Future Neutrino Facilities & Outlook

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Los Alamos National Lab

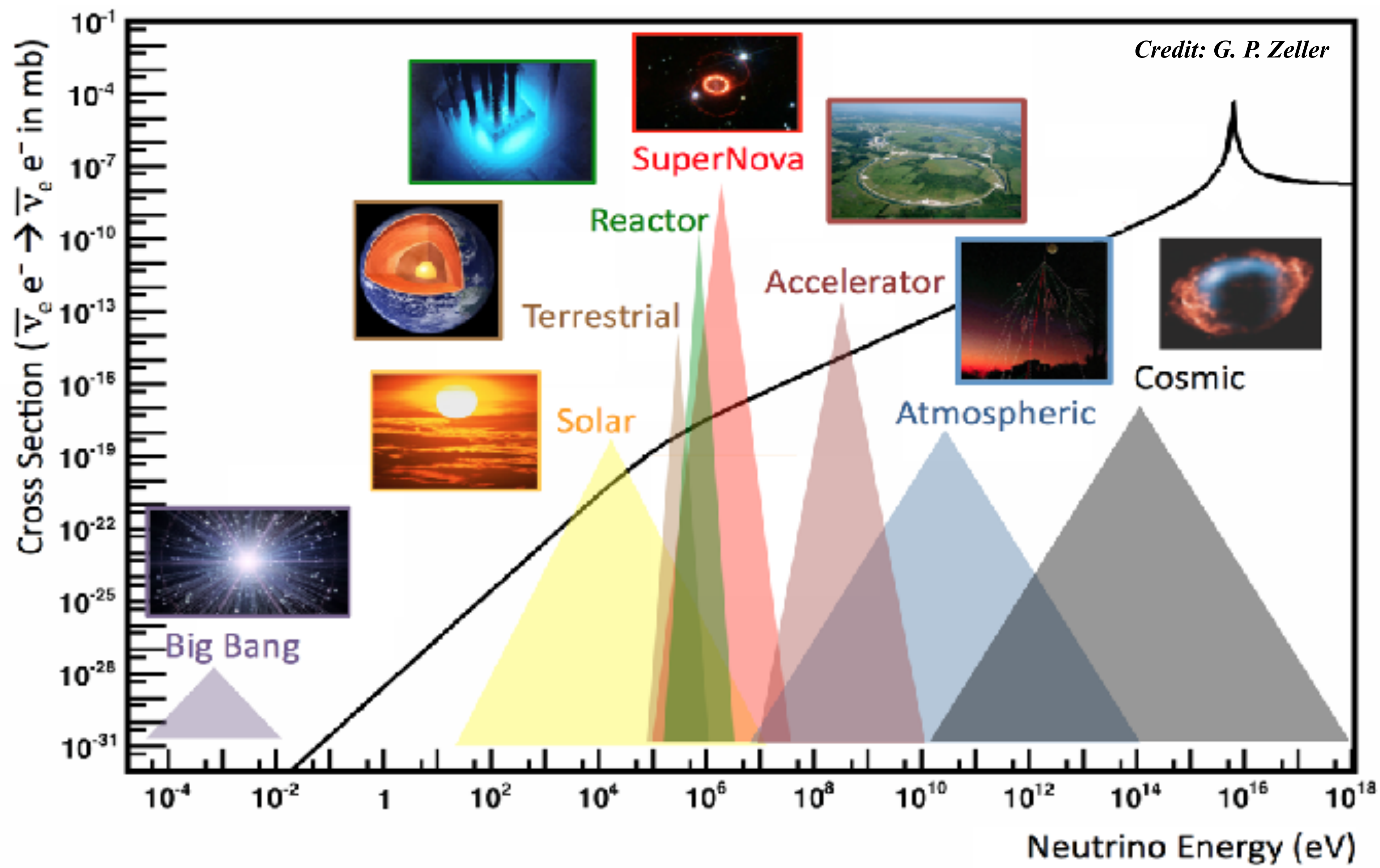
ICHEP 2020 — (virtual) Prague

August 6, 2020

First,

Congratulations to Organizers on an EXCELLENT conference & thanks for their ENORMOUS effort in taking it online!

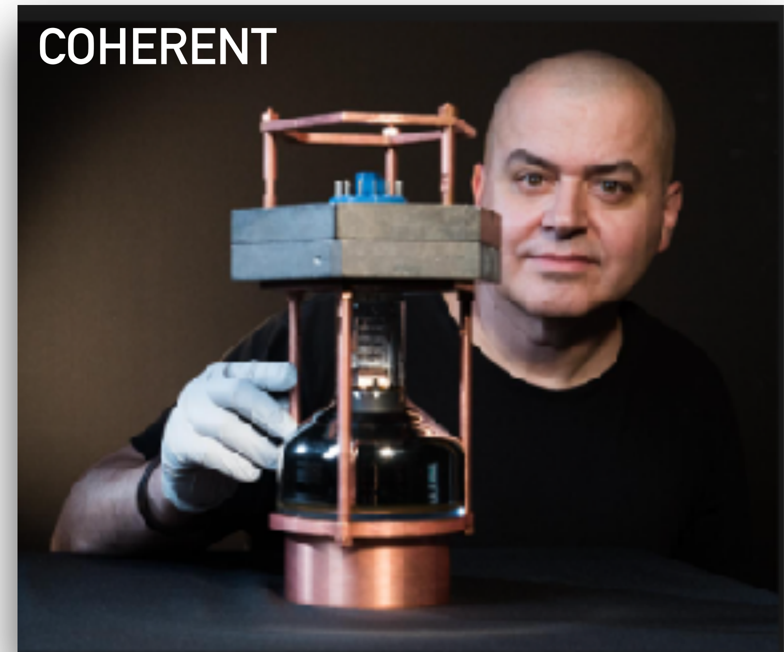
Neutrinos Span Multiple Frontiers!

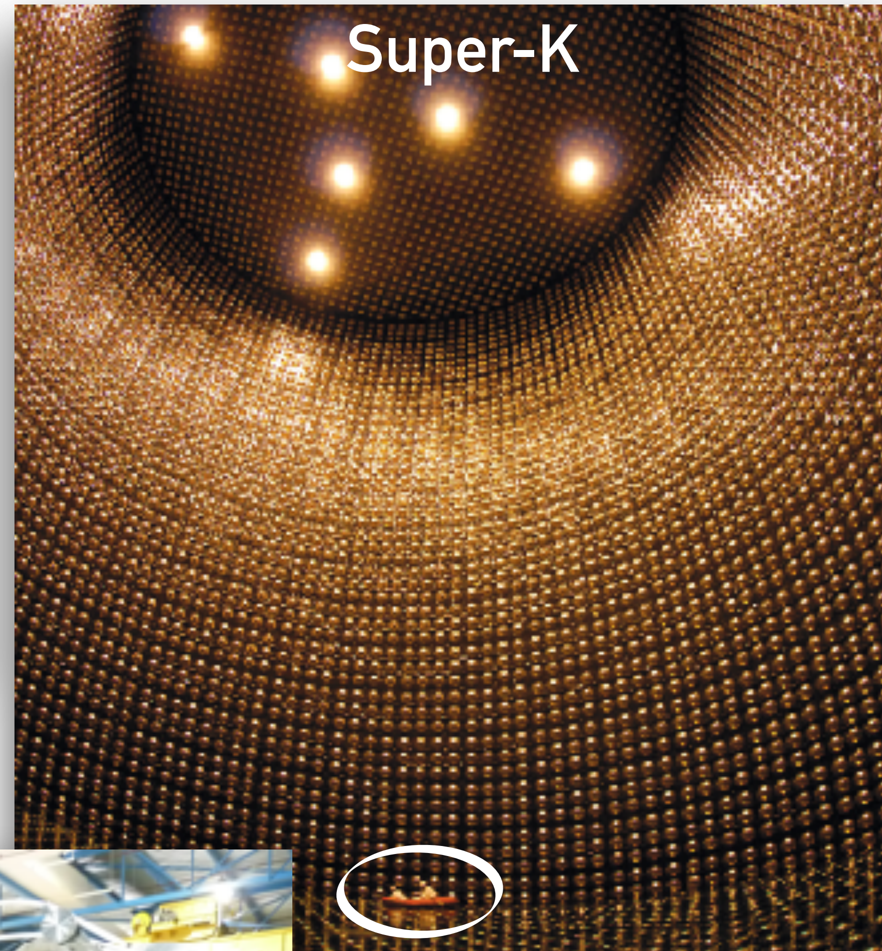


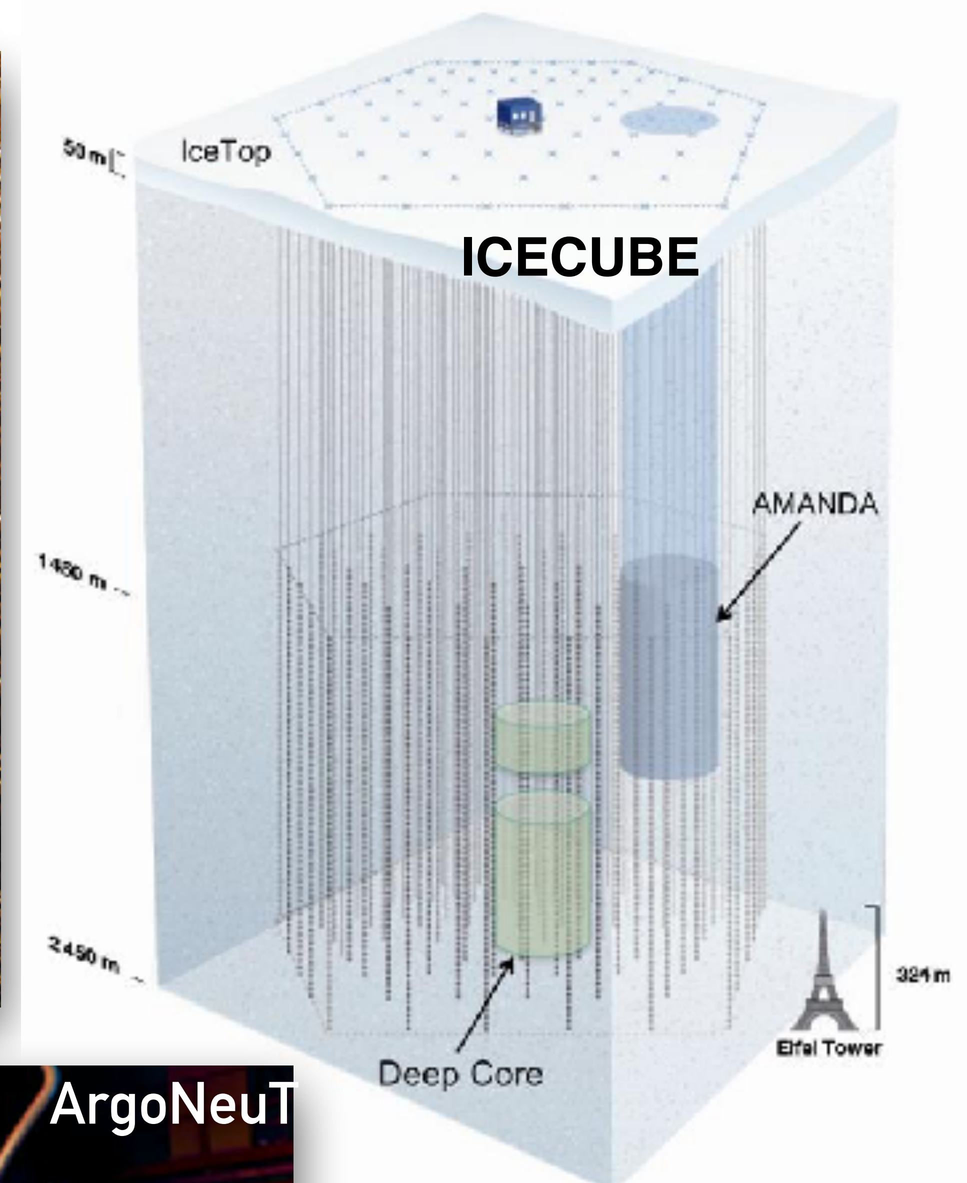
- **Particle Physics**
- **AstroPhysics**
- **Cosmology**
- **High energy Astro-particle physics**
- **Nuclear physics**

- Overwhelming number of sources, wide range of energies
- Need wide spectrum of experiments and technologies!

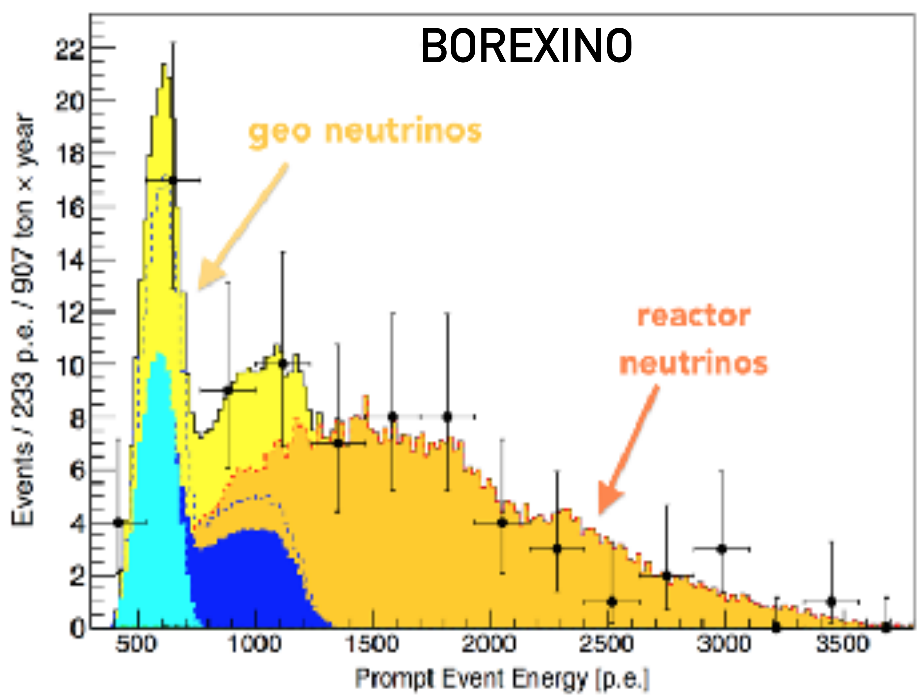
Neutrino Detectors at All Scales



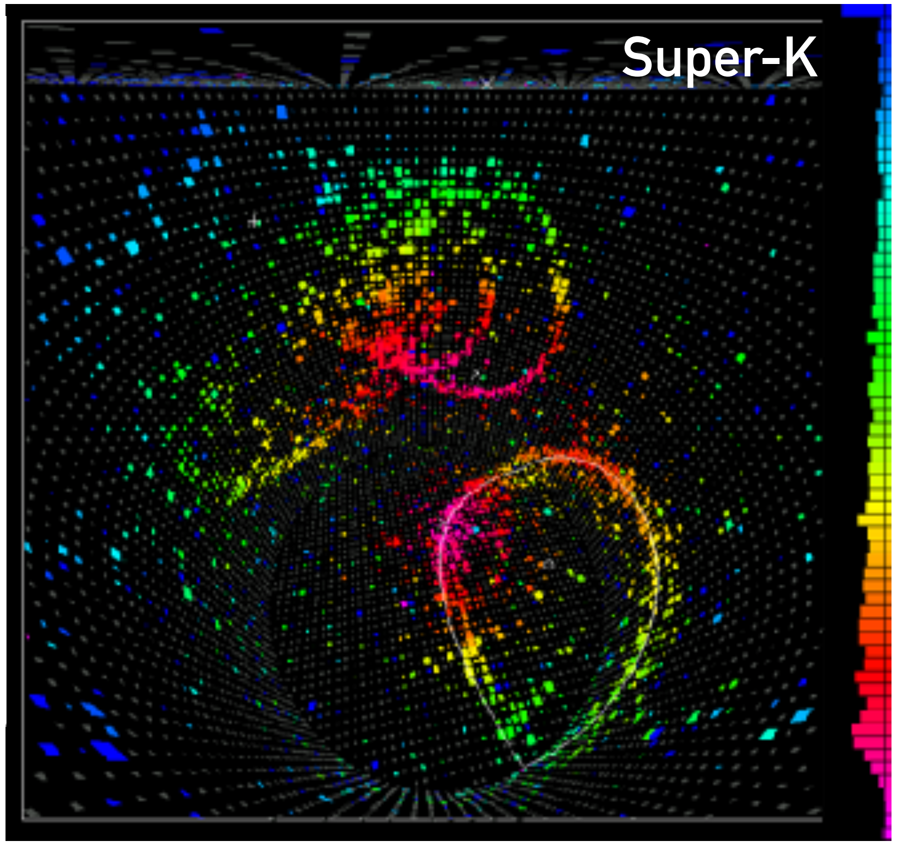




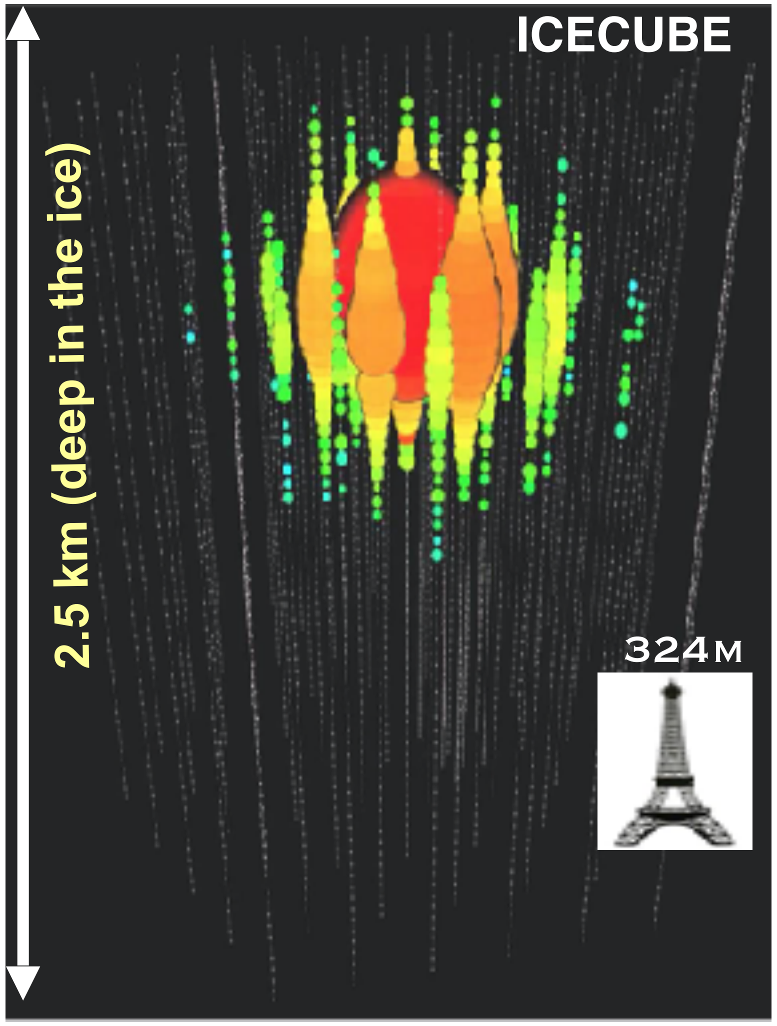
Visualizing Neutrinos



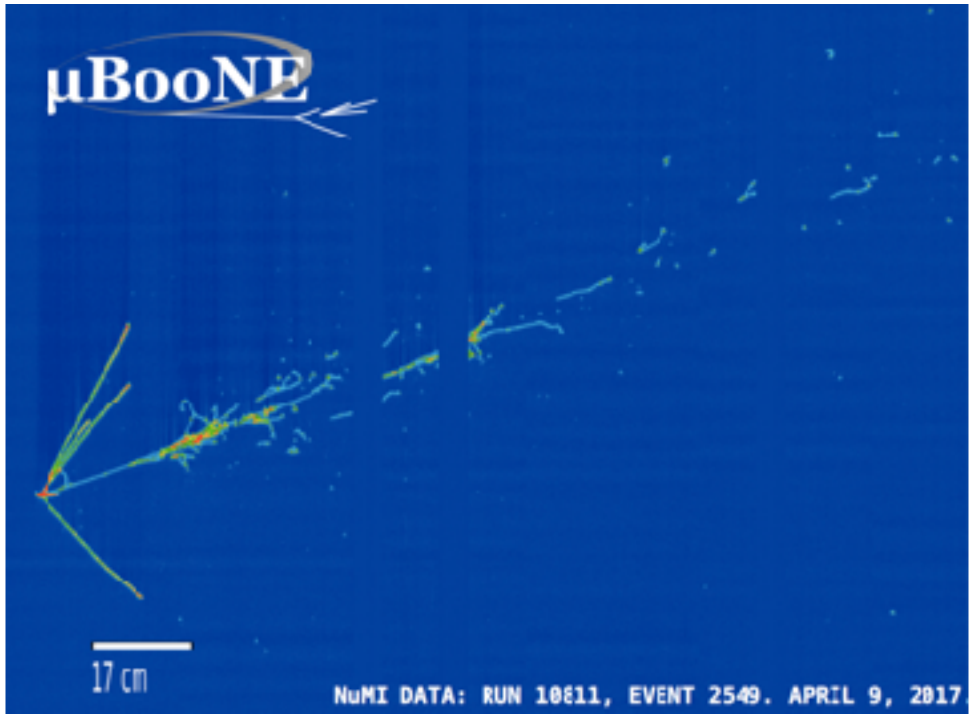
MeV-scale neutrino



A few-100 MeV neutrino



A 2 PeV scale astro physical event in the detector



MeV → PeV

We have observed neutrinos at wide range of energies

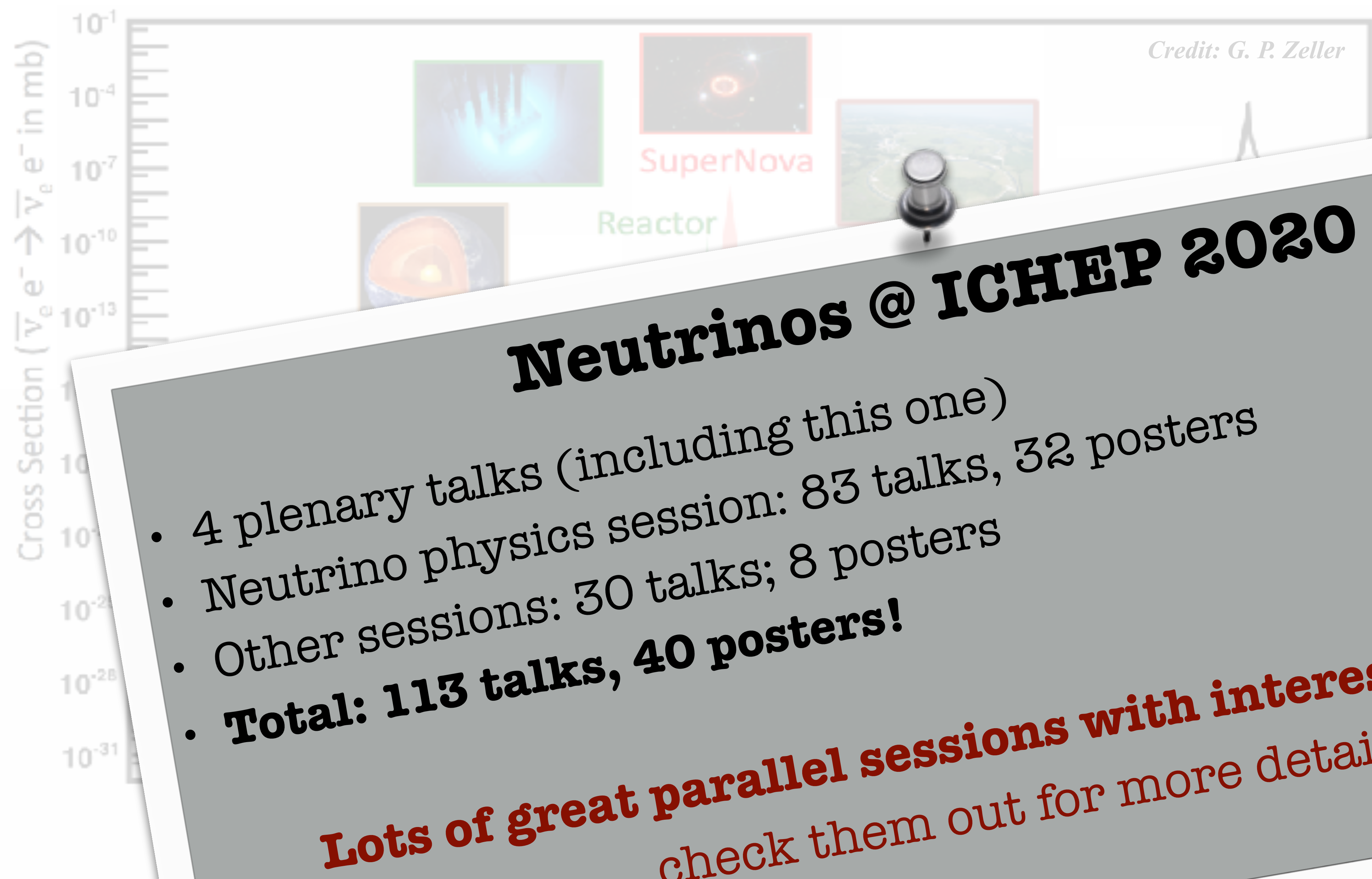
Neutrinos Span Multiple Frontiers!

Disclaimer

- The field is too broad — not possible to do justice in 25 minutes
- Apologies in advance if I am not covering your favorite topic…plus have my own biases
- I am not an expert on everything
- Biggest challenge in preparing the talk: getting capitalization right!

- Overwhelming number of sources, wide range of energies
- Need wide spectrum of experiments and technologies!

Neutrinos Span Multiple Frontiers!



Neutrinos @ ICHEP 2020

- 4 plenary talks (including this one)
- Neutrino physics session: 83 talks, 32 posters
- Other sessions: 30 talks; 8 posters
- **Total: 113 talks, 40 posters!**

Lots of great parallel sessions with interesting results,
check them out for more details

- Ov... sources, wide range of energies
- Nee... wide spectrum of experiments and technologies!

Mass Found in Elusive Particle; Universe May Never Be the Same

Discovery on Neutrino Rattles Basic Theory About All Matter

By MALCOLM W. BROWNE

TAKAYAMA, Japan, June 5 — In what colleagues hailed as a historic landmark, 120 physicists from 23 research institutions in Japan and the United States announced today that they had found the existence of mass in a notoriously elusive subatomic particle called the neutrino.

The neutrino, a particle that carries no electric charge, is so light that it was assumed for many years to have no mass at all. After today's announcement, cosmologists will have to confront the possibility that much of the mass of the universe is in the form of neutrinos. The discovery will also compel scientists to revise a highly successful theory of the composition of matter known as the Standard Model.

Word of the discovery had drawn some 300 physicists here to discuss neutrino research. Among other things, they said, the finding of neutrino mass might affect theories about the formation and evolution of galaxies and the ultimate fate of the universe. If neutrinos have sufficient mass, their presence throughout the universe would increase the overall mass of the universe, possibly slowing its present expansion.

Others said the newly detected but as yet unmeasured mass of the neutrino must be too small to cause cosmological effects. But whatever the case, there was general agreement here that the discovery will have far-reaching consequences for the investigation of the nature of matter.

Speaking for the collaboration of scientists who discovered the existence of neutrino mass using a huge underground detector called Super-Kamiokande, Dr. Takaaki Kajita of the Institute for Cosmic Ray Research of Tokyo University said that all explanations for the data collected by the detector except the existence of neutrino mass had been essentially ruled out.

Dr. Yoji Totsuka, leader of the coalition and director of the Kamioka Neutrino Observatory where the underground detector is situated, 30 miles north of here in the Japan Alps, acknowledged that his group's announcement was "very strong," but said, "We have investigated all

Continued on Page A14

Detecting Neutrinos

1. Neutrinos pass through the Earth's surface to a tank filled with 12.5 million gallons of ultra-pure water . . .
2. . . . and collide with other particles . . .
3. . . . producing a cone-shaped flash of light.
4. The light is recorded by 11,200 20-inch light amplifiers that cover the inside of the tank.

And Detecting Their Mass

By analyzing the cones of light, physicists determine that some neutrinos have changed form on their journey. If they can change form, they must have mass.

Source: University of Hawaii

The New York Times

Neutrinos Oscillate and they have mass!

(albeit very tiny)

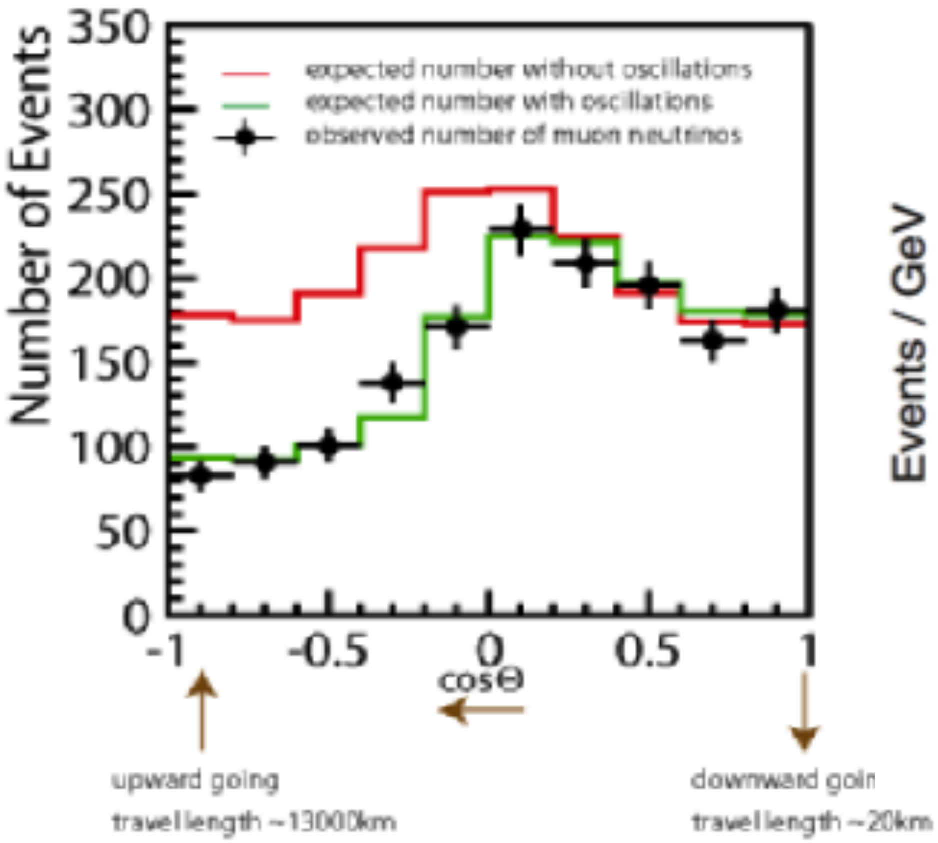
Until as recently as 1998, neutrinos were considered to be massless

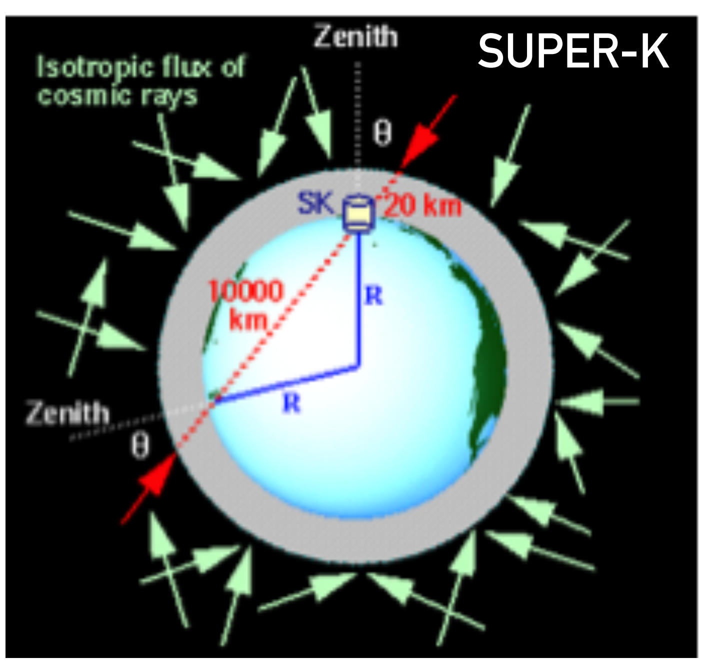
This discovery has revolutionized the field of **Neutrino Physics** in many ways!

Overwhelming Evidence for ν Oscillations

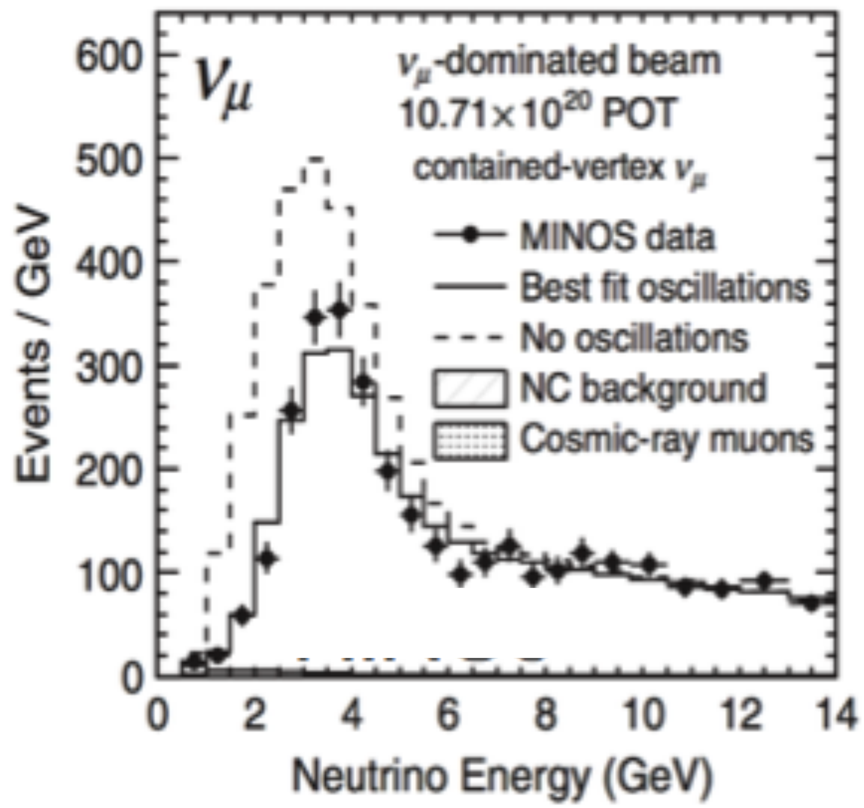
(from a variety of sources)

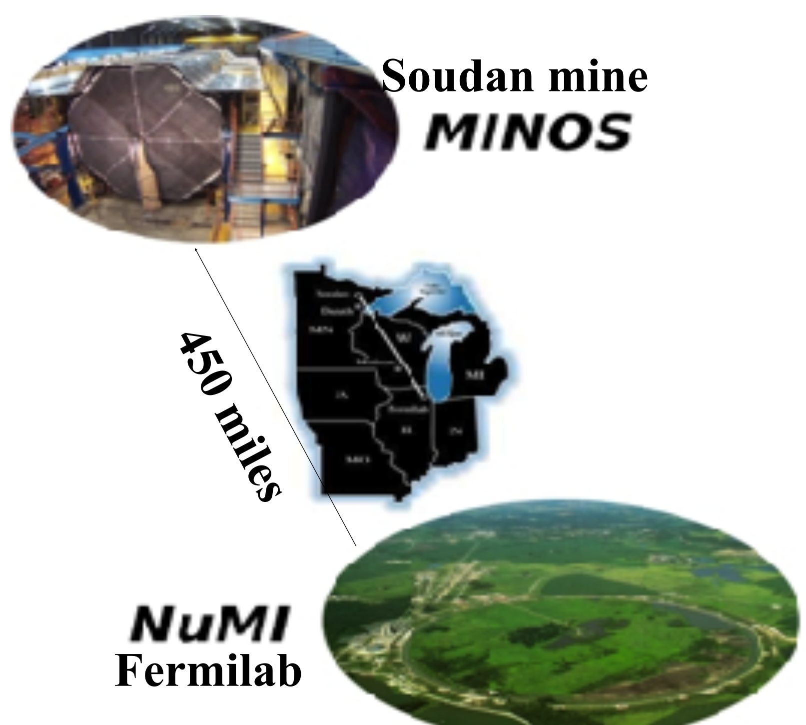
Atmospheric



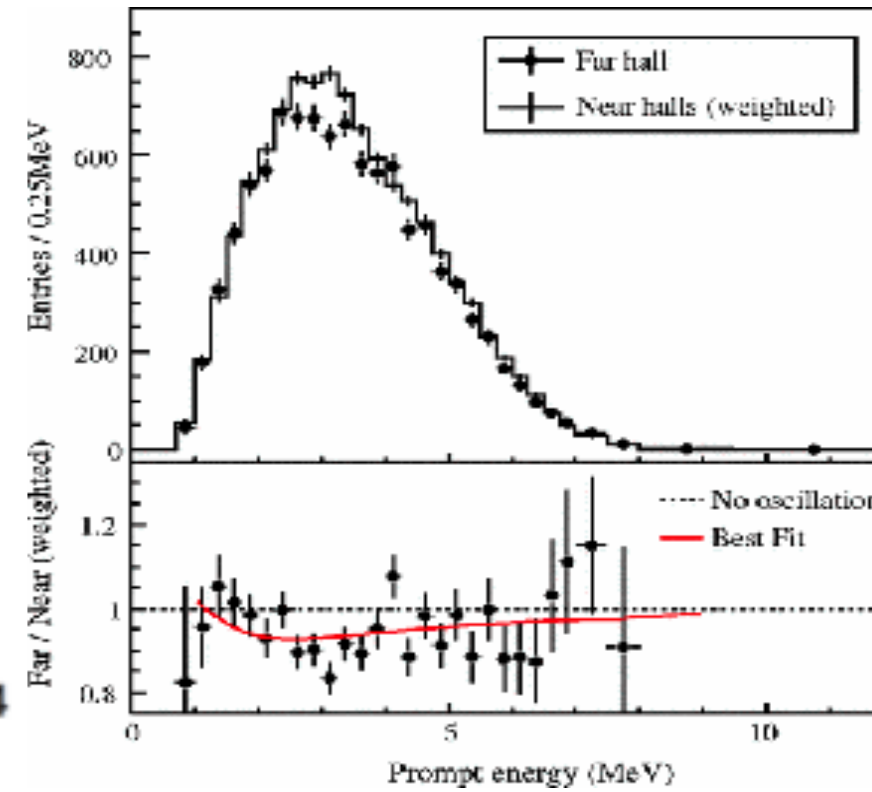


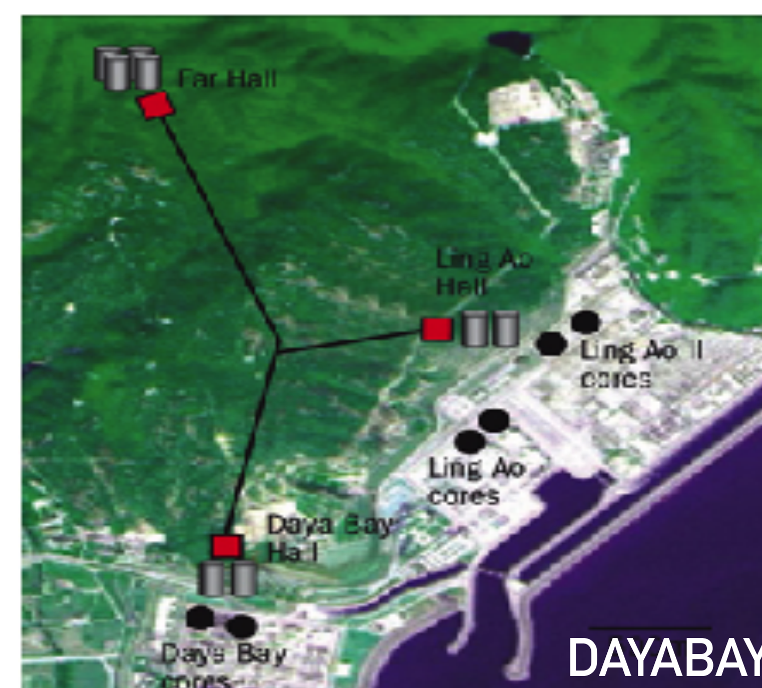
Accelerator





Reactor source





Overwhelming Evidence for ν Oscillations

(from a variety of sources)

We have detected oscillations from

- Atmospheric
- Solar
- Accelerator
- Reactor

3-flavor oscillations are a well established phenomenon

Neutrino Oscillation Parameters

"FLAVOR" STATES

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}}_{\text{The "PMNS" Matrix}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

"MASS" STATES

The "PMNS" Matrix

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

(Majorana phases)

Atmospheric & long baseline accelerator — *Reactor & Accelerator* — *Solar & long baseline Reactor*

- 3 mixing angles: θ_{12}, θ_{23}, θ_{13} *and a complex phase:* δ_{CP}
- If $\delta \neq \{0, \pi\}$ then results is CP Violation in leptonic sector
- 2 mass differences: Δm^2_{21}, Δm^2_{32}

- Thanks to Reactor experiments, $\theta_{13} \neq 0$, opened door to **CPV** in the leptonic sector

- δ_{CP} helps us understand why we live in a matter-dominated Universe

Open Questions

Within SM 3-flavor mixing

- Absolute mass of neutrinos?
- Neutrinos Majorana or Dirac?
- Precision Measurement of mixing parameters?
- Neutrino mass ordering?
- Is θ_{23} maximal mixing?
- CP violation in the neutrino sector?

Beyond SM 3-flavor mixing

- Absolute mass of neutrinos? Are there more than 3 neutrinos?
- Other BSM physics e.g. non-standard interactions

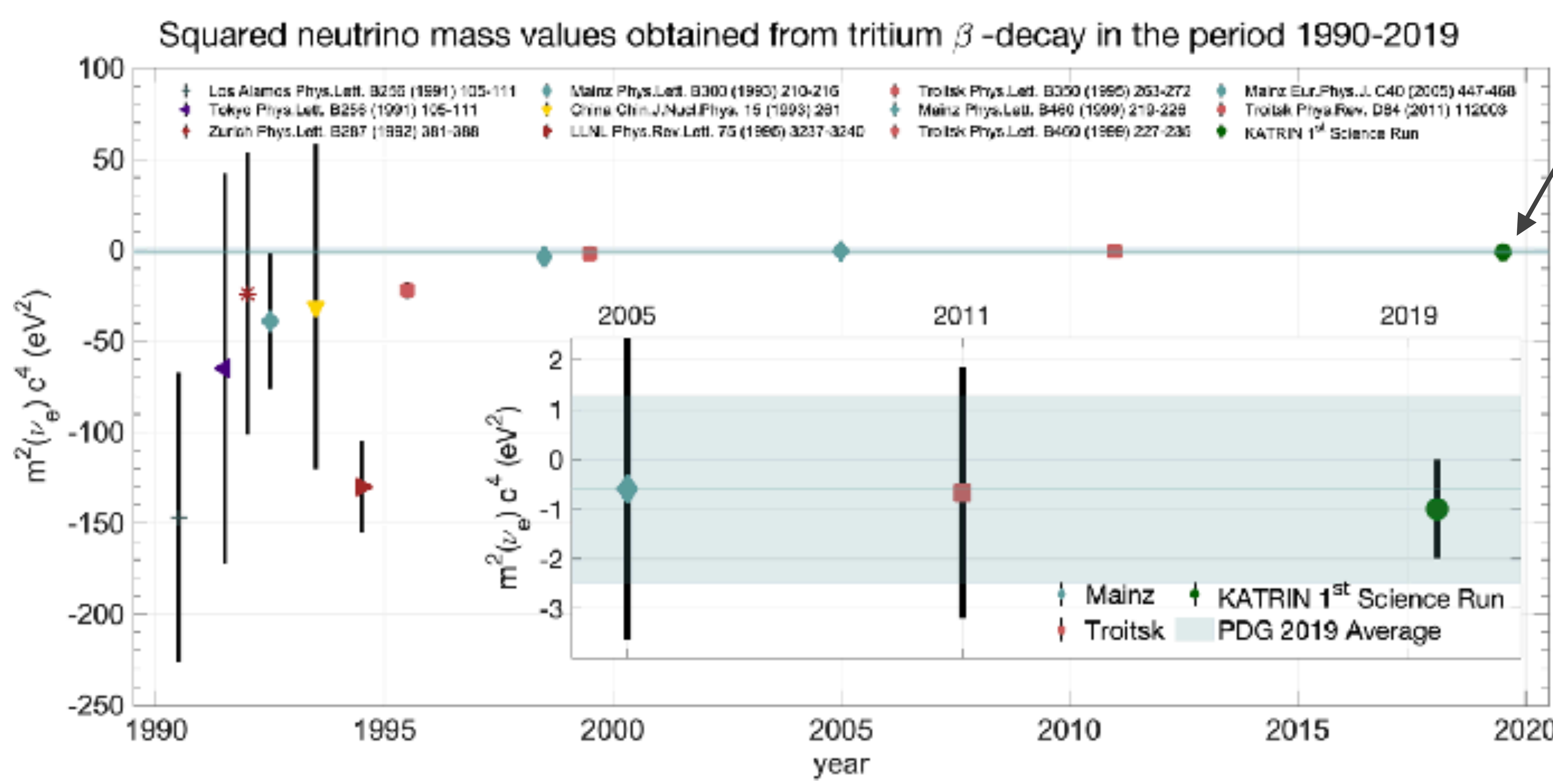
Open Questions: Within SM 3-flavor mixing

- **Absolute mass of neutrinos?**
  - Constraints from cosmological and astrophysical data and precision measurements from β-decay experiments
  - (Recent results: KATRIN, Neutrino 4)

PDG 2020 upper limit
(KATRIN Experiment)

Mass $m < 1.1$ eV, CL = 90% (tritium decay)

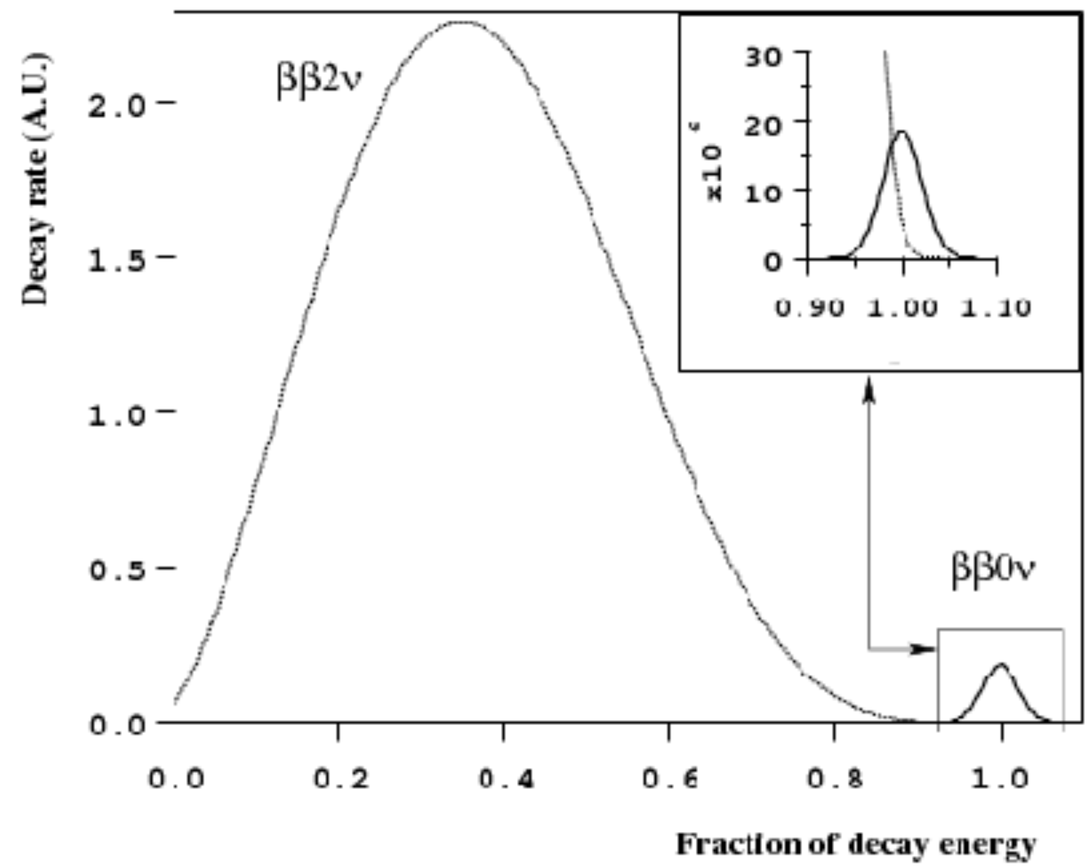
Phys. Rev. Lett. 123, 221802 (2019)



Open Questions: Within SM 3-flavor mixing

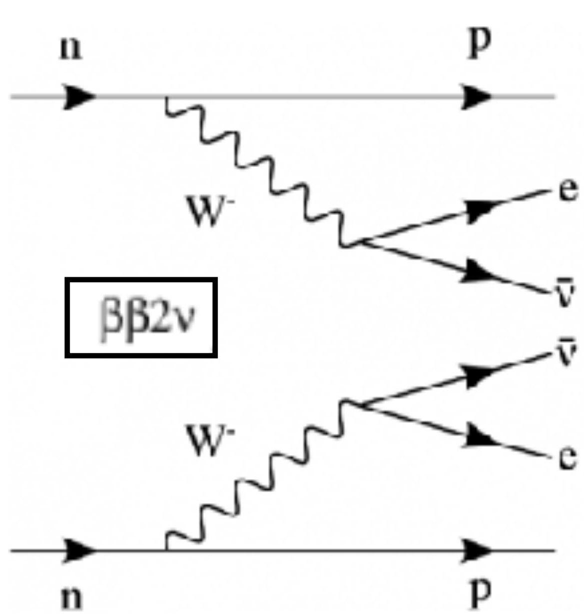
- Absolute mass of neutrinos?
- **Neutrinos Majorana or Dirac?**

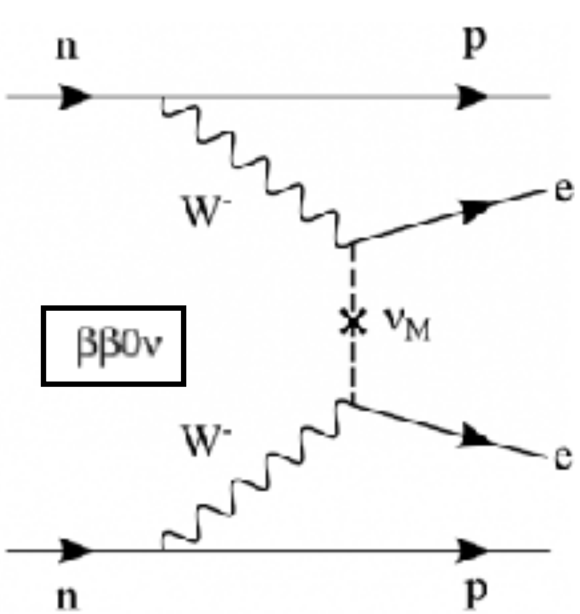
Observation of neutrino less double beta decay (0νββ) provides evidence for "Majorana" nature of neutrinos



Current Best Limits

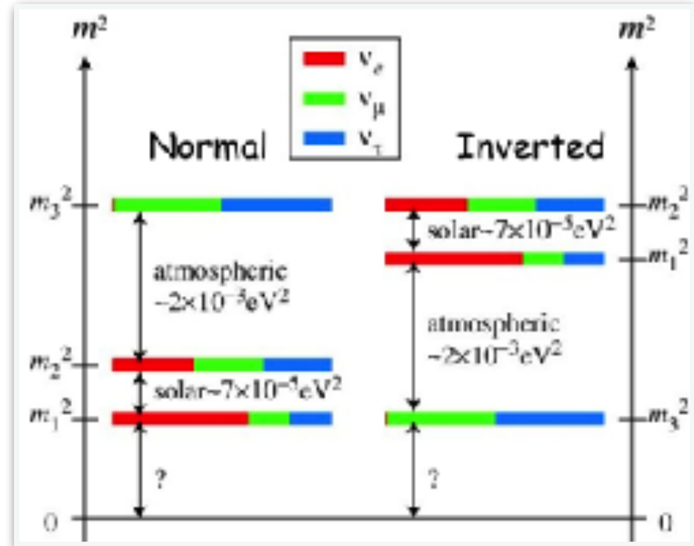
^{136}Xe (KamLAND-Zen): $T_{1/2} > 10^{26}$ yrs
^{76}Ge (GERDA): $T_{1/2} > 10^{26}$ yrs
^{130}Te (CUORE): $T_{1/2} > 3\times10^{25}$ yrs





Open Questions: Within SM 3-flavor mixing

- Absolute mass of neutrinos?
- Neutrinos Majorana or Dirac?
- **Precision Measurement of mixing parameters?**
- **Neutrino mass ordering?**
- **Is θ_{23} maximal mixing?**
- **CP violation in the neutrino sector?** $P[\nu_\mu \to \nu_e] \neq P[\overline{\nu}_\mu \to \overline{\nu}_e]$?

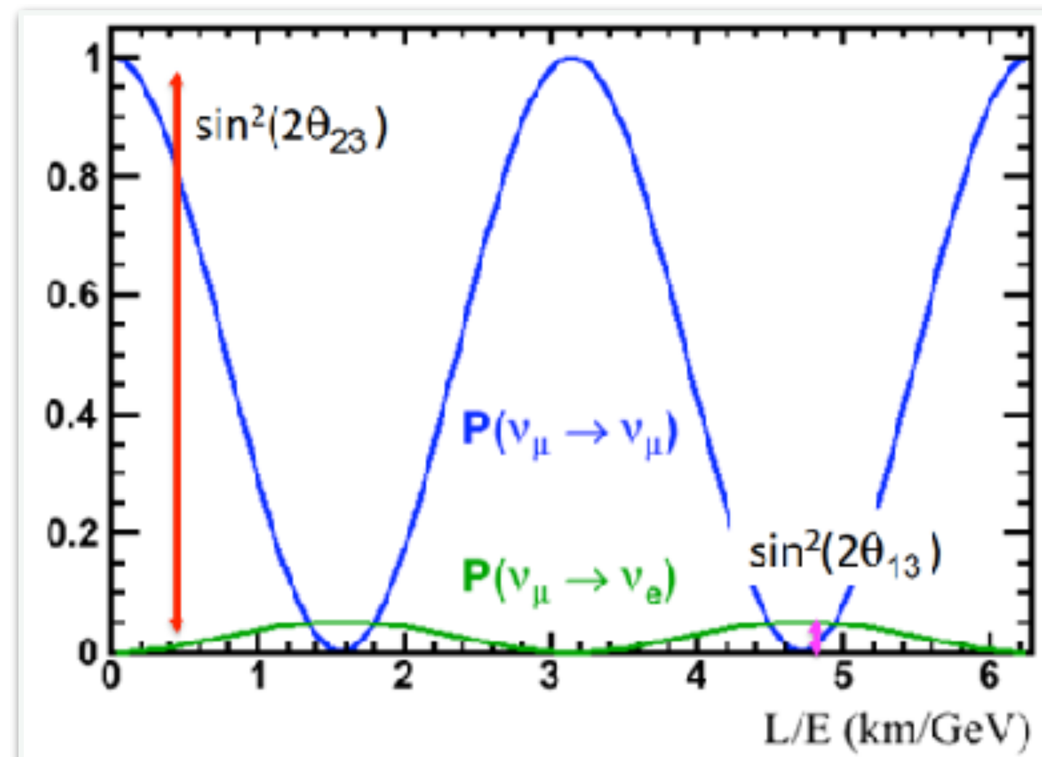


υ_e appearance

$$P_{\alpha\beta} = \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

υ_μ disappearance

$$P_{\alpha\alpha} = 1 - \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



PDG 2020

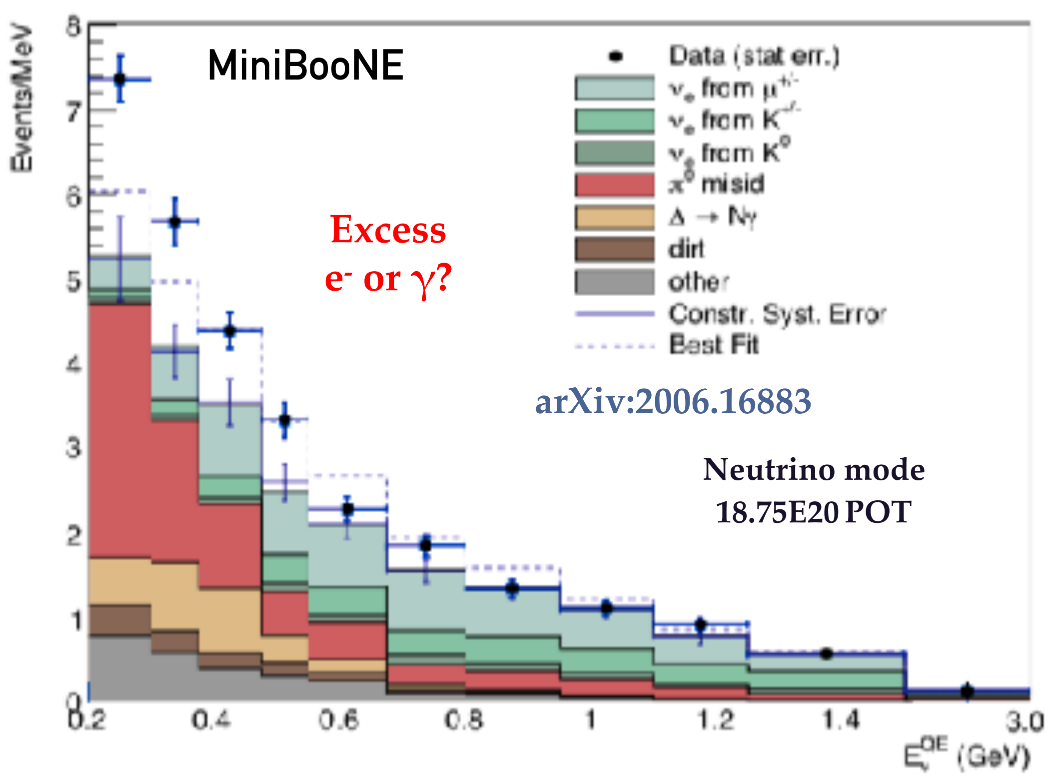
$\sin^2(\theta_{12}) = 0.307 \pm 0.013$
$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}$ eV^2
$\sin^2(\theta_{23}) = 0.547 \pm 0.021$ (Inverted order)
$\sin^2(\theta_{23}) = 0.545 \pm 0.021$ (Normal order)
$\Delta m^2_{32} = (-2.546^{+0.034}_{-0.040}) \times 10^{-3}$ eV^2 (Inverted order)
$\Delta m^2_{32} = (2.453 \pm 0.034) \times 10^{-3}$ eV^2 (Normal order)
$\sin^2(\theta_{13}) = (2.18 \pm 0.07) \times 10^{-2}$
δ, *CP* violating phase $= 1.36 \pm 0.17\ \pi$ rad
$\langle \Delta m^2_{21} - \Delta \overline{m}^2_{21} \rangle < 1.1 \times 10^{-4}$ eV^2, CL = 99.7%
$\langle \Delta m^2_{32} - \Delta \overline{m}^2_{32} \rangle = (-0.12 \pm 0.25) \times 10^{-3}$ eV^2

- υ_e appearance (θ_{13}, MH, CPV)
- υ_μ disappearance (θ_{23})
- Distortion to the neutrino spectrum (Δm^2_{32})
- **Searches at Long Baseline Experiments e.g. T2K**

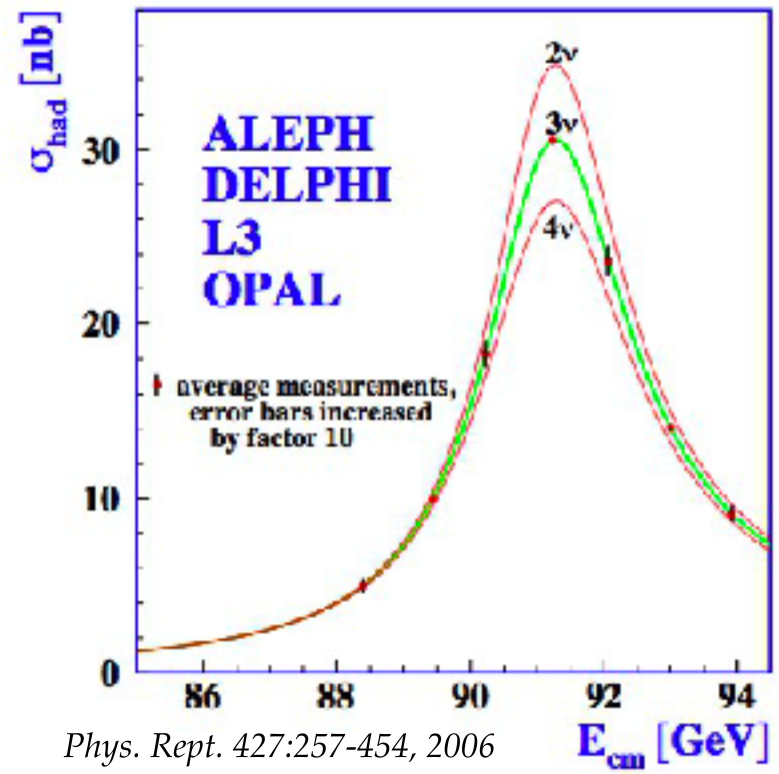
Open Questions: Beyond SM 3-flavor mixing

- **Are there more than 3 neutrinos?**

- Other BSM physics e.g. non-standard interactions



- MiniBooNE 2020 results
- Latest Results from MiniBooNE provide 4.8σ excess
- Combined LSND+MiniBooNE: 6.1σ



Phys. Rept. 427:257-454, 2006

Experimentally verified that only 3 flavors couple of SM Z boson

- Short-baseline (L<1 km) anomalies from reactor / accelerator experiments — can be interpreted as **high Δm^2 (around 1 eV^2) "sterile" neutrino oscillations**

- But, Tension in oscillation interpretations (null results, signal vs background, global fits, neutrino vs anti-neutrino fits etc.)

Synergy Across Experiments

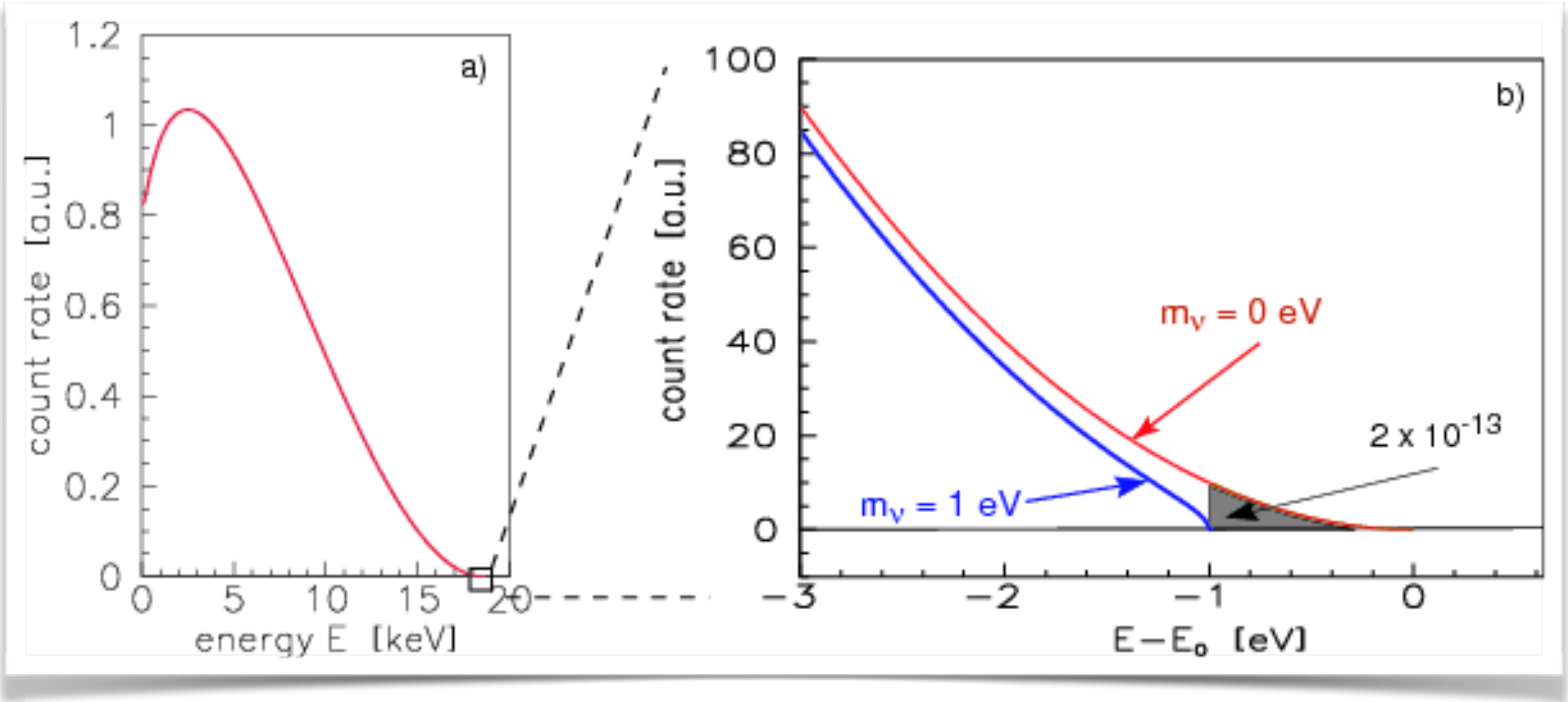
	What is the absolute neutrino mass?	Are neutrinos Dirac or Majorana particles?	What is the neutrino mass ordering?	Is there CP violation in the neutrino sector?	Are there more than 3 neutrino flavors?	Is our picture of neutrinos correct?
β decay	✓					✓
$0\nu\beta\beta$ decay	✓	✓				✓
astrophysics and cosmology	✓		(✓)		✓	✓
Atmospheric oscillations			(✓)	(✓)	✓	✓
Reactor oscillations			(✓)		✓	✓
Accelerator oscillations			✓	✓	✓	✓

- Broad Physics program — overlapping physics and technological goals

Direct Mass Measurements

Beta Decay Experiments

Experimental Landscape



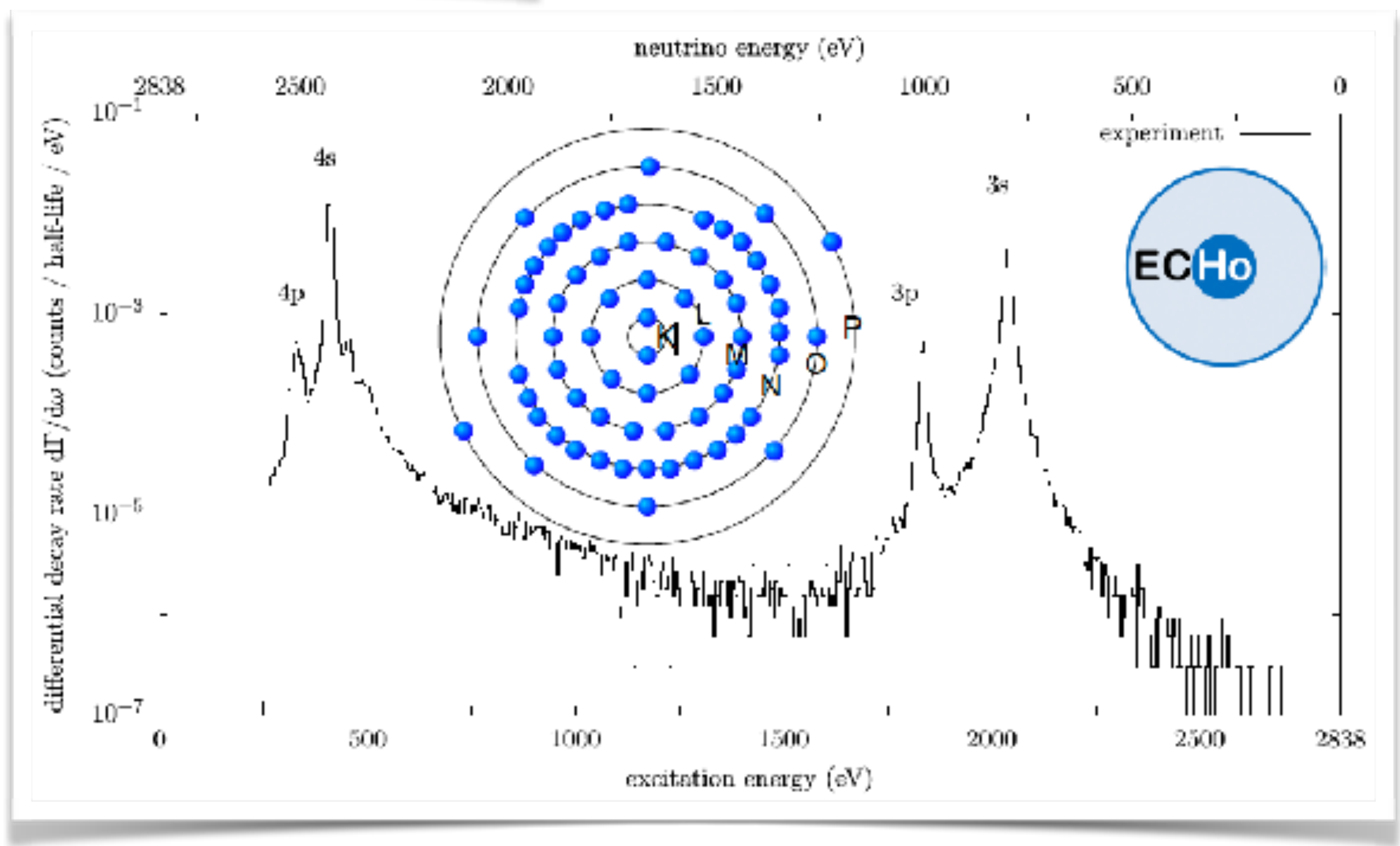
Tritium beta decay tagging experiments

- Spectrometer (**KATRIN**)
- Cyclotron radiation (**Project 8**)

Electron capture decay of ^{163}Ho

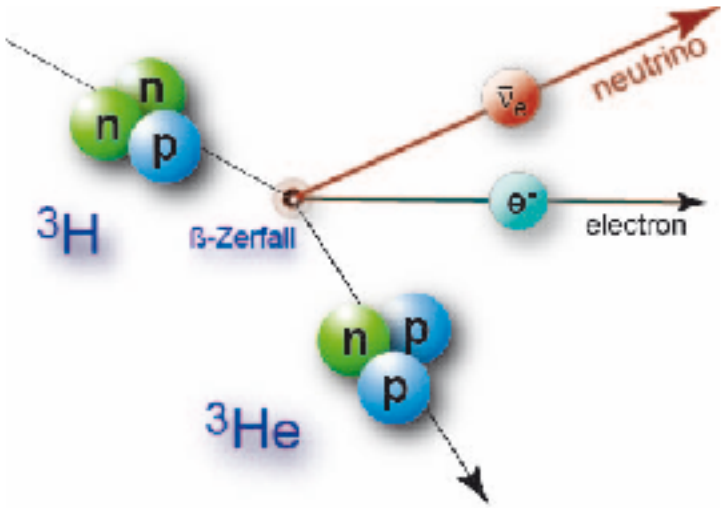
- **ECHO, HOLMES**
- Both use Calorimetric approach

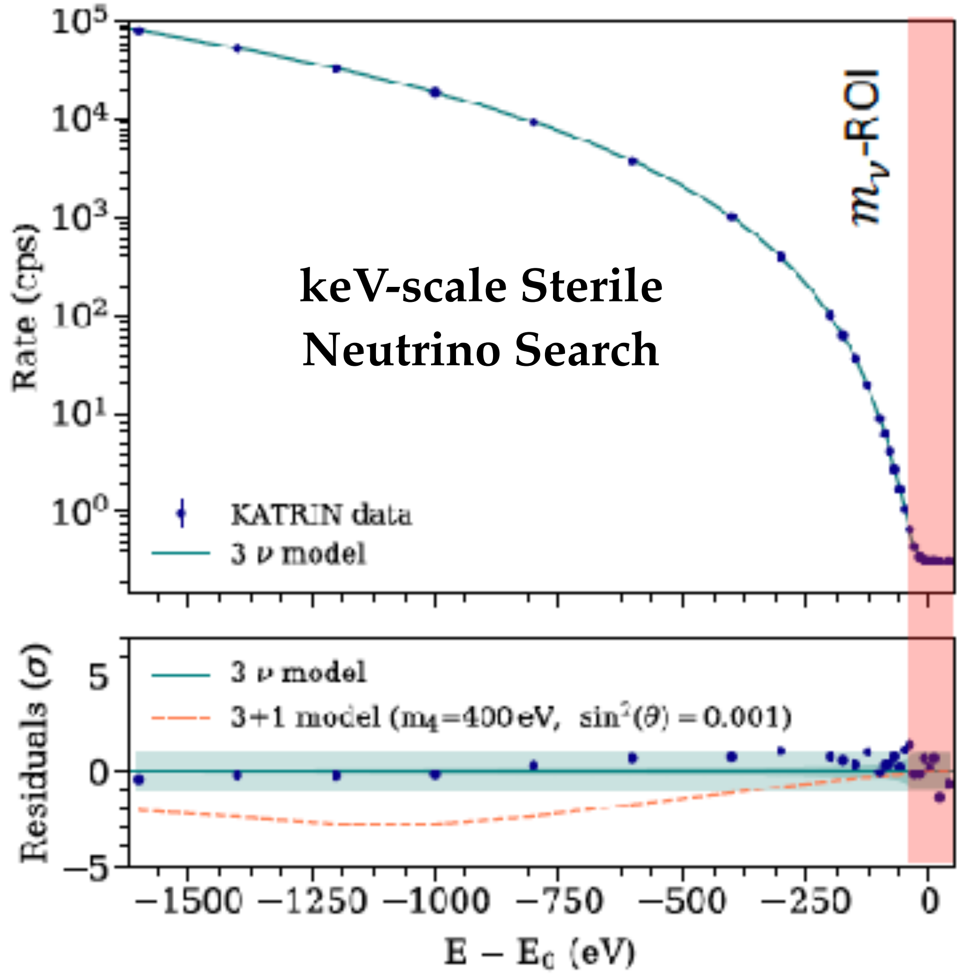
Also from other experiments such as **Neutrino 4**

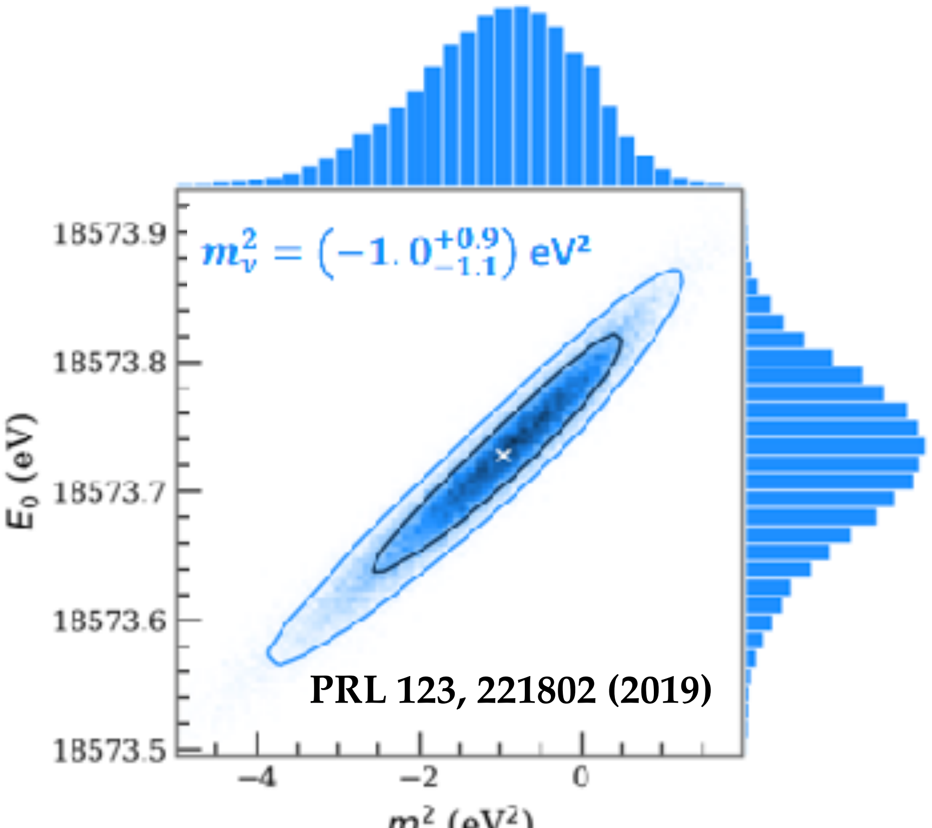


First Results from KATRIN

A 70-m Tritium
beta decay
tagging
experiment







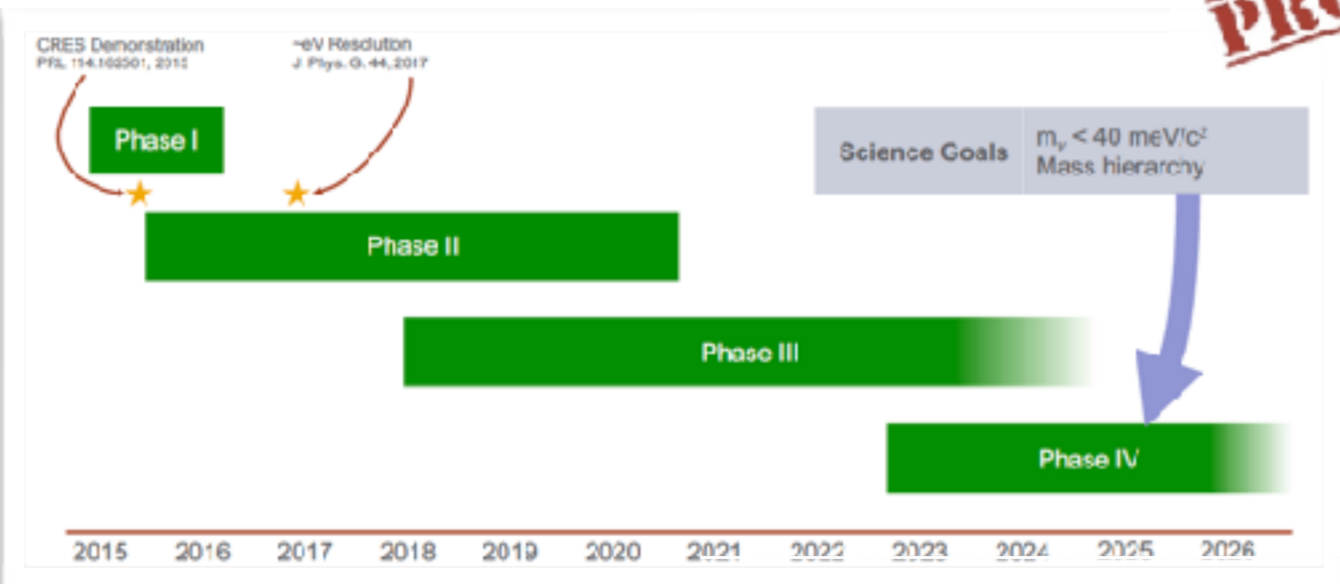
PRL 123, 221802 (2019)

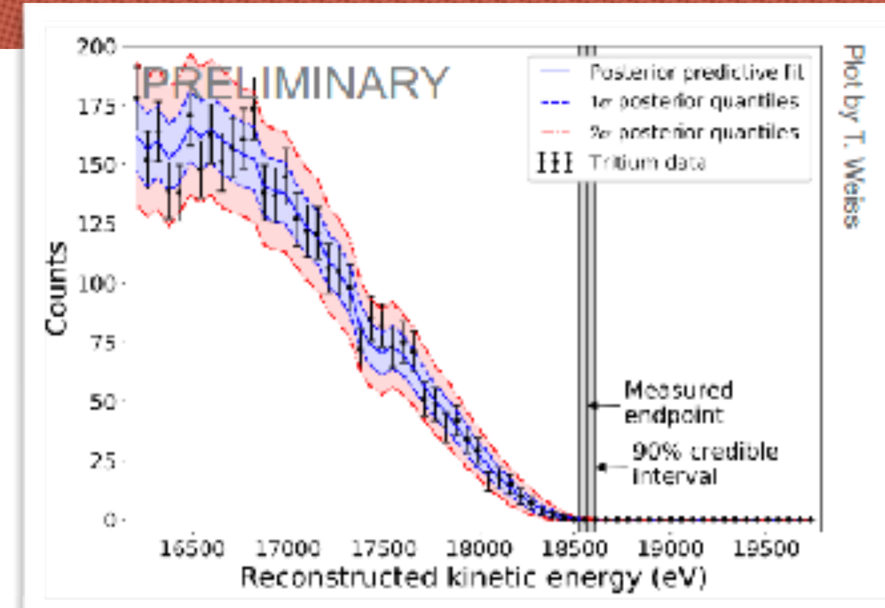
- **New world-best direct mass measurement, m_ν < 1.1 eV (90% C.L.)**
- **Future:** More data being collected for sub-eV sensitivity

- **First constraint on eV sterile neutrinos**
- **Future:**
  - high-statistics search
  - Target sensitivity of $\sin^2\theta < 10^{-6}$

Looking Towards Future

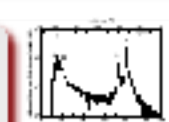
seeing electrons from tritium β-decay using
Cyclotron Radiation Emission Spectroscopy (CRES)



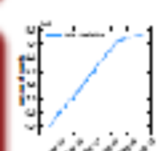


- Completing Phase II; **first measurement of Tritium spectrum**
- Entering Phase III of critical R&D

Published 2019 m_ν < 150 eV
(10^5 counts)



Data collection in 2020
10^8 counts
will allow to set an upper limit of less than 20 eV

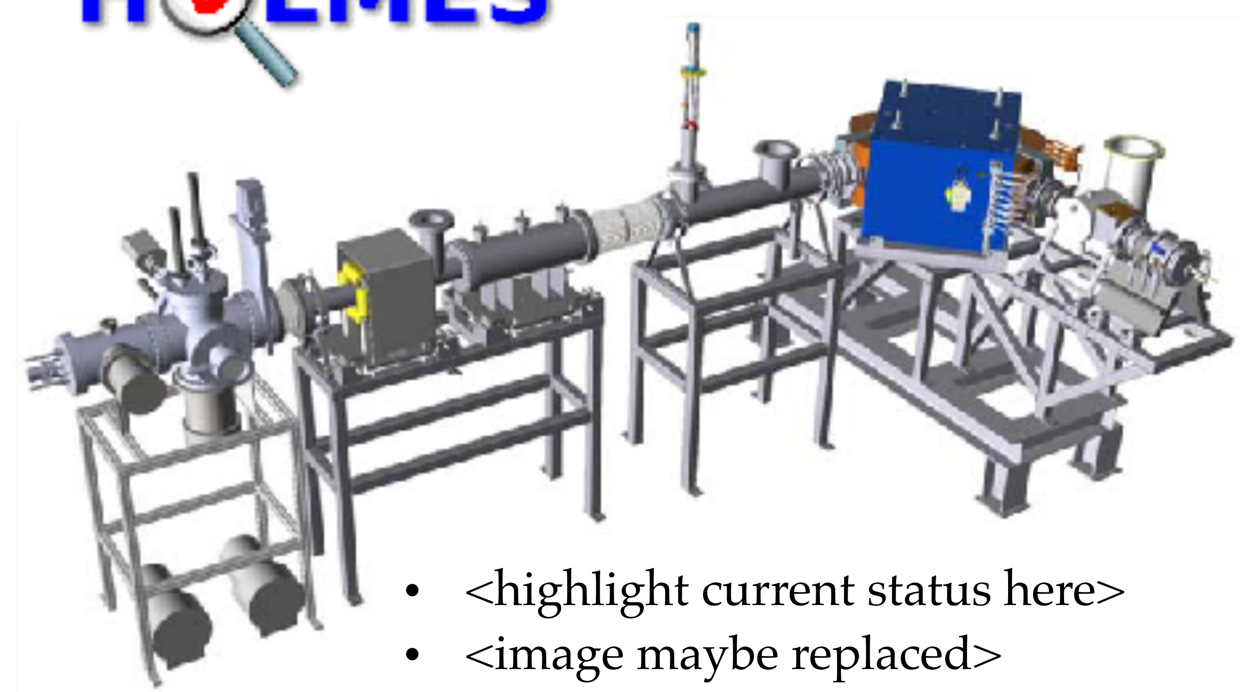


ECHo phase 2 is in progress
aims at an upper limit of
less than 2 eV

ECHo phase 3
Future plans (200 meV)

?

HOLMES



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Neutrino Majorana or Dirac?

Neutrinoless Double Beta Decay Experiments

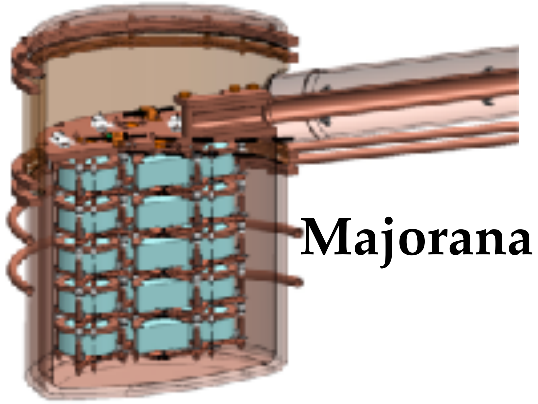
Experimental Landscape

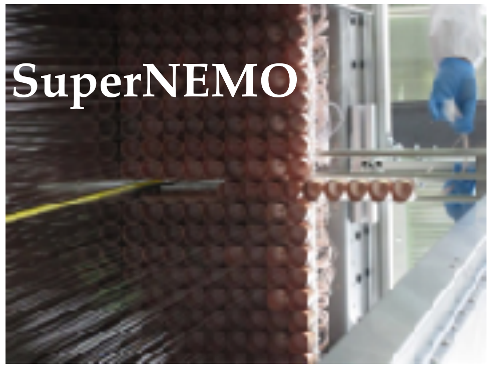
(J. Detwiler @ Neutrino 2020)

Collaboration	Isotope	Technique	mass ($0\nu\beta\beta$ isotope)	Status
CANDLES-III	^{48}Ca	305 kg CaF_2 crystals in liquid scintillator	0.3 kg	Operating
CANDLES-IV	^{48}Ca	CaF_2 scintillating bolometers	TBD	R&D
GERDA	^{76}Ge	Point contact Ge in active LAr	44 kg	Complete
MAJORANA DEMONSTRATOR	^{76}Ge	Point contact Ge in Lead	30 kg	Operating
LEGEND 200	^{76}Ge	Point contact Ge in active LAr	200 kg	Construction
LEGEND 1000	^{76}Ge	Point contact Ge in active LAr	1 tonne	R&D
SuperNEMO Demonstrator	^{82}Se	Foils with tracking	7 kg	Construction
SELENA	^{82}Se	Se CCDs	<1 kg	R&D
NvDEx	^{82}Se	SeF_6 high pressure gas TPC	50 kg	R&D
ZICOS	^{96}Zr	10% ^{nat}Zr in liquid scintillator	45 kg	R&D
AMoRE-I	^{100}Mo	$^{40}CaMoO_4$ scintillating bolometers	6 kg	Construction
AMoRE-II	^{100}Mo	Li_2MoO_4 scintillating bolometers	100 kg	Construction
CUPID	^{100}Mo	Li_2MoO_4 scintillating bolometers	250 kg	R&D
COBRA	$^{116}Cd/^{130}Te$	CdZnTe detectors	10 kg	Operating
CUORE	^{130}Te	TeO_2 Bolometer	206 kg	Operating
SNO+	^{130}Te	0.5% ^{nat}Te in liquid scintillator	1300 kg	Construction
SNO+ Phase II	^{130}Te	2.5% ^{nat}Te in liquid scintillator	8 tonnes	R&D
Theia-Te	^{130}Te	5% ^{nat}Te in liquid scintillator	31 tonnes	R&D
KamLAND-Zen 400	^{136}Xe	2.7% in liquid scintillator	370 kg	Complete
KamLAND-Zen 800	^{136}Xe	2.7% in liquid scintillator	750 kg	Operating
KamLAND2-Zen	^{136}Xe	2.7% in liquid scintillator	~tonne	R&D
EXO-200	^{136}Xe	Xe liquid TPC	160 kg	Complete
nEXO	^{136}Xe	Xe liquid TPC	5 tonnes	R&D
NEXT-WHITE	^{136}Xe	High pressure GXe TPC	~5 kg	Operating
NEXT-100	^{136}Xe	High pressure GXe TPC	100 kg	Construction
PandaX	^{136}Xe	High pressure GXe TPC	~tonne	R&D
AXEL	^{136}Xe	High pressure GXe TPC	~tonne	R&D
DARWIN	^{136}Xe	^{nat}Xe liquid TPC	3.5 tonnes	R&D
LZ	^{136}Xe	^{nat}Xe liquid TPC		R&D
Theia-Xe	^{136}Xe	3% in liquid scintillator	50 tonnes	R&D

R&D | Construction | Operating | Complete

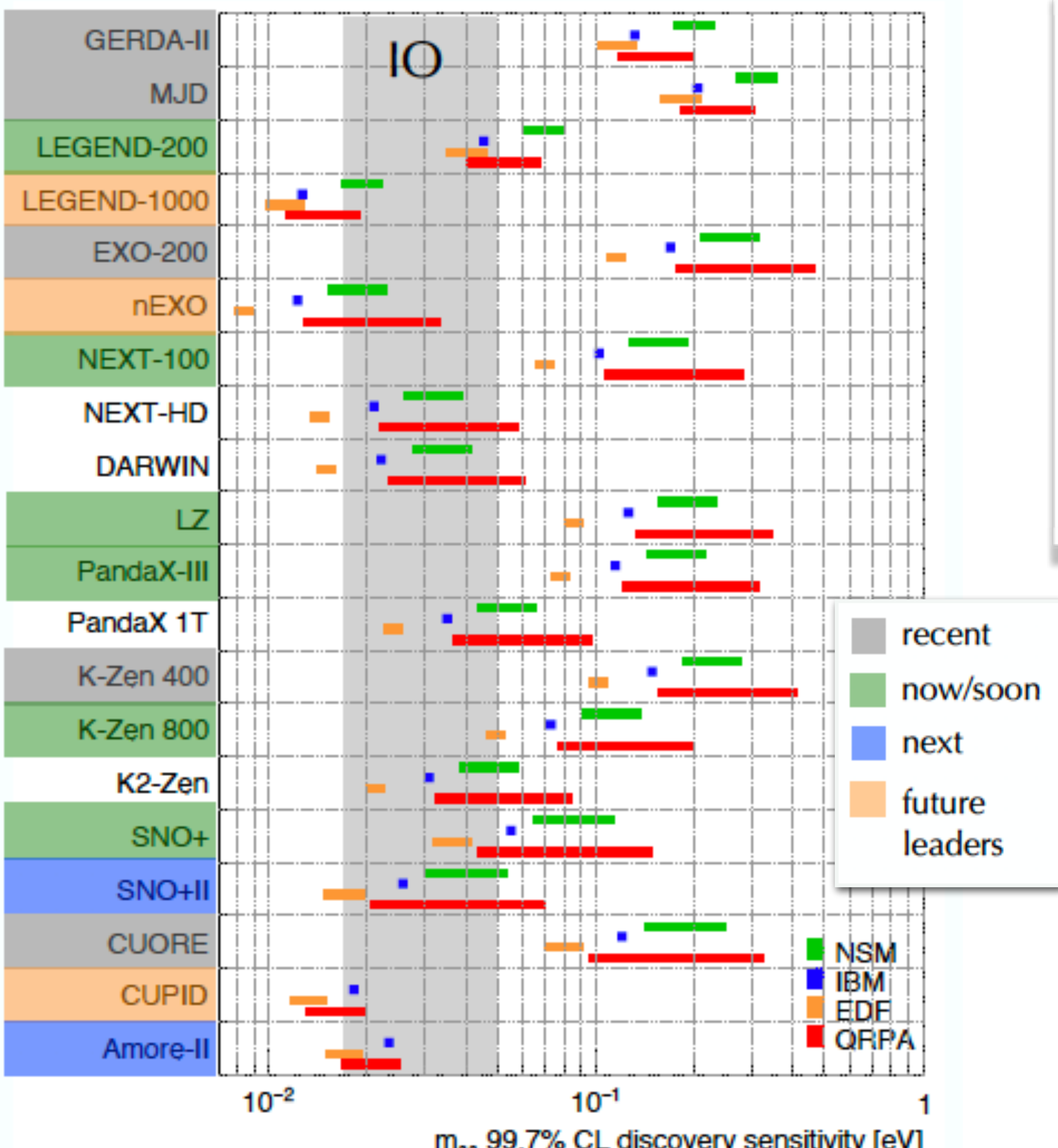
Very Active Program!



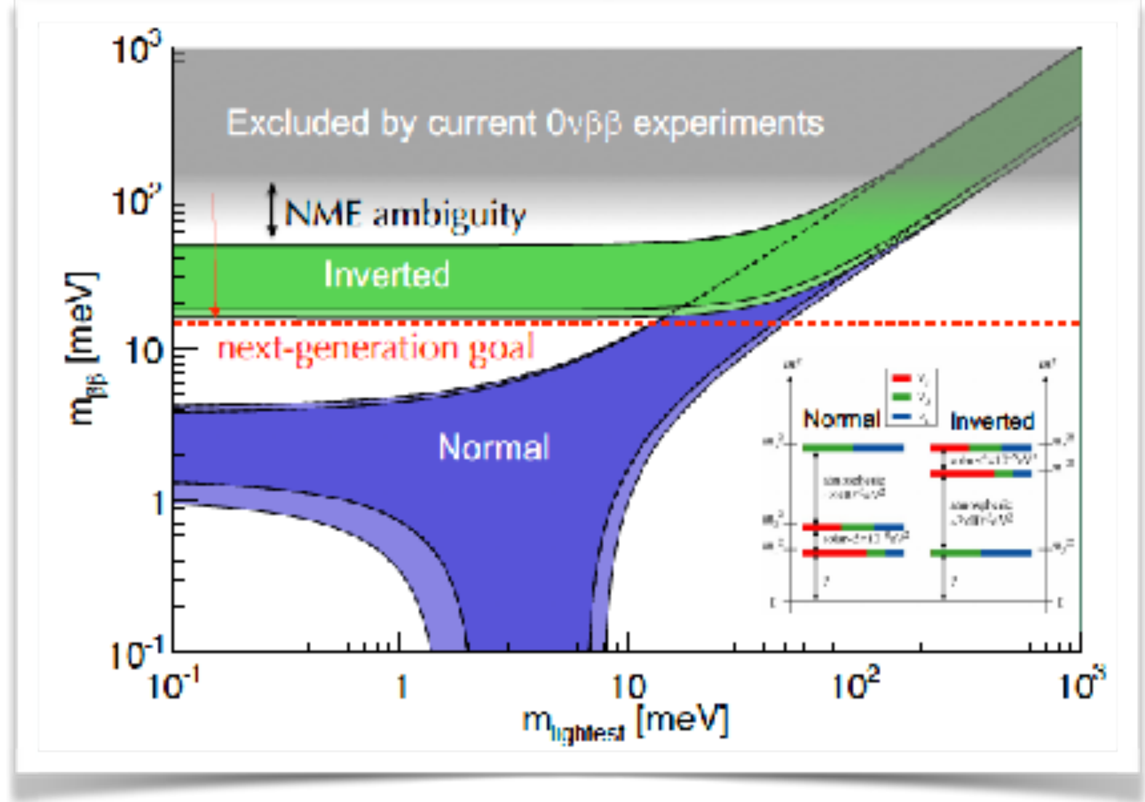


- **Challenges:** large mass to offset long 1/2 lifes; low backgrounds, excellent energy resolution/tracking
- **Multiple techniques:** Bolometers, Scintillators, Trackers, TPCs, Semiconductors
- Multiple Isotopes; larger sizes

Looking Towards Future



(J. Detwiler @ Neutrino2020)



- **Future experiments** aiming for ~2 OoM improvement and cover "Inverted Ordering" region

- A lot to look forward to in the near to far future!

Atmospheric Sector & CPV

Long-Baseline Accelerator Experiments

Long-Baseline Facilities Across the Globe

Current:
NOvA, MINOS+ (US)
T2K (Japan)

Future:
DUNE (US)
Hyper-K (Japan)

Long-Baseline Physics:
Where Are We & What Do we Need?

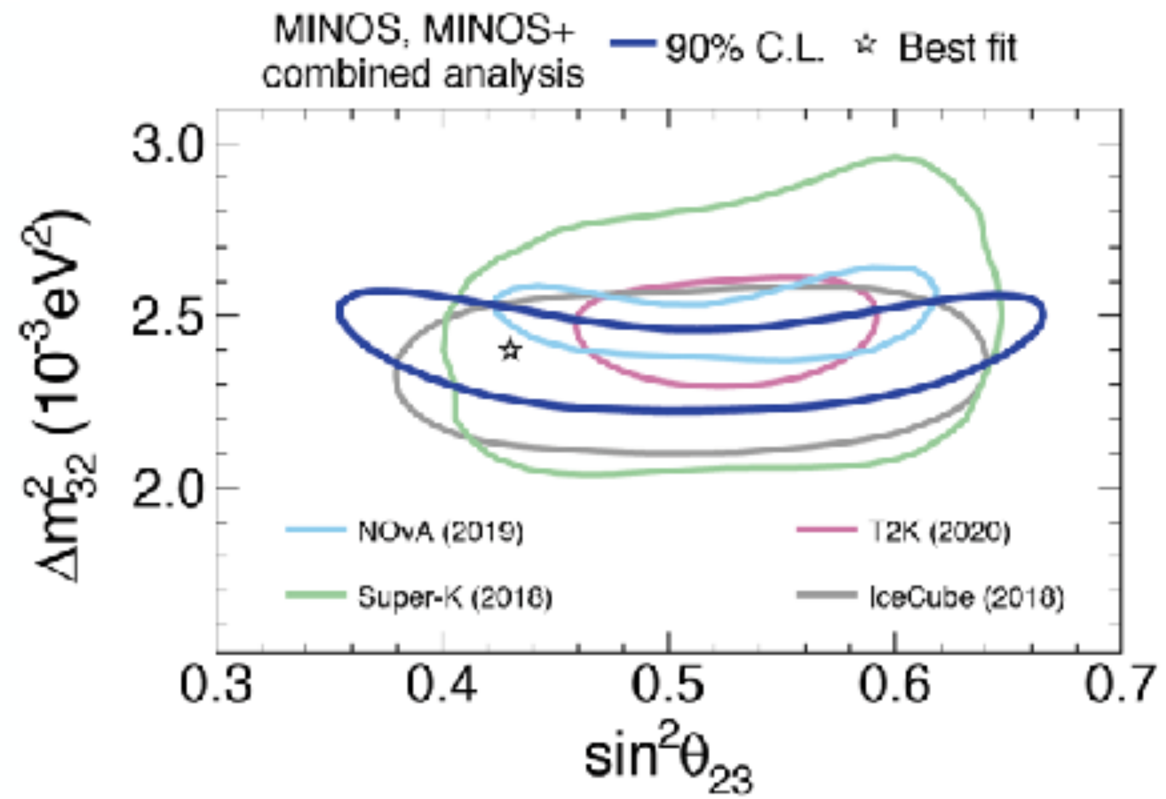
Current

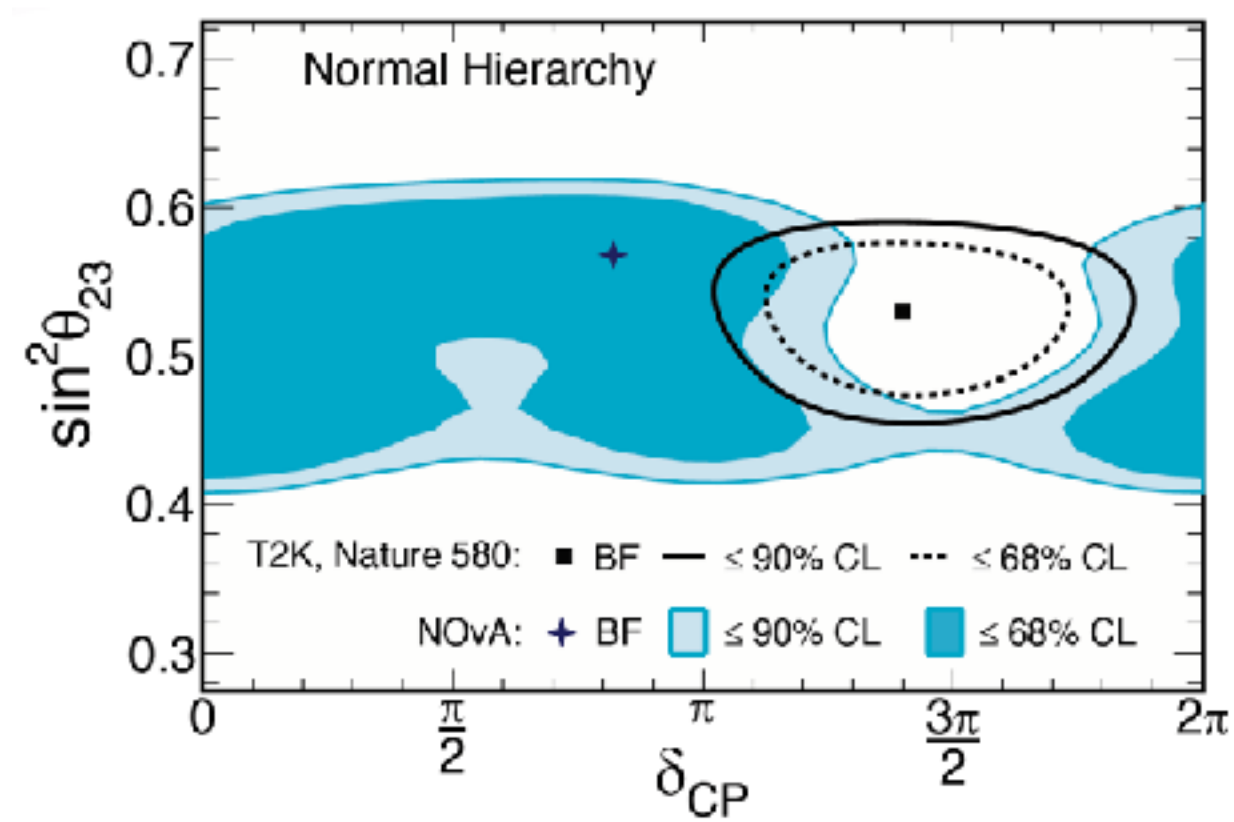
- **Atmospheric Sector** picture is looking consistent across experiments; all experiments prefer Normal Hierarchy and non-maximal mixing
- **CPV**: Clear tension b/n NOvA and T2K

Future

- **Joint fits** underway (T2K+NOvA and T2K+SK)
- **T2K:**
  - ND280 upgrades
  - SK-Gd loading for neutron tagging
  - Analyses with WAGASCI/BayMIND at other off-axis angles
- **NOvA**
  - expects to reach 3 sig hierarchy sensitivity for 30-50% of delta values
  - Reduction in systematics with test beam experiments

> - New Technology, high intensity beams, large volume detectors are needed for precision
> - **Next Generation Experiments: DUNE & Hyper-K**

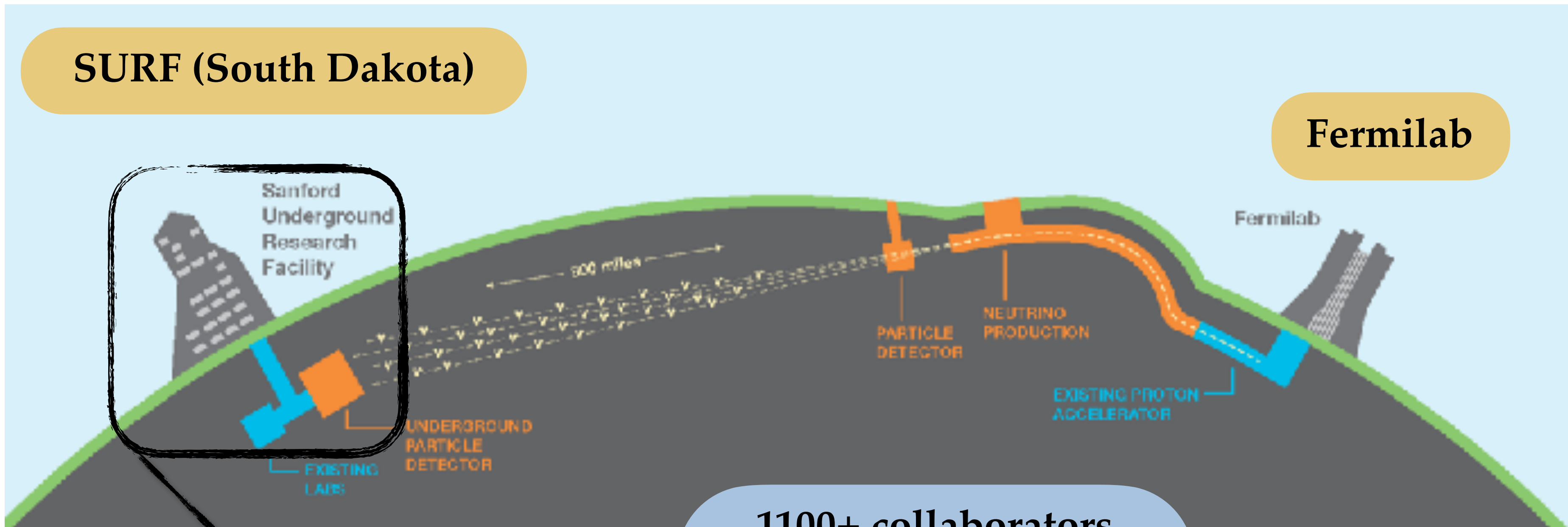




The Deep Underground Neutrino Experiment (DUNE)

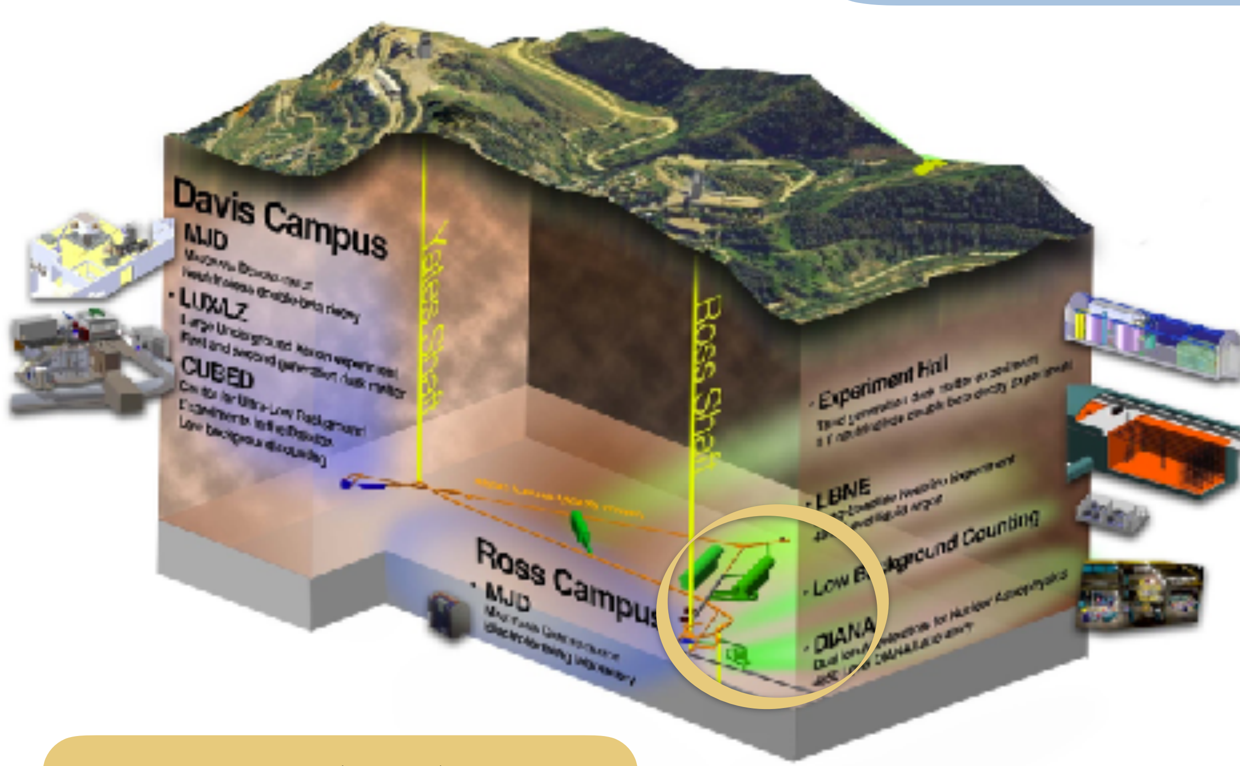
SURF (South Dakota)

Fermilab



- Deep underground location
- 70 kton Far Detector (FD)
- Multiple technologies for the Near Detector (ND)
- MW-scale neutrino beam
- 2024: first module operational
- 2026: first beam

1100+ collaborators
30+ countries
190+ institutes

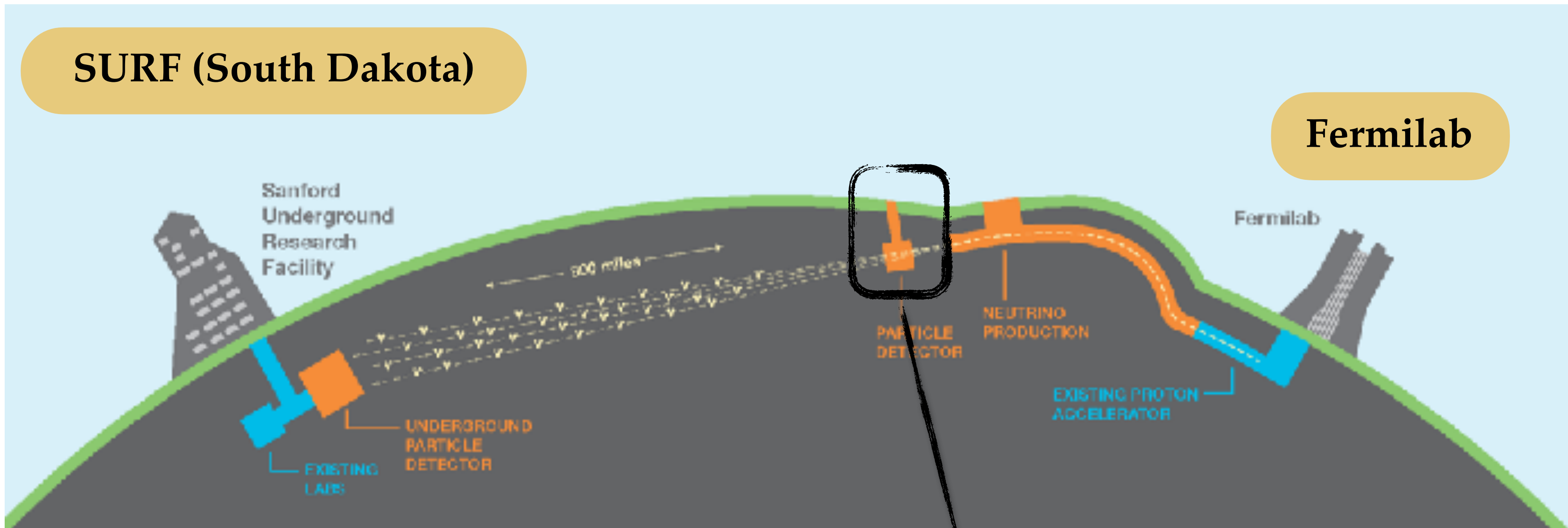


DUNE 1.5 km deep in Home Stake Mine

Very Rich Physics Program

- CP Violation
- Neutrino Mass Hierarchy
- Precision measurements of neutrino oscillation parameters
- Supernova & Astrophysics
- Nucleon Decay (e.g. $p \rightarrow K^{+}\nu$)
- Many BSM searches

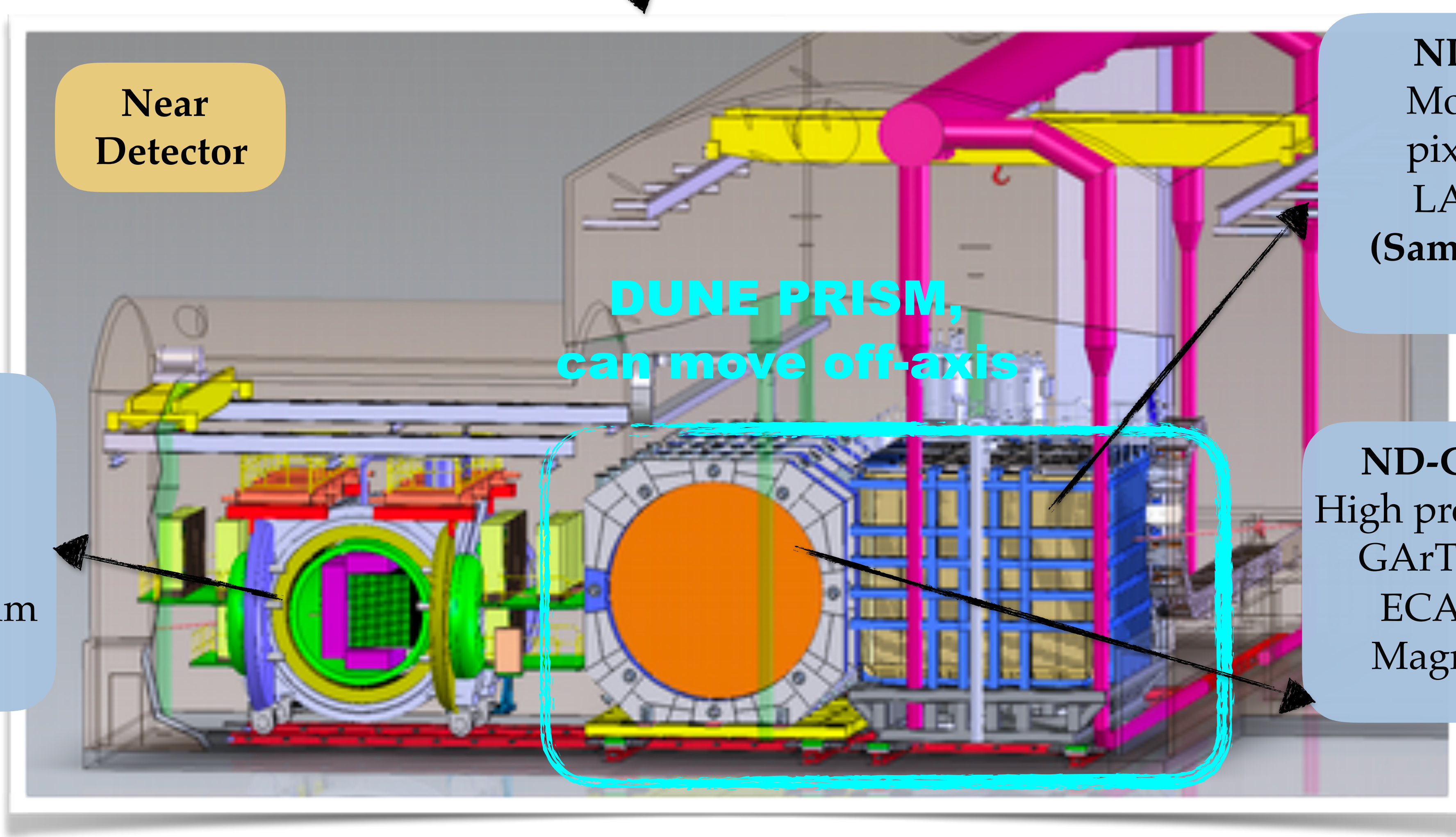
DUNE Near Detector



- located at **574 m** from neutrino beam target
- Multiple technologies

Primary Goals

- characterize neutrino beam
- constrain cross section uncertainties for oscillation analysis

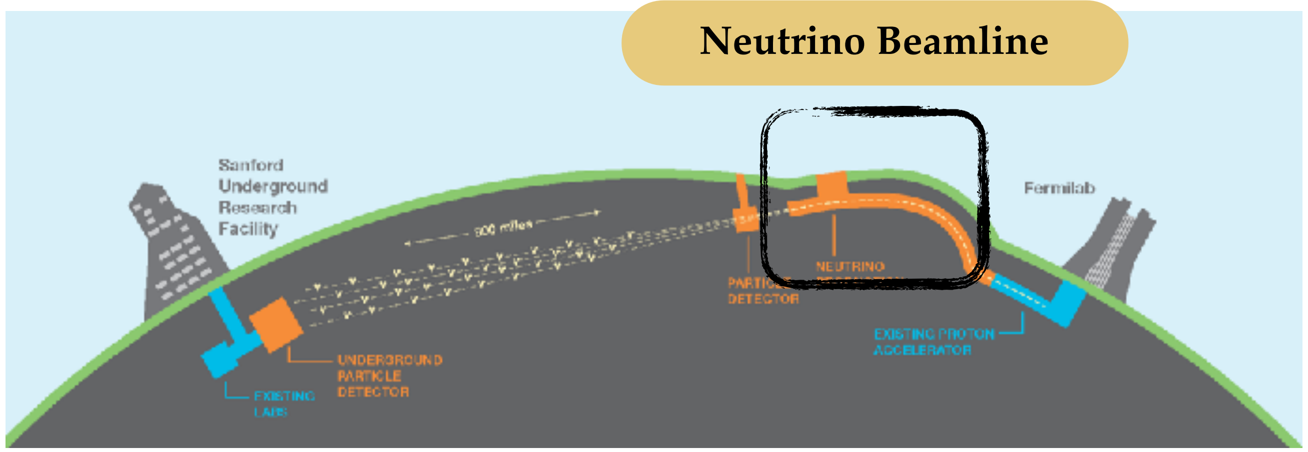


SAND
Tracker,
ECAL,
Magnet,
On axis beam monitor

ND-LAr
Modular,
pixelated
LArTPC
(Same as FD)

ND-GAr
High pressure
GArTPC,
ECAL,
Magnet

DUNE Neutrino Beam

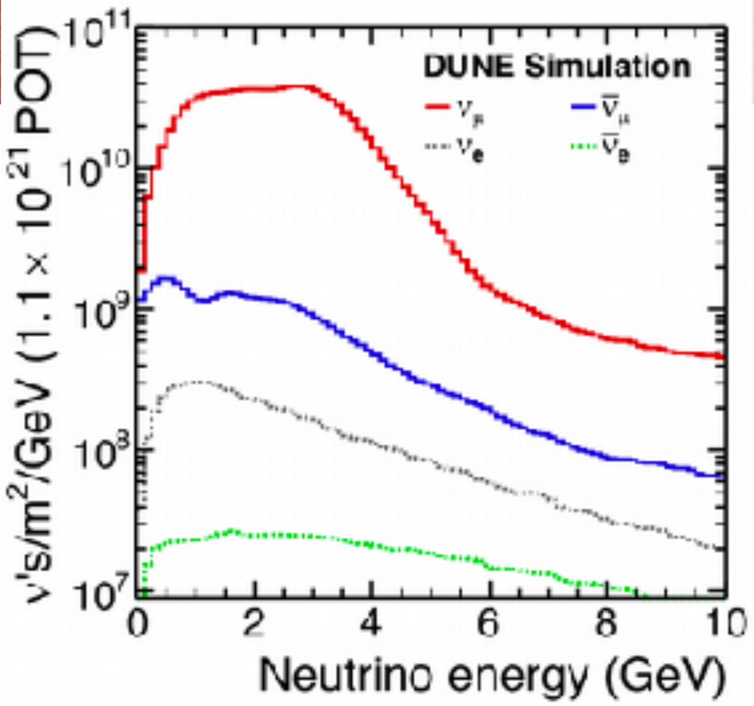


Proton Improvement Project (PIP-II)

60-120 GeV Proton beam

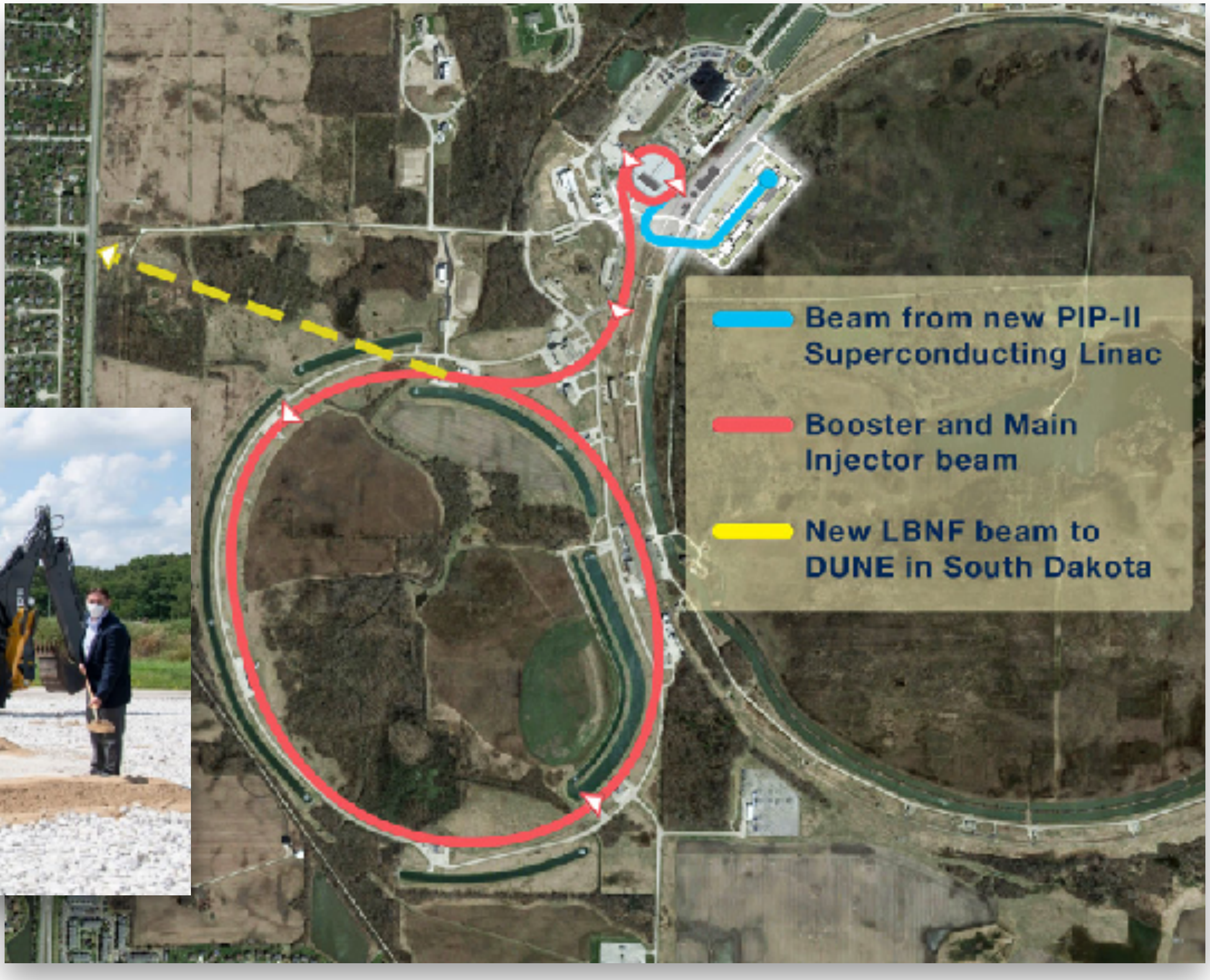
1.2 MW, upgradable to 2.4 MW

Goal: first MW-scale beam to SURF in 2026

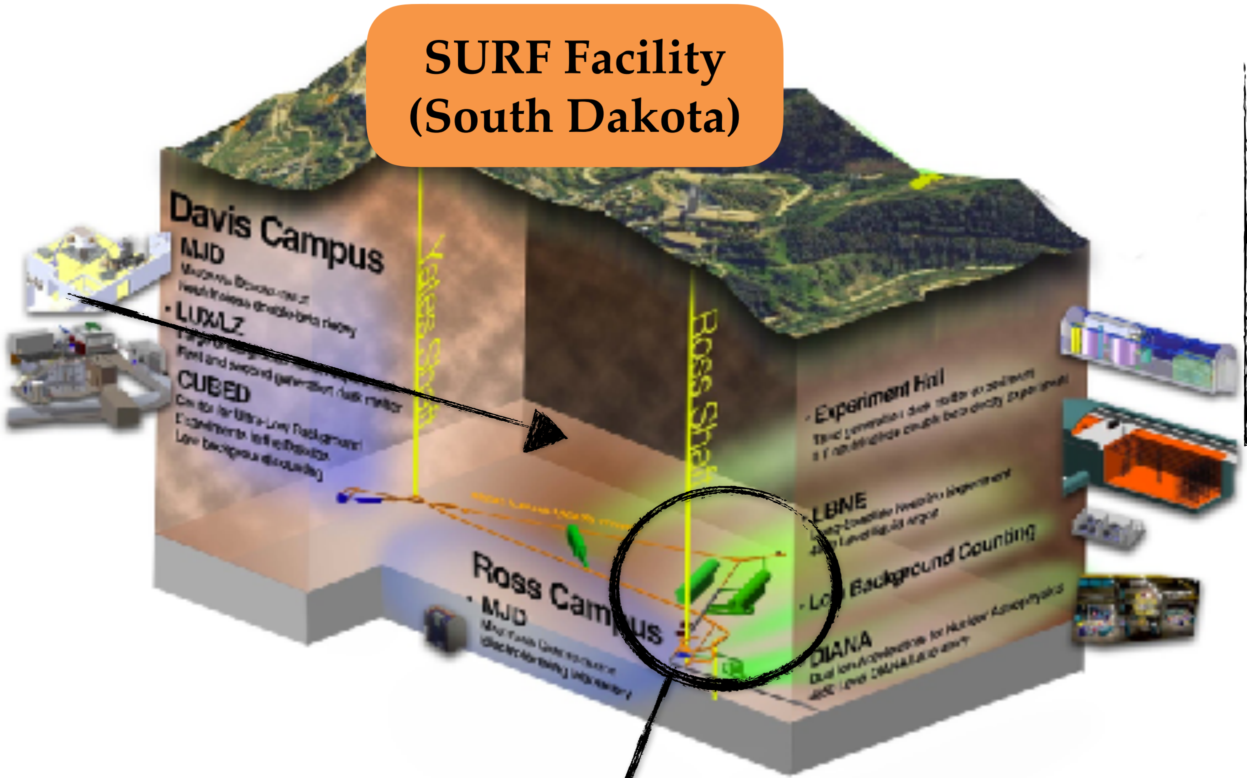


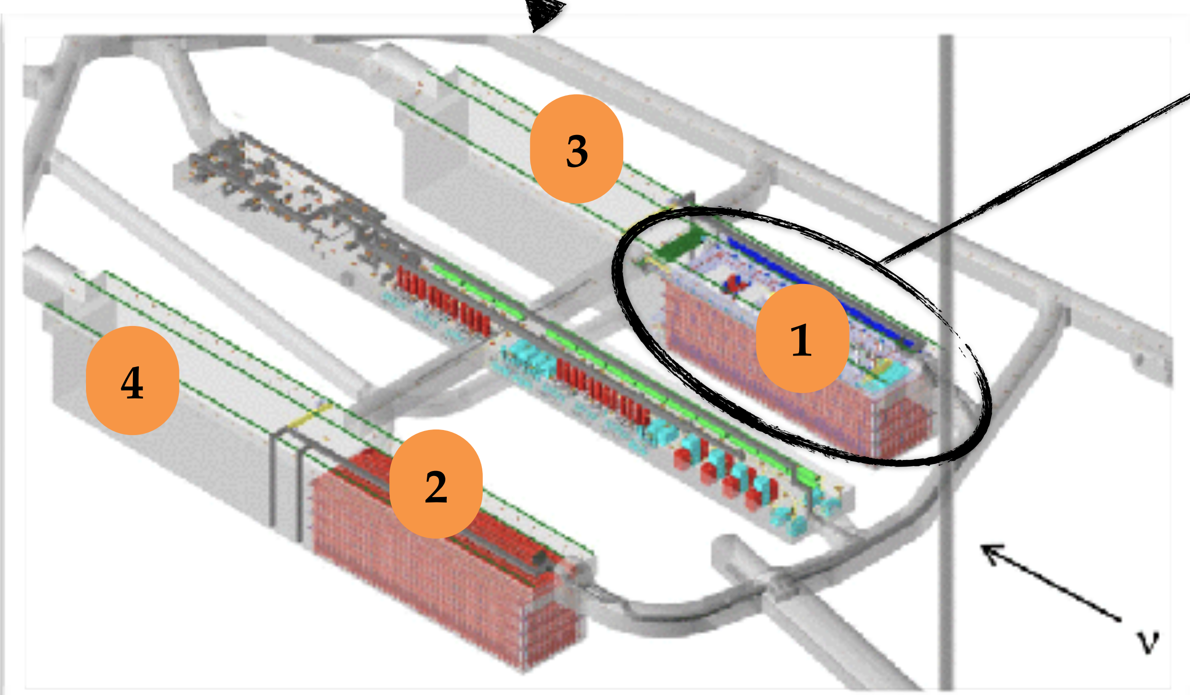
Milestones

July 2018: DOE CD-1 Approval
March 2019: PIP-II ground breaking
July 2020: Construction ground breaking



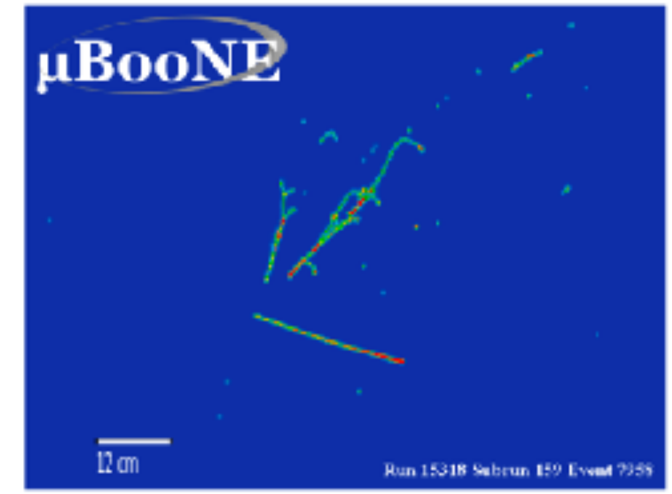
The DUNE Far Detector: Biggest LArTPC ever to be built!

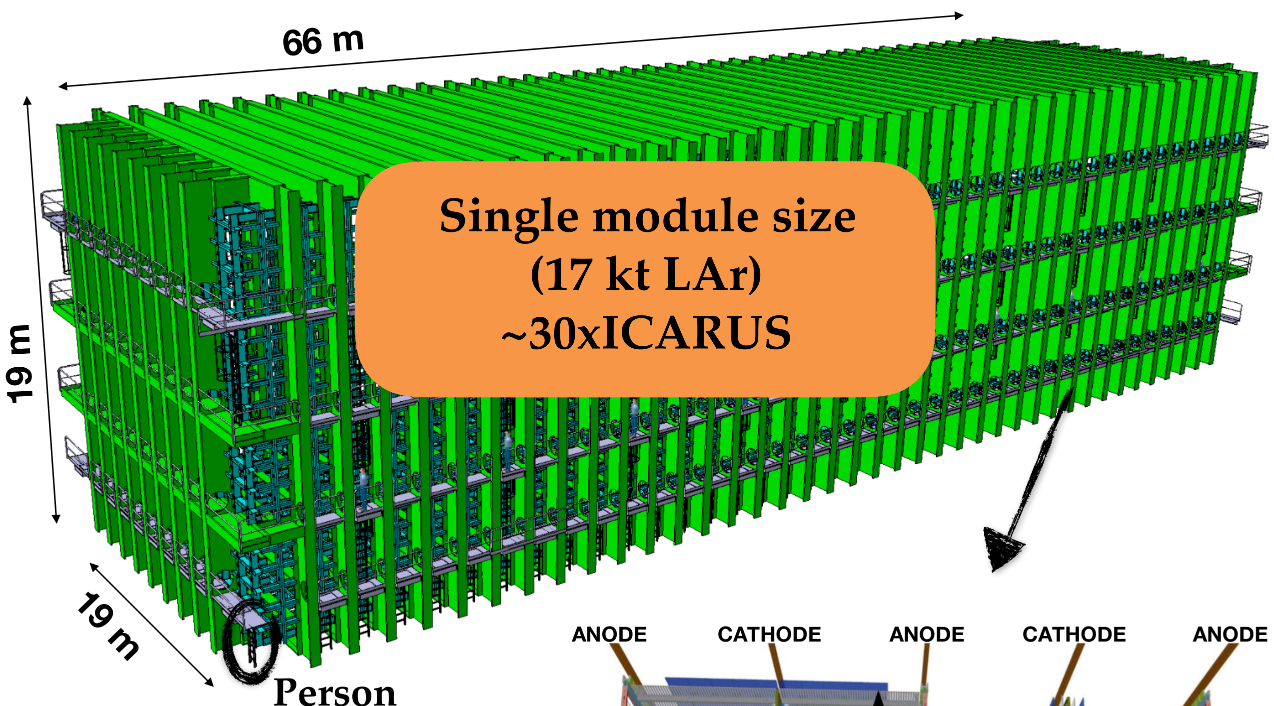




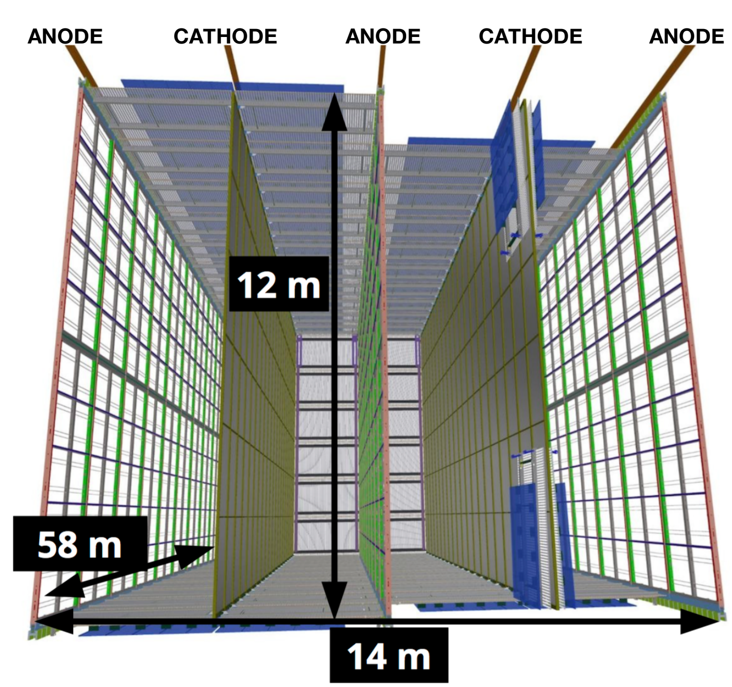
2 caverns, 4 detectors,
flexibility in design

Why LArTPC?
High resolution images
Fine granularity
Calorimetry
Scalability
LAr is cheap!

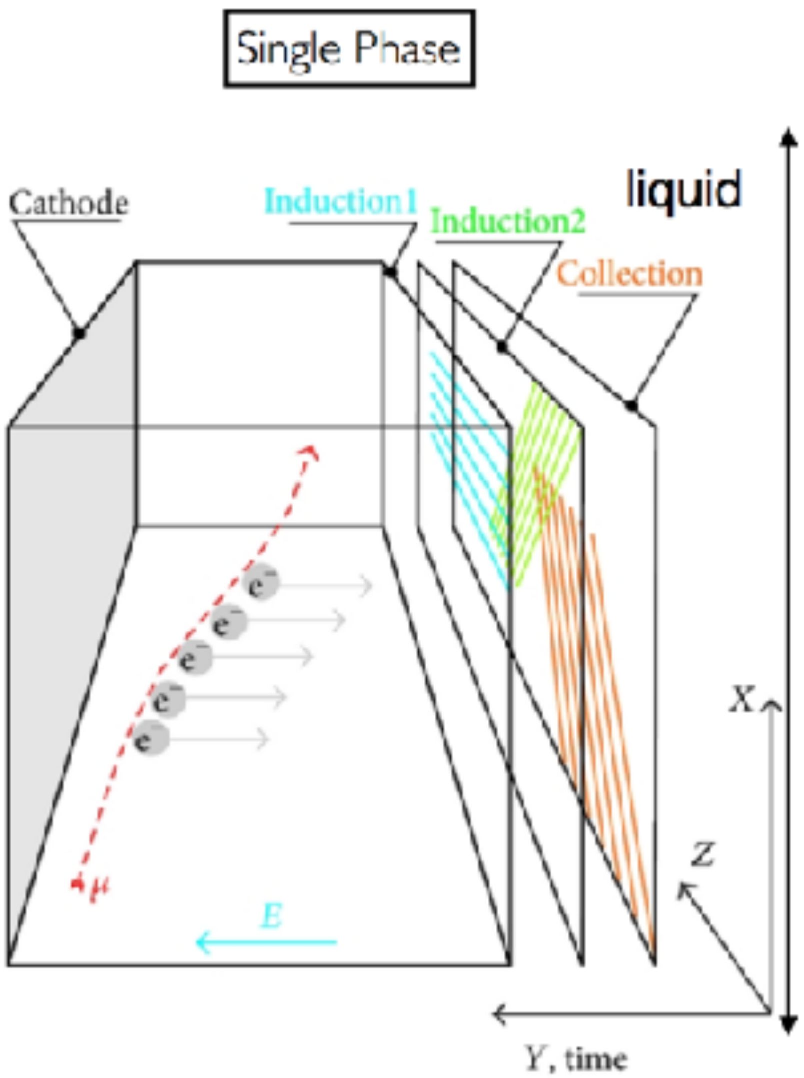


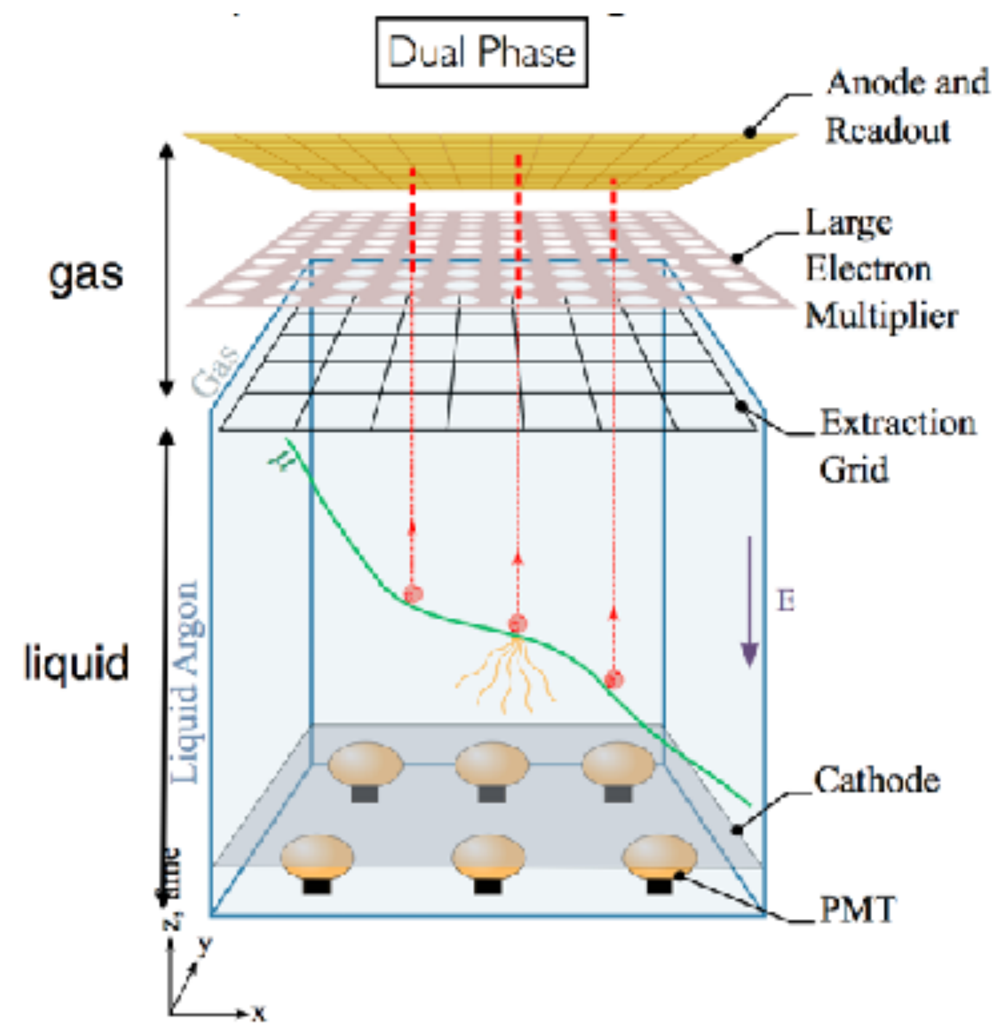


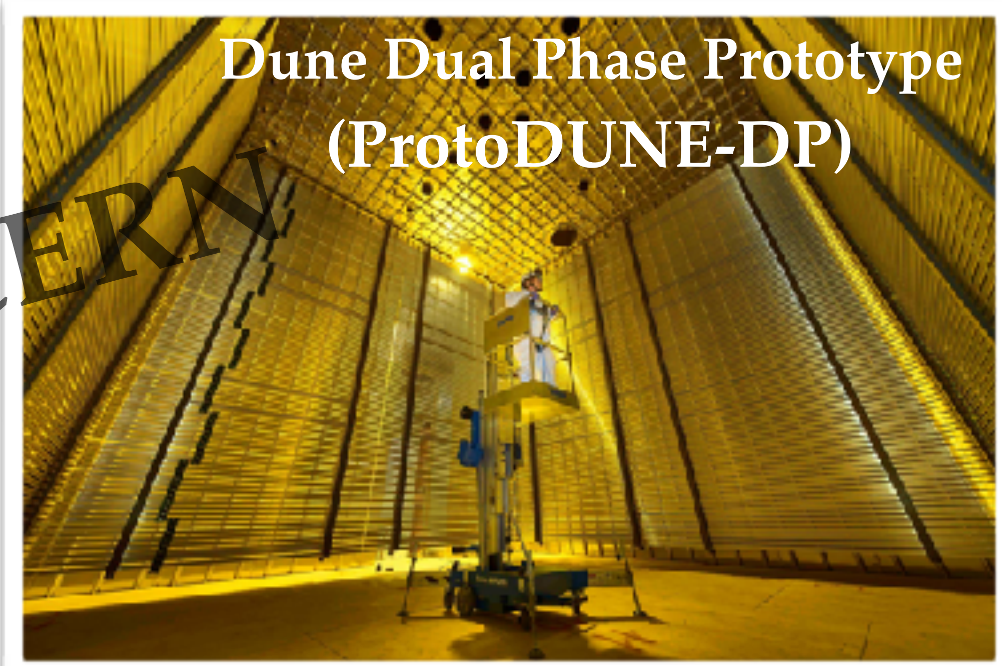
Highly segmented
detector
(single phase
technology)



Single & Dual Phase Technology for DUNE

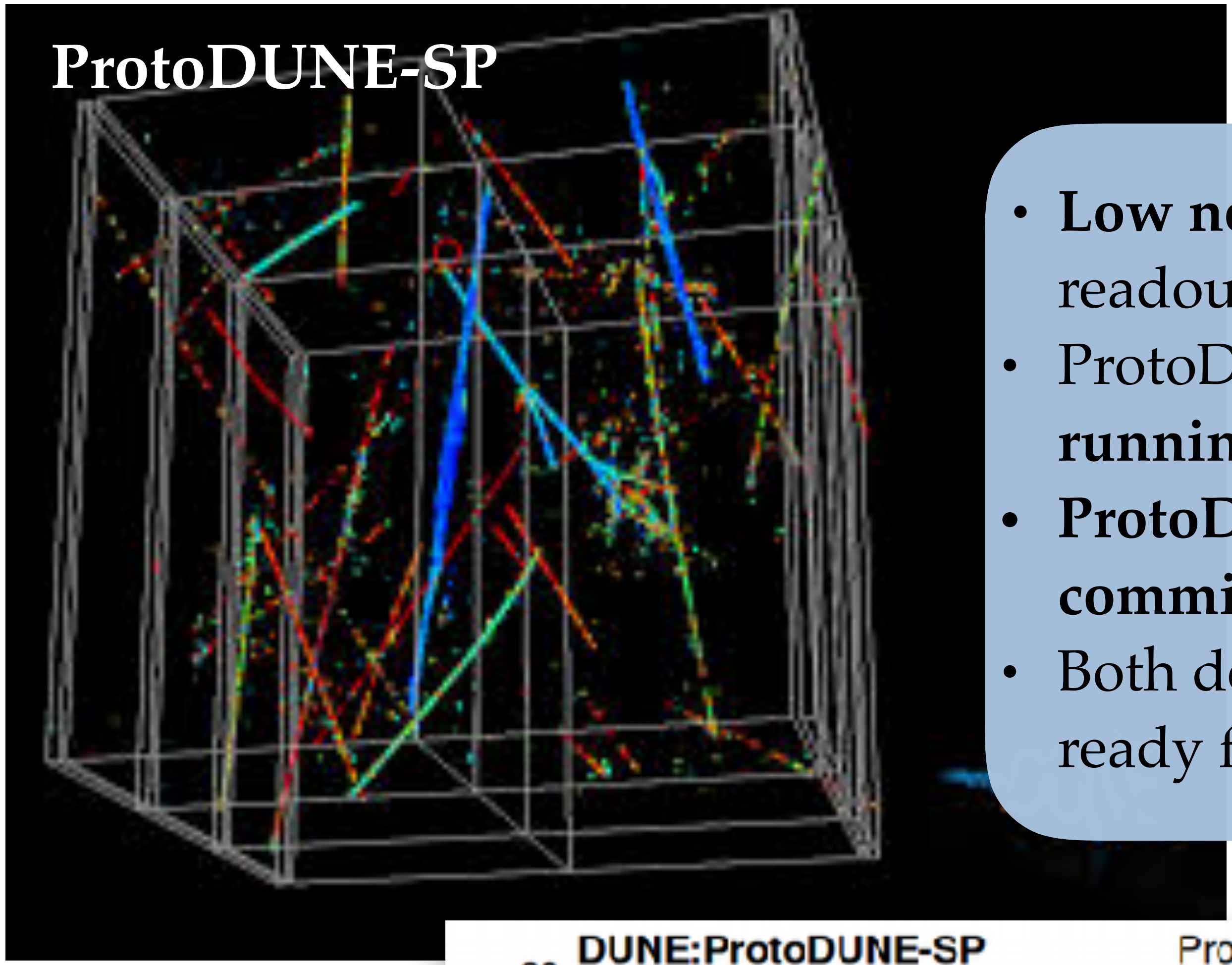




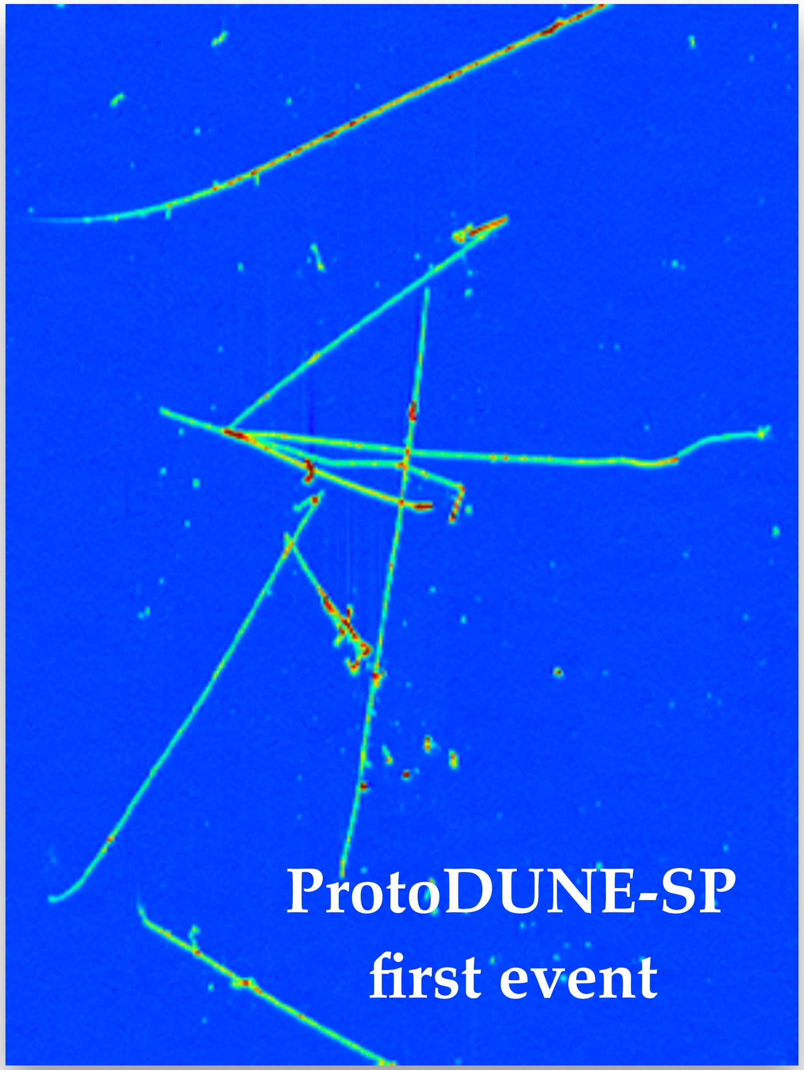


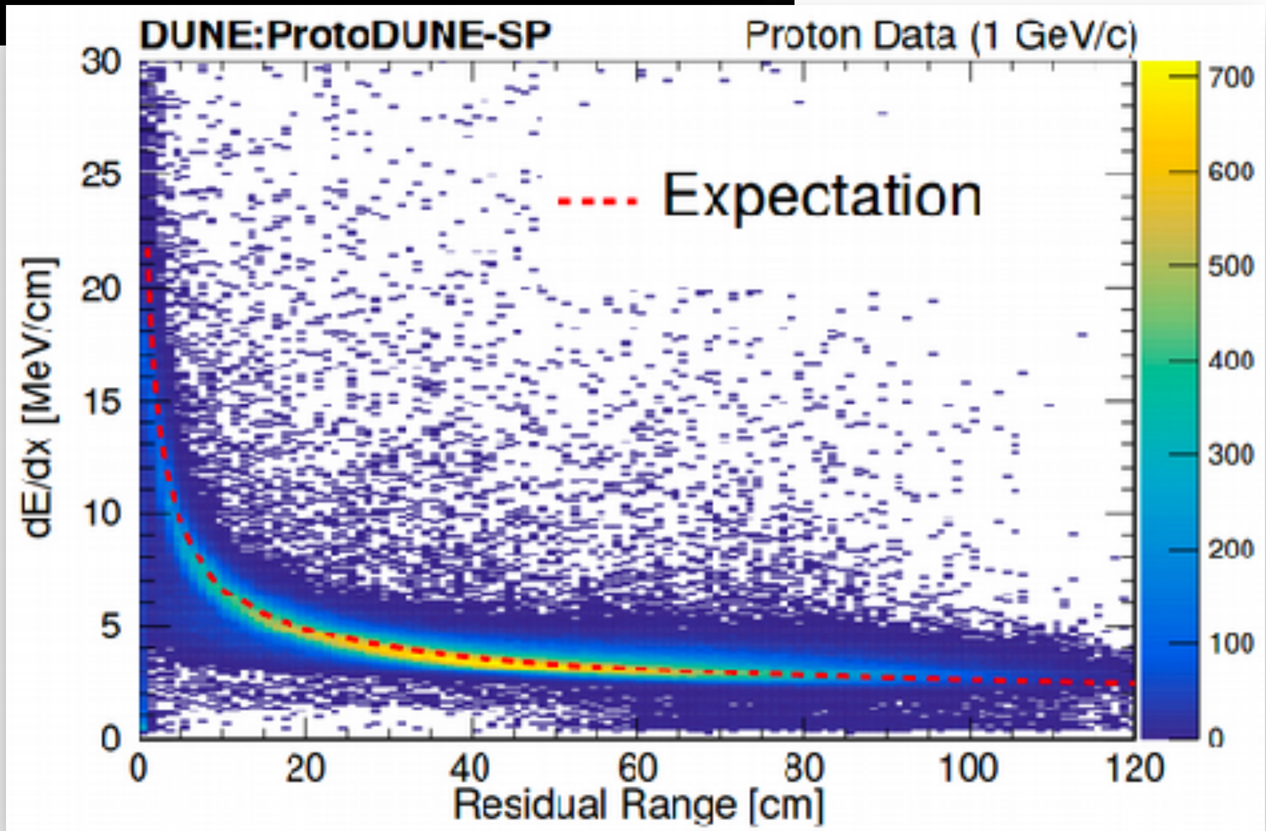
ProtoDUNES @CERN

ProtoDUNEs Status



- **Low noise** observed on all readout planes in SP
- ProtoDUNE-SP **stable running** since 2018
- **ProtoDUNE-DP commissioning** phase
- Both detectors getting ready for **Phase 2**





First Results on calibration/ reconstruction from ProtoDUNE-SP out soon!

The DUNE Far Detector: Biggest LArTPC ever to be built!

DUNE TDRs

SURF excavation

DUNE Overall Status

PIP II construction ground broken in July 2020

SURF Far Site excavation continues

DUNE TDRs on ArXiv (2019)!

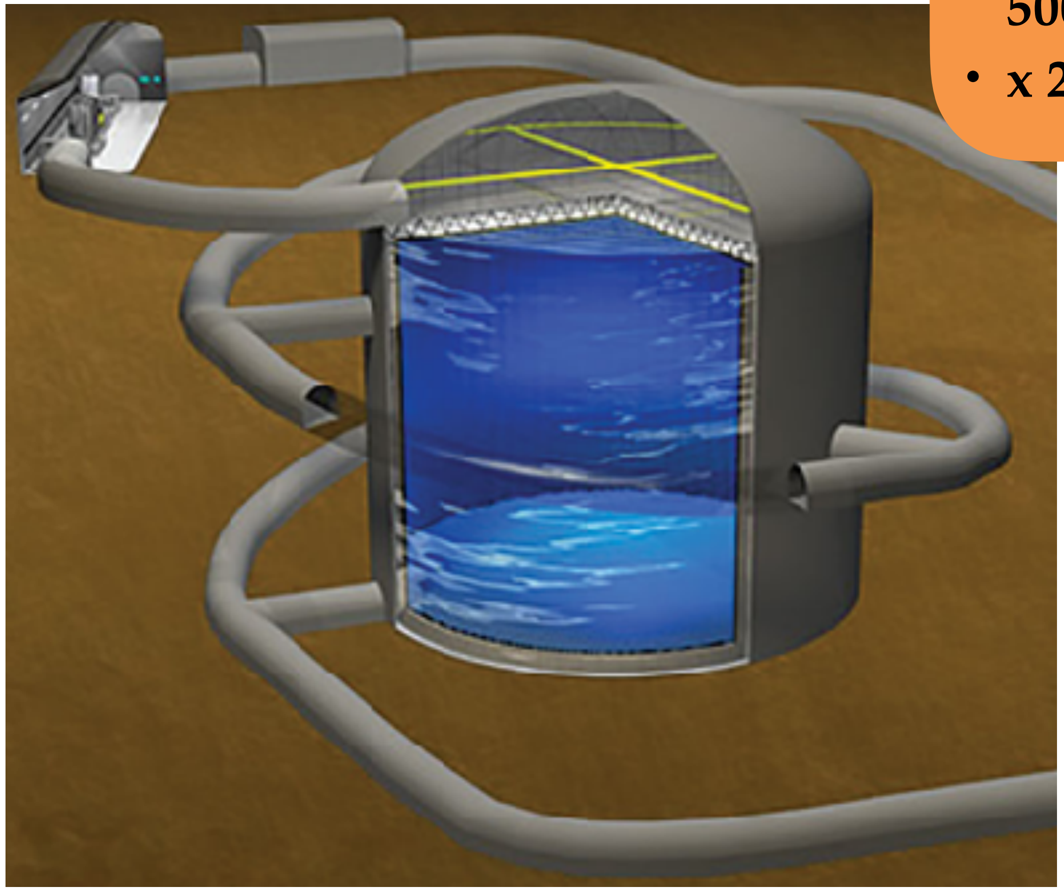
Near Detector towards CDR

Far Detector Prototyping efforts (ProtoDUNEs) actively underway: both R&D and physics! Moving into phase 2

The Hyper-K Experiment

390 collaborators
18 countries
82 institutes

- x 8.4 fiducial volume (SK → HK)
- x 2.6 beam power
- J-PARC upgrade: 500 kW → 1.3 MW
- x 20 Statistics



Highlights

- Very Rich Physics Program like DUNE
- Hyper-K under construction
- Operation to start in 2027
- Feb. 2020: First year construction budget approved
- May 2020: U. Of Tokyo and KEK sign MOU
- Two Near Detectors: upgraded T2K ND280 and IWCD

Hyper-K Near Detectors

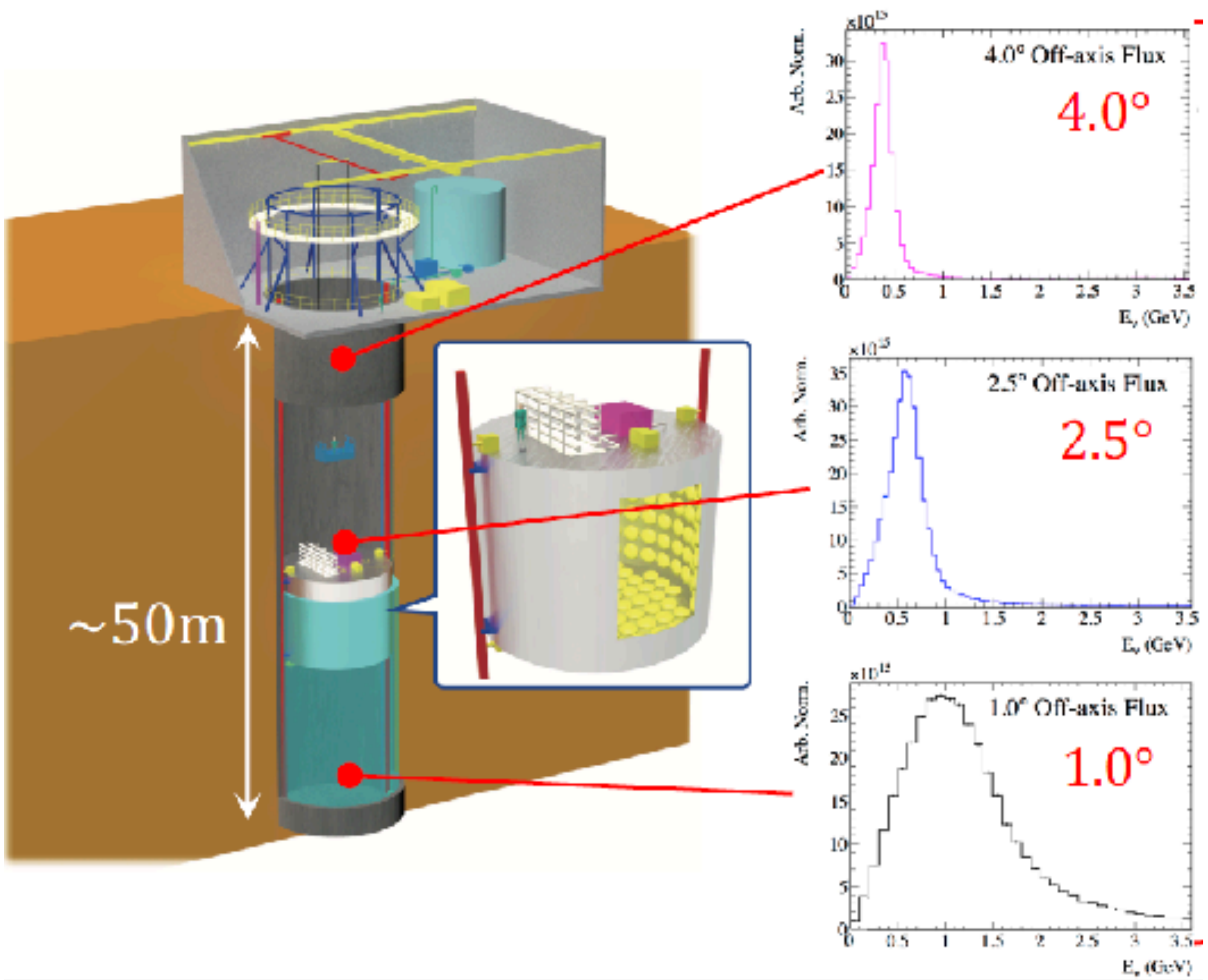
(..+ a lot of R&D towards near and far detectors underway; not covered here)

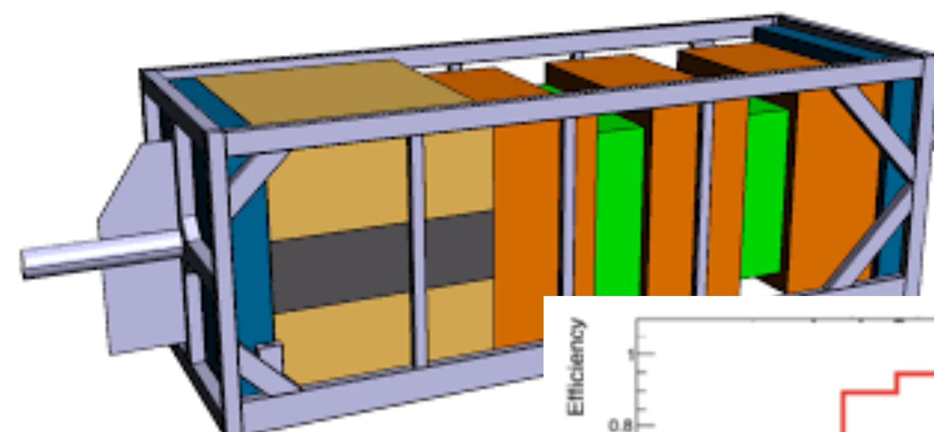
Intermediate Water Cherenkov Detector (IWCD)

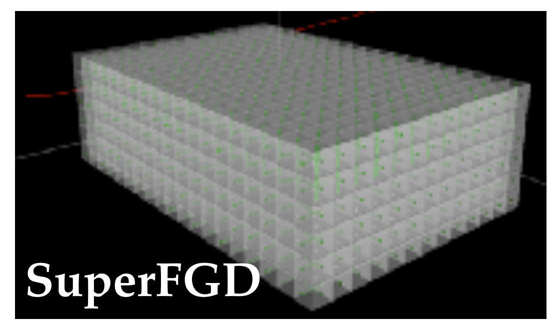
- 1 kton scale Water Cherenkov detector at ~1 km baseline
- Detector can vertically move for different off-axis angle measurements

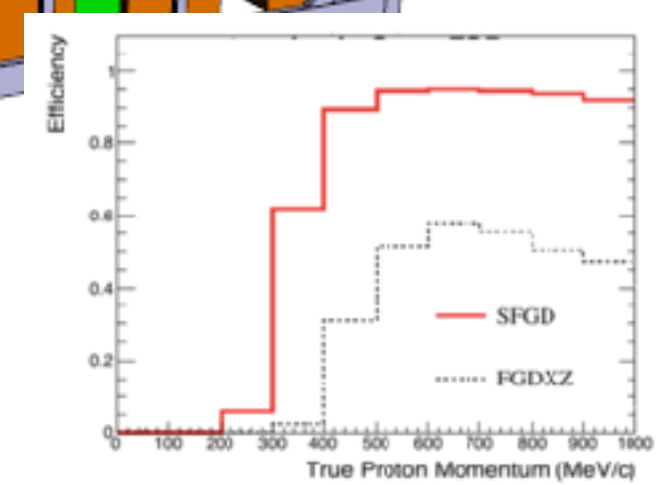
ND280 Upgrades

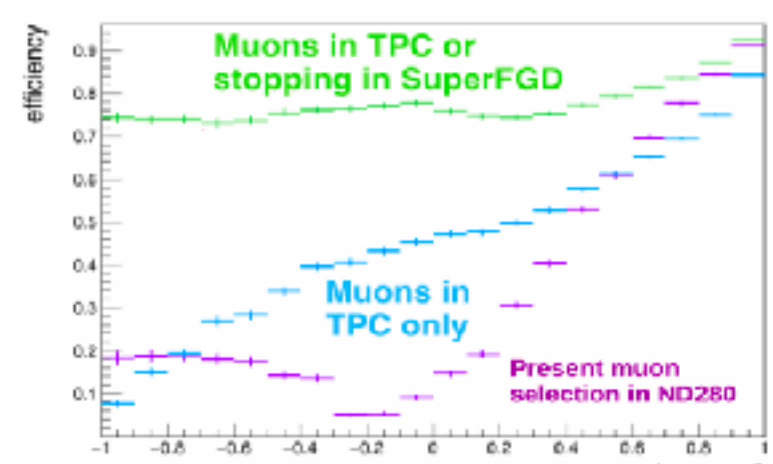
- T2K's near detector will be updated and used by Hyper-K
- Upgrade to SuperFGDs
- Improved short-track efficiency; high angle acceptance



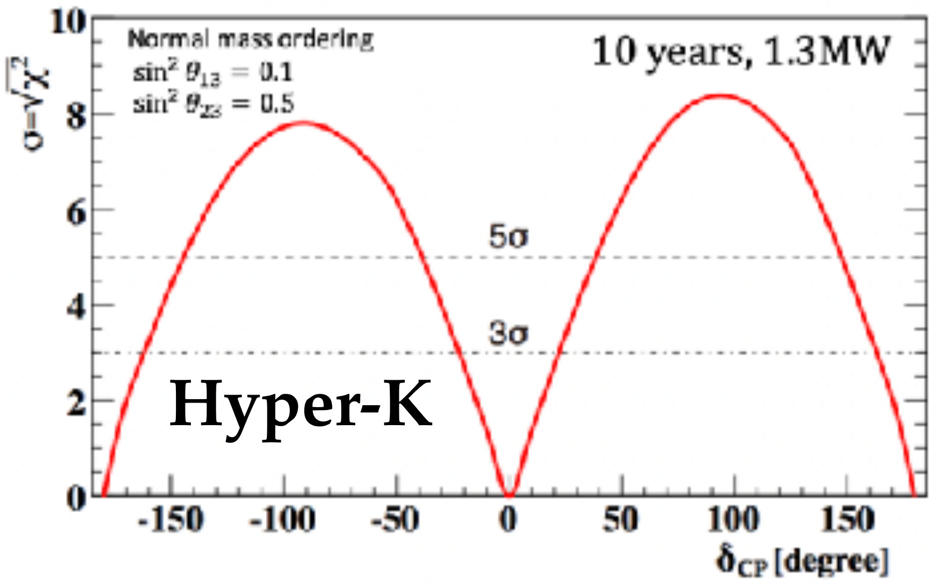




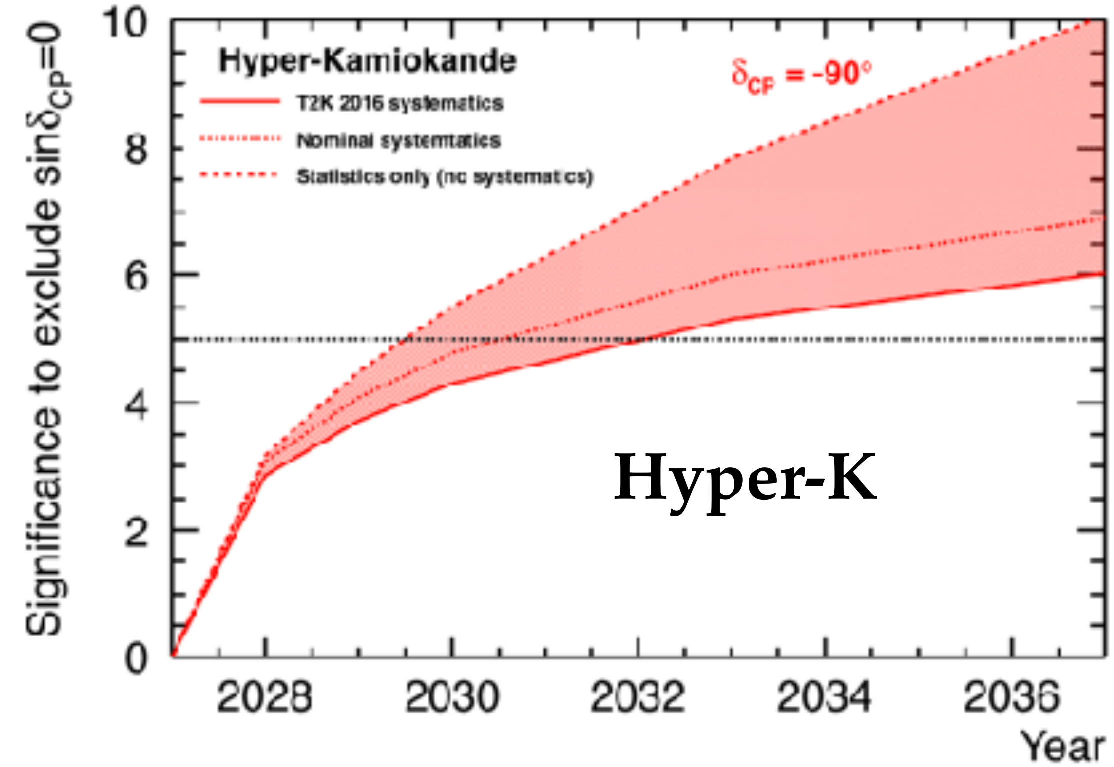


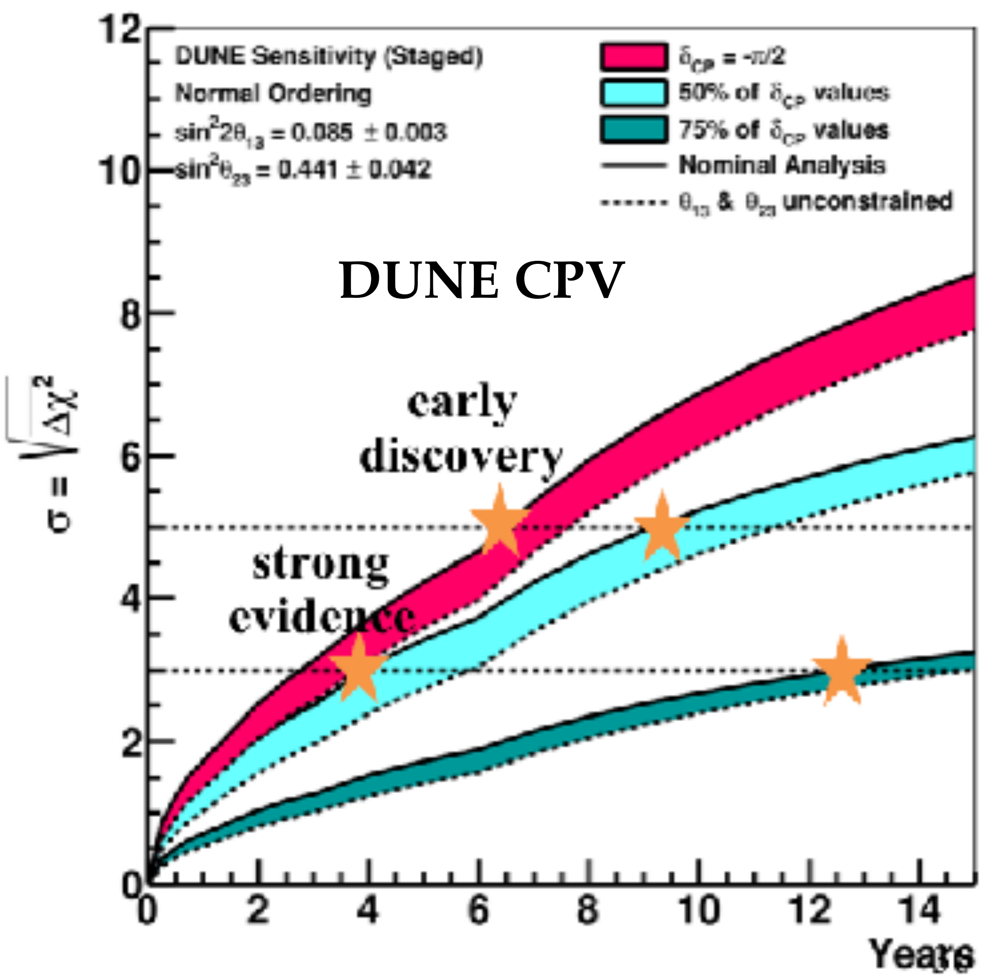


DUNE & Hyper-K Sensitivites



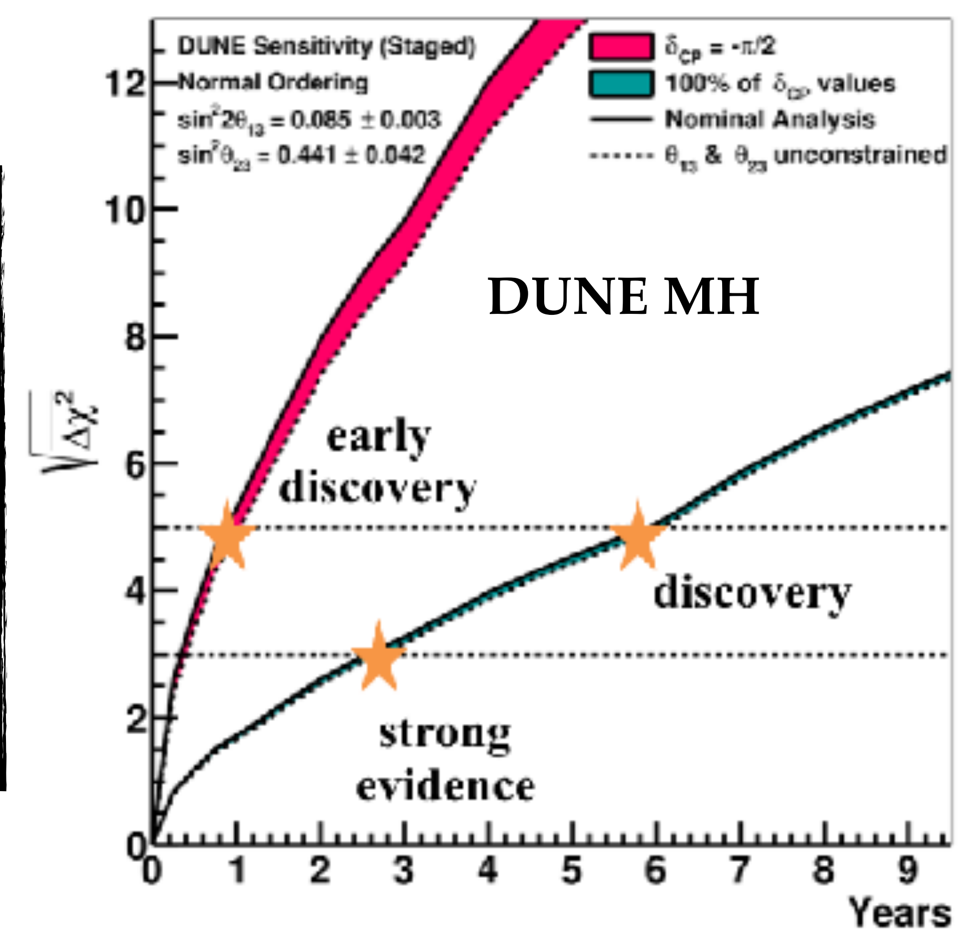
Near Detector designs to reduce systematics for Hyper-K significantly





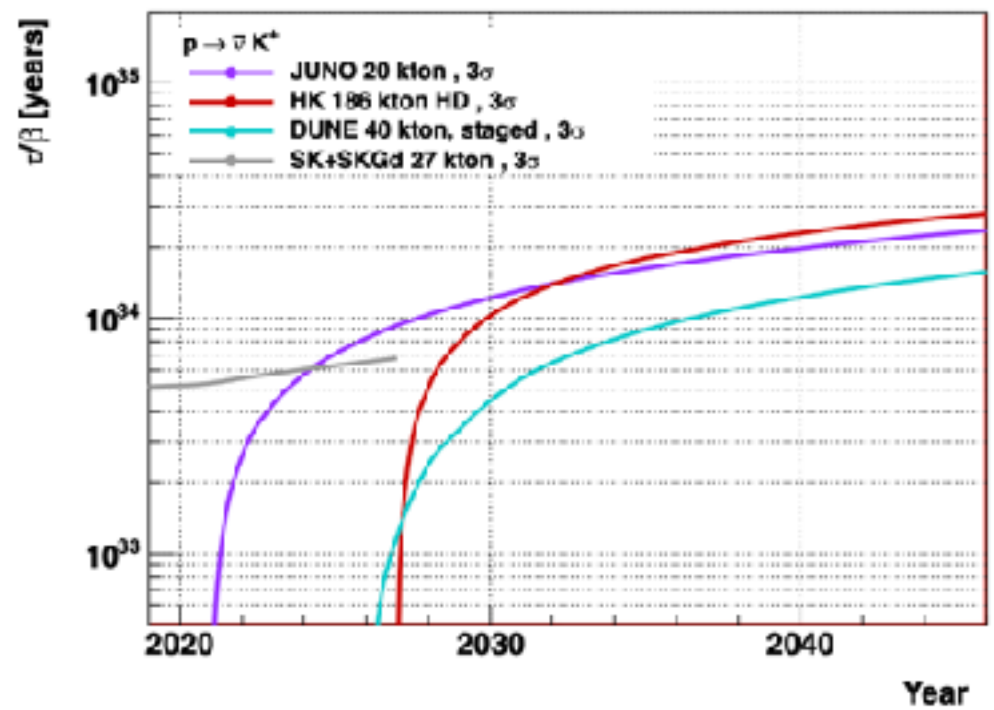
DUNE

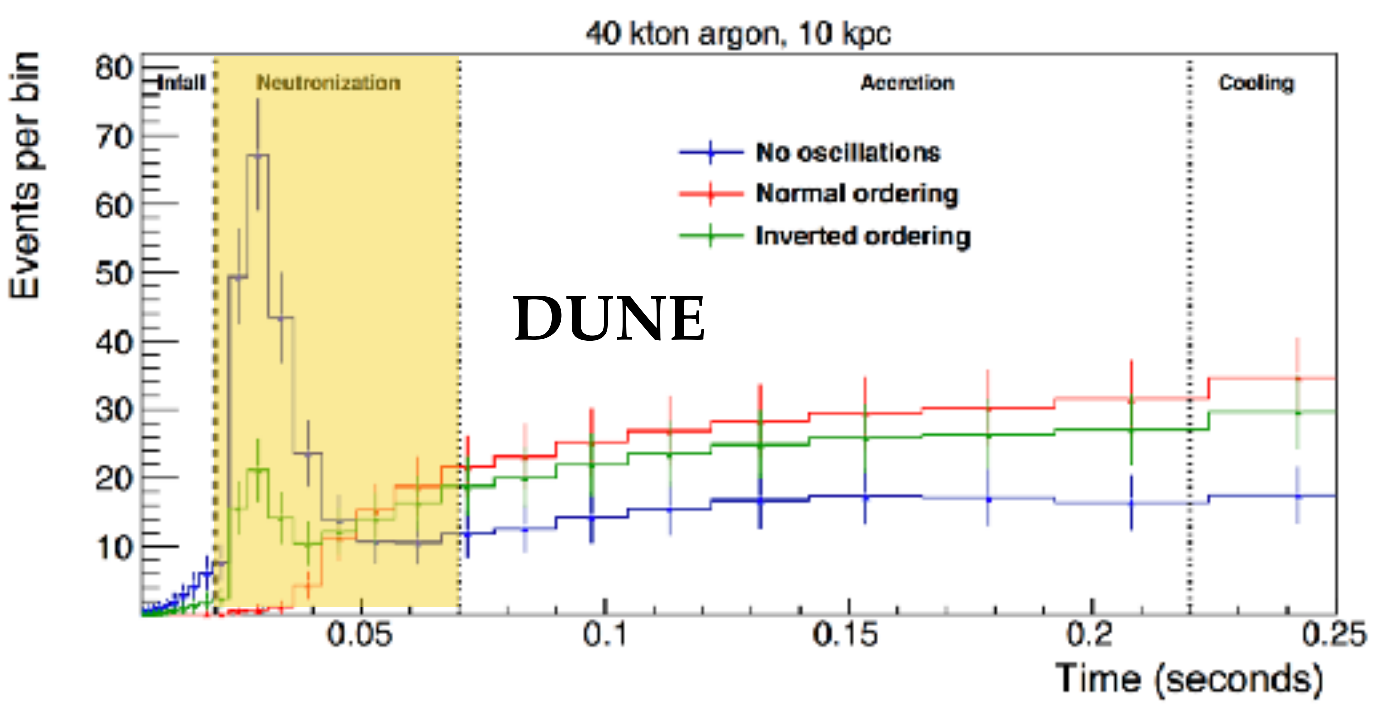
- Staged scenario
- Assumes equal running in neutrino and antineutrino mode
- CPV: 65% of δ range at 3σ in 7 years
- MH: $> 5\sigma$ regardless of other parameter choices



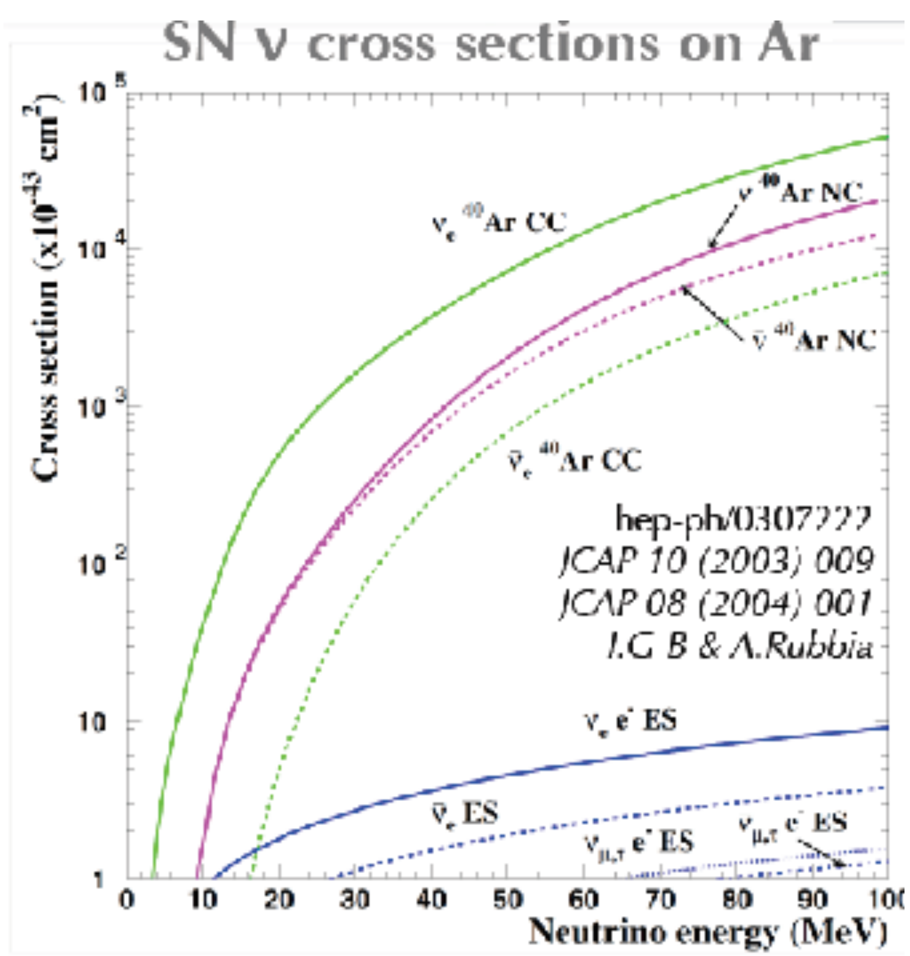
Beyond Long-Baseline Oscillations

- Nucleon decay searches
  - Hyper-K can extend proton decay search by an order of magnitude
- Supernovae physics
  - DUNE has a unique capability to detect SNB *electron neutrinos:* CC ν_e capture of SNB neutrinos on Ar
    $\nu_e + Ar^{40}(18) \rightarrow K^{40}(19) + e^-$
- Solar Neutrinos
- BSM Physics (sterile searches, non-standard interactions)



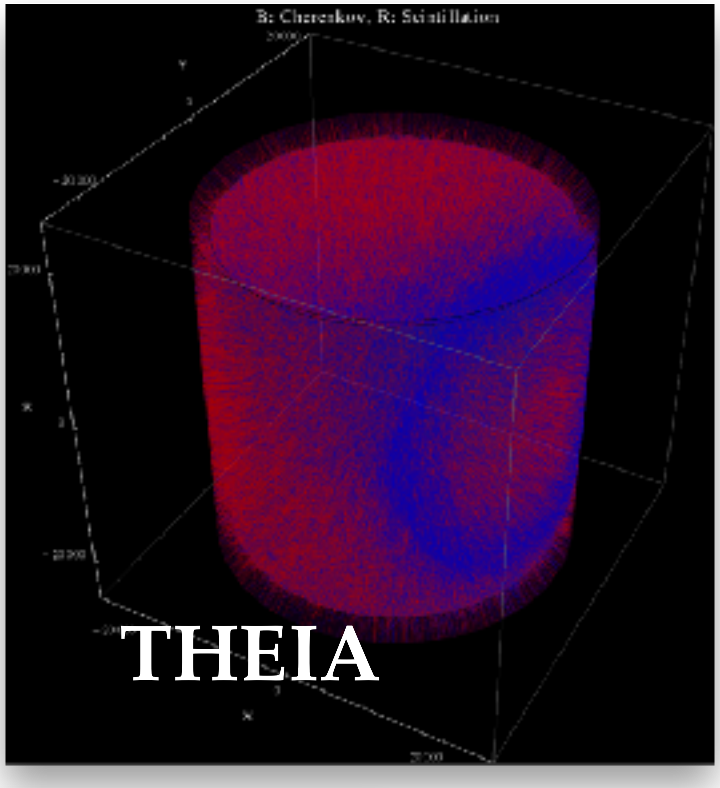


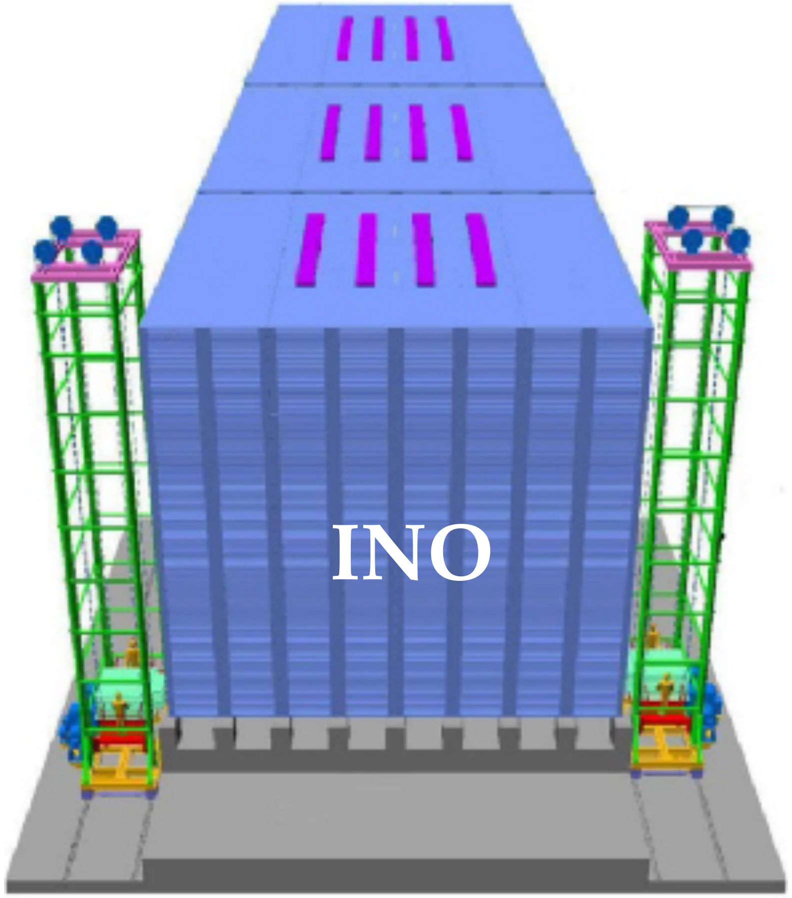
Early development of the supernovae signal is sensitive to neutrino mass ordering

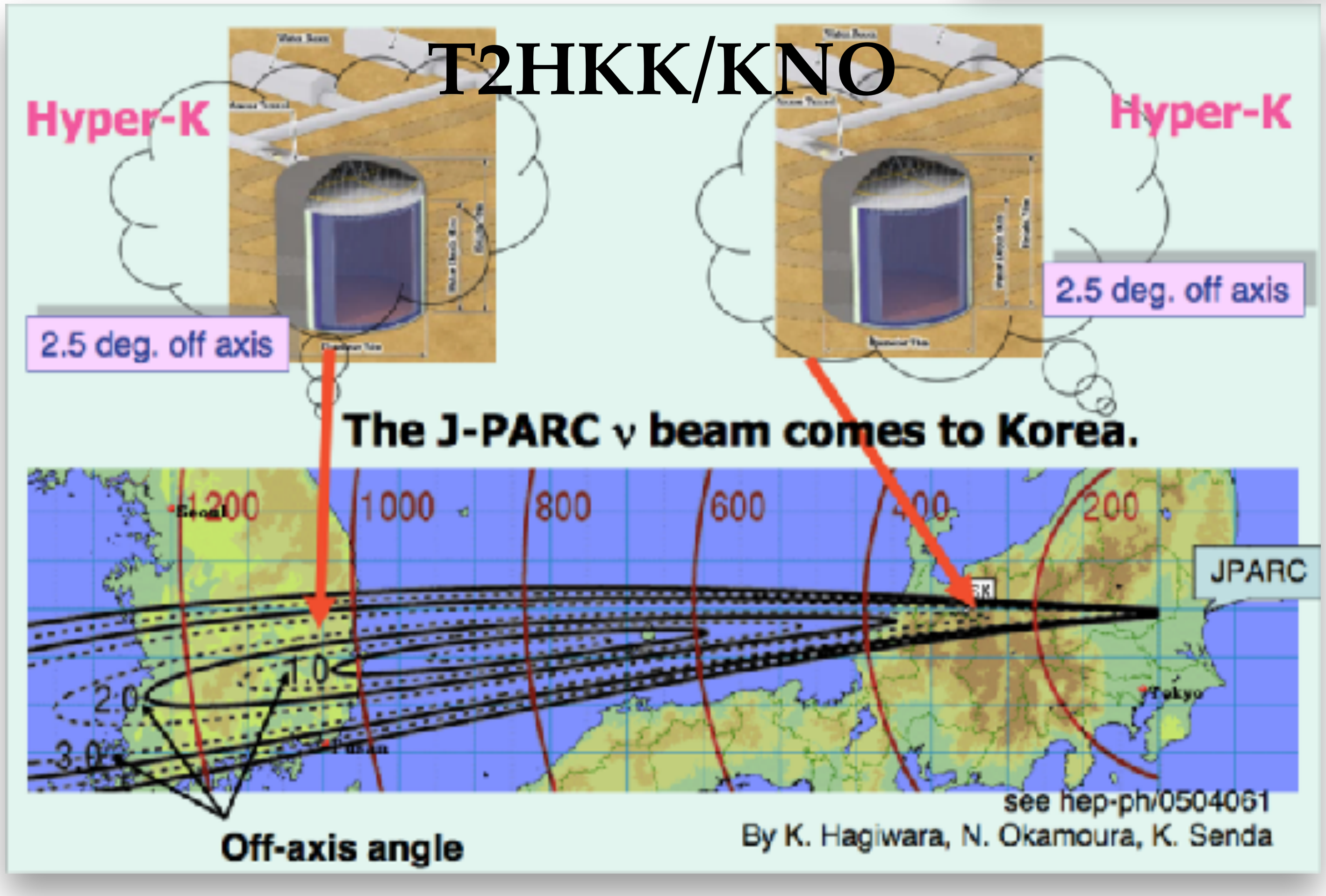


Beyond Next Generation

- More like **observatories**, very broad physics programs
- Precision tests of 3-flavor mixing, new physics, and much more than just oscillation experiments
- Exact goals will depend on where we will be with next generation!



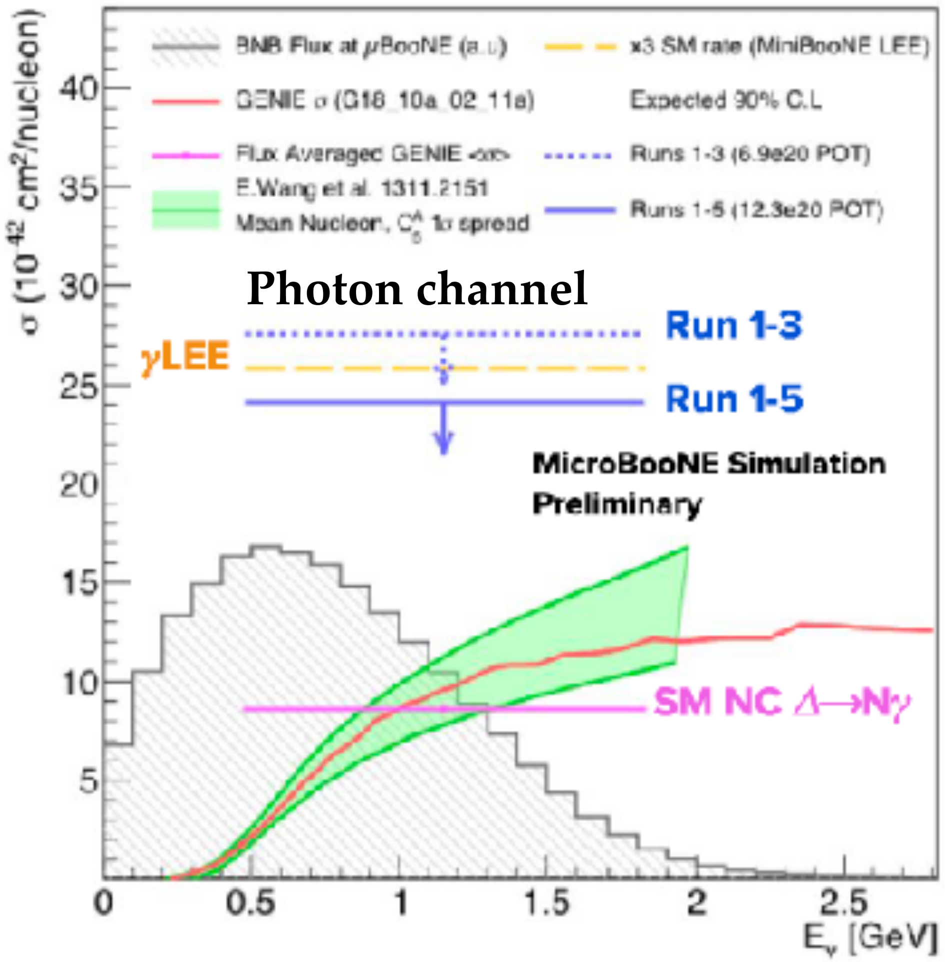


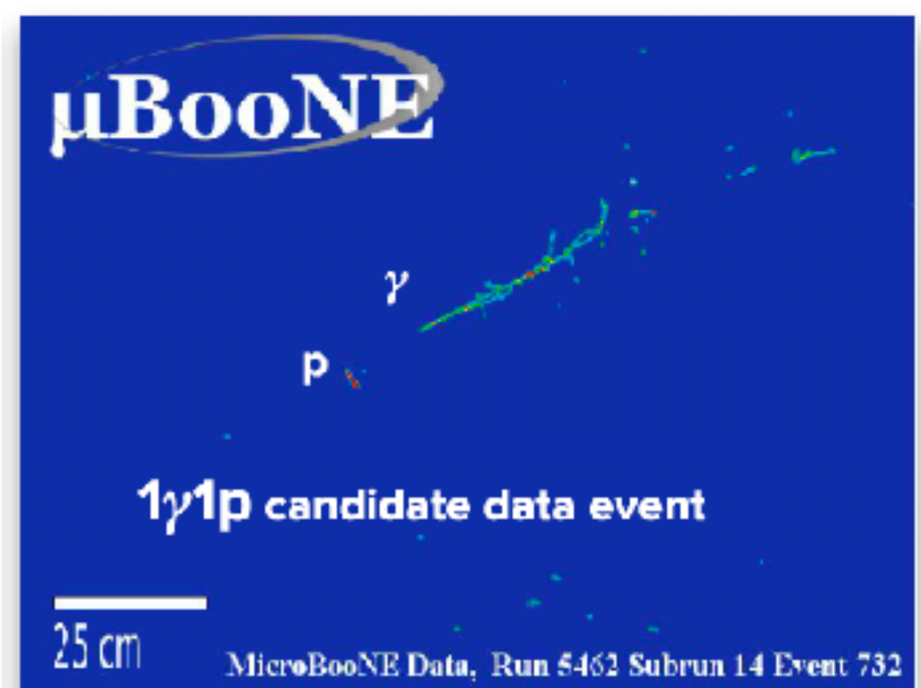


Beyond 3-flavor mixing: Sterile Neutrinos

Short-Baseline Accelerator & Reactor Experiments

MicroBooNE Accelerating Towards First Results!



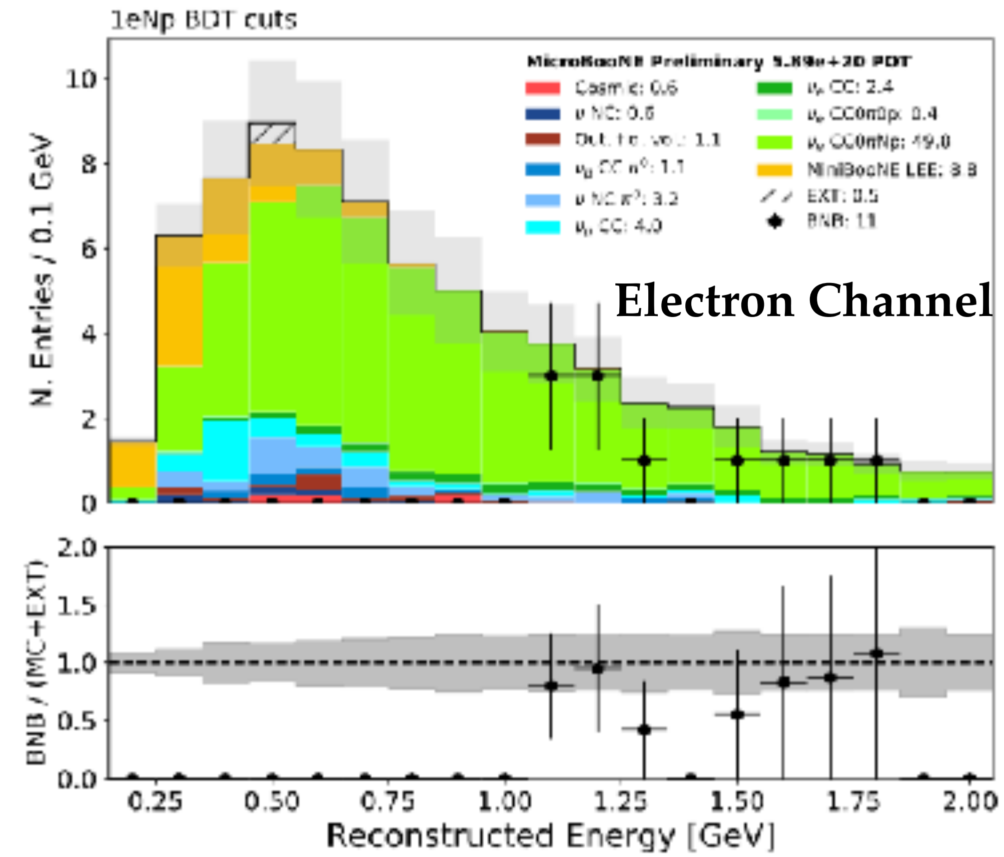


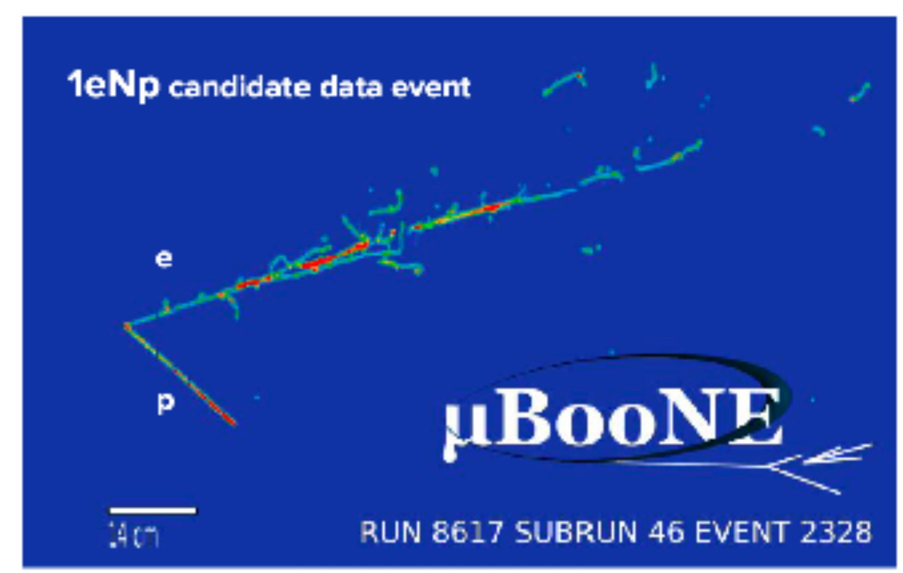
Photon channel

- 30 times more sensitive to SM NC $\Delta \longrightarrow N\gamma$ compared to T2K
- Exclude photon excess in favor of SM at >95% C.L.

Electron channel

- Would be able to exclude SM hypothesis in favor of electron excess at 3σ

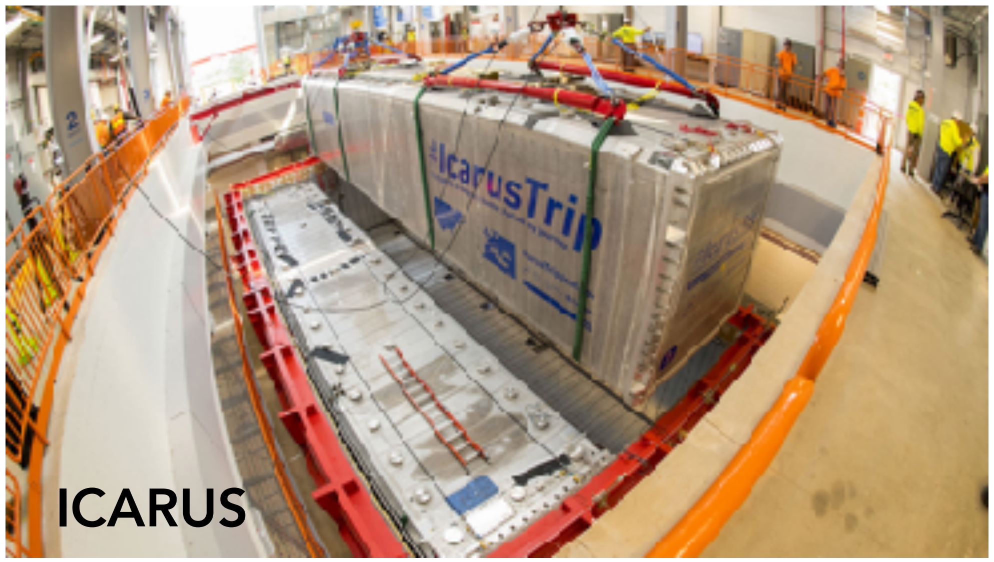


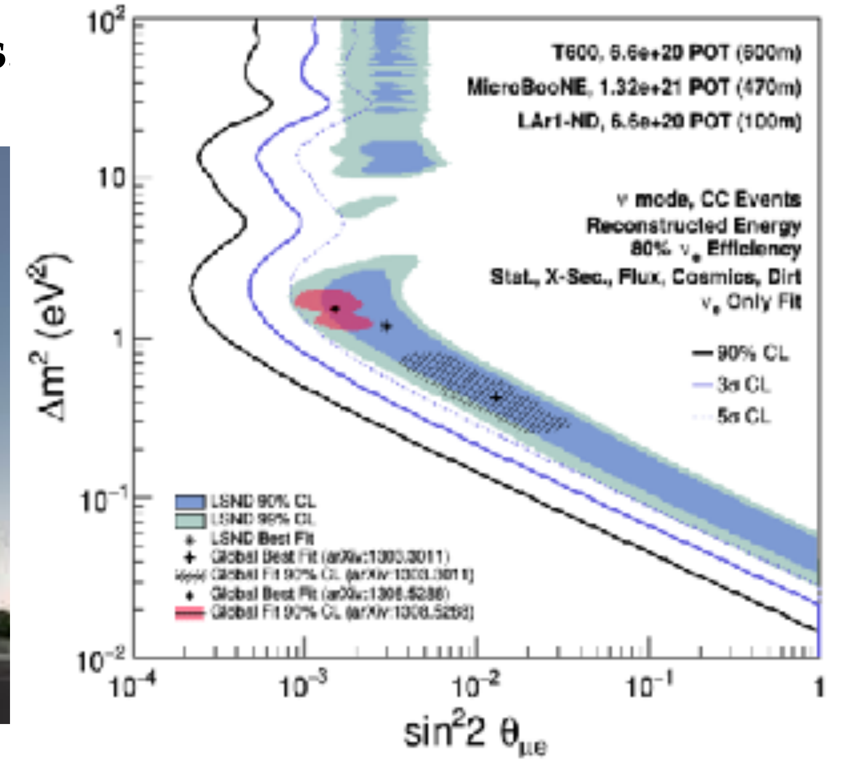


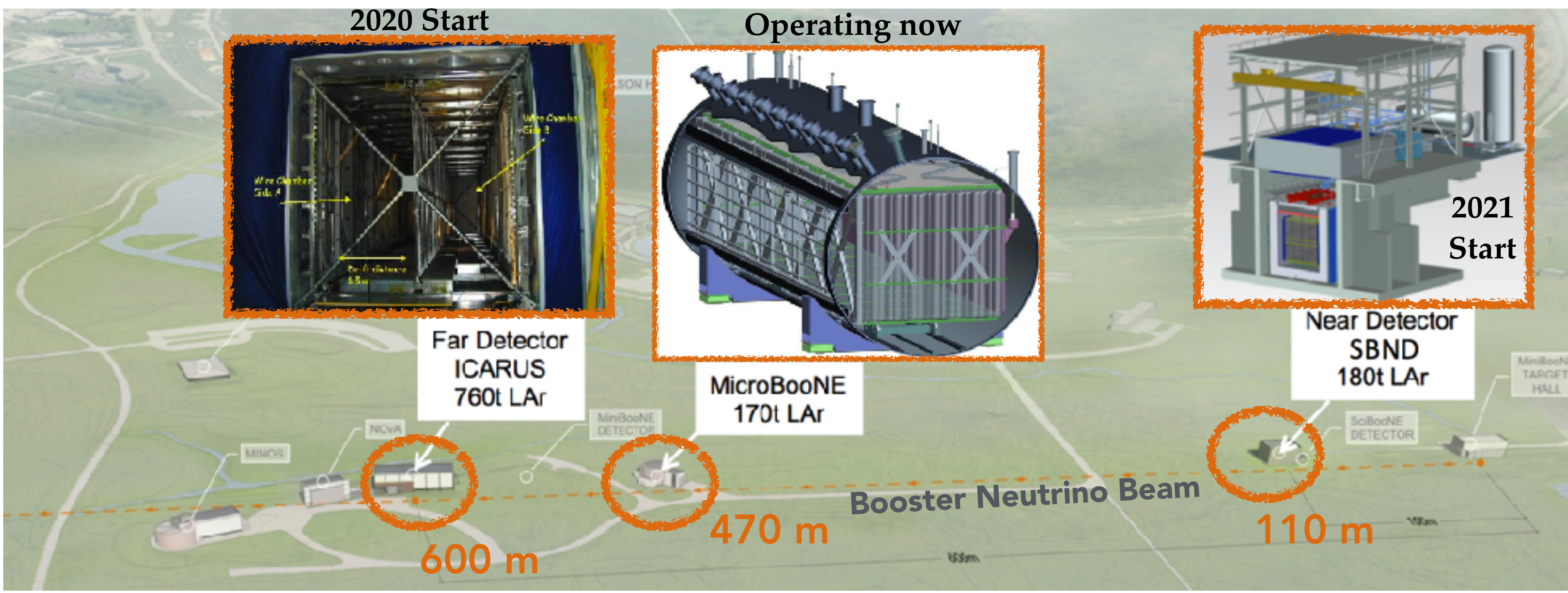
MicroBooNE at the cusp of unblinding;
Look forward to first results very soon!

Future Short-Baseline Accelerator:
SBN Program @ Fermilab

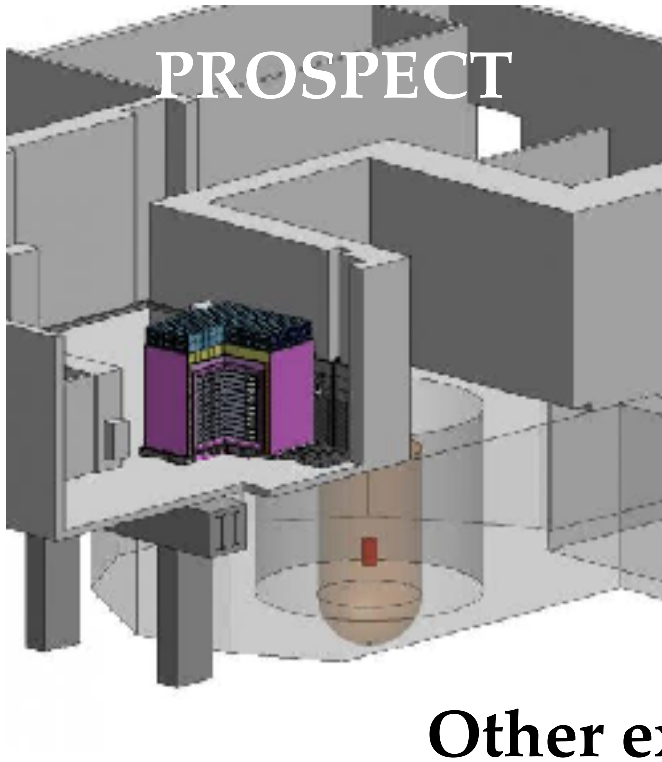
Also, extensive Liquid Argon R&D for next generation Long-Baseline expts

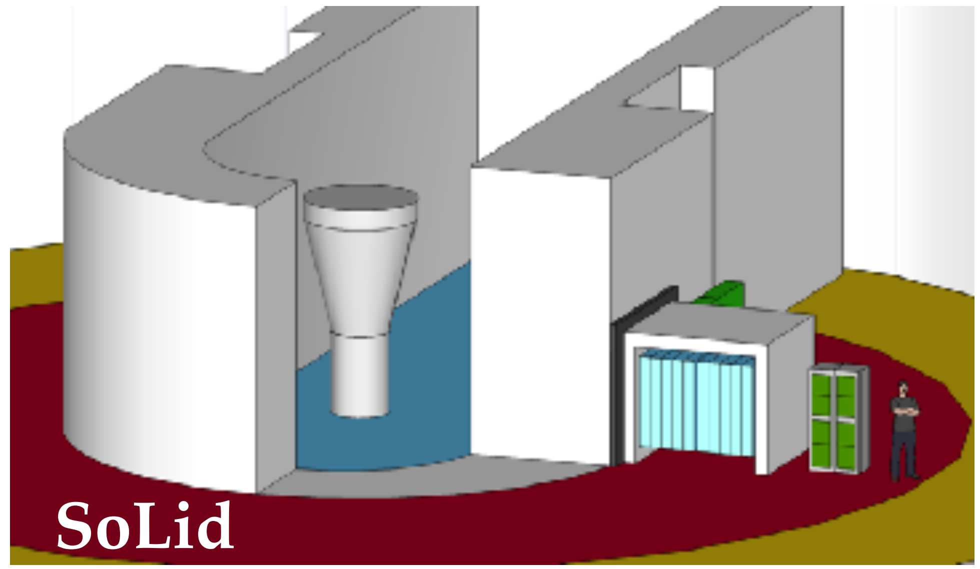


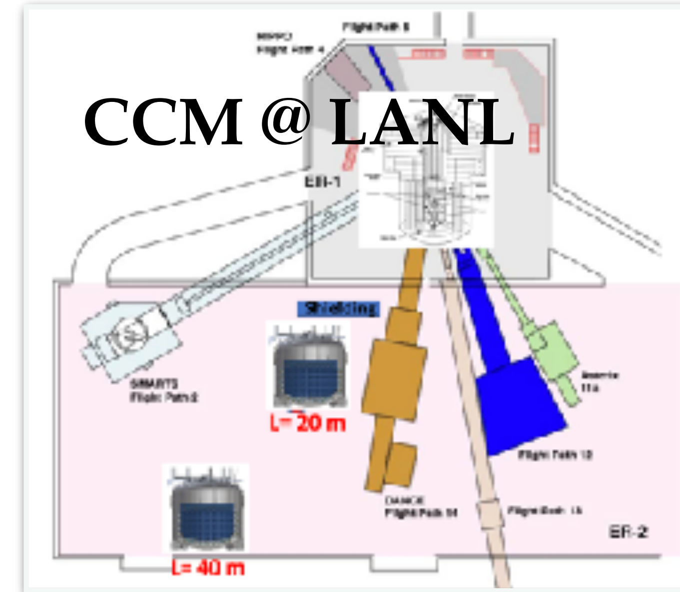




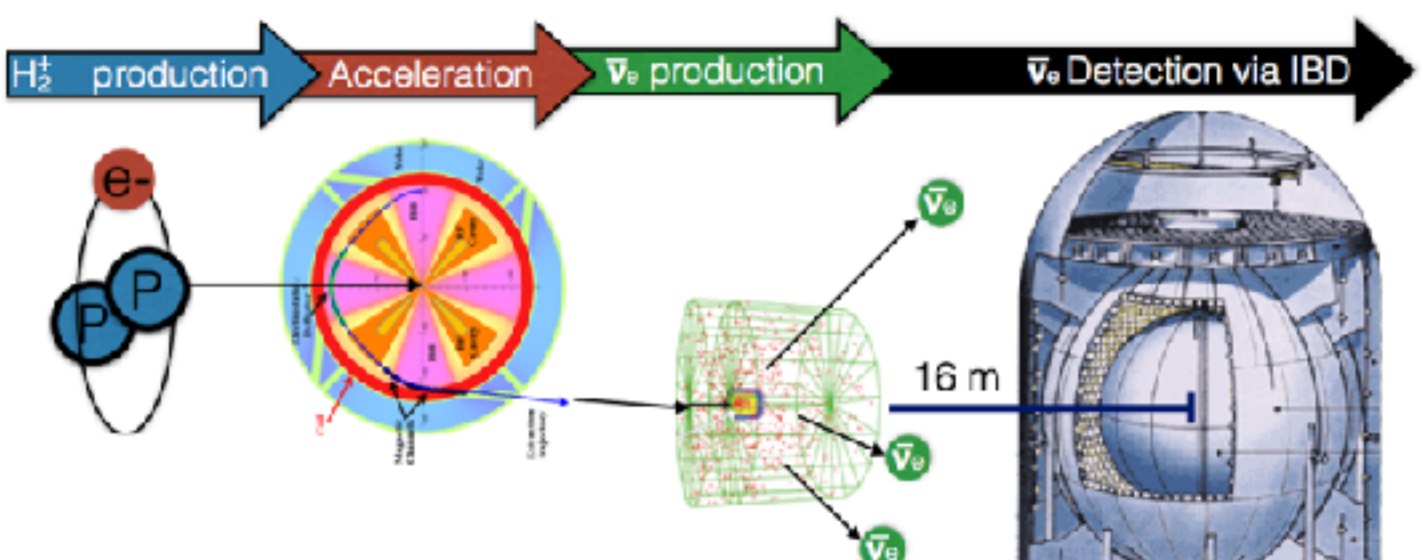
Very Short-Baseline (~1m) Experiments for Future: Accelerator & Reactor







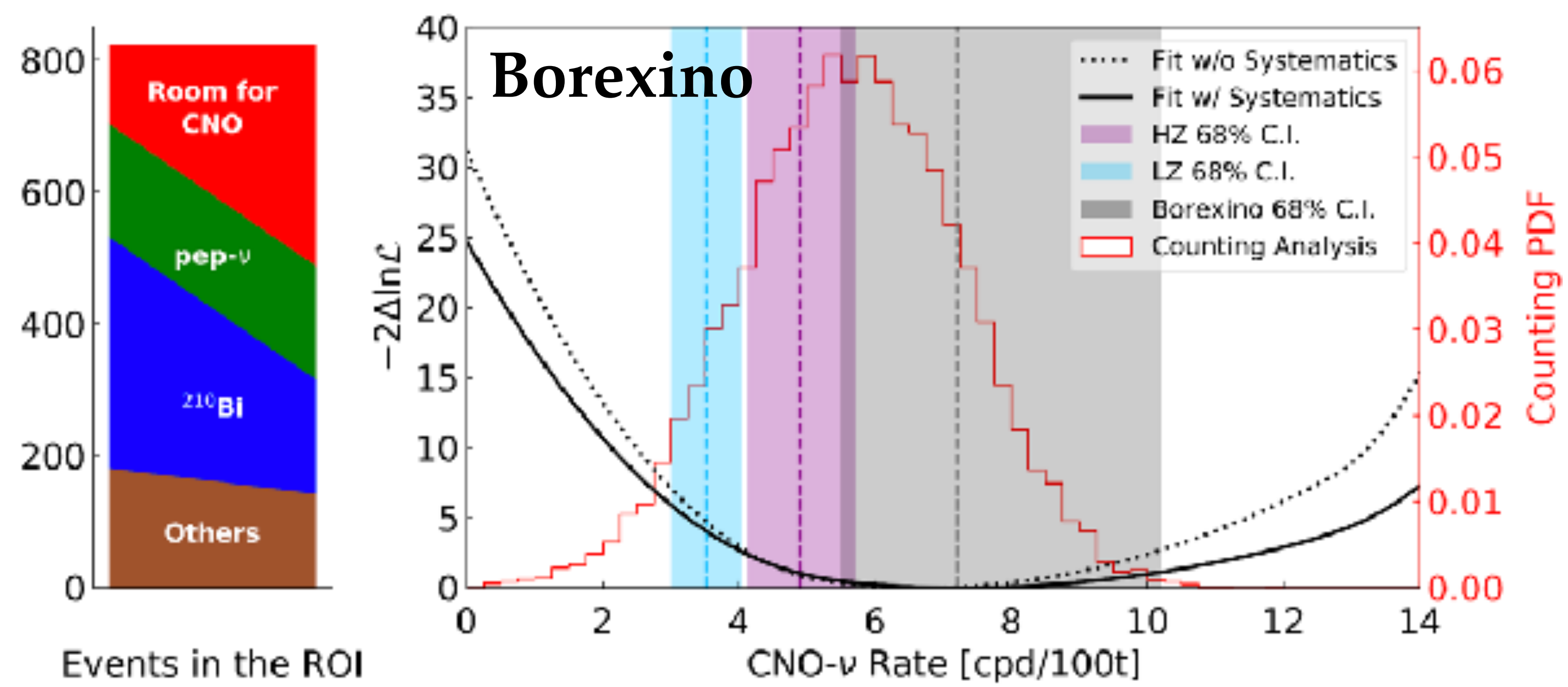
Other experiments: STEREO, NuLAT, Neutrino 4,…



IsoDAR = Isotope Decay-At-Rest

Future: Solar, Reactor & Other

- Undeterred effort of **Borexino**: first detection of CNO neutrinos at 5σ!
- Very many reactor experiments: **Daya Bay, Double Chooz, RENO, JUNO, Chandler, DANSS, NEOS, NuLat, PROSPECT, SoLiδ, Stereo, Neutrino-4, BEST** etc. Much progress on reactor anomaly, many results presented!
- Joint analysis in the future: PROSPECT, Daya Bay, STEREO
- **BEST** to address Ga Anomaly towards the end of the year
- **JSNS² at JPARC** just started taking data and aims for a direct test of LSND
- Emerging research in **neutrinos in nuclear energy and security**

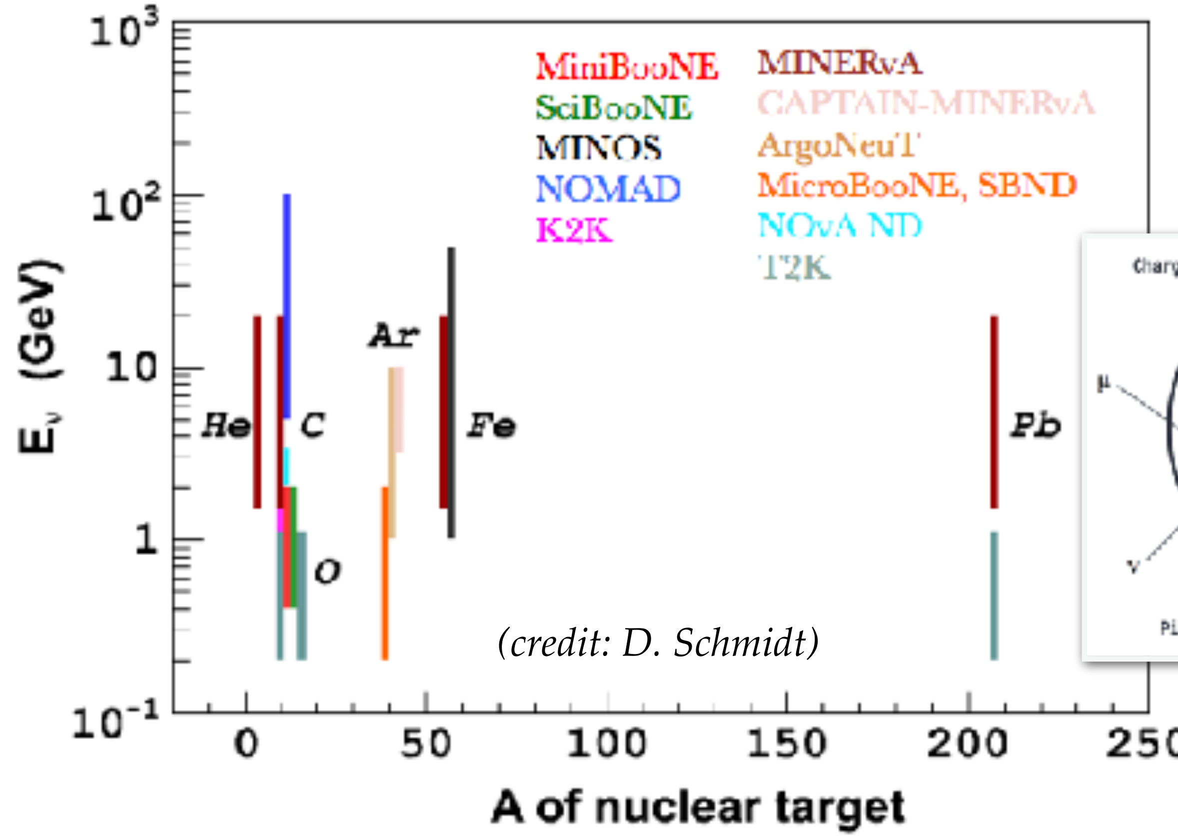


Neutrinos & Non-proliferation

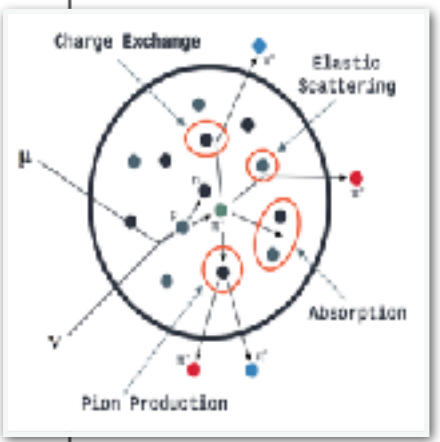
Understanding Neutrino-Nucleus Interactions Critical for Future

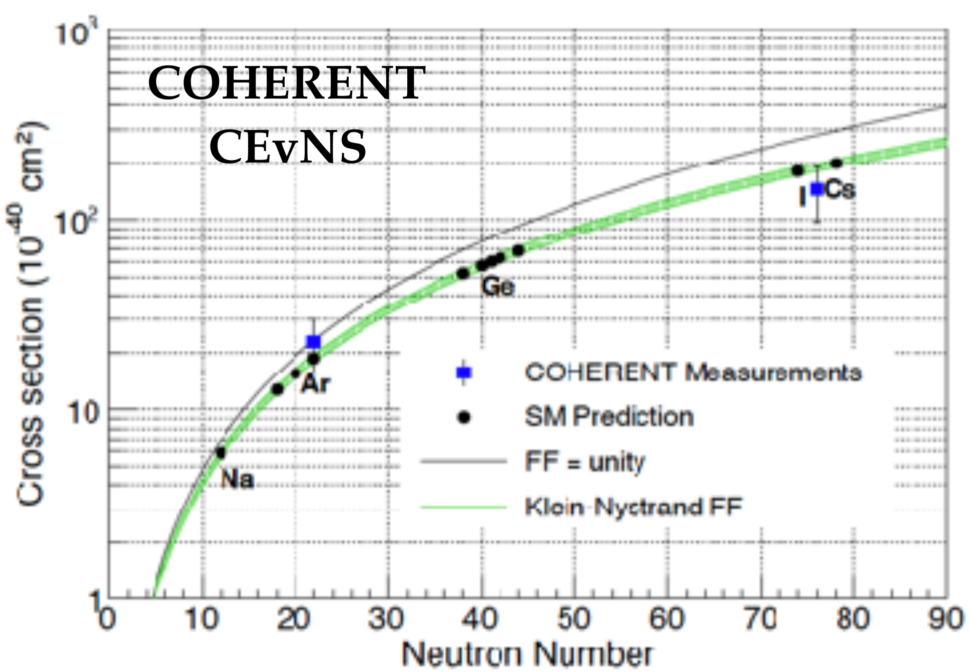
- Many great results from T2K, NOvA, MINERvA, COHERENT, ArgoNeuT, MicroBooNE!
- Understanding of neutrino-nuclear interactions constantly growing, more to come in the future!
- Future: LArIAT, ProtoDUNEs, SBND, ICARUS, Next generation Near Detectors
- Theory & experiments closely partnering to improve models and generators

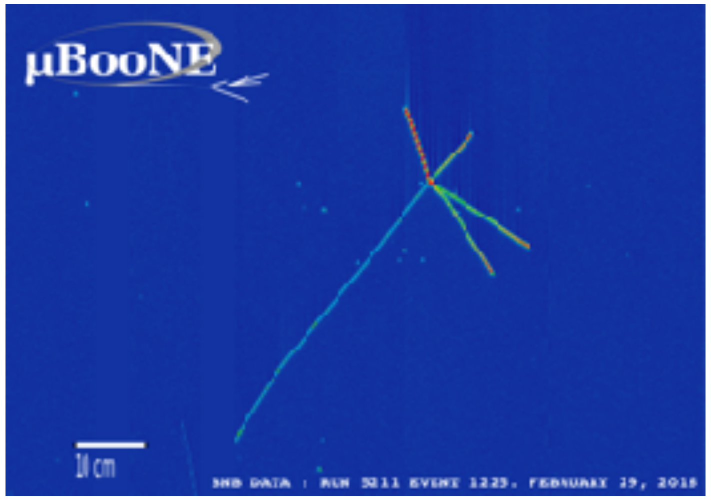
Experiments are using denser targets



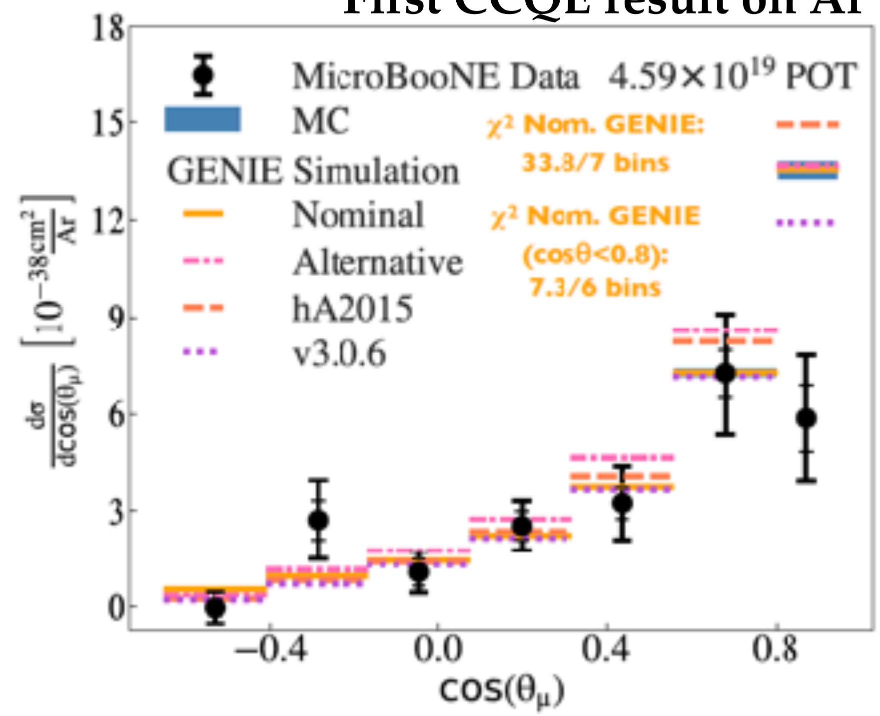
Final State Interactions







First CCQE result on Ar



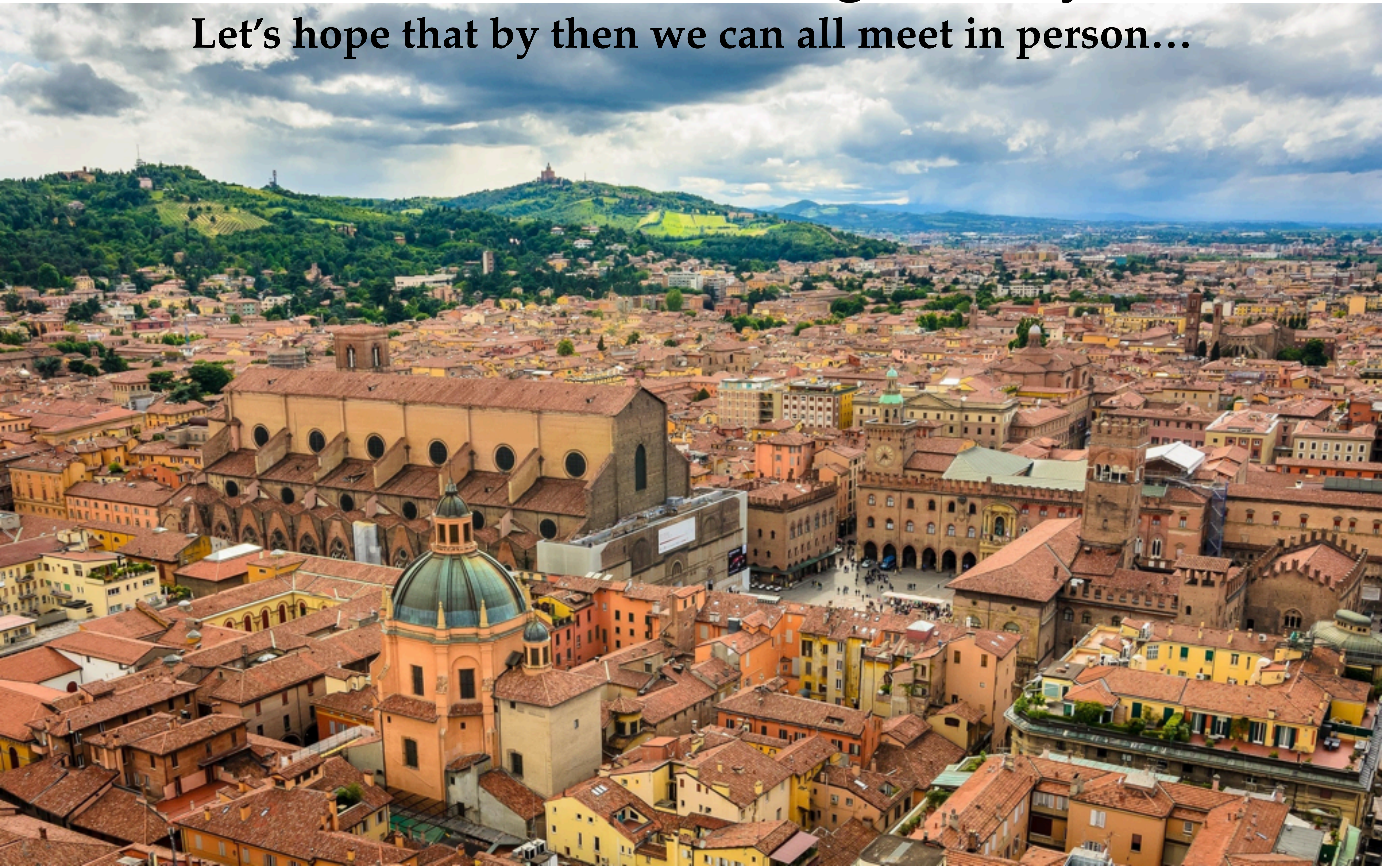
Summary & Outlook

- **Enormous progress across all fronts, congratulations to all teams!**
- **We heard many exciting first results in the last two months:**
  MicroBooNE, Borexino, KATRIN, PROSPECT, COHERENT,…the list goes on!
- **Next generation experiments are bigger/better and with broad physics programs; lot to look forward to in the next decade**
- **Together we are striving towards a *global picture* of neutrinos**
  - Joint fits and data analyses across experiments
  - Theory & experiment collaborating closely
  - Pushing boundaries with machine learning
  - Increased understanding of neutrino-nucleus interactions
  - Boldly moving towards creative new technologies suitable for precision era
- **Already thinking about beyond the next generation!**

Exciting & Challenging Future Ahead!

ICHEP 2022 in Bologna, Italy

Let's hope that by then we can all meet in person…



EXTRAS