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

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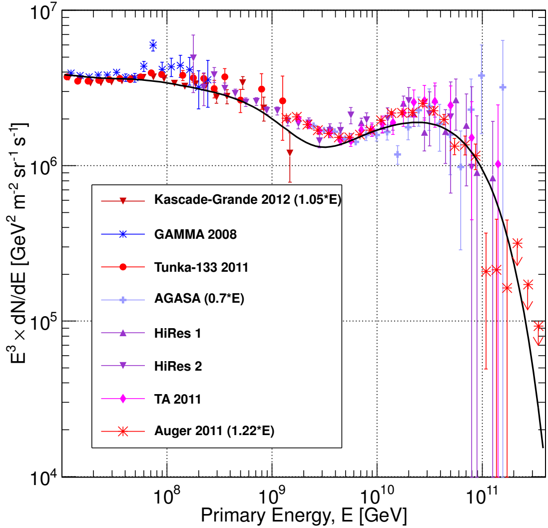
GRAND

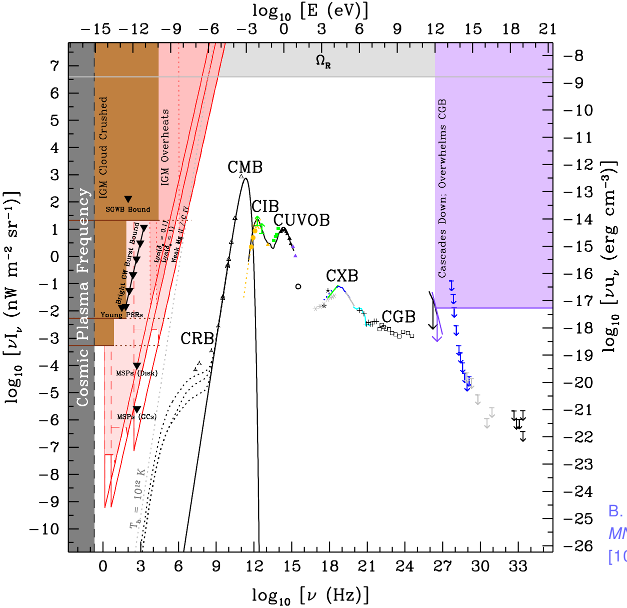
Ultra-high-energy cosmic rays

After 50+ years of UHECR measurements —



Gaisser, Stanev, Tilav, *Front. Phys. China* **8**, 748 (2013) [1303.3565]

The electromagnetic sky

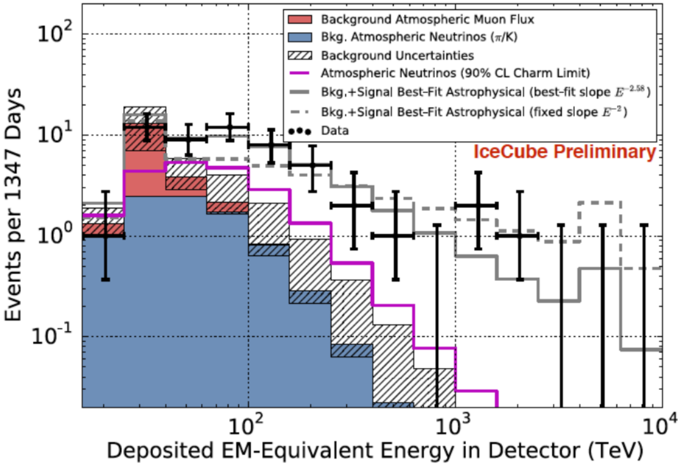


B. Lacki
MNRAS **406**, 863 (2010)
[1004.2049]

High-energy astrophysical neutrinos: they exist!

The era of neutrino astronomy has begun!

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



What lies beyond — cosmogenic neutrinos

We expect the > PeV ν sky to be populated: cosmogenic neutrinos

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

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

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

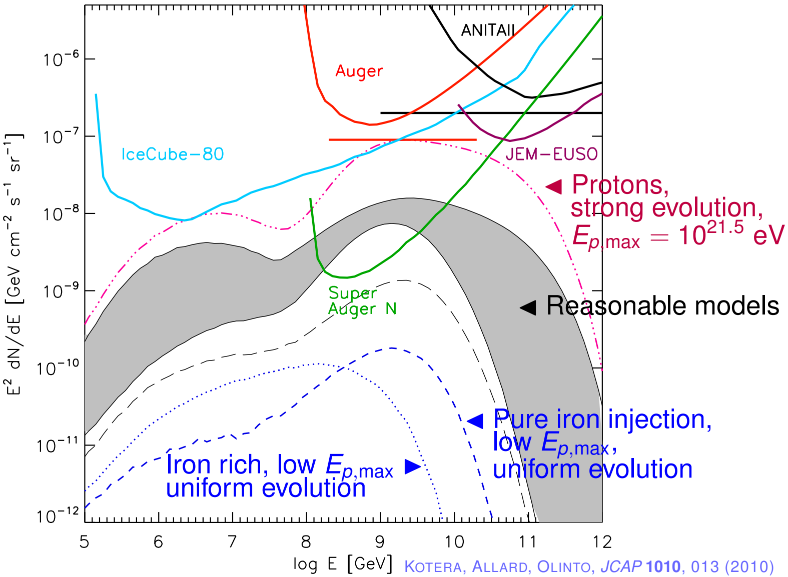
$\therefore$ The cosmogenic neutrino flux is low

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

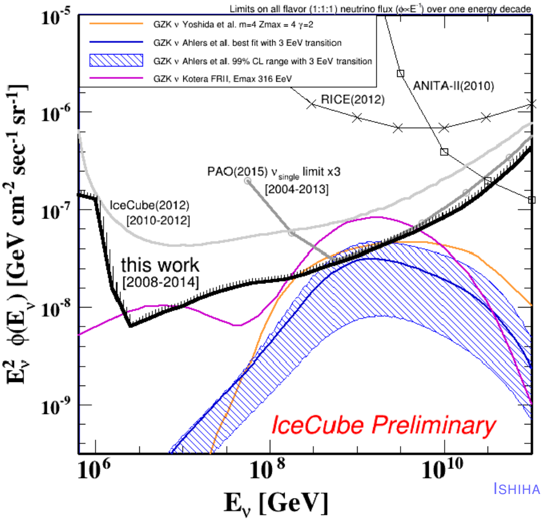
How low can low be?



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

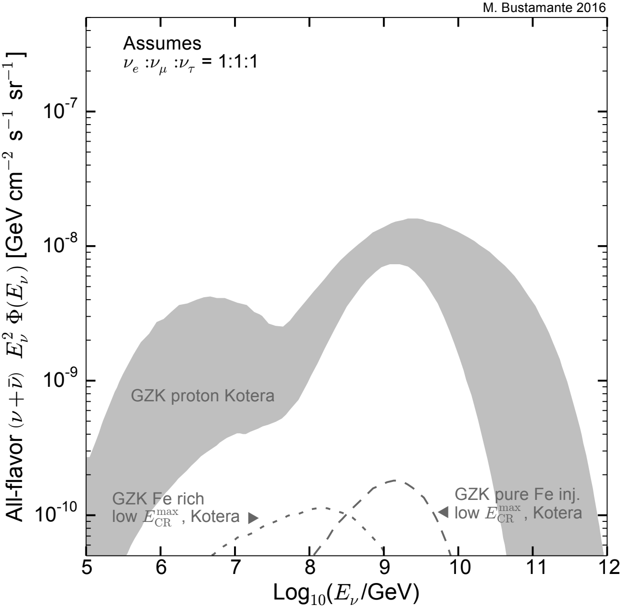
The present-day picture

The latest IceCube search (6 years) found only one candidate event — the most optimistic predictions are disfavored

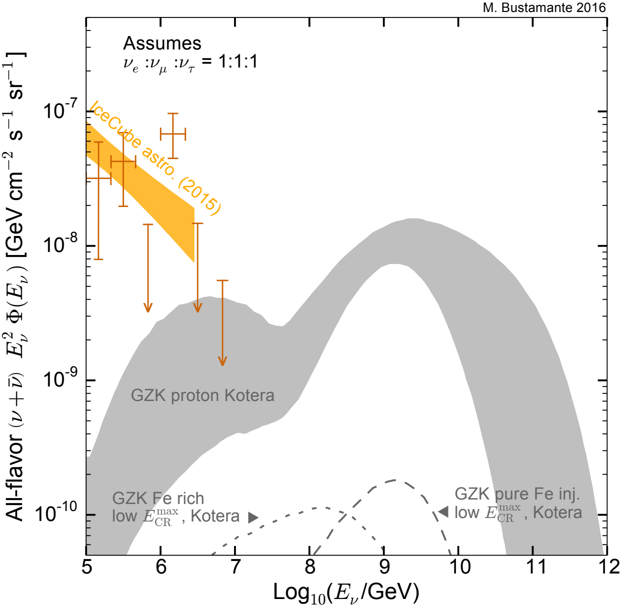


Ishihara, TeVPA 2015

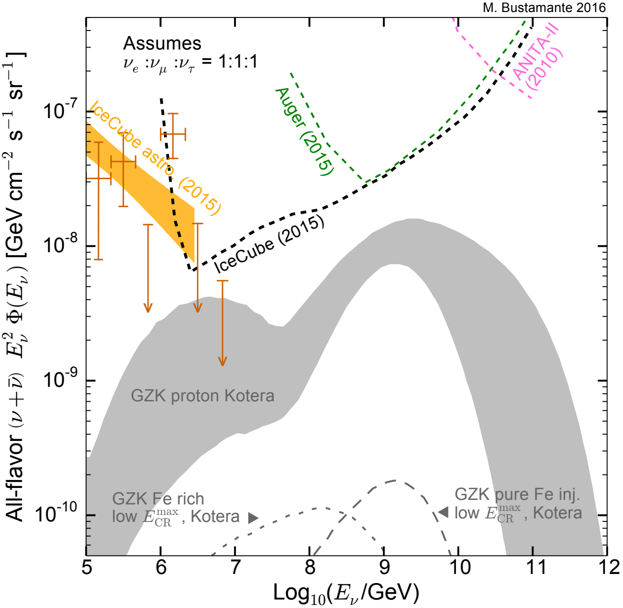
Predictions vs. detectors — now



Predictions vs. detectors — now



Predictions vs. detectors — now



The solution: build larger and/or build different

Two philosophies:

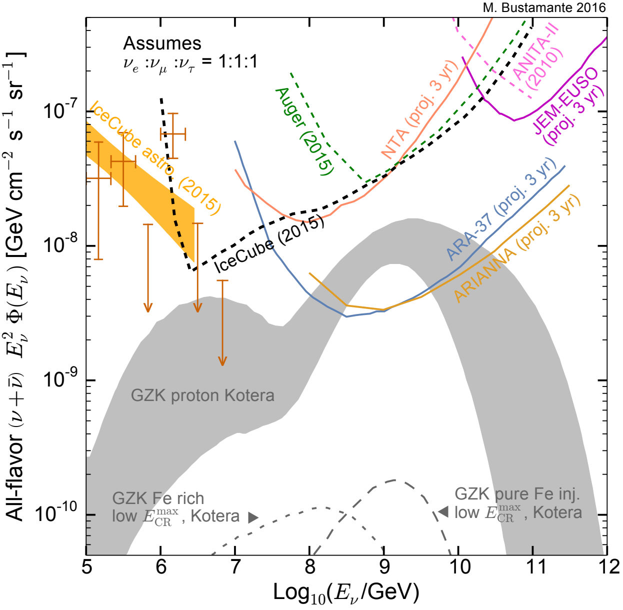
1 — Build larger water/ice Cherenkov detectors

- 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



Enter GRAND

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

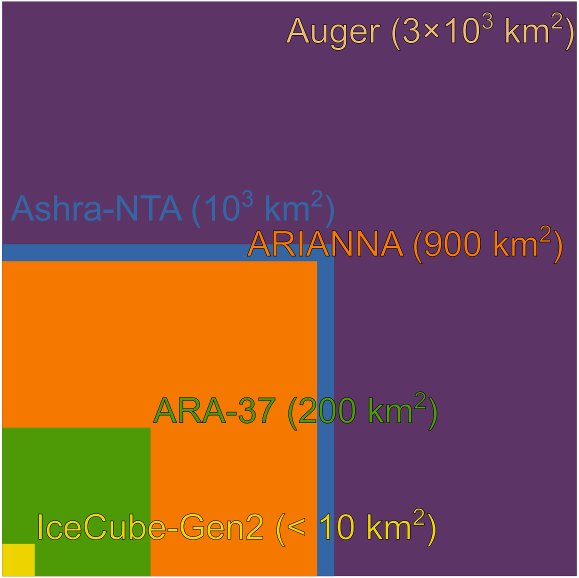
How can the nightmare scenario be overcome?

1. Build big. Really big.
2. Use radio emission — attenuation length is $\sim$ 100 km in air

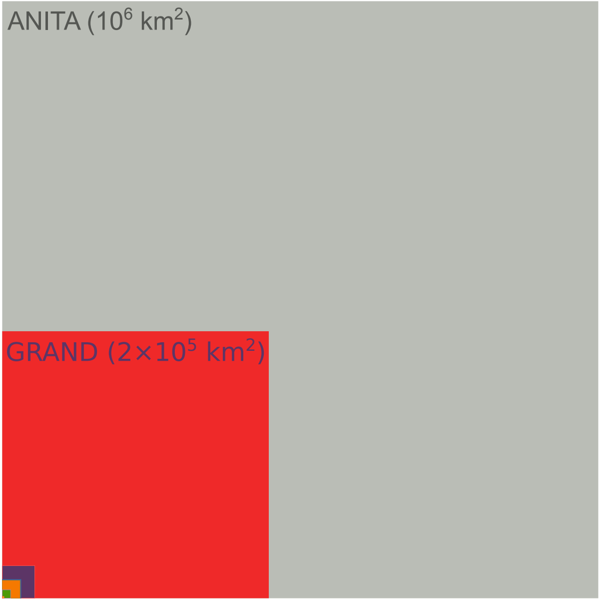
GRAND: Giant Radio Array for Neutrino Detection

- 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 km^2

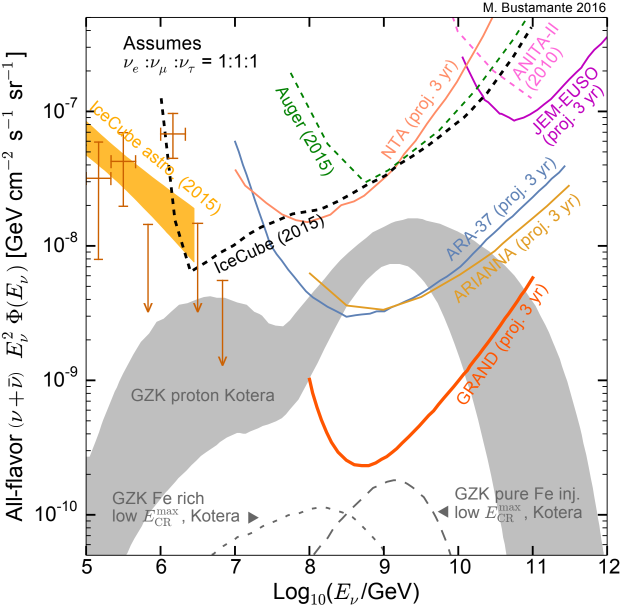
Building big — comparing the surface areas



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

- Let us start assuming UHECRs ($> 10^8$ GeV) are protons
- They create cosmogenic neutrinos of $\sim$ EeV by interacting with cosmological photons:

$$
\begin{aligned}
& p + \gamma \rightarrow \Delta^+(1232) \rightarrow \pi^+ + n \\
& \pi^+ \rightarrow \mu^+ + \nu_\mu \\
& \mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+ \\
& n \rightarrow \bar{\nu}_e + e + p
\end{aligned}
$$

- Δ resonance is $\sim$ 50% of the total
- There are 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 ($\mathrm{GeV}^{-1}\ \mathrm{cm}^{-3}$):

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

with n_p the real number density

- Transport equation (comoving source frame):

$$\dot{Y}_p = \partial_E\left(HEY_p\right) + \partial_E\left(b_{e^+e^-}Y_p\right) + \partial_E\left(b_{p\gamma}Y_p\right) + \mathcal{L}_{\mathrm{CR}}$$

adiabatic losses

pair production losses

photohadronic losses

CR injection from sources

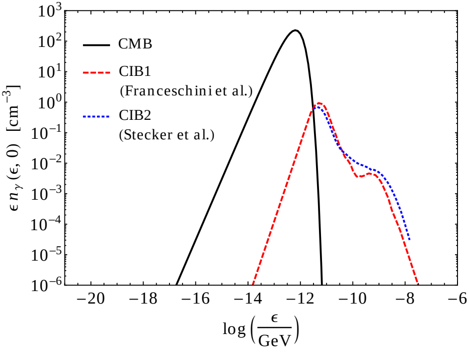
$$Q_{\mathrm{CR}}(E) \propto E^{-\alpha_p} e^{-E/E_{p,\max}}$$

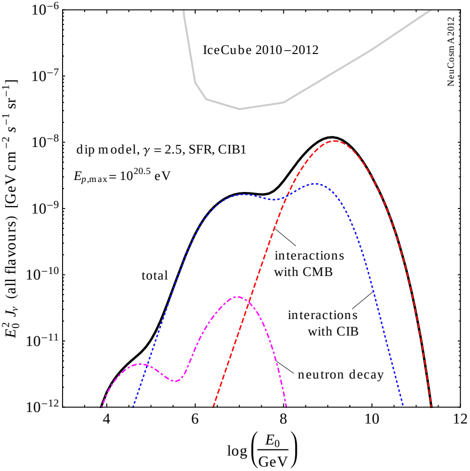
Spectral shape

Two main photon targets:

- CMB
- Cosmic infrared/optical background (CIB)

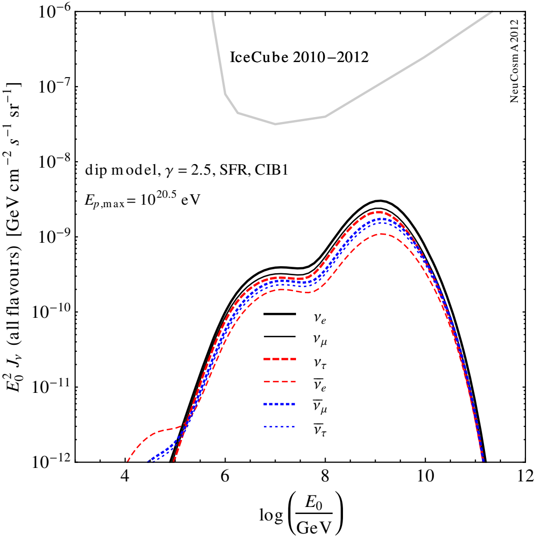
◀ Both evolve with redshift $\sim (1+z)^3$





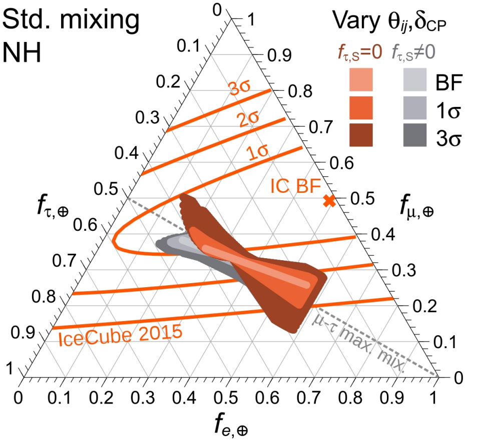
Cosmogenic neutrinos by flavor

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:

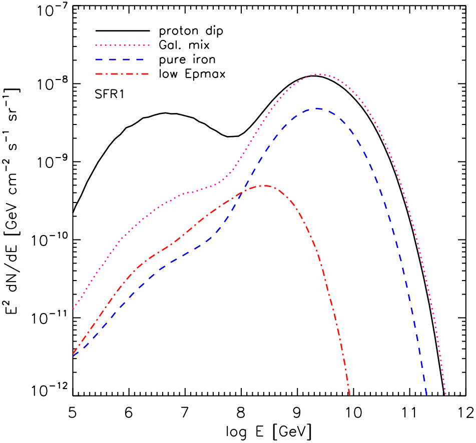
1. Mass composition
   — heavier CRs make fewer ν's
2. Redshift evolution of the density of CR sources
   — more sources at high redshift result in more ν's
3. Maximum CR energy reached at the sources
   — higher maximum energy results in more ν's
4. Spectral index of the CR injection spectrum
   — complicated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

Also:

5. Start energy of the transition to extragalactic CRs

Cosmogenic neutrinos — three broad scenarios

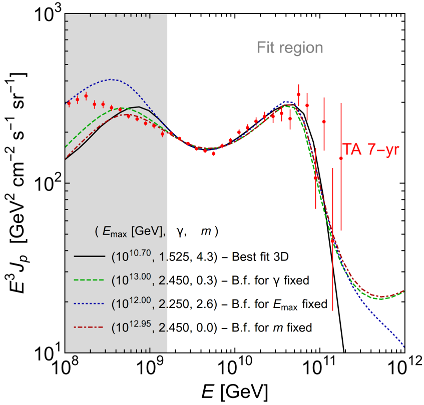
1. UHECRs are mostly extragalactic protons above 10^9 GeV
   — "proton dip model"
2. UHECRs are mostly extragalactic protons above the ankle (4 EeV)
   — "ankle model"
3. UHECRs are a mix of nuclei, maybe dominated by heavy ones
   — "mixed composition"

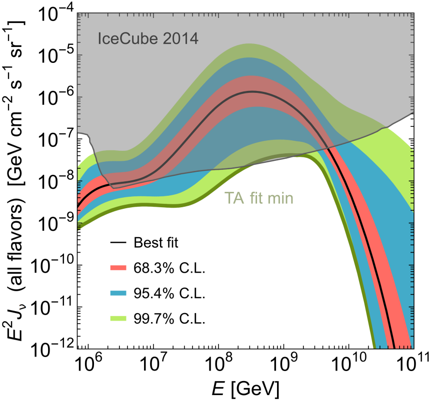


Kotera, Allard, Olinto, *JCAP* **1010**, 013 (2010)

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:



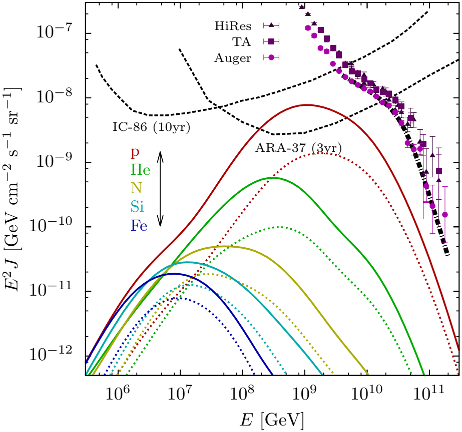


This challenges a pure proton UHECR composition

J. Heinze, D. Boncioli
W. Winter, MB, 1512.05988

Cosmogenic ν's from mixed-composition UHECRs

- Nuclei photodisintegrate on the CMB: $A + \gamma \to (A - 1) + n$
- 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: $\nu_l + N \to \nu_l + X$

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

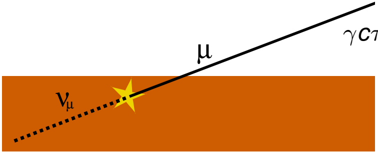
Charged current: $\nu_l + N \to l + X$

- 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 $E_{\rm sh} \approx E_\nu$

What happens to CC showers of different flavors?

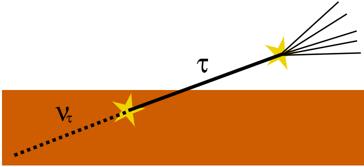
- The electron from CC ν_e quickly showers underground

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



$\gamma c \tau_\mu \approx 6 \cdot 10^6 \text{ km } (E/\text{PeV})$

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



$\gamma c \tau_\tau \approx 50 \text{ m } (E/\text{PeV})$

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."

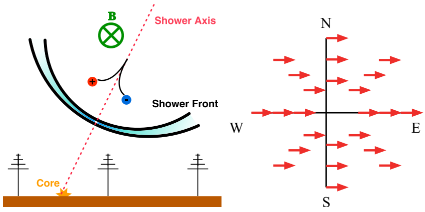
And they found large arrays are necessary:

"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 km^2 are considered**."

PRD **45**, 362 (1992)

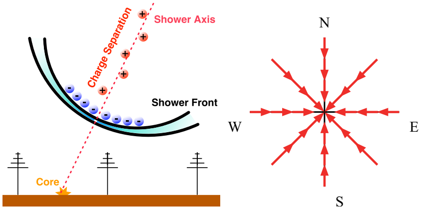
Radio emission: Askaryan and geomagnetic

Geomagnetic



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

Askaryan

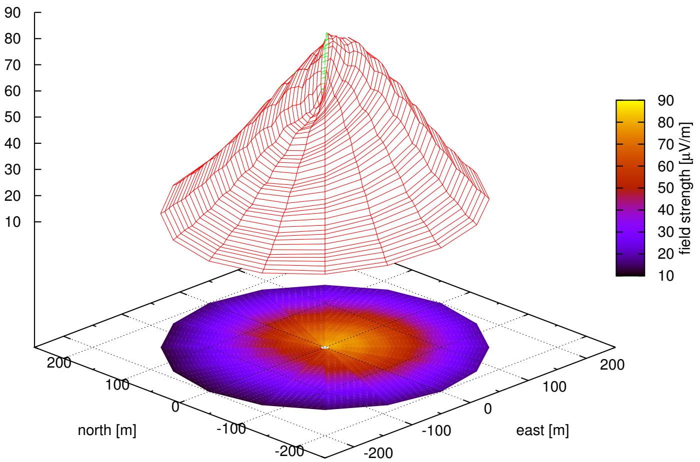


- Time-varying negative charge excess $\sim 20\%$
- Linearly polarized towards axis
- Subdominant in air showers (dominant in ice)

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

Lateral distribution of the radio signal

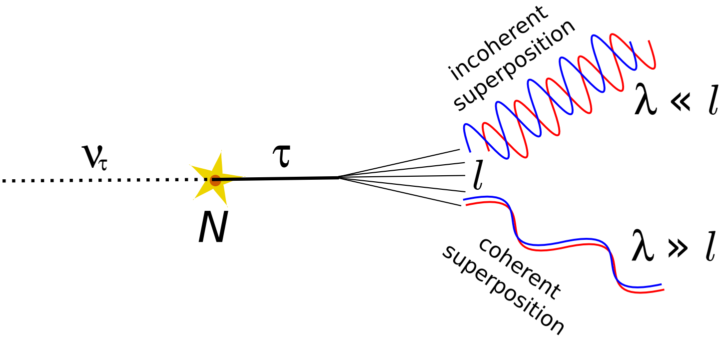
A superposition of geomagnetic and Askaryan emission:



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

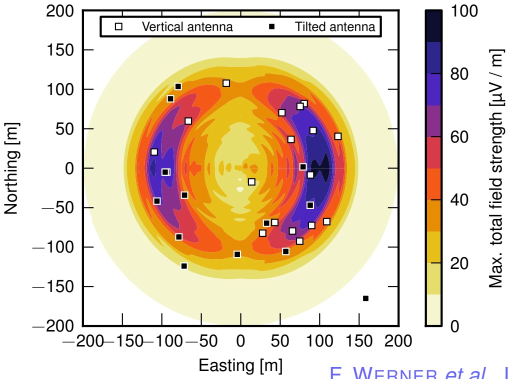
Coherent emission

- The shower front moves compactly as a "particle pancake" $\sim$ 1 cm thick and a few cm wide
- At radio wavelengths, emission adds coherently:



Cherenkov ring

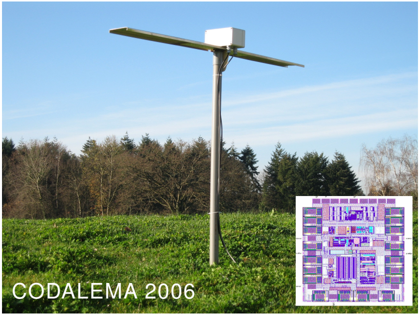
- Air shower front travels at $\sim$ light speed
- Radio signal propagates more slowly due to refraction
- This leads to Cherenkov-like time compression of radio pulses with high power
- Seen by CROME in the 3.4–4.2 GHz band (CoREAS overlaid):

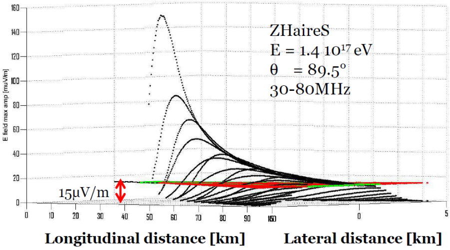


F. WERNER *et al.*, ICRC 2013

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 μV m^{-1} for 30–100 MHz





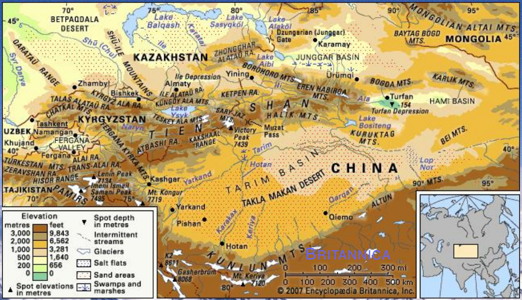
Adapted from O. Martineau

TREND, the predecessor of GRAND (2011-2014)

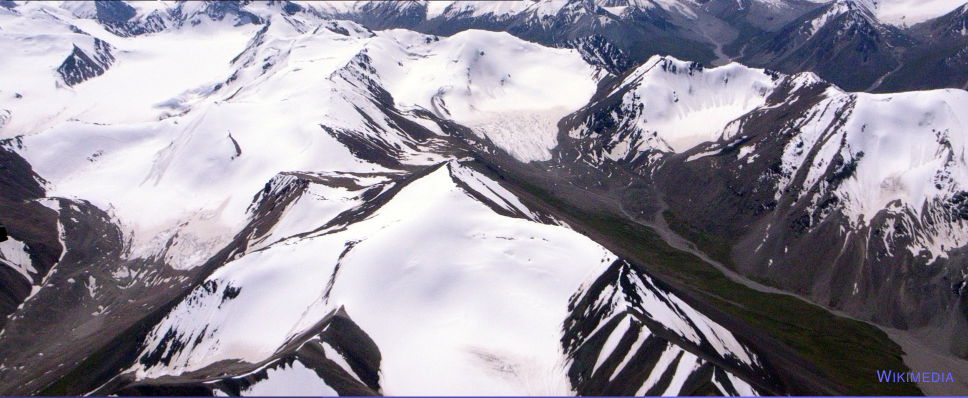
- TREND: Tianshan Radio Experiment for Neutrino Detection
- 50 monopolar antennas deployed over 1.5 km^2
- Proposed in 2008 by D. Ardouin *et al.* [*Astropart. Phys.* **34**, 717 (2011) [1007.4359]]
- Site: Ulastai, XinJiang Province, China (21CMA interferometer site)
- Main goal: autonomous EAS radio 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



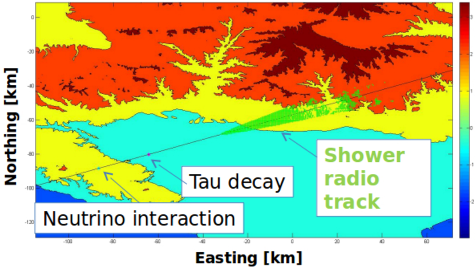
BRITANNICA



WIKIMEDIA

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

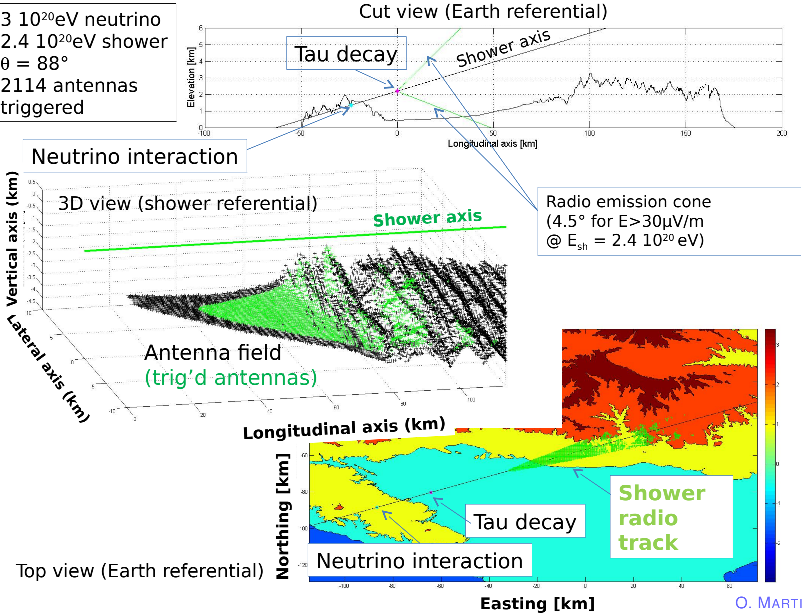


- Mountains are sizeable targets: $\sim$ 40% of total
- Antenna triggers if:
  - In direct view of shower
  - Inside a light cone of a few degrees (0.5–3°)
  - τ decay vertex is 14–120 km away
- Shower detected if one cluster of 8+ antennas fired
- Simulation array: 90000 antennas over 220 $\times$ 270 $\approx$ 60000 km^2 in Tianshan mountains (800 m step size)

Adapted from O. Martineau

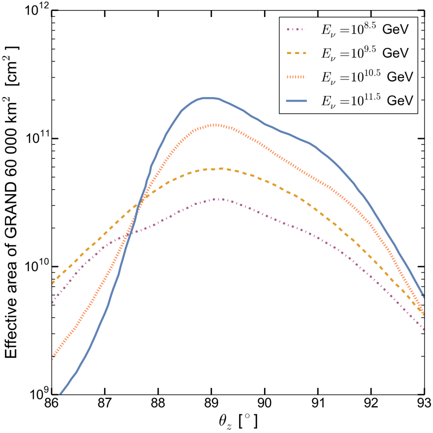
GRAND sensitivity study – simulation

3 10^{20}eV neutrino
2.4 10^{20}eV shower
θ = 88°
2114 antennas triggered



GRAND effective area

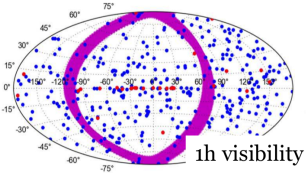
GRAND-60 effective area (preliminary):

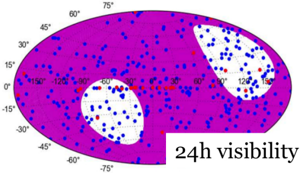


upgoing (Earth) ◀▶ downgoing (mountains)

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

GRAND field of view — at 1 EeV





3-year average:

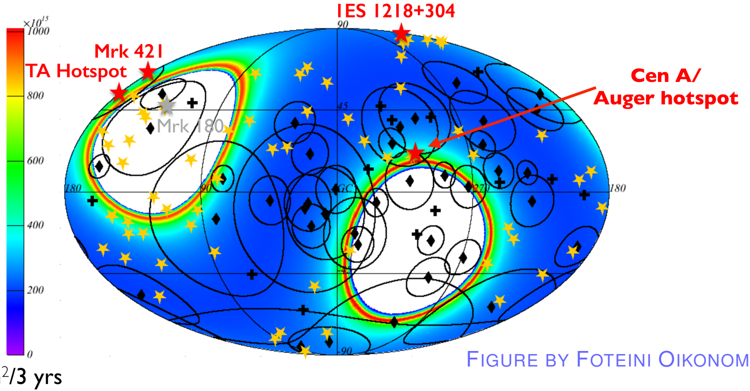
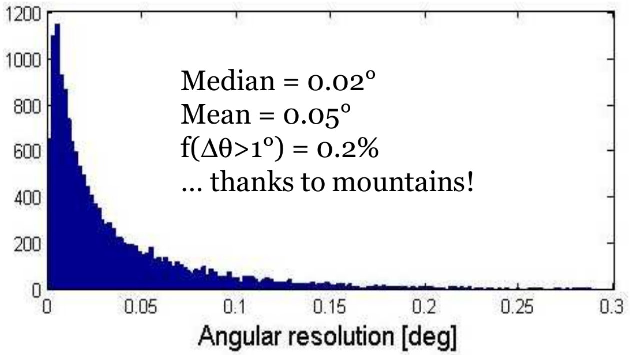


FIGURE BY FOTEINI OIKONOMOU

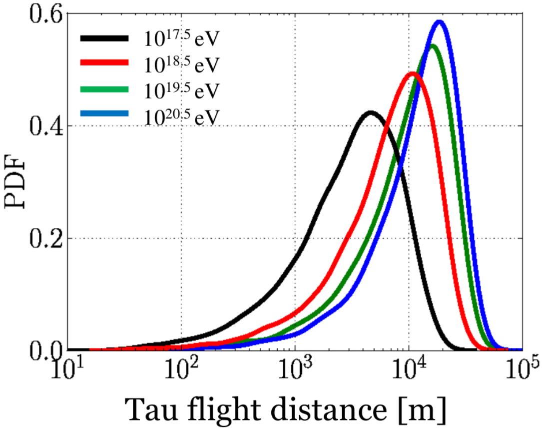
GRAND angular resolution

- 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



GRAND energy resolution

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



GRAND science case

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

Transients

Still to be determined:

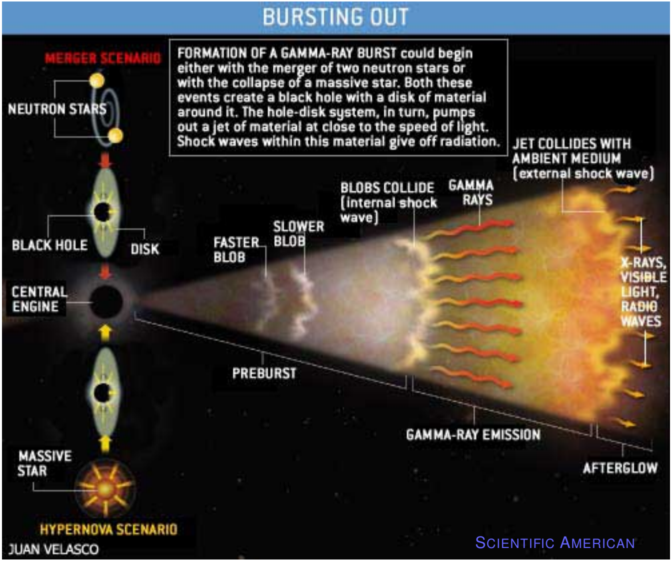
Will GRAND be able to reconstruct neutrino directions in real time?

- If yes, event excesses can triger 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 occuring 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

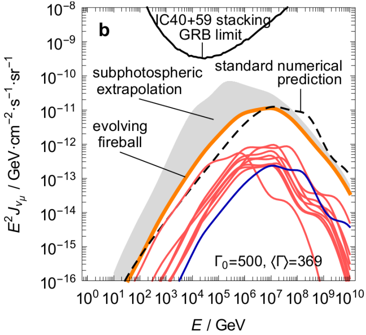
GRB prompt vs. afterglow neutrinos

Prompt neutrinos

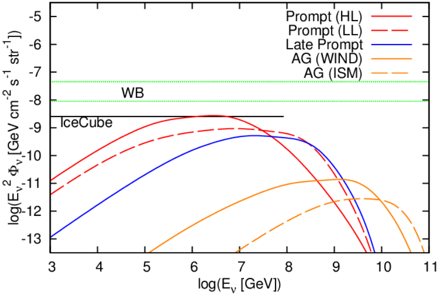
- Modeled via $p\gamma$ in internal in-jet collisions
- Flux peaks at $\sim$ PeV
- Use IceCube, ANTARES, KM3NeT

Afterglow neutrinos

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

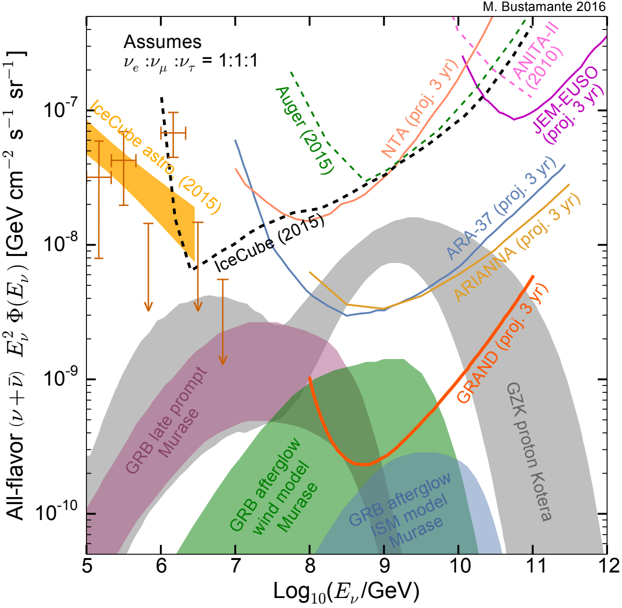


[MB, K. Murase *et al.*, *Nat. Comm.* **6**, 6783 (2015) [1409.2874]]



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

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)

Neutrino flavor composition at EeV

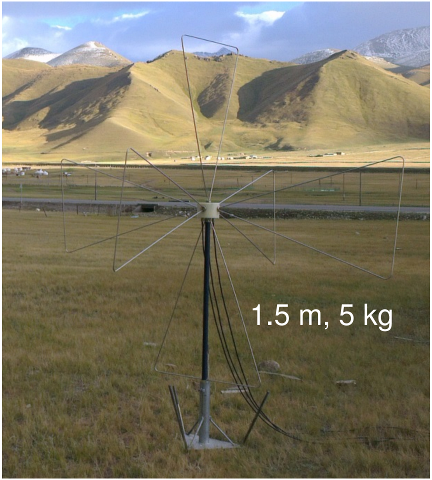
- IceCube measures the flavor ratios in the range 30 TeV – 2 PeV
- No measurement exists at higher energies (EHE)
- Since GRAND is sensitive only to ν_τ, it cannot determine the flavor composition by itself
- ARA, ARIANNA are sensitive to all flavors
  – however, it is unclear if they can tag flavors, 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?

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):

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

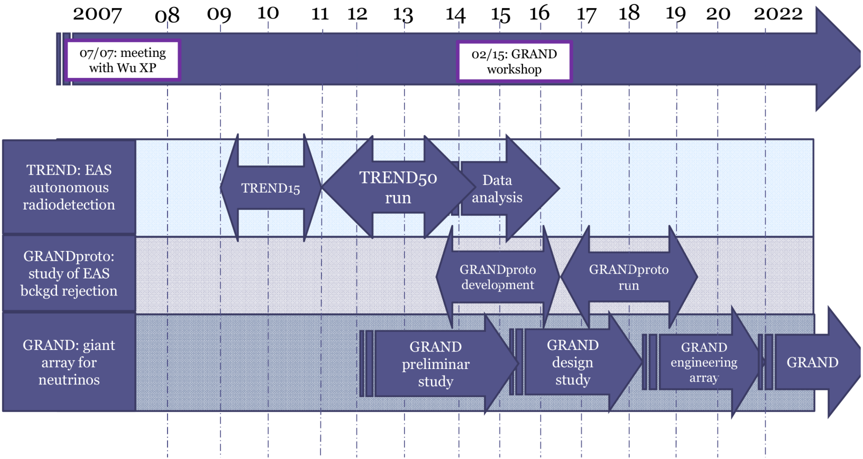


ADAPTED FROM K. KOTERA

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 $\sim$ 0–100 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?

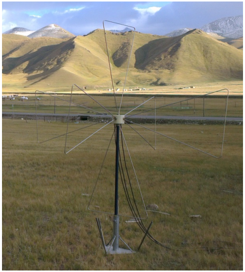
GRAND tentative timeline

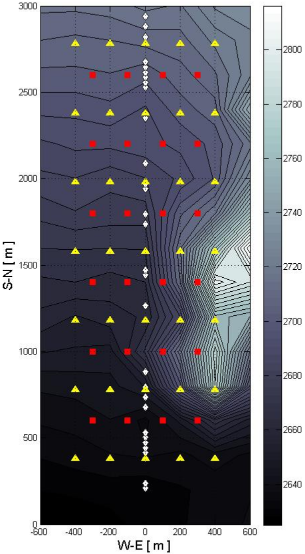


O. Martineau

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, to be completed in June 2016
- Proposal to perform similar tests at Auger-AERA





GRAND team

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)
- Julia Schmid (Laboratoire AIM, Université Paris Diderot/CEA-IRFU/CNRS)
- Charles Timmermans (SUBATECH, CNRS-IN2P3, Université de Nantes)

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)
- Jordan Hanson (Center for Cosmology and AstroParticle Physics, The Ohio State University)
- Kohta Murase (Pennsylvania State University)
- Foteini Oikonomou (Pennsylvania State University)

Netherlands, Belgium, Sweden:

- 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!

Perspectives

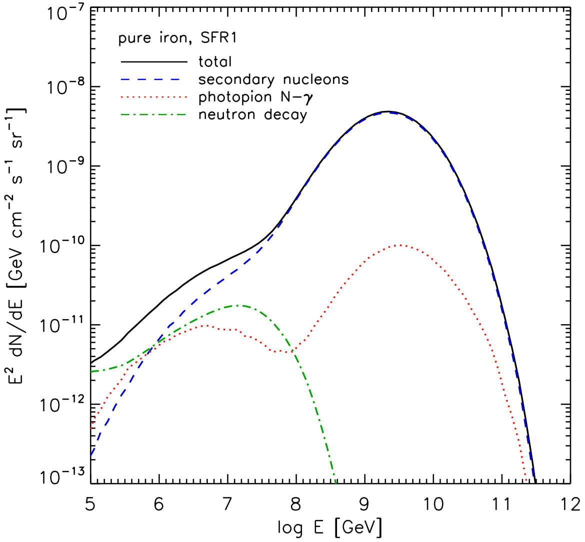
GRAND: an instrument to discover cosmogenic neutrinos even in nightmare scenarios and to make precision measurements otherwise

- A great tool for multi-messenger astronomy
- GRAND proposal is being set up (science case + detailed simulations)
- Possible timeline:
  - 2016: GRANDproto + proposal
  - 2018: engineering array of $\mathcal{O}\left(1000\ \text{km}^2\right)$
  - 2021: start building full array

Join us!

Backup slides

Neutrino production with heavy UHECRs



Kotera, Allard, Olinto, *JCAP* **1010**, 013 (2010)

Why should we expect $\nu_\tau' s$?

- Neutrino production via pion decay:

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

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

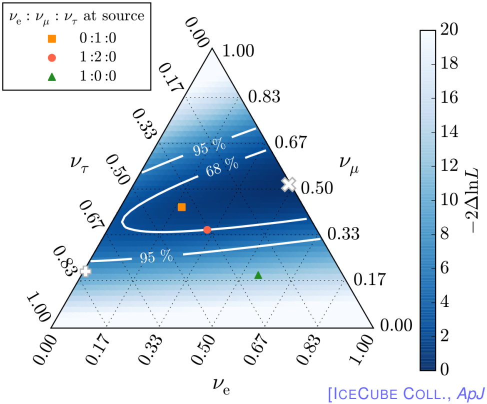
$$f_{\alpha,\oplus} = \sum_\beta P_{\nu_\beta \to \nu_\alpha} f_{\beta,S} = \sum_\beta \left(\sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2 \right) f_{\beta,S}$$

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

- Other compositions at the source:

$$(0 : 1 : 0)_S \longrightarrow (0.26 : 0.36 : 0.38)_\oplus \quad \text{("muon damped")}$$
$$(1 : 0 : 0)_S \longrightarrow (0.55 : 0.26 : 0.19)_\oplus \quad \text{("neutron decay")}$$
$$(1/2 : 1/2 : 0)_S \longrightarrow (0.40 : 0.31 : 0.29)_\oplus \quad \text{("charmed decays")}$$

Using contained events + throughgoing muons:



[IceCube Coll., *ApJ* **809**, 98 (2015)]

- 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:

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

where

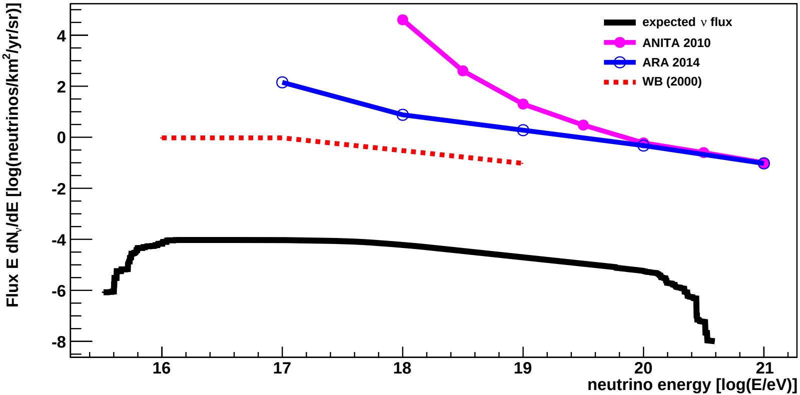
$t_{\rm exp} = 3$ yr: detector exposure time

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

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

Afterglow ν predictions for radio neutrino detectors

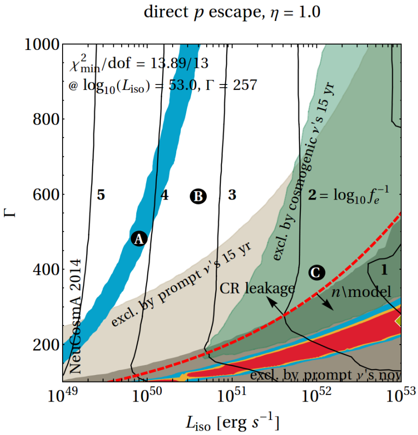
From recent work [G. Nir, D. Guetta, H. Landsman, E. Behar, [1511.07010]]:



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

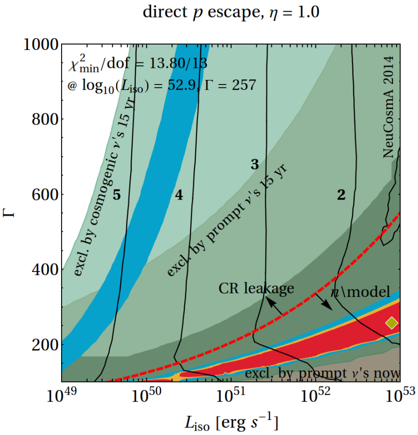
Probing UHECR + neutrino production in GRBs

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 —



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

(star formation rate)



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

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