Gravireggeons in Extra Dimensions and Interactions of Cosmic Neutrinos with Nucleons

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SUMMARY

- **Large compact extra dimensions**
- **Gravireggeons and multigravity scattering amplitude**
- **Ultra-high energy neutrino-nucleon interactions**
- **Conclusions**

Large Compact Extra Dimensions

(Arkani-Hamed, Dimopoulos and Dvali, 1998)

String inspired hypothesis **$(\mathrm{D} = 4 + \mathrm{d})$:**

$$\mathrm{E_D} = \mathrm{M_4} \times \mathrm{K_d}$$

$\mathrm{M_4}$ – Minkovsky space-time
$\mathrm{K_d}$ – d-dimensional compact space of size $\mathrm{R_c}$

$$\mathrm{ds^2} = \mathrm{g}_{\mu\nu}\,\mathrm{dx}^{\mu}\,\mathrm{dx}^{\nu} + \gamma_{\mathrm{ab}}\,\mathrm{dy^a}\,\mathrm{dy^b}$$

Gravity propagates in the bulk, gauge and matter fields are confined to 3-dimensional brane

Relation between Planck mass and gravity scale in D-dimensions:

$$\mathrm{M_{Pl} = V_d\, M_D^{2+d}}$$

$\mathrm{V_d = (2\pi\, R_c)^d}$ – volume of compactified ED

If $\mathrm{d = 6}$ and $\mathrm{R_c^{-1} = 10}$ MeV $\Rightarrow$ $\mathrm{M_D = 1}$ TeV

Linearized quantum gravity:

$$\mathrm{g_{AB} = \eta_{AB} + \frac{2}{M_D^{1+d/2}}\, h_{AB}(x, y)}$$

Kaluza-Klein (KK) expansion:

$$\mathrm{h_{AB}(x, y) = \frac{1}{V_d} \sum_n \exp[-n\, y/R_c]\, h_{AB}^{(n)}(x)}$$

Masses of KK modes:

$$\mathrm{m_n} = \frac{\mathrm{n}}{\mathrm{R_c}}$$

$\Rightarrow$ **mass splitting of spectrum: $\mathbf{\Delta m \sim R_c^{-1}}$**

Universal coupling of massive KK gravitons to SM fields

$$\mathcal{L} = -\frac{1}{\mathrm{M_{Pl}}} \mathrm{T}^{\mu\nu} \sum_{\mathrm{n}} \mathrm{G}_{\mu\nu}^{(\mathrm{n})}$$

Smallness of coupling constant is compensated by high multiplicity of final states

Production of KK gravitons:

$$\sigma_{\rm KK} \sim \frac{\rm s^{d/2}}{\rm M_D^{2+d}}$$

$\Rightarrow$ **collider phenomenology at TeV energies (gravity effects in the planckian region)**

What is multigraviton exchange contribution to high energy scattering? (at $\sqrt{\rm s} \gtrsim \rm M_D$)

Gravitational Regge-Eikonal Approach

(Kisselev and Petrov, 2003/04)

Scattering of two particles in transplanckian kinematical region

$$\sqrt{s} \gg M_D, \ -t$$

Massless graviton and its KK massive excitations lie on Regge trajectories

$$\frac{s^2}{-t+\frac{n^2}{R_c^2}} \to -\frac{1+\exp(-i\pi\alpha_n(t))}{\sin\pi\alpha_n(t)}\,\alpha'_g\left(\frac{s}{s_0}\right)^{\alpha_n(t)}$$

Leading vacuum trajectories:

$$\alpha_n(t) = 2 + \alpha'_g\, t - \frac{\alpha'_g}{R_c^2}\, n^2, \quad n = 0,\, 1, \ldots$$

n = KK number

Slop is related to the string scale:

$$\alpha'_g = M_s^{-2}, \qquad M_s = M_D \left(\frac{g_s^2}{4\pi} \right)^{2/(2+d)}$$

- **5-dimensional amplitude (d = 1)**

$$A(s, t, k) = -2iR_c\, s \int d^2b\, e^{iq_\perp b + k\phi} \int_{-\pi}^{\pi} d\phi \left[e^{i\chi(s,b,\phi)} - 1 \right]$$

$R_c\, \phi$ – 5-th component of impact parameter

Imaginary part of the eikonal:

$$\mathrm{Im}\,\chi(\mathrm{s},\mathrm{b},\phi) \simeq \frac{\mathrm{G_5\,s}}{8\pi^{1/2}}\,\frac{\alpha'_{\mathrm{g}}}{\mathrm{R_g^3(s)}}\,\exp\left[-\left(\mathrm{b}^2+\mathrm{R_c^2}\phi^2\right)/4\mathrm{R_g^2(s)}\right]$$

"Transverse gravitational radius"

$$\mathrm{R_g(s)} = \sqrt{\alpha'_{\mathrm{g}}\ln(\mathrm{s}/\mathrm{s_0})}$$

Generalization for* d > 1 *is straightforward

$\alpha'_{\mathrm{g}} = 0$ **(zero slope strings)**
$\Rightarrow$ **pure real eikonal**
(***Giudice, Rattazzi and Wells, 2002***)

Eikonal is small outside the region:

$$\mathrm{b}^2 \lesssim \mathrm{R}_0^2(\mathrm{s}) = 4\alpha'_{\mathrm{g}} \ln(\mathrm{s}/\mathrm{s}_0) \ln(\mathrm{s}/\mathrm{M}_{\mathrm{D}}^2)$$

$\Rightarrow$ ***inelastic (D-dimensional) cross section:***

$$\sigma_{\mathrm{D}}^{\mathrm{in}}(\mathrm{s}) \simeq \begin{cases} \mathrm{const}\, R_0^{2+d}(s) & R_c \gg R_0(s) \\ \mathrm{const}\, R_0^2(s)\, R_c^d & R_c \ll R_0(s) \end{cases}$$

- **Collision of SM particles on the brane**

Impact parameter is two-dimensional

$$\mathrm{Im}\,\chi(\mathrm{s},\mathrm{b}) \simeq \frac{\mathrm{s}}{\mathrm{M}_{\mathrm{D}}^2} \left(\frac{\mathrm{M}_{\mathrm{s}}}{\mathrm{M}_{\mathrm{D}}}\right)^{\mathrm{d}} \exp[-\mathrm{b}^2/4\mathrm{R}_{\mathrm{g}}(\mathrm{s})]$$

Inelastic cross section:

$$\sigma_{\rm in}(s) \simeq \frac{4\pi}{M_s^2} \ln(s/s_0) \ln(s/M_D^2)$$

$M_D \sim 1$ TeV, $M_s \simeq 0.46(0.56)\, M_D$, for $d = 4(6)$

Real part of the eikonal (with zero graviton mode subtracted):

$$\mathrm{Re}\,\tilde{\chi}(s,b)|_{b \gg R_g(s)} \simeq \frac{s}{M_D^2} \left(\frac{M_s}{M_D}\right)^d \left[R_g(s)/b\right]^2 J_2\left[b/R_g(s)\right]$$

Zero impact parameter

$$\frac{\mathrm{Re}\,\tilde{\chi}(s,0)}{\mathrm{Im}\,\chi(s,0)} \sim \ln s$$

Distinct behavior in D infinite flat dimensions

(Amati, Ciafaloni and Veneziano, 1987)

$\mathrm{Im}\,\chi_D(s,b)$ is the same, but

$$\mathrm{Re}\,\chi_D(s,b) = \left[\frac{b_c(s)}{b}\right]^d$$

- **4-dimensional scattering amplitude**

- ***Both real and imaginary part exhibits exponential fall-off:***

$$\mathrm{Re}\,\tilde{A}(s,t),\ \mathrm{Im}\,A(s,t)\big|_{|t|R_g(s)\gg 1} \sim \exp[t\alpha'_g \ln(s/s_0)]$$

- ***Real part (with pole term subtracted) dominates at*** $\mathbf{t = 0}$**:**

$$\frac{\mathrm{Re}\,\tilde{A}(s,0)}{\mathrm{Im}\,A(s,0)} \sim \ln s$$

To compare, D-dimensional amplitude

$$\mathrm{Re}\,A_D(s,t)\big|_{|t| \gg b_c^{-2}(s)} \sim |t|^{-(d+2)^2/4(d+1)}$$

$\mathbf{Im\,A_D(s,t)}$ **coincides with** $\mathbf{Im\,A(s,t)}$

Inelastic processes do not feel that colliding particles are confined to the brane

In what processes can we look for multigravity effects?

Weekly interacting particles with transplanckian energies ($\sqrt{s} \gtrsim M_D$)

$\Rightarrow$ cosmic neutrinos?

Ultra-High Energy Neutrino Interactions

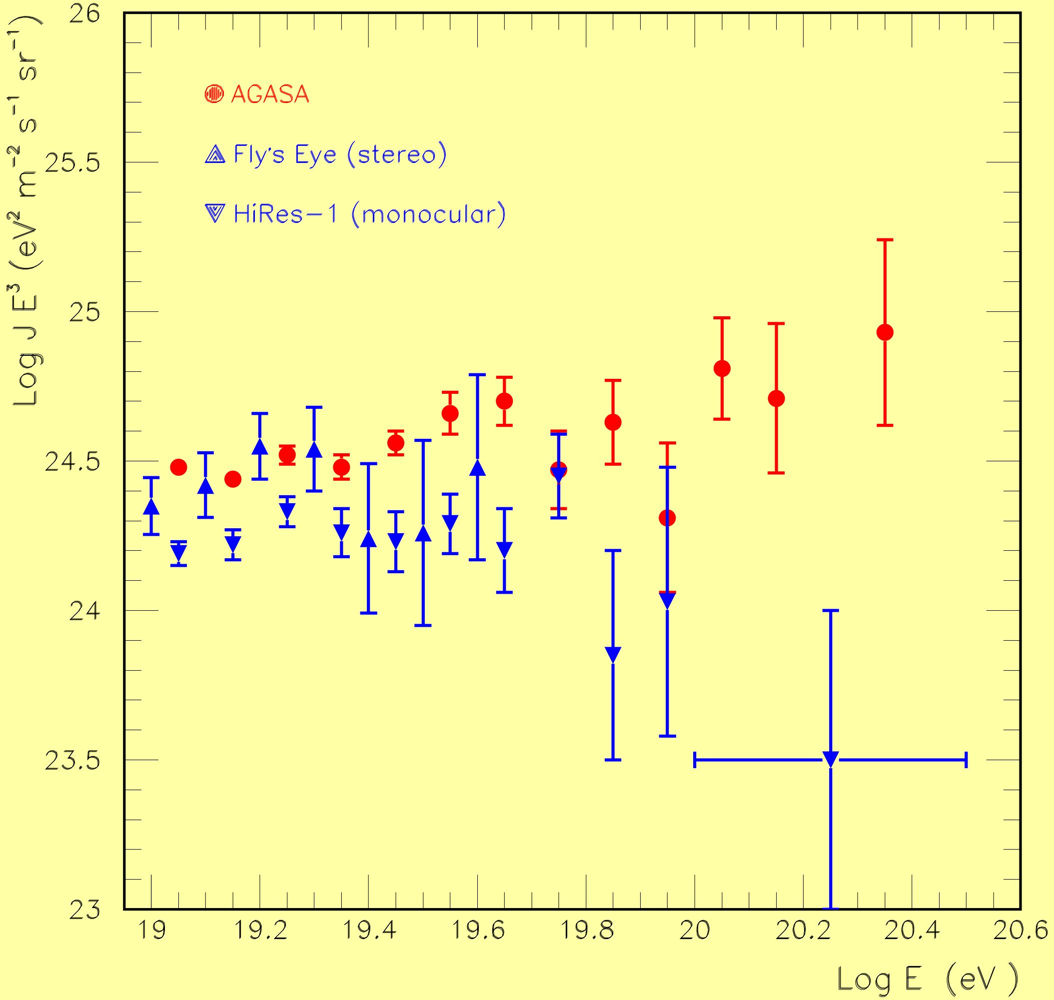
SM neutrino-nucleon scattering is very weak even at ultra-high energies (UHE)

$$\sigma_{\mathrm{SM}}^{\nu \mathrm{N}} \simeq 2.36 \cdot 10^{-5} \left(\frac{\mathrm{E}_\nu}{10^{19}\,\mathrm{eV}} \right)^{0.363} \mathrm{mb}$$

$(10^{16}\,\mathrm{eV} \lesssim \mathrm{E}_\nu \lesssim 10^{21}\,\mathrm{eV})$

New interactions may dominate

UHE cosmic neutrinos – one of possibilities to explain Greisen-Zatsepin-Kuzmin (GZK) puzzle



Upper end of the cosmic ray energy spectrum as observed by AGASA and HiRes/FlyEye (Anchordoqui *et. al*, 2004)

Proton scattering off cosmic microwave background during UHE cosmic ray (CR) propagation:

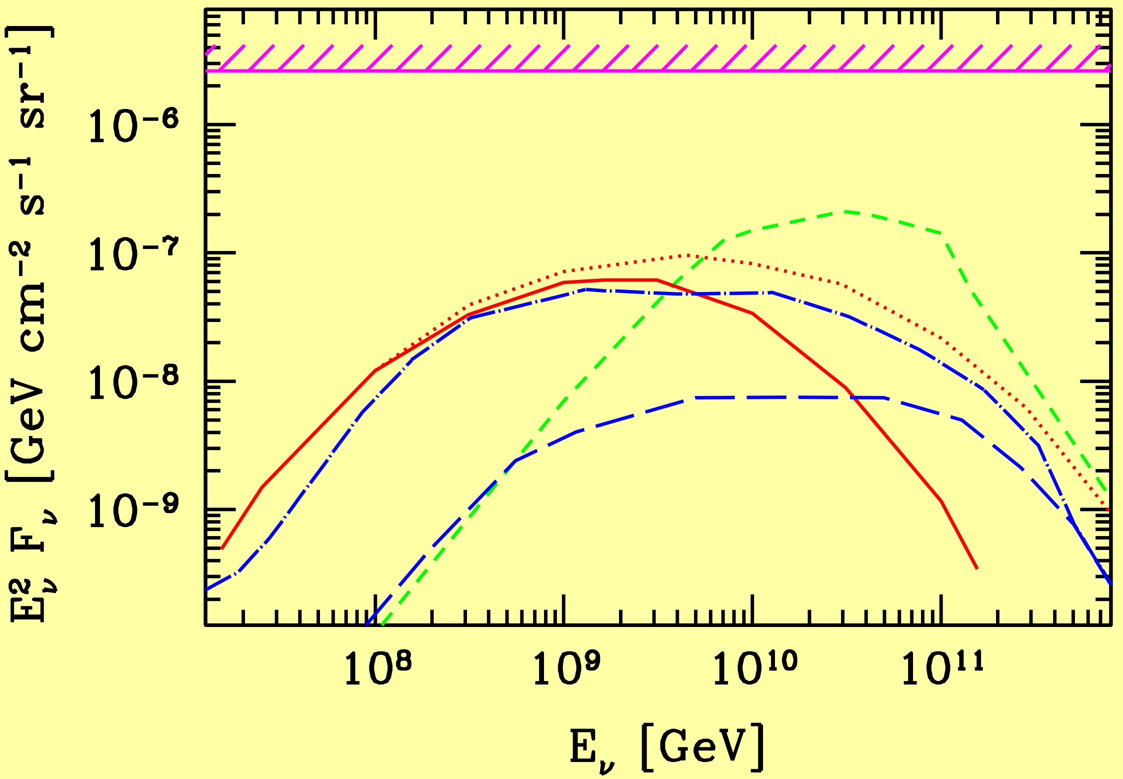
$$\mathrm{p} + \gamma_{\mathrm{CMB}} \to \mathrm{N} + \pi$$

$\Rightarrow$ GZK cut-off of CR spectrum at $\mathbf{E \simeq 5 \cdot 10^{19}}$ eV

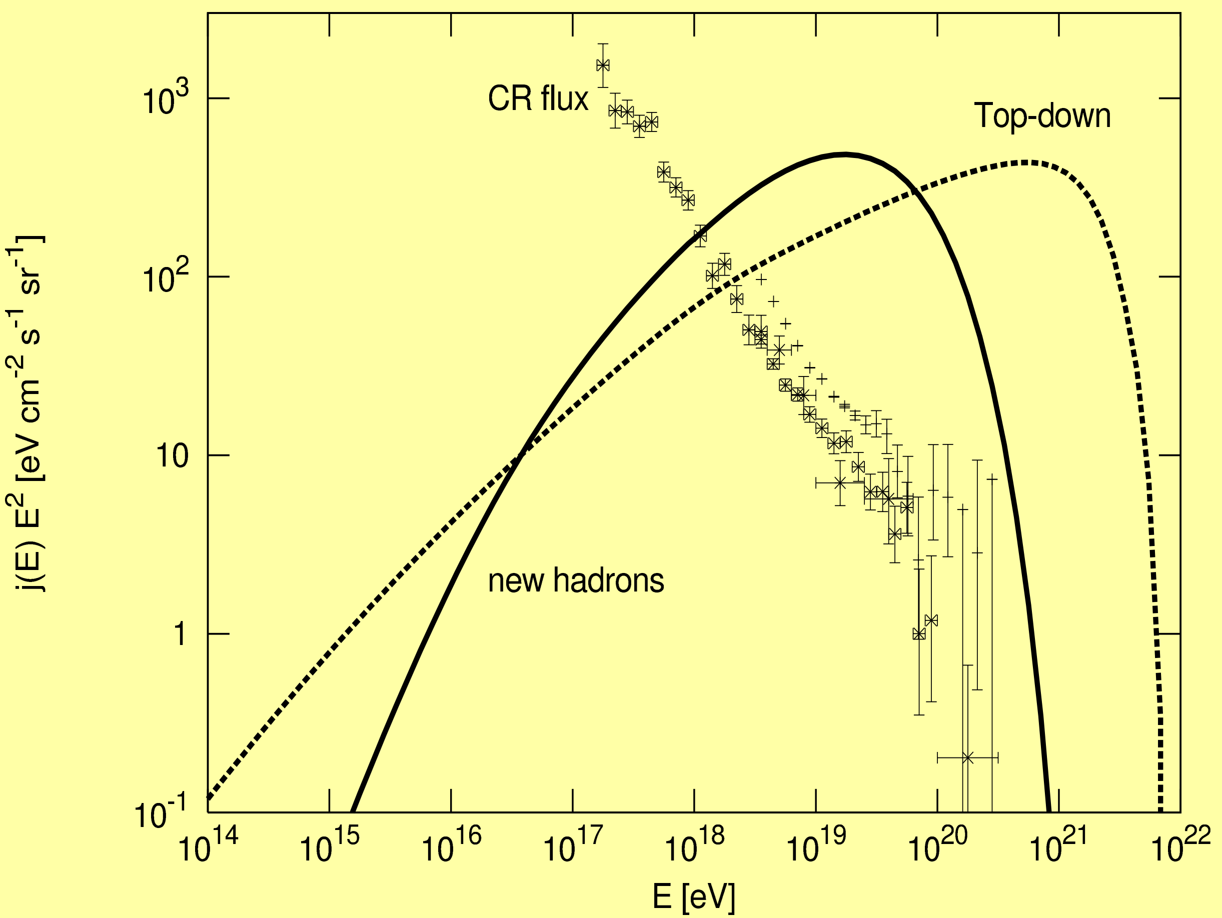
Consequence decays of charged pions
$(\pi^{\pm} \to \mu^{\pm} \nu_{\mu}, \quad \mu^{\pm} \to \mathrm{e}^{\pm} \nu_{\mathrm{e}} \nu_{\mu})$

$\Rightarrow$ **flux of cosmogenic UHE neutrinos**

UHE primaries of CR are neutrinos
+ neutrino interactions beyond SM
$\Rightarrow$ excess of UHECR flux?



Predictions of the cosmogenic neutrino flux, $F_\nu = \sum_i [F_{\nu_i} + F_{\bar{\nu}_i}]$. Dotted line: flux from paper by Protheroe *et al.* (1996) assuming a maximum energy of $E_{max} = 3 \cdot 10^{21}$ eV for the ultrahigh energy cosmic rays. Shaded: theoretical upper limit of the neutrino flux from "hidden" astrophysical sources that are non-transparent to ultrahigh energy nucleons (Mannheim *et al.* (2001)).



Neutrino fluxes in exotic ultra-high energy cosmic ray models. Solid line is the neutrino flux in model of new hadrons whereas dashed line is the neutrino flux in topological defect model (Aramo *et al.* (2004)).

Neutrino interaction length:

$$\mathbf{L}_\nu = \frac{\mathbf{m_N}}{\rho_\mathbf{w}\,\sigma_{\nu\mathbf{N}}} \simeq \mathbf{1.7 \cdot 10^7} \left(\frac{\mathbf{pb}}{\sigma_{\nu\mathbf{N}}}\right) \ \mathbf{km\ we}$$

(we ≡ water equivalent)

To separate neutrino-initiated showers from hadronic ones – looking for quasi-horizontal air showers

Non-observation of horizontal showers by Fly's Eye and AGASA ⇒ upper bound on the neutrino flux Φ_ν

$$(\Phi_\nu\,\sigma_{\nu\mathrm{N}})(\mathrm{E}_\nu) \leq 3.74 \cdot 10^{-42} \left(\frac{\mathrm{E}_\nu}{1\mathrm{GeV}}\right)^{-1.48} \mathrm{GeV}^{-1}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

(10^8 GeV $\leq \mathrm{E}_\nu \leq 10^{11}$ GeV)

• Multigravity neutrino-nucleon scattering

$$\sigma_{\text{grav}}^{\nu\text{N}}(\text{s}) = \sum_{\text{i}} \int_{\text{x}_{\text{min}}}^{1} \text{dx}\, \text{f}_{\text{i}}(\text{x}, \mu^2)\, \hat{\sigma}_{\text{i}}(\hat{\text{s}})$$

$\text{f}_{\text{i}}(\text{x}, \mu^2)$ – parton distribution function (PDF)
$\hat{\text{s}} = \text{xs}$ – partonic subprocess energy

PDF set based on analysis of DIS data

(Alekhin, 2002)

⇒ *multigravity (inelastic) cross section:*

$$\sigma_{\text{grav}}^{\nu\text{N}}(\text{E}_\nu = 10^{12}\ \text{GeV}) \simeq \begin{cases} 0.87 \cdot 10^{-1}\ \text{mb} & \text{d} = 2 \\ 0.46 \cdot 10^{-3}\ \text{mb} & \text{d} = 4 \end{cases}$$

Detection of UHE cosmic neutrinos:

- **Neutrino telescopes (MACRO, Baikal, AMANDA II)**

  Future detectors: NT200+ (Baikal), IceCube, ANTARES, NESTOR

- **Observation of neutrino-induced air showers (AGASA, Fly's Eye/HiRes, Yakutsk, RICE, GLUE, FORTE)**

  Future projects: NUTEL, EUSO, OWL, Telescope array, Pierre Auger observatory

- **Neutrino detection by ground arrays**

Number of air showers with energy larger than $\mathrm{E_{th}}$ for time interval T:

$$\mathrm{N_{sh}}(\mathrm{E} > \mathrm{E_{th}}) = \mathrm{T}\,\mathrm{N_A} \int_{\mathrm{E_{th}}}^{\infty} d\mathrm{E}_\nu\, \Phi_\nu(\mathrm{E}_\nu)\, \sigma_{\nu\mathrm{N}}(\mathrm{E}_\nu)\, \mathcal{A}(\mathrm{E}_\nu)$$

$(\mathrm{N_A} = 6.022 \cdot 10^{23}\ \mathrm{g^{-1}})$

$\mathcal{A}(\mathrm{E}_\nu)$ is the detector acceptance

Pierre Auger observatory:

$$\mathcal{A}(\mathrm{E} > 10^{10}\ \mathrm{GeV}) \approx 30\ \mathrm{km^3\ we\ sr}$$

(Capelle et al., 1998)

d	2	3	4	5	6
$E_{th} = 10^8$ GeV	34.9	2.00	0.32	0.21	0.20
$E_{th} = 10^9$ GeV	30.2	1.66	0.21	0.12	0.12
$E_{th} = 10^{10}$ GeV	13.2	0.74	0.06	0.03	0.02

Yearly event rates for nearly horizontal neutrino induced showers with $E_{sh} \geqslant E_{th}$ for *cosmogenic neutrino flux* (Protheroe, 1996) at three values of threshold energy E_{th} and $E_{max} = 3 \cdot 10^{21}$ eV. Number of events corresponds to one side of the Auger ground array.

d	2	3	4	5	6
$E_{th} = 10^8$ GeV	270	18.7	1.72	0.77	0.71
$E_{th} = 10^9$ GeV	264	18.2	1.55	0.63	0.57
$E_{th} = 10^{10}$ GeV	227	16.3	1.21	0.38	0.34

The same as in the previous Table, but for the netrino flux in topological defects model (Aramo *et al.*, 2004) and $E_{max} = 7 \cdot 10^{21}$ eV.

CONCLUSIONS

- **Summing up gravireggeons results in *D*-dimensional Planck mass in the eikonal**
- **Real part of 4-dimensional amplitude has exponential falloff in *t*, contrary to *D*-dimensional amplitude**
- **Inelastic processes are the same, whether colliding particles are confined to the brane or propagate in the bulk**
- **Ultra-high energy neutrino scattering off nucleons is one of promising processes to search for multigravity effects**
- **Up to tens of quasi-horizontal air showers induced by cosmic neutrinos can be detected at the Auger observatory per year**