SN $\nu$ Detector
Flavor Sensitivities

- **Water Cherenkov (w/o Gd)**
  - $\overline{\nu}_e$ CC
  - NC

- **Liquid Scintillator**
  - $\overline{\nu}_e$ CC
  - NC

- **Lead**
  - $\nu_e$ CC

- **Liquid Argon**
  - $\nu_e$ CC
  - Low thresholds see NC coherent scattering

- **Iron**
  - NC

**Need sensitivity to different $\nu$ flavors to disentangle the physics**

**Strong threshold dependence**

There are no planned Iron-based detectors.
Current and Near-Future SN $\nu$ detectors

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Type</th>
<th>Mass [kt]</th>
<th>Location</th>
<th>$11.2, M_\odot$</th>
<th>$27.0, M_\odot$</th>
<th>$40.0, M_\odot$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Super-K</td>
<td>H$_2$O/$\bar{\nu}_e$</td>
<td>32</td>
<td>Japan</td>
<td>4000/4100</td>
<td>7800/7600</td>
<td>7600/4900</td>
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<tr>
<td>Hyper-K</td>
<td>H$_2$O/$\bar{\nu}_e$</td>
<td>220</td>
<td>Japan</td>
<td>28K/28K</td>
<td>53K/52K</td>
<td>52K/34K</td>
</tr>
<tr>
<td>IceCube</td>
<td>String/$\bar{\nu}_e$</td>
<td>2500*</td>
<td>South Pole</td>
<td>320K/330K</td>
<td>660K/660K</td>
<td>820K/630K</td>
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<tr>
<td>KM3NeT</td>
<td>String/$\bar{\nu}_e$</td>
<td>150*</td>
<td>Italy/France</td>
<td>17K/18K</td>
<td>37K/38K</td>
<td>47K/38K</td>
</tr>
<tr>
<td>KamLAND</td>
<td>C$<em>n$H$</em>{2n}$/\bar{\nu}_e</td>
<td>1</td>
<td>Japan</td>
<td>190/190</td>
<td>360/350</td>
<td>340/240</td>
</tr>
<tr>
<td>Borexino</td>
<td>C$<em>n$H$</em>{2n}$/\bar{\nu}_e</td>
<td>0.278</td>
<td>Italy</td>
<td>52/52</td>
<td>100/97</td>
<td>96/65</td>
</tr>
<tr>
<td>JUNO</td>
<td>C$<em>n$H$</em>{2n}$/\bar{\nu}_e</td>
<td>20</td>
<td>China</td>
<td>3800/3800</td>
<td>7200/7000</td>
<td>6900/4700</td>
</tr>
<tr>
<td>SNO+</td>
<td>C$<em>n$H$</em>{2n}$/\bar{\nu}_e</td>
<td>0.7</td>
<td>Canada</td>
<td>130/130</td>
<td>250/240</td>
<td>240/160</td>
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<tr>
<td>NOvA</td>
<td>C$<em>n$H$</em>{2n}$/\bar{\nu}_e</td>
<td>14</td>
<td>USA</td>
<td>1900/2000</td>
<td>3700/3600</td>
<td>3600/2500</td>
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<tr>
<td>Baksan</td>
<td>C$<em>n$H$</em>{2n}$/\bar{\nu}_e</td>
<td>0.24</td>
<td>Russia</td>
<td>45/45</td>
<td>86/84</td>
<td>82/56</td>
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<tr>
<td>HALO</td>
<td>Lead/$\nu_e$</td>
<td>0.079</td>
<td>Canada</td>
<td>4/3</td>
<td>9/8</td>
<td>9/9</td>
</tr>
<tr>
<td>HALO-1kT</td>
<td>Lead/$\nu_e$</td>
<td>1</td>
<td>Italy</td>
<td>53/47</td>
<td>120/100</td>
<td>120/120</td>
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<tr>
<td>DUNE</td>
<td>Ar/$\nu_e$</td>
<td>40</td>
<td>USA</td>
<td>2700/2500</td>
<td>5500/5200</td>
<td>5800/6000</td>
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<tr>
<td>MicroBooNe</td>
<td>Ar/$\nu_e$</td>
<td>0.09</td>
<td>USA</td>
<td>6/5</td>
<td>12/11</td>
<td>13/13</td>
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<tr>
<td>SBNd</td>
<td>Ar/$\nu_e$</td>
<td>0.12</td>
<td>USA</td>
<td>8/7</td>
<td>16/15</td>
<td>17/18</td>
</tr>
<tr>
<td>DarkSide-20k</td>
<td>Ar/any $\nu$</td>
<td>0.0386</td>
<td>Italy</td>
<td>-</td>
<td>250</td>
<td>-</td>
</tr>
<tr>
<td>XENONnT</td>
<td>Xe/any $\nu$</td>
<td>0.008</td>
<td>Italy</td>
<td>75</td>
<td>140</td>
<td>-</td>
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<tr>
<td>LZ</td>
<td>Xe/any $\nu$</td>
<td>0.007</td>
<td>USA</td>
<td>65</td>
<td>123</td>
<td>-</td>
</tr>
<tr>
<td>PandaX-4T</td>
<td>Xe/any $\nu$</td>
<td>0.004</td>
<td>China</td>
<td>37</td>
<td>70</td>
<td>-</td>
</tr>
</tbody>
</table>

- From impending SNEWS2.0 whitepaper (table by Evan O’Connor)
- We will have handles on $\nu$ physics: those numbers are NH/IH predictions with adiabatic MSW
  - For 10kpc, progenitor models from Mirrizi (2016), O’Connor (2015)
- Spectral and time info by favor are also vital, of course
**Neutrinos and Lepton Number Violation:**

ν–particle physics frontier for compact objects/multi-messenger astro

**Physics at issue:**
- neutrino rest masses/hierarchy;
- neutrino character (Majorana or Dirac);
- measured mixing angles; CP-violating Phase(s);
- BSM issues: sterile states; NSIs

**core collapse supernovae and binary neutron star mergers:**
- Low entropy; large lepton numbers
- – highly degenerate lepton seas

Consequently, compact object Physics is *exquisitely sensitive* to
lepton number violating processes and neutrino flavor/spin physics:

nuclceosynthesis (e.g., the r-process) and a detected Core Collapse Supernova neutrino signal can be sensitive to neutrino mass hierarchy/flavor/spin (neutrino/antineutrino)/sterile states and BSM extensions especially in the neutrino sector
two venues where $\nu$'s dominate the energetics

$\nu$-flavor dynamics $\Rightarrow$ nuclear physics/isospin

- **Compact Objects** (e.g., core collapse SN; BNS-mergers)

  *exquisitely sensitive to lepton number violation!*

  Boltzmann neutrino transport (from the 1980s onward)

  Coherent flavor transformation – highly nonlinear, collective oscillations

  *Flavor Field Instability*

  (“Fast” flavor conversion — Sawyer 2016

  see also Raffelt; Tambora; others)

  L. Johns, H. Nagakura, GMF, A. Burrows

  arXiv:1910.05682

  $\nu$-scattering/collisions (“halo”; QKEs), e.g., Cherry et al. 2019; Richers, McLaughlin, Kneller, Vlasenko 2019

  quantum entanglement/entanglement entropy flow/frontier in computational field theory

  (see Balantekin, Patwardhan, Cervia 2019) *efficacy of mean field treatment?*

- **Early Universe** (e.g., weak decoupling/big bang nucleosynthesis)

  gravitation is weak and so the expansion rate is desperately slow enabling

  very weakly interacting particles to influence observables in *light elements*, $N_{\text{eff}}$, CMB
Generators

- The results from DUNE cannot be better than the generator used to extract them. BSM physics needs quantitative description of SM physics (example: MiniBooNE excess)
- The generator contains everything we know about neutrino-nucleus interactions and X-sections
- Widely used generators are good in their description of flux drivers and target geometries, but lack in the quality of implemented nuclear physics, patchwork of – often outdated – theory and code snippets. Excessive tuning hides physics problems and limits trustability

Work will advance in two directions:

- 'Practical' generator development:
  - Use of state-of-the-art initial state interactions (ISI): QE,2p2h,N*,DIS, no place for outdated physics
  - Use of state-of-the-art final state interactions (FSI), effects on both ejected particles and target remnants, replace 'home-made' FSI by quantum-kinetic transport calculations
  - Use consistency and coherence between various reaction types and ISI and FSI (e.g. pion production and absorption) to minimize tuning degrees of freedom

- Nuclear theory development:
  - descriptions of neutrino-nucleus interactions by methods from nuclear many-body theory (GFMC, …)
  - extension to heavier nuclei and relativistic regime,
  - extension to non-inclusive X-sections

Ulrich Mosel, Snowmass CPM 2020
Generator development needs resources:

- Cooperation of nuclear theorists + HEP experimenters + computer specialists
- Manpower support over development period (~3-5 yrs), done by university (theory) groups (typical: 1 senior, 1-2 Postdocs, 3 grad students), after that stable support for code maintenance. working example: QGP generators (transport + hydro)
- Access to computing facilities

Practical Observations:

1. Present data are often limited by flux uncertainties and limited knowledge of elementary ISI X-sections: Both need data on elementary target $H \rightarrow \text{nuStorm}$?
2. Electron-nucleus interactions provide a very useful testing ground for neutrino-nucleus interacts: JLAB, LDMX proposal at SLAC, constrain the vector-interaction part of any generator/theory,
3. Generator development work needs specific funding with quality control and leadership as in experimental developments (as a subproject inside an experimental project (e.g. DUNE)?)

Ulrich Mosel, Snowmass CPM 2020
Low energy neutrino scattering: Tayloe-095, Gardiner-194, NF3-141 (Snowden), Barbeau-067, Ifft-142, IF8-139 (Scholberg), Schober-168, Mahapatra-104, Hedges-153 CEvNS and inelastic scattering $E_\nu \sim 10 \text{ 's MeV}$

Importance of $\nu_e N$ cross sections: Aurisano-152, Aurisano-154, Kelly-126 accelerator beam & atmospheric SM: e.g., structure functions, FF, different kinematic ranges BSM: $U_{\tau 3}$ with and without unitarity

Theory: Wagman-177, Meyer-111, Katori-094, CompF0-193 (Kronfeld), TF11-167 (Gupta), Liu-040 lattice, pert. QCD, nuclear EFT, many body methods, phenomenological approaches, input to generators for FF, structure functions, nuclear physics inputs

Monte Carlo Generators for Neutrinos: TF0-132 (Andreaopoulos), Gardiner-131, Jay-144, Katori-094 need for General Purpose MC generators, with flexibility for SM, BSM components

Cross section measurements: SBND-166 (Palamara), RF6-122 (SAND), Katori-094, Sanchez-133, DUNE-053, Sanchez-139, Paley-068, Junk-165, Long-082 near detectors, variety of targets, high energy option, nuSTORM option

Complementary measurements: NFO-102 (Askenazi), TF0-091 (Akesson), Mahn-147 $e4\nu$, LDMX electron scattering data

MH Reno, Neutrino interactions across energies

1-15 GeV neutrino energy regime: -complementary experiments with electron and neutrino scattering -multiple targets: p and nuclear targets $-\nu_e$ cross section measurements for complementary kinematic regimes -require multiple strategies to approach problems: e.g., lattice, nuclear effective field theory, perturbative QCD, phenomenological modeling -flexible, modular Monte Carlo modeling

Reiterate conclusions of Neutrino Town Hall (CommF0-135 (Huber)): Importance of theory ↔ measurements ↔ MC generators Importance of nuclear physics ↔ particle physics connection
Connections across the frontiers:

**Neutrino – Energy Frontiers, Neutrino – Cosmic Frontiers**
- Active expansion of effective volume for neutrino interactions, innovative approaches to detection (upward air showers from tau decays)
- Cross sections for neutrinos tied to multiple processes at high energy, QCD at short distances & small-x physics
- Opportunities for BSM physics

MH Reno, Neutrino interactions across energies

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LHC neutrinos:
FASERnu2-06, Faser2-038, FPF-193, LAA-074
Fasernu2 w/ HL 3 ab^-1 luminosity to get TeV neutrino events $10^5 \nu_e, 10^6 \nu_\mu, 10^3 \nu_\tau$; synergy with astroparticle/CF

HE-UHE neutrinos:
Grant-106, Katori-073, Kowalski-101, CF7-020 (Resconi)
IceCube, Gen2, P-ONE (Pacific Ocean), cross sections, flavor physics

UHE neutrinos:
Bustamante-195, Bustamante-044, Prohira-109, Wissel-064
Detect surface particles, radio from surface or balloon, air shower imaging from ground or space (Ch & fluorescence), radar echo
LQCD: A very vibrant program providing non-perturbative input to the analysis of SM and BSM physics

Rajan Gupta
T-2, Theoretical Division
Los Alamos National Laboratory, USA

Overview of the LOIs covered in Session CPM 124

- Hadron structure and spectroscopy
- Light and heavy flavor physics
- Fundamental Symmetries
- $\nu$-Nucleus scattering
- BSM with LGT
- Computation and algorithms
- Hamiltonian simulation and sign problem (QC)
LQCD for $\nu$ Physics: Looking ahead

- What kind of joint efforts among frontiers/groups/communities/experiment/theory do you envision to progress?

  - Neutrino Oscillation experiments need to know incoming “real” $E_\nu$
  
  - Collaboration between experimentalists, $\nu$-theorists, LQCD, Nuclear many body theory, event generators
  
  - Yearly workshop bringing together experts. Creating a joint 5 page white paper. Export these meetings to global community via web tools

- What kind of resources do you need?

  - Leadership and cluster computing resources
  
  - Today, the US community can effectively use 10-15 M node hours/year on machines such as Summit at Oak Ridge (200PF). Get about 3-4M
  
  - A large student and postdoc pool → faculty positions
LQCD for ν Physics: Looking ahead

• What do you envision as big advances in your field in the next 10 years
  – High-statistics simulations over a range of lattice spacings $0.01 < a < 0.15$ fm
    • Reduce continuum extrapolation errors to $\leq 1\%$ for most observables
    • Facilitate b quark physics without extrapolation from heavy “charm” region
    • Novel algorithms to generate ensembles of decorrelated gauge configurations at $a < 0.06$ fm, $M_\pi = 135$ MeV
  – Simulations with u, d, s, c flavors – each tuned to their physical value.
    • Quantify iso-spin breaking effects
  – QCD+QED simulations to quantify electromagnetic effects
  – Matrix elements with 2—3 hadrons in initial and/or final states
    • Transition matrix elements: $\langle N\pi | A_w | N >, \cdots$
    • Matrix elements within multi-nucleon systems
  – Radiative corrections to weak decays
Neutrino experimental opportunities

Kendall Mahn, MSU
Windows of opportunity: **sources** and detectors

Credit: Rev. Mod. Phys. 84, 1307 (2012)
Windows of opportunity: sources and detectors

Credit: Rev. Mod. Phys. 84, 1307 (2012)

Credit: https://www.hephys.kyoto-u.ac.jp/nucosmos/index.html

Also:
- Calorimeters
- Scintillators
- Spectrometers

Credit: www.hephys.kyoto-u.ac.jp/nucosmos/index.html

nuclear emulsion

time projection chamber

photomultiplier tube
Neutrinos as probes of standard particle physics

Synergies/Optimism:
- Multi-purpose experiments operating or planned
- Coverage? in energy and tests of neutrino properties

Gaps/Pessimism:
- What properties of neutrinos should we be testing? Are there other physics tests neutrinos are well suited for? What is needed for those tests?
- *NF01 x NF06 ‘gaps’ in neutrino osc. program plan