Ограничение на диффузионный поток нейтрино сверхвысоких энергий в модели АДД

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Семинар ОТФ, 16 января 2019 года

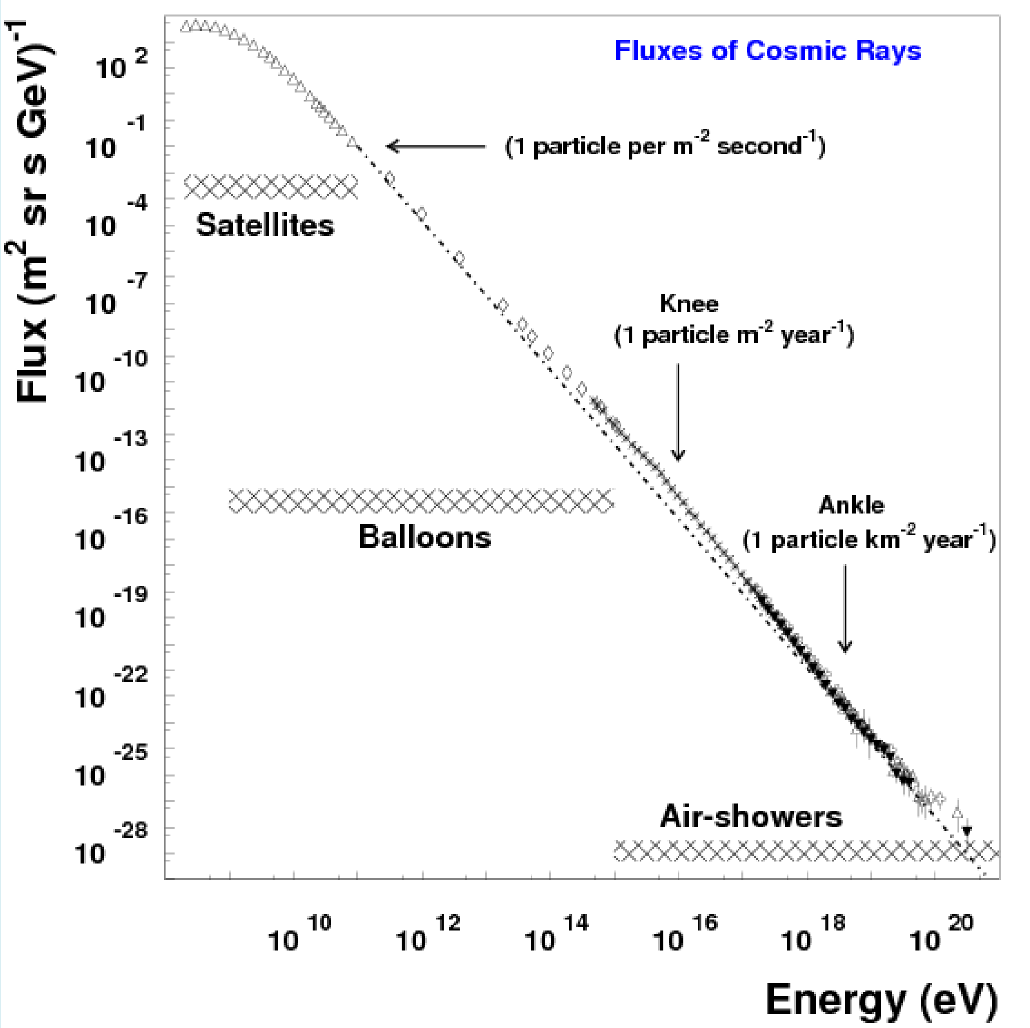
Огурцов — лектору «по распространению» Никадилову:
— *Так значит, вы выйдете и так, коротенько, минут на 40, больше, я думаю не надо, значит, дадите народу свою лекцию!*

Б. Ласкин, В. Поляков. Сценарий фильма «Карнавальная ночь»

План доклада

- Космические нейтрино сверхвысоких энергий
- Нейтринные события на детекторах IceCube и Pierre Auger Observatory (PAO)
- Сценарий с дополнительными измерениями (EDs) пространства-времени
- Рассеяние нейтрино на нуклонах в модели ADD с «большими»дополнительными измерениями
- Ограничение на диффузионный поток нейтрино сверхвысоких энергий
- Ограничения на параметры модели ADD
- Заключение

Neutrinos is an essential part of cosmic rays



Detection of signals from cosmic UHE neutrinos will allow us:

- *to discover cosmic ray (CR) point sources*
- *to define their position, in particular, to constrain the position of GW sources*
- *to understand mechanisms of CR acceleration*
- *to give information on the nature of primaries*
- *to define energy boundary between galactic and extragalactic parts of the CR spectrum*
- *to measure cosmic neutrino flux, flavor ratio, and UHE neutrino-nucleon cross section*

Diffuse flux of cosmic neutrinos

"Guaranteed" cosmogenic neutrino flux

$$p + \gamma_{CMB} \rightarrow n + \pi^+ \qquad \pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \mu^+ \rightarrow \bar{\nu}_\mu + e^+ + \nu_e$$

Flavor ratio: $\nu_e : \nu_\mu : \nu_\tau = 1:2:0$

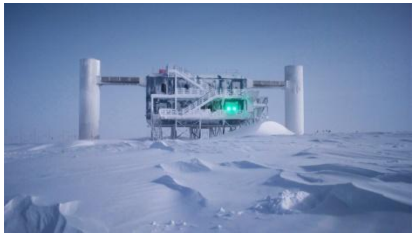
After oscillation: $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$

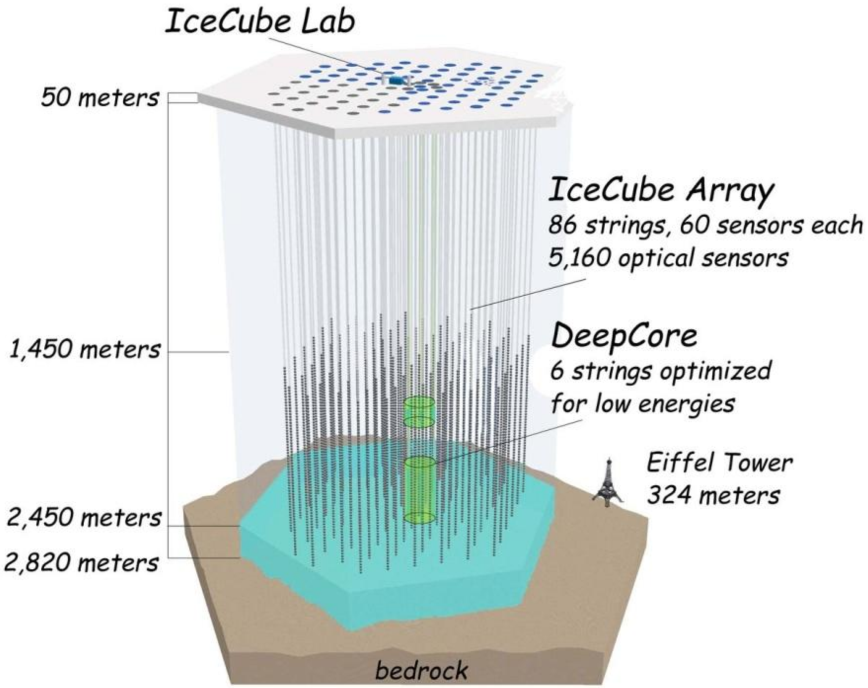
Benchmark WB bound on neutrino production in optically thin sources (single flavor, 10^{13} eV < E_ν < 10^{20} eV)

(Waxman & Bahcall, PRD 64 (2001) 023002)

$$E_\nu^2 \frac{dN}{dE_\nu} = 2.33 \times 10^{-8} \mathrm{GeV cm^{-2} s^{-1} sr^{-1}}$$

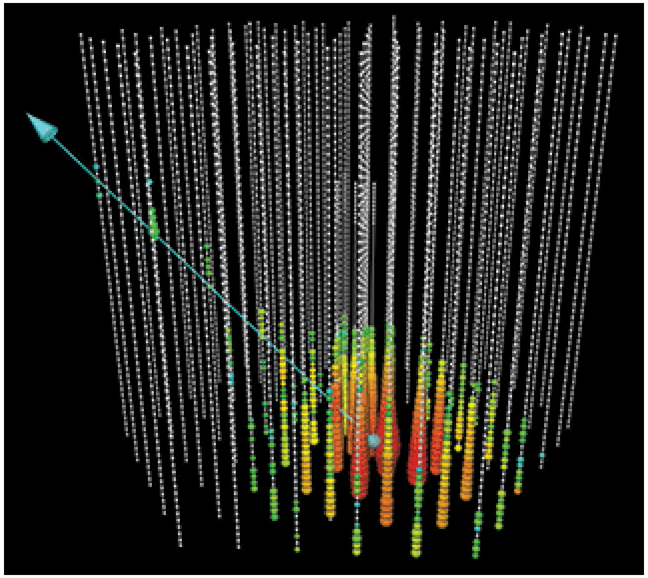
Neutrino detector IceCube





Cubic-kilometer detector made of Antarctic ice

250 TeV neutrino in IceCube



At the neutrino interaction point, a large particle shower is visible, with a muon produced (see arrow)

Neutrino detector IceCube: first observation of astrophysical neutrinos in the range 6.3 TeV-980 TeV

(IceCube Collab., PRL 113 (2014) 101101)

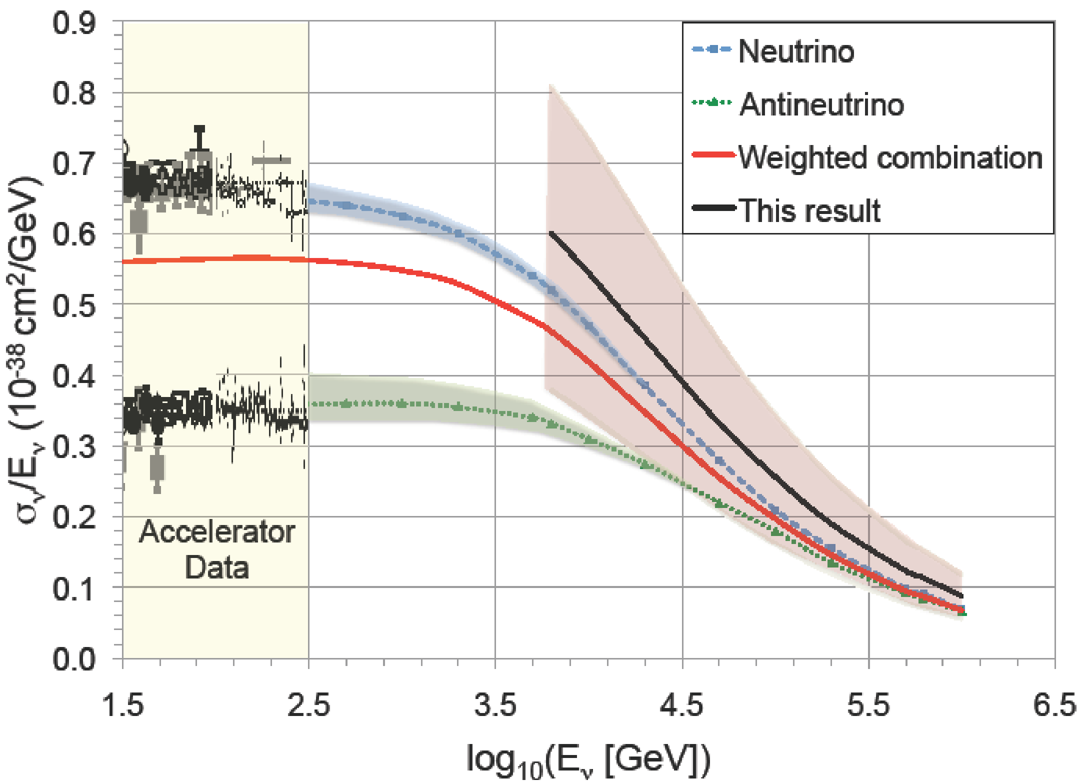
IceCube diffuse neutrino flux
(single flavor, 25 TeV< E_ν < 1.4 PeV) **(1PeV = 10^{15} eV)**

(IceCube Collab., PRD 91 (2015) 022001)

$$\frac{dN}{dE_\nu} = 2.06\times10^{-18}(E_0/E_\nu)^\gamma \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

$$E_0 = 10^5\,\mathrm{GeV}, \quad \gamma = 2.46$$

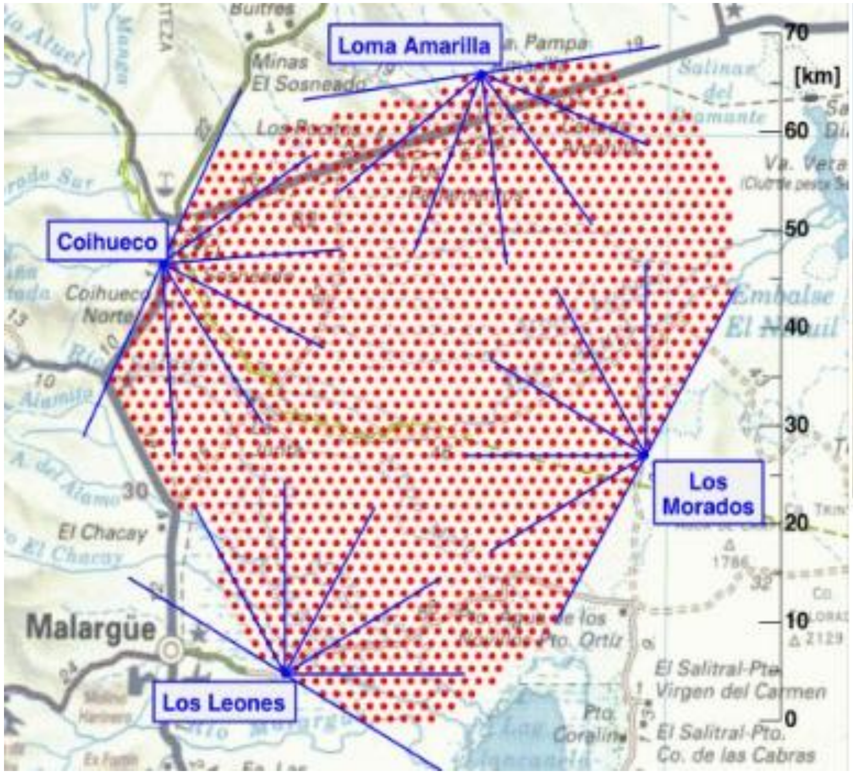
(flux is consistent with the WB bound)

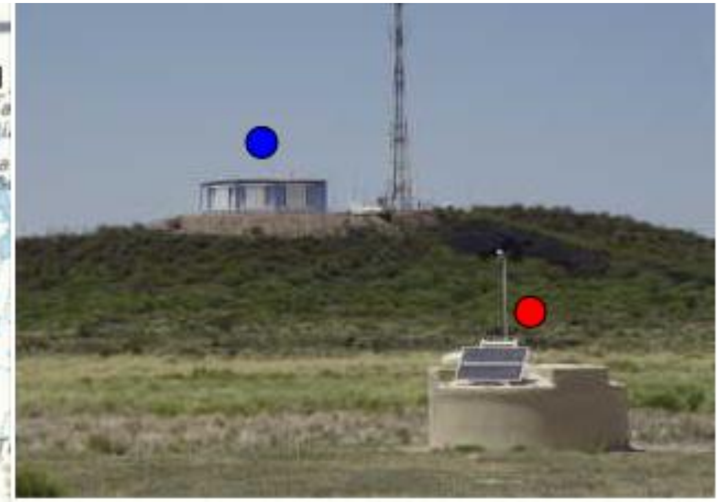


Compilation of neutrino charged current cross section measurements, divided by neutrino energy, from accelerator experiments and IceCube data

(IceCube Collab., Nature 551 (2017) 596)

Pierre Auger Observatory (PAO)



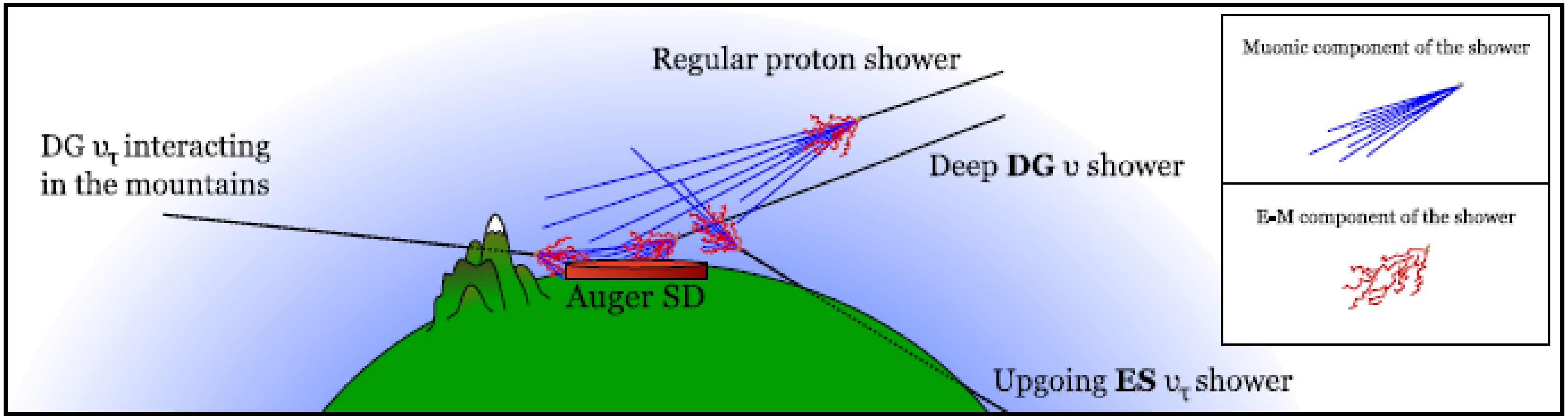


● set of fluorescence telescopes

● Cherenkov detector

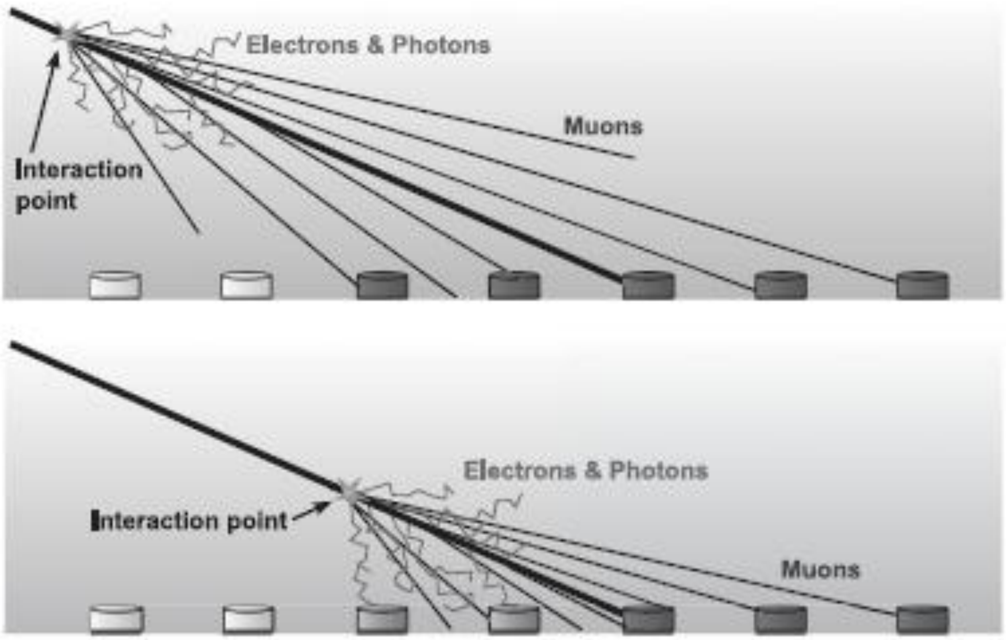
Surface Detector (SD) array: 1600 water-Cherenkov detectors spread over an area of 3000 km^2 (a bit larger than the country of Luxemburg)

Two types of air showers induced by UHE neutrinos at the Pierre Auger Observatory



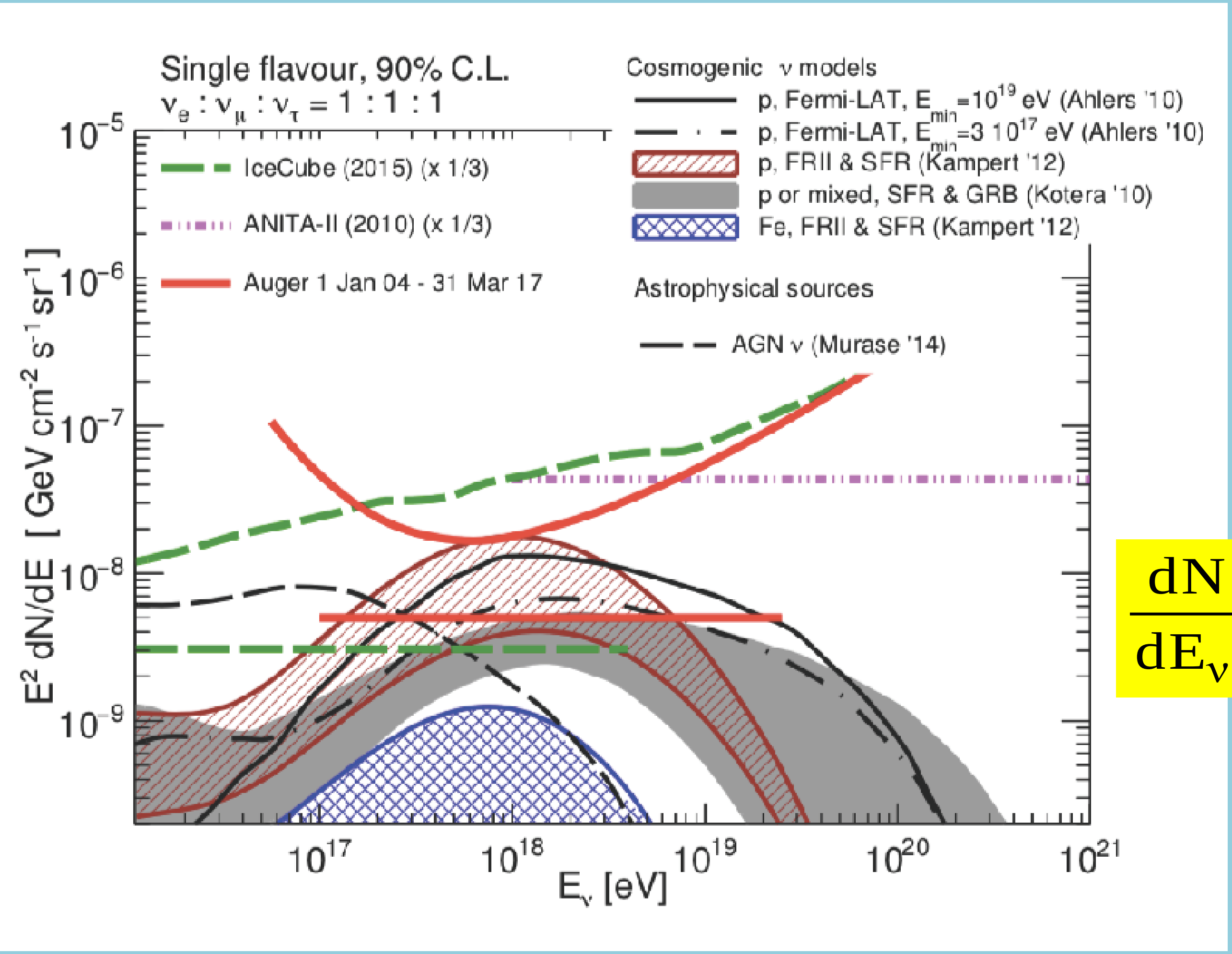
Downward-going high zenith angle (DG) neutrinos and up-going Earth-skimming (ES) tau neutrinos

Inclined showers (with zenith angle 75°-90°) are initiated by cosmic neutrinos, not by protons (nuclei)



Inclined shower induced by hadronic interactions high in the atmosphere (upper panel) and deep inclined shower (lower panel)

(*PAO Collab. PRD 84 (2011) 122005*)



$$\frac{dN}{dE_\nu} = k \times E_\nu^{-2}$$

Integral upper limits for the diffuse flux of UHE neutrinos (horizontal lines) and differential upper limits (non-horizontal curves) for PAO (red) and IceCube (green)

(arXiv: 1812.01036)

Single-flavor limit to diffuse flux of UHE neutrinos from PAO (10^{17} eV < E_ν < $2.5 \cdot 10^{19}$ eV)

(PAO Collab., PRD 91 (2015) 092008)

$$E_\nu^2 \frac{dN}{dE_\nu} < 6.4 \cdot 10^{-9}\,\mathrm{GeV cm^{-2} s^{-1} sr^{-1}}$$

IceCube diffuse neutrino flux if extrapolated to 1 EeV (10^{18} eV)

$$E_\nu^2 \frac{dN}{dE_\nu} = 0.3 \times 10^{-9}\,\mathrm{GeV cm^{-2} s^{-1} sr^{-1}}$$

Mergers of black holes are potentially environment for accelerating CRs to ultra-high energies

(Kotera and Silk, Astr. J. Lett. 823 (2016) L29)

UHECRs can interact with the surrounding matter or radiation to produce UHE gamma rays and neutrinos

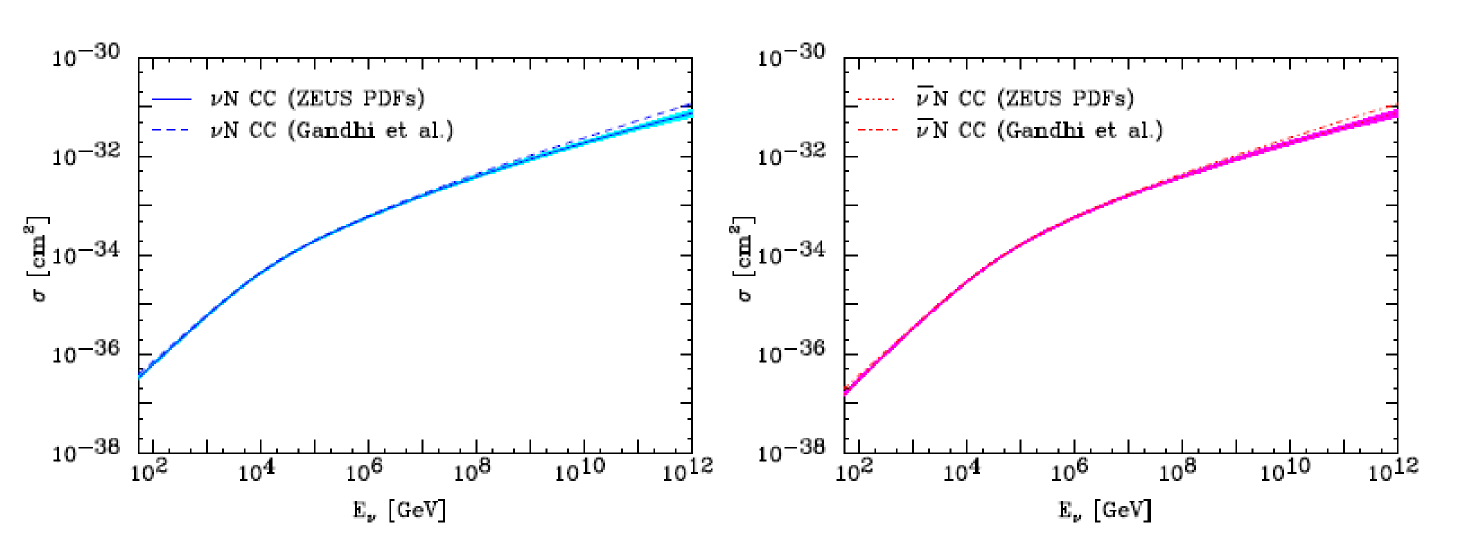
(PAO Collab., PRD 94 (2016) 122007)

Upper bound on the diffuse single-flavor flux integrated over population of GW sources

(Kotera and Silk, Astr. J. Lett. 823(2016) L29)

$$E_\nu^2 \frac{dN}{dE_\nu} = (1.5 - 6.9) \times 10^{-8} \,\mathrm{GeV cm^{-2} s^{-1} sr^{-1}}$$

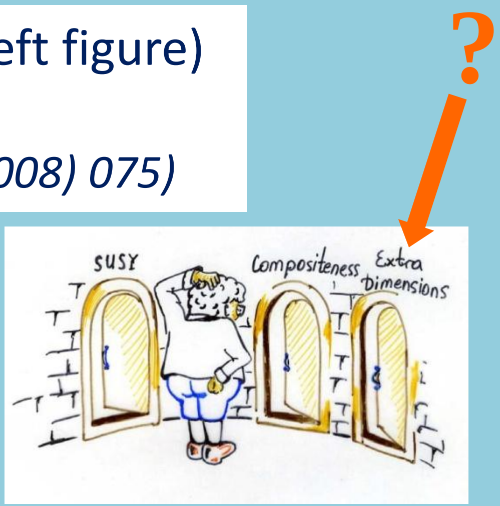
SM: $\sigma_{\nu N}$ is small and rises slowly with energy



The total CC cross sections for neutrinos (left figure) and antineutrinos (right figure)

(Cooper-Sarkar & Sarkar, JHEP 080 (2008) 075)

Significant (dominating) contribution from "new physics" is expected at ultra-high neutrino energies



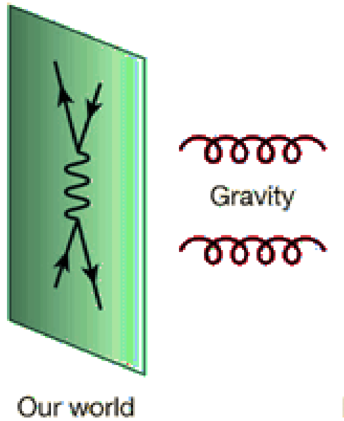
Рассматривая какой-нибудь вопрос, марксисты должны уметь видеть не только его часть, но и весь вопрос в целом. Лягушка, сидя в колодце, утверждала, что "небо величиной с колодец". Это неверно, так как ведь из колодца видно не все небо. Но если бы она сказала, что "некоторая часть неба величиной с колодец", она была бы права, так как это соответствовало бы фактам.

Мао Цзэдун. "О тактике борьбы против японского империализма"

Scenario with large flat extra dimensions (ADD model)

(Arkani-Hamed, Dimopoulos and Dvali, Antoniadis, 1998)

Parameters of the model: number of extra dimensions n (D=4+n), D-dimensional gravity scale M_D, compactification radius R_c



Hierarchy relation: $$M_{\mathrm{Pl}}^2 = (2\pi R_c)^n M_D^{n+2}$$

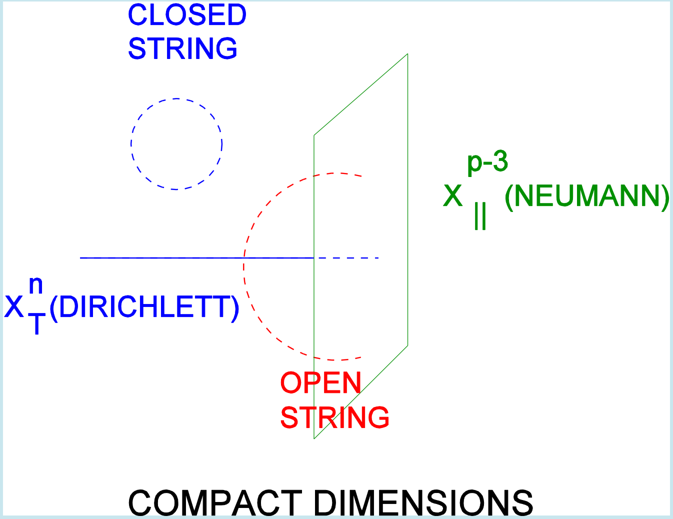
Masses of KK gravitons: $$m_n = n/R_c$$

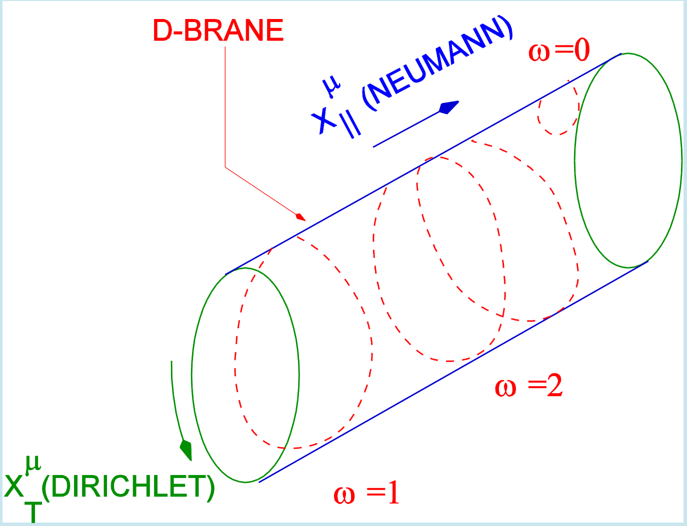
Interaction Lagrangian on the brane:
(massive gravitons only)

$$L(x) = -\frac{1}{\overline{M}_{\mathrm{Pl}}} \sum_{n=1}^{\infty} h_{\mu\nu}^{(n)}(x) T^{\mu\nu}(x)$$

Propagation of strings in extra dimensions

Six internal compact dimensions:
(p-3) longitudinal , n = (9-p) transverse





Closed strings propagate in the bulk

Open strings propagate with ends at x_T = const for different windings

- **String scale** $M_S = l_S^{-1}$
- **String coupling** λ_S
- **Planck scale** $M_{\rm Pl} = l_{\rm Pl}^{-1}$
- **Gauge coupling** g

String tension $\alpha' = M_S^{-2}$

Ten-dimensional action

$$S = \int_{bulk} d^{10}x \frac{1}{\lambda_S^2} l_S^{-8} \mathrm{R} + \int_{brane} d^{p+1}x \frac{1}{\lambda_S} l_S^{3-p} \mathrm{F}^2$$

Upon compactification of EDs:

$$\frac{1}{l_{\rm Pl}^2} = \frac{V_L V_T}{\lambda_S^2 l_S^8} \qquad \frac{1}{g^2} = \frac{V_L}{\lambda_S l_S^{p-3}}$$

Rescaled volume **(4+n) – dimensional Planck scale**

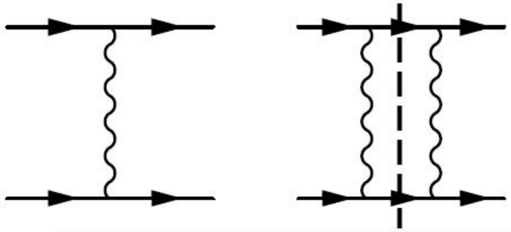
$$v_L = V_L l_S^{3-p} \qquad M_D^{2+n} = M_S^{2+4} / g^4 v_L \quad \rightarrow \quad M_{\rm Pl}^2 = M_D^{2+n} R_T^n$$

Scattering of UHE neutrinos in ADD model

Transplanckian region

$$E_\nu > 10^{17}\,\text{eV},\ \sqrt{s} >> M_D, -t$$

Sum of the ladder diagrams in the eikonal approximation. Wavy lines represent the exchange of *D*-dimensional gravitons



Scattering amplitude in the eikonal approximation

$$A_{\text{eik}}(s,t) = -2is\int_0^\infty db\, b J_0(b\sqrt{-t})\{1-\exp[i\chi(s,b)]\}$$

$$-t = q^2$$

D-dimensional Planck scale: $$G_D = \frac{(2\pi)^{n-1}\hbar^{n+1}}{4c^{n-1}M_D^{n+2}}$$

Planck length: $$\lambda_{\mathrm{Pl}} = \left(\frac{G_D\hbar}{c^3}\right)^{\frac{1}{n+2}}$$

Quantum gravity effects become important at distances below λ_{Pl}

In the limit $\hbar \to 0$, with G_D and $\sqrt{s}$ fixed, M_D and λ_{Pl} vanish

Transplanckian regime corresponds to a classical limit (b > R_S)

$$\sqrt{s} >> M_D, \ \ R_S >> \lambda_{\mathrm{Pl}}, \ \ \theta \sim (R_S / b)^{n+1}$$

R_S is Schwarzschild radius in D=4+n dimensions

Eikonal scattering phase

$$\chi(b) = \frac{1}{2s}\int \frac{d^2q}{(2\pi)^2}\, e^{iqb} A_{\mathrm{Born}}(q^2)$$

$$\chi(b) = \left(\frac{b_c}{b}\right)^n$$

$$b_c = \left(\frac{(4\pi)^{n/2-1} s\Gamma(n/2)}{2M_D^{n+2}}\right)^{1/n}$$

(Giudice, Rattazzi and Wells, Nucl. Phys. B 630 (2002) 293)

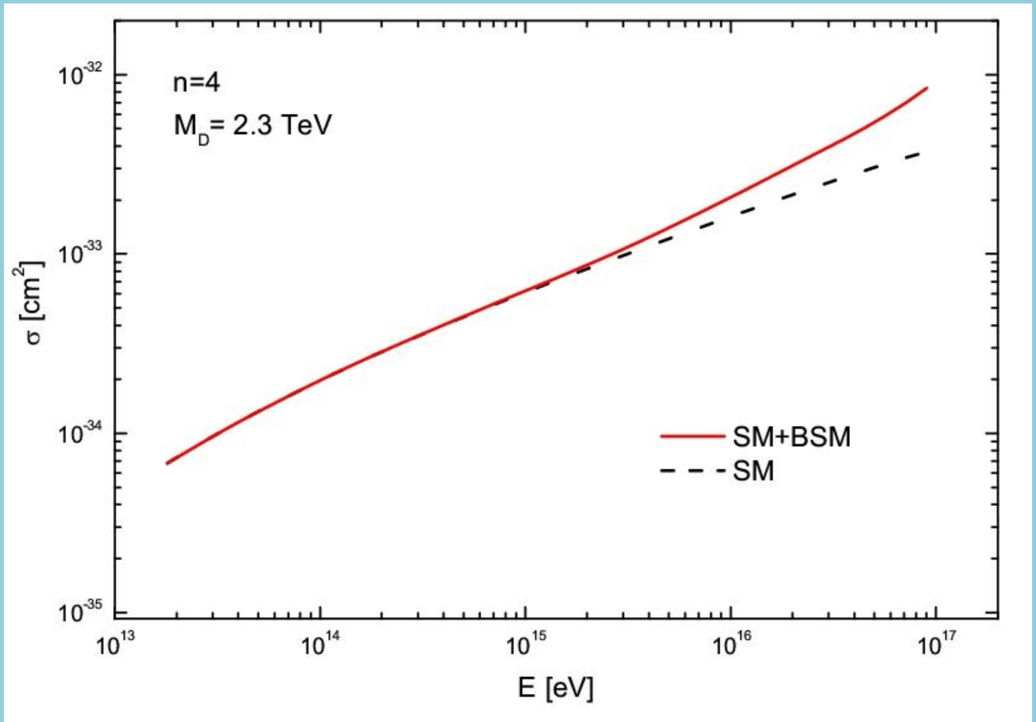
$b < R_S$ → black hole production

Geometric black-hole cross section

$$\sigma_{\mathrm{BH}} = \pi R_S^2$$

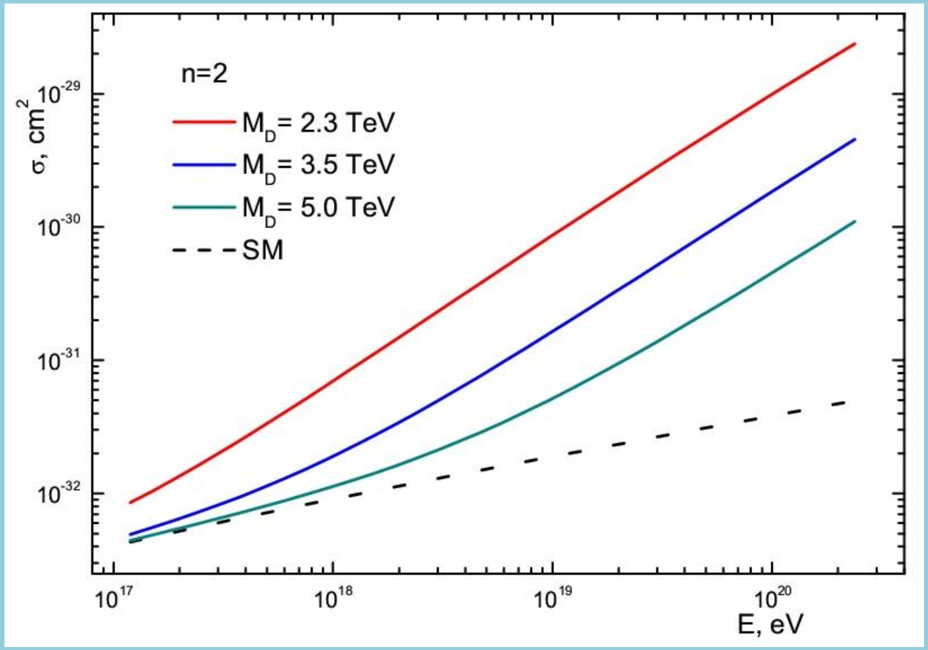
$$R_S \sim \left(\frac{\sqrt{s}}{M_D^{n+2}}\right)^{1/(n+1)}$$

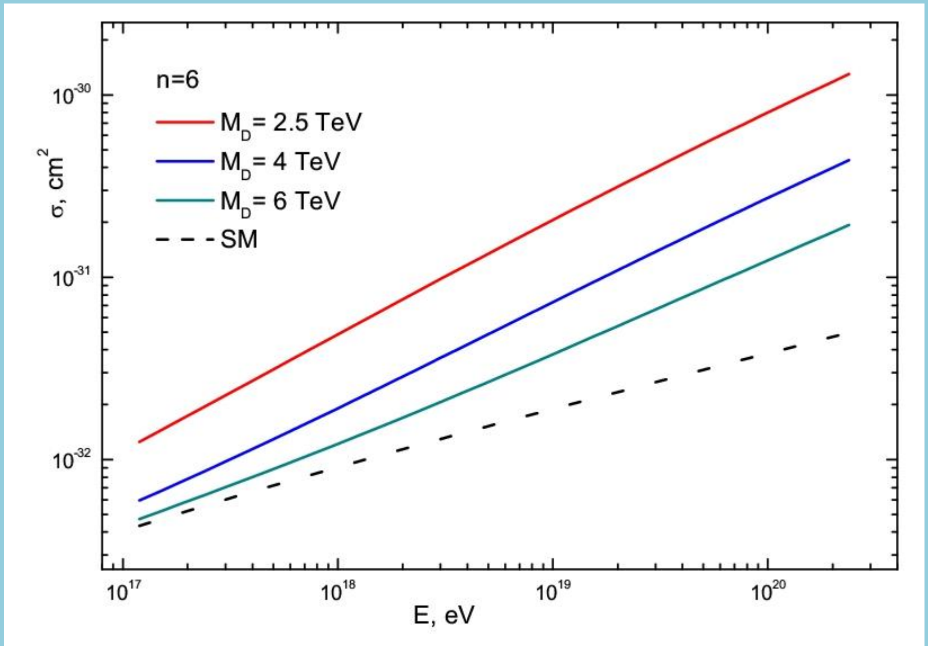
Neutrino-nucleon cross section in energy region of the detector IceCube ($E_\nu < 10^{17}$ eV)



No significant deviation from SM cross section at $E_\nu < 10^{16}$ eV

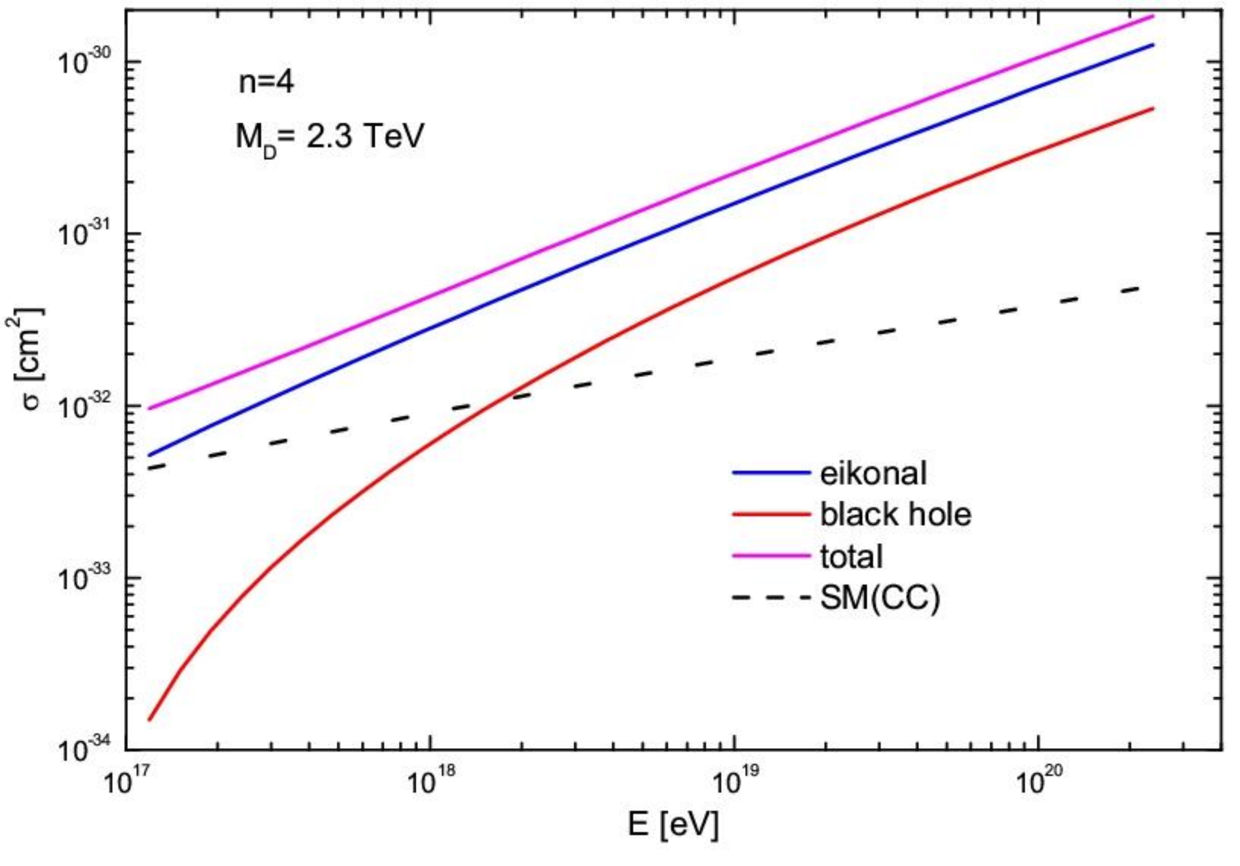
BSM: $\sigma_{\nu N}$ rises more rapidly than in SM as neutrino energy grows





The total neutrino-nucleon cross sections for **n=2** (left panel) and **n=6** (right panel) with different values of the gravity scale $\mathbf{M_D}$

Eikonal and black hole contributions to $\sigma_{\nu N}$



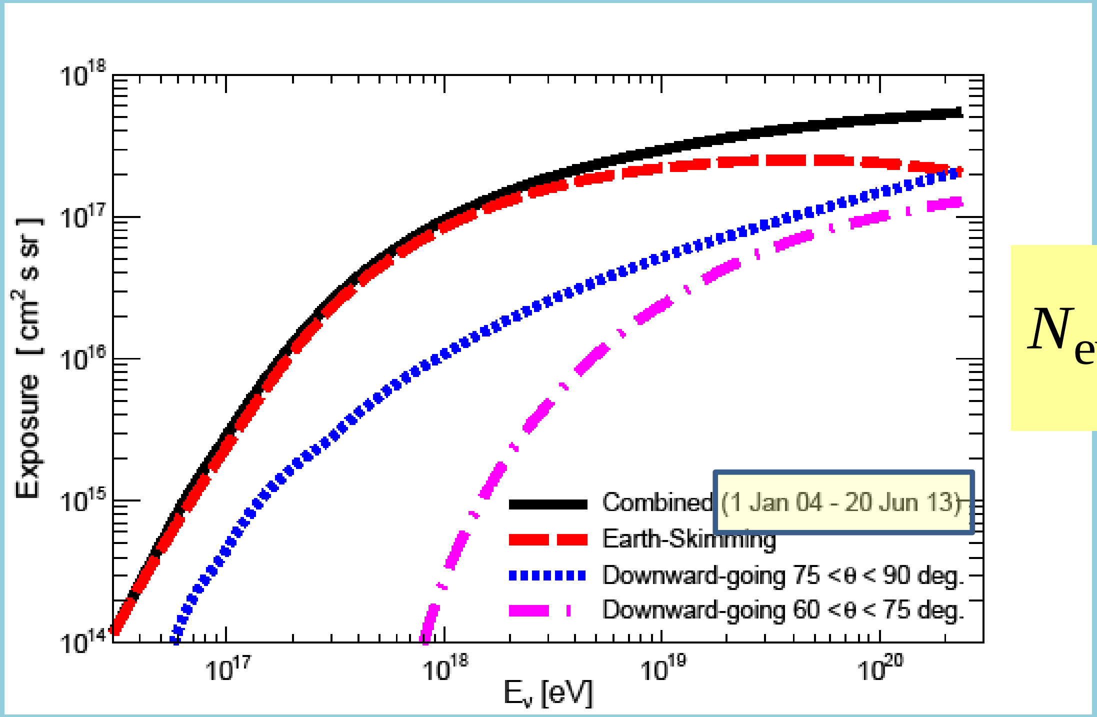
The eikonal, black hole and total neutrino-nucleon cross sections for **n=4** and **M_D = 2.3 TeV**

Exposures of DG and ES neutrino events

Efficiencies of the SD array depends on:
the neutrino energy E_ν, the incident zenith angle θ and interaction depth in the atmosphere D (DG events), or the altitude h (ES events)

Once efficiencies are obtained, exposure involves:
SD array aperture and ν interaction probability at the depth D, energy E_ν and the search period T (for DG events)
SD array aperture, probability density function of tau emerging from the Earth with energy E_τ, probability of tau decaying at the altitude h and the search period T (for ES events)

Exposures of the SD array of the Pierre Auger Observatory



$$N_{\text{ev}} = \int \frac{dN}{dE_\nu} \mathcal{E}(E_\nu) dE_\nu$$

Exposures of the SD of the PAO for the period equivalent to 6.4 years of continuous operation as a function of the neutrino energy

(PAO Collab., PRD 91 (2015) 092008)

DG neutrinos: enhanced interaction cross-section increases exposure:

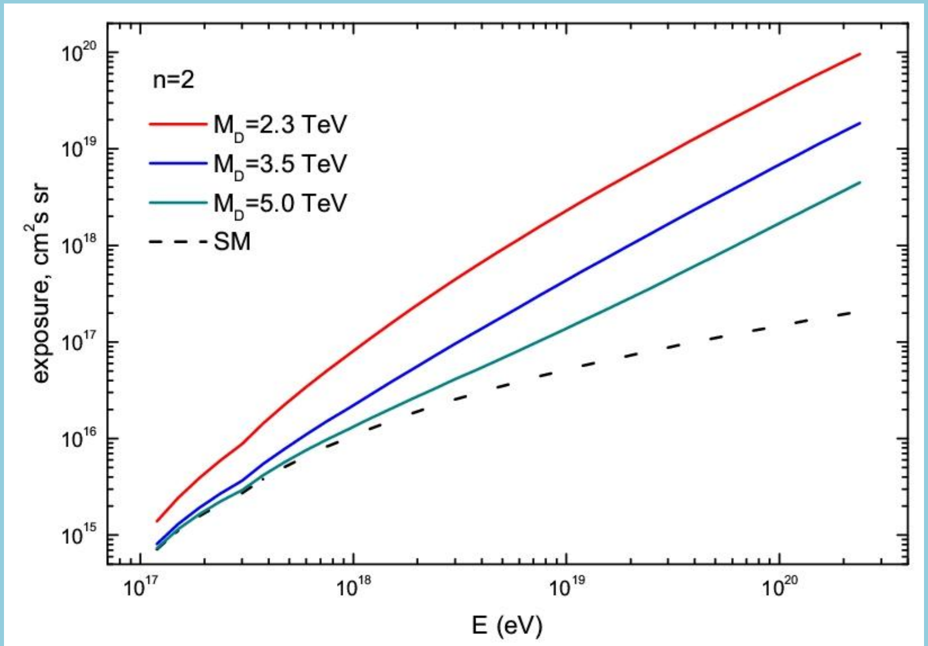
$$\varepsilon_{BSM}^{DG} = \varepsilon_{SM}^{DG} \frac{\sigma_{SM} + \sigma_{BSM}}{\sigma_{SM}}$$

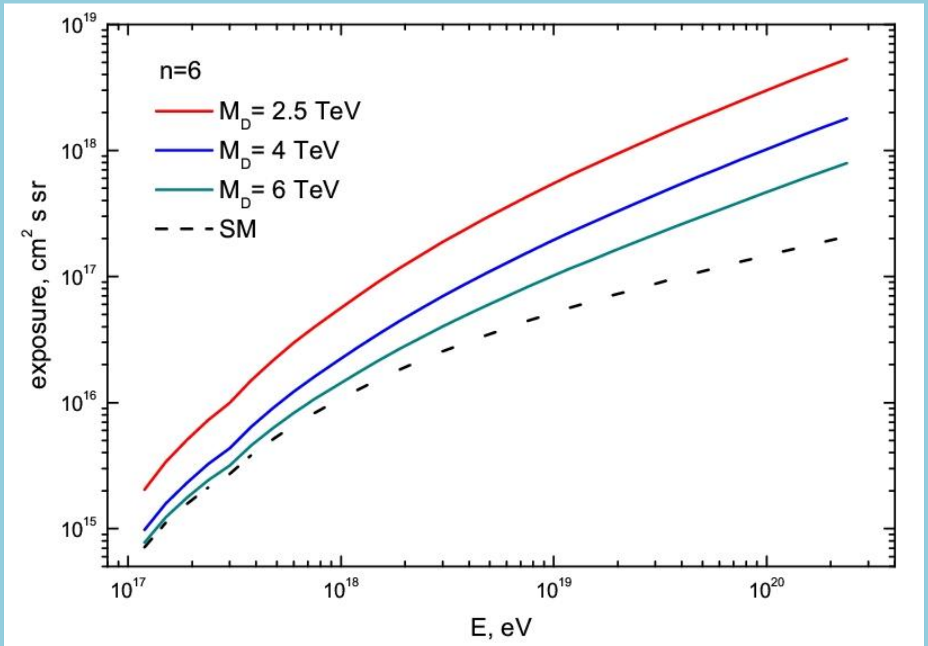
ES neutrinos: enhanced interaction cross-section suppresses exposure:

$$\varepsilon_{BSM}^{ES} = \varepsilon_{SM}^{ES} \left(\frac{\sigma_{CC}}{\sigma_{CC} + \sigma_{BSM}} \right)^2$$

(Anchordoqui et al, PRD 82 (2010) 043001)

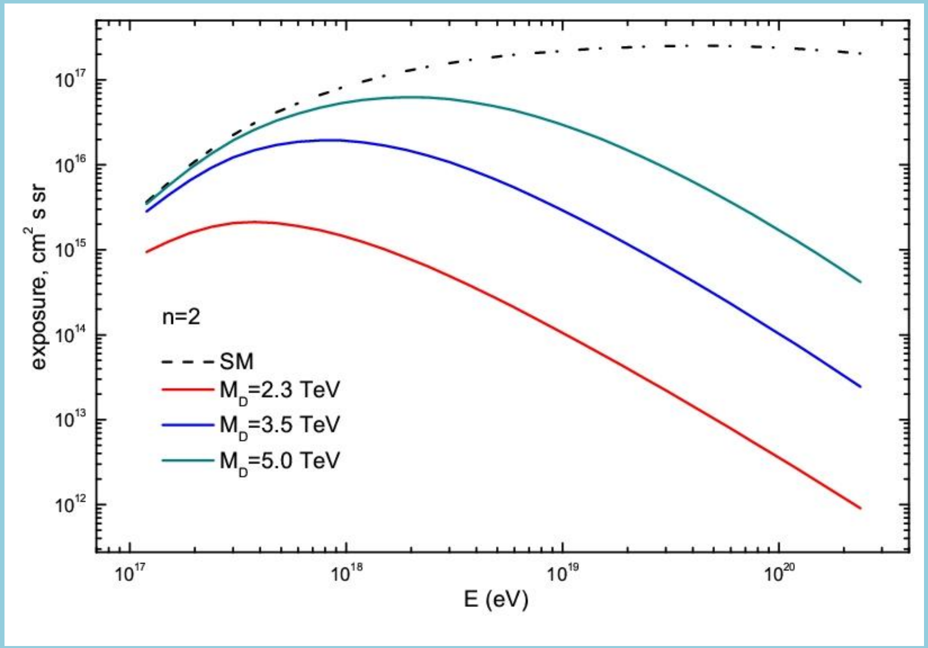
Exposures of the down-ward neutrino events in the ADD model

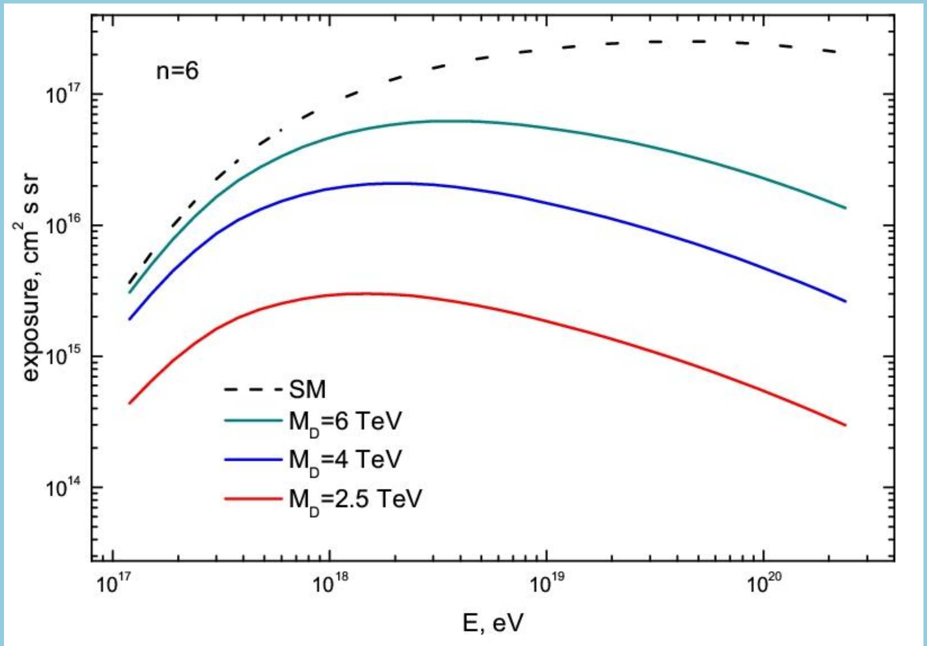




The exposures for the SD array of the PAO for the DG neutrino events with zenith angle **75° < θ < 90°** for different values of the gravity scale $\mathbf{M_D}$. Left panel: **n=2**. Right panel: **n=6**.

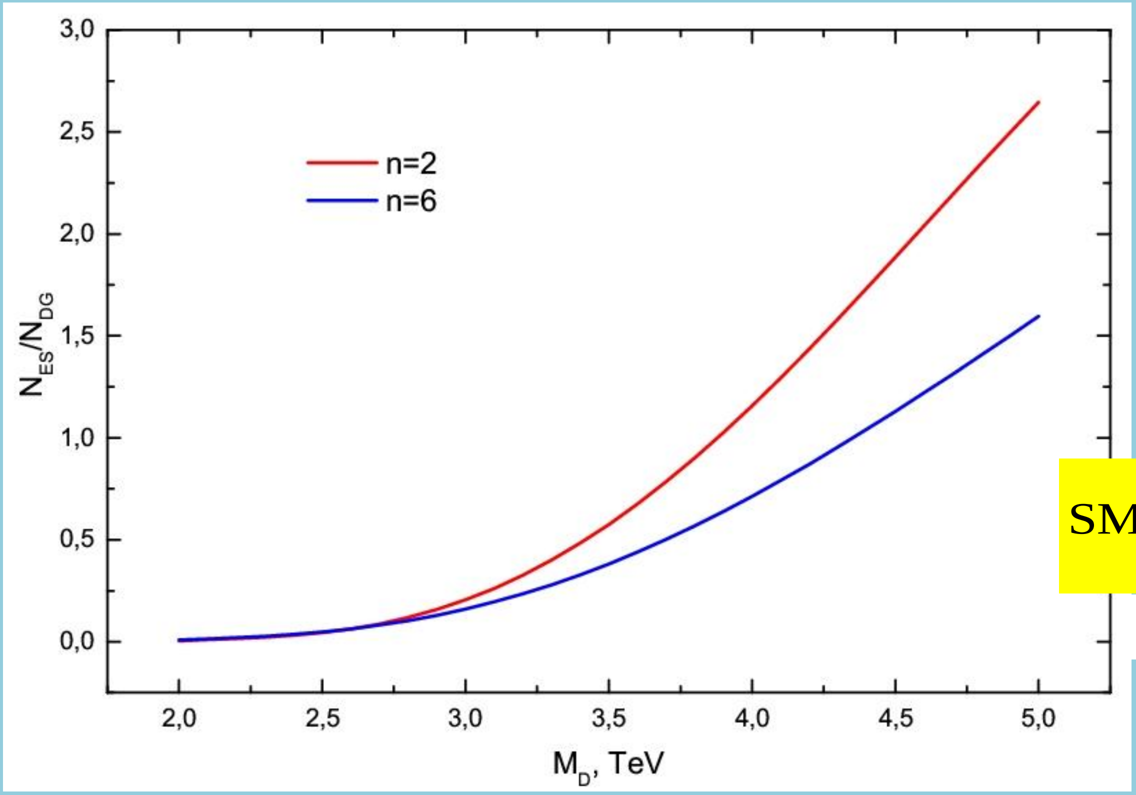
Exposures of the Earth-skimming neutrino events in the ADD model





The exposures for the SD array of the PAO for the ES neutrino events for different values of the gravity scale $\mathbf{M_D}$. Left panel: **n=2**. Right panel: **n=6**.

Numbers of downward-going and Earth-skimming neutrino events depend quite differently on $\sigma_{\nu N}$



$$\text{SM: } \frac{N_{ev}(ES)}{N_{ev}(DG)} \approx 6$$

(PAO Collab., 2015)

The expected ratio of the ES events to the DG events (with zenith angle **75° < θ < 90°**) at the SD array of the PAO as a function of $\mathbf{M_D}$ and **n.**

Bound on diffuse flux of UHE neutrinos

Diffuse neutrino flux: $$\frac{dN}{dE_\nu} = k\,E_\nu^{-2}$$

- number of observed events = 0

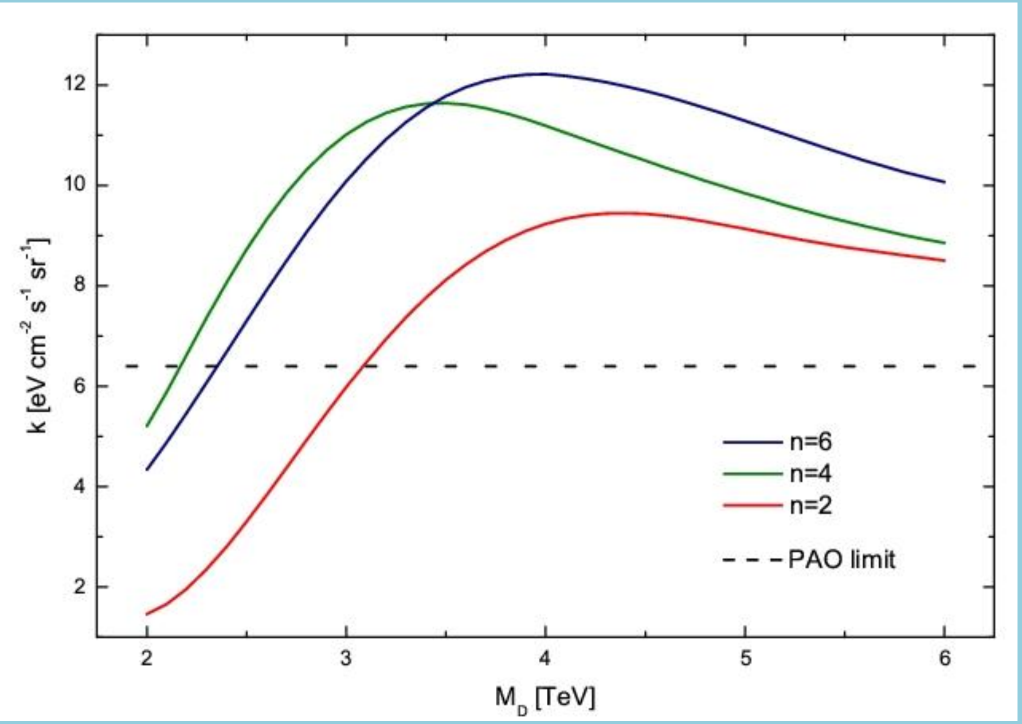
- number of expected background events = 0

Upper limit on signal events: $$N_{\rm up} = 2.39$$

Upper limit on k: $$k = \frac{N_{\rm up}}{\int \mathcal{E}(E_\nu)E_\nu^{-2}dE_\nu}$$

(PAO Collab., PRD 91 (2015) 092008)

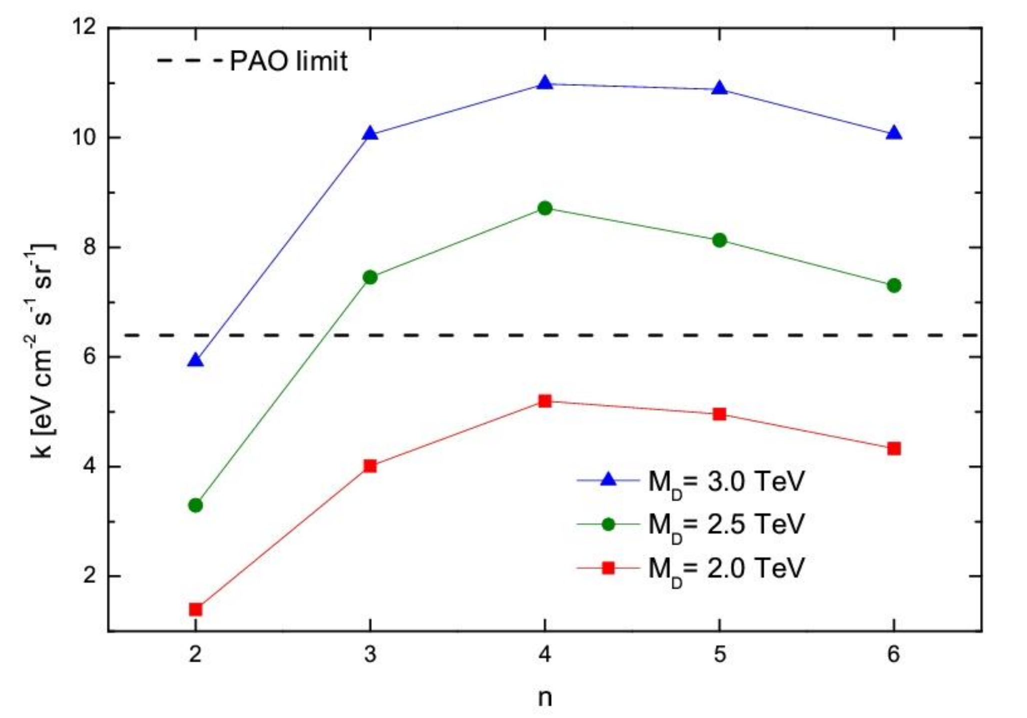
Upper limit on diffuse neutrino flux in comparison with the PAO upper limit



Upper bound on the flux normalizaion **k** in the ADD model as a function of **M_D** at fixed values of **n**

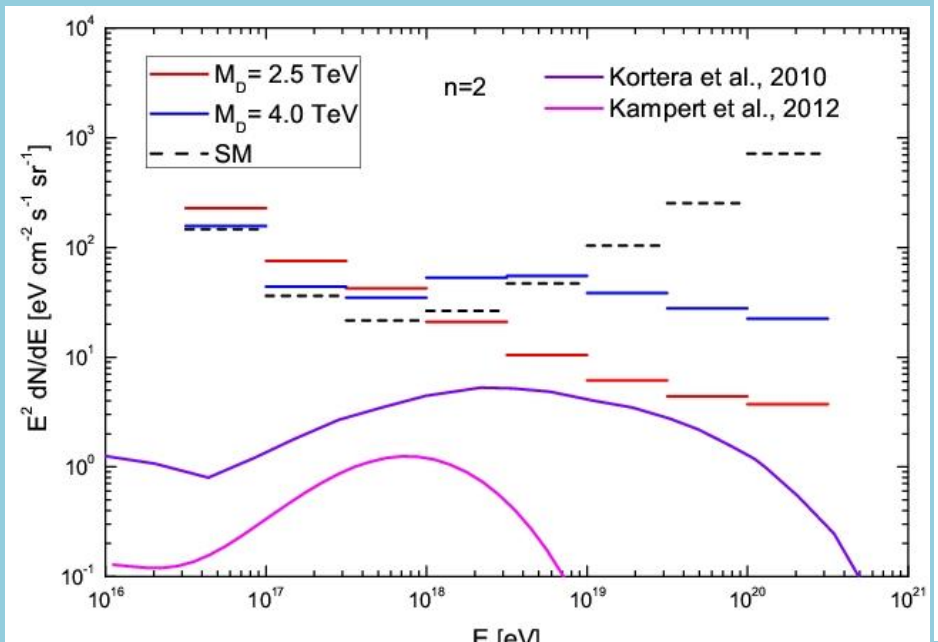
$$\frac{dN}{dE_\nu} = k \times E_\nu^{-2}$$

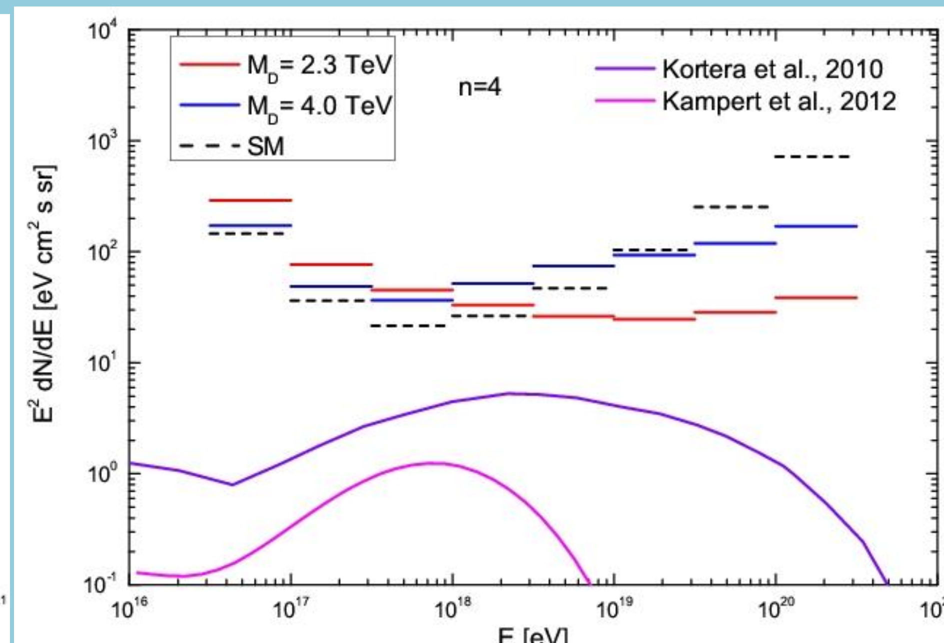
Upper limit on diffuse neutrino flux: nontrivial dependence on n



Upper bound on the flux normalizaion **k** in the ADD model as a function of **n** at fixed values of $\mathbf{M_D}$

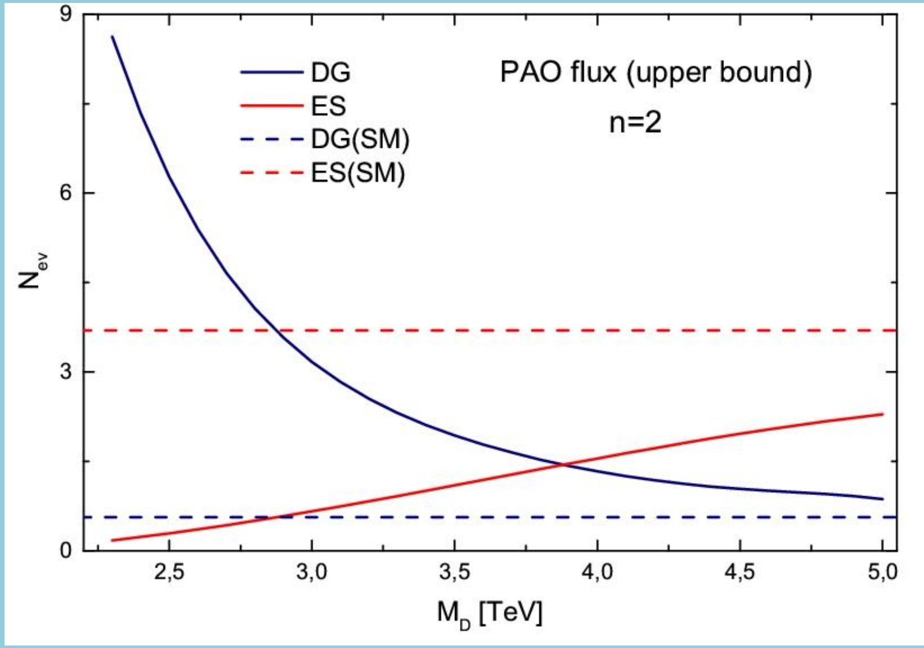
Upper limit on diffuse neutrino flux in energy bins

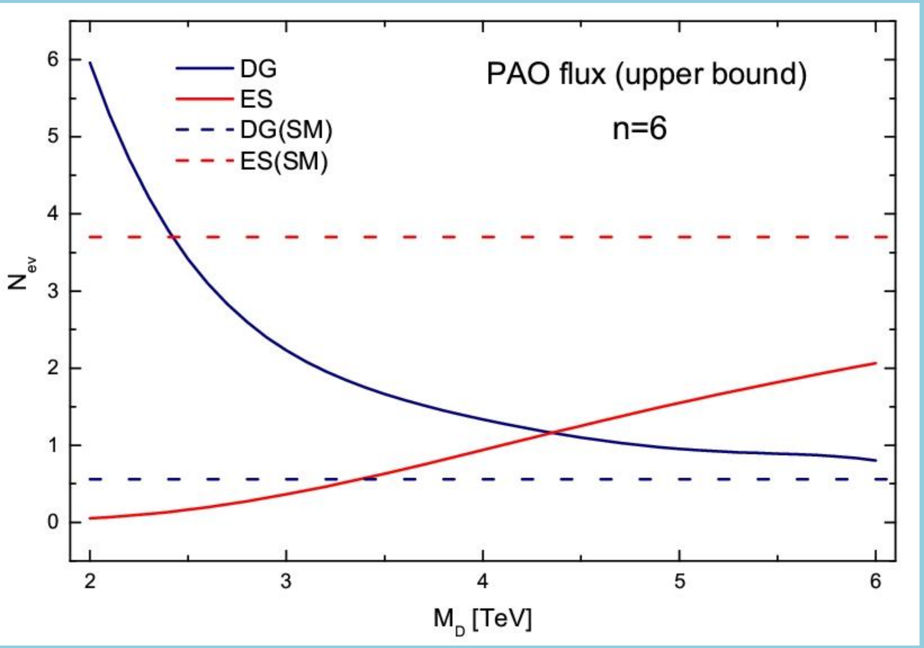




Upper bound on the normalizaion of the diffuse flux in bins of width **0.5** in **$\log_{10}E_\nu$** in comparison with the PAO bound in bins and two cosmogenic models

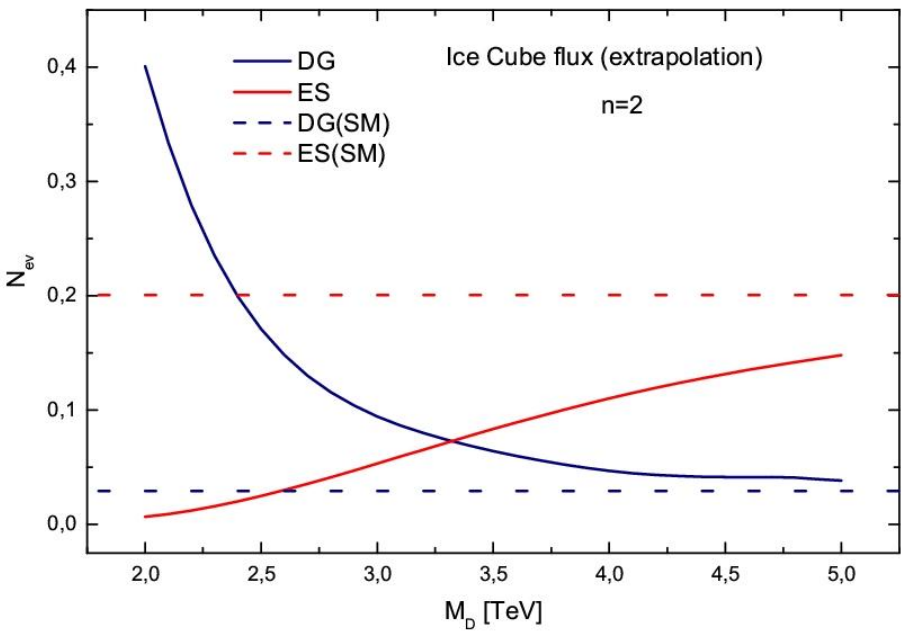
Expected number of events induced by UHE neutrinos with the Auger flux

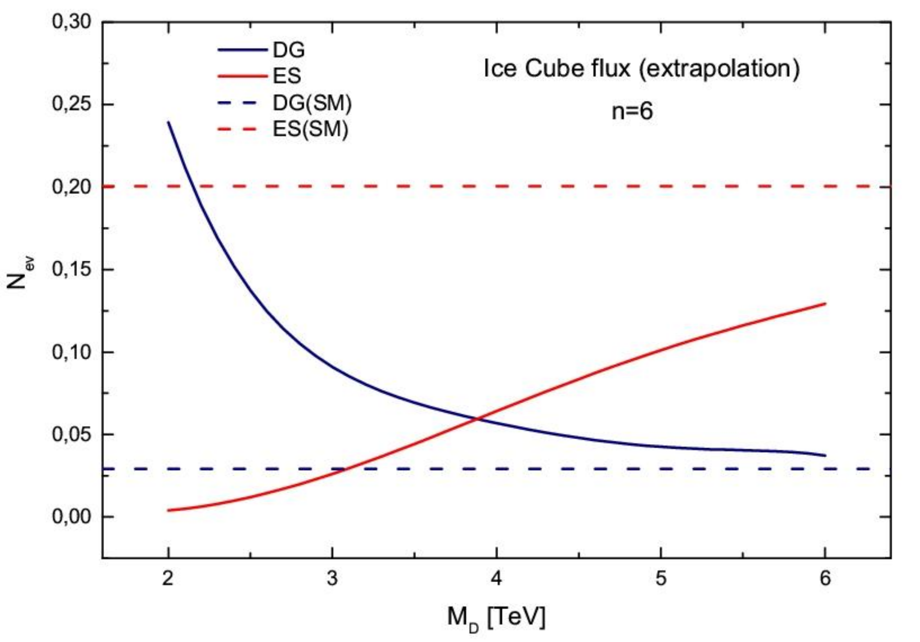




Expected number of neutrino events at the SD of the PAO for a period equivalent of 2•6.4 years of PAO working continuously

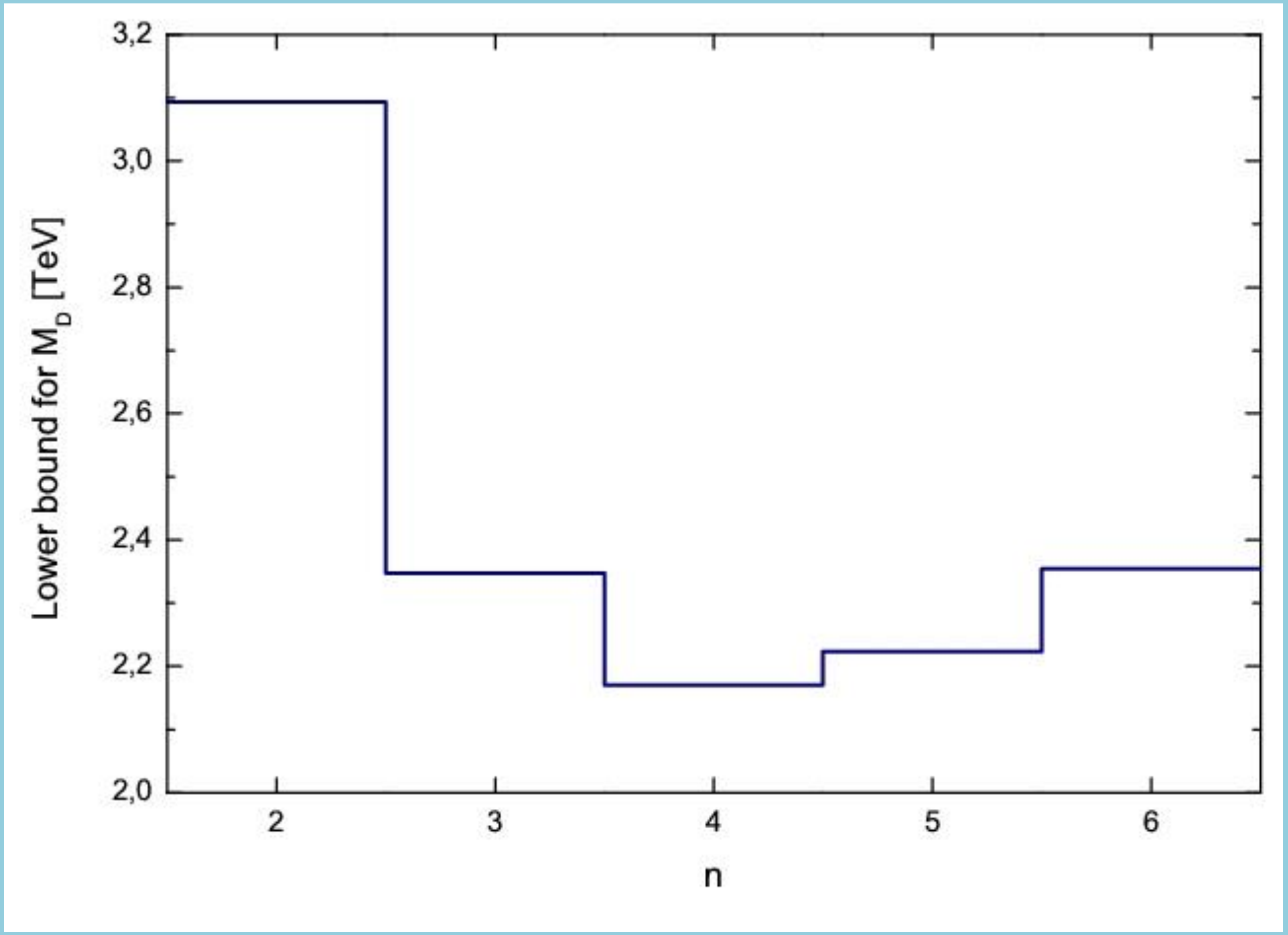
Expected number of events induced by UHE neutrinos with the IceCube flux





Expected number of neutrino events at the SD of the PAO for a period equivalent of 2•6.4 years of PAO working continuously

Lower bound on D-dimensional Planck scale M_D as a function of number of extra dimensions n



Заключение

- **Космические высоко-энергетичные нейтрино играют ключевую роль в понимании источника космических лучей (КЛ) сверхвысоких энергий**
- **Астрофизические нейтрино высоких энергий впервые зарегистрированы детектором IceCube**
- **Коллаборация Пьер Оже произвела поиск как квазигоризонтальных (downward-going) так и Earth-skimming нейтринных событий.**
  В результате получено верхнее ограничение на диффузионный поток нейтрино сверхвысоких энергий
- **В рамках сценария с дополнительными измерениями это ограничение оценено в зависимости от D-мерной массы Планка M_D и числа дополнительных измерений n**

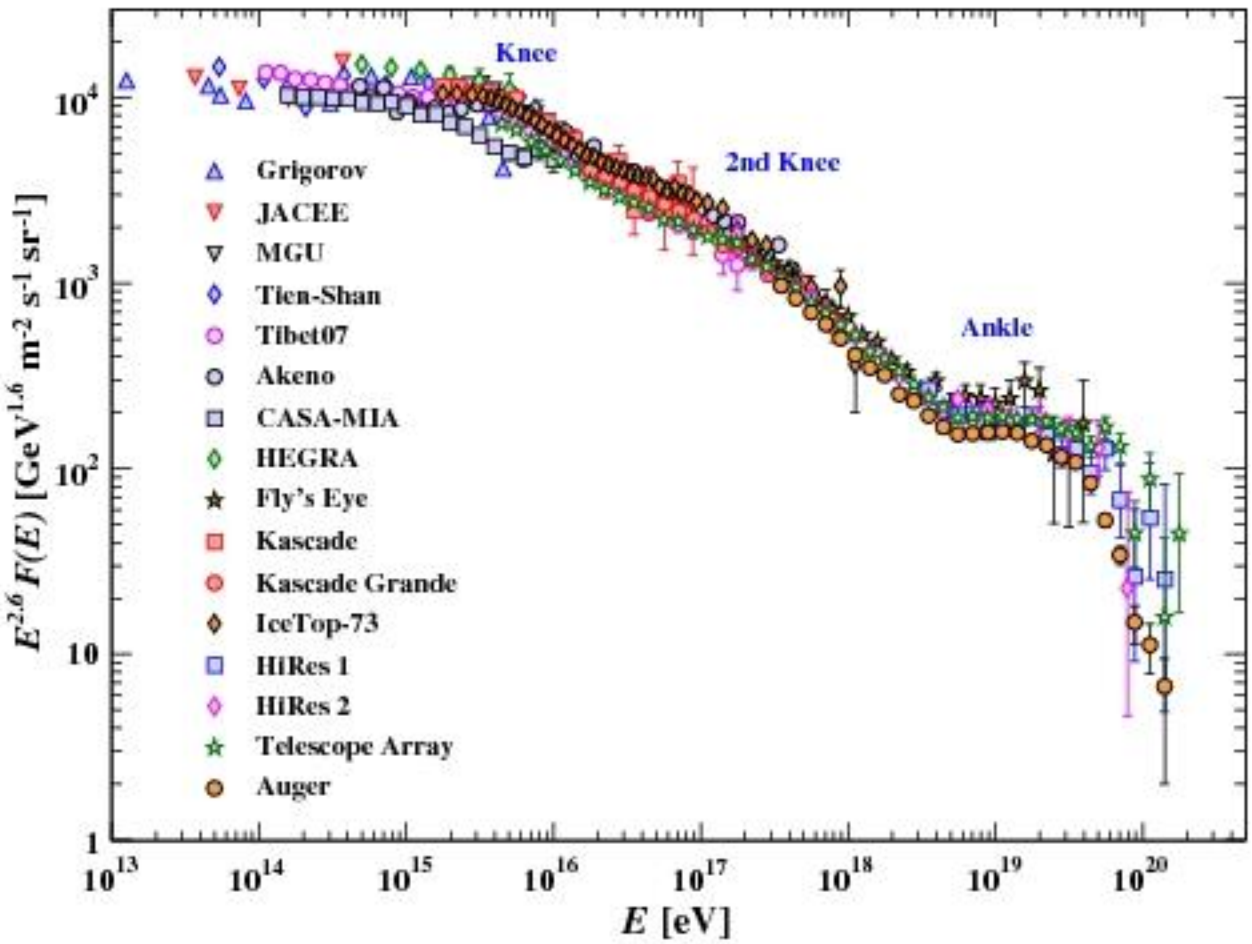
Заключение (продолжение)

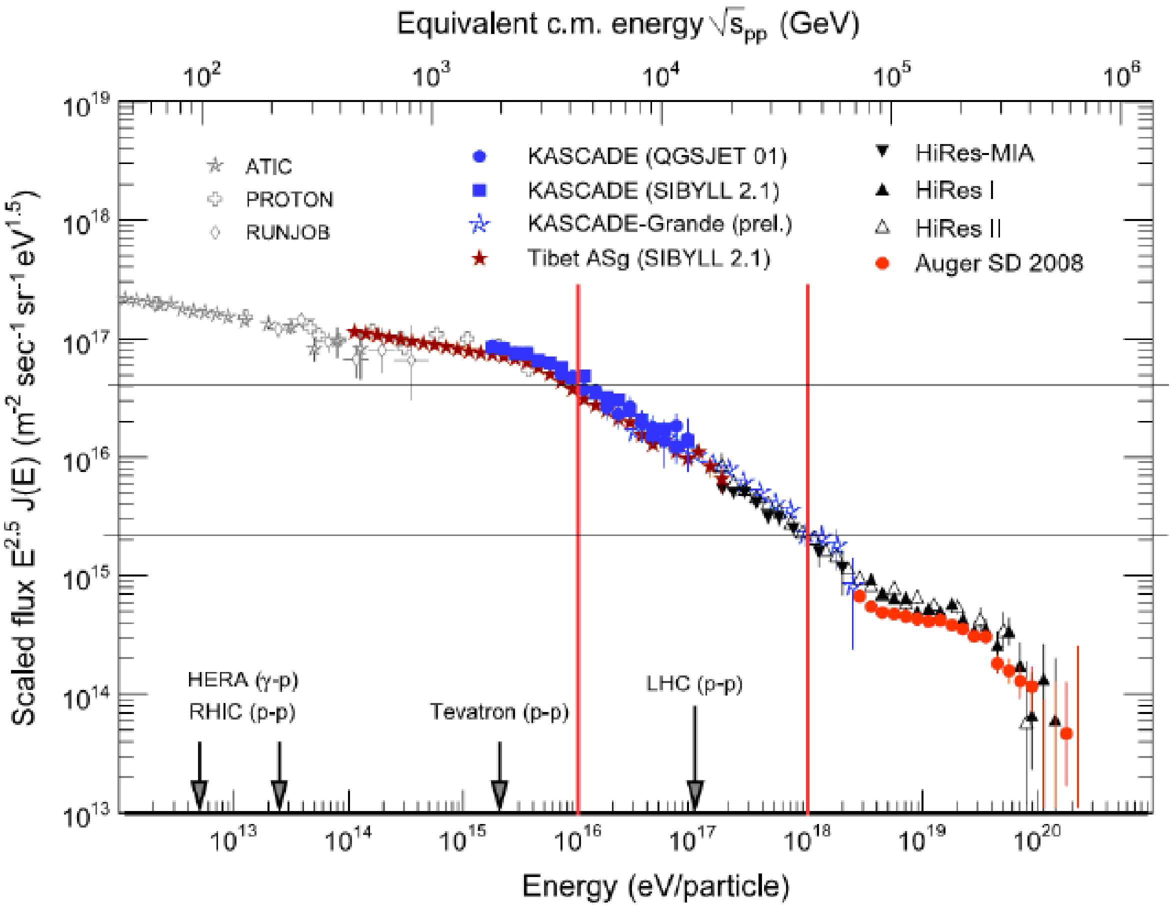
- Полученное ограничение оказалось более жестким, чем ограничение Оже, для M_D < 3.09 TeV (2.35 TeV), при n =2 (6)
- Вычислены ограничения на нейтринный поток по энергетическим бинам.
  Показано, что модели космогенических нейтрино, предполагающие смешанный или чисто ядерный первичный состав КЛ, не закрываются найденными ограничениями
- Оценено ожидаемое число нейтринных событий на детекторе Пьер Оже в случае его непрерывной работы в течение 2•6.4 лет

Спасибо
за внимание!

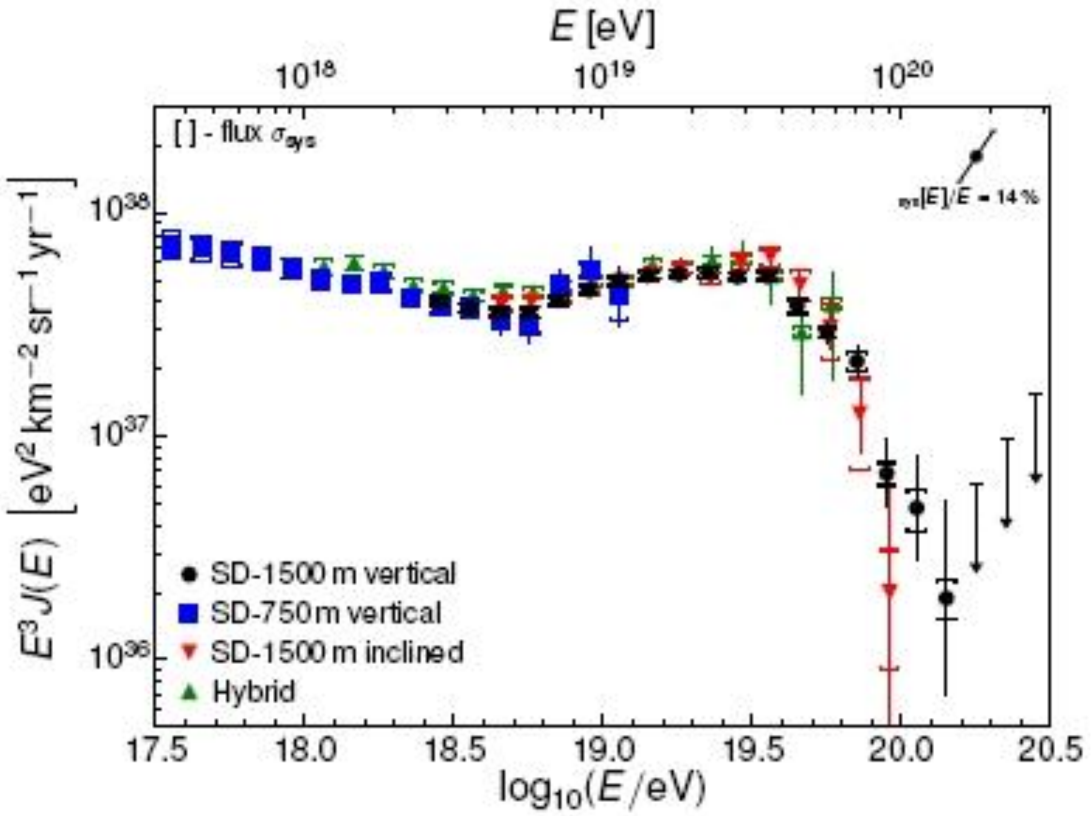
Back-up slides

GZK cutoff of the CR spectrum



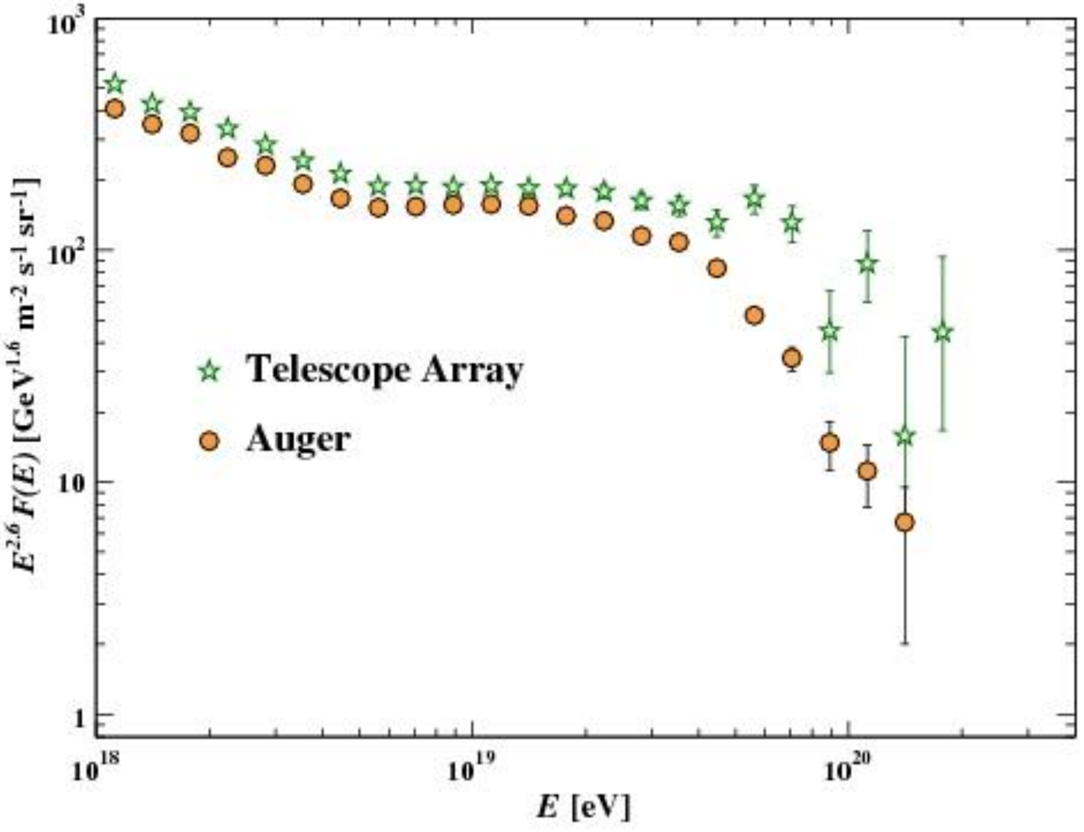


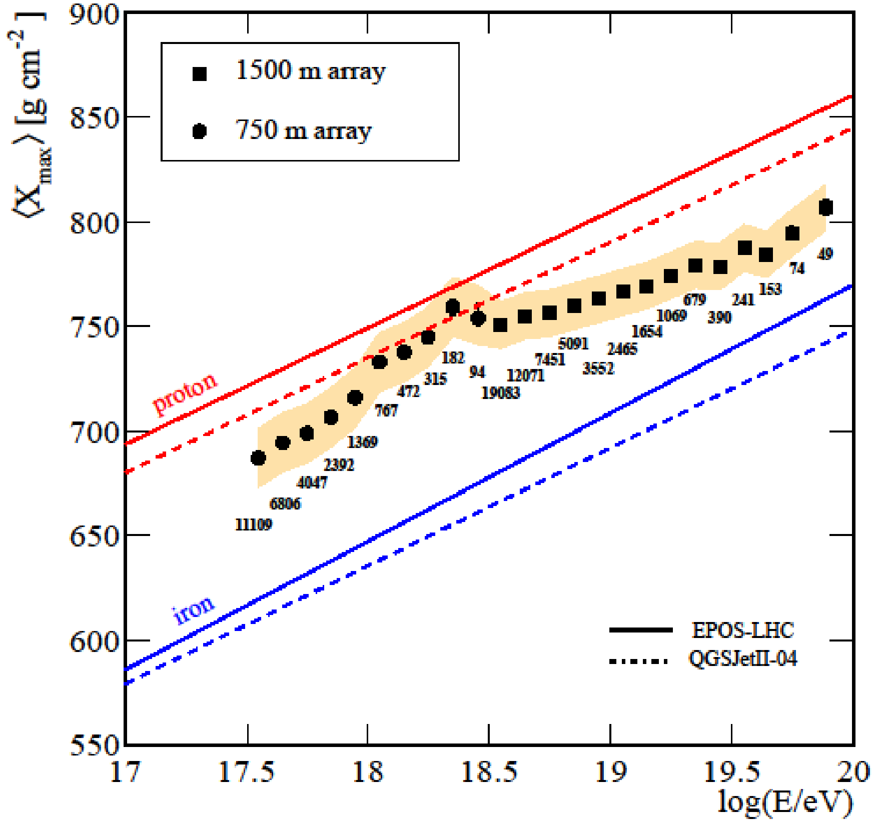
All-particle cosmic-ray energy spectrum



Energy spectrum derived from the Surface detector (SD) and hybrid data at the Pierre Auger Observatory (PAO)

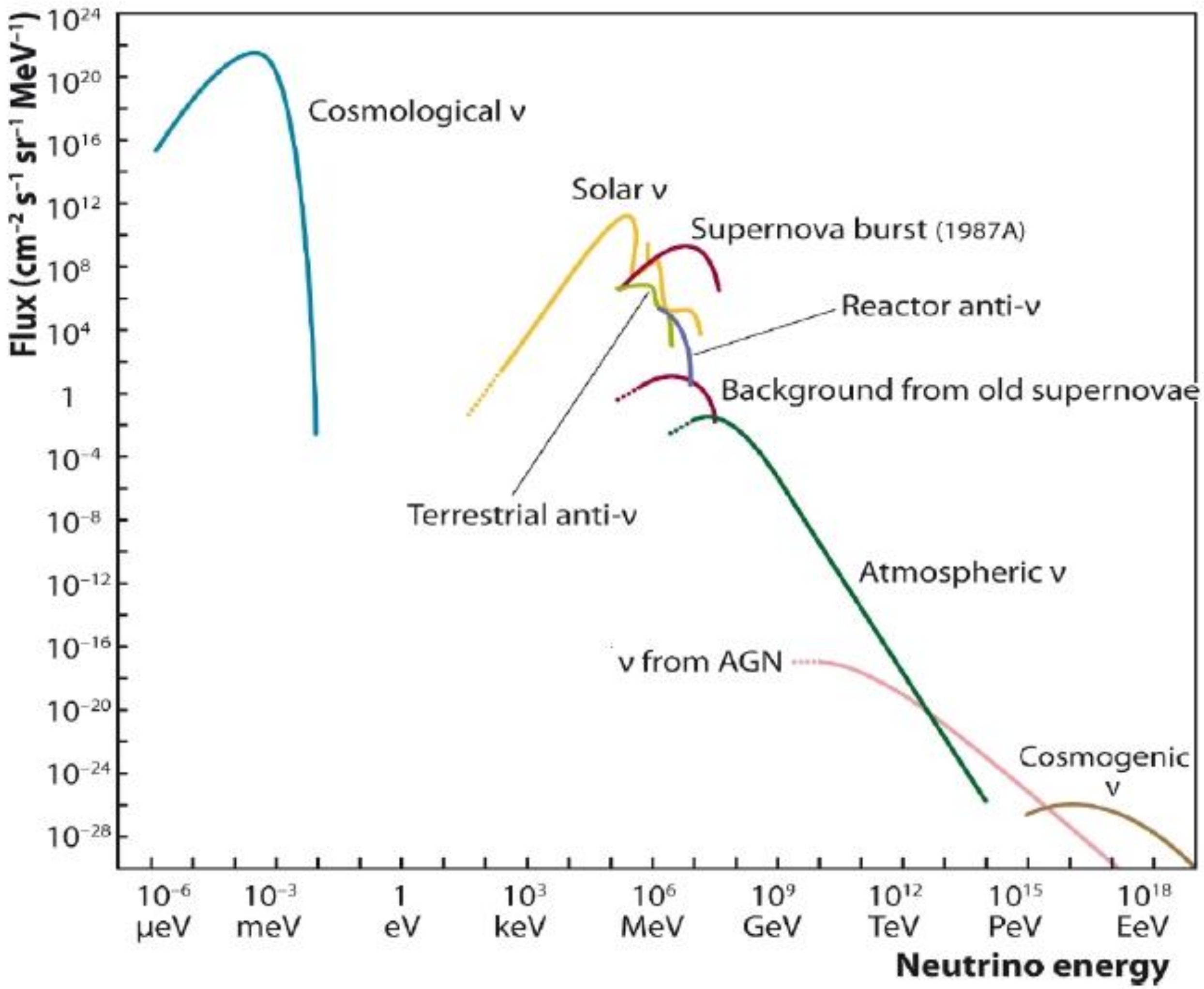
(PAO Collab., ICRC, 2015)

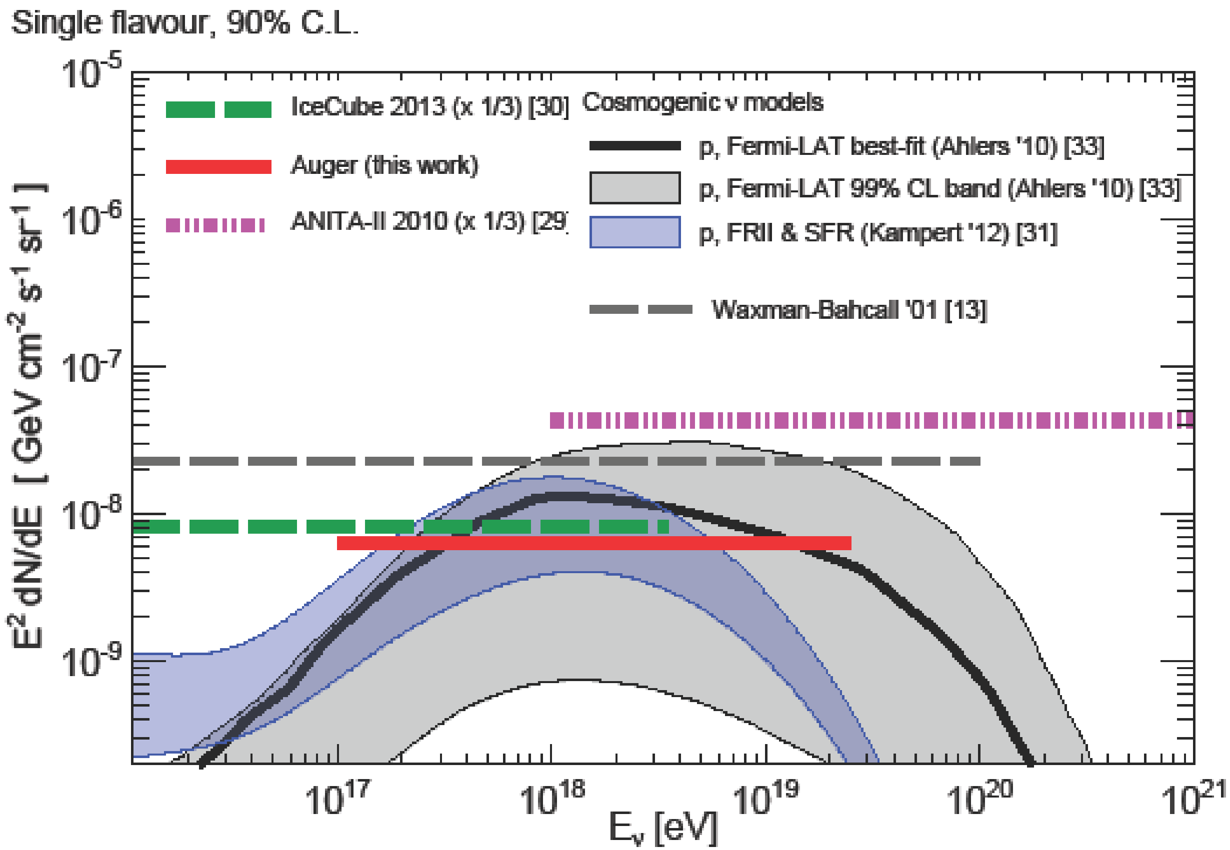

10^3
10^2
10
1
$E^{2.6} F(E)$ [GeV$^{1.6}$ m^{-2} s^{-1} sr^{-1}]
Telescope Array
Auger
10^{18}
10^{19}
10^{20}
E [eV]



Average depth of shower maxima as a function of energy

(*PAO Collaboration, PRD 96(2017)122003*)


Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
10^24
10^20
10^16
10^12
10^8
10^4
1
10^-4
10^-8
10^-12
10^-16
10^-20
10^-24
10^-28
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
10^-6 μeV
10^-3 meV
1 eV
10^3 keV
10^6 MeV
10^9 GeV
10^12 TeV
10^15 PeV
10^18 EeV
Neutrino energy



$$\frac{dN}{dE_\nu} = k \times E_\nu^{-2}$$

Upper limit to the normalization of the diffuse flux of UHE neutrinos from the PAO (red line), along with fluxes in several cosmogenic models (with protons as primaries)

(PAO Collab., PRD 91 (2015) 092008)

$\log E/\mathrm{eV}$	ν_e CC	ν_μ CC	ν_τ CC	ν_x NC	ν_τ Mount.
16.75	$4.35 \cdot 10^{21}$	$5.27 \cdot 10^{20}$	$1.82 \cdot 10^{21}$	$2.11 \cdot 10^{20}$	-
17	$1.27 \cdot 10^{22}$	$3.16 \cdot 10^{21}$	$1.09 \cdot 10^{22}$	$1.26 \cdot 10^{21}$	-
17.5	$7.94 \cdot 10^{22}$	$2.34 \cdot 10^{22}$	$6.02 \cdot 10^{22}$	$9.37 \cdot 10^{21}$	$1.98 \cdot 10^{22}$
18	$2.17 \cdot 10^{23}$	$8.01 \cdot 10^{22}$	$1.77 \cdot 10^{23}$	$3.20 \cdot 10^{22}$	$1.21 \cdot 10^{23}$
18.5	$3.95 \cdot 10^{23}$	$1.71 \cdot 10^{23}$	$2.84 \cdot 10^{23}$	$6.84 \cdot 10^{22}$	$2.51 \cdot 10^{23}$
19	$5.44 \cdot 10^{23}$	$2.56 \cdot 10^{23}$	$3.58 \cdot 10^{23}$	$1.03 \cdot 10^{23}$	$3.13 \cdot 10^{23}$
19.5	$6.32 \cdot 10^{23}$	$2.99 \cdot 10^{23}$	$4.36 \cdot 10^{23}$	$1.20 \cdot 10^{23}$	$3.06 \cdot 10^{23}$
20	$7.29 \cdot 10^{23}$	$3.45 \cdot 10^{23}$	$5.19 \cdot 10^{23}$	$1.38 \cdot 10^{23}$	$2.82 \cdot 10^{23}$

Effective mass apertures A_i for DG neutrinos of the PAO Surface Detector in units of [g s sr]

(PAO Collab., PRD 84 (2011) 122005)

Exposure of the SD for DG neutrinos:

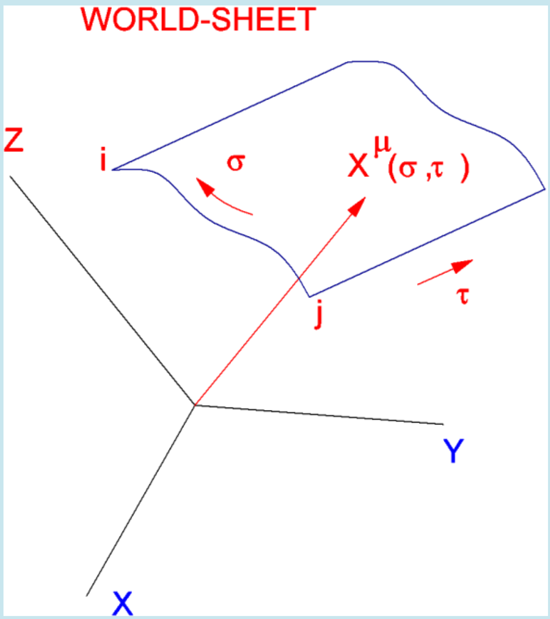
$$E(E_\nu) = \sum_i \sigma_i(E_\nu)\, A_i(E_\nu)/m_N$$

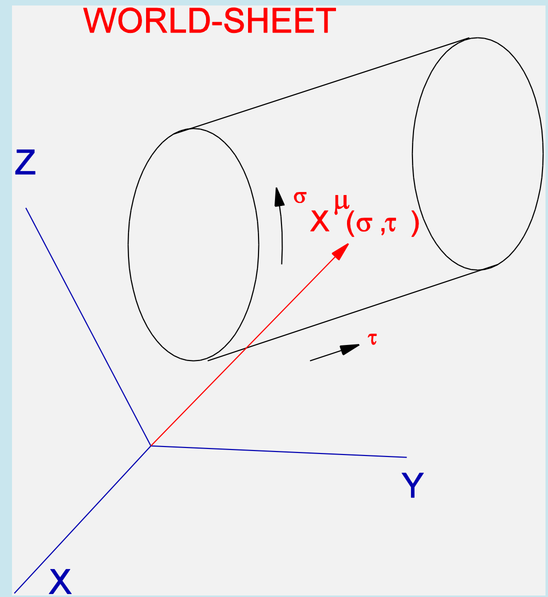
Diffuse flux Neutrino model	Expected number of events (1 January 2004–20 June 2013)	Probability of observing 0
Cosmogenic—proton, FRII [33]	~4.0	$\sim 1.8 \times 10^{-2}$
Cosmogenic—proton, SFR [33]	~0.9	~0.4
Cosmogenic—proton, Fermi-LAT, $E_{\rm min} = 10^{19}$ eV [34]	~3.2	$\sim 4 \times 10^{-2}$
Cosmogenic—proton, Fermi-LAT, $E_{\rm min} = 10^{17.5}$ eV [34]	~1.6	~0.2
Cosmogenic—proton or mixed, SFR & GRB [9]	~0.5–1.4	~0.6–0.2
Cosmogenic—iron, FRII [33]	~0.3	~0.7
Astrophysical ν (AGN) [35]	~7.2	$\sim 7 \times 10^{-4}$
Exotic [36]	~31.5	$\sim 2 \times 10^{-14}$

(PAO Collab., PRD 91 (2015) 092008)

Strings needs extra dimensions (EDs)

Superstrings: D= 10
(6 EDs must be compactified)





World sheets of open (left) and closed (right) strings propagating in the space-time

Why spatial (i.e. space-like) EDs?

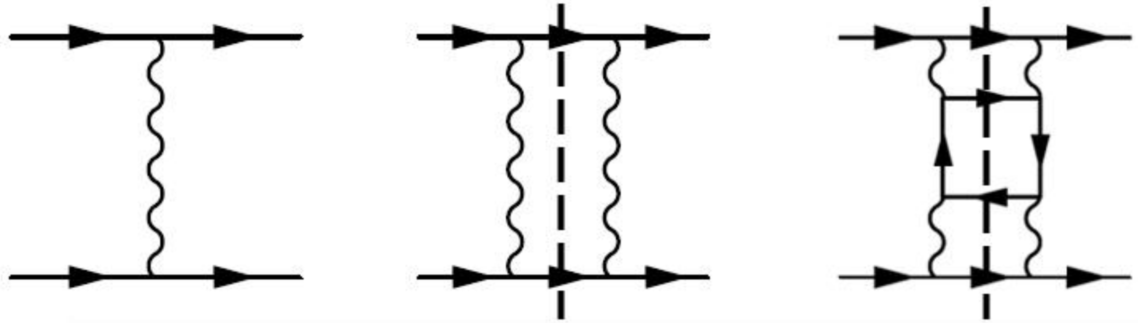
Metric tensor (D=5): $g_{MN} = \mathrm{diag}\,(1, -1, -1, -1, \pm 1)$

Massless particle in 5 dimensions
(Loretz invariance holds):

$$p^2 = 0 = g_{MN} p^M p^N = p_0^2 - \vec{p}^{\,2} \pm p_5^2$$

$$p_\mu p^\mu = m^2 = \mp p_5^2$$

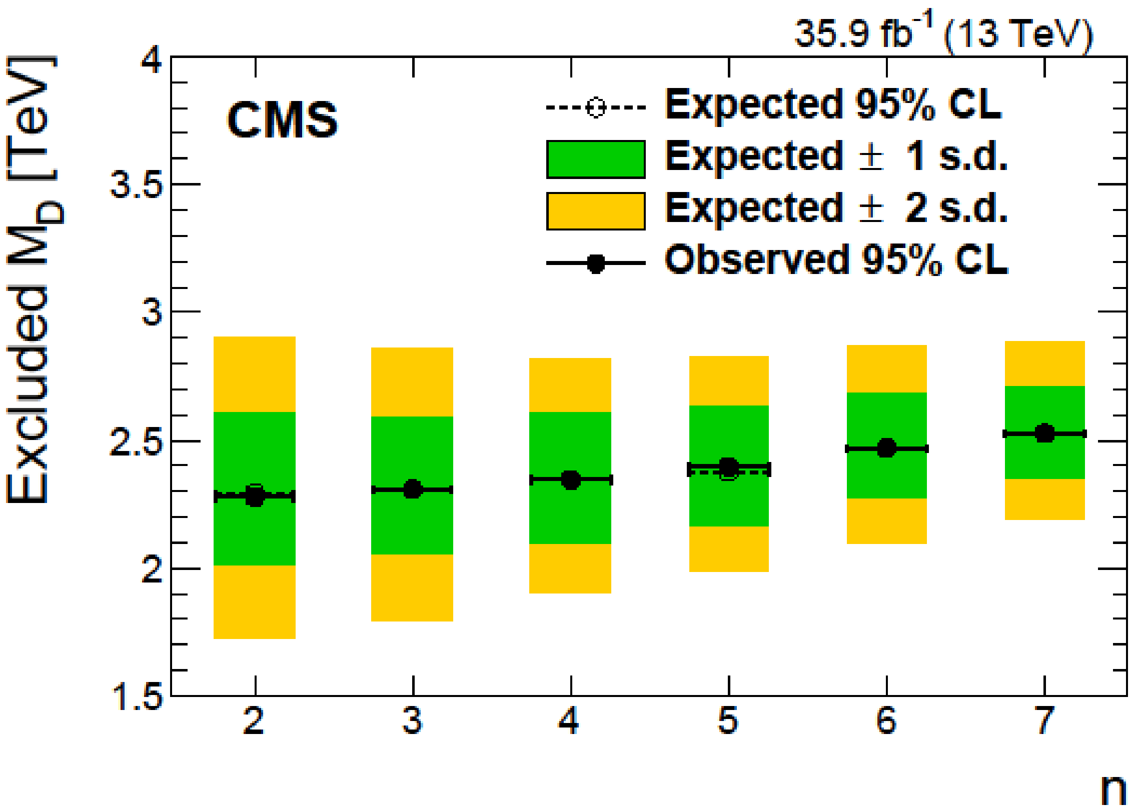
No tachyons → **Spatial extra dimension**



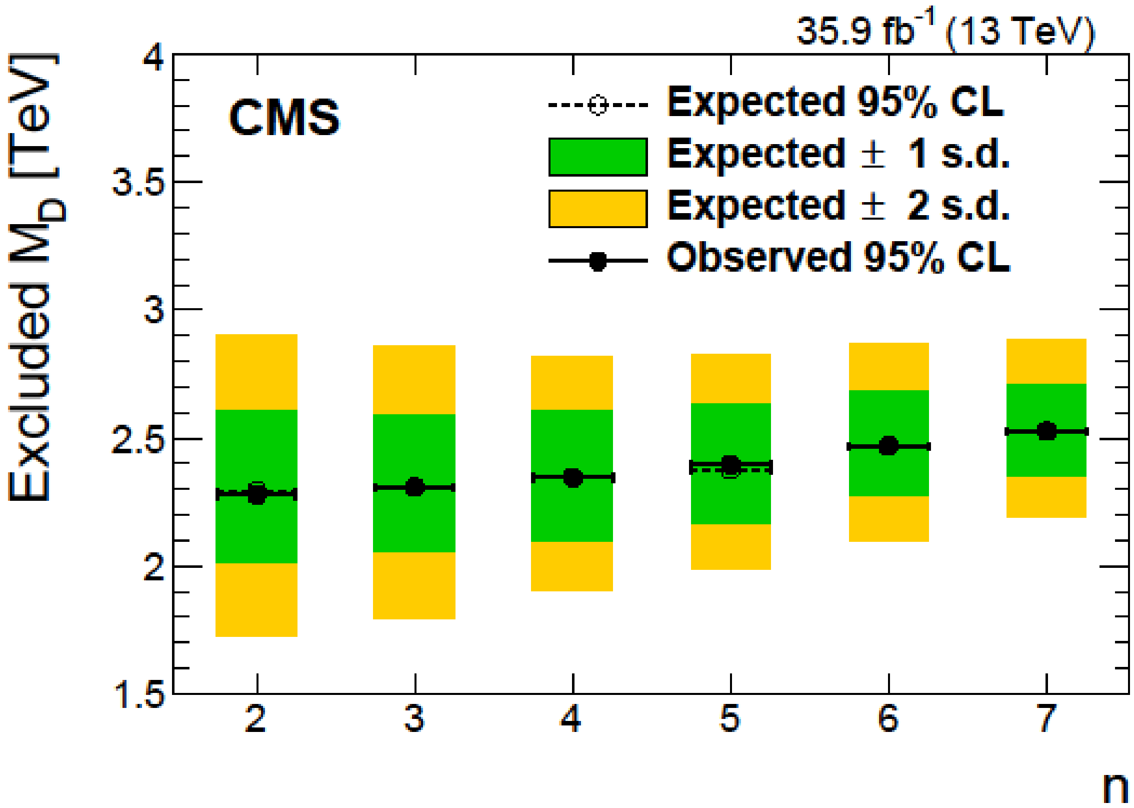
The s^2 dependence of the graviton-exchange Born term renders the sum of exchanges dominant with respect to the inelastic diagrams (see third diagram on this figure)

Ordinary gauge theory:
no classical limit

Different properties of spin-2 and spin-1 exchange – because energy itself plays the role of charge in gravity

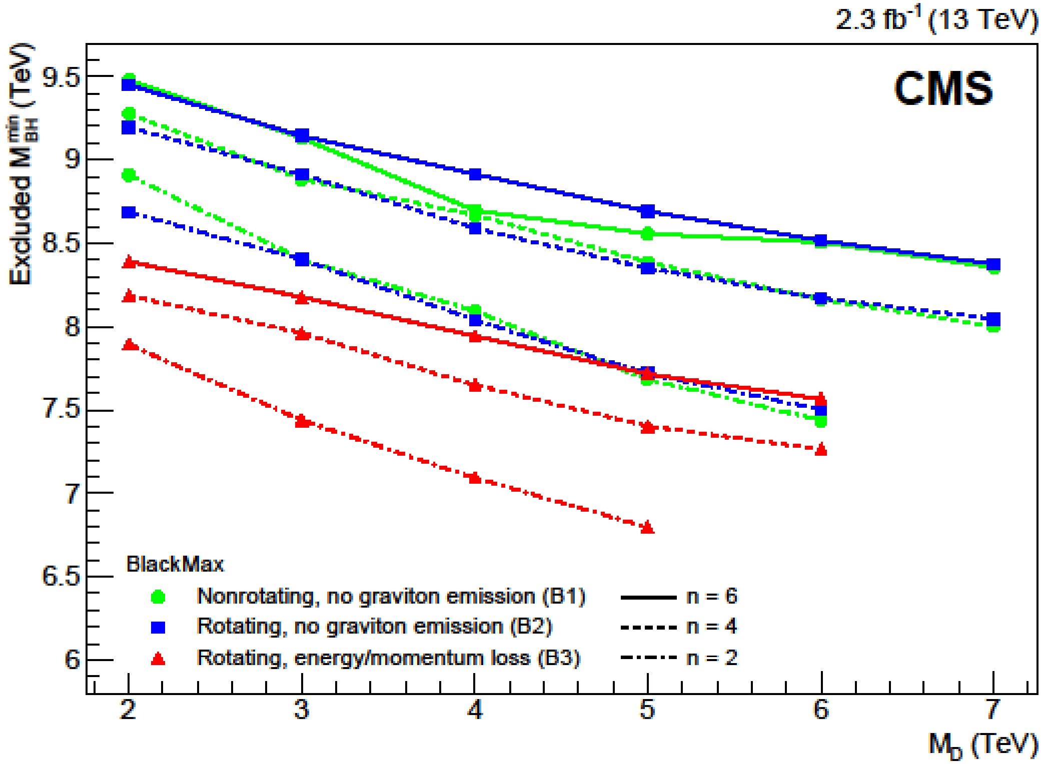


95% CL exclusion limits on M_D
in the ADD model for different values of n
(CMS Collab., EPJC 78 (2018) 291)



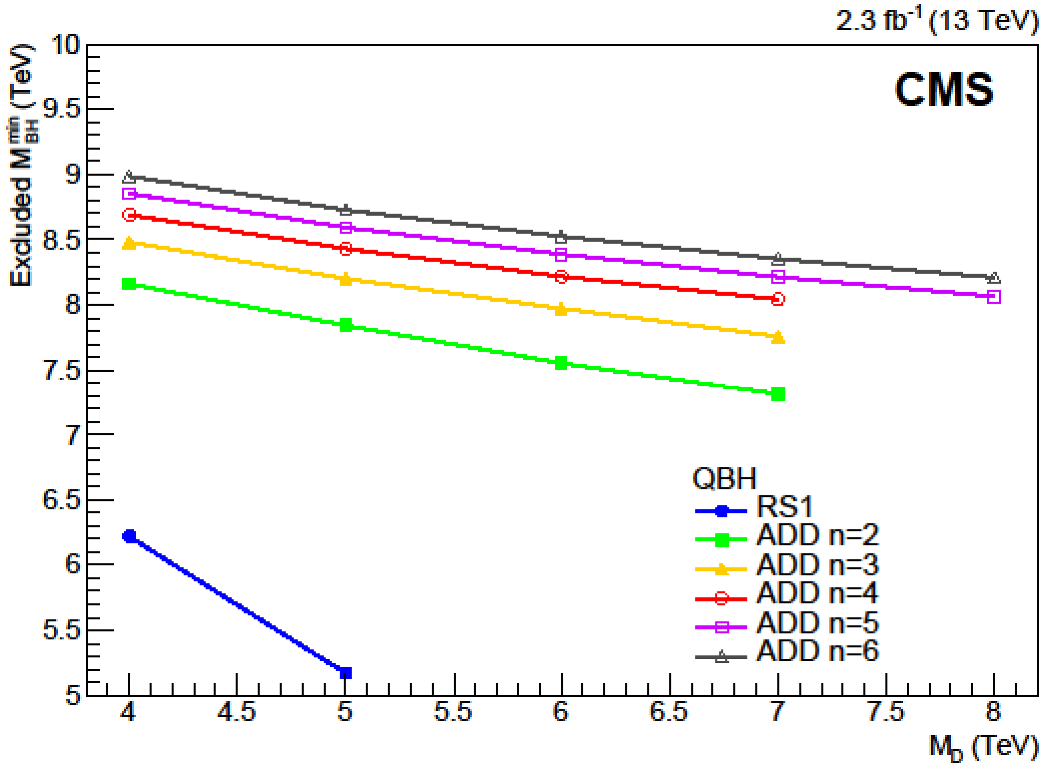
Expected and observed 95% CL exclusion limits on M_D in the ADD scenario for different values of n

(CMS Collab., EPJC 78 (2018) 291)



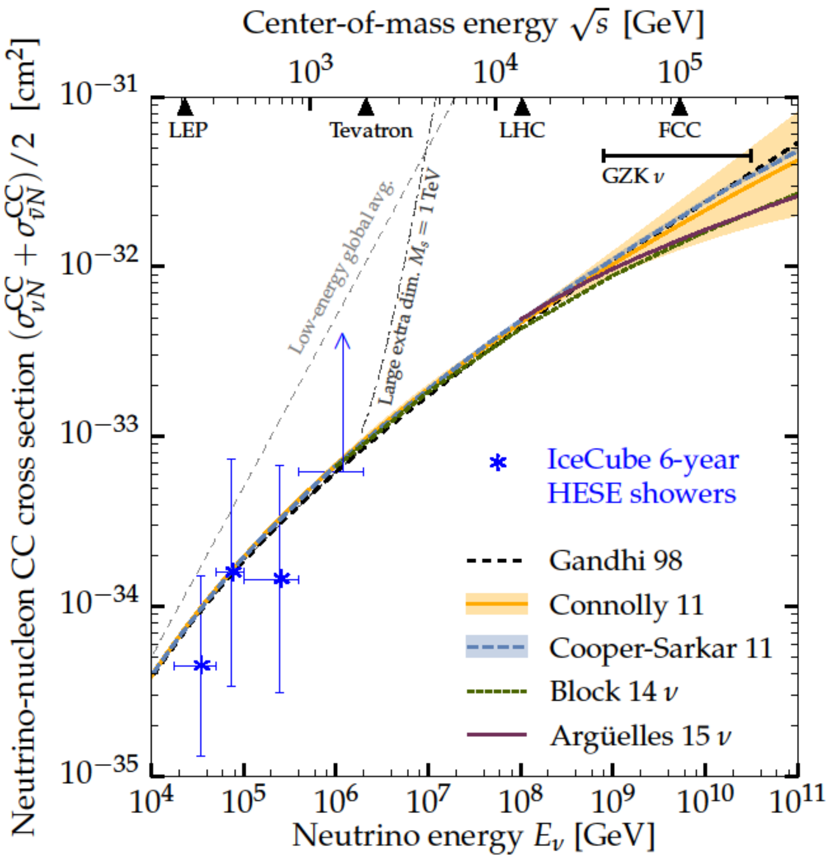
The 95% CL lower limits on minimum semiclassical black hole mass as a function of the Planck scale M_D, for several benchmark models

(CMS Collab., Phys. Lett. D 774 (2017) 279)



The 95% CL lower limits on minimum quantum black hole mass as a function of the Planck scale M_D, for several benchmark models (bound in the RS1 scenario is also shown)

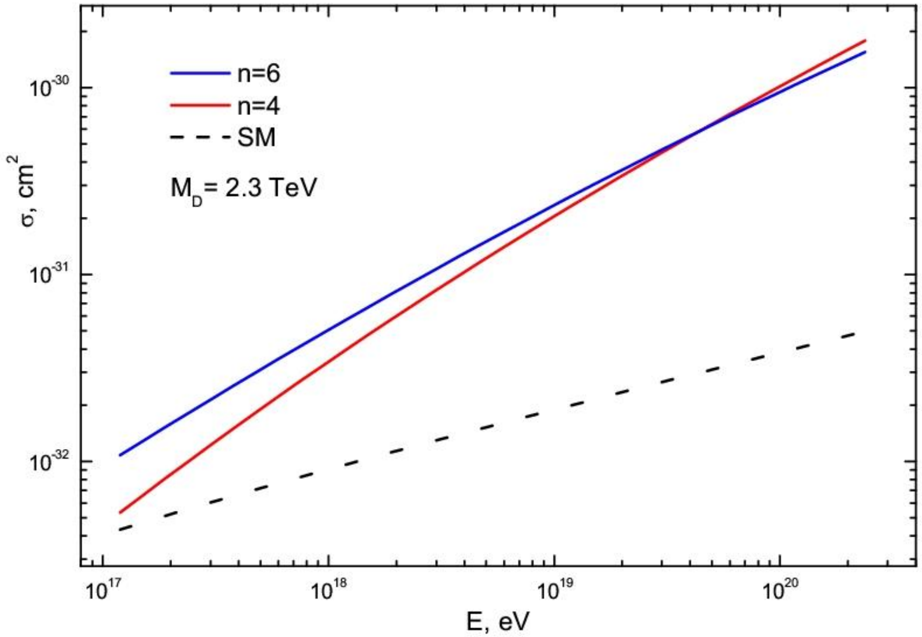
(CMS Collab., Phys. Lett. D 774 (2017) 279)

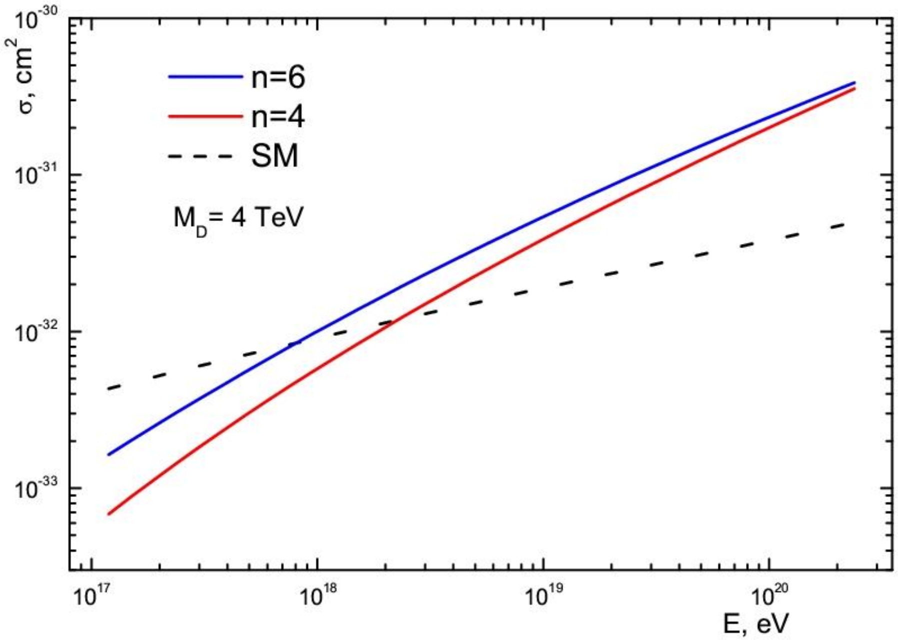


Neutrino-nucleon charged-current cross section, averaged for neutrino and antineutrino, from different predictions

(Bustamante and Connolly, arXiv:1711.11043)

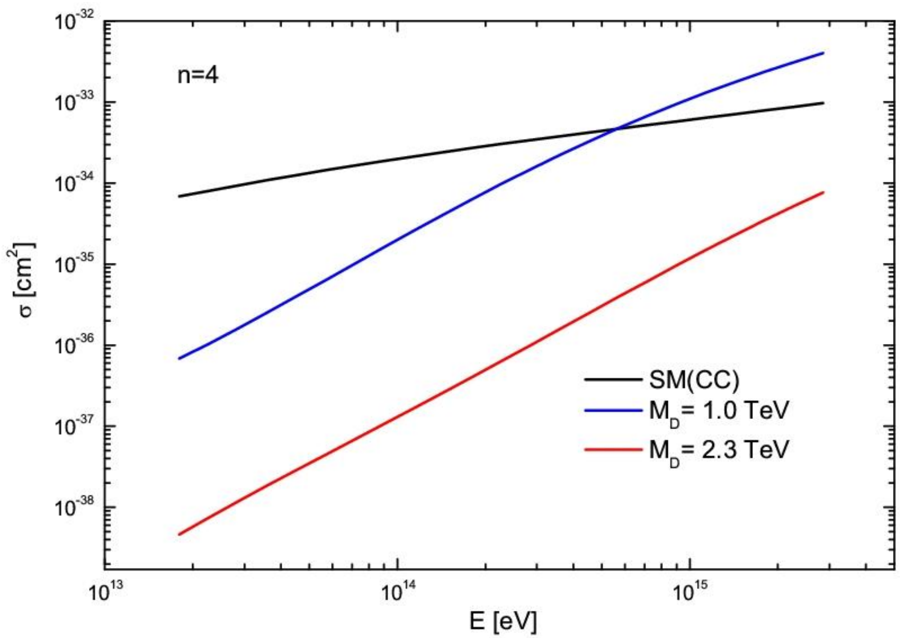
BSM: $\sigma_{\nu N}$ does not significantly depend on n for n ≥ 3 at high energies

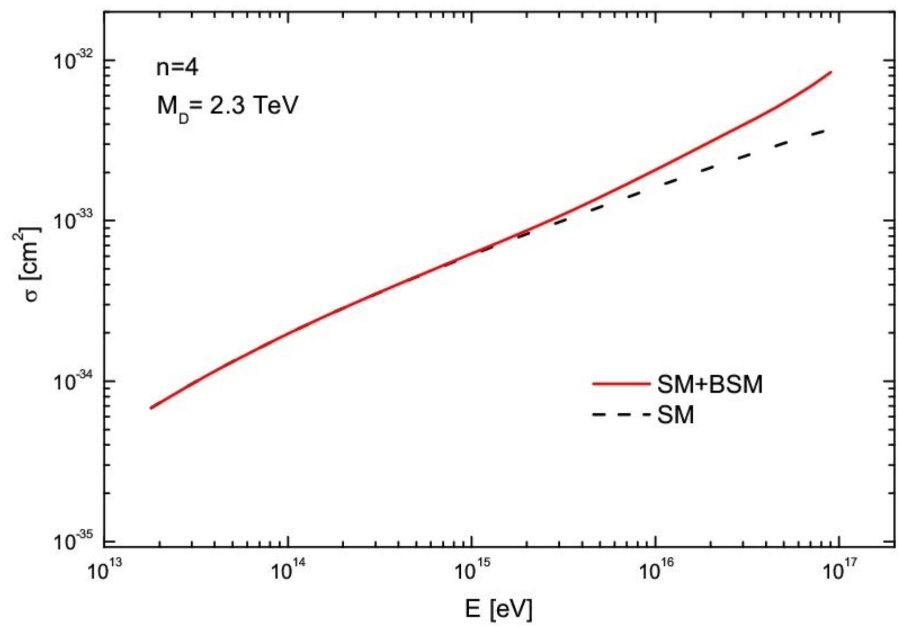




The total neutrino-nucleon cross sections for **M_D = 2.3 TeV** (left panel) and **M_D = 4 TeV** (right panel) with two values of the number of extra dimensions **n**

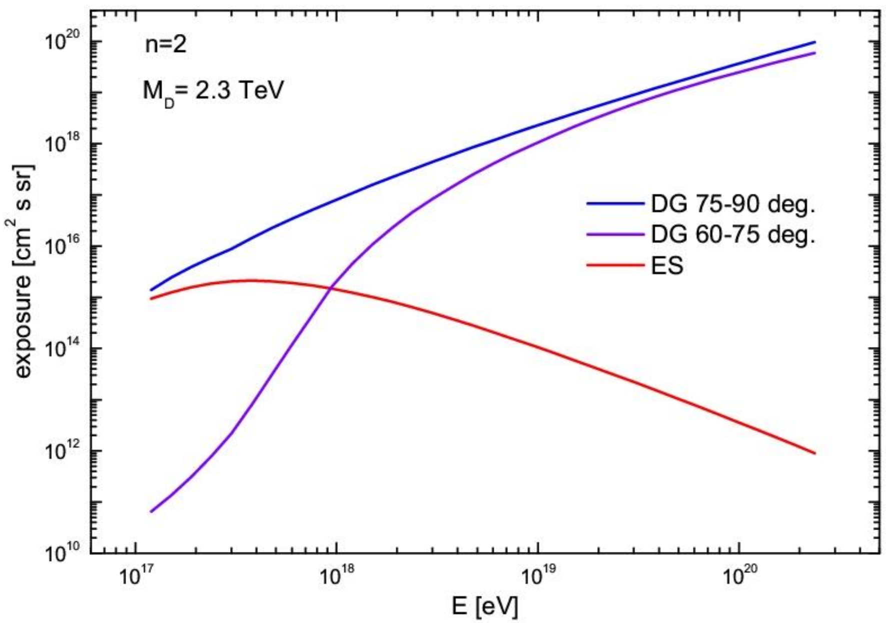
Neutrino-nucleon cross section in energy region of the detector IceCube ($E_\nu < 10^{17}$ eV)

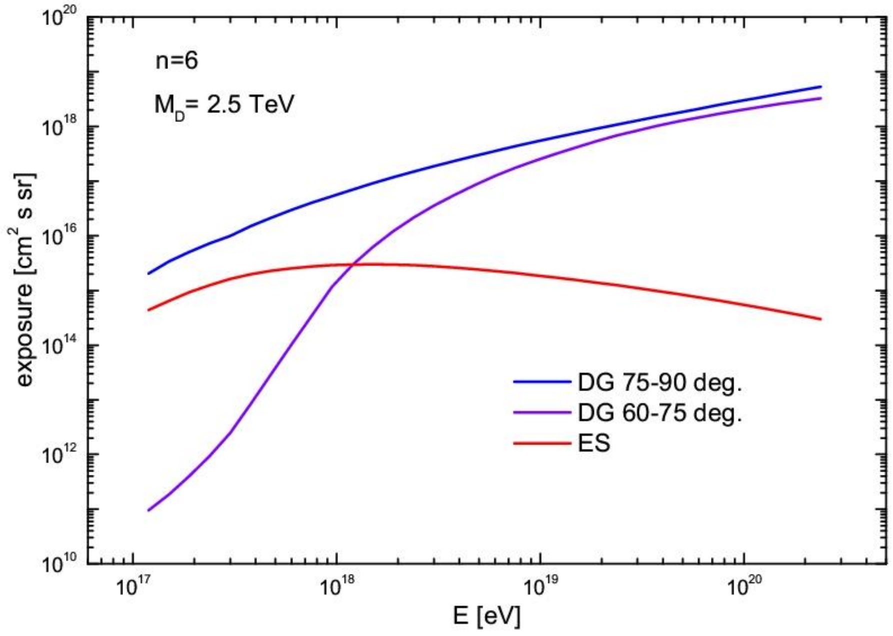




No significant deviation from SM cross section at $E_\nu < 10^{16}$ eV

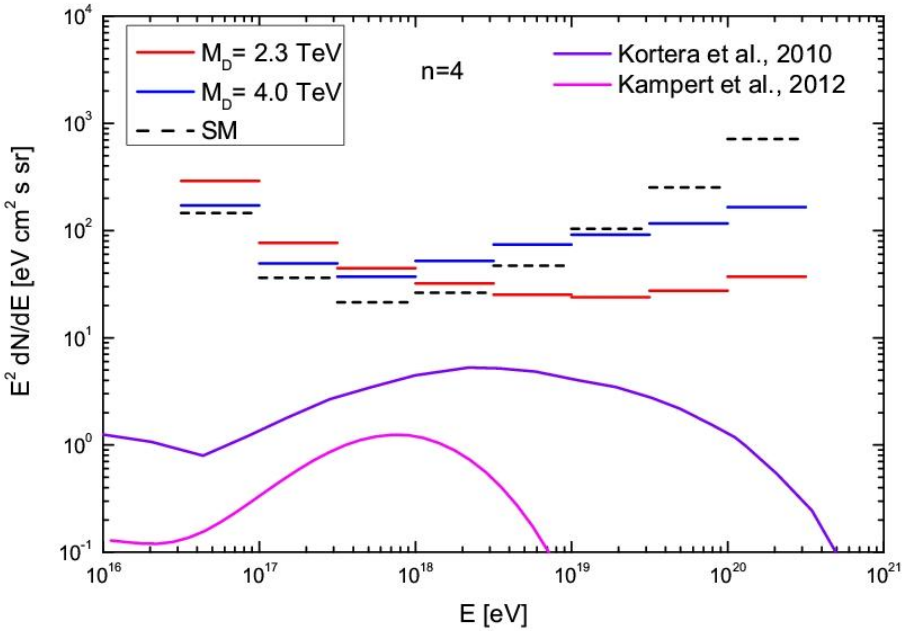
Comparison of exposures of DG and ES neutrino events at the PAO

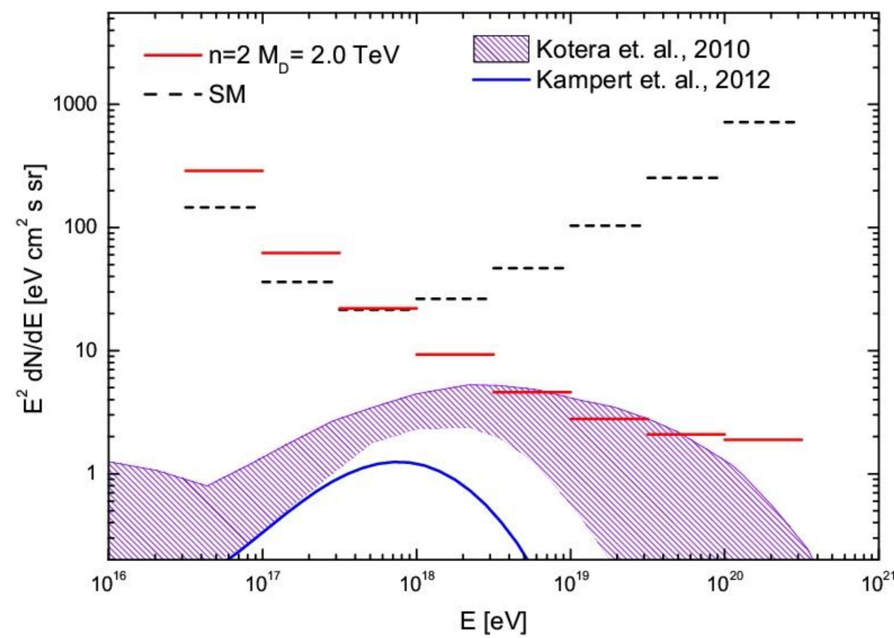




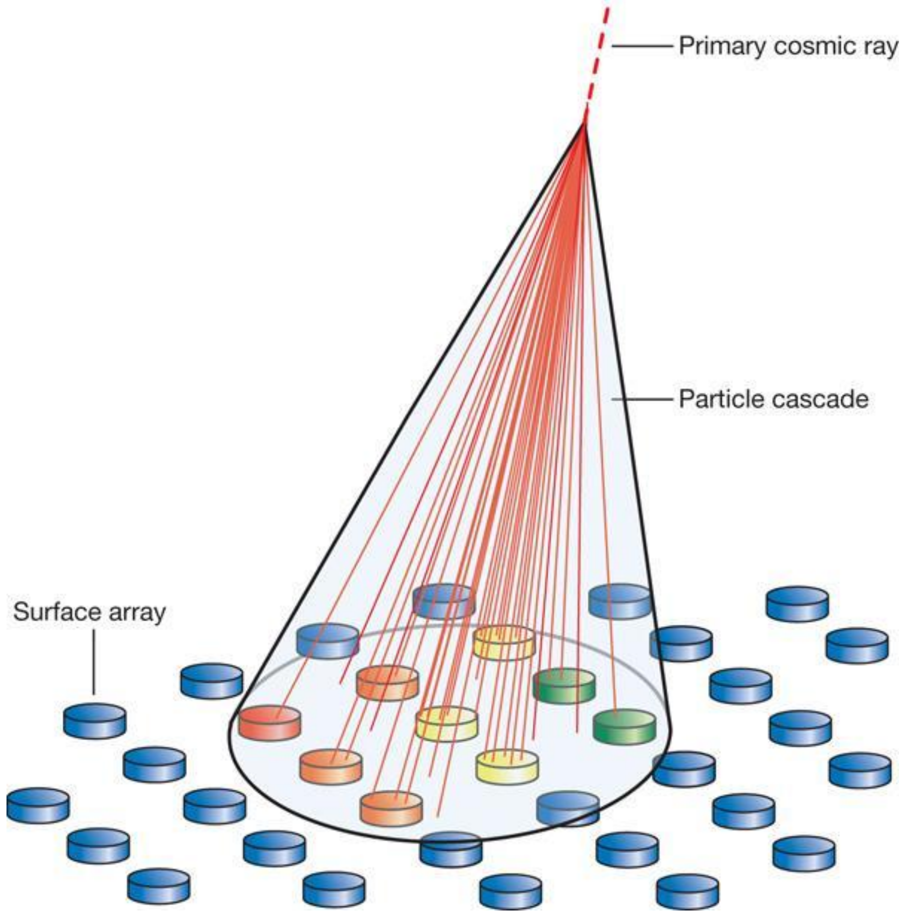
The exposures for the SD array of the PAO
for the DG and ES neutrino events (**n=2** and **n=6)**.

Upper limit on diffuse neutrino flux in energy bins

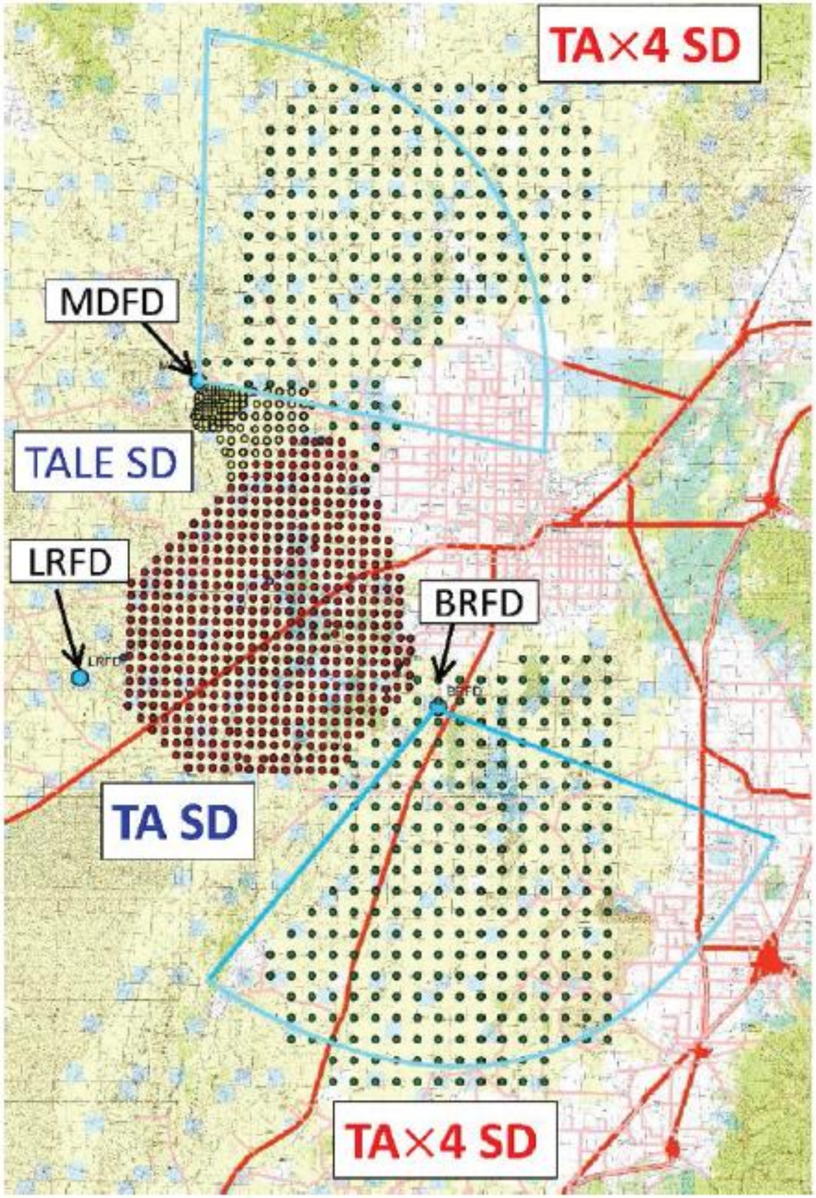




Upper bound on the normalizaion of the diffuse flux in bins of width **0.5** in **$\log_{10}E_\nu$** in comparison with the PAO bound in bins and two cosmogenic models



Detection of air showers by the Surface Detector (SD) of the PAO



Lay out of the Telescope Array extension (TA× 4)

In photography, **exposure** is the amount of light per unit area (the image plane **illuminance** times the **exposure time**) reaching a photographic film or electronic image sensor, as determined by shutter speed, lens aperture and scene luminance