Detection of an Astrophysical Antineutrino via the Glashow-Resonance with IceCube

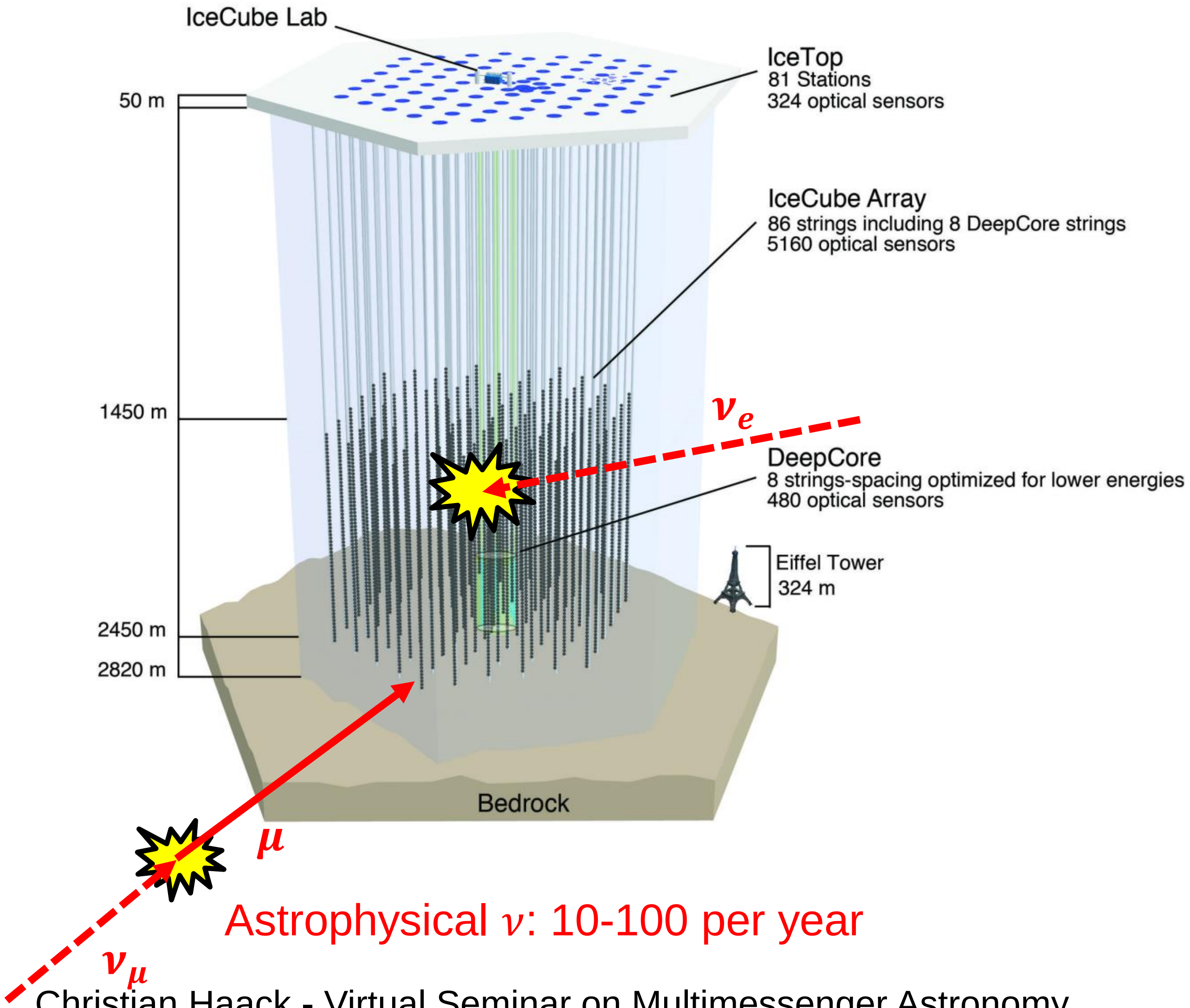
Christian Haack, TUM

Virtual Seminar on Multimessenger Astronomy, 01.06.2021

Outline

1. **The IceCube Neutrino Observatory**
2. How to detect neutrinos
3. Production mechanisms of high-energy astrophysical neutrinos
4. Observation of a neutrino interaction at the Glashow Resonance

The IceCube Neutrino Observatory



Multi-purpose detector at the South Pole

IceCube In-Ice Array

- 5160 **D**igital **O**ptical **M**odules (PMT with onboard digitization)
- 86 Strings in a depth of 1450m to 2450m

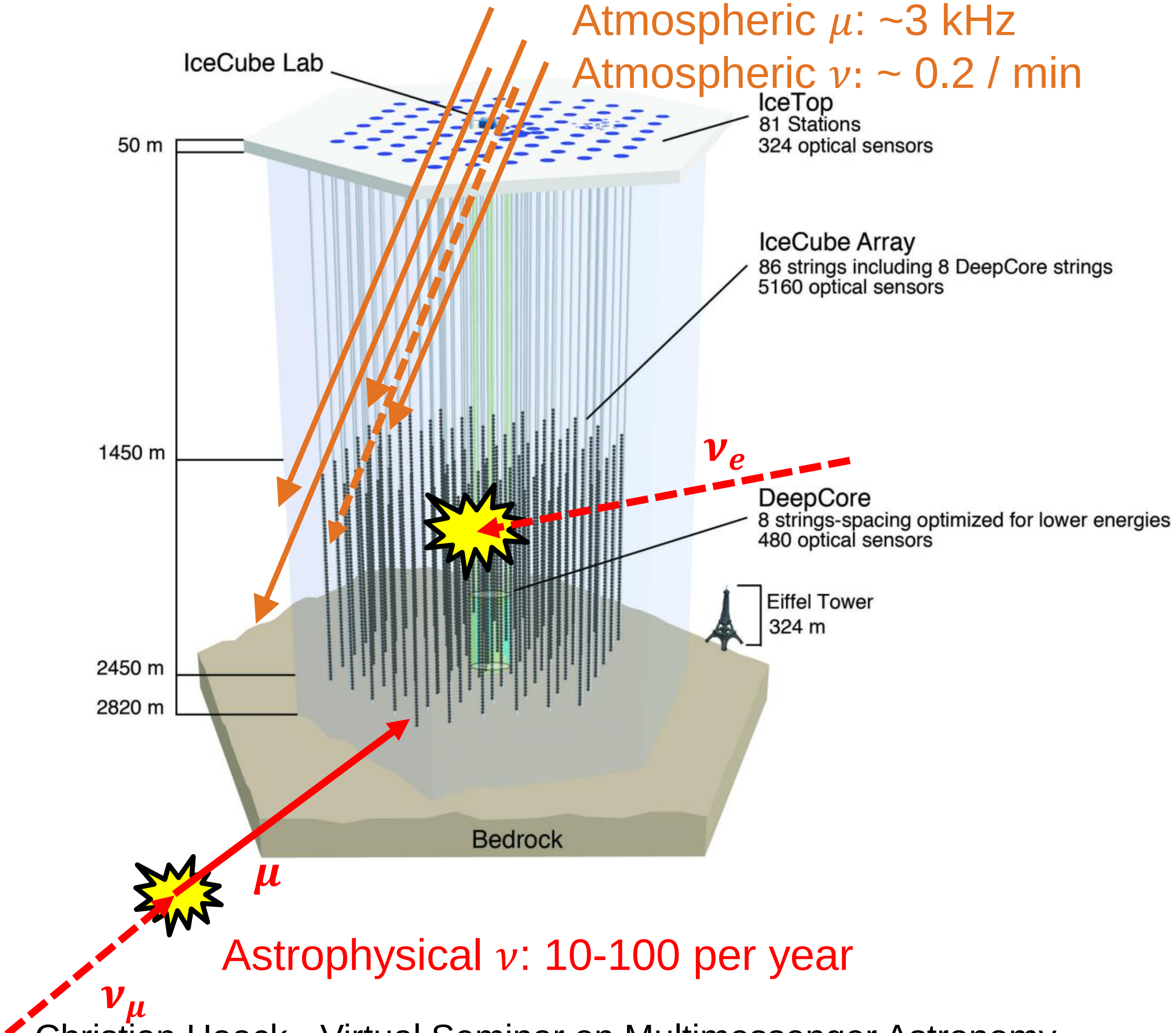
Detection Principle: Cherenkov emission of secondary particles produced by v-interaction in or near the detector

Trigger threshold ~10GeV (with DeepCore)

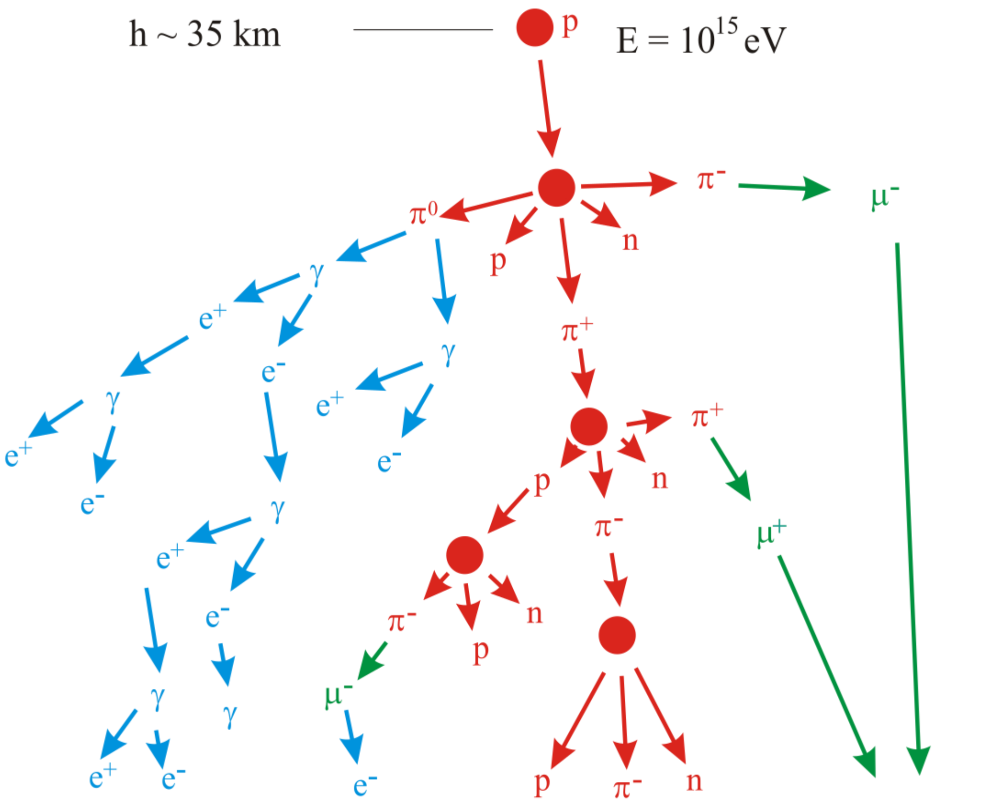
The IceCube Neutrino Observatory

Atmospheric μ: ~3 kHz

Atmospheric ν: ~ 0.2 / min



Astrophysical ν: 10-100 per year

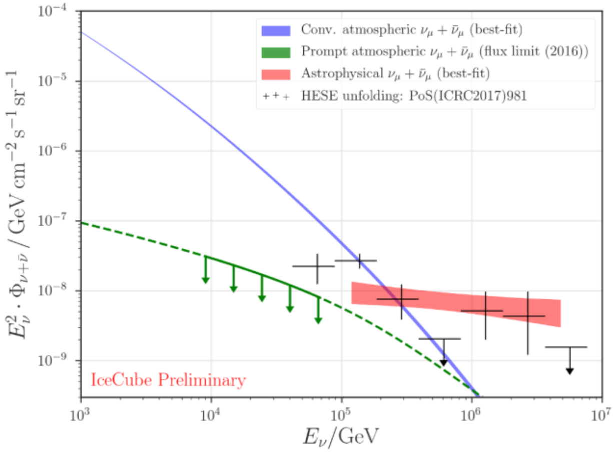


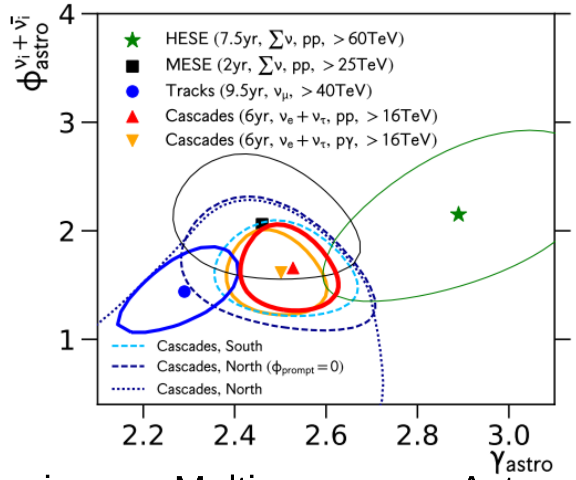
https://en.wikipedia.org/wiki/Air_shower_(physics)

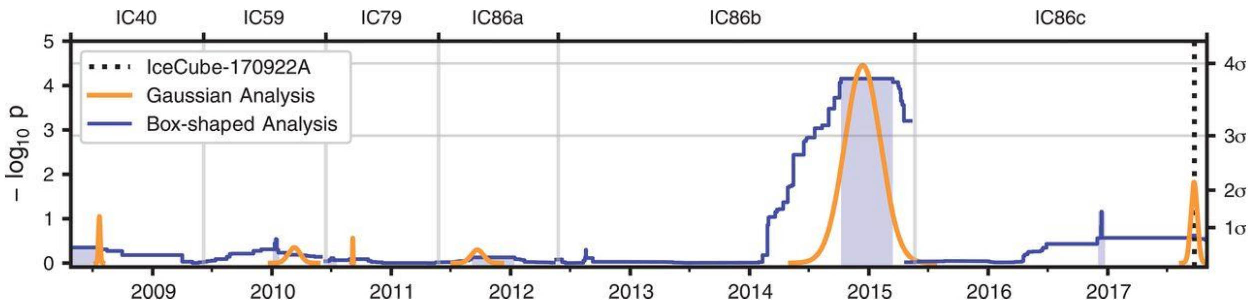
Discovery of Astrophysical Neutrinos

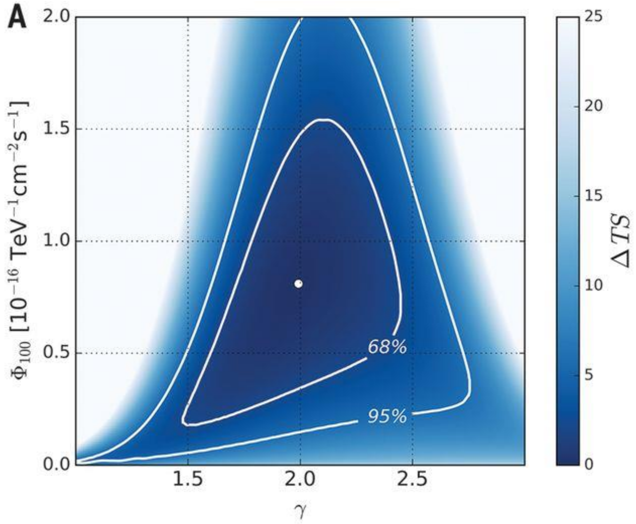
Diffuse flux: Integrated signal from all sources
Flux observed in many channels, spectrum (so far) consistent with a power law.

Flux from a source: Neutrino flare in TXS0506+056 and high-energy neutrino coincident with a gamma-ray flare









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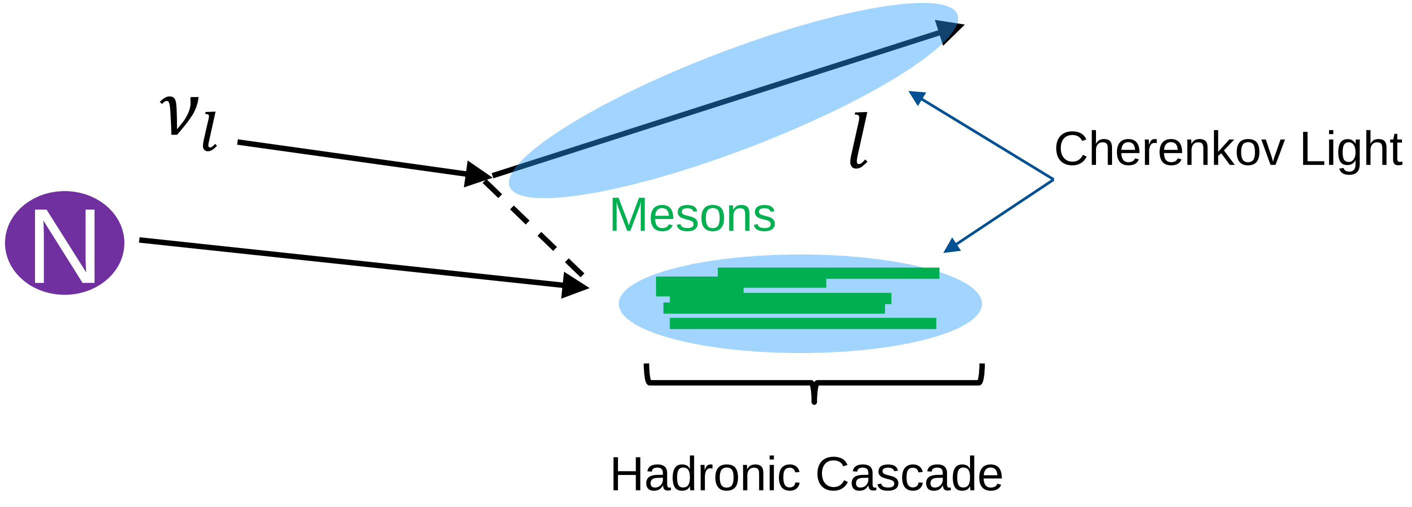
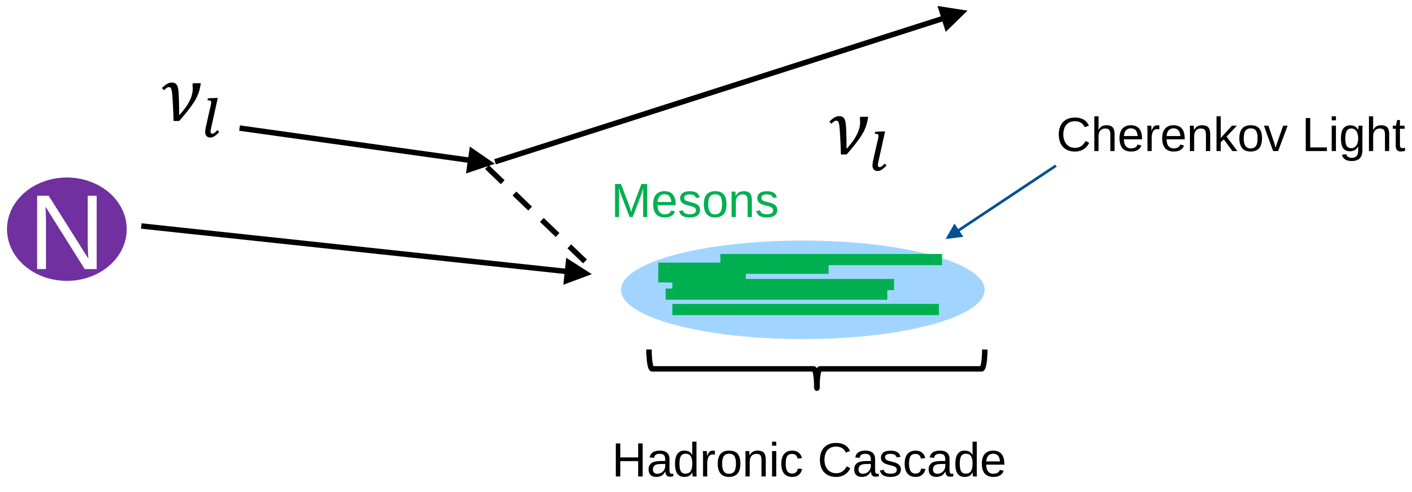
Neutrino Interactions in Ice



CC Deep Inelastic Scattering

$$\nu_l + X \rightarrow l + X'$$

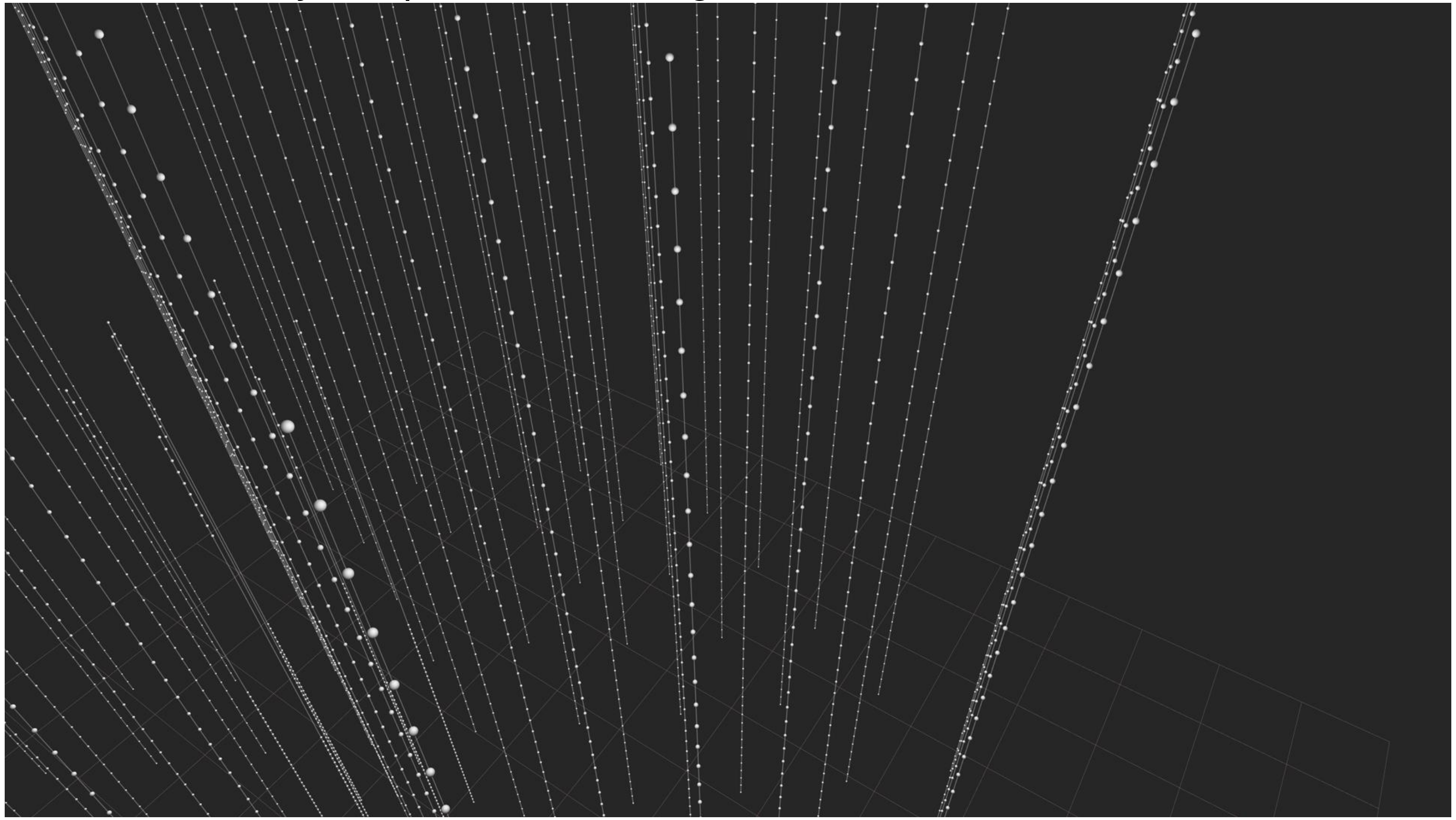


NC Deep Inelastic Scattering

$$\nu_l + X \rightarrow \nu_l + X'$$

Cascade in Ice

Color: Time delay compared to direct light

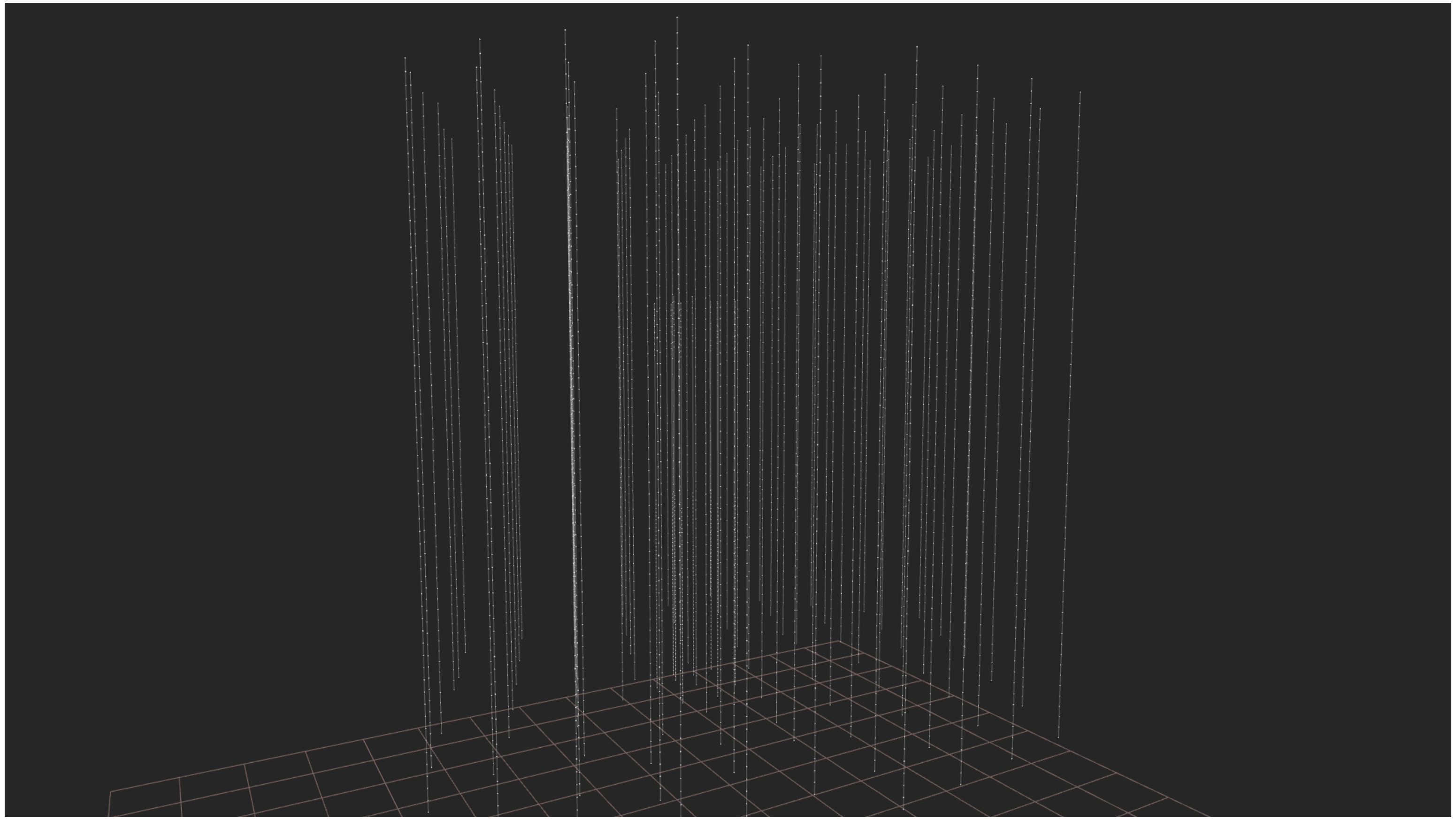


Calorimetric measurement of the energy: Good angular resolution

Small lever arm: Challenging directional reconstruction

Muon in Ice

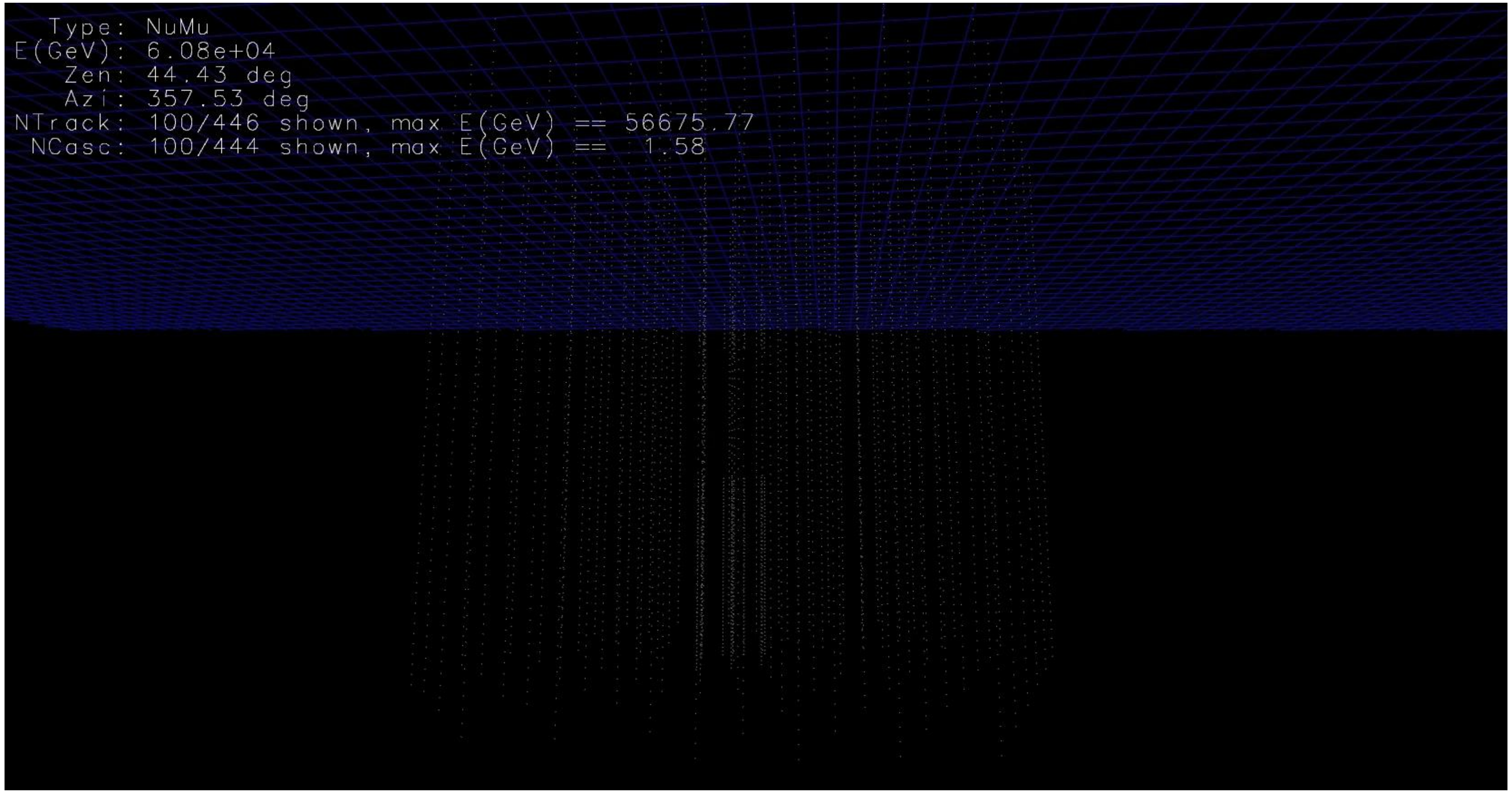
Color: Time delay compared to direct light



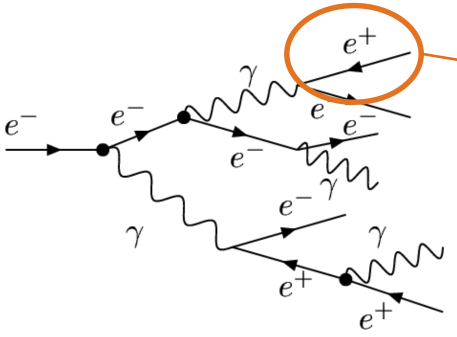
Can only measure dE/dX: Poor angular resolution

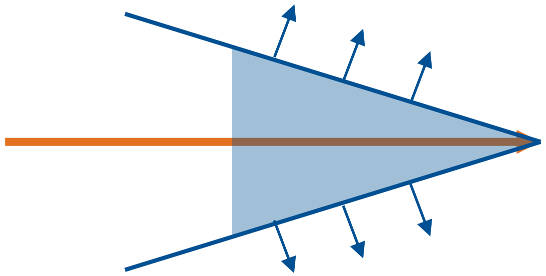
Large lever arm: Excellent directional reconstruction

Muon in IceCube



Cherenkov Light Yield for EM Cascades

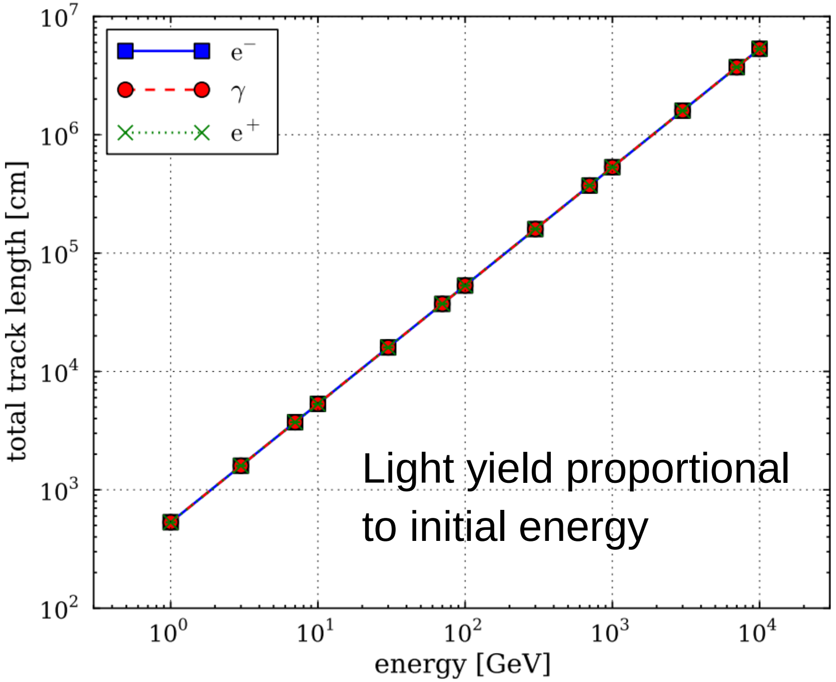




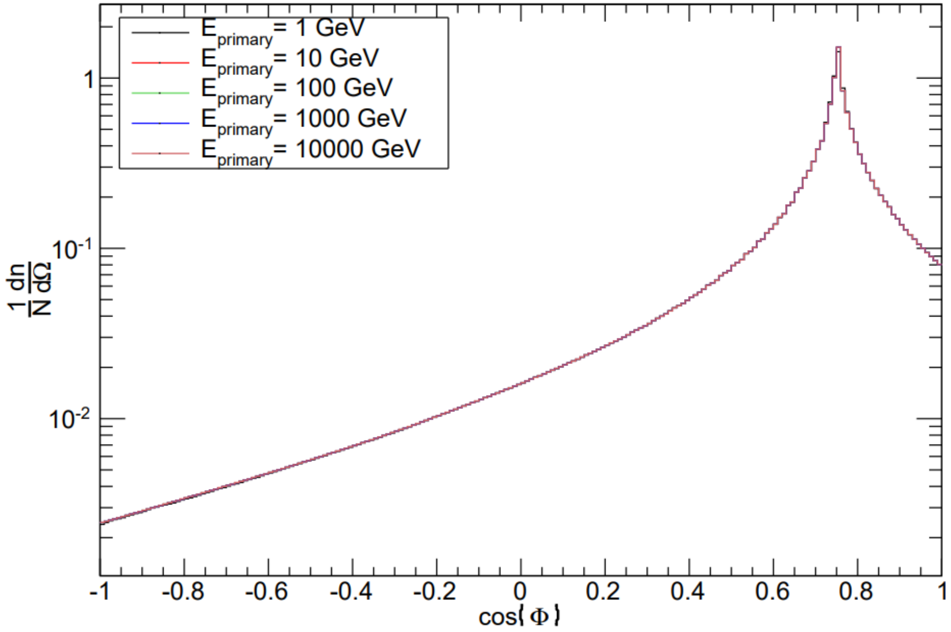
~250 photons / cm between 300nm and 500nm

Cascade → Sum of Cherenkov „tracks“

Light Yield



Light yield proportional to initial energy

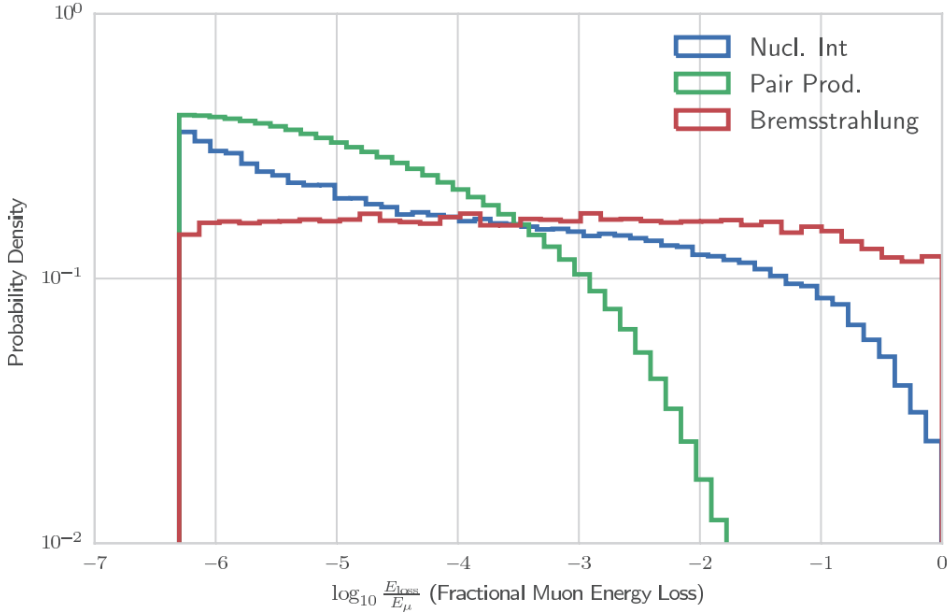


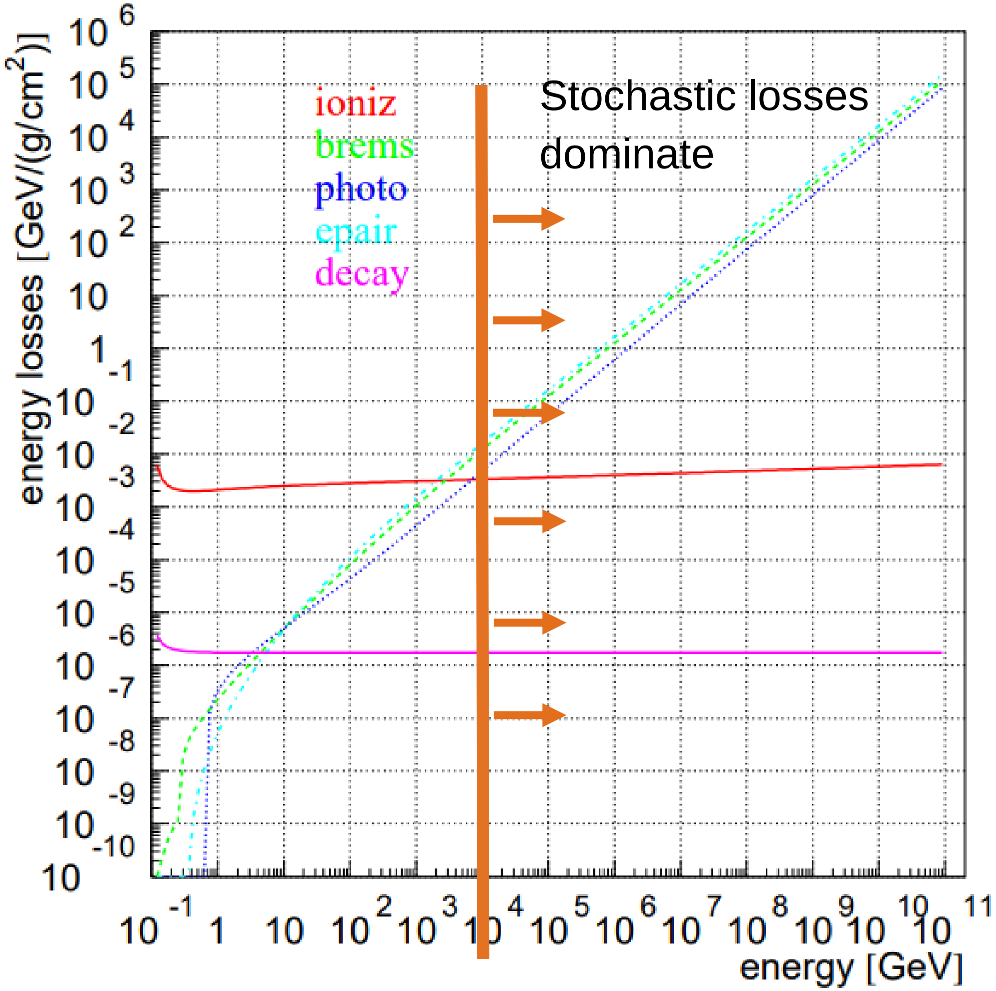
Energy Losses of High-Energy Muons

$$\frac{dE}{dX} = \underbrace{a}_{} + \underbrace{b(E) * E}_{}$$

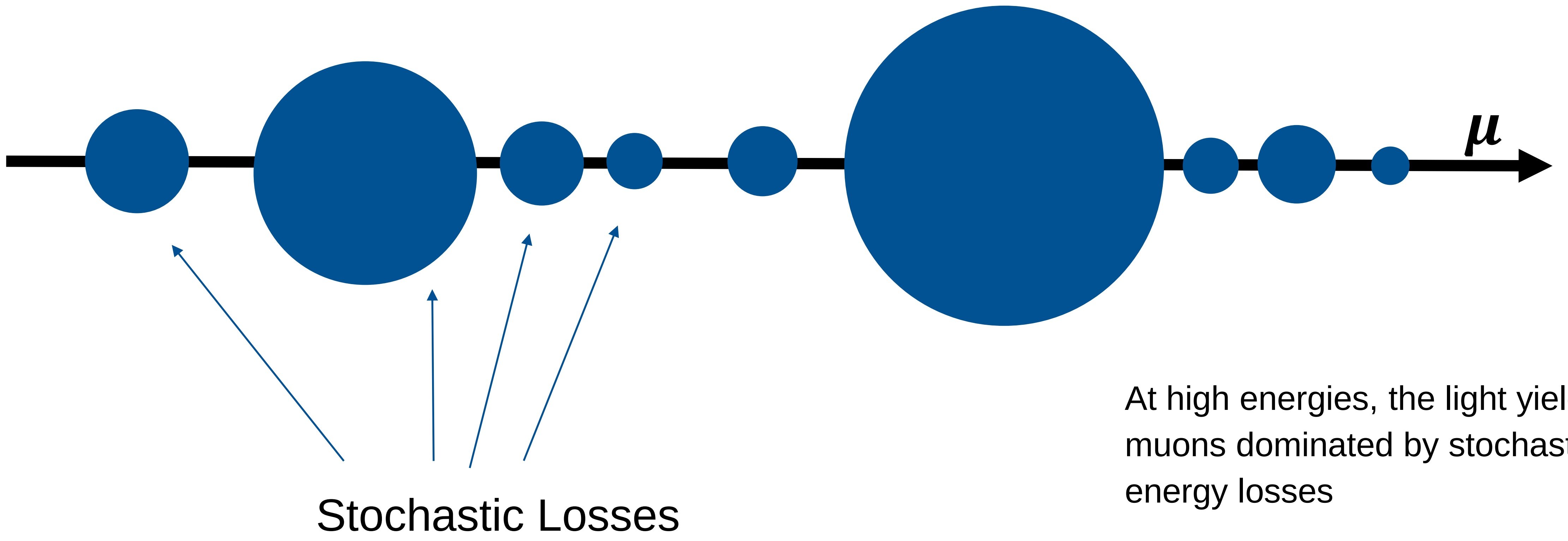
Continuous Losses (Ionization)

Stochastic Losses (Bremsstrahlung, Photohadronic, Pair Production)





Energy Losses of High-Energy Muons



At high energies, the light yield of muons dominated by stochastic energy losses

Modelling the ice in IceCube

What happens to photons in ice?

1. **They scatter (via Mie scattering on dust)**
   -> Mean free path over n multiple scatters: $\lambda_e = \frac{\lambda_s}{1-\langle\cos\theta\rangle}$
   -> A photon will scatter at an angle θ given by a PDF $p(\cos\theta)$

2. **They get absorbed (via three different absorption mechanisms)**
   -> Ice models use the *absorption coefficient* :

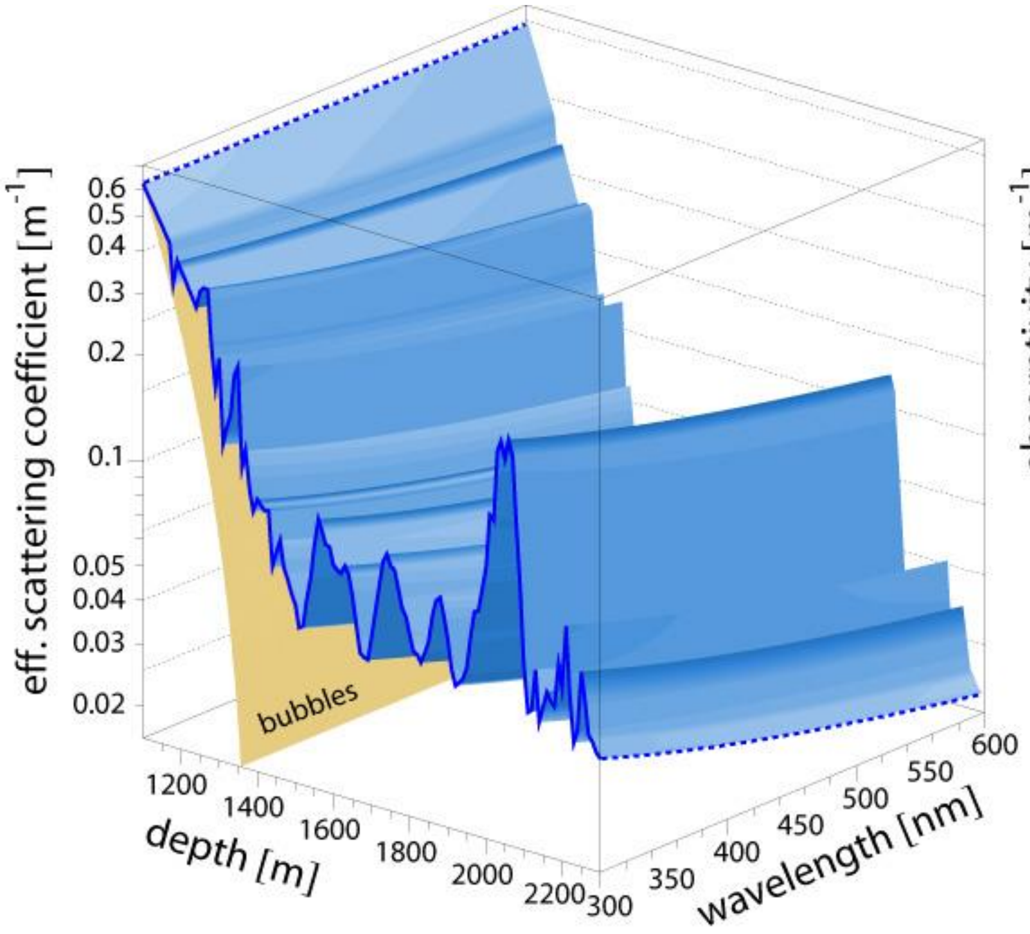
$$a(\lambda) = A_U e^{-B_U\lambda} + C_{dust}\lambda^{-\kappa} + A_{IR}e^{-\lambda_o/\lambda}$$

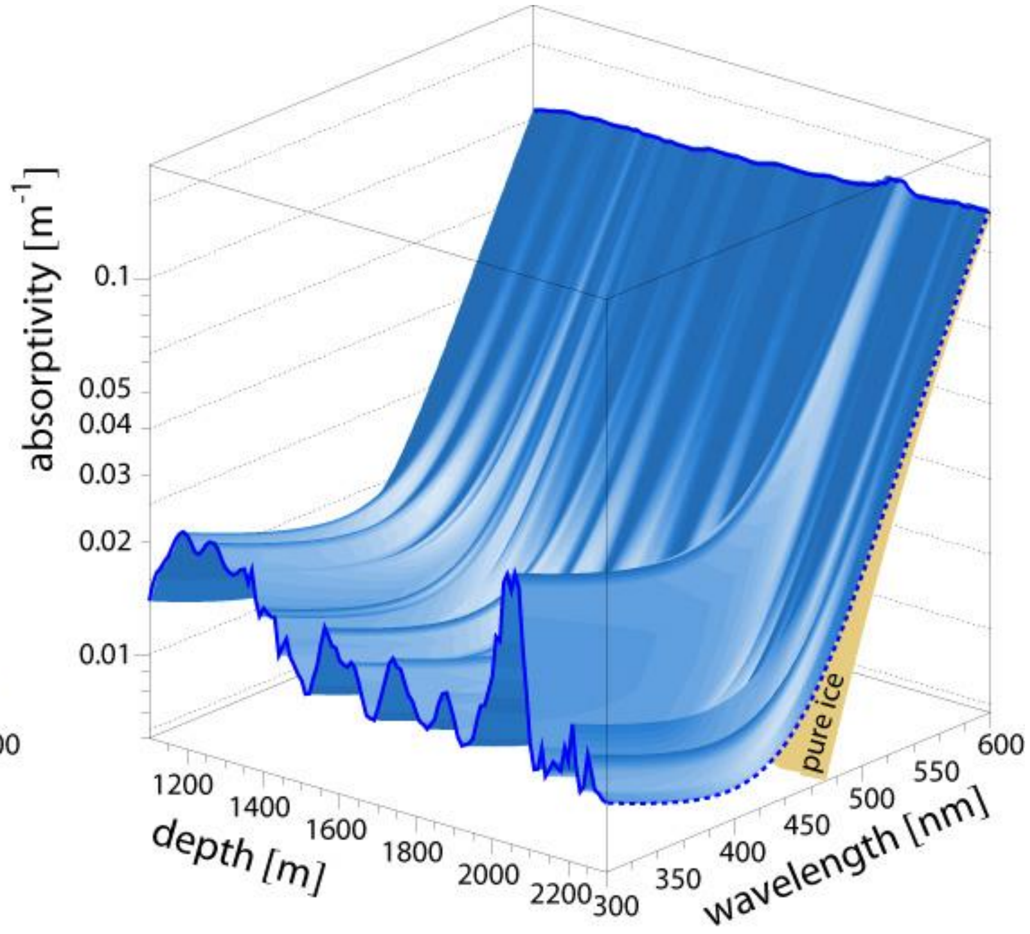
"Urbach tail":
electronic bandgap-thingy...
Effective at λ <200 nm

Absorption by dust particles:
Depends on the dust concentration
Effective at $\lambda \subset [200{,}500]$ nm

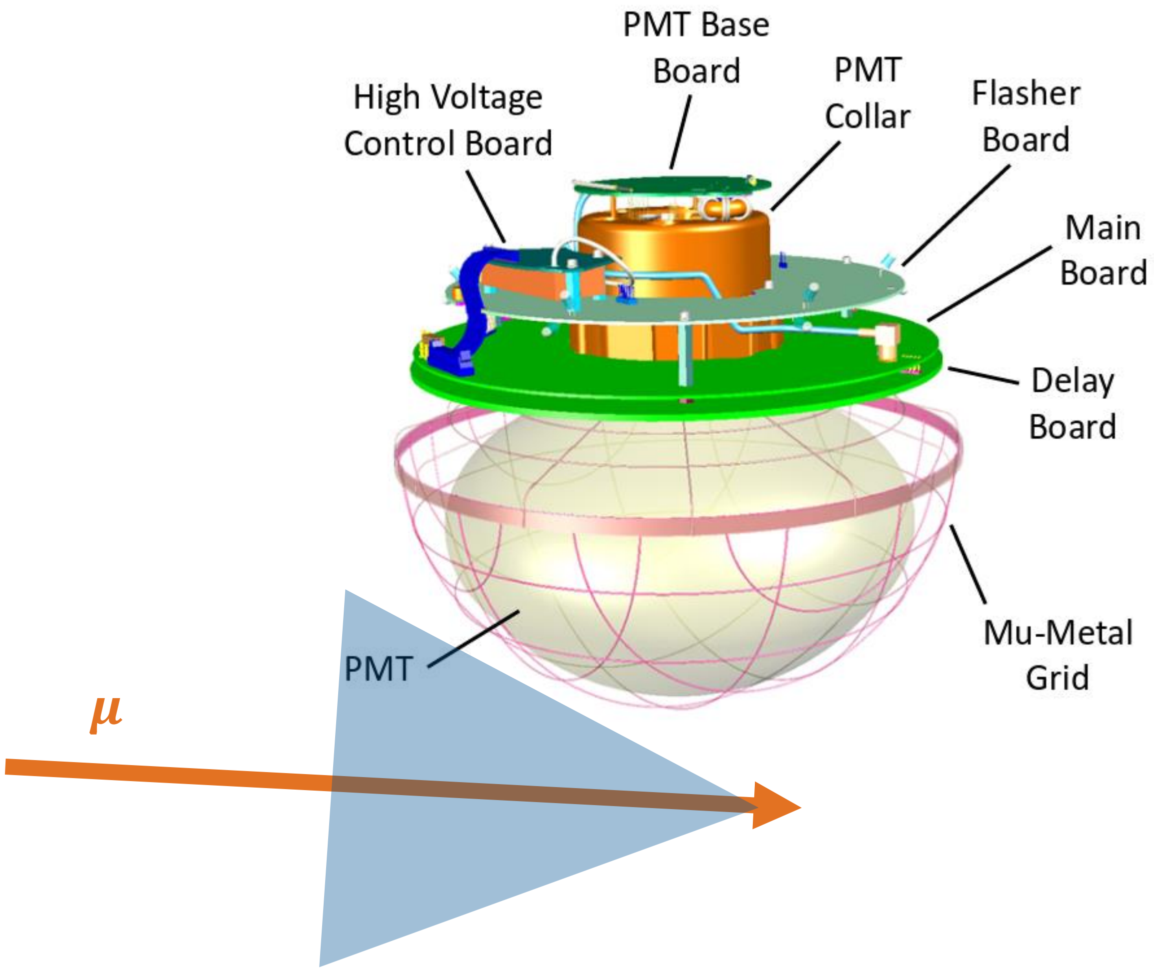
IR light excites vibro-rotational
modes of H_2O
Effective at λ>500 nm

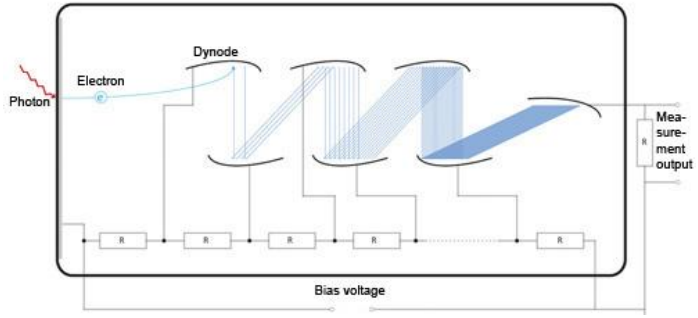
Depth Dependency

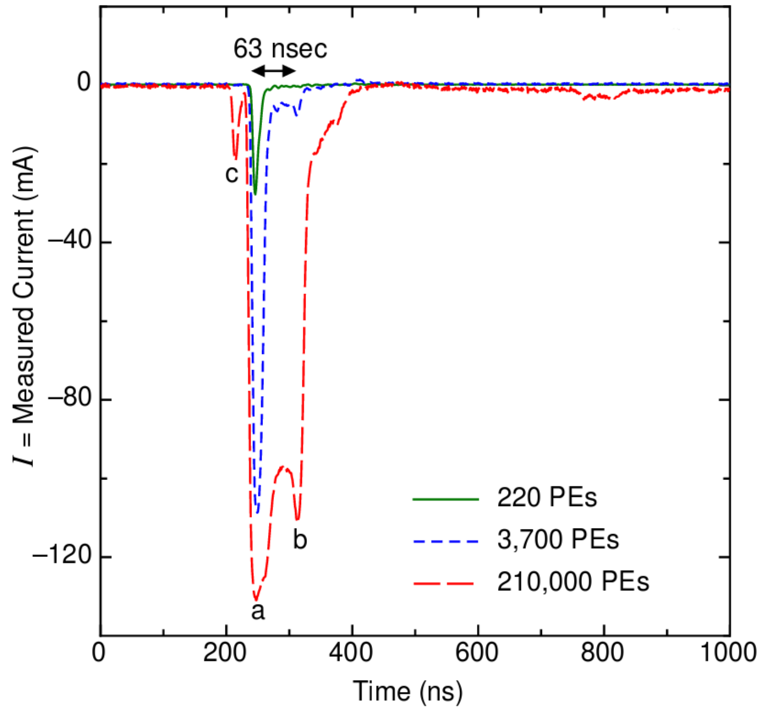




What does IceCube measure?

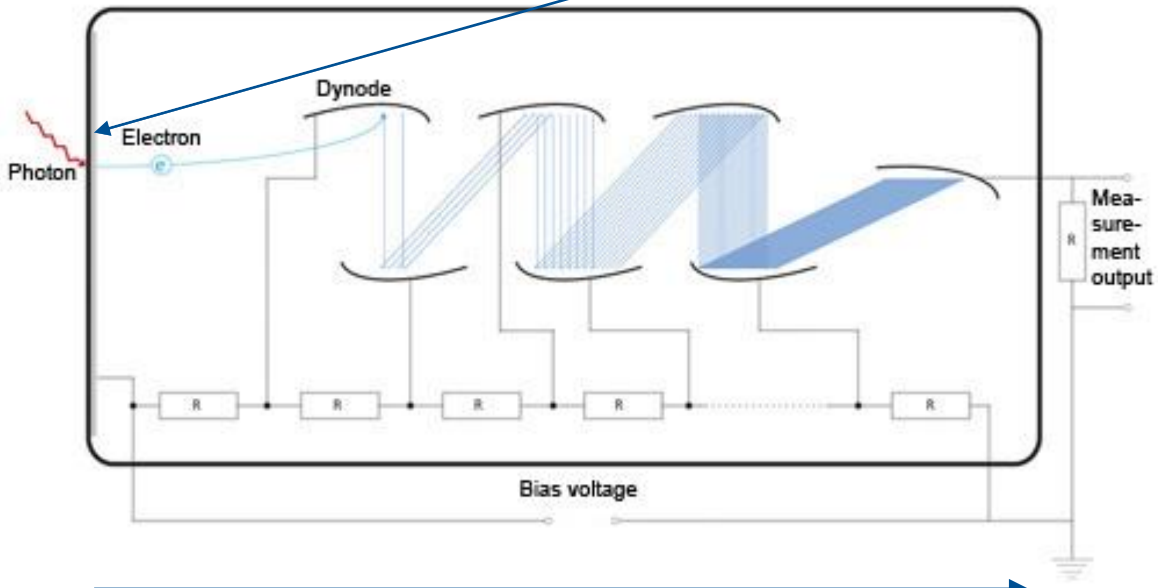




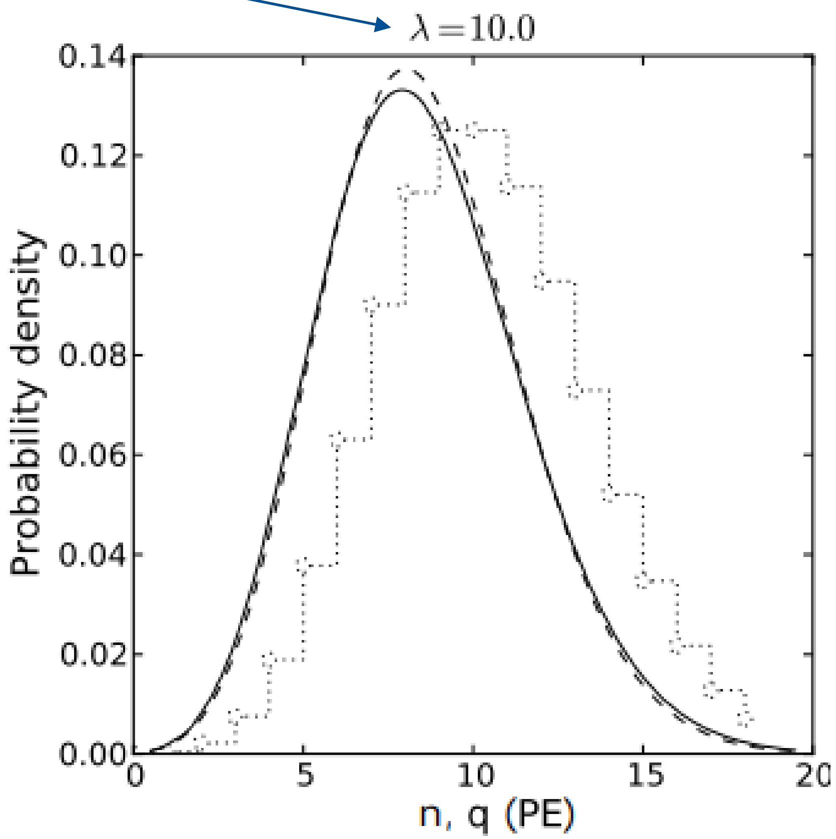


Charge Response

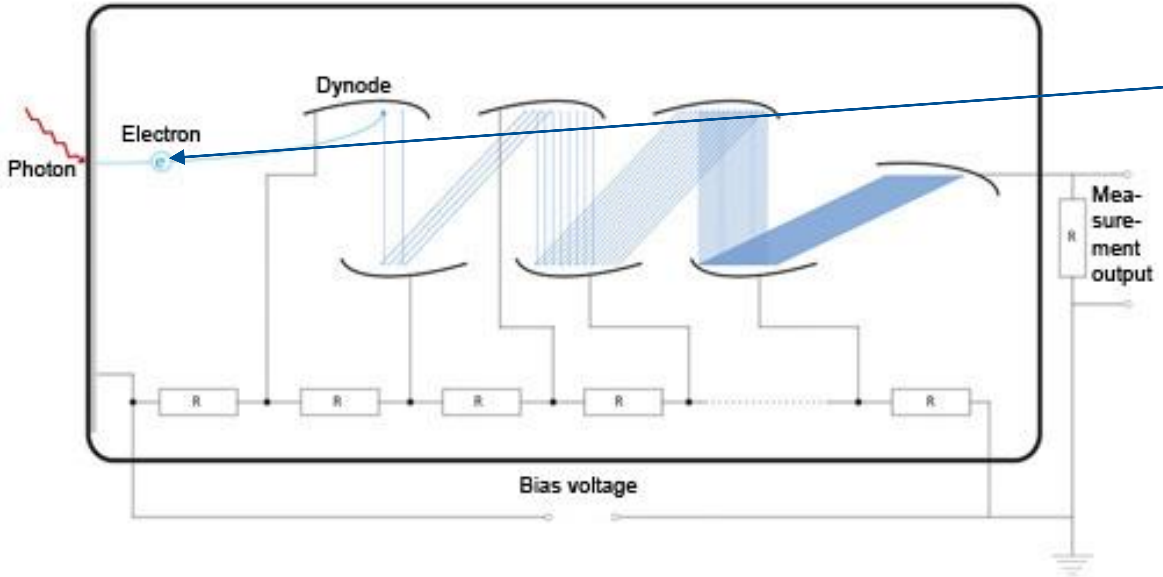
Detected number of detected photons at photocathode

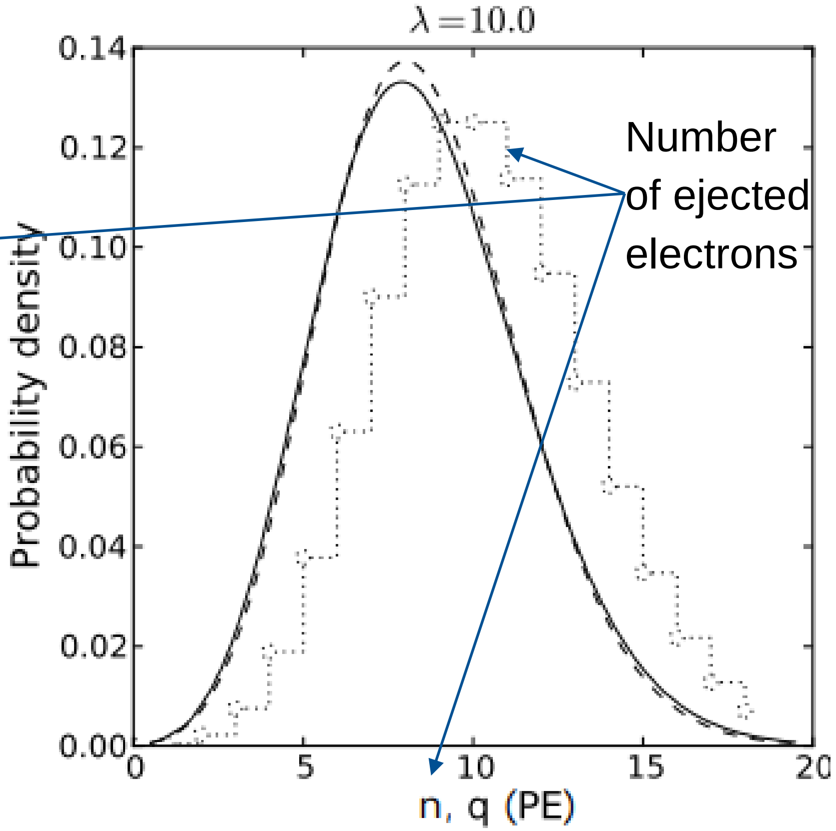


Transit time



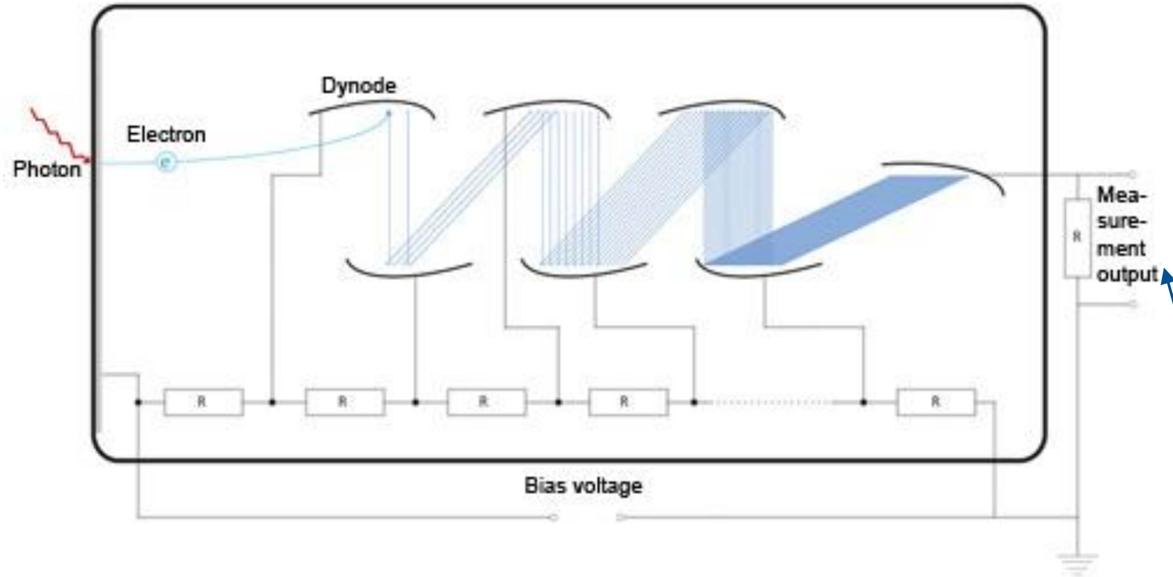
Charge Response

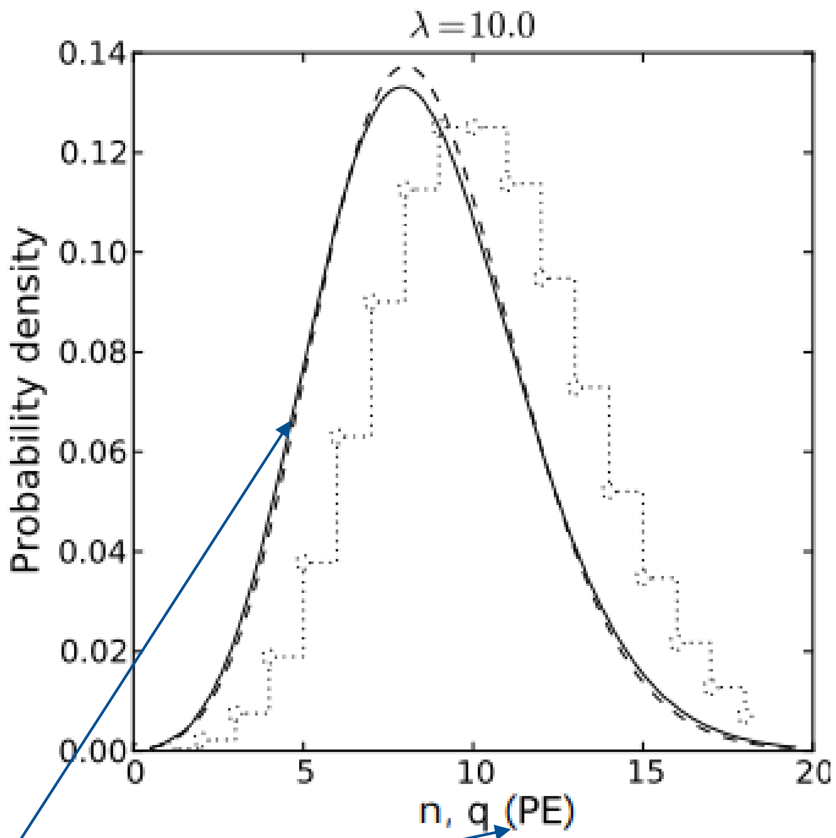




Number of ejected electrons

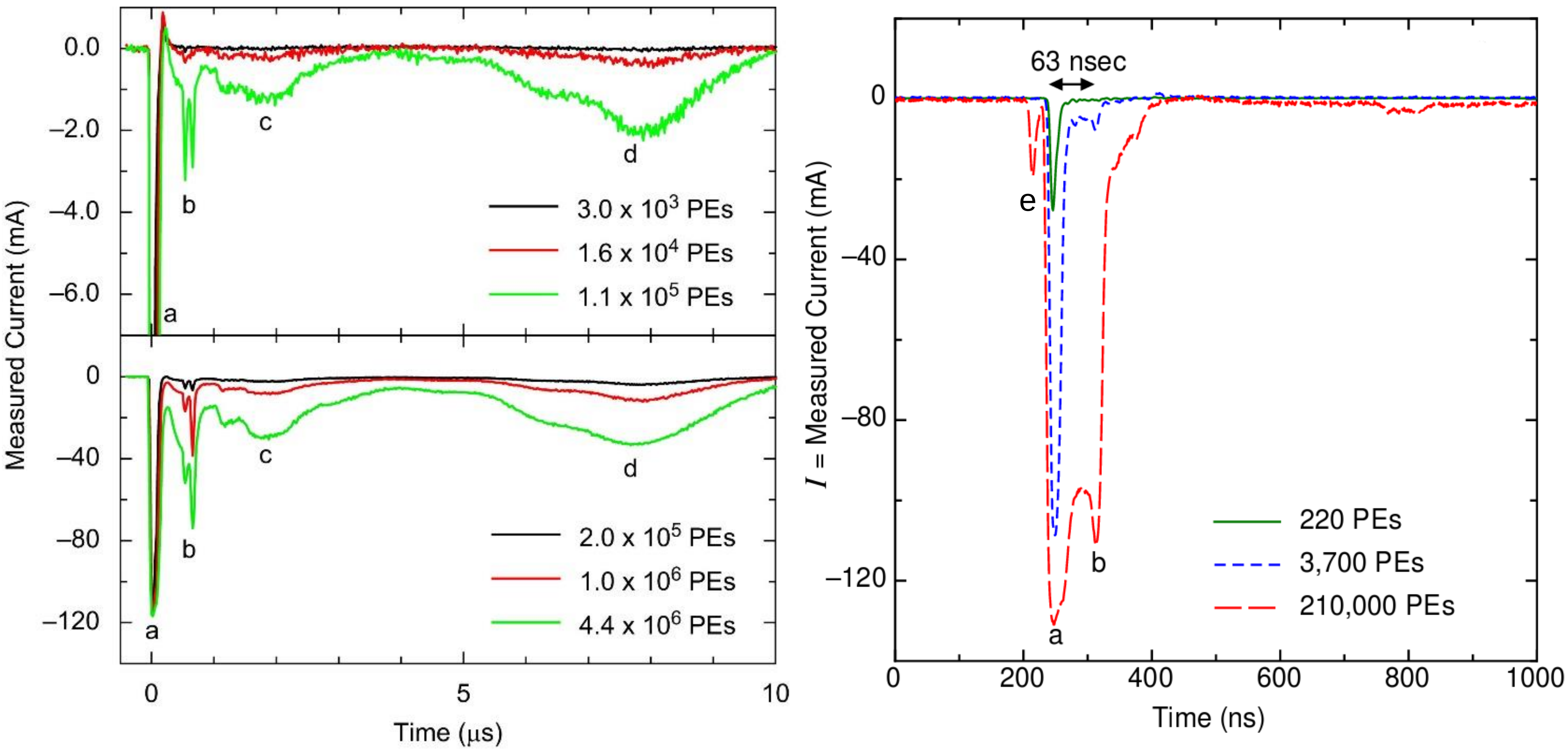
Charge Response





Charge (PE) at anode

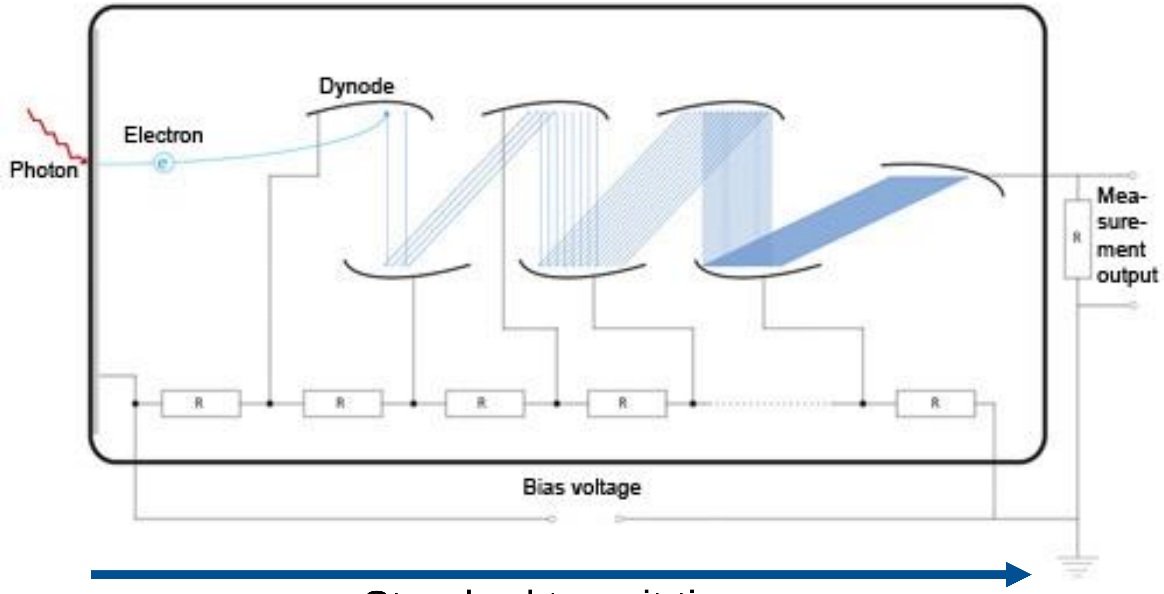
PMT Response to a 40ns Light Pulse



a: main pulse
b: late pulse
c/d: afterpulse
e: early pulse

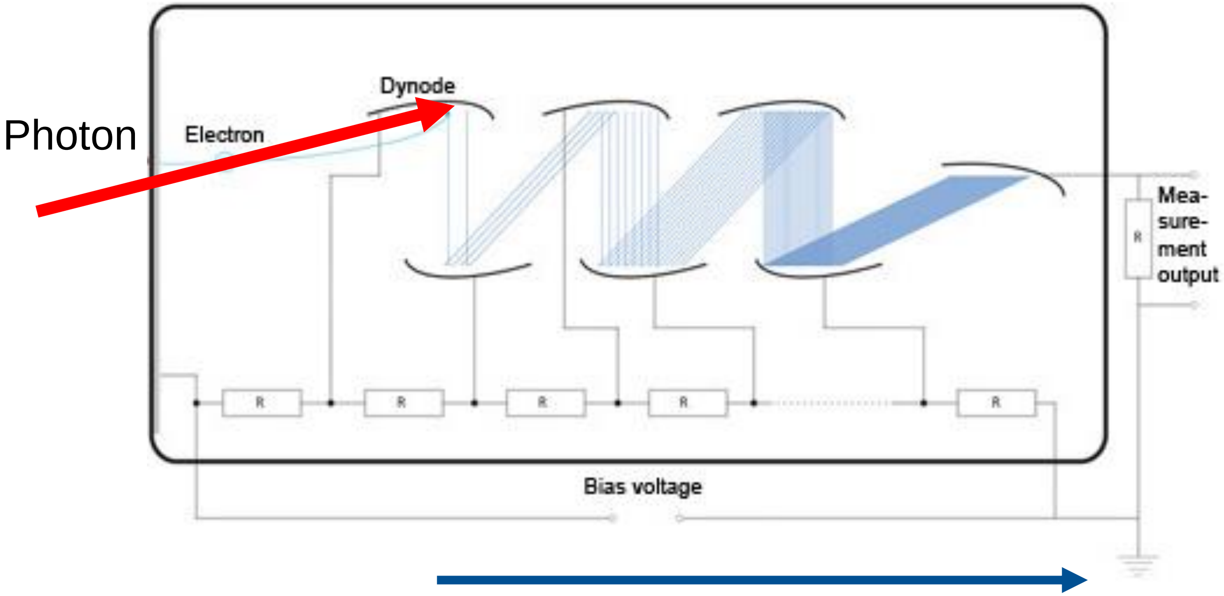
Early Pulses

Photon is converted at photo cathode



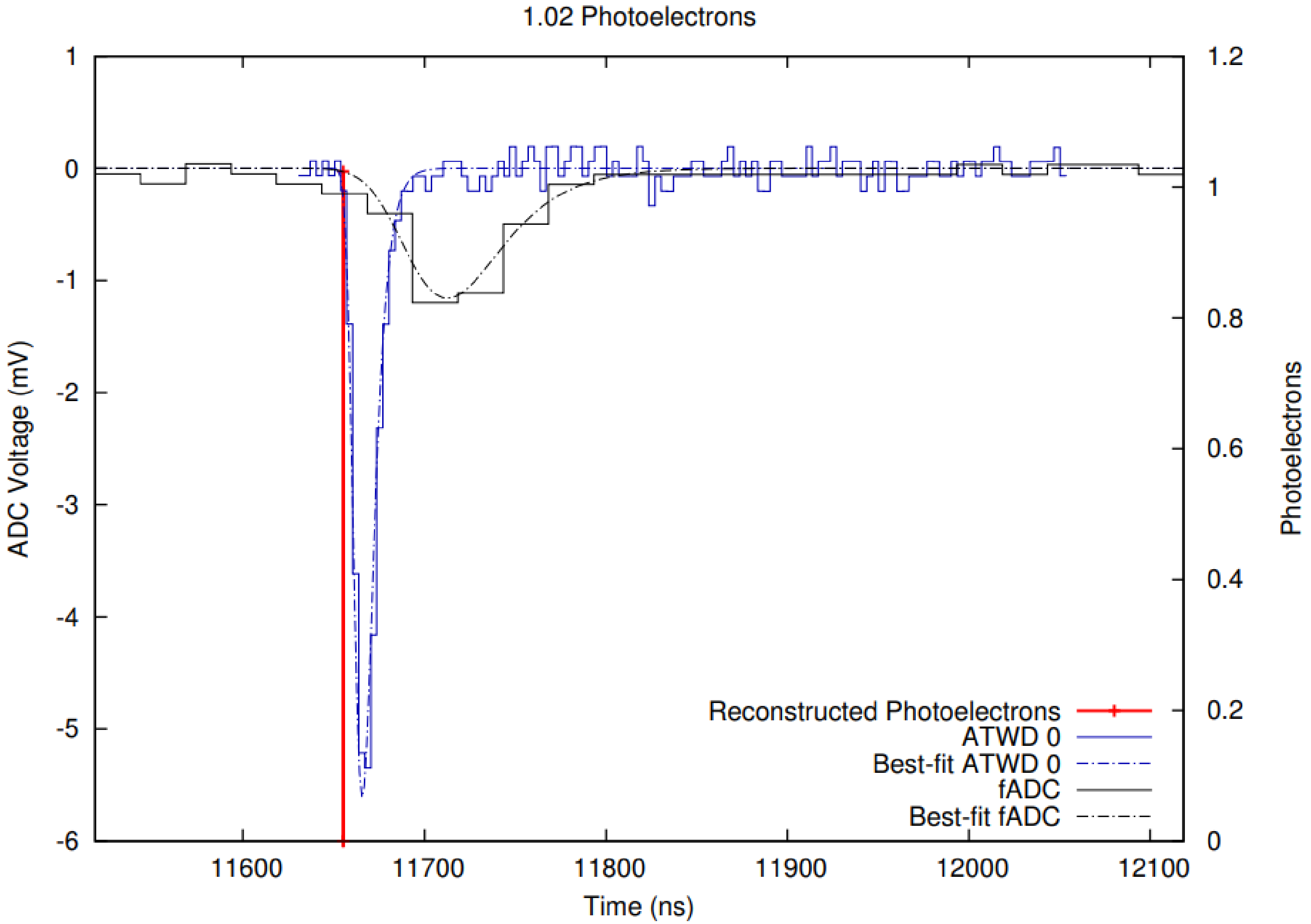
Standard transit time

Photon is converted at 1st dynode



Shorter transit time!

Waveform digitization & Photon detection

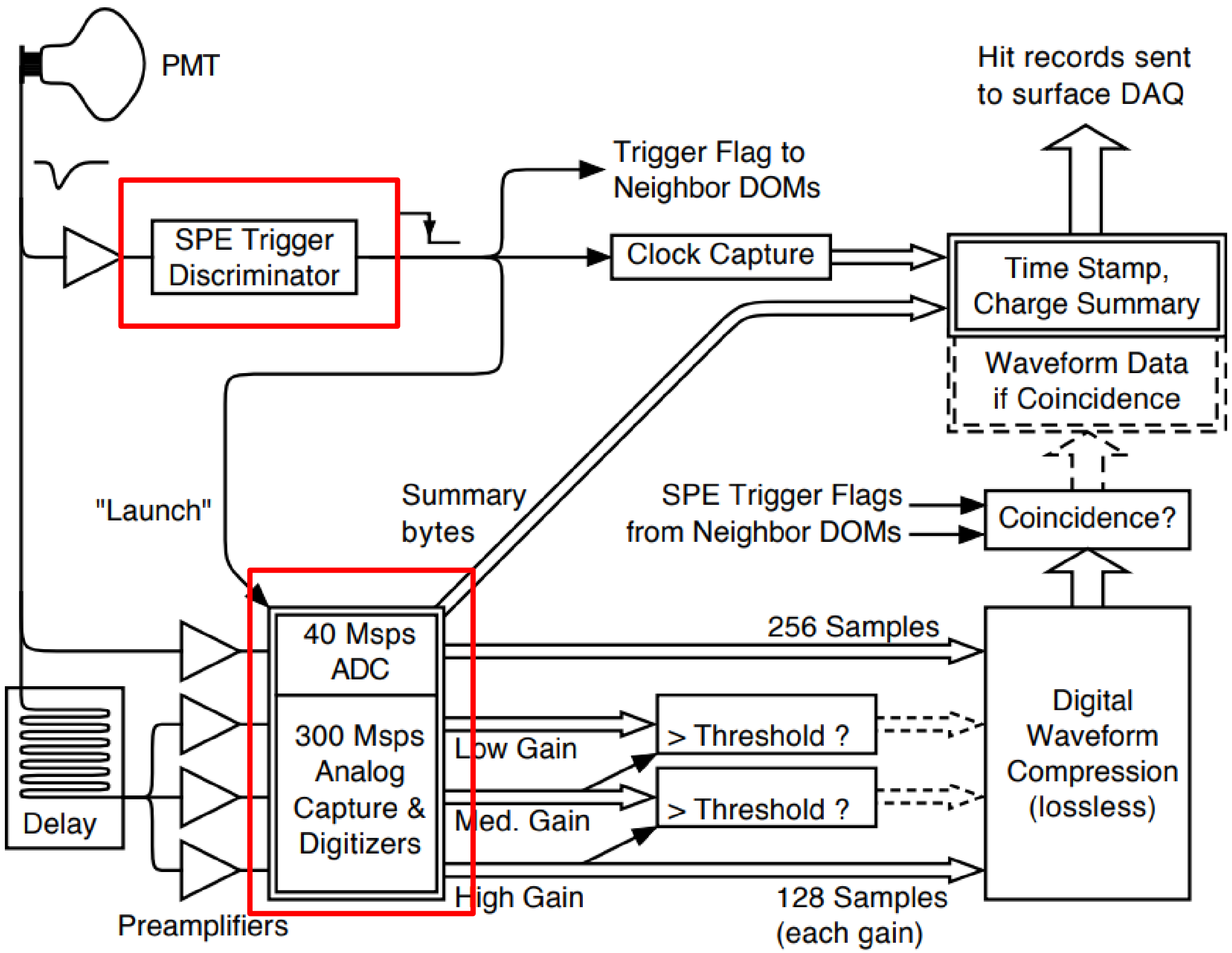


Recording PMT Waveforms in IceCube

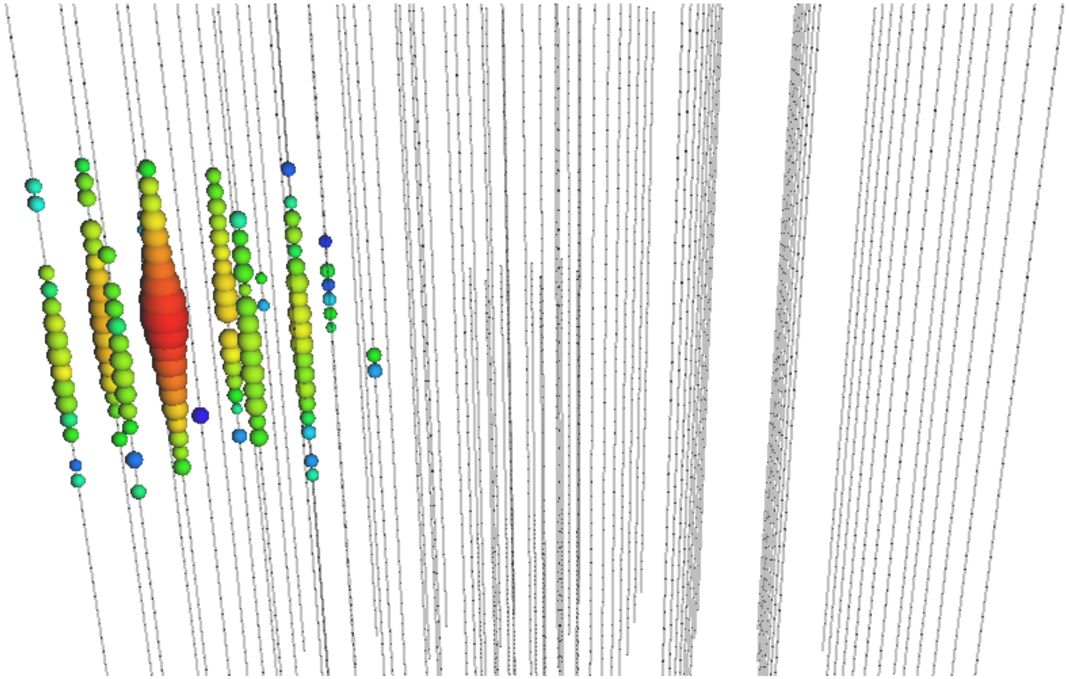
PMT signal cannot be continuously digitized.
Back-of-the-envelope calculation:
Need ~ns resolution.
Even with 1 bit (PMT current on/off) this results in 1Gbit / s per DOM.
5000 DOMs -> 5TBits / s for the entire detector.

⇒ Triggering: Only record „interesting“ data.

For IceCube, triggering is employed already at the lowest level: Only when the PMT current is above a certain threshold, data recording is started (a „DOM Launch“)



IceCube Cascade Event



$$\nu_l + N \rightarrow \nu_l + \text{hadronic cascade}$$
$$\nu_e + N \rightarrow \text{e} + \text{hadronic cascade}$$
$$\nu_\tau + N \rightarrow \tau + \text{hadronic cascade}$$ (< PeV energies)

Graphical representation of a real cascade event in IceCube.

Each colored „blob“ represents a launched DOM.

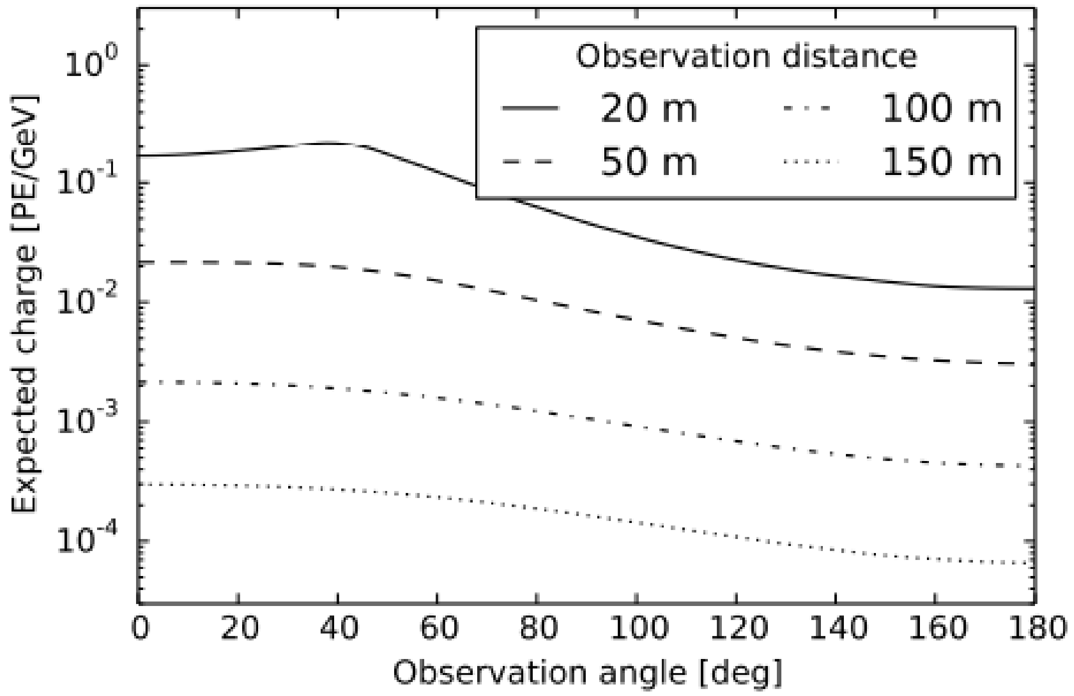
Colors indicate the time of the DOMLaunch, sizes indicate the number of detected photons.

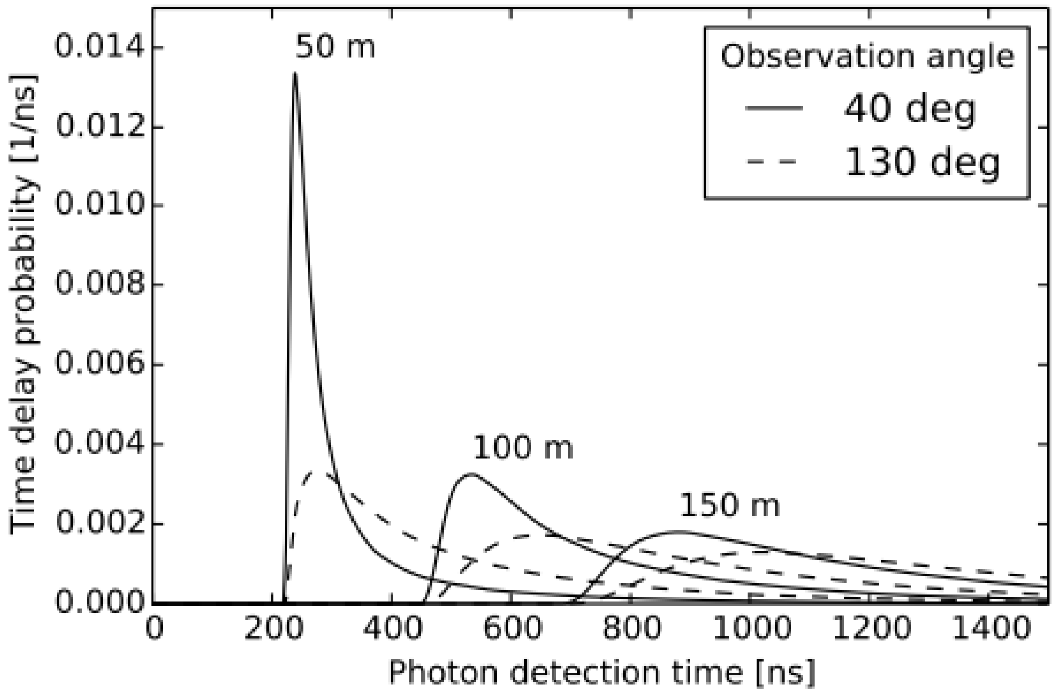
How do we infer the neutrino properties from the number of detected photons and their arrival times?

In order to study the neutrino origin, we are interested in the neutrino energy and the arrival direction

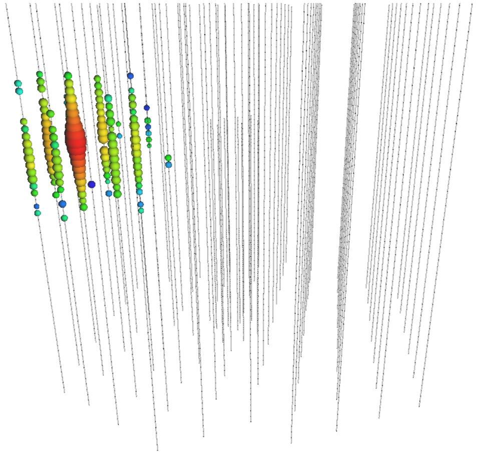
Expected Charge / Time distributions for Cascades

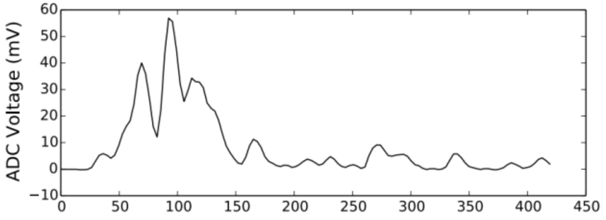
1 GeV EM Cascade

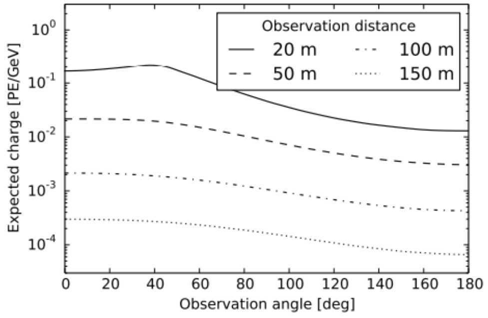


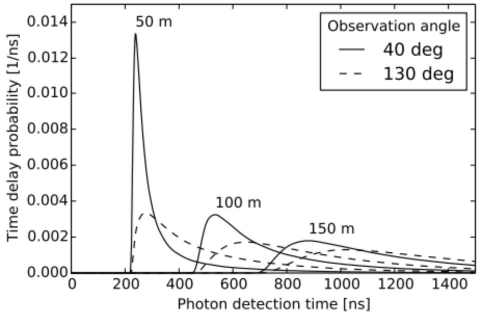


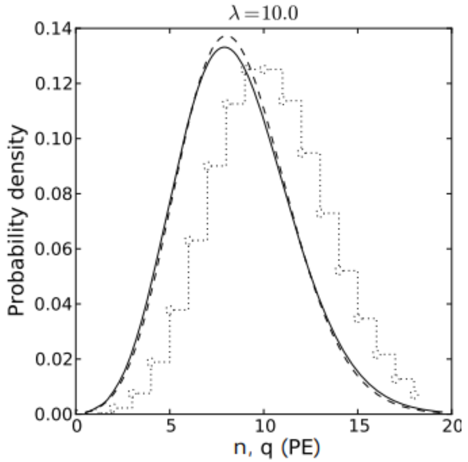
Combining Everything

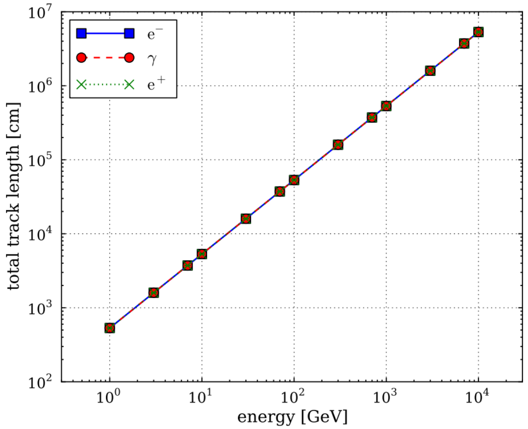




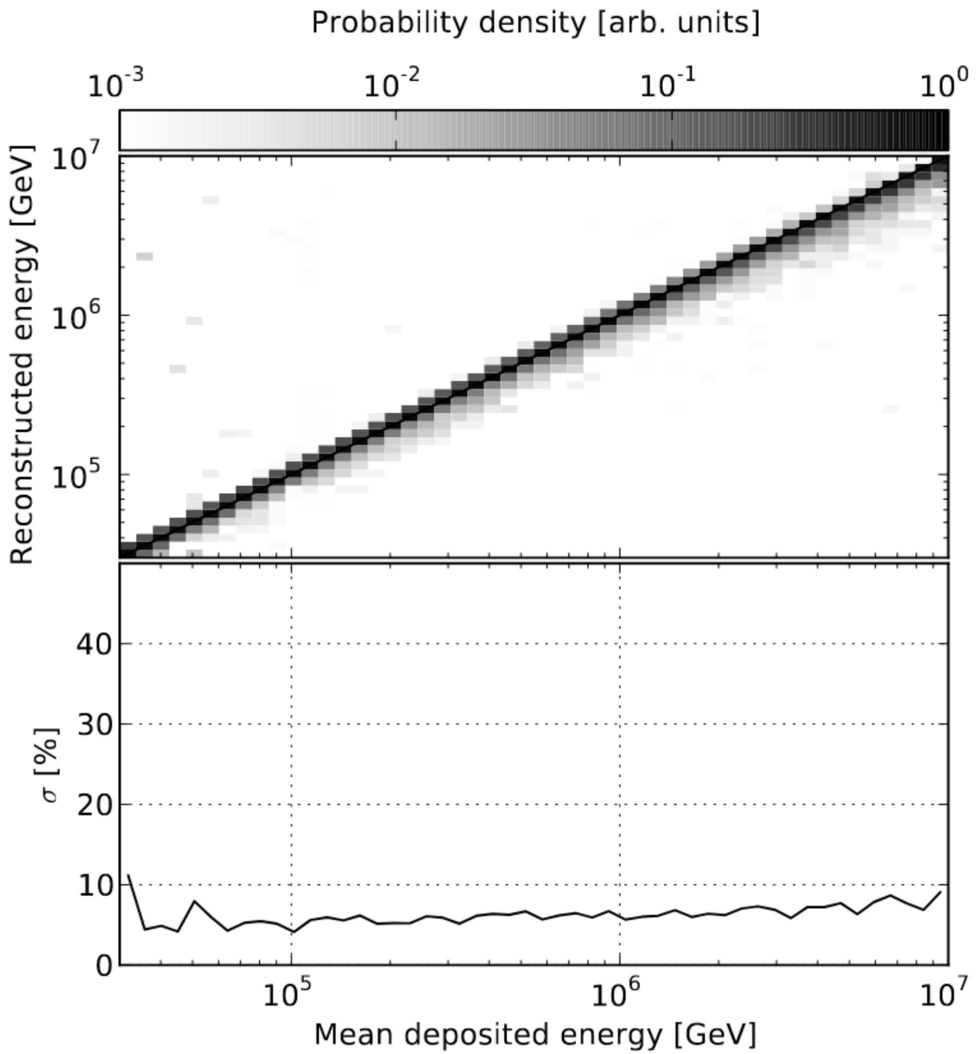


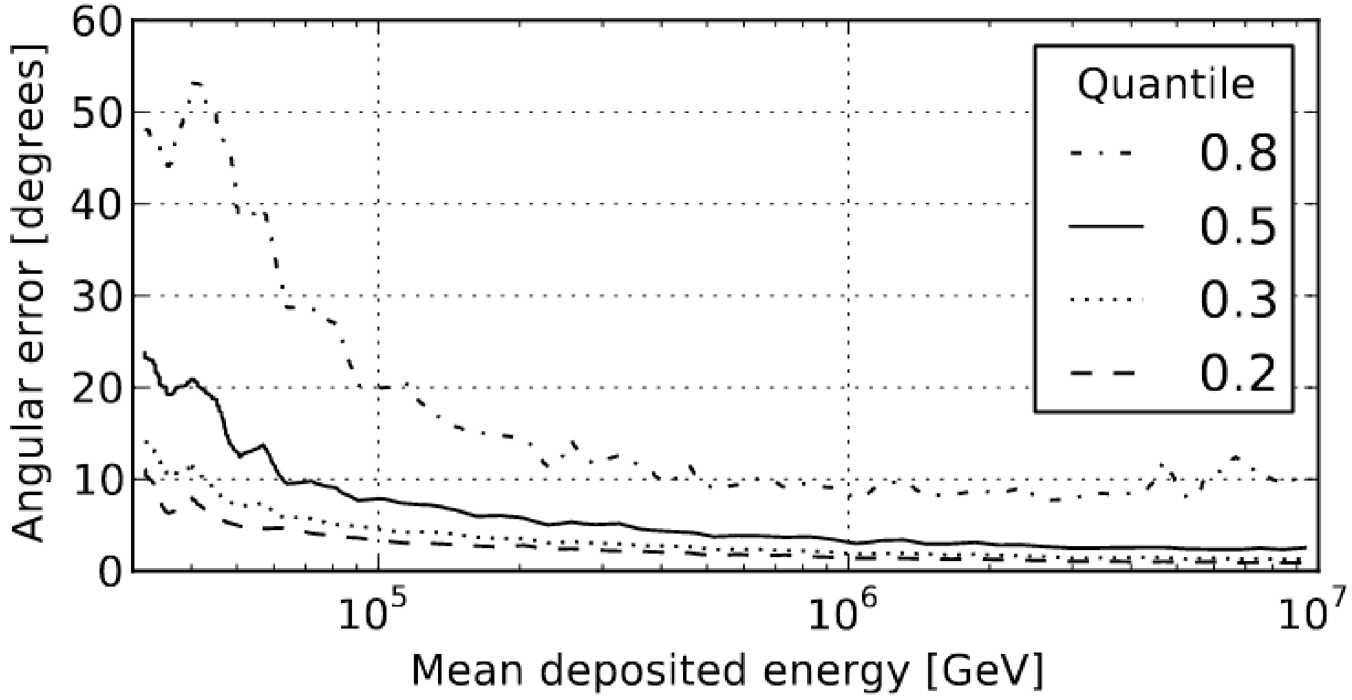






Cascade Resolutions





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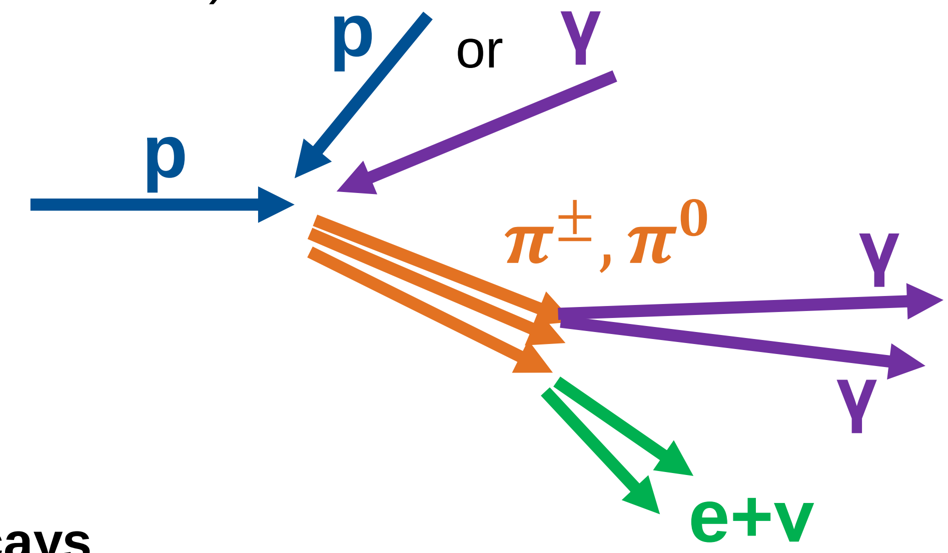
Production of Astrophysical Neutrinos

Accelerator (AGN, SNR, GRB, ..)



Idealized scenarios

$$p + p \rightarrow X + \begin{cases} \pi^{+} & 1/3 \\ \pi^{-} & 1/3 \\ \pi^{0} & 1/3 \end{cases}$$

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

Pion Decays

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

$$\pi^{-} \rightarrow \mu^{-} + \bar{\nu}_{\mu} \rightarrow e^{-} + \bar{\nu}_{e} + \bar{\nu}_{\mu} + \nu_{\mu}$$

$$\pi^{0} \rightarrow \gamma\gamma$$

Interaction of accelerated CR naturally leads to production of neutrinos and gamma rays

Astrophysical Neutrino Production

Proton-Proton (pp) interactions

Idealized scenario ($\pi^+ + \pi^-$)

$$\nu_e : \nu_\mu : \nu_\tau = 1:2:0$$

$$\bar{\nu}_e : \bar{\nu}_\mu : \bar{\nu}_\tau = 1:2:0$$

$$\nu:\ 1:1:1$$

$$\bar{\nu}:\ 1:1:1$$

Neutrino Oscillations

Proton-Photon ($p\gamma$) interactions

Idealized scenario (only π^+)

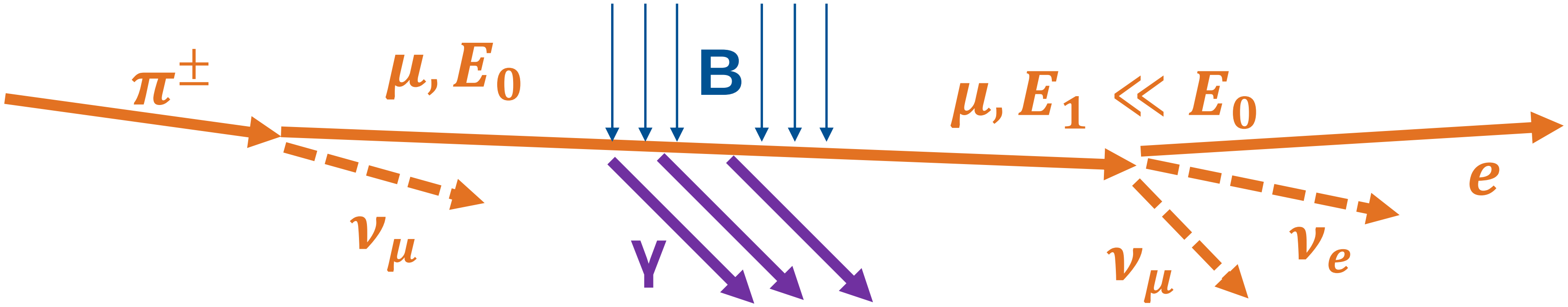
$$\nu_e : \nu_\mu : \nu_\tau = 1:1:0$$

$$\bar{\nu}_e : \bar{\nu}_\mu : \bar{\nu}_\tau = 0:1:0$$

$$\nu:\ 14:11:11$$

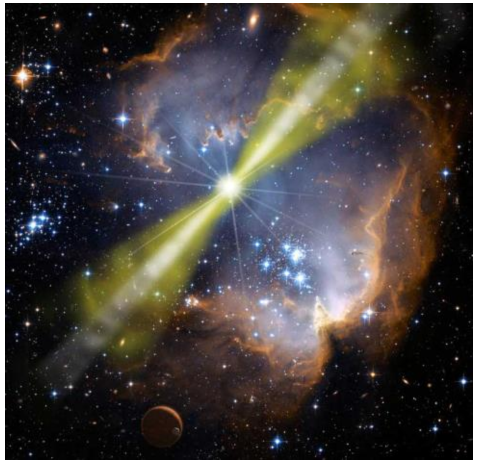
$$\bar{\nu}:\ 4:7:7$$

Muon Cooling



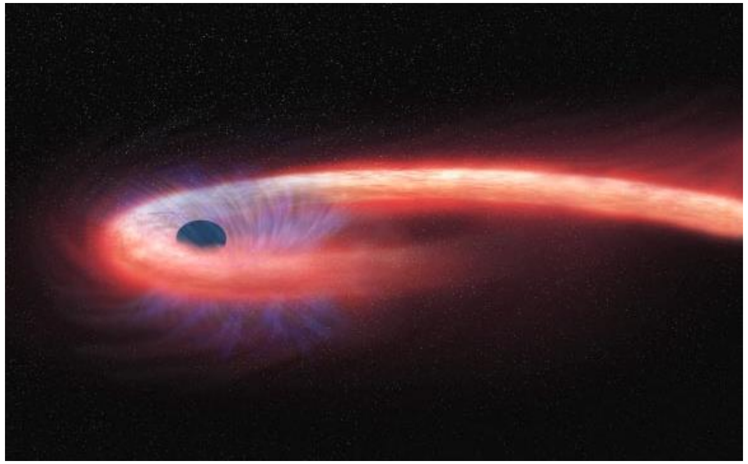
In sources with strong magnetic fields, muons lose energy due to synchrotron radiation

GRB



NASA/Swift/Mary Pat Hrybyk-Keith and John Jones

TDE



NASA / CXC / M. Weiss.

Muon Cooling

Strong magnetic fields in the interaction region can cool the intermediate muons via induced bremsstrahlung, effectively removing the resulting neutrinos from the high-energy neutrino flux.

Proton-Proton (pp) interactions

Muon Cooling:

$$\nu_e : \bar{\nu}_e : \nu_\mu : \bar{\nu}_\mu : \nu_\tau : \bar{\nu}_\tau = 0:0:1:1:0:0$$

$$4:4:7:7:7:7$$

Neutrino Oscillations

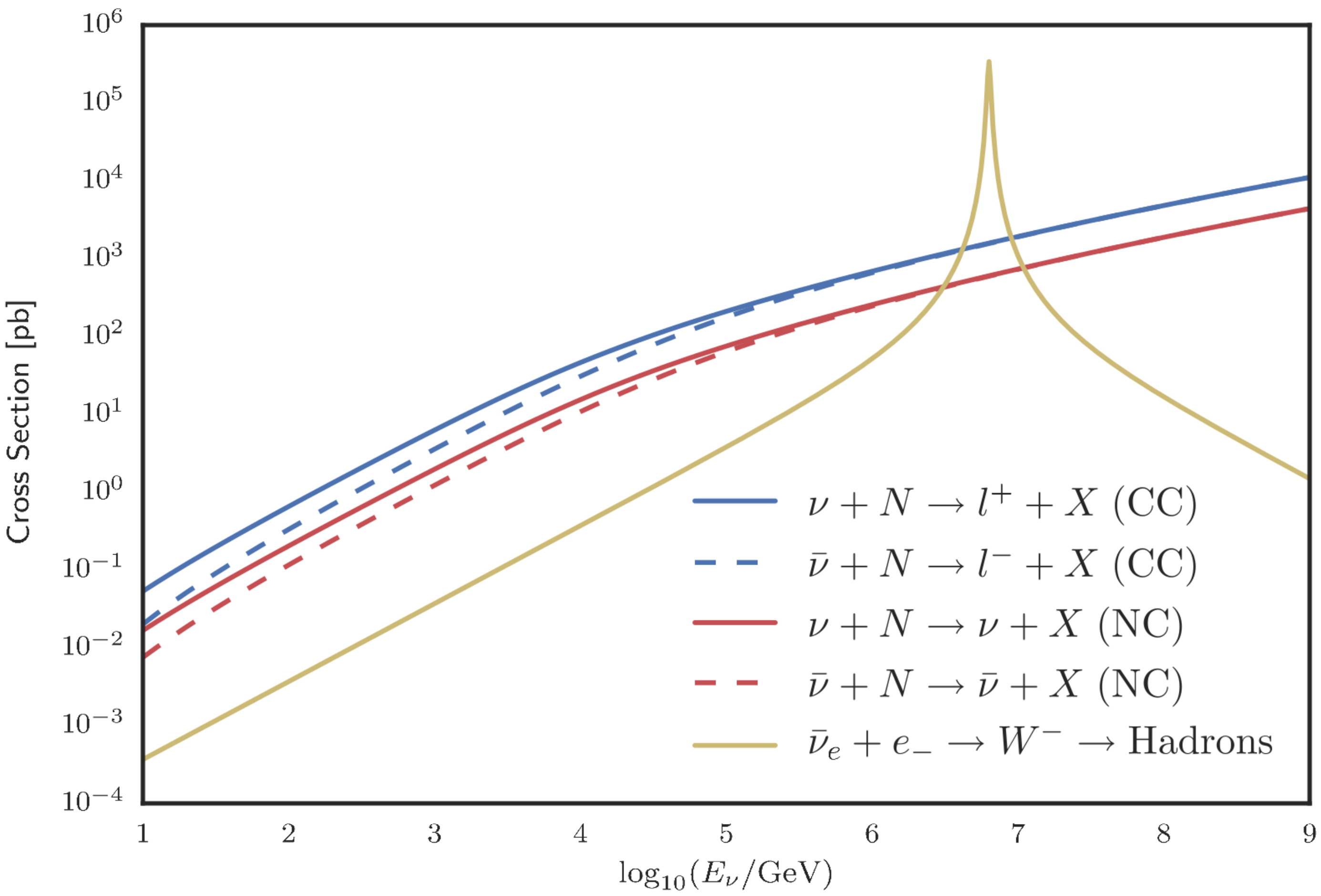
Proton-Photon ($p\gamma$) interactions

Muon Cooling :

$$\nu_e : \bar{\nu}_e : \nu_\mu : \bar{\nu}_\mu : \nu_\tau : \bar{\nu}_\tau = 0:0:1:0:0:0$$

$$4:0:7:0:7:0$$

The Glashow Resonance

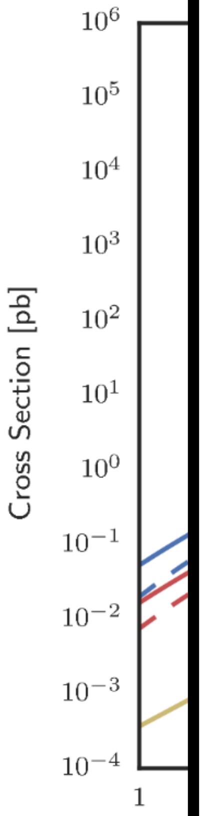


- Resonant W^- -production in $\bar{\nu}_e - \mathrm{e}^-$ interactions at 6.3 PeV neutrino energy (electron at rest)

$$\bar{\nu}_e + e^- \rightarrow W^- \rightarrow \begin{cases} \text{Hadrons } (67\%) \\ \text{Leptons } (33\%) \end{cases}$$

- x200 increase over DIS in $\bar{\nu}_e$ cross section
- So far not observed experimentally, despite being fundamental Standard Model process
- Allows (statistical) measurement of $\frac{\bar{\nu}_e}{\nu_e}$ ratio (1:1 for pp, 4:14 for pγ)

The Glashow Resonance



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

(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 $\bar{\nu}_e + e^- \to W^- \to$ 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 $9\times10^{14}-1\times10^{16}$ eV) the resonant effect should exceed by more than one order of magnitude the background due to the nonresonant neutrino events.

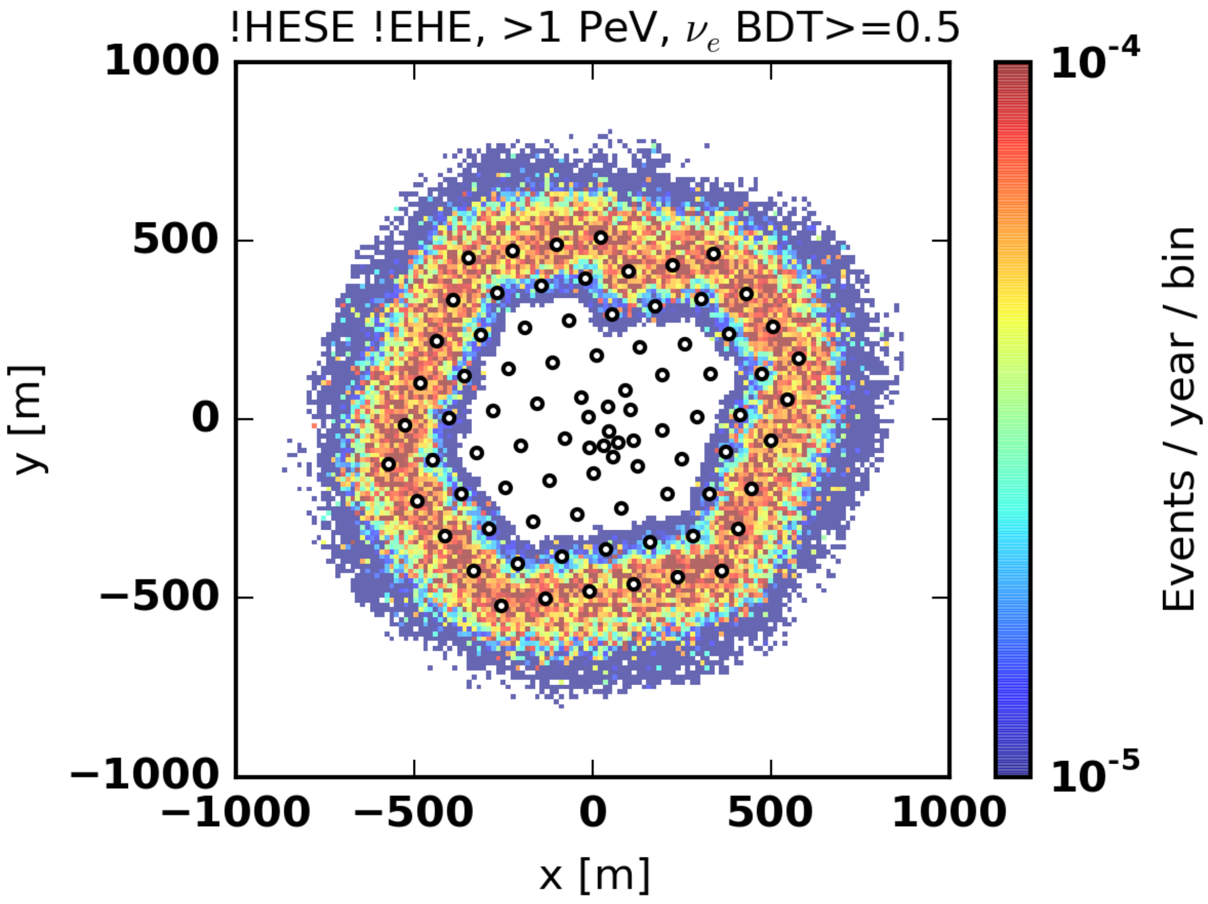
e^-
ergy
%)
%)
section
, despite
el process
f $\frac{\bar{\nu}_e}{\nu_e}$ ratio
uction

How to Measure the Glashow Resonance

Need good energy resolution:
→ Cascade Events

From conventional event selections expect ~0.2 GR events / year

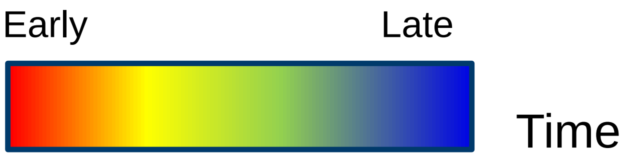
Solution: Use partially contained events
Caveat: Increased contamination by atmospheric muons



Outline

1. The IceCube Neutrino Observatory
2. How to detect neutrinos
3. Production mechanisms of high-energy astrophysical neutrinos
4. **Observation of a neutrino interaction at the Glashow Resonance**

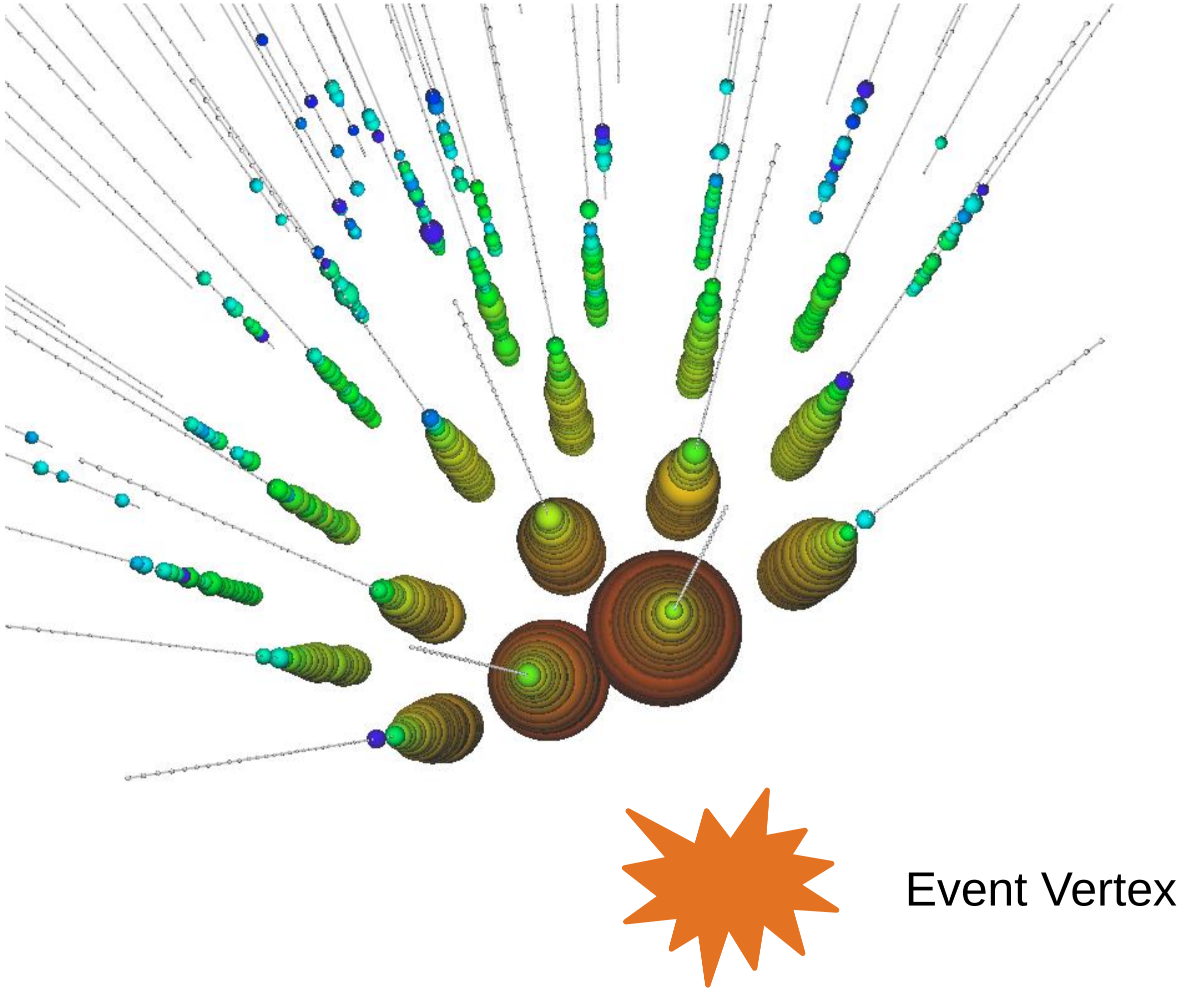
A Multi-PeV Uncontained Cascade



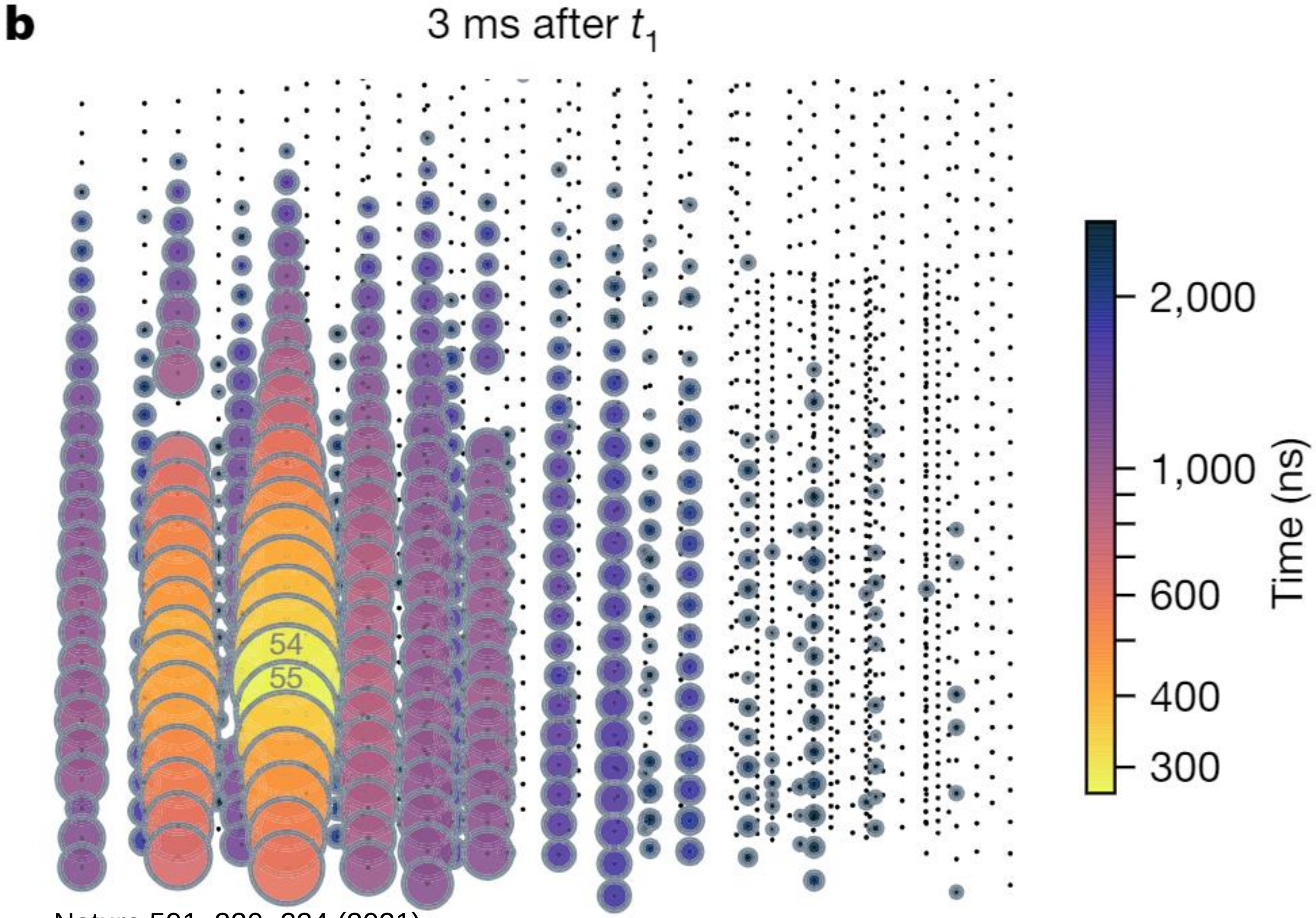
The event vertex is outside the detector and the PMTs closest to the vertex are saturated.

⇒ **Challenging Reconstruction**

Best reconstruction achieved by *DirectFit:* ABC (Approximate Bayesian Computing) method using event resimulations.



Event Display

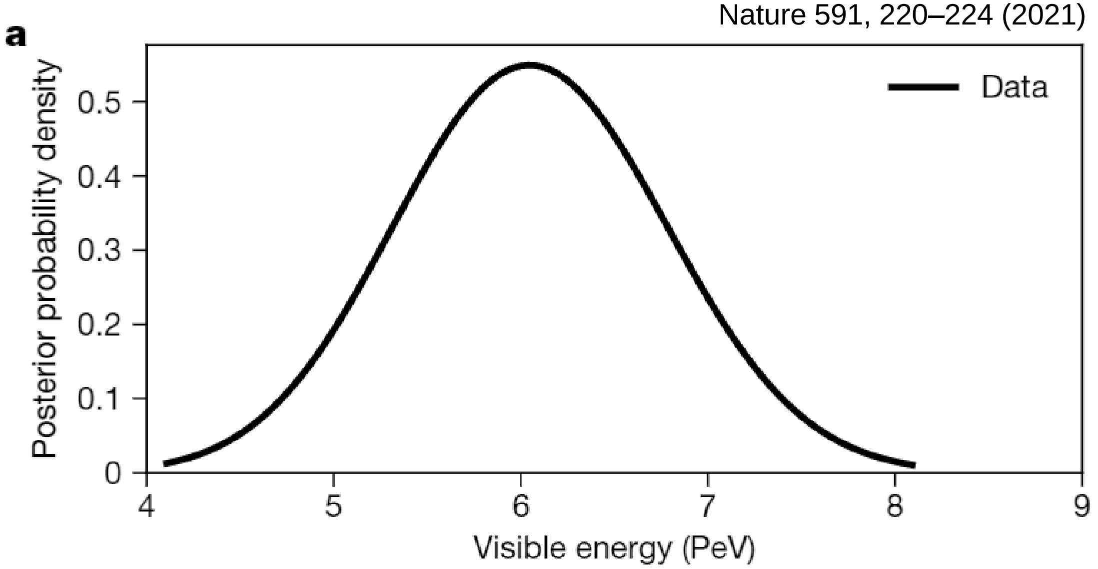


Nature 591, 220–224 (2021)

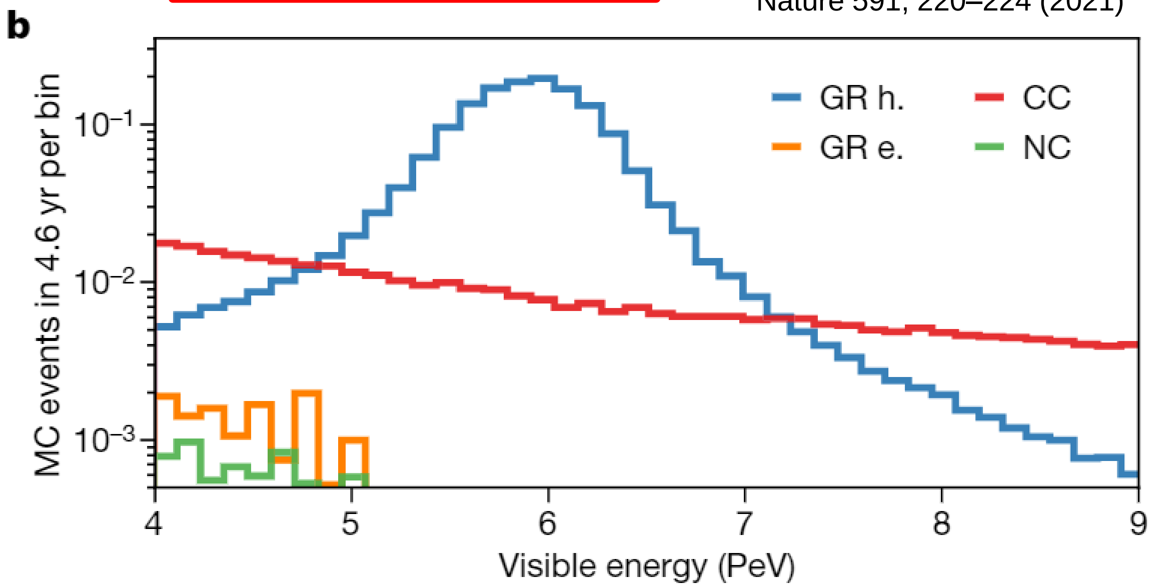
Energy Reconstruction

Need GR + non zero $\bar{\nu}_e$ flux to explain the measured event

Nature 591, 220–224 (2021)

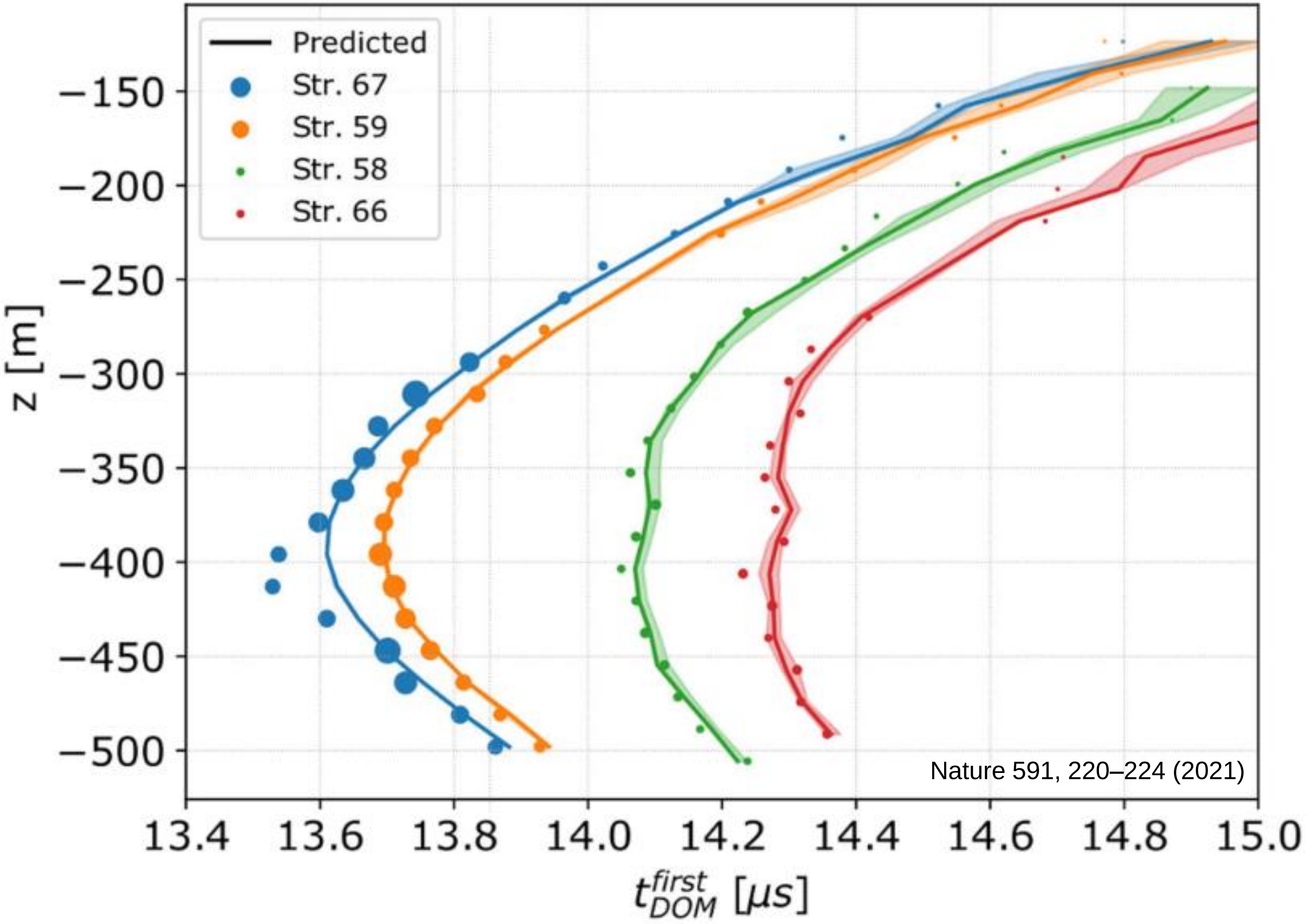


Nature 591, 220–224 (2021)



Reject NC/CC origin with 1% p-value

Verification via Resimulation



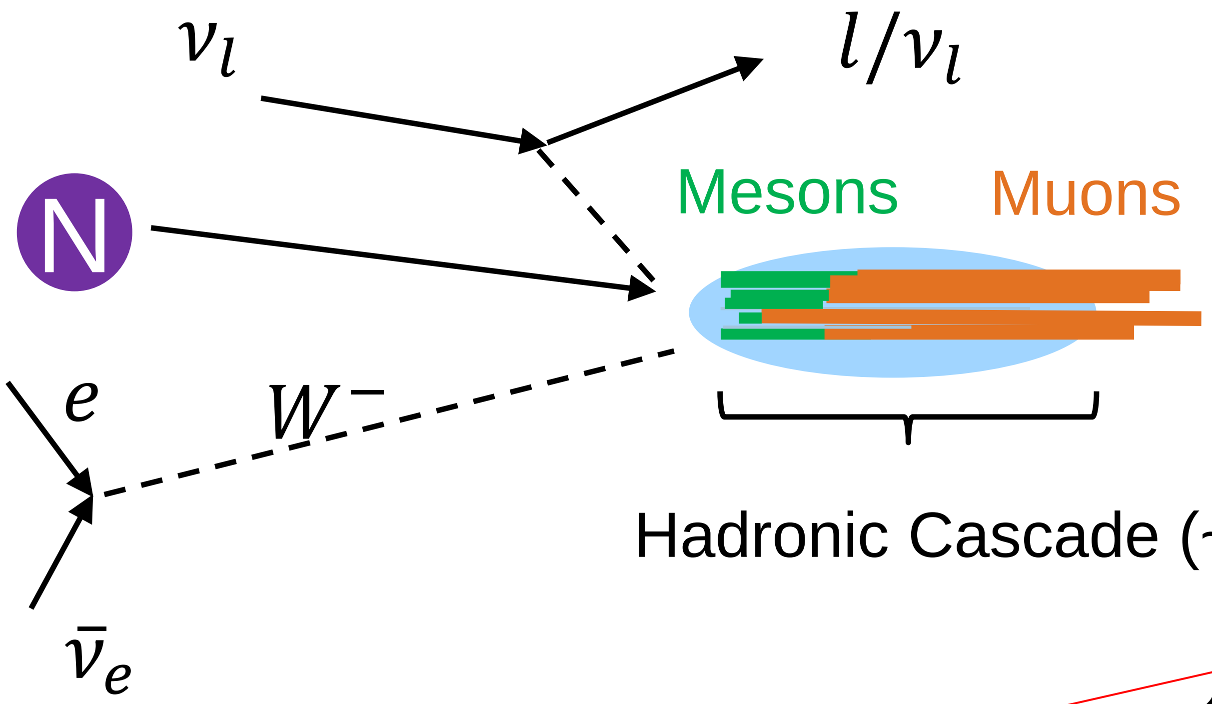
Nature 591, 220–224 (2021)

Muon Production in Hadronic Cascades

Neutrino DIS

OR

Glashow Resonance

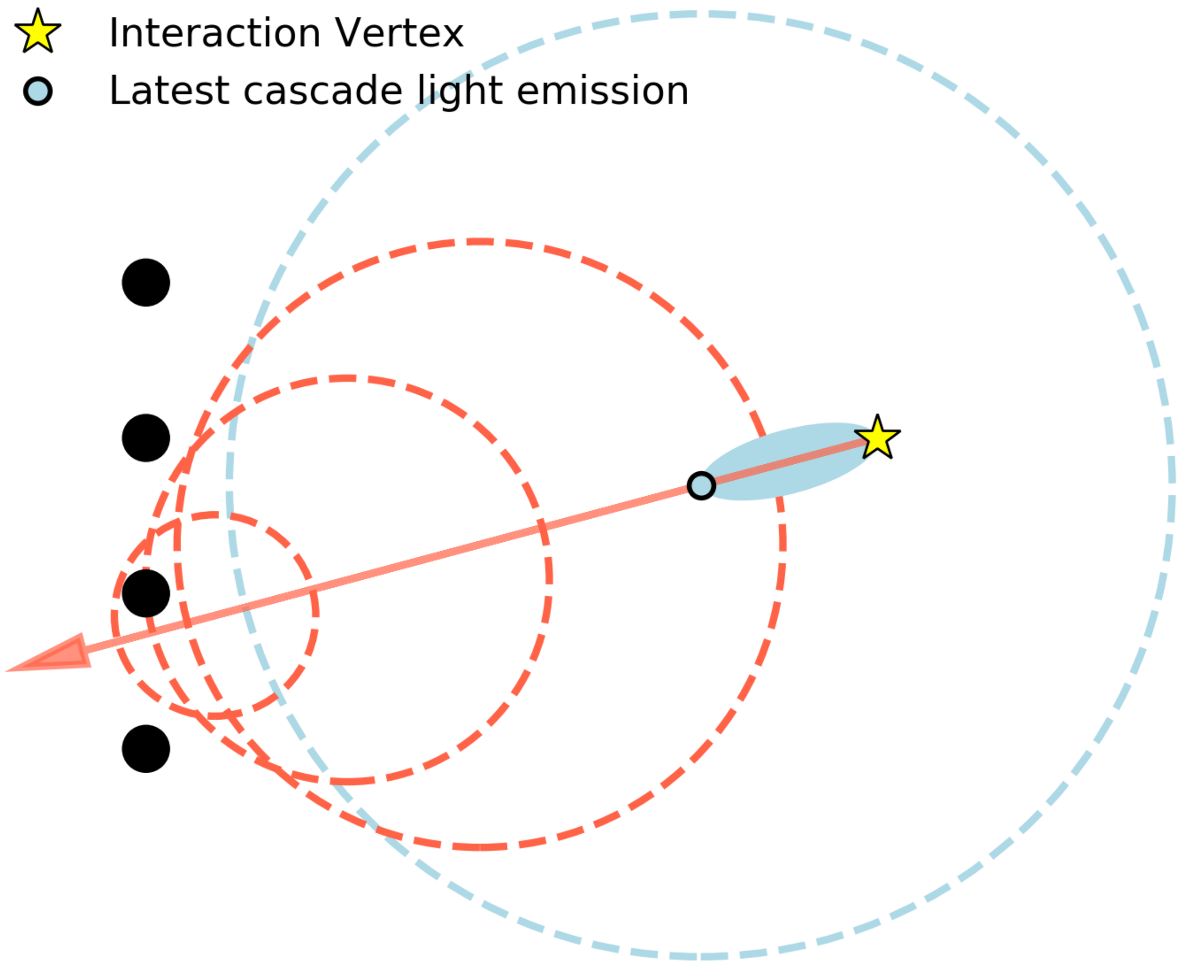


Muons can outrange the hadronic cascade

Hadronic Cascade (~15m length in ice)

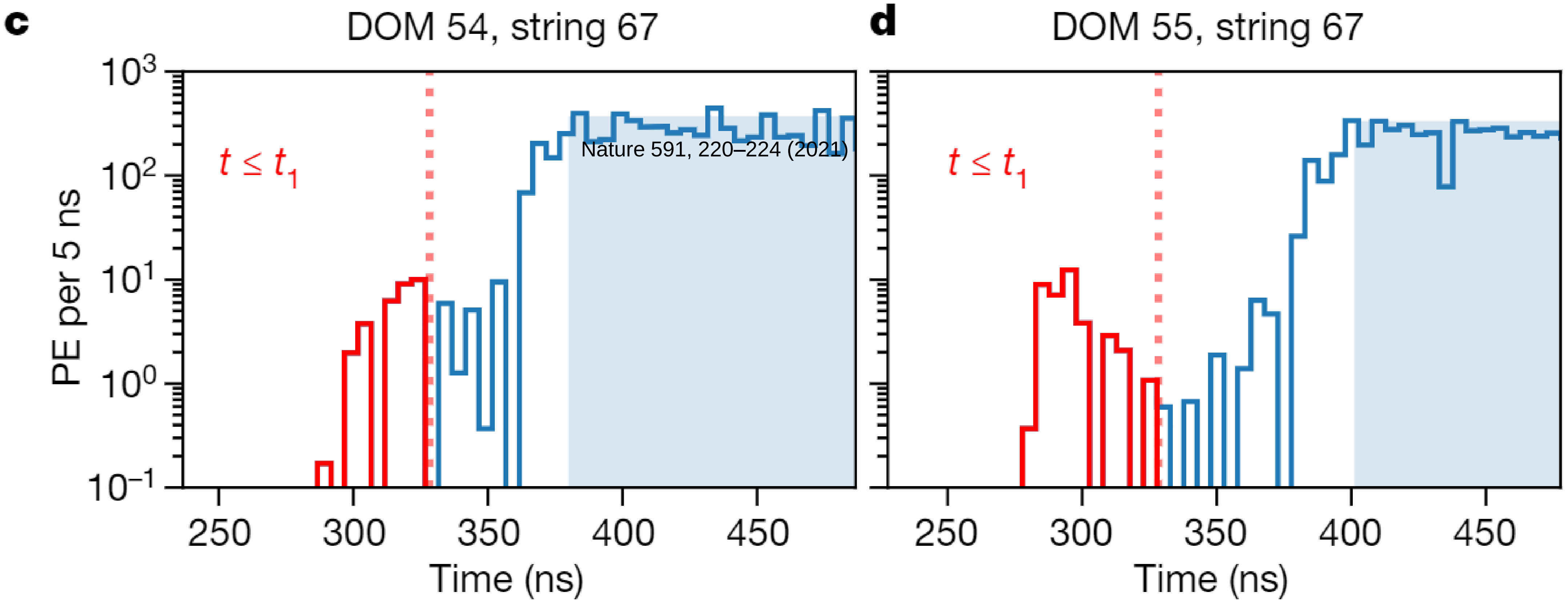
Expect leading muon energies ~10-100GeV for GR!

Early Pulses from Muonic Component



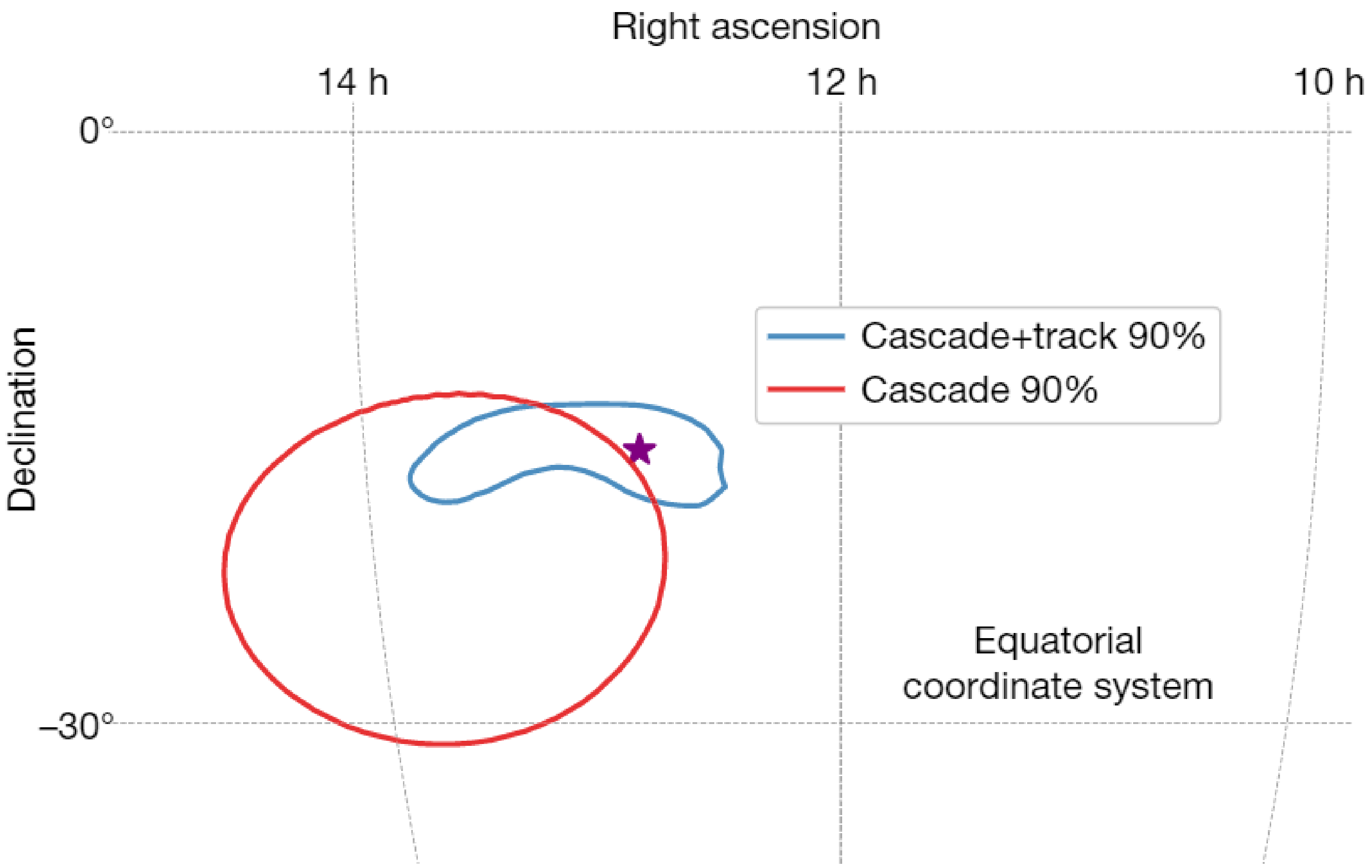
- Cherenkov light front propagates with c/n_{ice}
- Relativistic muons from hadronic cascade can “outrun” cascade light front
- Resulting early hit patterns can be used to reconstruct muon direction

Early Pulses from Muonic Component



Careful analysis rules out PMT prepulses (timing & charge doesn‘t match PMT prepulse characteristics)

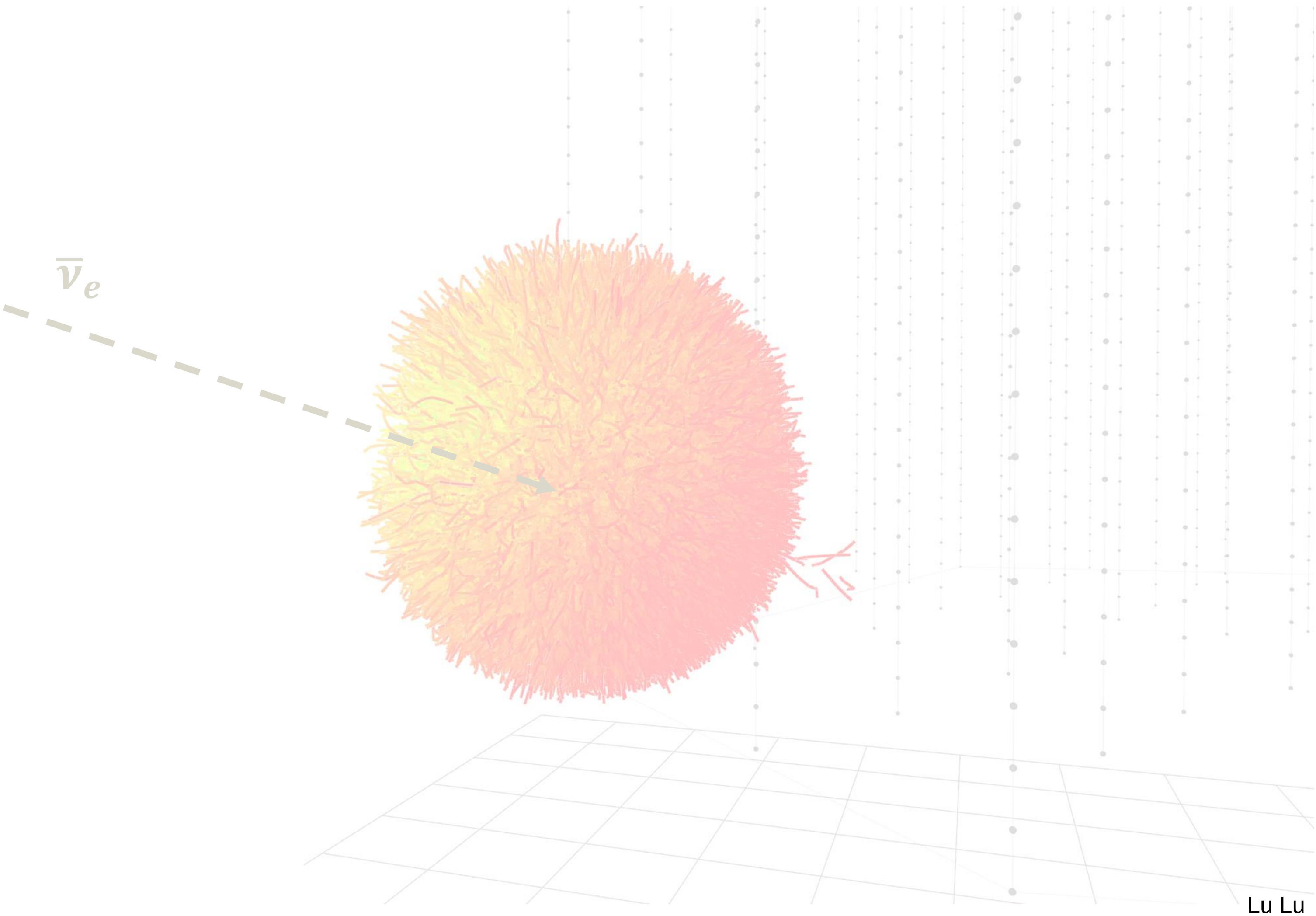
Angular Reconstruction



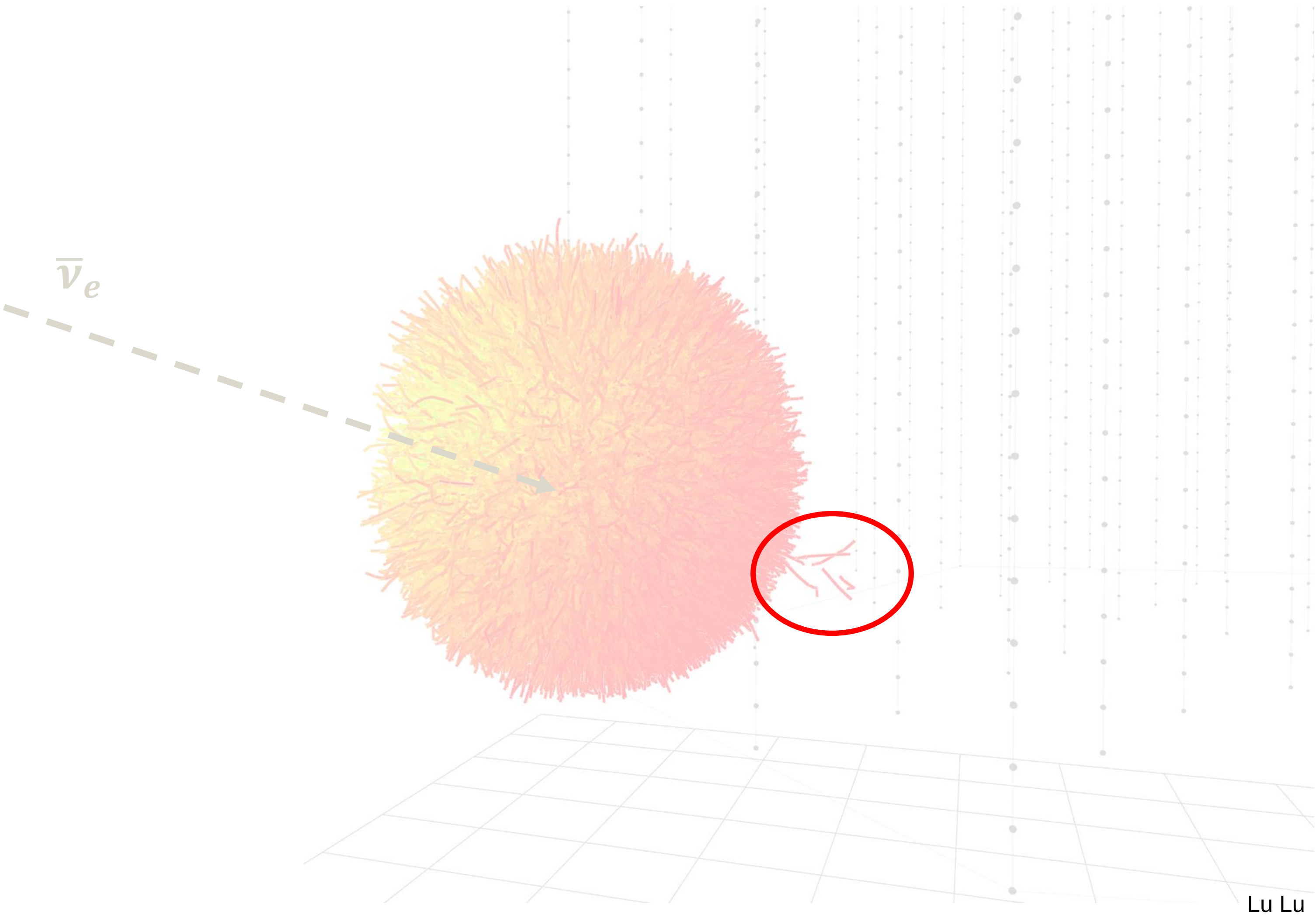
Use early pulses to fit a muon hypothesis.

Directional reconstruction completely independent from cascade reconstruction.

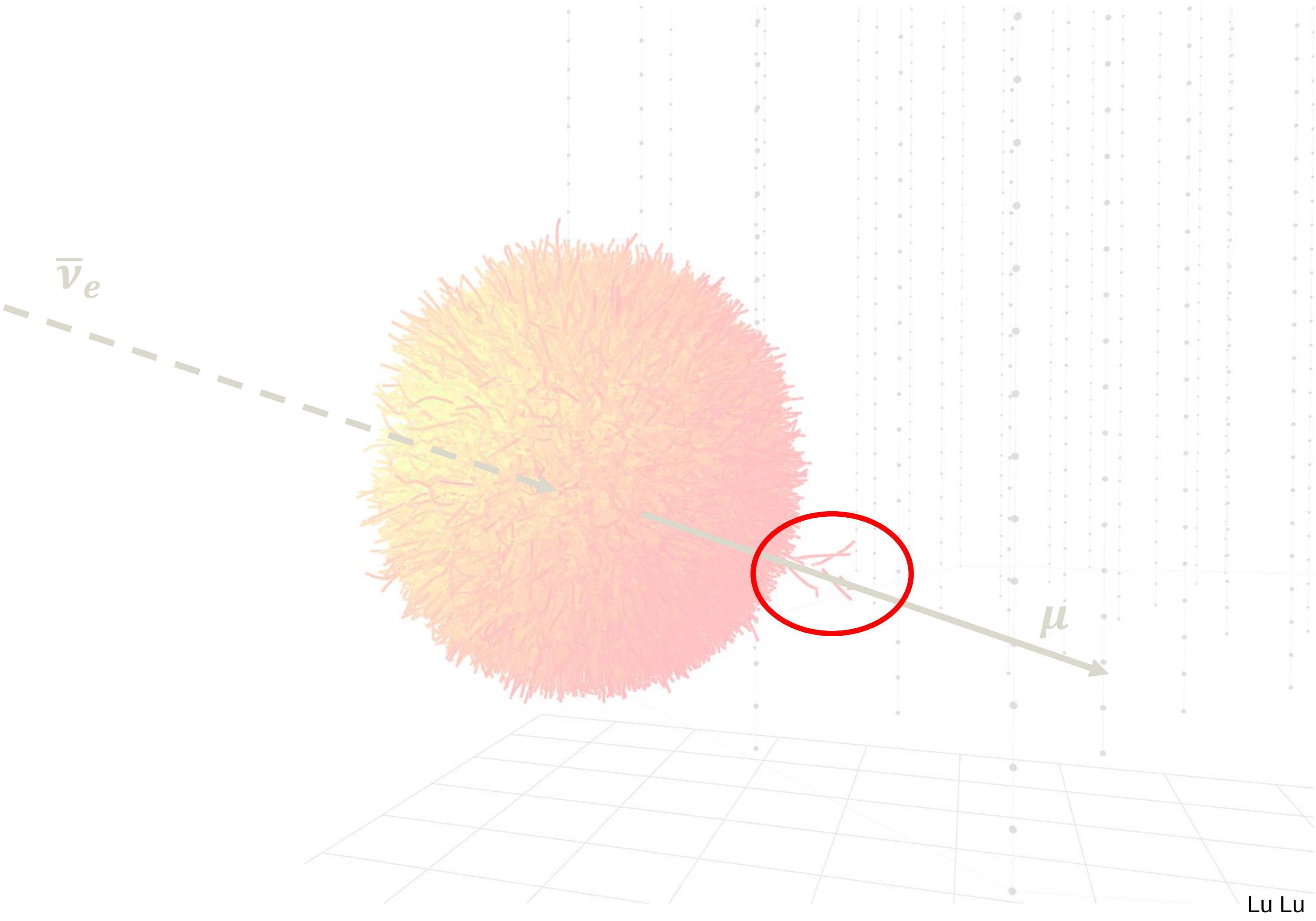
Photon Simulation



Photon Simulation

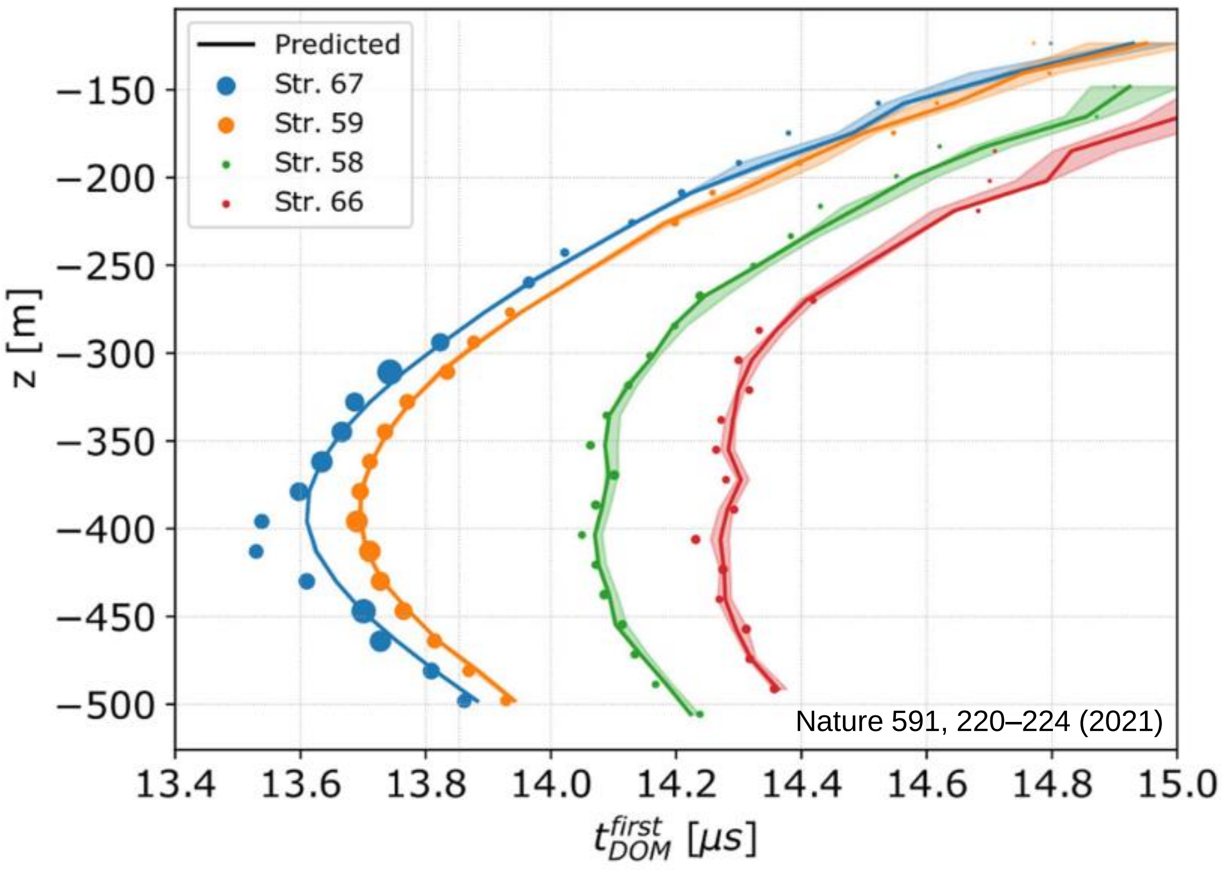


Photon Simulation



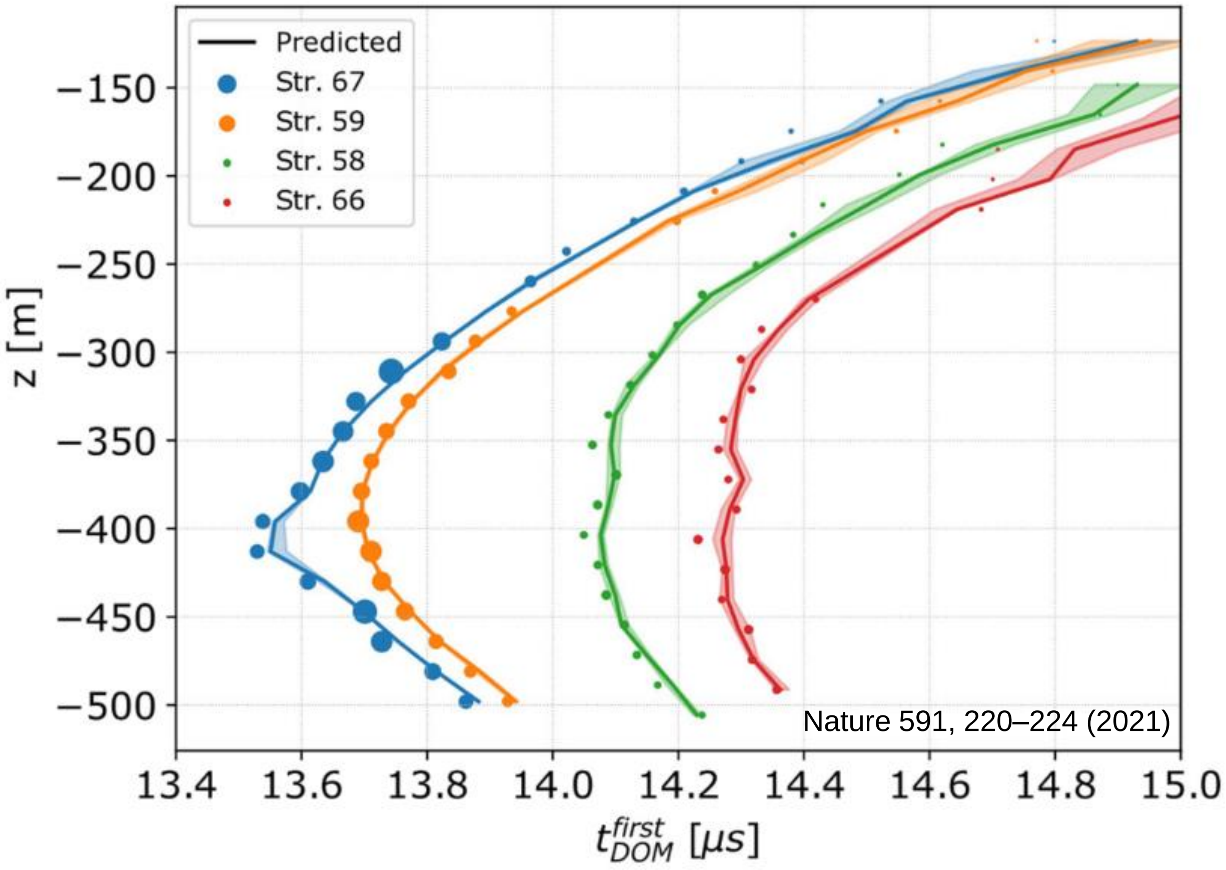
Resimulation with Muonic Component

Pure EM Cascade



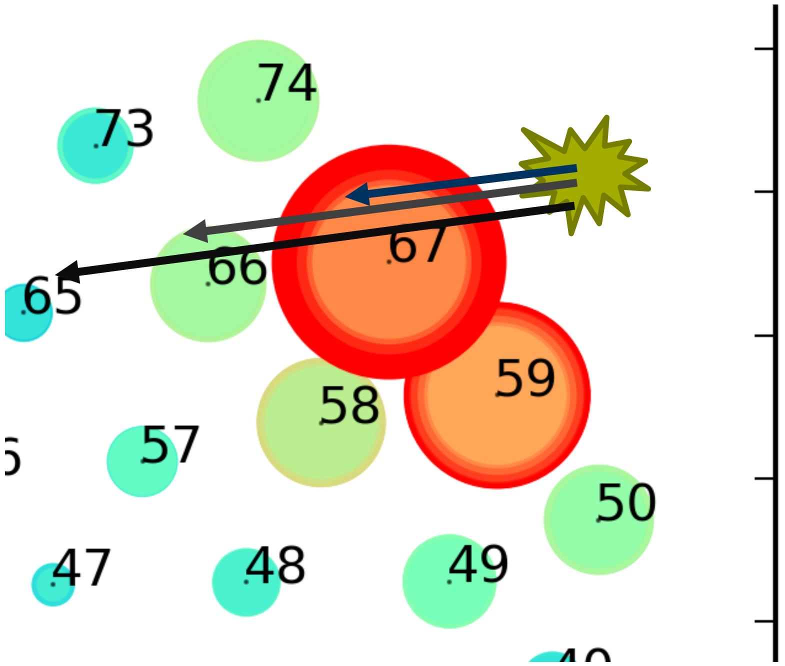
Nature 591, 220–224 (2021)

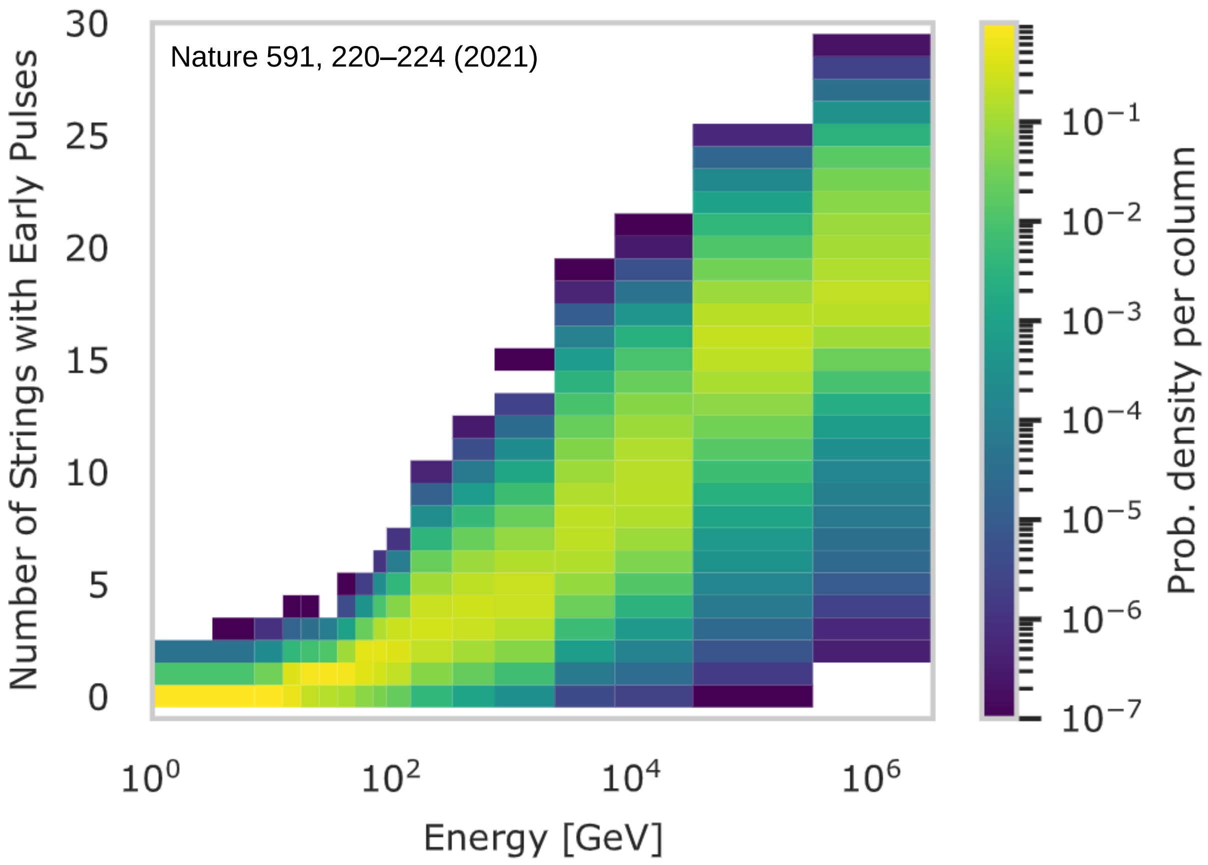
Hadronic Cascade



Nature 591, 220–224 (2021)

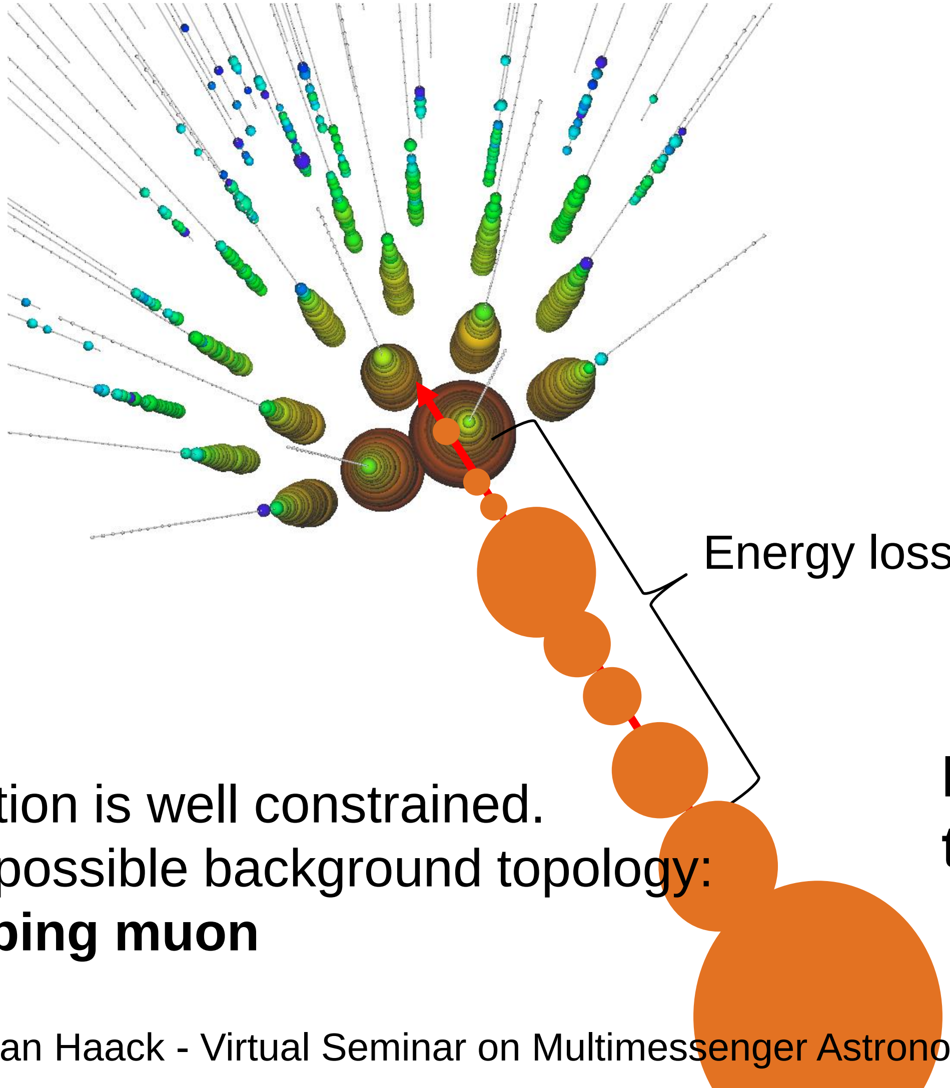
Maximum Muon Energy





Number of strings with early hits correlated to leading muon energy

Background Probability



Muon at Surface

↓

Propagate to detector

↓

Deposit ~6 PeV at reconstructed vertex

↓

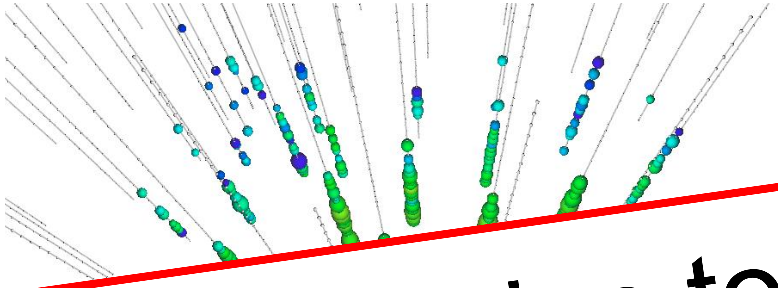
Remain with ~25 GeV

Direction is well constrained.
Only possible background topology:
Stopping muon

Expect less than 10^{-7} muon events with similar topology.

Background Probability

Muon at Surface



Also helps to exclude atmospheric neutrinos (self veto): $< 2 \cdot 10^{-7}$ events.

First astrophysical neutrino with >5σ

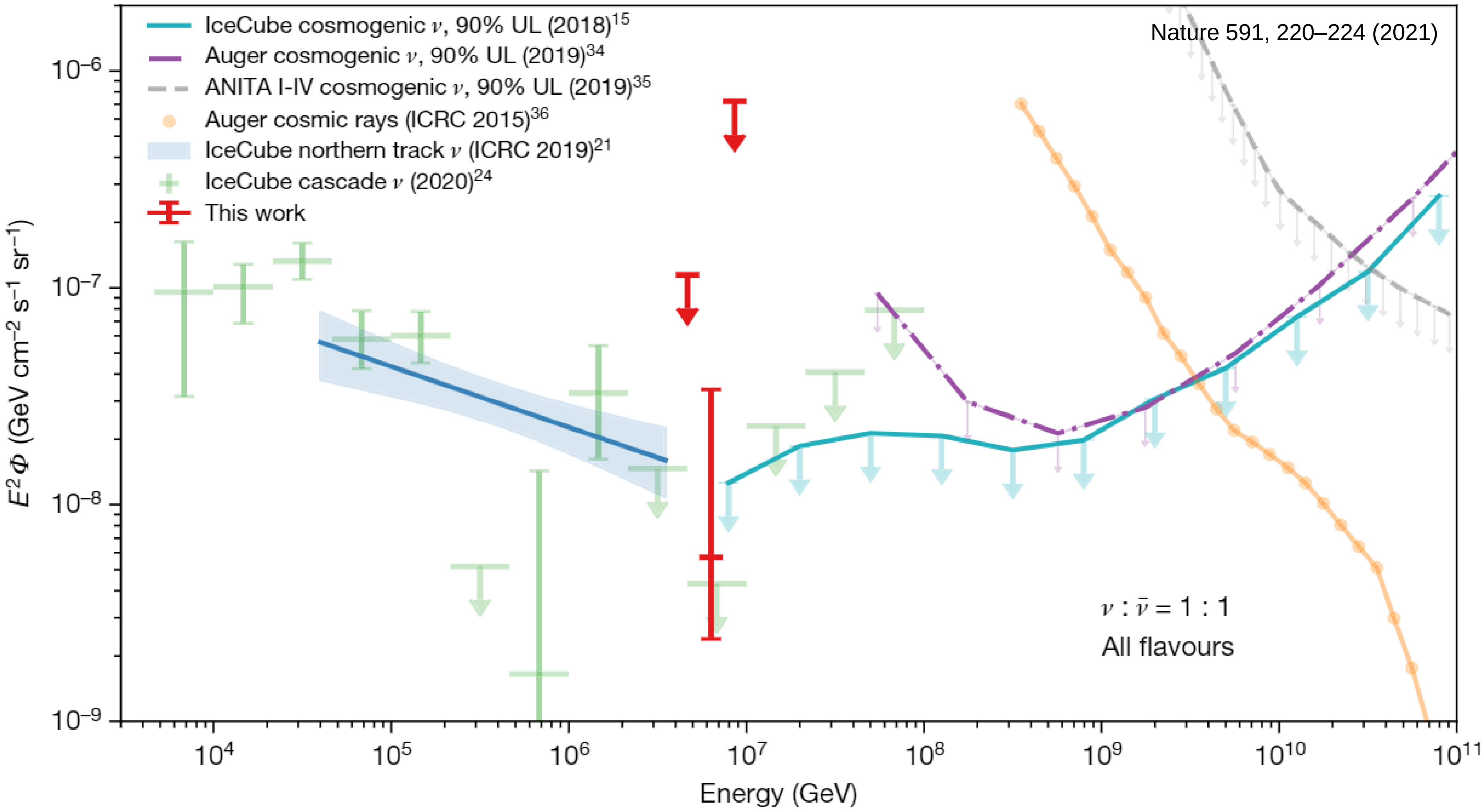
Directio

Only po ...ckground topology:

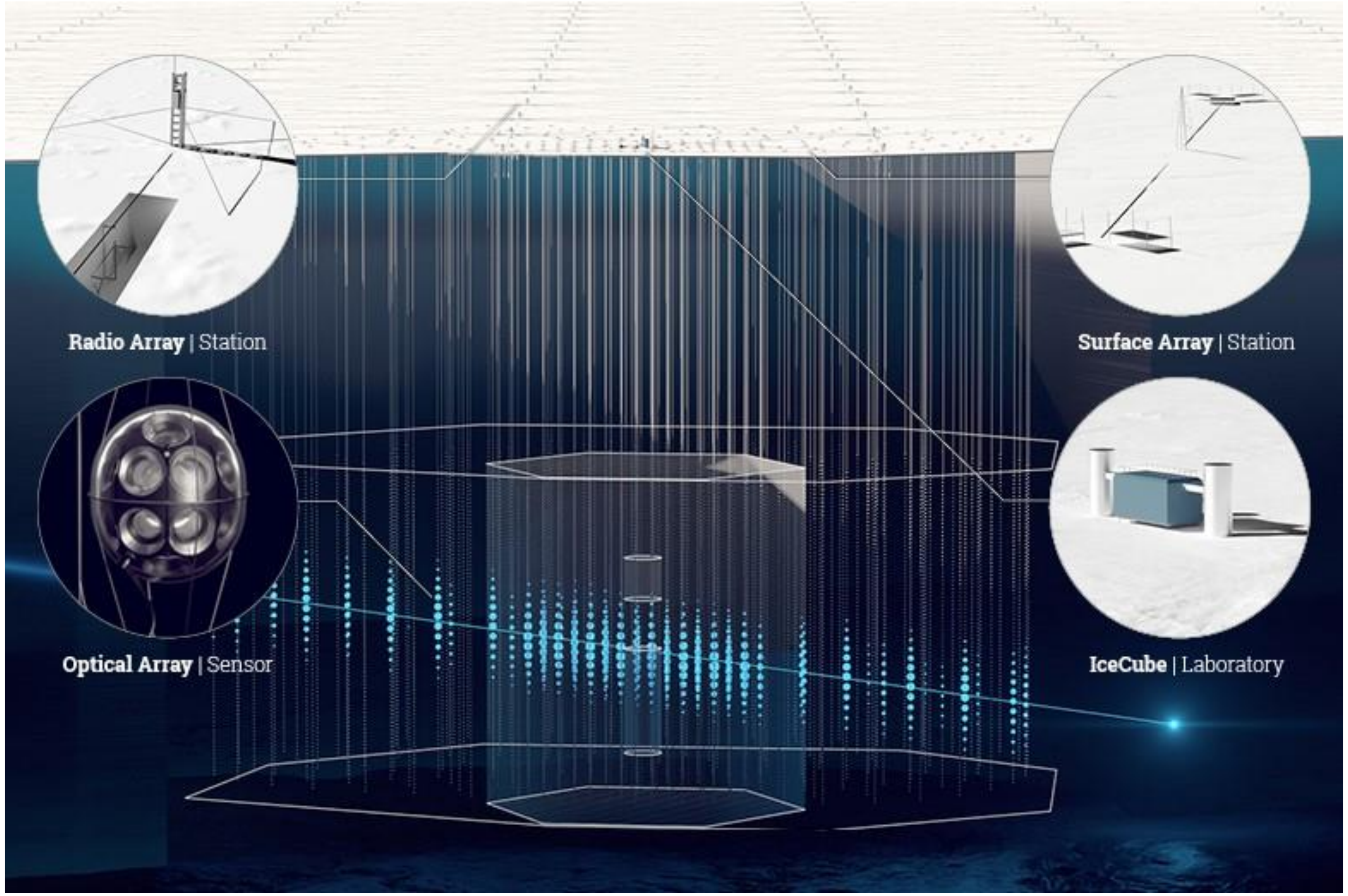
Stopping muon

Expect less than 10^{-7} muon events with similar topology.

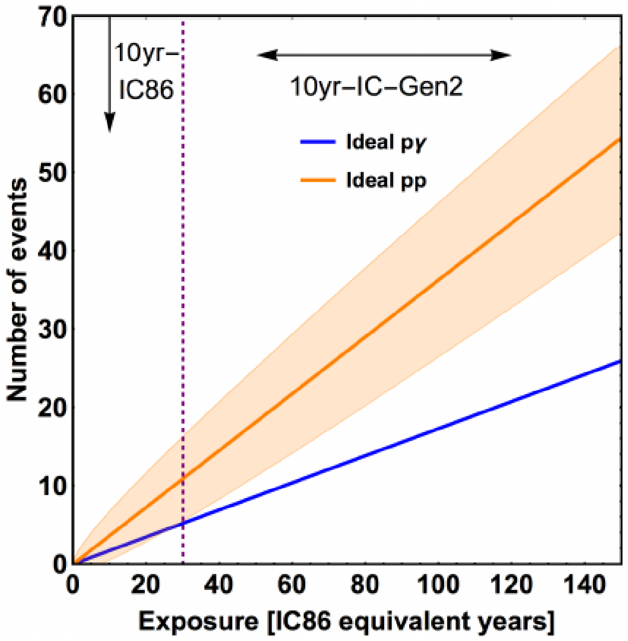
The Astrophysical Neutrino Spectrum



IceCube Gen2



(Credit: DESY, Science Communication Lab)



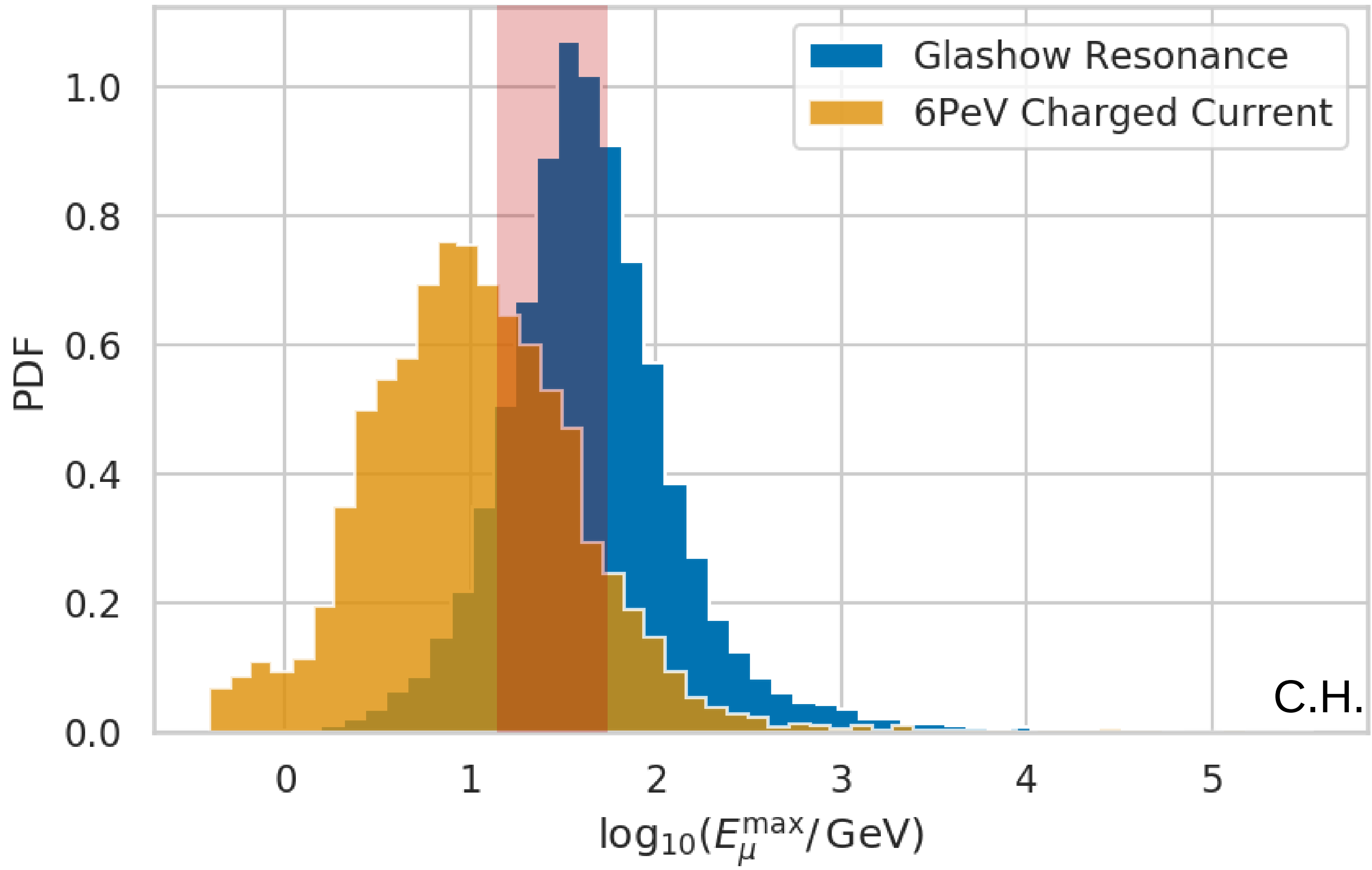
Biehl et al. https://arxiv.org/pdf/1611.07983.pdf

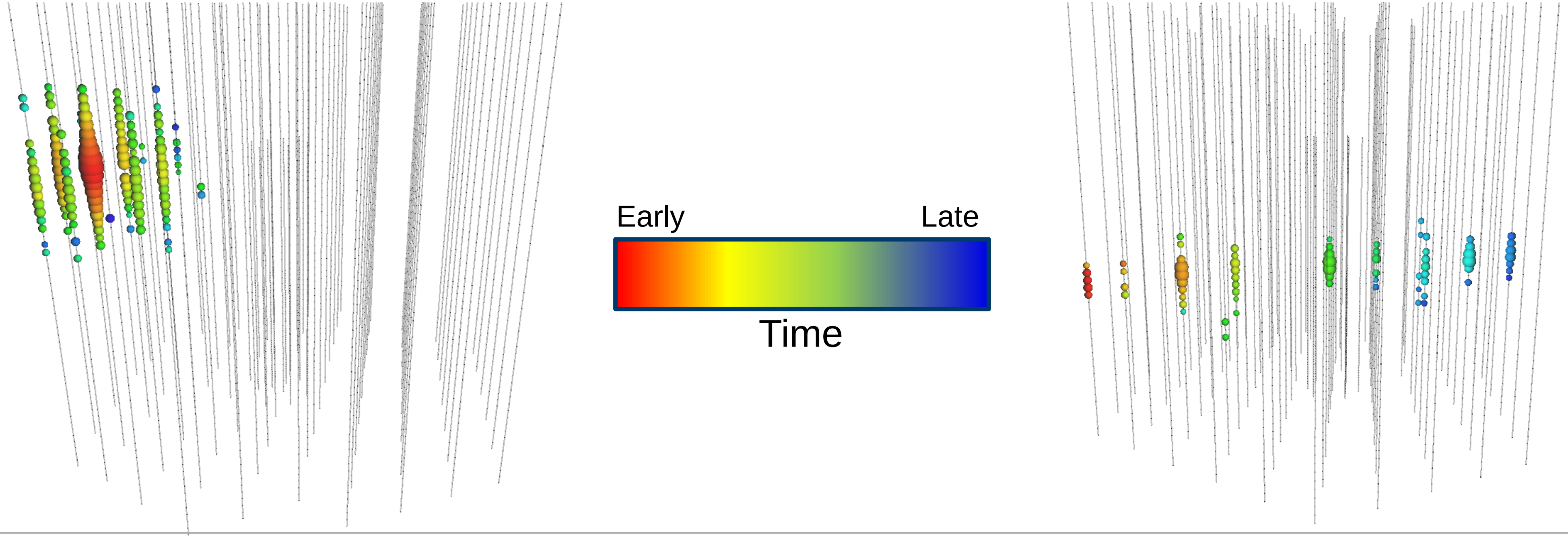
Take Away

- Neutrino telescopes are complex instruments; many steps from recording the raw data to physics analyses
- IceCube has detected a multi-PeV hadronic cascade event at the Glashow resonance
- Production via CC constrained at 1% p-value.
- Precise understanding of low-level data has enabled the identification of the muonic component of the event: Improved angular reconstruction and confirmation of hadronic nature
- In the future GR measurements can help constrain astrophysical source scenarios

Backup

Leading Muon Energy GR / CC



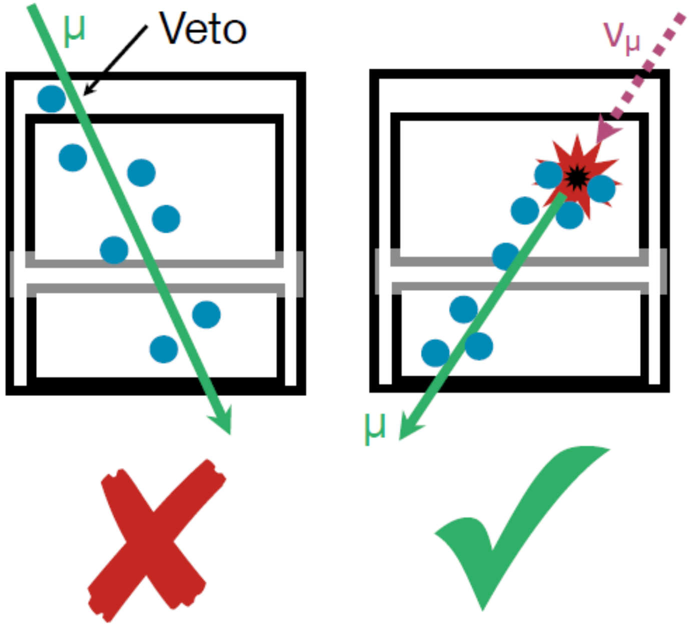


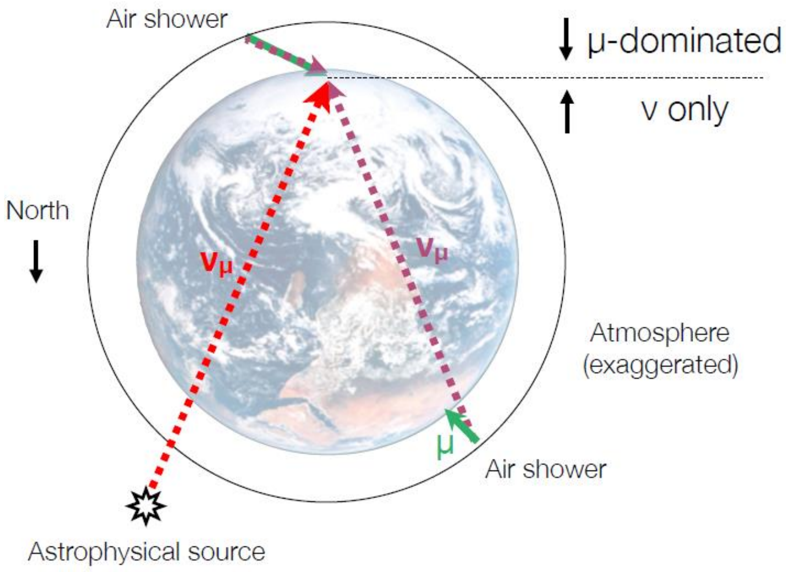
Cascades

Neutral Current (NC) & ν_e (ν_τ) Charged Current (CC)
Good energy resolution (~15%)
Poor angular resolution (~10°)
4π acceptance
Limited to instrumented volume

Throughgoing Tracks

ν_μ CC
Poor energy resolution (200%)
Good angular resolution (<0.5°)
2π acceptance
Not limited to instrumented volume

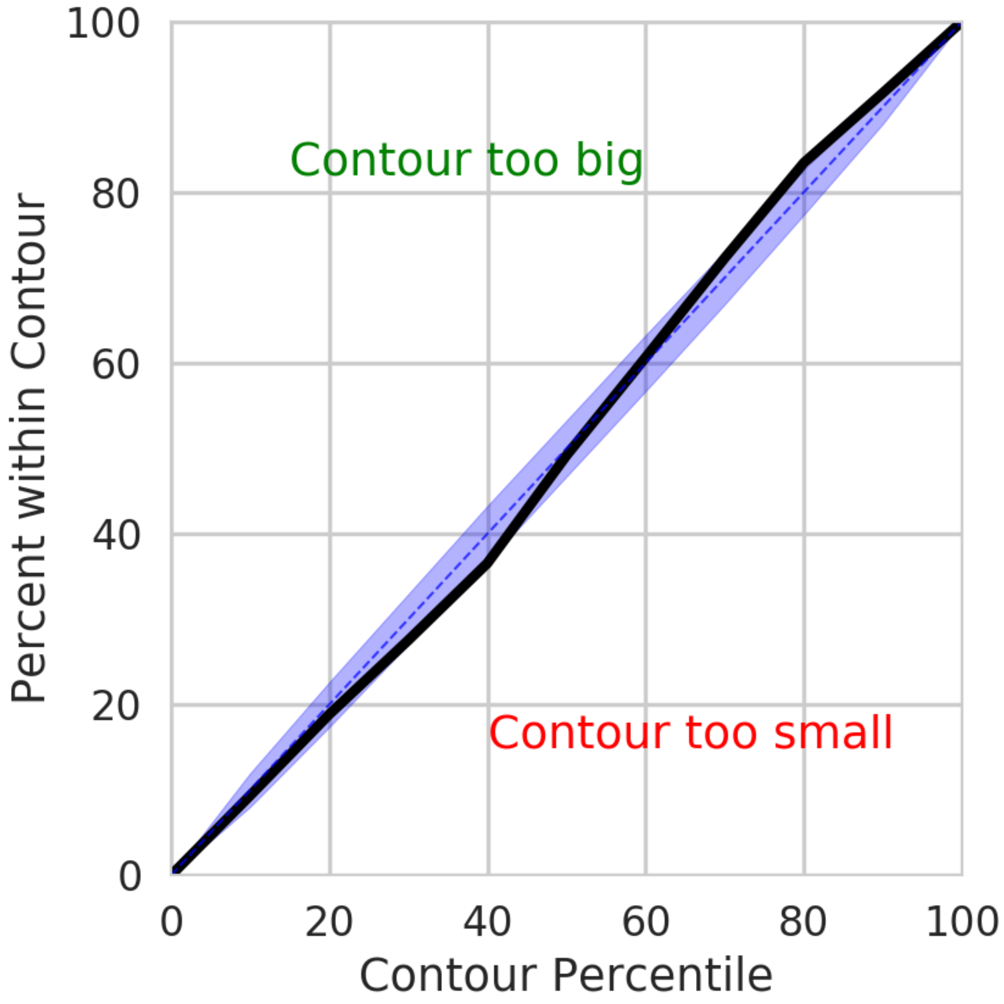




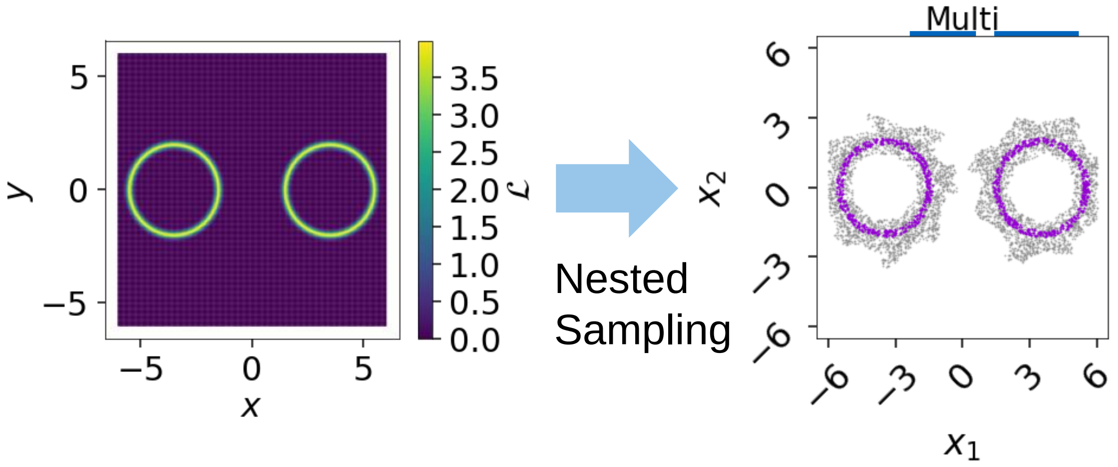
Cascades / Starting Events
Background reduction by fiducialization / veto

Throughgoing Tracks
Background reduction by using Earth as shield

The coverage of the contours obtained from Nested Sampling has been tested by counting how often the true direction lies in a certain contour percentile.



$$\mathcal{L}(\overrightarrow{x_0}, t_0, \vec{d}) = \prod_{Early\ Pulses\ t_i} P(t_i - t_{geo}, \vec{x}_{DOM} | H(\overrightarrow{x_0}, t_0, \vec{d}))$$



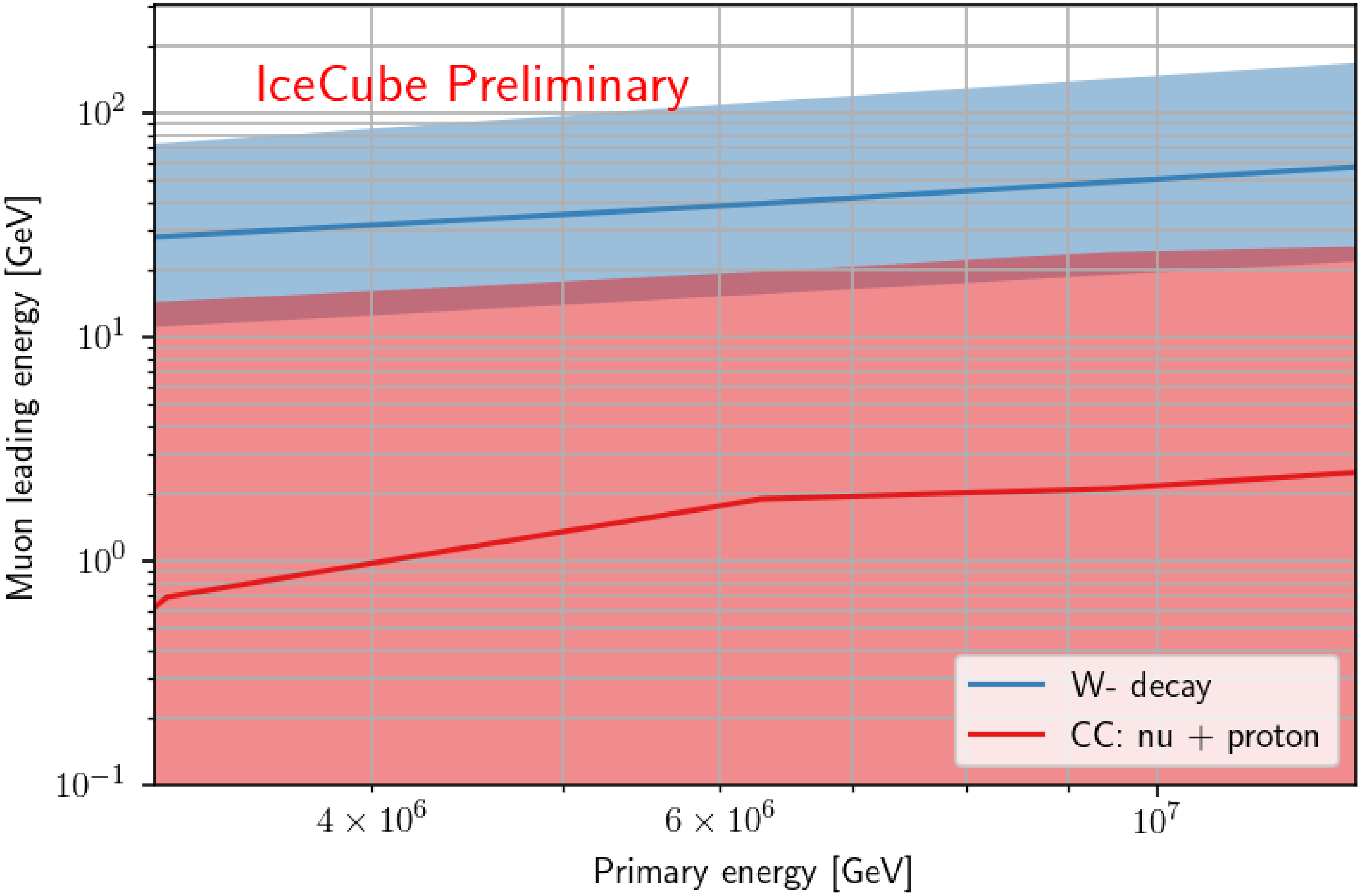
Flat prior for direction: $\pi(\vec{d})$

Gaussian prior for time: $\pi(t_0) = N(\mu = 0\,\mathrm{ns}, \sigma = 10\,\mathrm{ns})$

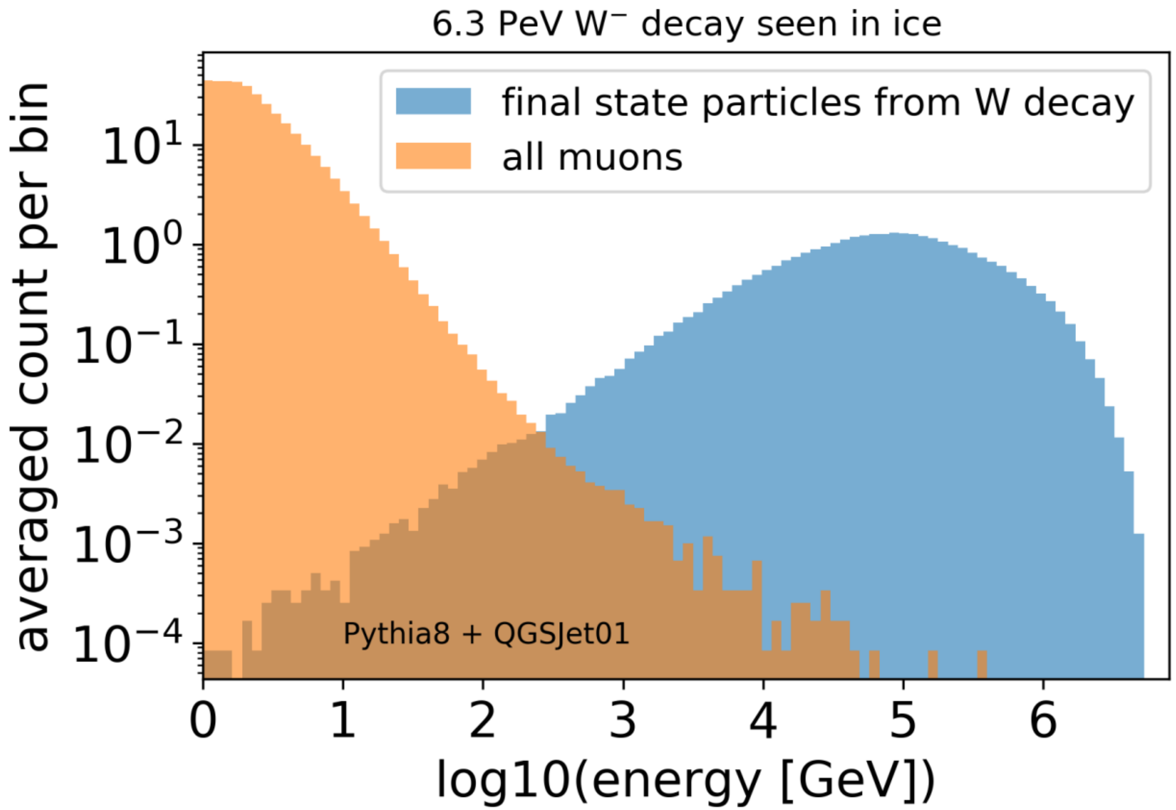
Gaussian prior with cov. from DirectFit for vertex: $\pi(\vec{d}) = N(\mu = \vec{d_{\mathrm{DF}}}, \Sigma = \Sigma_{\mathrm{DF}})$

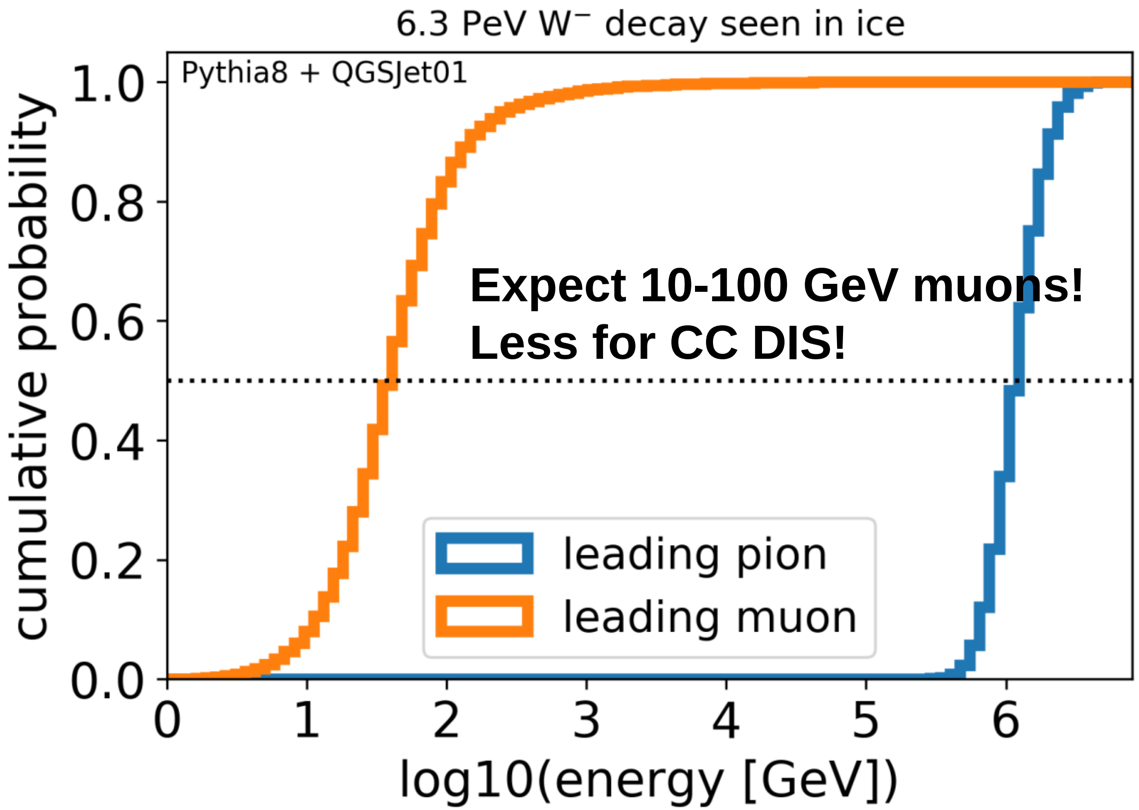
Sample from posterior with nested sampling algorithm:

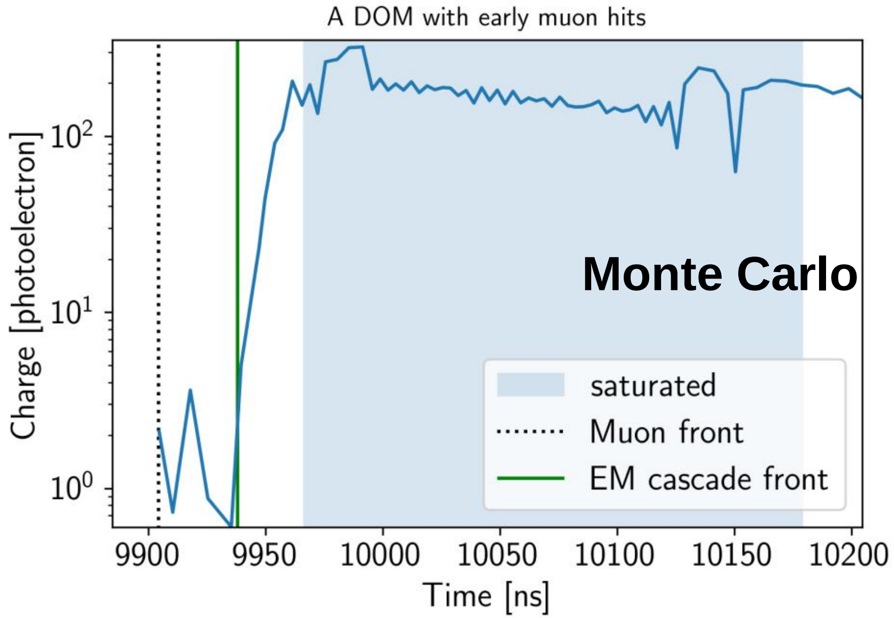
$$P(t_0, \vec{x}_0, \vec{d} | \mathrm{Early\ \ Pulses}) \propto \mathcal{L}(t_0, \vec{x}_0, \vec{d}) \cdot \pi(t_0) \cdot \pi(\vec{x}_0) \cdot \pi(\vec{d})$$



IceCube Preliminary
Muon leading energy [GeV]
10^{2}
10^{1}
10^{0}
10^{-1}
4×10^6
6×10^6
10^7
Primary energy [GeV]
W- decay
CC: nu + proton

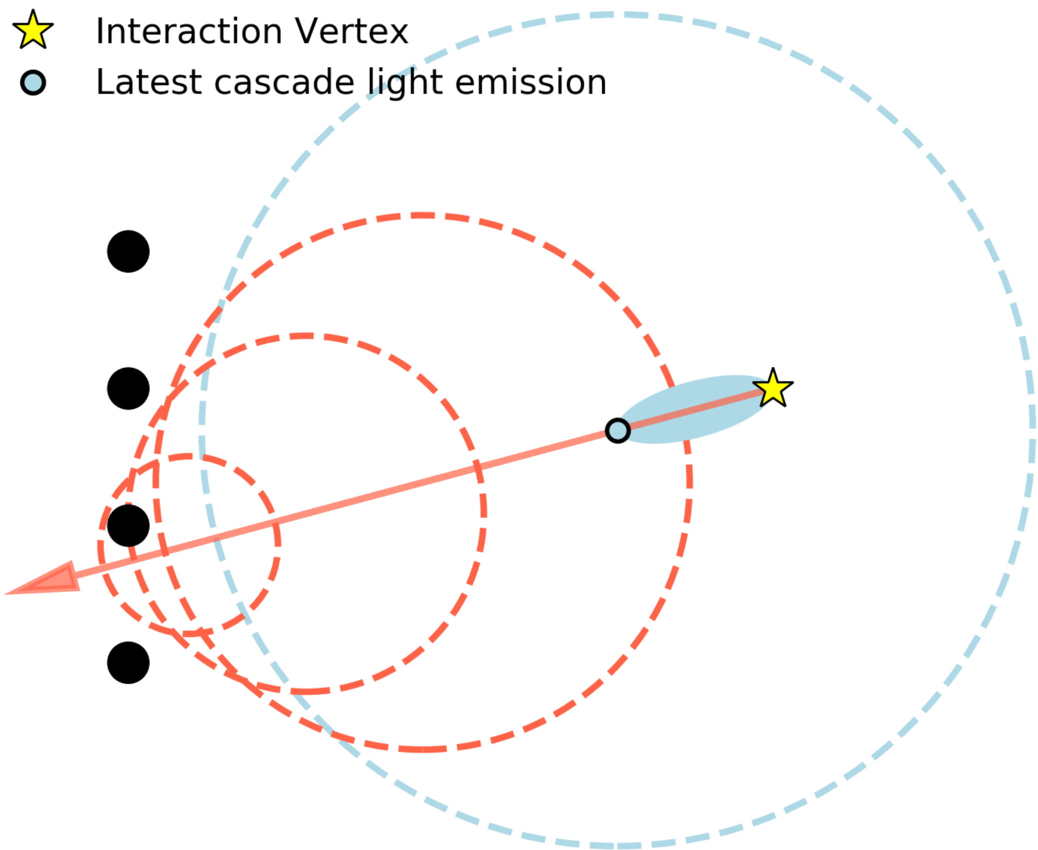

6.3 PeV W⁻ decay seen in ice
final state particles from W decay
all muons
Pythia8 + QGSJet01
averaged count per bin
log10(energy [GeV])


6.3 PeV W⁻ decay seen in ice
Pythia8 + QGSJet01
Expect 10-100 GeV muons!
Less for CC DIS!
leading pion
leading muon
cumulative probability
log10(energy [GeV])

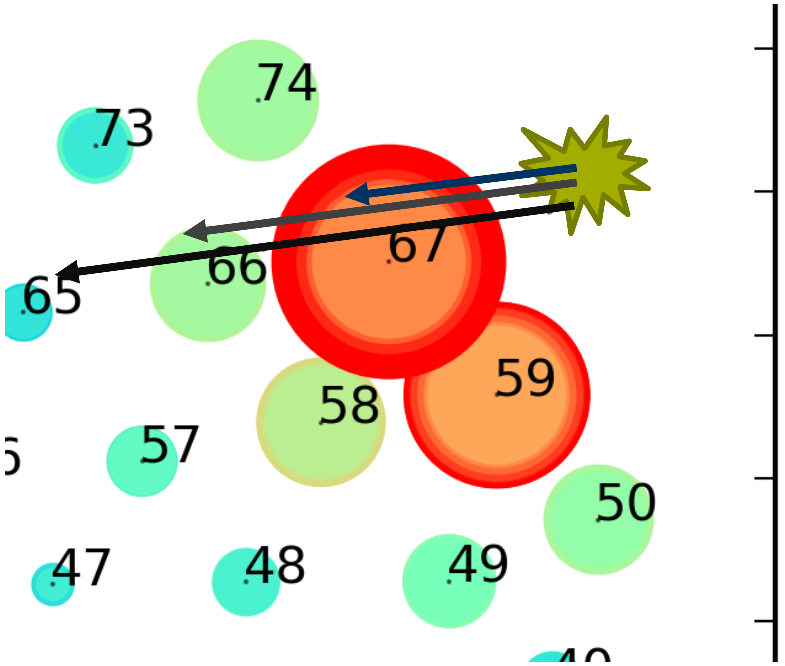


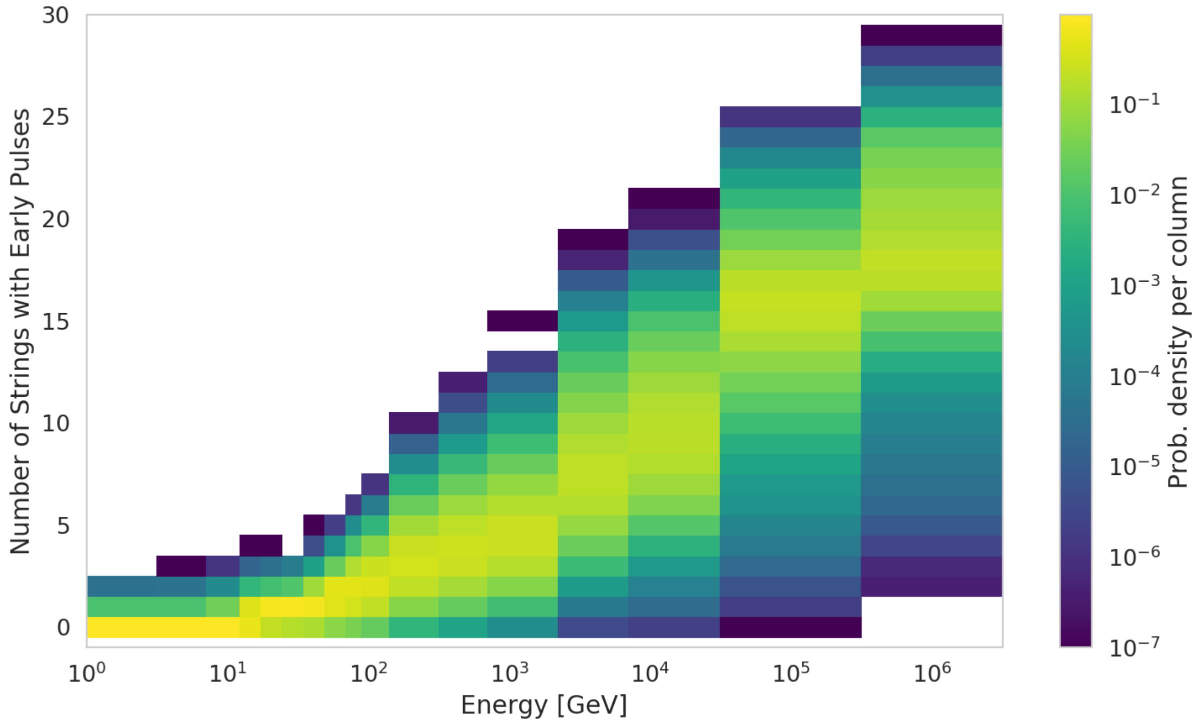
$$t_{\text{casc}} = t_{\text{vertex}} + \frac{|\vec{x}_{\text{DOM}} - \vec{x}_{\text{vertex}}|}{c_{\text{Ice}}}$$

$$t_{\mu} = t_{\text{vertex}} + \frac{|\vec{x}_{\text{DOM}} - \vec{x}_{\text{vertex}}|}{c}$$



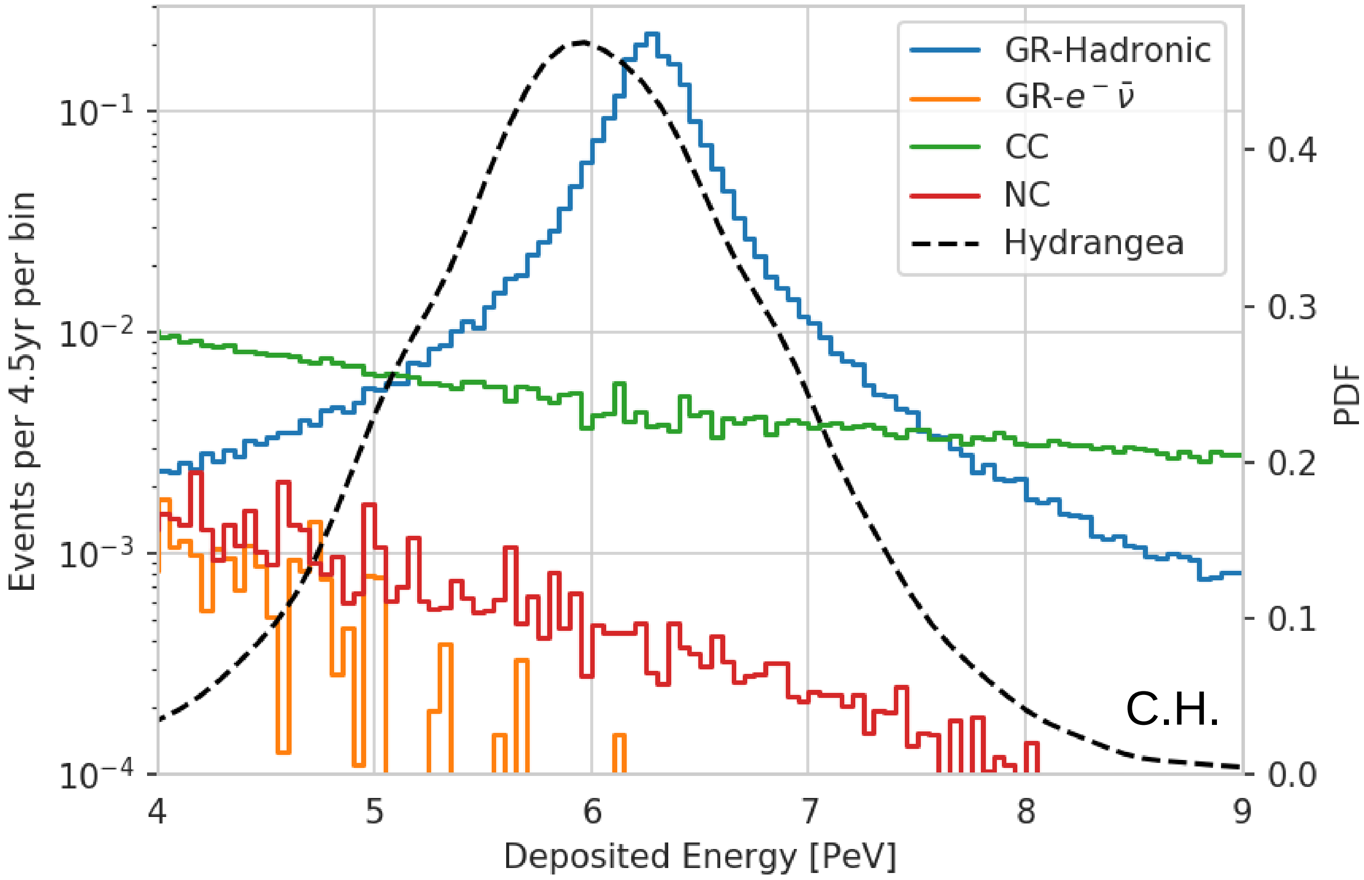
Maximum Muon Energy





Number of strings with early hits correlated to leading muon energy

Energy Reconstruction



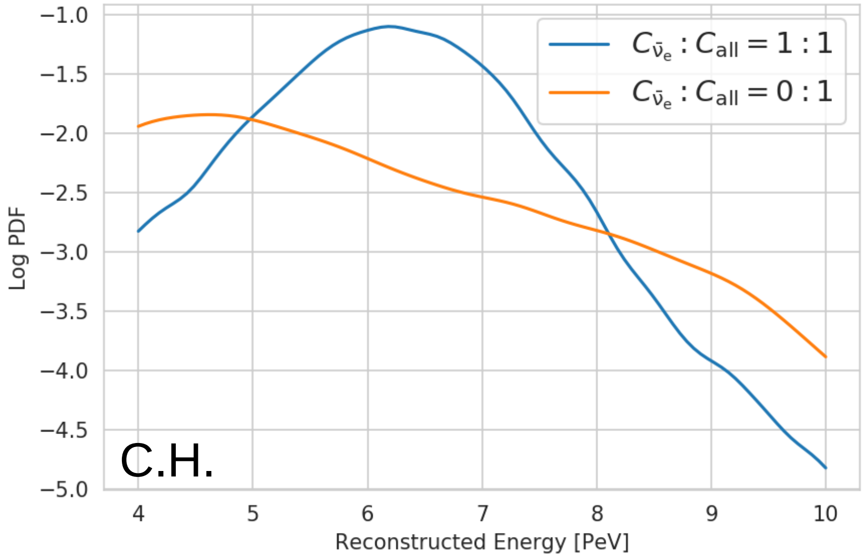
The reconstruction measures the deposited energy, ie. the total energy in contained in Hadronic / EM cascades.

For hadronic-GR and ν_e-CC, the entire neutrino energy is deposited, while for NC and leptonic GR a fraction of the energy is carried away by the outgoing neutrino.

CC interactions in this sample are almost exclusively ν_e

Measurement of the $\bar{\nu}_e$ Flux

Expected number of observed events:



$$\lambda = N_{CC} + N_{GR} = \int \left(\frac{d\Phi_{\nu_e}}{dE} + \frac{d\Phi_{\overline{\nu}_e}}{dE} \right) A_{eff}(CC) + \int \frac{d\Phi_{\overline{\nu}_e}}{dE} A_{eff}(GR)$$

$$\frac{d\Phi_{\nu_e}}{dE} = \frac{C_{all}}{\Phi_0} \cdot \left(\frac{E}{100TeV} \right)^{-\gamma}, \qquad \frac{d\Phi_{\overline{\nu}_e}}{dE} = \frac{C_{\overline{\nu}_e}}{\Phi_0} \cdot \left(\frac{E}{100TeV} \right)^{-\gamma}$$

$$p\left(E_{rec} | C_{all}, C_{\overline{\nu}_e}, \Phi_0, \gamma\right) = \frac{N_{GR}}{\lambda} P_{GR}\left(E_{rec} | E_{dep}\right) + \frac{N_{CC}}{\lambda} P_{CC}\left(E_{rec} | E_{dep}\right)$$

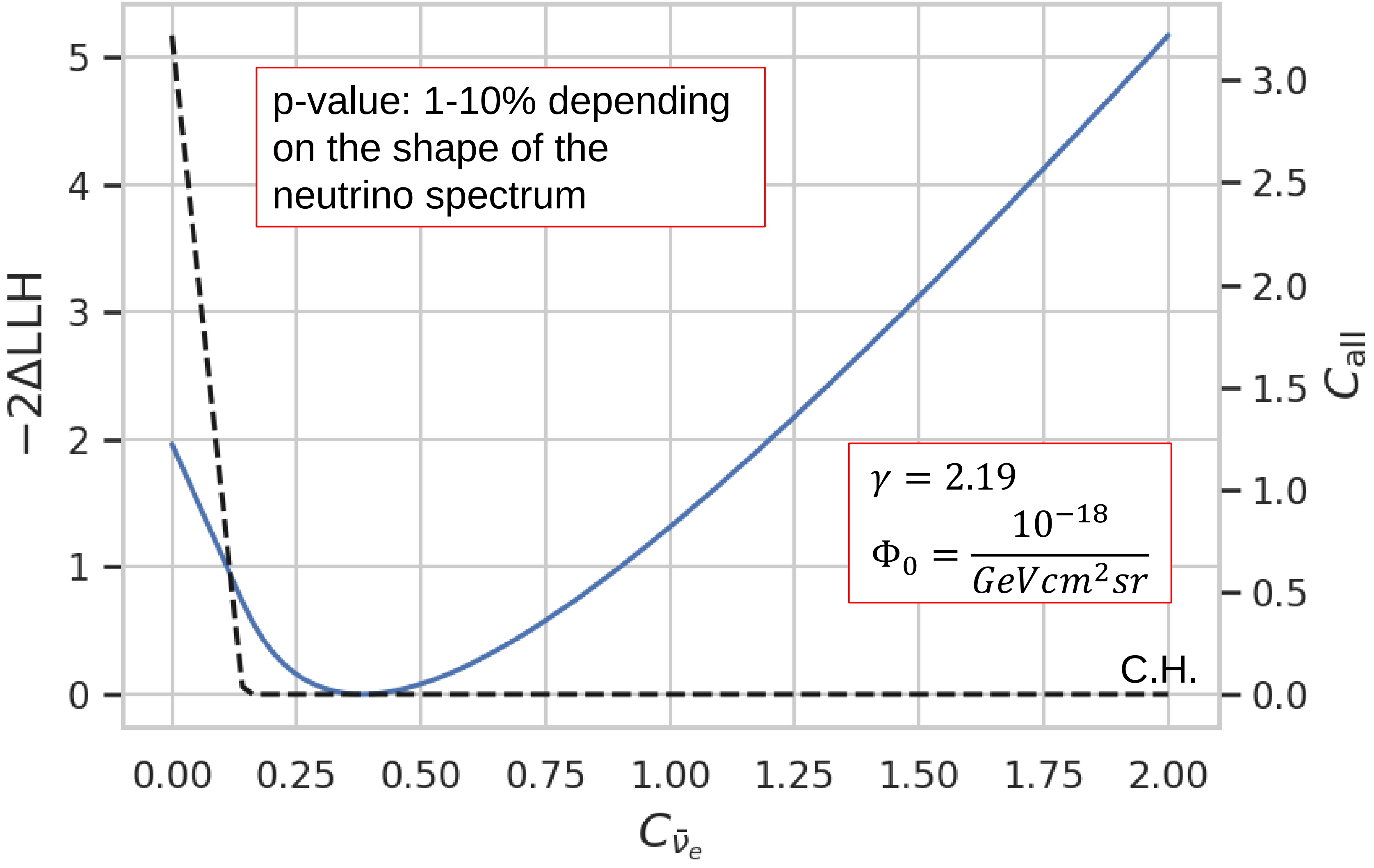
Extended poisson likelihood:

$$\mathcal{L} = p\left(E_{rec} | C_{all}, C_{\overline{\nu}_e}, \Phi_0, \gamma\right) \cdot \mathrm{Poisson}(k = 1 | \lambda)$$

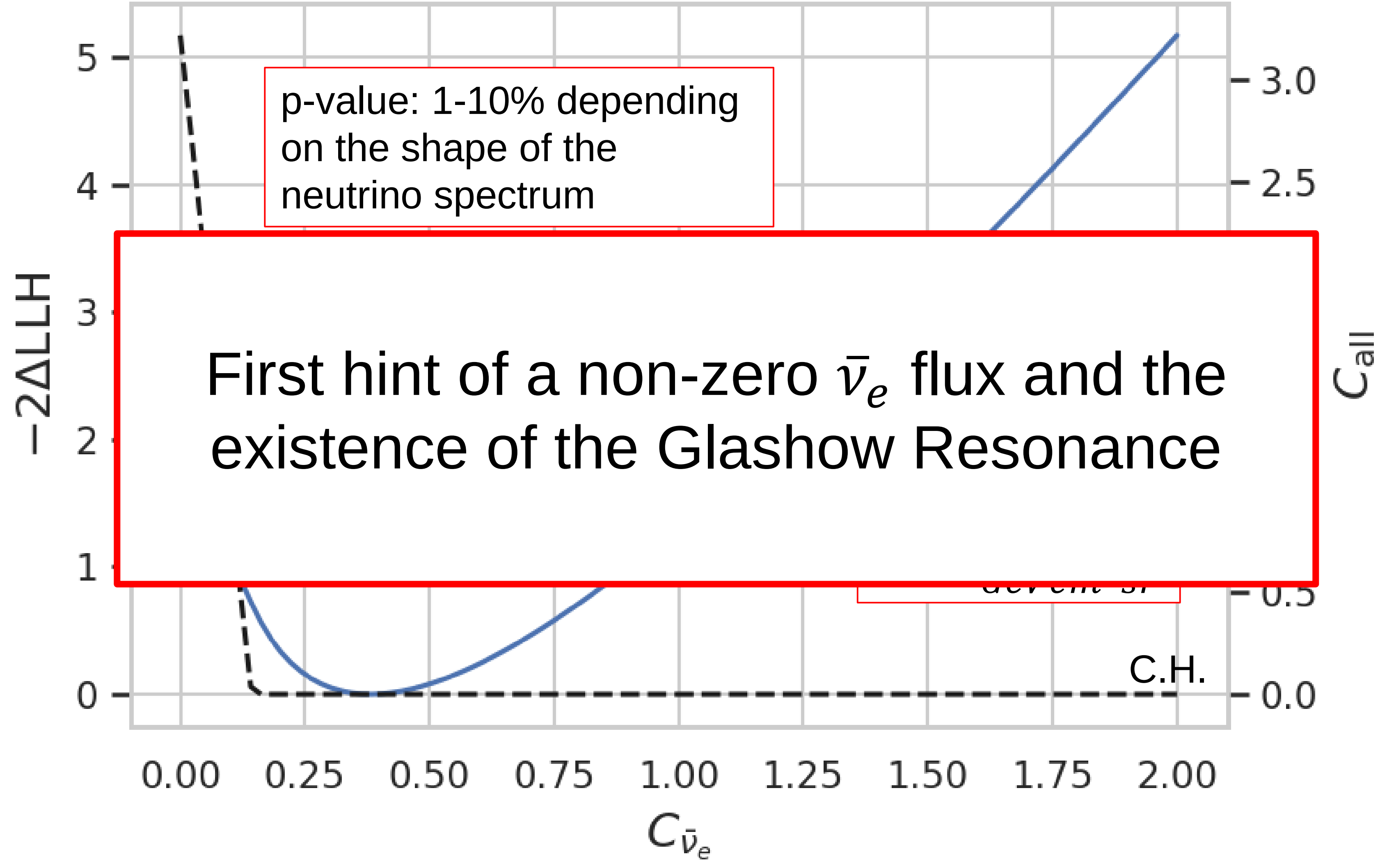
Likelihood-ratio test:

$$TS = 2 \log \frac{\mathcal{L}\left(\hat{C}_{\overline{\nu}_e}, \hat{C}_{all}, \widehat{\Phi}_0, \hat{\gamma}\right)}{\mathcal{L}\left(\hat{C}_{\overline{\nu}_e} = 0, \hat{\hat{C}}_{all}, \widehat{\widehat{\Phi}}_0, \hat{\hat{\gamma}}\right)}$$

Measurement of the $\bar{\nu}_e$ Flux



Measurement of the $\bar{\nu}_e$ Flux



First hint of a non-zero $\bar{\nu}_e$ flux and the existence of the Glashow Resonance