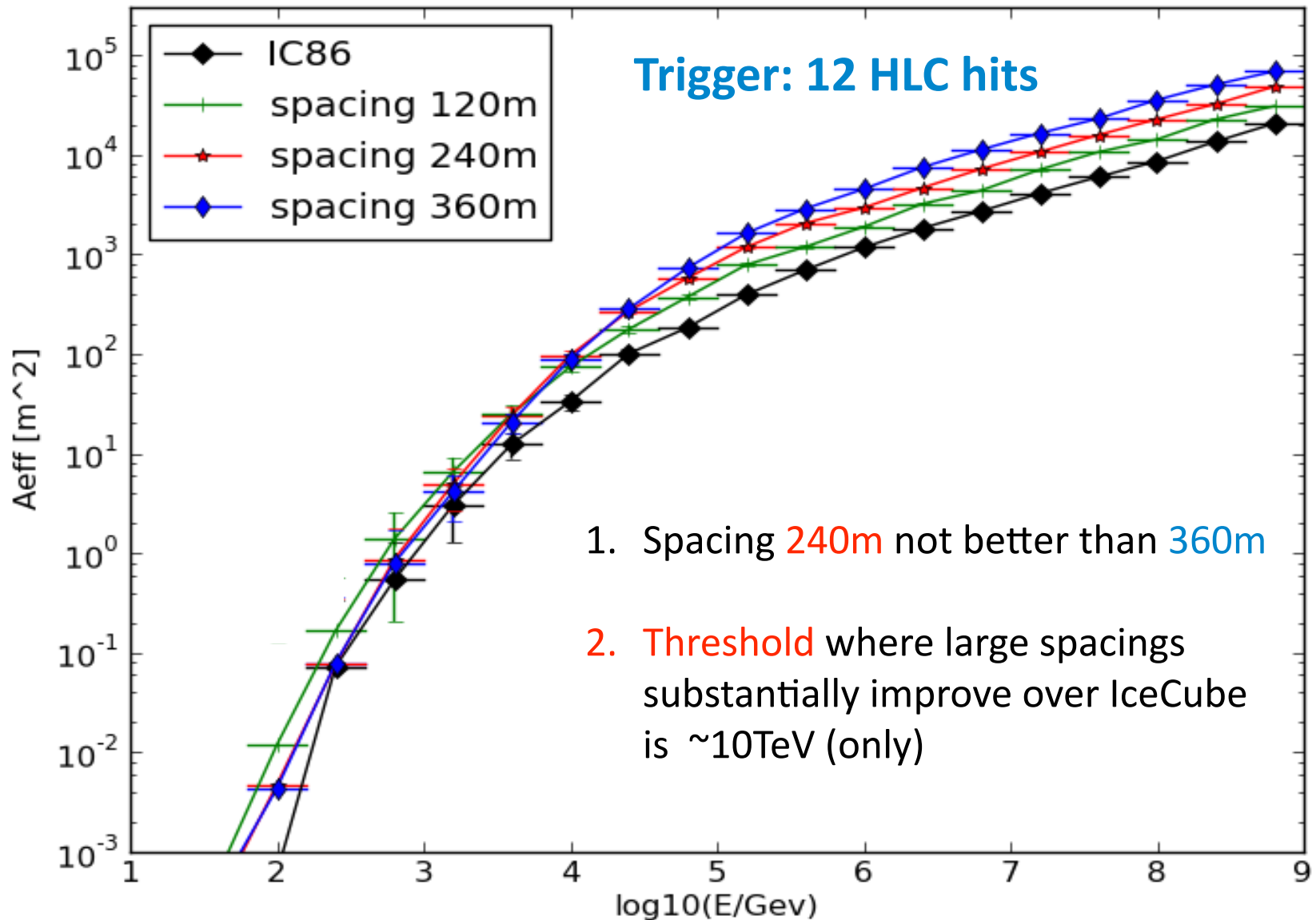
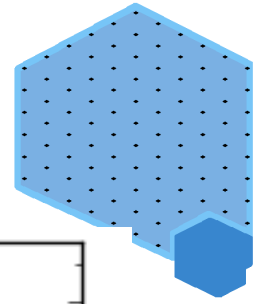


Type: NuMuBar
E(GeV): **4.42e+07** ~ 400 PeV
Zen: 78.72 deg
Azi: 141.19 deg
NTrack: 11/11 shown, min E(GeV) == 5.45
NCasc: 100/4250 shown, min E(GeV) == 1.30

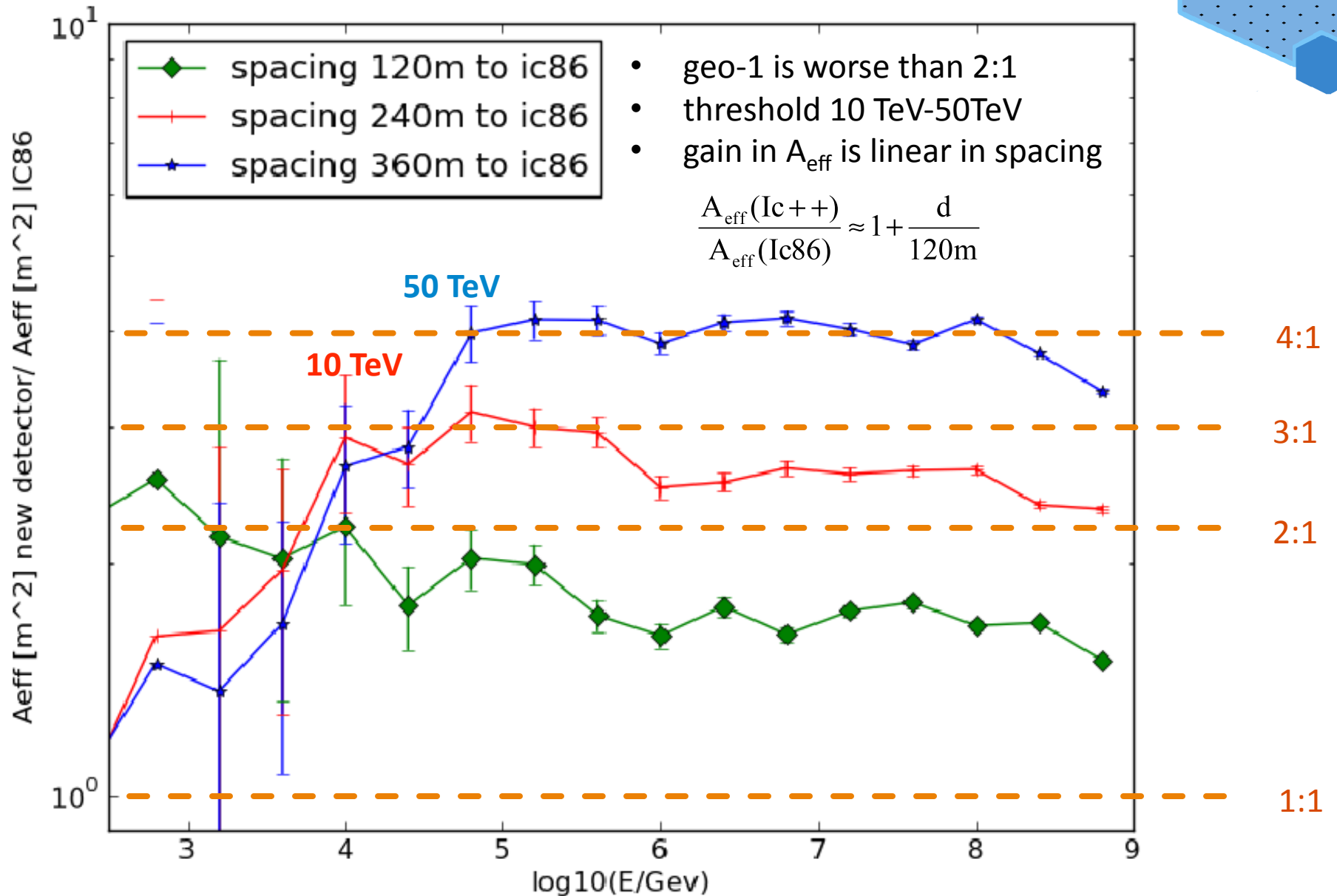
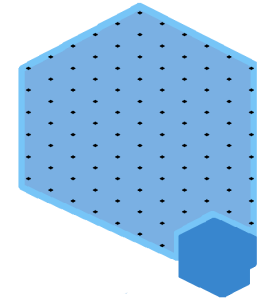
In DecaCube-2 the muon is
observed by several strings/layer



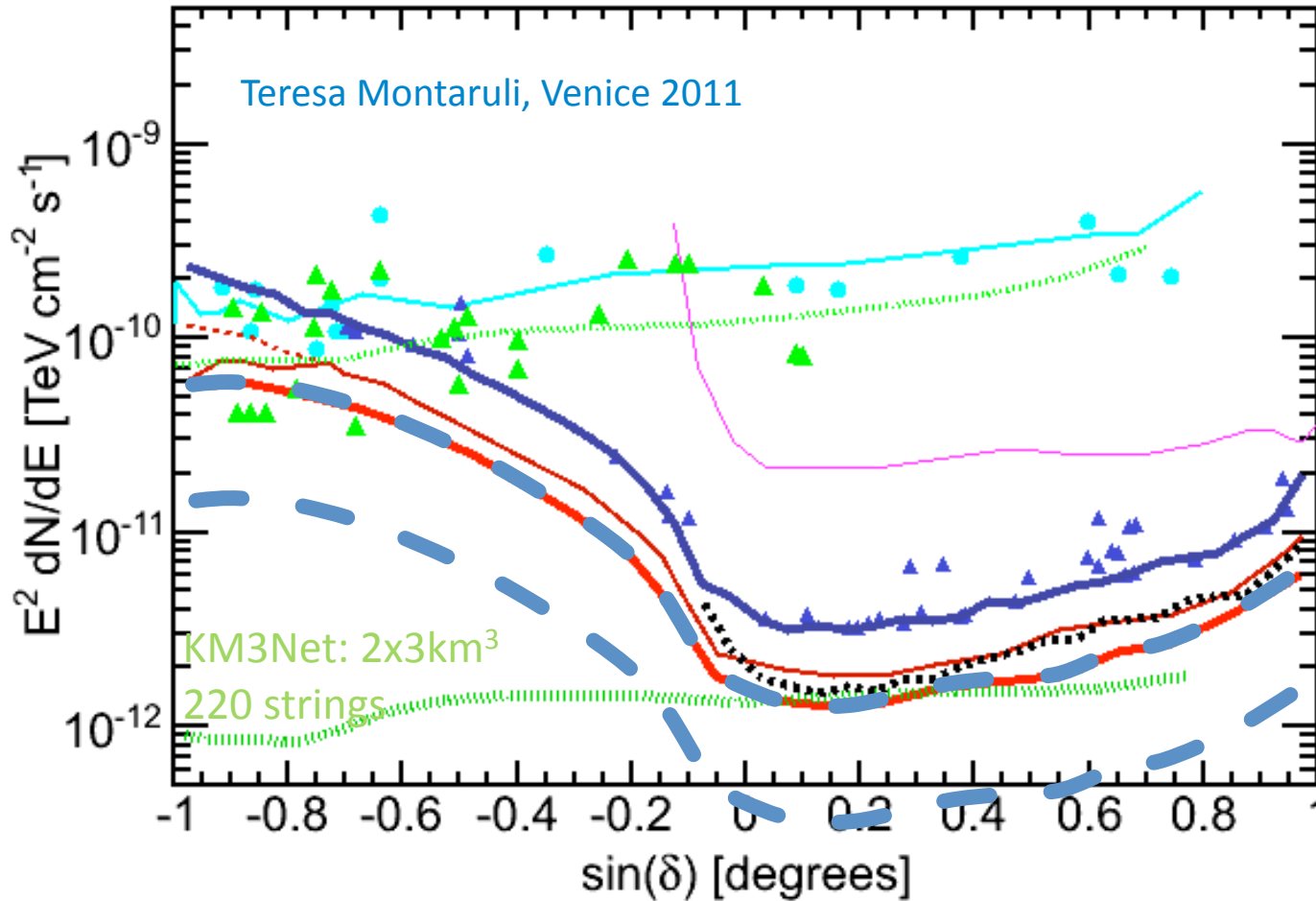
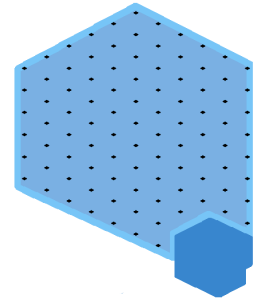
Effective Area on trigger level



Improvement Factor w.r. IceCube-86



What if a factor 4 ?



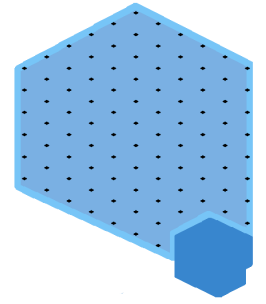
- Not considered !!!
1. angular resolution
 2. energy threshold
 3. background
 4. selection efficiency


Assuming
IC-86 \boxtimes IC40+IC59

Substantially exceeds KM3Net sensitivity at slightly higher energy with $\sim \frac{1}{4}$ of costs

\boxtimes Need to verify this with full event reconstruction & realistic event selection

Summary and Conclusions

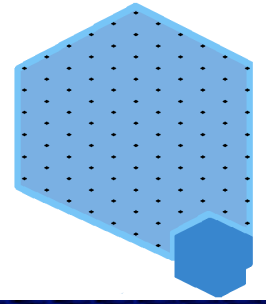


- If IceCube sees a signal then we want to **increase statistics with a DecaCube detector**
 - **Current working IceCube concept seems scalable to $\sim 10\text{km}^3$** without major new developments
Addition of ~ 100 strings, similar investment as IceCube
 - **Initial results of a MC study:**
 - volume increases quadratically with spacing (as expected)
 - gain in A_{eff} **overproportional w. t. #strings**: (factor 4 for doubling the strings)
 - gain in A_{eff} **is linear in spacing**
 - unexpectedly **low energy threshold**: 10TeV-50TeV, (galactic sources still in reach ?)
 - On trigger level **largest spacing looks best**
-  **need further investigations with a realistic data analysis**

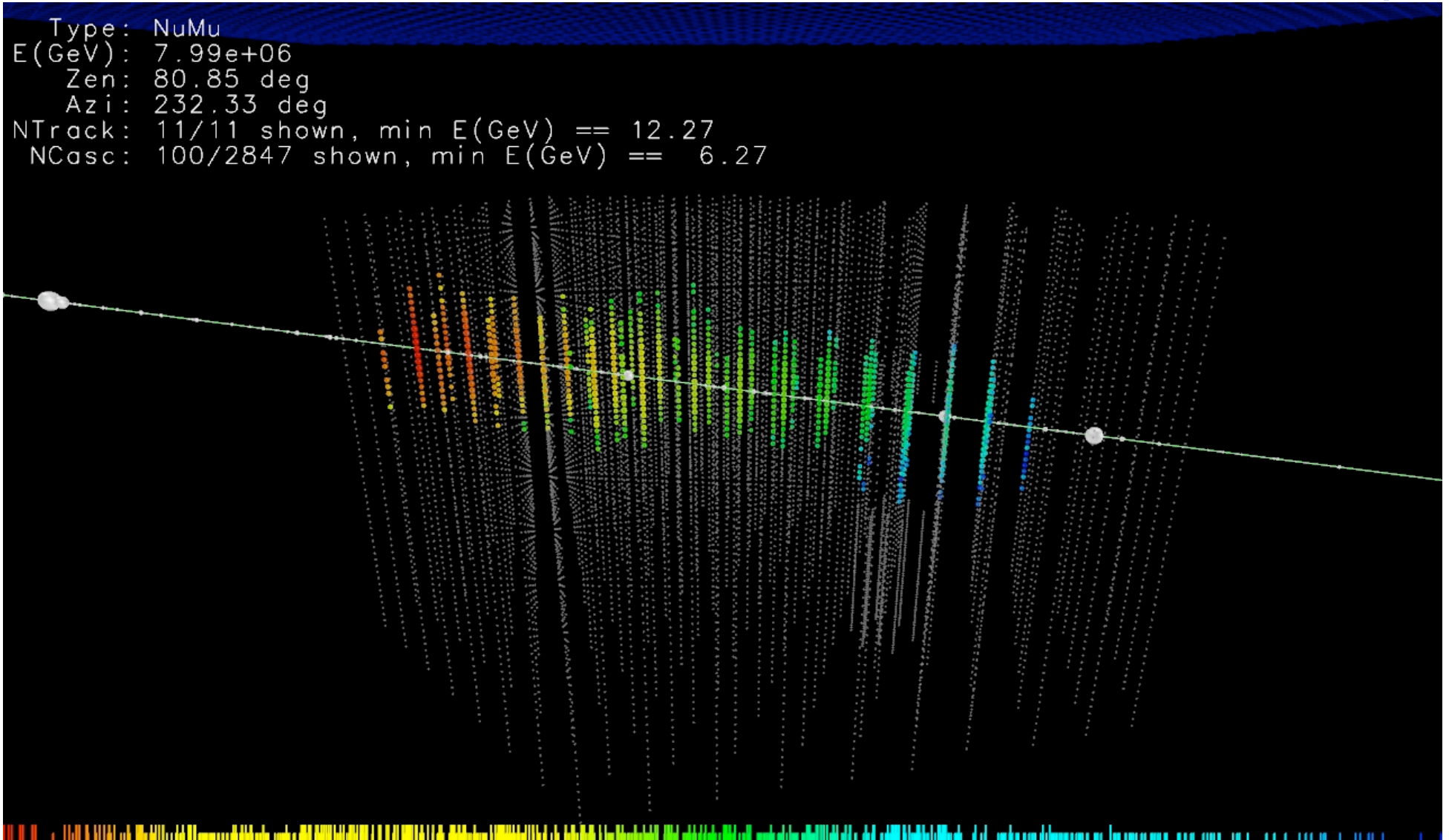
Further remarks

- The addition of ~ 60 central strings would allow for a **km^3 scale DeepCore** detector
- We expect an **substantially improved angular resolution** for IceCube-events
- Triggering and pile-up events in the sparse instrumented array should not be too difficult to solve (using current methods of the IceCube slow monopole trigger)

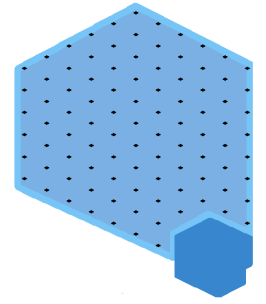
Events: Spacing 120m



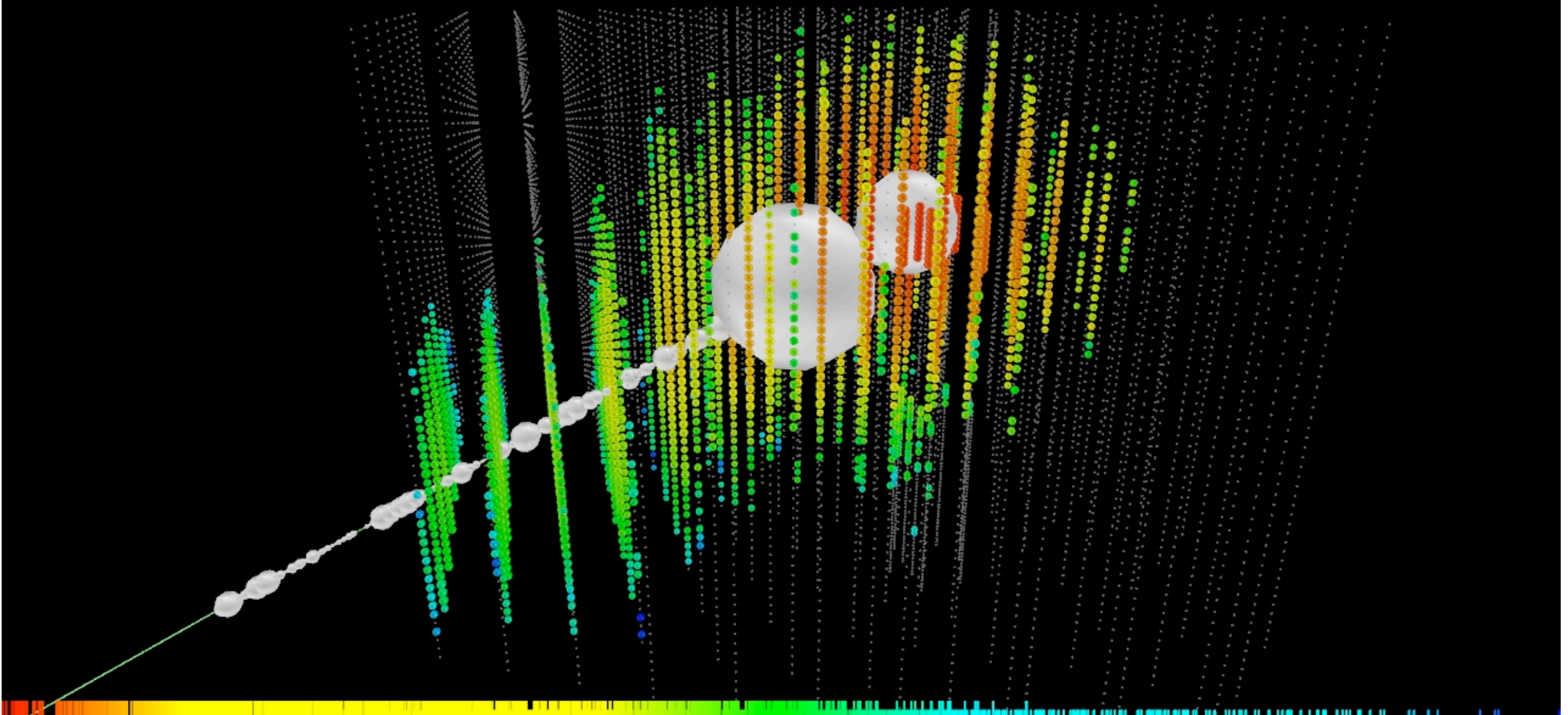
```
Type: NuMu  
E(GeV): 7.99e+06  
Zen: 80.85 deg  
Azi: 232.33 deg  
NTrack: 11/11 shown, min E(GeV) == 12.27  
NCasc: 100/2847 shown, min E(GeV) == 6.27
```



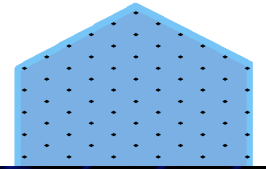
Events: Spacing 120m



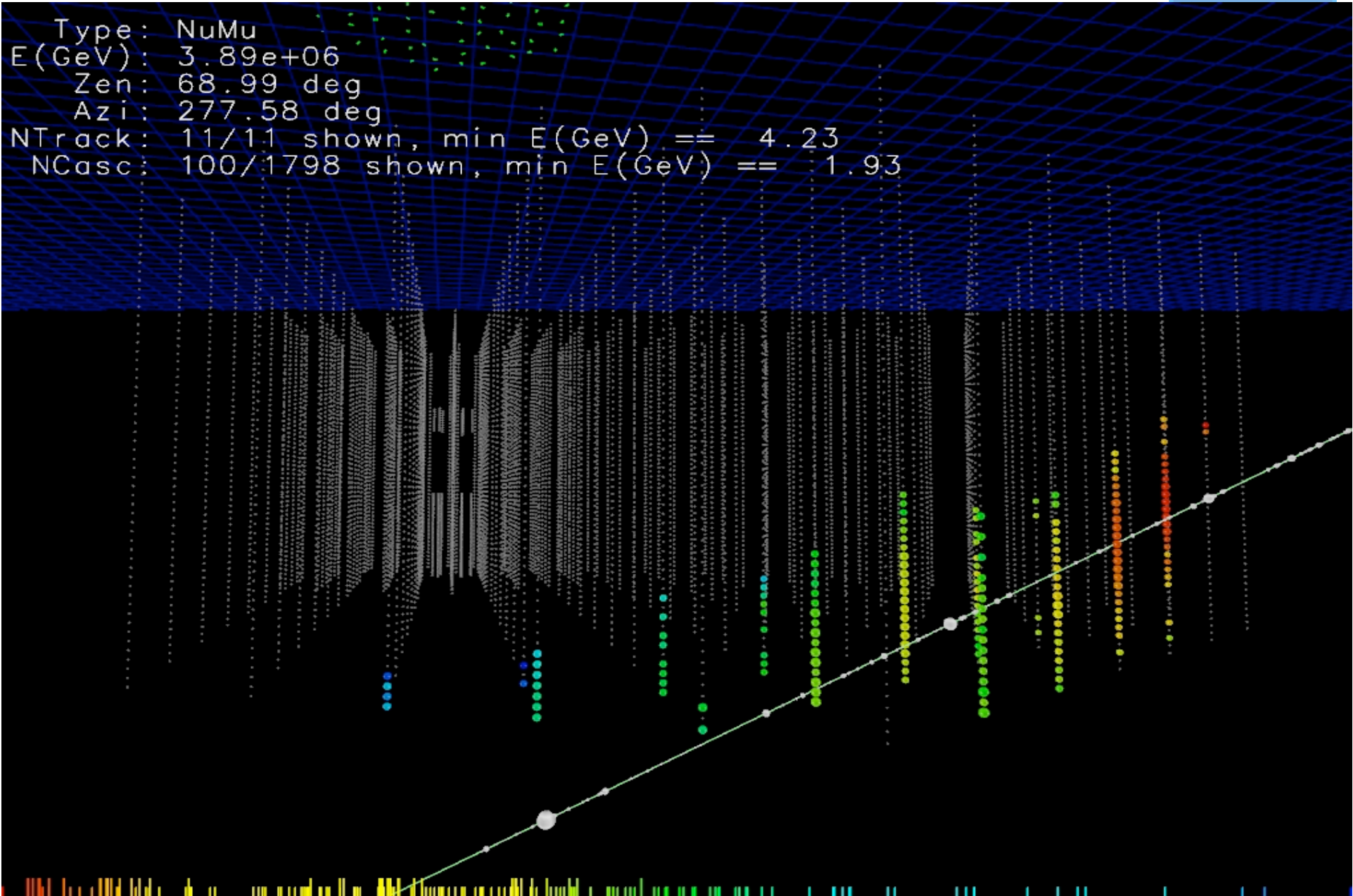
Type: NuMuBar
E(GeV): 6.91e+08
Zen: 58.93 deg
Azi: 72.03 deg
NTrack: 11/11 shown, min E(GeV) == 190.34
NCasc: 100/1886 shown, min E(GeV) == 599.81



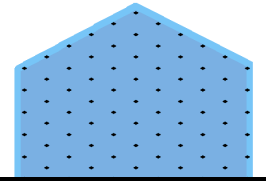
Spacing 240m



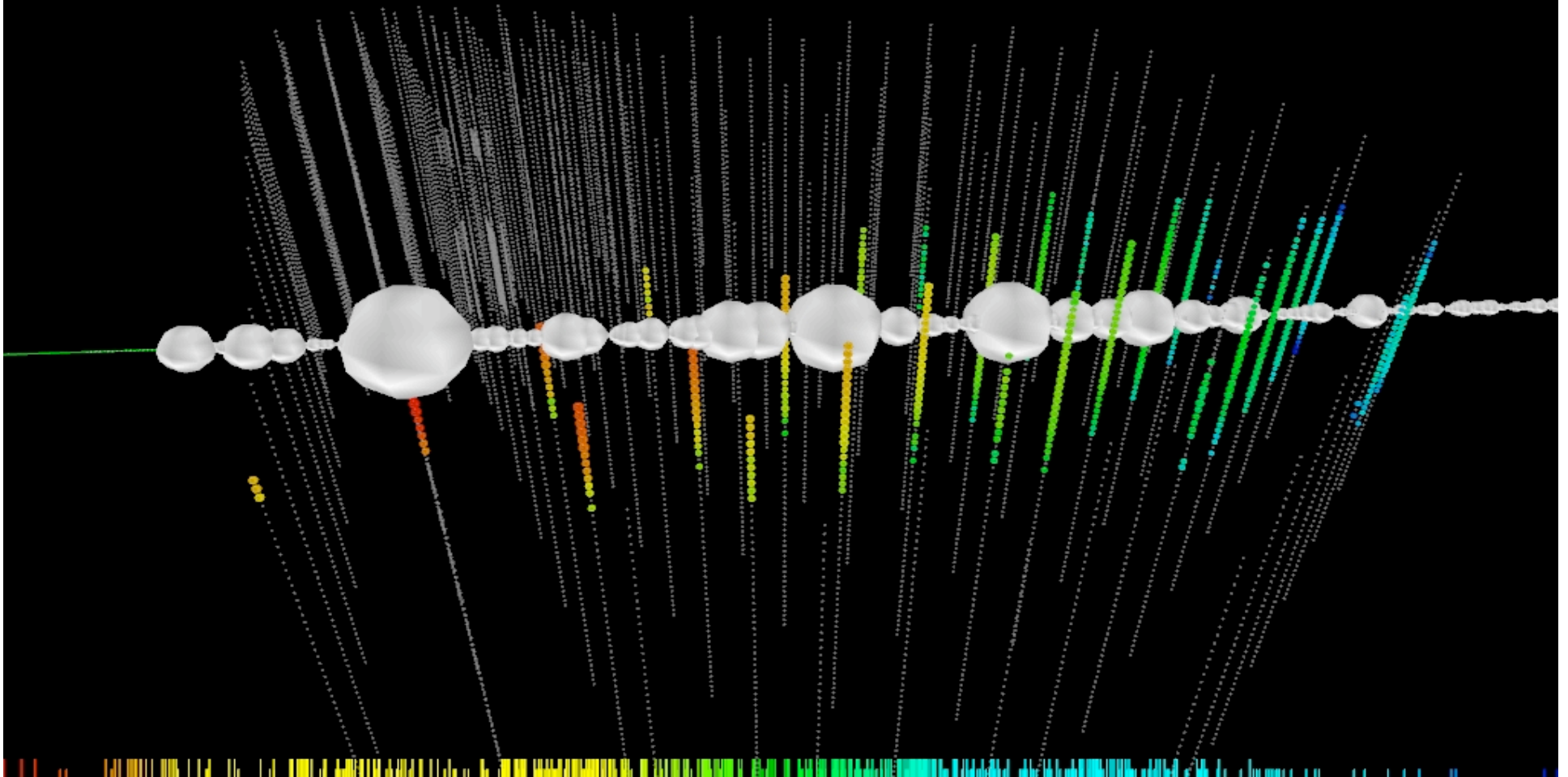
Type: NuMu
E(GeV): 3.89e+06
Zen: 68.99 deg
Azi: 277.58 deg
NTrack: 11/11 shown, min E(GeV) == 4.23
NCasc: 100/1798 shown, min E(GeV) == 1.93



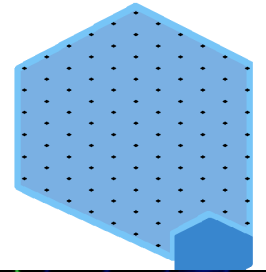
Spacing 240m



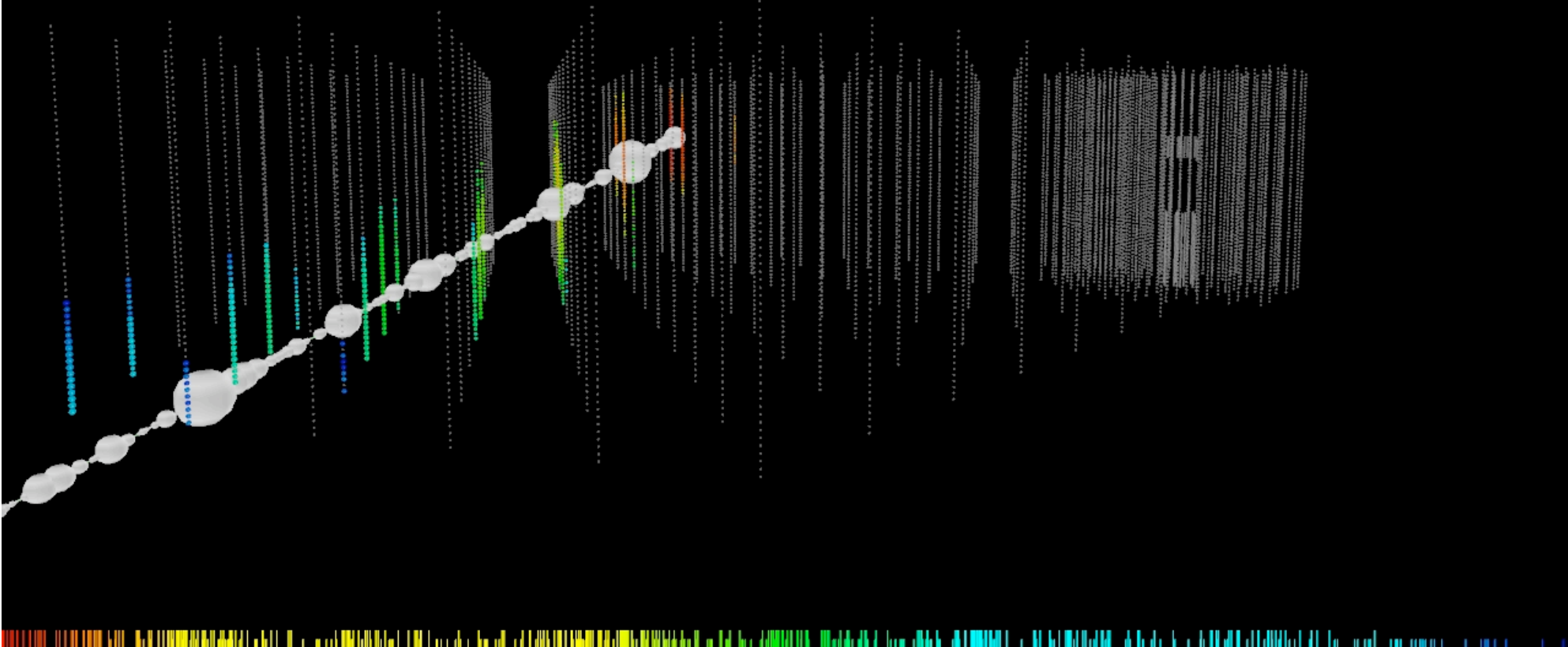
Type: NuMu
E(GeV): 5.23e+08
Zen: 74.78 deg
Azi: 94.07 deg
NTrack: 11/11 shown, min E(GeV) == 85.64
NCasc: 100/4494 shown, min E(GeV) == 4.22



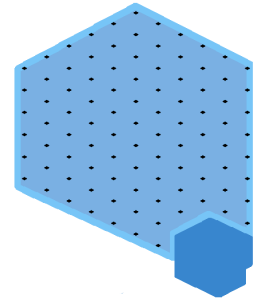
Spacing 360m



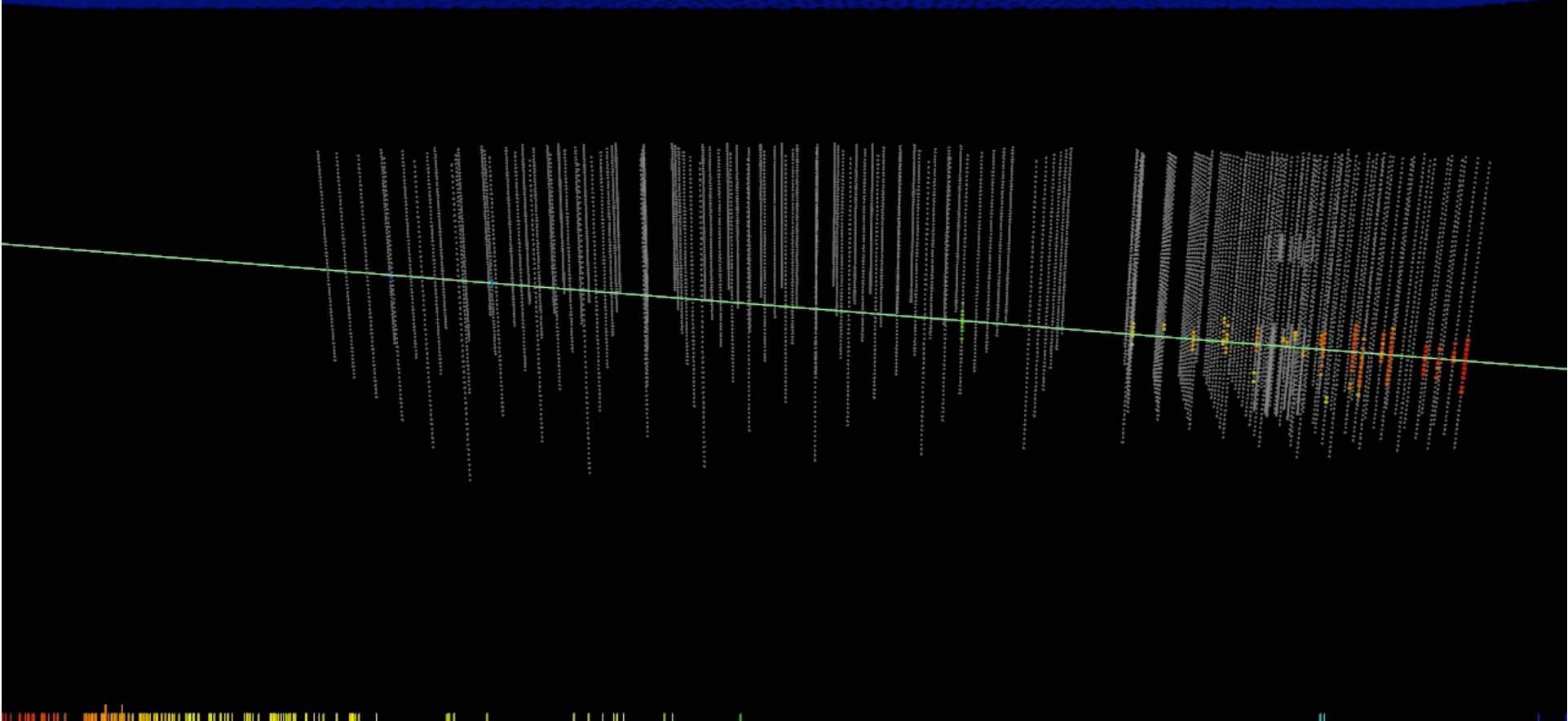
Type: NuMuBar
E(GeV): 6.99e+08
Zen: 73.70 deg
Azi: 77.86 deg
NTrack: 11/11 shown, min E(GeV) == 74.73
NCasc: 100/3700 shown, min E(GeV) == 0.54



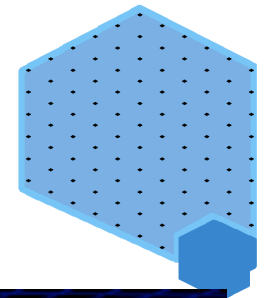
Low energy event spacing 360m



```
Type: NuMu  
E(GeV): 1.66e+04  
Zen: 90.86 deg  
Azi: 33.06 deg  
NTrack: 2/2 shown, min E(GeV) == 1.75  
NCasc: 100/546 shown, min E(GeV) == 7.37
```



single layer PeV event Spacing 360m



```
Type: NuMu  
E(GeV): 2.47e+06  
Zen: 77.54 deg  
Azi: 358.79 deg  
NTrack: 11/11 shown, min E(GeV) == 1.61  
NCasc: 100/2219 shown, min E(GeV) == 4.56
```

