High-energy cosmic rays and weak-scale string theories

Michael Plümacher
University of Oxford

M. Kachelrieß, M. P.:
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Outline

- Introduction
- Large extra dimensions
- Neutrino-Nucleon scattering
- Conclusions

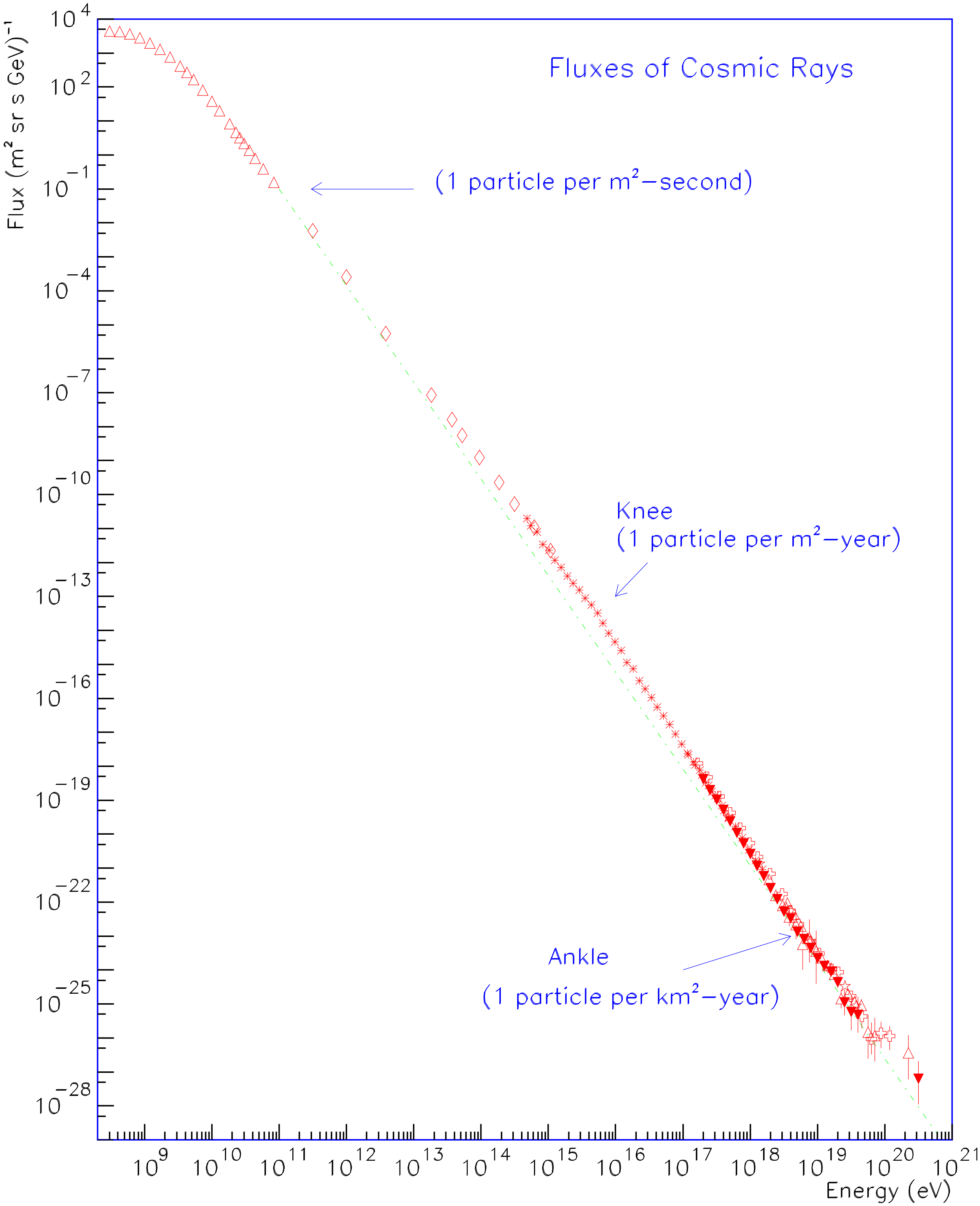
Introduction

Detection of cosmic rays:

- Energy spectrum: power law behaviour over a wide range of energies
- primaries are shielded by the atmosphere
- for energies less than ~ 100 TeV the cosmic ray flux is high enough to allow direct detection of primaries from space
- above ~ 100 TeV showers of secondary particles can be detected from the ground

Composition:

- muon content and depth of shower maximum provide information on the chemical composition
- rule of thumb: heavy nuclei produce air showers with a higher muon content and a shower maximum higher up in the atmosphere than light ones



Fluxes of Cosmic Rays
(1 particle per m²−second)
Knee
(1 particle per m²−year)
Ankle
(1 particle per km²−year)
Flux (m² sr s GeV)⁻¹
Energy (eV)

Greisen-Zatsepin-Kuzmin (GZK) cutoff

at energies $E > 6 \cdot 10^{19}$ eV protons lose energy due to pion photoproduction

$$p + \gamma_{\rm CMB} \longrightarrow \Delta^+ \longrightarrow p + \pi^0$$

for nuclei at $E \gtrsim 10^{19}$ eV: photodisintegration in the CMB and IR background

$$^{56}{\rm Fe} + \gamma_{\rm CMB} \longrightarrow {}^{55}{\rm Fe} + n$$

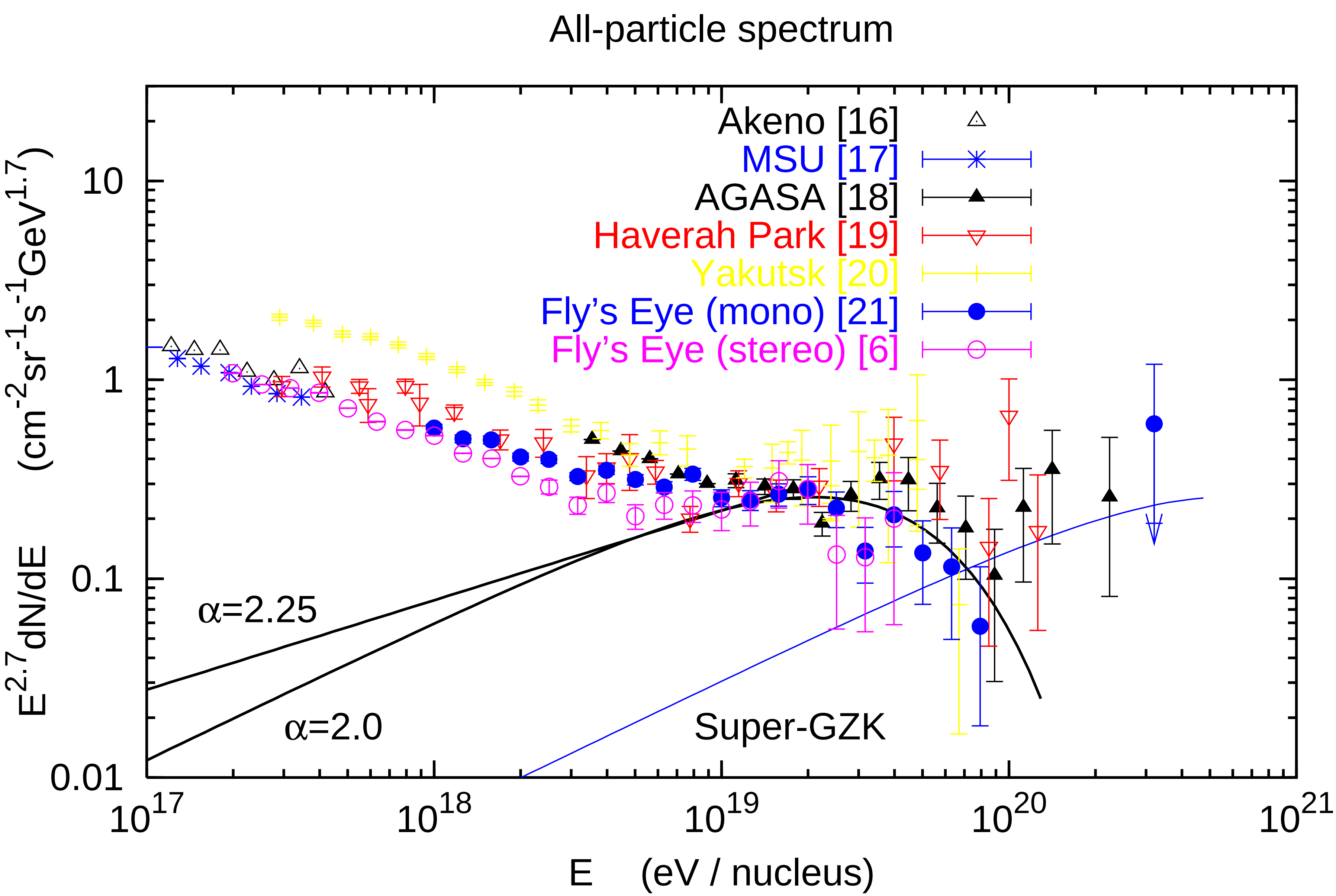
photons interact with the CMB and the geomagnetic field ⇒ pair production above ~ 200 TeV

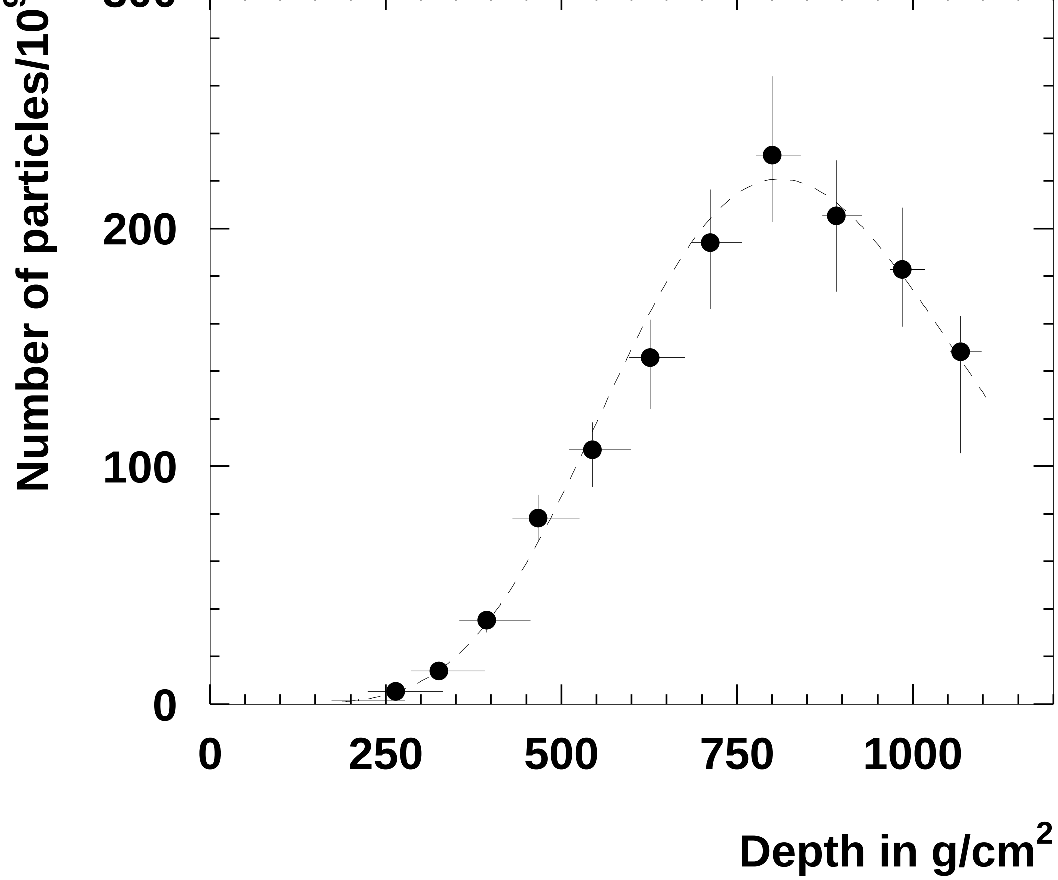
Events above 10^{20} eV have been observed:
events are consistent with nucleon primaries:

- longitudinal shower profile of the Fly's Eye event best fitted by a proton
- lateral electron and muon distributions measured by AGASA indicate that the primaries are nucleons

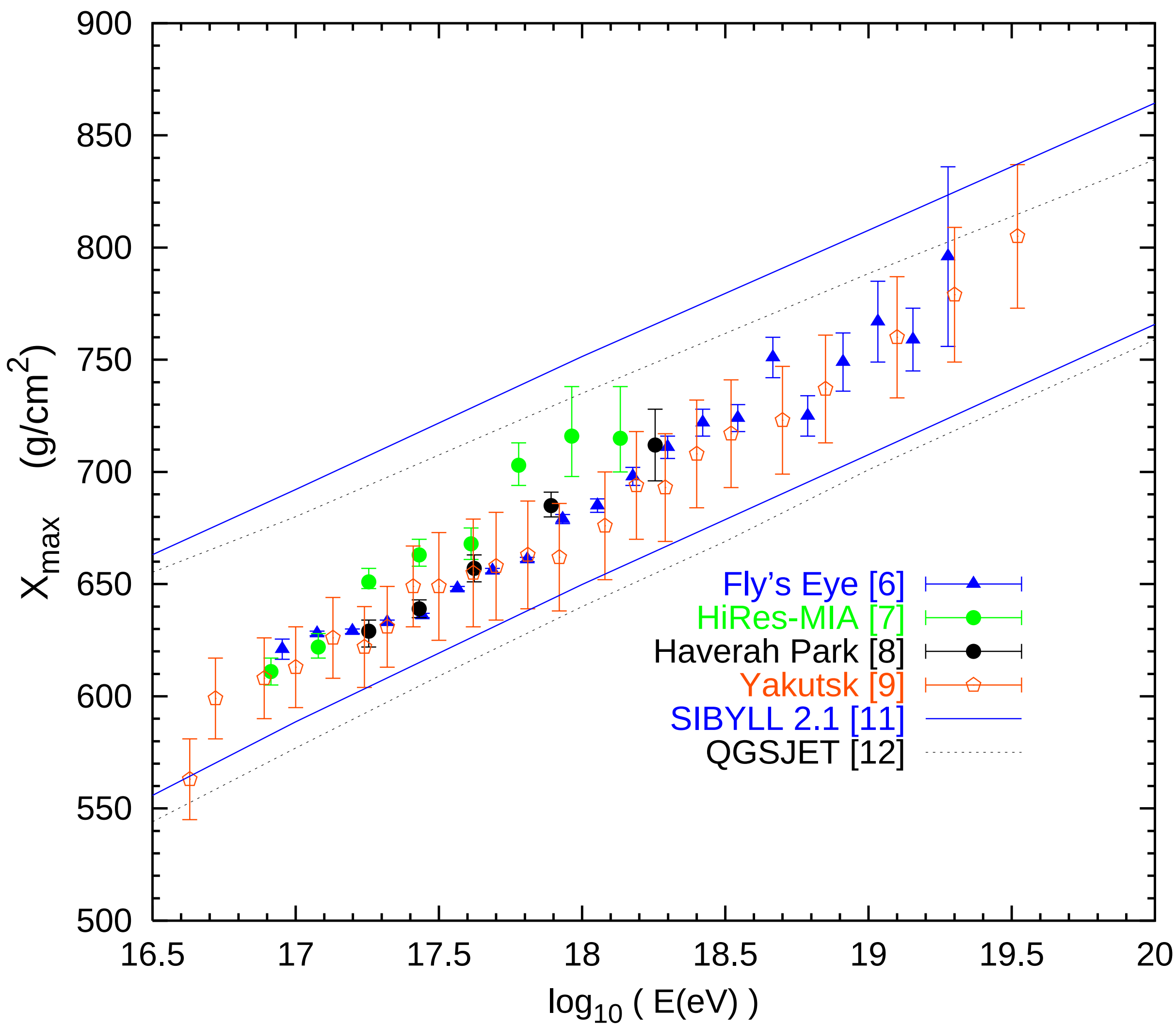
isotropic arrival directions ⇒ extragalactic origin
no plausible astrophysical sources within $\sim 100\,$Mpc

Could neutrinos be the primaries?


All-particle spectrum
Akeno [16]
MSU [17]
AGASA [18]
Haverah Park [19]
Yakutsk [20]
Fly's Eye (mono) [21]
Fly's Eye (stereo) [6]
α=2.25
α=2.0
Super-GZK
10
1
0.1
0.01
E^2.7 dN/dE (cm^-2 sr^-1 s^-1 GeV^1.7)
10^17
10^18
10^19
10^20
10^21
E (eV / nucleus)



Number of particles/10^9
200
100
0
0
250
500
750
1000
Depth in g/cm^2



900
850
800
750
700
650
600
550
500
X_{max} (g/cm^2)
16.5
17
17.5
18
18.5
19
19.5
20
$\log_{10}$ (E(eV))
Fly's Eye [6]
HiRes-MIA [7]
Haverah Park [8]
Yakutsk [9]
SIBYLL 2.1 [11]
QGSJET [12]

Large Extra Dimensions

Consider a world with δ extra dimensions

Compactification radius R

Standard model fields live on a 3-brane
$\Rightarrow$ they do not feel the extra dimensions

only gravity propagates in the higher dimensional space

$\Rightarrow$ Gravity is weak due to the large compactification radius

$$G_N^{-1} = 8\pi R^\delta M_D^{\delta+2}$$

Fundamental mass scale
$M_D \sim 1$ TeV $\Rightarrow R \sim 1$ mm for $\delta = 2$

Solution to the hierarchy problem?
4-d Planck scale $\gg$ electroweak scale
new hierarchy problem:
$M_D \sim 1$ TeV $\gg R^{-1} \sim 10^{-3}$ eV

Astrophysical bounds

Supernova bounds:

SN 1987a (Hanhart et al., astro-ph/0102063)

energy loss due to KK emission

$\Rightarrow$ shortening of the neutrino signal

$$\delta = 2 \quad \Rightarrow \quad M_D > 60 \text{ TeV}$$

$$\delta = 3 \quad \Rightarrow \quad M_D > 5 \text{ TeV}$$

SN contributions to γ-ray background:

(S. Hannestad et al., hep-ph/0103201)

decays of KK gravitons emitted by all SNe over the age of the universe

$$KK \to 2\gamma \ , \ e^+e^- \ , \ \nu\bar{\nu}$$

$\Rightarrow$ contribution to the diffuse γ-ray background

$$\delta = 2 \quad \Rightarrow \quad M_D > 84 \text{ TeV}$$

$$\delta = 3 \quad \Rightarrow \quad M_D > 7 \text{ TeV}$$

Cosmological Bounds

KK gravitons are produced in the early universe at high temperatures:

pair annihilation: 2γ , e^+e^- , $\nu\bar{\nu} \rightarrow KK$

gravi-bremsstrahlung

gravi-Compton scattering

contributions to γ-ray background:

(S. Hannestad, hep-ph/0102290)

T_{MAX} during reheating 1 GeV

$$\delta = 2 \quad \Rightarrow \quad M_D > 170 \text{ TeV}$$

$$\delta = 3 \quad \Rightarrow \quad M_D > 20 \text{ TeV}$$

$$\delta = 4 \quad \Rightarrow \quad M_D > 5 \text{ TeV}$$

$$\delta = 5 \quad \Rightarrow \quad M_D > 2 \text{ TeV}$$

contribution to the energy density of matter

(M. Fairbairn, hep-ph/0101131)

$\Rightarrow$ earlier matter-radiation equality

$\Rightarrow$ low age of the universe

$T_{REH} = 170$ MeV and $t > 12.8$ Gyrs

$$\delta = 2 \quad \Rightarrow \quad M_D > 10^3 \text{ TeV}$$

$$\delta = 3 \quad \Rightarrow \quad M_D > 60 \text{ TeV}$$

$$\delta = 4 \quad \Rightarrow \quad M_D > 9 \text{ TeV}$$

Naturally realized in Type I string theories:

- SM fields correspond to open strings beginning and ending on D-branes
- gravitons correspond to closed strings which can propagate in the higher dimensional space

$\Rightarrow$ from our 4-dimensional point of view the graviton is an infinite tower of Kaluza-Klein excitations with masses

$$m_{\vec{n}}^2 = \frac{\vec{n}^2}{R^2}$$

assume

$$g_{\vec{n}} = \frac{\sqrt{8\pi}}{M_{\rm Pl}}$$

in processes mediated by a virtual graviton one has to sum over all KK-modes

$$\sum_{\vec{n}} \frac{1}{p^2 - m_{\vec{n}}^2}$$

diverges for $\delta > 1$ $\rightarrow$ introduce cutoff by hand

$$|\vec{n}| < M_{\rm st} R$$

⇒ Neutrino-Nucleon cross section at high energies

$$\sigma_{\rm tot} \sim \xi \left(\frac{E}{10^{20}\ \text{eV}}\right)^2 \left(\frac{1\ \text{TeV}}{M_D}\right)^4\ \text{barn}$$

4-dim field theory result not valid for $E > M_D$

field theoretical unitarization:

$$\sigma_{\rm tot} \sim \frac{4\pi s}{M_D^4} \sim \left(\frac{E}{10^{20}\ \text{eV}}\right) \left(\frac{1\ \text{TeV}}{M_D}\right)^4\ \text{mbarn}$$

Right order of magnitude to explain the ultrahigh energy cosmic ray events!

However, low energy effective theory not valid for $E \sim 10^{20}$ eV
finite width of the branes becomes important

brane tension suppresses the couplings of higher KK modes

$$g_n = g\text{e}^{-c(n/R)^2/M_D^2}\ , \quad \text{where} \quad c = \frac{1}{2}\left(\frac{M_D}{f}\right)^4$$

Neutrino-Nucleon Scattering

mediated by graviton in the t-channel

Sum over all KK modes:

exponential suppresion of couplings of higher KK modes provides a dynamical cutoff

$$P(\hat{t}) = R^{-\delta} \sum_{\vec{n}} \frac{\exp\left(-c m_{\vec{n}}^2 / M_D^2\right)}{\hat{t} - m_{\vec{n}}^2}$$

$$= -\pi^{\delta/2} (-\hat{t})^{\delta/2-1} \exp\left(-\frac{c\hat{t}}{M_D^2}\right) \Gamma\left(1 - \frac{\delta}{2}, -\frac{c\hat{t}}{M_D^2}\right)$$

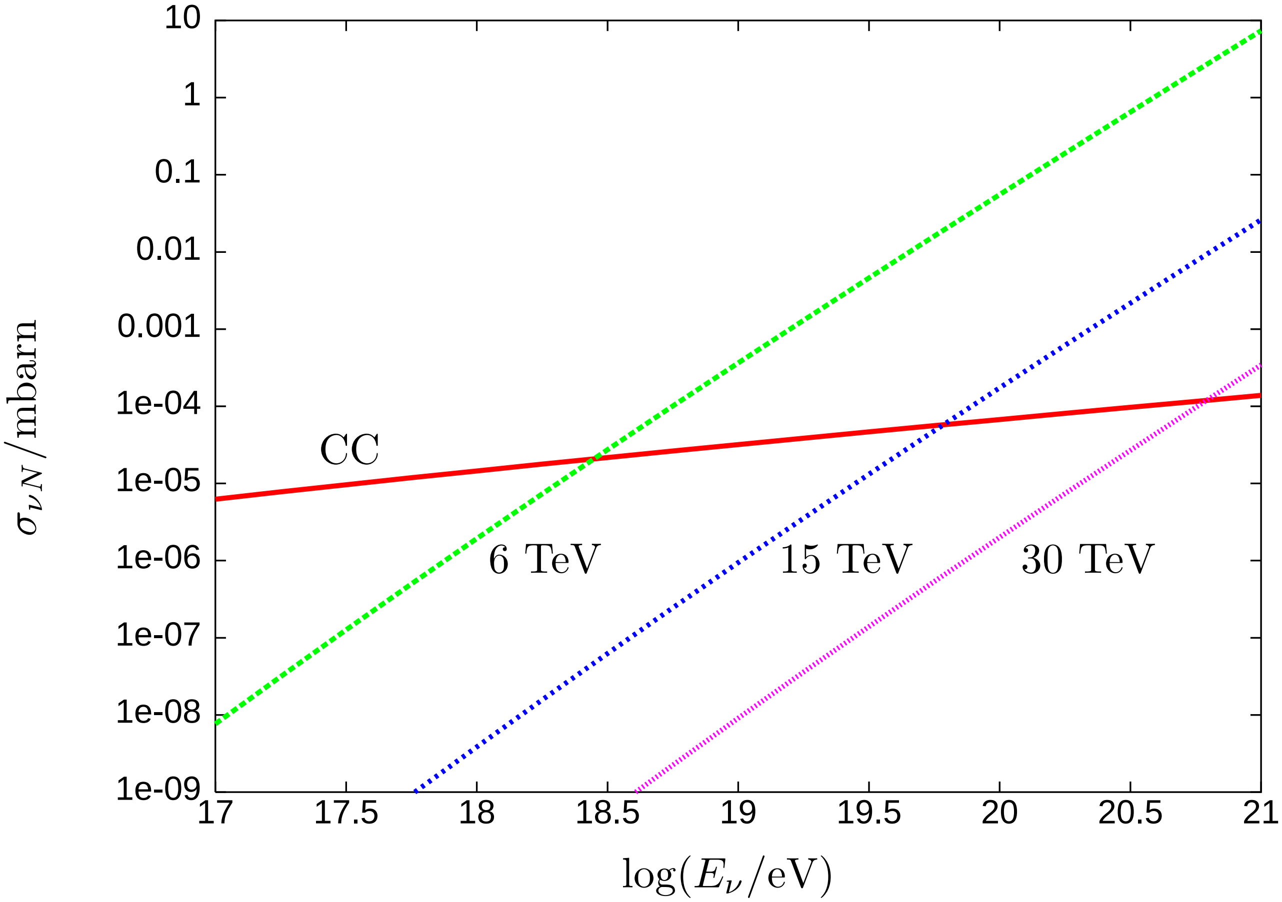
Cross-section in the low-energy limit, $s \ll M_D^2$
Neutrino-quark scattering:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x\mathrm{d}\hat{t}} = \frac{1}{512\pi\hat{s}^2} \frac{P^2(\hat{t})}{M_D^{4+2\delta}} \times \left[32\hat{s}^4 + 64\hat{s}^3\hat{t} + 42\hat{s}^2\hat{t}^2 + 10\hat{s}\hat{t}^3 + \hat{t}^4\right]$$

gluon-neutrino scattering

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x\mathrm{d}\hat{t}} = \frac{1}{32\pi\hat{s}^2} \frac{P^2(\hat{t})}{M_D^{4+2\delta}} \left[2\hat{s}^4 + 4\hat{s}^3\hat{t} + 3\hat{s}^2\hat{t}^2 + \hat{s}\hat{t}^3\right]$$

Total cross section:



$\Rightarrow$ $M_D \sim 1$ TeV needed for $\sigma_{N\nu}^{\mathrm{KK}} = 1 - 10$ mbarn

energy-loss in SN 1987a due to KK graviton production

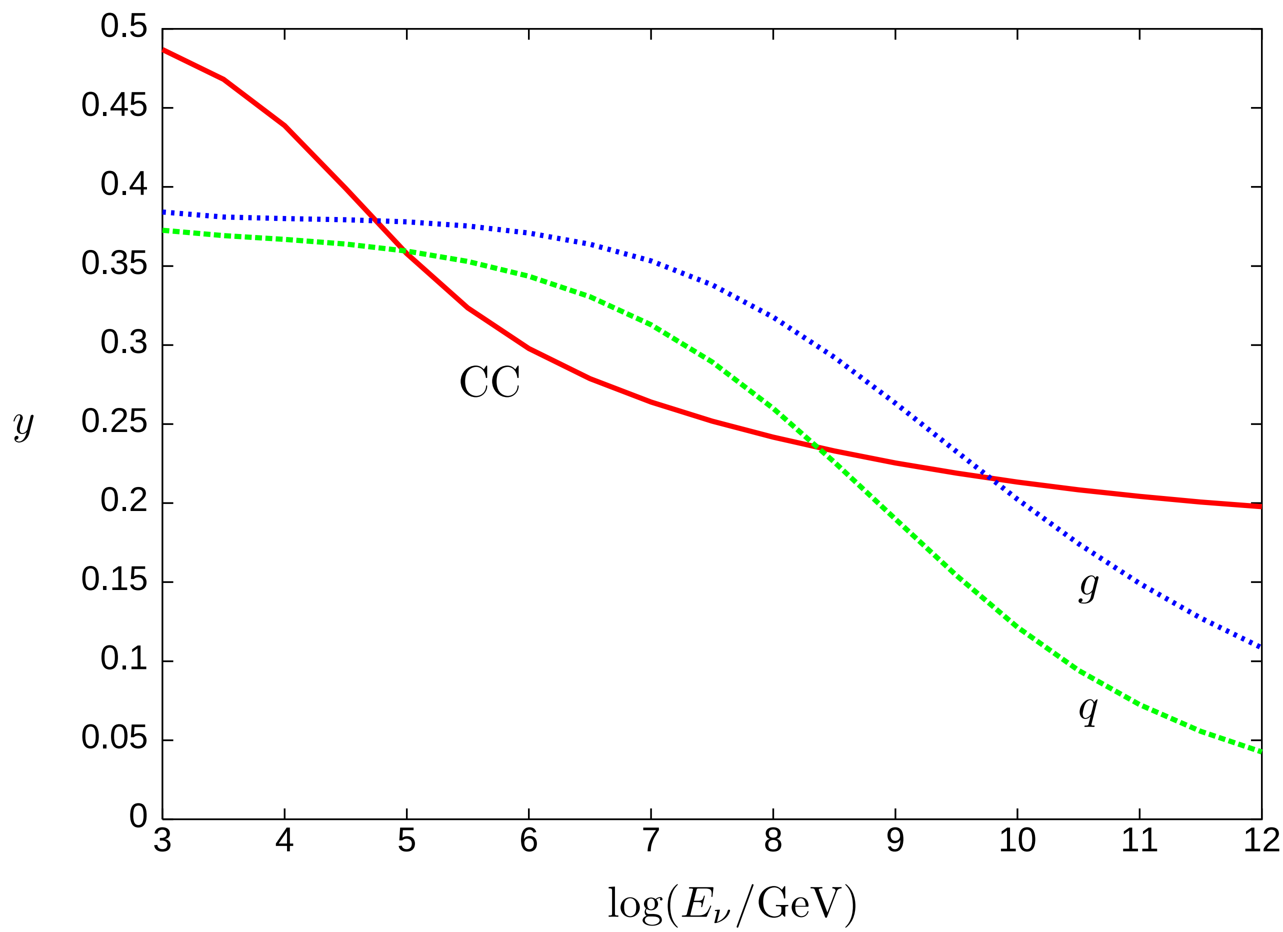
$$M_D \gtrsim 60 \text{ TeV}$$

Age of the universe $\gtrsim$12 Gyrs $\Rightarrow$ $M_D \gtrsim 10^3$ TeV

Energy transfer:

$$y = (E_\nu - E'_\nu)/E_\nu$$

nucleon-nucleon collisions: $y \approx 0.6$



$\Rightarrow$ neutrinos are deeply penetrating particles

Cross section in the high-energy limit $s \gg M_D^2$

1. eff. 4-dim. theory not valid for $s > M_D^2$

2. and $\sigma_{N\nu}^{\mathrm{KK}}$ violates unitarity

$\Rightarrow$ calculation of $\sigma_{N\nu}^{\mathrm{KK}}$ in string theory needed

Conservative upper bound:
Unitarize the cross section:

- Regge Amplitude

- eikonal method

fixes the energy dependence of the cross section:

$$\sigma_{\mathrm{tot}} \propto \ln^2(s/s_0)$$

choose constant as $\sigma_{N\nu}^{\mathrm{KK}}(s')$, where $s' \sim M_D$ is the scale where s-wave unitarity is violated

$$\sigma_{\mathrm{tot}}(s) = \sigma_{N\nu}^{\mathrm{KK}}(M_D^2) \ln^2 \left(s/M_D^2\right) \left(s/M_D^2\right)^{0.363}$$

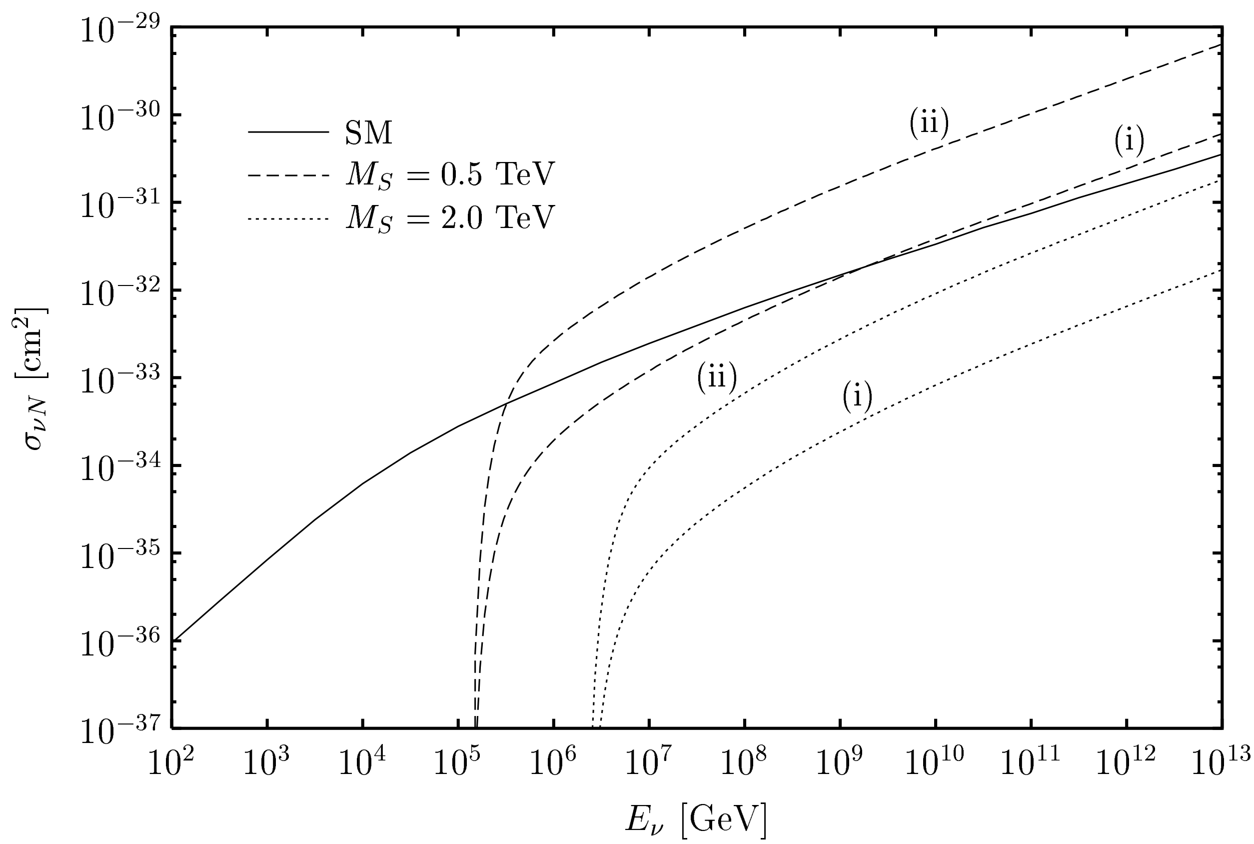
String theory calculation: (Cornet, Illana and Masip, hep-ph/0102065)

Type IIB orbifold
6 large extra dimensions
SM fields confined to N D3 branes
Veneziano Amplitude

$$\mathcal{S}(s,t) = \frac{\Gamma(1-\alpha' s)\Gamma(1-\alpha' t)}{\Gamma(1-\alpha' s-\alpha' t)}$$

gives a series of poles and zeroes
$\Rightarrow$ string amplitude can be approximated as a sum over s-channel resonances (leptoquarks)

Neutrino-Nucleon total cross section:



Conclusions

Neutrino-nucleon interactions via KK gravitons in models with large extra dimensions cannot explain the ultrahigh energy cosmic rays:

- suppression of KK couplings due to brane fluctuations
  $\Rightarrow \sigma_{N\nu}^{\mathrm{KK}}$ is small

- energy transfer per interaction is small
  neutrinos are deeply penetrating particles

$\Rightarrow$ showers initiated by protons and neutrinos are clearly distinguishable

Outlook:
neutrino induced horizontal air showers may give interesting bounds on the string scale