GRAND Science Case
– Notes –

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The Ohio State University

GRAND mini-workshop

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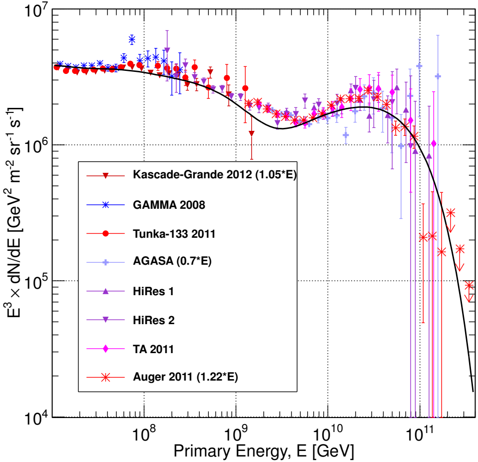
Challenging the proton dip (I)

There is a dip in UHECR spectrum around 10^9 GeV:



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

If UHECRs are mainly protons, the dip is due to energy losses through $p + \gamma_{\rm CMB} \to p + e^+ + e^-$ — “proton dip”

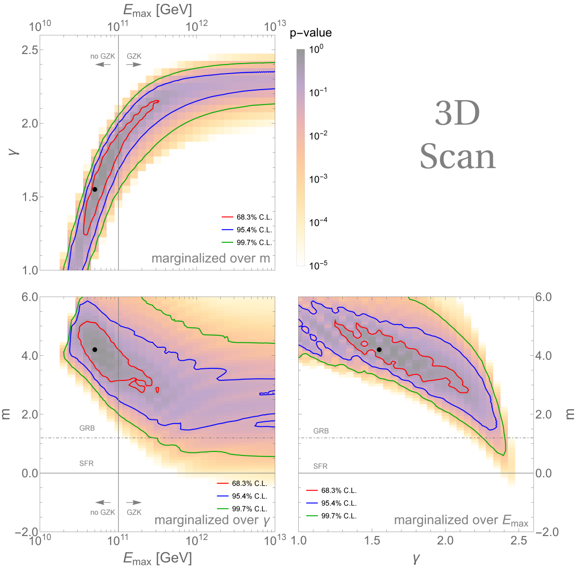
Challenging the proton dip (II)

We can test the proton origin of the dip using cosmogenic neutrinos:

- Assume a pure proton composition – compatible with TA
- Consider a population of generic UHECR proton sources
- Scan the 3D parameter space:
  - maximum injected *p* energy ($E_{\max}$)
  - spectral index of inject *p* spectrum (γ in $E^{-\gamma}$)
  - source redshift evolution (m in $(1+z)^m \cdot \mathrm{SFR}(z)$)
- At each point ($E_{\max}, \gamma, m$), generate the diffuse UHECR spectrum — fit it to TA data
- Calculate the associated cosmogenic ν spectrum — check if it is below IceCube bounds
- What's new? 2D scans missed important features

J. HEINZE, D. BONCIOLI, W. WINTER, MB, 1512.XXXXX

Challenging the proton dip (III)

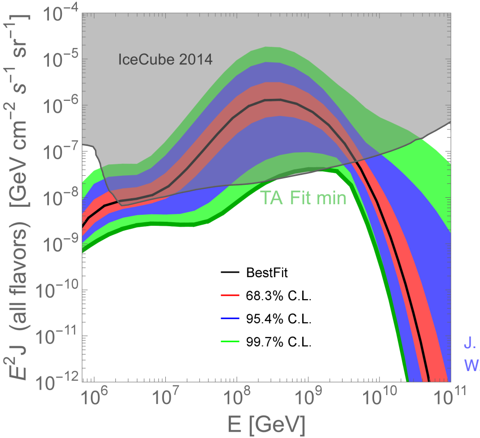


3D
Scan

J. Heinze, D. Boncioli, W. Winter, MB, 1512.XXXXX

Challenging the proton dip (IV)

Even the minimum associated cosmogenic ν's overshoot the IC bound:



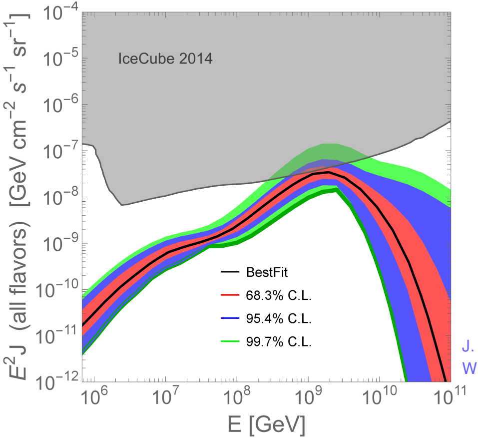
J. Heinze, D. Boncioli
W. Winter, MB, 1512.XXXXX

This challenges a pure proton UHECR composition
— minimum flux reachable with GRAND, not ARA or ARIANNA

Challenging the proton dip (V)

If there is no proton injection from sources located at $z > 1$:

- Little change to the UHECR flux
- Much lower cosmogenic ν flux

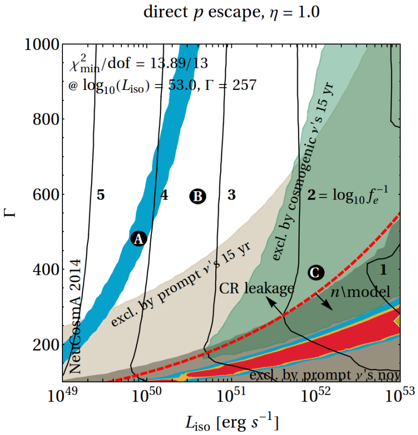


J. HEINZE, D. BONCIOLI
W. WINTER, MB, 1512.XXXXX

Only GRAND would be able to probe the high-z Universe

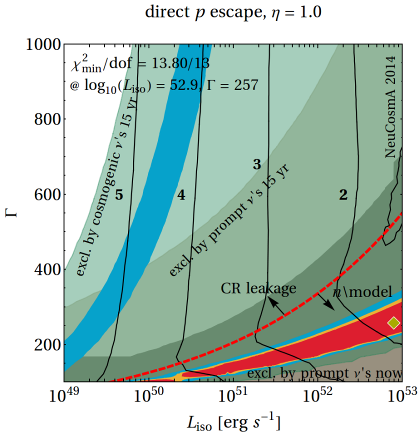
Probing UHECR + neutrino production in GRBs

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 —



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

(star formation rate)



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

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

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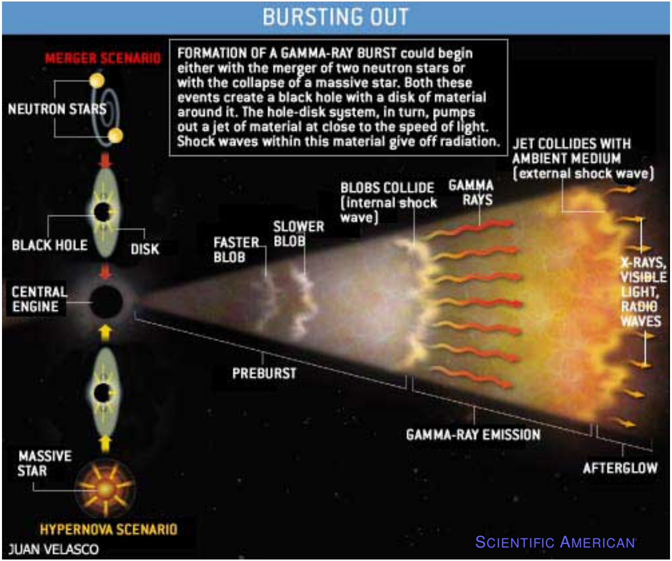
GRBs explained – the fireball model

Developed by Goodman, Mészáros, Reese, Piran, Waxman, *et al.* –



FORMATION OF A GAMMA-RAY BURST could begin either with the merger of two neutron stars or with the collapse of a massive star. Both these events create a black hole with a disk of material around it. The hole-disk system, in turn, pumps out a jet of material at close to the speed of light. Shock waves within this material give off radiation.

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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

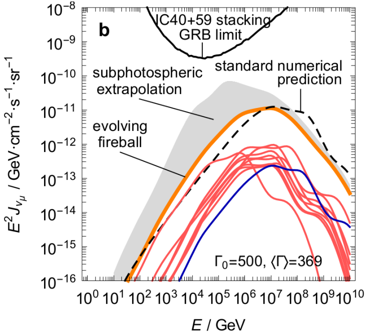
GRB prompt vs. afterglow neutrinos

Prompt neutrinos

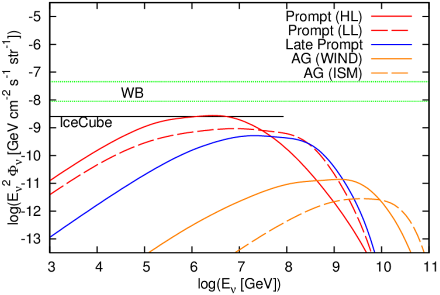
- Modeled via $p\gamma$ in internal in-jet collisions
- Flux peaks at $\sim$ PeV
- Use IceCube, ANTARES, KM3NeT

Afterglow neutrinos

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

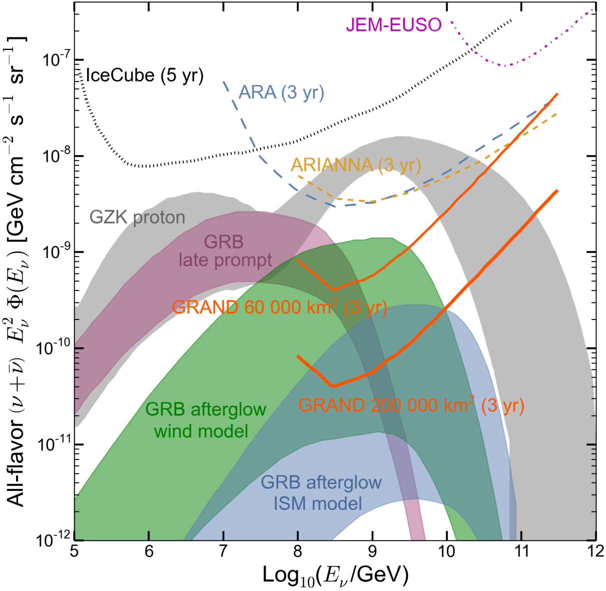


[MB, K. Murase *et al.*, *Nat. Comm.* **6**, 6783 (2015) [1409.2874]]



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

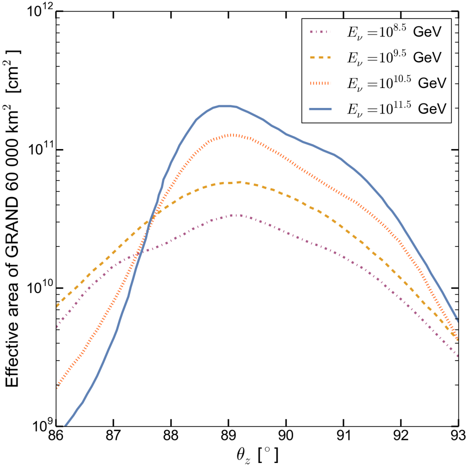
Sensitivity to GRB afterglow neutrinos



- GRAND vastly outperforms all others
- Only one capable of probing the GRB afterglow ν's after 3 yrs
- Event rates after 3 yrs ($10^{8.5}$ – $10^{11.5}$ GeV) for 60 000 km^2 (200 000 km^2) setup:
    - Late prompt: 9–46 (28–154)
    - Afterglow wind: 1–120 (4–400)
    - Afterglow ism: 20–534 (66-1780)
- (Ongoing work MB, I. Tamborra)

Sensitivity to GRB afterglow neutrinos: details (I)

GRAND-60 effective area (preliminary, data from ICRC 2015):



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

Sensitivity to GRB afterglow neutrinos: details (II)

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 $(\nu + \bar{\nu})$ fluxes from GRB afterglows (bands span fiducial to optimistic models by K. Murase [*PRD* **76**, 123001 (2007) [0707.1140]])

GRB afterglow neutrinos: some open questions

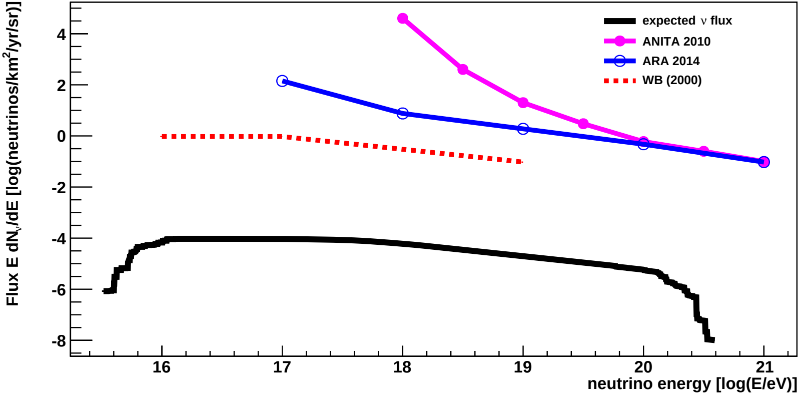
1. Are the event rates too high? In other words, how accurate is the preliminary effective area?

2. The diffuse flux of GRB afterglow neutrinos is subdominant to the GZK flux; therefore:
    - Does it make sense to try to distinguish it?
    - If so, how?

3. What about detecting the neutrinos from individual afterglows?

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)

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Looking for correlations with sources

Should it be done?

Definitely yes! – However, it should *not* be done blindly

The flaw of the blind search

- Gamma rays and UHECRs have horizons:
  - No gamma ray with > 1 PeV survives $\gtrsim$ 10 kpc on the CMB
  - CRs with $\gtrsim$ 40 EeV originate inside the GZK horizon ($\sim$ 75 Mpc)

- But there is no neutrino horizon
  – So they could have been generated anywhere in $z > 0$

- So what?
  - Since we have only incomplete catalogs, many unresolved potential neutrino sources lie in any direction in the sky
  - Coincidence of ν arrival direction with position of a known object does not preclude the enormously larger number of objects behind it from being the actual sources

Caveats: a meaningful correlation search *is* possible

Solution by selection: use only nearby, bright sources

The previous argument breaks down when looking for correlations with nearby, bright sources only

See, *e.g.*, [K. Emig, C. Lunardni, R. Windhorst [1507.05711]]

The exotic solution: secret neutrino interactions

BSM interactions (*e.g.*, via a Z') between EHE neutrinos and the cosmic ν background create a neutrino horizon

– Therefore, Nature itself selects that only nearby sources contribute to the flux at Earth

– And a correlation with them can be searched for easily

See, *e.g.*, [R. Laha, B. Dasgupta, J. Beacom, *PRD* **89**, 093025 (2013) [1304.3460]] [K. C. Y. Ng, J. Beacom, *PRD* **90**, 065035 (2014) [1404.2288]] [K. Ioka, K. Murase, *PTEP* **2014**, 061E01 (2014) [1404.2279]]

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Two flavor issues

Issue #1

What amount of τ flavor should we expect in the neutrino flux?
(Quick answer: prospects are good!)

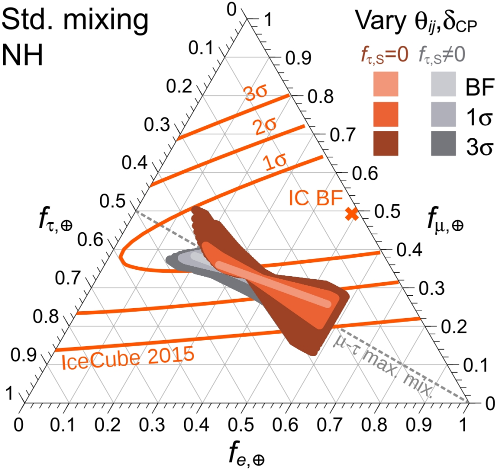
Issue #2

Can GRAND help determine the flavor ratios of EHE neutrinos?
(Quick answer: there is no quick answer)

Flavor issue #1: the τ flavor content

Refer to [MB, J. Beacom, W. Winter, *PRL* 2015 [1506.02645]]:

- Assume unconstrained flavor composition at source (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 source production mechanism
- Possible caveat: new physics



Flavor issue #2: determining flavor ratios with GRAND

- 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 data
  – rather a down-the-road goal (politically difficult?)

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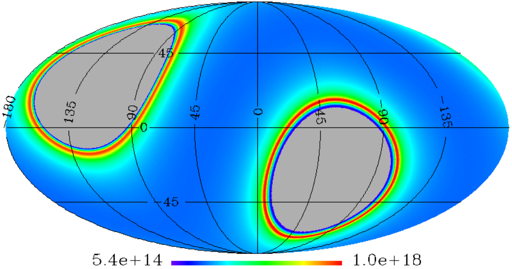
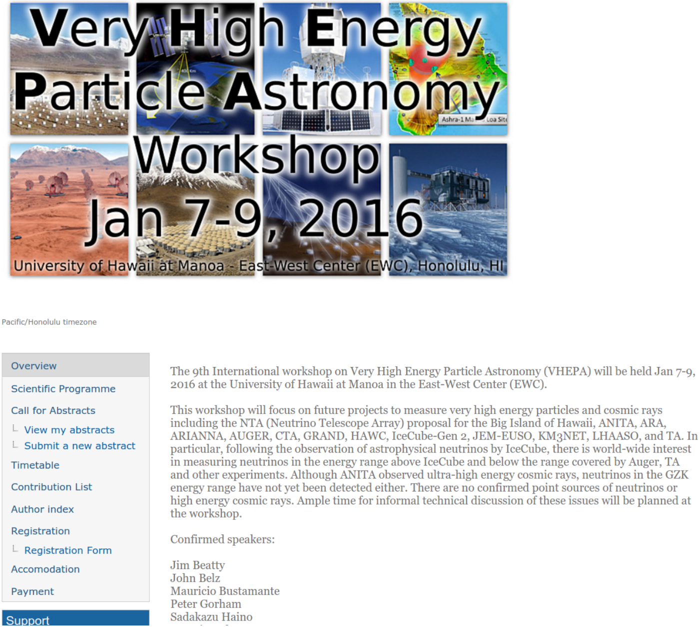
Galactic EeV neutrinos?

- Gamma-ray searches reveal that there is likely not more than one PeV source ("PeVatron") in the Milky Way
- It is unlikely that there is an EeV MW source (no indications from gamma rays or UHECRs)
- Regardless, ν's provide a unique way to search for > PeV sources
- And GRAND *can* see the Galactic Center with accuracy of $\sim 0.1^\circ$:



[O. Martineau, ICRC 2015 [1508.01919]]



Very High Energy Particle Astronomy Workshop

Jan 7-9, 2016

University of Hawaii at Manoa - East-West Center (EWC), Honolulu, HI

Pacific/Honolulu timezone

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Support

The 9th International workshop on Very High Energy Particle Astronomy (VHEPA) will be held Jan 7-9, 2016 at the University of Hawaii at Manoa in the East-West Center (EWC).

This workshop will focus on future projects to measure very high energy particles and cosmic rays including the NTA (Neutrino Telescope Array) proposal for the Big Island of Hawaii, ANITA, ARA, ARIANNA, AUGER, CTA, GRAND, HAWC, IceCube-Gen 2, JEM-EUSO, KM3NET, LHAASO, and TA. In particular, following the observation of astrophysical neutrinos by IceCube, there is world-wide interest in measuring neutrinos in the energy range above IceCube and below the range covered by Auger, TA and other experiments. Although ANITA observed ultra-high energy cosmic rays, neutrinos in the GZK energy range have not yet been detected either. There are no confirmed point sources of neutrinos or high energy cosmic rays. Ample time for informal technical discussion of these issues will be planned at the workshop.

Confirmed speakers:

Jim Beatty
John Belz
Mauricio Bustamante
Peter Gorham
Sadakazu Haino

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

Cosmogenic neutrinos, produced in interactions of ultra-high-energy cosmic rays (UHECRs) with cosmological background photons, should exist above 100 PeV, but remain undetected. Their flux depends on the uncertain composition and maximum energy of UHECRs. Pessimistic predictions, of 10^{-10} GeV cm^{-2} s^{-1} sr^{-1} or lower, are beyond reach of existing detectors after reasonable exposure times. The planned Giant Radio Array for Neutrino Detection (GRAND) addresses this possibility: **its main goal is the assured discovery of cosmogenic neutrinos, even in pessimistic flux scenarios**. It will detect the coherent radio emission from extensive air showers triggered by the decay of taus produced in interactions of cosmogenic ν_τ's in rock. By densely instrumenting a very large area –200 000 km^2 with 10^5 small radio antennas– GRAND could reach an exquisite sensitivity of $3 \cdot 10^{-11}$ GeV cm^{-2} s^{-1} sr^{-1} above 30 PeV in 3 years, corresponding to a handful of events per year. More reasonable flux scenarios predict up to 100 events per year. A precise angular resolution of 0.1° will allow to test isotropy and source correlations. I will discuss these and other science goals of GRAND, the status of the prototype array, and future prospects.