Ultra-high energy cosmic neutrinos in a scenario with extra dimensions

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"The Actual Problems of Microworld Physics ",
Grodno, Belarus, August 17, 2018

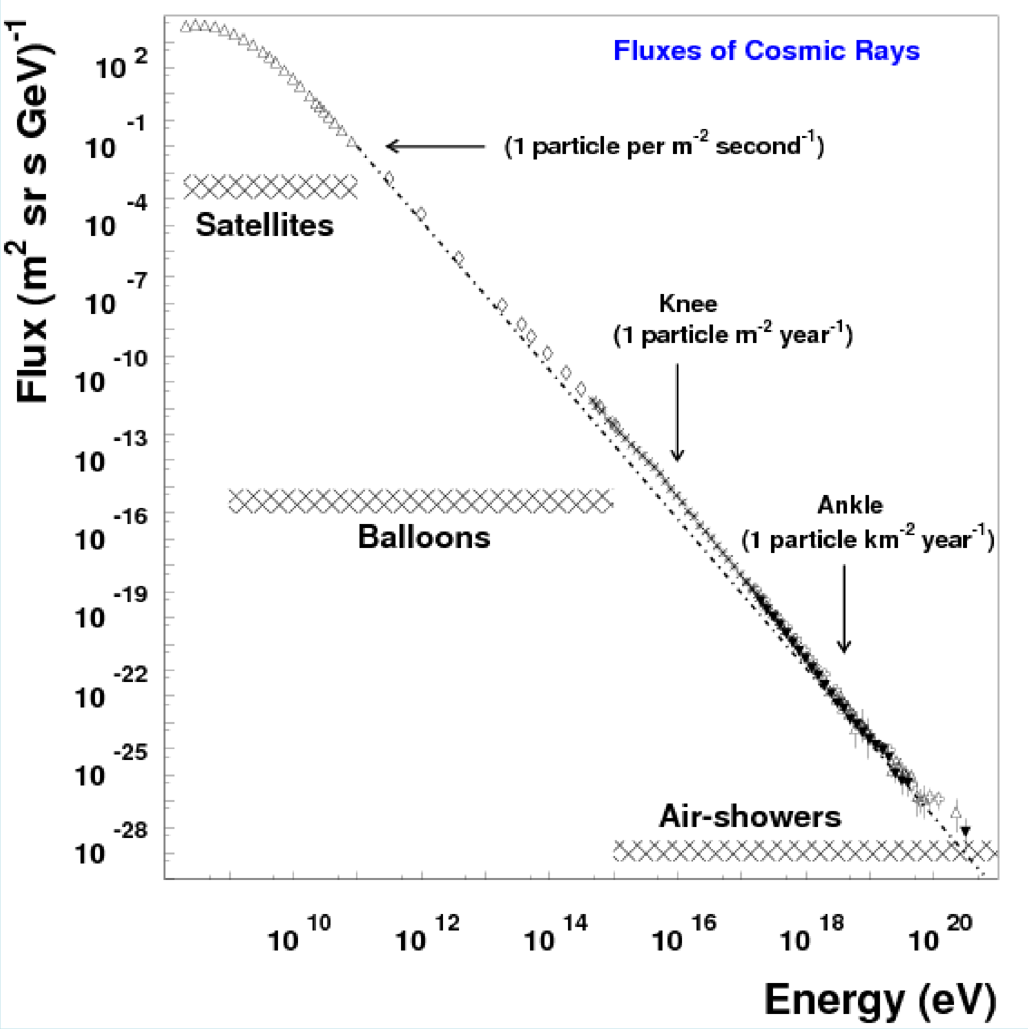
In memory of Nikolai Maksimovich Shumeiko

Nikolai Maksimovich gives a talk at the Workshop “Problems of High Energy Physics and Field Theory”, Protvino, USSR, July, 1988

Plan of the talk

- Ultra-high energy (UHE) cosmic neutrinos
- Neutrino events at the IceCube detector and Pierre Auger Observatory (PAO)
- Scenario with flat extra dimensions (EDs)
- Neutrino-nucleon scattering in the ADD model
- Bound on diffuse flux of UHE neutrinos in the ADD model
- Expected number of neutrino events at the Surface detector array (SD) of the PAO
- Conclusions

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 the GW sources*
- *to understand mechanisms of CR acceleration*
- *to give information on the nature of the primaries*
- *to define energy boundary between galactic and extragalactic parts of CR spectrum*
- *to measure cosmic neutrino flux, flavor ratio, and UHE neutrino-nucleon cross section*

Diffuse flux of cosmic neutrinos

"Guaranteed" cosmogenic neutrino flux

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

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

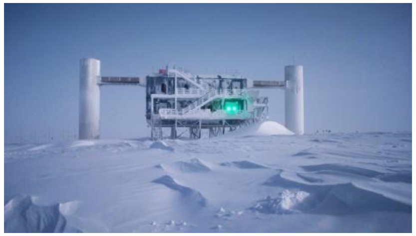
After oscillation: $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$

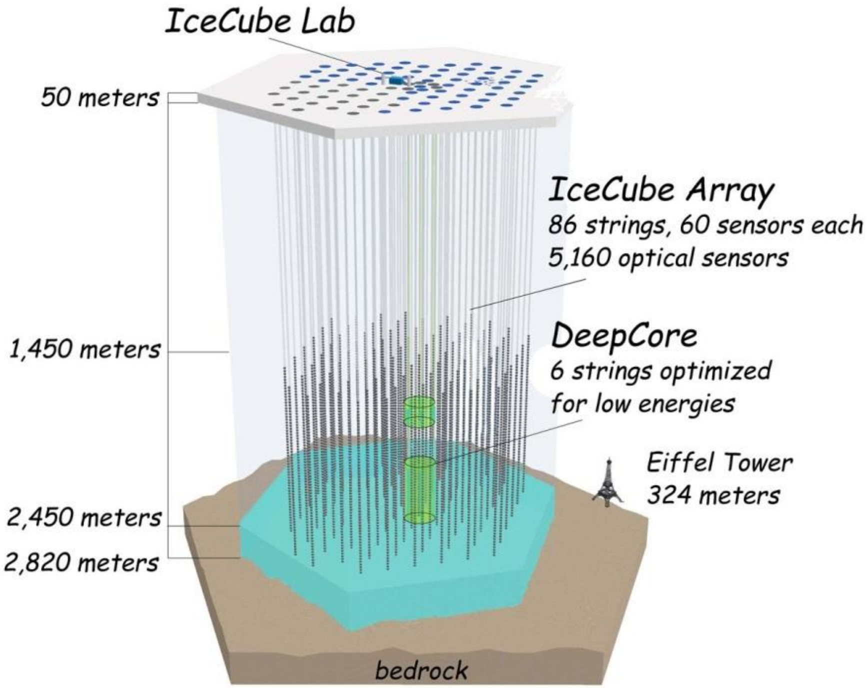
Benchmark WB bound on neutrino production in optically thin sources (single flavor, 10^{13} eV < E_ν < 10^{20} eV)

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

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

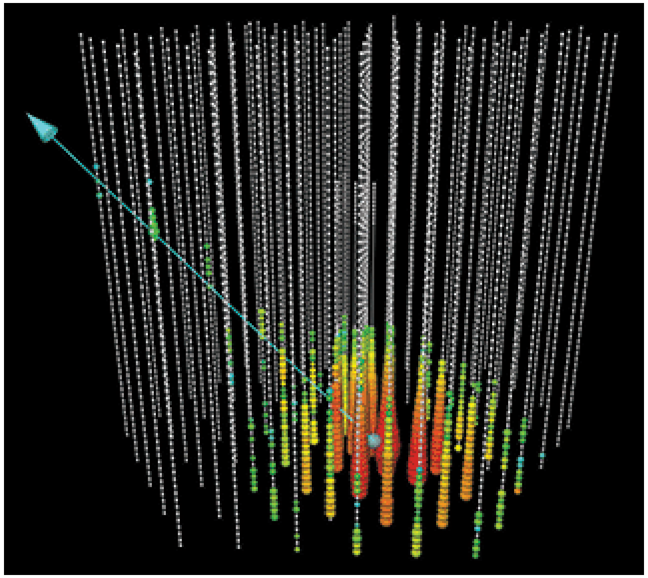
Neutrino detector IceCube





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)

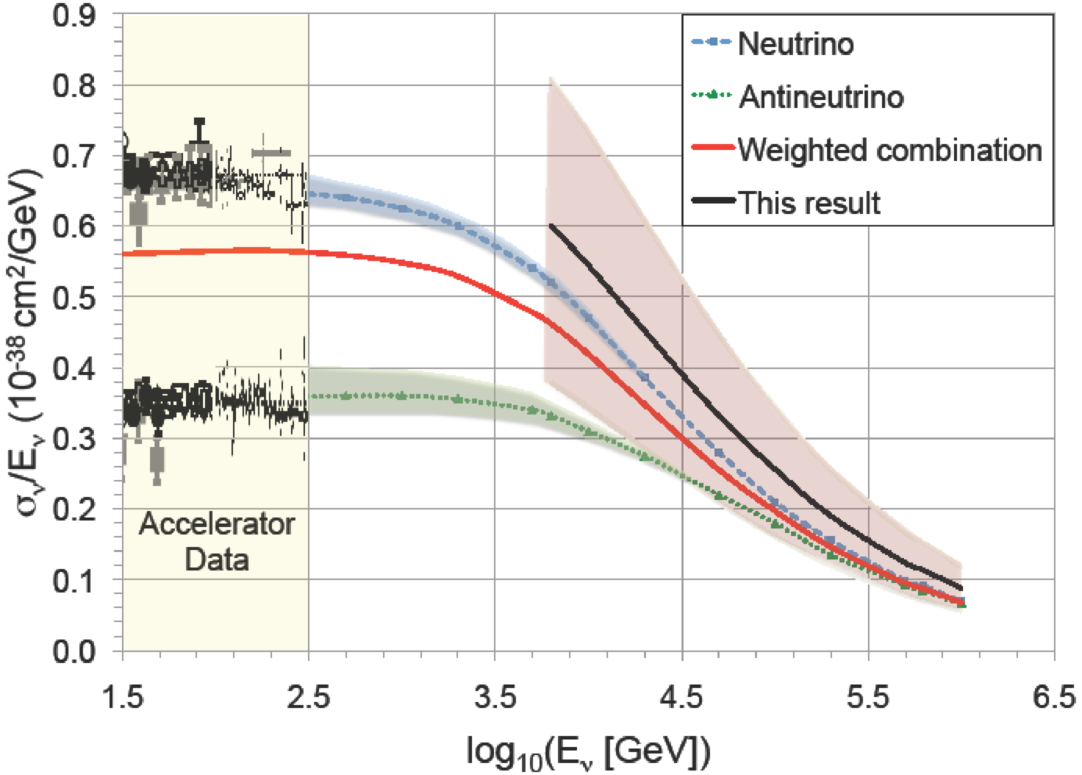
IceCube diffuse neutrino flux
(single flavor, 25 TeV< E_ν < 1.4 PeV) **(1PeV = 10^{15} eV)**

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

$$\frac{dN}{dE_\nu} = 2.06\times 10^{-18} (E_0/E_\nu)^\gamma \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

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

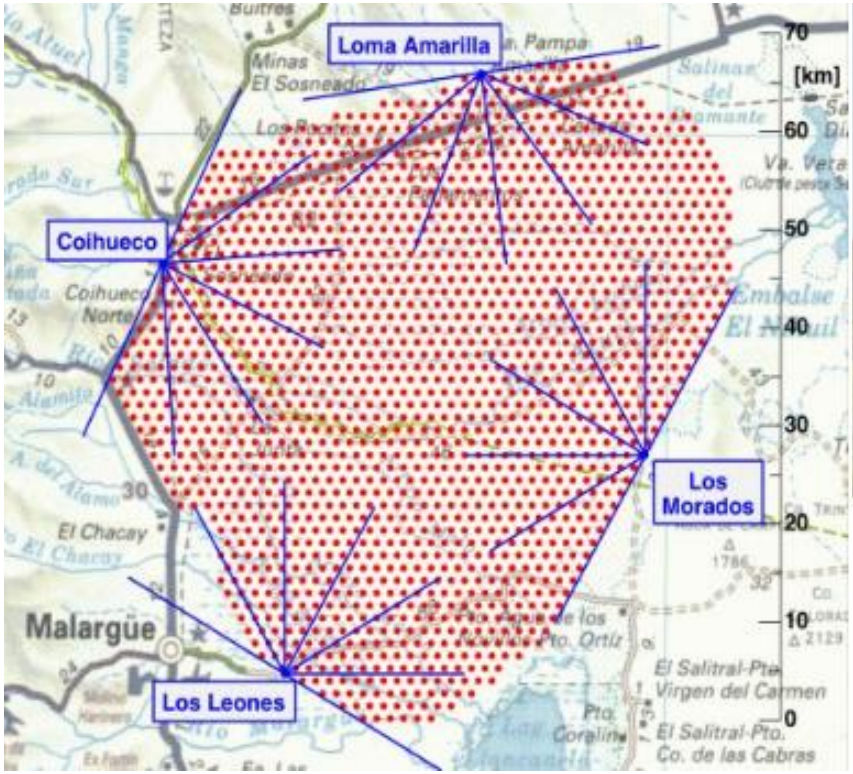
(flux is consistent with the WB bound)

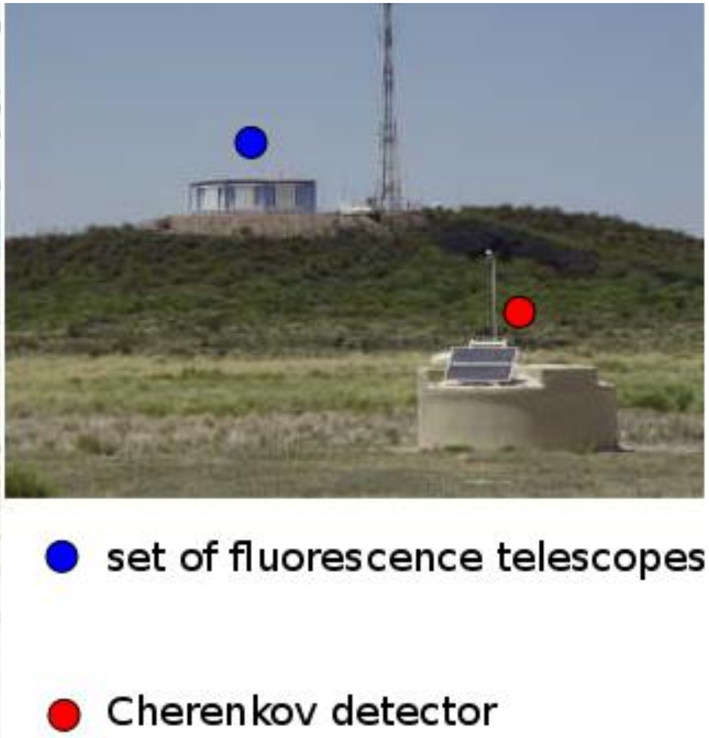


Compilation of neutrino charged current cross section measurements, divided by neutrino energy, from accelerator experiments and IceCube data

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

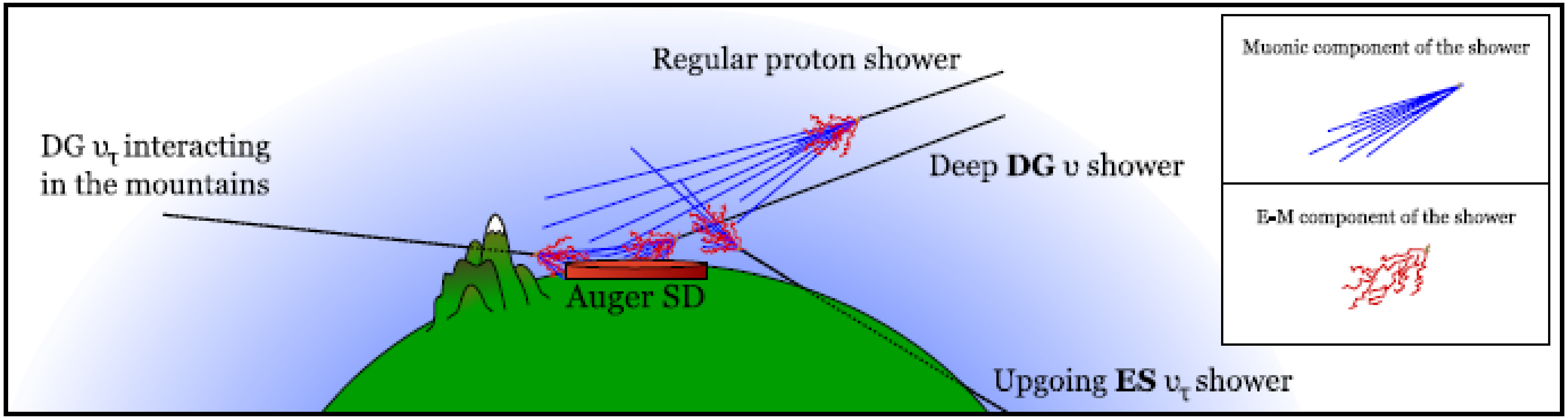
Pierre Auger Observatory (PAO)





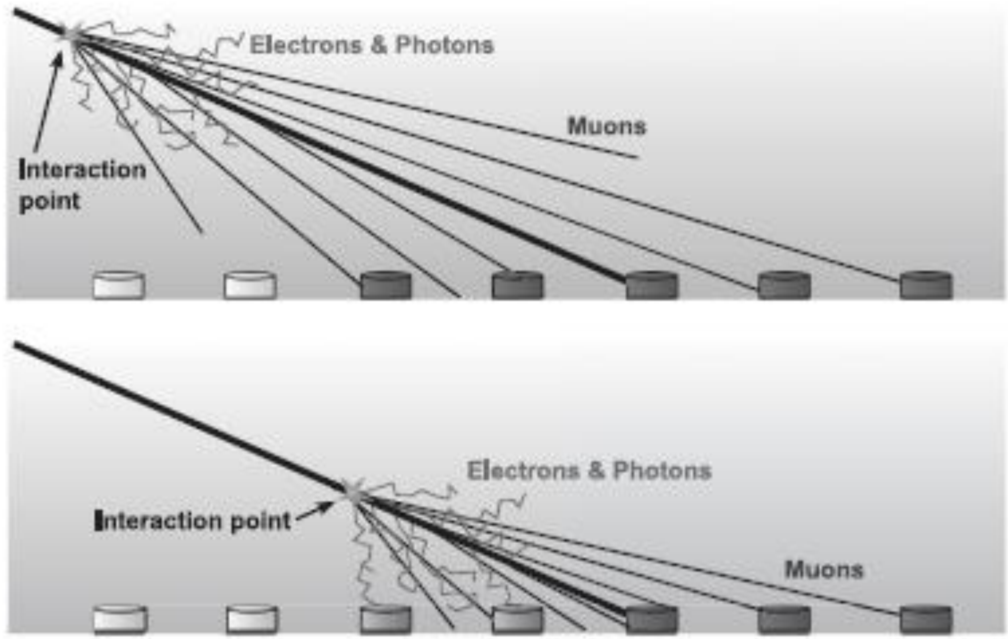
Surface Detector (SD) array: 1600 water-Cherenkov detectors spread over an area of 3000 km^2 (a bit larger than the country of Luxemburg)

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



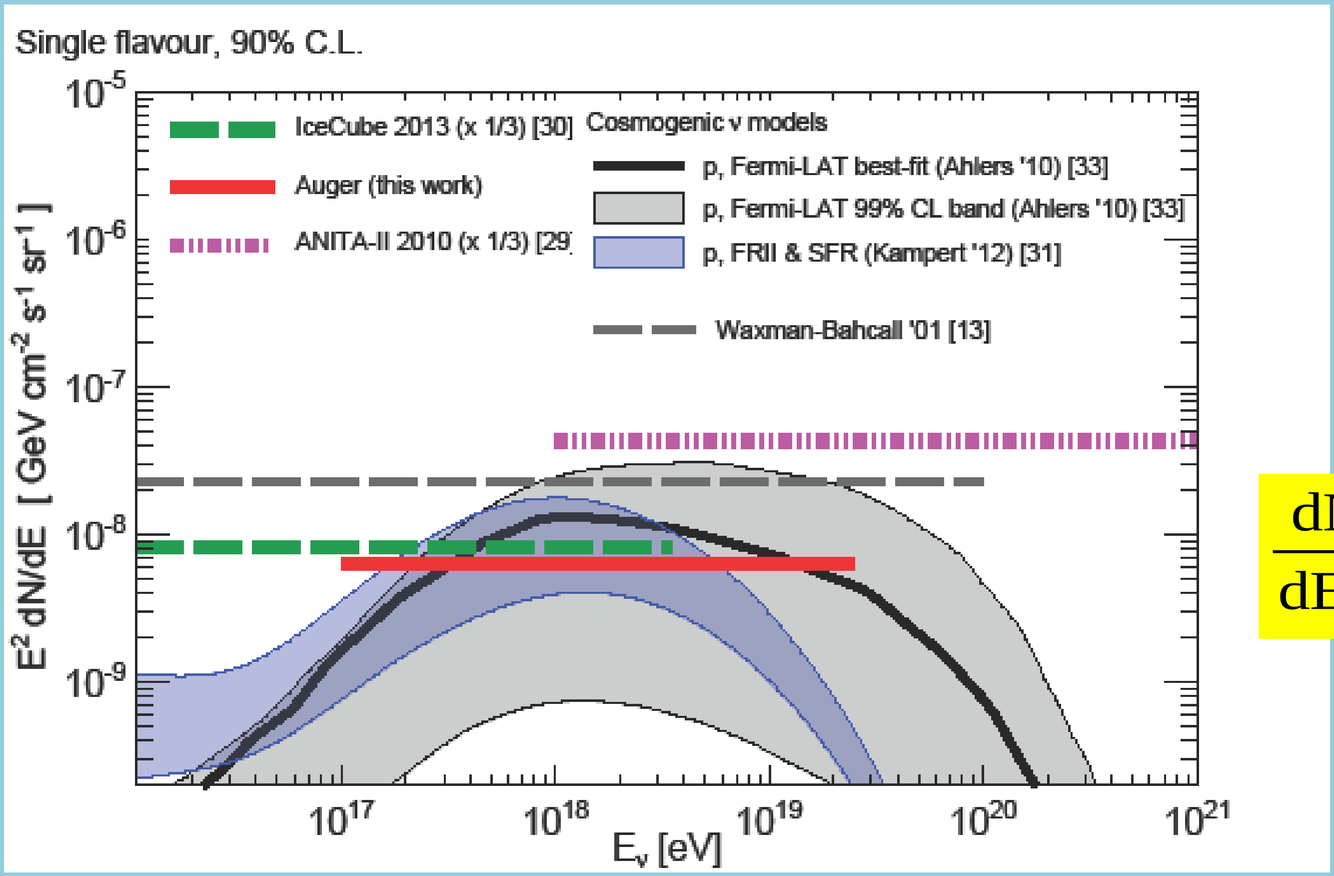
Downward-going high zenith angle (DG) neutrinos and up-going Earth-skimming (ES) tau neutrinos

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*)



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

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)

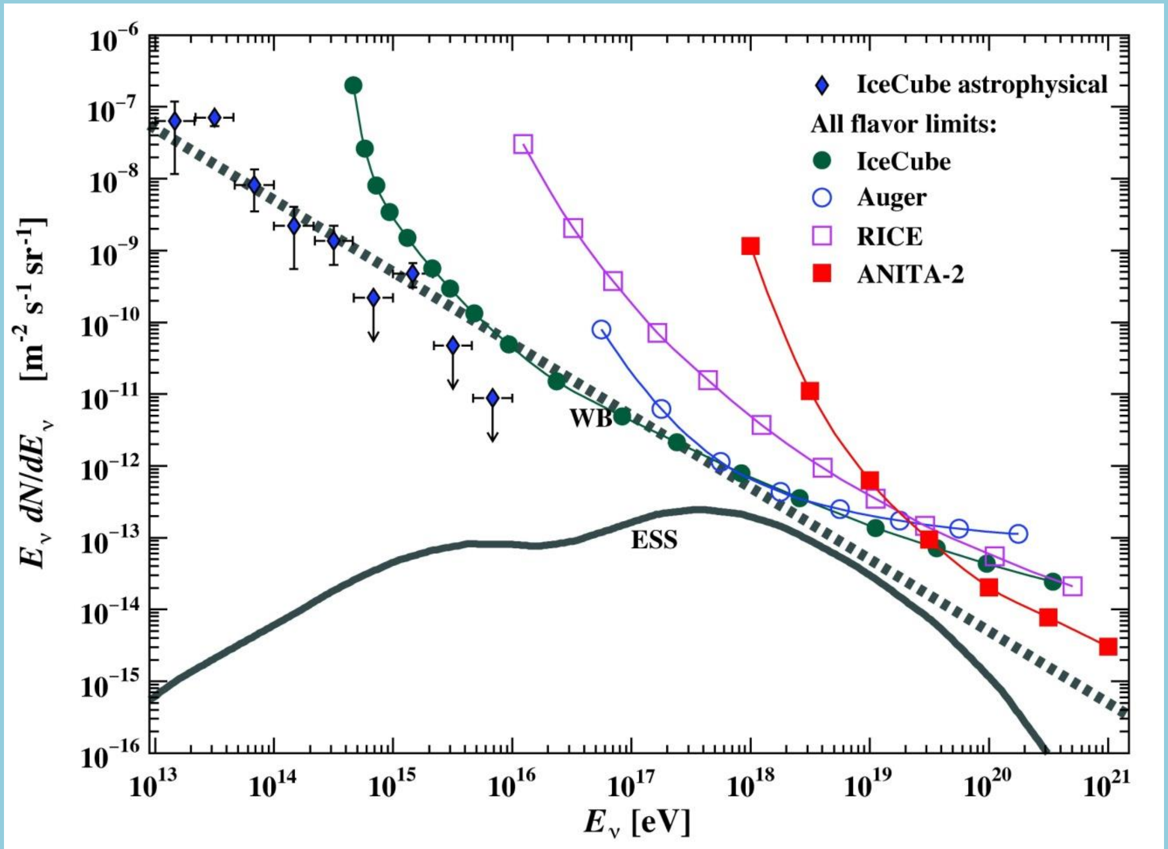
Single-flavor limit to diffuse flux of UHE neutrinos from PAO (10^{17} eV < E_ν < $2.5 \cdot 10^{19}$ eV)

(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)

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



The best-fit IceCube astrophysical all-flavor neutrino flux

(PDG, Chin. Phys. C, 40 (2016) 100001)

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

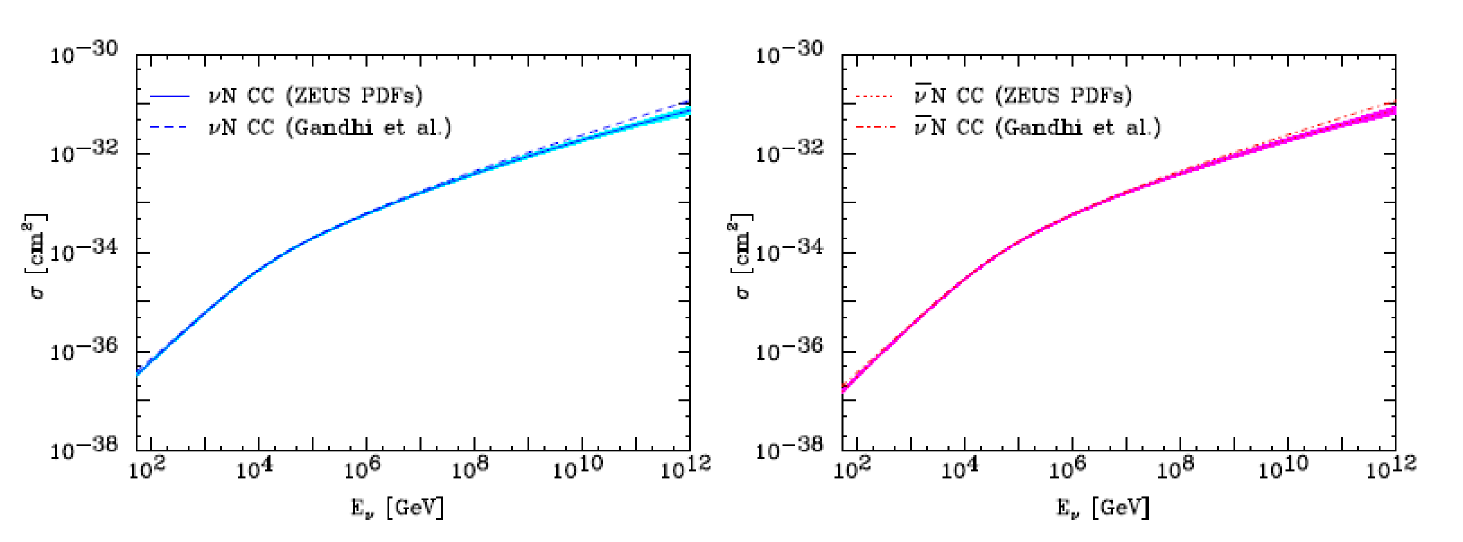
(PAO Collab., PRD 94 (2016) 122007)

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

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

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

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



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

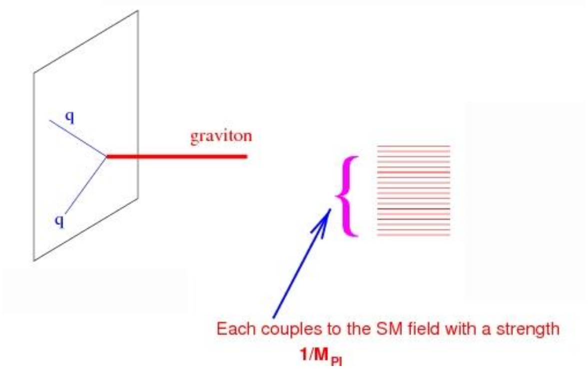
(Cooper-Sarkar & Sarkar, JHEP 080 (2008) 075)

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

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

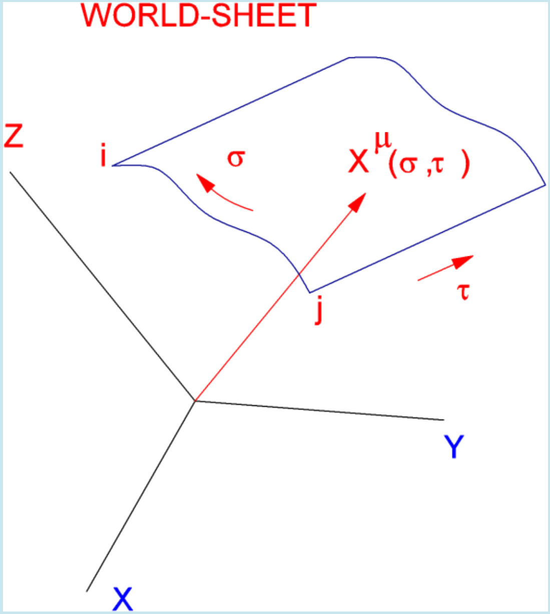
Masses of KK gravitons: $$m_n = n/R_c$$

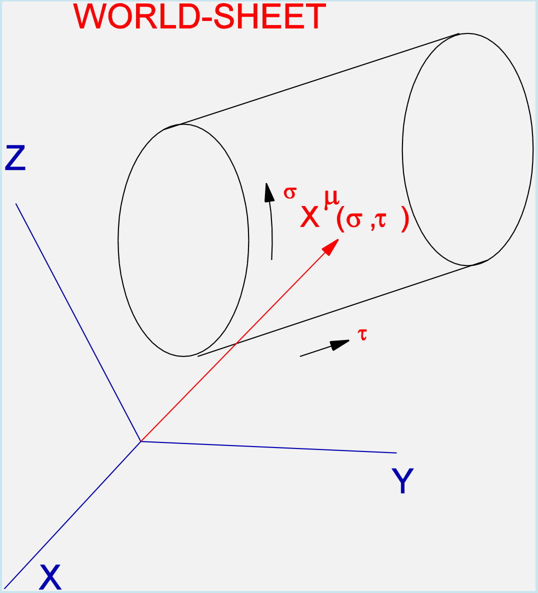
Interaction Lagrangian on the brane: *(massive gravitons only)*

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

Strings needs extra dimensions (EDs)

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

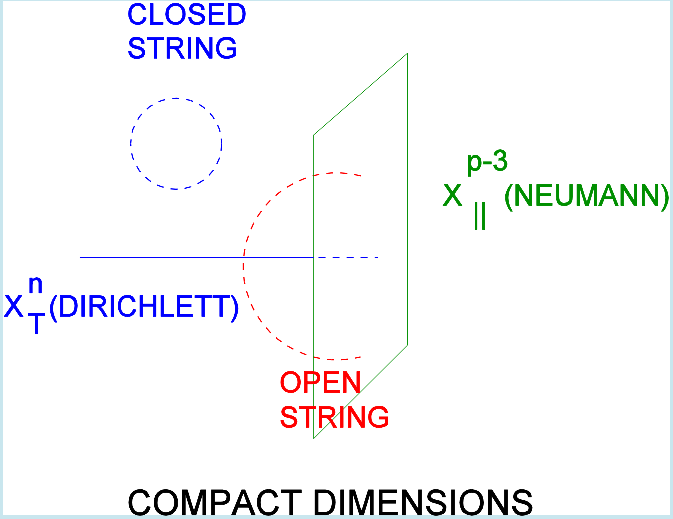


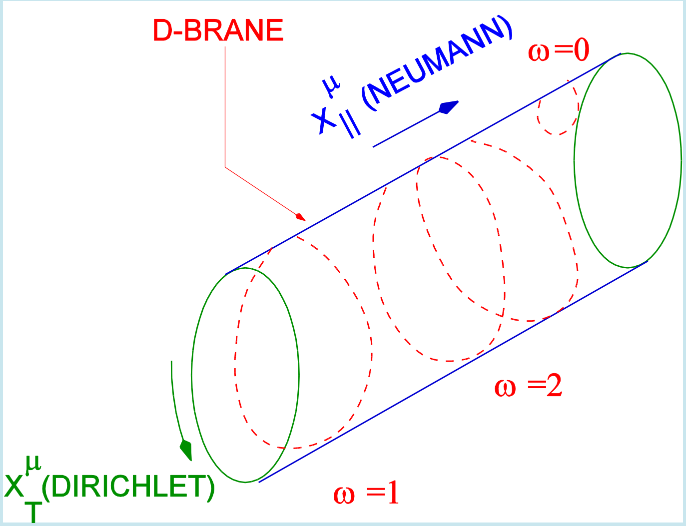


World sheets of open (left) and closed (right) strings propagating in the space-time

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

Rescaled volume (4+n) – dimensional Planck scale

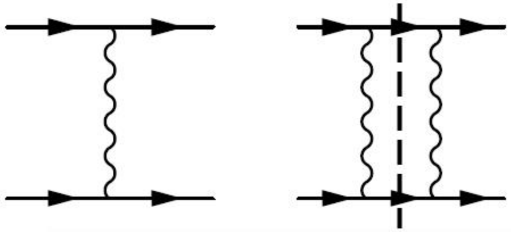
$v_L = V_L l_S^{3-p}$ $M_D^{2+n} = M_S^{2+4} / g^4 v_L$ → $M_{\rm Pl}^2 = M_D^{2+n} R_T^n$

Scattering of UHE neutrinos in ADD model

Transplanckian region

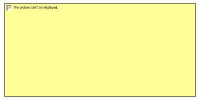
$$E_{\nu} > 10^{17}\,\mathrm{eV},\ \sqrt{s} >> M_D, -t$$

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



Scattering amplitude in the eikonal approximation

$$A_{\mathrm{eik}}(s,t) = -2is\int_0^{\infty} dbbJ_0(b\sqrt{-t})\{1-\exp[i\chi(s,b)]\}$$



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

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

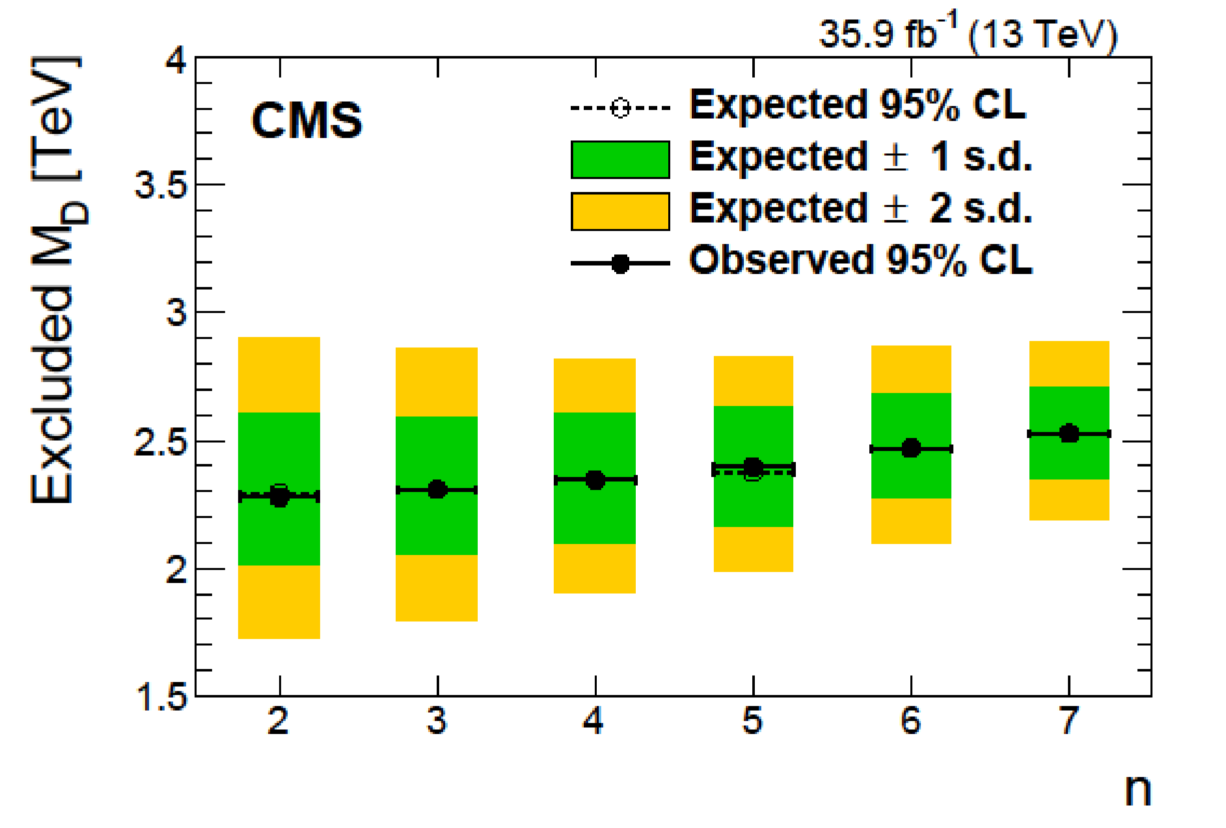
$$\chi(b) = \left(\frac{b_c}{b}\right)^n \qquad b_c = \left(\frac{(4\pi)^{n/2-1} s \Gamma(n/2)}{2 M_D^{n+2}}\right)^{1/n}$$

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

b < R$_S$ → **black hole production**

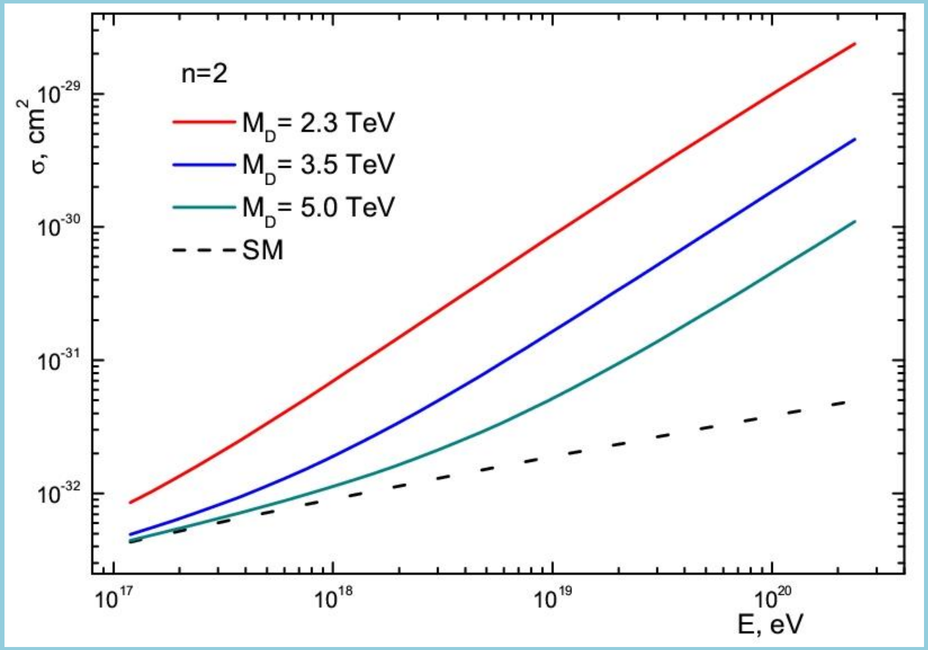
Geometric black-hole cross section

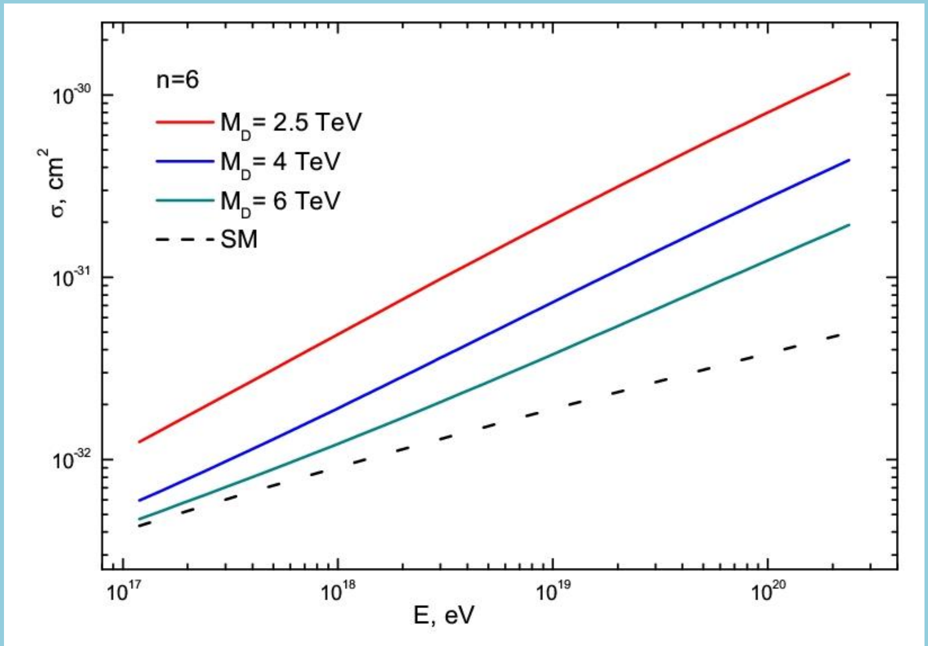
$$\sigma_{\text{BH}} = \pi R_S^2 \qquad R_S \sim \left(\frac{\sqrt{s}}{M_D^{n+2}}\right)^{1/(n+1)}$$



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

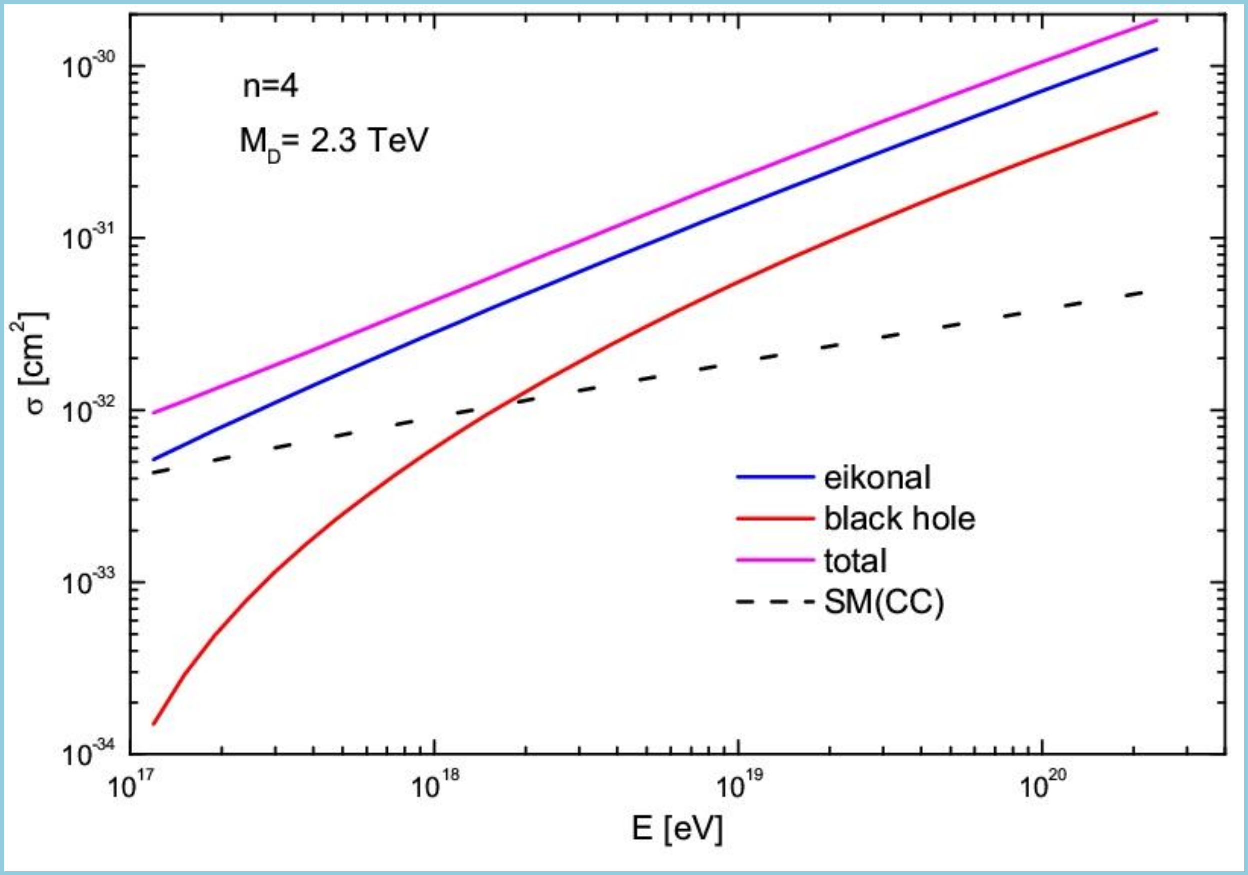
BSM: $\sigma_{\nu N}$ rises more rapidly than in SM as neutrino energy grows





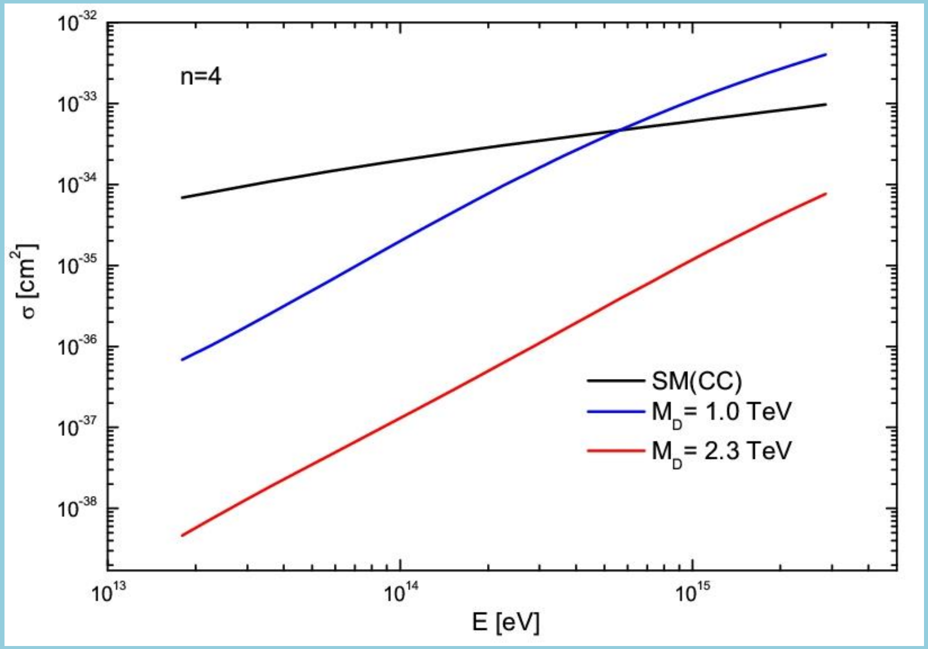
The total neutrino-nucleon cross sections for **n=2** (left panel) and **n=6** (right panel) with different values of the gravity scale $\mathbf{M_D}$

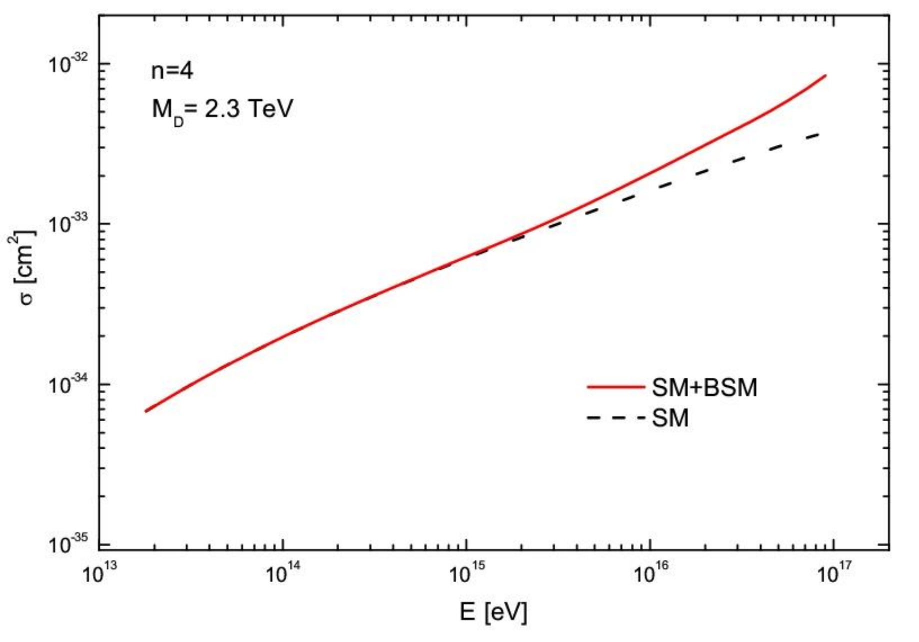
Eikonal and black hole contributions to $\sigma_{\nu N}$



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

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





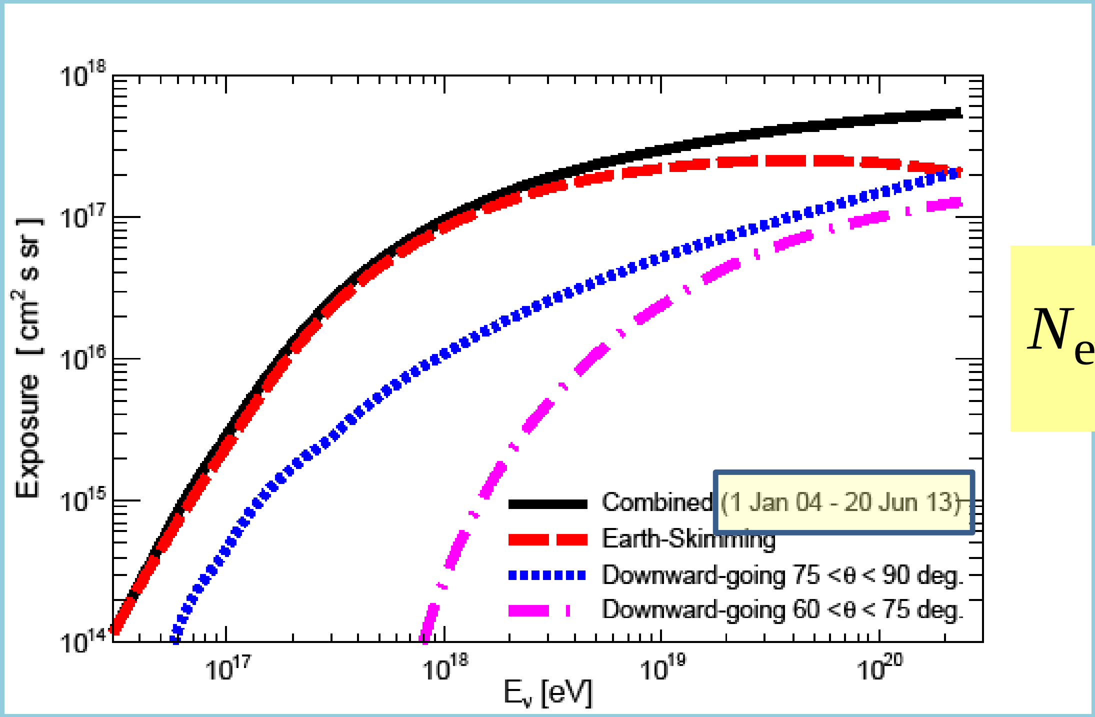
No significant deviation from SM cross section at $E_\nu < 10^{16}$ eV

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:

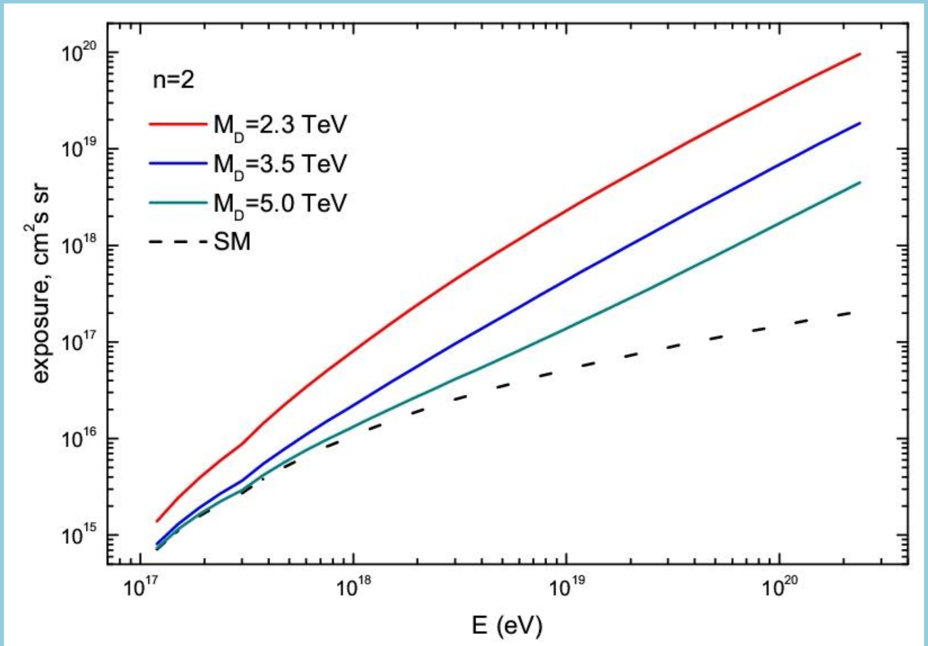
$$\mathcal{E}_{BSM}^{DG} = \mathcal{E}_{SM}^{DG} \frac{\sigma_{SM} + \sigma_{BSM}}{\sigma_{SM}}$$

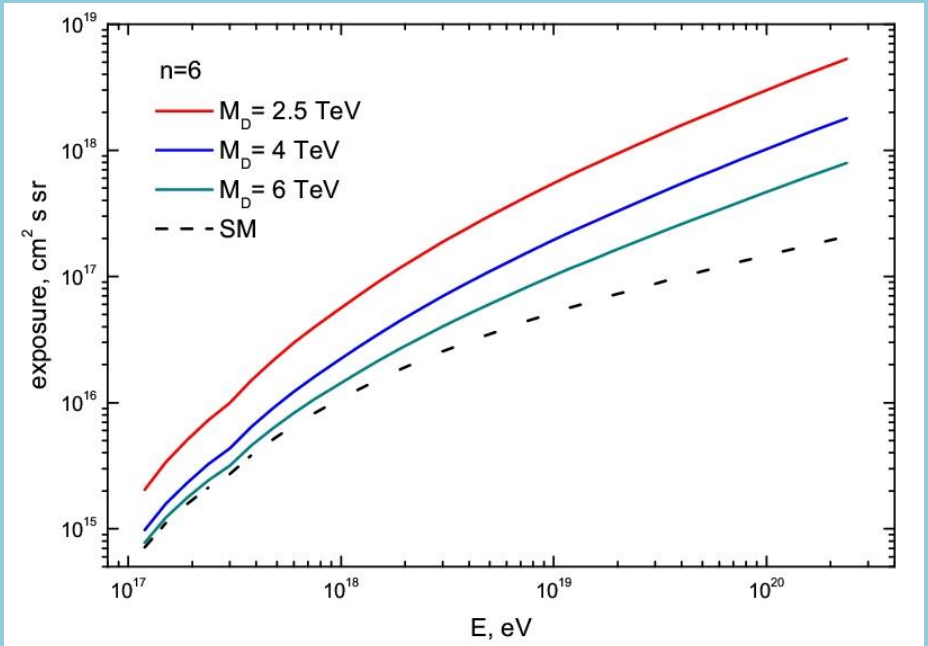
ES neutrinos: enhanced interaction cross-section suppresses exposure:

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

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

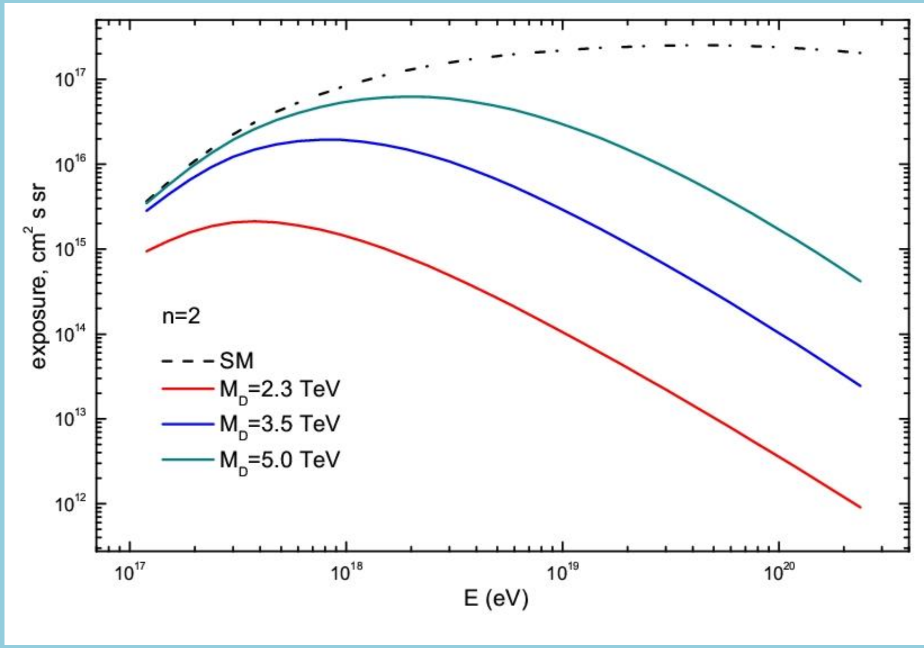
Exposures of the down-ward neutrino events in the ADD model

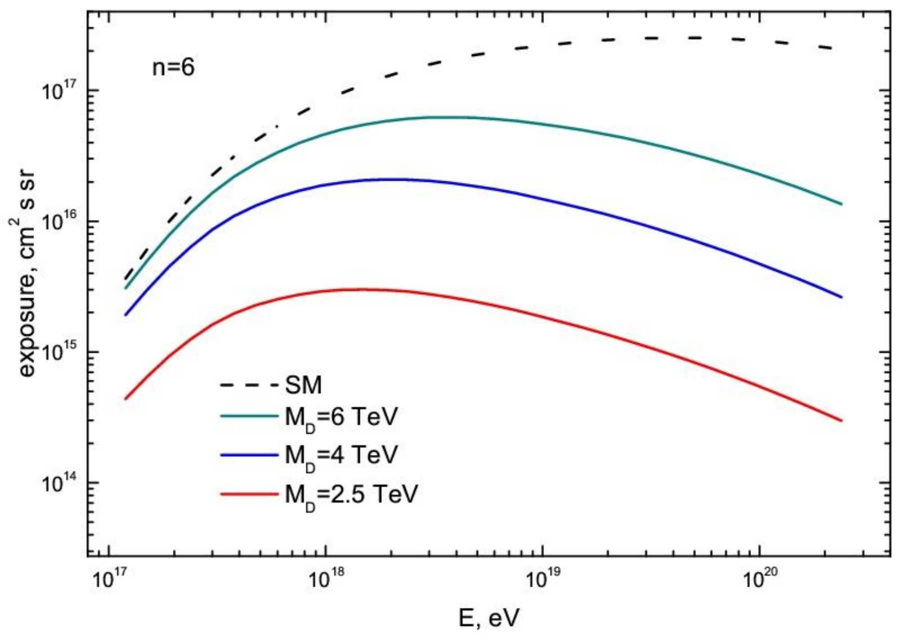




The exposures for the SD array of the PAO for the DG neutrino events with zenith angle **75° < θ < 90°** for different values of the gravity scale $\mathbf{M_D}$. Left panel: **n=2**. Right panel: **n=6**.

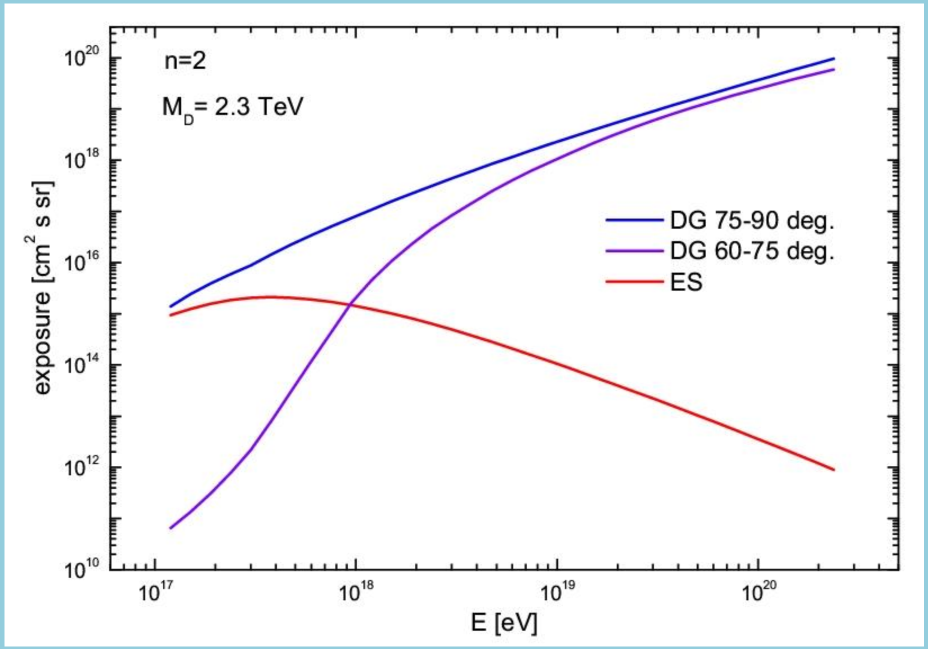
Exposures of the Earth-skimming neutrino events in the ADD model

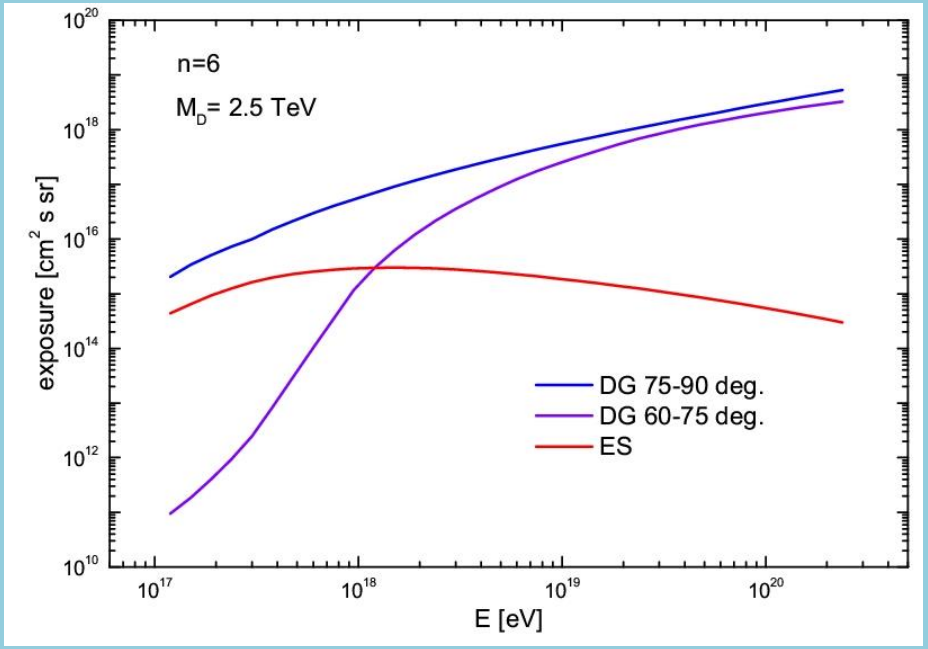




The exposures for the SD array of the PAO for the ES neutrino events for different values of the gravity scale $\mathbf{M_D}$. Left panel: **n=2**. Right panel: **n=6**.

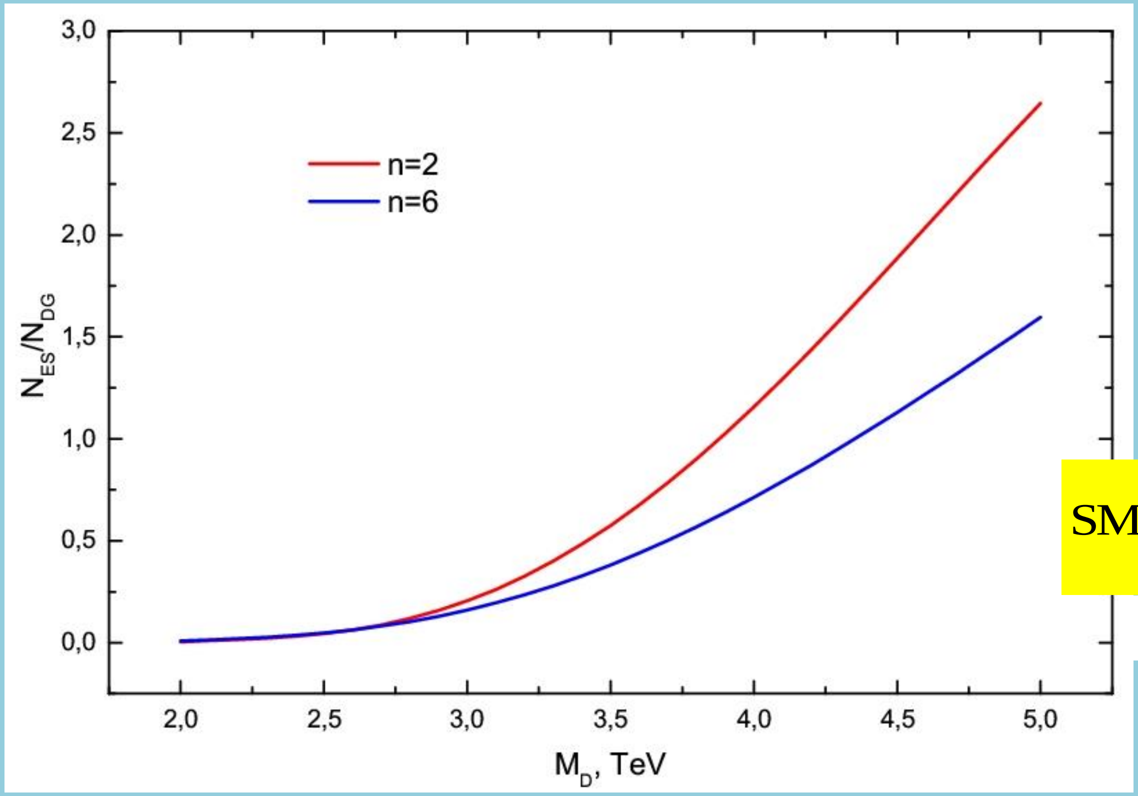
Comparison of exposures of DG and ES neutrino events at the PAO





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

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

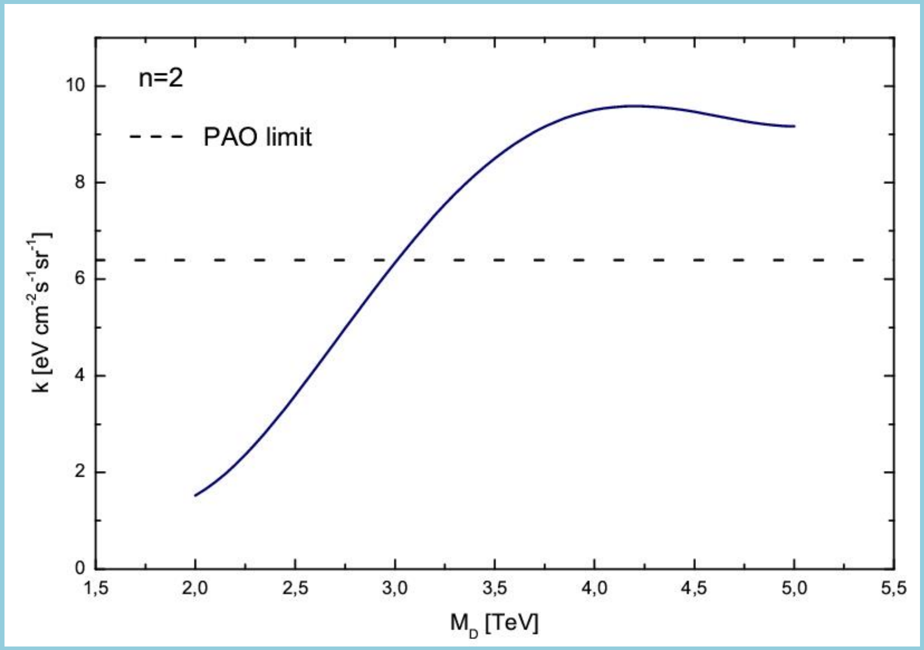
- number of expected background events = 0

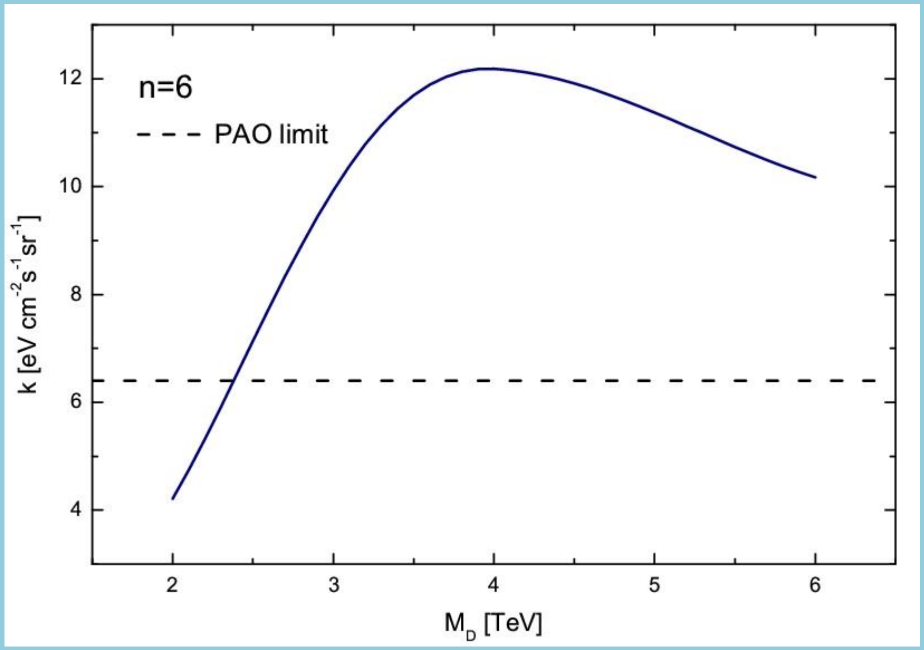
→ **Upper limit on signal events:** $$N_{\rm up} = 2.39$$

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



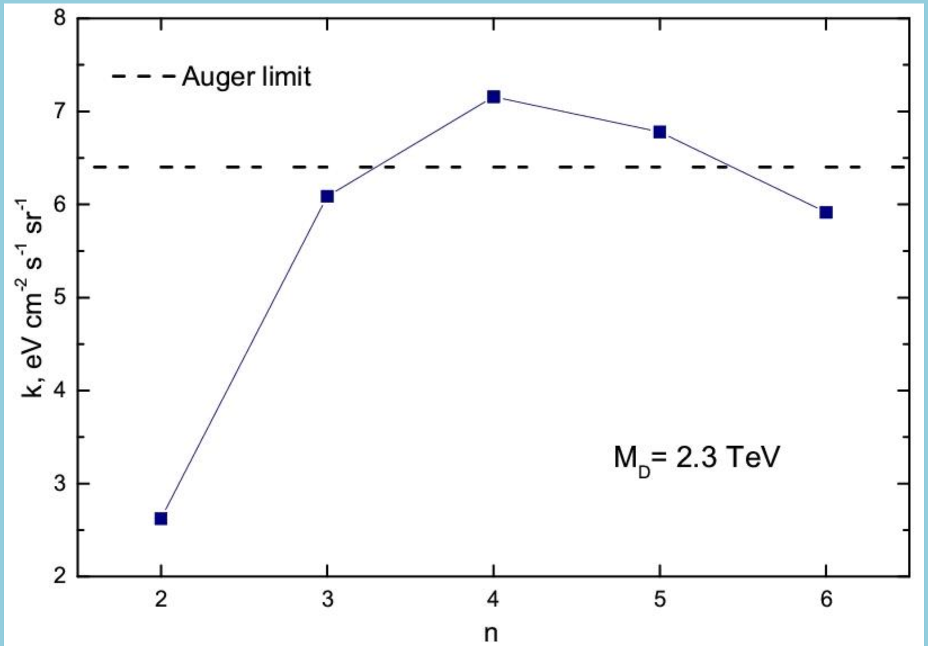


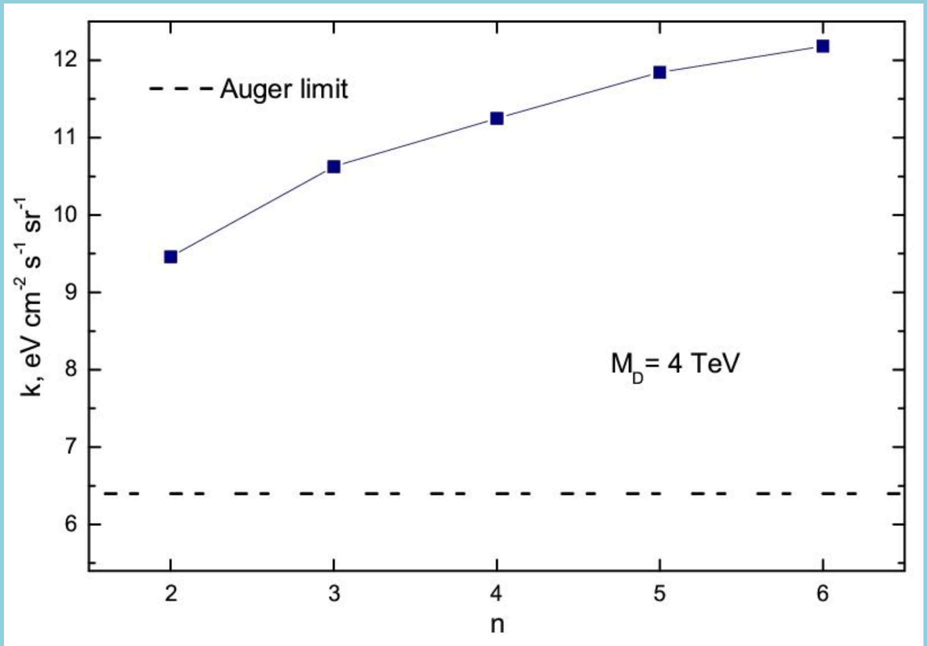
Upper bound on the flux normalizaion **k** in the ADD model as a function of $\mathbf{M_D}$ at fixed values of **n**

(M. Astashenkov and A. K., arXiv:1804.02351)

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

Upper limit on diffuse neutrino flux: nontrivial dependence on n

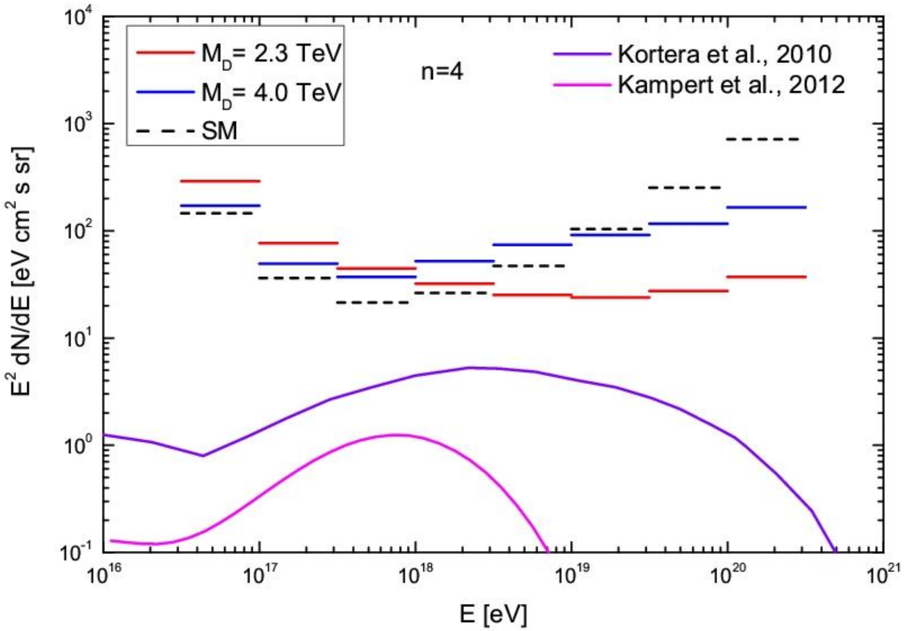


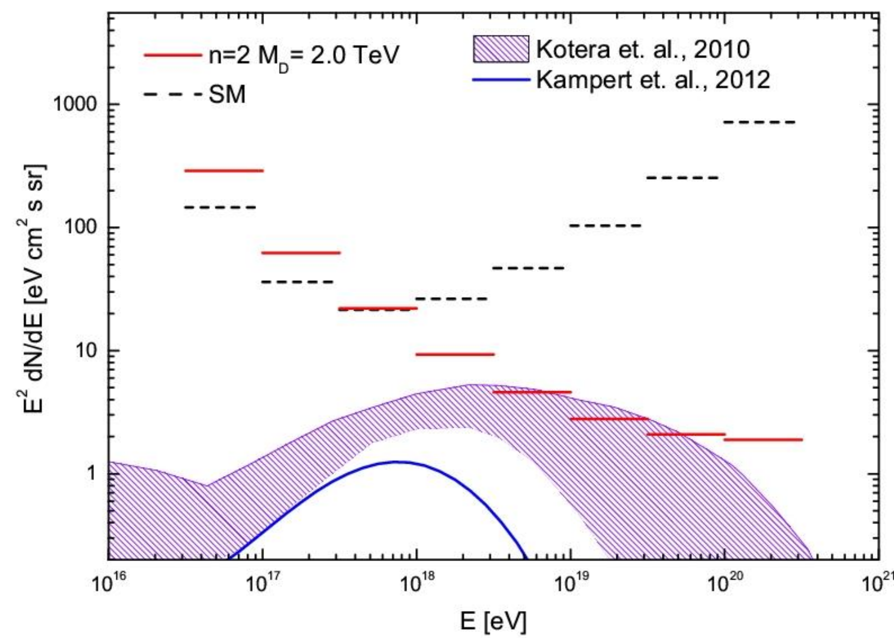


Upper bound on the flux normalizaion **k** in the ADD model as a function of **n** at fixed values of **M_D**

(M. Astashenkov and A. K., arXiv:1804.02351)

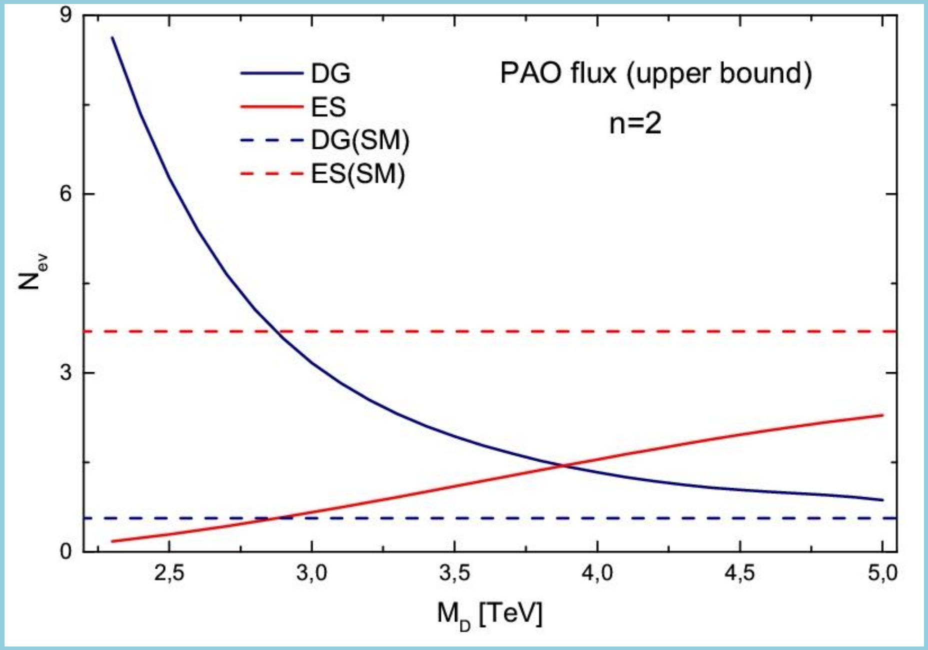
Upper limit on diffuse neutrino flux in energy bins

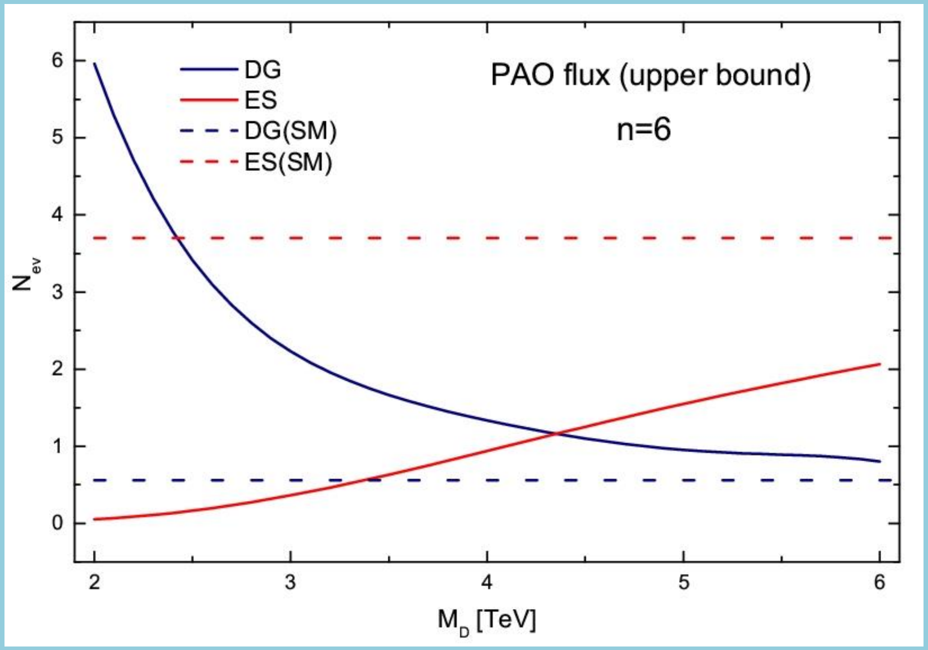




Upper bound on the normalizaion of the diffuse flux in bins of width **0.5** in $\log_{10}E_\nu$ in comparison with the PAO bound in bins and two cosmogenic models

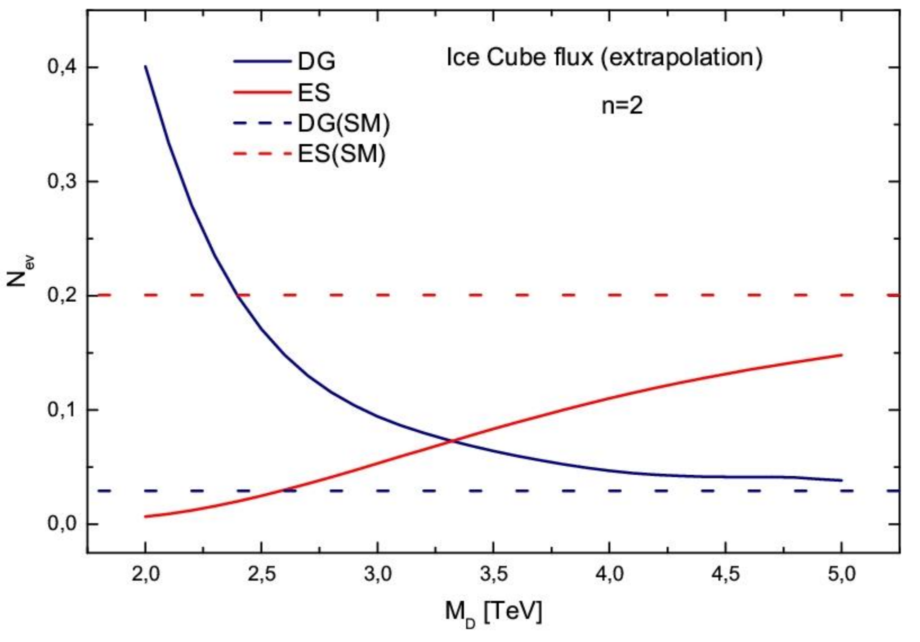
Expected number of events induced by UHE neutrinos with the Auger flux

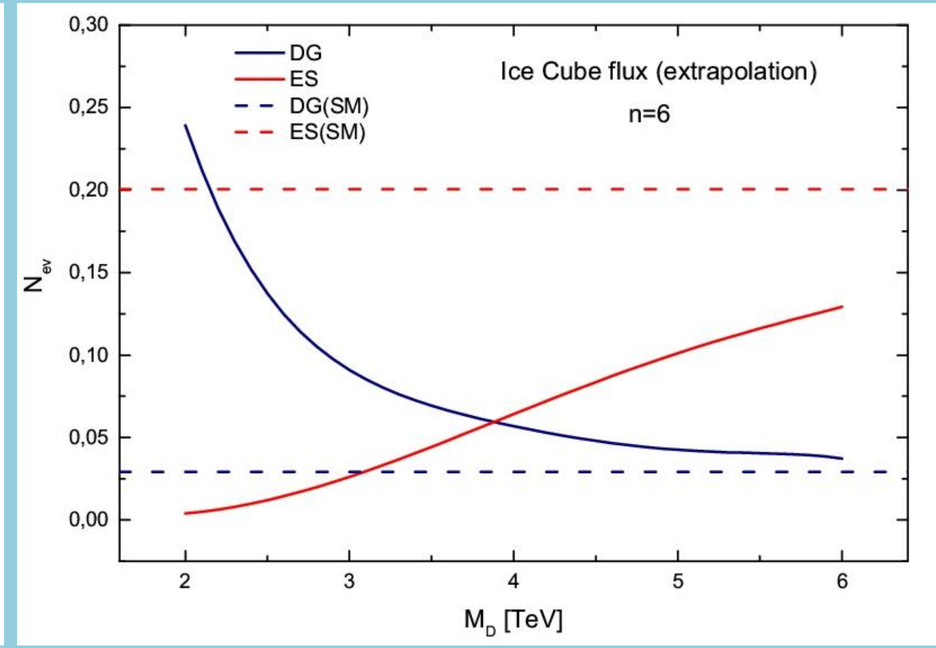




Expected number of neutrino events at the SD of the PAO for a period equivalent of 2•6.4 years of PAO working continuously

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

(M. Astashenkov and A. K., arXiv:1807.03504)

Conclusions

- Cosmic neutrinos play a key role in the understanding of the origin of the UHECRs
- The first evidence of the flux of high energy astrophysical neutrinos has been found by the IceCube detector
- Downward-going and Earth-skimming neutrino events were searched for at the Pierre Auger Observatory. The upper bound on the flux of UHE neutrino is obtained
- In the scenario with flat EDs the upper limit on the diffuse UHE neutrino flux is calculated as a function of number of extra dimensions n and D-dimensional Planck scale M_D
- This limit turned out to be more stringent than the PAO upper limit for $M_D < 3$ TeV (2.4 TeV), if $n = 2$ (6), as well as for $M_D = 2.3$ TeV, if $n \leq 3$ or $n \geq 6$

Conclusions (continued)

- For large values of the gravity scale, $M_D \geq 4$ TeV, our bound, on the contrary, exceeds the PAO bound for all n

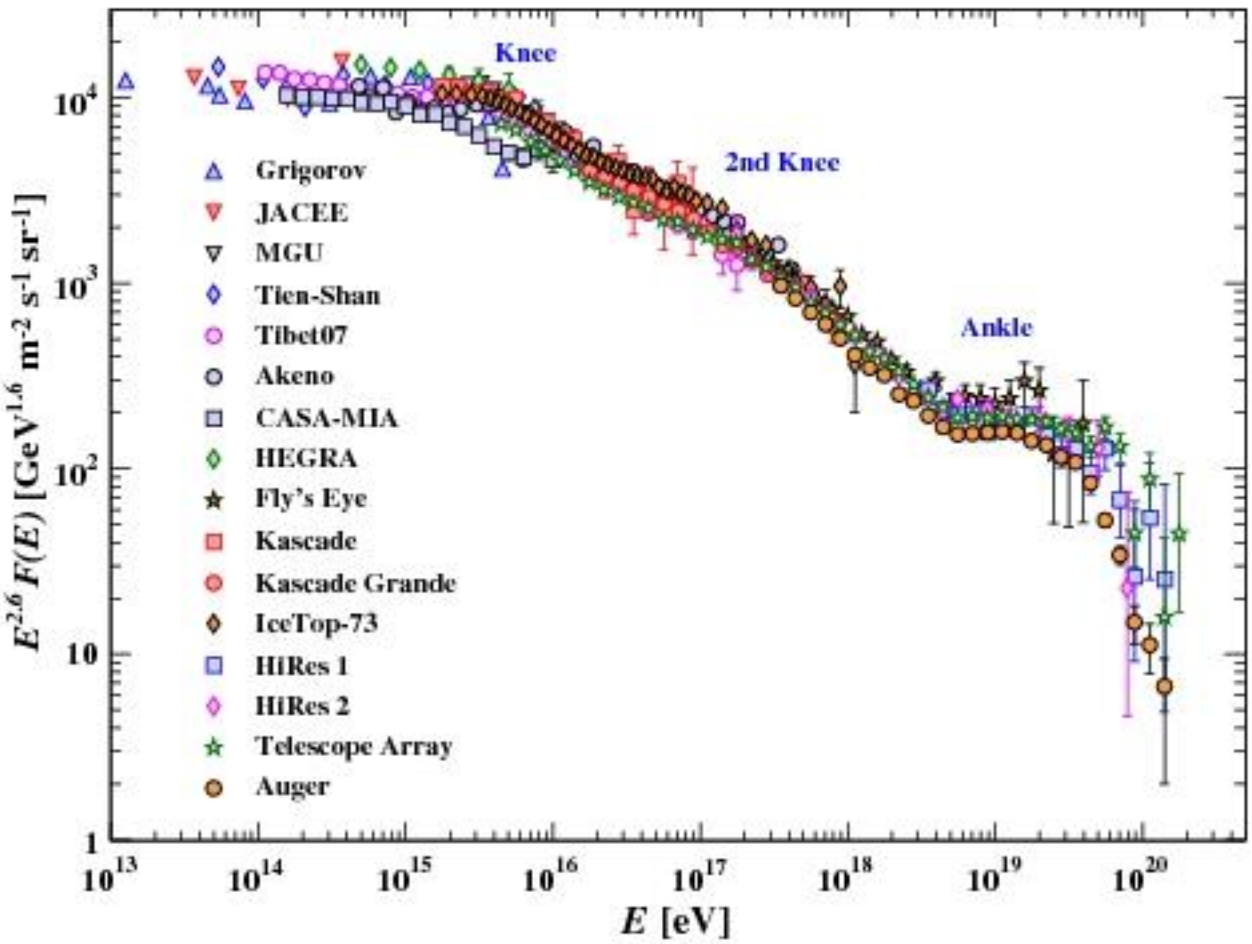
- Upper limit on the diffuse neutrino flux in bins is also calculated. It is lower than the PAO bound for $E_\nu \geq 1$ EeV. For M_D =2.0 TeV, n =2 and $E_\nu \geq 3$ EeV it overlaps with the prediction of the cosmogenic model with pure iron composition

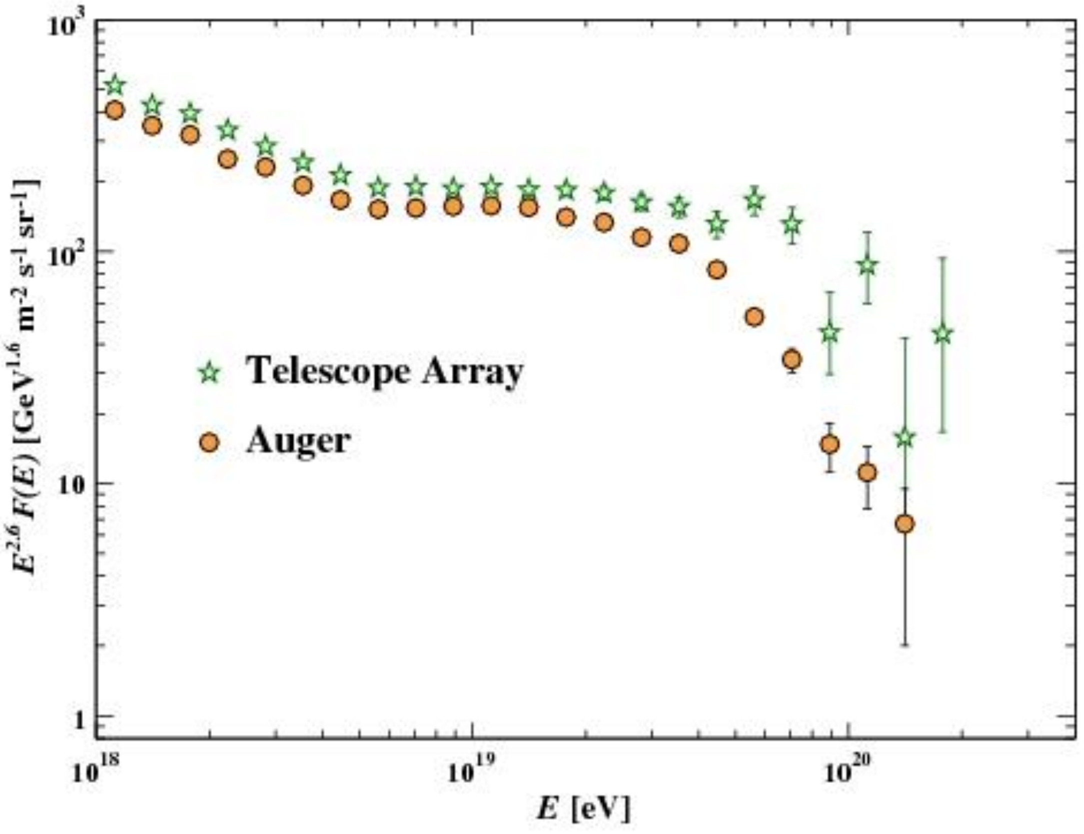
- Expected number of DG and ES neutrino events at the PAO is estimated both for the PAO bound and IceCube neutrino flux extrapolated to EeV energy range (for 2•6.4 years of a continuous operation)

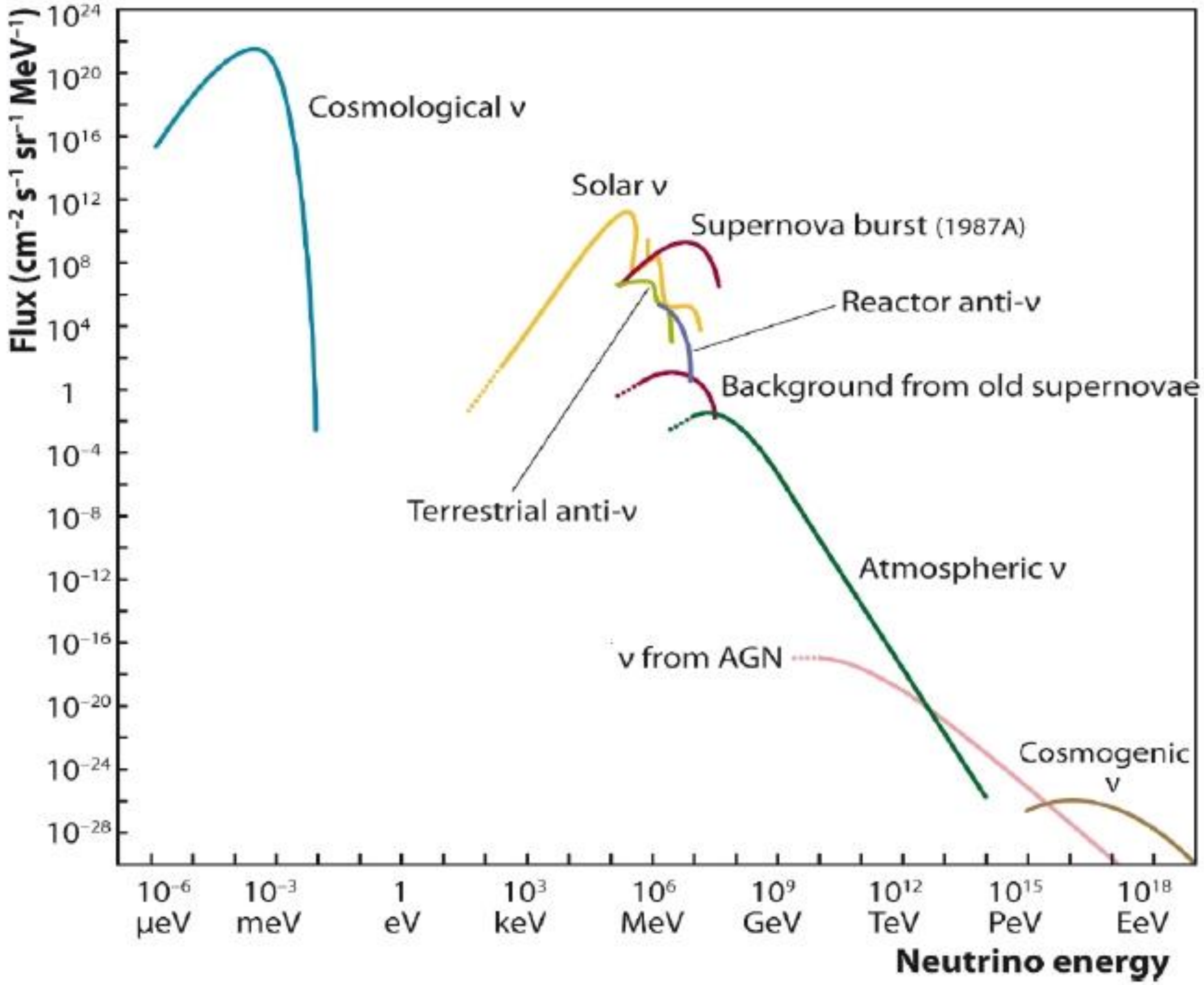
Thank you for attention

Back-up slides

GZK cutoff of the CR spectrum




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



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

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**

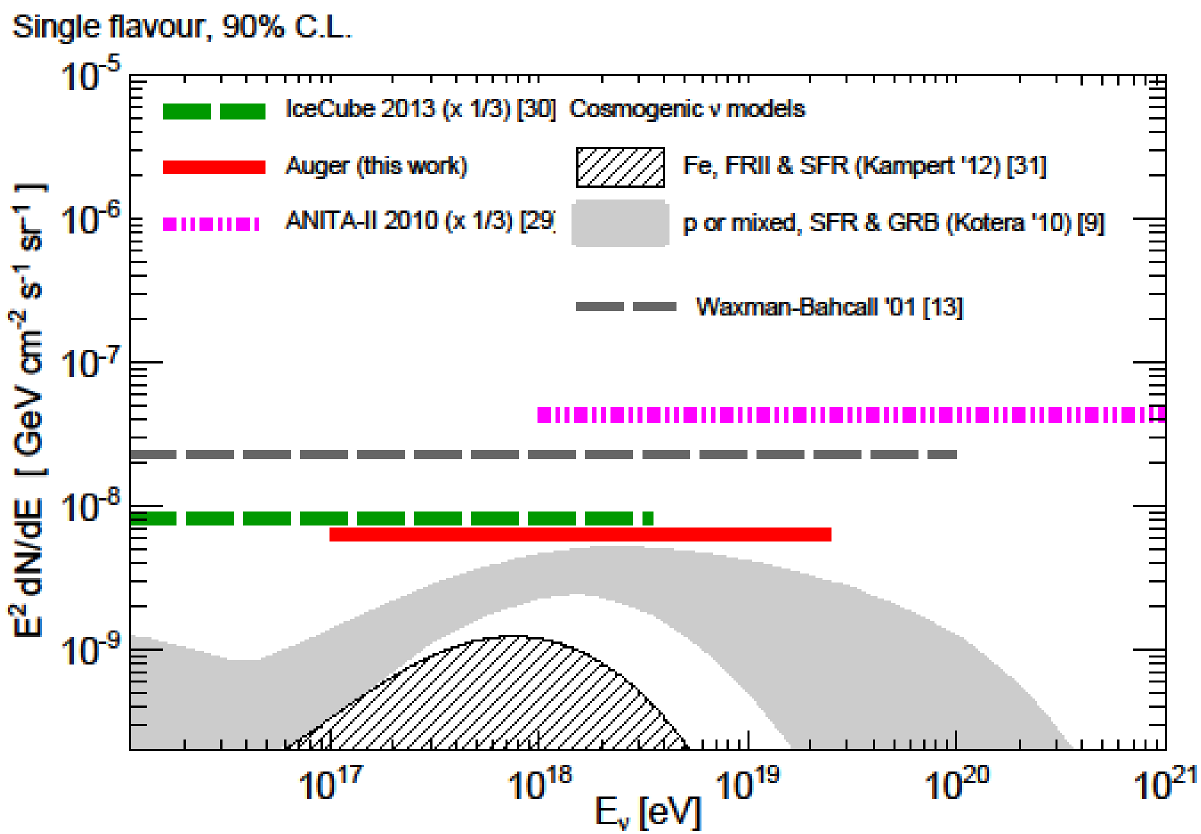
$\log E/\text{eV}$	ν_e CC	ν_μ CC	ν_τ CC	ν_x NC	ν_τ Mount.
16.75	$4.35 \cdot 10^{21}$	$5.27 \cdot 10^{20}$	$1.82 \cdot 10^{21}$	$2.11 \cdot 10^{20}$	-
17	$1.27 \cdot 10^{22}$	$3.16 \cdot 10^{21}$	$1.09 \cdot 10^{22}$	$1.26 \cdot 10^{21}$	-
17.5	$7.94 \cdot 10^{22}$	$2.34 \cdot 10^{22}$	$6.02 \cdot 10^{22}$	$9.37 \cdot 10^{21}$	$1.98 \cdot 10^{22}$
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)

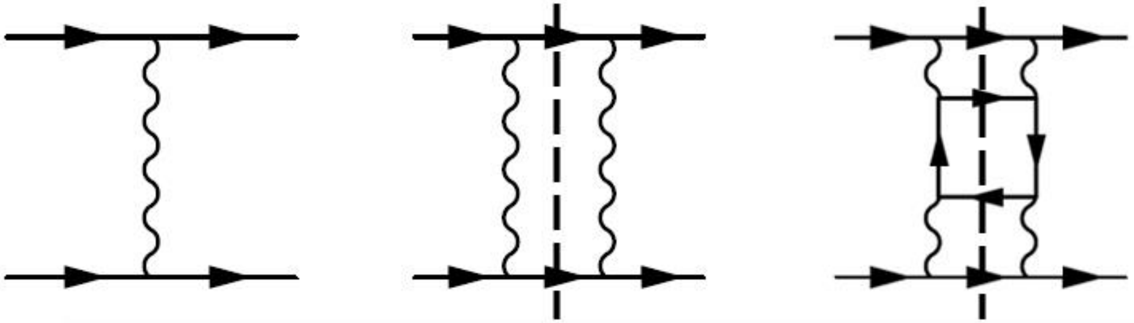
Exposure of the SD for DG neutrinos:

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


Single flavour, 90% C.L.
IceCube 2013 (x 1/3) [30]
Auger (this work)
ANITA-II 2010 (x 1/3) [29]
Cosmogenic ν models
Fe, FRII & SFR (Kampert '12) [31]
p or mixed, SFR & GRB (Kotera '10) [9]
Waxman-Bahcall '01 [13]
E^2 dN/dE [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
E_ν [eV]

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, $E_{\min} = 10^{19}$ eV [34]	~3.2	$\sim 4 \times 10^{-2}$
Cosmogenic—proton, Fermi-LAT, $E_{\min} = 10^{17.5}$ 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)

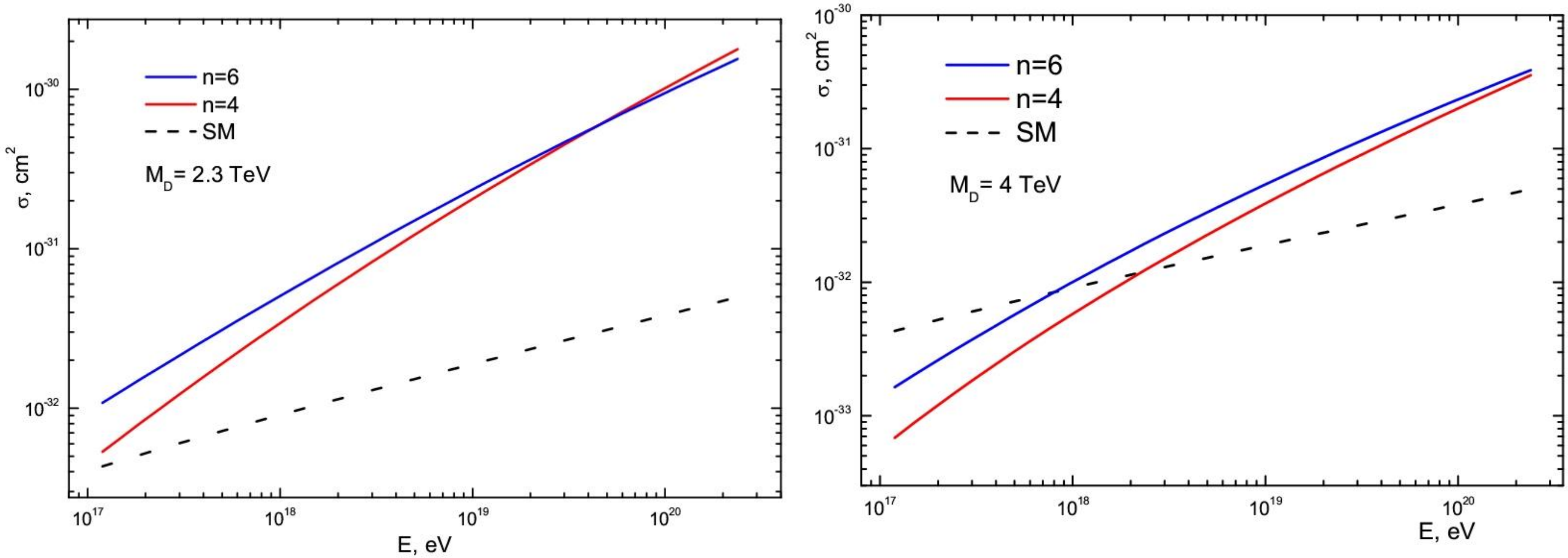


The s^2 dependence of the graviton-exchange Born term renders the sum of exchanges dominant with respect to the inelastic diagrams (see third diagram on this figure)

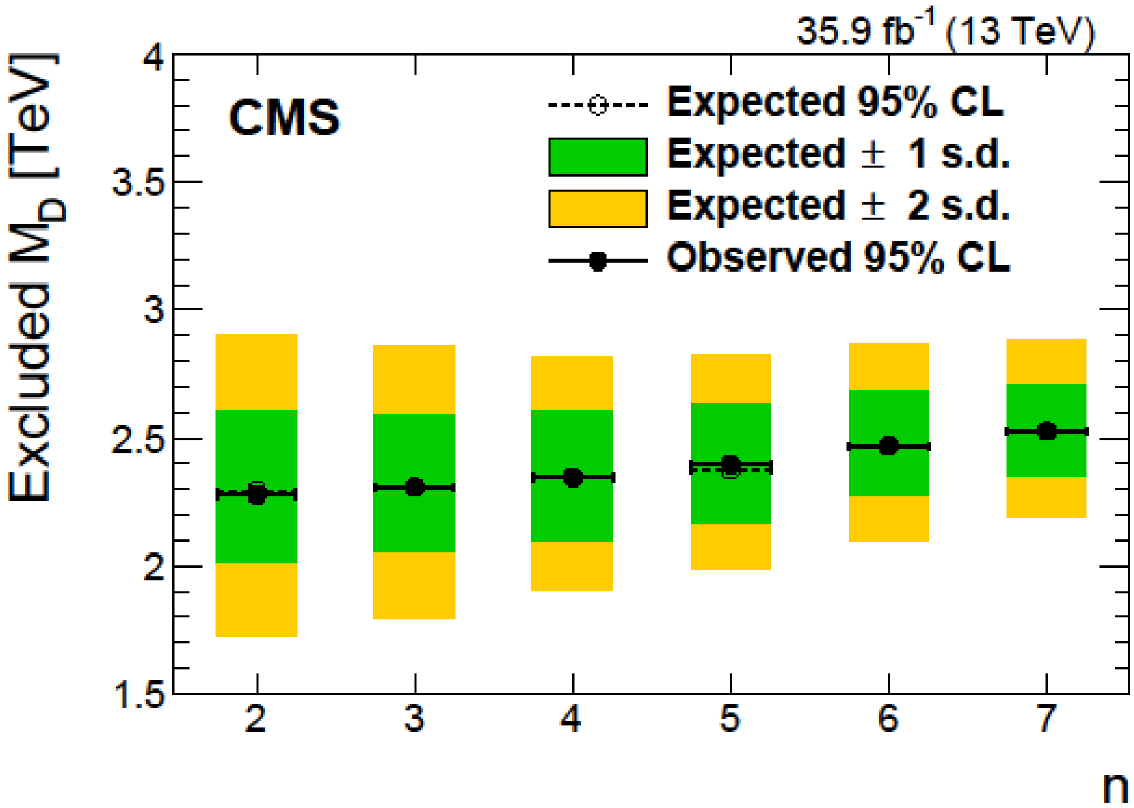
Ordinary gauge theory:
no classical limit

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

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

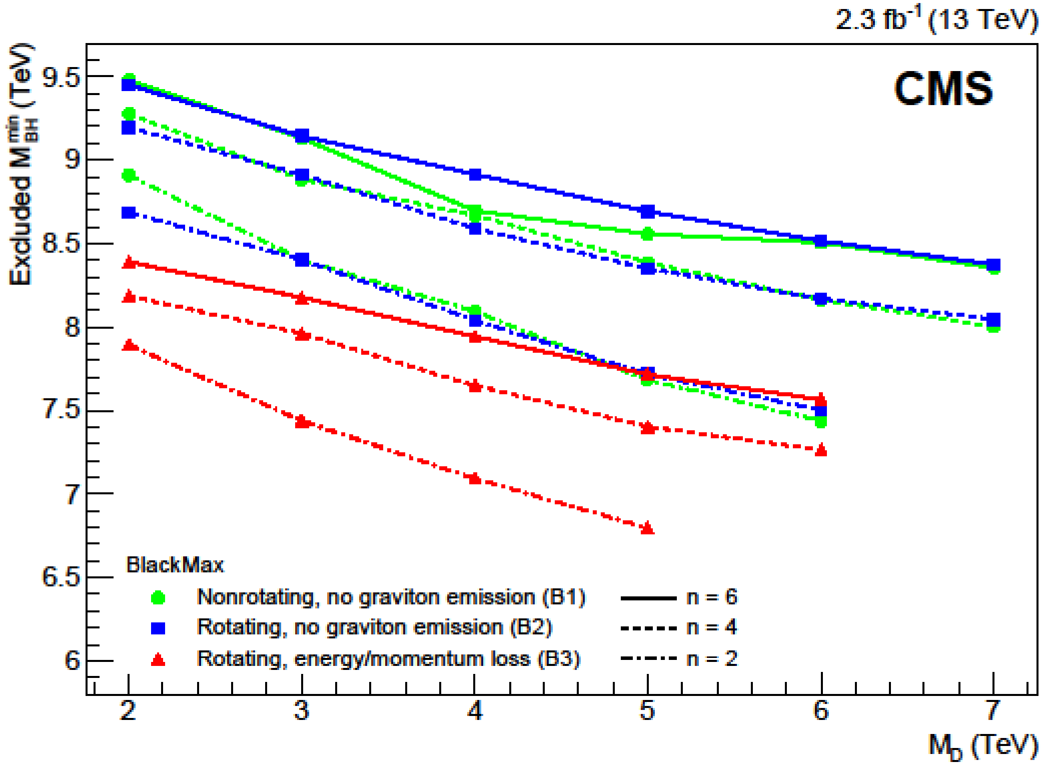


The total neutrino-nucleon cross sections for **M_D = 2.3 TeV** (left panel) and **M_D = 4 TeV** (right panel) with two values of the number of extra dimensions **n**



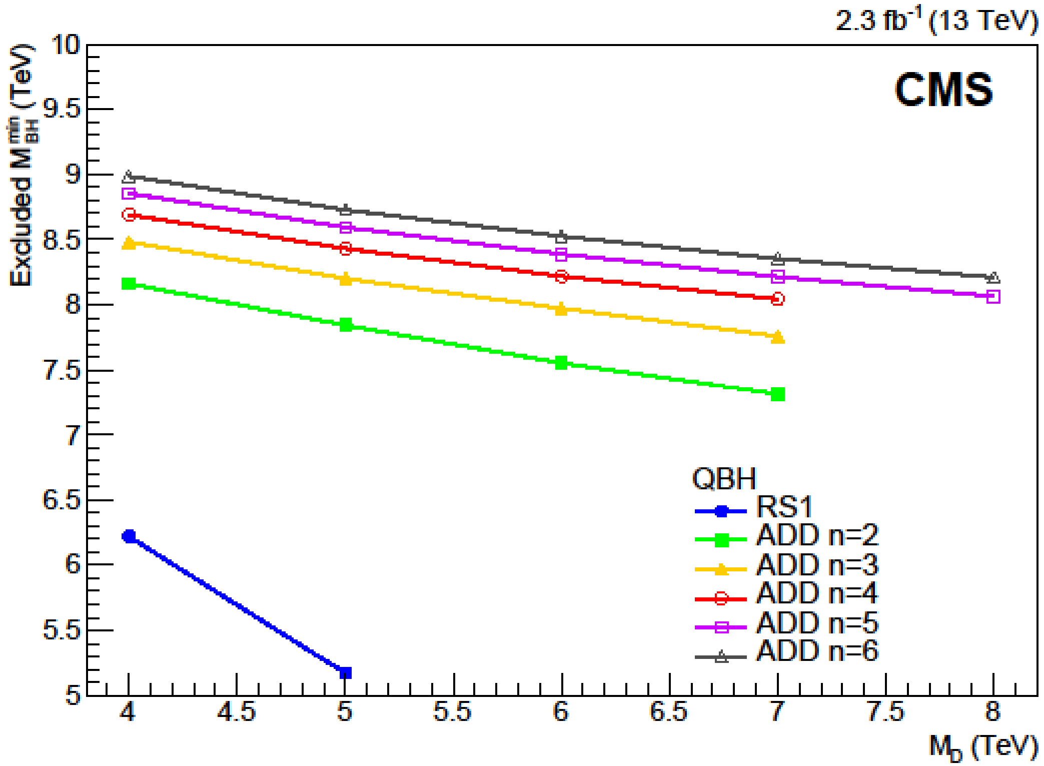
Expected and observed 95% CL exclusion limits on M_D in the ADD scenario for different values of n

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



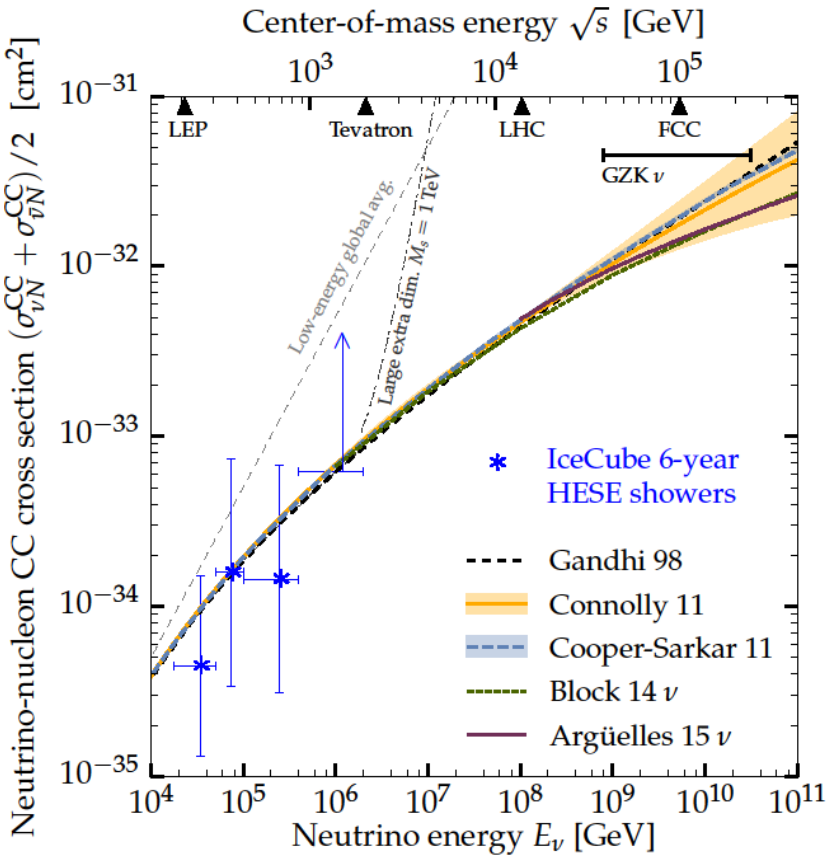
The 95% CL lower limits on minimum semiclassical black hole mass as a function of the Planck scale M_D, for several benchmark models

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



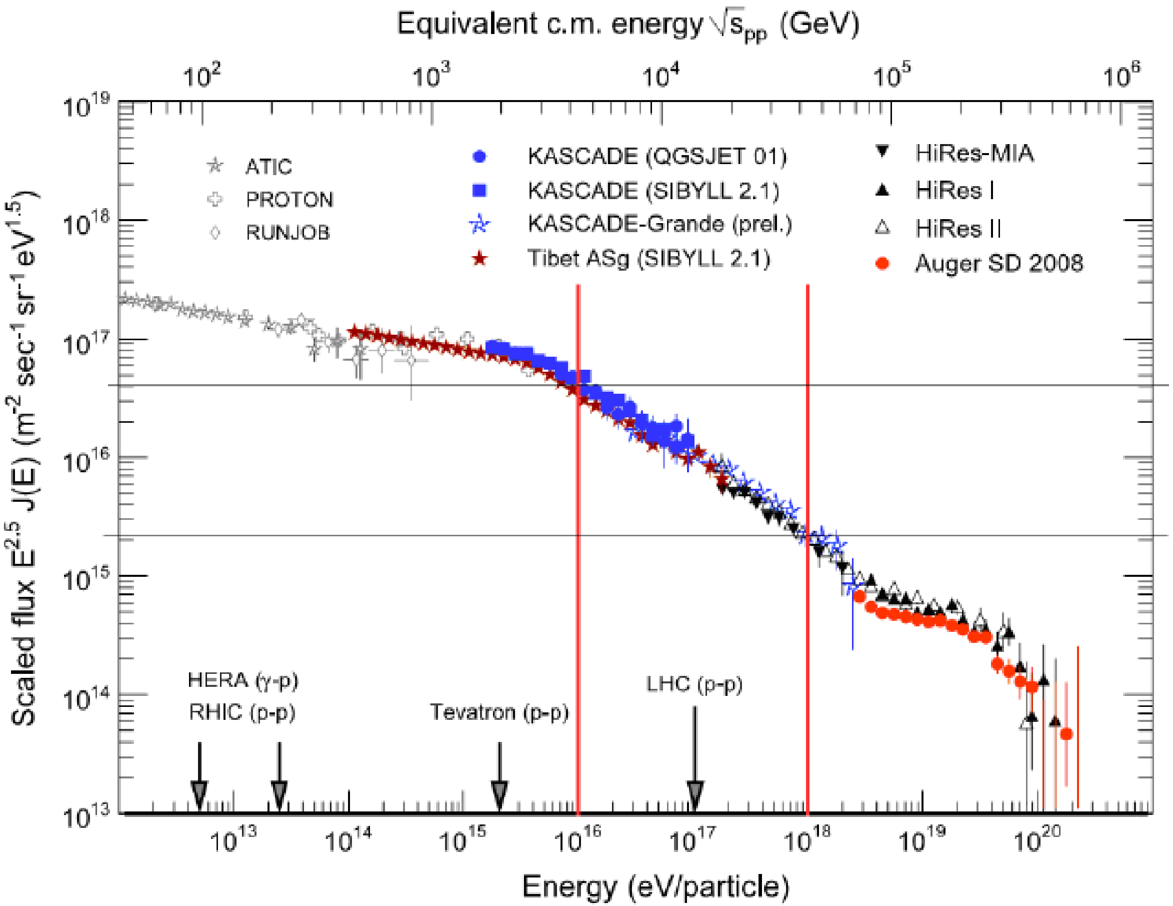
The 95% CL lower limits on minimum quantum black hole mass as a function of the Planck scale M_D, for several benchmark models (bound in the RS1 scenario is also shown)

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

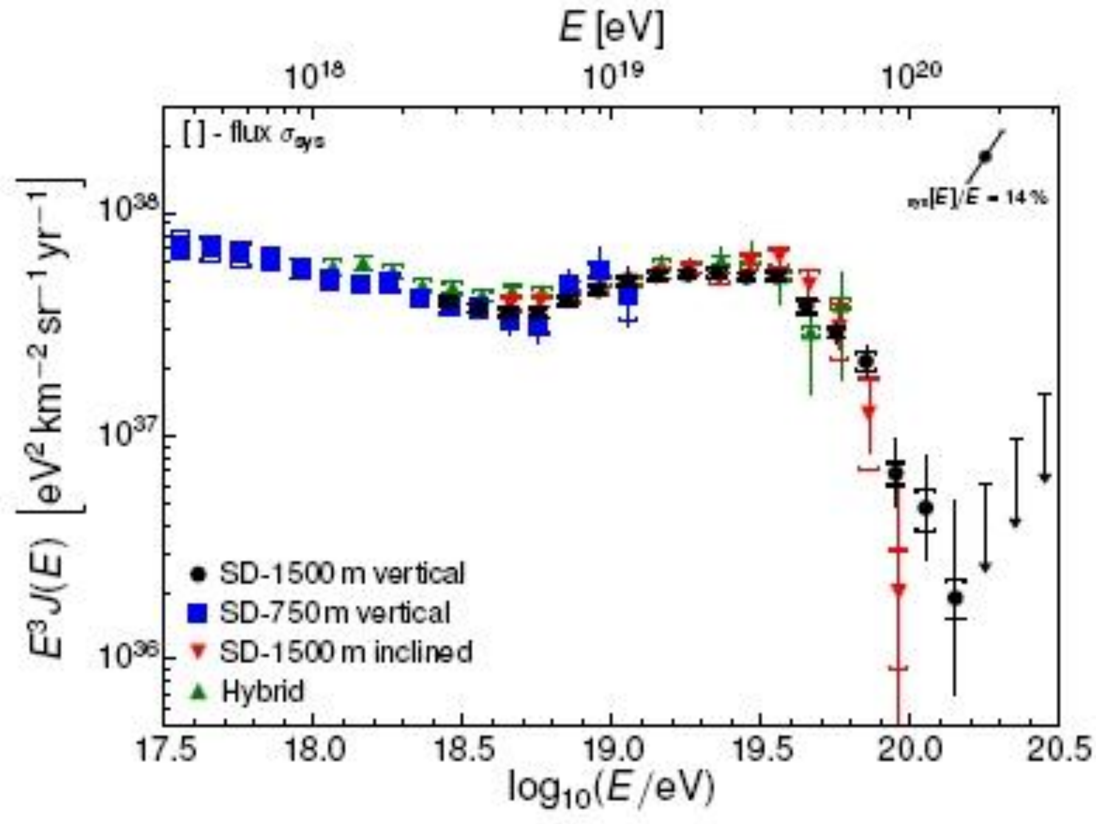


Neutrino-nucleon charged-current cross section, averaged for neutrino and antineutrino, from different predictions

(Bustamante and Connolly, arXiv:1711.11043)

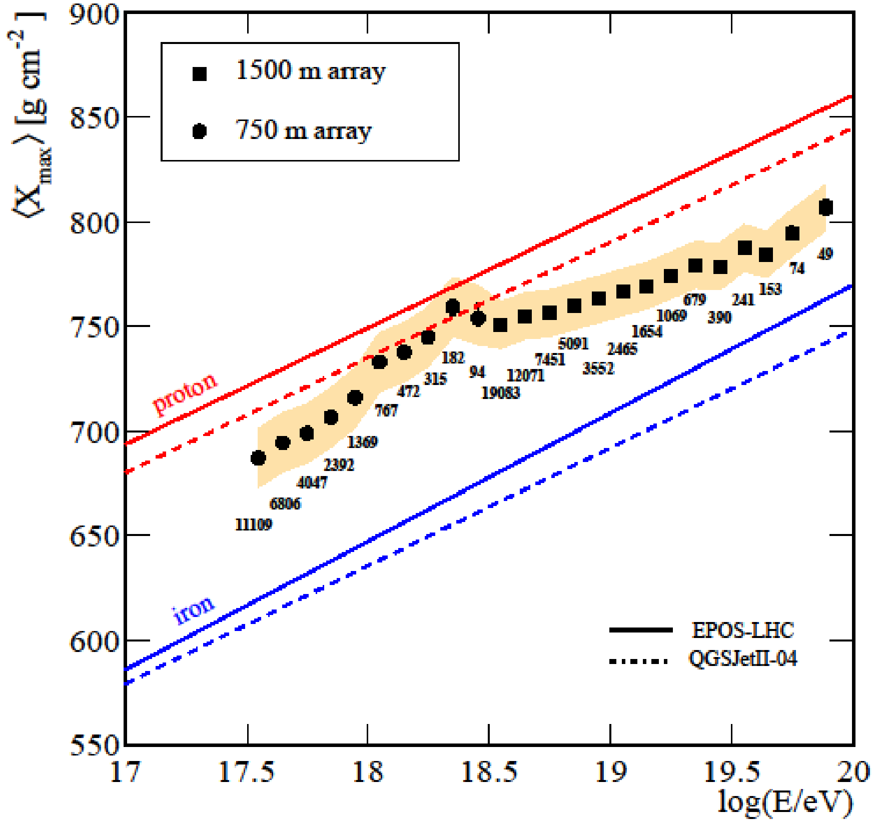


All-particle cosmic-ray energy spectrum



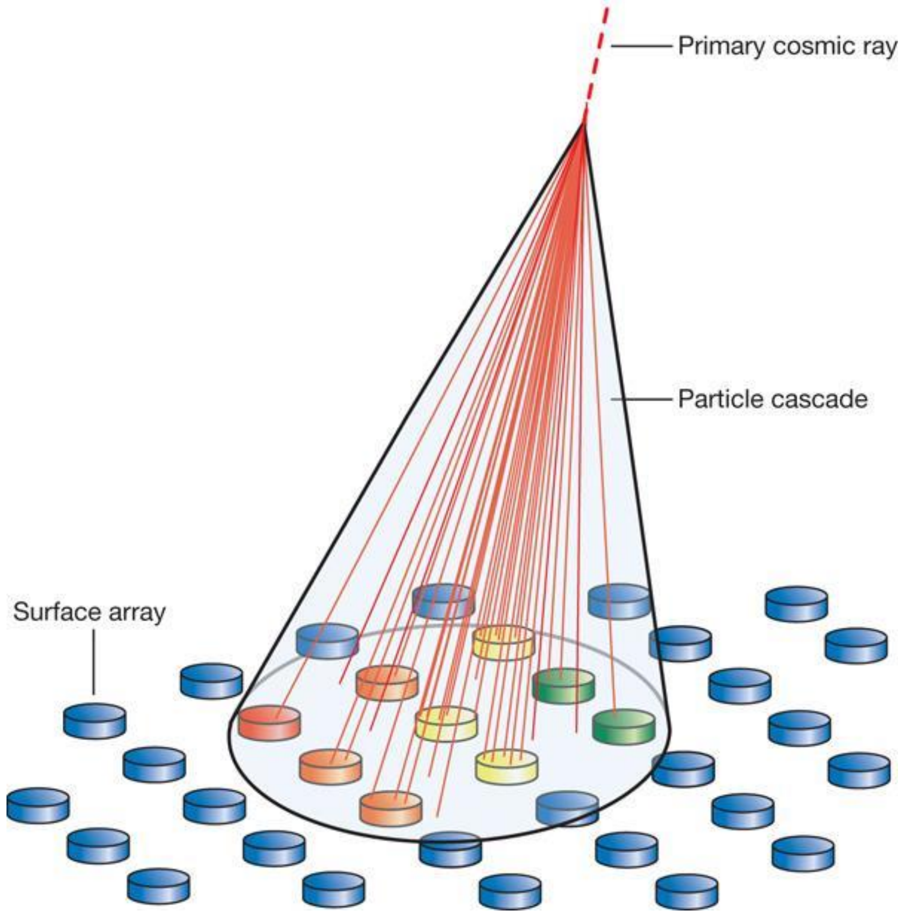
Energy spectrum derived from the Surface detector (SD) and hybrid data at the Pierre Auger Observatory (PAO)

(PAO Collab., ICRC, 2015)

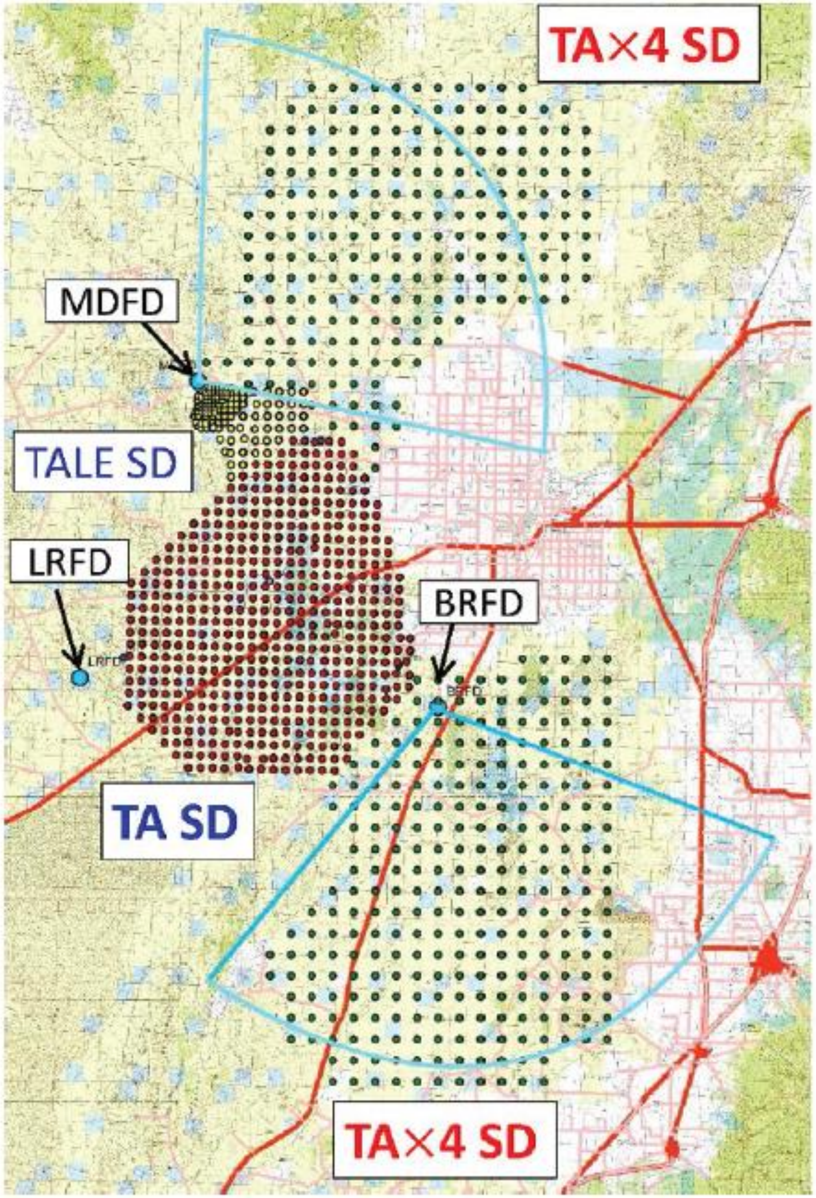


Average depth of shower maxima as a function of energy

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



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