Galactic Neutrinos

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Outline of the talk

1 Introduction
   ▶ Observations
   ▶ Cascade limit and implications

2 Neutrinos from the Galactic CR sea – Galactic plane

3 Neutrinos from Galactic CR sources

4 Neutrinos from extended sources
   ▶ TeV γ-ray excess in Fermi-LAT
   ▶ Interpretations

5 Conclusions
IceCube events: Soft “low-energy” spectrum?

![Graph showing atmospheric and astrophysical fluxes.]

**Atmospheric Fluxes (reduced by self-veto in analysis)**
- Prompt Upper Limit ($\nu_e + \bar{\nu}_e$) [1.04x ERS]
- Conventional ($\nu_\mu + \bar{\nu}_\mu$) (zenith-averaged) [1.07x Honda2006]

**Astrophysical Fluxes (on top of atmospheric)**
- •• HESE Differential
- $\nu_\mu$ Best Fit
- HESE 1-Component ($E^{-2.9}$)

**IceCube Preliminary**
IceCube events: power-law fit of energy spectrum
IceCube events: power-law fit of energy spectrum
The photon horizon

\[ \gamma \gamma \rightarrow e^+ e^- \]
Cascade limit: $\alpha = 2.1$
Cascade limit: $\alpha = 2.3$
Cascade limit: \( \alpha = 2.5 \)
Cascade limit:

\[ E^2 J(E) \, [eV/cm^2 \cdot s \cdot sr] \]

\( E/eV \)

\( \gamma \)

\( \nu \)

\( \text{Fermi EGRB} \)

Slope \( \alpha \gtrsim 2.2 \)

- requires “hidden sources” or
- Galactic origin
(Isotropic) photon limits

[Ahlers, Murase '13]
(Isotropic) photon limits

[Ahlers, Murase '13]

KASCADE limits

- reanalysed '17 and increased
Hints for a Galactic plane contribution? [Neronov, Semikoz '14,'15]
Hints for a Galactic plane contribution? \[\text{[Neronov, Semikoz '14,'15]}\]

- Neronov & Semikoz '15: Galactic latitude distribution of 4yr IceCube data with $> 100$ TeV inconsistent at $3\sigma$ with isotropy

- Palladino & Vissani '15: Two component fit, soft Galactic $E^{-2.4}$
  25% Galactic contribution
Expectation:

- CR interactions with gas in Galactic plane give guaranteed $\nu$ flux
  
  \[ Berezinsky, Smirnov '75 \]
  
  \[ Gaggero et al. '15, Pagliaroli, Evoli, Villante '17, \ldots \]
  
  agreement: 10-20% Galactic contribution at 100 TeV
Expectation:

- CR interactions with gas in Galactic plane give guaranteed $\nu$ flux
  - [Berezinsky, Smirnov '75]
  - [Gaggero et al. '15, Pagliaroli, Evoli, Villante '17, ...]

- agreement: 10-20% Galactic contribution at 100 TeV

However, uncertainties are very large:

- elemental composition unclear, but $Z_\nu \propto A^{1-\gamma}$
- CRs locally measured
- close to knee diffusion may be unreliable
- gas density
Uncertainties: CR composition

Kascade-Grande: dependence on interaction model
Uncertainties: CR composition

Kascade-Grande: dependence on interaction model

- Proton
- Helium
- CNO
- Si group
- Fe group
Uncertainties: CR composition

[Gaisser, Stanev & Tilav ’13]
Uncertainties: CR composition

\[ \tau E^{2.6} I(E) \text{ [GeV}^{1.6} \text{ m}^{-2} \text{ sr}^{-1} \text{ s}^{-1}] \]

- \( \tau \) and \( E \) axes
- \( I(E) \) and \( E/\text{eV} \) axes

- \( p \)
- \( \text{He} \)
- \( \text{Li-Fl} \)
- \( \text{Ne-Cr} \)
- \( \text{Mn-Co} \)
- \( \text{total} \)
Resulting $\nu$ fluxes ($\tau = 1$ at PeV) [MK, Ostapchenko '14]
Uncertainties: CR composition

ARGO-YBJ: position of \("p+\)He knee\) \(\approx 700 \text{ TeV}\)
Uncertainties: CR composition

ARGO-YBJ: position of “p+He knee” $\sim 700$ TeV
Uncertainties: CR composition

ARGO-YBJ: position of “p+He knee” $\approx 700$ TeV

- neutrino knee at $\approx 20$–$40$ TeV
Uncertainties: diffusion approach

- diffusion picture requires $R_L(E_\ast) \ll L_{\text{coh}}/(2\pi)$
- for $L_{\text{coh}} \sim 50$ pc and $B \sim \text{few} \, \mu \text{G}$: $E_\ast \sim 10^{16}$ eV
Uncertainties: diffusion approach

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- for $L_{\text{coh}} \sim 50$ pc and $B \sim \text{few} \mu G$: $E_* \approx 10^{16}$ eV

- LOFAR: $l_{\text{coh}} \lesssim 10$ pc in disc
- diffusion has to be anisotropic
- grammage $X(E)$ in the “escape model”

\[ \beta = 1, L = 10\text{pc} \]
\[ \beta = 0.1, L = 10\text{pc} \]
\[ \beta = 1/8, L = 25\text{pc} \]
\[ \delta = 1/3 \]

AMS-02 (a)
AMS-02 (b)
Jones

[Giacinti, MK, Semikoz '18]
[Giacinti, MK, Semikoz '14,'15]
Uncertainties: diffusion approach

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\[ \Rightarrow \text{reduced } \tau \text{ above few } \sim 10^{15} \text{ eV} \]
Uncertainties: deviations from local spectrum

- CR slope from molecular clouds: $\alpha \simeq 2.4$

[Nezhorov, Malyshev, Semikoz '17]
Neutrinos from the Galactic CR sea – Galactic plane

Uncertainties: deviations from local spectrum

- CR slope from molecular clouds: $\alpha \simeq 2.4$
  
  $\chi^2/NDF = 2.0/8$

  - agrees with local slope of nuclei (and $\delta = 1/3$).
  - deviation of $\alpha_p \simeq 2.7$ vs $\alpha_{\text{nuc}} \simeq 2.5$ local effect?

[Hernebo, Malychev, Semikoz ’17]
Uncertainties: deviation from local spectrum

- explanations: local source

[MK, Neronov, Semikoz '15]
Uncertainties: deviation from local spectrum

- explanations: local source
- diffusion depends on $\rho$, $D = D(\rho)$

[MK, Neronov, Semikoz '15]

[Yang, Aharonian, Evoli '16]
Neutrinos from the Galactic CR sea – Galactic plane

Detection prospects:  

\[ \phi_{\nu}(100\text{ TeV}) (10^{-6}\text{ GeV}^{-1} m^{-2} \text{ year}^{-1} \text{ sr}^{-1}) \]

- A: local;  
- B: \( \propto n_{\text{sources}} \),  
- C: \( \propto E^{\delta r} \)

Michael Kachelrieß (NTNU Trondheim)  
Galactic neutrinos  
VLVNT, 2. October '18
Detection prospects:

- Close to GC: always an excess rel. extragal.
- Detectability requires good angular resolution

[Pagliaroli, Evoli, Villante '16]
Galactic sources

- at low energies:
  - many sources, large confinement times
  - average CR sea plus few recent sources
Galactic sources

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- close to the knee:
  - CRs in PeV range spread fast
  - few extreme sources
  - inhomogenous CR sea, extended sources
  - no clear distinction between point sources vs. Galactic bulge + plane cases
Galactic sources

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- connection to $\gamma$ rays:
  - sources transparent: $\varphi_\gamma(E) \leftrightarrow \varphi_\nu(E)$
  - but requires extrapolation above 10 TeV

- young SNRs, Cygnus region, Fermi bubbles, Galactic center
Galactic center

![Graph showing E^2 dΦ/dE/γ/dΩ [GeV cm^-2 s^-1 sr^-1] vs. E [TeV]. The graph includes data points from Fermi Data PASS8, HESS Data 2006, and the best fit Fermi + HESS data. The graph also shows the comparison between conventional diffusion and hard diffusion models.]

[Graph source: Gaggero et al. '17]
Neutrinos from Galactic CR sources

Galactic center

\[
E^2 \frac{d\Phi}{dE}\frac{d\Omega}{d\Omega} \text{[GeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1}]
\]

\[
Pacman region
\]

- Hard diffusion
- Conventional diffusion
- Base model
- Gamma model
- Fermi Data PASS8
- HESS Data 2016
- Best Fit HESS+Fermi

\[\text{[Gaggero et al. '17]}\]
Antares–IceCube limit

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

- KRA\(\gamma\) model
- Combined UL KRA\(\gamma^5\)
- Combined UL KRA\(\gamma^{50}\)
- ANTARES UL KRA\(\gamma^5\)
- IceCube UL KRA\(\gamma^{50}\)
- IceCube starting events
- IceCube up-going \(\nu_\mu\)
Slow diffusion around sources: Geminga

possible explanations:
  ▶ weak regular field, smallish $L_{\text{ coh}}$
Neutrinos from Galactic CR sources

Slow diffusion around sources: Geminga

possible explanations:

▶ weak regular field, smallish $L_{\text{coh}}$
▶ self-generated turbulence by CRs

[López-Coto, Giacinti '17]

[ Evoli, Linden, Morlino '18]
Sources in Local & Loop I superbubble

[Andersen, MK, Semikoz '17]
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Sources in Local & Loop I superbubble

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\[ E^2 F(E) \ [\text{eV/cm}^2/\text{s/sr}] \]

- IceCube all flavors
- IceCube muon*3
- local flux
- EG 1/E^{2.1}
- total

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Sources in Local & Loop I superbubble

[Andersen, MK, Semikoz '17]

\[
\begin{array}{c|c}
E/eV & I(>E)/(cm^2 \cdot s \cdot sr) \\
\hline
10^{14} & 10^{-17} \\
10^{15} & 10^{-16} \\
10^{16} & 10^{-15} \\
10^{17} & 10^{-14} \\
10^{18} & 10^{-13} \\
10^{19} & 10^{-12} \\
10^{20} & 10^{-11} \\
\end{array}
\]
Are multi-TeV photons in the Fermi data? [Neronov, MK, Semikoz ’18]

Caveats Analyzing LAT Pass 8 Data:

- “. . . because the validation process was hampered by lack of statistics, using data below 30 MeV or above 1 TeV is discouraged.”

- gtlite tool has limit 850 GeV
Are multi-TeV photons in the Fermi data? 

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- \textit{gtlike} tool has limit 850 GeV

- eff. area & energy resolution up to 3.2 TeV:
  - 15% at 1 TeV & 25% at 3 TeV

⇒ aperture photometry possible
Cross calibration test: Galactic plane

- Galactic plane ($|b| < 5^\circ$ and $40^\circ < l < 100^\circ$) spectrum from ARGO-YBJ and Milagro
Extension to 3 TeV for $|b| > 20^\circ$:
Extension to 3 TeV for $|b| > 20^\circ$:

- bin 1–1.7 TeV: expected $14 \ (18.5)$ for nominal (renormalised) exposure
  observed (after subtr. CR): $47$
- bin 1.7–3 TeV: expected $2.4 \ (3.5.5)$, observed $17$
Adding neutrinos:

![Graph showing neutrino flux vs energy]

- LAT $\pi^0$ decay model
- Fermi/LAT all sky
- IceCube HESE, 6 yr
- IceCube HESE, 4 yr
- ANTARES
- IceCube

- IGRB
- $E^2dN/dE$, GeV/(cm$^2$ s)
Possible explanations:

- Interface Loop I/local superbubble: strong dipole?
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- extended CR halo

[Taylor, Gabici, Aharonian '14]

[Dolag '02]
Possible explanations:

- interface Loop I/local superbubble: strong dipole?
- extended CR halo

for $B \sim 0.01 \mu G$ and $L_{coh} \sim 100$ pc:

$\Rightarrow$ CR with $E_\pi = 100$ TeV is in large-angle scattering regime

$\Rightarrow D(E_\pi) \sim 10^{29} \text{cm}^2/\text{s}$

$\Rightarrow$ escape time $\tau = H^2/2D \sim t_0$
Possible explanations:

- interface Loop I/local superbubble: strong dipole?
- extended CR halo

- **PeV dark matter**: re-incarnation of SHDM idea for AGASA excess:
  - non-hermal DM
  - avoids cascade limit
  - Galactic anisotropy
PeV dark matter

\[ E_y^2 dJ/dE_y \,(\text{TeV} \, \text{cm}^{-2} \, \text{s}^{-1} \, \text{sr}^{-1}) \]

- \( DM \rightarrow \nu_e \bar{\nu}_e \,(15\%) \), \( b\bar{b} \,(85\%) \)
- \( DM \rightarrow \nu_e \bar{\nu}_e \,(12\%) \), \( c\bar{c} \,(88\%) \)
- \( DM \rightarrow e^- e^+ \,(40\%) \), \( q\bar{q} \,(60\%) \)

\[ E_y \,(\text{TeV}) \]

[Kusenko et al. '13, Esmaili, Serpico '13]
Possible explanations: heavy dark matter
Summary

1. EGRB constrains strongly neutrino sources:
   - slope of extragal. neutrino $\alpha \lesssim 2.2$
   - neutrino sources are not main source class of EGRB

2. Standard Galactic neutrinos:
   - northern km$^3$ telescope very useful
   - important info on propagation and acceleration

3. Soft neutrino signal in IceCube:
   - isotropy: extragalactic or large Galactic halo
   - TeV $\gamma$-ray excess consistent with neutrino flux