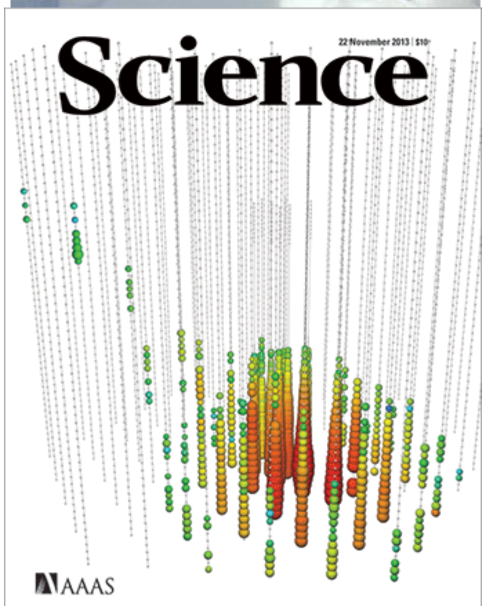
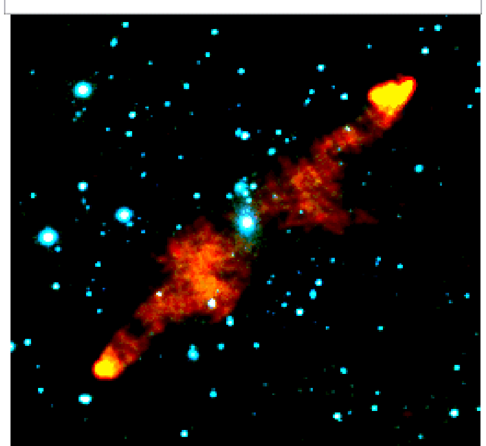




High-Energy Neutrinos in IceCube and DecaCube

Jenni Adams

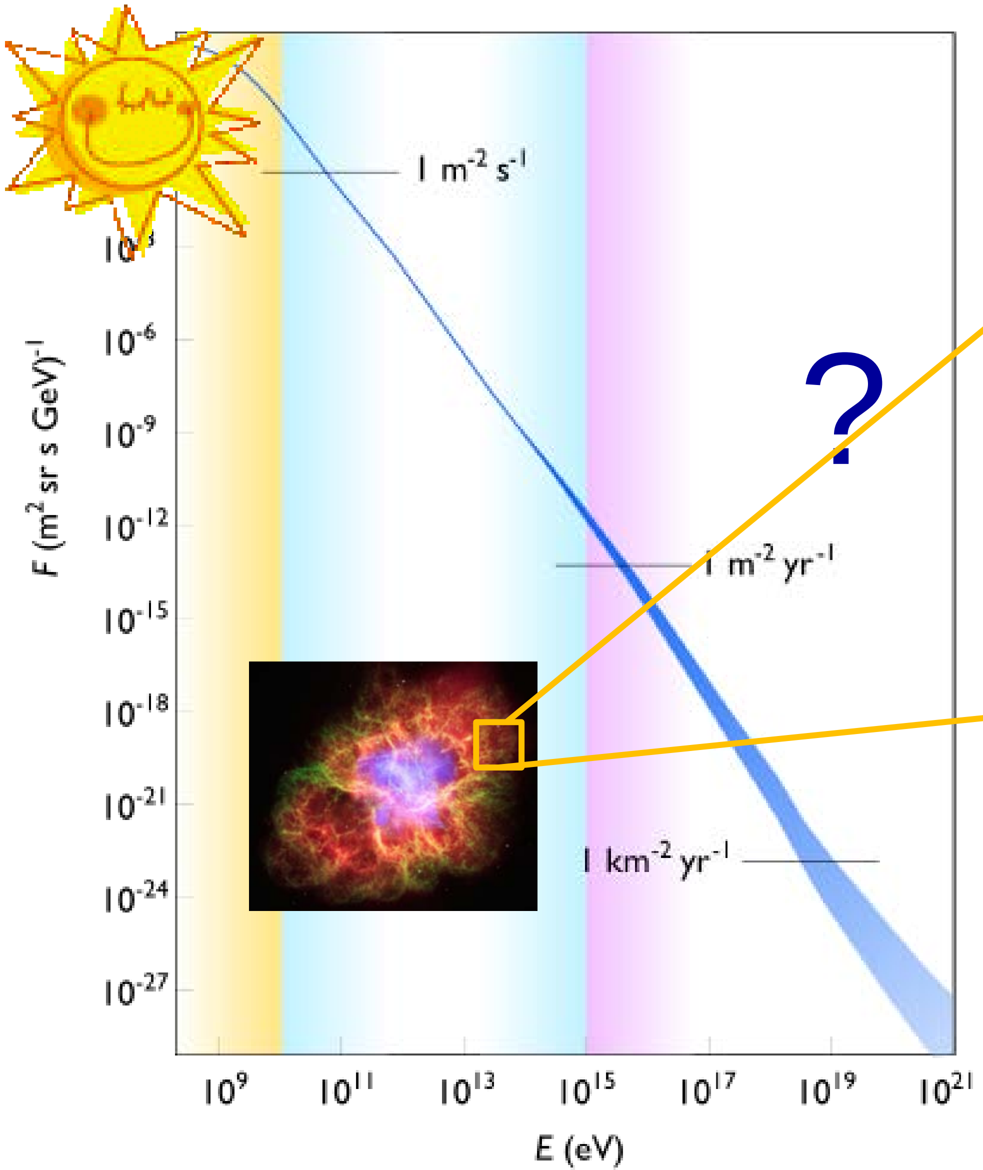
The Niels Bohr International Academy

UC
UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

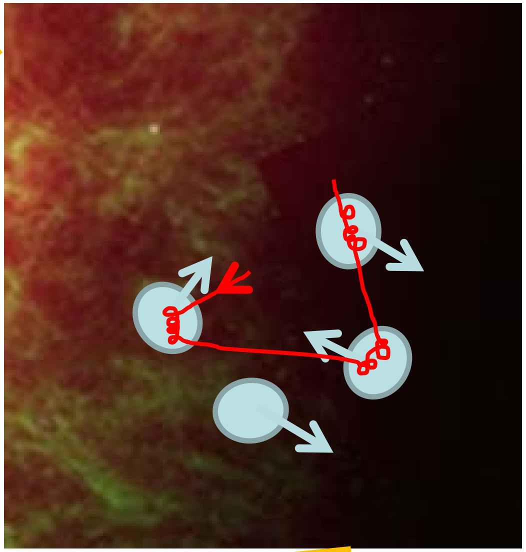
Design Question:

- What is the origin, and the physics describing the acceleration, of the highest energy cosmic rays?

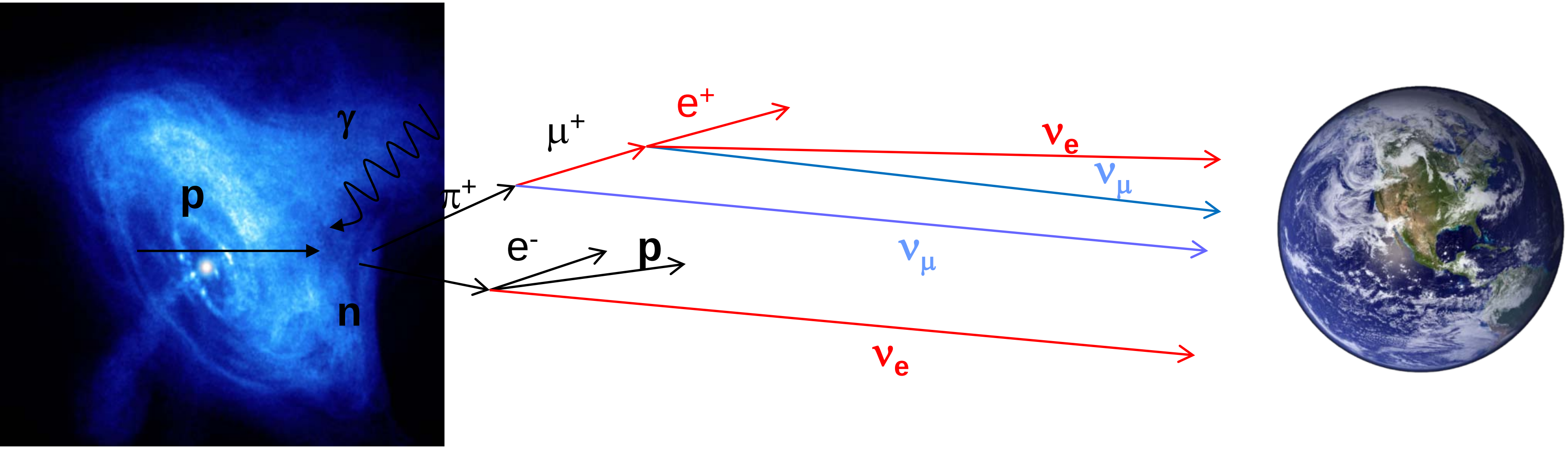
Cosmic Rays...



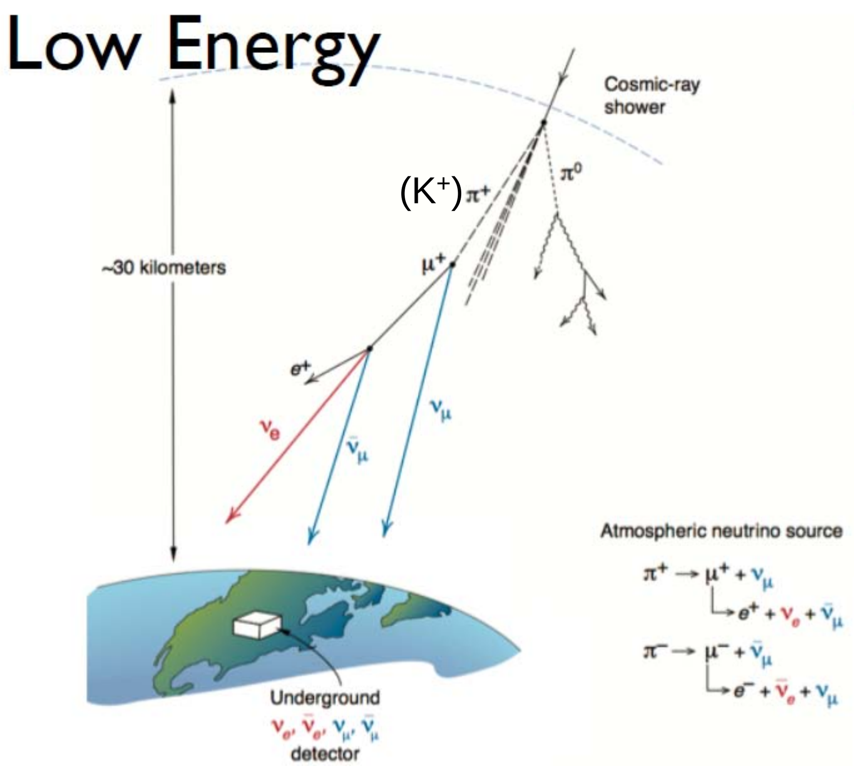
Fermi acceleration



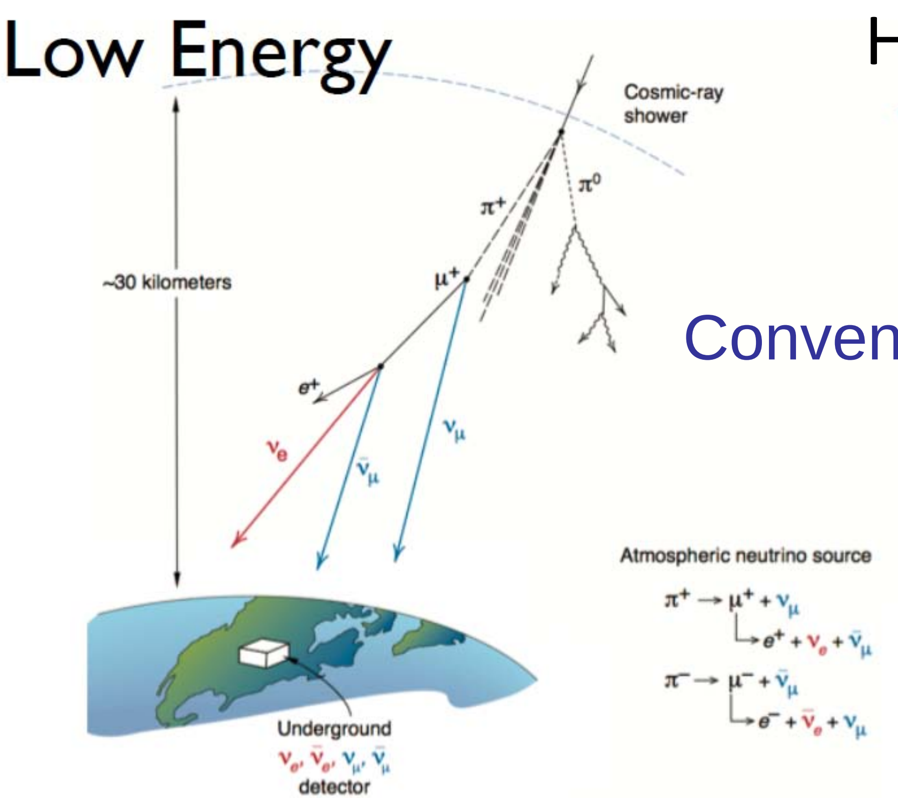
Neutrinos from cosmic ray interactions at **acceleration site**

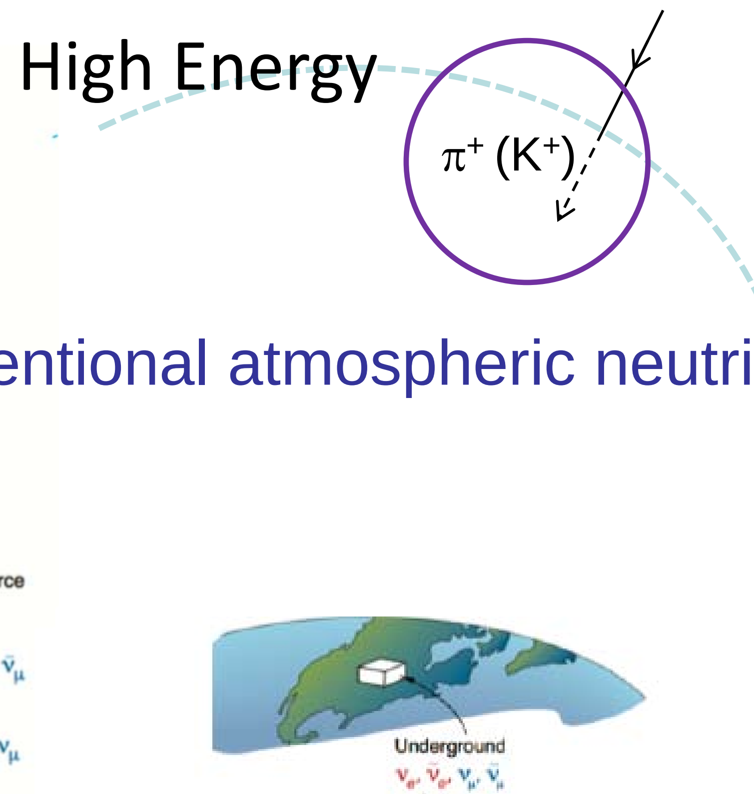


Neutrinos from cosmic ray interactions in the **Earth's atmosphere**



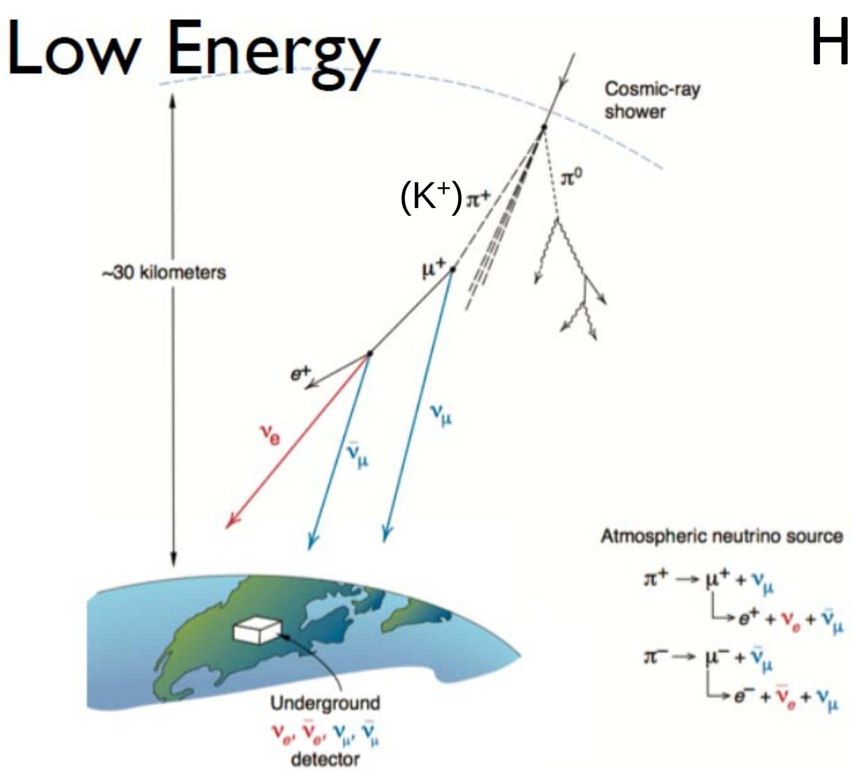
Neutrinos from cosmic ray interactions in the **Earth's atmosphere**

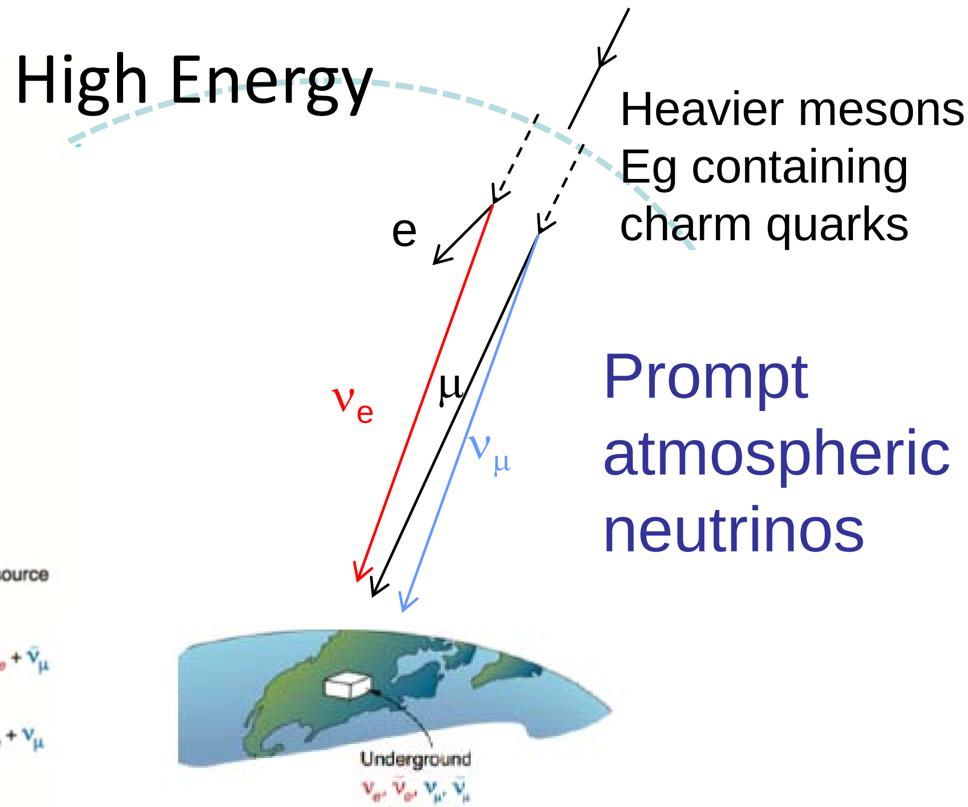




Conventional atmospheric neutrinos

Neutrinos from cosmic ray interactions in the **Earth's atmosphere**

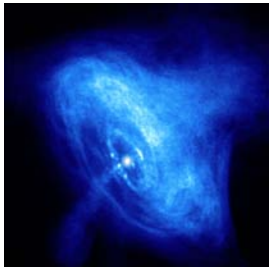




Summary

At source:

at source:



Astrophysical neutrinos

Signal

Cosmic rays interact

in the Earth's atmosphere:

Atmospheric neutrinos

At Earth:

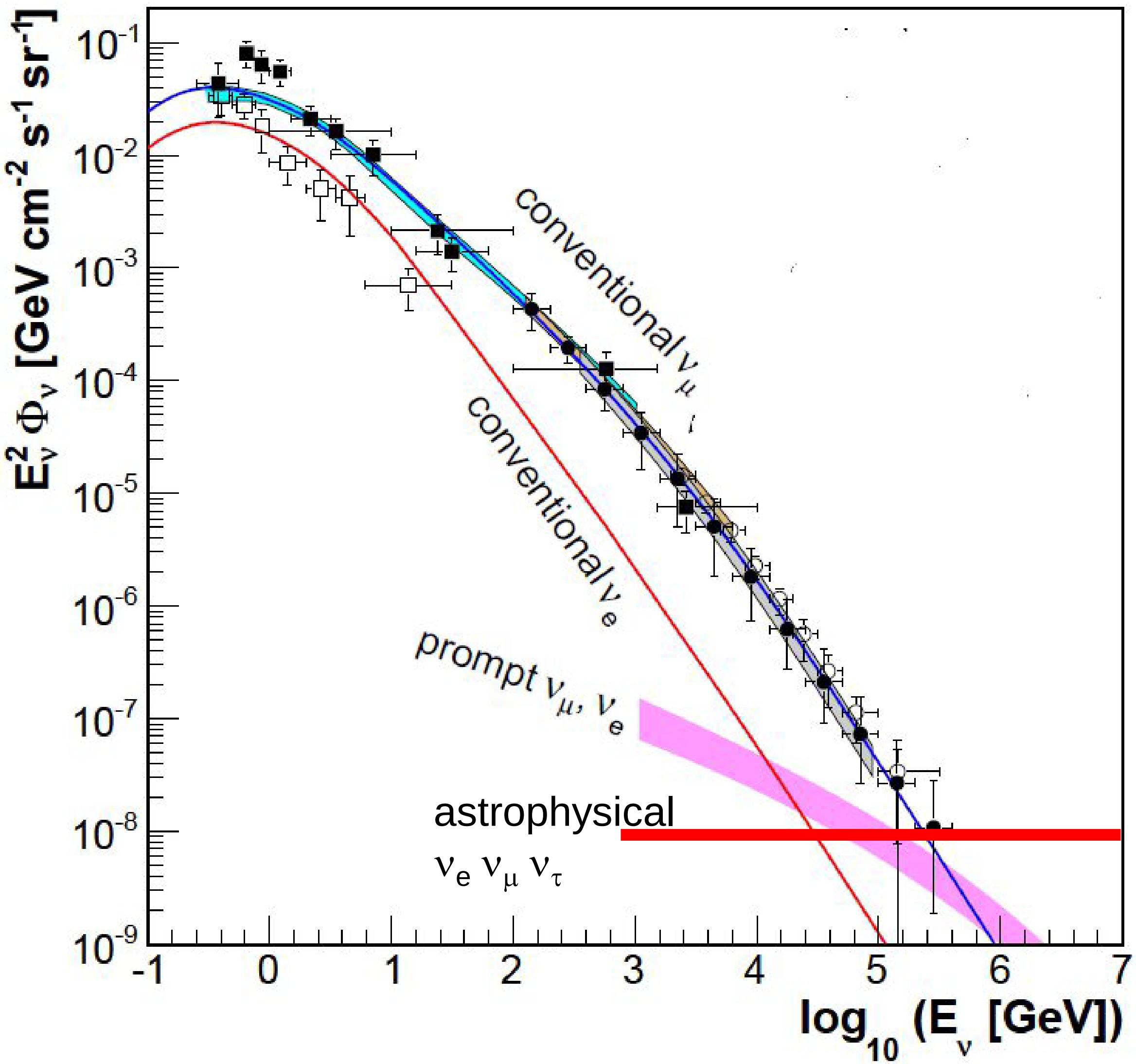
conventional

Background

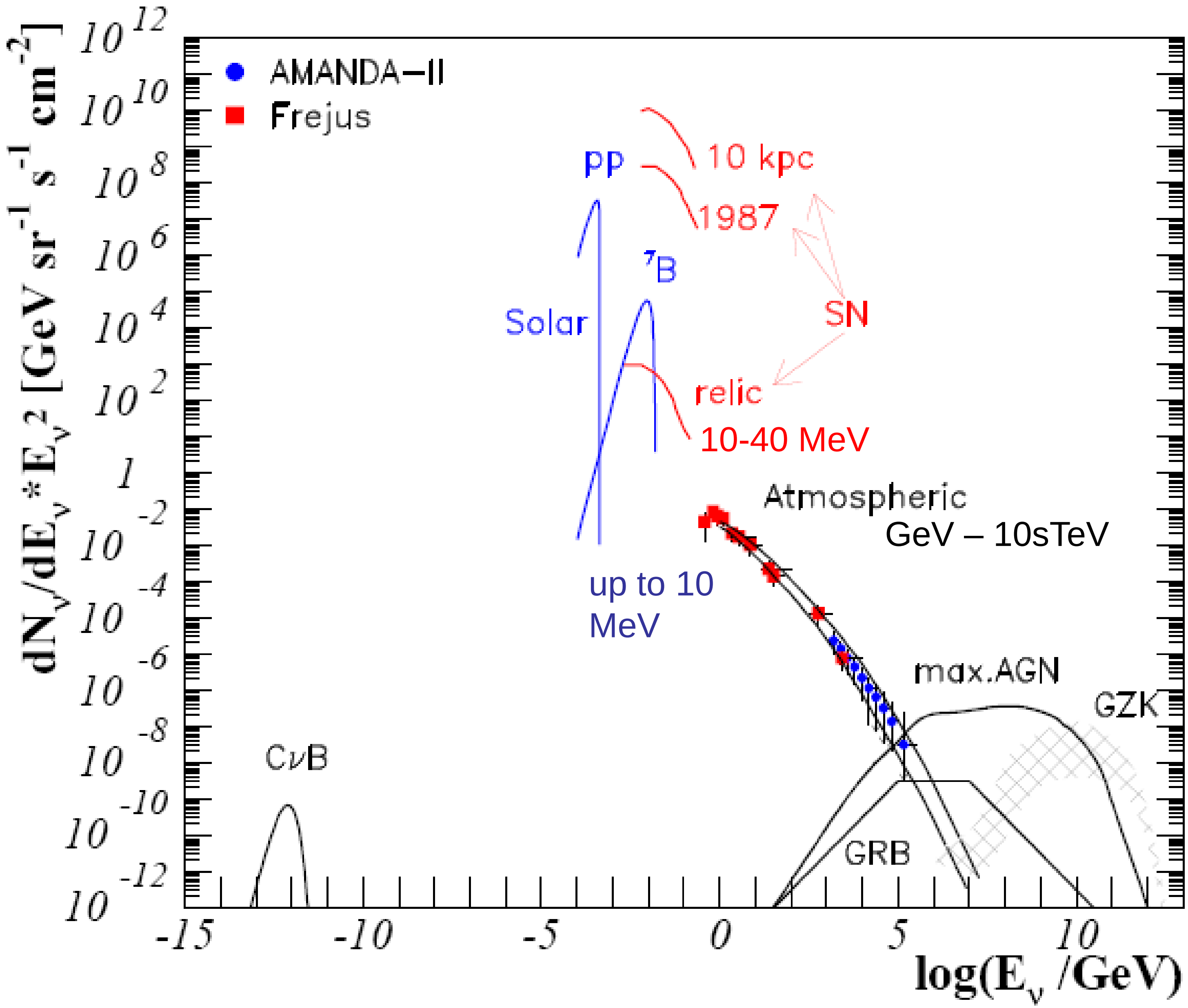
prompt

Background

Neutrino spectra

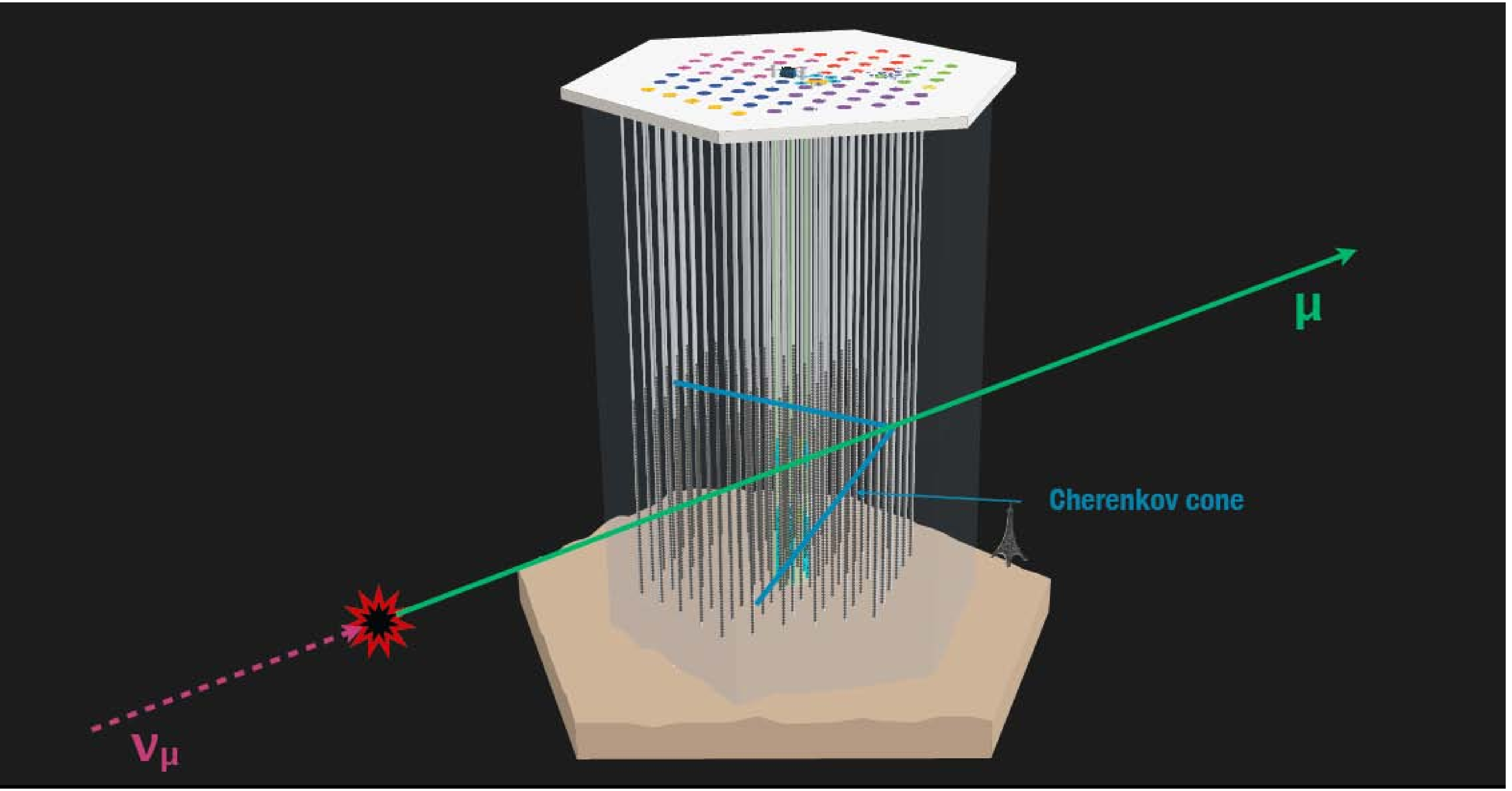


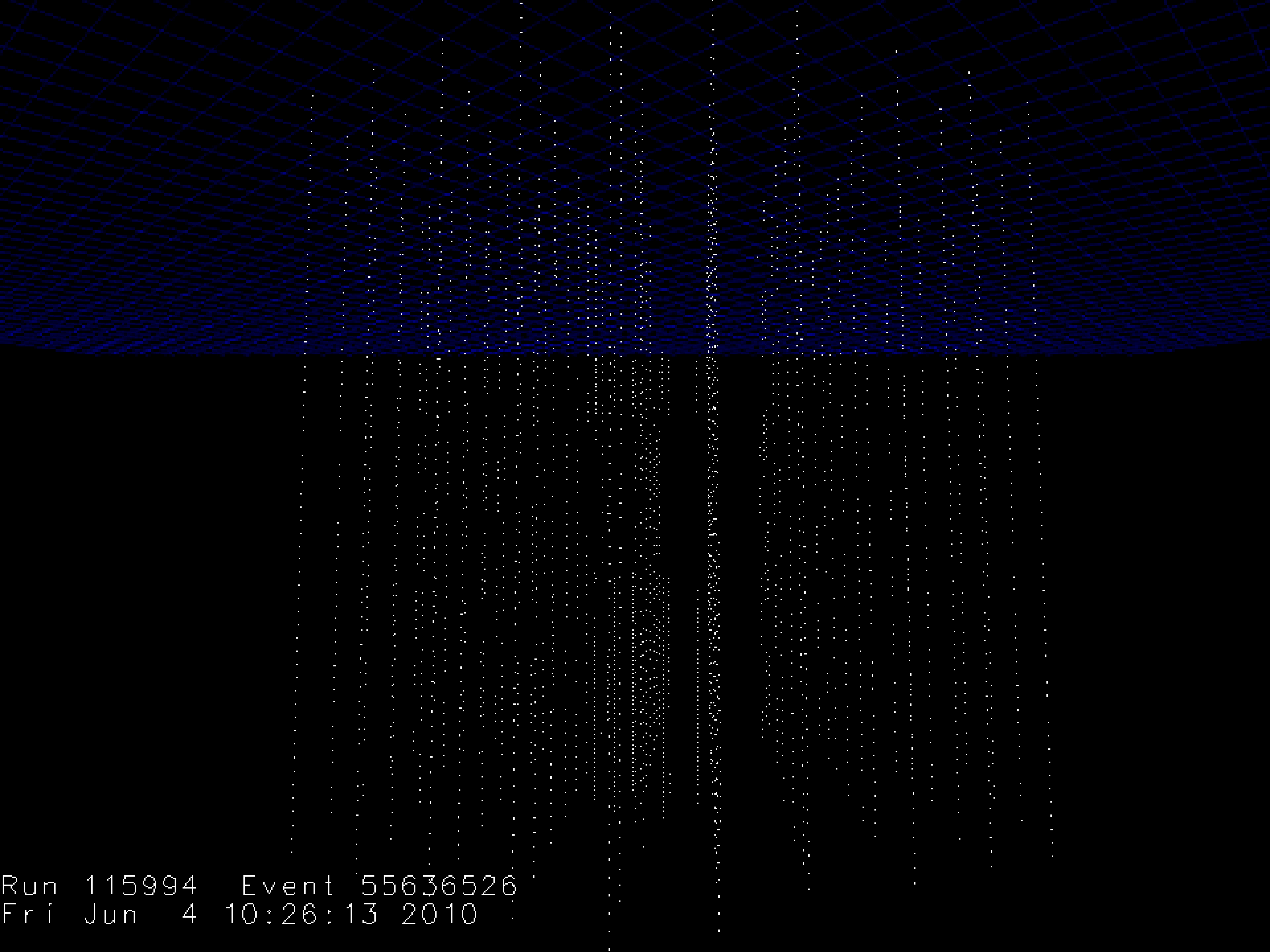
Neutrino source fluxes



J. Becker Phys. Rep. **458**

Need a large detector...
Can be sparsely instrumented





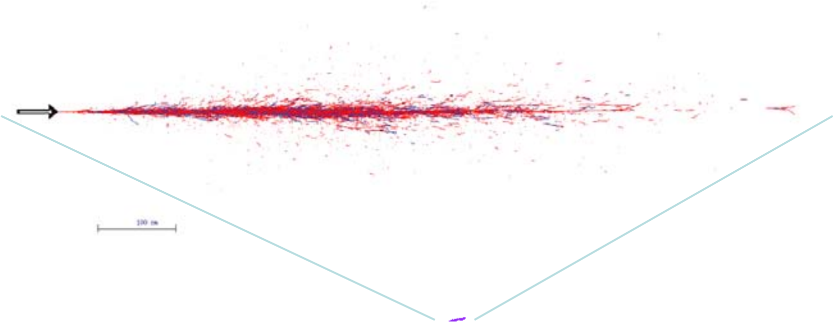
Run 115994 Event 55636526
Fri Jun 4 10:26:13 2010

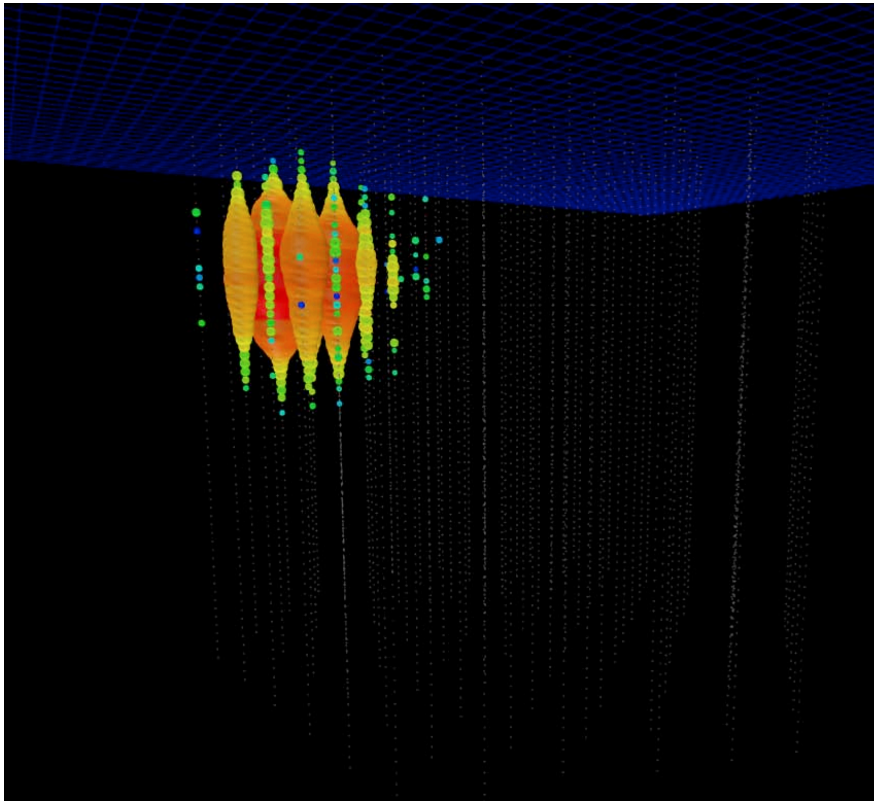
Neutrino interactions in the ice

	Charged Current ($W^{+/-}$)	Neutral Current (Z^0)
ν_e	$\nu_e + N \rightarrow e^- + X$	$\nu_e + N \rightarrow \nu_e + X$
ν_μ	$\nu_\mu + N \rightarrow \mu^- + X$	$\nu_\mu + N \rightarrow \nu_\mu + X$
ν_τ	$\nu_\tau + N \rightarrow \tau^- + X$	$\nu_\tau + N \rightarrow \nu_\tau + X$

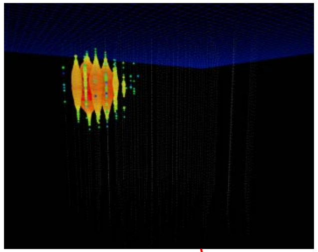
"Cascades"

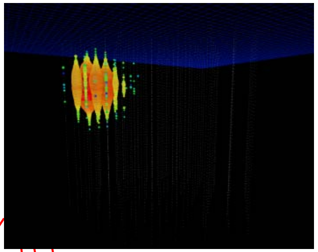
- Showers are initiated by 1)electrons and 2)the hadronization of the nuclei debris
- Cherenkov radiation is emitted from all charged particles in a particle shower
- The shower is contained in a volume of less than 5m^3 (for E < 10PeV)
- Due to scattering the Cherenkov light will have an isotropic distribution around 25m from the shower

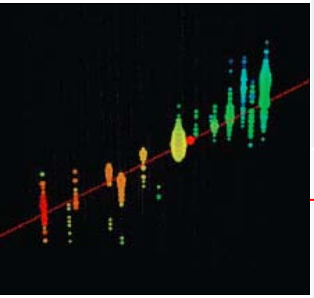




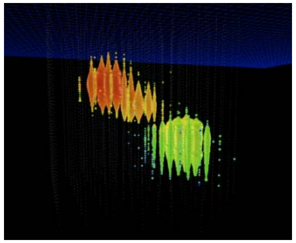
Neutrino signatures in IceCube







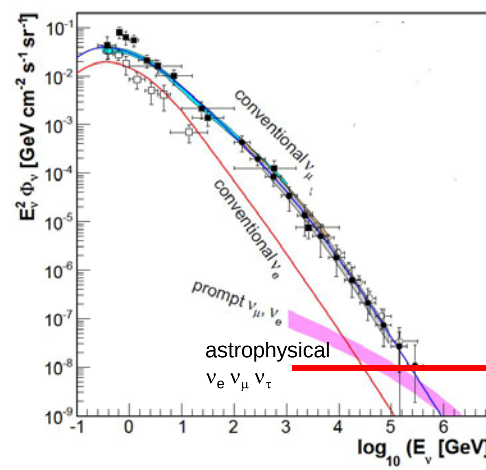
	Charged Current ($W^{+/-}$)	Neutral Current (Z^0)
ν_e	$\nu_e + N \rightarrow e^- + X$	$\nu_e + N \rightarrow \nu_e + X$
ν_μ	$\nu_\mu + N \rightarrow \mu^- + X$	$\nu_\mu + N \rightarrow \nu_\mu + X$
ν_τ	$\nu_\tau + N \rightarrow \tau^- + X$	$\nu_\tau + N \rightarrow \nu_\tau + X$



What do we want?

- Good pointing resolution to look for sources - best with muon neutrinos

- Good energy resolution (to obtain energy spectrum) – best with cascades

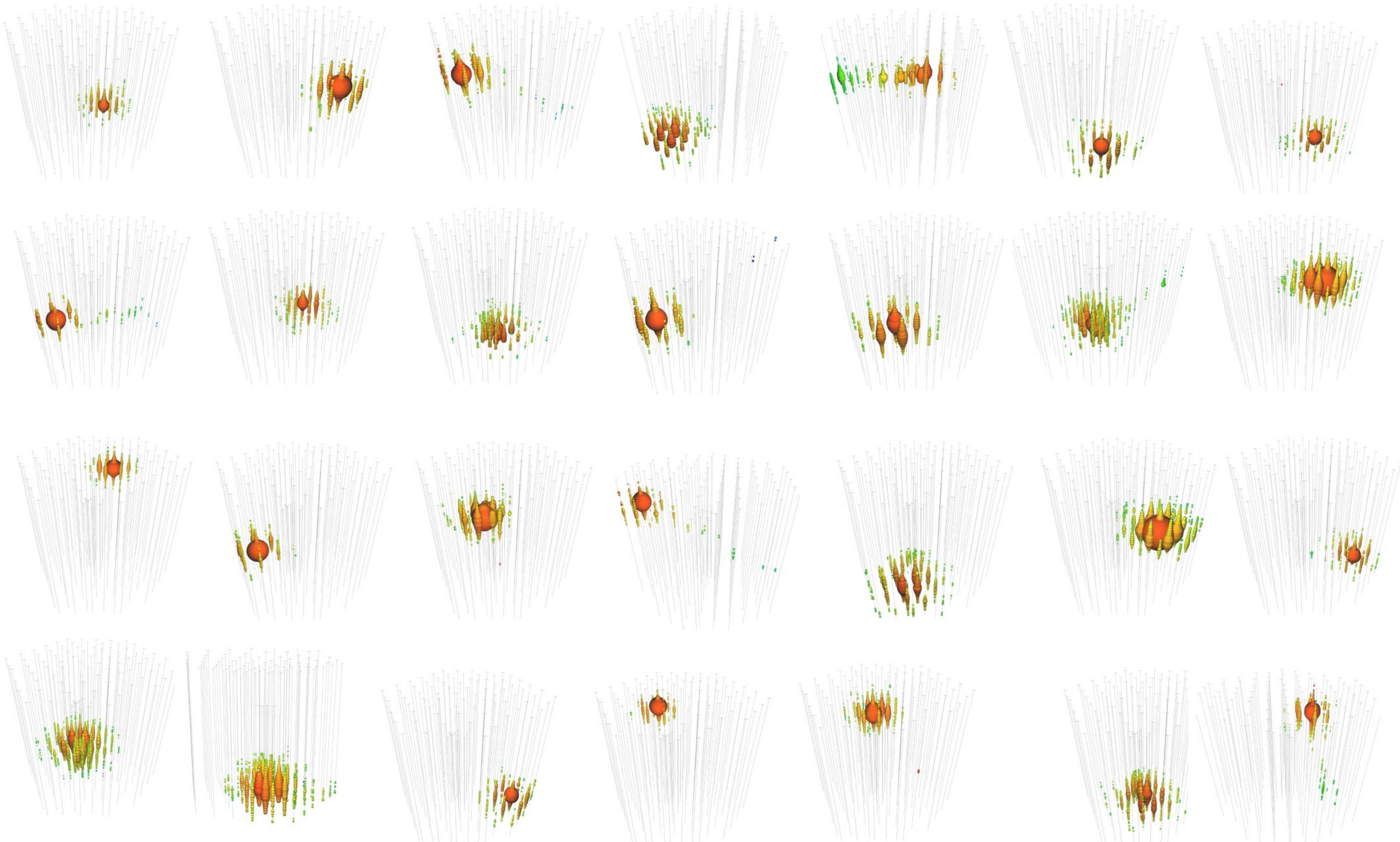


- Flavour identification

ν_e ν_μ ν_τ

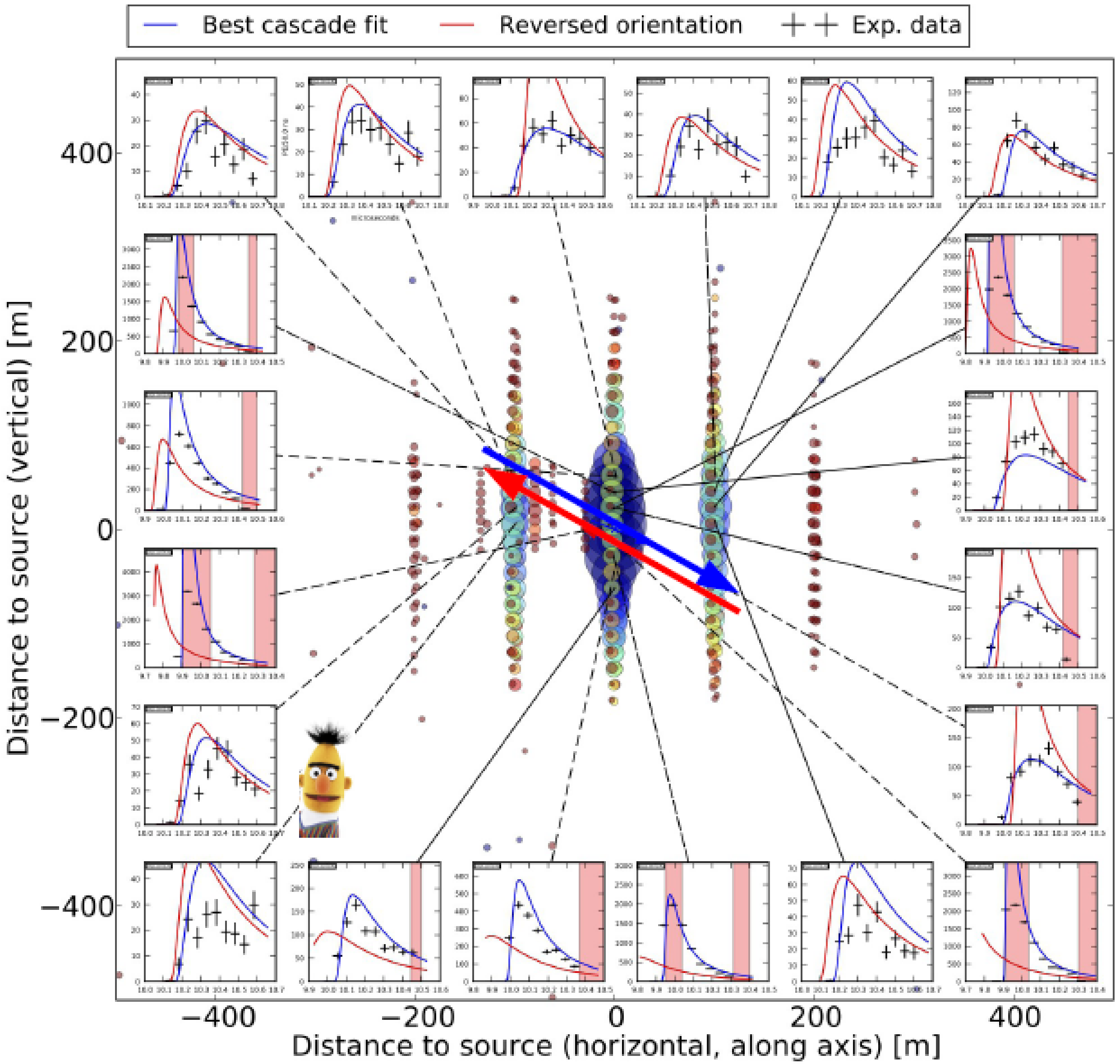
Search found: 28 events - 7 with visible muons

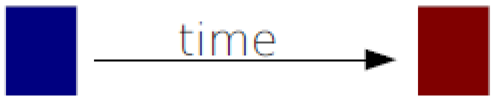
622 days May 2010–May 2012   Inconsistent with background at 4.1σ



Atmos ν background: 4.6 + 3.7/-1.2   Atmos μ background: 6 +/- 3.4

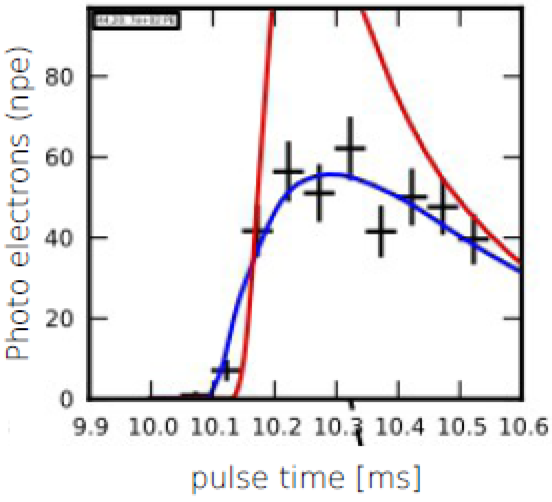
Angular reconstruction of cascade events





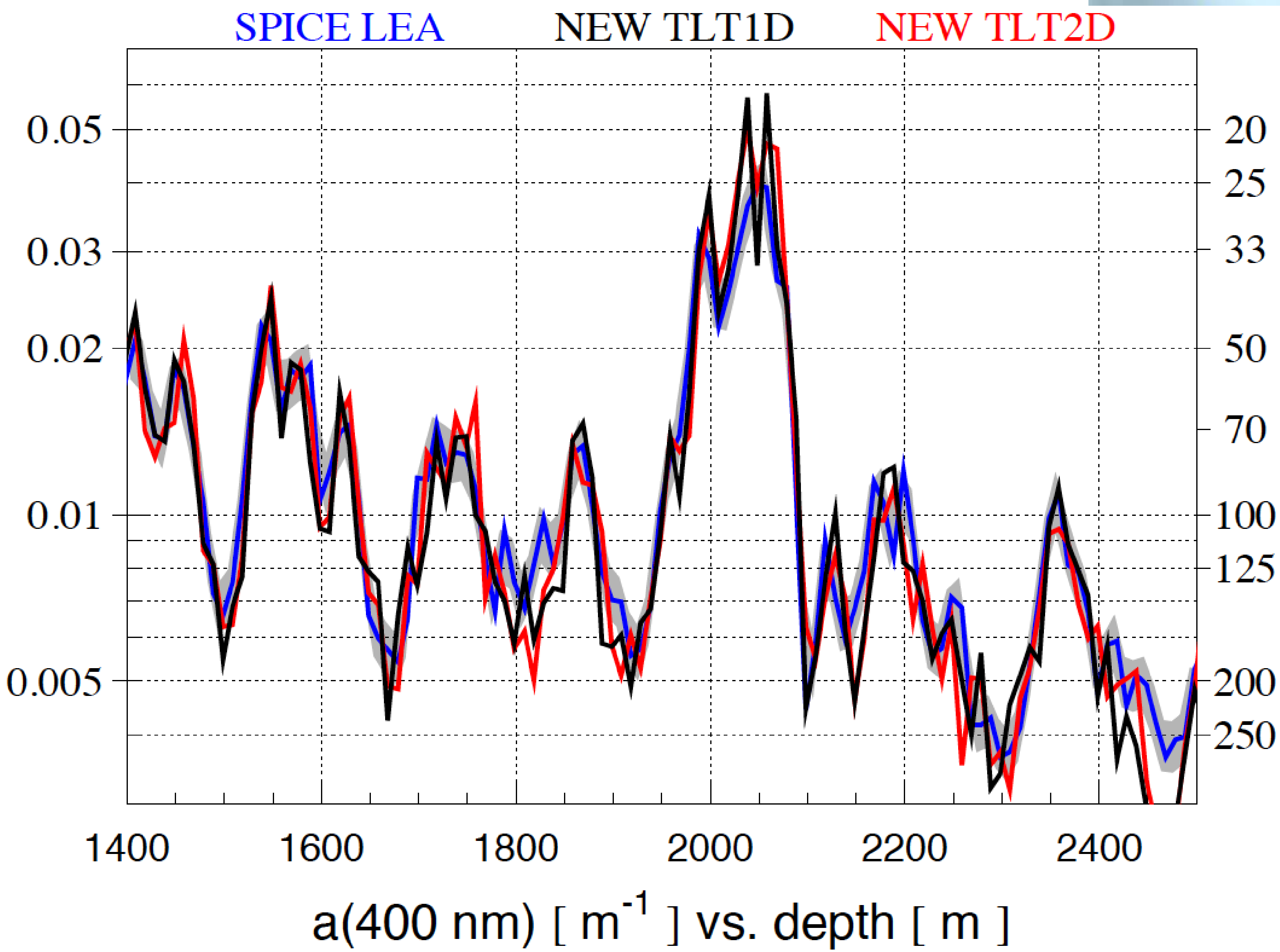
Width of waveform related to direction of Cherenkov cone

Height proportional to energy



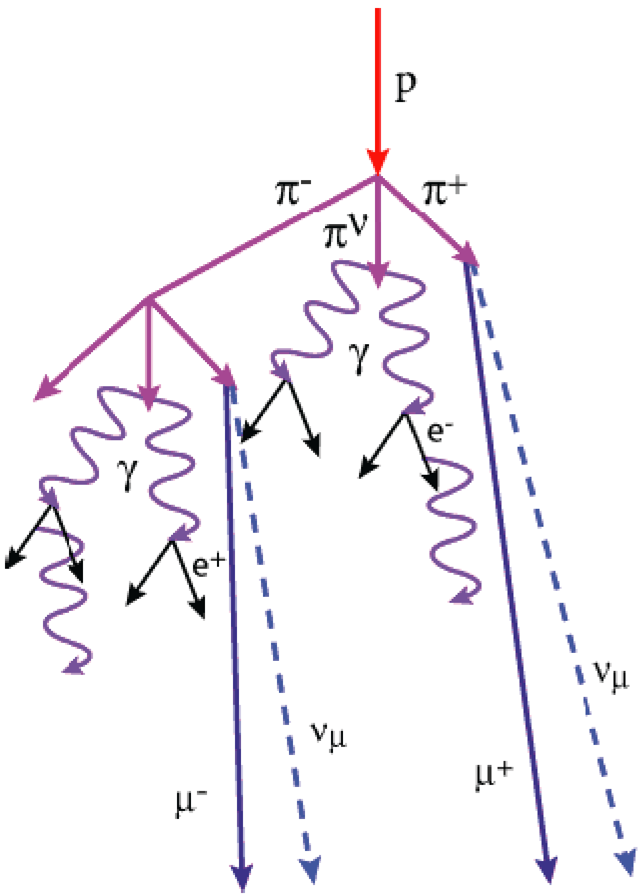
Accurate Ice properties

-to get a clean window on the Universe



Backgrounds to astrophysical neutrino searches...

Cosmic rays – source of atmospheric neutrinos and muon background detected by IceCube



Muon rate:
In ice: ~3000 Hz

Atmospheric neutrinos:
~1 neutrino/10 minutes

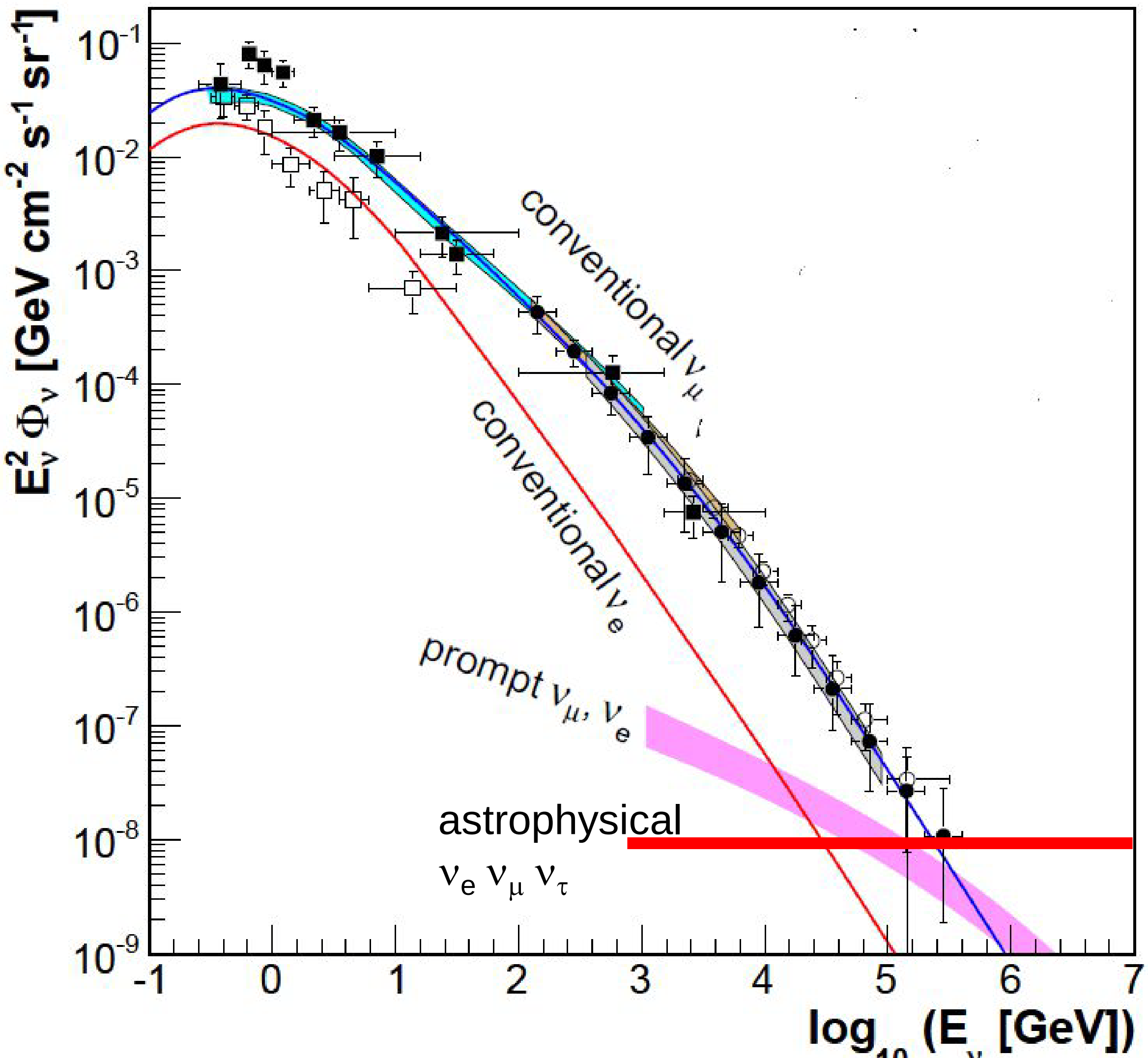
Neutrino Detection:
Requires 10^6 background rejection

Background rejection techniques

- Muon neutrinos – select upward going tracks
- Cascade channel – select events with cascade shape and no visible tracks, usually using veto cuts to remove events on the edge of the detector

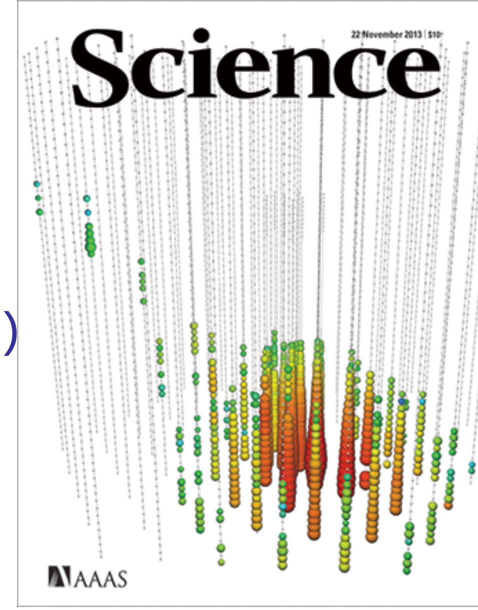
Require Monte Carlo simulation of signal and background

Neutrino spectra



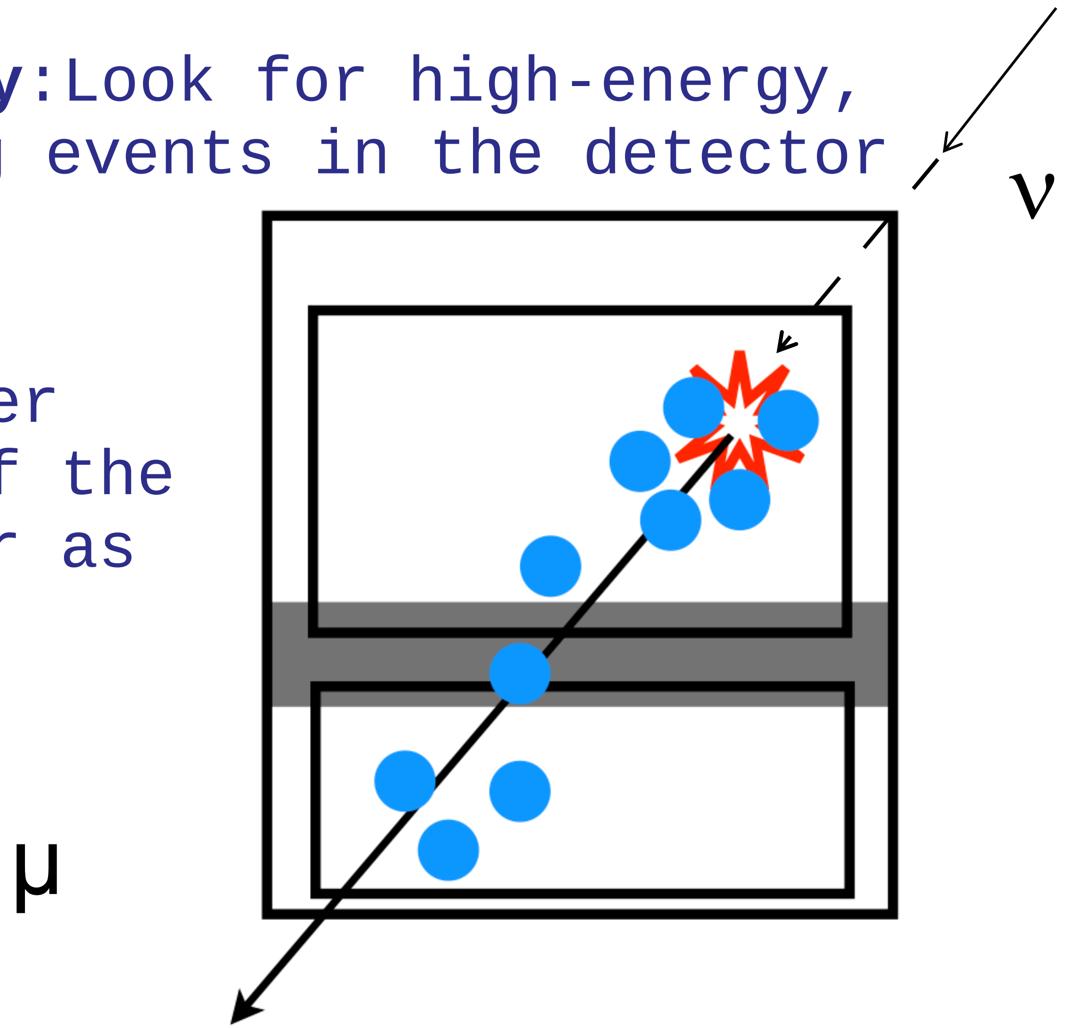
Evidence for extraterrestrial neutrinos

IceCube Collaboration, Science 342, 1242856 (2013)



- **Strategy:** Look for high-energy, starting events in the detector

Use outer parts of the detector as a veto-region

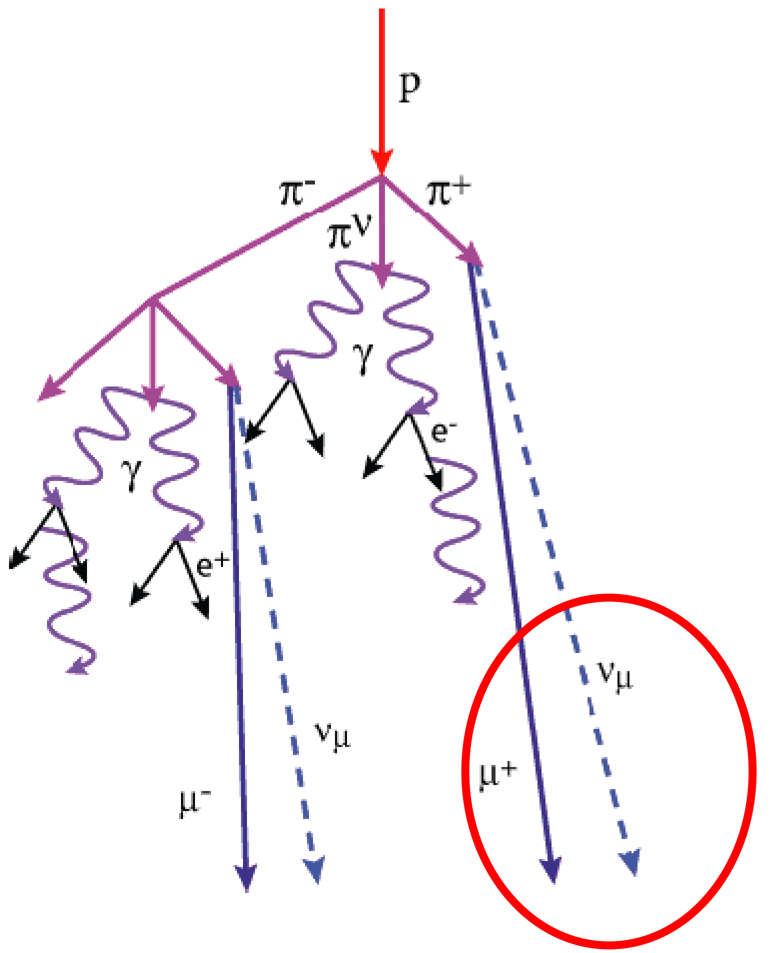


Veto criteria

reduces both muon and

<u>southern hemisphere atmospheric neutrino</u>

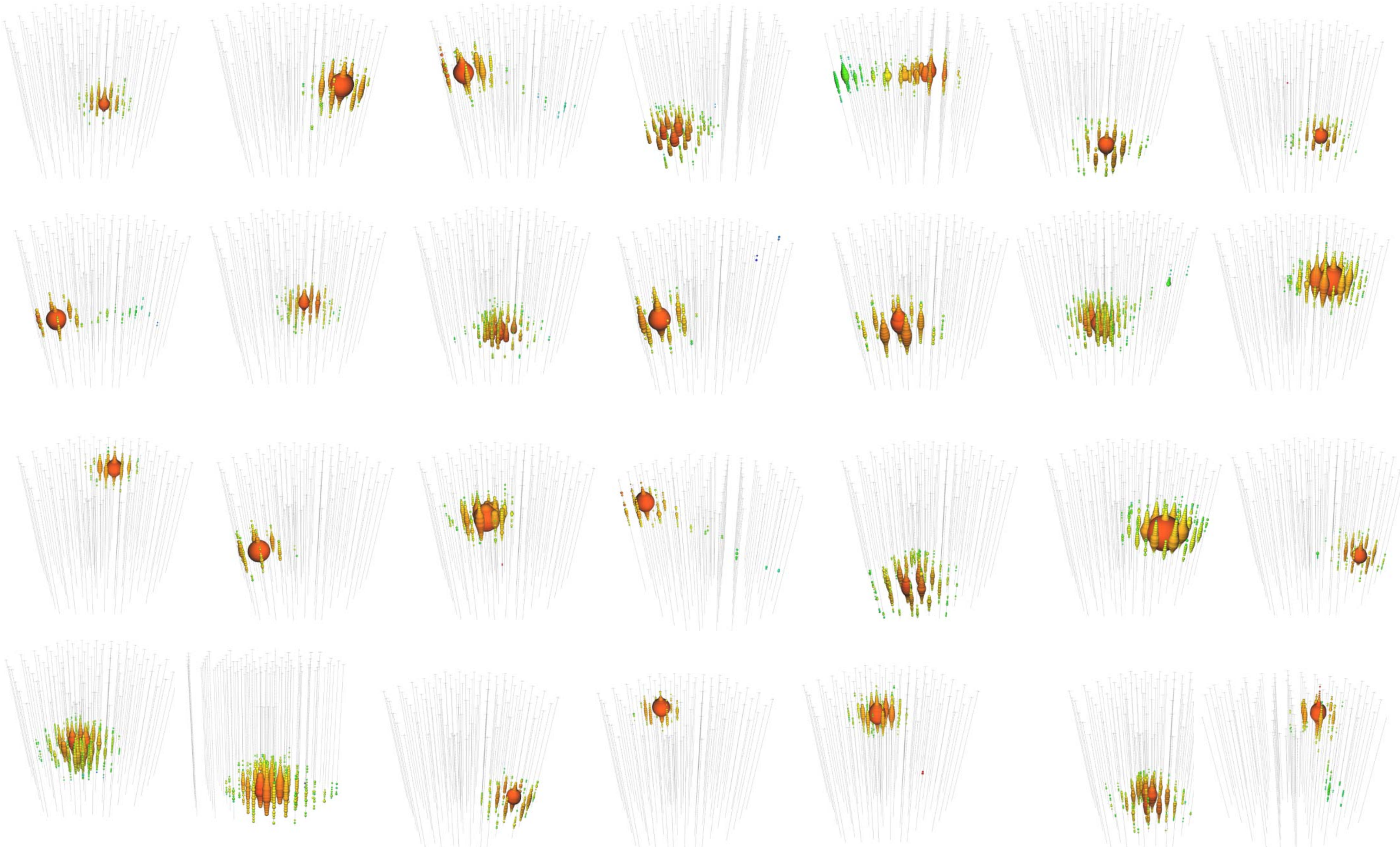
backgrounds



Accompanying muon trips the veto

Search found: 28 events - 7 with visible muons

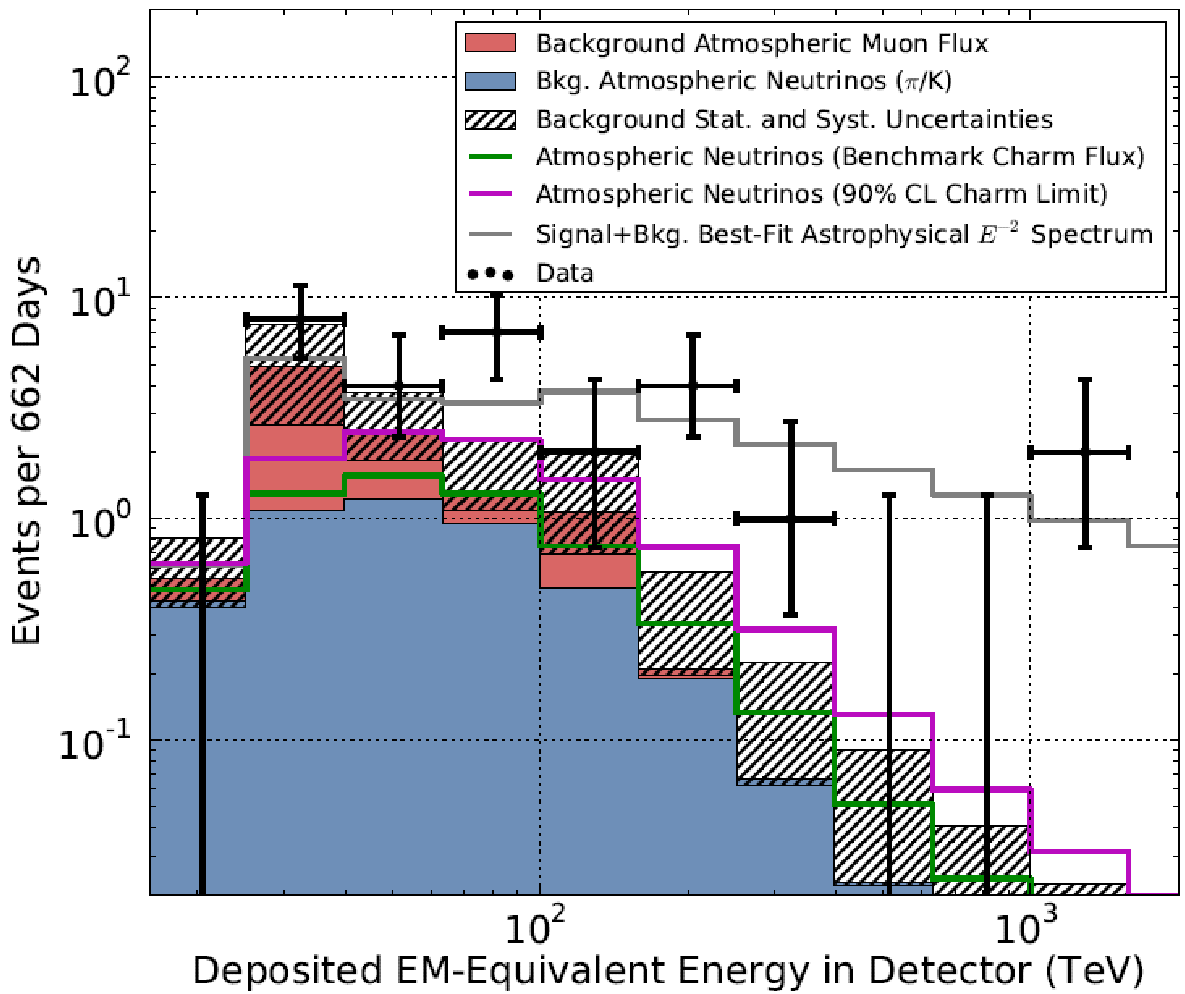
622 days May 2010–May 2012   Inconsistent with background at 4.1σ



Atmos ν background: 4.6 + 3.7/-1.2   Atmos μ background: 6 +/- 3.4

Energy spectrum

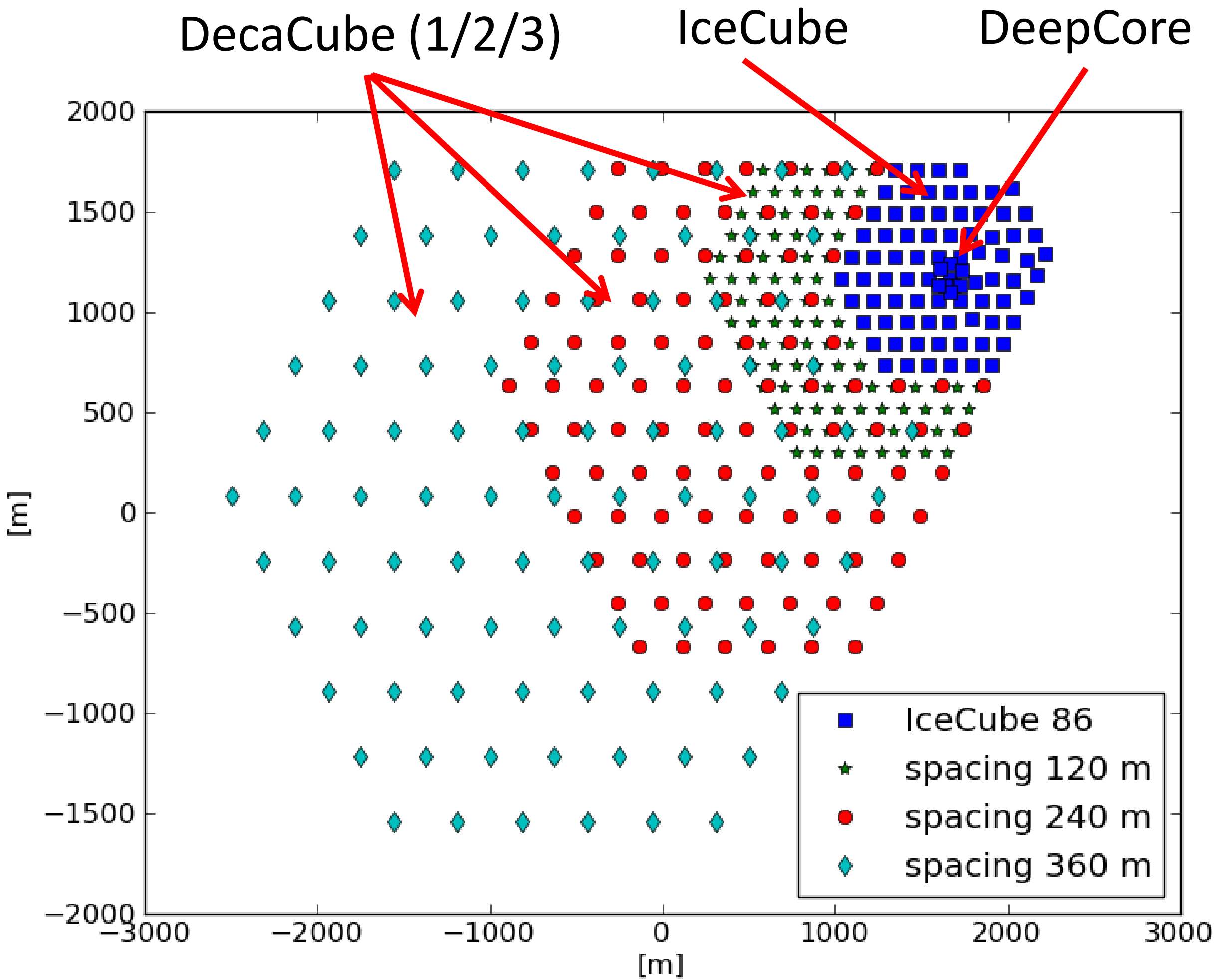
- Harder than expected from atmospheric backgrounds
- Merges well into backgrounds at low energies



IceCube Collaboration,
Science 342, 1242856 (2013)

DecaCube?

Christopher Wiebusch RWTHAachen



Spacing 1 ($120m$):
IceCube (1 km^3)
+ 98 strings (1,3 km^3)
= 2,3 km^3

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

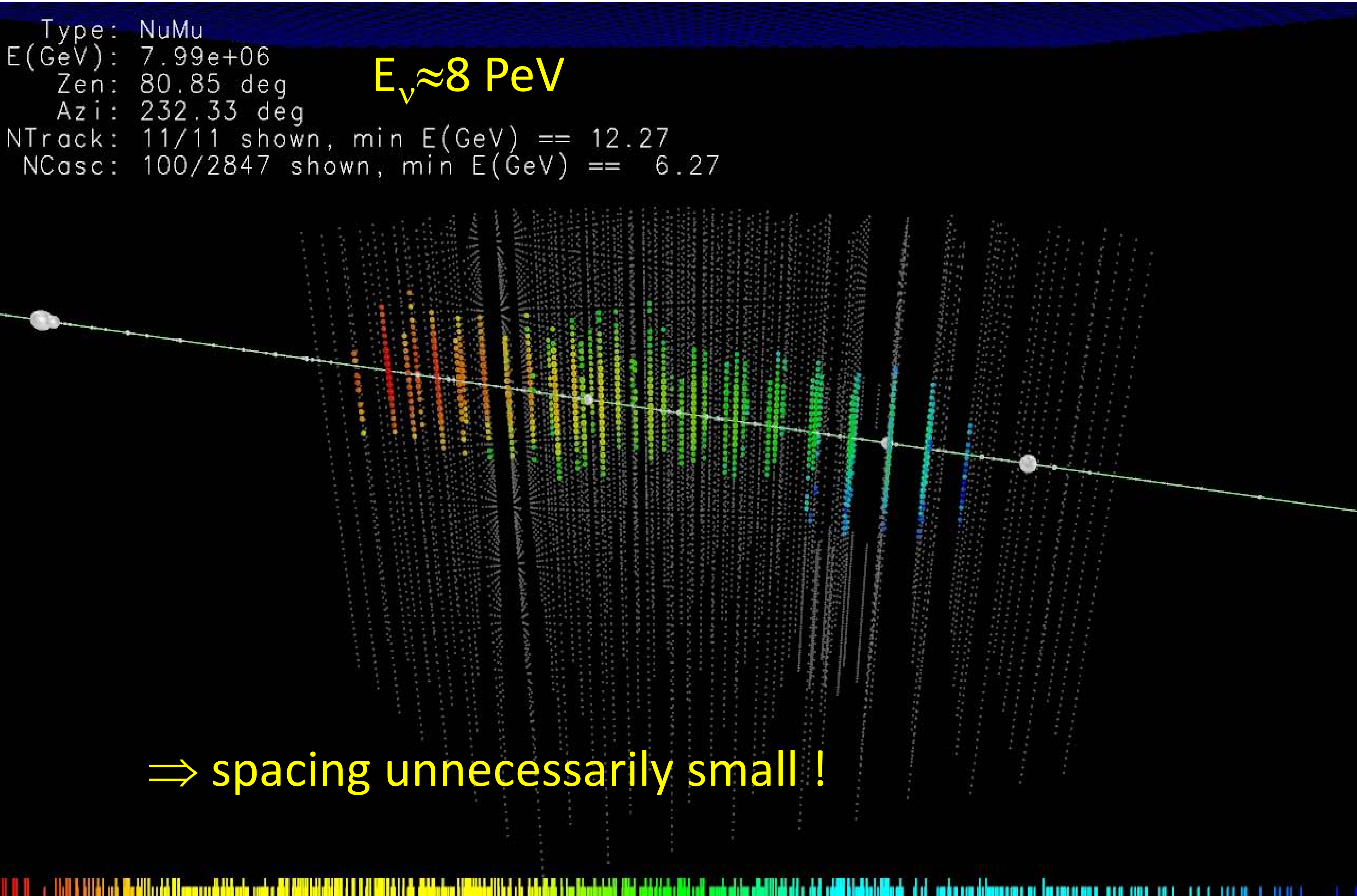
Spacing 3 (360m):
IceCube (1 km^3)
+ 95 strings (11,6 km^3)

= 12,6 km^3

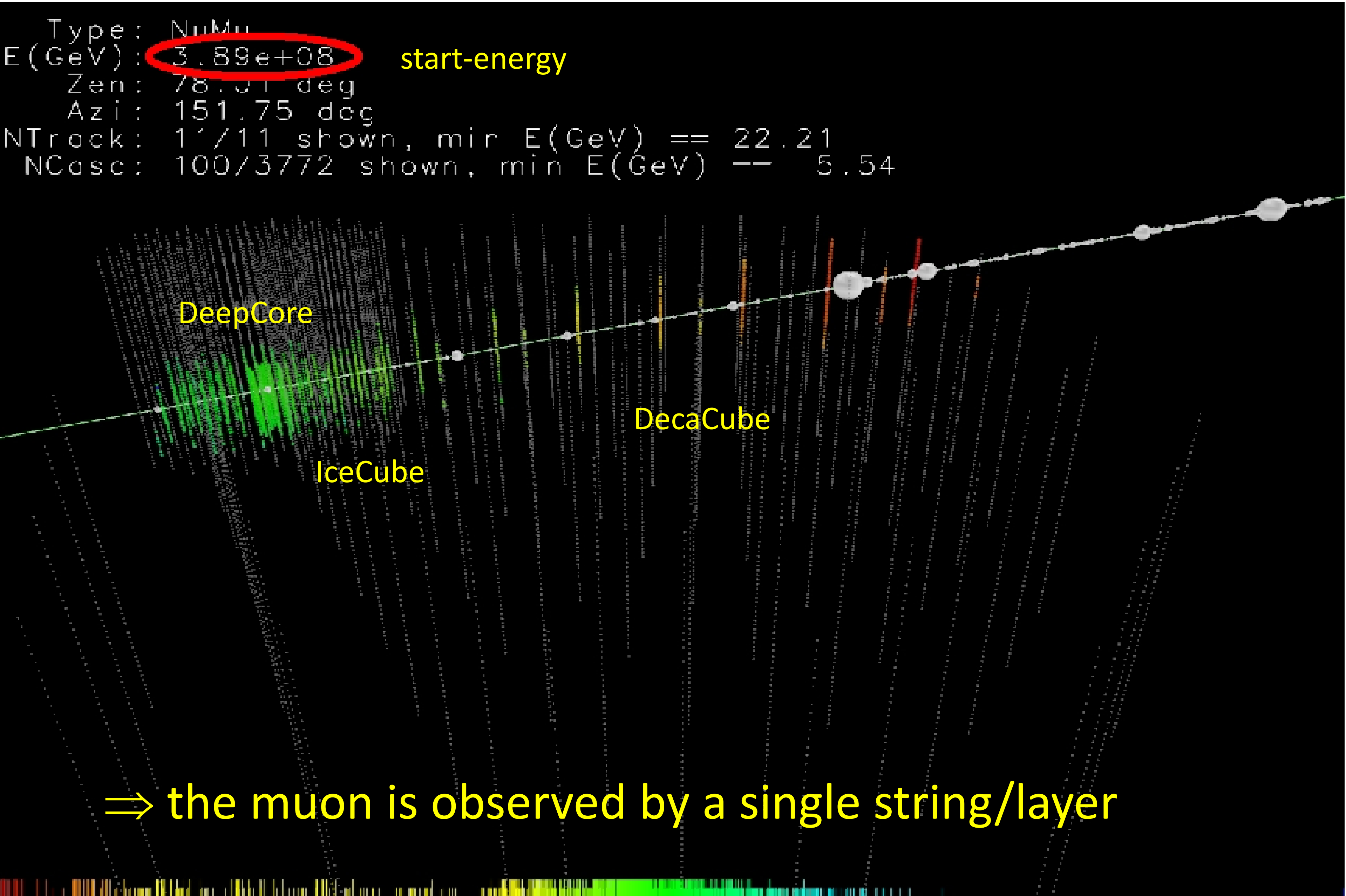
Chosen geometry not optimum (i.e. for HESE)

… historically chosen to demonstrate that we do respect boundary conditions

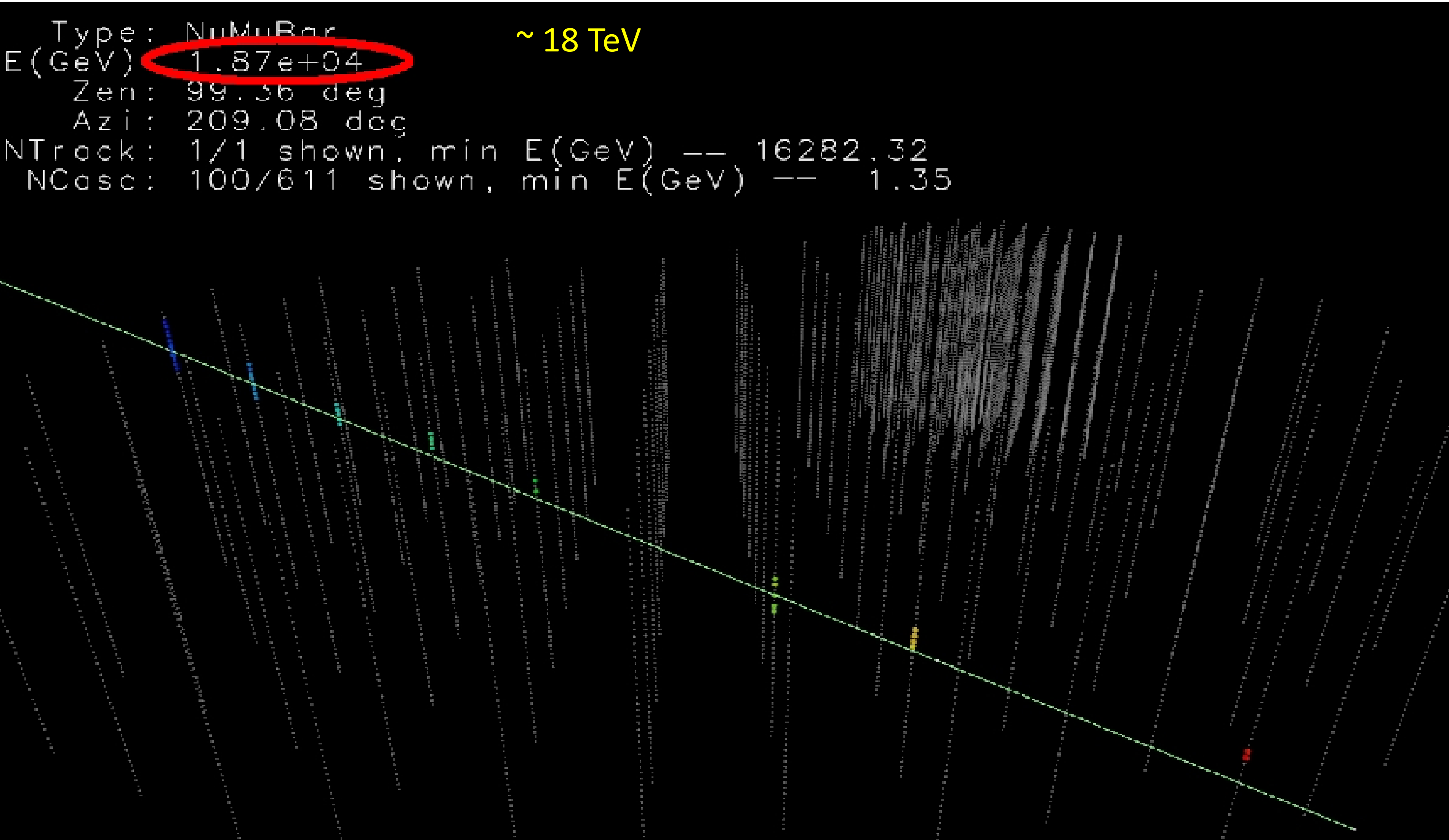
Spacing 1 – 120m



Spacing 3: 360m

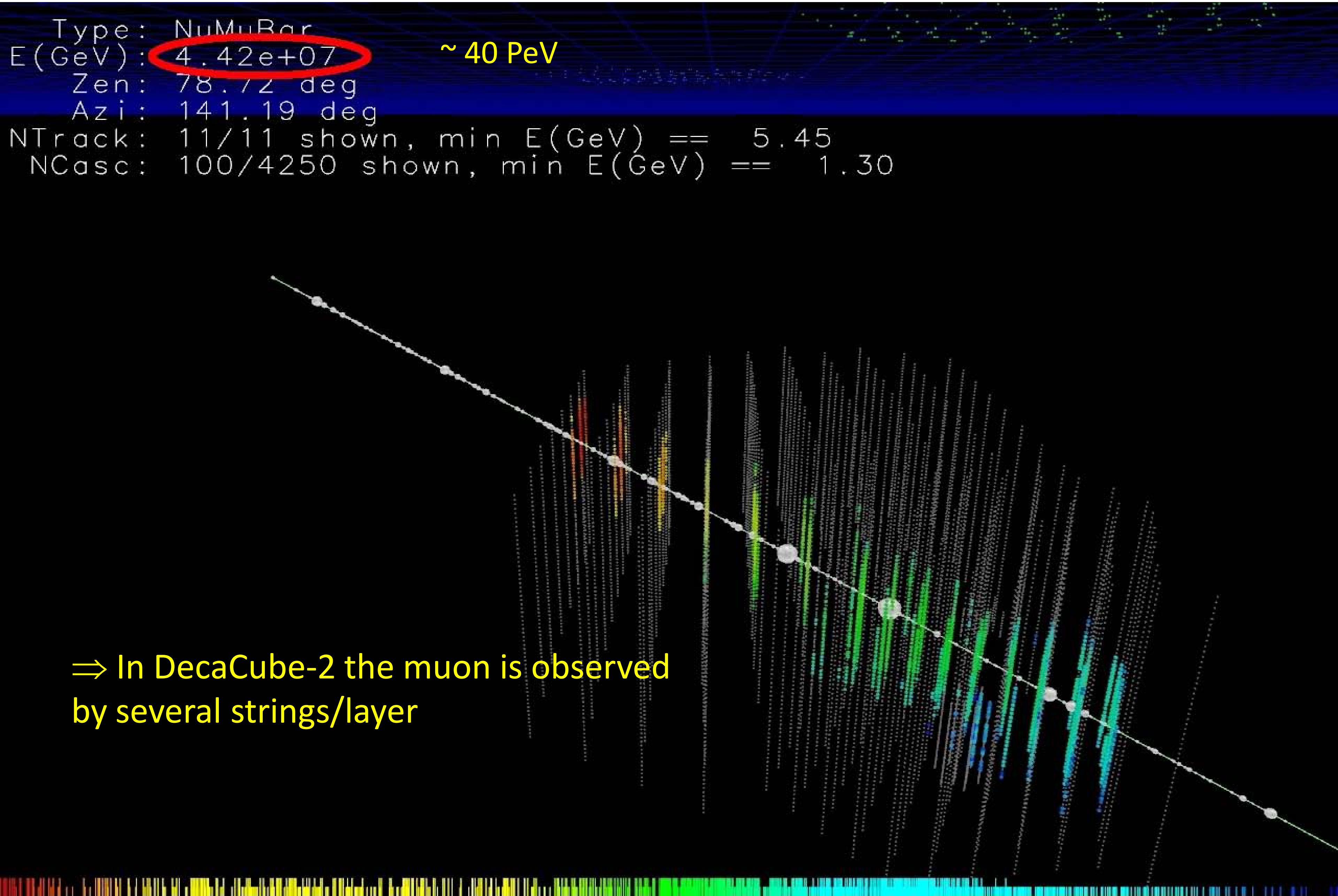


Spacing 3: 360m

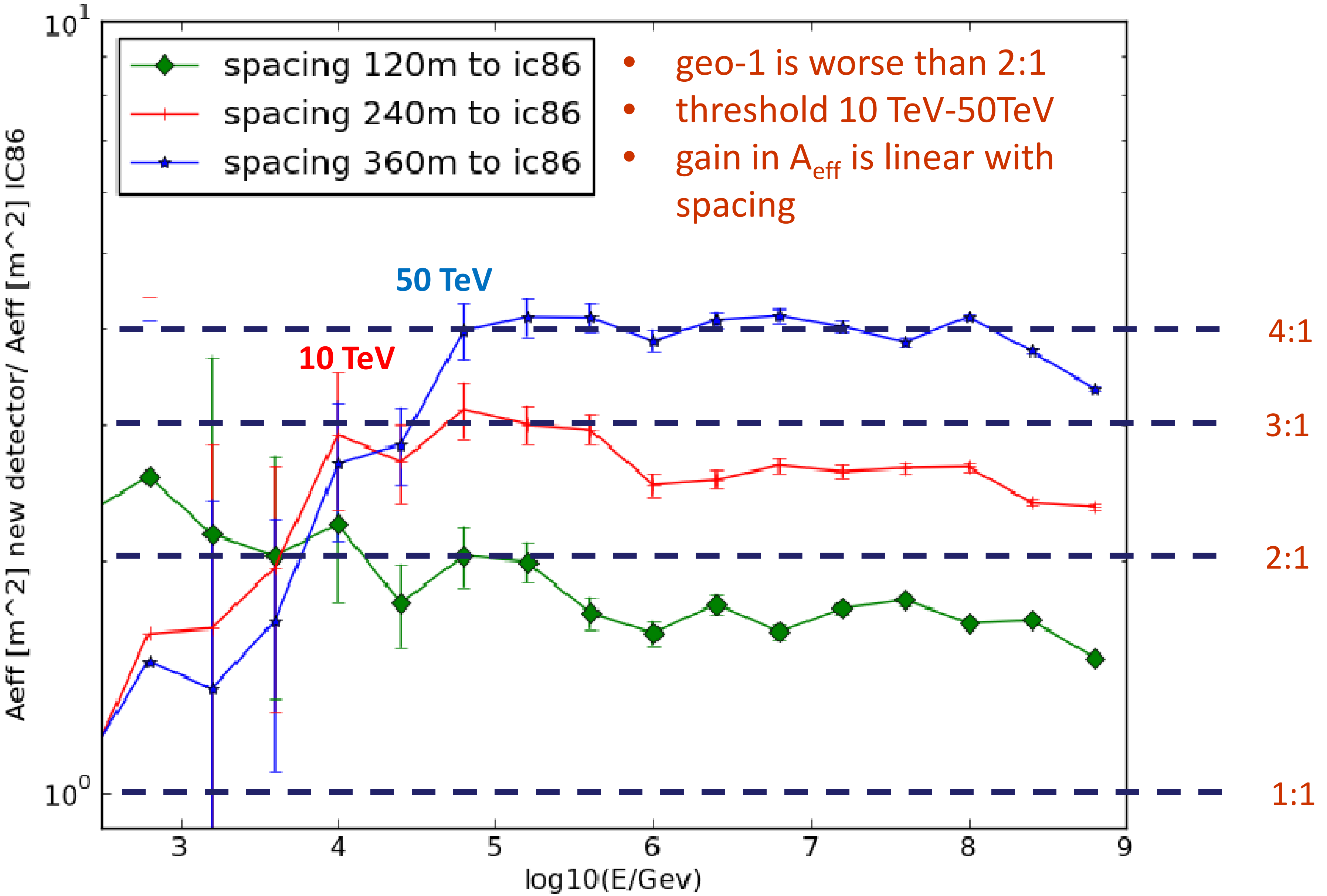


⇒ Even for large spacing the threshold will be of the order of a few 10 TeV (energy loss increases linearly)

Spacing 2

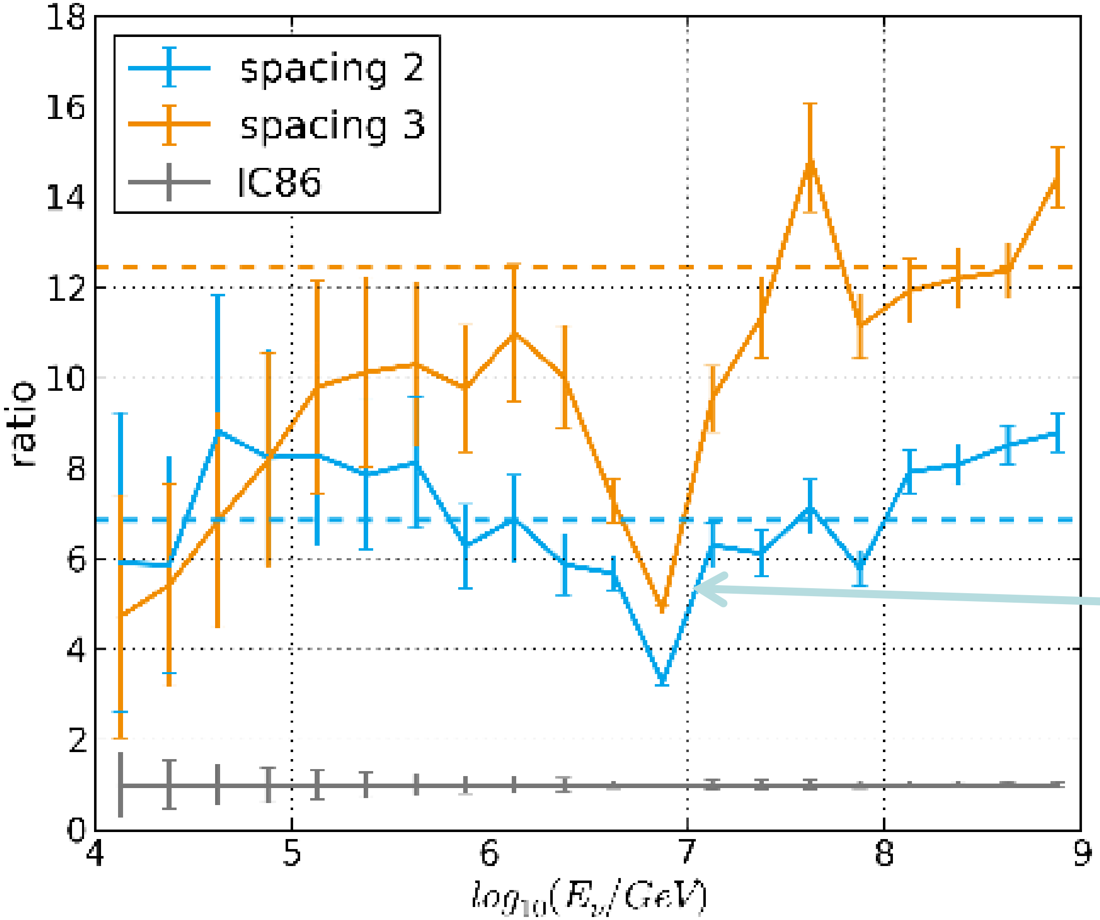

Type: NuMuBar
E(GeV): 4.42e+07
~ 40 PeV
Zen: 78.72 deg
Azi: 141.19 deg
NTrack: 11/11 shown, min E(GeV) == 5.45
NCasc: 100/4250 shown, min E(GeV) == 1.30
⇒ In DecaCube-2 the muon is observed by several strings/layer

Improvement Factor w.r. IceCube-86



- geo-1 is worse than 2:1
- threshold 10 TeV-50TeV
- gain in A_{eff} is linear with spacing

Cascades Improvement Factor w.r. IceCube-86



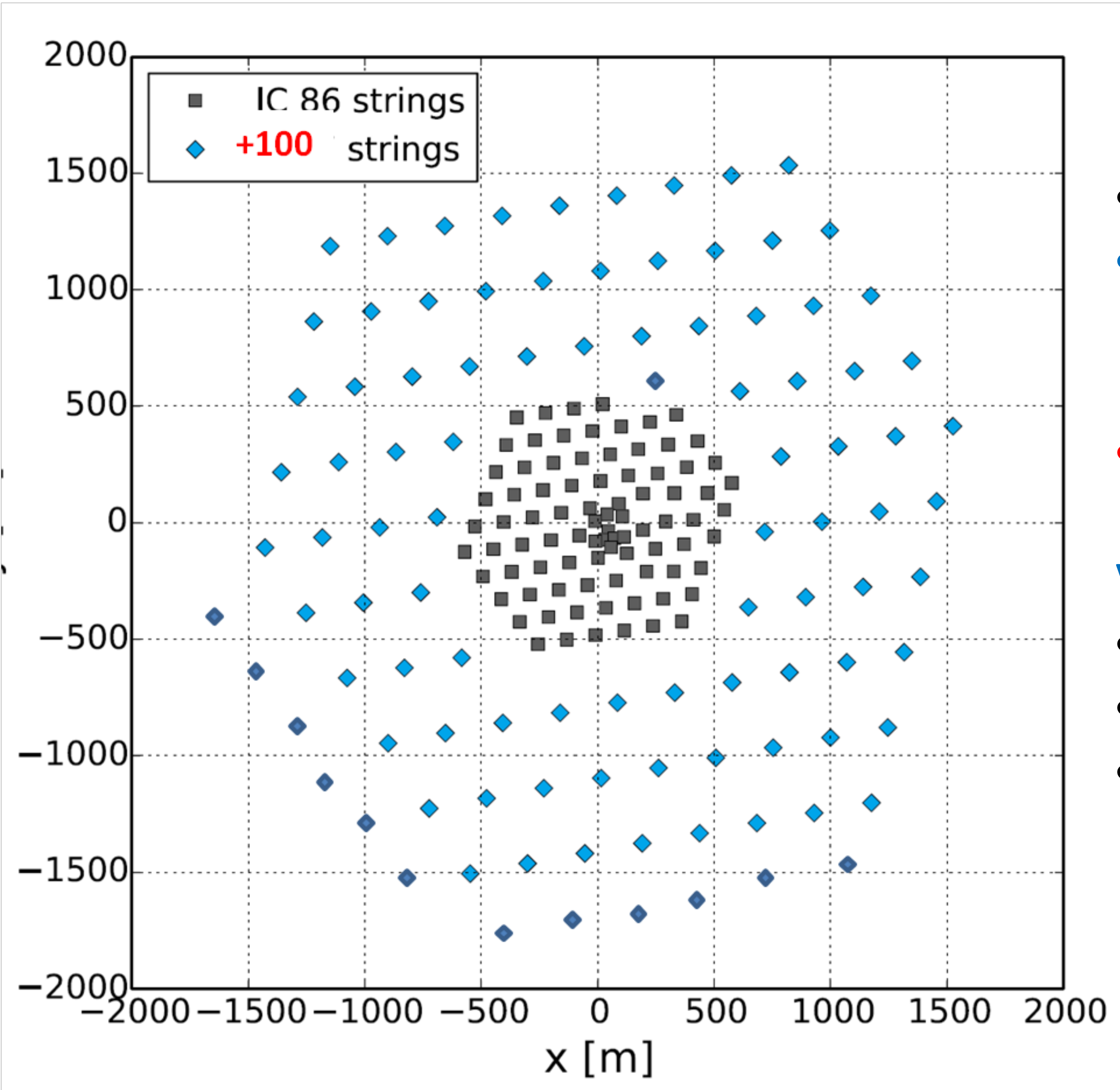
- Events contained
- Nchannel >= 15
- Nstring >= 3

Glashow resonance

- **Improvement ∝ Volume ∝ d²**
- **Large spacing fully effective only > 30 PeV**

Go for now with option 2

Symmetrical geometry (spacing 240m)

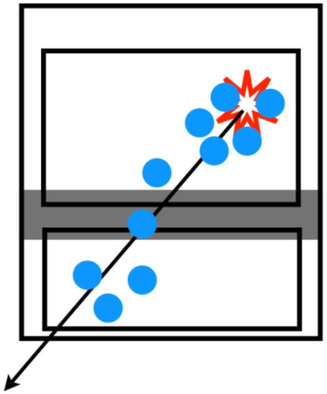


- +100 strings
- 4-3 layers of outer strings around IceCube
- ~7 km^3 volume

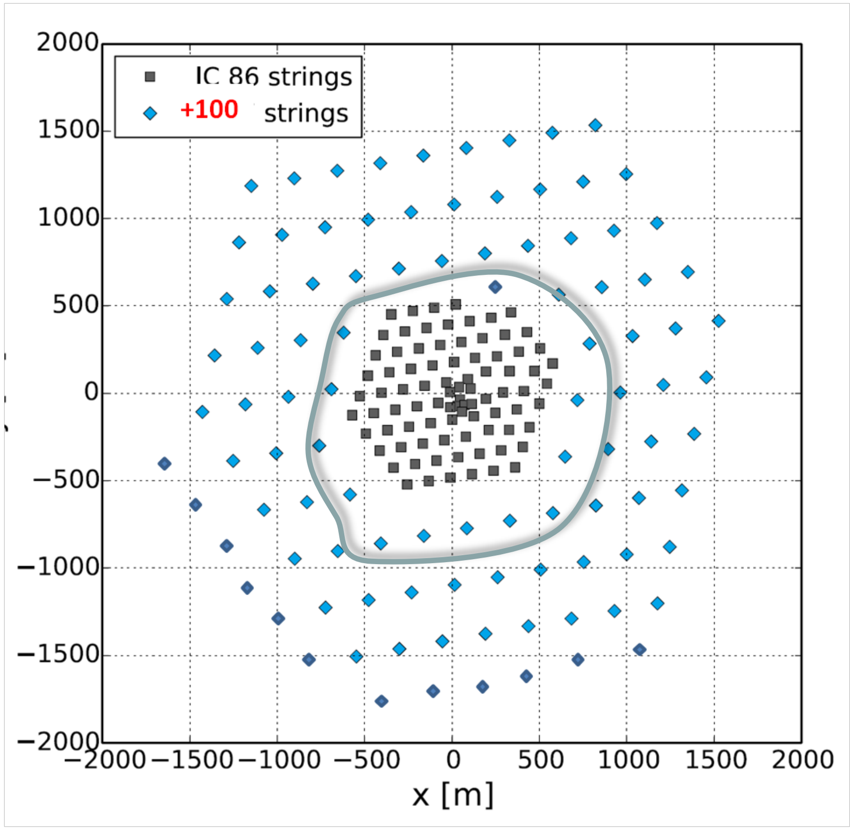
Version 2 result:

- Muons: 3x IC3
- Cascades : 7x IC3
- $E_{thresh} \lesssim 10$ TeV

Starting events estimation (A)



HESE volume
0.4 Gton



Outer strings improve veto :

- ✓ 3 outer layers more than sufficient
- ➢ Full IceCube volume can be used to the side - edges
- ➢ + 1 outer ring if 4 layers

Unidirectional DOMS & High QE PMT
-> better Veto !

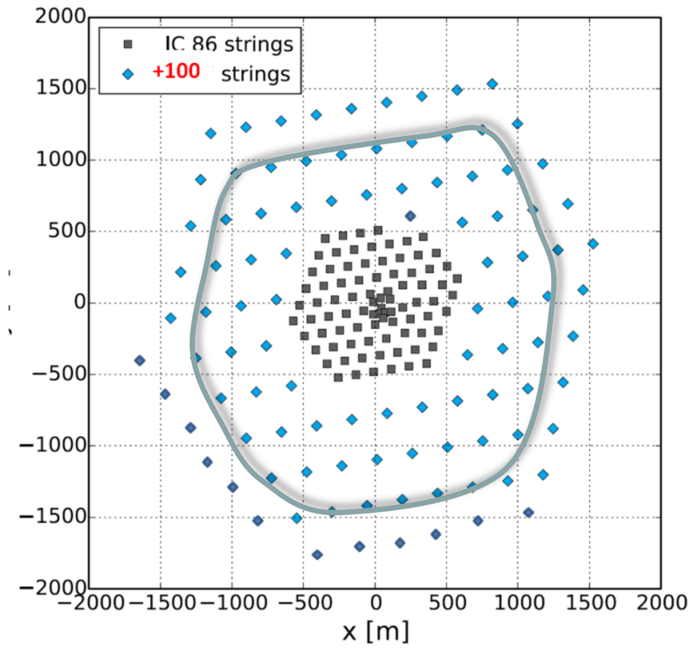
Config	eff. Vol. Gton	#events >30TeV /a
HESE	0.4	**14/a**
Full IC3	0.9	**31/a**
+ 1 Ring	1.4-1.8	**49-63 /a**

DecaCube strongly improves starting event capabilities

Starting events estimation (B)

Assume:

- One outer layer veto
 (but thicker Top Veto)
- atm. μ veto threshold increases with spacing
- No unidirectional DOMS & High QE PMT



➢ HESE volume can be extended if threshold is raised by factor ~2

Note that atmospheric neutrino BG (prompt/conventional) decrease

DecaCube will yield a high statistics Ernie&Bert sample

Config	Volume Gton	#events >60TeV /a	#events >200 TeV /a	#events > 1PeV /a
HESE	0.4	8	3	1
+ 1 outer veto ring	3-5	**60-100**	**22-37**	**7-12**

Ideal world: Surface veto

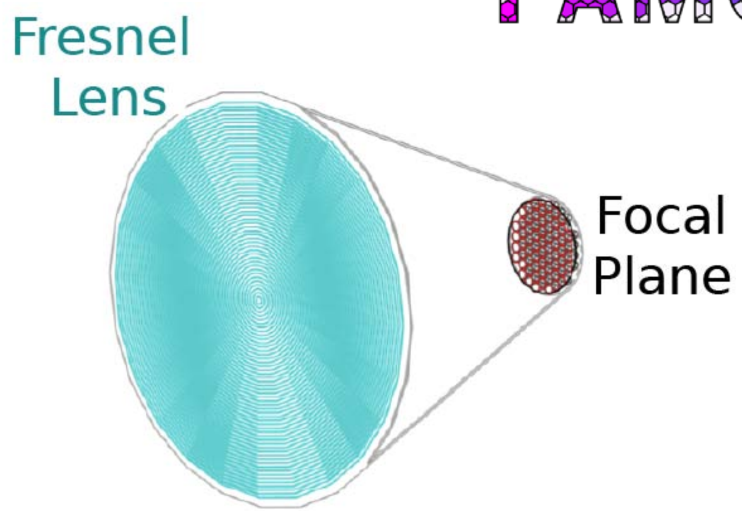
Extend IceTop (of course) but not possible to the most interesting horizontal regions

➢ Exploit (non-)imaging air Cherenkov technique

- New telescope concept FAMOUS for fluorescence detection

FAMOUS

- Silicon photo-mulitpliers



So where to now...

- Characterise astrophysical neutrino spectrum and search for point sources...
- Ice calibration
- Prompt neutrino component? To identify (will probably require combination of muon and neutrino spectrum)
- A bigger detector