FUTURE NEUTRINO EXPERIMENTS

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Note: My research is in neutrino oscillation physics so that will be the primary focus of this presentation. I am a collaborator on SBN & DUNE.
Neutrinos: What We Do & Don’t Know

- Neutral leptons with **3 active flavors**
- Small mass
  - Existing limits on sum of neutrino masses are order few hundred meV/c^2
- Flavor eigenstates \((\nu_e, \nu_\mu, \nu_\tau) \neq \text{mass eigenstates } (\nu_1, \nu_2, \nu_3)\)
  - Mixing described by PMNS matrix
  - All mixing angles and mass splittings have been measured
- Neutrinos detected via their interaction products
  - Neutrino interaction cross sections are small, \(\mathcal{O}(10^{-38} \text{ cm}^2/\text{nucleon})\) at 1 GeV
- May be Majorana or Dirac

Sterile neutrinos? (see talk by D. Caratelli)

Direct measurement limits currently <1 eV/c^2 (see talk by S. Mertens)

* More precise measurements of mixing angles needed
* CP violation in PMNS?
* Unitarity?

Neutrino-nucleus interaction model has large uncertainties

Majorana: additional CPV phases
Neutrino Mixing & Oscillation

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= \begin{pmatrix} \text{PMNS matrix} \end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[
\begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{13} & 0 & e^{-i\delta_{CP}} \sin \theta_{13} \\
0 & 1 & 0 \\
-e^{i\delta_{CP}} \sin \theta_{13} & 0 & \cos \theta_{13}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

\[\theta_{23} \approx 45^\circ\]

\[\theta_{13} \approx 9^\circ\]

\[\delta_{CP} = ?\]

Most parameters currently measured to \(\sim 3\%\)

Open questions:
- Mass ordering \((\Delta m^2_{32} > 0?)\)
- Octant \((\sin^2 \theta_{23} = 0.5?)\)
- CP violation \((\delta_{CP} \neq 0, \pi?)\)
- Only 3 flavors? PMNS unitary?
What Can We Discover?

- **CP Violation**
  - Symmetry and symmetry violation has been a major driver of discovery in particle physics
  - Leptogenesis requires CPV in high-energy Lagrangian (incl. right-handed neutrinos)
    - No model-independent connection between low-energy (PMNS) CPV and high-energy CPV required for leptogenesis
- **Flavor structure**
  - Why is the structure of the $\nu$ mixing matrix different from that of the quark mixing matrix
  - What flavor symmetry can produce this pattern of mixing and how is it broken?
  - Is $\nu_\mu \leftrightarrow \nu_\tau$ mixing symmetric? If so, why?
- **Model discrimination**
  - Many flavor and BSM models make specific predictions for values of oscillation parameters.
- **Non-neutrino BSM physics**
  - Neutrino experiments have sensitivity to non-neutrino physics
Neutrino Sources

- SNB $\nu$ ~10 MeV
- Reactor $\nu$ ~2–5 MeV
- Accelerator $\nu$ ~0.5–5 GeV

Extra-Galactic
Galactic
Accelerator
Atmospheric
SuperNova
Solar
Reactor
Terrestrial
Big Bang
Neutrino Sources

Reminder: \[ P_{\alpha \rightarrow \beta, \alpha \neq \beta} = \sin^2 (2\theta) \sin^2 \left( \frac{\Delta m^2 L}{4E} \right) \]

So different values of L/E are sensitive to different mass splittings/mixing angles and, where possible, we optimize the baseline and/or energy for the desired measurement.
Future Precision Oscillation Experiments

JUNO

Mass ordering, $\sin^2\theta_{12}$, $\Delta m^2_{12}$, $\Delta m^2_{32}$
Supernova vs, solar vs, geoneutrinos, baryon number violation, BSM

HyperK

$\delta_{CP}$, $\sin^2(2\theta_{13})$, $\sin^2(\theta_{23})$, $\Delta m^2_{32}$, mass ordering w/ atmospheric vs,
BSM including baryon number violation,
supernova vs, solar vs,

DUNE

Mass ordering, $\delta_{CP}$, $\sin^2(2\theta_{13})$, $\sin^2(\theta_{23})$, $\Delta m^2_{32}$, BSM including baryon number violation,
supernova vs, solar vs,
JUNO: Jiangmen Underground Neutrino Observatory

- Reactor antineutrino experiment
- 20 kt (active) liquid scintillator detects antineutrinos via inverse beta decay
- 53 km baseline from two reactors
- ~700 m overburden
- 3%/√E (MeV) energy resolution

See talk by D. Basilico
**JUNO Physics**

**Primary goals:**
- Mass ordering determination (>3σ)
- Measure $\sin^2 \theta_{12}$, $\Delta m^2_{21}$, $|\Delta m^2_{32}|$ to better than 0.6%

[Graph showing expected event rates for neutrino oscillations over 2000 days of data taking, with labels for $\sin^2 2\theta_{12}$, $\Delta m^2_{21}$, $\Delta m^2_{32}$, $\sin^2 2\theta_{13}$, and different oscillation scenarios like no oscillations, only solar term, normal ordering, and inverted ordering.]
Long-Baseline Oscillation Experiments

- Measure $\nu_\mu$ survival and $\nu_e$ appearance in a $\nu_\mu$ dominated beam
- Appearance probability depends on $\Delta m^2_{32}$, $\sin^2\theta_{23}$, $\sin^22\theta_{13}$, $\delta_{CP}$, and matter effects

- Value of $\delta_{CP}$ affects both rate and shape of appearance probability, with asymmetric impact on neutrinos and antineutrinos
- Degeneracy between matter-antimatter asymmetry from $\delta_{CP}$ and matter effects for baselines $<1000$ km
Current LBL Experiments

**T2K: Tokai to Kamioka**

**NOvA: FNAL to Ash River**

Current experiments have some sensitivity to mass ordering and $\delta_{\text{CP}}$ - we do not yet know the values of these parameters. Future sensitivity depends strongly on true values.
Future LBL Experiments

T2HK: Tokai to HyperK
• Maximize statistics and minimize matter effect to focus on CPV discovery (short baseline, very large far detector)
  • Requires separate atmospheric neutrino sample to determine mass ordering
• Beam: J-PARC, 1.3 MW
• Far detector: WCD (187 kt fiducial)
• Baseline: 295 km
• Far detector located off-axis such that observed $\nu$ flux is peaked at $\sim$600 MeV

DUNE: FNAL to SURF
• Measure all LBL parameters (incl. MO) in a single dataset and map oscillation pattern as a function of energy for precision measurements (long baseline, broadband beam, precision imaging far detector)
• Beam: LBNF (FNAL), 1.2-2.4 MW,
• Far detector: LArTPC (>40 kt fiducial)
• Baseline: 1300 km
• Far detector located on-axis such that observed $\nu$ flux is a broad spectrum (0.5-5 GeV)

See talk by M. Malek
HyperK Oscillation Physics

CP Violation Sensitivity:

*Snowmass years = $10^7\text{ s}$

10 years with 1.3MW, T2K 2018 systematic error

- True NO
  - M. Ishitsuka, Neutrino 2020

- Known mass ordering (external constraint)
  - Atm + Beam
  - Beam only

Precision Measurements:

- 90% CL

DUNE Oscillation Physics

Mass Ordering Sensitivity:

- Mass ordering determined with high significance for all parameter space with ~100 kt-MW-years of data

Precision Measurements:

Note: Time to reach milestones for early exposures depends on staging timeline, which is not yet fully determined, but does not dramatically impact ultimate sensitivity, as long as full scope is realized in a timely fashion. Opportunity!

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*kt-MW-years includes 0.56 historical accelerator uptime
DUNE Oscillation Physics

CP Violation Sensitivity:

- $3\sigma$ sensitivity to CPV after $\sim100$ kt-MW-years and $5\sigma$ sensitivity after 336 kt-MW-years if $\delta_{cp}=-\pi/2$
- $3\sigma$ sensitivity to CPV for 50% of $\delta_{cp}$ values after $\sim200$ kt-MW-years

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Systematic Uncertainty

- Order few percent uncertainty required for precision measurements
- Sources of uncertainty:
  - Neutrino flux
  - Neutrino interaction model
  - Detector effects
- Impact of biases due to shortcomings in the interaction model is potentially large
- Both DUNE & HyperK will require sophisticated NDs taking measurements at multiple off-axis angles to constrain impact of interaction model uncertainties
- DUNE and HyperK systematics largely uncorrelated, with different:
  - Neutrino energies
  - Far detector target nuclei
  - Detector calibration, reconstruction, and event selection effects

Experimental measurements of neutrino-nucleus scattering, development of nuclear interaction models, and development of event generators will all contribute to long-term success of LBL measurement program

DUNE: Impact of Interaction Model Uncertainty on CP Violation Sensitivity
Physics Beyond the Standard Model

Sensitivity to many different NP scenarios being investigated both by collaborations and by phenomenologists

- Deviations from 3-flavor oscillation (sterile \( \nu \), NSI, PMNS non-unitarity, CPT violation, etc)

  [Graph showing \( \Delta m^2_{41} \) vs. \( \sin^2 2\theta_{\mu e} \)]


- Other new physics signatures (neutrino trident rate, dark matter, baryon number violation, etc – both ND and FD)

  Proton decay: \( p \rightarrow e\pi^0 \)
  Hyper-K 10 years operation assuming \( T_{\text{proton}} = 1.7 \times 10^{34} \) years
  (near current SK limit)

  [Graph showing number of events vs. invariant proton mass]

Complementary measurements at both DUNE and HK may help disentangle degeneracy between BSM signatures and 3-flavor oscillation parameters.
Supernova Neutrinos

- Complementarity among experiments:
  - DUNE more sensitive to electron neutrinos
    - $\nu_e + ^{40}\text{Ar} \rightarrow ^{40}\text{K}^* + e^- \text{ (CC absorption)}$
  - JUNO and HyperK more sensitive to electron antineutrinos
    - $\bar{\nu}_e + p \rightarrow e^+ + n \text{ (IBD)}$
  - Information about both supernova physics and particle physics embedded in neutrino signal
    - Time profile, flavor composition, energy spectrum
  - Multi-messenger astronomy
Supernova Neutrinos

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**DUNE:**

- 40 kton argon, 10 kpc
- Time (seconds)
- Events per bin
- No oscillations
- Normal ordering
- Inverted ordering
- Dominated by $\nu_e$
- (No collective effects)

**HyperK:**

- Time profile, flavor composition, energy spectrum
- Multi-messenger astronomy

**JUNO:**

- Information about both supernova physics and particle physics embedded in neutrino signal
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[Graphs and data showing various neutrino interactions and experiments.

- LAr, IBD, LiqScint, water Cherenkov cross-sections.
- Neutrino energy vs. cross-section.
- Visible energy vs. events/0.22 MeV.
- JUNO: $\nu_e$ vs. $E_e$ vs. $E_{\nu}$, $E_{\nu}$ vs. $E_e$.]

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[Images and data showing the time profile and events distribution for different neutrino experiments and interactions.]
Solar Neutrinos

- $\Delta m^2_{21}$ from solar and reactor vs is an important comparison b/c of the very different physical conditions
  - Significant reduction in uncertainty of both measurements may be possible with next generation experiments
- $^8$B and hep neutrinos probe solar astrophysics
- HyperK expected to have some sensitivity to details of day-night asymmetry and the hep solar neutrino flux
- DUNE is currently studying ability to select and reconstruct solar neutrinos; initial results suggest potential for DUNE to select a sample of solar neutrinos that would allow a significant improvement in the measurement of $\Delta m^2_{21}$ as well as observations of the the hep and $^8$B solar neutrino flux
More future experiments & upgrades

• The IUPAP Neutrino Panel White Paper is a good resource (link)
• Neutrino mass: arXiv:2102.00594
• Neutrinoless double beta decay: arXiv:1902.04097
• IceCube: https://icecube.wisc.edu/
• KM3NET: https://www.km3net.org/
• Baikal GVD: https://baikalgvd.jinr.ru/
• Neutrinos at LHC: https://faser.web.cern.ch/physics/neutrino-program
• New detector concepts for DUNE:
• HyperK 2nd Detector in Korea: arXiv:1611.06118
• Theia: arXiv:1911.03501
• ESSνSB: https://essnusb.eu/
• νSTORM: https://indico.cern.ch/event/765096/contributions/3296001/
Summary

• Precision era of neutrino oscillation measurements is here
  • Most oscillation parameters known to $\sim$3%
  • **JUNO expects to reduce some of these uncertainties to <1%**
  • Current generation of long-baseline oscillation experiments have interesting results on mass ordering, CPV
  • **Major experimental advances in next generation of long-baseline oscillation experiments: thousands of events, 5$\sigma$-level sensitivity to CPV, precision measurements of oscillation parameters, including $\delta_{\text{CP}}$, significant sensitivity to physics beyond the Standard Model**
  • People are already thinking about next-next generation
• **Systematics are critical for precision measurements!**
  • Collaboration with neutrino and nuclear theorists
  • Stand-alone experiments to measure hadronization and neutrino interactions – improved input to modeling program
  • New experimental techniques to reduce model dependence
• **Neutrino oscillation experiments enable broad physics program**
  • Supernova $\nu$ physics, baryon number non-conservation, BSM searches, solar $\nu$ physics, atmospheric $\nu$ physics, geoneutrinos…
  • Opportunities to expand the physics reach of next generation experiments with new detector ideas
Neutrinos make beautiful science!