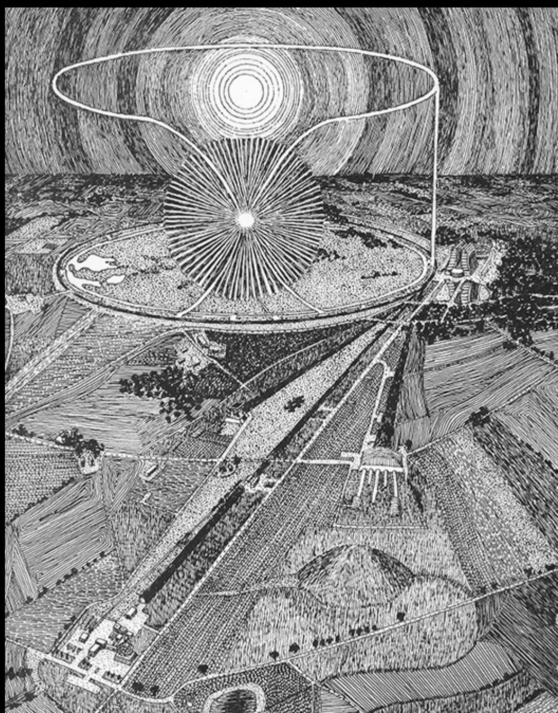
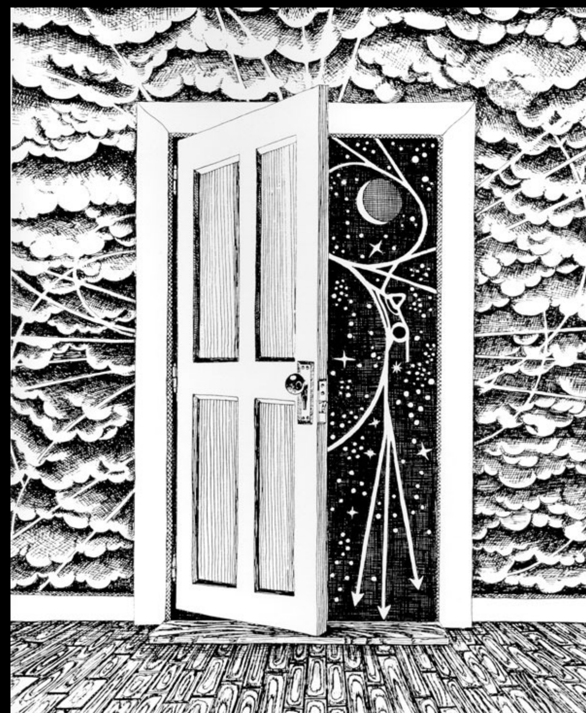
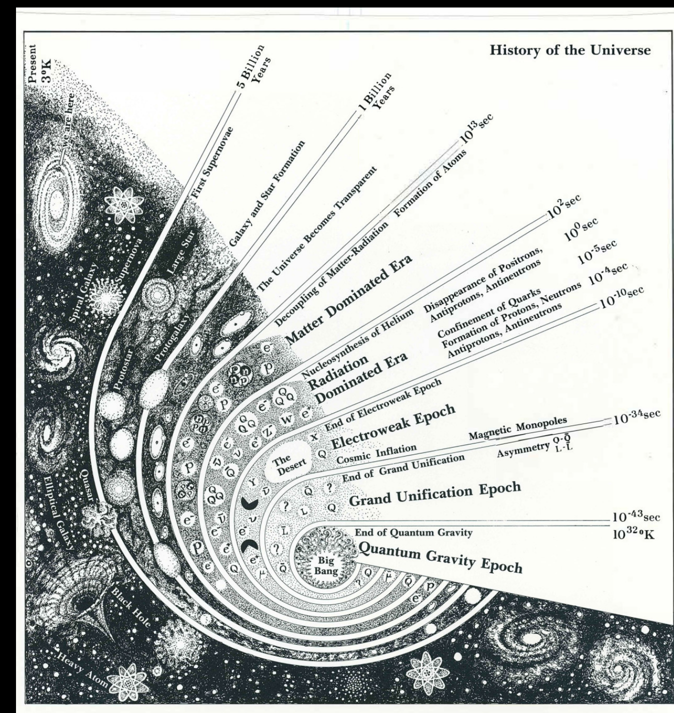
Neutrino Frontier: Progress and Promise

John Beacom, The Ohio State University

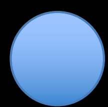






How Have We Known Neutrinos?

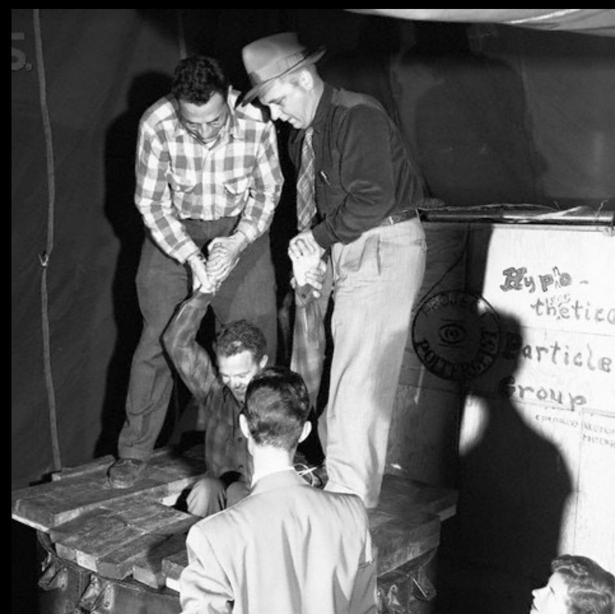
Concepts



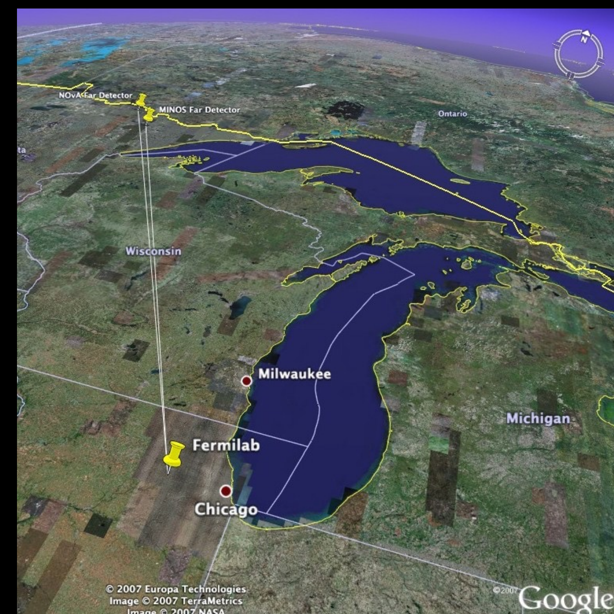
before

after

Realities



Messengers



Neutrinos take patience, but they reward it richly

What are the Goals of Particle Physics?

Probe fundamental particles and forces

Explain emergent phenomena

Search for BSM physics

Three Ways of Making Progress With Neutrinos

Laboratory

(Highest precision)

Cosmology

(Growing precision)

Astronomy

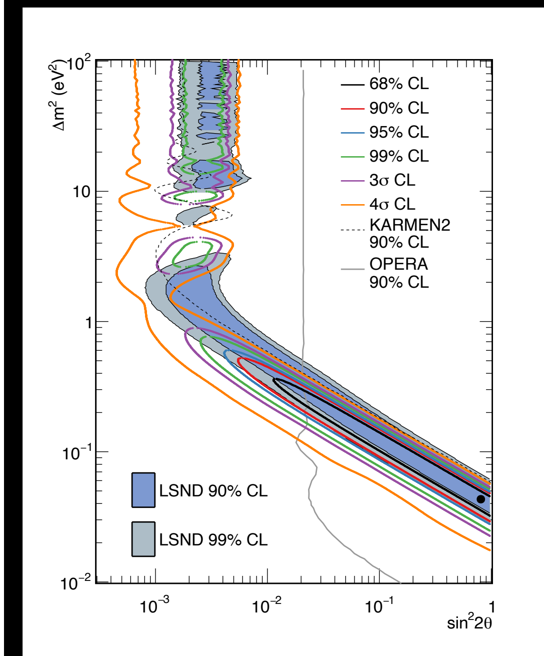
(Emerging precision)

Details of Directions for Progress

Laboratory Nu:	Cosmology Nu:	Astrophysics Nu:
Superpowers: Window to BSM physics at low mass scales; to feeble interactions	Superpowers: Windows to dark radiation and dark matter; possibly to the matter asymmetry	Superpowers: Windows to the interiors of sources; to the largest energies and distances
Kryptonite: Can't reach extremes needed	Kryptonite: Can't isolate particles	Kryptonite: Can't control conditions

Overlapping unknowns are liability … but also an opportunity

Example: Are Sterile Neutrinos Real?



MiniBooNE (2021)

Laboratory

Could have large dm^2, large sin^2 sterile neutrino mixing

This would reveal new particle physics

BUT

Cosmology

This would violate neutrino number, mass bounds

Evading requires new early universe physics

BUT

Astronomy

But this could change supernova neutrino signals

Evading could require new astrophysics

Inputs For This Presentation

- Snowmass Neutrino Frontier Report
  (Conveners: Huber, Scholberg, Worcester), arXiv:2211.08641

  NF01: Neutrino Oscillations
  NF02: Understanding Experimental Neutrino Anomalies
  NF03: BSM
  NF04: Neutrinos from natural sources
  NF05: Neutrino properties
  NF06: Neutrino Interaction Cross Sections
  NF07: Applications
  NF08 (and TF11): Theory of Neutrino Physics
  NF09: Artificial Neutrino Sources
  NF10: Neutrino Detectors

- Other Snowmass white papers, talks, and reports
- Other community planning documents in particle, nuclear, and astro
- My own opinions

What Questions Drive Us?

Overview of Questions

First in the laboratory:

- Neutrino mass
- Neutrino mass splitting and mixing
- Neutrino scattering

First in the skies:

- Neutrinos in the cosmos
- Neutrinos from astrophysical sources

Cross-cutting:

- Neutrino exotica

Questions: Neutrino Mass

First in the laboratory

Neutrino mass is BSM physics

- What mechanism sets the mass?
- Why is the mass scale so small?
- Dirac or Majorana masses?

What do the answers reveal about other BSM physics?

- New particles and interactions?
- Lepton-number violation?

Questions: Neutrino Mass Splitting and Mixing

First in the laboratory

Neutrino mass splitting and mixing is BSM physics
- What mechanism sets the mass splitting and order?
- Why sets the angles?
- CP violation?

What do the answers reveal about other BSM physics?
- New particles and interactions?
- Effects on emergent mixing in matter and in neutrinos?

Questions: Neutrino Scattering

First in the laboratory

Neutrino scattering is fundamental physics
- Complicated by the emergent properties of systems
- From quarks → nucleons → nuclei → nuclear matter

Essential to probing BSM physics
- Determines sensitivity to mixing
- New particles and interactions?
- Self-scattering in dense neutrino gases?

Questions: Neutrinos in the Cosmos

First in the skies

Neutrinos in the cosmos is fundamental physics

- Probe nu-genesis → BBN → CMB → LSS → direct detection
- Neutrino number density probes dark radiation
- Neutrino mass density probes small part of dark matter

Essential to probing BSM physics

- Enabled by precision cosmology and theoretical physics
- Sensitivity to a wide range of neutrino exotica

Questions: Neutrinos from Astrophysical Sources

First in the skies

Neutrinos from astrophysical sources are fundamental physics

- Probe nuclear fusion, with Sun as prototype for other stars
- Probe hot, dense matter in proto-neutron star formation
- Probe hadronic acceleration up to ultra-high energies

Essential to probing BSM physics

- Enabled by "precision astronomy" and theoretical physics
- Leveraged by MMA and nuclear-physics investments
- Sensitivity to a wide range of neutrino exotica

Questions: Neutrino Exotica

Cross-cutting

Neutrino exotica is BSM physics

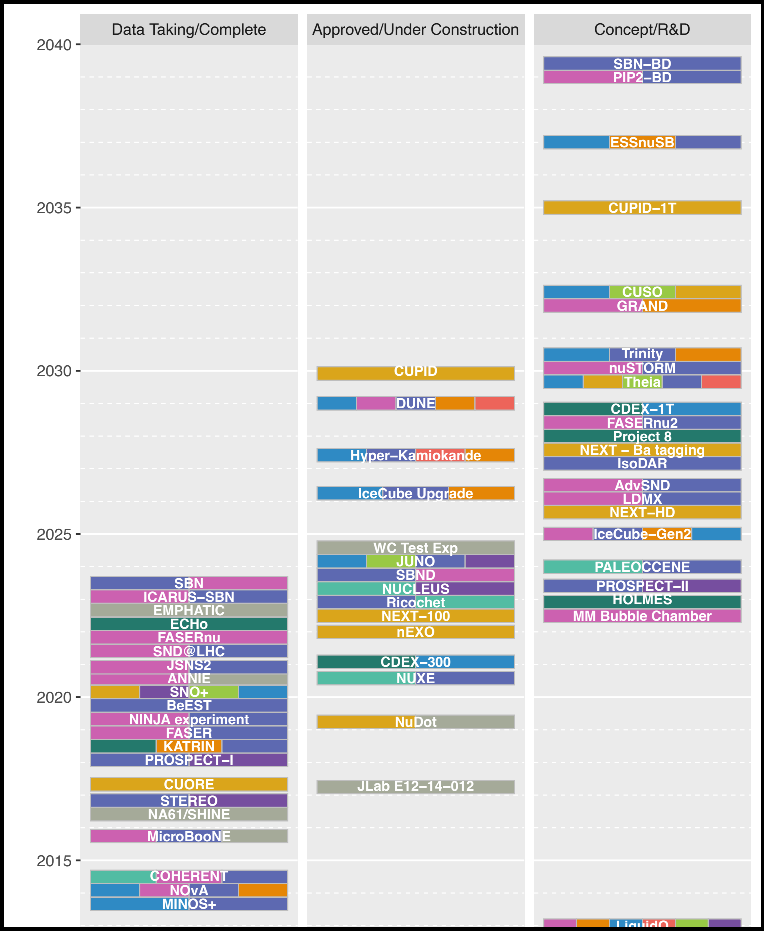
- Sterile neutrinos?
- New contributions to interactions with matter?
- New contributions to interactions among neutrinos?

Essential to understand the fundamentals

- Theoretical physics needed to connect inputs
- Many opportunities for surprises

What is the Reach of Our Programs?

Overview of Experimental Timelines



Snowmass Neutrino Frontier Report (2022)

Programs: Neutrino Mass

Knowing a number isn't enough; we want to know why it is

on track
needs more
send help

beta decay
(just m_nu)

KATRIN, Project8, etc.

double beta decay
(also Dirac/Majorana)

ton-scale experiments

cosmology
(also cosmic history)

CMB, LSS

SN time delay
(also propagation)

possible but unplanned
Mton-scale experiments

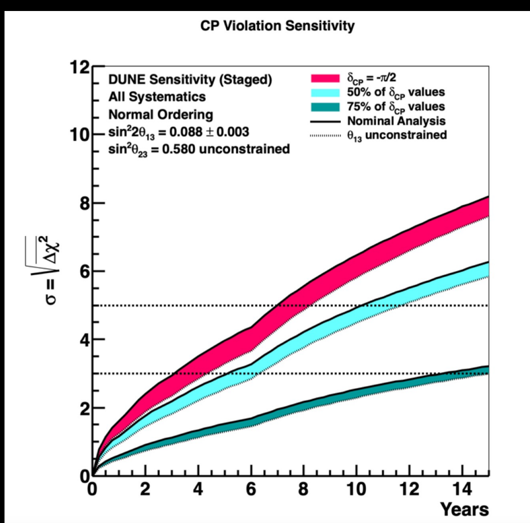
Winning means finding BSM physics; losing means doing great SM physics

Programs: Neutrino Mass Splitting and Mixing (1)

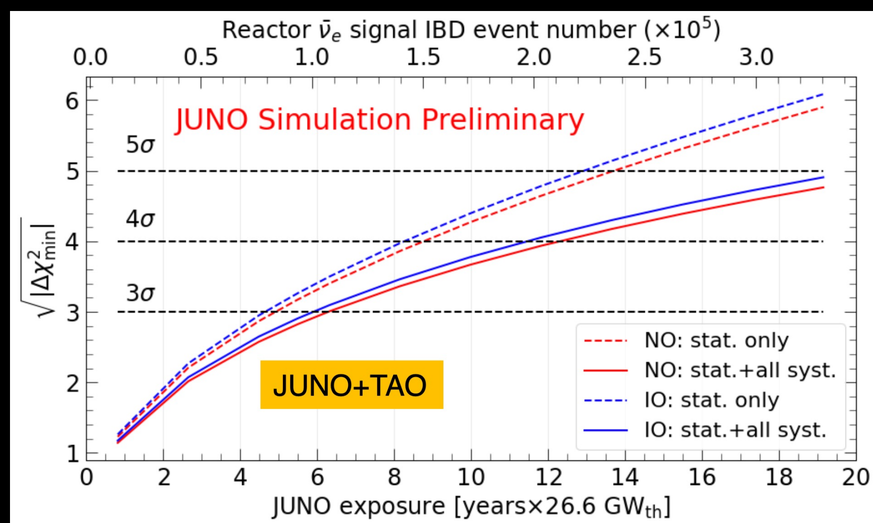
cosmology ← vacuum and moderate matter effects (just dm^2, sin^2, ordering, CP phase) → but also need …

Robust program with nu and nubar; many sources, detectors, and channels

Example: DUNE accelerator



Example:JUNO reactor



Also:

Hyper-K accelerator

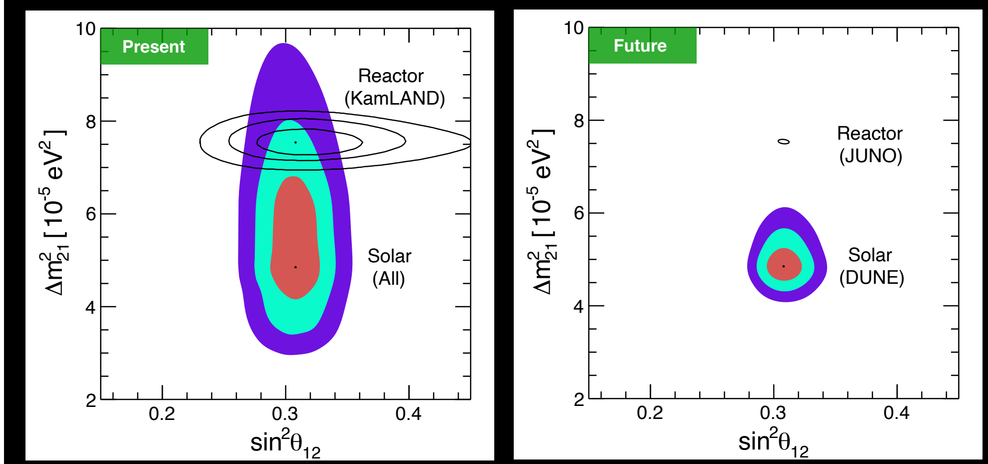
Super-K-Gd, IceCube, KM3NeT, JUNO, Hyper-K, DUNE, others for atmospherics

Programs: Neutrino Mass Splitting and Mixing (2)

large matter effects
(also $G_F N_e$ and BSM physics)

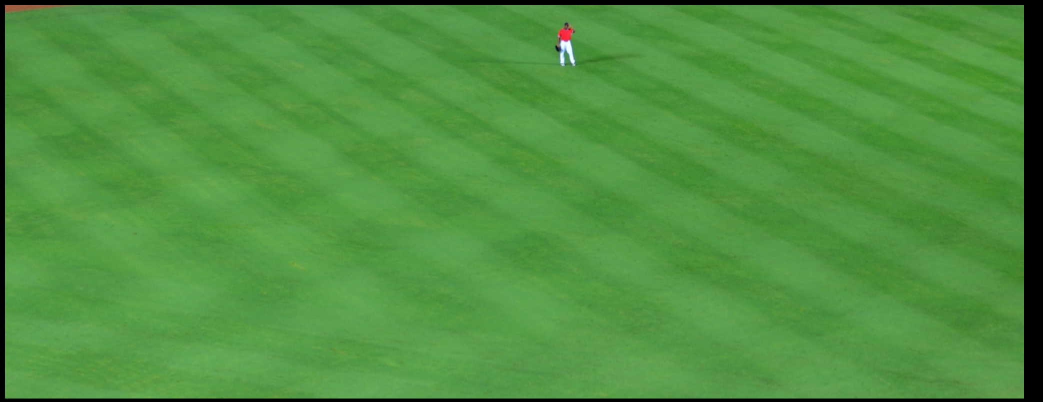
large neutrino effects
(also $G_F N_{nu}$ and BSM physics)

proposal for DUNE Solar



Capozzi, Li, Zhu, Beacom (2019)

Supernova waiting problem



What happens after DUNE et al.?

Programs: Neutrino Scattering

A comprehensive understanding of neutrino scattering on all scales would greatly leverage neutrino mixing and BSM studies

quarks ⟷ nucleons ⟷ nuclei ⟷ nuclear matter

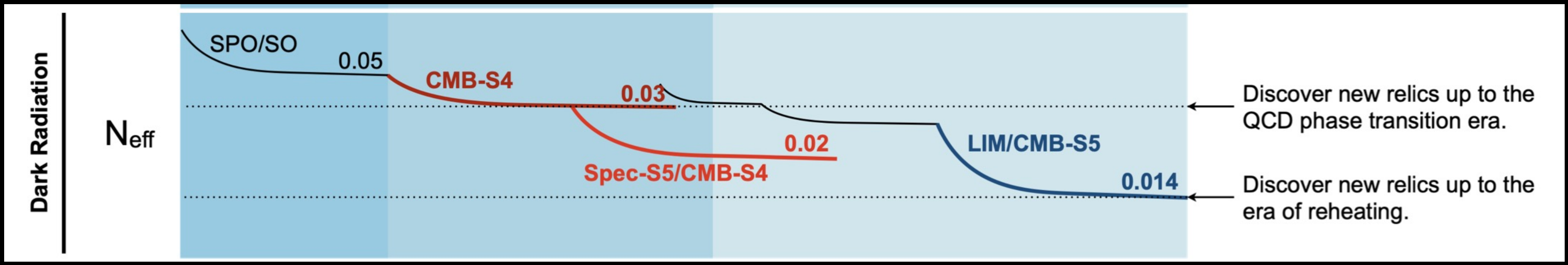
quarks	nucleons	nuclei	nuclear matter
FASERnu, FPF, UHE neutrino astronomy	many near detectors at accelerators	need lower-energy beams	supernova detection and interpretation

Dedicated new efforts are needed to connect experiment, theory, and simulation (generators), plus particle, nuclear, and astrophysics

Programs: Neutrinos in the Cosmos

Neutrinos are a unique probe of the physics of the universe

BBN (very early, probes n_{nu}) → CMB (early, probes n_{nu}) → LSS (late, probes rho_{nu}) → direct detection (now, probes n_{nu} and m_{nu})



Snowmass Cosmic Frontier Report (2022)

Cosmic neutrino mass would show that radiation is really neutrinos!

Programs: Neutrinos from Astrophysical Sources

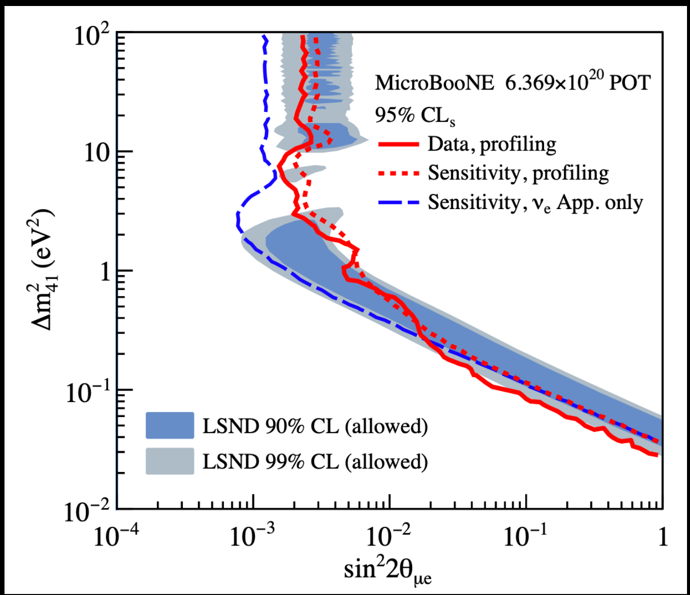
Exploiting neutrino astrophysics requires a wide range of detected sources

MeV–GeV	TeV–PeV	EeV–ZeV
solar low-E	AGN? TDEs?	UHECR sources
solar high-E	GRBs? FRBs?	what else?
supernova burst	starbursts?	dark matter?
DSNB	MMA sources?	
atmospheric	dark sources?	
dark matter?	dark matter?	

The better we understand the astrophysics, the better we can probe BSM physics of neutrinos, dark matter, and surprises

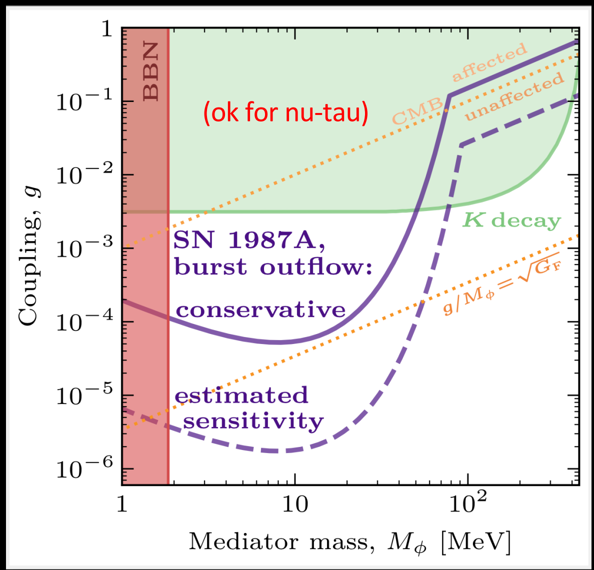
Programs: Neutrino Exotica

Example: sterile neutrinos



MicroBooNE (2022)

Example: neutrino self-interactions



Chang, Esteban, Beacom, Thompson, Hirata (2022)

Must use laboratory, cosmology, and astronomy data, connected by theory

What New Tools Do We Need?

Importance of Technical and Theory Development

What does fostering experimental and theoretical innovation bring us?

- Pathways from technology → small → medium → large experiments
- Attracting and retaining top talent
- Training on cutting-edge techniques
- Leadership development
- Spinoffs to benefit society

The entire present liquid-argon ecosystem is a wonderful example

- Successfully standing up a world-leading program at all scales
- Stimulating lots of new ideas to make the most of this incredible technology

Examples of Cross-Cutting Problems

- Improving the MeV-range response of MeV–GeV–TeV detectors
  Better nuclear physics (neutron tagging, nuclear gamma rays, positrons vs. electrons, etc.) means better particle physics

- Improving our understanding of neutrino cross sections
  Need to combine fields, experiment, theory, and simulation

- Improving our plans to measure supernovae well
  Experimental plans are incomplete; there is no standard theory

- Improving our leveraging of different approaches
  Need to better connect laboratory, cosmology, and astronomy

How Should We Lead Our Work?

Examples of Improving Our Approaches

- Accelerate progress with Diversity, Equity, and Inclusion efforts
  We need the most creative teams, plus our workforce should reflect our nation

- Accelerate progress with stronger connections within particle physics
  Synergies with dark matter, cosmic history, QCD, flavor physics, model building, …

- Accelerate progress with stronger connections outside particle physics
  Synergies with astrophysics, nuclear physics, gravitational physics, …

- Accelerate progress by new considerations of funding boundaries
  Some of the most exciting next steps may be outside the box

Concluding Remarks

Neutrino Frontier: Progress and Promise

The legacy of decades of investment is

1. Progress: we have outstanding, well-defined questions
2. Promise: we have outstanding prospects for getting answers!

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First in the skies:

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- Neutrinos from astrophysical sources

Cross-cutting:

- Neutrino exotica

Neutrinos take patience, but they reward it richly