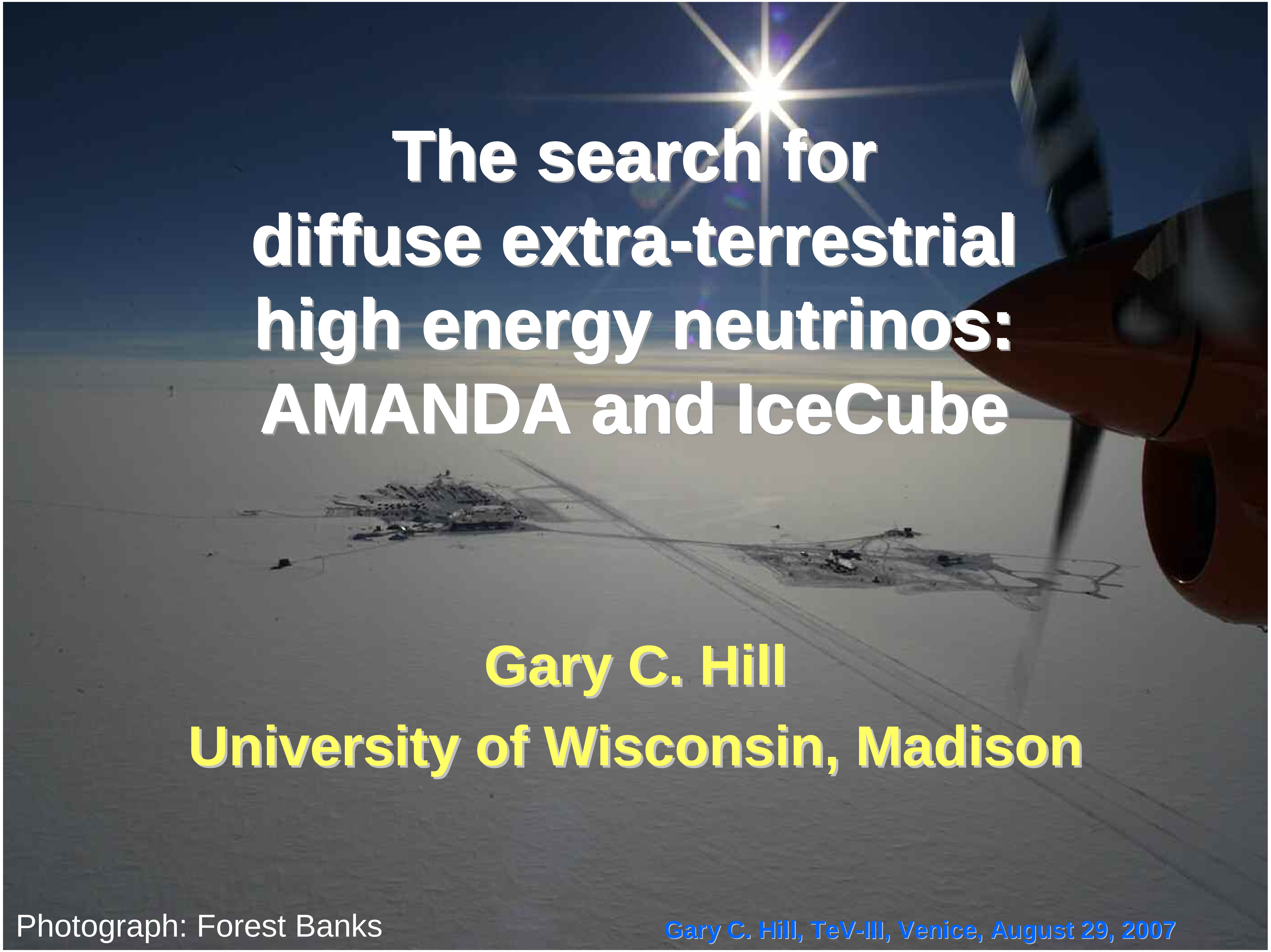


The search for diffuse extra-terrestrial high energy neutrinos: AMANDA and IceCube

Gary C. Hill

University of Wisconsin, Madison

Photograph: Forest Banks

Neutrino and gamma production in cosmic ray accelerators?

$$pp,\ p\gamma \rightarrow \pi^0 \rightarrow \gamma\,\gamma$$

The TeV gammas?

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

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

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

$$e^- + \bar{\nu}_e + \nu_\mu$$

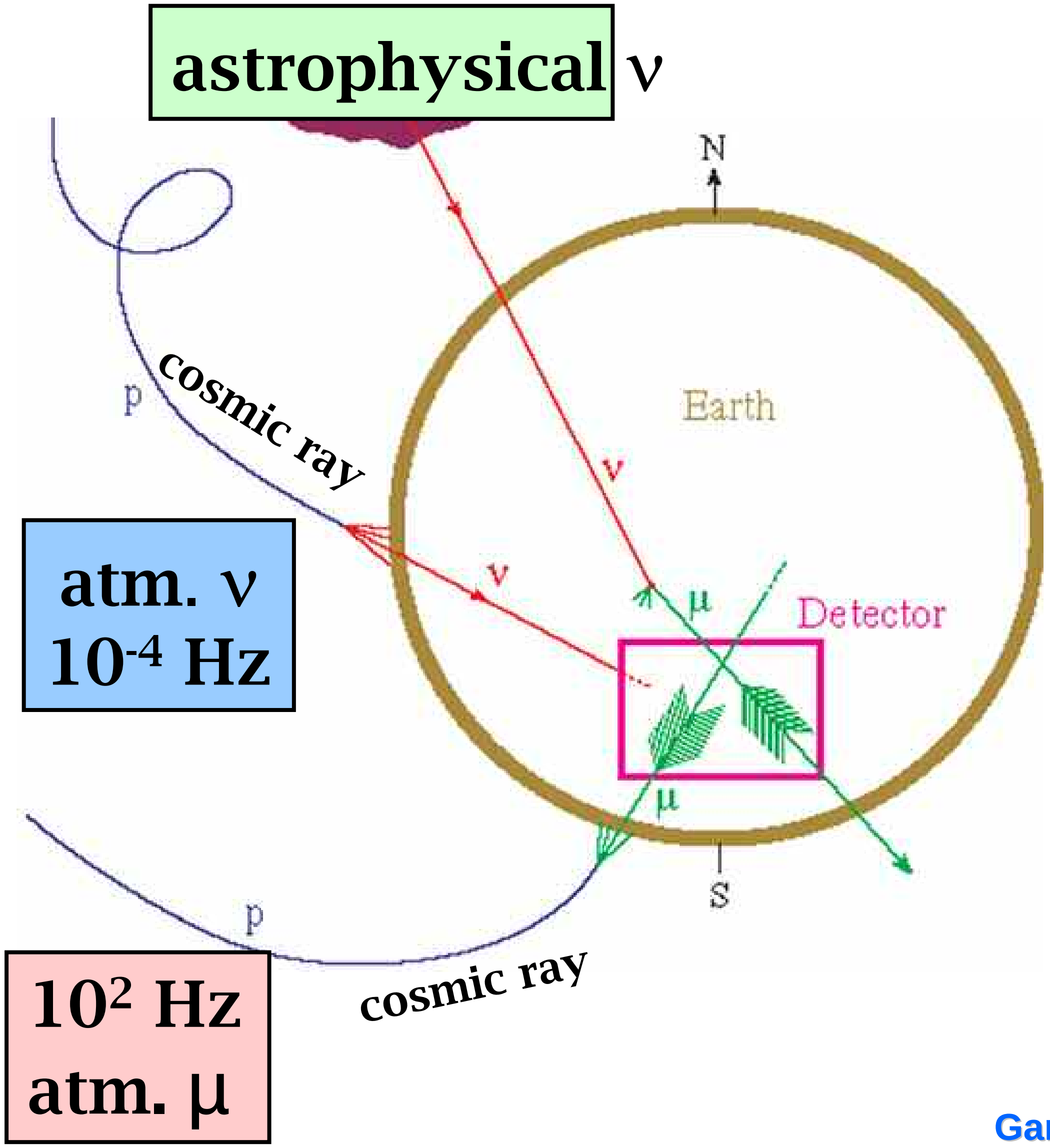
γ-rays from synchrotron

+

Let's look for these neutrinos!

Hadronic accelerator? – cosmic ray origin?

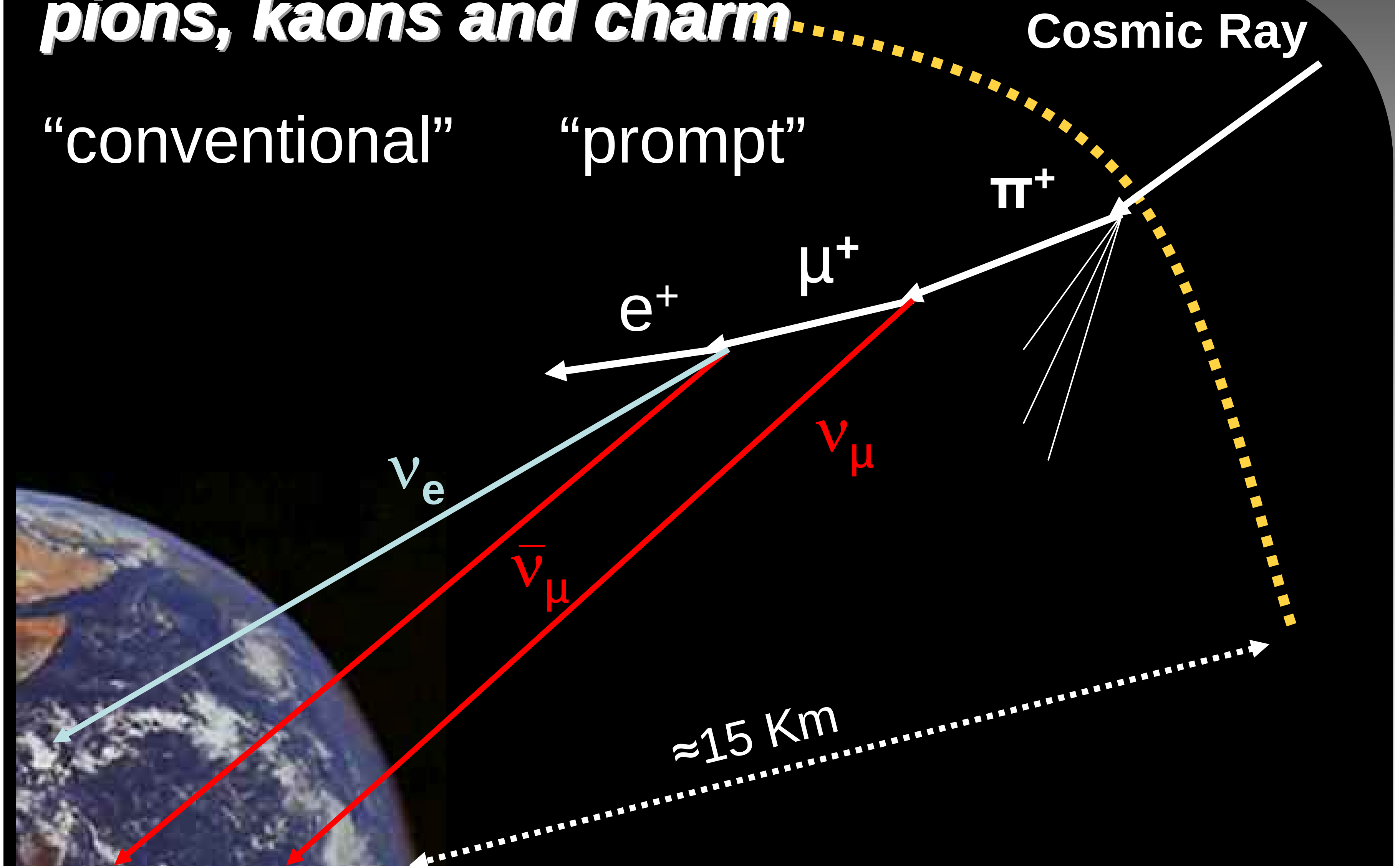
Neutrinos at the earth



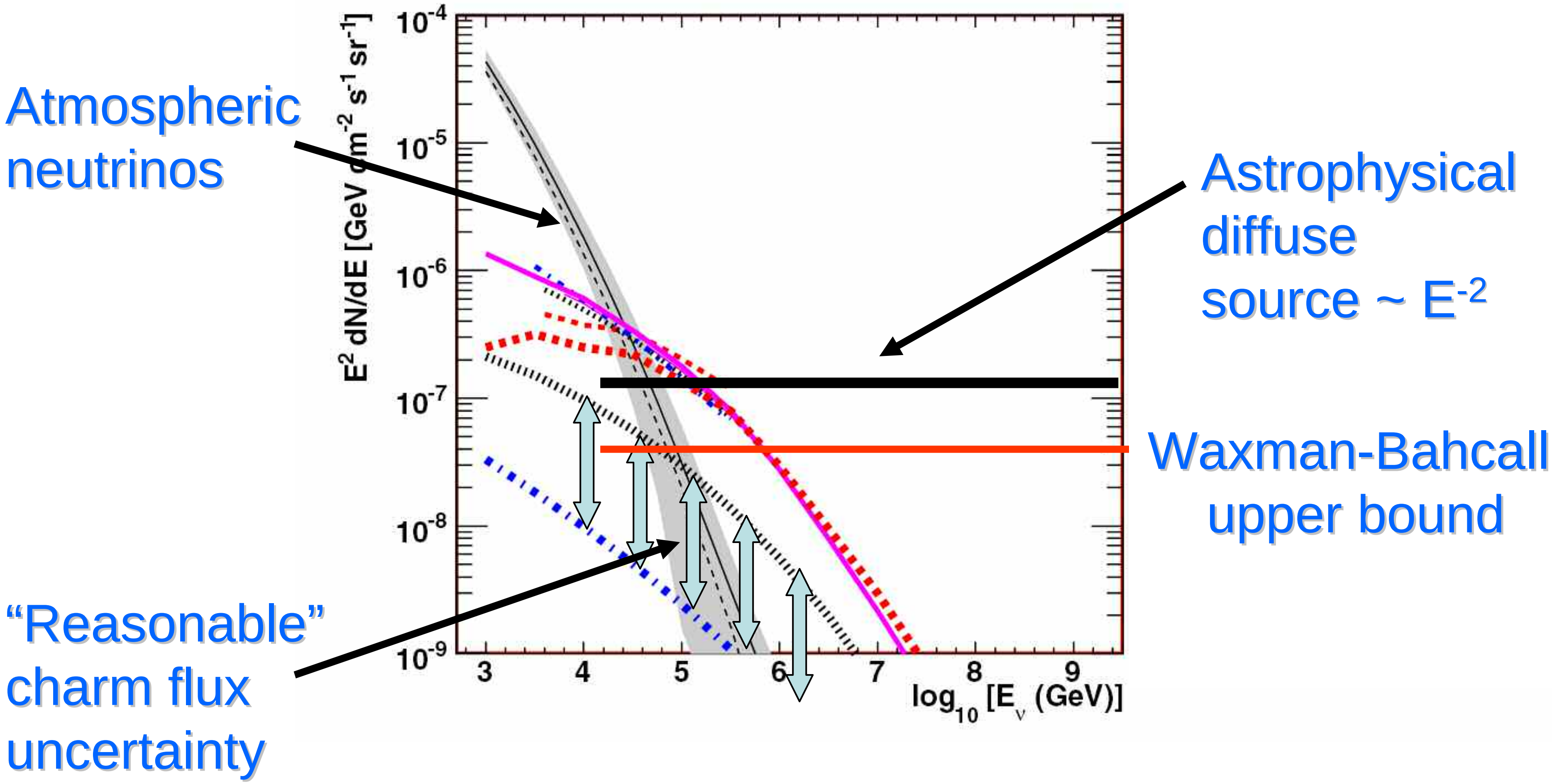
- "Atmospheric muons" from cosmic ray showers, penetrating to the detector from above
- "Atmospheric neutrinos" from the same air showers, forming a diffuse background and calibration beam
- Astrophysical neutrinos: interesting signal

Atmospheric Neutrinos

pions, kaons and charm



The diffuse HE neutrino sky



Diffuse searches are hard

- Background *must be well predicted from simulation* (no “off-source” / “side-band” region for direct measurement as in a point source search!)
- Backgrounds
  - atmospheric muons (angle)
  - atmospheric neutrinos (angle, energy)
    - pi, k decays (“conventional”)
    - charm decays (“prompt”)

Also search for prompt flux as a signal

IceCube Deployment

IceTop

Air shower detector

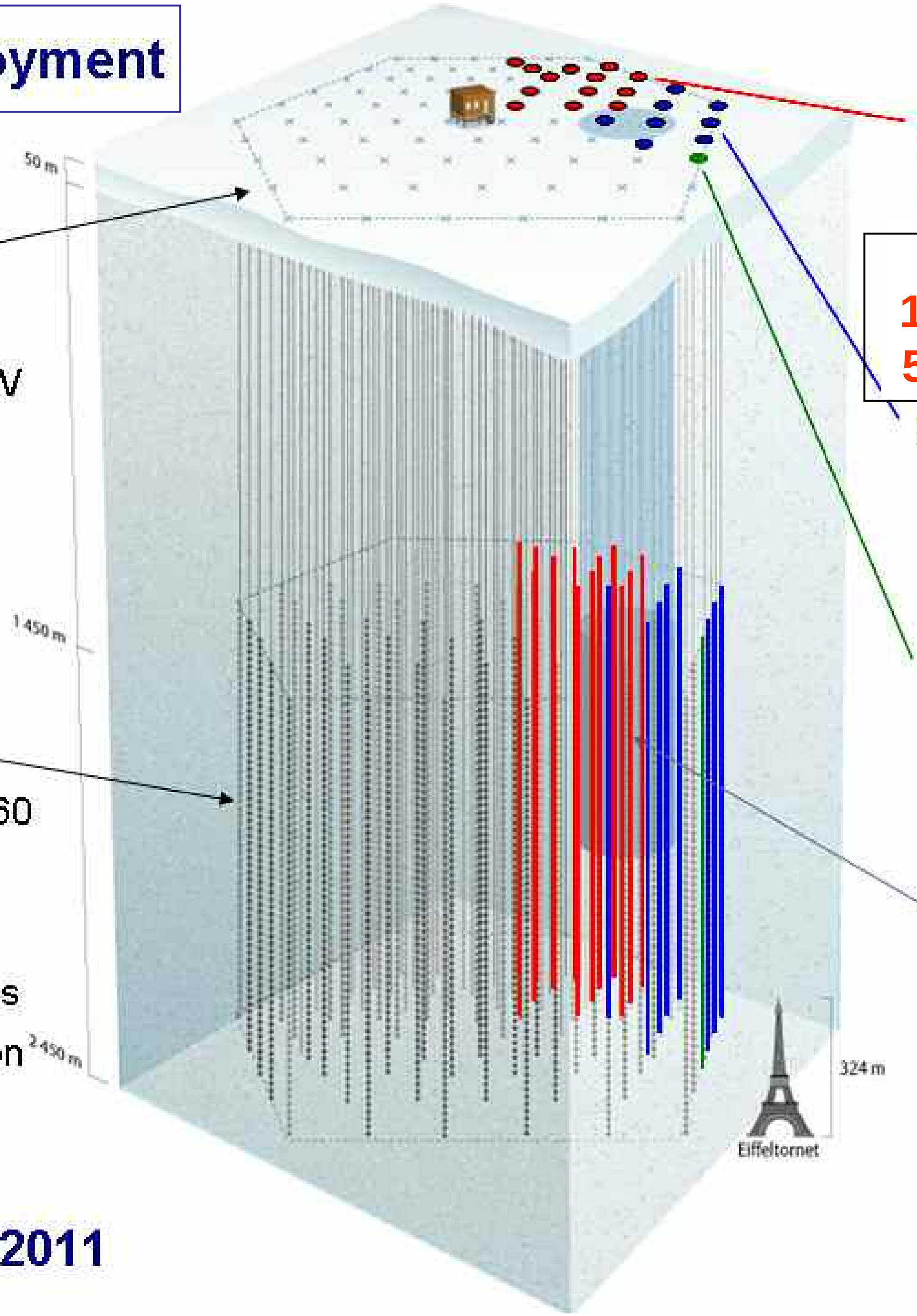
Threshold ~ 300 TeV

InIce

planned 80 strings of 60 optical modules each

17 m between modules

125 m string separation



2006-2007:

13 strings deployed

22 strings
1320 digital modules
52 surface detectors

2005-2006: 8 strings

2004-2005 : 1 string

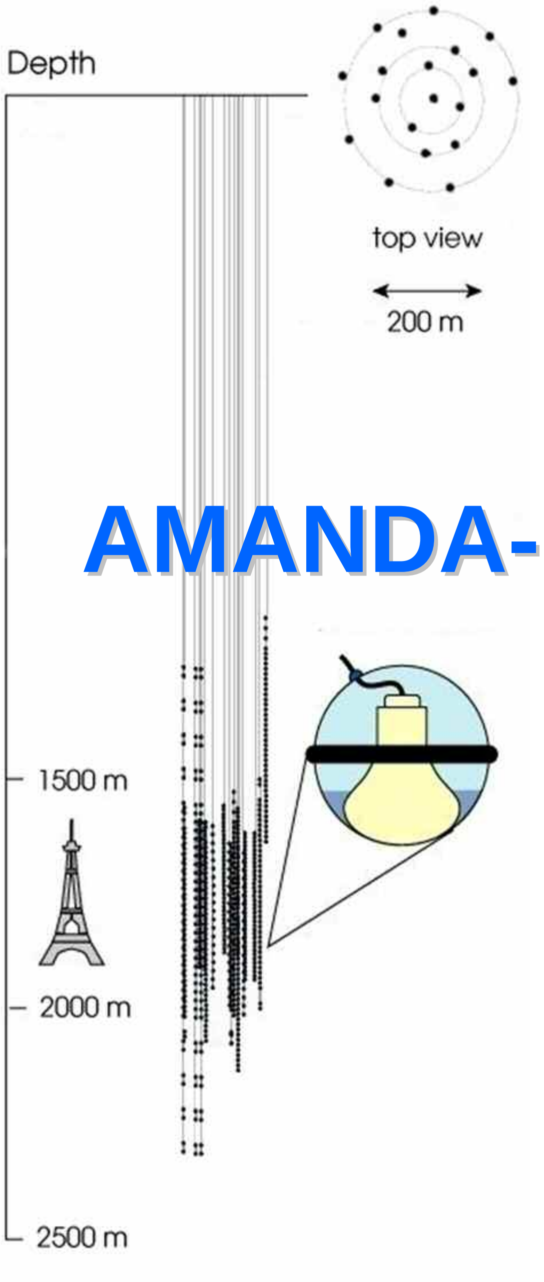
First data in 2005
first upgoing muon: July 18, 2005

AMANDA

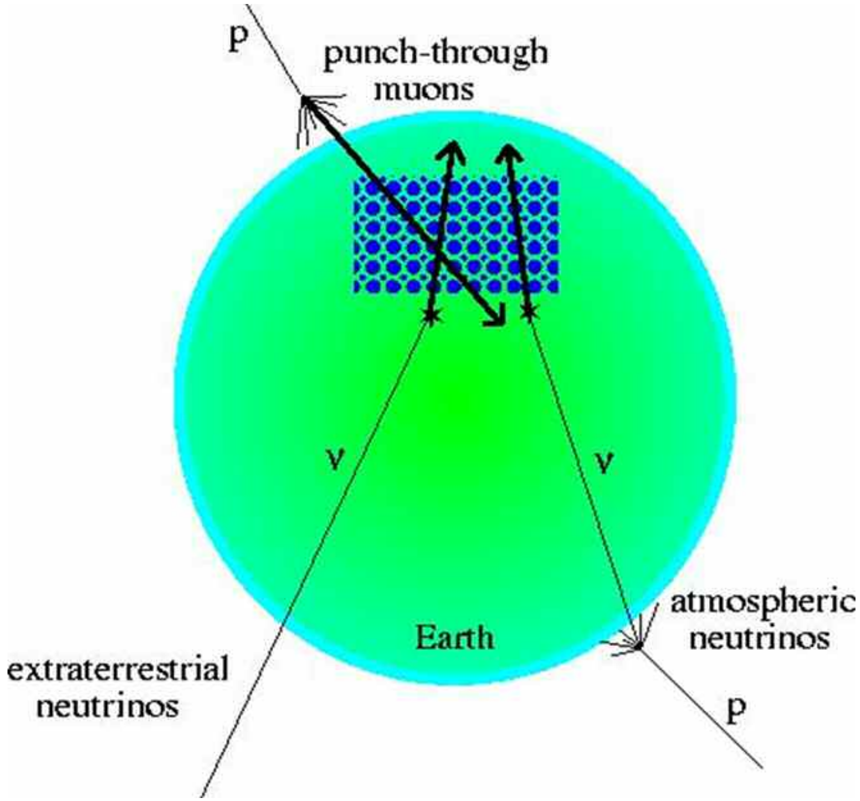
19 strings

677 modules

Completion by 2011

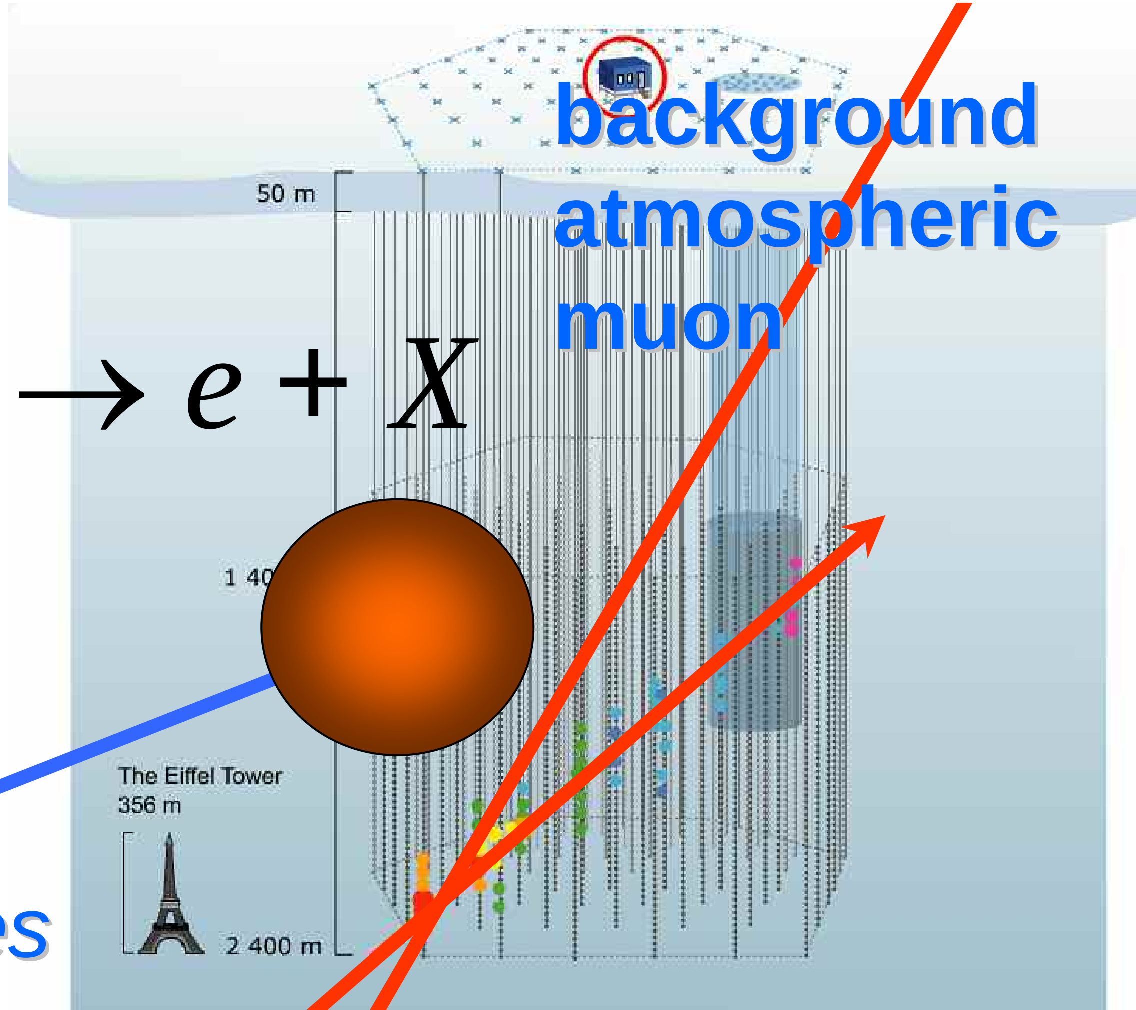


AMANDA-II



Construction: 1995-2000
19 strings, 677 Optical Modules (OMs)

background
atmospheric
muon



$$\nu_e + N \rightarrow e + X$$

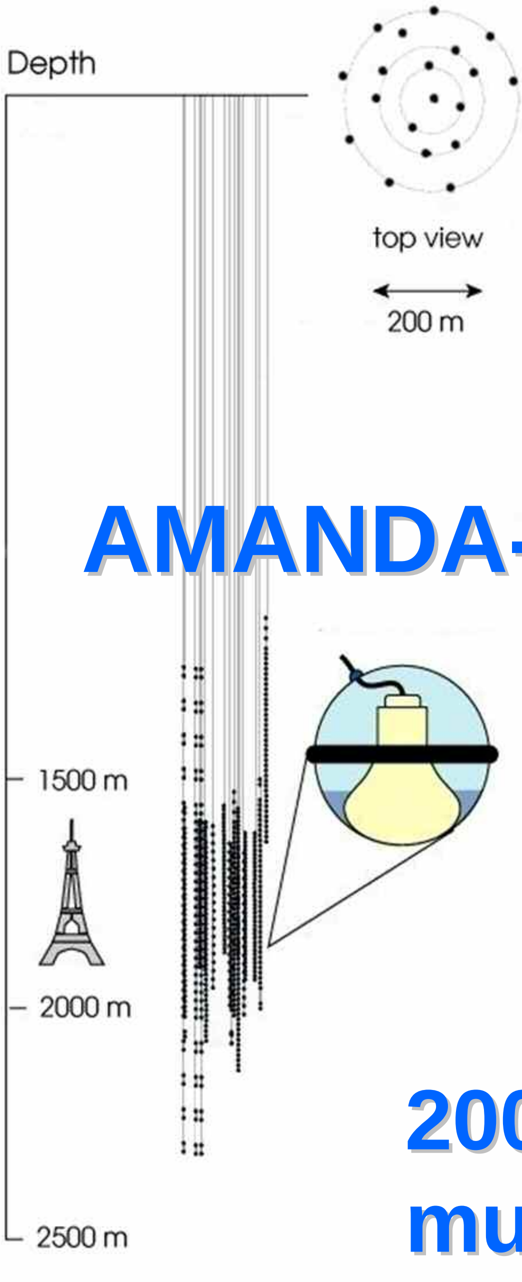
Direction:

Reconstruction of Cerenkov cone

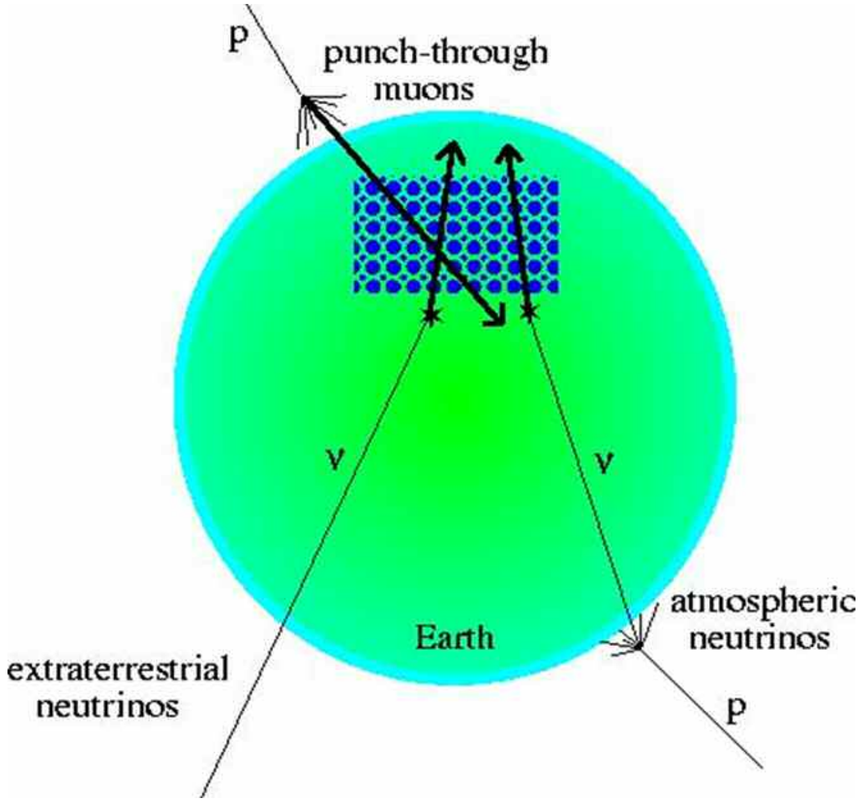
Energy:

Counting of modules that see photons

$$\nu_\mu + N \rightarrow \mu + X$$



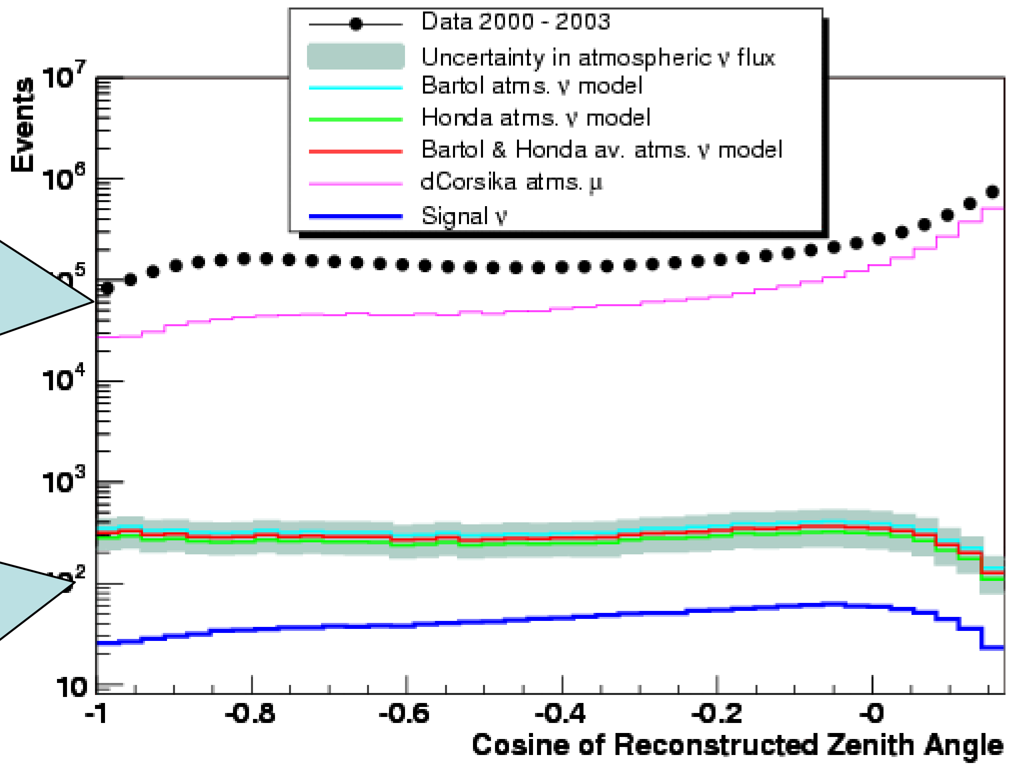
AMANDA-II



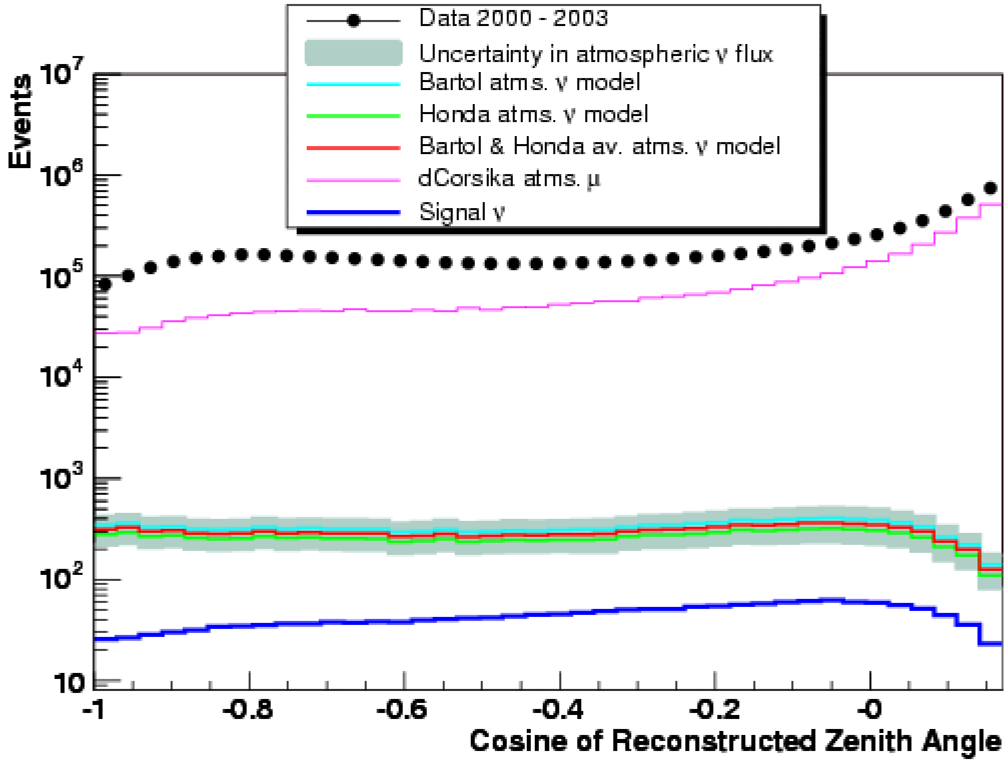
2000-03 diffuse through-going muon analysis - *Jessica Hodges*

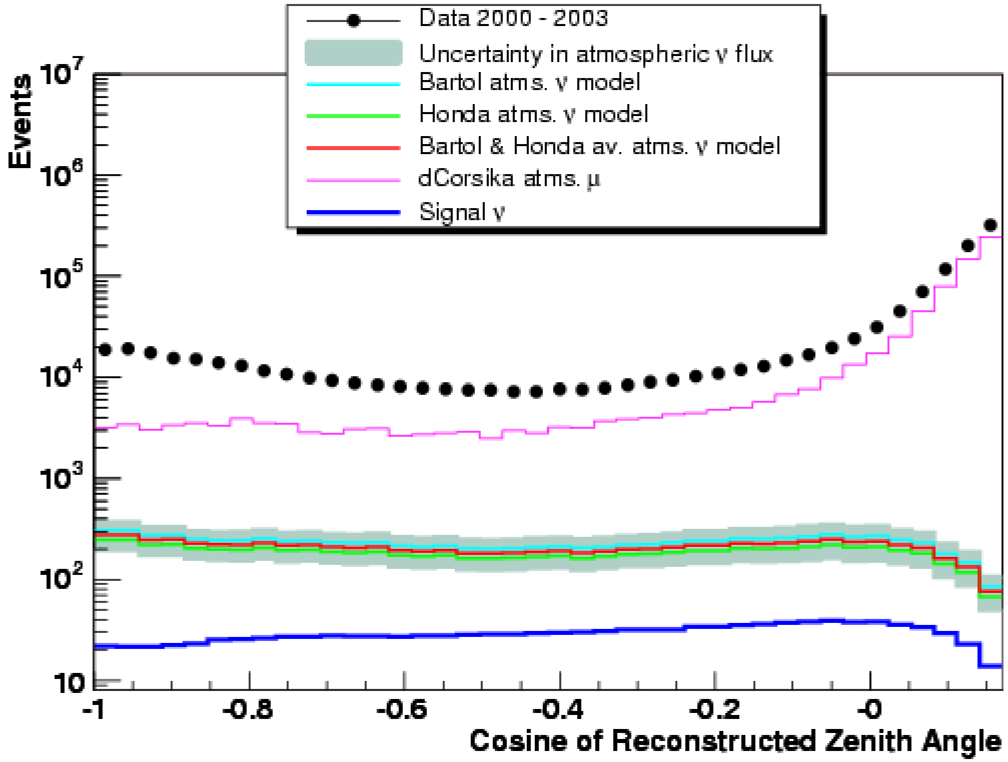
Real data, trigger level, after first directional reconstruction

mis-reconstructed atmospheric muons overwhelm atmospheric and extra-terrestrial neutrinos

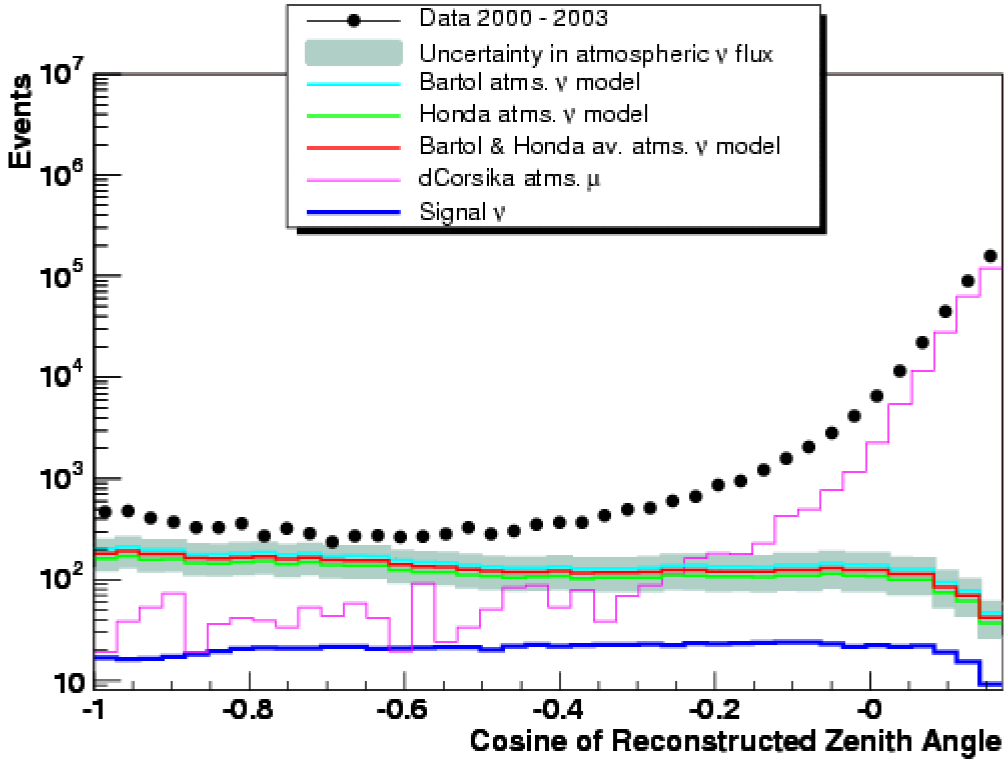


Remove wrongly reconstructed atmospheric muons by tightening event selection criteria…





Data 2000 - 2003
Uncertainty in atmospheric ν flux
Bartol atms. ν model
Honda atms. ν model
Bartol & Honda av. atms. ν model
dCorsika atms. μ
Signal ν
Events
10
10^2
10^3
10^4
10^5
10^6
10^7
-1
-0.8
-0.6
-0.4
-0.2
-0
Cosine of Reconstructed Zenith Angle


Data 2000 - 2003
Uncertainty in atmospheric ν flux
Bartol atms. ν model
Honda atms. ν model
Bartol & Honda av. atms. ν model
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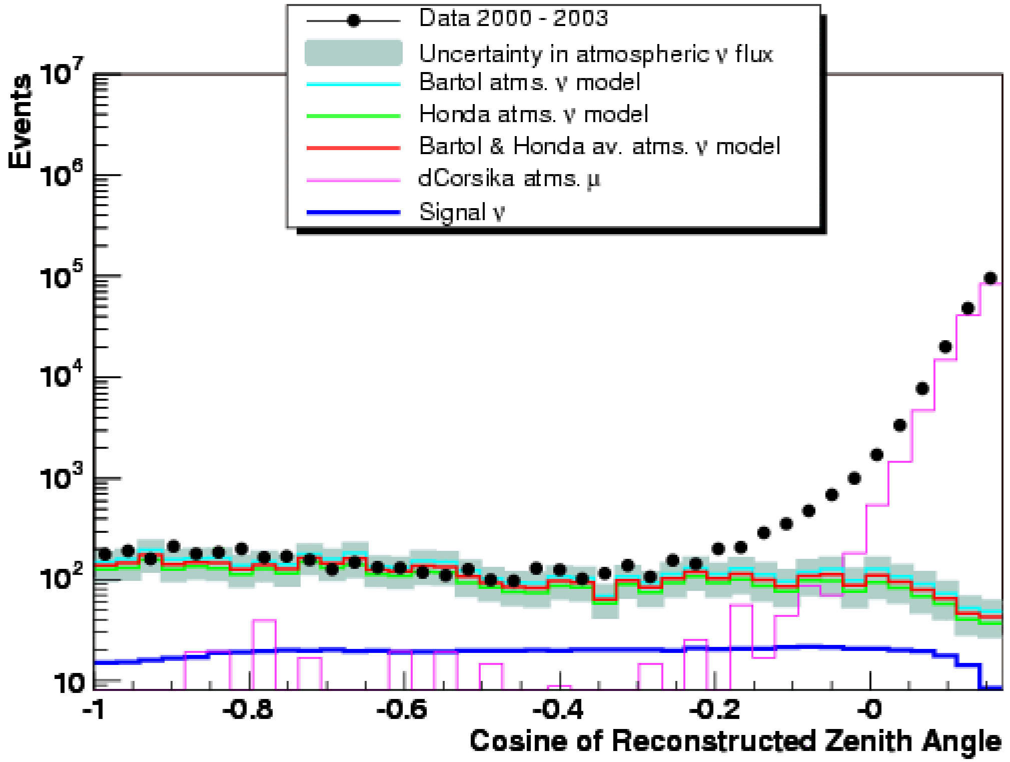
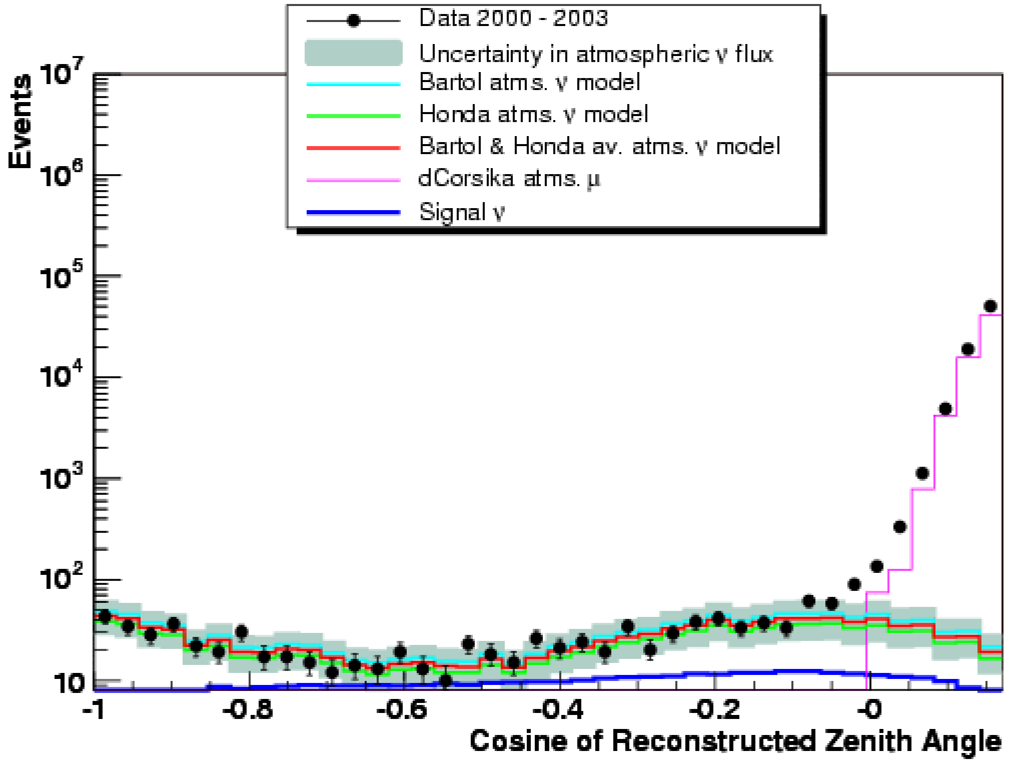
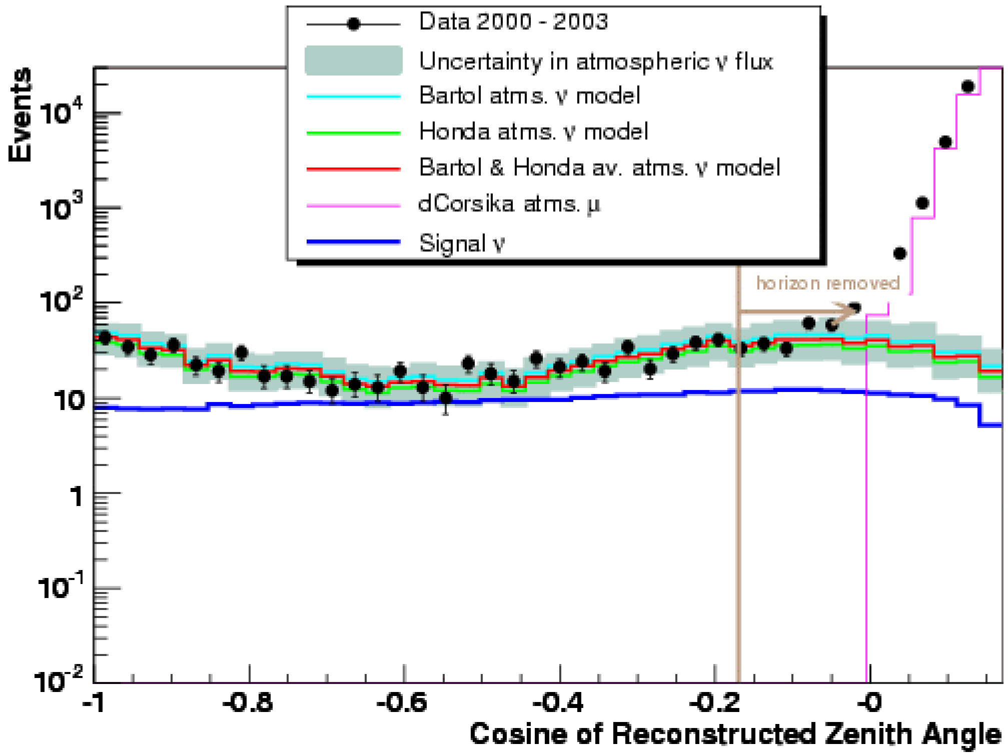
Signal ν
Events
Cosine of Reconstructed Zenith Angle



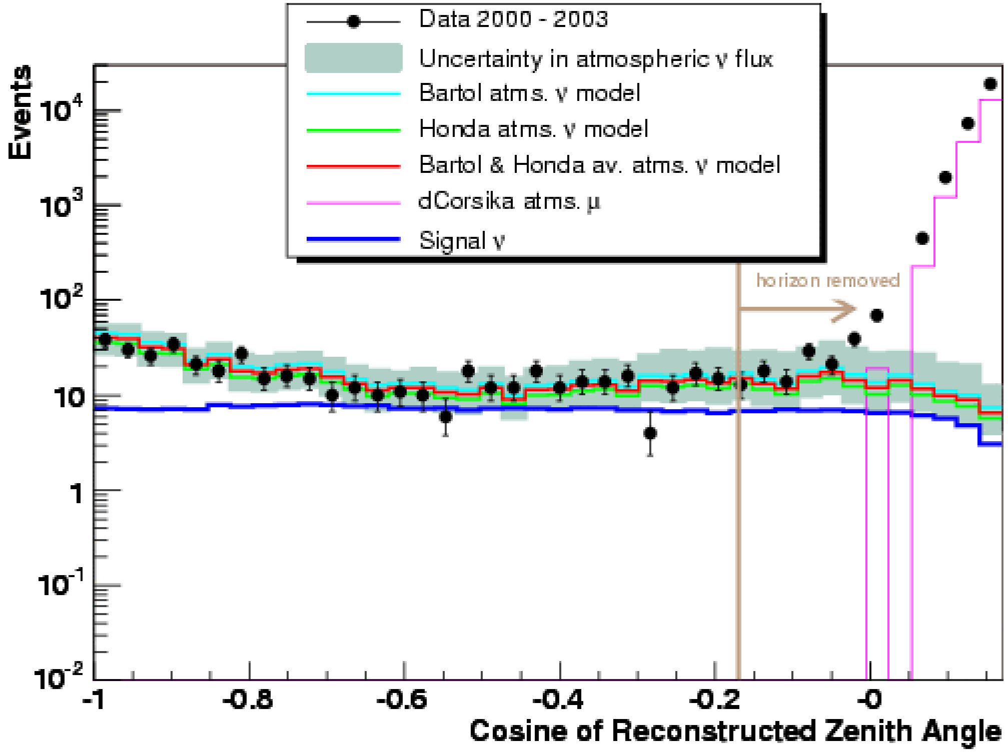
Data 2000 - 2003
Uncertainty in atmospheric ν flux
Bartol atms. ν model
Honda atms. ν model
Bartol & Honda av. atms. ν model
dCorsika atms. μ
Signal ν
Events
Cosine of Reconstructed Zenith Angle

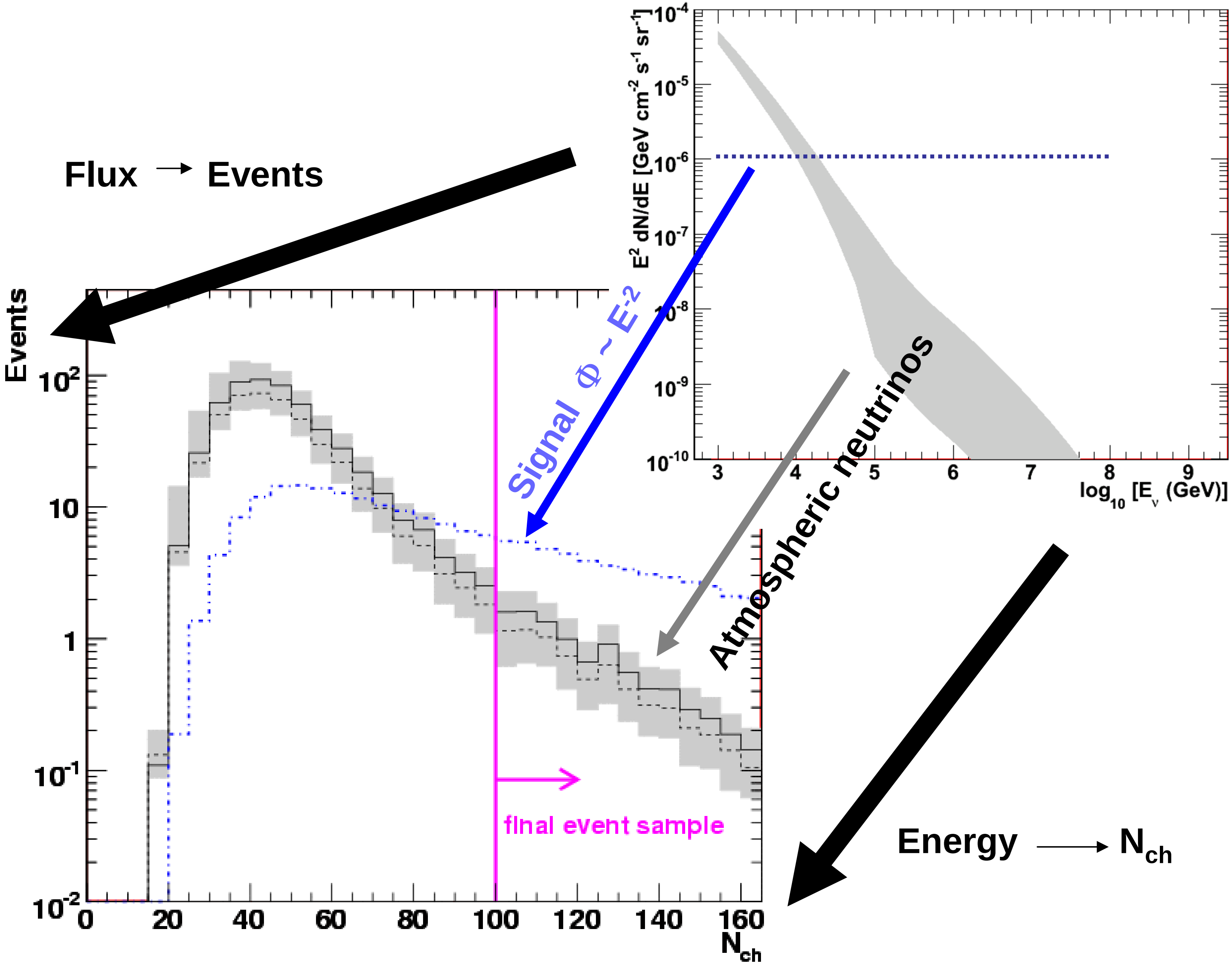

Data 2000 - 2003
Uncertainty in atmospheric ν flux
Bartol atms. ν model
Honda atms. ν model
Bartol & Honda av. atms. ν model
dCorsika atms. μ
Signal ν
Events
10^7
10^6
10^5
10^4
10^3
10^2
10
-1
-0.8
-0.6
-0.4
-0.2
-0
Cosine of Reconstructed Zenith Angle



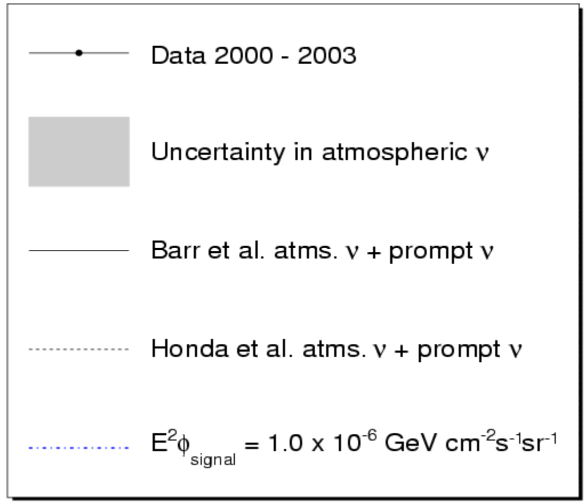
Data 2000 - 2003
Uncertainty in atmospheric ν flux
Bartol atms. ν model
Honda atms. ν model
Bartol & Honda av. atms. ν model
dCorsika atms. μ
Signal ν
horizon removed
Events
Cosine of Reconstructed Zenith Angle

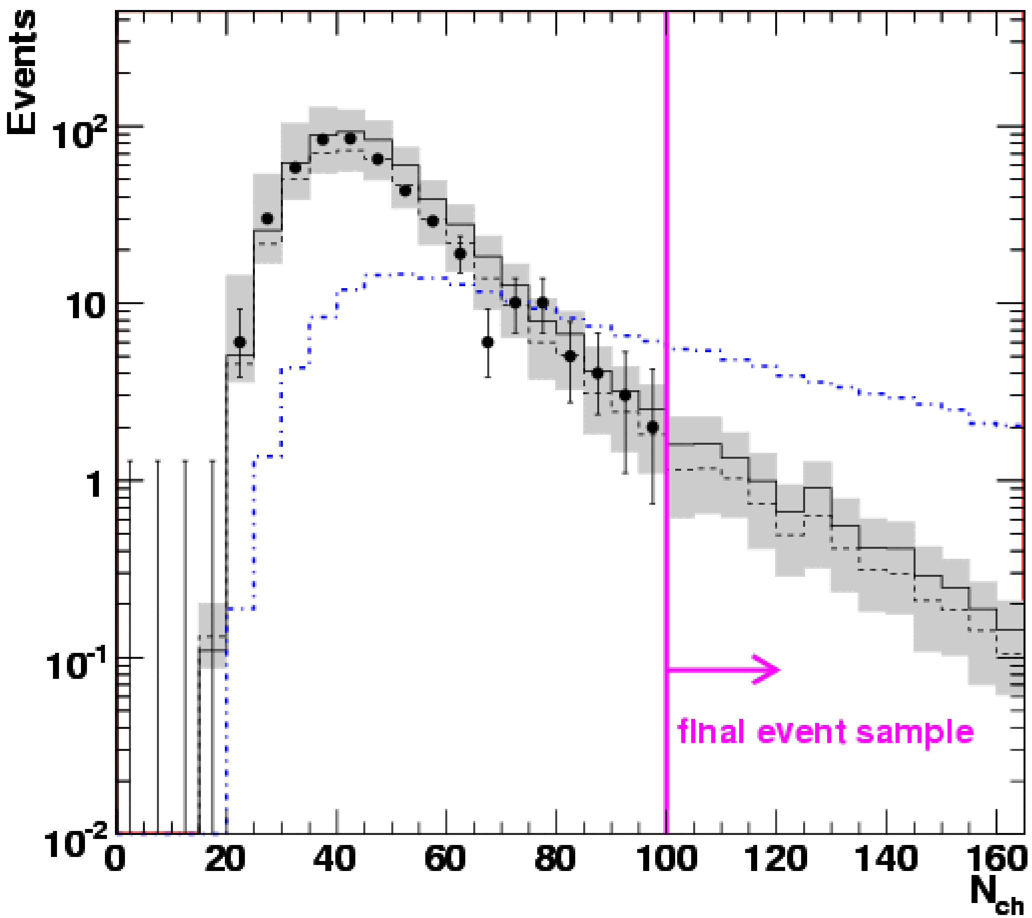
Clean upgoing neutrino sample mostly atmospheric neutrinos – diffuse analysis level



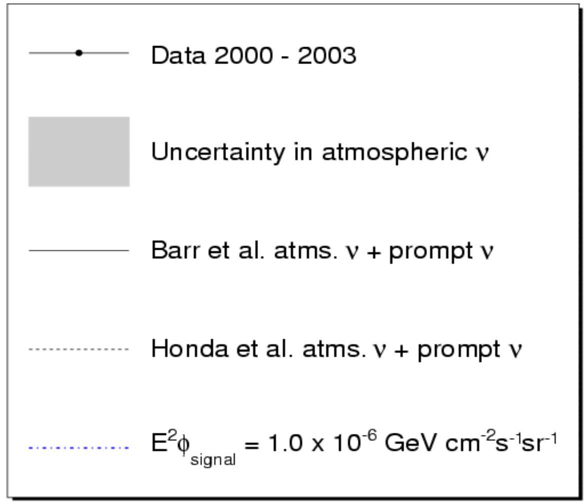

Flux → Events
Energy → N_{ch}
Signal Φ ~ E^-2
Atmospheric neutrinos
final event sample
Events
N_{ch}
E^2 dN/dE [GeV cm^-2 s^-1 sr^-1]
$\log_{10}$ [E_ν (GeV)]

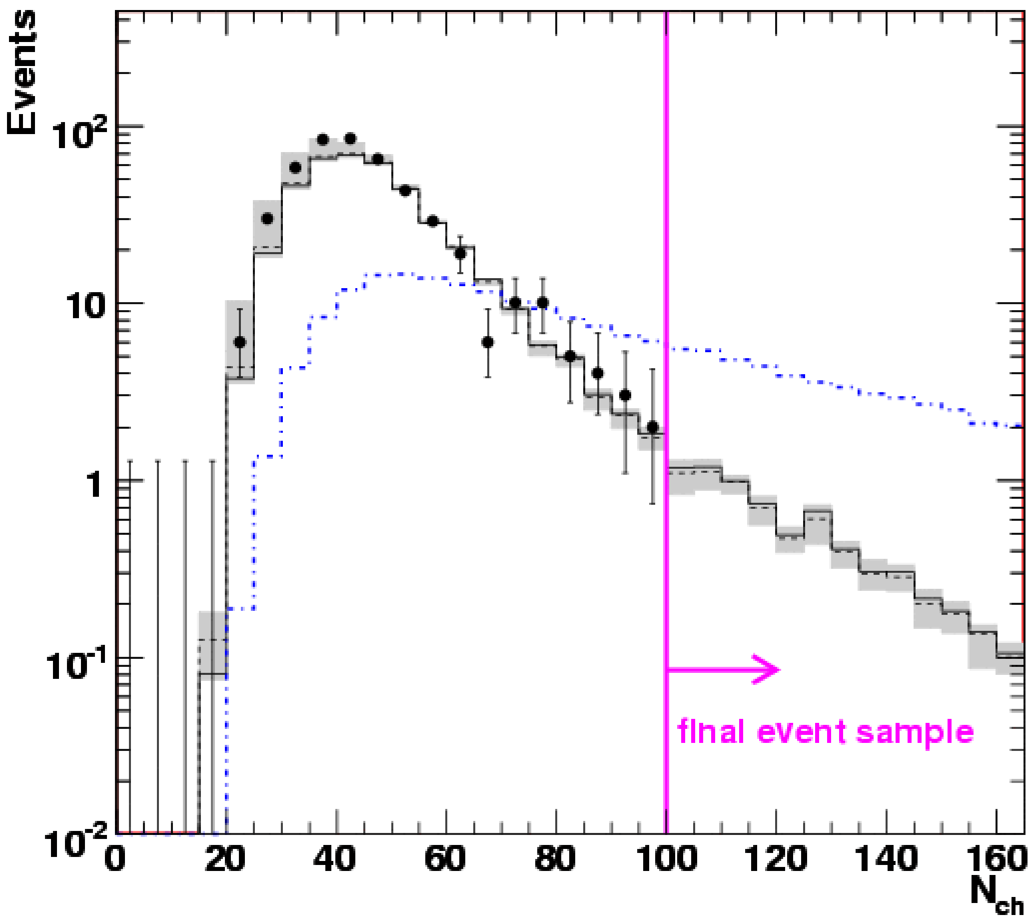
Low energy data is compared to the simulation.





The simulation is scaled so that the number of low energy events predicted matches the low energy data.





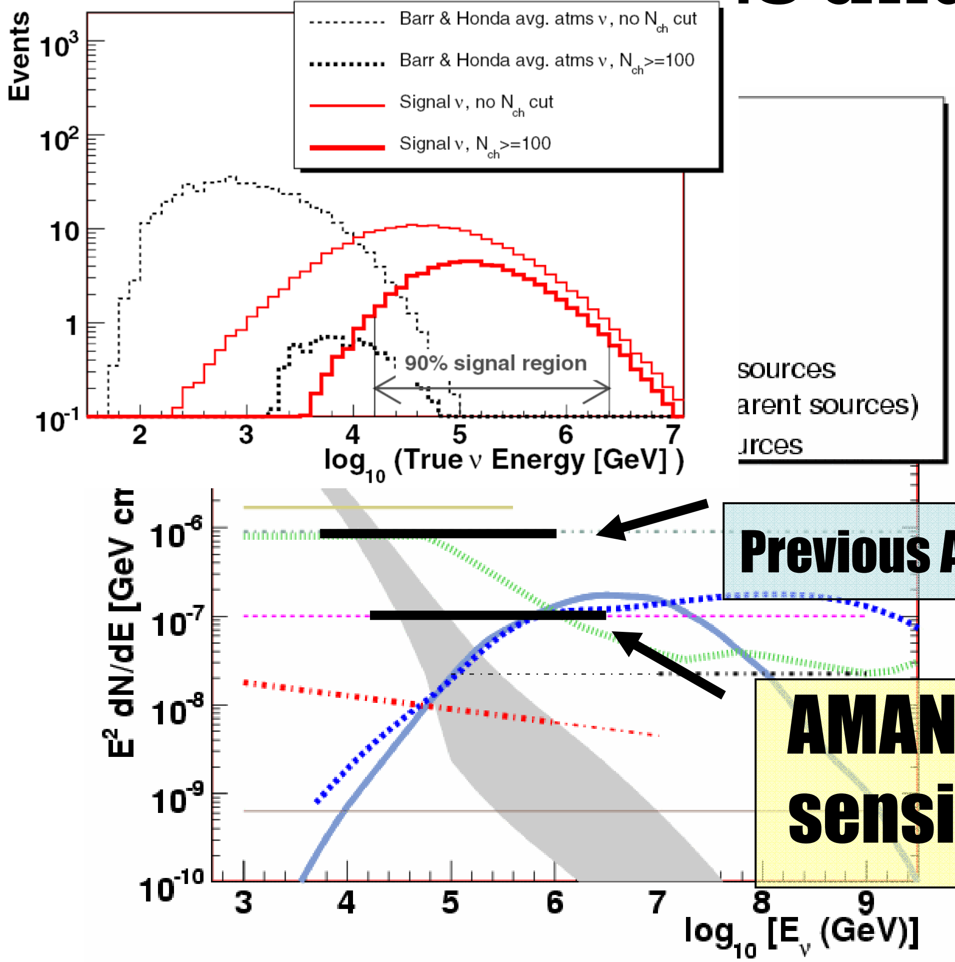
66.7 events

$E^2\phi_{signal} = 1.0 \times 10^{-6}$ GeV cm^{-2}s^{-1}sr^{-1}

bg = 7.0 (6.1-8.3) events
median limit = 6.36

MRF = 6.36/66.7 = 0.095

$\Phi \sim E^{-2}$ Flux Models and Upper Limits



Previous AMANDA-B10 limit

AMANDA-II 2000-2003 sensitivity to $\Phi \sim E^{-2}$ Flux

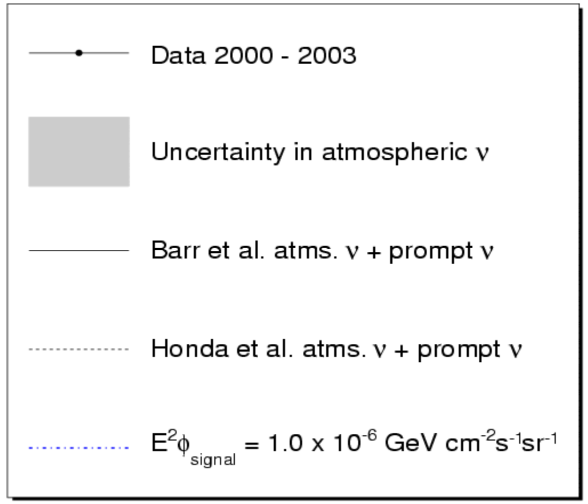
sensitivity

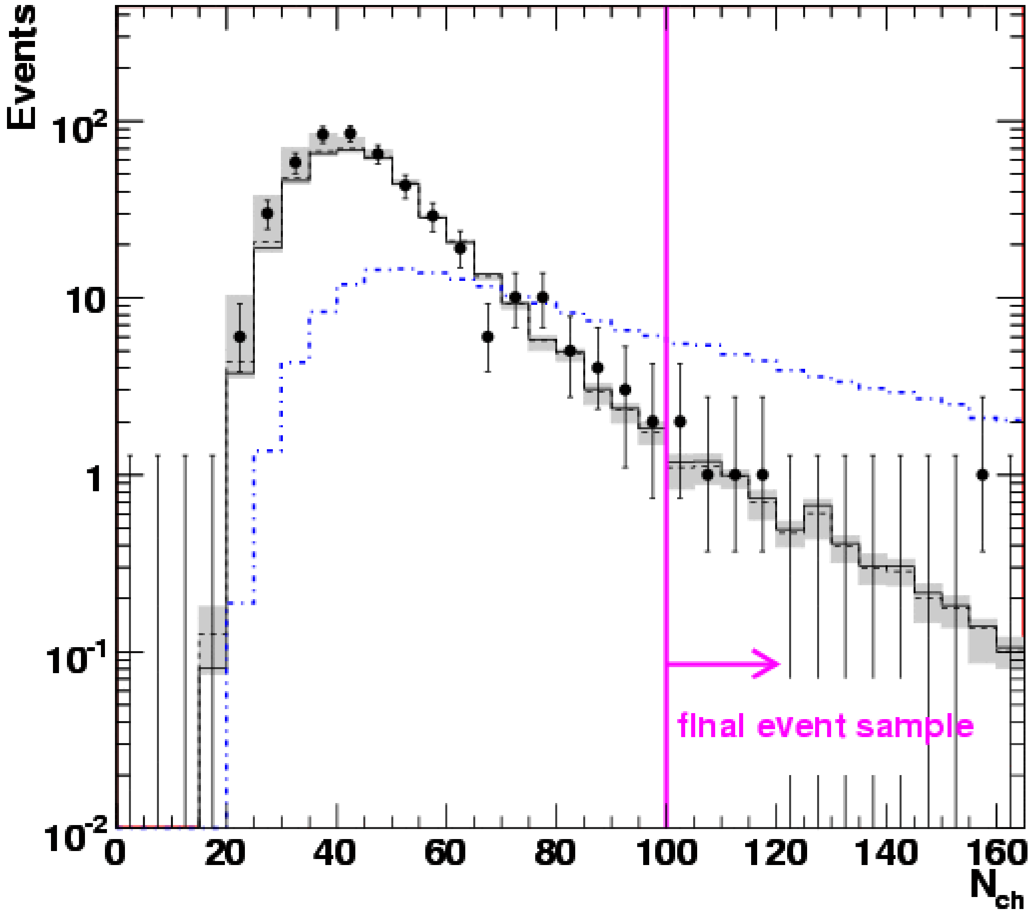
$E^2\ \Phi < 9.5 \times 10^{-8}$ GeV $cm^{-2}\ s^{-1}\ sr^{-1}$

16 TeV – 2.5 PeV

The high energy data set is unblinded.

The number of high energy (N_{ch}>100) data events is counted and compared to the background simulation.





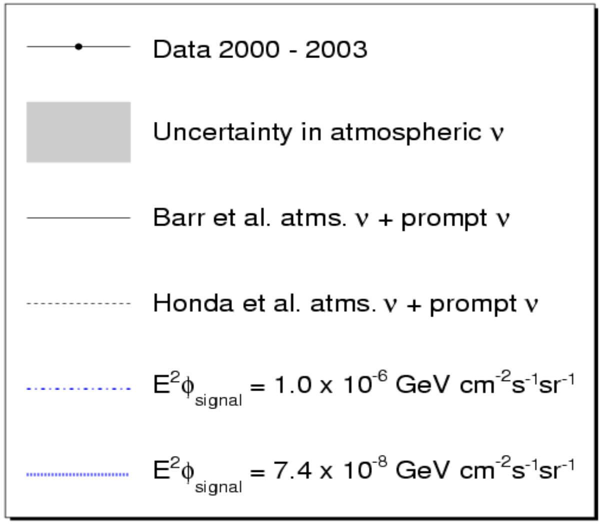
Background prediction varies between 6.1 and 8.3 events

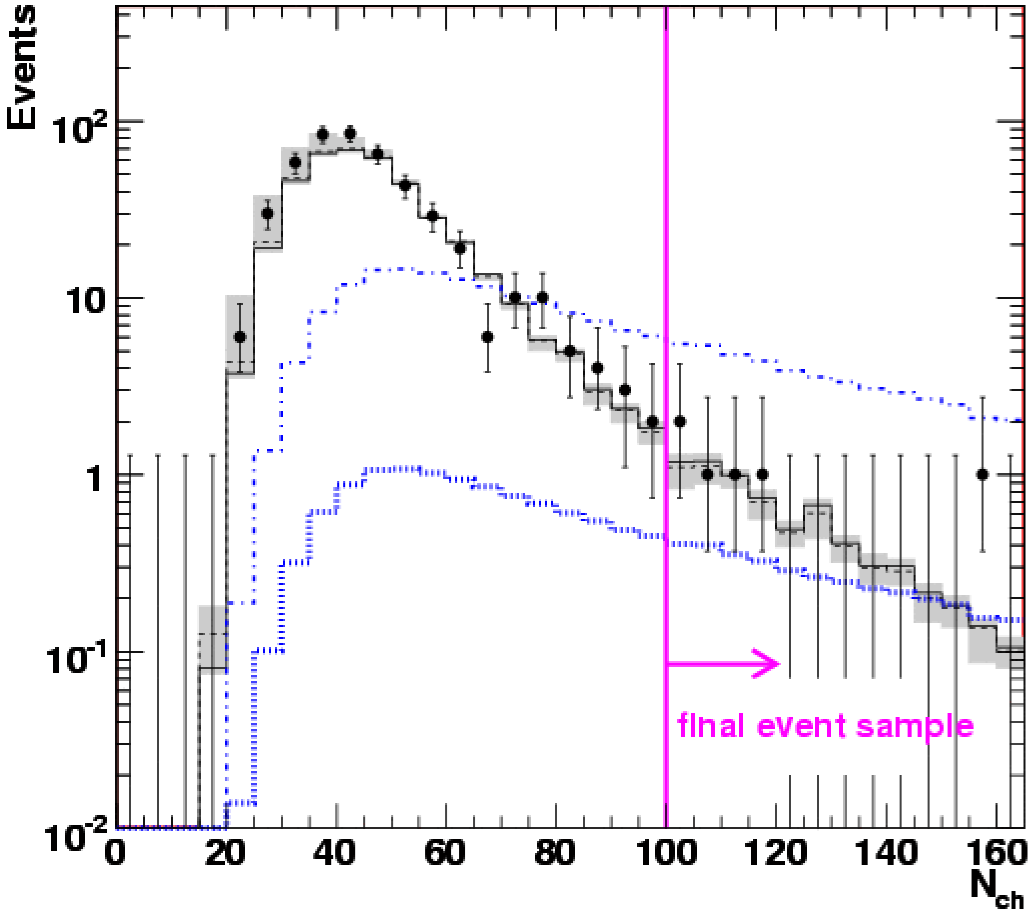
Average bg predicted = 7.0

6 data events observed

FC upper limit on signal contribution = 4.95

An upper limit on the level of the signal flux is established based on what was observed in the high N_{ch} region.





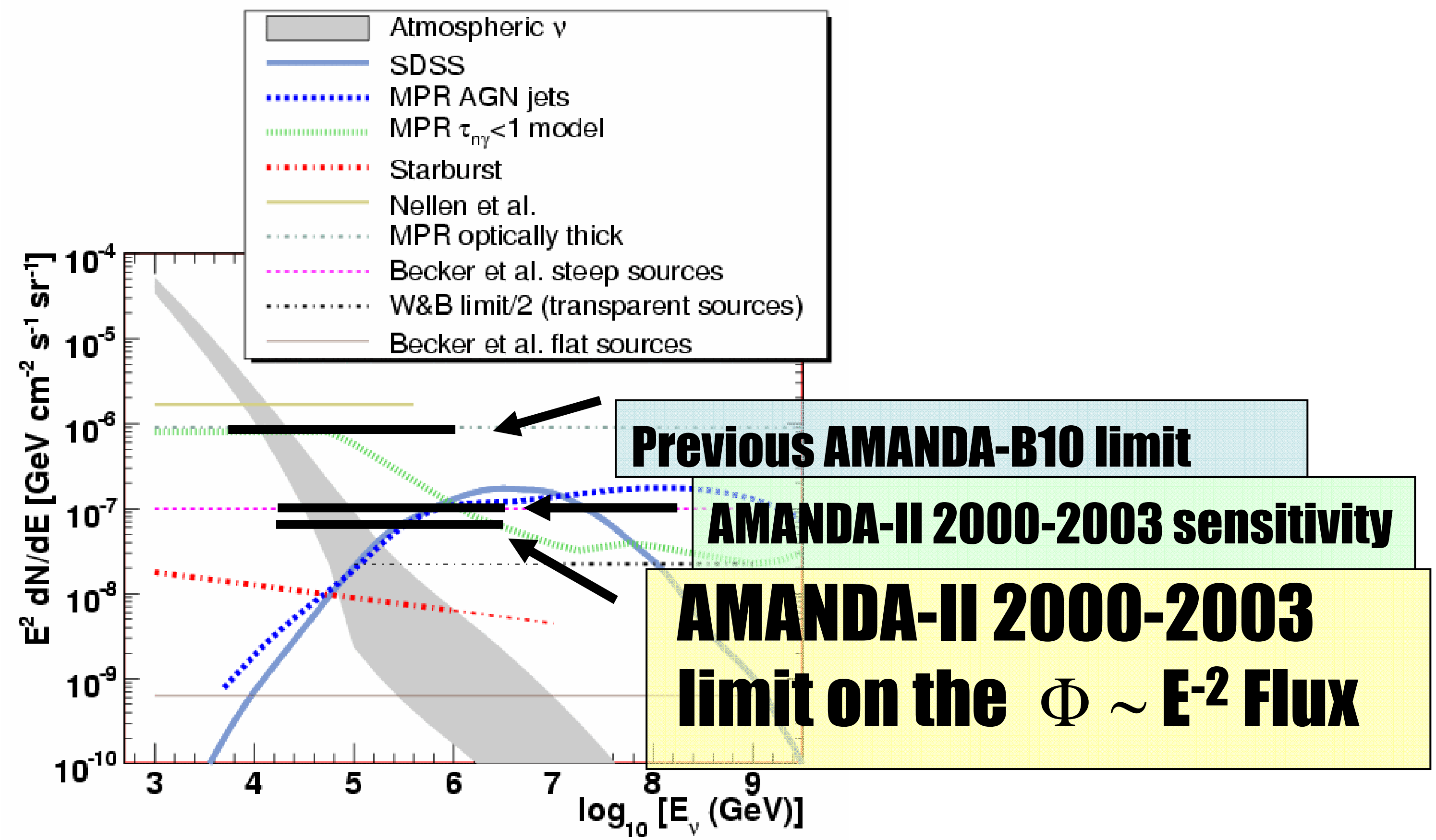
66.7 events

$E^2\phi_{signal} = 1.0 \times 10^{-6}$ GeV cm^{-2}s^{-1}sr^{-1}

4.95 events

$E^2\phi_{signal} = 7.4 \times 10^{-8}$ GeV cm^{-2}s^{-1}sr^{-1}

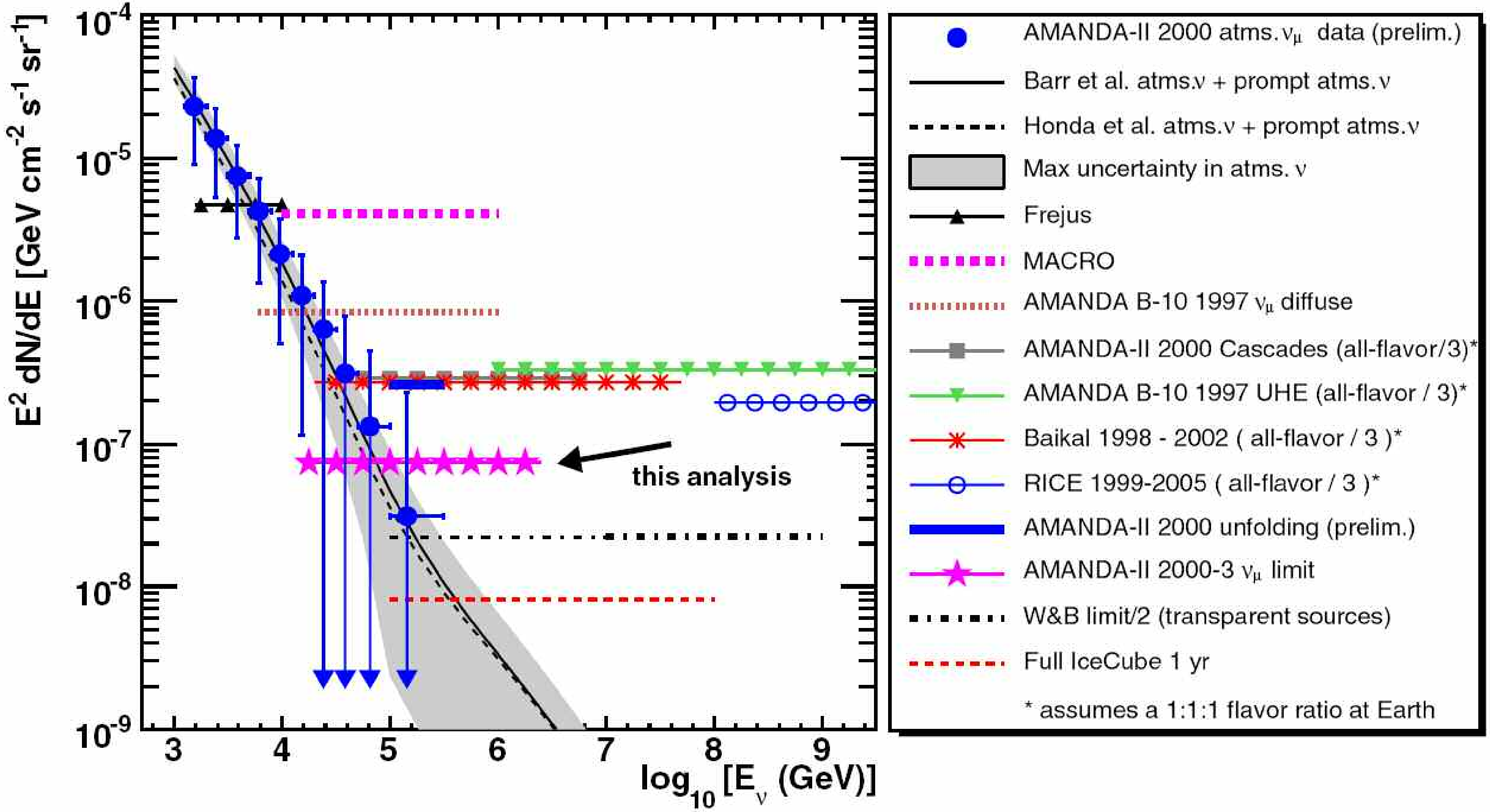
$\Phi \sim E^{-2}$ Flux Models and Upper Limits



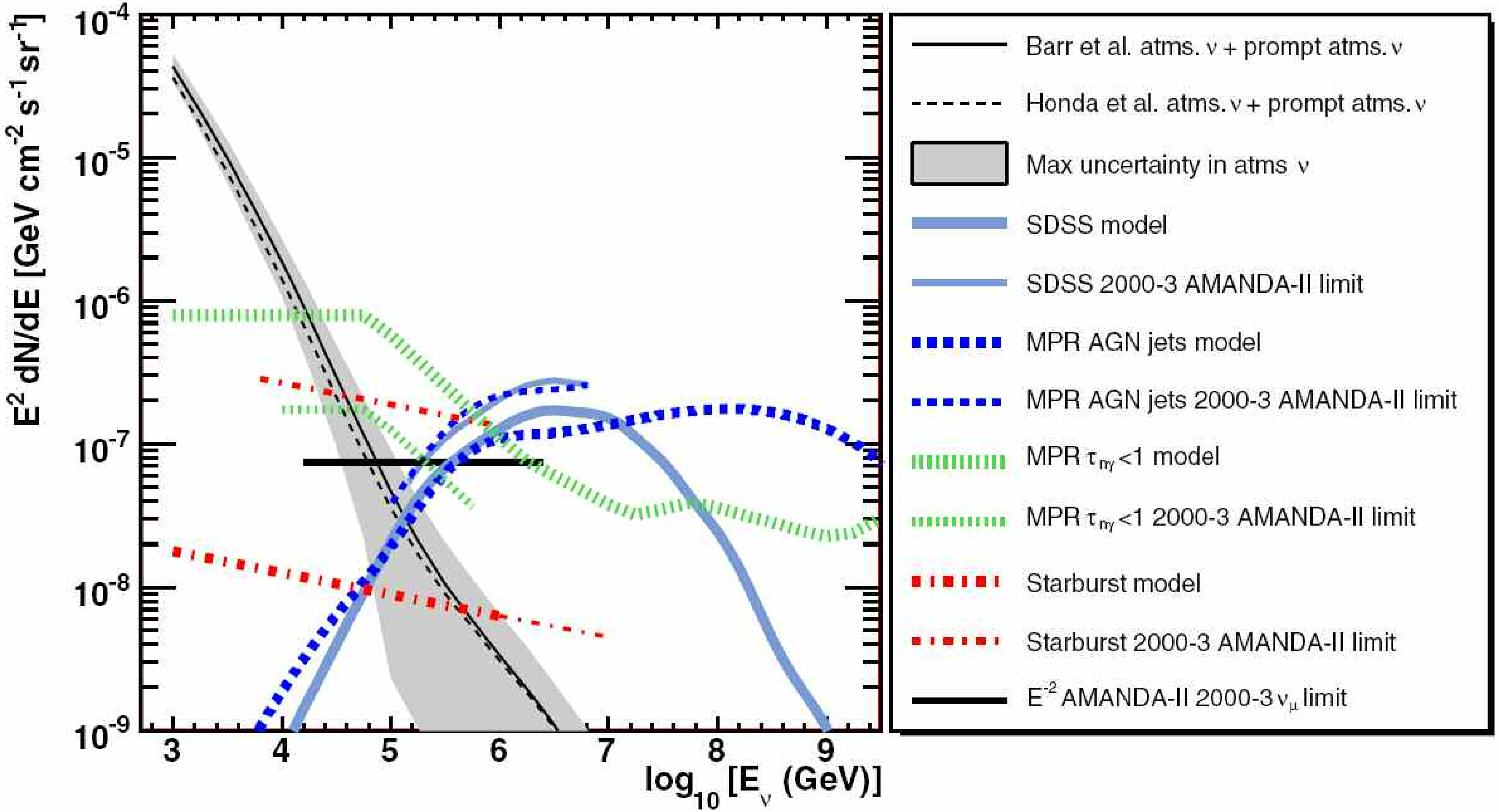
upper limit

$E^2 \Phi < 7.4 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

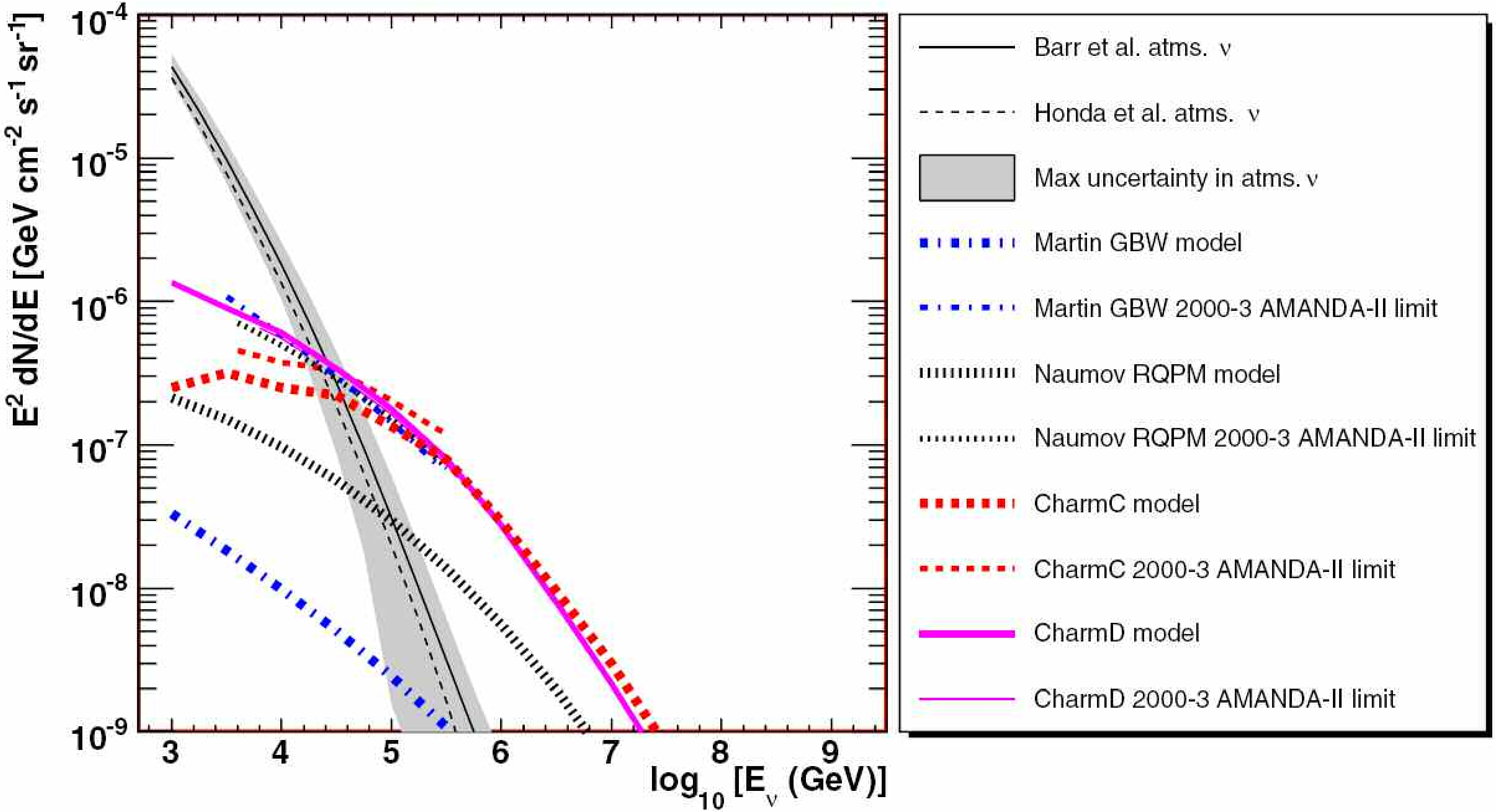
16 TeV – 2.5 PeV


E² dN/dE [GeV cm⁻² s⁻¹ sr⁻¹]
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
3
4
5
6
7
8
9
log₁₀ [E_ν (GeV)]
this analysis
AMANDA-II 2000 atms. ν_μ data (prelim.)
Barr et al. atms.ν + prompt atms.ν
Honda et al. atms.ν + prompt atms.ν
Max uncertainty in atms. ν
Frejus
MACRO
AMANDA B-10 1997 ν_μ diffuse
AMANDA-II 2000 Cascades (all-flavor/3)*
AMANDA B-10 1997 UHE (all-flavor / 3)*
Baikal 1998 - 2002 (all-flavor / 3)*
RICE 1999-2005 (all-flavor / 3)*
AMANDA-II 2000 unfolding (prelim.)
AMANDA-II 2000-3 ν_μ limit
W&B limit/2 (transparent sources)
Full IceCube 1 yr
* assumes a 1:1:1 flavor ratio at Earth

Other astrophysical models and upper limits

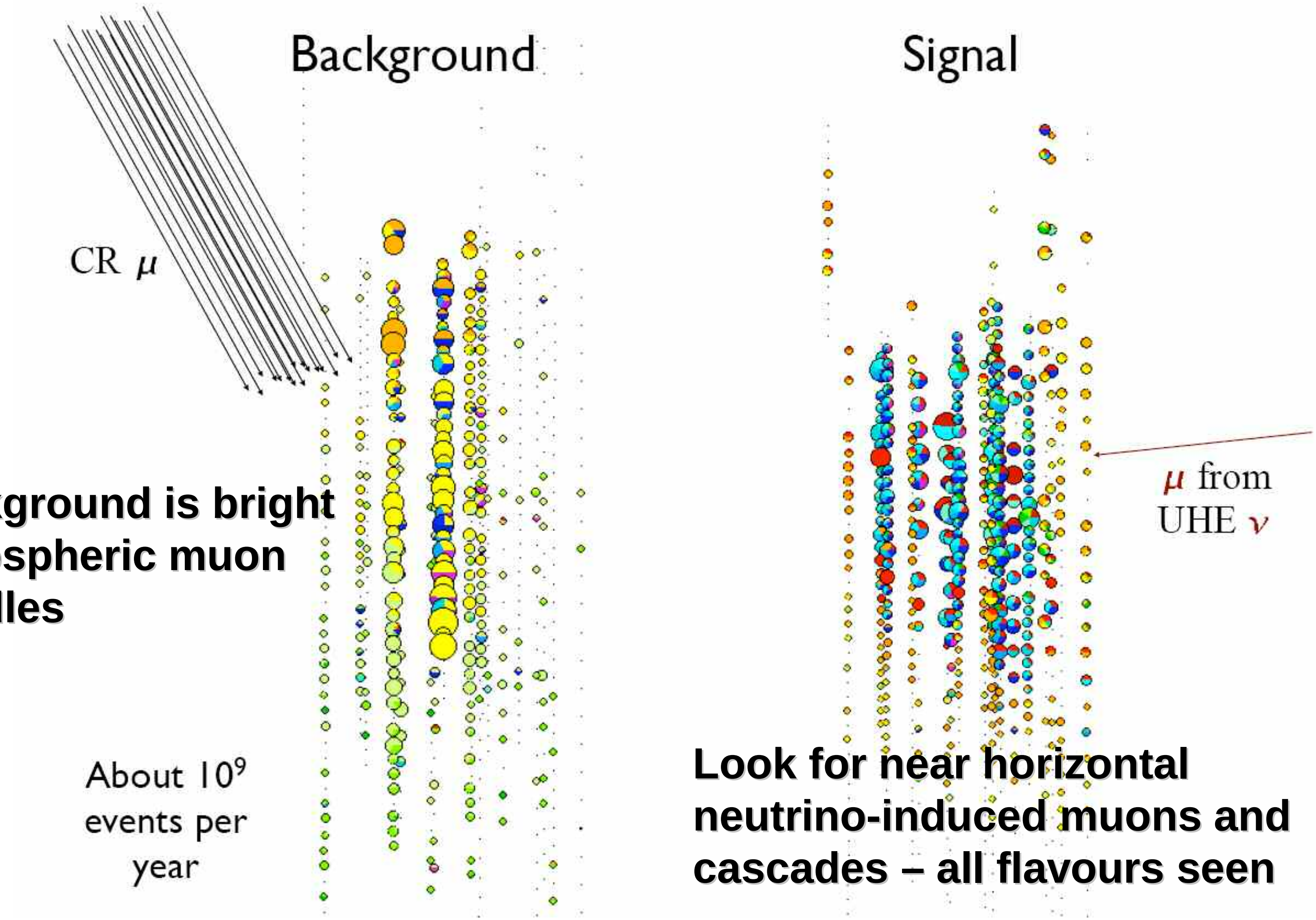


Prompt atmospheric neutrino models and upper limits



UHE diffuse analysis – 2000-02

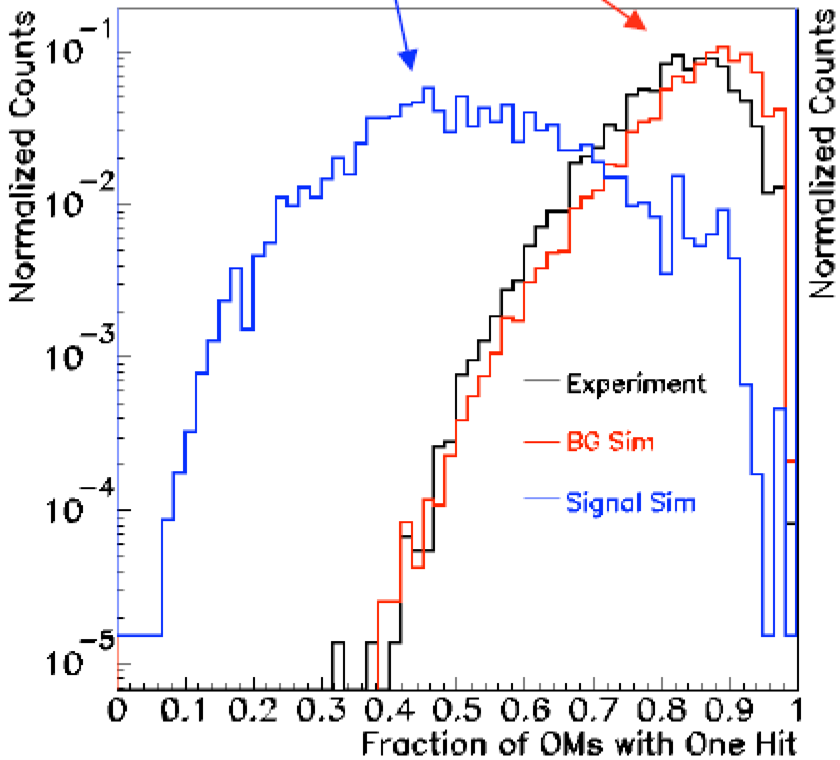
Lisa Gerhardt



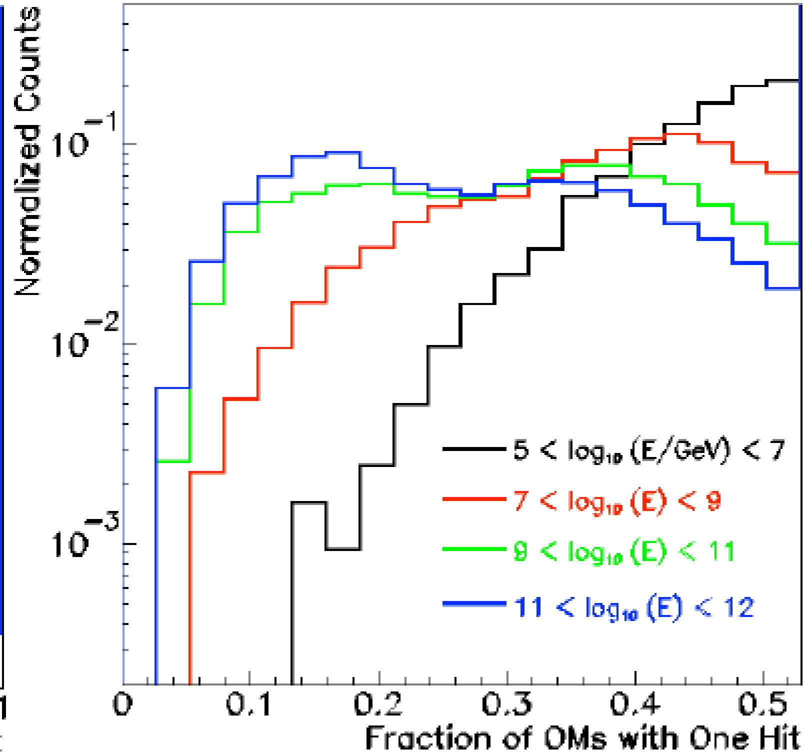
Background is bright atmospheric muon bundles

Look for near horizontal neutrino-induced muons and cascades – all flavours seen

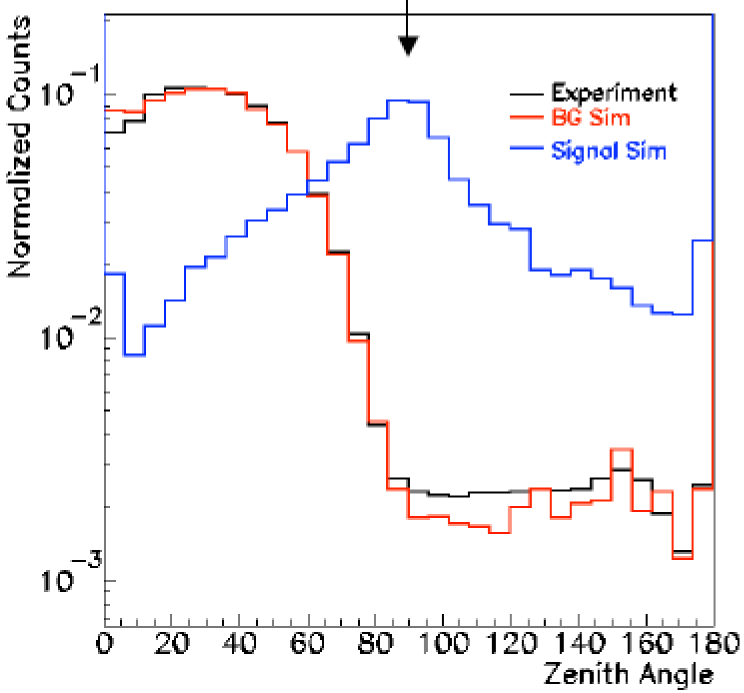
Good separation between BG and signal

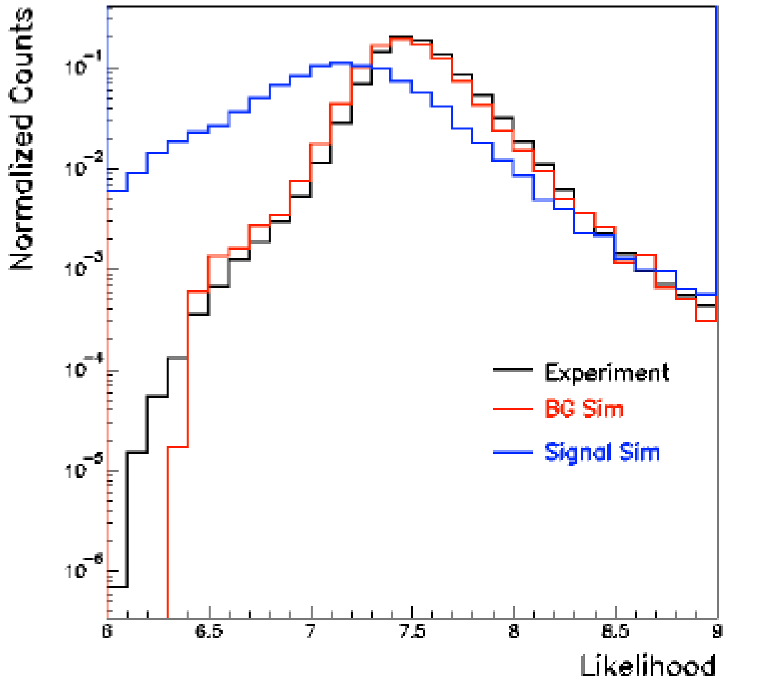


F1H is correlated with energy



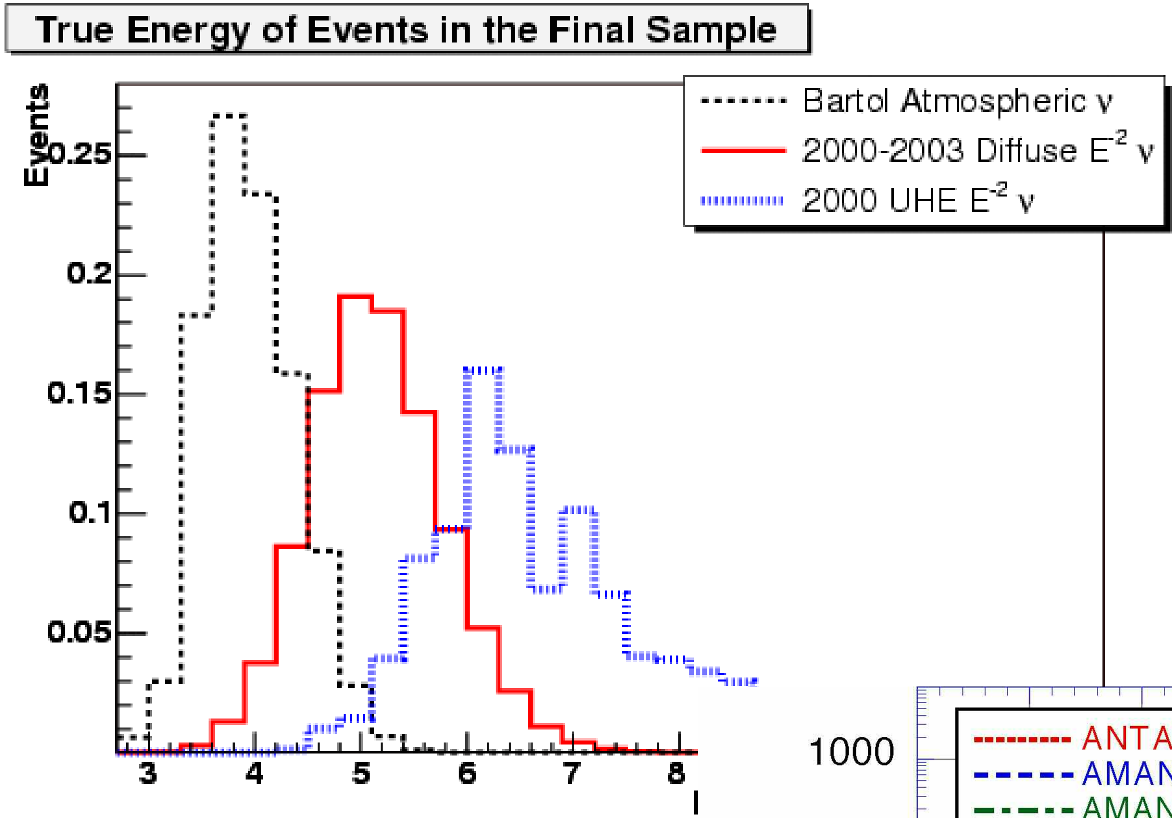
Signal concentrated at the horizon

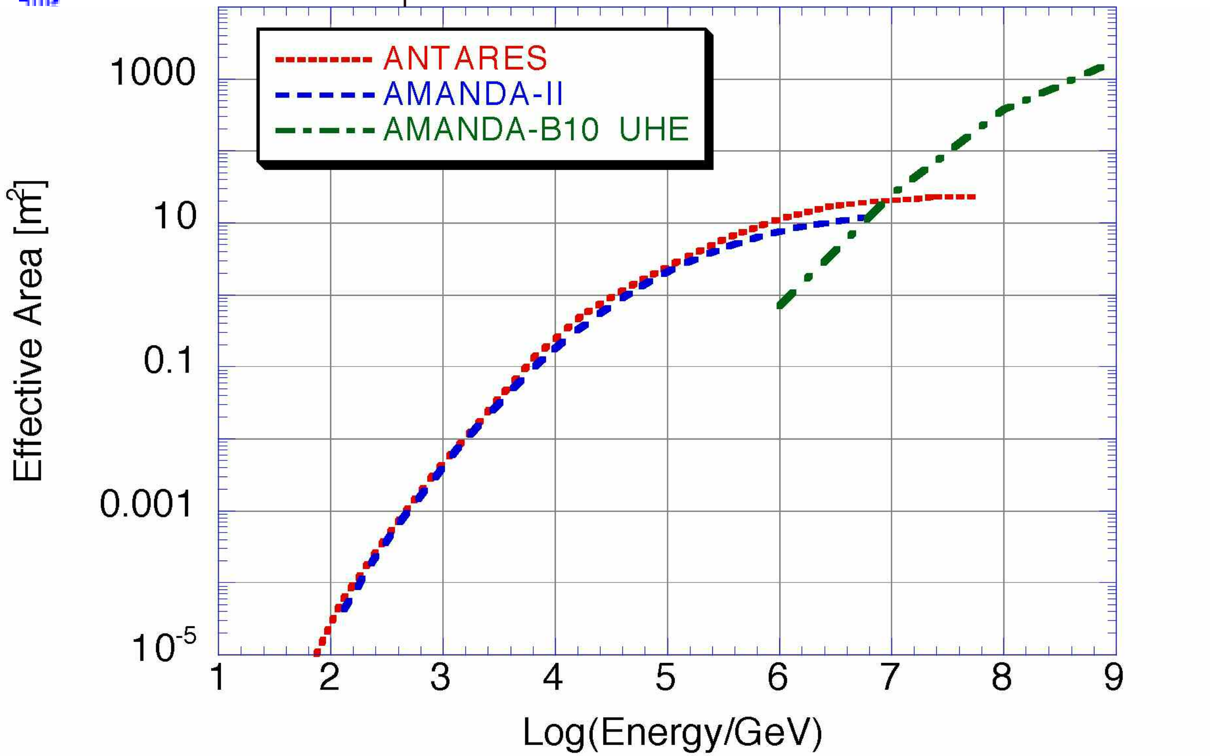




Can also use reconstruction variables to separate signal and background

UHE diffuse analysis





- Searched three years of data from 2000 - 2002
  - 456.8 days of livetime
- Found no significant excess

$$E^{-2}\,\Phi < 2.4 \times 10^{-7}\ \mathrm{GeV/(cm^2 ssr)}$$

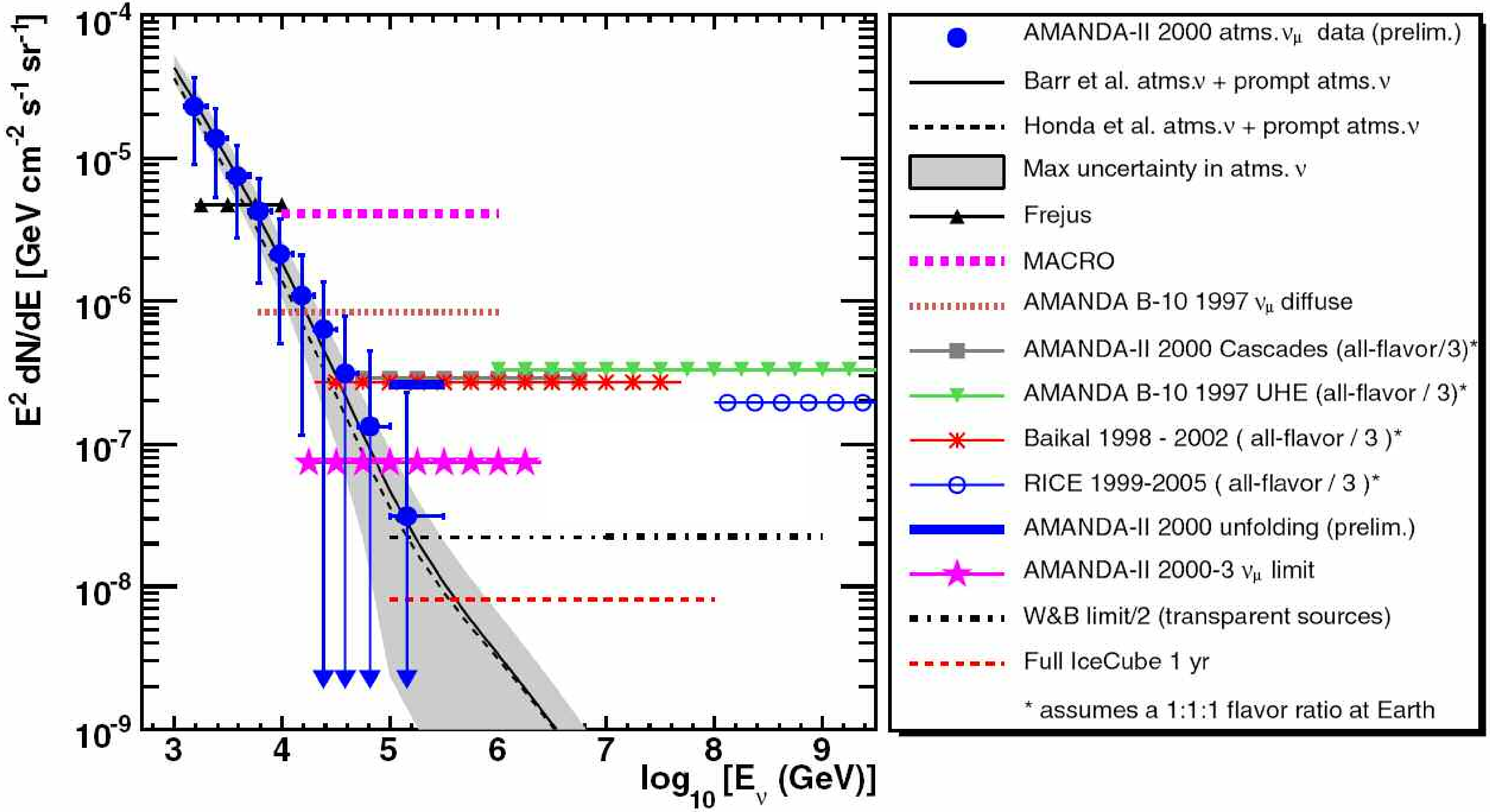
(PRELIMINARY)

valid over the energy range of

2×10^{5} GeV - 10^{9} GeV

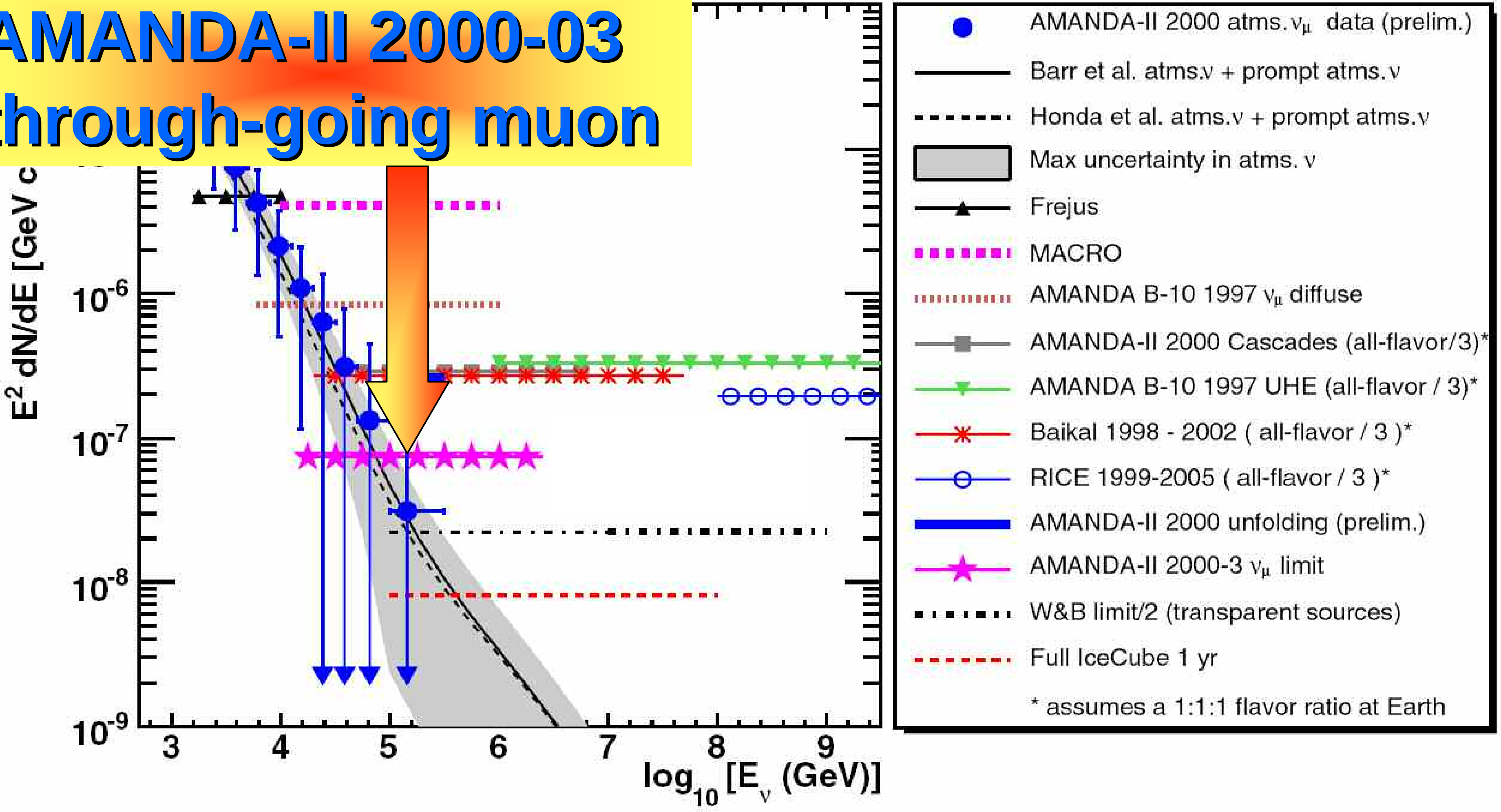
(including uncertainties)

All-flavour – divide by 3 to compare to muon limits

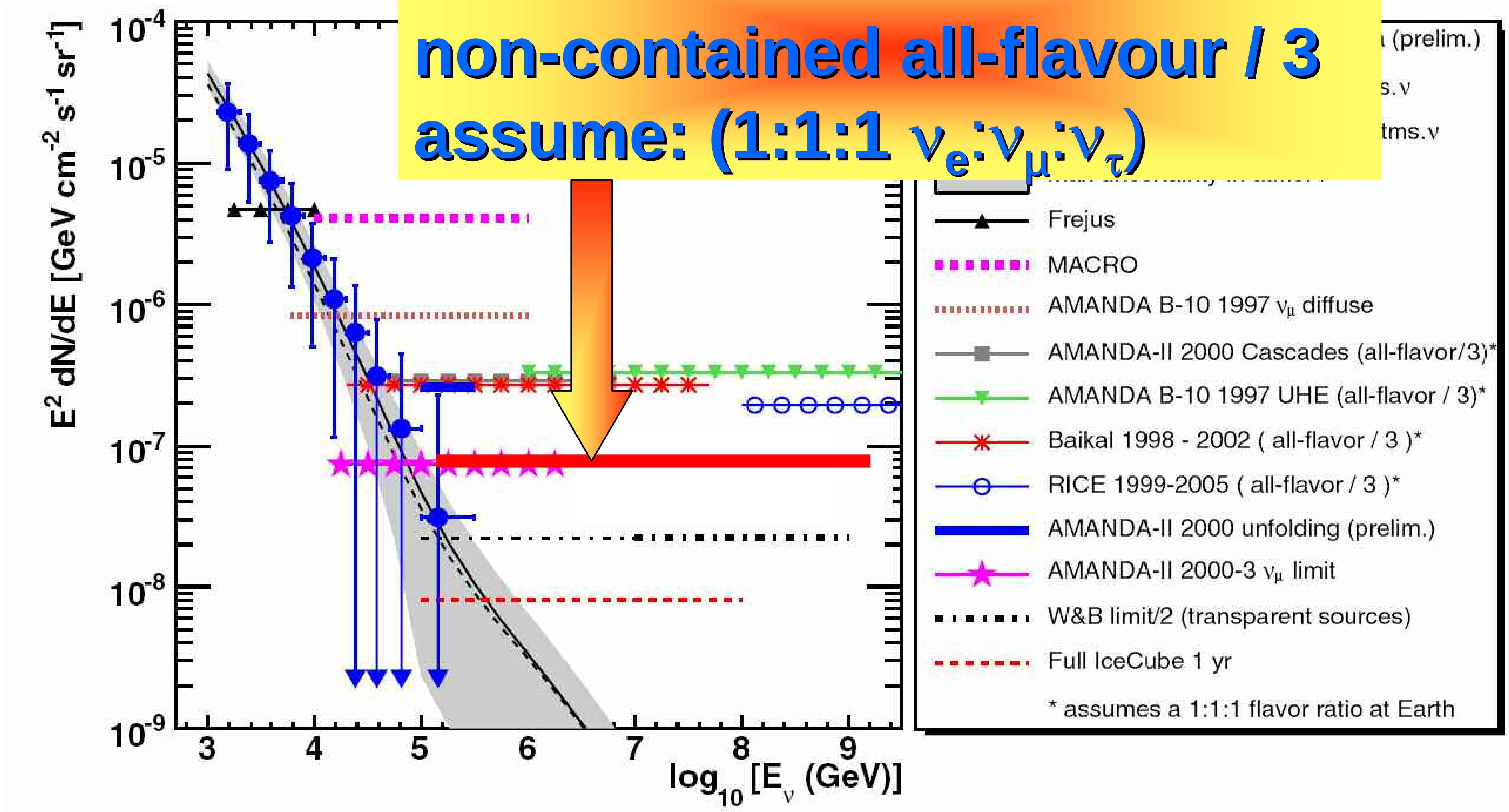


Gary C. Hill, TeV-III, Venice, August 29, 2007

AMANDA-II 2000-03 through-going muon

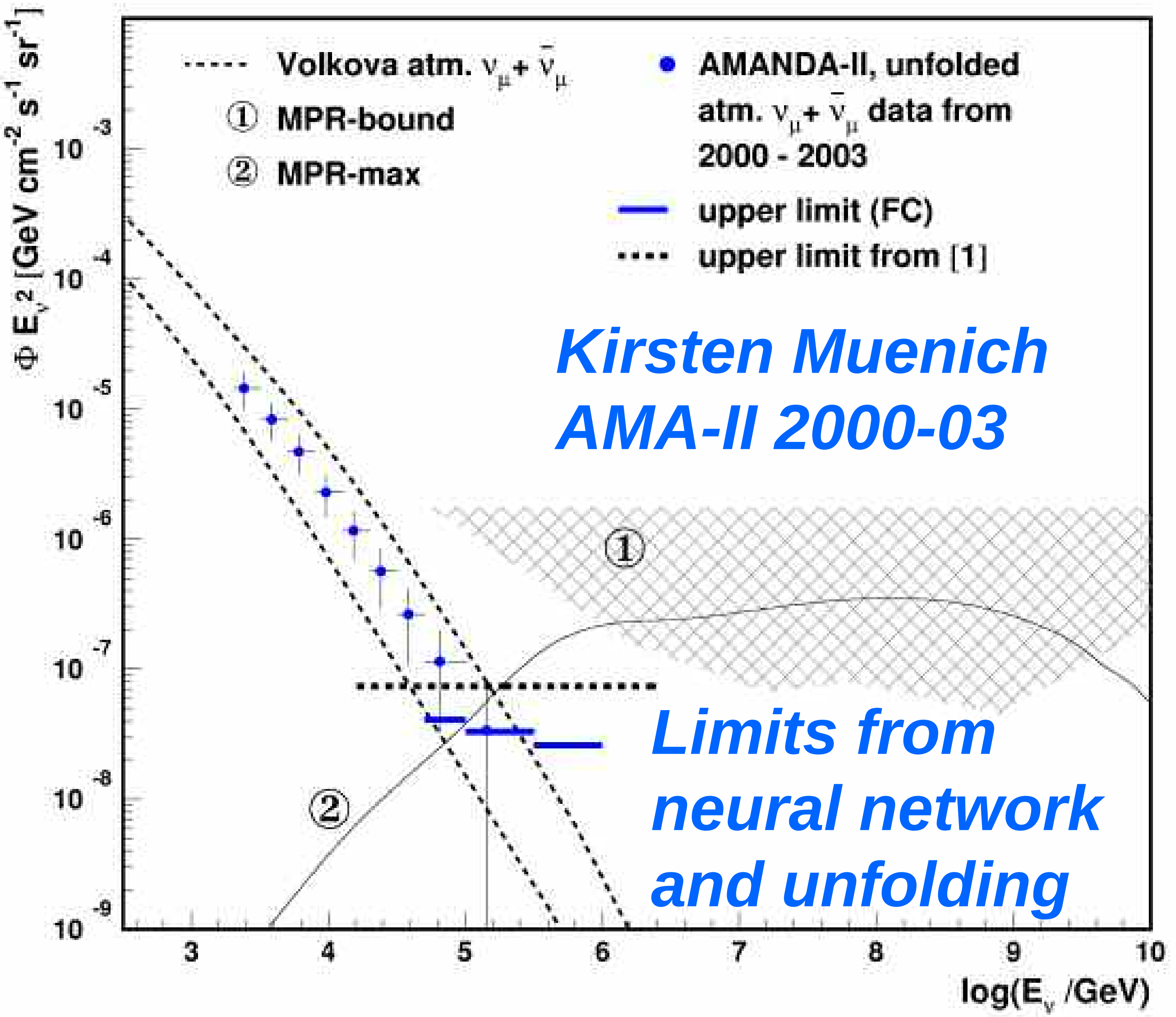


AMANDA-II 2000-02 UHE non-contained all-flavour / 3 assume: (1:1:1 $\nu_e:\nu_\mu:\nu_\tau$)



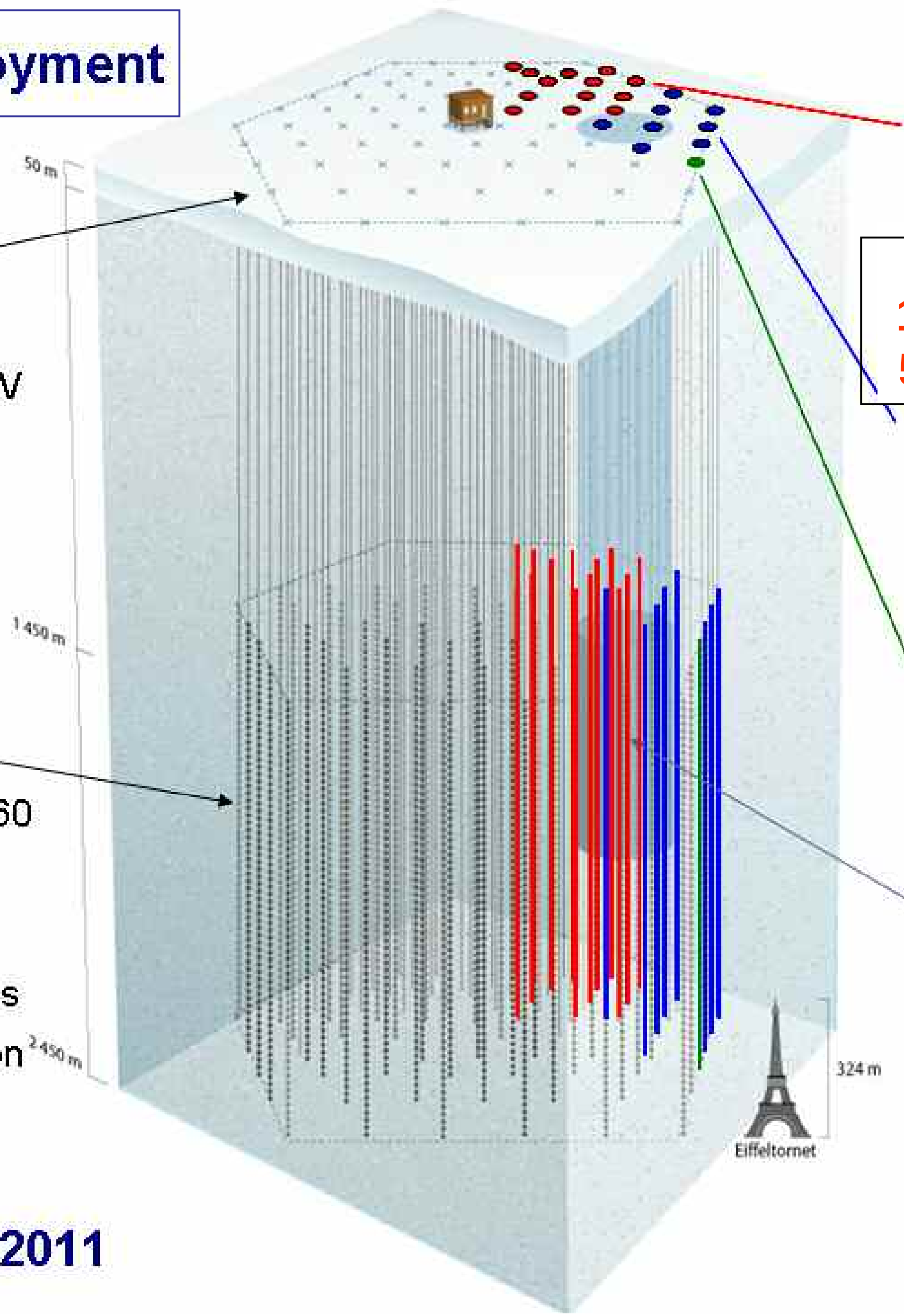
What next for diffuse analyses?

- IceCube 9 and 22 string analysis…
- "Cut and count" Poisson analysis constrains the sum of contributions in excess of the background
- Can constrain extra-terrestrial flux if you assume something about charm flux and vice-versa
- Will use information in the shape of the sensitive observables (likelihood analysis in e.g. Nch, zenith) to simultaneously detect/constrain the conventional, prompt and extra-terrestrial components
- multivariate methods, likelihood analysis



Volkova atm. $\nu_\mu + \bar{\nu}_\mu$
① MPR-bound
② MPR-max
AMANDA-II, unfolded atm. $\nu_\mu + \bar{\nu}_\mu$ data from 2000 - 2003
upper limit (FC)
upper limit from [1]
Kirsten Muenich
AMA-II 2000-03
Limits from neural network and unfolding
ΦE_ν^2 [GeV cm^{-2} s^{-1} sr^{-1}]
$\log(E_\nu$ /GeV)

IceCube Deployment



IceTop

Air shower detector

Threshold ~ 300 TeV

InIce

planned 80 strings of 60 optical modules each

17 m between modules

125 m string separation

2006-2007:

13 strings deployed

22 strings
1320 digital modules
52 surface detectors

2005-2006: 8 strings

2004-2005 : 1 string

First data in 2005
first upgoing muon:
July 18, 2005

AMANDA

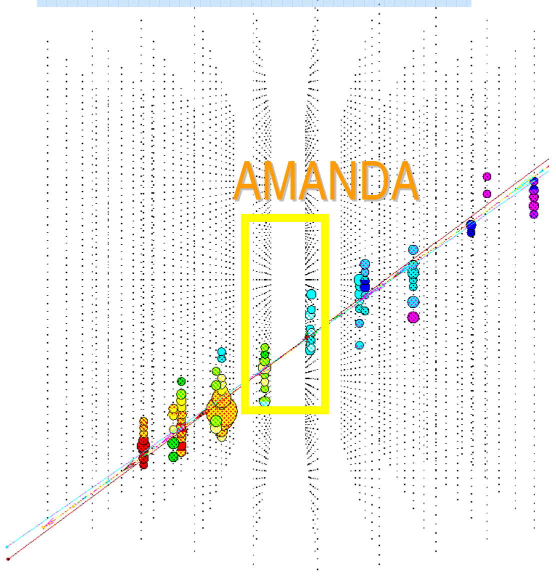
19 strings

677 modules

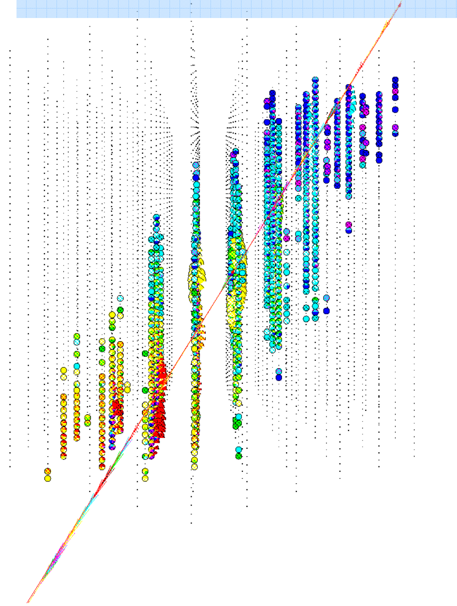
Completion by 2011

Event Signatures in IceCube

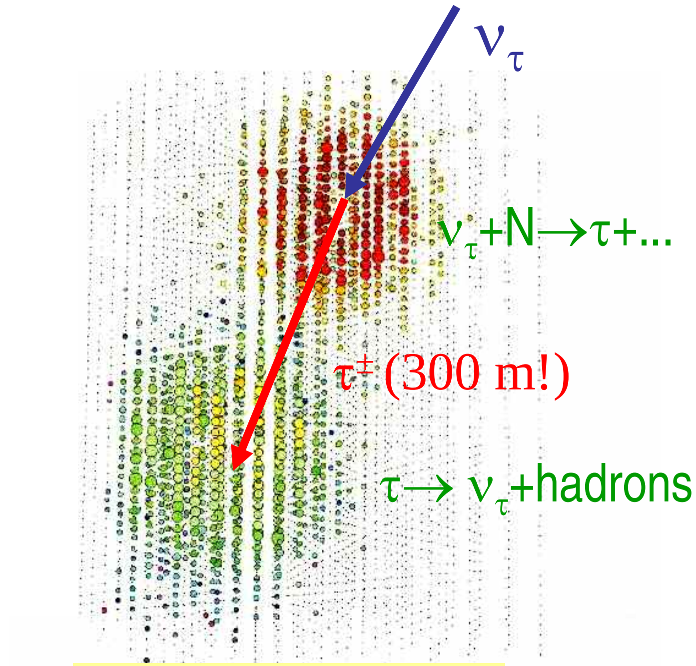
10^{13} eV (10 TeV)
~90 hits



6×10^{15} eV (6 PeV)
~1000 hits



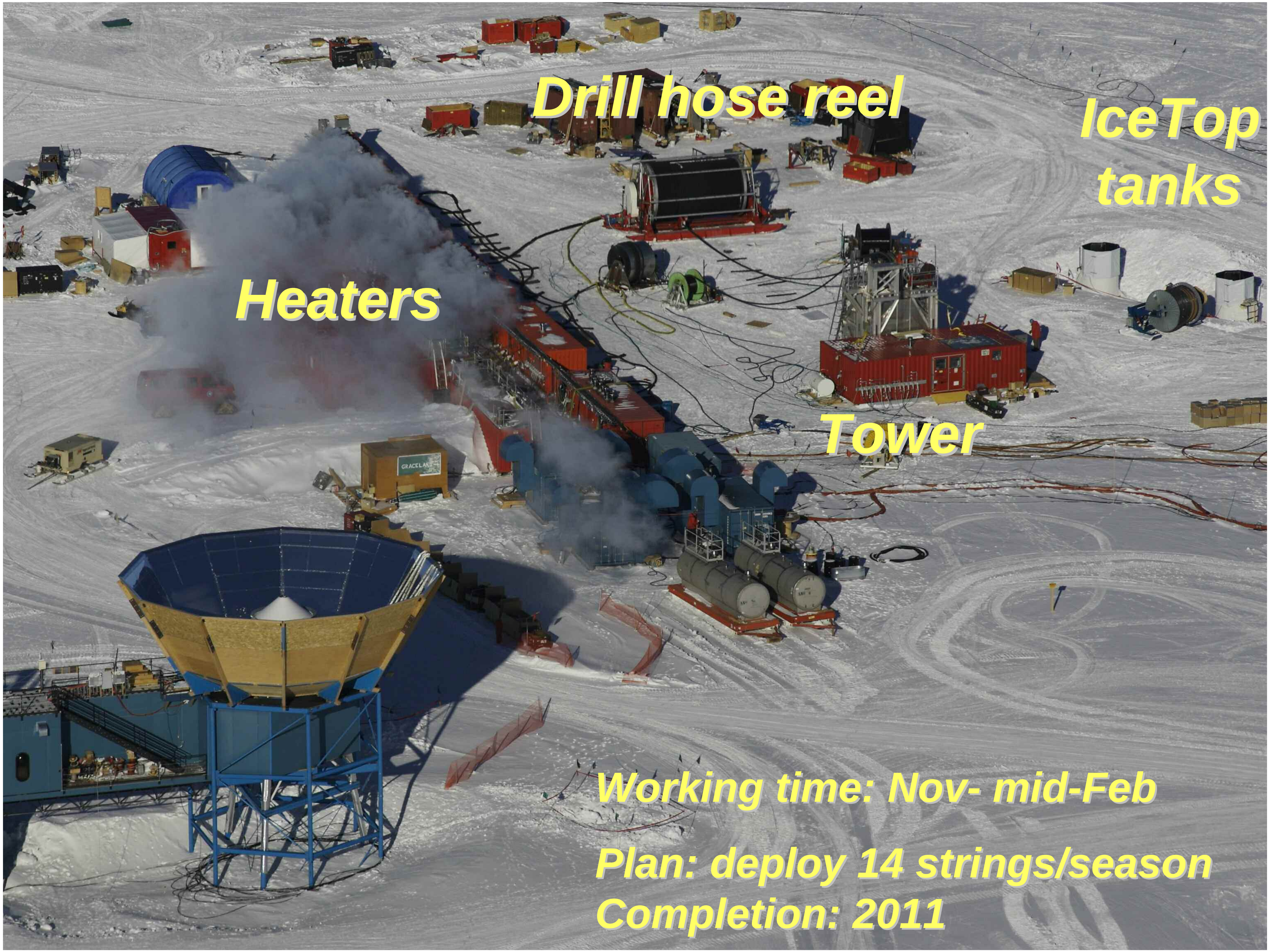
Multi-PeV



ν_μ signature

ν_τ signature

Expect about 100,000 events/yr

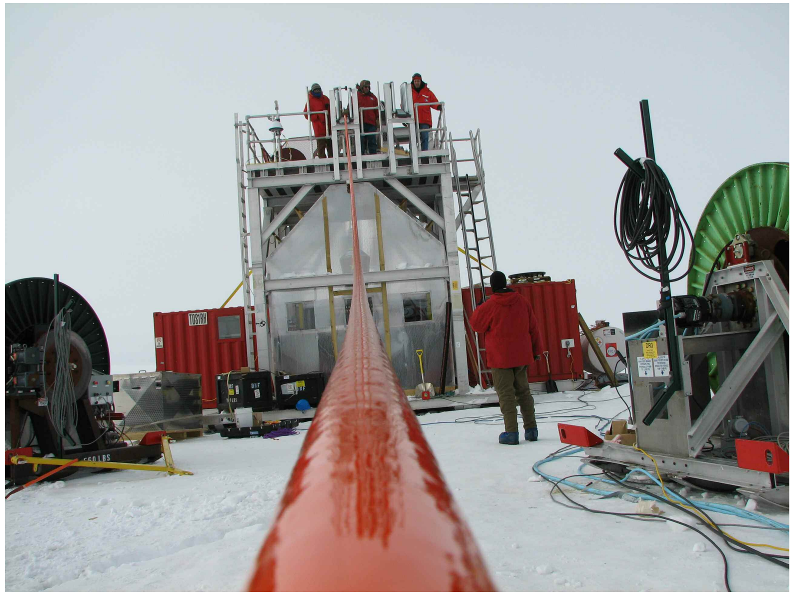

Drill hose reel
IceTop
tanks
Heaters
Tower
GRACELAND
Working time: Nov- mid-Feb
Plan: deploy 14 strings/season
Completion: 2011

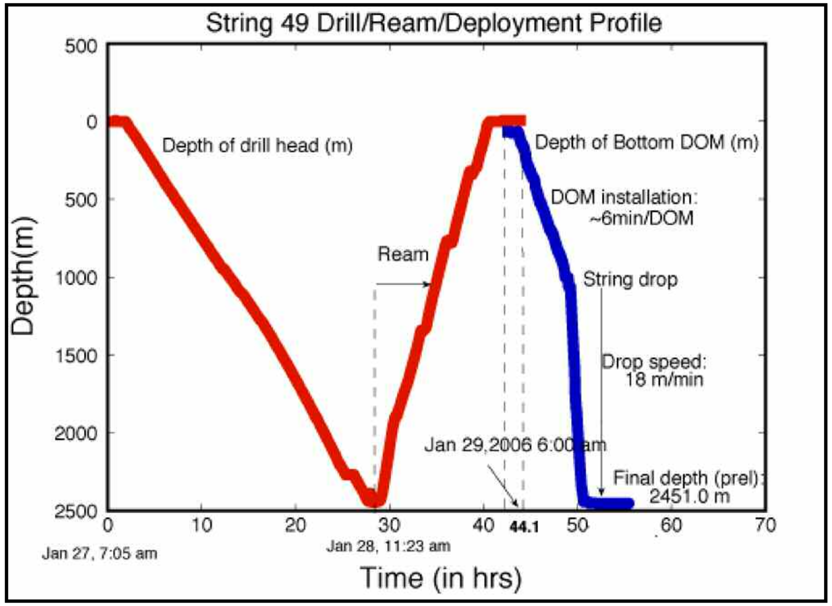
Hot Water Drilling

IceCube EHWD significant operation – entire drill camp setup, including generators, heater plants, fuel systems, and support workshops. This camp doesn't move during the season.

2 drill towers connect to central plants and leapfrog over holes.

Deployment

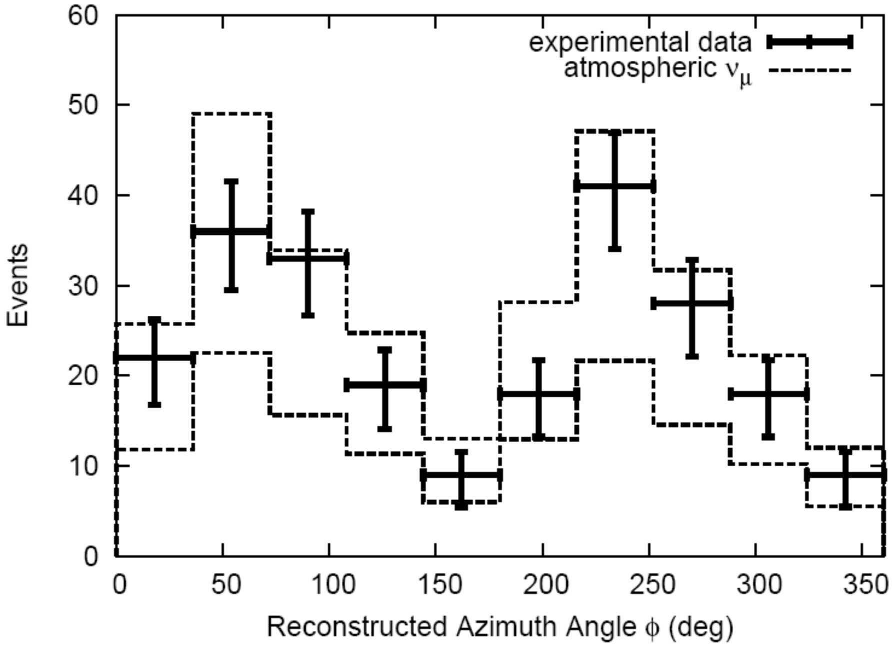


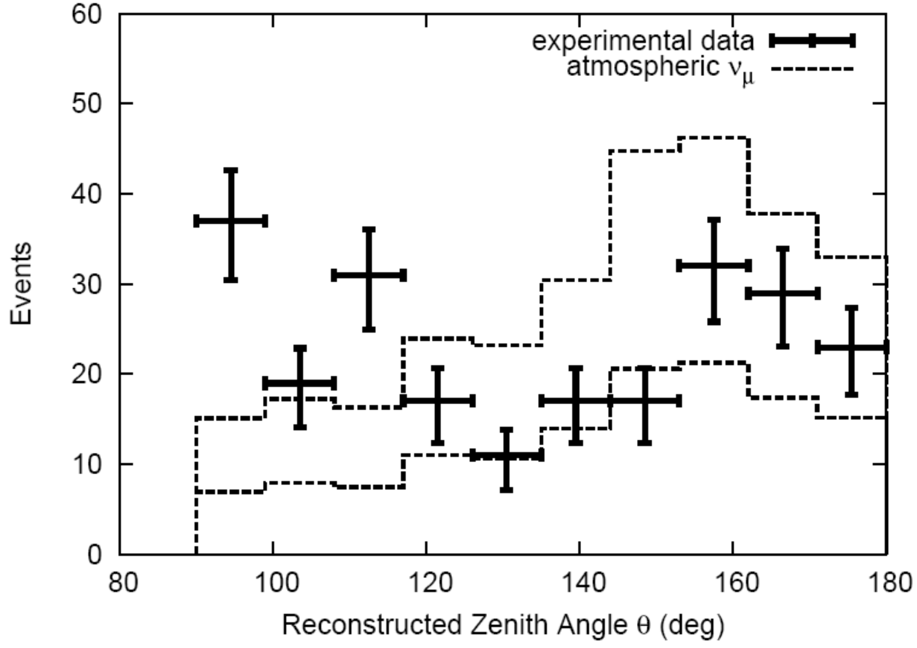


99% of 604 DOMs survive deployment and freeze-in

IC-9 atmospheric neutrinos

John Pretz





IC-9 diffuse – Kotoyo Hoshina
IC-22 under analysis!

Full IceCube detector

Table 3

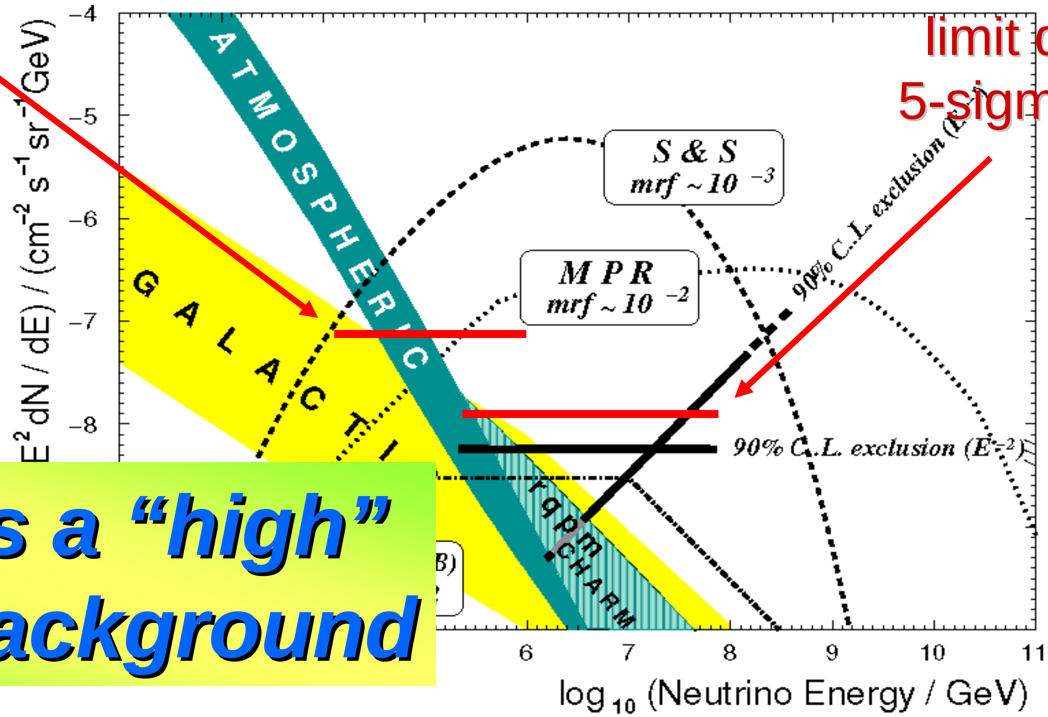
Sensitivity to diffuse neutrino fluxes. Expected limits and minimal detectable fluxes in units of $cm^{-2}s^{-1}sr^{-1}GeV$ for a generic E^{-2} source spectrum. Event numbers correspond to a hypothetical source strength of $E_\nu^2 \times dN_\nu/dE_\nu = 1 \times 10^{-7}\,cm^{-2}s^{-1}sr^{-1}GeV$.

years	N_{ch} **Cut**	$\langle n_s \rangle$	$\langle n_b \rangle$	$\bar{\mu}_{90}$	$E^2 \frac{dN}{dE}$ (90%c.l.)	$E^2 \frac{dN}{dE} (5\sigma)$
1	227	76.4	8.0	6.1	$8.1 \cdot 10^{-9}$	$2.6 \cdot 10^{-8}$
3	244	204.8	18.4	8.7	$4.2 \cdot 10^{-9}$	$1.2 \cdot 10^{-8}$
5	276	272.5	18.0	8.6	$3.2 \cdot 10^{-9}$	$9.9 \cdot 10^{-9}$

Using AMANDA simulation and analysis techniques

~1/10th of AMANDA-II limit detectable at 5-sigma in 3-5 years

AMANDA-II 2000-03 limit



Assumes a "high" charm background