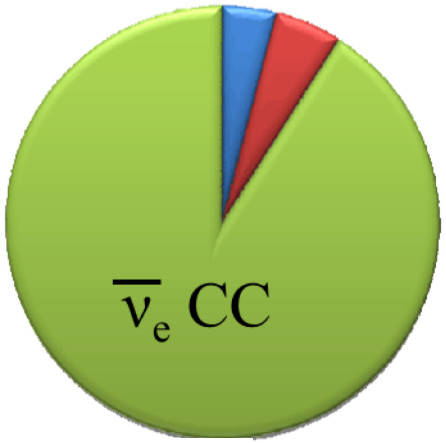
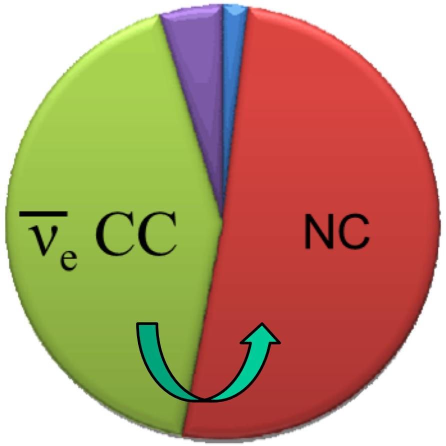
SN ν Detector
Flavor Sensitivities

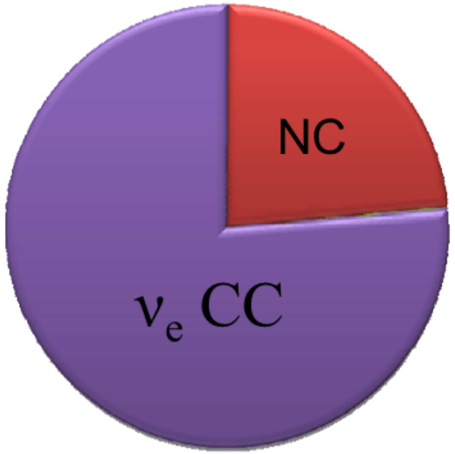


Water
Cherenkov
(w/o Gd)

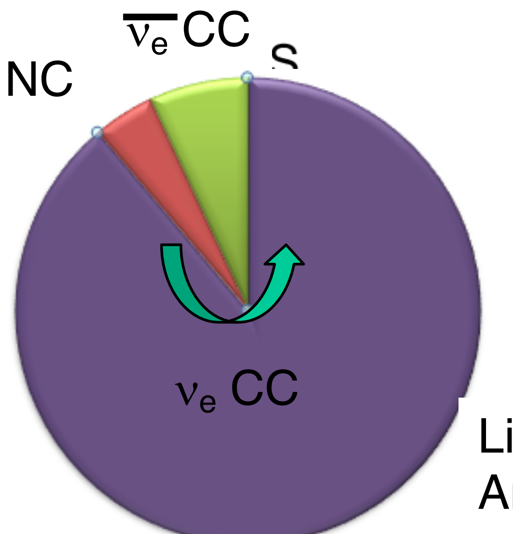
Liquid
Scintillator



Strong threshold dependence



Lead



Liquid
Argon

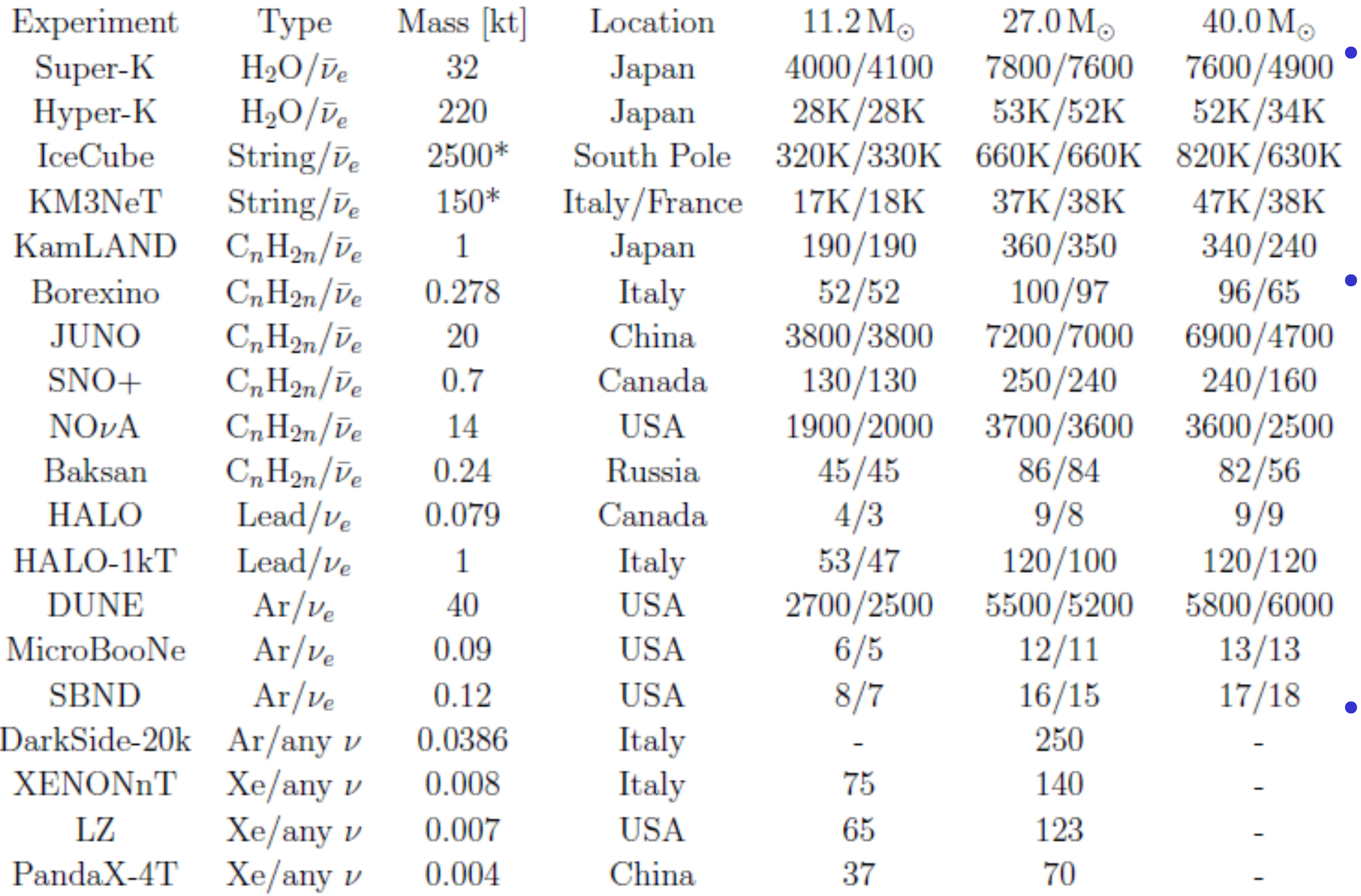
Low thresholds see NC
coherent scattering

Need sensitivity
to different ν flavors
to disentangle the
physics

Iron

There are no planned
Iron-based detectors

Current and Near-Future SN ν detectors



Experiment	Type	Mass [kt]	Location	11.2 $M_\odot$	27.0 $M_\odot$	40.0 $M_\odot$
Super-K	$H_2O/\bar{\nu}_e$	32	Japan	4000/4100	7800/7600	7600/4900
Hyper-K	$H_2O/\bar{\nu}_e$	220	Japan	28K/28K	53K/52K	52K/34K
IceCube	String/$\bar{\nu}_e$	2500*	South Pole	320K/330K	660K/660K	820K/630K
KM3NeT	String/$\bar{\nu}_e$	150*	Italy/France	17K/18K	37K/38K	47K/38K
KamLAND	$C_nH_{2n}/\bar{\nu}_e$	1	Japan	190/190	360/350	340/240
Borexino	$C_nH_{2n}/\bar{\nu}_e$	0.278	Italy	52/52	100/97	96/65
JUNO	$C_nH_{2n}/\bar{\nu}_e$	20	China	3800/3800	7200/7000	6900/4700
SNO+	$C_nH_{2n}/\bar{\nu}_e$	0.7	Canada	130/130	250/240	240/160
NOνA	$C_nH_{2n}/\bar{\nu}_e$	14	USA	1900/2000	3700/3600	3600/2500
Baksan	$C_nH_{2n}/\bar{\nu}_e$	0.24	Russia	45/45	86/84	82/56
HALO	Lead/ν_e	0.079	Canada	4/3	9/8	9/9
HALO-1kT	Lead/ν_e	1	Italy	53/47	120/100	120/120
DUNE	Ar/ν_e	40	USA	2700/2500	5500/5200	5800/6000
MicroBooNe	Ar/ν_e	0.09	USA	6/5	12/11	13/13
SBND	Ar/ν_e	0.12	USA	8/7	16/15	17/18
DarkSide-20k	Ar/any ν	0.0386	Italy	-	250	-
XENONnT	Xe/any ν	0.008	Italy	75	140	-
LZ	Xe/any ν	0.007	USA	65	123	-
PandaX-4T	Xe/any ν	0.004	China	37	70	-

- From impending SNEWS2.0 whitepaper (*table by Evan O'Connor*)
- We will have handles on ν 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:

nucleosynthesis (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 ν's dominate the energetics

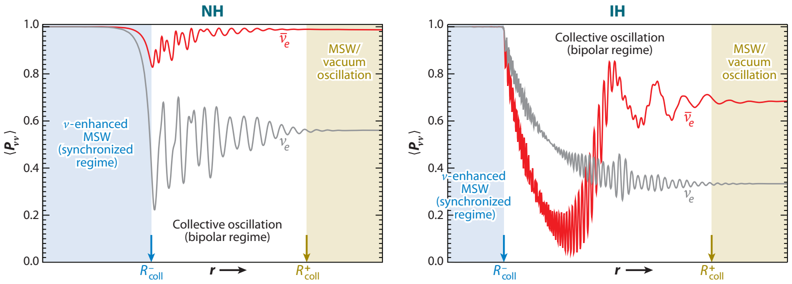
$\nu\text{-flavor dynamics} \rightleftharpoons \text{nuclear physics/isospin}$

- 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

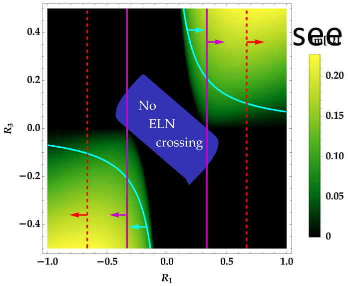


Duan, Huaiyu, et al. 2010.
Annu. Rev. Nucl. Part. Sci 60:569–594.

Flavor Field Instability

("Fast" flavor conversion – Sawyer 2016

see also Raffelt; Tambora; others)



L. Johns, H. Nagakura, GMF, A. Burrows
arXiv:1910.05682

ν-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?*

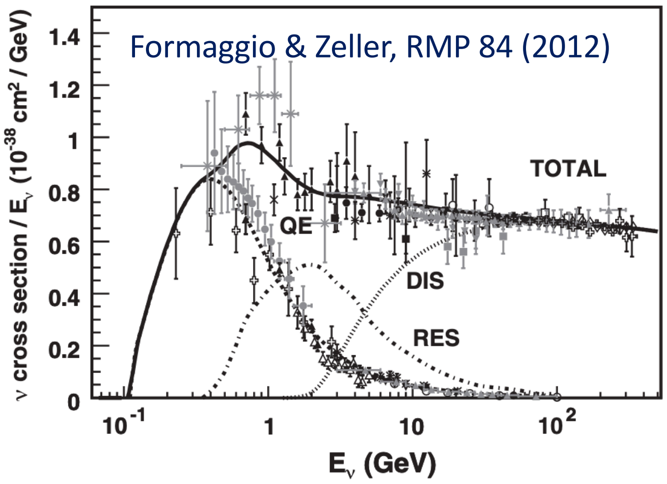
- Early Universe (e.g., weak decoupling/big bang nucleosynthesis)

gravitation is weak and so the expansion rate is desperately slow enabling very weakly interacting particles to influence observables in *light elements*, $N_{\rm eff}$, 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

- 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* → 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) ?)



Formaggio & Zeller, RMP 84 (2012)

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:
NF0-102 (Askenazi), TF0-091 (Akesson), Mahn-147
$e4\nu$, LDMX electron scattering data

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

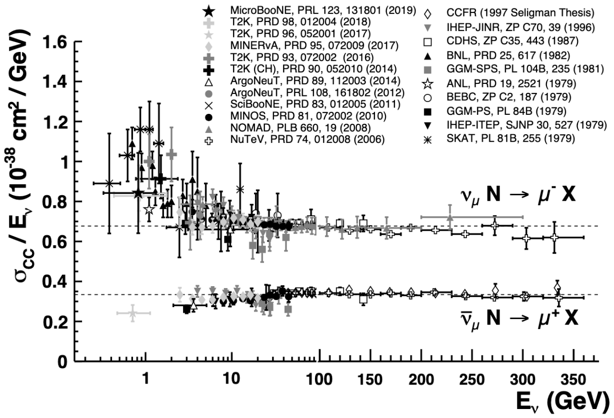
Importance of $\nu_\tau N$ cross sections: Aurisano-152, Aurisano-154,Kelly-126 accelerator beam & atmospheric
SM: e.g., structure functions, FF, different kinematic ranges
BSM: $U_{\tau 3}$ with and without unitarity

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

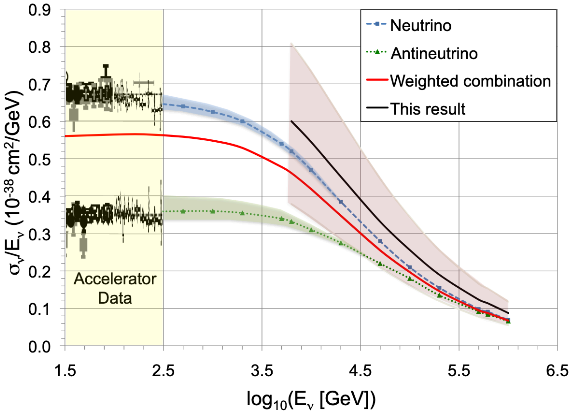
Monte Carlo Generators for Neutrinos:
TF0-132 (Andreaopoulos), Gardiner-131, Jay-144, Katori-094 need for General Purpose MC generators, with flexibility for SM, BSM components

1-15 GeV neutrino energy regime:
-complementary experiments with electron and neutrino scattering
-multiple targets: p and nuclear targets
-ν_τ 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

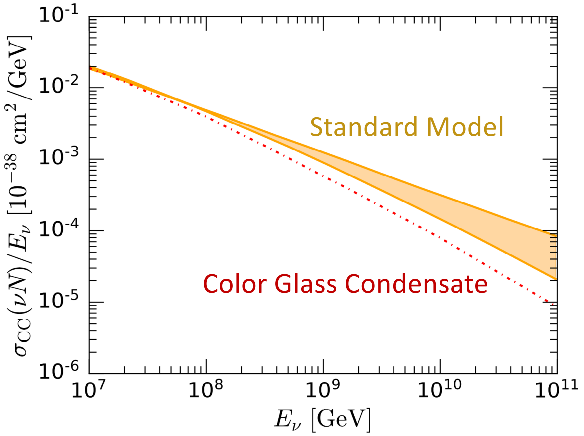
Zeller, pdg.lbl.gov



IceCube, Nature 551 (2017)



e.g., Ackermann et al., 1903.04333 Astro2020 WP



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

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

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
ν-Nucleus scattering
BSM with LGT
Computation and algorithms
Hamiltonian simulation and sign problem (QC)

LQCD for ν 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_ν
    - Collaboration between experimentalists, ν-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

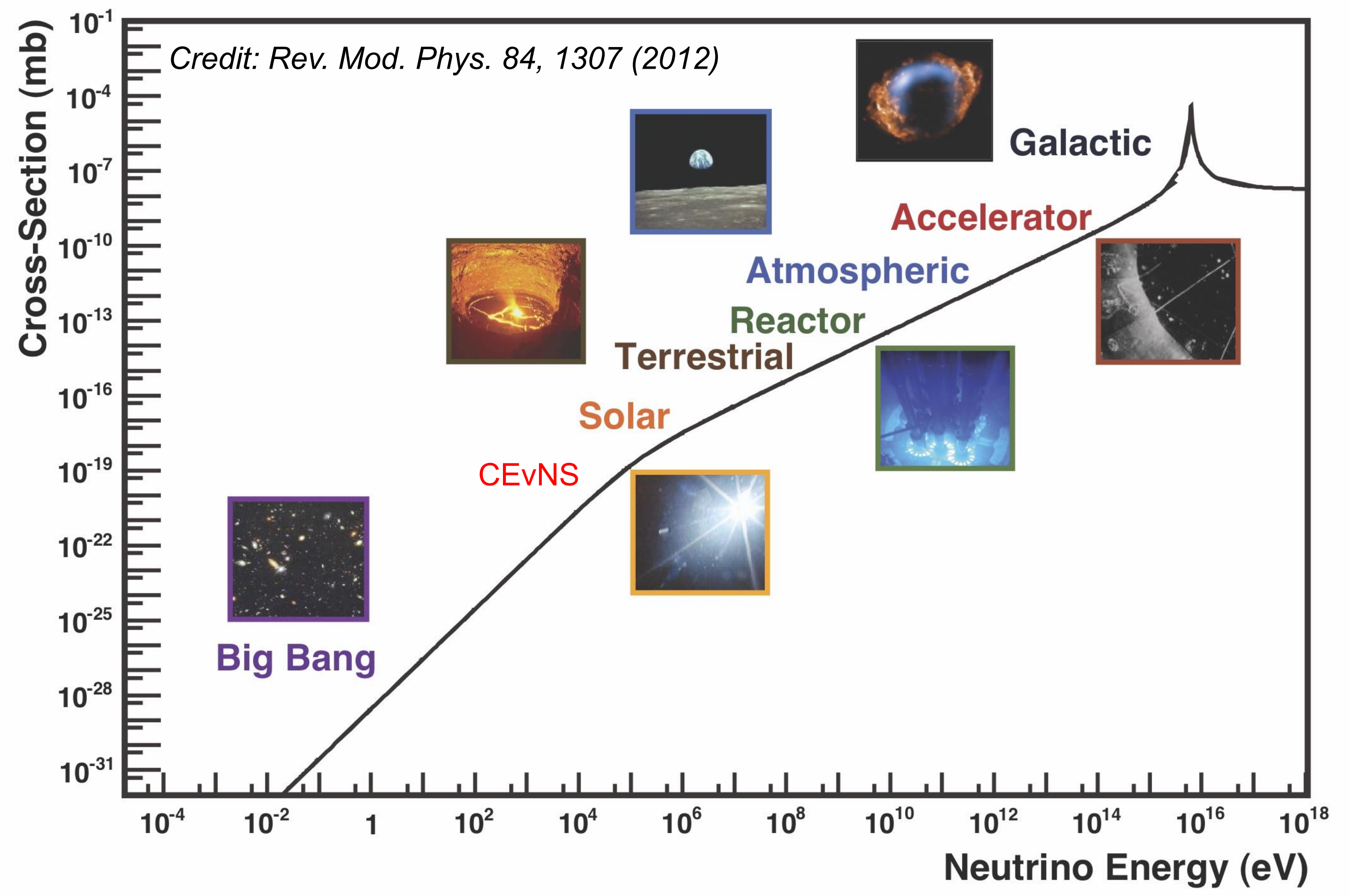
LQCD for ν Physics: Looking ahead

- 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

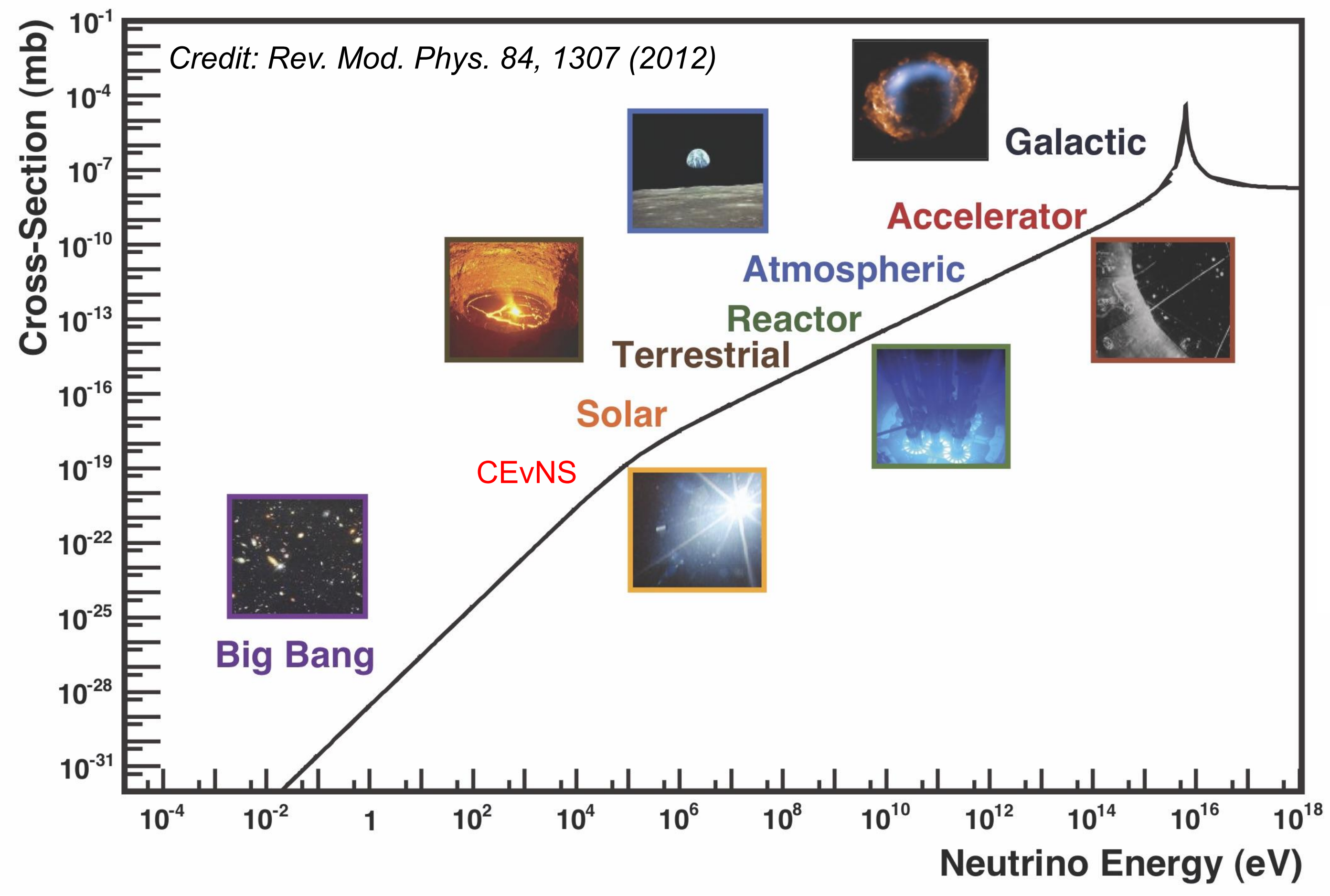
Windows of opportunity: **sources** and detectors



Windows of opportunity: sources and **detectors**

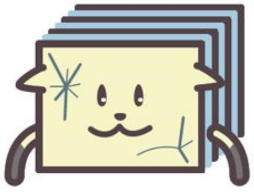
Also:

- **Calorimeters**
- **Scintillators**
- **Spectrometers**

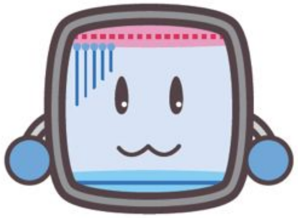


Credit: Rev. Mod. Phys. 84, 1307 (2012)

Credit: https://www-he.scphys.kyoto-u.ac.jp/nucosmos/en/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