Astrophysical neutrino theory

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High-energy neutrinos: Facts

- Detected: Starting events and up-going muon events
- Their distribution is consistent with isotropy
- No source has been identified yet
Neutrinos from TXS 0506+056?

A neutrino event (IceCube-170922A) at ~290 TeV coincident with gamma-ray flare (3σ)

Science 361, eaat1378 (2018)
Neutrinos from TXS 0506+056?

A neutrino event (IceCube-170922A) at ~290 TeV coincident with gamma-ray flare (3σ)

13±5 neutrinos above backgrounds in 2014-2015 (3.5σ)

But no gamma-ray counterpart

Science 361, eaat1378 (2018)
Possible astrophysical explanations

Active galactic nuclei (AGN)

Gamma-ray bursts (GRB)

Galaxy clusters

Star-forming galaxies (SFG)
Starburst galaxies (SB)

Unknown sources?
Particle dark matter?
Two origins

**Photohadron**

\[ p + \gamma \rightarrow \pi^0, \pi^\pm \]

*Usually, protons have to be very energetic, making pions very energetic too*

**Hadronuclear**

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*Interaction can happen for low-energy protons*
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**Pion decays**

\[ \pi^0 \rightarrow 2\gamma \]
\[ \pi^\pm \rightarrow \mu^\pm + \nu_\mu \]
\[ \mu^\pm \rightarrow e^\pm + \nu_e + \nu_\mu \]
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GRB sources: 0th order classification

AGN

SFG/SB

Galaxy clusters

pp and py sources: 0th order classification

Diffuse Coma

3R E S U L T S

3.1 Extended Relic
Blazars: py source

- The cosmic ray protons accelerated in jets interact with surrounding photons
- The neutrino spectrum depends on that of seed photons
- Consequences are in general much more model dependent

Starburst galaxies: pp source

- Starbursts are bright in gammas (M82 and NGC 253 at ~3 Mpc)
- Gamma-ray spectrum roughly follows $E^{-2.2}$
- Modeling the gamma-ray and neutrino luminosity functions using
  - IR luminosity function (Herschel)
  - IR-gamma correlation (Fermi)
Exotic scenario: Dark matter decay

Generic consideration: Personal take

- Given no source has been detected, it is important to take unbiased, *model-independent* approach

- Given we already have data, which will accumulate further, we want to adopt *data-driven* approaches
Traditional approaches

- Explain the energy spectrum of the diffuse neutrino background using models of astrophysical sources.
- Look for excess of events in localized regions compared with global average (individual point source searches).
- Both these can be interpreted in terms of flux distribution.
Flux distribution


- Number of detected sources: Integral above flux threshold
  - At the moment, the threshold is higher than the flux of the brightest source
- Energy spectrum: first moment of the flux distribution below the flux threshold
  - But we don’t have to stop here!
  - There are higher moments that can be used: e.g., variance
Simulated neutrino data

Characteristic number of sources: $N^*$

$N_\star = 10$

Dekker, Ando, JCAP 1902, 002 (2019)
Simulated neutrino data

$N_\star = 10^3$

Dekker, Ando, JCAP 1902, 002 (2019)
Simulated neutrino data

\[ N_\star = 10^5 \]

Simulated neutrino data

\[ N_* = \infty \]
Angular power spectrum

- For each simulated data set, we compute the angular power spectrum, i.e., variance.

- By repeating the procedure above, we construct the TS and its distribution.

\[ \chi^2 (C_\ell) = \sum_{\ell \ell'} (C_\ell - C_\ell^{\text{mean}}) (\text{Cov}_{\ell \ell'})^{-1} (C_{\ell'} - C_{\ell'}^{\text{mean}}) \]

- If the TS value of the actual data is found extreme, we can reject the value of \( N^* \).

Dekker, Ando, JCAP 1902, 002 (2019)
IceCube constraints

- 2 years of upgoing muon neutrino data from IceCube with energies $E_\mu > 50$ TeV: 21 events
- Source population with $N^* < 82$ is excluded at 95% CL


<table>
<thead>
<tr>
<th>Source</th>
<th>$N^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blazars</td>
<td>600</td>
</tr>
<tr>
<td>Radio galaxies</td>
<td>$10^5$</td>
</tr>
<tr>
<td>Starbursts</td>
<td>$10^7$</td>
</tr>
</tbody>
</table>
Future prospects

Case with $N^* = \infty$

Future prospects

Case with $N^* = 10^4$

Constraints on source phase space

Figure 9: Exclusion region with 10 years of IceCube-Gen2, shown for the neutrino luminosity, $L_{\nu}$, against the local number density of neutrino sources, $n_0$. The gray exclusion region is obtained by assuming an isotropic neutrino sky in future, where the two black dashed lines are the 95% exclusion limits, and all sources lying in that region are thus excluded. The blue region represents the observed diffuse neutrino emission, taken from Ref. [31], where the neutrino source emission contributes for $k = 1$ (blue) and $k = 0.1$ (red).

On the other hand, by observing bright sources in the future we can also find constraints on weak source classes with large number densities, such as starburst galaxies (N$^? = 10^7$), which could still be the case with current isotropic measurements. The angular power spectrum analysis on future neutrino data has been found to be a powerful probe to understand what astrophysical sources are dominating the neutrino sky, and in particular to predict what source classes will be observable with future neutrino telescopes, illustrated in Fig. 9 for various sources.

Acknowledgments

We thank Aart Heijboer for helpful discussions, especially for specification of KM3NeT. SA acknowledges support by JSPS KAKENHI Grant Numbers JP17H04836, JP18H04340, and JP18H04578.

References


Dekker, Ando, JCAP 1902, 002 (2019)
Application to heavy dark matter decay
Beyond variance: One-point fluctuation analysis

- One-point fluctuation analysis adopts all the information contained in the flux distribution
- Benefit is slim for now, but in the future can be large
  - E.g., test of Galactic component in the future KM3NeT data
Analysis by IceCube Collaboration

A Search for Neutrino Point-Source Populations in 7 Years of IceCube Data with Neutrino-count Statistics
Diffuse supernova neutrino background
Stars do explode and emit neutrinos

- SN 1987A in LMC: tens of neutrinos detected with Kamiokande II and IMB
- Corresponds to $\sim 10^{53}$ erg total energy released as a form of neutrinos
Stars do explode: Now and in the past

- Local rate: a few per century ($^{26}$Al decay line, etc.)
- Supernova rate increases as a function of redshift
- It is consistent with star formation rate and stellar initial mass function, assuming that stars for 8-50 $M_{\odot}$ explode as a supernova

Supernova explosion: A rough sketch

- Core collapse stars when iron can no longer sustain mass
- It stops when EOS stiffens, and bounces falling matter back
- Shocks wave stall until they are pushed further by neutrino wind
- The explosion leaves a neutron star or black hole as its remnant
- Gravitational binding energy:

\[ E_B = \frac{3GM_{NS}^2}{5R_{NS}} \approx 3 \times 10^{53} \text{ erg} \]

99% MeV neutrinos
1% Shock waves
0.01% Photons

Diffuse supernova neutrinos: How bright is the Universe?
Each supernova releases $3 \times 10^{53}$ erg by neutrinos
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Energy/SN
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Energy/SN  Global SN rate
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Energy/SN  Global SN rate  Cosmic age
How bright is the Universe?

<table>
<thead>
<tr>
<th>Source</th>
<th>Energy Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMB</td>
<td>$4 \times 10^{-13}$ erg cm$^{-3}$</td>
</tr>
<tr>
<td>CIB/EBL</td>
<td>$(2-3) \times 10^{-14}$ erg cm$^{-3}$</td>
</tr>
<tr>
<td>CXB</td>
<td>$10^{-16}$ erg cm$^{-3}$</td>
</tr>
<tr>
<td>CGB</td>
<td>$10^{-17}$ erg cm$^{-3}$</td>
</tr>
<tr>
<td>DSNB</td>
<td>$3 \times 10^{-14}$ erg cm$^{-3}$</td>
</tr>
<tr>
<td>TeVvB</td>
<td>$10^{-19}$ erg cm$^{-3}$</td>
</tr>
</tbody>
</table>
Spectrum of supernova neutrino background


Neutrino physics

Black-hole formation

Supernova model
**DSNB: Observational constraints**

![Graph showing neutrino energy and flux](image)

- Latest upper limits with Super-K are about factor 2-3 above predictions
- Good prospects for Super-K+Gd or large-volume scintillation detectors (e.g., LENA)

### Table V. 90% C.L. flux limit ($\bar{\nu}$ in $10^{33}$ erg)

<table>
<thead>
<tr>
<th>Error Source</th>
<th>SK-I</th>
<th>SK-II</th>
<th>SK-III</th>
<th>All</th>
<th>Predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas infall (97)</td>
<td>$&lt;2.1$</td>
<td>$&lt;7.5$</td>
<td>$&lt;7.8$</td>
<td>$&lt;2.8$</td>
<td>0.3</td>
</tr>
<tr>
<td>Chemical (97)</td>
<td>$&lt;2.2$</td>
<td>$&lt;7.2$</td>
<td>$&lt;7.8$</td>
<td>$&lt;2.8$</td>
<td>0.6</td>
</tr>
<tr>
<td>Heavy metal (00)</td>
<td>$&lt;2.2$</td>
<td>$&lt;7.4$</td>
<td>$&lt;7.8$</td>
<td>$&lt;2.8$</td>
<td>$&lt;1.8$</td>
</tr>
<tr>
<td>LMA (03)</td>
<td>$&lt;2.5$</td>
<td>$&lt;7.7$</td>
<td>$&lt;8.0$</td>
<td>$&lt;2.9$</td>
<td>1.7</td>
</tr>
<tr>
<td>Failed SN (09)</td>
<td>$&lt;2.4$</td>
<td>$&lt;8.0$</td>
<td>$&lt;8.4$</td>
<td>$&lt;3.0$</td>
<td>0.7</td>
</tr>
<tr>
<td>6 MeV (09)</td>
<td>$&lt;2.7$</td>
<td>$&lt;7.4$</td>
<td>$&lt;8.7$</td>
<td>$&lt;3.1$</td>
<td>1.5</td>
</tr>
</tbody>
</table>

90 % C.L. flux limit ($\bar{\nu}$ cm$^{-2}$ s$^{-1}$), $E_{\nu} > 17.3$ MeV
DSNB: Astrophysical uncertainties

\[ \Phi_\nu \left[ \text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1} \right] \]

Varying IMF, 21%
KamLAND
SK-I/II/III
M_t Error
IMF Error

Work in preparation with Thomas Edwards, Shunsaku Horiuchi, Anna Suliga, Irene Tamborra
Conclusions

• IceCube detected TeV-PeV neutrinos, but **no source has been identified**

• Potential sources include blazars, starburst galaxies, radio galaxies, etc.

• Given no source was detected, however, it is important to take **model-independent, data-drive** approaches

• Traditional approaches can be interpreted in terms of flux distribution: zeroth moment as number of sources; first moment as energy spectrum of diffuse flux

• **The second moment (variance)** can be adopted to constrain source populations: those with \( N^* < 100 \) are already excluded

• Supernovae power non-thermal activities in the Universe, and can be probed with neutrinos; **detection of diffuse supernova neutrino background is just around the corner**
Backup
Anisotropies: Lessons from gamma rays

Angular power spectrum: Observations with Fermi

- Analysis of Fermi data for the angular power spectrum of the diffuse gamma-ray background in 2012 → **Discovery of anisotropies**

- Reanalyzed in 2016, 2018

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**FIG. 4.** Left: Normalization factor resulting from the Poissonian fit of the Galactic foreground to the data outside the mask; for visualization purposes, we report the normalizations for the macro energy bins computed averaging the values of the micro ones. Right: autocorrelation anisotropy energy spectrum with and without foreground subtraction. In both cases monopole and dipole terms have been removed from intensity maps prior to the APS computation.

**FIG. 7.** Angular Power Spectra for all the energy bins. The shaded regions mark the ranges of multipoles considered in the fit of the APS to derive the anisotropy amplitudes \( C_P \). The red lines show the \( C_P \) values and their associated errors from the fit (represented by the red shaded band).

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\[ C_{\ell}^{\text{total}} = C_N + C_P + C_{\ell}^{\text{corr}} \]

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- Data are mostly **consistent with astrophysical expectations** (blazars; Ando et al. 2007)
Implications

• Anisotropy analyses have already been established for GeV gamma rays

• Solid measurement of the angular power spectrum (variance) implies (sub-threshold) point-source contribution

• The source population that cannot be detected individually can be detected statistically

• Same technique can be used for high-energy neutrinos, to identify sources
**Power spectrum analysis by IceCube**


- No angular power was found (everything is consistent with diffuse the background model)
- It can exceed the point-source limit for more than 100 sources
- But it is assumed that all these sources have the same flux
Flux distribution and implications

Ando, Feyereisen, Fornasa, Phys. Rev. D 95, 103003 (2017)

- Flux distribution of any astrophysical sources will follow a power law

- Particularly $F^{-2.5}$ for high-flux region

Procedure:
1. Pick $N^*$ as a parameter
2. From measured intensity $I$, calculate $F^*$, which will fix the distribution
3. Simulate neutrino data, calculate the power spectrum, and extract test statistic (TS) and TS distribution
4. Apply the method to the actual data to discuss what value of $N^*$ is already excluded
Galaxy clusters: Radio constraints

- pp interaction will produce electrons/positrons that will make clusters bright in radio in the cluster magnetic fields (~1 μG)

- Radio constraints are very tight, and clusters cannot contribute to γ & ν backgrounds strongly

Constraints with two-point statistics
Cross correlation with galaxy distribution


Cross correlation with galaxy distribution

Are these two maps similar to each other?


Cross correlation with galaxy distribution

Are these two maps similar to each other?

They must be, since both gamma-ray sources and galaxies trace dark matter distribution!

Cross correlation between IGRB and galaxies

• Yet another probe of gamma-ray sources due to measurements of cross correlations between IGRB and galaxy catalogs

• Originally proposed for dark matter annihilation (Ando et al. 2014) and was recently proven to be a strong probe

• This can also be applied to any neutrino sources if they are of pp origin!

• The neutrino spectrum is very similar to that of gamma rays

Spectral constraints

\[ \frac{dN}{dE} \propto E^{-\alpha}, \quad n_{\text{src}}(z) \propto (1+z)^\delta \]

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Dependence on $\alpha$ and $\delta$

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Soft spectrum

Dependence on $\alpha$ and $\delta$

**Soft spectrum**

**Fast evolution**

Constraints on high-energy neutrinos

- Spectral constraints: $\alpha$ has to be smaller than $\sim 2.2$ (cf. Murase, Ahlers, Lacki 2013)

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  - If $\delta$ is smaller than $\sim 3$, source with spectrum softer than $E^{-2.1}$ is disfavored
  - If $\delta \sim 4$, both spectral and tomographic data give comparable constraints

Possible pp sources

Star-forming/starburst galaxies

- No direct measurement of $\delta$ yet
- Infrared luminosity density suggests $\delta \sim 3–4$


Clusters of galaxies

- Cosmic rays accelerated through large-scale-structure shocks or provided by sources (AGNs, galaxies)
- In both cases, $\delta$ is very small (i.e., clusters are found only in low-$z$)
GRB-like jets, but richer with baryons (i.e., slower jets and optically thick): hence cannot be identified with gamma rays