Multi-Messenger Aspects of Cosmic Neutrinos

Markus Ahlers
UW-Madison & WIPAC

Next-Generation Techniques for UHE Astroparticle Physics
Chicago, March 2, 2015
Multi-Messenger Astronomy

- Cosmic Messengers:
  - Cosmic Rays
  - Gamma Rays
  - Neutrinos
  - Gravitational Waves

- Neutrino astronomy:
  - closely related to cosmic rays (CRs) and γ-rays
  - weak interaction during propagation
  - exclusive messenger for 10 TeV-10 EeV telescopes

- Challenges:
  - low statistics
  - large backgrounds

Markus Ahlers (UW-Madison)
Multi-Messenger Aspects of Cosmic Neutrinos
March 2, 2016  slide 2
IceCube HESE (4yr)

- **High-Energy Starting Event (HESE) sample:**
  - bright events \( E_{\text{th}} \gtrsim 30 \text{TeV} \) starting inside IceCube
  - efficient removal of atmospheric backgrounds by veto layer

- 54 events in about four years:
  - 39 *cascades* events
  - 14 *track* events
  - 1 *composite* event (removed)

- expected background events:
  - \( 9.0^{+8.0}_{-2.2} \) atmospheric neutrinos
  - \( 12.6 \pm 5.1 \) atmospheric muons

- **best-fit** \( E^{-2} \)-flux \((0.06 - 3)\text{PeV}\):

  \[
  E_{\nu}^{2} \phi_{\nu\alpha} \simeq (0.84 \pm 0.3) \times 10^{-8} \frac{\text{GeV}}{\text{s cm}^{2} \text{ sr}}
  \]
HESE 4yr with $E_{\text{dep}} > 60$ TeV (green) / Classical $\nu_\mu + \bar{\nu}_\mu$ 2yr with $E_\mu > 50$ TeV (red)

- 24 “cascade events” (circles) and 8 “tracks events” (diamonds) with $E_{\text{dep}} \gtrsim 60$ TeV
- 20 up-going muon neutrino events with $E_\mu \gtrsim 50$ TeV [IceCube PRL 115 (2015)]

no significant spatial or temporal correlation of events
Neutrino Flavors

- initial composition: $\nu_e : \nu_\mu : \nu_\tau$
  
  - pion & muon decay: $1 : 2 : 0$
  
  - neutron decay: $1 : 0 : 0$
  
  - muon-damped pion decay: $0 : 1 : 0$

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

- oscillation-averaged probability:

\[ P_{\nu_\alpha \rightarrow \nu_\beta} \simeq \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2 \]

- “NuFit 1.3”: $\sin^2 \theta_{12} = 0.304 / \sin^2 \theta_{23} = 0.577 / \sin^2 \theta_{13} = 0.0219 / \delta = 251^\circ$

- observed events consistent with equal contributions of all neutrino flavors

→ talk by Mauricio Bustamante
Neutrino Flavors

- initial composition: $\nu_e : \nu_\mu : \nu_\tau$
  - pion & muon decay: $1 : 2 : 0$
  - neutron decay: $1 : 0 : 0$
  - muon-damped pion decay: $0 : 1 : 0$

$$p + p \rightarrow \pi^+ + X \quad \Rightarrow \quad \mu^+ + \nu_\mu \quad \Rightarrow \quad e^+ + \nu_e + \bar{\nu}_\mu$$

- oscillation-averaged probability:

$$P_{\nu_\alpha \rightarrow \nu_\beta} \simeq \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

- “NuFit 1.3”: $\sin^2 \theta_{12} = 0.304 / \sin^2 \theta_{23} = 0.577 / \sin^2 \theta_{13} = 0.0219 / \delta = 251^\circ$

✓ observed events consistent with equal contributions of all neutrino flavors

→ talk by Mauricio Bustamante

[IceCube'15]
Multi-messenger Paradigm

- **Neutrino** production is closely related to the production of **cosmic rays** (CRs) and $\gamma$-rays.

- **pion production** in CR interactions with gas ("pp") or radiation ("p$\gamma$“); neutrinos with about 5% of CR nucleon energy

- **1 PeV neutrinos** correspond to 20 PeV CR nucleons and 2 PeV $\gamma$-rays

- **very interesting** energy range:
  - Glashow resonance?
  - galactic or extragalactic?
  - isotropic or point-sources?
The Cosmic “Beam”

Figure 27.8: The all-particle spectrum as a function of $E$ (energy-per-nucleus) from air shower measurements [88–99, 101–104].

...this structure is accompanied a transition to heavy...
Proposed Source Candidates I

- **Galactic**: (full or partial contribution)
  - diffuse Galactic $\gamma$-ray emission
    - [MA & Murase’13; Joshi J C, Winter W and Gupta’13]
    - [Kachelriess and Ostapchenko’14; Neronov, Semikoz & Tchernin’13]
    - [Neronov & Semikoz’14; Guo, Hu & Tian’14; Gaggero, Grasso, Marinelli, Urbano & Valli’15]
  - unidentified Galactic $\gamma$-ray emission
    - [Fox, Kashiyama & Meszaros’13]
    - [Gonzalez-Garcia, Halzen & Niro’14]
  - supernova remnants
    - [Mandelartz & Tjus’14]
  - pulsars
    - [Padovani & Resconi’14]
  - microquasars
    - [Anchordoqui, Goldberg, Paul, da Silva & Vlcek’14]
  - Sagittarius A*
    - [Bai, Barger, Barger, Lu, Peterson & Salvado’14; Fujita, Kimura & Murase’15]
  - *Fermi Bubbles*
    - [MA & Murase’13; Razzaque’13]
    - [Lunardini, Razzaque, Theodoseau & Yang’13; Lunardini, Razzaque & Yang’15]
  - Galactic Halo
    - [Taylor, Gabici & Aharonian’14]
  - heavy dark matter decay
    - [Feldstein, Kusenko, Matsumoto & Yanagida’13]
    - [Esmaili & Serpico ’13; Bai, Lu & Salvado’13; Cherry, Friedland & Shoemaker’14]
Galactic Emission Models: Two Examples

Hard Galactic Diffuse Emission

-\[ \gamma, \text{Fermi/LAT} \]
-\[ \nu, \text{IceCube} \]
-\[ \nu, \text{galaxies} \]

Extragalactic

\[ E^2 \Phi \text{[GeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}] \]
\[ E \text{[GeV]} \]

PeV Dark Matter Decay (\( e.g. \text{DM} \rightarrow \nu \bar{\nu}/q\bar{q} \))

-\[ \text{IceCube 2014} \]
-\[ \text{Fermi 2014} \]

\[ \text{KASCADE} \]
\[ \text{CASA-MIA} \]

-\[ \text{Galactic primary} + \text{extragalactic} \]
-\[ \text{total } \gamma \]
-\[ \text{total } \nu \]

\[ [\text{Neronov & Semikoz'14}] \]
\[ [\text{e.g. Murase, Laha, Ando & MA'15}] \]

-\[ \text{anisotropy limits on Galactic emission} \]
-\[ \text{limits on Galactic contribution from PeV } \gamma\text{-ray observation} \]

\[ [\text{MA & Bai, Barger & Yang'15}] \]
\[ [\text{Gupta'14; MA & Murase'14}] \]
Example: Galactic Diffuse Emission

HESE 3yr with $E_{\text{dep}} > 60$ TeV, $n_{\text{tot}} = 20$, $\tilde{f}_{\text{iso}} = 0.81$, $\lambda = 0.74$

- Strong Galactic diffuse emission up to PeV? [Neronov, Semikoz & Tchernin’13]
- simulated map: ◊/○ : Galactic $\nu$ | ◇/○ : isotropic $\nu$ | ◇/◦ : atmospheric $\nu$ | ◇/◦ : atmospheric $\mu$
sample with $f_{iso} = 0.00$, $n_{tot} = 29$, $\hat{f}_{iso} = 0.09$, $\lambda = 26.03$

- Strong Galactic diffuse emission up to PeV? [Neronov, Semikoz & Tchernin'13]
- simulated map: $\Diamond/\circ$: Galactic $\nu$ | $\Diamond/\circ$: isotropic $\nu$ | $\Diamond/\circ$: atmospheric $\nu$ | $\Diamond/\circ$: atmospheric $\mu$
Example: Galactic Diffuse Emission

sample with $f_{iso} = 1.00, n_{tot} = 31, \hat{f}_{iso} = 0.82, \lambda = 1.11$

- Strong Galactic diffuse emission up to PeV? [Neronov, Semikoz & Tchernin’13]
- simulated map: $\diamond/\circ$: Galactic $\nu$ | $\diamond/\circ$: isotropic $\nu$ | $\diamond/\circ$: atmospheric $\nu$ | $\diamond/\circ$: atmospheric $\mu$
Other Extended Galactic Emission

SNR (log_{10}(w_{signal}/w_{iso}))

DM decay (log_{10}(w_{signal}/w_{iso}))

Galactic

Fermi Bubbles

Unidentified & Dark Sources

Markus Ahlers (UW-Madison)
Galactic Limits

- maximum likelihood-ratio test for Galactic emission (signal)

- **IceCube 3yr HESE limits**
  \((E_{\text{dep}} > 60\ \text{TeV} & 90\%\ \text{C.L.}):\)
  - *Fermi Bubbles*: \(< 25\%\)
  - unidentified TeV \(\gamma\)-ray sources: \(< 25\%\)
  - Galactic diffuse emission: \(< 50\%\)
  - cumulative distribution of Galactic sources: \(< 65\%\)
  - PeV DM decay: *unconstrained*

- **stronger** limits possible:
  - spectral and flavor analysis
  - classical \(\nu_\mu + \bar{\nu}_\mu\) search
  - PeV \(\gamma\)-ray emission?

---

[MA, Bai, Barger & Lu’15]
PeV $\gamma$-ray Associations?

- PeV $\gamma$-rays from $\pi^0 \rightarrow 2\gamma$
- Strong absorption via $\gamma\gamma_{BG} \rightarrow e^+e^-$
  - Effect strongest for CMB in PeV range: $\lambda_{\gamma\gamma} \approx 10$ kpc
  - Plot indicate absorption from 8.5 kpc (GC) to 30 kpc
- Strong constraints on isotropic diffuse Galactic emission from $\gamma$-ray observatories
  [Gupta’13, MA & Murase’13]
PeV $\gamma$-ray Associations?

Diffuse TeV-PeV $\gamma$-ray Coverage

- large overlap of HESE events with TeV-PeV “blind spot”
- one PeV event (“Ernie”) within $10^\circ$ of PeV $\gamma$-ray “warm spot” [IceCube’12]
Proposed Source Candidates II

- **Extragalactic:**
  - association with sources of UHE CRs
    - [Kistler, Stanev & Yuksel'13]
    - [Katz, Waxman, Thompson & Loeb’13; Fang, Fujii, Linden & Olinto’14]
  - association with diffuse $\gamma$-ray background
    - [Murase, MA & Lacki’13]
    - [Chang & Wang’14; Ando, Tamborra & Zandanel’15]
  - active galactic nuclei (AGN)
    - [Stecker’13; Kalashev, Kusenko & Essey’13]
    - [Murase, Inoue & Dermer’14; Kimura, Murase & Toma’14; Kalashev, Semikoz & Tkachev’14]
    - [Padovani & Resconi’14; Petropoulou, Dimitrakoudis, Padovani, Mastichiadis & Resconi’15]
  - gamma-ray bursts (GRB)
    - [Murase & Ioka’13; Dado & Dar’14; Tamborra & Ando’15]
  - galaxies with intense star-formation
    - [He, Wang, Fan, Liu & Wei’13; Yoast-Hull, Gallagher, Zweibel & Everett’13]
    - [Murase, MA & Lacki’13; Anchordoqui, Paul, da Silva, Torres& Vlcek’14]
    - [Tamborra, Ando & Murase’14; Chang & Wang’14; Liu, Wang, Inoue, Crocker& Aharonian’14]
    - [Senno, Meszaros, Murase, Baerwald & Rees’15; Chakraborty & Izaguirre’15]
  - galaxy clusters/groups
    - [Murase, MA & Lacki’13; Zandanel, Tamborra, Gabici & Ando’14]
  - ...
Extragalactic Emission Models: Two Examples

Starburst Galaxies ("pp" scenario)

- CR-gas ($pp$) interactions: **mostly broken power-law** neutrino spectra.
- CR-photon ($p\gamma$) interactions: **strong spectral features** inherited from photon spectrum

Active Galactic Nuclei ("p\gamma" scenario)

[Loeb & Waxman’06]

[Mannheim’96; Halzen & Zas’97]
[e.g. Murase, Inoue & Dermer’14]
Identification of Extragalactic Point-Sources?

- total number of sources
  \[ n_s \simeq 10^6 - 10^7 \]
- total number of “shells”
  \[ n_{\text{shell}} \simeq (n_s)^{\frac{1}{3}} \]
- total number of events
  \[ \bar{N} \simeq m \times n_{\text{shell}} = m \times (n_s)^{\frac{1}{3}} \]
  
- required number of events to see a doublet \((m = 2)\)
  \[ \bar{N} \simeq 200 - 500 \]
- random clusters are very likely with bad angular resolution!

\[ \rightarrow \text{multi-messenger correlations!} \]
IceCube Stacking Searches

GRB Stacking

- $\nu_\mu$ emission following the GRB “fireball” model
- 492 GRBs (2008–2012) in IceCube’s FoV reported with GCN and Fermi GBM

Blazar Stacking

- Fermi blazar stacking
- plot shows limit on 310 FSRQ
- all 2LAC blazar limits of similar strength

The Journal's name

Table 1: Definitions of Blazar populations

<table>
<thead>
<tr>
<th>Type</th>
<th>No. of sources</th>
<th>Motivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>All 2LAC Blazars</td>
<td>862</td>
<td>No bias</td>
</tr>
<tr>
<td>FSRQ</td>
<td>1</td>
<td>310 BLR radiation [11]</td>
</tr>
<tr>
<td>LSP</td>
<td>2</td>
<td>FSRQ and LSP-BLLAC might be intrinsically similar [12]</td>
</tr>
<tr>
<td>ISP</td>
<td>2</td>
<td>HSP objects seem to evolve differently [13]</td>
</tr>
<tr>
<td>LSP &amp; BLLAC</td>
<td>12</td>
<td>Motivated by work in [9]</td>
</tr>
</tbody>
</table>

Table 2: Results of the Blazar population tests for both weighting schemes.

<table>
<thead>
<tr>
<th>Source</th>
<th>Equal Weighting</th>
<th>Lum. Weighting</th>
</tr>
</thead>
<tbody>
<tr>
<td>All 2LAC Blazars</td>
<td>36%</td>
<td>6%</td>
</tr>
<tr>
<td>FSRQs</td>
<td>34%</td>
<td>34%</td>
</tr>
<tr>
<td>LSPs</td>
<td>36%</td>
<td>28%</td>
</tr>
<tr>
<td>ISP/HSPs</td>
<td>&gt;50%</td>
<td>11%</td>
</tr>
<tr>
<td>LSP-BLLACs</td>
<td>13%</td>
<td>7%</td>
</tr>
</tbody>
</table>

Diffuse Flux Limit

- Neutrino Energy [GeV]
- $E^2d\Phi/dE$ [GeV cm$^{-2}$ sr$^{-1}$]
- Equal weighting - Lum. weighting

- IceCube Preliminary
- [M.Richman ICRC’13; arXiv:1412.6510]
- [Th.Gluesenkamp RICAP’14; arXiv:1502.03104]
Extragalactic Gamma-Rays

- **hadronic** $\gamma$-rays:
  
  \[
  \begin{align*}
  \pi^0 & \rightarrow \gamma + \gamma \\
  \pi^+ & \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu
  \end{align*}
  \]

- Cross-correlation of $\gamma$-ray and neutrino sources

- Electromagnetic cascades of super-TeV $\gamma$-rays in CMB

- Isotropic Diffuse Gamma-Ray Background (IGRB) constraints the energy density of hadronic $\gamma$-rays & neutrinos
Electromagnetic Cascades

- **CMB interactions (solid lines)** dominate in cascade:
  - **inverse Compton scattering (ICS)**
    \[ e^\pm + \gamma_{\text{CMB}} \rightarrow e^\pm + \gamma \]
  - **pair production (PP)**
    \[ \gamma + \gamma_{\text{CMB}} \rightarrow e^+ + e^- \]

- **extragalactic background light (red dashed line)** determines the "edge" of the spectrum.
  
  [EBL: Franceschini et al. ’08]

- **rapid cascade interactions produce universal GeV-TeV emission**
  
  [Berezinsky&Smirnov’75]

---

**Graph:**
- **pair production**
- **inverse-Compton**
- **CMB**
- **EBL**

**Axes:**
- **interaction length [Mpc]**
- **E [GeV]**

---

Markus Ahlers (UW-Madison)
Multi-Messenger Aspects of Cosmic Neutrinos
March 2, 2016
slide 23
Isotropic Diffuse Gamma-Ray Background (IGRB)

- neutrino and $\gamma$-ray fluxes in $pp$ scenarios follow initial CR spectrum $\propto E^{-\Gamma}$

- low energy tail of GeV-TeV neutrino/$\gamma$-ray spectra

- constrained by Fermi IGRB
  [Murase, MA & Lacki’13; Chang & Wang’14]

- extra-galactic emission (cascaded in EBL): $\Gamma \lesssim 2.15 - 2.2$

- Combined IceCube analysis:
  $\Gamma \simeq 2.4 - 2.6$
  [IceCube’15]

- hadronic $\gamma$-ray emission normalized to neutrino flux

- $\nu$ (per flavor)
- total $\gamma$
- direct $\gamma$
- cascade $\gamma$
- IGRB (Fermi)
- IceCube combined

- $pp$ scenario / $\Gamma = 2.15$ global fit range

[Ando, Tamborra & Zandanel’15]
Isotropic Diffuse Gamma-Ray Background (IGRB)

- neutrino and $\gamma$-ray fluxes in $pp$ scenarios follow initial CR spectrum $\propto E^{-\Gamma}$

$\Rightarrow$ low energy tail of GeV-TeV neutrino/$\gamma$-ray spectra

$\times$ constrained by *Fermi* IGRB
  
  [Murase, MA & Lacki’13; Chang & Wang’14]

- extra-galactic emission (cascaded in EBL): $\Gamma \lesssim 2.15 - 2.2$

$\times$ Combined IceCube analysis:
  
  $\Gamma \approx 2.4 - 2.6$

  [IceCube’15]

-Markus Ahlers (UW-Madison) Multi-Messenger Aspects of Cosmic Neutrinos March 2, 2016 slide 25
Isotropic Diffuse Gamma-Ray Background (IGRB)

- neutrino and $\gamma$-ray fluxes in $pp$ scenarios follow initial CR spectrum $\propto E^{-\Gamma}$

→ low energy tail of GeV-TeV neutrino/$\gamma$-ray spectra

✗ constrained by Fermi IGRB
  [Murase, MA & Lacki’13; Chang & Wang’14]

- extra-galactic emission (cascaded in EBL): $\Gamma \lesssim 2.15 - 2.2$

✗ Combined IceCube analysis:
  $\Gamma \approx 2.4 - 2.6$
  [IceCube’15]

[Ando, Tamborra & Zandanel’15]
Non-Blazar Limits on Gamma-Ray Background

**Total γ-ray background above 50 TeV dominated by blazars (~ 86%)**

- strong tension with IceCube observation

[Bechtol, MA, Ajello, Di Mauro & Vandenbroucke]

[Markus Ahlers (UW-Madison)]

Multi-Messenger Aspects of Cosmic Neutrinos

March 2, 2016 slide 27
Strong limits apply to **CR calorimeters**, like starburst galaxies or galaxy clusters.

Some direct $\gamma$-ray emission can be reduced in $\gamma\gamma_{BG}$ interactions in sources. [Chang & Wang'14]

Cascade emission alone contributes at the level of 10% above 100 GeV to the IGRB.

Is **blazar emission** above 50 GeV dominated by **hadronic interactions**?

Are there **Galactic** “contaminations” at $E_\nu \sim 1 - 10$ TeV that effectively lead to a softening of the observed neutrino spectrum? [IceCube’15; MA, Bai, Bargner & Lu’15]

Is secondary $\gamma$-ray emission “hidden” by **source radiation backgrounds**? [Murase, Guetta & MA’15]

The diffuse flux also saturates limits from **UHE CR sources**. Is this population also responsible for UHE CRs? [Katz, Waxman, Thompson & Loeb’13]
Fermi IGRB and $p\gamma$ Scenarios?

- also strong constraints from cascade emission of $p\gamma$ scenarios
- However, **high pion production efficiency** implies strong $\gamma\gamma$ absorption in sources!
  - Are strong neutrino sources “hidden” in $\gamma$-rays?

[Murase, Guetta & MA’15]
UHE CR association?

- UHE CR proton emission rate density: [MA & Halzen’12]
  \[ E_p^2 Q_p(E_p) \simeq (1 - 2) \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1} \]

- corresponding per flavor neutrino flux (\(\xi_z \simeq 0.5 - 2.4\) and \(K_\pi \simeq 1 - 2\)):
  \[ E_\nu^2 \phi_\nu(E_\nu) \simeq f_\pi \frac{\xi_z K_\pi}{1 + K_\pi} (2 - 4) \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr} \]

- **WB bound:** \(f_\pi \leq 1\) [Waxman & Bahcall’98]
  - \(f_\pi \simeq 1\) requires efficient pion production
  - \(\times\) how to reach \(E_{\text{max}} \simeq 10^{20}\) eV in environments of high energy loss?
  - → two-zone models: acceleration + CR “calorimeter”?
    - starburst galaxies [Loeb&Waxman’06]
    - galaxy clusters [Berezinsky, Blasi & Ptuskin’96; Beacom & Murase’13]
Anisotropies of UHE CRs

Auger 2010 $E > 55$ EeV (magenta) / TA 2014 $E > 57$ EeV (orange)

- $\theta_{\text{rms}} \simeq 1^\circ \left( D / \lambda_{\text{coh}} \right)^{1/2} \left( E / 55 \text{EeV} \right)^{-1} (\lambda_{\text{coh}} / 1 \text{Mpc}) (B / 1 \text{nG})$ [Waxman & Miralda-Escude'96]
- “hot spots” (dashed), but no significant auto-correlation in Auger and Telescope Array data
- cross correlation? only expected for $\lambda_{\text{GZK}} / \lambda_{\text{Hubble}} \sim 5\%$ of neutrino events
Ultra-High Energy Cosmic Rays

- particle confinement during acceleration requires: \[E \lesssim 10^{18} \text{ EeV} \left(\frac{B}{1 \mu \text{G}}\right) \left(\frac{R}{1 \text{kpc}}\right)\]  
  \[\text{[Hillas'84]}\]

**Low statistics:**
- large uncertainties in chemical composition and spectrum!

**“GZK” horizon (\(\lesssim 200 \text{ Mpc}\)):**
- resonant interactions of CR nuclei with CMB photons
  \[\text{[Greisen'66;Zatsepin & Kuzmin'66]}\]

**Guaranteed flux** of secondary \(\gamma\)-ray and neutrino emission
\[\text{[Berezinsky&Zatsepin'70;Berezinsky&Smirnov'75]}\]
Cosmogenic ("GZK") Neutrinos

- Observation of UHE CRs and extragalactic radiation backgrounds “guarantee” a flux of high-energy neutrinos, in particular via resonant production in CMB.
  
  [Berezinsky & Zatsepin’69]

- “Guaranteed”, but with many model uncertainties and constraints:
  
  - *(low cross-over) proton models + CMB (+ EBL)*
    
    [Berezinsky & Zatsepin’69; Yoshida & Teshima’93; Protheroe & Johnson’96; Engel, Seckel & Stanev’01; Fodor, Katz, Ringwald & Tu’03; Barger, Huber & Marfatia’06; Yuksel & Kistler’07; Takami, Murase, Nagataki & Sato’09, MA, Anchordoqui & Sarkar’09, Heinz, Boncioli, Bustamante & Winter’15]
  
  - *+ mixed compositions*
    
    [Hooper, Taylor & Sarkar’05; Ave, Busca, Olinto, Watson & Yamamoto’05; Allard, Ave, Busca, Malkan, Olinto, Parizot, Stecker & Yamamoto’06; Anchordoqui, Goldberg, Hooper, Sarkar & Taylor’07; Kotera, Allard & Olinto’10; Decerprit & Allard’11; MA & Halzen’12]
  
  - *+ extragalactic $\gamma$-ray background limits*
    
    [Berezinsky & Smirnov’75; Mannheim, Protheroe & Rachen’01; Keshet, Waxman, & Loeb’03; Berezinsky, Gazizov, Kachelriess & Ostapchenko’10; MA, Anchordoqui, Gonzalez–Garcia, Halzen & Sarkar’10; MA & Salvado’11; Gelmini, Kalashev & Semikoz’12]
→ **minimal** GZK flux from proton dominated models can be estimated from observed spectrum

- dependence on cosmic evolution of sources:
  - no evolution (dotted)
  - star-formation rate (solid)

→ **ultimate test** of UHE CR proton models feasible with future observatories like ARA.

[MA&Halzen'12]
Summary & Outlook

- Neutrinos are unique cosmic (pointing) probes in the 10TeV-10EeV energy range (six orders of magnitude!).

- Identification of PeV neutrino sources is challenging.

- Galactic neutrino emission unlikely the main source of the PeV diffuse flux.

- Local PeV $\gamma$-ray astronomy?

$\Rightarrow$ Multi-messenger correlations are the most promising scenario for point-source detection, in particular for transient sources.

- Similar diffuse energy densities of UHE CRs, $\gamma$-rays and neutrinos might indicate a common extragalactic origin.

$\Rightarrow$ Input from $\gamma$-ray astronomy will be essential to identify extragalactic source populations.

- How well can we determine the spectrum and flavor composition?
Appendix
Neutrino Point-Source Limits

- Diffuse neutrino flux normalizes the contribution of individual sources
- Dependence on local source density $\mathcal{H}$ (rate $\dot{\mathcal{H}}$) and redshift evolution $\xi_z$
- PS observation requires rare sources
- Non-observation of individual neutrino sources exclude source classes, e.g.
  - Flat-spectrum radio quasars ($\mathcal{H} \approx 10^{-9} \text{Mpc}^{-3} / \xi_z \approx 7$)
  - "Normal" GRBs ($\mathcal{H} \approx 10^{-9} \text{Mpc}^{-3} \text{yr}^{-1} / \xi_z \approx 2.4$)

[MA&Halzen'14]
AGN jets

- neutrino from $p\gamma$ interactions in AGN jets
- complex spectra due to various photon backgrounds
- typically, deficit of sub-PeV and excess of EeV neutrinos

[Mannheim’96; Halzen & Zas’97]

[Murase, Inoue & Dermer 1403.4089]
Figure 1: EBL models, measurements, and constraints. See Finke et al. for details and references.

The EBL photons interact with $\gamma$-rays from cosmological sources to produce $e^+e^-$ pairs, absorbing the $\gamma$-rays so that the observed flux $F_{\text{obs}}(E) = F_{\text{int}}(E) \exp[-\tau_{\gamma\gamma}(E)]$ where $F_{\text{int}}(E)$ is the unabsorbed source flux as a function of observed energy $E$, and $\tau_{\gamma\gamma}(E)$ is the EBL absorption optical depth. If $F_{\text{int}}(E)$ is known, a measurement of the observed $\gamma$-ray spectrum from these sources can be used to probe the EBL. The intrinsic spectrum is generally unknown, however it is possible to determine an upper limit either from theory or from extrapolating a lower energy, unattenuated spectrum to higher energies. This is discussed further in the next section. From the upper limit on $F_{\text{int}}(E)$ and the measurement of $F_{\text{obs}}(E)$ with a $\gamma$-ray telescope, an upper limit on $\tau_{\gamma\gamma}(E)$ can be calculated and compared to theoretical predictions.

2 Constraints with Atmospheric Cherenkov Telescopes

Nearby blazars—active galactic nuclei with relativistic jets pointed along our line of sight—are $\gamma$-ray-emitting sources up to VHE energies and are located at cosmological distances. They are thus a good candidate for constraining the EBL by measuring their $\gamma$-ray attenuation.

Atmospheric Cherenkov telescopes (ACTs) such as HESS, MAGIC, and VERITAS detect $\gamma$-rays through the Cherenkov radiation from particle cascades produced by $\gamma$-rays interacting with the Earth's atmosphere. TeV blazars are located nearby and VHE $\gamma$-rays are generally attenuated by the mid-IR EBL. Although they seem to be persistent sources, they are highly variable and the intrinsic spectrum cannot be determined. However, theory allows the determination of a maximum possible intrinsic spectrum. Assuming the $\gamma$-rays are produced by Compton scattering off of electrons accelerated by naive test particle acceleration theory, the hardest possible photon index will be $\Gamma_{\text{int,max}} = 1.5$. Using this, results from several blazars (e.g. 1ES 1011-232, 1ES0229+200, 3C279) have ruled out high levels of the IR EBL. However, physical mechanisms have been suggested to produce intrinsic VHE $\gamma$-ray spectra harder than $\Gamma = 1.5$. Withou a strong constraint on $F_{\text{int}}(E)$, the constraining upper limits on the EBL intensity are not well-accepted by some in the community.

3 Constraints with the Fermi-LAT

Higher $z$ sources can be probed in the GeV range using the Fermi telescope. The Fermi Gamma-Ray Space Telescope's primary instrument, the Large Area Telescope (LAT) is a pair conversion detector.

optical-UV background gives PeV neutrino peak

Appendix
DM decay

- heavy (>PeV) DM decay?
  
  [Feldstein et al. 1303.7320; Esmaili & Serpico 1308.1105; Bai, Lu & Salvado 1311.5864]

- initially motivated by PeV “line-feature”, but continuum spectrum with/without line spectrum equally possible

→ observable PeV $\gamma$-rays from the Milky Way halo?

![Graph showing fitted spectra for various DM decay channels.](image)

[Bai, Lu & Salvado’13]
Composition Dependence of UHE CRs

- large uncertainties on UHE CR mass composition
  - UHE CR examples in plot: only proton or only iron on emission
  - diffuse spectra of cosmogenic $\gamma$-rays (dashed lines) and neutrinos (dotted lines) vastly different

→ neutrino limits start to constrain most optimistic scenarios of proton-dominated UHE CR sources.

[MA&Salvado’11] [IceCube’13;ANITA’12]
Guaranteed Cosmogenic Neutrinos

→ neutrino emission depend on *nucleon spectrum*:

\[ \phi_N(E_N) = \sum_i A_i^2 \phi_i(A_iE_N) \]

→ **minimal** contribution can be estimated from observed mass composition

- dependence on cosmic evolution of sources:
  - no evolution (dotted)
  - star-formation rate (solid)

→ **ultimate test** of UHE CR proton models with **ARA-37**

[MA&Halzen’12]
TeV Associations?

TeVCat γ-ray sources

LBL, IBL, LBL, FRI, FSRQ
Globular Cluster, Star Forming Region, Massive Star Cluster
Binary PWN
Shell, SNR/Molec.Cloud, Composite SNR
Starburst Others [TeVCat'14]