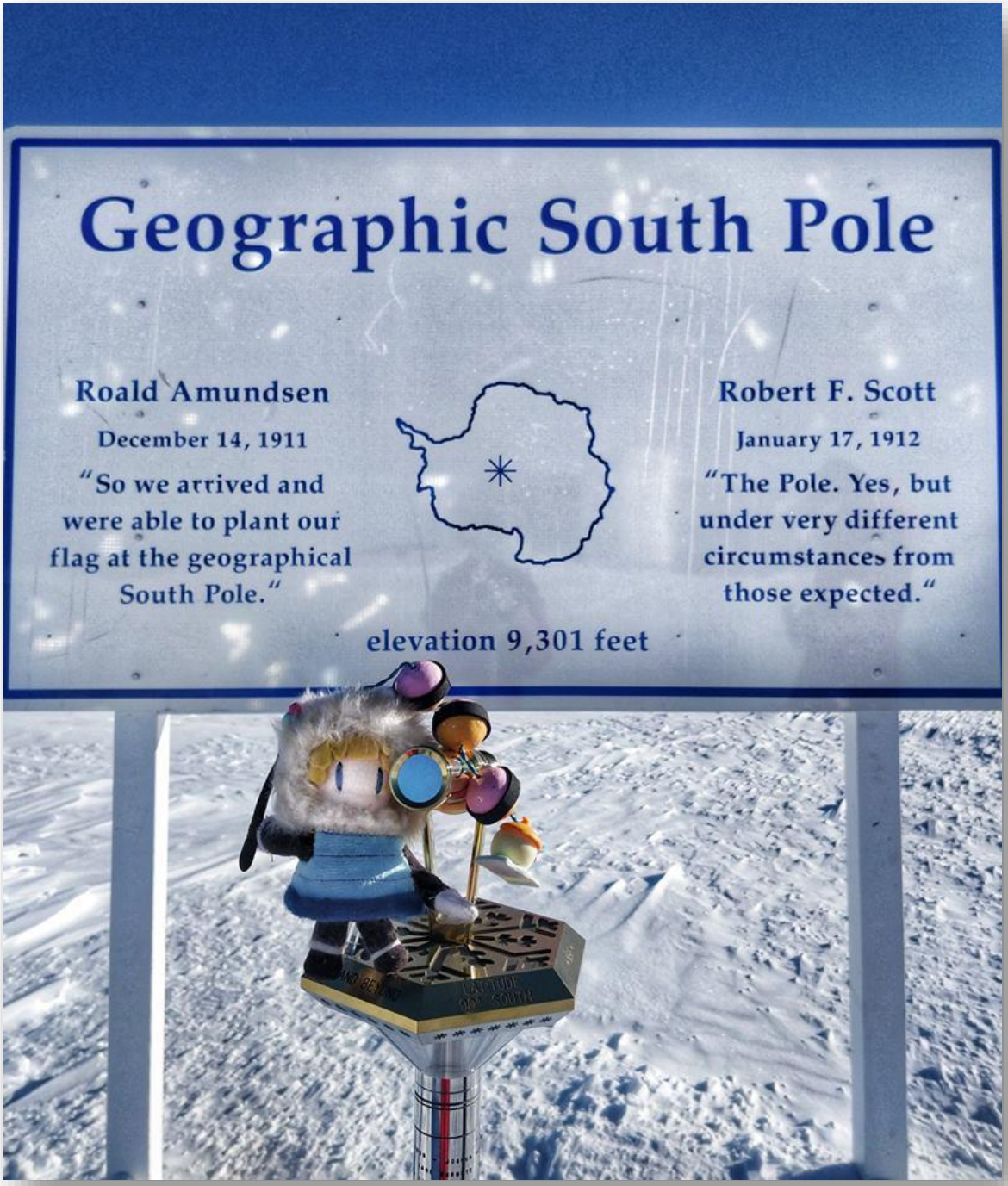
High Energy **tau** neutrino detections with IceCube

Lu Lu

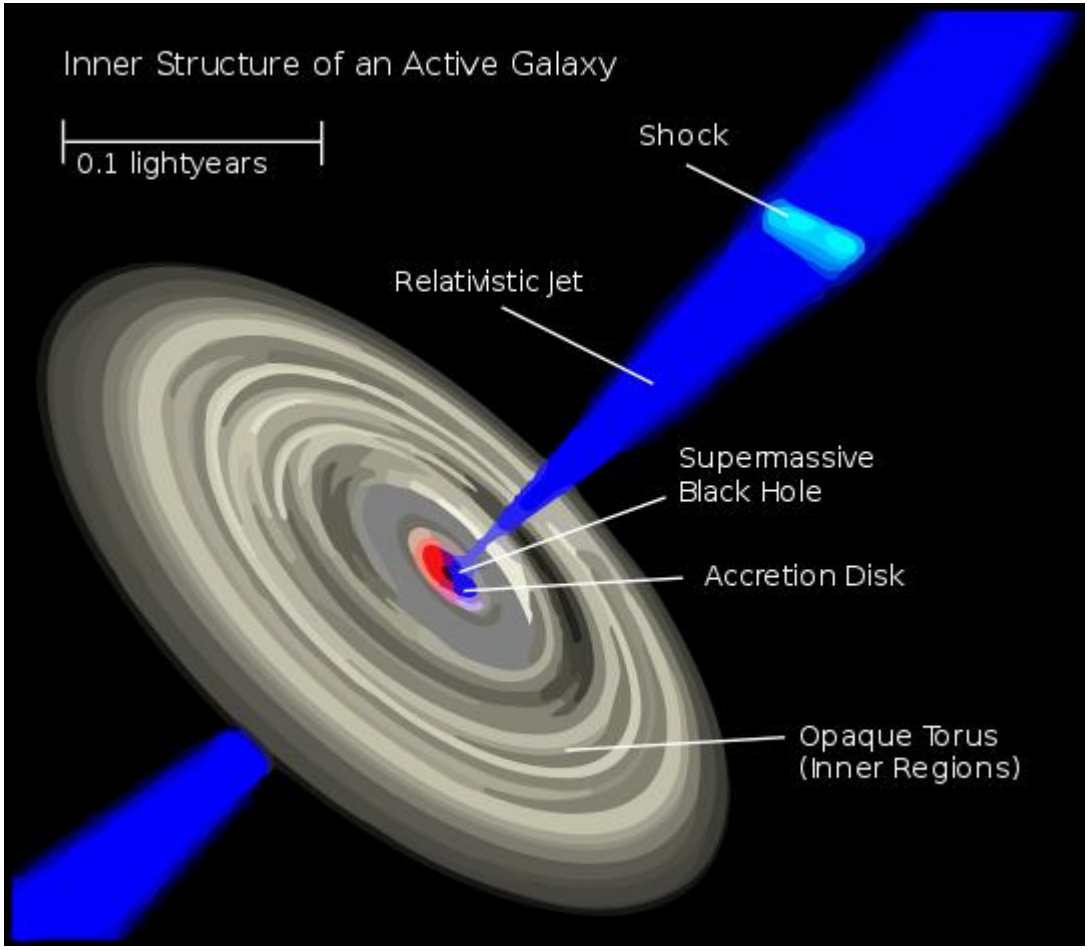


千葉大学
CHIBA UNIVERSITY

IceCube

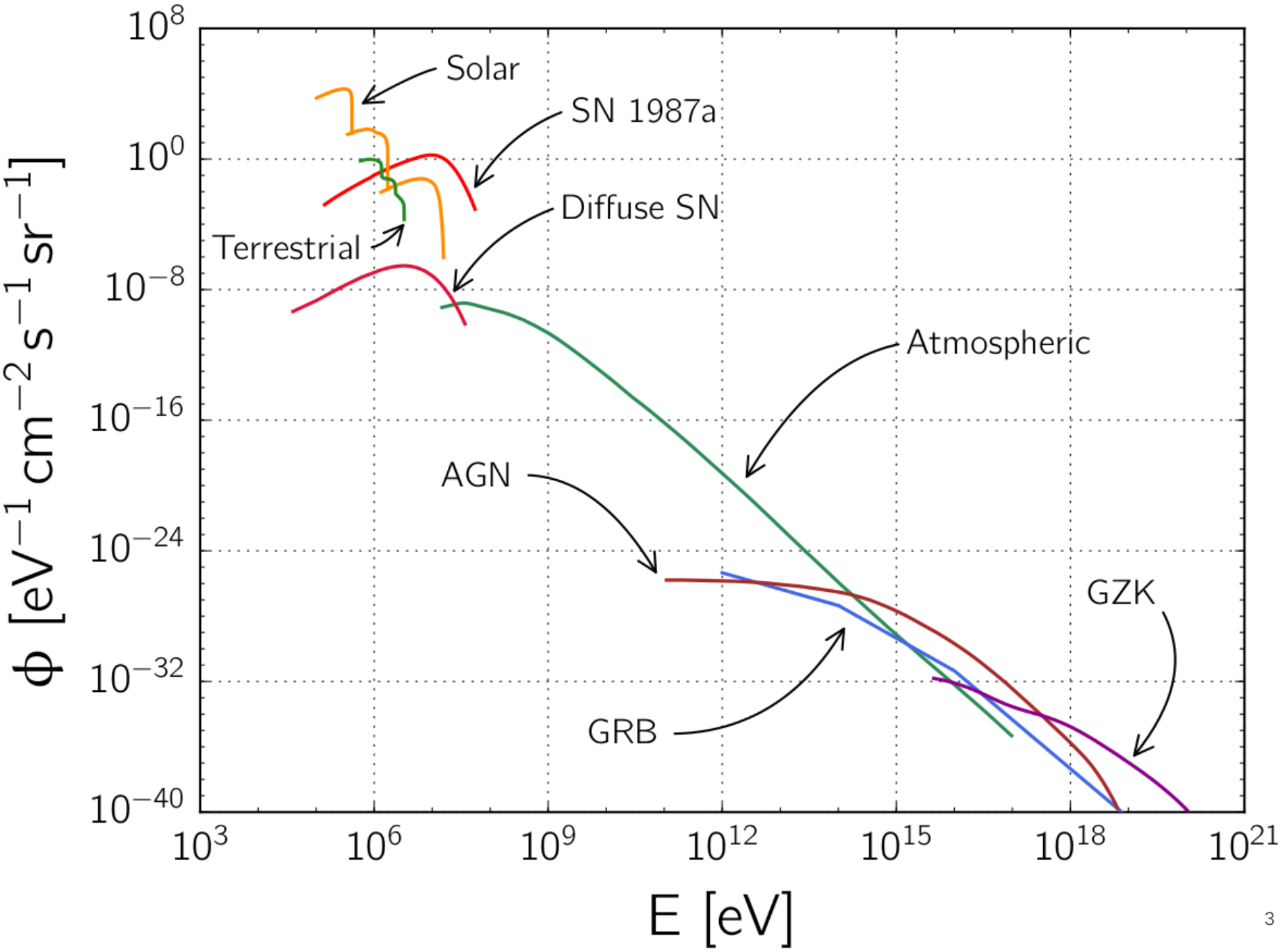
Extreme-High Energy accelerators from Nature

AGN, blazar, GRB, FRB, Hypernova, galaxy clusters...



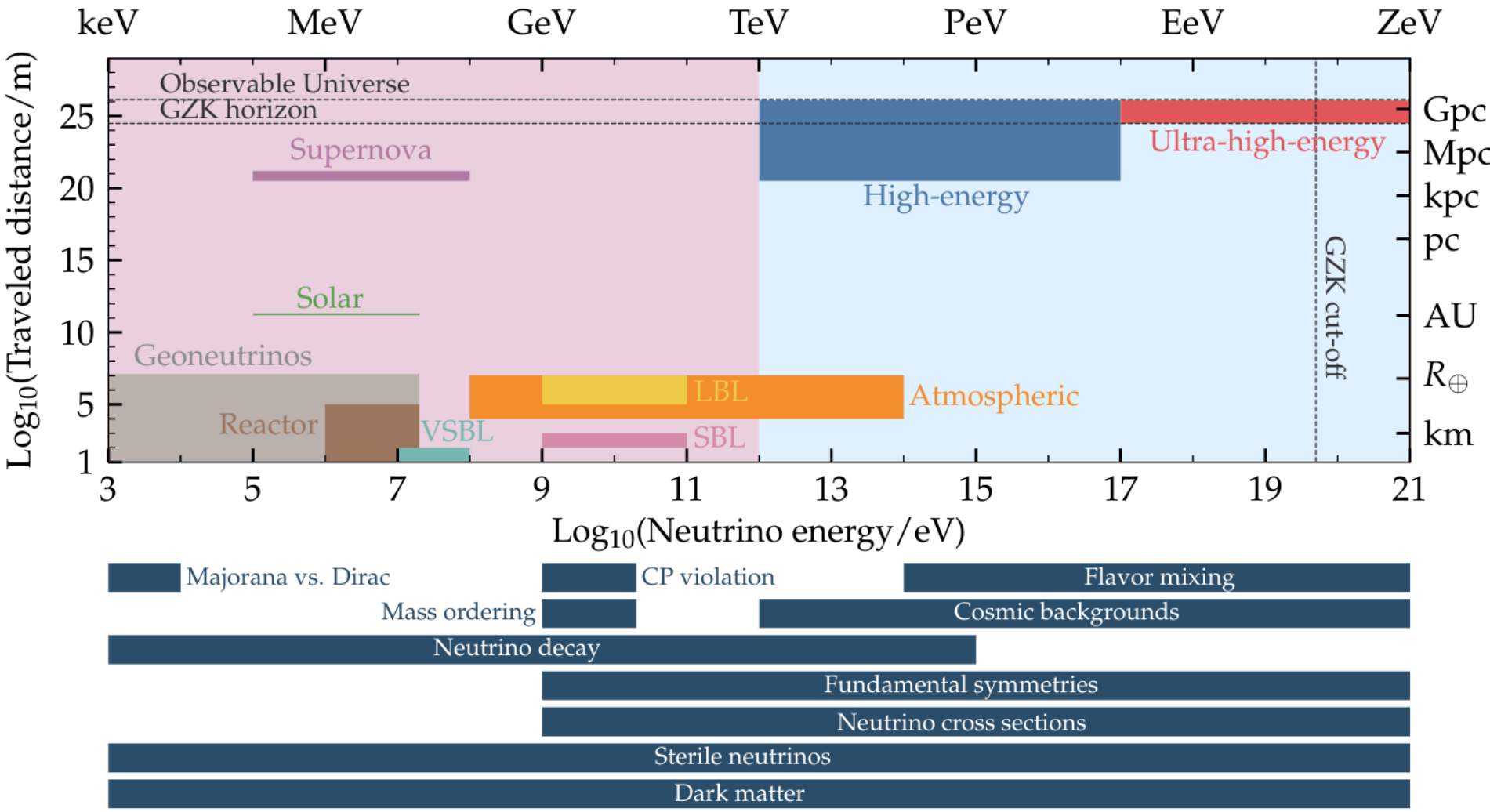
M87 jet
A beam with ~kpc

Images from wikipedia

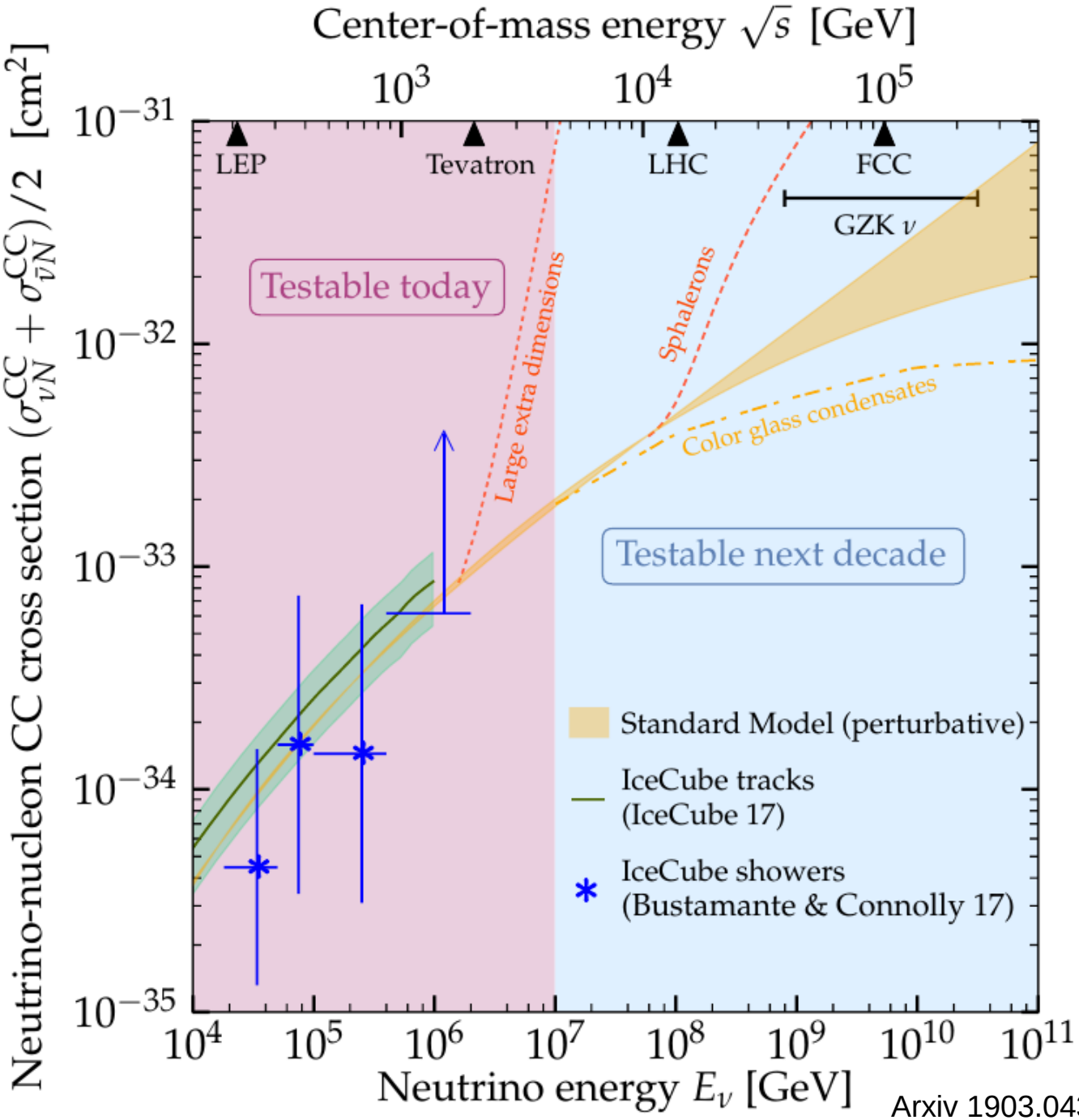

Solar
SN 1987a
Diffuse SN
Terrestrial
Atmospheric
AGN
GZK
GRB
Φ [eV^{-1} cm^{-2} s^{-1} sr^{-1}]
E [eV]
10^{8}
10^{0}
10^{-8}
10^{-16}
10^{-24}
10^{-32}
10^{-40}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}
10^{21}

「ニュートリノで拓く素粒子と宇宙」

High energy neutrinos:
cosmological baselines

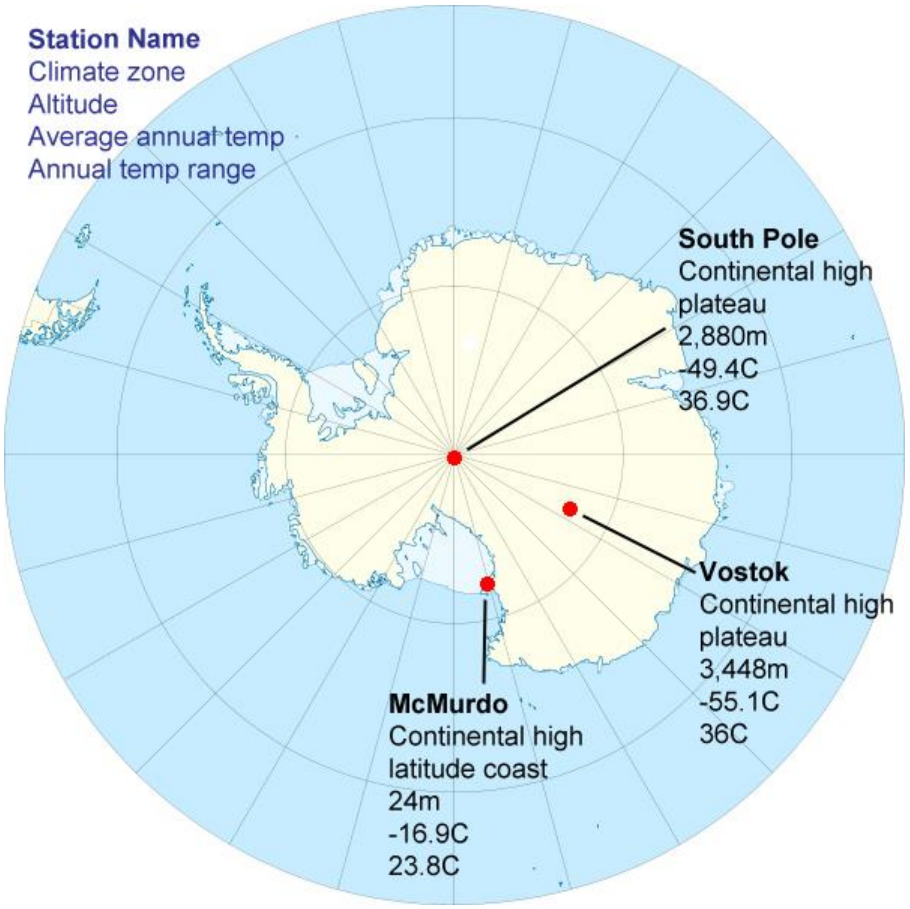


Arxiv 1903.04333v1



Arxiv 1903.04333v1

Trip to the bottom of the world



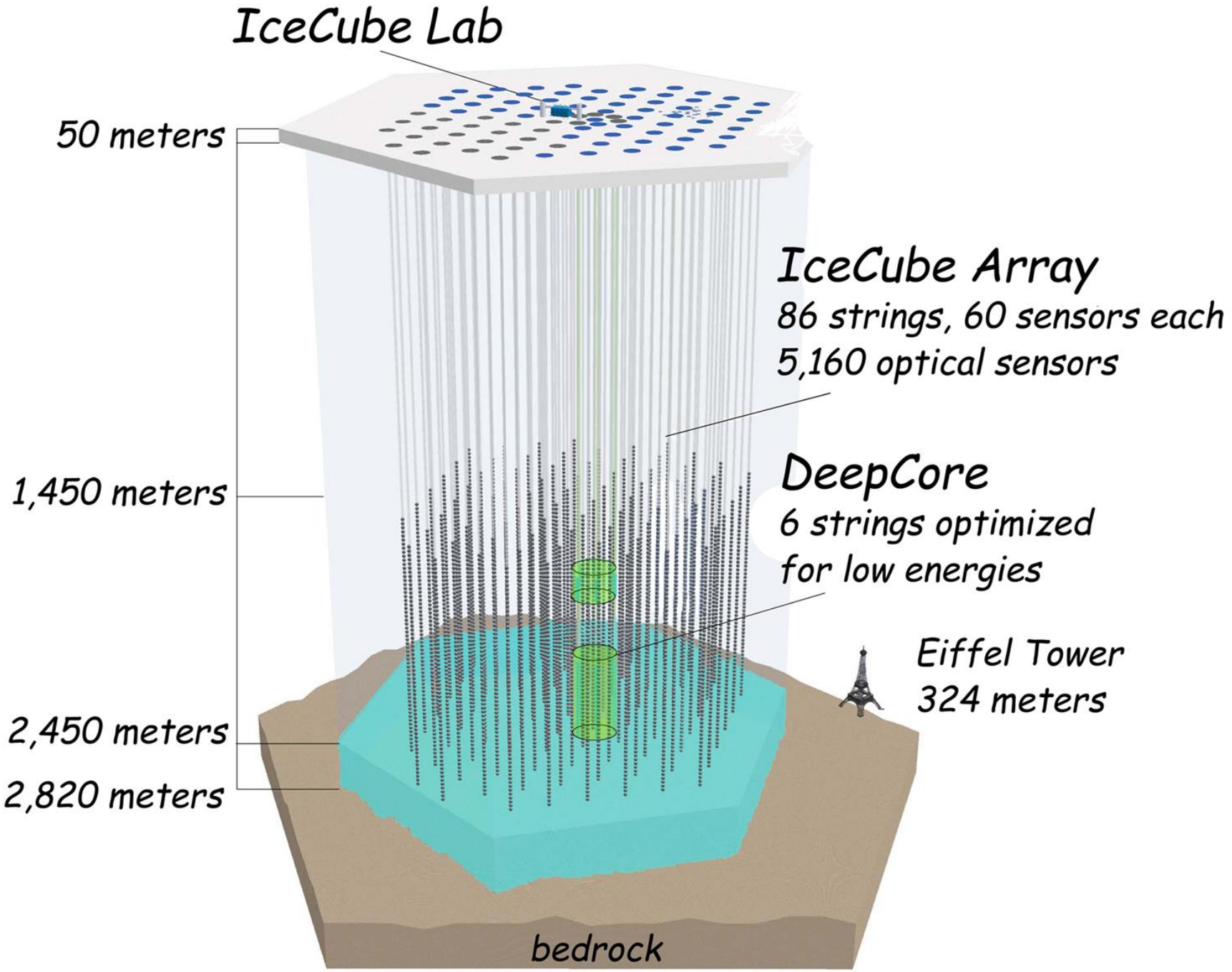
South Pole Station Weather

May 4, 2019 8:10 PM UTC

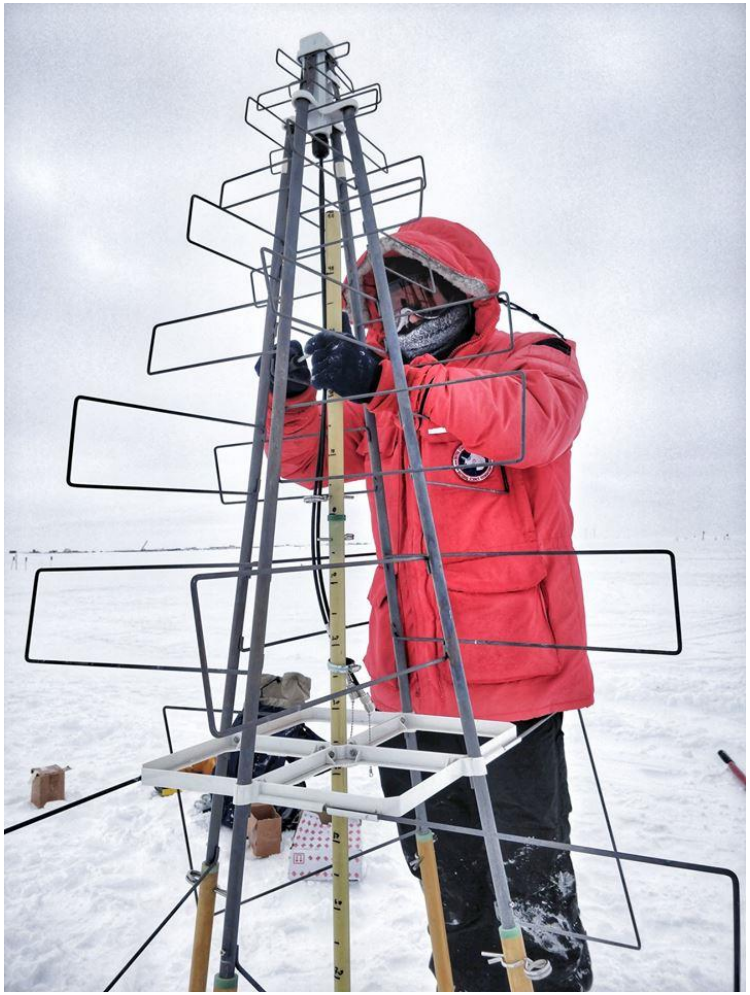
Temperature	-52° C	-62° F
Wind Chill	-74° C	-102° F
Wind Speed	17 knots	
Air Pressure	689 millibars	

Equivalent more than 3000 m

南極点
90 degree South

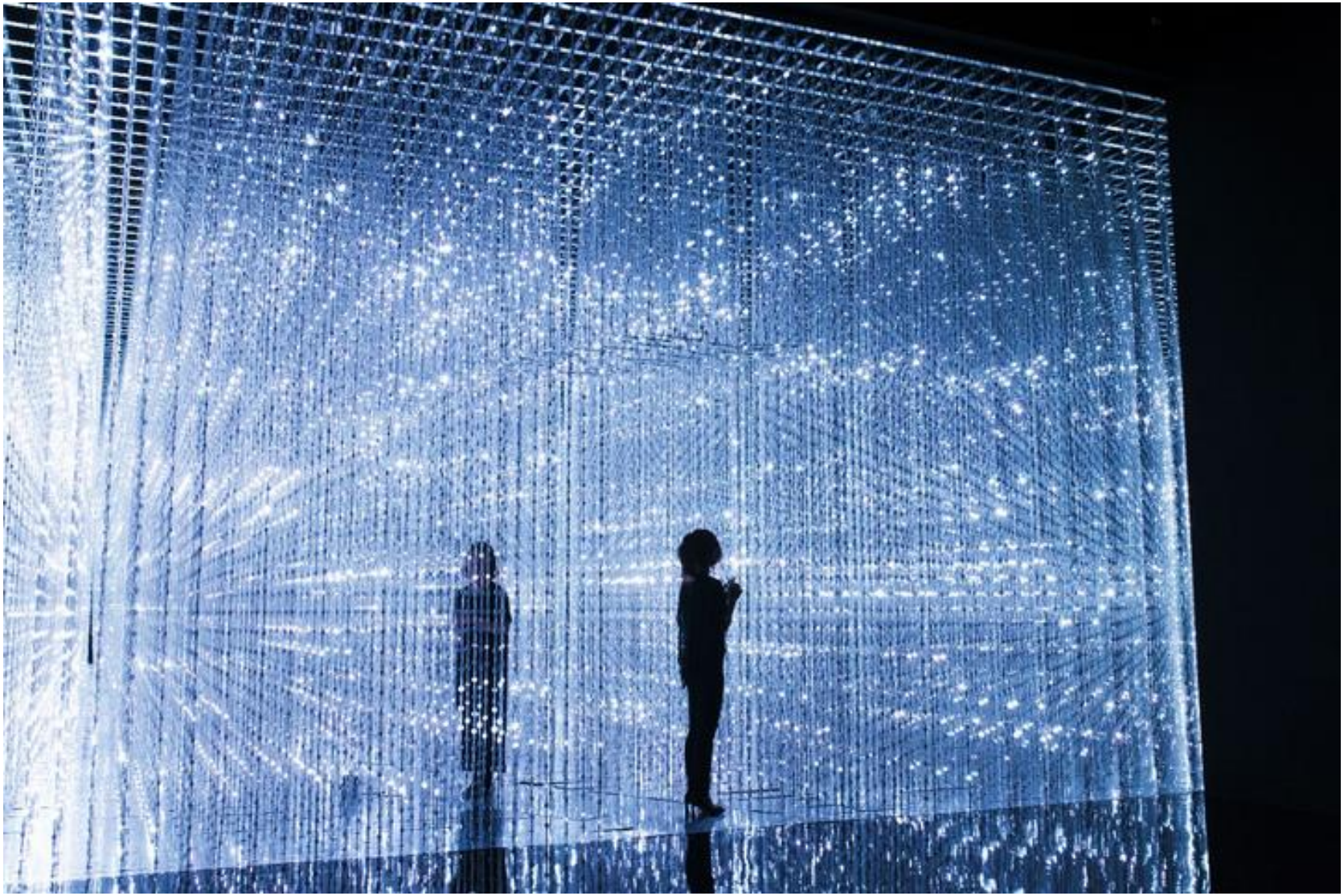

IceCube Lab
50 meters
IceCube Array
86 strings, 60 sensors each
5,160 optical sensors
1,450 meters
DeepCore
6 strings optimized
for low energies
Eiffel Tower
324 meters
2,450 meters
2,820 meters
bedrock

Show some pictures of southpole



A smaller version of ‘IceCube’ in Tokyo...

https://www.teamlab.art/w/crystaluniverse



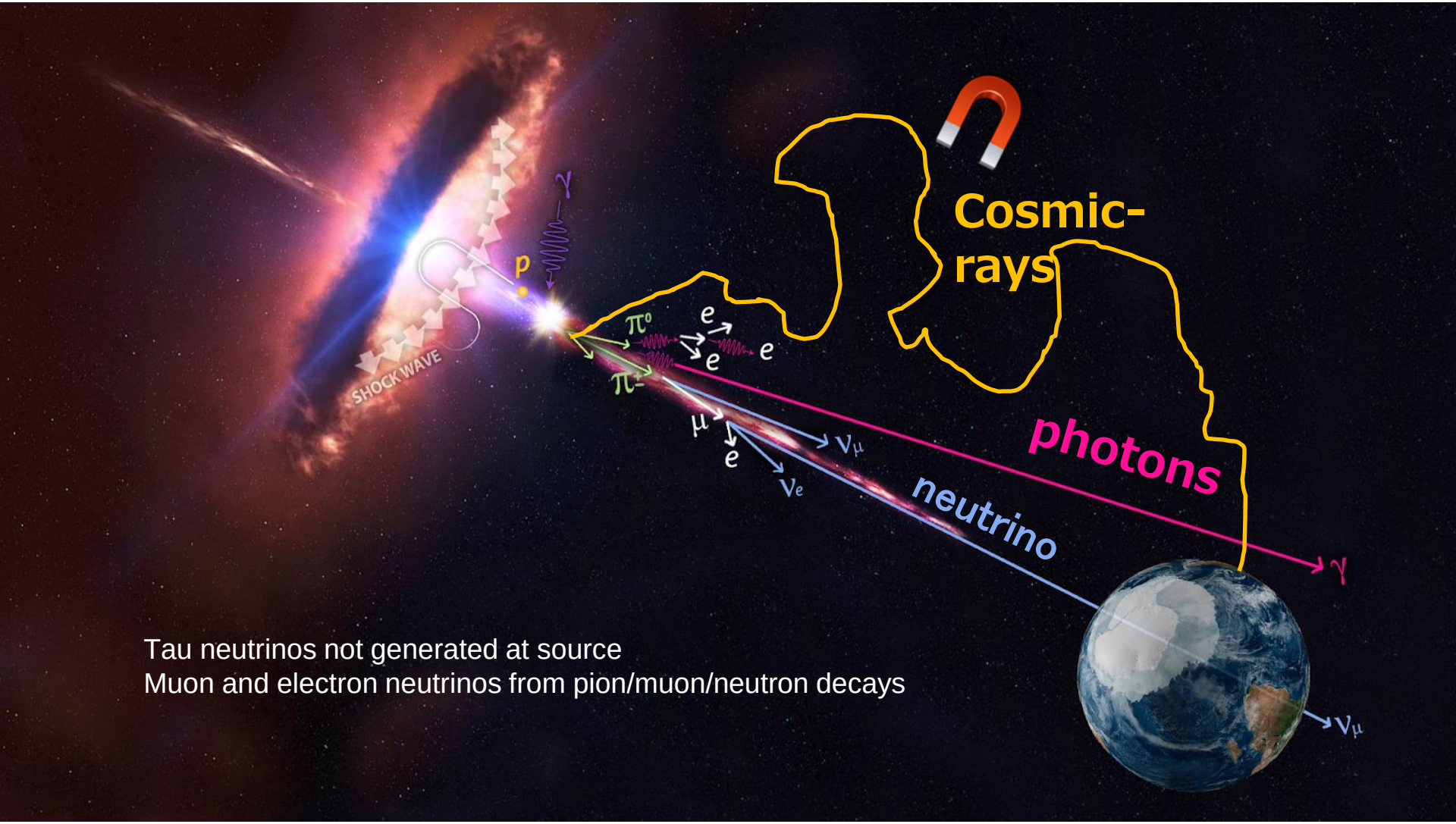
Discoveries by IceCube

- **Astrophysical neutrinos >200 TeV**
  - **Cross-section measurement at nu energy beyond accelerators**
- **First possible nu source TXS0506+056 (blazar)**
- **First Glashow resonance detection**
  - **First tau neutrino candidate [this talk]**

Future

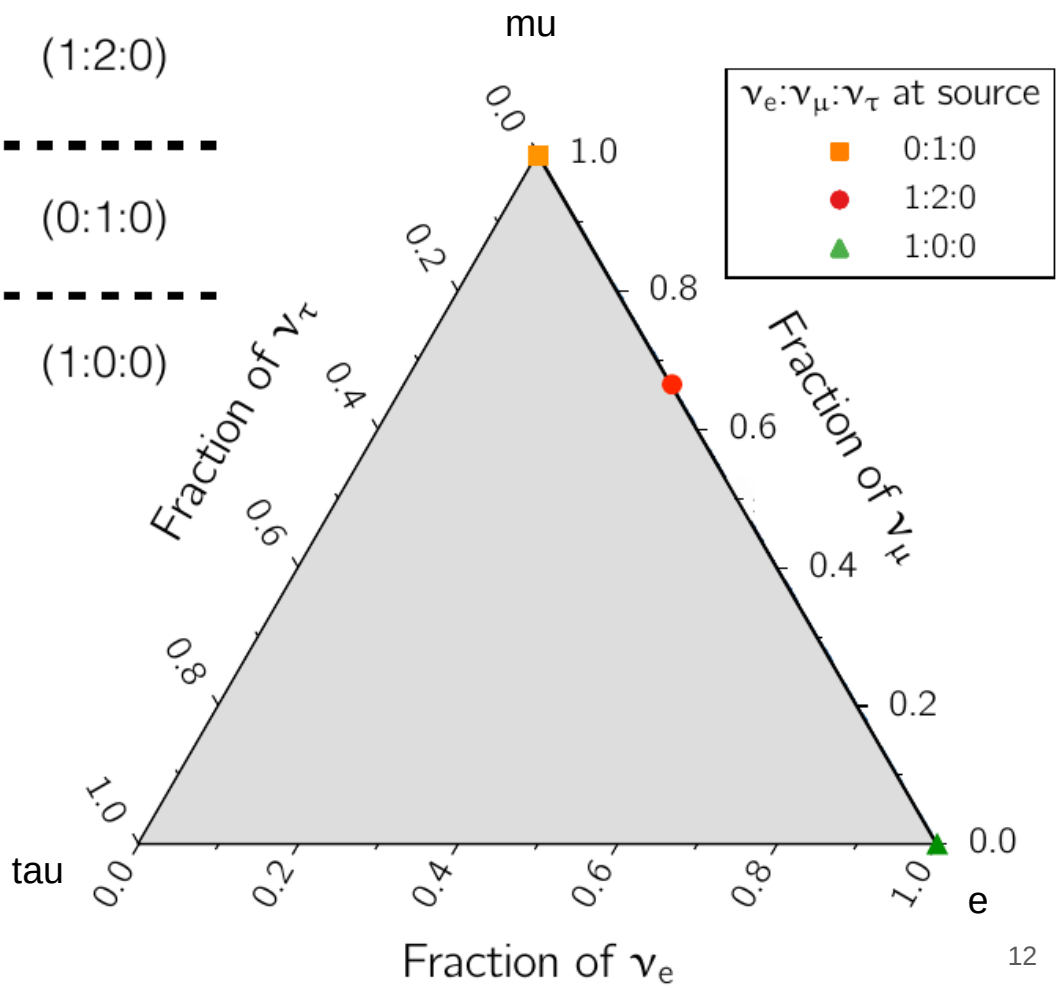
- Where are most of neutrinos from? (diffuse source)
- Related to UHECR sources? Acceleration mechanism?
- Cosmogenic neutrinos?
- Galactic neutrinos?
- Charm from atmospheric nu?
- ...

Neutrinos as ideal cosmic messenger



Tau neutrinos not generated at source
Muon and electron neutrinos from pion/muon/neutron decays

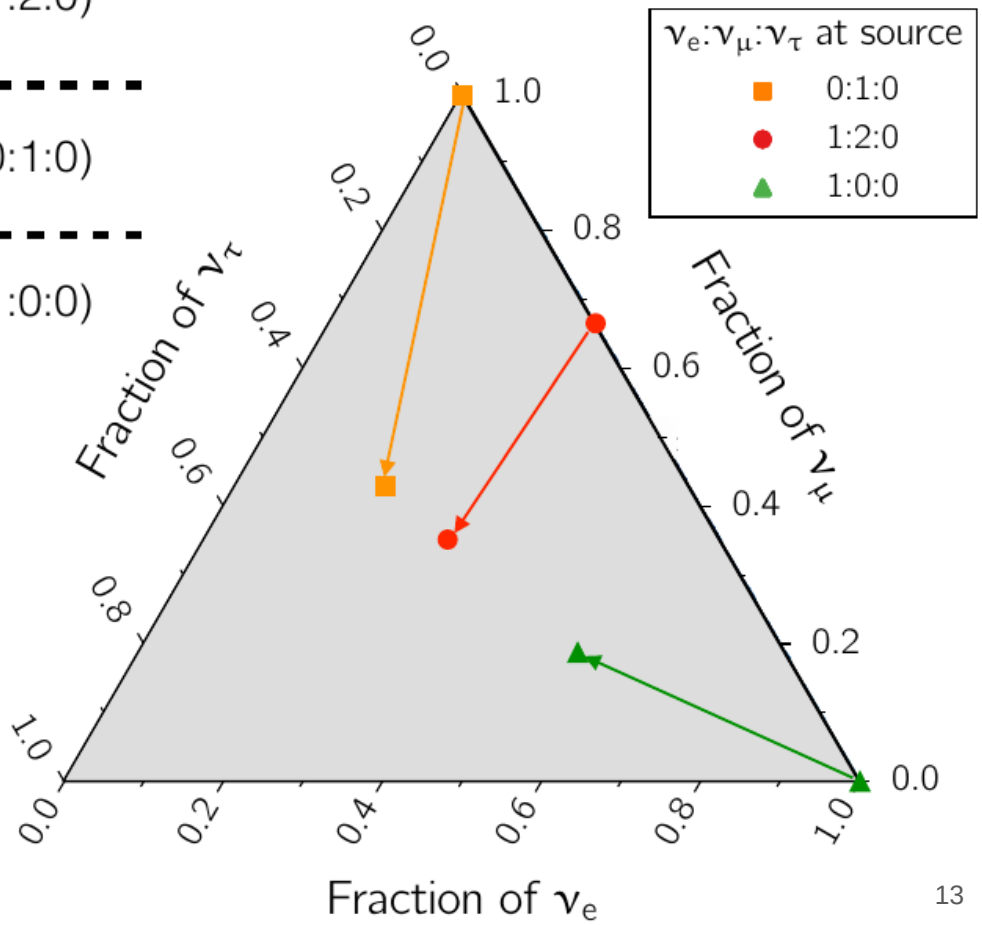
Cosmic particle accelerator	$\nu_e:\nu_\mu:\nu_\tau$
Pion decay $\pi^+ \to \mu^+ + \nu_\mu$ $\downarrow$ $\mu^+ \to e^+ + \nu_\mu + \bar{\nu}_e$	(1:2:0)
Muon-damped $\pi^+ \to \cancel{\mu^+} + \nu_\mu$	(0:1:0)
Neutron decay $n \to p + e^- + \bar{\nu}_e$	(1:0:0)



https://en.wikipedia.org/wiki/Ternary_plot

Courtesy to Stachurska

Cosmic particle accelerator		$\nu_e:\nu_\mu:\nu_\tau$
Pion decay	$\pi^+ \to \mu^+ + \nu_\mu$ $\mu^+ \to e^+ + \nu_\mu + \bar{\nu}_e$	(1:2:0)
Muon-damped	$\pi^+ \to \cancel{\mu^+} + \nu_\mu$	(0:1:0)
Neutron decay	$n \to p + e^- + \bar{\nu}_e$	(1:0:0)



Courtesy to Stachurska

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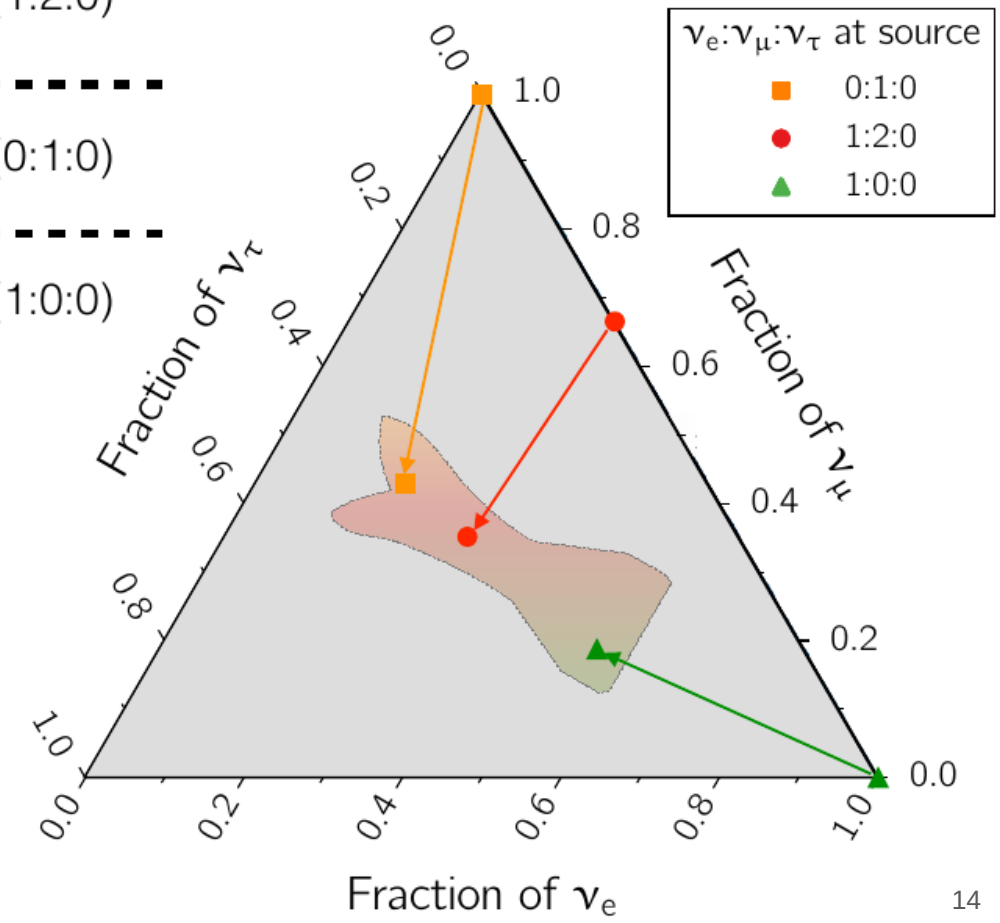
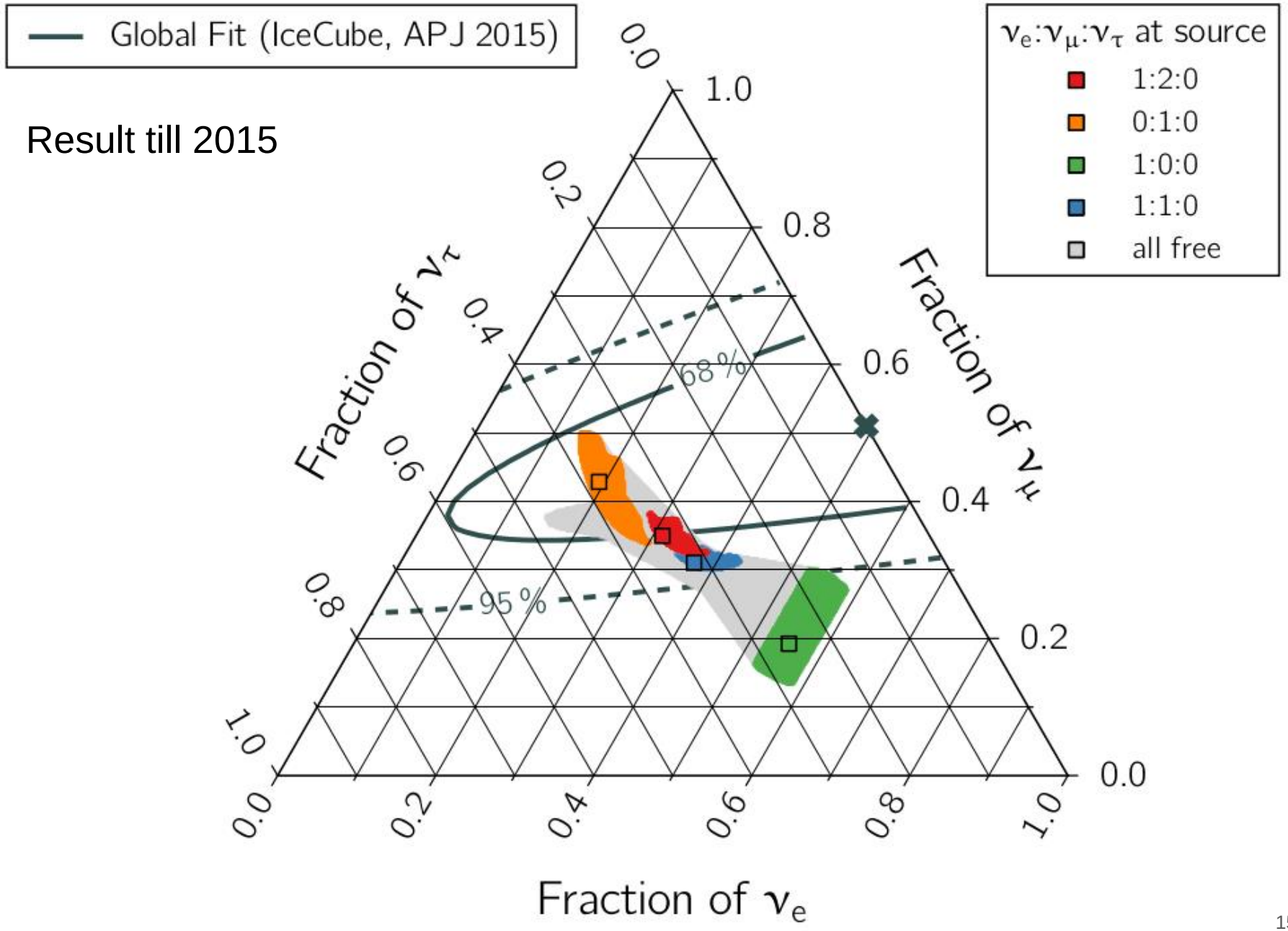
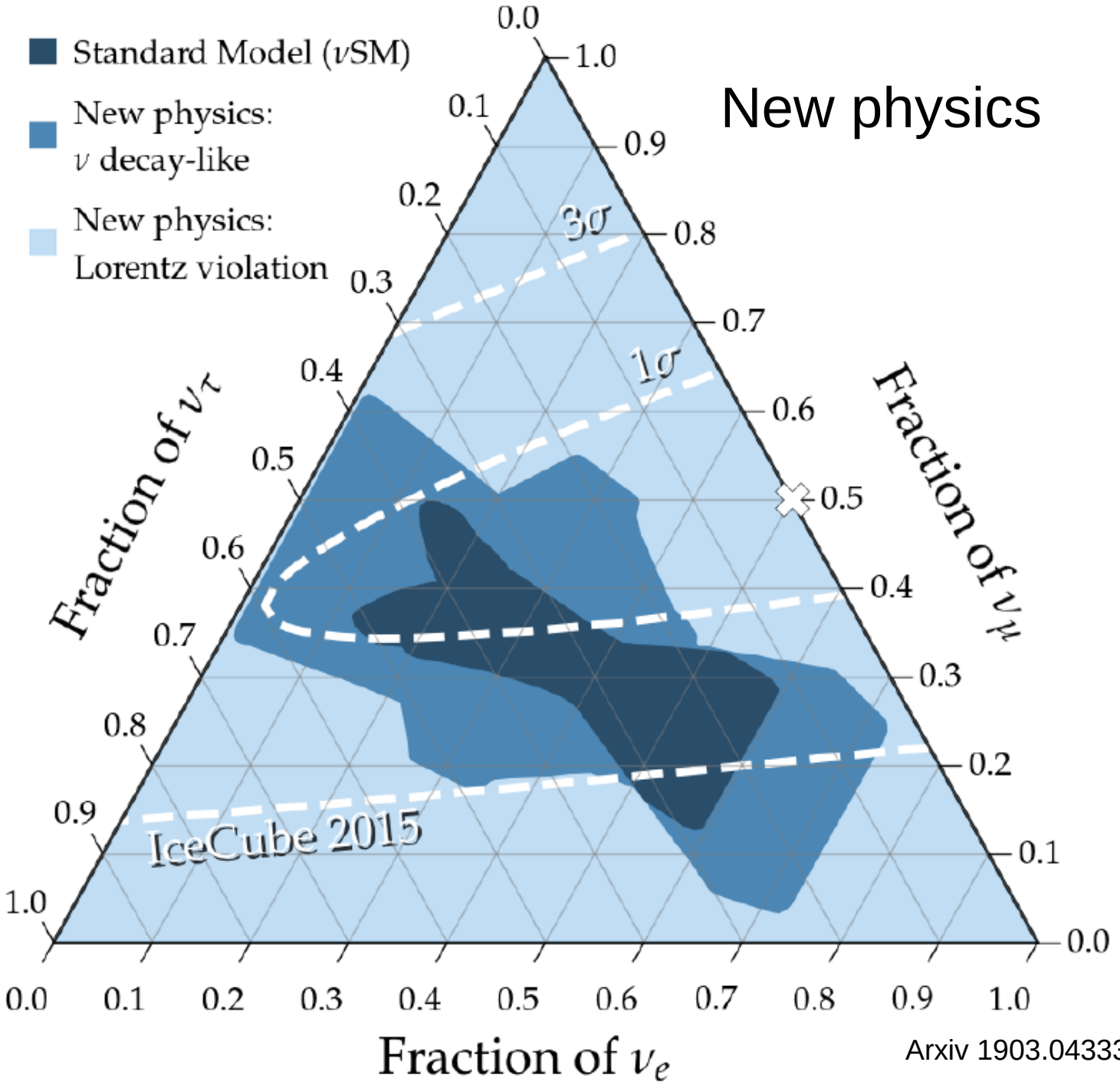


Courtesy to Stachurska

Result till 2015

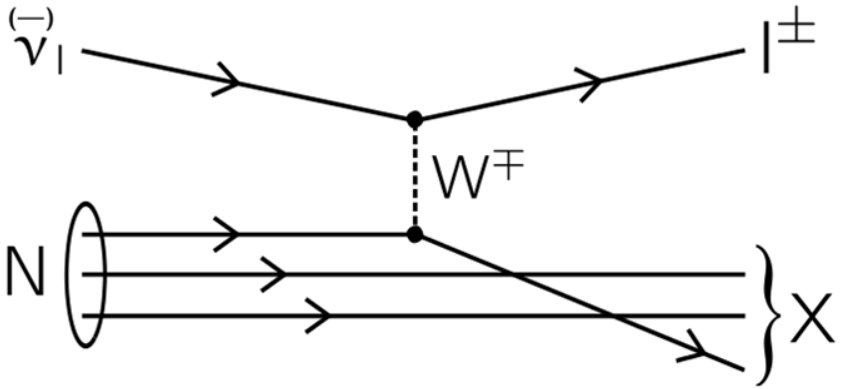


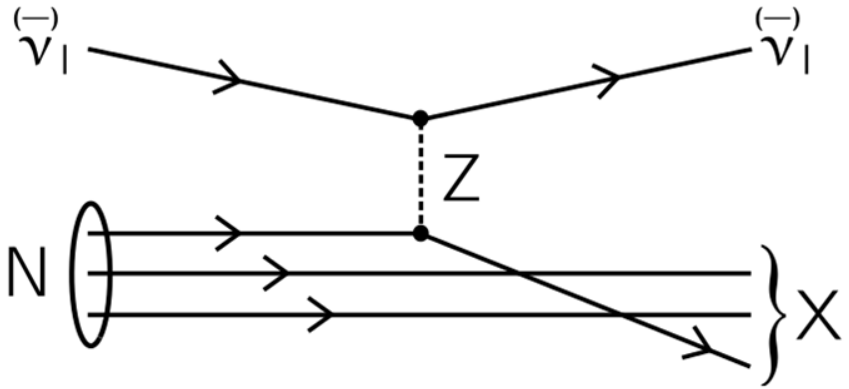


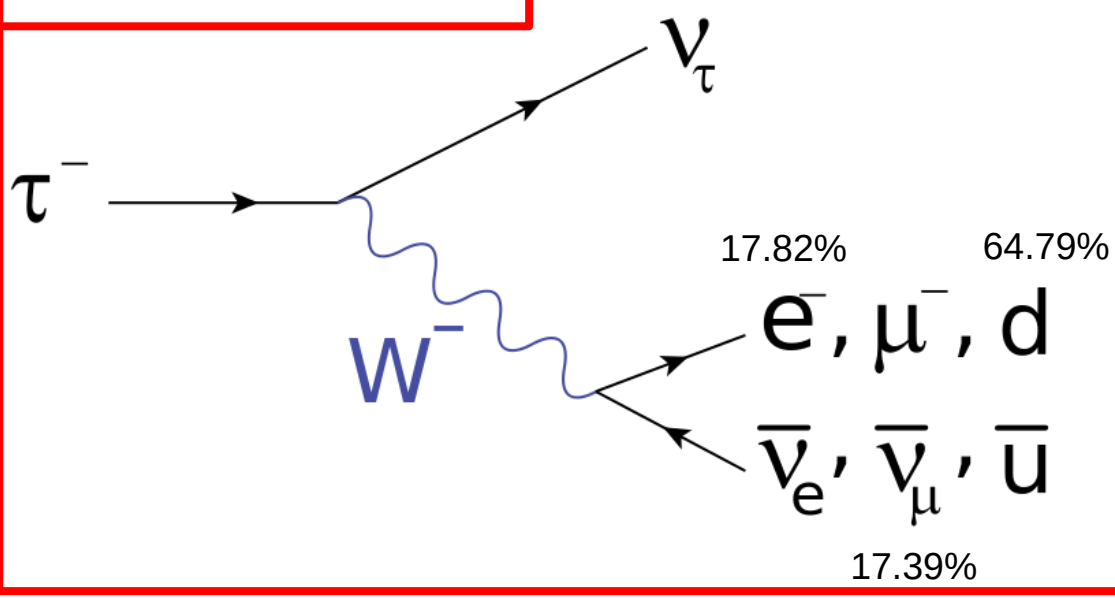
New physics

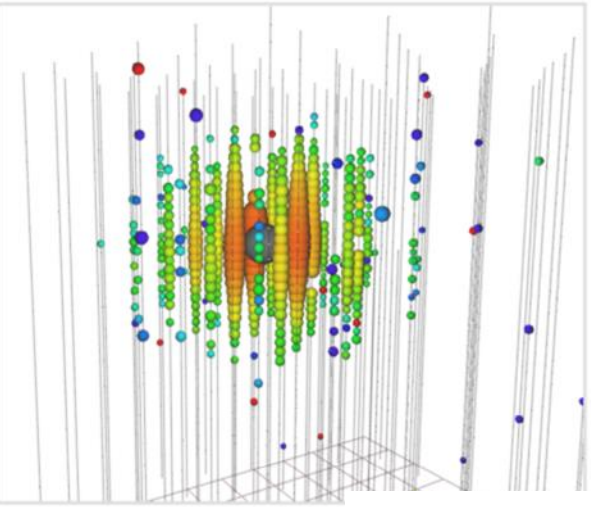
Arxiv 1903.04333v1

Tau signature

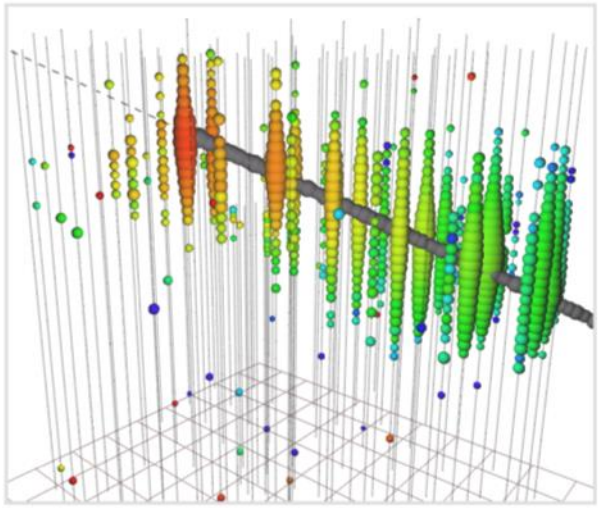


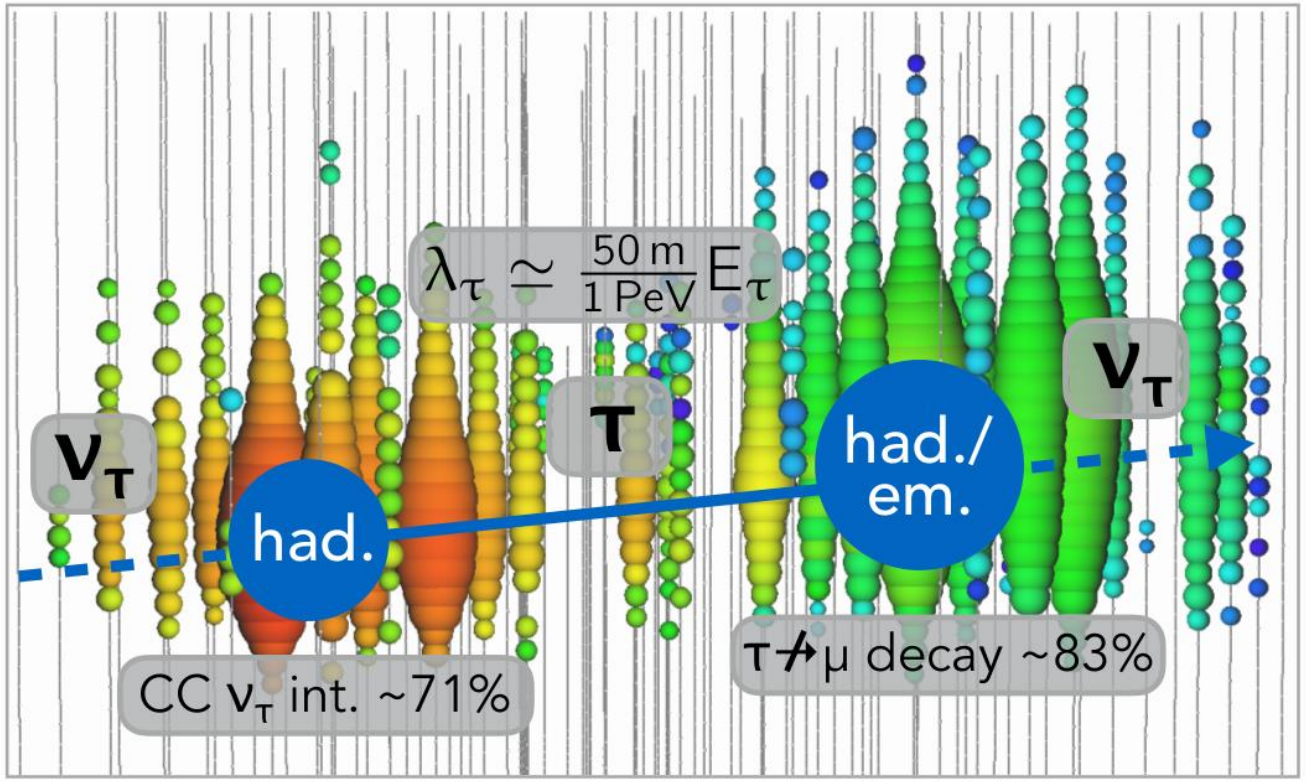


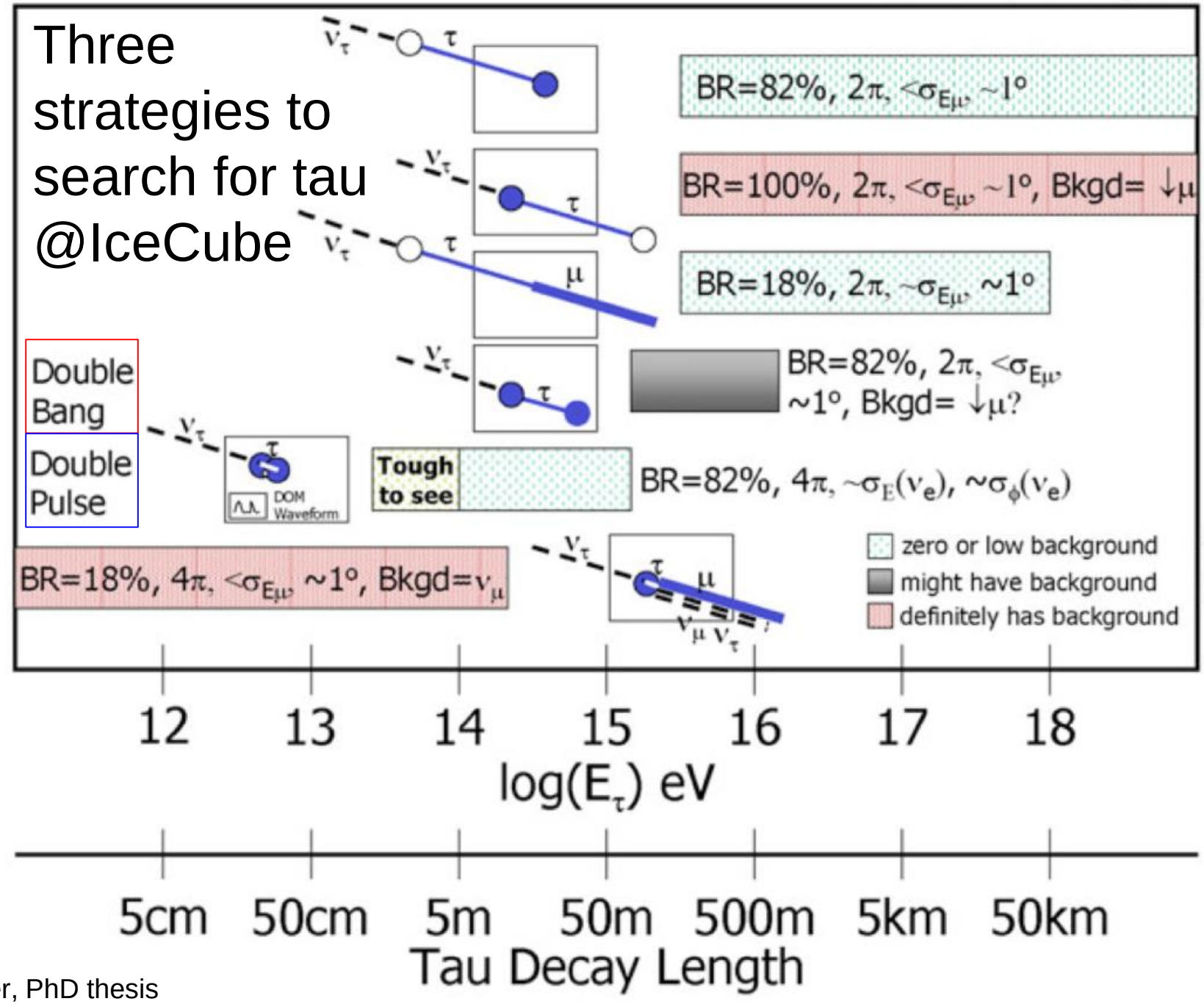




Cascade and track channel already detects tau but not event-by-event. Need tau feature to fit tau norm

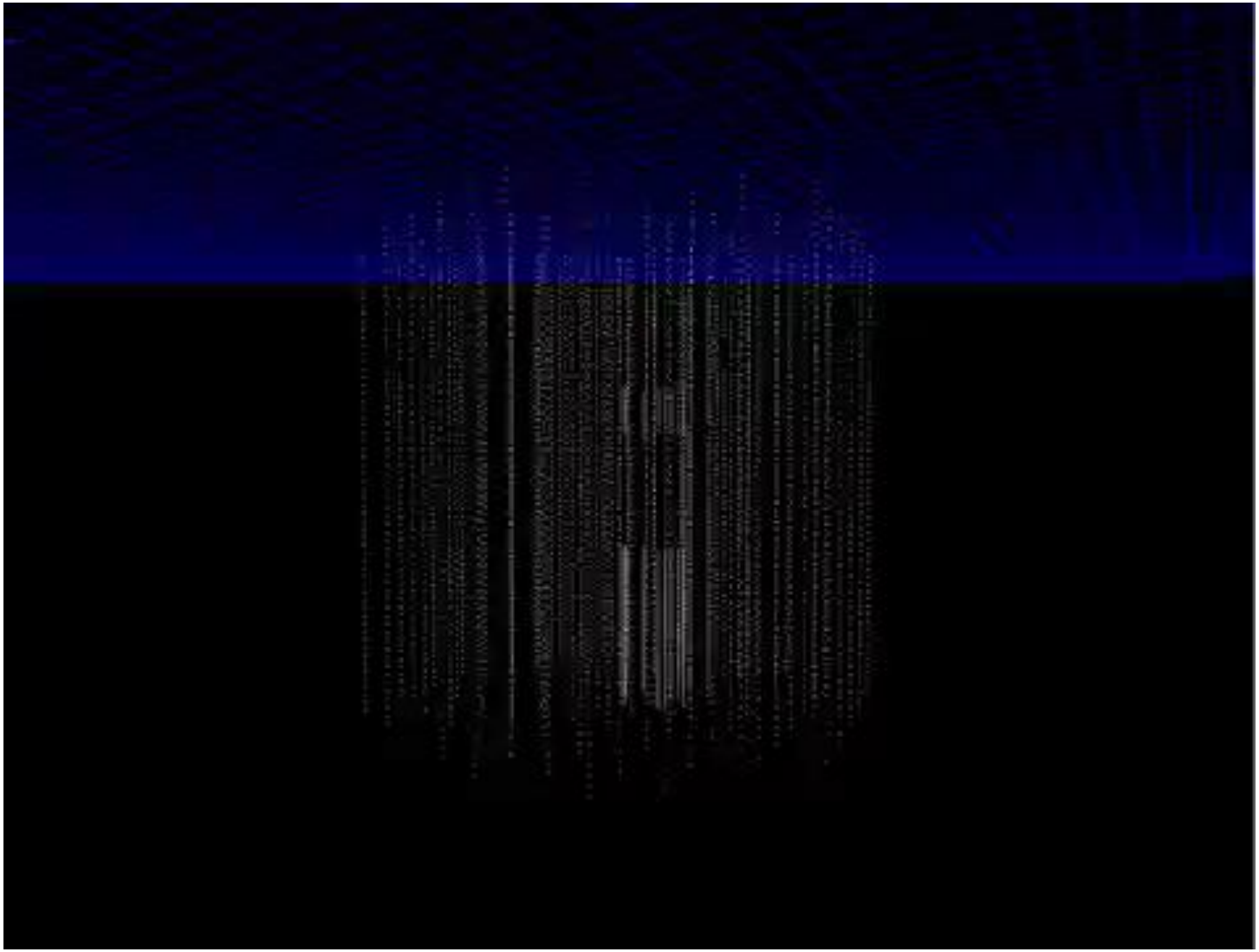


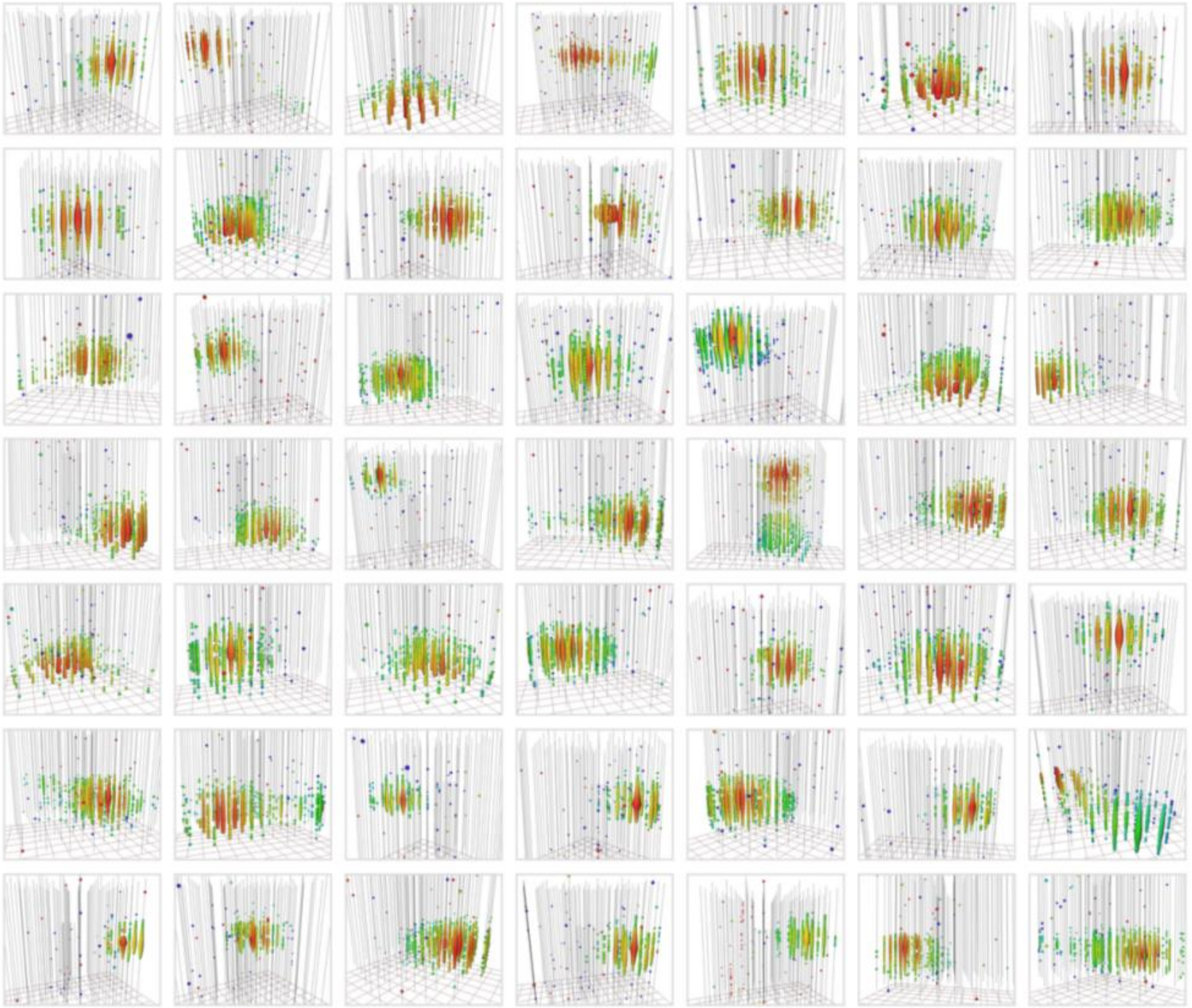




M Usner, PhD thesis

10 milliseconds data taking. ~3000 Hz, 1 TB data per day
10% satellite transferred

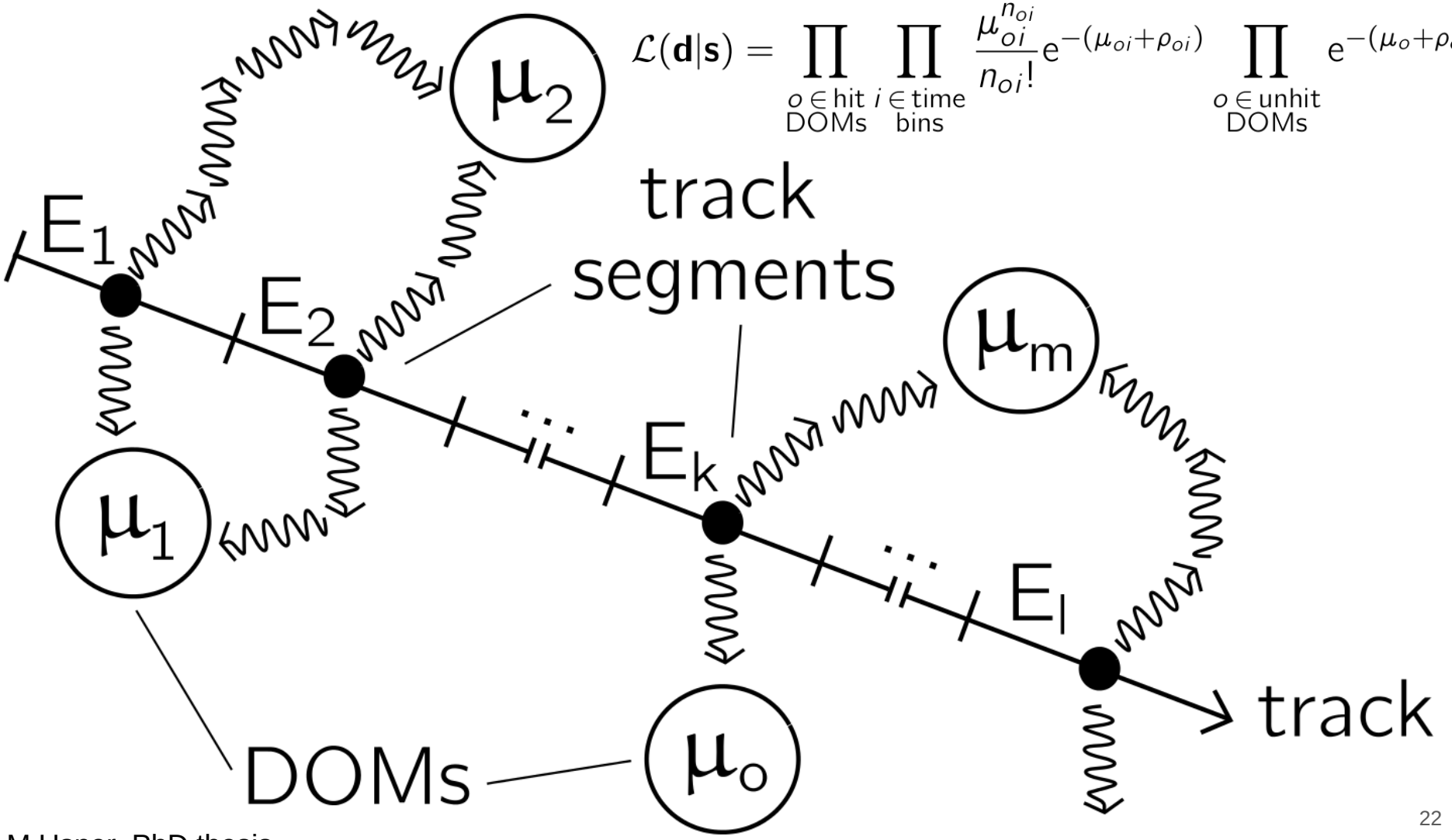




$$B_{oik} = B(x_k, y_k, z_k, t_k, \theta_k, \phi_k, x_o, y_o, z_o, t_{oi})$$

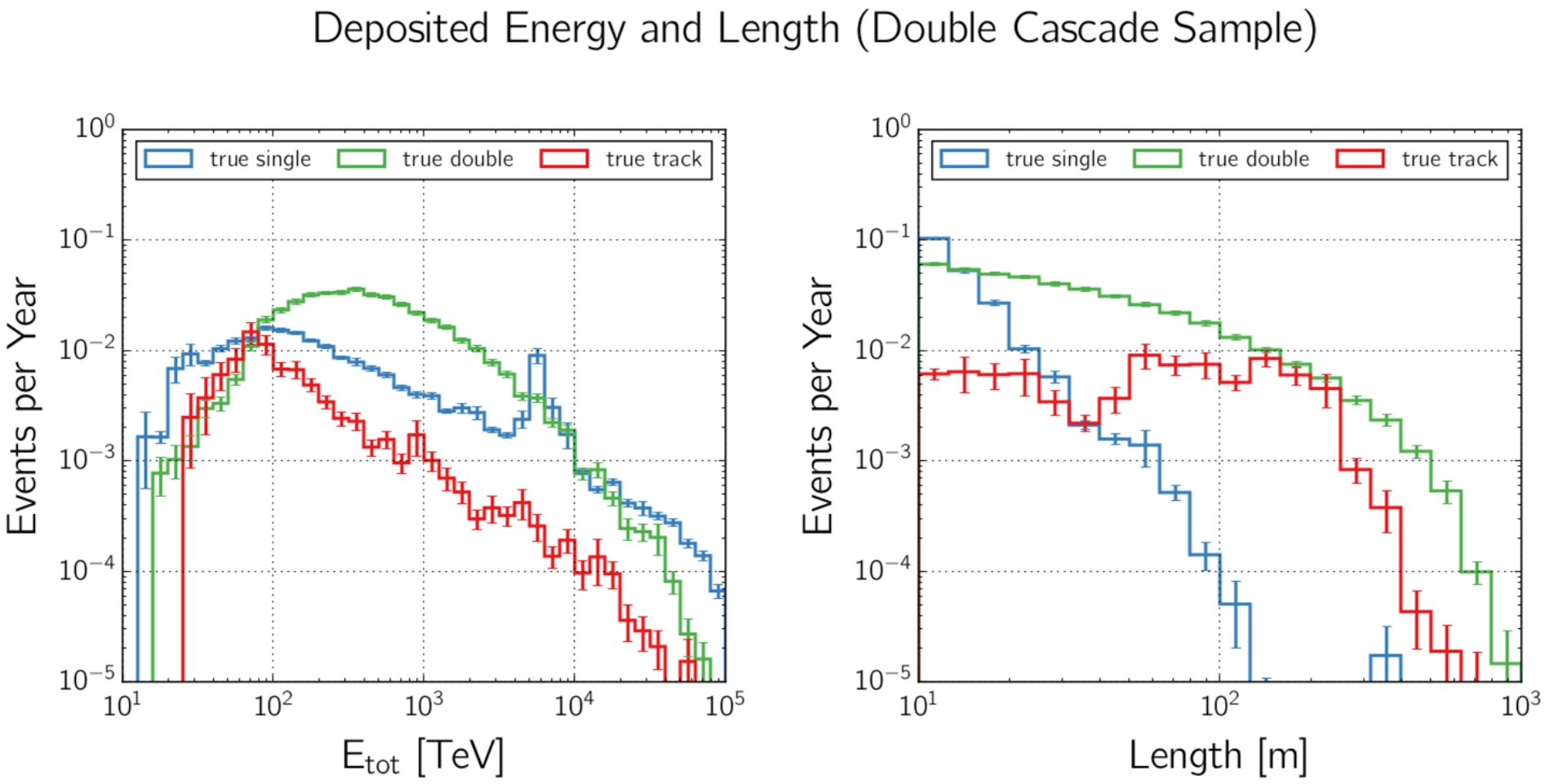
Analysis 1: double bang

$$\mathcal{L}(\mathbf{d}|\mathbf{s}) = \prod_{\substack{o \in \text{hit} \\ \text{DOMs}}} \prod_{\substack{i \in \text{time} \\ \text{bins}}} \frac{\mu_{oi}^{n_{oi}}}{n_{oi}!} e^{-(\mu_{oi}+\rho_{oi})} \prod_{\substack{o \in \text{unhit} \\ \text{DOMs}}} e^{-(\mu_o+\rho_o)}$$



M Usner, PhD thesis

Analysis 1 Double bang: signal and background

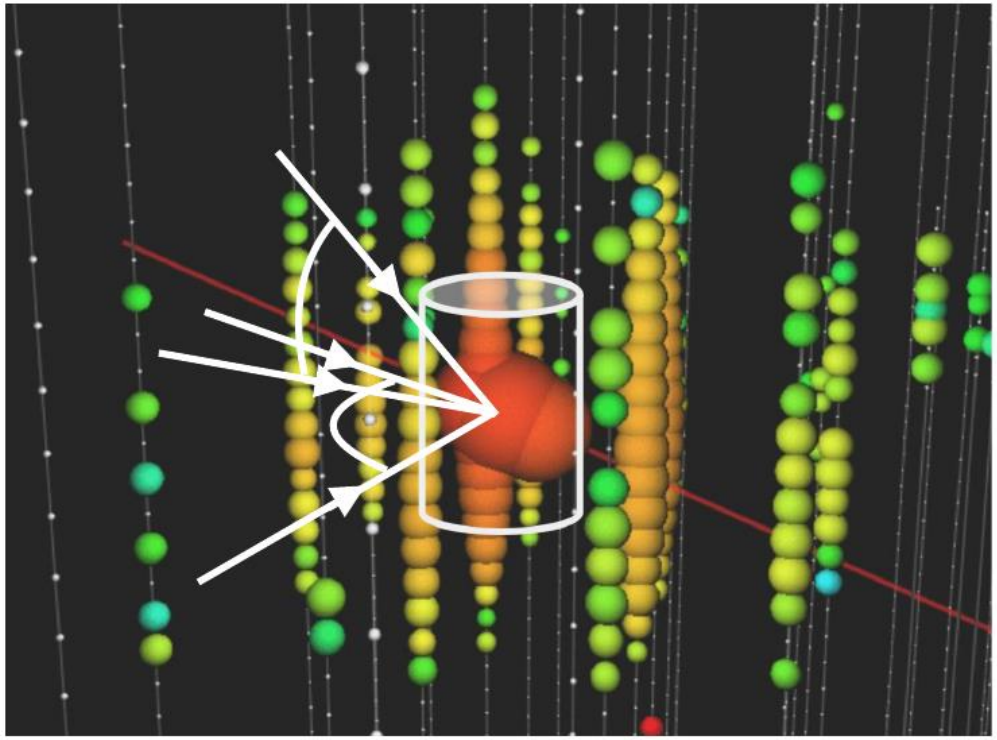


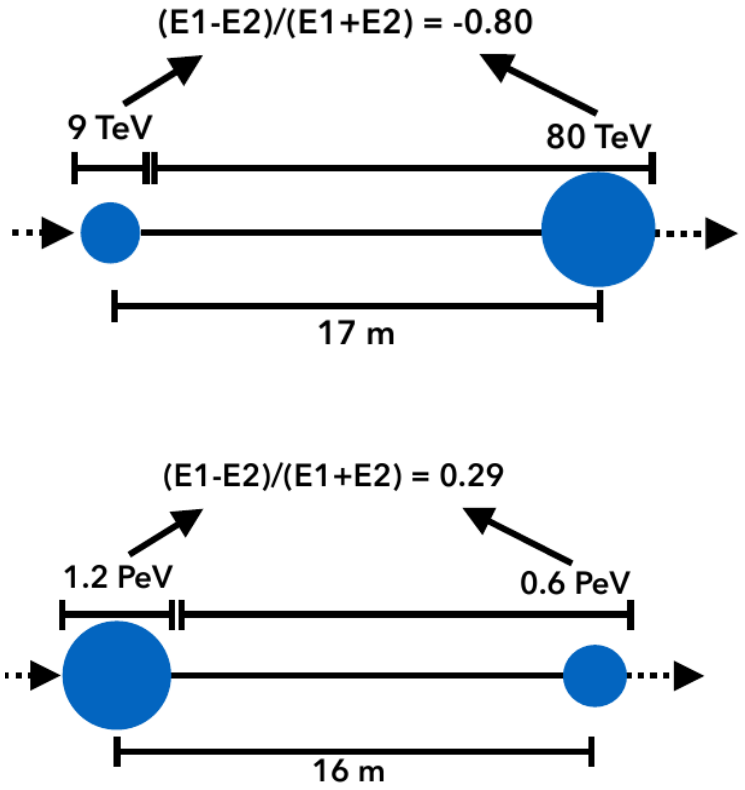
M Usner, PhD thesis

Results from analysis 1: found two candidates

7.5 years livetime

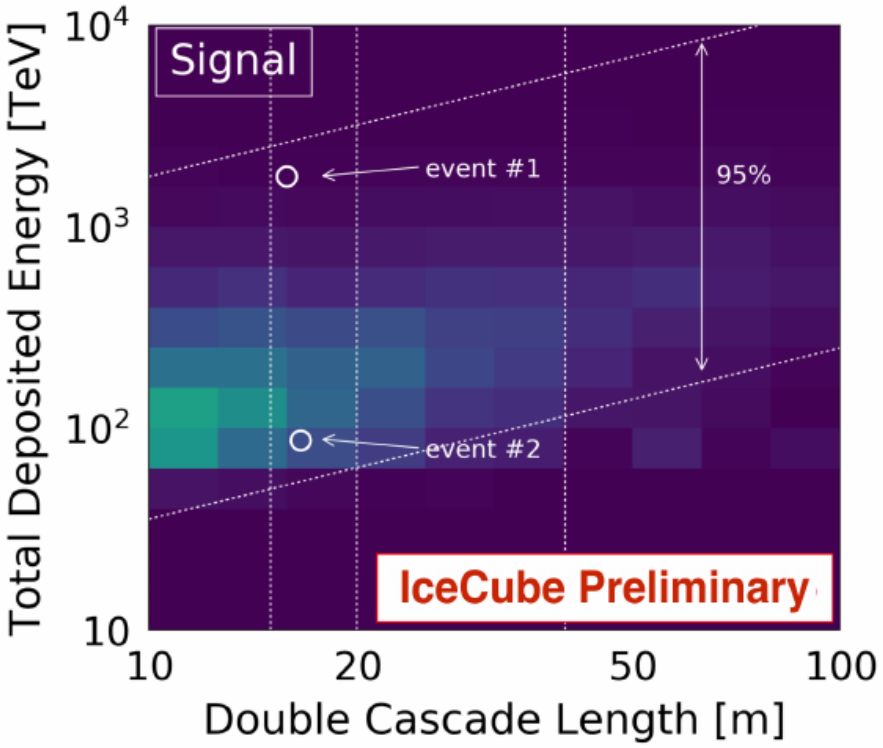
Event double-double

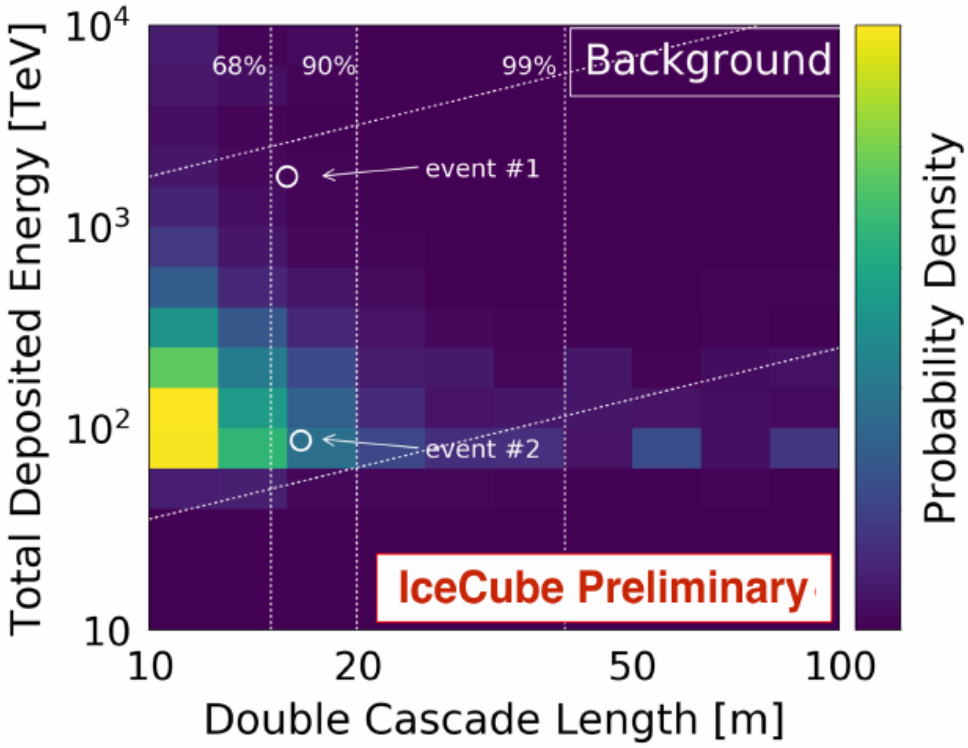




M Usner, PhD thesis

Result from analysis 1

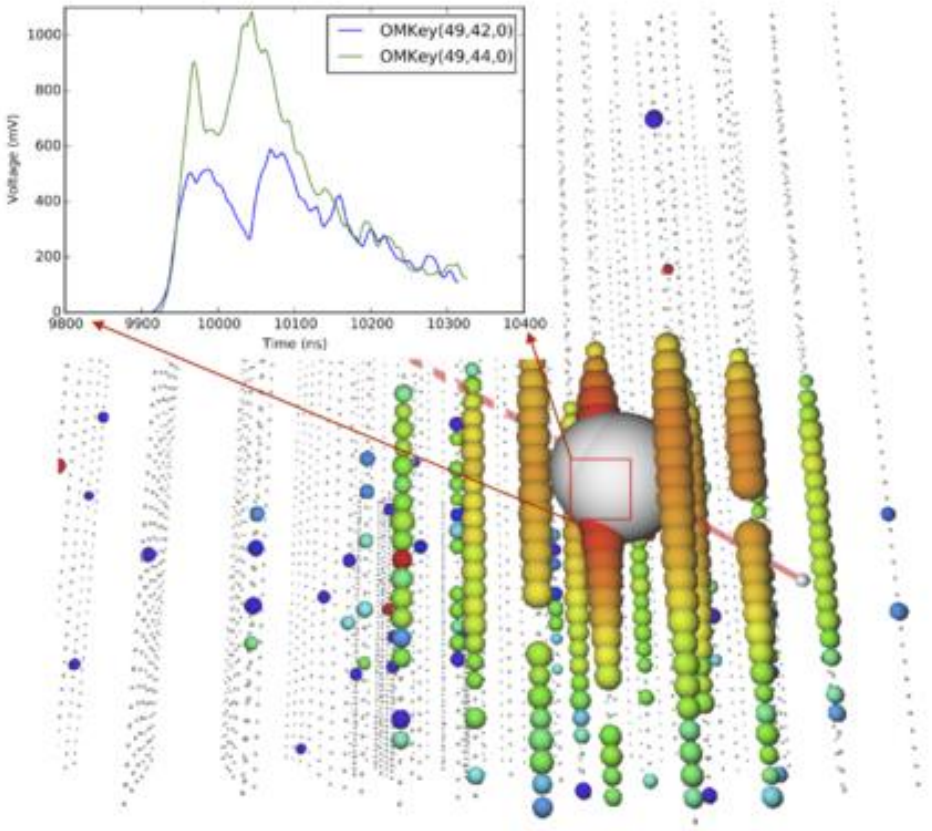




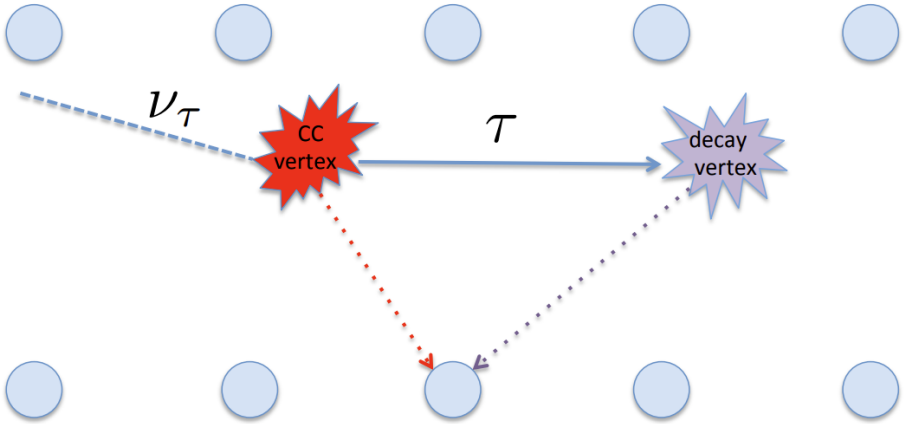
- 2 events in Double Cascade bin
- Soft spectral index: 2.9 → expect ~2.1 events (~1.4 signal + ~0.7 background)

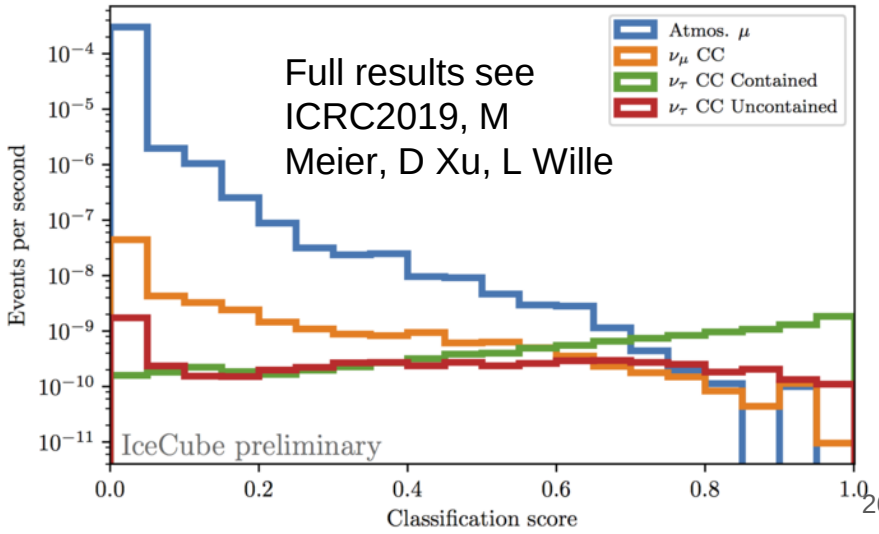
Analysis 2 & 3 Double pulse

Machine-learning
Vs
Human cuts

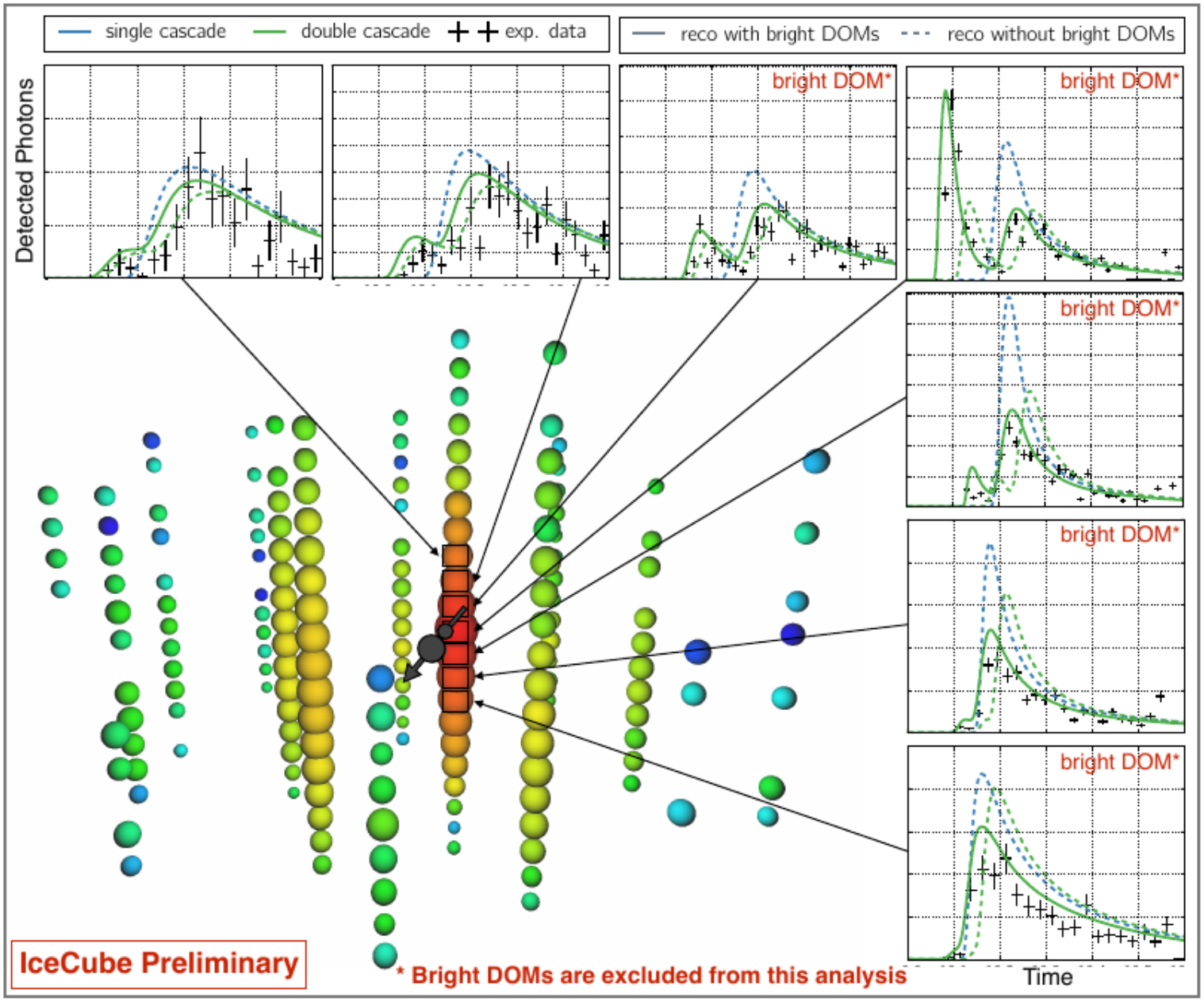


Simulation
https://arxiv.org/abs/1702.05238

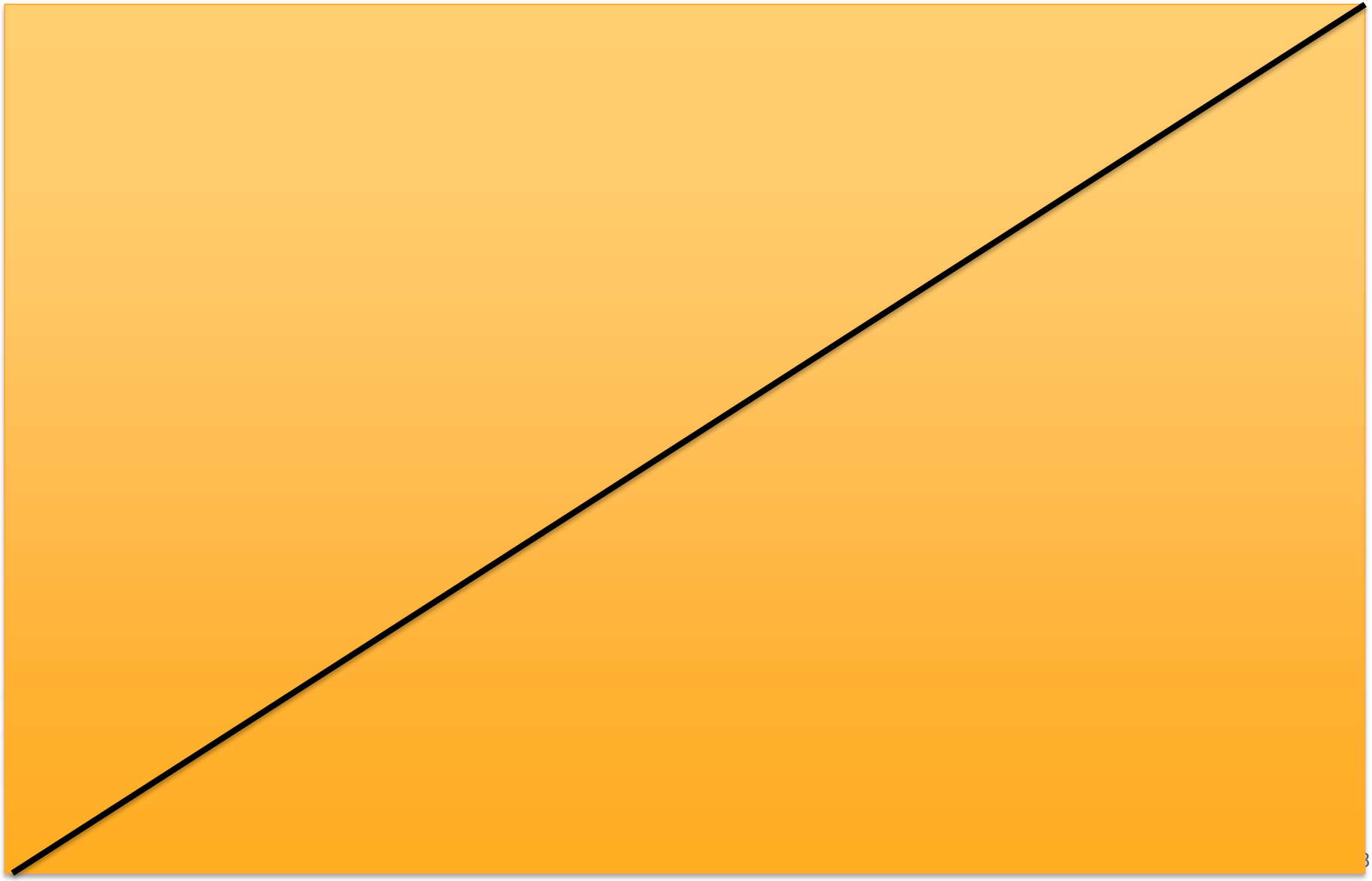


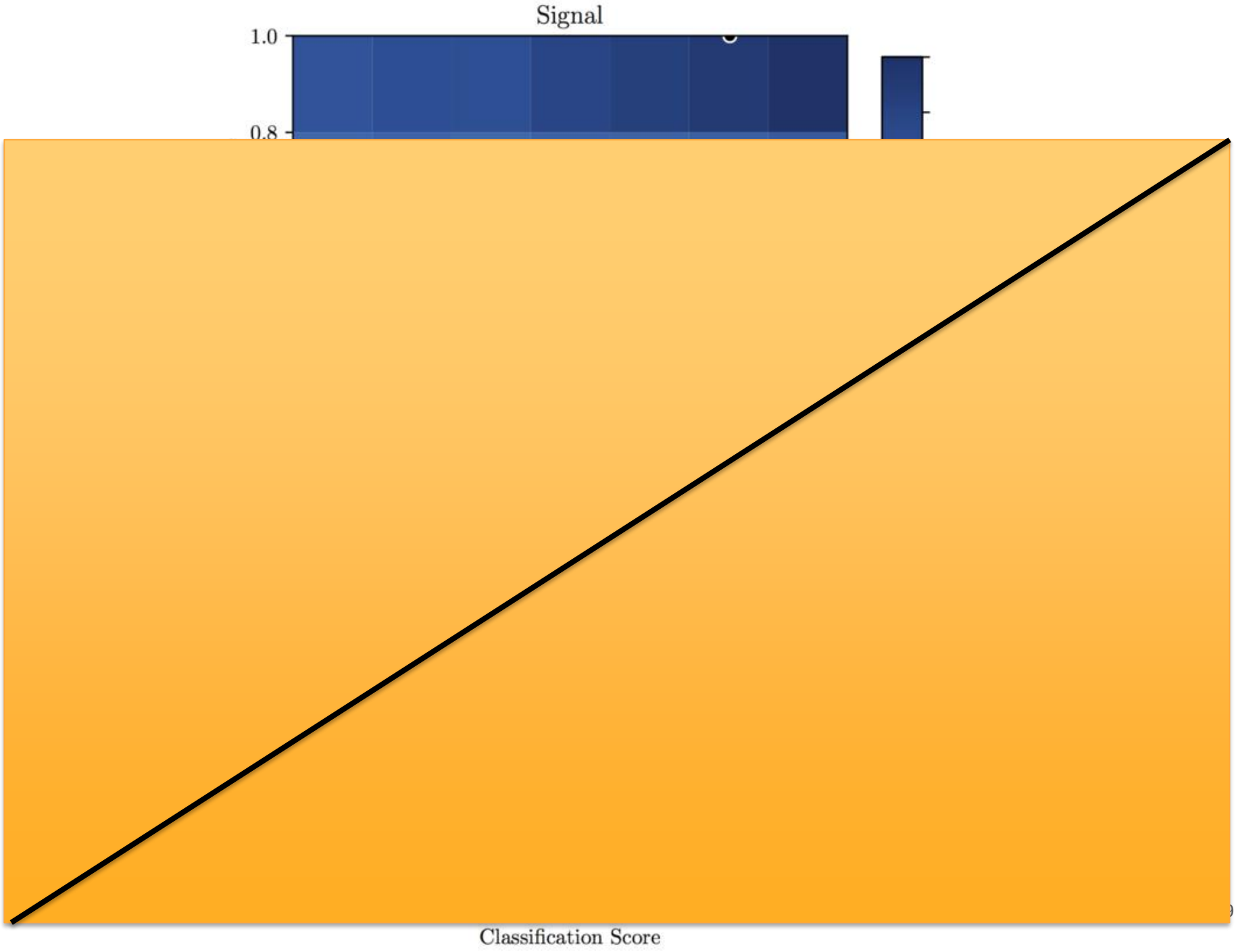


Also found two events. One is the same with analysis1

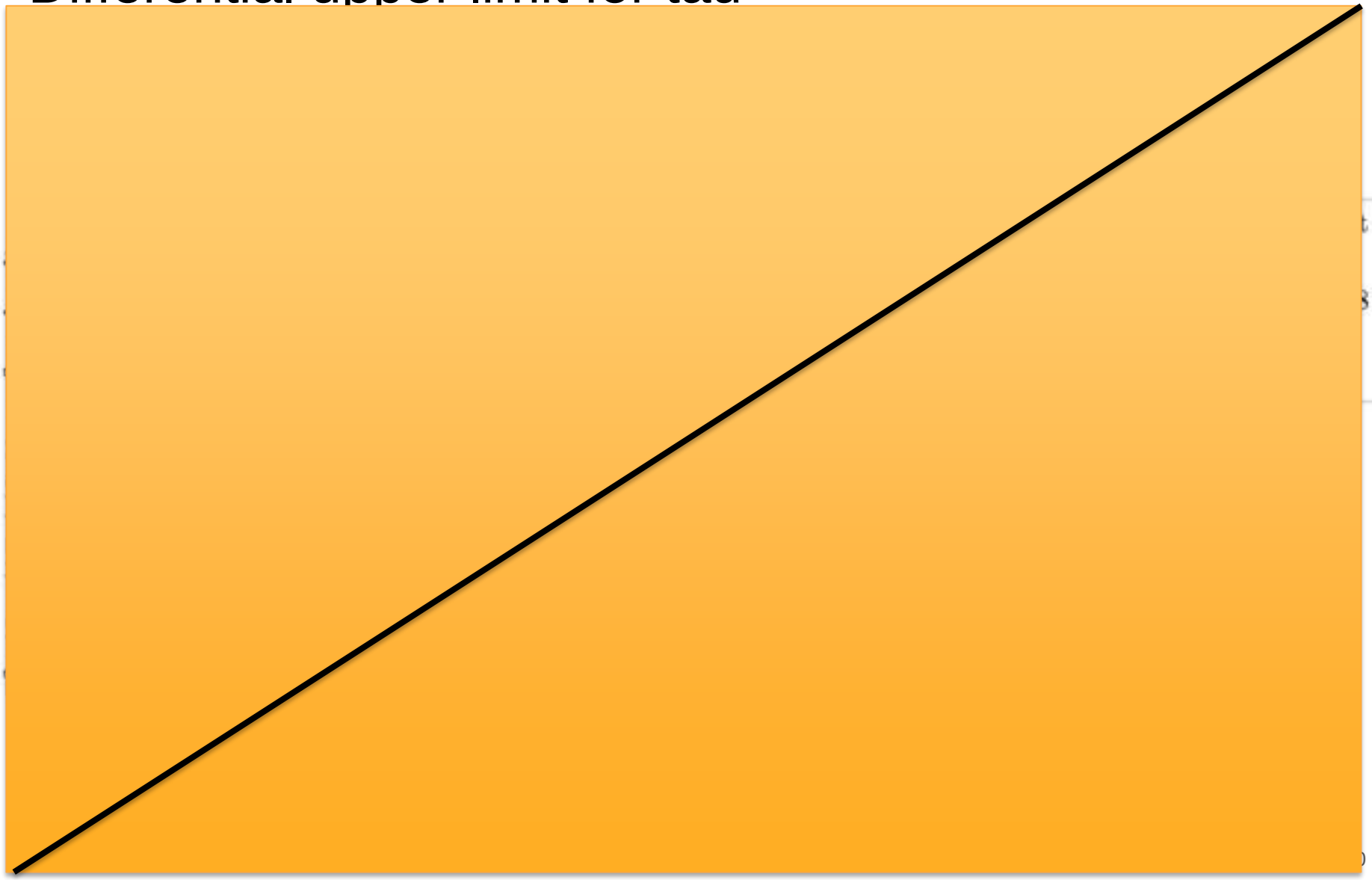


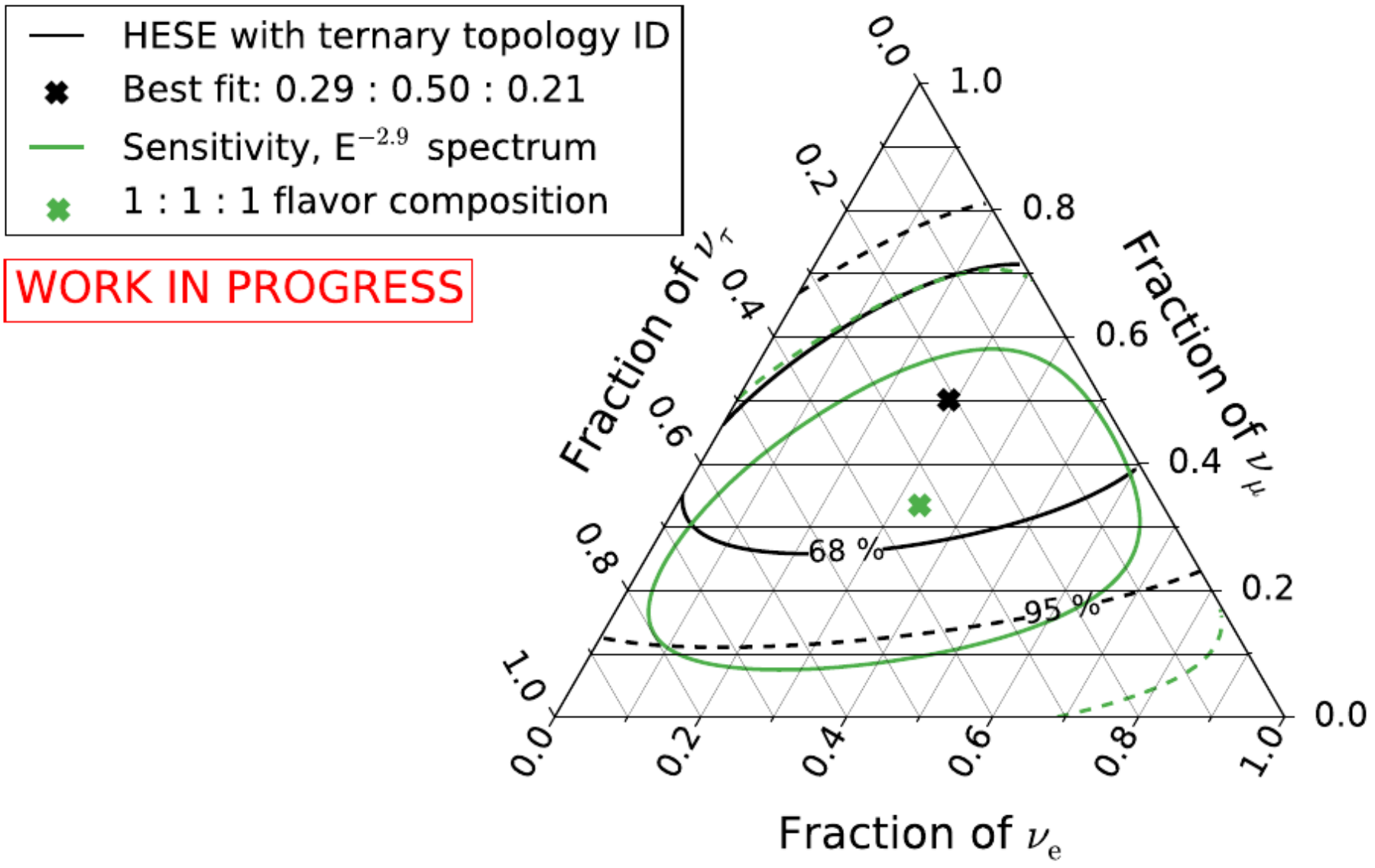
The second candidate from analysis 2&3




Signal
1.0
0.8
Classification Score

Differential upper limit for tau





- Best-fit ν_e:ν_μ:ν_τ = 0.29:0.50:0.21

Need a larger detector!

Conclusions

- nuTau appearance for 100TeV-10PeV with cosmological baselines possible with IceCube
- Flavour measurements with tau can shed light on the acceleration environment of high-energy-neutrino sources
- Possible to test beyond standard models

- Three independent tau searches found one common tau candidate, full statistical analysis for event-by-event tau probability in progress
- Preliminary results are consistent with expectations from astrophysical spectrum

- Need a larger detector…