Effects of Large extra dimensions on a cosmogenic neutrino flux

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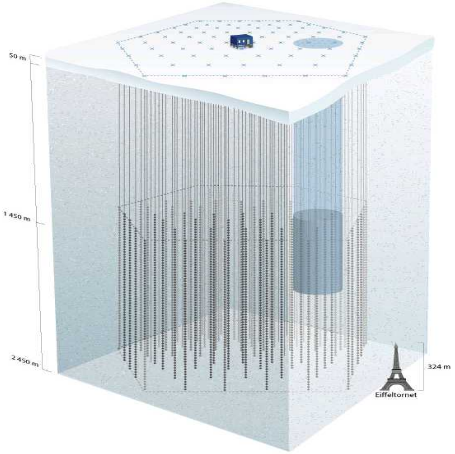
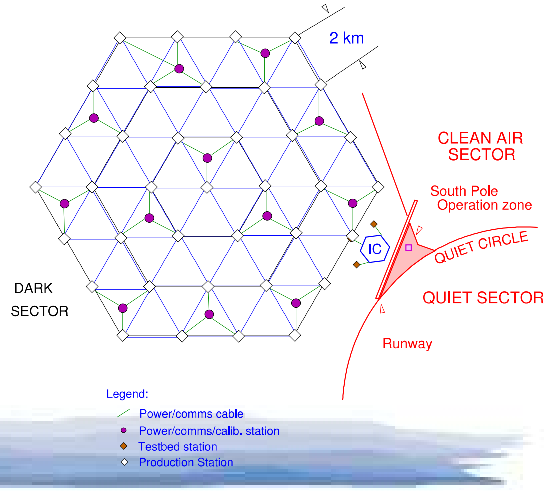
Exotic Physics on Neutrino Telescope, Marseille, 2013

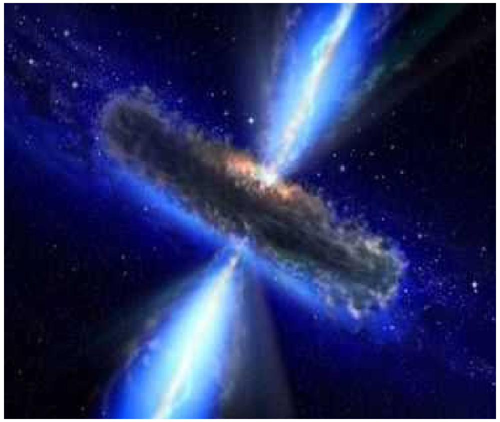
Content

- Motivation
- Neutrino-nucleon interactions in LED
- Cosmogenic neutrino flux through the Earth and downgoing
- Event rates estimation
- Final comments



Askaryan Radio Array ARA–37

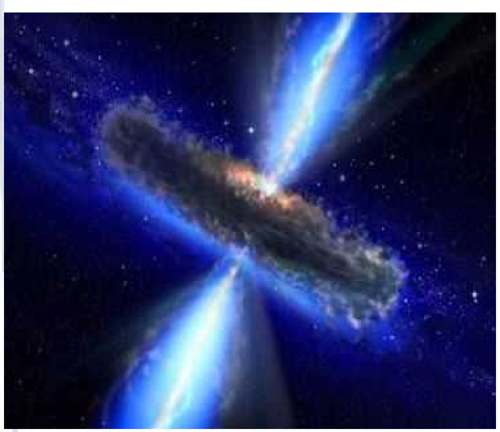




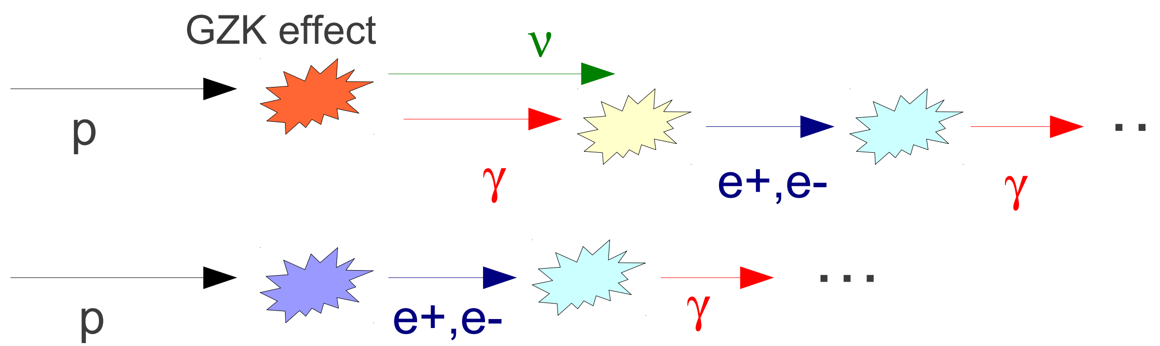
Motivation

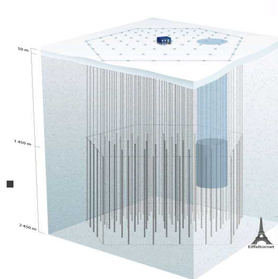
- Effects of exotic physics on UHE neutrino interactions can affect what we observe or leave an observable signature.
- In particular, Large Extra Dimensions (LED) theories (e.g. Illana, Masip & Melloni 2006, Hussain & McKay 2005, Anchordoqui et al. 2007).
- The comsmogenic neutrinos, produced by interactions of cosmic ray protons with the CMB, can serve to explore these exotic effects.

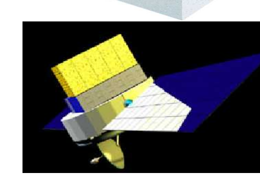
"p + background photon → pions → neutrinos + gamma rays"



Greisen (1966), Zatsepin & Kuzmin (1966)

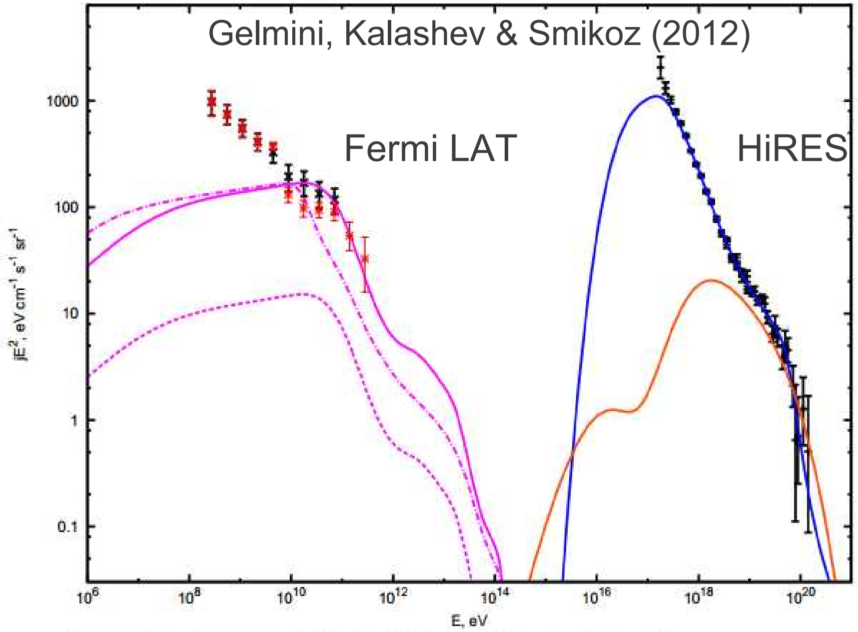


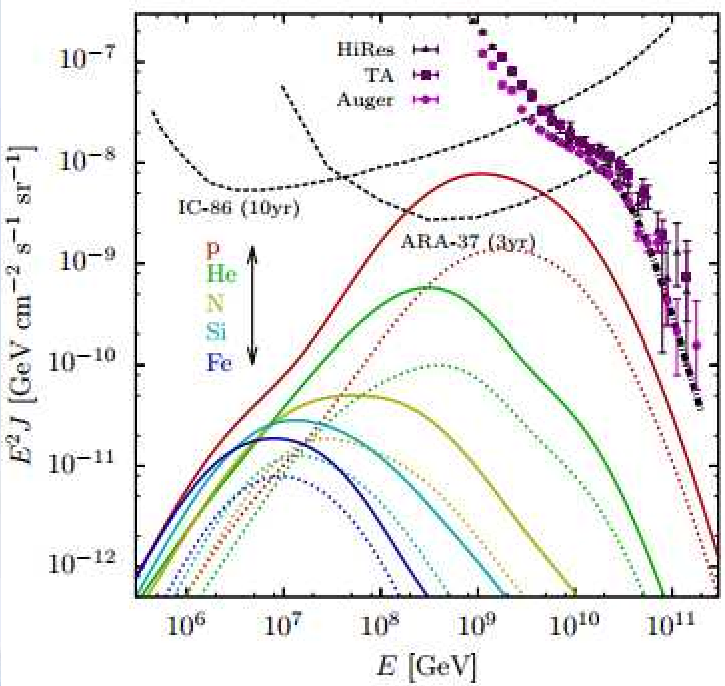


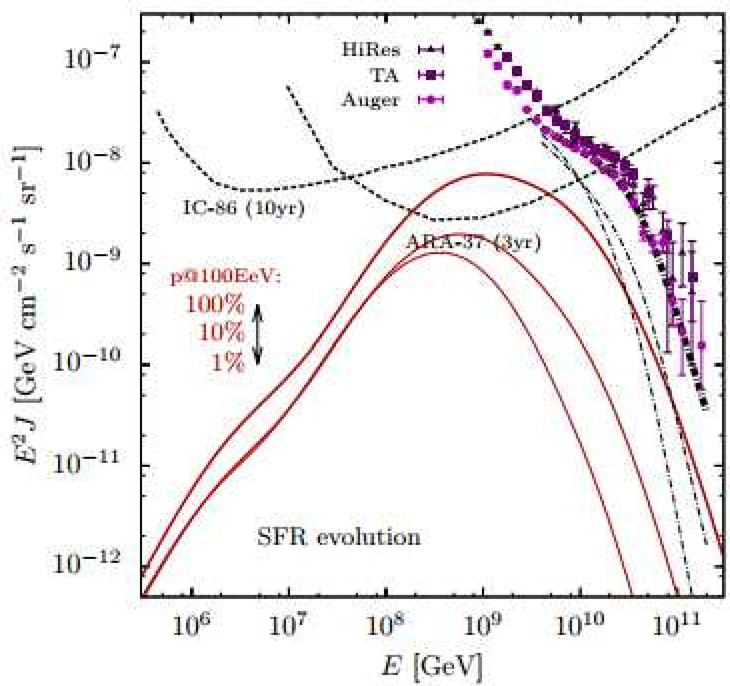


Cosmogenic neutrino flux predictions

- Depend on Cosmic-ray chemical composition
- CR spectrum, Emin, Emax
- Redshift distribution of CR sources
- Photon background



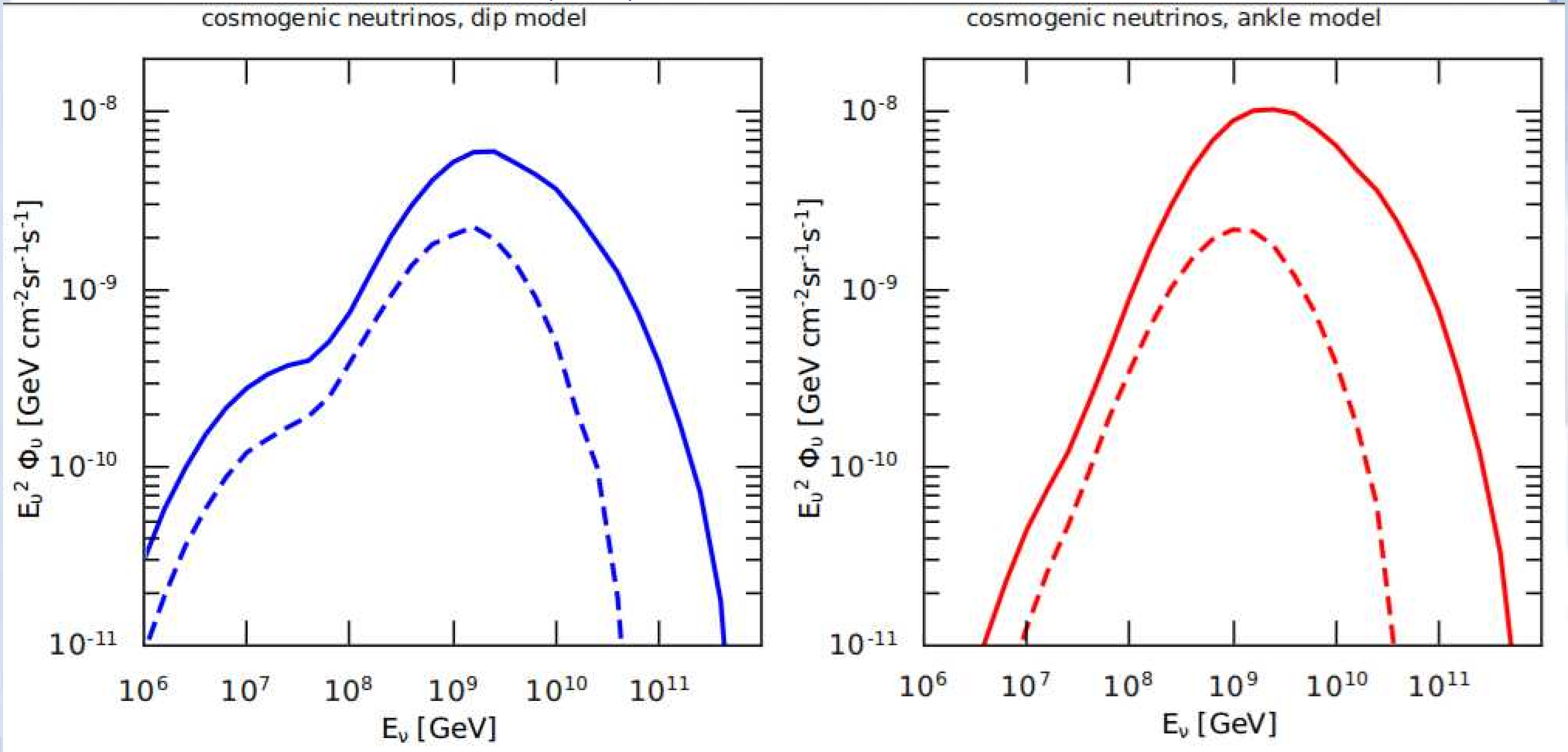




Alhers & Halzen (2012)

Cosmogenic neutrino flux predictions

From Gelmini, Kalashevb & Smikoz (2012)



"dip model": $E_{p\,min} = 10^{10}$GeV

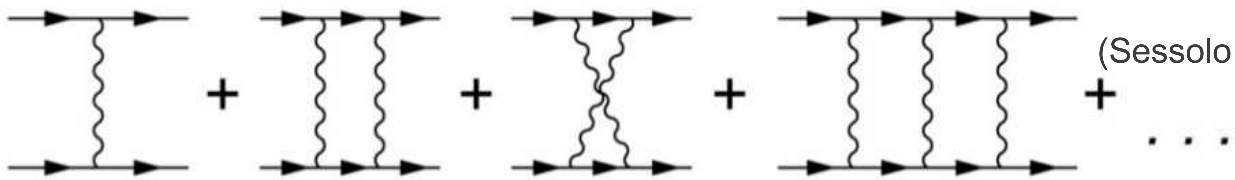
"ankle model": $E_{p\,min} = 10^{11}$GeV

Why Large Extra Dimensions (LED)?

- SM localized in a 3-brane embedded in a D=(4+n) space time. Only Gravity can propagate in the extra n dimensions (Arkani-Hamed, Dimopulos, Dvali, 1998).
- Solve the hierachy problem, bringing the gravity fundamental scale, M_D , to the order of TeVs, close to the electroweak scale.
- Fenomenology includes processes with exchange of virtual Kaluza Klein gravitons, and the production of micro black holes

Neutrino-nucleon interactions in large extra dimensions

Graviton exchange



(Sessolo & McKay 2008)

Eikonal scattering amplitude (e.g. Giudice et al. 1998, Emparan et al. 2002, Illana et al. 2005)

$\sqrt{\hat{s}} \gg M_D$

$$\frac{d\sigma_{\rm KK}}{dy}(s) = \int_0^1 \frac{dx}{16\pi x s} \sum_i f_i(x, \bar{q}) \left|\mathcal{M}(x, y, \sqrt{s}/M_D)\right|^2$$

$$i\mathcal{M} = 4\pi\, s\, b_{\rm c}^2 \int_0^\infty dx' x' J(x' q\, c\, b_{\rm c}) \left(e^{ix^{-n}} - 1\right)$$

Micro black hole production (e.g. Thorne 1994, Emparan et al. 2002, Anchordoqui et al. 2007)

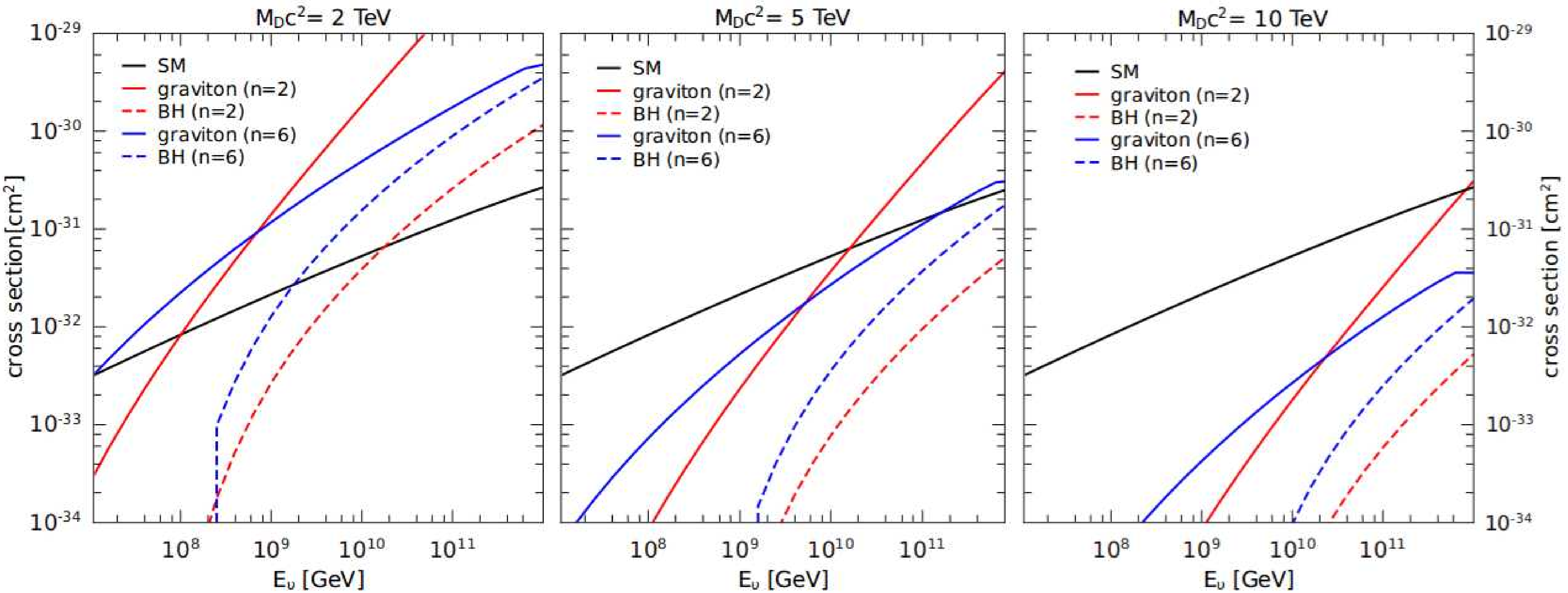
$$\sigma_{\nu N \to BH}(E_\nu) = \int_0^1 2z dz \int_{x_{min}}^1 dx \hat{\sigma}_{BH}(xs) \sum_i f_i(x, Q)$$

$$\hat{\sigma}_{\rm BH}(\hat{s}) = F\,\pi\, R_{\rm Sch}^2(\hat{s})$$

$$R_{\rm Sch}(\hat{s}) = \frac{\hbar}{c\, M_D} \left(\frac{M(\hat{s})}{M_D}\right)^{\frac{1}{n+1}} \left[\frac{2^n \pi^{\frac{n-3}{2}} \Gamma\left(\frac{n+3}{2}\right)}{n+2}\right]^{\frac{1}{n+1}}$$

Neutrino-nucleon interactions in large extra dimensions

Cross section contributions:



Evolution of neutrino flux through the Earth

$$\Phi_\nu \equiv \frac{d\mathcal{N}_\nu}{dE_\nu\, d\Omega\, dA\, dt}$$

$$\frac{d\Phi_\nu(E_\nu, X)}{dX} = -\frac{\Phi_\nu(E_\nu, X)}{\lambda_\nu(E_\nu, X)} + S_{\mathrm{BH}\to\nu}(E_\nu, X)$$
$$+ \int_0^1 \frac{dy}{1-y}\left[\frac{d\sigma_{\mathrm{NC}}(E_\nu, y)}{dy} + \frac{d\sigma_{\mathrm{KK}}(E_\nu, y)}{dy}\right]\frac{\Phi_\nu(E_y, X)}{\sigma_{\mathrm{tot}}(E_y)\lambda_\nu(E_\nu)}$$

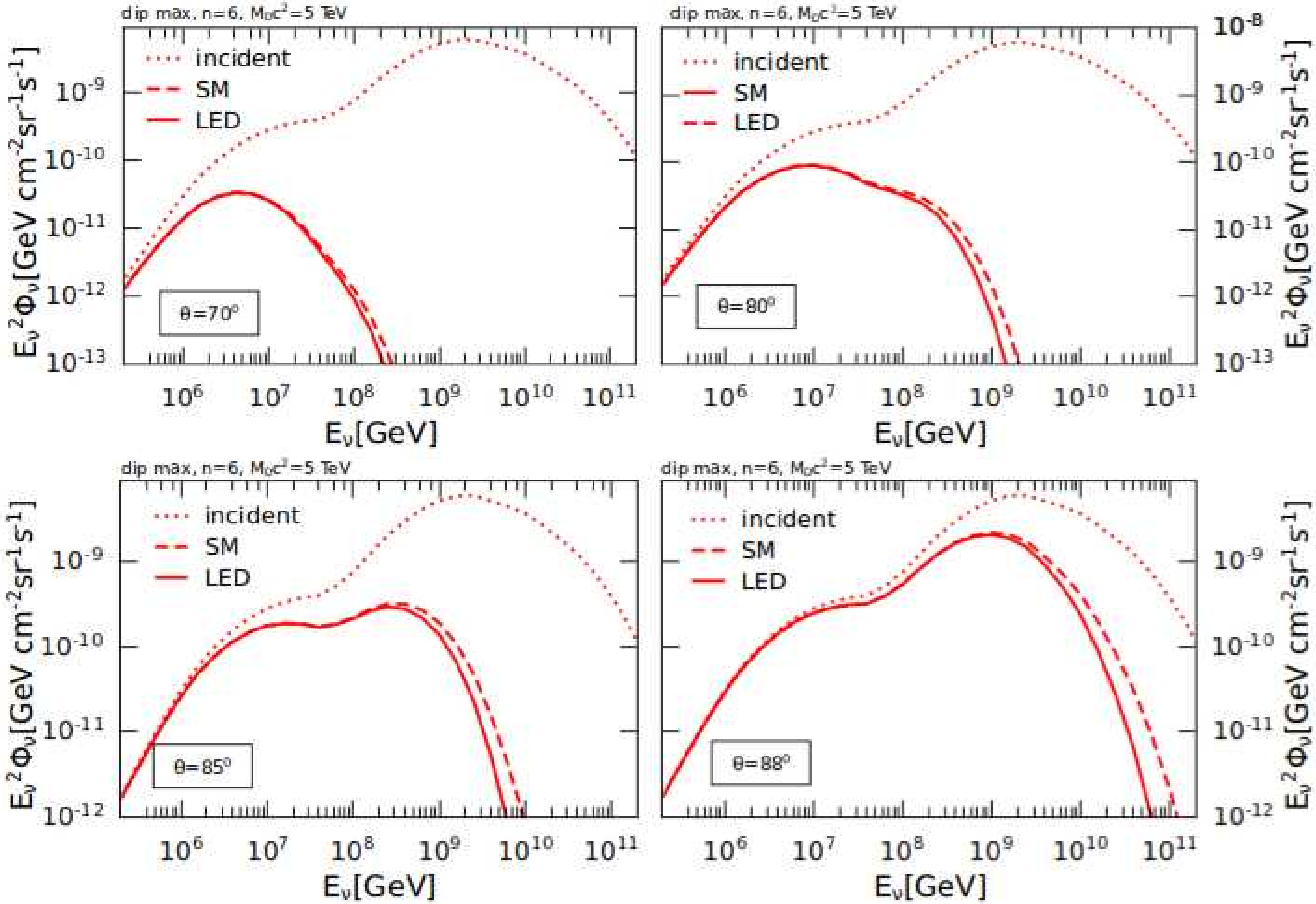
Naumov & Perrone (1999)

$$X(E_\nu, \theta) = \int_0^{2R_\otimes \cos\theta} dl\, \rho_\otimes(r(l)) + \int_{l_{\mathrm{atm}}} dl\, \rho_{\mathrm{atm}}$$

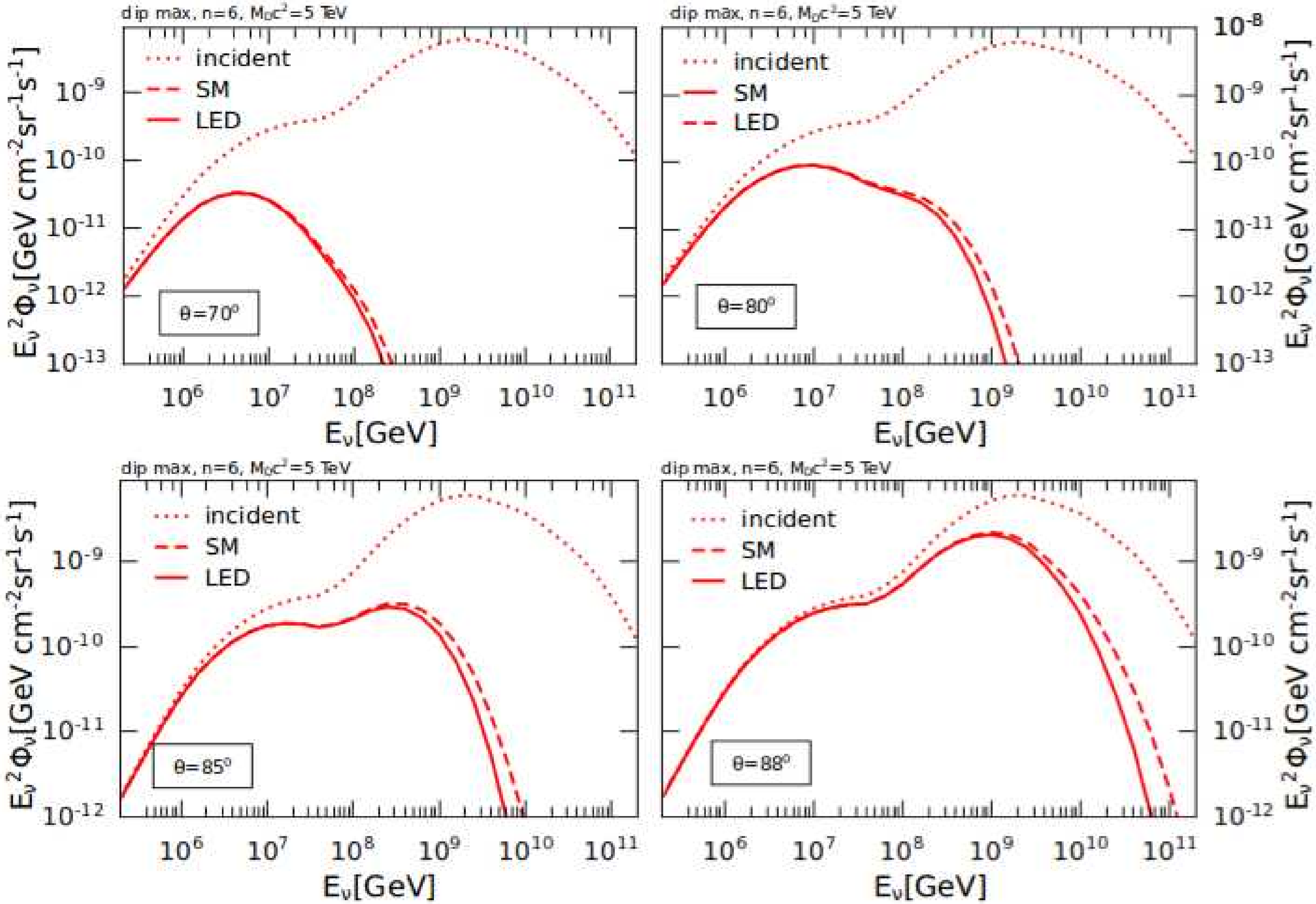
$$\sigma_{\mathrm{tot}}(E_\nu) = \sigma_{\mathrm{CC}}(E_\nu) + \sigma_{\mathrm{NC}}(E_\nu) + \sigma_{\mathrm{BH}}(E_\nu) + \sigma_{\mathrm{KK}}(E_\nu)$$

Surviving cosmogenic flux

dip model

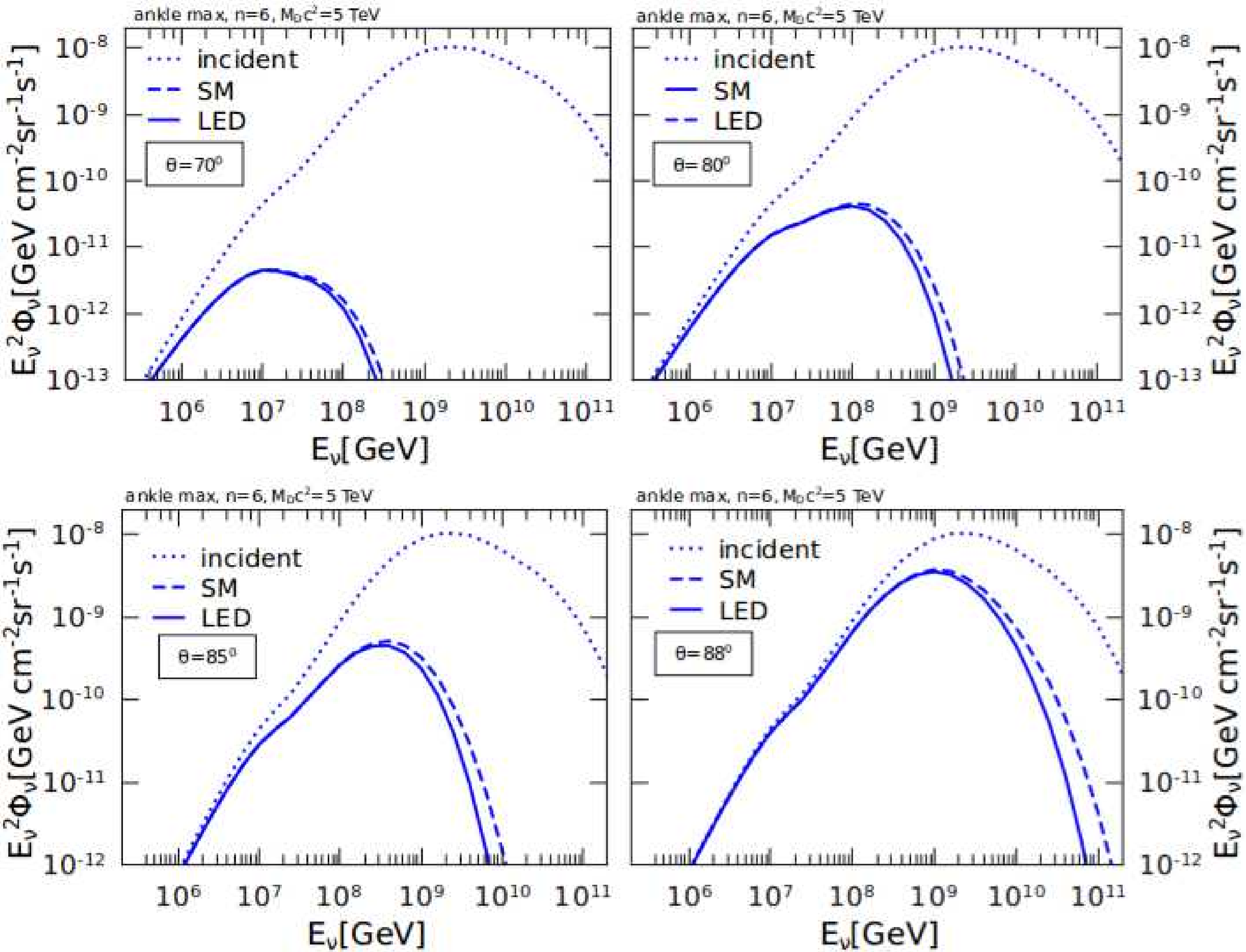


Surviving cosmogenic flux
dip model



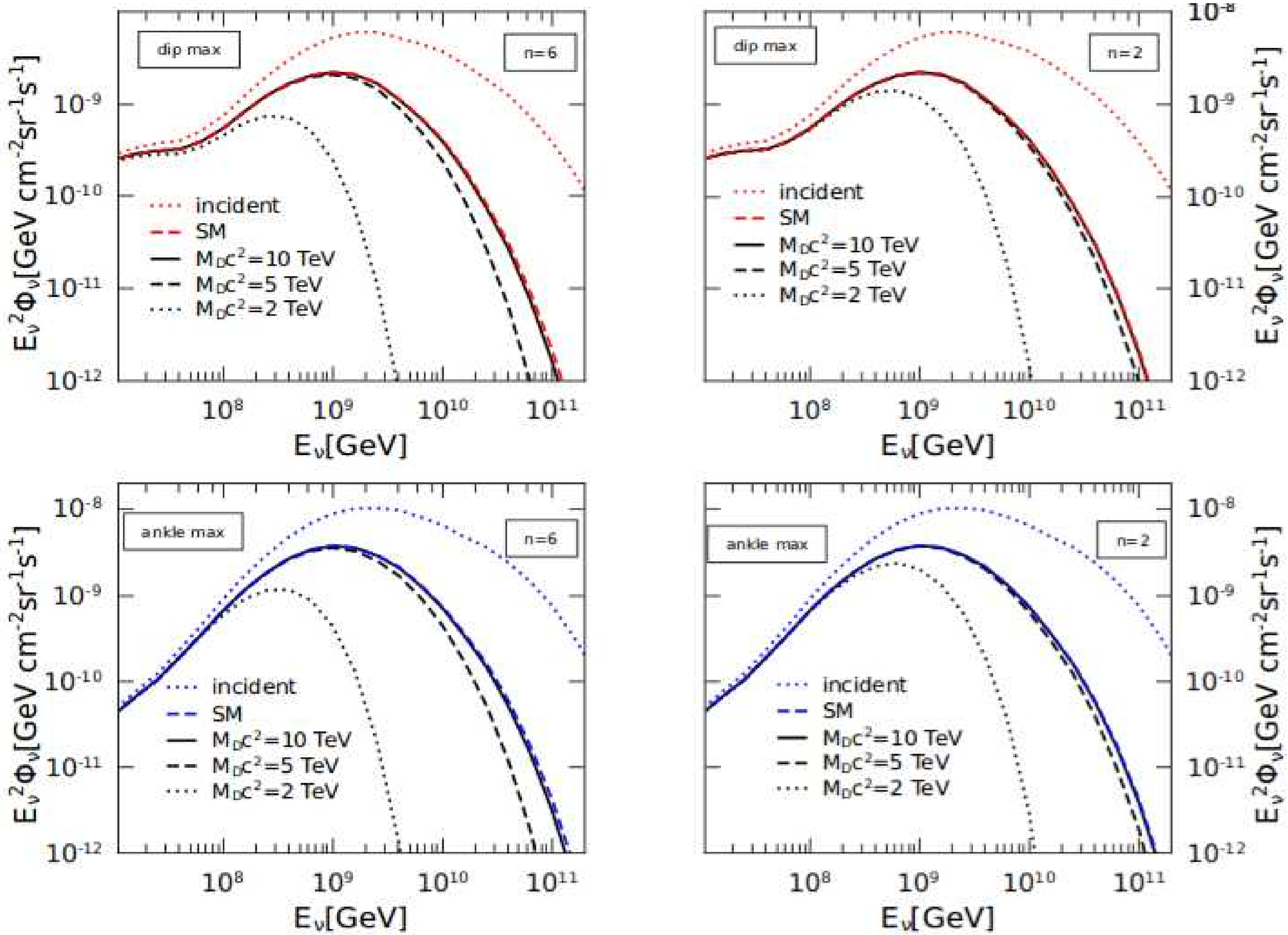
Surviving cosmogenic flux

ankle model

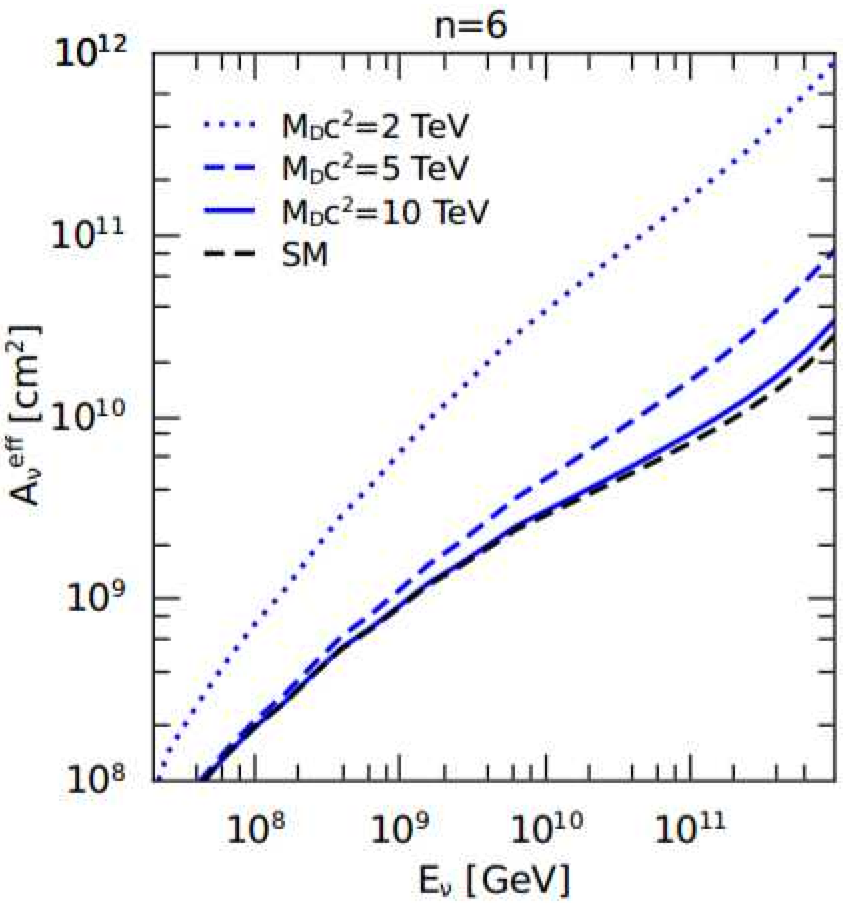


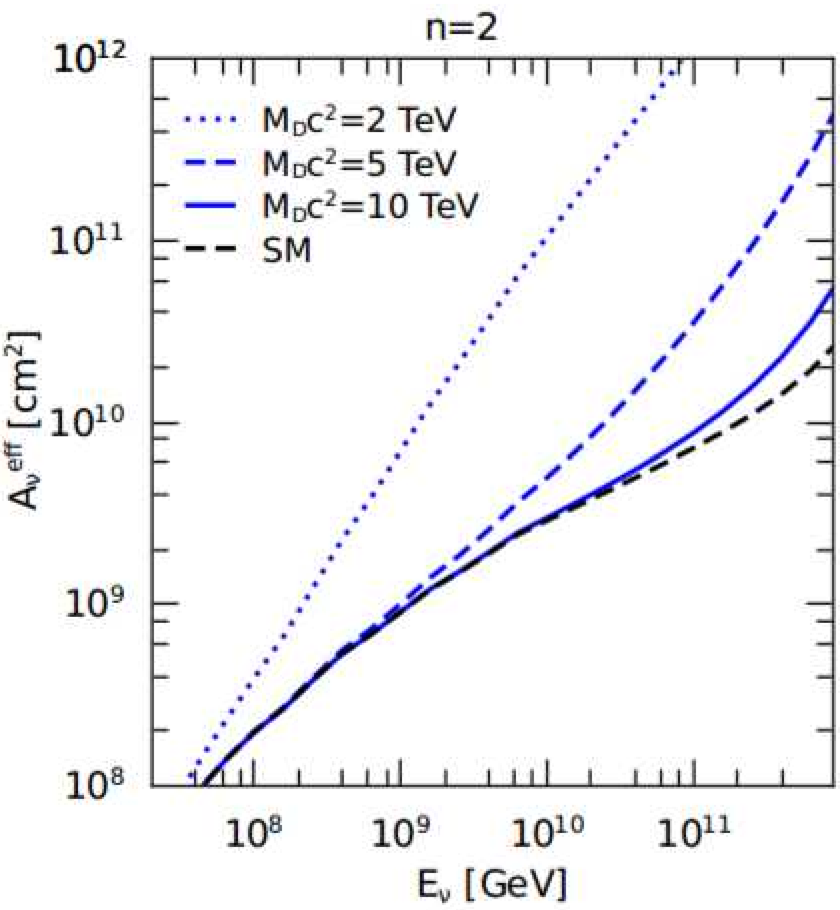
Surviving cosmogenic fluxes

n=2 and n=6, θ=88°



Neutrino effective areas





Estimation of number of shower events

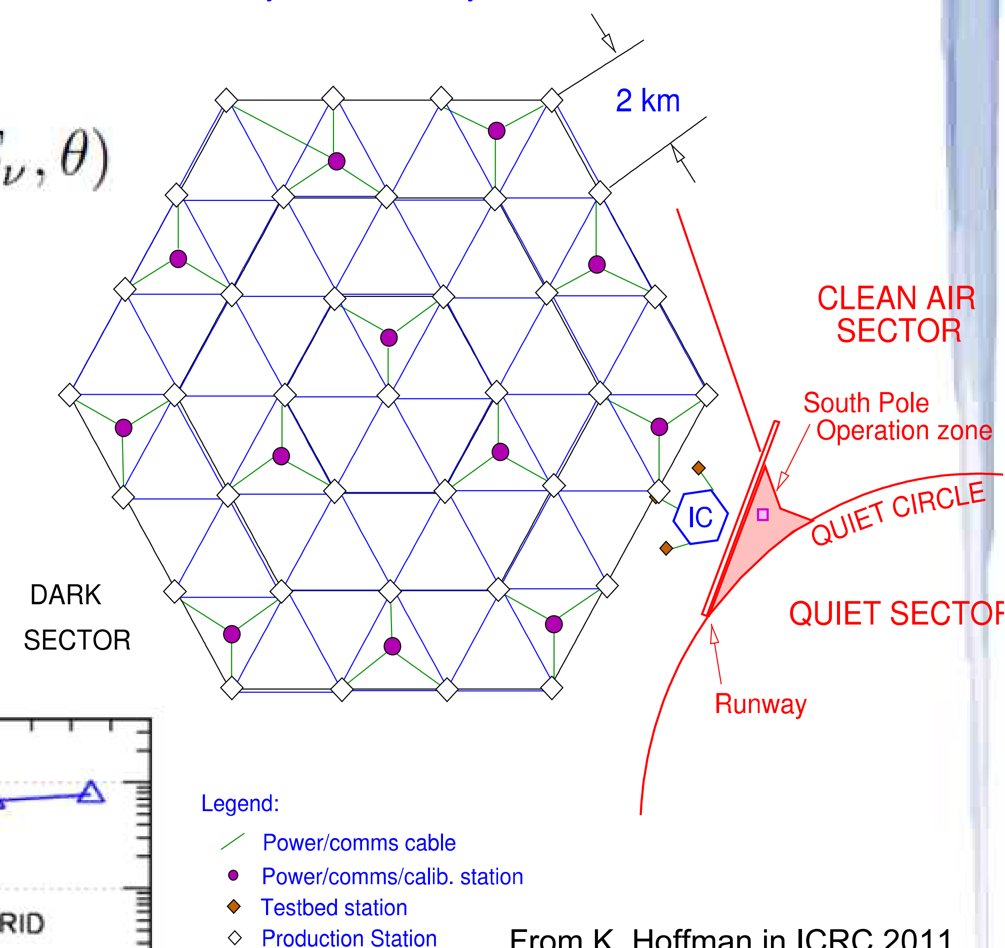
$$\frac{dN_{\rm sh}(\theta)}{d\Omega\, dt} \simeq 3 \int_{E_{\rm min}} dE_\nu \Phi_\nu(E_\nu,\theta)\, A_\nu^{\rm eff}(E_\nu,\theta)$$

$$V_\nu^{\rm eff}(E_\nu)\Omega = \bar{A}_\nu^{\rm eff}\ \Omega\, N_{\rm Av}\rho_{\rm ice}\sigma_{\rm tot}(E_\nu)$$

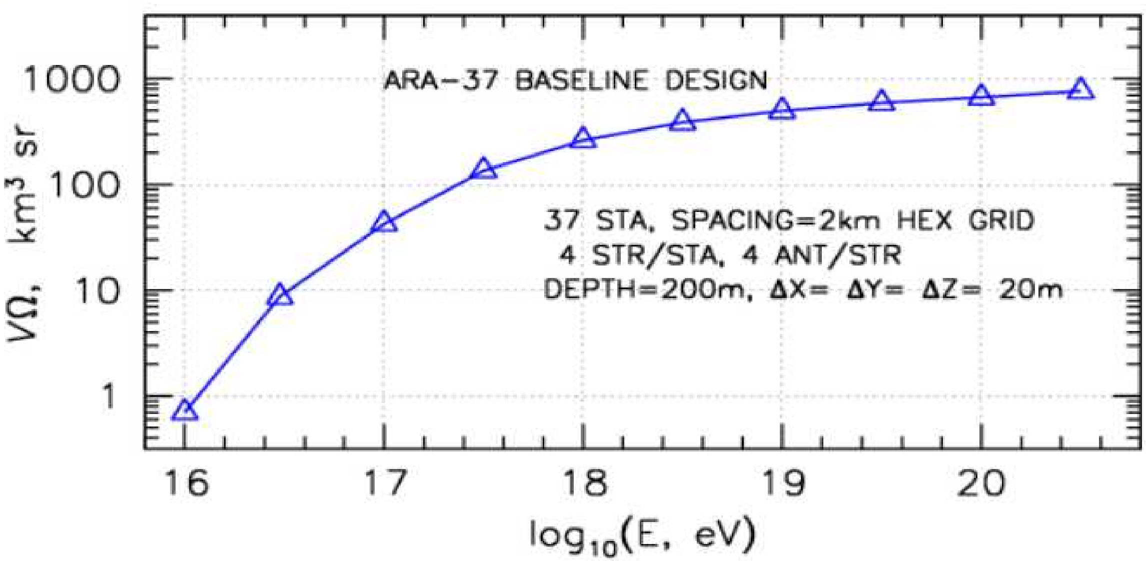
$$A_\nu^{\rm eff}(E_\nu,\theta) = A_{\rm proj}(\theta) P_{\rm sh}(E_\nu,\theta)$$

$$P_{\rm sh}(E_\nu,\theta) = L_{\rm det}(\theta)\, N_{\rm Av}\rho_{\rm ice}\sigma_{\rm tot}(E_\nu)$$

Hussain et al,. PRL (2006)



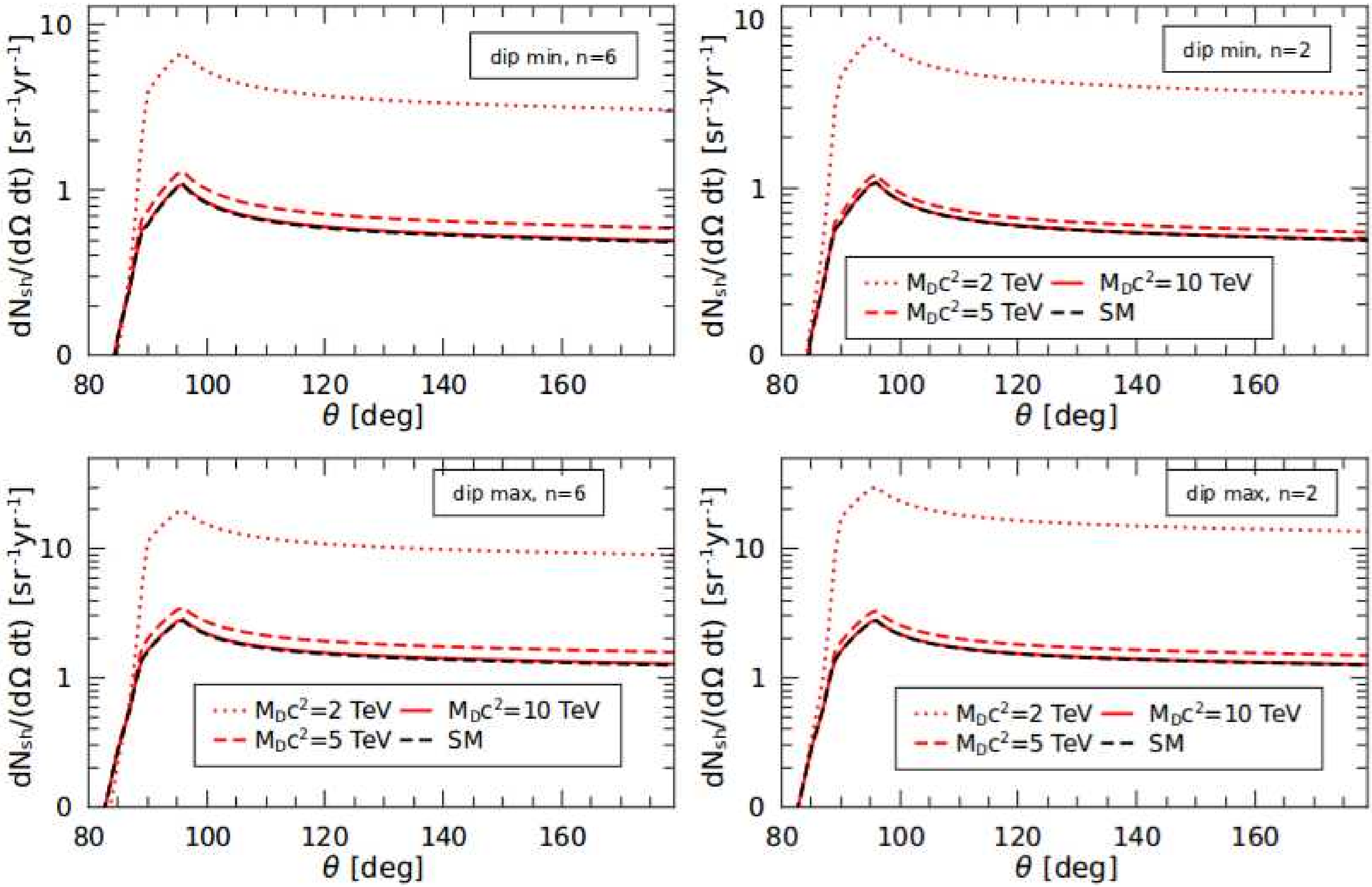
From K. Hoffman in ICRC 2011



P. Allison, et al. ARA Collab. (2012) Astropart Phys.,arXiv:1105.2854v2

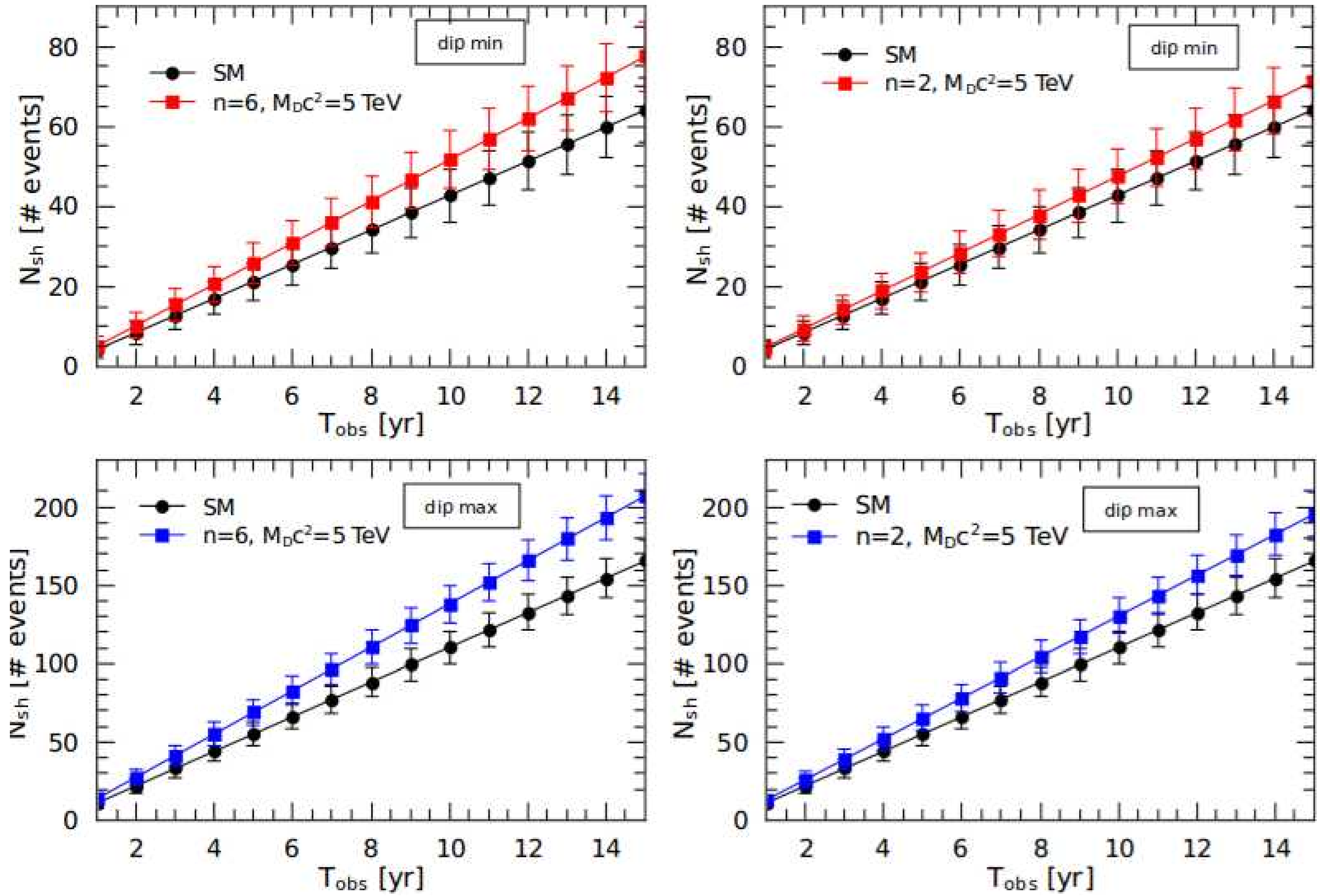
Number of shower events

for ARA at different angles



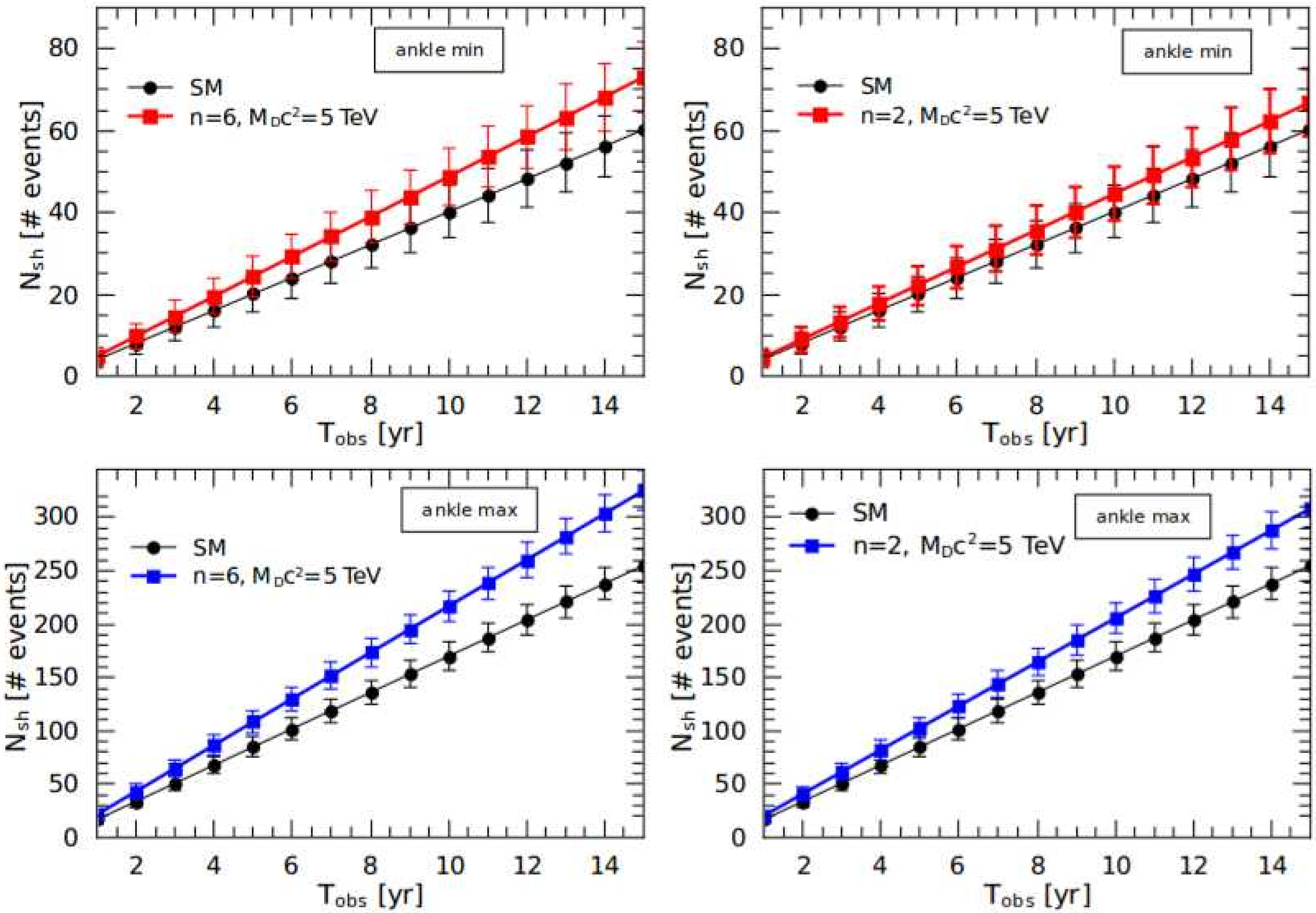
Number of shower events

vs observation time - dip model



Number of shower events

vs observation time - ankle model



Improved estimation of event number

- Event rate due to KK exchange

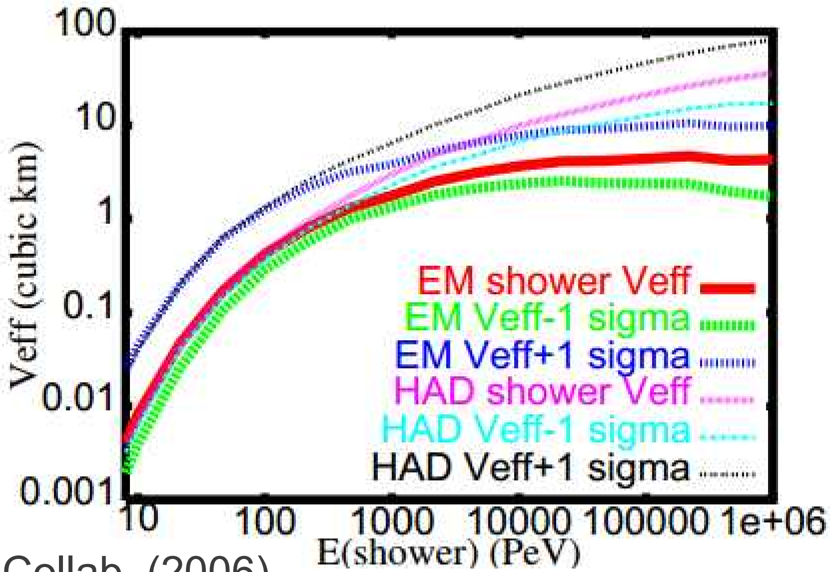
$$\frac{dN_{\rm sh}^{\rm Eik}}{dt} = 2\pi\,\rho_{\rm ice} N_{\rm Av} \int_{E_{\rm th}}^{E_\nu^{\rm max}} dE_\nu \Phi_\nu(E_\nu) \int_{E_{\rm th}/E_\nu}^{1} dy V_{\rm eff}(yE_\nu) \int_{\frac{M_D c^2}{s}}^{1} dx \frac{d\sigma_{\rm KK}}{dx dy}$$

- Event rate due to BH production

Hussain & McKay (2006)

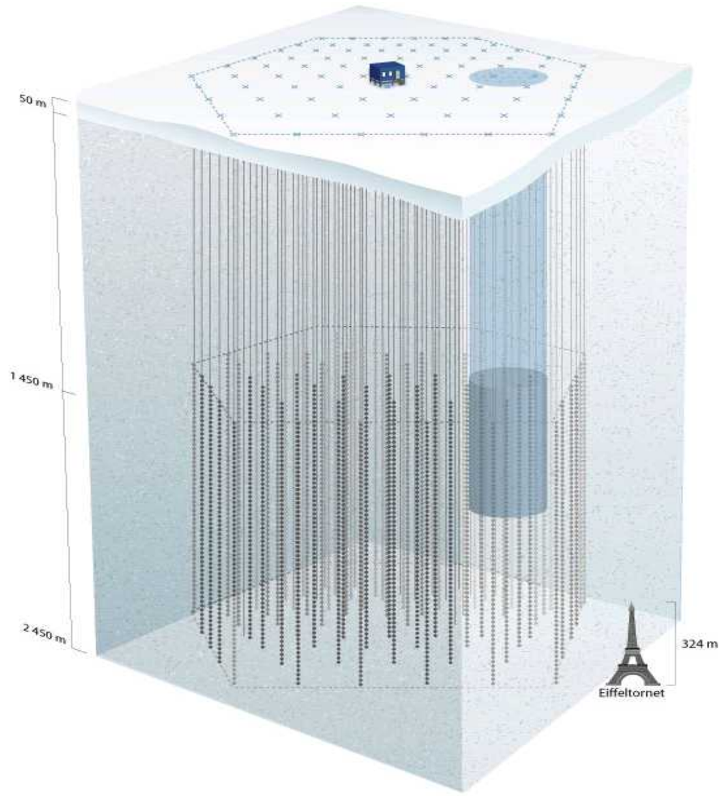
$$\frac{dN_{\rm sh}^{\rm BH}}{dt} = 2\pi\rho_{\rm ice} N_{\rm Av} \int_{E_{\rm min}} \Phi_\nu(E_\nu) V_{\rm eff}(E_\nu)\sigma_{\rm BH}(E_\nu)$$

Effective volume for hadronic showers in ARA: RICE result times 100



Kravchenko et al. RICE Collab. (2006)

Event rate estimation for IceCube



Contained events

$$\frac{dN_{\rm sh}^{\rm BH}}{dt} = 2\pi\, \rho_{\rm ice} N_{\rm Av} V_{\rm IceCube} \int_{E_{\rm min}} dE_\nu \Phi_\nu(E_\nu)\sigma_{\rm BH}(E_\nu)$$

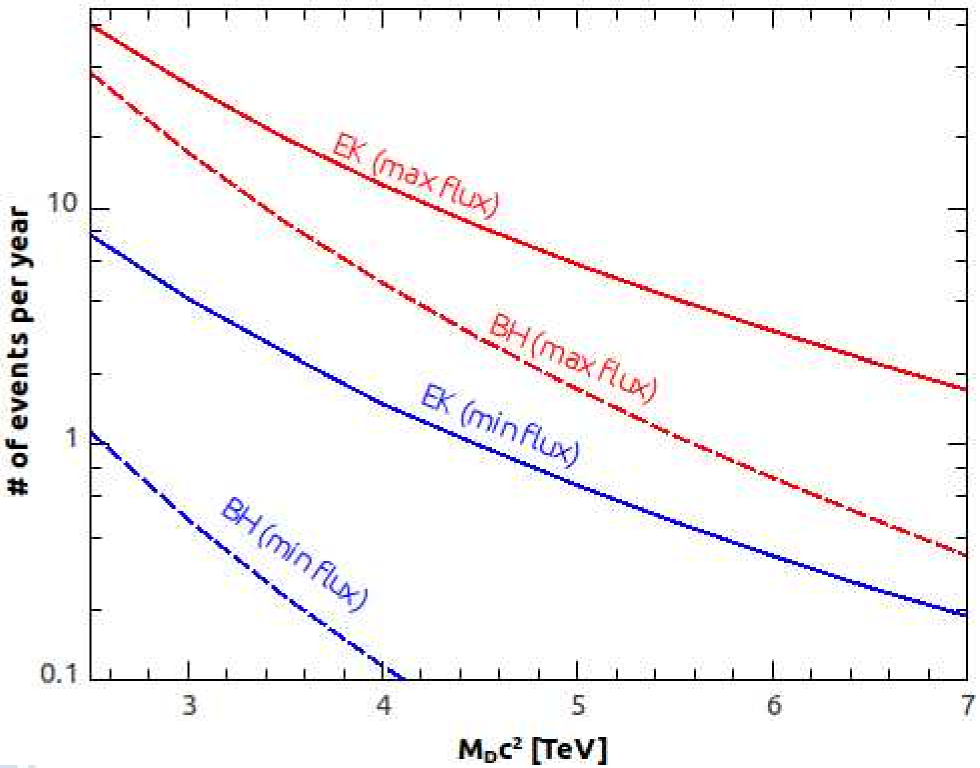
$$\frac{dN_{\rm sh}^{\rm EK}}{dt} = 2\pi\, \rho_{\rm ice} N_{\rm Av} V_{\rm IceCube} \int_{E_{\rm min}} dE_\nu \Phi_\nu(E_\nu)\sigma_{\rm KK}(E_\nu)$$

Illana et al. (2005)
Anchordoqui et al. (2007)

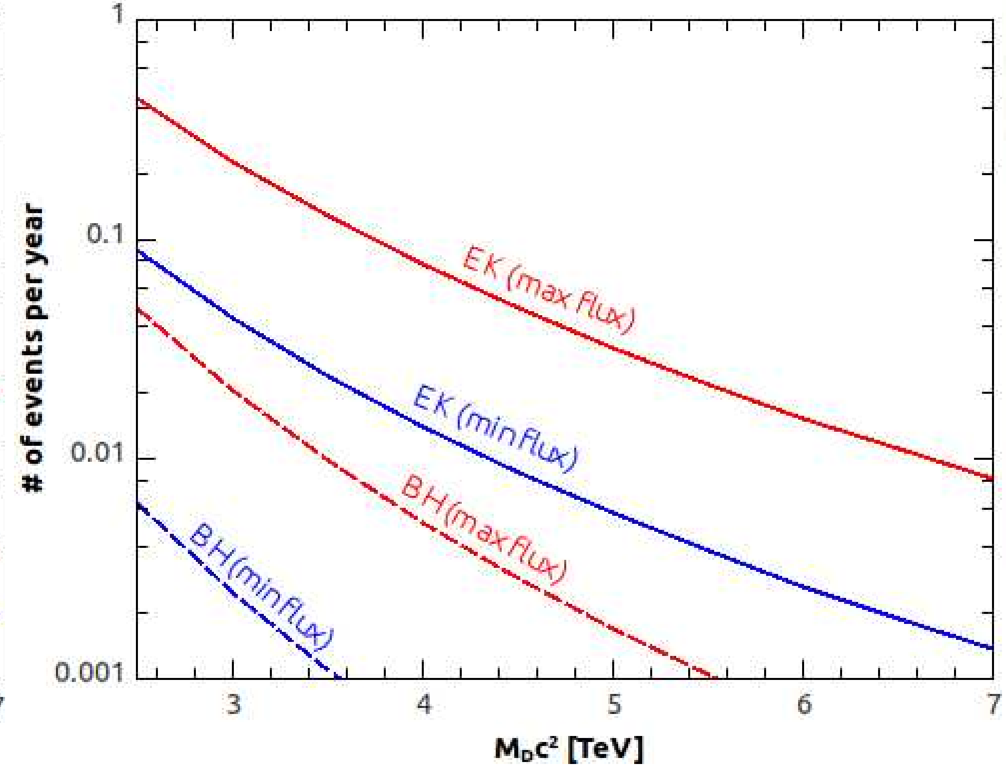
Improved estimation of event rates

for n=6

In ARA



In IceCube



Final words

- We analyzed the effects of Large Extra Dimensions on the detection of cosmogenic neutrino fluxes at levels compatible with gamma-ray constraints from Fermi-LAT.
- For M_D values not excluded by LHC, less than 10 events per year are estimated for a Radio Chrerenkov neutrino detector like ARA, including both micro black hole and elastic graviton exchange events.
- A cosmic ray compostition domitated by heavy nucleons will lower this prediction. Hence large extra dimension could remain unseen by neutrino telescopes.

Thank you!

Previous results...

Black Holes at the IceCube Neutrino Telescope

Luis A. Anchordoqui, Matthew M. Glenz, and Leonard Parker
Department of Physics, University of Wisconsin-Milwaukee, P.O. Box 413, Milwaukee, WI 53201, USA
(Dated: October 2006)

TABLE II: Expected number of BH events for $M_{10} = 1$ TeV and different values of the infrared cutoff. We have taken an integration time of 15 yr corresponding to the lifetime of the experiment and used the new (old) values of F and y. The event rates roughly scale $\propto M_{10}^{-16/7}$.

$x_{\min}$	$\mathcal{N}_{\rm BH}$ [WB]		$\mathcal{N}_{\rm BH}$ [AARGHW]	
3	43	(19)	69	(30)
4	34	(15)	43	(19)
5	27	(12)	28	(12)
6	22	(9)	20	(9)

TeV gravity at neutrino telescopes

J. I. Illana,[1,*] M. Masip,[1,†] and D. Meloni[2,‡]
[1] *CAFPE and Depto. de Física Teórica y del Cosmos, Universidad de Granada, 18071 Granada, Spain*
[2] *INFN and Dipto. di Fisica, Università degli Studi di Roma "La Sapienza", 00185 Rome, Italy*

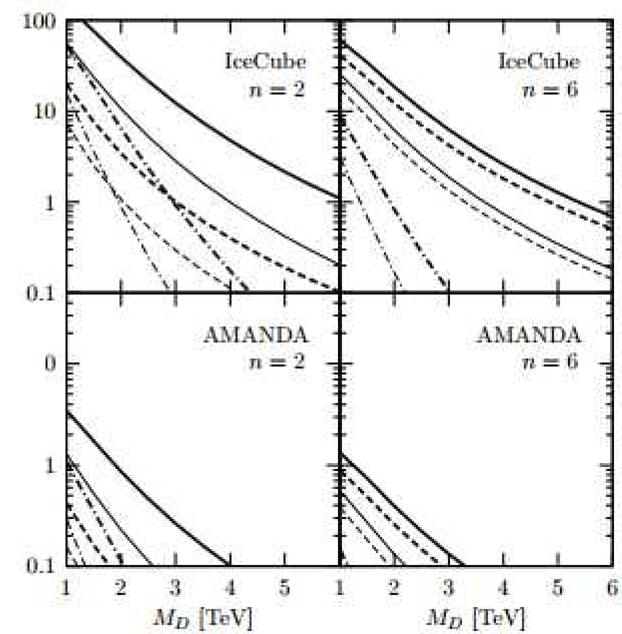


FIG. 7: Contained events per year in IceCube and AMANDA for the *higher* (thick) and the *lower* (thin) cosmogenic fluxes and $n = 2, 6$. We show eikonal (solid), multi-bang (dashed-dotted) and BH (dashed) events.

Neutrinos

- Proposed by Pauli in 1930

  to reconcile energy conservation with experiments

- First detected in 1956

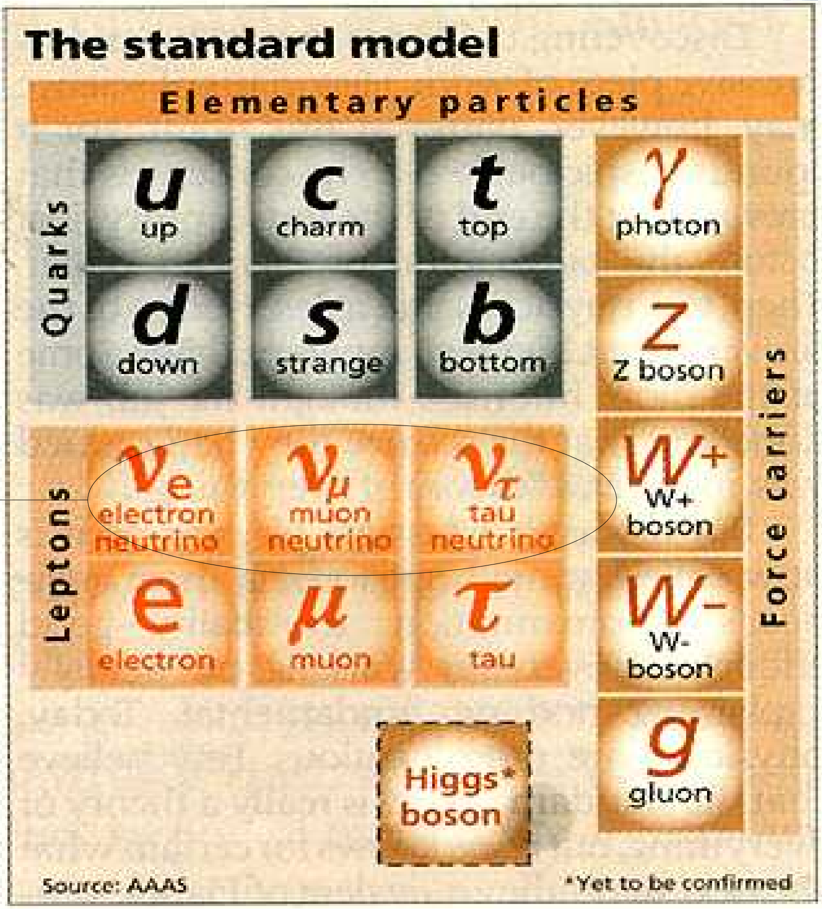
  electron antineutrinos from reactor

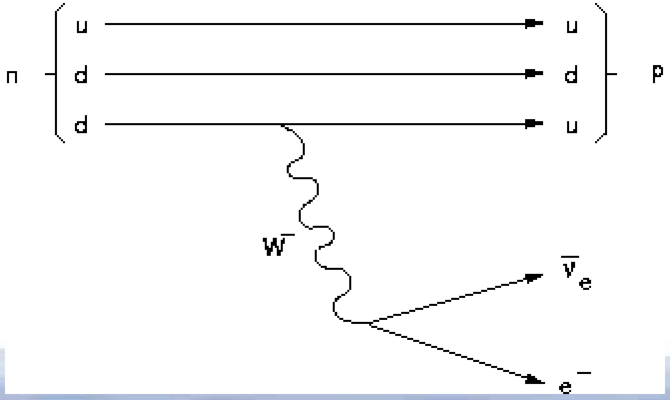
- Come in 3 flavors

  electron, muon, and tau

- Only weakly interacting

  low cross section, can pass easily pass through matter





Neutrino production channels

- Photo-hadronic interactions:

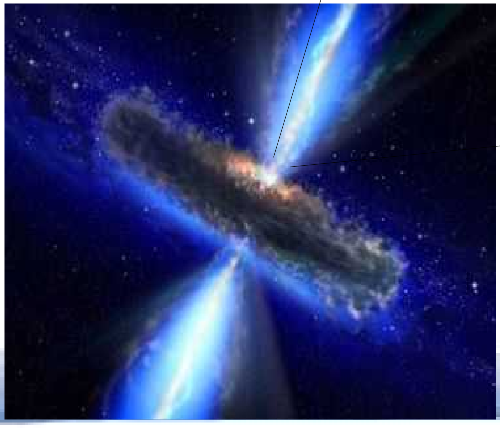
$$p + \gamma \longrightarrow \Delta^+ \longrightarrow p + \pi^0$$
$$p + \gamma \longrightarrow \Delta^+ \longrightarrow n + \pi^+$$
$$p + \gamma \longrightarrow p + \pi^+ + \pi^-$$
$$p + \gamma \longrightarrow p + \pi^+ + a\pi^0 + b(\pi^+ + \pi^-) \qquad a, b = 0, 1, 2...$$

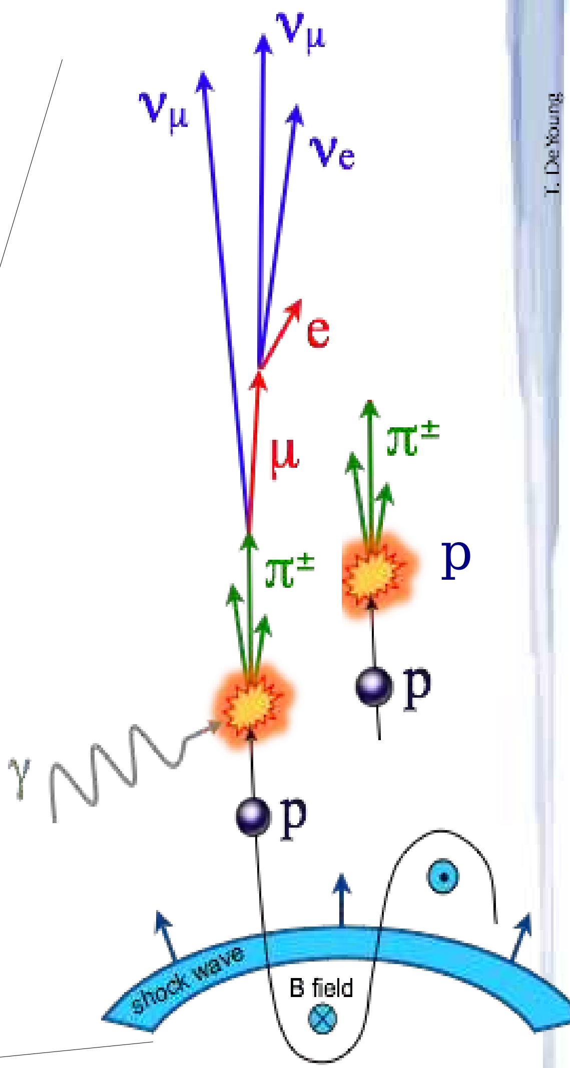
- Hadronic interactions:

$$p + p \longrightarrow p + p + a\pi^0 + b(\pi^+ + \pi^-)$$
$$p + p \longrightarrow p + n + \pi^+ + a\pi^0 + b(\pi^+ + \pi^-)$$
$$p + p \longrightarrow n + n + 2\pi^+ + a\pi^0 + b(\pi^+ + \pi^-)$$

Pion and muon decays:

$$\pi^0 \longrightarrow 2\gamma$$
$$\pi^+ \longrightarrow \nu_\mu + \mu^+ \longrightarrow \nu_\mu + e^+ + \nu_e + \bar{\nu}_\mu$$
$$\pi^- \longrightarrow \bar{\nu}_\mu + \mu^- \longrightarrow \bar{\nu}_\mu + e^- + \bar{\nu}_e + \nu_\mu$$





Neutrino production channels

- Photo-hadronic interactions:

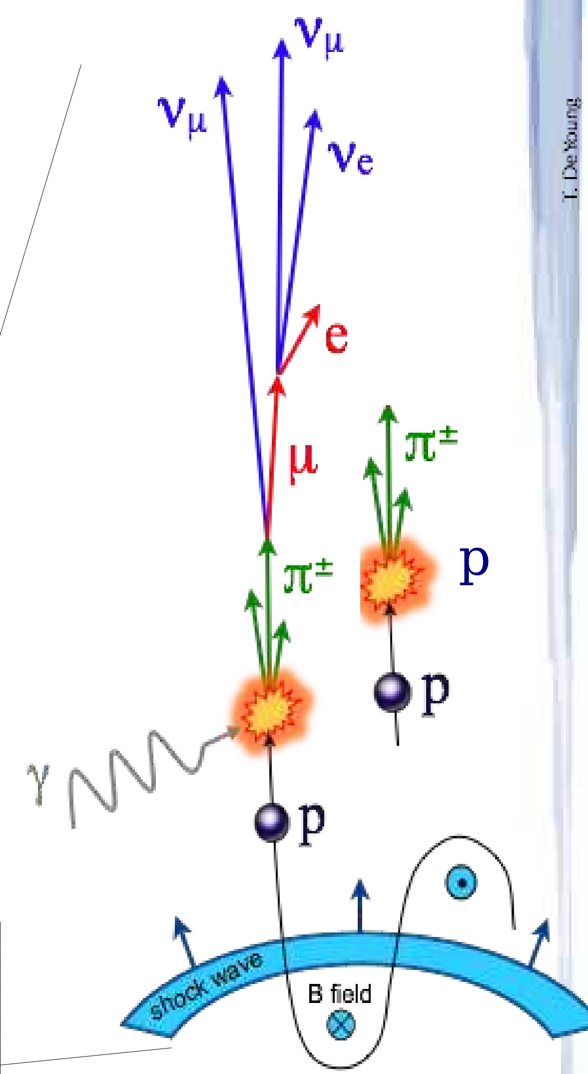
$$
\begin{aligned}
p+\gamma &\longrightarrow \Delta^+ \longrightarrow p+\pi^0 \\
p+\gamma &\longrightarrow \Delta^+ \longrightarrow n+\pi^+ \\
p+\gamma &\longrightarrow p+\pi^+ +\pi^- \\
p+\gamma &\longrightarrow p+\pi^+ + a\pi^0 + b(\pi^+ + \pi^-) \qquad a,b=0,1,2\ldots
\end{aligned}
$$

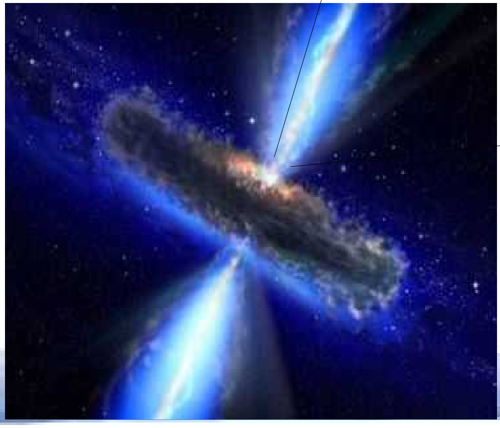
- Hadronic interactions:

$$
\begin{aligned}
p+p &\longrightarrow p+p+a\pi^0+b(\pi^+ + \pi^-) \\
p+p &\longrightarrow p+n+\pi^+ + a\pi^0+b(\pi^+ + \pi^-) \\
p+p &\longrightarrow n+n+2\pi^+ + a\pi^0+b(\pi^+ + \pi^-)
\end{aligned}
$$

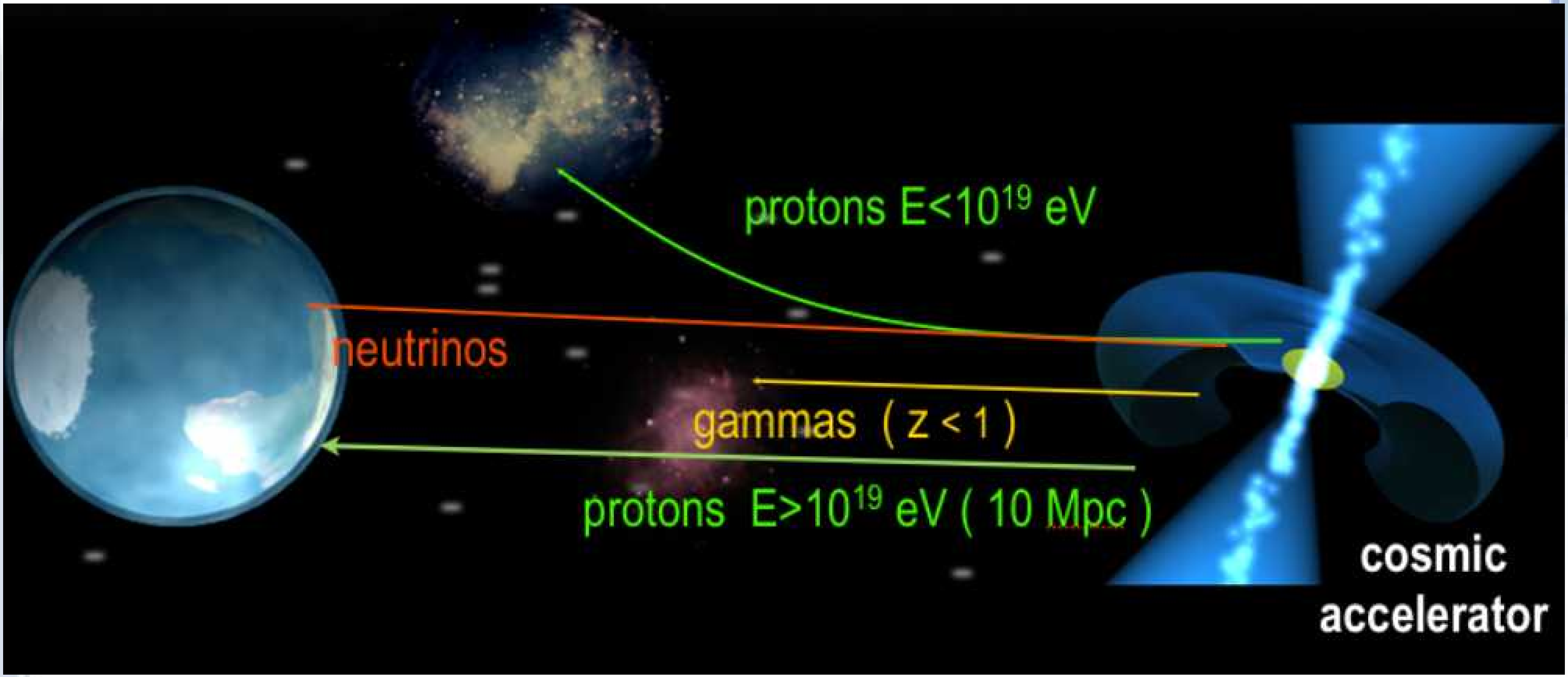
Pion and muon decays:

$$
\begin{aligned}
\pi^0 &\longrightarrow 2\gamma \\
\pi^+ &\longrightarrow \nu_\mu + \mu^+ \longrightarrow \nu_\mu + e^+ + \nu_e + \bar{\nu}_\mu \\
\pi^- &\longrightarrow \bar{\nu}_\mu + \mu^- \longrightarrow \bar{\nu}_\mu + e^- + \bar{\nu}_e + \nu_\mu
\end{aligned}
$$





Why search for neutrinos?



(From T. Montaruli, Trieste 2011)

Cosmic ray – neutrino connection

Discussion

- IceCube is completed since december 2010

- But no astrophysical neutrino flux has been observed! (yet)

- ARA (Askaryan Radio Array) upgrade of RICE

  will be built with A_{eff}=100 km^2.

  Target: cosmogenic neutrinos (E_ν>10^{16}eV)

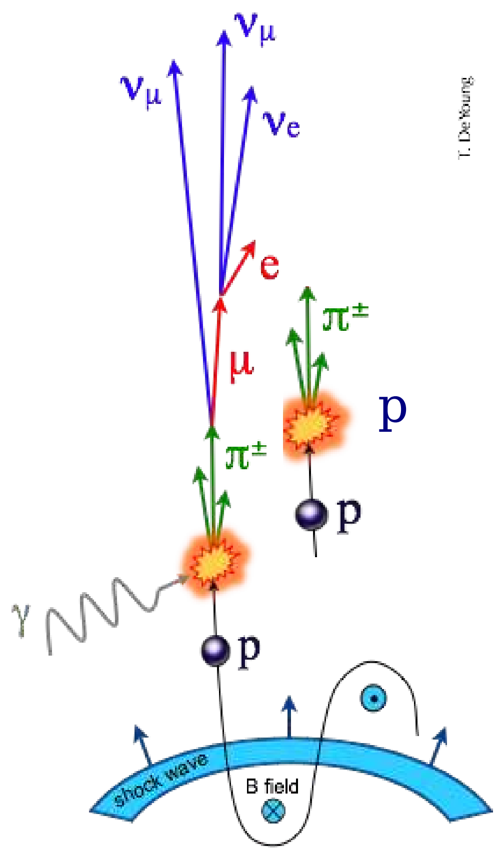
- In the northern hemisphere: KM3Net

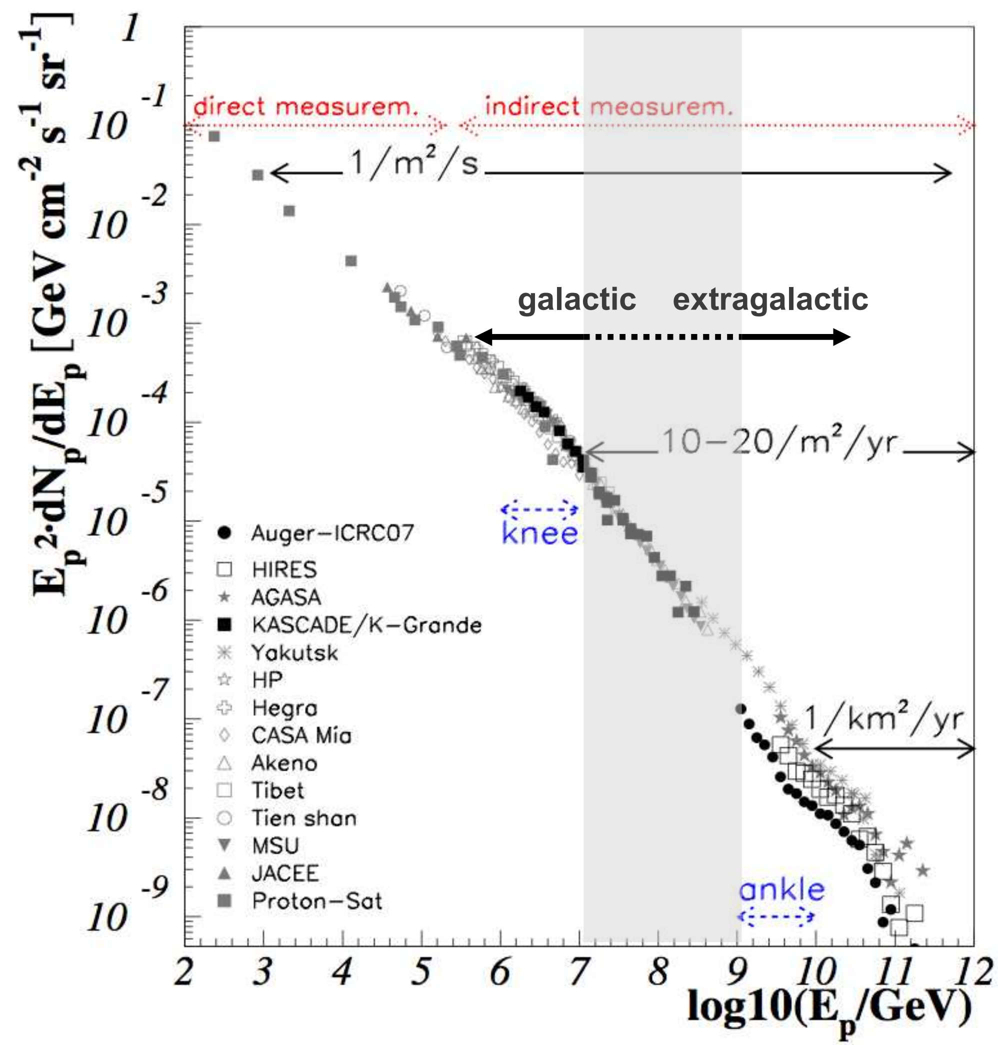
  Now anounced as a ”multi-km3” neutrino telescope

From K. Hoffman in ICRC 2011

Cosmic ray-neutrino connection

- Evidence for proton acceleration...





pp or pγ interactions in the source

↓

A neutrino flux is expected!

CR-ν connection: ν production at the CR sources

- Waxman-Bahcall upper bound for diffuse neutrino flux

Global, integrated flux from all the sources in the sky

Energy production rate of CR of E>10[19] eV

$$E^2 \frac{d\dot{N}_{\rm cr}}{dE} \approx 10^{44} {\rm erg~Mpc^{-3} yr^{-1}}$$

Assuming proton interact before leaving the source:

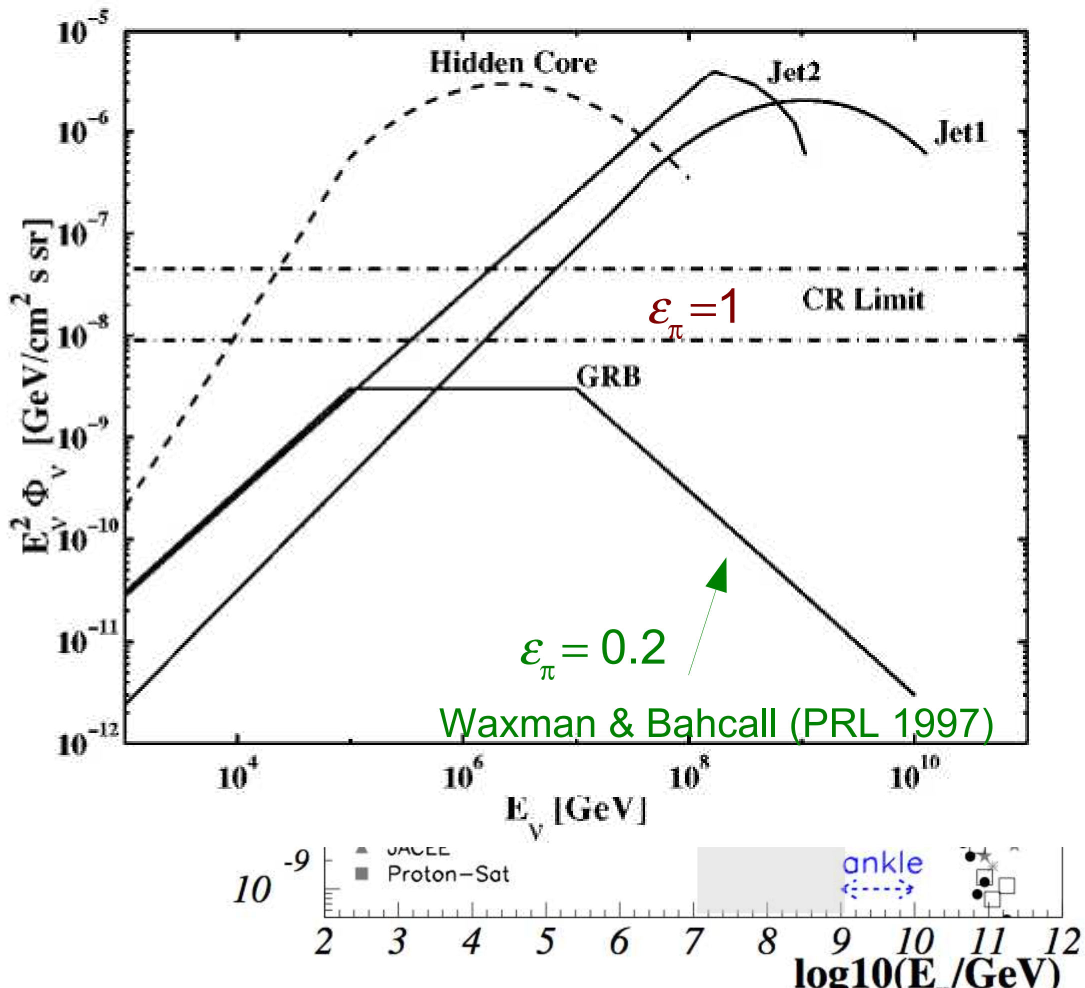
$$E_\nu^2 \frac{dN_\nu}{dE_\nu} < \epsilon_\pi \xi_z t_{\rm H} E^2 \frac{d\dot{N}_{\rm cr}}{dE}$$

Neutrino energy density

ε_π: ratio E_π/E_p

t_H : Hubble time

ξ_z =0.6 – 3, cosmological evolution factor



ε_π =1 →

$$E_\nu^2 \Phi_\nu < 5 \times 10^{-8} {\rm GeV~cm^{-2} sr^{-1} s^{-1}}$$

CR-ν connection: ν production from CR propagation

- CRs + background photons
  (Microwave, IR, Optical, UV)

Cosmogenic neutrino flux
(Beresinsky & Zatsepin 1969)

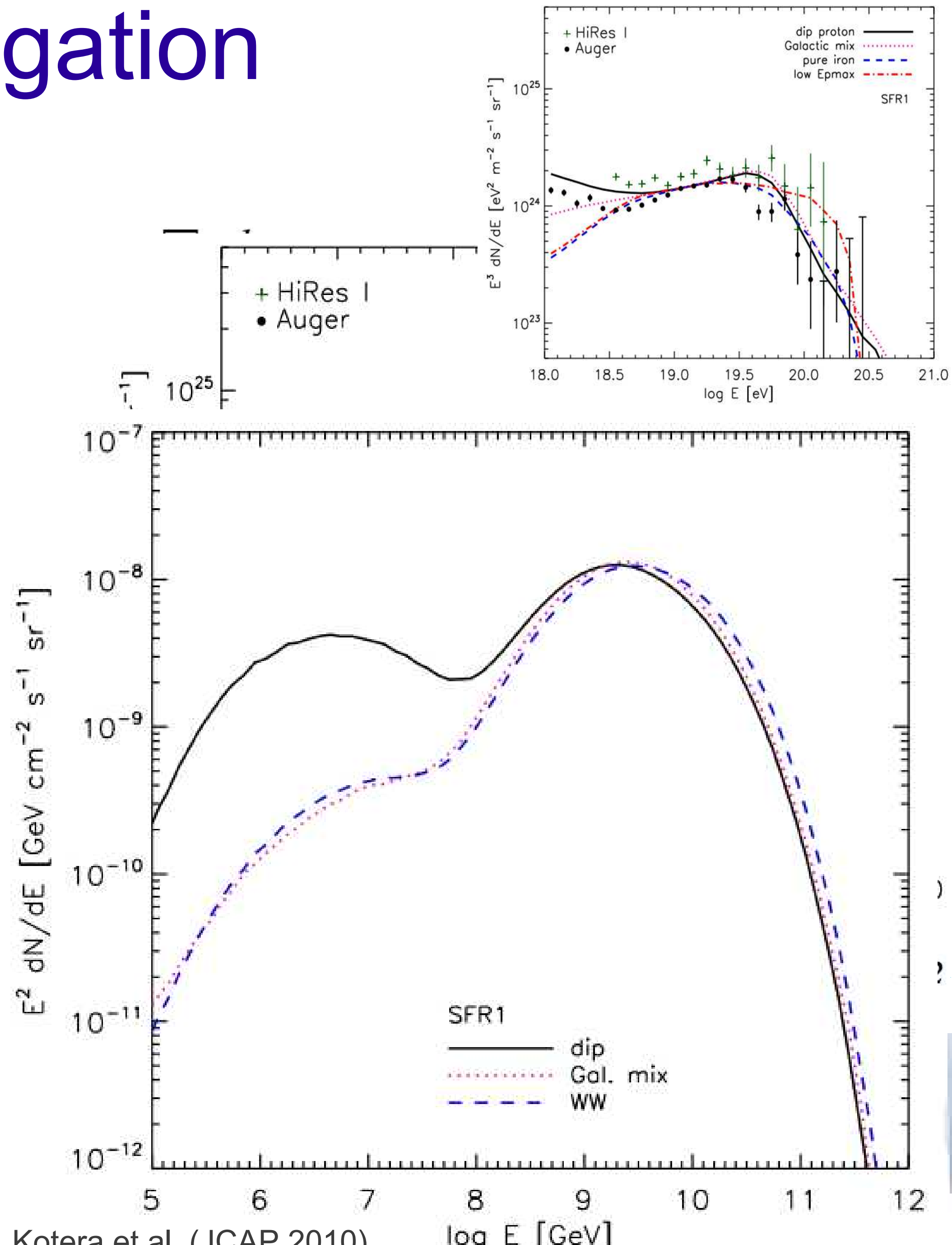
$$p + \gamma_{\rm bkgd} \longrightarrow \Delta^+ \longrightarrow \pi^+ + n$$

$$\pi^+ \longrightarrow \nu_\mu + \mu^+ \longrightarrow \nu_\mu + e^+ + \nu_e + \bar{\nu}_\mu$$

$$n \longrightarrow p + e^- + \bar{\nu}_e$$

Also know as ”GZK neutrino flux”
Often called ”A guaranteed neutrino flux”...

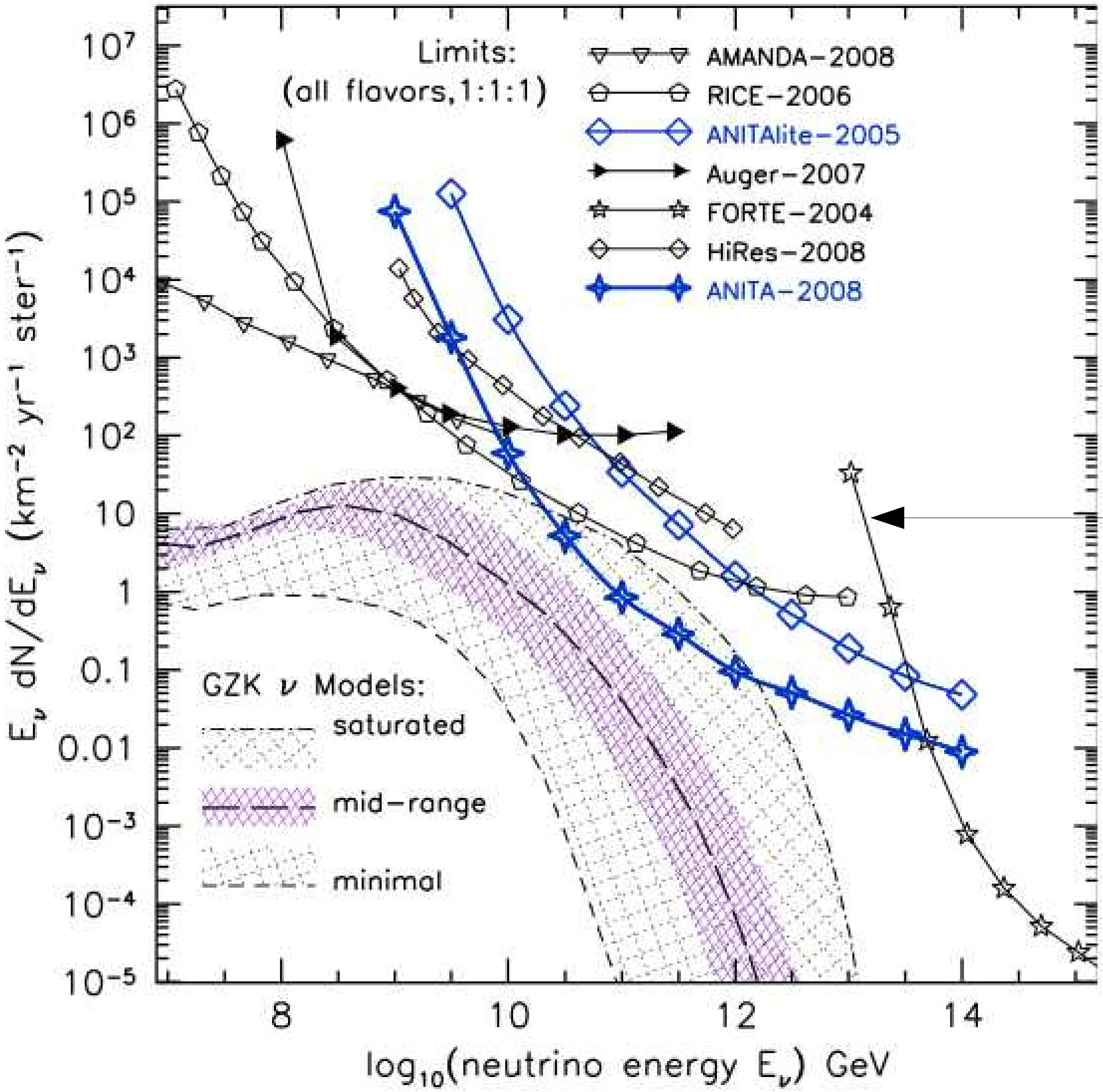
Depends on
- CR composition
- Transition galactic-extragalactic origin
- Redshift evolution of the sources
  (e.g. Star Formation Rate)



Kotera et al. (JCAP 2010)

See also Engel et al (PRD 2001) and Anchordoqui et al. (PRD 2007)

Observations by RICE, ANITA and AUGER



FORTE (Fast on-Orbit Recording of Transient Events) satellite. Aim: detect radio emission from hadronic showers in the ice sheet of Greenland