Searching for Diffuse Astrophysical Muon Neutrinos with IceCube

Sean Grullon
University of Wisconsin - Madison

Overview

Overview

- High Energy Neutrino Astronomy

Overview

- High Energy Neutrino Astronomy
- The IceCube Detector

Overview

- High Energy Neutrino Astronomy
- The IceCube Detector
- Energy Reconstruction

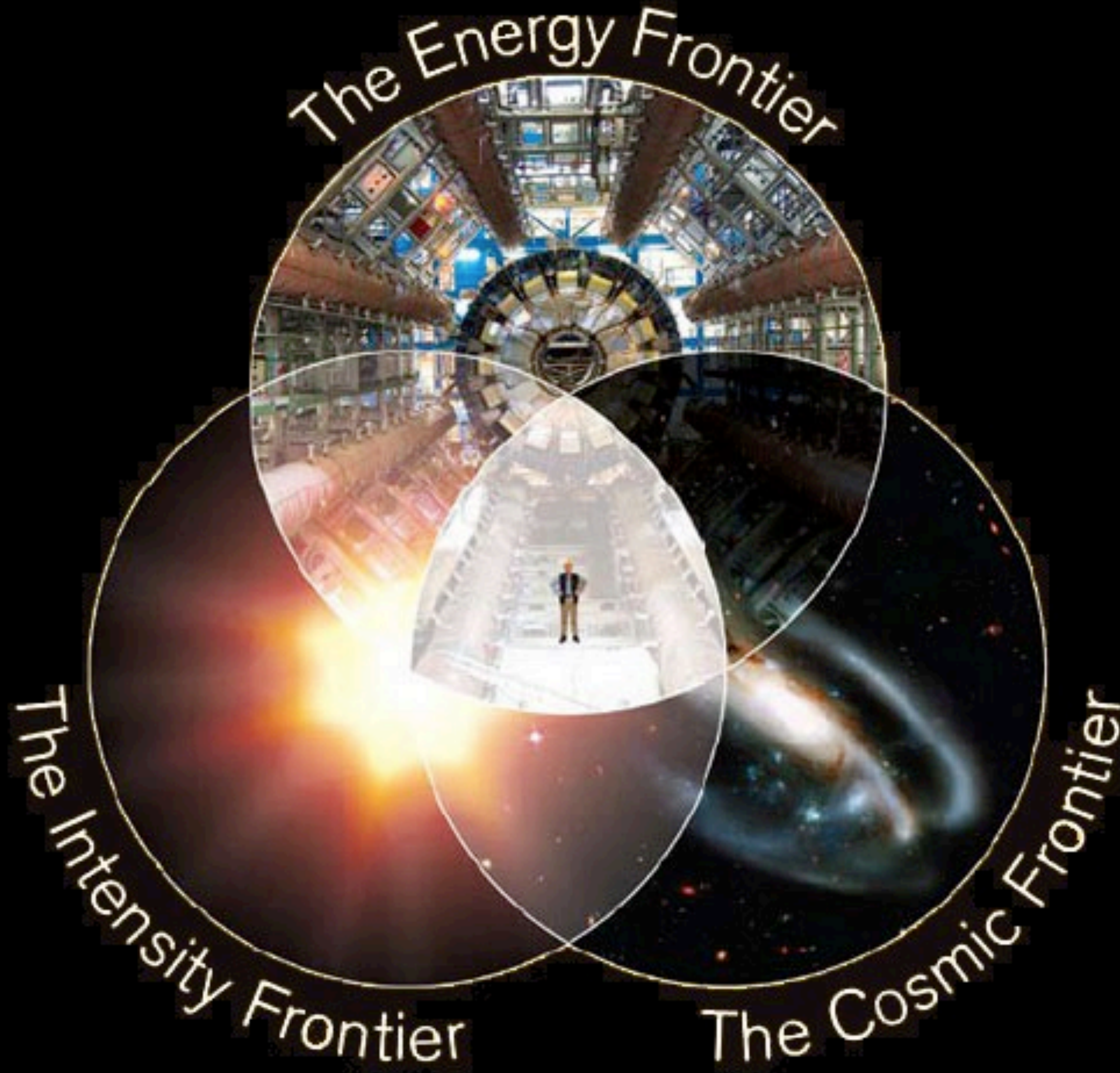
Overview

- High Energy Neutrino Astronomy
- The IceCube Detector
- Energy Reconstruction
- Diffuse Analysis Method

Overview

- High Energy Neutrino Astronomy
- The IceCube Detector
- Energy Reconstruction
- Diffuse Analysis Method
- Final Analysis Results from 2008

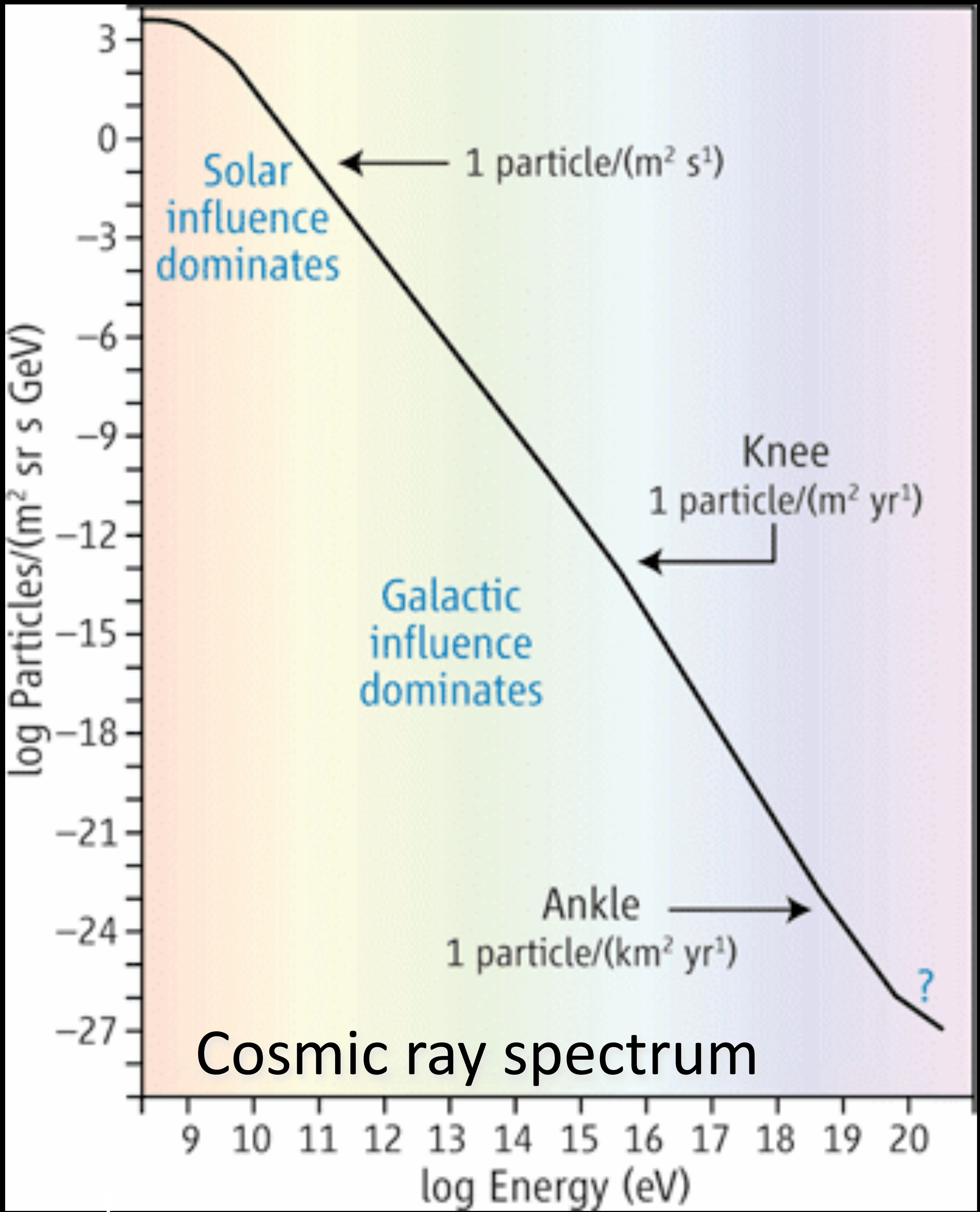
Particle Physics Today: Three Frontiers of Science



Cosmic Rays: A 100 year old mystery

Balloon flights
1911-1913

Victor Hess
Nobel Prize
1936

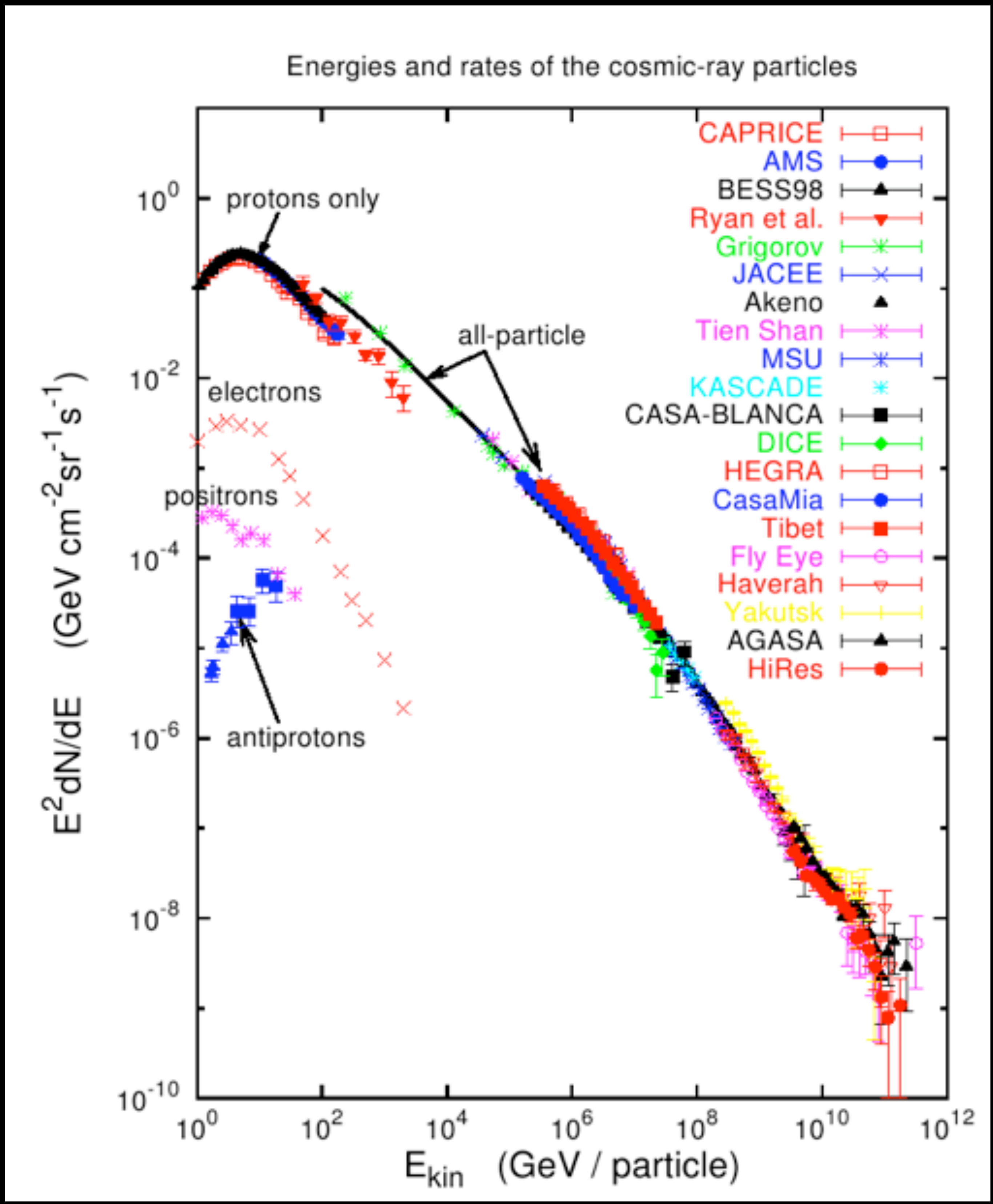


- Power law over many decades
- Origin Uncertain

Cosmic Rays: A 100 year old mystery

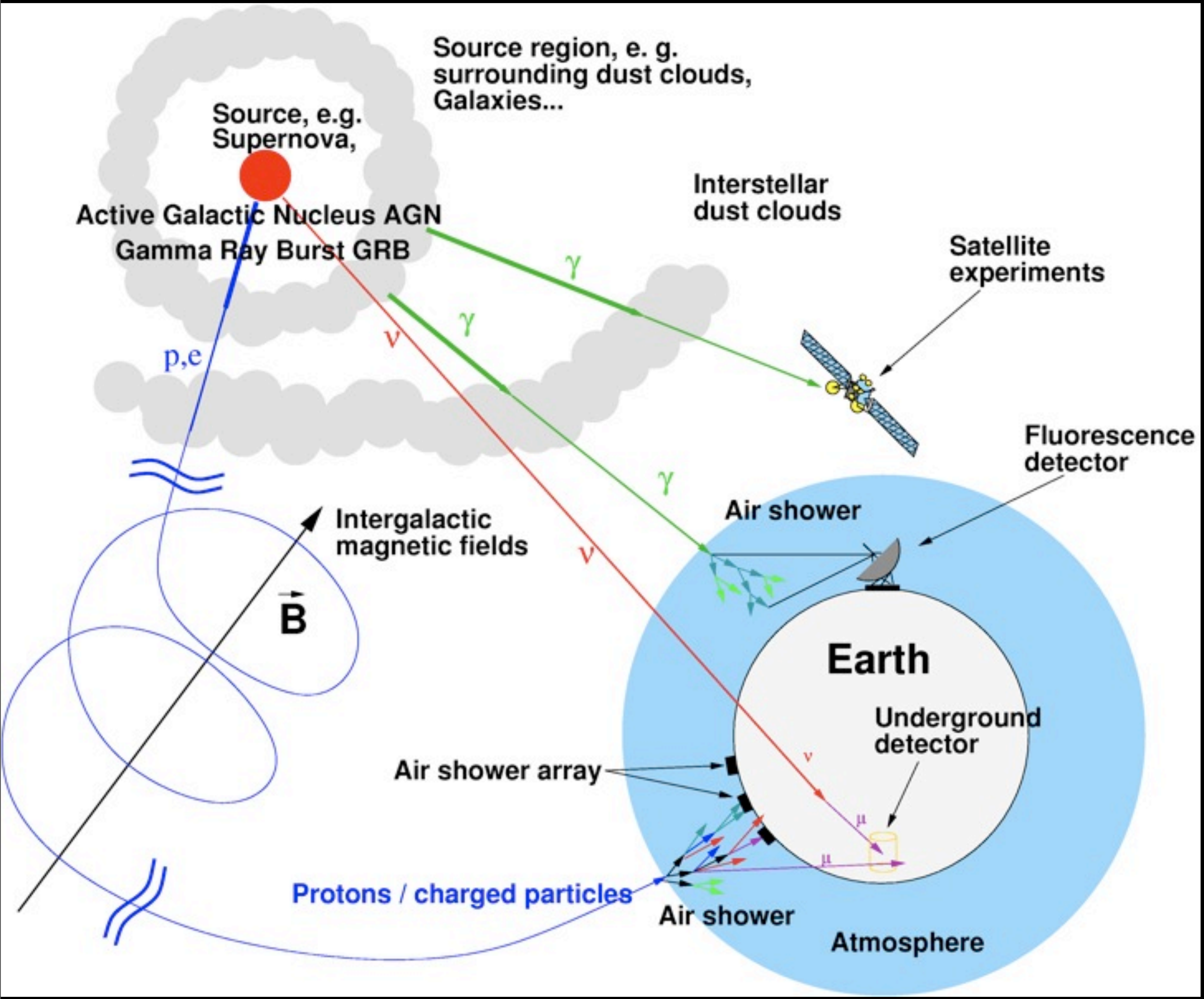
Balloon flights
1911-1913

Victor Hess
Nobel Prize
1936



- Power law over many decades
- Origin Uncertain

Neutrinos as Cosmic Messengers



p *Protons:* deflected by magnetic fields.

γ *Photons:* easily absorbed by CMB and IR backgrounds. EM/Hadronic discrimination difficult

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

Potential Astrophysical Sources of High Energy Neutrinos

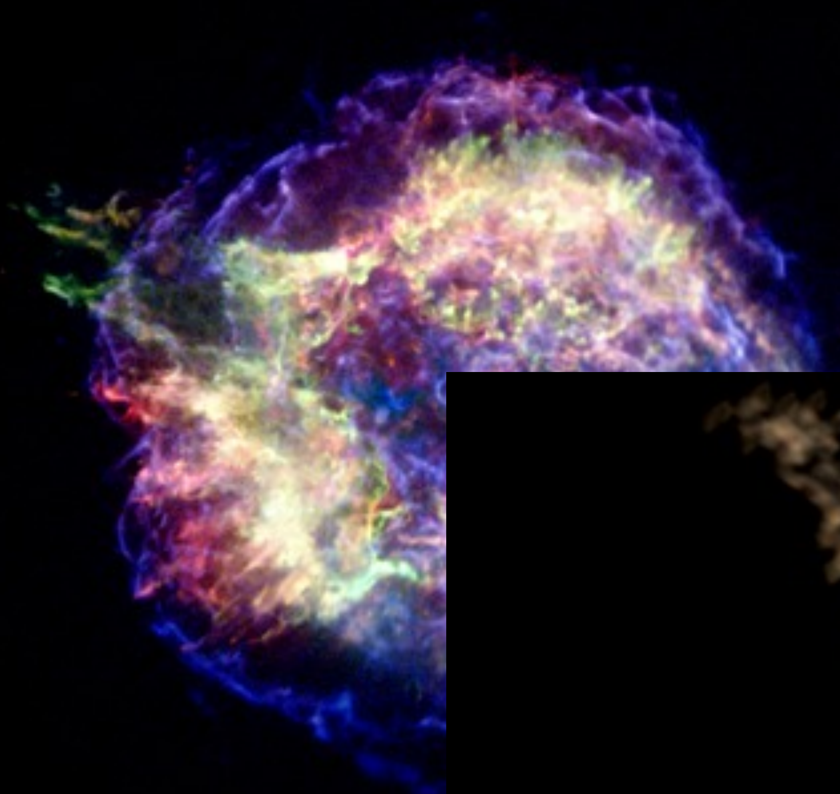
Potential Astrophysical Sources of High Energy Neutrinos

Potential Astrophysical Sources of High Energy Neutrinos

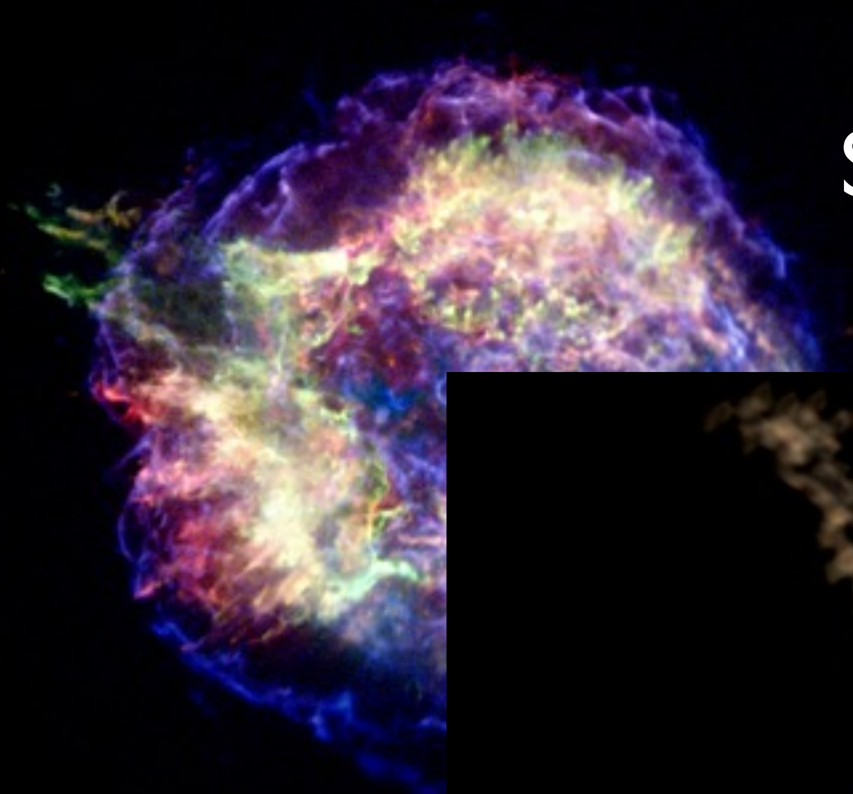
Supernova Remnants

Potential Astrophysical Sources of High Energy Neutrinos

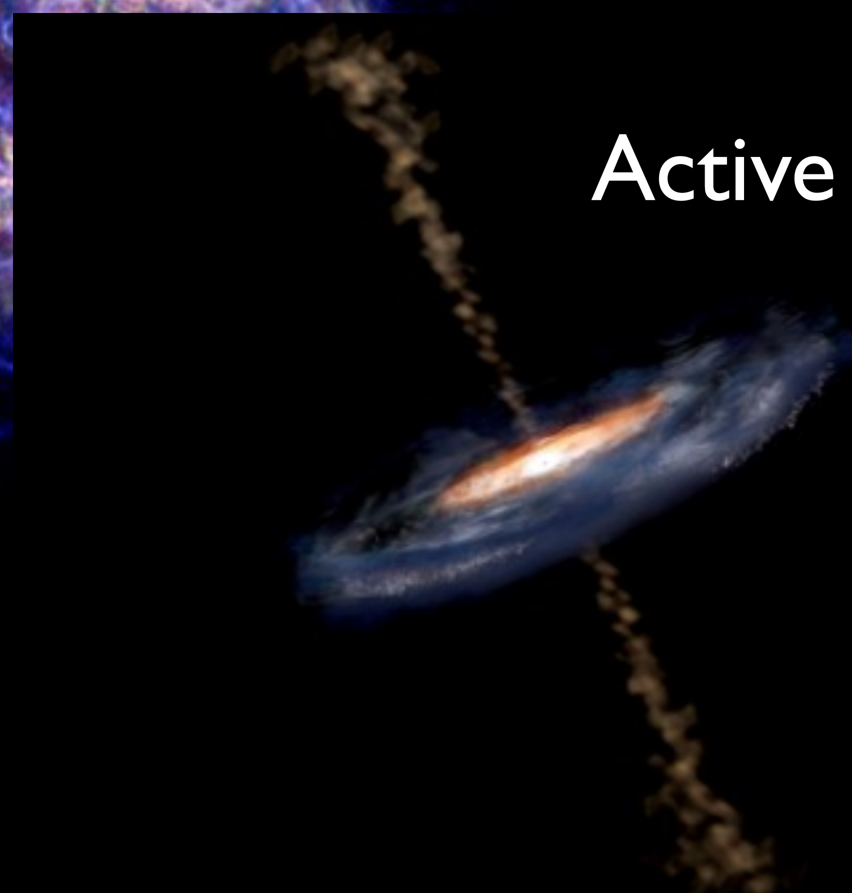
Supernova Remnants



Potential Astrophysical Sources of High Energy Neutrinos

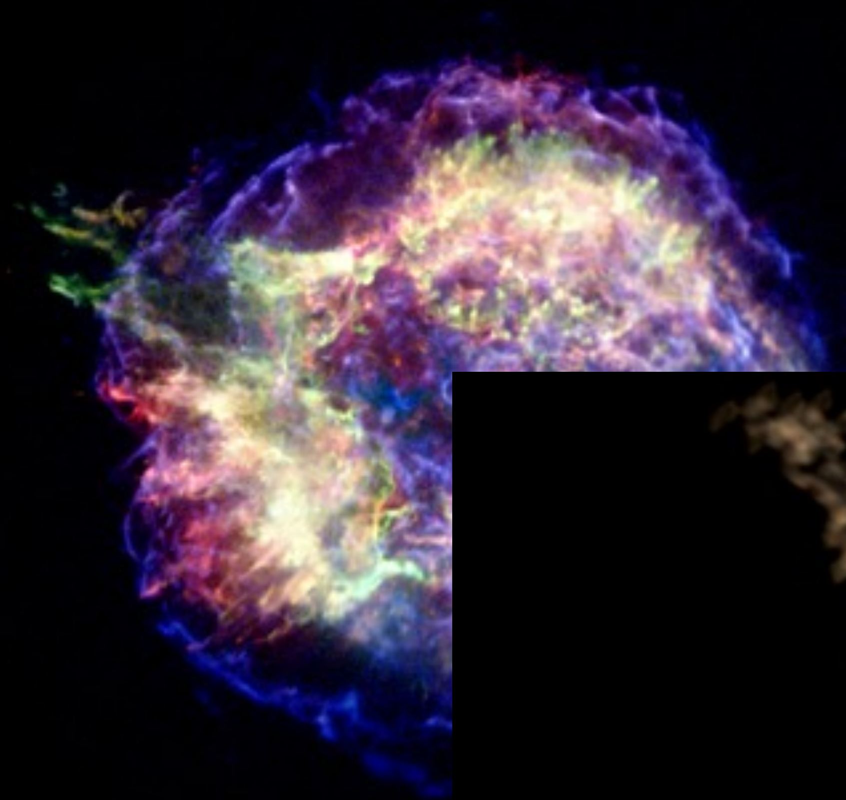


Supernova Remnants

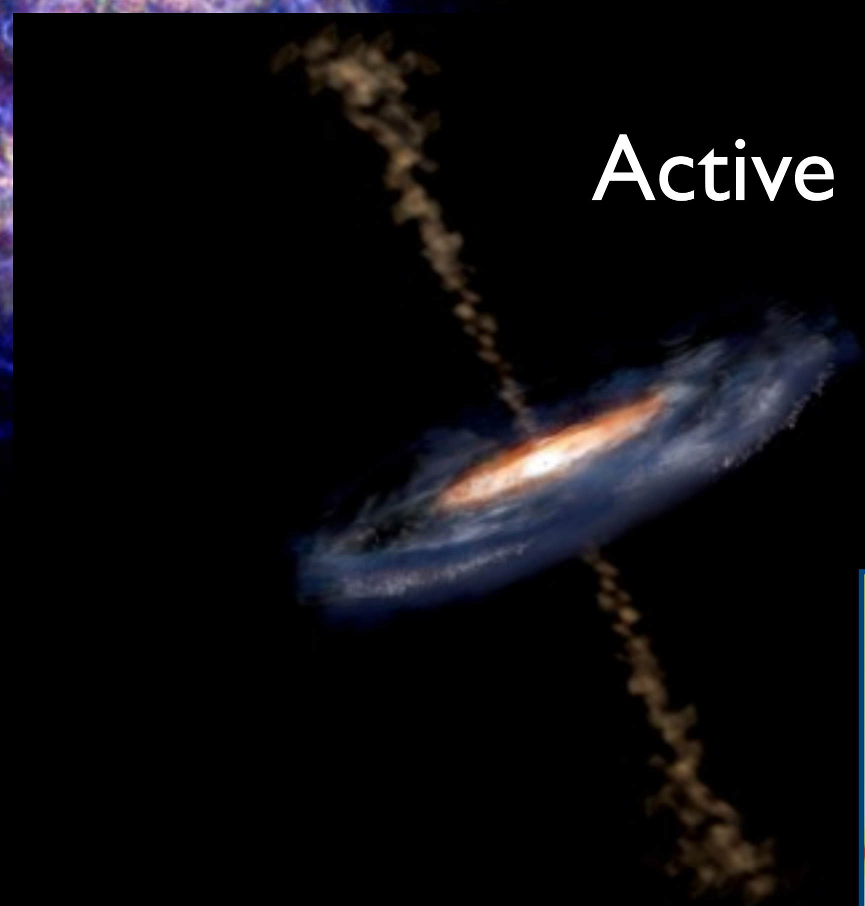


Active Galactic Nuclei

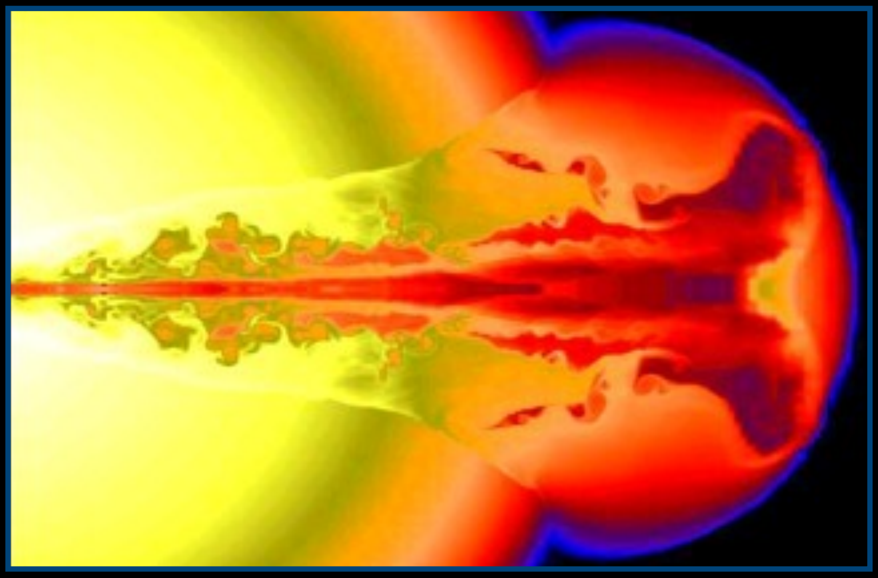
Potential Astrophysical Sources of High Energy Neutrinos



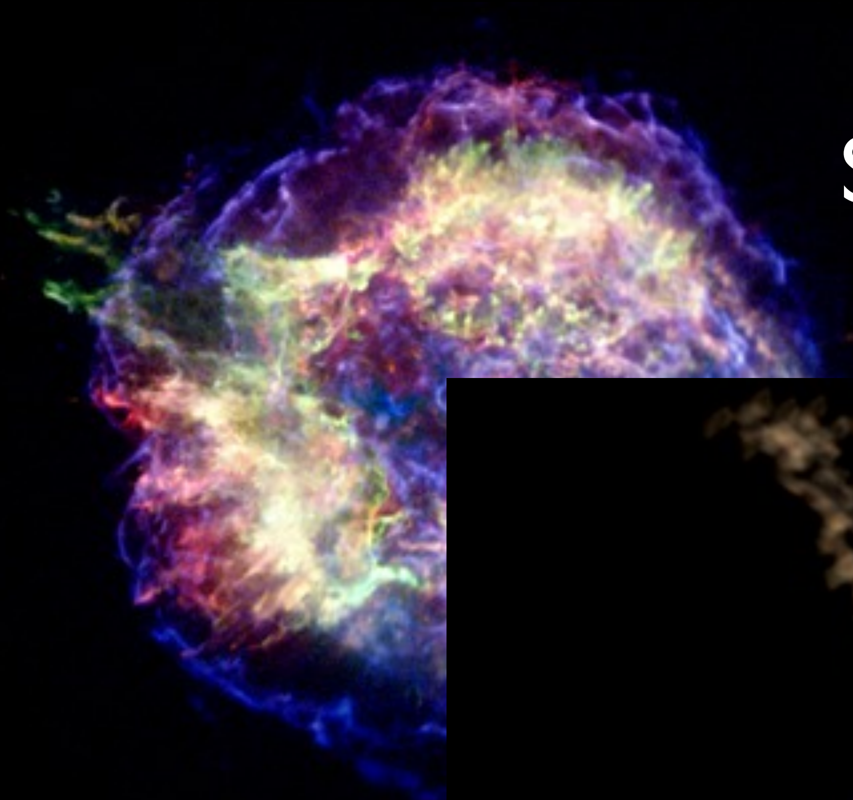
Supernova Remnants



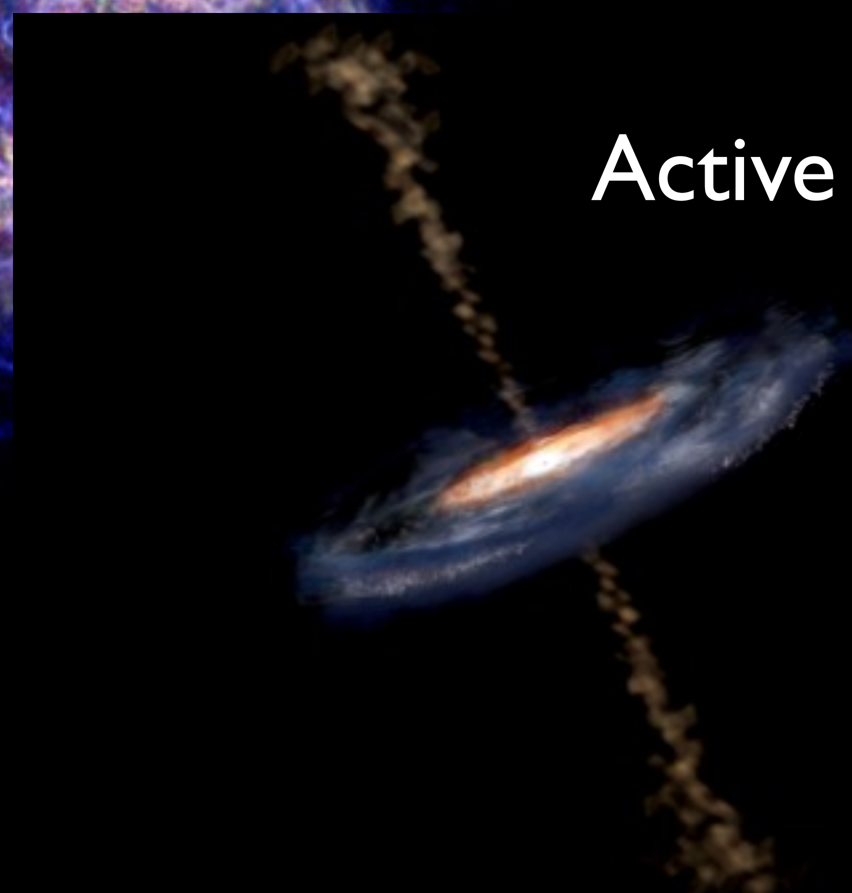
Active Galactic Nuclei



Potential Astrophysical Sources of High Energy Neutrinos

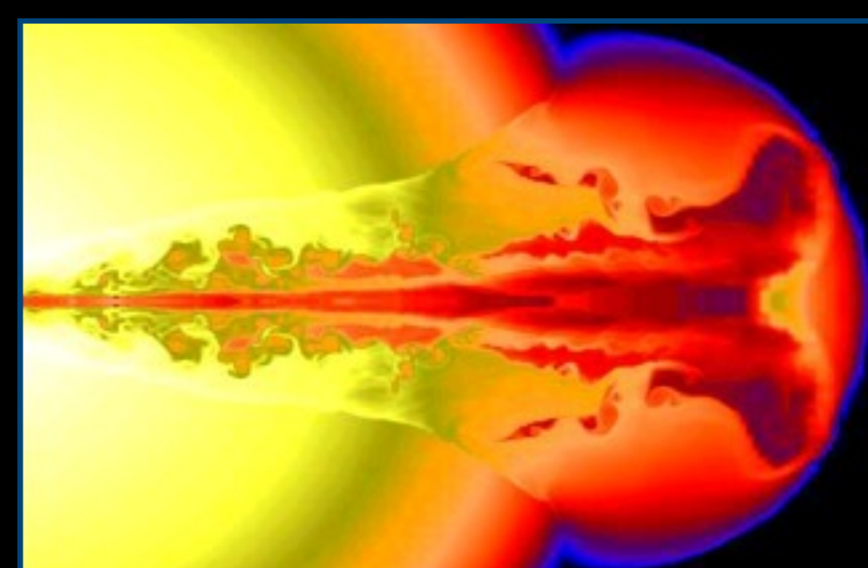


Supernova Remnants

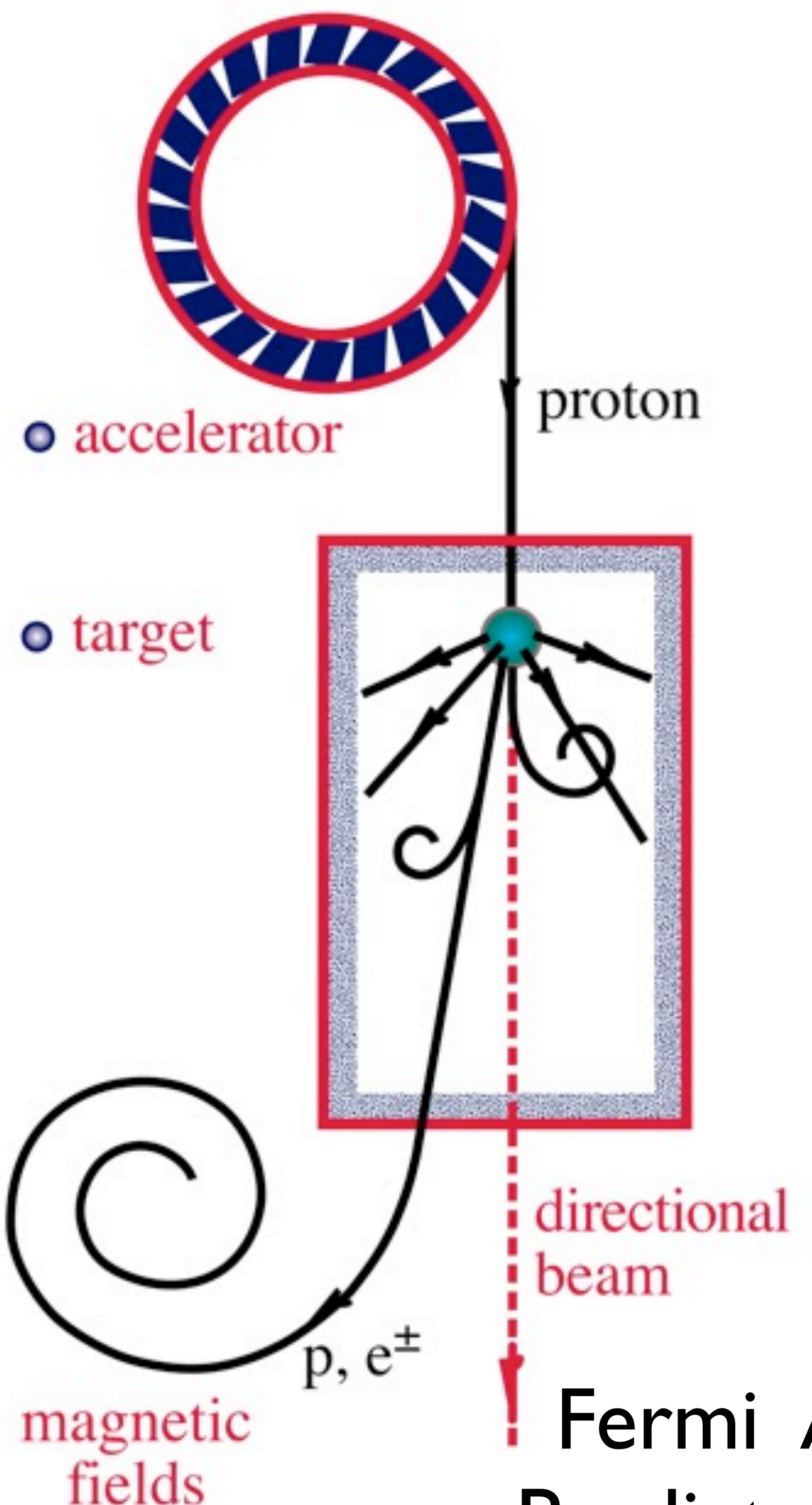


Active Galactic Nuclei

Gamma Ray Bursts

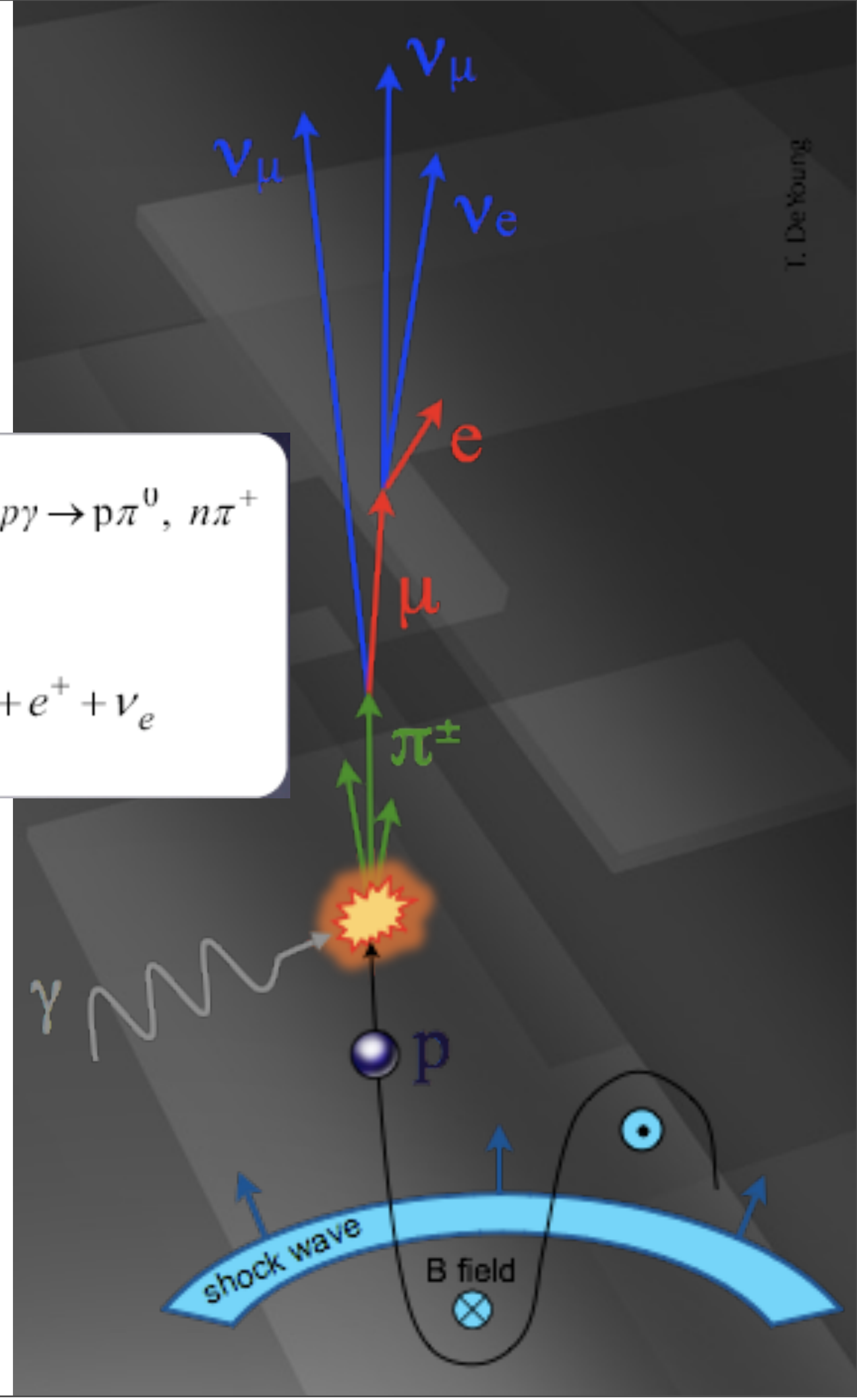


ν beams : heaven and earth



$$pp \rightarrow NN + \text{pions}; \qquad p\gamma \rightarrow p\pi^0,\ n\pi^+$$

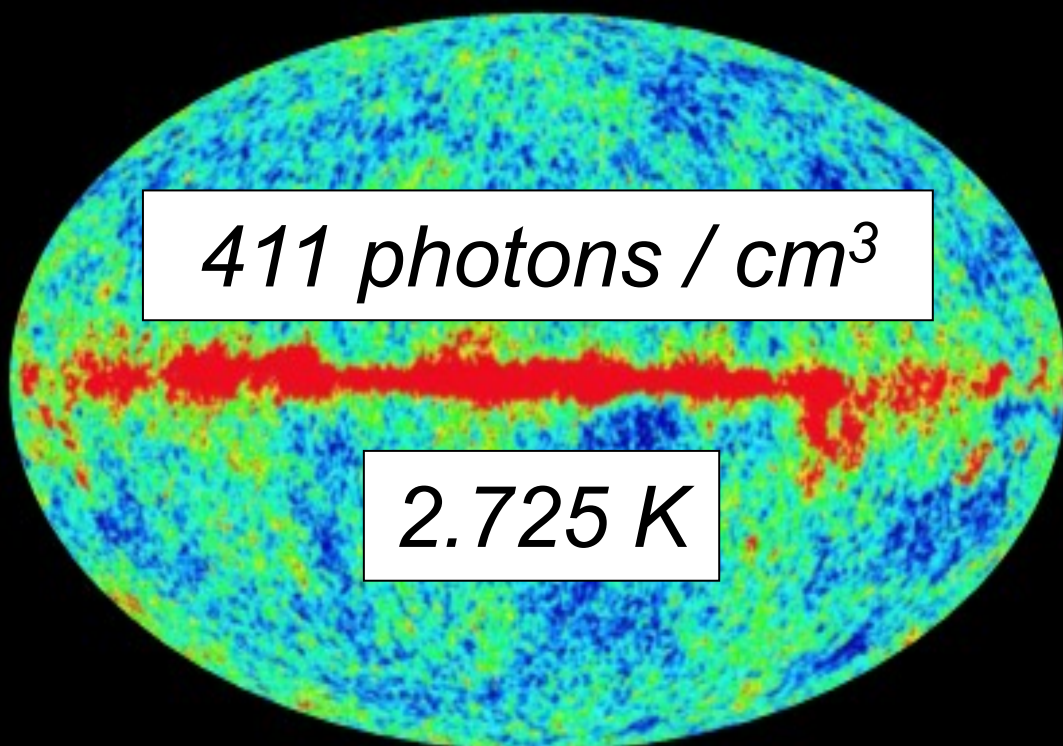
$$\pi^+ \rightarrow \nu_\mu + \mu^+$$
$$\mu^+ \rightarrow \bar{\nu}_\mu + e^+ + \nu_e$$



Fermi Acceleration Predicts E^{-2} Spectrum

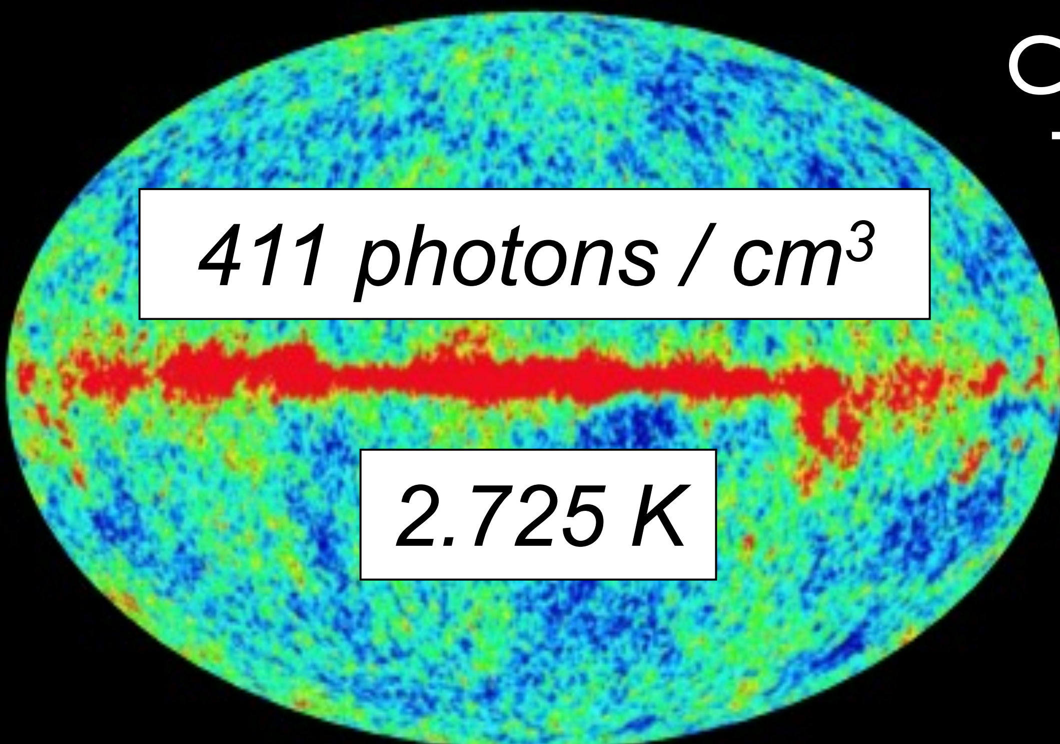
“Guaranteed” Sources of Cosmic Ray-induced Neutrinos

"Guaranteed" Sources of Cosmic Ray-induced Neutrinos



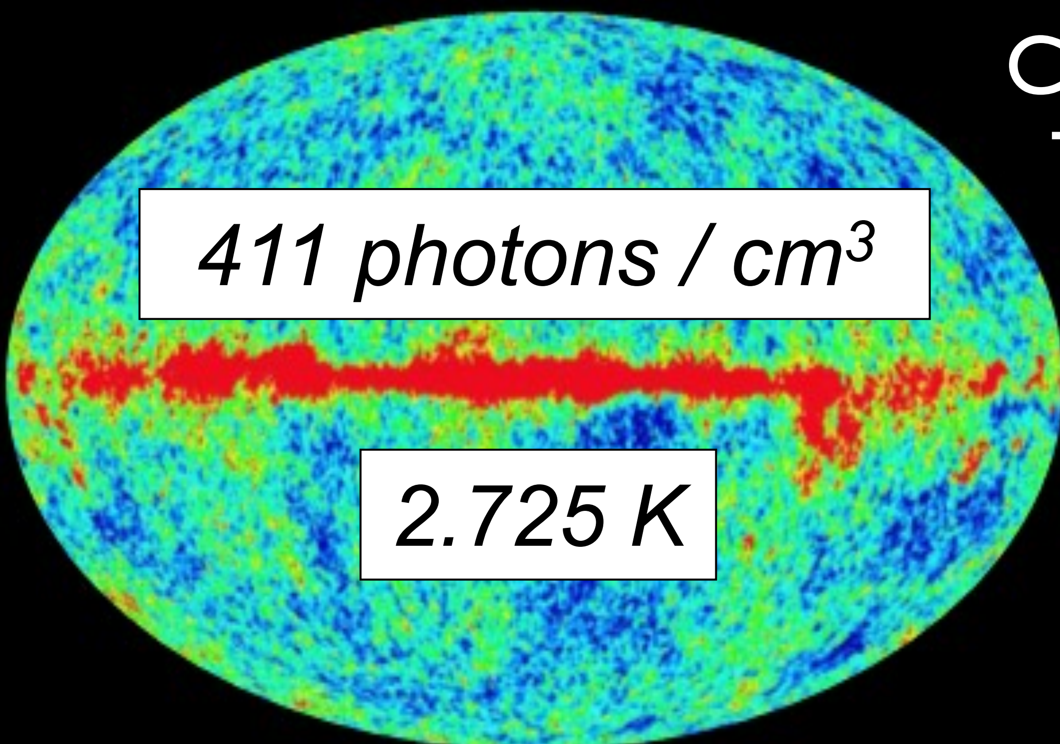
“Guaranteed” Sources of Cosmic Ray-induced Neutrinos

Cosmic Microwave Background
Cosmogenic Neutrinos
Threshold: 10^{10} GeV



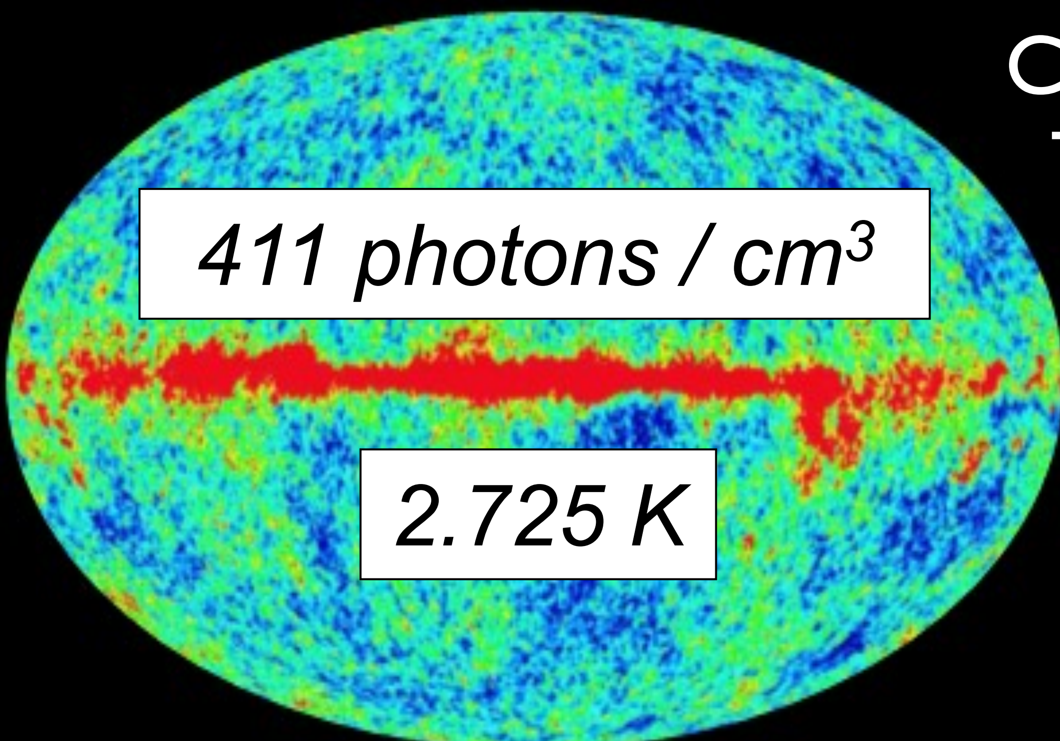
“Guaranteed” Sources of Cosmic Ray-induced Neutrinos

Cosmic Microwave Background
Cosmogenic Neutrinos
Threshold: 10^{10} GeV



"Guaranteed" Sources of Cosmic Ray-induced Neutrinos

Cosmic Microwave Background
Cosmogenic Neutrinos
Threshold: 10^{10} GeV



Interaction with
Interstellar Medium

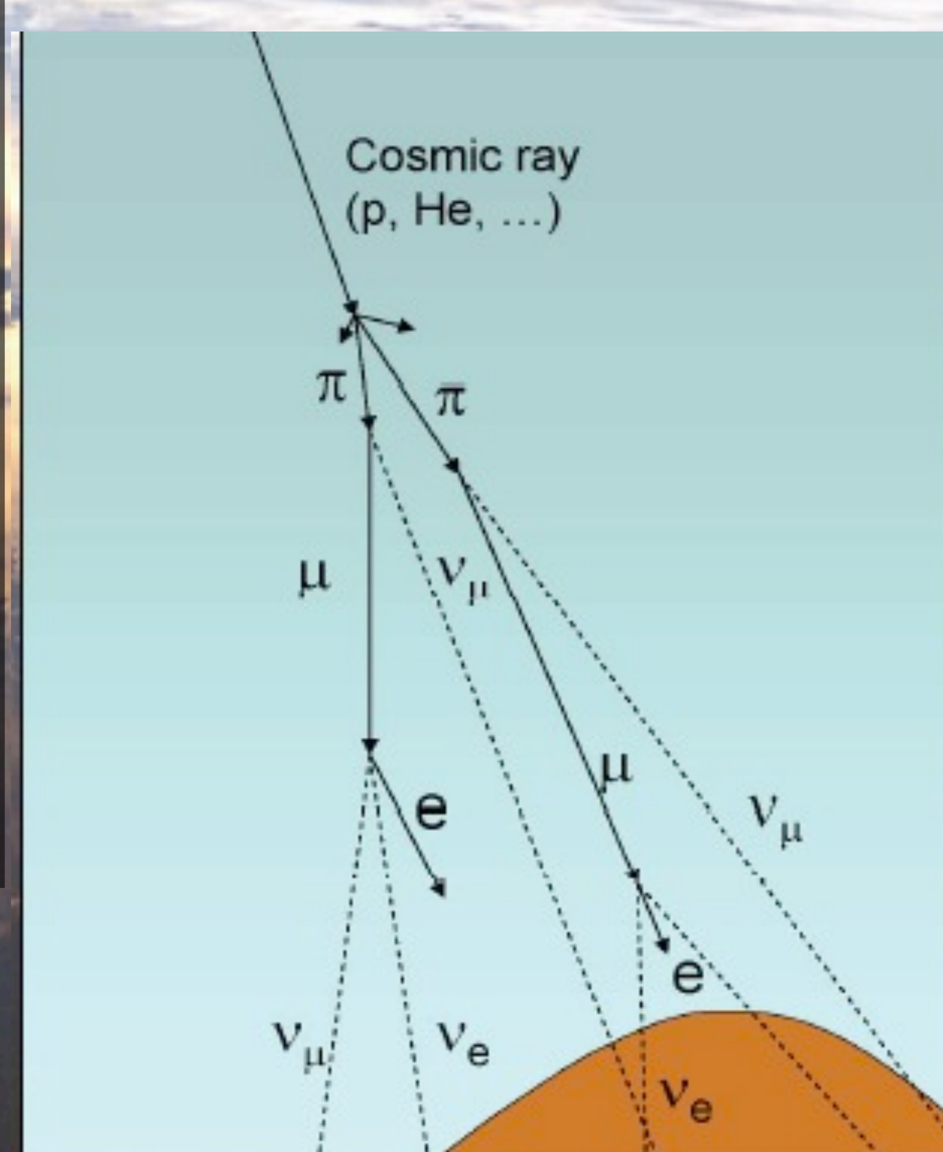
Atmospheric Neutrinos

- Main Background to Astrophysical Search
- Created by high energy cosmic rays impeding on Earth’s atmosphere
- Conventional (Pions & Kaons) vs. Prompt (Charmed Mesons)
- Conventional ~ $E^{-3.7}$ Spectrum
- Prompt ~ $E^{-2.7}$ Spectrum

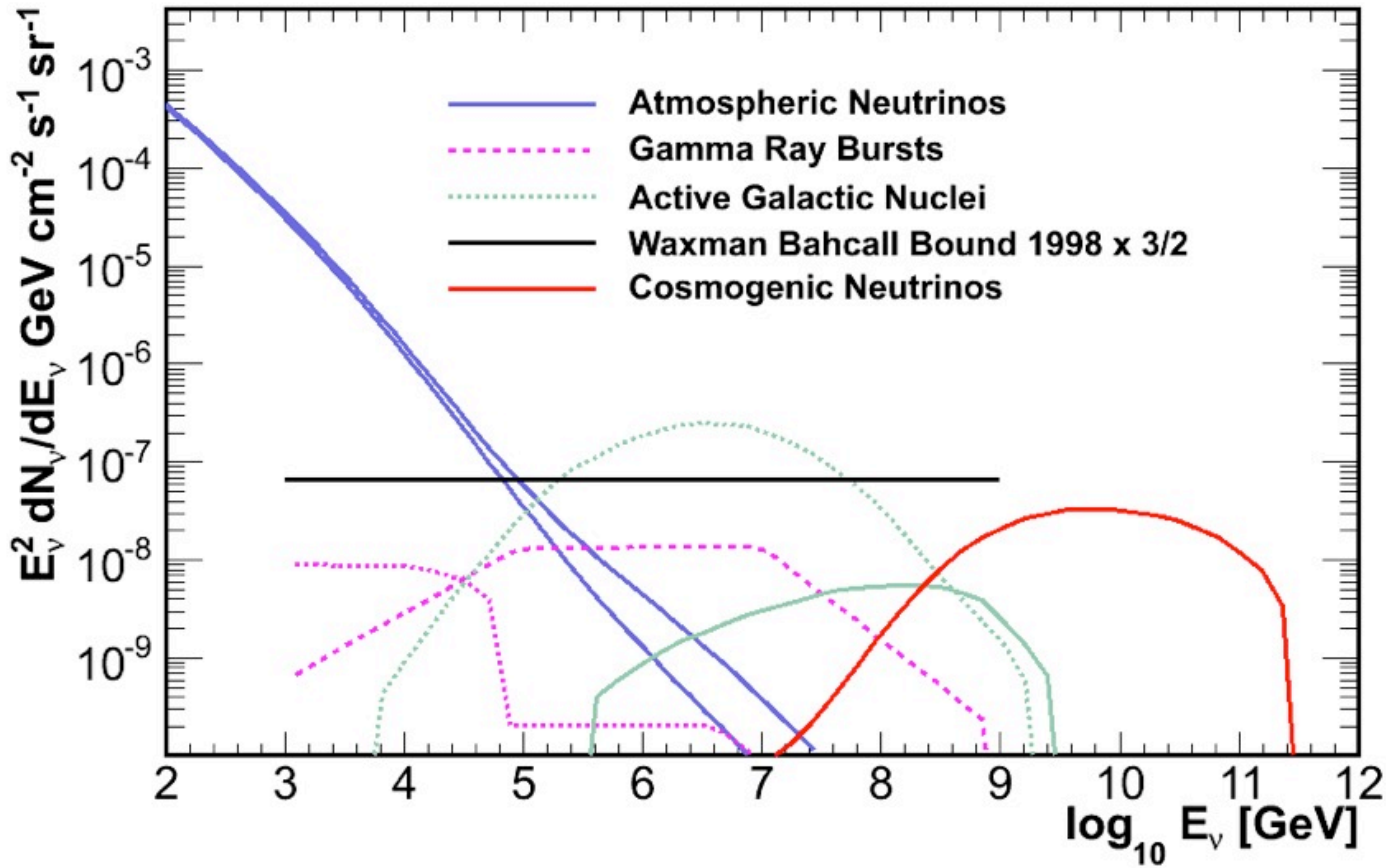
$$p + {}^{14}N \rightarrow \pi^{+}, K^{+}, D^{+}, \text{etc.}$$

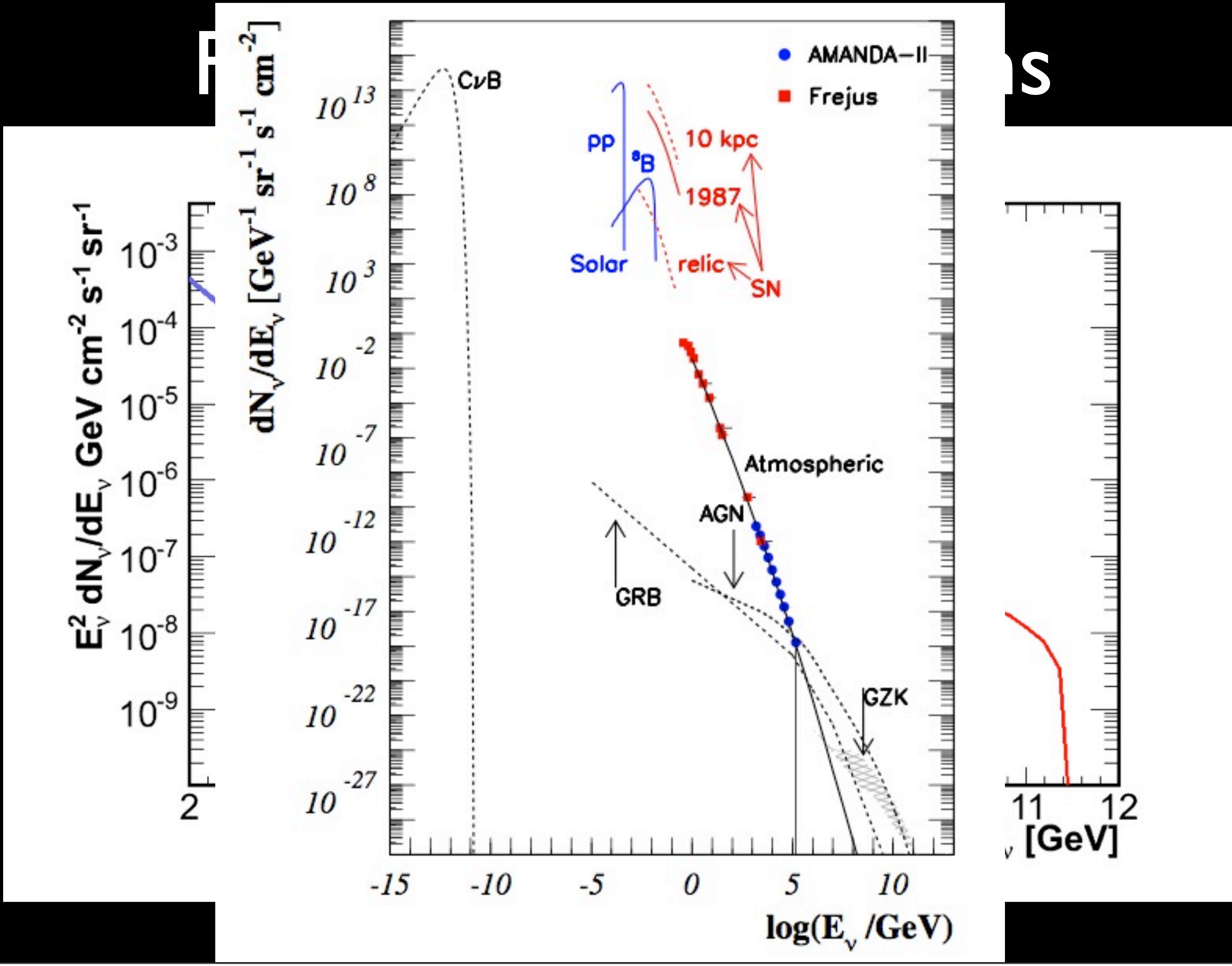
$$\pi^{+} \rightarrow \nu_{\mu} + \mu^{+}$$

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

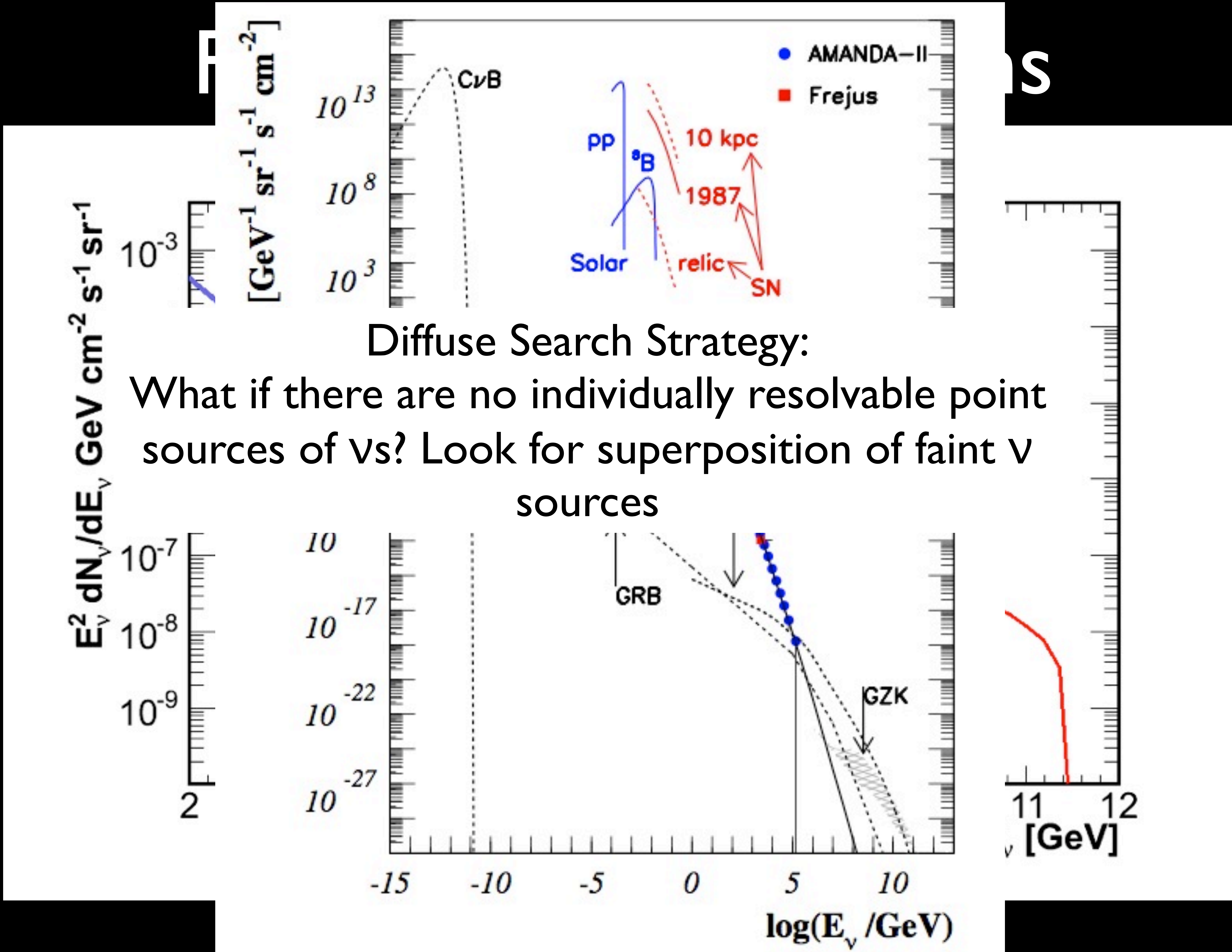


Flux Model Predictions





E$_\nu^2$ dN$_\nu$/dE$_\nu$ GeV cm^{-2} s^{-1} sr^{-1}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
2
11
12
[GeV]
dN$_\nu$/dE$_\nu$ [GeV^{-1} sr^{-1} s^{-1} cm^{-2}]
10^{13}
10^{8}
10^{3}
10^{-2}
10^{-7}
10^{-12}
10^{-17}
10^{-22}
10^{-27}
-15
-10
-5
0
5
10
log(E$_\nu$ /GeV)
AMANDA–II
Frejus
CνB
pp
^{8}B
Solar
10 kpc
1987
relic
SN
Atmospheric
AGN
GRB
GZK

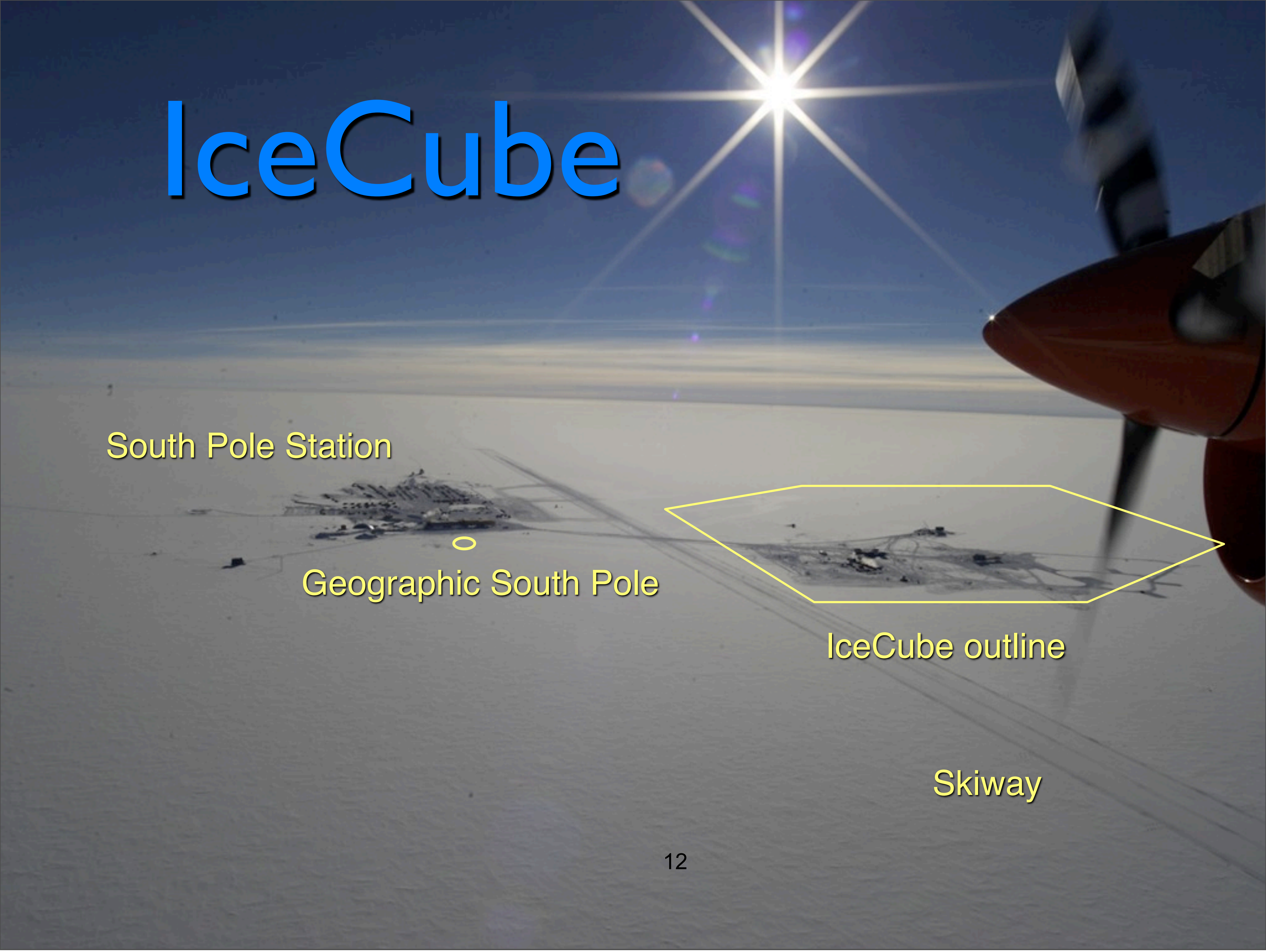


Diffuse Search Strategy:

What if there are no individually resolvable point sources of νs? Look for superposition of faint ν sources


High Energy Neutrino Astronomy
The IceCube Detector
Energy Reconstruction
Diffuse Analysis Method
Final Analysis Results from 2008

IceCube

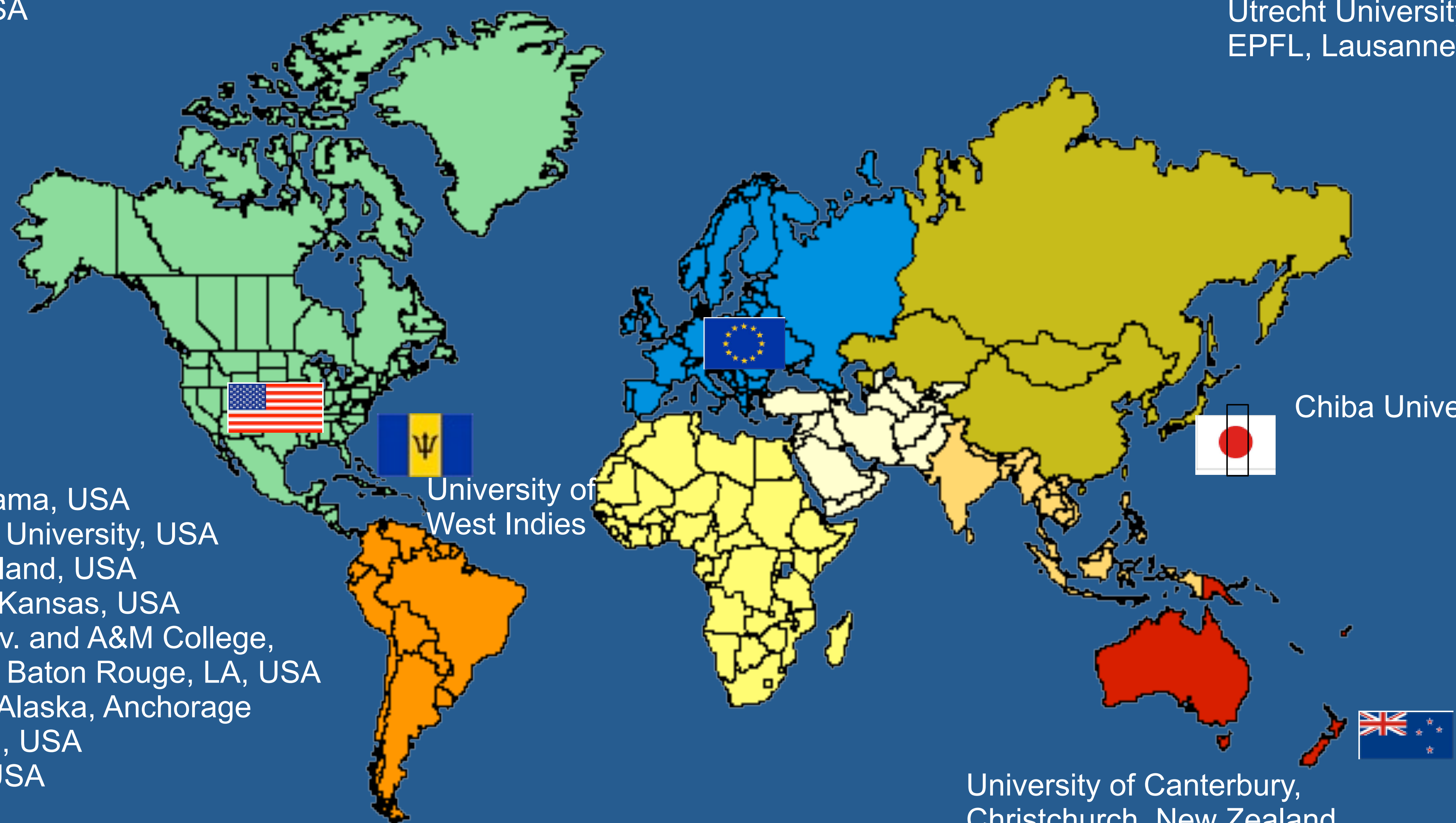

South Pole Station
Geographic South Pole
IceCube outline
Skiway

IceCube Collaboration

Université Libre de Bruxelles, Belgium
Vrije Universiteit Brussel, Belgium
Université de Mons-Hainaut, Belgium
Universiteit Gent, Belgium
Universität Mainz, Germany
DESY Zeuthen, Germany
Universität Wuppertal, Germany
Universität Dortmund, Germany

Humboldt Universität, Germany
MPI, Heidelberg
Ruhr-Universität, Bochum
Uppsala Universitet, Sweden
Stockholm Universitet, Sweden
Kalmar Universitet, Sweden
Imperial College, London, UK
University of Oxford, UK
Utrecht University, Netherlands
EPFL, Lausanne, Switserland

Bartol Research Inst, Univ of Delaware, USA
Pennsylvania State University, USA
University of Wisconsin-Madison, USA
University of Wisconsin-River Falls, USA
LBNL, Berkeley, USA
UC Berkeley, USA
UC Irvine, USA



Chiba University, Japan

University of West Indies

Univ. of Alabama, USA
Clark-Atlanta University, USA
Univ. of Maryland, USA
University of Kansas, USA
Southern Univ. and A&M College, Baton Rouge, LA, USA
University of Alaska, Anchorage
Georgia Tech, USA
Ohio State, USA

University of Canterbury, Christchurch, New Zealand

36 collaborating institutions

The IceCube Detector

IceTop

Air shower detector

threshold ~ 300 TeV

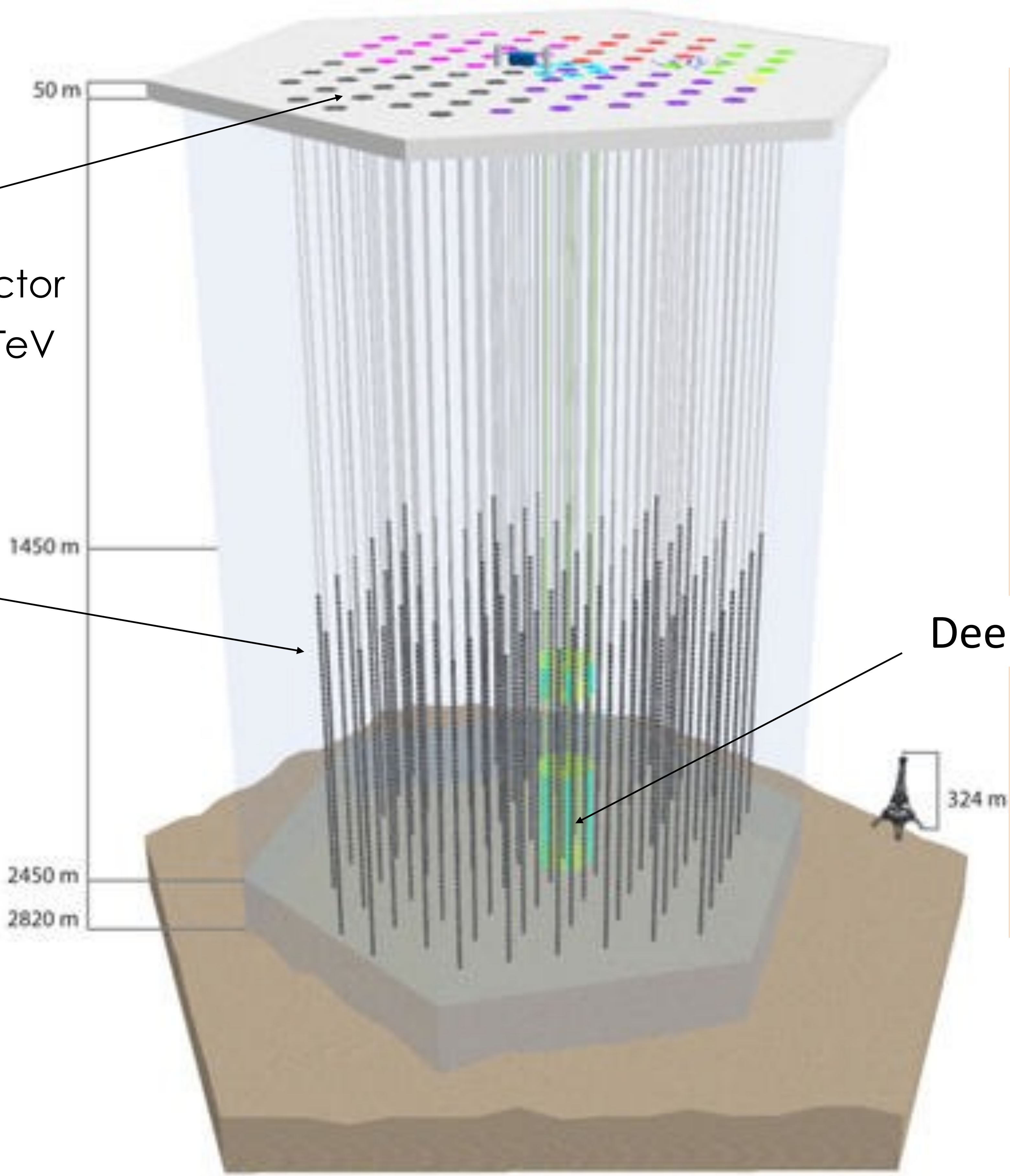
InIce

80-86 Strings,

60 Optical

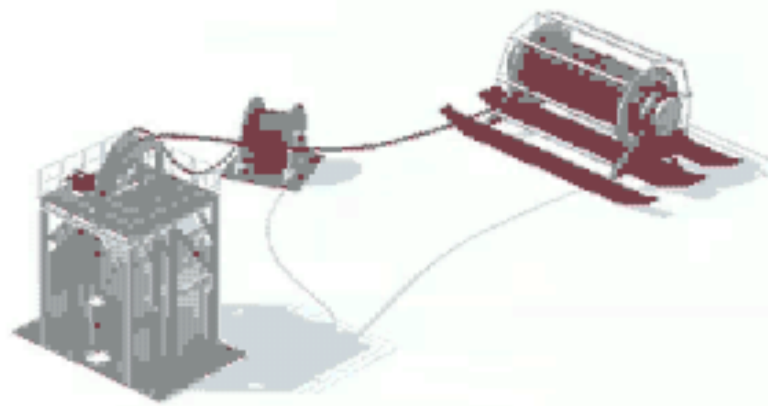
Modules per

String



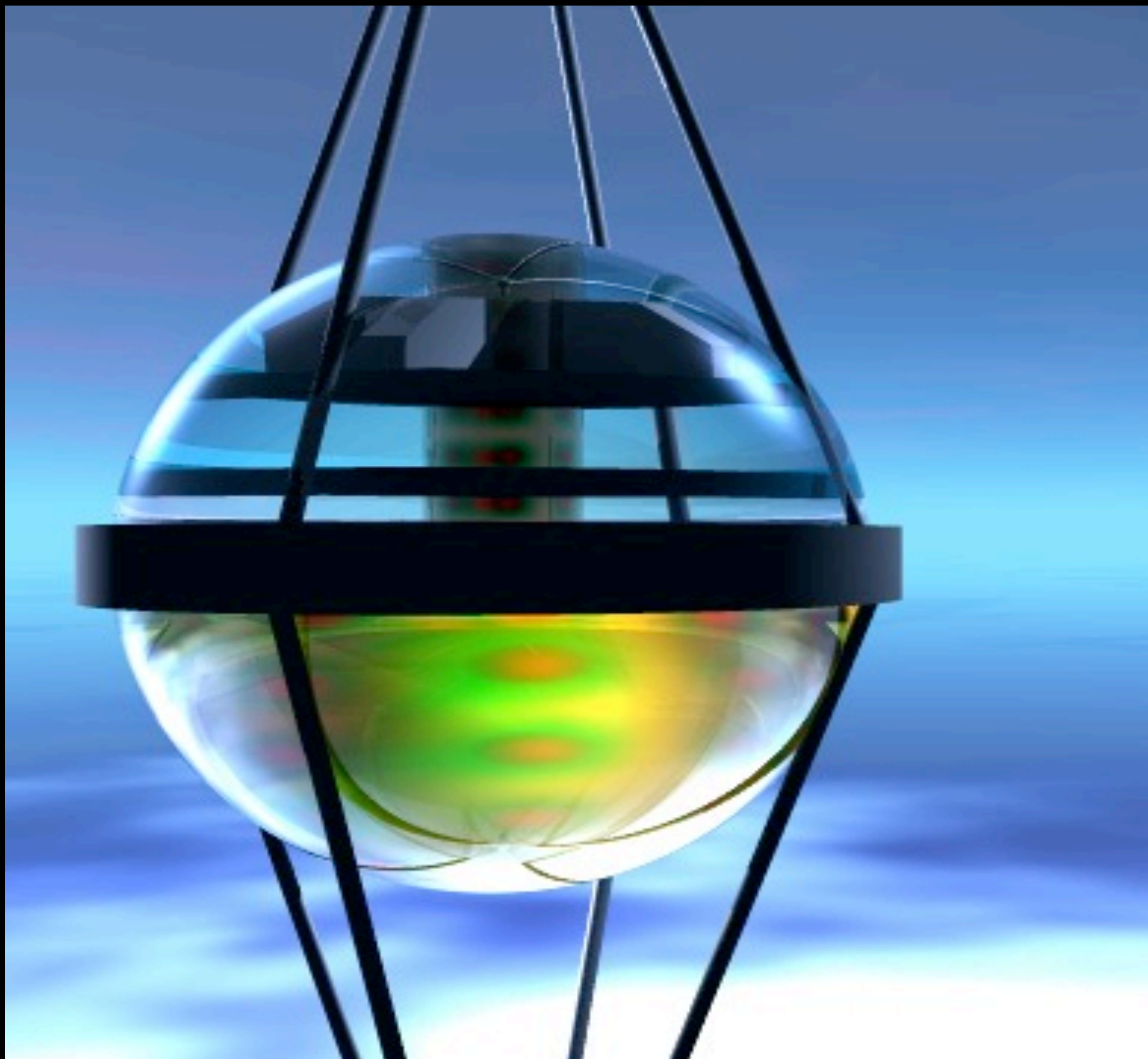
Deep Core

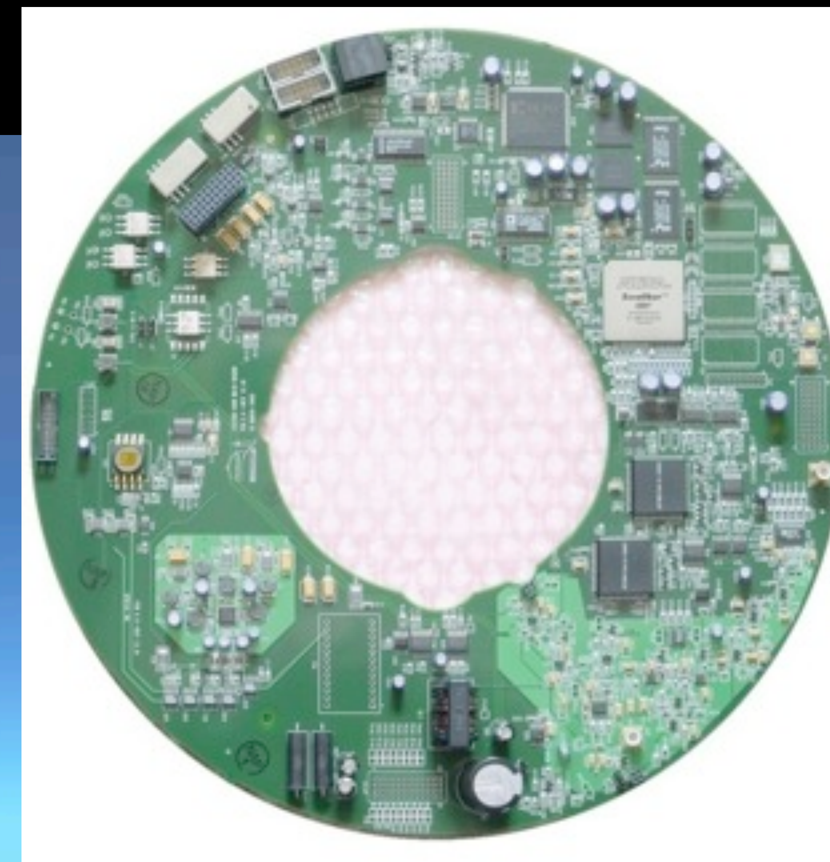
- ✓Completion: January 2011
- ✓**2008: 40 Strings (This Analysis)**
- ✓2009: 59 Strings
- ✓2010: 79 Strings



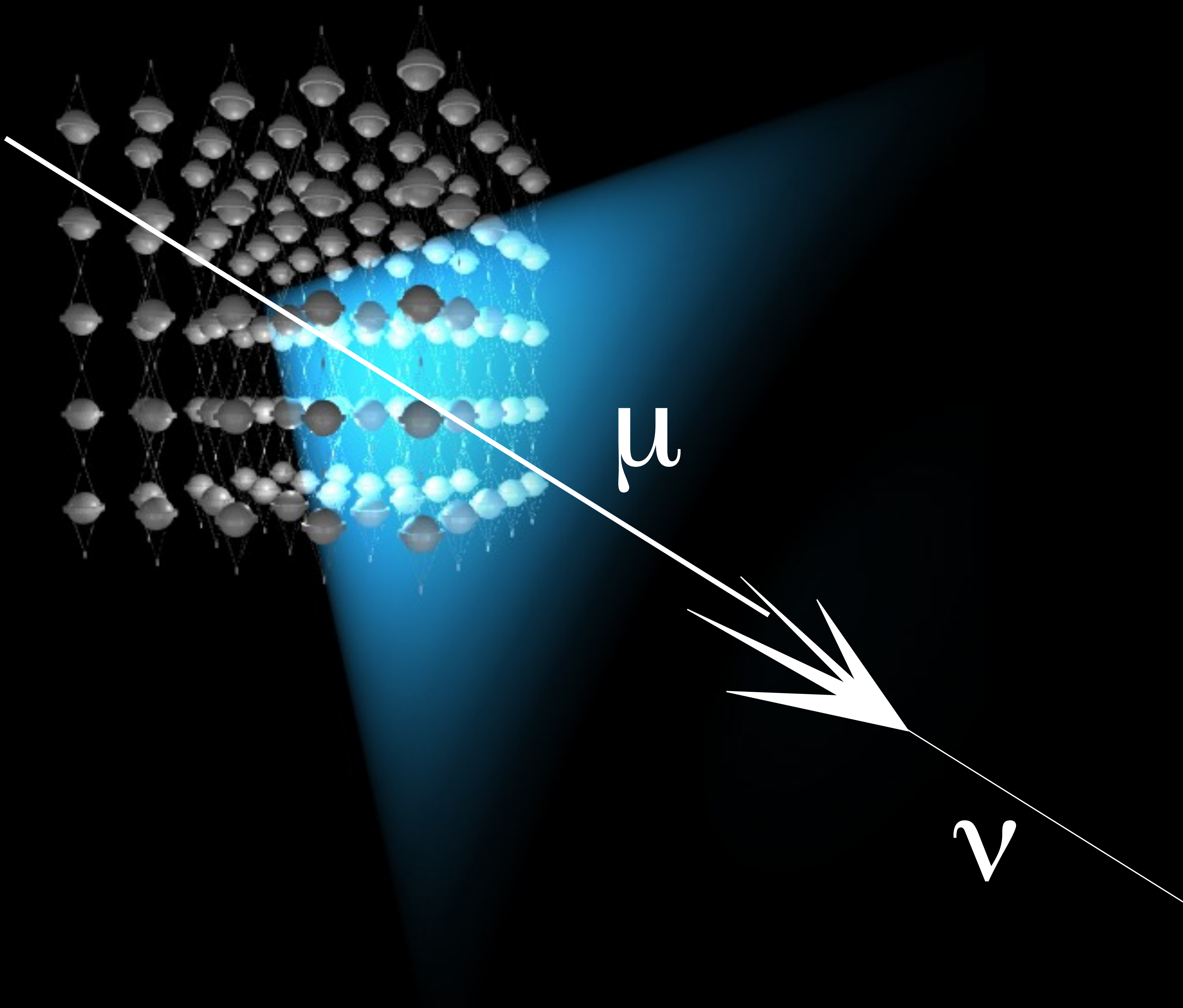
Digital Optical Module

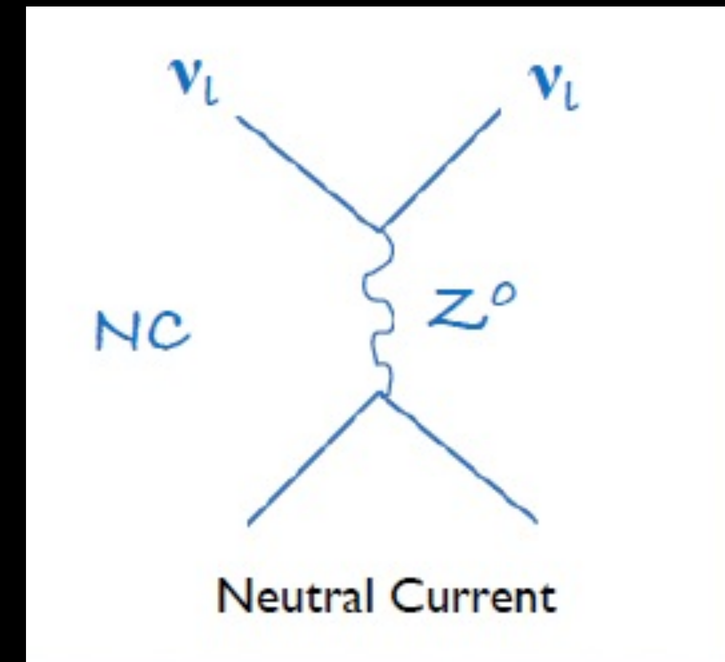
MainBoard

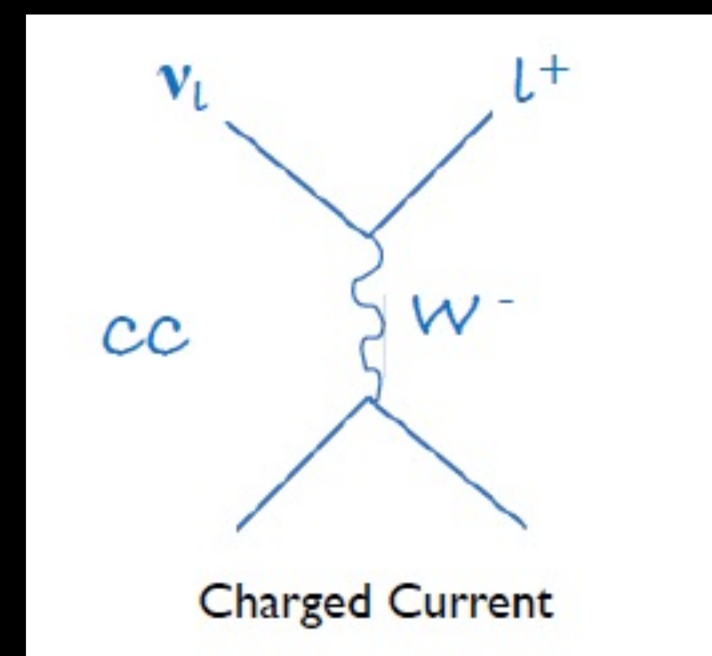




Photomultiplier Tube



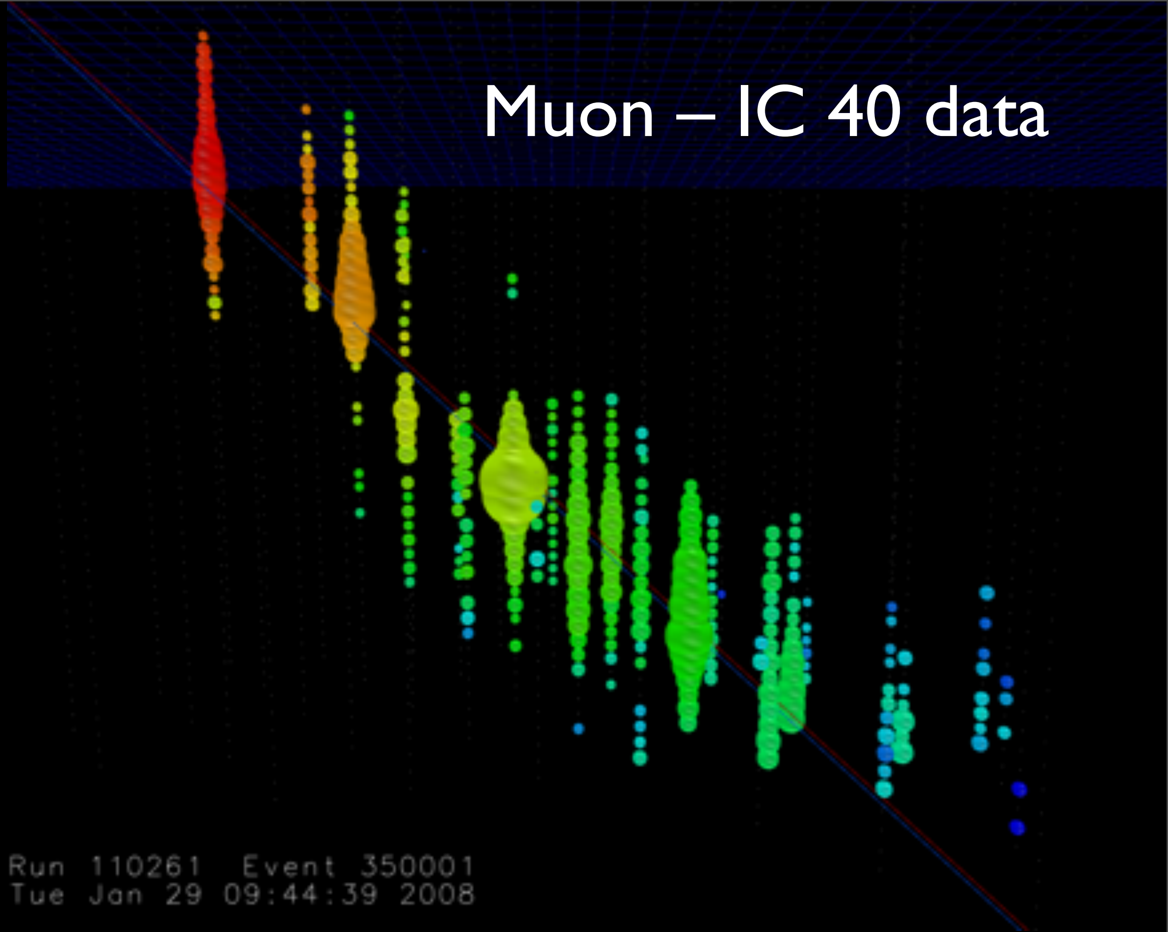




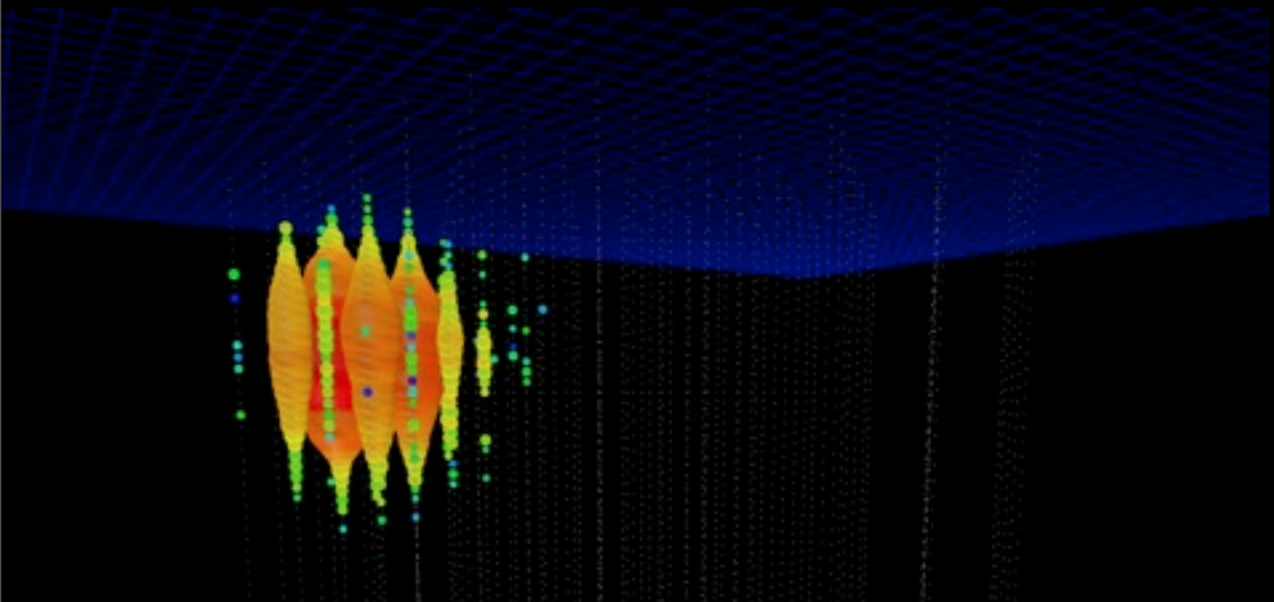
- Cherenkov cone provides direction

Event Topologies

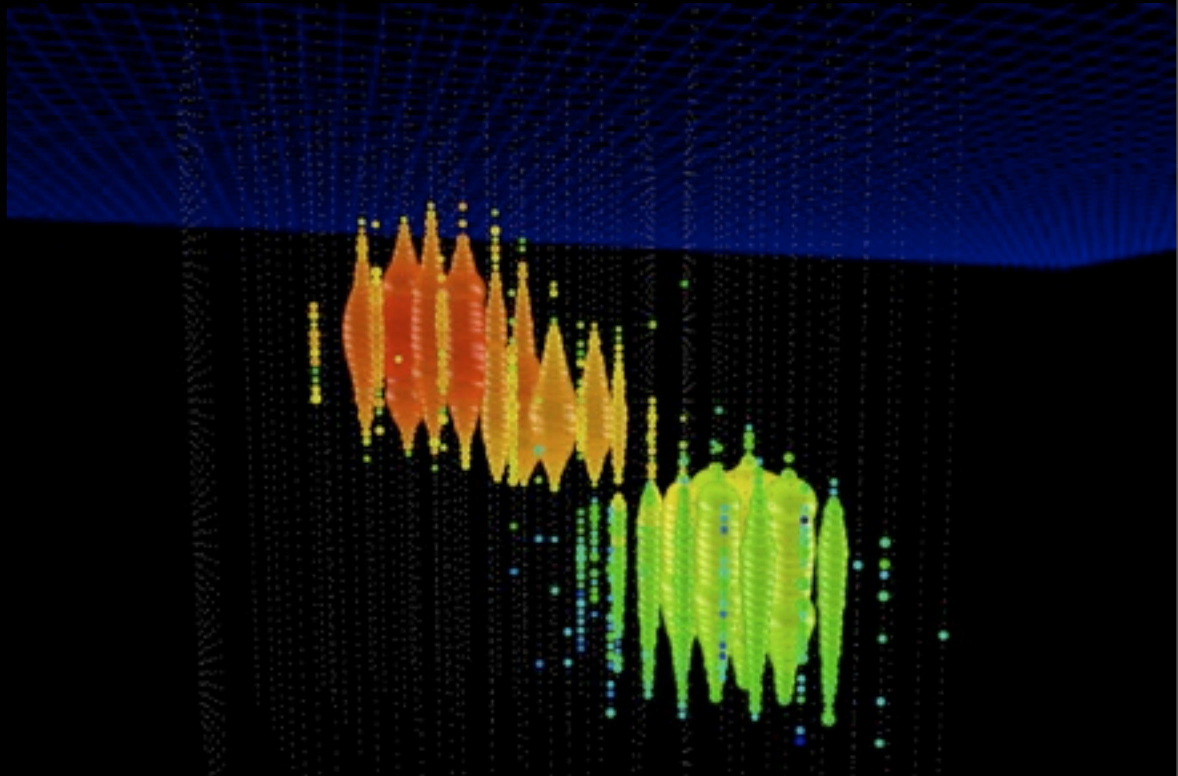
- ν_μ produce μ tracks
  - Angular Res ~ 0.7^0 Eres log(E)~0.3
- ν_e CC, ν_x NC create showers
  - ~ point sources, 'cascades'
  - Eres log(E)=0.1-0.2
- ν_τ double bang events, others



Muon – IC 40 data

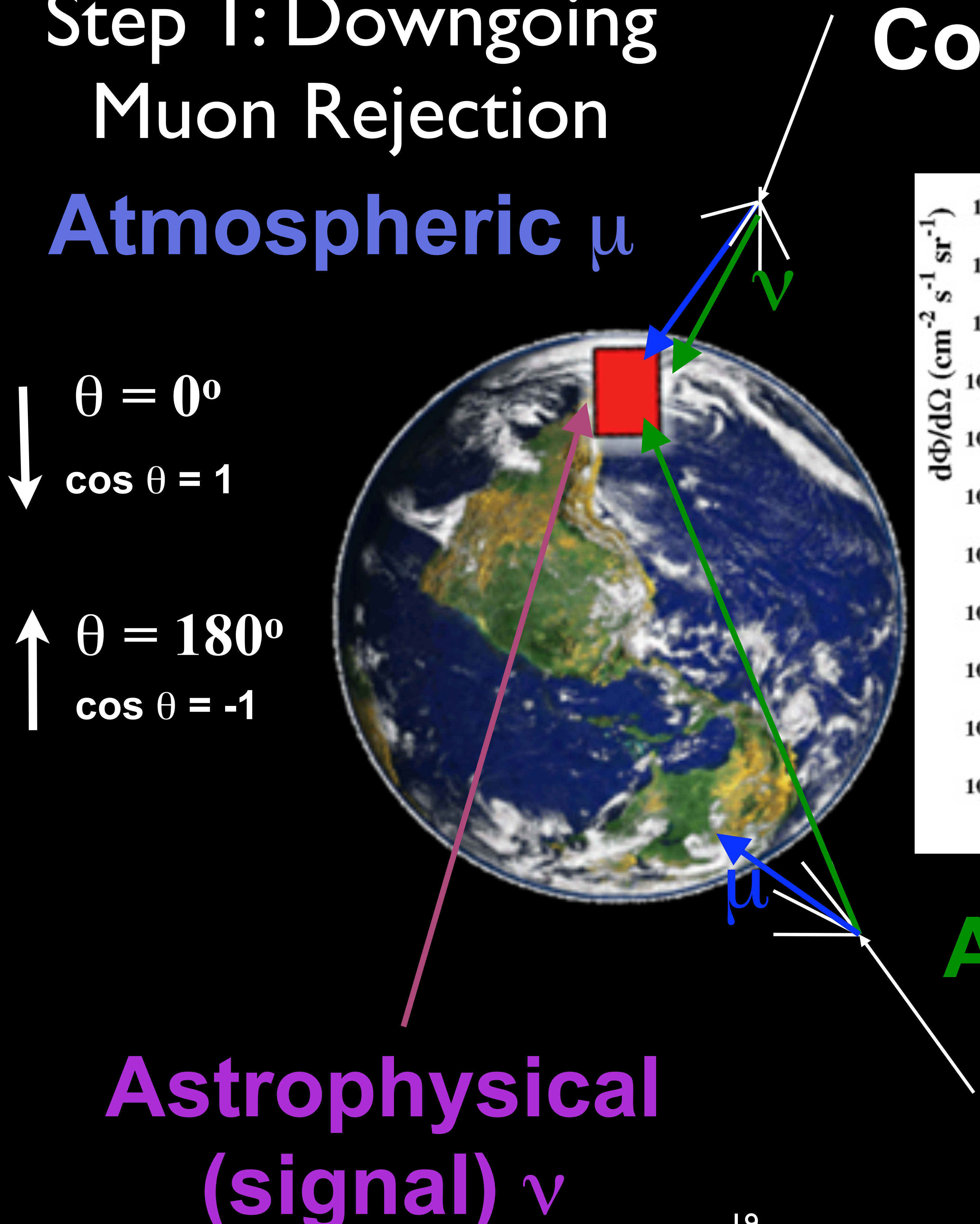


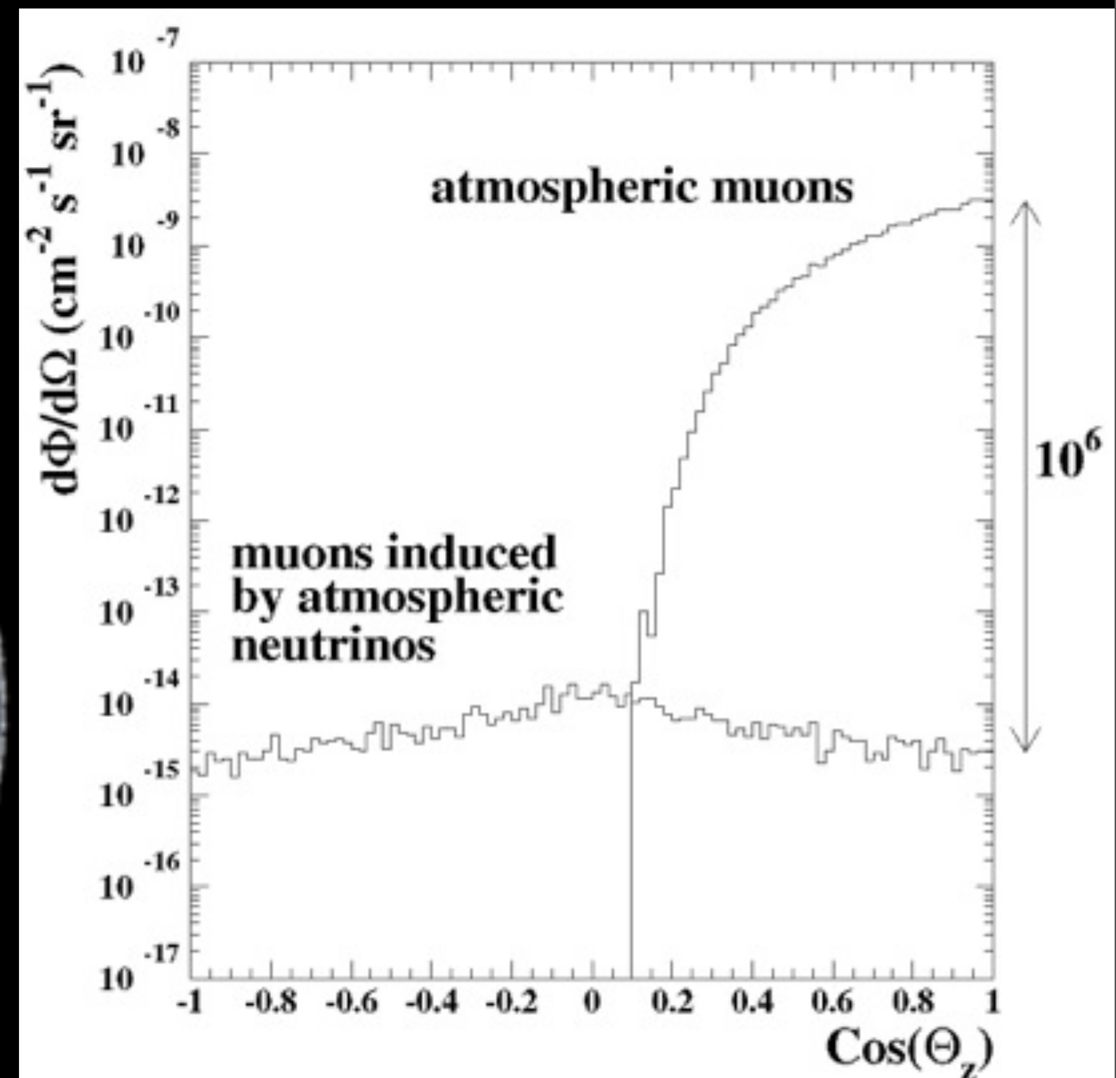
350 TeV ν_e simulation



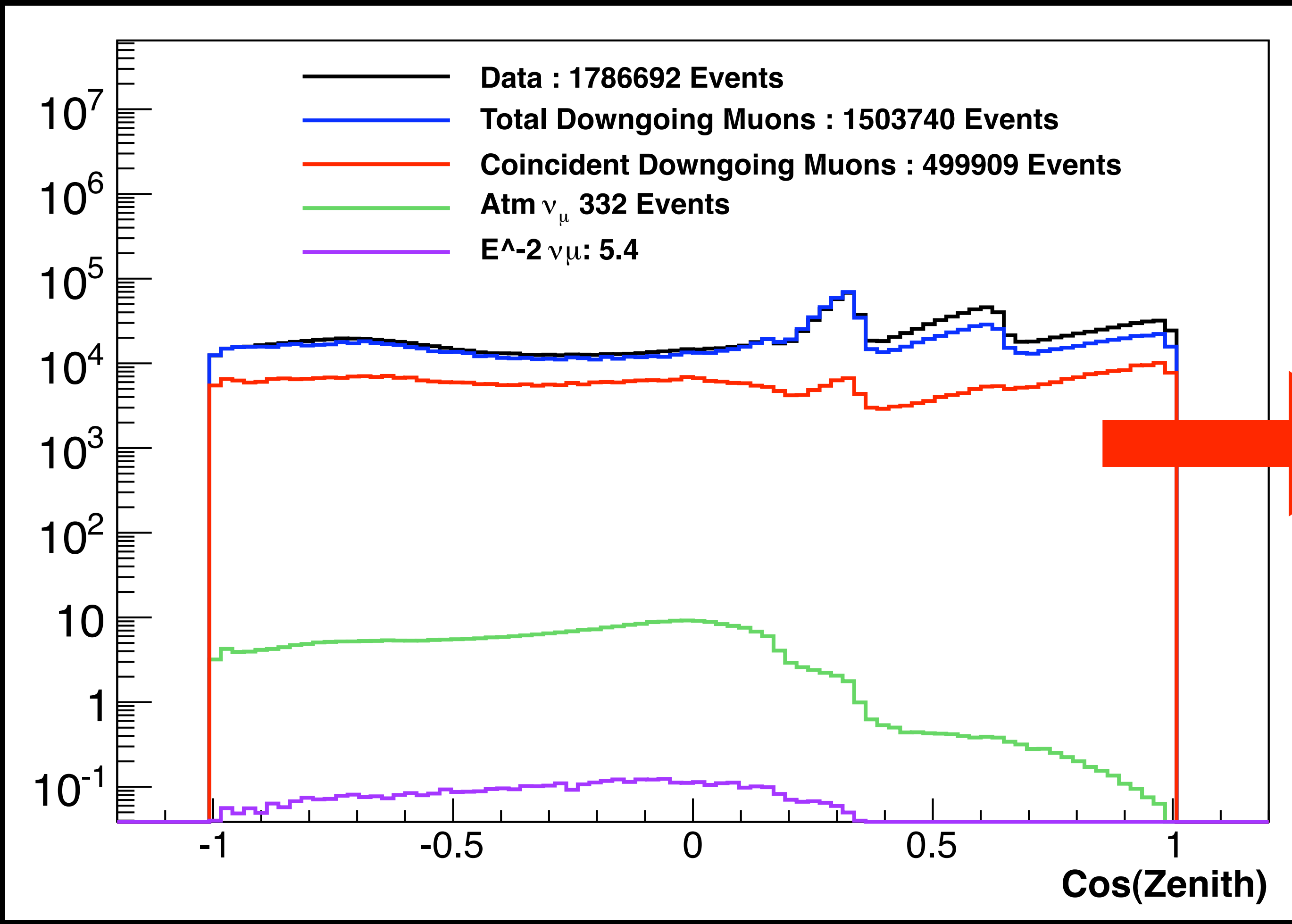
16 PeV ν_τ simulation

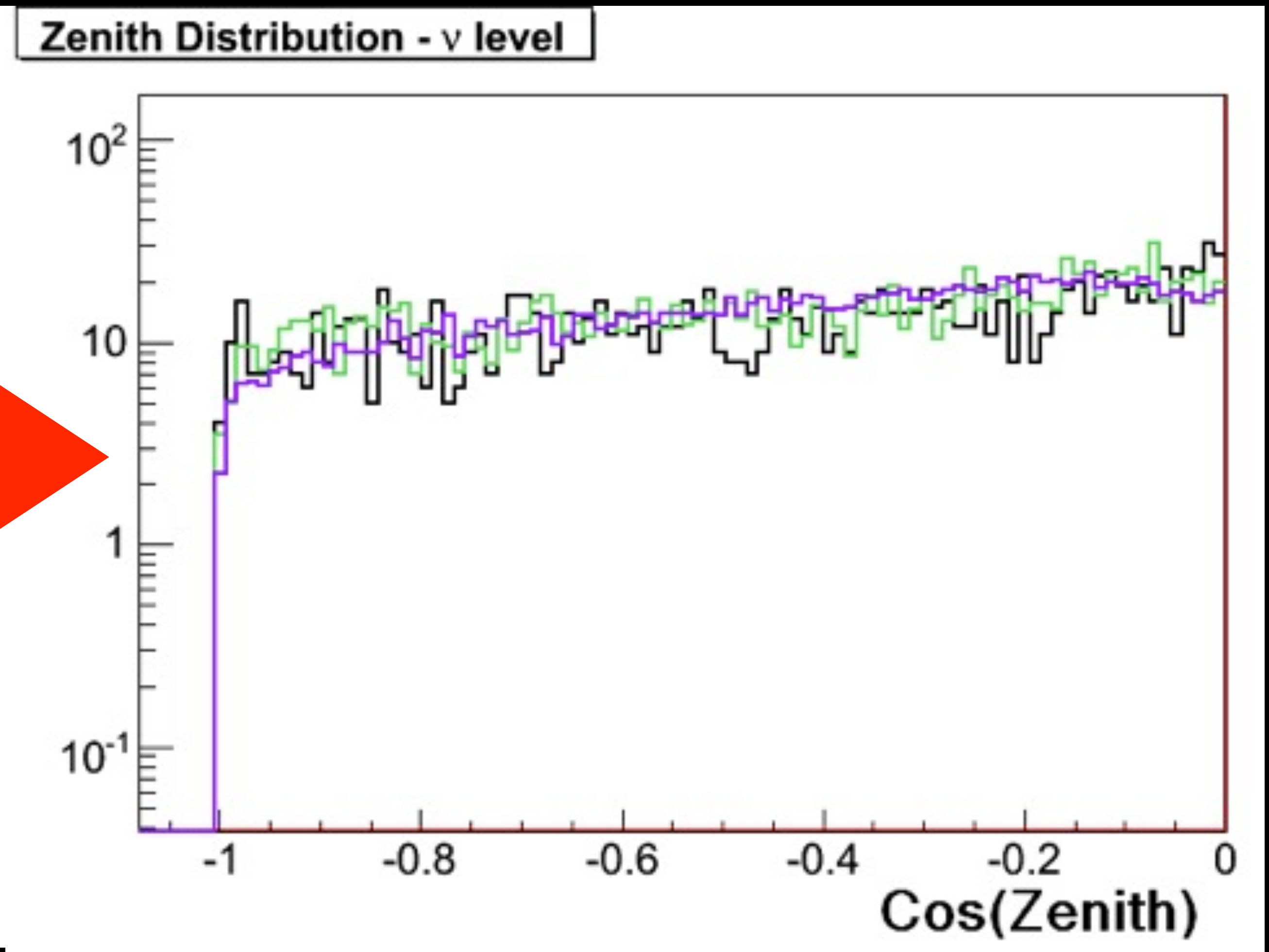
Step 1: Downgoing Muon Rejection





Event Selection

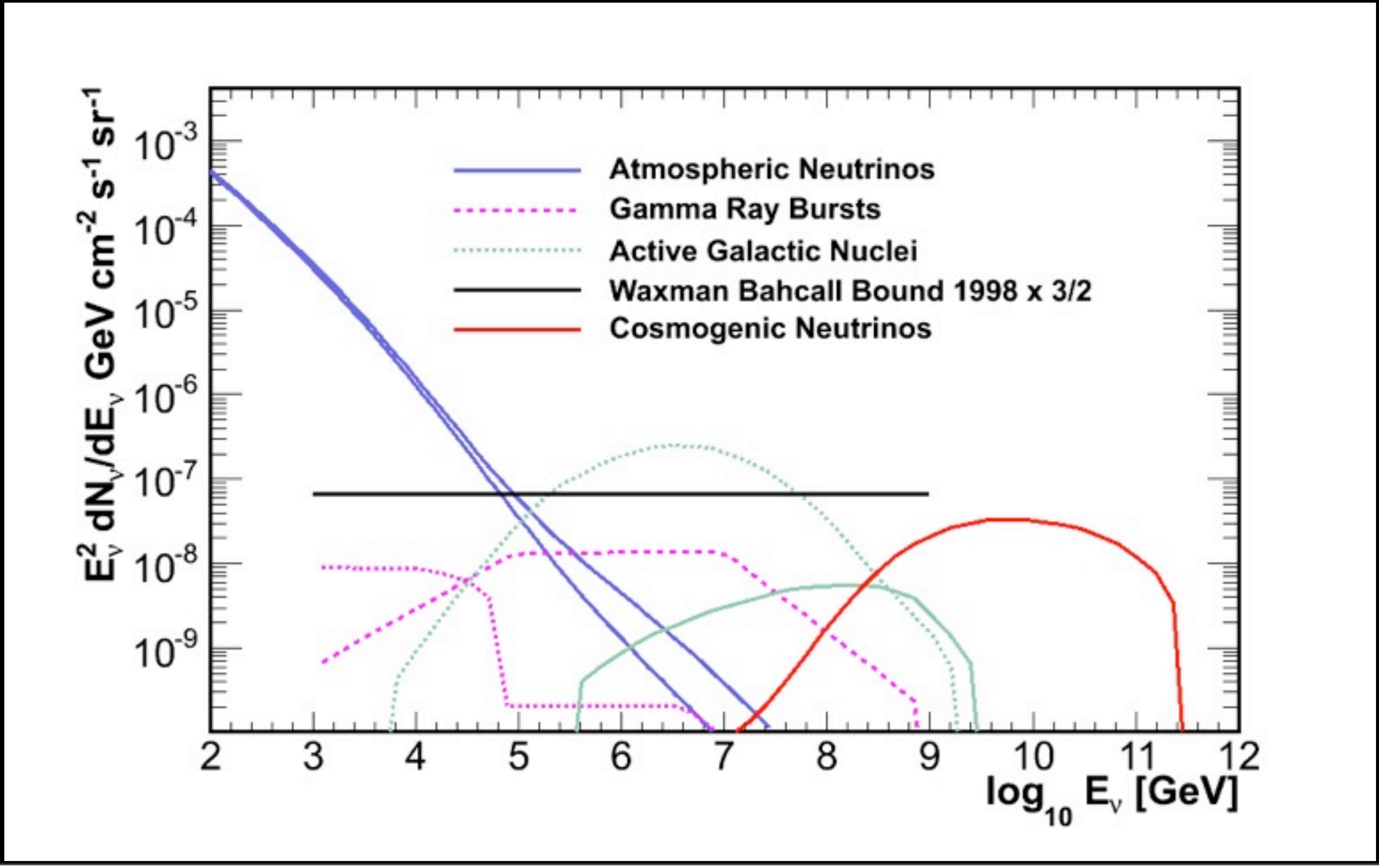




Apply quality cuts on **Data**, **Atmospheric Muon MC**, and **Atmospheric Neutrino MC**

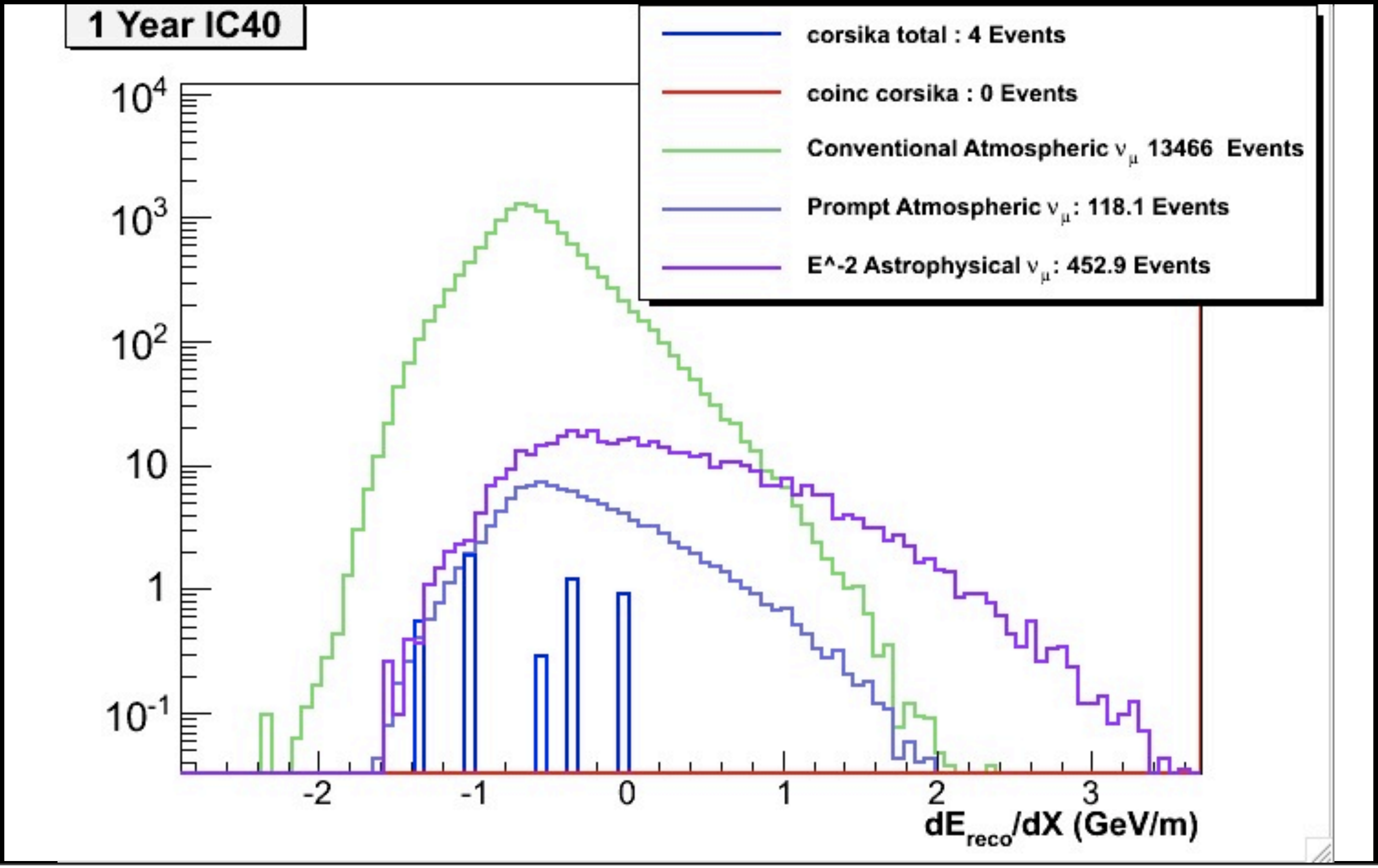
Step 2: Diffuse Analysis Strategy

Find an excess of astrophysical neutrinos (E^{-2}) over atmospheric neutrinos ($E^{-3.7}$) at the high-energy tail of the energy distribution



Step 2: Diffuse Analysis Strategy

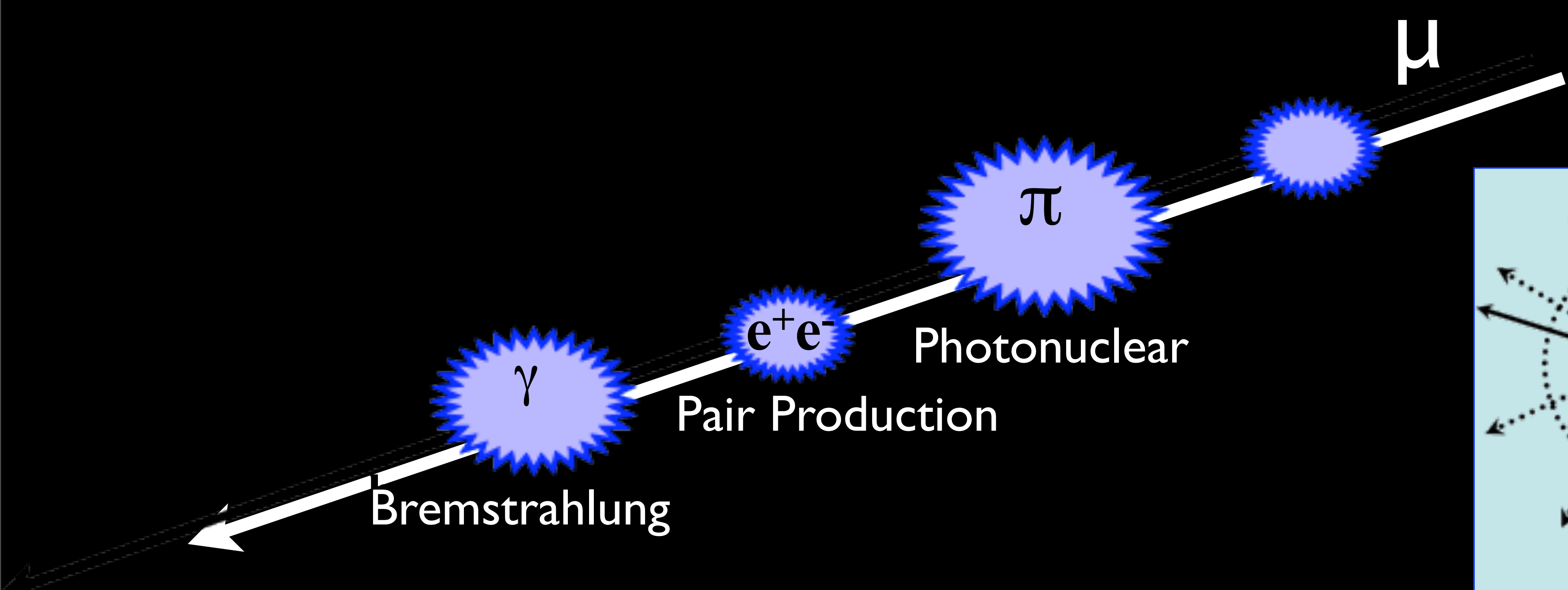
Find an excess of astrophysical neutrinos (E^{-2}) over atmospheric neutrinos ($E^{-3.7}$) at the high-energy tail of the energy distribution

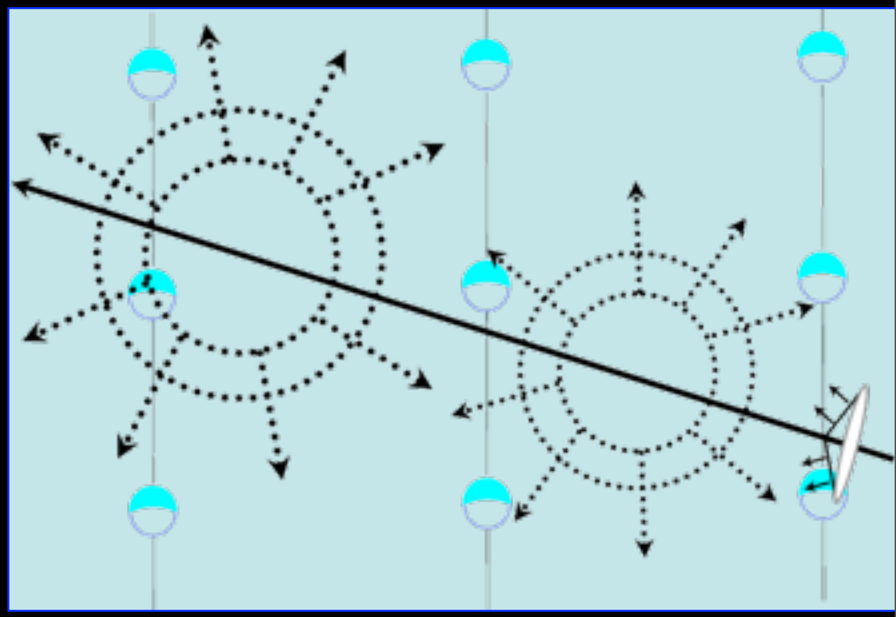


- High Energy Neutrino Astronomy
- The IceCube Detector
- **Energy Reconstruction**
- Diffuse Analysis Method
- Final Analysis Results from 2008

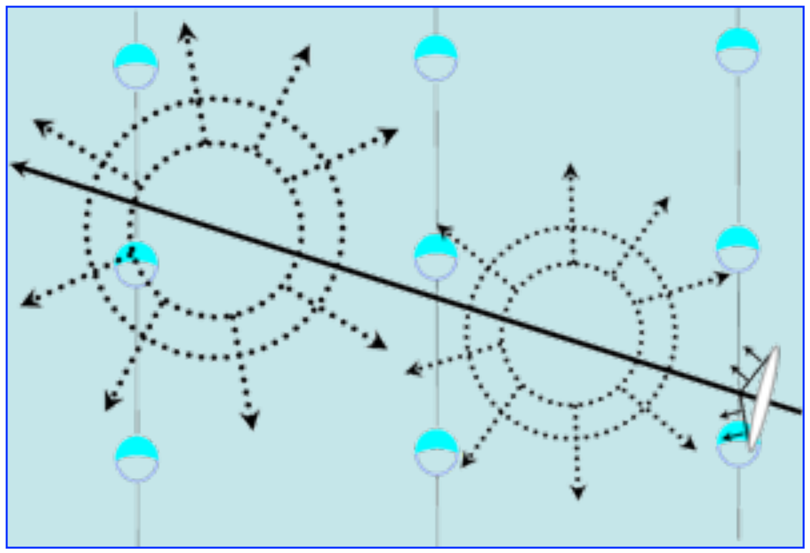
Energy Reconstruction

- Convert what is measured, Cherenkov light, to an estimate of the Muon energy.
- Simplest estimation: **Number of Triggered Optical Modules (NCh)**
- More Sophisticated: **Muon Energy Loss (dE/dX)**

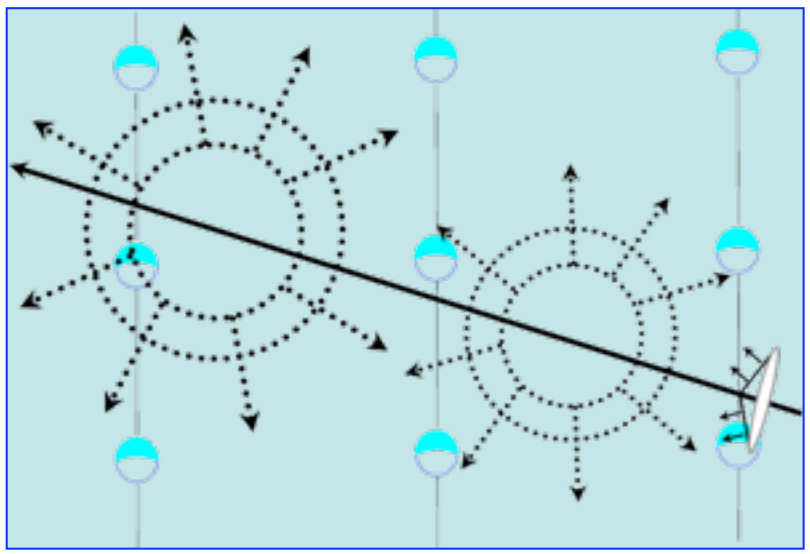




Reconstructing The Muon Energy Loss

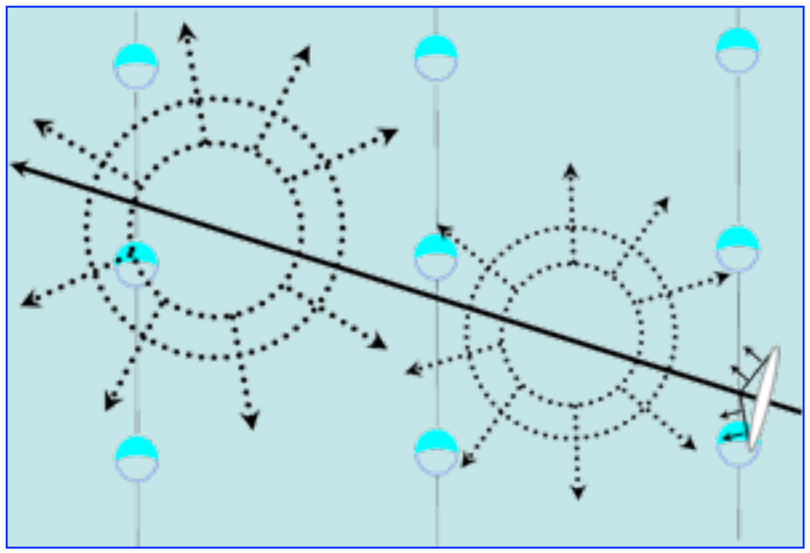


Reconstructing The Muon Energy Loss



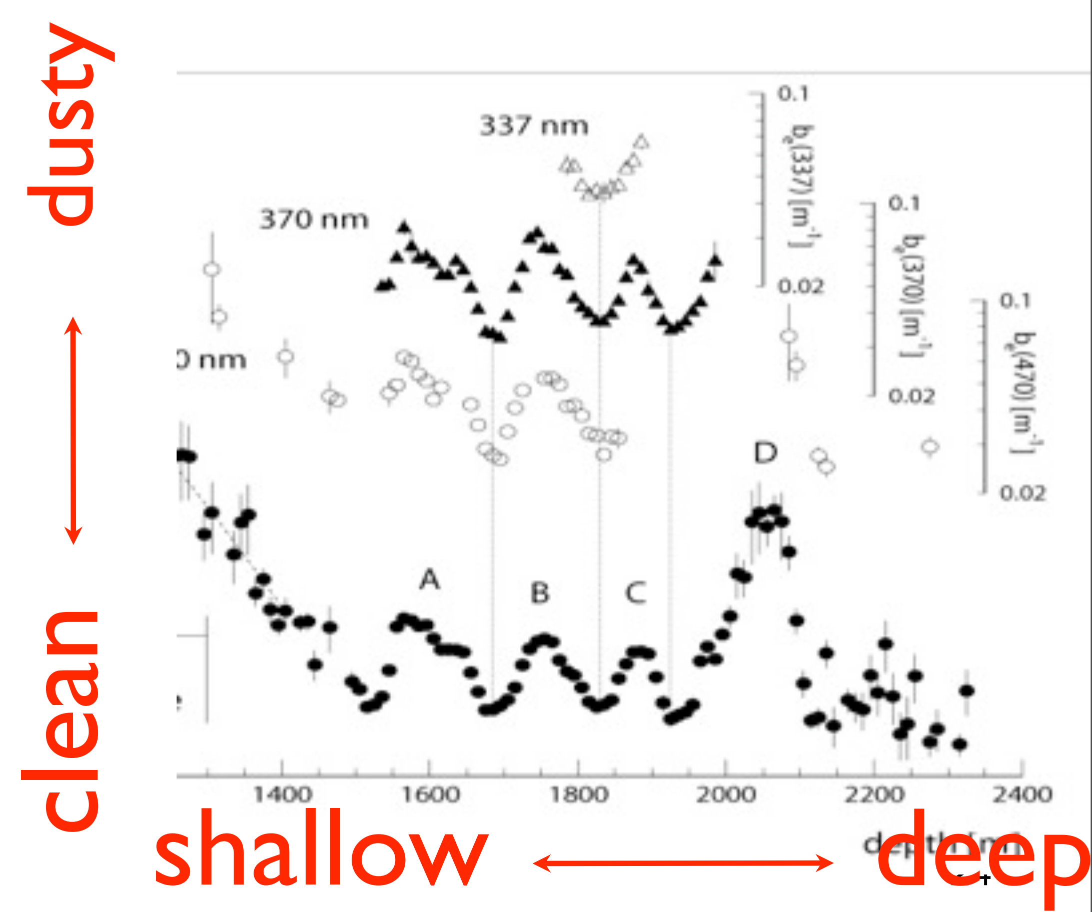
Approximate as:

Reconstructing The Muon Energy Loss

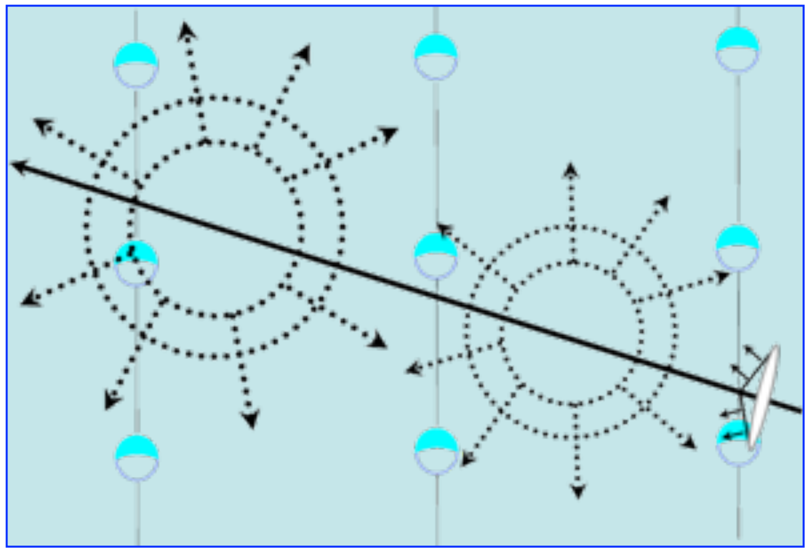


Approximate as:

Incorporate Ice Properties:



Reconstructing The Muon Energy Loss



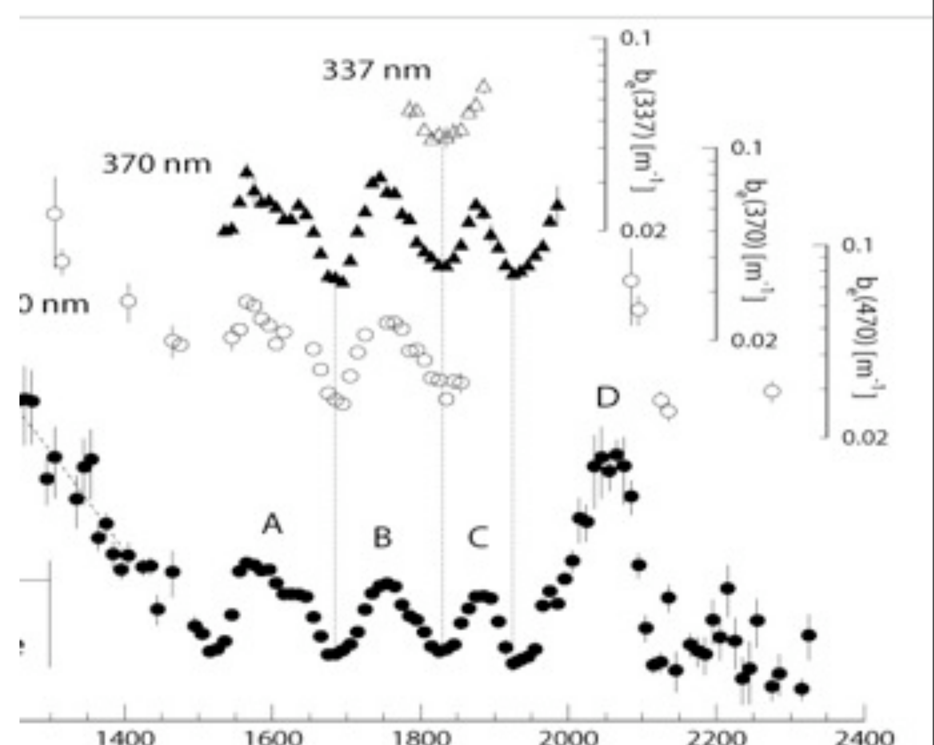
Formulate LLH:

Approximate as:

Incorporate Ice Properties:

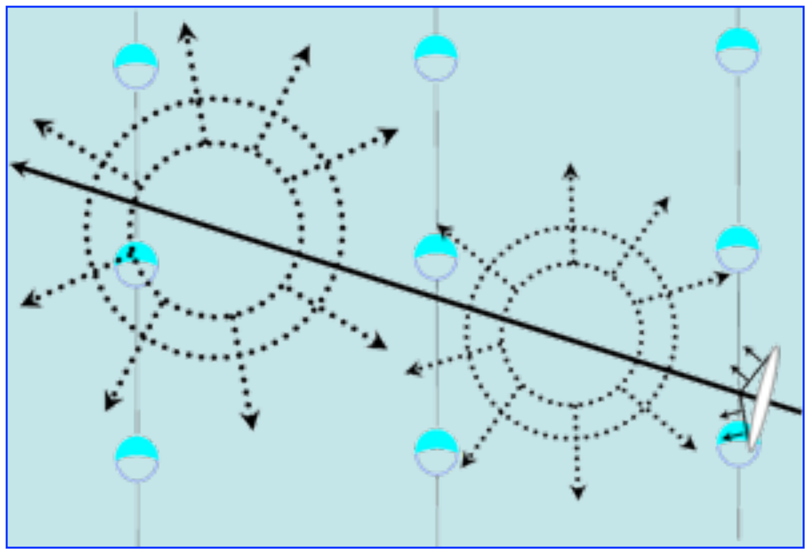
dusty

clean



shallow deep

Reconstructing The Muon Energy Loss

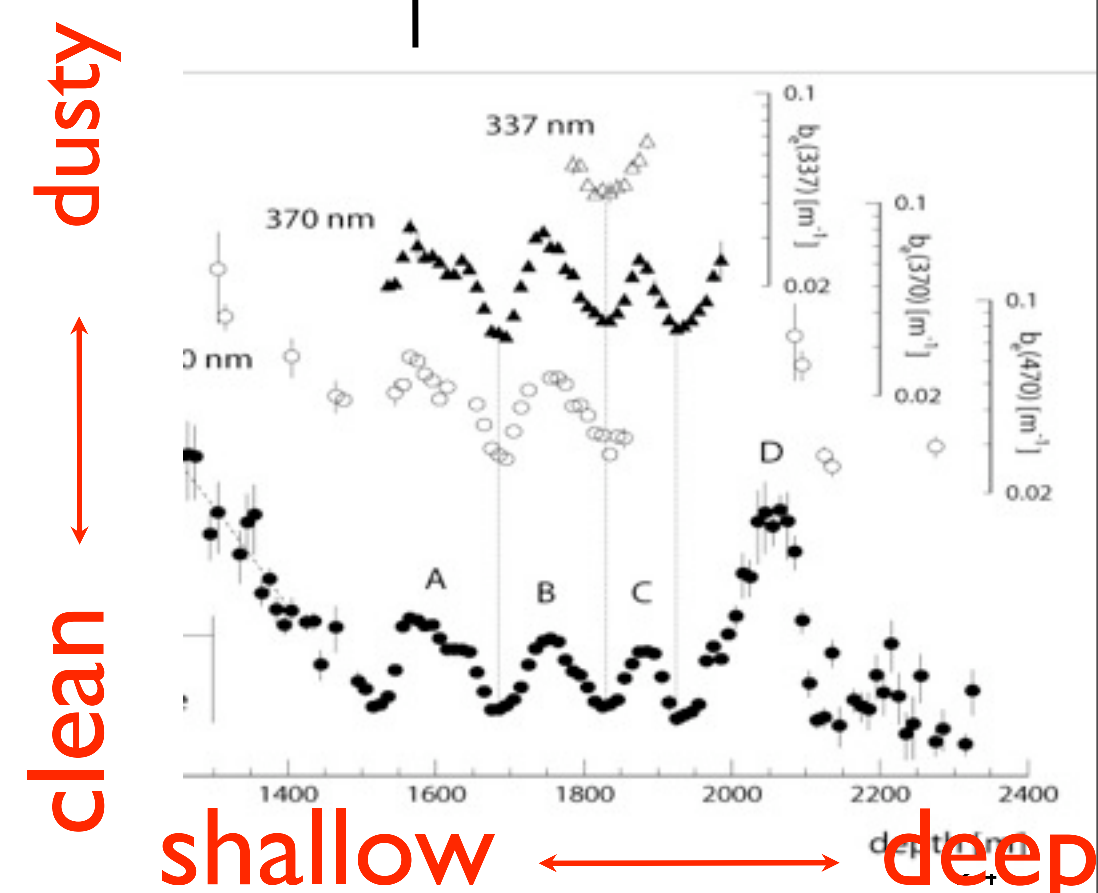


Formulate LLH:

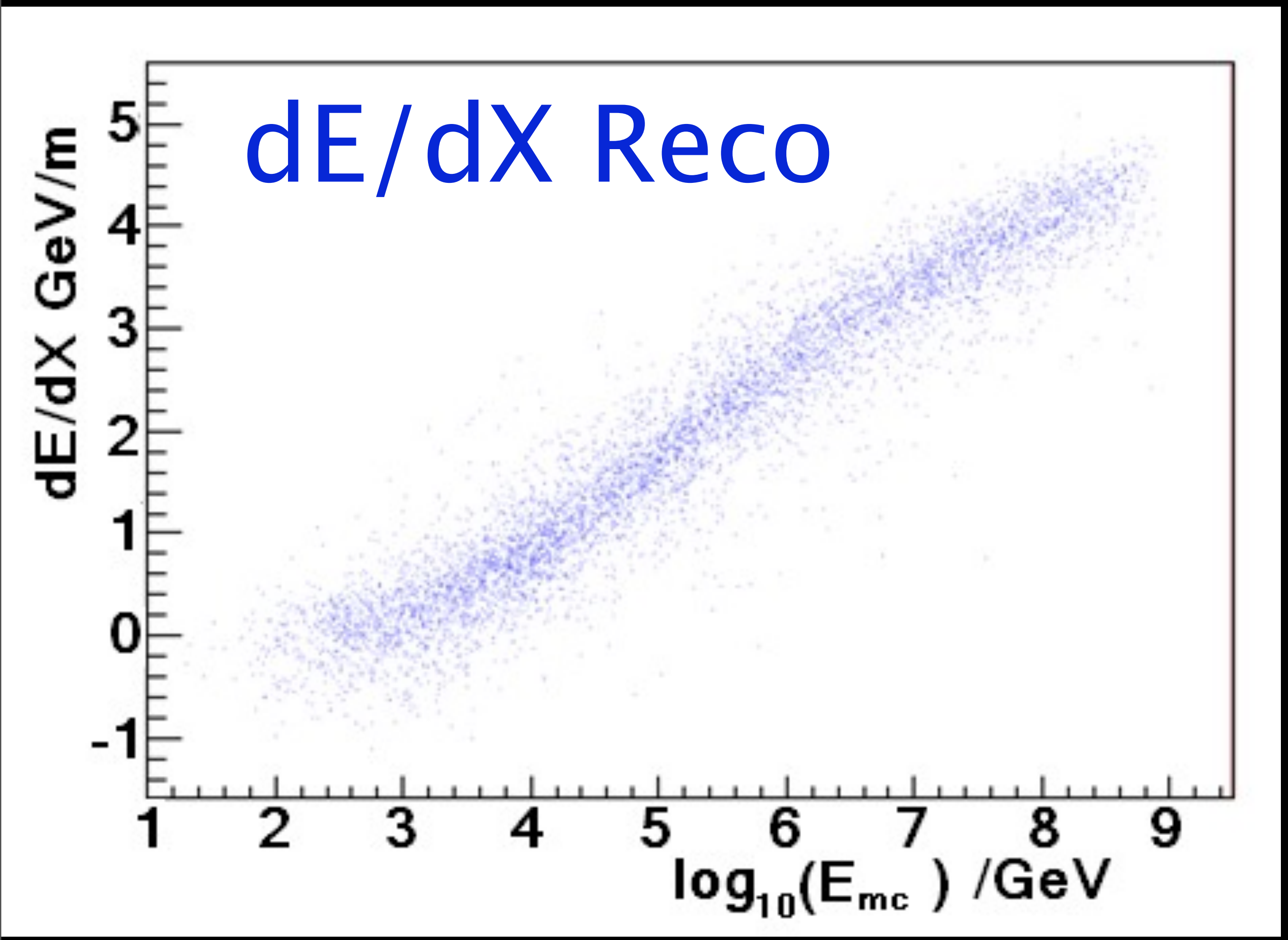
$$-\log P(\{n_i\}\,|\,\{\mu_i\}) = -\sum_{i=1}^{k} n_i \log(\mu_i/\mu) - N\log\mu + \mu$$

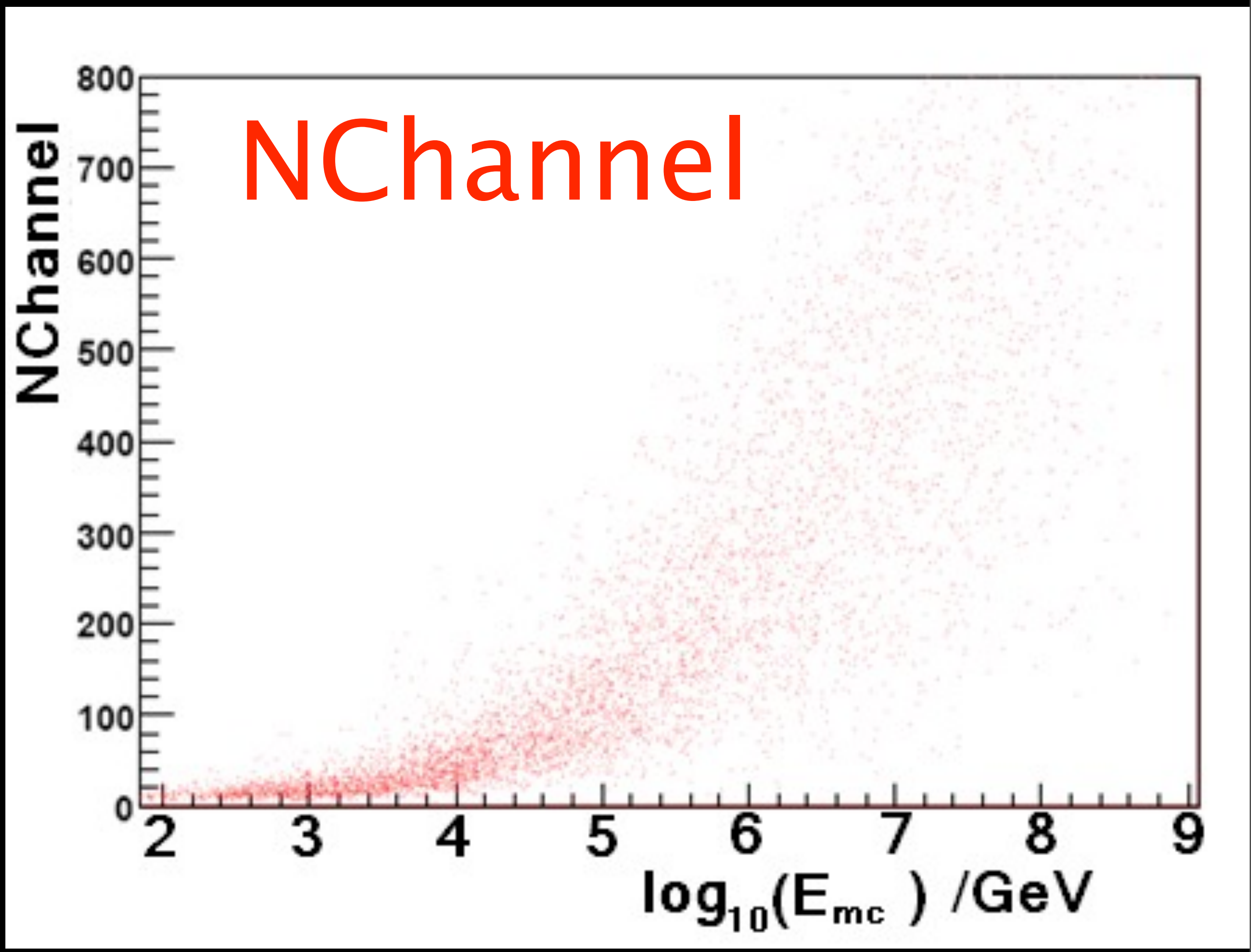
Approximate as:

Incorporate Ice Properties:



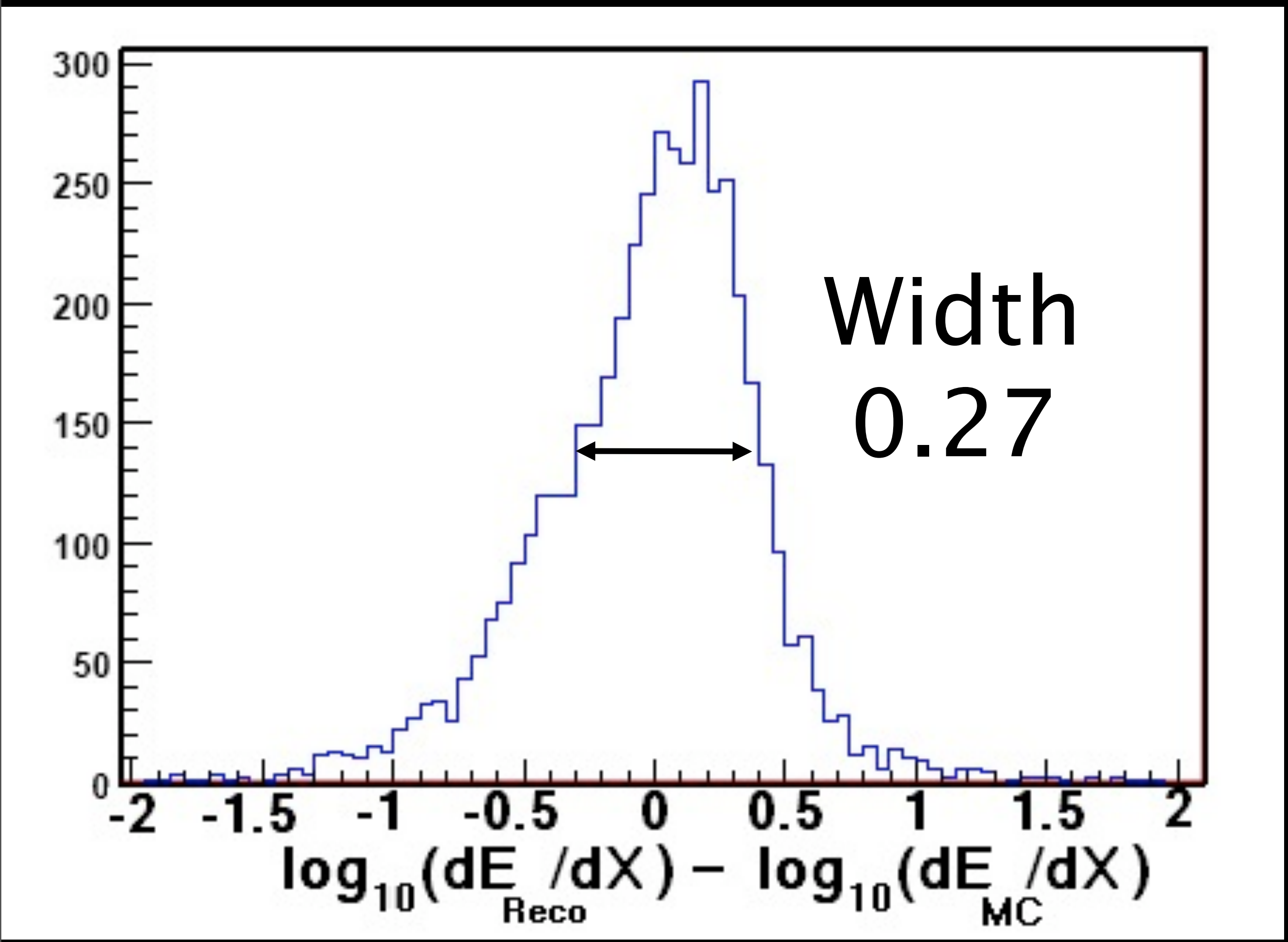
Muon Energy Correlation – 40 Strings

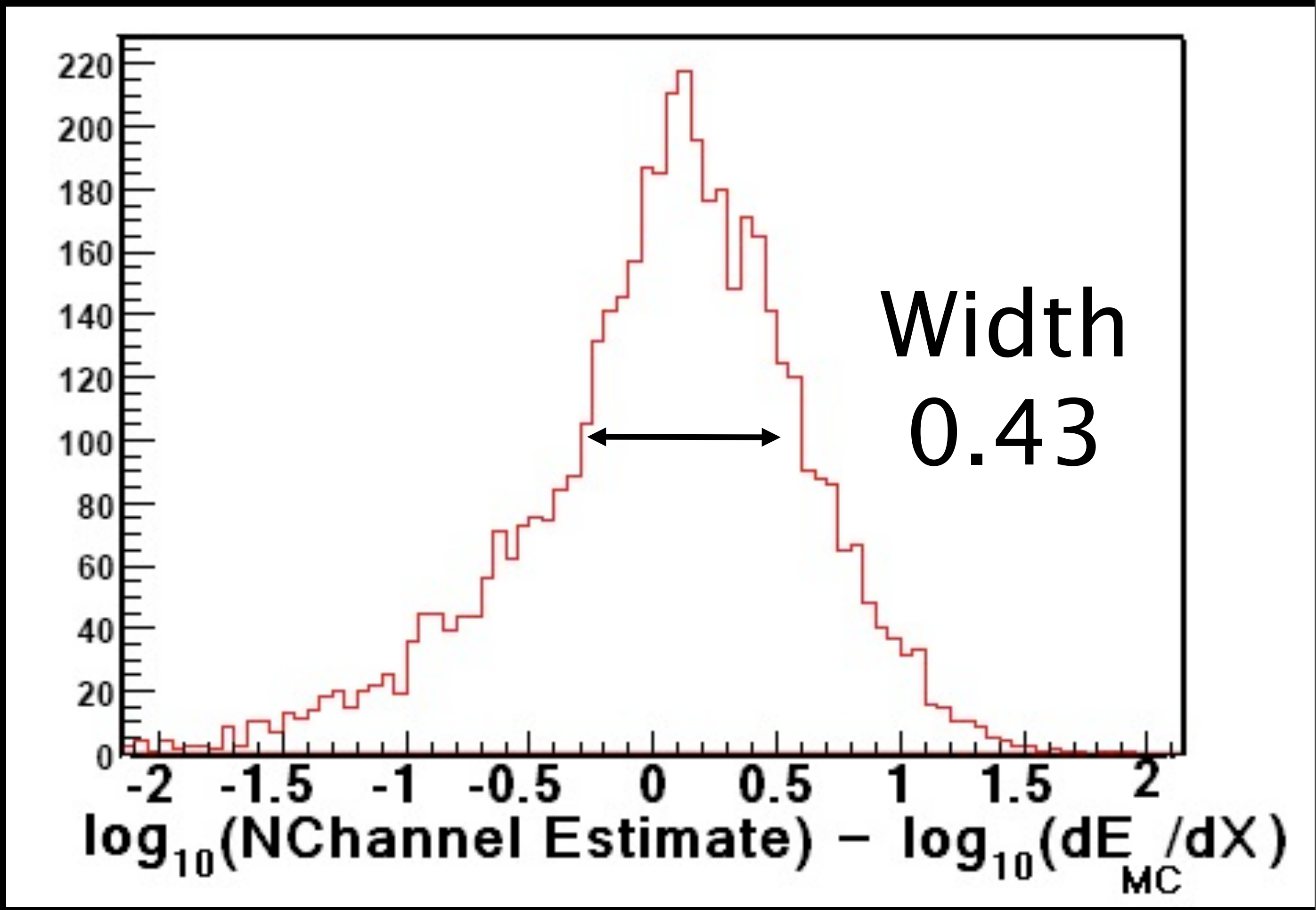




- dE/dX reco more linearly correlated with Muon energy

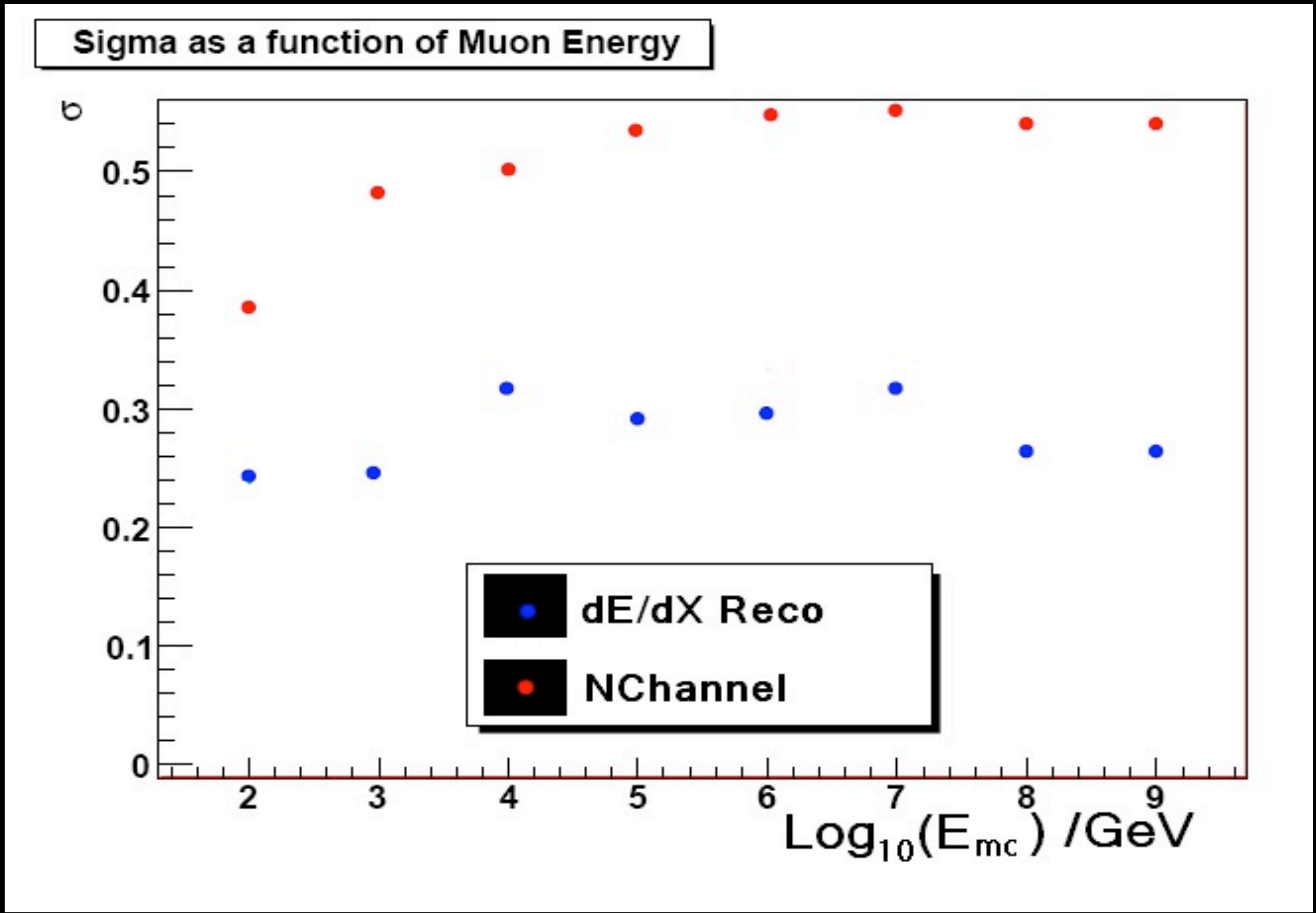
Energy Resolution – 40 Strings





- dE/dX reco has narrower energy resolution

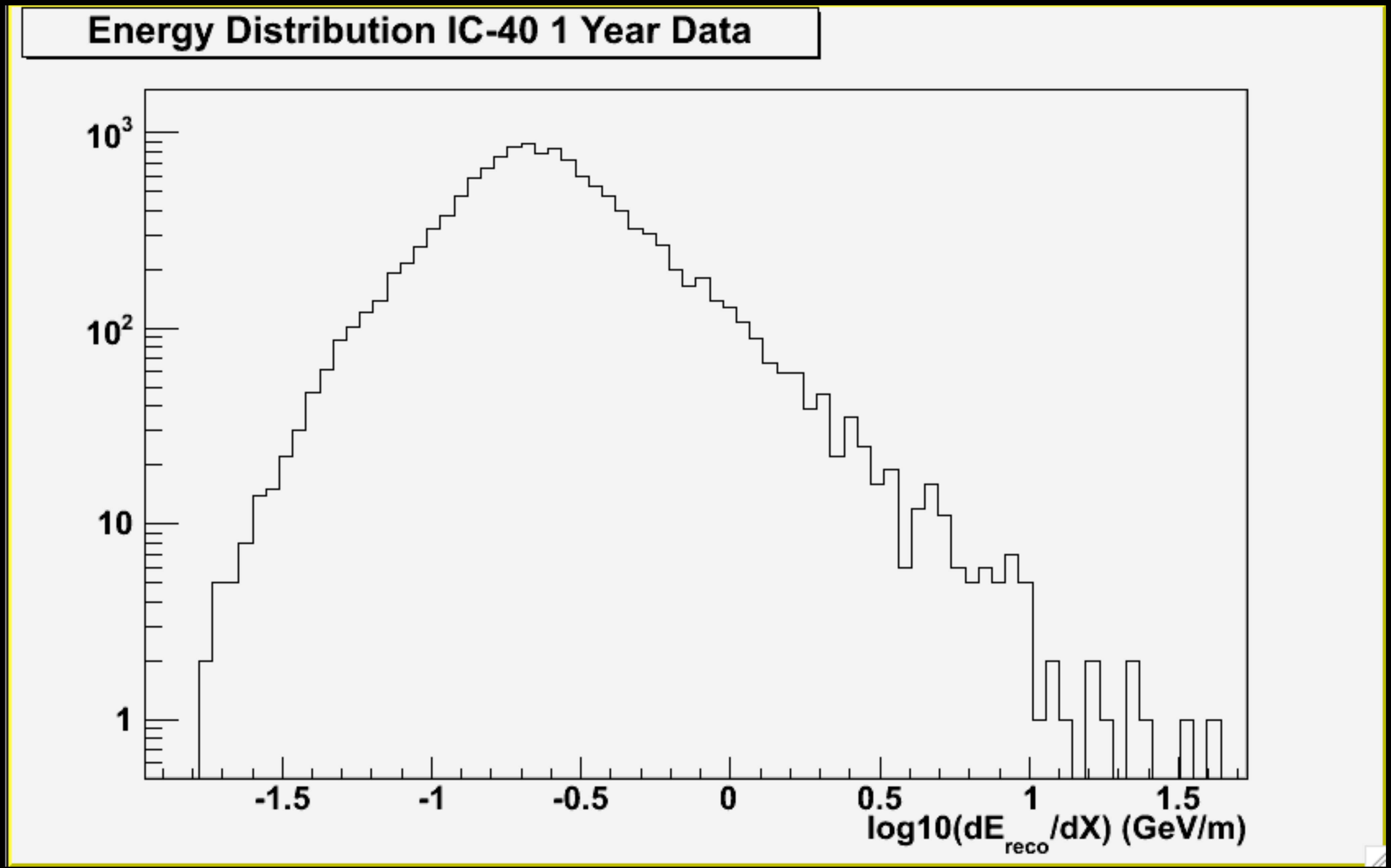
Energy Resolution Vs. Muon Energy – 40 Strings




High Energy Neutrino Astronomy
The IceCube Detector
Muon Energy Reconstruction
Diffuse Analysis Method
Final Analysis Results from 2008
28

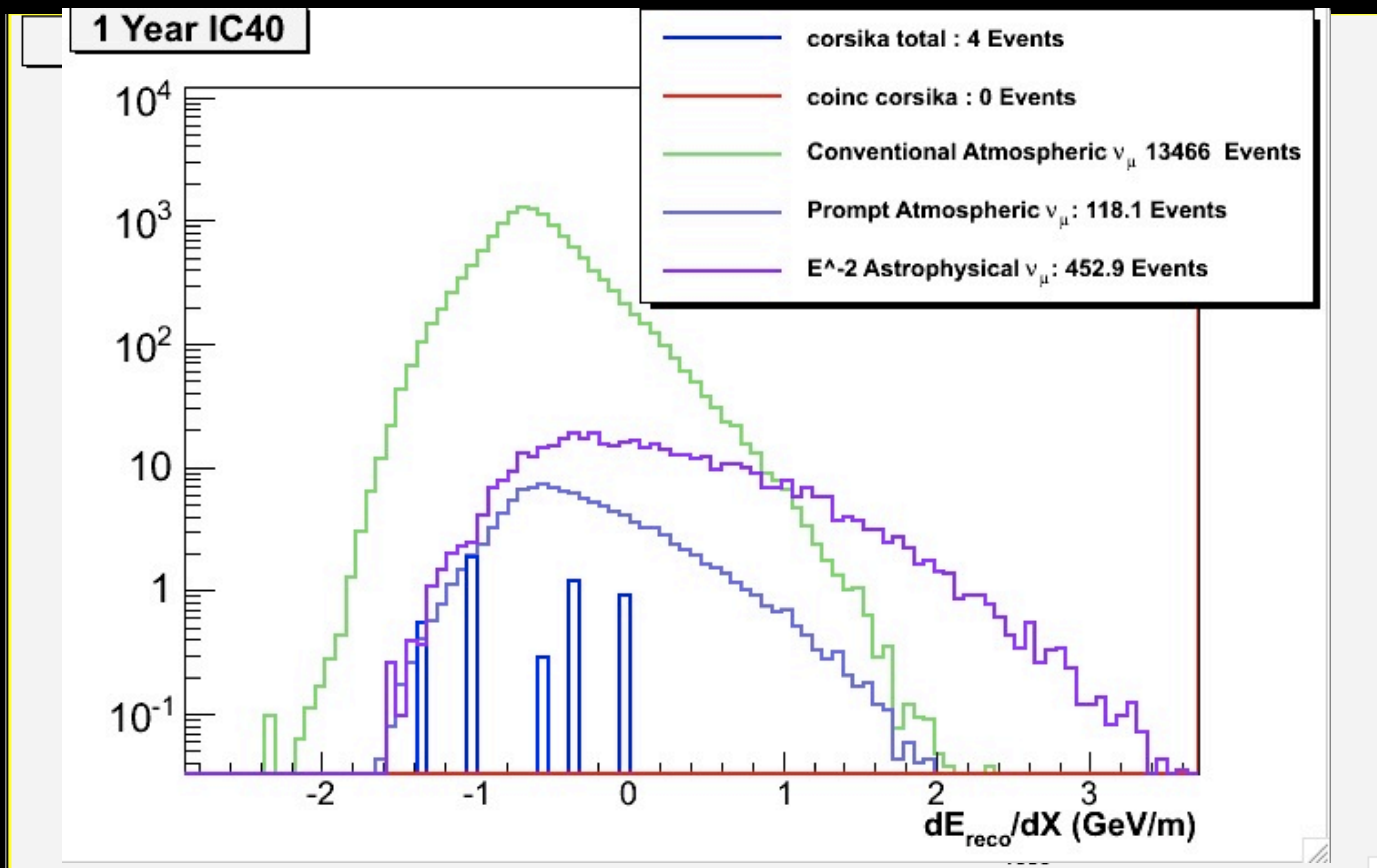
Analysis Method

Fit contributions from Atmospheric and Astrophysical Neutrinos to the Data



Analysis Method

Fit contributions from Atmospheric and Astrophysical Neutrinos to the Data



Likelihood Method

- Likelihood - Product over binned Poisson Probabilities:

$$L = P\left(\{n_i\}\,|\,\{\mu_i\}\right) = \prod_{i=1}^{k} \frac{\mu_i^{n_i}}{n_i!} e^{\mu_i}$$

$$\mu_i = \epsilon\left(N_c p_{c,i} \Delta\gamma_c + N_p p_{p,i} \Delta\gamma_p + N_a p_{a,i} \Delta\gamma_a\right)$$

Total Expected Events

Atmo ν **Prompt ν** **Astro ν**

$$p_{k,i} = \text{PDF of kth neutrino model}$$

$$N_k = \int \Phi_k A_{eff}$$

Effective Area

Number of Events

Final Parameter List

- Observable: **Reconstructed dE/dX**
- **Physics Parameter:**
    - Astrophysical Normalization **(N_a)**
- **Nuisance Parameters:**
    - Conventional Normalization Deviation **($1+\alpha_c$)**
    - Prompt Normalization Deviation **($1+\alpha_p$)**
    - Cosmic Ray Spectral Slope **($\Delta\gamma$)**
    - Detector Efficiency **(ε)**
    - Scattering/Absorption of Ice*

$$\Phi_a = N_a E^{-2}$$

Astrophysical Flux

Atmospheric Neutrino Flux

$$\Phi_{c,p} = (1+\alpha_{c,p})(E/E')^{\Delta\gamma}\Phi_{\mathrm{ref\ c,p}}$$

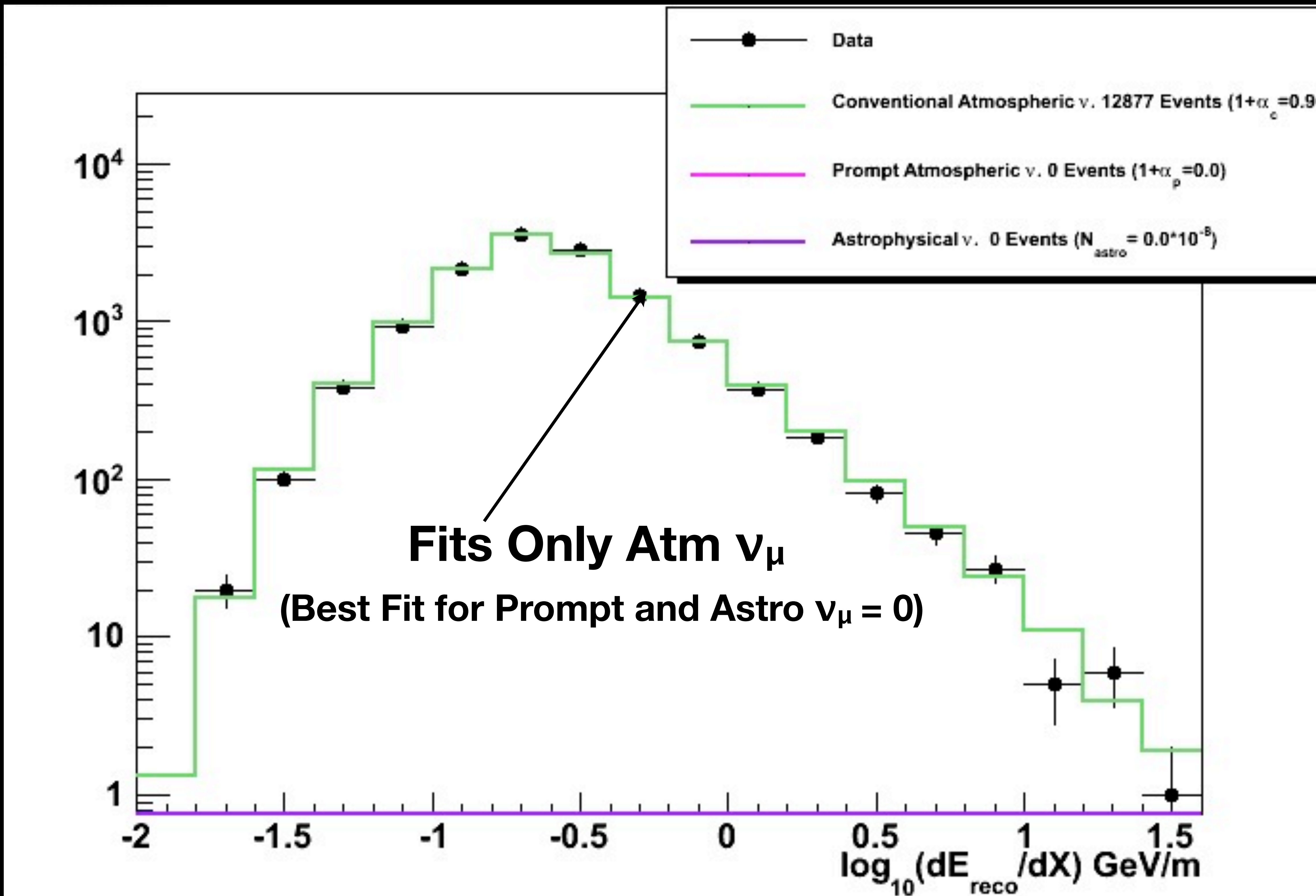
Deviation in Absolute Normalization

Shape Change

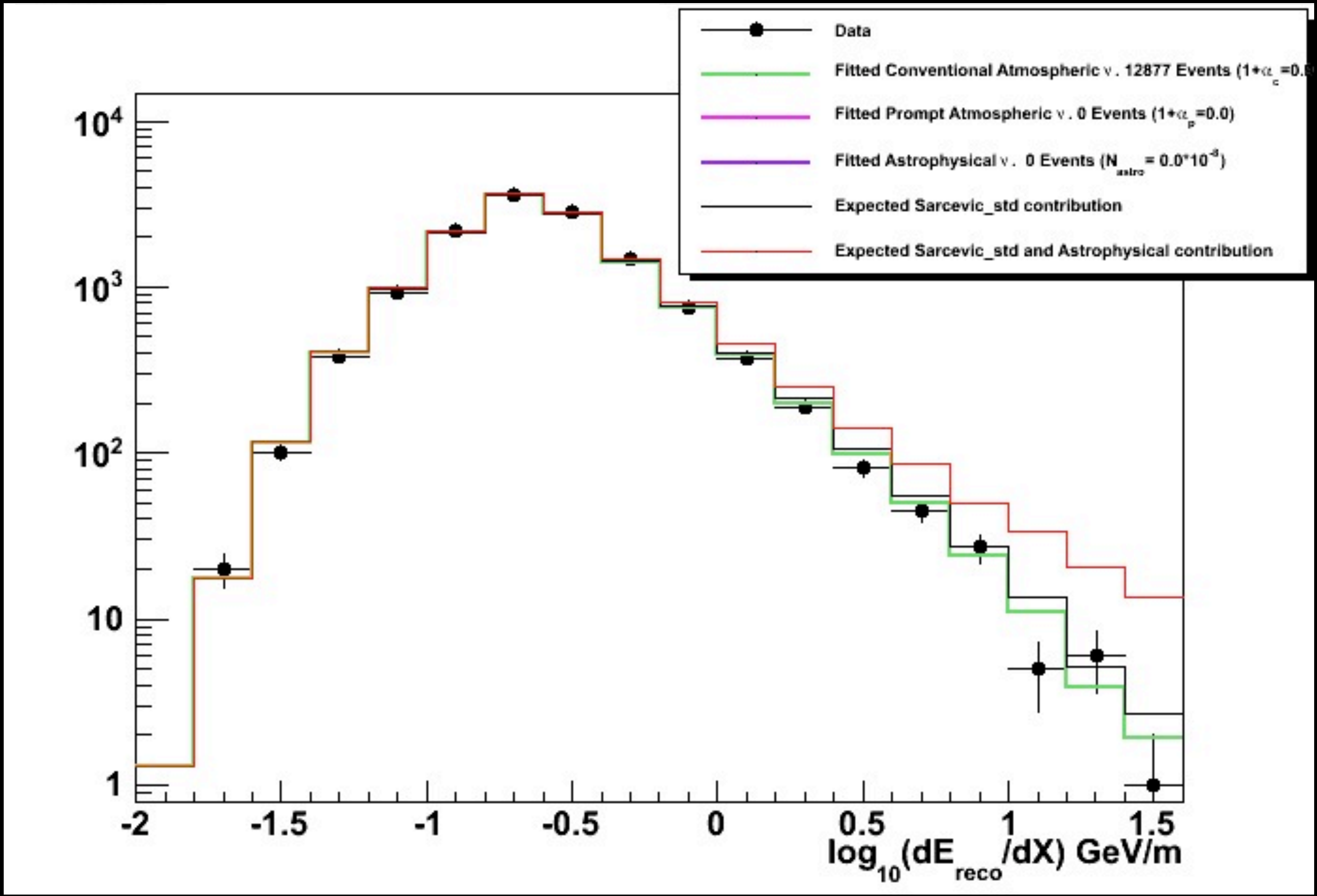
Reference Flux Model

- High Energy Neutrino Astronomy
- The IceCube Detector
- Energy Reconstruction
- Diffuse Analysis Method
- **Final Analysis Results from 2008**

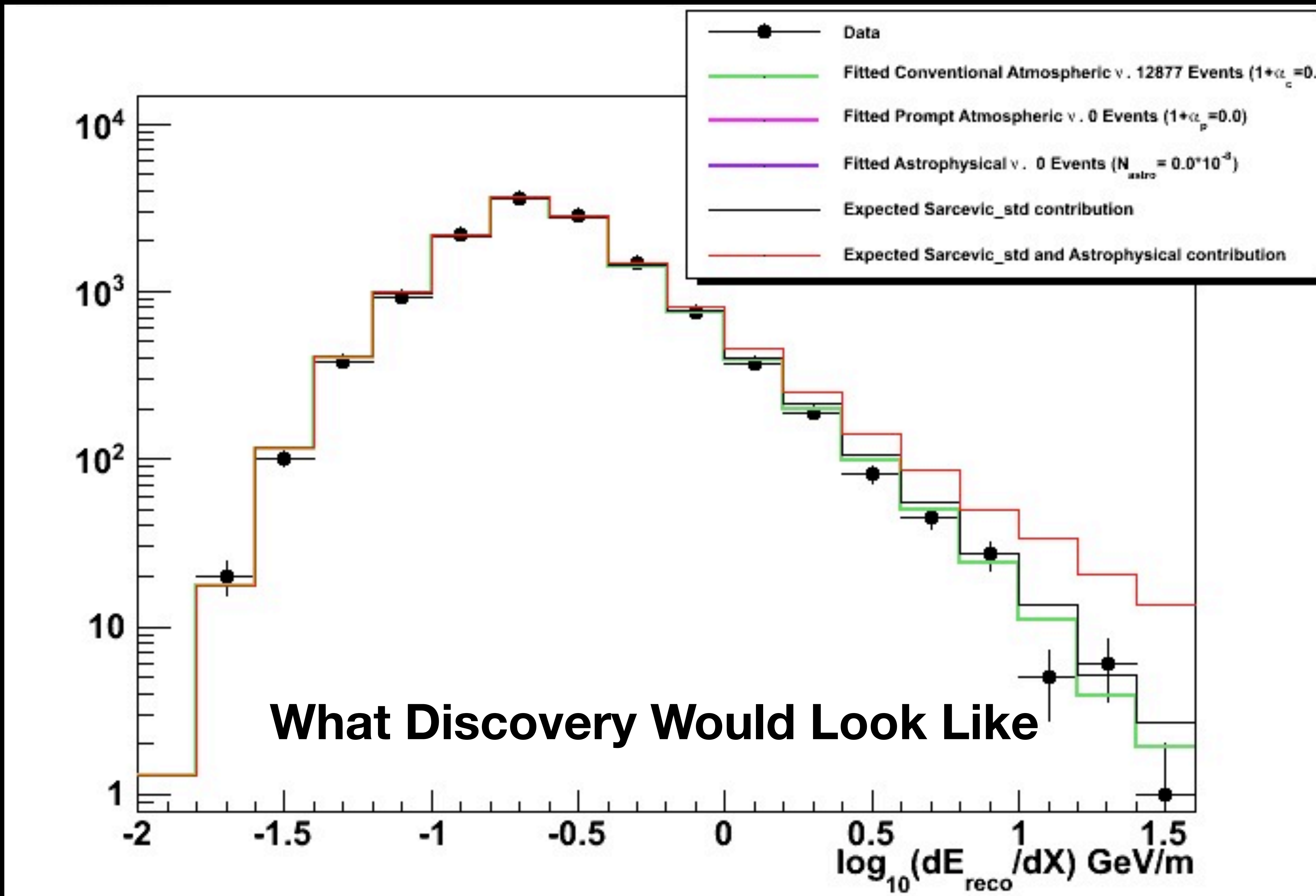
Fitted Muon Energy Loss Distribution



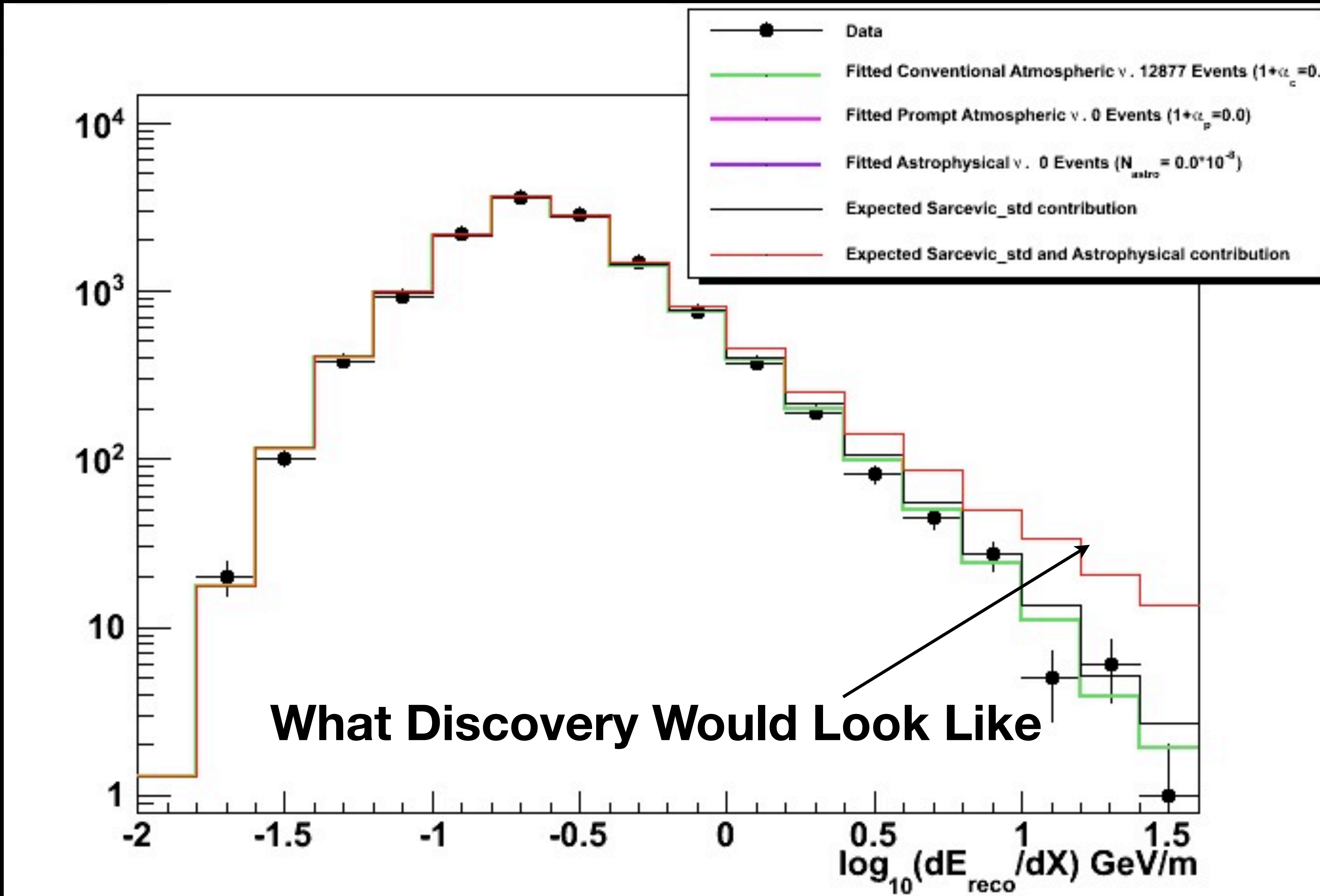
Fitted Muon Energy Loss Distribution



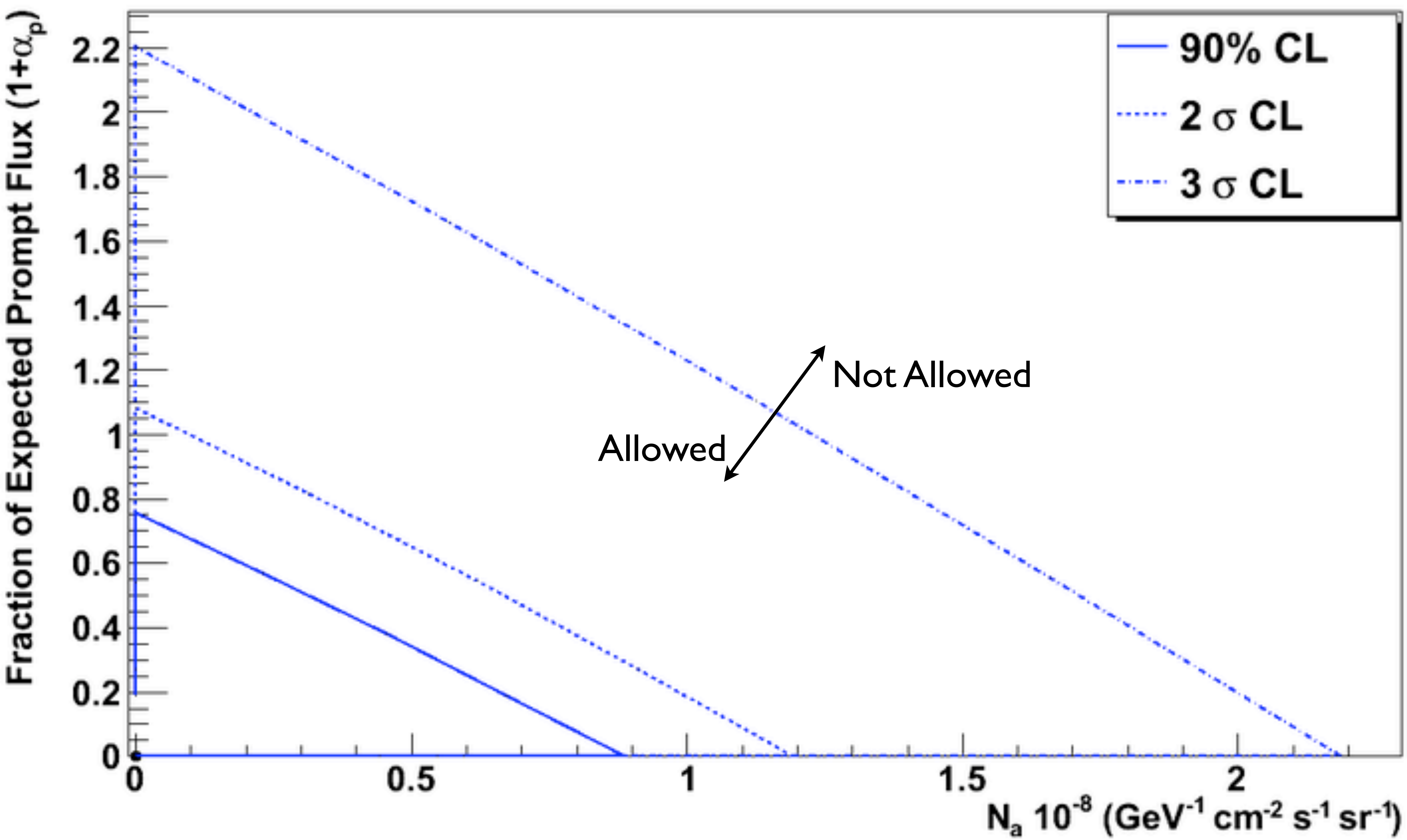
Fitted Muon Energy Loss Distribution



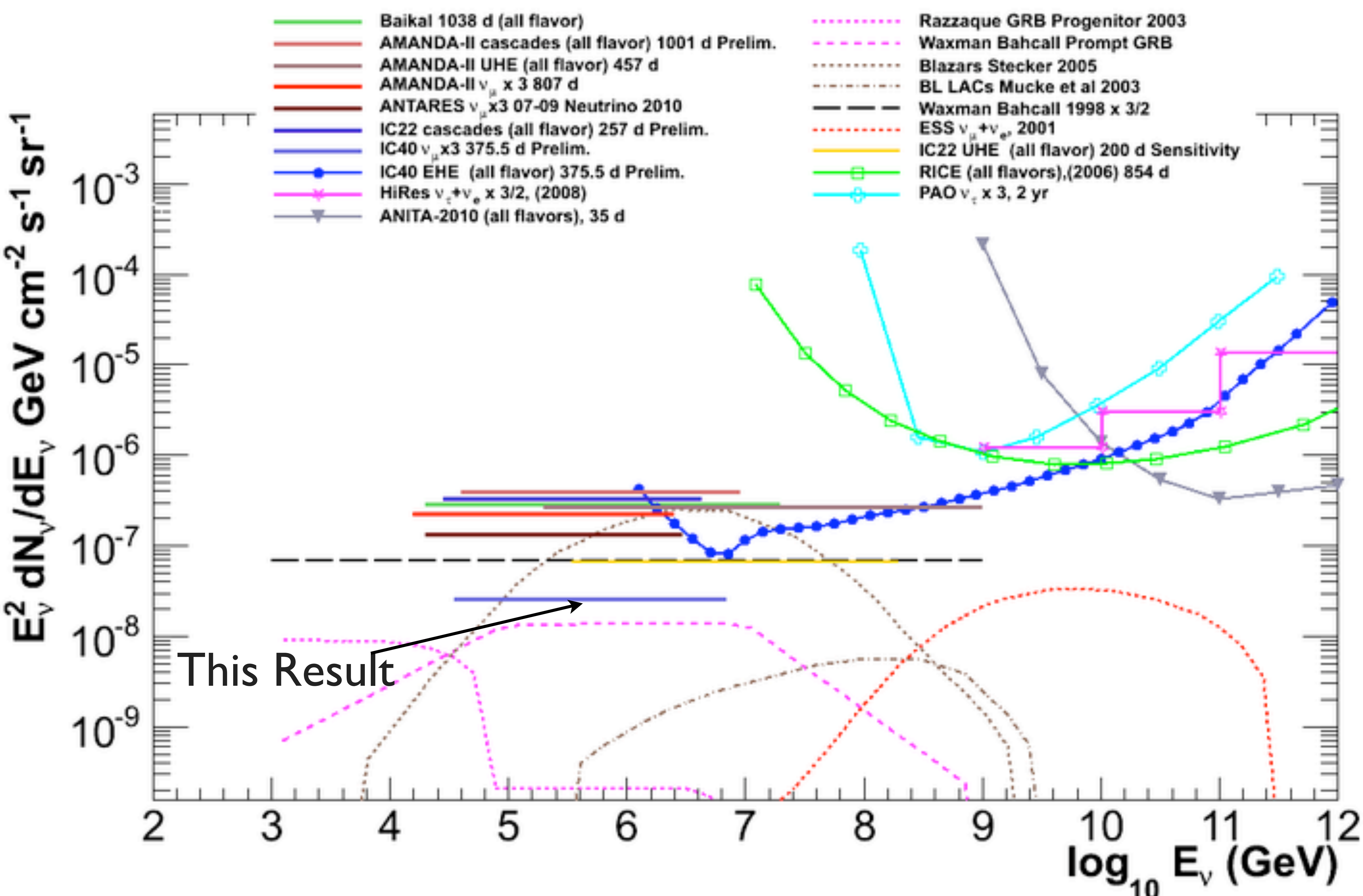
Fitted Muon Energy Loss Distribution



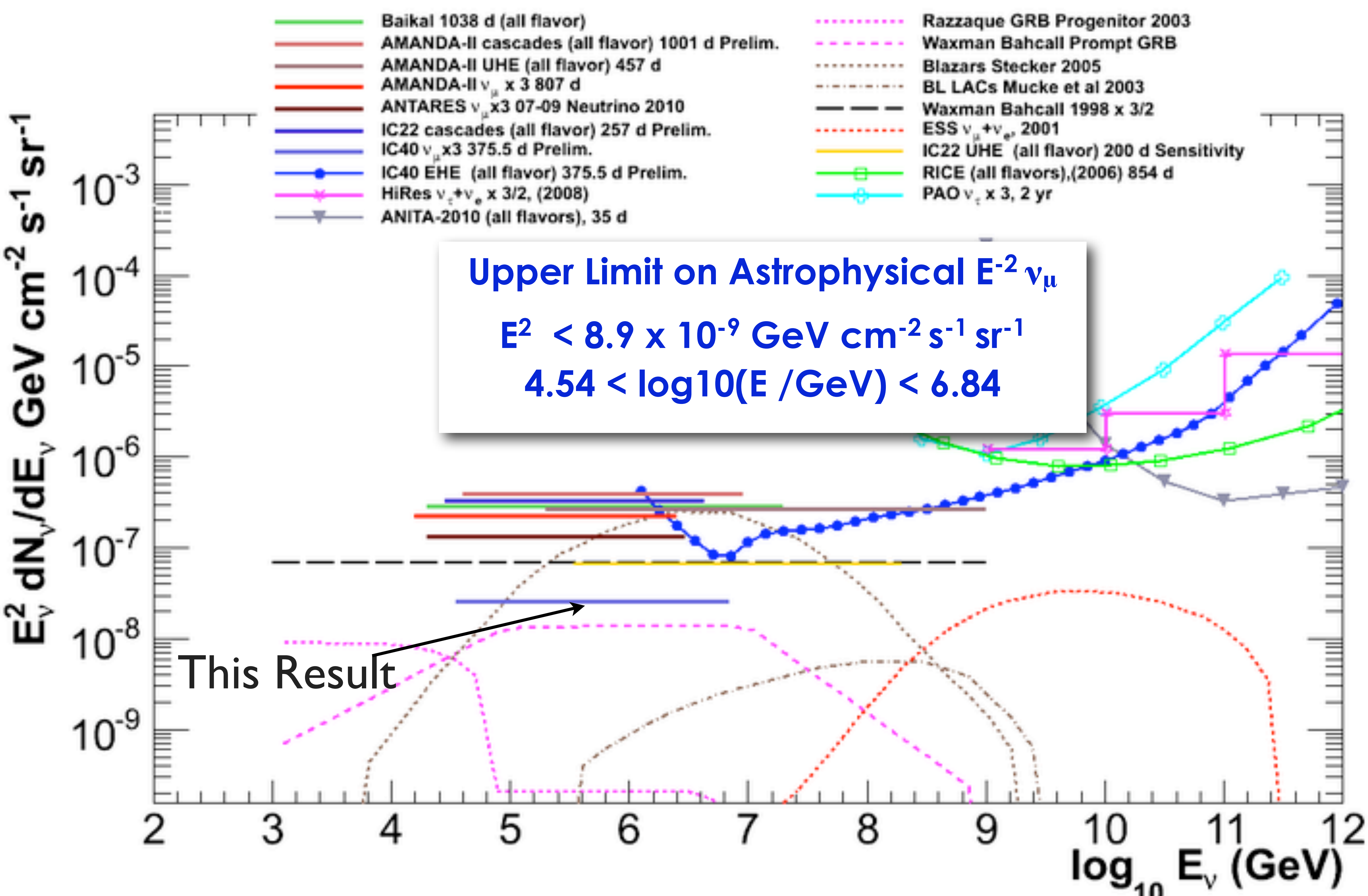
Allowed Regions for Astrophysical and Prompt Neutrinos



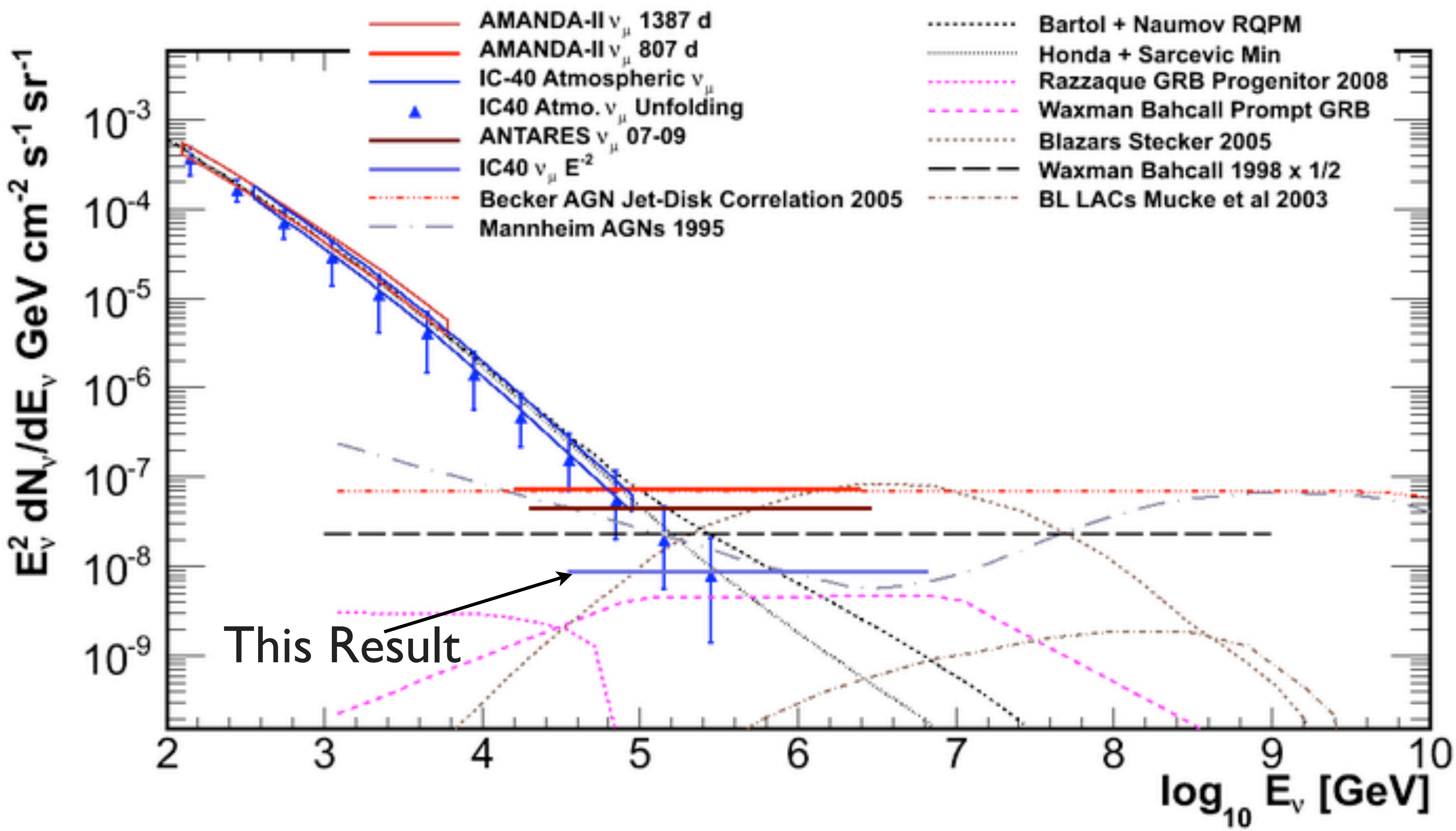
Flux Models and Limits



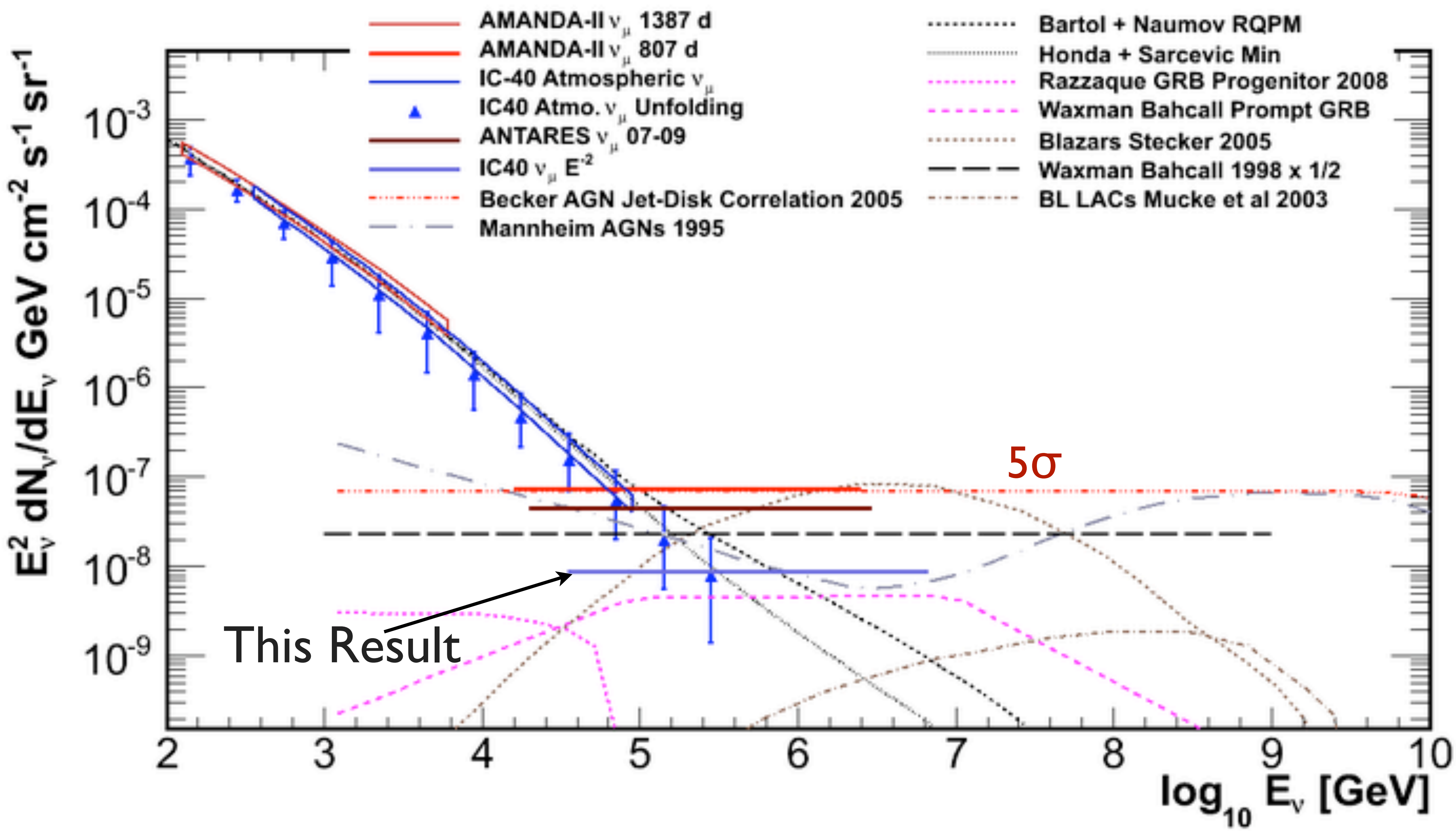
Flux Models and Limits



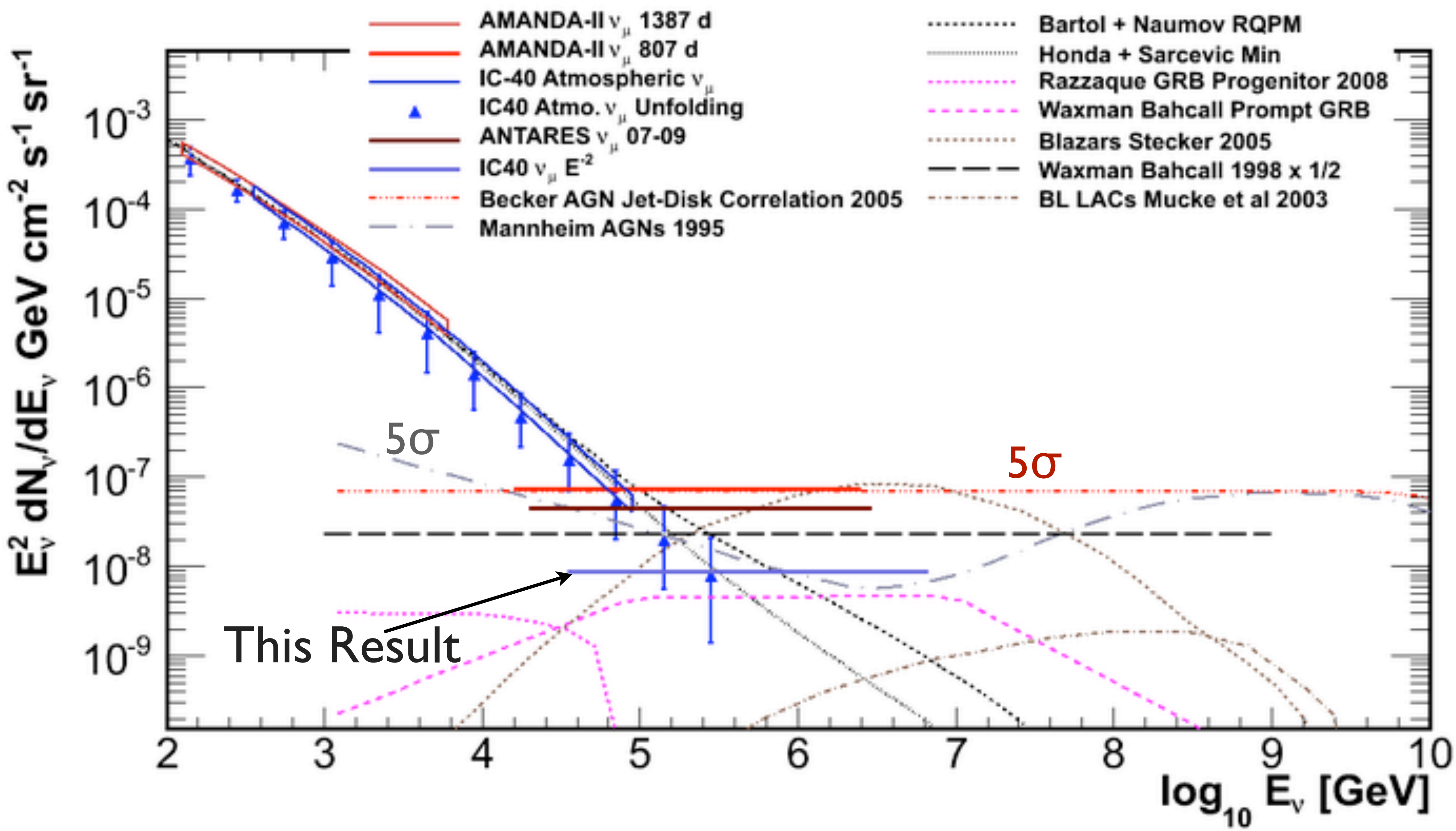
Astrophysical Model Tests



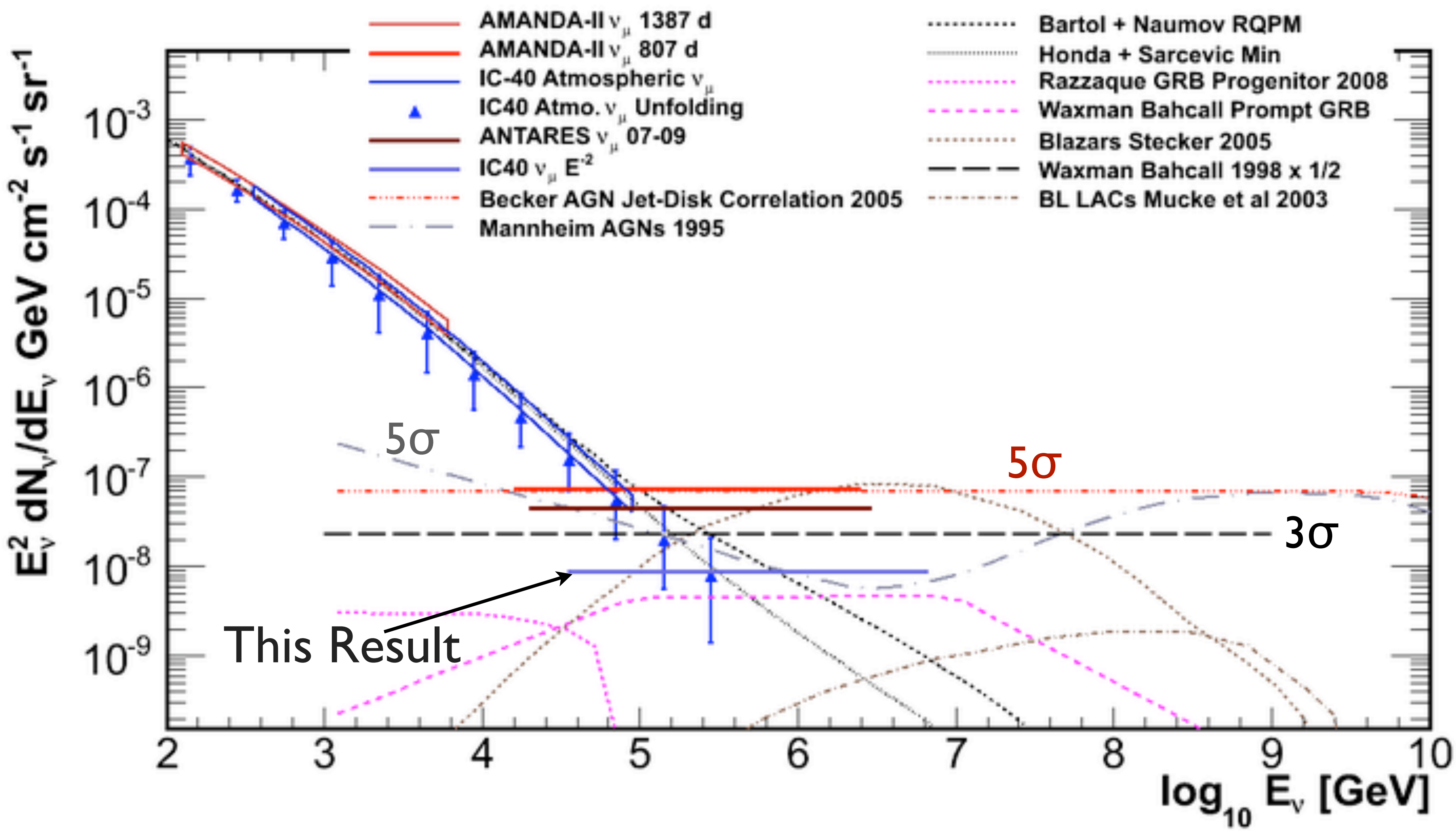
Astrophysical Model Tests



Astrophysical Model Tests

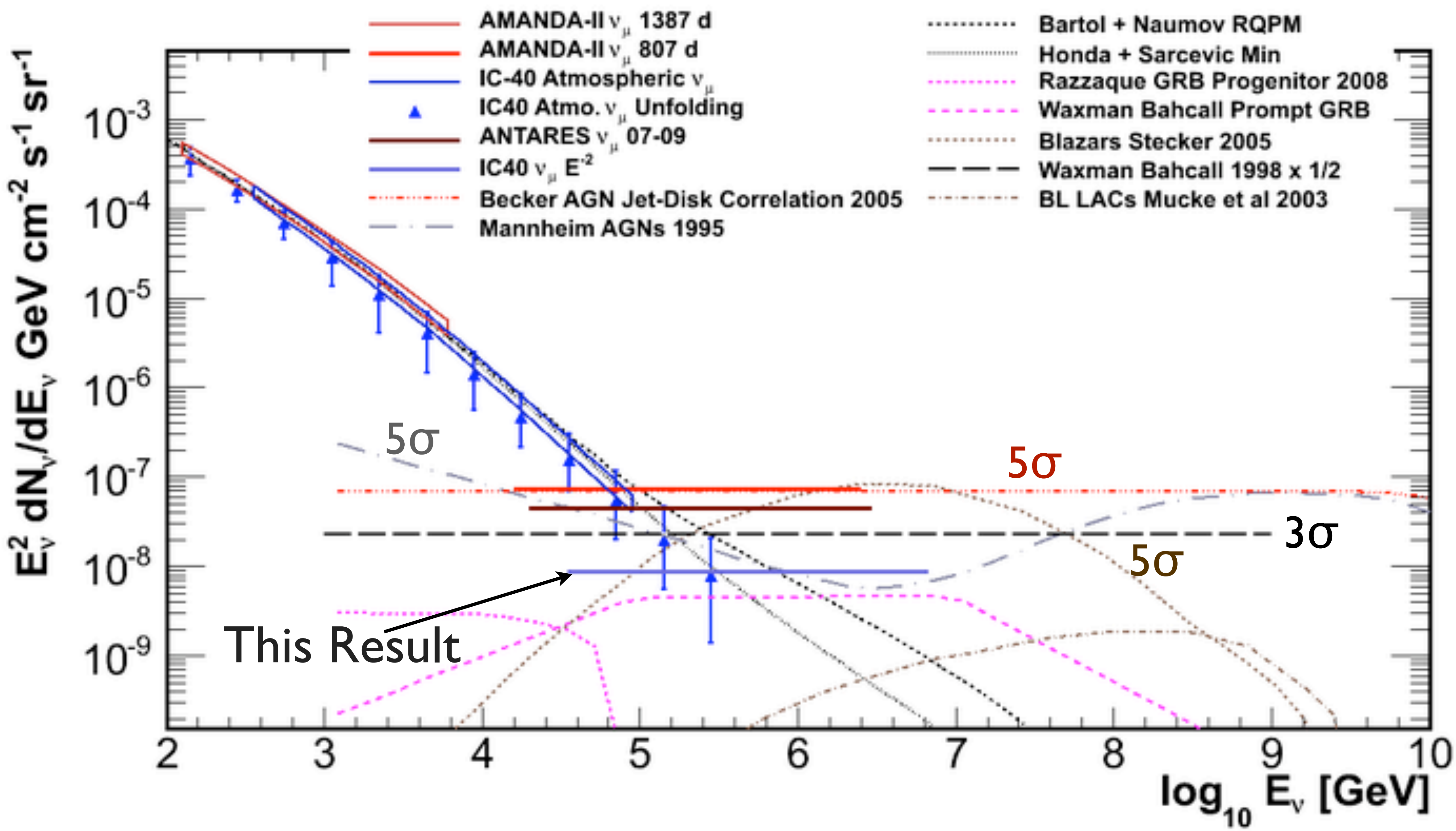


Astrophysical Model Tests



Sunday, August 21, 2011

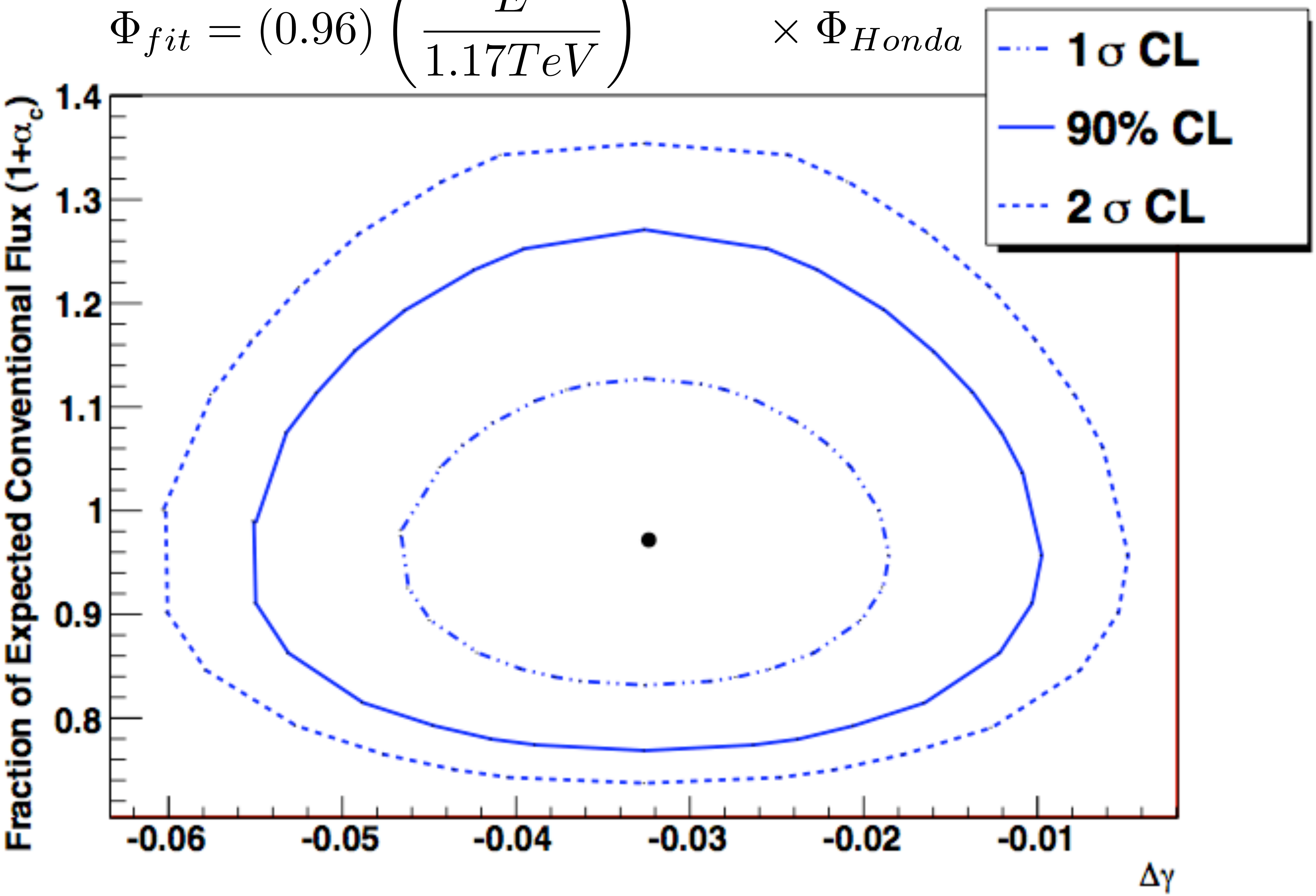
Astrophysical Model Tests



Sunday, August 21, 2011

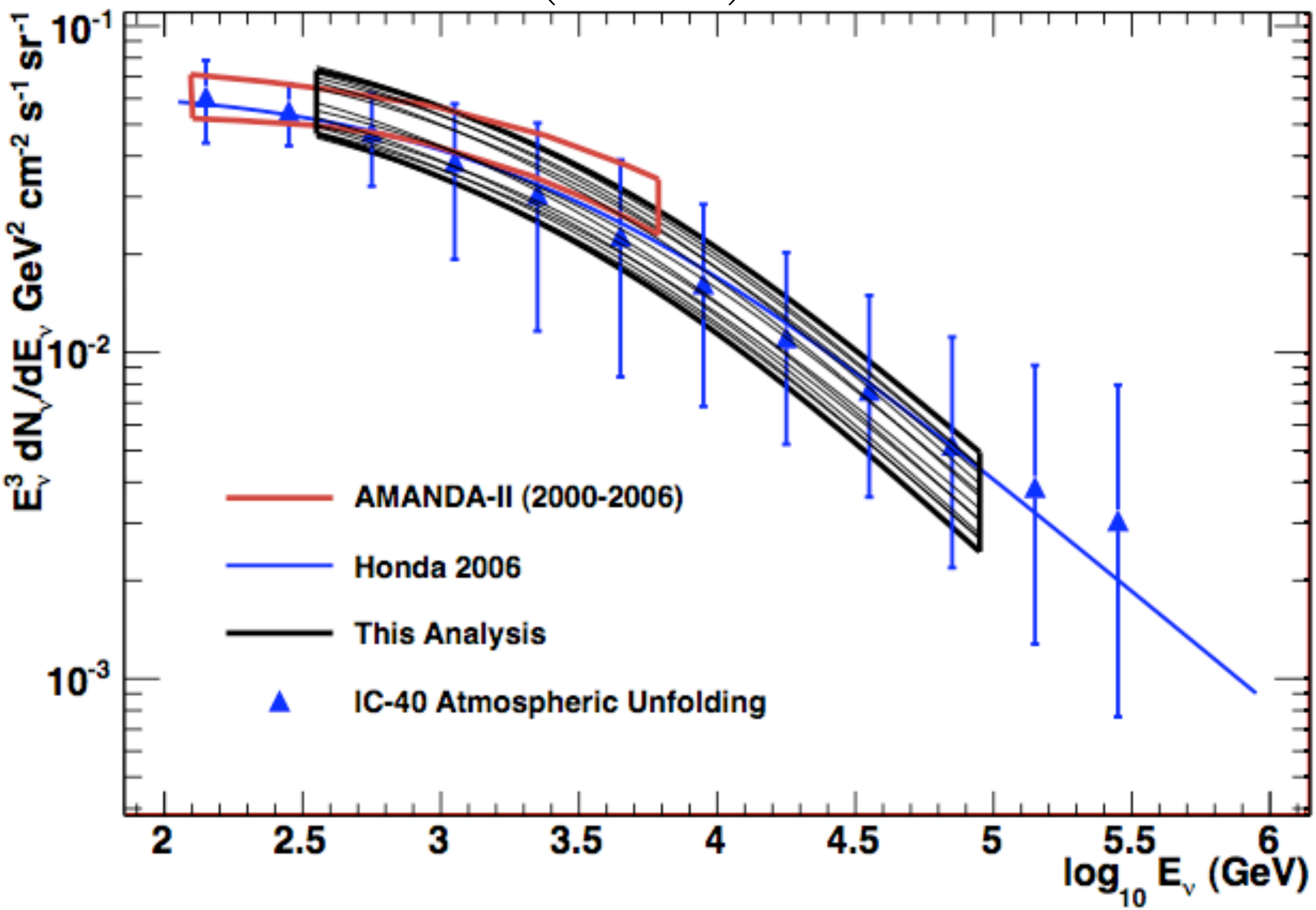
Allowed Regions - Conventional Atmospheric Neutrinos

$$\Phi_{fit} = (0.96)\left(\frac{E}{1.17TeV}\right)^{-0.026} \times \Phi_{Honda}$$

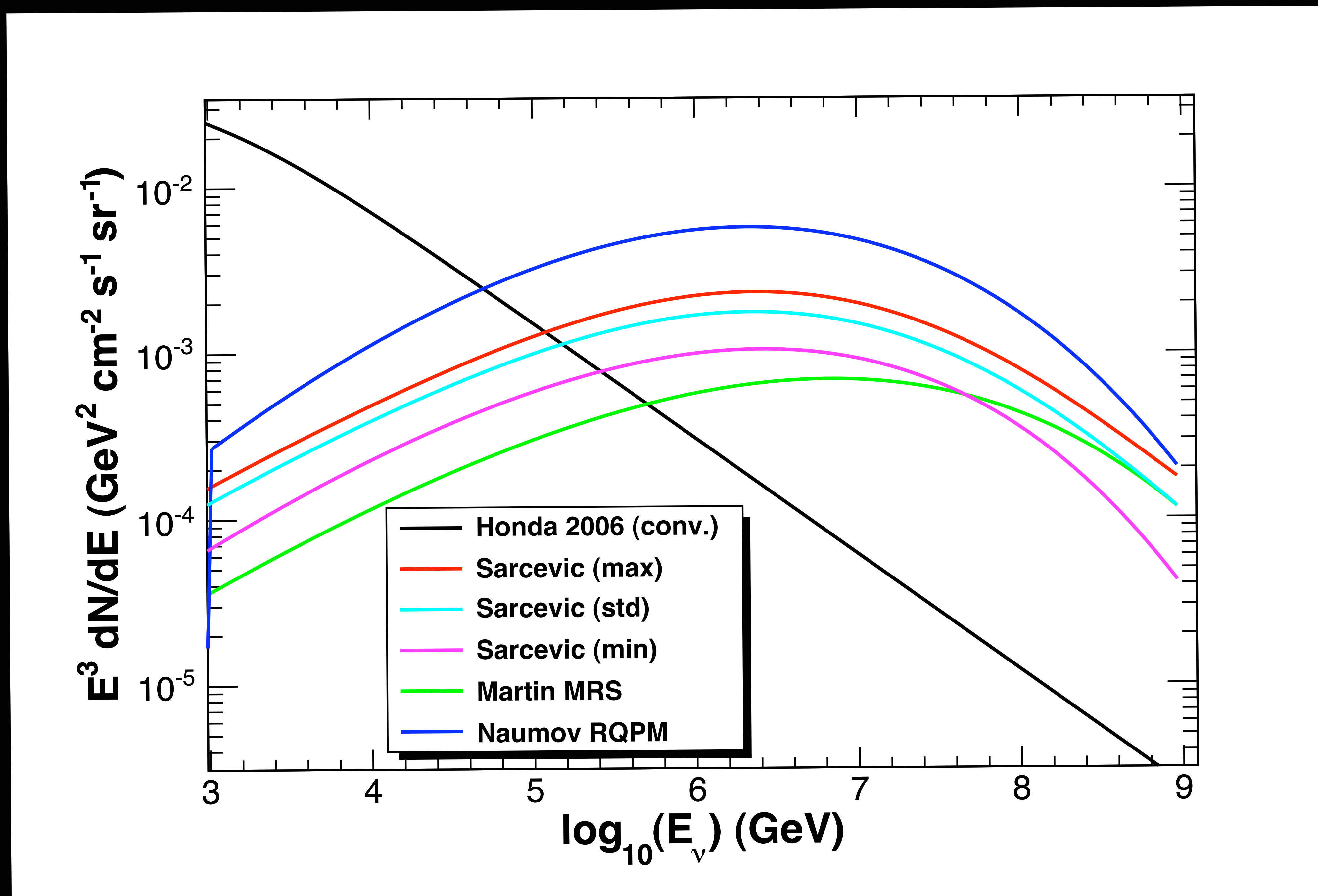


Measured Atmospheric Neutrino Spectrum

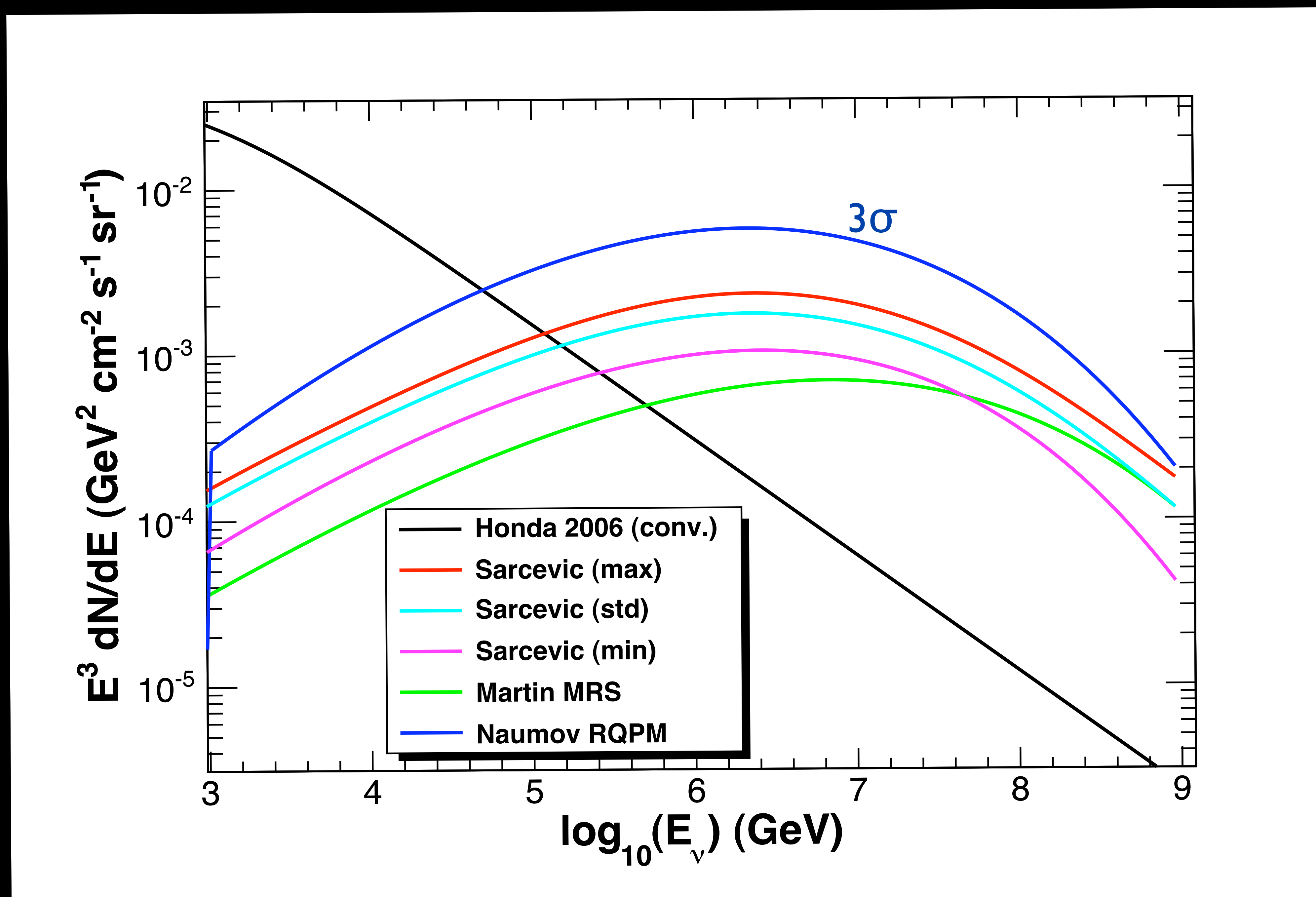
$$\Phi_{fit} = (0.96)\left(\frac{E}{1.17TeV}\right)^{-0.026} \times \Phi_{Honda}$$



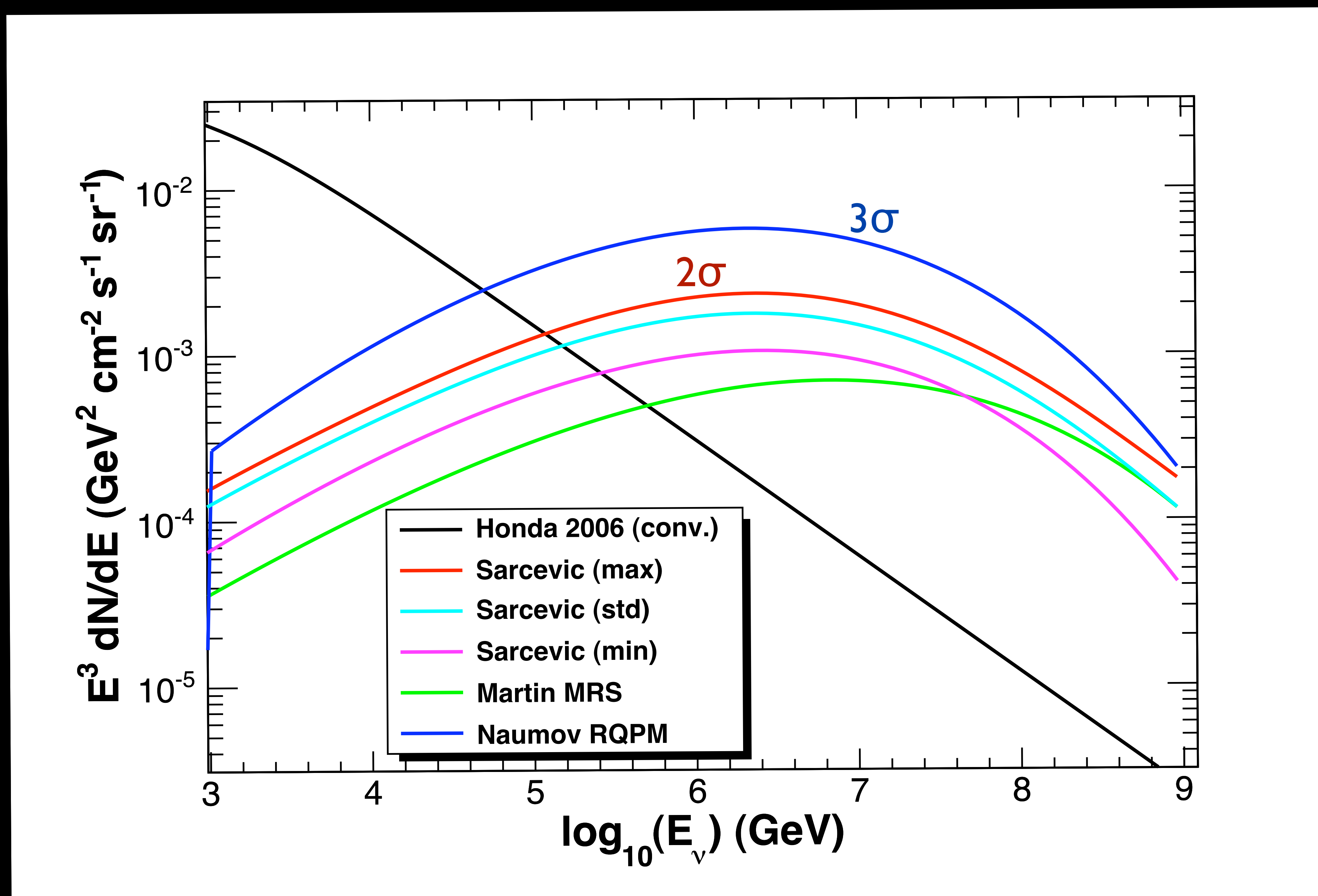
Charm Flux Model Tests



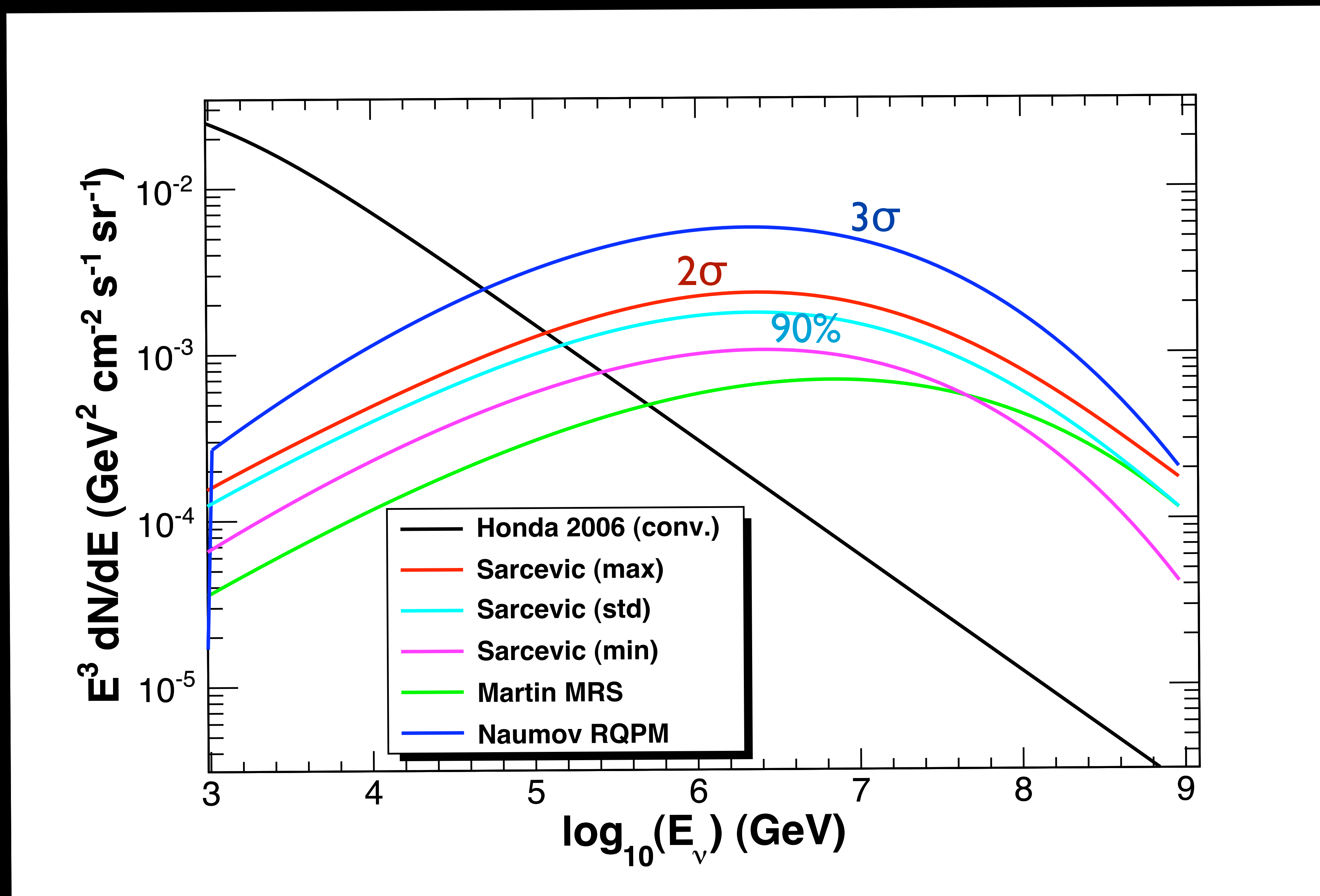
Charm Flux Model Tests



Charm Flux Model Tests



Charm Flux Model Tests



Results Summary

Results Summary

- Diffuse Astrophysical Muon Neutrino Upper Limit is **$E^2 < 8.9 \times 10^{-9}$ GeV cm^{-2} s^{-1} sr^{-1}**

Results Summary

- Diffuse Astrophysical Muon Neutrino Upper Limit is **$E^2 < 8.9 \times 10^{-9}$ GeV cm^{-2} s^{-1} sr^{-1}**
- Optimistic Astrophysical models ruled out: No surprises and IceCube is in it for the long haul

Results Summary

- Diffuse Astrophysical Muon Neutrino Upper Limit is **$E^2 < 8.9 \times 10^{-9}$ GeV cm^{-2} s^{-1} sr^{-1}**
- Optimistic Astrophysical models ruled out: No surprises and IceCube is in it for the long haul
- Atmospheric neutrino spectrum measured at high energies from 332.4 GeV to 83.7 TeV

Results Summary

- Diffuse Astrophysical Muon Neutrino Upper Limit is **$E^2 < 8.9 \times 10^{-9}$ GeV cm^{-2} s^{-1} sr^{-1}**
- Optimistic Astrophysical models ruled out: No surprises and IceCube is in it for the long haul
- Atmospheric neutrino spectrum measured at high energies from 332.4 GeV to 83.7 TeV
- No Evidence for Prompt Atmospheric Flux

Results Summary

- Diffuse Astrophysical Muon Neutrino Upper Limit is **$E^2 < 8.9 \times 10^{-9}$ GeV cm^{-2} s^{-1} sr^{-1}**
- Optimistic Astrophysical models ruled out: No surprises and IceCube is in it for the long haul
- Atmospheric neutrino spectrum measured at high energies from 332.4 GeV to 83.7 TeV
- No Evidence for Prompt Atmospheric Flux
- Prompt Atmospheric Models constrained

Outlook & Conclusion

Outlook & Conclusion

- A Diffuse flux at this limit would take 3-4 years of IC-86 for a 5 sigma discovery

Outlook & Conclusion

- A Diffuse flux at this limit would take 3-4 years of IC-86 for a 5 sigma discovery
- New analysis techniques needed and handling of systematics need to be improved

Outlook & Conclusion

- A Diffuse flux at this limit would take 3-4 years of IC-86 for a 5 sigma discovery
- New analysis techniques needed and handling of systematics need to be improved
- A measurement of the prompt flux is needed

Outlook & Conclusion

- A Diffuse flux at this limit would take 3-4 years of IC-86 for a 5 sigma discovery
- New analysis techniques needed and handling of systematics need to be improved
- A measurement of the prompt flux is needed
- Incorporate multi-channel information for better sensitivity

Backup Slides

Systematic Uncertainties

Systematic Uncertainties

- Background Systematic Uncertainty
  - Cosmic Ray Spectrum & Hadronic Interaction Model
  - Conventional & Prompt Atmospheric Neutrino Flux

Systematic Uncertainties

- Background Systematic Uncertainty
  - Cosmic Ray Spectrum & Hadronic Interaction Model
  - Conventional & Prompt Atmospheric Neutrino Flux
- Optical Module Sensitivity
  - OM calibration error +/- 8%.

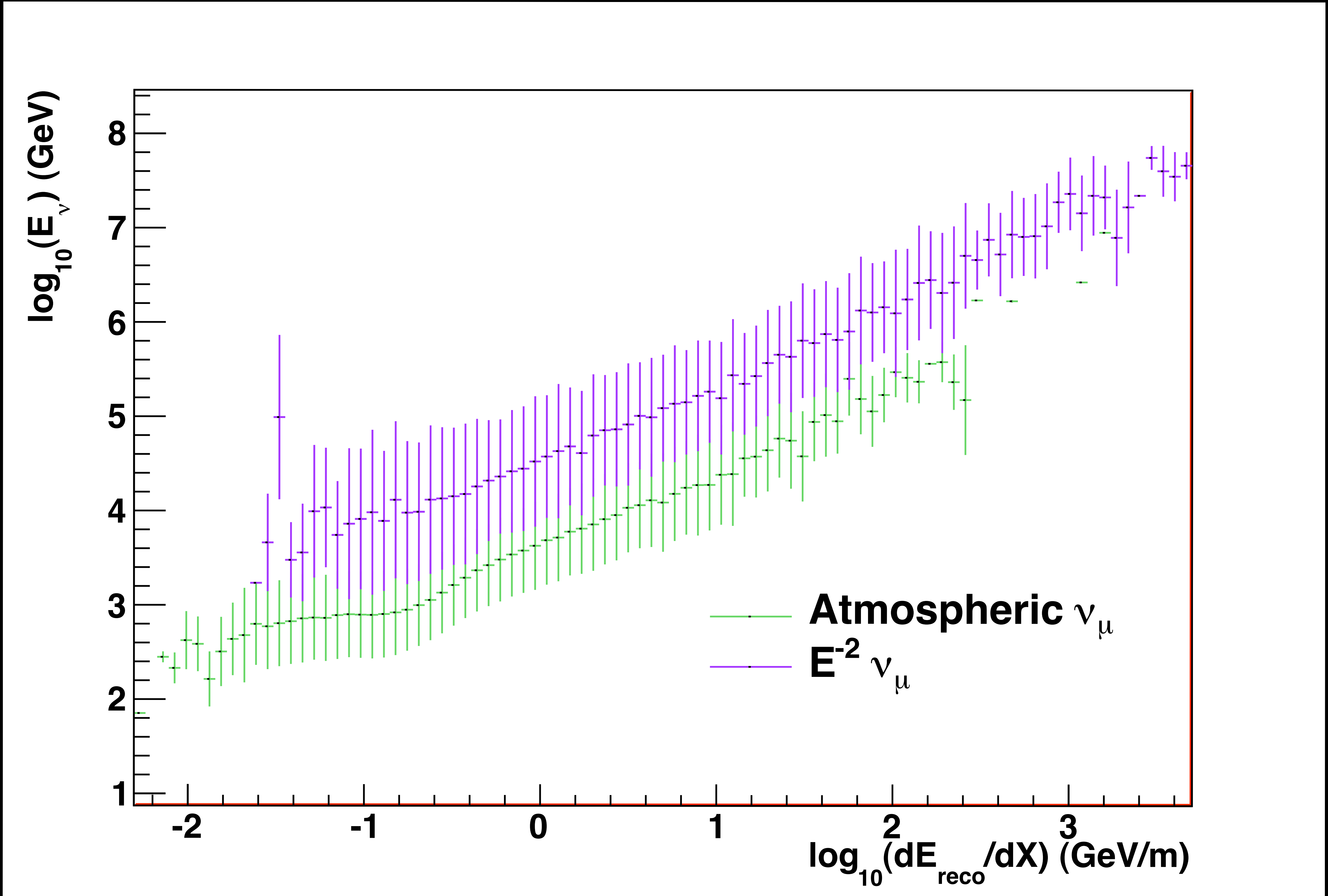
Systematic Uncertainties

- Background Systematic Uncertainty
  - Cosmic Ray Spectrum & Hadronic Interaction Model
  - Conventional & Prompt Atmospheric Neutrino Flux
- Optical Module Sensitivity
  - OM calibration error +/- 8%.
- Systematic Errors in the Simulation

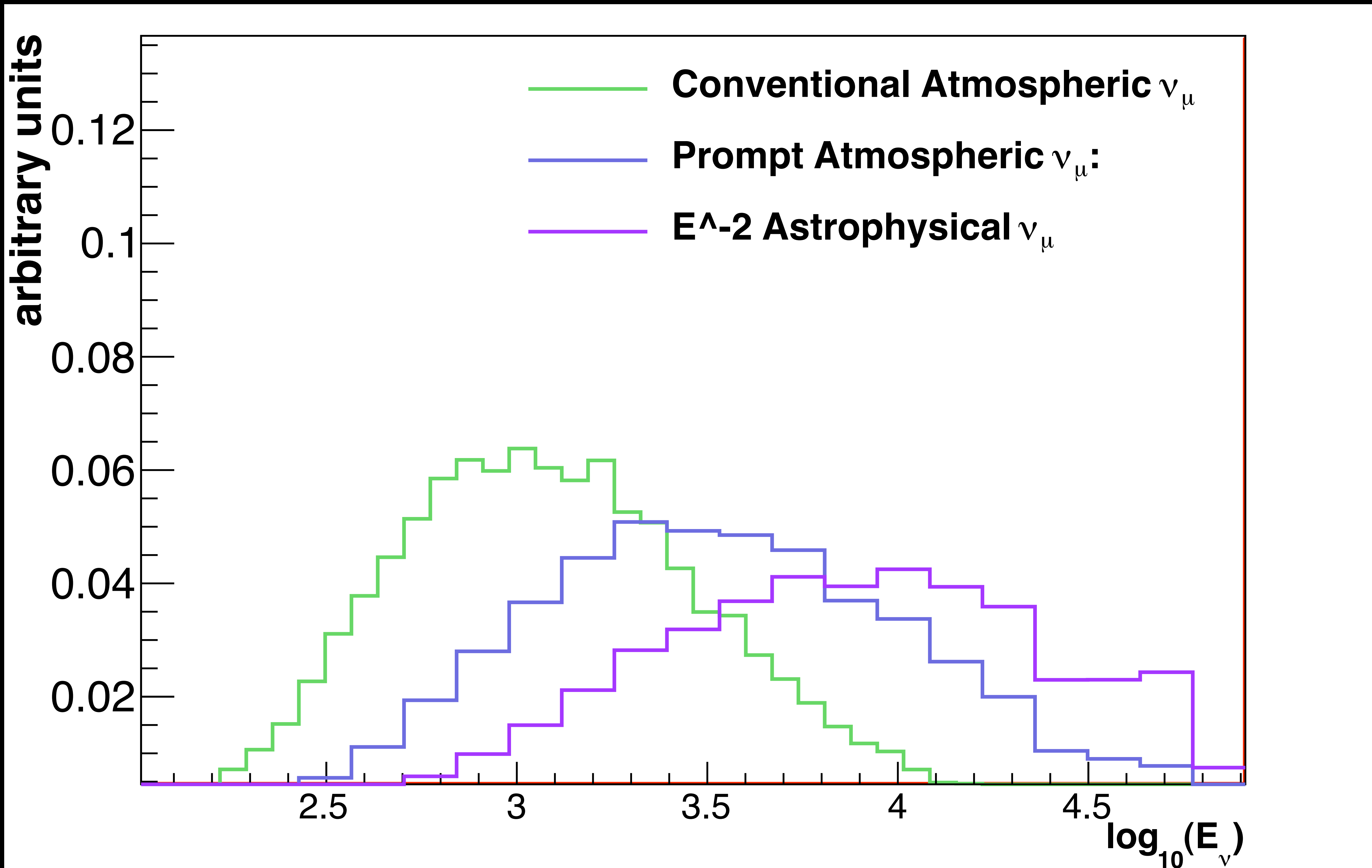
Systematic Uncertainties

- Background Systematic Uncertainty
  - Cosmic Ray Spectrum & Hadronic Interaction Model
  - Conventional & Prompt Atmospheric Neutrino Flux
- Optical Module Sensitivity
  - OM calibration error +/- 8%.
- Systematic Errors in the Simulation
- Systematic Uncertainties of the Ice Properties
  - Scattering/Absorption varies w/ depth. Uncertainty +/- 10%

Neutrino Energy Correlation with dE/dX



Muon Neutrino PDF for a dE/dX of 0.252 GeV/m



IceCube performance

Low noise rates: ~500Hz (SPE/sec)

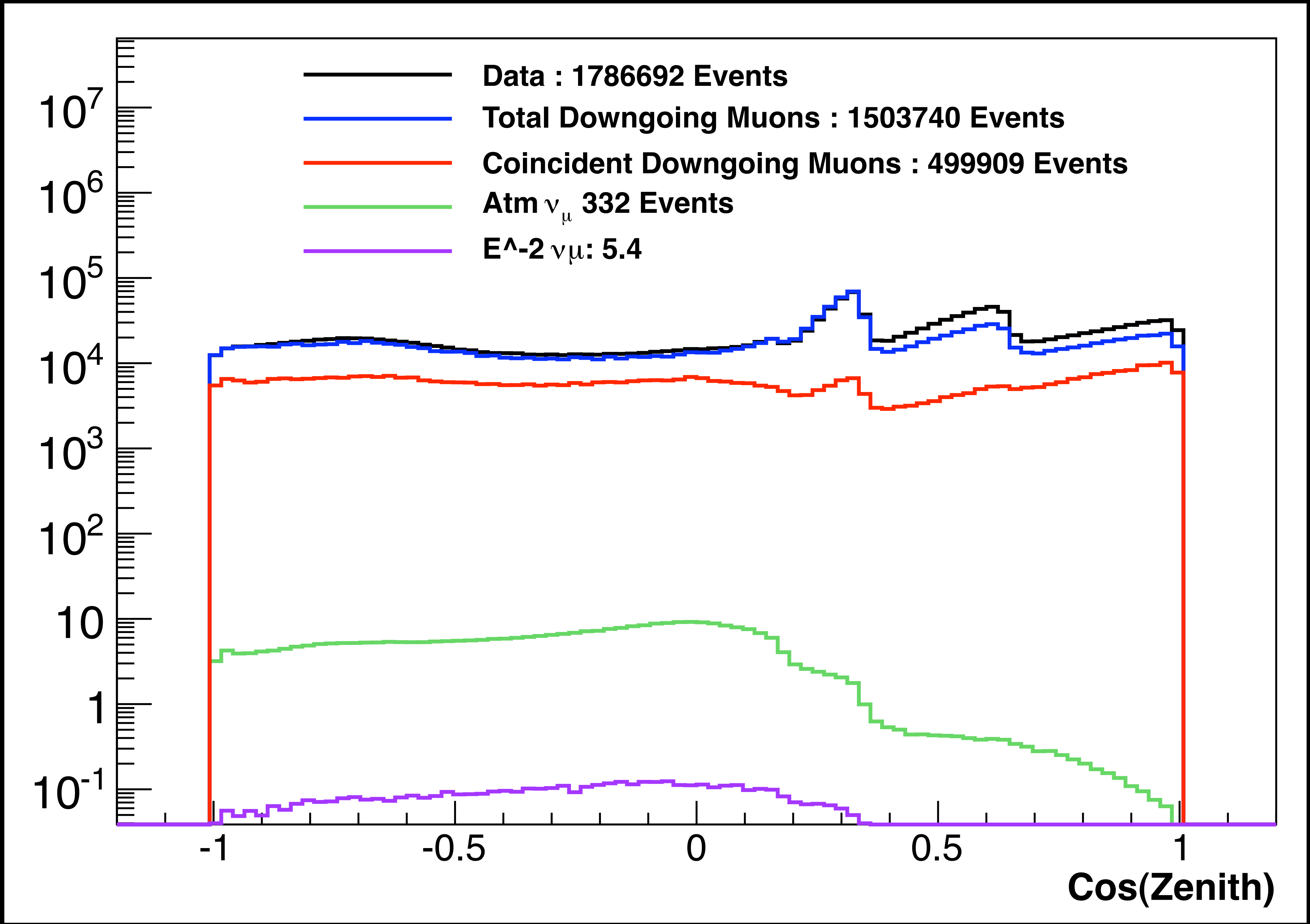
High duty cycle: >96%

Event rates (59 strings)

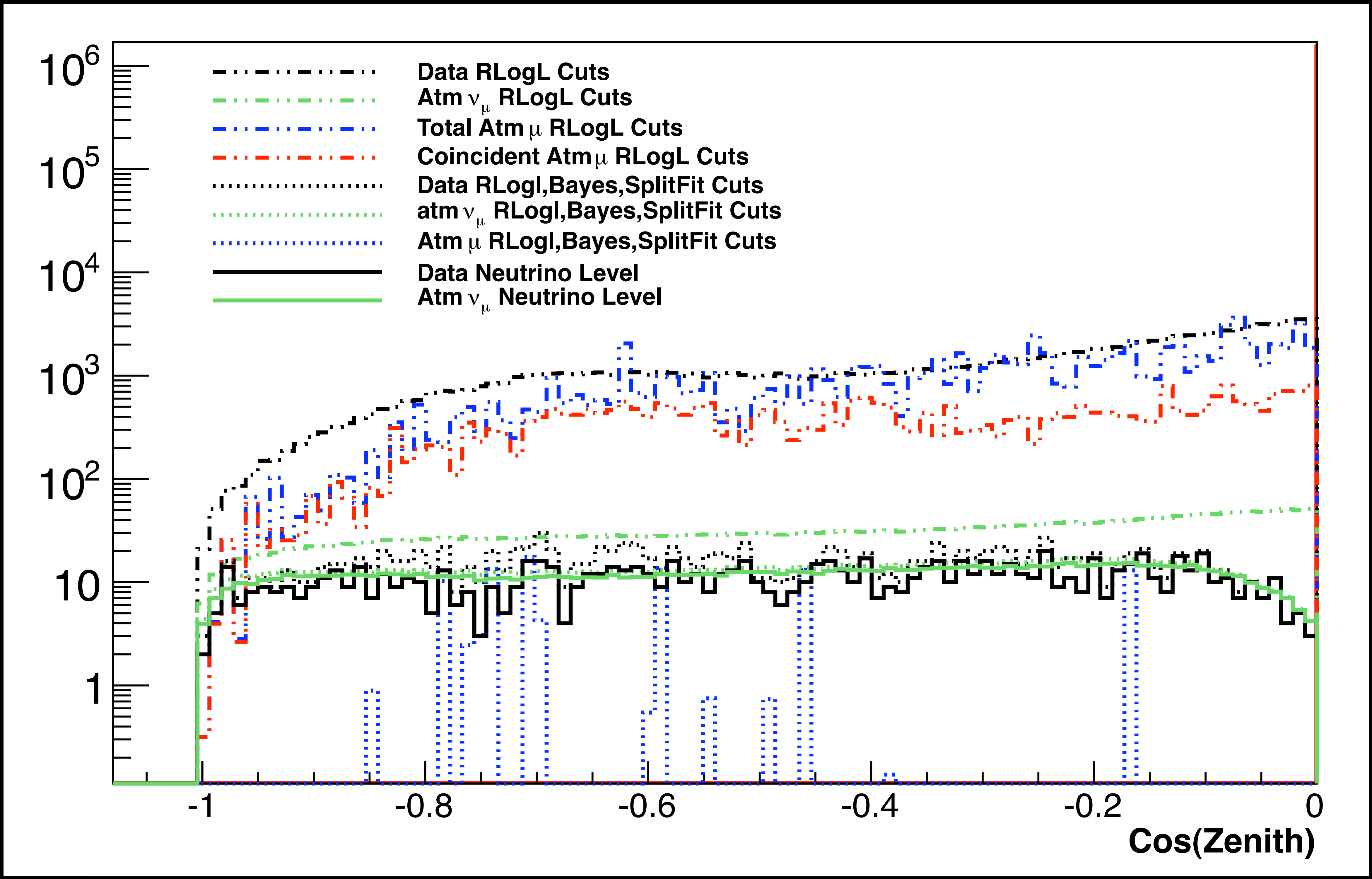
- Muons: ~1.5 kHz
- Neutrinos: ~160/day

Strings	Year	Livetime	μ rate	ν rate
IC9	2006	137 days	80 Hz	1.7 / day
IC22	2007	275 days	550 Hz	28 / day
IC40	2008	~365 days	1000 Hz	110 / day
IC59	2009	~365 days	1500 Hz	160 / day
IC86*	2011	~365 days	1650 Hz	220 / day

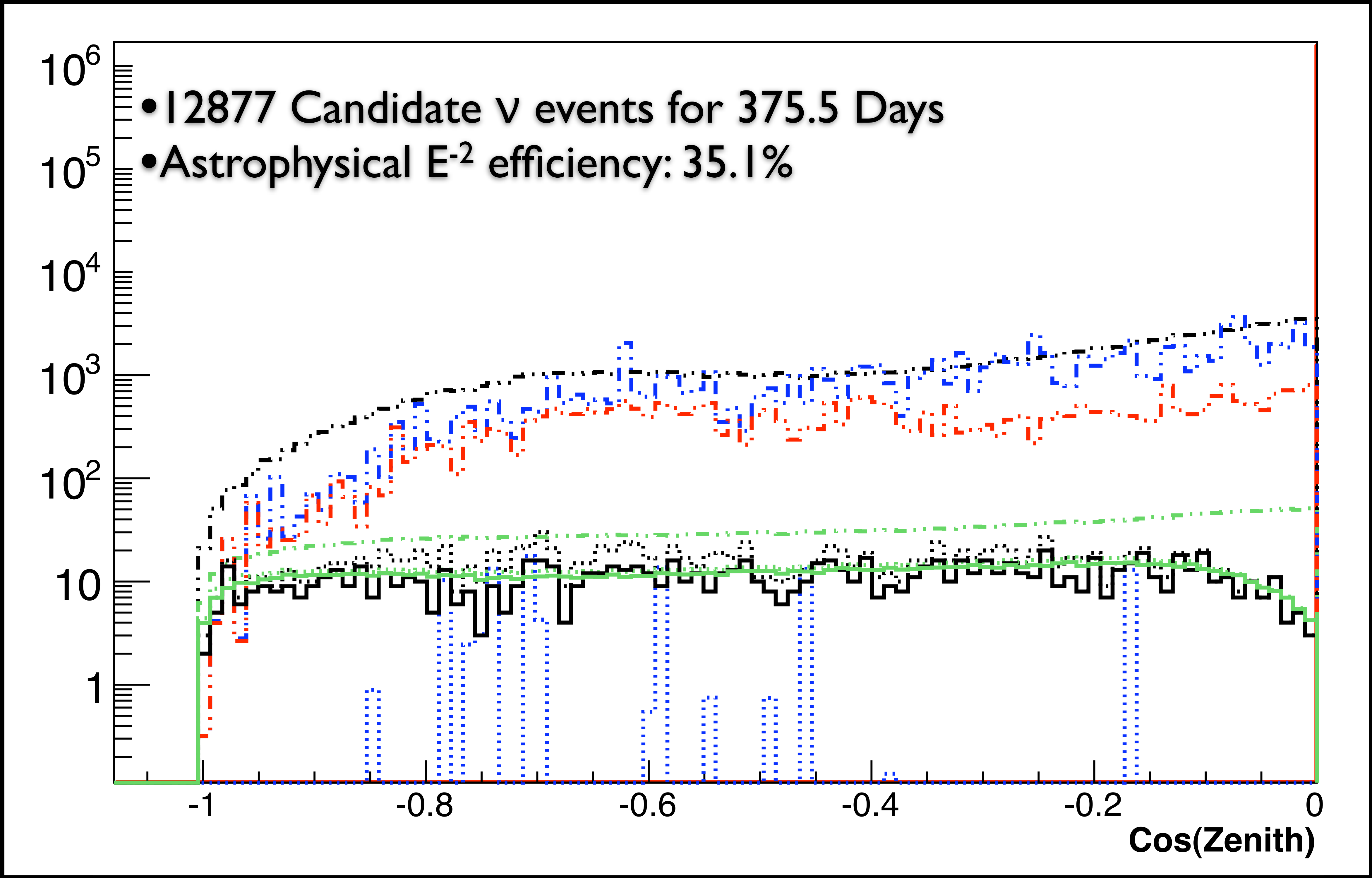
Event Selection Progression



Event Selection Progression



Event Selection Progression



Systematic Uncertainties

Parameter	Magnitude
Conventional Normalization	+/- 0.25
Prompt Normalization	0.56-1.25
$\Delta\gamma$	+/- 0.03
ε	+/- 0.083
a(405)/b(405)	+/- 10%

Fit Details

Parameter	Fit	Error
$1+\alpha_c$	0.96	+/- 0.096
$1+\alpha_p$	0	+0.73 (90%)
$\Delta\gamma$	-0.026	+/- 0.012
ε	+2%	+/- 0.09
N_astro	0	8.9×10^{-9} (90%)

Charm Upper Limits

Model	90%	2σ	3σ
sarcevic-std	0.73	1.1	2.2
sarcevic-min	1.25	1.8	3.6
sarcevic-max	0.53	0.85	1.89
naumov_rqpm	0.2	0.41	0.87

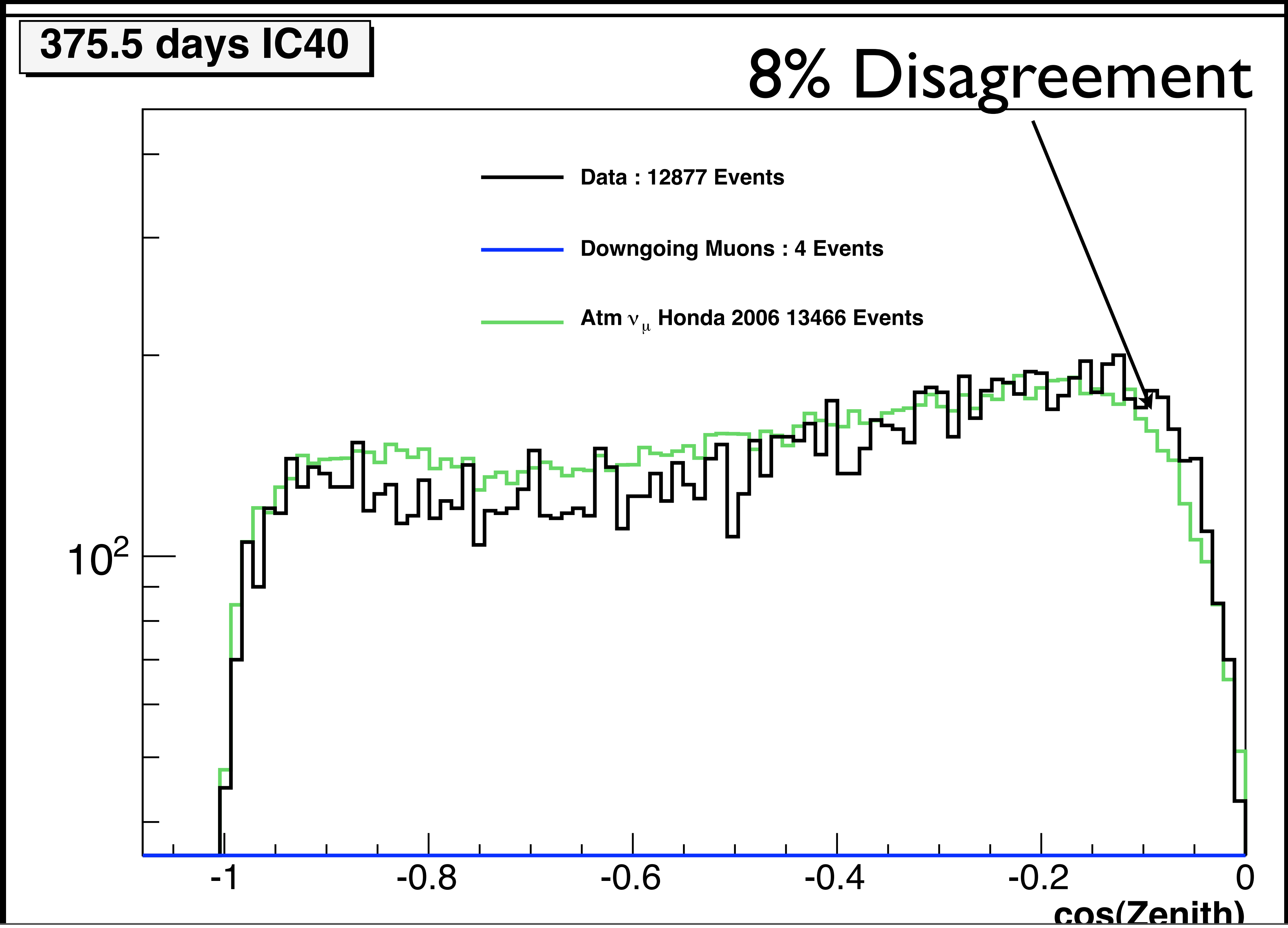
Astrophysical Model Upper Limits

Model	90%	3σ	5σ
Stecker Blazar Model	0.1	0.32	0.42
Diffuse GRB Model	0.54	1.2	1.5
FSRQ Model	0.02	0.09	0.12
Mannheim AGN Model	0.02	0.14	0.02

Systematic Uncertainties in the Simulation

- Uncertainties in neutrino cross-section (3%)
- Uncertainties in muon energy loss (1%)
- Reconstruction & Cut bias (2%)
- Background Contamination (0.5%)

Zenith Distribution



IceCube performance

Low noise rates: ~500Hz (SPE/sec)

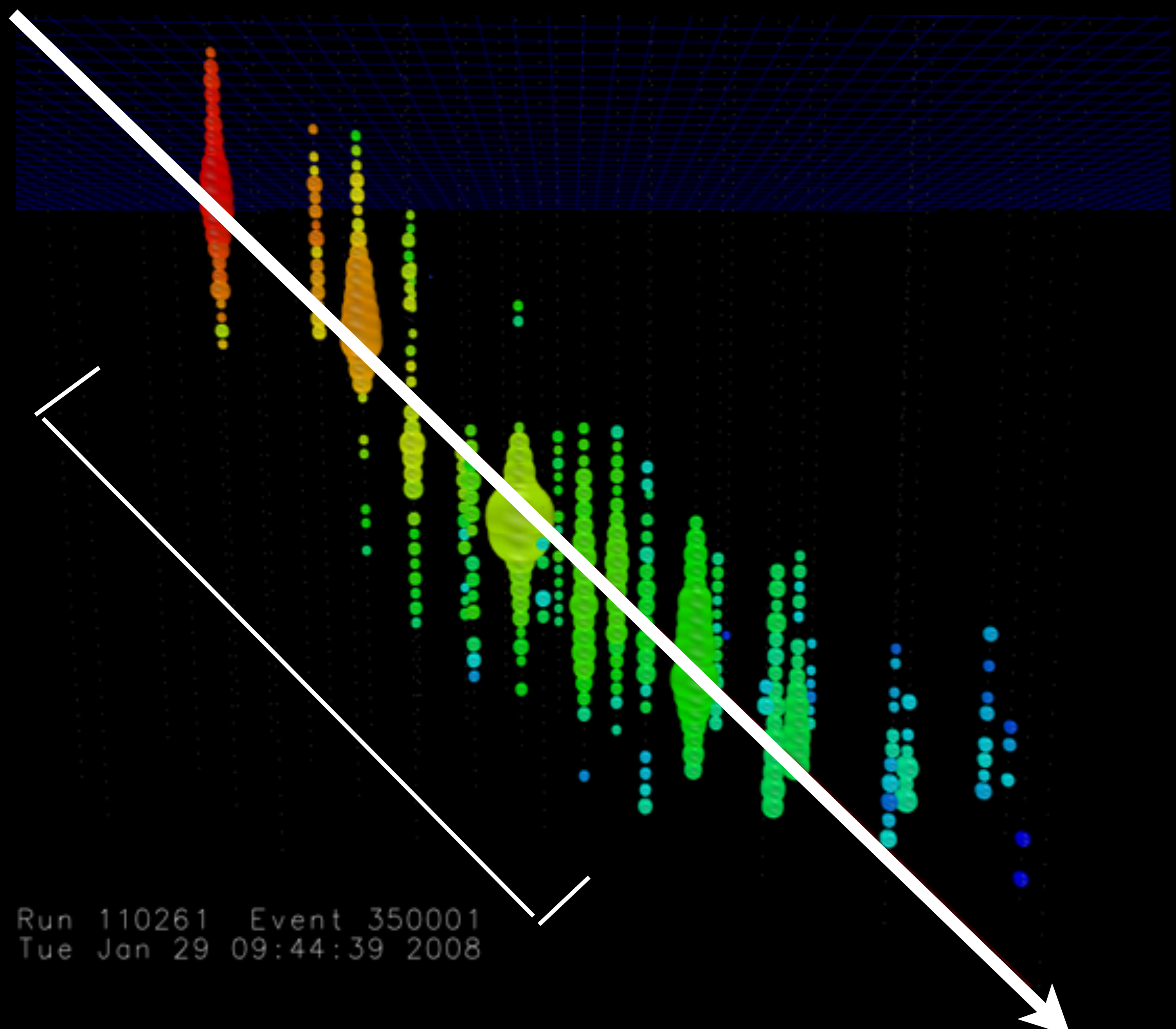
High duty cycle: >96%

Event rates (59 strings)

- Muons: ~1.5 kHz
- Neutrinos: ~160/day

Strings	Year	Livetime	μ rate	ν rate
IC9	2006	137 days	80 Hz	1.7 / day
IC22	2007	275 days	550 Hz	28 / day
IC40	2008	~365 days	1000 Hz	110 / day
IC59	2009	~365 days	1500 Hz	160 / day
IC86*	2011	~365 days	1650 Hz	220 / day

Quality Parameters - Direct Hits

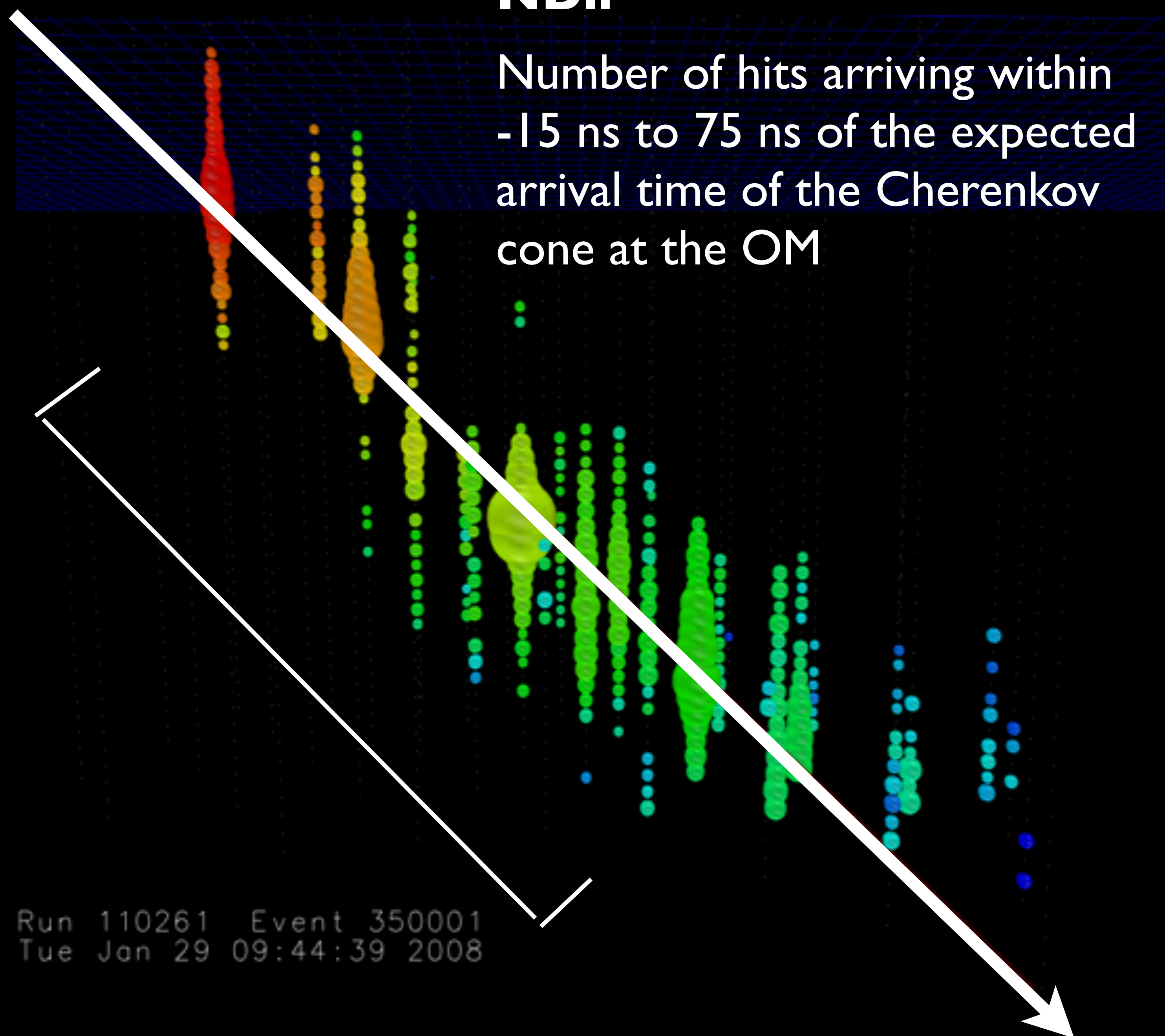


Quality Parameters - Direct Hits

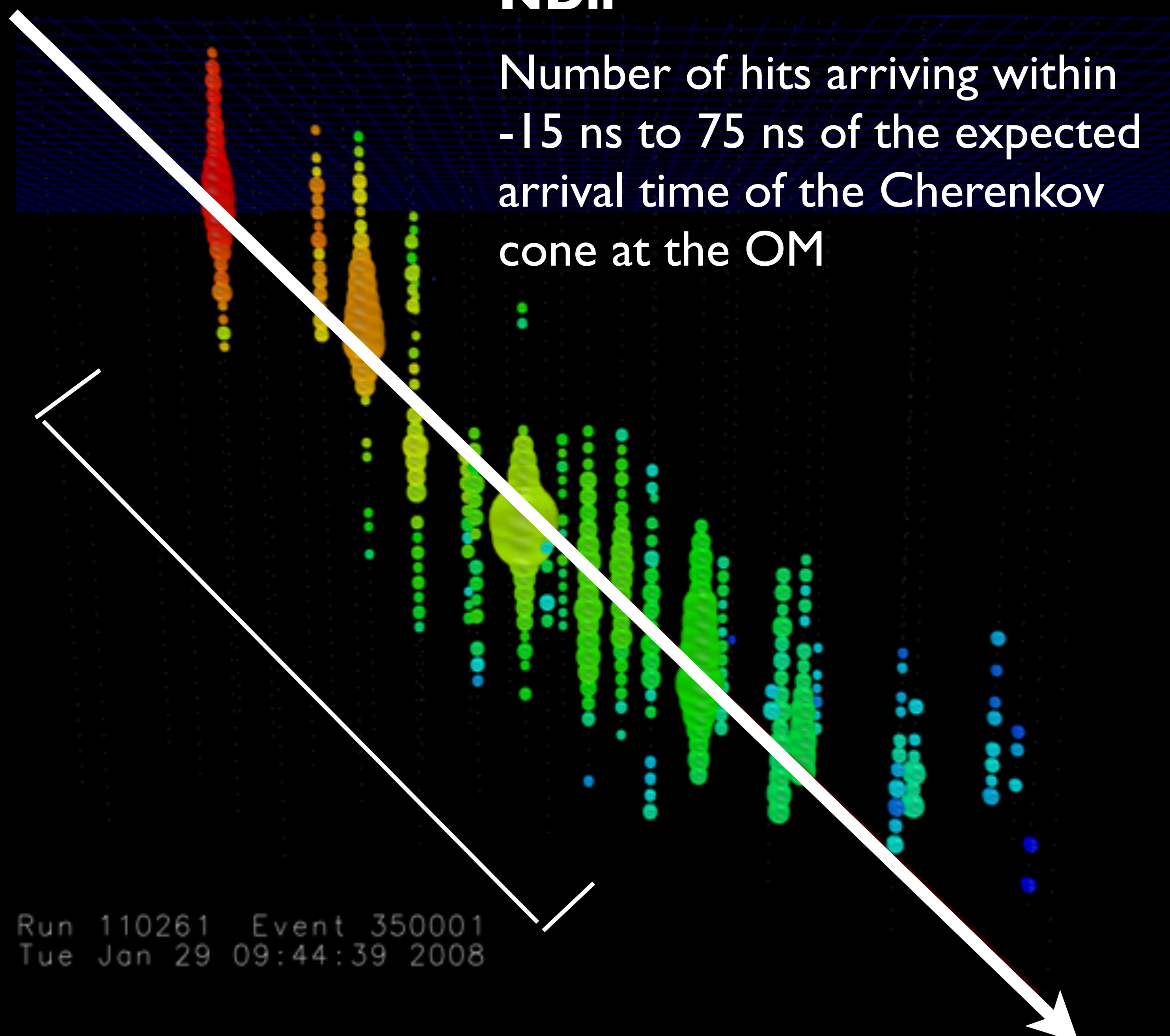
Number of Direct Hits

NDir

Number of hits arriving within -15 ns to 75 ns of the expected arrival time of the Cherenkov cone at the OM



Quality Parameters - Direct Hits



Number of Direct Hits

NDir

Number of hits arriving within -15 ns to 75 ns of the expected arrival time of the Cherenkov cone at the OM

Smoothness

SDir

SDir = +1 if direct hits are near the beginning of track

SDir = -1 if direct hits are near the end of track

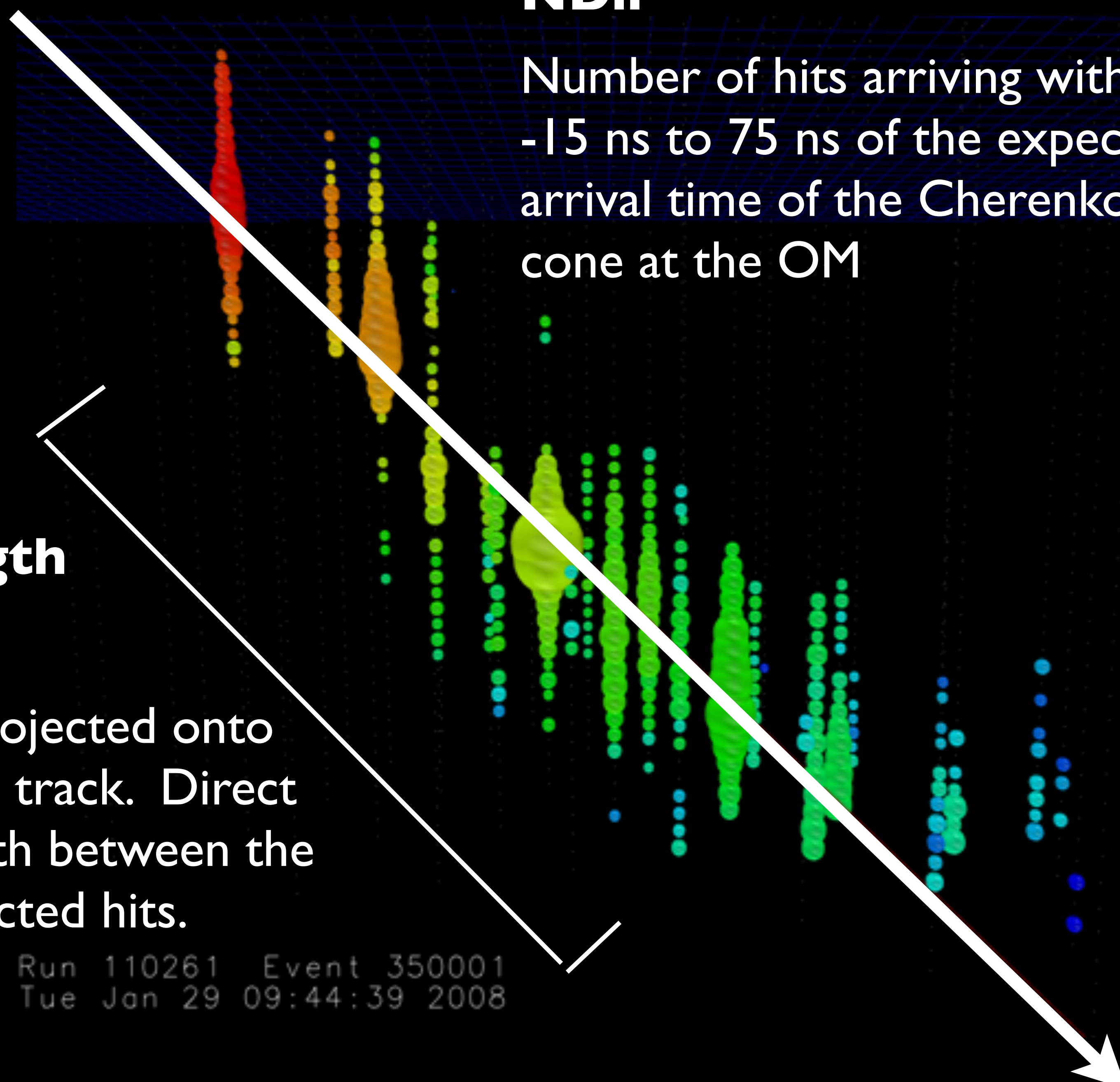
SDir = 0 if evenly distributed along track

Quality Parameters - Direct Hits

Number of Direct Hits

NDir

Number of hits arriving within -15 ns to 75 ns of the expected arrival time of the Cherenkov cone at the OM



Direct Length

LDir

Direct Hits projected onto reconstructed track. Direct Length is length between the furthest projected hits.

Smoothness

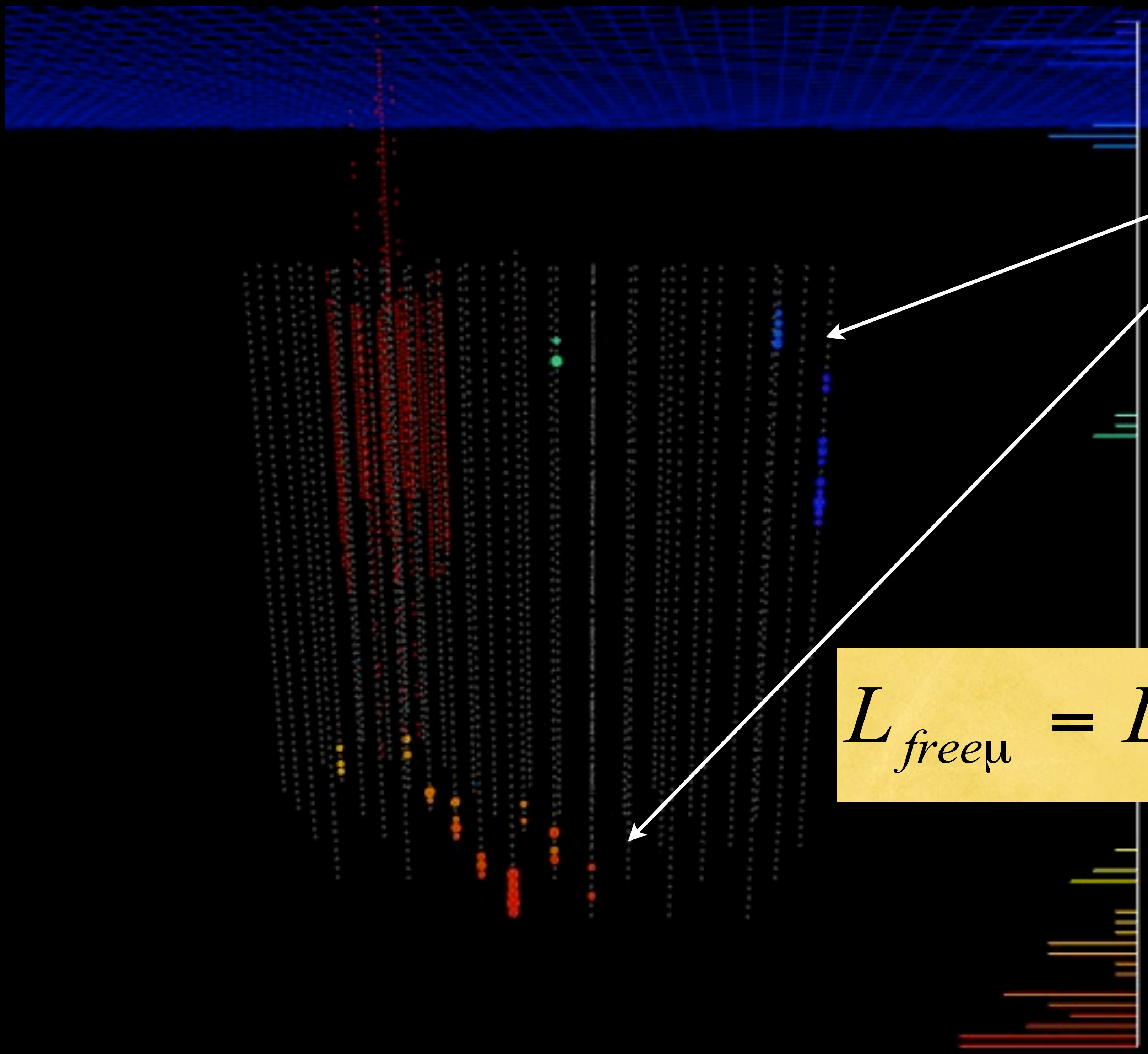
SDir

SDir = +1 if direct hits are near the beginning of track

SDir = -1 if direct hits are near the end of track

SDir = 0 if evenly distributed along track

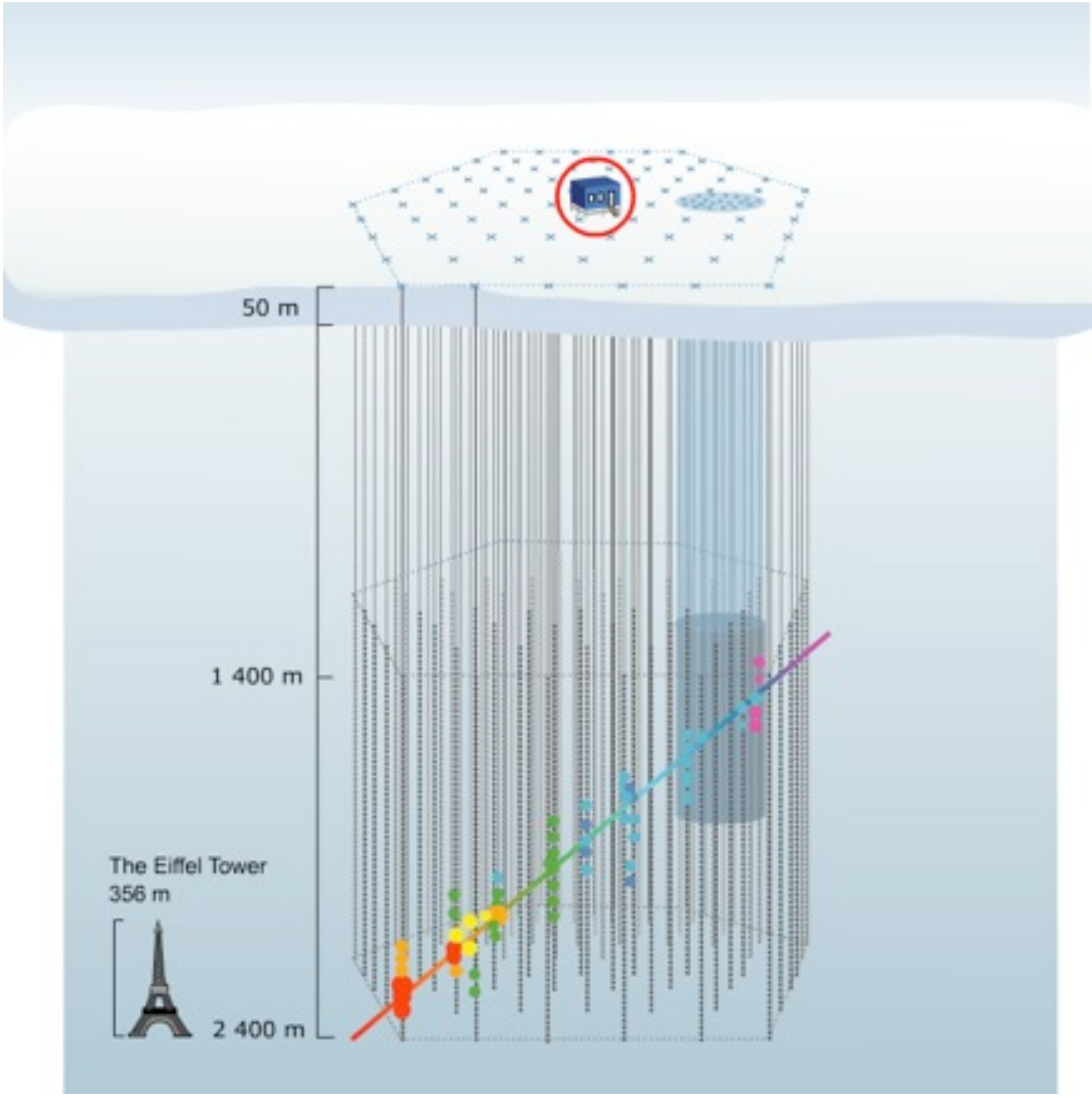
Split Reconstruction



Split hits in space/time to reconstruct two muons

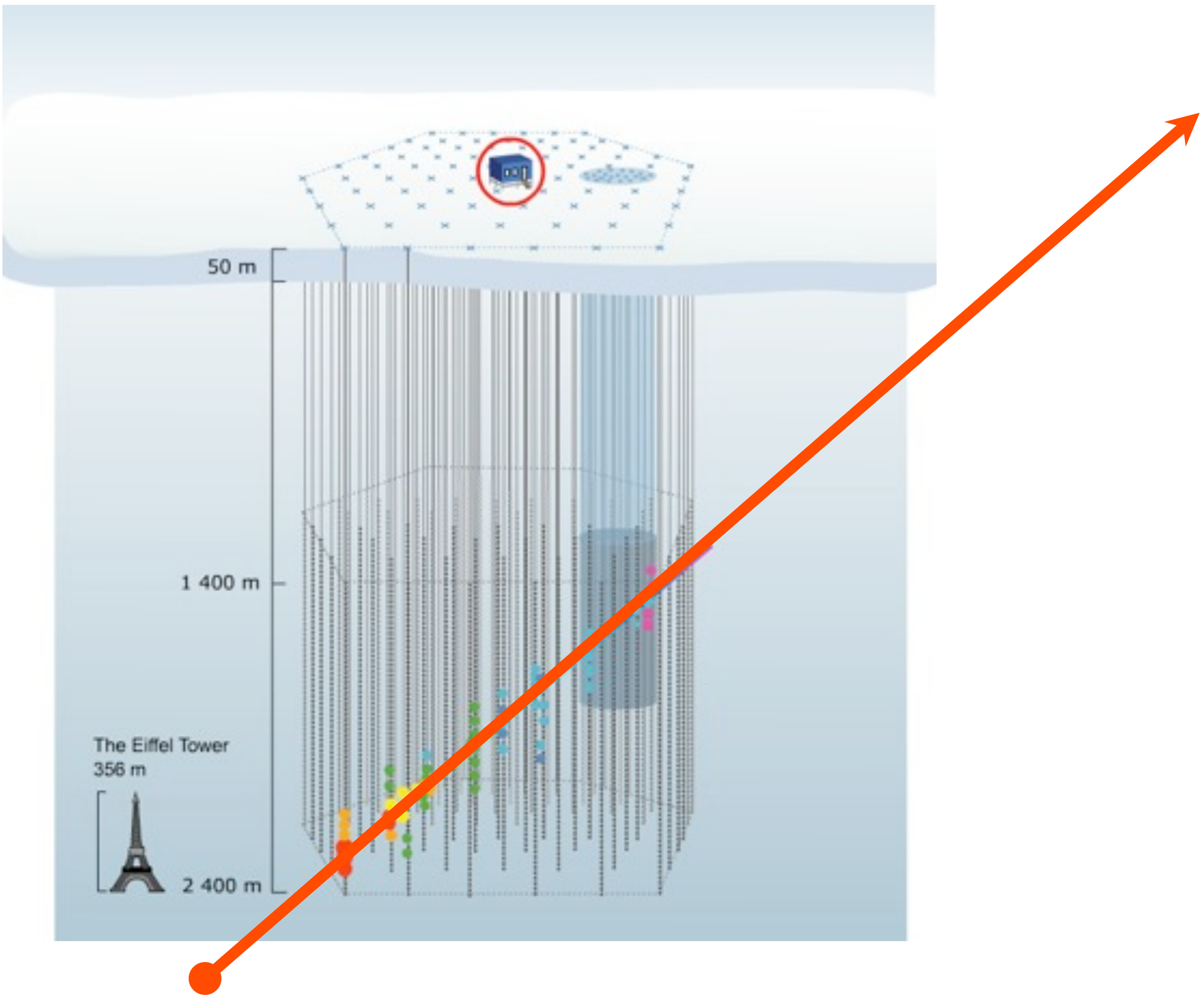
$$L_{free\mu} = L(E \mid \mu(\theta, \phi, x, y, z))$$

Quality Parameters: Bayesian Ratio



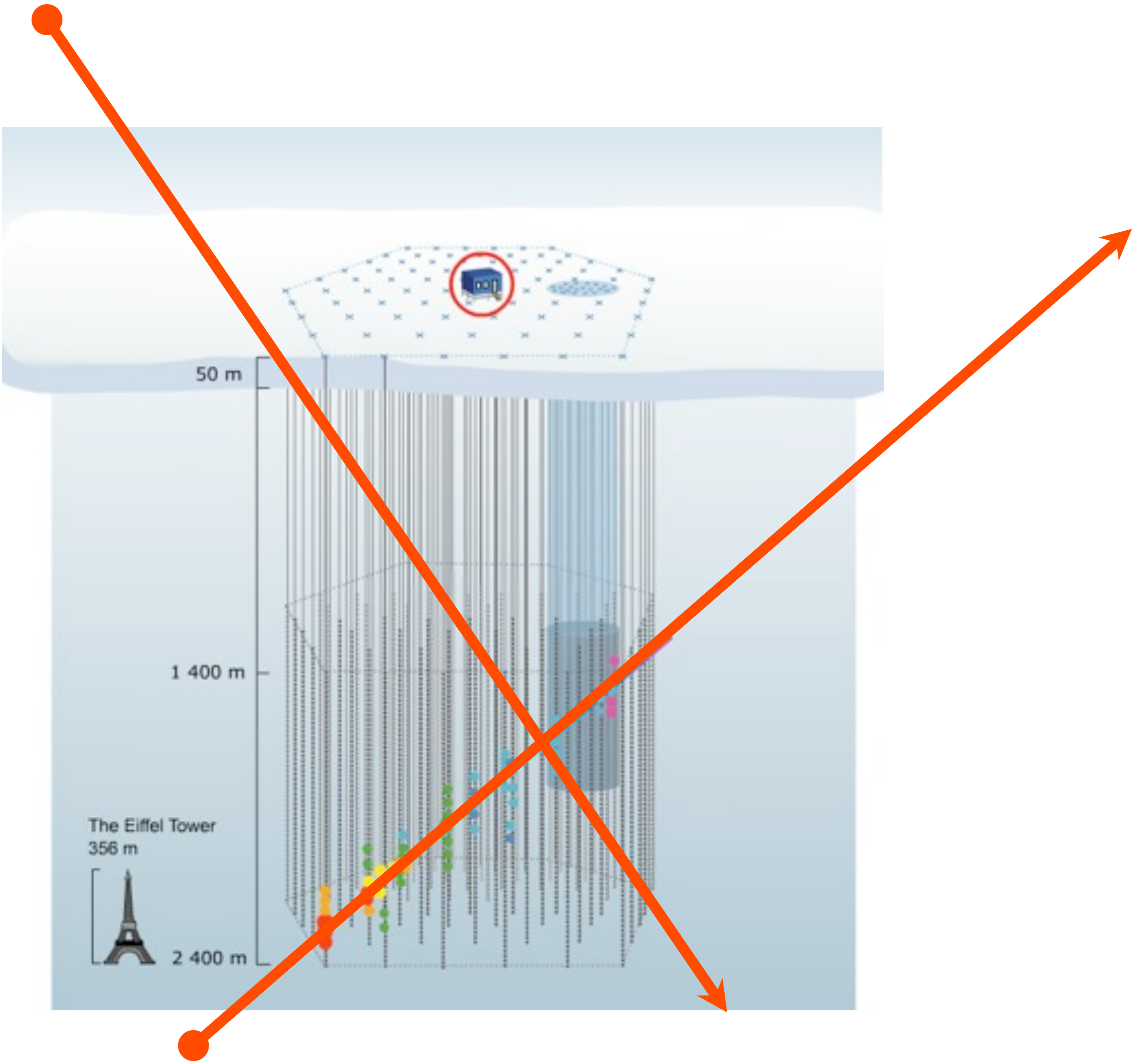
$$L_{free\mu} = L(E \mid \mu(\theta, \phi, x, y, z))$$

Quality Parameters: Bayesian Ratio



$$L_{free\mu} = L(E \mid \mu(\theta, \phi, x, y, z))$$

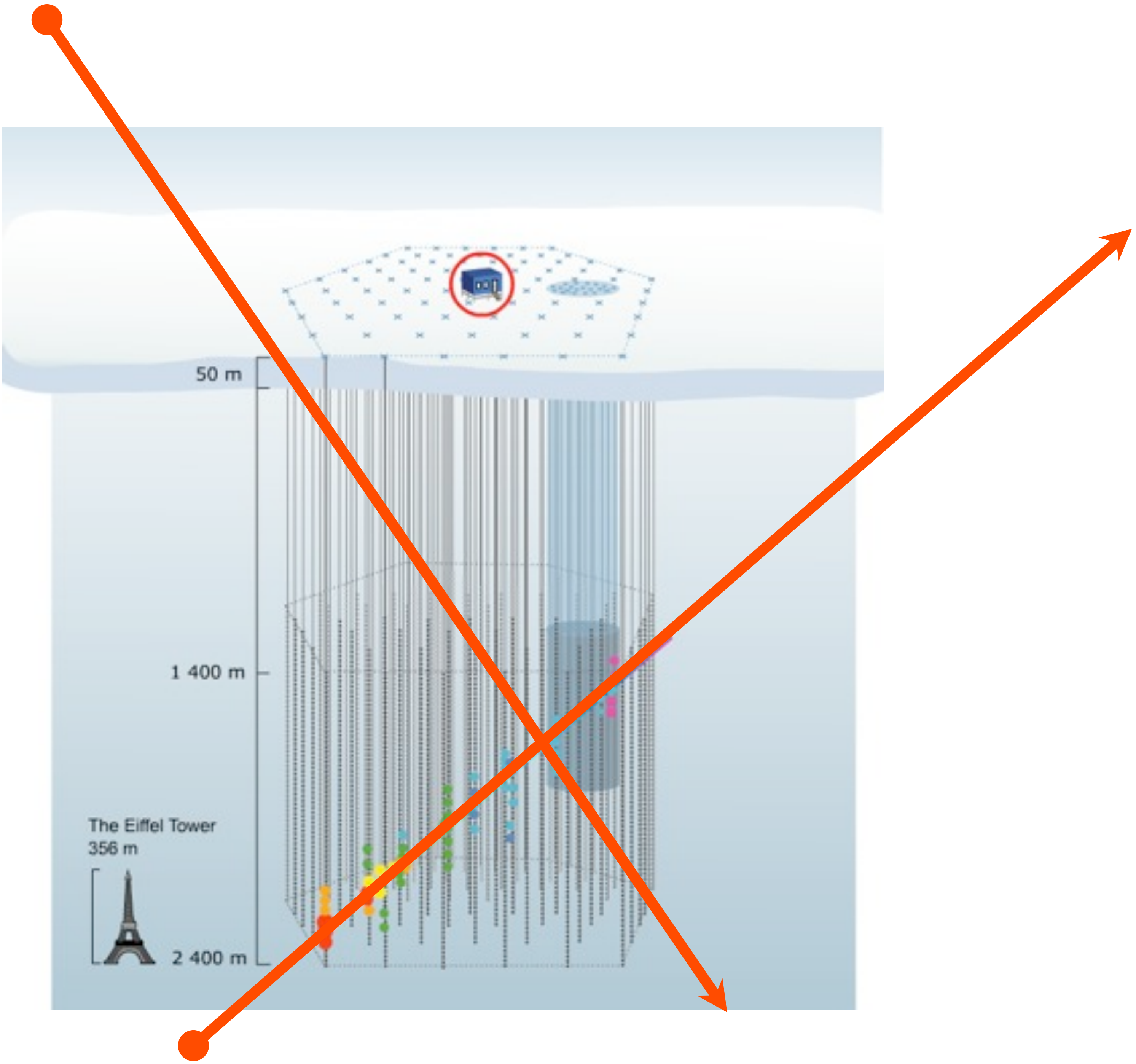
Quality Parameters: Bayesian Ratio



$$L_{free\mu} = L(E \mid \mu(\theta, \phi, x, y, z))$$

Quality Parameters: Bayesian Ratio

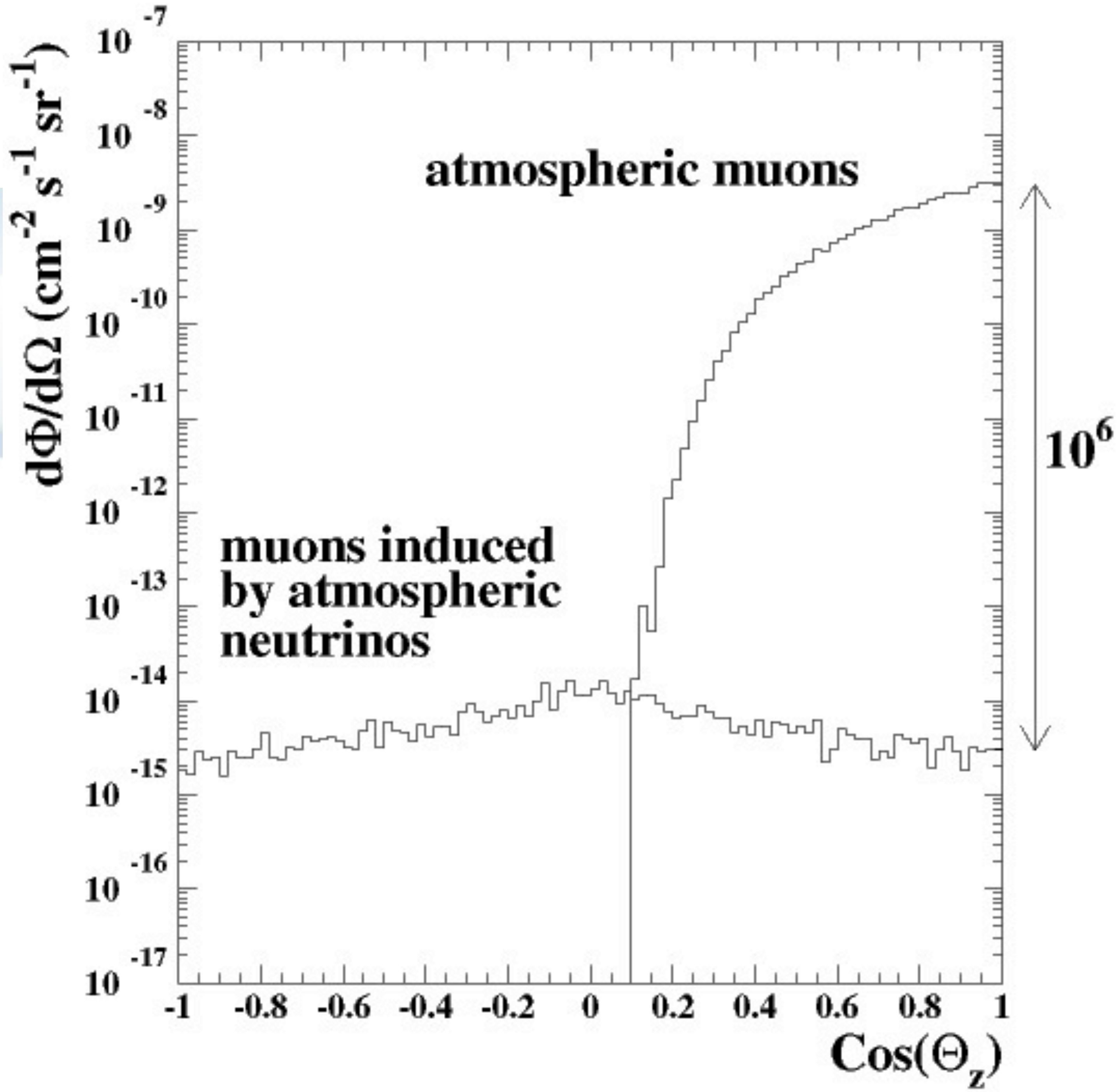
$$\Phi_{down\mu}(\theta)$$



$$L_{free\mu} = L(E \mid \mu(\theta, \phi, x, y, z))$$

Quality Parameters: Bayesian Ratio

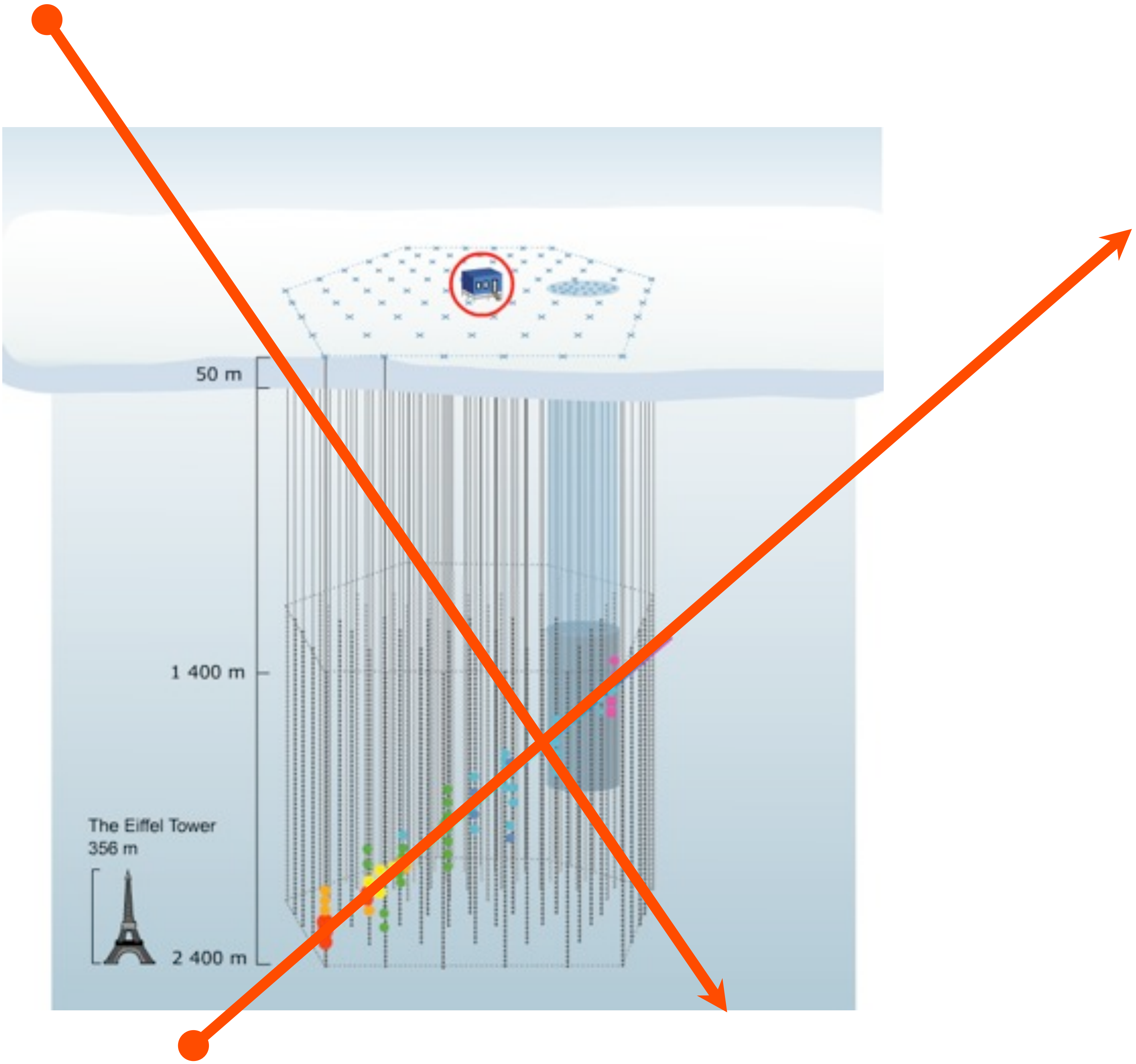
$\Phi_{down\mu}(\theta)$



$$L_{free\mu} = L(E \mid \mu(\theta, \phi, x, y, z))$$

Quality Parameters: Bayesian Ratio

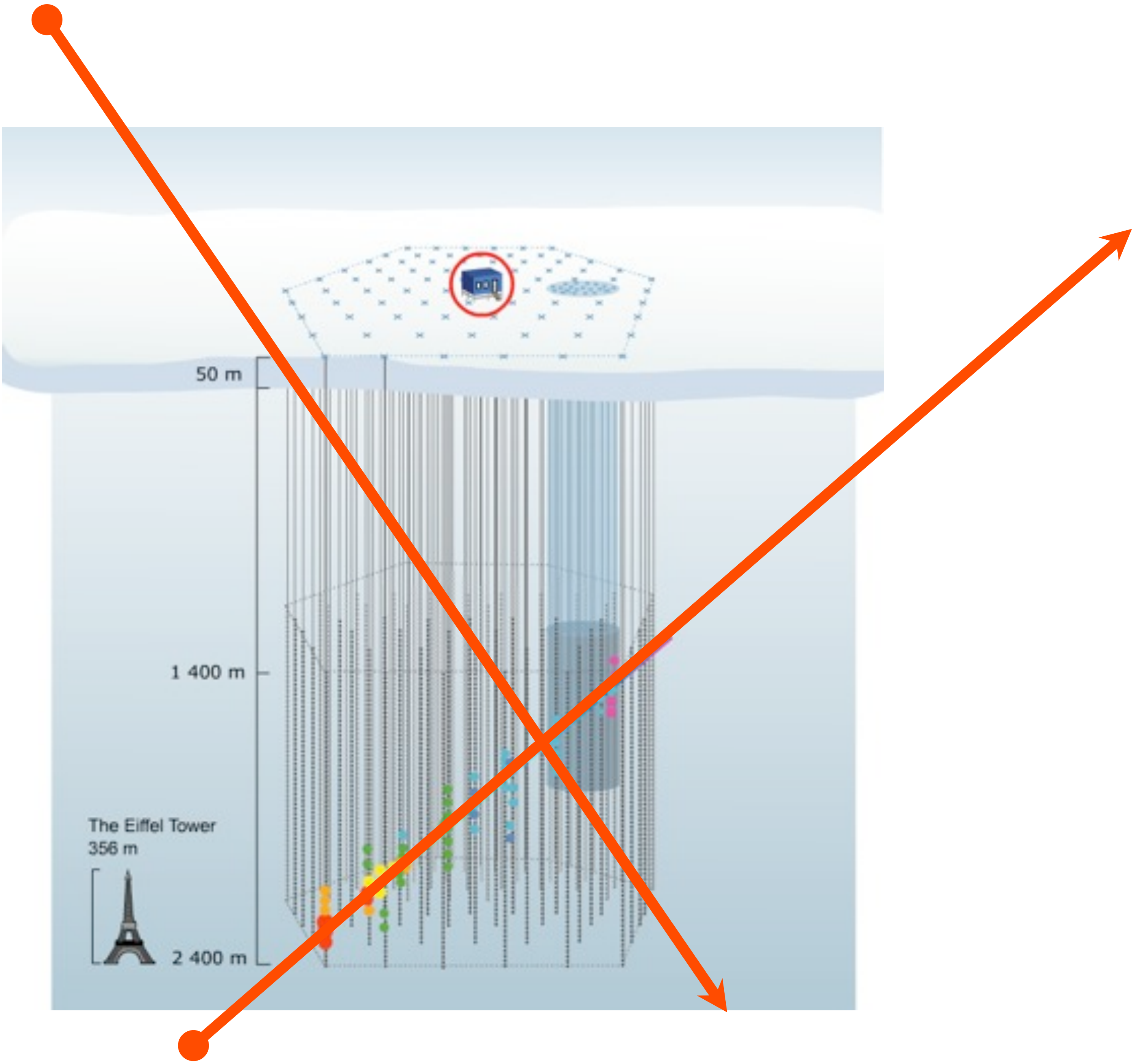
$\Phi_{down\mu}(\theta)$



$$L_{free\mu} = L(E \mid \mu(\theta, \phi, x, y, z))$$

Quality Parameters: Bayesian Ratio

$$\Phi_{down\mu}(\theta)$$

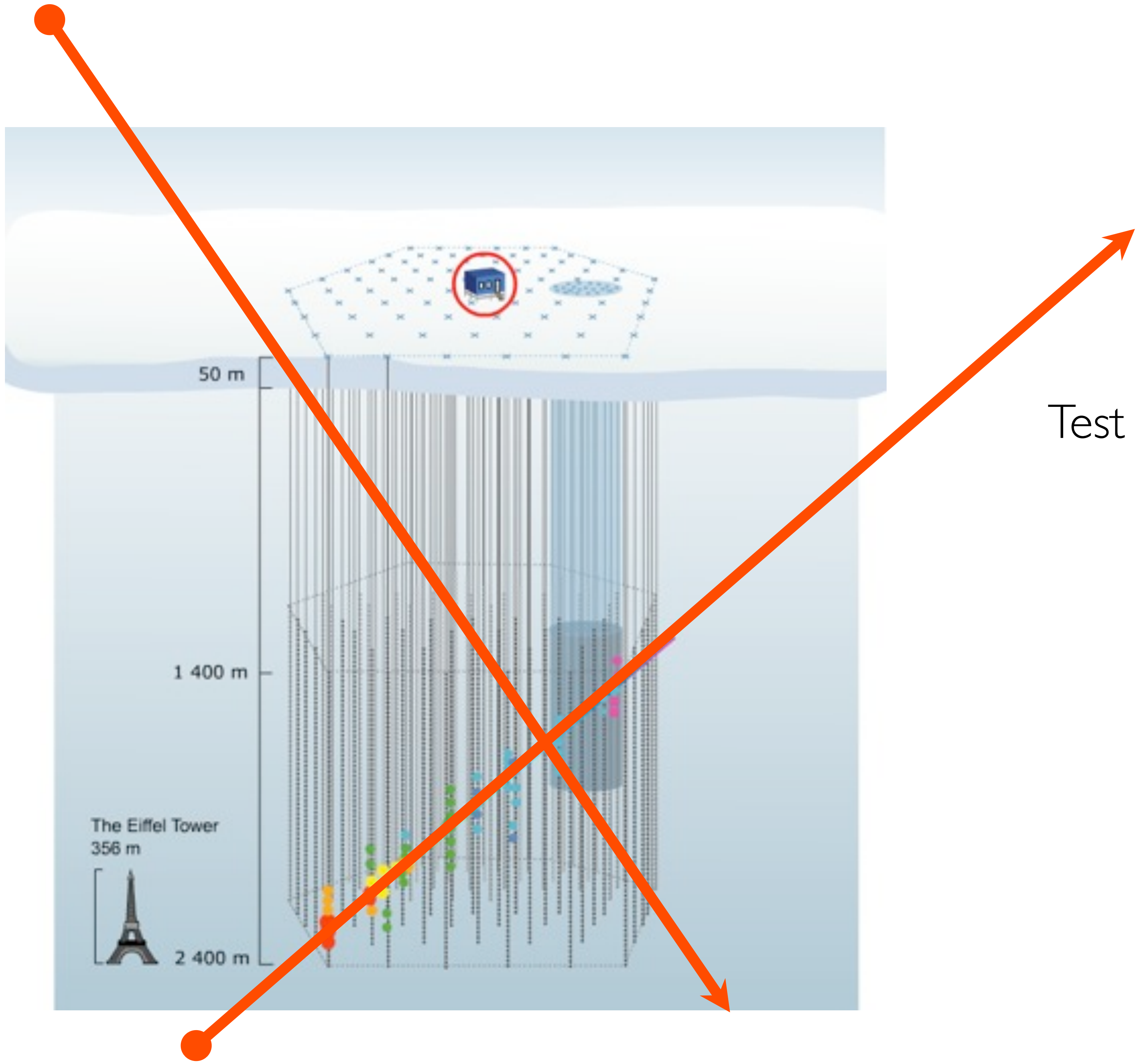


$$L_{free\mu} = L(E \mid \mu(\theta, \phi, x, y, z))$$

$$L_{down\mu} = L(E \mid \mu(\theta, \phi, x, y, z))\, \Phi_{down\mu}(\theta)$$

Quality Parameters: Bayesian Ratio

$\Phi_{down\mu}(\theta)$



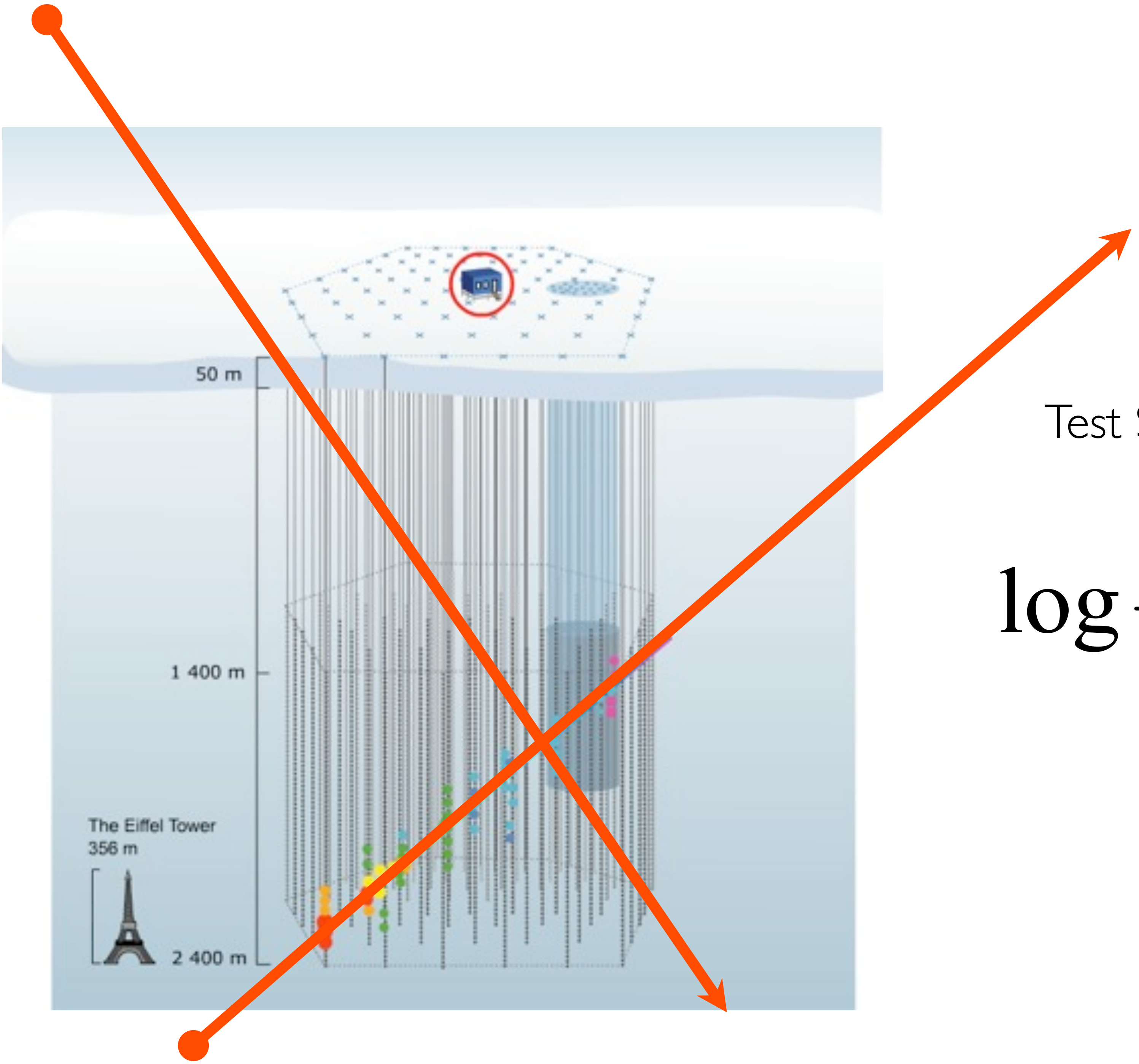
Test Statistic:

$$L_{free\mu} = L(E \mid \mu(\theta, \phi, x, y, z))$$

$$L_{down\mu} = L(E \mid \mu(\theta, \phi, x, y, z))\, \Phi_{down\mu}(\theta)$$

Quality Parameters: Bayesian Ratio

$$\Phi_{down\mu}(\theta)$$



Test Statistic:

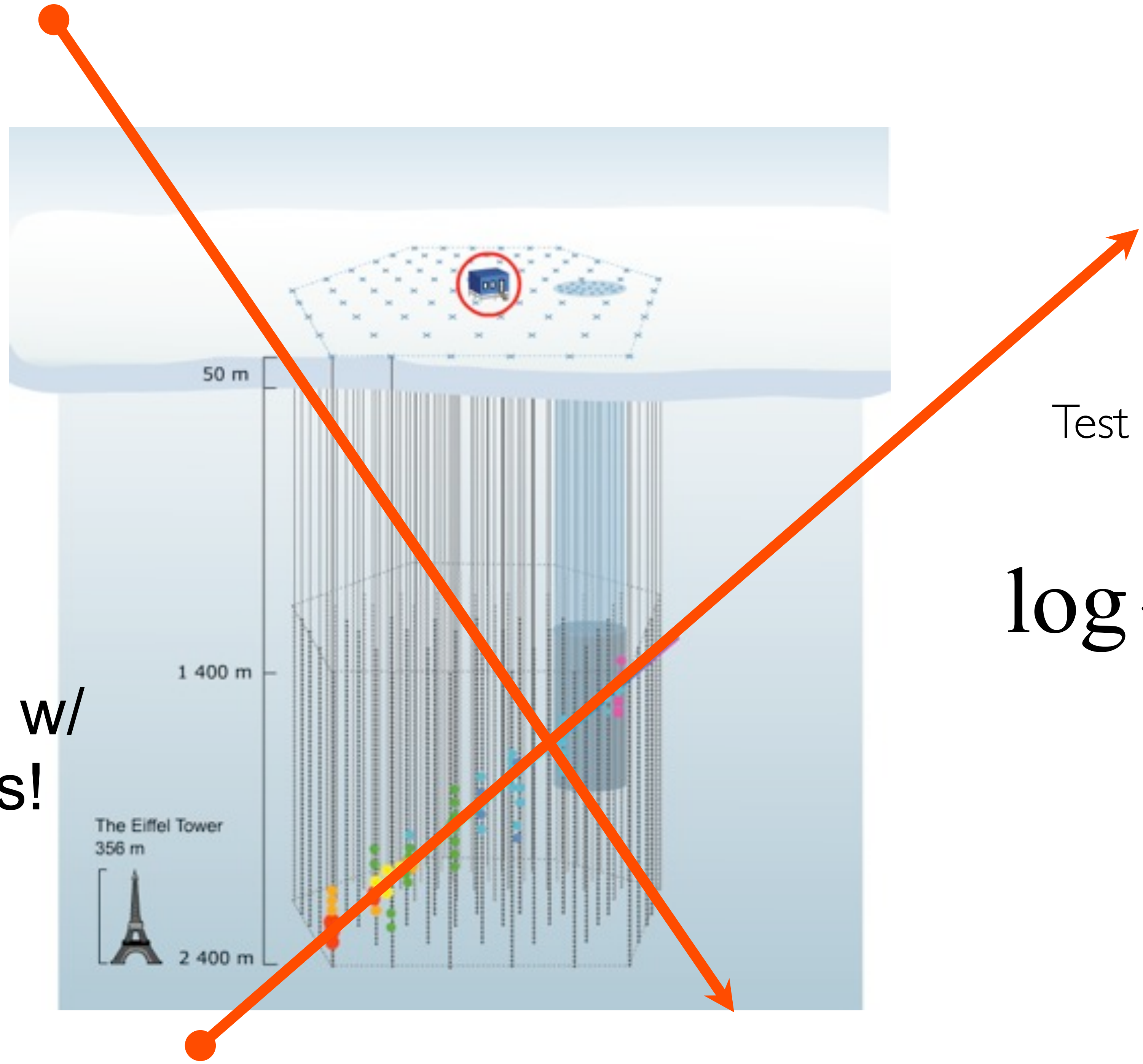
$$\log \frac{L_{free\mu}}{L_{down\mu}}$$

$$L_{free\mu} = L(E \mid \mu(\theta, \phi, x, y, z))$$

$$L_{down\mu} = L(E \mid \mu(\theta, \phi, x, y, z))\, \Phi_{down\mu}(\theta)$$

Quality Parameters: Bayesian Ratio

$$\Phi_{down\mu}(\theta)$$



Test Statistic:

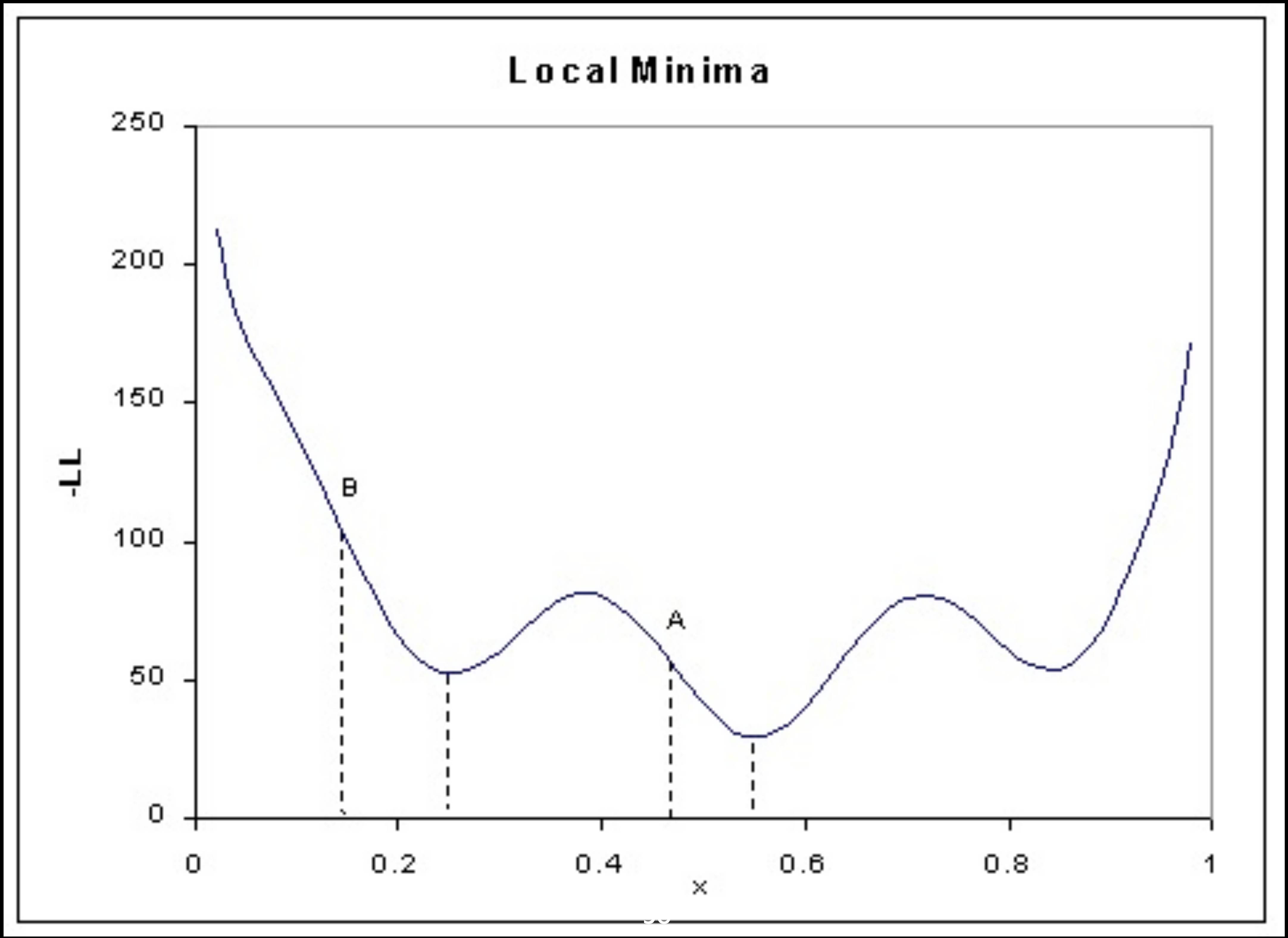
$$\log \frac{L_{free\mu}}{L_{down\mu}}$$

Can do the same w/ Coincident Muons!

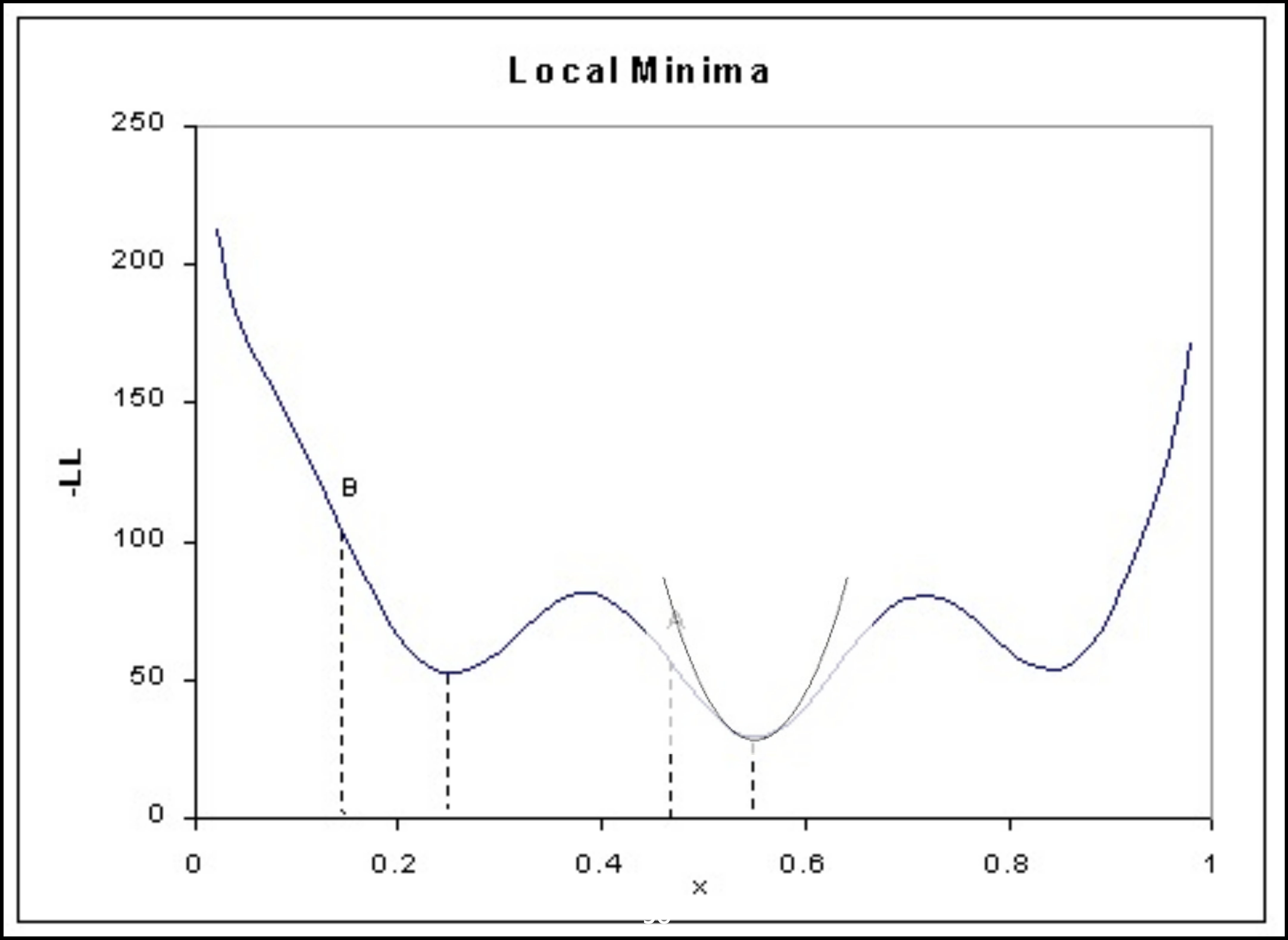
$$L_{free\mu} = L(E \mid \mu(\theta,\phi,x,y,z))$$

$$L_{down\mu} = L(E \mid \mu(\theta,\phi,x,y,z))\,\Phi_{down\mu}(\theta)$$

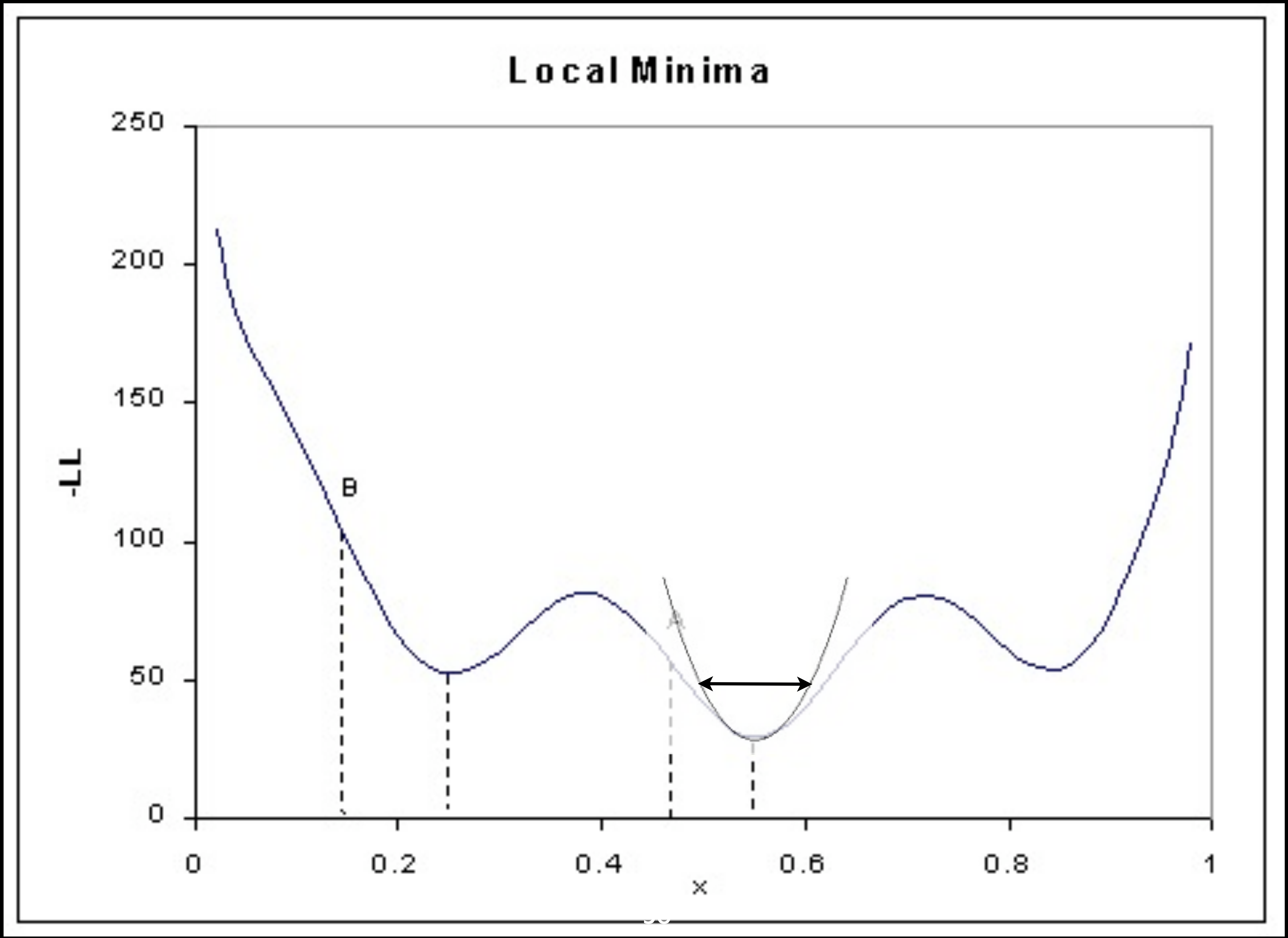
Quality Parameters - Paraboloid Sigma



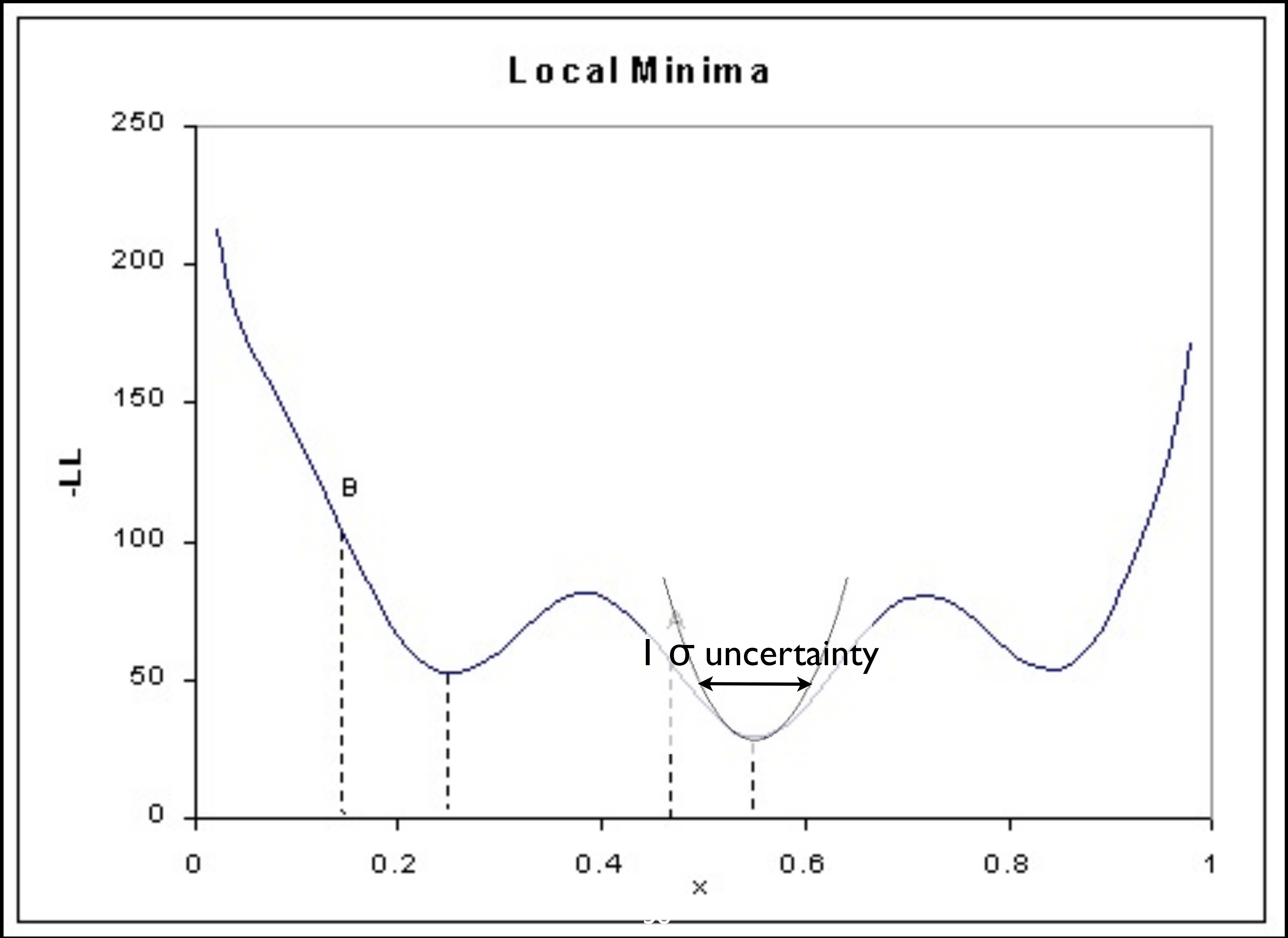
Quality Parameters - Paraboloid Sigma



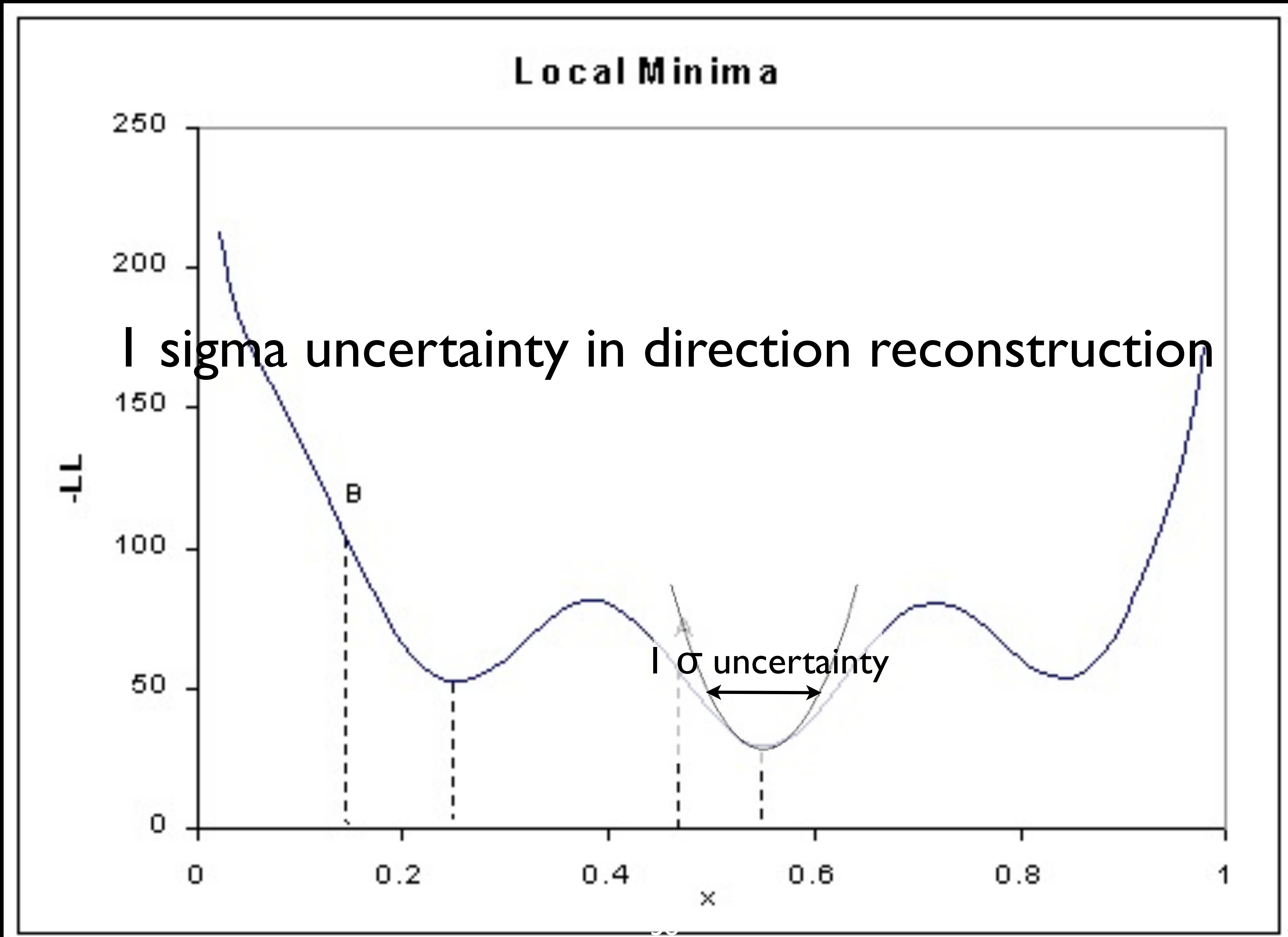
Quality Parameters - Paraboloid Sigma



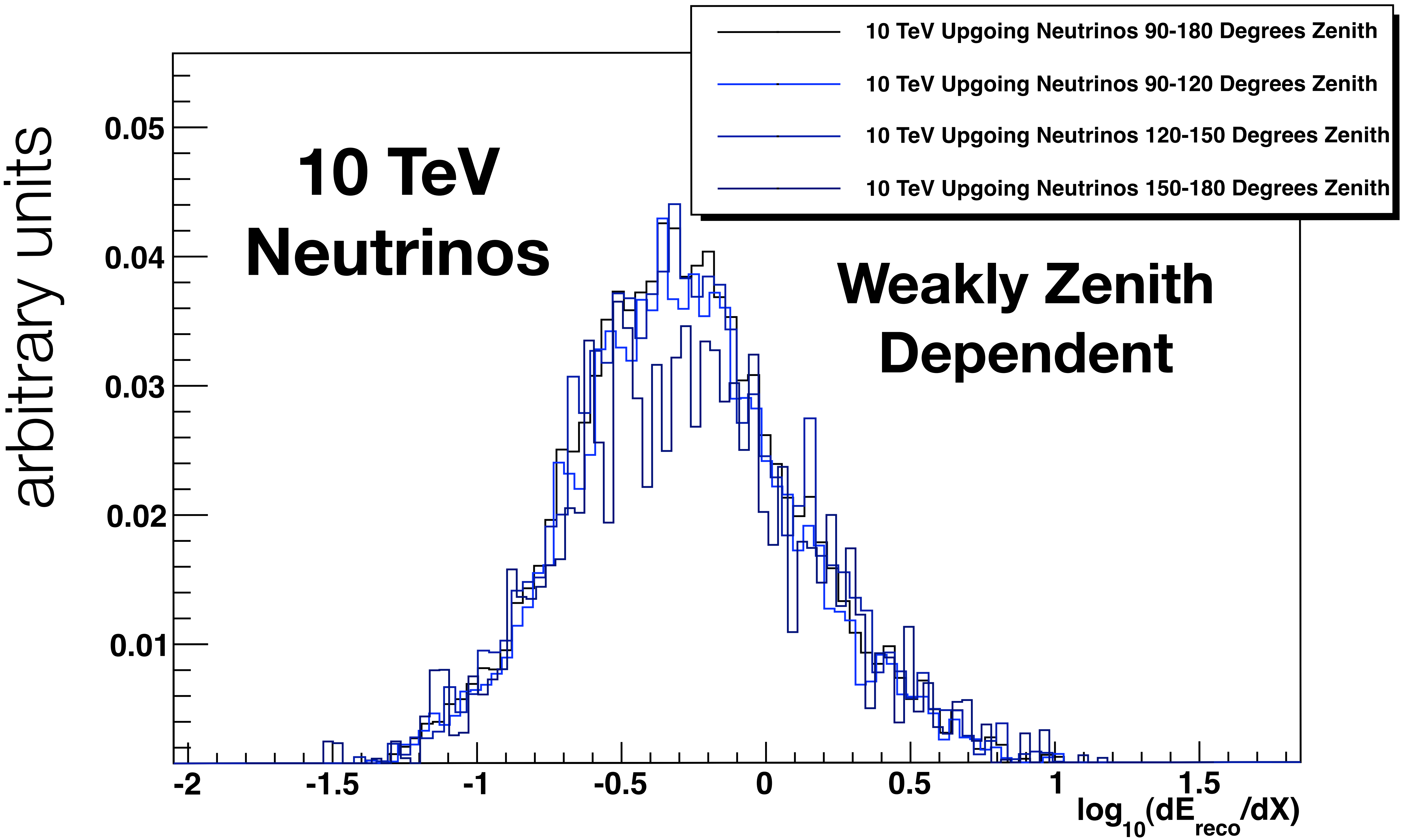
Quality Parameters - Paraboloid Sigma



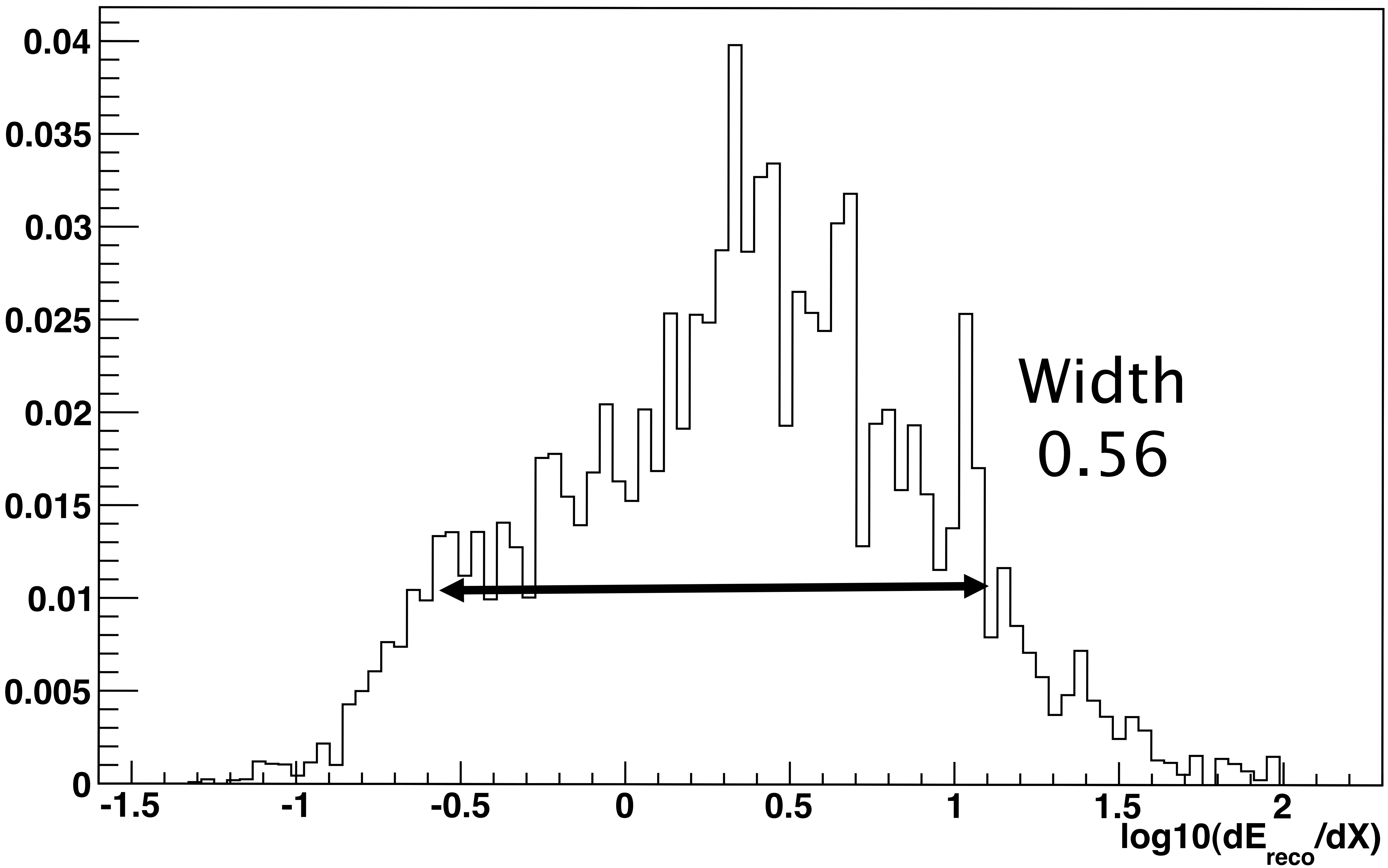
Quality Parameters - Paraboloid Sigma



Muon dE/dX PDF Zenith Dependence

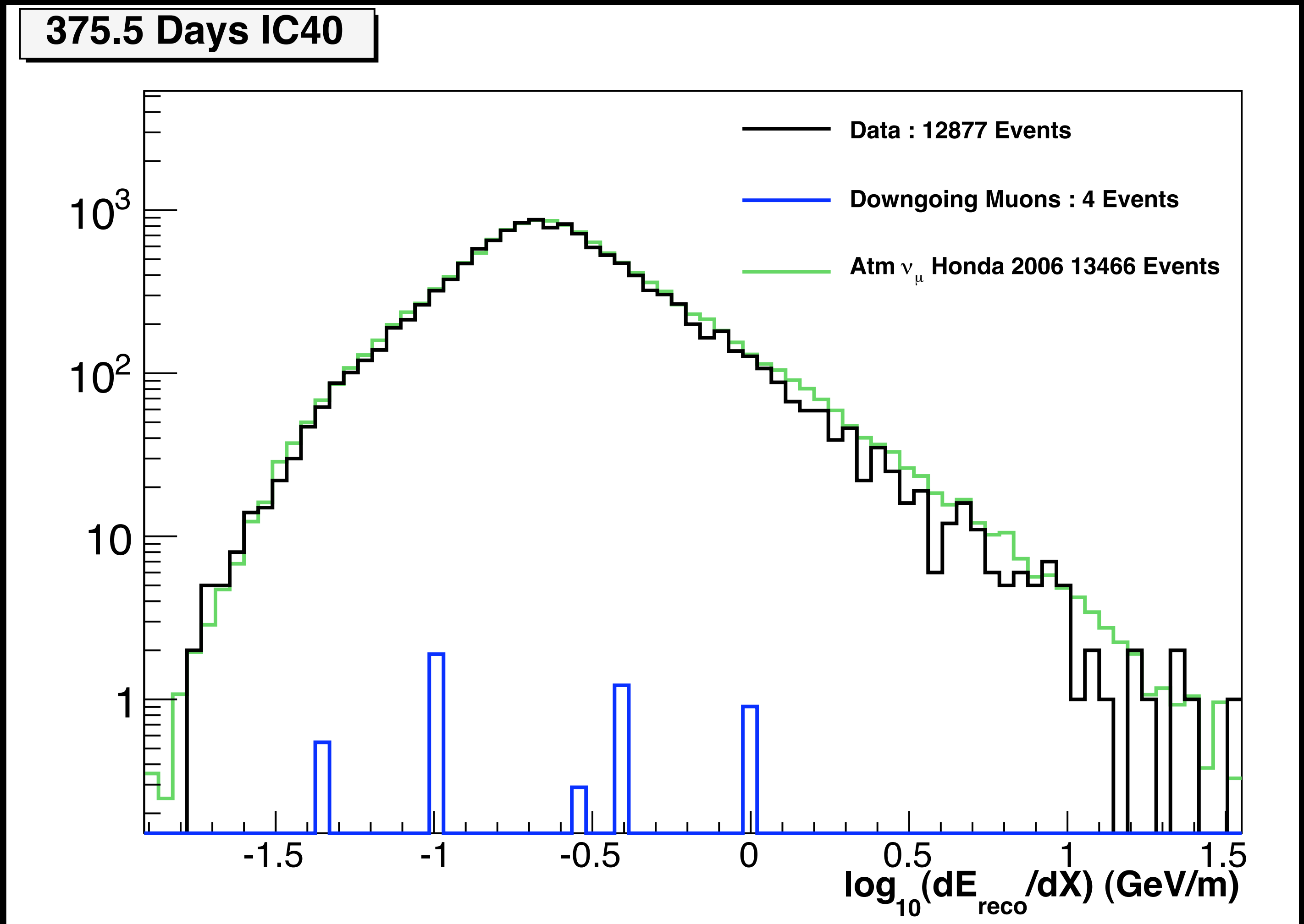


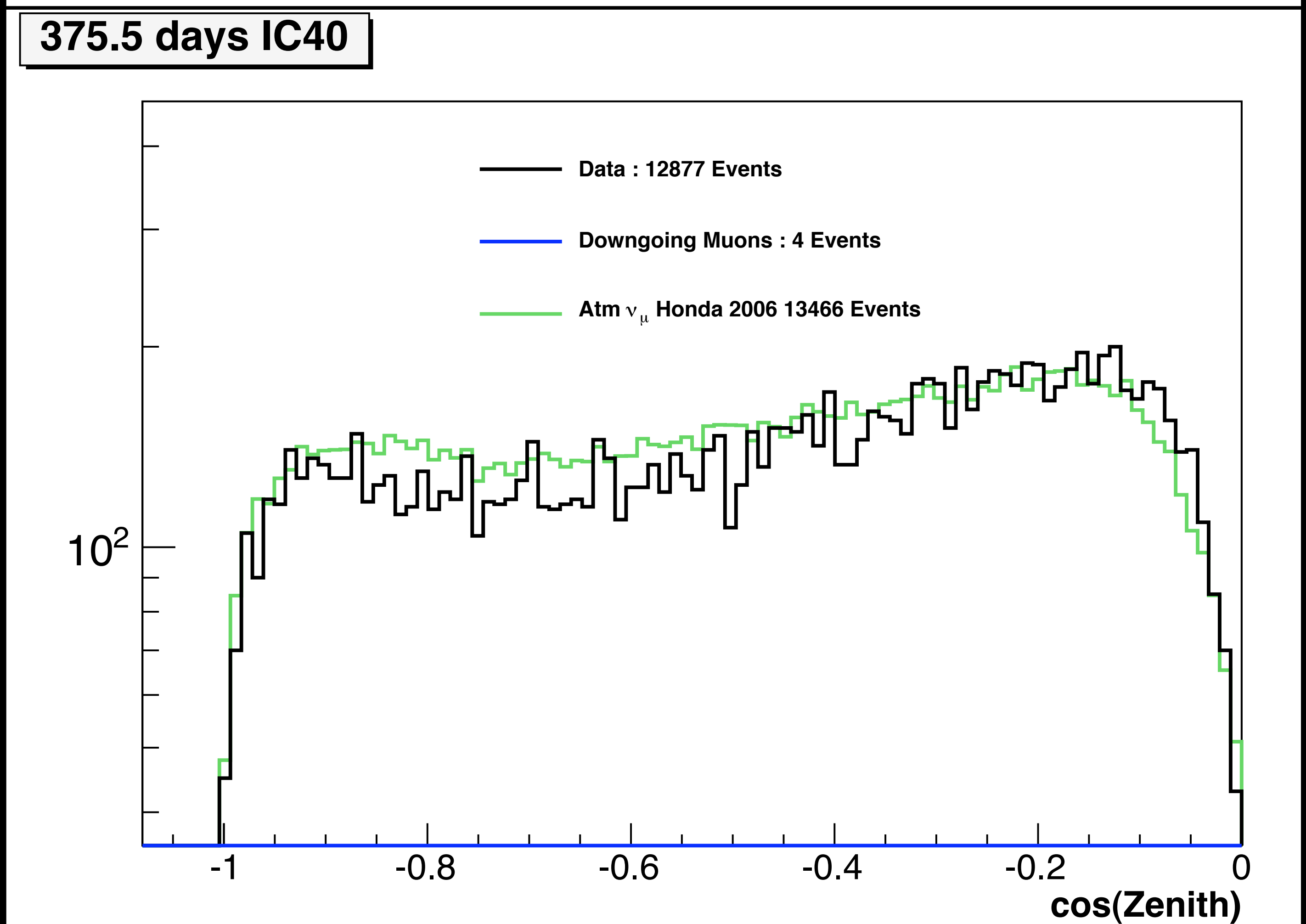
Muon dE/dX PDF for 100 TeV Neutrino Sample



Final Neutrino Sample

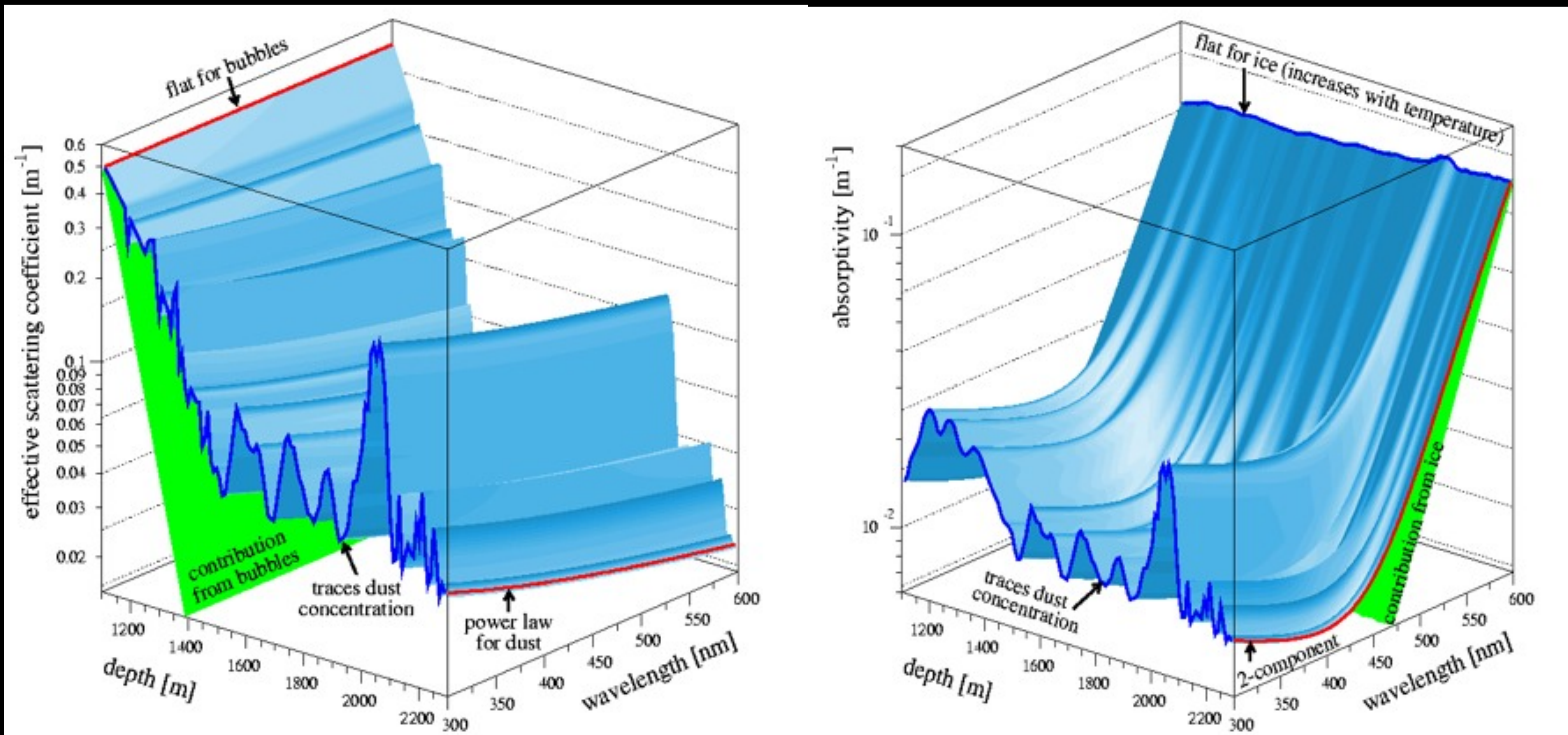
LDirC > 240	BayesRatio > 25 for Cos(Zenith) < -0.2 BayesRatio > 75*Cos(Zenith)+40 for Cos(Zenith) > -0.2	MPE Zenith > 90
|SDirC| < 0.54	Split BayesRatio > 35	MinSplitZenith > 80
NDirC > 5	logl/(NCh-5) < 8 OR logl/(NCh-2.5) < 7.1	Paraboloid Sigma < 3





Sunday, August 21, 2011

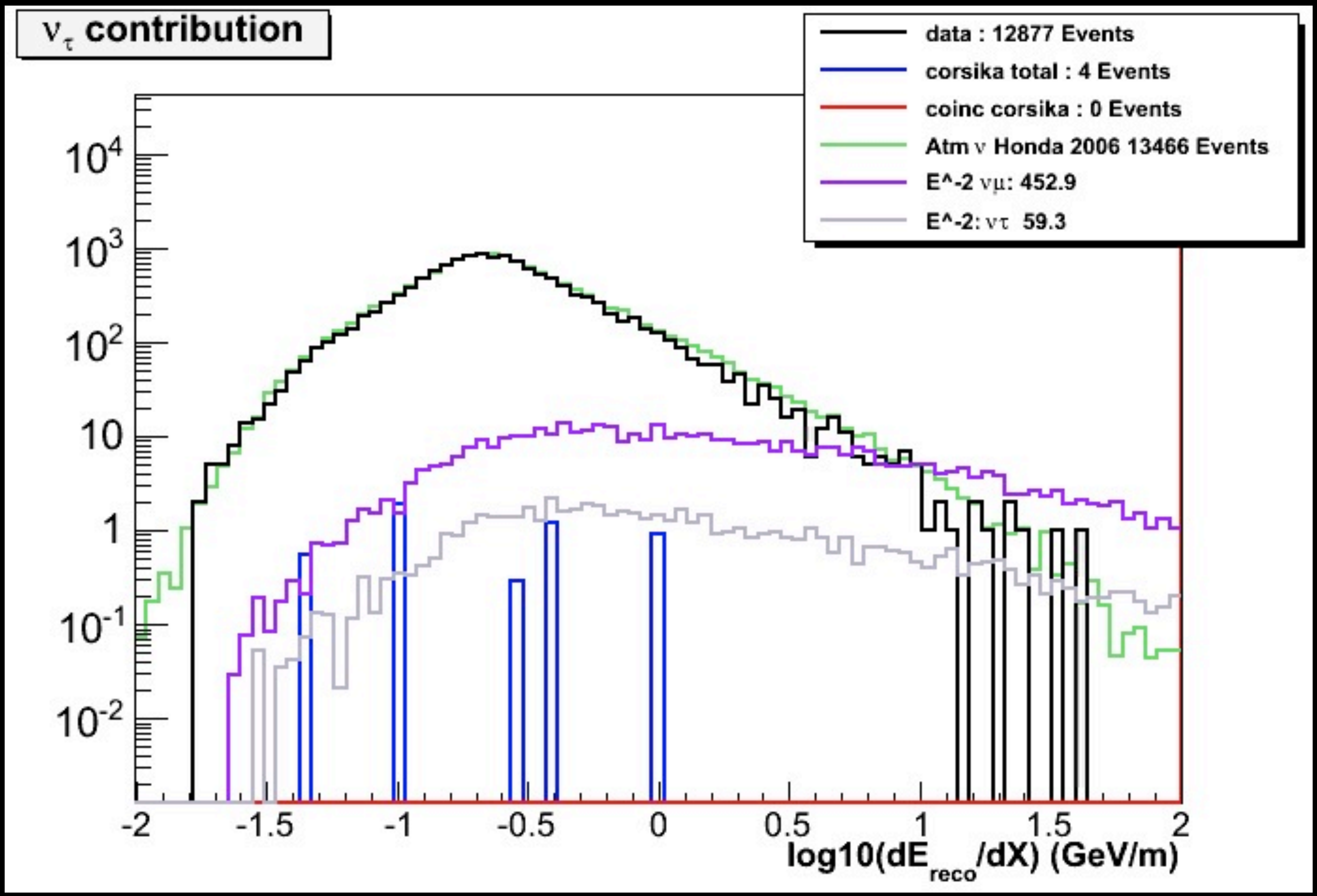
Systematic Uncertainties of the Ice properties



Scattering **Absorption**

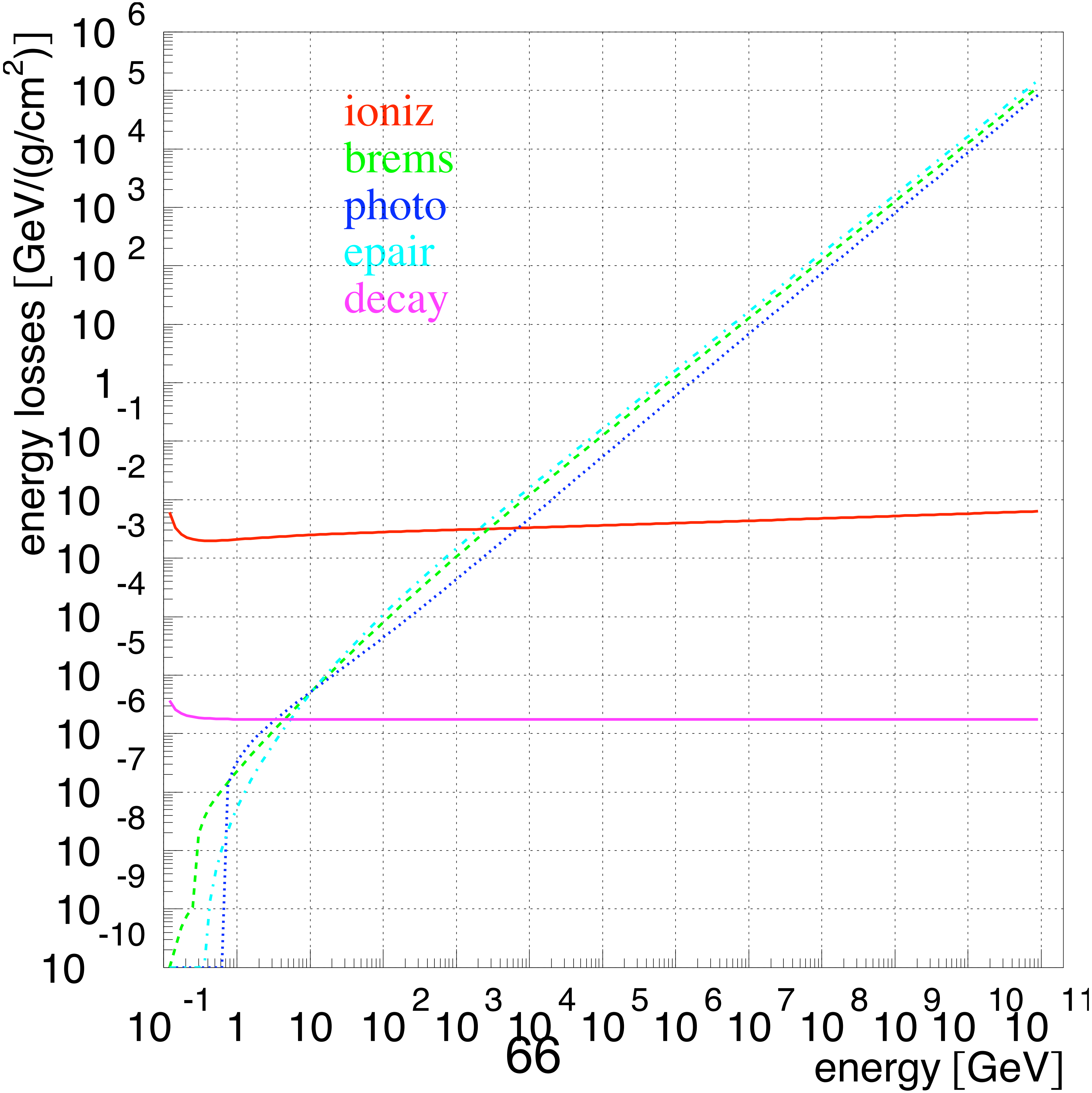
- Uncertainty in scattering and absorption +/- 10%
- Systematically vary ice properties in the simulation to get effect on sensitivity & final limit (underway)

Tau Neutrino Contribution



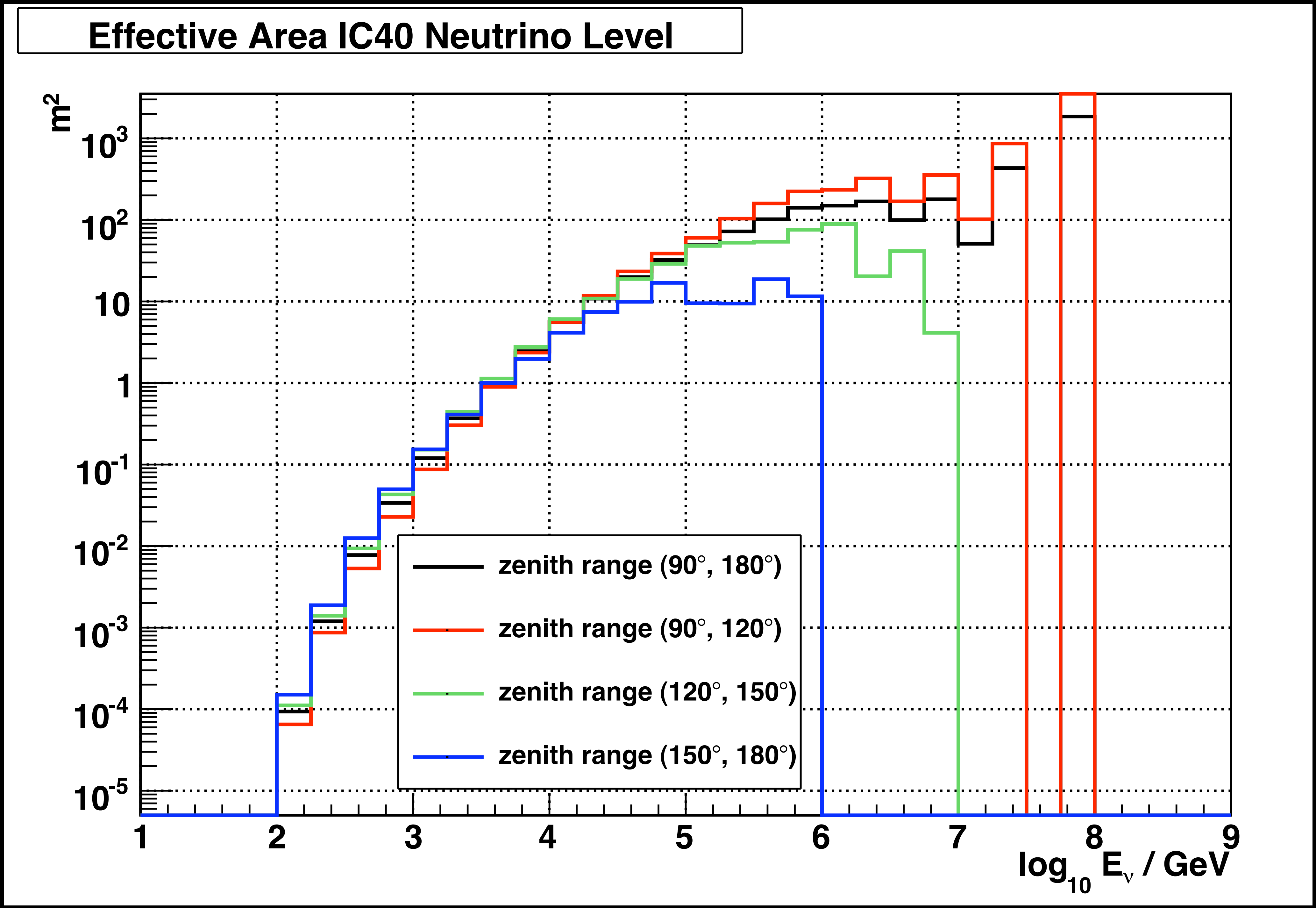
Tau Contribution - Astrophysical Upper Limits

Model	ν_μ	$\nu_\mu + \nu_\tau$	$\nu_\mu + \nu_e + \nu_\tau$
E^{-2}	8.9×10^{-9}	1.64×10^{-8}	2.53×10^{-8}
Stecker Blazar Model	0.1	0.17	0.27
WB-Upper Bound	0.54	1.02	1.56
FSRQ Model	0.02	0.037	0.057
Mannheim AGN Model	0.02	0.039	0.059

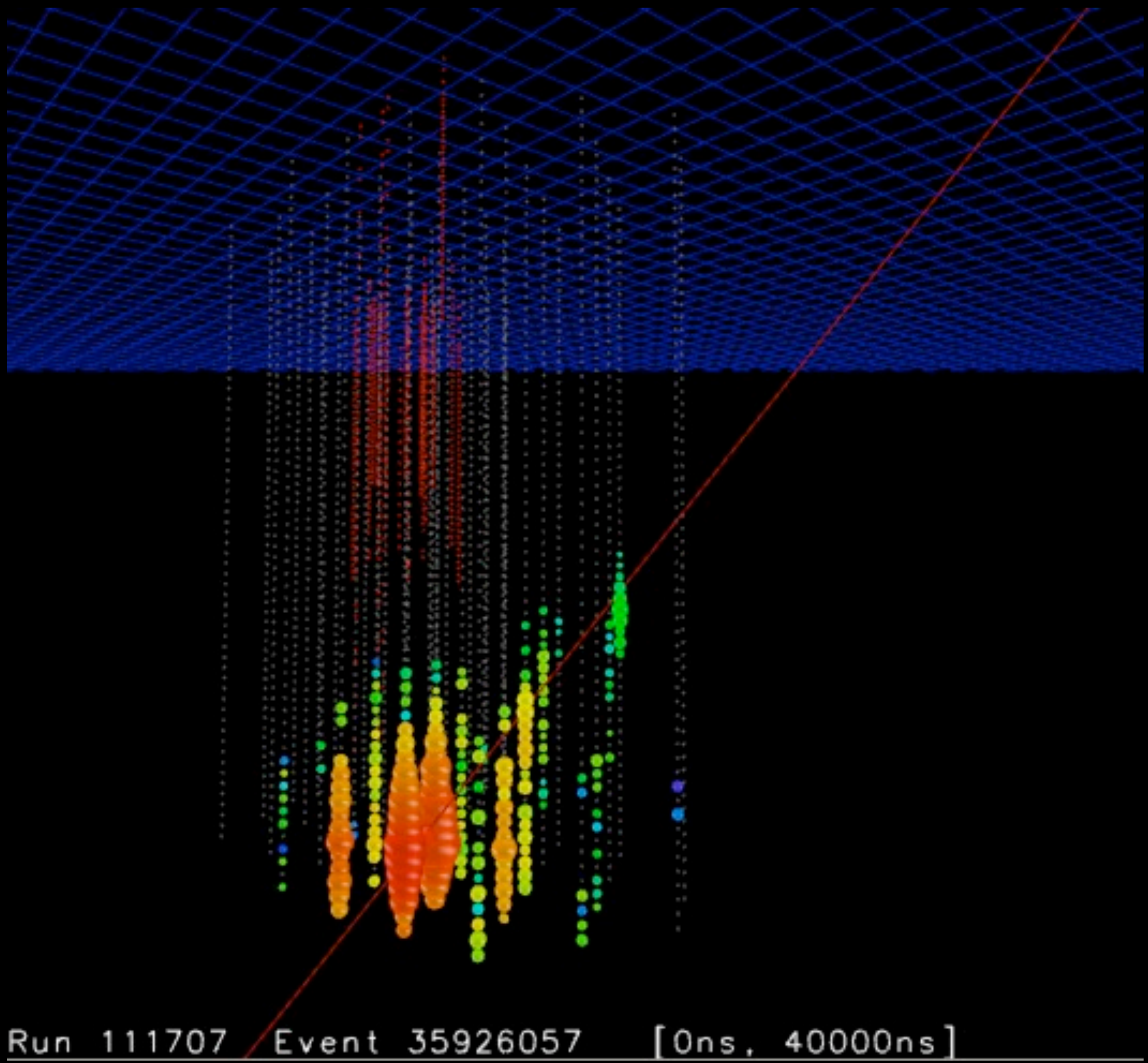


ioniz
brems
photo
epair
decay
energy losses [GeV/(g/cm^2)]
energy [GeV]

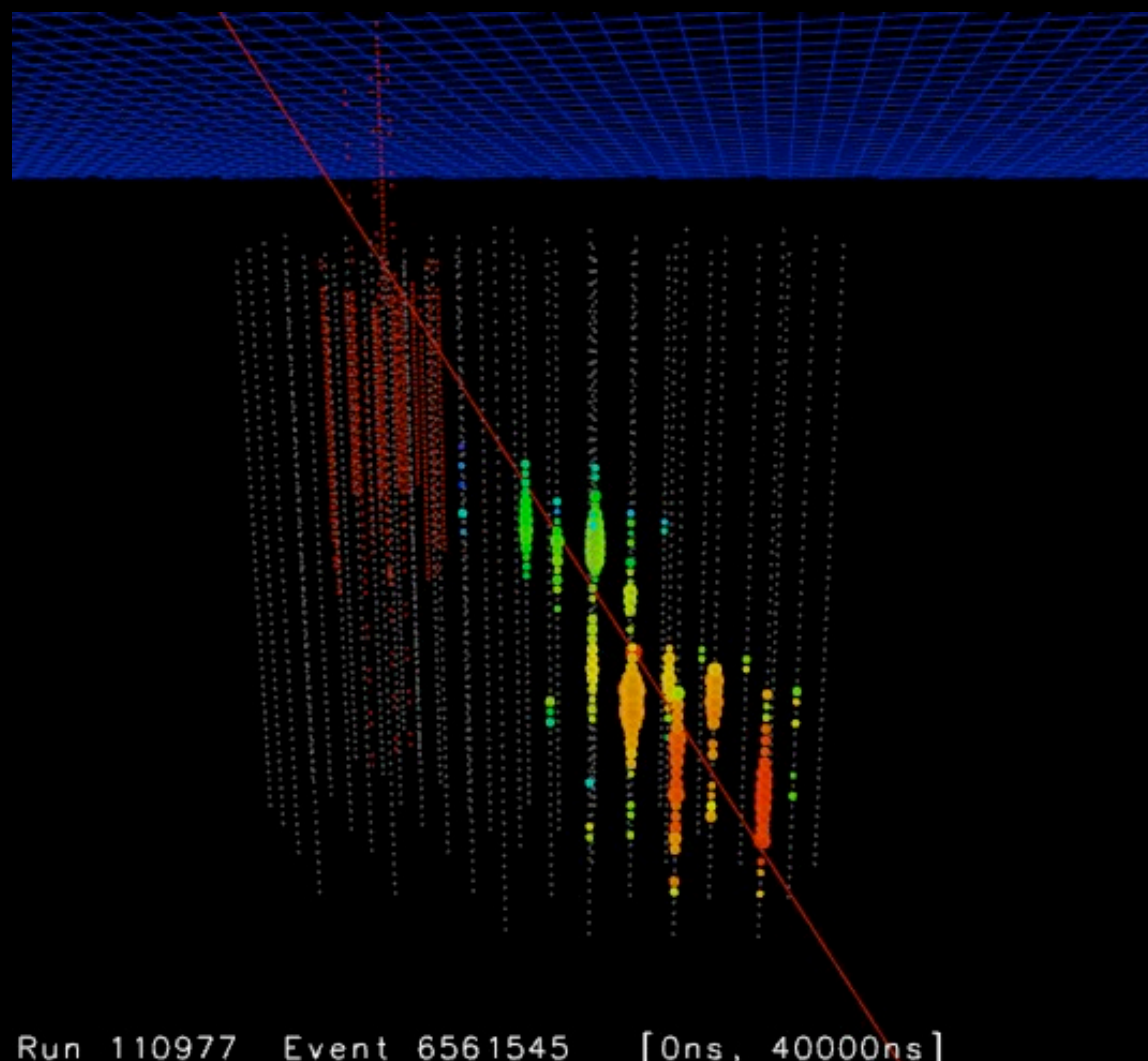
Effective Area



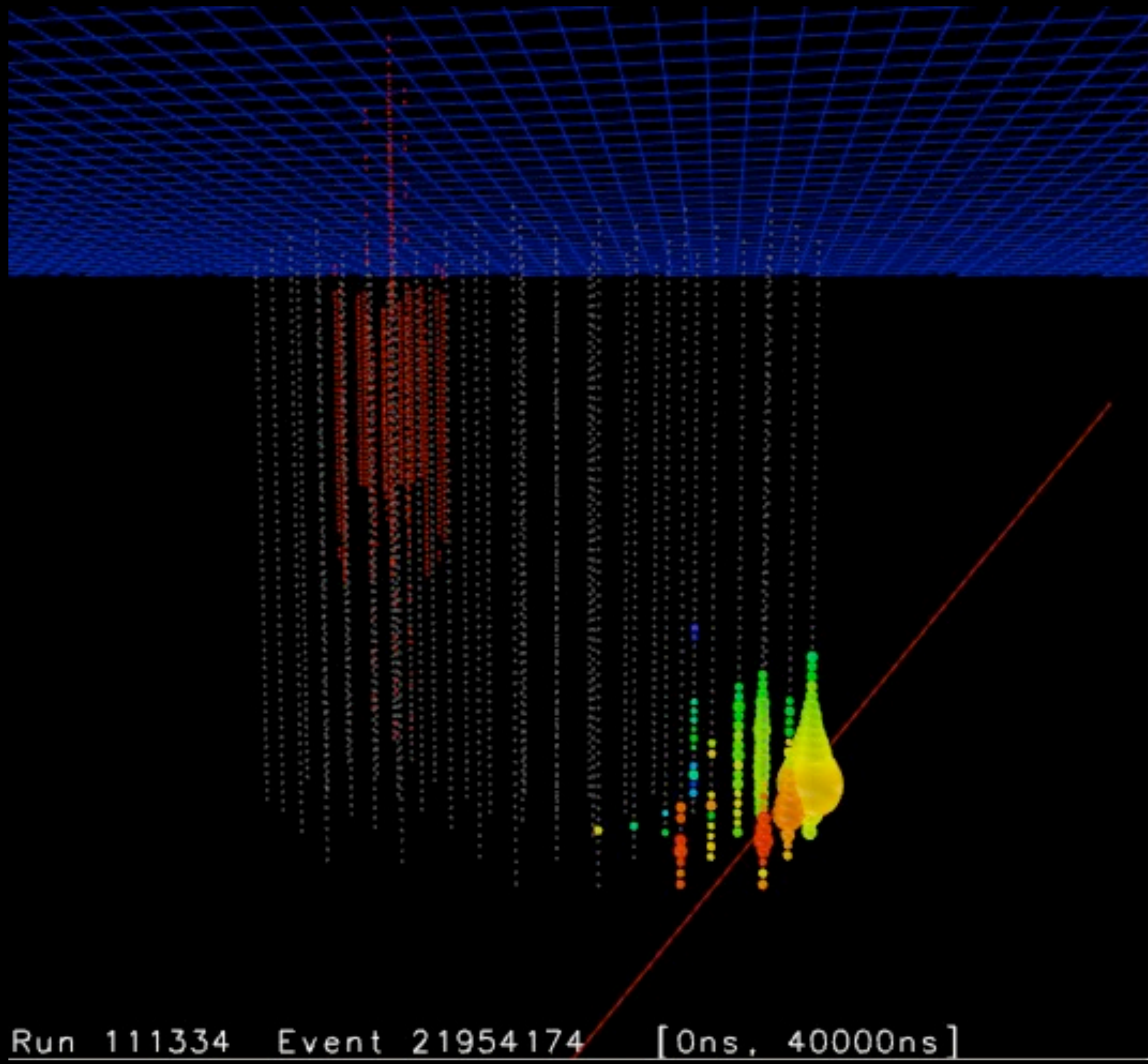
107 TeV



89 TeV



186 TeV



103 TeV