Beyond the Next Generation
(INO, T2HKK, ESSυSB, THEIA)
Where Will We Be?

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Probably:

• Mass ordering will be determined at several sigma
• Mixing matrix *parameters* all measured
• A supernova will have happened in the Milky Way
• Majorana phases unknown
• Understanding of neutrino interactions will be improved
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But...?

- Sterile evidence/discovery?
- $\Delta m^2_{12}$ tension between reactor and solar?
- Majorana vs. Dirac?
- Absolute neutrino mass?
- A theory of flavor...?
- Other tensions/anomalies/problems...?
Where Will We Be?

Goals for experiments beyond next generation:

• Precision tests of the 3-flavor model
  • e.g., Is $\delta$ maximal?
  • e.g., Is leptonic CP described entirely by $\delta$?
  • *Focus on reduction of systematics*

• Searches for new physics

• Investigating new (and possibly old) anomalies

• Astrophysical/geophysical measurements and precision tests

• Continued exploration of the Majorana question

• Continued work to measure absolute masses
India-Based Neutrino Observatory (INO)

Goal: Precision tests of 3-flavor model with atmospherics

51 kt Magnetized Iron Calorimeter (10^5 m^2 glass RPC, 3.6M electronics channels)

85-ton prototype, 4m×4m×11 layer magnet, with 2m×2m RPCs and ICAL electronics operating for 2 years.

Sample cosmic muon tracks

Comparison of azimuthal muon flux with CORSIKA and HONDA simulations

Comparison of the muon momentum spectra with CORSIKA simulations, negative (positive) values correspond to μ^+ (μ^-)

Collaborating Institutions:
- AMU
- American C
- BHU
- BARC
- Calcutta U
- Calicut U
- Delhi U
- HPU
- HNBGU
- HRI
- Hyd. U
- ISER (M)
- IIT (B)
- IIT (D)
- IIT (M)
- IoP
- JAM
- Jinnah U
- JNU
- Kanpur U
- Lucknow U
- N Bengal U
- Panjab U
- PRL
- Sikkim MU
- SNB
- Tempur U
- TIFR U
- Utkal U
- VEGC
- Visva Bharati

INO @ Theni, Tamil Nadu

The INO Collaboration

Participation from nearly 100 scientists and engineers from 28 national labs, IITs and universities from all over the country.
Engineering Toward Full ICAL

Scintillator Veto for mini-ICAL

Scintillator veto upgrade for Mini-CAL

700 ton magnetised ICAL prototype (8m×8m× 2.1m, with 352 RPCs, 45K electronics channels)

Industrial production of RPC detectors and closed loop gas system for the engineering prototype

Size 4.6m×4.6m×1.8m, extruded plastic scintillators (courtesy Fermilab), muon efficiency > 99.99%
Combination of high mass, tracking, and charge ID via magnet, provides precision handle on atmospheric direction and energy up to 25 GeV.
T2HKK/KNO

Goal: Precision measurements of PMNS parameters + broad program

Remarkable luck: J-PARC beam re-emerges in Korea—Hyper-Kamiokande is the “near detector”

~1000 m overburden provides broad program
Off-axis beam+long baseline---
Sensitivity to 2\textsuperscript{nd} oscillation max enhancing CPV sensitivity

Additional matter allows high sensitivity to MO
(and sensitivity to NSI)

Precision on $\delta_{cp}$
significantly improved with KNO---
Single HK has $\sigma_{\delta_{cp}} \sim 22^\circ$
with KNO+HK $\sigma_{\delta_{cp}} \sim 13^\circ$
At max CPV

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*Prog, Theor, Exp, Phys. 2018, 063C01*
T2HKK/KNO

Broad program beyond LBL oscillations

SuperNova Relic $\nu$

- Additional mass and depth provide excellent NDK sensitivity
- Low photocoverage could be compensated by Gd loading

- KNO Organization and WGs formed in 2018
- Sensitivity studies and Detector R&D in progress
- Funding for KNO feasibility studies from Korean government granted in May 2020
Goal: CPV via targeted measurements at 2nd Oscillation Max

Neutrino Superbeam at European Spallation Source

- Zinkgruvan (1500 m)
- Garpenberg (1200 m)

@ Far Site:
- Megaton-scale underground Water Cherenkov detector
  - Allows broad program including PDK, astrophysical vs
- 5 MW/2.5 GeV protons
- Accumulation ring of ~400 m
  - Shortens pulse from 2.86 ms to few μs
  - Required by 350 kA horn
  - Also allows for decay-at-rest experiments using neutron target
- 4 target/horn system, 25 m decay tunnel
  - ~300 MeV neutrinos
  - Near detector

Also about 10^{20} μ/year produced—provides R&D opportunity for Neutrino Factory or muon collider.
ESSνSB

Physics Sensitivities

2nd Oscillation max provides excellent CP sensitivity

Large detector size provides big atmospheric sample for higher sensitivity, resolution of $\theta_{23}$ octant

> 5 $\sigma$ for 60% of CP phase space

At $\delta_{cp}$ = 0 or $\pi$; 5$^\circ$ resolution
At max CP, as low as 12$^\circ$

Far site may depend on prior results
**ESSνSB**

**Status and Progress**

**ESSnuSB**: H2020 Design Study, 4.7 M€ (3 M€ by EU)

- 17 institutes including ESS and CERN
- Approved in August 2017
- Started beginning of January 2018
- Duration: 4 years (2018-2021)

- **2012**: Inception of the project
- **2016-2019**: Beginning of COST Action EuroNuNet
- **2018**: Beginning of ESSνSB Design Study, CDR and preliminary costing
- **2021**: End of ESSνSB Design Study, Preparatory Phase, TDR
- **2022-2024**: Preconstruction Phase, International Agreement
- **2025-2026**: Construction of the facility and detectors, including commissioning. Muon option also possible.
- **2027-2034**: Data taking
- **2035-2036**: Data taking

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THEIA

Goal: A very broad range of world-leading physics

keV | MeV | GeV | TeV
---|---|---|---

Requirements:
- Low radio backgrounds
- Excellent energy resolution
- Directional information

Requirements:
- Excellent PID
- Directional information
- Very big detector

Solar vs Geo, reactor $\bar{\nu}$
Long Baseline Atmospherics
Extragalactic vs

$0_{\nu}\beta\beta$
SN burst vs
Hybrid Cherenkov/Scintillation

Target can be adjusted for different physics goals

Water-based liquid scintillator (WbLS)

- Water-like
  - >70% water
  - Cherenkov+ scintillation
  - cost-effective

- Oil-like
  - loading of hydrophilic elements

Scintillator
- Borexino
- KamLAND

Photon yield (MeV)

A tenation length (m)
Many new technologies for discriminating “chertons” from “scintons”

**THEIA**

**Timing**
“instantaneous chertons” vs. delayed “scintons” → ns resolution or better

**Spectrum**
UV/blue scintillation vs. blue/green Cherenkov → wavelength-sensitivity

**Angular distribution**
increased PMT hit density under Cherenkov angle → sufficient granularity

Multiple independent handles achieve:
- 90% purity for Chertons
- Little loss of scintons

LAPPDs

Biller, Leming, Paton NIMA 972 (2020) 164106

Kaptanoglu et al, PRD 101 (2020) 7, 072002

B. Land #472

J. Caravaca #490

FlatDot measurements

Gruszko et al, JINST 14 (2019) 02, P02005

CHESS Measurements


5% WbLS

L. Pickard #551

Caravaca et al, EPJC (2017) 77:811

M. Wurm

J. Paton #422

L. Pickard #551

LAB-PPO
THEIA: an advanced optical neutrino detector

Examined two detectors @ LBNF:

THEIA-25 (kt)
- LBNF beam
- Super-K like performance
- Scintons ignored
- T2K-like reconstruction ("fitQUN")
- Includes multi-ring events
- Systematics like DUNE CDR
- "3DST" scintillator near detector

THEIA-100 (kt)
- Assesses

Phased program to increase light yield, Cher/Scint separation

THEIA-25 (17 kt fid.) ~ Single DUNE 10 kt
THEIA-100 (70 kt fid) > 3 σ CP sensitivity over large fraction of phase space
Precision CNO measurement via pointing

Possibility of CC on $^7$Li for $^8$B and SN

"Clean" geo-neutrino signal

DSNB Background rejection exploiting Cher/Scint Ratio

SN Burst neutrino spectra

SN pointing ~ 2 degrees

Pre-SN burst neutrinos

Low reactor/geo background--3 $\sigma$ detection 1 day before SN out to 3.3 kpc

~200 events total from LMC
IBD tagging via n capture
Literally complementary to LAr

10 kpc

D. Guffanti #475

Burst Trigger latency ~100 ns

THEIA-100

M. Smiley #312

Josh Klein, University of Pennsylvania

THEIA

$\nu$ astrophysics

THEIA-100

THEIA-100

THEIA-100

THEIA-100

THEIA-100

THEIA-100
Neutrinoless Double Beta Decay

Requires inner containment bag for high LY scintillator

Dominant $^8$B ν background reduced by pointing

$T_{1/2} > 10^{28}$ y in 10 y for Te loading

Assumes:
- 5% loading of nat Te
- 3% energy resolution at endpoint
- 50% removal of $^8$B ν background

See also talk by J. Detwiler and S.D. Biller PRD 87 (2013) 7, 071301
Might make sense if scintillator adds to PID or background rejection at high energy
Or to broaden programs if depth accommodates it
But transparency of scintillator might limit size of detector
Summary

• Exciting prospects for future large-scale experiments!
• Broad suite of creative R&D driving capabilities
• A lot will depend on what the current generation tells us...

Thanks to INO, T2HKK, ESS vSB and THEIA Collaborations!