# The Dune Experiment: Physics Reach and Progress on Prototyping

INSTITUTE OF PARTICLE PHYSICS
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DUNE

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**Institute of Particle Physics & University of Toronto**

**Virtual CAP Congress 2020**

# Outline

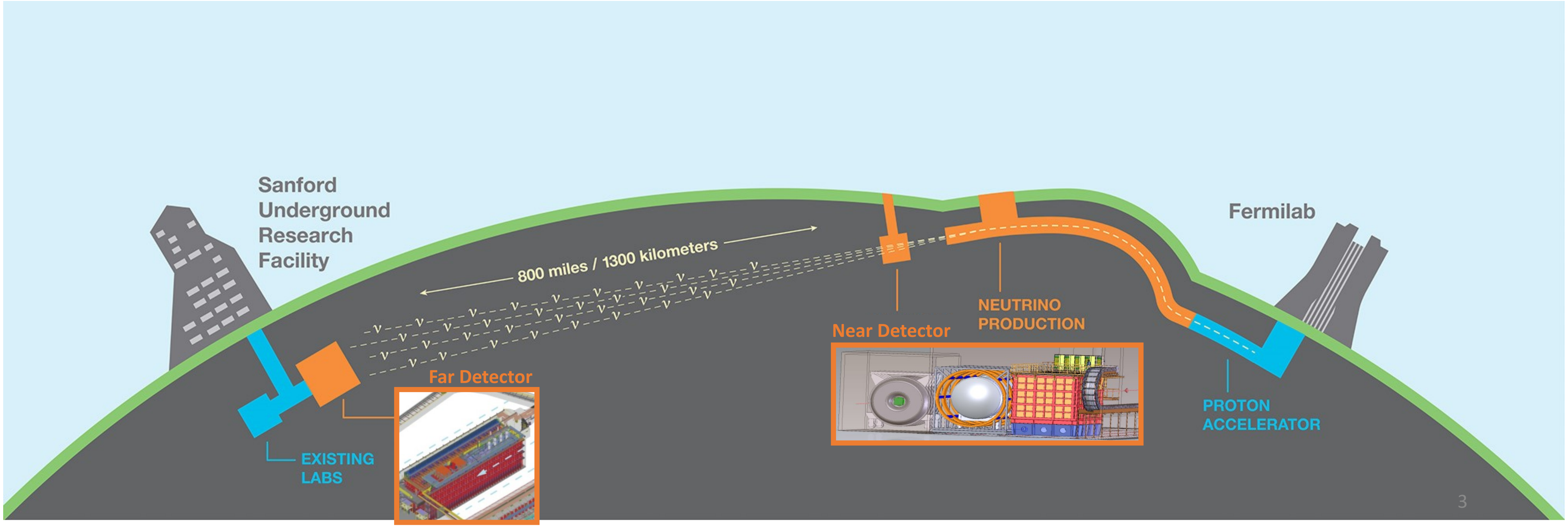
- Introduction: LBNF & DUNE Far Detector
- Progress on Prototyping: ProtoDUNE
- DUNE Physics sensitivity

# LBNF DUNE Facility

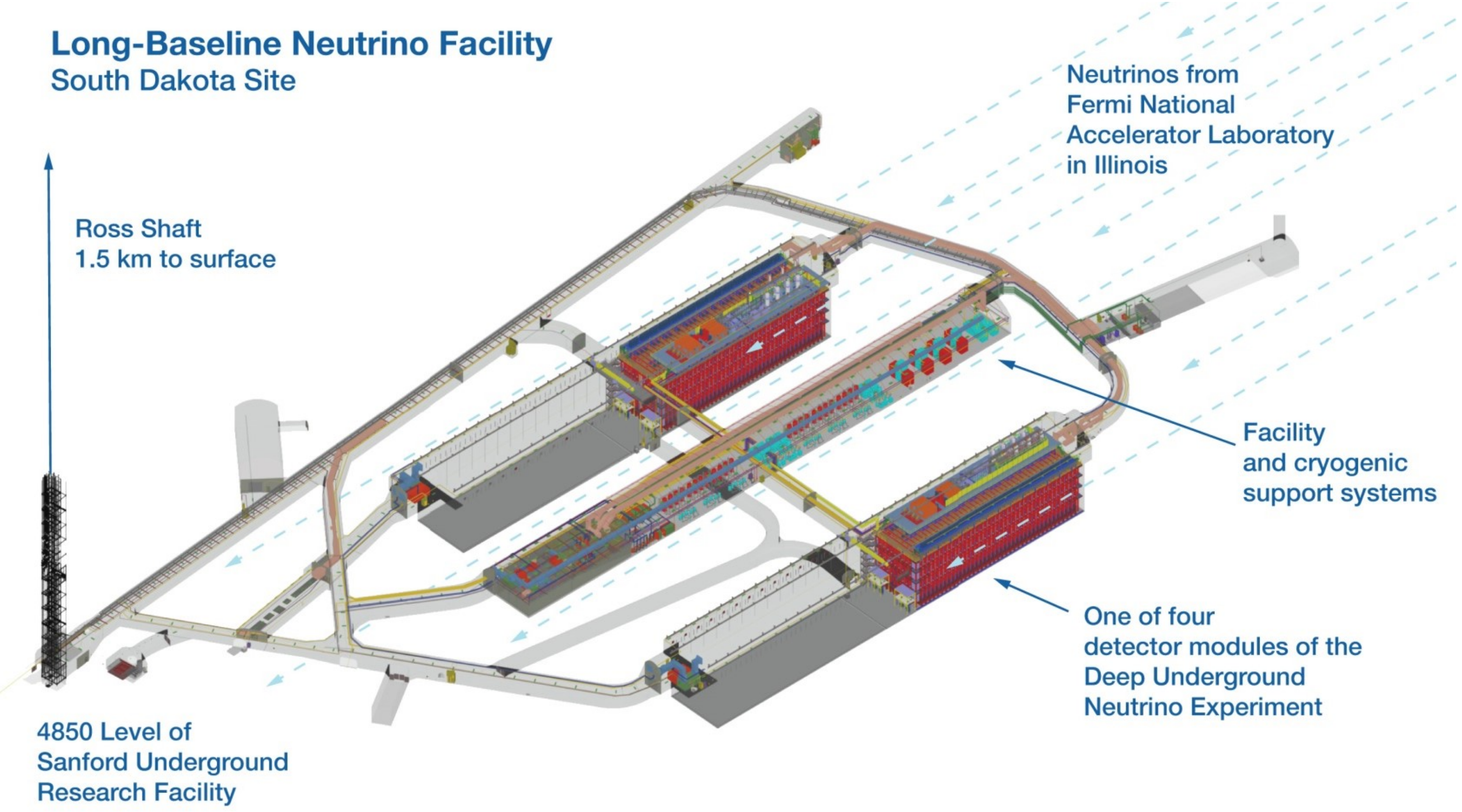
1-6 GeV muon neutrinos/antineutrinos obtained from high-power proton beam (1.2 MW – upgradable to 2.4 MW)

Near detector will characterize the beam (100s of millions of neutrino interactions)

Far Detector is >40 kton fiducial mass Liquid Argon Time Projection Chambers (LAr TPC) – fine granularity

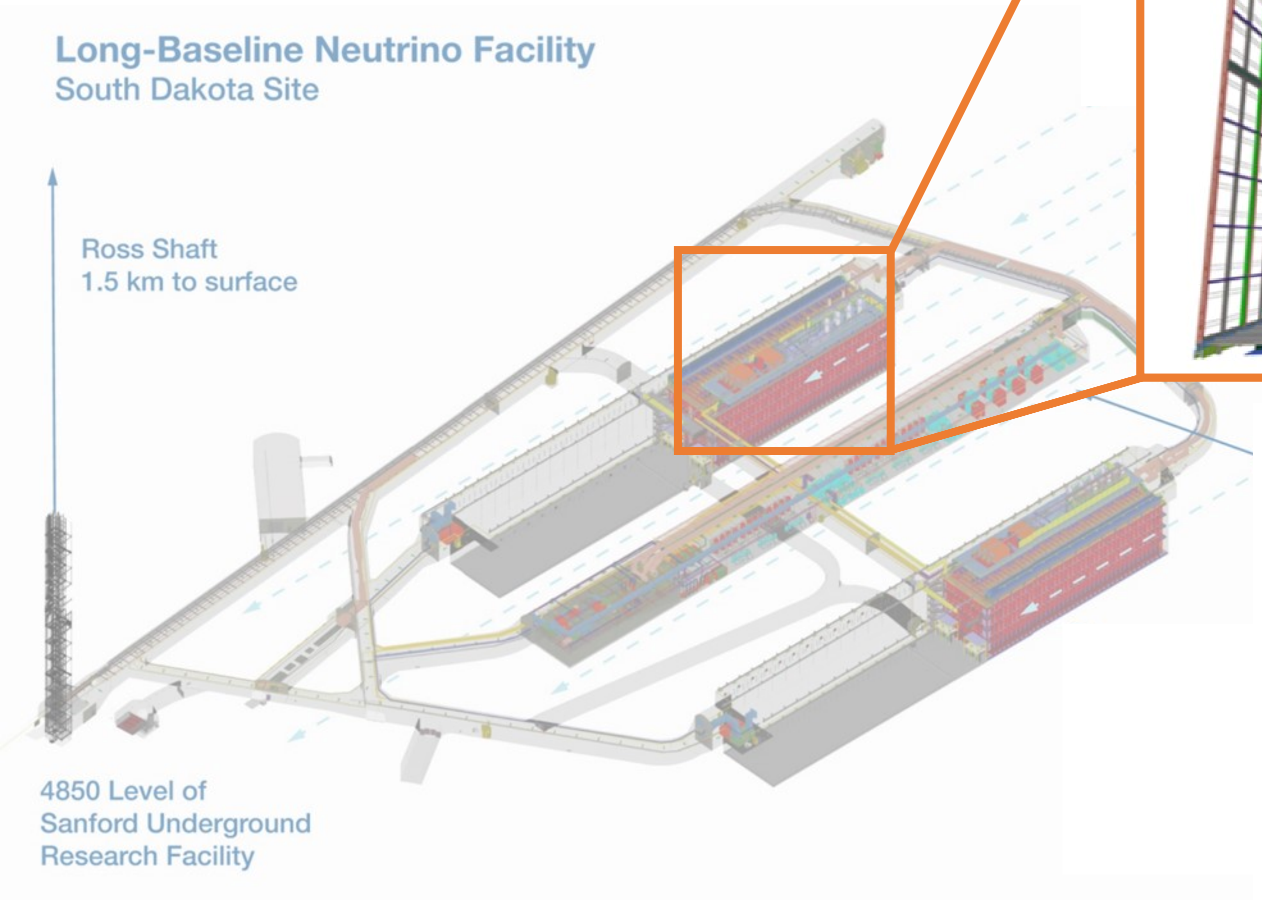


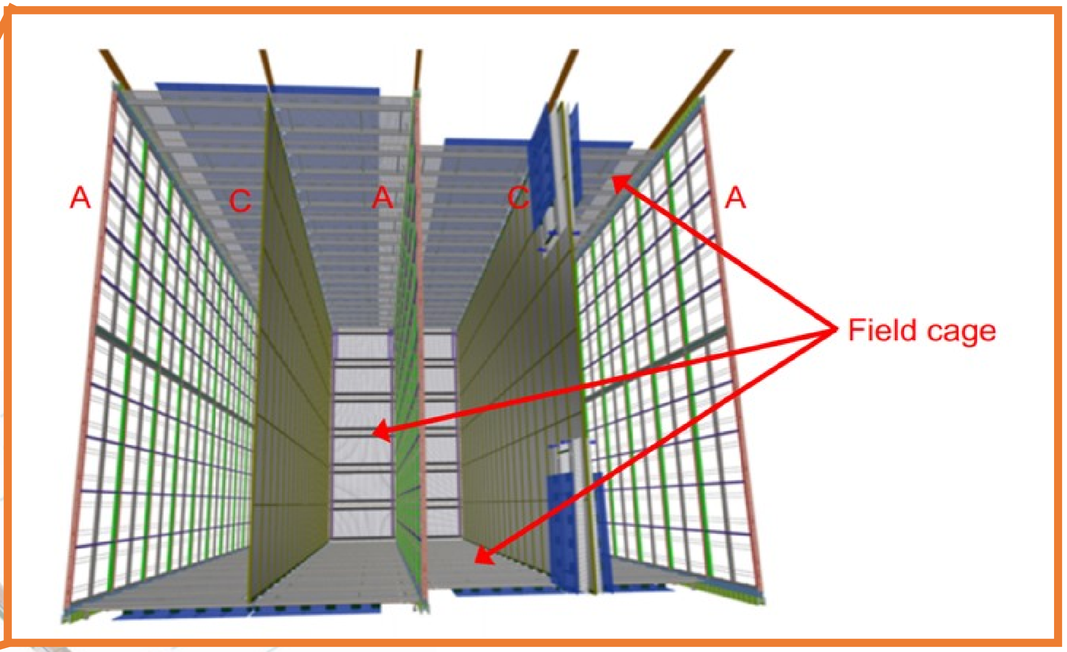
# DUNE Far Detector




4 chambers, 10kt fiducial mass each

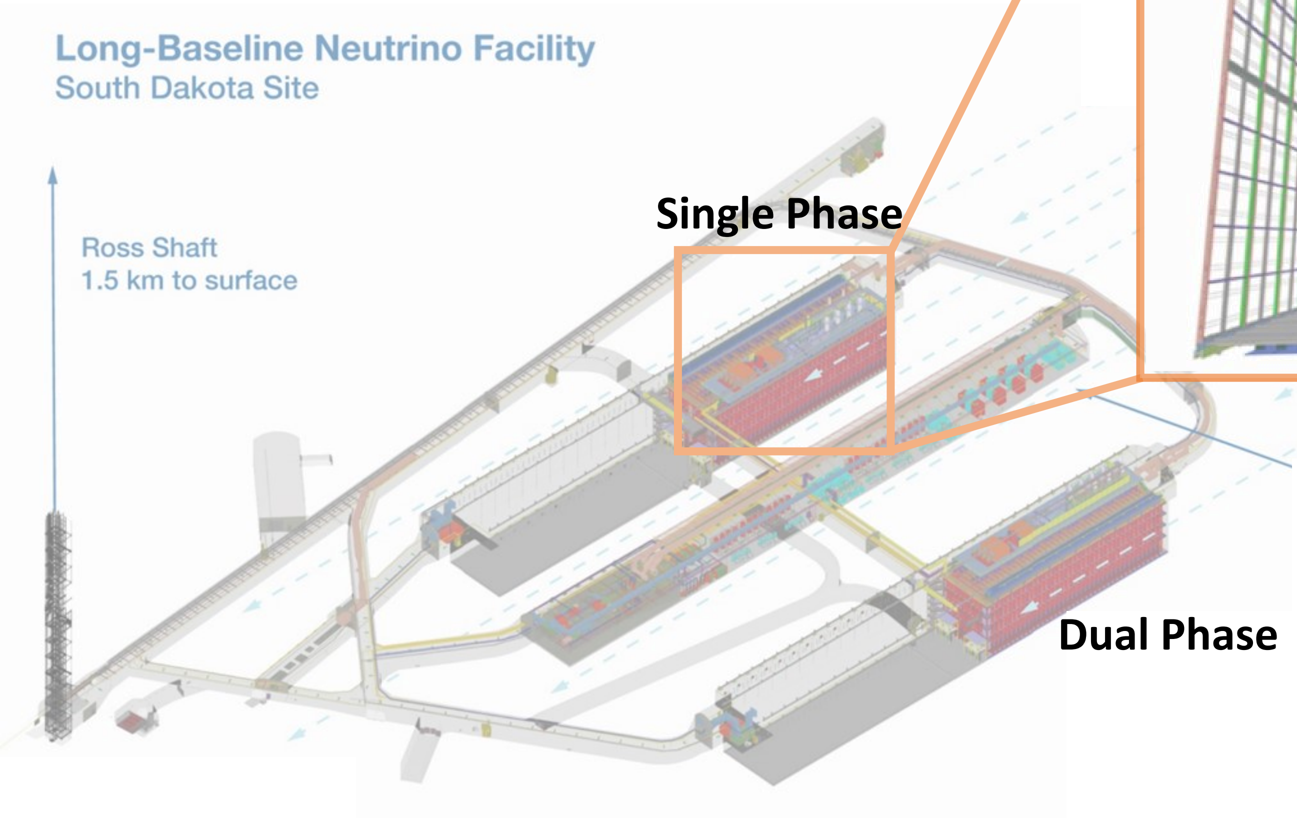
# DUNE Far Detector

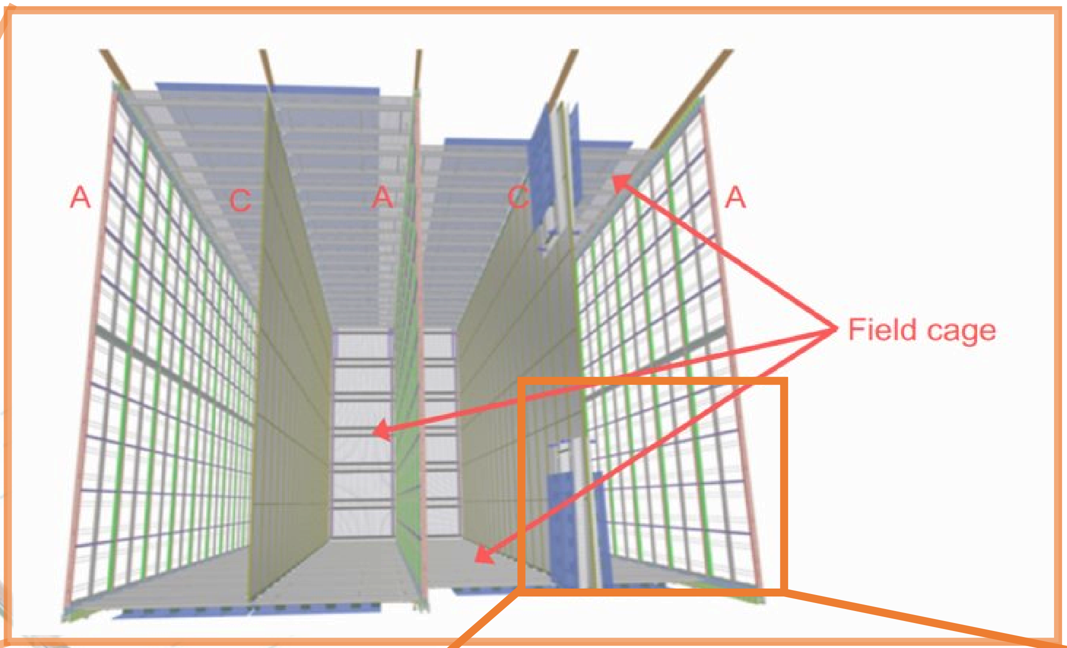


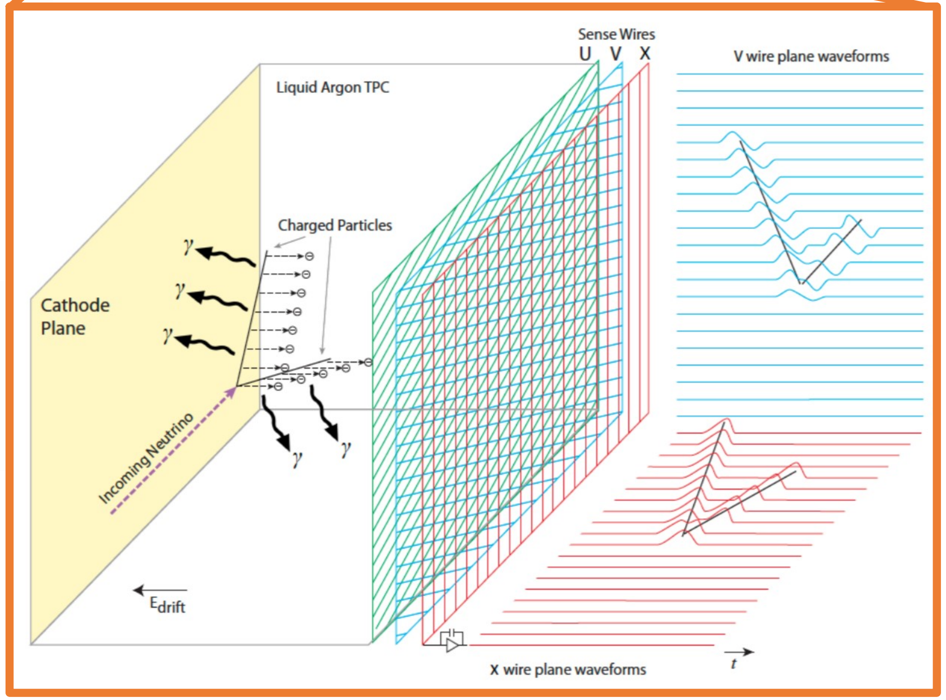




First 10 kt module will be Single Phase (SP) design,  LAr Time Projection Chamber (LArTPC) divided  into 4 drift volumes

# DUNE Far Detector

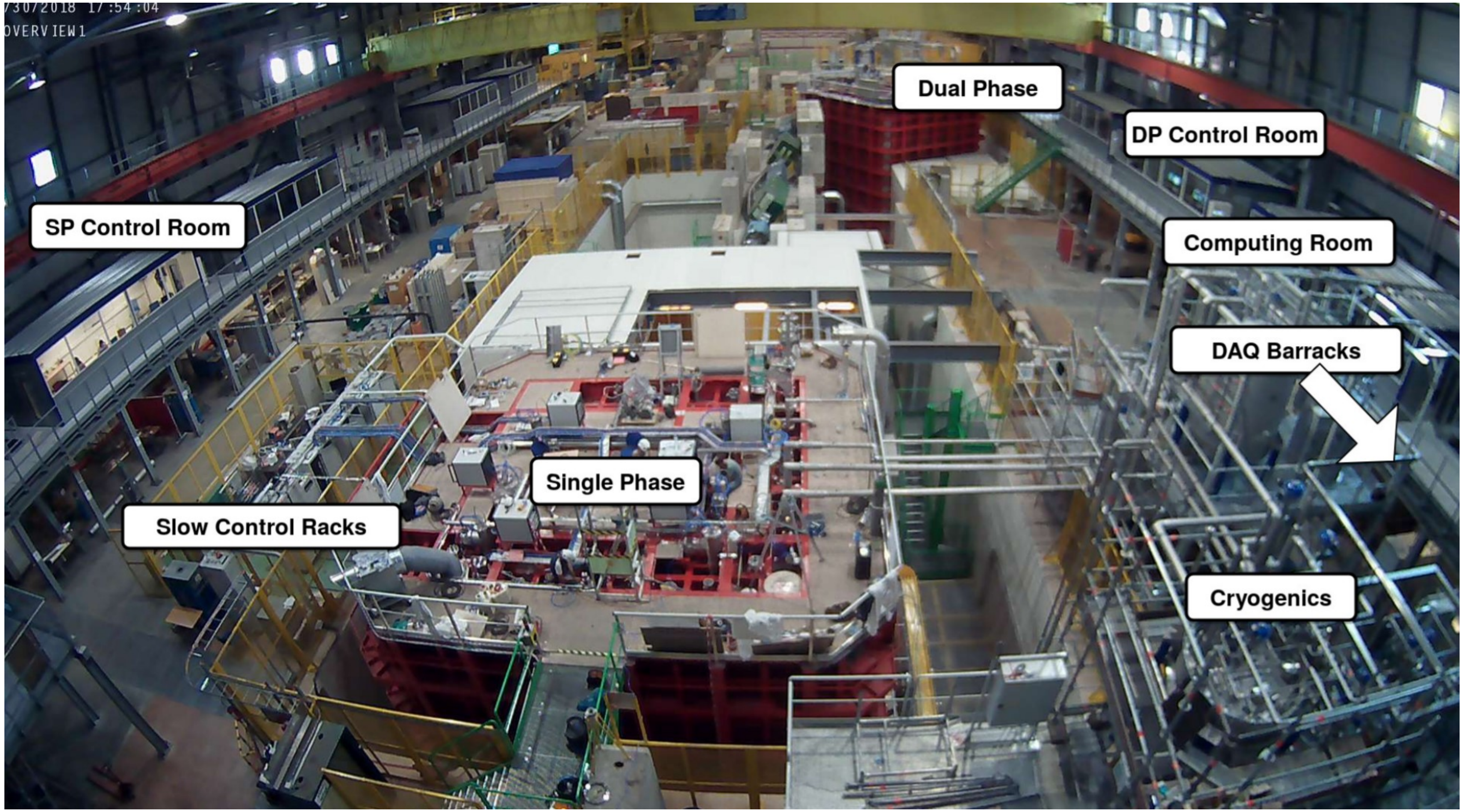


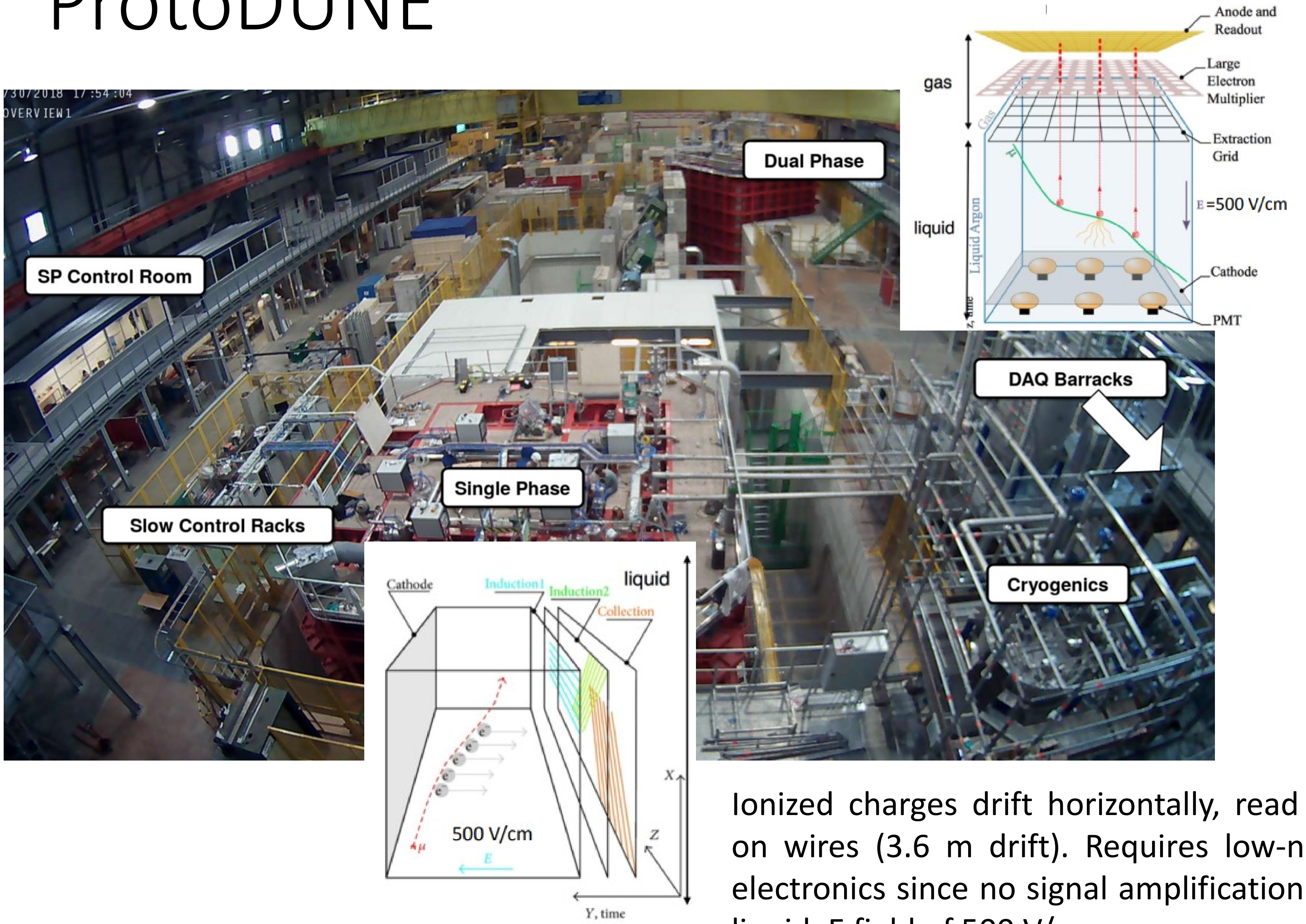

few mm resolution, 3D imagine
LAr is good scintillator, released light collected by photon detectors placed between inner wire planes,
and provide $t_0$ (when electrons start to drift)

# ProtoDUNE




- At CERN neutrino platform, have built 2 prototypes, 1/20$^{th}$ the size of planned DUNE
- Single Phase detector collected hadron data and cosmic ray data from Fall 2018
- Dual Phase detector completed June 2019, started operations Sept 2019

# ProtoDUNE

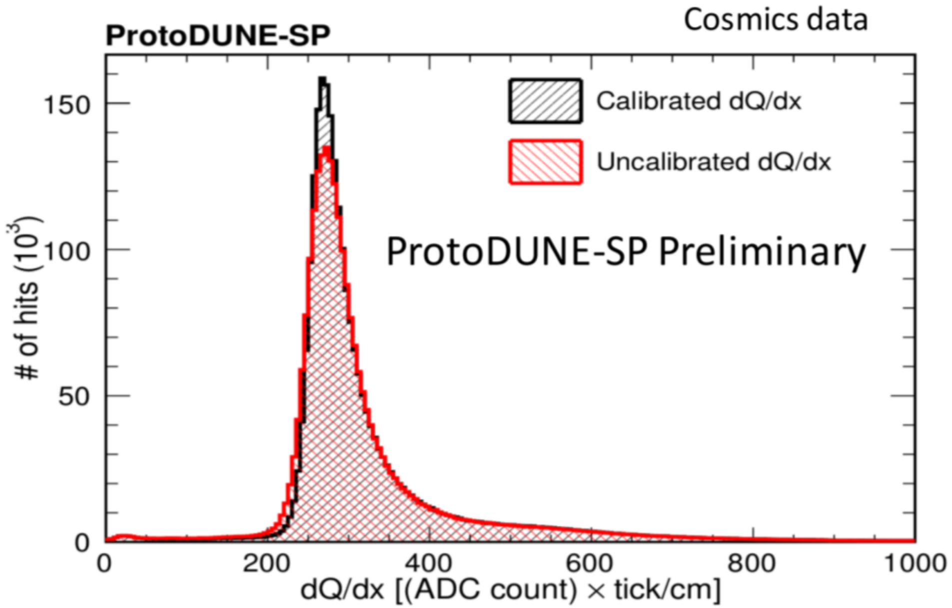


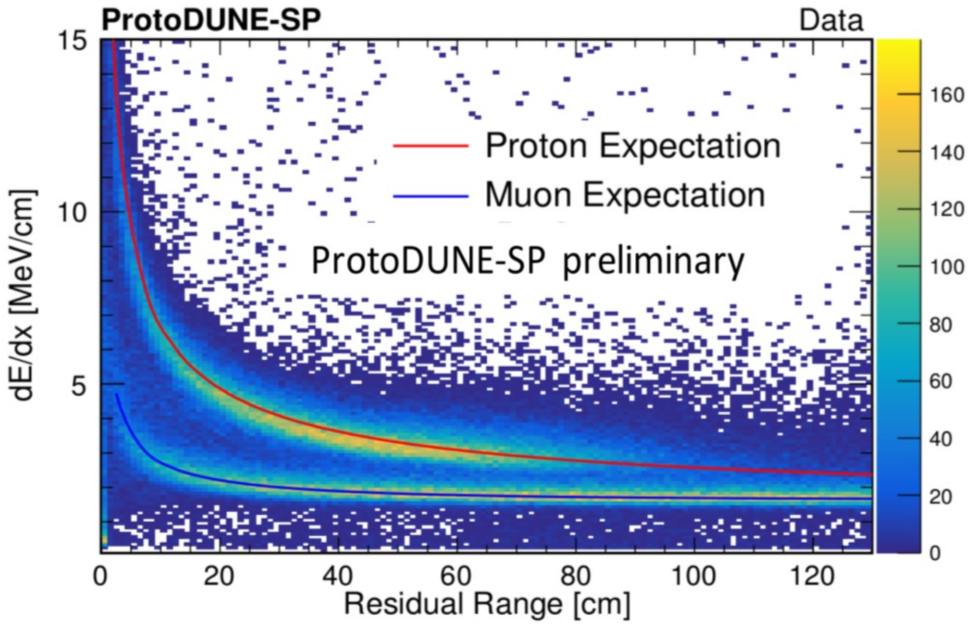

Ionized charges drift vertically and read out on PCB anode. Signal amplified in gas phase by micro-pattern gas detector (LEM). Gain in gas phase reduces stringent requirements on electronics – 6m drift (12 m drift for FD)

Ionized charges drift horizontally, read out on wires (3.6 m drift). Requires low-noise electronics since no signal amplification the liquid. E field of 500 V/cm

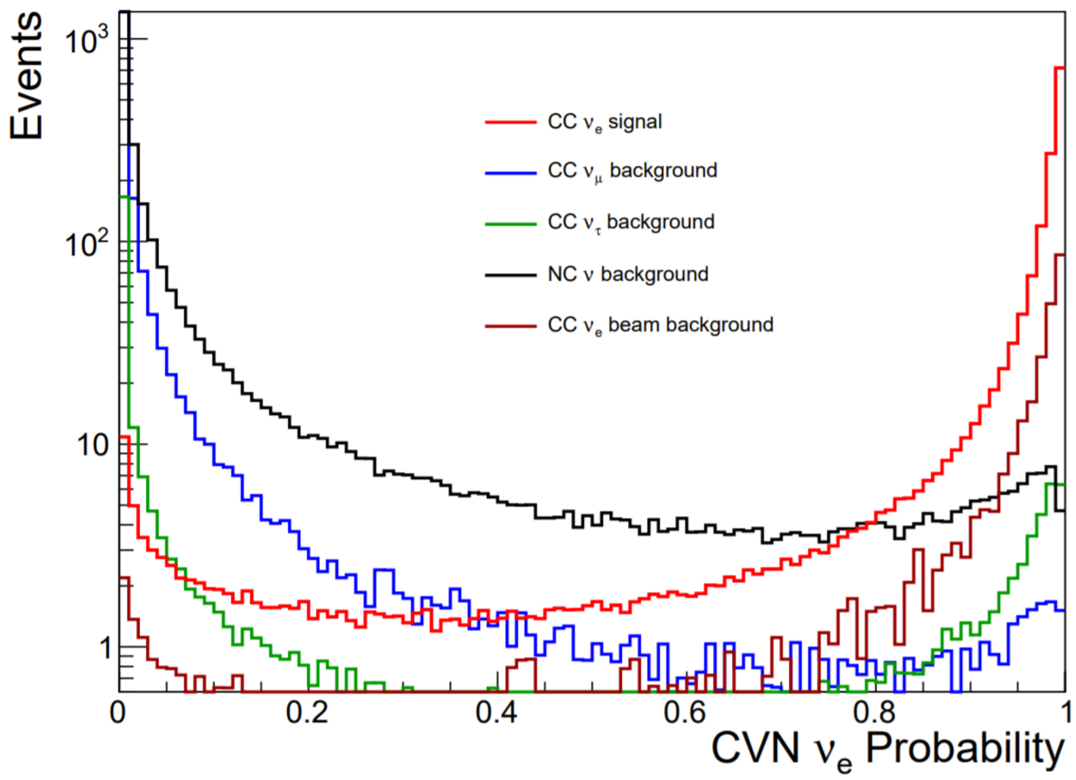
# ProtoDUNE SP

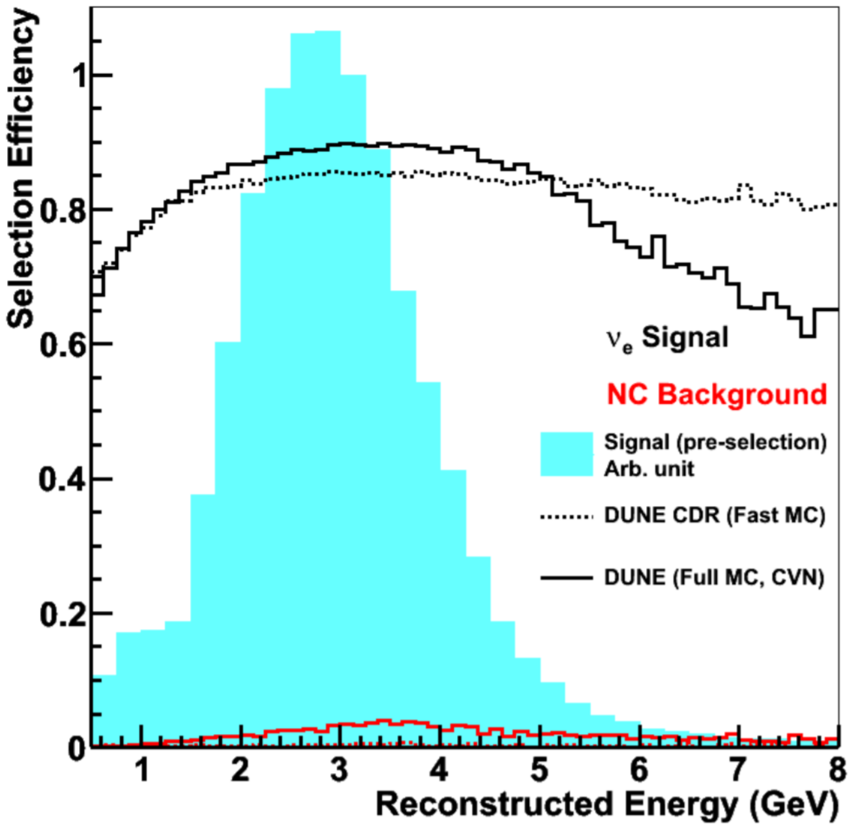
- Charge deposition per unit length (dQ/dx) affected by space-charge effect, recombination effect, electron attenuation, diffusion, electronics gain variation
- Detector response calibration is based on cosmic muons – shows good results for test beam protons and muons
- High quality of ProtoDUNE-SP demonstrated by excellent proton-muon separation



# DUNE Analysis Techniques



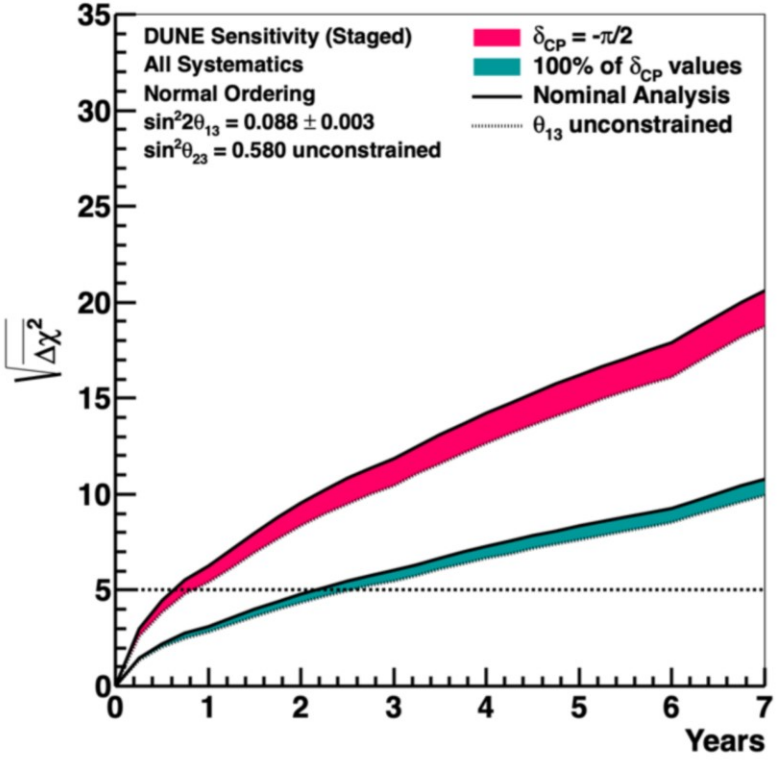




- Image recognition (convolutional visual network - CVN) classify neutrino interactions in FD

- Appearance efficiency – neutrino beam mode
- Work in progress to evaluate DUNE CVN for ProtoDUNE-SP data

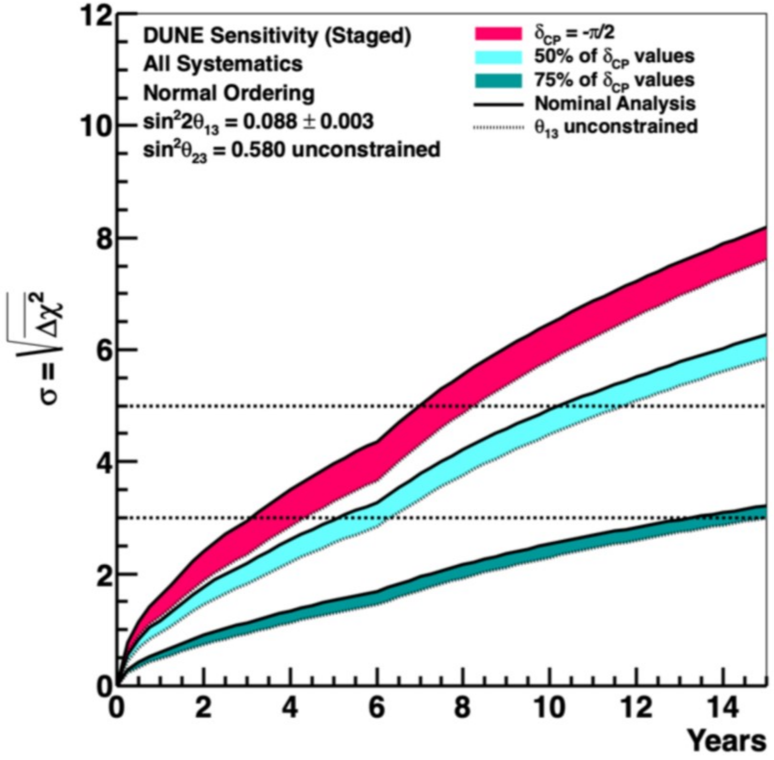
# Mass Ordering and CP violation

Mass Ordering Sensitivity




- $5\sigma$ sensitivty after 2 years of running

*CP* violation Sensitivity




- 5 $\sigma$ sensitivity after 10 years of running for 50% of $\delta_{CP}$ values

Staged plan:

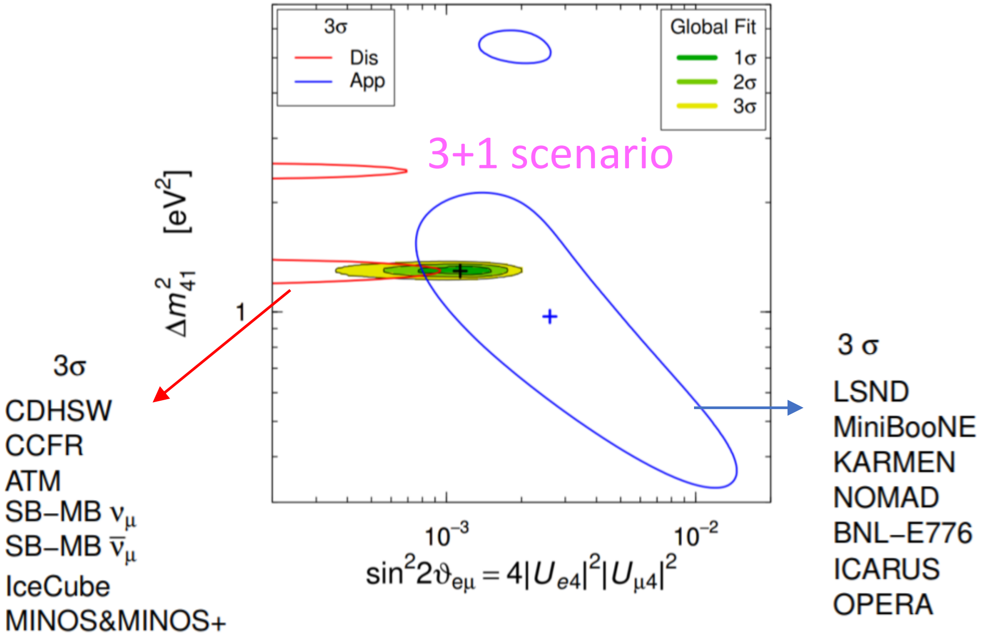
2 FD modules (20 kt), 1.2 MW beam $\xrightarrow{\text{1 yr}}$ + 1 FD module $\xrightarrow{\text{3 yrs}}$ + 1 FD module $\xrightarrow{\text{6 yrs}}$ Upgrade to 2.4 MW beam

# Hints Extra Neutrinos?

Most theories explaining neutrino masses need extra neutrinos and/or non-standard neutrino interactions (NSI)

LSND, MiniBoone, Gallium, Reactor anomalies

Arxiv:1901.08330v1 (2019)

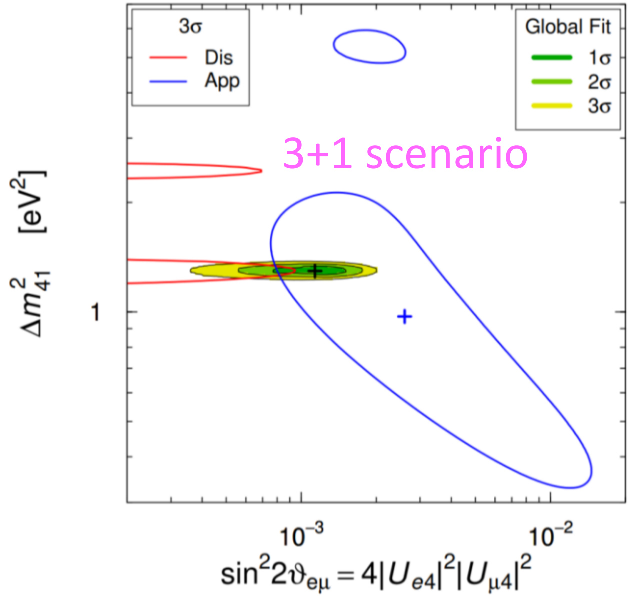



- some preference for $3\nu$ + NSI with current data in NSI + matter: arXiv:1907.00991v1

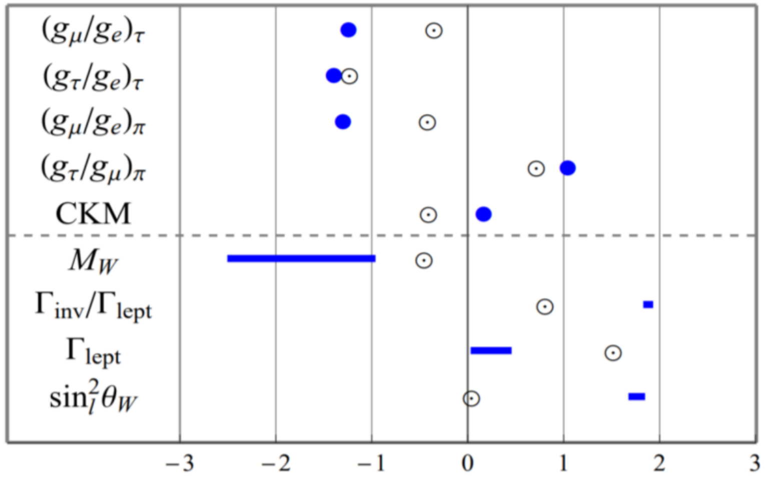
$10^{-3}$eV .1 eV eV KeV MeV GeV $10^2$GeV TeV $10^2$ TeV $10^3$ TeV

Extra $\nu$ affect oscillations | Neutrino Factories | B-factories | High Energy Collider

# Hints Extra Neutrinos?




lepton universality violation at $3\sigma$
(due to PMNS non-unitarity?)




arXiv:1310.2057v2 (2014)

Preference for non-unitary PMNS: arXiv:1407.6607v2

Lepton Flavor Violation: some preference for non-zero heavy neutrino mixing in $e$ & $\tau$: arXiv:1605.08774v2

Sensitivity to NSI have reached levels to explain B-anamolies : Phys Rev. B 784 (2018) 248-254

$10^{-3}$eV .1 eV eV KeV MeV GeV $10^2$GeV TeV $10^2$ TeV $10^3$ TeV

Extra $\nu$ affect oscillations Neutrino Factories B-factories High Energy Collider

# Sensitivity to Extra Neutrinos

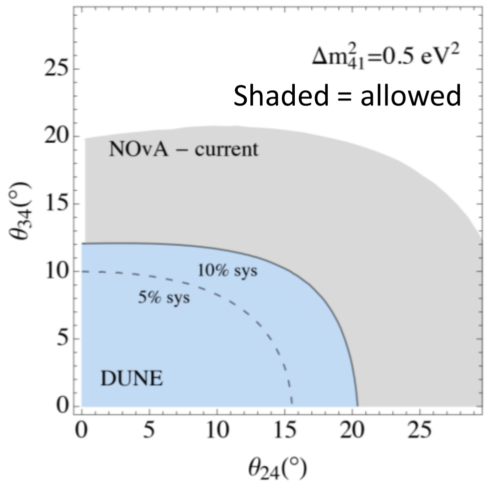
Case 1 ( $\Delta m^2_{14} \sim 0.1 - 1\ eV^2$ ): slow light-sterile neutrino oscillations, underdeveloped in ND, averaged out in FD

$\Delta m^2_{14} > 0.1\ eV^2$ (LSND)

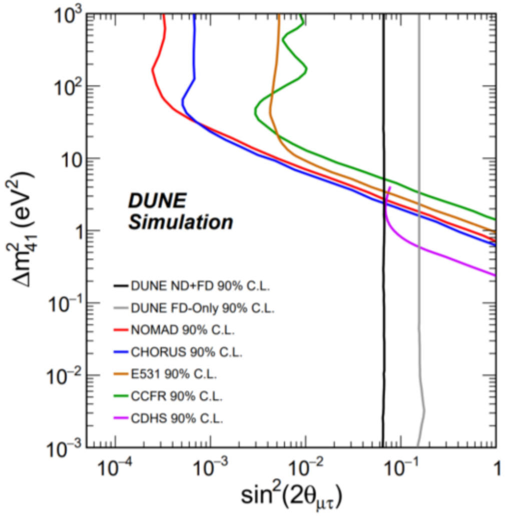
$> 0.5\ eV^2$ (reactor)

Arxiv:1901.08330v1

arXiv:1707.05348v1




3+1




$10^{-3}$eV $10^{-2}$eV $10^{-1}$eV eV KeV MeV GeV 100 GeV

Extra Neutrino mass

# Sensitivity to Extra Neutrinos

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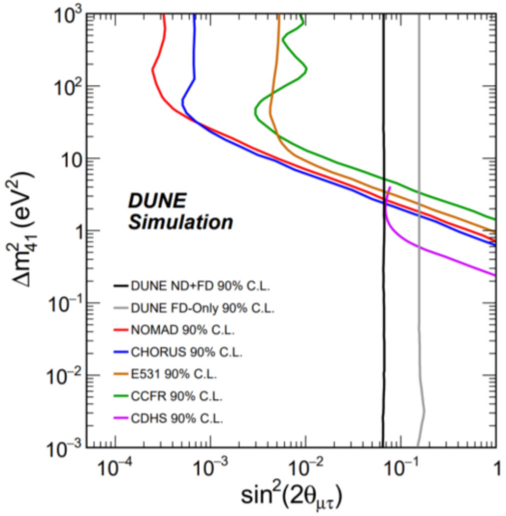


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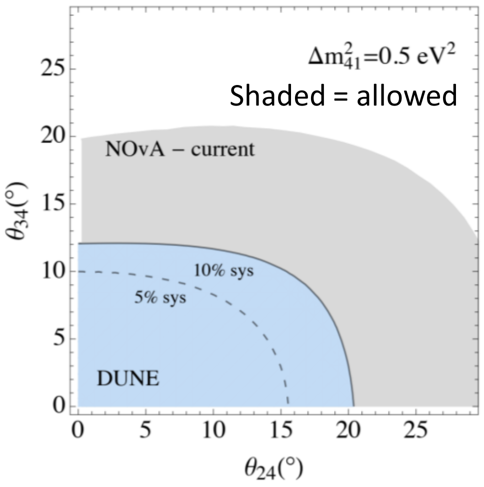
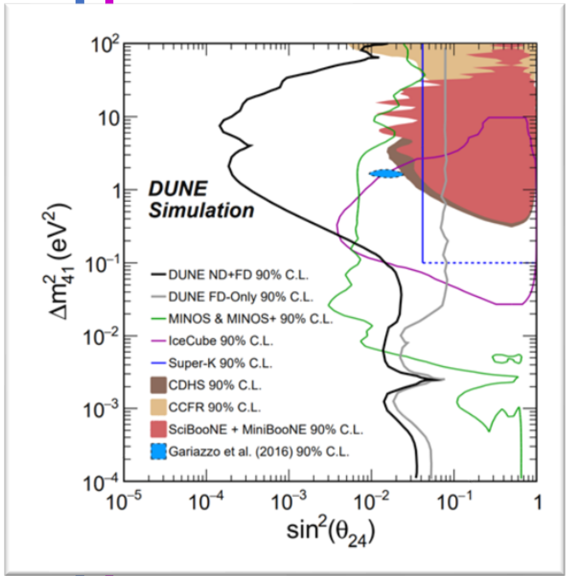



Case 2 ($\Delta m_{14} > 1\ eV^2$ ) : light-sterile oscillation frequency matches ND distance.
Preferred by LSND & MiniBoone anomalies & DANSS & NEOS : arXiV: 1803.10661v1 (2018)




$10^{-3}$eV $10^{-2}$eV $10^{-1}$eV eV KeV MeV GeV 100 GeV

Extra Neutrino mass

# Sensitivity to Extra Neutrinos

Case 1 ( $\Delta m_{14}^2 \sim 0.1 - 1\ eV^2$ ): slow light-sterile neutrino oscillations, underdeveloped in ND, averaged out in FD

$\Delta m_{14}^2 > 0.1\ eV^2$ (LSND)
$> 0.5\ eV^2$ (reactor)
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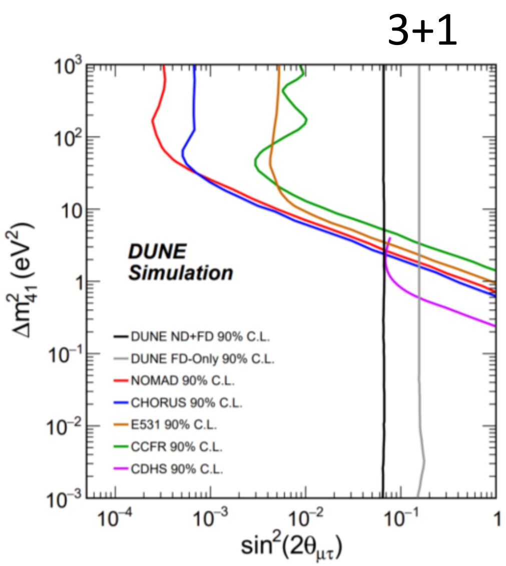


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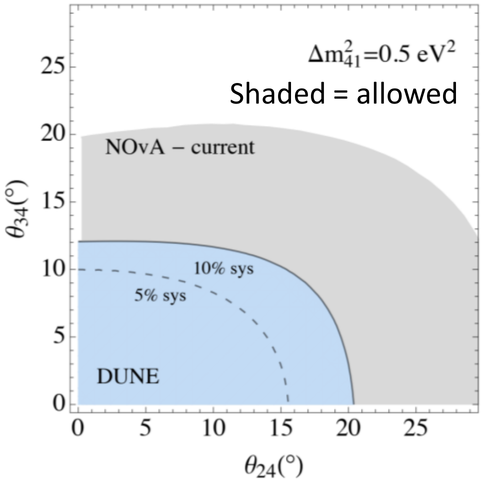


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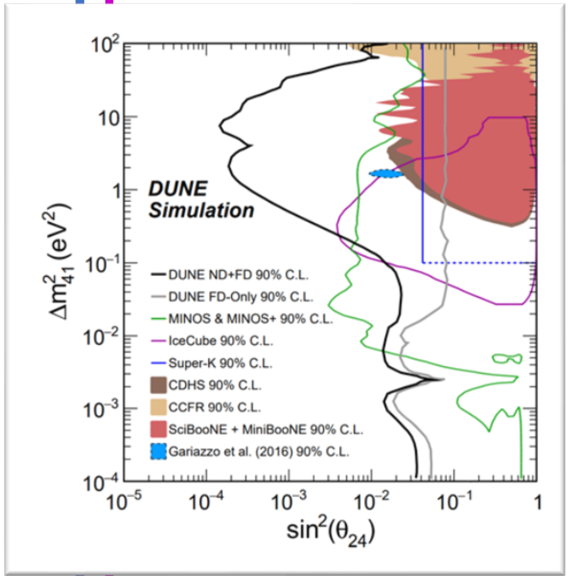
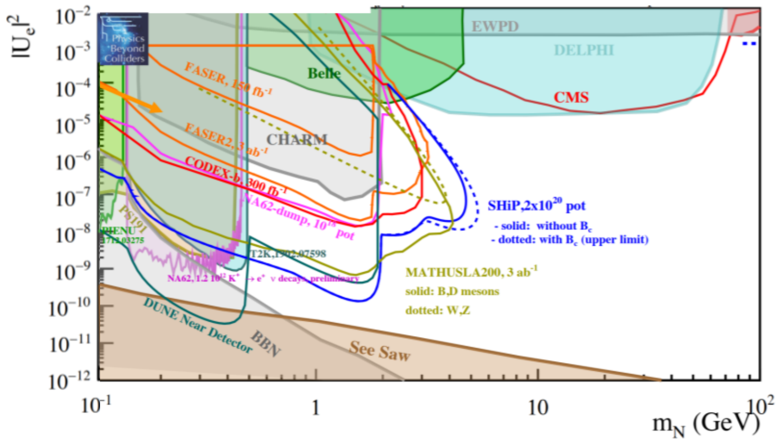



Case 3 ($\Delta m_{14}^2 > 100\ eV^2$) : fast sterile neutrino oscillations, averaged out in ND and FD (same as PMNS non-unitarity from heavy neutrinos)

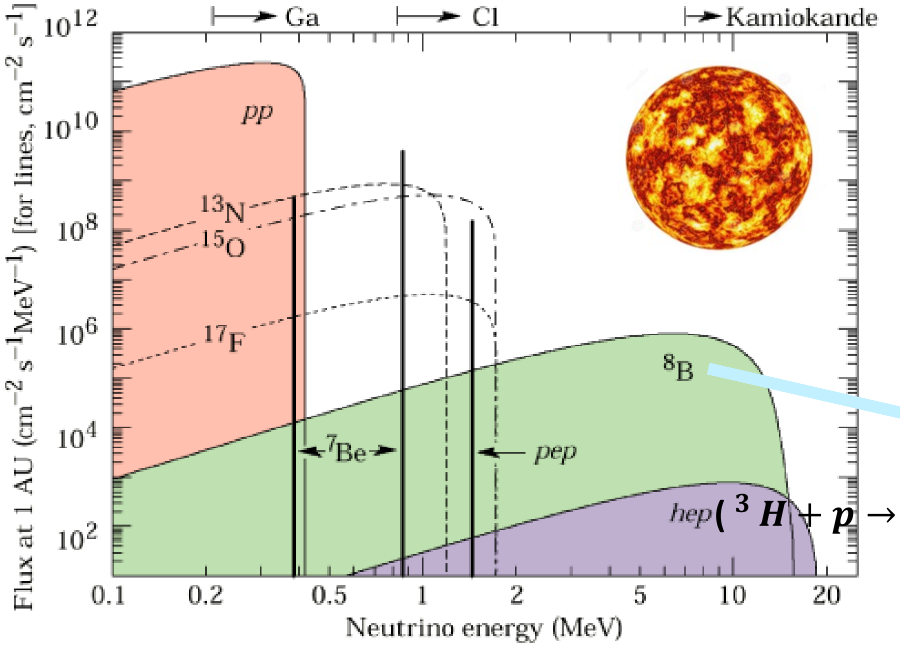
Near Detector (preliminary)



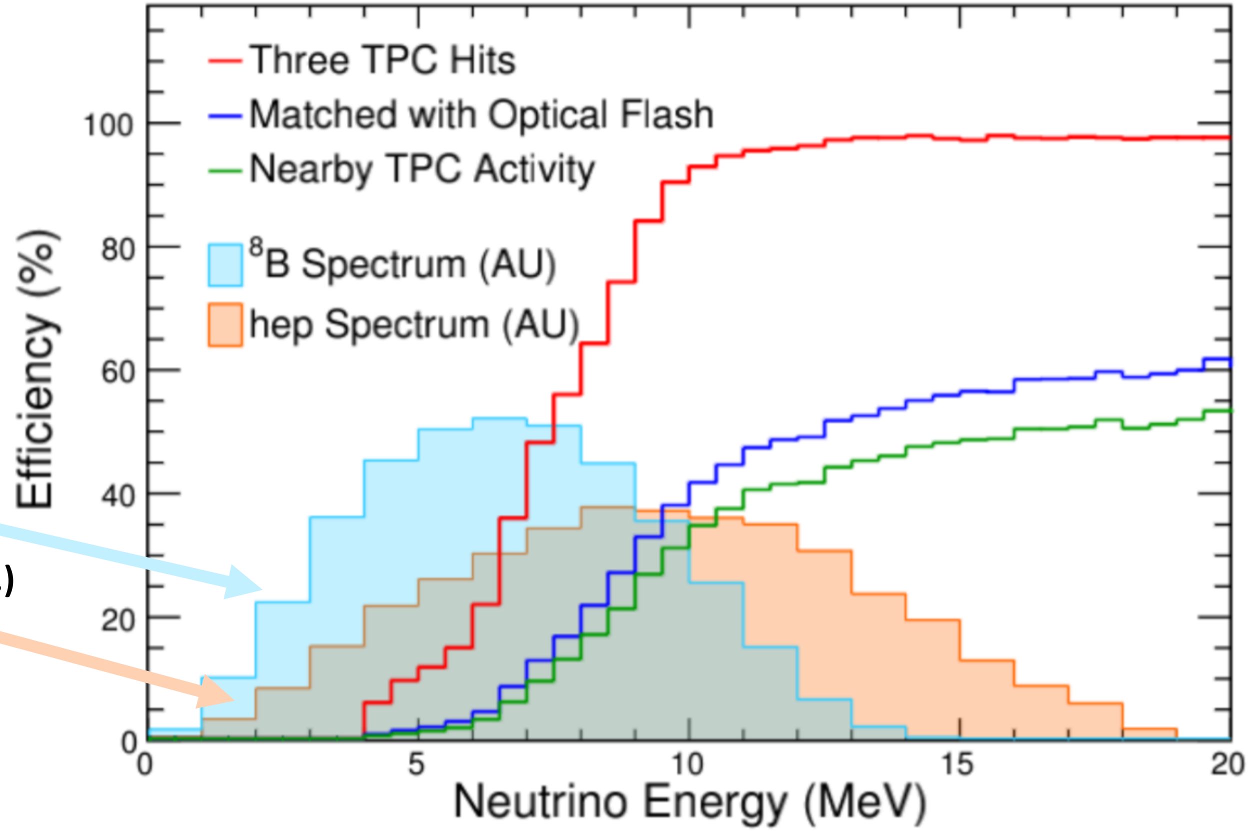

$10^{-3}$eV $10^{-2}$eV $10^{-1}$eV eV KeV MeV GeV 100 GeV

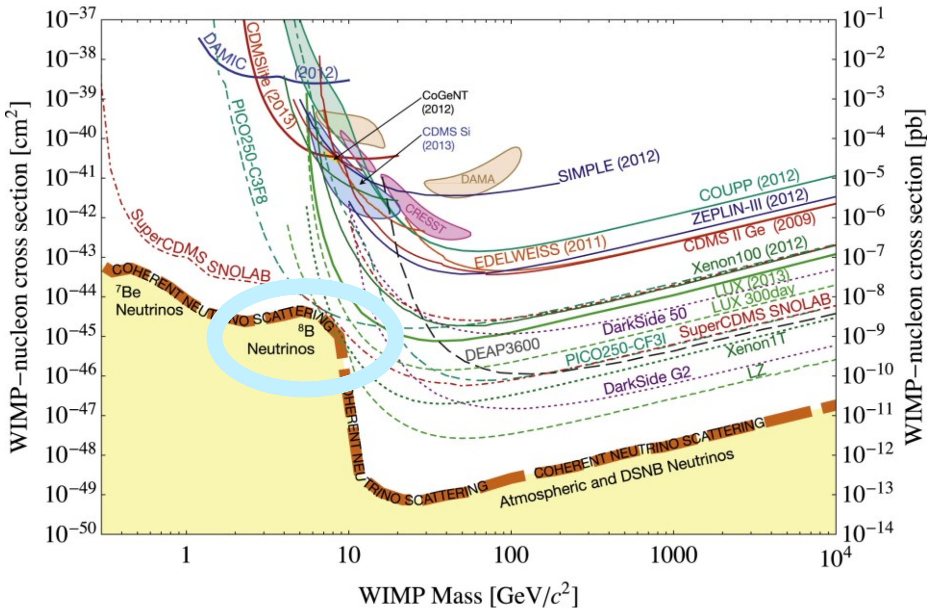
Extra Neutrino mass

# Solar Neutrinos




$hep(^3H + p \rightarrow {}^4H + e^+ + \nu_e)$

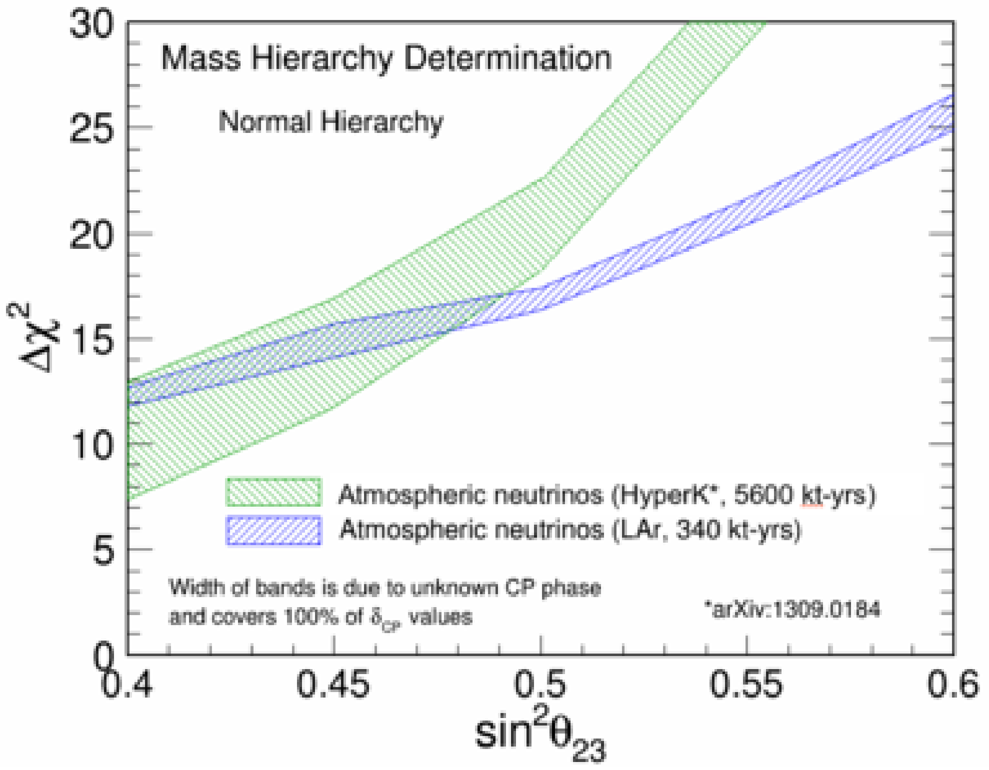



- DUNE can measure solar neutrinos to help verify the standard solar model, measure sun's core temperature, characterize neutrino floor, resolve tension between global solar neutrino measurements & KamLAND (arXiv:1808.08232), characterize MSW affect

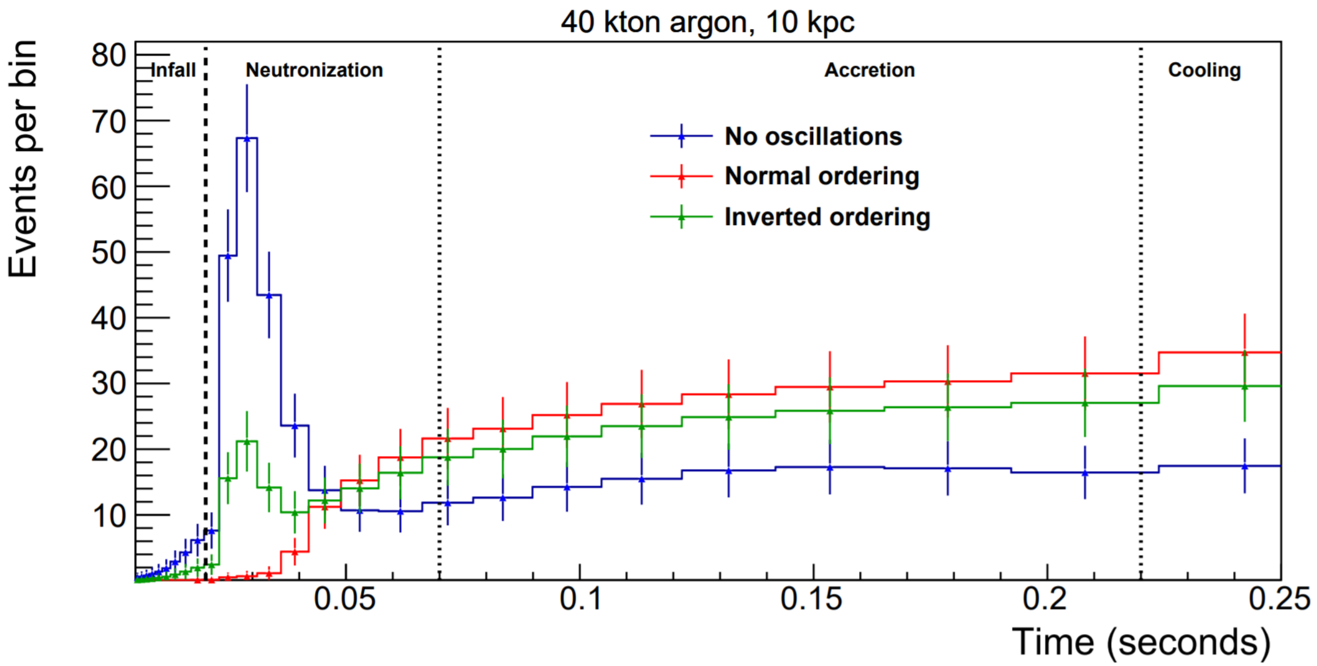
# Atmospheric & SuperNova Neutrinos

- Can use atmospheric neutrinos to extract neutrino properties



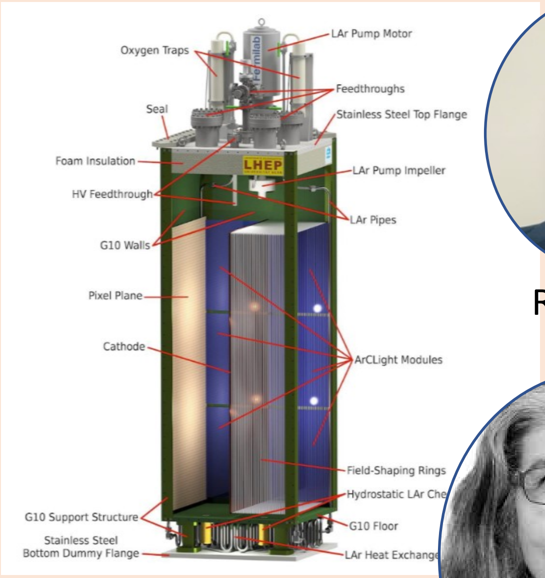

- Core collapses expected to occur few times per century (at 10-15 kpc): test astrophysical theories, probe new physics
- When massive star collapses to neutron star/black hole, $\sim 10^{58}$ of ~ 10 MeV $\nu$ emitted for a few seconds.
- DUNE sensitive to $\nu_e$ supernova neutrinos- this is unique among supernova neutrino detectors for the next decades. Tracks can indicate direction of supernova

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$



# Planned Canadian Contributions

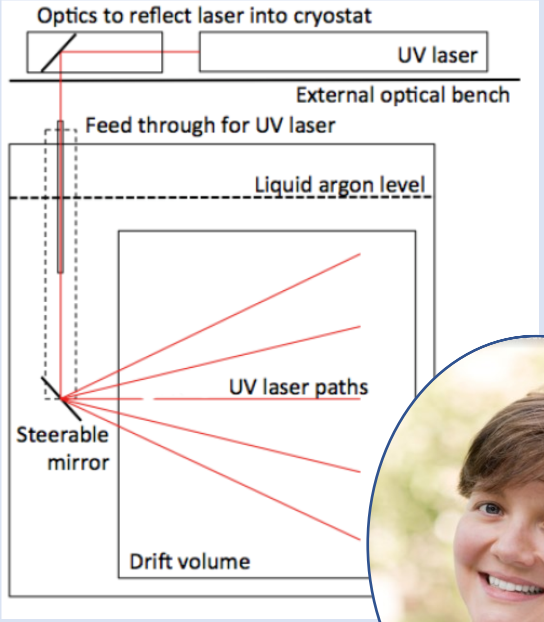
## Near Detector Prototype & Neutrino Interaction model




Rowan Zaki

**Deborah Harris**
Dharris@fnal.gov

## Computing, Calibration & Supernova neutrinos




**Claire David**
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## FELIX readout system & Extra neutrino & NSI searches

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Mathew Man

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More manpower is very welcome! If you have other project ideas or expertise in LAr technologies, data acquisition, electronics etc., please contact us! We will organize expertise sharing workshop soon.

# Summary & Outlook

- DUNE is a broad band energy neutrino experiment
- ProtoDUNE is running smoothly and performing well
- DUNE will have unprecedent sensitivity to neutrino mass hierarchy, CP violation, and searches for extra neutrinos. A rich atmospheric and solar neutrino program is under development.
- Canada is getting involved – please feel free to join
- TDR completed (https://arxiv.org/pdf/2002.03005.pdf)

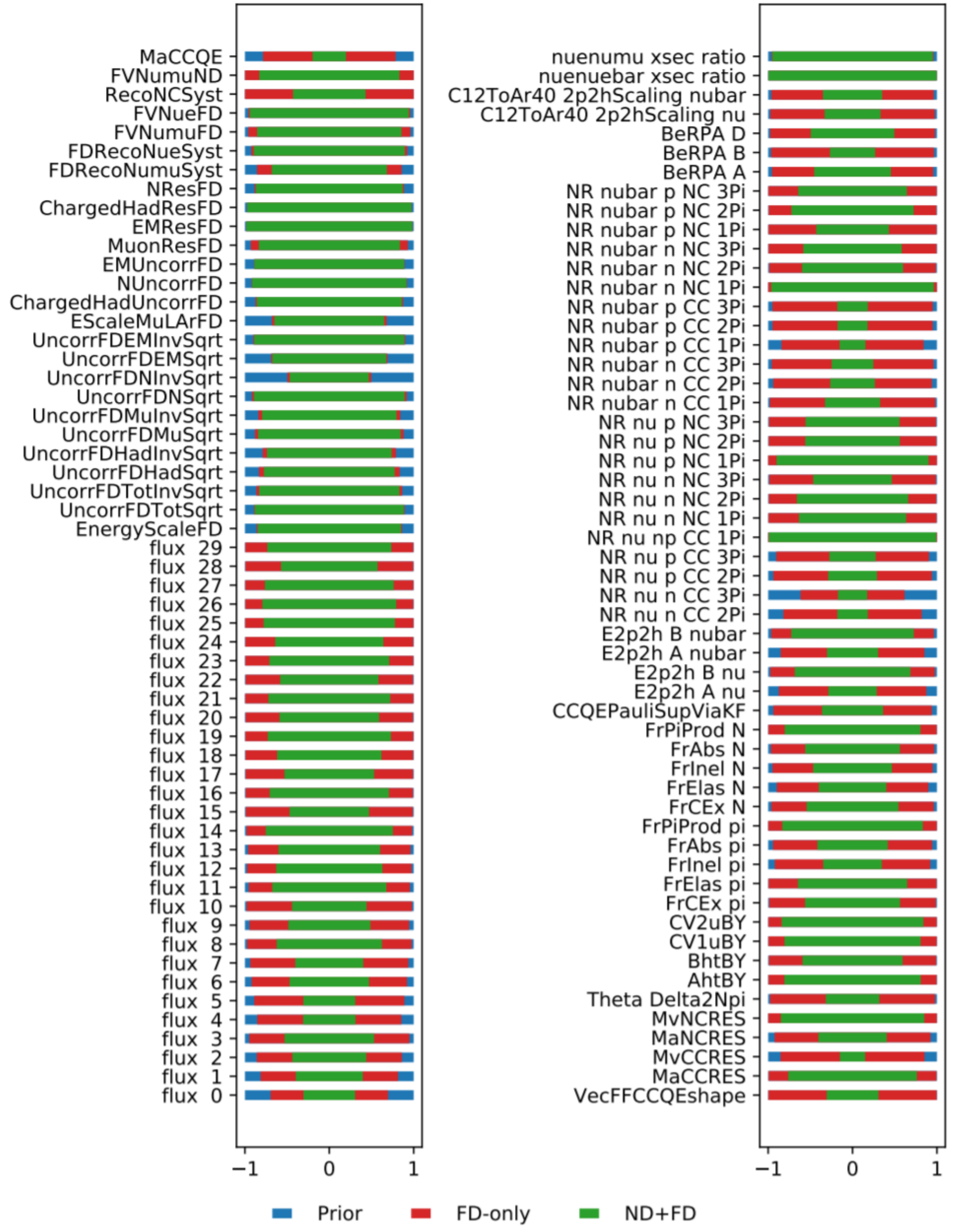
# Backup

# Uncertainties

## Energy Scale Uncertainties

$$E'_{rec} = E_{rec} \times (p_0 + p_1\sqrt{E_{rec}} + \frac{p_2}{\sqrt{E_{rec}}})$$

| Particle | $p_0$ | $p_1$ | $p_2$ |
|---|---|---|---|
| all (except muons) | 2% | 1% | 2% |
| $\mu$ (range) | 2% | 2% | 2% |
| $\mu$ (curvature) | 1% | 1% | 1% |
| p, $\pi^{\pm}$ | 5% | 5% | 5% |
| e, $\gamma$, $\pi^0$ | 2.5% | 2.5% | 2.5% |
| n | 20% | 30% | 30% |



# Extra Neutrino Searches & NSI $\mathcal{L} = \mathcal{L}_{SM} + \ldots$

$+\,\delta\mathcal{L}^{d=5}$

Neutrino mass generation (if mass hierarchy too big, naturally get light $3\nu$), but other dimensions suppressed – and get no observable phenomena at energies we can reach (**Seesaw I/II/III**)

$+\delta\mathcal{L}^{d=6}$

Non Standard Neutrino Interactions (NSI)
Minimal Unitarity violation (MUV)
After EW symmetry breaking ->PMNS non-unitarity induced by mixing with heavy neutrinos. Implies breaking lepton universality and lepton flavor violation
(**inverse or linear seesaw**)

$$H = \frac{1}{2E}\left[U_{\text{PMNS}}\begin{pmatrix}0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31}\end{pmatrix}U^\dagger_{\text{PMNS}} + a\begin{pmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau}\end{pmatrix}\right]$$

$+\delta\mathcal{L}^{d=8}$

NSI – strong matter effects. Not sensitive at Colliders, but are at neutrino facilities

$+\delta\mathcal{L}^{d=9}$

Dark photon & extra neutrino motivated by LNSD/ MiniBoone

$$P^{\text{SBL}}_{\alpha\beta} = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2 \sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$

$+\,\phi$

Add new Scaler - Radiative models. (some type 1 radiative models have NSI, all type II radiative models don't have NSI)

$10^{-3}$eV .1 eV eV KeV MeV GeV $10^2$GeV TeV 10 TeV $10^2$ TeV $10^3$ TeV $10^{12}$ TeV

Extra neutrinos can participate in oscillations

accessible at osc. Exp

Accessible at B-factories

Accessible at LHC

# Parameterizations for Extra Neutrinos Searches

3x3 active $\nu$ — Active-heavy mix

$$\mathcal{U} = \begin{pmatrix} N & \Theta \\ R & S \end{pmatrix}$$

Active-sterile mix — Sterile-heavy mix

**$\epsilon, \alpha, \eta, \theta$ can be related to each other:** **arXiv:1609.08637v3**

R allowed at % level since it can only be probed at osc exp.

If sterile $\nu$ would participate in neutrino oscillations – ie: $P_{\alpha\beta}$ depends on $\mathcal{U}$

3+1, 3+N scenarios : $\theta_{14}, \theta_{24}, \delta_{14}$

$$\mathcal{U} = \begin{pmatrix} c_{12}c_{13}c_{14} & s_{12}c_{13}c_{14} & c_{14}s_{13}e^{-i\delta_{13}} & s_{14}e^{-i\delta_{14}} \\ \cdots & \cdots & \begin{matrix} c_{13}c_{24}s_{23} \\ -s_{13}s_{14}s_{24}e^{i(\delta_{14}-\delta_{13})} \end{matrix} & c_{14}s_{24} \\ \cdots & \cdots & \cdots & c_{14}c_{24}s_{34}e^{-i\delta_{34}} \end{pmatrix}$$

arXiv:1901.08330v1

Direct Heavy Neutrino Searches at LHC

Here N is not unitary – 2 common parametrizations

Triangular

$$\boldsymbol{N} = (I - \alpha)U$$

$$\begin{pmatrix} \alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & \alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & \alpha_{\tau\tau} \end{pmatrix}$$

Unitary PMNS

Hermitian

$$\boldsymbol{N} = (I - \eta)U'$$

$$\begin{pmatrix} \eta_{ee} & \eta_{e\mu} & \eta_{e\tau} \\ \eta^*_{e\mu} & \eta_{\mu\mu} & \eta_{\mu\tau} \\ \eta^*_{e\tau} & \eta^*_{\mu\tau} & \eta_{\tau\tau} \end{pmatrix}$$

$10^{-3}$eV  .1 eV  eV  KeV  MeV  GeV  $10^2$GeV  TeV  10 TeV  $10^2$ TeV  $10^3$ TeV  $10^{12}$ TeV

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# Limits on Extra Neutrinos

For neutrinos with masses below the electroweak scale, best limits from oscillation data. BUT most future experiments (DUNE) won't add too much here (see arXiv:1609.08637v3) – maybe Hyper-K can?

arXiv:1609.08637v3

| | "Light steriles" $\Delta m^2 \gtrsim 100$ eV$^2$ | $\Delta m^2 \sim 0.1 - 1$ eV$^2$ |
|---|---|---|
| $\alpha_{ee}$ | $2.4 \cdot 10^{-2}$ [48] | $1.0 \cdot 10^{-2}$ [48] |
| $\alpha_{\mu\mu}$ | $2.2 \cdot 10^{-2}$ [49] | $1.4 \cdot 10^{-2}$ [50] |
| $\alpha_{\tau\tau}$ | $1.0 \cdot 10^{-1}$ [49] | $1.0 \cdot 10^{-1}$ [49] |
| $\|\alpha_{\mu e}\|$ | $2.5 \cdot 10^{-2}$ [51] | $1.7 \cdot 10^{-2}$ |
| $\|\alpha_{\tau e}\|$ | $6.9 \cdot 10^{-2}$ | $4.5 \cdot 10^{-2}$ |
| $\|\alpha_{\tau\mu}\|$ | $1.2 \cdot 10^{-2}$ [52] | $5.3 \cdot 10^{-2}$ |

48: Buggy

**49: SuperK atmospheric**

50: Minos

51/52: Nomad

PMNS non-unitarity bounded at per mil level from Lepton Universality, Lepton Flavor Violation EW observables, (B-factories ,MEG, LHC)

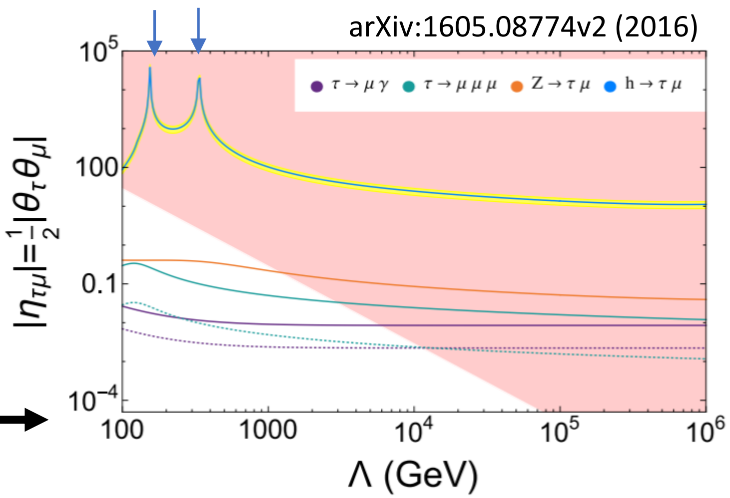
arXiv:1609.08637v3

| | "Non-Unitarity" ($m >$ EW) |
|---|---|
| $\alpha_{ee}$ | $1.3 \cdot 10^{-3}$ [46] |
| $\alpha_{\mu\mu}$ | $2.2 \cdot 10^{-4}$ [46] |
| $\alpha_{\tau\tau}$ | $2.8 \cdot 10^{-3}$ [46] |
| $\|\alpha_{\mu e}\|$ | $6.8 \cdot 10^{-4}$ ($2.4 \cdot 10^{-5}$) [46] |
| $\|\alpha_{\tau e}\|$ | $2.7 \cdot 10^{-3}$ [46] |
| $\|\alpha_{\tau\mu}\|$ | $1.2 \cdot 10^{-3}$ [46] |

LFV: best limits from $\alpha \to \gamma\alpha$ & $\alpha \to 3\beta$ for 3 extra neutrino model

$H \to \tau\mu$ has small preference for non zero (arXiv:1502.07400, arXiv:1508.03372)

arXiv:1605.08774v2 (2016)




$10^{-3}$eV .1 eV eV KeV MeV GeV $10^2$GeV TeV 10 TeV $10^2$ TeV $10^3$ TeV $10^{12}$ TeV

Extra neutrinos can participate in oscillations

accessible at osc. Exp

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Accessible at LHC

# Lepton Flavor Violation & non Unitarity of PMNS

arXiv:1407.6607v2 [hep-ph] 6 Aug 2014

$$\Gamma_{W,\alpha} = \sum_i \Gamma(W \to \ell_\alpha \nu_i) = \frac{G_\mu M_W^3}{6\sqrt{2}\pi} \frac{(NN^\dagger)_{\alpha\alpha} F_W(m_{\ell_\alpha})}{\sqrt{(NN^\dagger)_{ee}(NN^\dagger)_{\mu\mu}}}$$

$$F_W(m_{\ell_\alpha}) = \left(1 - \frac{m_{\ell_\alpha}^2}{m_W^2}\right)^2 \left(1 + \frac{m_{\ell_\alpha}^2}{m_W^2}\right) .$$

$$R_{\alpha\beta}^W = \sqrt{\frac{\Gamma_{W,\alpha} F(m_{\ell_\beta})}{\Gamma_{W,\beta} F(m_{\ell_\alpha})}} = \sqrt{\frac{(NN^\dagger)_{\alpha\alpha}}{(NN^\dagger)_{\beta\beta}}}$$

arXiv:1605.08774v2, 21 Dec 2016

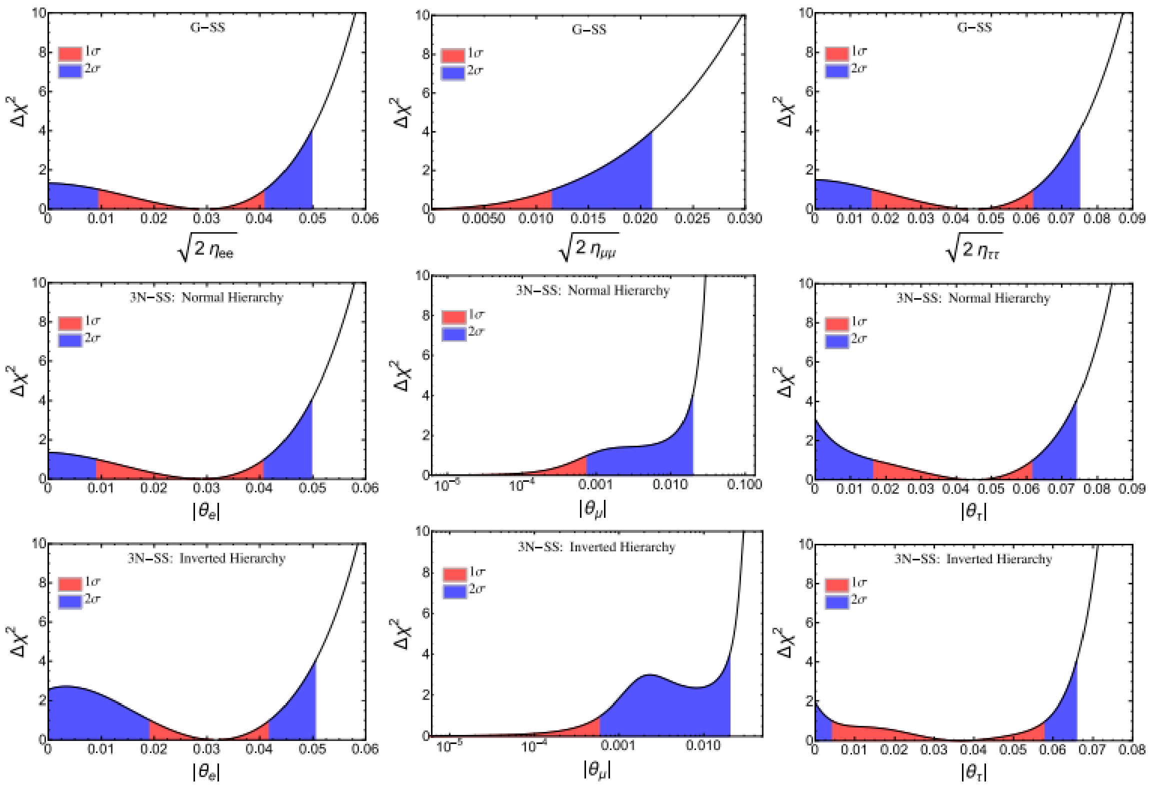



FIG. 3: $\Delta\chi^2$ profile minimized over all fit variables except for one $\theta_\alpha$ (or $\sqrt{2\eta_{\alpha\alpha}}$) in the case of the G-SS) at a time. The upper panels are for the G-SS, and the middle and lower panels for the 3N-SS for a normal and inverted hierarchy respectively.

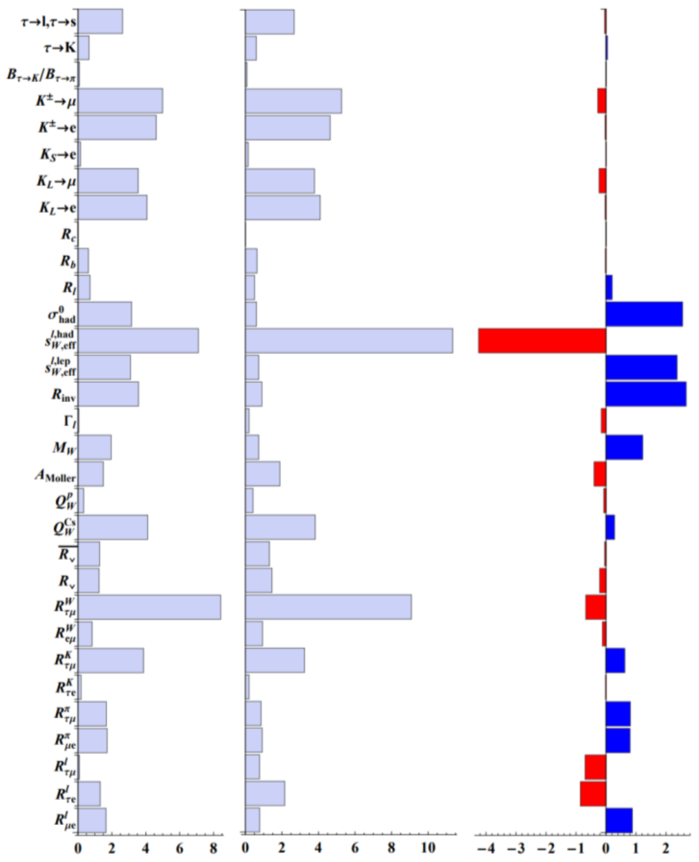
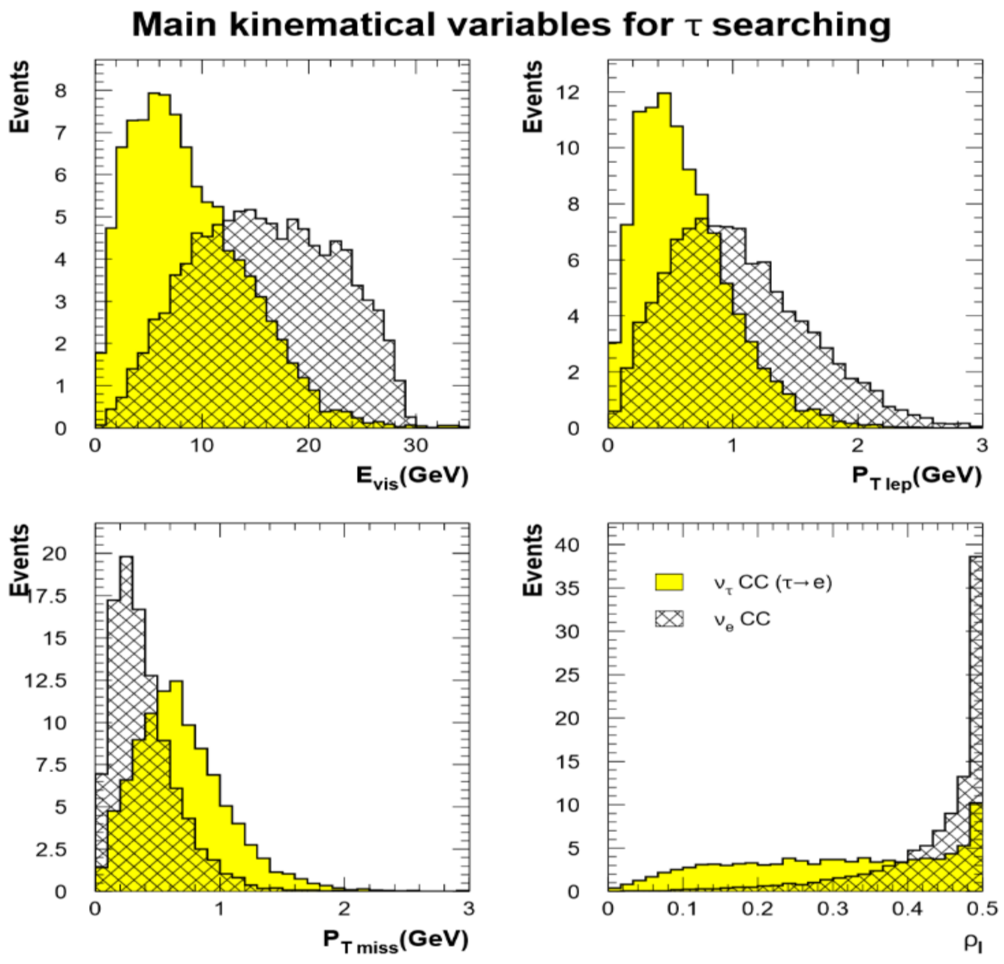


Figure 1: Individual contributions to the total $\chi^2$ from the considered observables. The left column shows the SM and the middle column the MUV scheme with best-fit parameters. The right column shows $\chi_i^2(SM) - \chi_i^2(MUV)$ for the observable $i$. The positive blue (negative red) bars indicate an improvement (worsening) of the MUV scheme best fit compared to the SM.

# Tau Neutrinos in DUNE

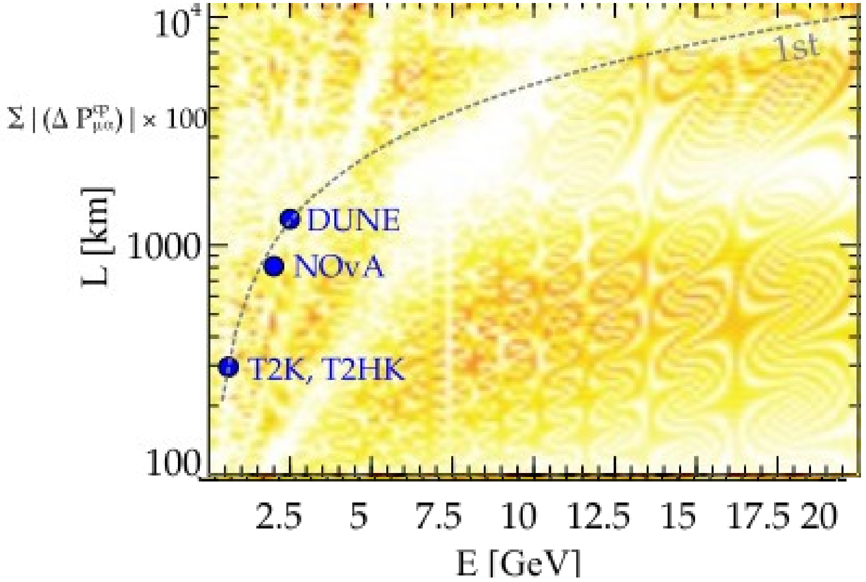



$$\rho = \frac{P_T^{lepton}}{P_T^{lepton} + P_T^{hadron} + P_T^{miss}}$$

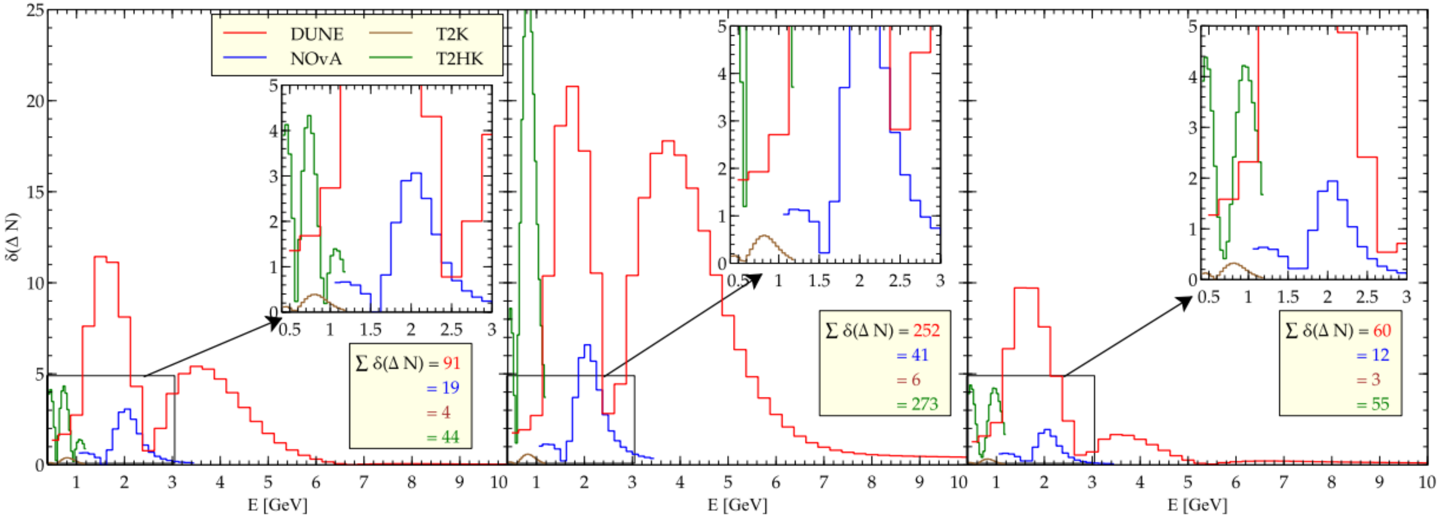
The discriminating power of $E_{vis}$, $P_T$, $P_T^{miss}$, $\rho$ between $\nu_\tau$ induced interactions, represented by the filled yellow distributions, and the $\nu_e$ background events represented by the hashed distribution.

# Sensitivity to Extra Neutrinos and NSI

Darker regions = larger amount of non-unitarity in sterile
Can’t probe non-unitarity at better than 6%




SI NSI Sterile




$$\delta[\Delta N^{CP}_{\alpha\beta}] = [\Delta N^{CP}_{\alpha\beta}](\delta_{13} = \pi/2) - [\Delta N^{CP}_{\alpha\beta}](\delta_{13} = 0)$$

- NSI with matter gives rise to NSI at source and/or detector (arXiv:0807.1003v3). Bounds on source & detector NSI an order of magnitude more strict than matter NSI. DUNE can probe matter (dim 8), Hyper – K source & detector NSI (dim 6)
- NSI can be probed with supernova neutrinos in Hyper-K : arXiv:1907.01059v2

$10^{-5}$eV $10^{-3}$eV $10^{-1}$eV eV KeV MeV GeV 100 GeV

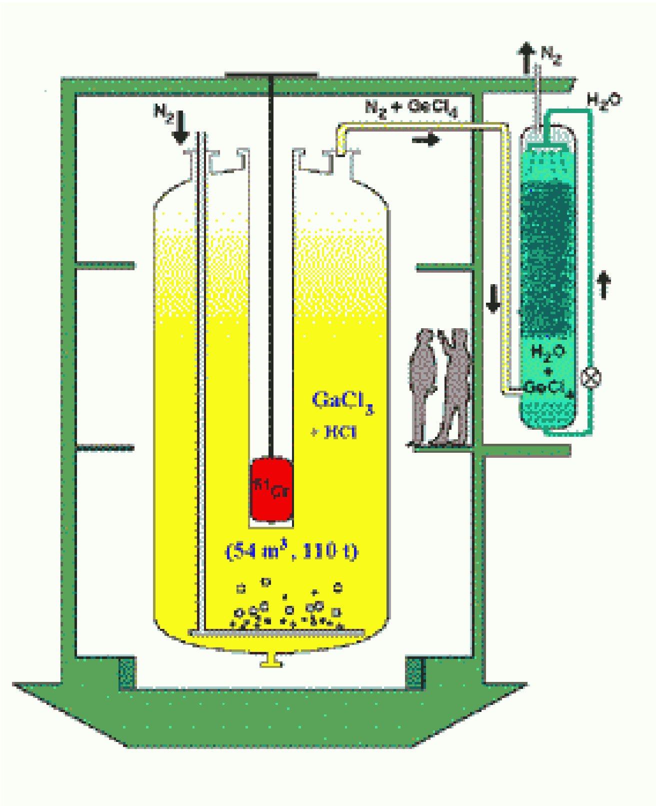
Extra neutrinos can participate in oscillations

accessible at osc. Exp

Accessible at B-factories

Gallium anomaly: GALLEX and SAGE collaborations place detectors besides artificial radioactive sources producing high fluxes of electron neutrinos ($\nu_e$) - 2.9 σ deficit of the $\nu_e$.

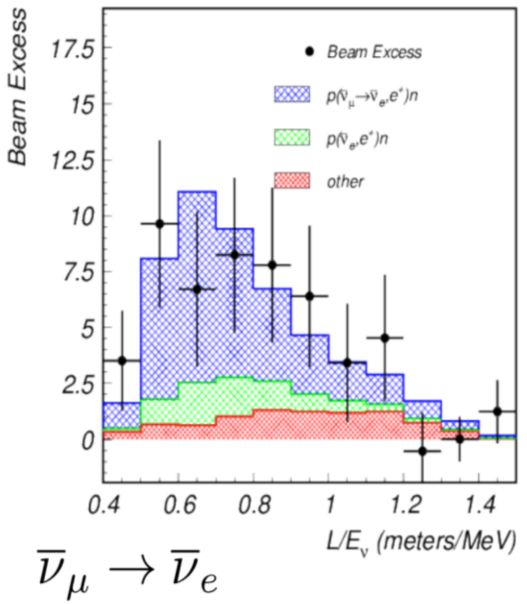
Kaether F, et al. Phys. Lett. B685:47 (2010)
Abdurashitov JN, et al. Phys.Rev. C73:045805 (2006))




https://oglez.web.cern.ch/oglez/public/EPPSU-CMS-Week-v0.pdf

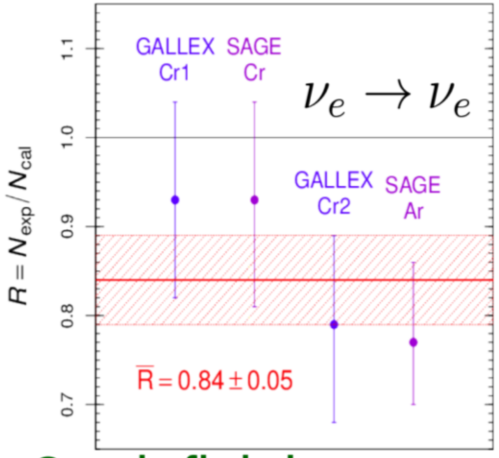
# Anomalies in oscillations

- 3.8σ excess in **LSND**

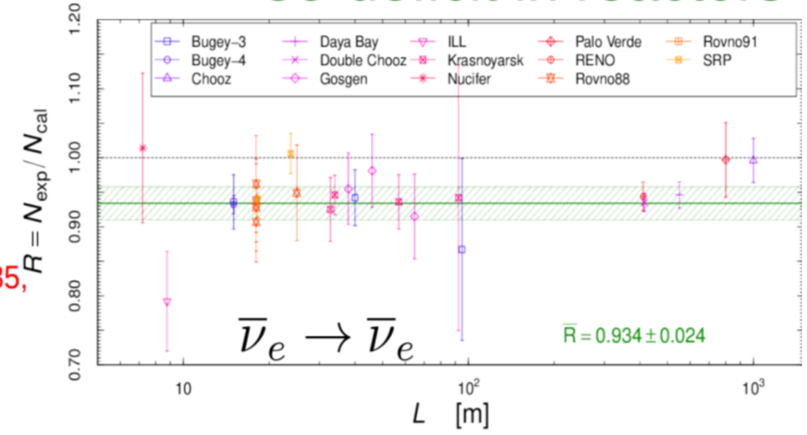



- No signal **@Karmen**

- ~3σ deficit in **Gallium**



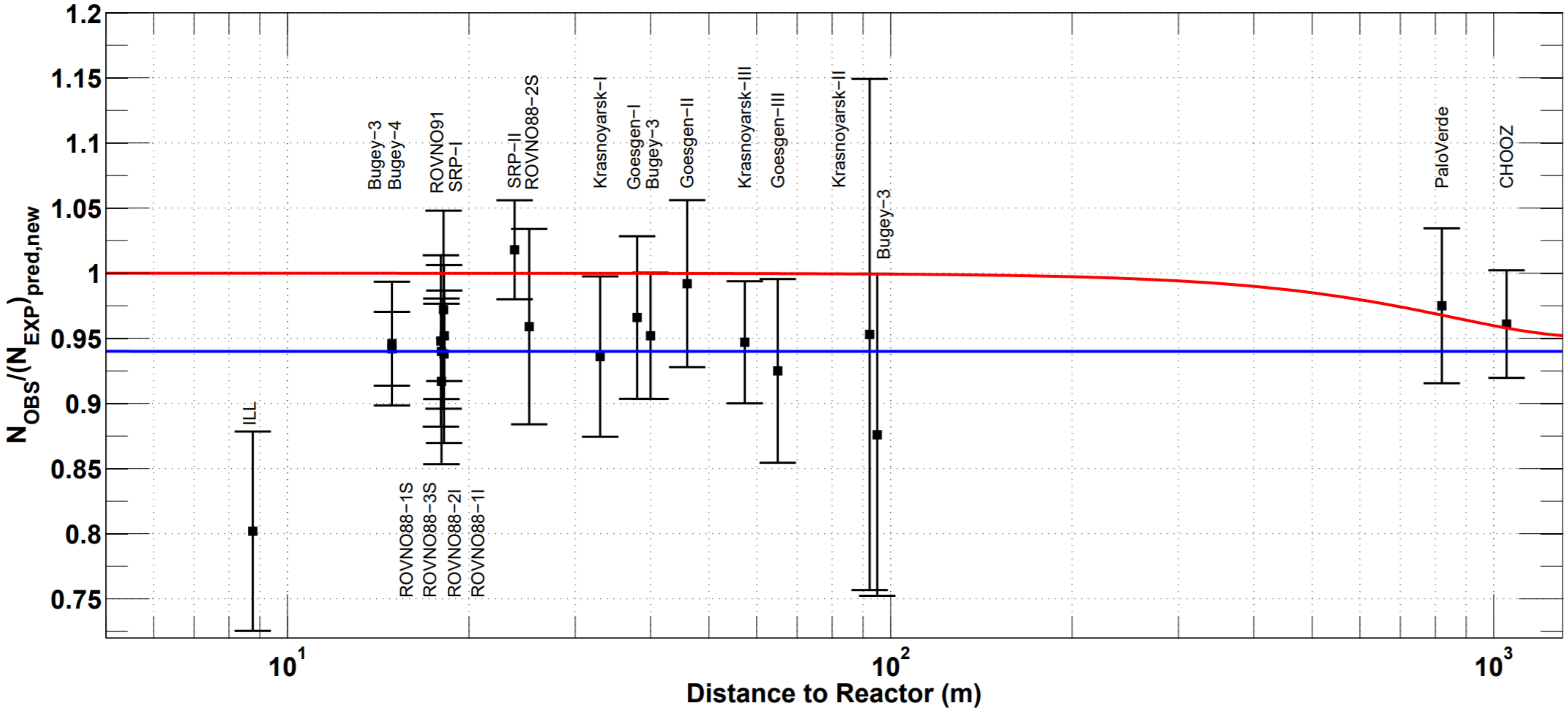

- ~3σ deficit in reactors




**LSND:** PRL 75 (1995) 2650, PRC 54 (1996) 2685, PRL 77 (1996) 3082, PRD 64 (2001) 112007
**Karmen:** PRD 65 (2002) 112001
**Gallium:** PRC 80 (2009) 015807, **SAGE,** Nucl.Phys.Proc.Suppl. 168 (2007) 344, Laveder et al, PRD 78 (2008) 073009 and PRC 83 (2011) 065504, C. Giunti et al
**Reactor:** PRD 83 (2011) 073006, Mention et al. PRC 83 (2011) 054615, Mueller et al. PRC 84 (2011) 024617, Huber

# Reactor anti neutrino anomaly. arXiv:1101.2755v4 [hep-ex] 23 Mar 2011

Bugey-4, ROVNO91, Bugey-3, Gosgen, ILL, Krasnoyarsk, Rovno88, SRP, Chooz, Palo Verde, Nucifer, Double Chooz, Daya Bay, and RENO measured a 2.9 σ deficit of $\bar{\nu}_e$. NEOS and DANSS see similar effects, but in theory independent way.



| Analysis | $\Delta m^2_{41}$ [eV$^2$] | $\lvert U^2_{e4}\rvert$ | $\chi^2_{\min}$/dof | $\Delta\chi^2$(no-osc) | significance |
|---|---|---|---|---|---|
| DANSS+NEOS | 1.3 | 0.00964 | 74.4/(84 − 2) | 13.6 | 3.3$\sigma$ |
| all reactor (flux-free) | 1.3 | 0.00887 | 185.8/(233 − 5) | 11.5 | 2.9$\sigma$ |
| all reactor (flux-fixed) | 1.3 | 0.00964 | 196.0/(233 − 3) | 15.5 | 3.5$\sigma$ |
| $\overset{(-)}{\nu}_e$ disap. (flux-free) | 1.3 | 0.00901 | 542.9/(594 − 8) | 13.4 | 3.2$\sigma$ |
| $\overset{(-)}{\nu}_e$ disap. (flux-fixed) | 1.3 | 0.0102 | 552.8/(594 − 6) | 17.5 | 3.8$\sigma$ |

$\nu_e$ disappearance data (In the $\nu_e$ and $\bar{\nu}_e$ disappearance channels, the most important constraints on sterile neutrinos come from reactor experiments at short baseline (L= .1 km)). But we include also data from solar neutrinos, ve scattering on 12C, and radioactive source experiments.

Fits: arXiv:1803.10661v1 [hep-ph] 28 Mar 2018

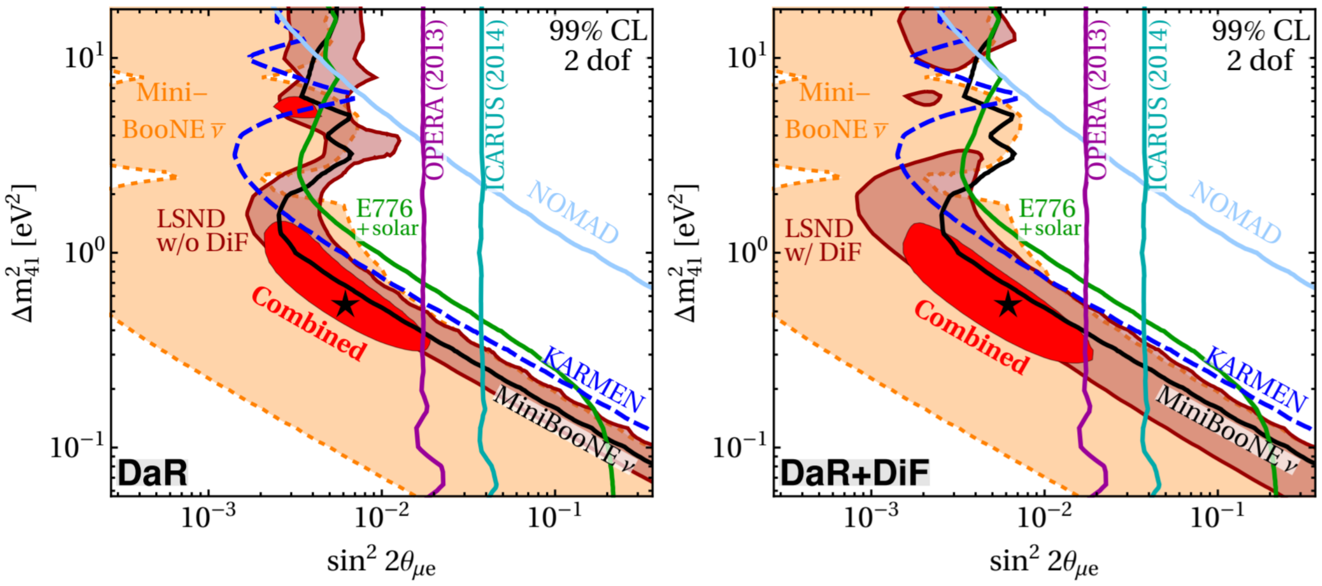


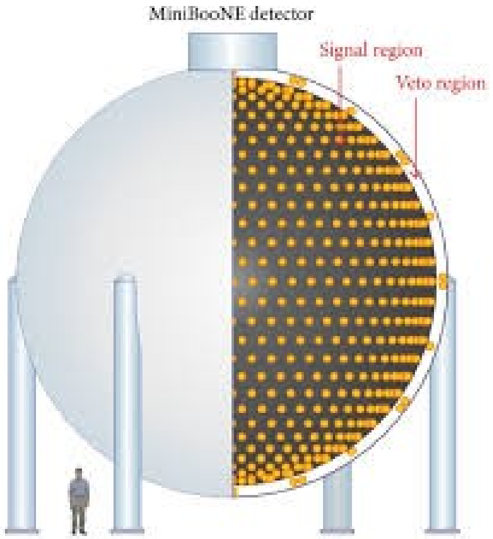

FIG. 4. Constraints on short-baseline $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations in the presence of sterile neutrinos in $3+1$ scenarios. We show the allowed parameter regions, projected onto the plane spanned by the effective mixing angle $\sin^2 2\theta_{\mu e} \equiv 4|U_{e4}|^2|U_{\mu 4}|^2$ and the mass squared difference $\Delta m^2_{41}$. In the left panel only decay-at-rest (DaR) data from LSND is included, while in the right panel also decay-in-flight data (DiF) is used.

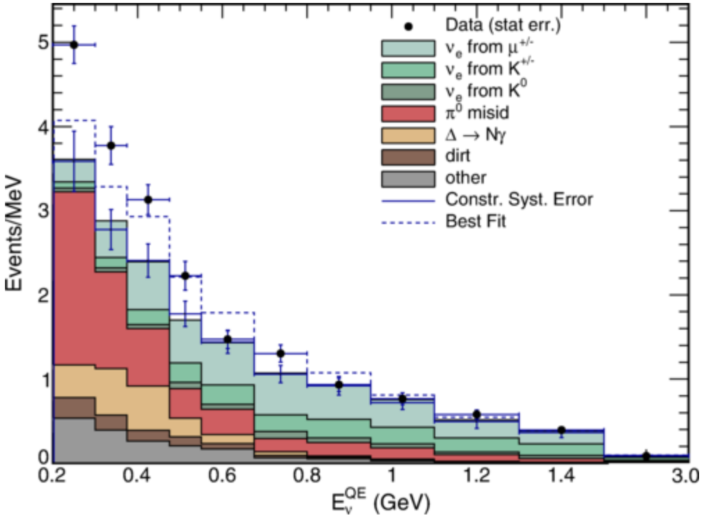
DANSS and NEOS reactor experiments support sterile neutrino explanation of reactor anomalies (Phys.Rev.Lett. 118:121802 (2017), Phys.Lett. B787:56 (2018))

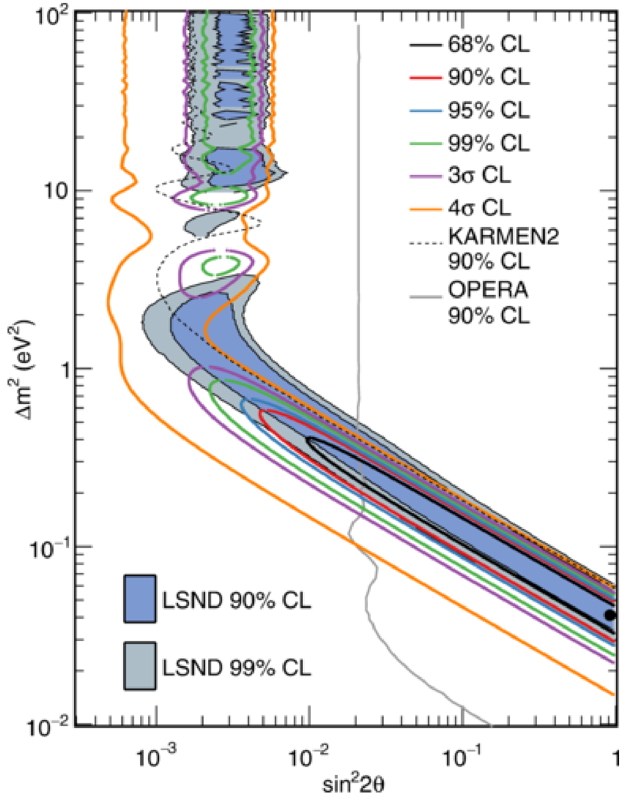
# MiniBooNe & LSND

Short baseline experiments: the abundant appearance of electron (anti)-neutrinos ($\nu_e$) that started off as a of muon (anti)-neutrinos ($\nu_\mu$) beam give combined 6.0 $\sigma$ deviation from theory (*Phys. Rev. Lett. 121, 221801 (2018)*)

**MiniBooNe: Phys. Rev. Lett. 121, 221801 (2018)**. **LSND: Phys. Rev. D 64, 112007 (2001)**.



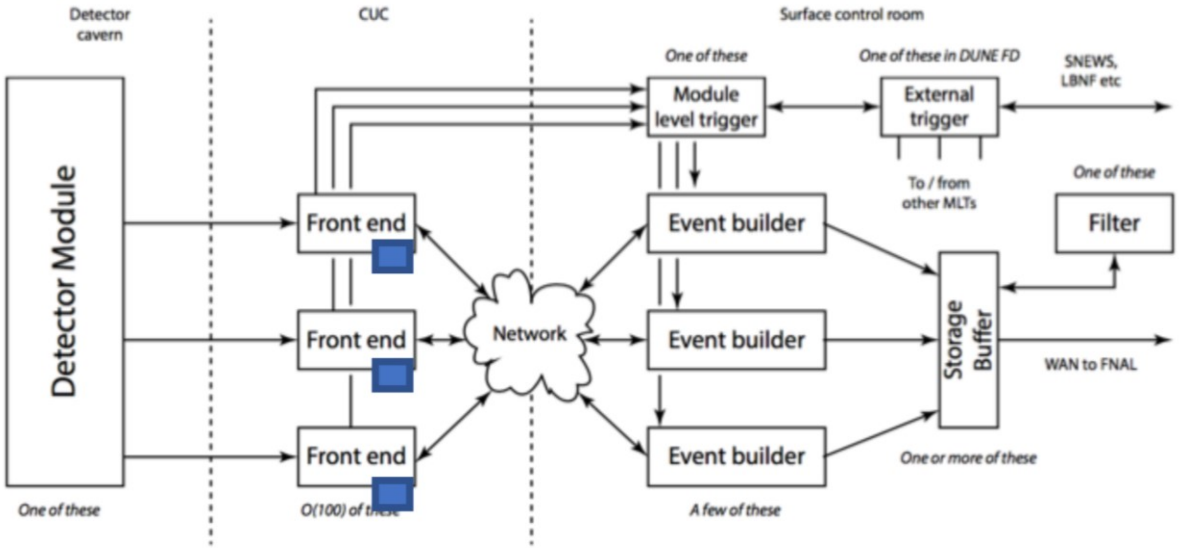

Two neutrino oscillation model: Neutrino & anti-neutrino mode (shaded areas LSND allowed, black point MiniBooNE best fit point). Karmen & Opera limits shown.

* KARMEN experiment in Karlsruhe examined a [low energy] region similar to the LSND experiment, but saw no indications of neutrino oscillations, but this experiment was less sensitive than LSND

# FELIX Readout System & Extra Neutrinos

- High performance I/O and compute system - Detector input (~1.5 TB/s)

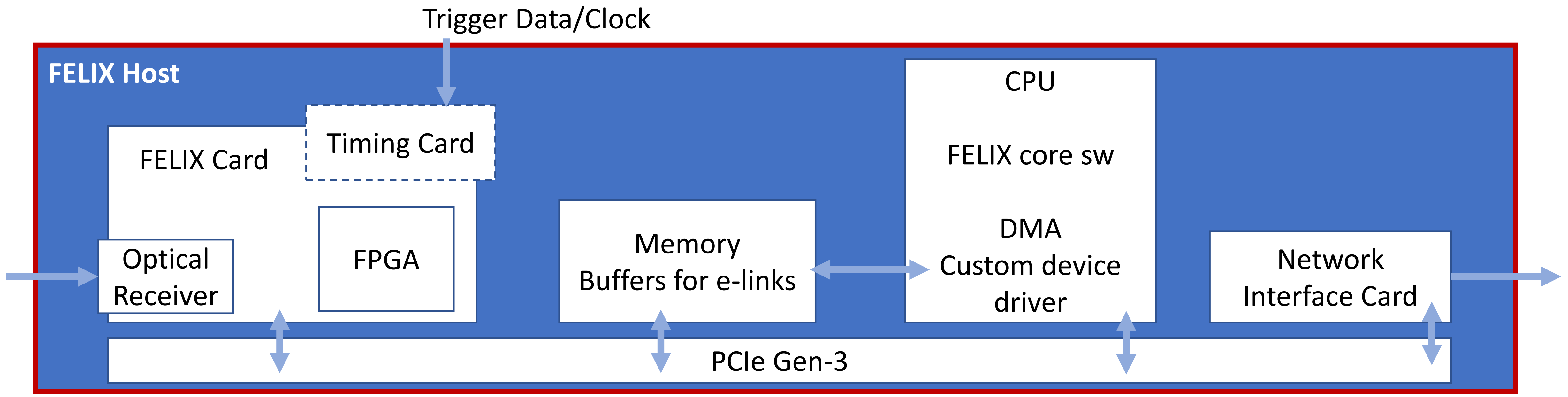
- FELIX deals with data reception from detectors, data exchange with server & co-processor on FELIX board

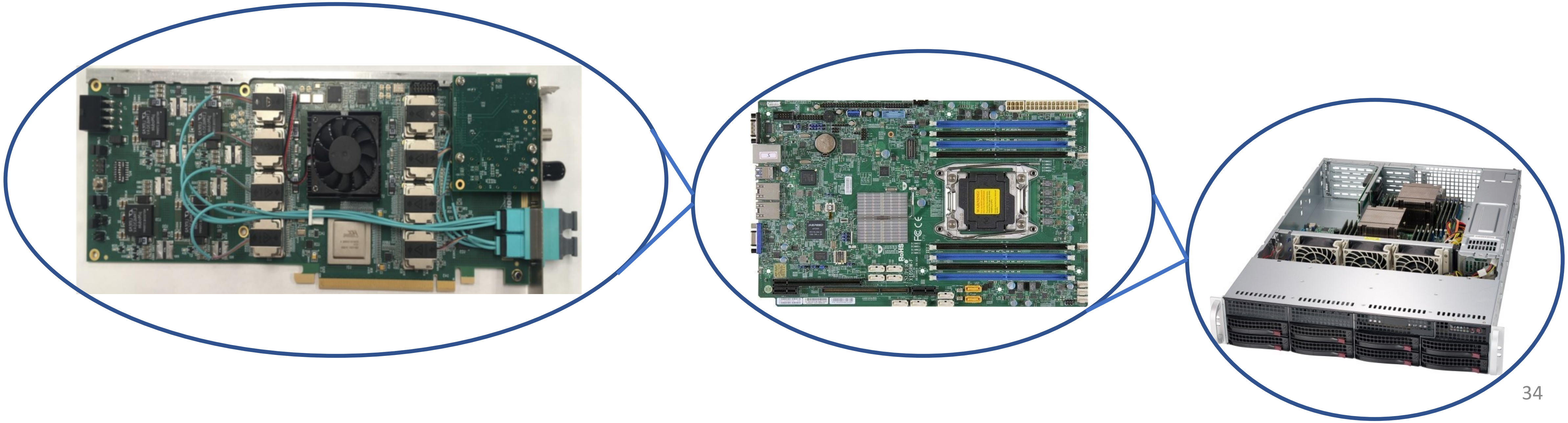



- FELIX possibly relays control, config, monitoring to/from detectors

- On receipt of supernova trigger must be able to record 100s of full waveform data including O(10s) before the trigger signal

# FELIX Readout System



# DUNE Readout Requirements

| Requirement | Description | Value |
|---|---|---|
| Off-beam High-energy Trigger | The detector shall trigger on the visible energy* of underground physics events from decays or interactions within the active volume with high efficiency. | >100MeV |
| Off-beam Low-energy Trigger | The detector shall be capable of triggering on the visible energy of single low energy neutrino interactions inside the active volume. | >10MeV |
| Trigger for Beam | The detector shall trigger on the visible energy of beam interactions within the active volume with efficiency high enough that it has a sub-dominant impact on physics sensitivity. | > 100 MeV |
| Trigger for Calibration | The detector shall provide triggers to and trigger on calibration stimuli and tag the data from these triggers as such | |
| Trigger for Supernova Burst | A trigger shall be generated when a collection of signals is detected that constitute a candidate supernova burst with high galactic coverage*, while meeting offline storage requirements and overall bandwidth limitations. | |
| Physics Event Record | The DAQ shall merge data into a form suitable for offline analysis. Furthermore, tags shall be provided to allow the data collection conditions at the time and the livetime to be determined. | |
| DAQ Deadtime | The DAQ shall operate with deadtime that does not contribute significantly to overall loss of detector livetime. | |

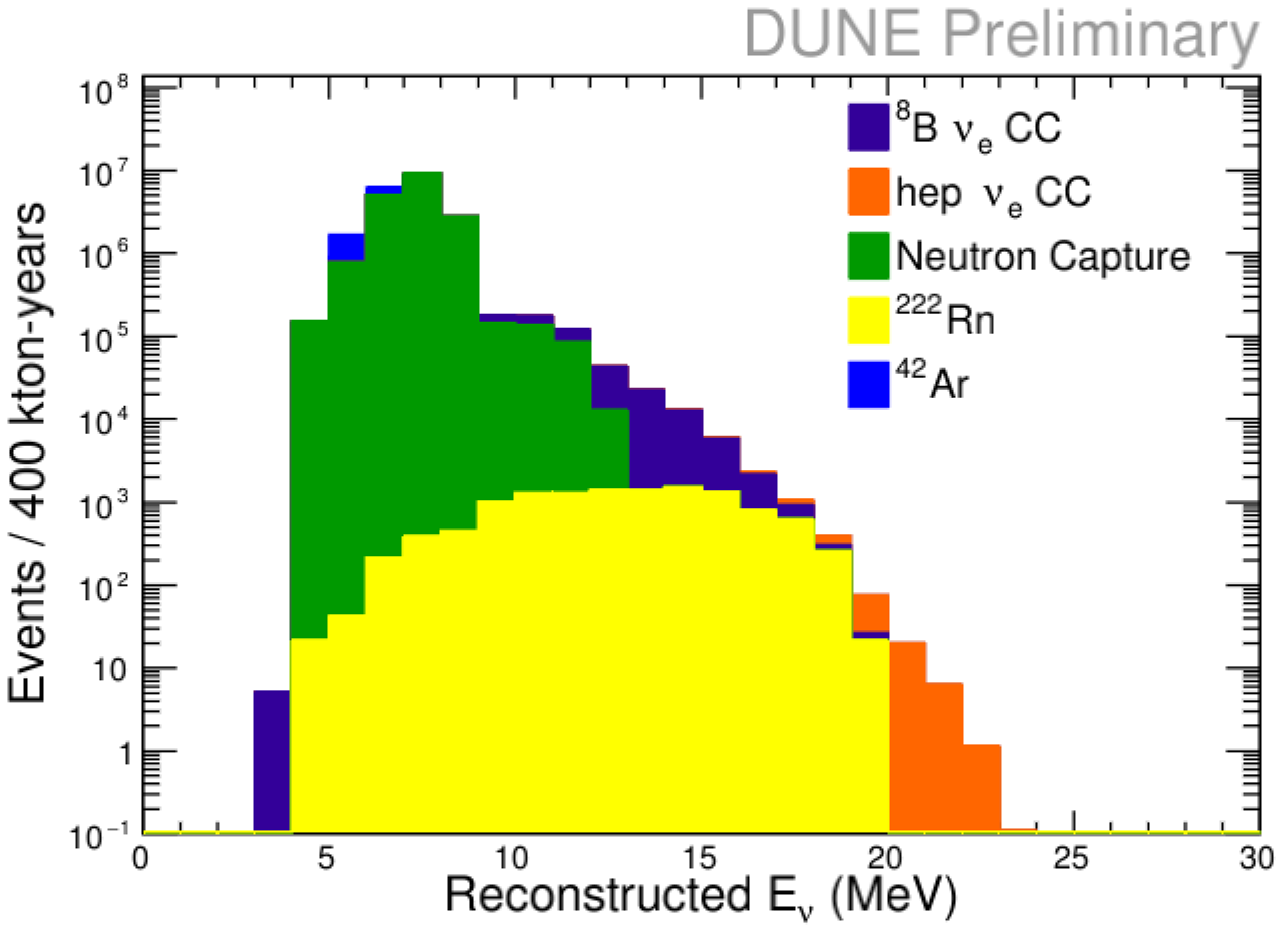
*Visible energy = deposited energy in the active volume as ionization and/or scintillation
*Galactic coverage = SBN probability-weighted efficiency, integrated over the physical extent of the Milkyway

# FELIX in DUNE Timeline

G. Lehmann Miotto

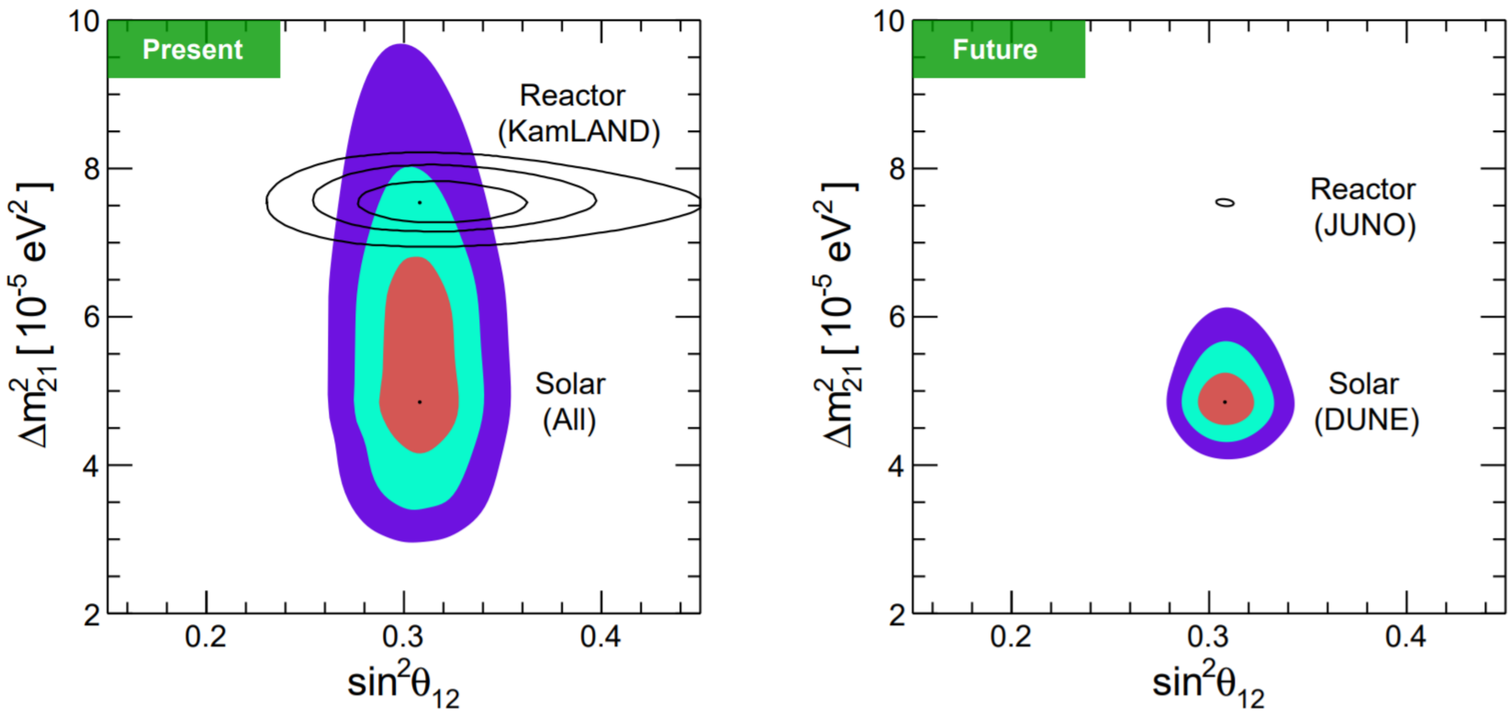
- Final FELIX card layout -> Q1 2021
  - FW, SW development & integration
- Test boards, test servers -> Q4 2021
  - FW, SW testing & optimization
- Pre-production -> Q2 2022 (also for detector commissioning)
  - Overall readout system validation •
- Production -> Q2 2023
  - Installation and commissioning

# Solar Neutrino Backgrounds



# DUNE as the Next-Generation Solar Neutrino Experiment

- https://arxiv.org/pdf/1808.08232.pdf



# ProtoDUNE calibration

$$\left(\frac{dE}{dx}\right)_{\text{calibrated}} = \left(\exp\left(\frac{(\frac{dQ}{dx})_{\text{calibrated}}}{C_{\text{cal}}}\frac{\beta' W_{\text{ion}}}{\rho \mathscr{E}}\right) - \alpha\right)\left(\frac{\rho \mathscr{E}}{\beta'}\right)$$

$C_{\text{cal}}$ = Calibration constant used to convert ADC values to number of electrons,
$W_{\text{ion}}$ = $23.6 \times 10^{-6}$ MeV/electron (the work function of argon),
$\mathscr{E}$ = $E$ field based on the measured space charge map,
$\rho$ = 1.38 g/cm$^3$ (liquid argon density at a pressure of 124.106 kPa),
$\alpha$ = 0.93, and
$\beta'$ = 0.212 (kV/cm)(g/cm$^2$)/MeV.

The calibration constant $C_{\text{cal}}$ is normalized so that the unit ("ADC×tick") corresponds to 200 electrons. In the case where the detector response is perfectly modeled (e.g. in the simulation), the calibration constant $C_{\text{cal}}$ should be exactly $1/200 = 5\times10^{-3}$ ADC×tick/e. The calibration constants derived for the collection plane by fitting the stopping muon samples to the predicted $dE/dx$ curve are shown in table 5. The uncertainties are statistical only. The difference between data and MC calibration constants is caused by the uncertainties on the gain measurement and the simulation of detector response.