DSF-36-2007, FERMILAB-PUB-07-582-A, IFIC/07-60

Disentangling neutrino-nucleon cross section and high energy neutrino flux with a km^3 neutrino telescope

E. Borriello[1,2], A. Cuoco[3], G. Mangano[1], G. Miele[1,2], S. Pastor[2], O. Pisanti[1], and P. D. Serpico[4]

[1] *Università "Federico II" Dipartimento di Scienze Fisiche, & INFN Sezione di Napoli, Napoli, Italy*

[2] *AHEP Group, Institut de Física Corpuscular, CSIC/Universitat de València, Apt. 22085, 46071 València, Spain*

[3] *Department of Physics and Astronomy, University of Aarhus, Ny Munkegade, 8000 Aarhus, Denmark, and*

[4] *Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, IL 60510-0500 USA*

(Dated: November 1, 2007)

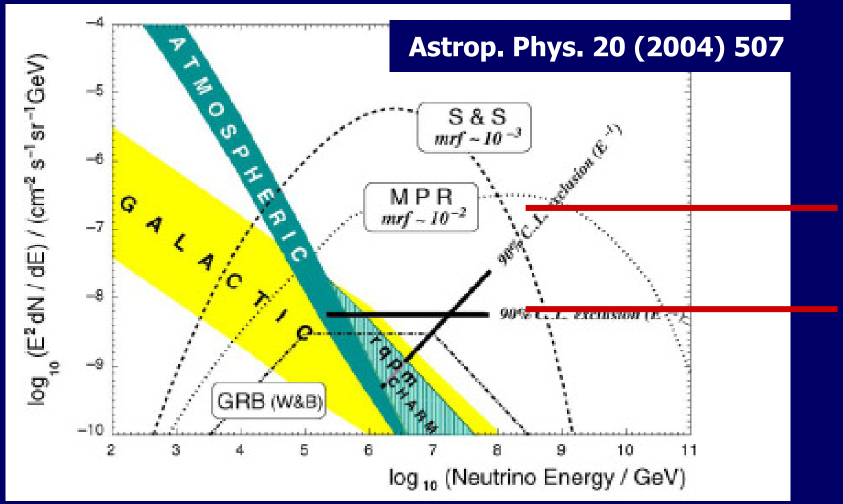
Ofelia Pisanti

Dipartimento di Scienze Fisiche and INFN - Napo

Seminari teorici del giovedì, 22 novembre 2007

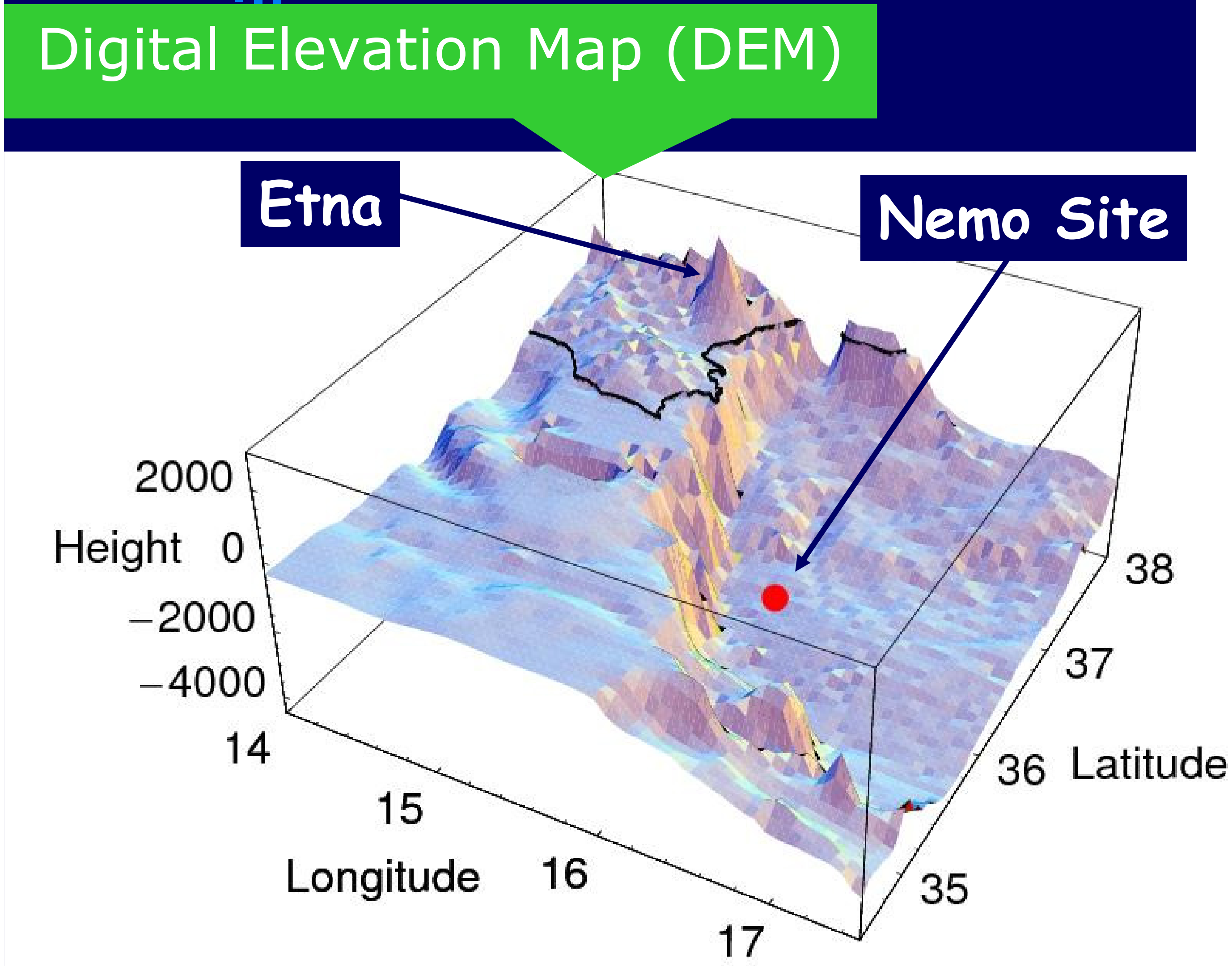
Why to detect UHE ν at a 1 km^3 neutrino telescope?

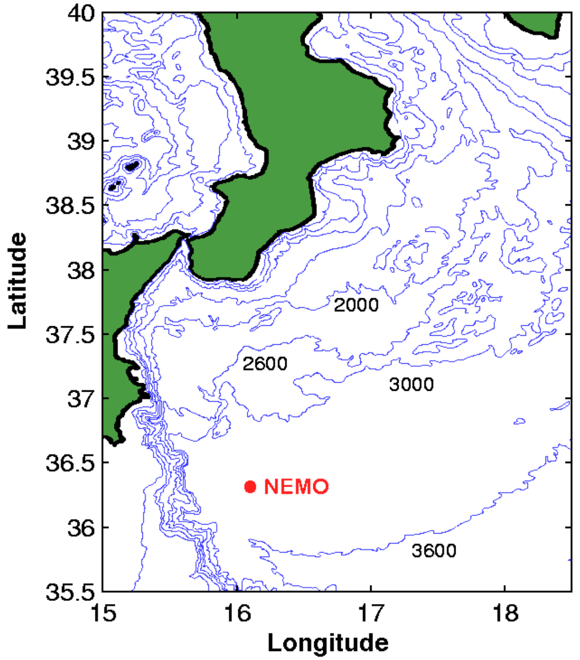
• ***Astrophysical motivation***. Neutrinos are a component of the cosmic radiation and, at these energies, the extragalactic contribution dominates on the galactic one. One can do neutrino astronomy pointing to sources at cosmological distances and get information on their internal engines.



• ***Particle physics motivation***. Neutrinos only interact weakly in the SM. Any new physics that affects particle interactions is more likely to be detected in the neutrino sector.

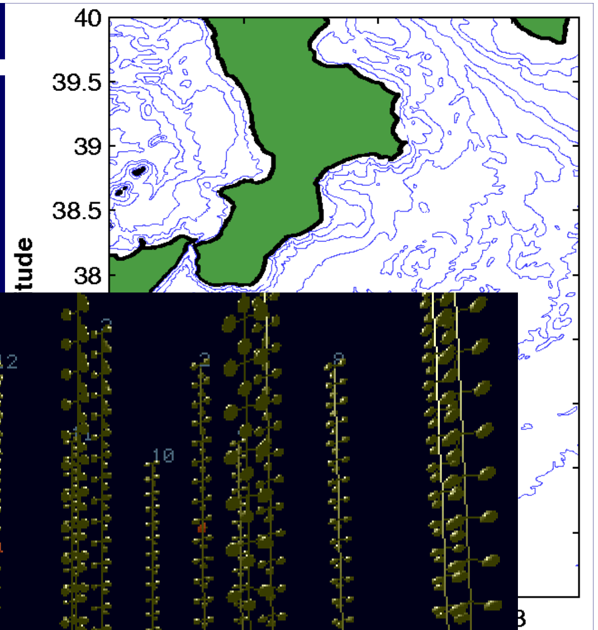
Nemo experiment

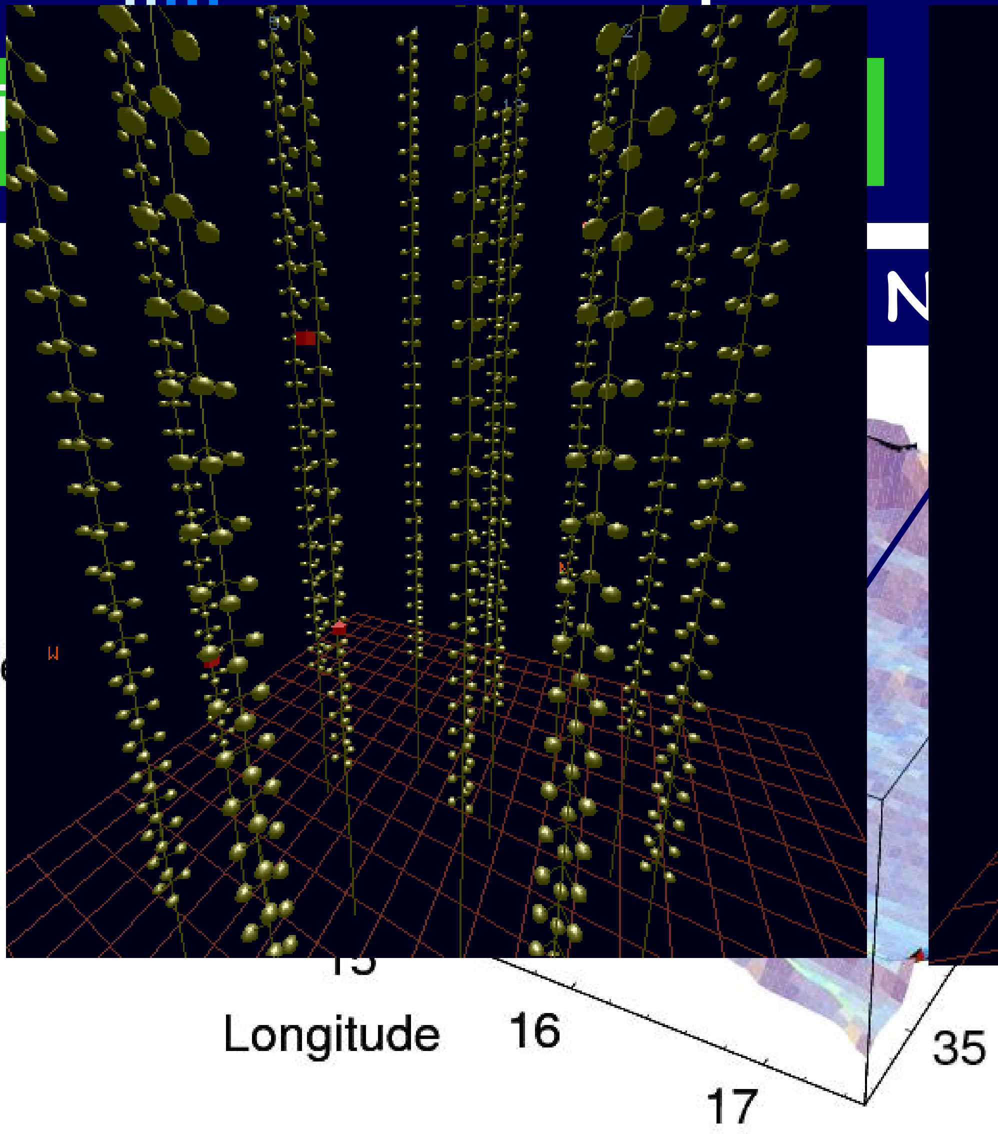


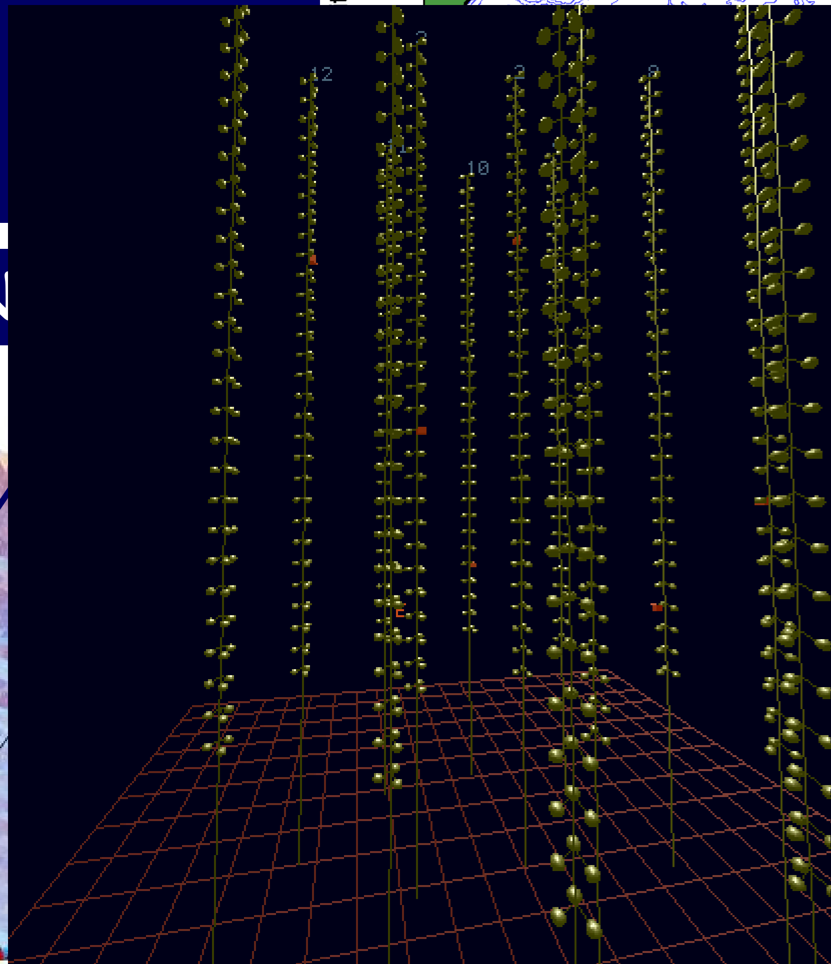


- Site Location
  36°21′ N, 16°10′ E
- Average Deep
  ~3500 m
  (3424 in our simulation)

Nemo experiment

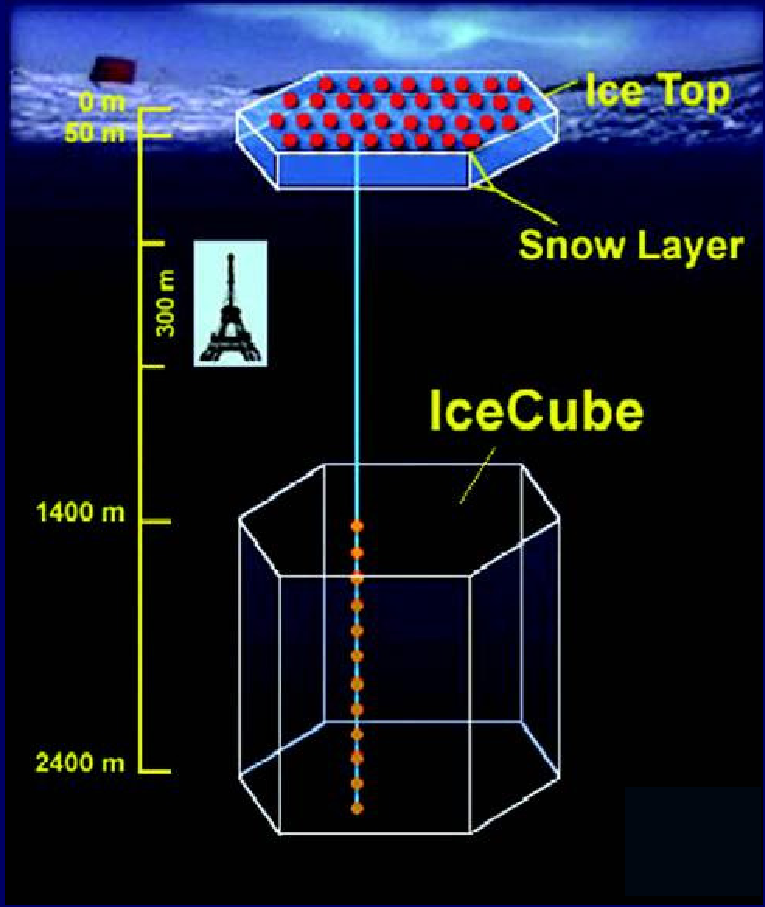






IceCube experiment

After the completion, in the same location, of the successful experiment Amanda-II, the extension to a km3, IceCube, is being installed at the South Pole during Austral summers and will be operational in 2010 approximately. The IceCube In-Ice detector will consist of a minimum of 4800 optical modules deployed on 80 vertical strings buried 1400 to 2400 meters under the surface of the ice, and an IceTop surface air-shower detector array with 160 Auger-like Ĉerenkov detectors.



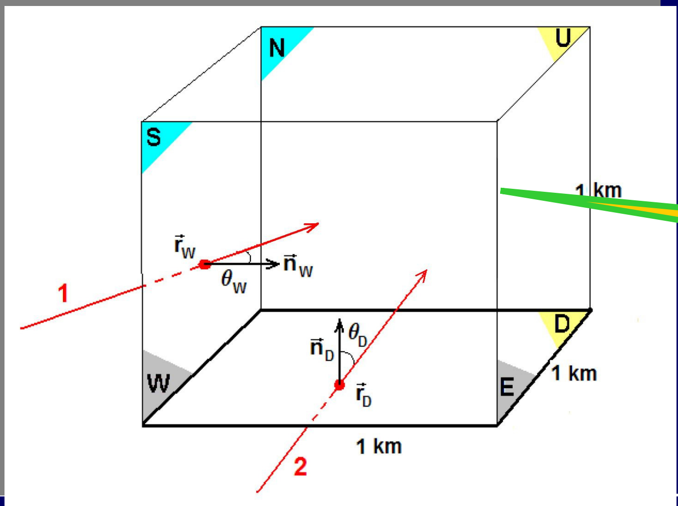
The rate of events in 1 km^3

$$\frac{dN_l}{dt} = D \sum_a \int d\Omega_a \int dS_a \int dE_\nu \frac{d^2\Phi_\nu(E_\nu)}{dE_\nu d\Omega_a} \int dE_l\, \varepsilon(E_l) \cos(\theta_a)\, k_a^l(E_\nu, E_l; \vec{r}_a, \Omega_a)$$

From now on equal to 1

Probability that an incoming ν, with energy E_ν and direction Ω_a, crossing the earth or the water, produces a lepton l which enters the fiducial volume with energy E_l, through the lateral surface dS_a at the position r_a.

Same calculation for Auger in PLB634:137-142,2006



Fiducial volume,
no experiment characteristics, just able to distinguish track and showers

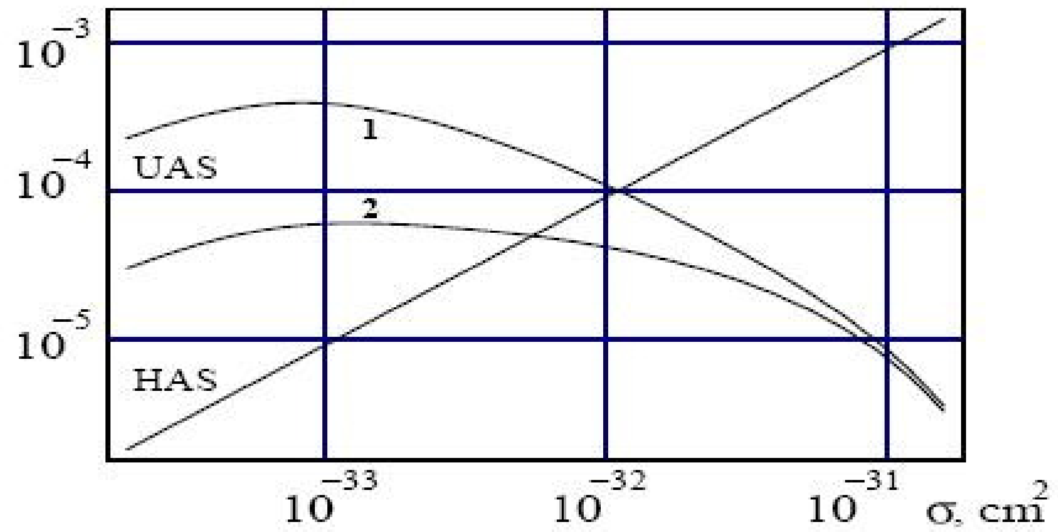
a = W, E, S, N, U, D

Disentangling flux from cross section

Event rate at neutrino telescopes depend on cross section and flux. Is there any possibility of inferring both of them with some “clever” measurement?

Kusenko & Weiler, Phys.Rev.Lett.88:161101,2002

$E_\nu = 10^{20}$ eV



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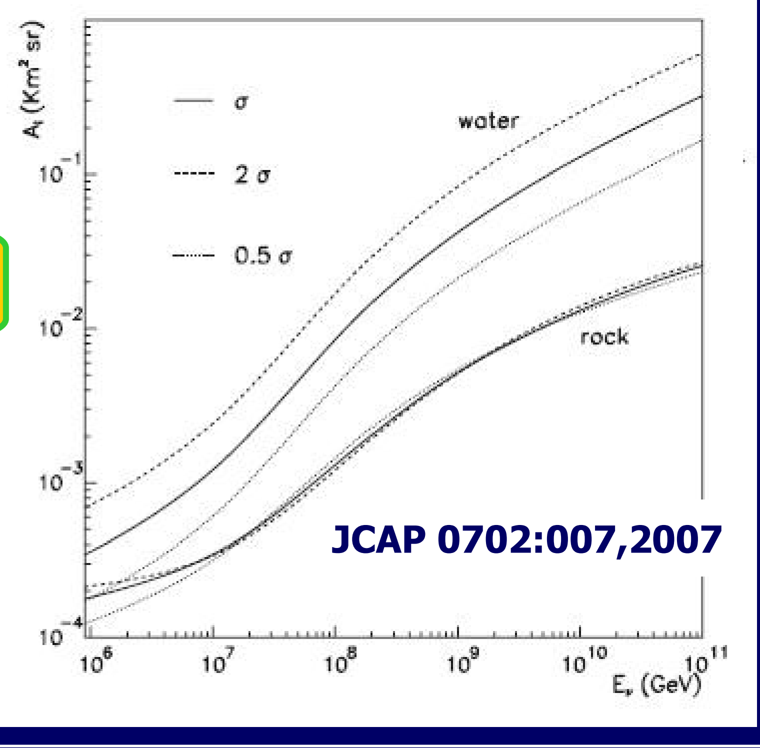
In a previous work we had observed that two class of events (***water*** and ***rock***) had a different behavior with cross section.

$$\frac{dN_\tau}{dt} = \sum_a \int dE_\nu \frac{d^2\Phi_\nu(E_\nu)}{dE_\nu d\Omega_a} A_a^\tau(E_\nu)$$

aperture



JCAP 0702:007,2007

But this classification correspond to a very simple angular binning. Can we do better?

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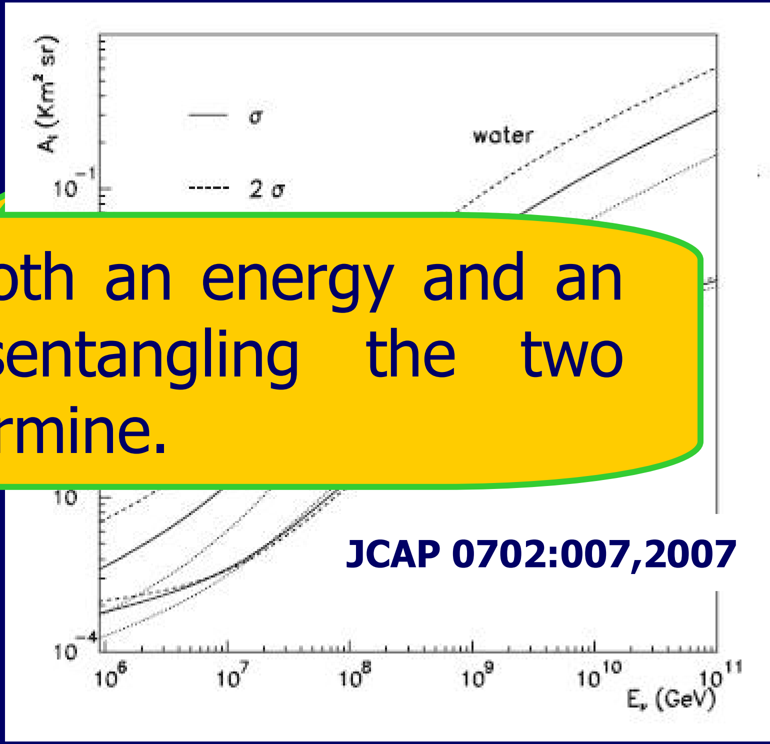
$$\frac{dN}{dt}$$

The idea is then to use both an energy and an angular binning for disentangling the two quantities we want to determine.



JCAP 0702:007,2007

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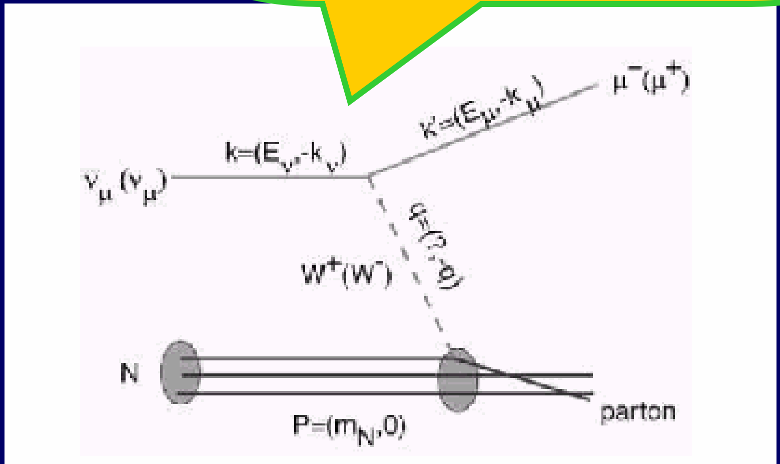
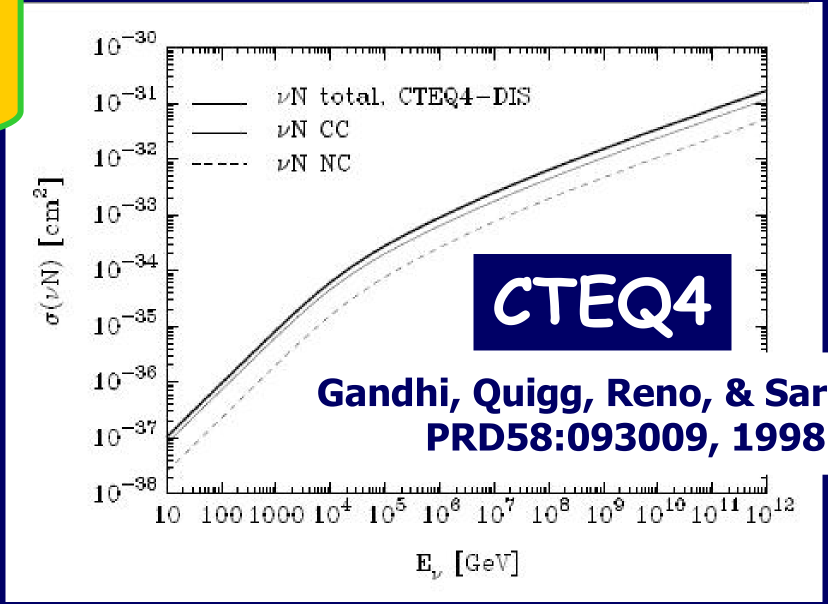
Neutrino interactions

$x = Q^2/2m_N E_\nu$
$E_\nu = 10^7$ GeV $\Leftrightarrow$ $x \sim 10^{-4}$





CTEQ4

Gandhi, Quigg, Reno, & Sarcevic, PRD58:093009, 1998

$$\frac{\sigma_{CC}^{\nu N}}{10^{-33}\,\mathrm{cm}^2} = \begin{cases} 0.344\left(\frac{E_\nu}{E_1}\right)^{0.492\,A} & E_1 \le E_\nu \le E_2 \\ 0.344\left(\frac{E_2}{E_1}\right)^{0.492\,A}\left(\frac{E_\nu}{E_2}\right)^{0.492\,B} & E_\nu > E_2 \end{cases},$$

$$\frac{\sigma_{NC}^{\nu N}}{0.418\cdot 10^{-33}\,\mathrm{cm}^2} = \begin{cases} 0.344\left(\frac{E_\nu}{E_1}\right)^{0.492\,A'} & E_1 \le E_\nu \le E_2 \\ 0.344\left(\frac{E_2}{E_1}\right)^{0.492\,A'}\left(\frac{E_\nu}{E_2}\right)^{0.492\,B'} & E_\nu > E_2 \end{cases}.$$

$$E_1 = 10^{5.5}\,GeV \quad E_2 = 10^6\,GeV$$

Simple parameterization with possible deviations from the standard value at $E > E_1 = 10^{5.5}$ GeV

The ratio between CC and NC cross section is "standard" at E_1 and in case A=A' and B=B'.

Theoretical scenarios

We will considered two scenarios:

• CC and NC cross section changes proportionally to each other: A=A' and B=B'

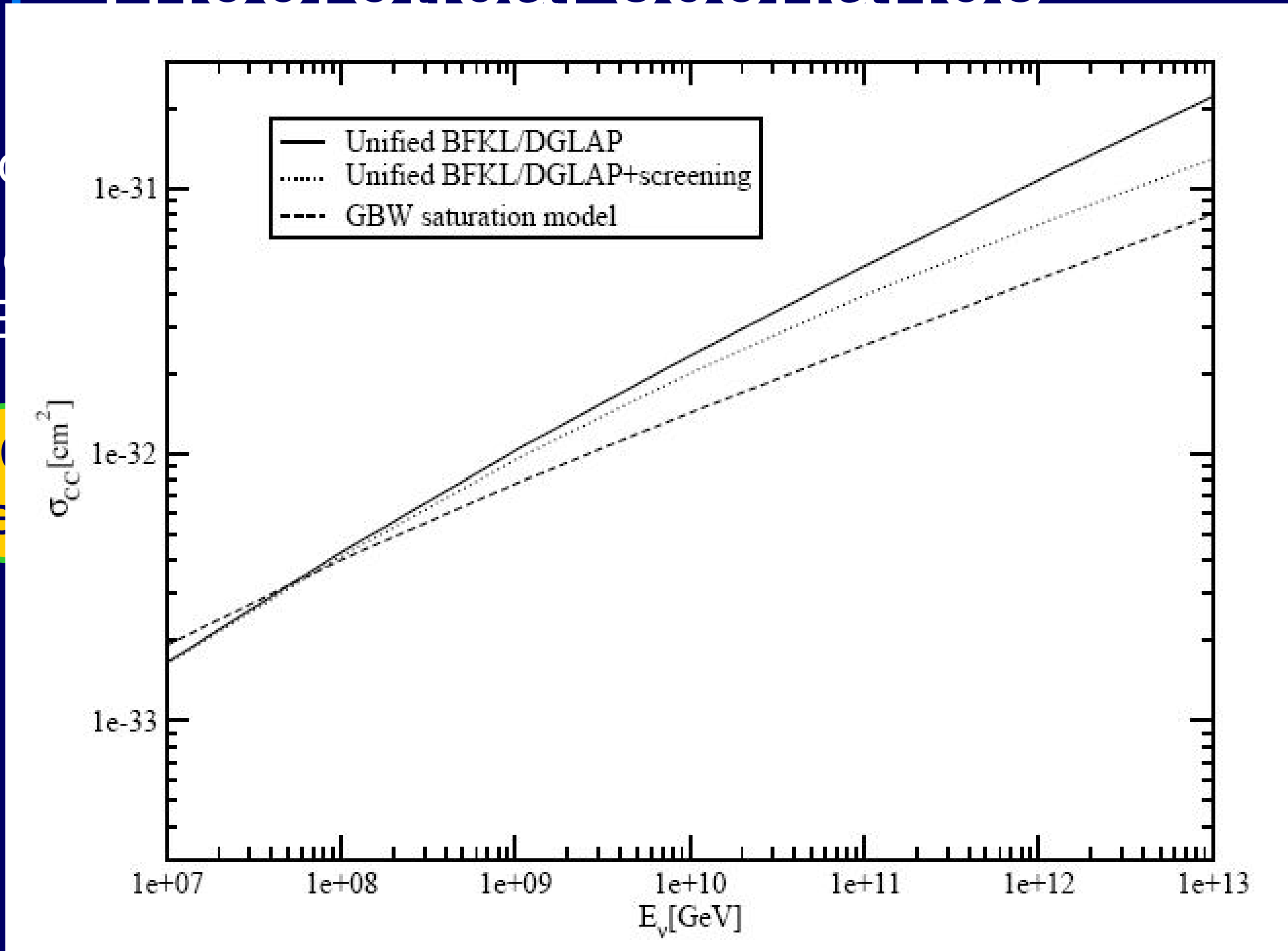
QCD saturation effects alter the growth predicted for cross sections (Kutak & Kwiecinski, Eur.Phys.J.C29:521,2003).

Theoretical scenarios

We will c

• CC an ... er: A=A' and B=B

Q ... ss
se



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• CC cross section is standard, only NC cross section is free: A=B=1

New neutral current interactions, such as might occur due to graviton exchange (Alvarez-Muniz, Halzen, Han & Hooper, Phys.Rev.Lett.88:021301,2002.

Theoretical scenarios

We will c

• CC an[...]er: A=A'
and B=B

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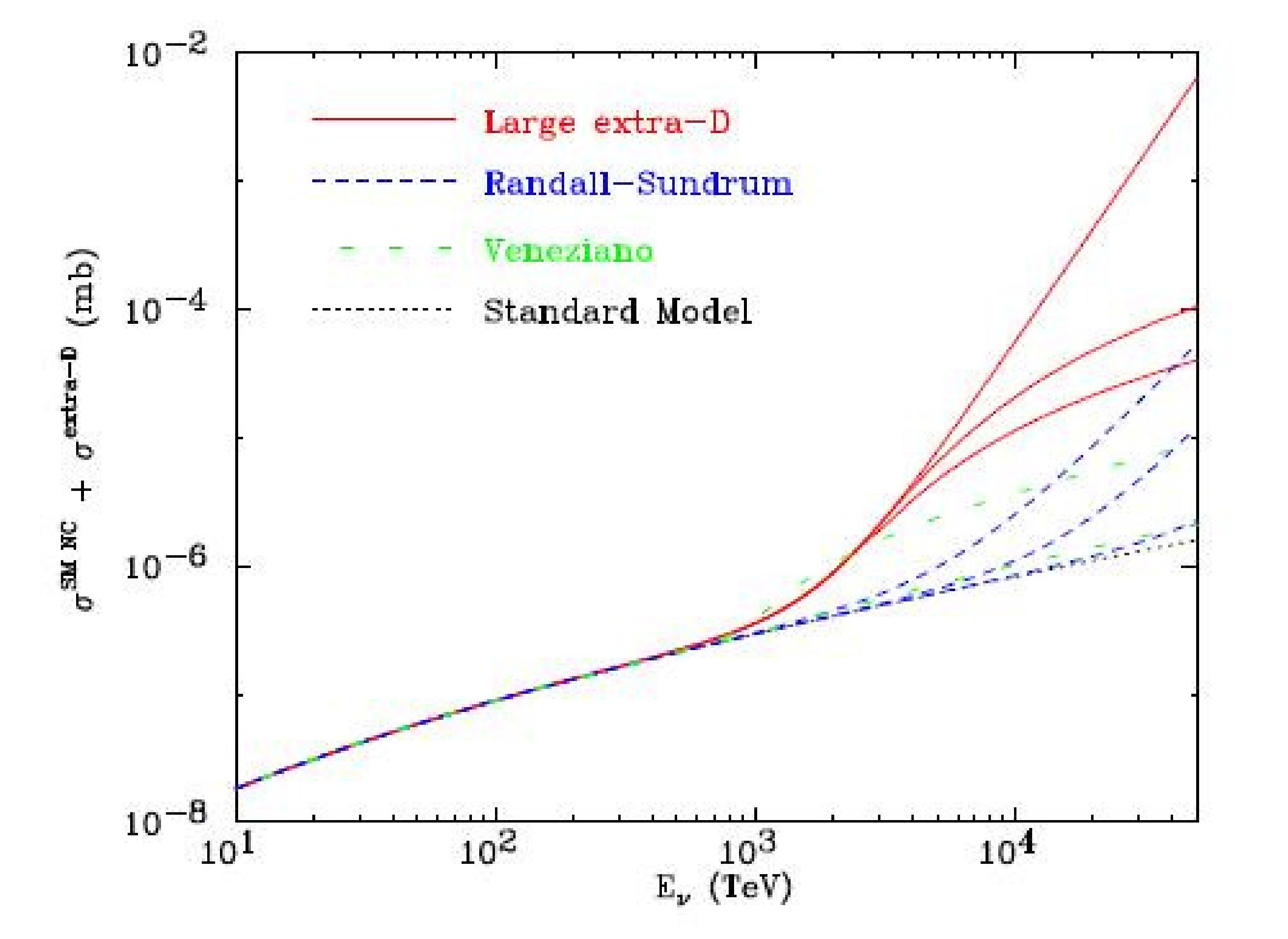

Neutrino fluxes

Anchordoqui & Halzen, Annals Phys.321:2660-2716,2006

We parameterize the neutrino flux per flavor (oscillations imply flavor ratios 1:1:1 at earth), summing neutrinos and antineutrinos, as

$$\phi_\nu(E_\nu) \equiv \frac{\mathrm{d}^2\Phi_\nu}{\mathrm{d}E_\nu\,\mathrm{d}\Omega}(E_\nu) = 1.3 \cdot 10^{-20}\, C\, \left(\frac{E_\nu}{1\,\mathrm{PeV}}\right)^{-2\,D} \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1},$$

C=D=1 corresponds to the case of a Waxman-Bahcall flux. Note that, in the theoretical model generation, one can fix *C=1*, since it is just a multiplicative normalization, with the same effect on the event number of the exposure time, *T*, needed to achieve the proper event statistics.

This does not mean that we are only sensible to the product *CT,* since the final χ^2 will be sensible to both of them separately.

Experiment observables

Electron neutrinos can only induce ***shower events (NC or CC) inside the fiducial volume***, while muon and tau neutrinos can also ***produce leptons in a CC interaction out of it***, which then can propagate to the telescope. A ***track*** is an event for which the intersection of the trajectory of the lepton with the fiducial volume is longer than 0 and shorter than the lepton decay length. The remaining detectable events are classified as ***showers***. Taking this into account, we end with three observables:

- the energy deposited in the detector, ΔE
- the topology of the event (shower or track)
- the direction of the event

Energy deposited

NC events are detectable only if they are ***contained*** (that is, neutrino converts inside the fiducial volume). In this case, the energy deposited, known the inelasticity *y*, is given by $y\,E_\nu$. For CC events, the remaining energy, $(1-y)\,E_\nu$, is deposited too if the event is a shower. A track event, on the other side, releases an energy corresponding to the energy loss of the given lepton in water.

$$\frac{dE_l}{dx} = -\beta_l E_l \rho_w$$

$$\beta_\mu = 0.58 \cdot 10^{-5}\, cm^2 g^{-1}$$
$$\beta_\tau = 0.71 \cdot 10^{-6}\, cm^2 g^{-1}$$

$$l_\mu = 60 \cdot 10^5\, km \left(E_\mu / 10^6\, GeV\right)$$
$$l_\tau = 50m \left(E_\tau / 10^6\, GeV\right)$$

CC events not contained, where the neutrino converts out of the detector, gives a lepton which can propagate up to the fiducial volume, with energy losses calculated in rock (***upgoing events***) or water (***downgoing events***).

Energy deposited

NC events are detectable only if they are ***co*** … trino
converts inside the fi… In this ca… ed,
known the inelastici… For … ing
energy, *(1-y)* E_ν, is … vent i… ent,
on the other side, r… rresp… oss
of the given lepton in wa…

the muon energy losses are larger than the tau ones

the tau decay length is much smaller than the muon one

$$\frac{dE_l}{dx} = -\beta_l E_l \rho_w$$

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Energy deposited

NC events ... trino conv... ed, know... ng ener... nt, on t... ss of the g...

Since it is not always possible to use the detailed topology of the event for distinguishing among different flavors, we will sum on all flavors in calculating the event rates.

$$\frac{dE_l}{dx} = -\beta_l E_l \rho_w$$

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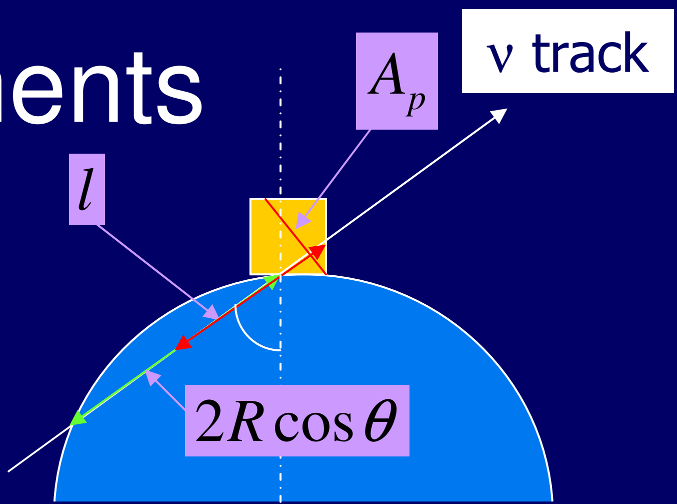
Qualitative arguments



s^{-1} m^{-2} sr^{-1} GeV^{-1}

Event rate can be written as

$$\Gamma(E_\nu) = \int d\Omega \, A_{eff} \frac{d\phi}{d\Omega}$$

where the ***effective area***, $A_{eff} \cong n\sigma V_{eff}$, can be approximated as the detector effective volume, $A_p l$, divided by the neutrino interaction length.

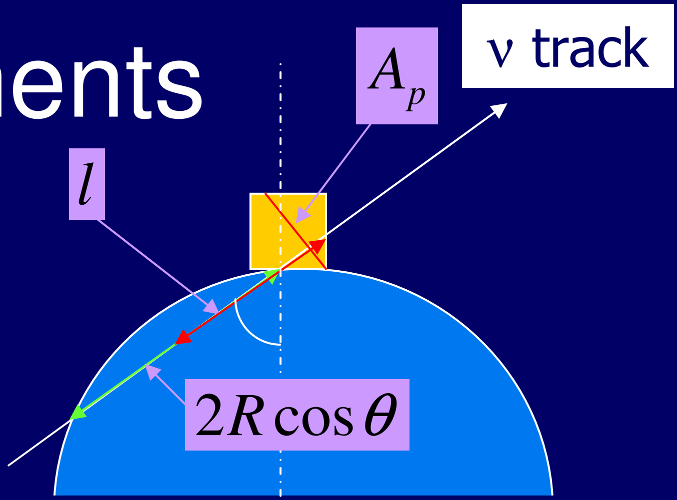
$$A_{eff} \cong \frac{A_p l}{\lambda} \quad \Rightarrow \quad \Gamma(E_\nu) \cong \Omega_d \frac{d\phi}{d\Omega} \frac{A_p l}{\lambda}$$

A_p = area of the detector projected against the neutrino direction

l = portion of the neutrino path to which the detector is sensitive

Ω_d = solid angle over which event flux is not zero

Qualitative arguments



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A_p = area of the detector projected against the neutrino direction

l = portion of the neutrino path to which the detector is sensitive

Ω_d = $2\pi - \int_0^{\theta} \sin\theta' \, d\theta' \int_0^{2\pi} d\varphi = 2\pi\cos\theta$ flux is not zero

Shower events

For downgoing neutrinos, one can assume that there is no attenuation of the flux in water (the detector is at a shallow depth, *d*, compared to the absorption length for neutrinos). Then, the solid angle is 2π, *l* coincides with the detector scale, *s*, and the interaction length is given by the total cross section,

$$\Gamma_{sh,dw}(E_\nu) \cong 2\pi \frac{d\phi}{d\Omega}\frac{A_p s}{\lambda_t} \approx \frac{d\phi}{d\Omega}\sigma_t$$

For upgoing neutrinos, the solid angle is limited by the attenuation length in earth, λ_a, $2R\cos\theta < \lambda_a$

$$\Omega_d = 2\pi\sin\theta = \frac{\pi\lambda_a}{R}$$

→

$$\Gamma_{sh,up}(E_\nu) \cong \frac{\pi\lambda_a}{R}\frac{d\phi}{d\Omega}\frac{A_p s}{\lambda_t} \approx \frac{d\phi}{d\Omega}\frac{\sigma_t}{\sigma_a}$$

Track events

Differently from the previous case, here the interaction length is given by the CC cross section and *l* is the minimum distance among the lepton stopping range due to energy loss, the decay length, and the path length in the matter out of the detector. For downgoing neutrinos

$$\Gamma_{tr,dw}(E_\nu) \cong 2\pi \frac{d\phi}{d\Omega}\frac{A_p l}{\lambda_{CC}} \approx \frac{d\phi}{d\Omega}\sigma_{CC}$$

For upgoing neutrinos, the same considerations of the shower case are valid for the solid angle

$$\Omega_d = 2\pi \sin\theta = \frac{\pi\lambda_a}{R} \quad \Rightarrow \quad \Gamma_{tr,up}(E_\nu) \cong \frac{\pi\lambda_a}{R}\frac{d\phi}{d\Omega}\frac{A_p l}{\lambda_{CC}} \approx \frac{d\phi}{d\Omega}\frac{\sigma_{CC}}{\sigma_a}$$

Expectations

Scenario I

$$\sigma_t = (1+k)\sigma_{CC}$$

$$\sigma_a = \sigma_t = (1+k)\sigma_{CC}$$

$$\Gamma_{sh,dw}(E_\nu) \approx \frac{d\phi}{d\Omega}\sigma_t = \frac{d\phi}{d\Omega}(1+k)\sigma_{CC}$$

$$\Gamma_{tr,dw}(E_\nu) \approx \frac{d\phi}{d\Omega}\sigma_{CC}$$

$$\Gamma_{sh,up}(E_\nu) \approx \frac{d\phi}{d\Omega}\frac{\sigma_t}{\sigma_a} = \frac{d\phi}{d\Omega}$$

$$\Gamma_{tr,up}(E_\nu) \approx \frac{d\phi}{d\Omega}\frac{1}{(1+k)}$$

Scenario II

$$\sigma_t = \sigma_{CC}^{st} + \sigma_{NC}$$

$$\sigma_a = \sigma_t = \sigma_{CC}^{st} + \sigma_{NC}$$

$$\Gamma_{sh,dw}(E_\nu) \approx \frac{d\phi}{d\Omega}\sigma_t = \frac{d\phi}{d\Omega}\left(\sigma_{CC}^{st} + \sigma_{NC}\right)$$

$$\Gamma_{tr,dw}(E_\nu) \approx \frac{d\phi}{d\Omega}\sigma_{CC}^{st}$$

$$\Gamma_{sh,up}(E_\nu) \approx \frac{d\phi}{d\Omega}\frac{\sigma_t}{\sigma_a} = \frac{d\phi}{d\Omega}$$

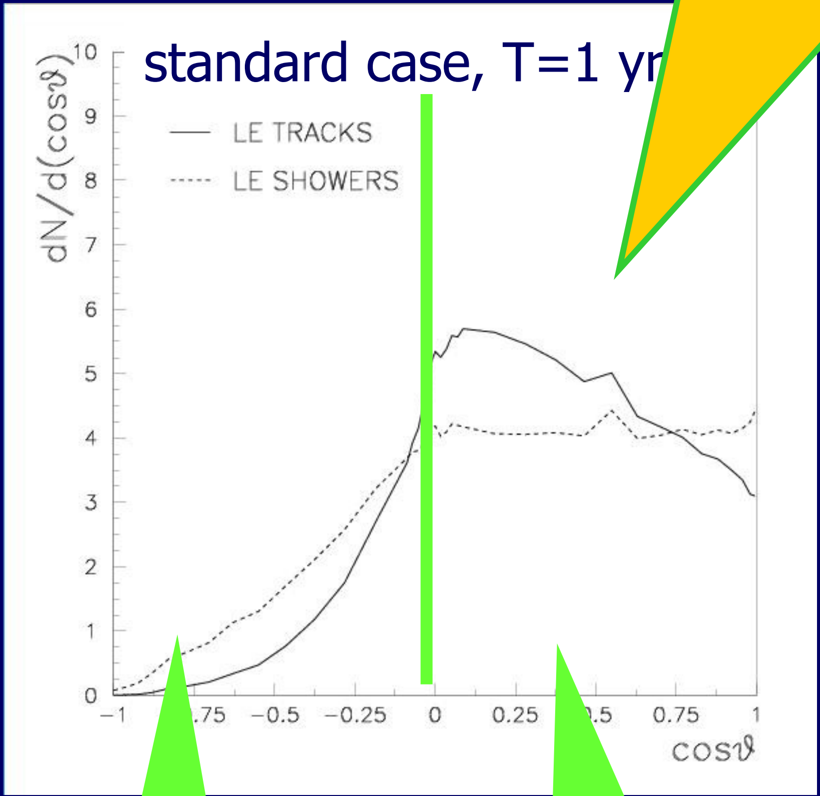
$$\Gamma_{tr,up}(E_\nu) \approx \frac{d\phi}{d\Omega}\frac{\sigma_{CC}^{st}}{\sigma_{CC}^{st} + \sigma_{NC}}$$

Energy binning

same of before: reasonable choice

Two energy bins:
$$E_1 \leq \Delta E \leq E_2$$
$$E_2 \leq \Delta E$$

effect of the cubic geometry



Upgoing

Downgoing

- different LE and HE shape: energy dependence of the cross section
- peak of the tracks near the horizon: larger grammage crossed and larger interaction probability
- flat downgoing showers at LE and HE: dominant contribution of contained events
- suppression of upgoing shower and track: earth opacity

Energy binning

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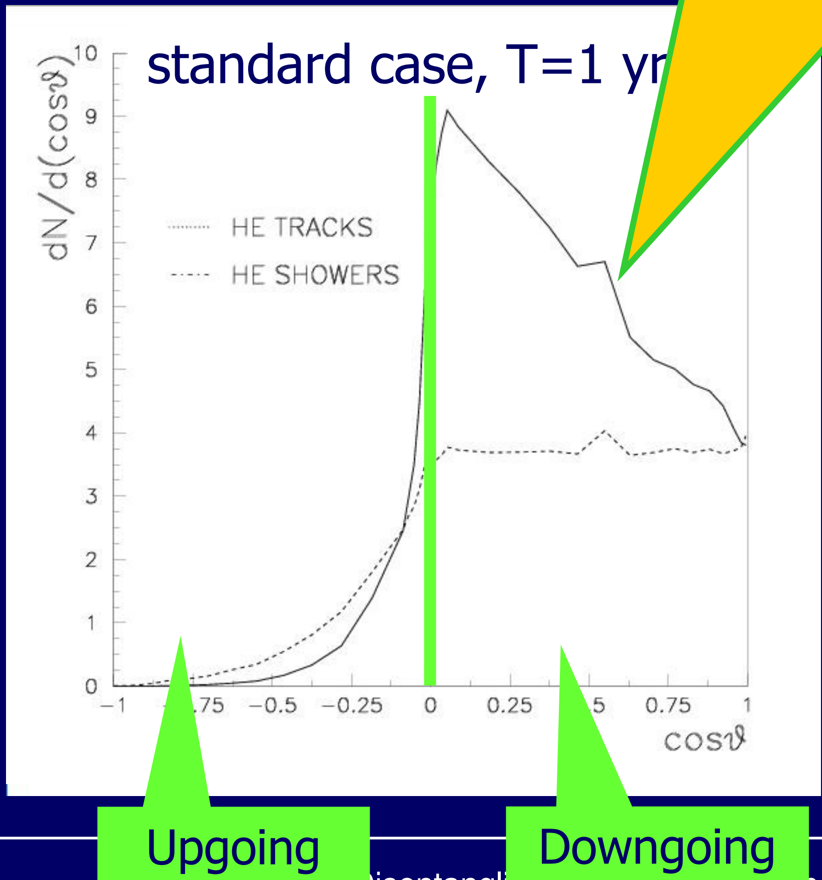

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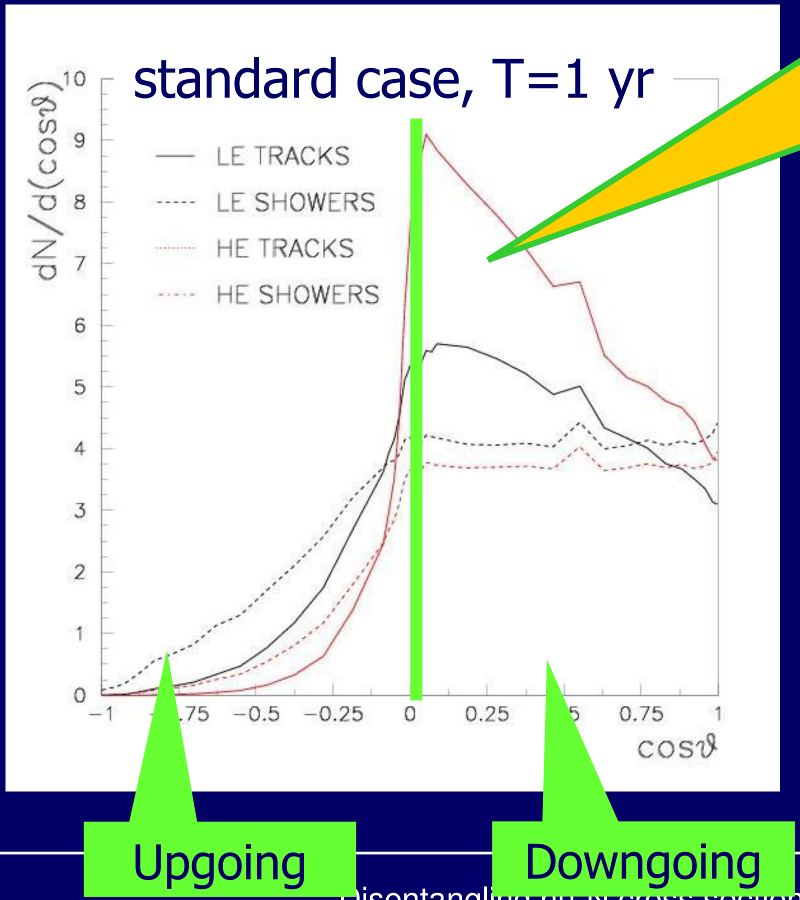
- flat downgoing showers at LE and HE: dominant contribution of contained events
- suppression of upgoing shower and track: earth opacity

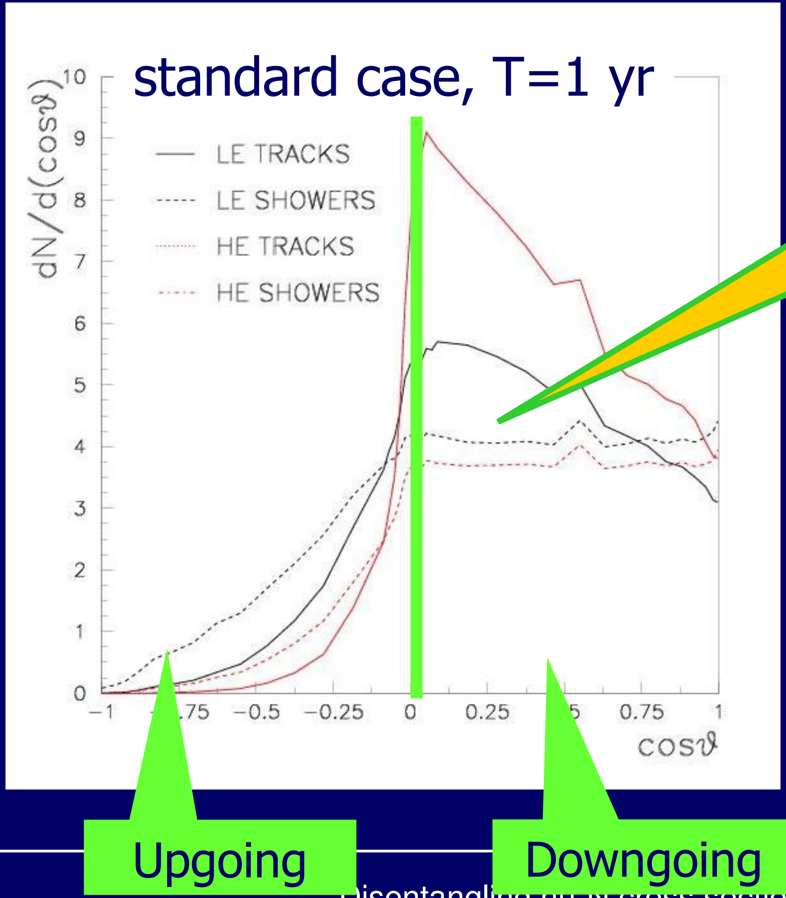
Event numbe

Track events increase with energy for the downgoing contribution, due to the increase of the portion of the neutrino path to which the detector is sensitive.



#/yr	Tracks	Showers
LE	1.2/4.7	1.7/4.0
HE	0.7/6.6	0.8/3.7
TOT	1.9/11.3	2.5/7.7

Event numbers



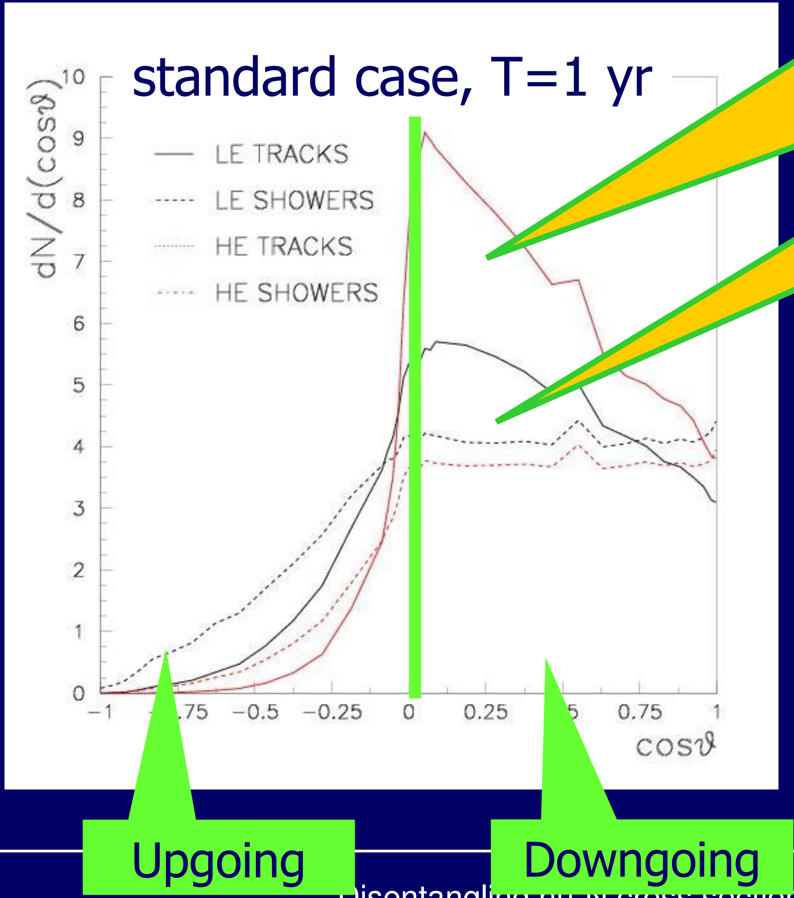
Shower events decrease with energy, due to the increase of the lepton decay length.

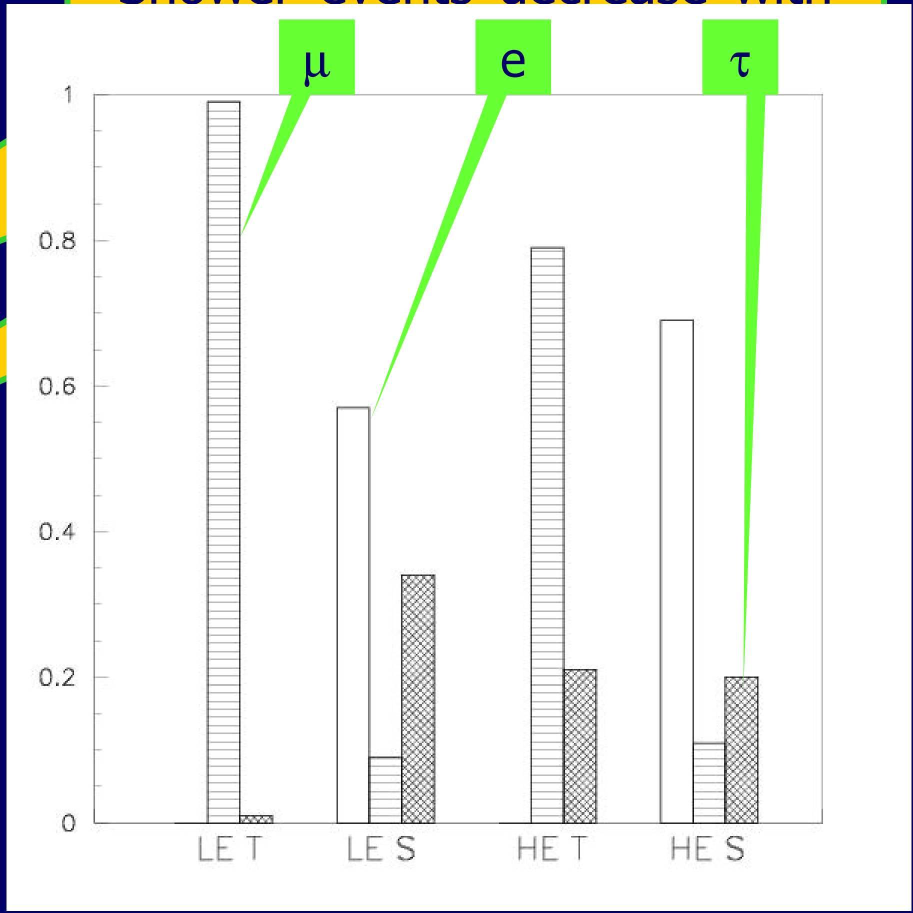
#/yr	Tracks	Showers
LE	1.2/4.7	1.7/4.0
HE	0.7/6.6	0.8/3.7
TOT	1.9/11.3	2.5/7.7

Event numbe

Track events increase with

Shower events decrease with





Angular binning

A simple choice with two bins (upgoing & downgoing) seems satisfying. But…

Has a Mediterranean neutrino telescope the possibility to tag downgoing neutrino induced events as the signal against the background coming from secondary muons from cosmic ray showers?

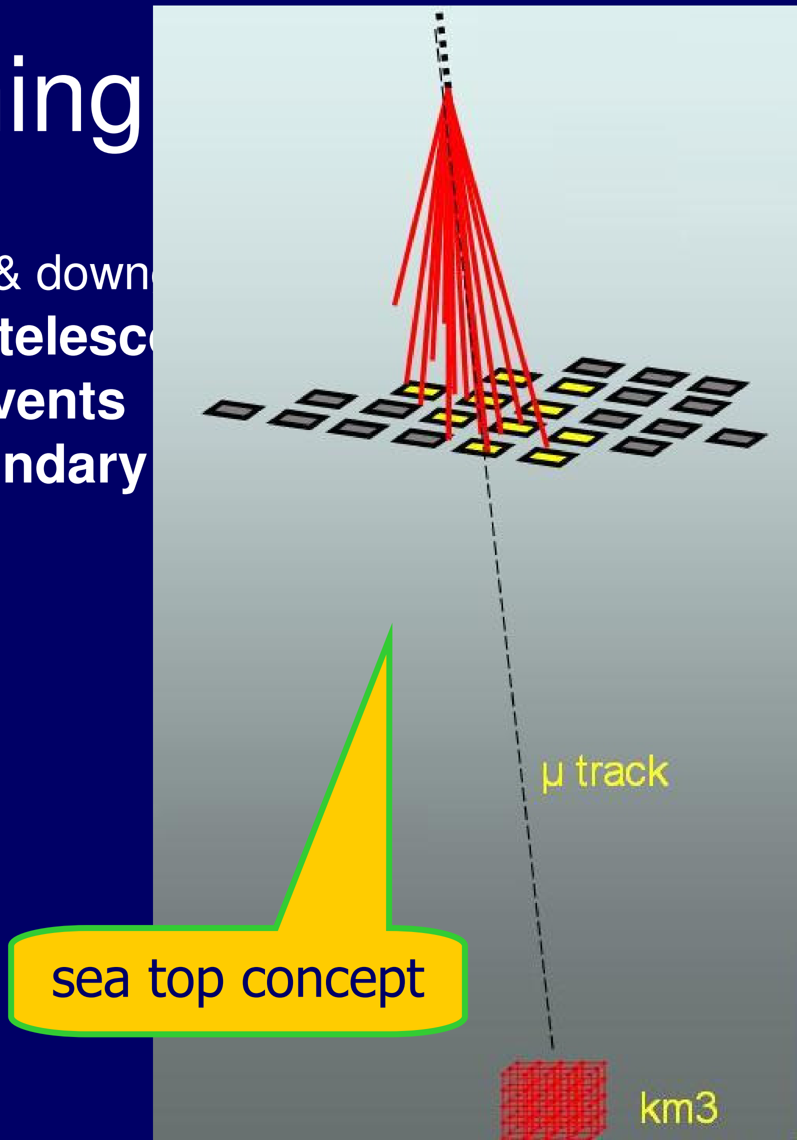
Ice-Top

Angular binning

A simple choice with two bins (upgoing & down

Has a Mediterranean neutrino telesc ag downgoing neutrino induced events he background coming from secondary ay showers?

Ice-Top



Likelihood analysis

We have considered two scenarios:

• CC and NC cross section changes proportionally to each other: A=A' and B=B'

• CC cross section is standard, only NC cross section is free: A=B=1

In both cases, we have produced the observables $N_{i,\alpha}^{K}$ for a grid of 125 theoretical models. Then, we have made a multi-Poisson likelihood analysis, with likelihood function $L \propto e^{-\chi^2/2}$ and

$$\chi^2 = 2\sum_{i,\alpha,K}\left[N_{i,\alpha}^{K} - C_{i,\alpha}^{K} + C_{i,\alpha}^{K}\ln\left(\frac{C_{i,\alpha}^{K}}{N_{i,\alpha}^{K}}\right)\right]$$

Baker & Cousins, Nucl.Instrum.Meth.A221:437-442,1984

$C^{K}_{i\alpha}$ = expected counts

Expectation

As long as CC and NC cross sections change proportionally, then the upward rates are independent of them, with or without new physics involved. The two observables are just proportional to the integrated flux in the corresponding energy bin.

Scenario I

$$\sigma_t = (1+k)\sigma_{CC}$$

$$\sigma_a = \sigma_t = (1+k)\sigma_{CC}$$

$$\Gamma_{sh,dw}(E_\nu) \approx \frac{d\phi}{d\Omega}\sigma_t = \frac{d\phi}{d\Omega}(1+k)\sigma_{CC}$$

$$\Gamma_{tr,dw}(E_\nu) \approx \frac{d\phi}{d\Omega}\sigma_{CC}$$

$$\Gamma_{sh,up}(E_\nu) \approx \frac{d\phi}{d\Omega}\frac{\sigma_t}{\sigma_a} = \frac{d\phi}{d\Omega}$$

$$\Gamma_{tr,up}(E_\nu) \approx \frac{d\phi}{d\Omega}\frac{1}{(1+k)}$$

$$\ldots) \approx \frac{d\phi}{d\Omega}\sigma_t = \frac{d\phi}{d\Omega}\left(\sigma_{CC}^{st} + \sigma_{NC}\right)$$

$$\Gamma_{tr,dw}(E_\nu) \approx \frac{d\phi}{d\Omega}\sigma_{CC}^{st}$$

$$\Gamma_{sh,up}(E_\nu) \approx \frac{d\phi}{d\Omega}\frac{\sigma_t}{\sigma_a} = \frac{d\phi}{d\Omega}$$

$$\Gamma_{tr,up}(E_\nu) \approx \frac{d\phi}{d\Omega}\frac{\sigma_{CC}^{st}}{\sigma_{CC}^{st} + \sigma_{NC}}$$

CC cross section, contributing to downgoing tracks, is assumed to be known. On the other side, upward shower rates are virtually independent of cross sections: good accuracy in determining flux parameters.

$$\Gamma_{sh,dw}(E_\nu) \approx \frac{d\phi}{d\Omega}\sigma_t = \frac{d\phi}{d\Omega}(1+k)\sigma_{CC}$$

$$\Gamma_{tr,dw}(E_\nu) \approx \frac{d\phi}{d\Omega}\sigma_{CC}$$

$$\Gamma_{sh,up}(E_\nu) \approx \frac{d\phi}{d\Omega}\frac{\sigma_t}{\sigma_a} = \frac{d\phi}{d\Omega}$$

$$\Gamma_{tr,up}(E_\nu) \approx \frac{d\phi}{d\Omega}\frac{1}{(1+k)}$$

Scenario II

$$\sigma_t = \sigma_{CC}^{st} + \sigma_{NC}$$

$$\sigma_a = \sigma_t = \sigma_{CC}^{st} + \sigma_{NC}$$

$$\Gamma_{sh,dw}(E_\nu) \approx \frac{d\phi}{d\Omega}\sigma_t = \frac{d\phi}{d\Omega}\left(\sigma_{CC}^{st} + \sigma_{NC}\right)$$

$$\Gamma_{tr,dw}(E_\nu) \approx \frac{d\phi}{d\Omega}\sigma_{CC}^{st}$$

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When the departure from the standard case is large, NC contribution dominates: upward tracks suppressed. Moreover, NC events mostly sensitive to the high energy behavior of the cross section, due to the smaller inelasticity: worse determination of A′, which influence the uncertainty on B′ in the second energy bin.

$$\Gamma_{sh,dw}(E_\nu) \approx \frac{\quad}{d\Omega}\sigma_t = \frac{\quad}{d\Omega}$$

$$\Gamma_{tr,dw}(E_\nu) \approx \frac{d\phi}{d\Omega}\sigma_{CC}$$

$$\Gamma_{sh,up}(E_\nu) \approx \frac{d\phi}{d\Omega}\frac{\sigma_t}{\sigma_a} = \frac{d\phi}{d\Omega}$$

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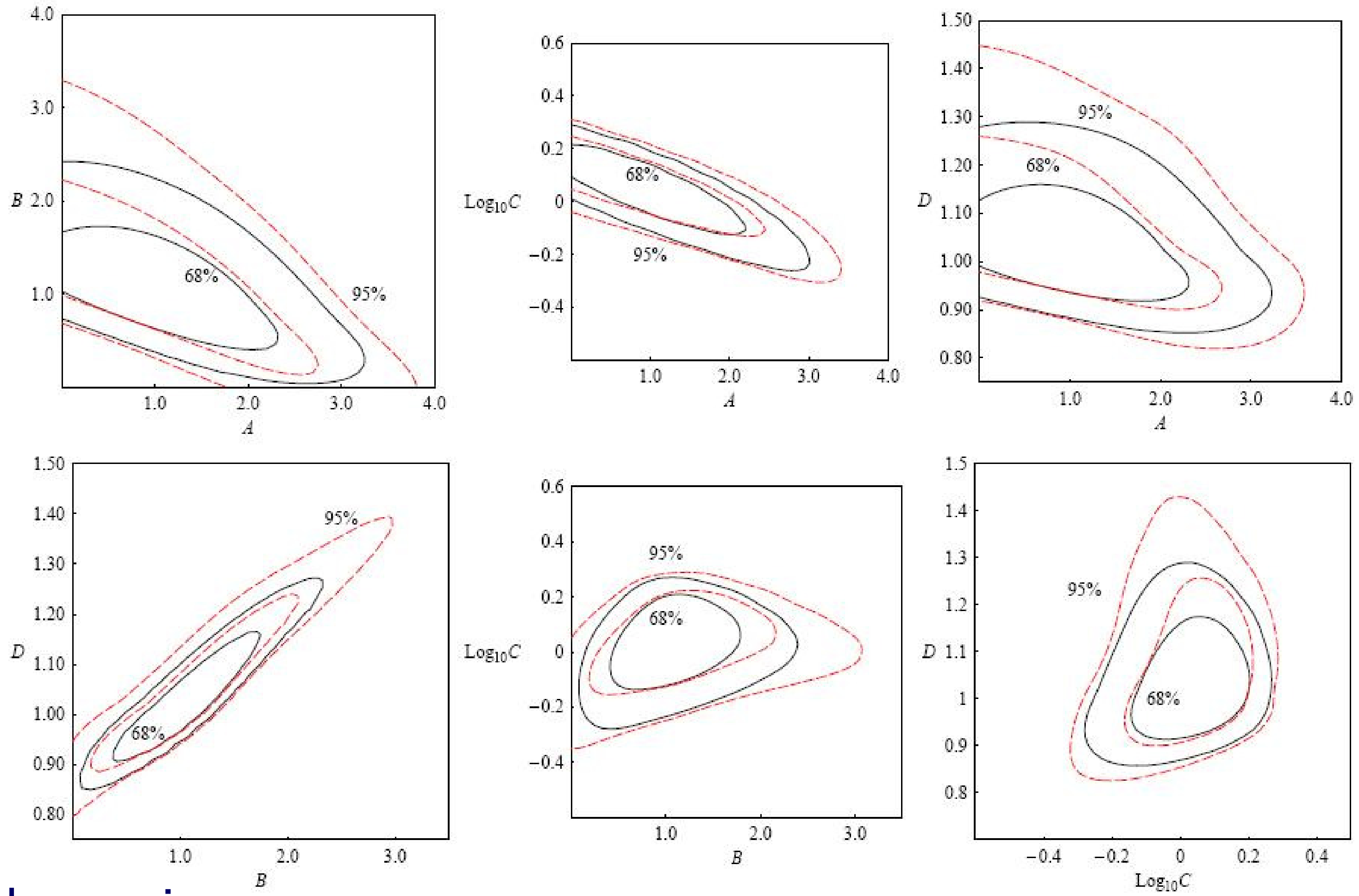
Scenario I

with or without topological information

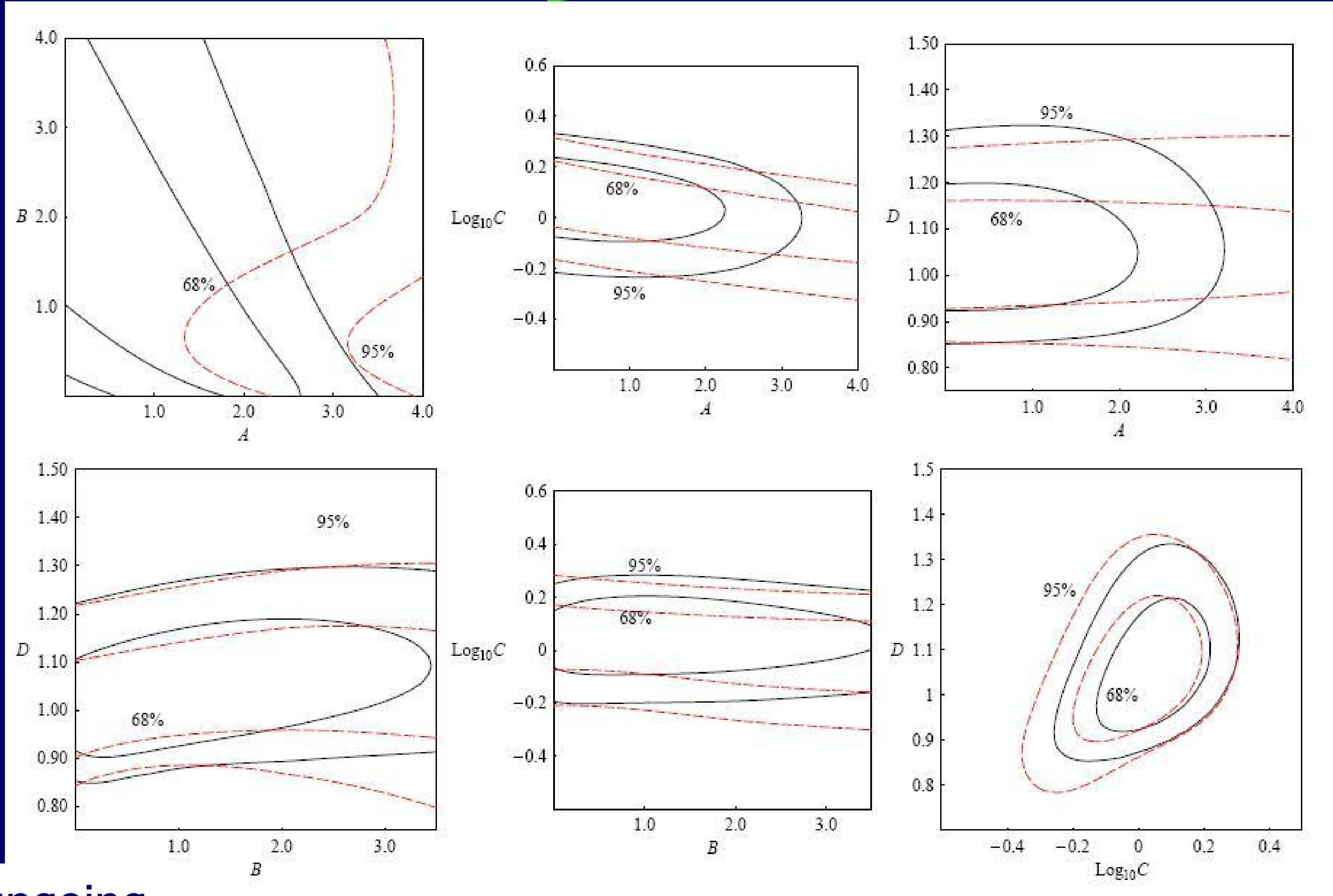


upgoing+downgoing observables

T=5 years

Scenario I

two or one angular bins



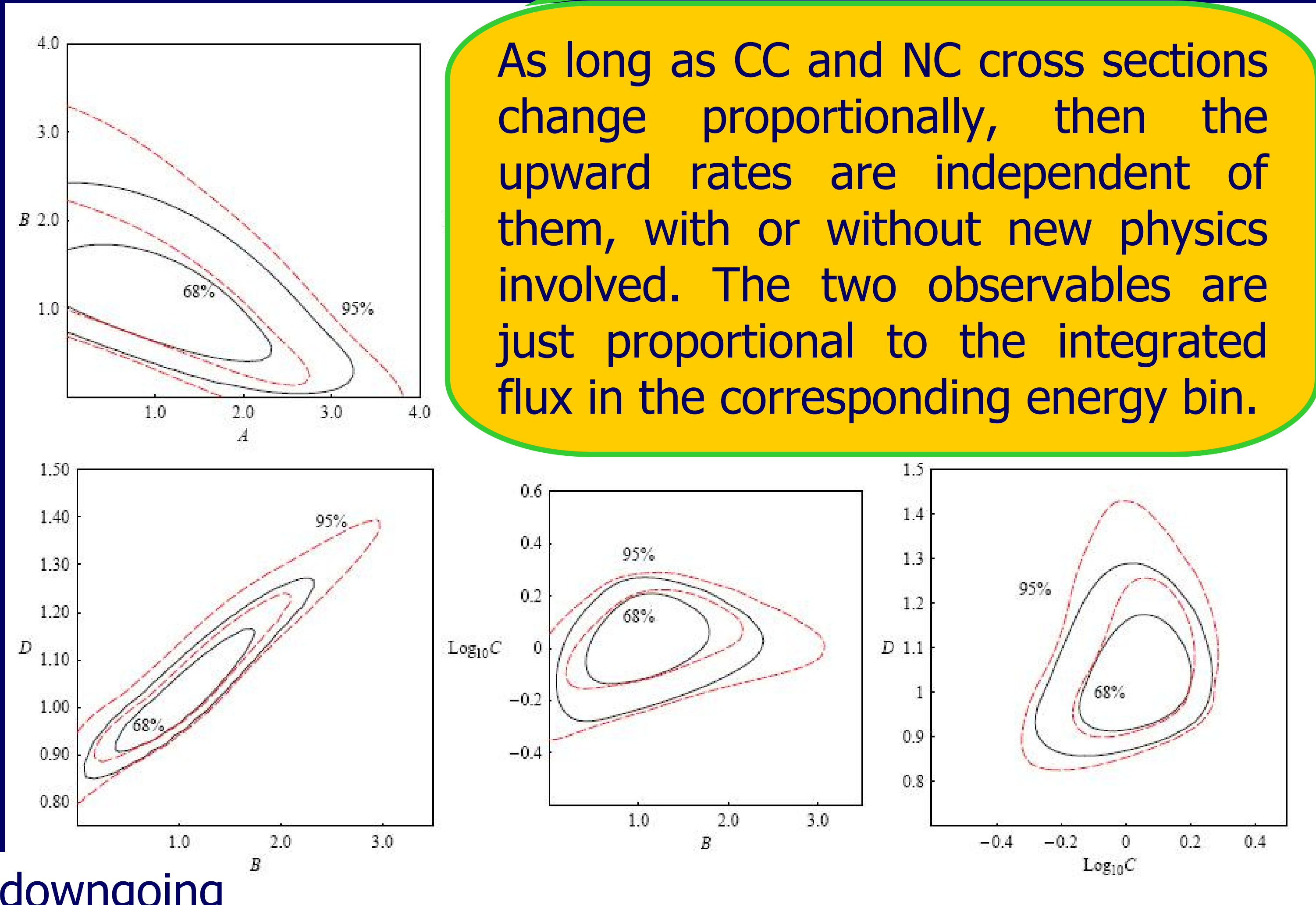
only upgoing observables

T=5 years

Scenario I

with or without topological information

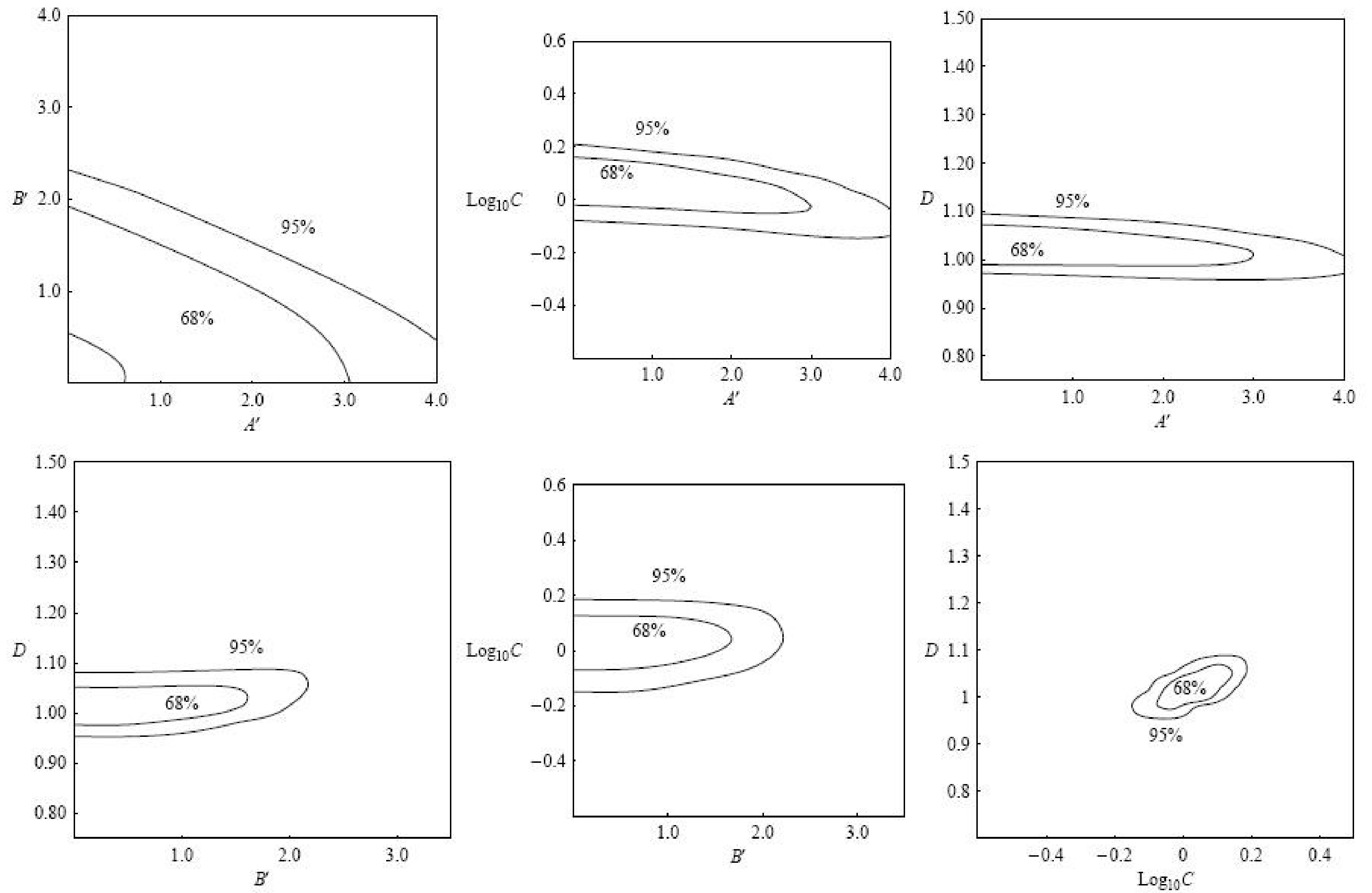
As long as CC and NC cross sections change proportionally, then the upward rates are independent of them, with or without new physics involved. The two observables are just proportional to the integrated flux in the corresponding energy bin.



upgoing+downgoing observables

T=5 years

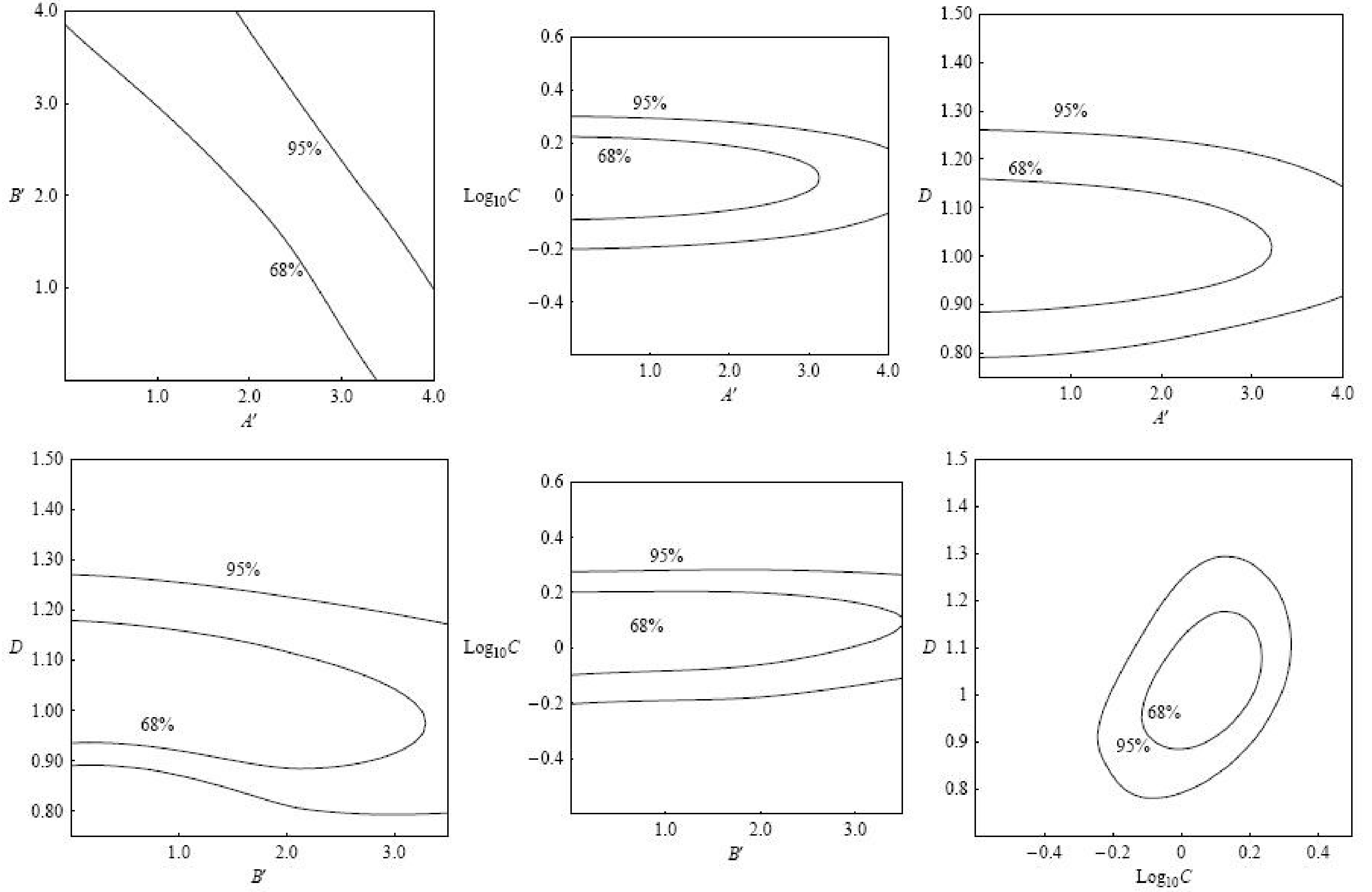
Scenario II



upgoing+downgoing observables

T=5 years

Scenario II

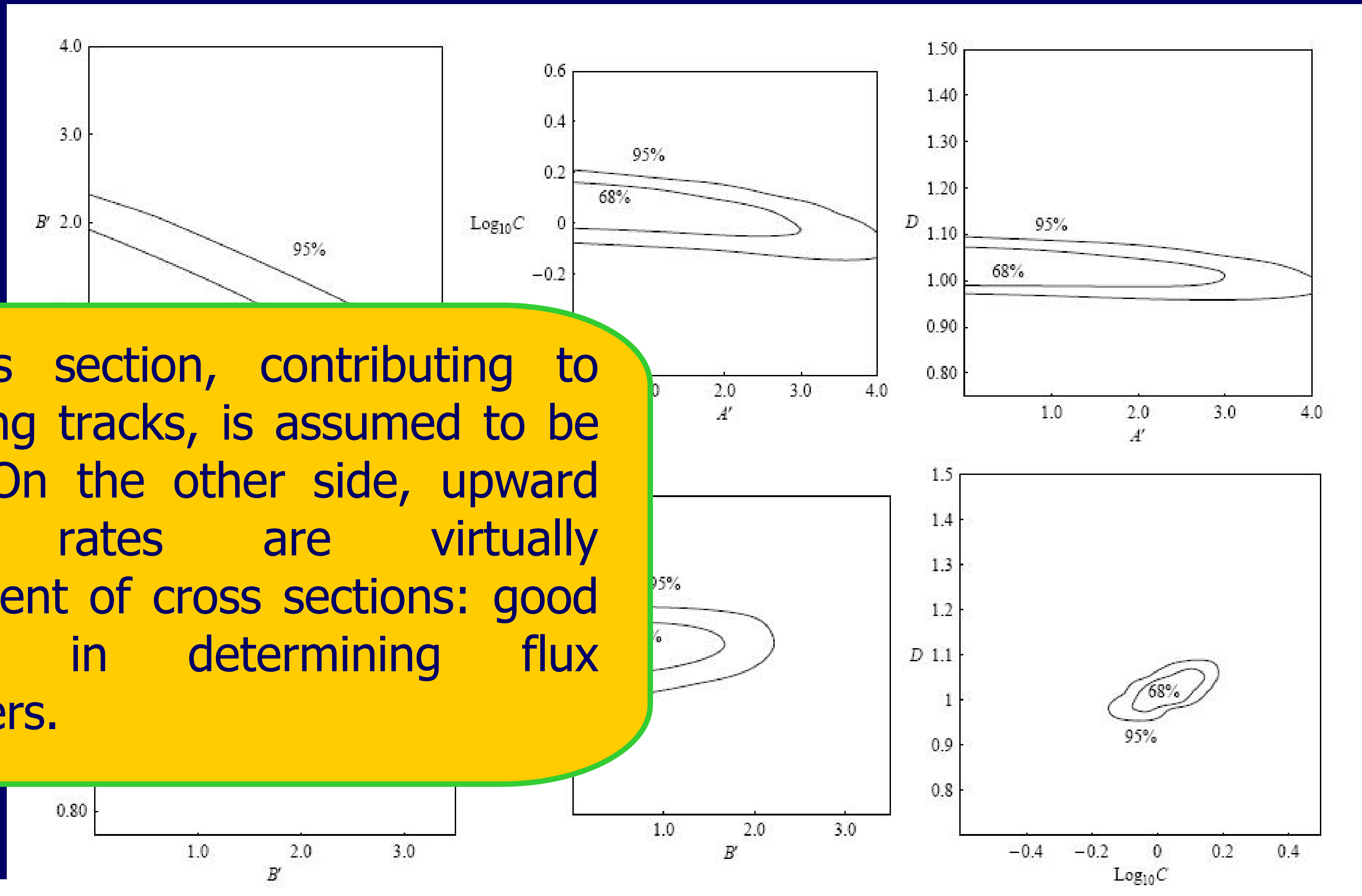


only upgoing observables

nu-N cross section and flux with a km3 neutrino telescope

T=5 years

Scenario II



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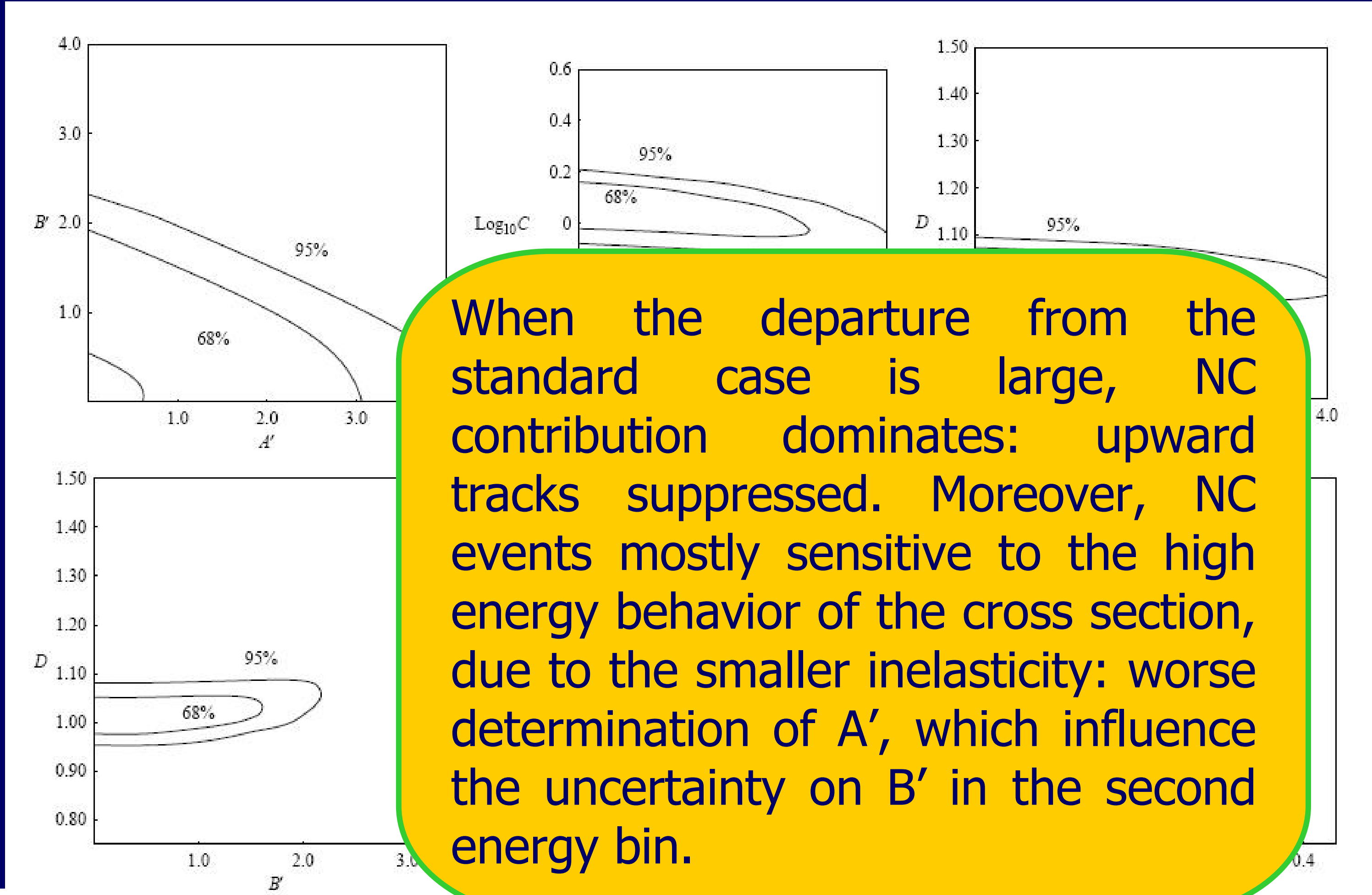
upgoing+downgoing observables

T=5 years

Scenario II



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upgoing+downgoing observables

T=5 years

Conclusions

• ***Crucial requirement to constrain flux and cross section is the capability to tag downgoing events***. In fact, upgoing events are almost independent of the cross section (but things can change for non standard assumptions on inelasticity, see hep-ph/0606246).

• ***Increased sensitivity to cross section from improvement of angular binning***. In case of only upgoing event this can help a little bit, but is limited by statistics.

• ***Details can modify quantitative predictions***. Simulations should include the geometry of the site and detector, efficiency, stochastic energy losses of leptons, second order effects, etc.