# SEARCH FOR POINT-LIKE SOURCES OF ULTRA-HIGH ENERGY NEUTRINOS AT THE PIERRE AUGER OBSERVATORY AND IMPROVED LIMIT ON THE DIFFUSE FLUX OF TAU NEUTRINOS

**THE PIERRE AUGER COLLABORATION**[†],
P. Abreu[63], M. Aglietta[51], M. Ahlers[94], E.J. Ahn[81], I.F.M. Albuquerque[15], D. Allard[29],
I. Allekotte[1], J. Allen[85], P. Allison[87], A. Almela[11, 7], J. Alvarez Castillo[56],
J. Alvarez-Muñiz[73], R. Alves Batista[16], M. Ambrosio[45], A. Aminaei[57], L. Anchordoqui[95],
S. Andringa[63], T. Antiči'c[23], C. Aramo[45], E. Arganda[4, 70], F. Arqueros[70], H. Asorey[1],
P. Assis[63], J. Aublin[31], M. Ave[37], M. Avenier[32], G. Avila[10], A.M. Badescu[66], M. Balzer[36],
K.B. Barber[12], A.F. Barbosa[13, 97], R. Bardenet[30], S.L.C. Barroso[18], B. Baughman[87, 98],
J. Bäuml[35], C. Baus[37], J.J. Beatty[87], K.H. Becker[34], A. Bellétoile[33], J.A. Bellido[12],
S. BenZvi[94], C. Berat[32], X. Bertou[1], P.L. Biermann[38], P. Billoir[31], O. Blanch-Bigas[31, 99],
F. Blanco[70], M. Blanco[31, 71], C. Bleve[34], H. Blümer[37, 35], M. Boháčová[25], D. Boncioli[46],
C. Bonifazi[21, 31], R. Bonino[51], N. Borodai[61], J. Brack[79], I. Brancus[64], P. Brogueira[63],
W.C. Brown[80], R. Bruijn[75, 100], P. Buchholz[41], A. Bueno[72], L. Buroker[95], R.E. Burton[77],
K.S. Caballero-Mora[88], B. Caccianiga[44], L. Caramete[38], R. Caruso[47], A. Castellina[51],
O. Catalano[50], G. Cataldi[49], L. Cazon[63], R. Cester[48], J. Chauvin[32], S.H. Cheng[88],
A. Chiavassa[51], J.A. Chinellato[16], J. Chirinos Diaz[84], J. Chudoba[25], M. Cilmo[45],
R.W. Clay[12], G. Cocciolo[49], L. Collica[44], M.R. Coluccia[49], R. Conceição[63], F. Contreras[9],
H. Cook[75], M.J. Cooper[12], J. Coppens[57, 59], A. Cordier[30], S. Coutu[88], C.E. Covault[77],
A. Creusot[29], A. Criss[88], J. Cronin[90], A. Curutiu[38], S. Dagoret-Campagne[30], R. Dallier[33],
B. Daniel[16], S. Dasso[5, 3], K. Daumiller[35], B.R. Dawson[12], R.M. de Almeida[22], M. De
Domenico[47], C. De Donato[56], S.J. de Jong[57, 59], G. De La Vega[8], W.J.M. de Mello Junior[16],
J.R.T. de Mello Neto[21], I. De Mitri[49], V. de Souza[14], K.D. de Vries[58], L. del Peral[71], M. del
Río[46, 9], O. Deligny[28], H. Dembinski[37], N. Dhital[84], C. Di Giulio[46, 43], M.L. Díaz Castro[13],
P.N. Diep[96], F. Diogo[63], C. Dobrigkeit [16], W. Docters[58], J.C. D'Olivo[56], P.N. Dong[96, 28],
A. Dorofeev[79], J.C. dos Anjos[13], M.T. Dova[4], D. D'Urso[45], I. Dutan[38], J. Ebr[25], R. Engel[35],
M. Erdmann[39], C.O. Escobar[81, 16], J. Espadanal[63], A. Etchegoyen[7, 11], P. Facal San Luis[90],
H. Falcke[57, 60, 59], G. Farrar[85], A.C. Fauth[16], N. Fazzini[81], A.P. Ferguson[77], B. Fick[84],
J.M. Figueira[7], A. Filevich[7], A. Filipčič[67, 68], S. Fliescher[39], C.E. Fracchiolla[79],
E.D. Fraenkel[58], O. Fratu[66], U. Fröhlich[41], B. Fuchs[37], R. Gaior[31], R.F. Gamarra[7],
S. Gambetta[42], B. García[8], S.T. Garcia Roca[73], D. Garcia-Gamez[30], D. Garcia-Pinto[70],
A. Gascon Bravo[72], H. Gemmeke[36], P.L. Ghia[31], M. Giller[62], J. Gitto[8], H. Glass[81],
M.S. Gold[93], G. Golup[1], F. Gomez Albarracin[4], M. Gómez Berisso[1], P.F. Gómez Vitale[10],
P. Gonçalves[63], J.G. Gonzalez[35], B. Gookin[79], A. Gorgi[51], P. Gouffon[15], E. Grashorn[87],
S. Grebe[57, 59], N. Griffith[87], M. Grigat[39], A.F. Grillo[52], Y. Guardincerri[3], F. Guarino[45],

G.P. Guedes[17], P. Hansen[4], D. Harari[1], T.A. Harrison[12], J.L. Harton[79], A. Haungs[35], T. Hebbeker[39], D. Heck[35], A.E. Herve[12], C. Hojvat[81], N. Hollon[90], V.C. Holmes[12], P. Homola[61], J.R. Hörandel[57, 59], P. Horvath[26], M. Hrabovský[26, 25], D. Huber[37], T. Huege[35], A. Insolia[47], F. Ionita[90], A. Italiano[47], S. Jansen[57, 59], C. Jarne[4], S. Jiraskova[57], M. Josebachuili[7], K. Kadija[23], K.H. Kampert[34], P. Karhan[24], P. Kasper[81], I. Katkov[37], B. Kégl[30], B. Keilhauer[35], A. Keivani[83], J.L. Kelley[57], E. Kemp[16], R.M. Kieckhafer[84], H.O. Klages[35], M. Kleifges[36], J. Kleinfeller[9, 35], J. Knapp[75], D.-H. Koang[32], K. Kotera[90], N. Krohm[34], O. Krömer[36], D. Kruppke-Hansen[34], D. Kuempel[39, 41], J.K. Kulbartz[40], N. Kunka[36], G. La Rosa[50], C. Lachaud[29], D. LaHurd[77], L. Latronico[51], R. Lauer[93], P. Lautridou[33], S. Le Coz[32], M.S.A.B. Leão[20], D. Lebrun[32], P. Lebrun[81], M.A. Leigui de Oliveira[20], A. Letessier-Selvon[31], I. Lhenry-Yvon[28], K. Link[37], R. López[53], A. Lopez Agüera[73], K. Louedec[32, 30], J. Lozano Bahilo[72], L. Lu[75], A. Lucero[7], M. Ludwig[37], H. Lyberis[21, 28], M.C. Maccarone[50], C. Macolino[31], S. Maldera[51], J. Maller[33], D. Mandat[25], P. Mantsch[81], A.G. Mariazzi[4], J. Marin[9, 51], V. Marin[33], I.C. Maris[31], H.R. Marquez Falcon[55], G. Marsella[49], D. Martello[49], L. Martin[33], H. Martinez[54], O. Martínez Bravo[53], D. Martraire[28], J.J. Masías Meza[3], H.J. Mathes[35], J. Matthews[83, 89], J.A.J. Matthews[93], G. Matthiae[46], D. Maurel[35], D. Maurizio[13, 48], P.O. Mazur[81], G. Medina-Tanco[56], M. Melissas[37], D. Melo[7], E. Menichetti[48], A. Menshikov[36], P. Mertsch[74], C. Meurer[39], R. Meyhandan[91], S. Mi'canovi'c[23], M.I. Micheletti[6], I.A. Minaya[70], L. Miramonti[44], L. Molina-Bueno[72], S. Mollerach[1], M. Monasor[90], D. Monnier Ragaigne[30], F. Montanet[32], B. Morales[56], C. Morello[51], E. Moreno[53], J.C. Moreno[4], M. Mostafá[79], C.A. Moura[20], M.A. Muller[16], G. Müller[39], M. Münchmeyer[31], R. Mussa[48], G. Navarra[51, 97], J.L. Navarro[72], S. Navas[72], P. Necesal[25], L. Nellen[56], A. Nelles[57, 59], J. Neuser[34], P.T. Nhung[96], M. Niechciol[41], L. Niemietz[34], N. Nierstenhoefer[34], D. Nitz[84], D. Nosek[24], L. Nožka[25], J. Oehlschläger[35], A. Olinto[90], M. Ortiz[70], N. Pacheco[71], D. Pakk Selmi-Dei[16], M. Palatka[25], J. Pallotta[2], N. Palmieri[37], G. Parente[73], E. Parizot[29], A. Parra[73], S. Pastor[69], T. Paul[86], M. Pech[25], J. Pękala[61], R. Pelayo[53, 73], I.M. Pepe[19], L. Perrone[49], R. Pesce[42], E. Petermann[92], S. Petrera[43], A. Petrolini[42], Y. Petrov[79], C. Pfendner[94], R. Piegaia[3], T. Pierog[35], P. Pieroni[3], M. Pimenta[63], V. Pirronello[47], M. Platino[7], M. Plum[39], V.H. Ponce[1], M. Pontz[41], A. Porcelli[35], P. Privitera[90], M. Prouza[25], E.J. Quel[2], S. Querchfeld[34], J. Rautenberg[34], O. Ravel[33], D. Ravignani[7], B. Revenu[33], J. Ridky[25], S. Riggi[73], M. Risse[41], P. Ristori[2], H. Rivera[44], V. Rizi[43], J. Roberts[85], W. Rodrigues de Carvalho[73], G. Rodriguez[73], I. Rodriguez Cabo[73], J. Rodriguez Martino[9], J. Rodriguez Rojo[9], M.D. Rodríguez-Frías[71], G. Ros[71], J. Rosado[70], T. Rossler[26], M. Roth[35], B. Rouillé-d'Orfeuil[90], E. Roulet[1], A.C. Rovero[5], C. Rühle[36], A. Saftoiu[64], F. Salamida[28], H. Salazar[53], F. Salesa Greus[79], G. Salina[46], F. Sánchez[7], C.E. Santo[63], E. Santos[63], E.M. Santos[21], F. Sarazin[78], B. Sarkar[34], S. Sarkar[74], R. Sato[9], N. Scharf[39], V. Scherini[44], H. Schieler[35], P. Schiffer[40, 39], A. Schmidt[36], O. Scholten[58], H. Schoorlemmer[57, 59],

J. Schovancova[25], P. Schovánek[25], F. Schröder[35], S. Schulte[39], D. Schuster[78], S.J. Sciutto[4], M. Scuderi[47], A. Segreto[50], M. Settimo[41], A. Shadkam[83], R.C. Shellard[13], I. Sidelnik[7], G. Sigl[40], H.H. Silva Lopez[56], O. Sima[65], A. 'Smiałkowski[62], R. Šmída[35], G.R. Snow[92], P. Sommers[88], J. Sorokin[12], H. Spinka[76, 81], R. Squartini[9], Y.N. Srivastava[86], S. Stanic[68], J. Stapleton[87], J. Stasielak[61], M. Stephan[39], A. Stutz[32], F. Suarez[7], T. Suomijärvi[28], A.D. Supanitsky[5], T. Šuša[23], M.S. Sutherland[83], J. Swain[86], Z. Szadkowski[62], M. Szuba[35], A. Tapia[7], M. Tartare[32], O. Taşcău[34], R. Tcaciuc[41], N.T. Thao[96], D. Thomas[79], J. Tiffenberg[3], C. Timmermans[59, 57], W. Tkaczyk[62, 97], C.J. Todero Peixoto[14], G. Toma[64], L. Tomankova[25], B. Tomé[63], A. Tonachini[48], P. Travnicek[25], D.B. Tridapalli[15], G. Tristram[29], E. Trovato[47], M. Tueros[73], R. Ulrich[35], M. Unger[35], M. Urban[30], J.F. Valdés Galicia[56], I. Valiño[73], L. Valore[45], G. van Aar[57], A.M. van den Berg[58], A. van Vliet[40], E. Varela[53], B. Vargas Cárdenas[56], J.R. Vázquez[70], R.A. Vázquez[73], D. Veberič[68, 67], V. Verzi[46], J. Vicha[25], M. Videla[8], L. Villaseñor[55], H. Wahlberg[4], P. Wahrlich[12], O. Wainberg[7, 11], D. Walz[39], A.A. Watson[75], M. Weber[36], K. Weidenhaupt[39], A. Weindl[35], F. Werner[35], S. Westerhoff[94], B.J. Whelan[88, 12], A. Widom[86], G. Wieczorek[62], L. Wiencke[78], B. Wilczyńska[61], H. Wilczyński[61], M. Will[35], C. Williams[90], T. Winchen[39], M. Wommer[35], B. Wundheiler[7], T. Yamamoto[90, 101], T. Yapici[84], P. Younk[41, 82], G. Yuan[83], A. Yushkov[73], B. Zamorano Garcia[72], E. Zas[73], D. Zavrtanik[68, 67], M. Zavrtanik[67, 68], I. Zaw[85, 102], A. Zepeda[54, 103], J. Zhou[90], Y. Zhu[36], M. Zimbres Silva[34, 16], AND M. Ziolkowski[41]

[†] *Observatorio Pierre Auger, Av. San Martín Norte 304, 5613 Malargüe, Argentina*

[1] *Centro Atómico Bariloche and Instituto Balseiro (CNEA-UNCuyo-CONICET), San Carlos de Bariloche, Argentina*

[2] *Centro de Investigaciones en Láseres y Aplicaciones, CITEDEF and CONICET, Argentina*

[3] *Departamento de Física, FCEyN, Universidad de Buenos Aires y CONICET, Argentina*

[4] *IFLP, Universidad Nacional de La Plata and CONICET, La Plata, Argentina*

[5] *Instituto de Astronomía y Física del Espacio (CONICET-UBA), Buenos Aires, Argentina*

[6] *Instituto de Física de Rosario (IFIR) - CONICET/U.N.R. and Facultad de Ciencias Bioquímicas y Farmacéuticas U.N.R., Rosario, Argentina*

[7] *Instituto de Tecnologías en Detección y Astropartículas (CNEA, CONICET, UNSAM), Buenos Aires, Argentina*

[8] *National Technological University, Faculty Mendoza (CONICET/CNEA), Mendoza, Argentina*

[9] *Observatorio Pierre Auger, Malargüe, Argentina*

[10] *Observatorio Pierre Auger and Comisión Nacional de Energía Atómica, Malargüe, Argentina*

[11] *Universidad Tecnológica Nacional - Facultad Regional Buenos Aires, Buenos Aires,*

*Argentina*
[12] *University of Adelaide, Adelaide, S.A., Australia*
[13] *Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, RJ, Brazil*
[14] *Universidade de São Paulo, Instituto de Física, São Carlos, SP, Brazil*
[15] *Universidade de São Paulo, Instituto de Física, São Paulo, SP, Brazil*
[16] *Universidade Estadual de Campinas, IFGW, Campinas, SP, Brazil*
[17] *Universidade Estadual de Feira de Santana, Brazil*
[18] *Universidade Estadual do Sudoeste da Bahia, Vitoria da Conquista, BA, Brazil*
[19] *Universidade Federal da Bahia, Salvador, BA, Brazil*
[20] *Universidade Federal do ABC, Santo André, SP, Brazil*
[21] *Universidade Federal do Rio de Janeiro, Instituto de Física, Rio de Janeiro, RJ, Brazil*
[22] *Universidade Federal Fluminense, EEIMVR, Volta Redonda, RJ, Brazil*
[23] *Rudjer Boškovi'c Institute, 10000 Zagreb, Croatia*
[24] *Faculty of Mathematics and Physics, Institute of Particle and Nuclear Physics, Charles University, Prague, Czech Republic*
[25] *Institute of Physics of the Academy of Sciences of the Czech Republic, Prague, Czech Republic*
[26] *Palacky University, RCPTM, Olomouc, Czech Republic*
[28] *Institut de Physique Nucléaire d'Orsay (IPNO), Université Paris 11, CNRS-IN2P3, Orsay, France*
[29] *Laboratoire AstroParticule et Cosmologie (APC), Université Paris 7, CNRS-IN2P3, Paris, France*
[30] *Laboratoire de l'Accélérateur Linéaire (LAL), Université Paris 11, CNRS-IN2P3, France*
[31] *Laboratoire de Physique Nucléaire et de Hautes Energies (LPNHE), Universités Paris 6 et Paris 7, CNRS-IN2P3, Paris, France*
[32] *Laboratoire de Physique Subatomique et de Cosmologie (LPSC), Université Joseph Fourier, INPG, CNRS-IN2P3, Grenoble, France*
[33] *SUBATECH, École des Mines de Nantes, CNRS-IN2P3, Université de Nantes, France*
[34] *Bergische Universität Wuppertal, Wuppertal, Germany*
[35] *Karlsruhe Institute of Technology - Campus North - Institut für Kernphysik, Karlsruhe, Germany*
[36] *Karlsruhe Institute of Technology - Campus North - Institut für Prozessdatenverarbeitung und Elektronik, Karlsruhe, Germany*
[37] *Karlsruhe Institute of Technology - Campus South - Institut für Experimentelle Kernphysik (IEKP), Karlsruhe, Germany*
[38] *Max-Planck-Institut für Radioastronomie, Bonn, Germany*
[39] *RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*
[40] *Universität Hamburg, Hamburg, Germany*

[41] *Universität Siegen, Siegen, Germany*
[42] *Dipartimento di Fisica dell'Università and INFN, Genova, Italy*
[43] *Università dell'Aquila and INFN, L'Aquila, Italy*
[44] *Università di Milano and Sezione INFN, Milan, Italy*
[45] *Università di Napoli "Federico II" and Sezione INFN, Napoli, Italy*
[46] *Università di Roma II "Tor Vergata" and Sezione INFN, Roma, Italy*
[47] *Università di Catania and Sezione INFN, Catania, Italy*
[48] *Università di Torino and Sezione INFN, Torino, Italy*
[49] *Dipartimento di Matematica e Fisica "E. De Giorgi" dell'Università del Salento and Sezione INFN, Lecce, Italy*
[50] *Istituto di Astrofisica Spaziale e Fisica Cosmica di Palermo (INAF), Palermo, Italy*
[51] *Istituto di Fisica dello Spazio Interplanetario (INAF), Università di Torino and Sezione INFN, Torino, Italy*
[52] *INFN, Laboratori Nazionali del Gran Sasso, Assergi (L'Aquila), Italy*
[53] *Benemérita Universidad Autónoma de Puebla, Puebla, Mexico*
[54] *Centro de Investigación y de Estudios Avanzados del IPN (CINVESTAV), México, Mexico*
[55] *Universidad Michoacana de San Nicolas de Hidalgo, Morelia, Michoacan, Mexico*
[56] *Universidad Nacional Autonoma de Mexico, Mexico, D.F., Mexico*
[57] *IMAPP, Radboud University Nijmegen, The Netherlands*
[58] *Kernfysisch Versneller Instituut, University of Groningen, Groningen, The Netherlands*
[59] *Nikhef, Science Park, Amsterdam, The Netherlands*
[60] *ASTRON, Dwingeloo, The Netherlands*
[61] *Institute of Nuclear Physics PAN, Krakow, Poland*
[62] *University of Łódź, Łódź, Poland*
[63] *LIP and Instituto Superior Técnico, Technical University of Lisbon, Portugal*
[64] *'Horia Hulubei' National Institute for Physics and Nuclear Engineering, Bucharest-Magurele, Romania*
[65] *Physics Department, University of Bucharest, Romania*
[66] *University Politehnica of Bucharest, Romania*
[67] *J. Stefan Institute, Ljubljana, Slovenia*
[68] *Laboratory for Astroparticle Physics, University of Nova Gorica, Slovenia*
[69] *Instituto de Física Corpuscular, CSIC-Universitat de València, Valencia, Spain*
[70] *Universidad Complutense de Madrid, Madrid, Spain*
[71] *Universidad de Alcalá, Alcalá de Henares (Madrid), Spain*
[72] *Universidad de Granada & C.A.F.P.E., Granada, Spain*
[73] *Universidad de Santiago de Compostela, Spain*
[74] *Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Oxford, UK*

[75] *School of Physics and Astronomy, University of Leeds, UK*
[76] *Argonne National Laboratory, Argonne, IL, USA*
[77] *Case Western Reserve University, Cleveland, OH, USA*
[78] *Colorado School of Mines, Golden, CO, USA*
[79] *Colorado State University, Fort Collins, CO, USA*
[80] *Colorado State University, Pueblo, CO, USA*
[81] *Fermilab, Batavia, IL, USA*
[82] *Los Alamos National Laboratory, Los Alamos, NM, USA*
[83] *Louisiana State University, Baton Rouge, LA, USA*
[84] *Michigan Technological University, Houghton, MI, USA*
[85] *New York University, New York, NY, USA*
[86] *Northeastern University, Boston, MA, USA*
[87] *Ohio State University, Columbus, OH, USA*
[88] *Pennsylvania State University, University Park, PA, USA*
[89] *Southern University, Baton Rouge, LA, USA*
[90] *Enrico Fermi Institute, University of Chicago, Chicago, IL, USA*
[91] *University of Hawaii, Honolulu, HI, USA*
[92] *University of Nebraska, Lincoln, NE, USA*
[93] *University of New Mexico, Albuquerque, NM, USA*
[94] *University of Wisconsin, Madison, WI, USA*
[95] *University of Wisconsin, Milwaukee, WI, USA*
[96] *Institute for Nuclear Science and Technology (INST), Hanoi, Vietnam*
*(97) Deceased*
*(98) now at University of Maryland, USA*
*(99) now at Institut de Física d'Altes Energies, Bellaterra, Spain*
*(100) now at Université de Lausanne, Switzerland*
*(101) now at Konan University, Kobe, Japan*
*(102) now at NYU Abu Dhabi*
*(103) now at the Universidad Autonoma de Chiapas on leave of absence from Cinvestav*

## ABSTRACT

The Surface Detector array of the Pierre Auger Observatory can detect neutrinos with energy $E_\nu$ between $10^{17}$ eV and $10^{20}$ eV from point-like sources across the sky south of $+55^\circ$ and north of $-65^\circ$ declinations. A search has been performed for highly inclined extensive air showers produced by the interaction of neutrinos of all flavours in the atmosphere (downward-going neutrinos), and by the decay of tau leptons originating from tau neutrinos interactions in the Earth's crust (Earth-skimming neutrinos). No candidate neutrinos have been found in data up to 2010 May 31. This corresponds to an equivalent exposure of ∼3.5 years of a full surface detector array for the Earth-skimming channel and ∼2 years for the downward-going channel. An improved upper limit on the diffuse flux of tau neutrinos has been derived. Upper limits on the neutrino flux from point-like sources have been derived as a function of the source declination. Assuming a differential neutrino flux $k_{PS} \cdot E_\nu^{-2}$ from a point-like source, 90% C.L. upper limits for $k_{PS}$ at the level of $\approx 5 \times 10^{-7}$ and $2.5 \times 10^{-6}$ GeV cm$^{-2}$ s$^{-1}$ have been obtained over a broad range of declinations from the searches of Earth-skimming and downward-going neutrinos, respectively.

*Subject headings:* astroparticle physics — cosmic rays — neutrinos — telescopes

## 1. INTRODUCTION

The nature and production mechanisms of ultra-high energy cosmic rays (UHECRs), with energies above $10^{18}$ eV, are still unknown Nagano & Watson (2000); Bhattacharjee & Sigl (2000); Halzen & Hooper (2002). The observation of UHECRs makes an associated flux of ultra-high energy cosmic neutrinos (UHE$\nu$s) Becker (2008) very likely. All models of UHECR production predict neutrinos as a result of the decay of charged pions generated in interactions of cosmic rays within the sources themselves ("astrophysical" neutrinos), and/or in their propagation through background radiation fields ("cosmogenic" neutrinos) Berezinsky & Zatsepin (1969); Stecker (1973). In fact, charged pions, which are photoproduced by UHECR protons interacting with the Cosmic Microwave Background radiation, decay into UHE$\nu$s. However, the predicted flux has large uncertainties, since it depends on the UHECR spectrum and on the spatial distribution and cosmological evolution of the sources Becker (2008); Ahlers et al. (2010); Kotera et al. (2010). If UHECRs are heavy nuclei, the UHE$\nu$ yield is strongly suppressed Ave et al. (2005).

The observation of UHE neutrinos would open a new window to the Universe. Neutrinos travel unaffected by magnetic fields and can give information on astrophysical regions that are otherwise hidden from observation by large amounts of matter. The discovery of astrophysical neutrino sources would shed light on the long-standing question of the origin of cosmic rays, and clarify the production mechanism of the GeV-TeV gamma-rays observed on Earth Gaisser (1995); Alvarez-Muñiz & Halzen (2002).

The Pierre Auger Observatory Abraham et al. (2004) – located in the province of Mendoza, Argentina, at a mean altitude of 1400 m above sea level (∼875 g cm$^{-2}$) – was designed to measure extensive air showers (EAS) induced by UHECRs. The Fluorescence Detector (FD) Abraham et al. (2010a) comprises a set of imaging telescopes to measure the light emitted by excited atmospheric nitrogen molecules as the EAS develops. A Surface Detector (SD) Allekotte et al. (2008), measures EAS particles at ground with an array of water-Cherenkov detectors ("stations"). Each SD station contains 12 tonnes of water viewed by three 9" photomultipliers (PMTs). Arranged on a triangular grid with 1.5 km spacing, 1660 SD stations are deployed over an area of $\sim$ 3000 km$^2$, overlooked by 27 fluorescence telescopes.

Although the primary goal of the SD is to detect UHECRs, it can also identify ultra-high energy neutrinos. Neutrinos of all flavours can interact at any atmospheric depth through charged or neutral currents and induce a "downward-going" (*DG*) shower. In addition, tau neutrinos can undergo charged current interactions in the Earth crust and produce a tau lepton which, after emerging from the Earth surface and decaying in the atmosphere, will induce an "Earth-skimming" (*ES*) upward-going shower. Even if tau neutrinos are not expected to be produced at the astrophysical source, approximately equal fluxes for each neutrino flavour should reach the Earth as a result of neutrino oscillations over cosmological distances. Neutrino candidate events must be identified against the overwhelming background of showers initiated by standard UHECRs (protons or nuclei) and, in a much smaller proportion, photons Abraham et al. (2010b). Highly inclined (zenith angle $\theta > 75°$) *ES* and *DG* neutrino-induced showers will present a significant electromagnetic component at the ground ("young" showers), producing signals spread over hundreds of nanoseconds in several of the triggered SD stations. Inclined showers initiated by standard UHECRs are, by contrast, dominated by muons at ground level ("old" showers), with signals typically spread over only tens of nanoseconds. Thanks to the fast sampling (25 ns) of the SD digital electronics, several observables sensitive to the signal time structure can be used to discriminate between young and old showers, allowing for detection of UHE$\nu$s. Candidates for UHE$\nu$s are searched for in inclined showers in the ranges $75° < \theta < 90°$ and $90° < \theta < 96°$ for the *DG* and *ES* analysis, respectively.

## 2. LIMITS ON THE DIFFUSE FLUX OF UHE TAU NEUTRINOS

An upper limit on the diffuse flux of tau neutrinos from the search of Earth-skimming events in data through 2008 April 30 ($\sim$2 years of exposure with a full SD array) was reported in Abraham et al. (2009). Here, the search is extended to data until 2010 May 31 ($\sim$3.5 years of exposure with a full SD array), and an improved limit is obtained. A preliminary report of this result was presented in Guardincerri et al. (2011).

Details of the neutrino selection procedure, of the calculation of the detector exposure for *ES* showers, and of sources of systematic uncertainties are given in Abraham et al. (2009). The neutrino selection criteria were optimized with an early data set collected between 2004 November 1 and 2004 December 31. By using data rather than Monte Carlo simulations, all possible detector effects and shower-to-shower fluctuations, which constitute the main background to UHE$\nu$s and may not be well reproduced by simulations, are taken into account. The neutrino selection established with the training sample was then applied to a "blind search sample" of data collected between 2004 January 1 and 2010 May 31 (excluding November and December 2004). The blind search sample is equivalent to $\sim 3.5$ years of data collected by a fully efficient SD array, *i.e.* with all stations working continuously. The time evolution of the SD array, which was growing during the construction phase, as well as the dead times of individual stations, were accounted for in this calculation. The integrated exposure for detection of *ES* tau neutrinos as a function of energy is shown in Figure 1. No neutrino candidates were found in the blind search. Assuming a differential spectrum $\Phi(E_\nu) = dN_\nu/dE_\nu = k \cdot E_\nu^{-2}$ for the diffuse flux of UHE$\nu$s and zero background Abraham et al. (2009); Abreu et al. (2011a), a 90% C.L. upper limit on the integrated flux of tau neutrinos is derived:

$$k < 3.2 \times 10^{-8} \quad \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}. \tag{1}$$

Systematic uncertainties in the exposure were taken into account in the upper limit by using a semi-Bayesian extension Conrad et al. (2003) of the Feldman-Cousins approach Feldman & Cousins (1998). The limit, shown as a horizontal line in Figure 2, is valid in the energy range $1.6 \times 10^{17}$ eV $\leq E_\nu \leq 2.0 \times 10^{19}$ eV, where $\approx 90\%$ of neutrino events would be detected for a $E_\nu^{-2}$ flux . Also shown is the 90% C.L. upper limit in differential form, where the limit was calculated independently in each energy bin of width 0.5 in $\log_{10} E_\nu$. The integrated and differential limits from the search for downward-going neutrinos Abreu et al. (2011a) at the Pierre Auger Observatory, based on a "blind search sample" of data collected from 2007 November 1 until 2010 May 31 (equivalent to $\sim 2.0$ years of exposure with the full SD array), are also shown in Figure 2, together with limits from the IceCube Neutrino Observatory Abbasi et al. (2011a) and the ANITA experiment Gorham et al. (2010). The shaded area in Figure 2 brackets the cosmogenic neutrinos fluxes predicted under a wide range of assumptions for the cosmological evolution of the sources, for the transition between the galactic and extragalactic component of cosmic rays, and for the UHECR composition Kotera et al. (2010). The corresponding number of cosmogenic neutrino events expected in the blind search sample ranges between 0.1 and 0.3, approximately. For the diffuse flux of cosmogenic neutrinos predicted in Ahlers et al. (2010), 0.6 neutrino events are expected at the Pierre Auger Observatory with the integrated exposure of the present analysis, to be compared with 0.43 events expected in the 333.5 days of live-time of the IceCube-40 neutrino telescope Abbasi et al. (2011a). The current bound to a cosmogenic neutrino flux with energy dependence as in Ahlers et al. (2010) and shown in Figure 2 is 4 times larger than the predicted value. With the current selection criteria the exposure accumulated in ∼10 more years with the Pierre Auger Observatory may exclude this cosmogenic neutrino flux at 90% C.L.. Notice that the maximum sensitivity of the Pierre Auger Observatory, obtained for $E_\nu \sim 10^{18}$ eV, matches well the peak of the expected neutrino flux.

## 3. SENSITIVITY TO POINT-LIKE SOURCES

The neutrino search at the Pierre Auger Observatory is limited to highly inclined showers, with zenith angles between 90° and 96° in the Earth-skimming analysis, and between 75° and 90° in the downward-going analysis. Thus, at each instant, neutrinos can be detected only from a specific portion of the sky corresponding to these zenith angle ranges. A point-like source of declination $\delta$ and right ascension $\alpha$ (equatorial coordinates) is seen at our latitude ($\lambda = -35.2°$), at a given sidereal time $t$, with a zenith angle $\theta(t)$ given by:

$$\cos\theta(t) = \sin\lambda \, \sin\delta + \cos\lambda \, \cos\delta \, \sin(2\pi t/T - \alpha) \; , \tag{2}$$

where $T$ is the duration of one sidereal day. From equation 2, the fraction of a sidereal day during which a source is detectable (i.e., within the zenith angle ranges for the *ES* and *DG* analyses) is shown in Figure 3; it depends only on the source declination. The SD of the Pierre Auger Observatory is sensitive to point-like sources of neutrinos over a broad declination range spanning north of $\delta \sim -65°$ and south of $\delta \sim 55°$. The regions of the sky close to the Northern ($\delta = 90°$) and Southern ($\delta = -90°$) Terrestrial Poles are not accessible by this analysis. As an example, Centaurus A ($\delta \sim -43°$) is observed $\sim 7\%$ ($\sim 15\%$) of one sidereal day in the range of zenith angles corresponding to the *ES* (*DG*) search. The peaks in Figure 3 are a consequence of the relatively smaller rate of variation of zenith angle with time for directions near the edges of the range accessible to this analysis.

The exposure of the SD as a function of the neutrino energy and of the source position in the sky, $\mathcal{E}(E_\nu, \delta)$, is evaluated by folding the SD aperture with the neutrino interaction probability and the selection efficiency for each neutrino channel. The procedure is identical to that used for the calculation of the exposure for a diffuse flux of UHE$\nu$s (Abraham et al. (2009); Abreu et al. (2011a); Guardincerri et al. (2011)), with the exception of the solid angle integration over the sky. The integration over the blind search time period takes into account the growth of the SD array during its construction phase and dead times of individual stations. For example, the exposure for the *DG* analysis is given by:

$$\mathcal{E}(E_\nu, \delta) = \frac{1}{m} \sum_i \left[ \omega_i \ \sigma_i(E_\nu) \int \int \int \cos\theta(t) \ \varepsilon_i(\vec{r}, E_\nu, \theta(t), D, t) \ \mathrm{d}A \ \mathrm{d}D \ \mathrm{d}t \right] \tag{3}$$

where the integration is performed over the area $A$ of the SD, the interaction depth $D$ of the neutrino, and the search period. In equation 3, $m$ is the mass of a nucleon, $\sigma_i(E_\nu)$ is the neutrino-nucleon cross-section Cooper-Sarkar & Sarkar (2008), and $\varepsilon_i$ is the neutrino selection efficiency, with the sum running over the 3 neutrino flavours ($\omega_i = 1$, corresponding to a 1:1:1 flavour ratio) and over the neutrino charged and neutral current interactions. The dependence of $\varepsilon$ on several parameters (the point of impact at ground of the shower core, $\vec{r}$, the neutrino interaction depth, its energy and zenith angle, and time) is also explicitly included in equation 3. The dependence of the exposure on the source declination comes through $\theta(t)$ as obtained from equation 2. When integrating over time, only those periods when the source is within the zenith angle range of the neutrino selection are considered. The exposure for ES neutrinos is derived analogously to equation 3.

Changes in the detector configuration during data taking, due to the dead times of the SD stations, and to the increase of the array size during the construction phase, may introduce a dependence of the exposure on the right ascension. In particular, fluctuations in the number of stations cause a small diurnal variation, but this effect is only apparent in solar time. When averaged over a large number of sidereal days, as in this analysis, the modulation in right ascension caused by this effect is less than 1% Abreu et al. (2011b). For this reason, the dependence of the exposure on $\alpha$ has been neglected in the evaluation of the upper limits.

Due to the finite resolution of the SD on the reconstruction of the variables used in the selection of neutrino-induced showers, events close to the edges of the zenith angle range for the neutrino selection may be wrongly rejected (or wrongly accepted). In the exposure as given in equation 3 we account for this effect by evaluating the selection efficiency $\varepsilon$ through Monte Carlo simulations.

Several other sources of systematic uncertainties on the exposure have been investigated (Abraham et al. (2009); Abreu et al. (2011a)). For the *DG* analysis, the major contributions in terms of deviation from a reference exposure come from the knowledge of neutrino-induced shower simulations (+9%, −33%), of the neutrino cross-section (±7%), and of the topography (±6%). Only uncertainties compatible with the conventional NLO DGLAP formalism of $\nu$ cross-section calculation – see Cooper-Sarkar & Sarkar (2008) for details – have been considered. We have not accounted for gluon saturation models that would give rise to considerable smaller $\nu$ cross-sections (as small as a factor $\sim 2$ at $10^{18}$ eV Henley & Jalilian-Marian (2006);

Armesto et al. (2008)), and hence to a larger systematic uncertainty than the one quoted here. For the *ES* analysis, the systematic uncertainties are dominated by the tau energy losses $(+25\%, -10\%)$, the shower simulations $(+20\%, -5\%)$ and the topography $(+18\%, 0\%)$.

## 4. LIMITS ON THE FLUX OF UHE NEUTRINOS FROM POINT-LIKE SOURCES

The expected number of neutrino events in an energy range $[E_{\rm min}, E_{\rm max}]$ from a point-like source located at a declination $\delta$ is given by:

$$N_{\rm expected}^{\rm point\ source}(\delta) = \int_{E_{\rm min}}^{E_{\rm max}} F(E_\nu)\,\mathcal{E}(E_\nu,\delta)\,{\rm d}E_\nu\ , \tag{4}$$

where $F(E_\nu)$ is the flux of UHE$\nu$s from the source. No candidate events were selected using the *ES* and *DG* analyses. Under the conservative assumption of zero background, a 90% C.L. upper limit on the neutrino flux from point-like sources is derived. To set the upper limit, a differential flux $F(E_\nu) = k_{PS}(\delta)\cdot E_\nu^{-2}$ was assumed, as well as a 1:1:1 neutrino flavour ratio. Systematic uncertainties on the exposure were calculated using the semi-Bayesian approach described above in section 2.

In Figure 4, the 90% C.L. upper limits on $k_{PS}$ derived from the *ES* and *DG* analyses are shown as a function of source declination. Limits for $k_{PS}$ at the level of $\approx 5\times10^{-7}$ and $2.5\times10^{-6}$ GeV cm$^{-2}$ s$^{-1}$ were obtained over a broad range of declinations from the searches of Earth-skimming and downward-going neutrinos, respectively.

The shape of the declination-dependent upper limits is largely determined by the fraction of time a source is within the field of view of the *ES* or *DG* analyses (cf. Figure 3), and, to a lesser extent, by the zenith angle dependence of the exposure.

The upper limits are derived for neutrinos in the energy range $1.6\times10^{17}$ eV$-2.0\times10^{19}$ eV for the Earth-skimming analysis, and in the energy range $1\times10^{17}$ eV $-\ 1\times10^{20}$ eV for the downward-going analysis, with a negligible dependence of these energy intervals on the source declination. These are the best limits around 1 EeV.

The IceCube Neutrino Observatory and the Antares Neutrino Telescope have also searched for UHE$\nu$s from point-like sources (Abbasi et al. (2011b) and Adrián-Martínez et al. (2011), respectively). The bounds obtained by these two experiments apply to energies below the Auger energy range.

Limits for the particular case of the active galaxy Centaurus A, a potential source of

UHECRs, are shown in Figure 5, together with constraints from other experiments. The predicted fluxes for two theoretical models of UHE$\nu$ production – in the jets Cuoco & Hannestad (2008) and close to the core of Centaurus A Kachelriess et al. (2009) – are also shown for comparison. The expected number of events in our blind search samples for a flux like in Cuoco & Hannestad (2008) is about 0.1 and 0.02 for the *ES* and *DG* selection respectively, the expected number for Kachelriess et al. (2009) being one order of magnitude smaller.

## 5. SUMMARY

The sensitivity of the Pierre Auger Observatory to point-like sources of neutrinos with ultra high-energy has been obtained. Highly inclined extensive air showers produced by the interaction of neutrinos of all flavours in the atmosphere and by the decay of tau leptons originating from tau neutrinos interactions in the Earth crust were searched for, and discriminated from the background of standard UHECRs thanks to the distinctive time structure of the signals measured by the Surface Detector array. The search for neutrinos was performed over a broad range of declination, north of $\sim -65^\circ$ and south of $\sim 55^\circ$, and for neutrino energies between $10^{17}$ eV and $10^{20}$ eV.

No neutrino candidates were found in data collected through 2010 May 31, and an improved upper limit on the diffuse flux of tau neutrinos was correspondingly placed. Also, the exposure for neutrino fluxes from point-like sources was evaluated as a function of source declination. Upper limits at 90% C.L. for neutrino fluxes from point-like sources were established, which are currently the most stringent at energies around and above 1 EeV in a large fraction of the sky spanning more than 100° in declination.

## 6. Acknowledgements

The successful installation, commissioning, and operation of the Pierre Auger Observatory would not have been possible without the strong commitment and effort from the technical and administrative staff in Malargüe.

We are very grateful to the following agencies and organizations for financial support: Comisión Nacional de Energía Atómica, Fundación Antorchas, Gobierno De La Provincia de Mendoza, Municipalidad de Malargüe, NDM Holdings and Valle Las Leñas, in gratitude for their continuing cooperation over land access, Argentina; the Australian Research Council; Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Financiadora de

Estudos e Projetos (FINEP), Fundação de Amparo à Pesquisa do Estado de Rio de Janeiro (FAPERJ), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), Ministério de Ciência e Tecnologia (MCT), Brazil; AVCR AV0Z10100502 and AV0Z10100522, GAAV KJB100100904, MSMT-CR LA08016, LG11044, MEB111003, MSM0021620859, LA08015 and TACR TA01010517, Czech Republic; Centre de Calcul IN2P3/CNRS, Centre National de la Recherche Scientifique (CNRS), Conseil Régional Ile-de-France, Département Physique Nucléaire et Corpusculaire (PNC-IN2P3/CNRS), Département Sciences de l'Univers (SDU-INSU/CNRS), France; Bundesministerium für Bildung und Forschung (BMBF), Deutsche Forschungsgemeinschaft (DFG), Finanzministerium Baden-Württemberg, Helmholtz-Gemeinschaft Deutscher Forschungszentren (HGF), Ministerium für Wissenschaft und Forschung, Nordrhein-Westfalen, Ministerium für Wissenschaft, Forschung und Kunst, Baden-Württemberg, Germany; Istituto Nazionale di Fisica Nucleare (INFN), Ministero dell'Istruzione, dell'Università e della Ricerca (MIUR), Italy; Consejo Nacional de Ciencia y Tecnología (CONACYT), Mexico; Ministerie van Onderwijs, Cultuur en Wetenschap, Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO), Stichting voor Fundamenteel Onderzoek der Materie (FOM), Netherlands; Ministry of Science and Higher Education, Grant Nos. N N202 200239 and N N202 207238, Poland; Fundação para a Ciência e a Tecnologia, Portugal; Ministry for Higher Education, Science, and Technology, Slovenian Research Agency, Slovenia; Comunidad de Madrid, Consejería de Educación de la Comunidad de Castilla La Mancha, FEDER funds, Ministerio de Ciencia e Innovación and Consolider-Ingenio 2010 (CPAN), Xunta de Galicia, Spain; Science and Technology Facilities Council, United Kingdom; Department of Energy, Contract Nos. DE-AC02-07CH11359, DE-FR02-04ER41300, National Science Foundation, Grant No. 0450696, The Grainger Foundation USA; NAFOSTED, Vietnam; ALFA-EC / HELEN and UNESCO.

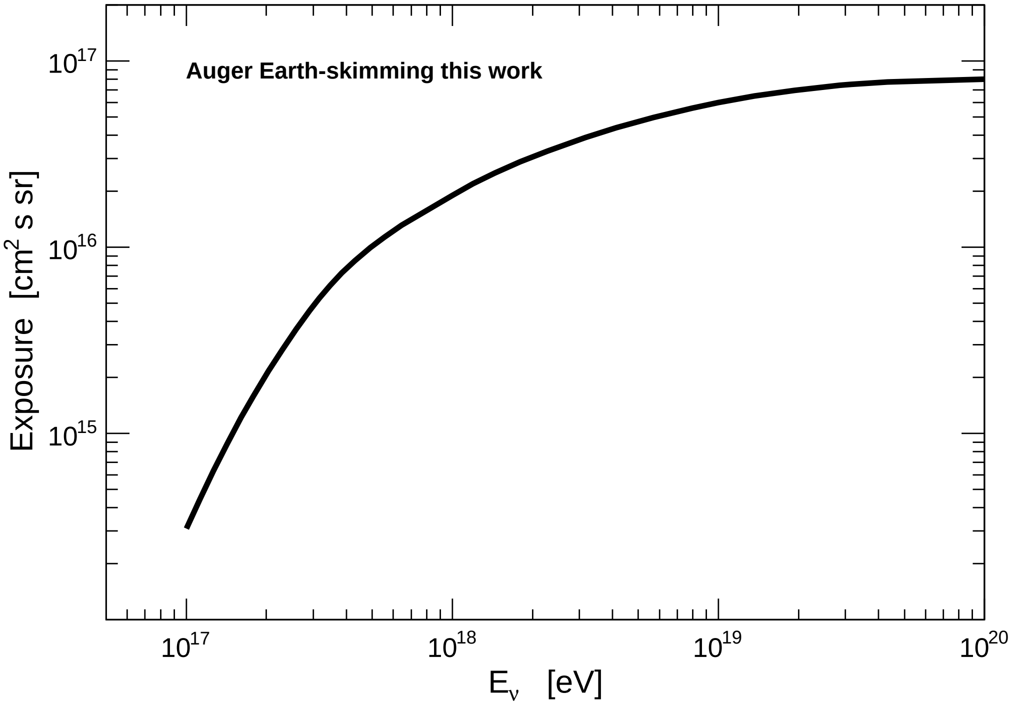

Fig. 1.— Exposure of the Surface Detector of the Pierre Auger Observatory for Earth-skimming neutrino initiated showers as a function of the neutrino energy, for data collected between 2004 January 1 and 2010 May 31.

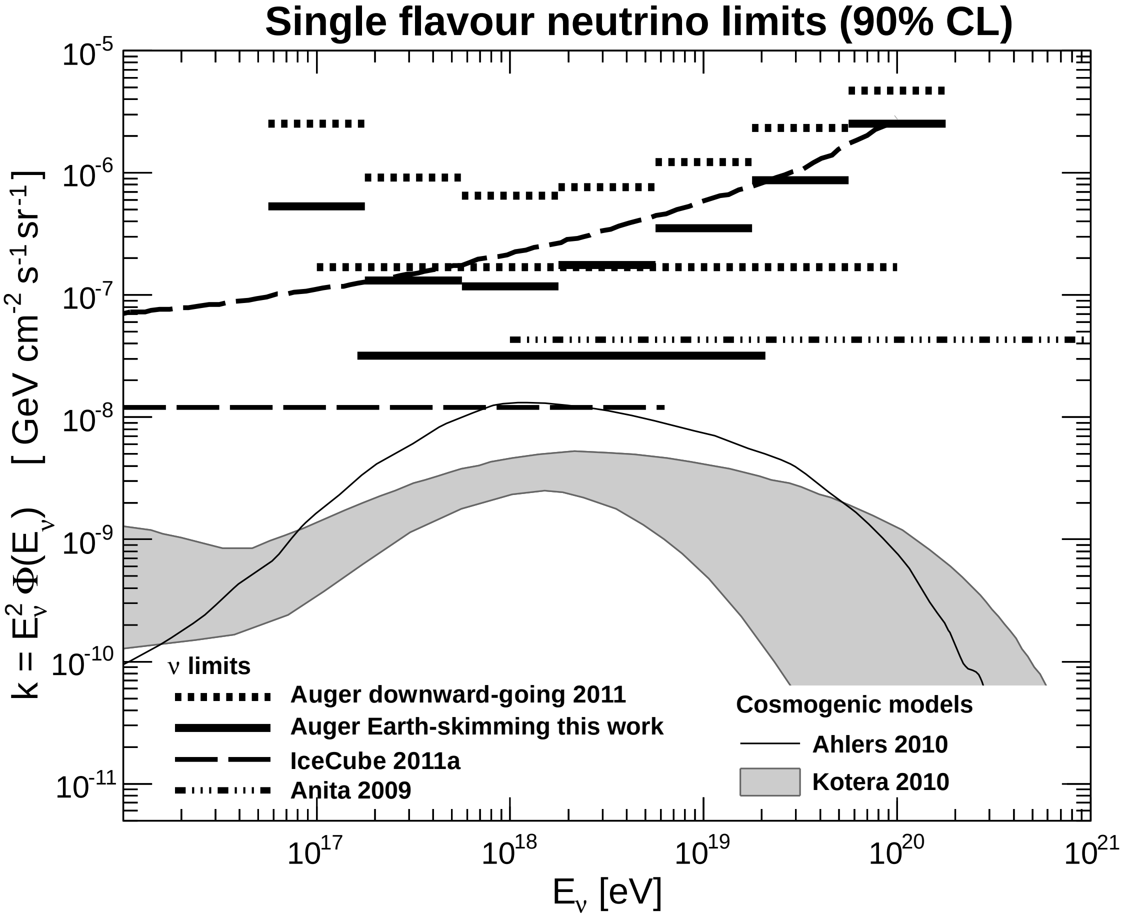

Fig. 2.— Differential and integrated upper limits at 90% C.L. on the single flavour $E_\nu^{-2}$ neutrino flux from the search for downward-going and Earth-skimming neutrinos at the Pierre Auger Observatory. Integrated upper limits are indicated by horizontal lines, with the corresponding differential limits being represented by segments of width 0.5 in $\log_{10} E_\nu$. Limits from the IceCube Neutrino Observatory Abbasi et al. (2011a) and from the ANITA experiment Gorham et al. (2010) are also shown after proper rescaling to account for single flavour neutrino flux and different energy binning. Predictions for cosmogenic neutrinos under different assumptions Ahlers et al. (2010); Kotera et al. (2010) are also shown, although predictions almost one order of magnitude lower or higher exist.

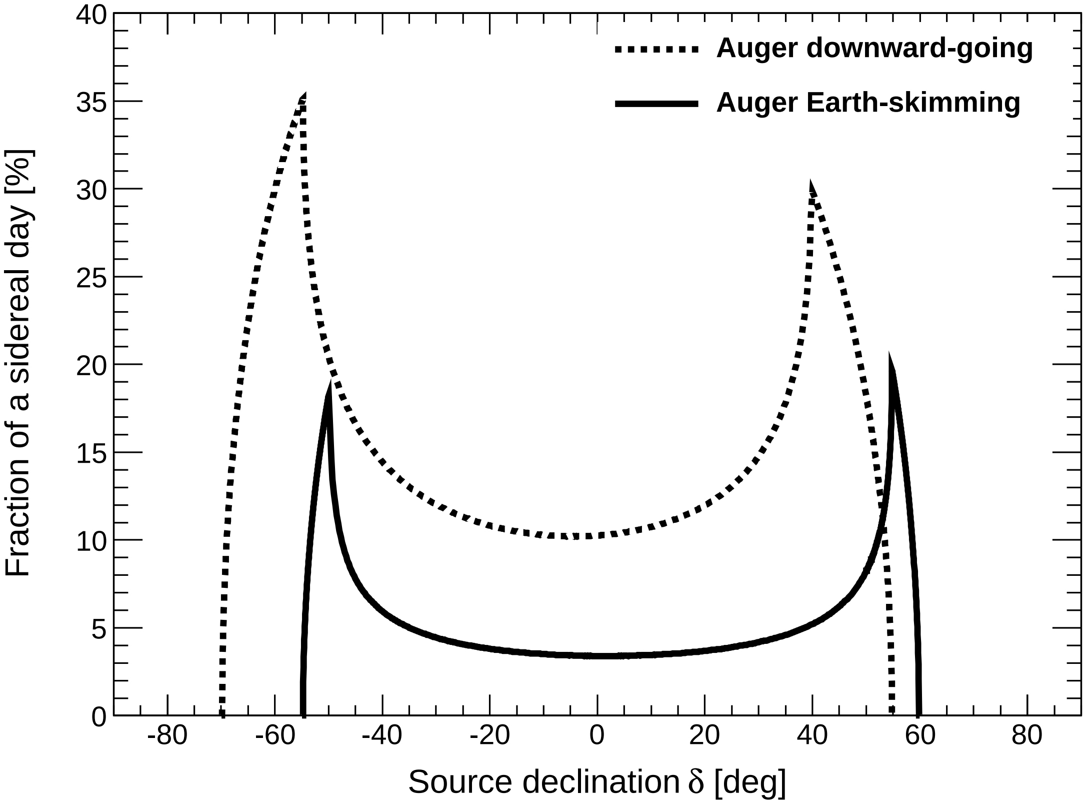

Fig. 3.— Fraction of a sidereal day having a point-like source at declination $\delta$ detectable by the Pierre Auger Observatory with the Earth-skimming and downward-going neutrino selection.

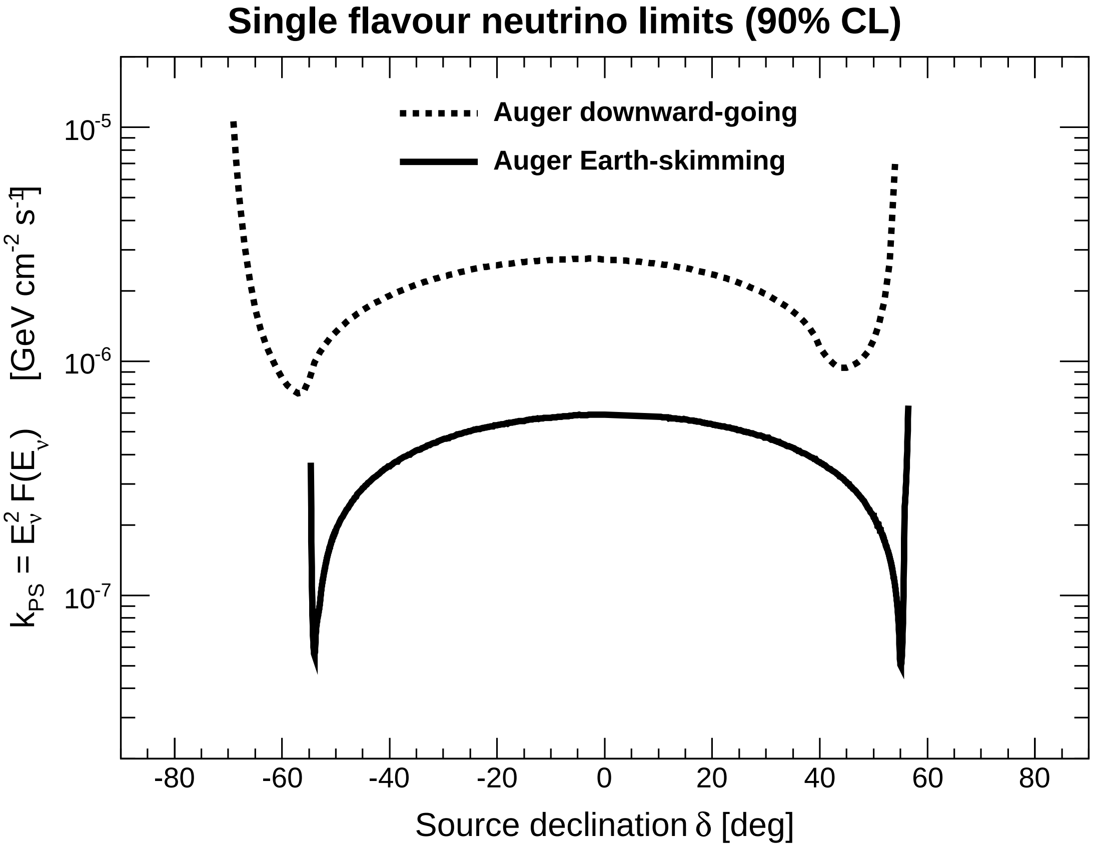

Fig. 4.— Upper limits at 90% C.L. on a single flavour $E_\nu^{-2}$ flux from a specific point-like source as a function of the source declination. The bounds from the Earth-skimming and downward-going neutrino analyses hold for a neutrino energy range $10^{17} - 10^{20}$ eV (see text for details).

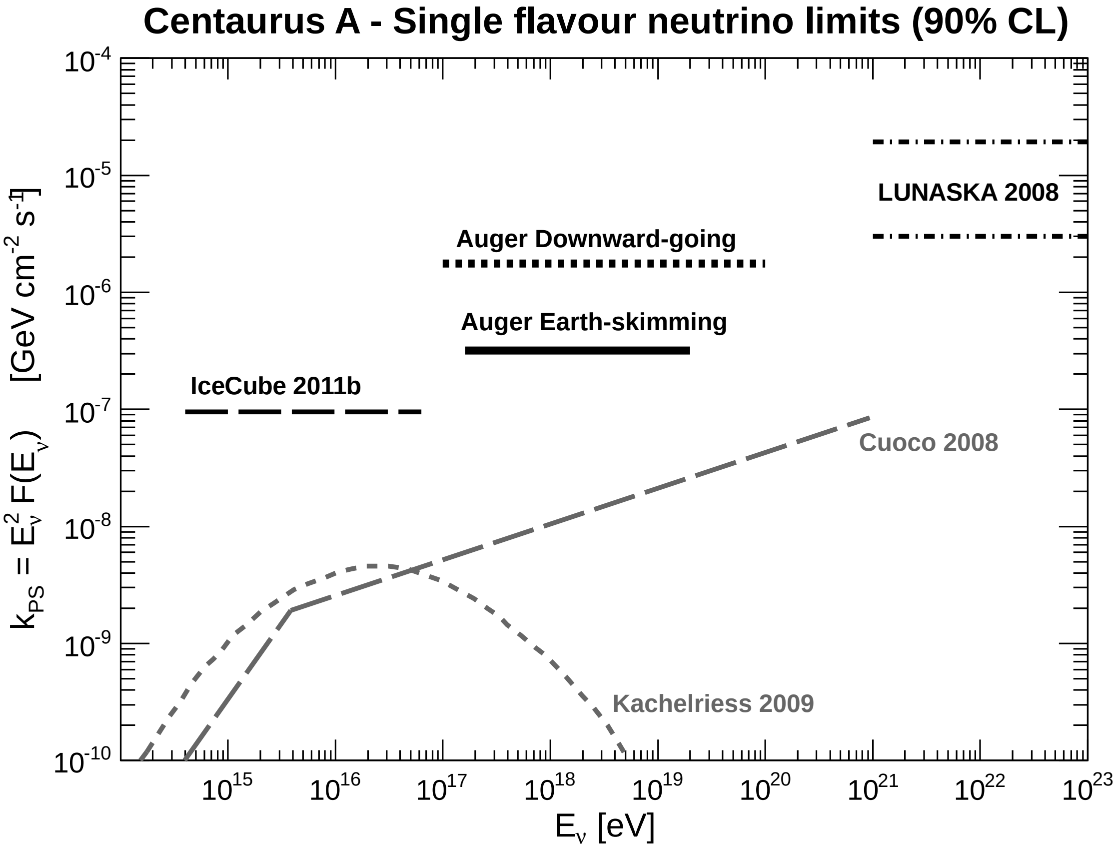

Fig. 5.— Upper limits at 90% C.L. on a single flavour $E_\nu^{-2}$ flux from the active galaxy Centaurus A from the Earth-skimming and downward-going neutrino analyses, together with bounds from the IceCube Neutrino Observatory Abbasi et al. (2011b) and LUNASKA James et al. (2011). The predictions for two models of UHE$\nu$ production – in the jets Cuoco & Hannestad (2008), and close to the core of Centaurus A Kachelriess et al. (2009) – are also shown.

## REFERENCES

Abbasi, R., Abdou, Y., Abu-Zayyad, T., et al. (IceCube Collaboration) 2011a, Phys. Rev. D, 83, 092003

Abbasi, R., Abdou, Y., Abu-Zayyad, T., et al. (IceCube Collaboration) 2011b, ApJ, 732, 18

Abraham, J., Abreu, P., Aglietta, M., et al. (Pierre Auger Collaboration) 2009, Phys. Rev. D, 79, 102001

Abraham, J., Abreu, P., Aglietta, M., et al. (Pierre Auger Collaboration) 2010a, Nucl. Instrum. Methods Phys. Res. A, 620, 227

Abraham, J., Abreu, P., Aglietta, M., et al. (Pierre Auger Collaboration) 2010b, Astropart. Phys., 31, 399

Abraham, J., Aglietta, M., Aguirre, I. C., et al. (Pierre Auger Collaboration) 2004, Nucl. Instrum. Methods Phys. Res. A, 523, 50

Abreu, P., Aglietta, M., Ahn, E. J., et al. (Pierre Auger Collaboration) 2011a, Phys. Rev. D, 84, 122005

Abreu, P., Aglietta, M., Ahn, E. J., et al. (Pierre Auger Collaboration) 2011b, Astropart. Phys., 34, 627

Adrián-Martínez, S., Aguilar, J. A., Samarai, I. A., et al. (Antares Collaboration) 2011, ApJ, 743, L14

Ahlers, M., Anchordoqui, L.A., Gonzalez-García, M.C., Halzen, F., & Sarkar, S. 2010, Astropart. Phys., 34, 106

Allekotte, I., Barbosa, A. F., Bauleo, P., et al. 2008, Nucl. Instrum. Methods Phys. Res. A, 586, 409

Alvarez-Muñiz, J., & Halzen, F. 2002, ApJ, 576, 33

Armesto, N., Merino, C., Parente, G., & Zas, E. 2008, Phys. Rev. D, 77, 013001

Ave, M., Busca, N., Olinto, A. V., Watson, A. A., & Yamamoto, T. 2005, Astropart. Phys., 23, 19

Becker, J.K. 2008, Phys. Rep., 458, 173

Berezinsky, V.S., & Zatsepin, G.T. 1969, Phys. Lett. B, 28, 423

Bhattacharjee, P., & Sigl, G. 2000, Phys. Rep., 327, 109

Cooper-Sarkar, A., & Sarkar, S. 2008, J. High Energy Phys., JHEP01(2008)075

Conrad, J., Botner, O., Hallgren, A., & Perez de los Heros, C. 2003, Phys. Rev. D, 67, 012002

Cuoco, A., & Hannestad, S. 2008, Phys. Rev. D, 78, 023007

Feldman, G.J., & Cousins, R.D. 1998, Phys. Rev. D, 57, 3873

Gaisser, T.K., Halzen, F., & Stanev, T. 1995, Phys. Rep., 258, 173

Gorham, P., Allison, P., Baughman, B. M., et al. (ANITA Collaboration) 2010, Phys. Rev. D, 82, 022004 (erratum: Phys. Rev. D, 85, 049901(E))

Guardincerri, Y. et al. (Pierre Auger Collaboration) 2011, in Proc. 32$^{\rm st}$ International Cosmic Ray Conference 2011 (Contribution No.0682), Beijing, China

Halzen, F., & Hooper, D. 2002, Rep. Prog. Phys., 65, 1025

Henley, E. M., & Jalilian-Marian, J. 2006, Phys. Rev. D, 73, 094004

James, C.W., Protheroe, R. J., Ekers, R. D., et al. (LUNASKA Collaboration) 2011, MNRAS, 410, 885

Kachelriess, M., Ostapchenko, S., & Tomas, R. 2009, New J. Phys., 11, 065017

Kotera, K., Allard, D., & Olinto, A. 2010, J. Cosmol. Astropart. Phys., JCAP10(2010)013

Nagano, M., & Watson, A. 2000, Rev. Mod. Phys., 72, 689

Stecker, F.W. 1973, Astrophys. Space Sci., 20, 47

---

This preprint was prepared with the AAS LaTeX macros v5.2.