Neutrino Physics Overview:

Where are we & where we are going?

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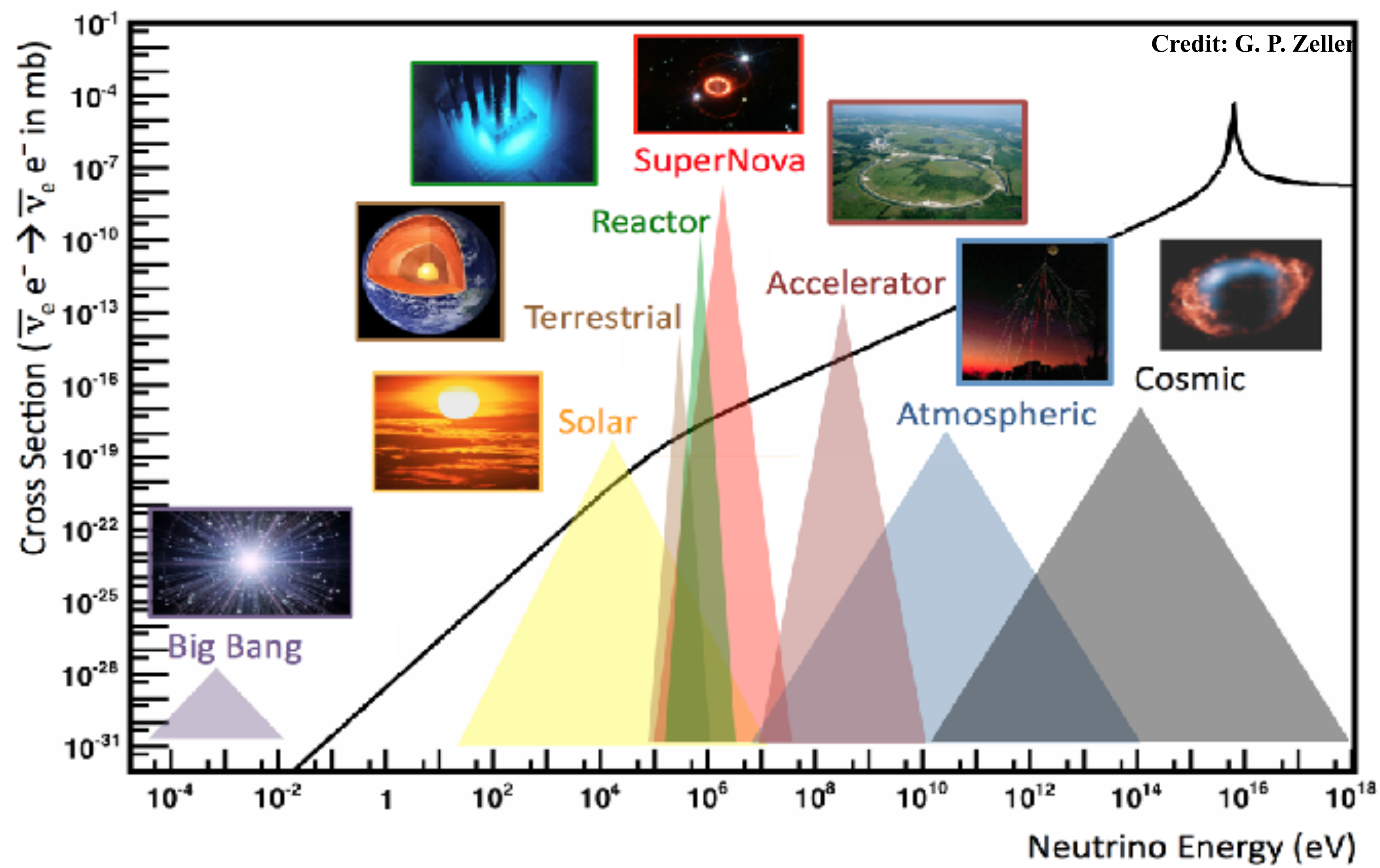
CPAD 2018, Dec. 9, 2018

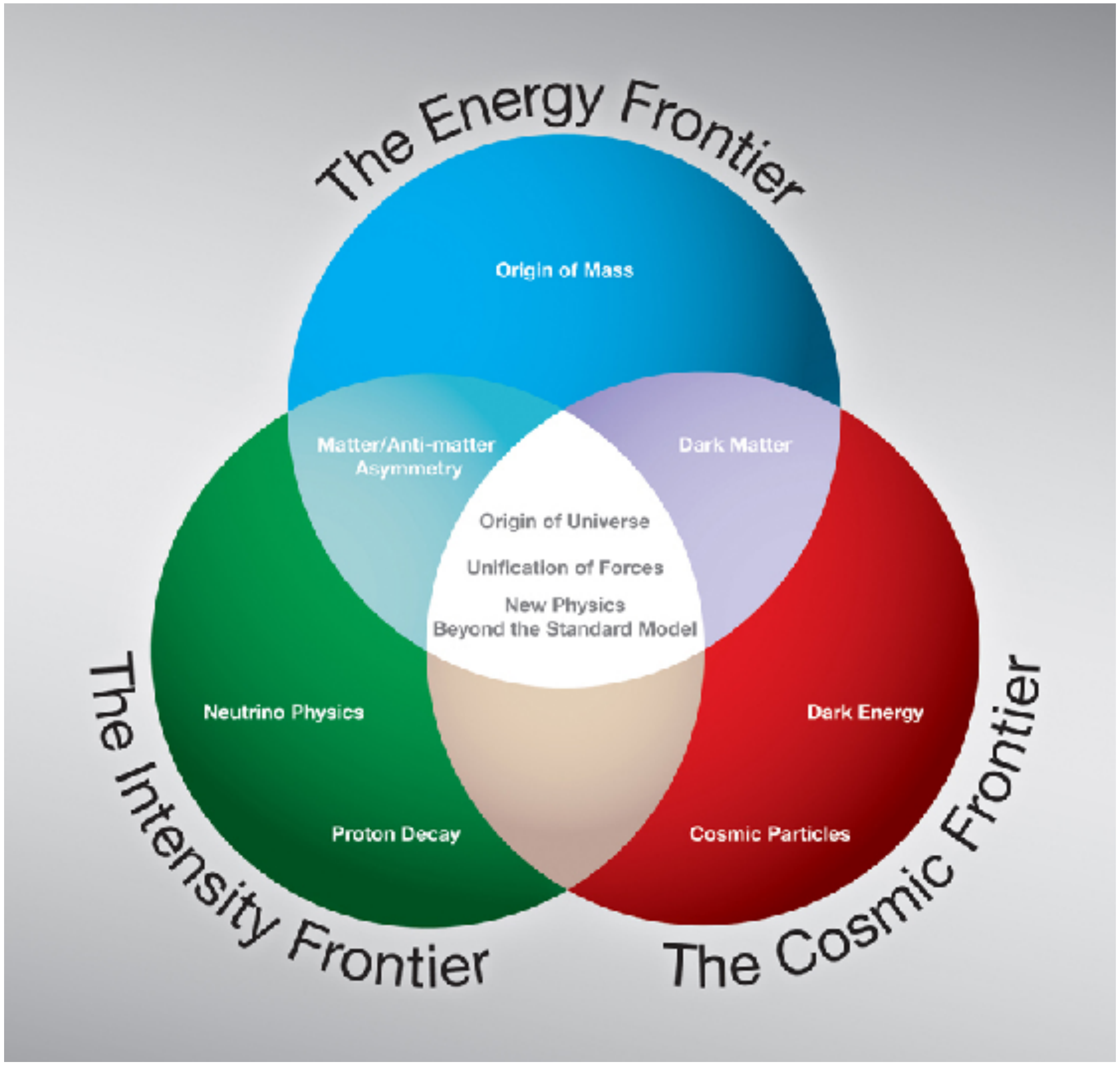
Providence, Rhode Island

Neutrinos are everywhere!

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

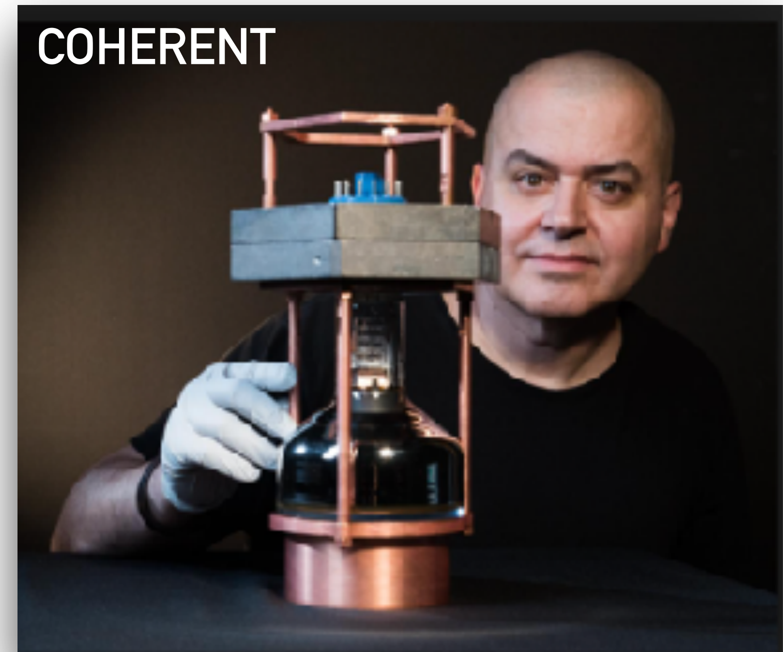


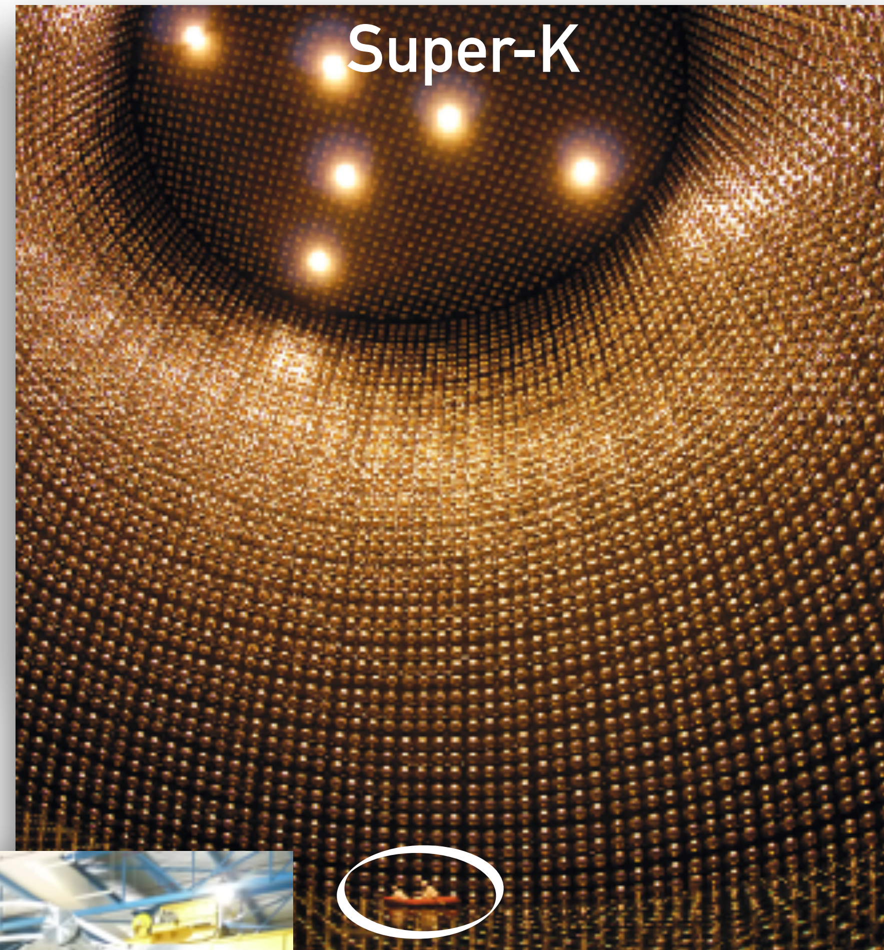
Neutrinos Span Multi-Frontiers

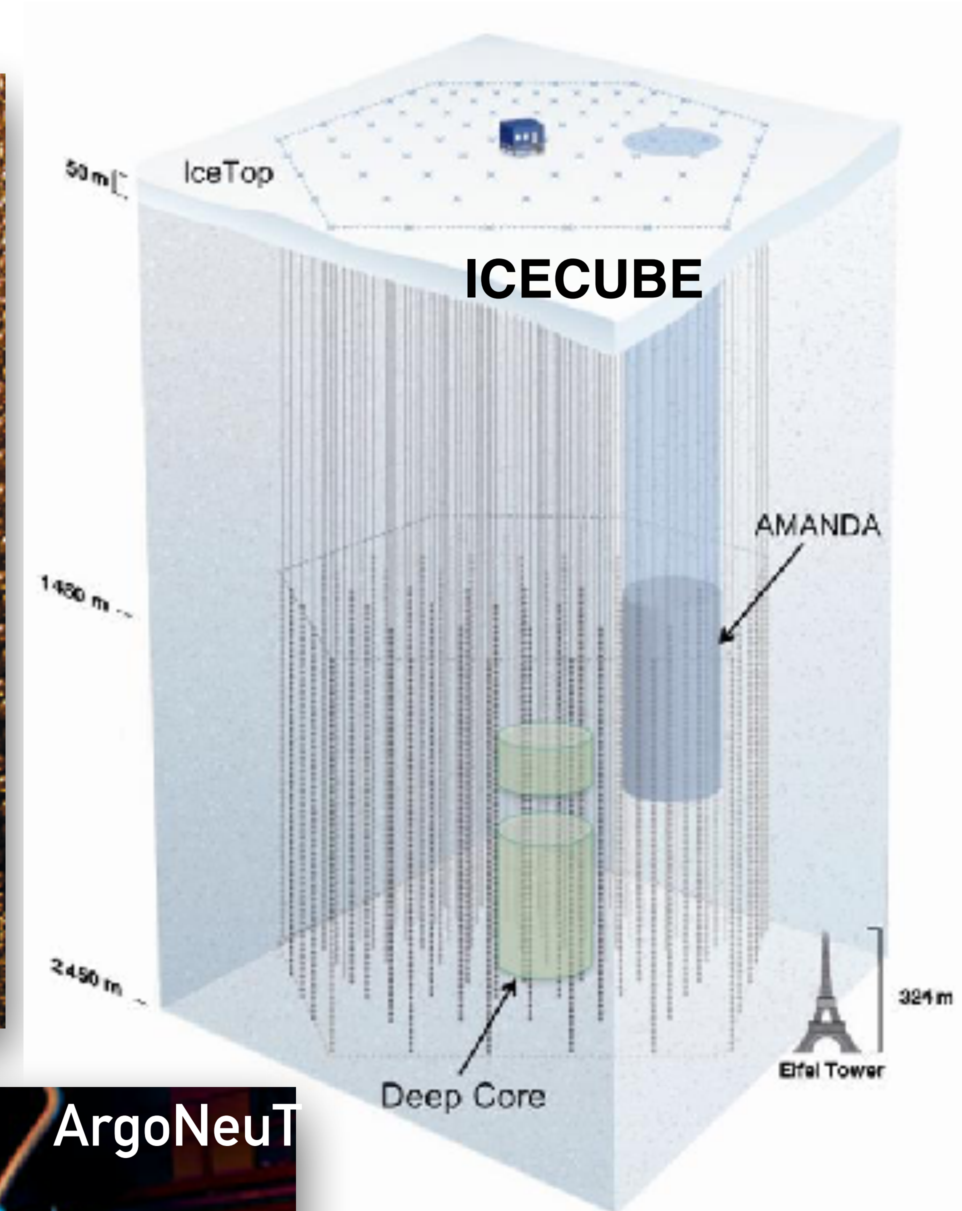


- Particle Physics
- AstroPhysics
- Cosmology
- High energy Astro-particle physics
- Nuclear physics

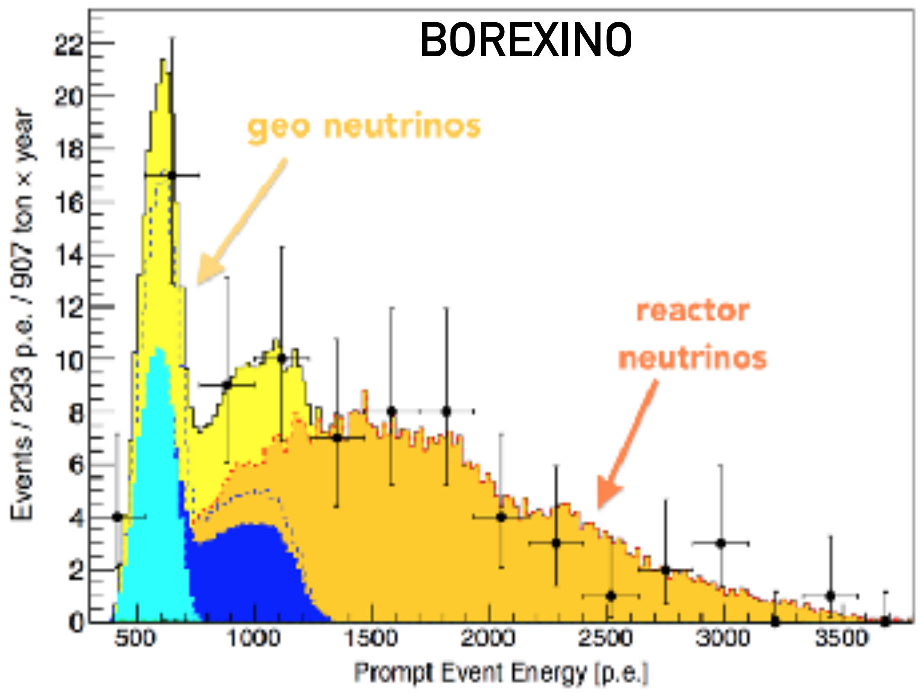
Neutrino detectors come in all sizes/shapes



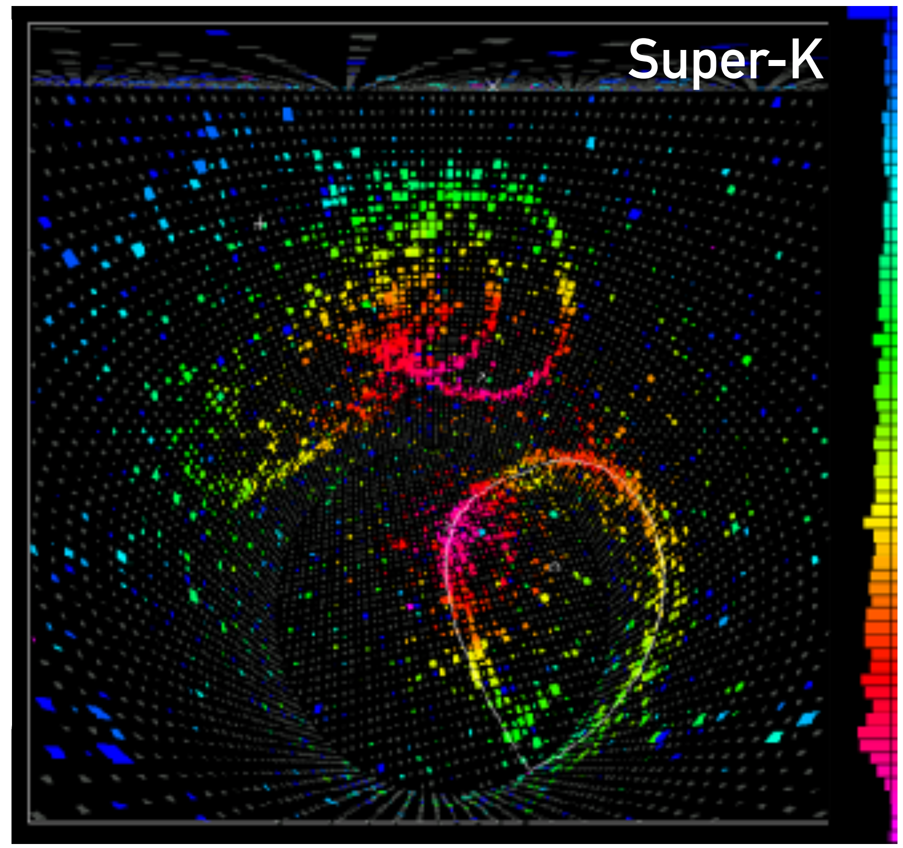




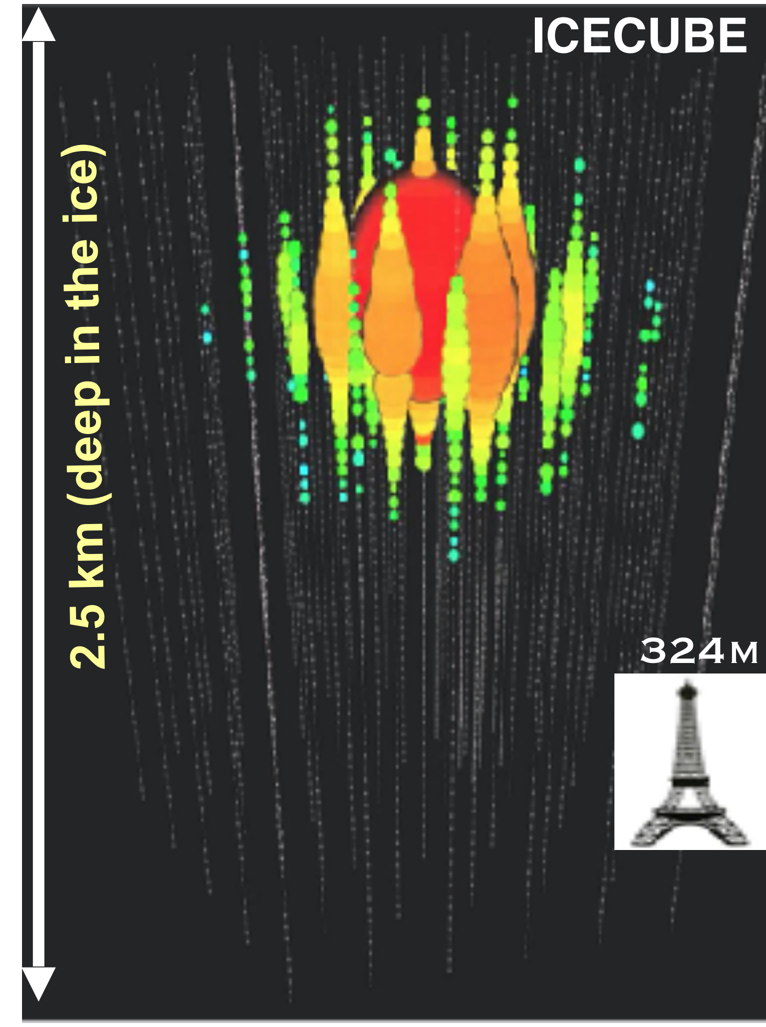
Neutrinos can look very different!



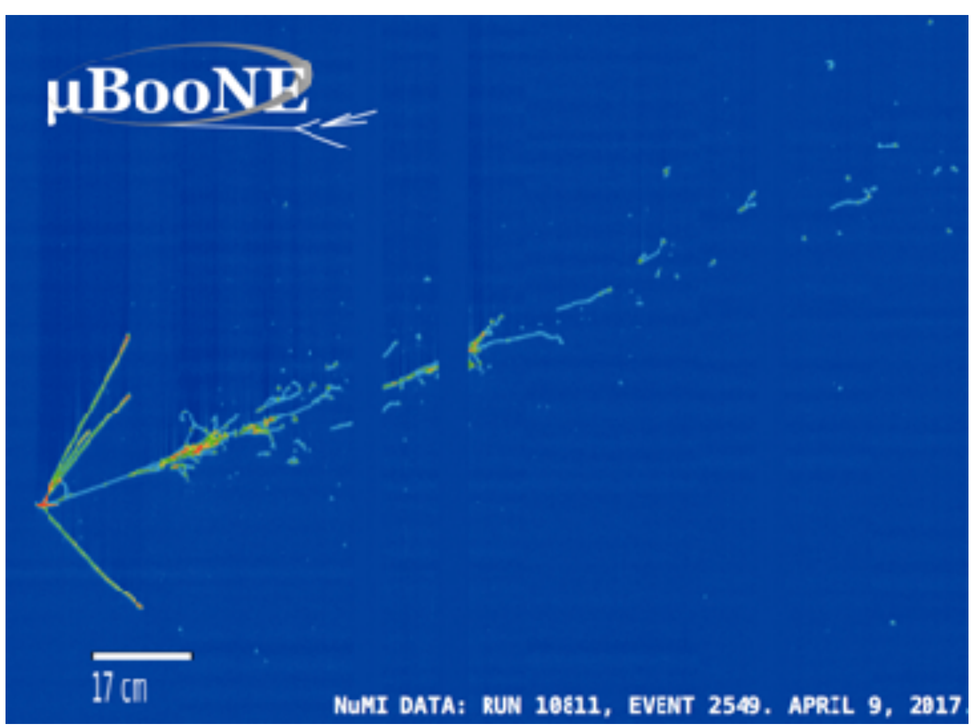
MeV-scale neutrino



A few-100 MeV neutrino



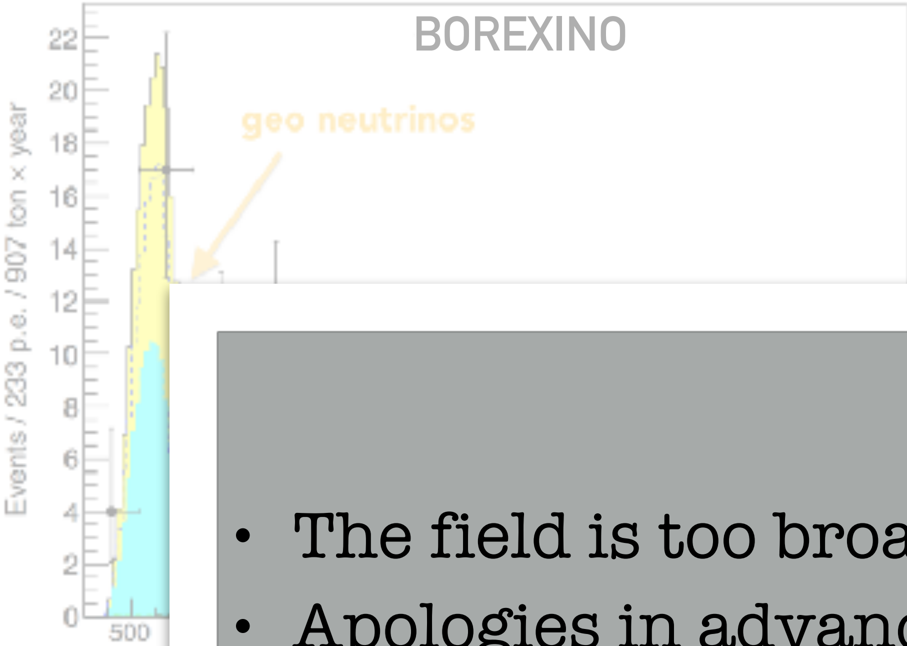
A 2 PeV scale astro physical event in the detector

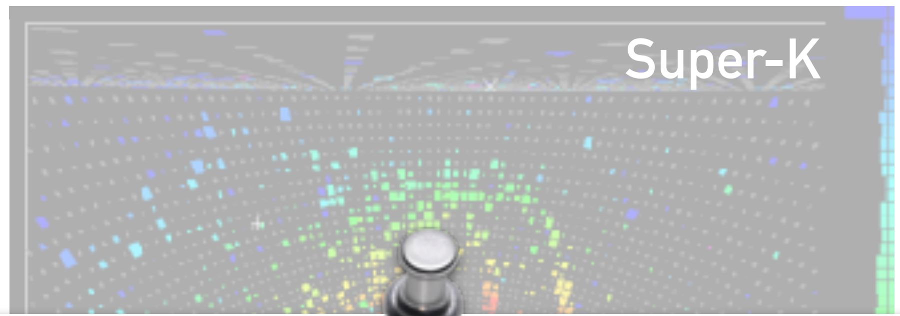


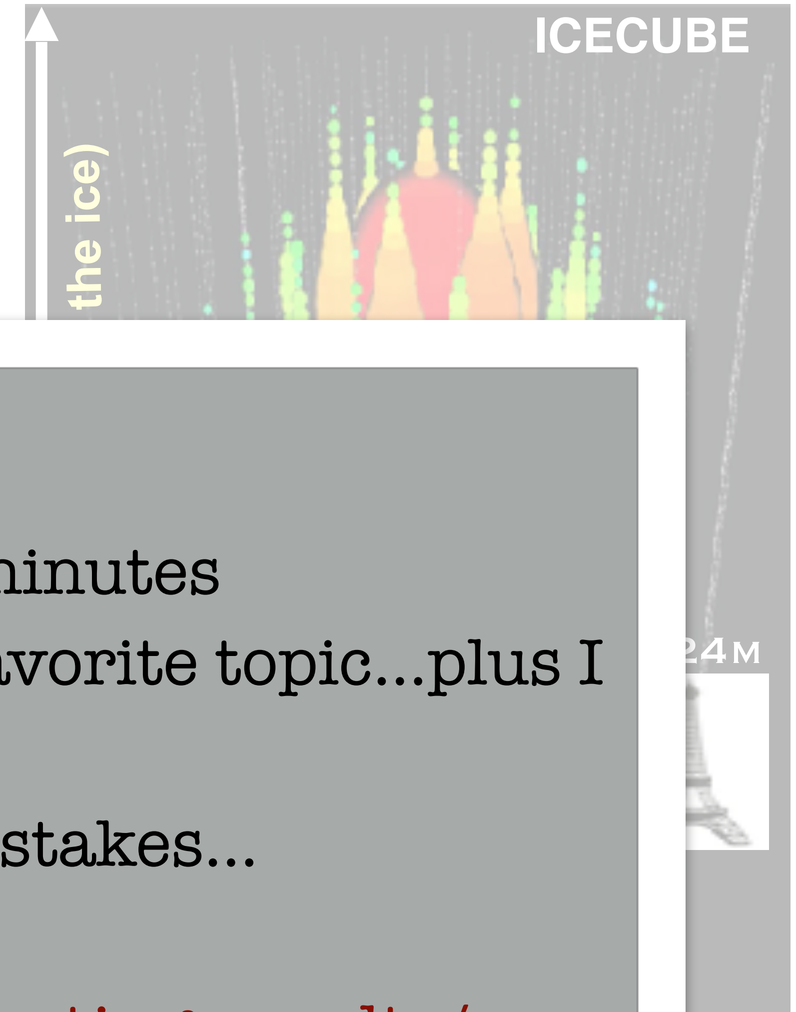
MeV → PeV

We have observed neutrinos at wide range of energies

S







Disclaimer

- The field is too broad — hard to do justice in 30 minutes
- Apologies in advance if I am not covering your favorite topic…plus I have my own biases)
- I am not an expert on everything, I will make mistakes…

Lots of great parallel sessions pouring interesting results/ challenges, please do attend, I have highlighted where I can

MeV → PeV

at wide range of energies

Outline

- Neutrino Physics
  - What do we know so far?
  - What we don't know?
  - Experimental Landscape
  - R&D Challenges/Opportunities
  - Summary

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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)

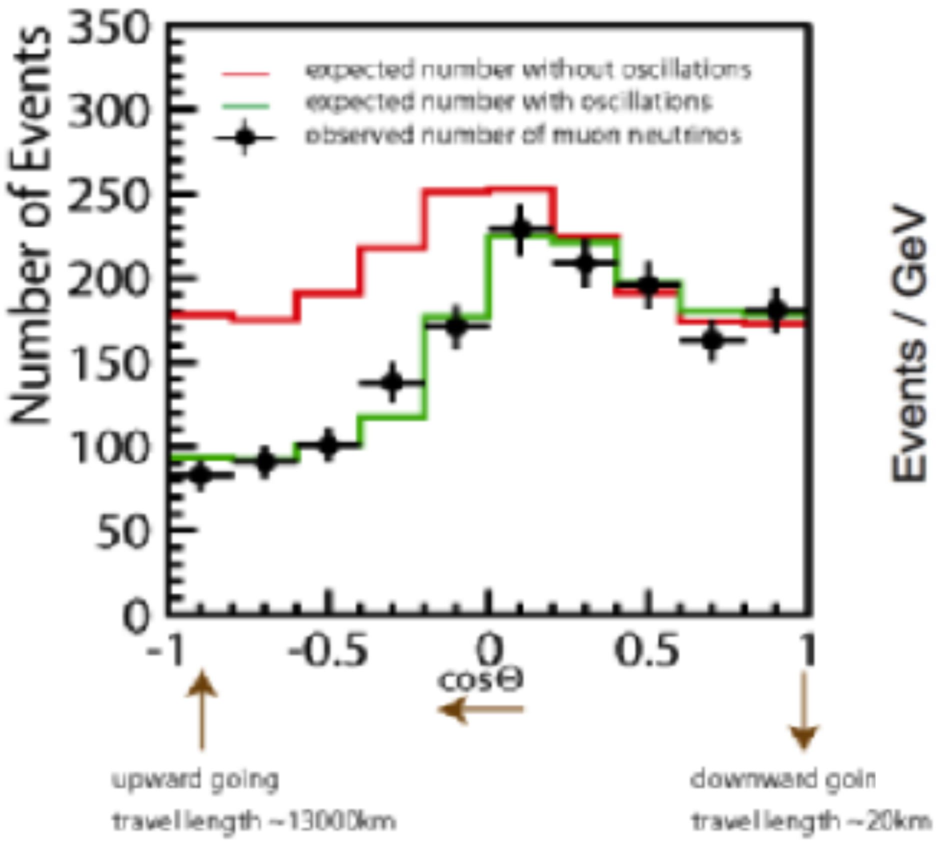
Until as recently as 1998, neutrinos were considered to be massless

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

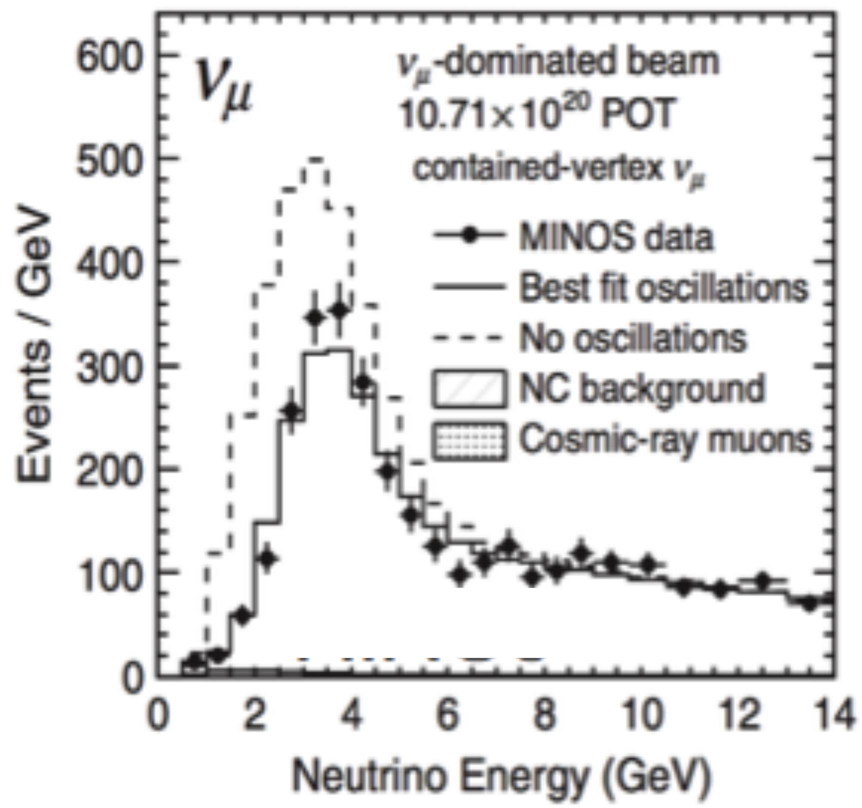
Overwhelming evidence for ν oscillations

(from a variety of sources)

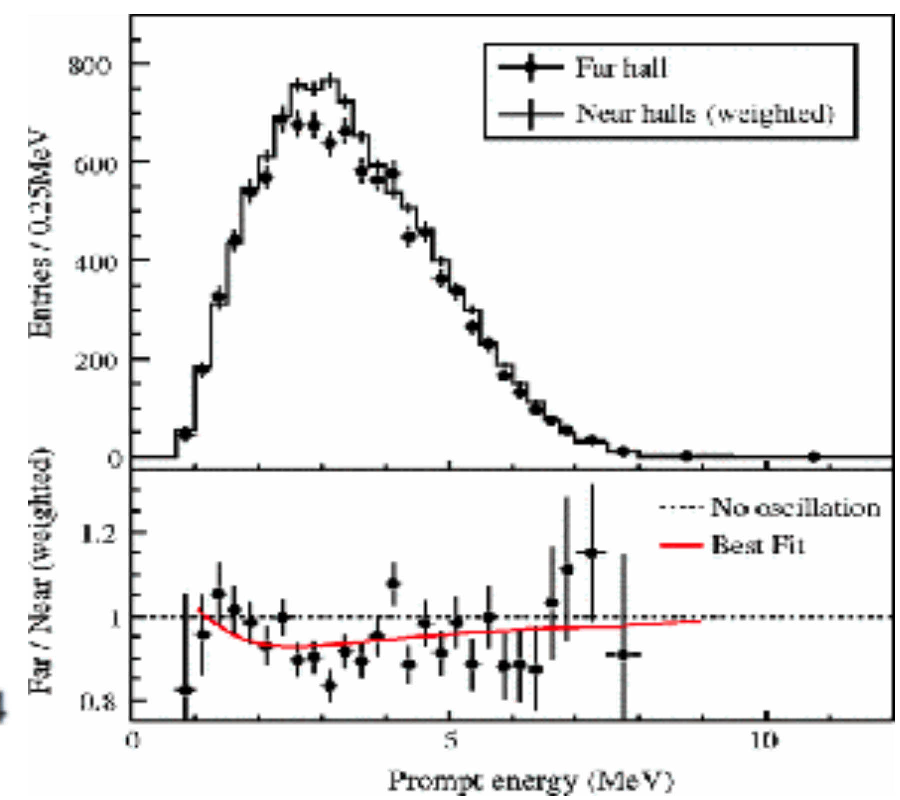
Atmospheric

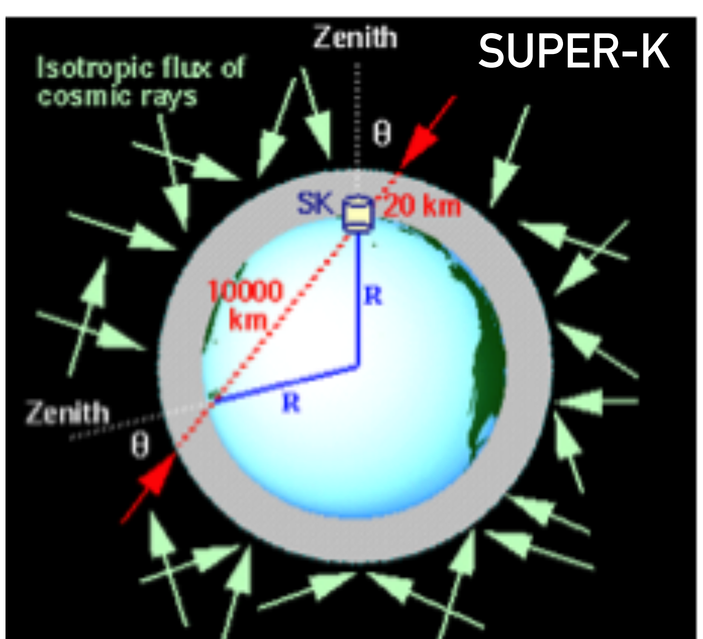


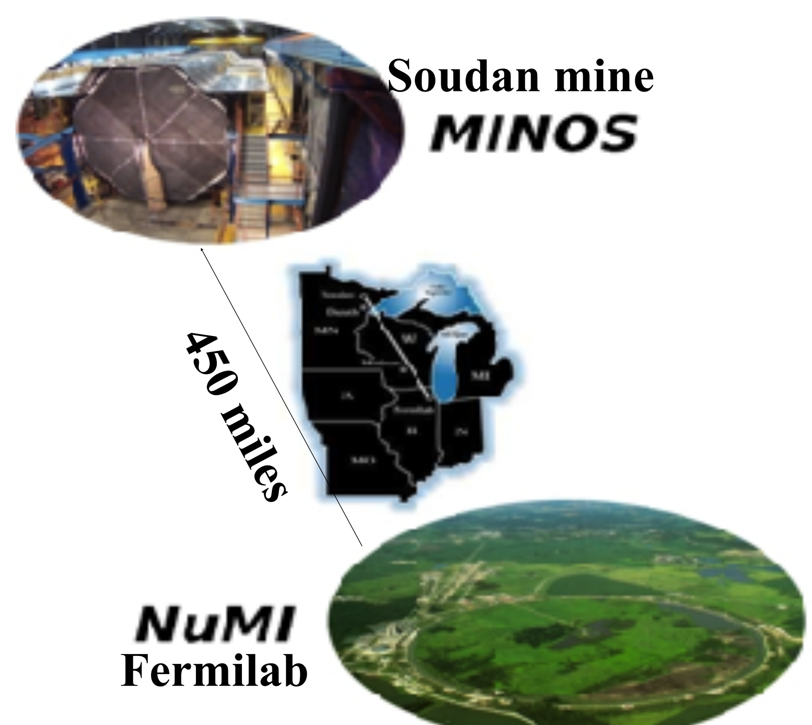
Accelerator

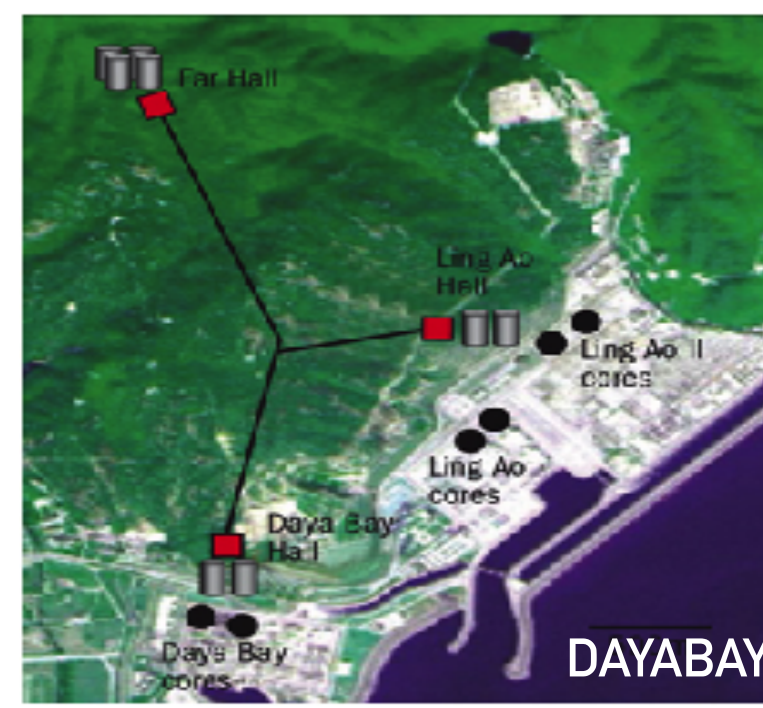


Reactor source









Neutrino Oscillation Parameters

"FLAVOR" STATES

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

"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*

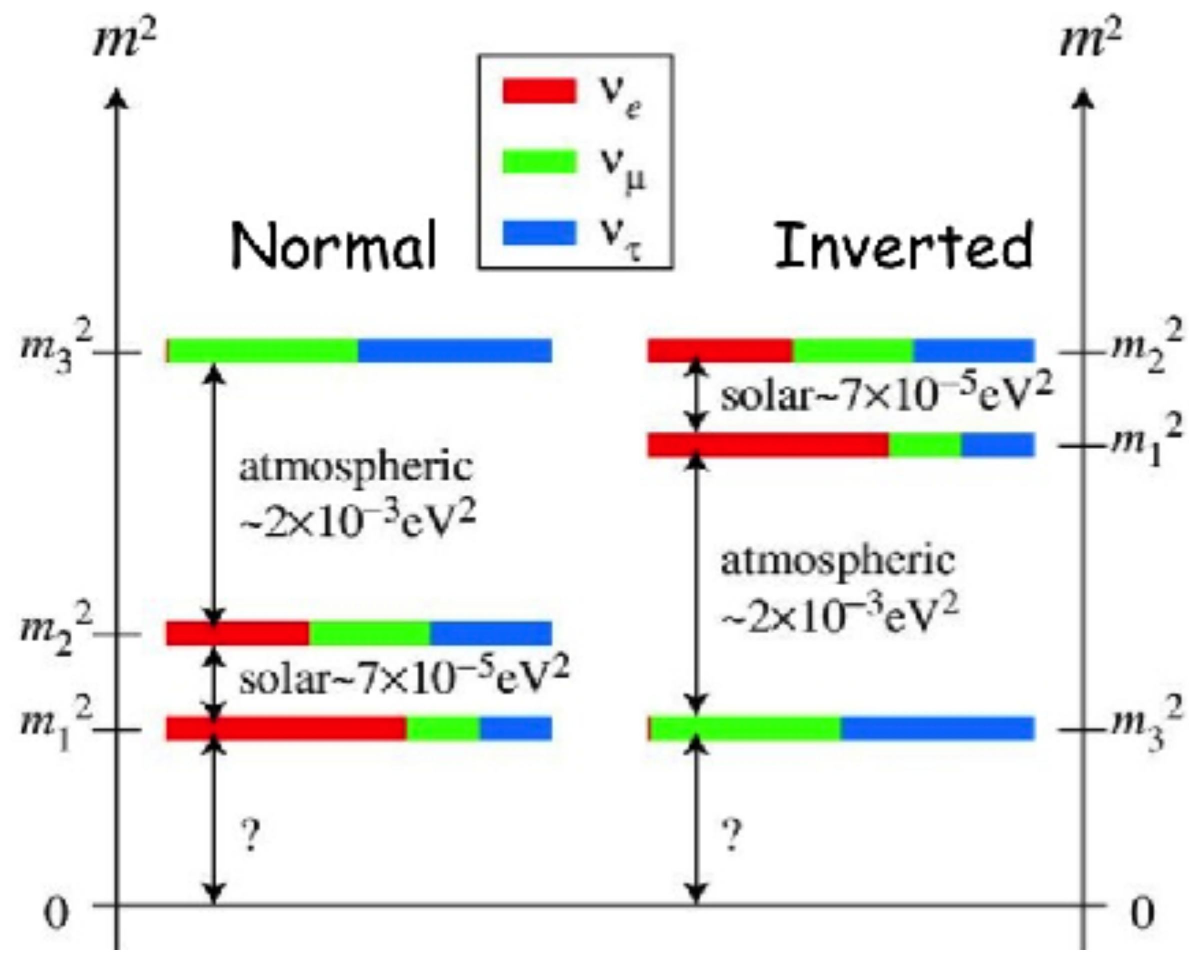
- 3 mixing angles: **θ_{12}, θ_{23}, θ_{13}** and a complex phase: **δ_{CP}**
- If $\delta \neq \{0,\pi\}$ then results is CP Violation in leptonic sector
- 2 mass differences: **Δm^2_{21}, Δm^2_{32}**

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

Neutrino Mass Hierarchy (MH)

Which neutrino is the lightest and which one is the heaviest?

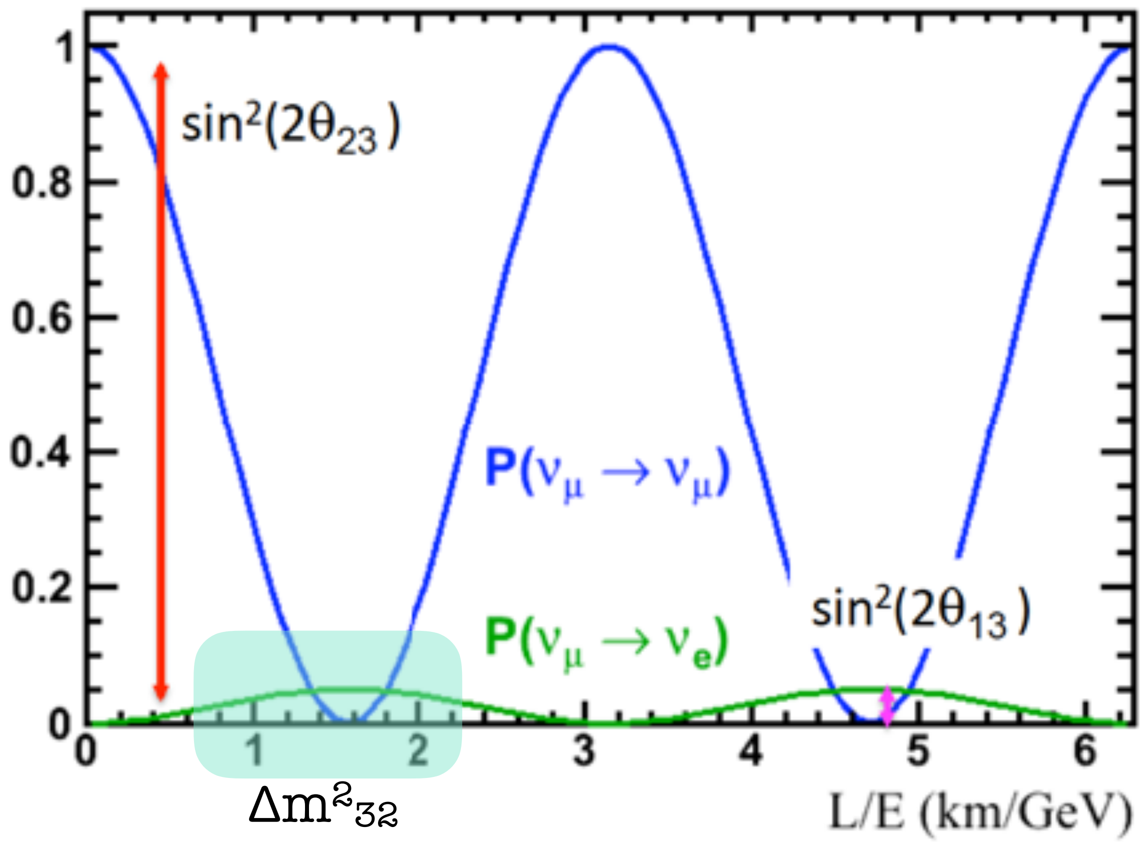
$\Delta m^2_{32/31} > 0$: "Normal" Hierarchy
$\Delta m^2_{32/31} < 0$: "Inverted" Hierarchy



- 2 mass differences: **Δm^2_{21}, Δm^2_{32}**

Neutrino Oscillation Measurements

Quantum mechanical mixing and evolution of states determine what is measured



(Simplified 2-flavor case)

Appearance probability ($\alpha \longrightarrow \beta$)

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

Disappearance/Survival probability ($\alpha = \alpha$)

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

- ν_e appearance measurements (θ_{13}, MH, CPV)
- ν_μ disappearance measurements (θ_{23})
- Distortion to the neutrino spectrum (Δm^2_{32})

3-flavor Oscillations are a well established Phenomena

We have detected oscillations from

- Atmospheric
- Solar
- Accelerator
- Reactor

Current status of Oscillation parameters

PDG 2018

Parameter	best-fit	3σ
Δm^2_{21} $[10^{-5}$ eV $^2]$	7.37	6.93 – 7.96
$\Delta m^2_{31(23)}$ $[10^{-3}$ eV $^2]$	2.56 (2.54)	2.45 – 2.69 (2.42 – 2.66)
$\sin^2\theta_{12}$	0.297	0.250 – 0.354
$\sin^2\theta_{23}$, $\Delta m^2_{31(32)} > 0$	0.425	0.381 – 0.615
$\sin^2\theta_{23}$, $\Delta m^2_{32(31)} < 0$	0.589	0.384 – 0.636
$\sin^2\theta_{13}$, $\Delta m^2_{31(32)} > 0$	0.0215	0.0190 – 0.0240
$\sin^2\theta_{13}$, $\Delta m^2_{32(31)} < 0$	0.0216	0.0190 – 0.0242
δ/π	1.38 (1.31)	2σ: (1.0 - 1.9) (2σ: (0.92-1.88))

ν Oscillations: Solar Parameters

The solar parameters are well measured

Current status of Oscillation parameters (PDG 2018)

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Δm^2_{21} $[10^{-5}$ eV $^2]$	7.37	6.93 – 7.96
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ν Oscillations: θ_{13}

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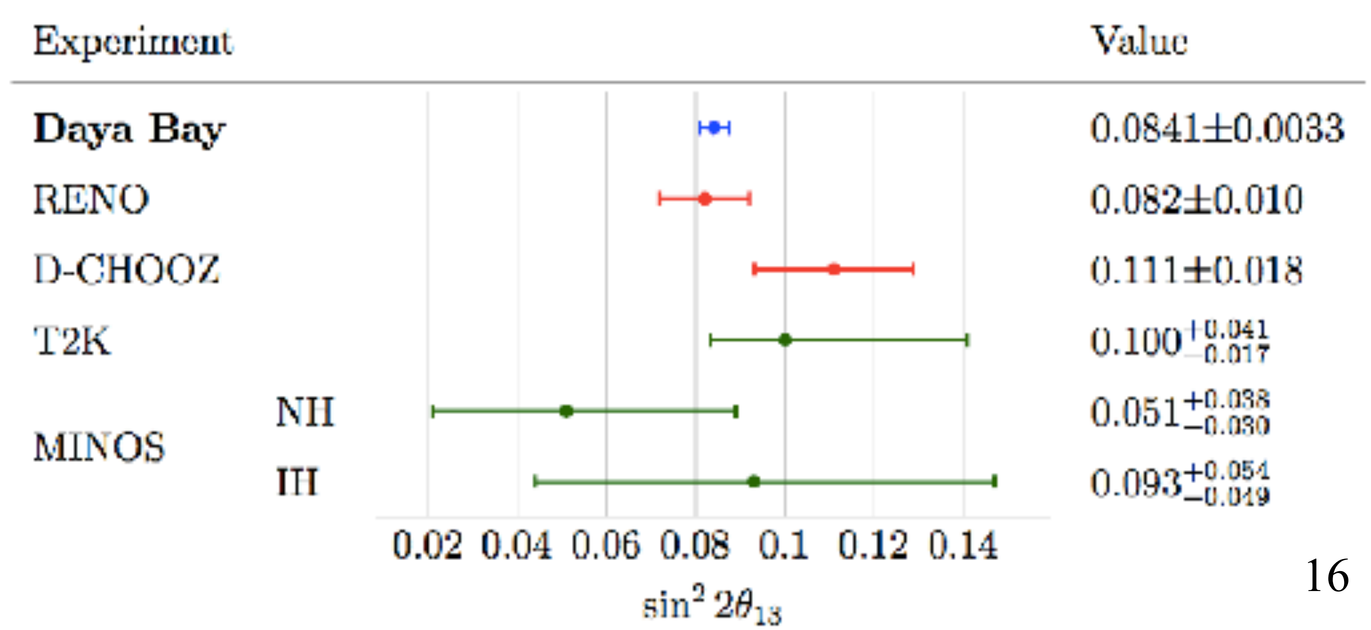
- Thanks to reactor experiments, the measurement of **θ_{13}** opened door to **CPV** in the leptonic sector
- This will help us understand why we live in a matter dominated universe

CPV effects proportional to **$\sin\theta_{13}$**

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

Reactor & Accelerator



ν Oscillations: Atmospheric Parameters

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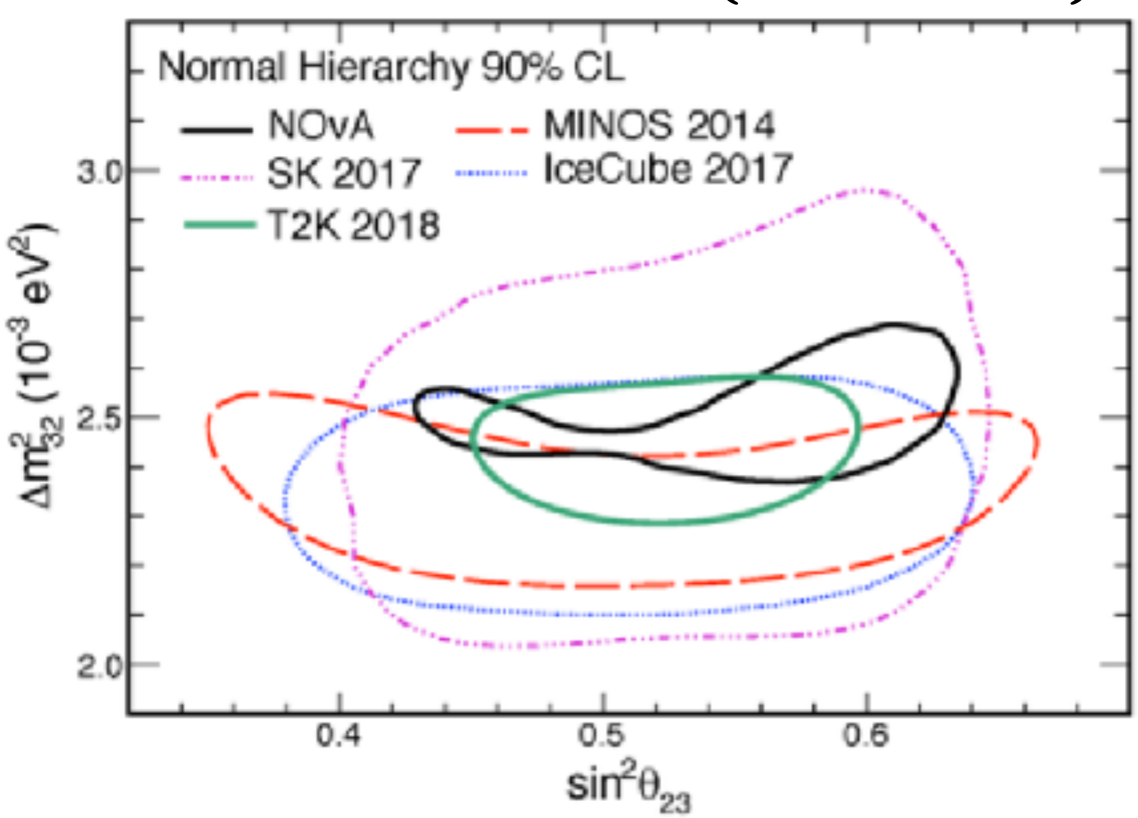
Currently least constrained

Is θ_{23} maximal (= 45^0)?

NovA (Neutrino 2018)



Some tension:

- T2K continues to favor maximal mixing
- NOvA disfavors maximal mixing

ν Oscillations: Mass Ordering & CPV

Current status of Oscillation parameters (PDG 2018)

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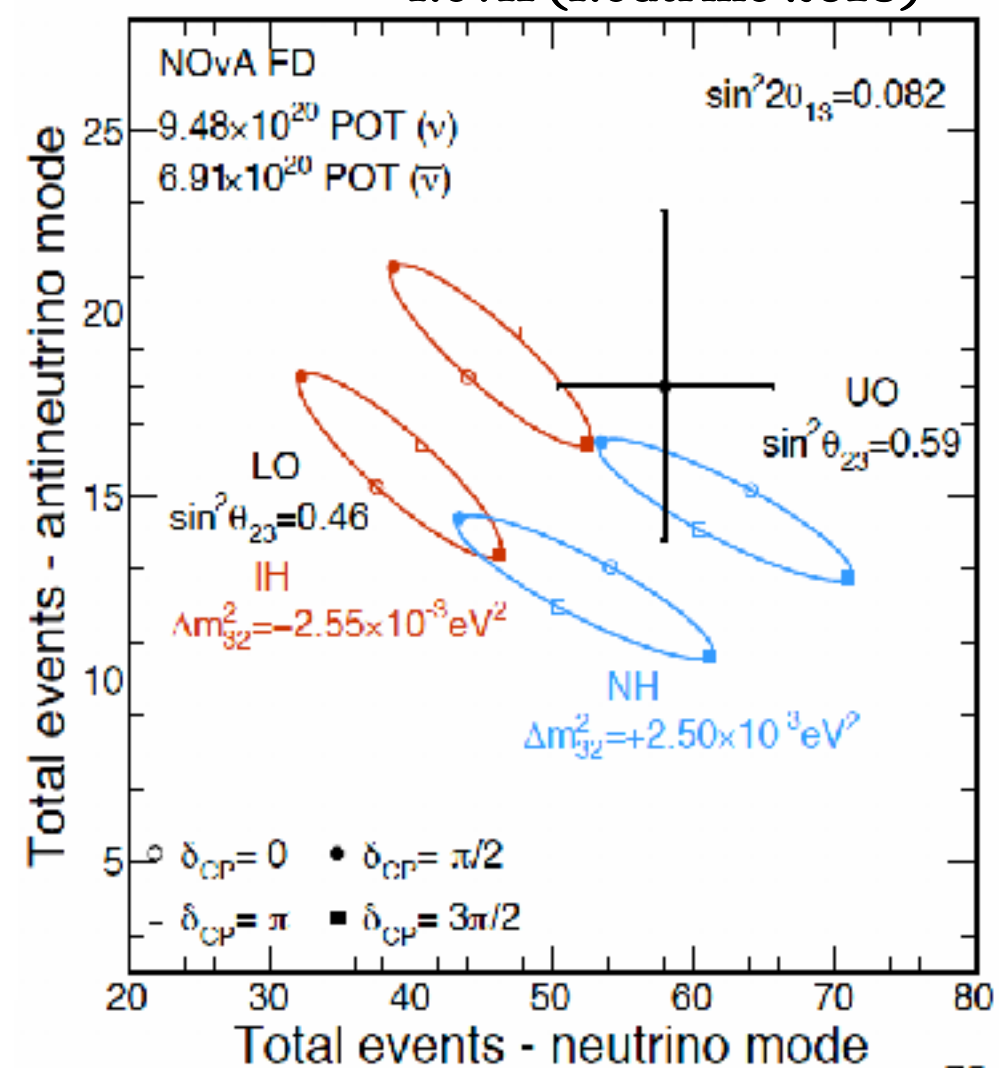
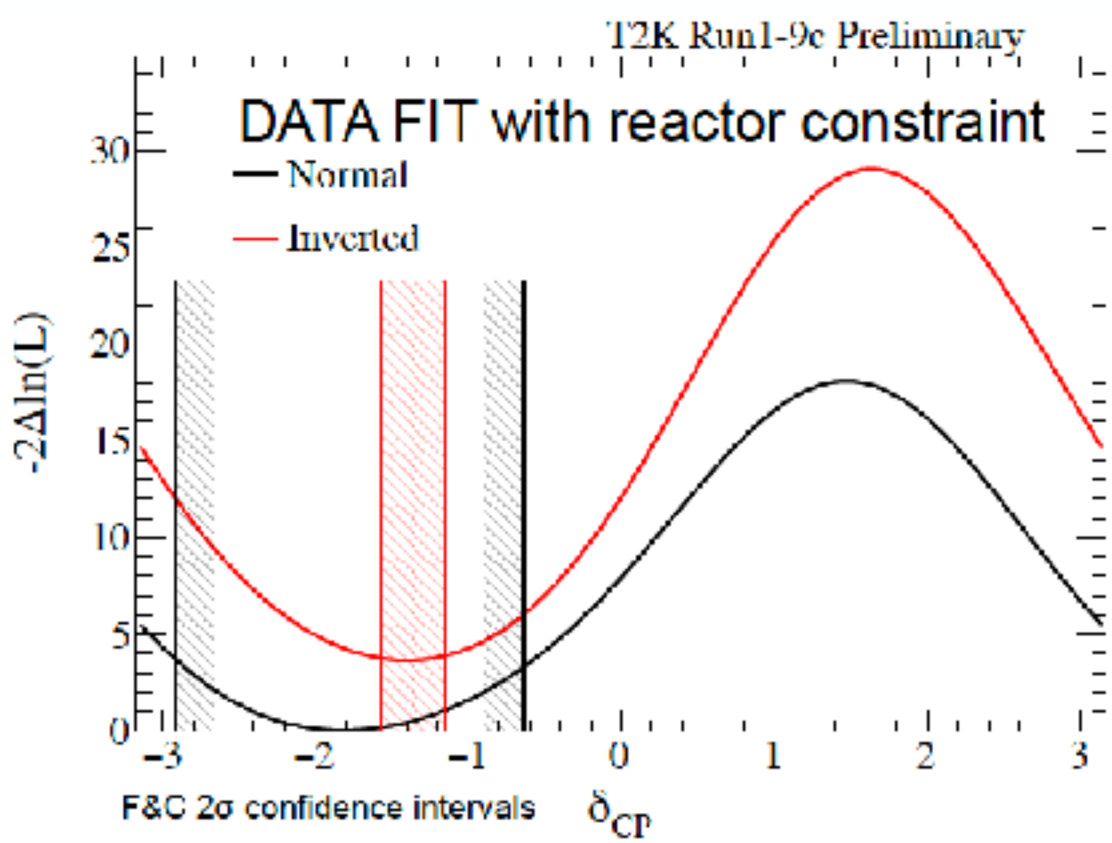
Not well constrained

NovA (Neutrino 2018)





T2K:

- CP conserving values outside of 2 σ region for both NH and IH; Favors maximal mixing for theta23

NOvA:

- Prefers NH, non-maximal θ_{23} mixing and disfavors lower octant; exclude δ_{CP} = Π/2 in IH at > 3 σ

Outline

- Neutrino Physics
  - What do we know so far?
  - **What we don't know?**
  - Experimental Landscape
  - R&D Challenges/Opportunities
  - Summary

Open Questions

- Which neutrino is the lightest?
- Leptonic CP Violation?
- Is θ_{23} maximal mixing?
- Precision Oscillation Measurements?

we discussed these four, but, there are more

Open Questions

- Which neutrino is the lightest?
- Leptonic CP Violation?
- Is θ_{23} maximal mixing?
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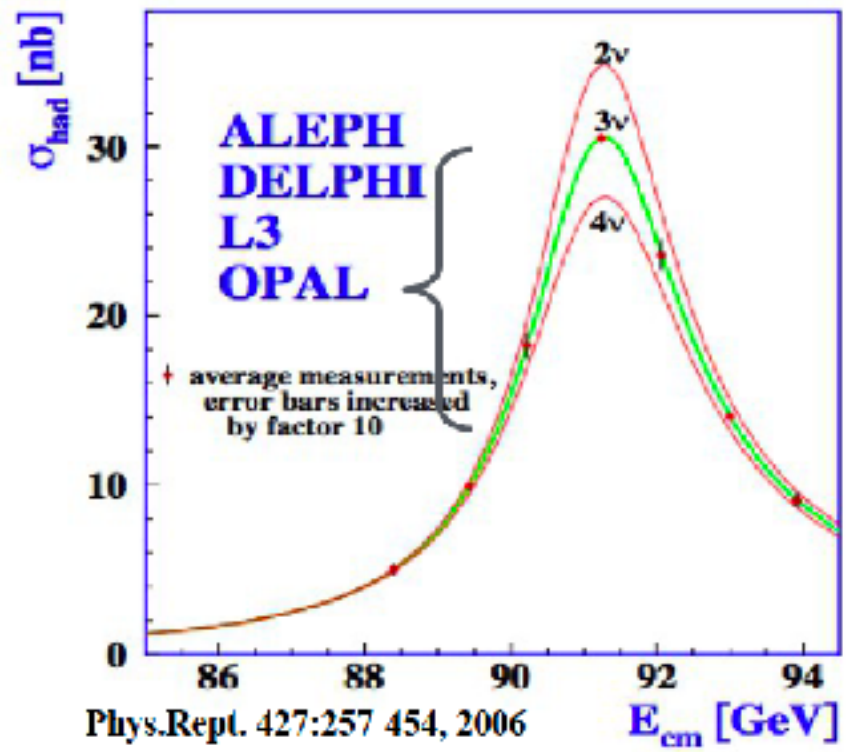
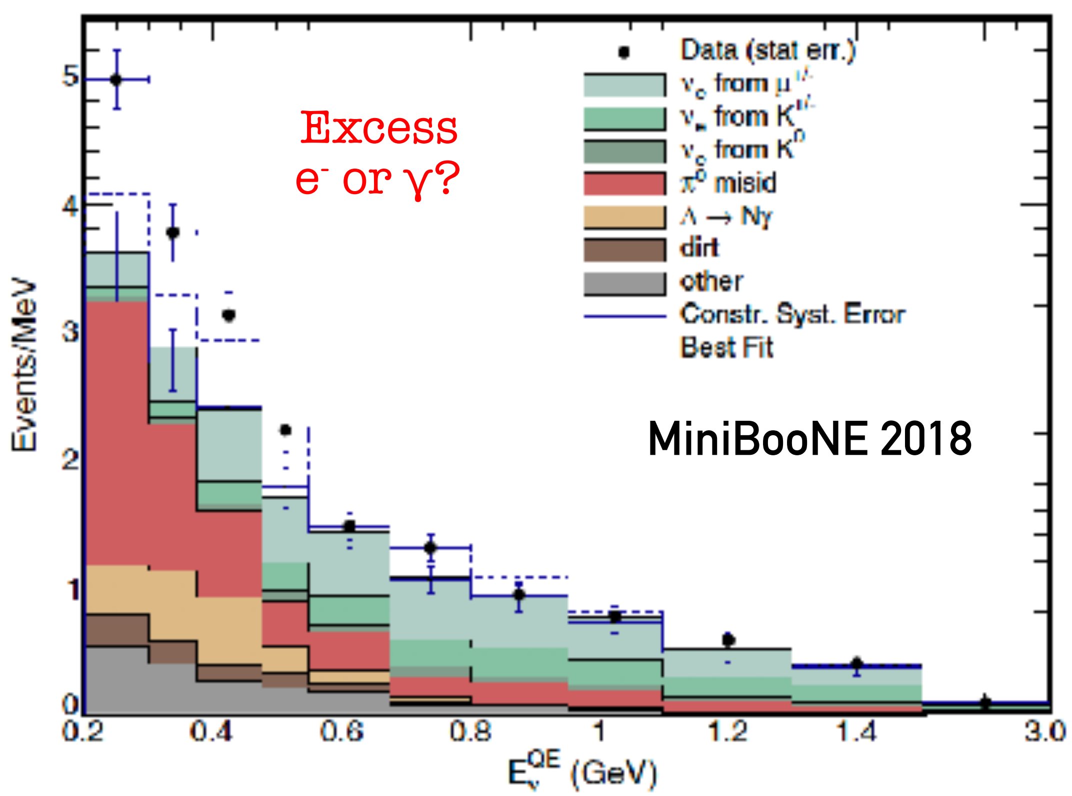
- **Are there more than 3 neutrinos?**



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.)

Open Questions

- Which neutrino is the lightest?
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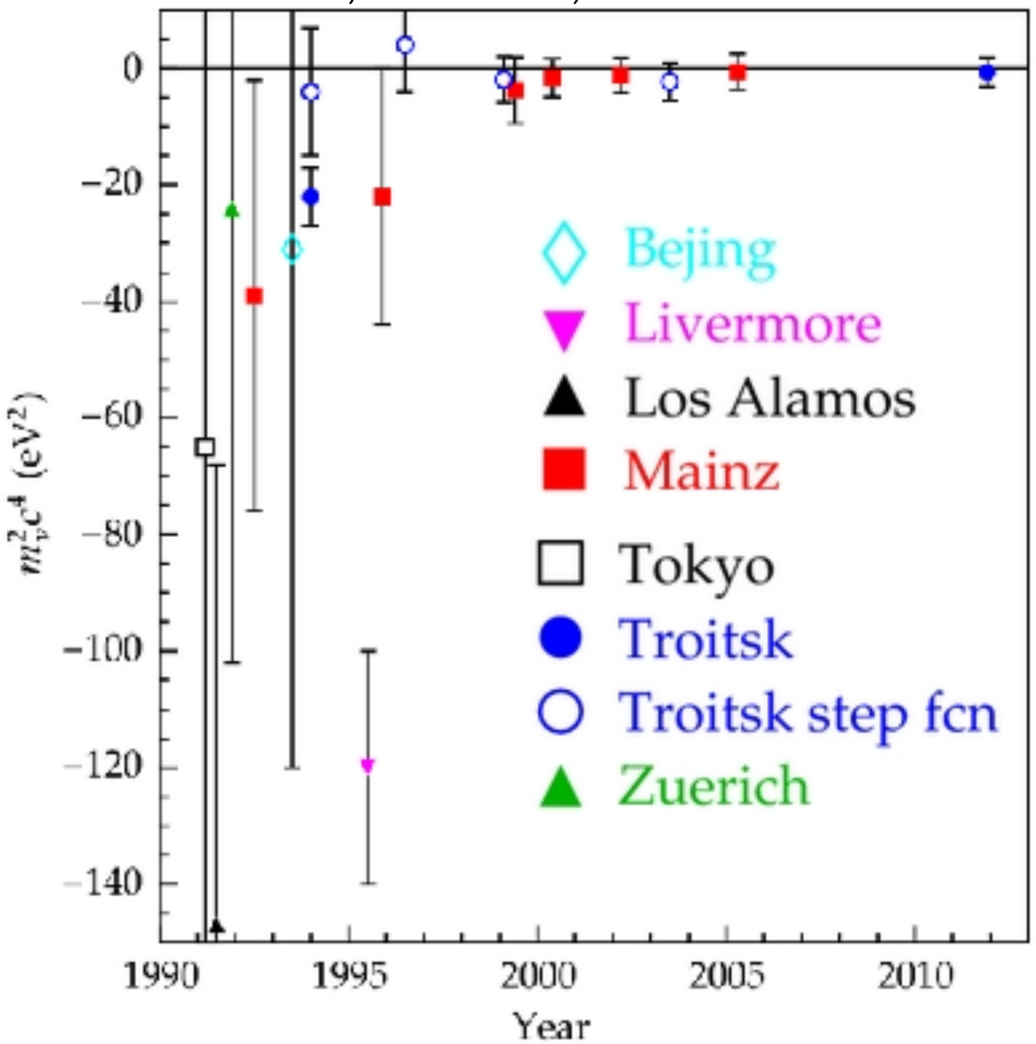
- Are there more than 3 neutrinos?
- **Absolute mass of neutrinos?**

Constraints from cosmological and astrophysical data and precision measurements from β-decay experiments

AHEP, Vol. 2013, Article ID 293986



PDG 2018 upper limit:

$$\sum_j m_j < 0.170\ eV, \quad 95\%\ CL$$

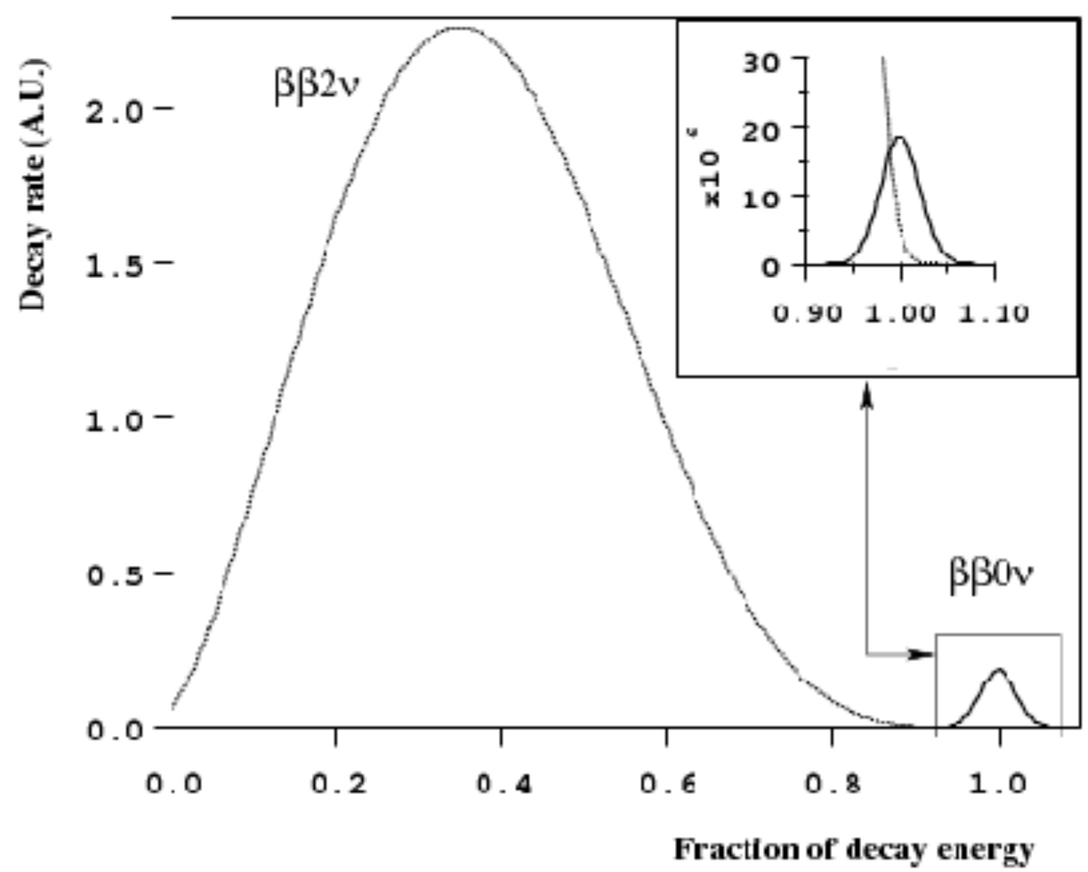
Upper limit on anti-ν_e mass (Troitzk experiment)

$$m_{\bar{\nu}_e} < 2.05\ \text{eV} \quad \text{at}\ 95\%\ \text{CL.}$$

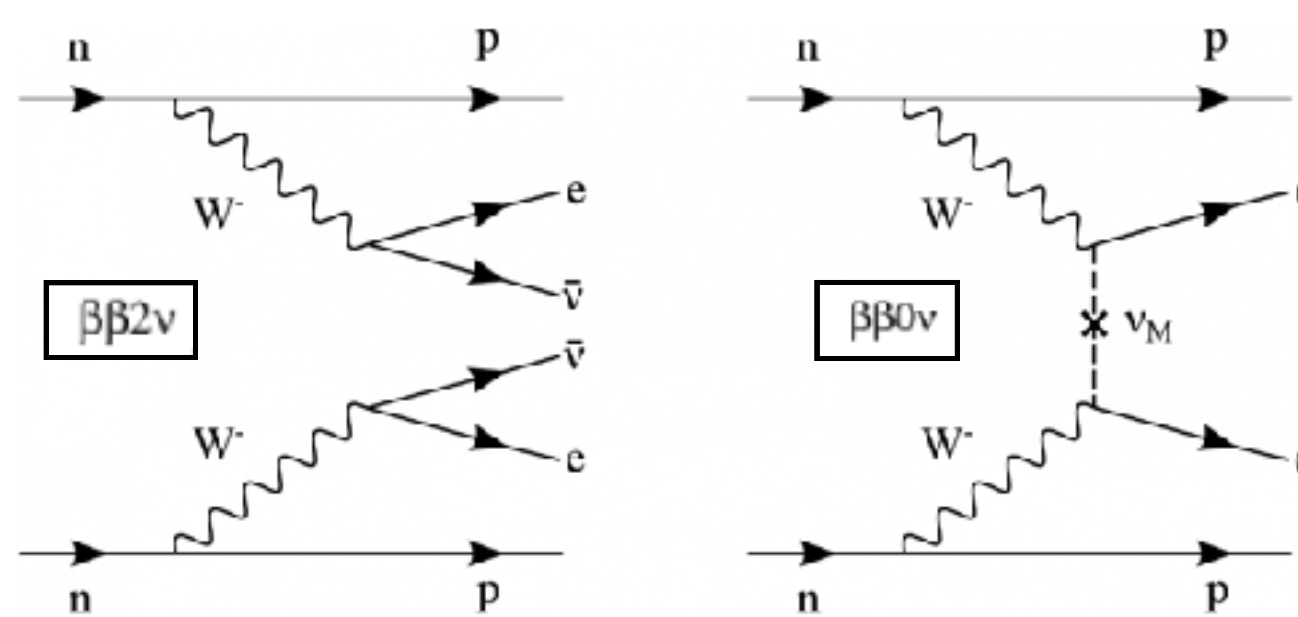
Phys. Rev. D 84 (2011) 112003

Open Questions

- Which neutrino is the lightest?
- Leptonic CP Violation?
- Is θ_{23} maximal mixing?
- Precision Oscillation Measurements?
- Are there more than 3 neutrinos?
- Absolute mass of neutrinos?
- **Neutrinos Majorana or Dirac?**



Observation of neutrino less double beta decay (ββ0ν) provides evidence for "Majorana" nature of neutrinos



Multiple Experiments addressing same questions

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 programs — overlap b/n experimental goals

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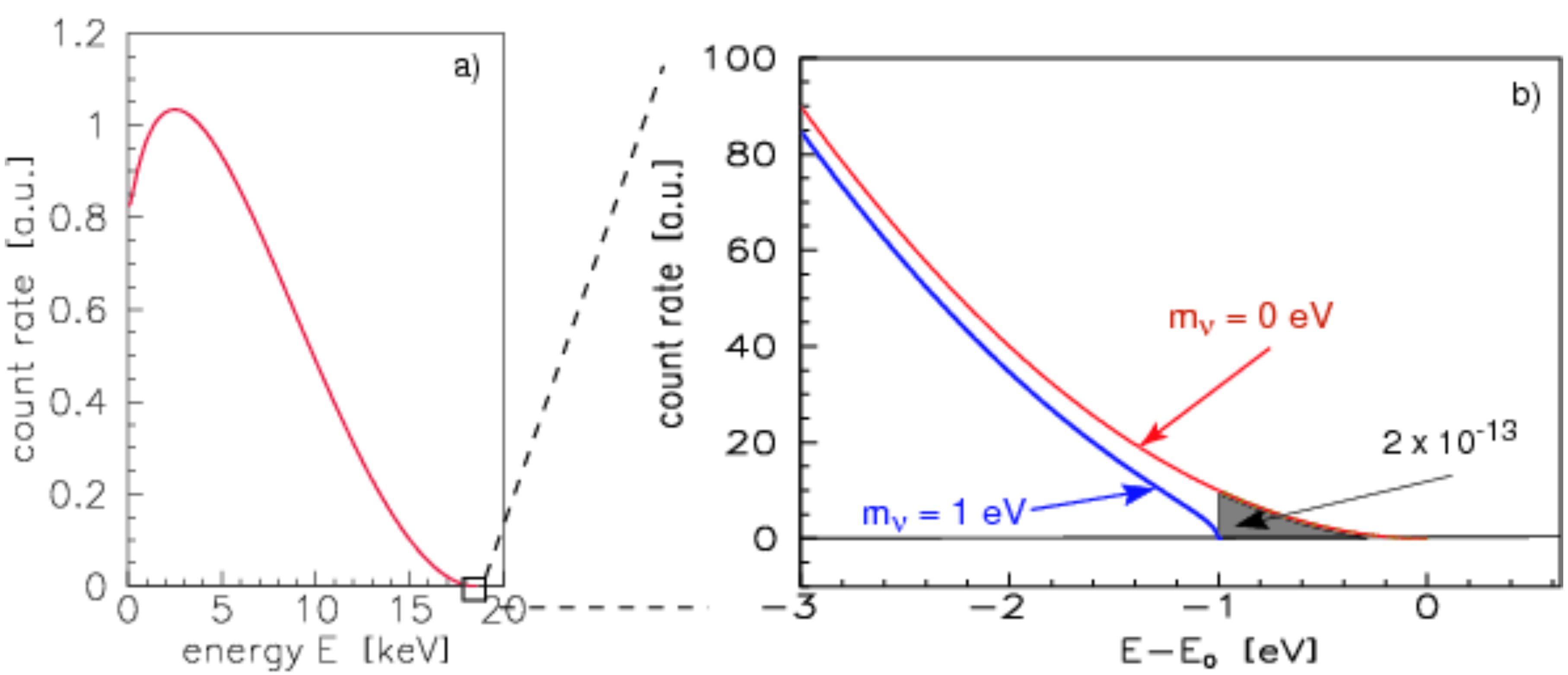
Direct Mass Measurement Experiments

- KATRIN
- Project 8

Tritium beta decay tagging experiments
- Spectrometer (KATRIN)
- Cyclotron radiation (Project 8)

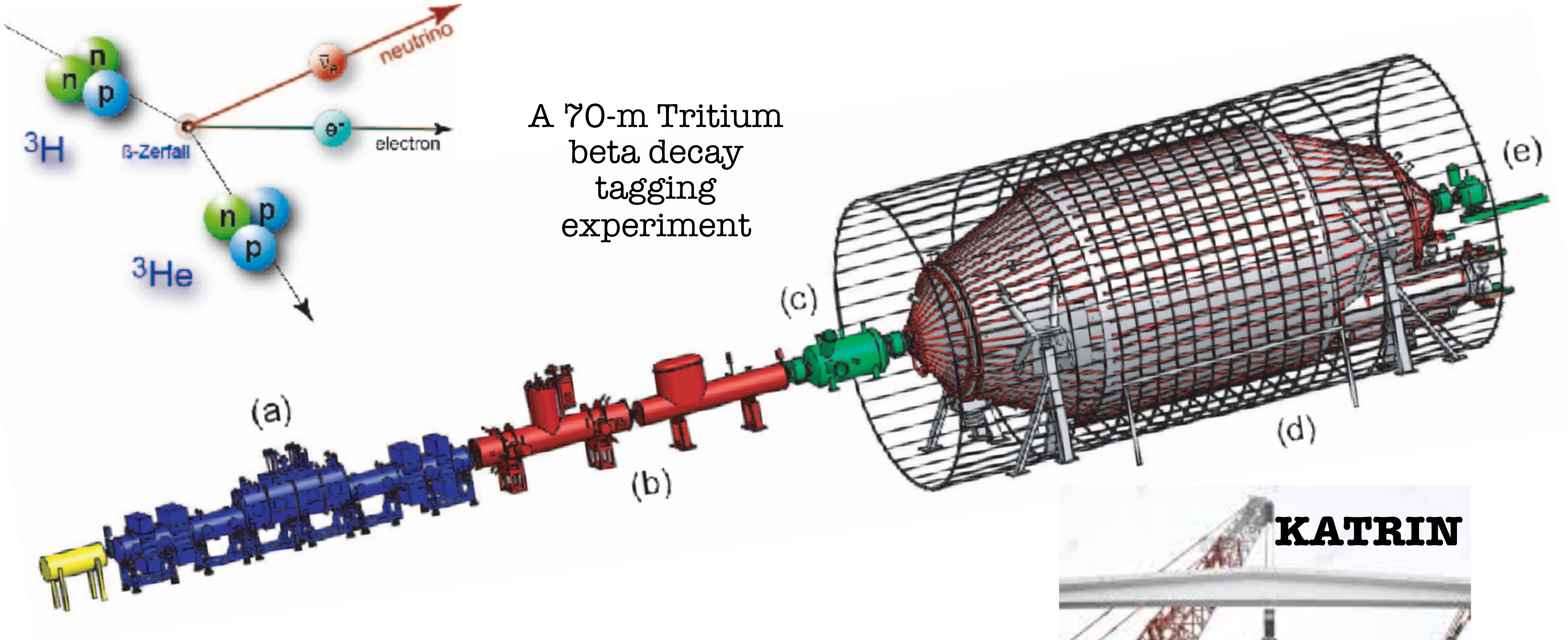
- ECHo
- HOLMES

Electron capture decay of ^{163}Ho
- Both use Calorimetric approach



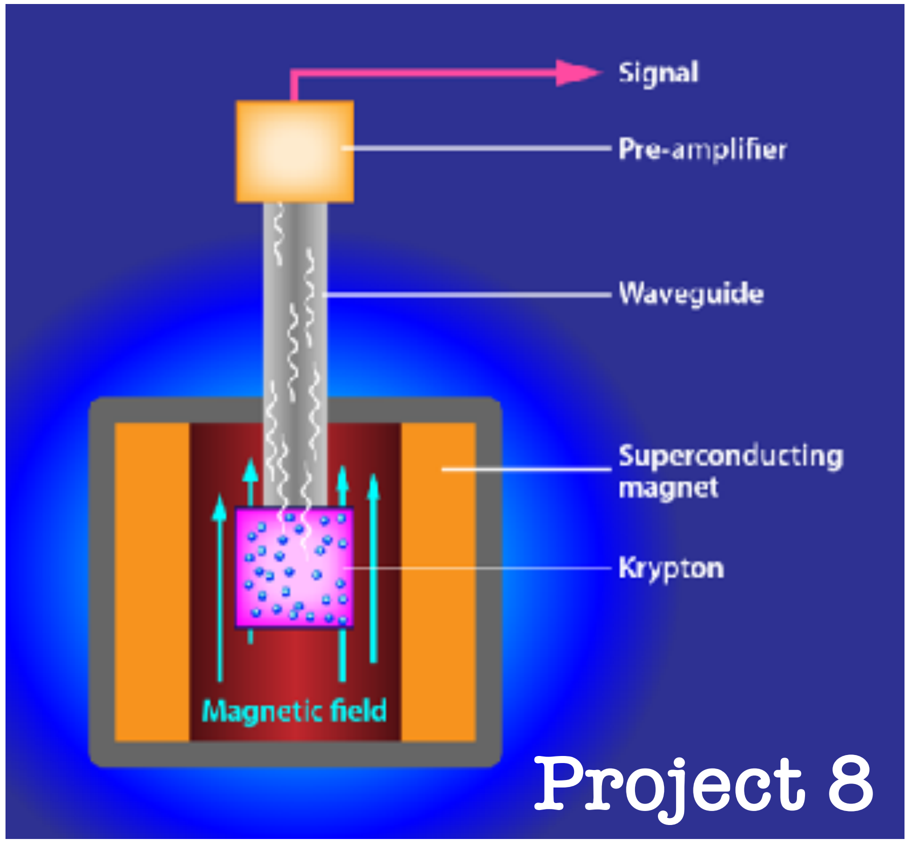
Electron energy spectrum of Tritium beta decay and end-point zoomed in

Direct Mass Measurement Experiments:
KATRIN, Project 8



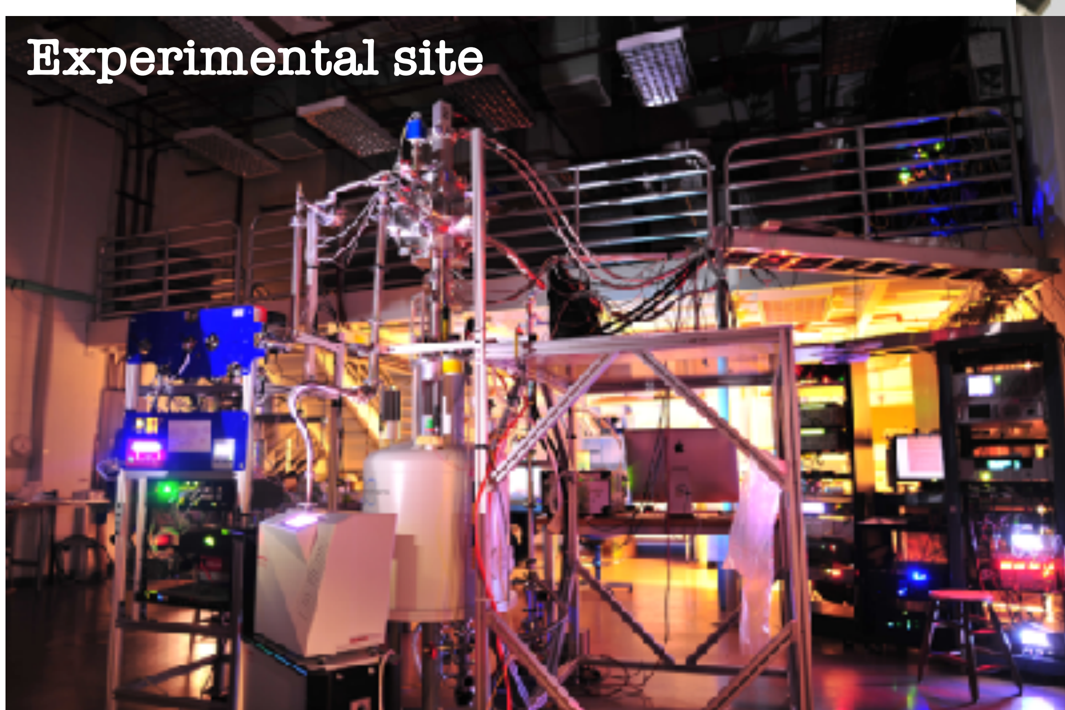
- 200-ton spectrometer; “MACE-E-Filters” technique
- An order of magnitude improvement in upper limit on anti-ν_e mass 0.20 eV (90% CL)
- If anti-ν_e mass > 0.35 eV, discovery at 5 σ
- Experiment installed and commissioned, data early 2019

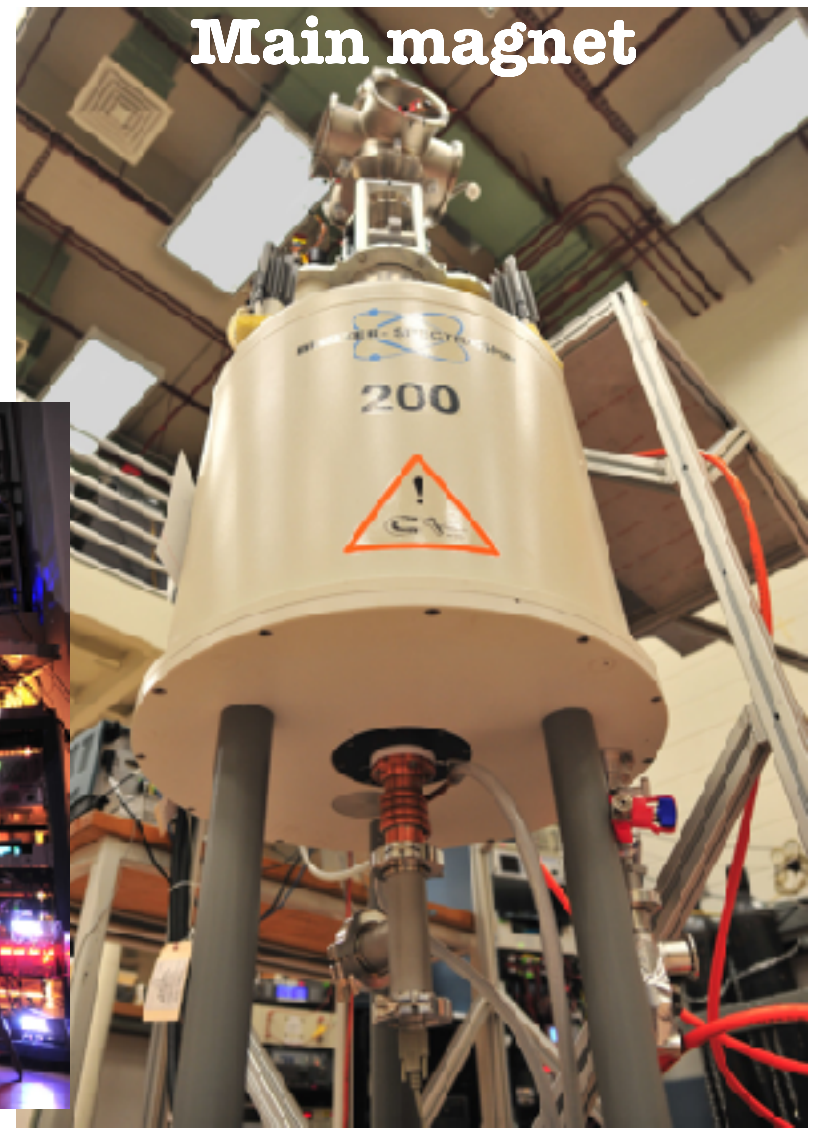
Direct Mass Measurements Experiments:
KATRIN, **Project 8**



Novel technique:

- seeing electrons from tritium β-decay using Cyclotron Radiation Emission Spectroscopy (CRES)
- Frequency measurement
- Full spectrum sampling
- No need to separate electrons from source
- Can reach a mass of 0.05 eV





- Currently in Phase-II (demonstrate measurement of the tritium spectrum using CRES)
- Identified the first CRES signal from an electron from T_2 beta decay within three hours.

ββ0ν Experiments

- Multiple isotopes; larger size
- Many active experimental techniques

Experiment	Isotope	Technique
Majorana Demonstrator	^{76}Ge	Point contact Ge
GERDA II	^{76}Ge	Semicoax/BE Ge + veto
CDEX	^{76}Ge	Point contact Ge
NG-Ge76	^{76}Ge	Point contact Ge
COBRA	^{116}Cd	CdZnTe
CANDLES	^{48}Ca	CaF_2 scintillator + veto
AMoRE	^{100}Mo	Low-T MMC
DCBA/MTD	^{100}Mo	Foils + tracker
MOON	^{100}Mo	Foils + scintillator
EXO200	^{136}Xe	LXe TPC
nEXO	^{136}Xe	LXe TPC
NEXT	^{136}Xe	High-P TPC
PandaX III	^{136}Xe	High-P TPC
KamLAND-Zen	^{136}Xe	Liquid scintillator
SuperNEMO	^{82}Se	Foils + tracker
CUPID	^{130}Te, ^{82}Se	Hybrid bolometers
CUORE/CUORE-0	^{130}Te	TeO2 bolometers
SNO+	^{130}Te	Liquid scintillator

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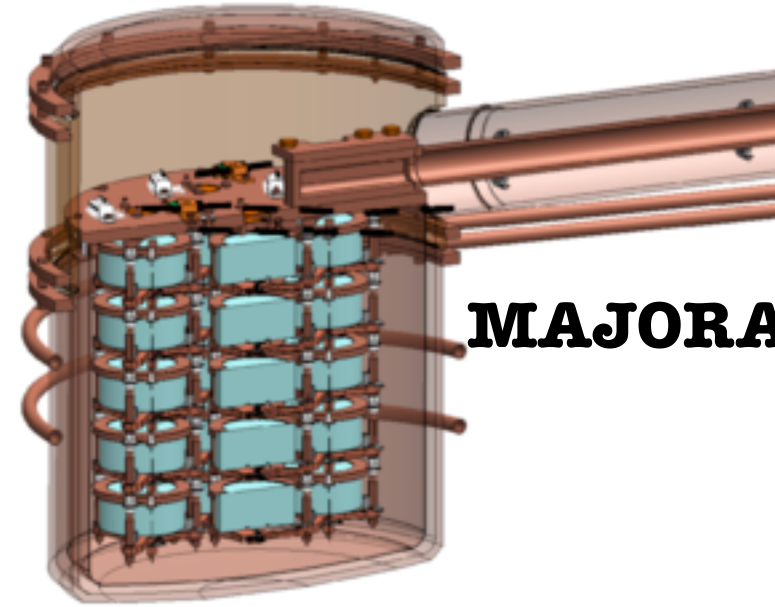
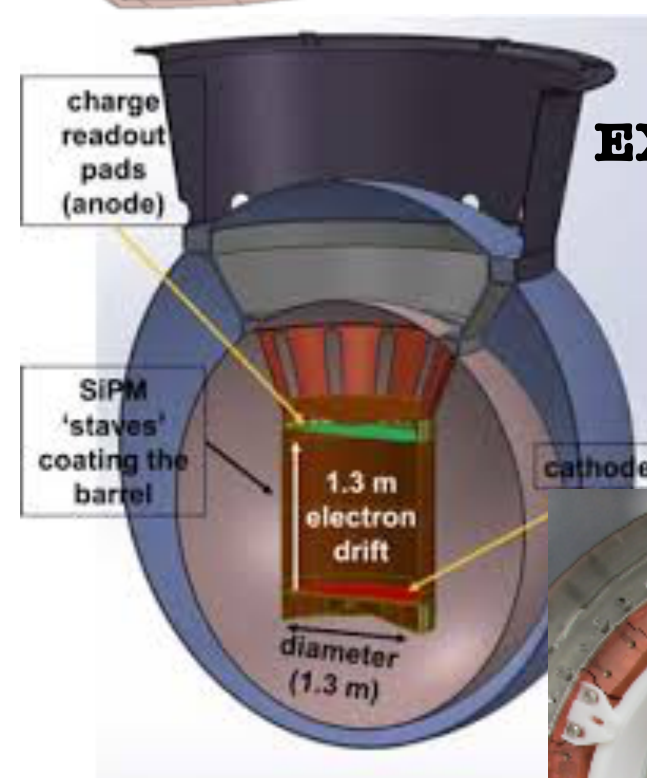
- **Challenges:** large mass to offset long 1/2 lifes; low backgrounds, excellent energy resolution/tracking



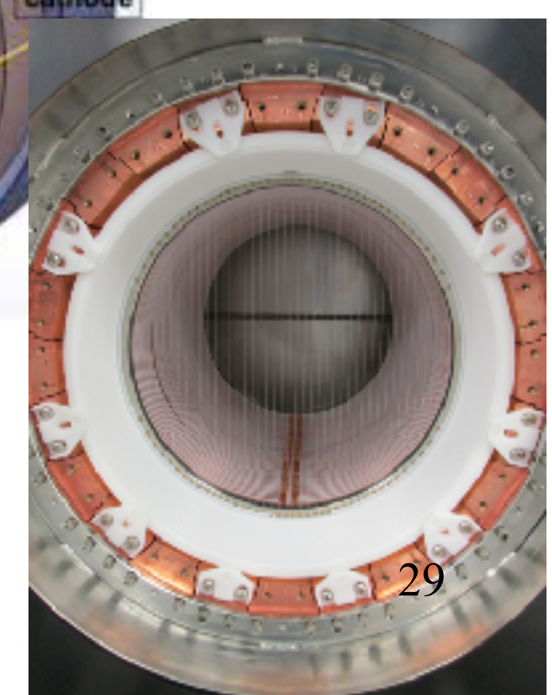
MAJORANA



EXO200 to nEXO

Ba tagging to reduce backgrounds

see talks by D. Moore, J. Also



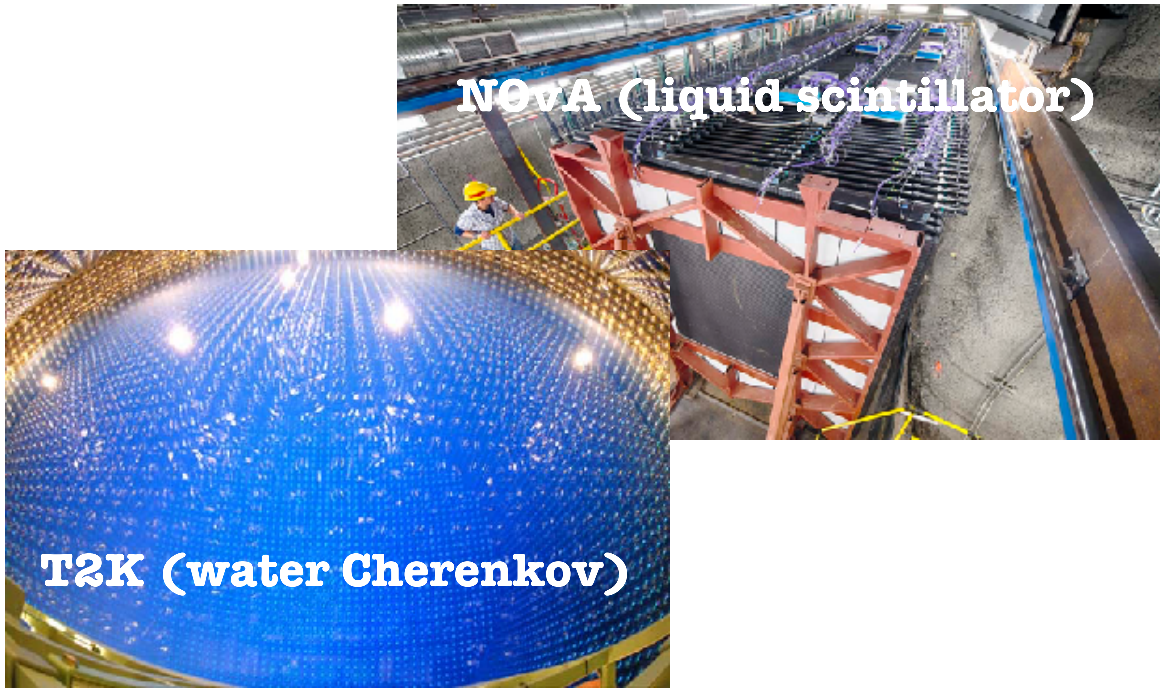
NEXT

Accelerator Experiments

Current Landscape: T2K, NOvA, MINOS+,..

- T2K+NOvA can reach around 2-3 σ for CPV and MH (if CP phase is confirmed to be maximal)
- Extended run of T2K can improve sensitivity
- New experiments/technology are needed for precision measurement of CPV phase

Accelerator Experiments



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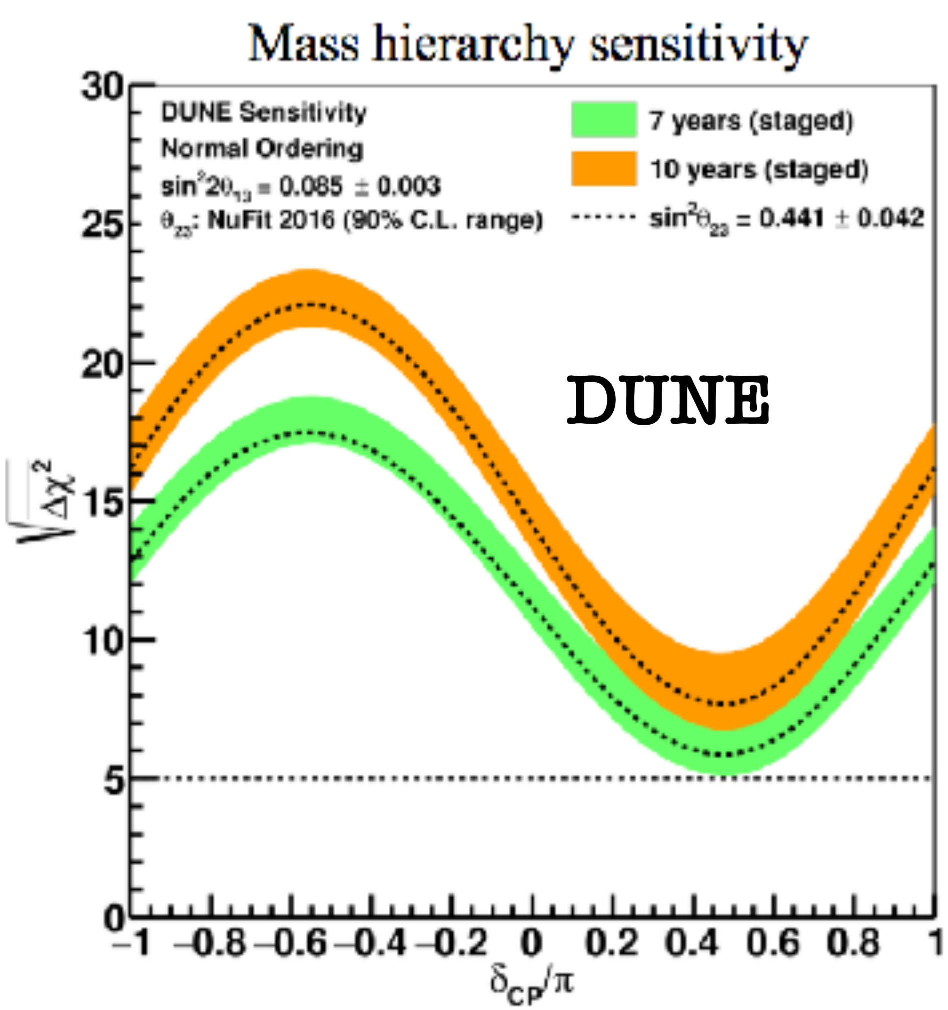
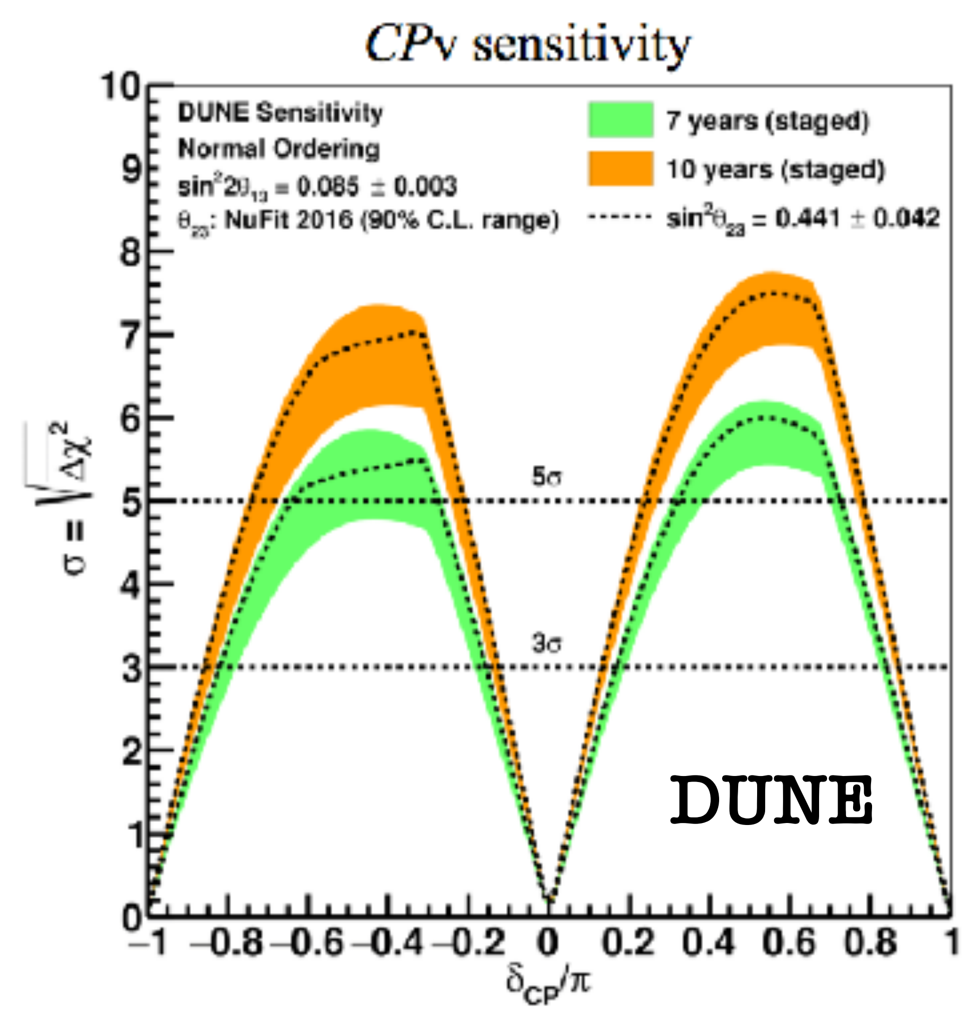
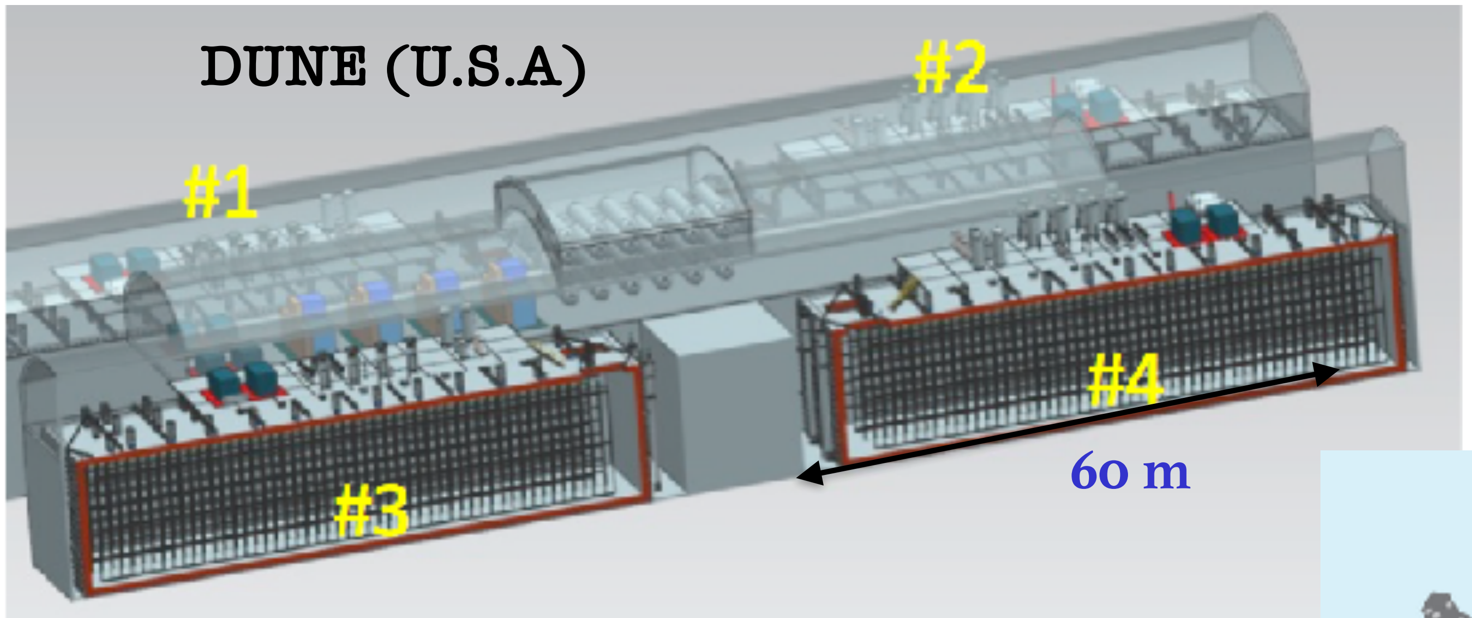
Future: DUNE, Hyper-K

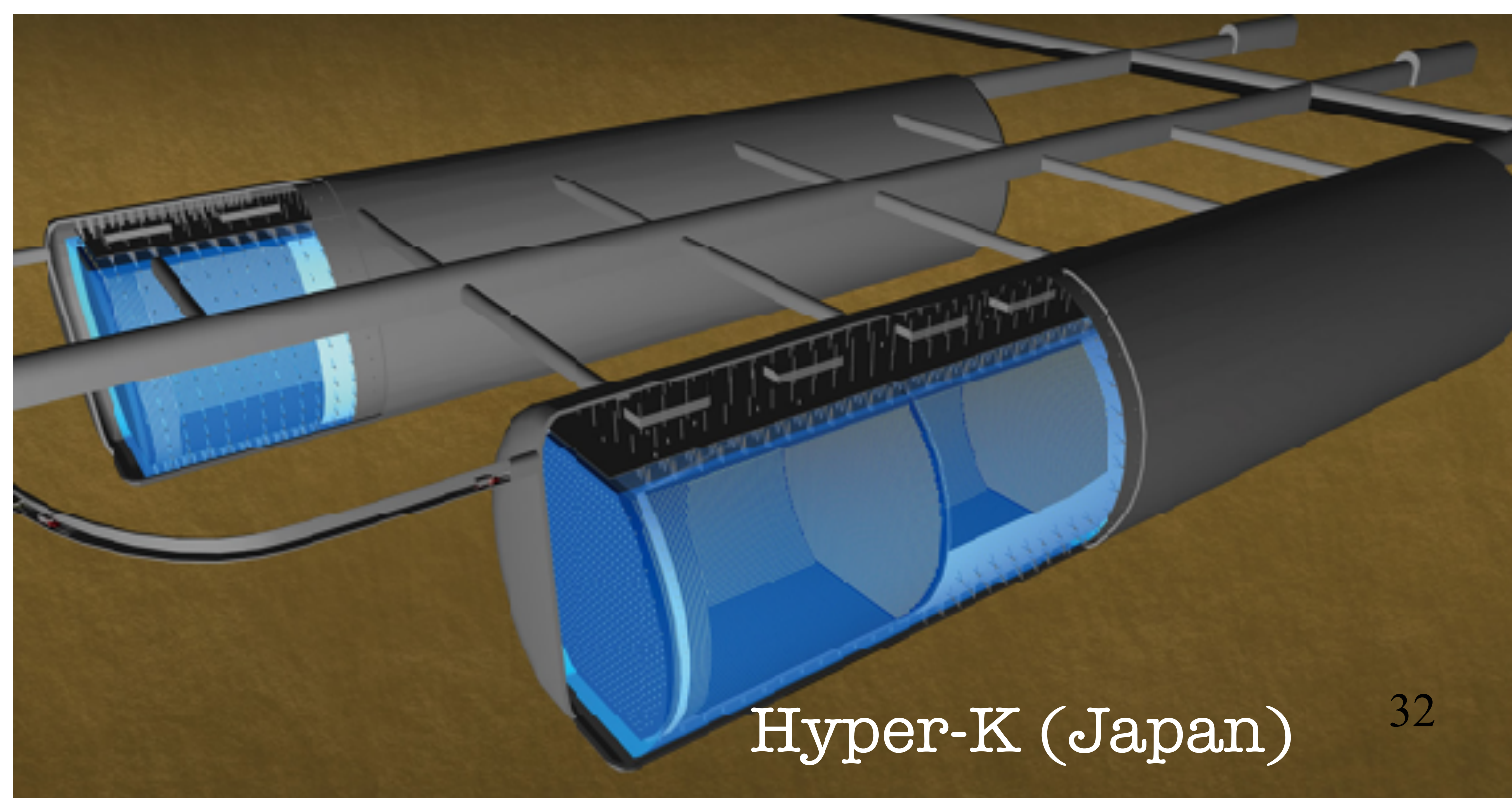




Next generation Long-Baseline: DUNE & Hyper-K



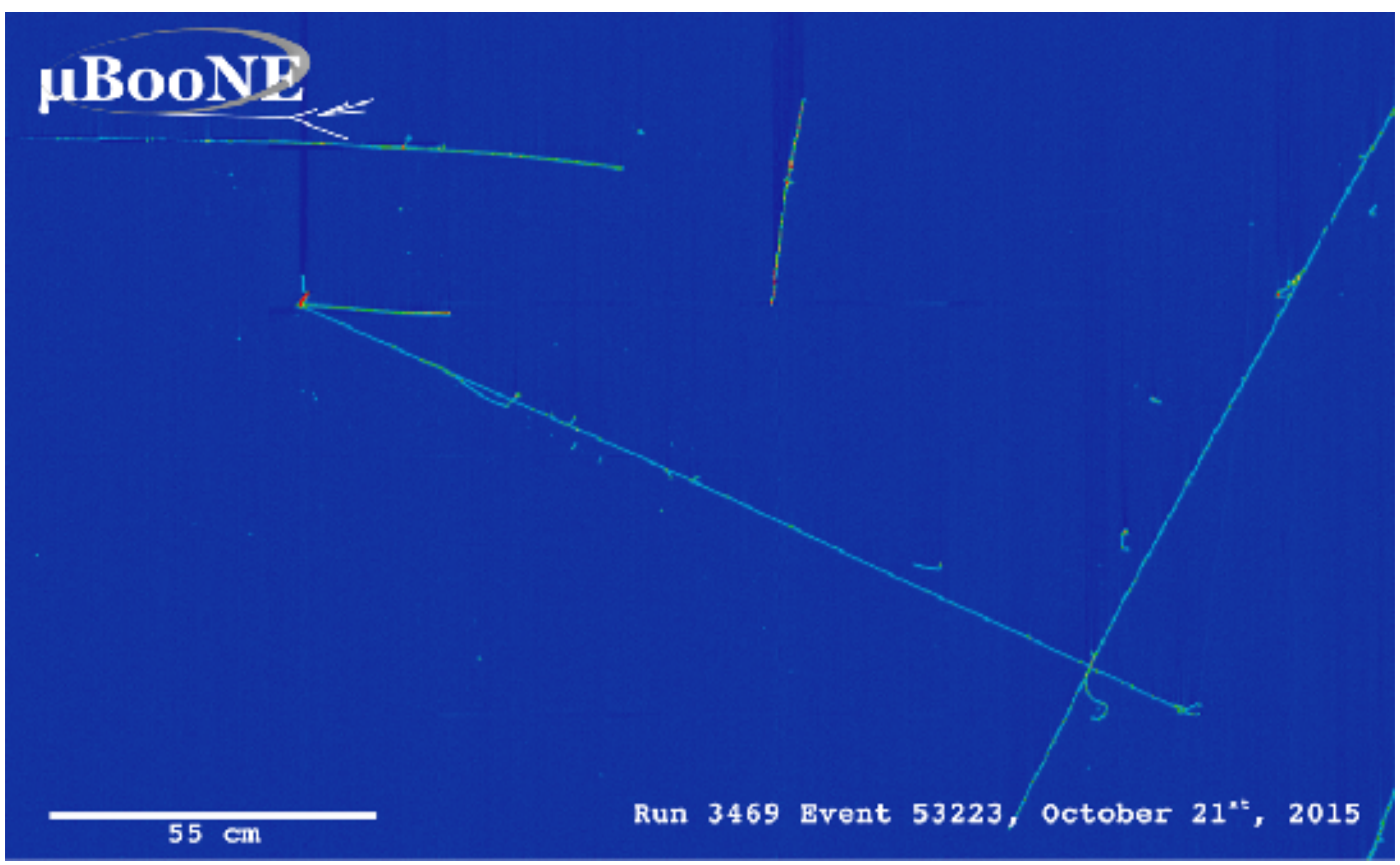
- **Liquid Argon Time Projection Chamber (LArTPC)**
  - Aiming for 2024
  - 40 kton LArTPC detector
  - MW-scale beam from Fermilab
  - Four separate caverns, flexibility in design



- **Complementary to DUNE**
  - 1 Mega ton Water Cherenkov technology
  - off-axis: narrow range of E (< 1 GeV)
  - Measure CPV at > 5σ (timeline depends on beam power)

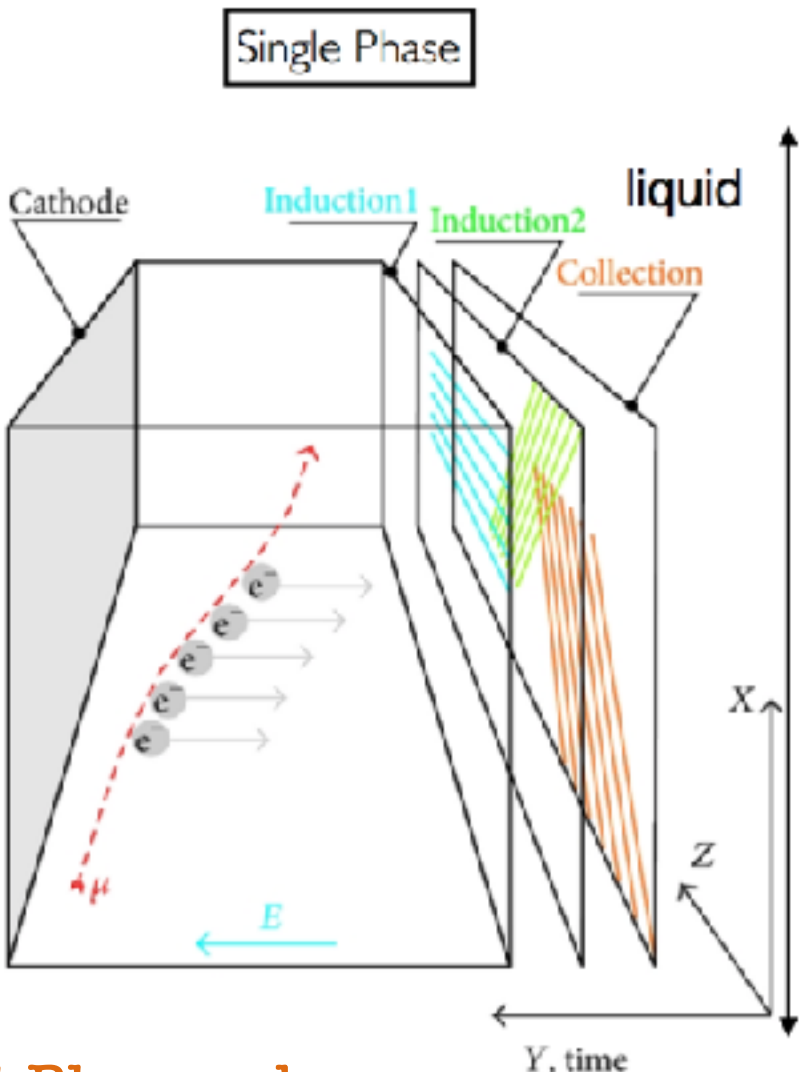
Why Liquid Argon Detectors?

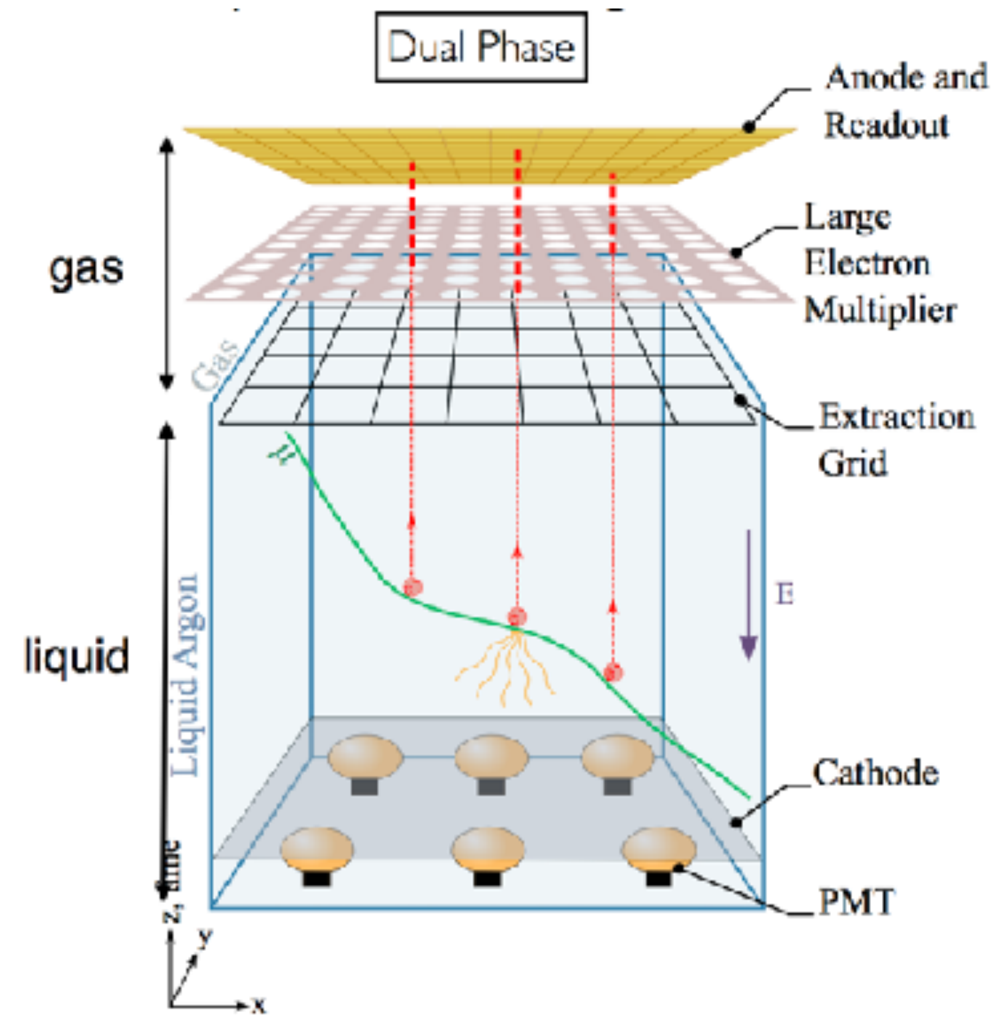
- Features of a LArTPC
  - Argon makes an excellent target (dense, abundant, cheap etc.) — challenging for cross sections though
  - Fine granularity & excellent calorimetry
  - Can separate Signal (υ_e CC) from background (NC π^0)
  - Low energy thresholds
  - Technology allows for scalability which means massive detectors



LArTPCs are imaging detectors providing high resolution images

Single & Dual Phase LArTPCs for DUNE



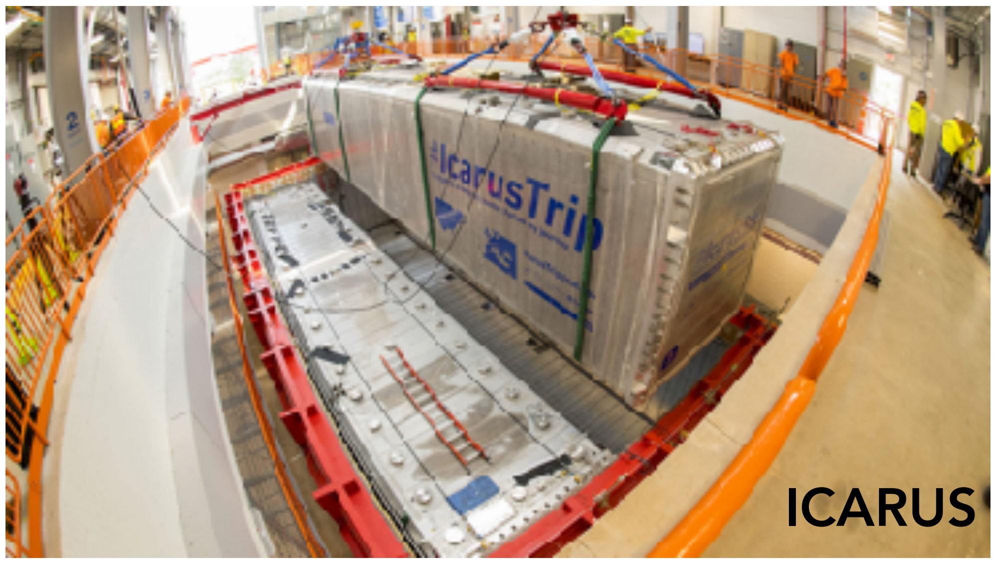


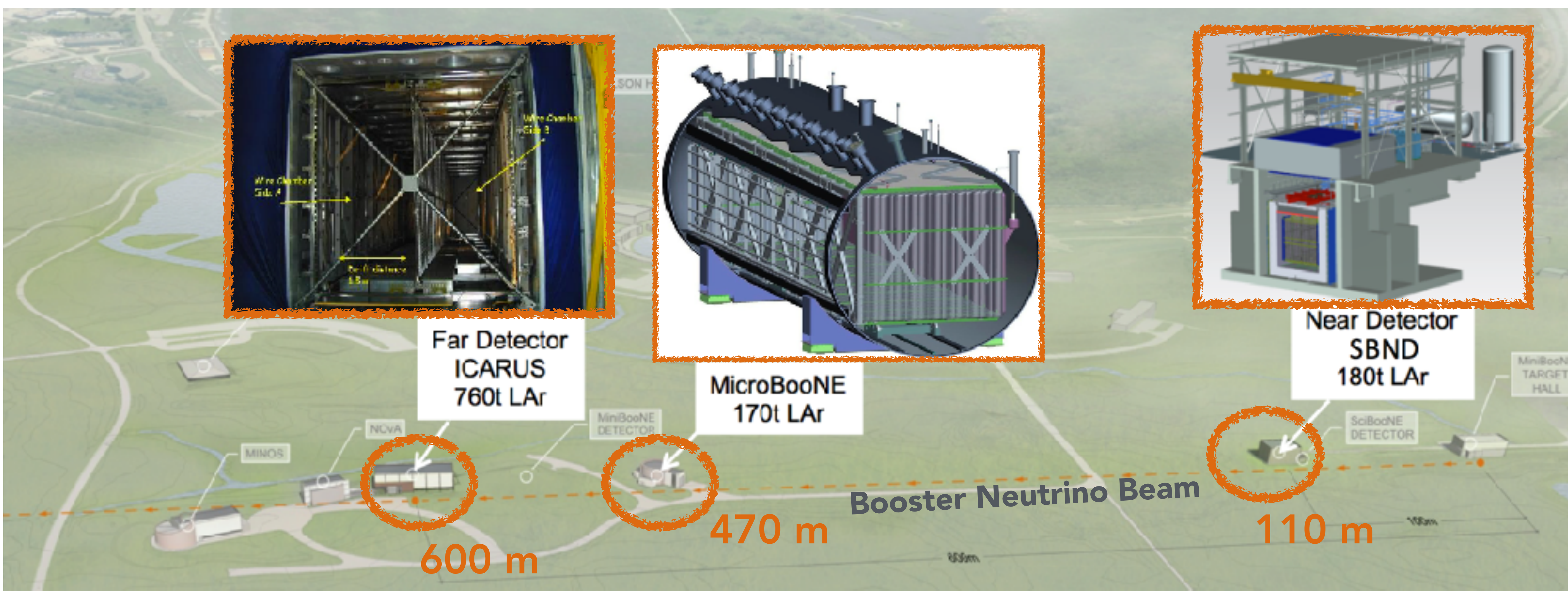
talk by F. Blaszczyk

talk by A. Chatterjee

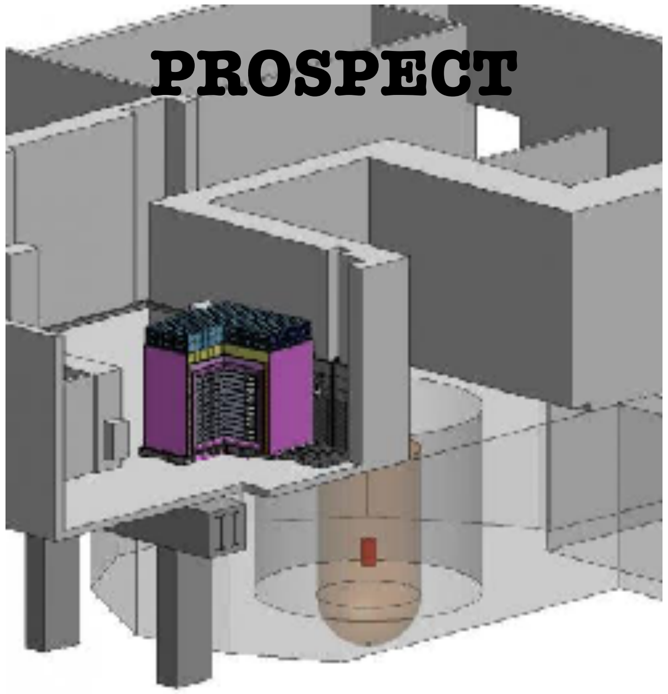
Liquid Argon Detectors:
Fermilab Short-Baseline Program (Future)

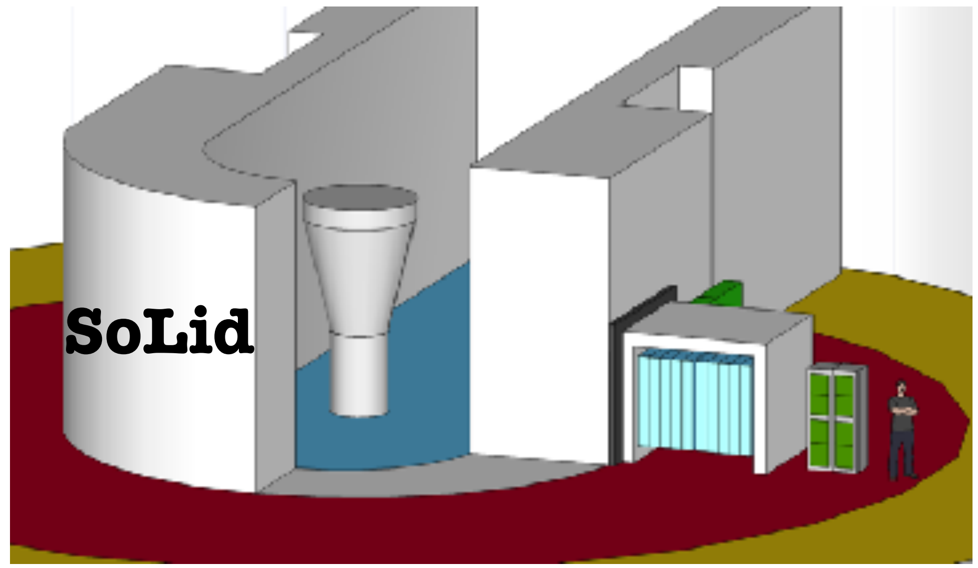
(to more definitively address the sterile ν question where we have existing hints)





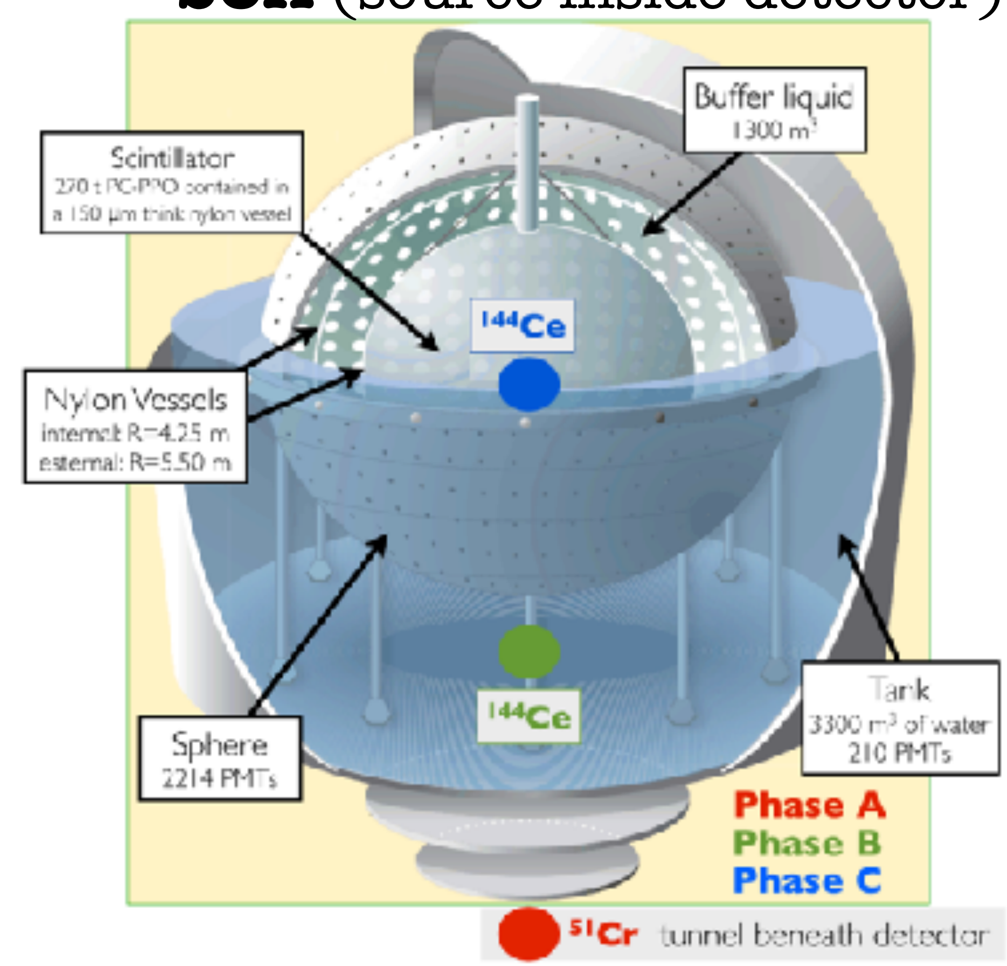
Very Short-Baseline (~1m) Experiments for Future

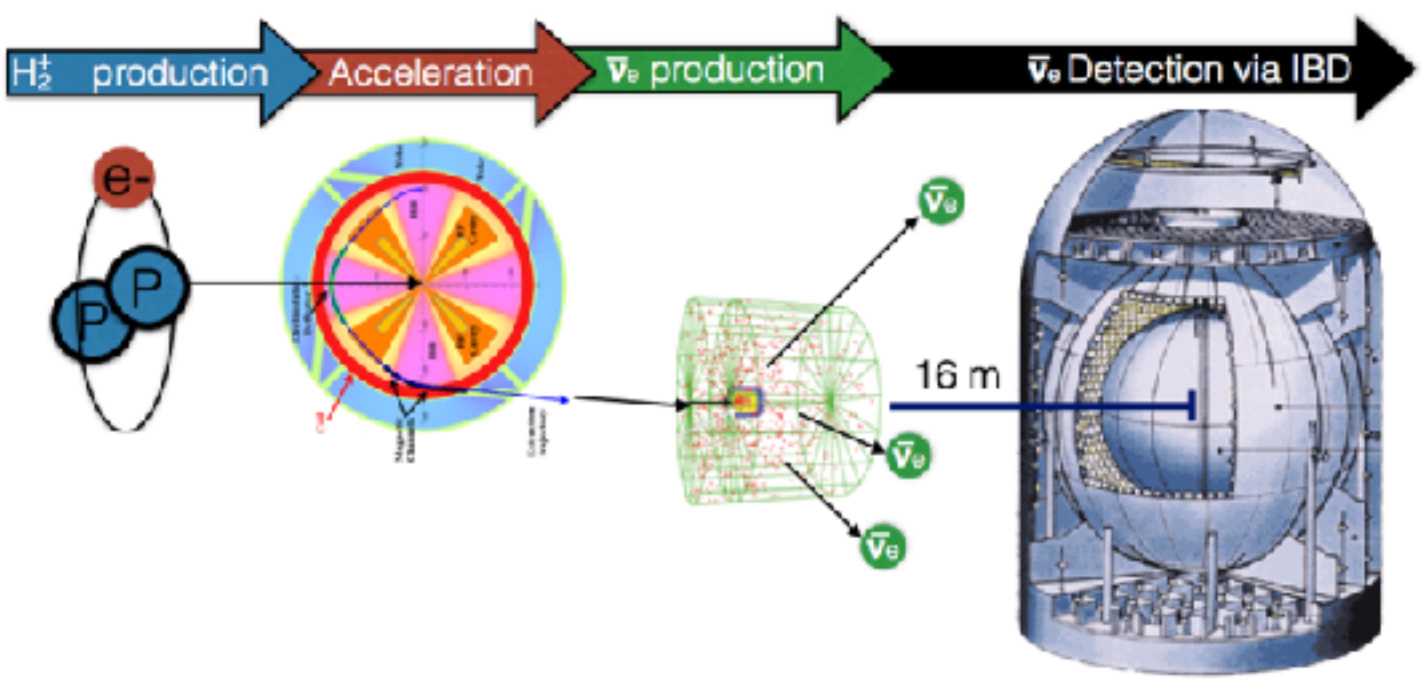




Other experiments:
STEREO, NuLAT,..

SOX (source inside detector)





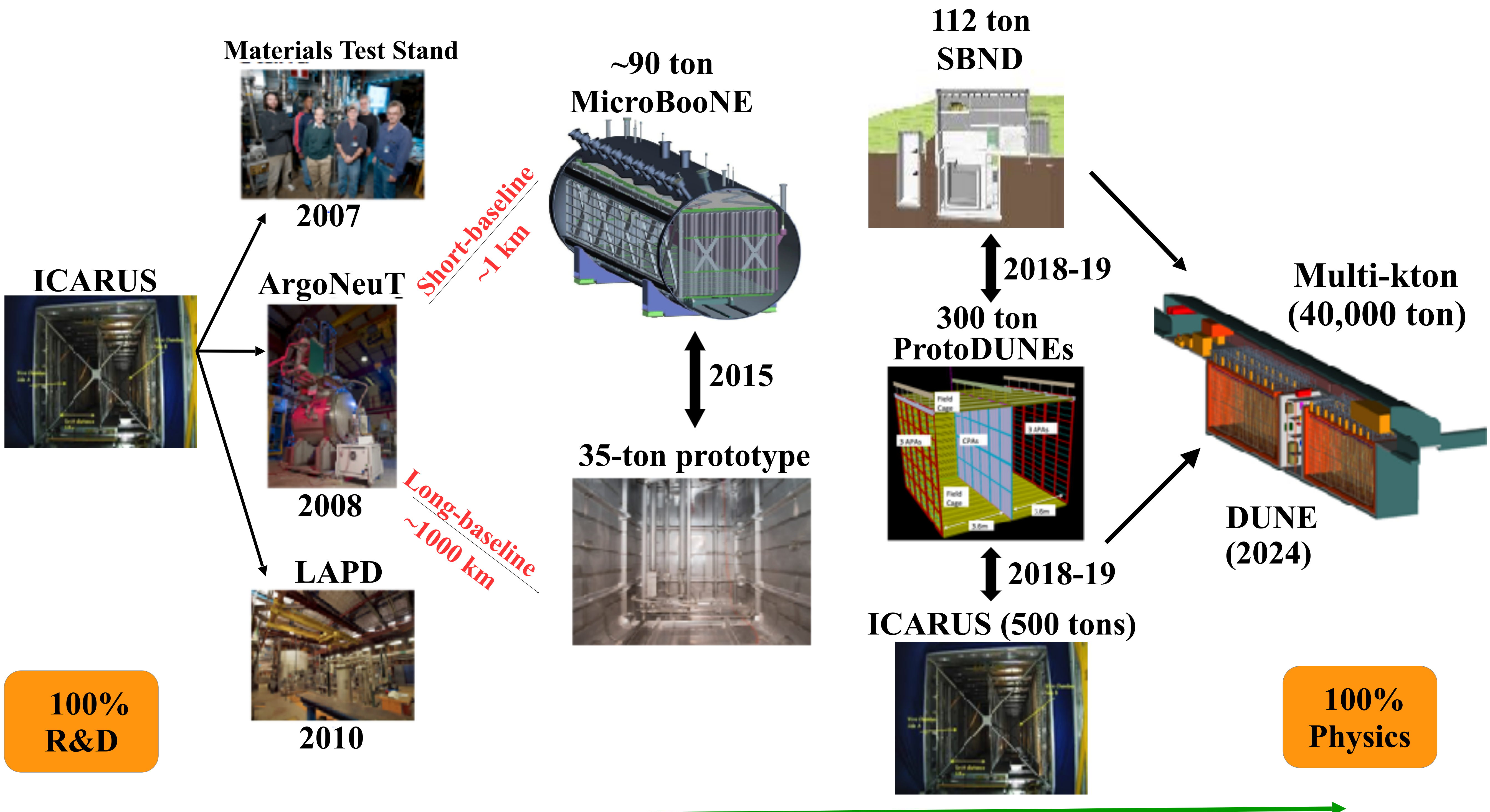
IsoDAR = Isotope Decay-At-Rest

Outline

- Neutrino Physics
  - What do we know so far?
  - What we don't know?
  - Experimental Landscape
  - **R&D Challenges/Opportunities**
  - Summary

Liquid Argon Detectors R&D path

Tremendous progress in LArTPC development in the past few years

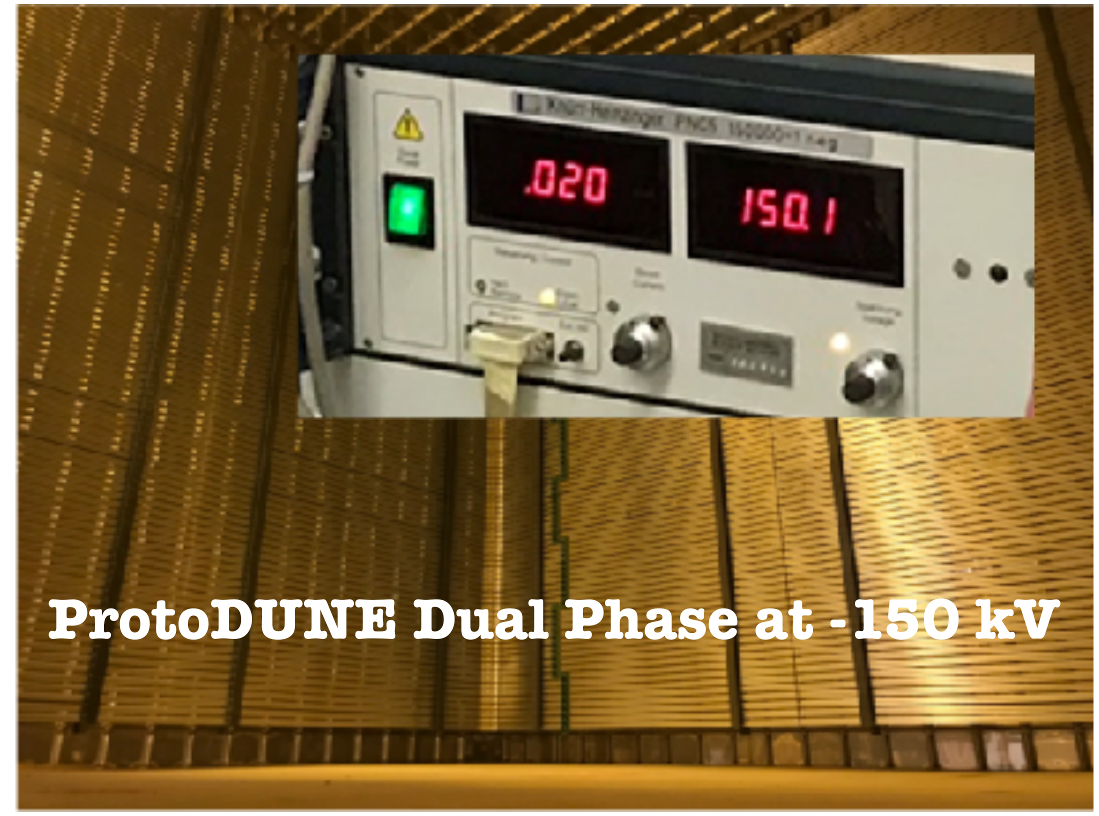


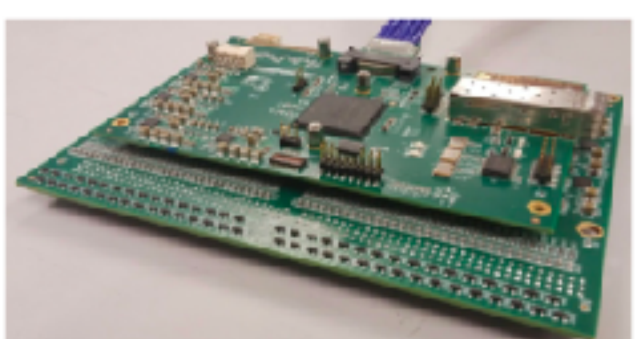
Quickly moving from pure R&D to exploring great physics with large detectors

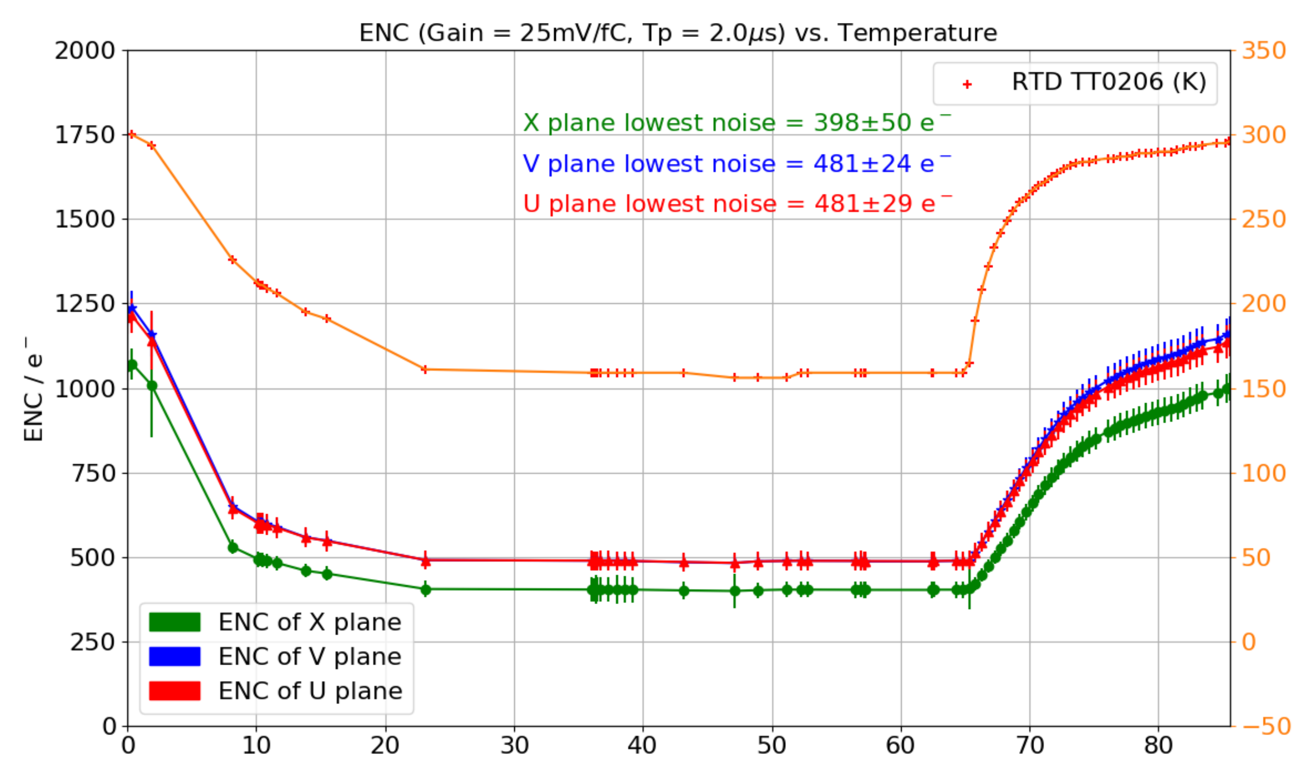
Liquid Argon Detector Challenges

See talk by L. Tvrznikova

- High Voltage R&D
  - Typically need few 100 kV
  - Stability is an issue, mechanical design matters
- Noise
- Cold Electronics → (talk by M. Convery)
- Light detection
- Modular Design
- Readout
- DAQ
- ν- Nucleus cross sections
- Computing
- Reconstruction
- Calibration





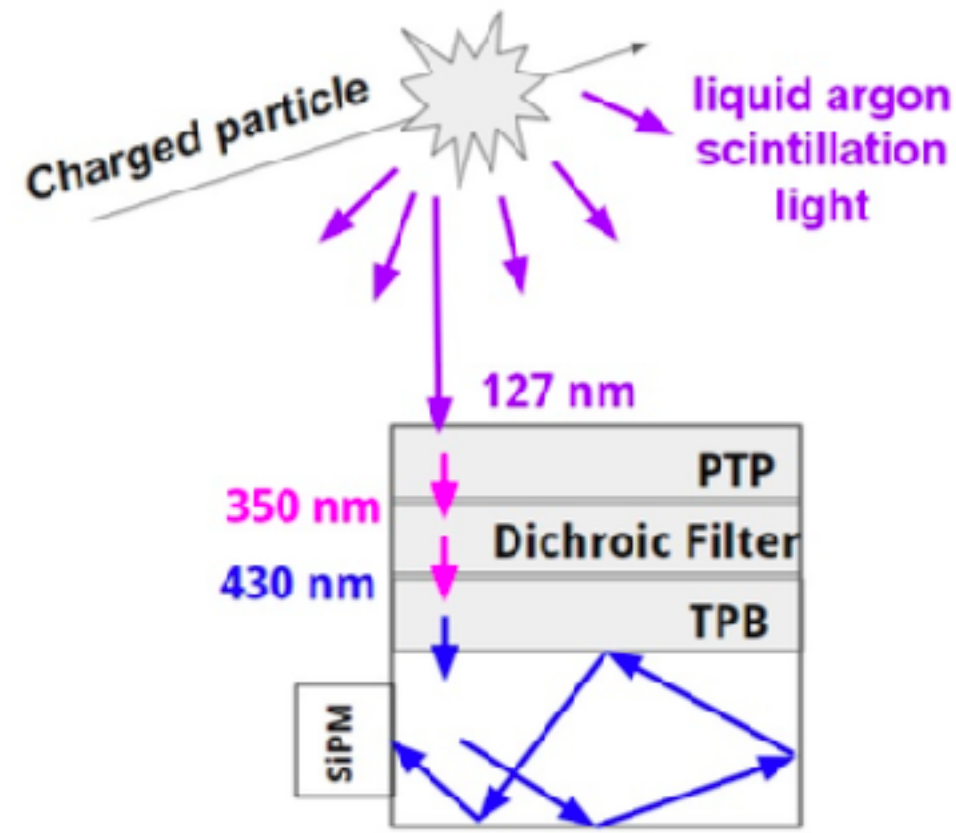


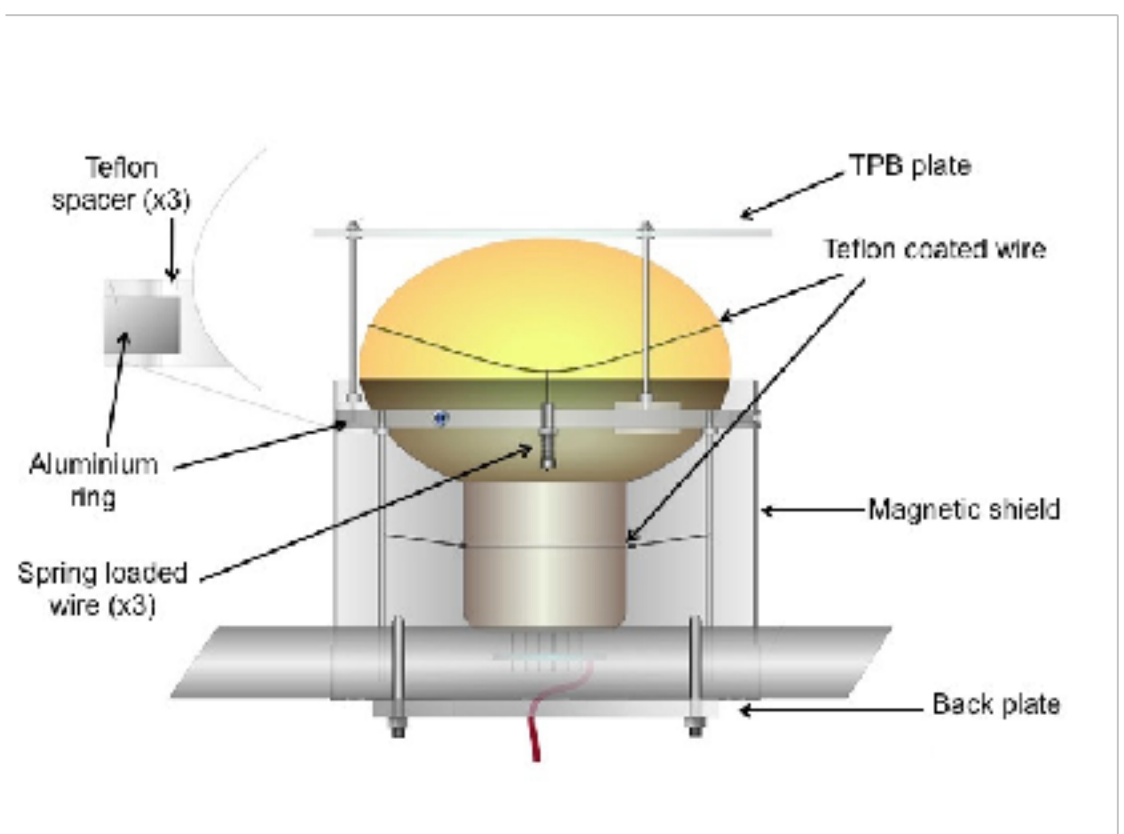
Photon Detector Challenges/Opportunities

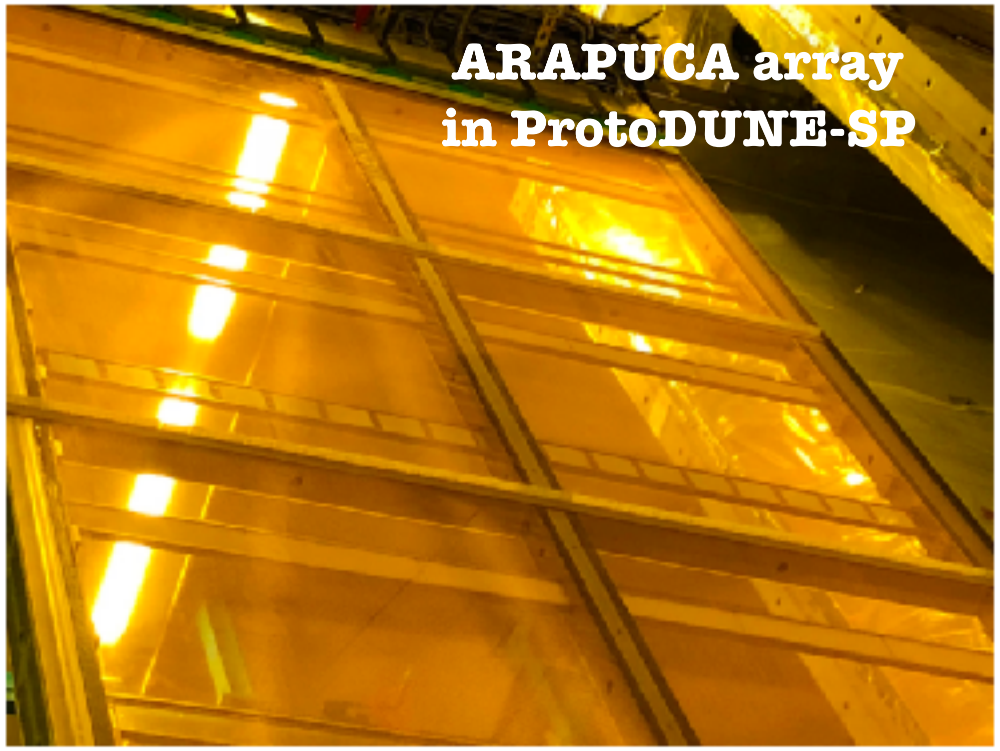
Full set of parallel sessions on this topic!

A very active area of R&D!

- Increasing light efficiency (ARAPUCA)
- Direct detection of 128 nm light in LAr
- Xe doping of liquid argon A. Zani
- Light guides
- SiPM R&D
- Wave length Shifting coating techniques D. Whittington
    - Chemistry/physics of coating
    - Stability
    - How to coat large areas?







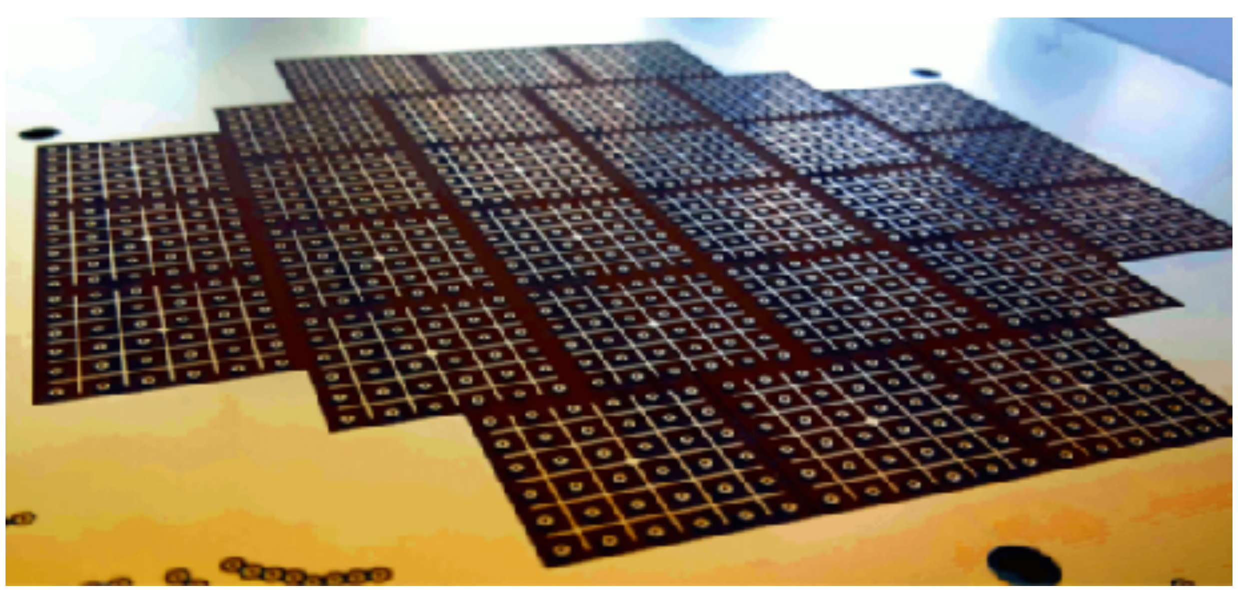
Liquid Argon Detector Challenges: Modular Design & Readout

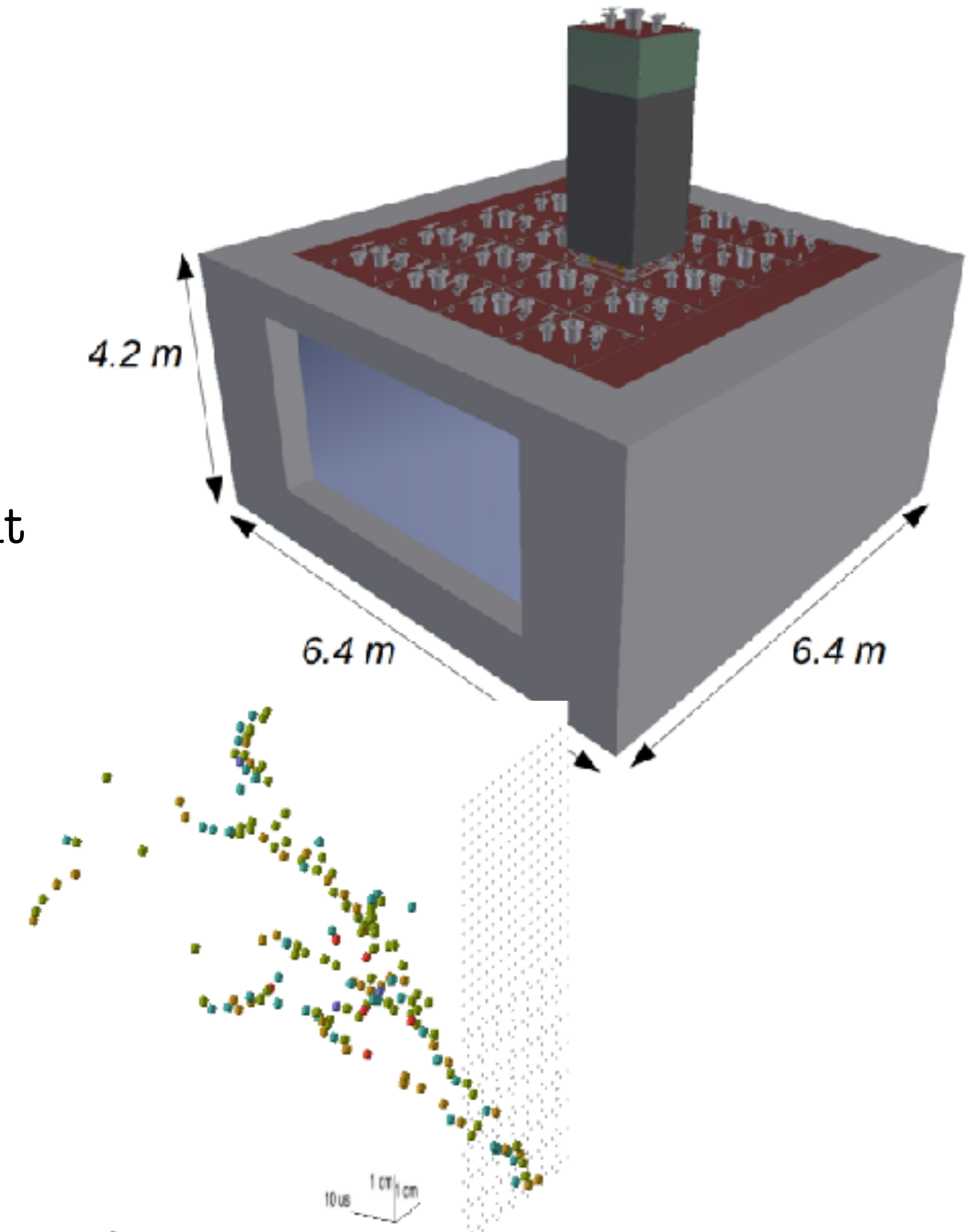
Why modular design?

- Long drift paths can result in losses
- pile up an issue
- ease of maintenance

Why Pixel Readout? **(D. Dwyer, next talk)**

- High event rates (e.g. DUNE Near detector) can overwhelm wire readout
- ease of reconstruction





see talks by D. Dwyer, C. Grace, Y. Mei, S. Kohn, P. Madigan in parallel sessions

Some General Challenges

- **Detectors are getting bigger and bigger** resulting in many challenges e.g. mechanical designs, alignment, installation
- **Experiments are taking longer to run** (e.g. DUNE nominal running is 20 years) — longevity and stability a challenge
    - Some detectors (e.g. LArTPCs) have limited access impacting replicability — require creative approaches
- **Computing, reconstruction a challenge** — Machine learning an exciting opportunity! — demonstrated by many experiments (e.g. MicroBooNE, NOvA)
- **Calibration is also becoming challenging** (e.g. for LArTPCs)
    - Calibration important for (especially low) energy reconstruction
    - For underground detectors (e.g. DUNE) cosmics are sparse, need to develop dedication calibration systems
    - Strong synergy b/n various noble-element experiments
    - Radiopurity requirements in large detectors also a challenge

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Full set of parallel sessions on this topic

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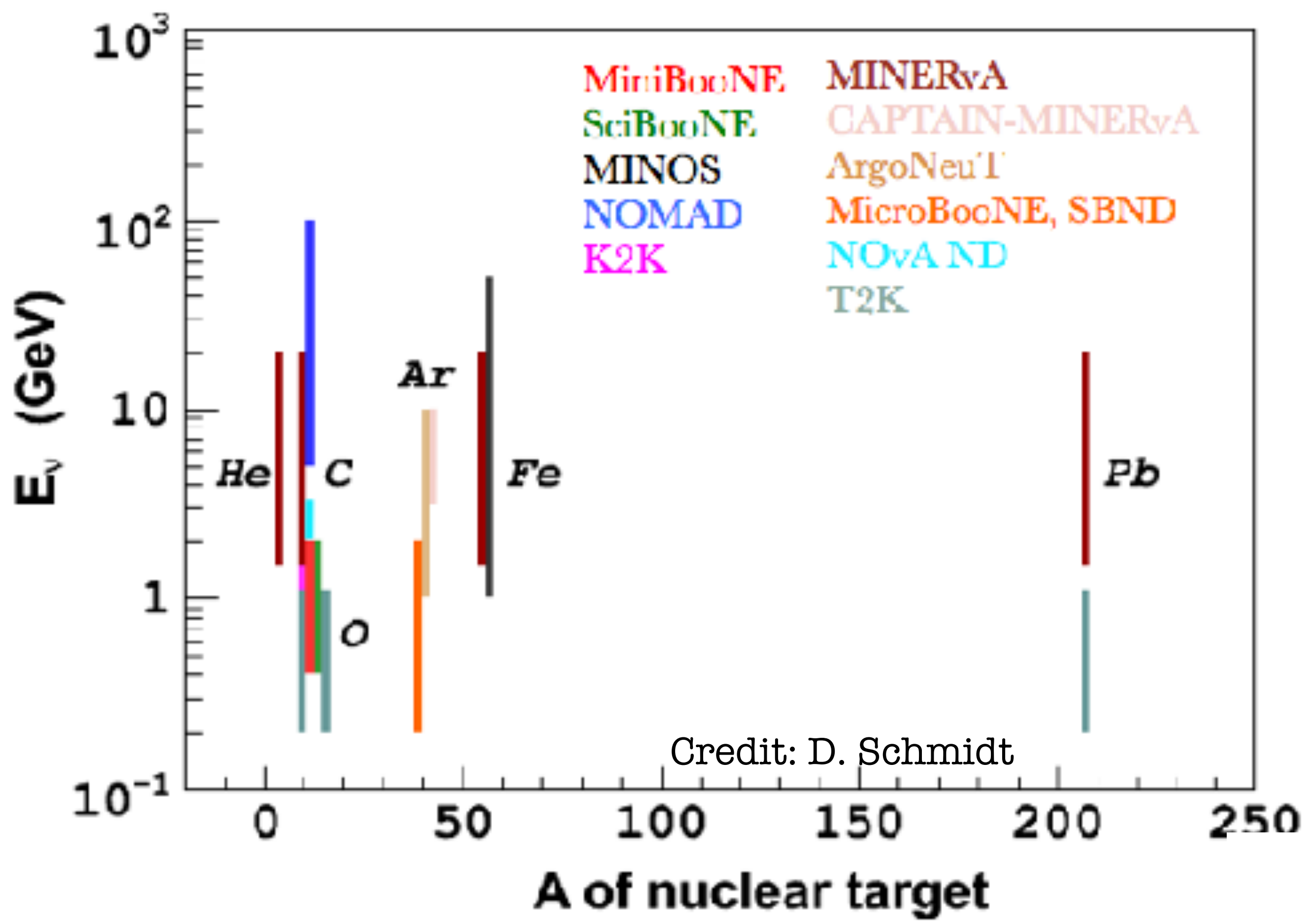
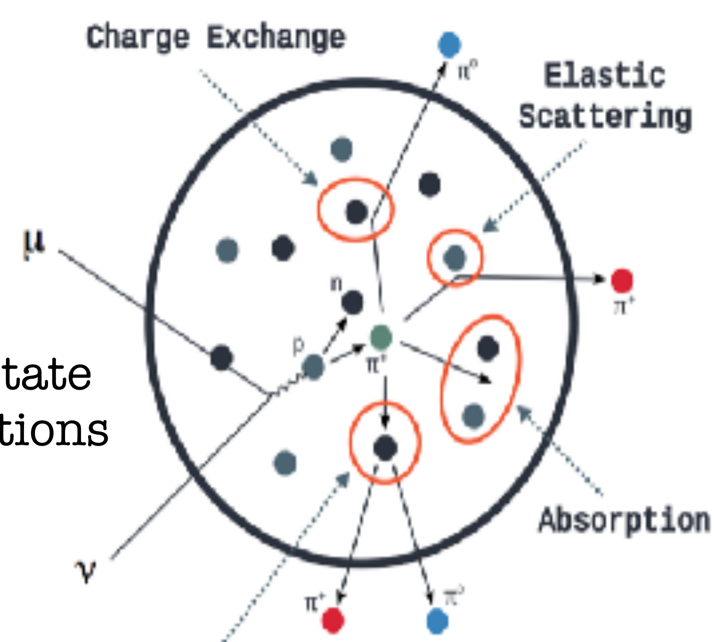
Another important Challenge: ν-N cross sections

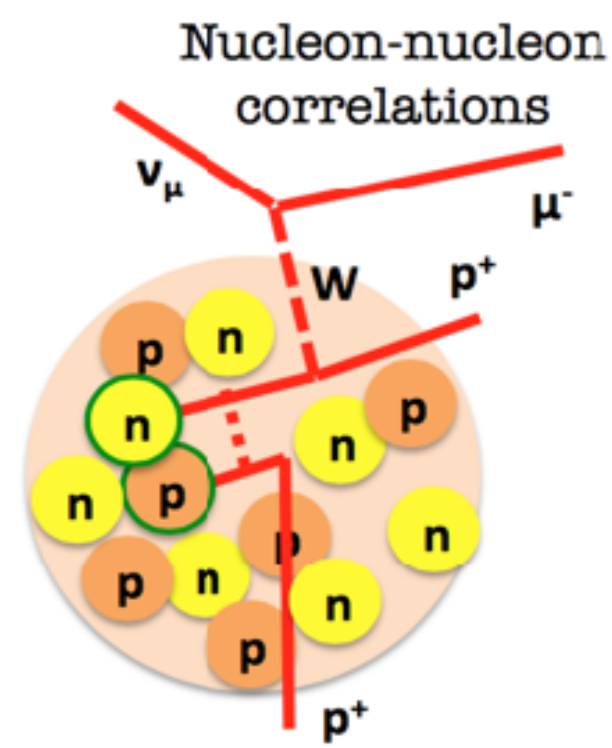
(Important R&D for future experiments like DUNE)

Experiments are using denser targets



Final State Interactions





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- **Summary**

Summary

- Neutrino physics is very rich/diverse spanning multi-frontiers

- Experimental results are driving the field demanding new detectors and instrumentation be built to achieve precision

- Neutrino physics has the potential for many new discoveries in the coming year.

- The "technical" and "measurement" challenges are overwhelming but the R&D opportunities are also exciting!

Thank you!

Apologies again for not being able to cover everything.

Please go to parallel sessions where lot more details are presented.