Recent Results from IceCube



Jon Dumm
OKC, Stockholm Univ.

Oct 27, 2014
Partikeldagarna
Linné University

IceCube in Sweden



Uppsala University:
Olga Botner *
Allan Hallgren
Carlos de los Heros
David Boersma
Henric Taavola
Rickard Ström
Leif Gustafsson
Sebastian Euler
Elisabeth Unger

Stockholm University:
Klas Hultqvist
Per Olof Hulth
Christian Walck
Chad Finley
Marcel Zoll
Samuel Flis
Martin Wolf
Maryon Ahrens
Jon Dumm

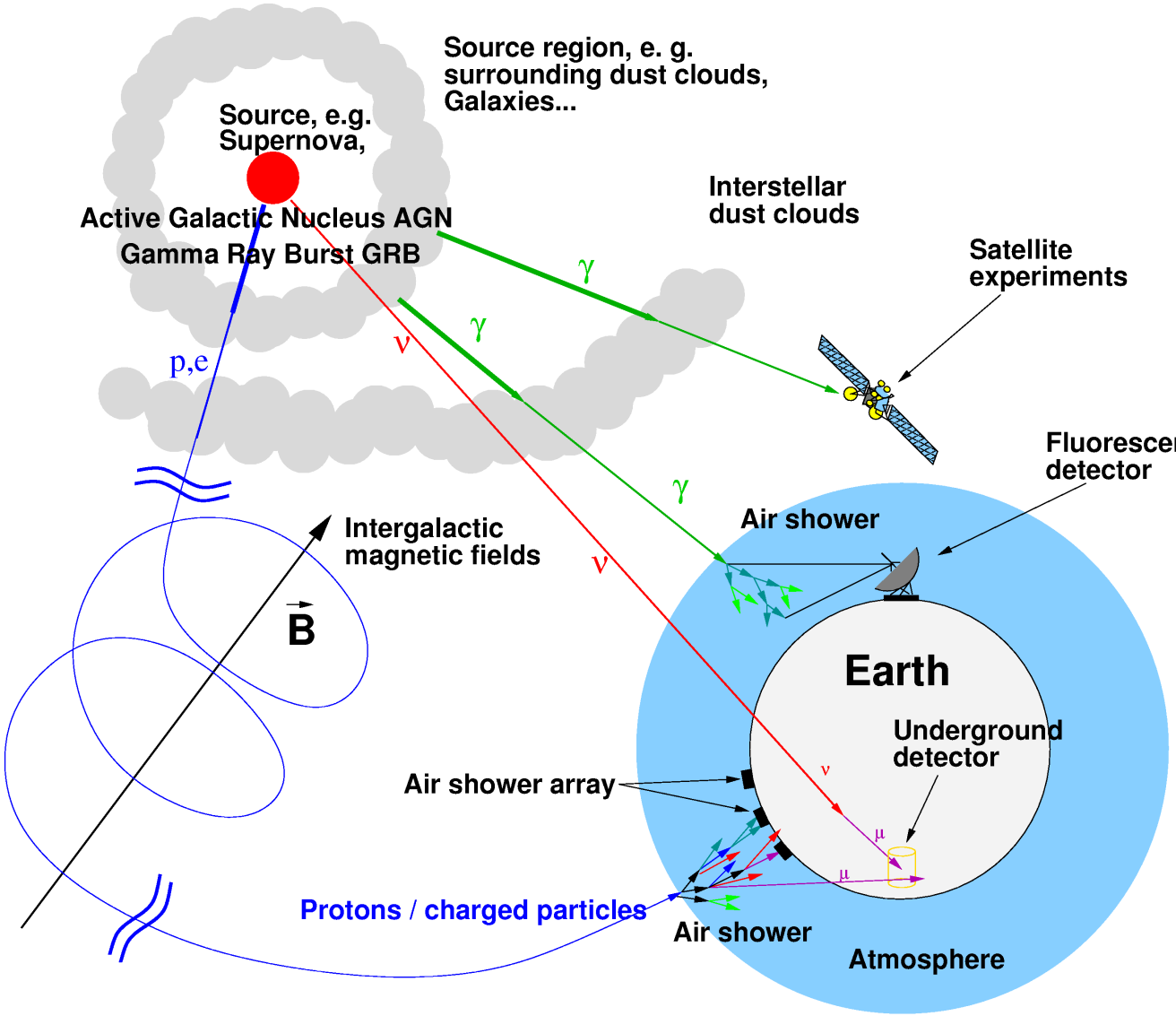
IceCube as a whole:
~300 members in 11 countries

Key Swedish Contributions:
Low energy
Dark matter (see Martin's talk)
Point source & multimessenger
Diffuse flux
Future extensions

*IceCube Spokesperson

photo: Patrick Cullis, NSF

Neutrinos as Cosmic Messengers



γ *Photons:* easily absorbed by CMB and IR backgrounds.

p *Protons:* deflected by magnetic fields.

ν *Neutrinos:* not deflected by magnetic fields. Low interaction cross-section.

Why look for neutrinos?

Extraordinary particle accelerators **somewhere**,

but still **poorly identified** after a century

- Supernova remnants?
- Active galactic nuclei?
- Gamma ray bursts?
- Other?

Cosmic ray interactions with matter and photons produce:

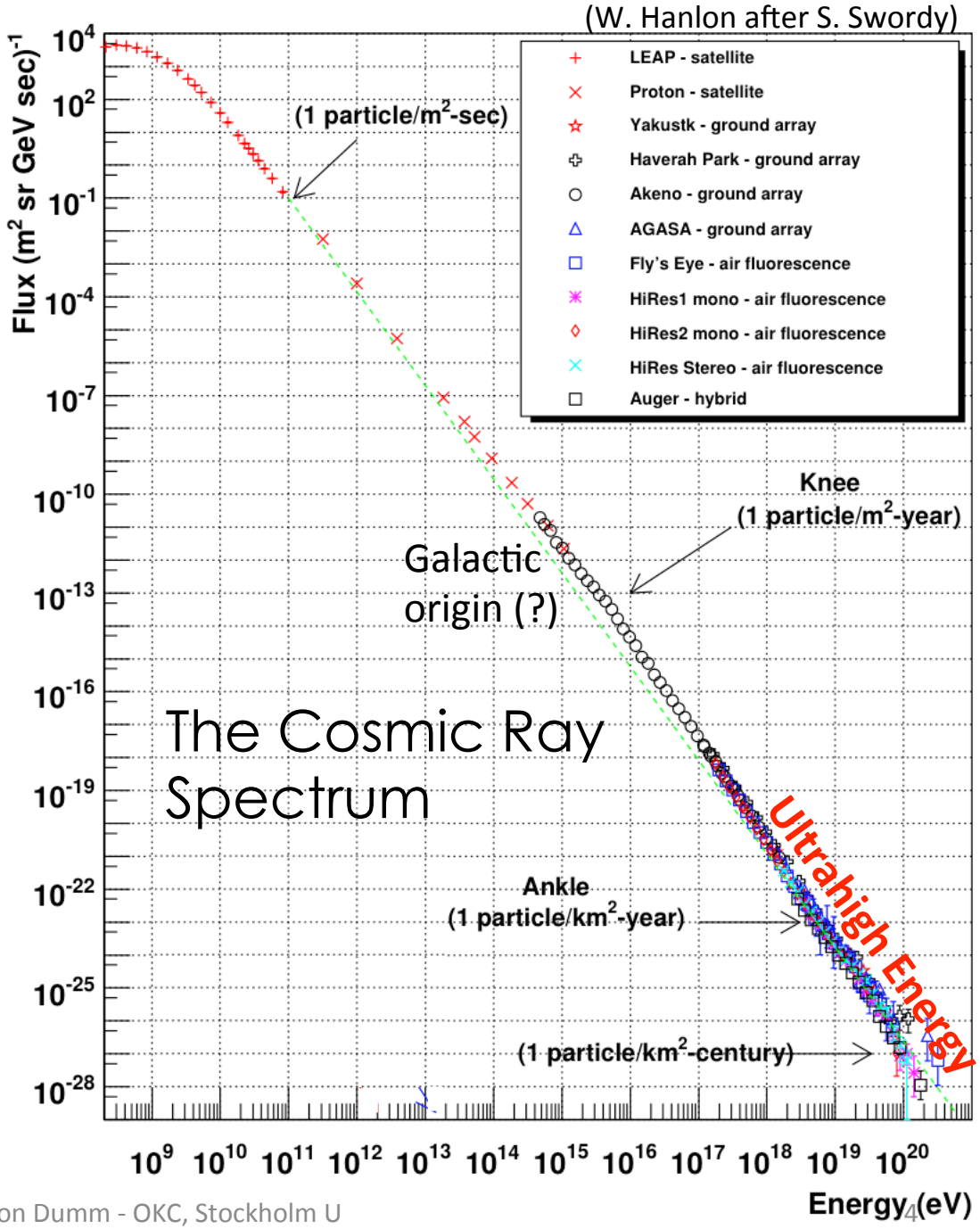
$$p + N \rightarrow X + \{\pi^+, \pi^-, \pi^0\}$$

$$\pi^0 \rightarrow \gamma + \gamma$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

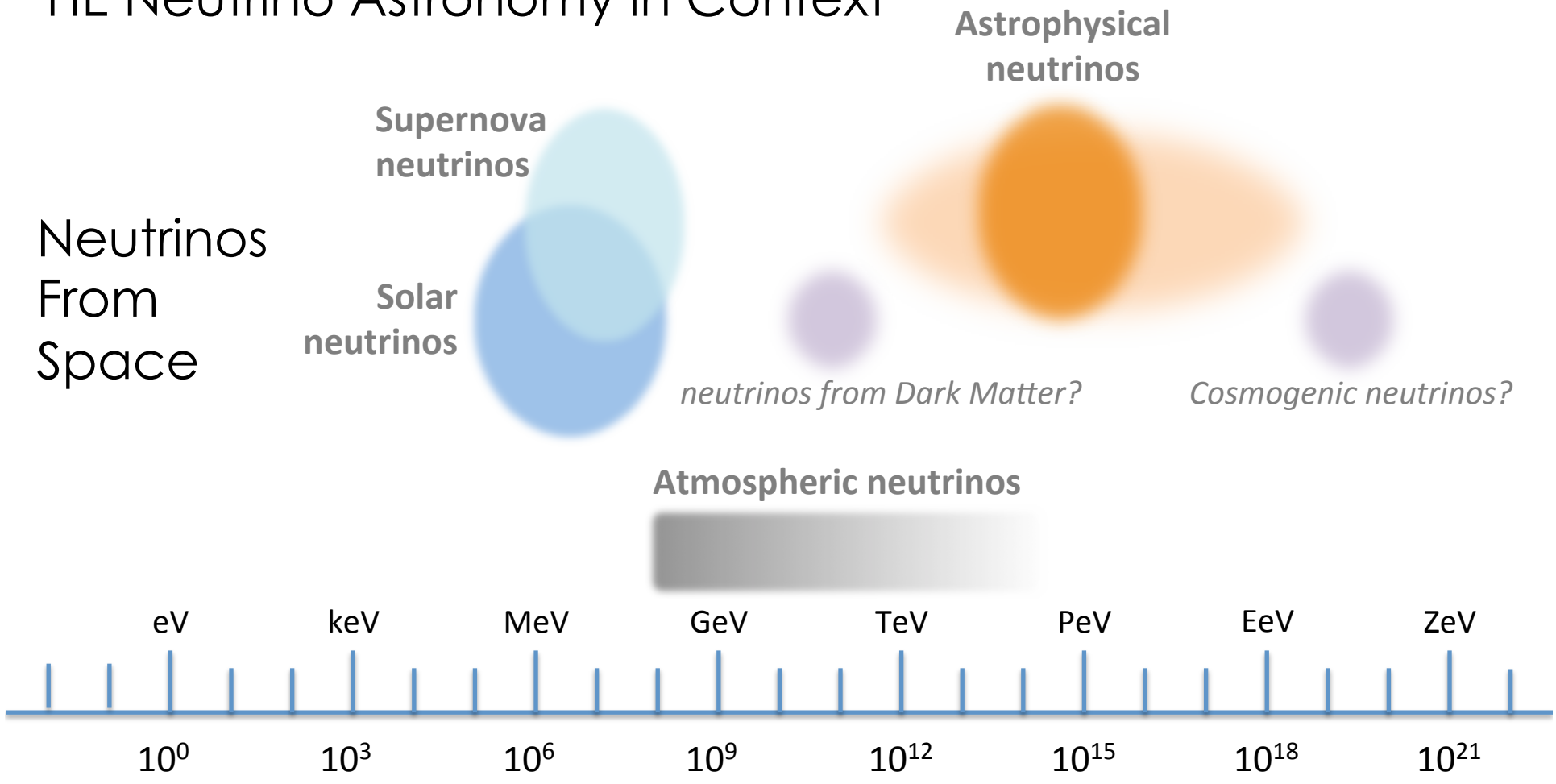
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

(W. Hanlon after S. Swordy)



HE Neutrino Astronomy in Context

Neutrinos From Space



HE Neutrino Astronomy in Context

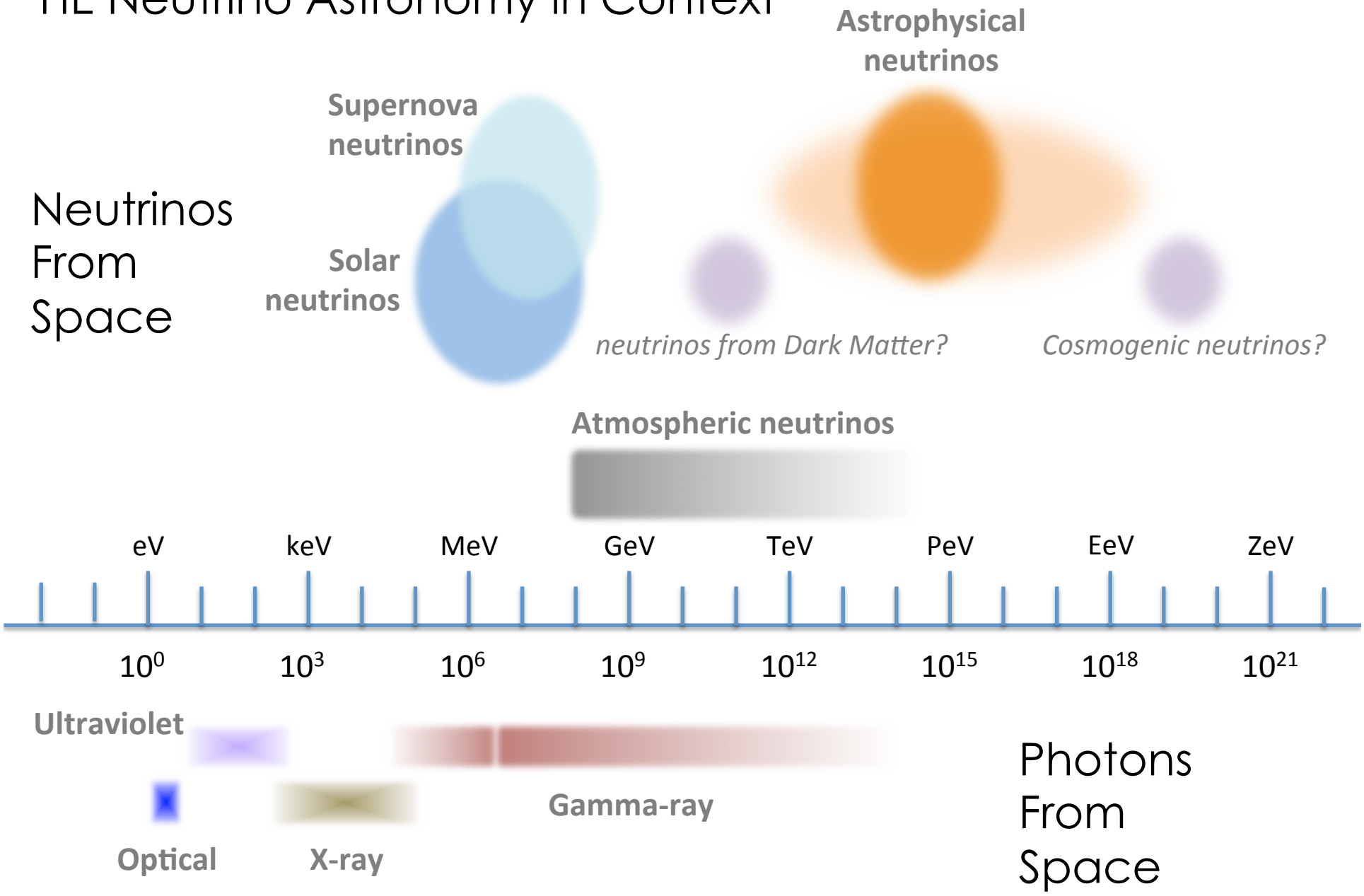




Photo: Haley Buffman

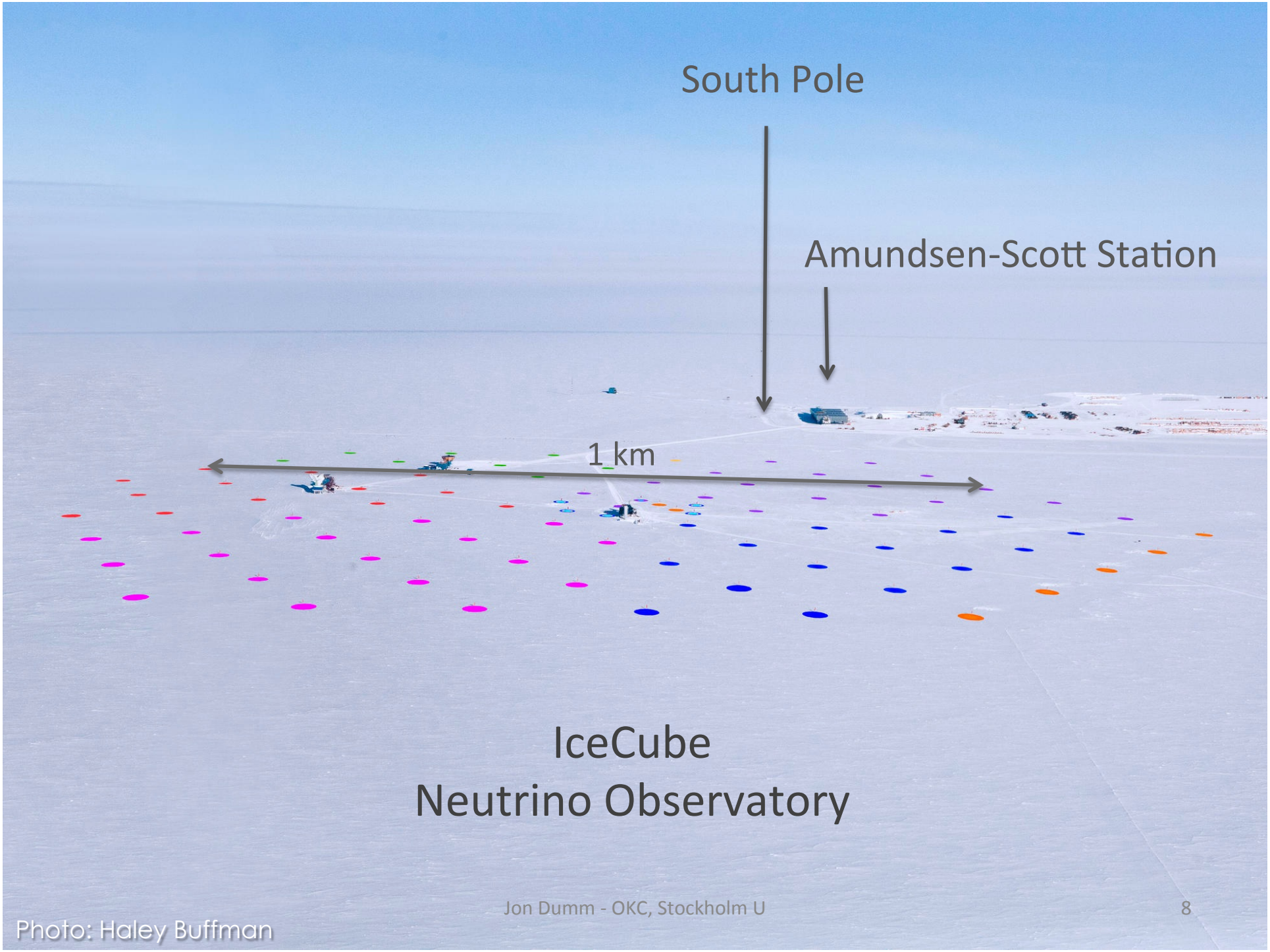


Photo: Haley Buffman

IceCube Neutrino Observatory

86 strings

60 Optical Modules per string

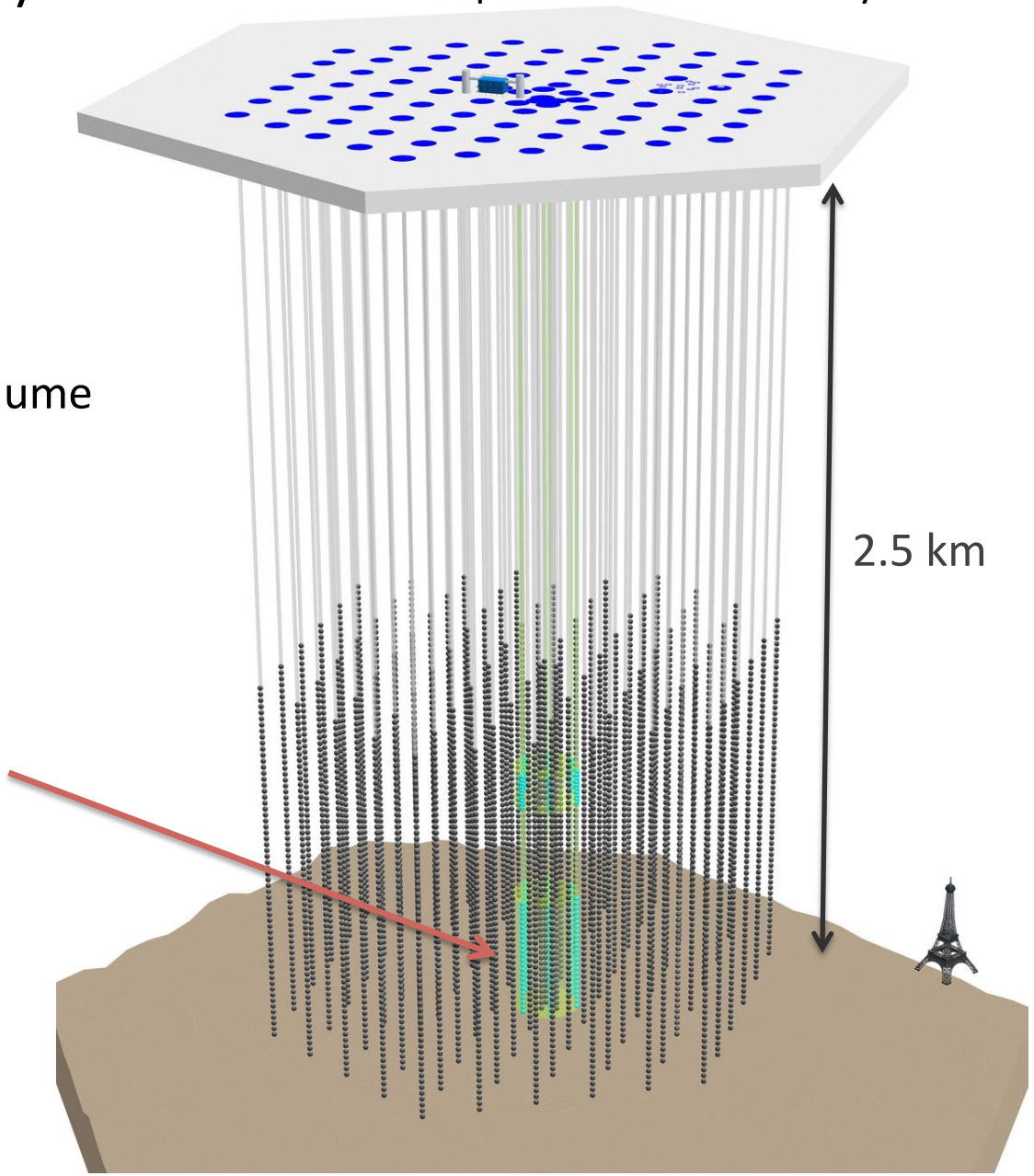
5 160 total modules in Ice

1 km^3 = Gigaton instrumented volume

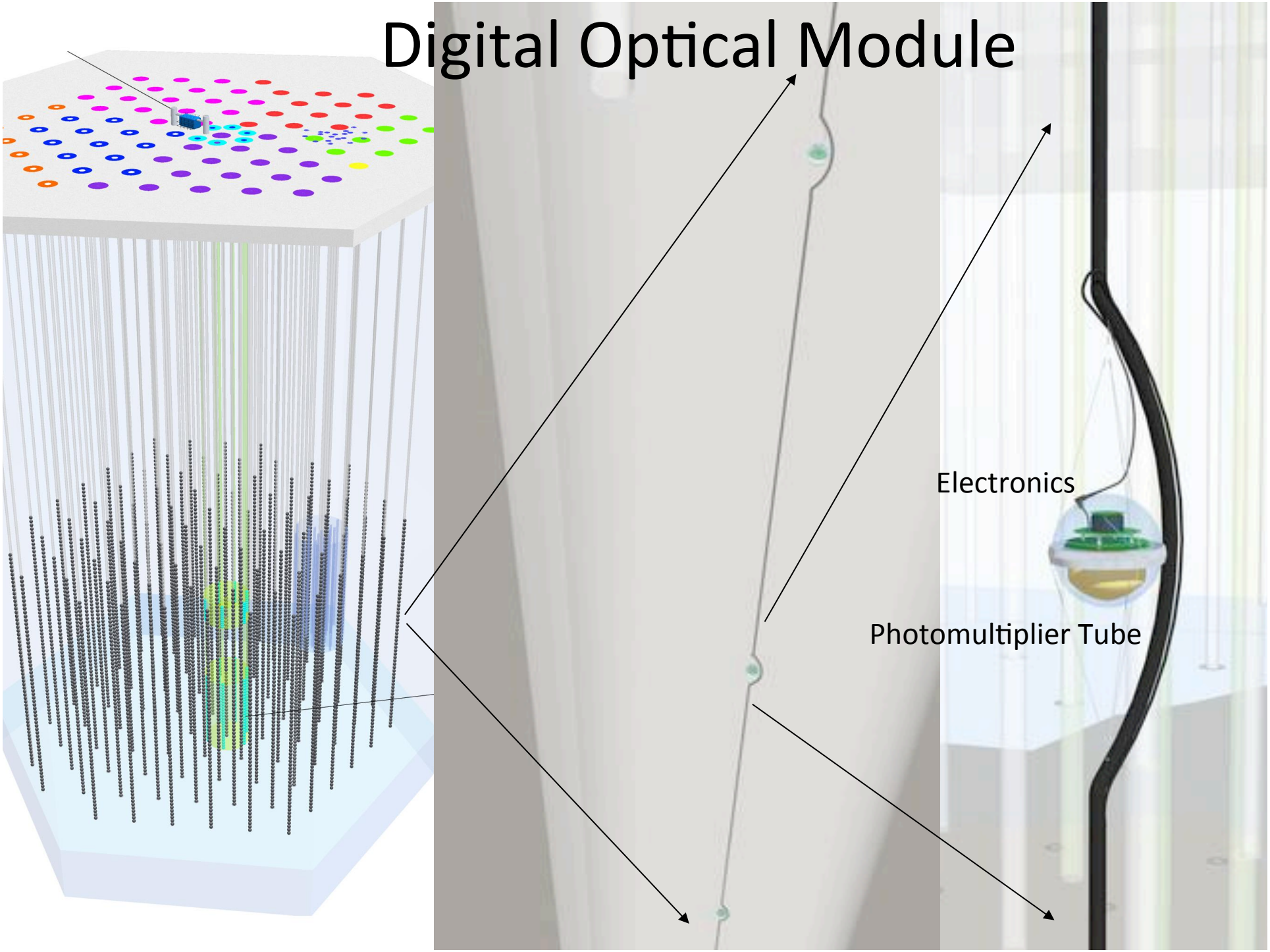
Began full operations May 2011

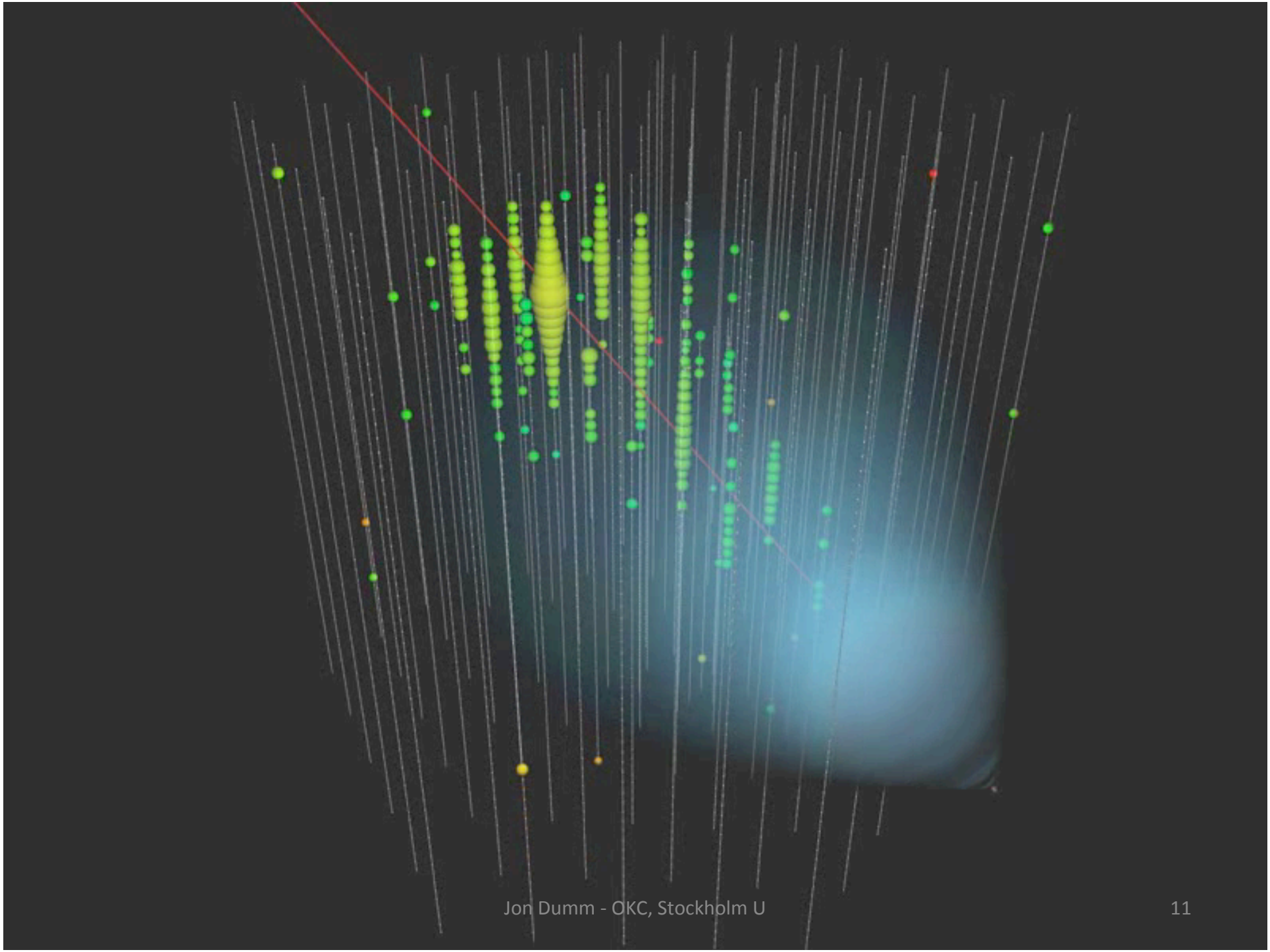
DeepCore
Low-energy Extension

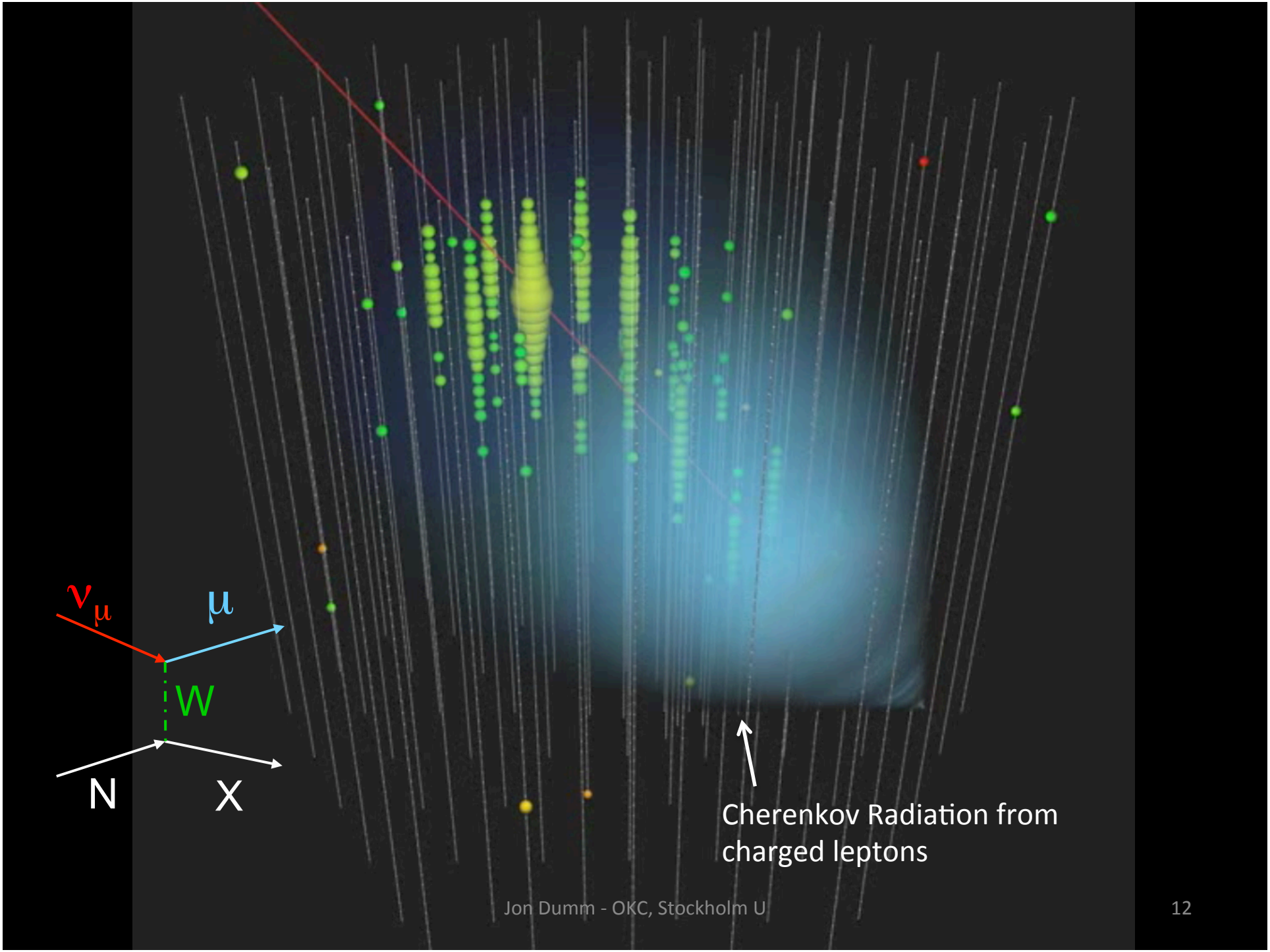
Dark Matter,
Neutrino Oscillations



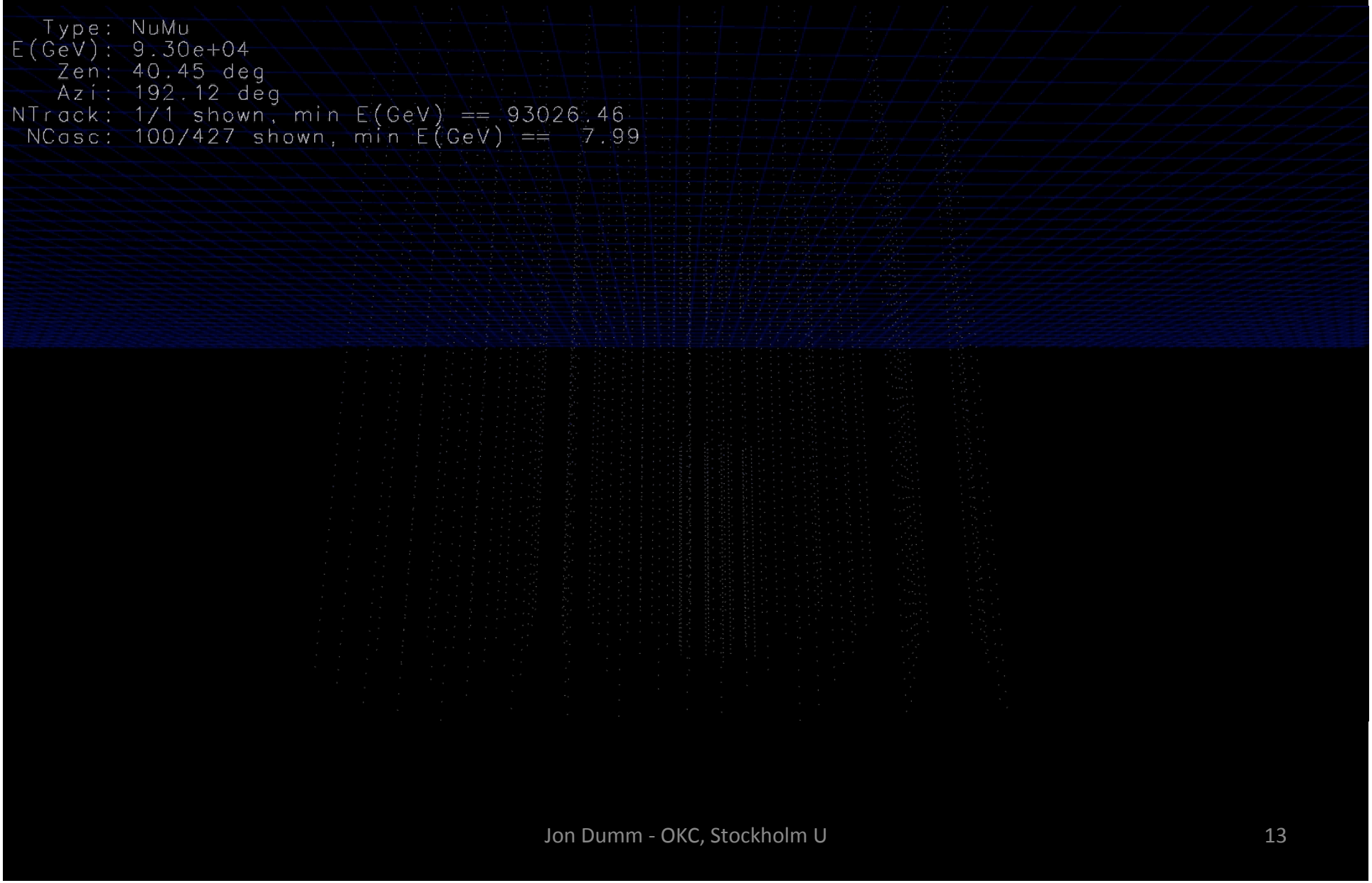
Digital Optical Module



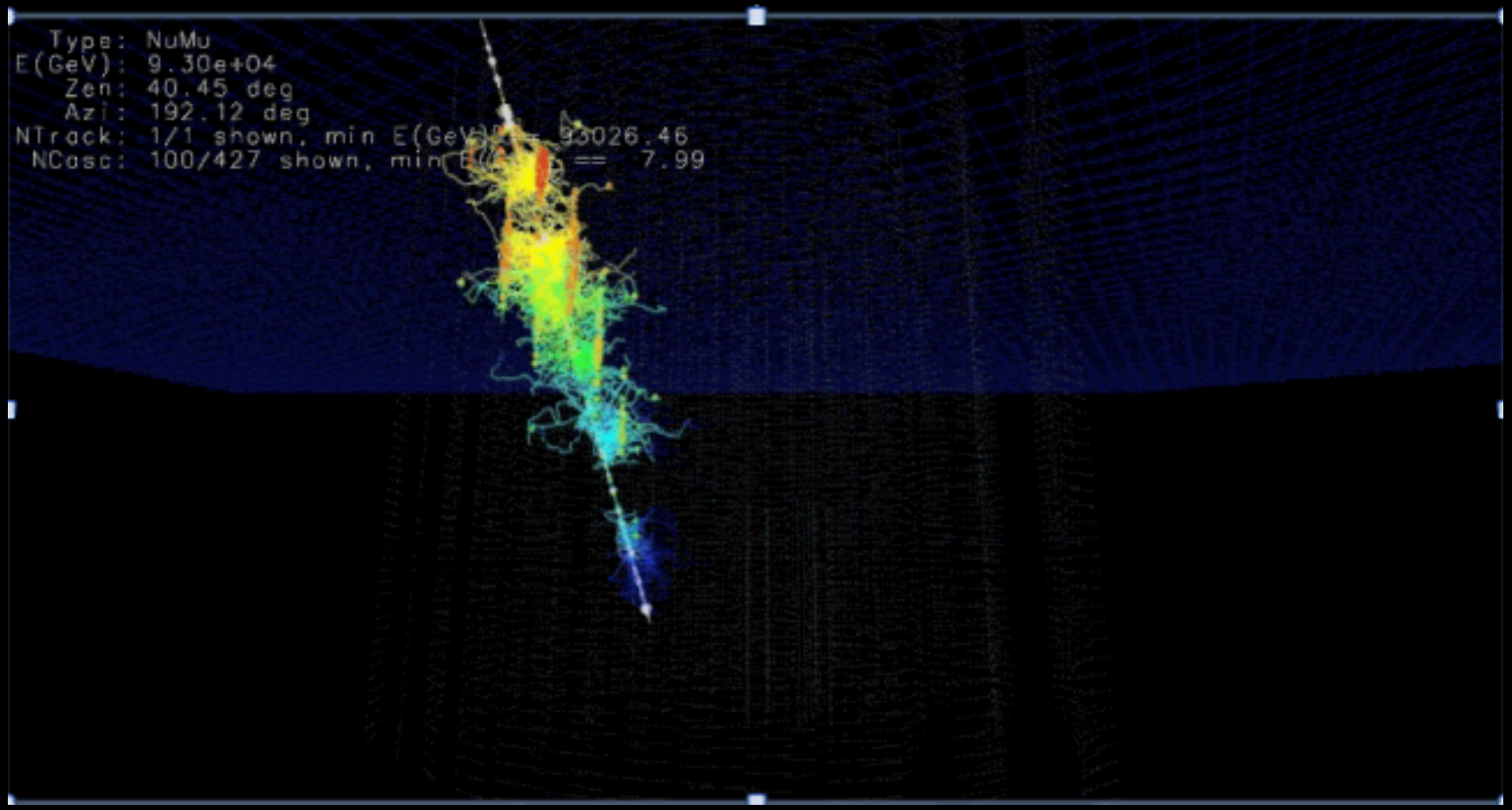



ν_μ
μ
W
N
X
Cherenkov Radiation from
charged leptons

93 TeV muon


Type: NuMu
E(GeV): 9.30e+04
Zen: 40.45 deg
Azi: 192.12 deg
NTrack: 1/1 shown, min E(GeV) == 93026.46
NCasc: 100/427 shown, min E(GeV) == 7.99

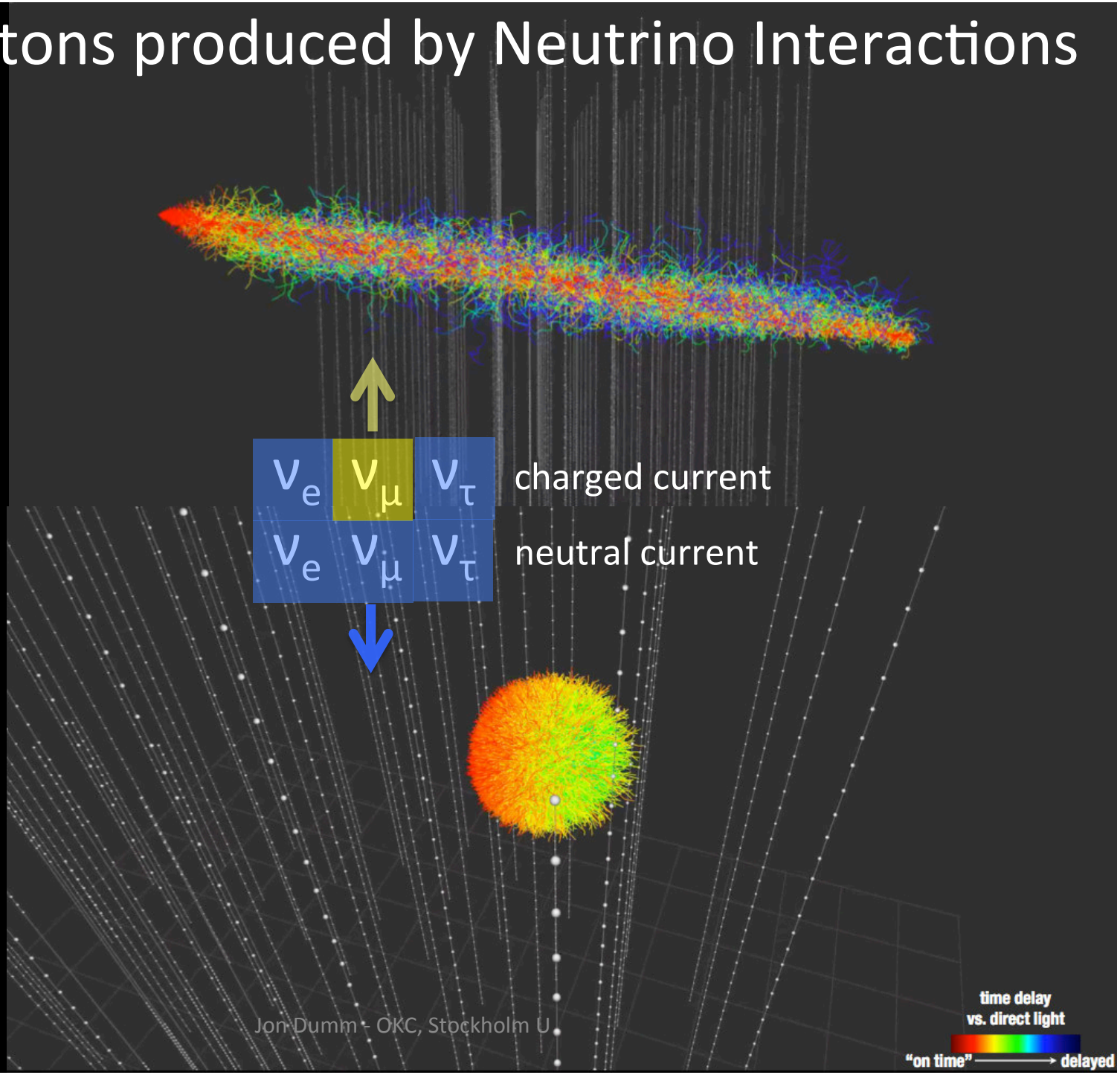
93 TeV muon


Type: NuMu
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Zen: 40.45 deg
Azi: 192.12 deg
NTrack: 1/1 shown, min E(GeV) = 93026.46
NCasc: 100/427 shown, min E(GeV) == 7.99

Photons produced by Neutrino Interactions

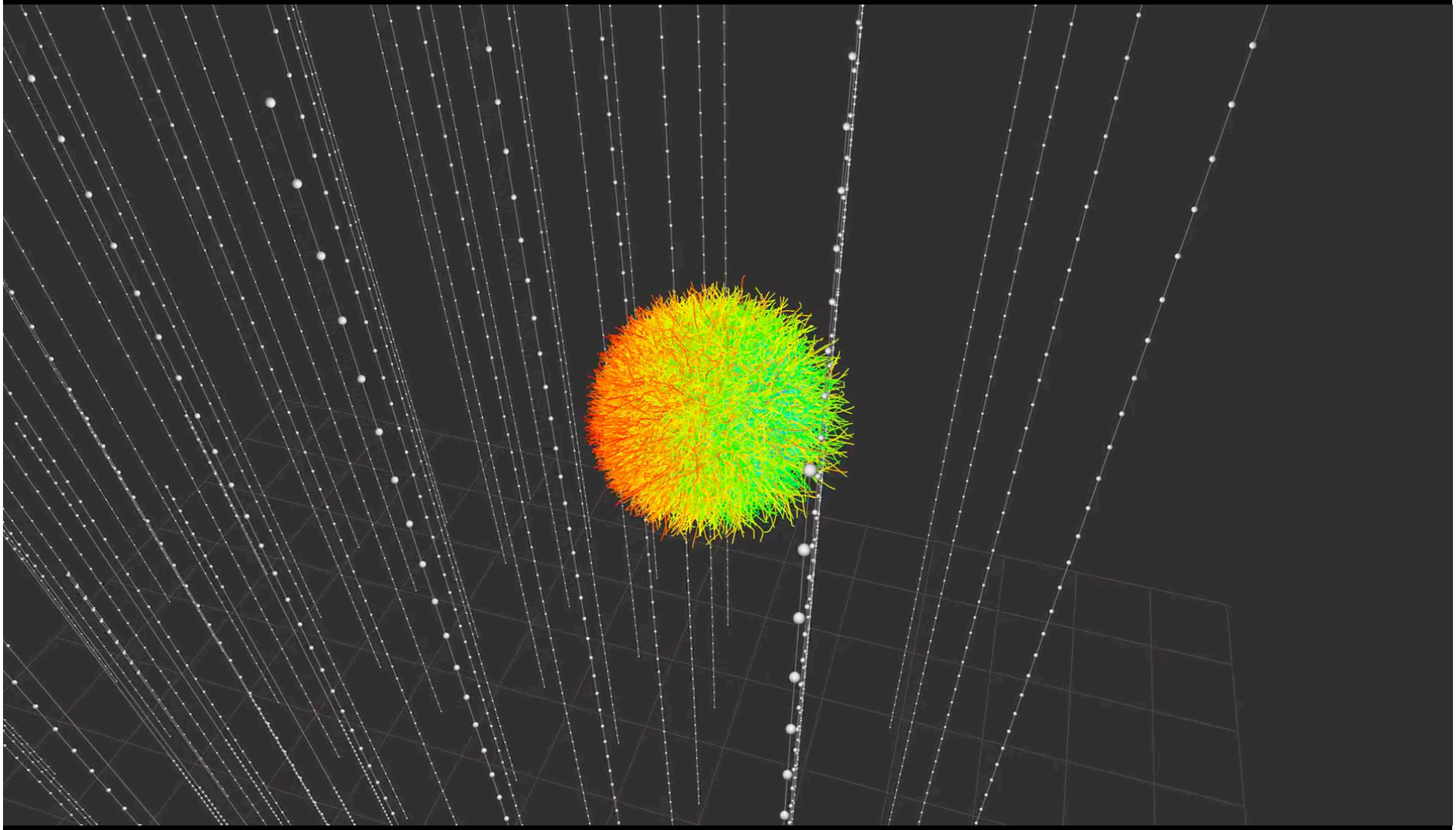
Track topology
(e.g. induced by muon neutrino)

Good pointing, 0.2° - 1°
Lower bound on energy

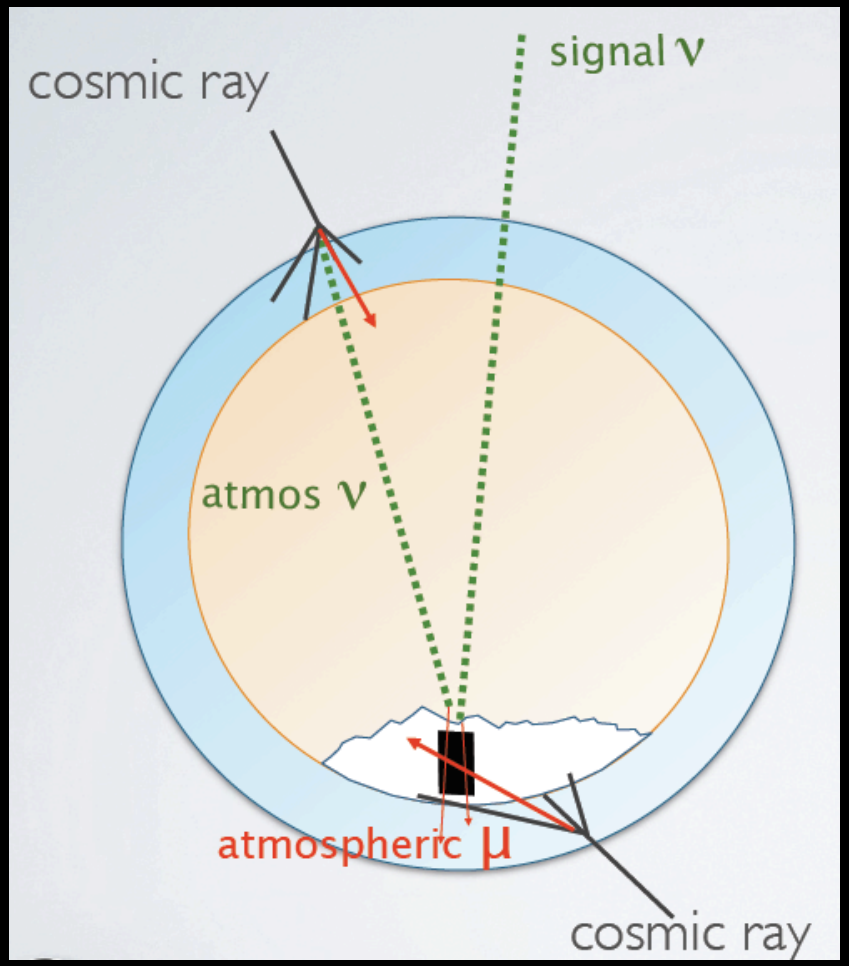


Cascade topology
(e.g. induced by electron neutrino)

Good energy resolution, 15%
Some pointing, 10° - 15°



Backgrounds

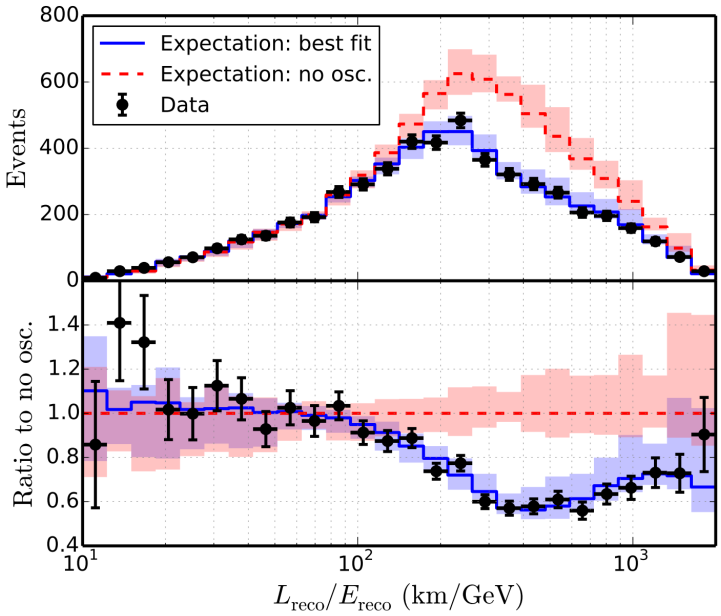


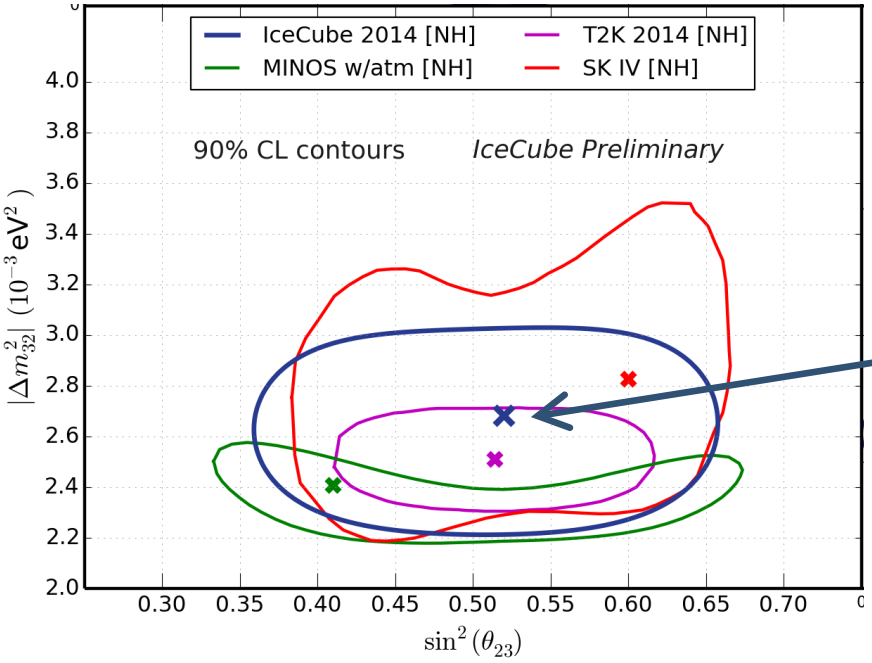
- Northern sky
  - Use the Earth as a filter
  - Atmospheric neutrinos
- Southern sky
  - Even at ~2 km deep, "Swamped" by CR muons in the downgoing region
  - Requires strong veto... but unique opportunity for >PeV neutrinos that would be absorbed in earth

Neutrino Physics with IceCube: Oscillations

Measurement of Neutrino Oscillation parameters (IceCube-DeepCore)

L/E shown for illustration: Full analysis performed with 2D representation





1-year analysis: PRL **111**, 081801 (2013)

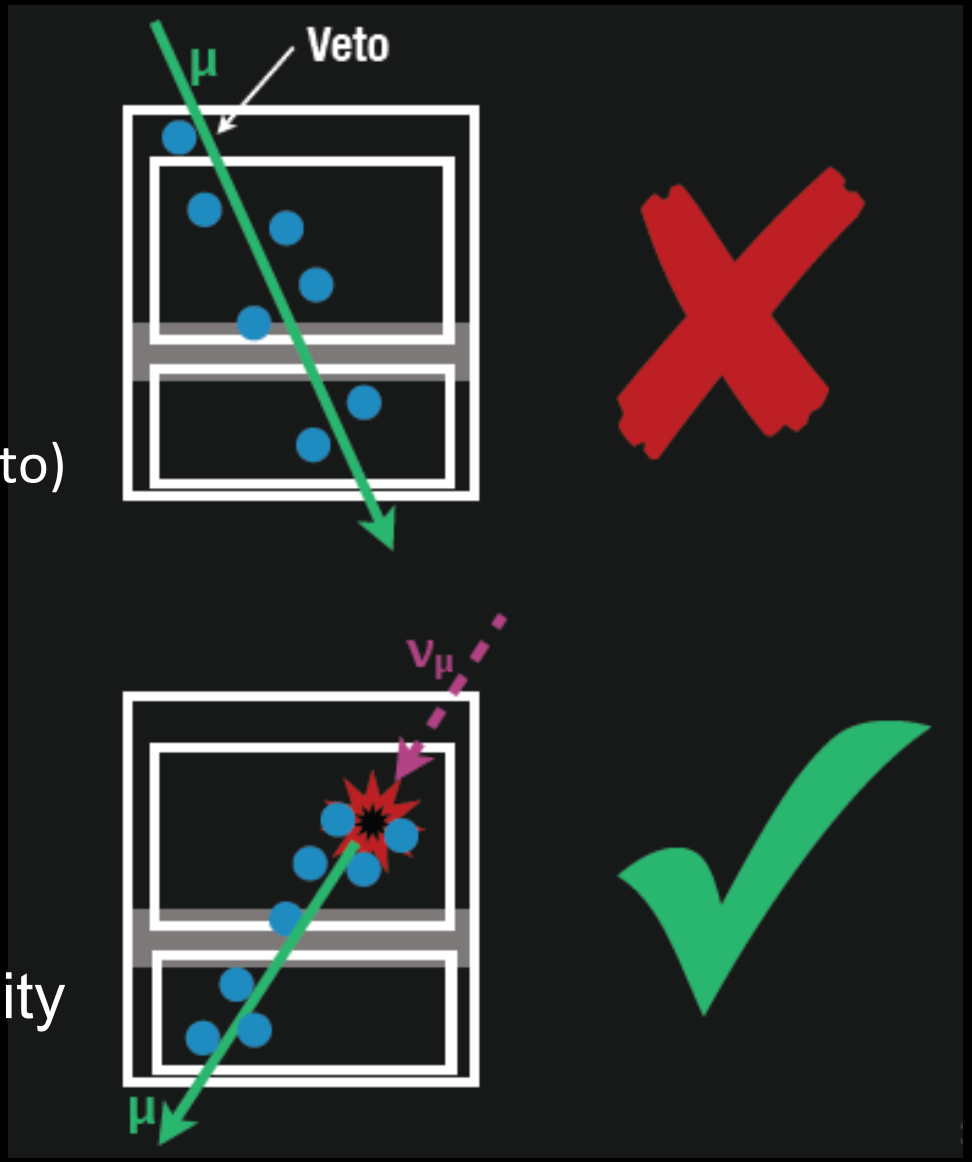
3-year analysis: preliminary (Neutrino 2014)

Pathway to future **PINGU** low-energy extension detector for precision measurements and determination of **Neutrino Mass Hierarchy**

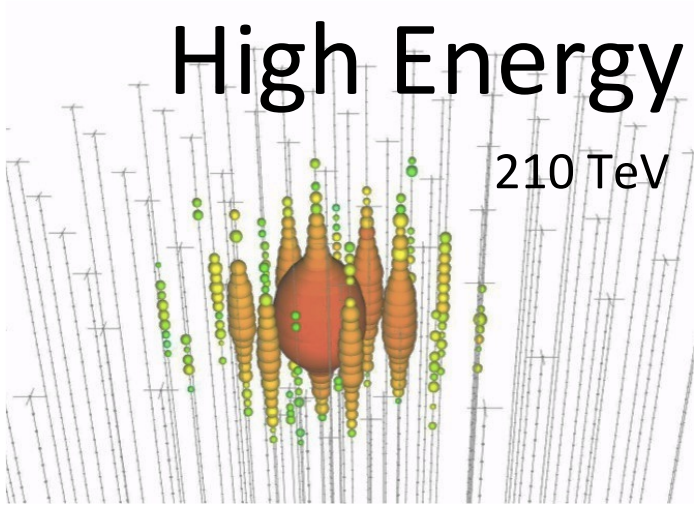
High Energy Starting Event Analysis

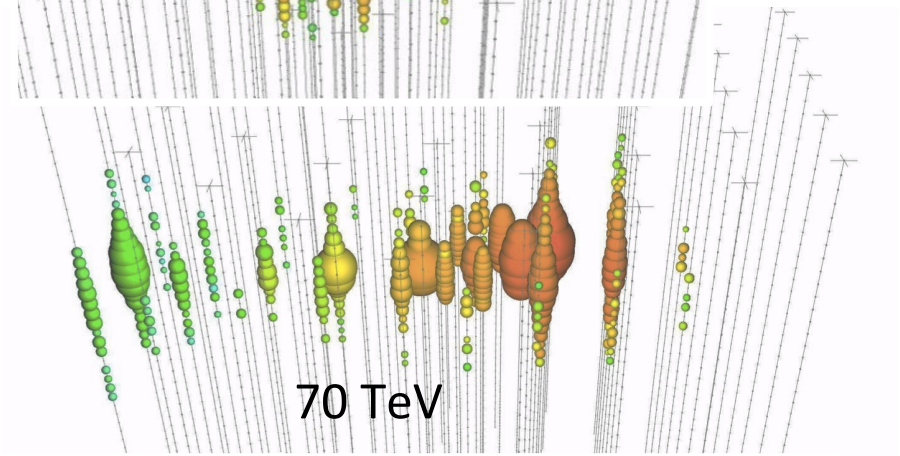
- Find contained events
  (420 Mton)
- Good calorimetry
- Complete sky coverage
  (atm. nu self-veto)
- Some will be muon neutrinos with good angular resolution

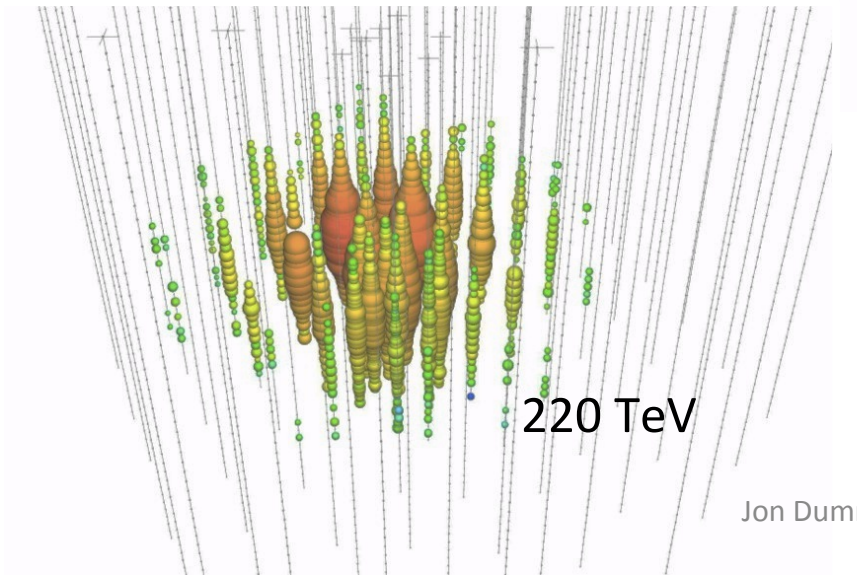
Loss in statistics is compensated by event quality

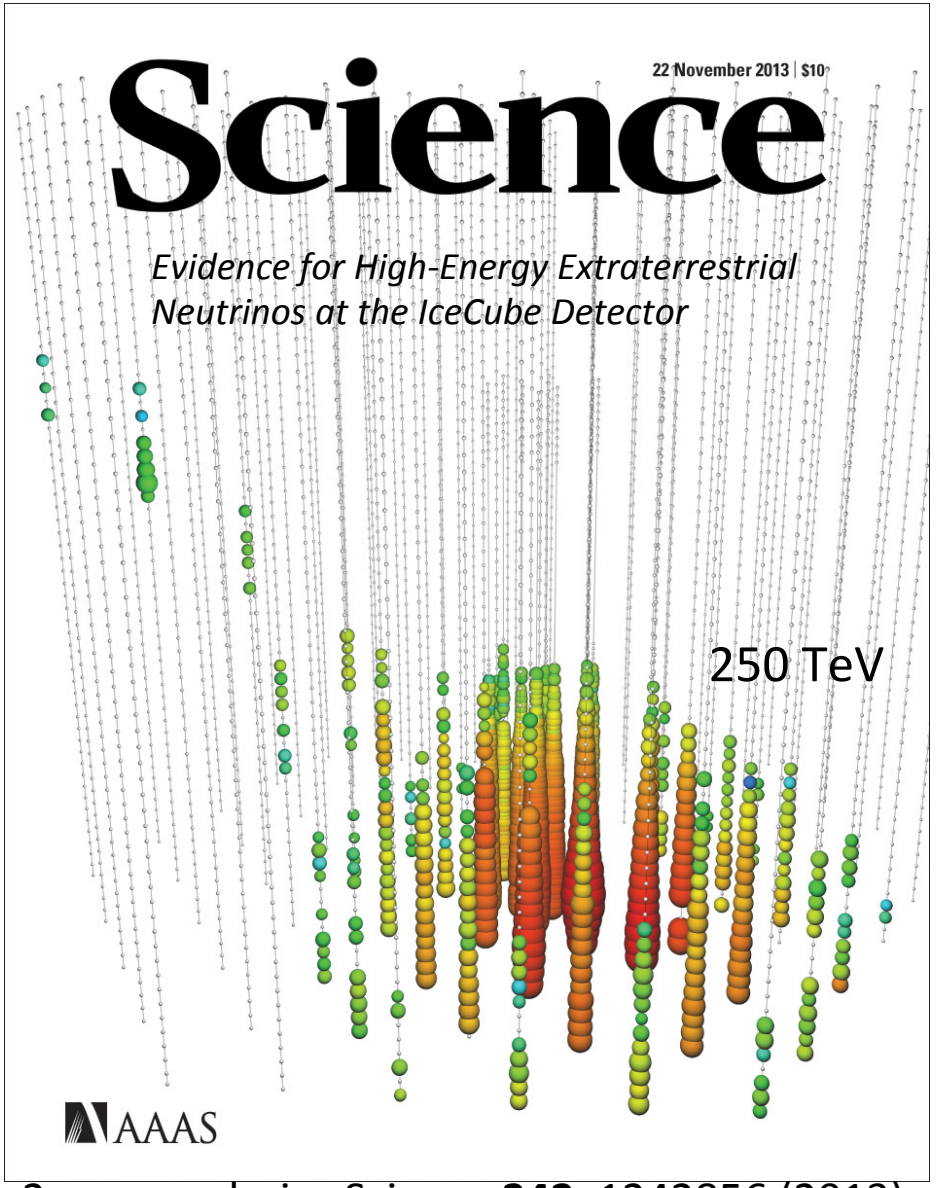


High Energy Starting Event Analysis









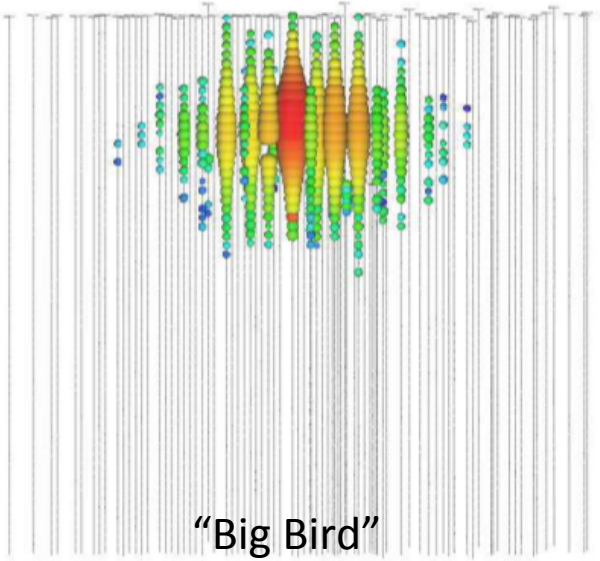
2-year analysis: Science **342**, 1242856 (2013)

High Energy Starting Event Analysis

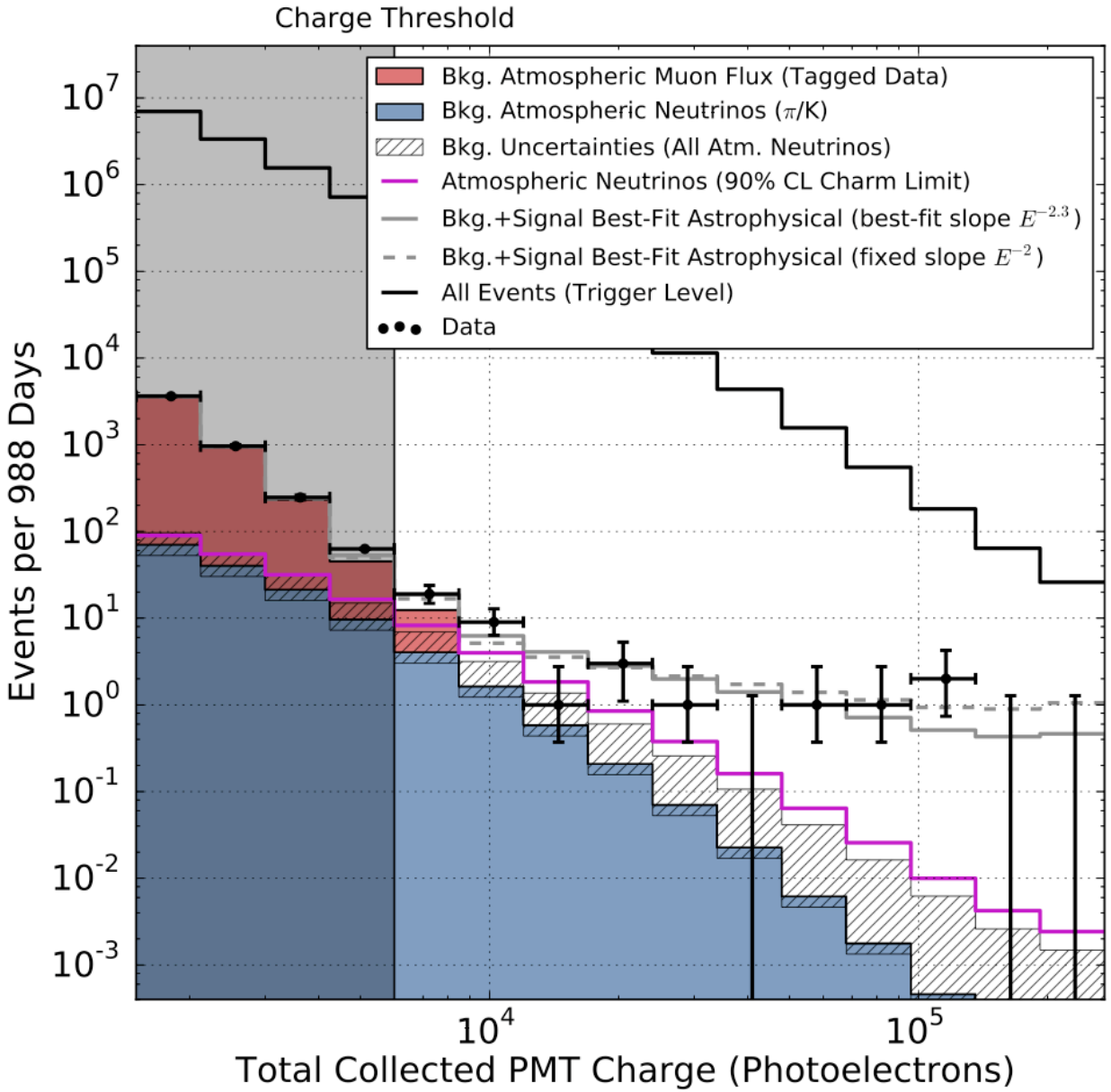
3-Year Analysis
PRL **113**, 101101 (2014)

36 events & **5.7 σ**
(~1/2 expected to be background)

Three > PeV events seen in three years, including a 2-PeV neutrino



"Big Bird"



High Energy Starting Event Analysis

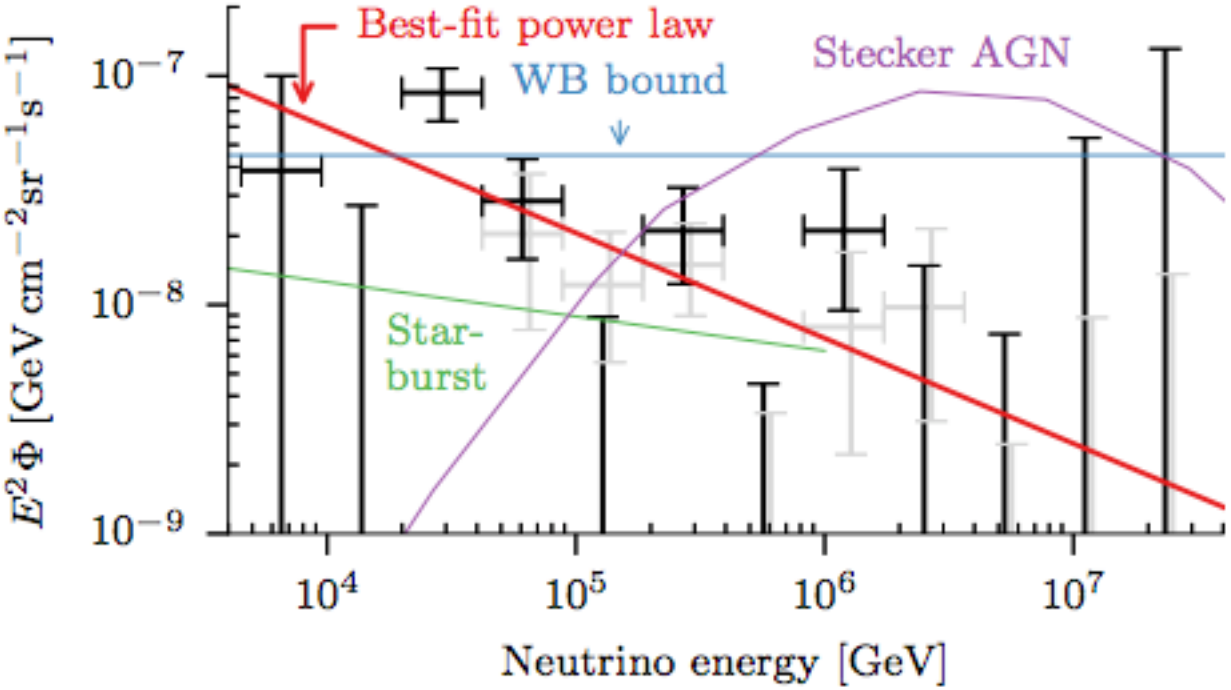
Latest spectral results: [arXiv:1410.1749]

$$\Phi_\nu = 2.06^{+0.4}_{-0.3} \times 10^{-18} \left(E_\nu/10^5 \text{ GeV}\right)^{-2.46\pm0.12} \text{GeV}^{-1}\,\text{cm}^{-2}\,\text{sr}^{-1}\,\text{s}^{-1}$$

Assuming an unbroken power law, standard expectation of **E^{-2} disfavored at 99% CL**

Atmospheric charmed-meson cross section limited to <1.52 x ERS (benchmark) 90% CL

ERS ref: R. Enberg, M. H. Reno, and I. Sarcevic, Phys. Rev. D 78, 043005 (2008)



Muon Neutrino Diffuse Analysis

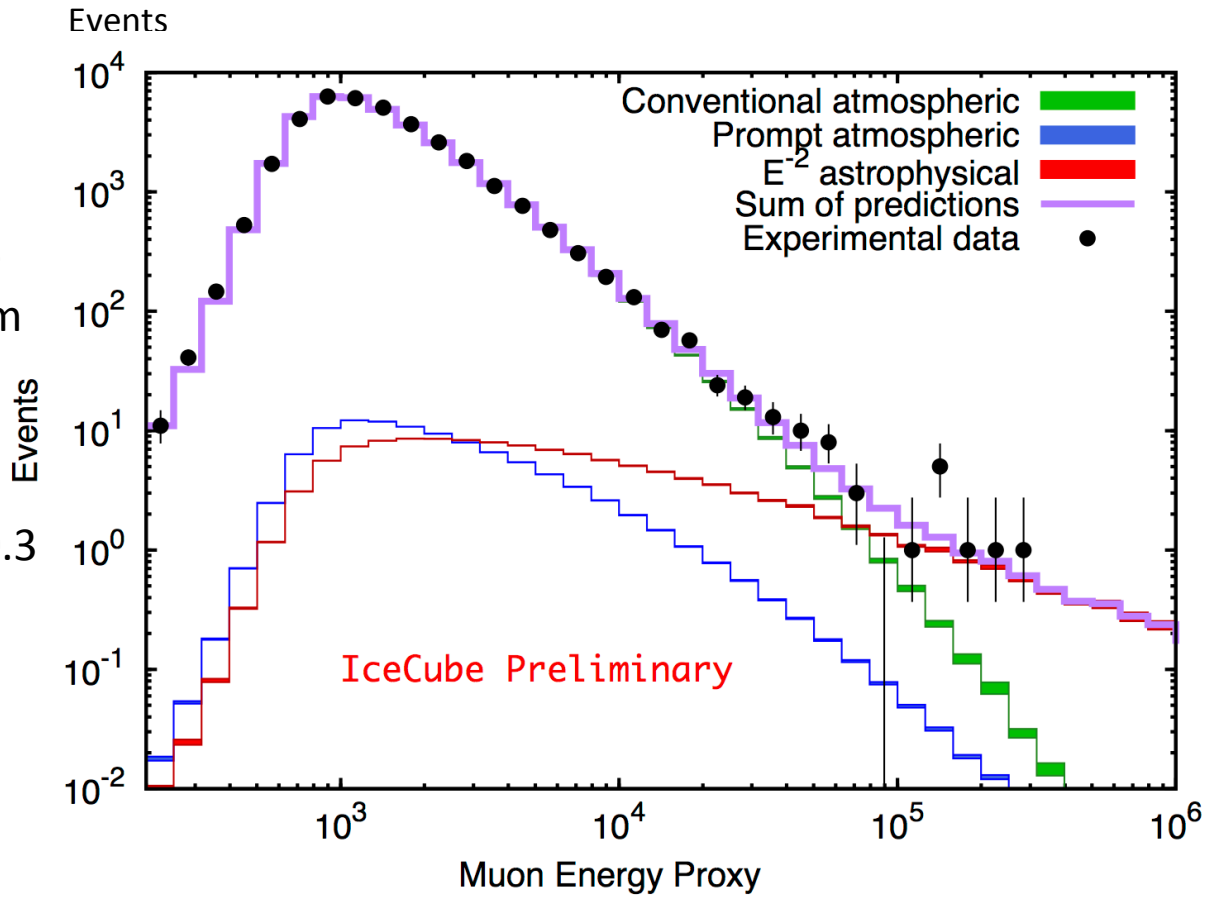
Complementary analysis to Starting Event analysis

Northern sky – allow events to enter from **outside** detector, use Earth as filter against muons from cosmic rays

Good pointing: ~ 0.5°
$\log_{10}$ muon energy resolution ~ 0.3 (at energies ~ 100 TeV)

35 000 events in 2-year analysis

Estimated 99.9% pure muon neutrino sample



Energy estimate for the muon track.
Only lower-bound on neutrino energy
(interacted before reaching detector)

Muon Neutrino Diffuse Analysis

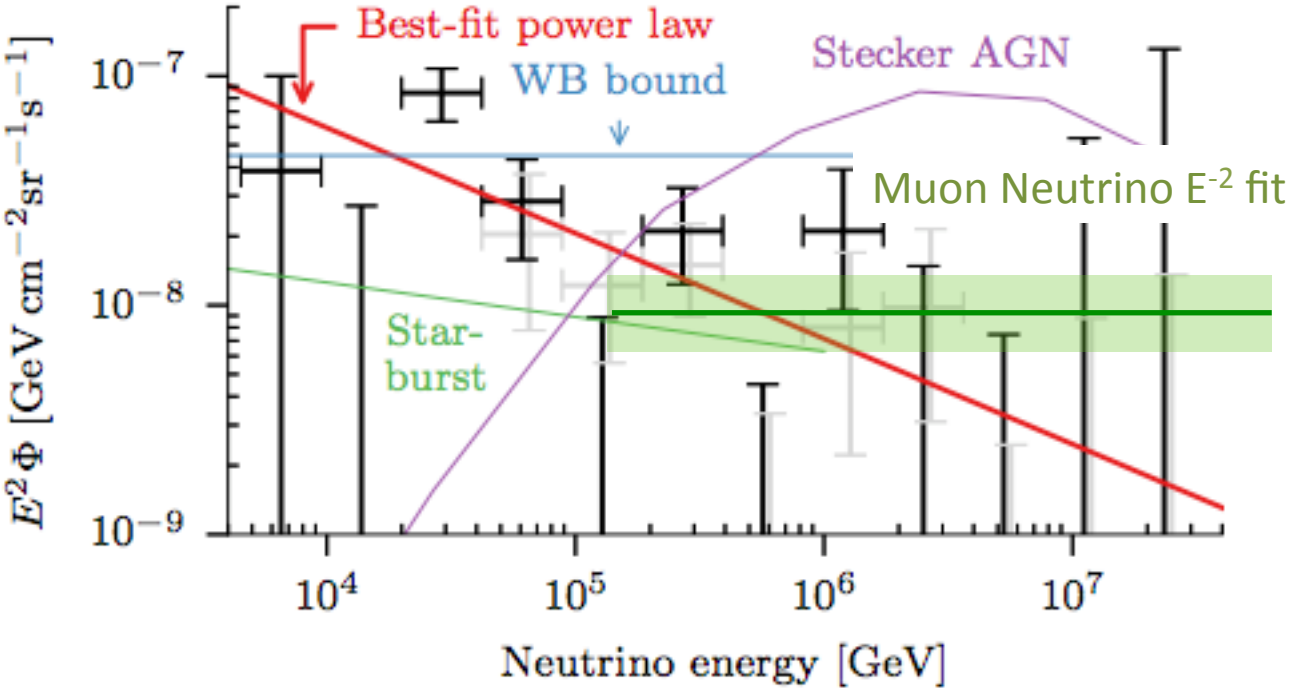
Best fit for E^{-2} astrophysical spectrum is:

$0.96 \pm 0.35 \times 10^{-8}$ GeV^{-1} cm^{-2} s^{-1} sr^{-1}

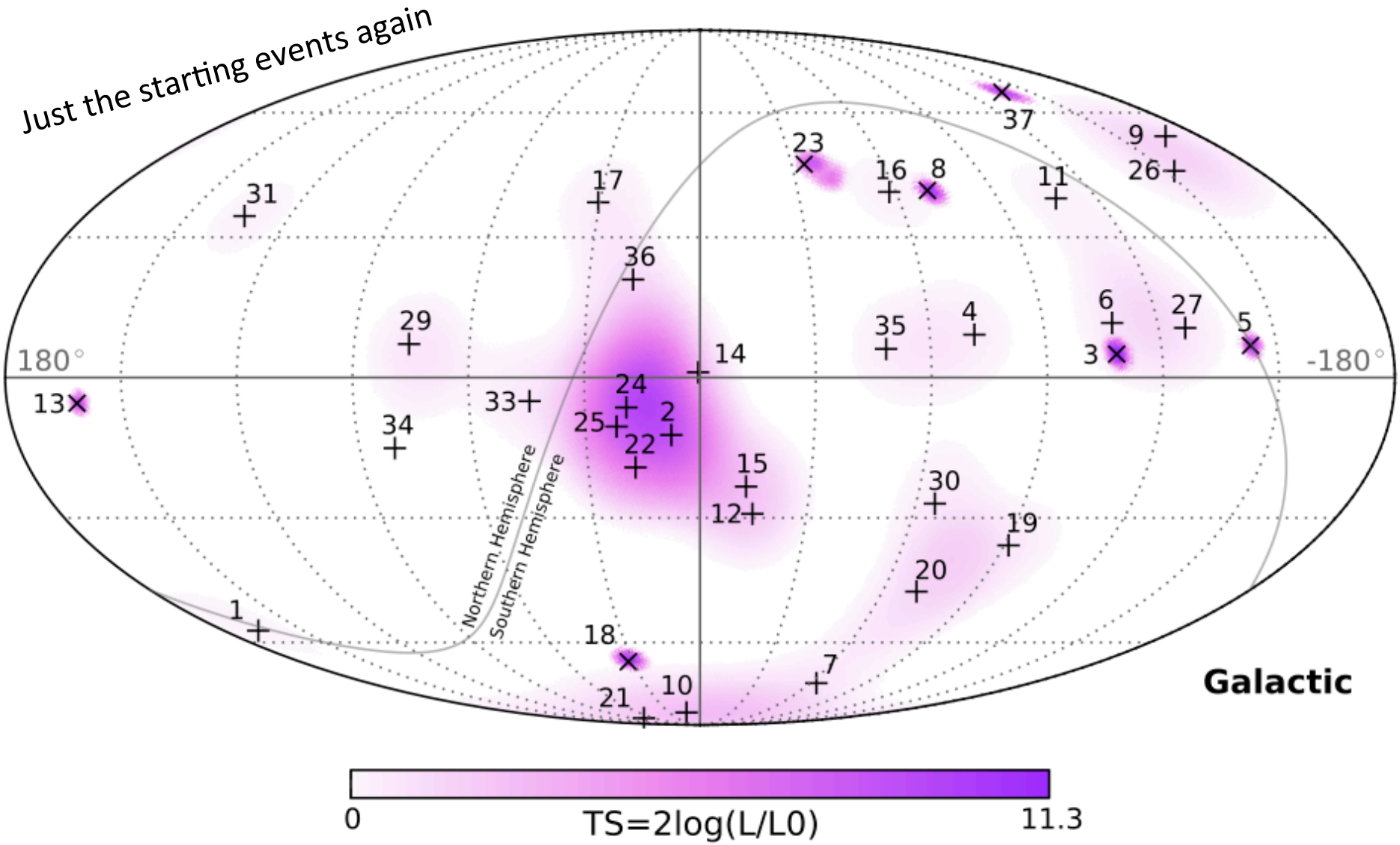
3.9σ evidence of astrophysical flux

(nearly) **independent** of starting track analysis

Strengthens evidence that flux is **all-flavor and all-sky**

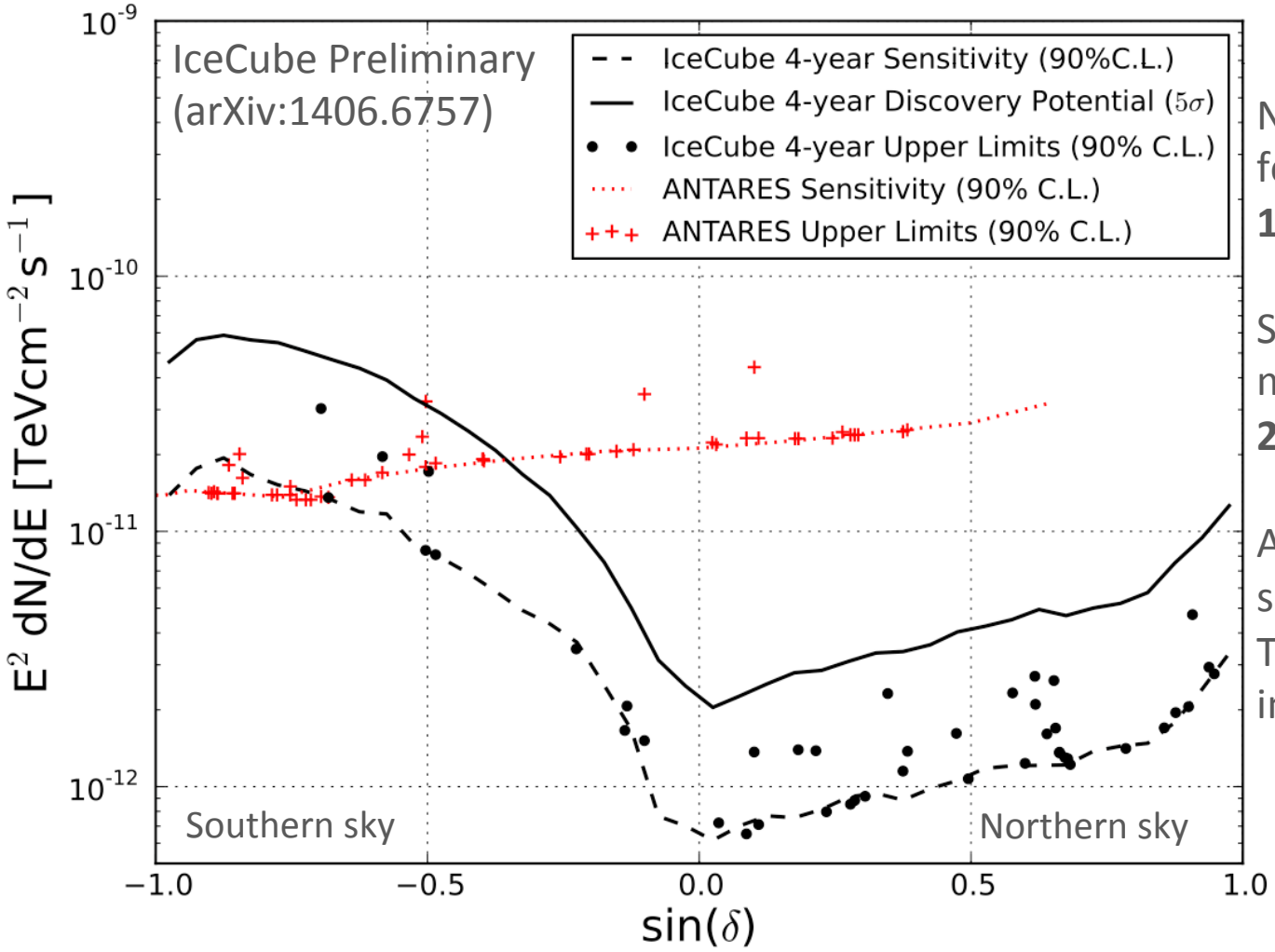


High Energy Starting Event **PS** Analysis



- No significant clustering: Several variations on point-source hypotheses performed
- If the flux extends as power law to lower energies, will it show up in muon PS search?

Muon Point Source Analysis

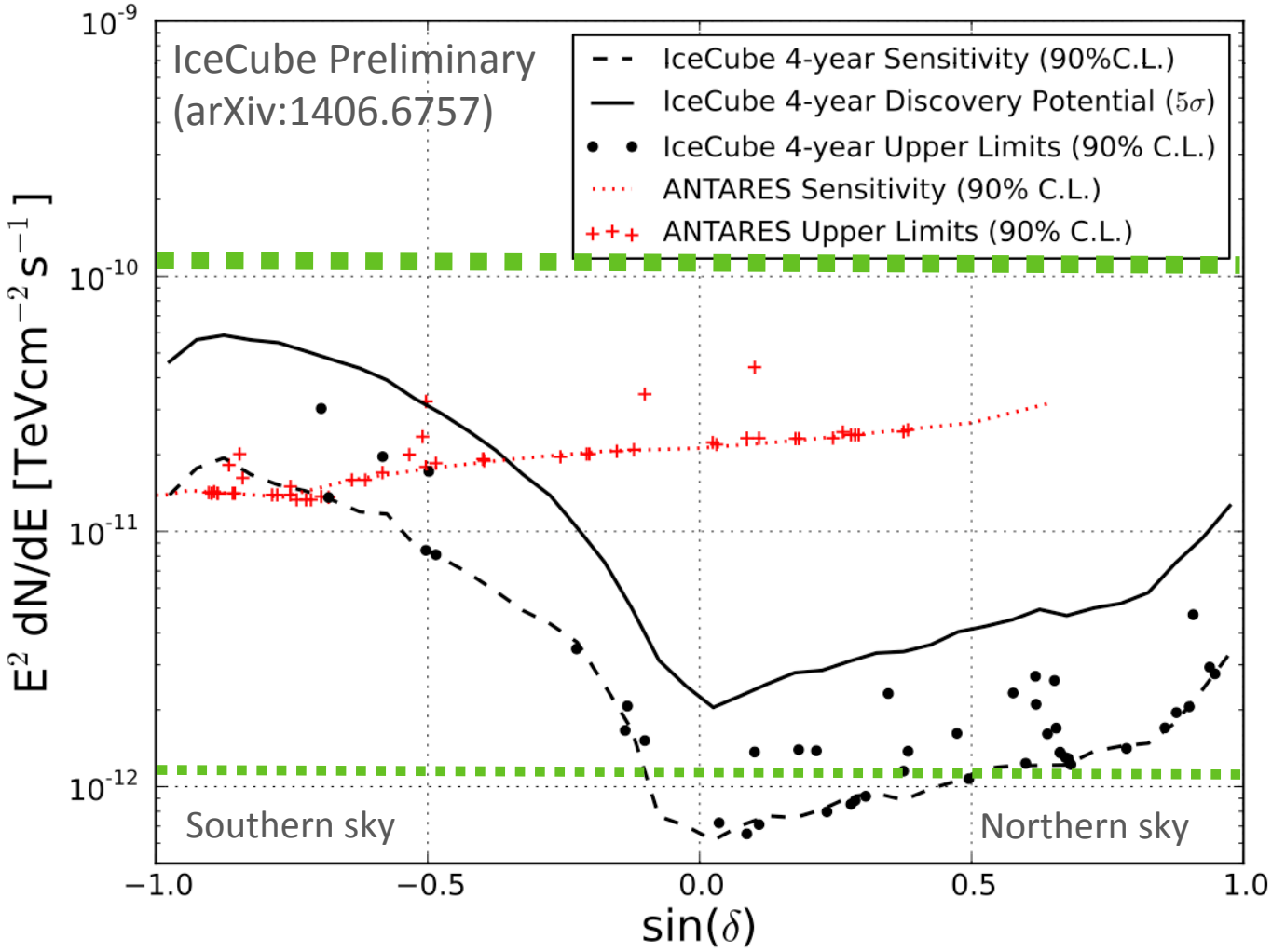


Northern Sky sensitive for TeV – PeV:
178k upgoing neutrinos

Southern Sky sensitive mainly > PeV:
216k downgoing muons

ANTARES sensitive to TeV – PEV in both skies

Point Source Analysis



Point-source equivalent flux if the diffuse flux came from:

one point in the sky

100 points in the sky

Can also perform population studies for specific source classes (e.g. AGN)

Summary

- First significant detection of an astrophysical neutrino flux up to 2 PeV
  - Shows up in complementary analyses
    - all-flavor contained cascades and tracks (primarily southern sky)
    - through-going muon-neutrino tracks (northern sky)

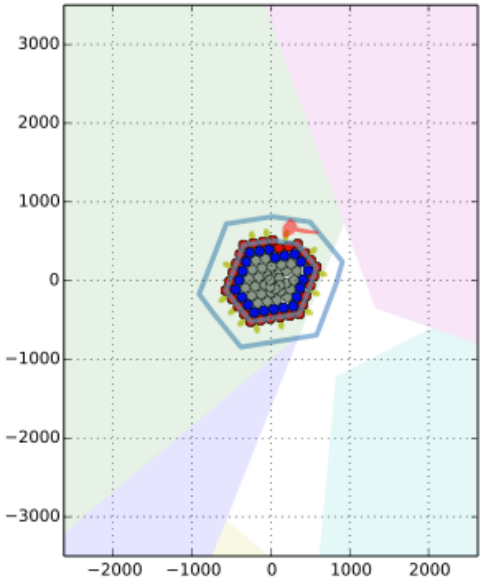
- Origins of this flux remain elusive
  - Consistent with isotropy and 1:1:1 flavor ratio
  - Ongoing work to use source catalogs to set limits on contribution to astrophysical flux (e.g. AGN)
  - Spectrum appears to be softer than E^{-2} (the standard expectation)
    - Possibly cut-off above few PeV

- What do other people think about the possible origins?

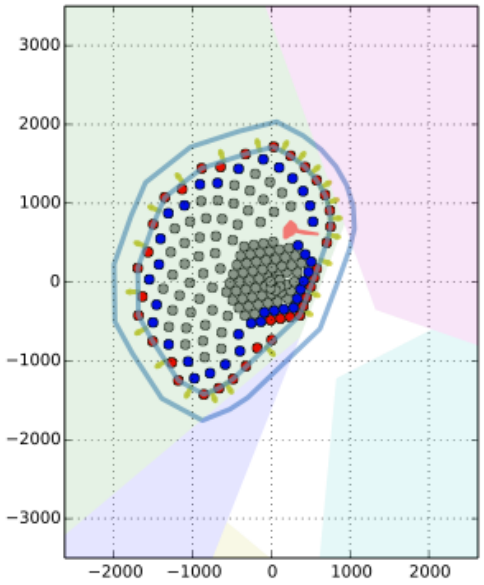
Questions?

78	Implications of Fermi-LAT observations on the origin of IceCube neutrinos	Wang, Zhao, Li	---	1407.2536	Extragalactic (starburst galaxies)
79	Cosmic neutrino background absorption line in the neutrino spectrum at IceCube	Ibe, Kaneta	PRD 90, 053011 (2014)	1407.2848	Energy gap
80	Charm decay in slow-jet supernovae as the origin of the IceCube ultra-high energy neutrino events	Bhattacharya, Enberg, Reno, Sarcevic	---	1407.2985	Slow-jet supernovae
81	Glashow resonance as a window into cosmic neutrino sources	Barger, Fu, Learned, Marfatia, Pakvasa, Weiler	---	1407.3255	Glashow resonance
82	Astrophysical neutrinos, PeV events at IceCube, and the Direct Detection of Dark Matter	Bhattacharya, Gandhi, Gupta	---	1407.3280	Exotic (dark matter)
83	High-energy neutrino fluxes and flavor ratio in the Earth atmosphere	Sinegovskaya, Morozova, Sinegovsky	---	1407.3591	Prompt background, flavor ratios
84	Constraining Astrophysical Neutrino Flavor Composition from Leptonic Unitarity	Xu, He, Rodejohann	---	1407.3736	Flavor composition
85	PeV Neutrinos from Ultra-High-Energy Cosmic Rays	Sigl, Vliet	---	1407.6577	Not cosmogenic
86	Describing the Observed Cosmic Neutrinos by Interactions of Nuclei with Matter	Winter	---	1407.7536	Extragalactic (UHECR sources)
87	Some possible sources of IceCube TeV-PeV neutrino events	Sahu, Miranda	---	1408.3664	Extragalactic (blazars)
88	Constraints to a Galactic Component of the Ice Cube cosmic neutrino flux from ANTARES	Spurio	---	1409.4552	ANTARES
89	Estimating the contribution of Galactic sources to the diffuse neutrino flux	Anchordoqui, Goldberg, Paul, da Silva, Vlcek	---	1410.0348	Galactic
90	Flavor ratios of extragalactical neutrinos and neutrino shortcuts in extra dimensions	Aeikens, Päs, Pakvasa, Sicking	---	1410.0408	Flavor ratios
91	IceCube astrophysical neutrinos without a spectral cutoff and (10^15-10^17) eV cosmic gamma radiation	Kalashev, Troitsky	---	1410.2600	Spectrum, gamma connection
92	A new physics interpretation of the IceCube data	Illana, Masip, Meloni	---	1410.3208	Exotic
93	IceCube events and decaying dark matter: hints and constraints	Esmaili, Kang, Serpico	---	[1]	Exotic (dark matter)

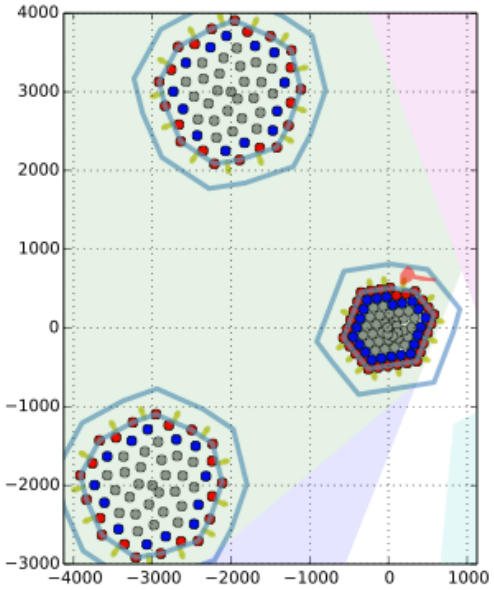
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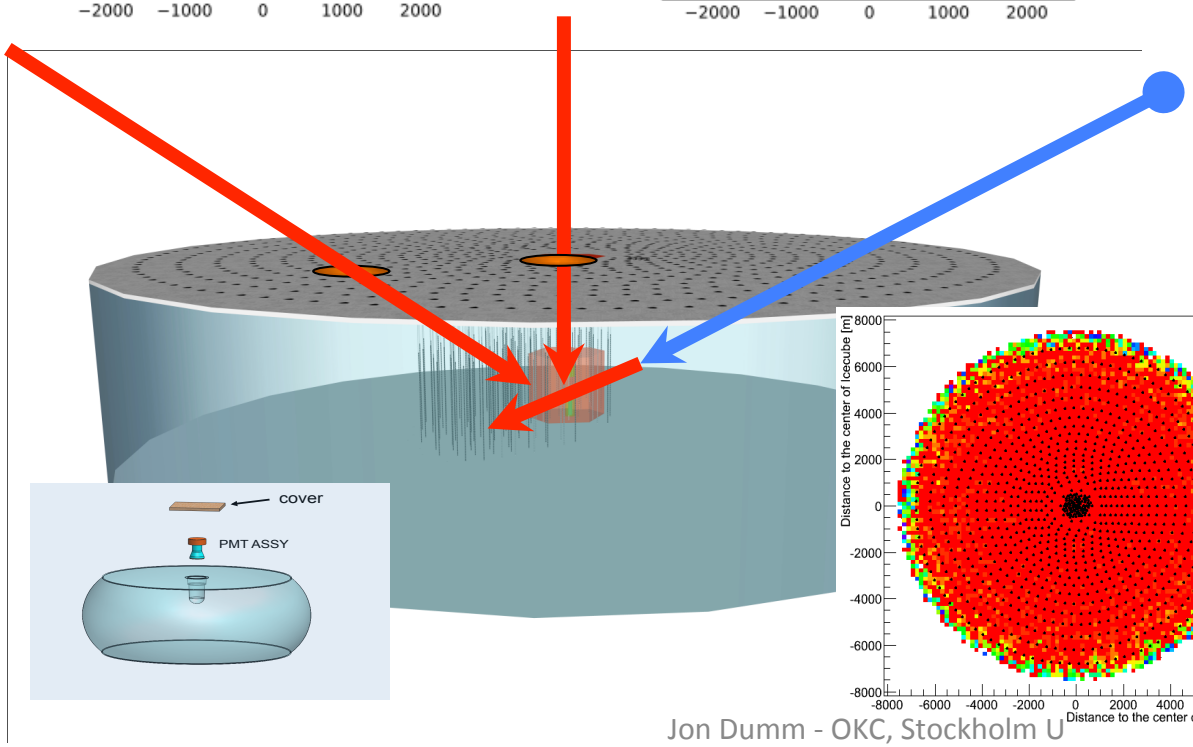


strings: IC86+96 spacing: ~240m



strings: IC86+2x60 spacing: ~240m

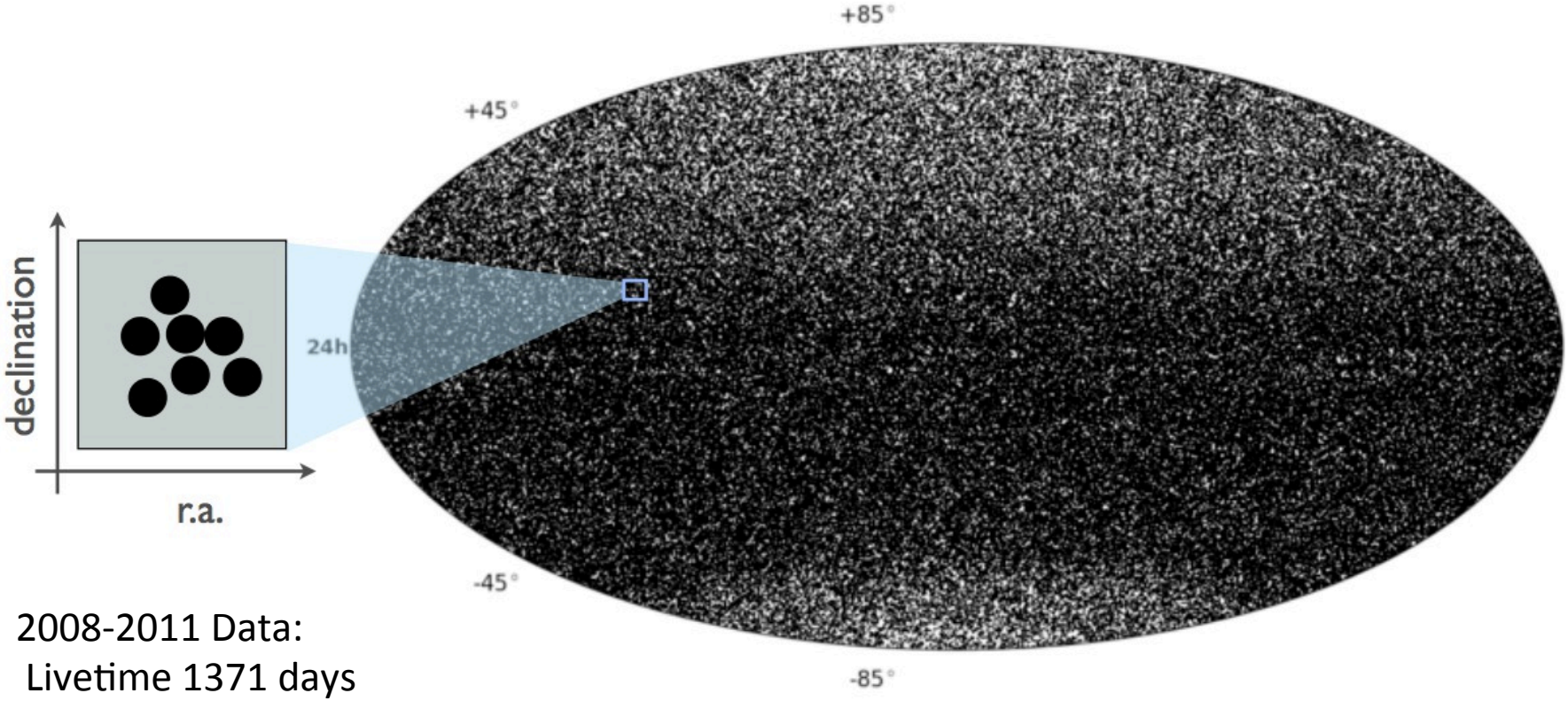




High Energy Extension

InIce Strings
+
Surface Veto

Point Source Analysis



2008-2011 Data:
Livetime 1371 days

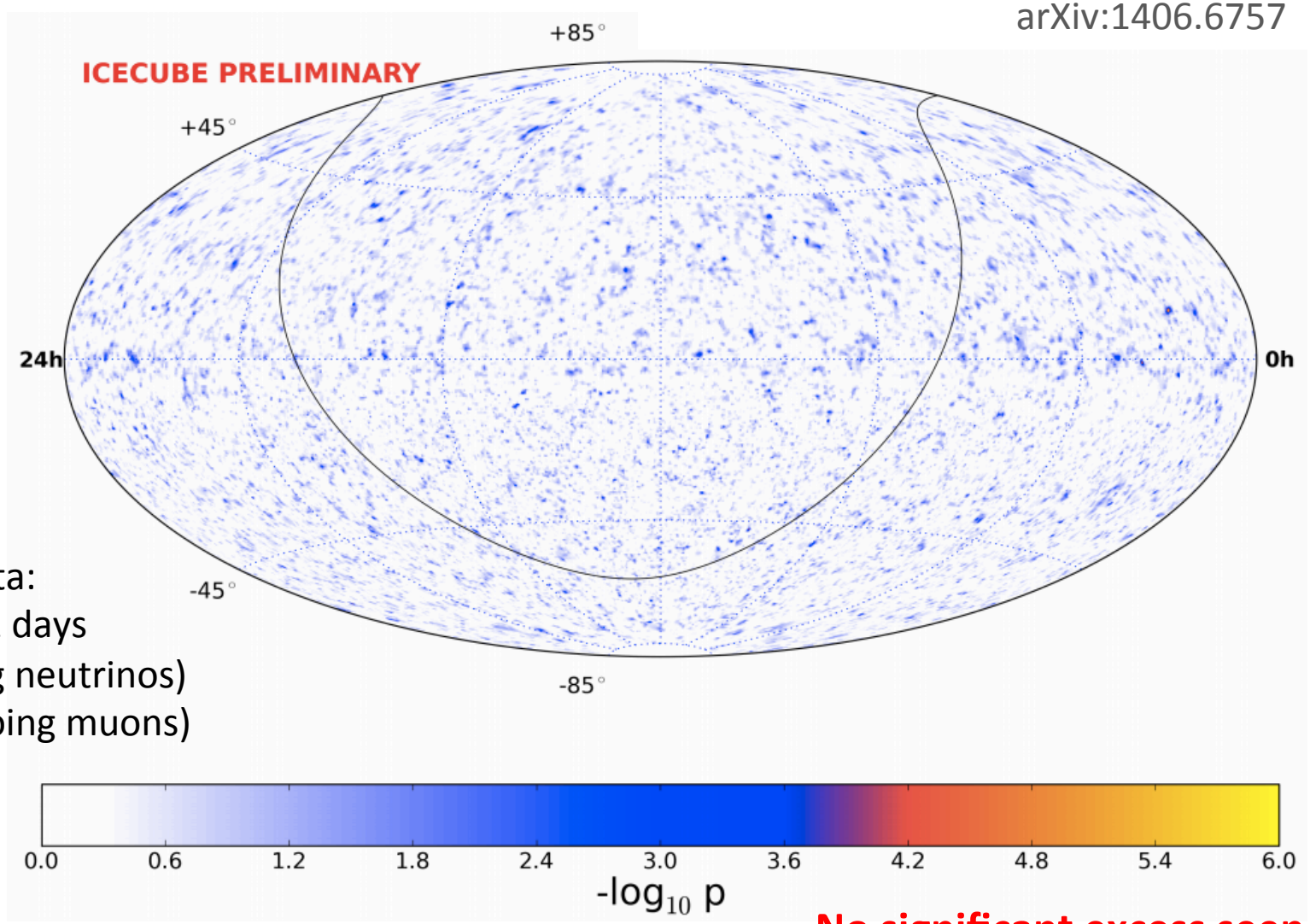
178 000 upgoing neutrinos

216 000 downgoing CR muons

Perform a search looking for significant clustering of events above random background expectation (unbinned maximum likelihood analysis)

Point Source Analysis

arXiv:1406.6757



2008-2011 Data:
Livetime 1371 days
178k (upgoing neutrinos)
216k (downgoing muons)

No significant excess seen

Lack of signal in PS analysis in lower energy range can be used to set limits on contribution from individual sources and source populations to diffuse flux

High Energy Starting Event Analysis

Assuming unbroken E^{-2} spectrum, best-fit astrophysical normalization is:

$$E^2\phi(E) = 0.95 \pm 0.3 \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

Lack of events above 2 PeV (3.1 expected in this analysis; more in the EHE analysis, PRL 111, 021103 (2013)) suggests **unbroken E^{-2} disfavored**

Best power-law fit yields a spectral index of **-2.3** (and fits 0 charm component):

$$E^2\phi(E) = 1.5 \times 10^{-8}(E/100\mathrm{TeV})^{-0.3}\mathrm{GeVcm^{-2}s^{-1}sr^{-1}}$$

