



Neutrinos:
The Future

Mary Bishai
Brookhaven
National
Laboratory

Overview

ν Properties

Absolute mass

Majorana or Dirac?

Neutrino interaction
crosssections

ν SM

Mixing, Oscillations
and PMNS

ν_T

ν in
Astrophysics
& Cosmology

Solar Neutrinos

SN ν

UHE ν probes

ν Applications

Summary

Neutrinos: The Future

International Conference on High Energy Physics (ICHEP
2022)

July 6-13, 2022 Bologna Italy

Mary Bishai
Brookhaven National Laboratory

July 10, 2022



Topics

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The Neutrino Experimental Landscape

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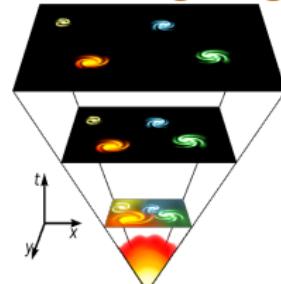
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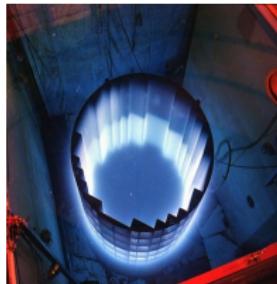
Sources of Neutrinos

Big Bang



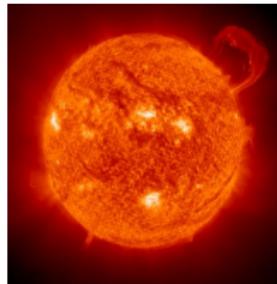
10^{-4} eV
 $300/\text{cm}^3$

Reactors



few MeV
 $10^{21}/\text{GW}_{\text{th}}/\text{s}$

Sun



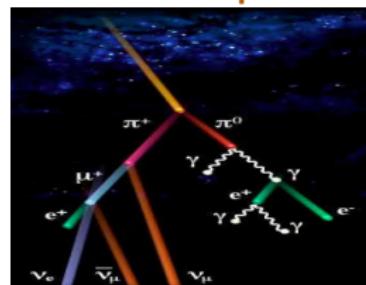
0.1-14 MeV
 $10^{10}/\text{cm}^2/\text{s}$

SuperNova



~ 10 MeV
 $10^9/\text{cm}^2/\text{s}$

Atmosphere



~ 1 GeV
 $\text{few}/\text{cm}^2/\text{s}$

Accelerators



1-20 GeV
 $10^6/\text{cm}^2/\text{s}/\text{MW}$ (at 1km)

Extragalactic



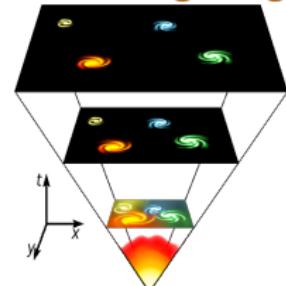
TeV-PeV
varies



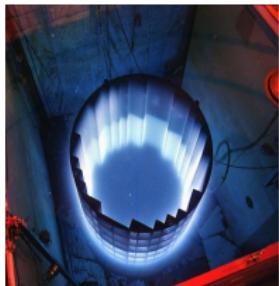
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Examples of Neutrino Experiments (current, future)

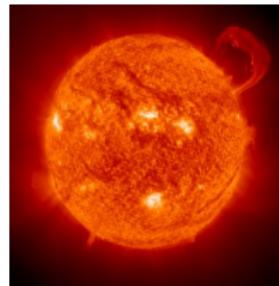
Big Bang



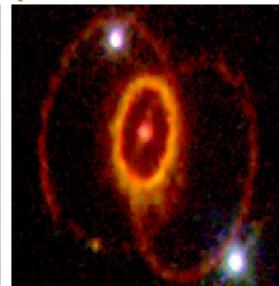
Reactors



Sun

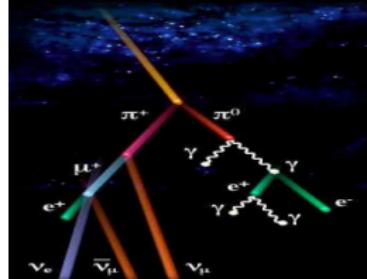


SuperNova



PTOLEMY

Atmosphere



Daya Bay
JUNO

BOREXINO
SNO+ / JUNO

SuperK-GD
DUNE / HK / JUNO

Accelerators



Extragalactic



SuperK / IC-DeepCore

HyperK / KM3NeT / ORCA

T2K / NoVA

T2HK / DUNE / ESS ν SB

IceCUBE

IceCUBE-Gen2_{4 / 63}

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And many many more.....

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- Neutrino absolute mass experiments: **KATRIN, ECHo, Project 8, HOLMES**
- Neutrino AMO experiments: **HUNTER**
- Short baseline accelerator experiments: **MicroBooNE, SBND, ICARUS, nuSTORM, IsoDAR**
- Reactor neutrino experiments: **Daya Bay, RENO, Double Chooz, DANSS, Neutrino-4, STEREO, SoLid, JUNO**
- Neutrinoless Double Beta Decay experiments: **CUORE, NEMO3, Amore, GERDA, MAJORANA Demonstrator, Kamland-Zen, EXO, ton scale: nEXO, NEXT, PandaX, SNO+, LEGEND, CUPID, JUNO- $\beta\beta$**
- Coherent elastic neutrino scattering (CE ν NS) experiments: **COHERENT, TEXONO, CONUS, CONNIE, MINER, NuCLEUS, Ricochet, RED100**
- Neutrino experiments at high energy colliders (LHC): **FASER ν , SND@LHC, FASER 2, AdvSND, FLArE**
- Neutrino telescopes (Cherenkov, radio, airshower...):

Tiny mass, minuscule cross-sections, large range of energies accessible \Rightarrow need many different sources of neutrinos with very different experimental techniques to fully understand neutrinos and then we use neutrinos to understand the sources !

In this presentation I will highlight some future experiments



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Probing the Fundamental Nature of Neutrinos

(see previous talk by Christian Weinheimer)



Future prospects in determining the neutrino absolute mass: Project-8

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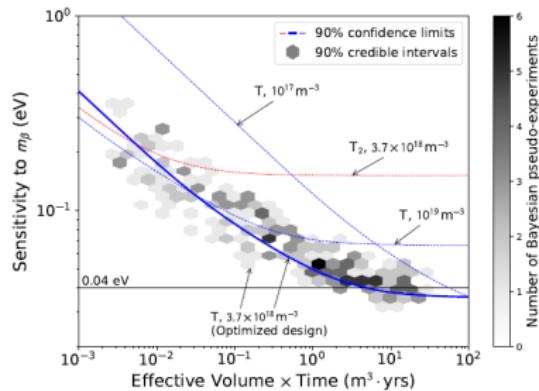
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Project 8 will investigate neutrino mass using Cyclotron Radiation Emission Spectroscopy (CRES) with an atomic tritium source. Atomic tritium avoids an irreducible systematic uncertainty associated with the final states populated by the decay of molecular tritium.
Projected sensitivity of the Project 8 experiment arxiv:2203.07349v1:



The largest neutrino mass splitting is about 50 meV, Next gen direct neutrino mass experiments aim to push to $m_\beta < 50$ meV limits.



0ν Double Beta Decay: Future Prospects

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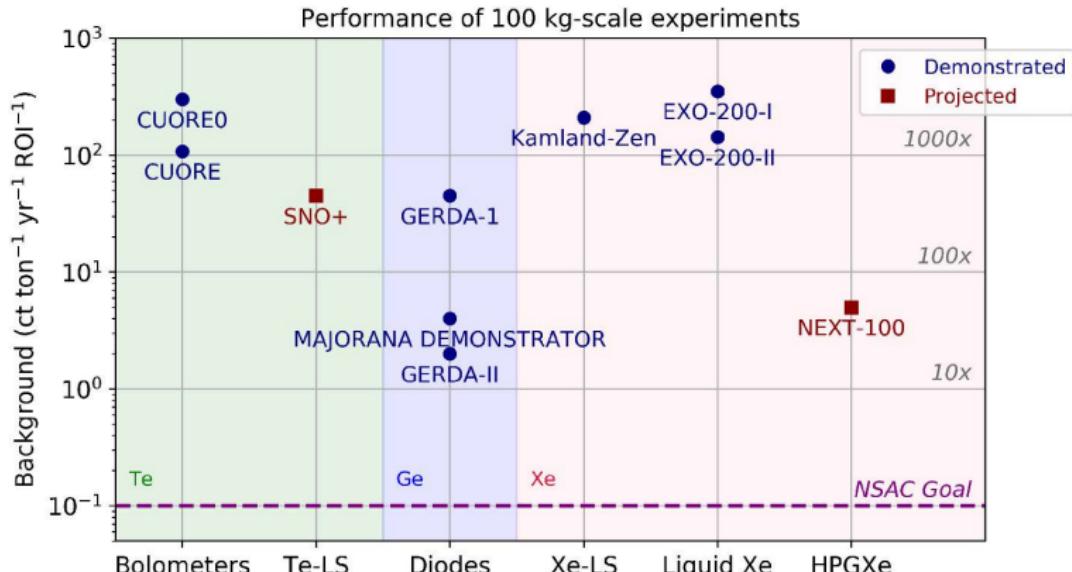
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Approximate background indices in present 100kg scale 0ν Double Beta Decay experiments (arXiv:2108.09364 [nucl-ex])





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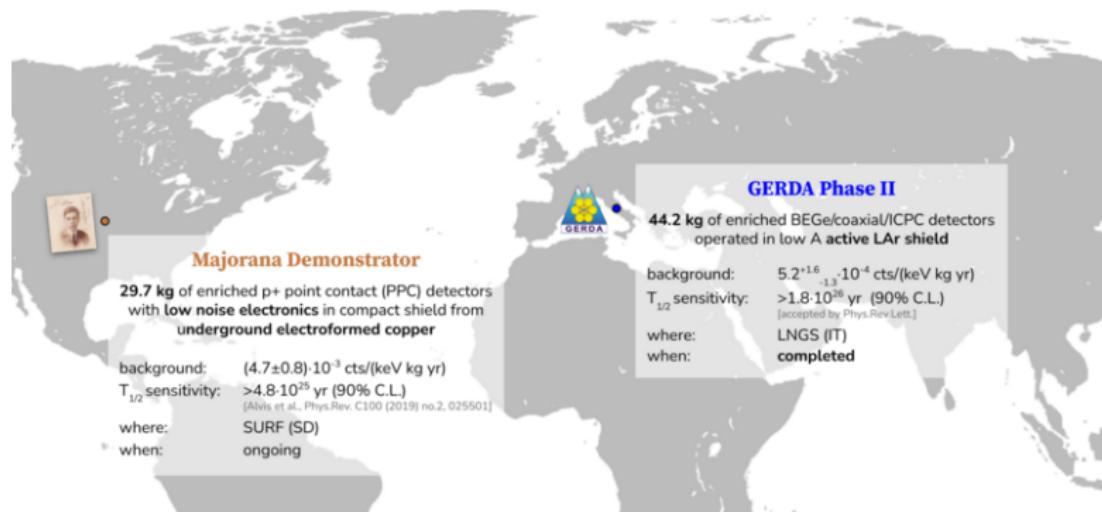
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LEGEND: Combining the best of Ge expts and aiming for 1ton
(arXiv:2107.11462 [physics.ins-det])





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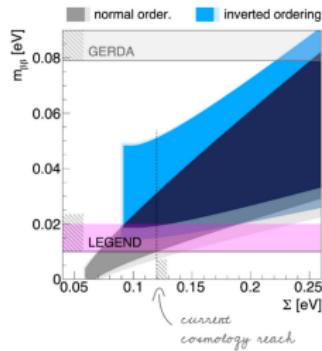
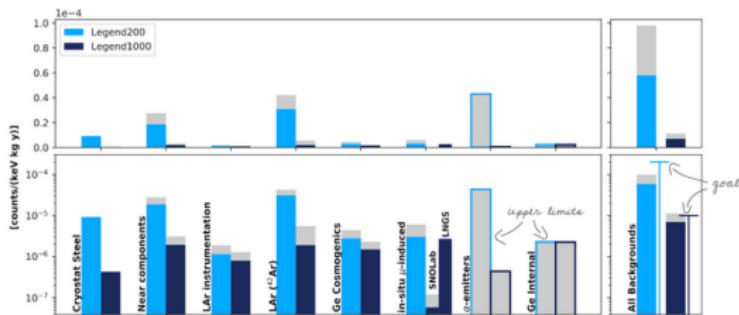
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Discovery sensitivity in the ^{76}Ge half-life of 1.3×10^{28} yrs, corresponding to an effective Majorana mass upper limit in the range of 9-21 meV, to cover the inverted-ordering neutrino mass scale with 10 yr of live time.



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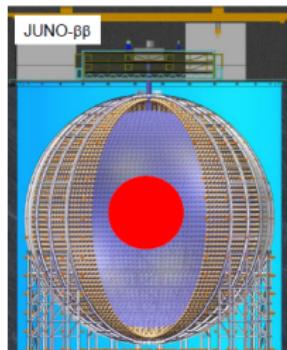
Summary

From Yifang Wang's summary at Neutrino 2022:

$\beta\beta$ decays: Future Prospects

Zolotarova,Schoenert

	Isotope	Mass(t)	$\langle m_{\bar{\nu}\nu} \rangle, \text{meV}$
SNO+	^{130}Te	8	19-46
KamLAND2-Zen	^{136}Xe	1	~20
NEXT-HD	^{136}Xe	1	14-40
nEXO	^{136}Xe	5	7-22
LEGEND-1000	^{76}Ge	1	10-40
AMoRE-II	^{100}Mo	0.1	12-22
CUPID	^{100}Mo	0.24	12-20
CUPID-1T	^{100}Mo	1	4-7
JUNO- $\beta\beta$	^{136}Xe	50	4-10
	^{130}Te	100	3-14



Zhao et al., arXiv: 1610.07143,
CPC 41 (2017) 5

We may be very close to 1 meV



Neutrino cross-sections - what we dont know

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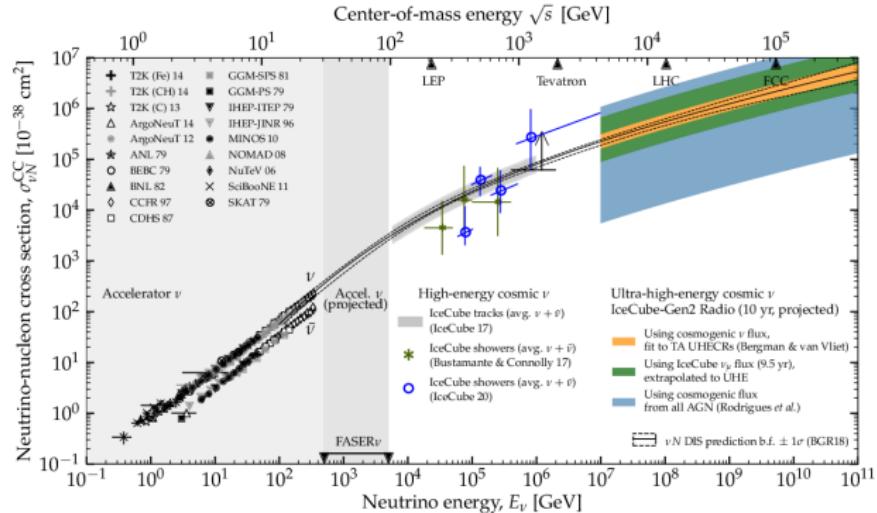
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Neutrino cross-sections are well measured up to 10's of GeV ($\mathcal{O}(10\%)$). Improvements in the 100 MeV- few GeV region are still needed to serve the next generation of high precision oscillation experiments which require $\mathcal{O}(\text{few \%})$. Large gaps in the TeV range and low precision at ultra-high energy (UHE). The DIS cross-sections are good tests of lepton universality among other topics!



TeV Neutrino Beam: The Forward Physics Facility at the HL-LHC

2203.05090 [hep-ex]

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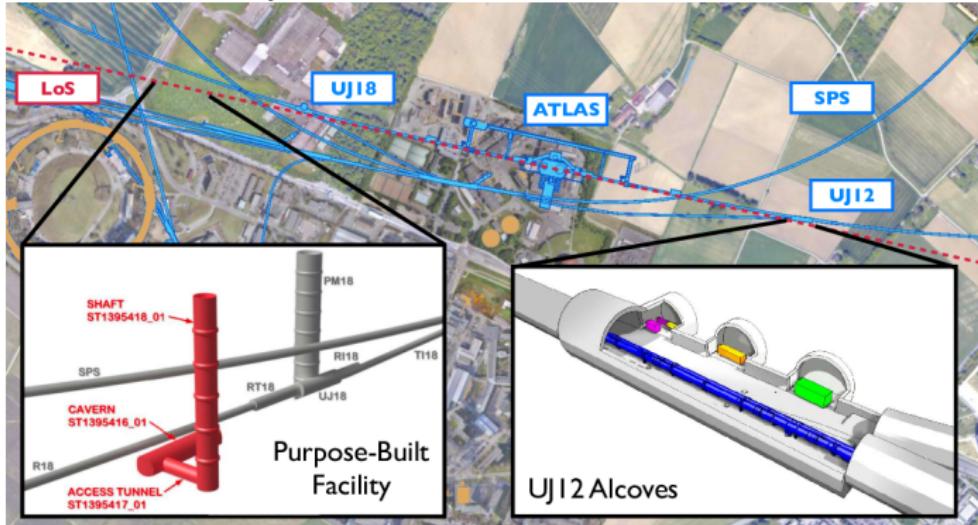
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Future neutrino experiments are proposed along Line-of-Sight from the ATLAS collision point





TeV Neutrino Beam: The Forward Physics Facility at the HL-LHC

2203.05090 [hep-ex]

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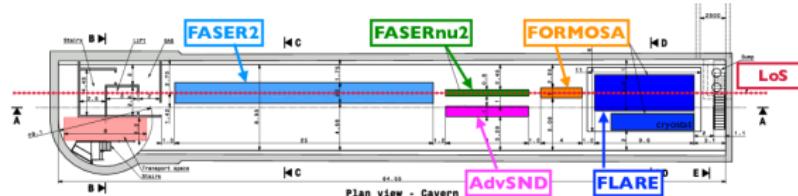
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$SN \nu$

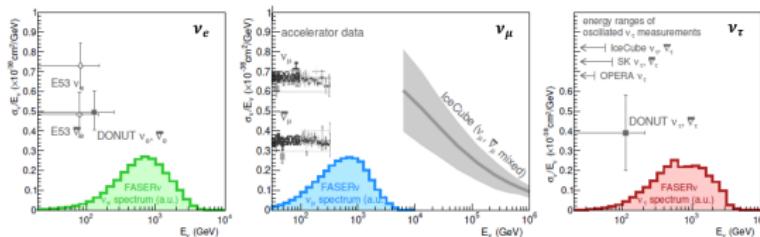
UHE ν probes

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Summary



Existing constraints on neutrino charged-current interaction cross sections, and the expected energy spectra of neutrinos interacting in FASER ν - an existing demonstrator located 480m downstream of ATLAS along LoS.



Large flux of all 3 flavors of neutrinos in the 100's GeV to TeV range at FPF - no previous precision studies of neutrino properties and interactions in this energy range



Coherent elastic ν -nucleus scattering (CE ν NS): future prospects

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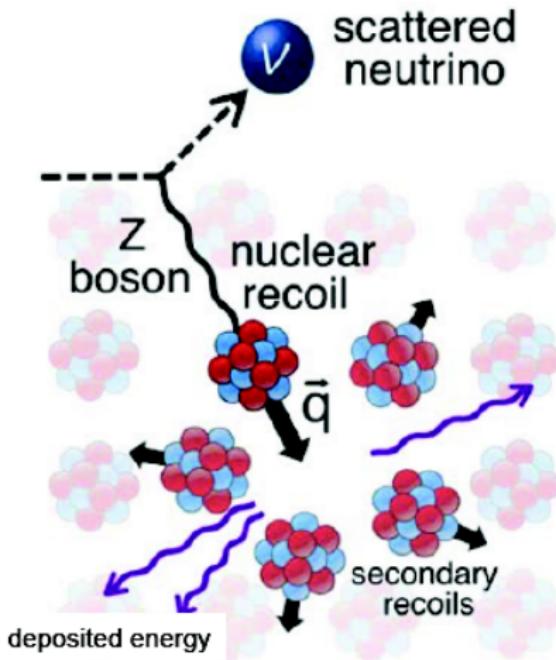
ν Applications

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Measurement of Coherent ν -Nucleus Scattering:

The only
experimental
signature:

tiny energy
deposited
by nuclear
recoils in the
target material





Coherent elastic ν -nucleus scattering (CE ν NS): future prospects

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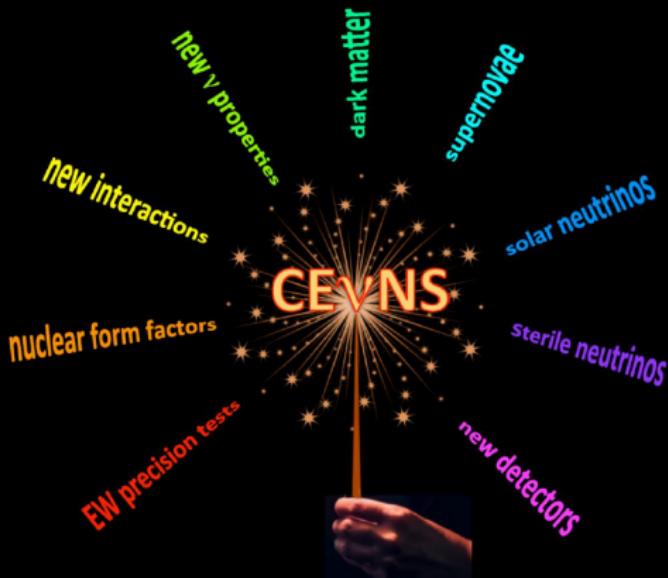
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Why measure CE ν NS?



E Lisi, Neutrino
2018



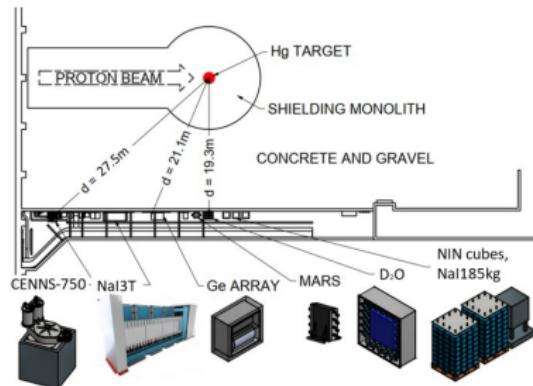
Coherent elastic ν -nucleus scattering (CE ν NS): future prospects

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The COHERENT CE ν NS detectors at the SNS “Neutrino Alley”



Future upgrades at COHERENT: Ar scintillation calorimeter of 10-t fiducial volume, CsI upgrade to 10(700) kg of crystal with threshold of ~ 0.1 keV_{ee} at 1st(2nd) target station



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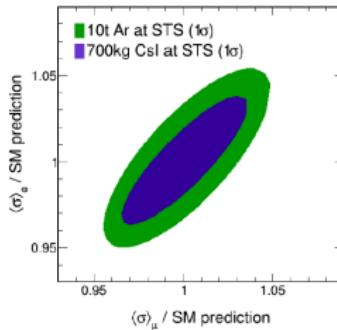
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Summary

Physics goals for CEvNS at the SNS

- ❑ Search for dark matter with strong sensitivity
 - Larger exposure
 - On-axis detector to increase DM/CEvNS ratio
- ❑ Can explore expected relic abundance of DM for scalar and fermionic scenarios
- ❑ Test of lepton-flavor universality of CEvNS
- ❑ Timing differences in ν_e/ν_μ fluxes allow 1% test of difference in flavored cross sections
- ❑ Explore exotic oscillation phenomena
- ❑ Will cover parameter space favored by LSND / MiniBooNE and other short-baseline oscillation searches
- ❑ Unique opportunity at SNS – measure oscillations on two baselines using data from first and second target stations



D. Pershey

New results from COHERENT

Duke
UNIVERSITY
COHERENT

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**Recent evidence of CE ν NS from reactor anti-neutrinos
(arXiv 2202.09672 [hep-ex]) opening up more possibilities of future experiments and results pushing further on precision tests of the SM.**



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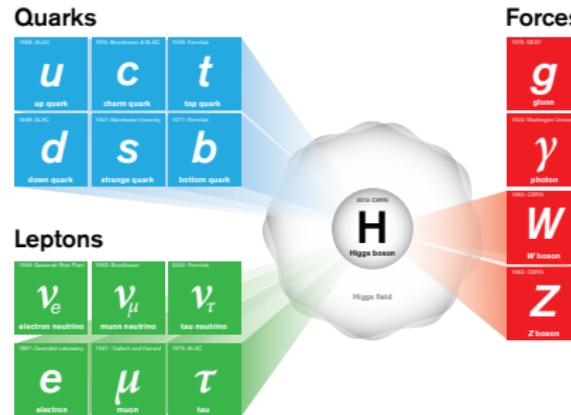
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Completing the Neutrino Standard Model





Neutrino Mixing

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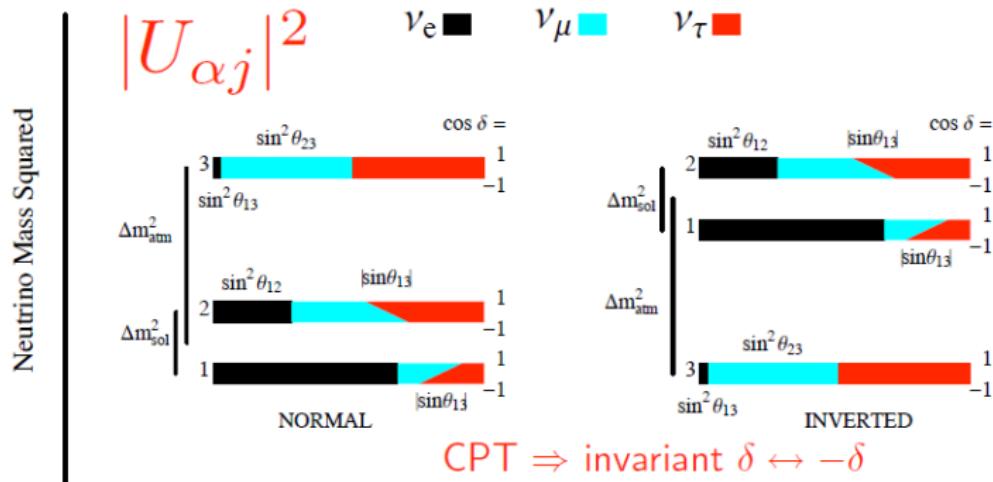
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From Stephen Parke:



Fractional Flavor Content varying $\cos \delta$



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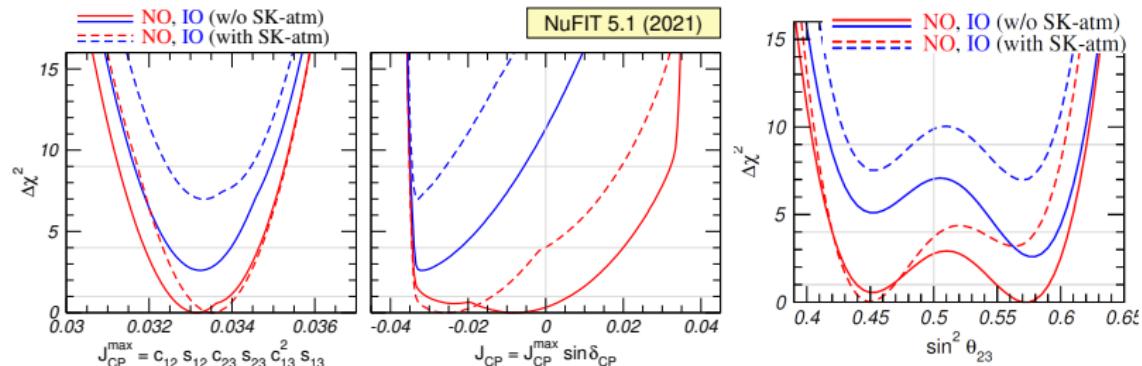
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Open questions in the ν SM: What is the mass hierarchy? Is the mixing of 2, 3 maximal ($\sin^2 \theta_{23} = 0.5$)? Is there CP violation? And if so how large is it (value of J_{cp})? If we see a ν ($\bar{\nu}$) asymmetry are we even sure it is from 3-flavor CP violation? Are there other mass states/generations (see Joachim Kopp's presentation next)?

Direct Measurements of the Mass Hierarchy: JUNO

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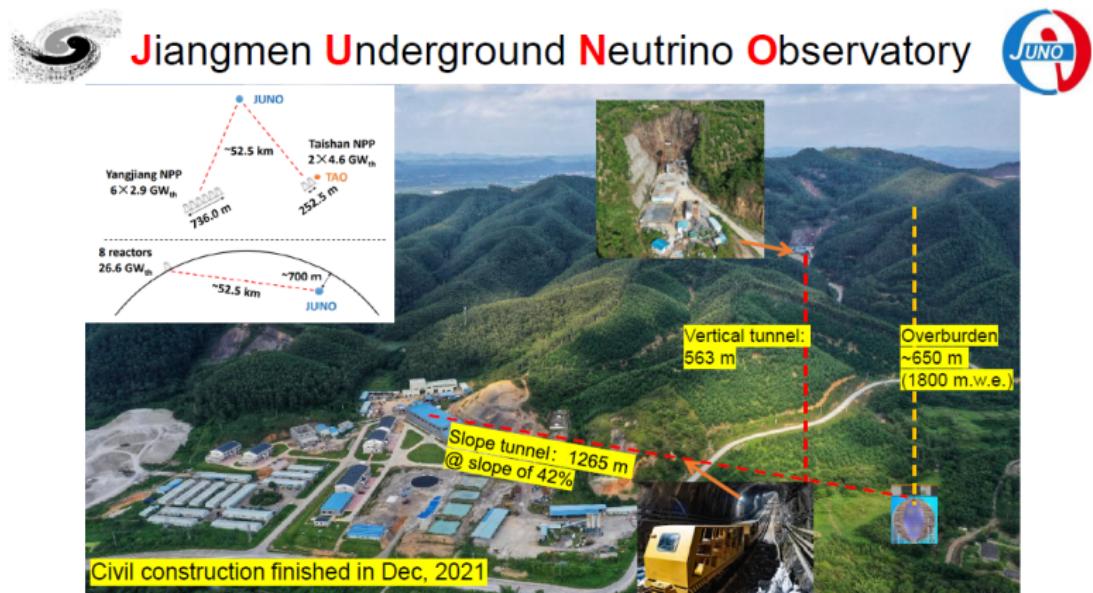
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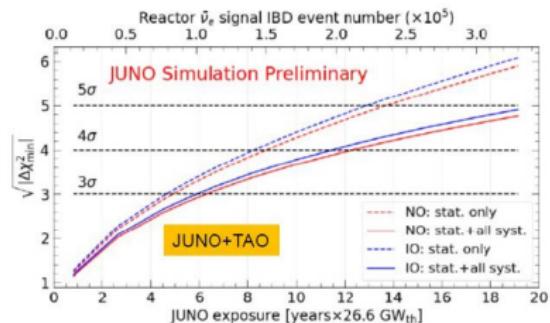
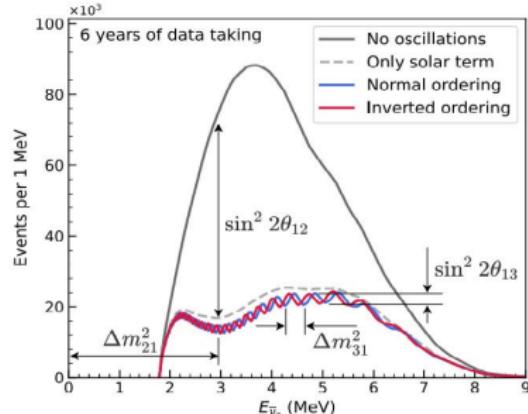
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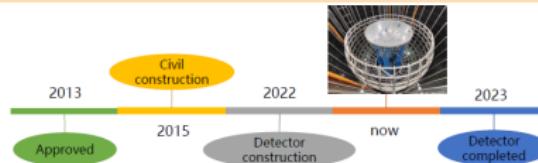
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JUNO detects the mass hierarchy directly by the phase shift in the oscillation pattern in a 20kton scintillator detector. Energy resolution is 3% at 1 MeV and nonlinearity < 1%





PMNS measurements with $\nu_\mu \rightarrow \nu_e$

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Majority of mixing parameters including δ_{cp} can be probed using $\nu_\mu/\bar{\nu}_\mu \rightarrow \nu_e/\bar{\nu}_e$ oscillations over long baselines. With terms up to second order in $\alpha \equiv \Delta m_{21}^2/\Delta m_{31}^2$ and $\sin^2 \theta_{13}$, (M. Freund. Phys. Rev. D 64, 053003):

$$P(\nu_\mu \rightarrow \nu_e) \cong P(\nu_e \rightarrow \nu_\mu) \cong \underbrace{P_0}_{\theta_{13}} + \underbrace{P_{\sin \delta}}_{\text{CP violating}} + \underbrace{P_{\cos \delta}}_{\text{CP conserving}} + \underbrace{P_3}_{\text{solar oscillation}}$$

where for oscillations in vacuum:

$$P_0 = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2(\Delta),$$

$$P_{\sin \delta} = \alpha 8J_{\text{cp}} \sin^3(\Delta),$$

$$P_{\cos \delta} = \alpha 8J_{\text{cp}} \cot \delta_{\text{CP}} \cos \Delta \sin^2(\Delta),$$

$$P_3 = \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2(\Delta),$$

where $\Delta = \Delta m_{31}^2 L / 4E$

For $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, $\underbrace{P_{\sin \delta} \rightarrow -P_{\sin \delta}}_{\text{CP asymmetry } (\delta \neq 0)},$



PMNS measurements with $\nu_\mu \rightarrow \nu_e$

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Majority of mixing parameters including δ_{cp} can be probed using $\nu_\mu/\bar{\nu}_\mu \rightarrow \nu_e/\bar{\nu}_e$ oscillations over long baselines. With terms up to second order in $\alpha \equiv \Delta m_{21}^2/\Delta m_{31}^2$ and $\sin^2 \theta_{13}$, (M. Freund. Phys. Rev. D 64, 053003):

$$P(\nu_\mu \rightarrow \nu_e) \cong P(\nu_e \rightarrow \nu_\mu) \cong \underbrace{P_0}_{\theta_{13}} + \underbrace{P_{\sin \delta}}_{CP \text{ violating}} + \underbrace{P_{\cos \delta}}_{CP \text{ conserving}} + \underbrace{P_3}_{\text{solar oscillation}}$$

where for oscillations in matter with constant density:

$$P_0 = \sin^2 \theta_{23} \frac{\sin^2 2\theta_{13}}{(A - 1)^2} \sin^2[(A - 1)\Delta],$$

$$P_{\sin \delta} = \alpha \frac{8J_{cp}}{A(1 - A)} \sin \Delta \sin(A\Delta) \sin[(1 - A)\Delta],$$

$$P_{\cos \delta} = \alpha \frac{8J_{cp} \cot \delta_{CP}}{A(1 - A)} \cos \Delta \sin(A\Delta) \sin[(1 - A)\Delta],$$

$$P_3 = \alpha^2 \cos^2 \theta_{23} \frac{\sin^2 2\theta_{12}}{A^2} \sin^2(A\Delta),$$

where $\Delta = \Delta m_{31}^2 L / 4E$ and $A = \sqrt{2} G_F N_e 2E / \Delta m_{31}^2$.

For $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, $\underbrace{P_{\sin \delta} \rightarrow -P_{\sin \delta}}_{CP \text{ asymmetry } (\delta \neq 0)}, \quad \underbrace{A \rightarrow -A}_{\text{matter asymmetry}}$



$P(\nu_\mu \rightarrow \nu_e)$ vs L and E ($\delta_{cp} = 0$)

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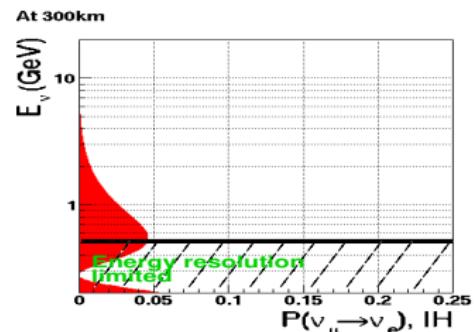
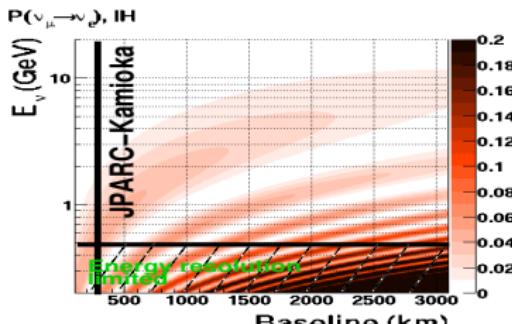
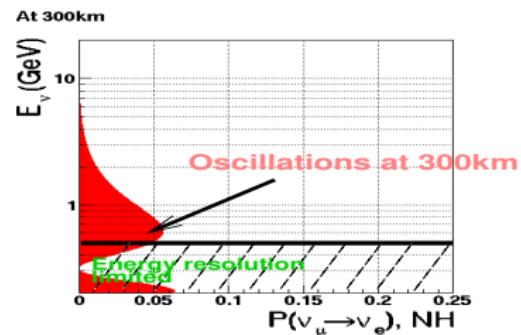
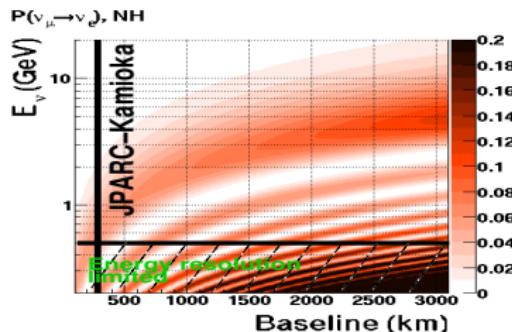
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The $\nu_\mu \rightarrow \nu_e$ oscillation probability maxima occur at

$$\frac{L \text{ (km)}}{E_n \text{ (GeV)}} = \left(\frac{\pi}{2} \right) \frac{(2n - 1)}{1.27 \times \Delta m_{31}^2 \text{ (eV}^2\text{)}} \approx (2n - 1) \times \frac{515 \text{ km}}{\text{GeV}}$$





$P(\nu_\mu \rightarrow \nu_e)$ vs L and E ($\delta_{cp} = 0$)

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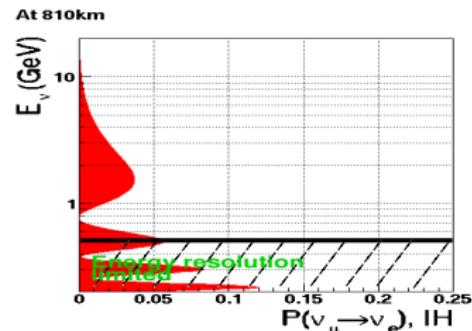
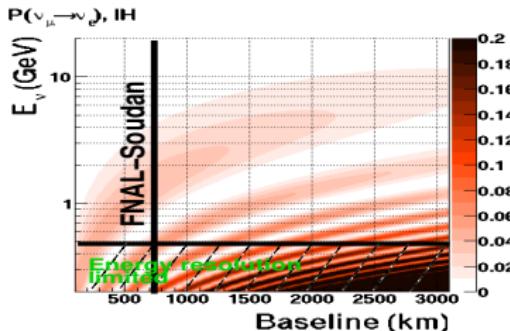
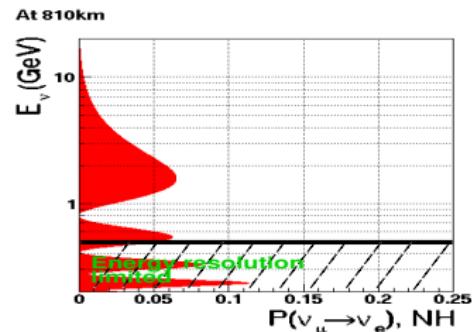
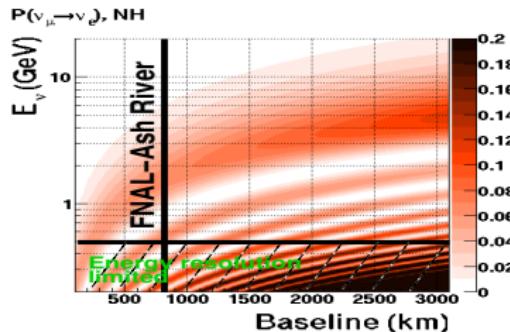
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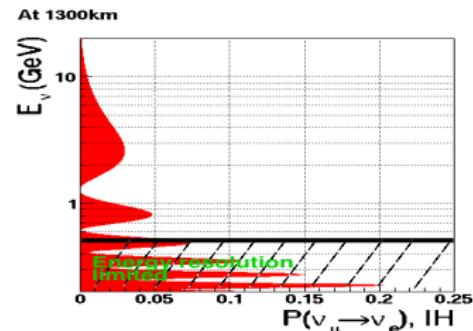
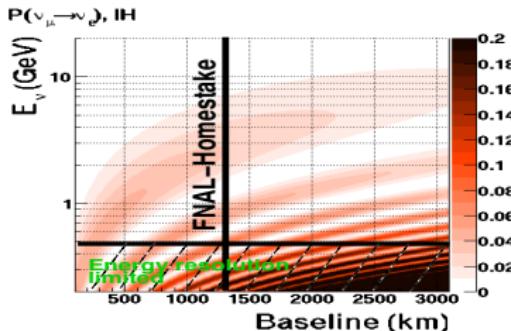
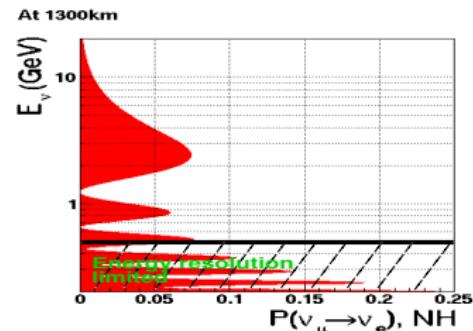
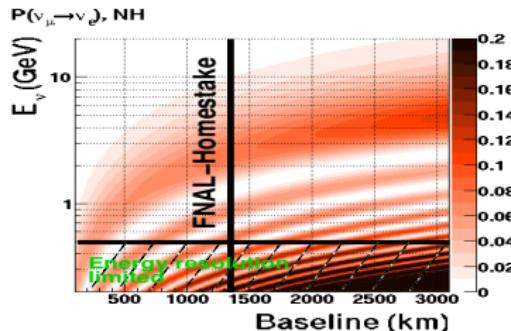
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Atm. ν_μ Oscillations

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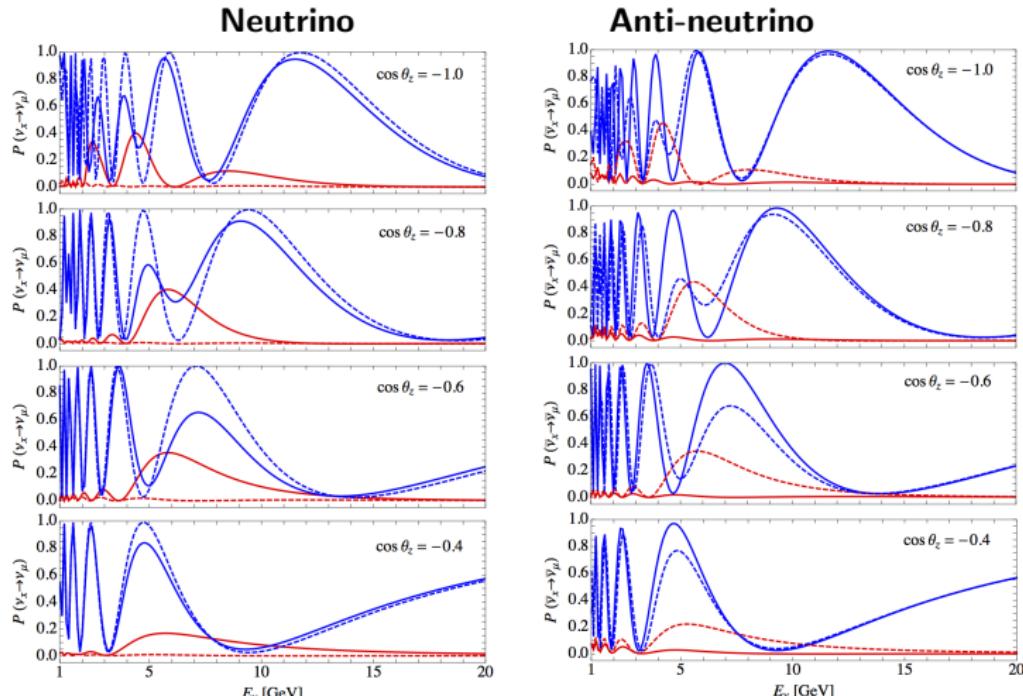
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$\nu_e \rightarrow \nu_\mu$ $\nu_\mu \rightarrow \nu_\mu$ --- NH ($\Delta m_{atm}^2 > 0$) - - - IH ($\Delta m_{atm}^2 < 0$)

Effects are largest in the 3-10 GeV range



The Deep Underground Neutrino Experiment (DUNE)

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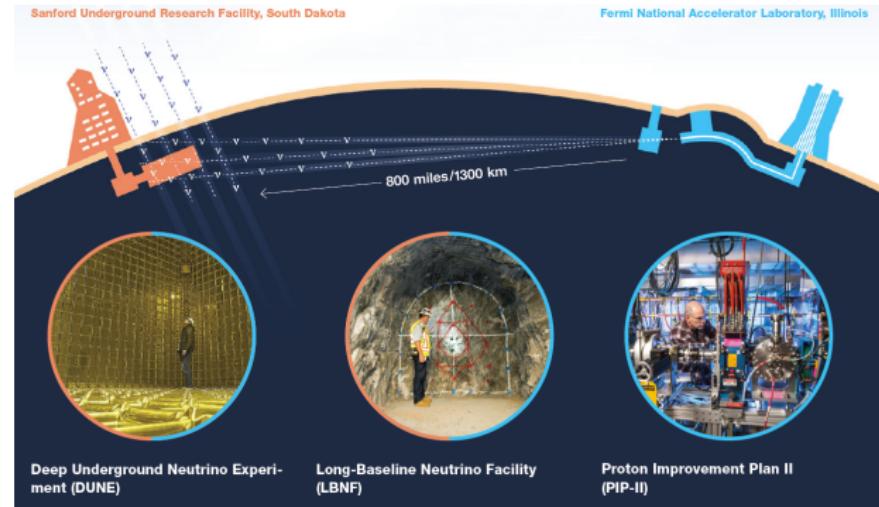
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- **A very long baseline experiment: 1300km from Fermilab in Batavia, IL to the Sanford Underground Research Facility (former Homestake Mine) in Lead, SD.**
- **A highly capable system of near detectors at Fermilab including movement off-axis.**
- **A very deep (1.5 km underground) far detector at SURF: 4 × 10-kton fiducial Liquid Argon Time-Projection-Chambers**



DUNE Phases

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The LBNF beamline and DUNE near and far detectors will proceed in phases.

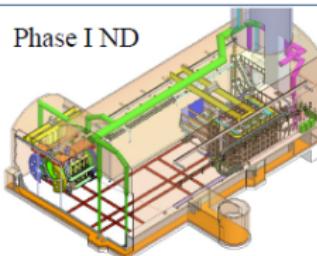
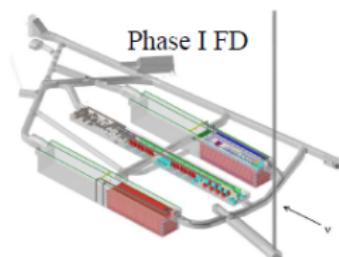
The LBNF beamline will start at 1.2MW at Phase-I and be upgraded to 2.4 MW in PhaseII.

Phase I

- .Ramp to 1.2 MW beam intensity
- .Two 17kt (10kt fid.) LAr TPC FD modules. One HD on VD.
- .Near detector: ND-LAr + TMS (steel/scint. range stack) + SAND
- .Moveable to enable PRISM

Phase II Upgrades

- .Proton beam increase to 2.4 MW
- .Four 17kt LAr TPC FD modules
- .TMS Upgraded to ND-Gar to provide enhanced ND interaction physics capabilities.





DUNE Phases

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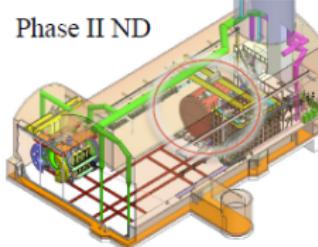
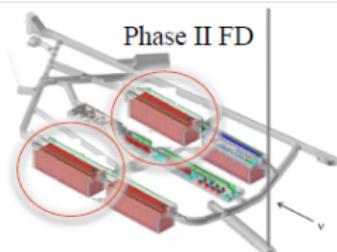
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DUNE Prototypes ($\sim 5\%$) in charged particle beam at CERN

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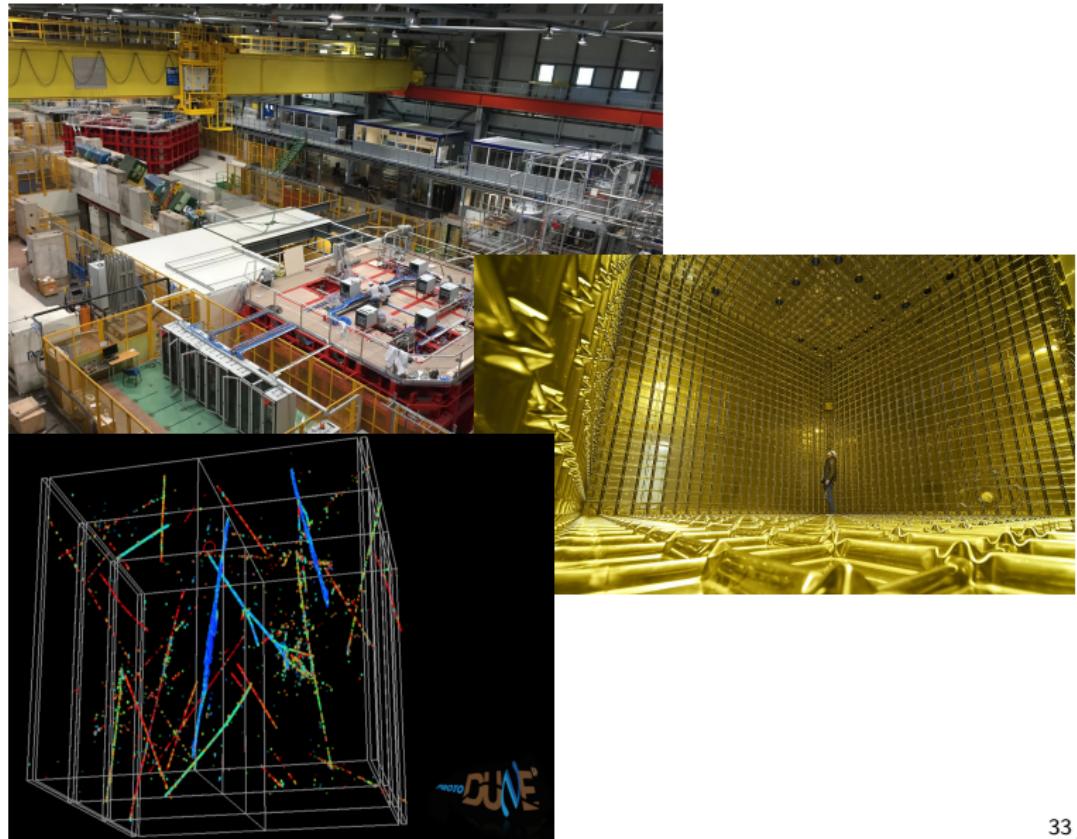
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DUNE Far Site Construction Progress

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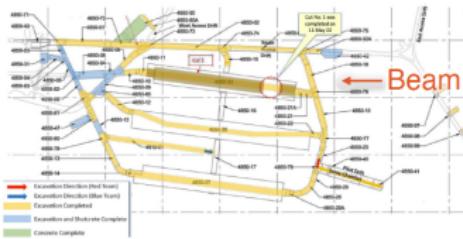
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Construction at the Far Site



- Rock excavation work is in progress!
- 27% complete by total rock volume.
- Advancing on schedule and budget.



13 July 07, 2022

Alexander Booth | DUNE Overview



Expect beam to Phase I detectors by \sim 2030



DUNE Event Spectra

Exposure: 150 kT.MW.yr (equal $\nu/\bar{\nu}$) 1MW.yr = 1×10^{21}

p.o.t at 120 GeV. ($\sin^2 2\theta_{13} = 0.085$, $\sin^2 \theta_{23} = 0.45$, $\delta m_{31}^2 = 2.46 \times 10^{-3}$ eV 2)

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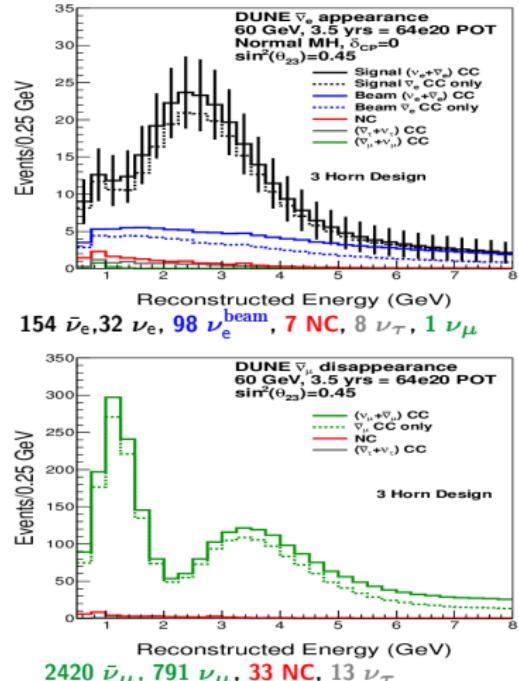
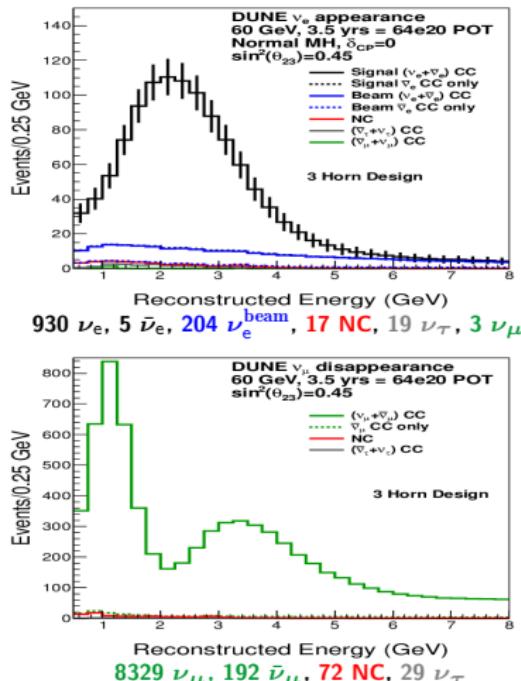
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Simultaneous fit to all four samples. Richness of spectral information in both ν_μ and $\bar{\nu}_\mu \Rightarrow$ explicit demonstration of 3-flavor CPV



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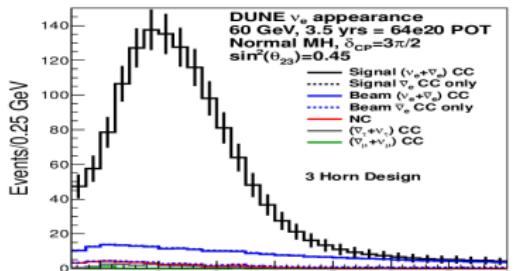
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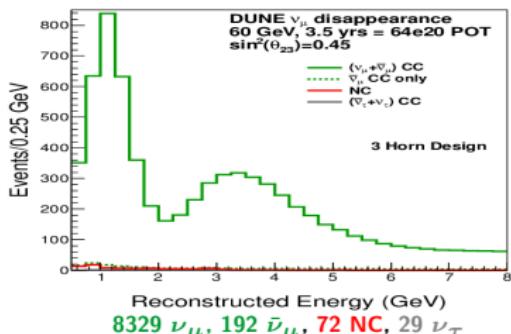
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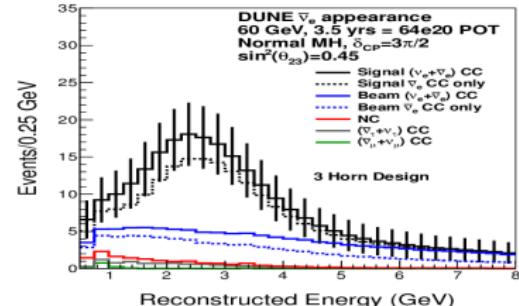
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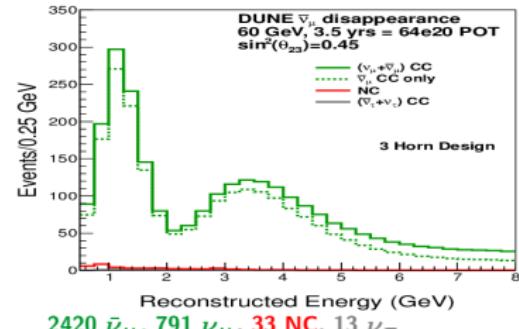
1171 ν_e , 3 $\bar{\nu}_e$, 204 ν_e^{beam} , 17 NC, 19 ν_τ , 3 ν_μ



8329 ν_μ , 192 $\bar{\nu}_\mu$, 72 NC, 29 ν_τ



94 $\bar{\nu}_e$, 39 ν_e , 98 ν_e^{beam} , 7 NC, 8 ν_τ , 1 ν_μ



2420 $\bar{\nu}_\mu$, 791 ν_μ , 33 NC, 13 ν_τ

Simultaneous fit to all four samples. Richness of spectral information in both ν_μ and $\bar{\nu}_\mu \Rightarrow$ explicit demonstration of 3-flavor CPV



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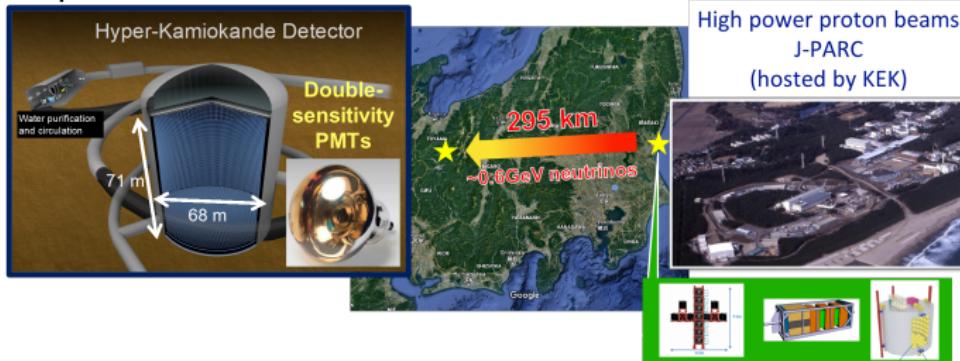
Summary

The Hyper-Kamiokande Experiment

From Masato Shiozawa:

HYPER-KAMIOKANDE: Operation start in 2027

	Super-K	Hyper-K
Site (overburden)	Mozumi, 1,000m	Tochibora, 650m
Total / Fiducial Mass	50 / 22.5 kton	260 / 187 kton



1. Hyper-K detector to be built with **8.4 times larger fiducial mass** (190 kiloton) than Super-K and to be instrumented with **double-sensitivity PMTs**.
2. J-PARC neutrino beam to be **upgraded from 0.5 to 1.3 Mega Watt**
 - **x8 Natural Neutrino Rate and x20 Accelerator Neutrino Rate**
3. New and upgraded near detectors to control systematic errors

The Hyper-Kamiokande Experiment

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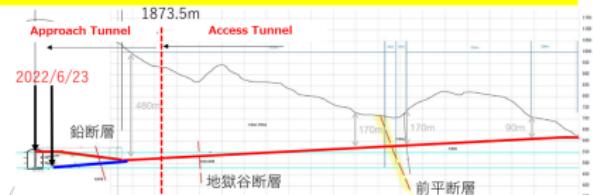
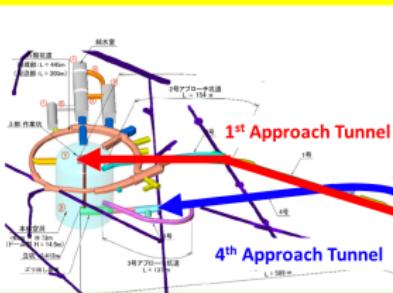
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From Masato Shiozawa:

Construction of the detector

- 23-June,2022: Approach has reached the center of the main cavern dorm.
- Cavern excavation is about to begin on schedule.
- Start its operation in 2027.



2021.5 Groundbreaking Ceremony @ entrance



T2HK Beam Spectra

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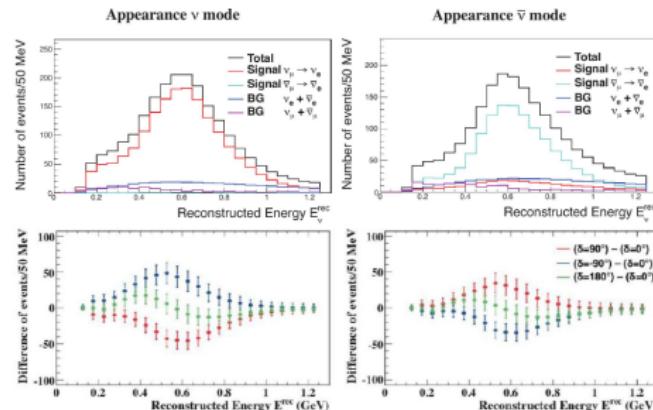
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- 10 years of data-taking
- 2.7×10^{22} POT
- Fully contained events with vertex in the fiducial volume
- $\nu/\text{anti-}\nu$ mode = $1/3$
- Normal hierarchy, $\delta_{\text{CP}} = 0$
- **3.2% statistical uncertainty on the CPV measurement**

	$\nu_{\mu} \rightarrow \nu_e$	$\text{anti-}\nu_{\mu} \rightarrow \text{anti-}\nu_e$	Beam cont.	NC	ν_{μ} and $\text{anti-}\nu_{\mu}$
v mode	1643	15	259	134	7
anti-v mode	206	1183	317	196	4



HyperK Atmospheric ν Oscillations

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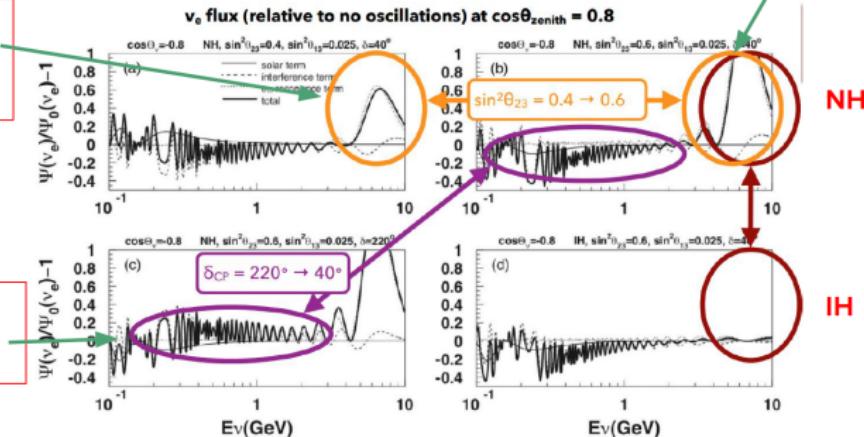
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Atmospheric neutrinos

- Sensitive to CPV, mass hierarchy and θ_{23} octant

Matter effect creates resonance in multi-GeV region → present for NH

Size of the
resonance is
affected by
 $\sin^2\theta_{23}$





HyperK Project Status

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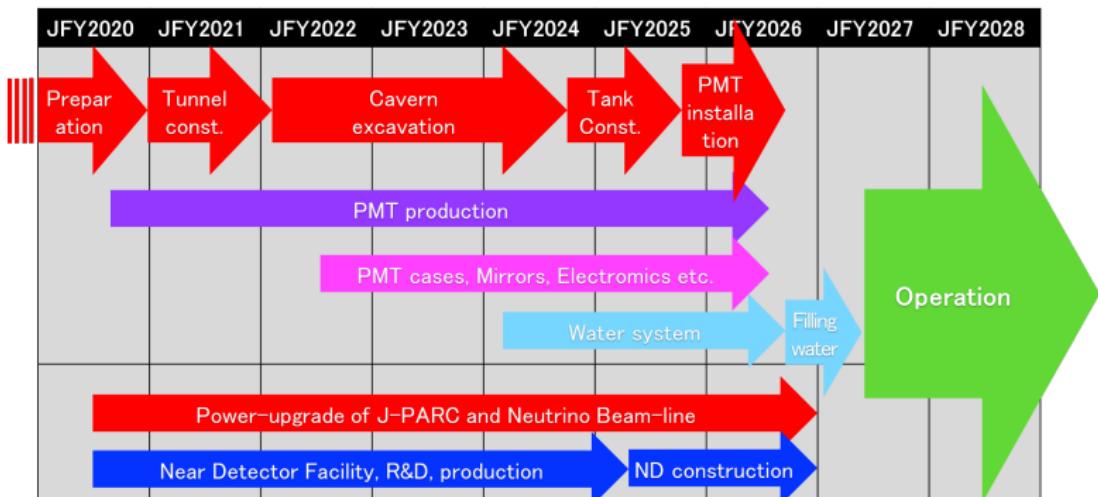
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DUNE and T2HK/HK sensitivities to Mixing

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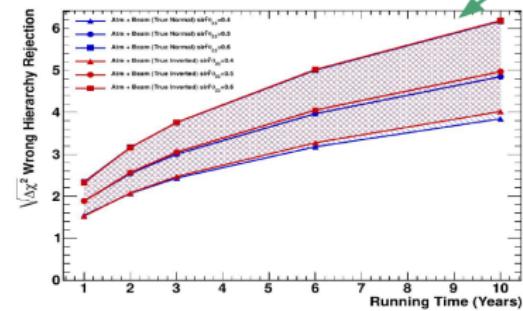
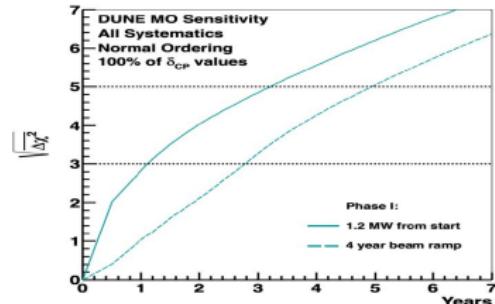
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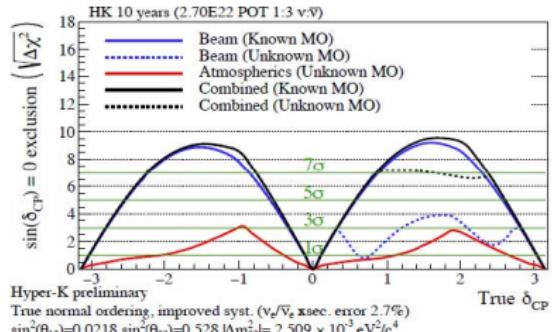
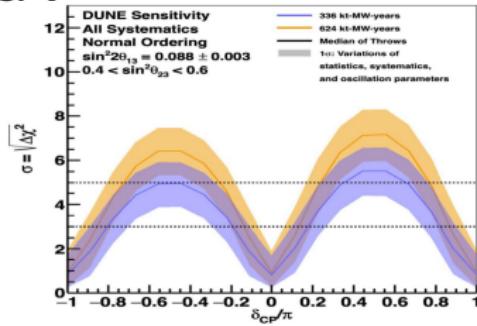
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Mass hierarchy



CPV





Beyond the ν SM in Long Baseline Oscillations

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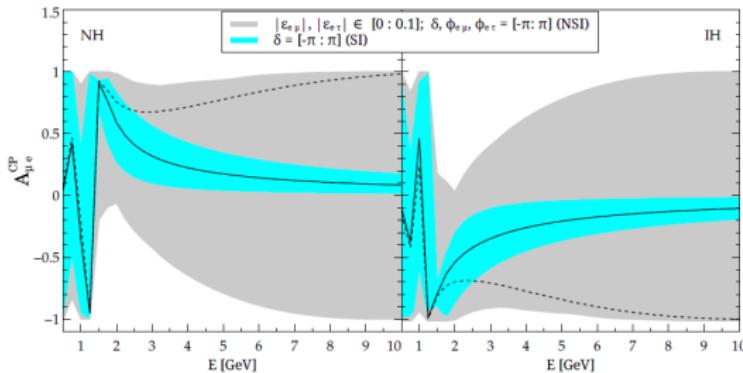
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Experiments probing ν oscillations over long baselines act as **interferometers** due to the large mixing. Future experiments With high intensity beams and/or large detectors, large band-width (from beam and atmospheric), and improved spectral resolution can probe new sources of physics and search for new weak interactions.



(M. Masud, A. Chatterjee, P. Mehta arXiv:1510.08261)

New physics could produce asymmetries that mimic CP violation. A diverse landscape of experiments is necessary to disentangle 3-flavor oscillations from new physics. (See following presentation from Joachim Kopp)



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The 3rd Generation of neutral leptons: ν_τ The least studied particle in the Standard Model



Physics Topics Probed by ν_τ

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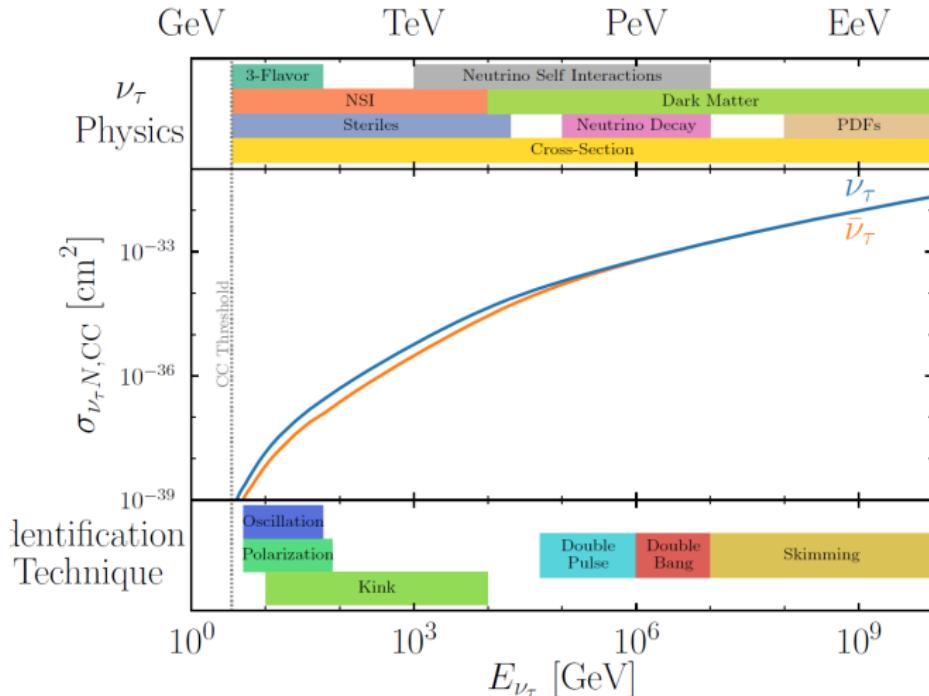
SN ν

UHE ν probes

ν Applications

Summary

From the Snowmass Whitepaper on Tau Neutrinos in the Next Decade: from GeV to EeV (arXiv:2203.05591 [hep-ph]):





Unitarity tests of PMNS

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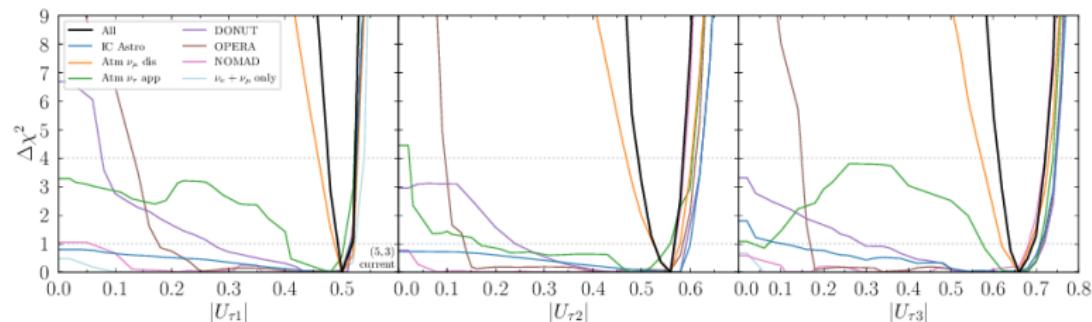
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Summary

The elements of the 3rd row of PMNS matrix elements are the least well measured. Experiments probing ν_τ physics are key to unitarity tests of PMNS.

Precision from current experiments (arXiv:2109.14575v2 [hep-ph]):



It takes a combination of many very different experiments to constrain the 3rd row of the PMNS matrix!



Unitarity tests of PMNS

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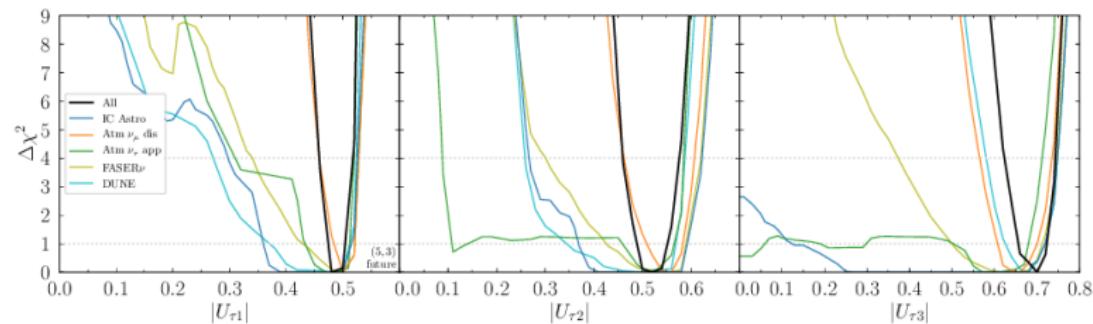
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Summary

The elements of the 3rd row of PMNS matrix elements are the least well measured. Experiments probing ν_τ physics are key to unitarity tests of PMNS.

Precision from future experiments (arXiv:2109.14575v2 [hep-ph]):



It takes a combination of many very different experiments to constrain the 3rd row of the PMNS matrix!



Future DUNE ?(beyond Phase I+II): $\nu_\mu \rightarrow \nu_\tau$ oscillations

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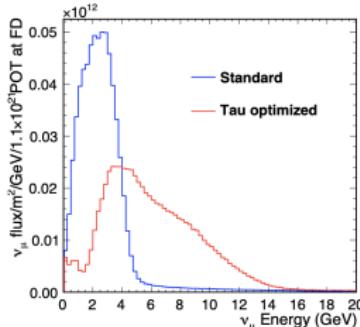
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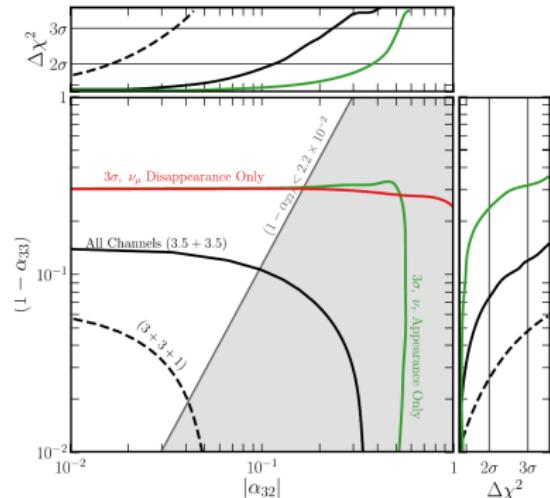
Summary

Run in 3.5 (ν) +3.5 ($\bar{\nu}$) years with ν_μ disappearance, ν_e appearance and ν_τ appearance in the default low-energy beam or combine all 3 modes with 3+3 years in LE + 1 year in a τ optimized beam



U: Unitary matrix, N: non-unitary matrix

$$U \rightarrow NU = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U$$





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Neutrinos as Telescopes and Cosmological Probes



CNO neutrinos now detected!

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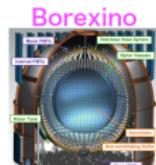
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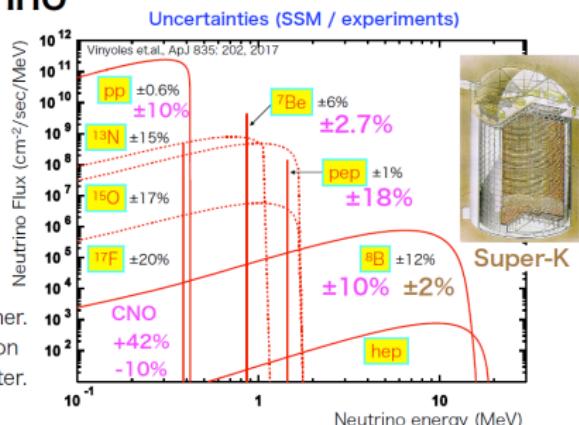
From Y. Koshio presentation at Neutrino 2022:



Solar neutrino Recent results



New observations were reported one after another. Its measurement precision becomes better and better.



Current generation will continue to push on precision including SNO+. New experiments coming online soon like JUNO and future concepts include THEIA a 100kton scale water-based liquid-scintillator detector.



Supernova Neutrinos: Prospects

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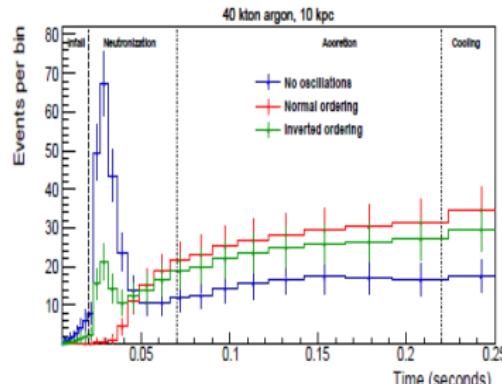
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DUNE is uniquely sensitive to the ν_e component of a supernova neutrino burst:

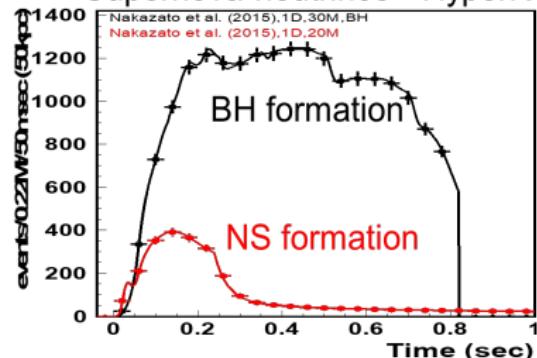


Expected time-dependent signal in 40 kton of liquid argon for a Supernova at 10 kpc:



HyperK is sensitive to $\bar{\nu}_e$

Supernova neutrinos - HyperK





Supernova Neutrinos: Prospects

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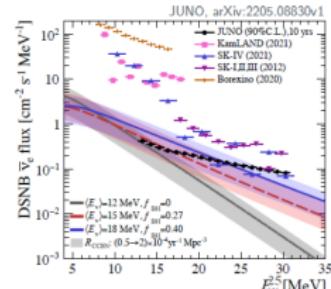
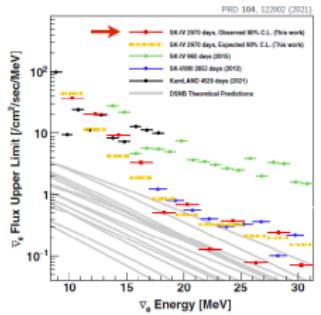
Summary

From Yifang Wang summary at neutrino 2020:

Diffused Supernova Neutrinos

- Latest results from SuperK
 - Sensitive to $1.5 \bar{\nu}_e/\text{cm}^2/\text{s}$, Horiuchi+09 model is 1.9
 - Combined upper limit of $2.6 \bar{\nu}_e/\text{cm}^2/\text{s}$
 - Most optimistic signals are excluded
 - Best fit is $1.3^{+0.90}_{-0.85} \bar{\nu}_e/\text{cm}^2/\text{s}$
 - 1.5σ excess over background expectation
- Signal right at the corner ?
- SuperK-Gd successfully operated for 2 years with 0.01% loading. Phase 2 with 0.03% loading just started
- JUNO can significantly improve the sensitivity
- Future experiments: HyperK, DUNE, THEIA, ...
- Shall be discovered in ~ 15 years from now !

Mastbaum,Vagins,Zhao





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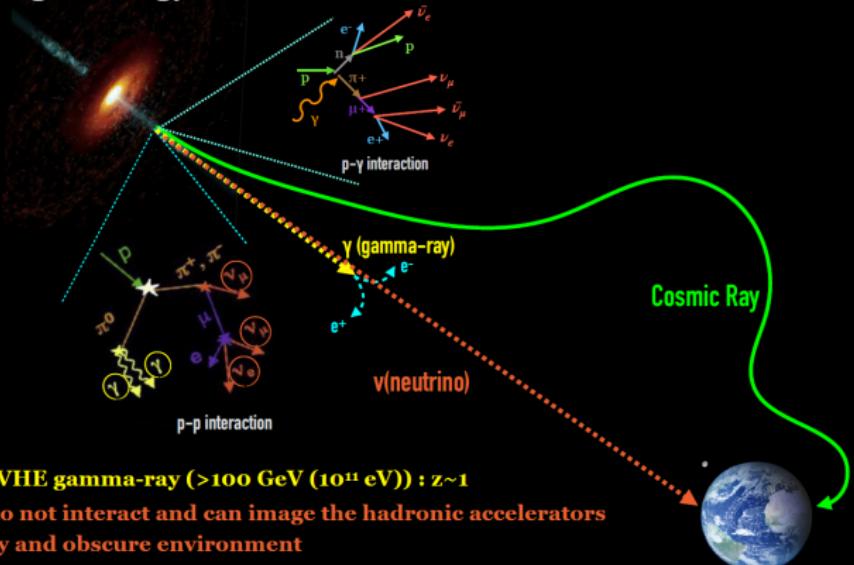
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Neutrino is the best messenger to study the high-energy hadronic particle interactions in the Universe





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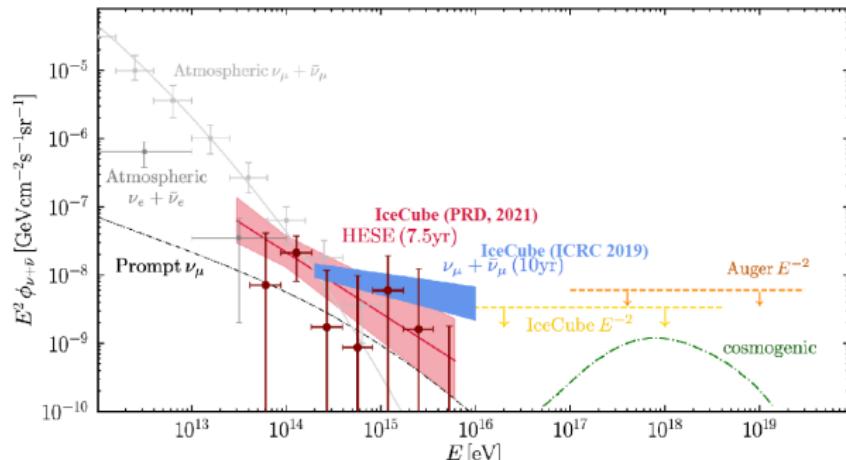
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High-Energy Astronomical Neutrinos

IceCube has measured the astrophysical neutrino flux with multiple independent analyses



F. Halzen and A. Kheirandish (arXiv:2202.00694)



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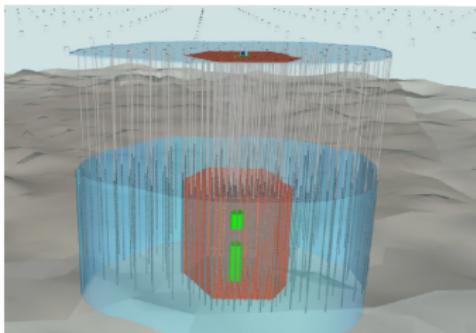
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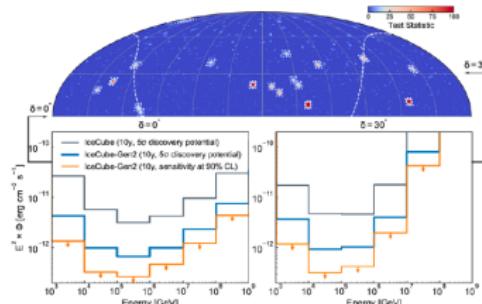
IceCube Gen-2

Designed to achieve five times better sensitivity than IceCube array

- Optical array: Eight times larger active volume compared to IceCube filled with improved optical module based on the R&D studies from IceCube Upgrade
- Surface air shower array: Matching with the optical array throughput, ~40 times higher coincident events
- Radio array: ~ 500 km² area of the antenna array for the detection of EeV neutrinos



"Deep-ice Optical Sensor Array for IceCube-Gen2"
- Poster IV-a/5F MT12-044 by A. Ishihara





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Practical Applications of Neutrino Technologies



Neutrinos for Nuclear Security

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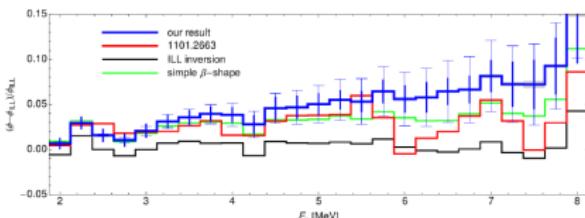
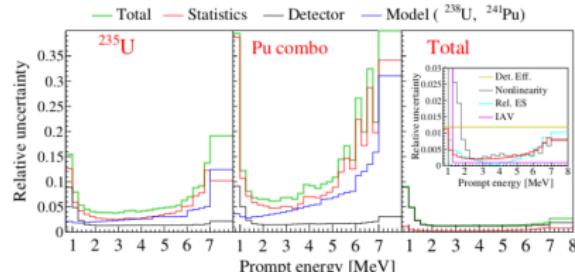
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Source term

To-date the most precise and widely used reactor neutrino flux for U-235 and Pu-239, Pu-241.



P. Huber, Phys. Rev. C 85 (2012) 029901.

Most precise and accurate measurement of U-235 and Pu reactor fluxes by the Daya Bay experiment (3.2 million inverse beta decay events).

Daya Bay collaboration, arXiv:2102.04614



Neutrinos for Nuclear Security

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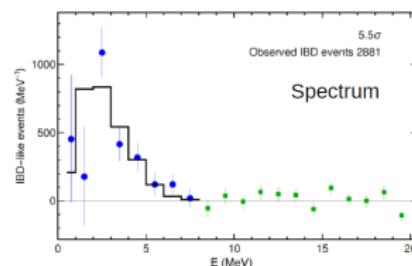
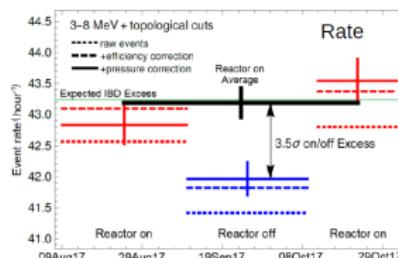
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CHANDLER

Based on commercially available scintillators EJ-426/260.

3D segmentation, very clean neutron ID.

One of the first detectors to show surface operation, spectral capabilities and high-efficiency.



A. Haghighat, P. Huber, S. Li, J.M. Link, C. Mariani, J. Park, T. Subedi, Phys. Rev. Appl. 13 (2020) 034028.



Neutrinos and Earth's Geology

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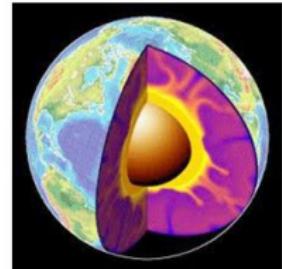
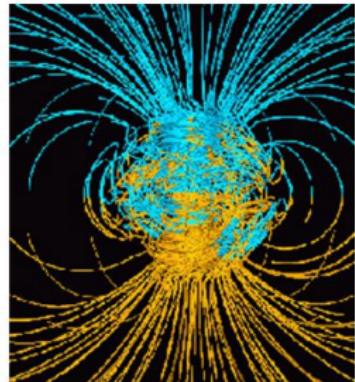
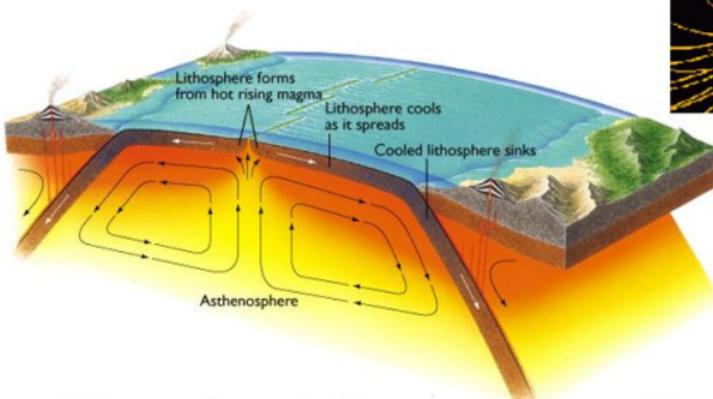
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Plate Tectonics, Convection, Geodynamo



Does heat from radioactive decay
drive the Earth's engine?



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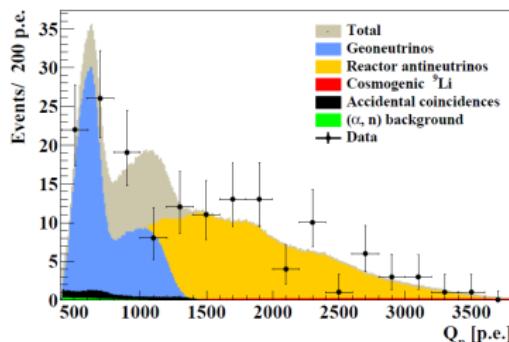
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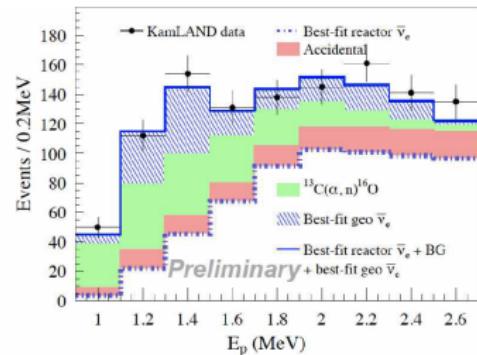
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Signal of $\bar{\nu}_e$ from radioactive decays of U/TH in the earth:

BOREXINO 2020



KamLAND 2019





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Summary

- *Neutrino experiments span the range from sub eV to EeV energy scales and include both experiments probing fundamental properties of neutrinos and experiments where neutrinos themselves are probes of other physics*
- **Next gen expts are moving into the discovery phases in the next 2 decades:**
 - **0 ν DBD and absolute mass measurements < 10 meV range**
 - **Oscillation experiments using MW beams and 100 kton scale detectors will reach % level precision and unambiguously determine the neutrino mass hierarchy, CPV, resolve the octant and search for beyond the ν SM effects like non-standard interactions, sterile neutrinos ...etc**
 - **Solar metallicity determination with CNO neutrinos has commenced, diffuse Supernova flux will be discovered and UHE experiments are entering a new discovery phase.**
- **A wide range of experiments will probe properties of the least known particle of the Standard Model - the ν_τ from GeV to EeV**
- **The TeV scale accelerator neutrino frontier is commencing at the LHC and HL-IHC**



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THANK YOU

Click for Neutrino rap!!

