Searching for Diffuse Astrophysical Muon Neutrinos with IceCube

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University of Wisconsin - Madison

Tuesday, January 19, 2010

Overview

- High Energy Neutrino Astronomy

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- High Energy Neutrino Astronomy
- The IceCube Detector

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- Diffuse Search Strategy

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- High Energy Neutrino Astronomy
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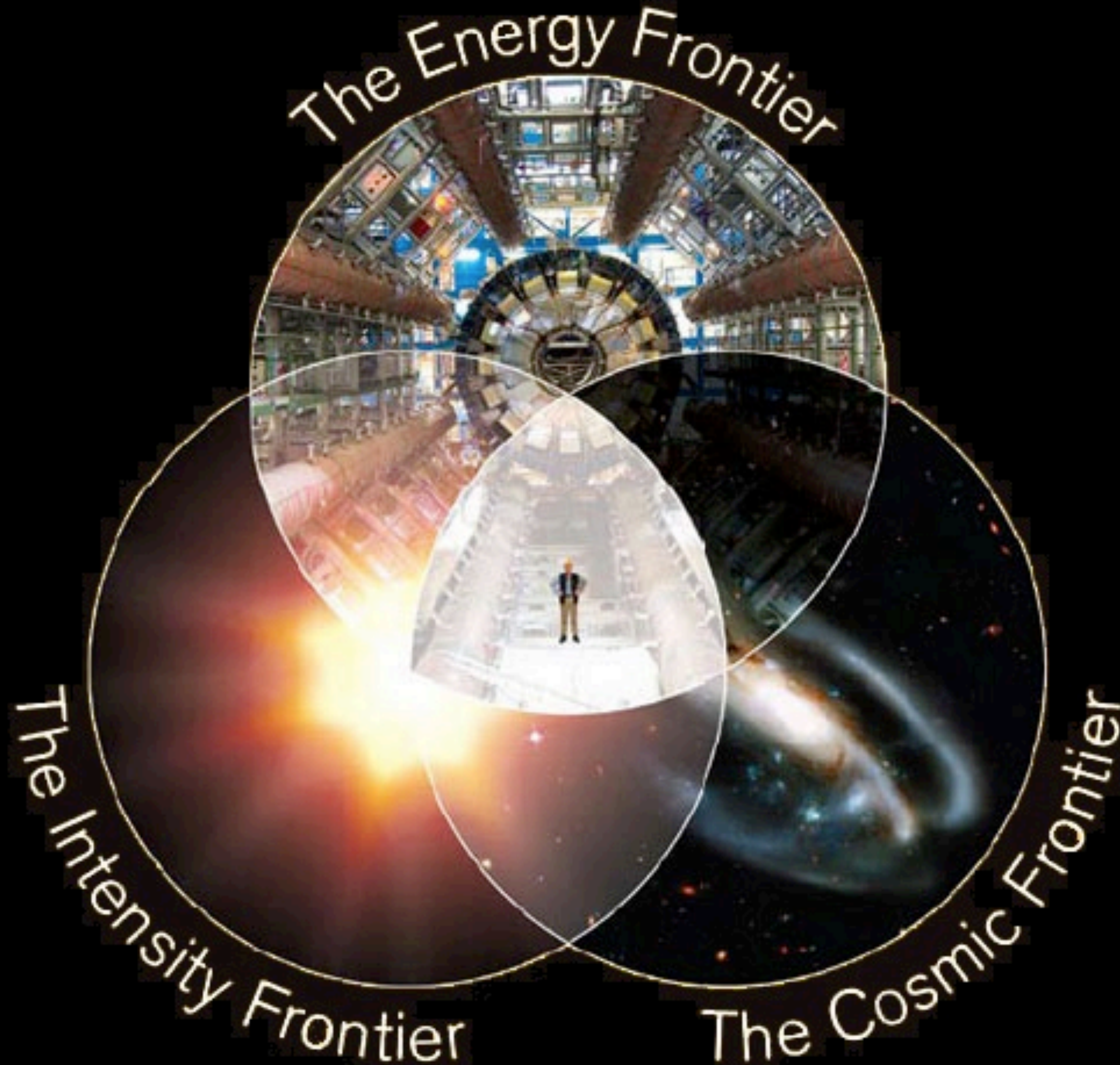
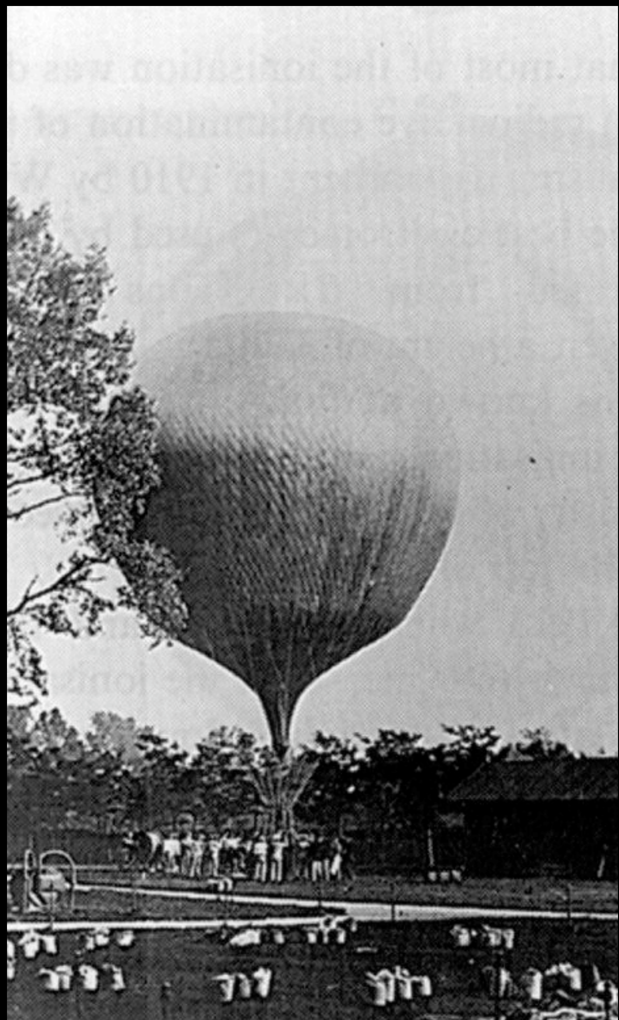
- Diffuse Search Strategy
- Analysis Results from 2008

Particle Physics Today: Three Frontiers of Science

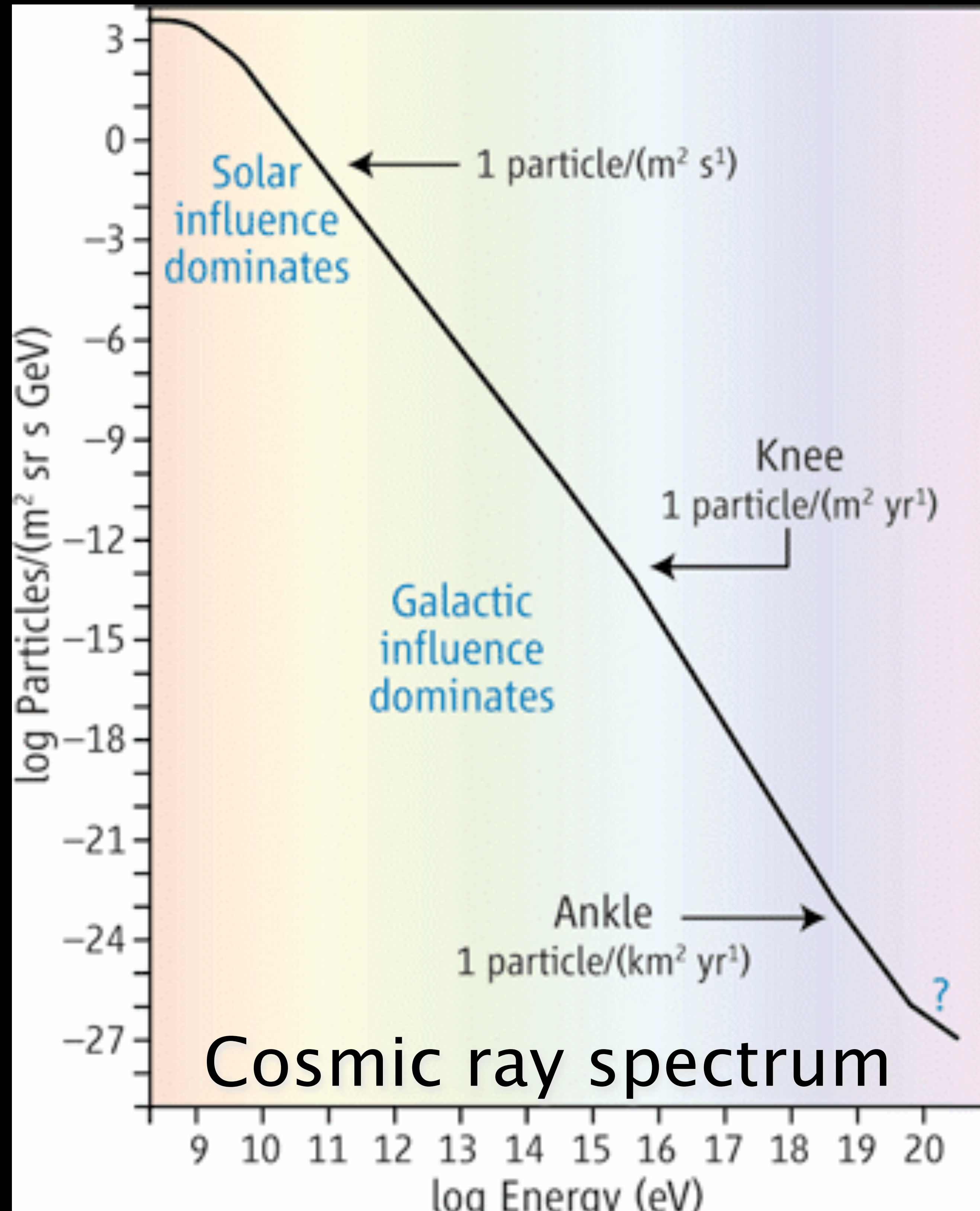


Cosmic Rays: A 100 year old mystery



Balloon flights
1911-1913

Victor Hess
Nobel Prize
1936



- Power law over many decades
- Origin Uncertain

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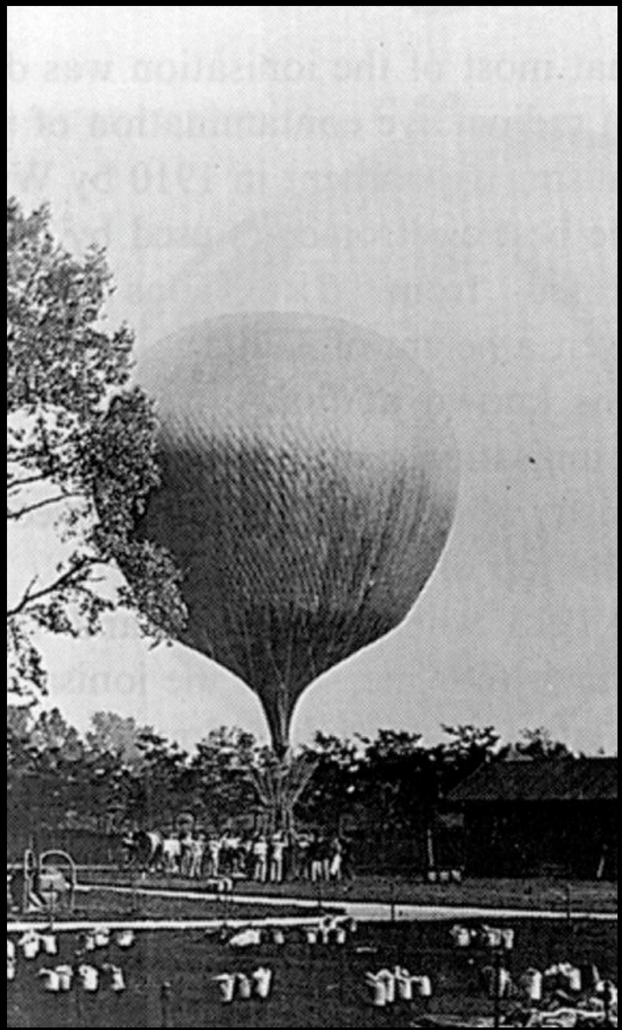

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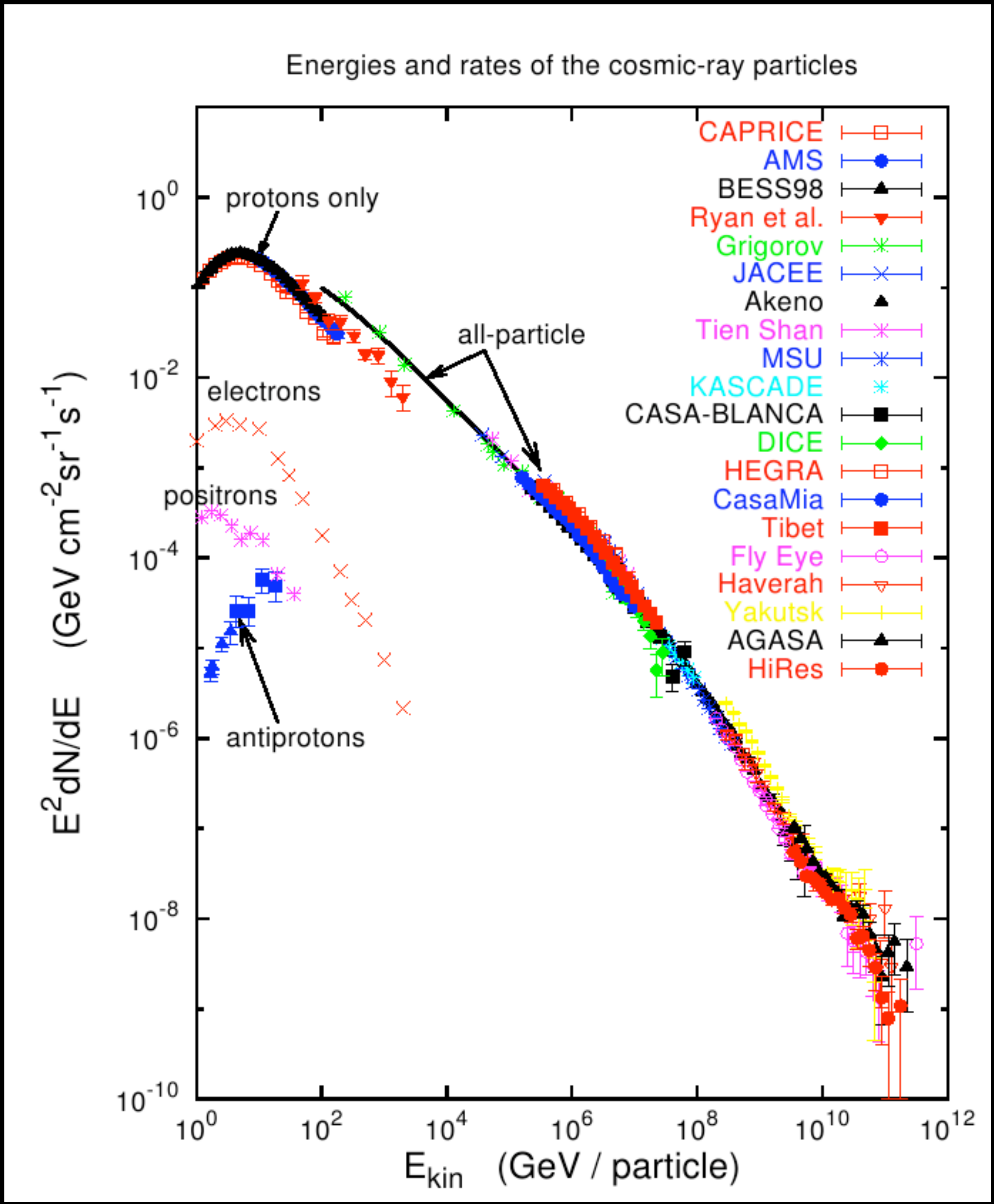

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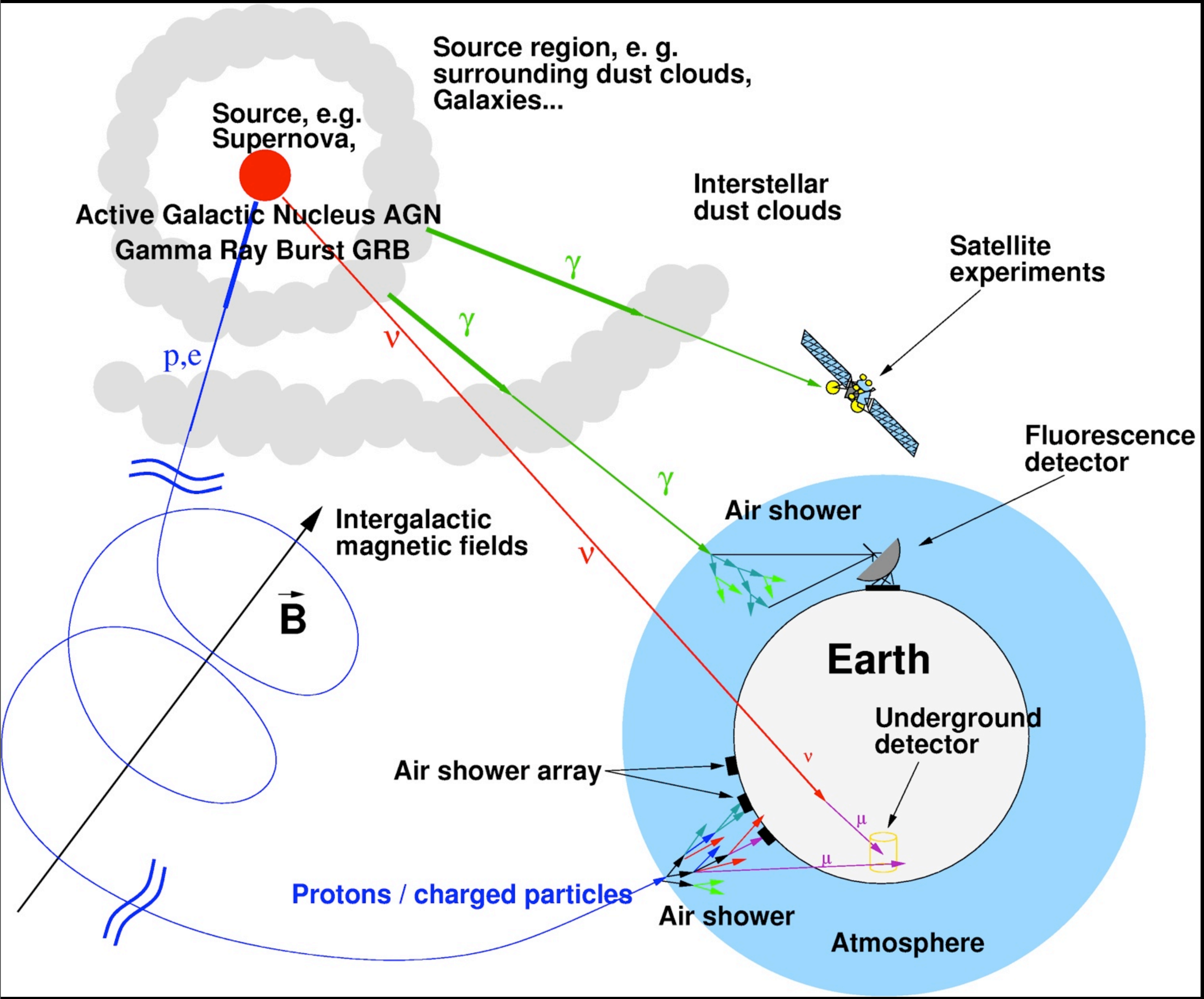
Neutrinos as Cosmic Messengers



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.**

Sources of High Energy Astrophysical Neutrinos

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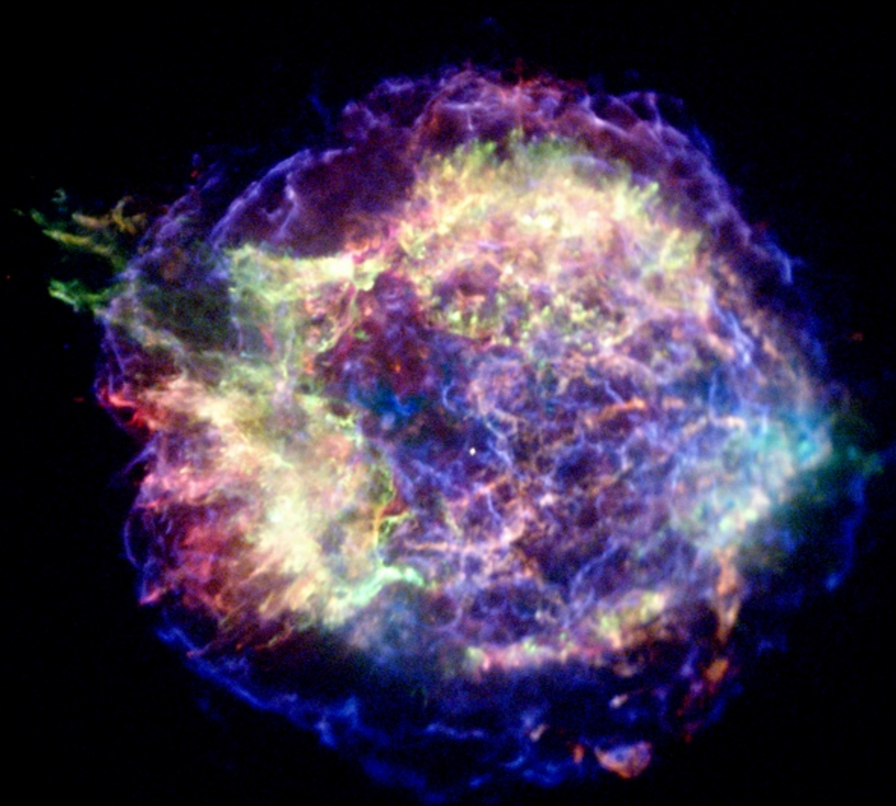

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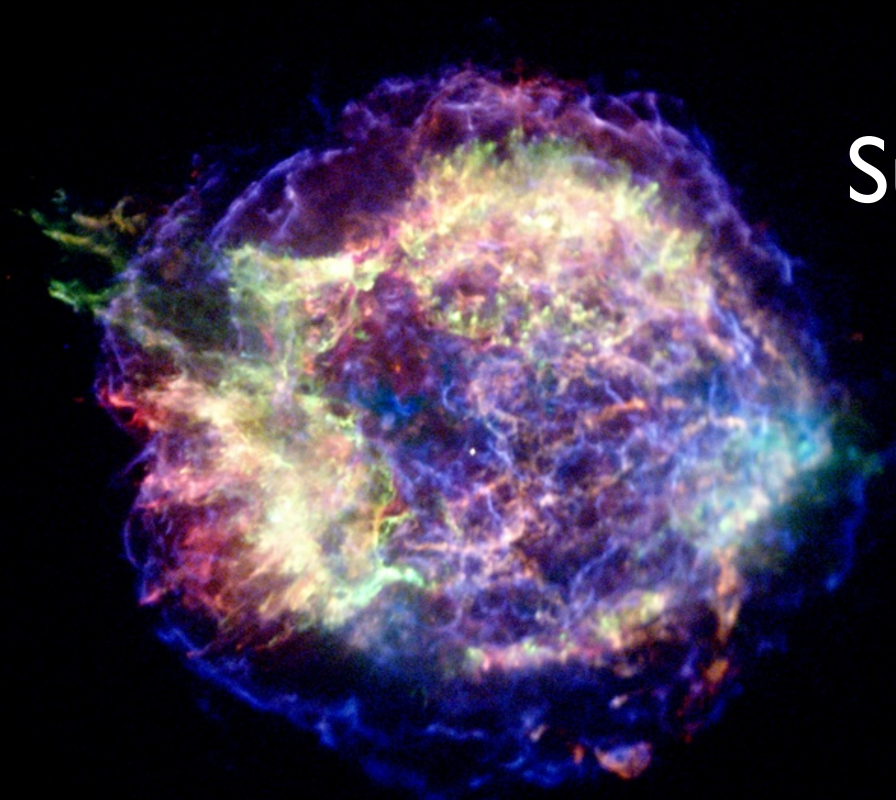

Supernova Remnants

Sources of High Energy Astrophysical Neutrinos

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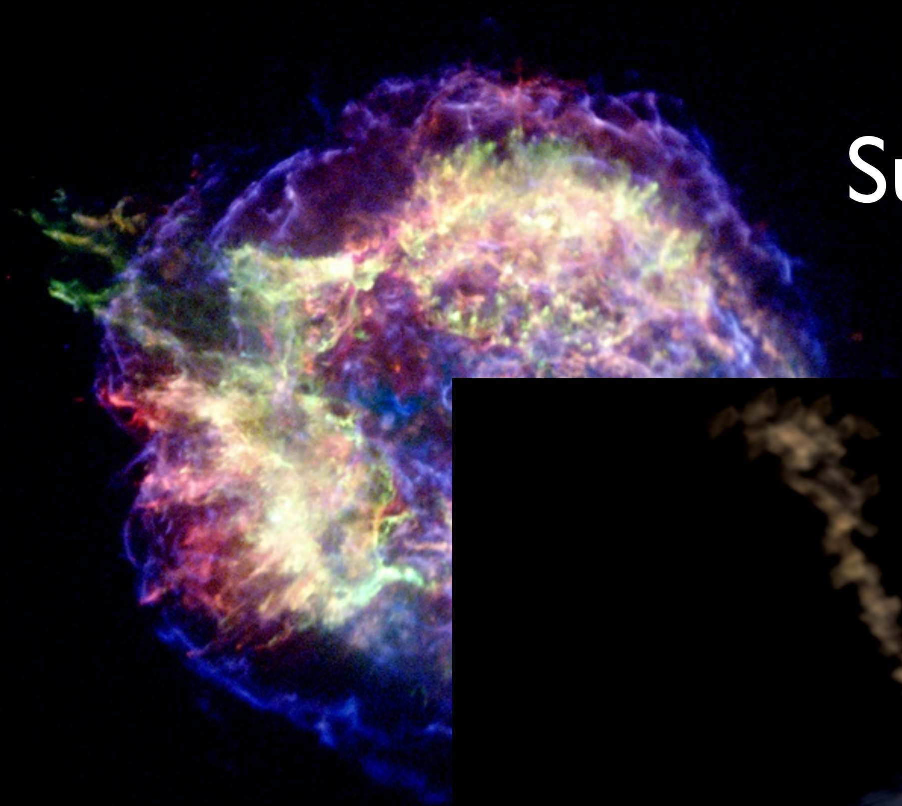

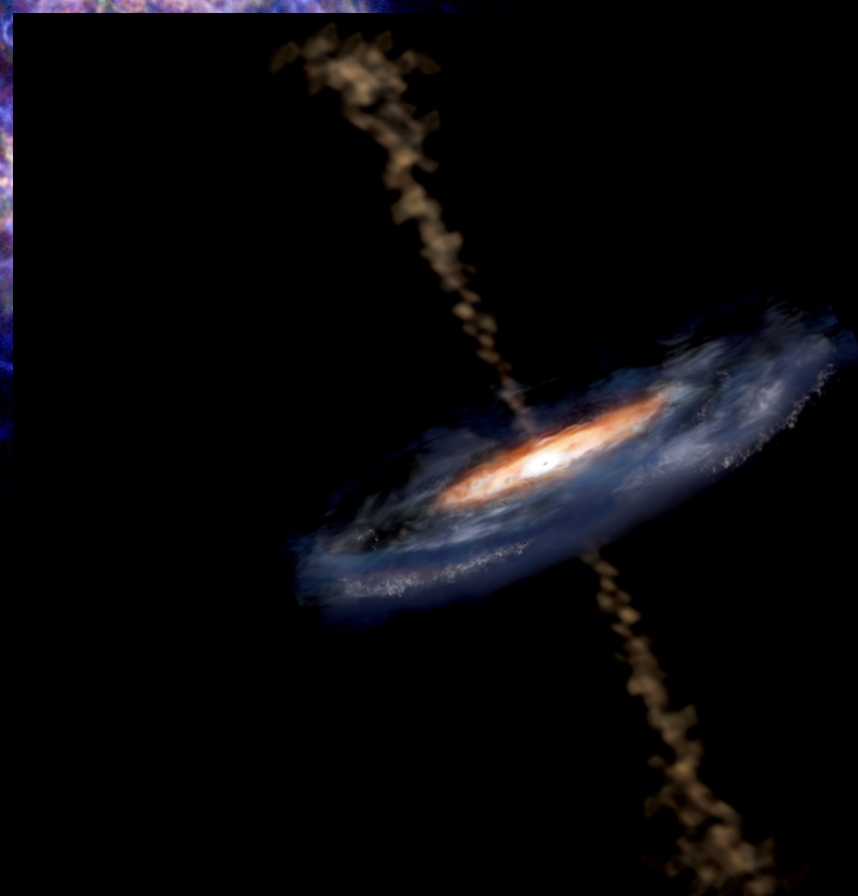

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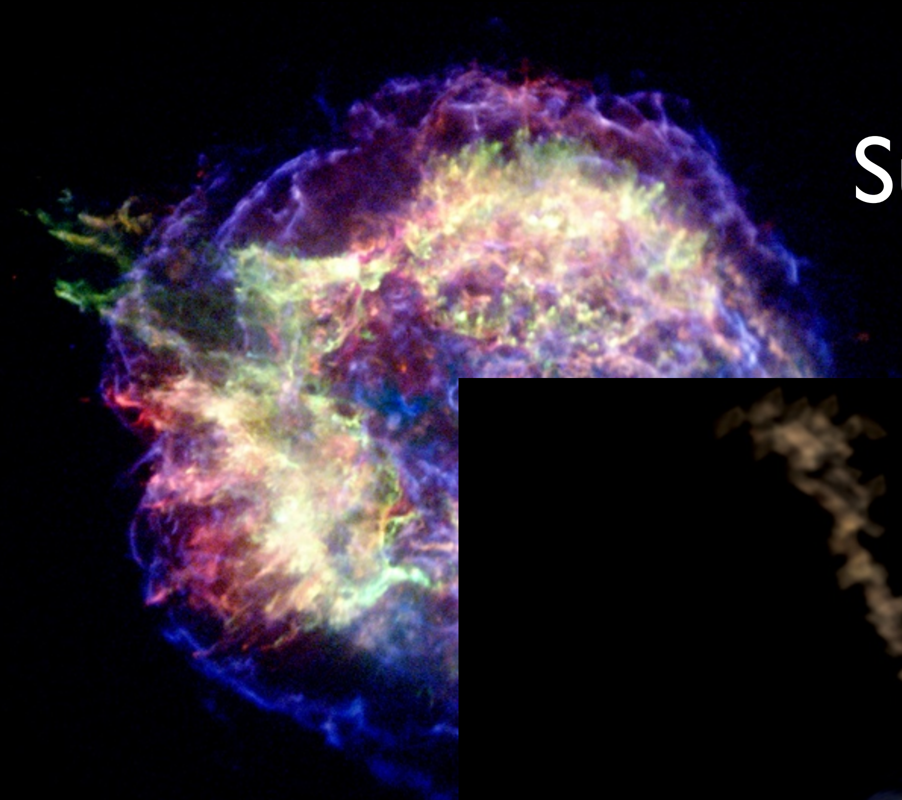

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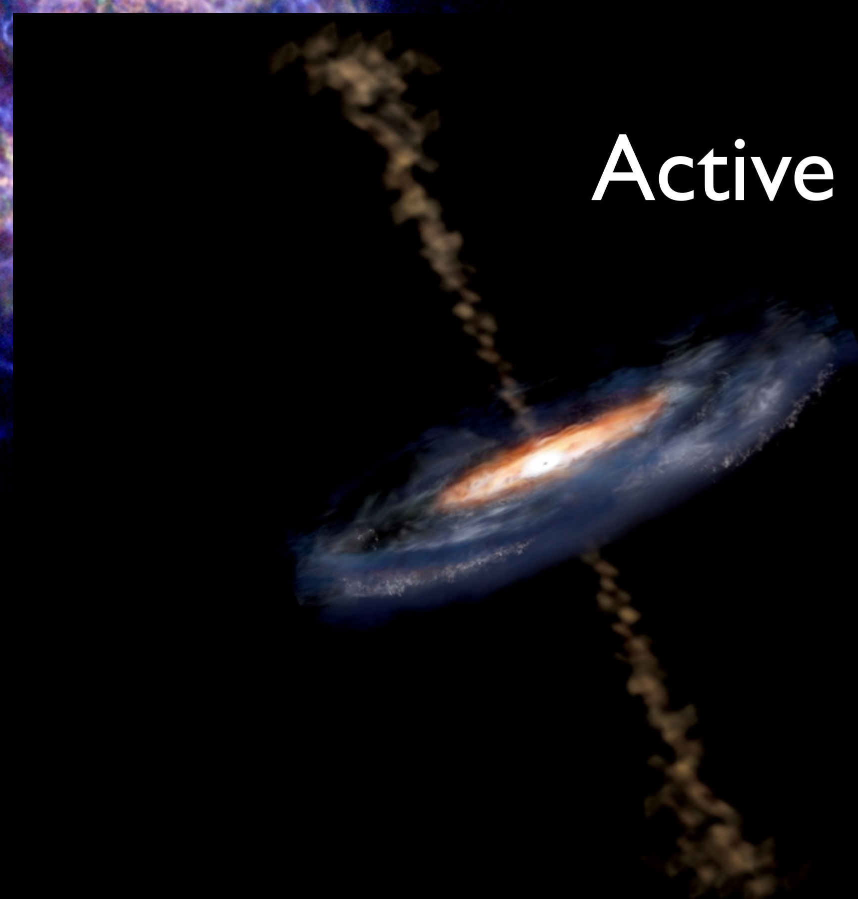
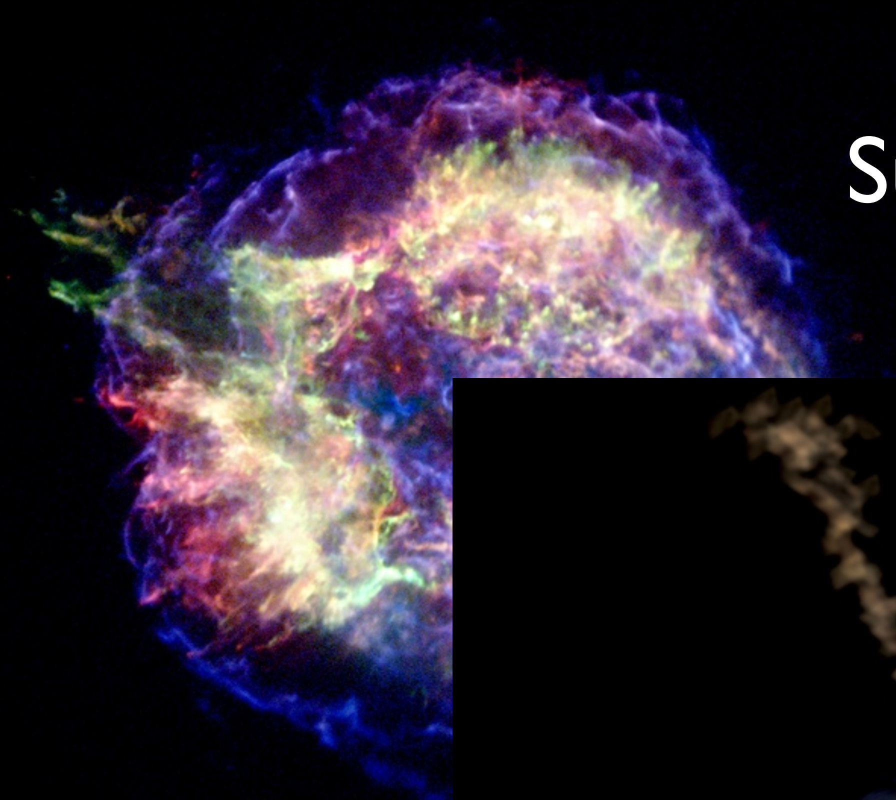


Active Galactic Nuclei

Sources of High Energy Astrophysical Neutrinos



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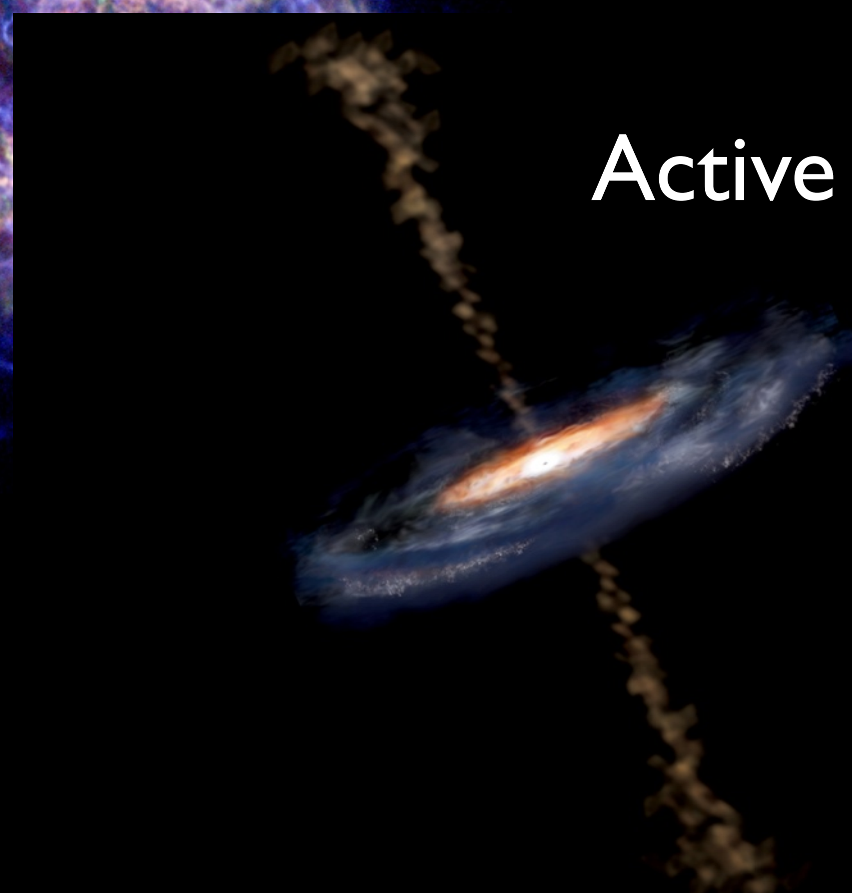

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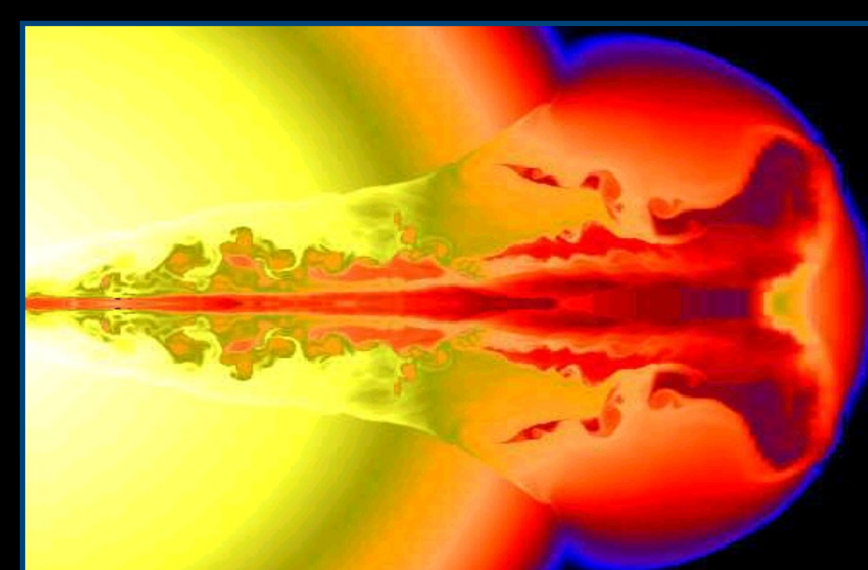

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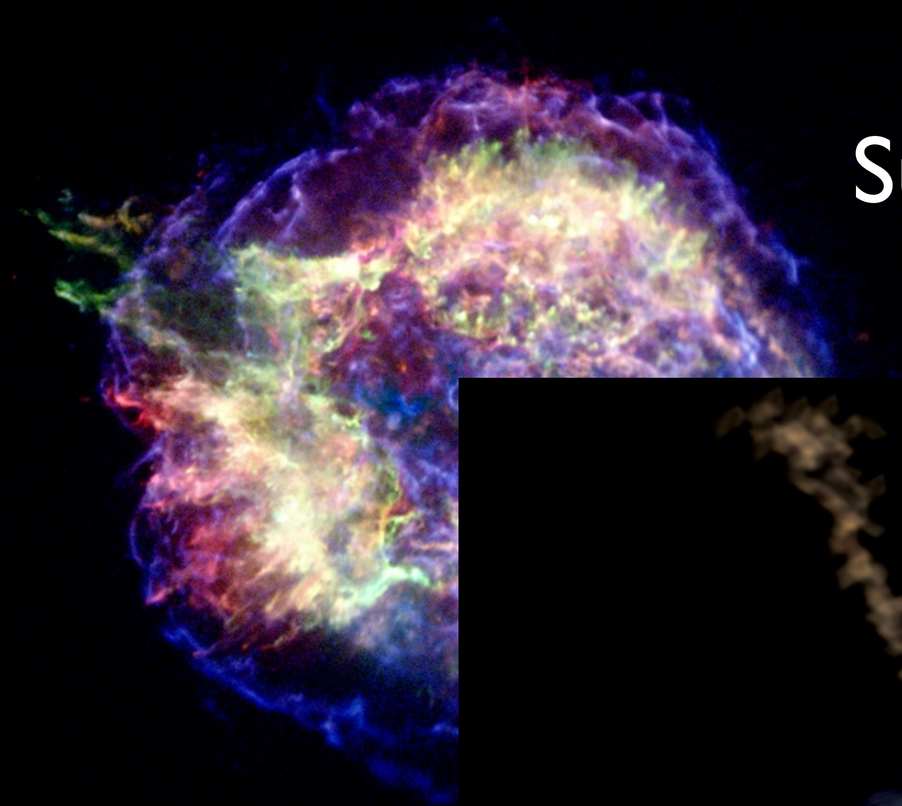

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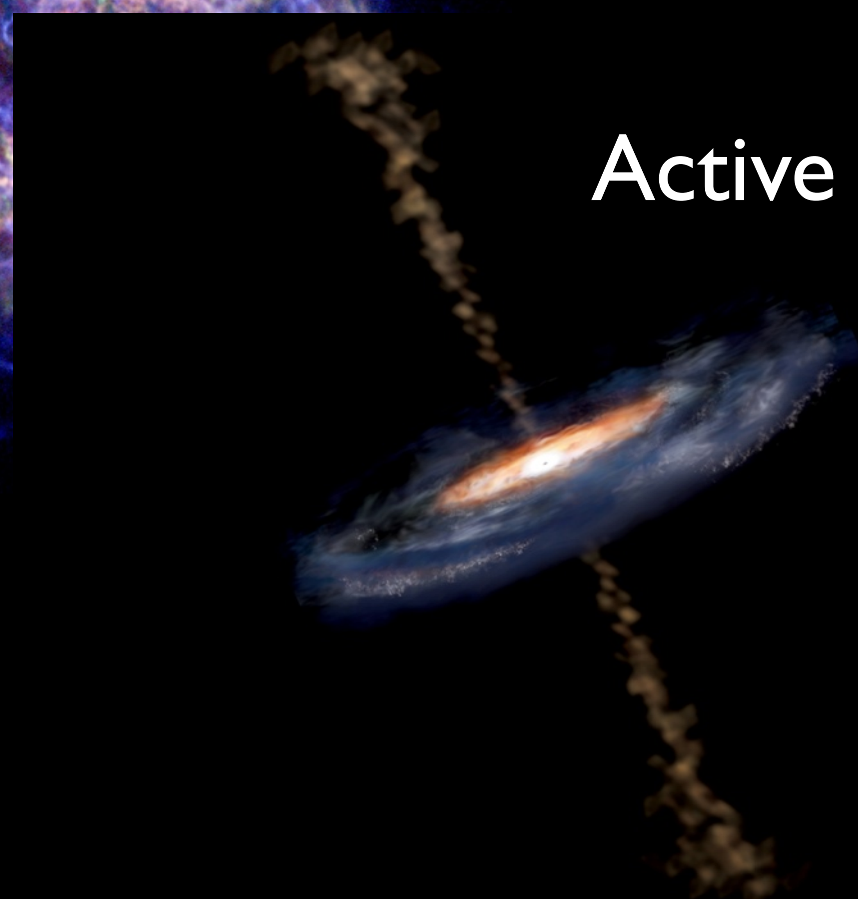
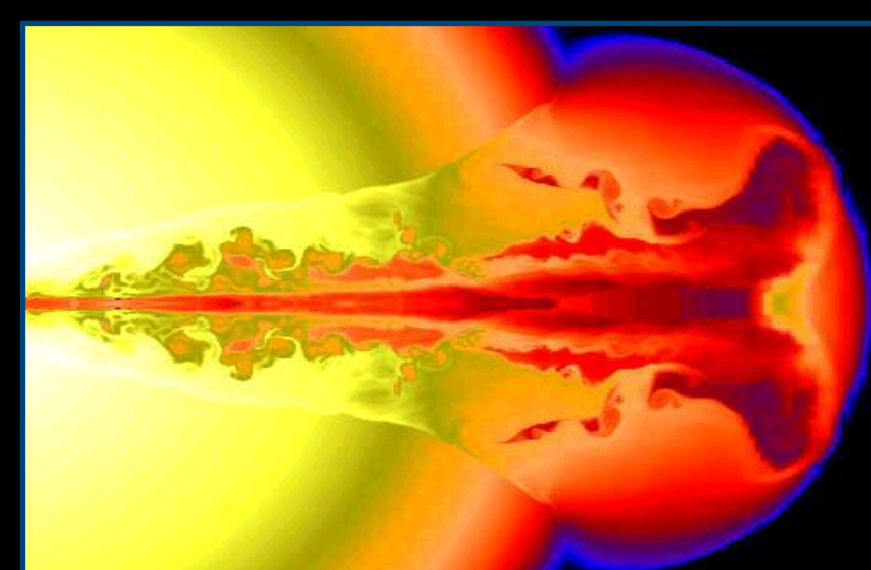
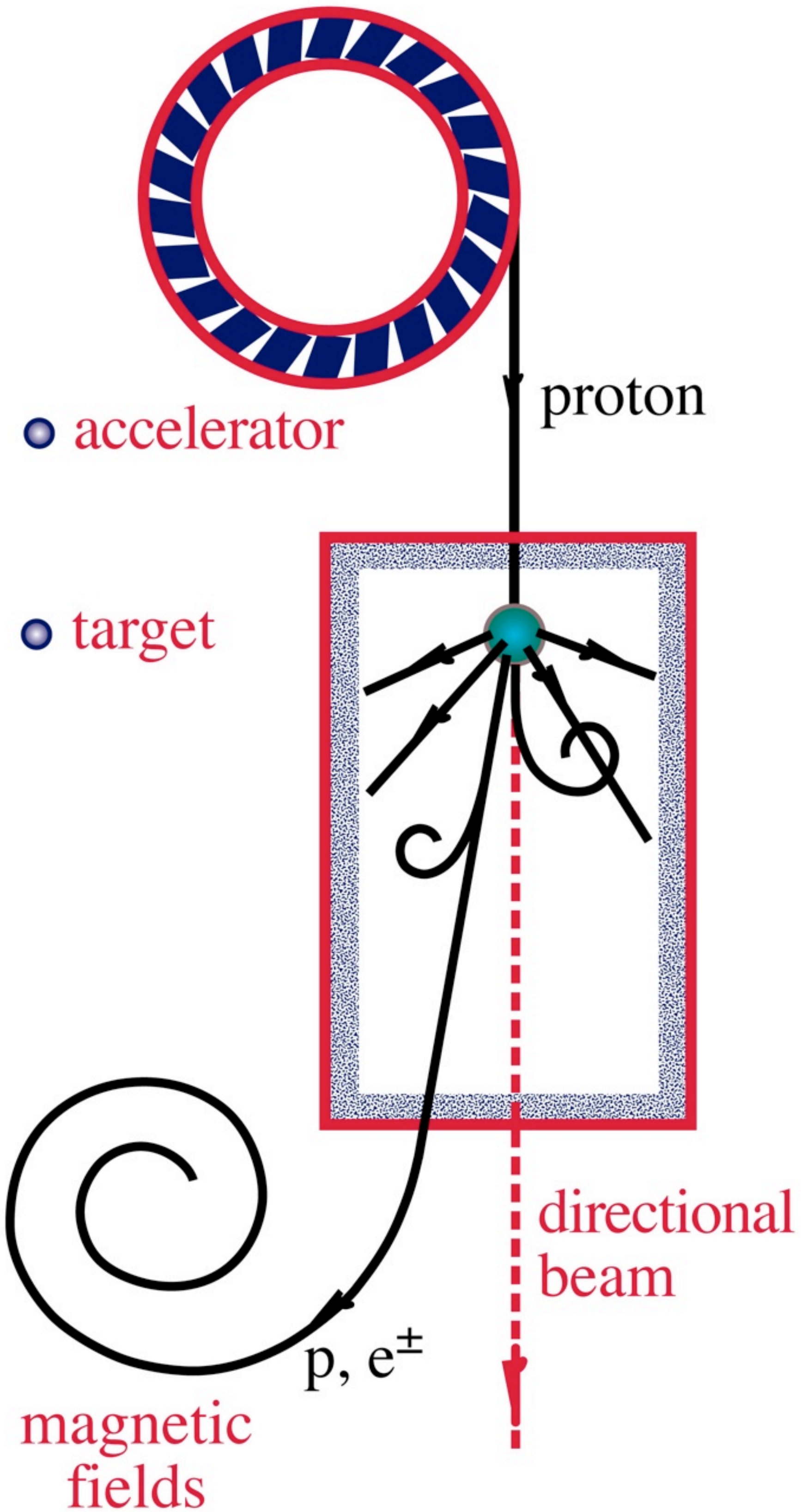


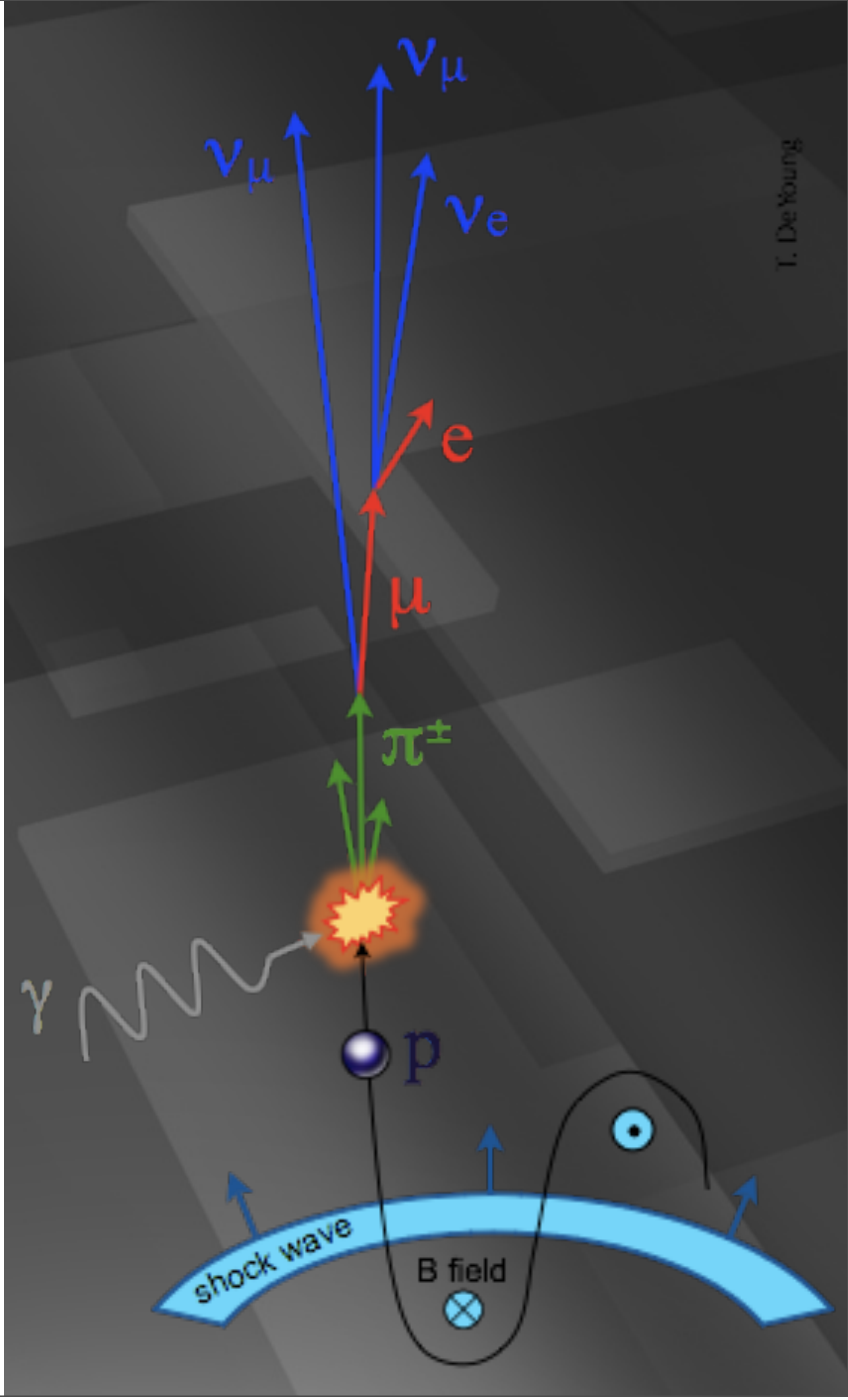
Active Galactic Nuclei

Gamma Ray Bursts



ν beams : heaven and earth





Atmospheric Neutrinos

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- Main Background to Astrophysical Search
- Created by high energy cosmic rays impeding on Earth’s atmosphere
- Conventional (Pions & Kaons) vs. Prompt (Charmed Mesons)

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$$p +^{16} N \rightarrow \pi^+, K^+, D^+, \text{etc.}$$

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

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

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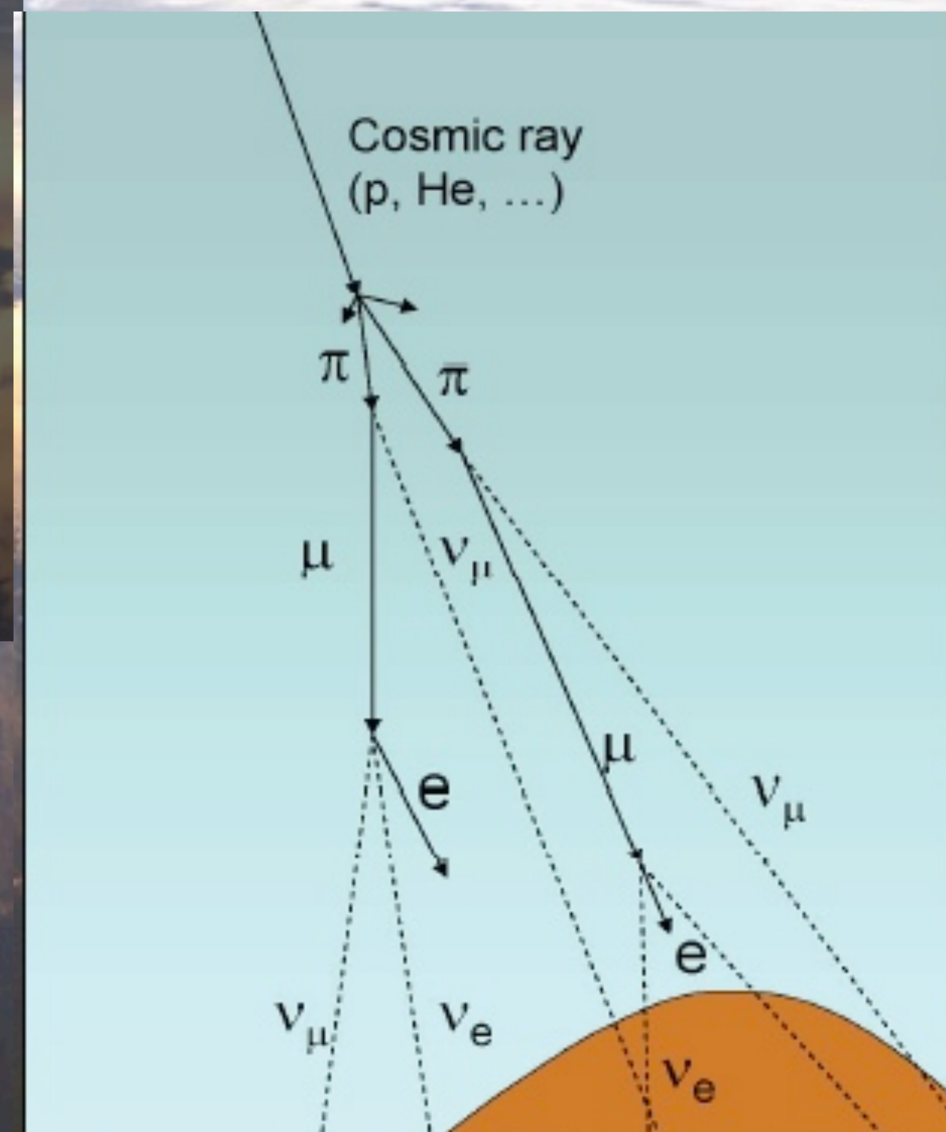

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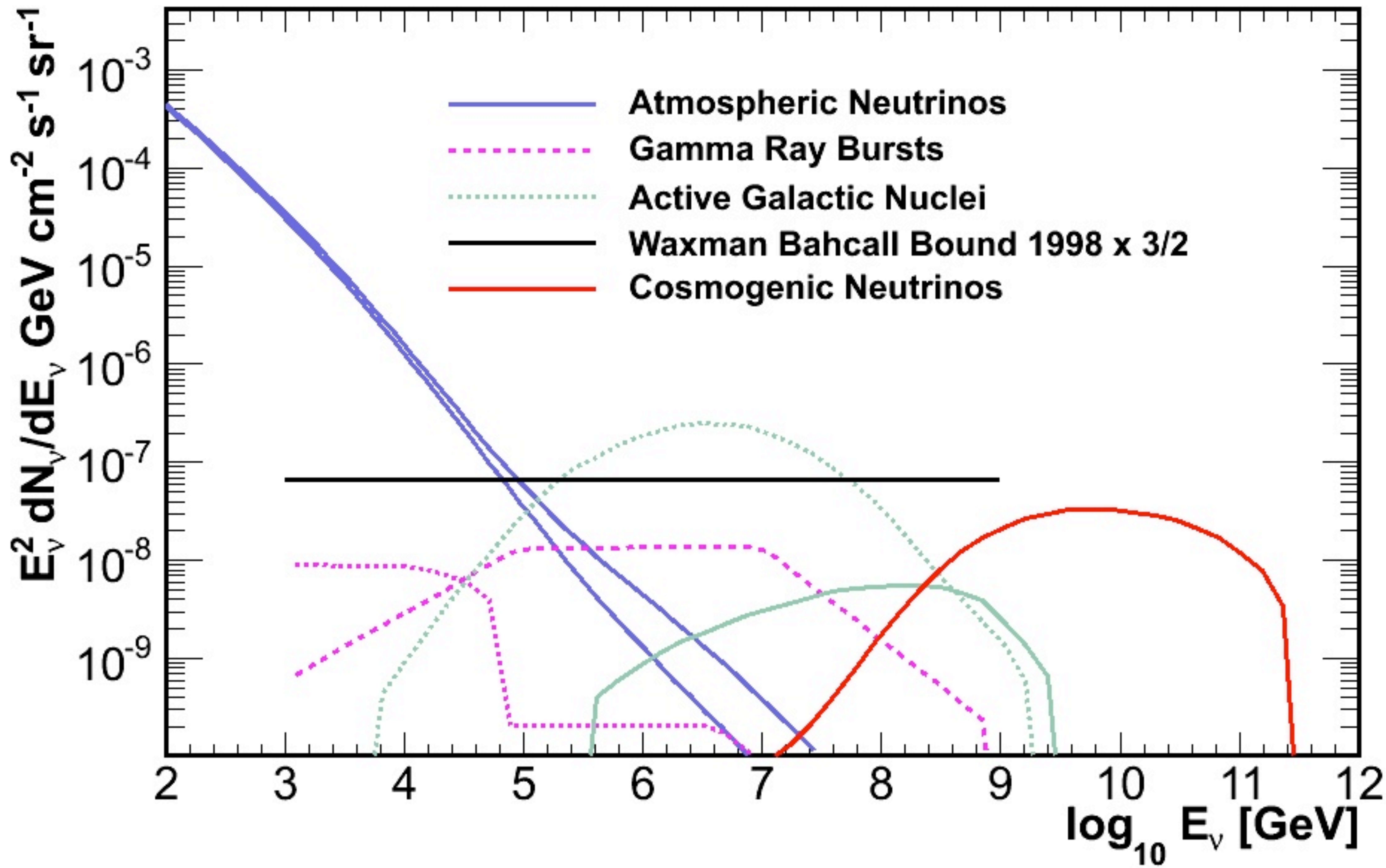
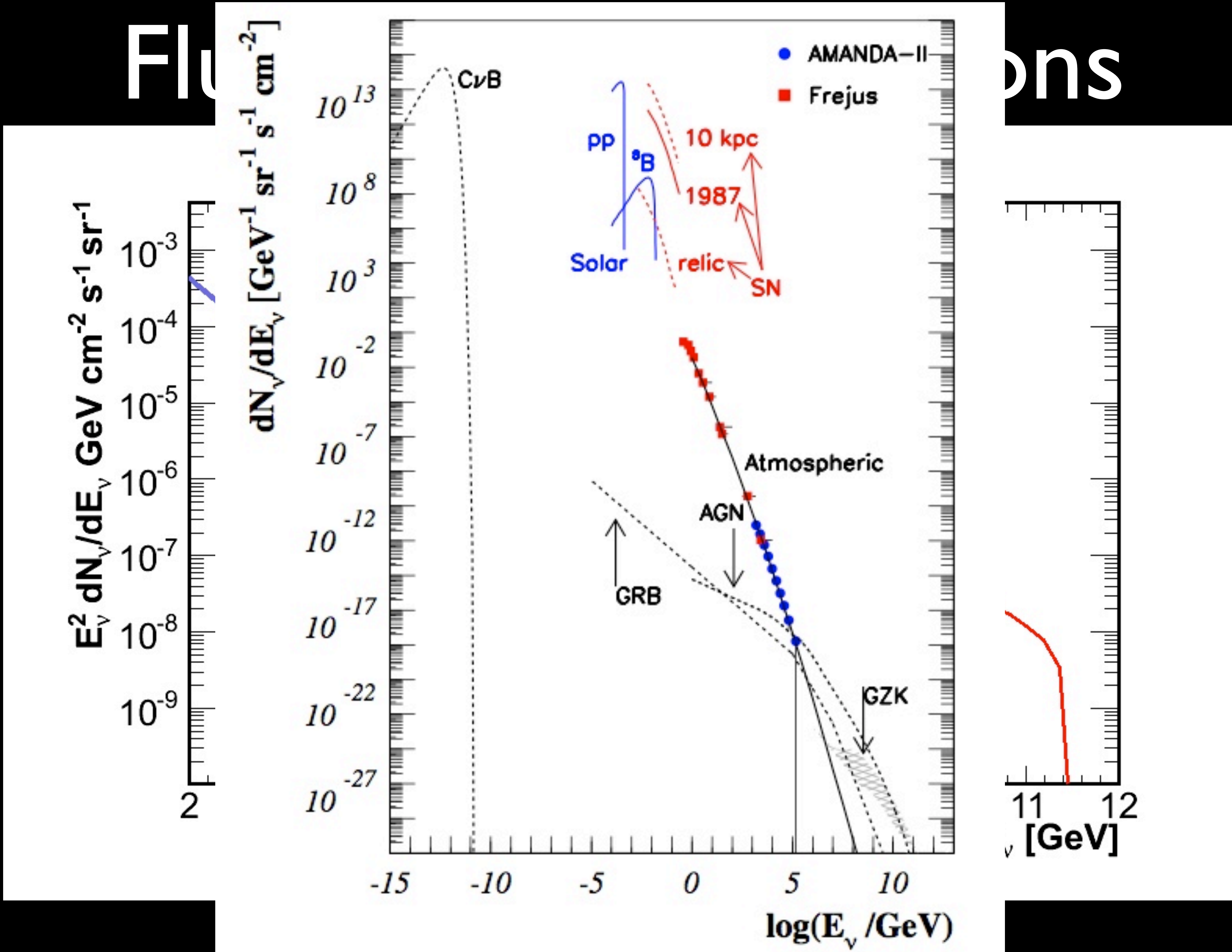
Flux Model Predictions

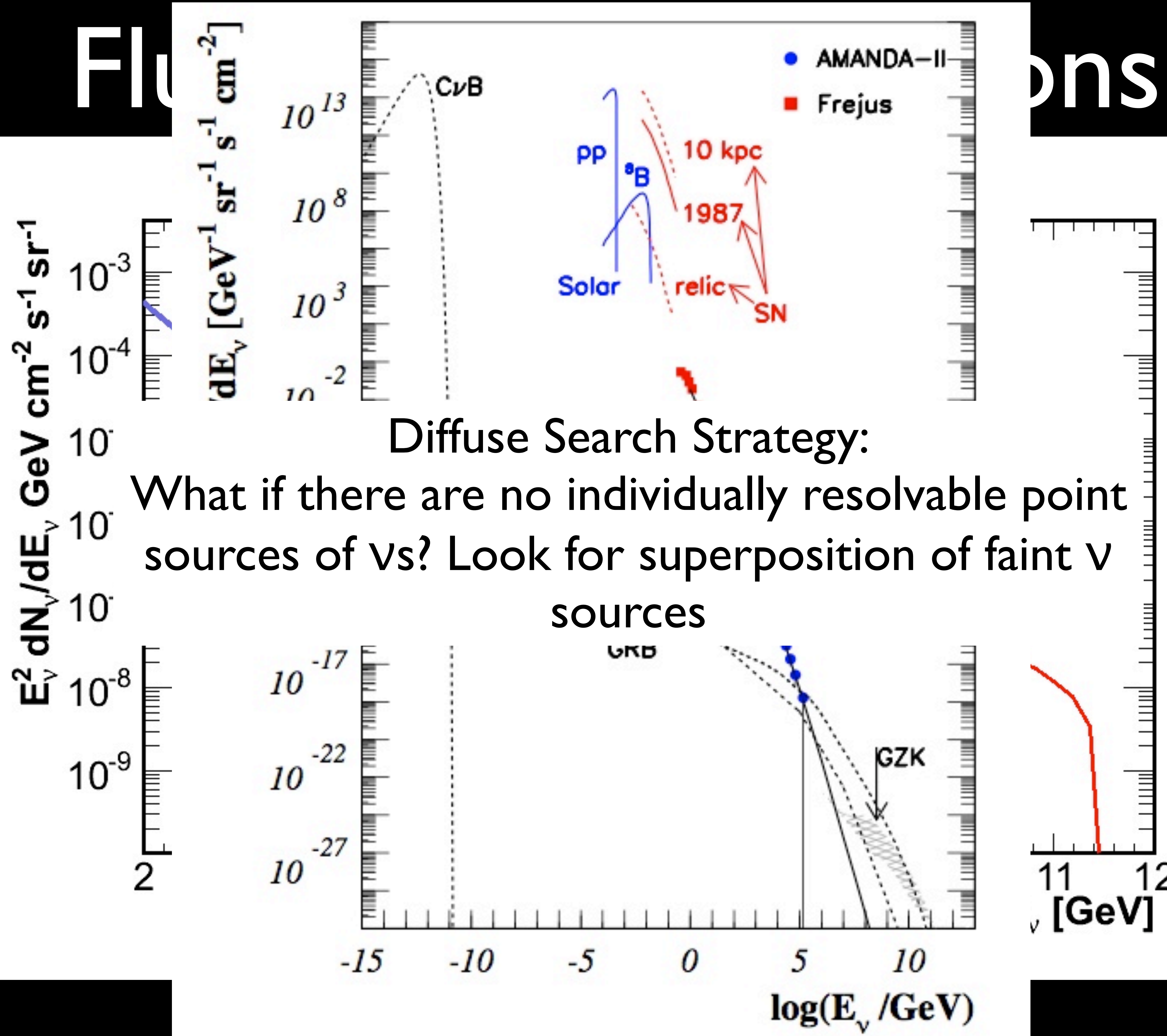


Flu ons



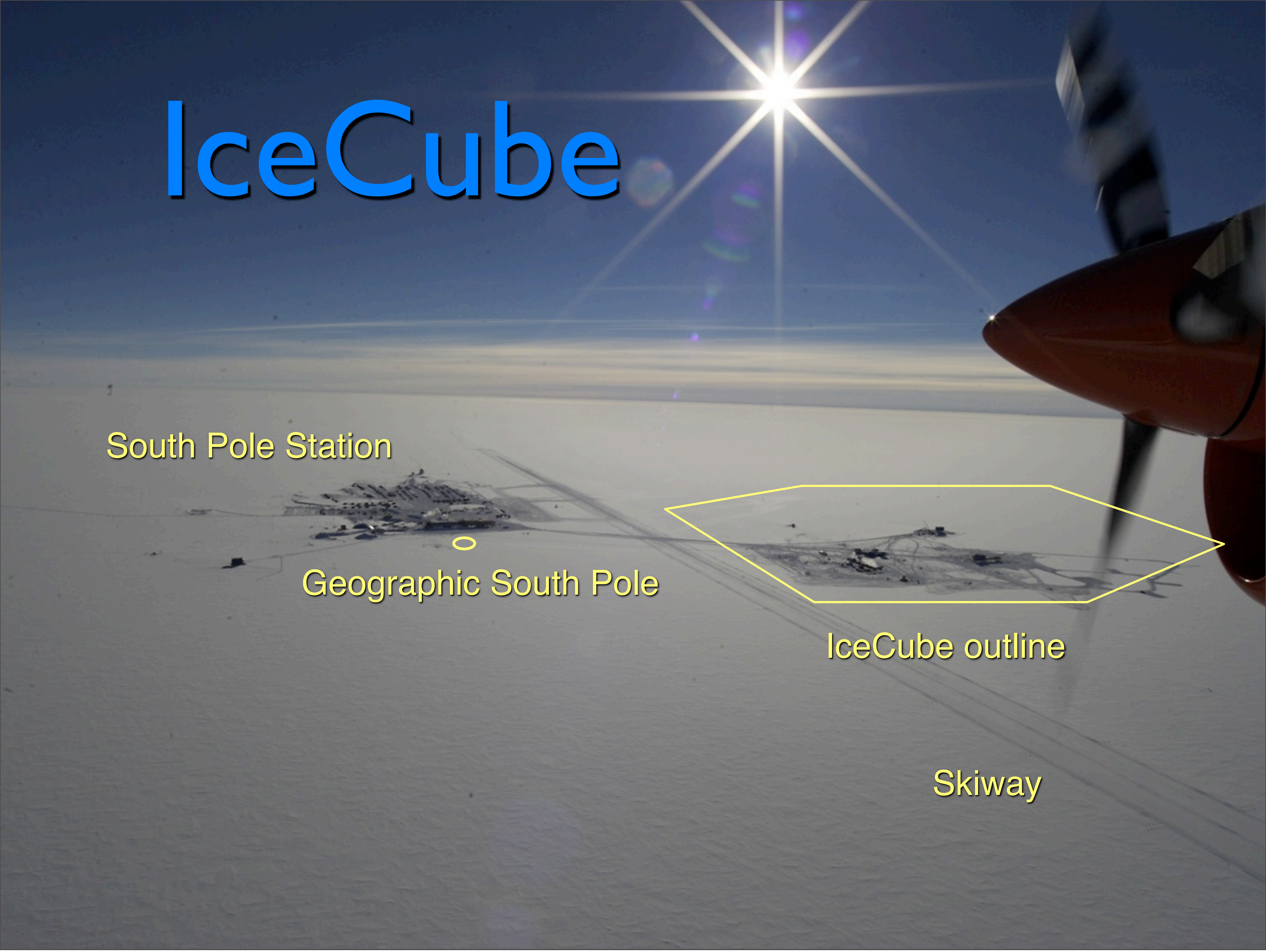
$E_\nu^2\, dN_\nu/dE_\nu$ GeV cm^{-2} s^{-1} sr^{-1}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
2
11
12
[GeV]
dN_ν/dE_ν [GeV^{-1} sr^{-1} s^{-1} cm^{-2}]
10^{13}
10^{8}
10^{3}
10^{-2}
10^{-7}
10^{-12}
10^{-17}
10^{-22}
10^{-27}
-15
-10
-5
0
5
10
log(E_ν/GeV)
CνB
AMANDA−II
Frejus
pp
^{8}B
Solar
10 kpc
1987
relic
SN
Atmospheric
AGN
GRB
GZK

Flu ons



Diffuse Search Strategy:

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

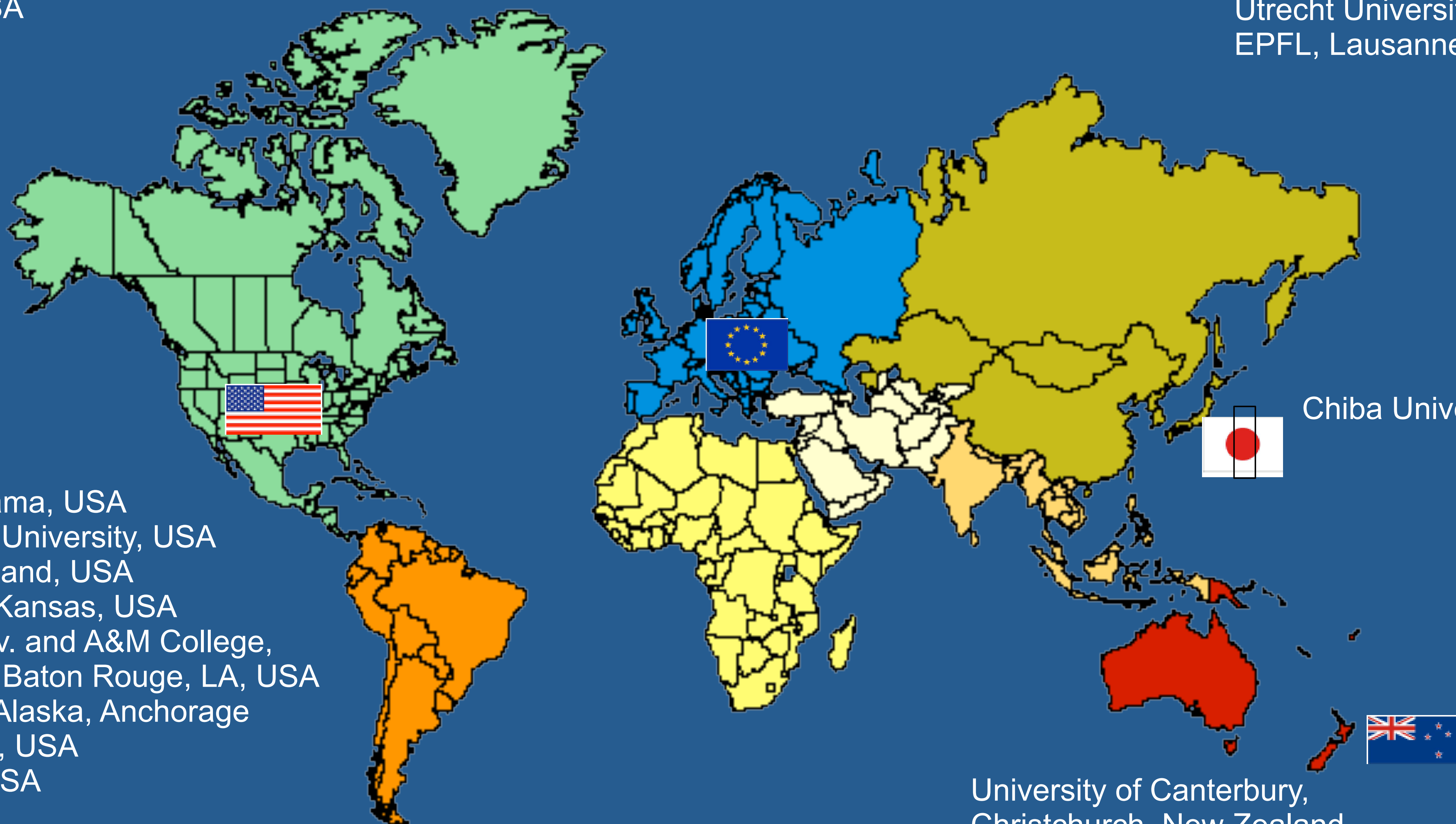

IceCube
South Pole Station
Geographic South Pole
IceCube outline
Skiway

IceCube Collaboration

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

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



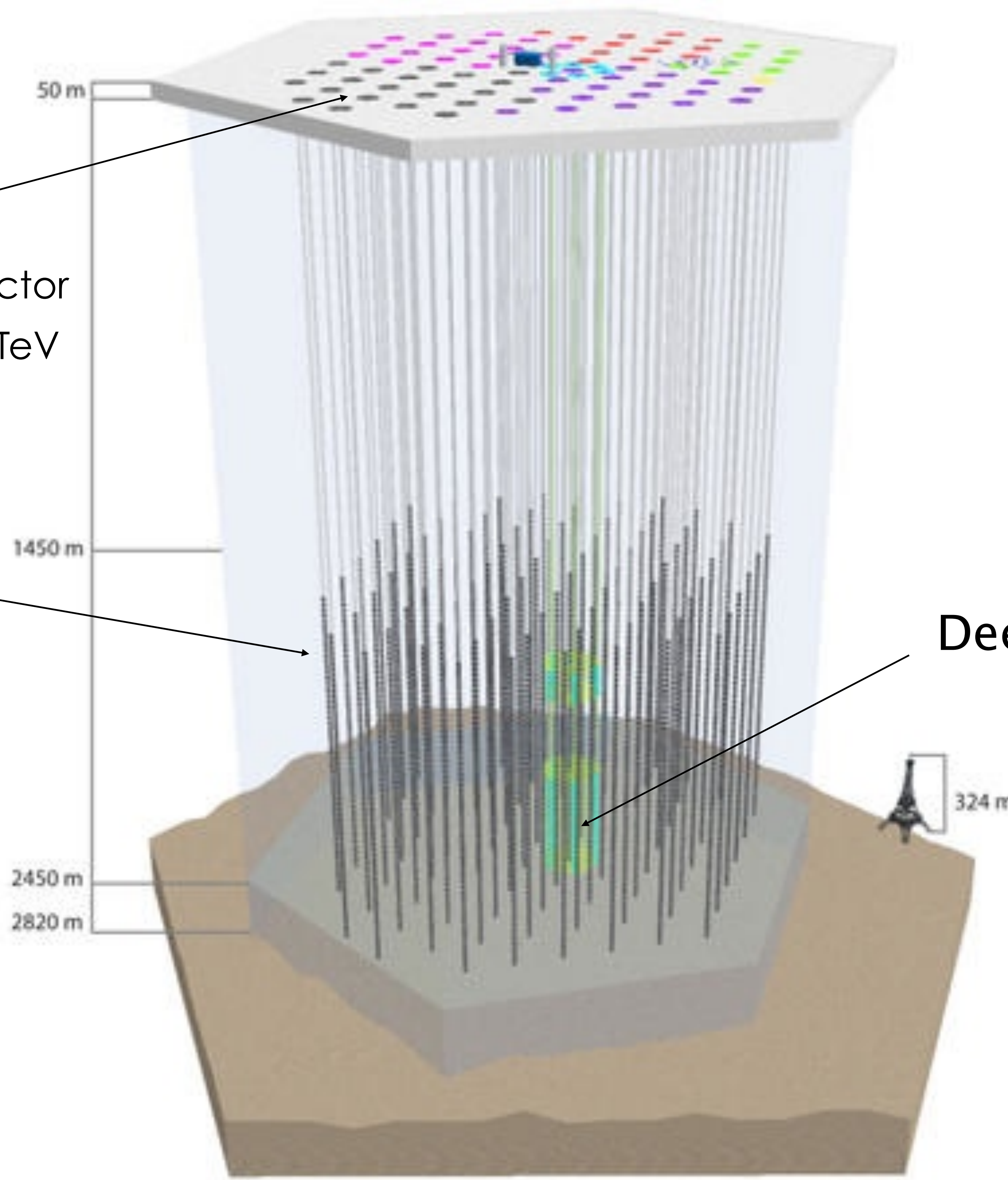
Chiba University, Japan

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

35 collaborating institutions

The IceCube Detector



IceTop

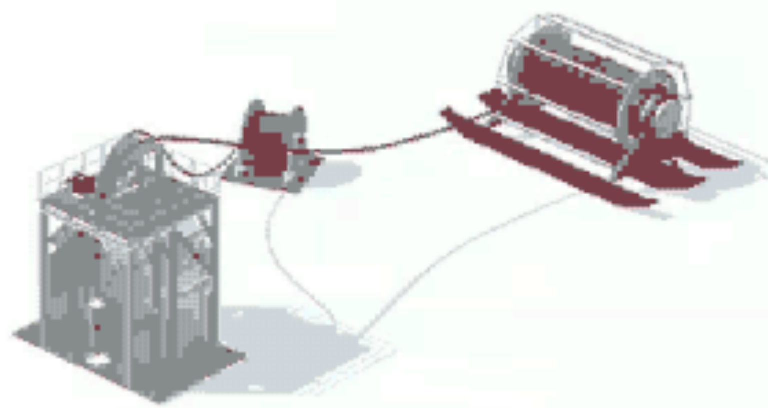
Air shower detector threshold ~ 300 TeV

InIce

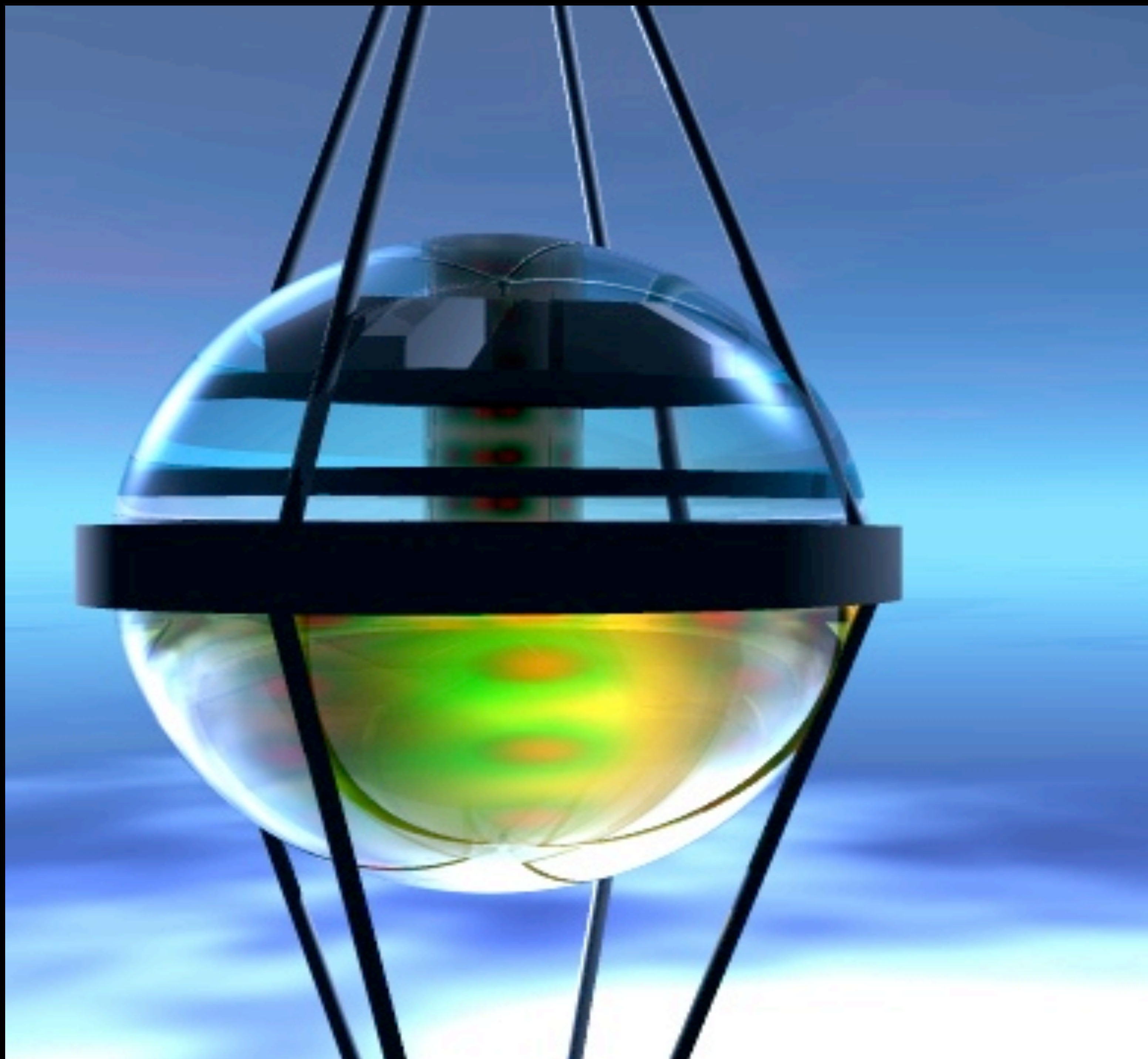
80-86 Strings, 60 Optical Modules per String

Deep Core

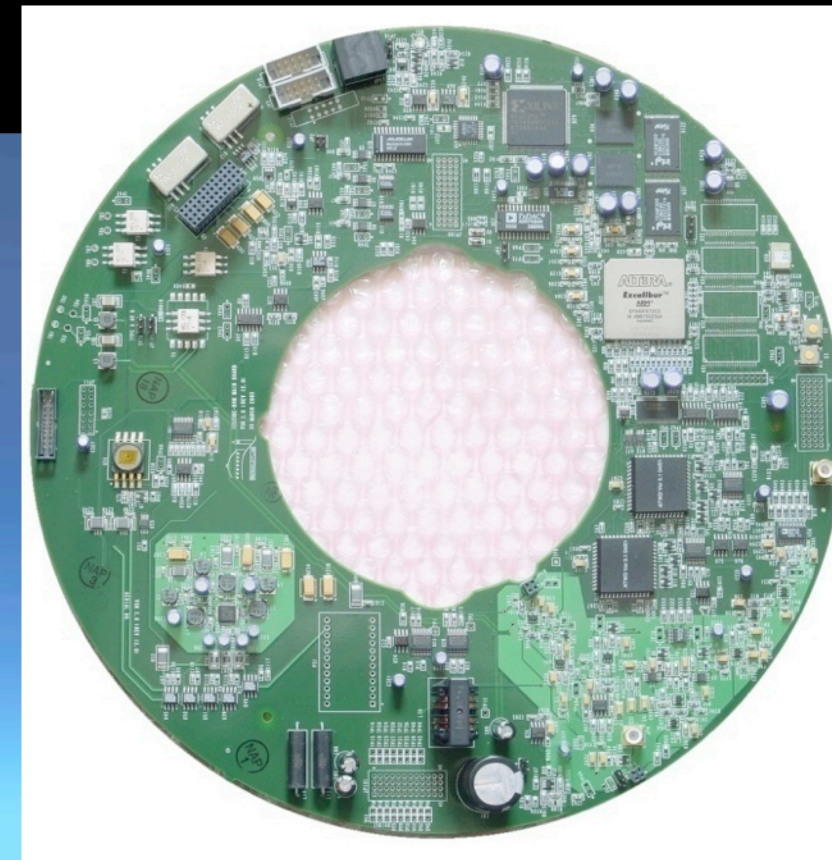
- ✓Completion: January 2011
- ✓**2008: 40 Strings (This Analysis)**
- ✓2009: 59 Strings



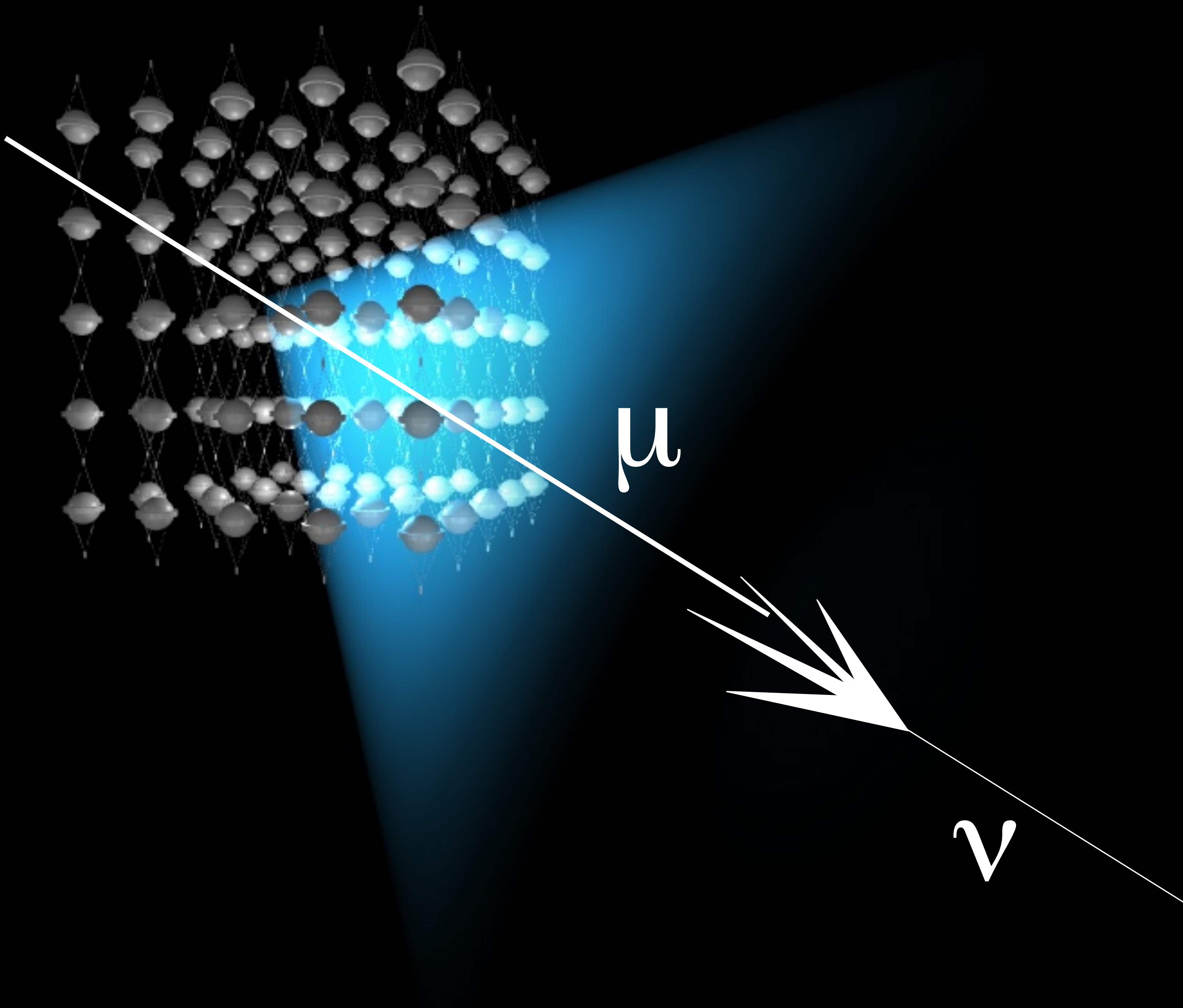
Digital Optical Module

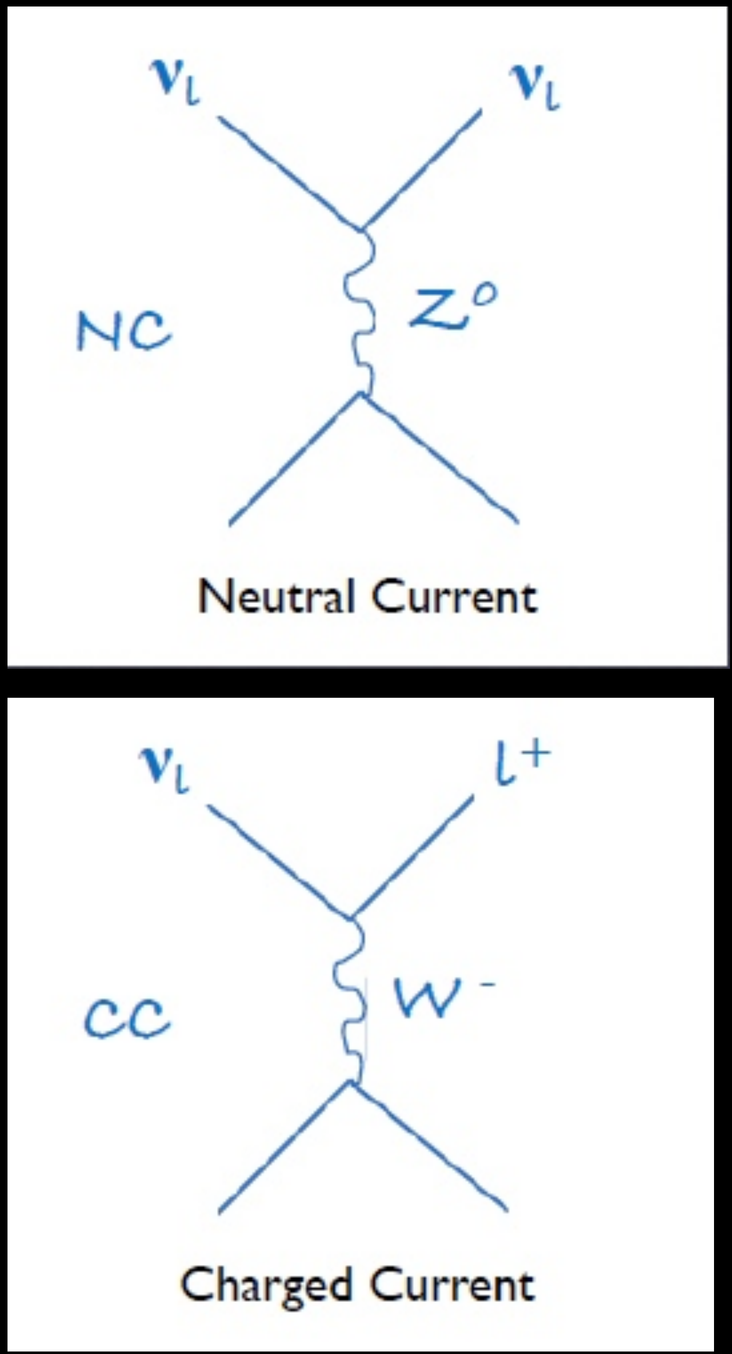


MainBoard

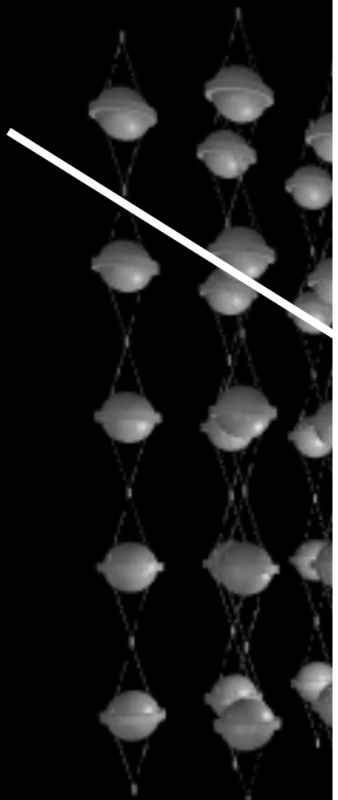


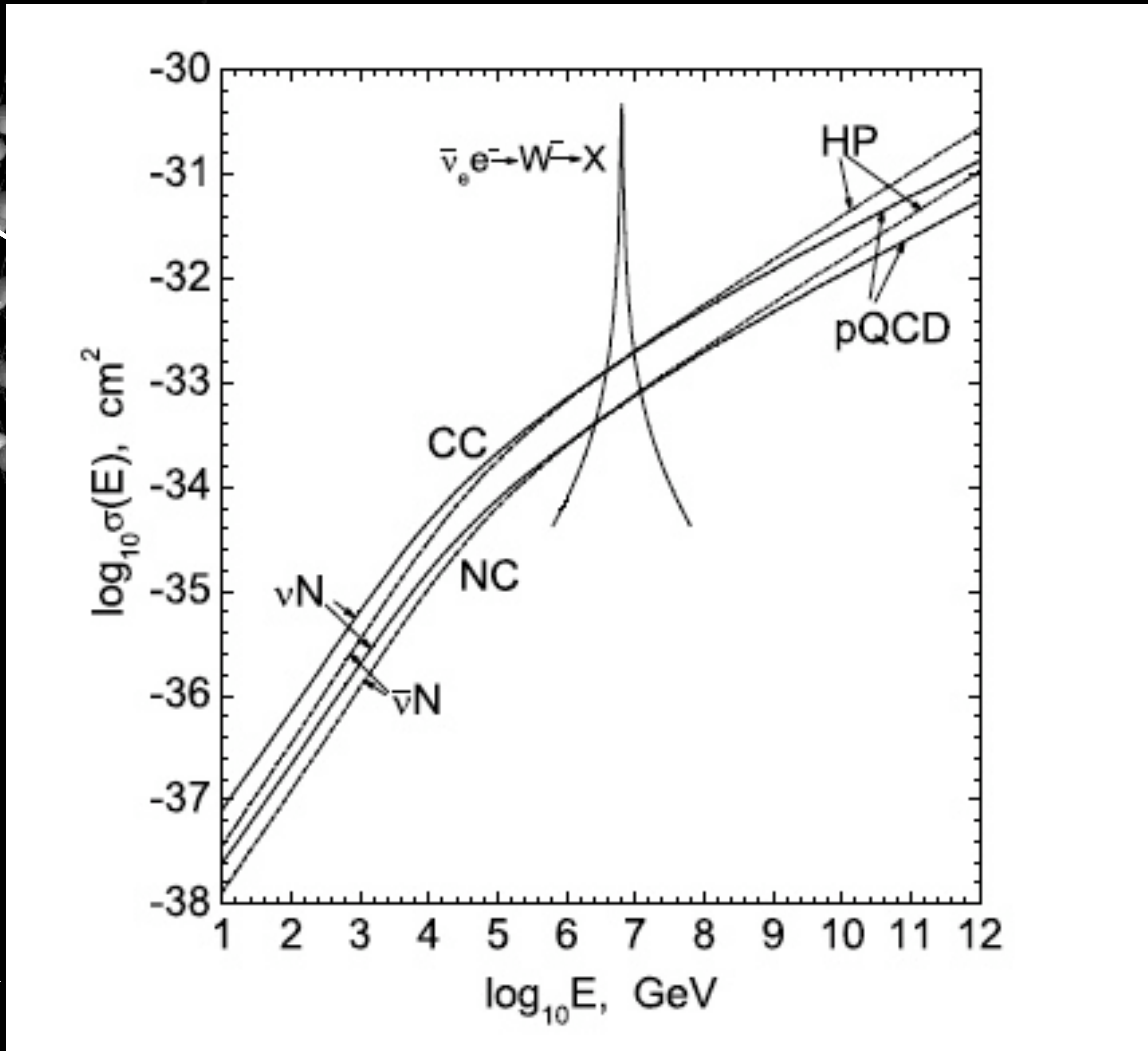
Photomultiplier Tube

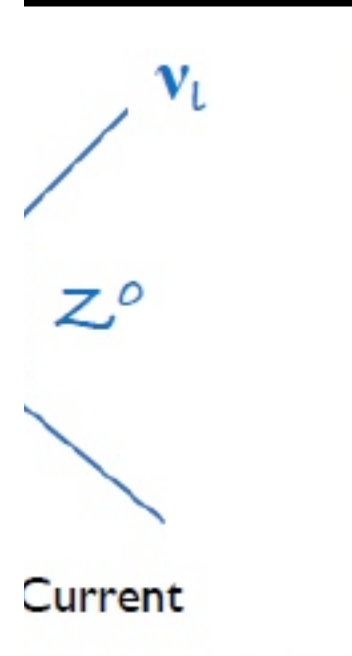




- Cherenkov cone provides direction




-30
-31
-32
-33
-34
-35
-36
-37
-38
1 2 3 4 5 6 7 8 9 10 11 12
$\log_{10}\sigma(E)$, cm^2
$\log_{10}E$, GeV
$\bar{\nu}_e e^- \to W^- \to X$
HP
pQCD
CC
NC
νN
$\bar{\nu} N$

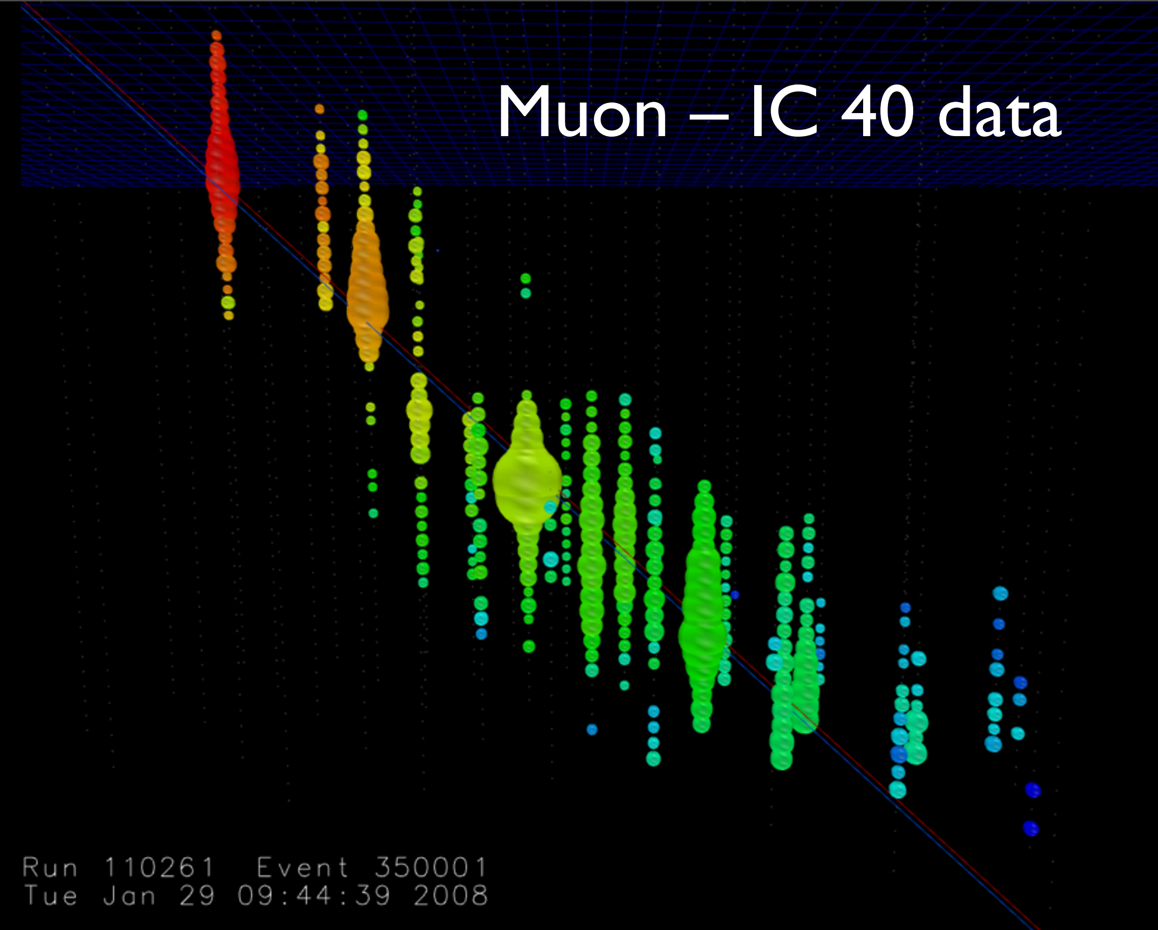

ν_l
Z^0
Current


l^+
W^-
Current

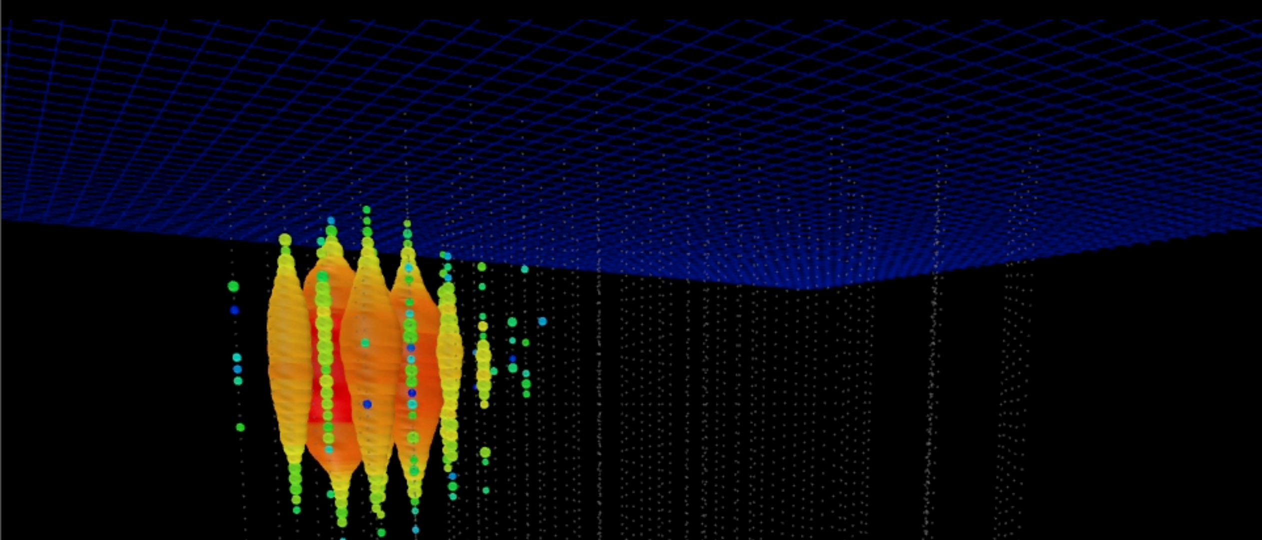
- C

Event Topologies

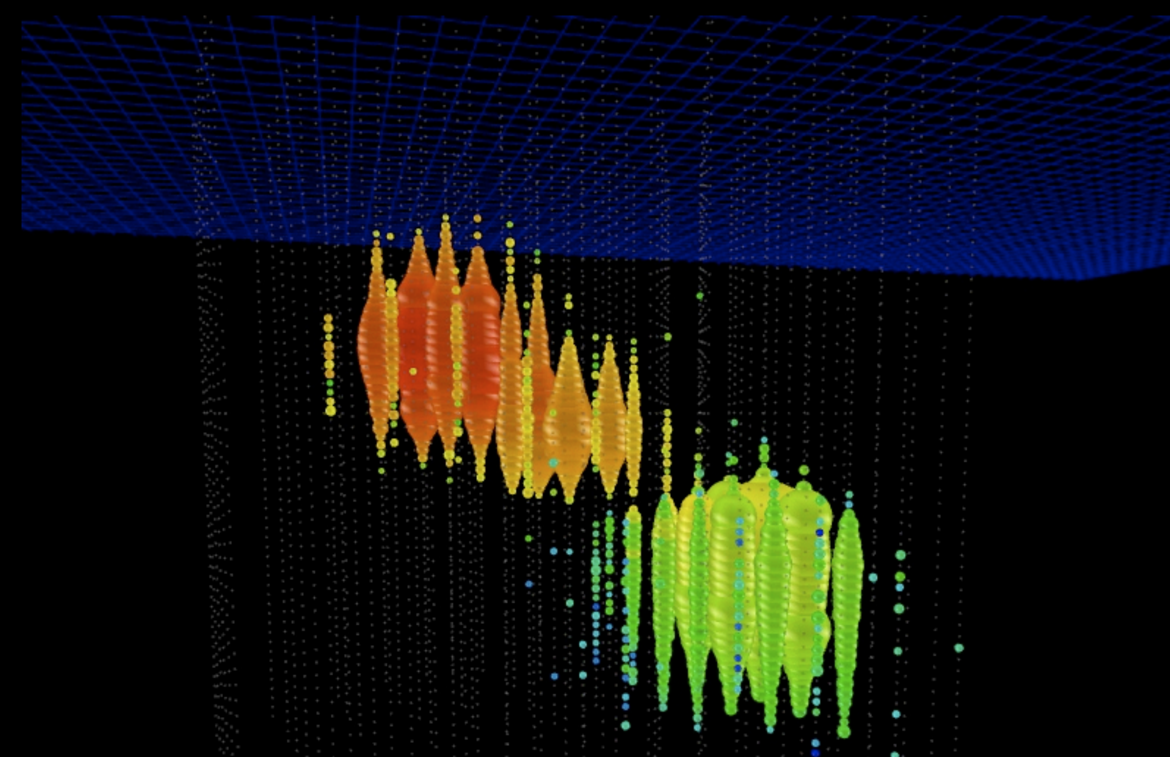
- ν_μ produce μ tracks
  - Angular Res ~ 0.7^0 Eres log(E)~0.3
- ν_e CC, ν_x NC create showers
  - ~ point sources, 'cascades'
  - Eres log(E)=0.1-0.2
- ν_τ double bang events, others



Muon – IC 40 data



350 TeV ν_e simulation



16 PeV ν_τ simulation

IceCube performance

Low noise rates: ~300Hz (SPE/sec)

Rate with correlated pulses ~500Hz

Supernova detection

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

Cosmic ray

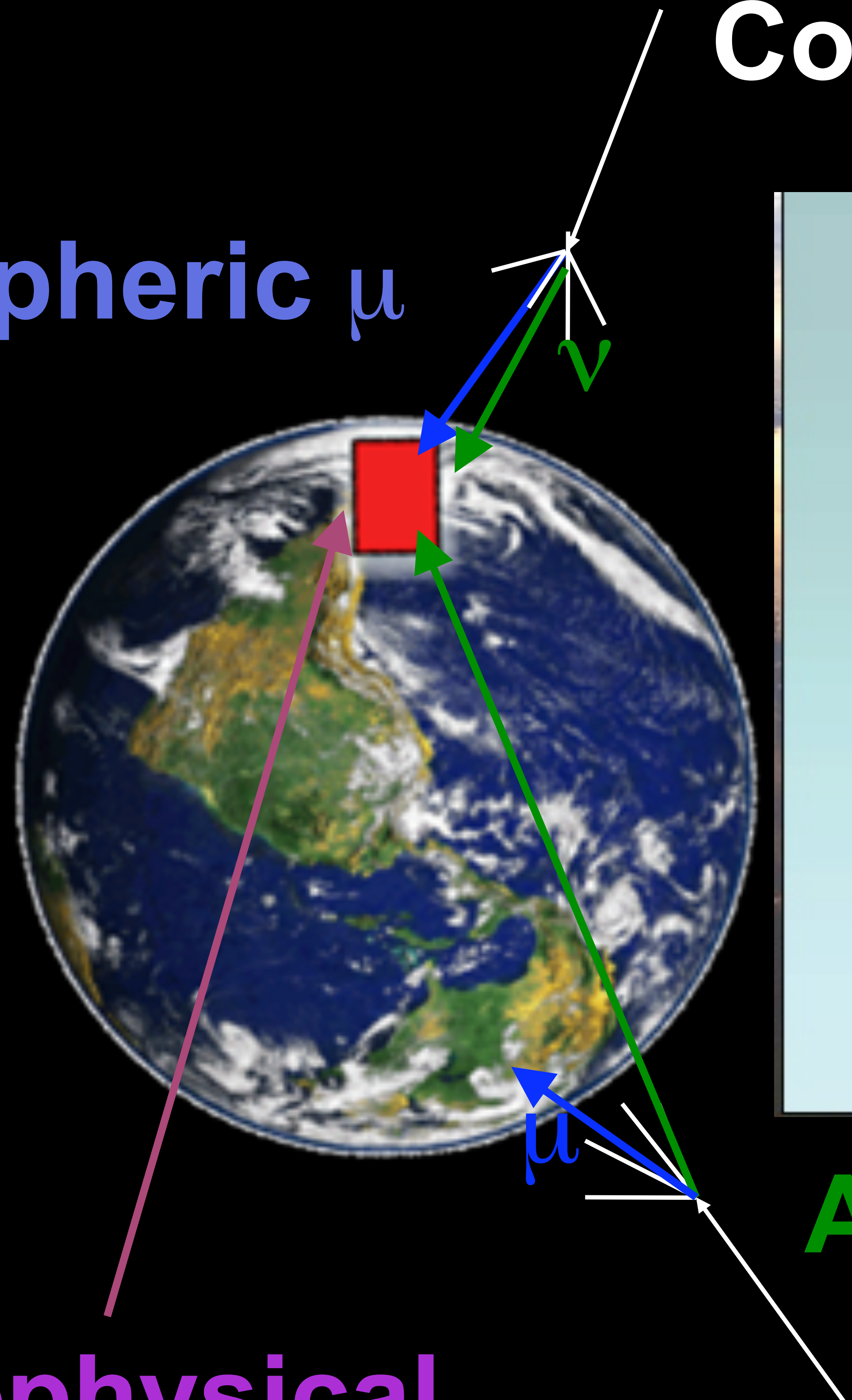
Atmospheric μ

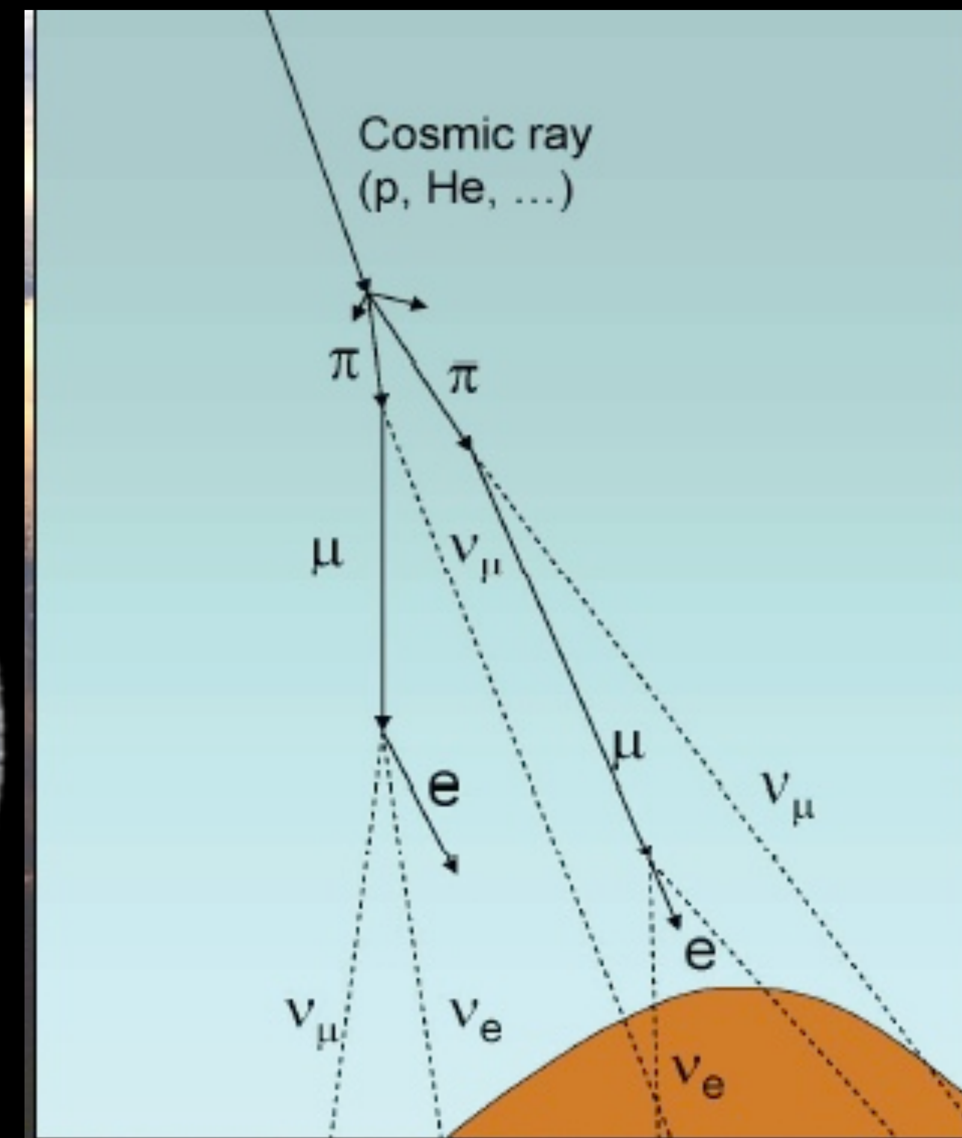
$\theta = 0^o$

$\cos\theta = 1$

$\theta = 180^o$

$\cos\theta = -1$

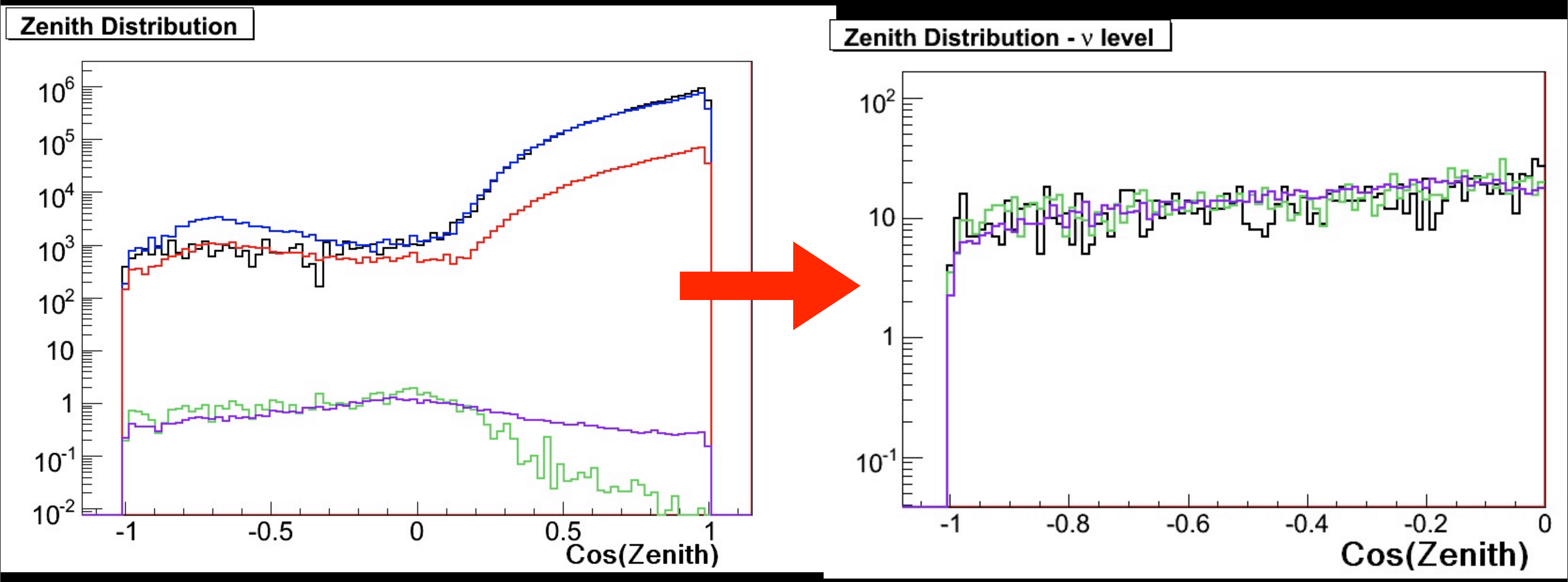




Atmospheric ν

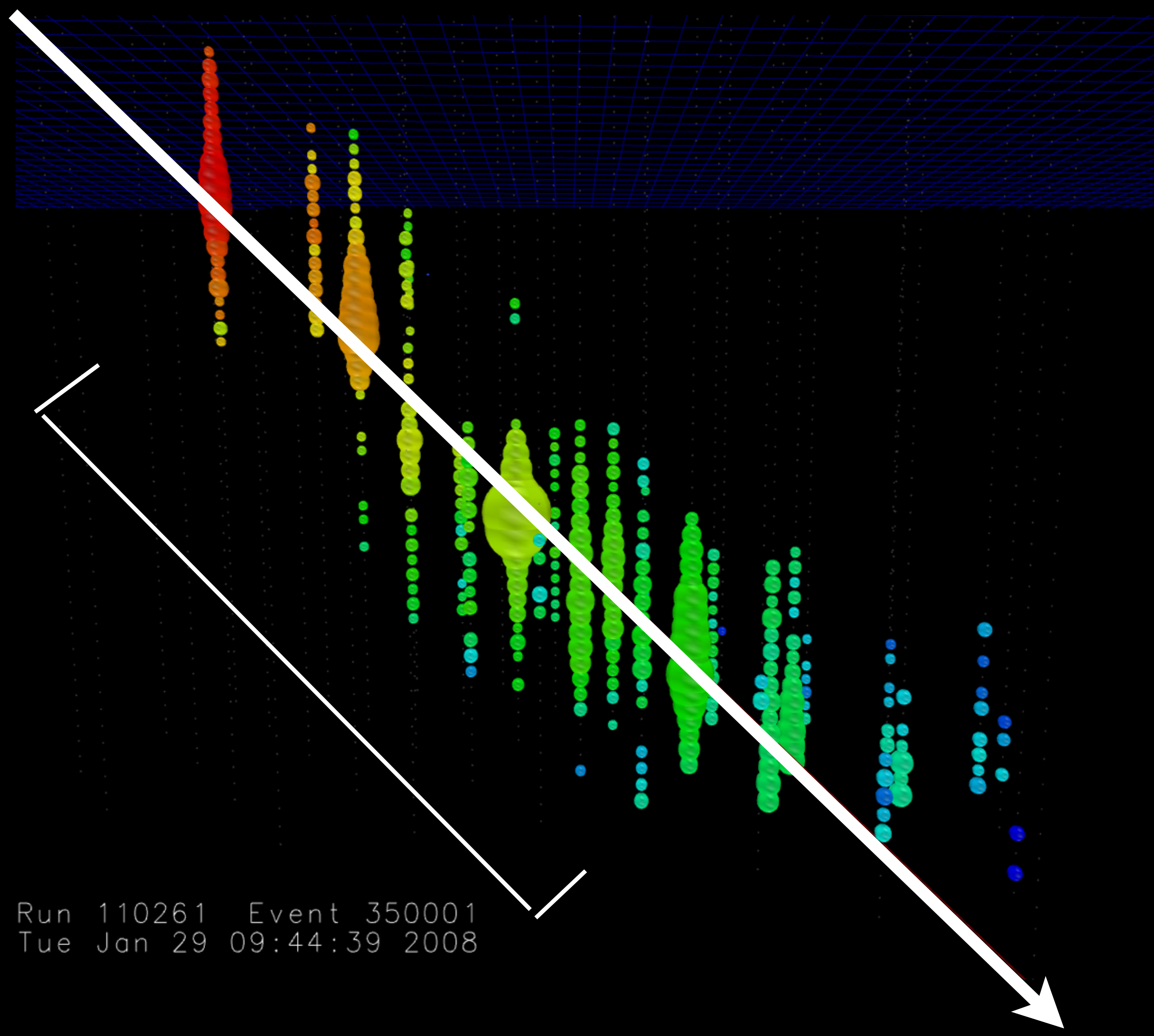
Astrophysical (signal) ν

Step 1: Downgoing Muon Rejection



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

Quality Parameters - Direct Hits



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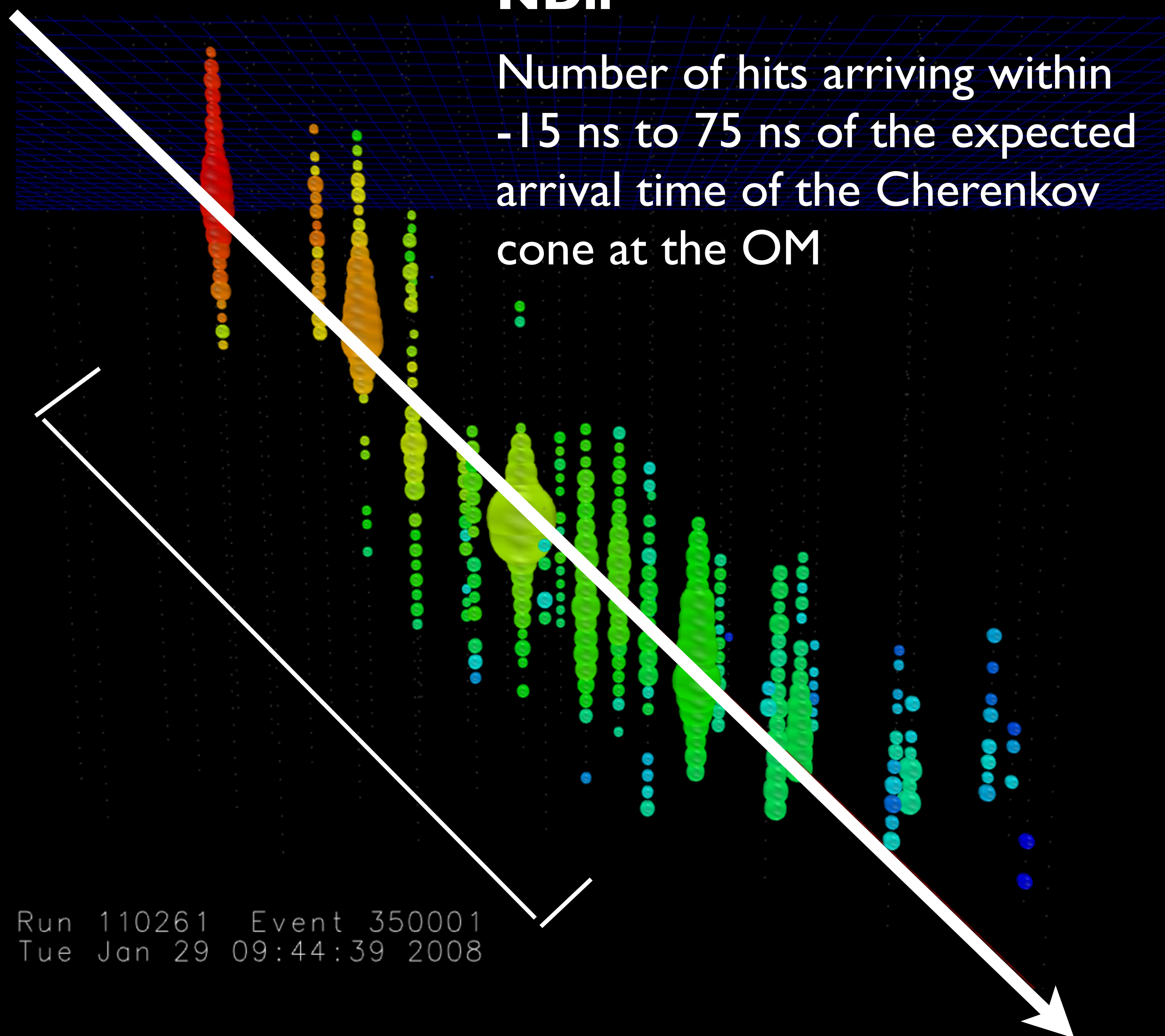

Number of Direct Hits

NDir

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

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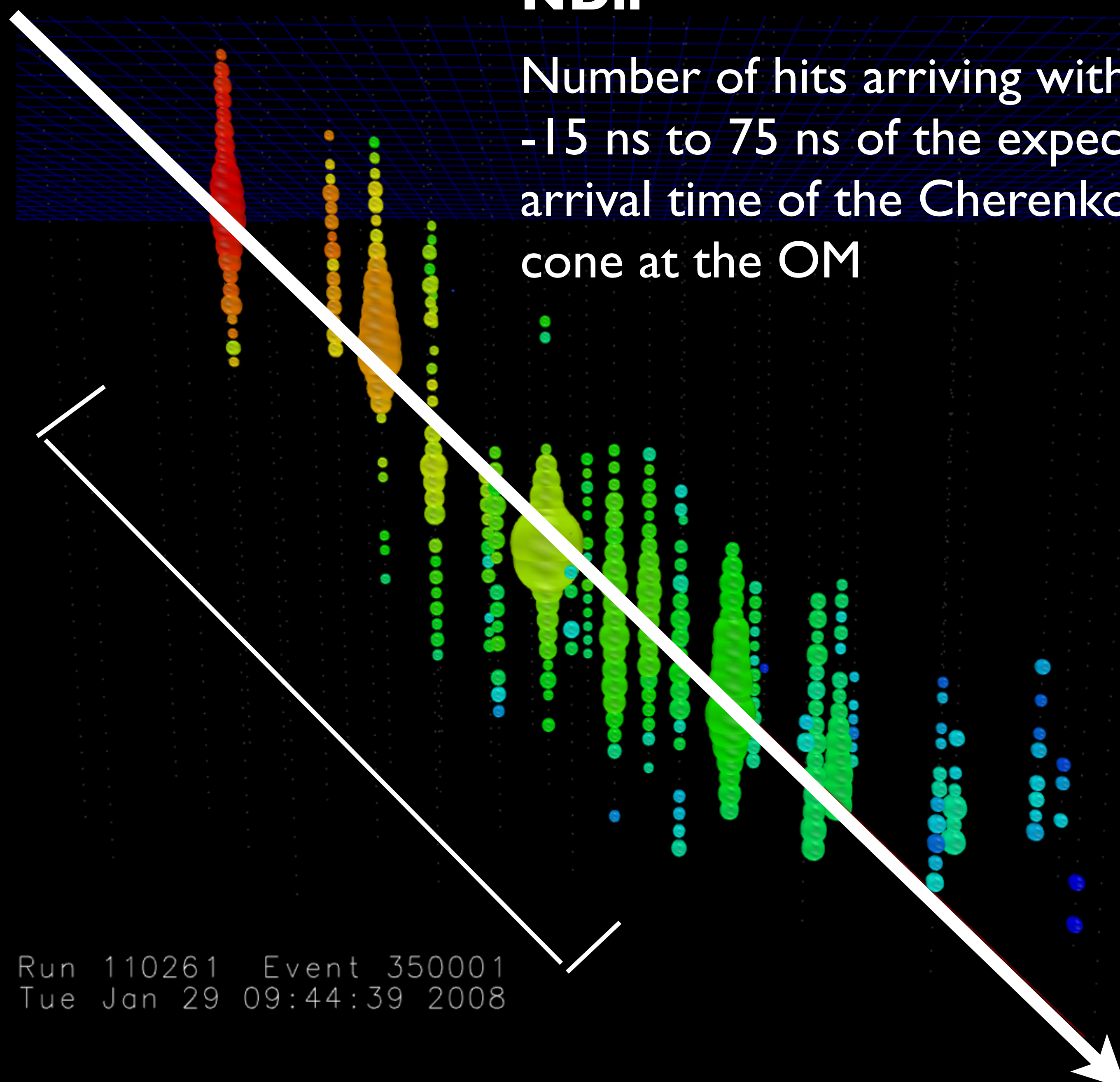

Smoothness

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

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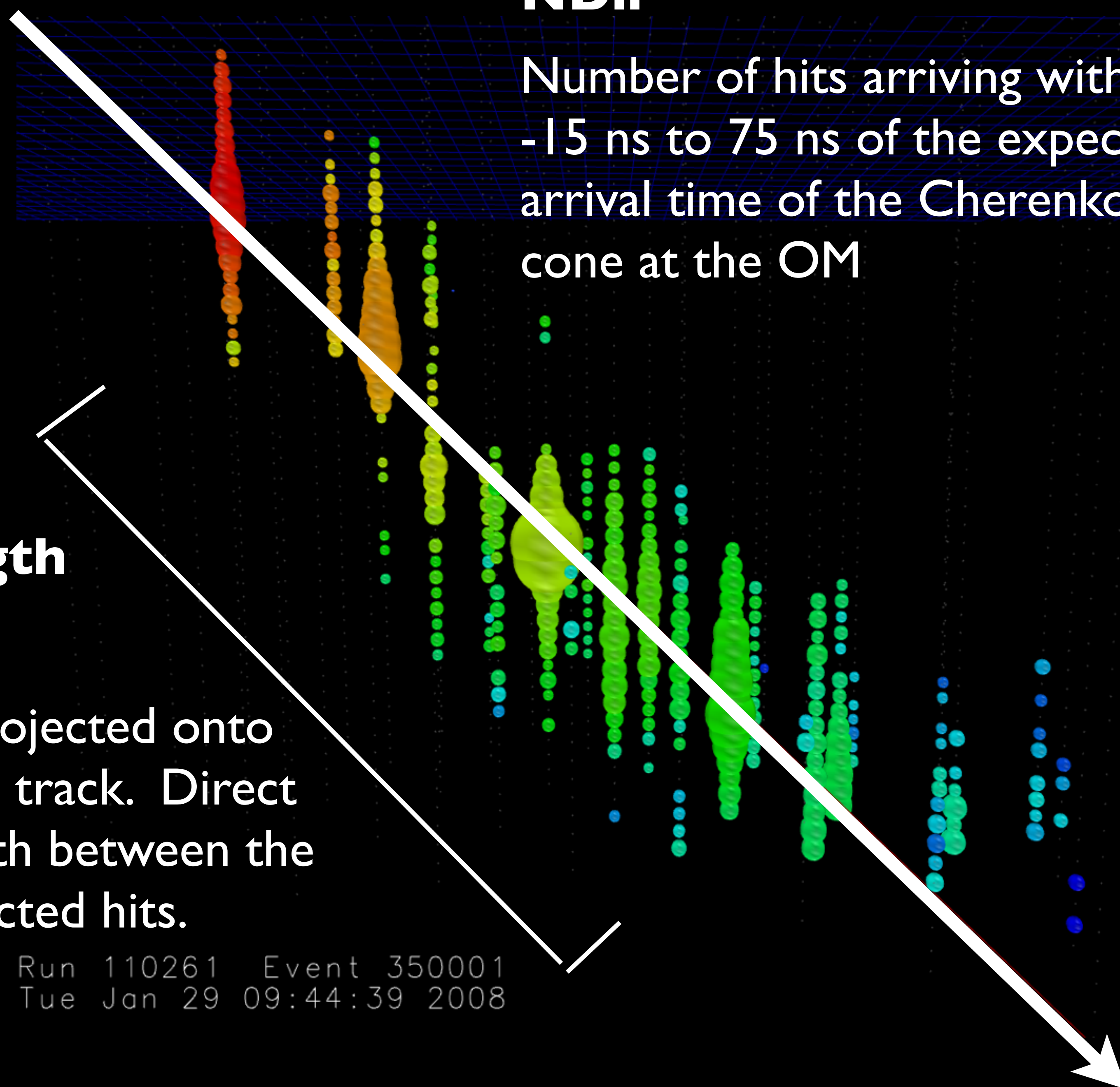

Direct Length

LDir

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

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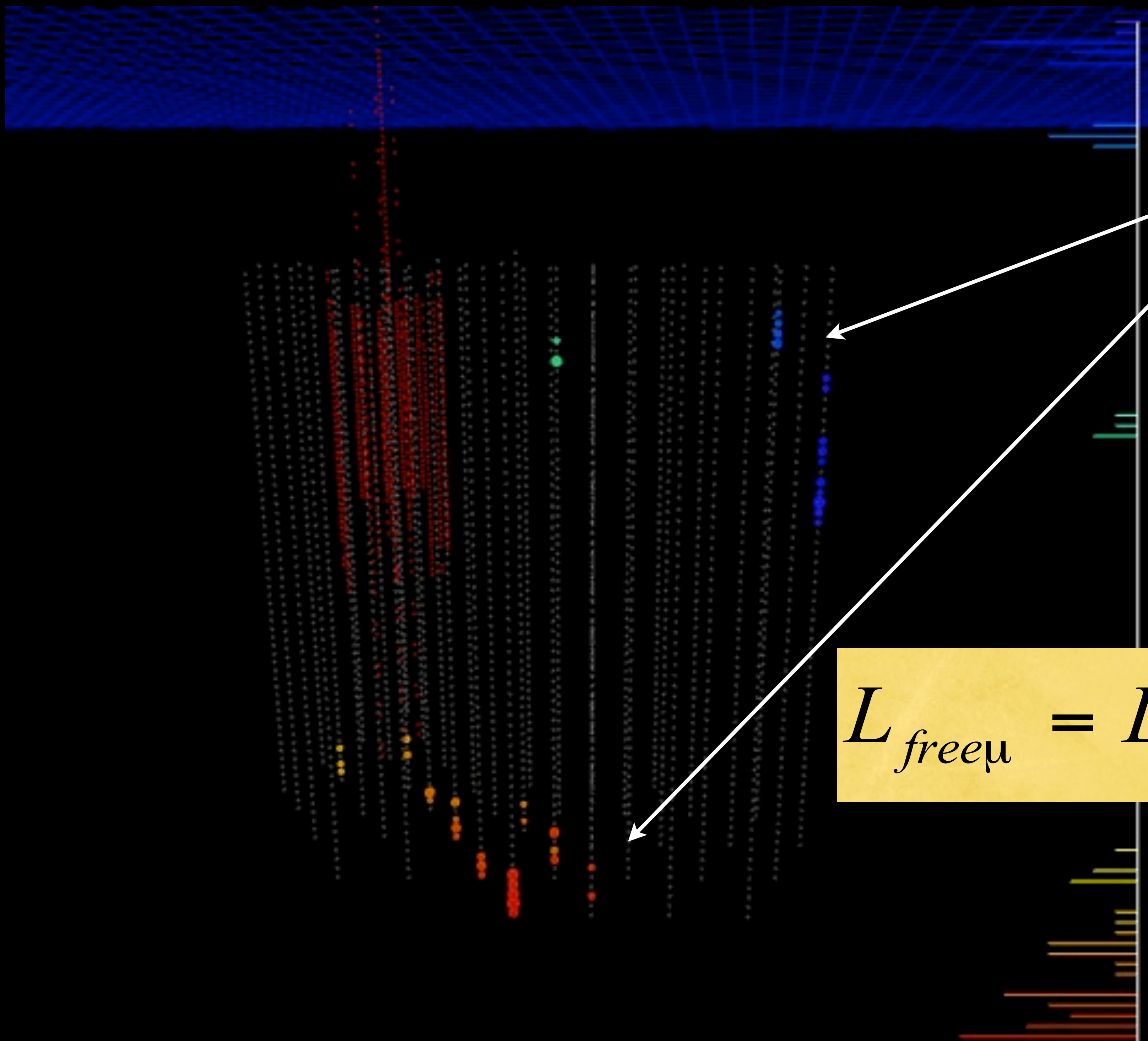
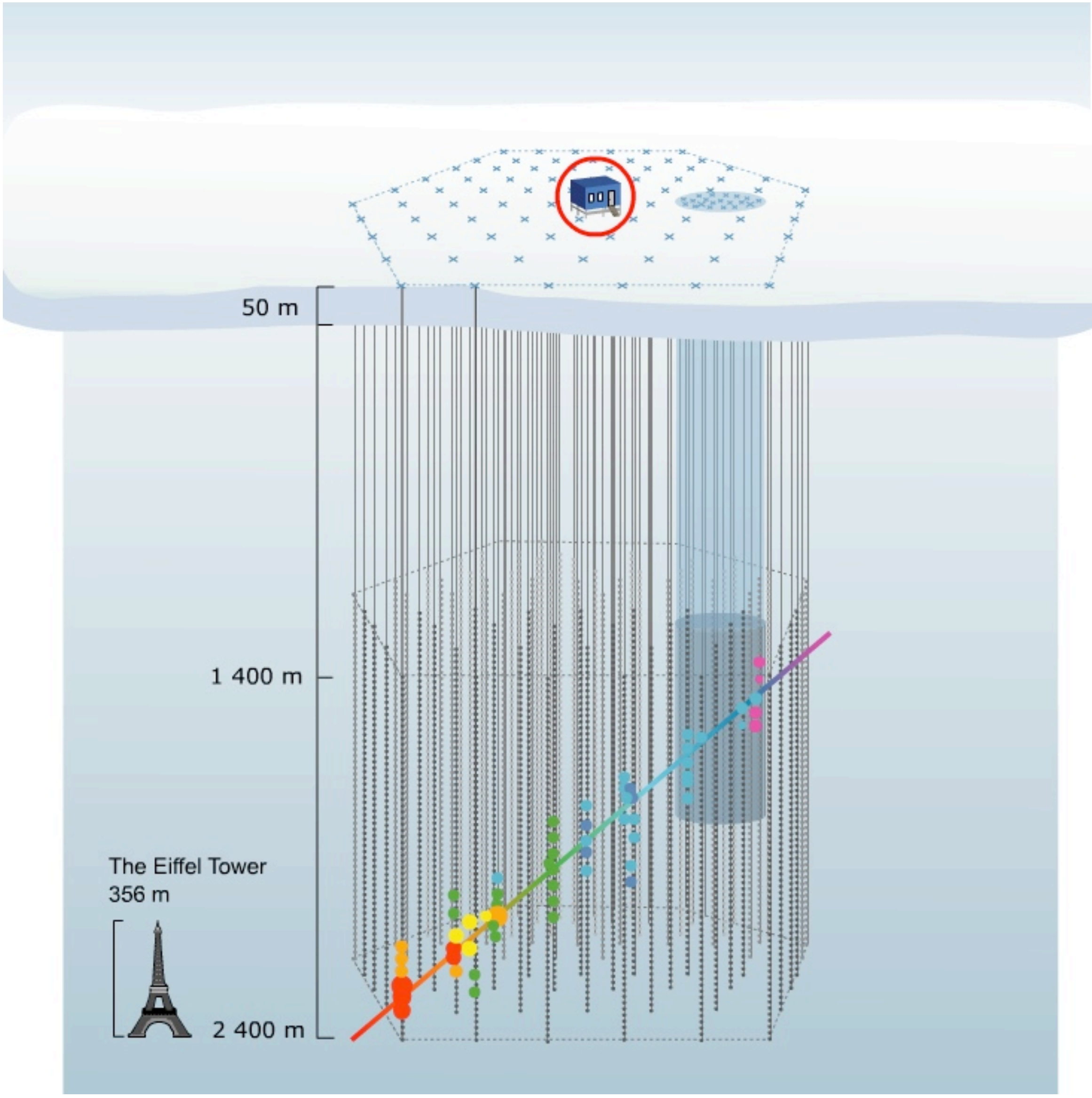
Split Reconstruction



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



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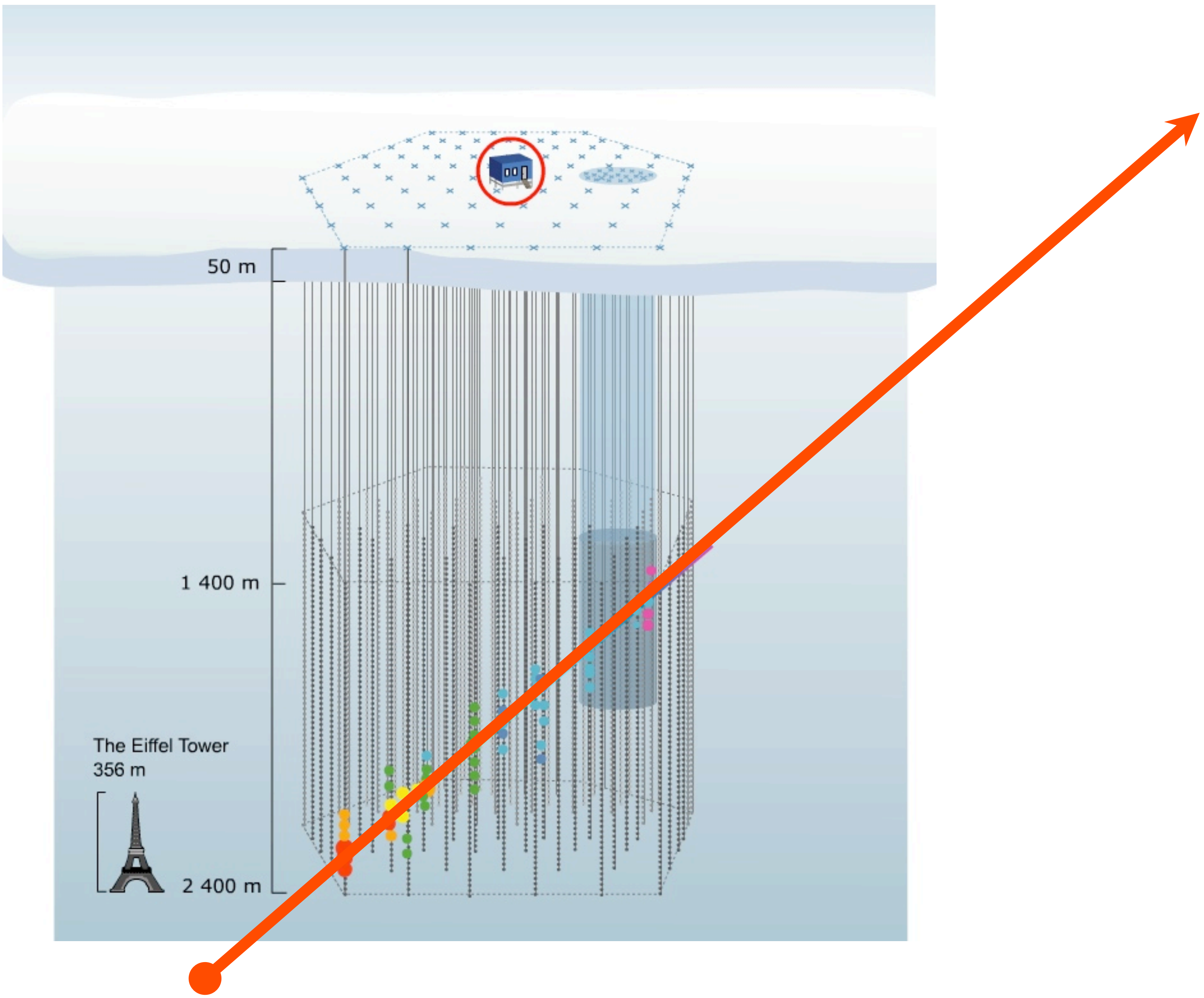
Quality Parameters: Bayesian Ratio



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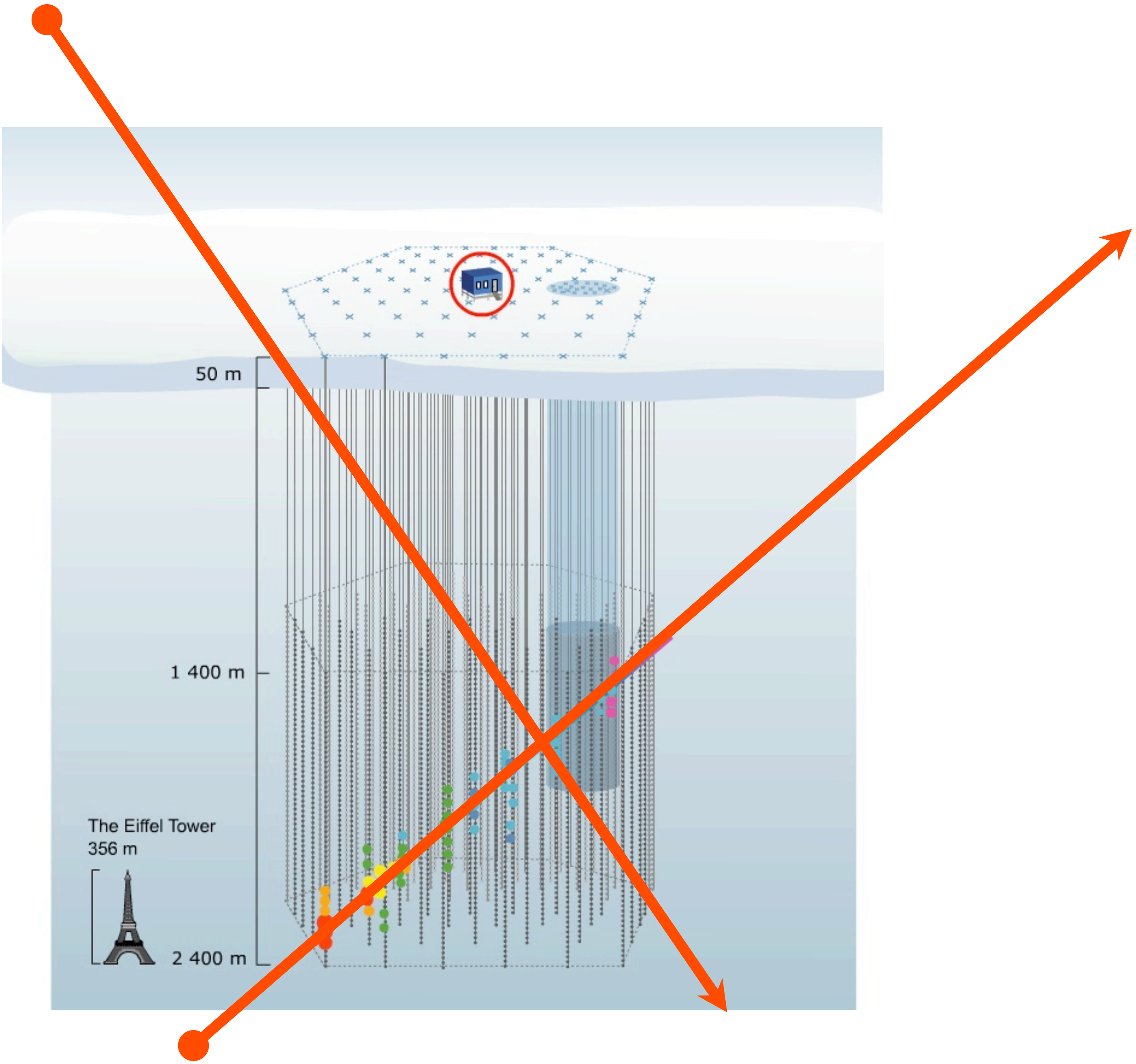
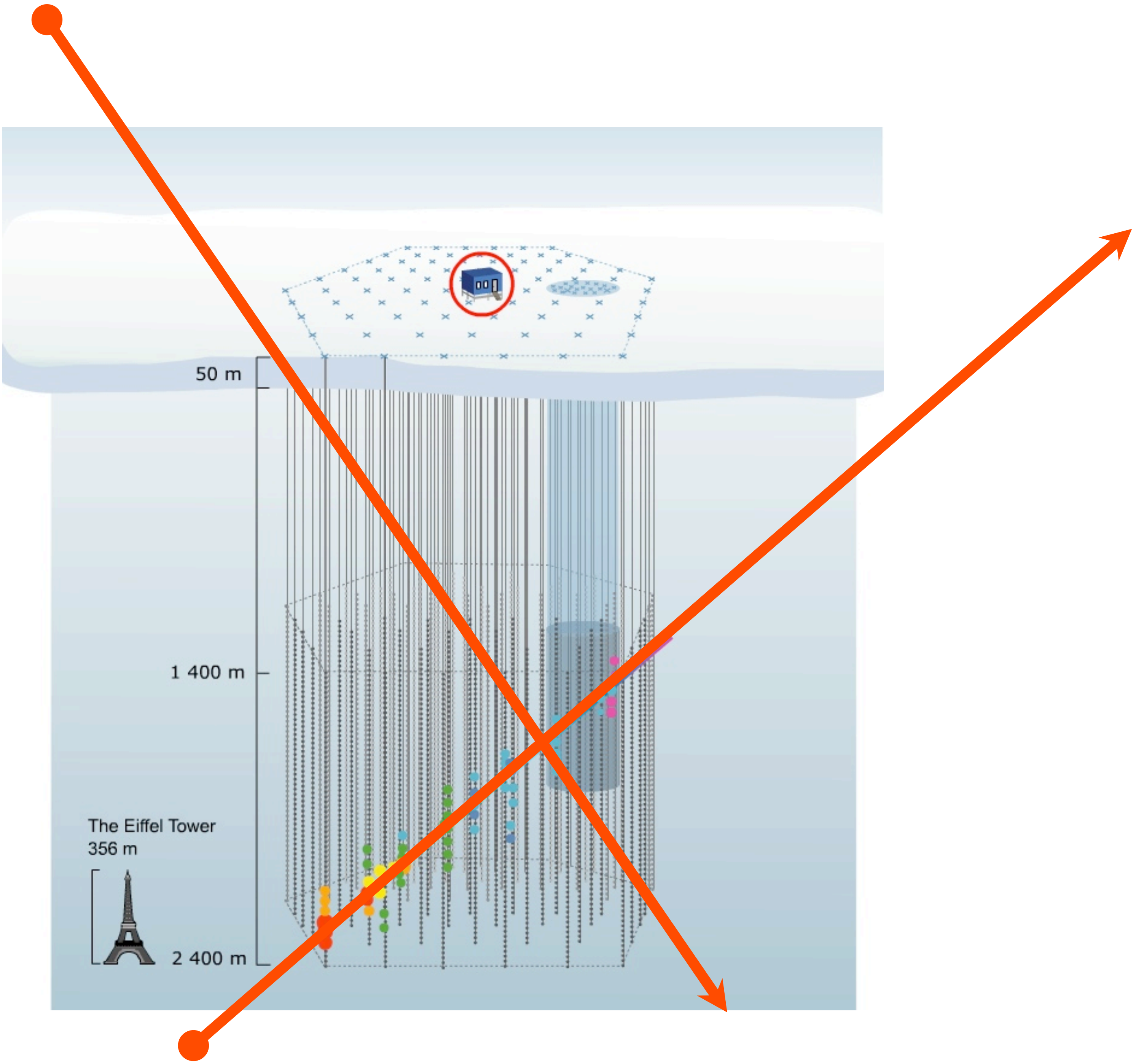


$$L_{free\mu} = L(E \mid \mu(\theta, \phi, x, y, z))$$

Quality Parameters: Bayesian Ratio

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



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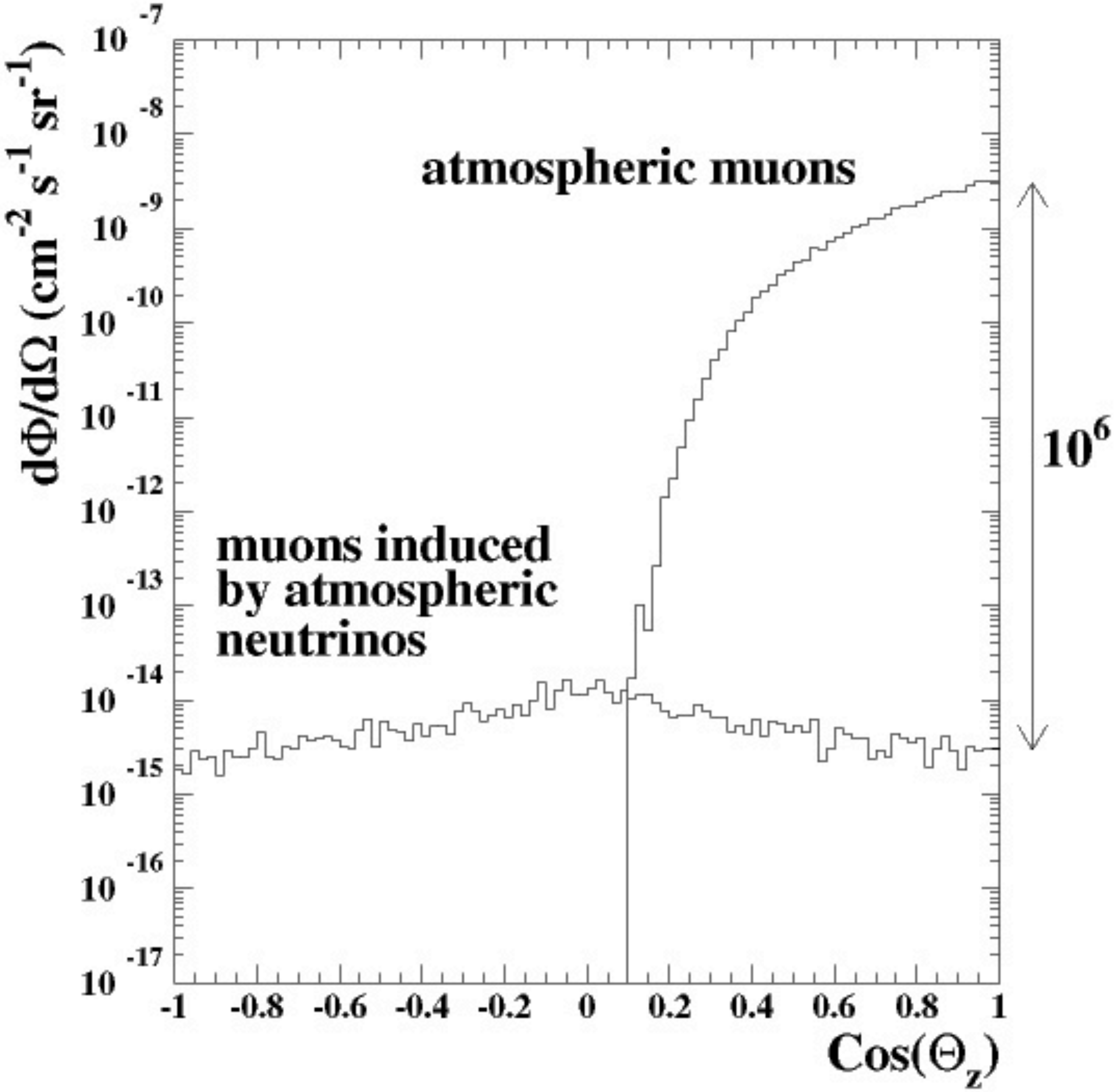

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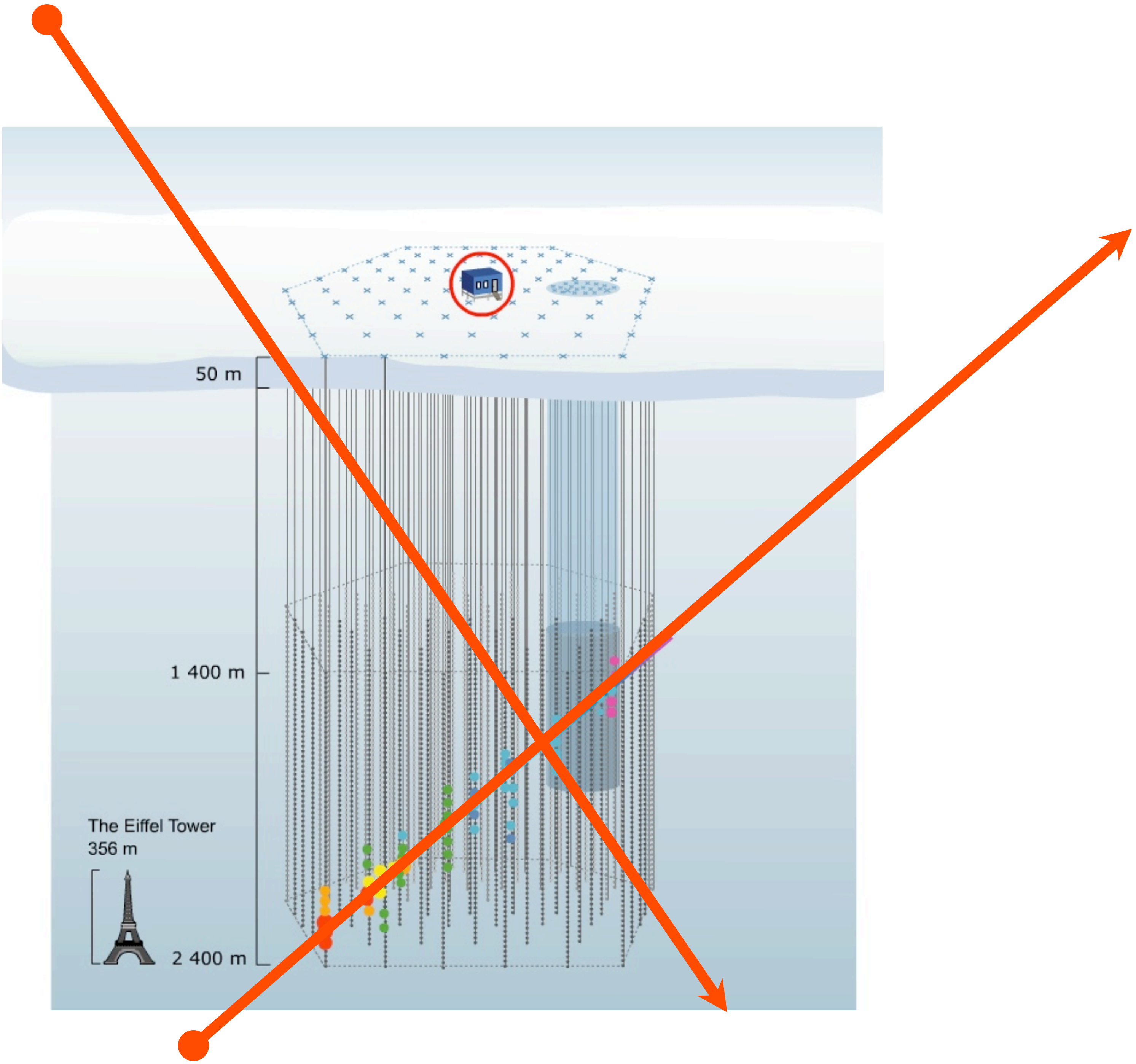

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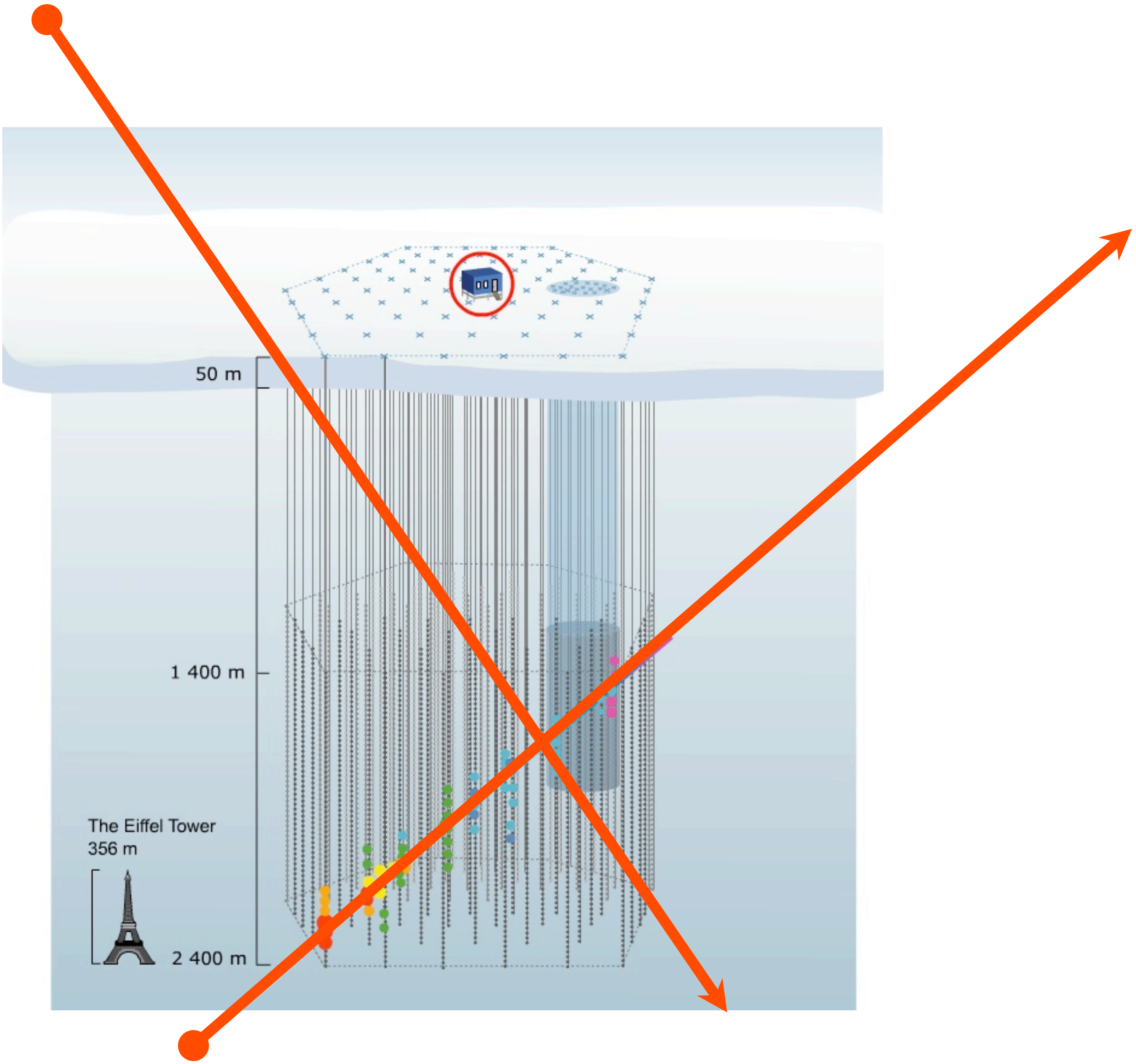
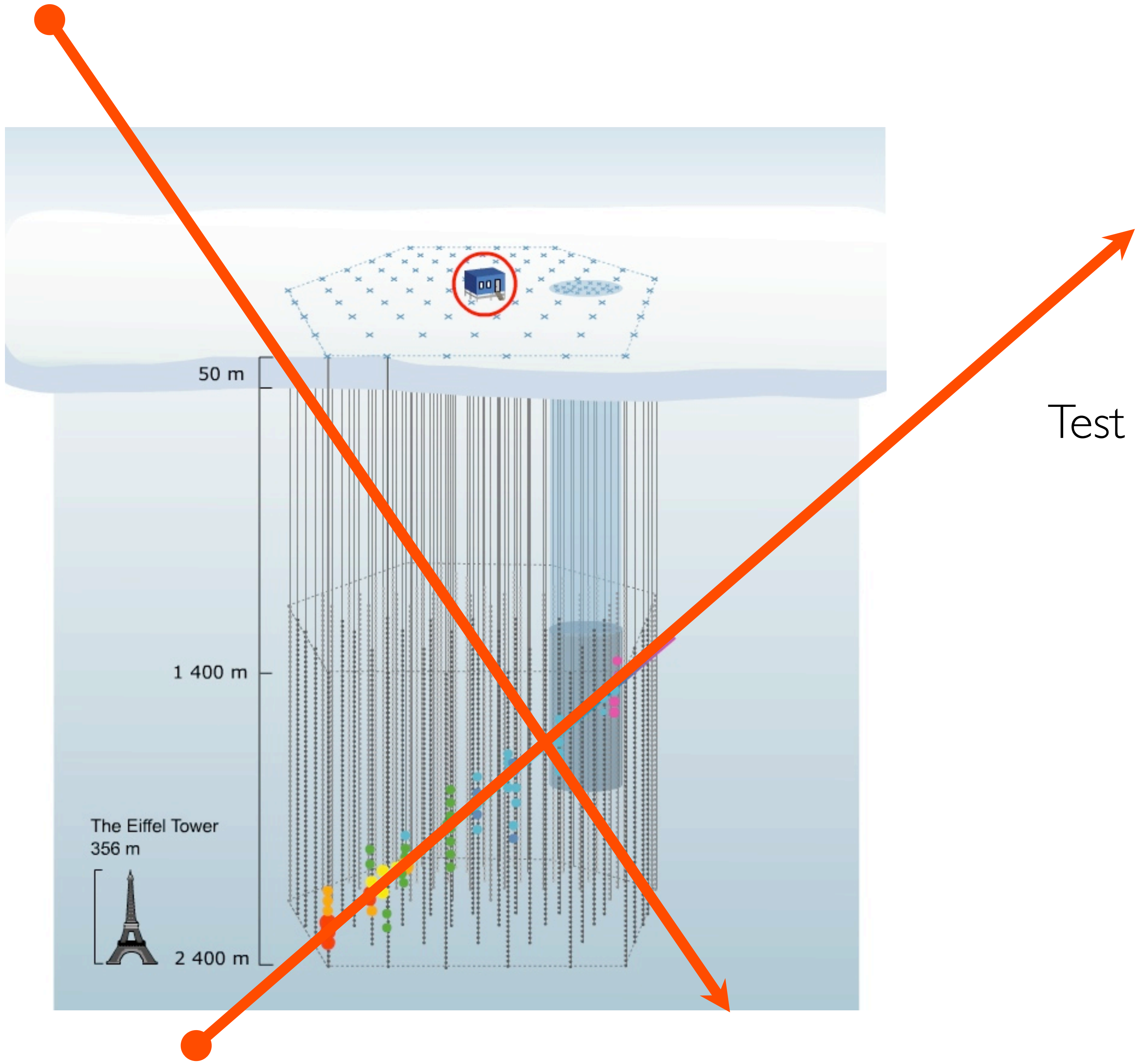


$$L_{free\mu} = L(E \mid \mu(\theta, \phi, x, y, z))$$

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

Quality Parameters: Bayesian Ratio

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



Test Statistic:

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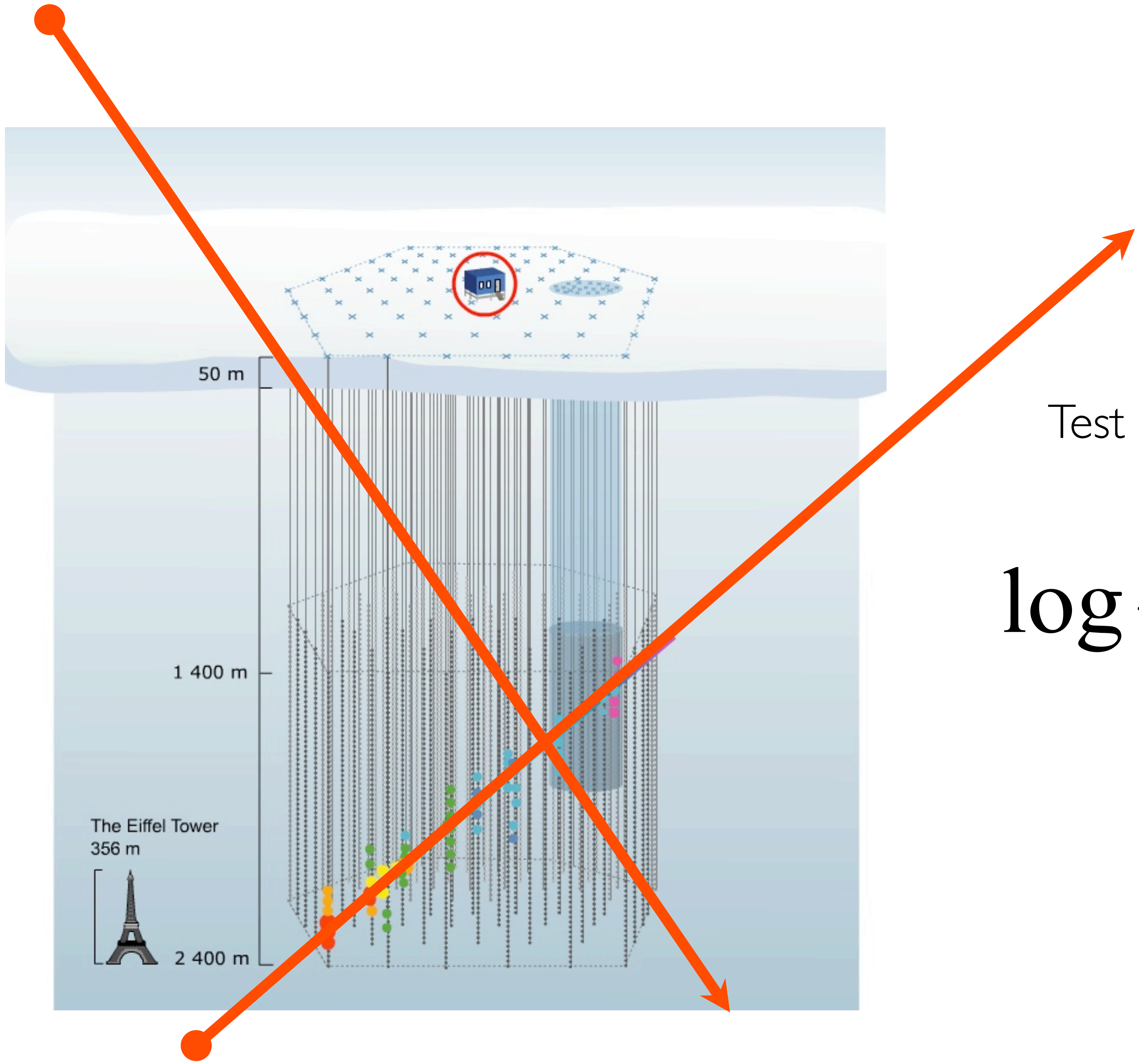

Test Statistic:

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

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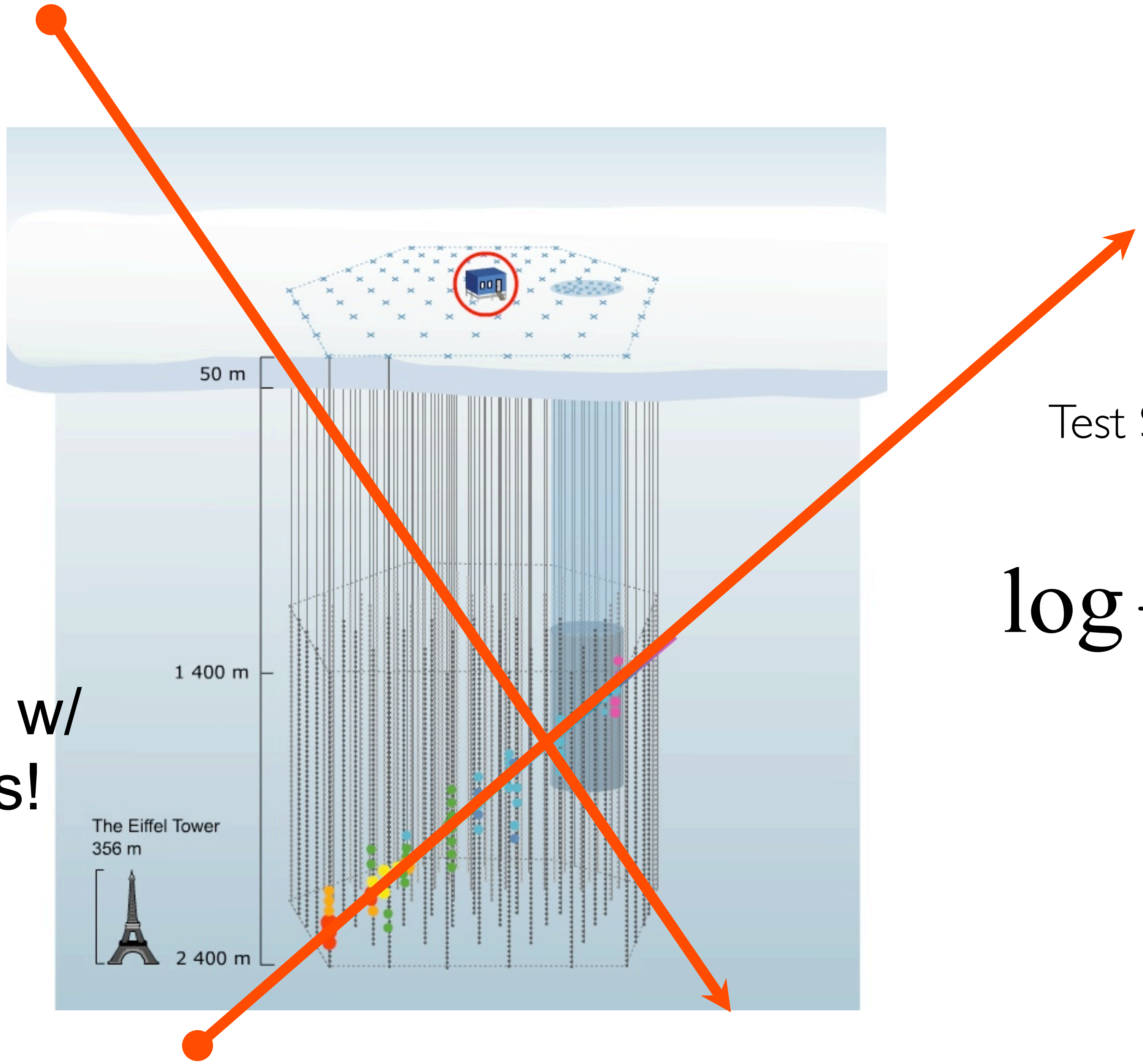

Test Statistic:

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

Can do the same w/ Coincident Muons!

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

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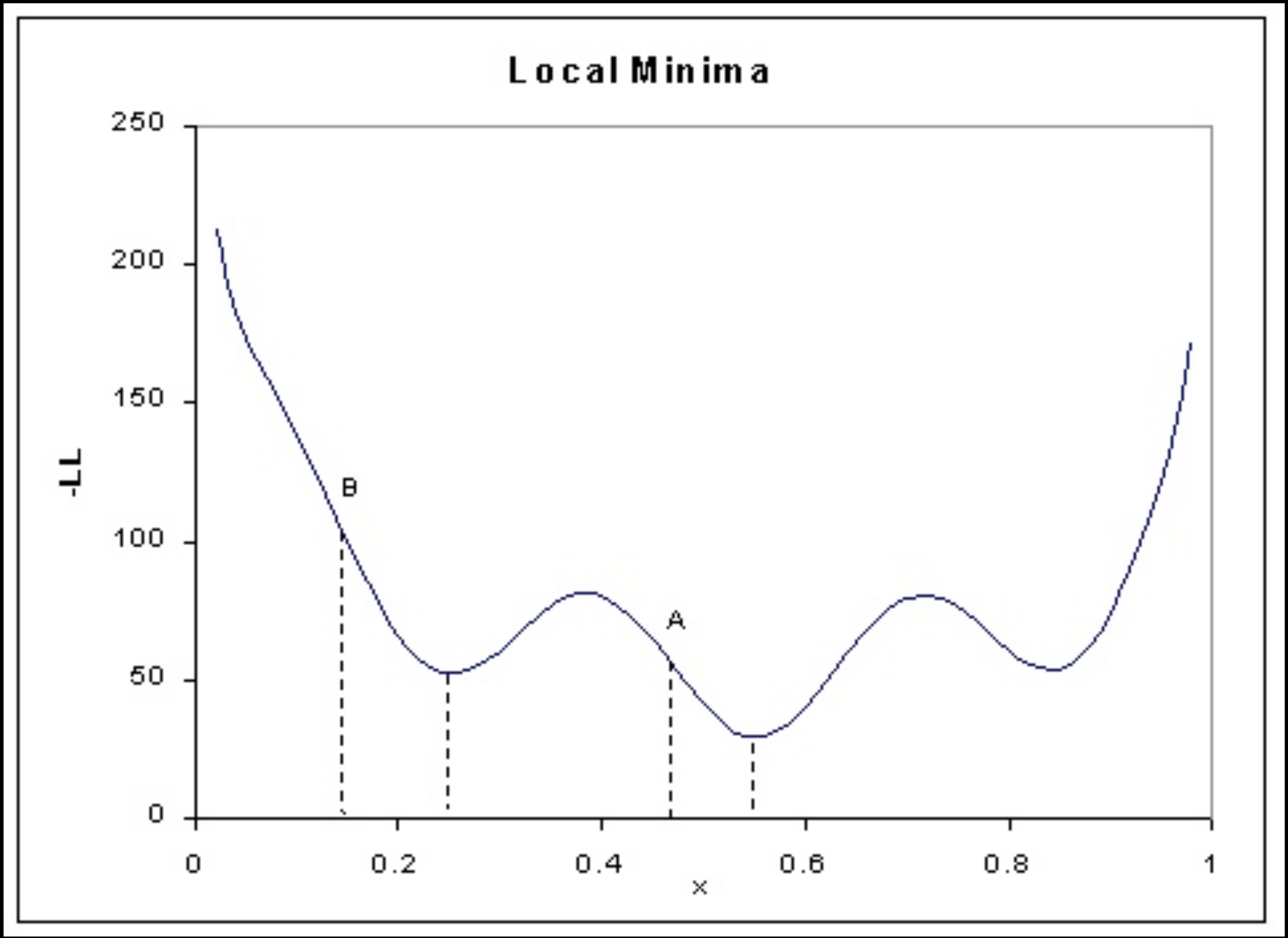
Quality Parameters - Paraboloid Sigma



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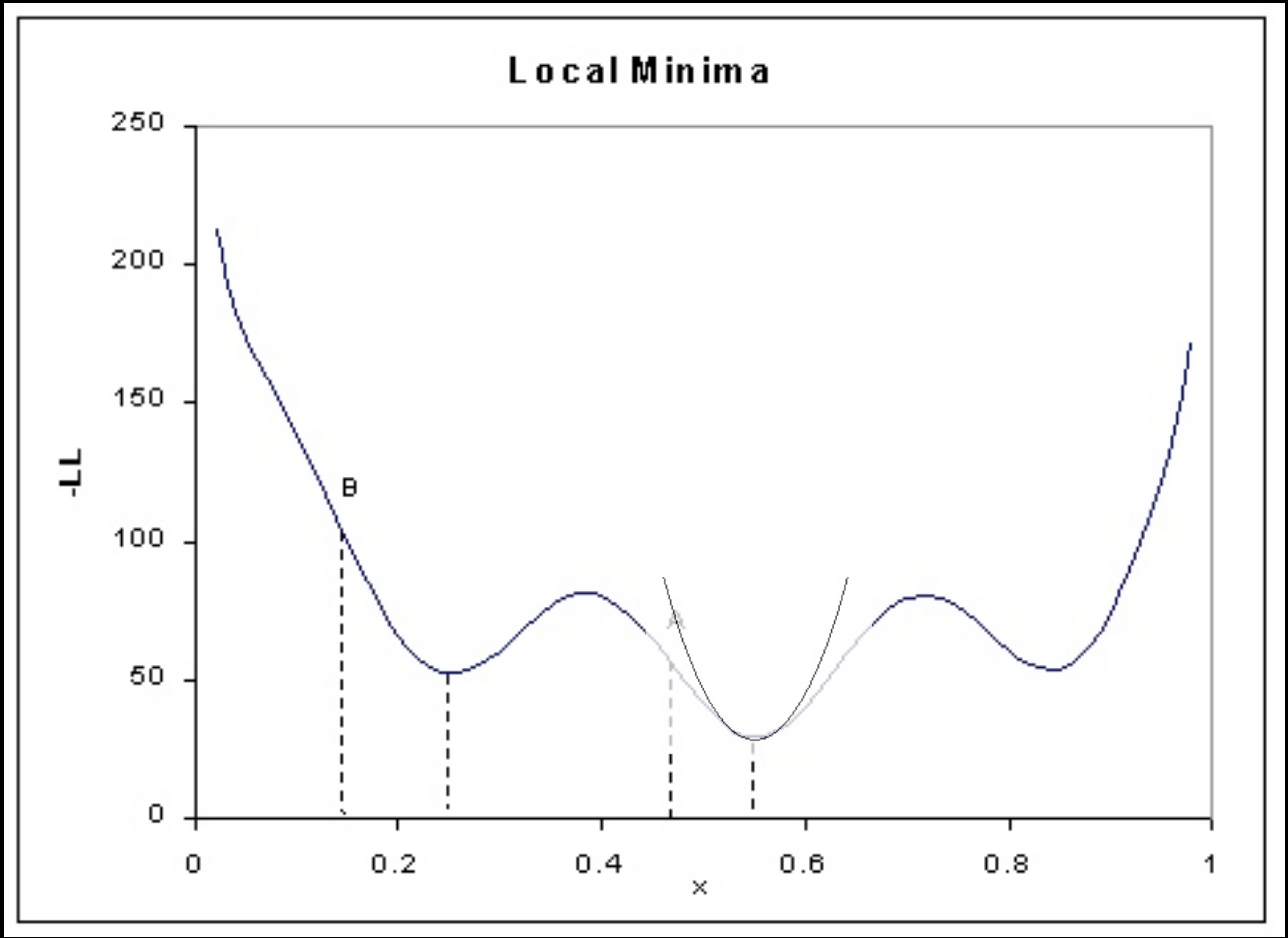

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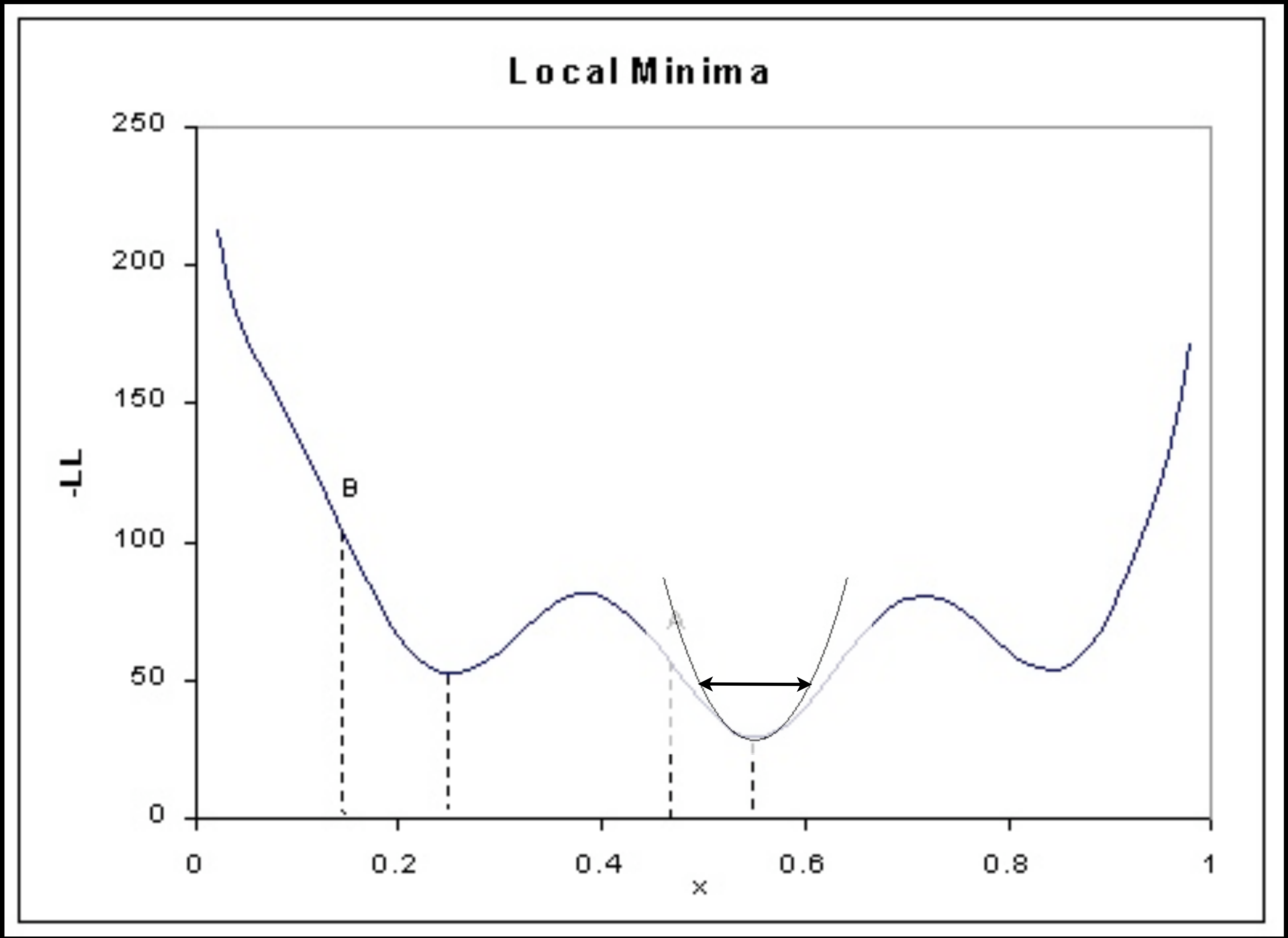

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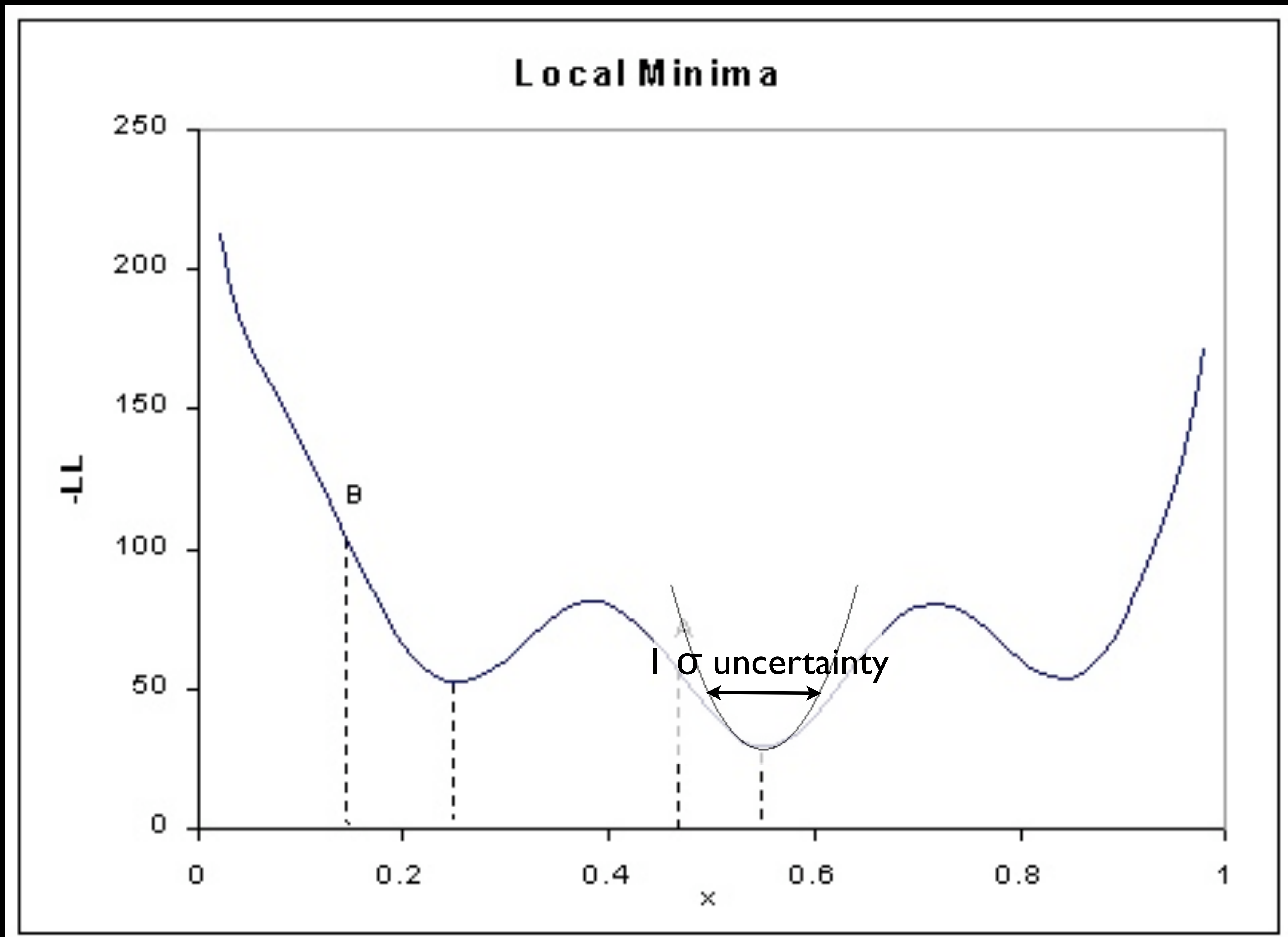

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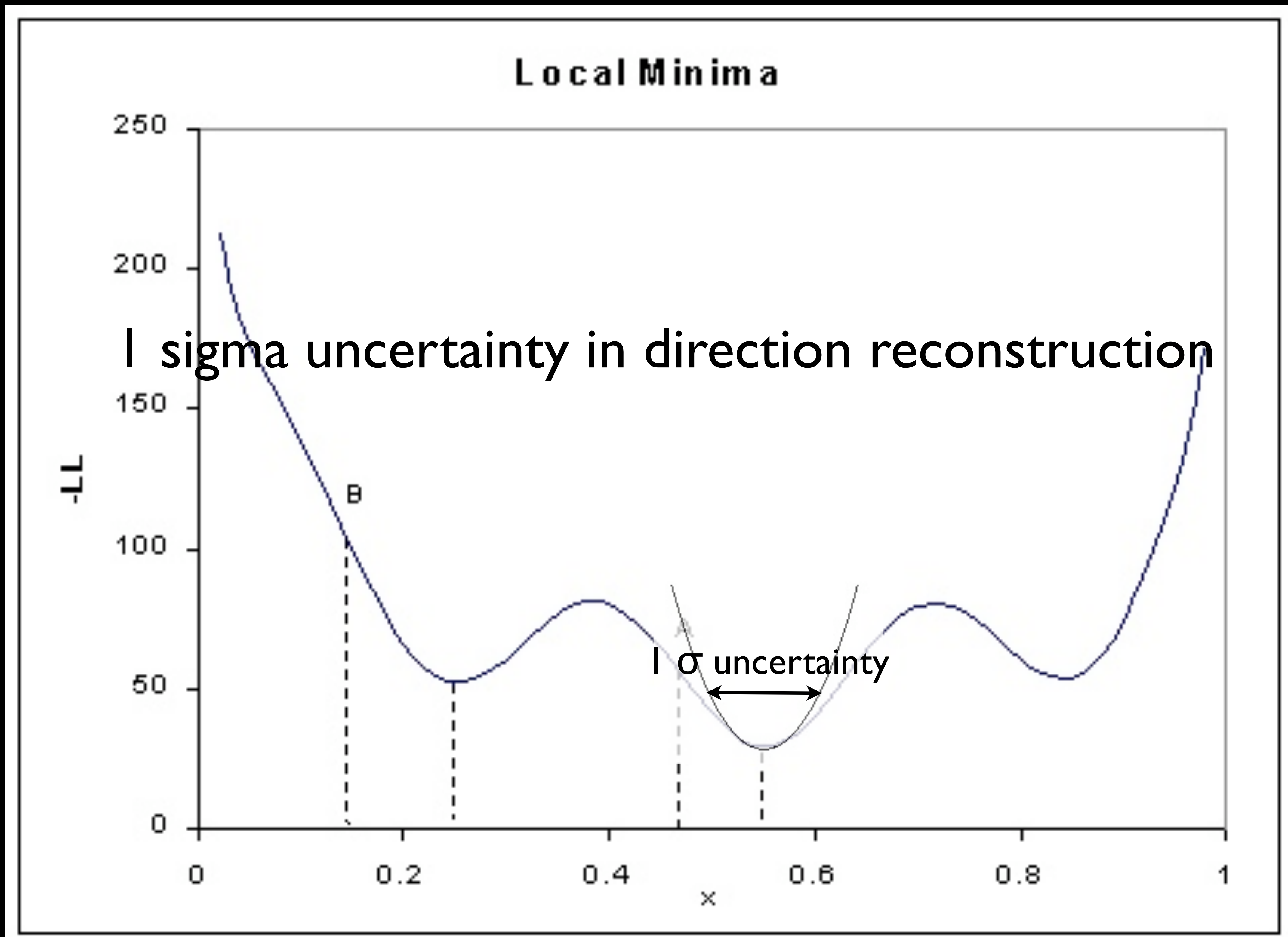
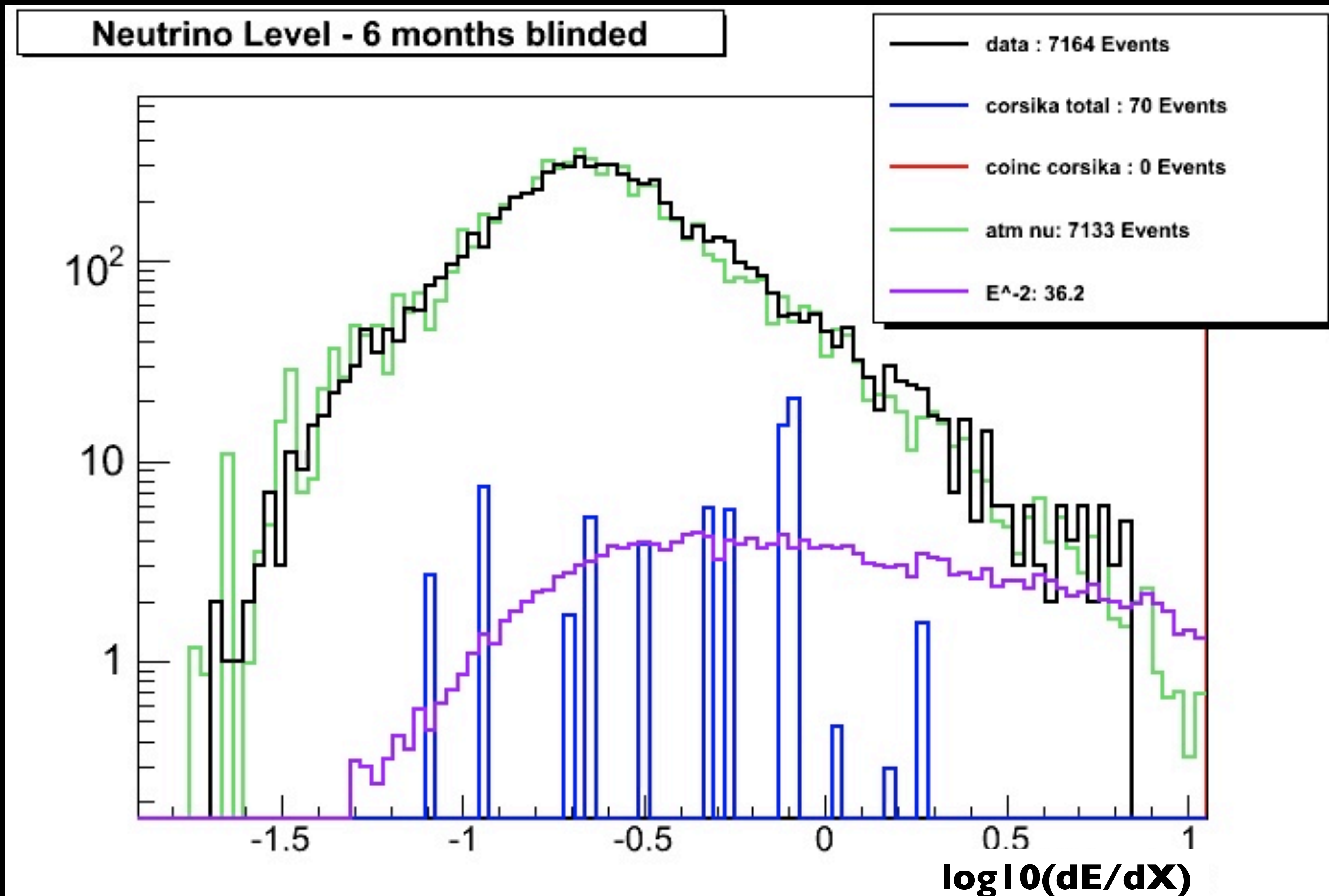


Final Neutrino Sample

- Strict **Blindness** policy in IceCube.
- 6 months of data below region of interest **log10(dE/dX) < 0.8 GeV/m**
- data sample **7164 events** given an expectation of **7133 atmospheric neutrinos** with **99.5% purity**
- **Astrophysical E^{-2} efficiency:** 36.2%
- **Straight cuts** used:

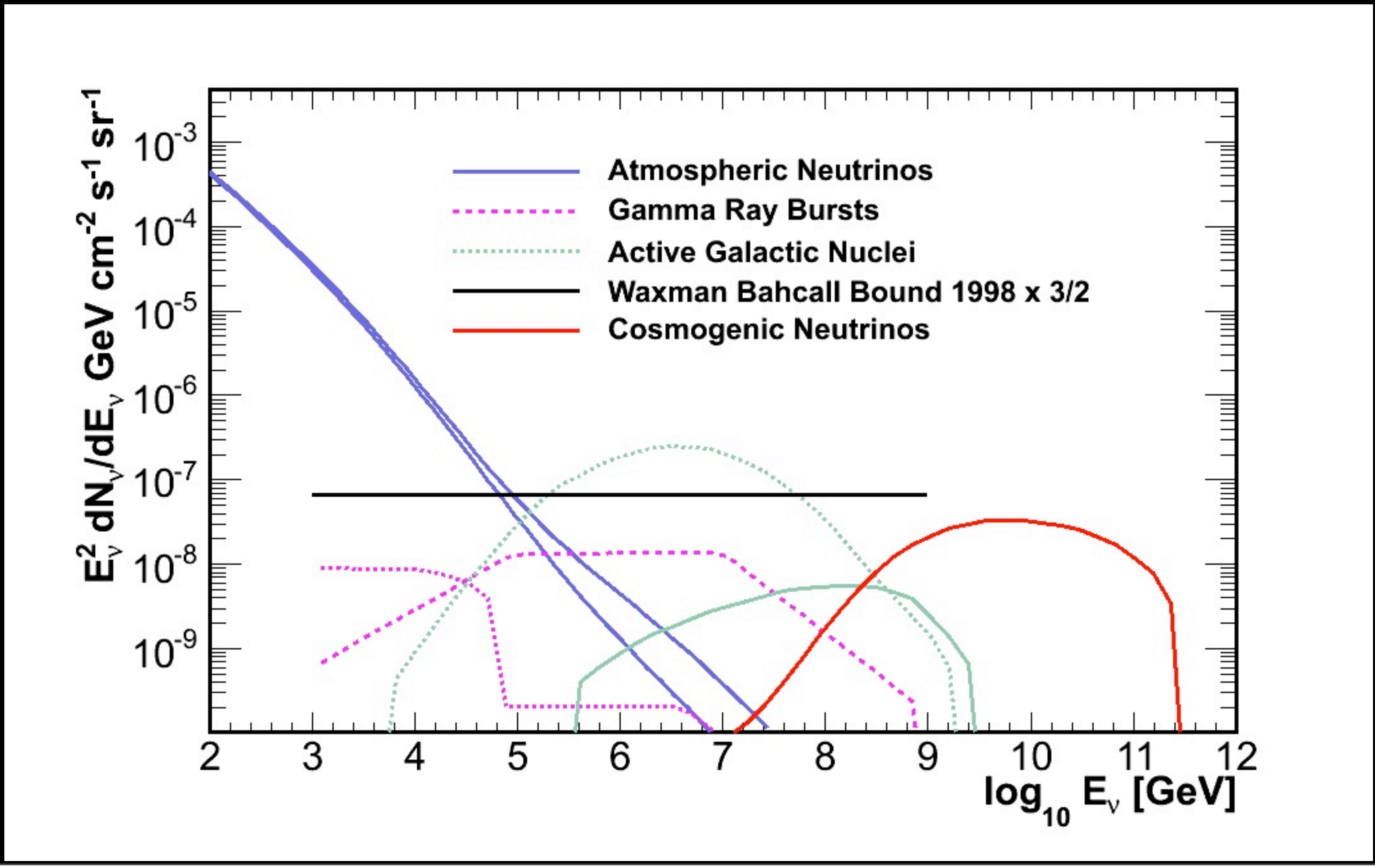
LDirC > 240	BayesRatio > 25	MPE Zenith > 90
|SDirC| < 0.54	Split BayesRatio > 35	MinSplitZenith > 80
NDirC > 5	Paraboloid Sigma < 3	mrlogl < 8

Energy Distribution - 6 Months IC40 Data



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 an energy distribution



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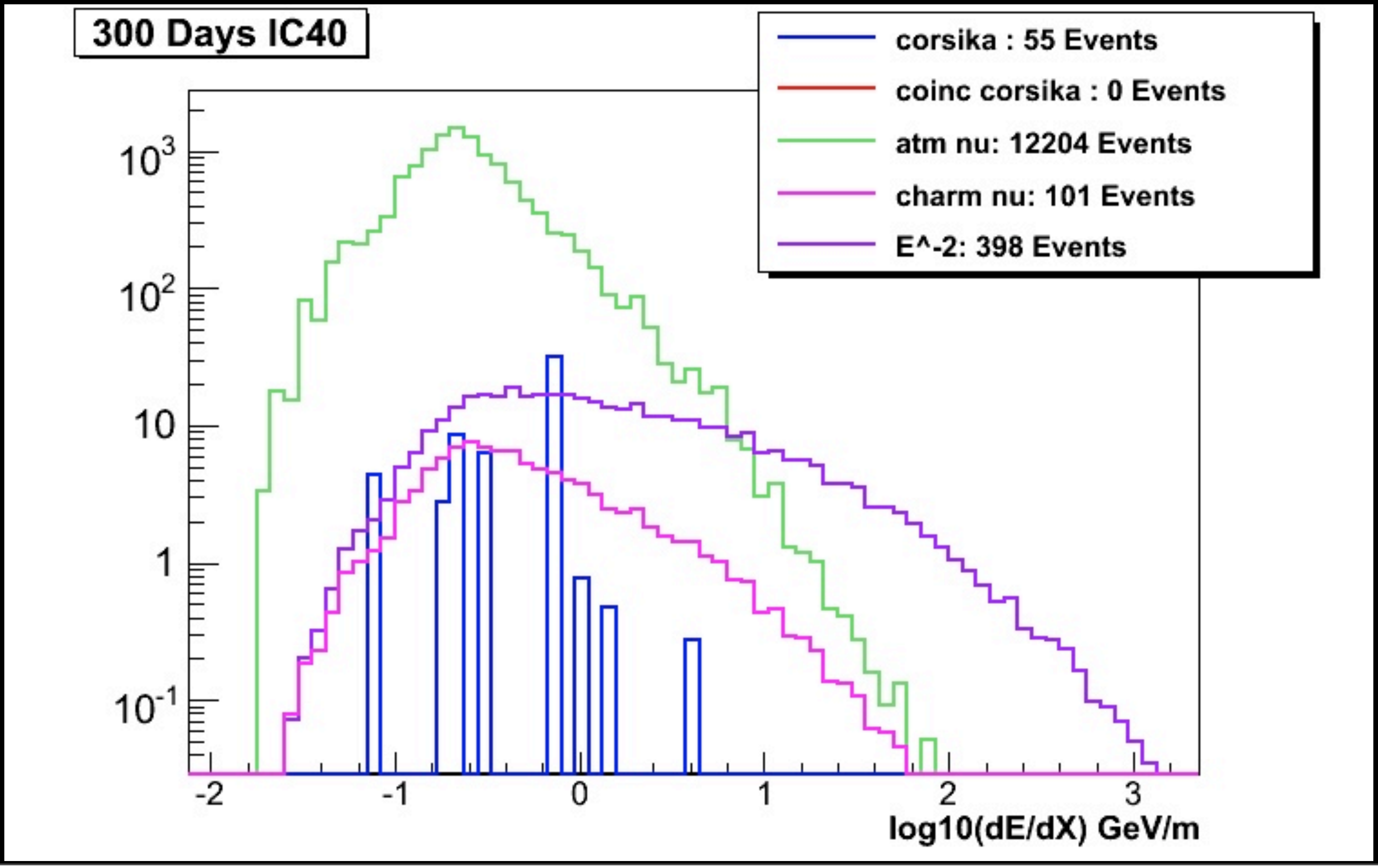
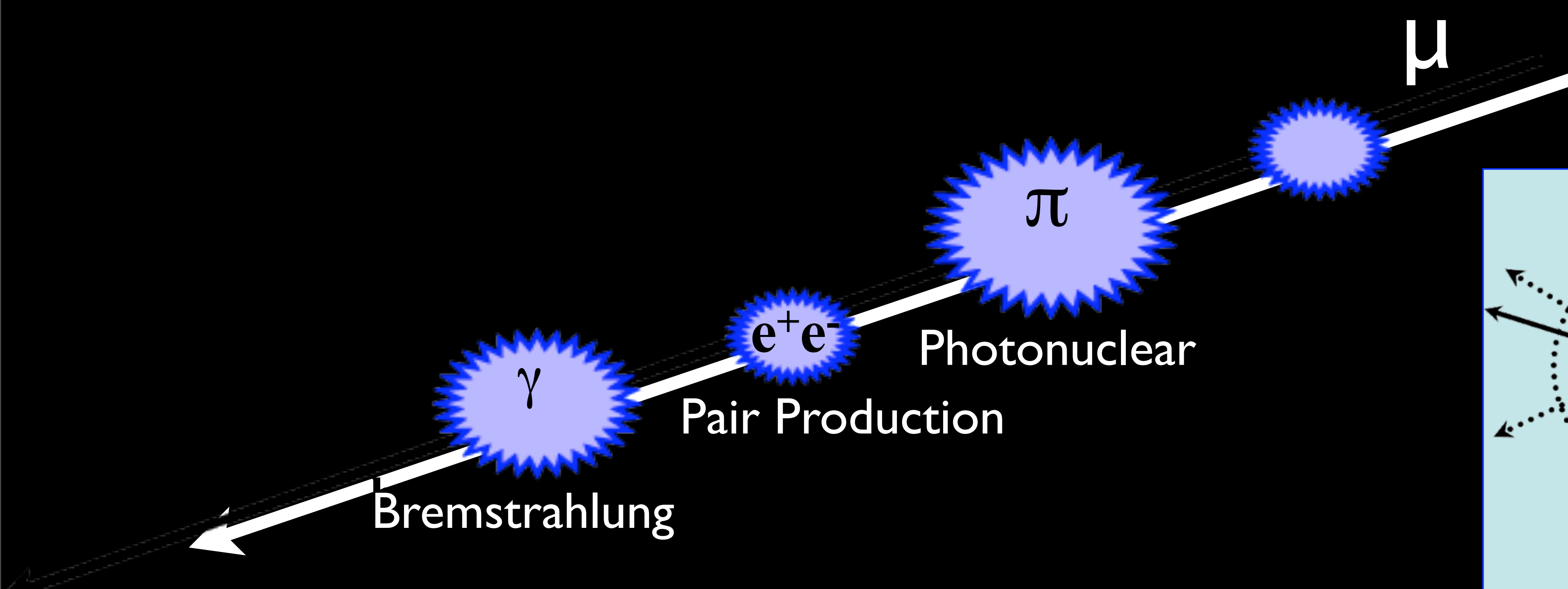
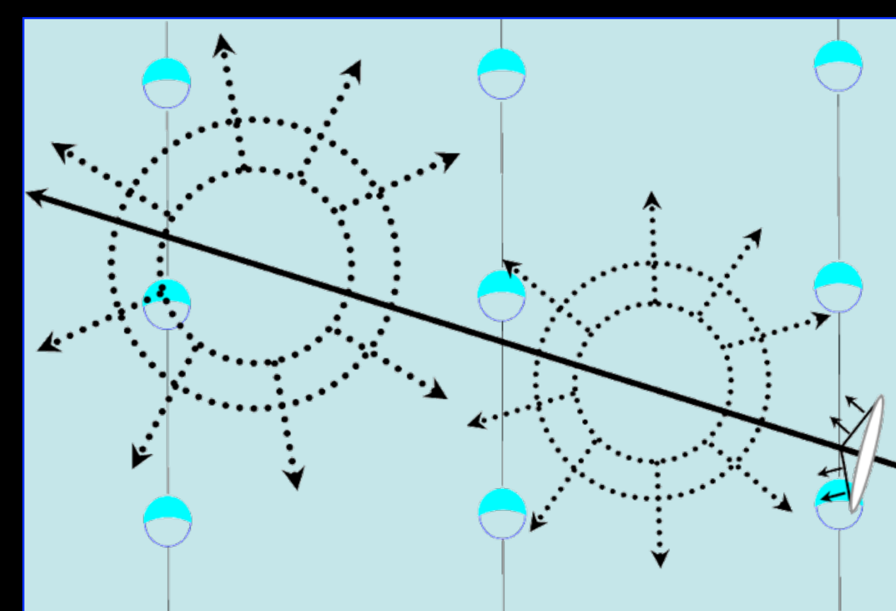


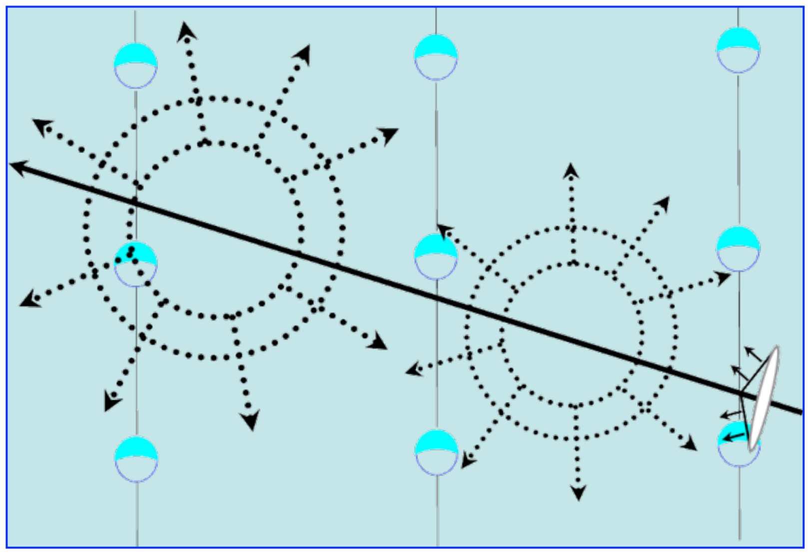
Energy Estimation

- 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



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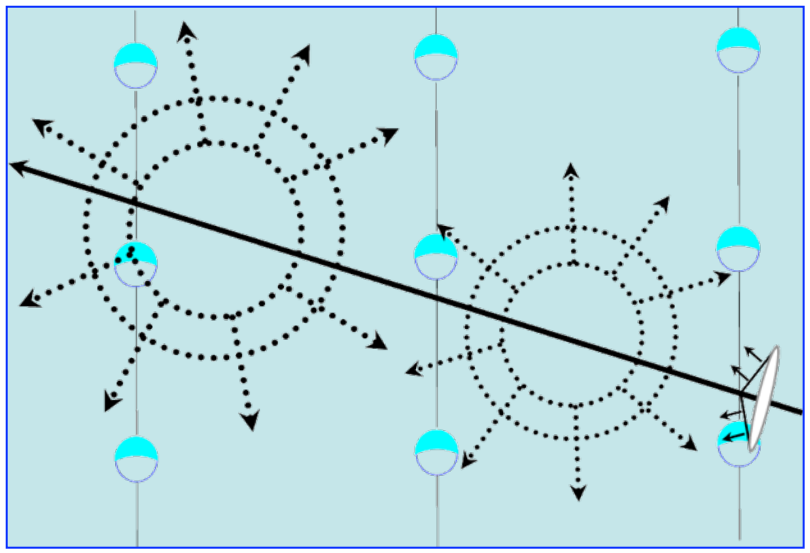
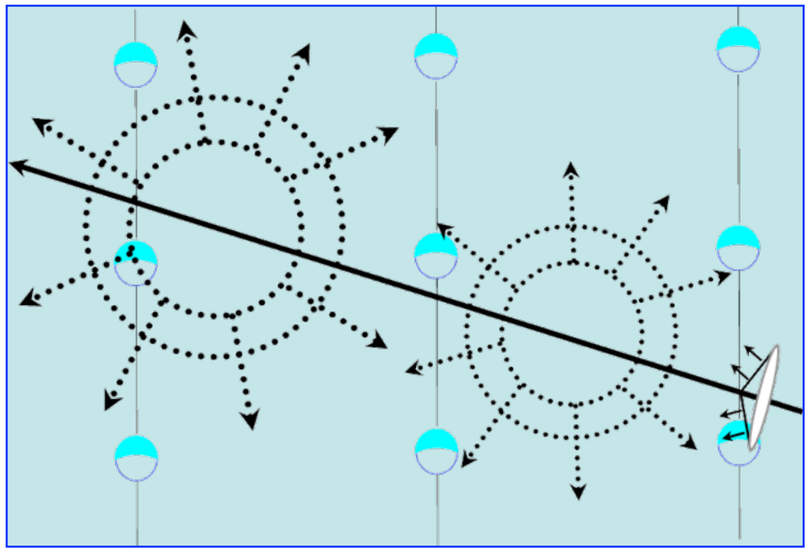


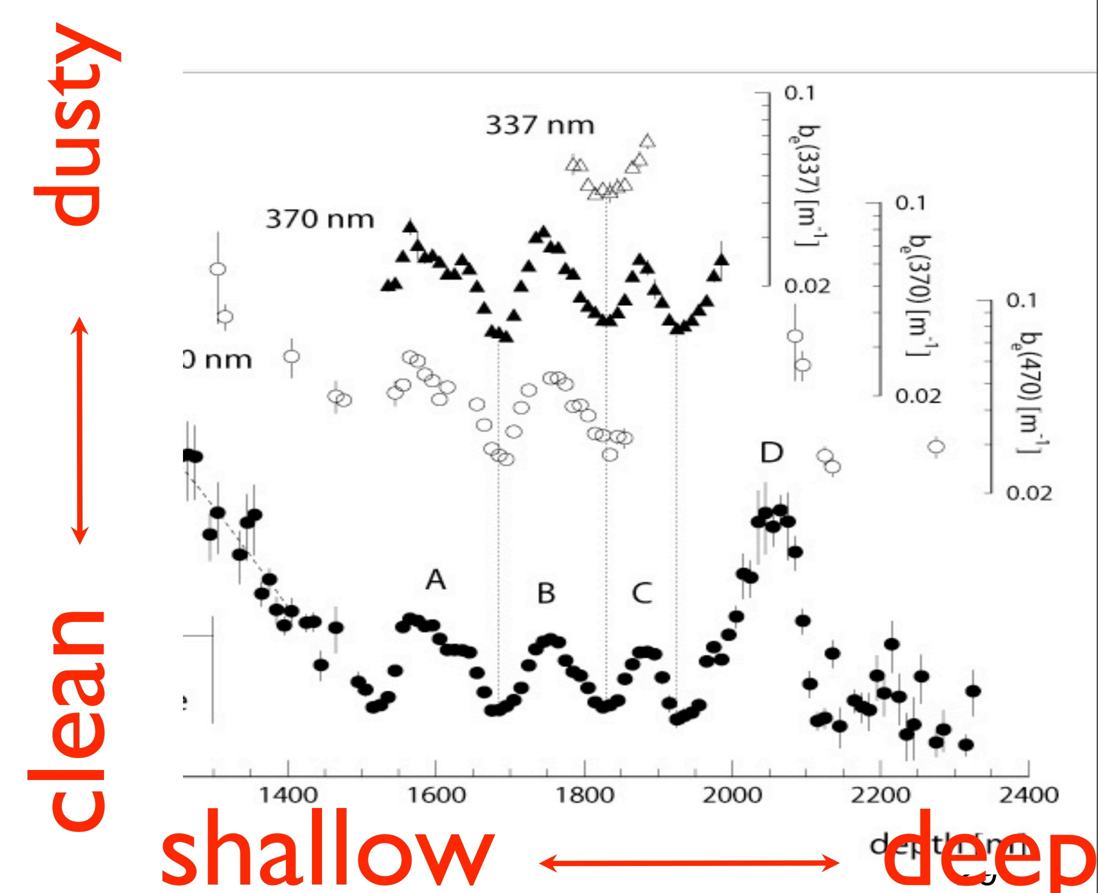
Approximate as:

Reconstructing The Muon Energy Loss



Approximate as:

Incorporate Ice Properties:



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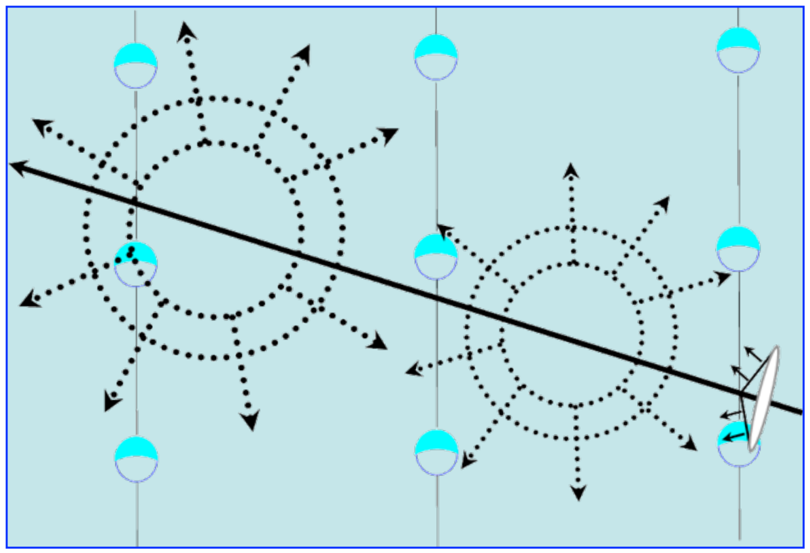
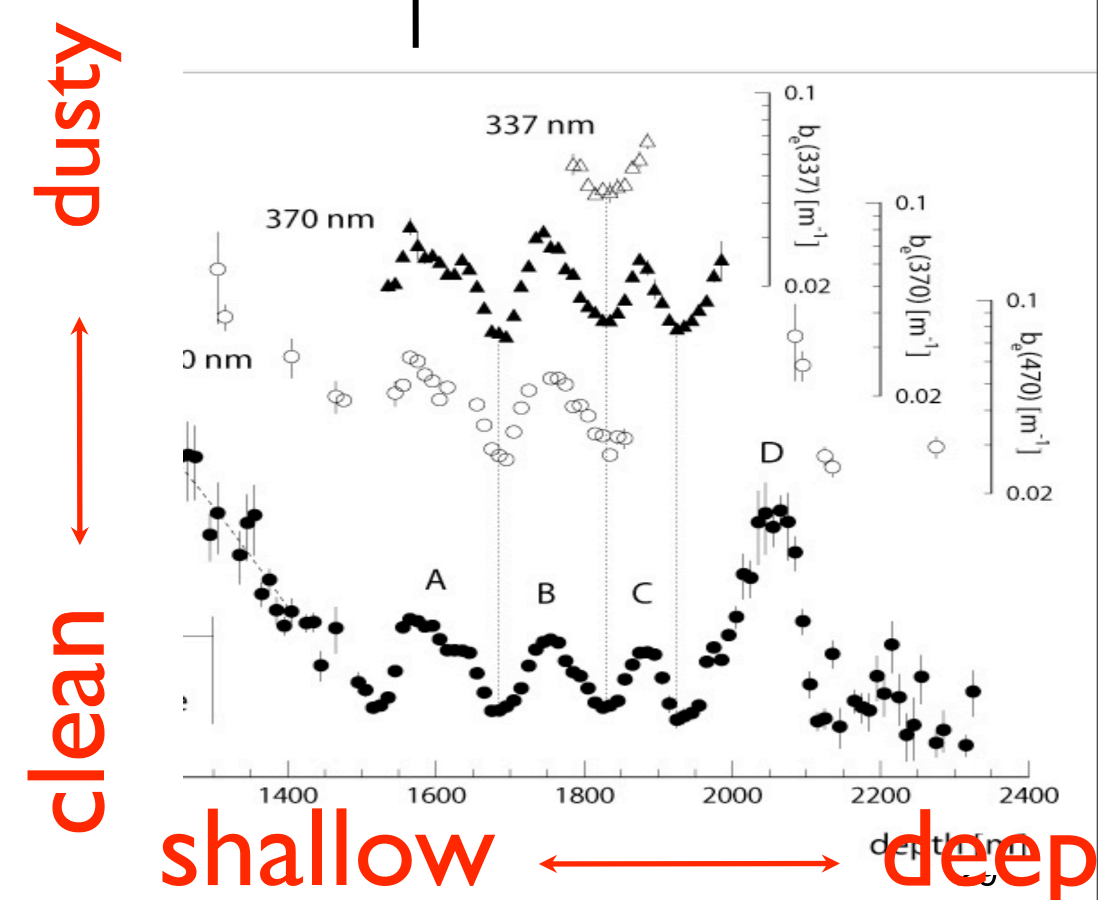


Formulate LLH:

Approximate as:

Incorporate Ice Properties:



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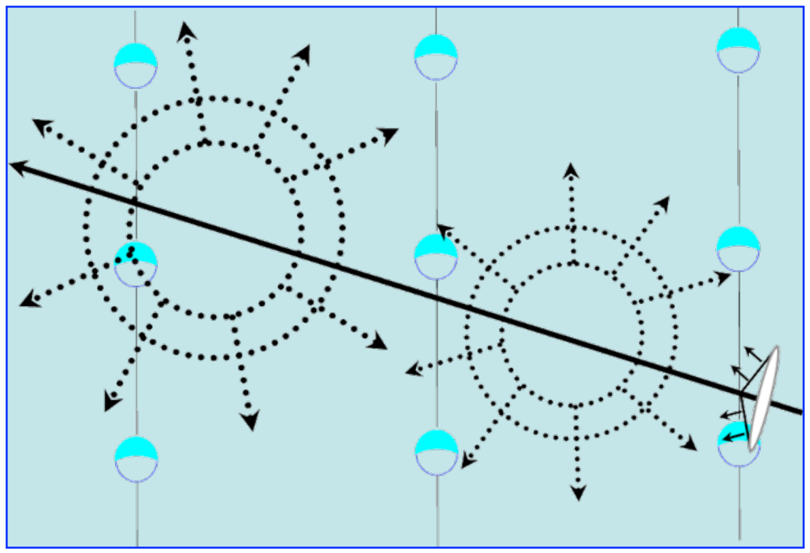
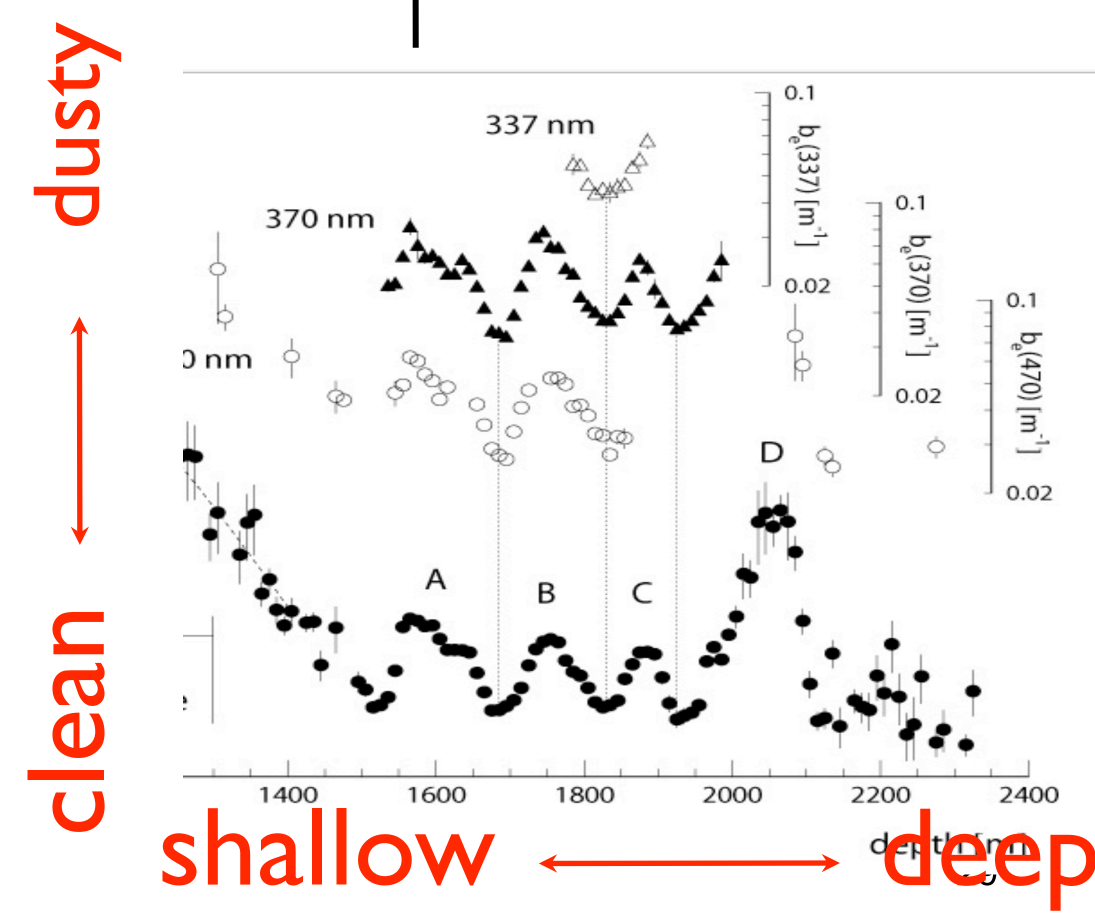


Formulate LLH:

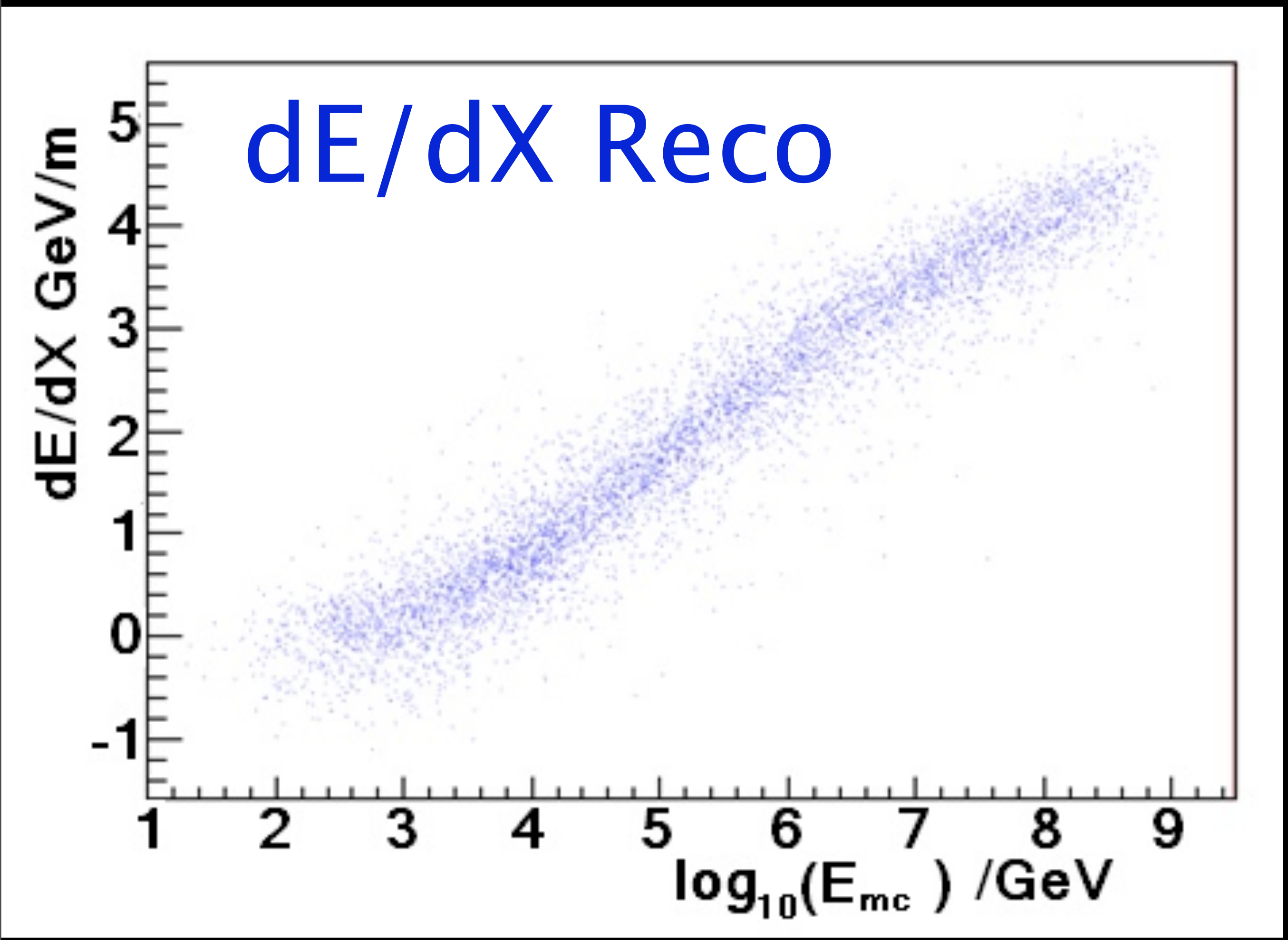
$$-\log P(\{n_i\}\,|\,\{\mu_i\}) = -\sum_{i=1}^{k} n_i \log(\mu_i/\mu) - N\log\mu + \mu$$

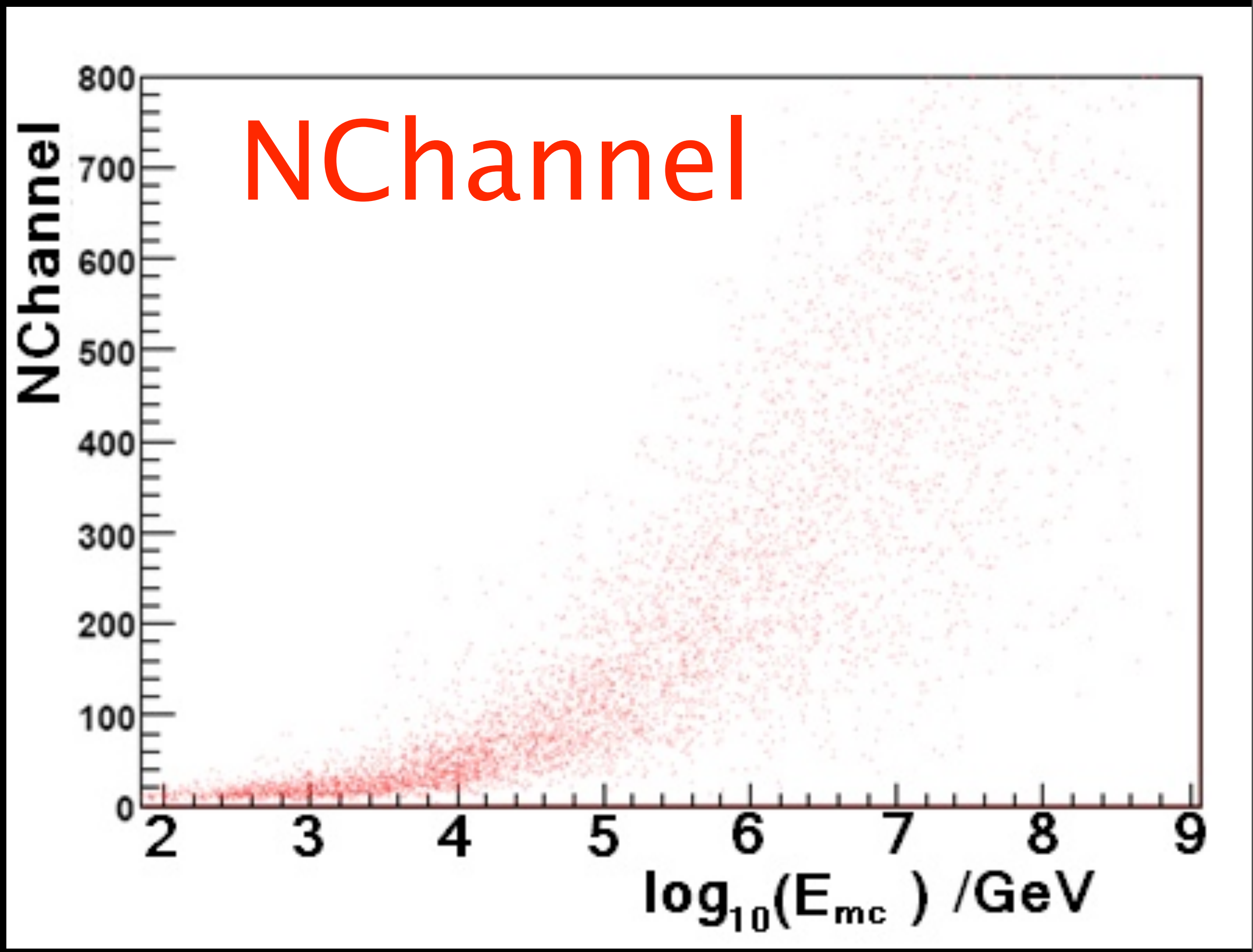
Approximate as:

Incorporate Ice Properties:



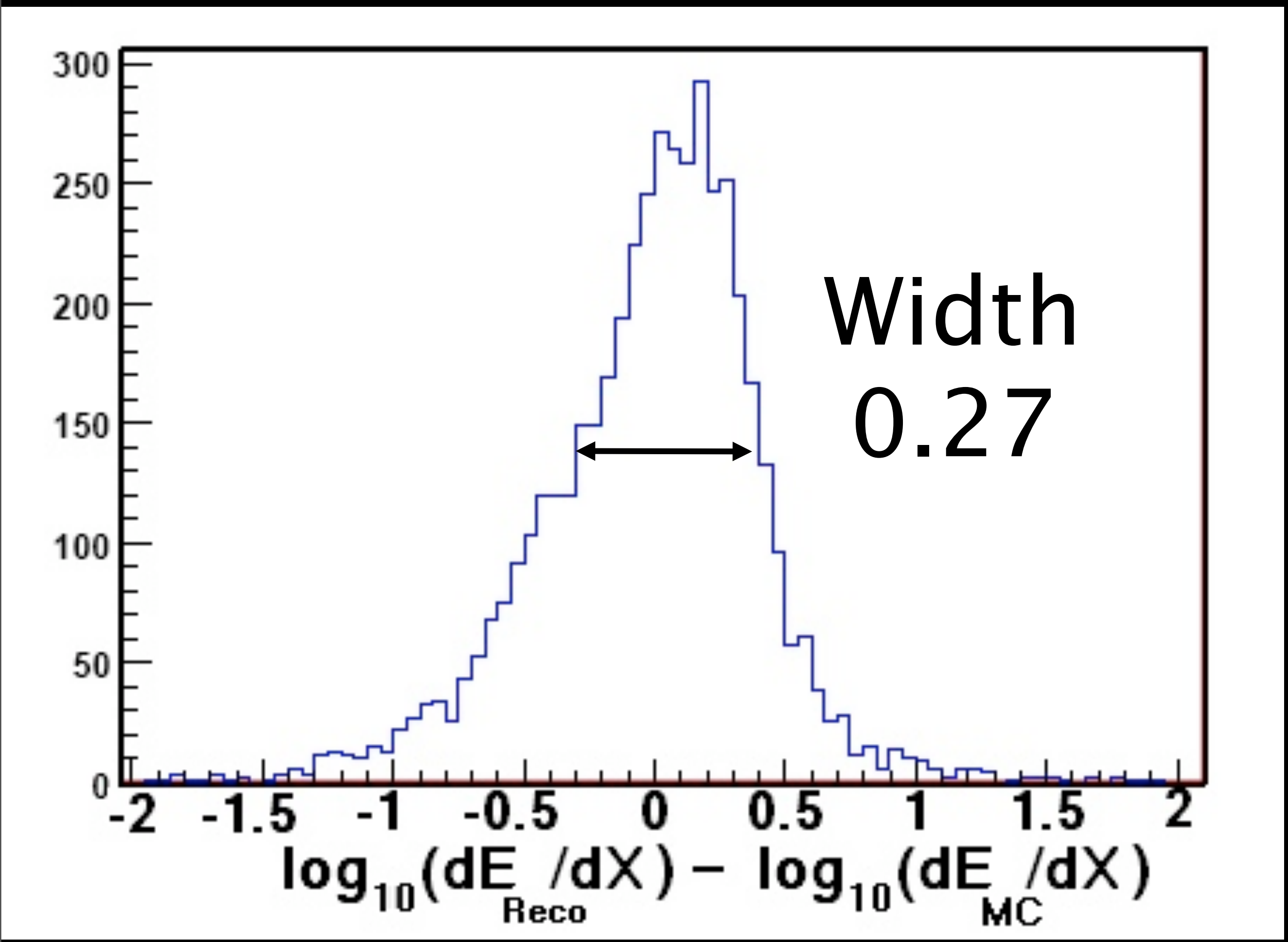
Muon Energy Correlation – 40 Strings

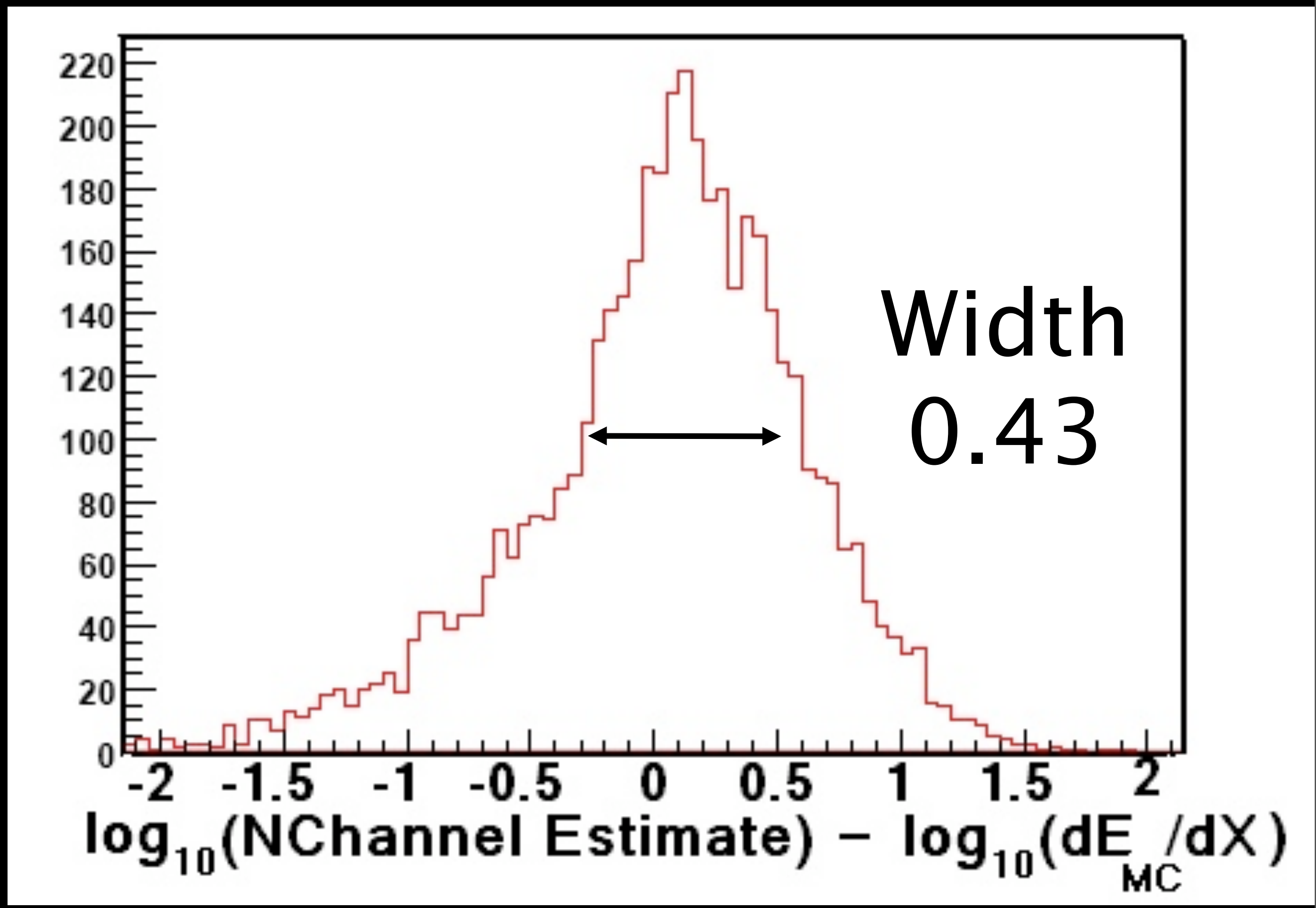




- dE/dX reco more linearly correlated with Muon energy

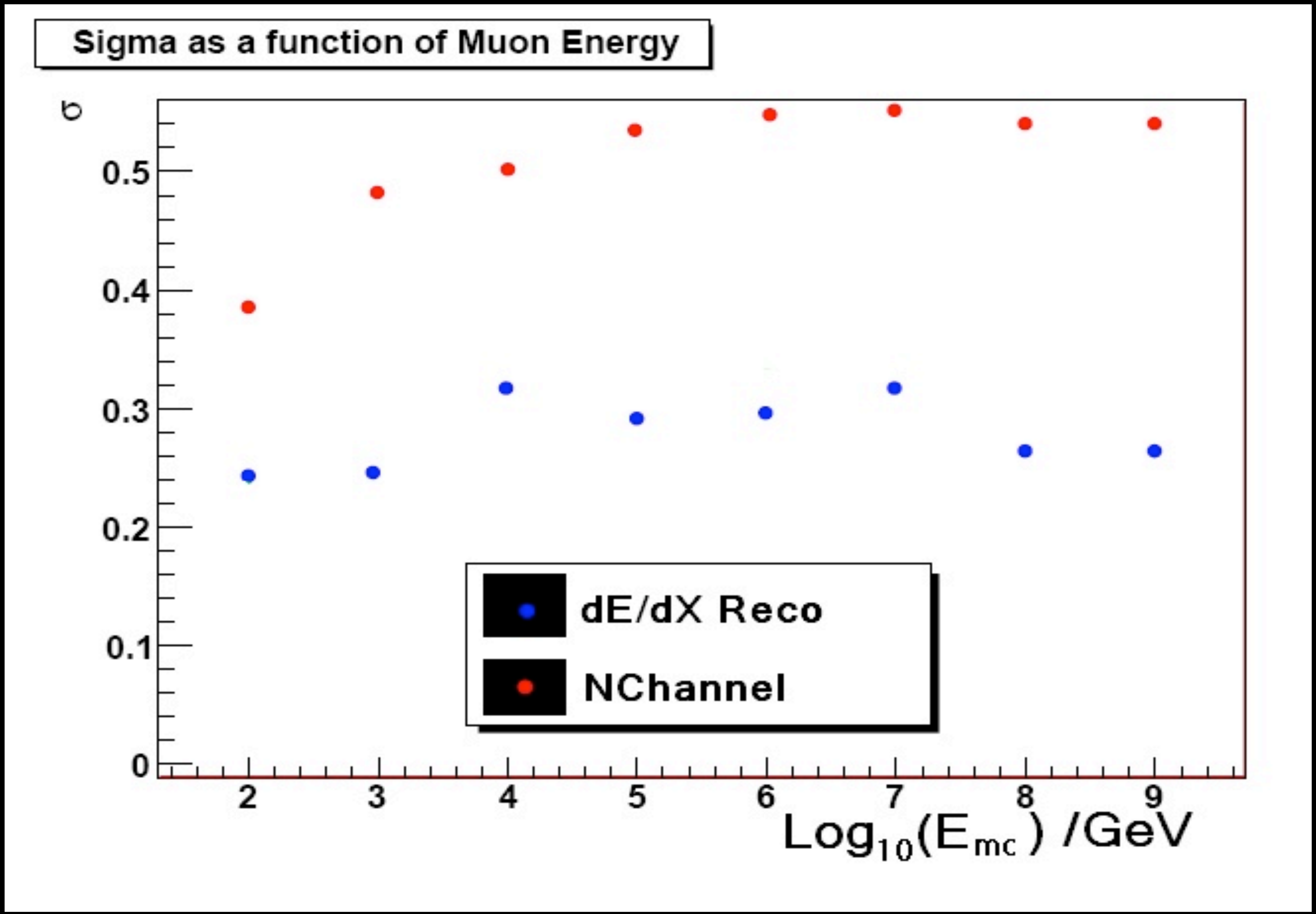
Energy Resolution – 40 Strings





- dE/dX reco has narrower energy resolution

Energy Resolution Vs. Muon Energy – 40 Strings



Likelihood Methodology

- Likelihood - Product over binned Poisson Probabilities:

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

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

Atmo ν **Prompt ν** **Astro ν**

- Observable: **Muon Energy Loss dE/dX**
- **Physics Parameters:**
  - Astrophysical Normalization **(N_a)**
- **Nuisance Parameters:**
  - Conventional Normalization **(N_c)**
  - Prompt Normalization **(N_p)**
  - Detector Efficiency **(ε)**
  - Conventional Spectral Slope **($\Delta\gamma_c$)**
  - Prompt Spectral Slope **($\Delta\gamma_a$)**

Fit Example: IC40 Discovery Potential

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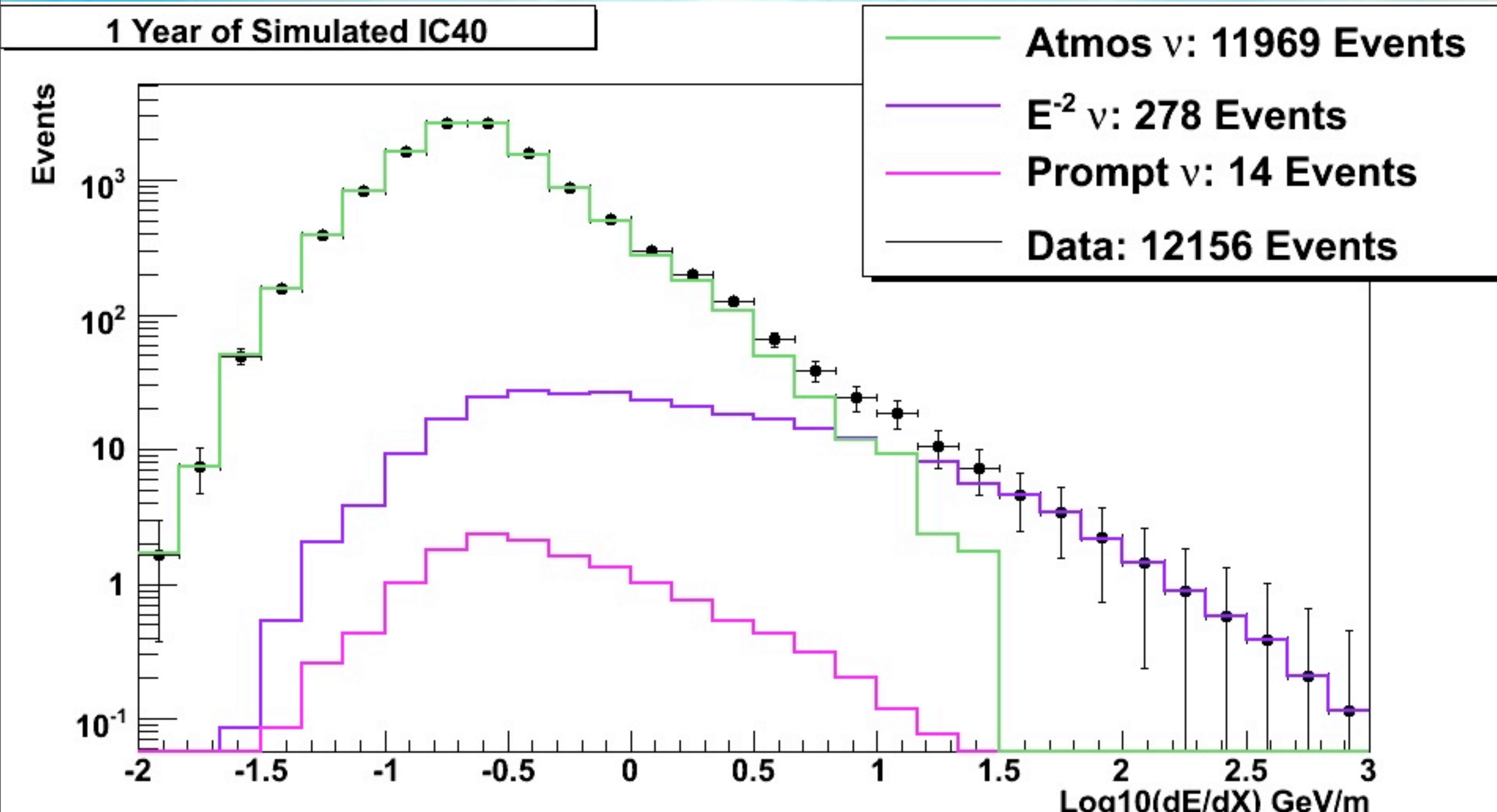
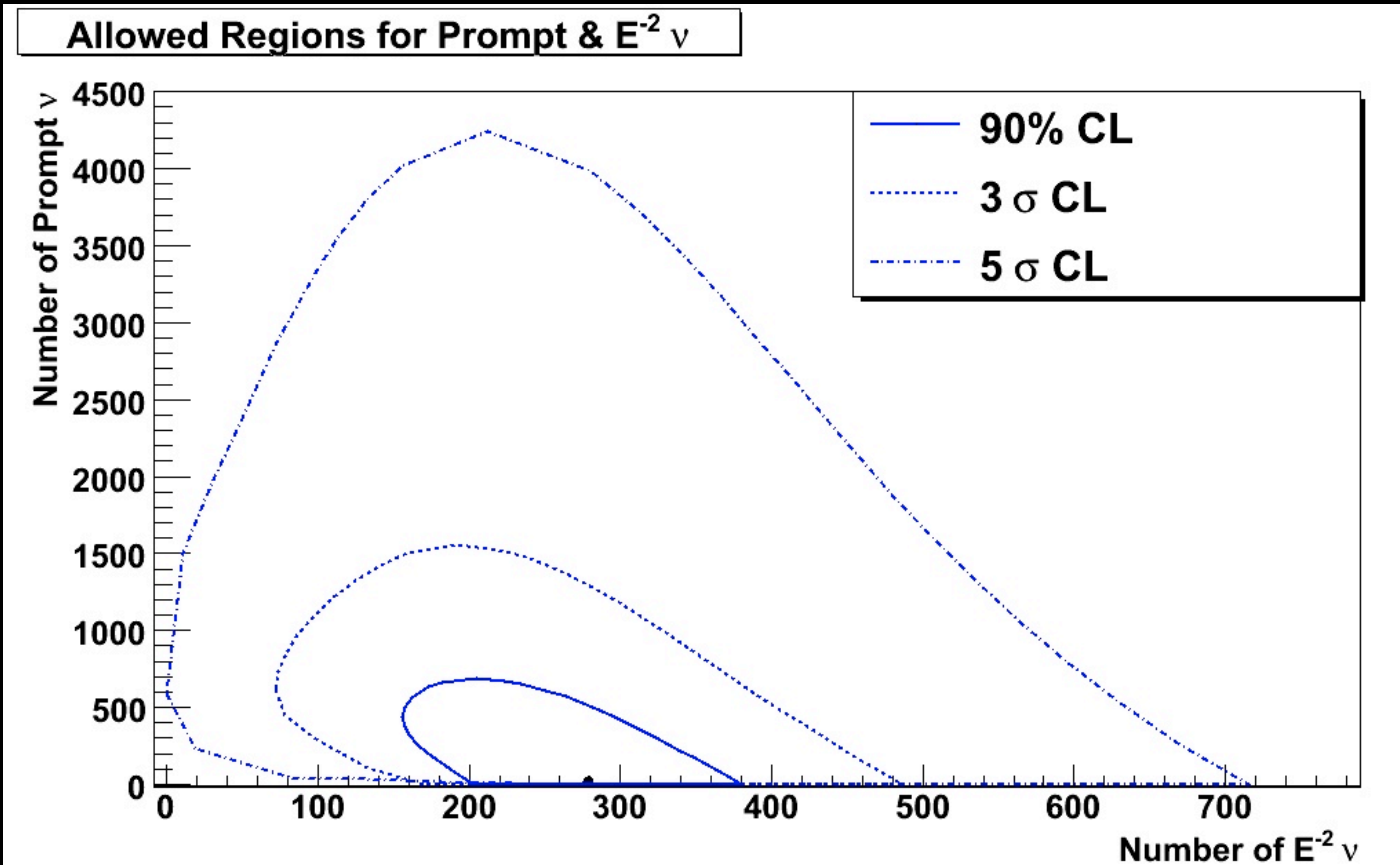


Tuesday, January 19, 2010

Allowed Regions - 300 Days IC40



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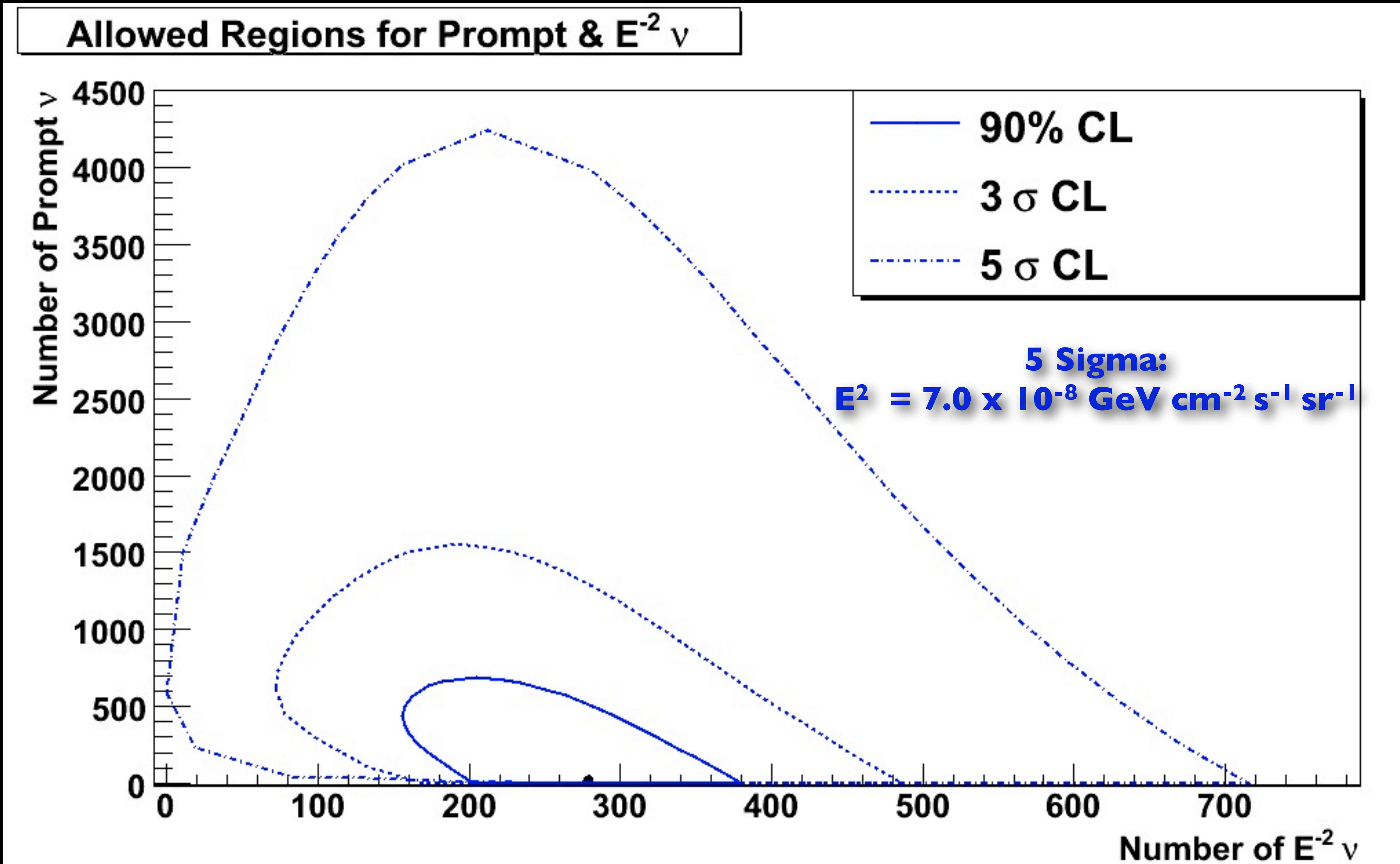

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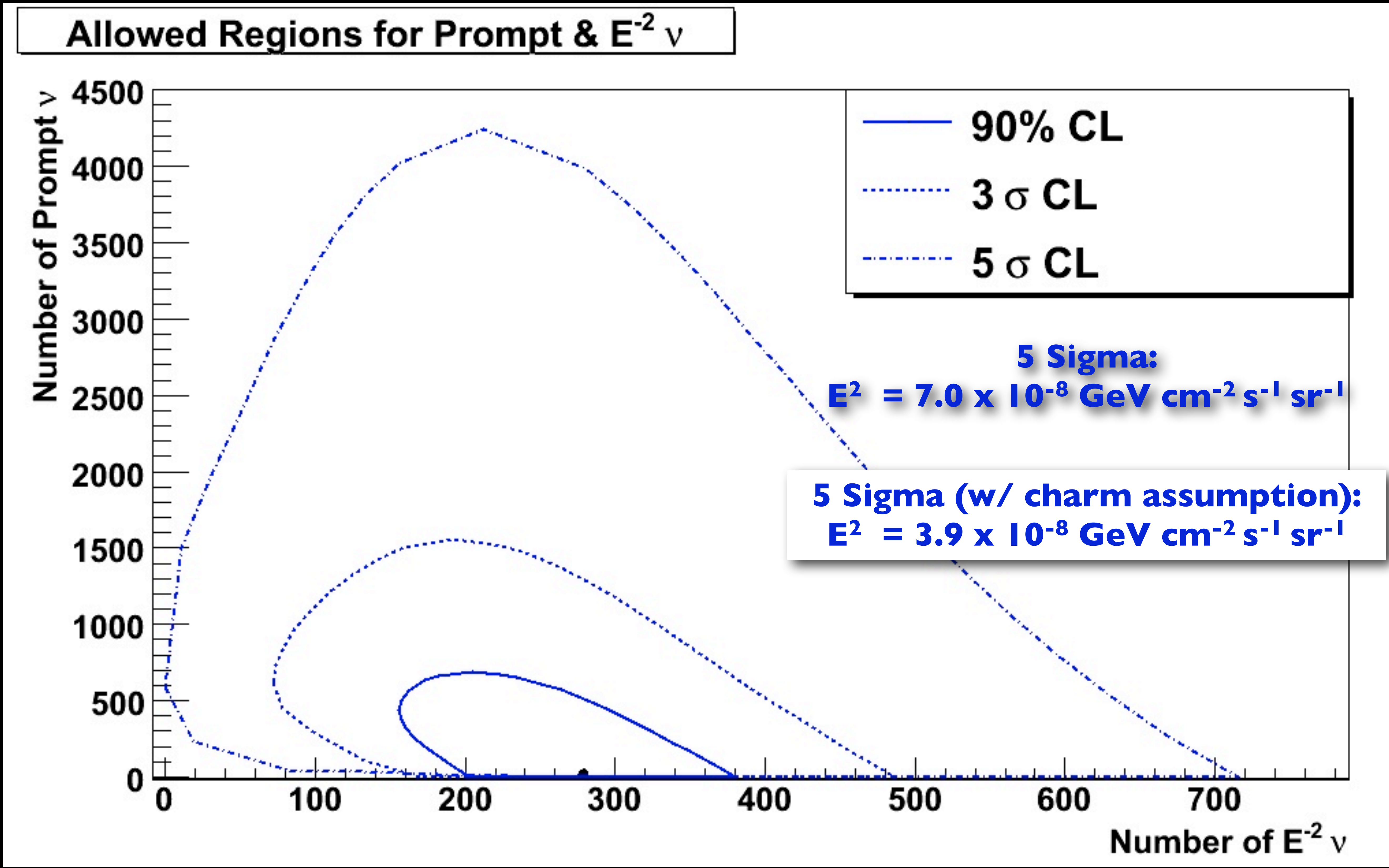
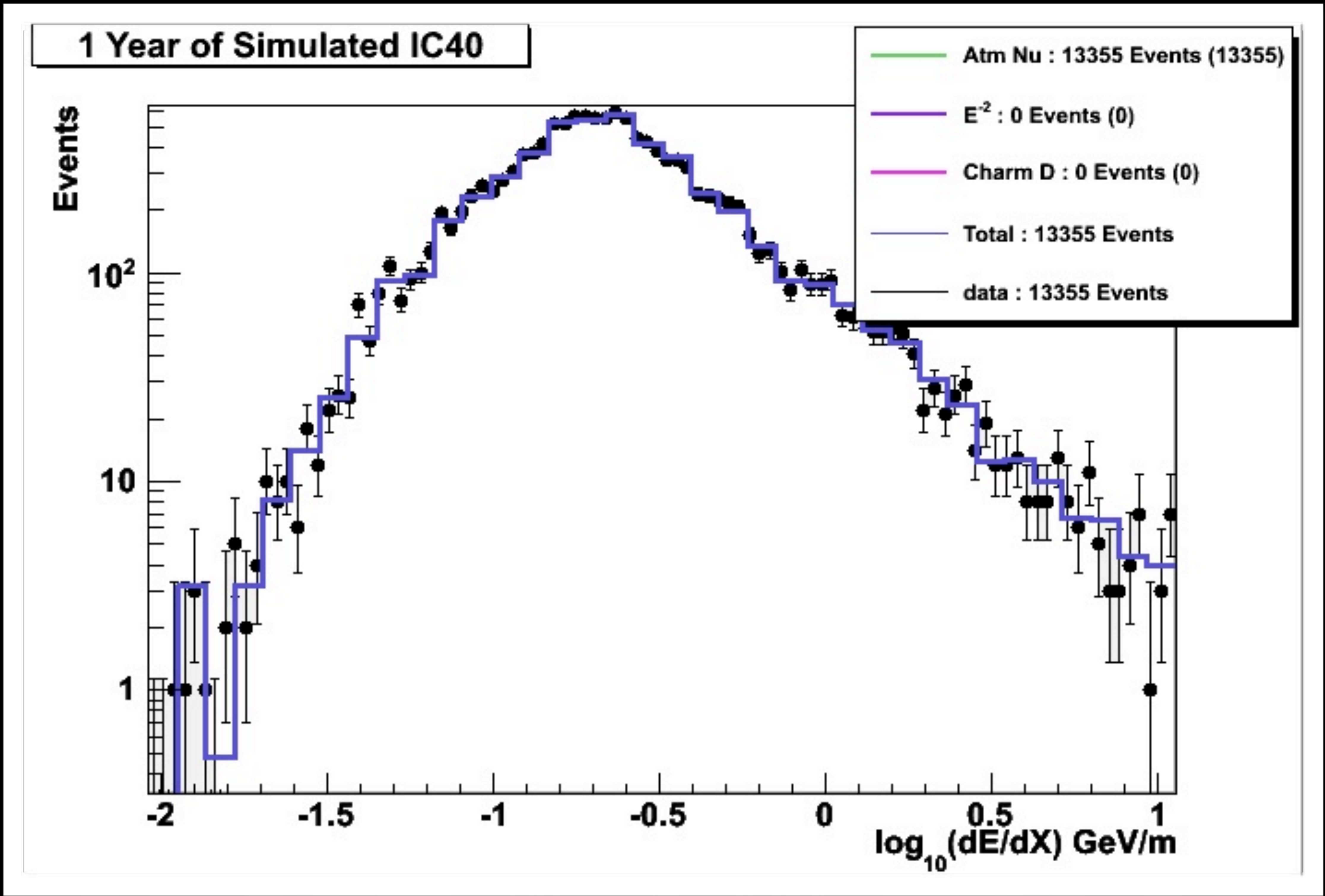
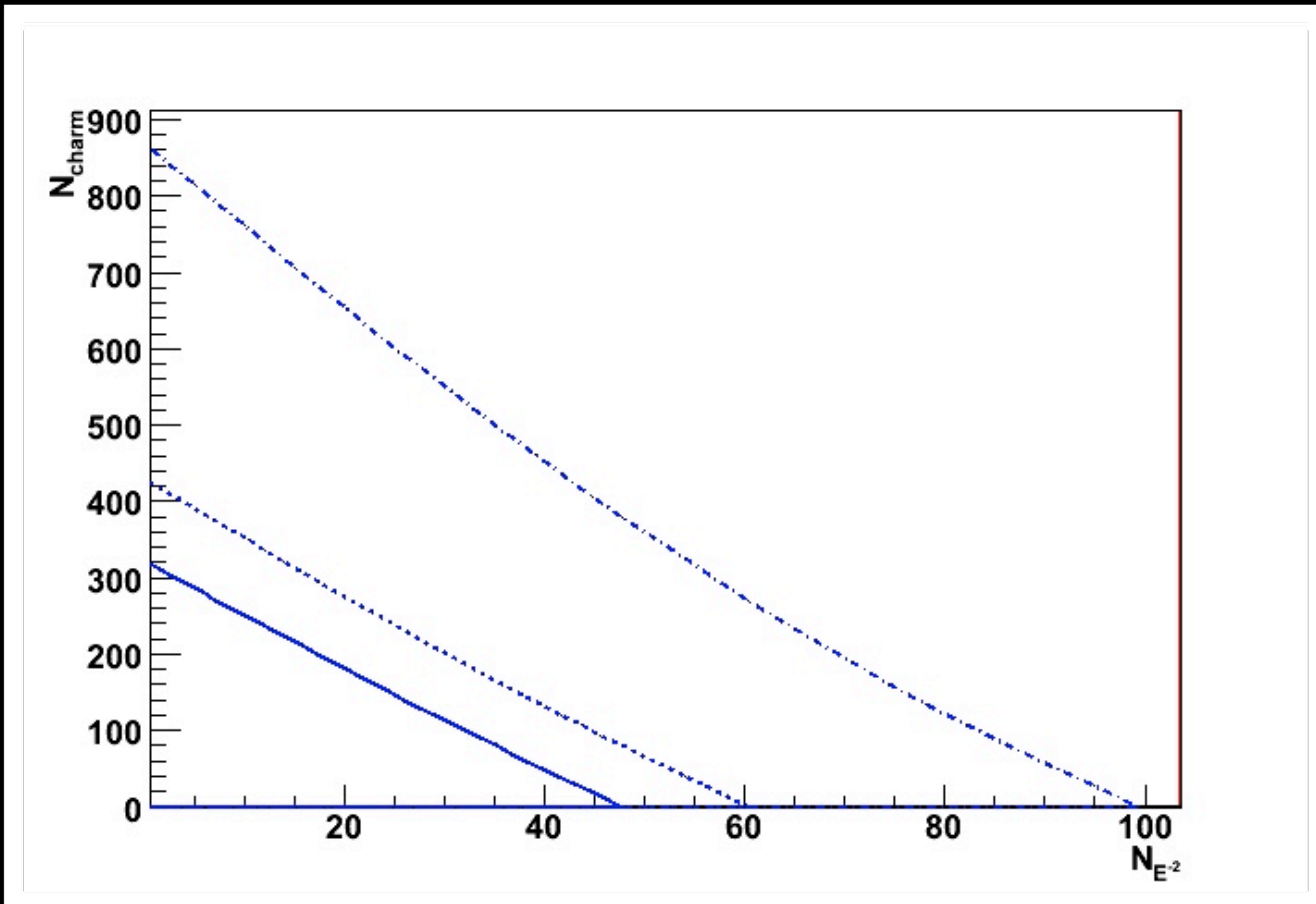


LLH Fit Example: 300 days IC40, No Signal



Allowed Regions - 300 Days Atmospheric ν only



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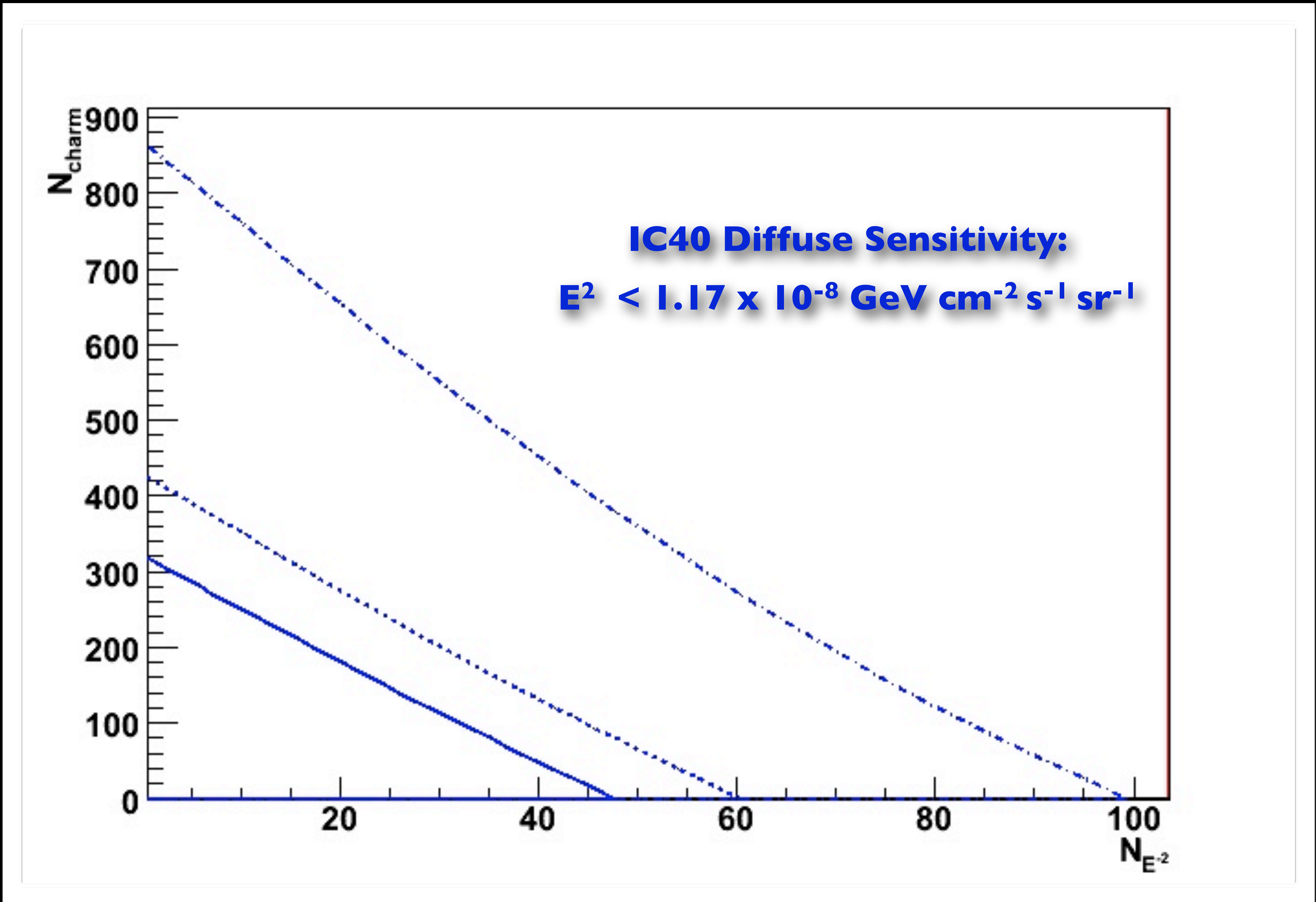
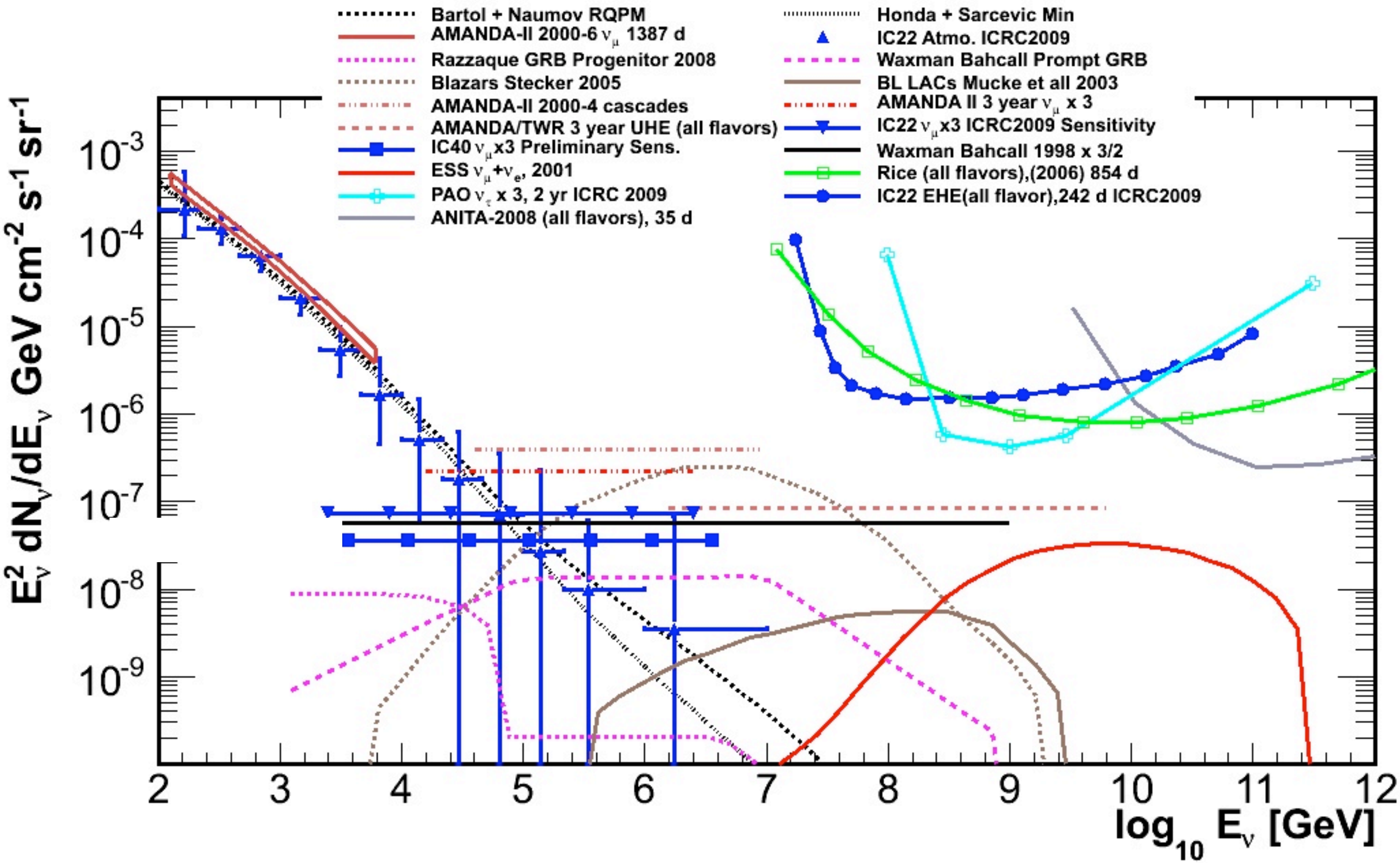


Flux Models, Sensitivities & Limits



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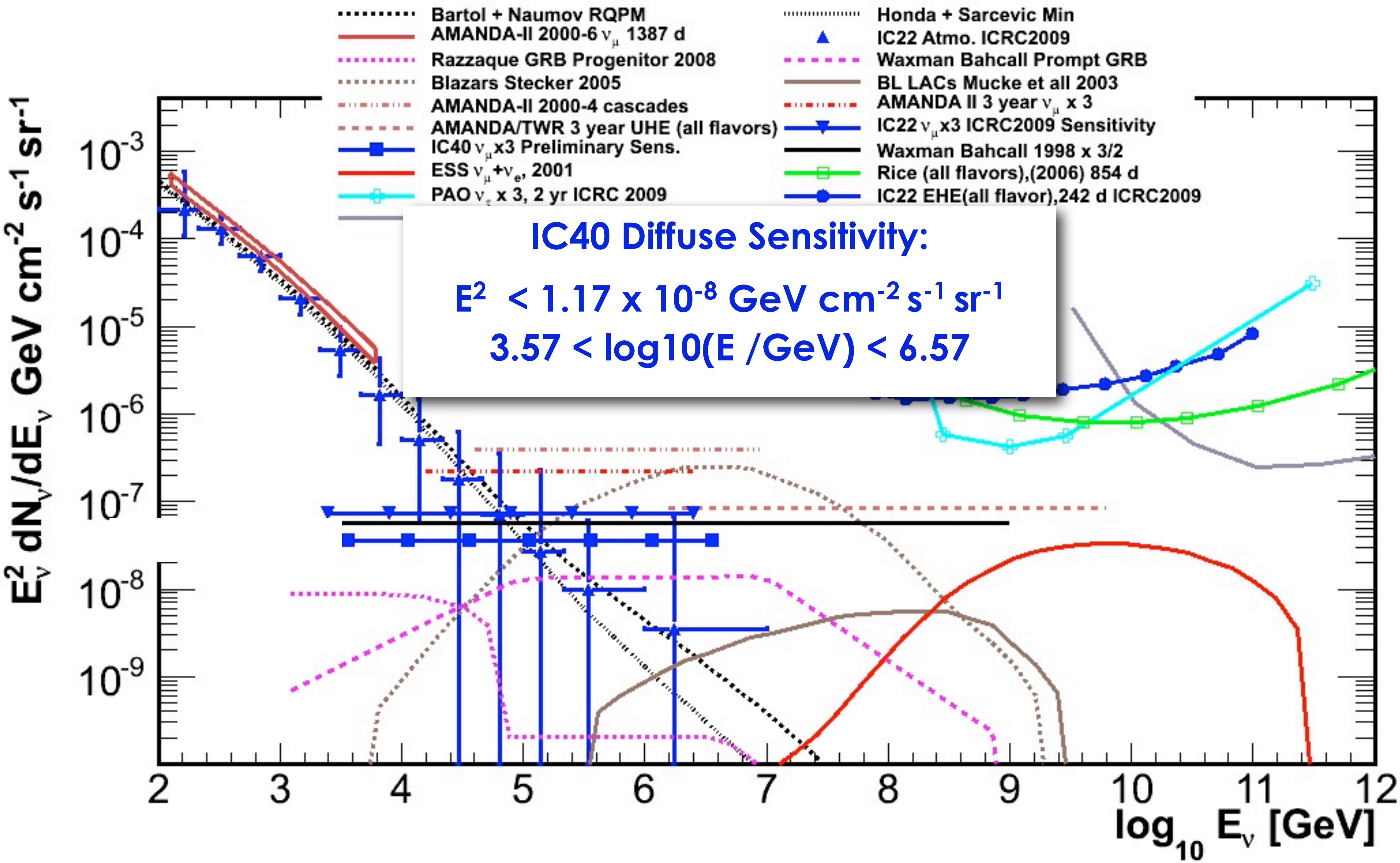

Tuesday, January 19, 2010

Systematic Uncertainties

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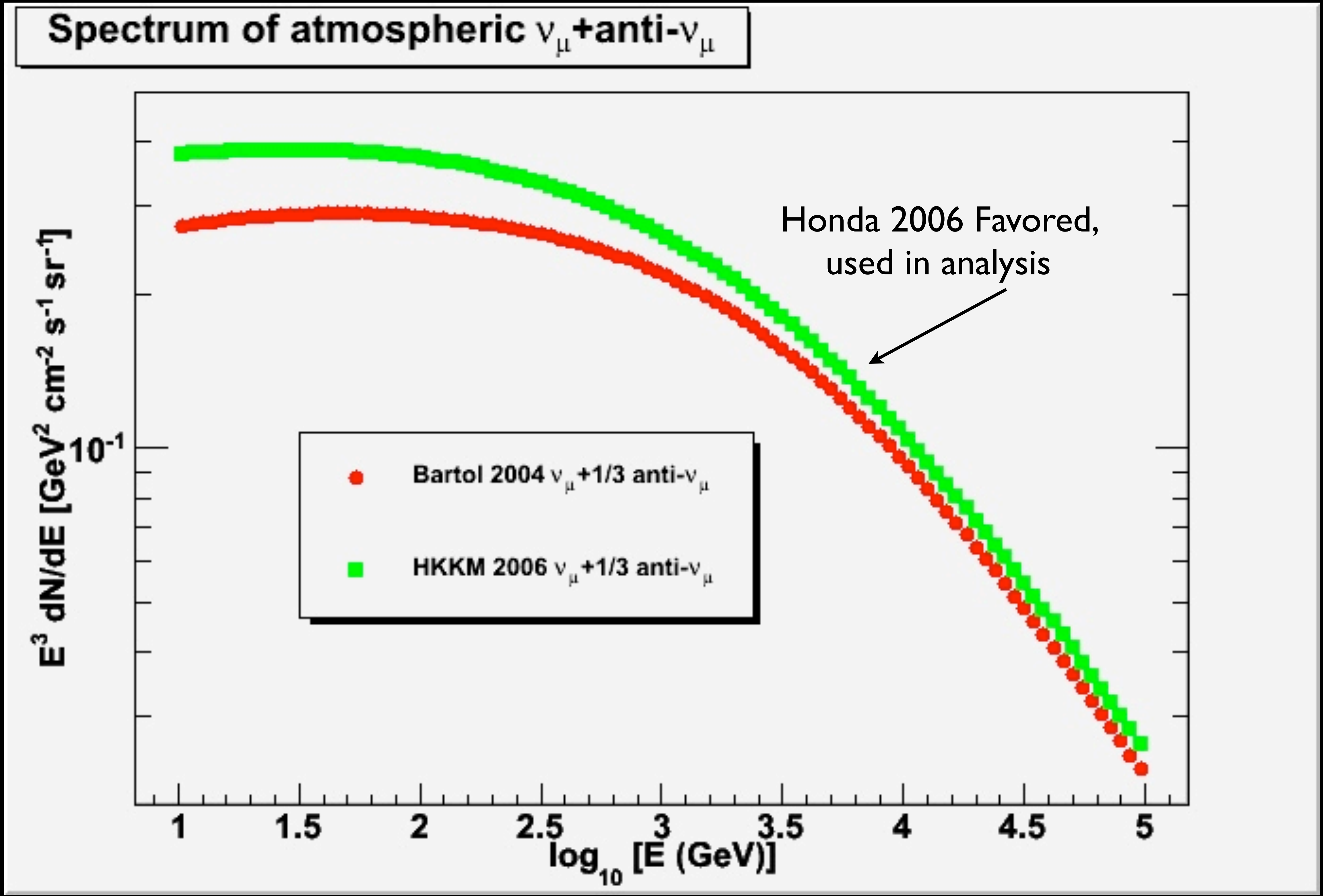
- Systematic Uncertainties of the Ice Properties

Atmospheric ν systematic uncertainty



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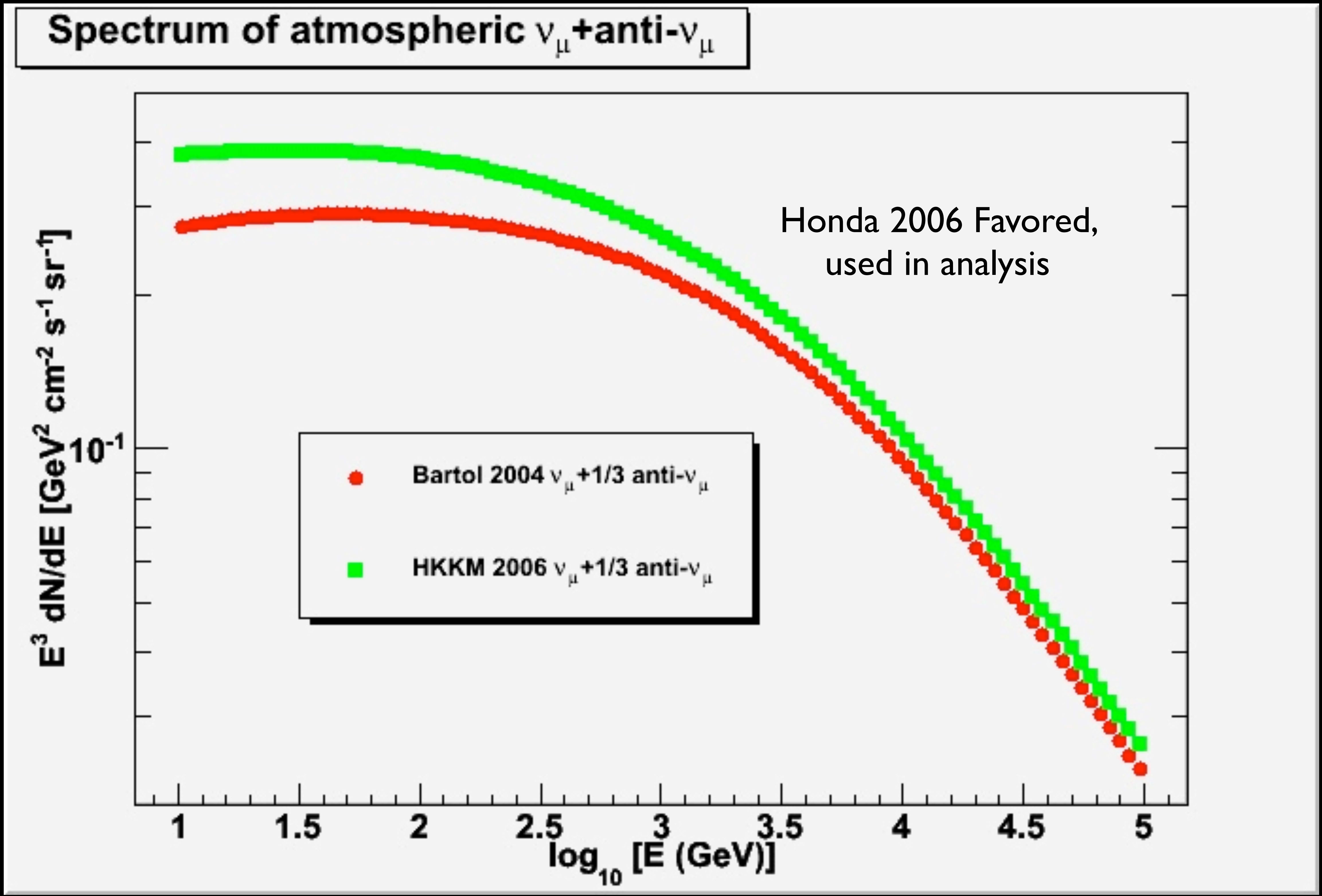

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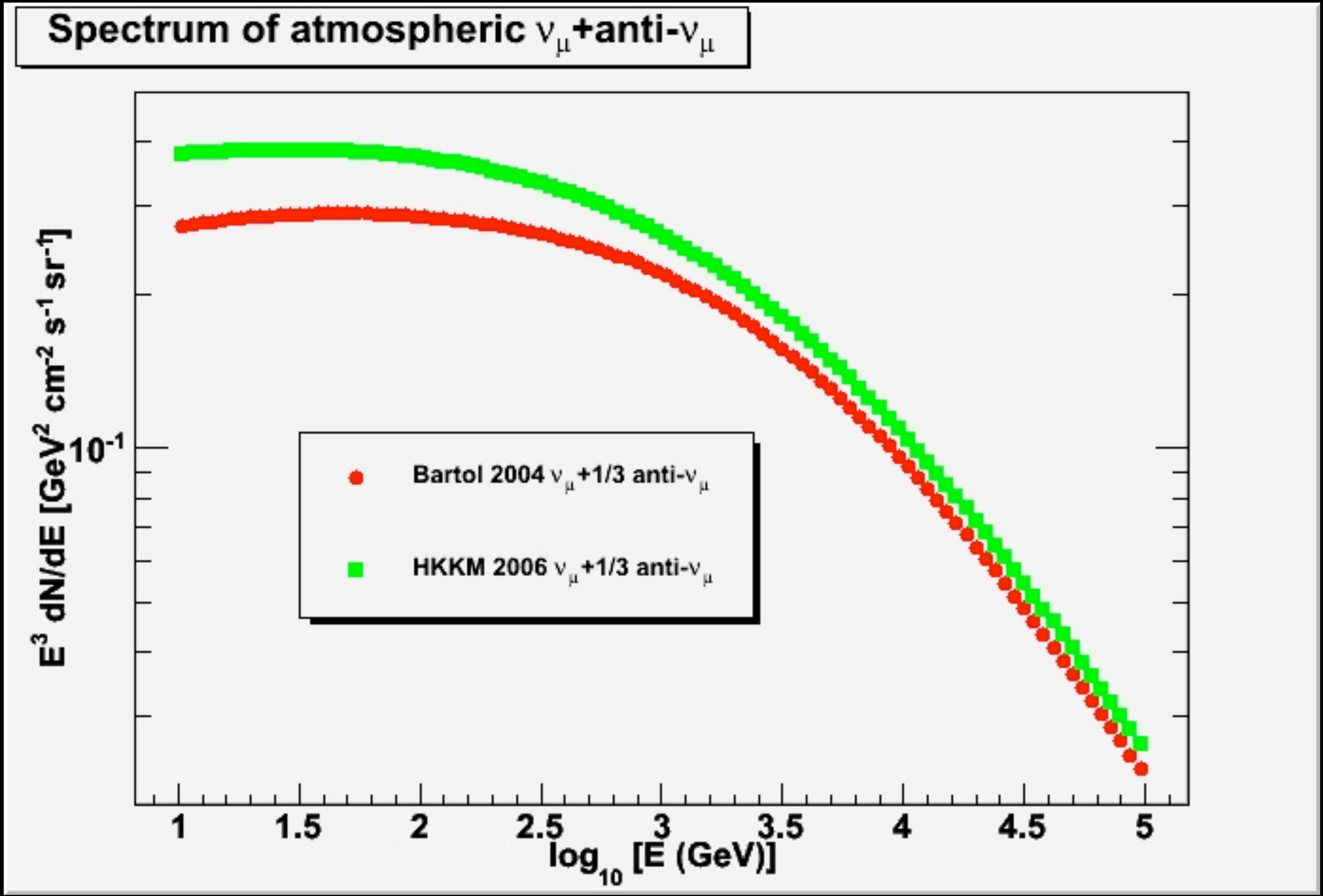

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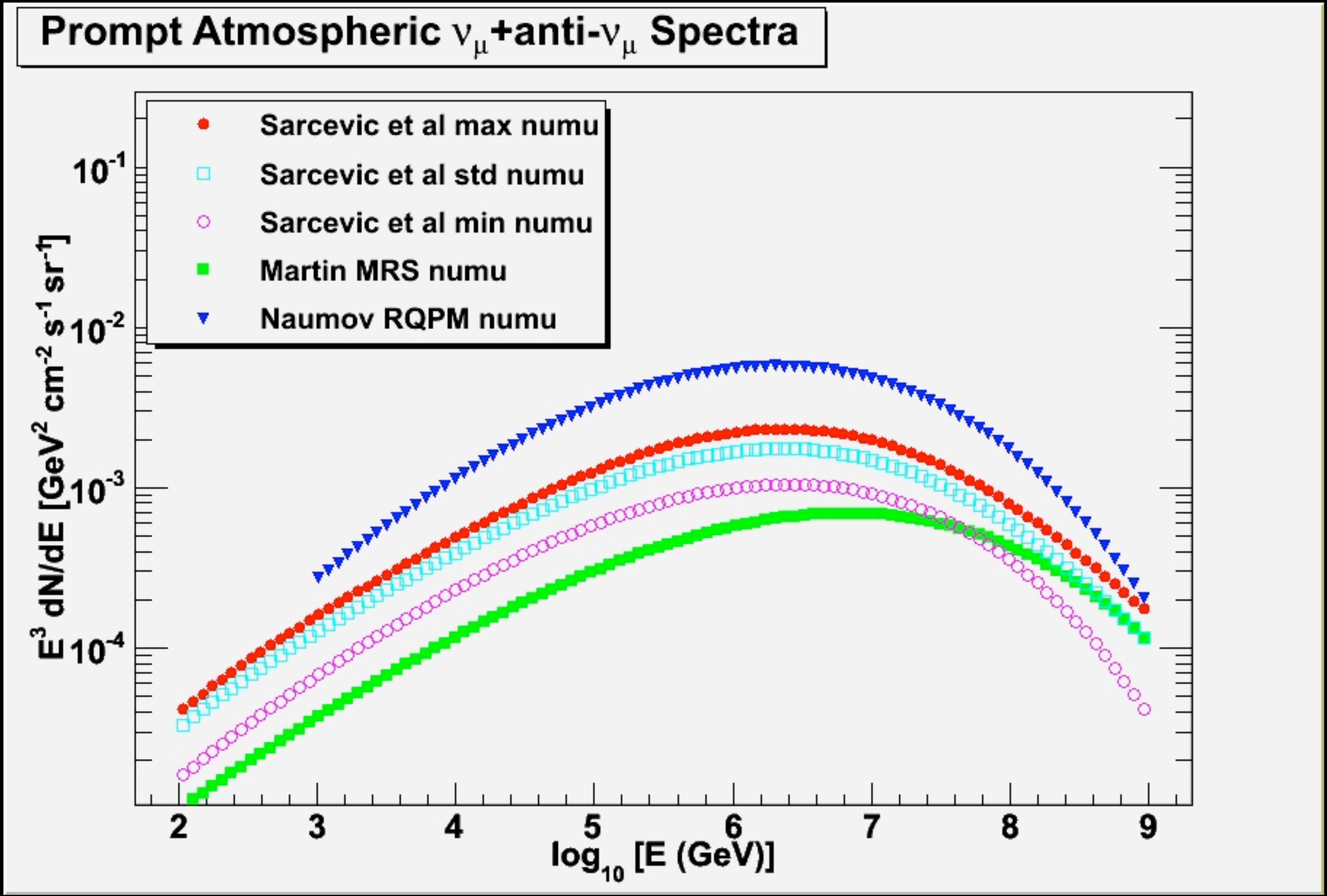

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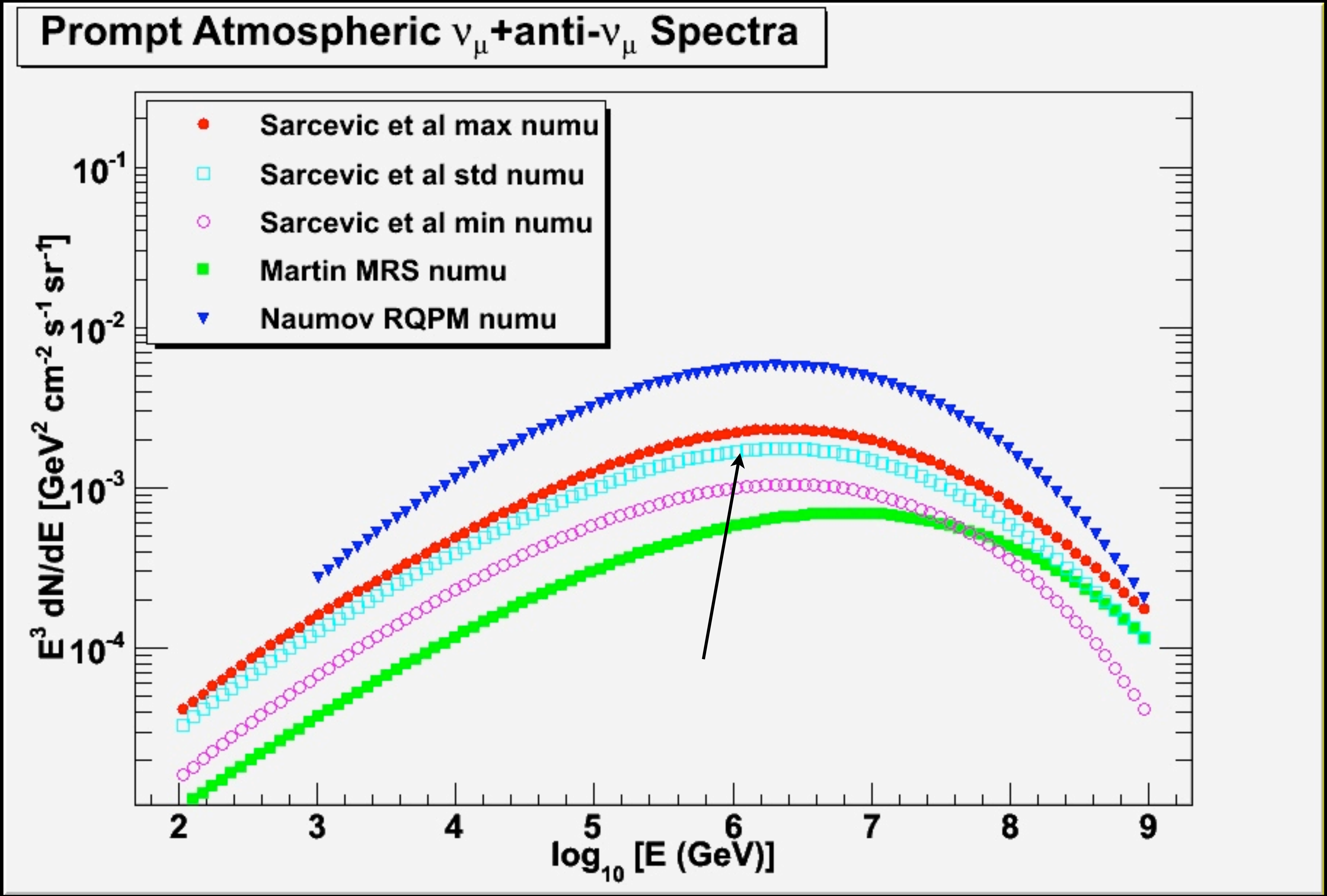

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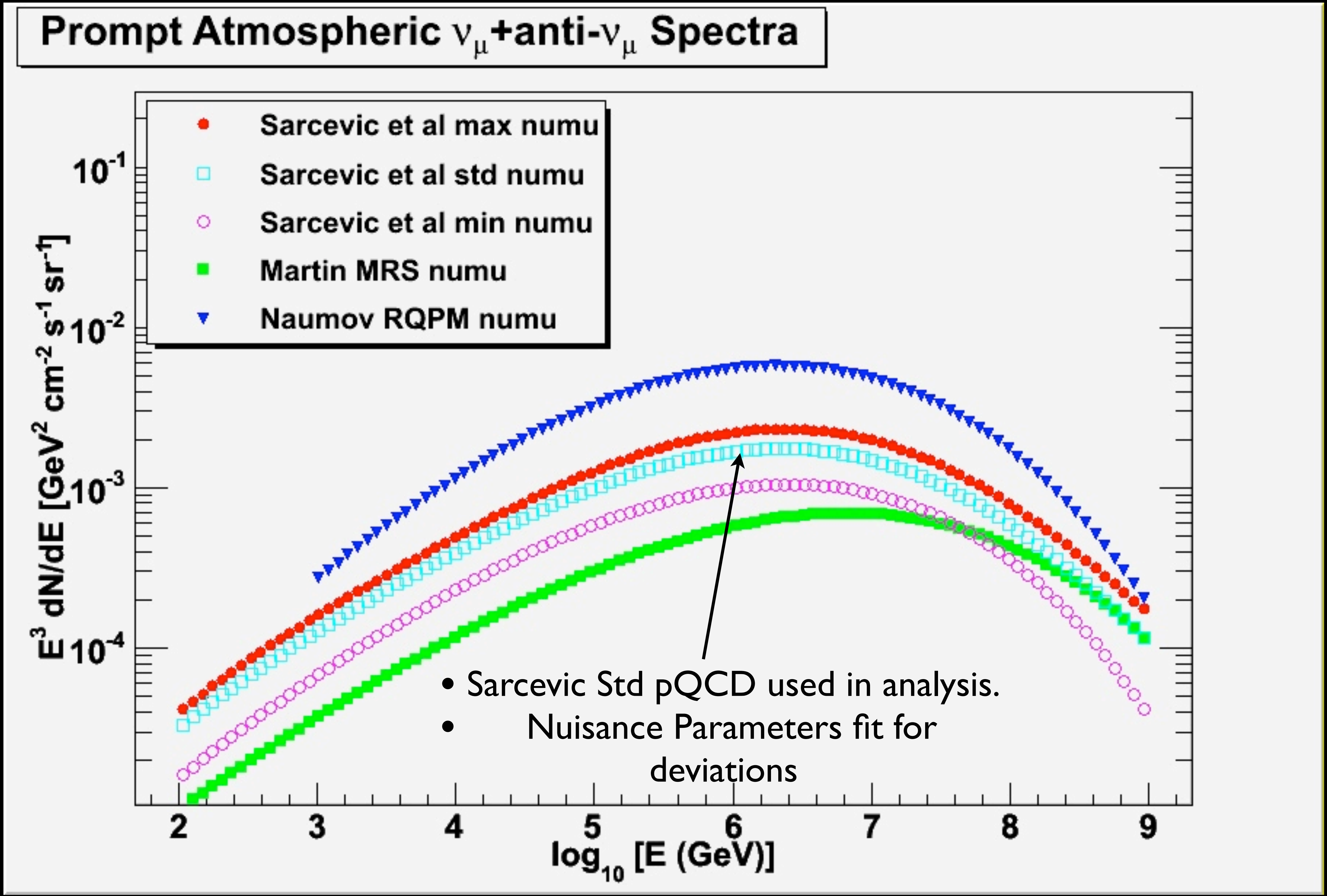

- Sarcevic Std pQCD used in analysis.
- Nuisance Parameters fit for deviations

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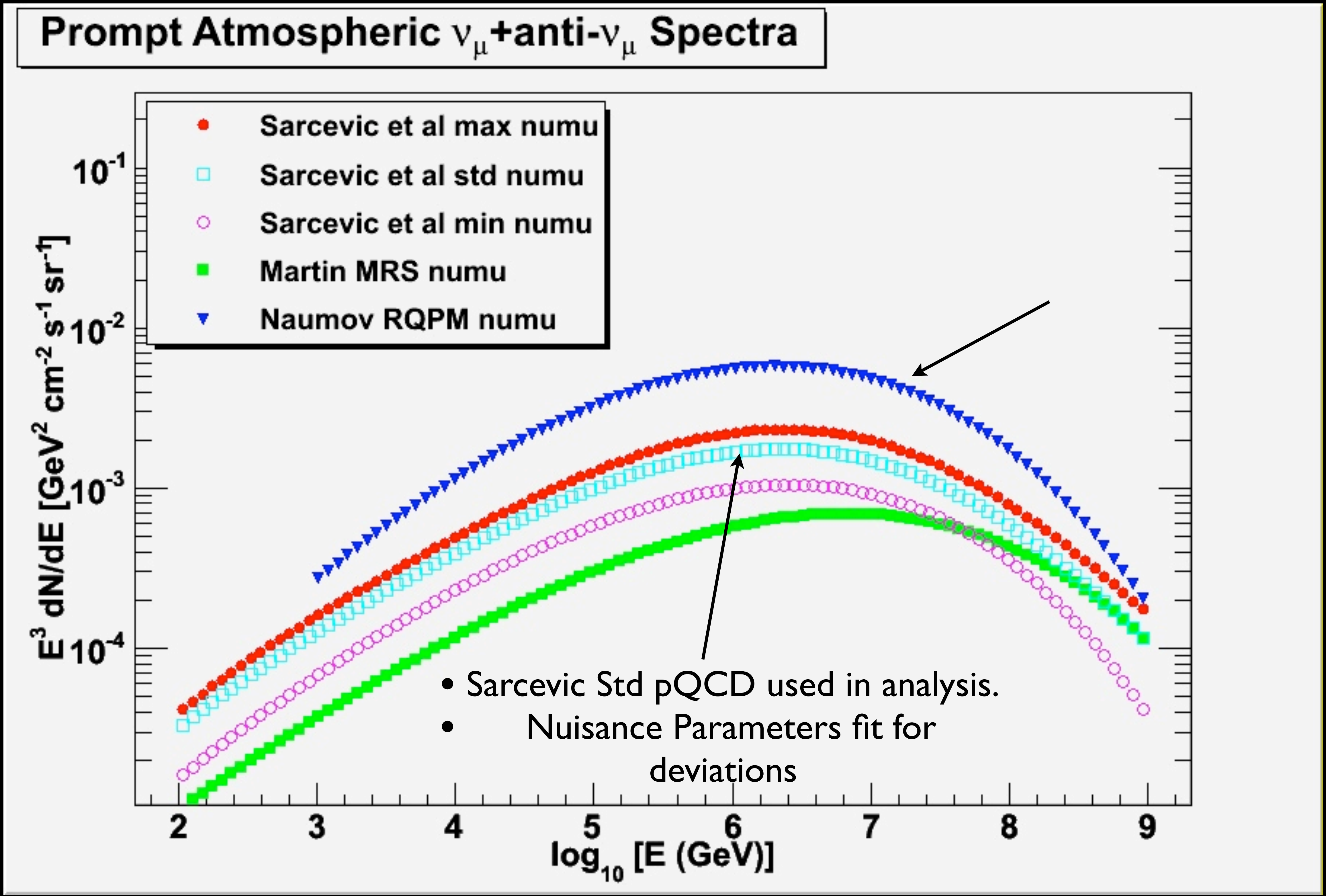

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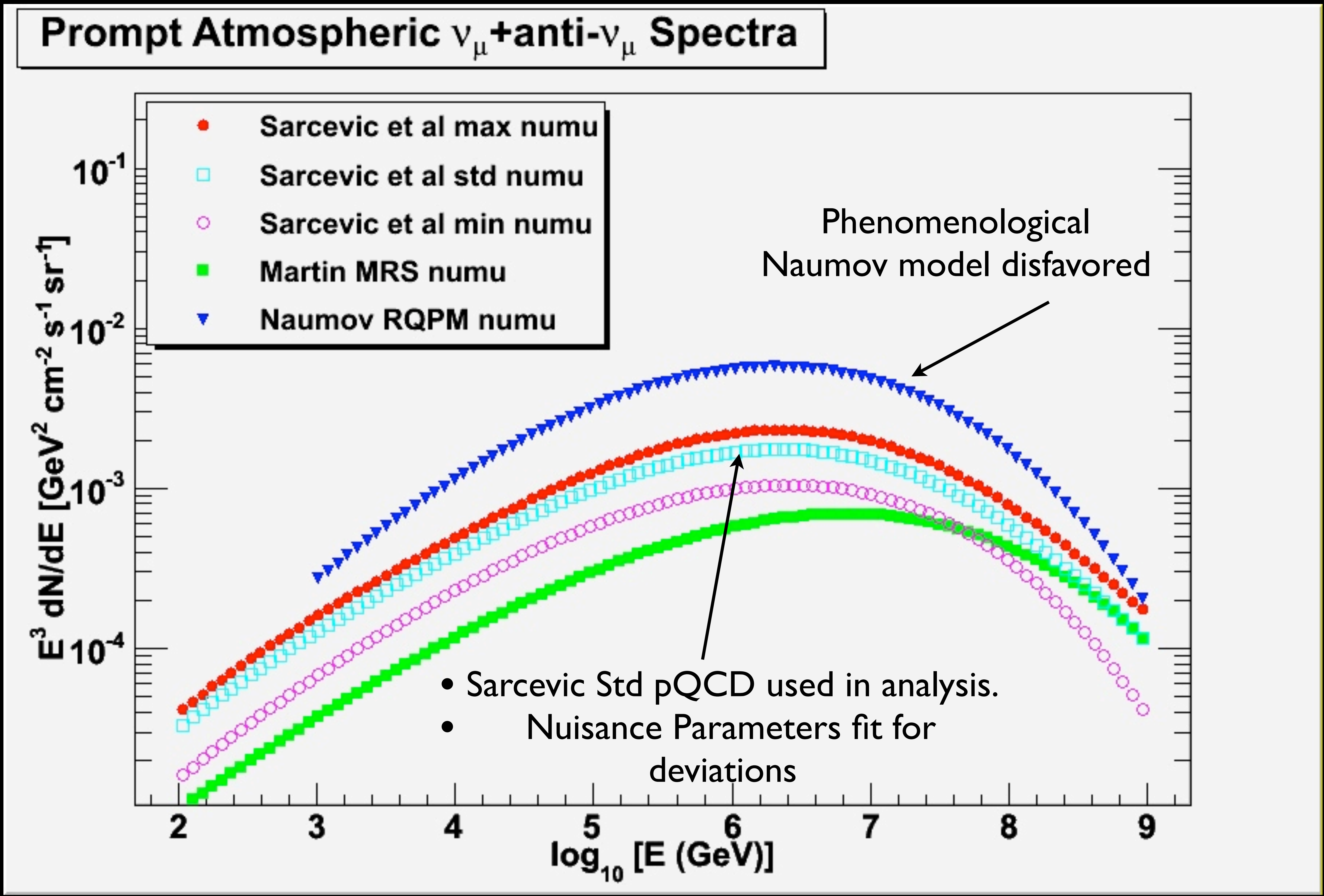

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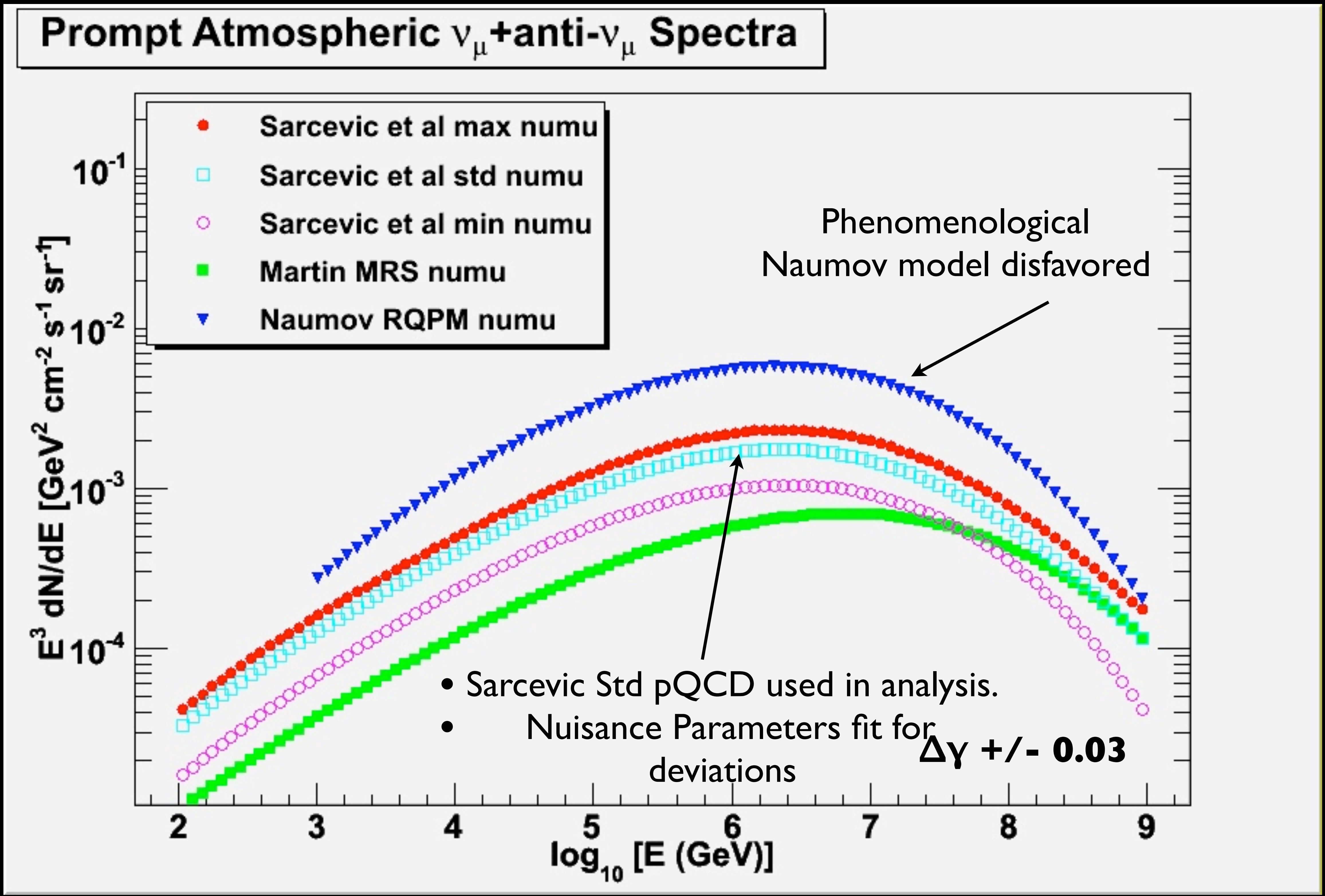


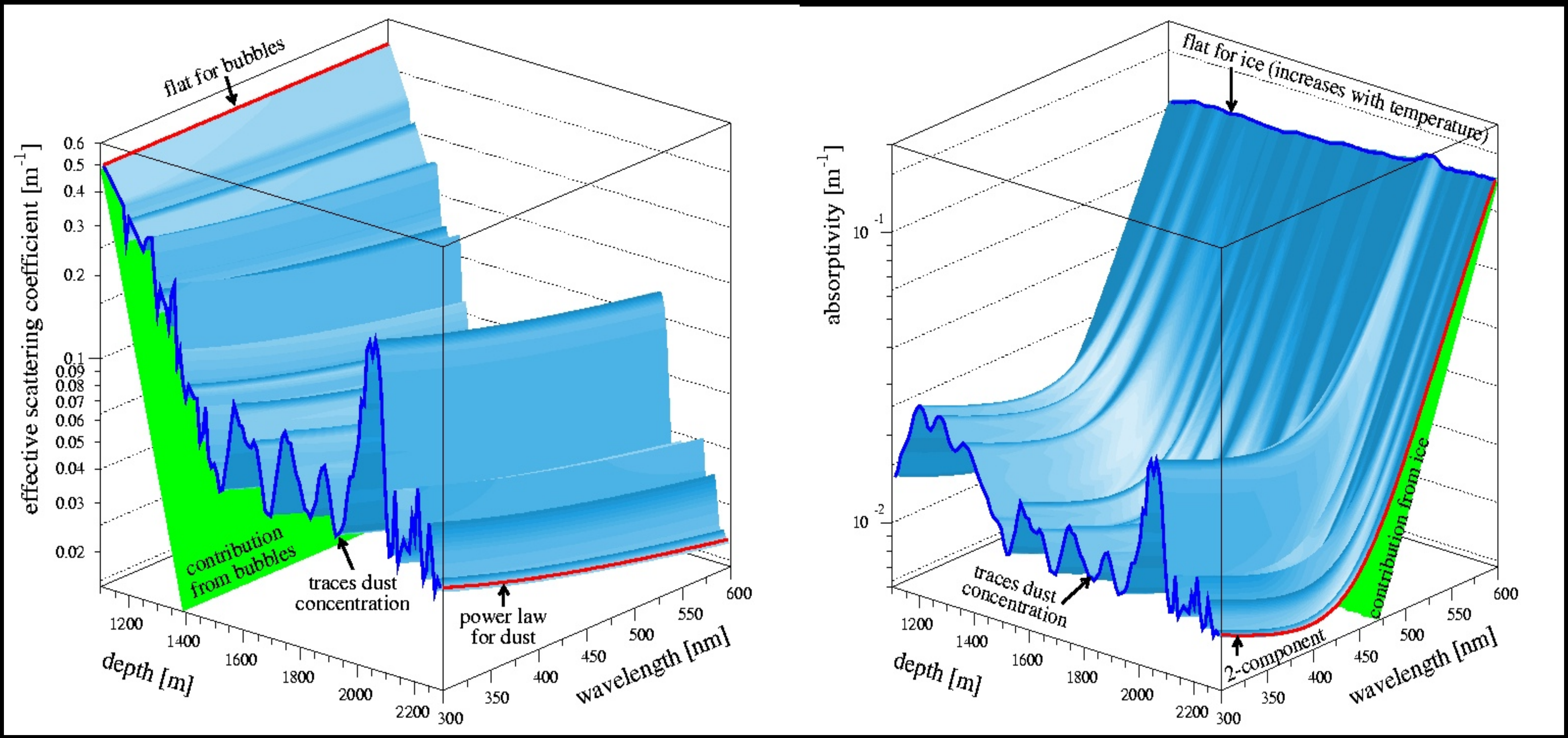
- Sarcevic Std pQCD used in analysis.
- Nuisance Parameters fit for deviations

Δγ +/- 0.03

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%)

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)

Outlook & Conclusion

- IC40 Sensitivity is
  $E^2 < 1.17 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}
- Finish Systematic Ice Property Study
- Unblind full year of IC40 data
- Incorporate multi-channel information in future analyses.