

Discovering ultra-high-energy neutrinos with GRAND, the Giant Radio Array for Neutrino Detection

Mauricio Bustamante

Center for Cosmology and AstroParticle Physics (CCAPP)
The Ohio State University

WIPAC

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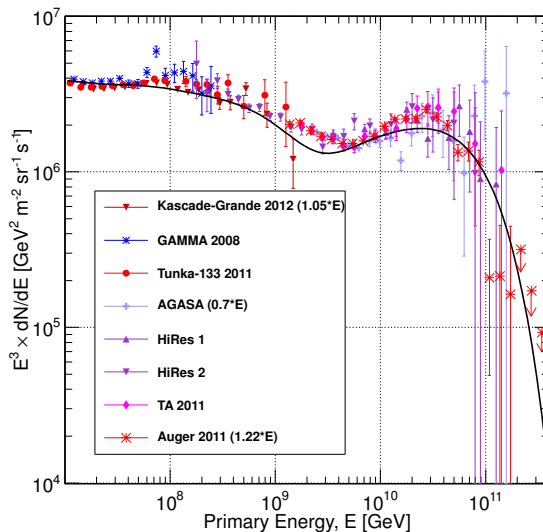


THE OHIO STATE UNIVERSITY



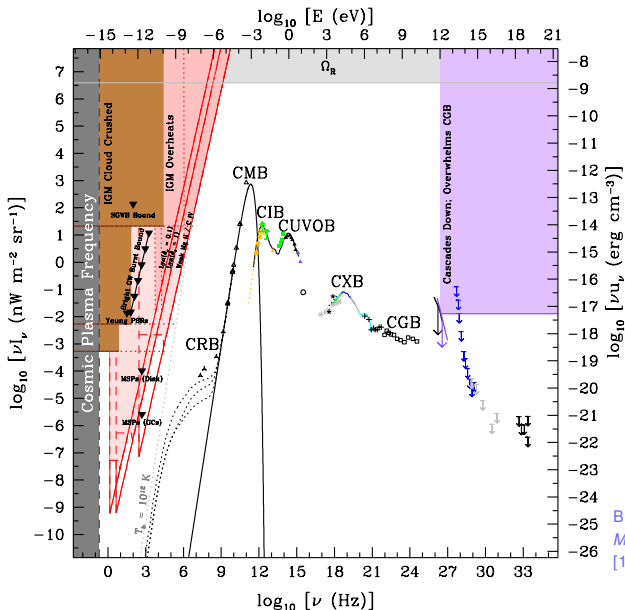
Ultra-high-energy cosmic rays

After 50+ years of UHECR measurements —



GAISSER, STANEV, TILAV,
Front. Phys. China 8, 748 (2013)
[1303.3565]

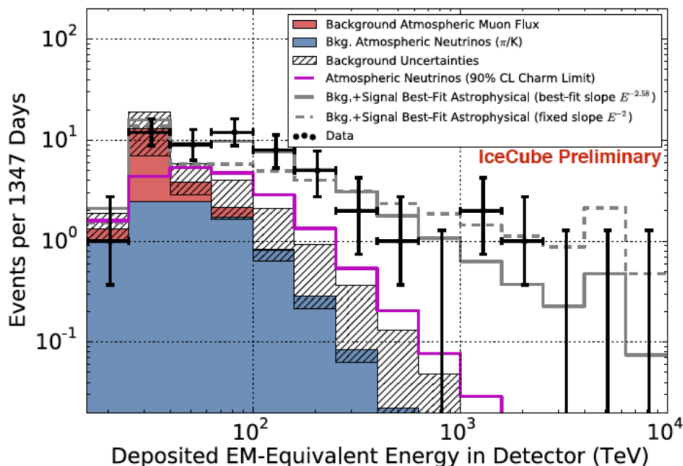
The electromagnetic sky



B. LACKI
MNRAS **406**, 863 (2010)
 [1004.2049]

High-energy astrophysical neutrinos: they exist!

IceCube has reported 54 events with 30 TeV–2 PeV in 4 years —



What lies beyond — cosmogenic neutrinos

We expect the $> \text{PeV}$ ν sky to be populated: cosmogenic neutrinos

They are produced in proton (or nuclei) interactions with CMB photons:

$$\underbrace{p}_{10^{20} \text{ eV}} + \underbrace{\gamma_{\text{CMB}}}_{0.1 \text{ meV}} \rightarrow \underbrace{\nu_{\mu} + \bar{\nu}_{\mu} + \nu_e + \dots}_{10^{18} \text{ eV} \equiv \text{EeV}}$$

We have not seen them — why are they worth looking for?

- ▶ They are sensitive to the UHECR composition (fewer ν 's if nuclei)
- ▶ They probe the high-redshift UHECR evolution
- ▶ Probe ν properties at previously unexplored energies
- ▶ (Because they are out there)

The problem: the flux is low. Possibly very low.

CMB photons are abundant but UHECRs are much less so

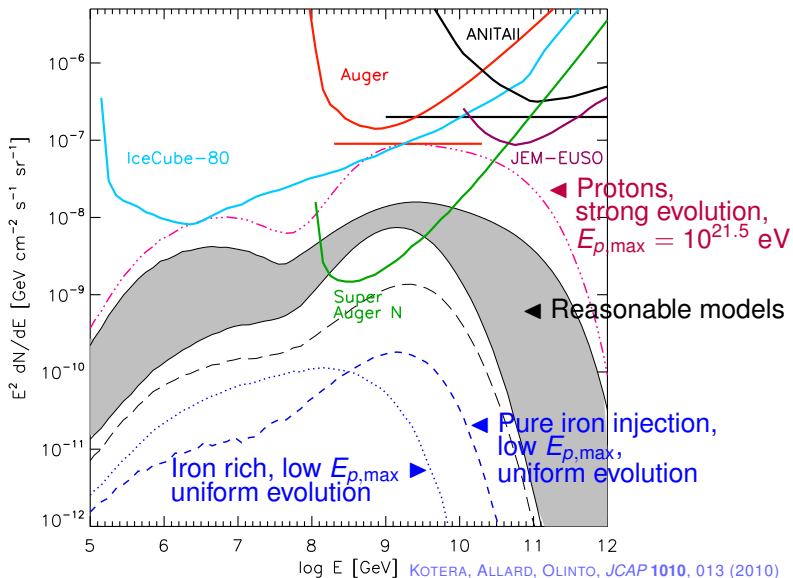
$\therefore$ The cosmogenic neutrino flux is low

The ν flux is affected by UHECR properties, *e.g.*,

- ▶ **composition**: lower for heavier composition
- ▶ **maximum CR energy**: lower for lower maximum energy
- ▶ **redshift evolution of source density**: lower for weaker evolution

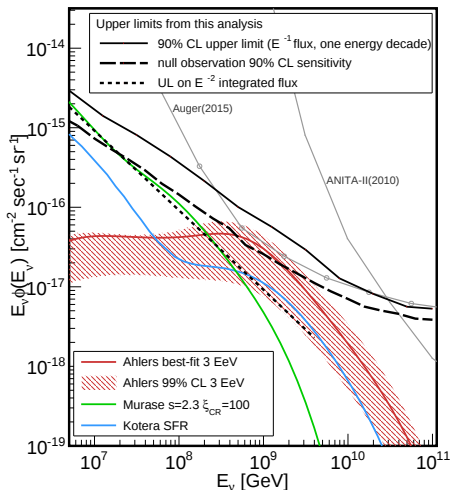
But at least the detection cross section (ν -nucleon) grows with energy

How low can low be?



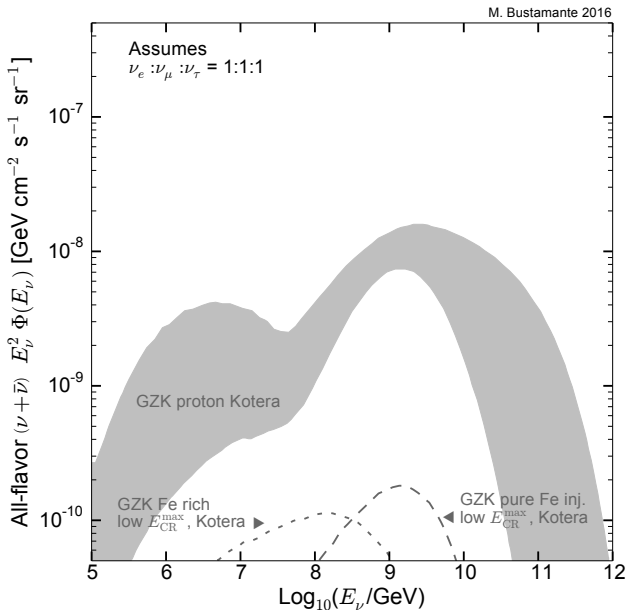
The present-day picture

The latest IceCube search (6 years) found two candidate events
— the most optimistic predictions are disfavored



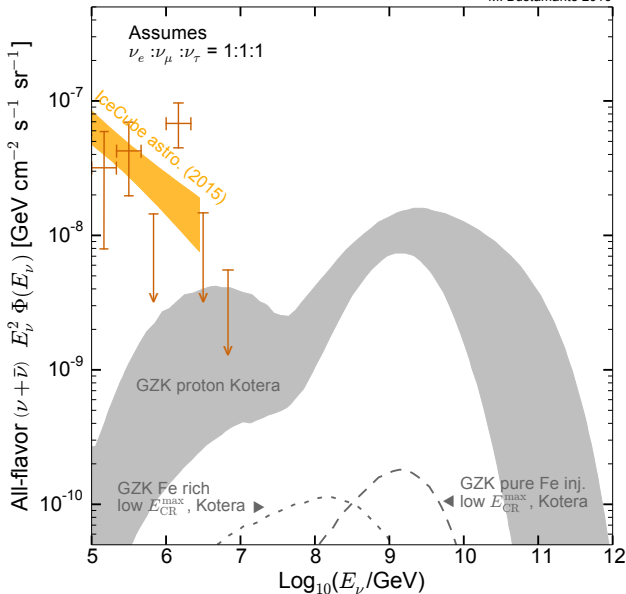
ICECUBE, 1607.05886

Predictions vs. detectors — now

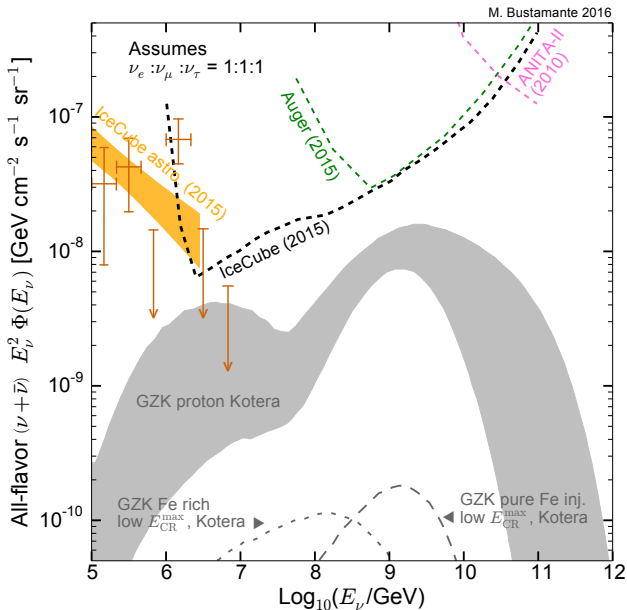


Predictions vs. detectors — now

M. Bustamante 2016



Predictions vs. detectors — now



The solution: build larger and/or build different

Two philosophies:

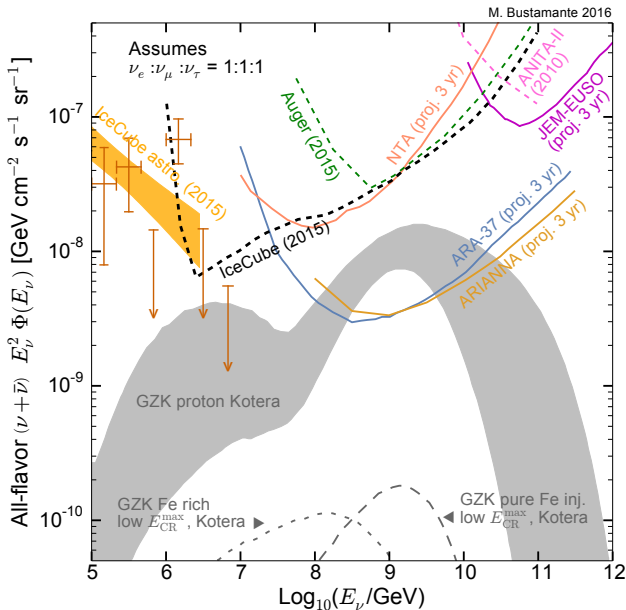
1 — Build larger water/ice Cherenkov detectors

- ▶ **Pro:** the technique is mature (IceCube-Gen2, KM3NeT)
- ▶ **Con:** unfeasible to cover very large area

2 — Use more suitable techniques: EAS detection

- ▶ **Pro:** surface arrays can cover large areas (*e.g.*, Auger, ANITA)
- ▶ **Con:** limited exposure, technique has not been as developed

Predictions vs. detectors — future



Sensitivity to pessimistic scenarios of cosmogenic neutrinos can realistically be achieved only with dedicated EAS detectors

How can the nightmare scenario be overcome?

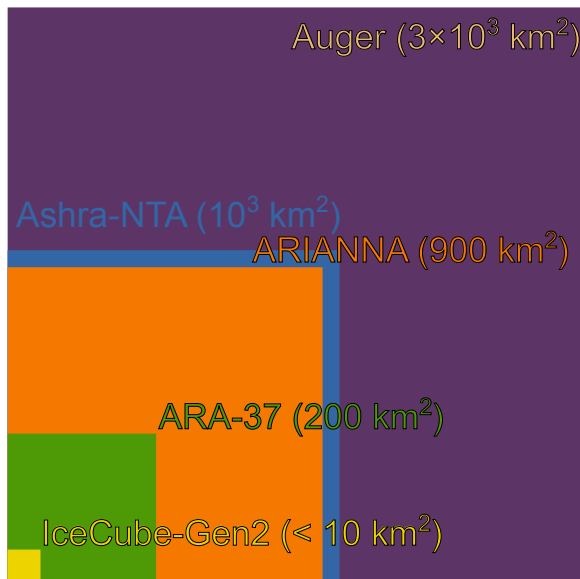
- 1 Build big. Really big.
- 2 Use radio emission — attenuation length is ~ 100 km in air

GRAND: Giant Radio Array for Neutrino Detection

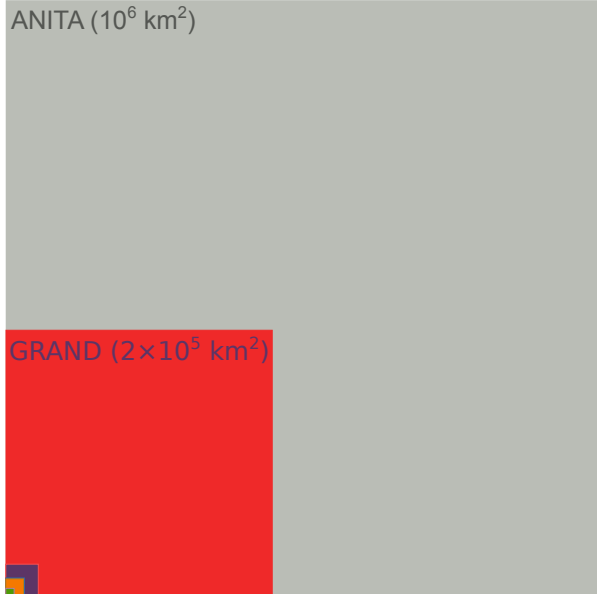


- ▶ Detects Earth-skimming ν_τ 's with $10^{8.5}$ – $10^{11.5}$ GeV
- ▶ Via radio emission of τ -initiated extensive air showers
- ▶ $\sim 10^5$ antennas covering 2×10^5 km²

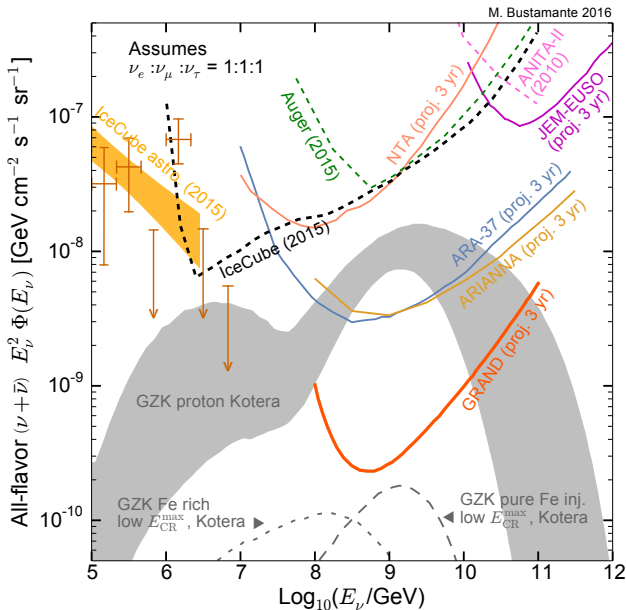
Building big — comparing the surface areas



Building big — comparing the surface areas



GRAND cuts deep



A win-win-win situation

For cosmogenic neutrinos, GRAND is ...

- ▶ ... a discovery *and* precision instrument for **optimistic** fluxes:
600–1400 events yr^{-1}
- ▶ ... a discovery instrument for **pessimistic** fluxes:
6–15 events yr^{-1}
- ▶ ... and a strong-exclusion instrument, if < 1 event yr^{-1}



Cosmogenic neutrinos — the quick and dirty review

- ▶ Assume first UHECRs ($> 10^8$ GeV) are protons
- ▶ Interaction with cosmological photons creates neutrinos of $\sim$ EeV:

$$p + \gamma \rightarrow \Delta^+(1232) \rightarrow \pi^+ + n$$

$$\pi^+ \rightarrow \mu^+ + \nu_{\mu}$$

$$\mu^+ \rightarrow \bar{\nu}_{\mu} + \nu_e + e^+$$

$$n \rightarrow \bar{\nu}_e + e + p$$

- ▶ Δ resonance is $\sim$ 50% of the total contribution
- ▶ More channels: heavier resonances, multi-pion production
(see, e.g., [HÜMMER et al., ApJ 721, 630 \(2010\) \[1002.1310\]](#))

Propagating the UHECRs to Earth

We propagate protons to Earth:

- ▶ Comoving number density of protons ($\text{GeV}^{-1} \text{cm}^{-3}$):

$$Y_p(E, z) = n_p(E, z) / (1 + z)^3,$$

with n_p the real number density

- ▶ Transport equation (comoving source frame):

$$\dot{Y}_p = \underbrace{\partial_E (H E Y_p)}_{\text{adiabatic losses}} + \underbrace{\partial_E (b_{e^+e^-} Y_p)}_{\text{pair production losses}} + \underbrace{\partial_E (b_{p\gamma} Y_p)}_{\text{photohadronic losses}} + \underbrace{\mathcal{L}_{\text{CR}}}_{\text{CR injection from sources}}$$

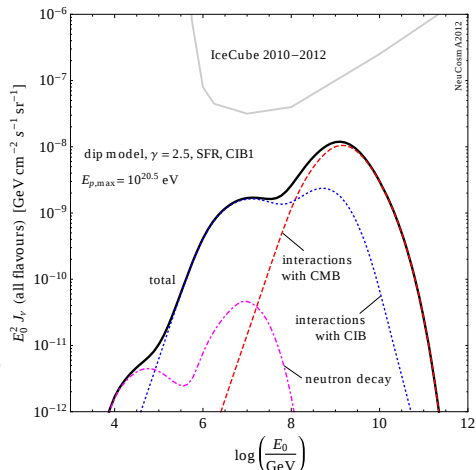
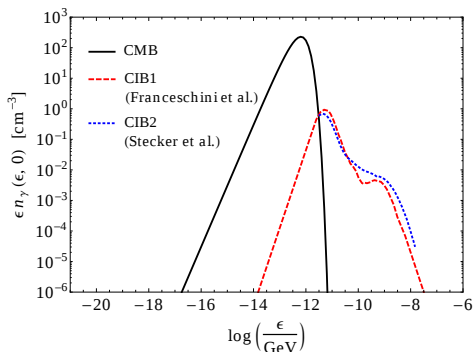
$Q_{\text{CR}}(E) \propto E^{-\alpha_p} e^{-E/E_{p,\text{max}}}$

Spectral shape

Two main photon targets:

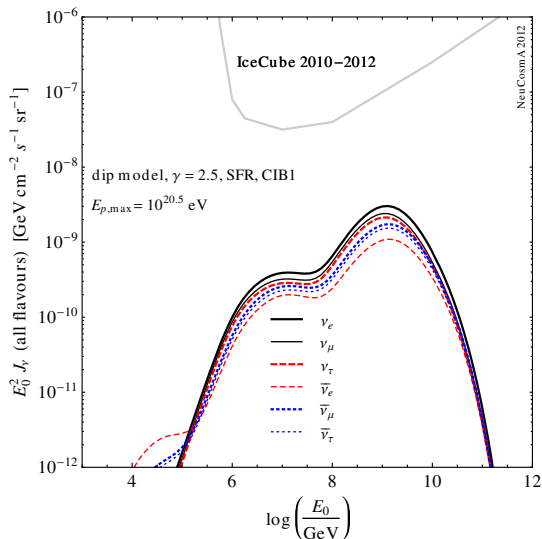
- ▶ CMB
- ▶ Cosmic infrared/optical background (CIB)

◀ Both evolve with redshift
 $\sim (1+z)^3$



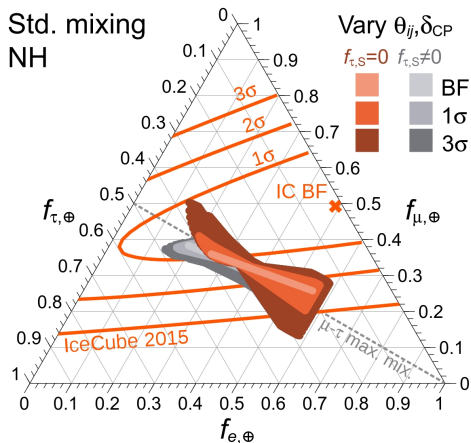
Cosmogenic neutrinos by flavor

Roughly equal flux of each flavor at Earth:



A “guaranteed” flux of cosmogenic ν_τ

- ▶ Assume unconstrained flavor composition at production time (with and w/o ν_τ)
- ▶ Vary the mixing parameters within their 1σ , 3σ ranges
- ▶ Use standard flavor mixing to find the flavor ratios at Earth, $f_{\alpha,\oplus}$
- ▶ **Guaranteed τ -flavor content between 15% – 50% of total**
- ▶ $\therefore$ A ν_τ signal is “guaranteed” even if we do not know the production mechanism
- ▶ Possible caveat: new physics



[MB, J. BEACOM, W. WINTER, *PRL* **115**, 161302 (2015) [1506.02645]]

Four UHECR knobs control cosmogenic neutrinos

The spectrum (shape and normalization) of cosmogenic neutrinos depends mainly on four UHECR properties:

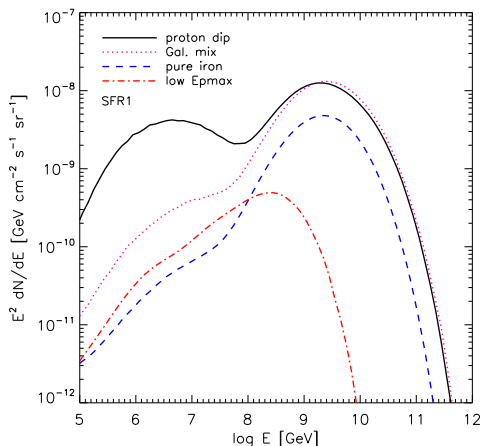
- 1 Mass composition
— heavier CRs make fewer ν 's
- 2 Redshift evolution of the density of CR sources
— more sources at high redshift result in more ν 's
- 3 Maximum CR energy reached at the sources
— higher maximum energy results in more ν 's
- 4 Spectral index of the CR injection spectrum
— complicated dependence, depends on the other parameters

Also:

- 5 Start energy of the transition to extragalactic CRs

Cosmogenic neutrinos — three broad scenarios

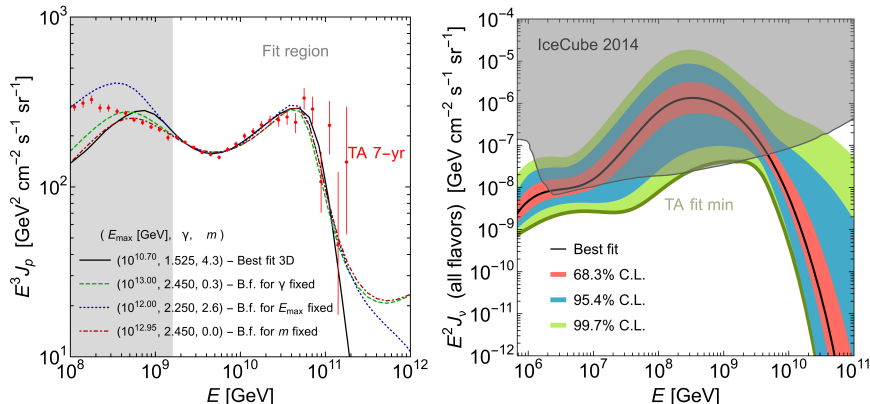
- 1 UHECRs are mostly extragalactic protons above 10^9 GeV
— “proton dip model”
- 2 UHECRs are mostly extragalactic protons above the ankle (4 EeV)
— “ankle model”
- 3 UHECRs are a mix of nuclei,
maybe dominated by heavy ones
— “mixed composition”



KOTERA, ALLARD, OLINTO, *JCAP* **1010**, 013 (2010)

Challenging the proton dip

We can fit UHECR pure-proton fluxes to 7-year TA spectrum — the associated cosmogenic ν fluxes already overshoot the IceCube bound:

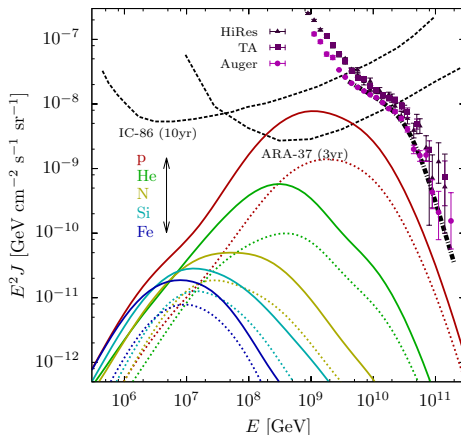


This challenges a pure proton UHECR composition

J. HEINZE, D. BONCIOLI, MB
W. WINTER, *ApJ* **825**, 122 (2016)

Cosmogenic ν 's from mixed-composition UHECRs

- ▶ Nuclei photodisintegrate on the CMB: $A + \gamma \rightarrow (A - 1) + n$
- ▶ Less efficient at producing neutrinos
- ▶ In ankle models, minimum fluxes yield $\lesssim 1$ event yr^{-1} in GRAND:



M. AHLERS, F. HALZEN, *PRD* **86**, 083010 (2012)

High-energy neutrino interactions

- ▶ $\gtrsim 100$ GeV ν -nucleon interactions are deep-inelastic scattering
- ▶ $\gtrsim 100$ TeV: outgoing leptons carry $\sim 70\%$ of the initial ν energy

Neutral current: $\nu_l + N \rightarrow \nu_l + X$

- ▶ Final hadrons X create hadronic shower
- ▶ $\sigma_{\text{NC}} \approx 0.4 \sigma_{\text{CC}}$
- ▶ Compensated by three flavors
- ▶ NC showers have $E_{\text{sh}} \approx 0.3 E_\nu$
- ▶ So they are subdominant

Charged current: $\nu_l + N \rightarrow l + X$

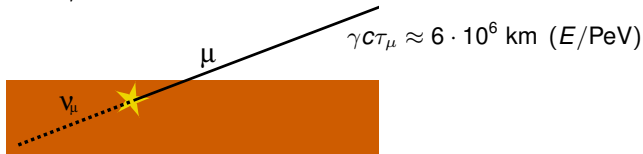
- ▶ ν_μ : final μ creates muon track
- ▶ ν_e : final e creates e.m. shower
- ▶ ν_τ : final τ creates hadronic (e.m.) shower 83% (17%) of the time
- ▶ CC showers have $E_{\text{sh}} \approx E_\nu$

What happens to CC showers of different flavors?

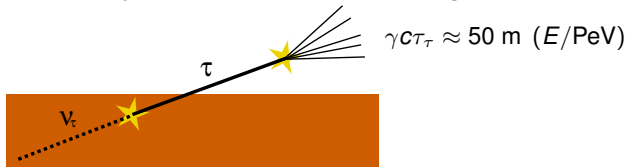
- ▶ The electron from CC ν_e quickly showers underground



- ▶ The muon from CC ν_μ travels into air and decays much later



- ▶ The tau from CC ν_τ decays in air and creates a large shower



Using radio emission to detect neutrinos

In 1992, Zas, Halzen, and Stanev discussed radio detection of ν 's:

“It has been claimed that the relatively **low cost of electromagnetic [radio] pulse detectors may allow a large detection area to be covered with arrays of aerials**, providing a cost effective method for detection of neutrino interactions in the energy range above 1 TeV.”

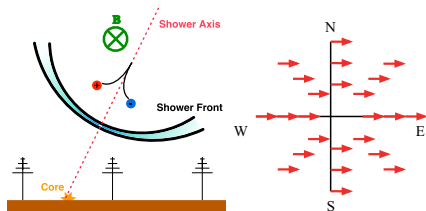
And they found large arrays are necessary:

“To sample 1 km in depth, a 5-PeV neutrino is anticipated and the existing limits on high energy neutrinos imply **very low event rates unless detectors of area much larger than 1 km² are considered.**”

PRD 45, 362 (1992)

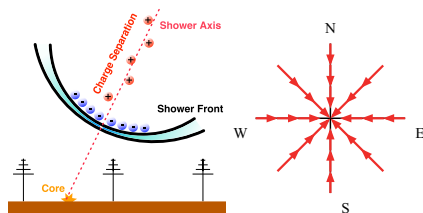
Radio emission: Askaryan and geomagnetic

Geomagnetic



- ▶ Time-varying transverse current
- ▶ Linearly polarized in the direction of the Lorentz force
- ▶ **Main mechanism in air showers**

Askaryan

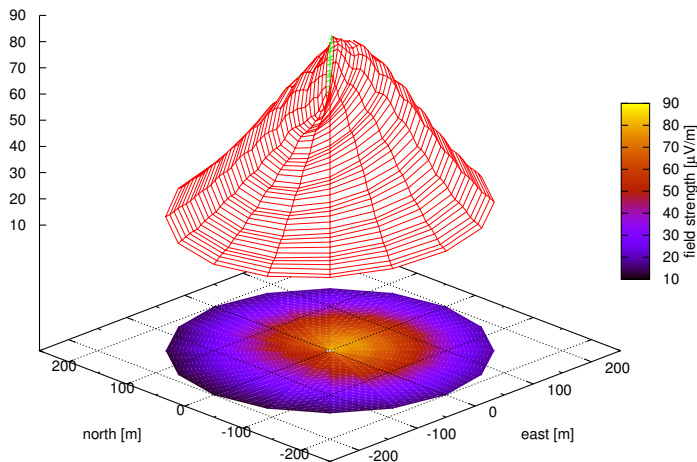


- ▶ Time-varying negative charge excess $\sim 20\%$
- ▶ Linearly polarized towards axis
- ▶ Subdominant in air showers (dominant in ice)

FIGURES BY H. SCHOORLEMMER AND K. D. DE VRIES

Lateral distribution of the radio signal

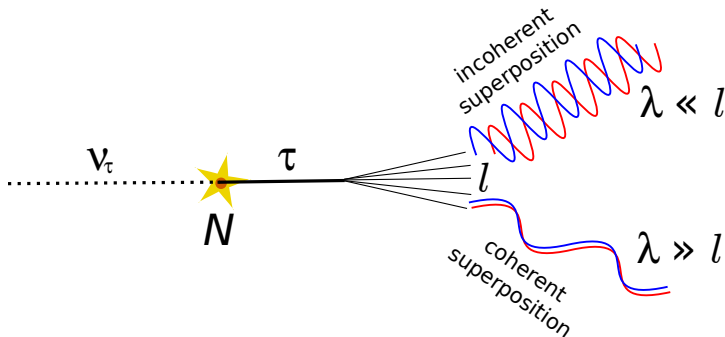
A superposition of geomagnetic and Askaryan emission:



CoREAS simulation from [HUEGE, LUDWIG, JAMES, *AIP Conf. Proc.* **1535**, 128 \(2013\)](#)

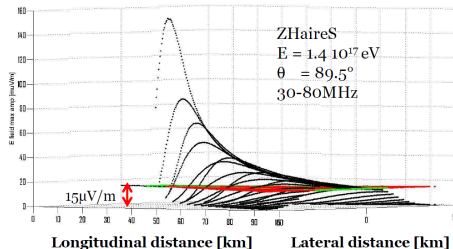
Coherent emission

- ▶ The shower front moves compactly as a “particle pancake” ~ 1 cm thick and a few cm wide
- ▶ At radio wavelengths, emission adds coherently:



EAS radio detection

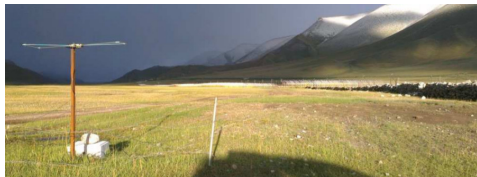
- ▶ Radio antennas are well-suited for very large arrays:
 - ▶ They are simple detectors
 - ▶ Extensive technical development
- ▶ Atmosphere transparent to radio
- ▶ Emission from horizontal EAS of $\gtrsim 2 \cdot 10^8$ GeV still detectable 100 km away from interaction vertex
- ▶ Short waves prevent detection below 25 MHz
- ▶ Sky noise level: $15 \mu\text{V m}^{-1}$ for 30–100 MHz



ADAPTED FROM O. MARTINEAU

TREND, the predecessor of GRAND (2011-2014)

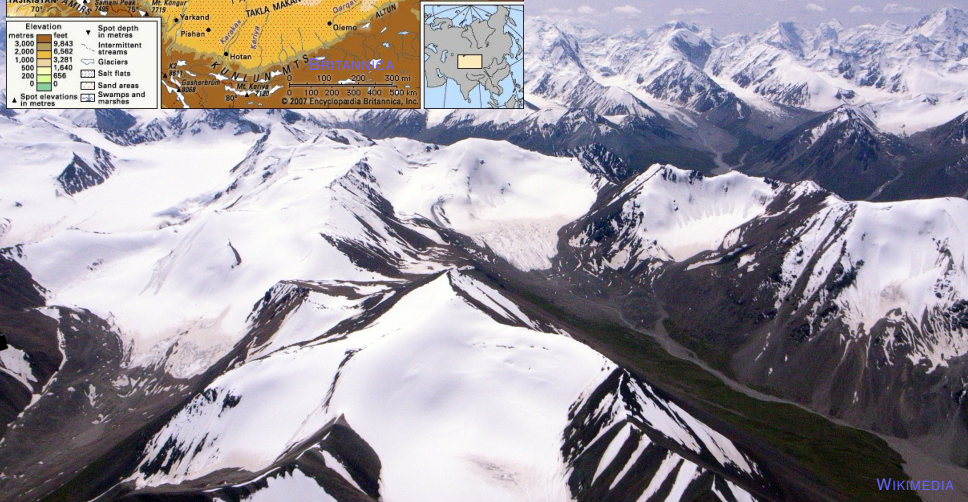
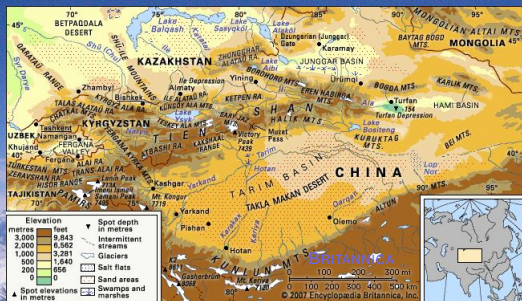
- ▶ TREND: Tianshan Radio Experiment for Neutrino Detection
- ▶ 50 monopolar antennas deployed over 1.5 km²
- ▶ Proposed in 2008 by D. Ardouin *et al.* [*Astropart. Phys.* **34**, 717 (2011) [1007.4359]]
- ▶ Site: Ulastai, XinJiang Province, China (21CMA interferometer site)
- ▶ **Main goal:** autonomous EAS radio detection and identification
- ▶ 465 EAS candidates in 317 live days (offline analysis)



Goal achieved:
autonomous EAS detection with radio
antennas is possible

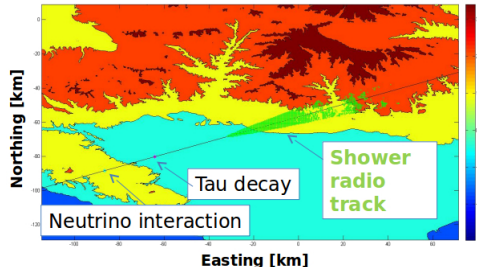
ADAPTED FROM O. MARTINEAU





GRAND sensitivity study — setup

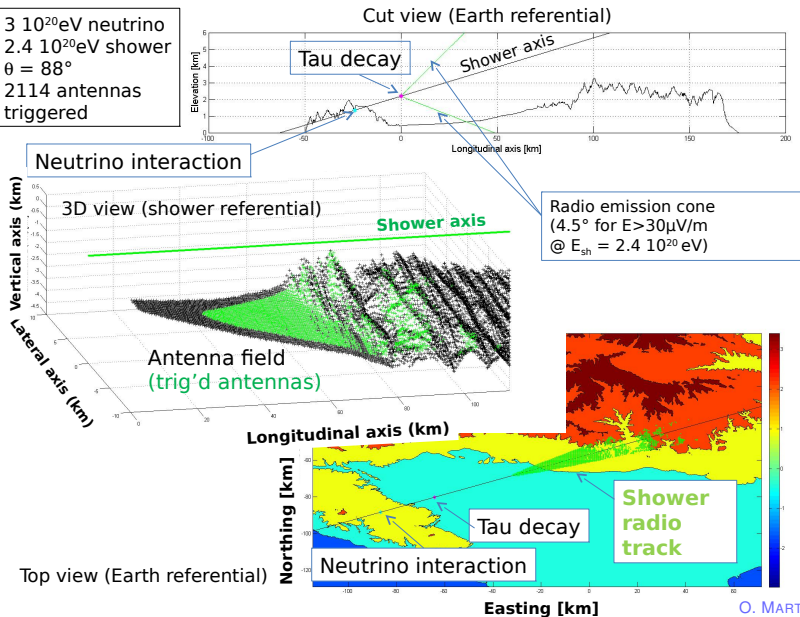
- ▶ MC simulation includes:
 - ▶ ν_τ propagation
 - ▶ τ propagation + decay
 - ▶ shower development
 - ▶ radio emission
- ▶ Primary energy 10^8 – 10^{12} GeV
- ▶ Earth-skimming only:
 $\pm 4^\circ$ around the horizon
- ▶ Mountains are sizeable targets: $\sim 40\%$ of total
- ▶ Antenna triggers if:
 - ▶ In direct view of shower
 - ▶ Inside a light cone of a few degrees (0.5 – 3°)
 - ▶ τ decay vertex is 14 – 120 km away
- ▶ Shower detected if one cluster of $8+$ antennas fired
- ▶ Simulation array: 90000 antennas over $220 \times 270 \approx 60000$ km² in Tianshan mountains (800 m step size)



ADAPTED FROM O. MARTINEAU

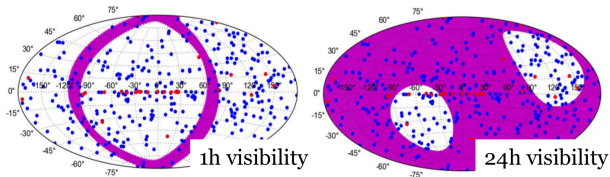
GRAND sensitivity study – simulation

3 10^{20} eV neutrino
2.4 10^{20} eV shower
 $\theta = 88^\circ$
2114 antennas triggered

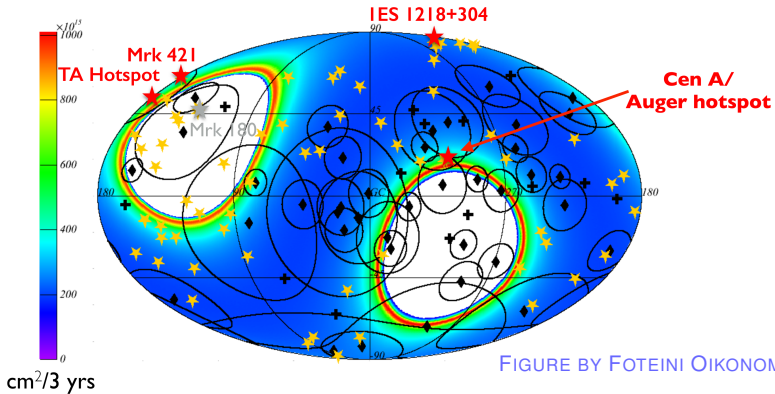


O. MARTINEAU

GRAND field of view — at 1 EeV

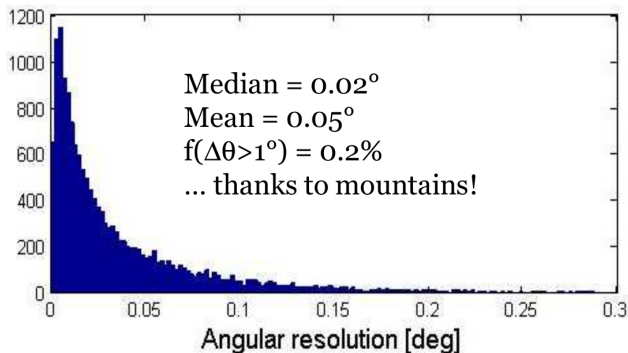


3-year average:



GRAND angular resolution

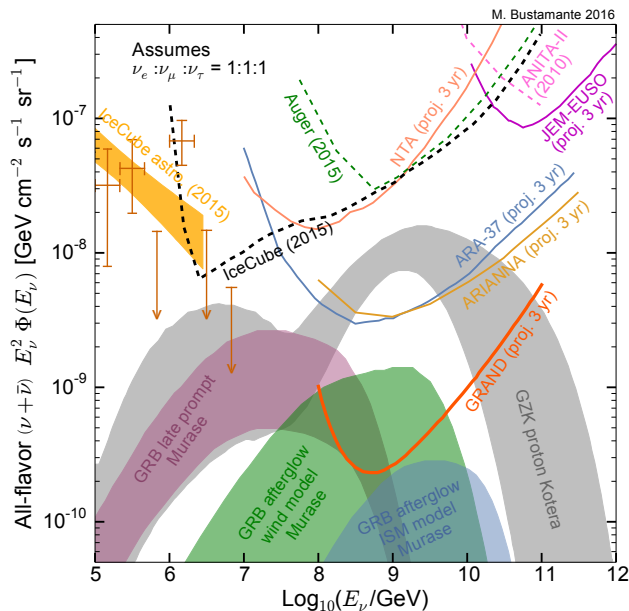
- ▶ Computed analytically for all detected showers following simulation by Ardouin *et al.* [\[1007.4359\]](#)
- ▶ Assumes 3 ns trigger timing precision
- ▶ High resolution due to extended trigger zone



Main goal: discovery of cosmogenic neutrinos regardless of flux

- ▶ Point sources
- ▶ Transient sources
- ▶ Neutrinos from GRB afterglows
- ▶ UHECR detection (á la AERA)
- ▶ Flavor composition at EeV
- ▶ New physics

Sensitivity to GRB afterglow neutrinos

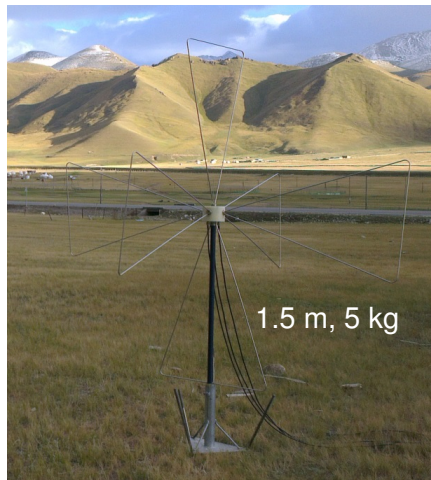


- ▶ GRAND **vastly** outperforms all others
- ▶ Only one capable of probing the GRB afterglow ν 's after 3 yrs
- ▶ Event rates in 3 yrs ($10^{8.5} - 10^{11.5}$ GeV):
 - ▶ Late prompt: 28–154
 - ▶ Afterglow wind: 4–400
 - ▶ Afterglow ism: 0.6–66
- ▶ (Ongoing work MB, I. Tamborra)

Challenge: antenna design and deployment

- ▶ How realistic/affordable is it to deploy, run, and maintain an array of 200 000 antennas?
- ▶ Answer: **keep it as basic as possible**
 - ▶ Basic (analog) trigger on transient signal
 - ▶ Record 4 words/trigger (max. amplitude $\times$ 3 channels + GPS trigger time)
 - ▶ Rely on commercial solutions for electronics and data transfer
- ▶ **<1 W and < USD 500 / antenna**
- ▶ Total budget (instrument):

$$\frac{\text{USD } 500}{\text{antenna}} \cdot 10^5 \text{ antennas} = \text{USD } 50 \text{ million}$$



ADAPTED FROM K. KOTERA

Challenge: background rejection

① Atmospheric muons and neutrinos: negligible above 10^7 GeV



② UHECR showers can be filtered out by looking below the horizon:

- ▶ Only use showers coming from 1° below horizon
- ▶ For 0.2° angular resolution, suppression factor is $5 \cdot 10^{-7}$
- ▶ Affects marginally the detection efficiency ($< 10\%$)



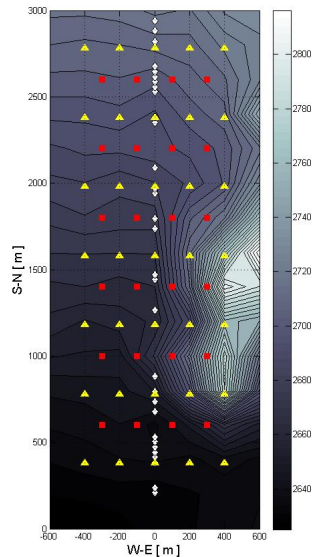
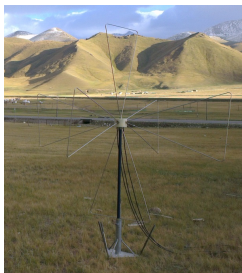
③ Terrestrial (man-made) background:

- ▶ Scaling up TREND background yields $\sim 3 \cdot 10^8$ events yr^{-1}
- ▶ To see a neutrino signal of $\sim 0\text{--}100$ events yr^{-1} , we need a rejection factor of $\sim 10^9$
- ▶ How?
 - cut out data from the direction of known man-made sources
 - filter by trigger pattern on the ground?
 - use polarization?



GRANDproto

- ▶ **Hybrid setup:** 35 3-polar antennas + 24 scintillators
- ▶ Deployed at the noisiest location of the TREND array
- ▶ **Target:** (standard) air showers coming from the north with $40^\circ < \theta_z < 70^\circ$
- ▶ **Principle:** select radio candidates from polar information, use scintillators as cross-check
- ▶ Quantitative determination of the rejection factor
- ▶ Deployment ongoing
- ▶ Proposal to perform similar tests at Auger-AERA



France:

- ▶ Olivier Martineau-Huynh (LPNHE, CNRS-IN2P3, Universités Paris VI & VII)
- ▶ Kumiko Kotera (Institut d'Astrophysique de Paris)
- ▶ Didier Charrier (SUBATECH, CNRS-IN2P3, Université de Nantes)
- ▶ Valentin Niess (Clermont Université, Université Blaise Pascal, CNRS-IN2P3)
- ▶ Nicolas Renault-Tinacci (Institut d'Astrophysique de Paris)

23 people
Expertise from TREND
and theory

USA:

- ▶ Mauricio Bustamante (Center for Cosmology and AstroParticle Physics, The Ohio State University)
- ▶ Ke Fang (University of Maryland)
- ▶ Kohta Murase (Pennsylvania State University)
- ▶ Foteini Oikonomou (Pennsylvania State University)
- ▶ Jordan Hanson (Center for Cosmology and AstroParticle Physics, The Ohio State University)

Netherlands, Belgium, Sweden:

- ▶ Charles Timmermans (Nikhef/Radboud University, The Netherlands)
- ▶ Sijbrand De Jong (Nikhef/Radboud University, The Netherlands)
- ▶ Krijn D. de Vries (Vrije Universiteit Brussel, Belgium)
- ▶ Chad Finley (Oskar Klein Centre and Dept. of Physics, Stockholm University, Sweden)

China:

- ▶ Zhaoyang Feng (Key Laboratory of Particle Astrophysics, Institute of High Energy Physics)
- ▶ Quanbu Gou (Key Laboratory of Particle Astrophysics, Institute of High Energy Physics)
- ▶ Junhua Gu (National Astronomical Observatory)
- ▶ Hongbo Hu (Key Laboratory of Particle Astrophysics, Institute of High Energy Physics)
- ▶ Zhen Wang (Key Laboratory of Particle Astrophysics, Institute of High Energy Physics)
- ▶ Xiangping Wu (National Astronomical Observatory)
- ▶ Jianli Zhang (National Astronomical Observatory)
- ▶ Yi Zhang (Key Laboratory of Particle Astrophysics, Institute of High Energy Physics)

GRAND activities and documentation

GRAND workshops and slides:

- ▶ **GRAND workshop**

LPNHE, Paris, Feb 2015

<http://indico.in2p3.fr/event/10976/>

- ▶ **GRAND mini-workshop**

KICP, Chicago, Dec 2015

<http://kicp.uchicago.edu/kicp-workshops/grand2015/>

GRAND proceedings:

- ▶ **ICRC 2015**

<http://arxiv.org/abs/1508.01919>

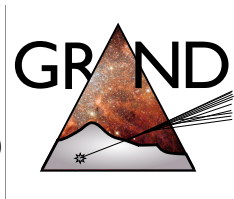
- ▶ **VLVnT 2015**

<https://goo.gl/hbIJbI>

White paper: soon!

GRAND: an instrument to discover cosmogenic neutrinos even in nightmare scenarios and to make precision measurements otherwise

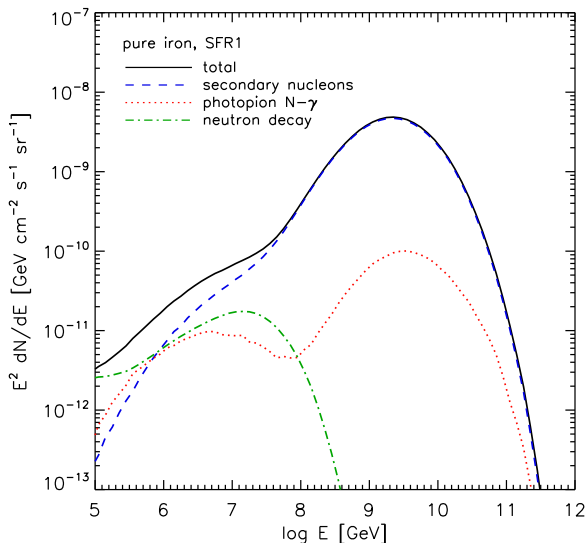
- ▶ A great tool for multi-messenger astronomy
- ▶ GRAND proposal is being set up (science case + detailed simulations)
- ▶ Timeline:
 - ▶ 2016-2023: GRANDproto23 + GRANDproto300
 - ▶ 2028: GRAND3k completed
 - ▶ 2033: GRAND30k completed
 - ▶ 2038: GRAND200k completed



Join us!

Backup slides

Neutrino production with heavy UHECRs



KOTERA, ALLARD, OLINTO, *JCAP* **1010**, 013 (2010)

Why should we expect ν'_τ s?

- ▶ Neutrino production via pion decay:

$$p\gamma \rightarrow \Delta^+(1232) \rightarrow \pi^+ n \quad \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \bar{\nu}_\mu \nu_\mu$$

- ▶ Flavor ratios at the **source**: $(f_e : f_\mu : f_\tau)_S \approx (1/3 : 2/3 : 0)$
- ▶ At **Earth**, due to flavor mixing:

$$f_{\alpha,\oplus} = \sum_{\beta} P_{\nu_\beta \rightarrow \nu_\alpha} f_{\beta,S} = \sum_{\beta} \left(\sum_{i=1}^3 |U_{\alpha i}|^2 |U_{\beta i}|^2 \right) f_{\beta,S}$$

$$(1/3 : 2/3 : 0)_S \xrightarrow{\text{flavor mixing, NH, best-fit}} (0.36 : 0.32 : 0.32)_{\oplus}$$

- ▶ Other compositions at the source:

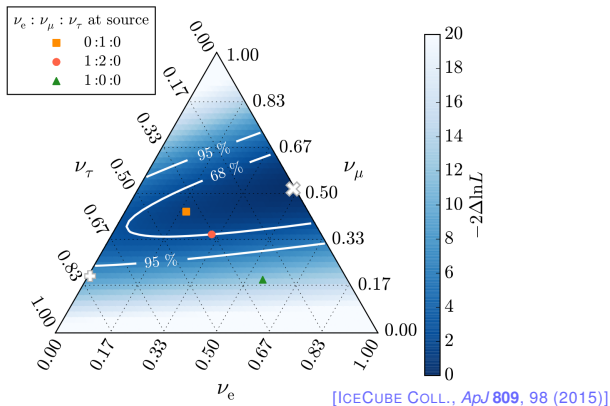
$$(0 : 1 : 0)_S \longrightarrow (0.26 : 0.36 : 0.38)_{\oplus} \text{ (“muon damped”)}$$

$$(1 : 0 : 0)_S \longrightarrow (0.55 : 0.26 : 0.19)_{\oplus} \text{ (“neutron decay”)}$$

$$(1/2 : 1/2 : 0)_S \longrightarrow (0.40 : 0.31 : 0.29)_{\oplus} \text{ (“charmed decays”)}$$

IceCube analysis of flavor composition

Using contained events + throughgoing muons:



- ▶ Best fit: $(f_e : f_\mu : f_\tau)_\oplus = (0.49 : 0.51 : 0)_\oplus$
- ▶ Compatible with standard source compositions
- ▶ Bounds are weak – need more data and better flavor-tagging

Event rate calculation

Number of events:

$$N_{\nu} = 2\pi \cdot t_{\text{exp}} \cdot f_{\tau,\oplus} \times \int_{10^{8.5}}^{10^{11.5}} dE_{\nu} \int_{86^{\circ}}^{93^{\circ}} \sin \theta_z d\theta_z A_{\text{eff}}(E_{\nu}, \theta_z) \Phi_{\nu_{\text{all}}}(E_{\nu}) ,$$

where

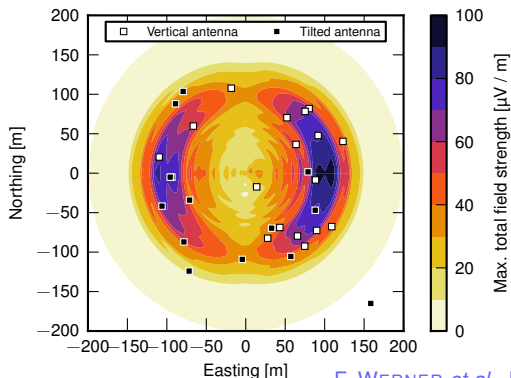
$t_{\text{exp}} = 3 \text{ yr}$: detector exposure time

$f_{\tau,\oplus}$: fraction of total flux that is $\nu_{\tau} + \bar{\nu}_{\tau}$ – assumed 1/3 here

$\Phi_{\nu_{\text{all}}}$: diffuse all-flavor ($\nu + \bar{\nu}$) flux

Cherenkov ring

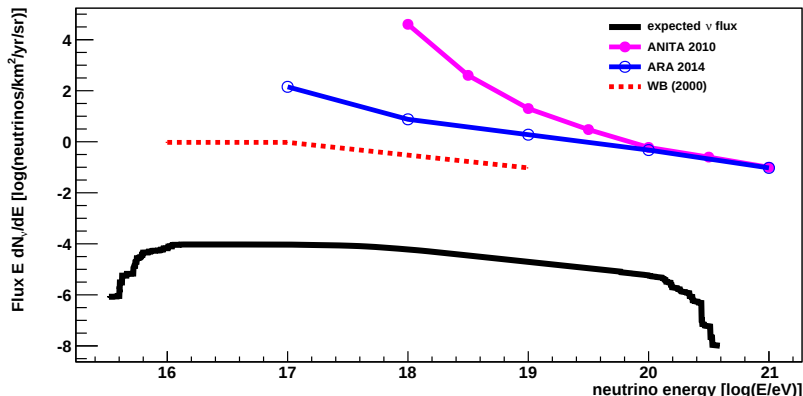
- ▶ Air shower front travels at $\sim$ light speed
- ▶ Radio signal propagates more slowly due to refractive index
- ▶ This leads to Cherenkov-like time compression of radio pulses with high power
- ▶ Seen by CROME in the 3.4–4.2 GHz band (CoREAS overlaid):



F. WERNER *et al.*, ICRC 2013

Afterglow ν predictions for radio neutrino detectors

From recent work [G. NIR, D. GUETTA, H. LANDSMAN, E. BEHAR, [1511.07010]]:

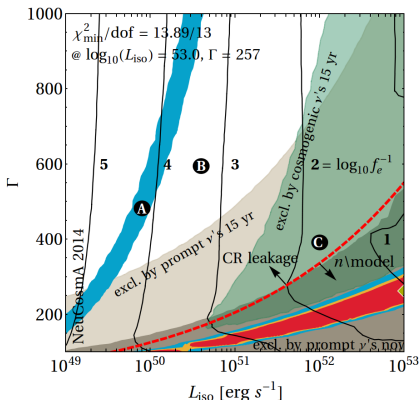


- ▶ $\lesssim 3 \cdot 10^{-11} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ needs > 3 yr of GRAND exposure
- ▶ Alternative calculation with more models and parameter variations in preparation (MB, I. Tamborra)

Probing UHECR + neutrino production in GRBs

If no cosmogenic ν 's are detected in 15 yr, the parameter space for GRBs as sources of UHECRs + ν 's will be tightly constrained —

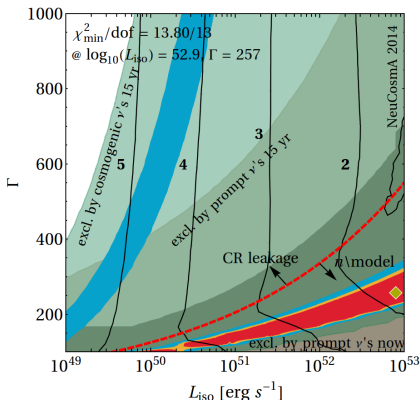
direct p escape, $\eta = 1.0$



$$n_{\text{GRB}}(z) \propto \rho_{\text{SFR}}(z)$$

(star formation rate)

direct p escape, $\eta = 1.0$

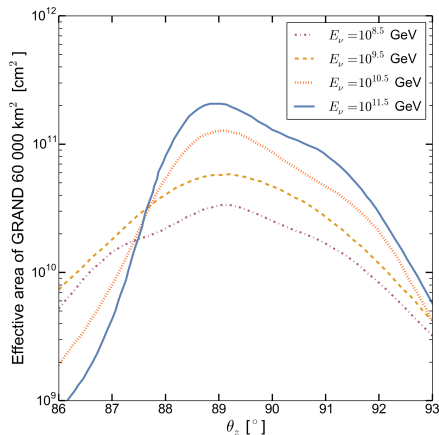


$$n_{\text{GRB}}(z) \propto \rho_{\text{SFR}}(z) \times (1+z)^{1.2}$$

P. BAERWALD, MB, W. WINTER, *Astropart. Phys.* **62**, 66 (2015) [1401.1820]

GRAND effective area

GRAND-60 effective area (preliminary):

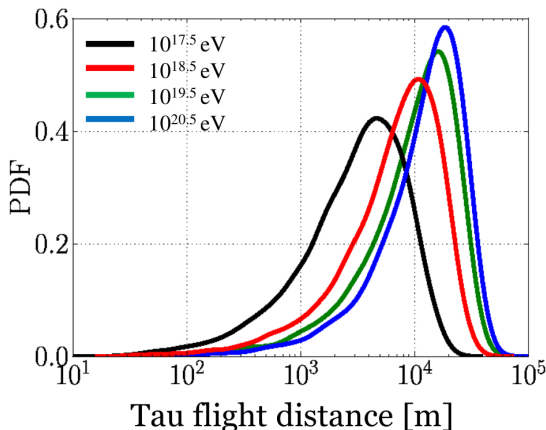


upgoing (Earth) ◀▶ downgoing (mountains)

For GRAND-200, scale by $200/60 \approx 3.33$

GRAND energy resolution

- ▶ Presently, we do not reconstruct neutrino energy
- ▶ But we know that $E_\nu > E_{\text{sh}}$
- ▶ The flight distance of the τ may help:



Still to be determined:

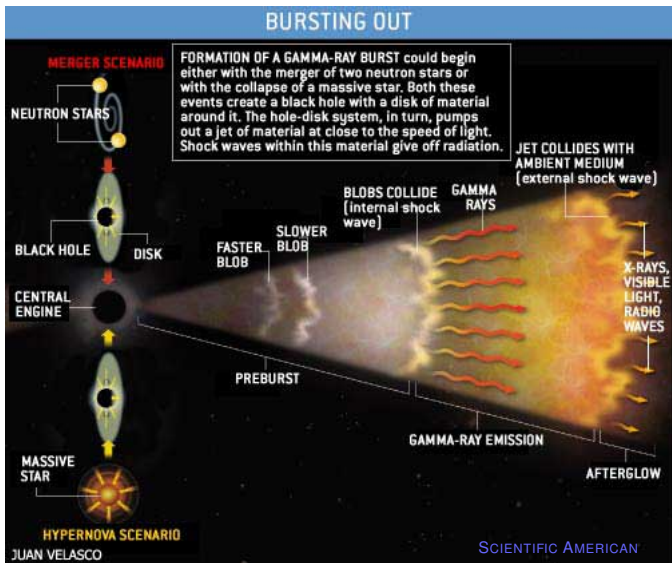
Will GRAND be able to reconstruct neutrino directions in real time?

- ▶ If **yes**, event excesses can trigger follow-up by other instruments (*e.g.*, via GCN, AMON)
- ▶ If **no**, GRAND can act as a follow-up partner in archival searches for temporal and spatial Coincidence

For transient astronomy, the shorter the latency,
the better for a crude reconstruction of arrival direction

FOTEINI OIKONOMOU

GRBs explained – the fireball model



Neutrinos from GRB afterglows

What?

Emission occurring when the GRB jet reaches the circumburst medium

When?

Between a few hours and a day after the prompt emission

How?

Neutrino production via $p\gamma$ – depends on the matter profile of medium

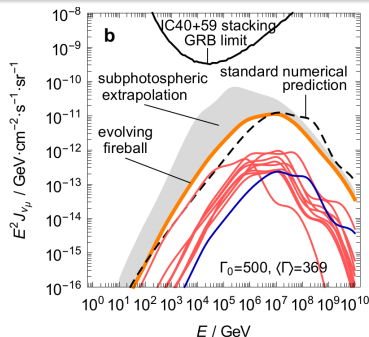
Why interesting?

Flux sits right where EAS detectors –including GRAND– are sensitive

GRB prompt vs. afterglow neutrinos

Prompt neutrinos

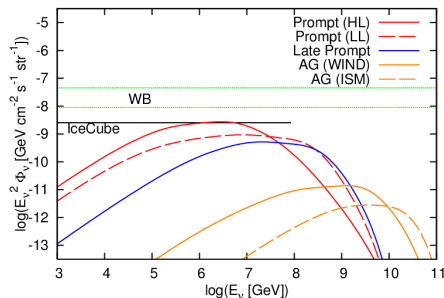
- ▶ Modeled via $p\gamma$ in internal in-jet collisions
- ▶ Flux peaks at $\sim$ PeV
- ▶ Use IceCube, ANTARES, KM3NeT



[MB, K. MURASE *et al.*, *Nat. Comm.* **6**, 6783 (2015) [1409.2874]]

Afterglow neutrinos

- ▶ Modeled via $p\gamma$ in jet-medium collisions
- ▶ Flux peaks at $\sim$ EeV
- ▶ Use ARA, ARIANNA, ANITA, **GRAND**



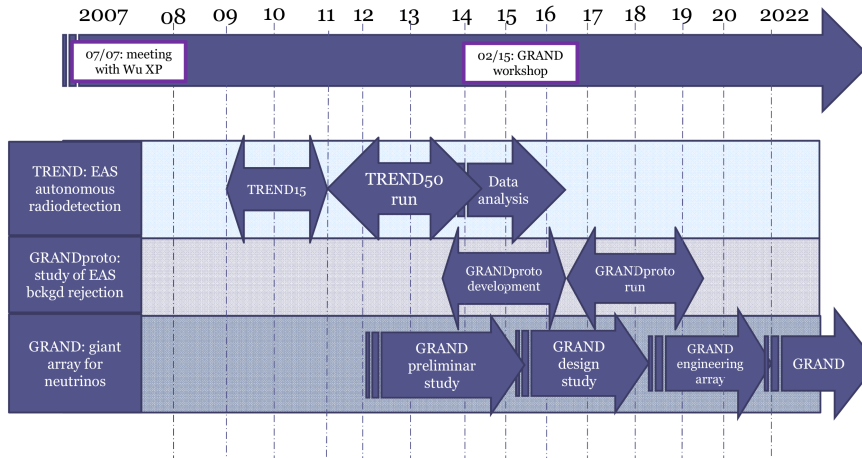
[K. MURASE, *PRD* **76**, 123001 (2007) [0707.1140]]

Neutrino flavor composition at EeV

- ▶ IceCube measures the flavor ratios in the range 30 TeV – 2 PeV
- ▶ No measurement exists at higher energies (EHE)
- ▶ Since GRAND is sensitive only to ν_τ , it cannot determine the flavor composition **by itself**
- ▶ ARA, ARIANNA are sensitive to all flavors
 - however, it is unclear if they can tag flavors, and how well
- ▶ EHE flavor ratios might be determined by **combining GRAND+ARA+ARIANNA+ANITA data**

What are the flavor-tagging capabilities of ARA, ARIANNA, ANITA?

GRAND tentative timeline



O. MARTINEAU