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(Will be submitted for publication)
46 authors
~100 pages
Several overview plots
Particle physics & astrophysics are inextricably linked

For Snowmass: focus on particle-physics opportunities, point out complementarity

Complementarity highlighted in the Astro2020 Decadal Survey:

- **Fundamental Physics with High-Energy Cosmic Neutrinos**, 1903.04333
- **Astrophysics Uniquely Enabled by Observations of High-Energy Cosmic Neutrinos**, 1903.04334

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1 Introduction and overview

Cosmic neutrinos are unique probes of extreme environments surrounding the most energetic sources in the Universe and a unique test beam for weak interactions at energies inaccessible through accelerators. Within the last decade, the discovery of high-energy (HE, TeV to 100 PeV) astrophysical neutrinos by IceCube [8] has opened a new window to learn more about cosmic accelerators and neutrino interactions at the highest energies. With next-generation experiments pushing sensitivity and energy reach, we anticipate that the wealth of information will expand dramatically. Ultra-high-energy (UHE, >100 PeV) neutrinos, long-sought but not yet detected, provide the only means of directly investigating processes that occur at energy scales of EeV (e.g. 10^{20} eV) and above in the distant Universe. Discovering them would open new regimes of exploration in high-energy physics, astrophysics, and cosmology. In this white paper, we describe the significant physics opportunities offered by cosmic neutrinos and map out the experimental landscape in the coming decades.

Observations of neutrinos from different sources, across different energies and traveled distances, have led to the fundamental-physics conclusions that neutrino masses and mix among flavors. These Nobel-prize winning experimental tests include measurements of neutrinos in the sub-GeV-to-10-PeV energy range from cosmic-ray interactions in the atmosphere [9] and of neutrinos from the Sun [10-15]. Indeed, neutrinos across important questions in the complementary fields of high-energy physics and astrophysics. The wide range of neutrino energies and traveled distances allow us to explore neutrino properties, their interactions, and fundamental symmetries across a wide breadth of parameter space, as shown in Fig. 1. And because they are neutral and weakly interacting, they carry information about the physical conditions at their points of origin; at the highest energies, even from powerful cosmic accelerators at the edge of the observable Universe.

Recently, the discovery of a diffuse flux of HE astrophysical neutrinos, in the TeV-PeV range [8, 16] opened a new view to the Universe. They have made possible the direct measurement of weak interactions in a new energy regime, including the neutrino-nucleon cross section [17-19], inelasticity distribution [19],
High-energy neutrinos: TeV–PeV

(Discovered)

Ultra-high-energy neutrinos: $> 100$ PeV

(Predicted but undiscovered)
Ackermann, MB, et al., Astro2020 Decadal Survey (1903.04333), adapted
They have the **highest energies**

They travel the **longest distances**
Ackermann, MB, et al., Astro2020 Decadal Survey (1903.04333), adapted
Synergies with lower energies

Increase TeV–PeV \( \nu \) statistics

Discover > EeV \( \nu \)
TeV–PeV $\nu$

*High-energy*

Current status:

Discovered (by IceCube, 2013)

Accumulating statistics

First tests of high-energy $\nu$ physics

First promising source candidates

$\nu > 100$-PeV $\nu$

*Ultra-high-energy*
TeV–PeV $\nu$

*High-energy*

**Current status**
- Discovered (by IceCube, 2013)
- Accumulating statistics
- First tests of high-energy $\nu$ physics
- First promising source candidates

$> 100$-PeV $\nu$

*Ultra-high-energy*

**Current status**
- Predicted (1960s), but undiscovered
- Upper limits on their flux
- Flux predictions uncertain, improving
- Aim for discovery in next-gen detectors
What are the main physics goals for the next 10–20 years?

What theoretical developments do we need to realize these goals?

What experiments do we need to realize these goals?

Take-home messages
1. What are the main physics goals for the next 10–20 years?

2. What theoretical developments do we need to realize these goals?

3. What experiments do we need to realize these goals?

4. Take-home messages
TeV–PeV $\nu$
High-energy

$> 100$-PeV $\nu$
Ultra-high-energy
Two energy regimes

Two science thrusts

TeV–PeV $\nu$

$High$-$energy$

$> 100$-PeV $\nu$

$Ultra$-$high$-$energy$
TeV–PeV $\nu$

High-energy

Two energy regimes

Two science thrusts

$> 100$-PeV $\nu$

Ultra-high-energy

Explore with high statistics

Discover
TeV–PeV $\nu$

*High-energy*

Two energy regimes

Two science thrusts

$> 100$-PeV $\nu$

*Ultra-high-energy*

*Explore with high statistics*

*Particle physics*

Measure high-energy SM predictions

Test BSM predictions

*Astrophysics*

Find the neutrino sources

Characterize the diffuse flux precisely

*Discover*
Particle physics

Measure high-energy SM predictions
Test BSM predictions

Astrophysics

Find the neutrino sources
Characterize the diffuse flux precisely

Two energy regimes
High-energy

Two science thrusts

Explore with high statistics

> 100-PeV ν
Ultra-high-energy

Discover

Particle physics

Test physics at highest expected energies

Astrophysics

Find sources of UHE cosmic rays
**TeV–PeV ν**

*High-energy*

*Explore with high statistics*

*Particle physics*
Measure high-energy SM predictions
Test BSM predictions

*Astrophysics*
Find the neutrino sources
Characterize the diffuse flux precisely

Potential also in the multi-PeV transition regime

**> 100-PeV ν**

*Ultra-high-energy*

*Discover*

*Particle physics*
Test physics at highest expected energies

*Astrophysics*
Find sources of UHE cosmic rays
Main high-energy neutrino observables
Standard expectation: Power-law energy spectrum

Standard expectation: Isotropy (for diffuse flux)

Main high-energy $\nu$ observables

Standard expectation: $\nu$ and $\gamma$ from transients arrive simultaneously

Standard expectation: Equal number of $\nu_e$, $\nu_\mu$, $\nu_\tau$
Note: Not an exhaustive list
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Note: Not an exhaustive list
Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

Acts at production
- Heavy relics
- DM annihilation
- DM decay
- DM-$\nu$ interaction
- Lorentz+CPT violation
- DE-$\nu$ interaction
- Neutrino decay
- Long-range interactions
- Secret $\nu\nu$ interactions
- Supersymmetry
- Effective operators
- Leptoquarks
- Extra dimensions
- Superluminal $\nu$
- Monopoles

Acts at detection

Standard expectation:
$\nu$ and $\gamma$ from transients arrive simultaneously

Note: Not an exhaustive list
Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

Standard expectation:
$\nu$ and $\gamma$ from transients arrive simultaneously

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\begin{itemize}
    \item \textbf{Standard expectation:} Power-law energy spectrum
    \item \textbf{Standard expectation:} Isotropy (for diffuse flux)
    \item \textbf{Standard expectation:} \( \nu \) and \( \gamma \) from transients arrive simultaneously
    \item Equal number of \( \nu_e, \nu_\mu, \nu_\tau \)
\end{itemize}
Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

Standard expectation:
$\nu$ and $\gamma$ from transients arrive simultaneously

Note: Not an exhaustive list
Standard expectation:
- Power-law energy spectrum
- Isotropy (for diffuse flux)

Standard expectation:
- Equal number of $\nu_e$, $\nu_\mu$, $\nu_\tau$

Note: Not an exhaustive list

More: PoS ICRC2019 (1907.08690)
Argüelles, MB, Kheirandish, Palomares-Ruiz, Salvadó, Vincent
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Argüelles, MB, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

Note: Not an exhaustive list

Standard expectation:
- Power-law energy spectrum
- Isotropy (for diffuse flux)

Standard expectation: ν and γ from transients arrive simultaneously

Acts during propagation:
- DM–ν interaction
- DE–ν interaction
- Lorentz+CPT violation
- Neutrino decay
- Long-range interactions
- Secret ν interactions
- Supersymmetry
- Effective operators
- Leptoquarks
- Extra dimensions
- Superluminal ν
- Monopoles

Acts at detection:
- Heavy relics
- DM annihilation
- DM decay
- Sterile ν
- NSI
- Boosted DM

Acts at production:
- νe
- νμ
- ντ

Acts at arrival times:
- Equal number of νe, νμ, ντ
Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

Reviews:
Ahlers, Helbing, De los Heros, EPJC 2018
Argüelles, MB, Kheirandish, Palomares-Ruiz, Salvadó, Vincent, ICRC 2019 [1907.08690]
Ackermann, Ahlers, Anchordoqui, MB, et al., Astro2020 Decadal Survey [1903.04333]

Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_μ, ν_τ

Note: Not an exhaustive list
First observation of a Glashow resonance

Predicted in 1960:

IceCube, *Nature* 2021
Glashow, *PR* 1960
First observation of a Glashow resonance

Predicted in 1960:

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

\[ 6.3 \text{ PeV} \]
First observation of a Glashow resonance

Predicted in 1960:

\[
\begin{align*}
\bar{\nu}_e & \quad W \\
6.3 \text{ PeV} & \quad \text{hadrons} \\
(\pi, n, \ldots) & \quad \text{Br} \approx 67\%
\end{align*}
\]
First observation of a Glashow resonance

Predicted in 1960:

\[
\begin{align*}
&\bar{\nu}_e \quad 6.3 \text{ PeV} \\
&\quad \rightarrow W \quad \text{hadrons} \quad (\pi, n, \ldots) \\
&e \\
&\quad \rightarrow \quad Br \approx 67\% \\
\end{align*}
\]

\[
\begin{align*}
&\bar{\nu}_e \quad 6.3 \text{ PeV} \\
&\quad \rightarrow W \\
&e \\
&\quad \rightarrow l^+ \quad Br \approx 33\% \\
&\quad \rightarrow l^- \\
\end{align*}
\]
First observation of a Glashow resonance

Predicted in 1960:

\[ \bar{\nu}_e \rightarrow W \rightarrow \text{hadrons} \ (\pi, n, \ldots) \]

\[ \text{Br} \approx 67\% \]

First reported by IceCube in 2021:

\[ \bar{\nu}_e \rightarrow W \rightarrow \ell^+ \]

\[ \text{Br} \approx 33\% \]
Measuring the high-energy neutrino-nucleon cross section

Valera, MB, Glaser, JCAP 2022
Adapted for Snowmass
Physics in the flavor composition

Important:
Improvement possible only from synergy with mixing-parameter measurements in oscillations experiments (DUNE, JUNO, Hyper-K, IceCube Upgrade)

See the talk by Teppei Katori
Neutrinos from heavy dark-matter annihilation
Characterizing the TeV–PeV neutrino flux

1. What are the main physics goals for the next 10–20 years?

2. What theoretical developments do we need to realize these goals?

3. What experiments do we need to realize these goals?

4. Take-home messages
Make predictions & analyses more sophisticated

Particle physics
Explore larger model parameter spaces
Fully account for astrophysical uncertainties

Astrophysics
Abandon assumption that all sources are identical
More complete multi-messenger models
1. What are the main physics goals for the next 10–20 years?

2. What theoretical developments do we need to realize these goals?

3. What experiments do we need to realize these goals?

4. Take-home messages
TeV–PeV $\nu$

*High-energy*

**Strategy**

Multi km-scale in-ice & in-water Cherenkov detectors

**Status**

Under design, prototype, deployment
(IceCube, IceCube-Gen2, KM3NeT, Baikal-GVD, P-ONE)

**Challenges**

Familiar tech; mainly logistical + funding

$\nu$ > 100-PeV $\nu$

*Ultra-high-energy*
**TeV–PeV $\nu$**

*High-energy*

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Familiar tech; mainly logistical + funding

---

**> 100-PeV $\nu$**

*Ultra-high-energy*

**Strategy**
In-ice & in-water Cherenkov too expensive; use more scalable techniques

**Status**
Multiple techniques under consideration & in pathfinding stage (radio in-ice, in-air, from ground, radar, imaging, fluorescence, particles on ground)

**Challenges**
New techniques, capabilities in flux
Diffuse Flux, 1:1:1 Flavor Ratio

1. What are the main physics goals for the next 10–20 years?

2. What theoretical developments do we need to realize these goals?

3. What experiments do we need to realize these goals?

4. Take-home messages
The potential

High-energy and ultra-high-energy neutrinos have vast potential for particle physics (& astrophysics!)

The delivery

These studies are being done already today, in spite of limited statistics and astrophysical unknowns

Theory: need more nuance to achieve robustness—
- Particle physics: factor in astrophysical uncertainties
- Astrophysics: move beyond identical-source estimates

Experiment: need new detectors for statistics & discovery—
- Build bigger: more statistics in the TeV–PeV range
- Study the tail end of the PeV neutrino spectrum
- Build different: discover > 100 PeV neutrinos
- Ongoing work to study new detection techniques
Thanks!
Redshift

$z = 0$

Note: $\nu$ sources can be steady-state or transient
Redshift $z = 0$

- MeV $\gamma$
- PeV $p$
- TeV–PeV $\nu$
- "High-energy"

**Photohadronic or $pp$ interaction**

*inside the source*

**Discovered**

- HE $\nu$

**$\nu$ propagation**

*inside the Earth*

**$\nu$ detection**

*Note: $\nu$ sources can be steady-state or transient*
Redshift $z = 0$

Note: $\nu$ sources can be steady-state or transient

UHE source $\nu$

HE $\nu$

$\nu$ propagation inside the Earth

$\nu$ detection

Undiscovered

meV $\gamma$

EeV $\nu$

"Ultra-high-energy"

EeV $p$

Photohadronic or $pp$ interaction inside the source
Redshift \rightarrow z = 0

Note: $\nu$ sources can be steady-state or transient
Redshift

\[ z = 0 \]

- **Discovered**
  - MeV \( \gamma \)
  - PeV \( p \)
  - Photohadronic or \( pp \) interaction
    - inside the source
  - \( \text{"High-energy"} \)
  - \( \text{UHE} \) \( p \) + nuclei
  - UHE cosmogenic \( \nu \)

- **Undiscovered**
  - meV \( \gamma \)
  - EeV \( p \)
  - Photohadronic or \( pp \) interaction
    - inside the source
  - \( \text{EeV} \) \( \nu \)
  - \( \text{"Ultra-high-energy"} \)
  - CMB/EBL \( \gamma \)
  - EeV \( p \)
  - Photohadronic interaction
    - during propagation
  - \( \text{EeV} \) \( \nu \)
  - \( \text{"Ultra-high-energy"} \)

**Note:** \( \nu \) sources can be steady-state or transient.
TeV–EeV ν cross sections

MB & Connolly, PRL 2019
TeV–EeV ν cross sections

ν self-interactions

MB & Connolly, PRL 2019

MB, Rosenstreu, Shalgar, Tamborra, PRD 2020
TeV–EeV ν cross sections

[Graph showing NuInnucleon CC cross section vs. ν energy and mediator mass with various markers and labels, including "Testable today" and "Testable next decade".]

MB & Connolly, PRL 2019

ν self-interactions

[Graph showing mediator coupling vs. mediator mass log(M/MeV) with various data points and labels, including "IceCube HESE 5 years (this work)."

MB, Rosenstern, Shalgar, Tamborra, PRD 2020

ν scattering on Galactic DM

[Graph showing Galactic distribution with various markers and labels, including "IceCube Sun."

Argüelles, Kheirandish, Vincent, PRL 2017]
TeV–EeV $\nu$ cross sections

- Center-of-mass energy $\sqrt{s}$ [GeV]
- Neutrino energy $E_{\nu}$ [GeV]
- Neutrino–nucleon CC cross section ($\sigma^{CC}_{\nu N}$) [cm$^2$]

MB & Connolly, PRL 2019

v self-interactions

- Neutrino–neutrino self-interactions
- mb, Rosenstrøm, Shalgar, Tamborra, PRD 2020

v scattering on Galactic DM

- Neutrino–scattering on Galactic DM
- Argüelles, Kheirandish, Vincent, PRL 2017

v decay

- Neutrino $\nu$ decay
- Fraction of $\nu_e \rightarrow \ell_\mu$
- Song, Li, Argüelles, MB, Vincent, JCAP 2021
Dark matter decay

Chianese, Fiorillo, Miele, Morisi, Pisanti, JCAP 2019

TeV–EeV ν cross sections

MB & Connolly, PRL 2019

ν self-interactions

MB, Rosenstrøm, Shalgar, Tamborra, PRD 2020

ν scattering on Galactic DM

Argüelles, Kheirandish, Vincent, PRL 2017

ν decay

Song, Li, Argüelles, MB, Vincent, JCAP 2021

ν decay

Song, Li, Argüelles, MB, Vincent, JCAP 2021
**TeV–EeV ν cross sections**

- Center-of-mass energy $\sqrt{s}$ [GeV]
- Neutrino energy $E_\nu$ [GeV]

**ν self-interactions**

- Mediation coupling $g_{\nu H}$
- Neutrino mass $M_{\nu}$ [MeV]

**ν scattering on Galactic DM**

- Fraction of $\nu$, $f_{\nu}(\nu)$
- Galactic distribution

**ν decay**

- Fraction of $\nu_\alpha$, $f_{\nu_\alpha}(\nu)$
- Neutrino decay patterns

**Dark matter decay**

- Decay rate $\Gamma$ [GeV$^{-1}$]
- Mass $m_{\chi}$ [GeV]

**ν-electron interaction**

- Standard mixing parameters
- Varying $\theta_\nu$ (0°)

**References:**

- Chianese, Fiorillo, Miele, Morisi, Pisanti, JCAP 2019
- MB & Agarwalla, PRL 2019
- MB, Rosenstrom, Shalgar, Tamborra, PRD 2020
- Argüelles, Kheirandish, Vincent, PRL 2017
- Song, Li, Argüelles, MB, Vincent, JCAP 2021
**TeV–EeV ν cross sections**

- Testable today: Center-of-mass energy $\sqrt{s}$ [GeV]
- Testable next decade: Neutrino-nucleus CC cross section ($f^{\nuNN}_{\nu N}$) [cm$^2$]

**ν self-interactions**

- Mediator coupling $g_{\nu M}$ vs mediator mass log$_{10}(M/M_{\text{MeV}})$

**ν scattering on Galactic DM**

- IceCube HESE 3 years (this work)

**ν decay**

- Fraction of $\nu_\alpha f_{\nu_\alpha}$ vs $f_{\nu_\alpha}$

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**Dark matter decay**

- Chianese, Fiorillo, Miele, Morisi, Pisanti, JCAP 2019

**ν-electron interaction**

- MB & Agarwalla, PRL 2019

**Lorentz-invariance violation**

- IceCube, Nature Phys. 2018
**Dark matter decay**

- MB & Connolly, PRL 2019
- MB, Rosenstern, Shalgar, Tambugra, PRD 2020
- Argüelles, Kheirandish, Vincent, PRL 2017
- Song, Li, Argüelles, MB, Vincent, JCAP 2021

**ν-self-interactions**

- MB & Connolly, PRL 2019
- MB, Rosenstern, Shalgar, Tambugra, PRD 2020

**ν scattering on Galactic DM**

- MB & Connolly, PRL 2019
- MB, Rosenstern, Shalgar, Tambugra, PRD 2020
- Argüelles, Kheirandish, Vincent, PRL 2017
- Song, Li, Argüelles, MB, Vincent, JCAP 2021

**ν decay**

- MB & Connolly, PRL 2019
- MB, Rosenstern, Shalgar, Tambugra, PRD 2020
- Argüelles, Kheirandish, Vincent, PRL 2017
- Song, Li, Argüelles, MB, Vincent, JCAP 2021

**ν-electron interaction**

- MB & Agarwalla, PRL 2019

**Lorentz-invariance violation**

- MB & Agarwalla, PRL 2019

**Sterile neutrinos**

- IceCube, Nature Phys. 2018

**ν-electron interaction**

- IceCube, Nature Phys. 2018

**Lorentz-invariance violation**

- IceCube, Nature Phys. 2018

**Sterile neutrinos**

- IceCube, Nature Phys. 2018
non-anthropogenic neutrino fluxes
($\nu + \bar{\nu}$ per flavour)
Figure courtesy of Markus Ahlers

Maoloud, De Wasseige, Ahlers, MB, Van Elewyck, PoS(ICRC2019), 1023
Abundant, not yet detected

non-anthropogenic neutrino fluxes

\( (\nu + \bar{\nu} \text{ per flavour}) \)

Abundant and detected

\[ E^2 \phi_{\nu+\bar{\nu}} \text{ [GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}] \]

\[ E_\nu \text{ [eV]} \]

Figure courtesy of Markus Ahlers
Maoloud, De Wasseige, Ahlers, MB, Van Elewyck, PoS(ICRC2019), 1023
Maoloud, De Wasseige, Ahlers, MB, Van Elewyck, PoS(ICRC2019), 1023
Today: TeV–PeV

Next decade: PeV–EeV

non-anthropogenic neutrino fluxes
($\nu + \bar{\nu}$ per flavour)

Abundant, not yet detected

Abundant and detected

Figure courtesy of Markus Ahlers
Maoloud, De Wasseige, Ahlers, MB, Van Elewyck, PoS(ICRC2019), 1023
Fundamental physics with high-energy cosmic neutrinos

- Numerous new $\nu$ physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$

- So we can probe $\kappa_n \sim 4 \cdot 10^{-47} (E/\text{PeV})^{-n} (L/\text{Gpc})^{-1} \text{PeV}^{1-n}$

- Improvement over limits using atmospheric $\nu$: $\kappa_0 < 10^{-29} \text{ PeV}, \kappa_1 < 10^{-33}$

- Fundamental physics can be extracted from four neutrino observables:
  - Spectral shape
  - Angular distribution
  - Flavor composition
  - Timing
Fundamental physics with high-energy cosmic neutrinos

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  - Spectral shape
  - Angular distribution
  - Flavor composition
  - Timing

\[ \{ \text{E.g.,} \]
\[ n = -1: \text{neutrino decay} \]
\[ n = 0: \text{CPT-odd Lorentz violation} \]
\[ n = +1: \text{CPT-even Lorentz violation} \]
Fundamental physics with high-energy cosmic neutrinos

- Numerous new $\nu$ physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$

- So we can probe $\kappa_n \sim 4 \cdot 10^{-47} (E/\text{PeV})^{-n} (L/\text{Gpc})^{-1} \text{PeV}^{1-n}$

- Improvement over limits using atmospheric $\nu$: $\kappa_0 < 10^{-29} \text{PeV}$, $\kappa_1 < 10^{-33}$

- Fundamental physics can be extracted from four neutrino observables:
  - Spectral shape
  - Angular distribution
  - Flavor composition
  - Timing

E.g.,
- $n = -1$: neutrino decay
- $n = 0$: CPT-odd Lorentz violation
- $n = +1$: CPT-even Lorentz violation

In spite of poor energy, angular, flavor reconstruction & astrophysical unknowns
Making high-energy astrophysical neutrinos

(or \( p + p \))

\[
p + \gamma_{\text{target}} \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0, & \text{Br} = 2/3 \\ n + \pi^+, & \text{Br} = 1/3 \end{cases}
\]
Making high-energy astrophysical neutrinos

(or $p + p$)

$\gamma_{\text{target}} \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0, & \text{Br} = 2/3 \\ n + \pi^+, & \text{Br} = 1/3 \end{cases}$

Energy dependence $\sim E^{-2}$
Making high-energy astrophysical neutrinos
(or $p + p$)

$p + \gamma_{\text{target}} \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0, & \text{Br} = 2/3 \\ n + \pi^+, & \text{Br} = 1/3 \end{cases}$
Making high-energy astrophysical neutrinos

(or $p + p$)

\[
p + \gamma_{\text{target}} \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0, \quad \text{Br} = 2/3 \\ n + \pi^+, \quad \text{Br} = 1/3 \end{cases}
\]

\[
\pi^0 \rightarrow \gamma + \gamma
\]

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

\[n \text{ (escapes)} \rightarrow p + e^- + \bar{\nu}_e\]
Making high-energy astrophysical neutrinos

(or $p + p$)

$$p + \gamma_{\text{target}} \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0, & \text{Br} = 2/3 \\ n + \pi^+, & \text{Br} = 1/3 \end{cases}$$

$$\pi^0 \rightarrow \gamma + \gamma$$

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

$n$ (escapes) $\rightarrow p + e^- + \bar{\nu}_e$

Neutrino energy = Proton energy / 20
Gamma-ray energy = Proton energy / 10
Astrophysical sources

Up to a few Gpc

Oscillations change the number of \( \nu \) of each flavor, \( N_e, N_\mu, N_\tau \)

Different production mechanisms yield different flavor ratios:

\[
(f_{e,S}, f_{\mu,S}, f_{\tau,S}) \equiv (N_{e,S}, N_{\mu,S}, N_{\tau,S}) / N_{\text{tot}}
\]

Flavor ratios at Earth (\( \alpha = e, \mu, \tau \)):

\[
f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \rightarrow \nu_\alpha} f_{\beta,S}
\]
Astrophysical sources

Up to a few Gpc

Earth

Oscillations change the number

of ν of each flavor, $N_e, N_\mu, N_\tau$

Different production mechanisms yield different flavor ratios:

$$(f_{e,S}, f_{\mu,S}, f_{\tau,S}) \equiv (N_{e,S}, N_{\mu,S}, N_{\tau,S}) / N_{\text{tot}}$$

Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

$$f_{\alpha, \oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \rightarrow \nu_\alpha} f_{\beta,S}$$

Standard oscillations or new physics
GRAND & POEMMA

Both sensitive to extensive air showers induced by Earth-skimming UHE $\nu_\tau$

If they see 100 events from $\nu_\tau$ with initial energy of $10^9$ GeV (pre-attenuation):

Denton & Kini, PRD 2020

Measured to within 20%
Oscillations change the number of $\nu$ of each flavor, $N_e, N_\mu, N_\tau$.

Different production mechanisms yield different flavor ratios:

$$ (f_{e,S}, f_{\mu,S}, f_{\tau,S}) \equiv (N_{e,S}, N_{\mu,S}, N_{\tau,S})/N_{\text{tot}} $$

Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

$$ f_{\alpha, \oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_{\beta} \to \nu_{\alpha}} \ f_{\beta,S} $$
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Different production mechanisms yield different flavor ratios:

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Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \rightarrow \nu_\alpha} f_{\beta,S}$$

Standard oscillations or new physics.
Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

≡

Allowed regions of flavor ratios at Earth derived from oscillations

---

**Note:**
The original palatable regions were frequentist [MB, Beacom, Winter, PRL 2015];
the new ones are Bayesian
Flavor at the Earth: *theoretically palatable regions*

**Theoretically palatable flavor regions**

\[ \equiv \]

Allowed regions of flavor ratios at Earth derived from oscillations

**Ingredient #1:**
Flavor ratios at the source,
\[ (f_{e,S}, f_{\mu,S}, f_{\tau,S}) \]

Fix at one of the benchmarks
(pion decay, muon-damped, neutron decay)

*or*

Explore all possible combinations

---

*Note:*
The original palatable regions were frequentist [MB, Beacom, Winter, *PRL* 2015];
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\[ \equiv \]  
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**Ingredient #2:**  
Probability density of mixing parameters \((\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\text{CP}})\)

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2020: Use \( \chi^2 \) profiles from the NuFit 5.0 global fit
(solar + atmospheric + reactor + accelerator)

*Note:*
The original palatable regions were frequentist [MB, Beacom, Winter, PRL 2015];
the new ones are Bayesian

[Image of a graph showing the \( \chi^2 \) profiles from the NuFit 5.0 global fit]
Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

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Allowed regions of flavor ratios at Earth derived from oscillations

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Probability density of mixing parameters \((\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\text{CP}})\)

**2020:** Use \(\chi^2\) profiles from the NuFit 5.0 global fit (solar + atmospheric + reactor + accelerator)

Esteban et al., JHEP 2020

www.nu-fit.org

**Post-2020:** Build our own profiles using simulations of JUNO, DUNE, Hyper-K


DUNE, 2002.03005


*Note:* The original palatable regions were frequentist [MB, Beacom, Winter, PRL 2015]; the new ones are Bayesian.
One likely TeV–PeV $\nu$ production scenario:

$$p + \gamma \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu$$

followed by

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Full $\pi$ decay chain

$$(1/3:2/3:0)_s$$

Note: $\nu$ and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes
One likely TeV–PeV ν production scenario:

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

Full π decay chain  
\((1/3:2/3:0)_\delta\)

Note: ν and \(\bar{\nu}\) are (so far) indistinguishable in neutrino telescopes
One likely TeV–PeV $\nu$ production scenario:
\[
p + \gamma \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu \quad \text{followed by} \quad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu
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Full $\pi$ decay chain
\((1/3:2/3:0)_S\)

Note: $\nu$ and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes
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Muon damped

$$(0:1:0)_S$$

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**Full $\pi$ decay chain**

$$(1/3:2/3:0)_S$$

**Muon damped**

$$(0:1:0)_S$$

**Neutron decay**

$$(1:0:0)_S$$

Note: $\nu$ and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes.
Theoretically palatable regions: today (2020)

Note:
All plots shown are for normal neutrino mass ordering (NO); inverted ordering looks similar.
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Song, Li, MB, Argüelles, Vincent, 2012.XXXX
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Theoretically palatable regions: today (2020)

Note:
All plots shown are for normal neutrino mass ordering (NO); inverted ordering looks similar.

Song, Li, MB, Argüelles, Vincent, 2012.
Theoretically palatable regions: 2020 vs. 2040

By 2040:

**Theory** –
Mixing parameters known precisely: allowed flavor regions are *almost* points (already by 2030)

**Measurement of flavor ratios** –
Can distinguish between similar predictions at 99.7% C.R. (3σ)

Can finally use the full power of flavor composition for astrophysics and neutrino physics
UHE neutrinos: *steady-state sources*

![Graph showing the all-flavor flux $E^2 \Phi_\nu (E_\nu)$ and the neutrino energy $E_\nu$. The graph includes data from IceCube measurements and theoretical predictions. The ratio $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$.](attachment:image.png)

References:

- Fang & Murase, Nature Phys. 2018
- POEMMA, 2012.07945
- RNO-G, JINST 2021
- IceCube-Gen2, J. Phys. G 2021
UHE neutrinos: steady-state sources

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UHE neutrinos: steady-state sources

**Graph:**
- **Axes:**
  - Vertical: All-flavor flux $E^2 \Phi_{\nu} (E_{\nu})$ [GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$]
  - Horizontal: Neutrino energy $E_{\nu}$ [GeV]

**Data Points:**
- IceCube measurements
- IceCube upper limit
- ARA upper limit
- ANTARES upper limit
- ARBANNA upper limit
- ANITA upper limit

**Legend:**
- $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$

**Interpretation:**
- The graph shows the flux of UHE neutrinos as a function of energy.
- The data points indicate a downward trend with energy, suggesting a decrease in flux.
- The uncertainties are represented by shaded regions.

** Annotations:**
- Higher UHECR properties uncertainly known
- Higher v flux
- Lower v flux

**Additional Notes:**
- UHECR properties are uncertainly known.
- The graph reflects the current understanding of UHE neutrino sources and their properties.
- The flux values range from $10^{-10}$ to $10^{-6}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$.
- The energy range spans from $10^5$ to $10^{11}$ GeV.
UHE neutrinos: steady-state sources

Fang & Murase, Nature Phys. 2018
POEMMA, 2012.07945
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Cosmogenic neutrinos
UHE neutrinos: steady-state sources

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Cosmogenic neutrinos

Neutrinos from the sources (possibly dominant flux!)
UHE neutrinos: steady-state sources

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POEMMA, 2012.07945
RNO-G, JINST 2021
IceCube-Gen2, J. Phys. G 2021
UHE neutrinos: steady-state sources

Ultimate target sensitivity for next-gen detectors
(if protons are ~10% of the highest-energy UHECRs)
UHE neutrinos: transient sources

Guépin, Kotera, Barausse, Fang, Murase, A&A 2018
Murase, PRD 2017
Zhang et al., Nature Commun. 2018
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RNO-G, JINST 2021
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