Characterizing Cosmic Neutrino Sources

A Measurement of the Energy Spectrum and Flavor Composition of the Cosmic Neutrino Flux Observed with the IceCube Neutrino Observatory

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Outline

PART I

What are cosmic neutrinos and why are they interesting?

PART II

How are neutrinos observed with the IceCube detector?

PART III

What are the properties of the cosmic neutrino flux detected with IceCube?

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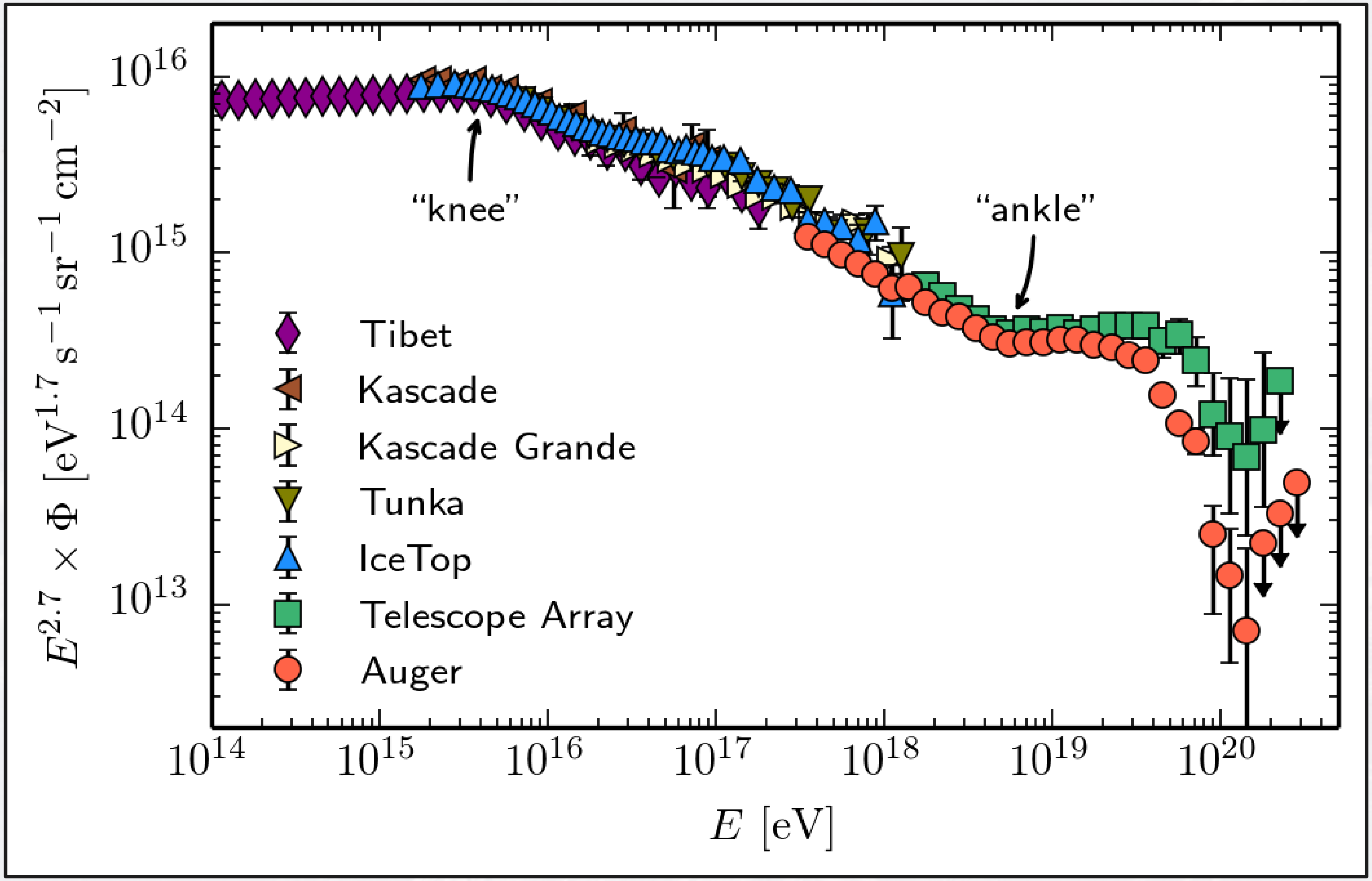
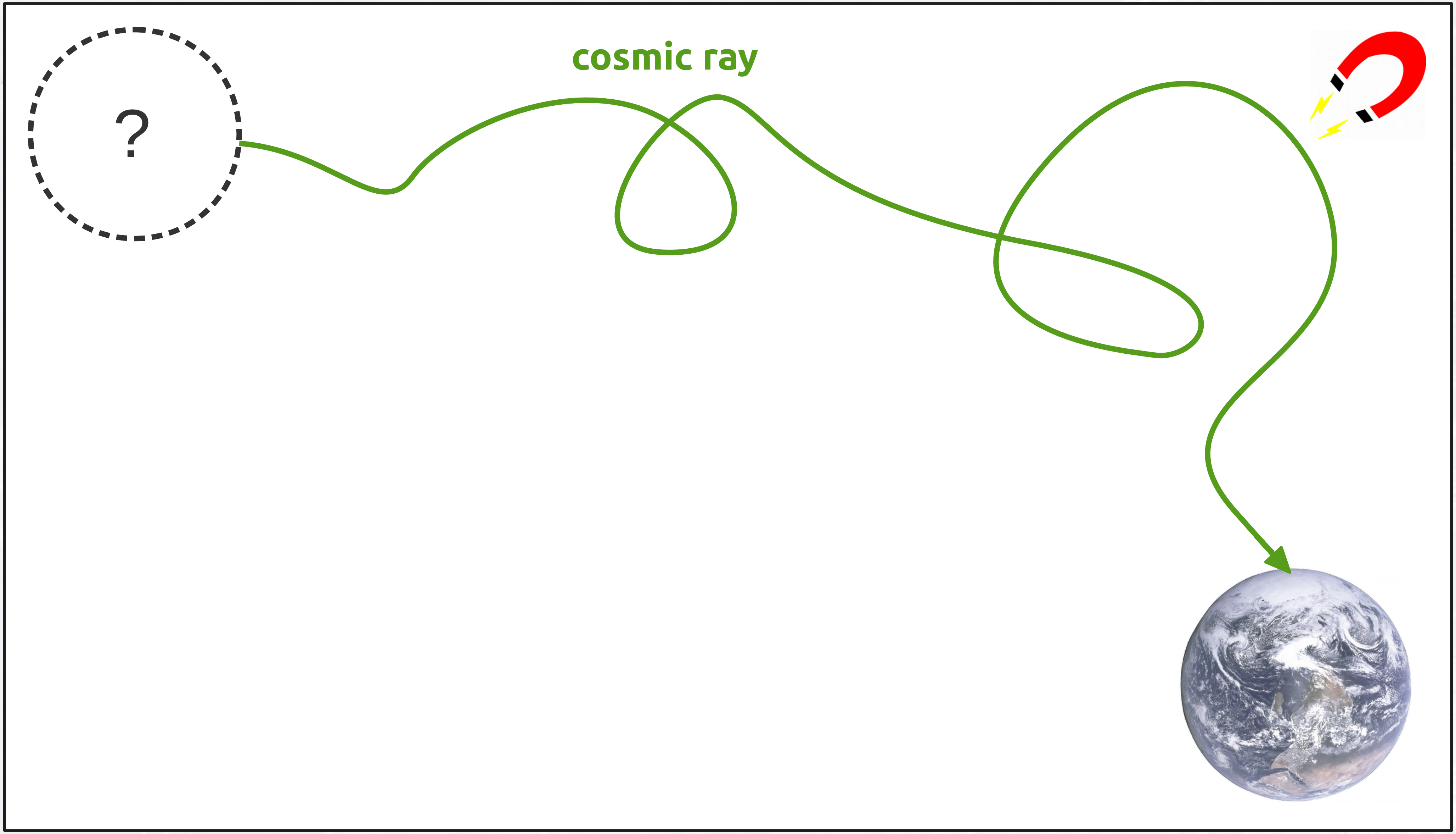
Motivation: The Cosmic-Ray Energy Spectrum



→ **Cosmic rays with extremely high energies observed**

→ **Sources + acceleration mechanism unknown**

Neutrinos and Cosmic Rays



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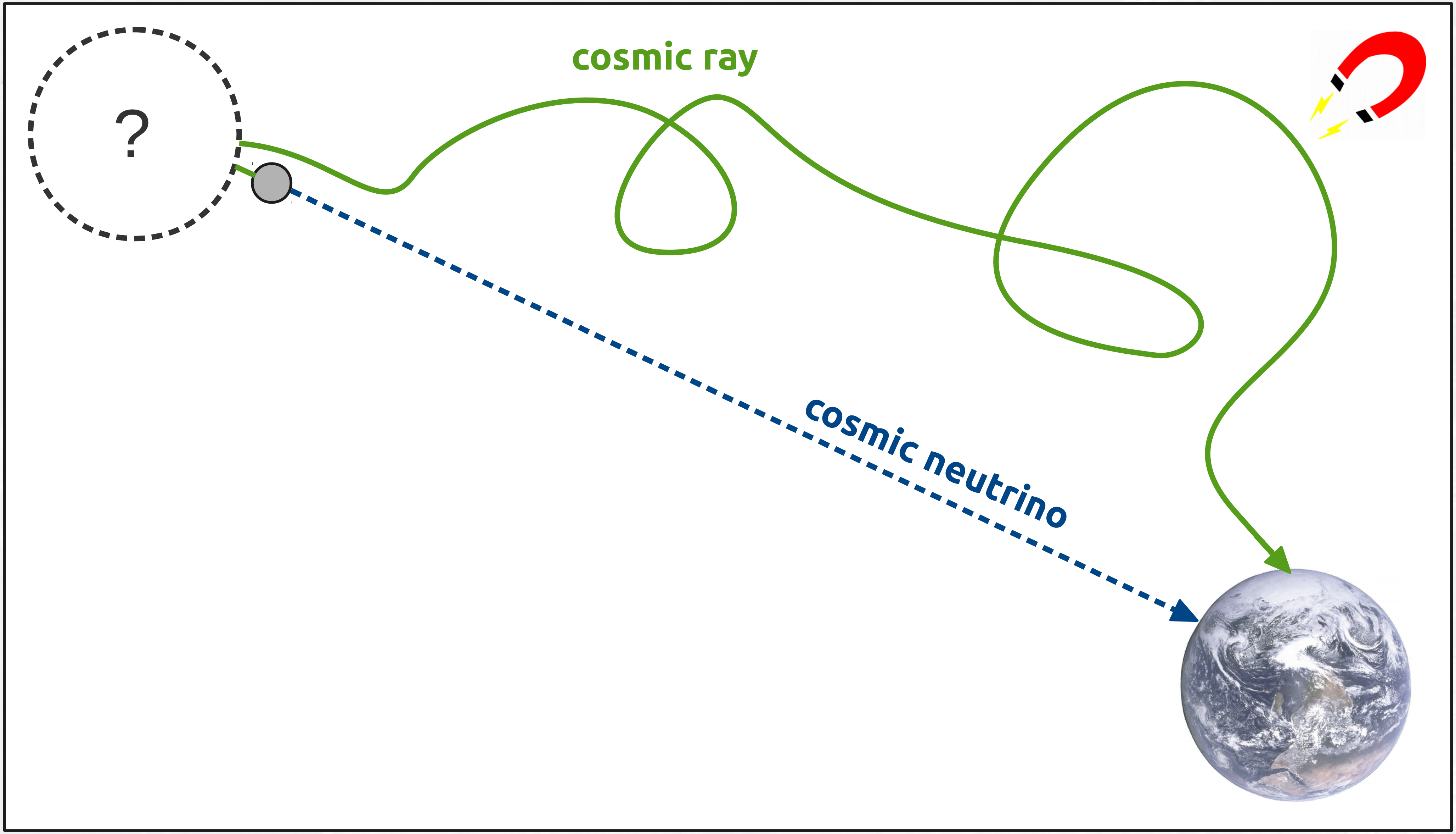
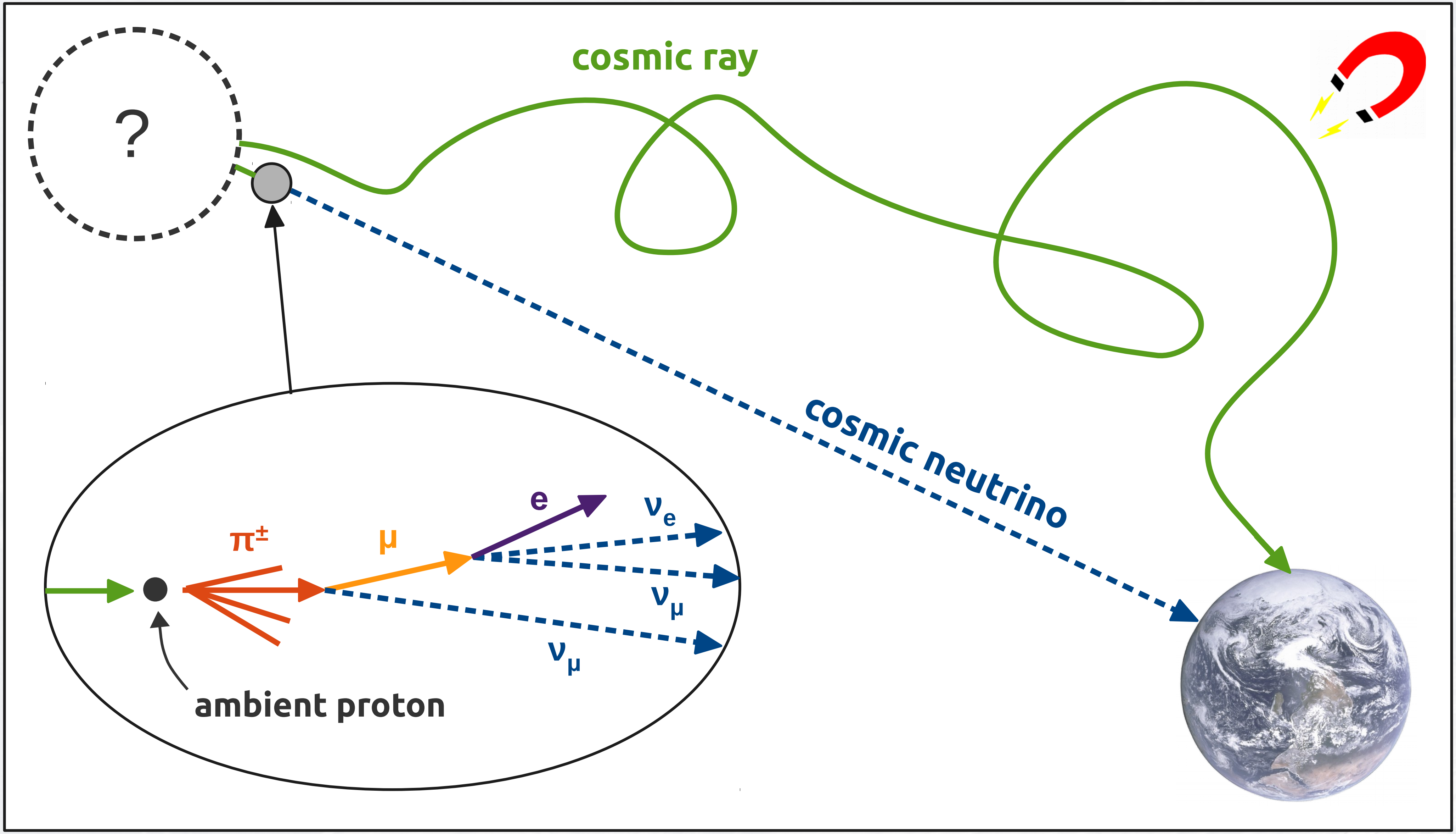


→ **Cosmic neutrinos can reveal cosmic-ray acceleration sites!**

Neutrinos and Cosmic Rays



→ Cosmic neutrinos can reveal cosmic-ray acceleration sites!

Expectations for the Energy Spectrum

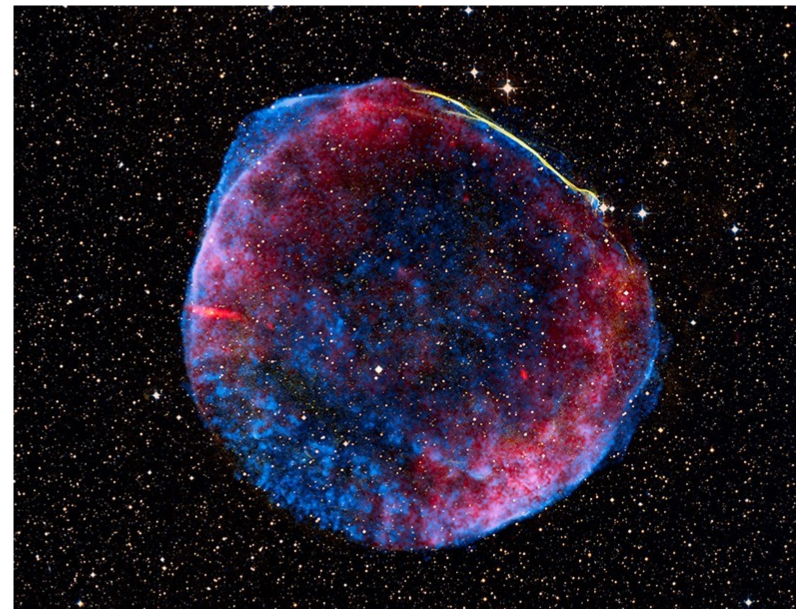
Strongly depends on source properties!

General arguments:

- Fermi shock acceleration
  → cosmic-ray spectrum ~ E^{-2}

- pp- interactions, no energy losses, …
  → neutrino spectrum ~ E^{-2}

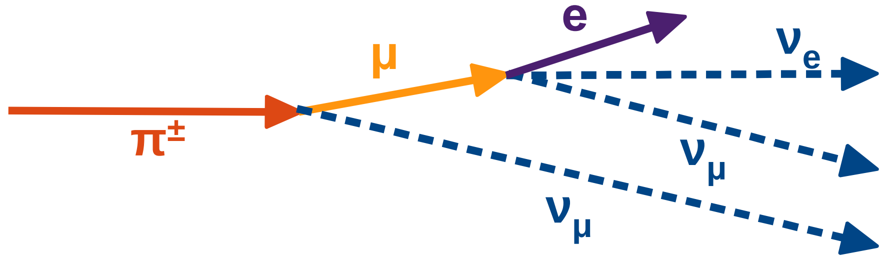
- Expect distortions from:
  → pγ-interactions
  → muon energy losses
  → muon acceleration
  → …



Benchmark: $\Phi_\nu \sim E^{-2}$

Expectations for the Flavor Composition

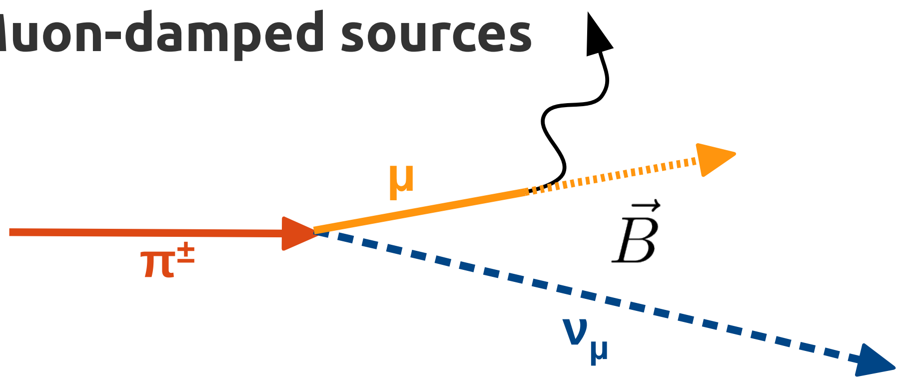
Pion-decay sources



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

→ "standard scenario"

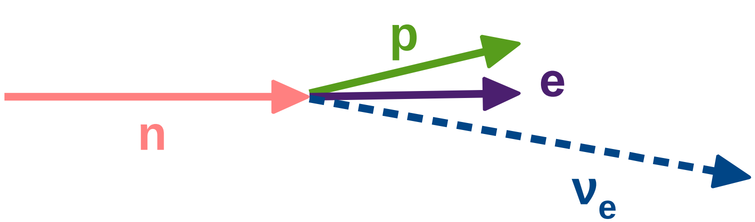
Muon-damped sources



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

→ strong magnetic fields

Neutron-beam sources



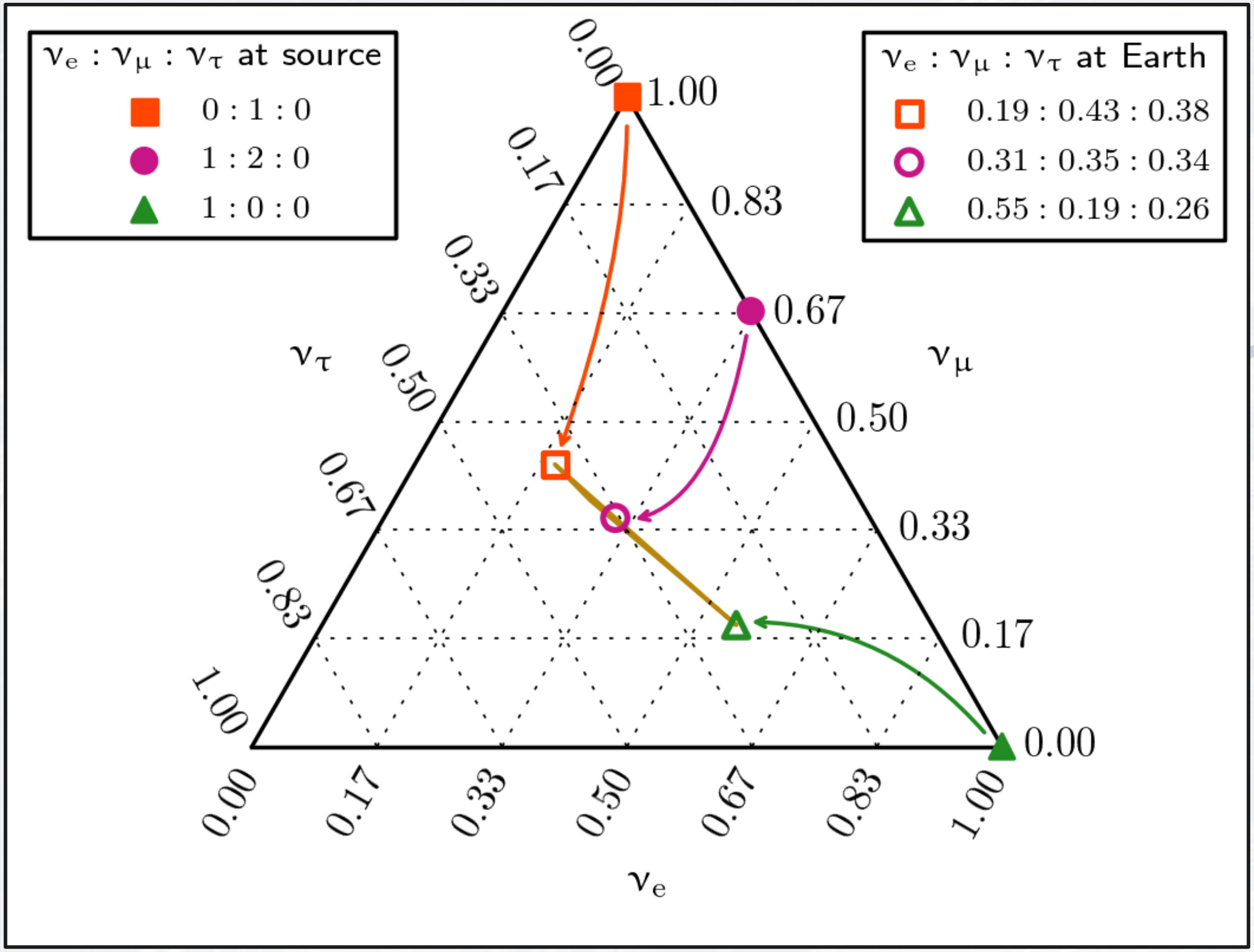
→ $\nu_e : \nu_\mu : \nu_\tau = 1 : 0 : 0$

→ very strong magnetic fields

→ cosmic rays are heavy nuclei

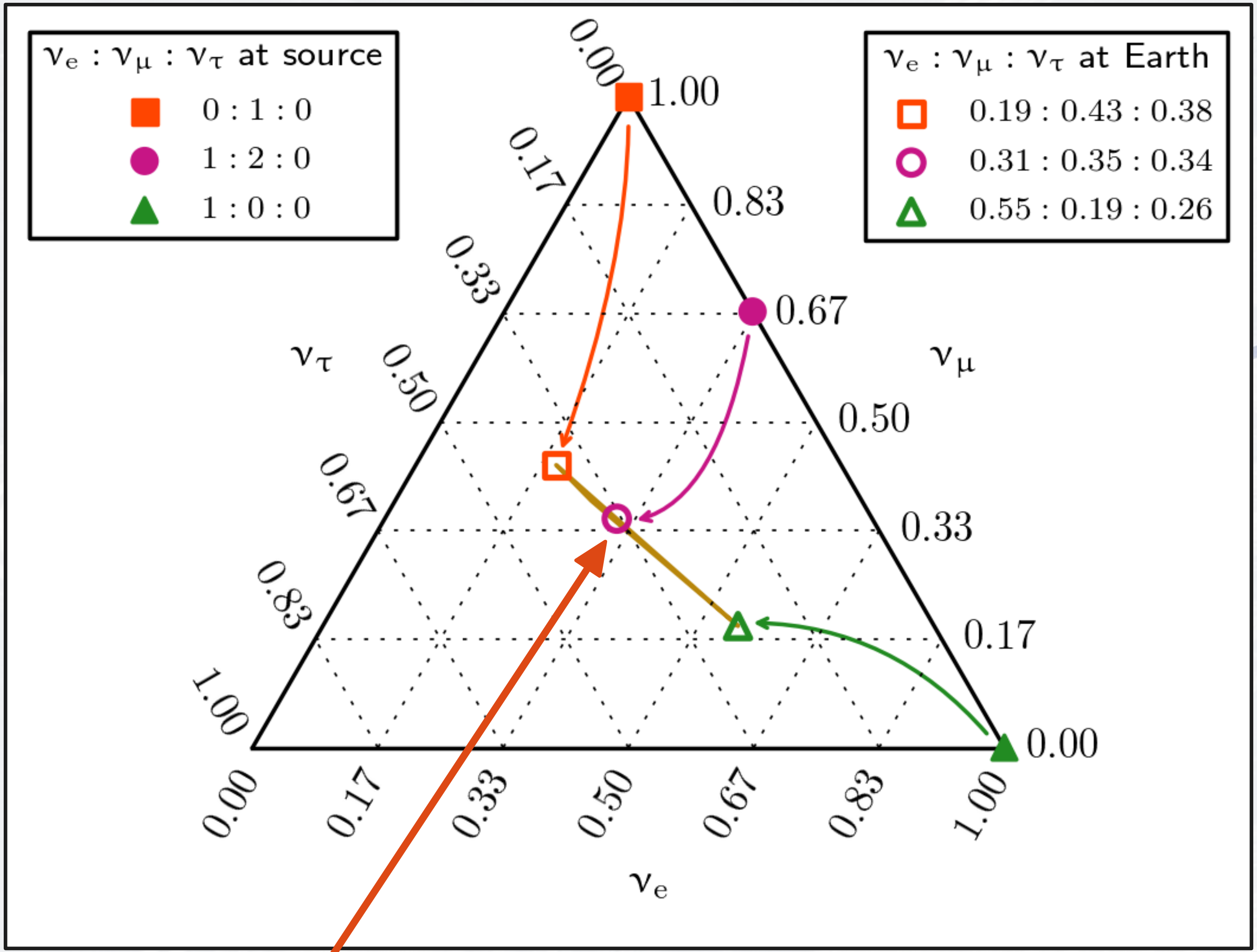
Expectations for the Flavor Composition

Flavor composition modified by long-baseline neutrino oscillations



Expectations for the Flavor Composition

Flavor composition modified by long-baseline neutrino oscillations

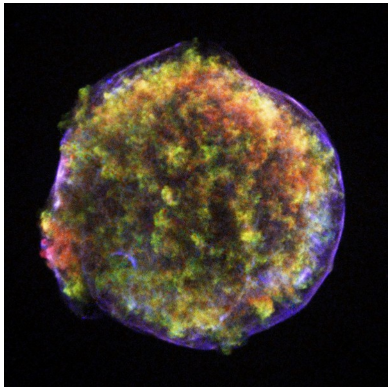
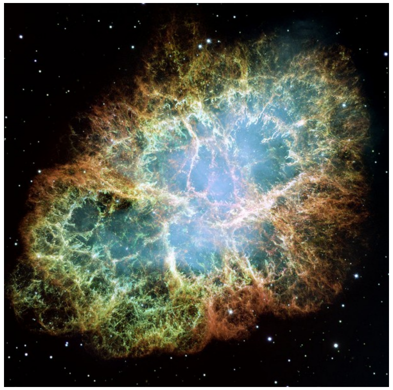


Standard scenario: $\nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 1$ at Earth

Source Candidates

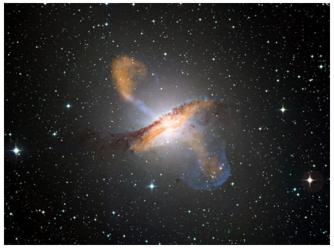
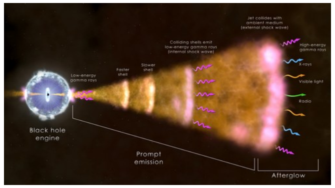
Within the Milky Way

- Supernova remnants
- Pulsar wind nebulae
- …

“Extragalactic”

- Active galactic nuclei
- Gamma-ray bursts
- Starburst galaxies
- Galaxy clusters
- …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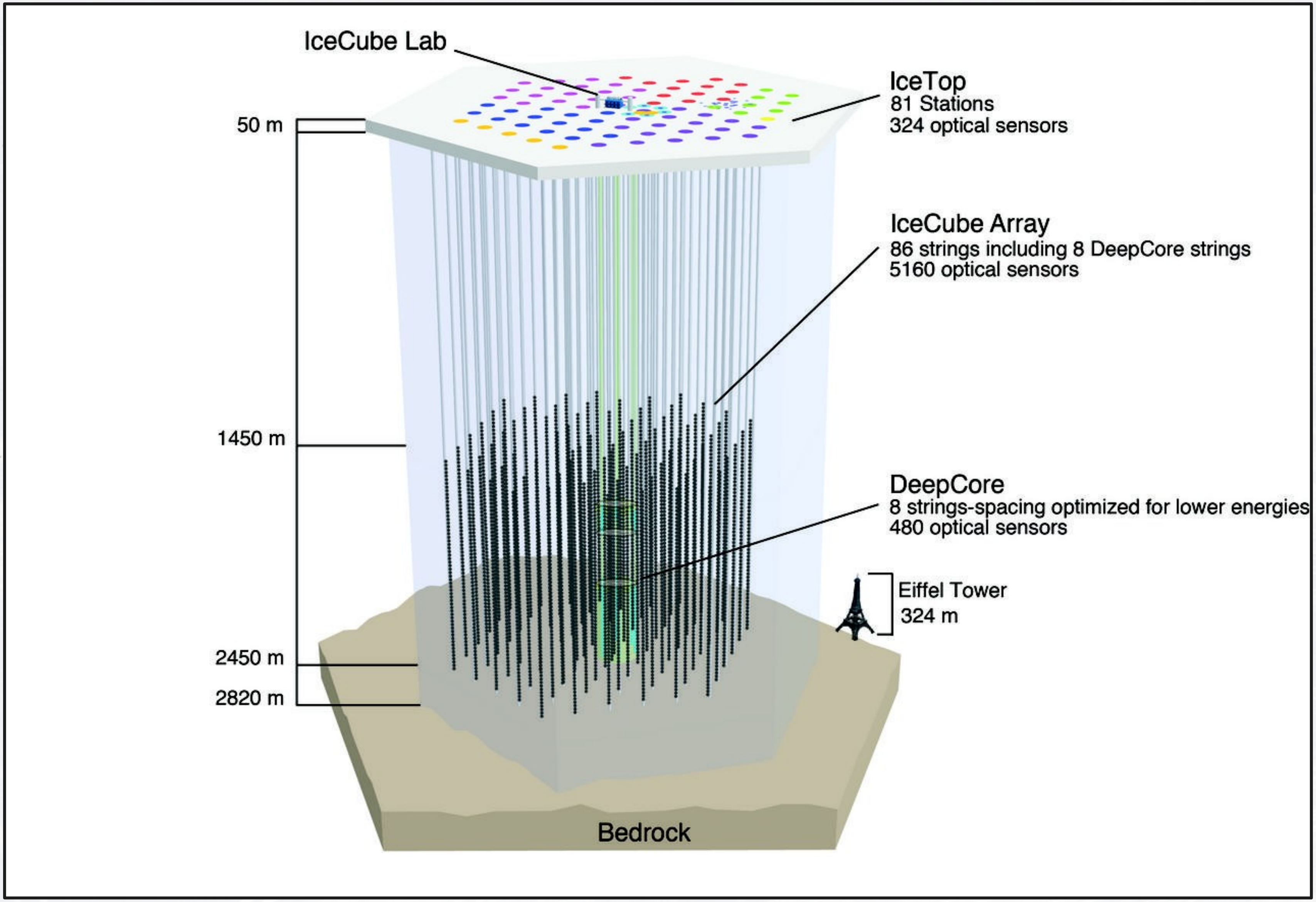
The IceCube Neutrino Observatory



Detection principle: Observe Cherenkov radiation from secondary particles produced in neutrino interactions

Neutrino Event Signatures

Throughgoing track

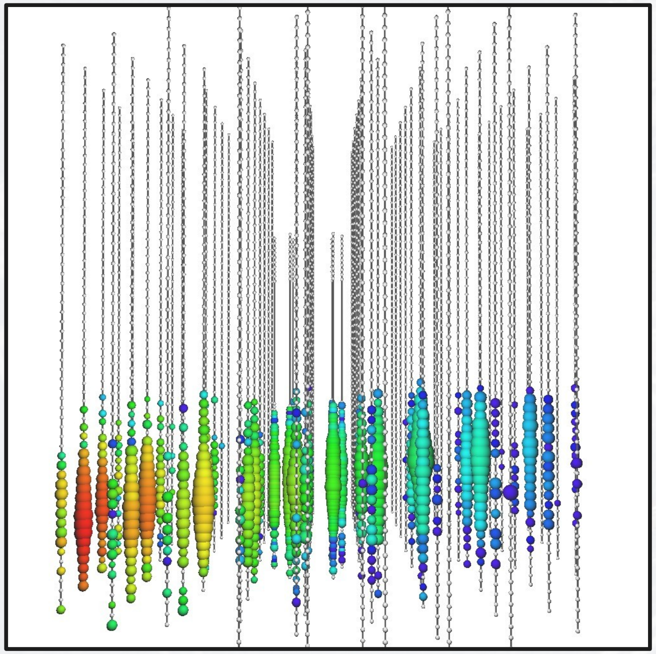
→ ν_μ charged-current interaction outside instrumented volume

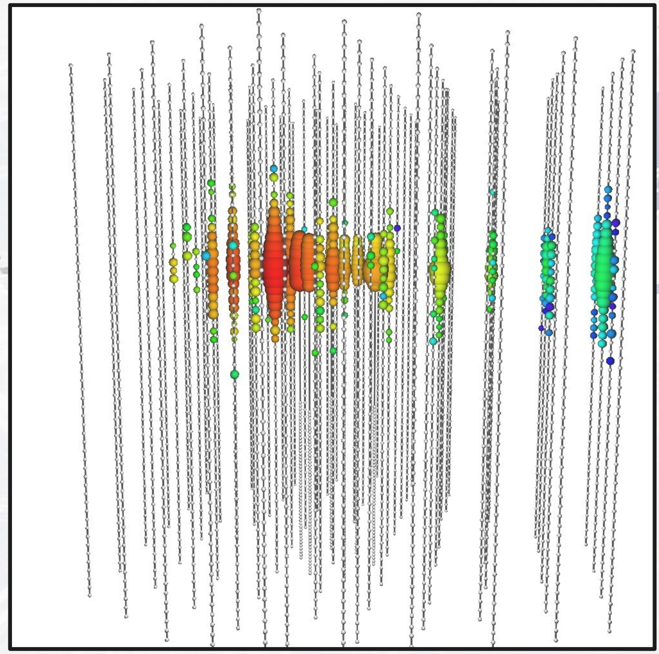
Starting track

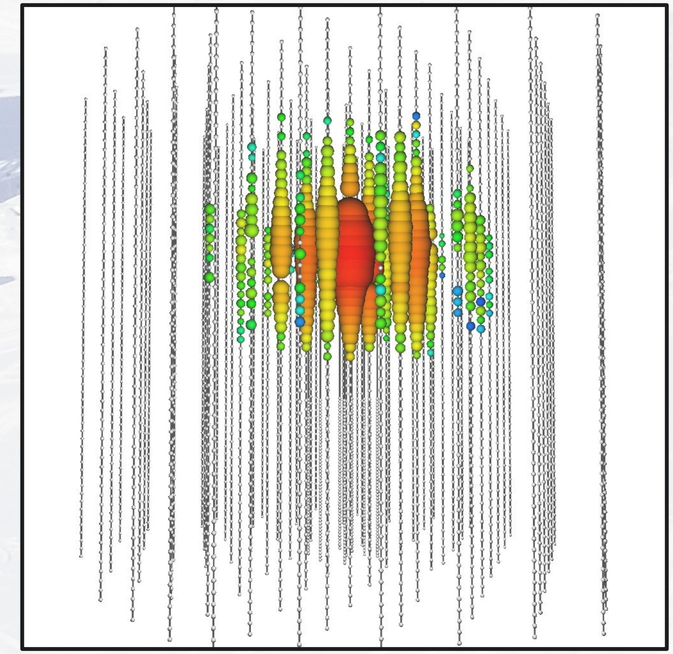
→ ν_μ charged-current interaction inside instrumented volume

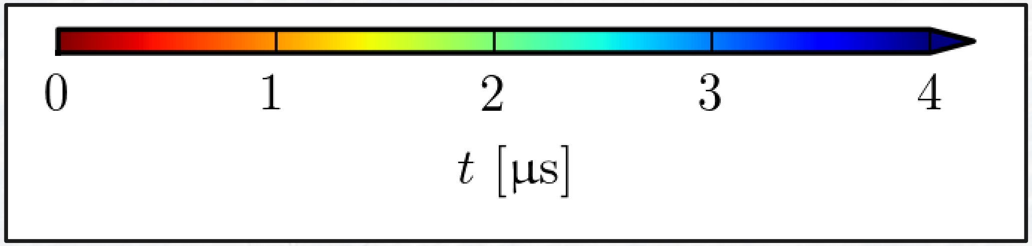
Shower

→ Any other interaction inside instrumented volume









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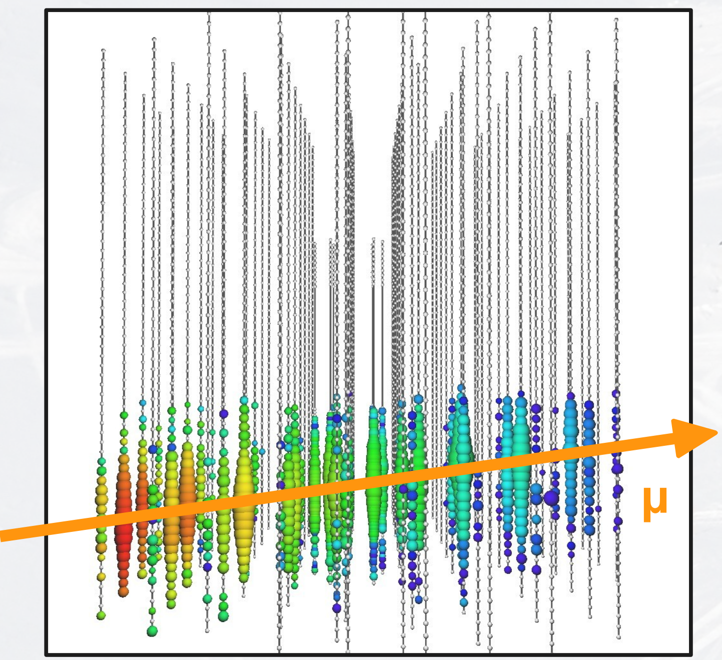

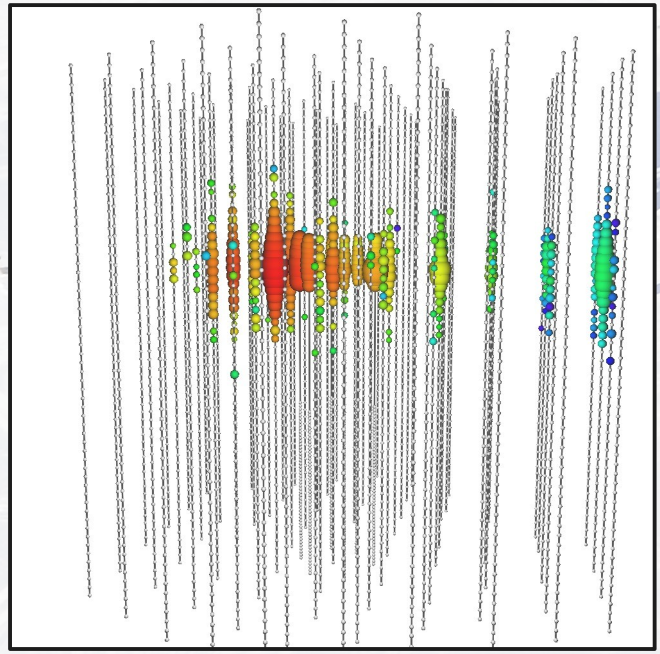

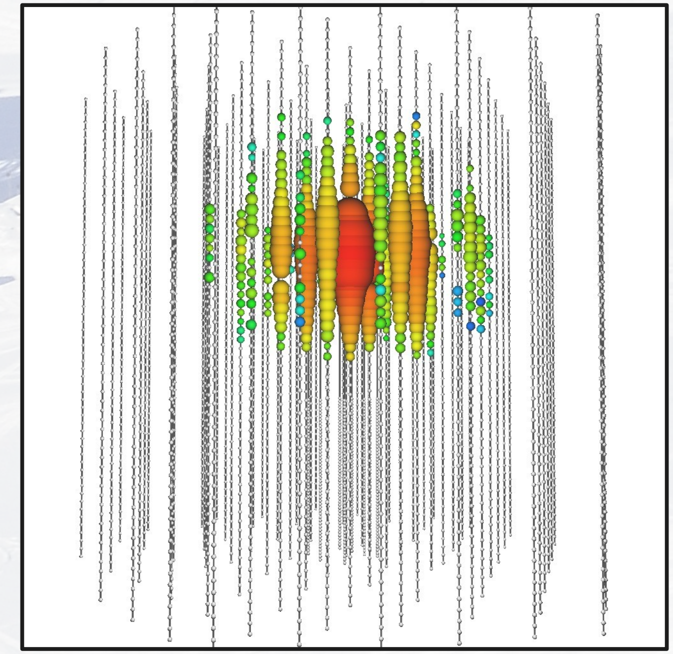

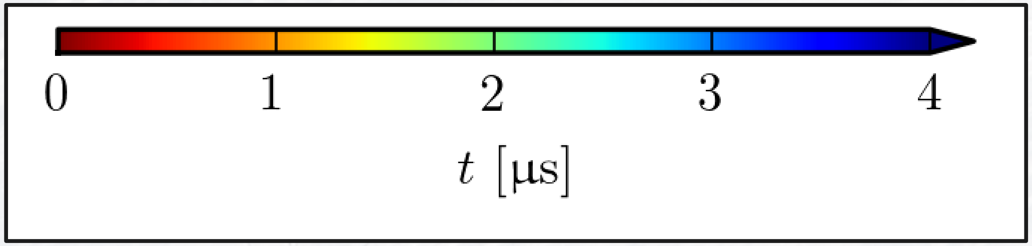

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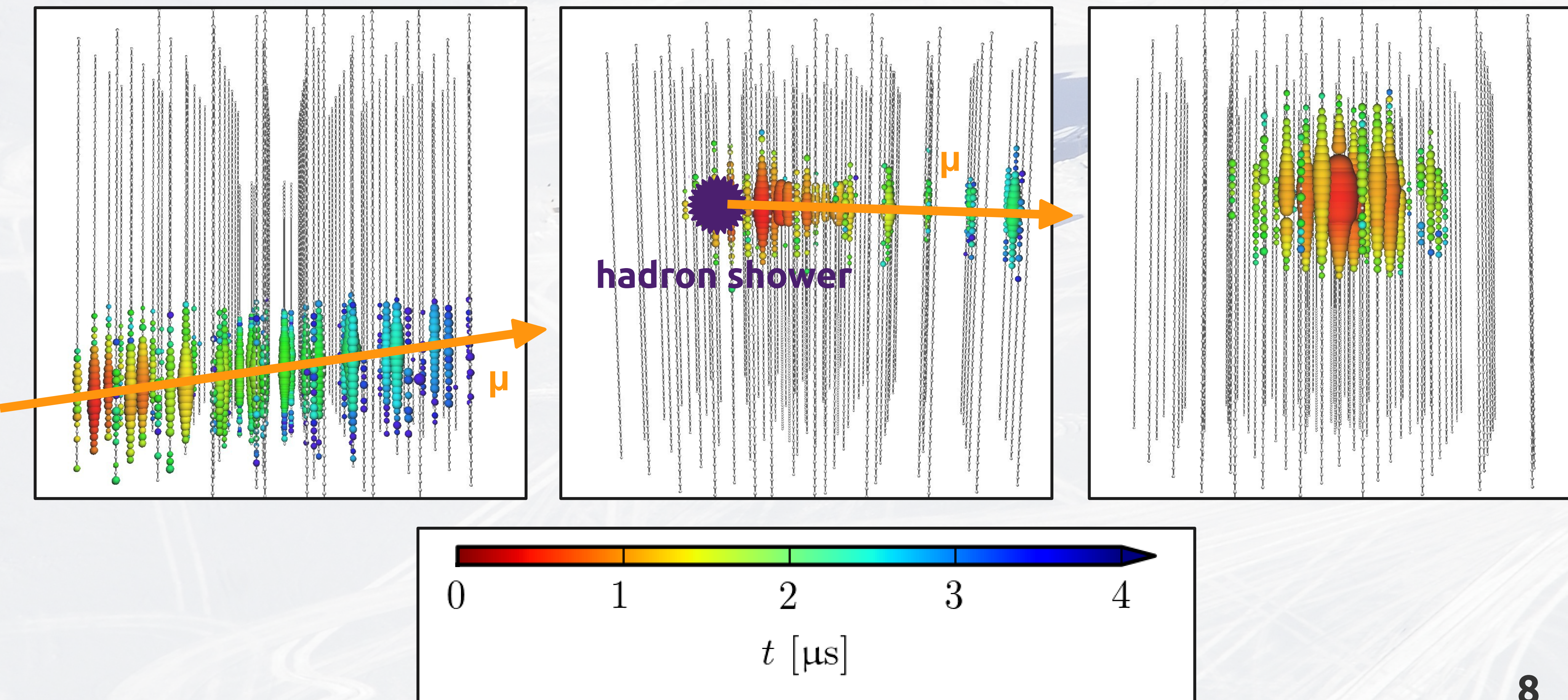

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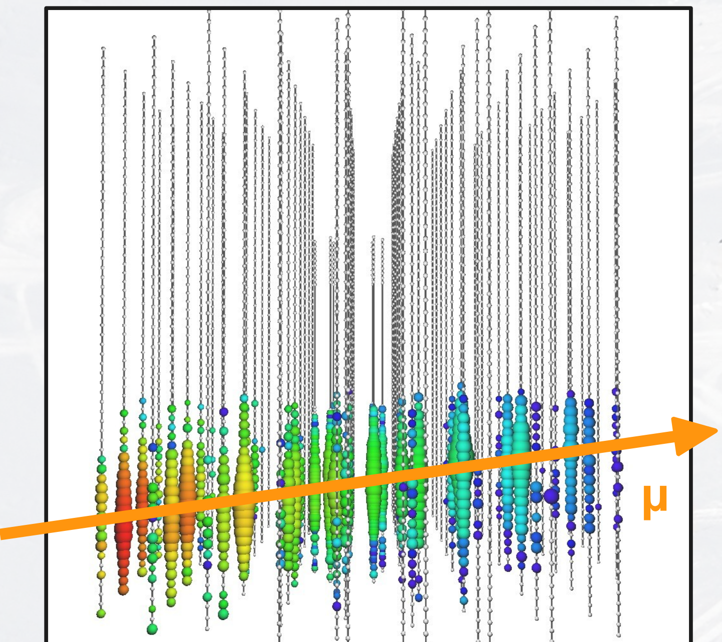

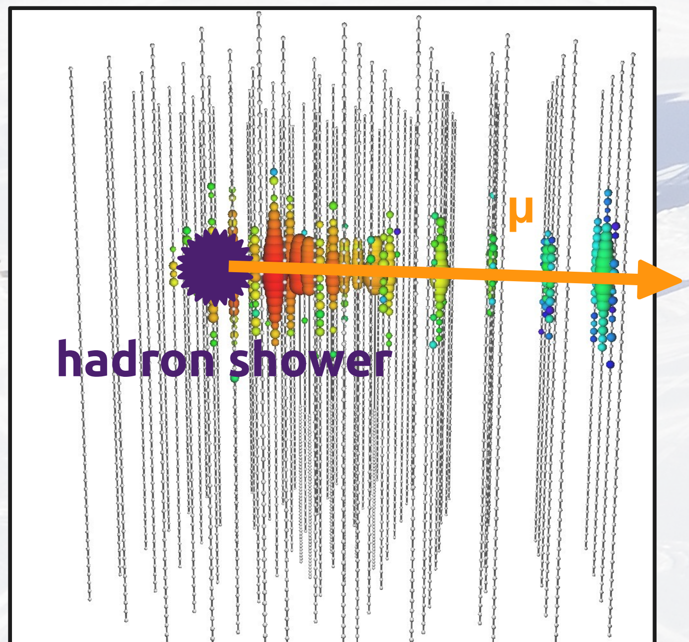

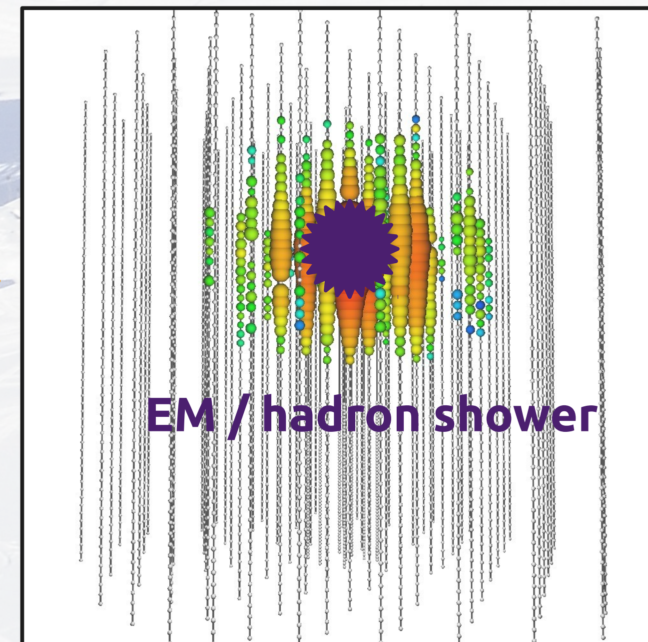

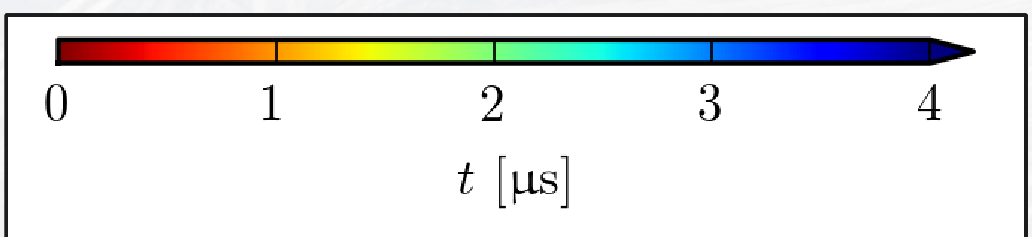

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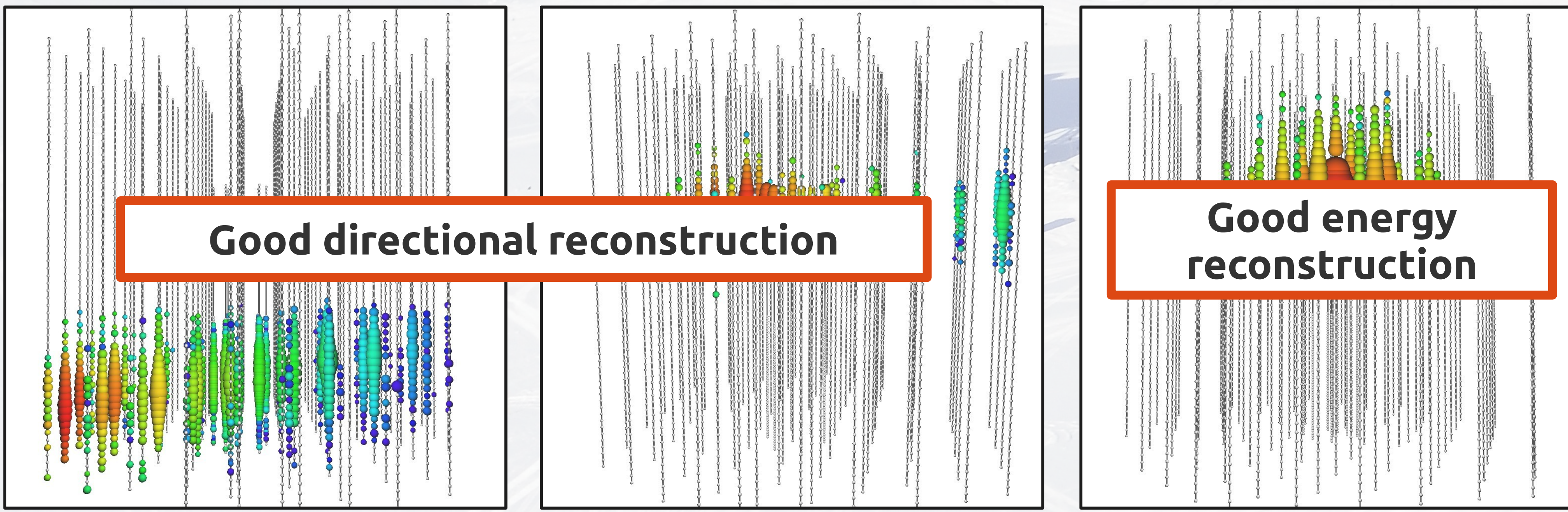
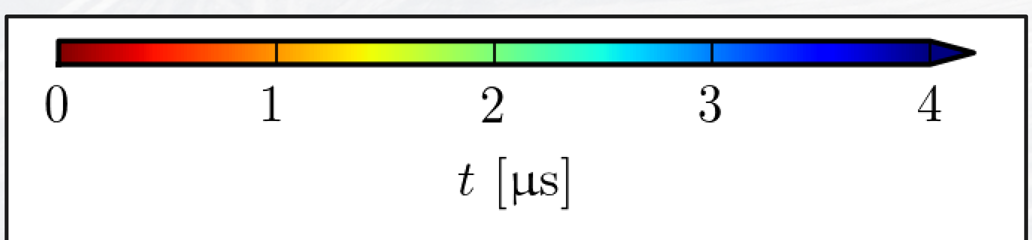
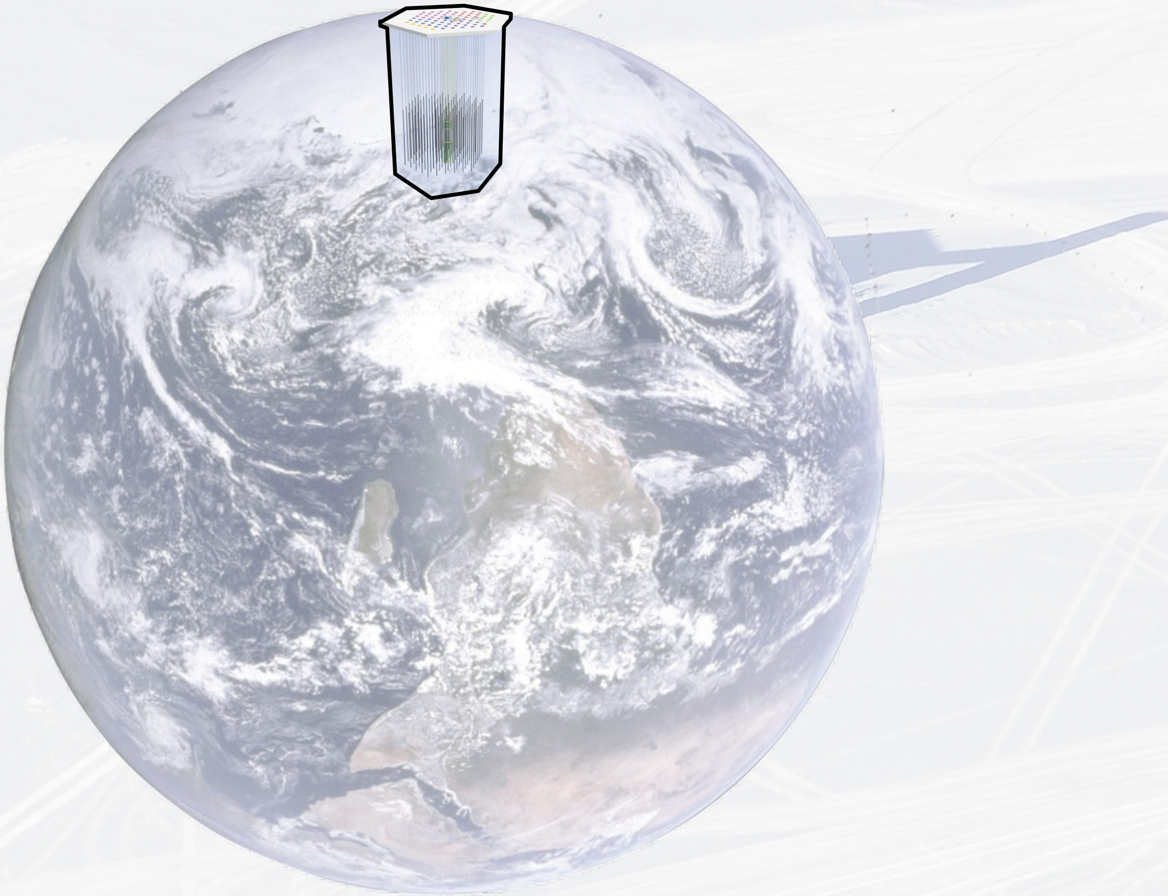




Atmospheric Backgrounds and Cosmic Signal



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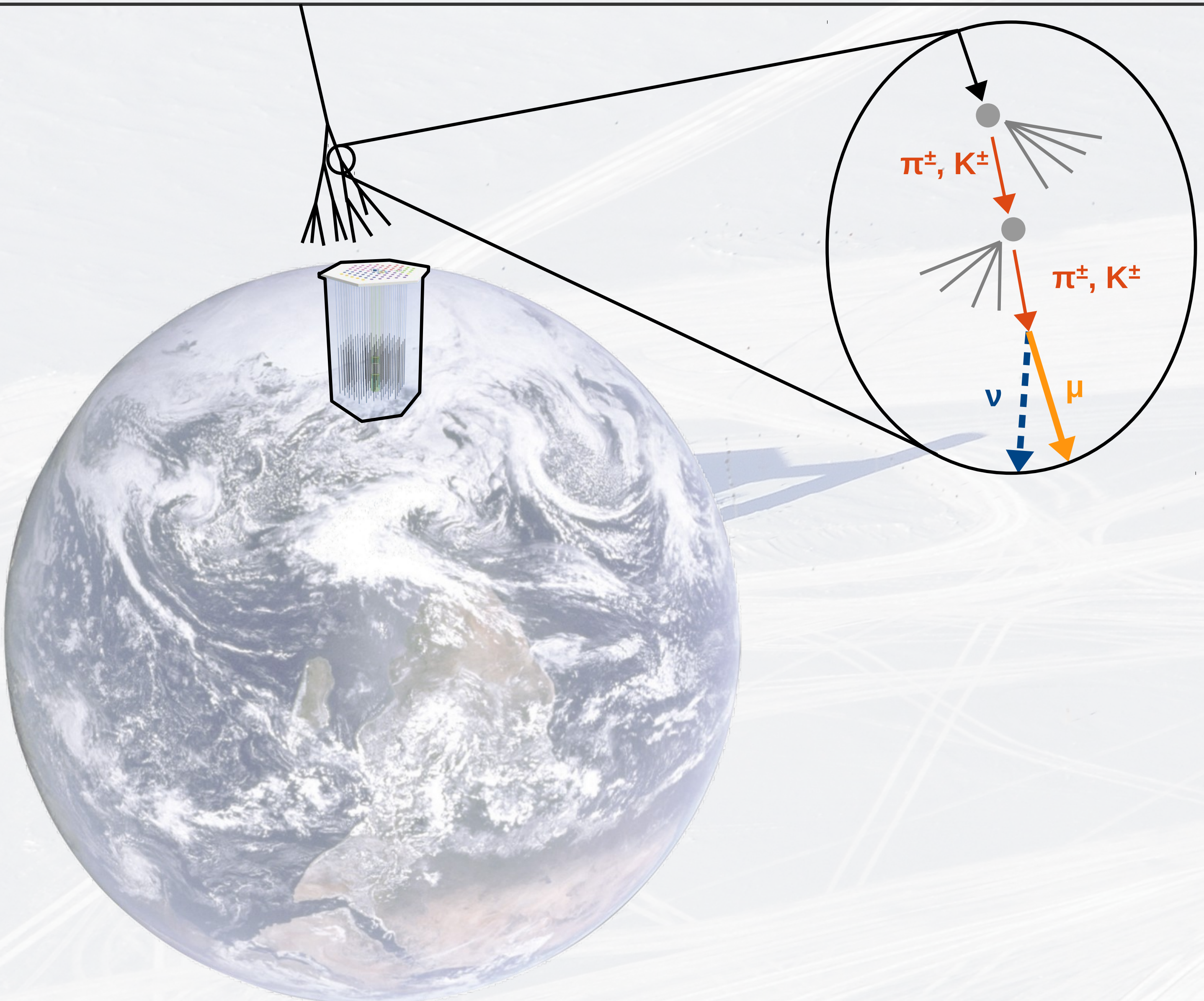
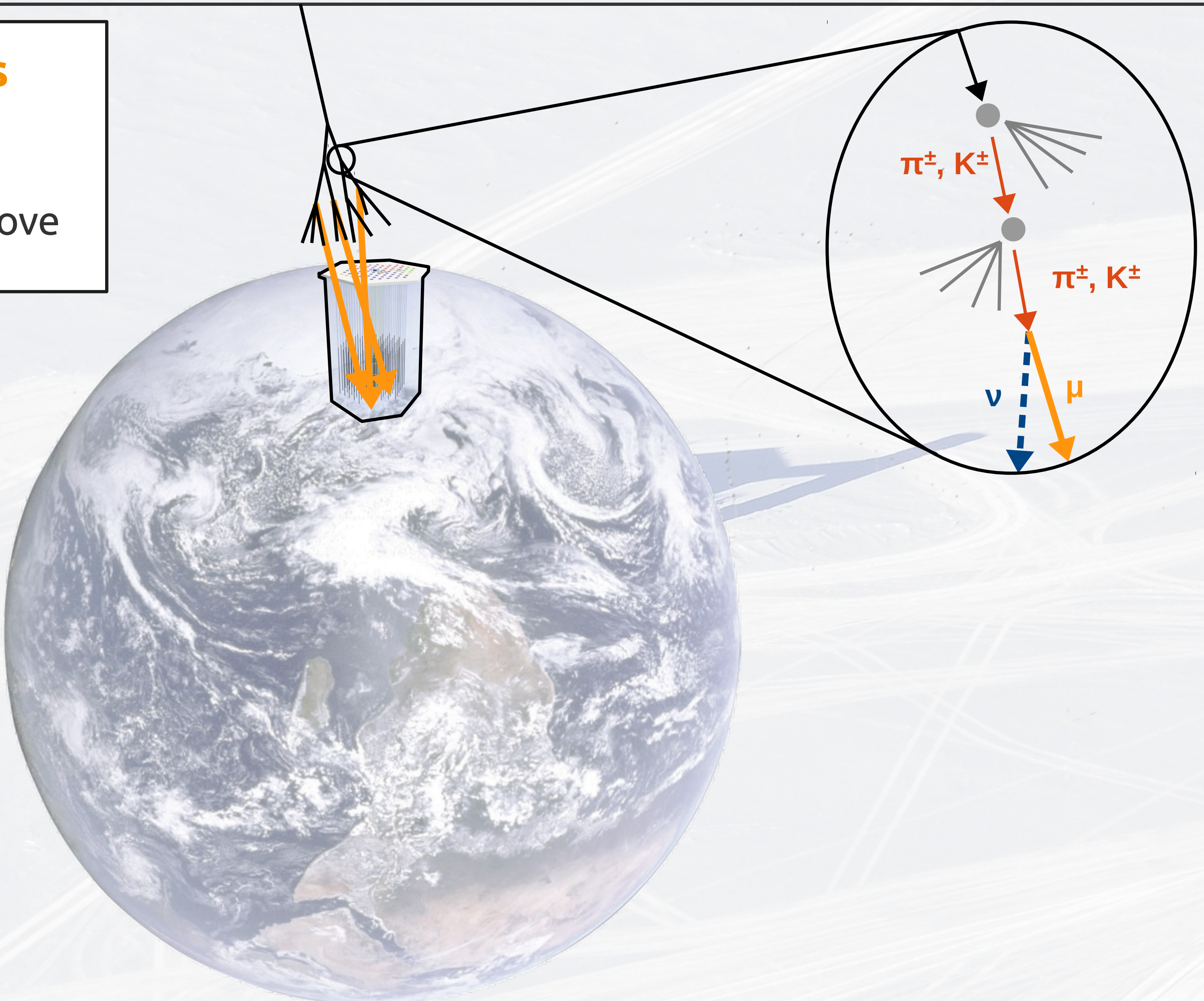


Atmospheric Backgrounds and Cosmic Signal

Atmospheric muons

- ~ 250 million / day
- Track-like, from above



Atmospheric Backgrounds and Cosmic Signal

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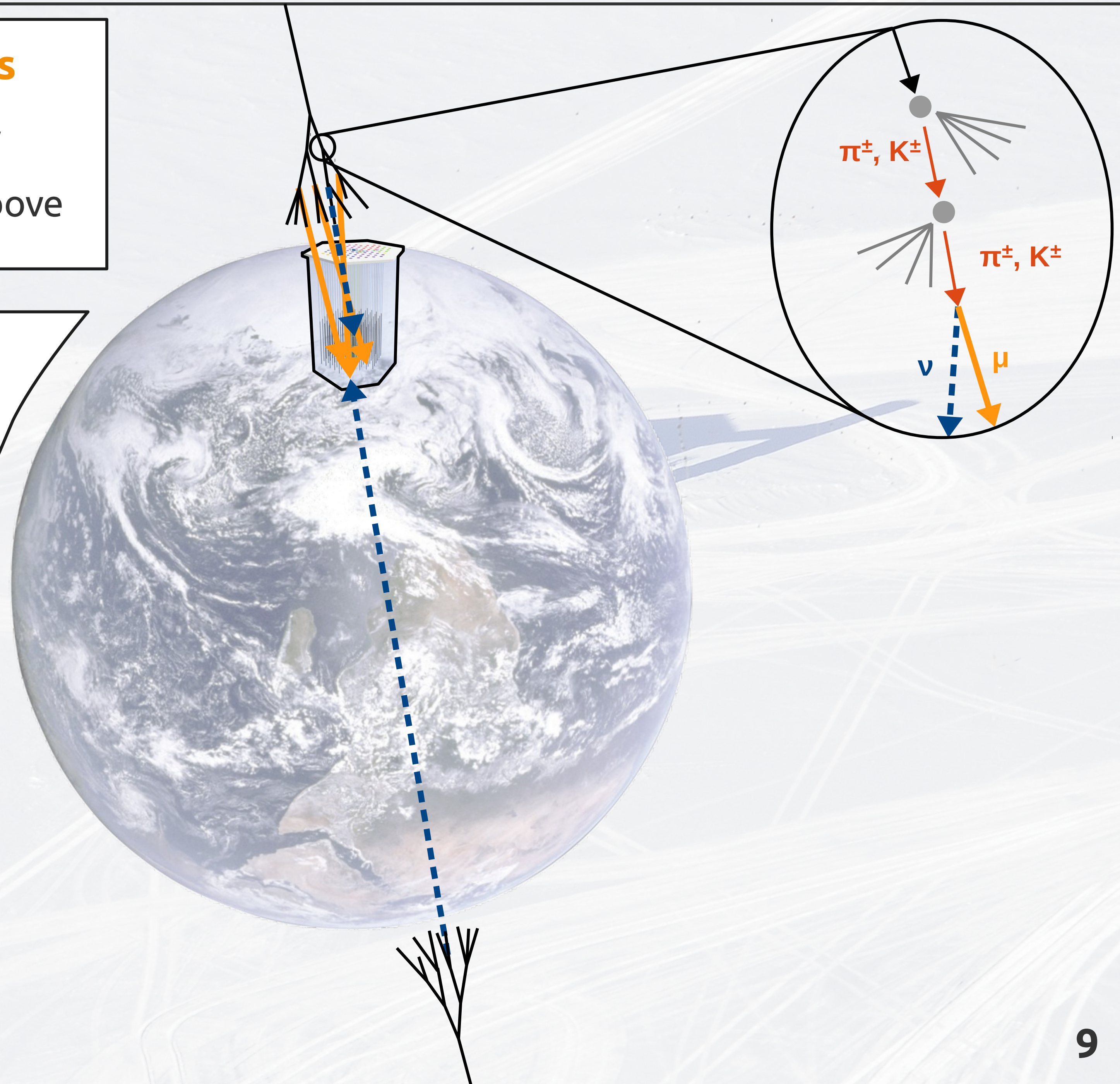
Conventional atmospheric neutrinos

- ~ few 100 / day
- Low-energy



Atmospheric Backgrounds and Cosmic Signal

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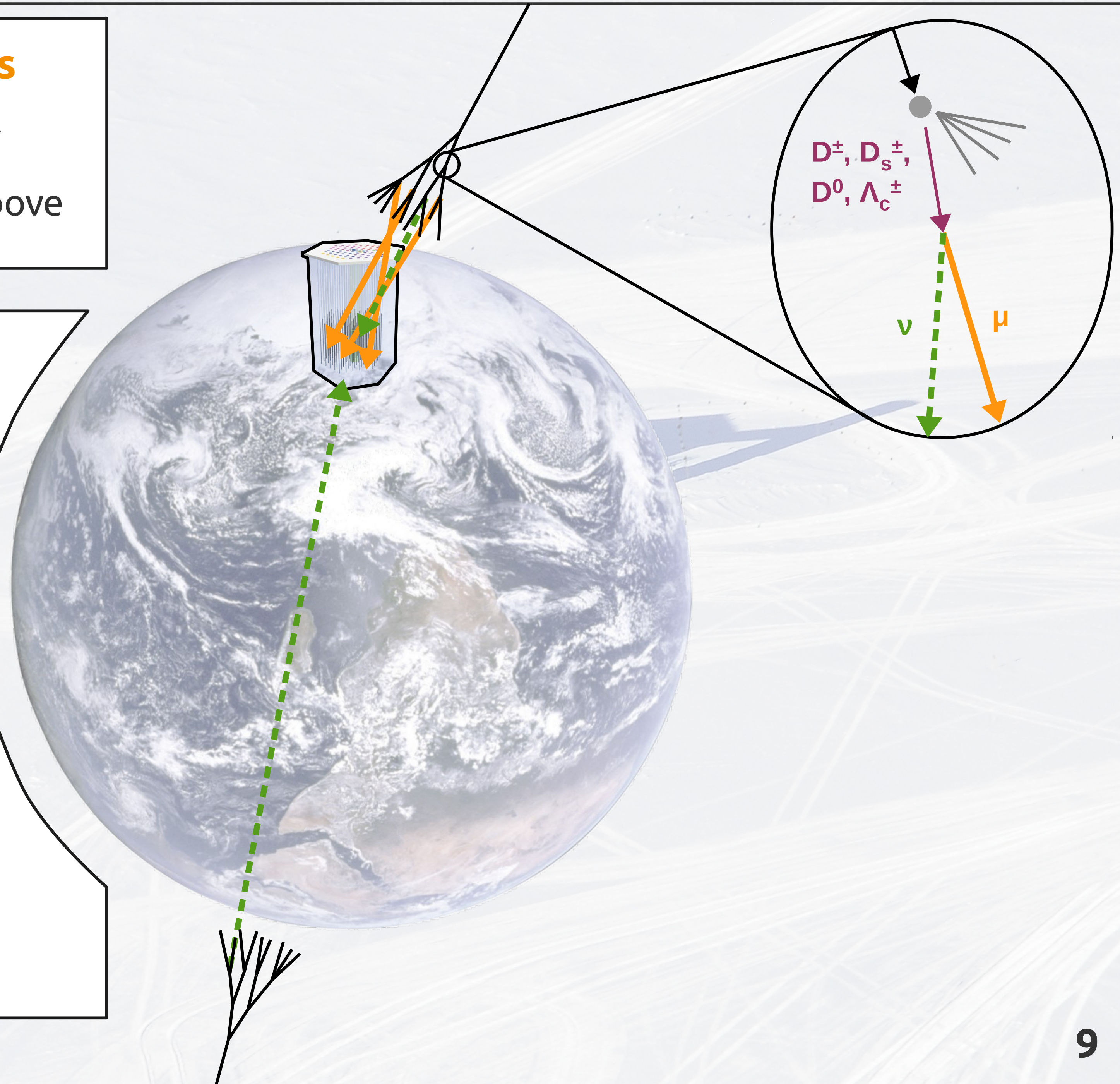
Prompt atmospheric neutrinos

- ~ few / day
- Higher-energy



Atmospheric Backgrounds and Cosmic Signal

Atmospheric muons

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Conventional atmospheric neutrinos

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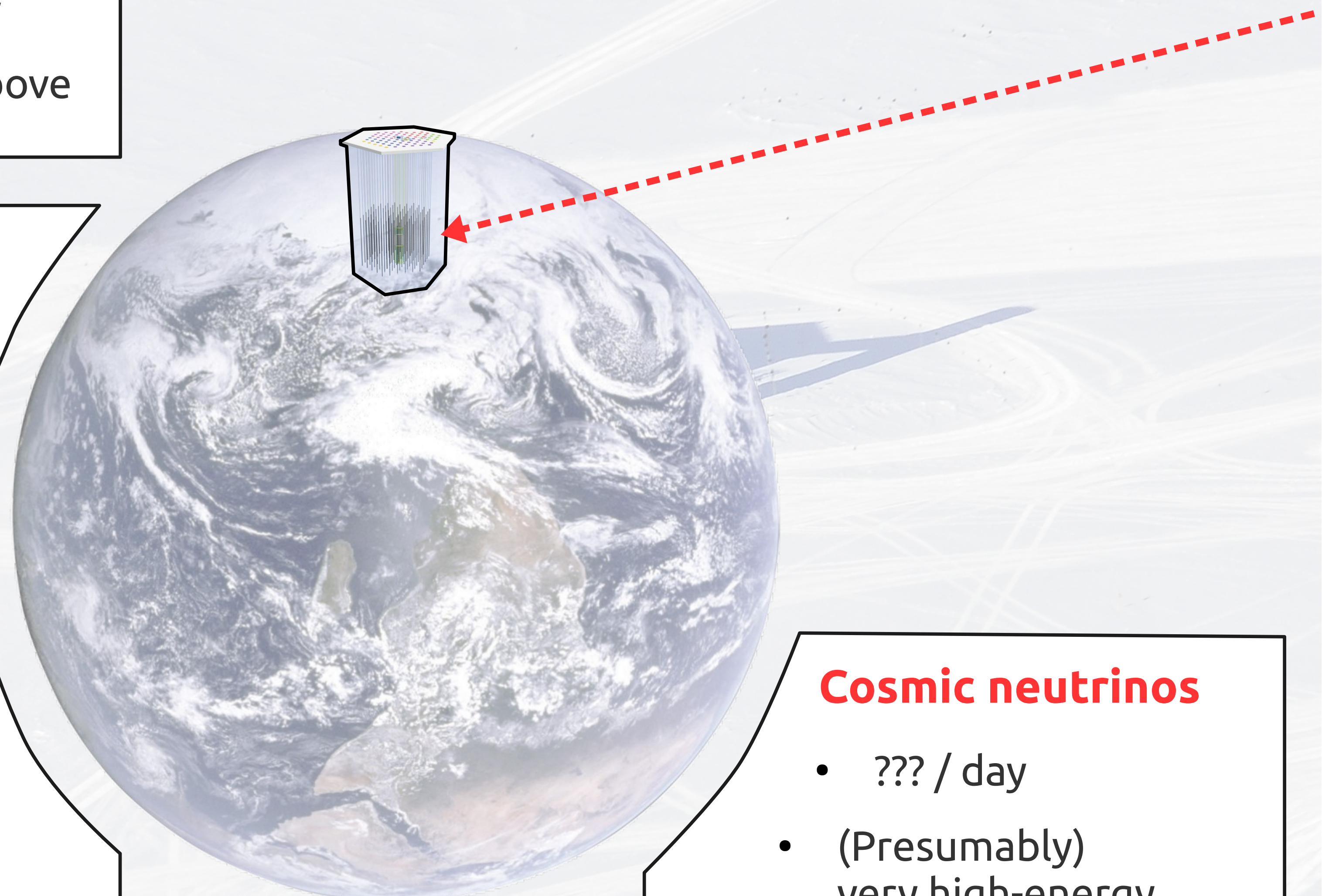


Prompt atmospheric neutrinos

- ~ few / day
- Higher-energy

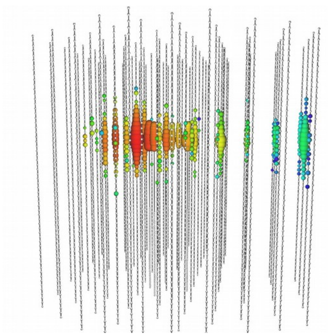
Cosmic neutrinos

- ??? / day
- (Presumably) very high-energy

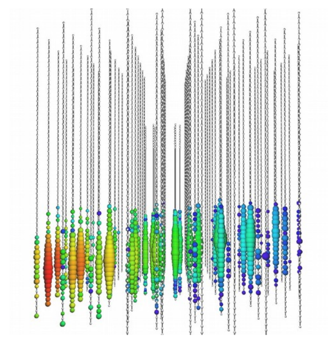
Event Selection Techniques

1) Select upgoing / horizontal track events

- \+ Active volume >> detector
- \+ Negligible muon background



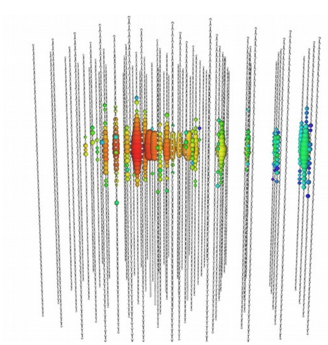
\+



- – ν_μ charged-current interactions
- – Northern Hemisphere
- – Cannot suppress atmos. neutrinos

2) Select starting events

- – Active volume ≤ detector
- – Residual muon background



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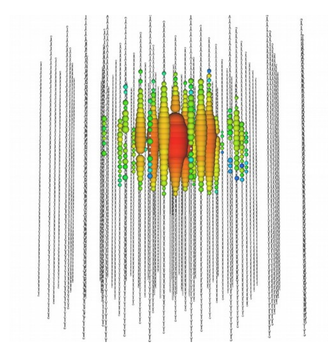

- \+ All neutrino interactions
- \+ Full sky
- \+ Downgoing atmos. neutrinos suppressed

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The Cosmic Neutrino Flux Observed with IceCube

Discovery in 2013

→ Energy range: $10^{13} – 10^{15}$ eV (10 TeV – 1 PeV)

Sources yet unknown

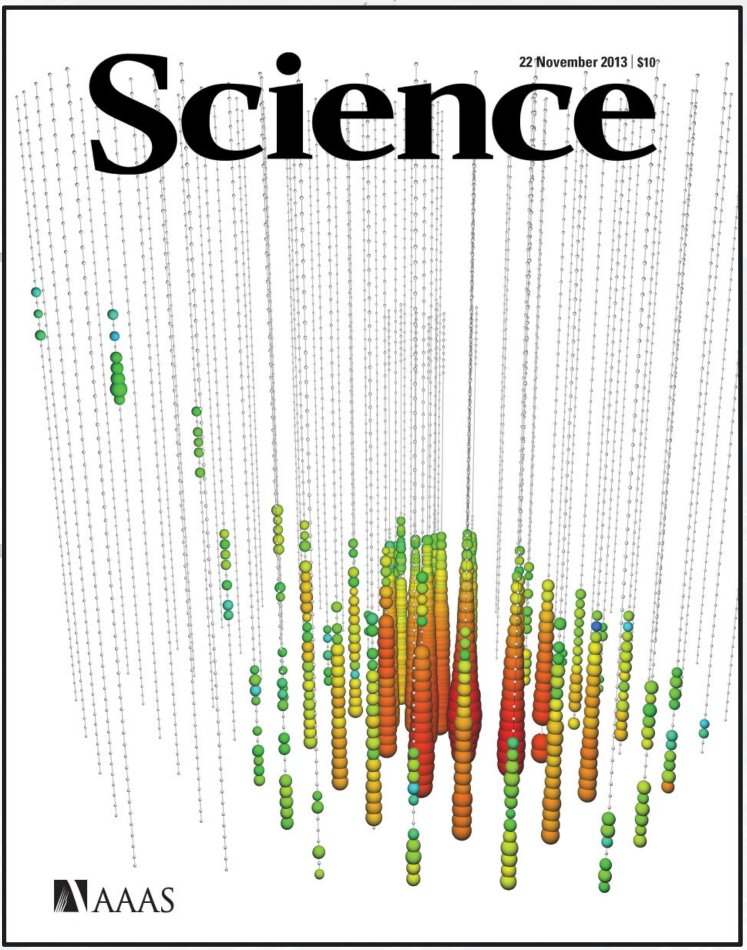
→ arrival directions consistent with isotropy

Measurements of flux properties

→ draw conclusions on source properties

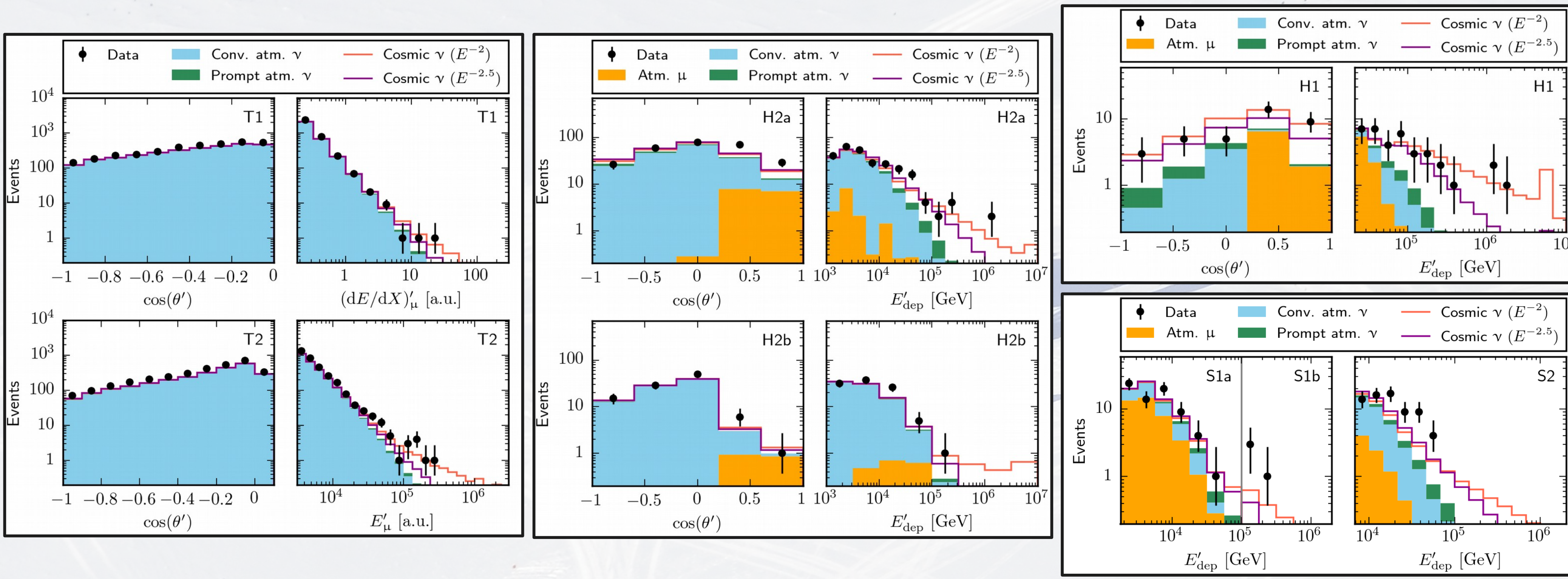
Previously:

→ measurements of specific properties, based on specific event selections



Unique Feature of the Analysis

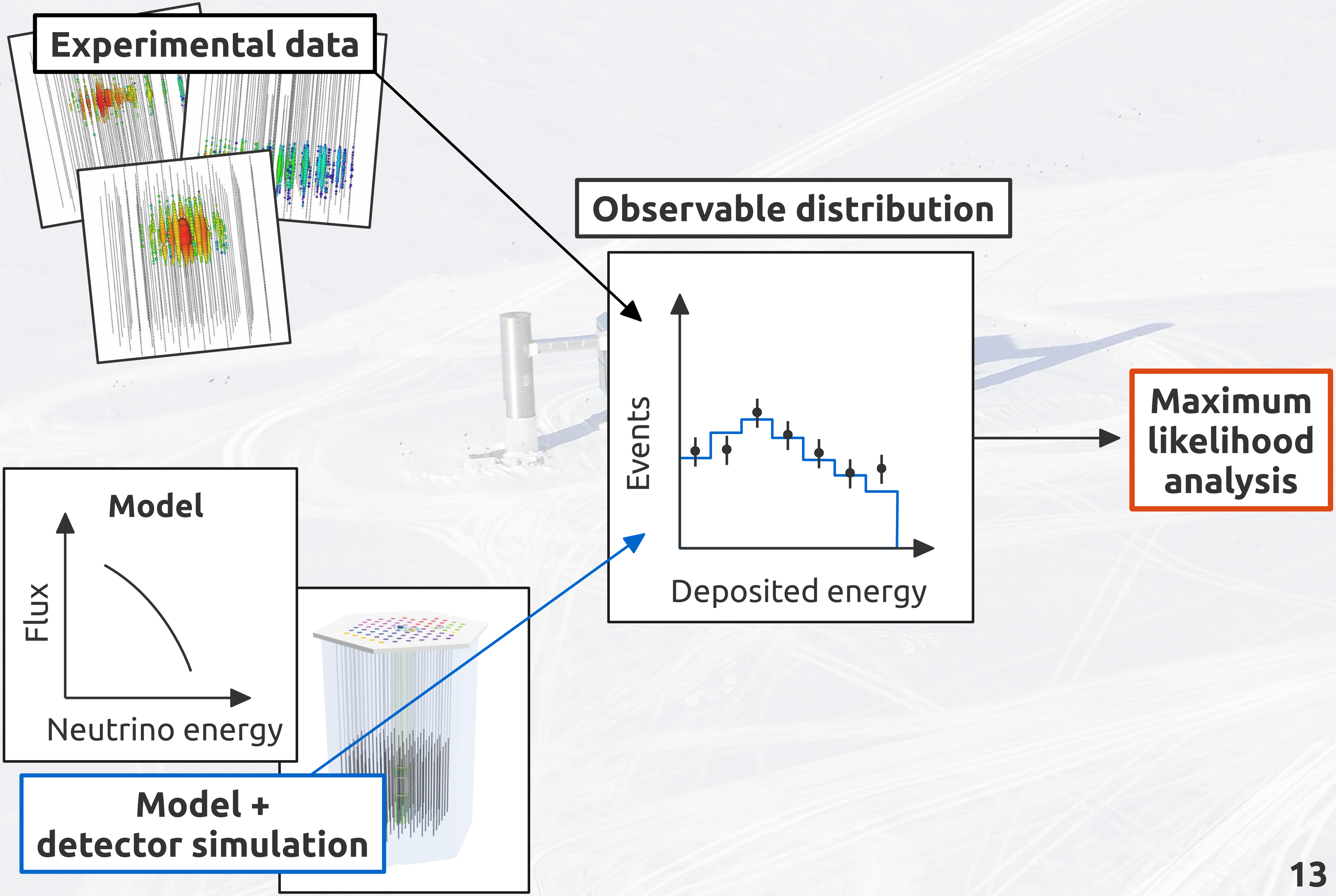
Comprehensive characterization through a combined analysis of data from six different event selections



Key challenges:

- Compile and combine the data
- Develop techniques to treat systematic uncertainties consistently
- Implement, test and apply maximum likelihood fit

Analysis Technique



Background Models

Atmospheric muons

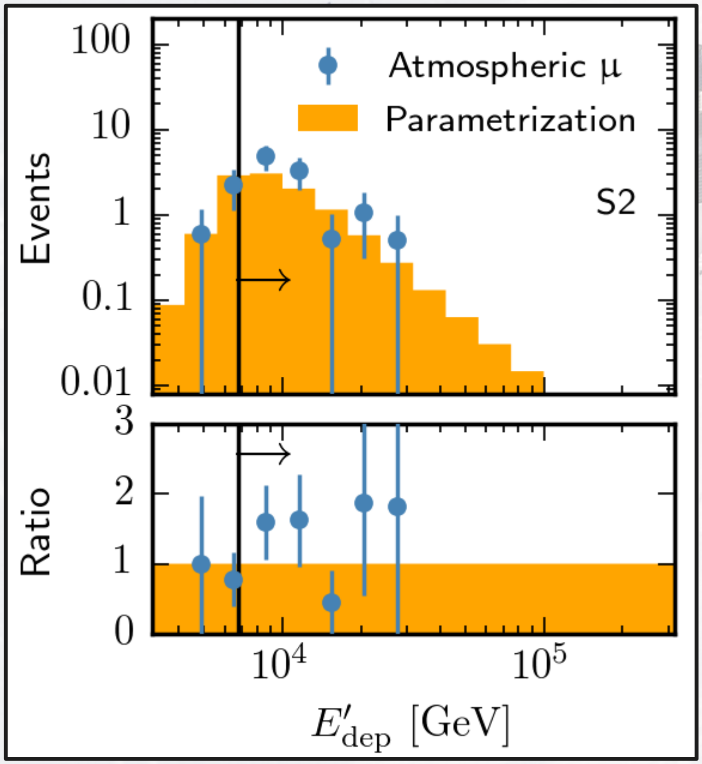
→ Air shower simulations with CORSIKA

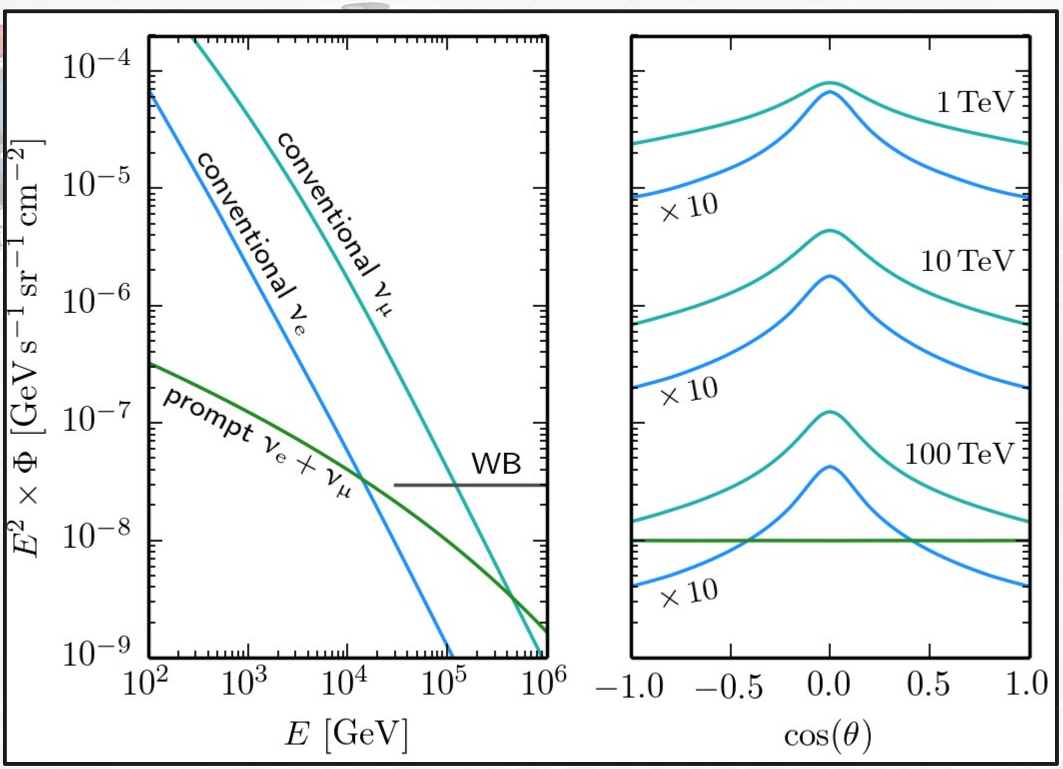
→ Parametrizations at high energies

Atmospheric neutrinos

→ Calculations from literature

→ Apply detector-related corrections





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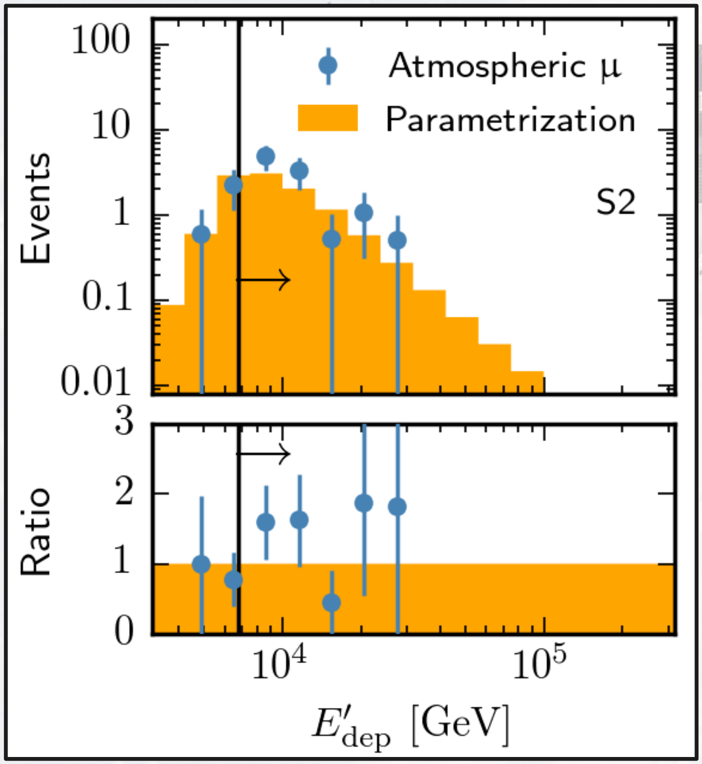
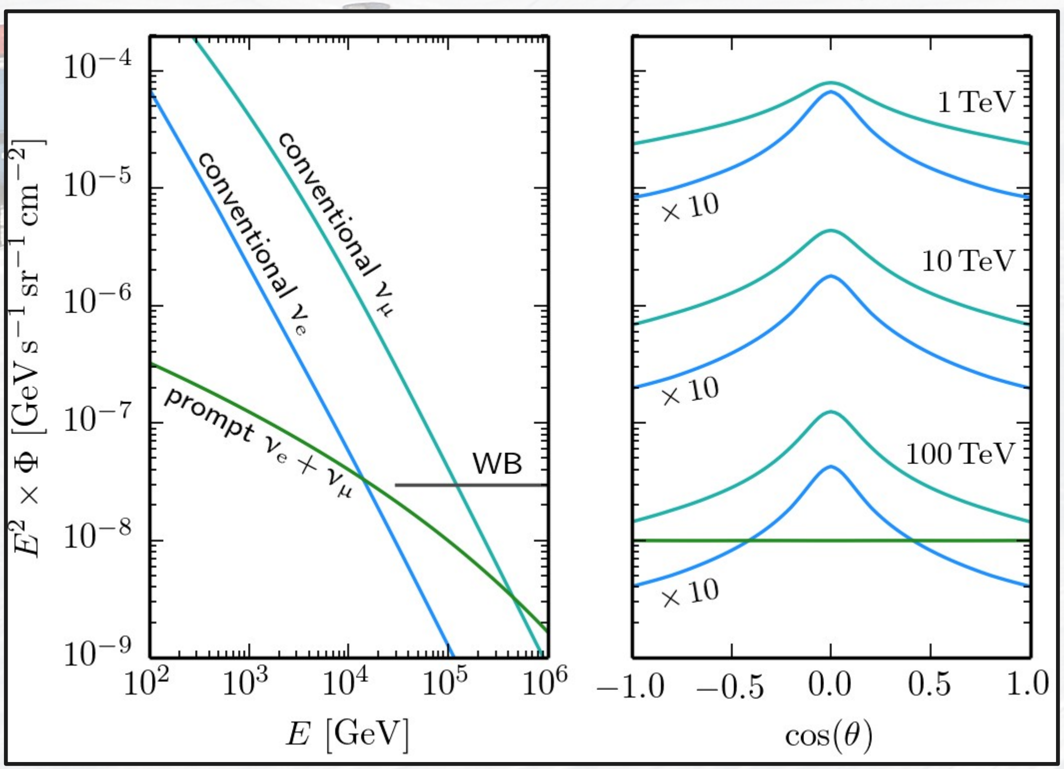
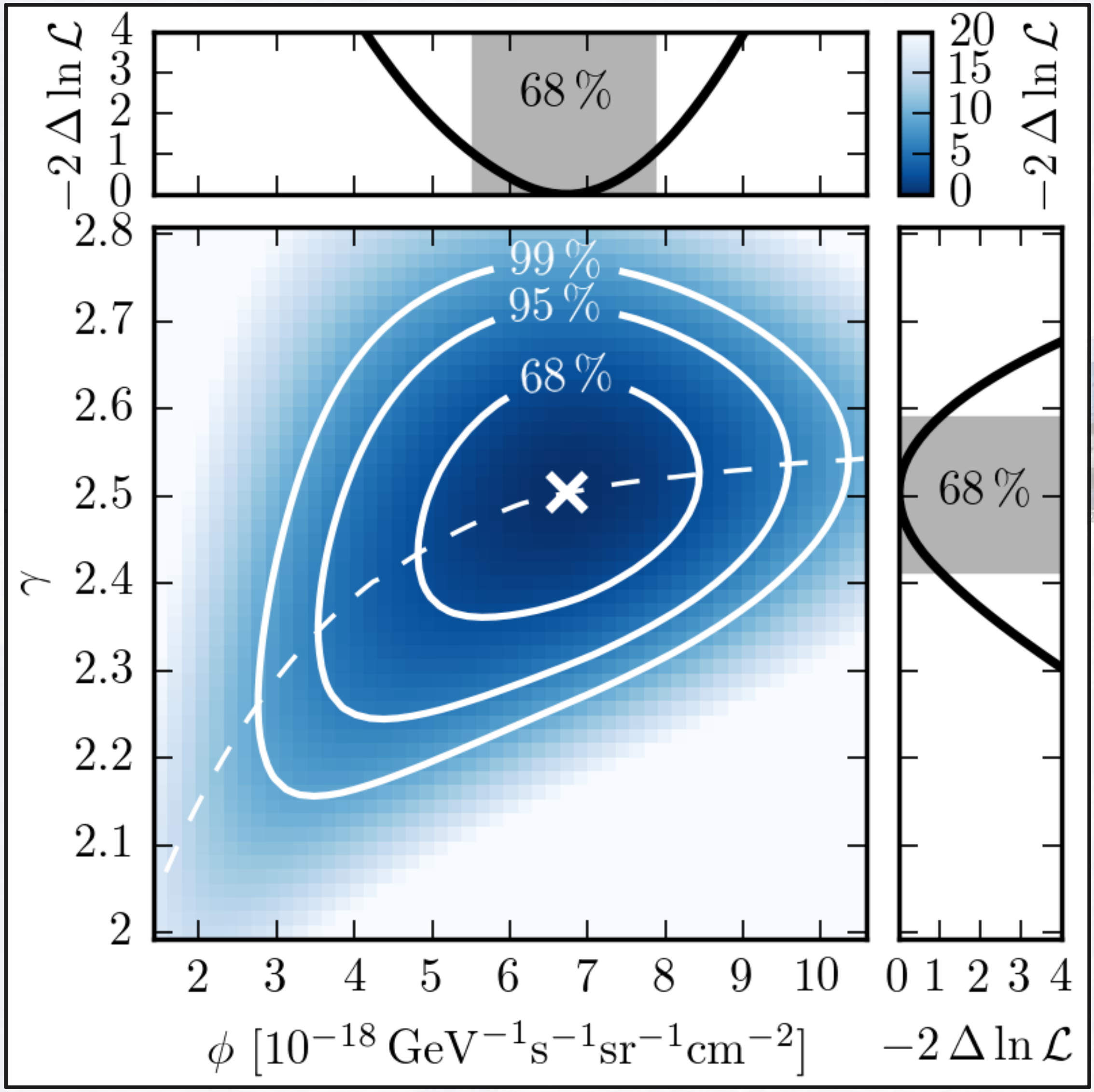




Absolute flux levels → free fit parameters!

Results – Energy Spectrum

"Power Law Model"



"Power Law Model":

$$\Phi(E) = \phi \times \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-\gamma}$$

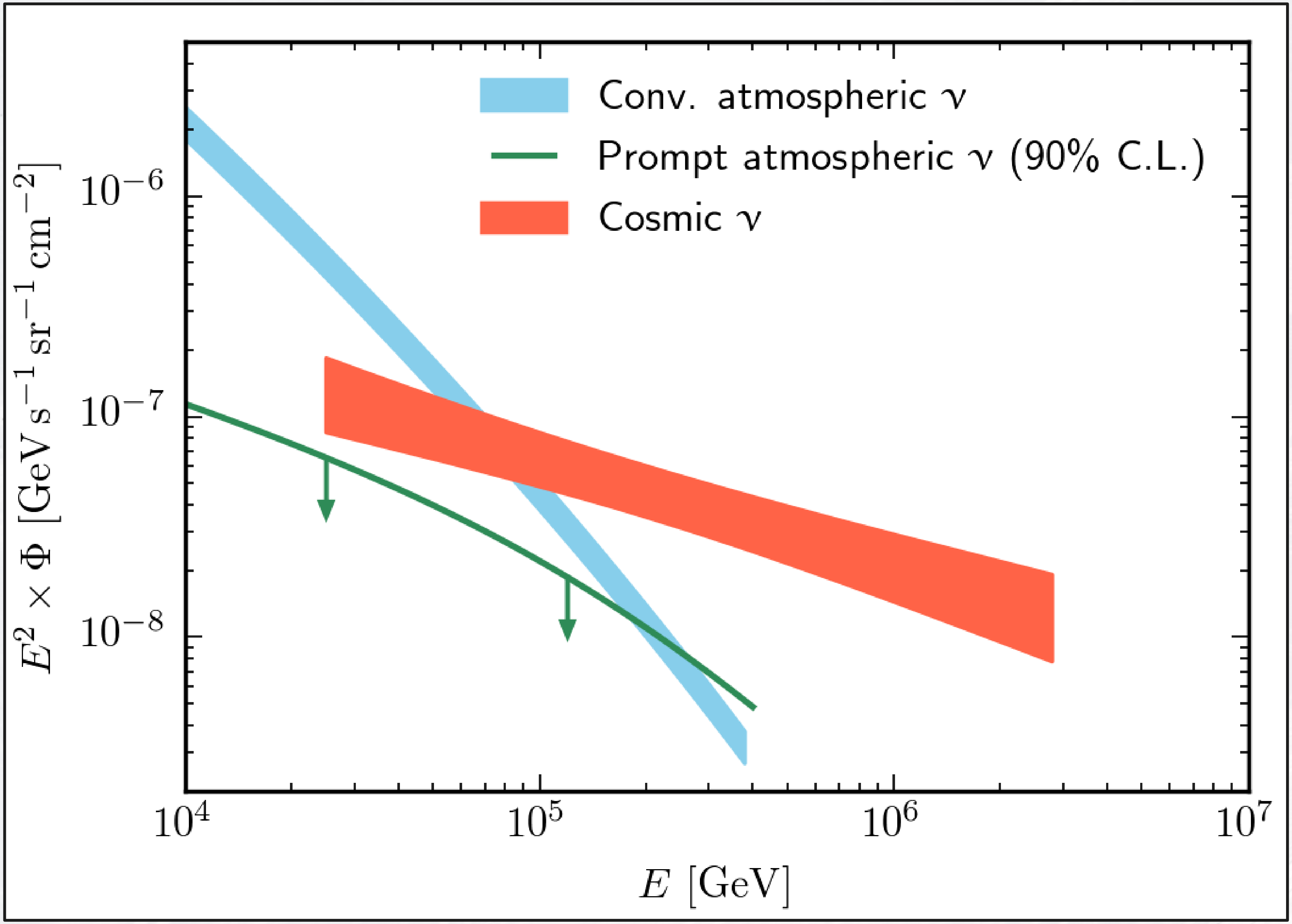
$$(\ \nu_e : \nu_\mu : \nu_\tau = 1:1:1\ )$$

$$\gamma = 2.50 \pm 0.09$$

→ **benchmark** $\gamma = 2$ **rejected with** **3.8 σ**

Results – Energy Spectrum

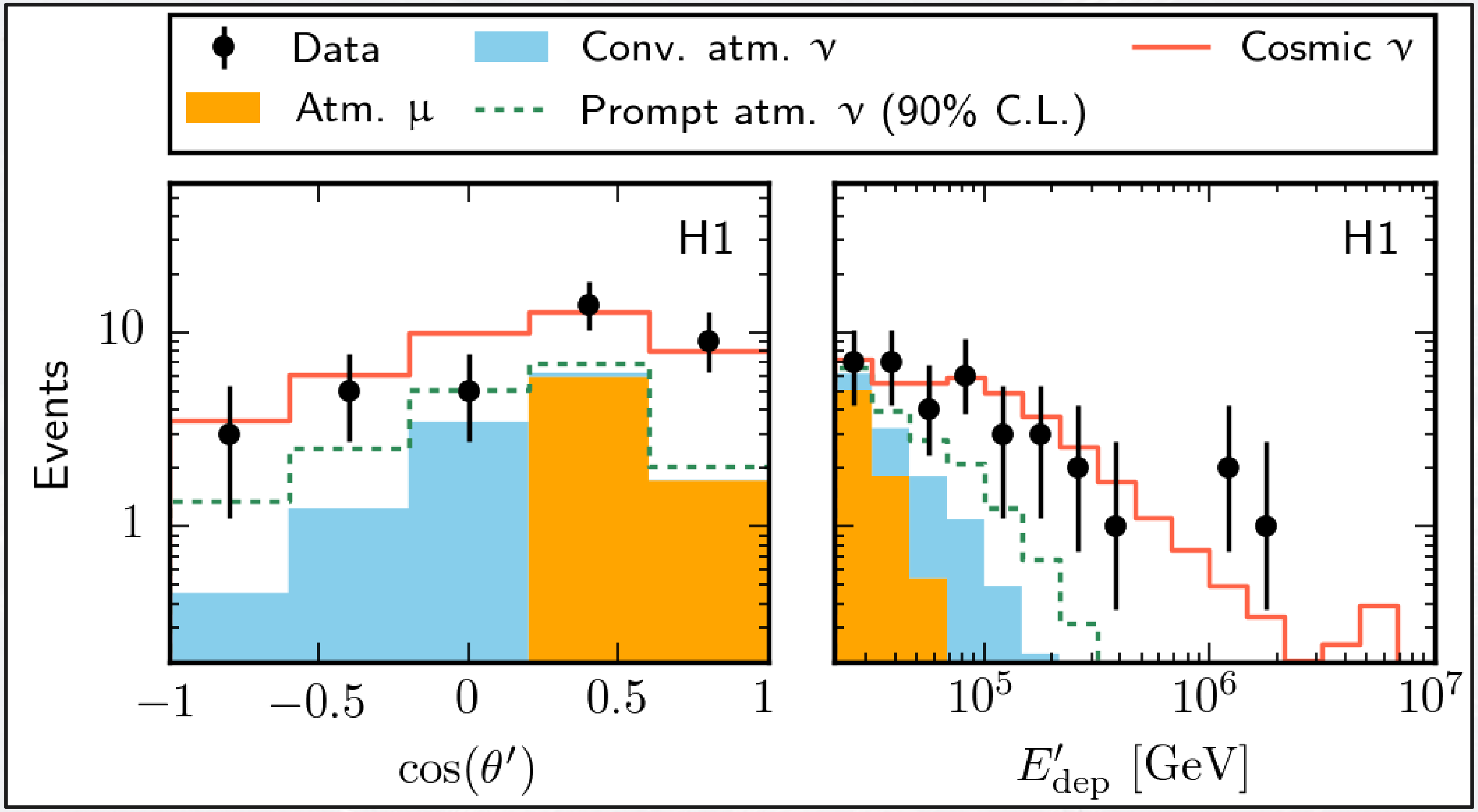
"Power Law Model"



Results – Energy Spectrum

"Power Law Model"

Example best-fit observable distribution:



Goodness-of-fit p-value:

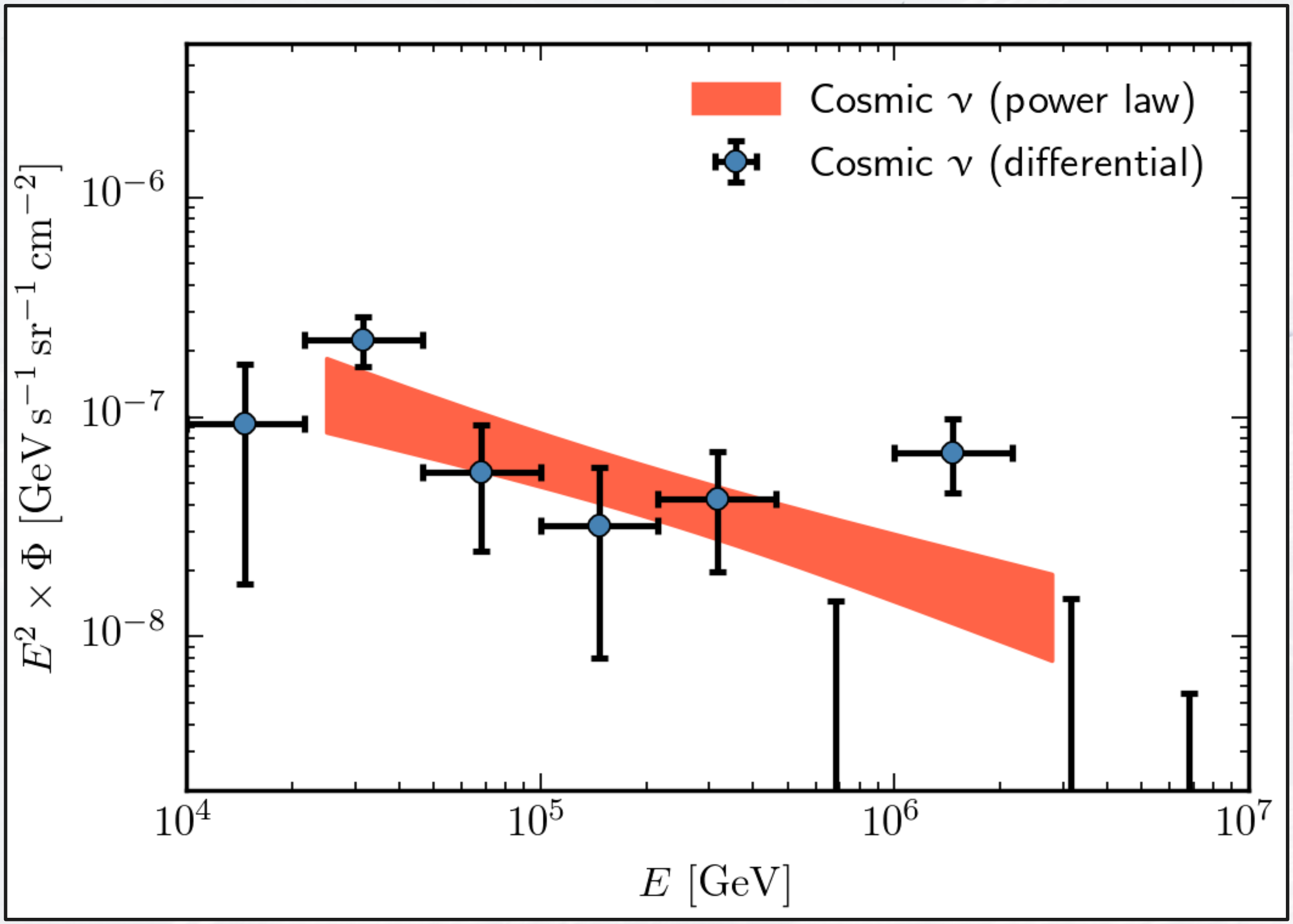
<u>37.6%</u>

→ no indication for significant discrepancies

Results – Energy Spectrum

"Differential Model"

"Differential Model" → "Unfold" flux in 9 separate energy bins

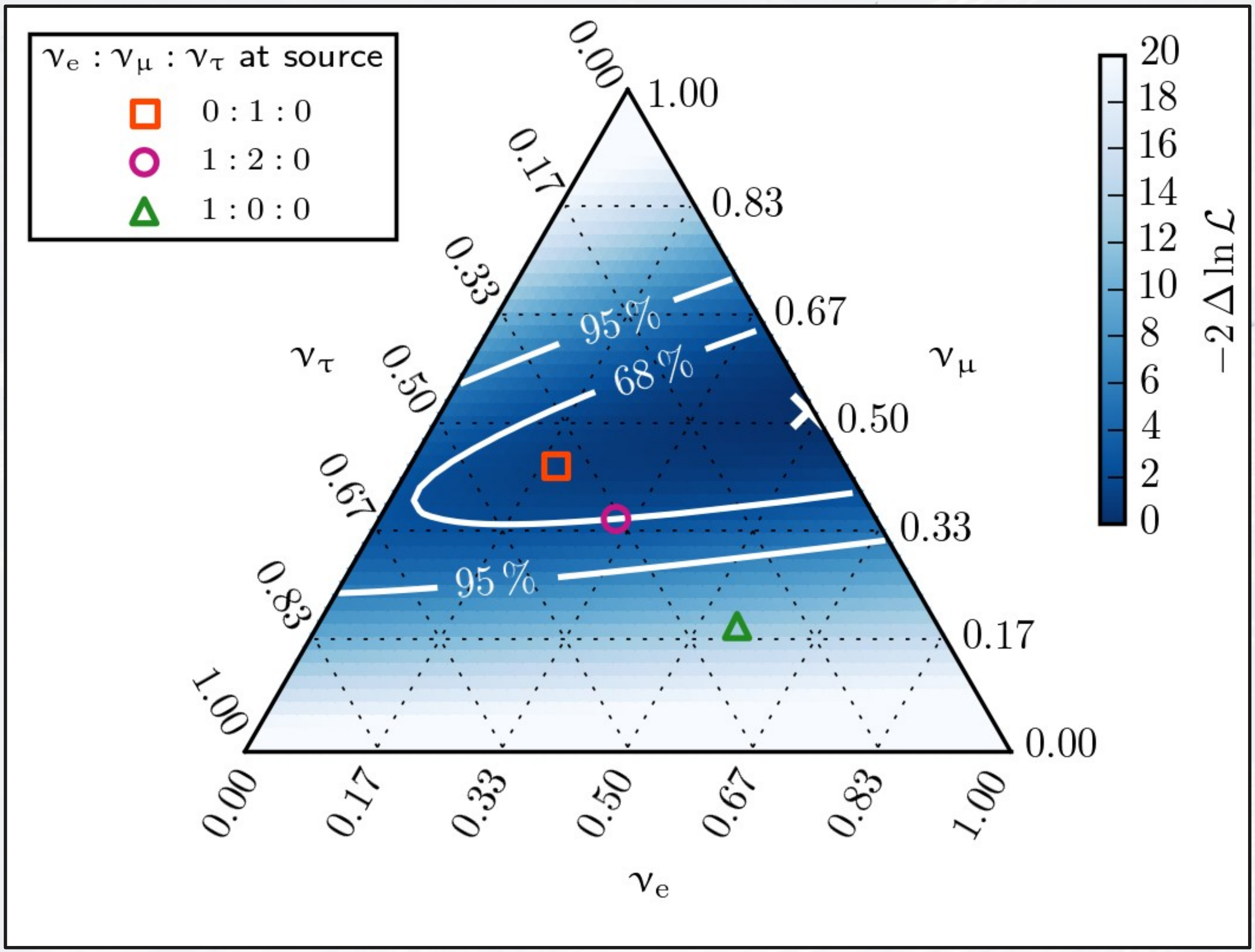


→ steep spectrum caused by excess around 30 TeV
<u>and</u> lack of events above 2 PeV

Results – Flavor Composition

"Flavor Model"

"Flavor Model" → measure unconstrained flavor composition

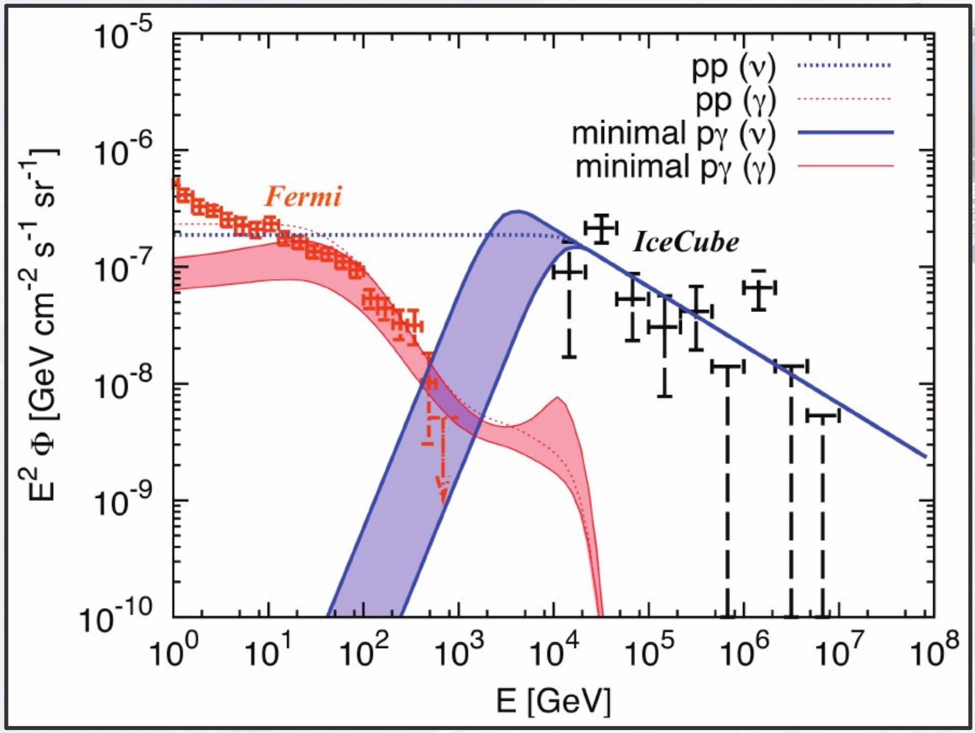


→ can reject neutron-decay scenario (1 : 0 : 0) with 3.6σ

Impact of the Results

Energy Spectrum:
Combine with measurement of diffuse gamma-ray background

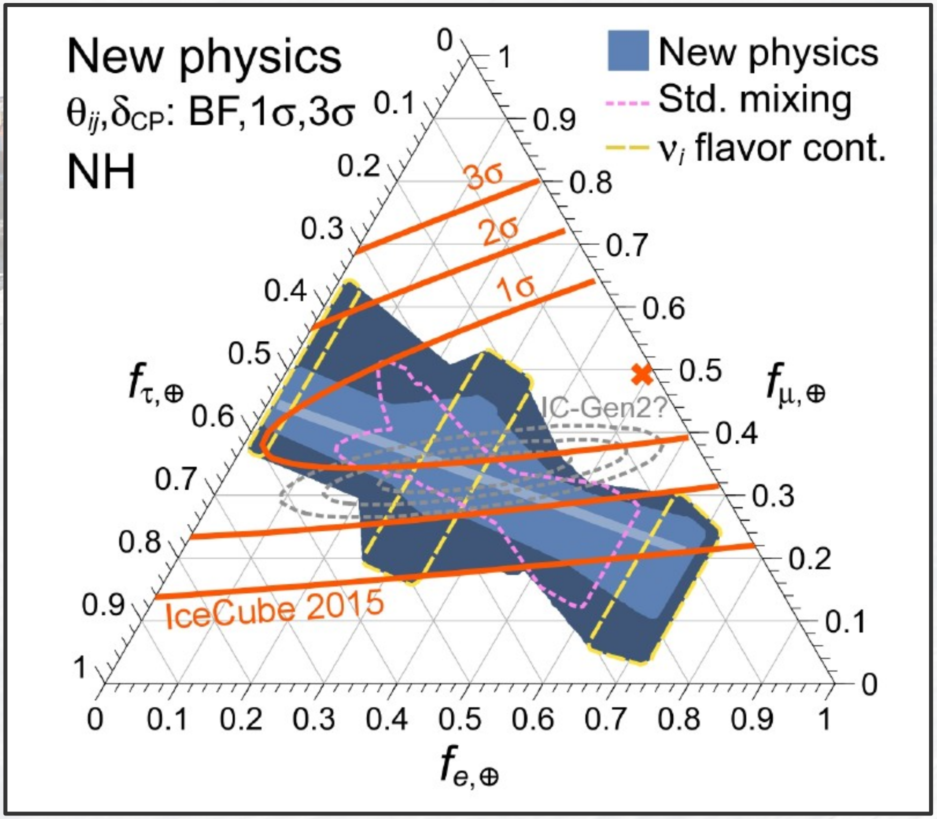
→ strong constraints on production mechanism



Murase et al., PRL **116**, 071101 (2016)

Flavor composition:
Test exotic models, e.g. neutrino decay

Common scenario: only ν_1 stable
→ ruled out for NH at 2σ

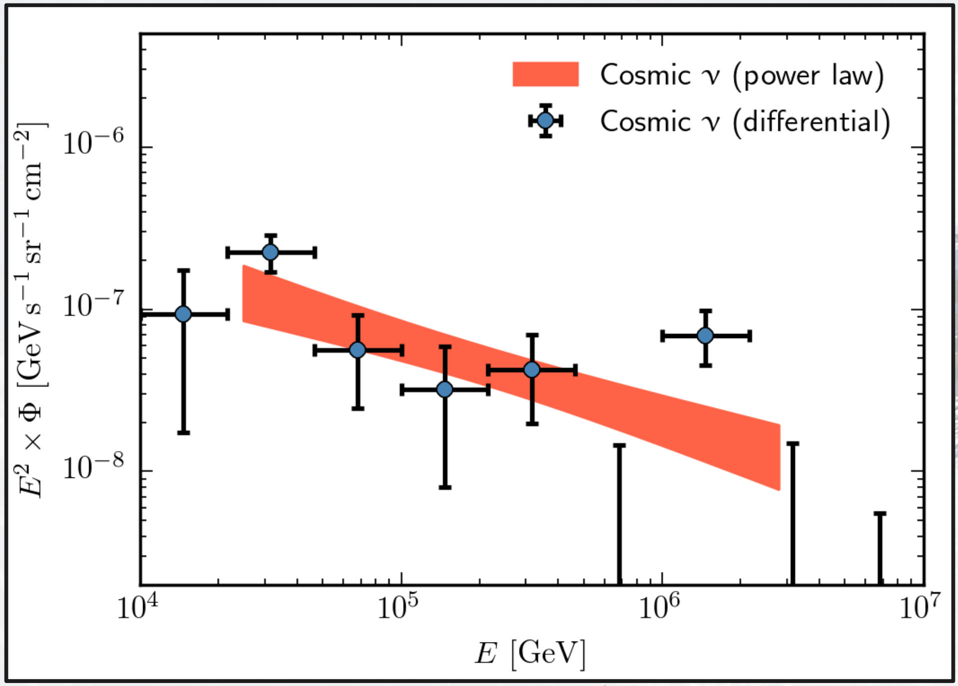


Bustamante et al., PRL **115**, 161302 (2015)

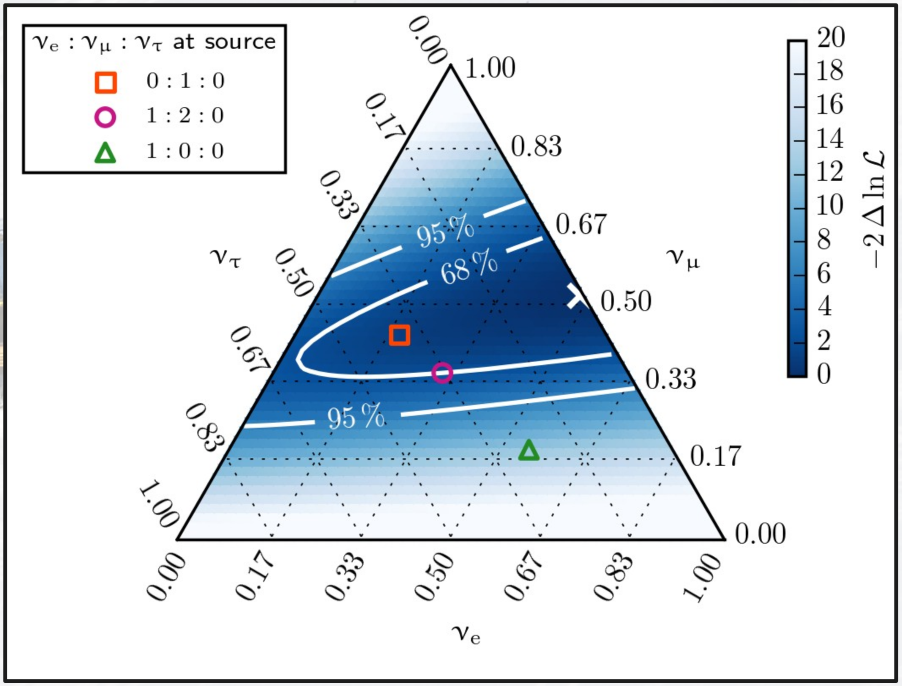
Conclusion

Presented first comprehensive characterization of cosmic neutrino flux:

Energy spectrum



Flavor composition



Want to learn more?

→ **Publication:** Aartsen et al., Astrophysical Journal **809**, 98 (2015)

→ **Thesis:** contact me! [lars.mohrmann@fau.de]