

Neutrinos and Astrophysics

Kate Scholberg, Duke University

Snowmass CSS July 22, 2022

Natural neutrinos pervade the Universe....

Grand Unified Neutrino Spectrum at Earth Edoardo Vitagliano, Irene Tamborra, Georg Raffelt. Oct 25, 2019. 54 pp. MPP-2019-205 e-Print: arXiv:1910.11878 [astro-ph.HE] | PDF



Neutrinos bring unique information about the nature of natural sources



And astrophysical objects in turn give us sources for the study of **neutrino physics**...



... 3-flavor oscillations, anomalies, BSM searches...

Many opportunities to probe BSM physics

Neutrino observables*: energy, direction, time, flavor



*also, non-neutrino-sector BSM signatures in neutrino detectors

And astrophysical objects in turn give us sources for the study of **neutrino physics**...



...for free! Just need to look up (and down!)

And astrophysical objects in turn give us sources for the study of **neutrino physics**...



There is information over ~25 orders of magnitude in energy



There is a vast array of detector technologies, and detector instances, existing and proposed



From arXiv:2203.08096v2

Multi-Messenger Astrophysics Many, many detectors



Shunsaku Horiuchi, Snowmass Neutrino Colloquium

The standard disclaimer...



Multi-messenger astronomy

Neutrino astrophysics



A "flight" of examples



*More detail in NF reports



Detectors for ultra-high energy neutrinos (>TeV)

Long-string Water Cherenkov





Water and ice

Antenna-based detectors





Cosmic-ray shower detectors





Ground-based or space-based

IceCube

hugely successful program @South Pole





possible "jetted AGN"

TXS0506+056

IceCube-170922



"Multimessenger observations of a flaring blazar coincident with highenergy neutrino IceCube-170922A", The IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, Swift/NuSTAR, VERITAS, and VLA/17B-403 teams. Science 361, 2018

A. Olinto @ "Blue Sky" session

Cosmogenic Neutrinos



Batista et al, arXiv:1903.06714.pdf

Multiple programs going after these





Large (multi-kton) detector technologies for ~GeV scale

Water Cherenkov Trackers **Liquid Argon** Time Projection Chamber (a diverse category) **Excellent** particle Cheap material, Good particle proven at very reconstruction reconstruction large scale





Water & tracking detectors made the original atmospheric neutrino oscillation measurements, and are now combined w/beams...



...they make good neutrino telescopes too!

Next-generation long-baseline beam experiments



- 295-km baseline
- 260k (188k) ton mass water Cherenkov detector
- First data in 2027





- 1300-km baseline
- 4 10-kton LArTPC modules
- 4850-ft depth
- Phase 2 "Module of Opportunity" for 3&4



Multi-purpose detectors, broad physics programs in both cases, including astrophysical neutrinos (over a range of energies)

Now moving down in energy to the few-100 MeV scale



Large detector technologies for low energies



Generally limited by efficiency & background at ~MeV scale

Neutrinos from core-collapse supernovae

When a star's core collapses, ~99% of the gravitational binding energy of the proto-nstar goes into v's of all flavors with ~tens-of-MeV energies

(Energy can escape via v's) Mostly v-vbar pairs from proto-nstar cooling



Timescale: prompt after core collapse, overall ∆t~10's of seconds



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On this flux plot, for ~10 seconds,
diffuse supernova neutrino background x 10<sup>9-1010</sup> !
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Supernova neutrino detector types



Future Large Supernova-Burst-Sensitive Neutrino Detectors







Hyper-Kamiokande 260 kton water Japan JUNO 20 kton scintillator (hydrocarbon) China **DUNE** 40 kton argon USA

• Hyper-K /JUNO are primarily sensitive to nuebar

 $\bar{\nu}_e + p \to e^+ + n$

• DUNE is primarily sensitive to **nue**

$$\nu_e + {}^{40}\mathrm{Ar} \to e^- + {}^{40}\mathrm{K}^*$$

extreme complementarity



In general, the whole is more than the sum of the parts for multi-messenger astronomy



K. Nakamura et al., MNRAS 2016



Neutrinos arrive earlier than the first light from a supernova... combine signals for a high-confidence prompt alert, enabling more physics & astrophysics

Dark matter detectors as neutrino observatories



Plot from CF01 Image: J. Link *Science* Perspectives Once nuclear recoil detectors get sensitive enough, they are blinded by natural neutrinos

Interesting things may eventually emerge from the fog...





O'Hare [2109.03116]

And now, down at the lowest energy end....



Indirect information about CNB from cosmology

Yvonne Wong, Snowmass Neutrino colloquium



Indirect information about CNB from cosmology

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Future cosmological probes				
			1σ sensitivity to $\sum m_{ u}$	1σ sensitivity to $N_{ m eff}$
	ESA Euclid	2024	0.011 - 0.02 eV	0.05
	LSST	2024	0.015 eV	0.05
CMB-S4 Next Generation CMB Experiment	CMB-S4	2027	0.015 eV	0.02 - 0.04
Minimum $\sum m_{\nu} = 0.06 \text{ eV}$ From neutrino oscillations (assuming normal mass ordering)			Detection of the absolute neutrino mass may be possible!	

Neutrinos and Cosmology: indirect CNB

Yvonne Wong, Snowmass Neutrino colloquium



- Cosmological measurements tell us about v properties
- Lab experiments help to constrain cosmological fits



Direct detection of Cosmic Neutrino Background

Very, very hard... lots of ideas but few promising... Best possibility: "zero-threshold reactions"

C.Tully, Snowmass white paper workshop talk



Final comment

Event spectrum as a function of observed energy E', for a real detector*

 $flux \otimes xscn \otimes interaction \ products \otimes detector \ response$



- E': observed energy
- k: observed energy for given neutrino energy
- T: detector efficiency
- V: detector resolution

*For astro, t, θ , ϕ also matter

Event spectrum as a function of observed energy E', for a real detector

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Event spectrum as a function of observed energy E', for a real detector

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Take-Away Messages

Neutrinos are messengers of astrophysics and cosmology

- They tell us what's happening deep inside objects, and point from far away
- Not a competition!
 We want to catch them all!

Natural neutrinos are messengers of *physics*

- Astrophysical sources are free!
 Just need to build the detector...
- Enable 3-flavor osc and huge range of BSM searches

catching rain water in many different sized buckets in a big field and a dancing person in a raincoat catching rain in a cup



Many inter-connections between frontiers... most effective as part of a broad program across scales