Detection of a Particle Shower at the Glashow Resonance with IceCube

Lu Lu

UW Madison

Discovery of antimatter (Carl Anderson, 1932)

- Cosmic rays in cloud chamber
- Long before the start of particle accelerators

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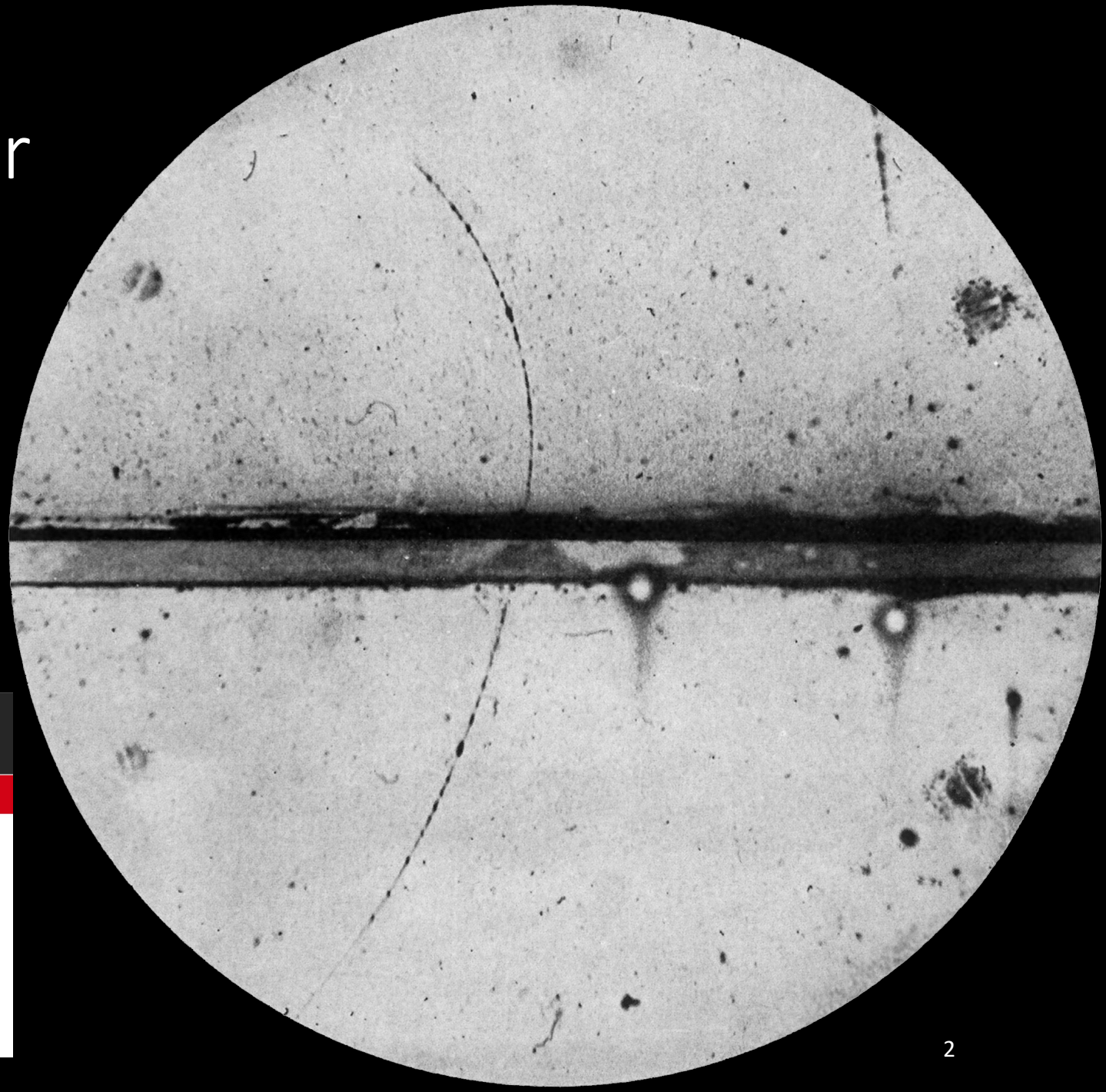
THE APPARENT EXISTENCE OF EASILY DEFLECTABLE POSITIVES

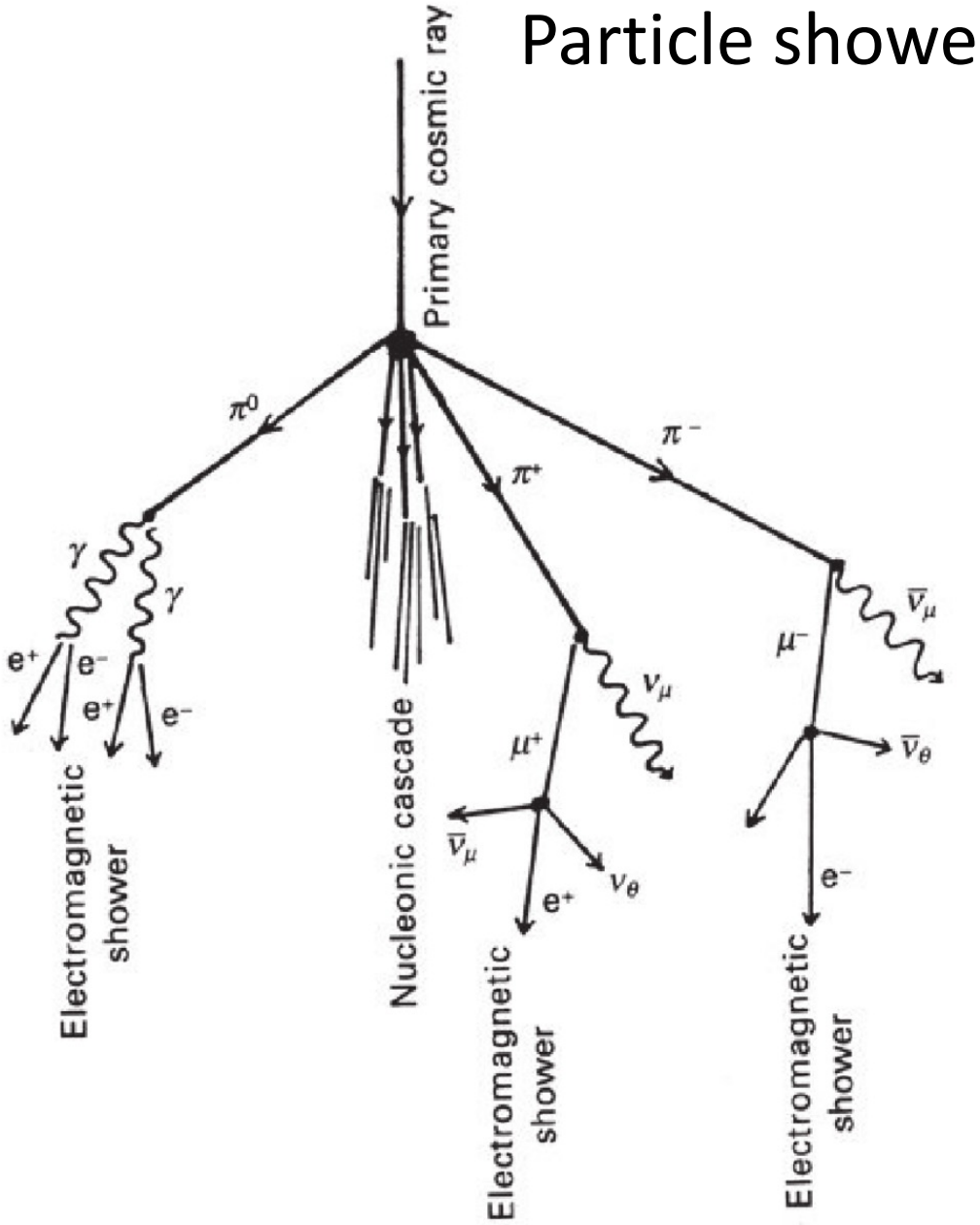
By Carl D. Anderson

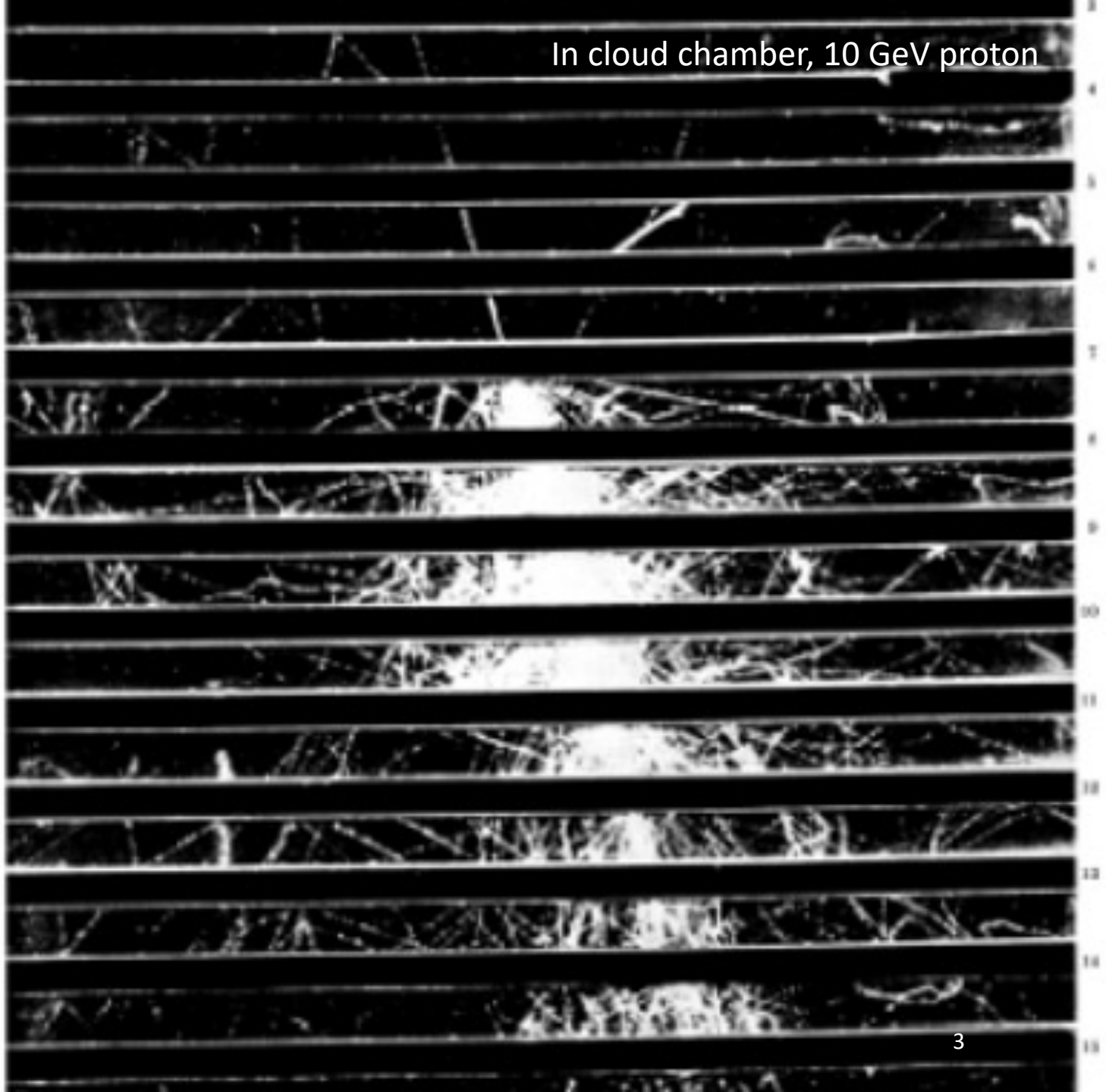
+ See all authors and affiliations

Science 09 Sep 1932:
Vol. 76, Issue 1967, pp. 238-239
DOI: 10.1126/science.76.1967.238

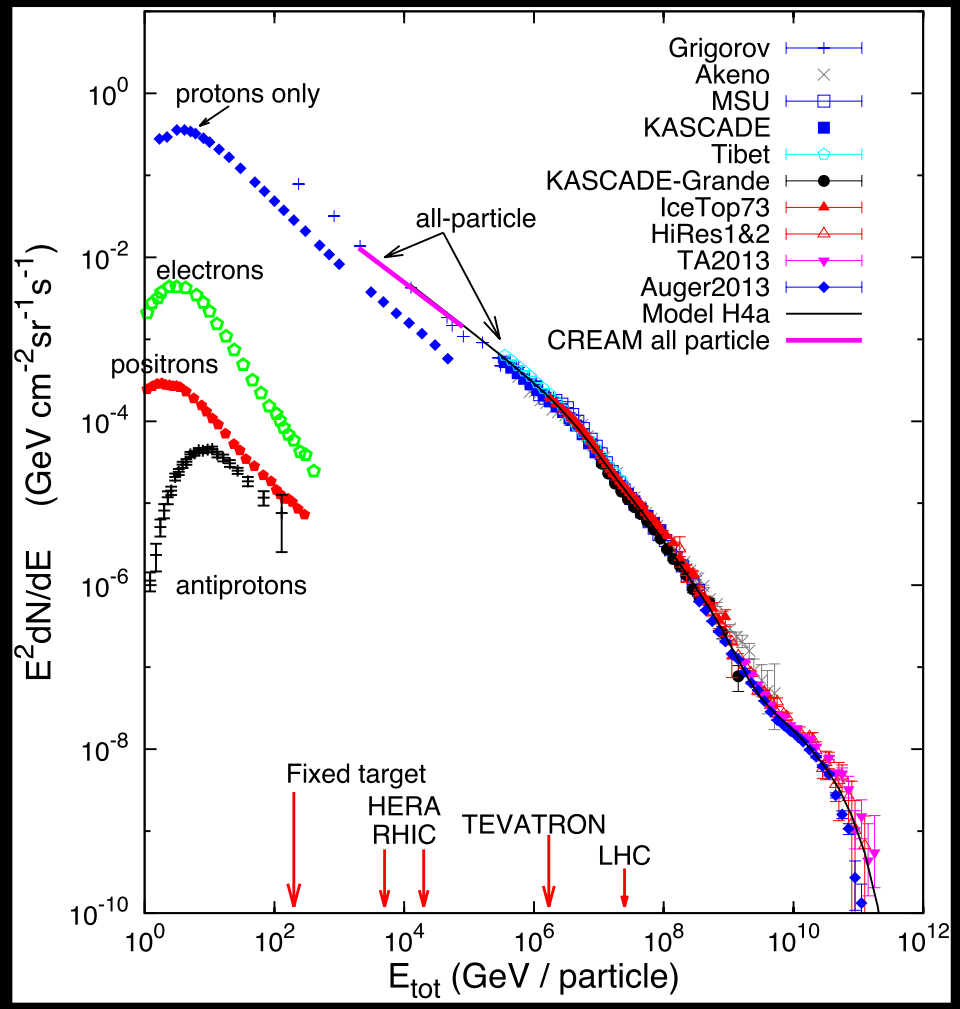


Particle shower





10^{20} eV charged particles do exist



We know their energy spectrum over 11 orders of magnitude

Their sources (especially at the highest energies) are still mostly unknown

Charged particles diffuse and deflect during propagations

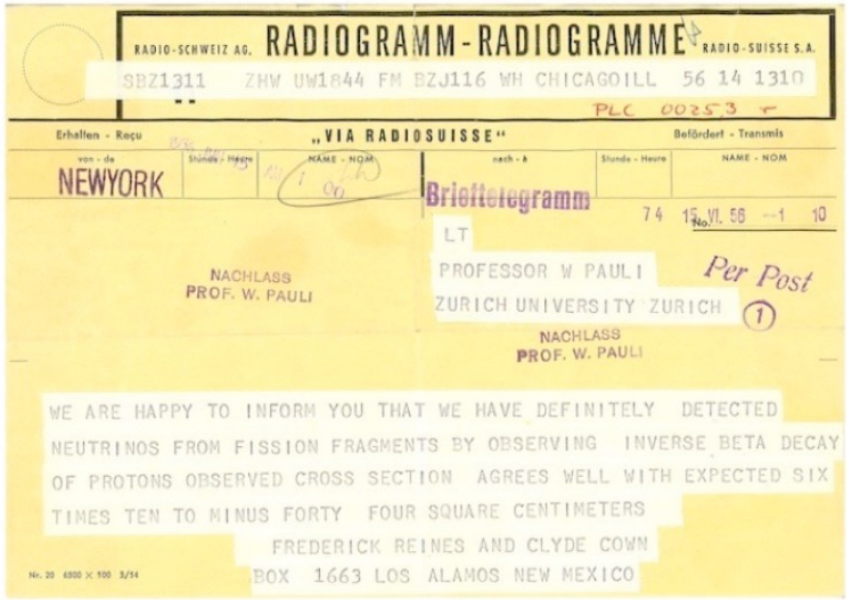
Expected neutrinos

Discovery of neutrinos

Telegram by Reines and Cowan 1956

Frederick Reines

Clyde Cowan



RADIO-SCHWEIZ AG. RADIOGRAMM-RADIOGRAMME RADIO-SUISSE S.A.

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von - de NEWYORK

Stunde - Heure NAME - NOM

nach - à Brieftelegramm

Stunde - Heure NAME - NOM

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LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

1

NACHLASS PROF. W. PAULI

NACHLASS PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN

BOX 1663 LOS ALAMOS NEW MEXICO

detection of an electron anti-neutrino via inverse β-decay

$$\bar{\nu}_e + p \rightarrow n + e^+$$

You need a slab of lead of 1,000,000,000,000 meters to scatter a 1 GeV neutrino

Link to paper

W boson mass? – a shifted resonance energy

PHYSICAL REVIEW VOLUME 118, NUMBER 1 APRIL 1, 1960

Resonant Scattering of Antineutrinos

SHELDON L. GLASHOW*
Institute for Theoretical Physics, Copenhagen, Denmark

(Received October 26, 1959)

1960

The hypothesis of an unstable charged boson to mediate muon decay radically affects the cross section for the process $\bar{\nu}+e \rightarrow \bar{\nu}+\mu^-$ near the energy at which the intermediary may be produced. If the boson is assumed to have K-meson mass, the resonance occurs at an incident antineutrino energy of $\sim 2\times 10^{12}$ ev. The flux of energetic antineutrinos produced in association with cosmic-ray muons will then produce two muon counts per day per square meter of detector, independently of the depth and the orientation at which the experiment is performed.

~2 TeV

Cosmic neutrino and the possibility of searching for *W* bosons with masses 30–100 GeV in underwater experiments

V. S. Berezinskiĭ and A. Z. Gazizov

Institute of Nuclear Reseach, USSR Academy of Sciences

1977

(Submitted February 3, 1977)
Pis'ma Zh. Eksp. Teor. Fiz. **25**, No. 5, 276–278 (5 March 1977)

The possibility is discussed for searching for W bosons in underwater experiments with the aid of the resonant reaction $\bar{\nu}_e + e^- \rightarrow W^- \rightarrow$ hadrons. The resonance production of W bosons manifests itself as a narrow peak in the energy spectrum of the underwater nuclear-electromagnetic cascades. For W-boson masses 30–100 GeV (resonant antineutrino energies $9\times 10^{14} - 1\times 10^{16}$ eV) the resonant effect should exceed by more than one order of magnitude the background due to the nonresonant neutrino events.

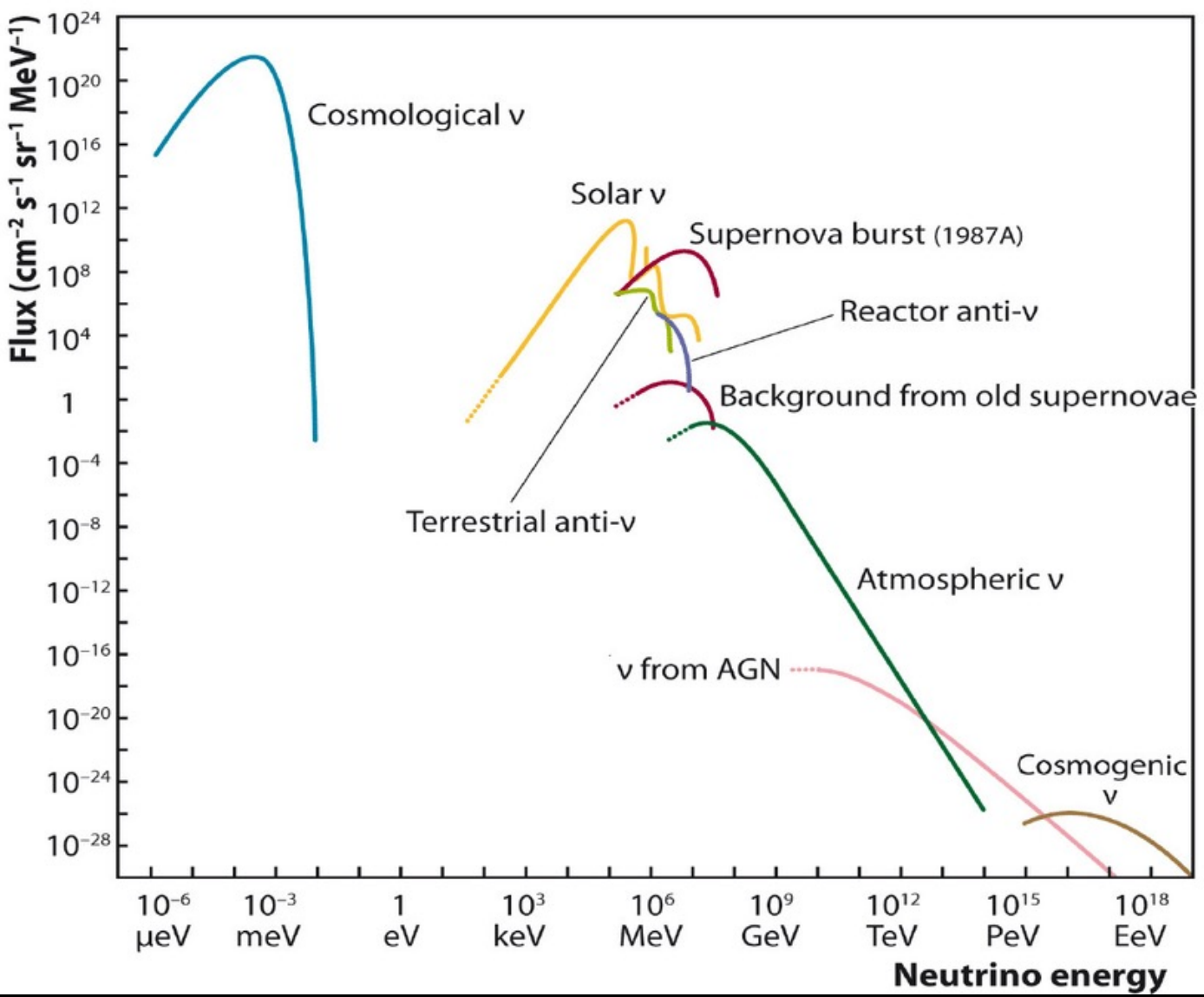
PACS numbers: 13.15.+g, 14.80.Fs

~5 PeV

The search for the W boson in underwater neutrino experiments is most effective with the aid of the Glashow resonant reaction[1] $\bar{\nu}_e + e^- \rightarrow W^- \rightarrow$ hadrons. The W-boson masses (m_W) from 30 to 100 GeV correspond to antineutrino energies $E_0 = m_W^2/2m_e$ from 9×10^4 to 1×10^{16} eV. The W-boson mass in the Weinberg model ($m_W \approx 70$ Gev) corresponds to an antineutrino energy 5×10^{15} eV. Neutrino fluxes of such energies, sufficient for the search for the W bosons, can be expected from extragalactic sources.[2] The background due to atmospheric muons is negligibly small at such energies, and the resonant production of W

Neutrino flux

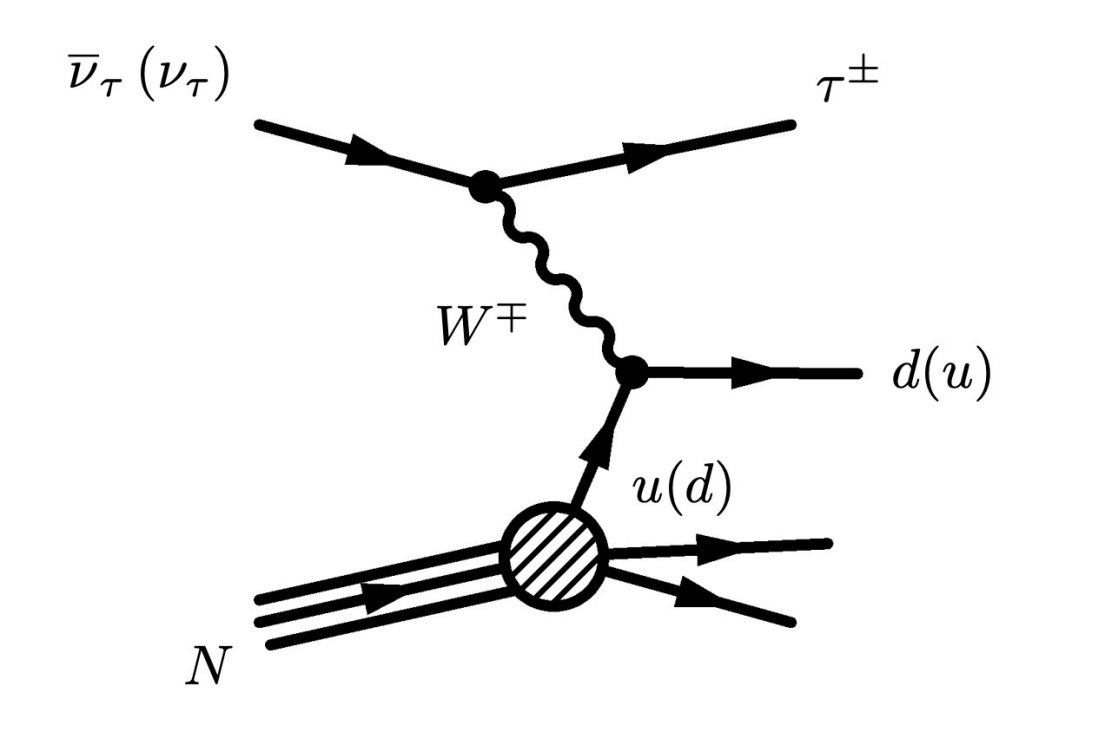
~ **100 trillion** neutrinos pass through your body every second

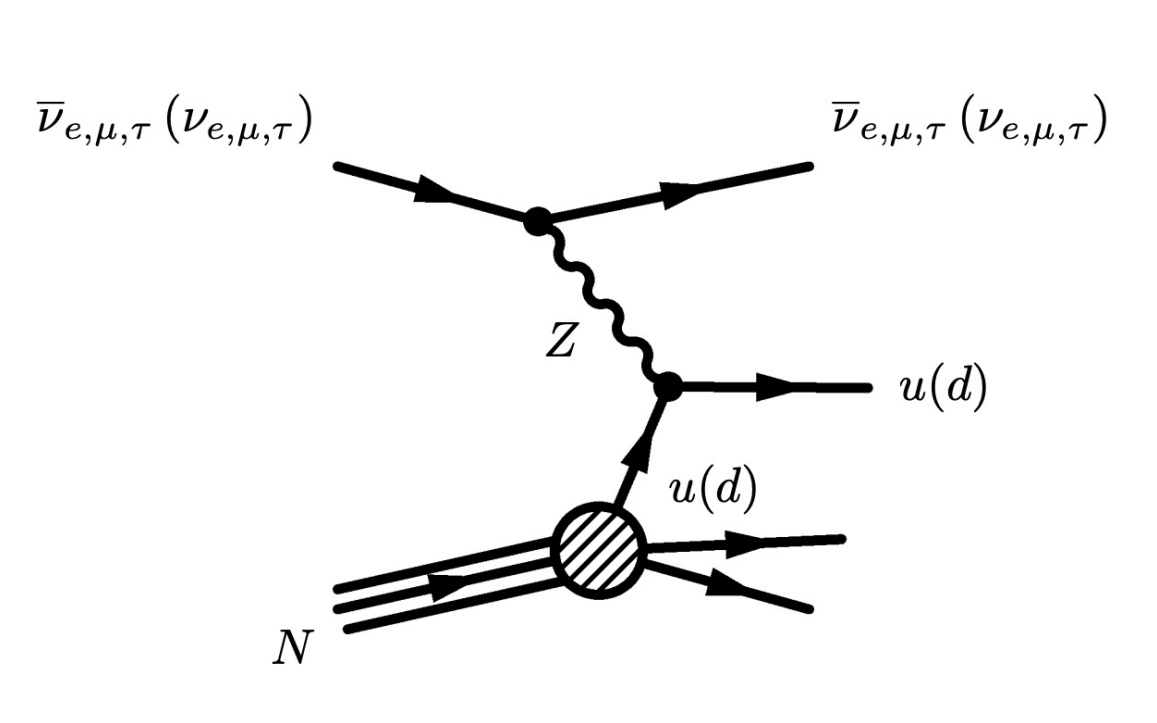


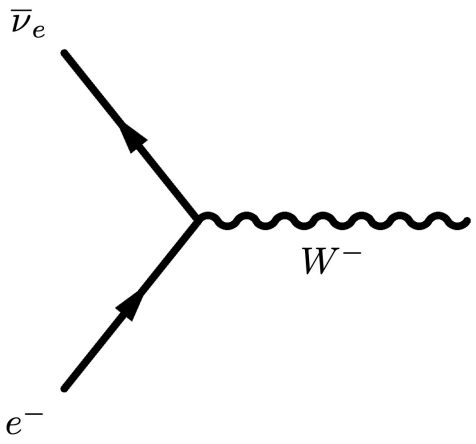
Neutrino interaction with matter

Deep inelastic neutrino-nucleon scattering

- Charged current and neutral current interactions

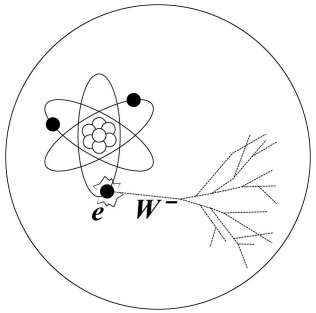






Neutrino-electron scattering

at a neutrino energy of 6.3 PeV, the centre-of-mass energy (80.5 GeV) is large enough to produce a real W boson

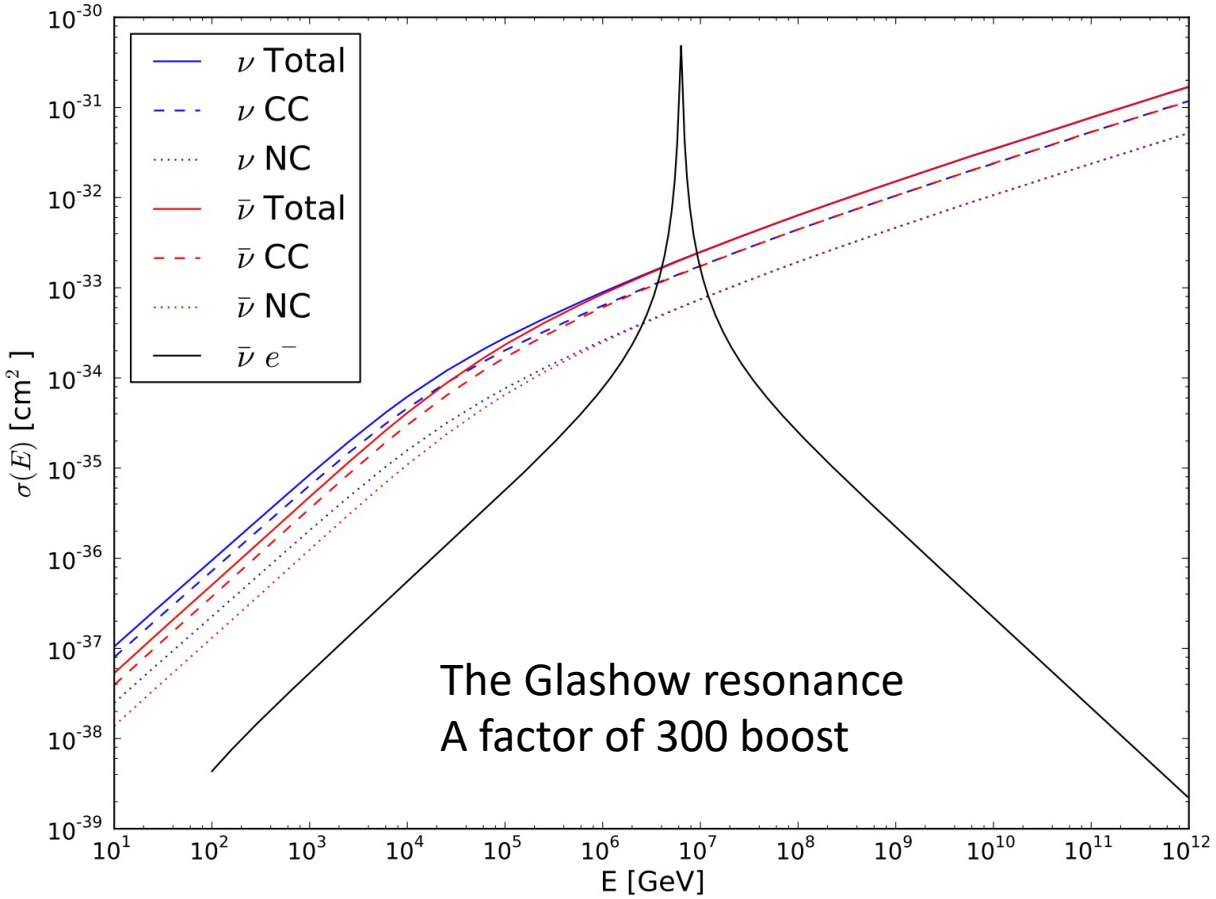


$$\sigma(s) = 24\pi\Gamma_W^2 B_{W^-\to\bar{\nu}_e+e^-} \frac{s/M_W^2}{(s-M_W^2)^2 + \Gamma_W^2 M_W^2}$$

$$\overline{\nu_e} + e \quad \to W^- \to \quad \overline{\nu_l} + l$$

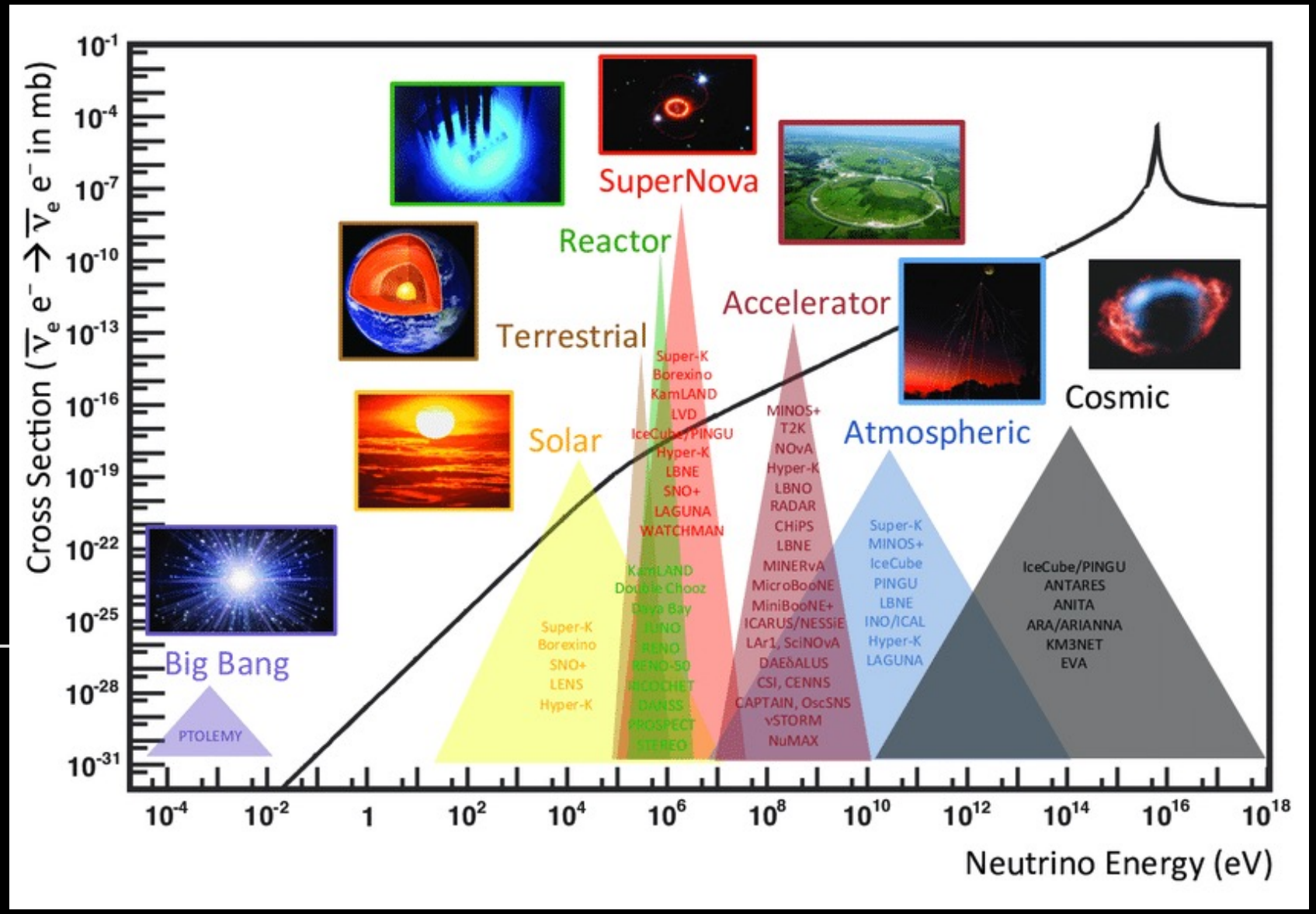
$$\overline{\nu_e} + e \quad \to W^- \to \quad X \quad ,$$

$$E_{\mathrm{R}} = M_W^2/(2m_e) = \ 6.32\mathrm{PeV}$$

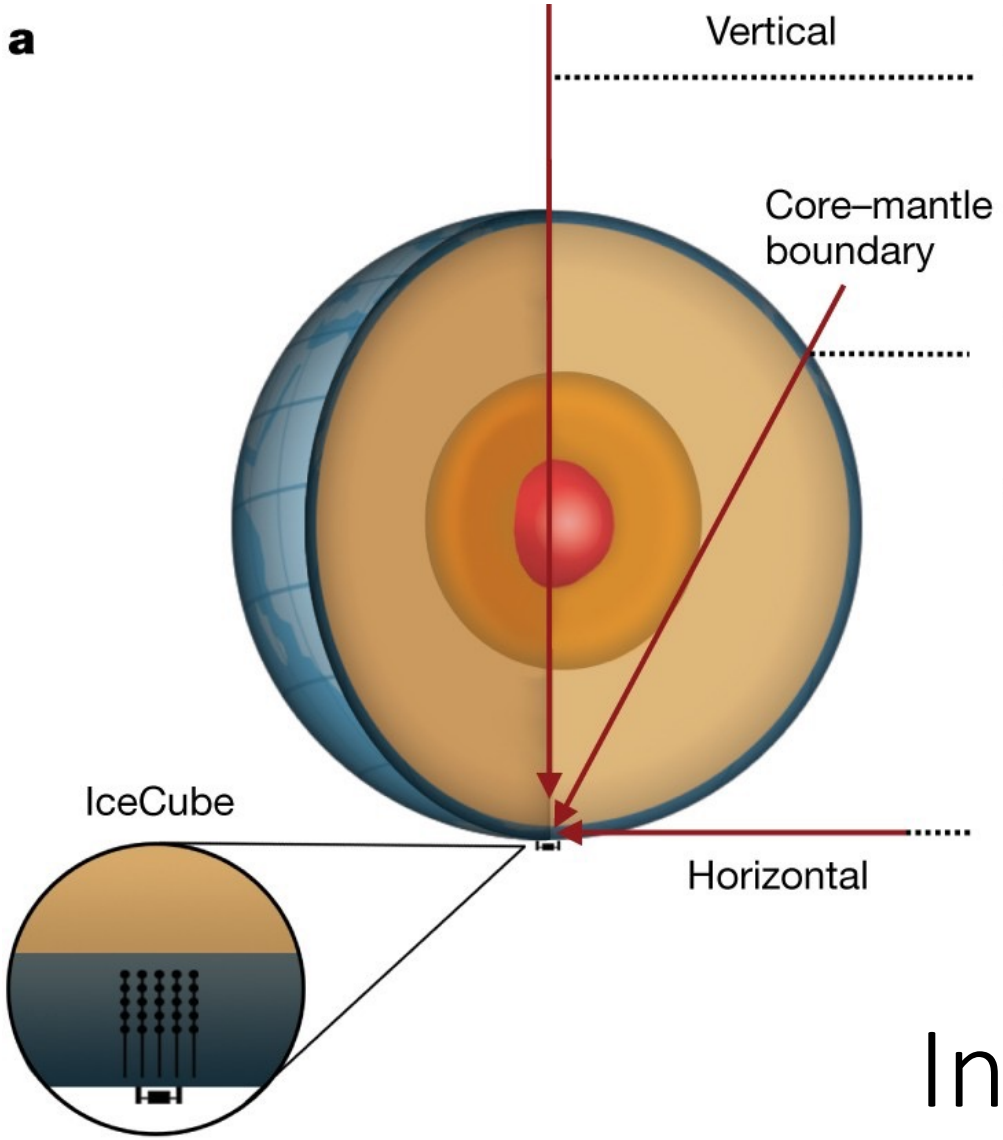


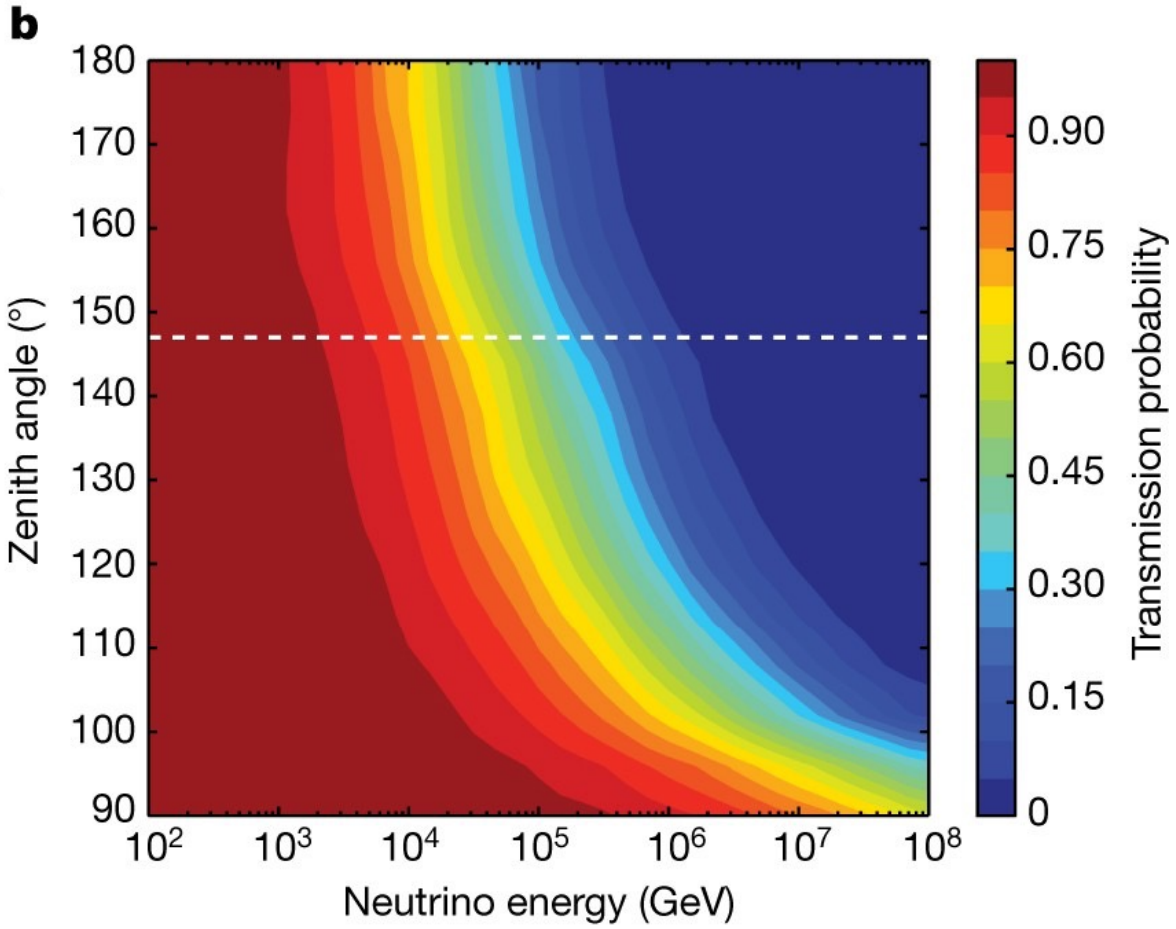
Neutrino cross section

~MeV neutrinos need ~1 light year of lead to interact



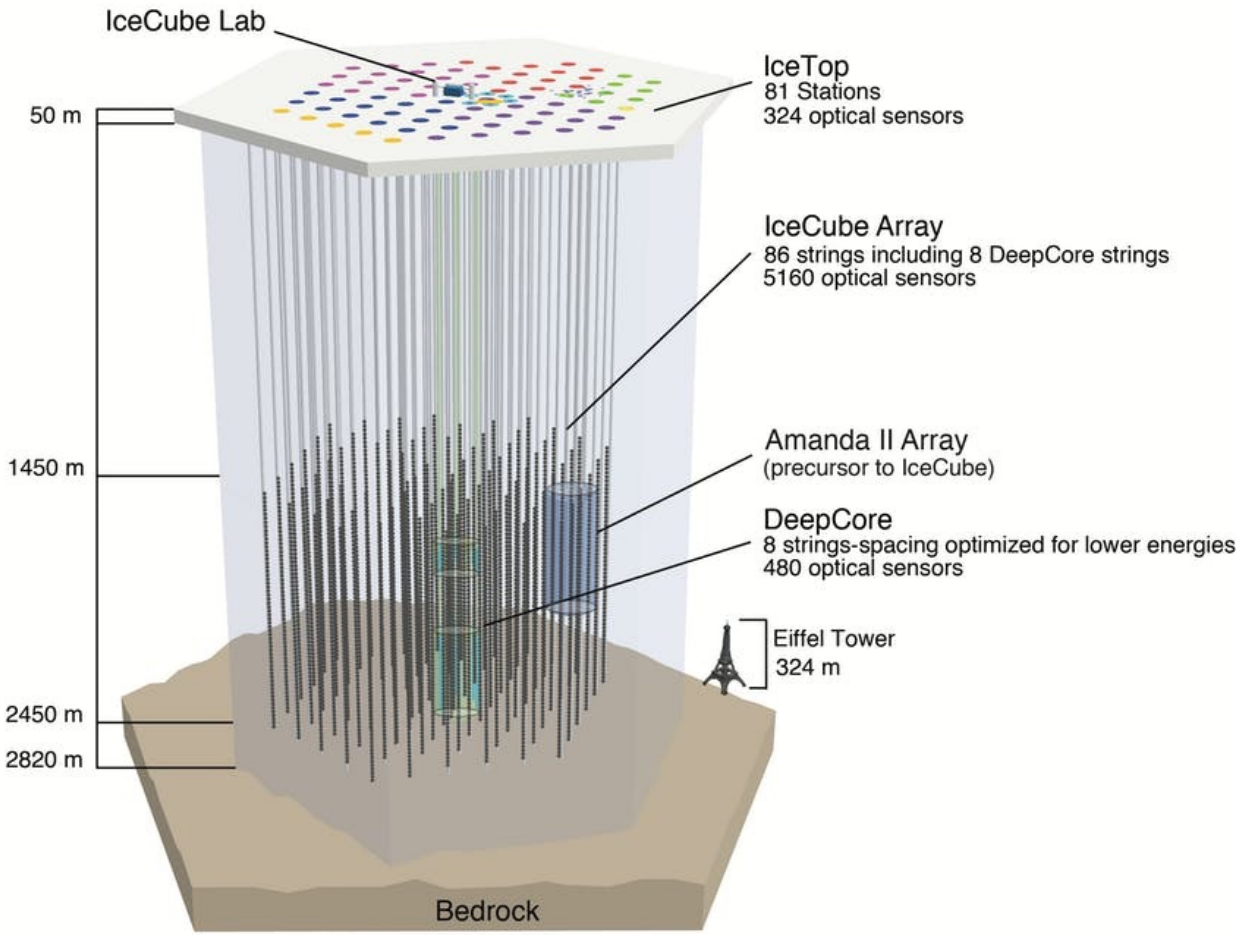
High energy events are likely to come from southern sky

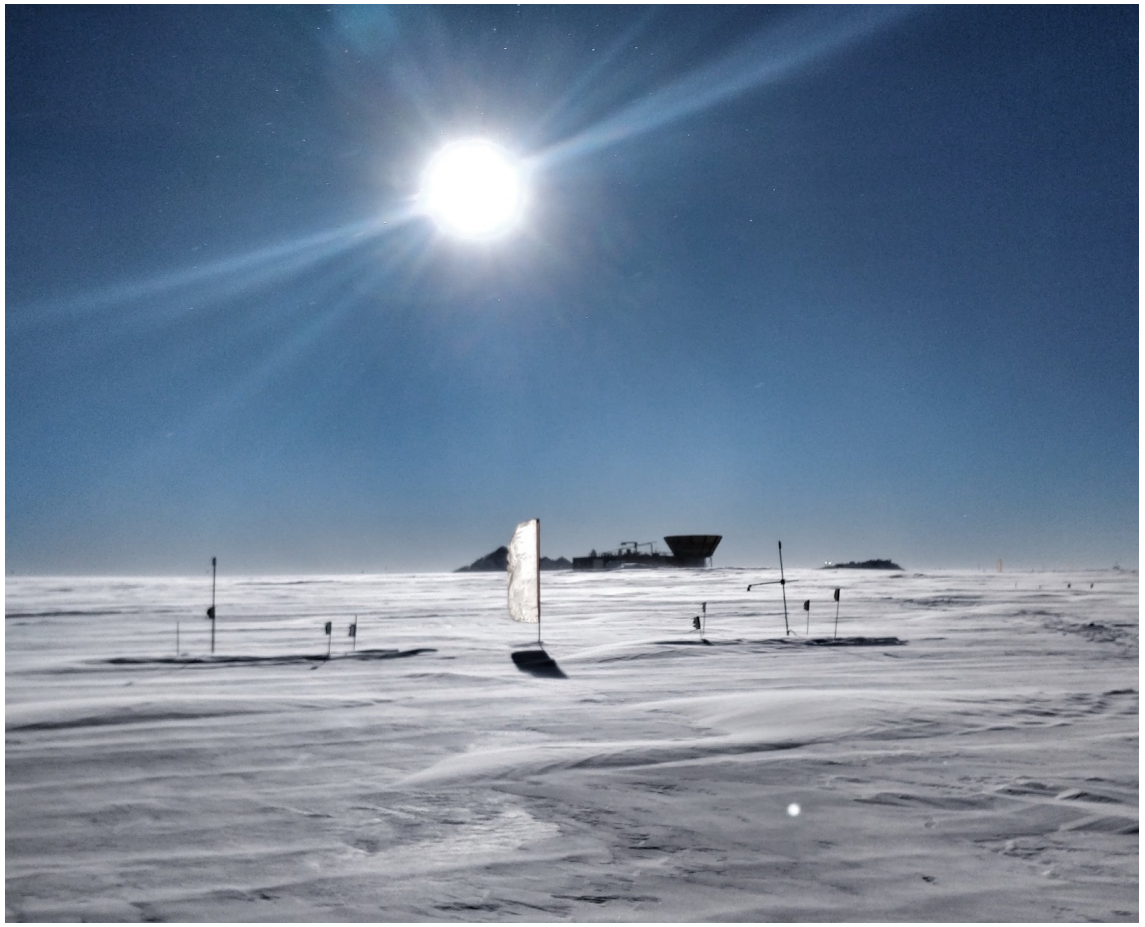




In-earth flux attenuation

THE ICECUBE NEUTRINO OBSERVATORY





Cherenkov detector in ice, 4pi acceptance

1998
Super-Kamiokande collaboration announces evidence of nonzero neutrino mass

NT200 neutrino detector in Lake Baikal completed

1999
IceCube submits proposal for cubic-kilometer South Pole neutrino detector

2000
AMANDA (Antarctic Muon And Neutrino Detector Array) at the South Pole completed

2001
AMANDA publishes first neutrino sky map with 600 events in *Nature*

2008
ANTARES (Astronomy with a Neutrino Telescope and Abyss environmental RESearch) neutrino detector in the Mediterranean Sea completed

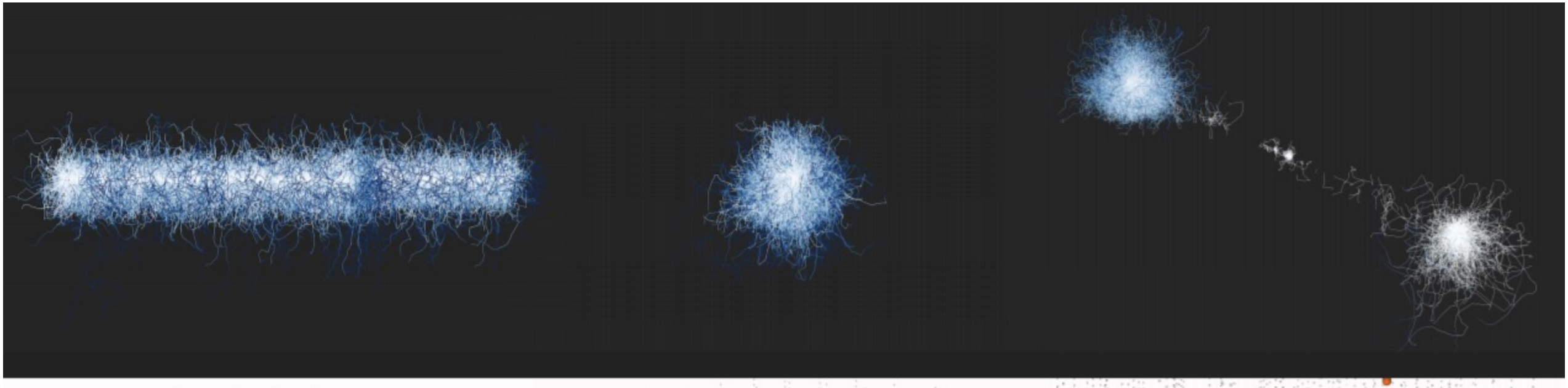
2010
IceCube construction completed

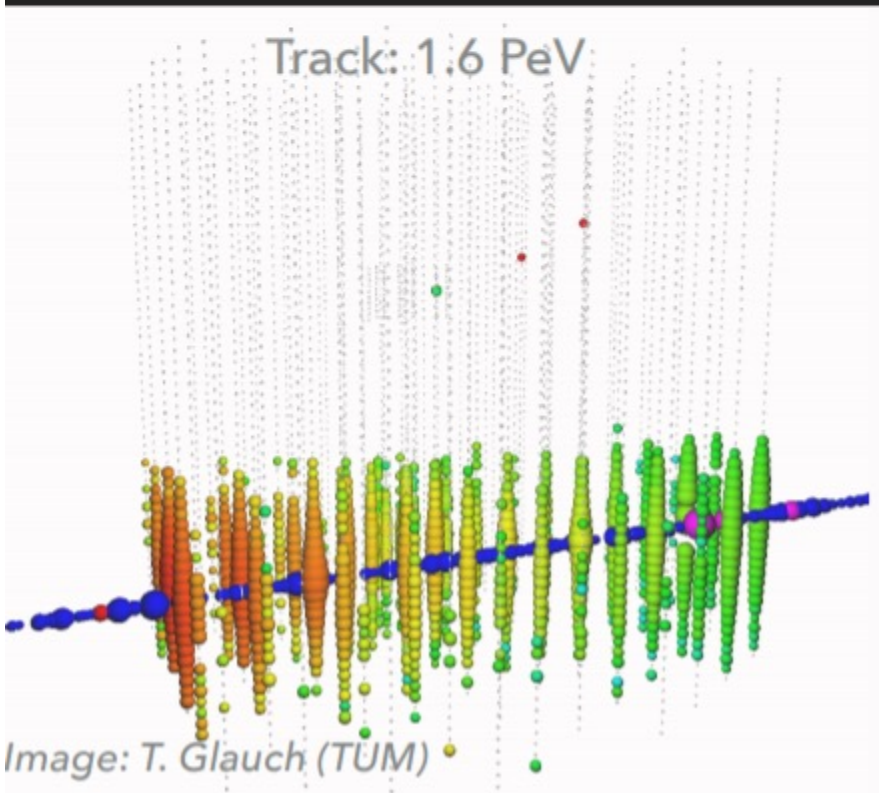
2013
IceCube discovers astrophysical neutrinos with energies greater than 10^{14} eV

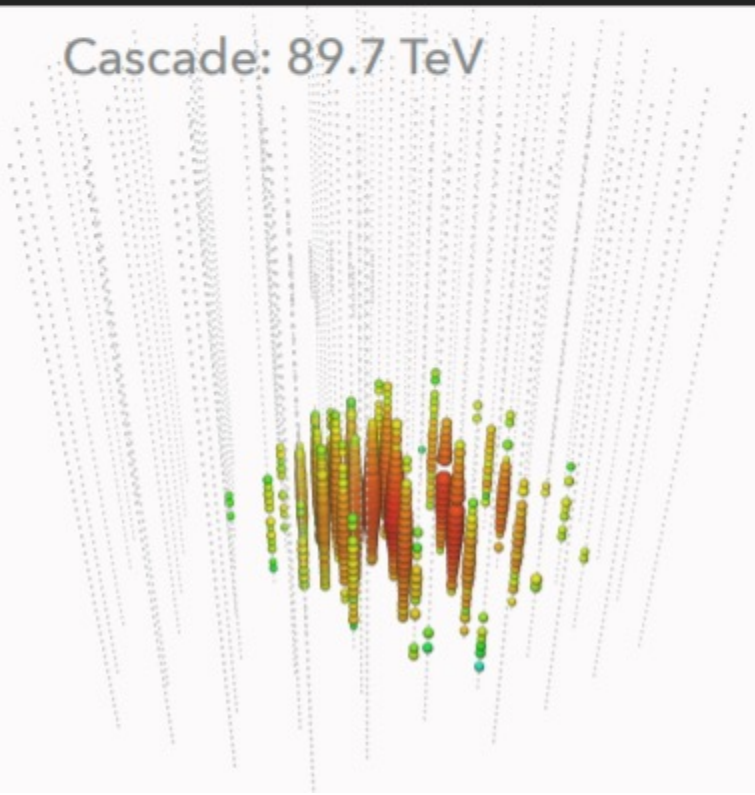
2014
IceCube discovers highest energy neutrino to date, nicknamed Big Bird (2×10^{15} eV)

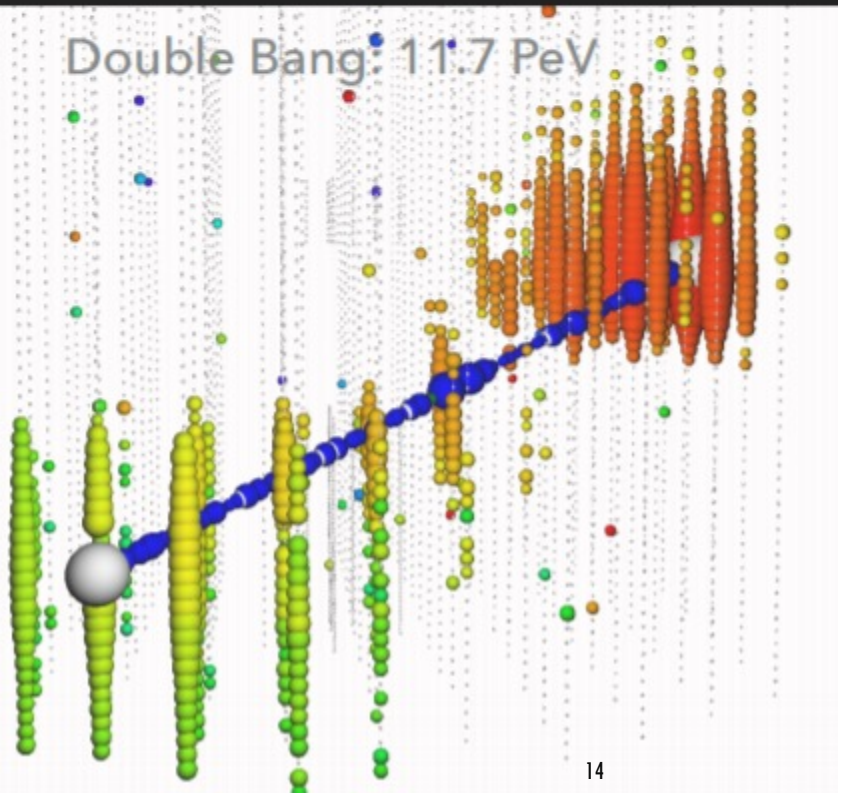
2015
IceCube confirms cosmic neutrino flux with muon neutrinos traversing Earth, including a 7×10^{15} eV neutrino

2018
Science papers describe first detected source of neutrinos—active galaxy TXS 0506+056, identified in 2017 by first successful multimessenger campaign



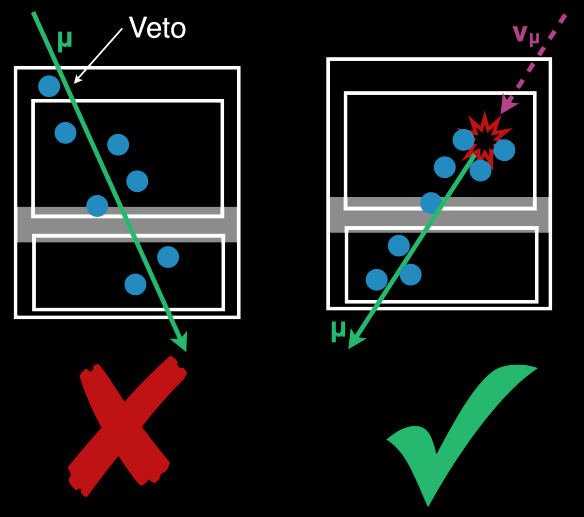

Track: 1.6 PeV
Image: T. Glauch (TUM)


Cascade: 89.7 TeV


Double Bang: 11.7 PeV

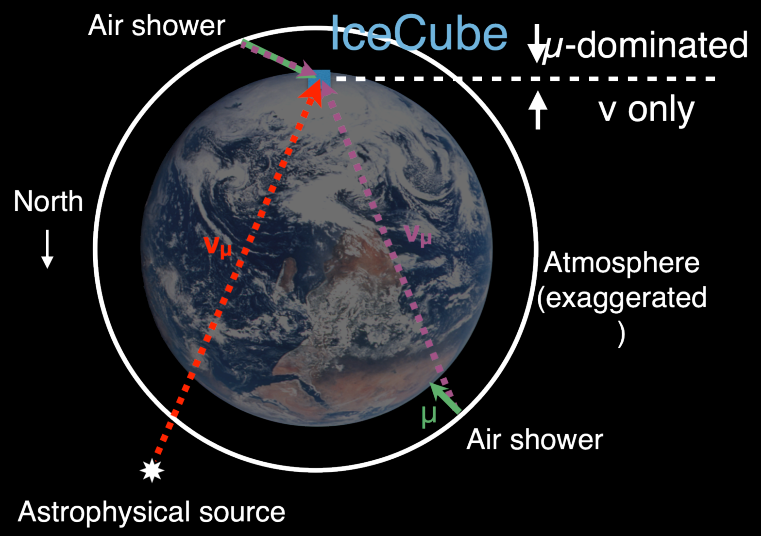
S:B~1:10million

Active veto



Veto detects penetrating muons
Effective volume smaller than detector
Sensitive to all flavors
Sensitive to the entire sky

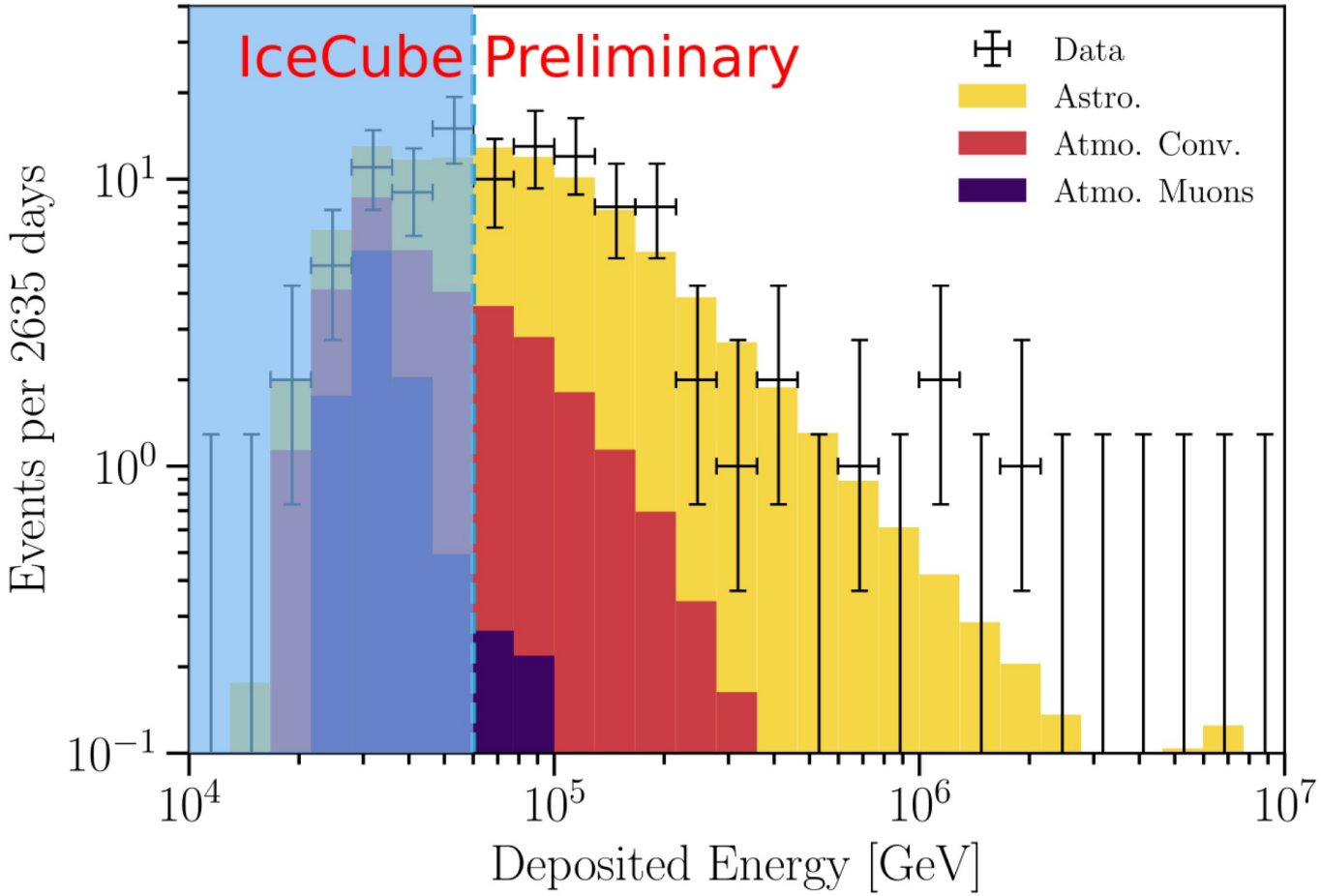
Up-going tracks

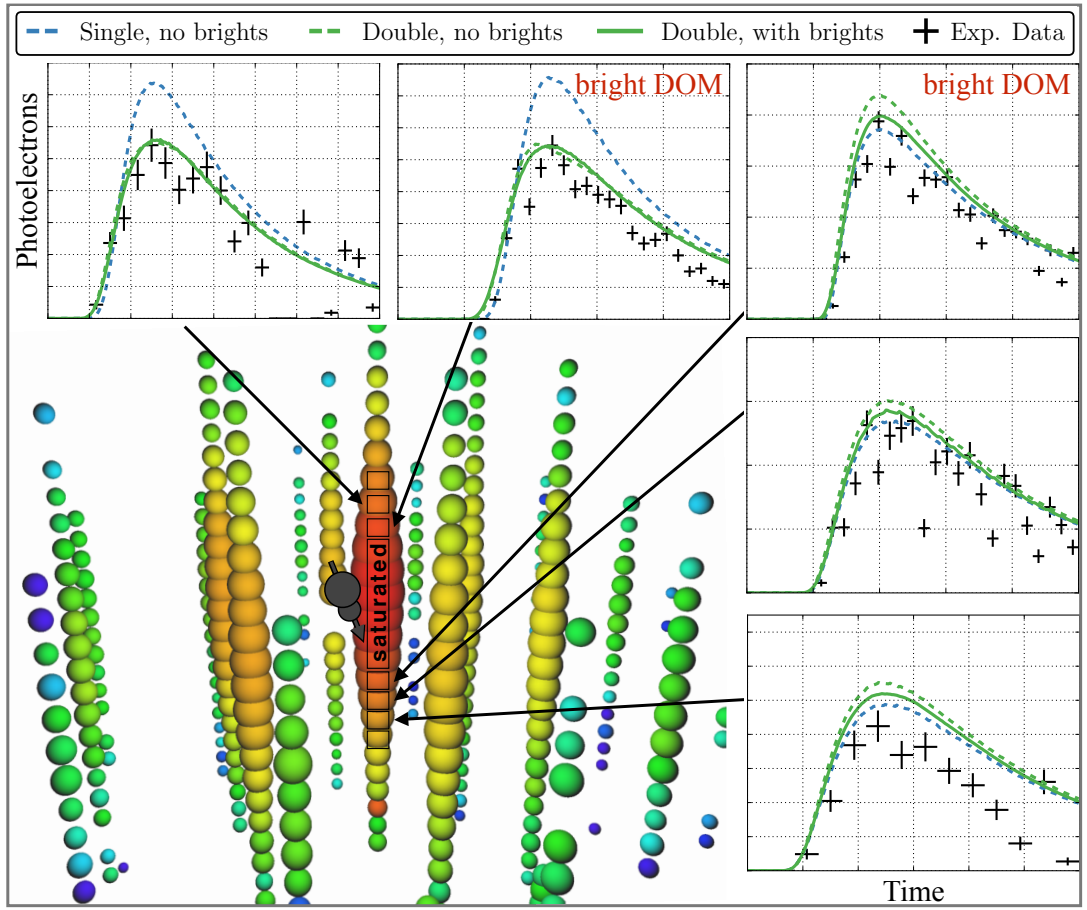


Earth stops penetrating muons
Effective volume larger than detector
Sensitive to ν_μ only
Sensitive to "half" the sky

The diffuse neutrino flux with HESE (high-energy starting events)

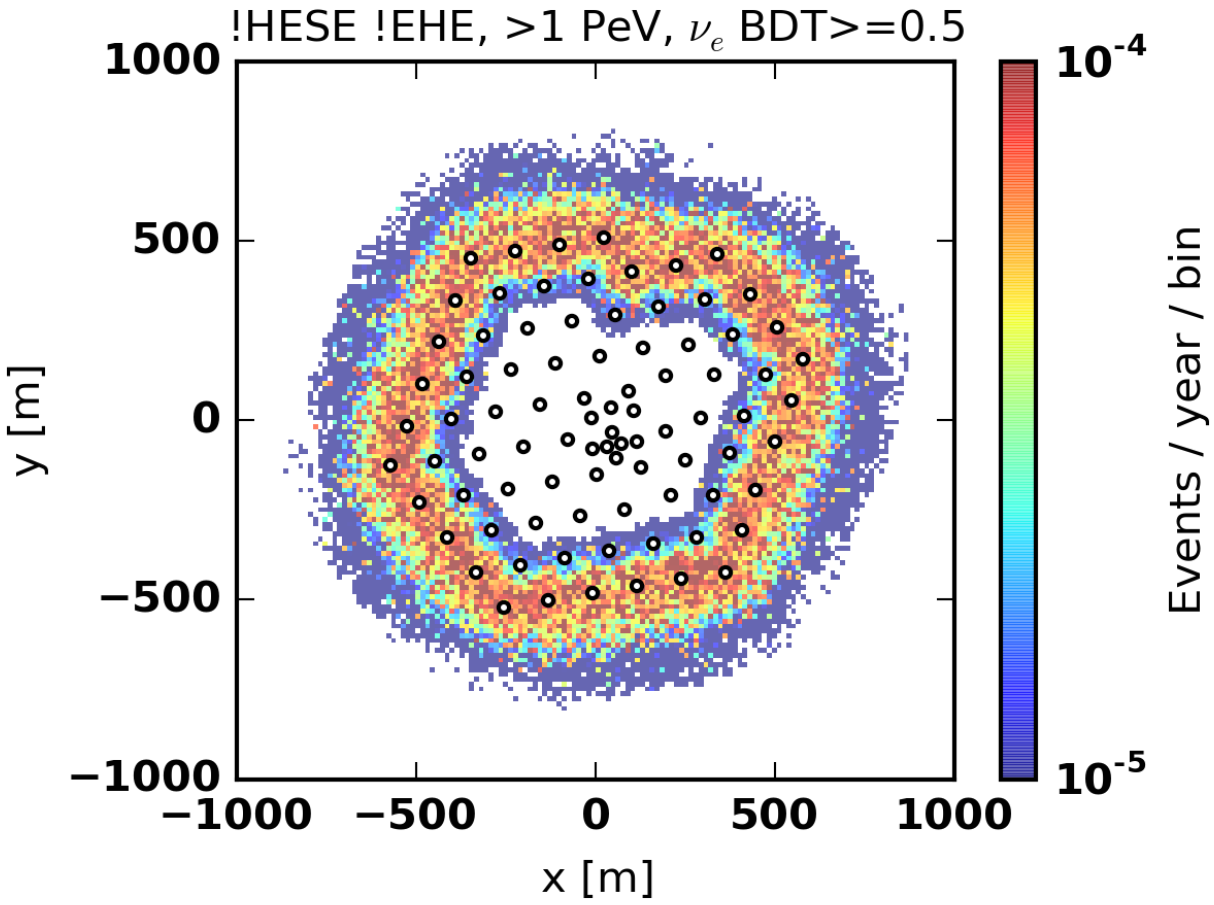
Does the spectrum stop?
Why no Glashow resonance?
-> Need to explore event selection dedicated at PeV range

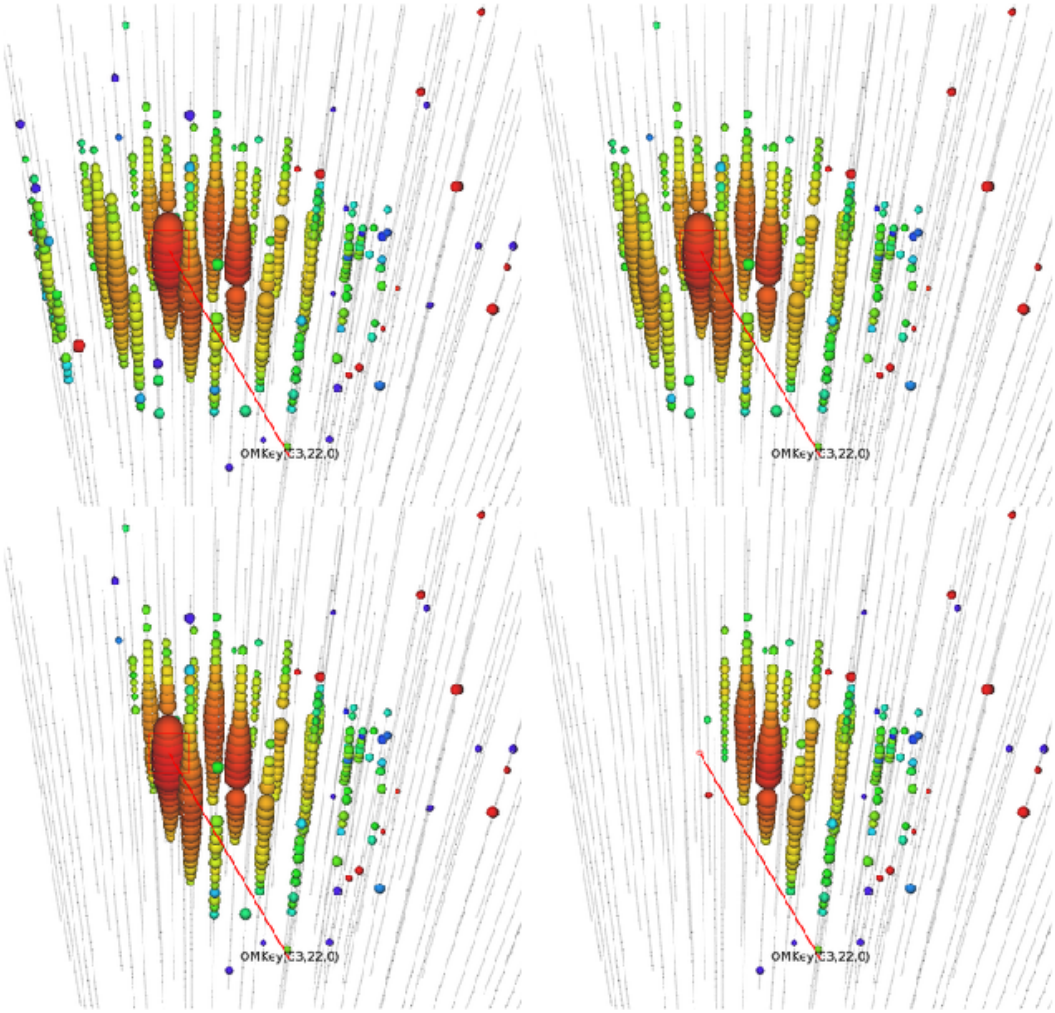




Highest energy event ~2 PeV

PeV Energy Partially-contained Events (PEPE)



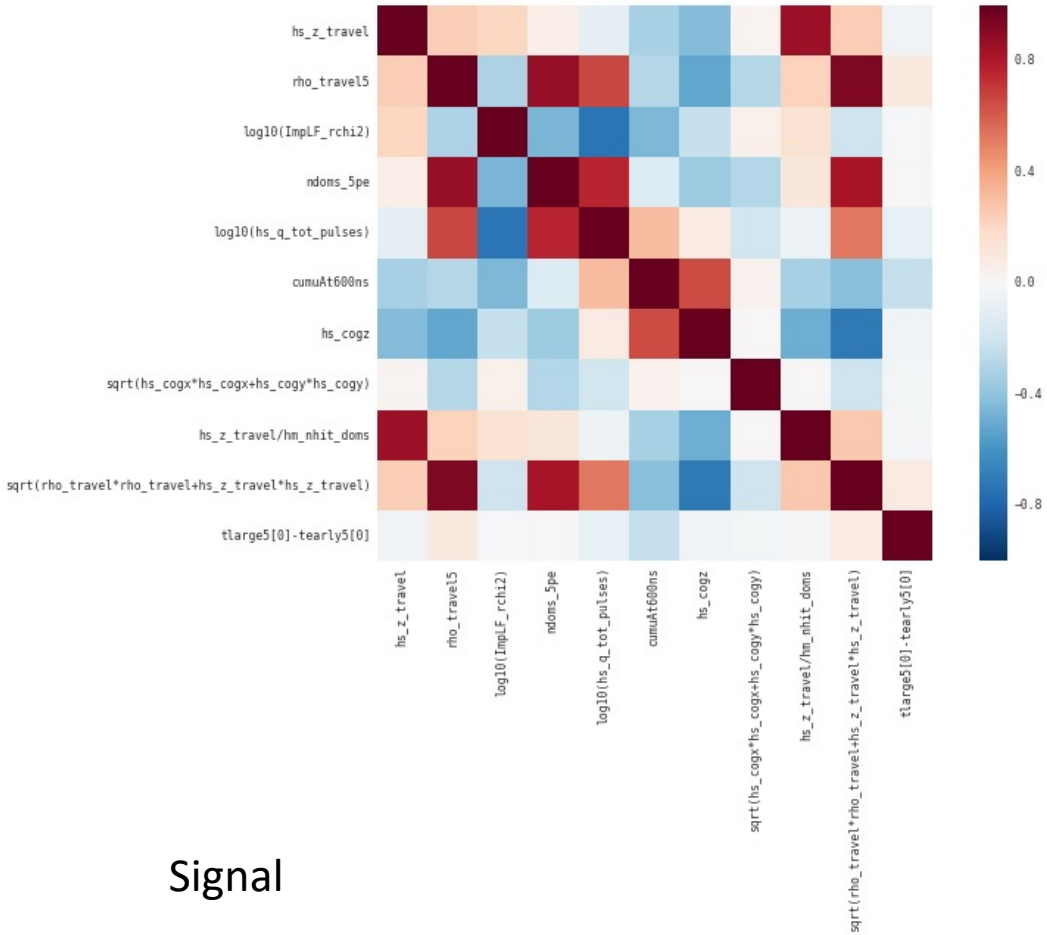


Selection

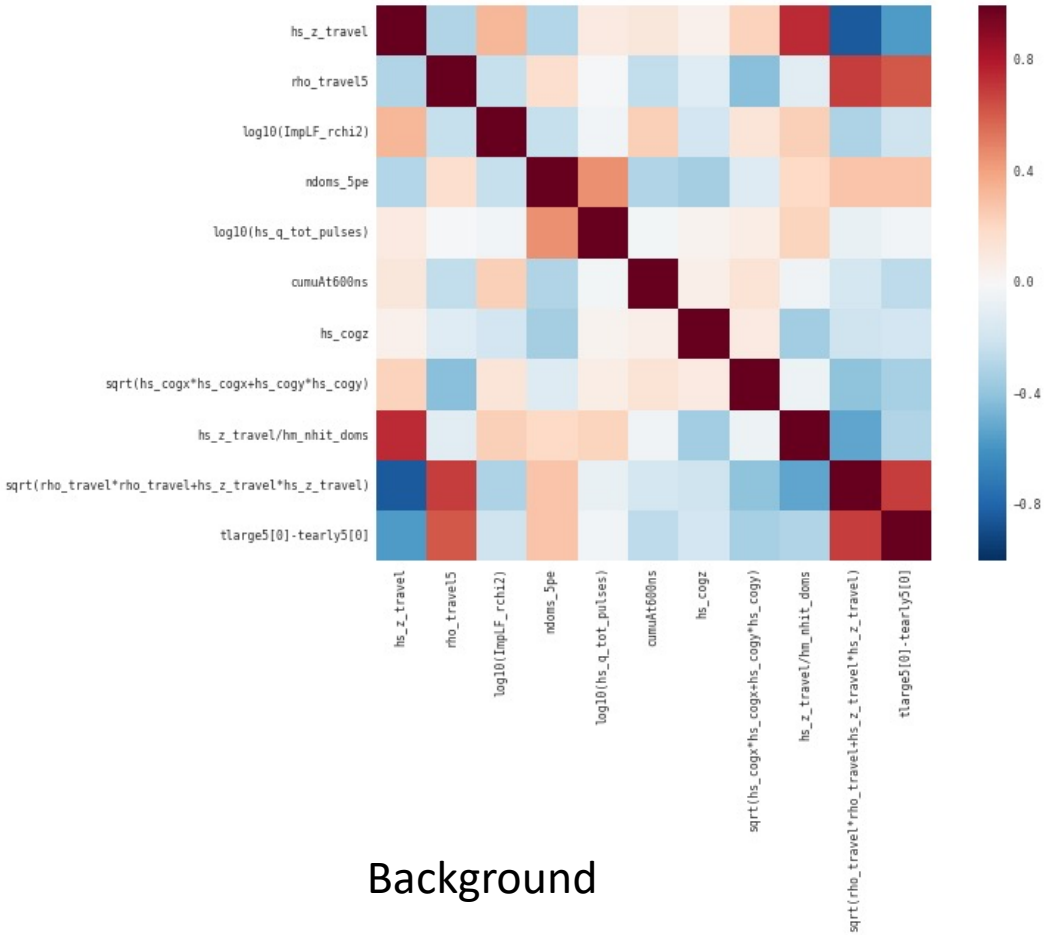
Partial contained PeV events “PEPE” – BDT based event selection

- Large background from atmospheric muons

Train BDT on 11 features



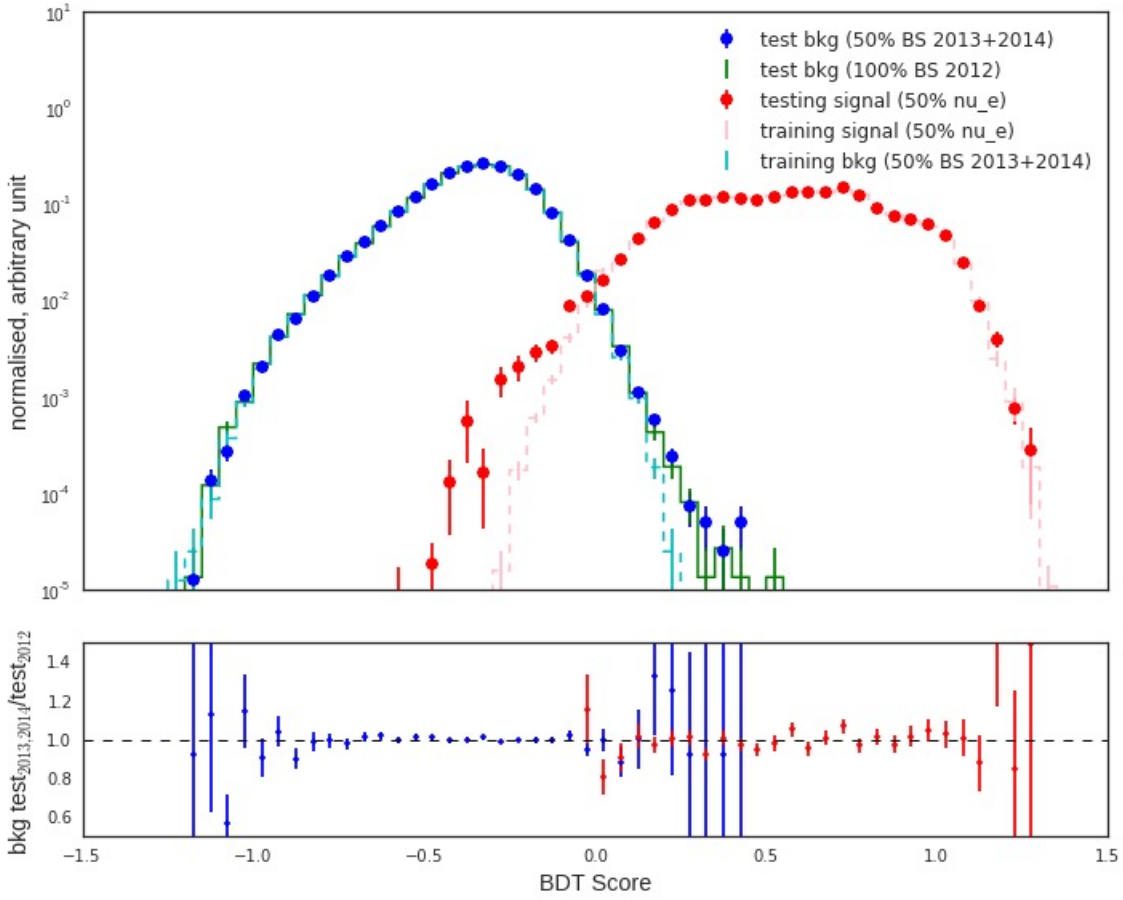
Signal

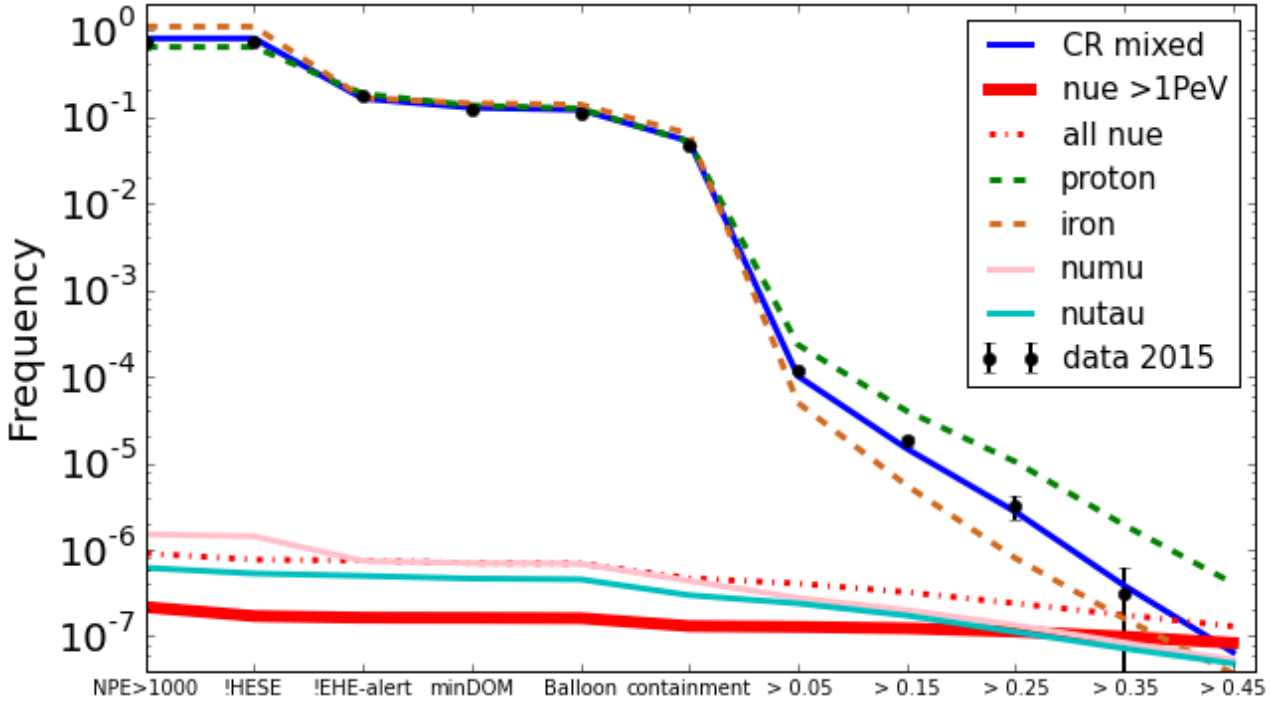


Background

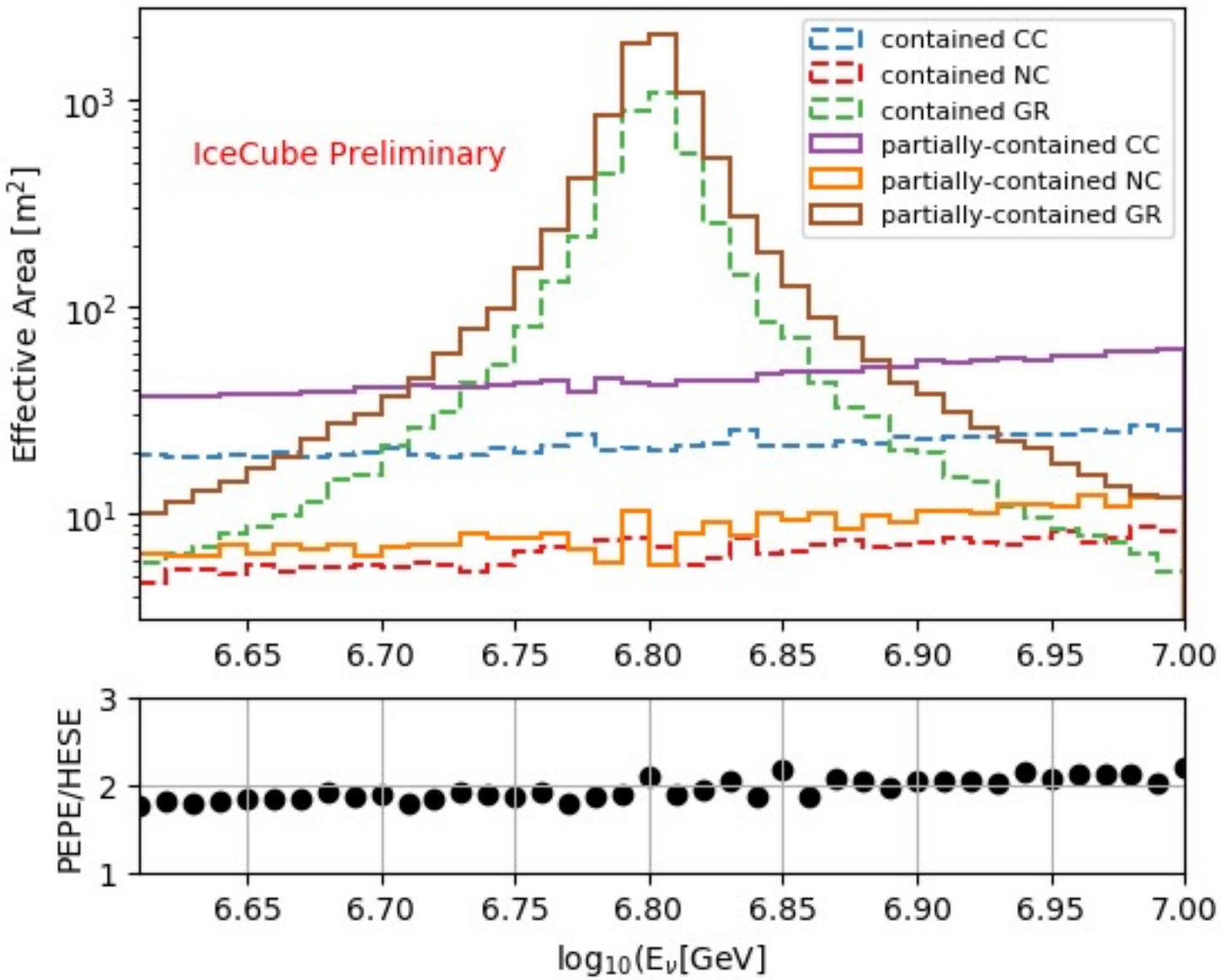
A boosted decision tree based method

Supressing background to 1 in 10 million





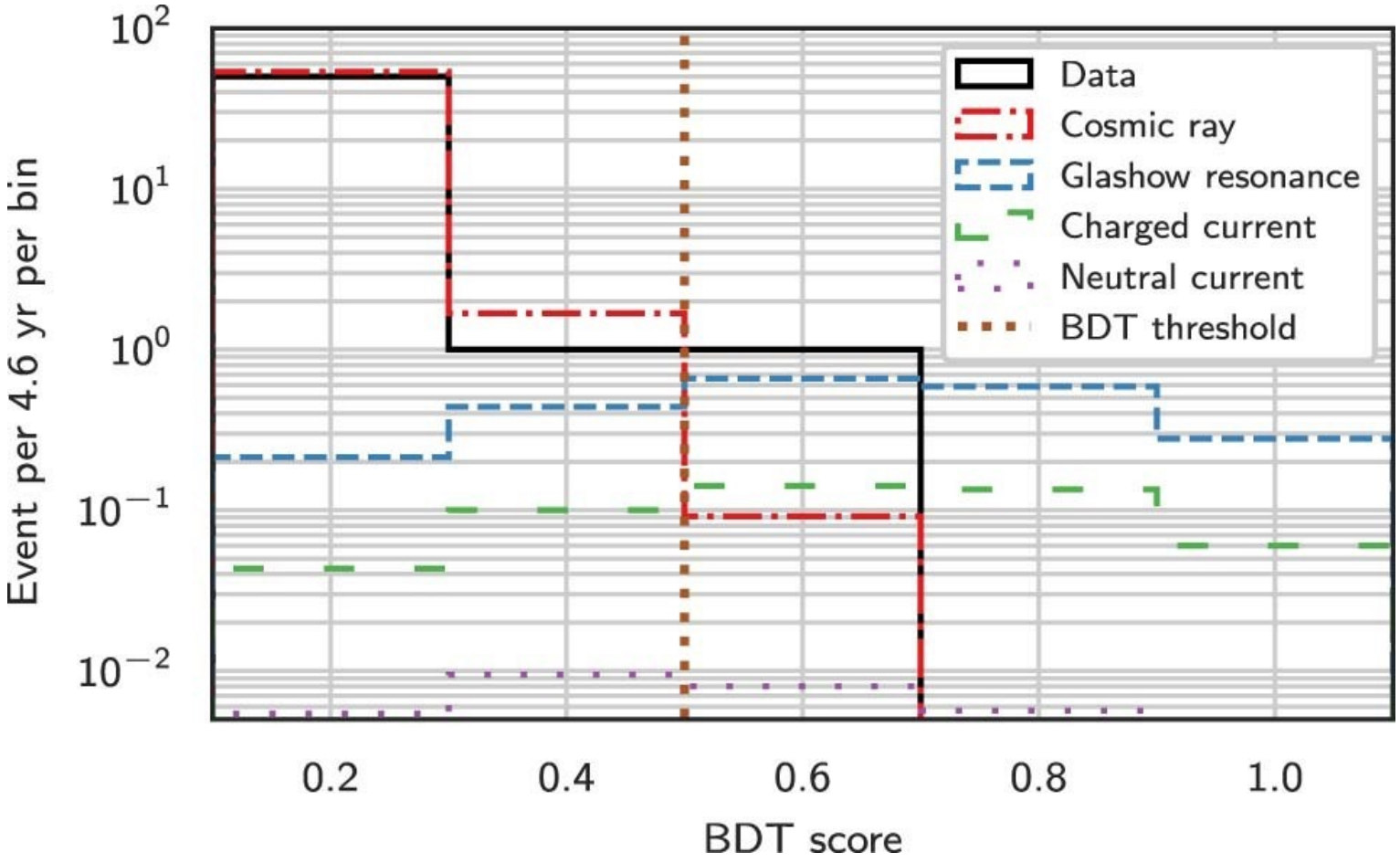
X2 previous search sensitivity at the Glashow resonance energy



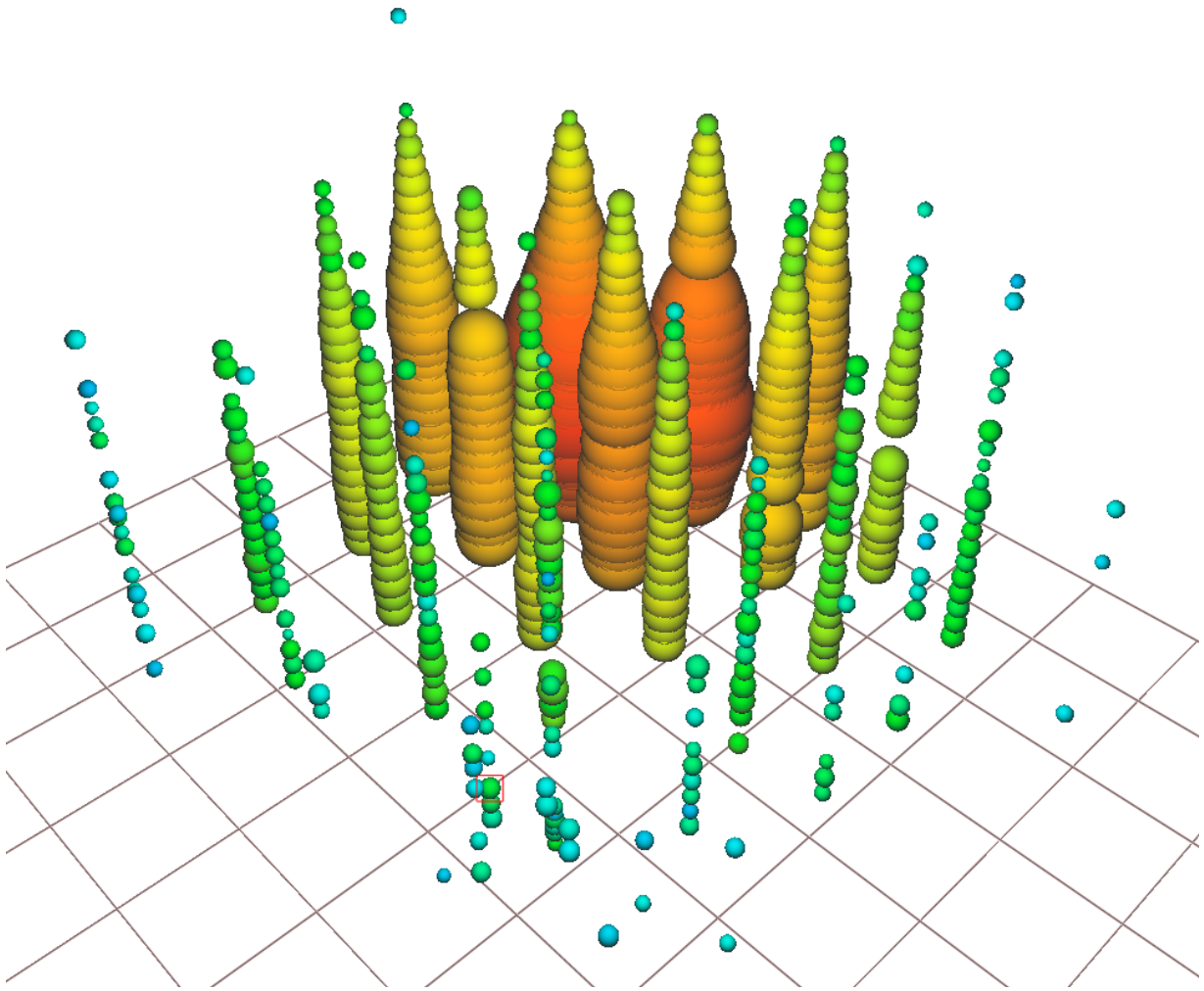
BDT scores above 4 PeV

BDT threshold 0.5

One event above 4 PeV with score 0.65



Unblinded result – one event with multi PeV



* Energy reconstruction
* Direction reconstruction
* Background rate
* Glashow probability
* Systematics

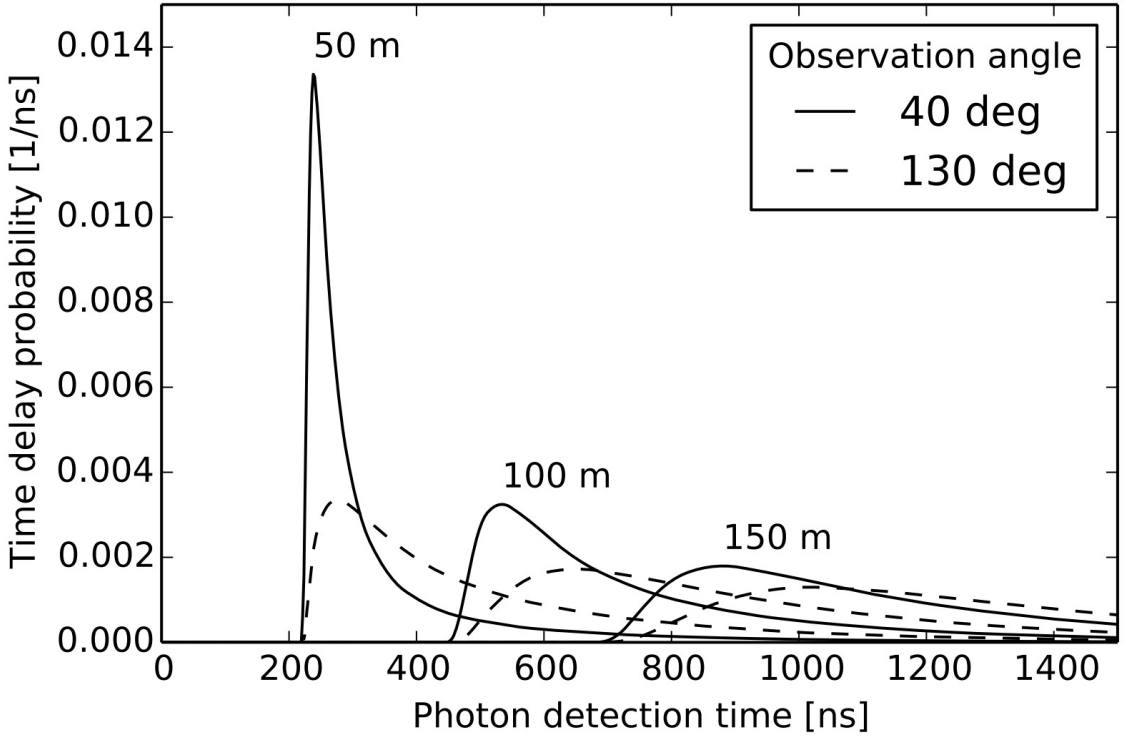
Energy reconstruction – resimulations and approximate Bayesian calculation (ABC) method

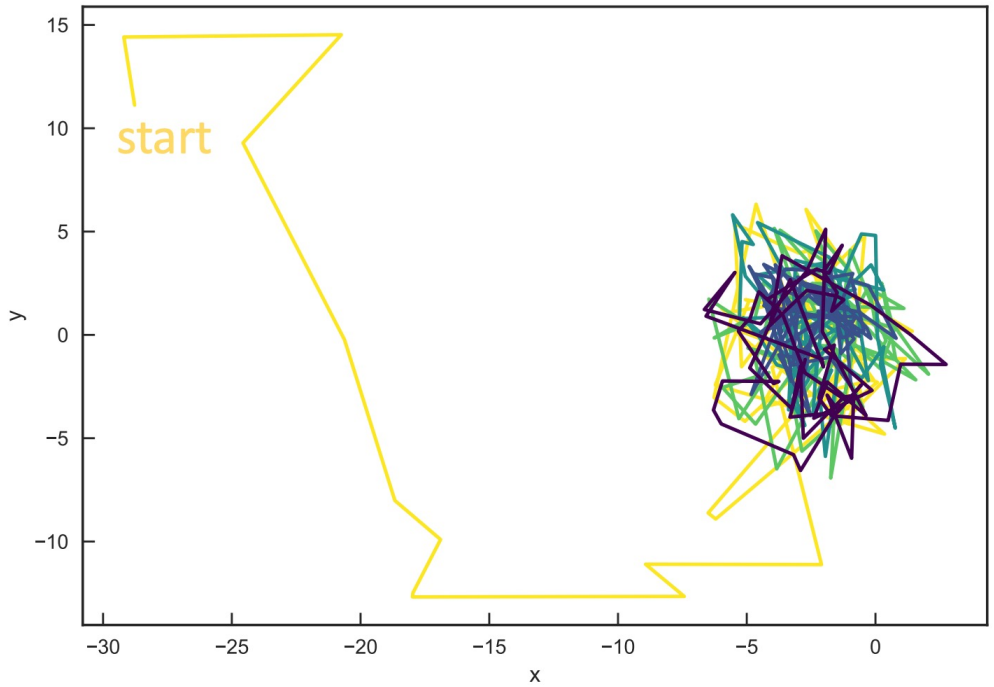
Physics model (emission, absorption, scattering)

$\mathbf{\Theta} = (x, y, z, \theta, \phi, E, t)$

$X = q_{DOM}\,(t)$

Maximize $\mathcal{L}(\mathbf{\Theta}|\mathrm{X}_{\mathrm{Data}})$



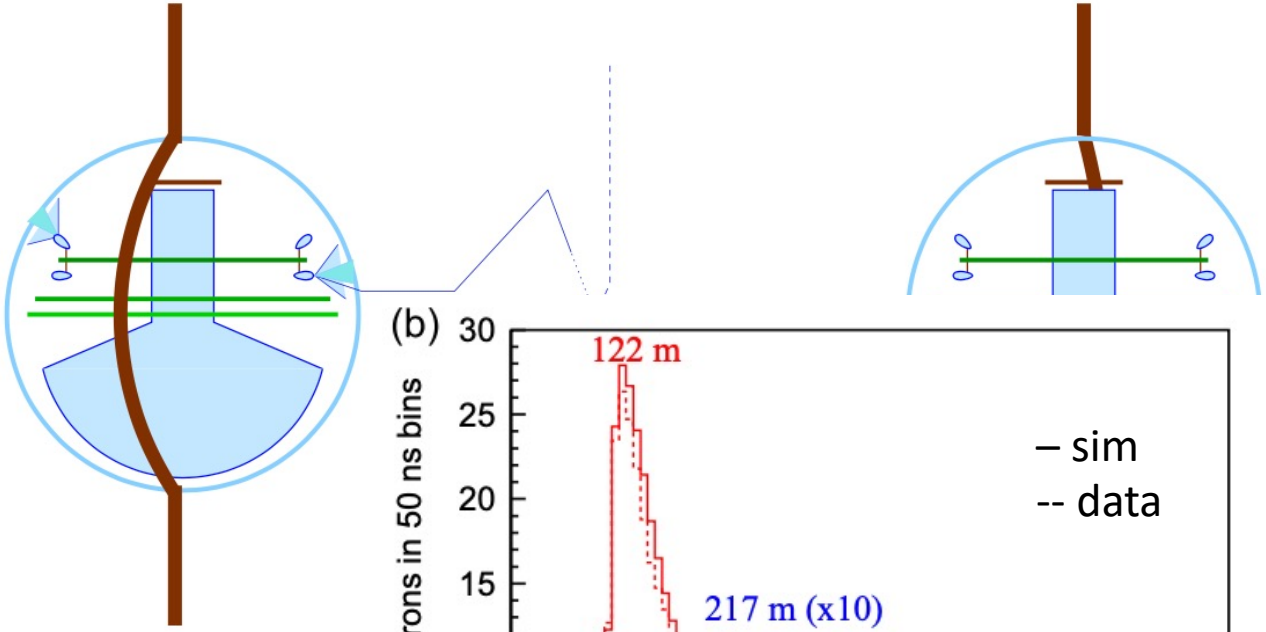


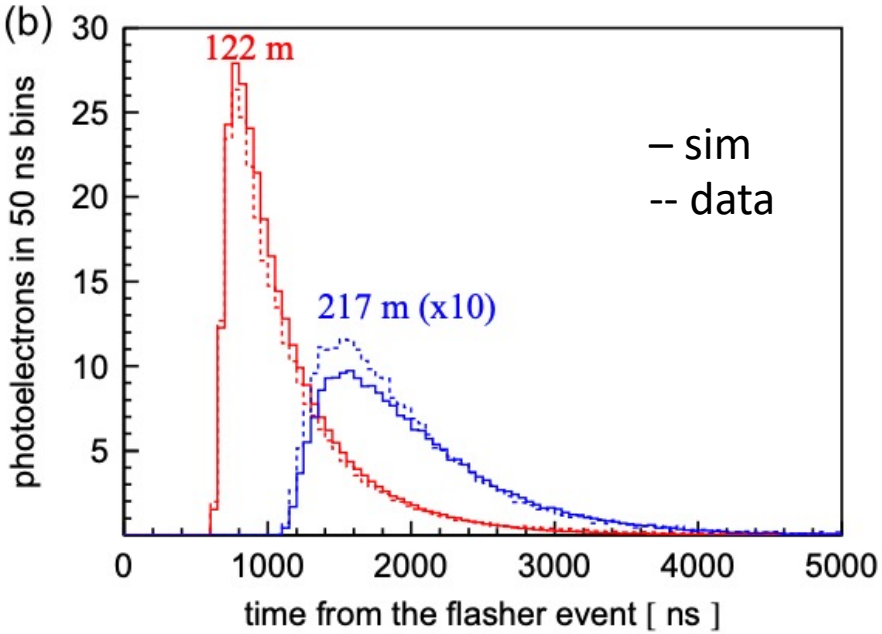
Energy reconstruction systematics

NIMA 711 (2013) 73-89

Considerations for this event's energy reconstruction

1. Parametrization of bulk ice scattering and absorption
2. Ice anisotropy
3. Energy scale calibration





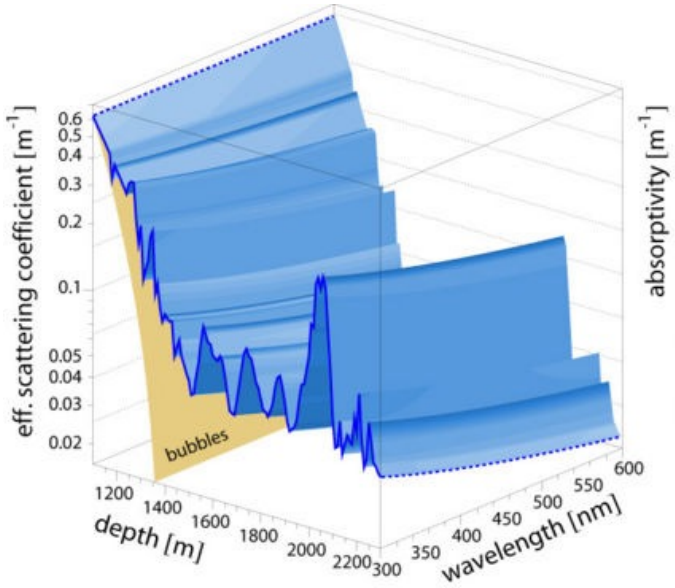
Six horizontal and six tilted LEDs on each DOM

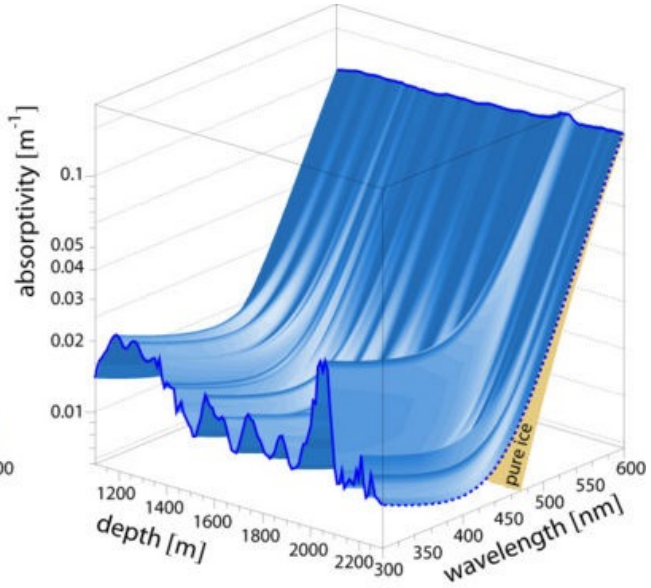
"Flasher" data used for calibration

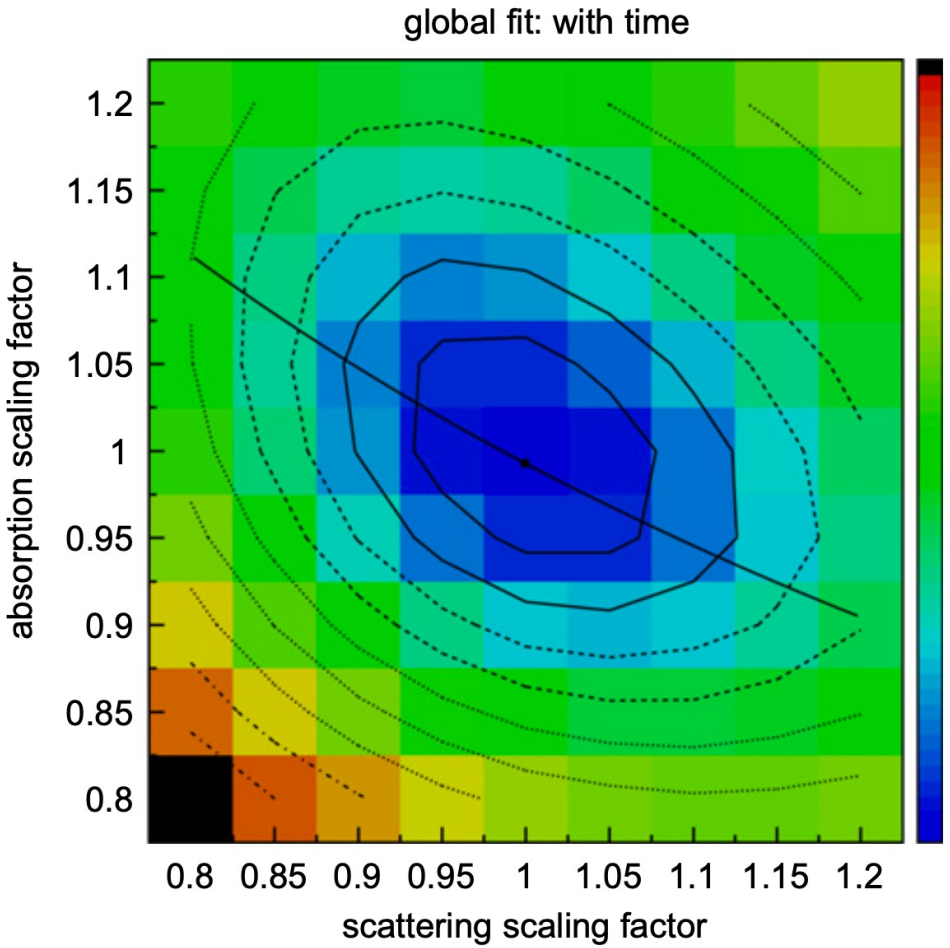
Ice model calibration and uncertainties

Fit for **bulk scattering and absorption** parameters vs depth

Constraints can be placed on sca/abs scaling factors (+/- 5%)







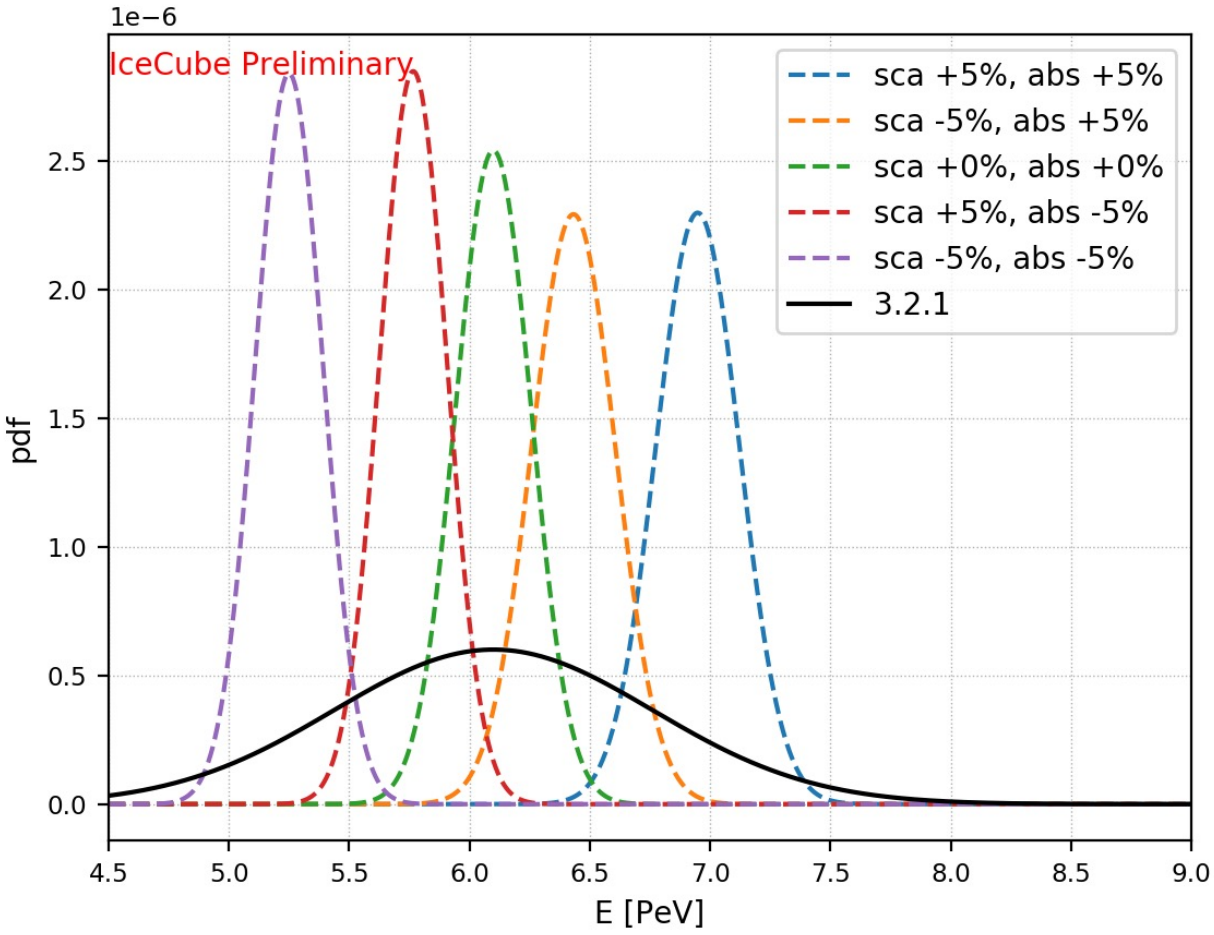
Reconstructed energy for different bulk ice models

Five distinct bulk-ice models

- Direct resimulation (as opposed to using look up tables)

Linearly interpolate to obtain $E(sca, abs)$ and propagate to obtain bulk-ice error

Vertex and direction reco'd as well

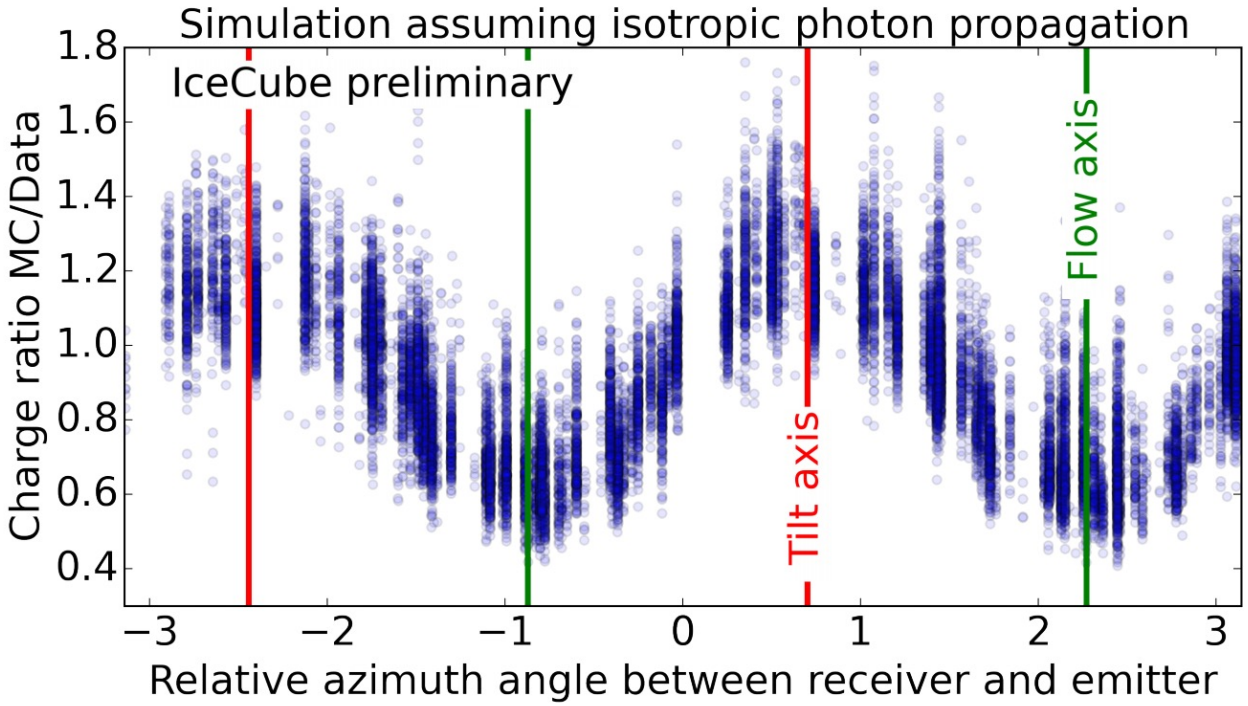


Ice anisotropy systematic

Glacial ice exhibits anisotropic light attenuation

Exact causes unknown, but modeling ice as birefringent has been recently put forth as a possible explanation for some of the features

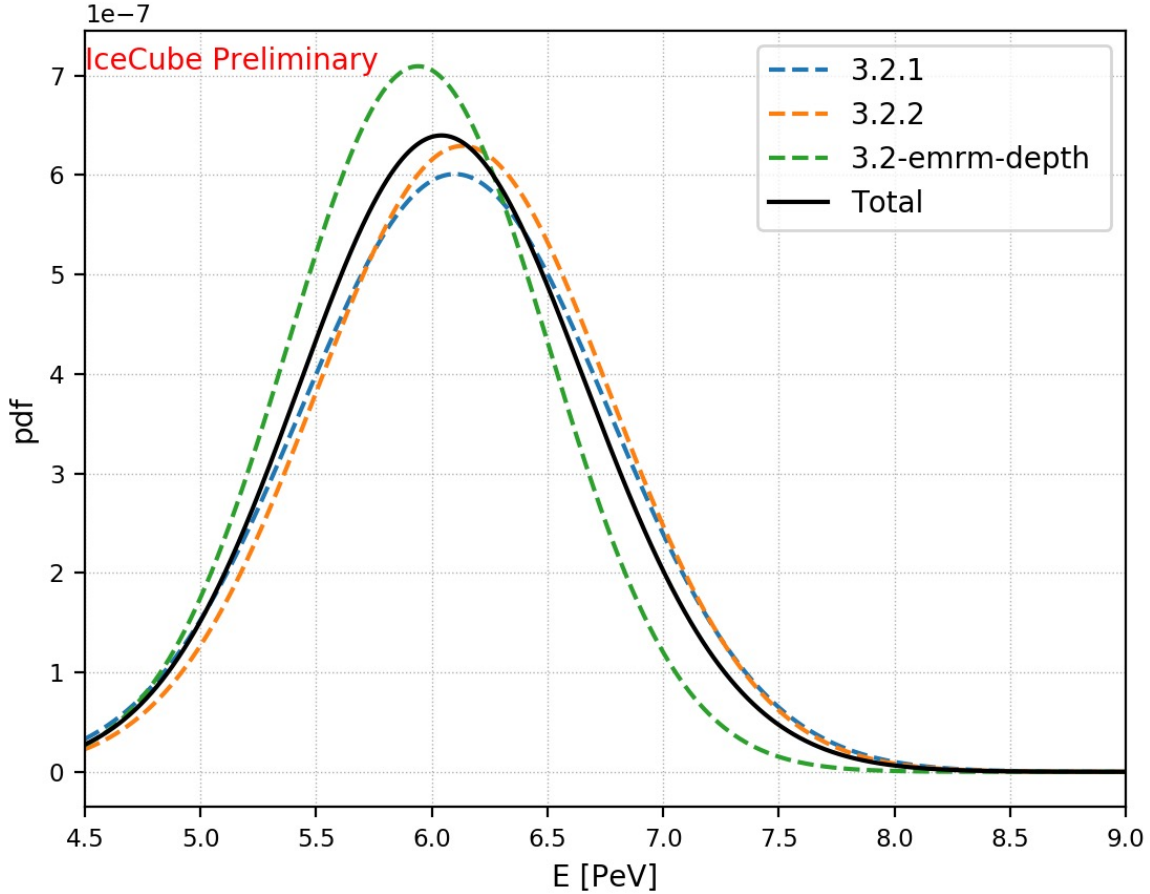
See: arxiv:1908.07608



Reconstructed energy for different anisotropies

Produced three discrete reconstructions for 3 different ice anisotropy models, each with bulk-ice systematic included

Obtain energy uncertainty due to bulk-ice+anisotropy



Energy-scale systematic

Rely on MIPs to calibration overall energy scale

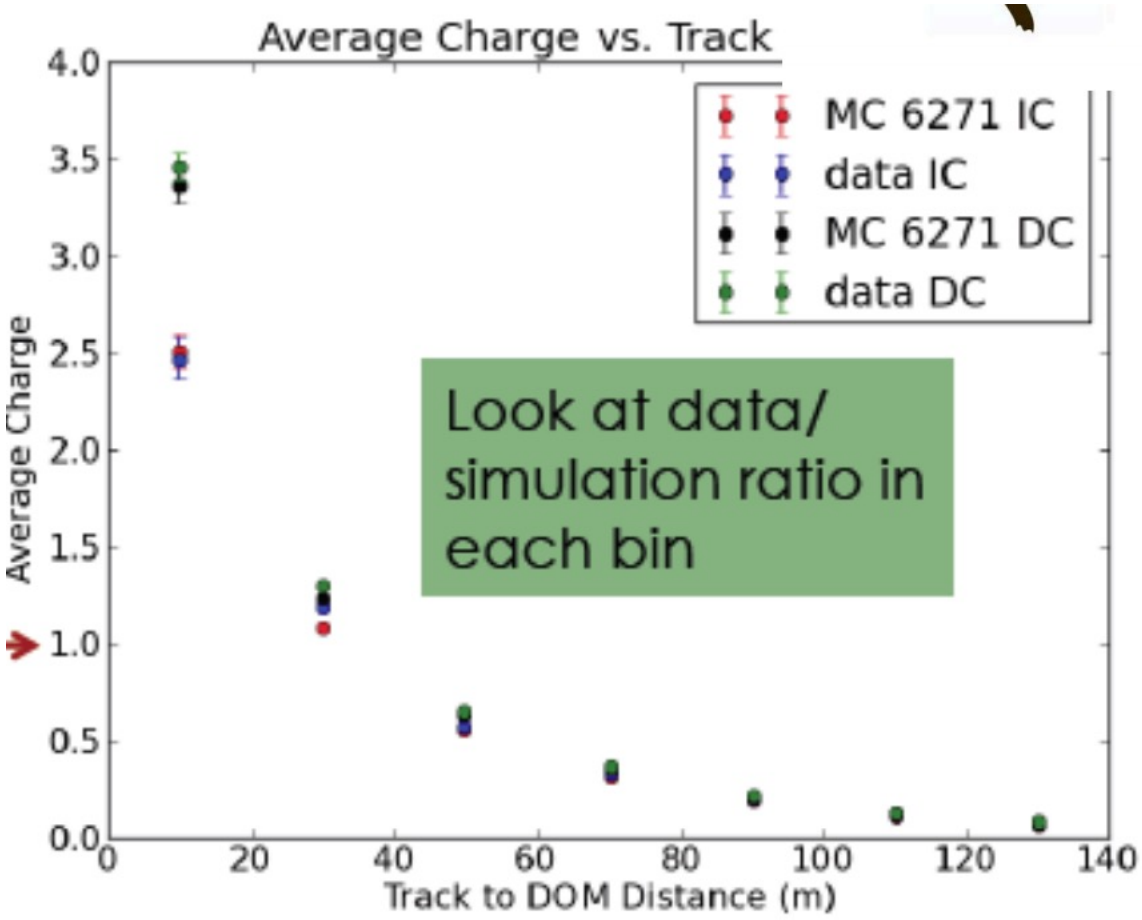
- Constant energy loss, know light emission
- High stats

Compare charge in data to MC as a function of distance to DOM

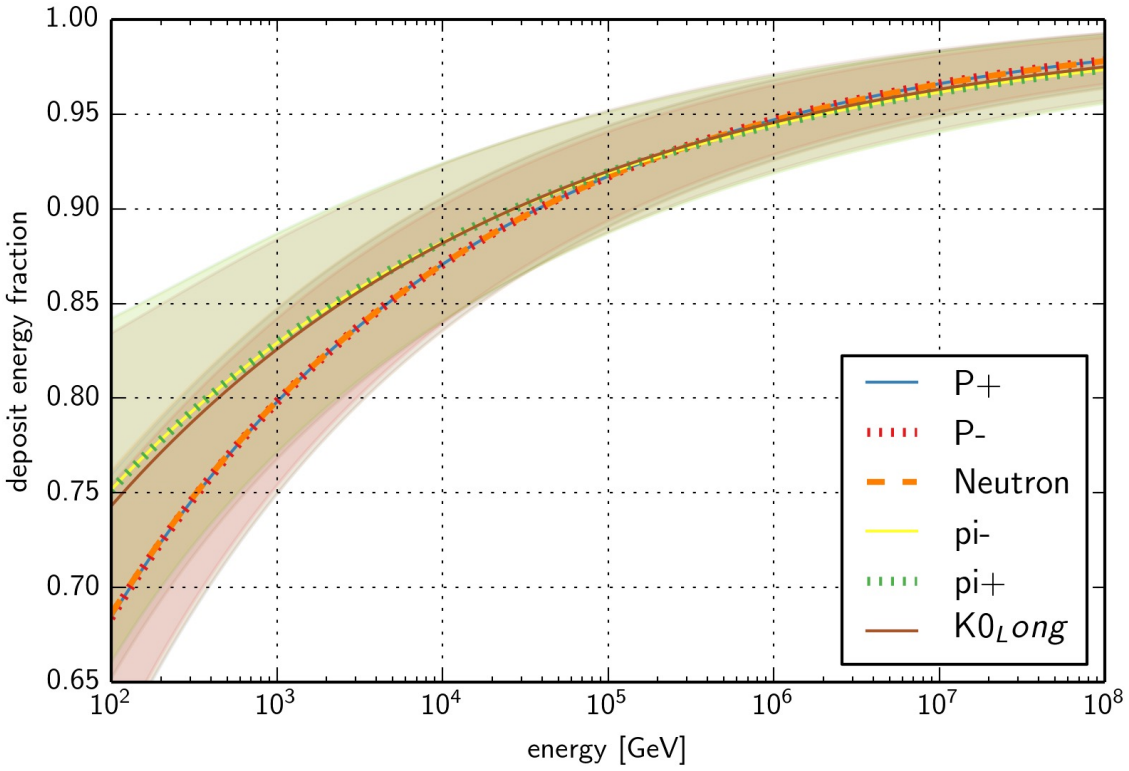
→ Current estimate is +/- 10% uniform uncertainty

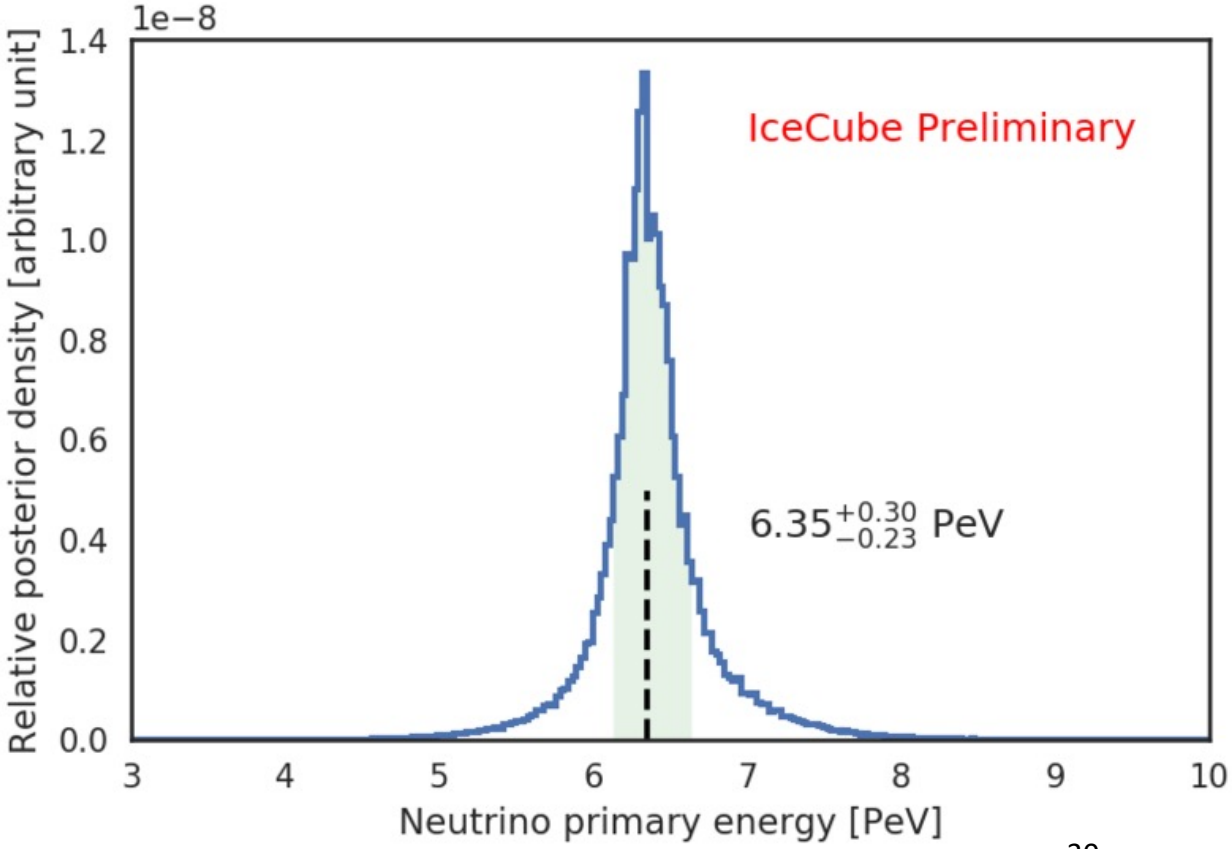
Final reconstructed *visible* energy:

$\mathbf{6.05 \pm 0.72}$ **PeV**

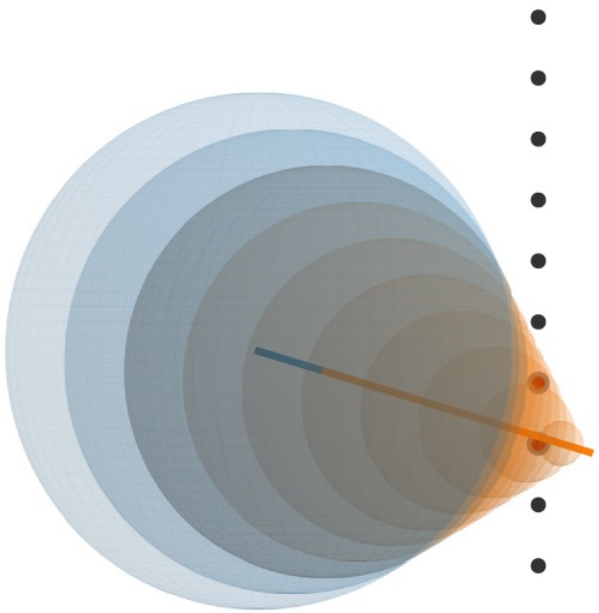


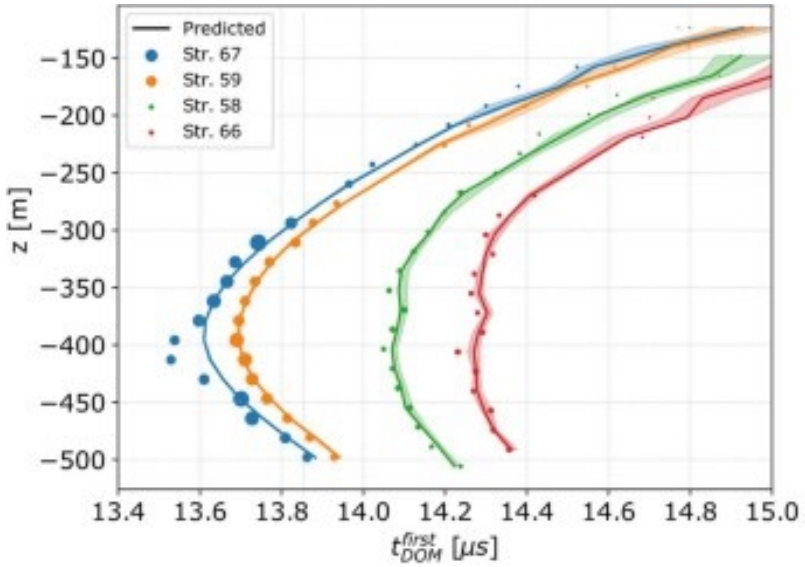
The most likeliy neutrino energy

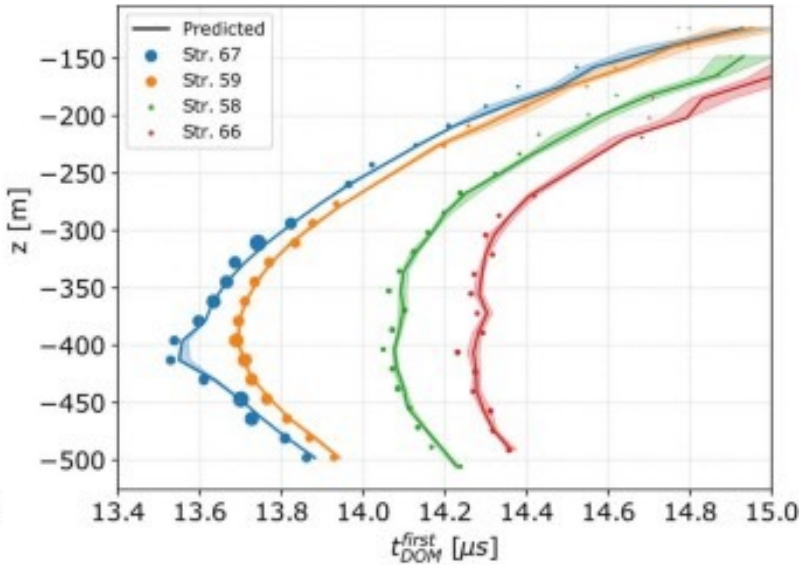


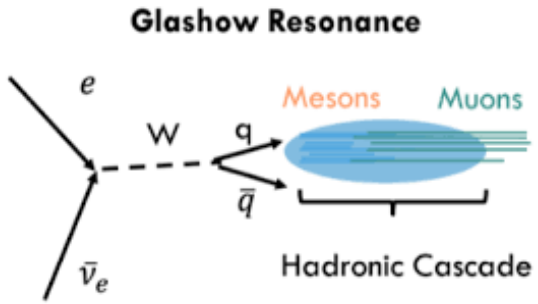


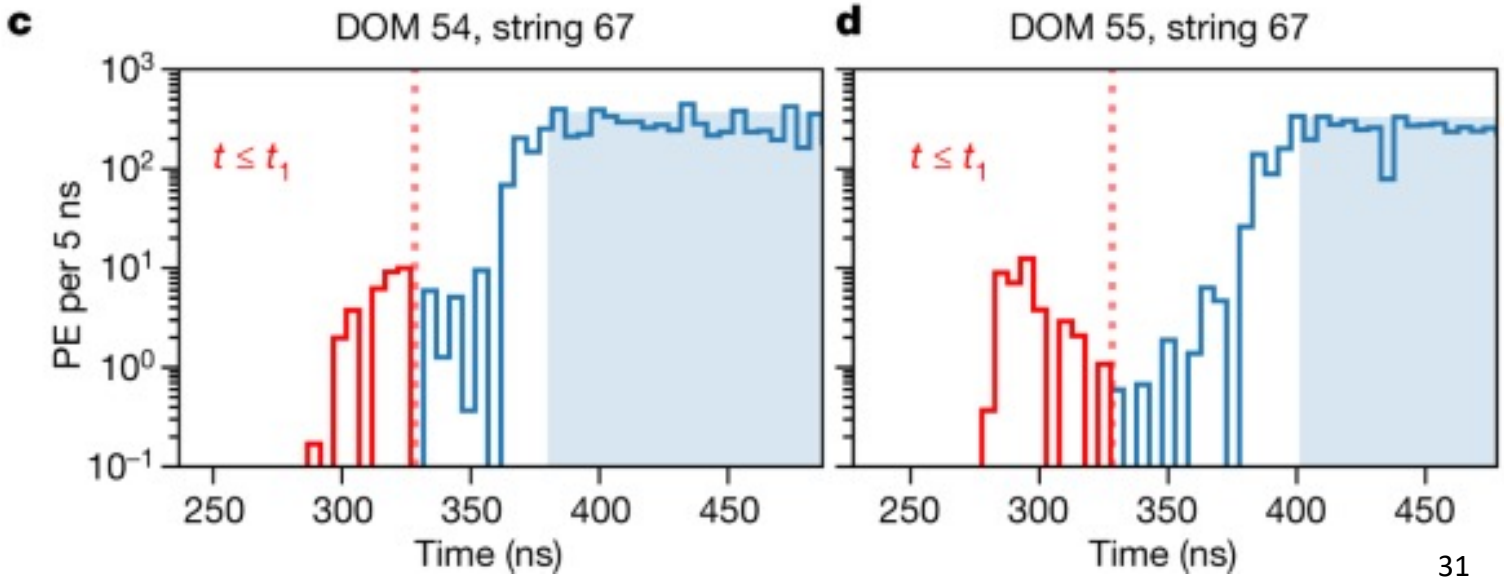
Early muons in hadronic cascade!

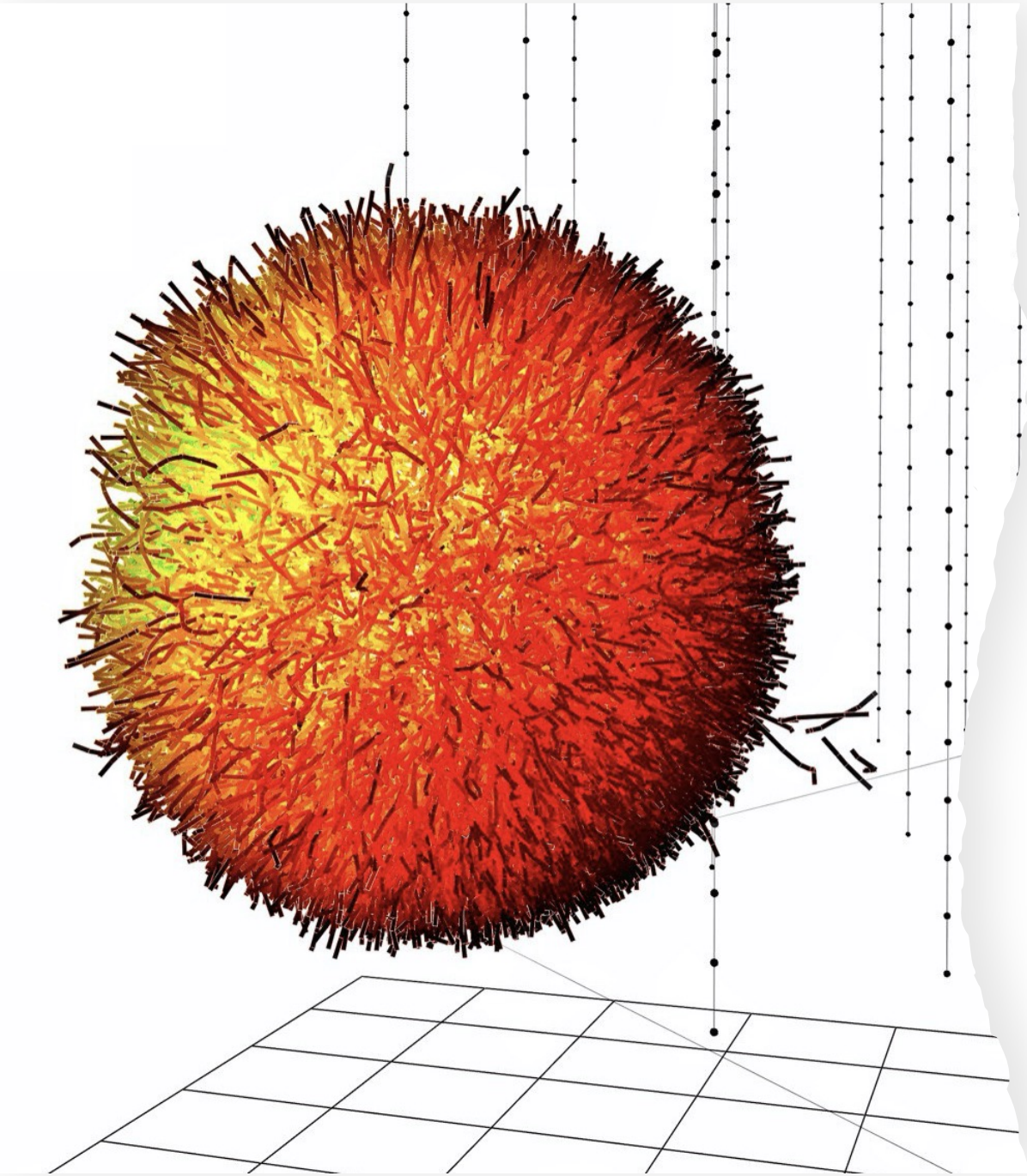




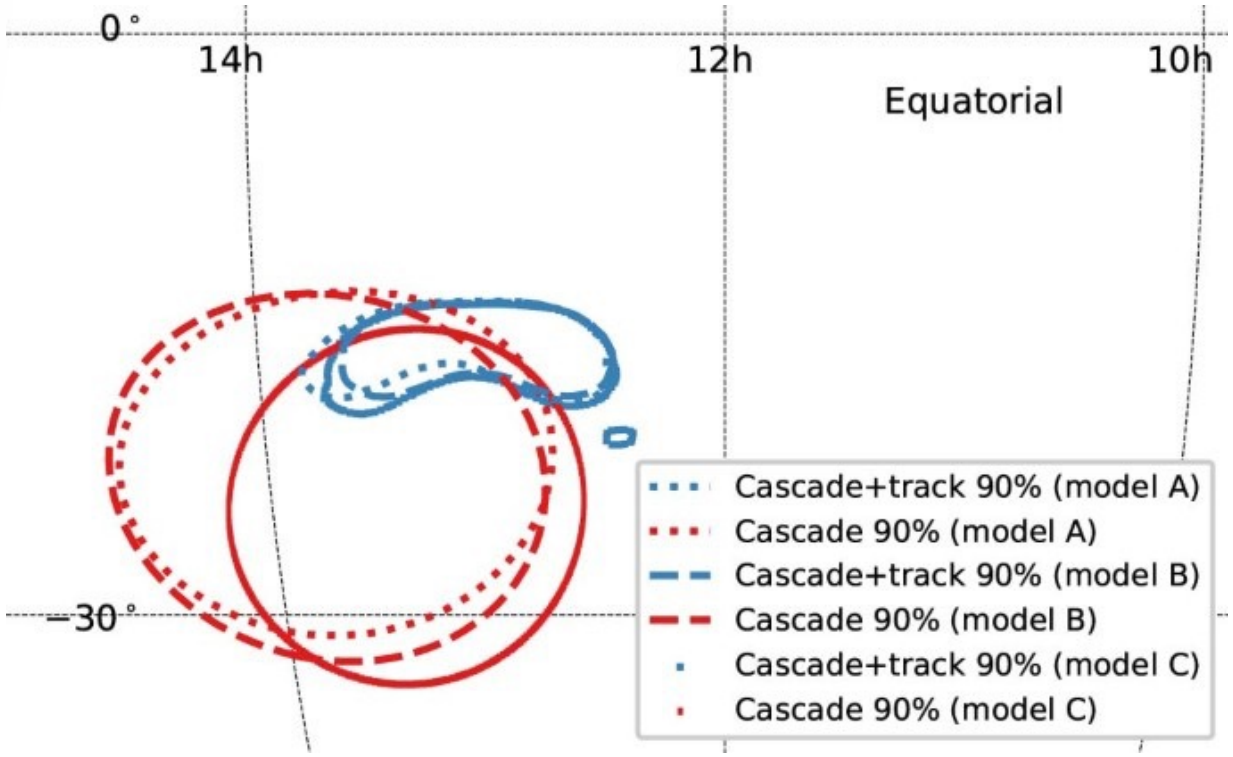








angular resolution of hadronic cascade



Improved by a factor of 5 compared to the traditional cascade reconstruction

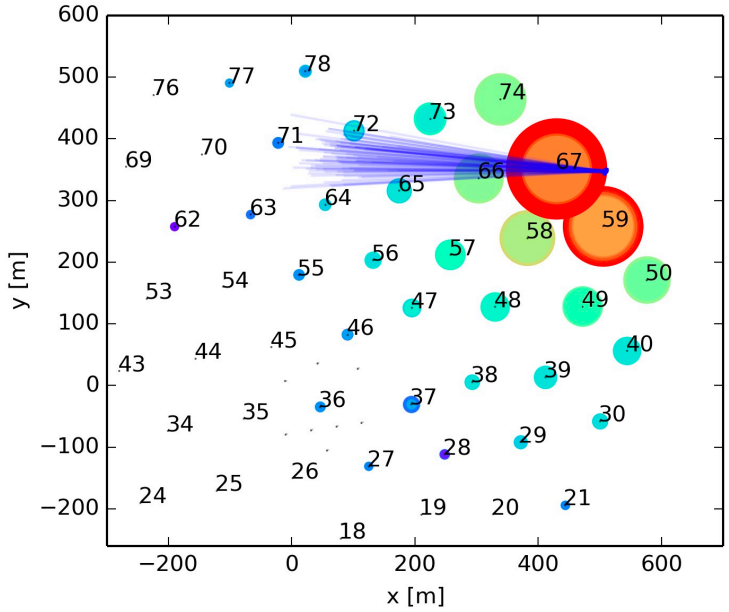
Leading muon energy

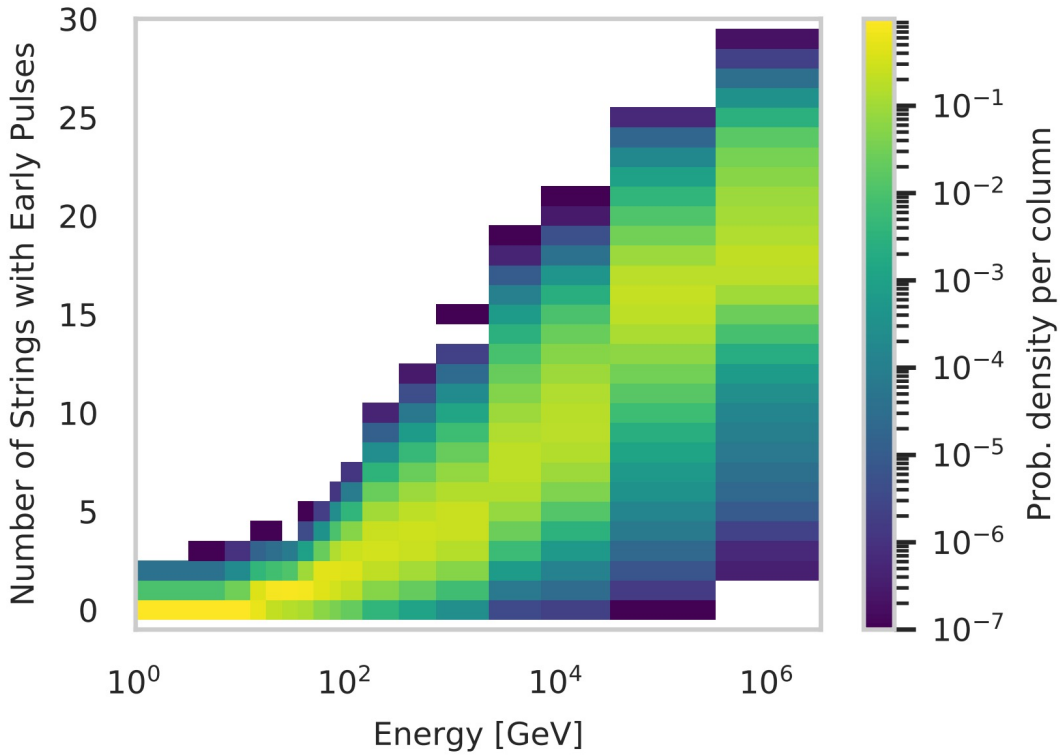
Simulate muons with varying energies along reconstructed direction

Count how many strings observe early pulses

Data observed N_{str}=1,

$$E_{\mu,lead} = 26.4^{+28.6}_{-12.4} \text{ GeV}$$





Atmospheric muon background rejection

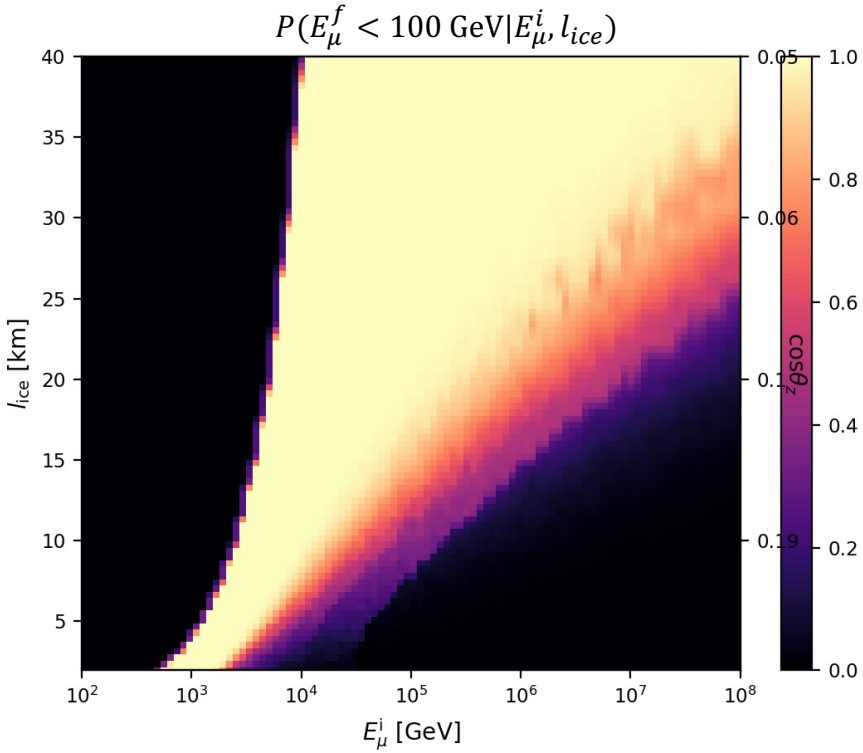
With leading muon energy, can constrain atmospheric muon background

1. Take surface muon flux (calculated with MCEq)
2. Propagate to depth to get flux of muons intersecting with cylinder around IceCube
3. Ask how many 6 PeV muons lose ~all its energy over 20m distance

Conservative estimate

~1.1e-7 events expected

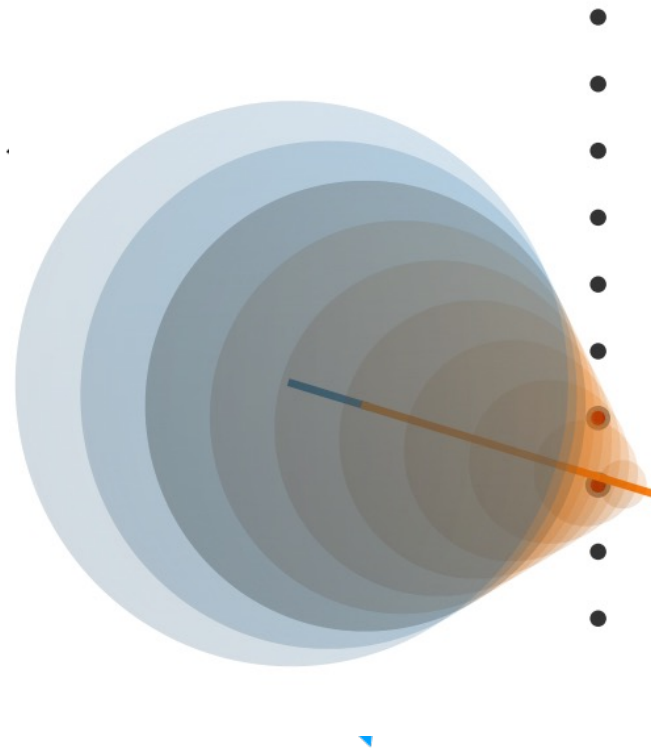
→ reject atm. muon hypothesis



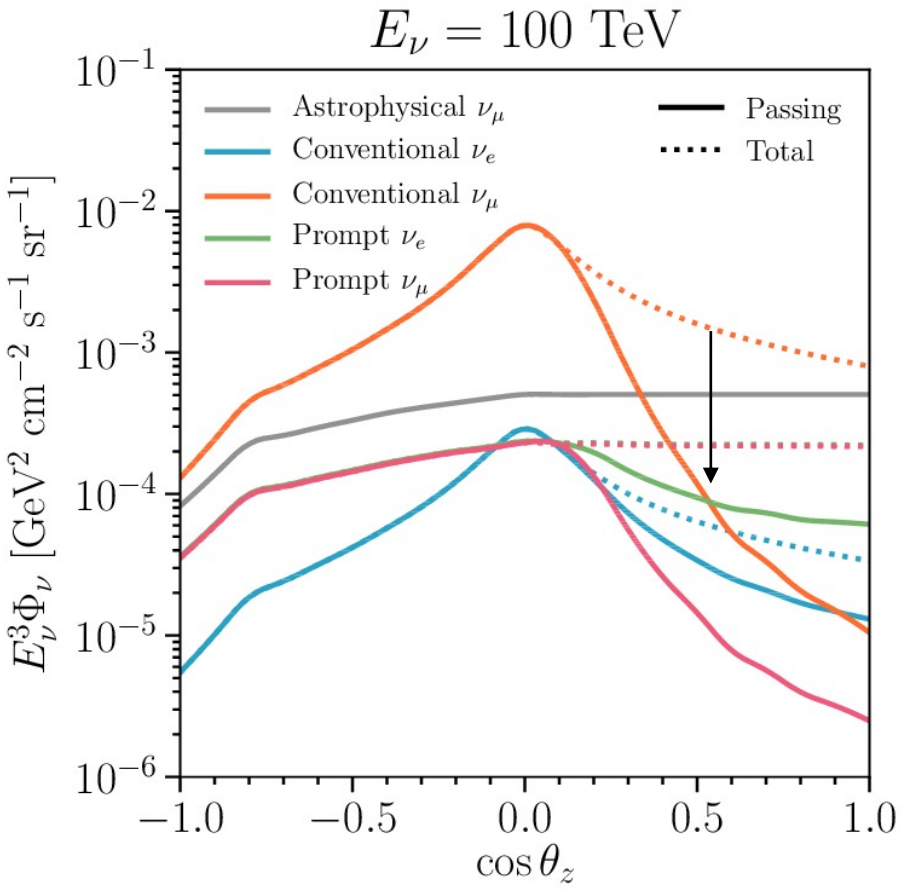
Atmospheric ν background rejection

Can also constrain atmospheric ν background

A ~6 PeV neutrino produced in the atmosphere is produced alongside high-energy muons



Expect **2E-7** atmospheric neutrinos in 4.6 years of live-time with similar signature as data



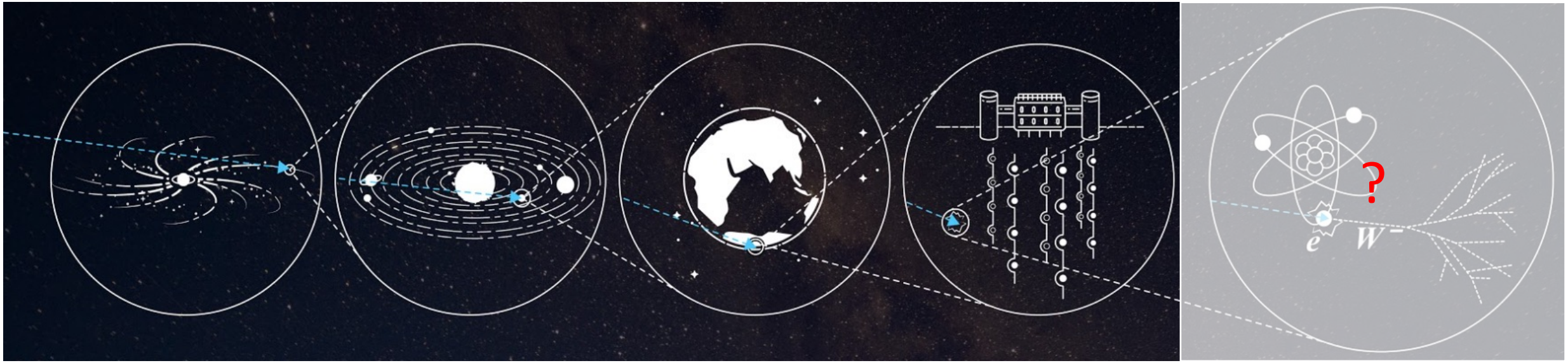
Summary thus far

Shower energy: 6.05 ± 0.72 PeV

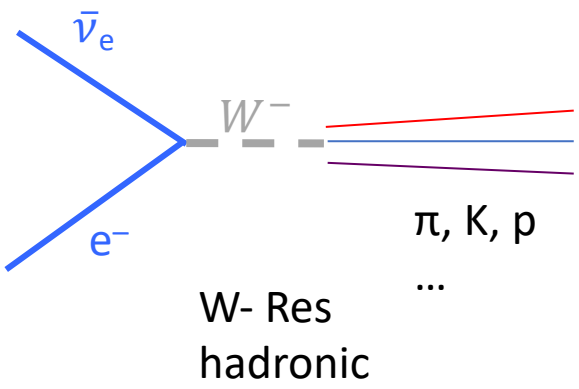
Early pulses observed on three DOMs on nearest string

Leading muon energy: $26.4^{+28.6}_{-12.4}$ GeV

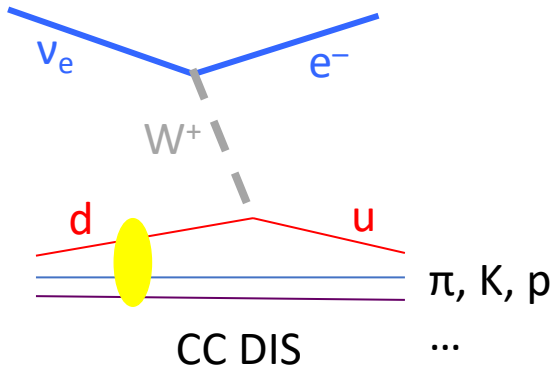
Combining two pieces → particle shower induced by **astrophysical** $\nu/\bar{\nu}$



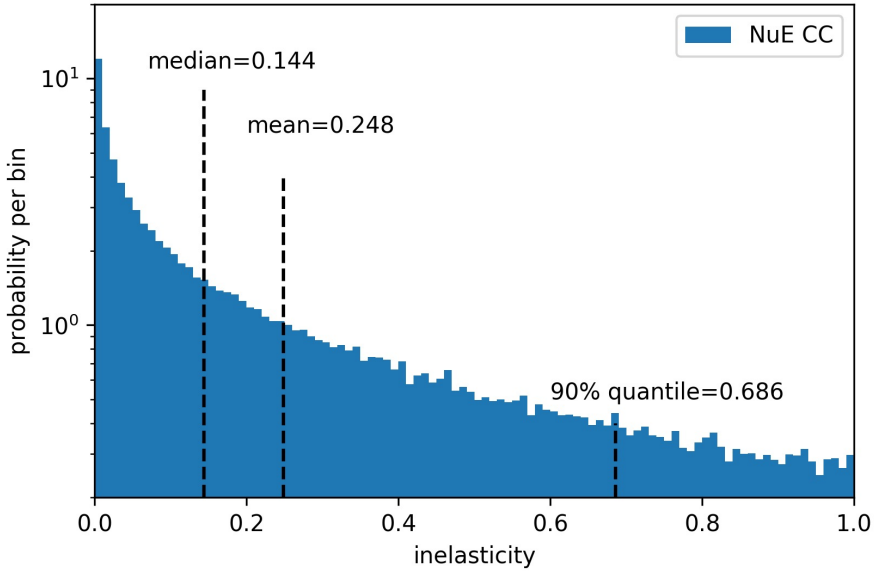
Interaction channels and visible energy



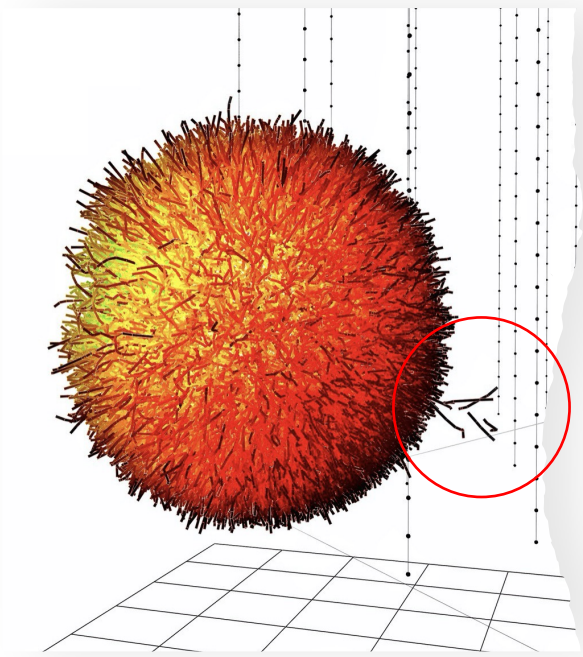
W-boson to hadrons 67%
95% of total energy detectable

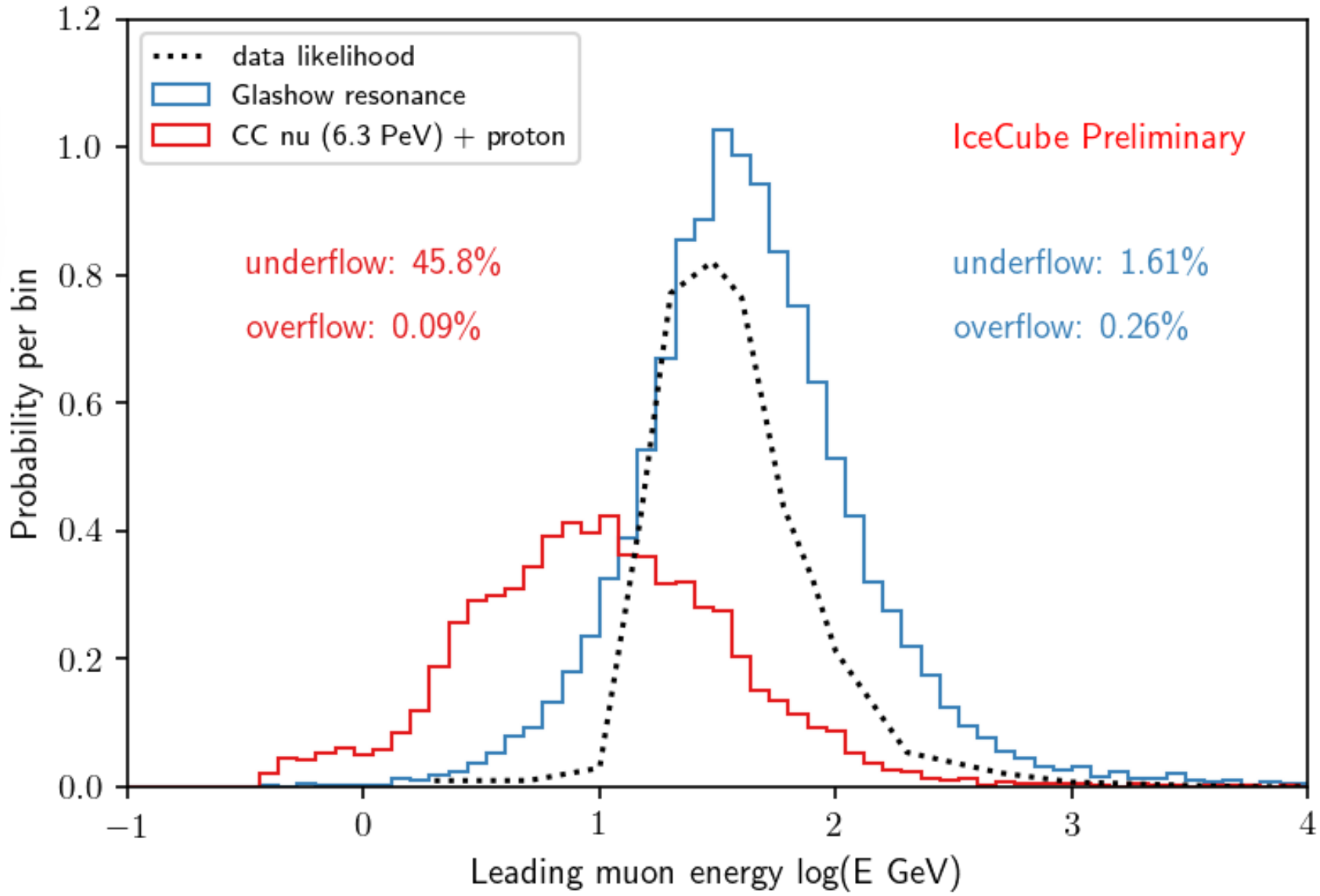


EM and hadronic shower
EM typically dominates
(inelasticity)



Hadronic portion can produce secondary muons → early pulses!





The leading muon energy is consistent with mu from W hadronicly decayed shower

Secondary muons

A function of the hadronic energy component

→ 6.3 PeV hadronic shower is more consistent with data than CC (assuming QGSJET-01C)

Muon energetics are well understood, but hadronic models more difficult

→ DPMJETIII, EPOS-LHC, SIBYLL, QGSJET-01C

Uncertainties are large and not well-constrained by data at PeV energies

Decide to evaluate based on reconstructed visible energy (~6.05 PeV) alone

Expectation rates

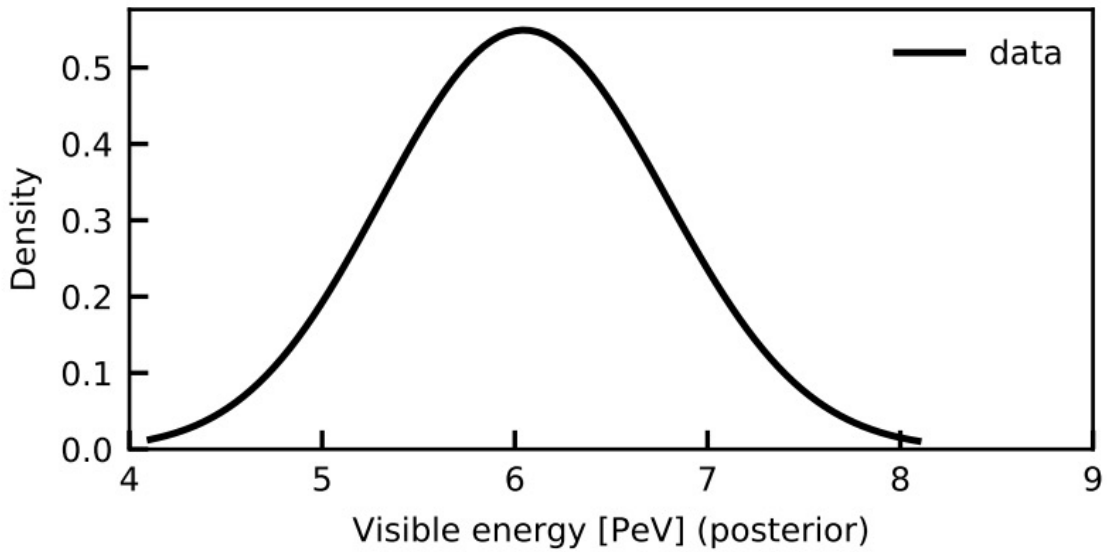
Dominant DIS background is CC nue

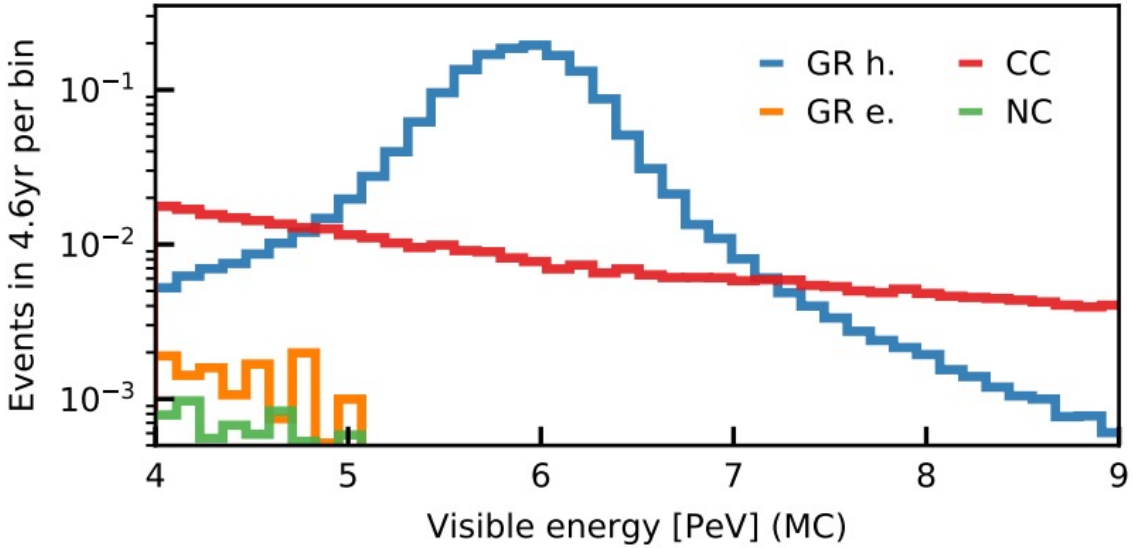
NC suppressed as flux drops off

Resonance clearly visible

Assuming single-power-law astrophysical flux ~ $E^{-2.49}$

- Latest global-fit best-fit





Likelihood ratio test

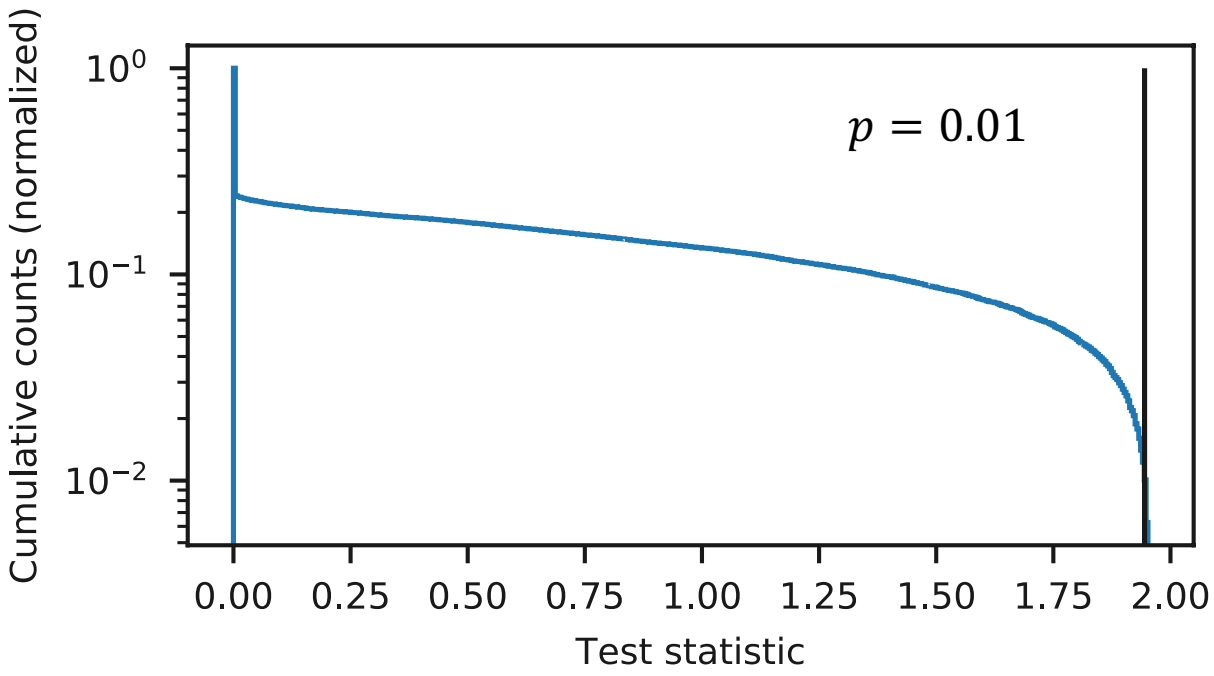
Assuming energy is sampled from inhomogenous Poisson point process

Single free parameter S with null $S = 0$

Construct likelihood ratio Γ

$$\mathcal{L}(S) = e^{-(B+S)} \prod \{B\mathscr{P}_{\mathrm{B}}(E_i) + S\mathscr{P}_{\mathrm{S}}(E_i)\}$$

$$\Gamma = \log \frac{\mathcal{L}(S = S_{\max})}{\mathcal{L}(S = 0)}$$



What does nuebar mean for astronomy?

By measuring nu/nubar -> probe source environment directly

$$p + \gamma \to \Delta^+ \to \begin{cases} \pi^+ + n & 1/3 \text{ of all cases} \\ \pi^0 + p & 2/3 \text{ of all cases} \end{cases}$$

$$\pi^+ \to \mu^+ + \nu_\mu \,, \qquad \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu \,,$$

$$\mathrm{p} + \mathrm{p} \to \begin{cases} \pi^+ + \text{anything} & 1/3 \text{ of all cases} \\ \pi^- + \text{anything} & 1/3 \text{ of all cases} \\ \pi^0 + \text{anything} & 1/3 \text{ of all cases} \end{cases}$$

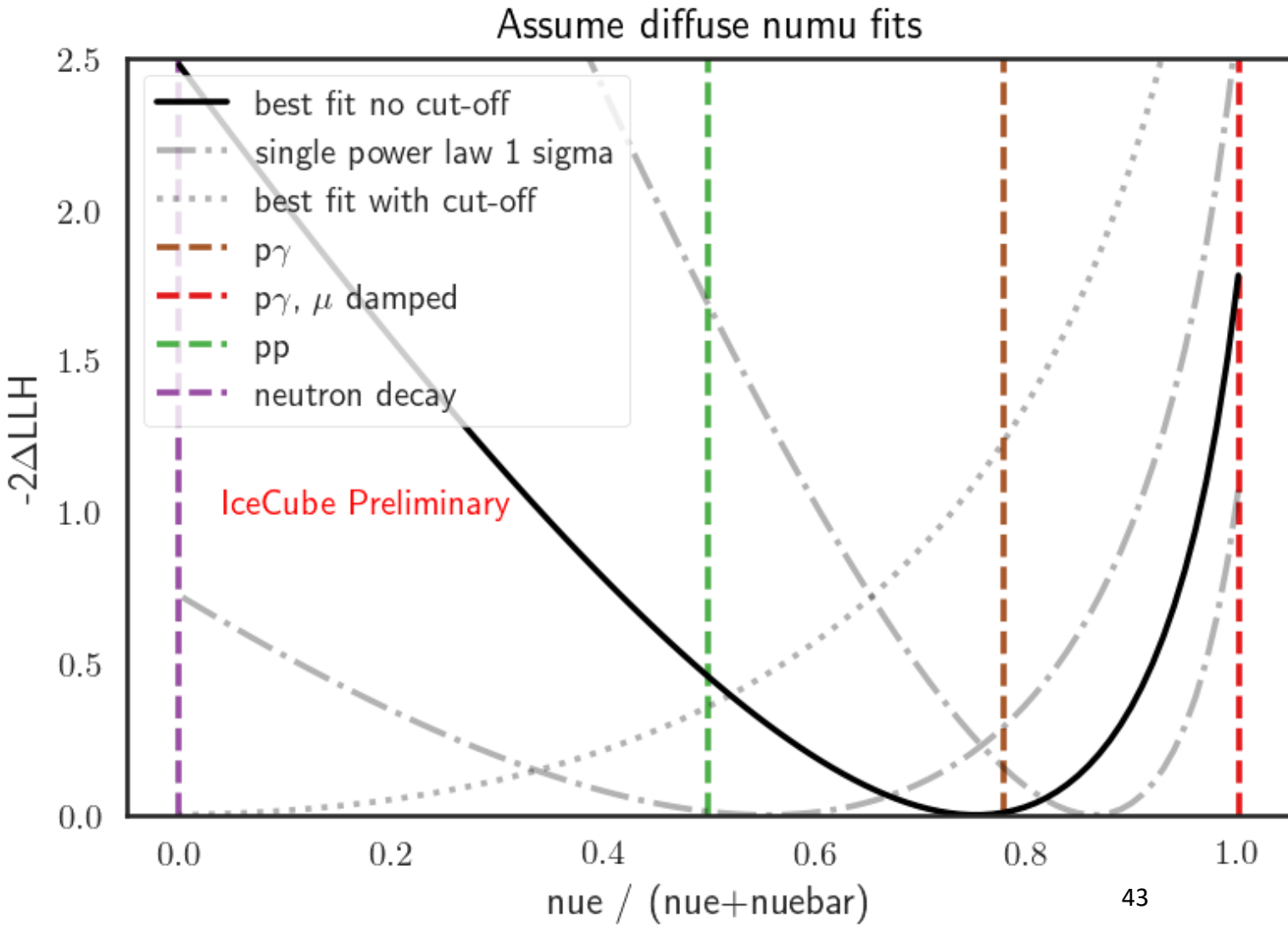
Muon damped: strong B field and synchrotron losses before muon decay

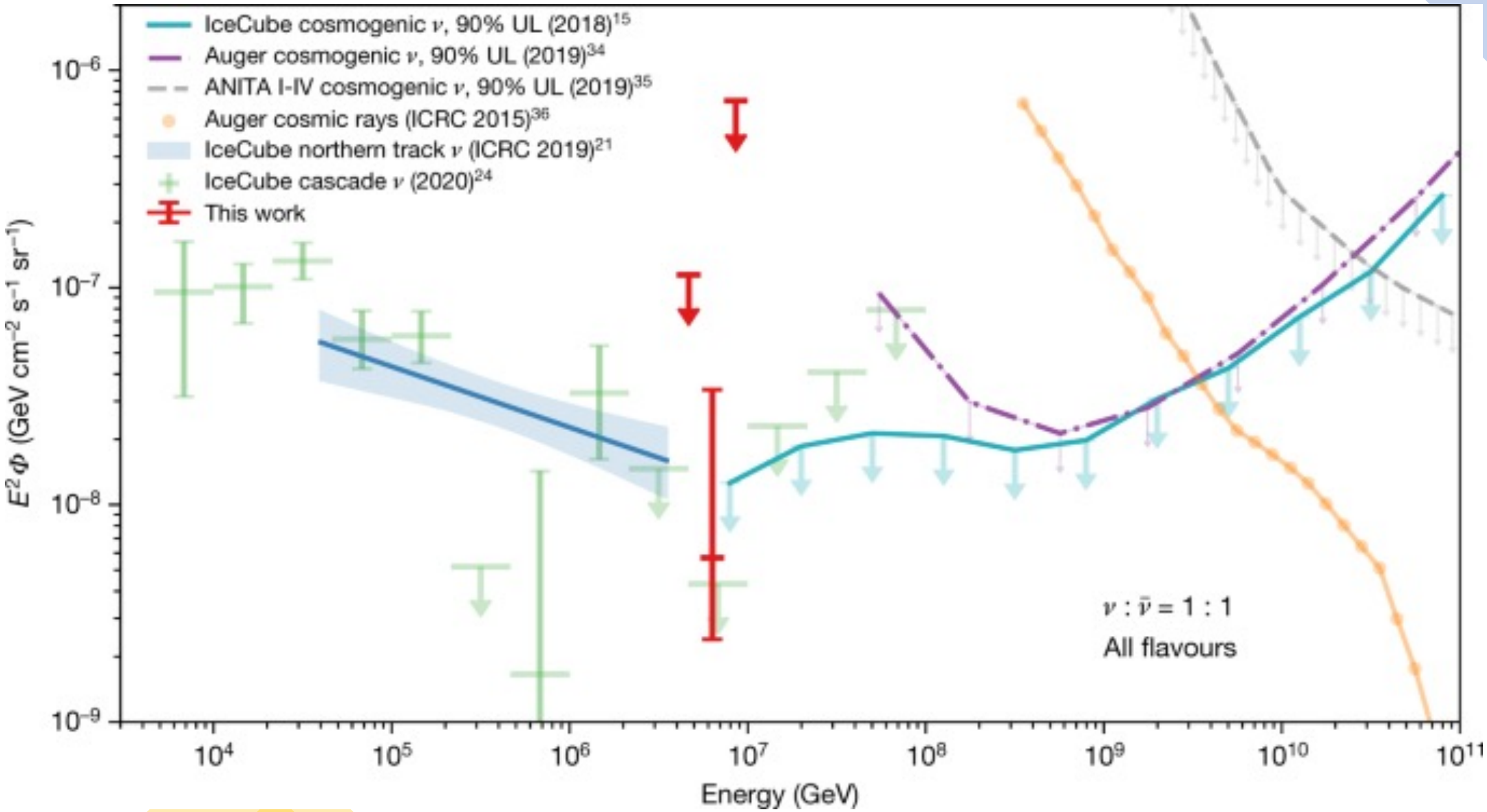
	Source flavor composition $(\phi_e : \phi_\mu : \phi_\tau)$		Earthly flavor composition $(\phi_e^f : \phi_\mu^f : \phi_\tau^f)$		Earthly $\bar{\nu}_e$ fraction $\xi^f_{\bar{\nu}_e}$ in cosmic neutrino flux
pp $\to \pi^\pm$ pairs	(1:2:0)		(1:1:1)		$9/54 = 17\%$
w/ damped $\mu^\pm$	(0:1:0)		(4:7:7)		$6/54 = 11\%$
	ν	$\bar{\nu}$	ν	$\bar{\nu}$	
p$\gamma \to \pi^+$ only	(1:1:0)	(0:1:0)	(14:11:11)	(4:7:7)	$4/54 = 7.4\%$
w/ damped μ^+	(0:1:0)	(0:0:0)	(4:7:7)	(0:0:0)	0

With one event it is still difficult (but Gen2 would help)

γ_{astro}	2.28	2.49	2.89
Φ_{astro}	4.32	7.0	6.45
PEPE *pp*	2.27	1.55	0.28
HESE *pp*	1.15	0.79	0.14
PEPE *pγ*	1.01	0.69	0.12
HESE *pγ*	0.51	0.35	0.06

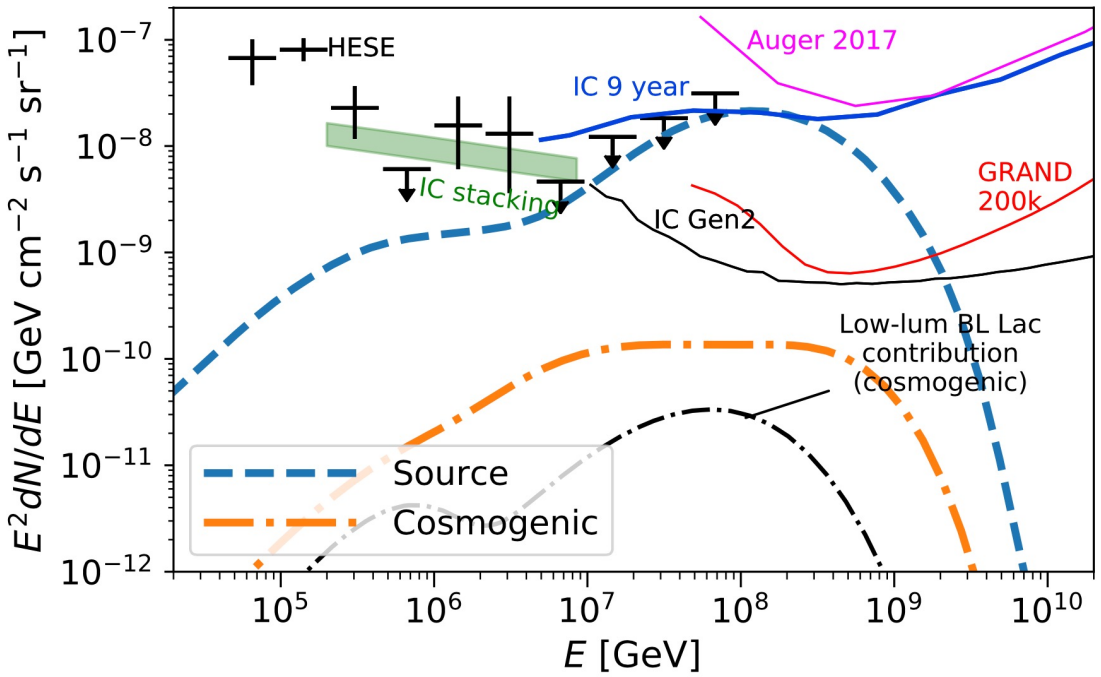
Result strongly depends on spectrum shape

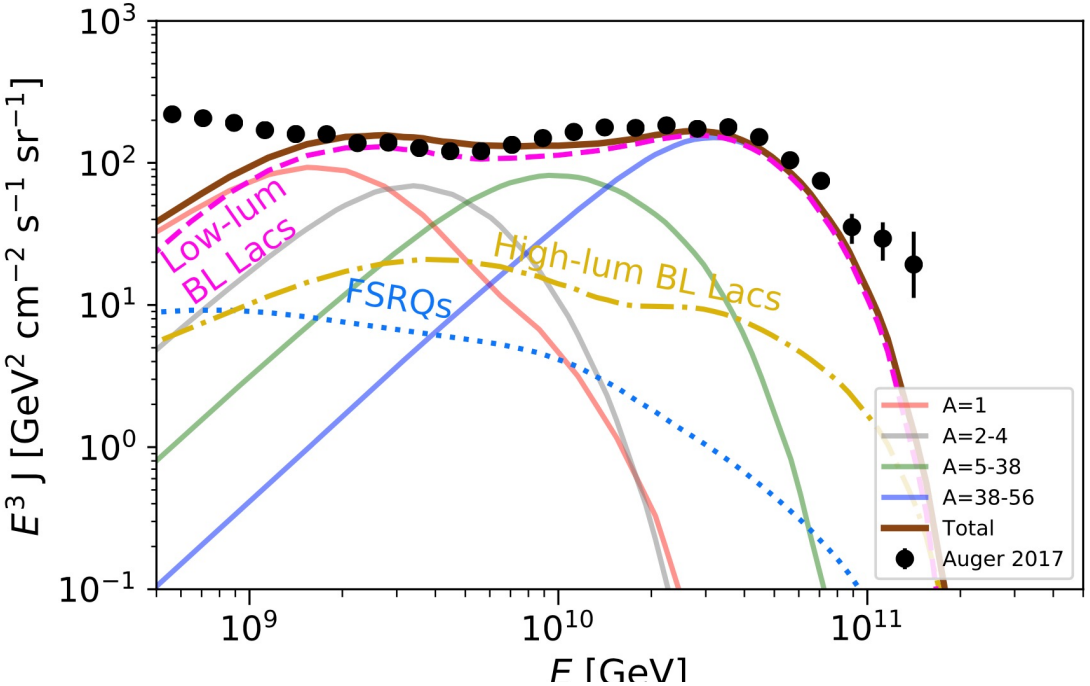



IceCube cosmogenic ν, 90% UL (2018)15
Auger cosmogenic ν, 90% UL (2019)34
ANITA I-IV cosmogenic ν, 90% UL (2019)35
Auger cosmic rays (ICRC 2015)36
IceCube northern track ν (ICRC 2019)21
IceCube cascade ν (2020)24
This work
ν : ν̄ = 1 : 1
All flavours
E²Φ (GeV cm⁻² s⁻¹ sr⁻¹)
Energy (GeV)

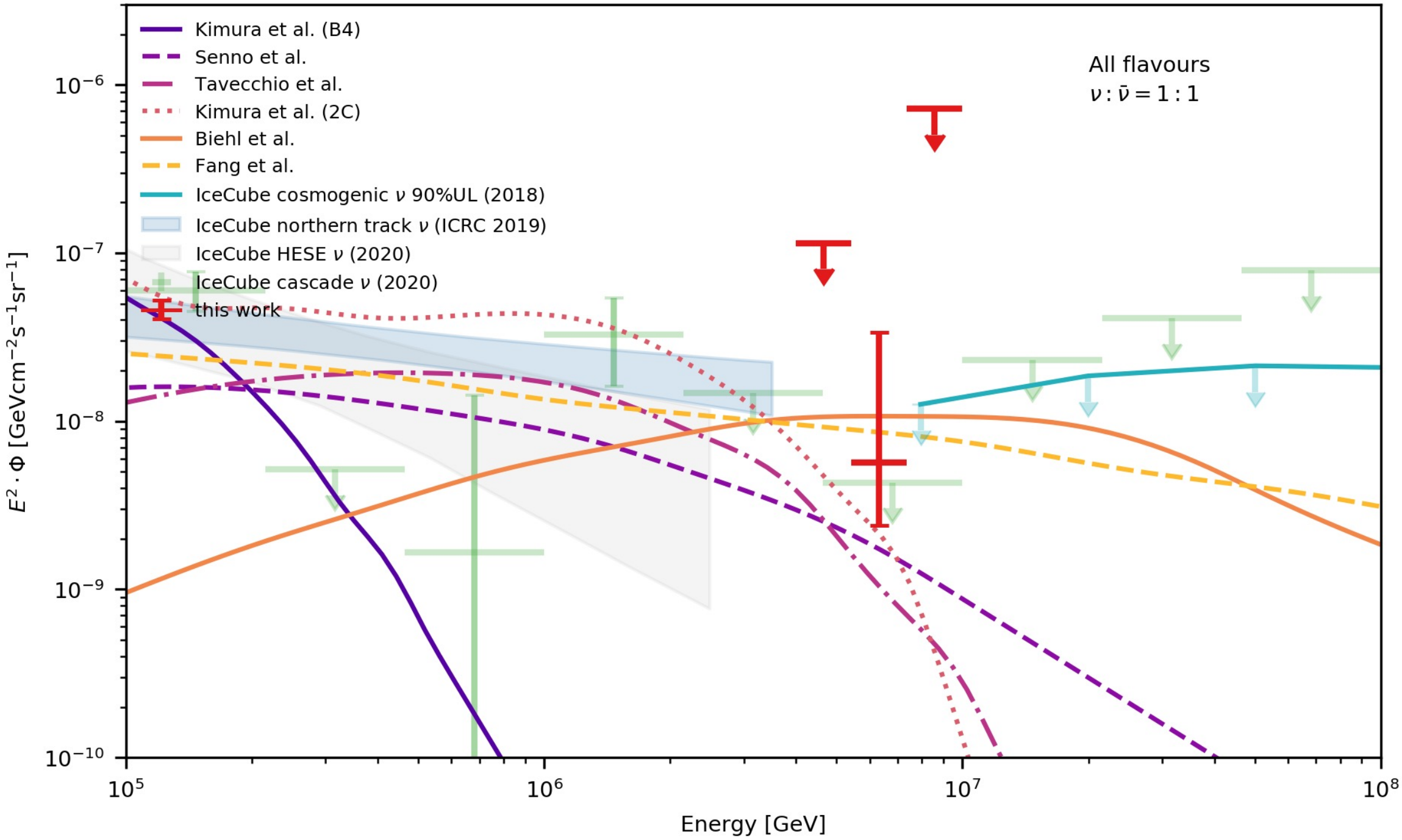
Towards to the highest energies

10 PeV key for linking with ultra high cosmic rays

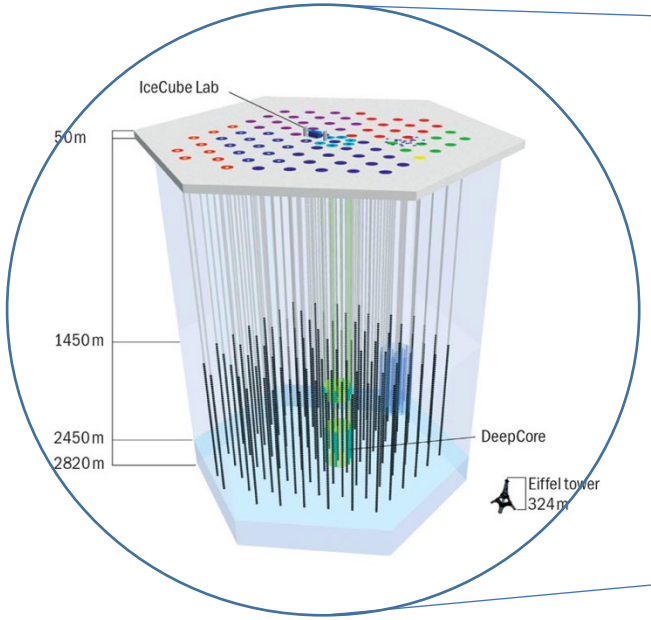


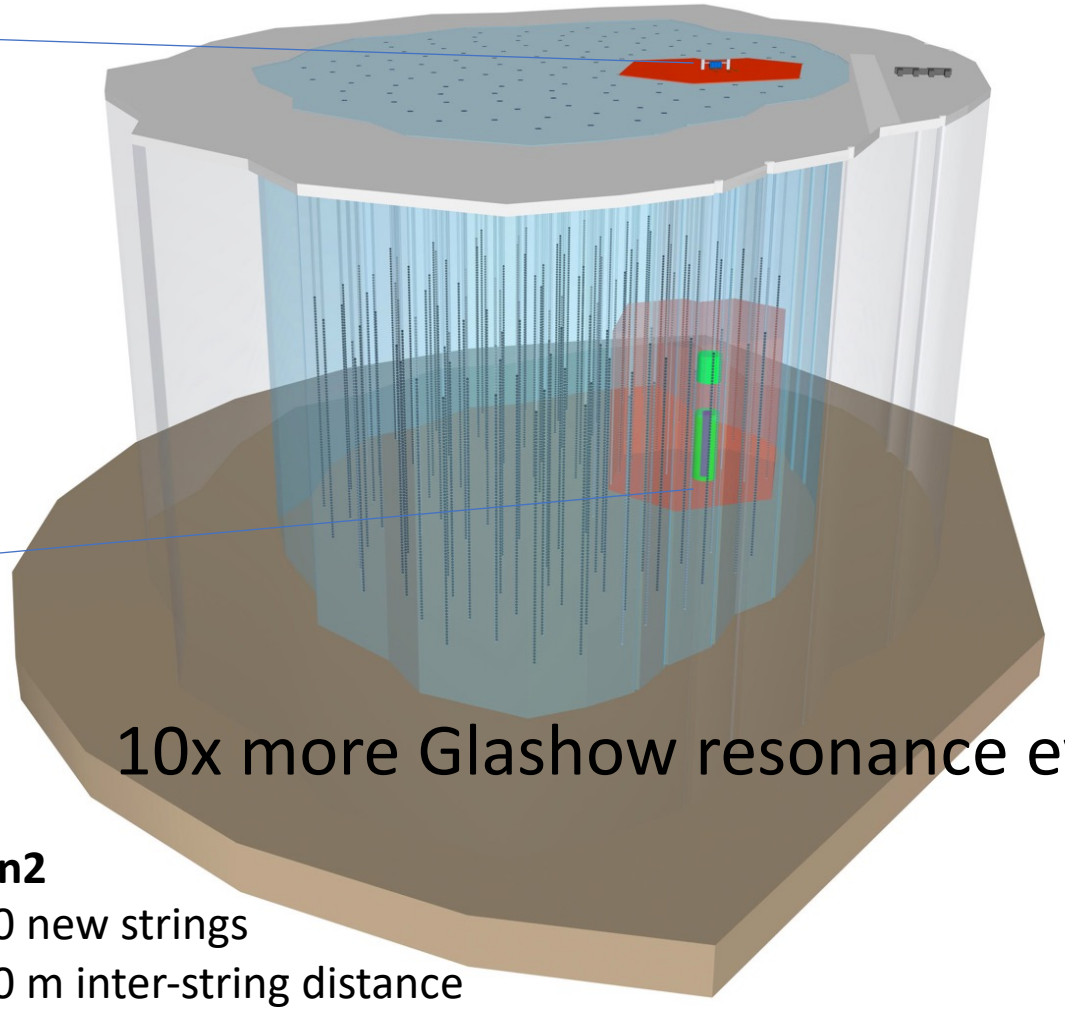


X. Rodrigues, J. Heinze, A. Palladino, AvV and W. Winter, arXiv:2003.08392, accepted for publication in PRL


Kimura et al. (B4)
Senno et al.
Tavecchio et al.
Kimura et al. (2C)
Biehl et al.
Fang et al.
IceCube cosmogenic ν 90%UL (2018)
IceCube northern track ν (ICRC 2019)
IceCube HESE ν (2020)
IceCube cascade ν (2020)
this work
All flavours
ν : ν̄ = 1 : 1
E² · Φ [GeVcm⁻²s⁻¹sr⁻¹]
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁵
10⁶
10⁷
10⁸
Energy [GeV]

Towards IceCube-Gen2





10x more Glashow resonance events

IceCube
86 strings
125 m inter-string distance
60 OMs per string
1 km^3 volume

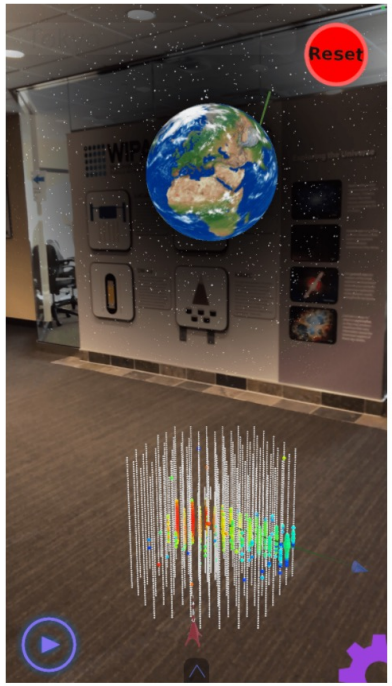
Gen2
120 new strings
240 m inter-string distance
80 OMs per string
8 km^3 volume

Conclusion

- First hint of Glashow resonance after 60 years of theory prediction (only possible with accelerators from nature)
- Consistent with standard model (W boson mass)
- Open a new window to study particle physics from extreme sources with nu/nubar ratio
- Future Gen2 is going to be important to make statistical significant conclusions on pp/pgamma

From outer space, to the South Pole, to your phone: A new AR app for IceCube

Posted on October 8, 2020 by Madeleine O'Keefe



A screenshot from the IceCubeAR app.

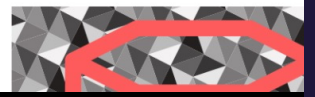
Located in the frigid desert that is the South Pole, the IceC
Neutrino Observatory isn't your typical telescope. It doesn'
an observatory dome or satellite dish. In fact, if you were
standing at the South Pole looking at IceCube, you would s
nothing but a small building in a vast, barren, snowy landsc

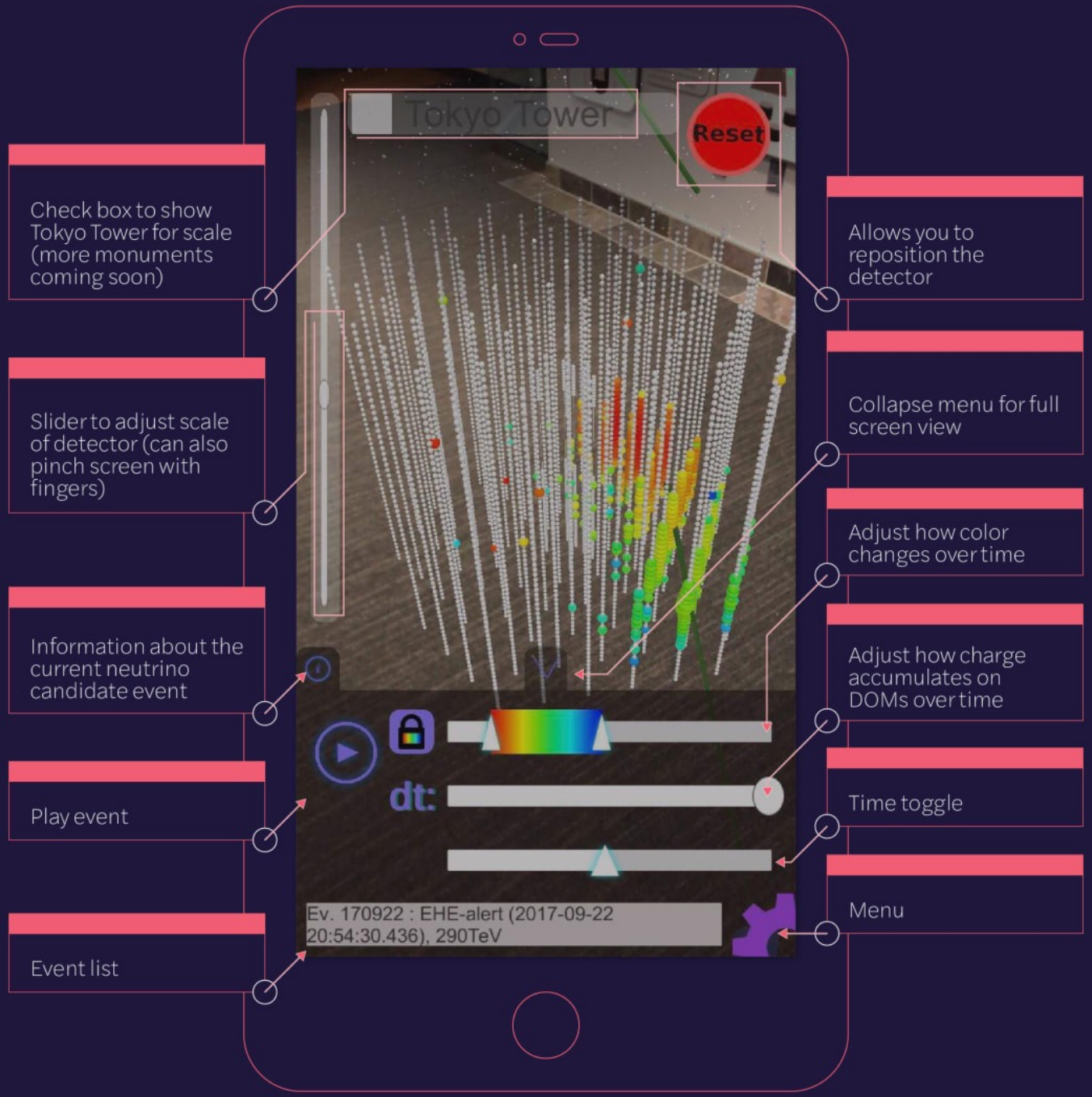
That's because the IceCube detector is *underground*. It
comprises an array of 5,160 optical sensors that are frozen
beneath a cubic kilometer of ice a mile beneath the surface
These sensors pick up signals left behind by mysterious pa
called neutrinos.

Now, thanks to a new augmented reality (AR) app, anyone i
world can see what's happening under the ice at the South
And when a neutrino candidate sails through the detector,
will find out in real time!

Introducing IceCubeAR, aka IceBear.

Neutrinos are fundamental particles that travel through the cosmos. They come from





Article | Published: 10 March 2021

Detection of a particle shower at the Glashow resonance with IceCube

The IceCube Collaboration

Nature **591**, 220–224(2021) | Cite this article