PEV NEUTRINOS FROM THE PROPAGATION OF ULTRA-HIGH ENERGY COSMIC RAYS

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THE ENERGETIC UNIVERSE

multi-messenger astronomy
DIFFUSE PHOTON BACKGROUND

Energy (eV) →

log(E/eV)

log [Flux/(erg cm^{-2} s^{-1} sr^{-1})]

Flux

log(\lambda/cm)

log(\lambda/cm)

1 TeV

= 1 Fermilab

Radio

CMB

Visible

GeV γ-rays
THE NEUTRINO SKY
Power law flux $\rightarrow$ stochastic (Fermi) acceleration in shocks

Small fractional energy gain after each shock crossing $\rightarrow$

$$\frac{dN}{dE} \sim E^{-\alpha} \quad \text{with } \alpha \approx 2 - 2.4$$
TYPES OF COSMIC RAY DETECTORS

- **Cherenkov telescopes**
  - E < 100 GeV
- **Satellites**
  - E ~ TeV
- **Arrays of particle detectors**
  - E > PeV
Examples of powerful astrophysical Objects/potential CR accelerators:

- AGN
- SNR
- Radio Galaxy
- Colliding galaxies
- Pulsar
- GRB
- Diffuse emission
TeV $\gamma$ Astrophysical Sources
Discriminating leptonic vs. hadronic scenarios
(a way to know if protons are indeed accelerated in SNR)

Brems: \( e + \text{gas} \rightarrow \gamma + \ldots \)

Synch: \( e + \text{Bfield} \rightarrow e + \text{Xray} \)

IC: \( e + \text{Xray} \rightarrow \gamma + e \)

Hadronic: \( CR + \gamma(p) \rightarrow \pi + X \)

\( \pi^0 \rightarrow \gamma\gamma \), \( \pi^- \rightarrow e + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu \)

e.g. CasA \( \gamma \) spectrum

Often inconclusive, observation of neutrinos would be unambiguous!
FERMI found 2 SN remnants with clear signals of gammas from pion decays (low E supp.)

Proton acceleration in SuperNovae to beyond 10 TeV proved, associated ν flux expected

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Distant $\gamma$ sources are strongly attenuated by background photons (starlight, CMB, radio, ...): $\gamma\gamma \rightarrow e^+ e^-$

Can even measure IR background from observed attenuation beyond few TeV, high redshift Universe is unobservable with photons
CR AIR SHOWER DETECTORS

AUGER, 3000 km²

Lateral distribution at ground

ID 762238

Longitudinal distribution in air

(FD duty cycle ~15%)

Measure Xmax
Energy calibration
angular resolution < 1°

(SD duty cycle ~100%)
Photons produce deep showers
nuclei of mass A behave as p with with E/A \rightarrow\ shallower showers
E^3 x FLUX (before Auger)
the Greisen-Zatsepin-Kuzmin effect (1966)

AT THE HIGHEST ENERGIES, PROTONS LOOSE ENERGY BY INTERACTIONS WITH THE CMB BACKGROUND

PROTONS CAN NOT ARRIVE WITH 
E > 6x10^{19} eV FROM D > 200 Mpc

( π^{0} produce GZK photons)
( π^{±} produce cosmogenic neutrinos)
(Berezinsky & Zatsepin 69)

For Fe nuclei:
after ~ 200 Mpc the leading fragment has  E < 6x10^{19} eV

lighter nuclei get disintegrated on shorter distances
(fewer neutrinos produced)
Ankle:
1- Galactic–extragalactic transition? (ankle model)

2 - or $e^+e^-$ dip in Xgal protons? (dip model)

GZK: proton or Fe suppression? (and/or exhaustion of sources?)
ASSOCIATED PHOTON FLUXES

\[ p \gamma \rightarrow \pi^0 p \quad \pi^0 \rightarrow \gamma \gamma \quad p \gamma \rightarrow p e^+ e^- \]

\[ \gamma \gamma_{\text{bckg}} \rightarrow e^+ e^- \quad e \gamma_{\text{bckg}} \rightarrow e \gamma \]

Cascades down to GeV-TeV

- dip models lead to significant cascade fluxes from pair production
- ankle models (harder fluxes) lead to larger GZK photon fluxes
AUGER SD photon bound

Photon showers are quite penetrating (small curvature radius) and lack muons (electromagnetic signal in detectors have long rise times) → essentially no UHE photon candidates observed

Photon fraction:
- < 2% at $E > 10 \text{ EeV}$
- < 31% at $E > 40 \text{ EeV}$

Excludes most top-down models, but still above optimistic GZK photons.
COSMOGENIC NEUTRINO FLUXES:

- ankle models (harder fluxes) lead to larger cosmogenic neutrino fluxes than dip models

- fluxes at EeV could be comparable to CR fluxes, but cross section tiny (~ 10 nb)
  → probability of interacting in atmosphere small (~10^{-5} for vertical)
**Neutrino detection in AUGER**

Only neutrinos can produce young horizontal showers

For downgoing showers: (assuming 1:1:1 flavor ratios)
- 38% from $\nu_e$
- 18% from $\nu_\mu$
- 29% from $\nu_\tau$ – air
- 15% from $\nu_\tau$ – mountain

but Earth-skimming $\nu_\tau$ searches are more sensitive
Up-going Earth-skimming $\nu_\tau$ showers

\[ \sigma_{CC} \approx 10^{-32} \text{cm}^2 E^{0.36} \quad (E [EeV]) \]

Probability of interacting in the last 10 km \( \sim 0.01 \)

\( \Rightarrow \) Effective exposure \( \sim 0.1 \text{km}^2 \text{sr} \)

(c.f. \( \sim 10^4 \text{km}^2 \text{sr} \) for UHECR)
unlike hadronic CRs, neutrinos can produce young horizontal showers above the detector (in particular from upcoming near horizontal tau lepton induced showers)

Horizontal young showers?

ZERO CANDIDATES
0 events observed → bounds scale linearly with exposure
km³ detector at South Pole, completed by 2011, looking at northern ν sky (and to southern sky above PeV)

km³ detector at Mediterranean looking at southern neutrino sky (proposed km3NET & GVD in Baikal)
Deep inelastic Neutrino nucleon interactions

Earth opaque for $E>40$ TeV $\rightarrow$ Need to look above horizon
One may even distinguish neutrino flavors

- muon neutrino (track)
- electron neutrino (cascade, also from NC)
- tau neutrino (double bang)

\[ \gamma c \tau \approx \frac{E}{PeV} \]

50 m
No point sources observed by Icecube nor Antares
Targeted searches (galactic and extra-galactic candidates): SNR, AGN,...
ICECUBE stacked search for neutrinos coincident with observed GRB 2008/2010

Bound factor 4 below standard predictions → GRB are not main source of UHECRs or production models need revision

Revised model: (Hummer et al.): E losses, flavor mix, spectral shapes...
BOUNDS ON DIFFUSE NEUTRINO FLUXES

\[ E_V^2 \frac{dN_V}{dE_V} \text{ [GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}] \]

- Honda + Sarcevic Atmos.νµ
- ESS νµ + νe, 2001
- Decerprit et al. Proton
- Baikal Cascade Limit 1038 d, non-contained
- AMANDA Forward Folding νµ
- ANTARES Diffuse νµ Limit × 3
- IceCube 2012 All Flavor Limit (Prelim.)
- RICE 2011 Diffuse Limit
- Waxman Bahcall 1998× 3/2
- Ahlers et al. Best Fit
- IC22 Cascade Limit
- AMANDA-II Diffuse νµ Limit × 3
- IC40 Atmos.νµ Unfolding
- IC59 Diffuse νµ Limit × 3
- IceCube 2 Year Starting
- Auger 2013 νµ Limit × 3

\[ E_V \text{ [GeV]} \]

\[ 10^3 \rightarrow 10^{10} \]
High energy atmospheric neutrinos

decay length \[ L = \gamma c \tau \]

\[ L_{\pi} \approx 6 \text{ km} \left( \frac{E_{\pi}}{100 \text{ GeV}} \right) \]

\[ L_K \approx 7.5 \text{ km} \left( \frac{E_K}{\text{TeV}} \right) \]

\[ L_D \approx 2 \text{ km} \left( \frac{E_D}{10 \text{ PeV}} \right) \]

Atmospheric vs mainly from pion decays at low energies,

but above 100 GeV pions are stopped before decay \( \rightarrow \)

kaons become the main source,

but above \( \sim 100 \text{ TeV} \) prompt charm decays dominate
Prompt charm production

For $E > 200$ TeV $\rightarrow \nu$ mostly from c decays

FIG. 5: Prompt and conventional $\nu_\mu + \bar{\nu}_\mu$ fluxes in the vertical

sample gluon density distribution at $x_2 < 10^{-5}$ for $E > 10^{15}$ eV

need to extrapolate from measured values

also requires to include NLO processes
The two highest energy neutrino events observed by ICECUBE

E = 1.04 and 1.14 PeV (+-0.17)

Possibility of the origin includes
- cosmogenic \( \nu \)
- on-site \( \nu \) production from the cosmic-ray accelerators
- atmospheric prompt \( \nu \)
- atmospheric conventional \( \nu \)

(PRD 2012)
Recently 26 additional events found above ~ 20 TeV

21 showers and 7 tracks   (consistent with 1:1:1 flavor ratios)

Only ~ 10.6^{+5}_{-3.6} expected from atmospheric background

(Science 2013)
Recent Big Bird event of 2 PeV

Distribution in $E$ and declination compatible with isotropic $E^{-2}$ flux with cutoff

$$E^2 \Phi(E) \sim 3 \times 10^{-8} \text{GeV/cm}^2 \text{s sr}, E < \text{few PeV}$$
Cosmogenic neutrinos from proton sources:

**Threshold:**

\[ p\gamma \rightarrow \pi^+ n \]

\[ s = (p_p + p_\gamma)^2 > (m_p + m_\pi)^2 \Rightarrow E_p > \frac{m_\pi(2m_p + m_\pi)}{4 E_\gamma} \approx \frac{70 \text{ EeV}}{E_\gamma/10^{-3} \text{ eV}} \]

\[ \rightarrow 10^{20} \text{ eV for CMB photons, } 10^{17} \text{ eV for optical photons} \]

\[ \nu \text{ energies:} \]

\[ p\gamma \rightarrow \pi^+ n \]

\[ \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \bar{\nu}_\mu \nu_\mu \nu_e \]

\[ E_{\nu_\mu} \approx E_{\nu_e} \approx E_{\nu_\pi} \approx E_{\nu}/4 \approx E_p/20 \]

\[ n \rightarrow p e \bar{\nu}_e \]

\[ E_{\bar{\nu}_e} \approx \frac{m_n - m_p - m_e}{2 m_n} E_n \approx 4 \times 10^{-4} E_n \]

**Redshift (production at 0<z<4):**

\[ T_{CMB} = (1+z) \times 2.7 \text{ K} \rightarrow \text{redshifted threshold} \]

**Redshifted \( \nu \) energy**

\[ E_{\nu}^{\pi- \text{dec}} \approx \frac{E_p}{20(1+z)} \]

\[ E_{\nu}^{\pi- \text{dec}} \approx \frac{5 \text{ EeV}}{(1+z)(E_\gamma/10^{-3} \text{ eV})} \]

**EeV \( \nu \) from interactions with CMB photons**

**PeV \( \nu \) from interactions with UV/O/IR photons**

or PeV \( \nu \) from n-decays from interactions with CMB?
Mostly $\pi$ decays from UV/IR int

Height of PeV $\nu$ peak from n-decay related to height of EeV $\nu$ peak from $\pi$-decay

$$\frac{d\Phi_{\bar{\nu}_e}}{d\log E} (E_{\nu}^{n-dec}) \simeq \frac{d\Phi_{\nu_e}}{d\log E} (E_{\nu}^{\pi-dec}) \Rightarrow \left[ \frac{E_{\nu}^2}{dE} \frac{d\Phi_{\nu_e}}{dE} \right]_{E_{\nu}=6\times10^{15} E_{\nu}} \simeq \frac{E_{\bar{\nu}_e}^{n-d}}{E_{\nu}^{\pi-d}} \left[ \frac{E_{\nu}^2}{dE} \frac{d\Phi_{\nu_e}}{dE} \right]_{E_{\nu}=10^{18} E_{\nu}}$$
\[ \nu \text{ and } \gamma \text{ for different source evolutions & cascade bound} \]

proton sources, \( E_{\text{max}} = 200 \text{ EeV} \)

\[ E^2 \frac{d \Phi_{\nu}}{d \nu} < 5 \times 10^{-8} \frac{\text{GeV}}{\text{cm}^2 \text{ s sr}} \Rightarrow \]

\[ E^2 \frac{d \Phi_{\nu_e}}{d \nu} < 10^{-10} \frac{\text{GeV}}{\text{cm}^2 \text{ s sr}} \]

\[ \nu_e \text{ flux from n-decay tiny at PeV} \]
Cosmogenic neutrinos from nuclei:

**photo-disintegration:**

\[ A \gamma \rightarrow A' + \text{nucleons} \]

\[ A' \rightarrow A e \bar{\nu}_e \]

\[ n \rightarrow p e \bar{\nu}_e \]

\[ p \gamma \rightarrow \pi^+ n \]

\[ \pi^+ \rightarrow e^+ \bar{\nu}_\mu \nu_\mu \nu_e \]

Giant dipole resonance for \( E'_\gamma \sim 10\text{-}30 \text{ MeV} \)

**Threshold:**

\[
S = (p_A + p_\gamma)^2 > (m_A + 10 \text{ MeV})^2 \Rightarrow E_A > \frac{A}{56} \frac{2 \times 10^{20} \text{ eV}}{E_\gamma/10^{-3} \text{ eV}}
\]

For Fe, similar cutoff as p

lighter nuclei \( \rightarrow \) smaller cutoffs

**Photo-pion:**

\[ A \gamma \rightarrow A' + \pi \]

(need to account for nuclear suppression)

For \( E/A > 10^{17} \text{ eV} \), nuclei disintegrate 'a lot' (from IR & CMB)

\( \rightarrow \) low energy neutrinos from n-decays (& beta decay)

\[ E_\nu \approx 4 \times 10^{-4} E/A \]

Secondary nucleons with \( E/A \) interact producing pions

for \( E/A < 10^{17} \text{ eV} \) interaction probabilities small

\( \rightarrow \) few nuclei disintegrate, fewer nuclei emit pions, but those may still dominate PeV neutrino flux production
PeV $\nu$ from n-decays bounded by EeV neutrons, which are bounded by overall CR fluxes

$$\left[ \frac{d \Phi_{\bar{\nu}_e}}{d \log E} \right]_{E=10^{15} eV}^{n-dec} \ll \left[ \frac{d \Phi_n'}{d \log E} \right]_{E=2 \times 10^{18} eV} < \left[ \frac{1}{2} \frac{d \Phi_{CR}}{d \log E} \right]_{E=2 \times 10^{18} eV} \Rightarrow \left[ E^2 \frac{d \Phi_{\bar{\nu}_e}}{d E} \right]_{E=10^{15} eV}^{n-dec} < 10^{-11} \frac{GeV}{cm^2 s sr}$$
Mixed extragalactic p / Fe composition with low cutoff ($E_p < 4$ EeV)

$p$ component below ankle leads to significant PeV $\nu$ fluxes from $\pi$-decay no EeV $\nu$ due to low cutoff
Flavor oscillations

Incoherent flavor conversions

\[ P_{\alpha \beta} = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2 \]

\[ \pi\text{-decays:} \quad (\nu_e: \nu_\mu: \nu_\tau) = (1:1:0) \rightarrow (0.78:0.61:0.61) \]
\[ (\bar{\nu}_e: \bar{\nu}_\mu: \bar{\nu}_\tau) = (0:1:0) \rightarrow (0.22:0.39:0.39) \]

\[ \text{(adopting TBM)} \quad \sin^2 \Theta_{23} \approx 1/2 \quad \sin^2 \Theta_{12} \approx 1/3 \quad \sin^2 \Theta_{13} \approx 0 \]

\[ \text{n-decays:} \quad (\nu_e: \nu_\mu: \nu_\tau) = (0:0:0) \rightarrow (0:0:0) \]
\[ (\bar{\nu}_e: \bar{\nu}_\mu: \bar{\nu}_\tau) = (1:0:0) \rightarrow (0.56:0.22:0.22) \]
THE GLASHOW RESONANCE

\[ \bar{\nu}_e e \rightarrow W \rightarrow f f' \]

resonant for:

\[ E = \frac{M_W^2}{2m_e} = 6.3 \text{ PeV} \]

at the peak,

\[ \sigma(\bar{\nu}_e e \rightarrow all) \approx 350 \sigma^{CC}(\nu_i N \rightarrow l_i X) \]

but peak narrow (0.17 PeV), electron antineutrino flavor not dominant,

\[ n_{\bar{\nu}_e}/n_N = 5/9 \]

→ overall contribution to the IceCube rates

of \( \nu \) from \( \pi \)–decays is similar to the

CC+NC ones within 2.5 PeV of the resonance

→ does not allow to achieve strong enhancements
PeV neutrinos of Galactic origin?

But: Composition becoming heavy above the knee, individual sources too faint, Bounds from CASA-MIA on 100 TeV gammas, ...

Correlated with Fermi diffuse gammas? produced by interaction with gas in galactic arms?

Correlated with Fermi Bubbles?
PeV neutrinos of extra-Galactic origin?

Sources could be AGN, GRBs, ....

Need about 10\% of energy in few $10^{16}$ CRs to go to pions

Optical photons at or around the source could be the target

Sources need not be too far away (unlike for cosmogenic nus)

Is there a gap between 300 TeV and 1 PeV ?

PeV neutrinos from dark matter decay?

Need more data to test spectrum, cutoff, tracks/showers, arrival directions, ....  IceCube will soon provide that
CONCLUSIONS

Detection of 2 PeV $\nu$ produced a revolution in the field of $\nu$ astronomy

- are they atmospheric ? (enhanced by charm production)
- are they cosmogenic ? (produced during propagation of CRs)

Significant PeV $\nu$ fluxes can arise from $10^{16} - 10^{17}$ eV protons producing $\pi$ in interactions with UV/IR (but probably not enough)

Cosmogenic neutrinos from n-decays tiny at PeV energies

Glashow resonance has moderate impact (narrow width, only anti-$\nu_e$)

- are they Galactic ? Produced by CR interaction with ISM
- are they produced at the sources ? (GRB, AGN, …)

We are at the dawn of the era of high energy neutrino astronomy