Neutrons in the DUNE experiment

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Neutron physics in Neutrino Astronomy
IoP workshop at King's College London, 2019.11.08

Content

- **Overview of the DUNE experiment**
- **Supernova detection and solar neutrinos**
- **Sources of neutrons in DUNE**
- **Neutron interaction and propagation in Liquid Argon**

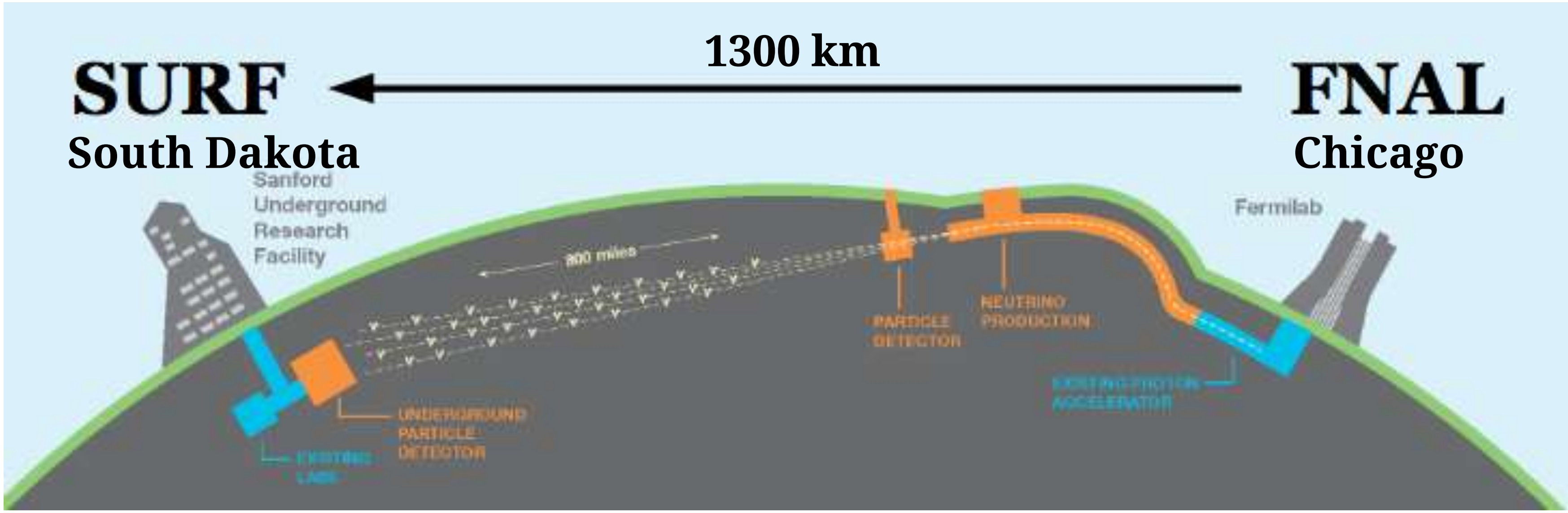
Overview of DUNE

DEEP UNDERGROUND NEUTRINO EXPERIMENT

An international science collaboration

1093 collaborators from **188 institutions** in **32 countries**

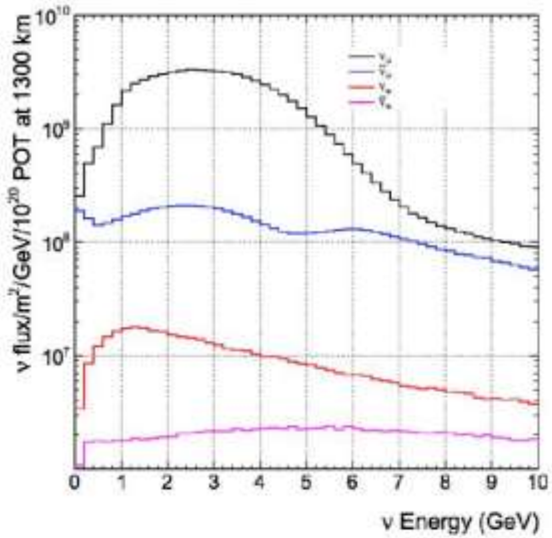
Deep Underground Neutrino Experiment



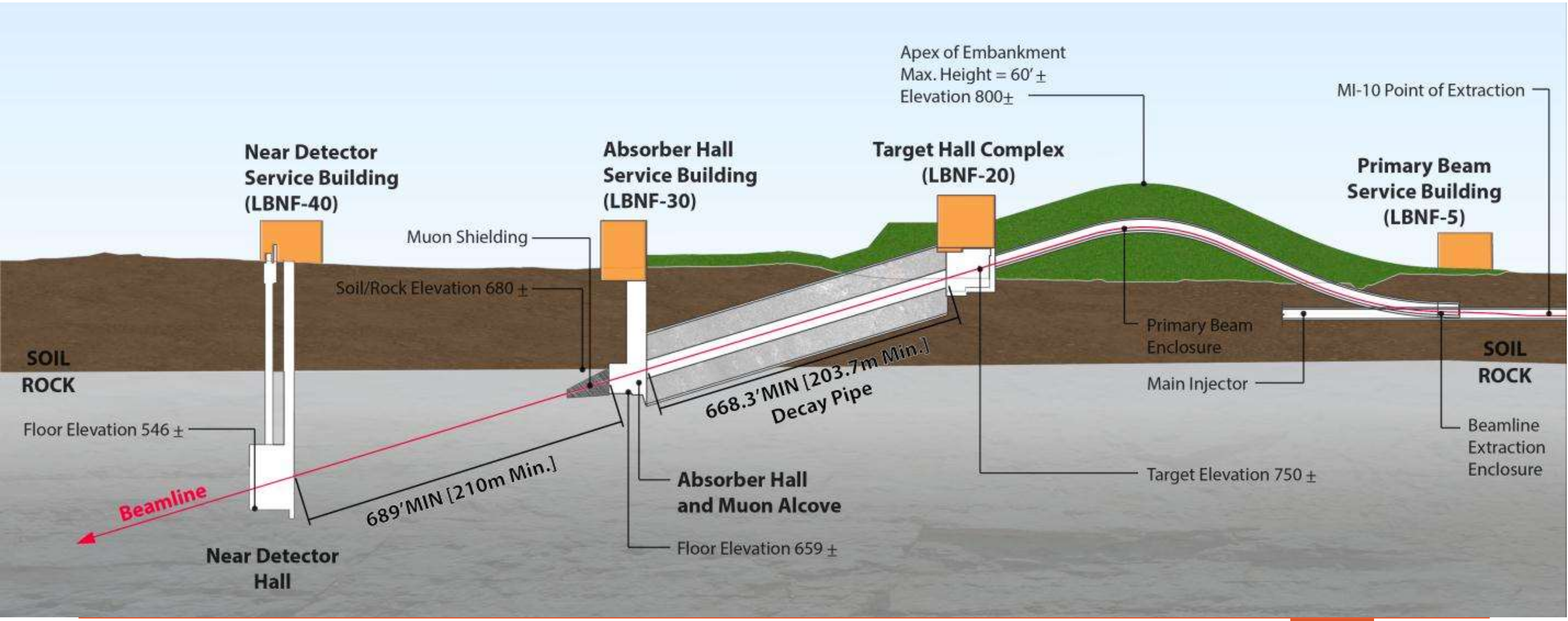
- 1.5 km underground
- On-axis 40 ktonne LAr TPC
- ν_μ disappearance and ν_e appearance to measure MH, CPV, and mixing angles
- Large detector, capable of observing supernova neutrinos, solar neutrinos, nucleon decay and other BSM processes

- New ν_μ beam: 1.2 MW @ 80 GeV protons, upgradable to 2.4 MW
- It can run in neutrino and antineutrino modes by switching the polarity of the magnetic horns.
- Wide band neutrino beam.
- Highly capable near-detector

At Fermilab

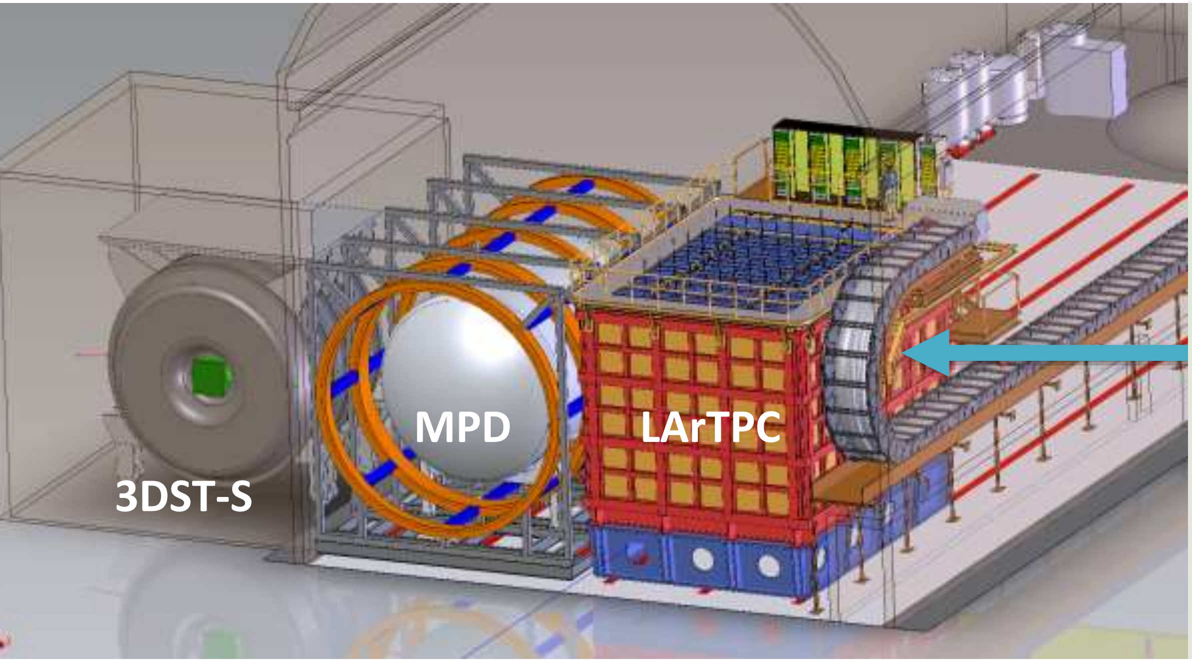


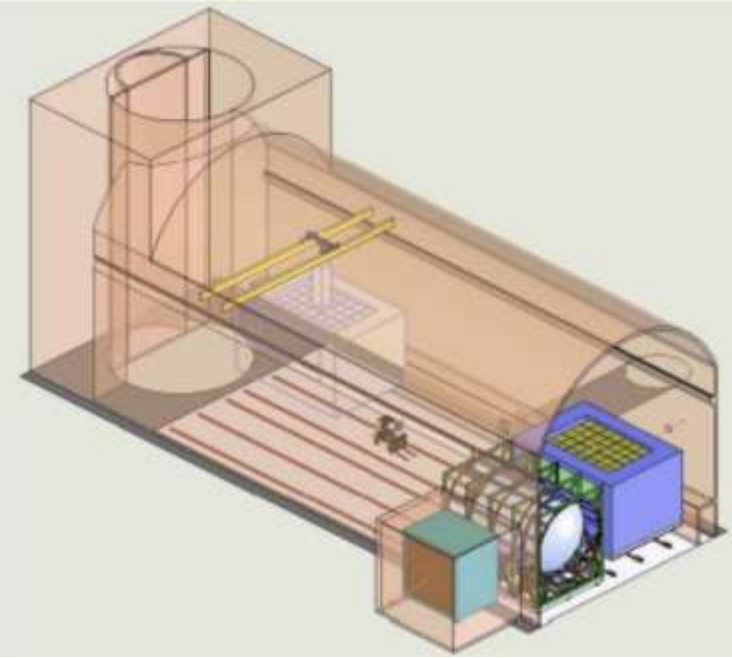
Near Detector Hall at edge of Fermilab site
Initial upward pitch, 101 mrad pitch to get to South Dakota



Near detector design

Moveable between on-axis and off-axis: PRISM concept



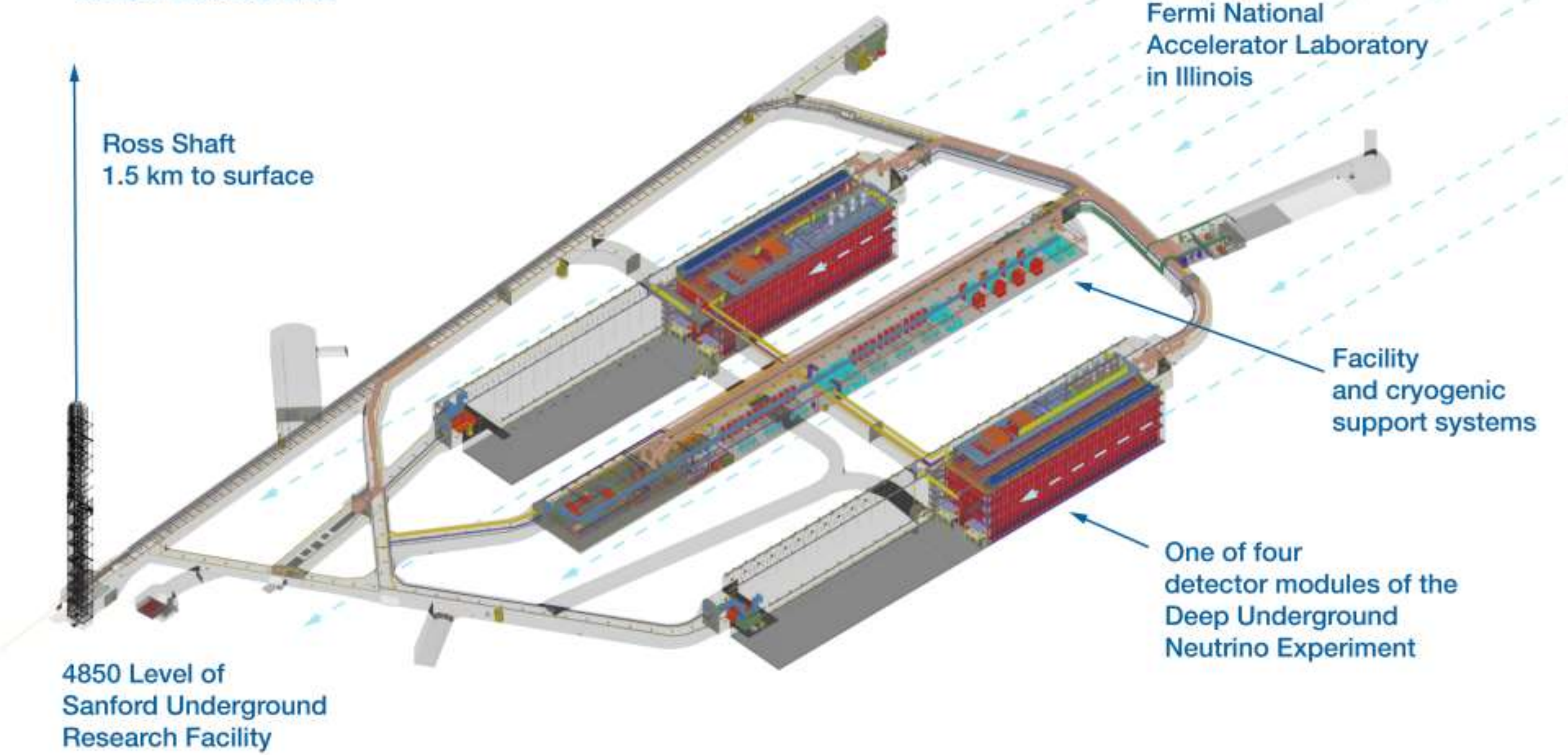


Designed to constrain flux and cross section systematics in oscillation analysis:

574 m from LBNF target
~60 m underground

- LArTPC with pixelated readout (50 tonne)
- Multi-Purpose Detector (MPD)
  - Magnetised high-pressure GAr TPC (HPgTPC) (1 tonne) + ECAL
- Three-Dimensional Scintillator Tracker-Spectrometer (3DST-S)

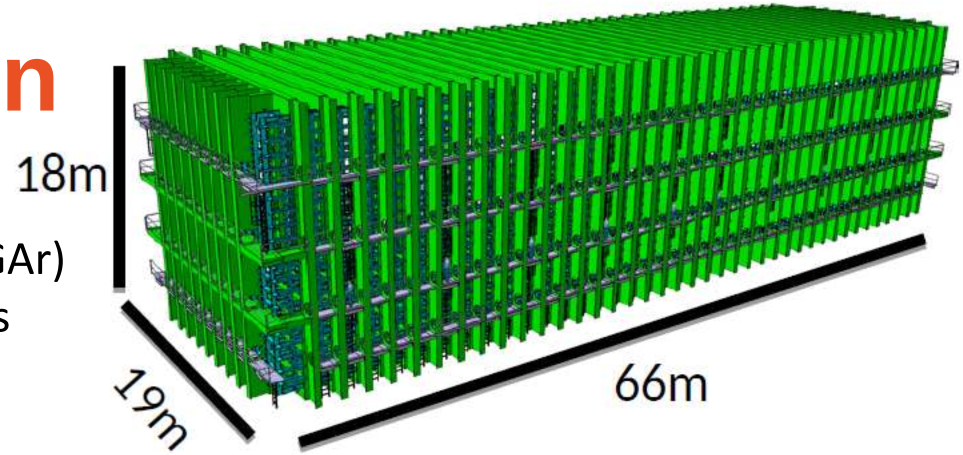
Long-Baseline Neutrino Facility
South Dakota Site

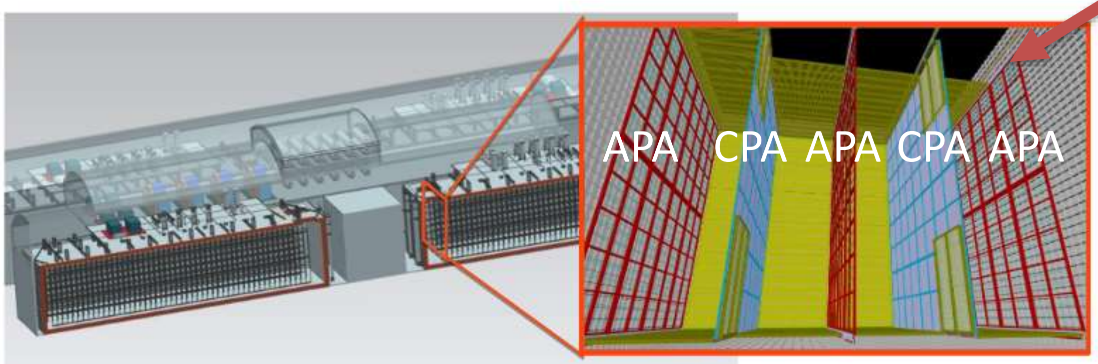


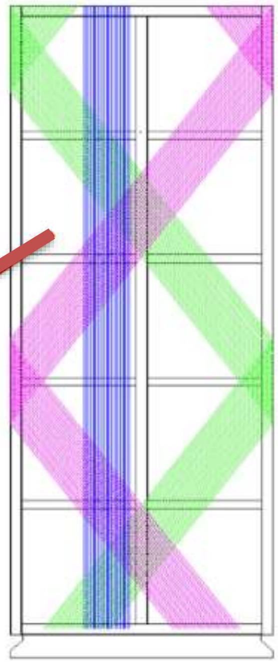
Far detector design

Two designs being considered:
Single Phase (LAr) and Dual Phase (LAr + GAr)

- Single Phase FD uses modular drift cells (scalable)
- Suspended Anode and Cathode Plane Assemblies (APAs and CPAs), 3.6 m drift, 500 V/cm field
- Wrapped wire to reduce number of readout channels needed and cabling complexity
- Four 10 ktonne modules deployed in stages

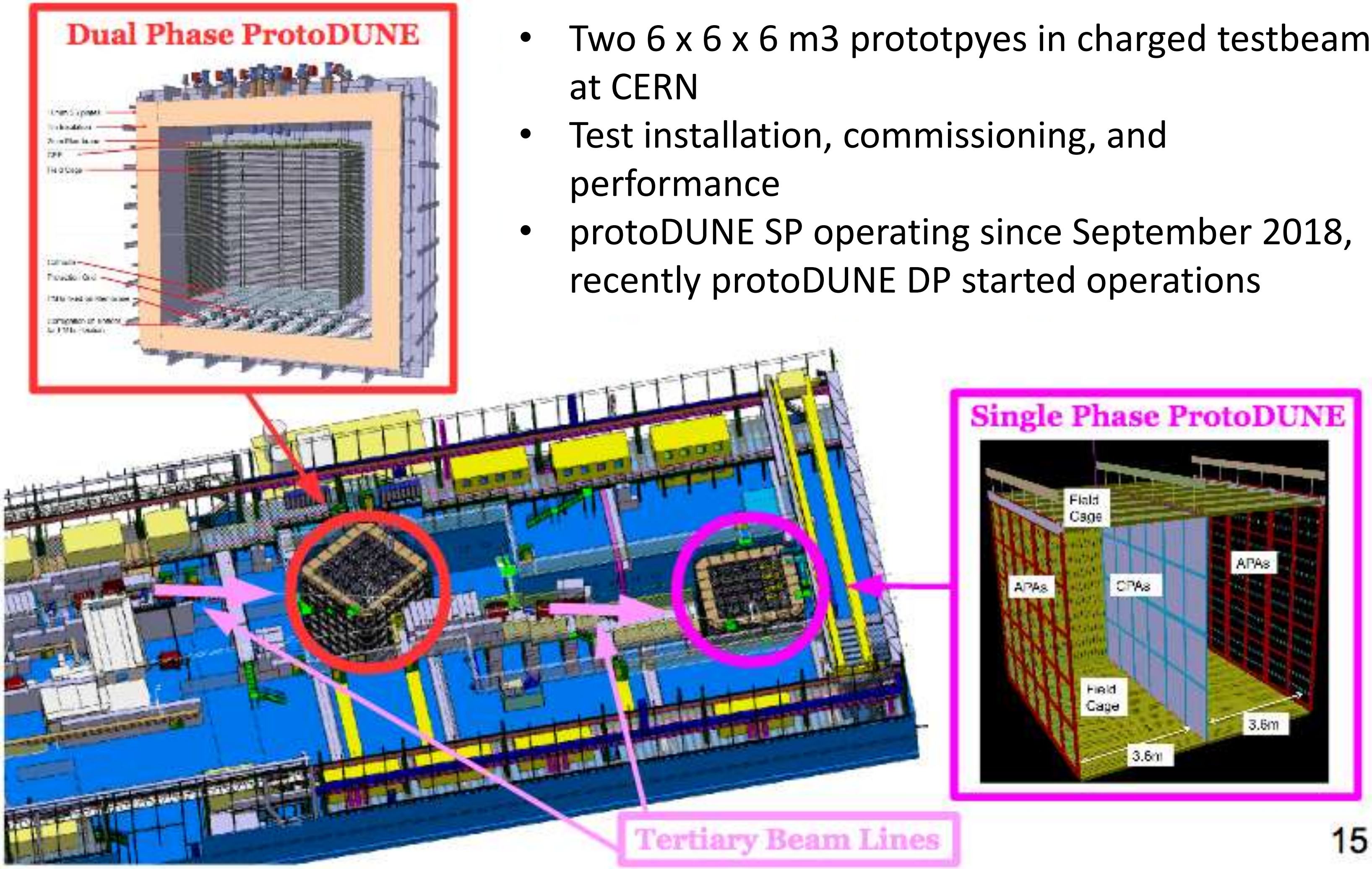






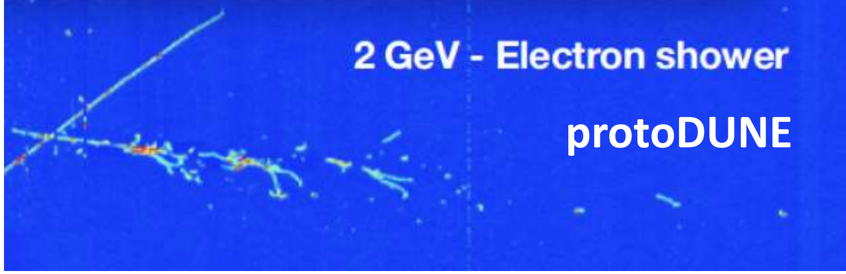
protoDUNE(s)

- Two 6 x 6 x 6 m3 prototpyes in charged testbeam at CERN
- Test installation, commissioning, and performance
- protoDUNE SP operating since September 2018, recently protoDUNE DP started operations

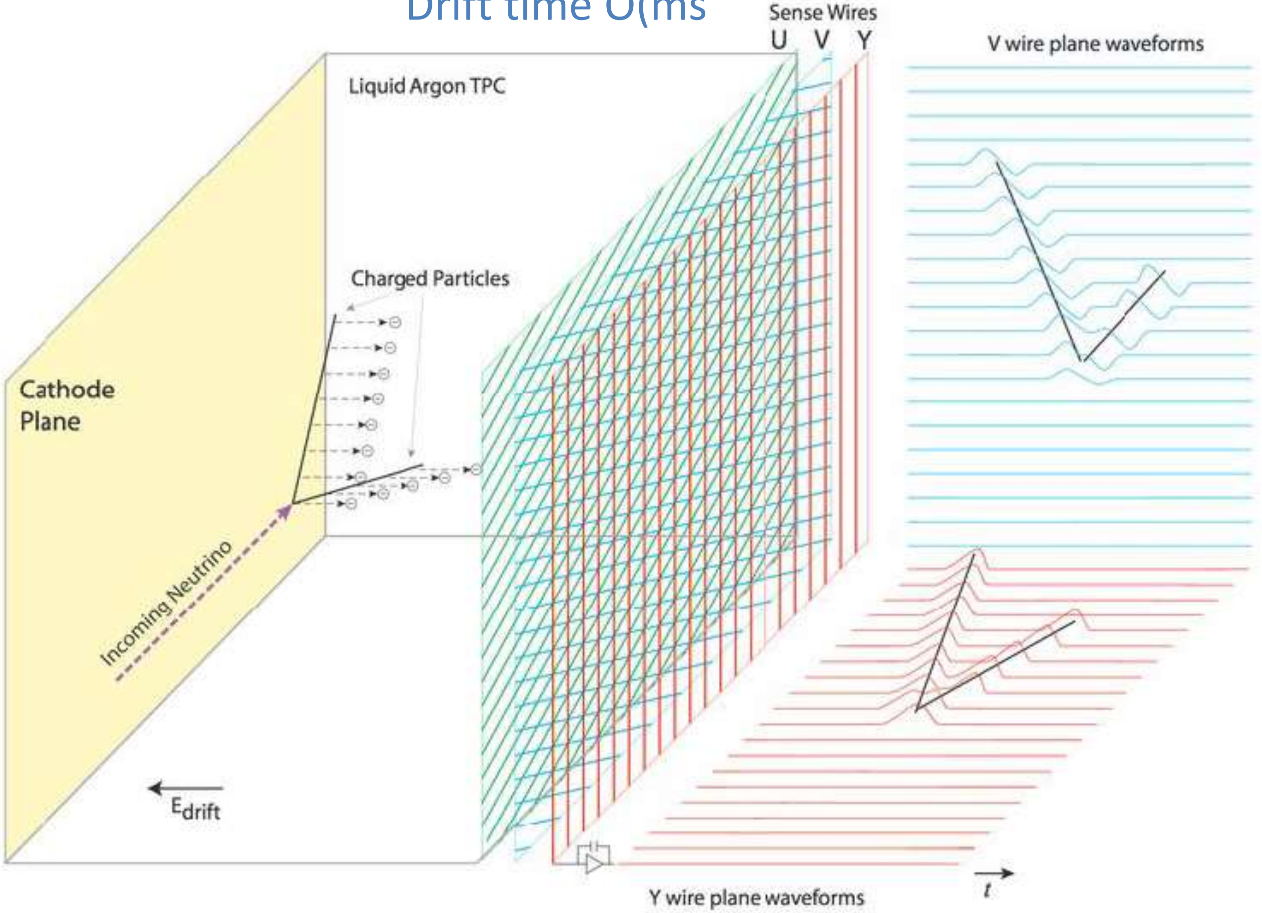


protoDUNE @ CERN

Signal formation



Drift time O(ms

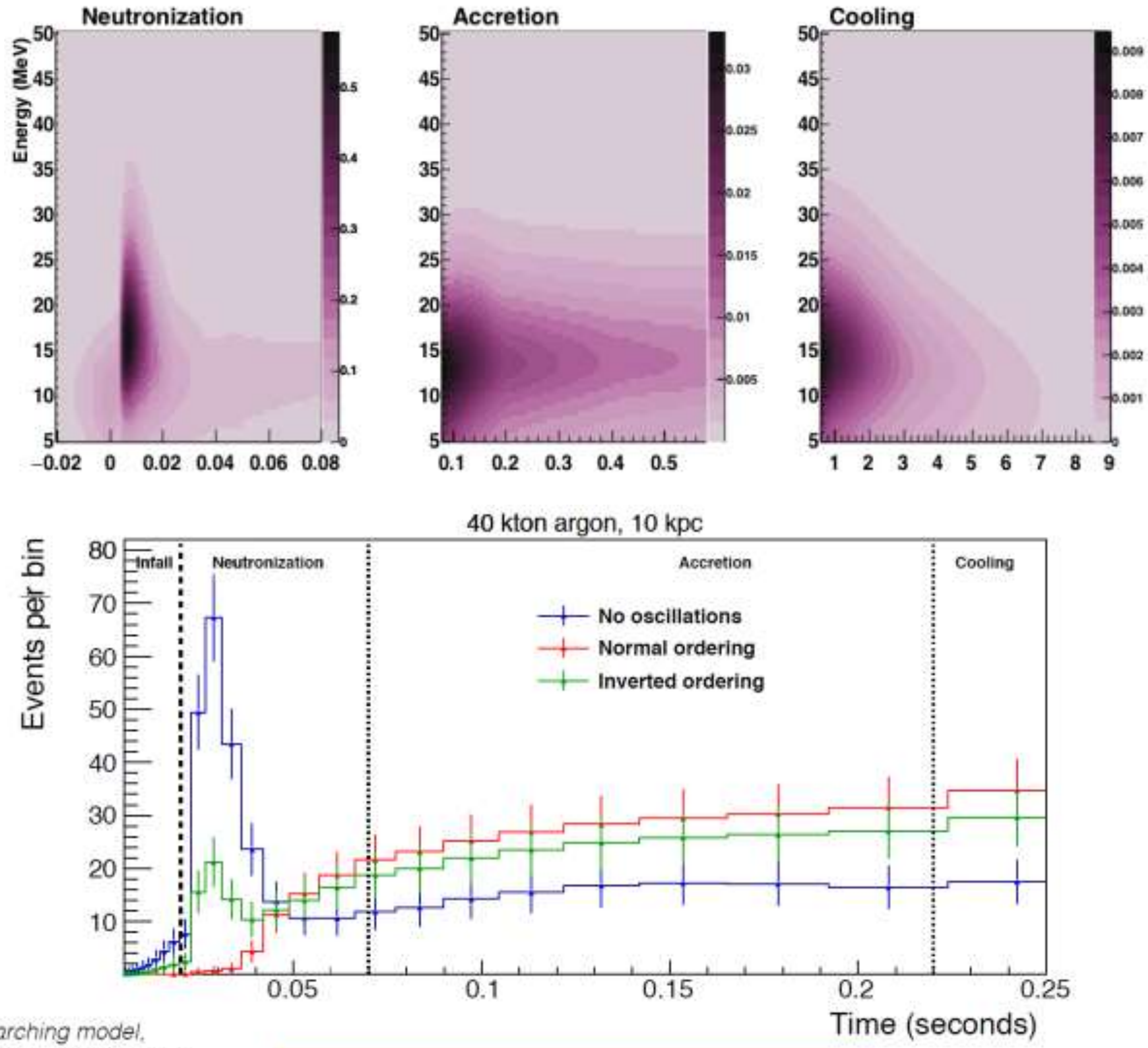


Argon scintillation light (~ns) detected by photon detectors, providing *t₀*

Supernova and solar neutrinos in DUNE

Supernova neutrinos in DUNE

- DUNE will be able to observe the ν_e flux through capture on ^{40}Ar
- Unique sensitivity to the electron flavour component of the flux
- Provides information on time, energy and flavour structure

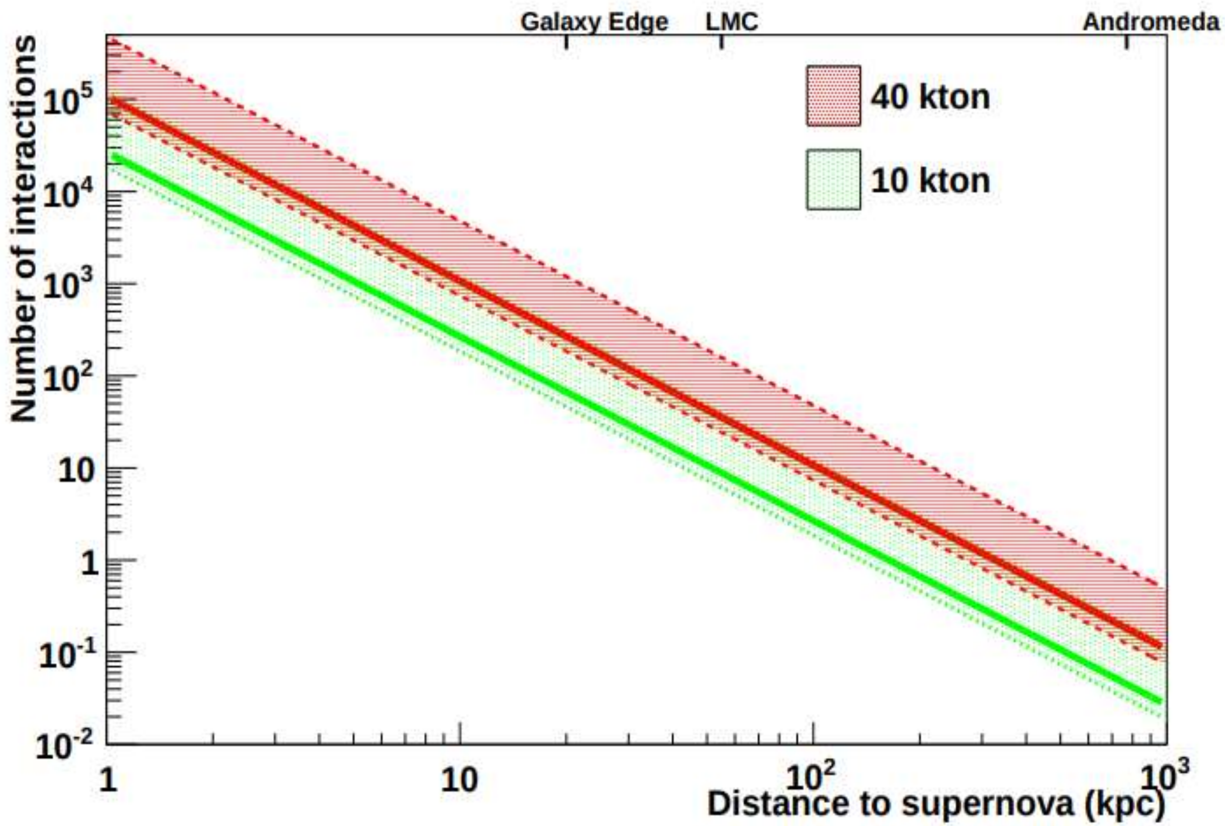


Garching model, MSW transitions only, total events (mostly ν_e)

Robust mass ordering signature

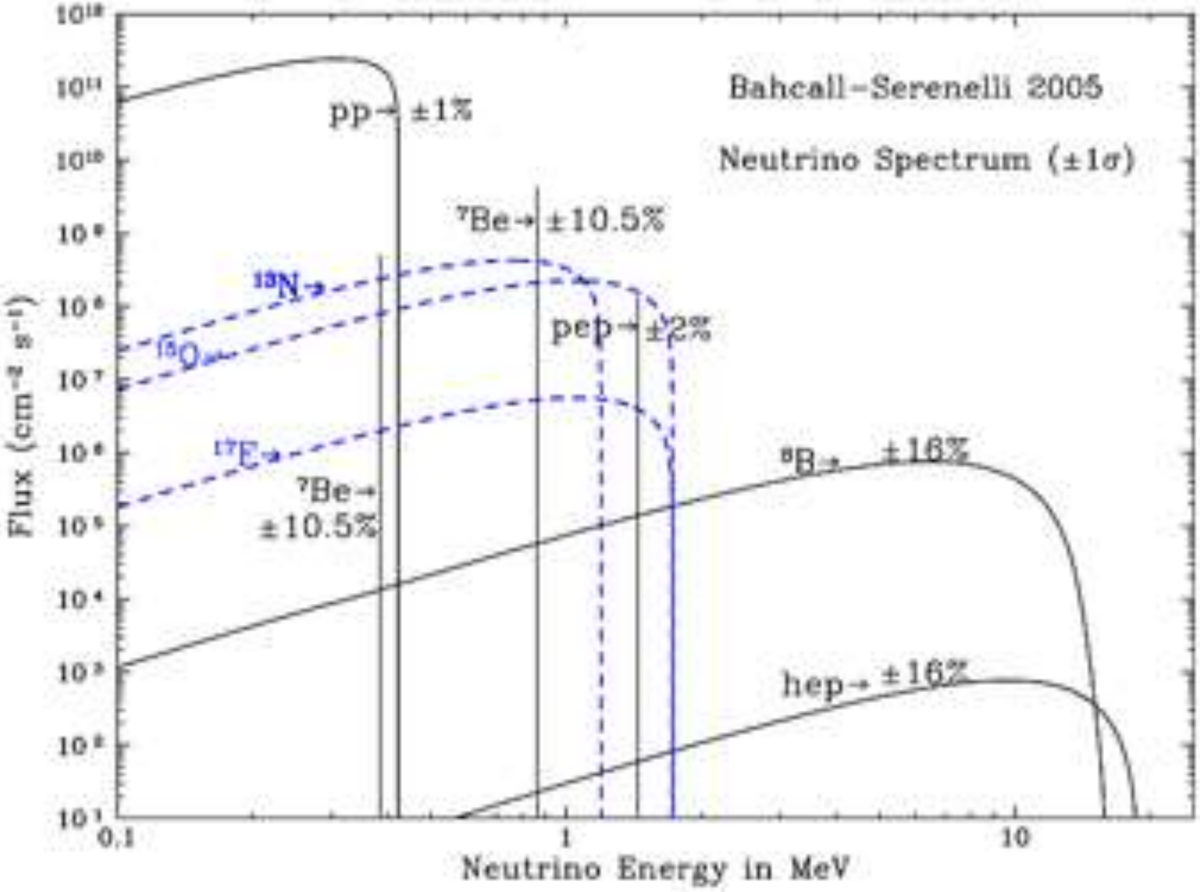
Supernova neutrinos in DUNE

- Requires an efficient non-beam trigger: neutrons could mimic a signal
- DAQ goal for galaxy: trigger on 60 electron neutrinos (of at least 10 MeV) in 10 s (assuming a flat time distribution)
- Rates depend on core collapse model, ν oscillation models, and distance.



Channel	Events "Livermore" model	Events "GKVM" model
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	2720	3350
$\overline{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	230	160
$\nu_x + e^- \rightarrow \nu_x + e^-$	350	260
Total	3300	3770

Solar neutrinos



DUNE has the potential to record about 3,000 solar neutrinos/ktonne-year

Physics objectives

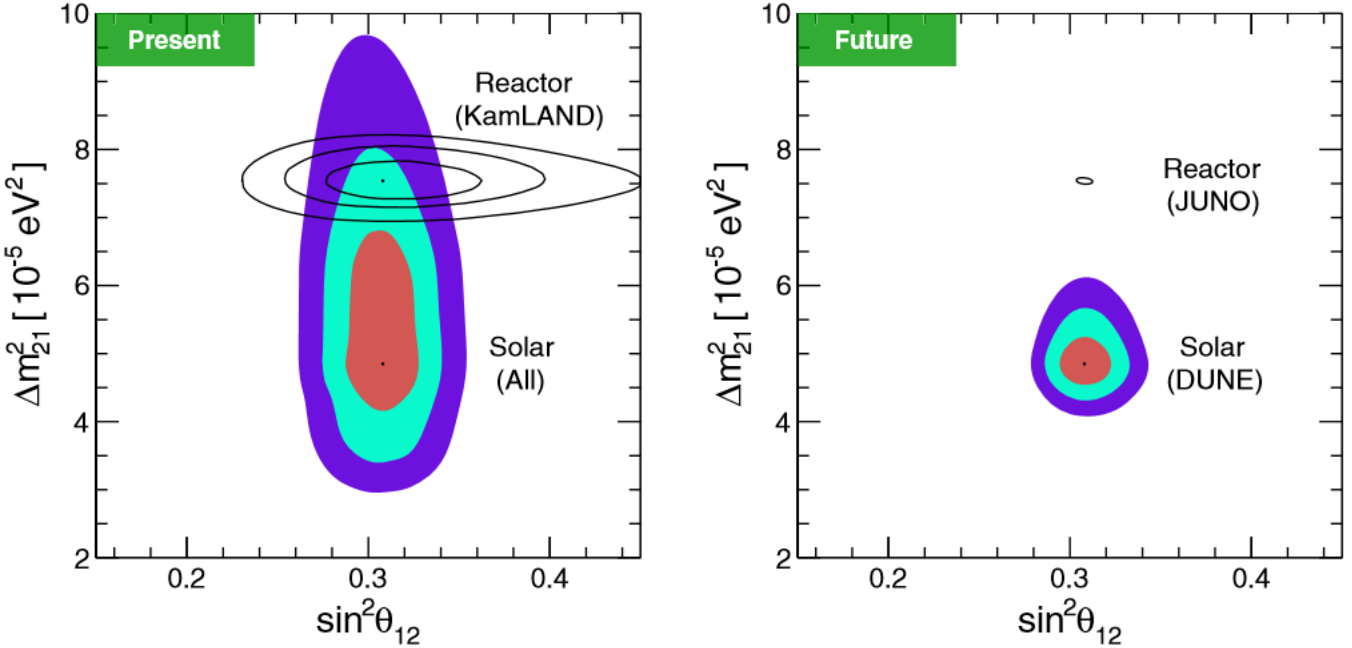
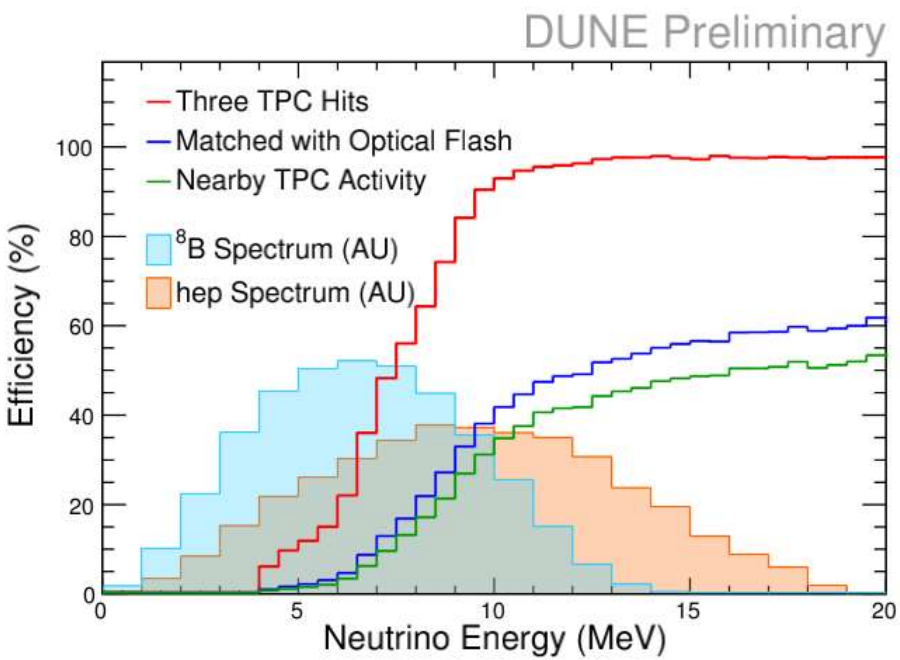


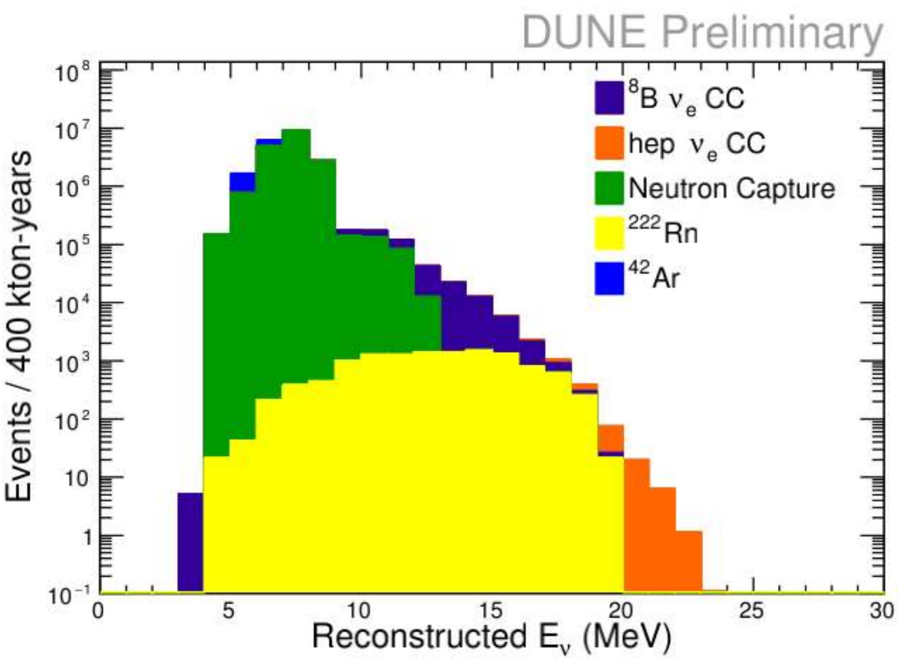
FIG. 1. Present measurements (1, 2, and 3σ) of neutrino mixing with solar [1–6] and reactor [15] neutrinos.

FIG. 2. Future precision of neutrino mixing with solar (DUNE alone; 1, 2, and 3σ) and reactor (JUNO alone; 3σ [18,22]) neutrinos, using present best-fit points and 100 kton-yr for each.

PhysRevLett.123.131803

Solar neutrino observation

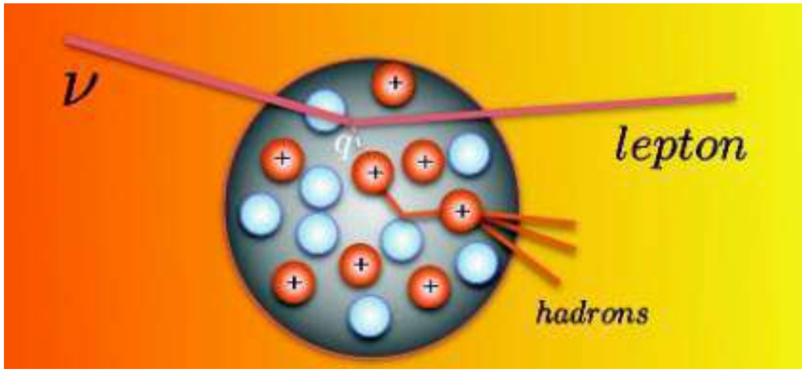




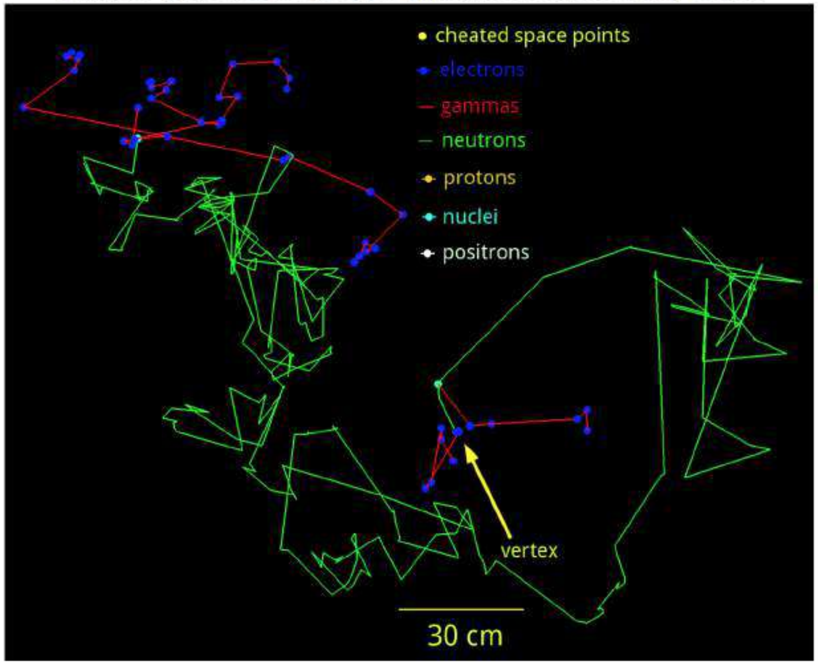
Needs a good understanding of the detector and neutrons.

Importance of neutrons in DUNE

- To turn neutrino physics into a precision science, we need to understand the complex neutrino nucleus interactions
  - Neutrons carry away a large fraction of energy
  - Neutron yield is model dependent
  - Neutrons are hard to detect in LArTPC
- Understanding the neutrons are also essential for low energy physics
  - Modelling the supernova and solar neutrino events



Particle trajectories from a simulated SN event in DUNE



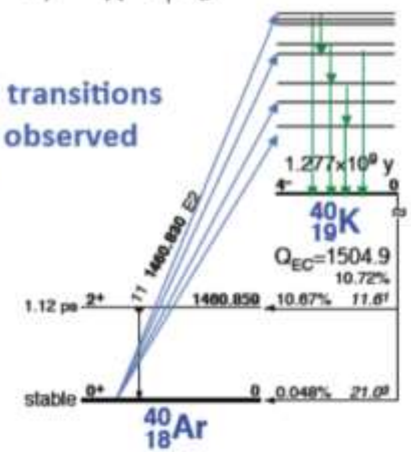
Importance of neutrons in DUNE

Charged-current absorption:

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

At least 25 transitions have been observed indirectly

(g.s. to g.s. is 3rd forbidden transition)



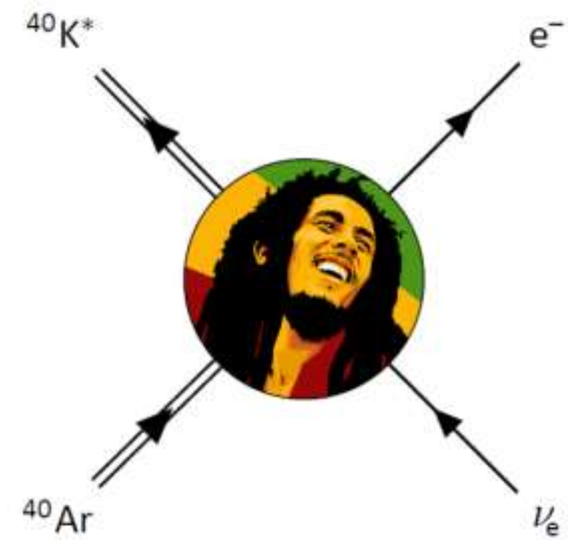
Low-energy event

BR(%)	Event Type	Average Fraction of Final-State KE e⁻	γ	n	p
82.5%	e^- + γs only	75.6%	24.4%	0%	0%
15.9%	single n	67.3%	16.2%	16.0%	0%
1.4%	single p	54.0%	14.1%	0%	31.0%
0.2%	other	44.7%	14.1%	1.5%	2.6%
100%	all events	73.9%	22.9%	2.5%	0.4%

Courtesy S. Gardiner

Marley event generator

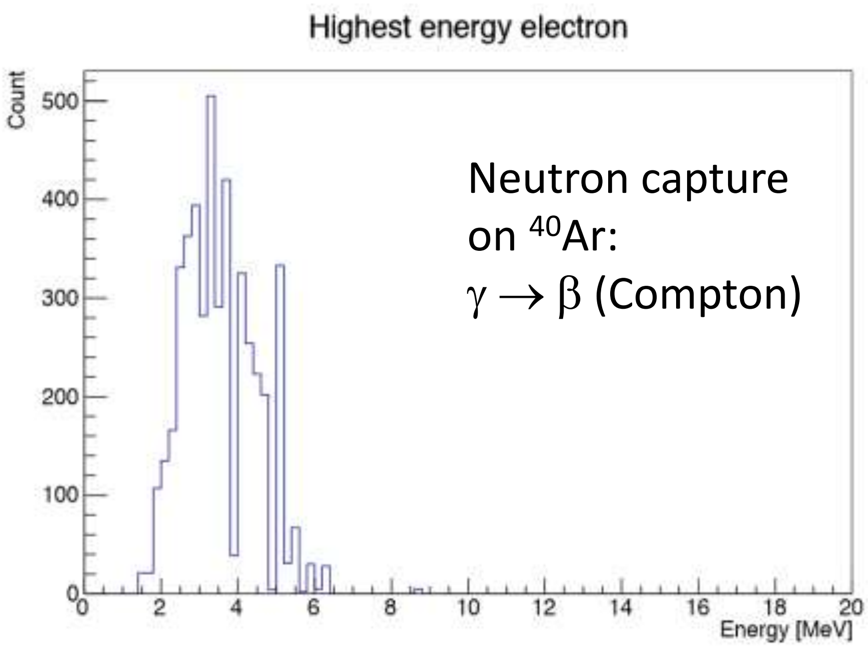
Model of Argon Reaction Low-Energy Yields

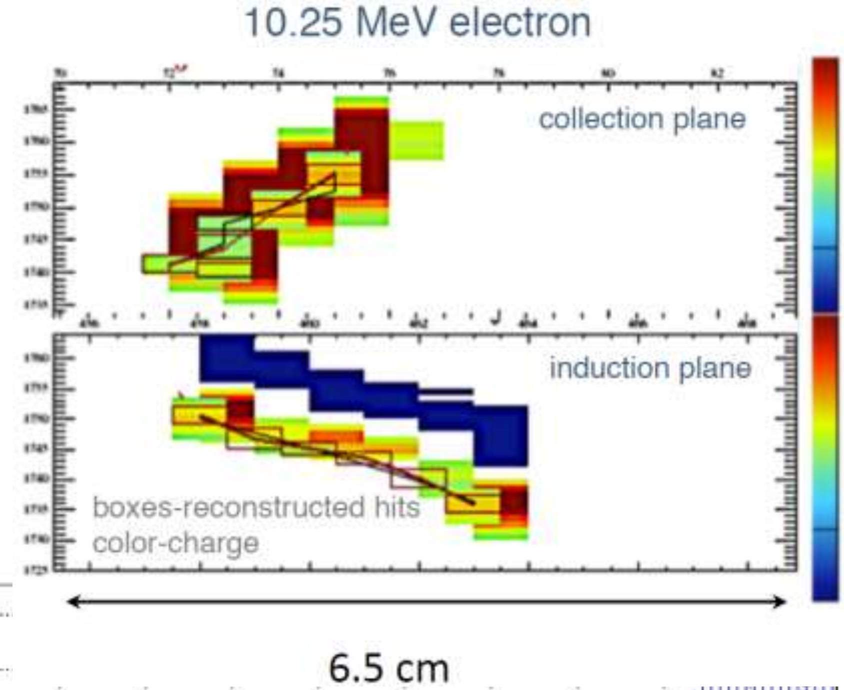


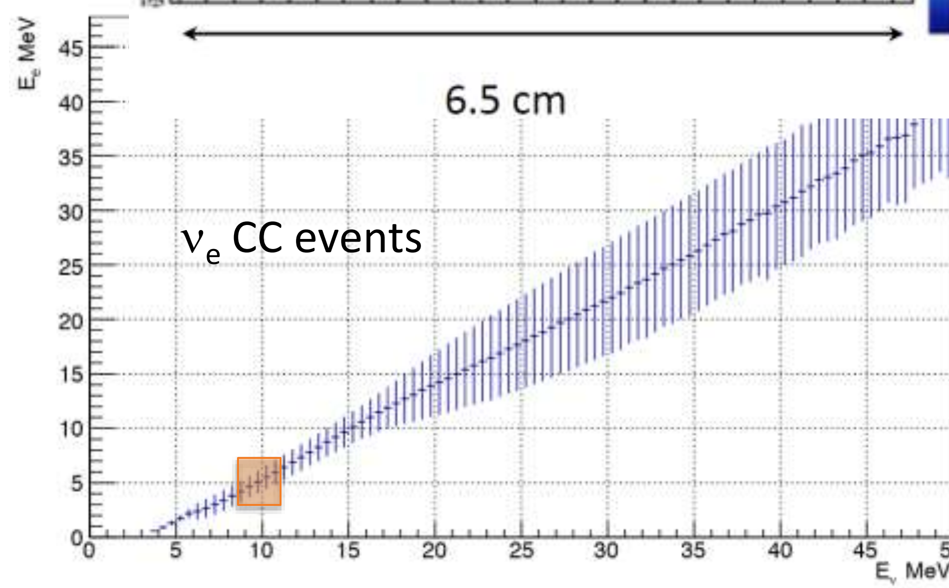
https://www.marleygen.org

gardiner@fnal.gov

Low energy events







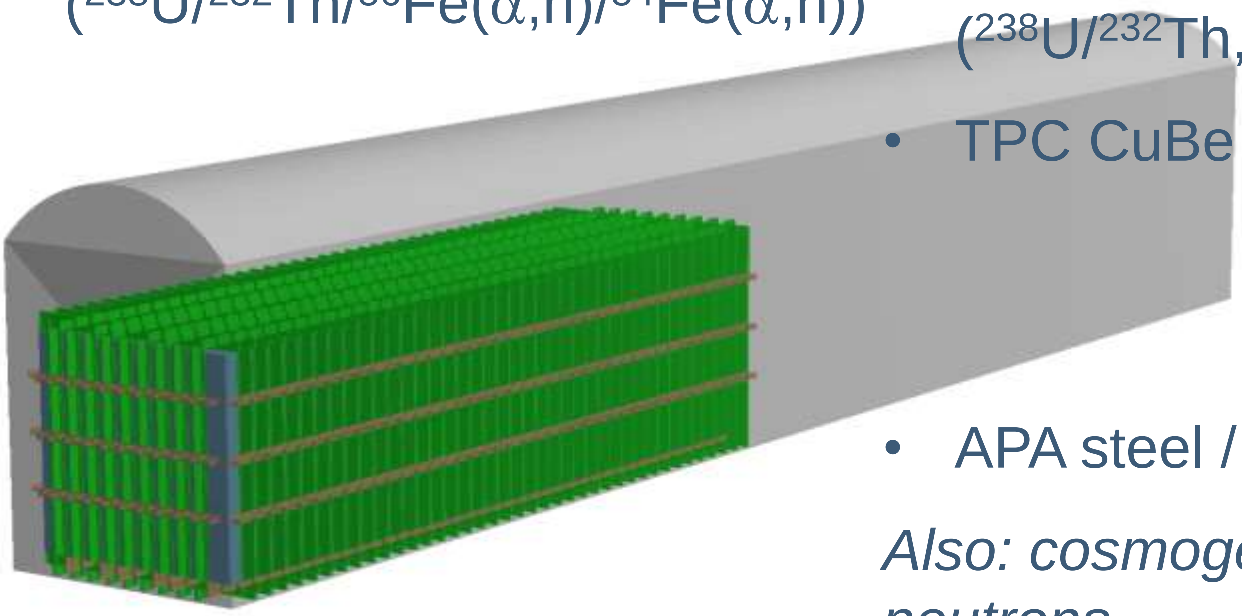
Neutrons need to be distinguished from neutrinos events for supernova neutrinos(online)
Neutrons need to be distinguished from neutrino events for solar neutrinos (offline)

Sources of neutrons in DUNE

Overview

Dominant (large mass):

- Rock ($^{238}U/^{232}Th$)
- Shotcrete ($^{238}U/^{232}Th$)
- Support structure (1.5 ktonne) ($^{238}U/^{232}Th/^{56}Fe(\alpha,n)/^{54}Fe(\alpha,n)$)

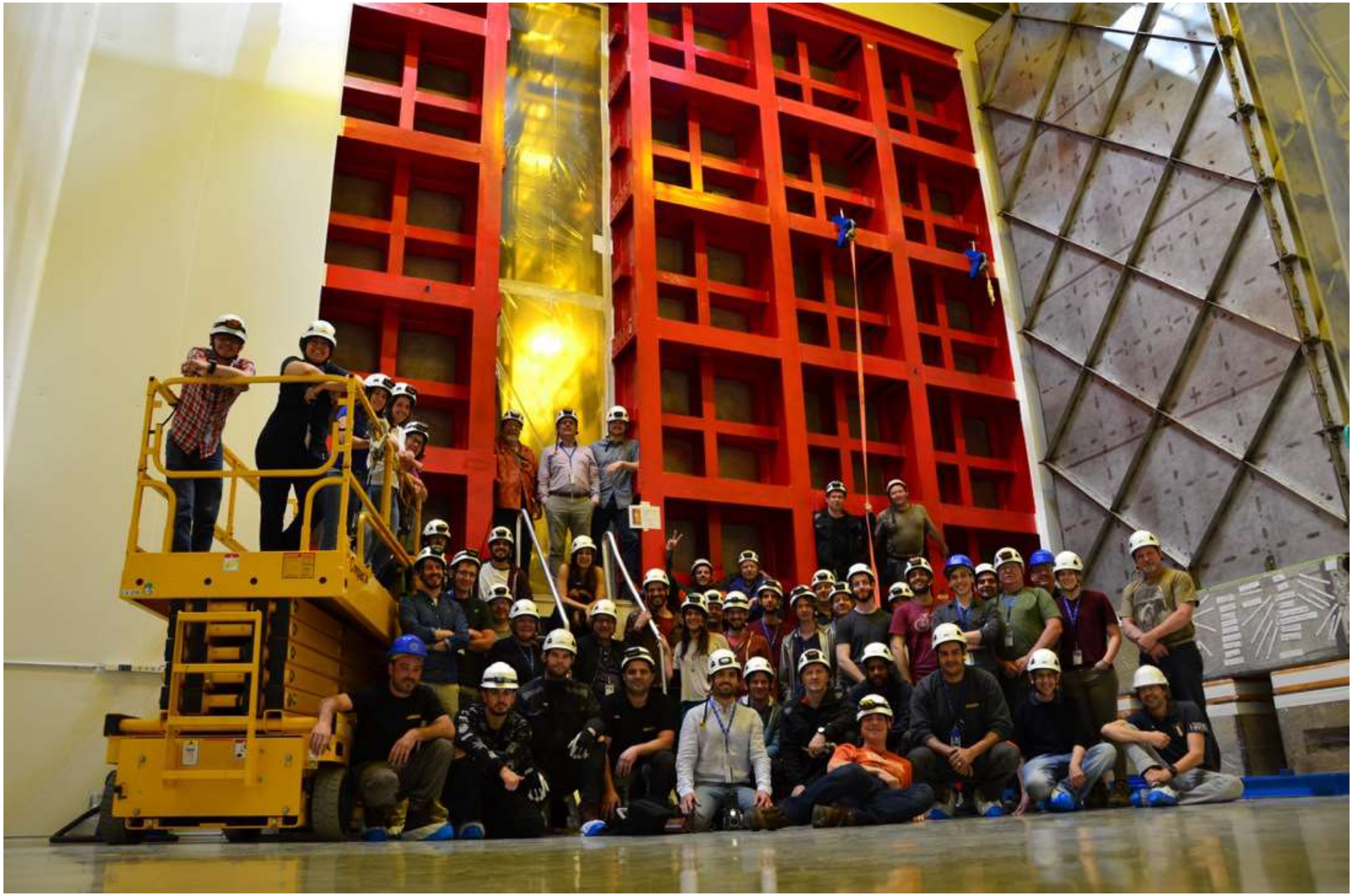


Subdominant (low mass/activity):

- ^{222}Rn in LAr: source of αs: $^{40}Ar(\alpha,n)$
- Insulation (glass fibre) ($^{238}U/^{232}Th$)
- Cryostat steel ($^{238}U/^{232}Th, ^{56}Fe(\alpha,n)/^{54}Fe(\alpha,n)$)
- TPC CuBe wires $Be(\alpha,n)$
- APA steel / materials ($^{238}U/^{232}Th$)

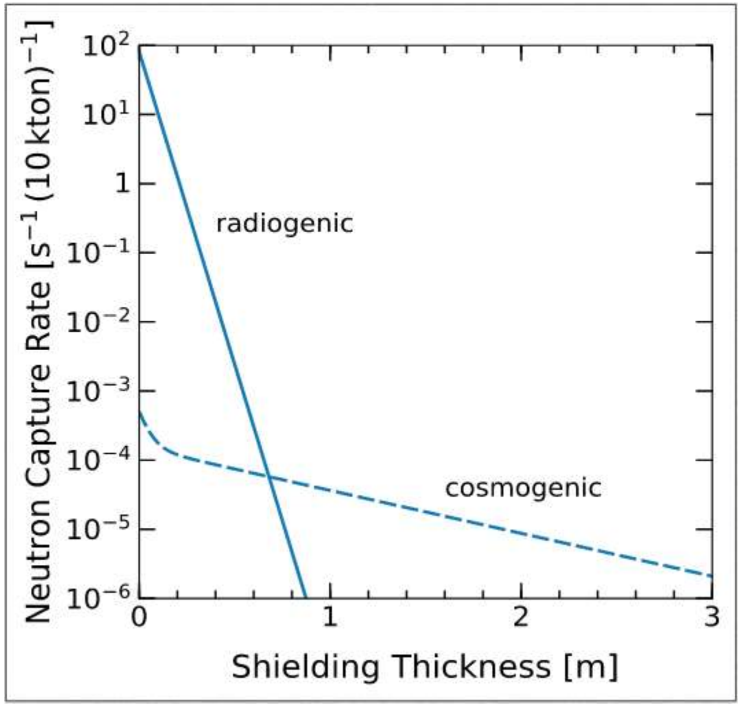
Also: cosmogenically generated neutrons

Support structure



Background mitigation

- Rock & shotcrete:
  considering shielding
  (water or plastics)
- Steel support structure:
  quality control
- Internal material:
  background screening,
  minimise exposure to mine air,
  maximise air from surface
- Internal radioactivity (LAr):
  background screening and
  quality control of
  filter materials

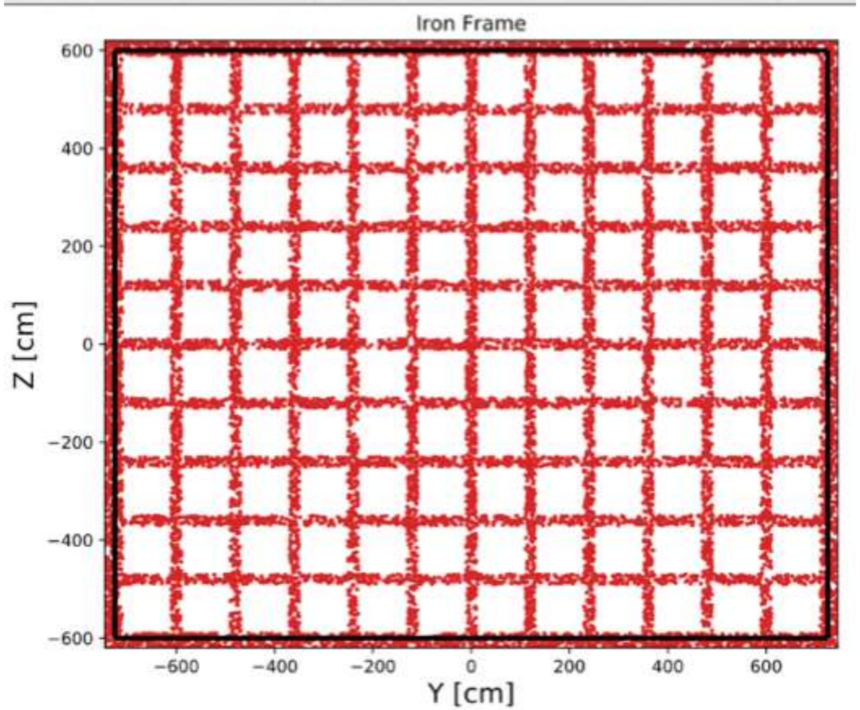


Possible effect of screening:
Arxiv:1808.08232

Screening in 'waffle structure'

(expensive and poses many challenges)

John Beacom



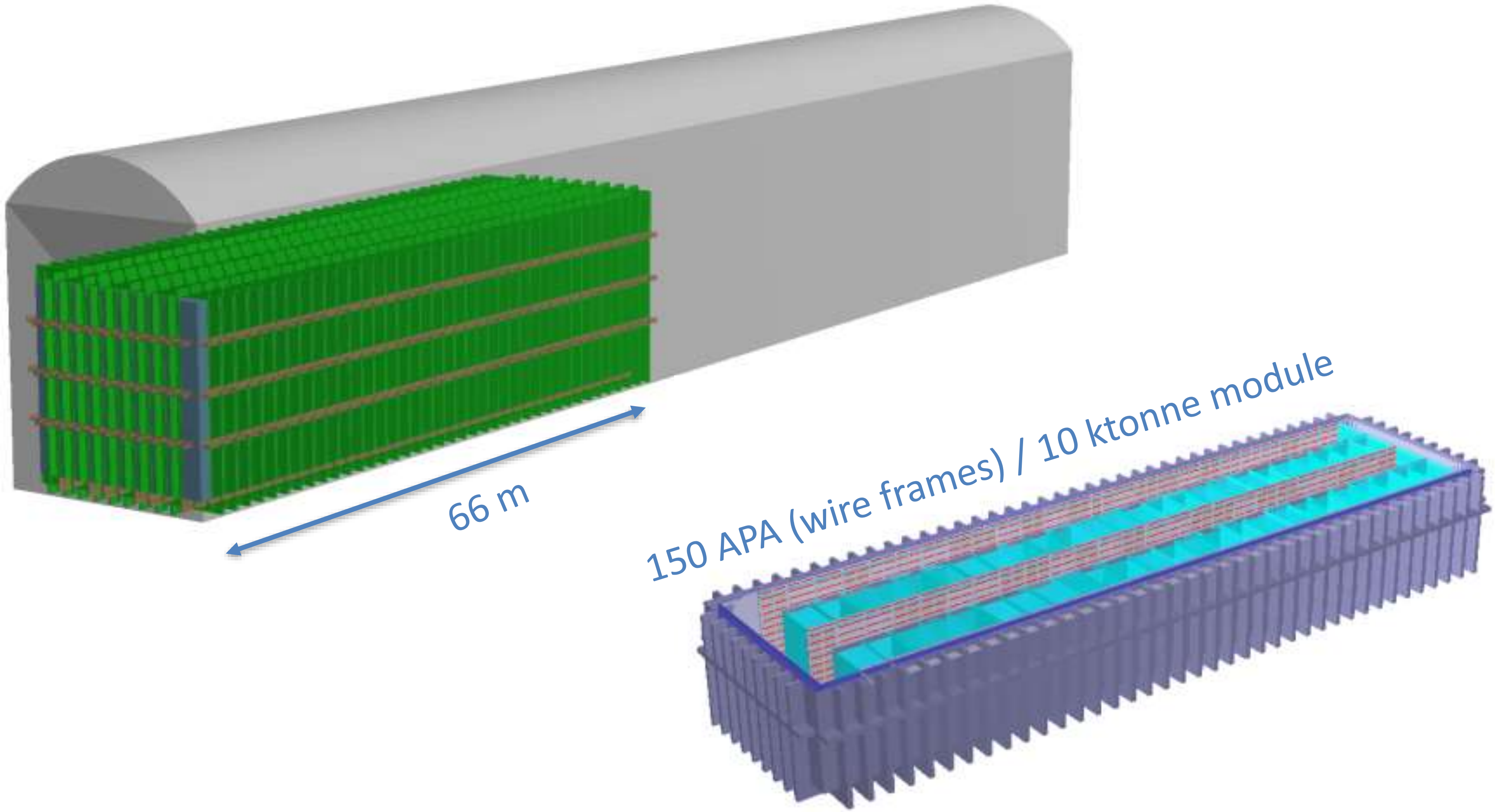
Depth [cm]	Water Shielding [Hz]	Waffle Shielding [Hz]
0	81	
10	7	9.4
20	0.7	2.6
30	0.1	0.9
40	0.02	0.4

But, do neutrons *really* move deep into the volume?

…and how well do we understand the capture final states?

Simulation is computing intense!

(but the challenge has been taken up enthusiastically!)



neutrons

in

liquid argon

Neutron capture cascade

ENDF Data Base
(CapGam)

Target Nucleus=^{40}Ar
Strongest transition Eγ=167.30+-0.00 keV %Iγ=74.03+-0.00

Eγ (keV)	ΔEγ (keV)	Iγ/Iγ(max) (%)	Δ(Iγ/Iγ(max))
167.30	0.20		
348.70	0.30		
516.00	0.30		
837.70	0.30		
867.30	0.60		
1044.30	0.40		
1186.80	0.30		
1354.00	0.40		
1828.80	1.20		
1881.50	1.00		
1972.70	1.20		
2130.80	0.80		
2229.50	2.00		
2291.70	2.00		
2432.50	0.80	1.05	0.00
2566.10	0.80	3.51	0.00
2614.40	0.80	3.65	0.00
2668.20	2.00	0.63	0.00
2668.20	2.00	0.63	0.00
2771.90	0.80	10.81	0.00
2781.80	1.50	2.13	0.00
2810.60	0.80	7.42	0.00
2842.60	1.00	1.11	0.00
3089.50	1.00	1.38	0.00
3111.40	2.20	0.50	0.00
3111.40	2.20	0.50	0.00
3150.30	1.00	5.02	0.00
3365.60	1.00	5.28	0.00
3405.50	2.50	0.09	0.00
3405.50	2.50	0.09	0.00
3452.00	1.00	2.51	0.00
3564.70	2.50	0.16	0.00
3564.70	2.50	0.16	0.00
3658.70	1.80	0.31	0.00
3700.60	0.80	12.31	0.00

Let M_{ij} be a matrix whose elements are all 0 and 1 in order to indicate if a certain gamma of energy E_i is a member of cascade j. For example, if cascade $j = 3$ were composed of gammas $1, 2, 5$ then $M_{13} = 1$, $M_{23} = 1$, $M_{33} = 0$, $M_{43} = 0$, $M_{53} = 1$, ... with all the rest of the elements in the row being 0.

Clearly, every cascade must add up to the Q value, so:

$$Q = \sum_{i=1}^{n} M_{ij} E_i \qquad (2)$$

also, the line intensities are given by summing over all the cascade schemes: $I_i = \sum_{j=1}^{m} \beta_j M_{ij}$

With this, you can show: $\sum_{j=1}^{m} \beta_j = \frac{1}{Q} \cdot \sum_{i=1}^{n} I_i E_i$ = 1

Ignoring repeated lines, CapGam gives 0.912: off by about 9%!?

Neutron capture in LAr

n + ^{40}Ar $\rightarrow$ ^{41}Ar* : dominant
n + ^{36}Ar $\rightarrow$ ^{37}Ar*

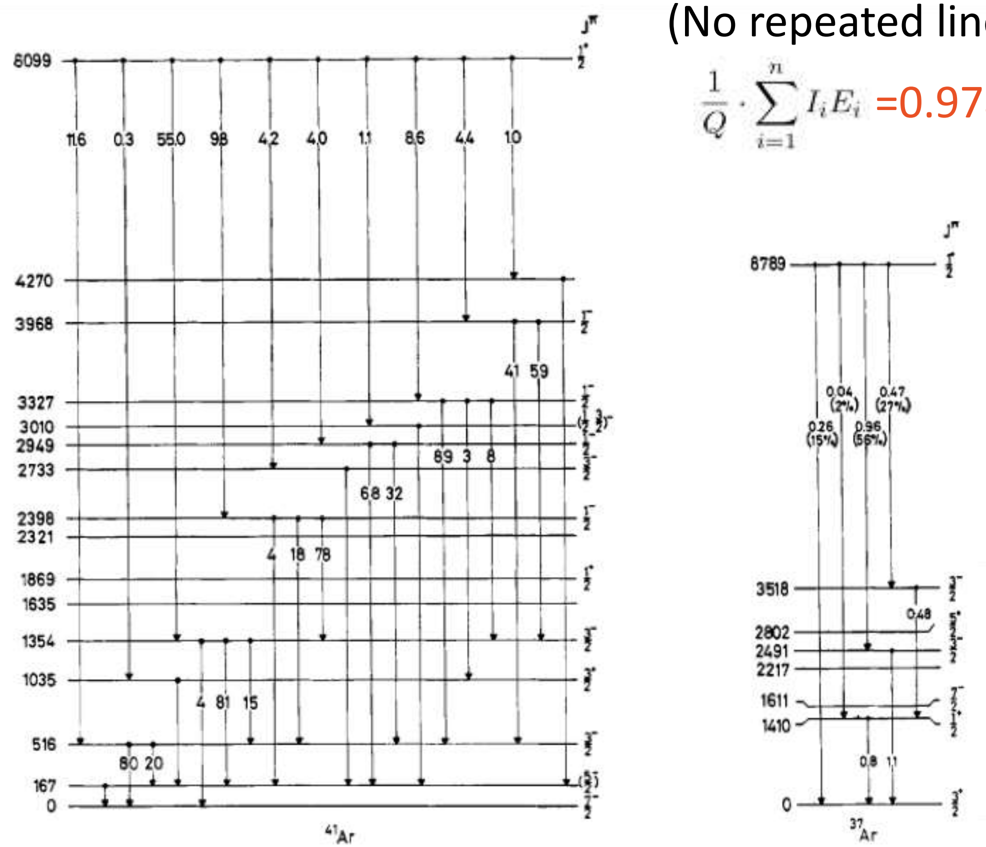
Radiative neutron capture on Argon results in an excited atom of the next heaviest argon isotope.

The excited argon isotopes de-excite with very specific total energy:
6.1 MeV for ^{41}Ar,
8.8 MeV for ^{37}Ar.

This energy is carried away by at least one photon on the case of ^{37}Ar and at least two photons in the case of ^{41}Ar.

(No repeated lines)

$$\frac{1}{Q}\cdot\sum_{i=1}^{n} I_i E_i = 0.978$$



Hardell, R. and Beer, C., 1970. Thermal Neutron Capture in Natural Argon. *Physica Scripta*, *1*(2-3), p.85.

Neutron capture in LAr

Three measurements from 1960's
All claiming ~5% uncertainty, but differing by about 50%

..also averaged over a thermal spectrum from a reactor rather than as a function of energy

kT = (8.617x10^{-11} MeV/K)(293 K) =2.53x10^{-8} MeV
(for DUNE this would be 0.75x10^{-8} MeV)

$E_{neutron}$ MeV	$\sigma(n,\gamma)$ barns	uncertainty barns	Year	Author
2.53E-08	**0.51**	**0.025**	**1969**	**N.RANAKUMAR+**
2.53E-08	**0.723**	**0.025**	**1965**	**R.L.D.FRENCH+**
2.53E-08	**0.63**	**0.02**	**1963**	**W.KOEHLER**
0.005	0.0032	0.00018	1989	R.L.Macklin+
0.01751	0.01702	0.02442	1989	R.L.Macklin+
0.136	0.0022	0.0008	1959	N.A.BOSTROM+
0.37	0.00119	6.00E-05	2014	M.Bhike+
0.03	0.00254	0.0001	2000	Z.Y.Bao+
0.03	0.00245	0	2006	S.F.Mughabghab
0.0234	0.00255	0.00015	2002	H.Beer+

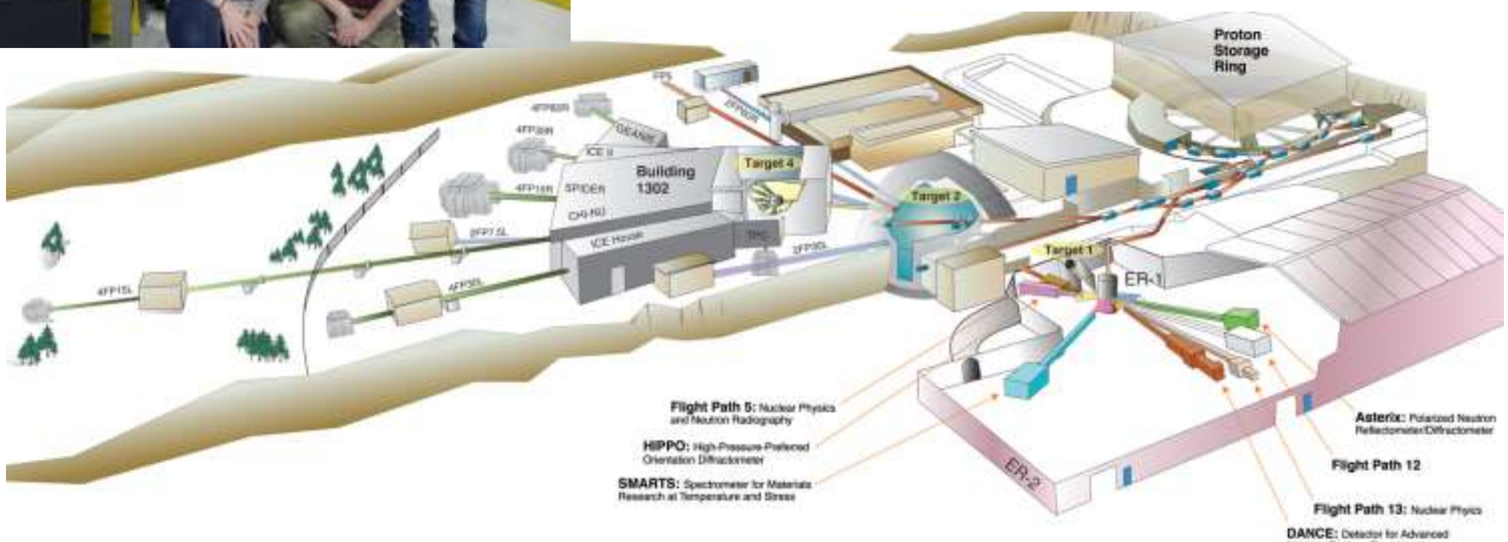
TABLE 1 PUBLISHED MEASUREMENTS OF THE NEUTRON CAPTURE CROSS SECTION ON ARGON. THERMAL MEASUREMENT ARE SHOWN IN BOLD

New measurement: ACED
Argon Capture Experiment at DANCE

V. Fischer,[1] L. Pagani,[1,*] L. Pickard,[1] A. Couture,[2] S. Gardiner,[1] C. Grant,[3] J. He,[1] T. Johnson,[1] E. Pantic,[1] C. Prokop,[2] R. Svoboda,[1] J. Ullmann,[2] and J. Wang[1]
(ACED Collaboration)

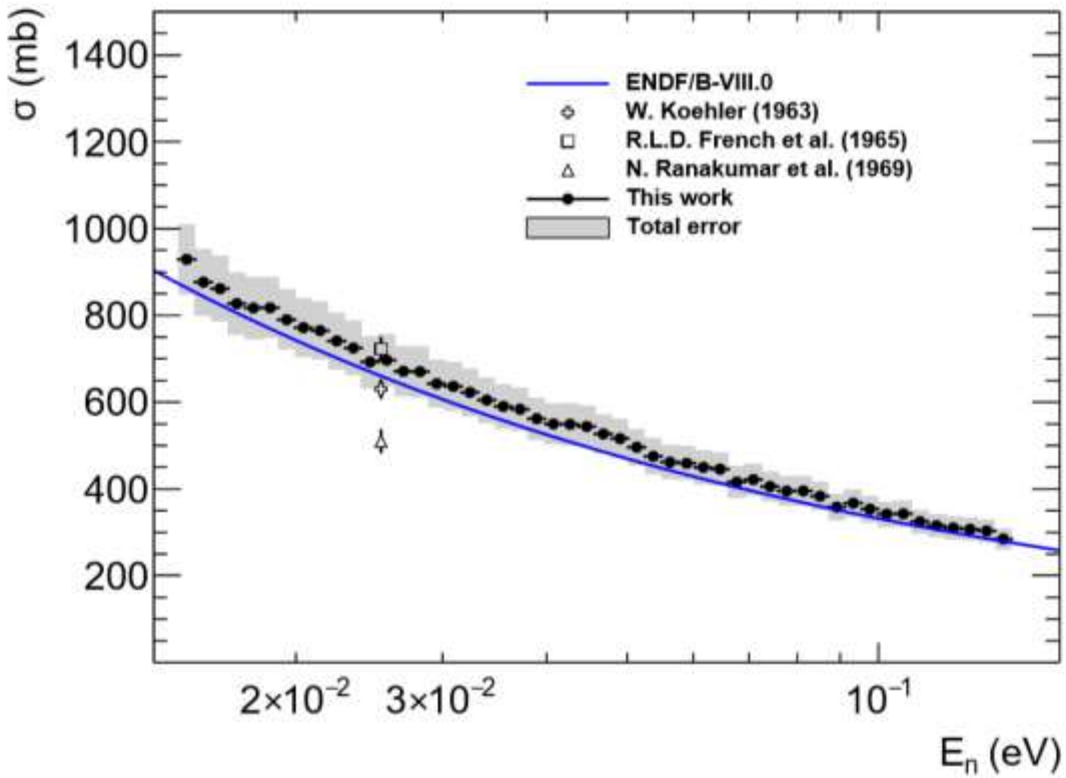
[1]*University of California at Davis, Department of Physics, Davis, CA 95616, U.S.A.*
[2]*Los Alamos National Laboratory, LANSCE, Los Alamos, NM 87545, U.S.A.*
[3]*Boston University, Department of Physics, Boston, MA 02215, U.S.A.*

DANCE is located on Time-Of-Flight beam at Los Alamos
TOF can discriminate energy from 0.01 eV to ~10^5 eV



ACED results

Error	Stat. (%)	Sys. (%)	
$\delta\rho/\rho$	0.0	0.3	density
$\delta L/L$	0.0	2.2	length
$\delta\varepsilon/\varepsilon$	0.3	0.9	efficiency
$\langle\delta G_i/G_i\rangle$	2.0	0.0	#captures
$\langle\delta N_i/N_i\rangle$	1.6	5.8	normalization



arXiv:1902.00596

σ^{2200} = 673 +/- 26 (stat.) +/- 59 (sys) mb

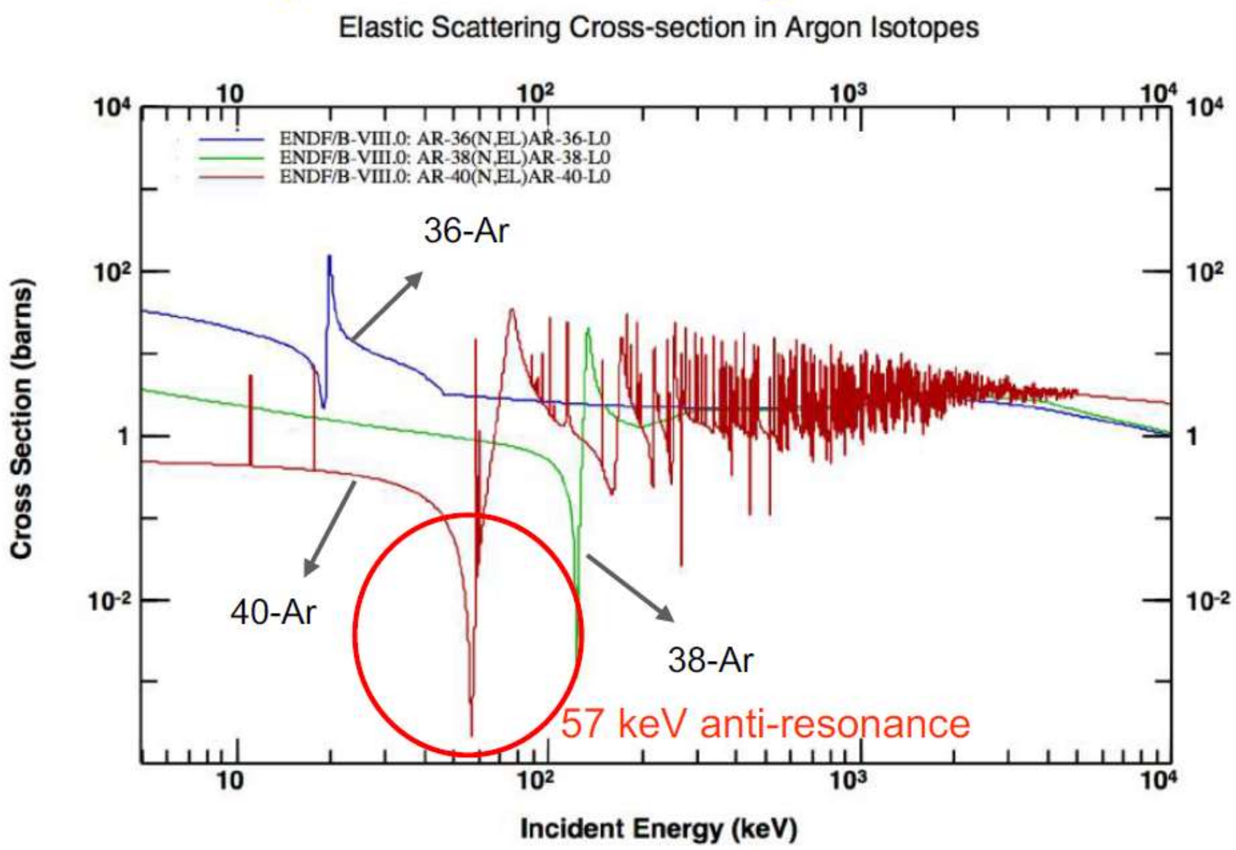
Neutron transport

Effective neutron mean free path could be ~30 m!
(ENDF: as currently in GEANT4)

40-Ar, 99.6035%
λ = 1.5 km @ 57 keV

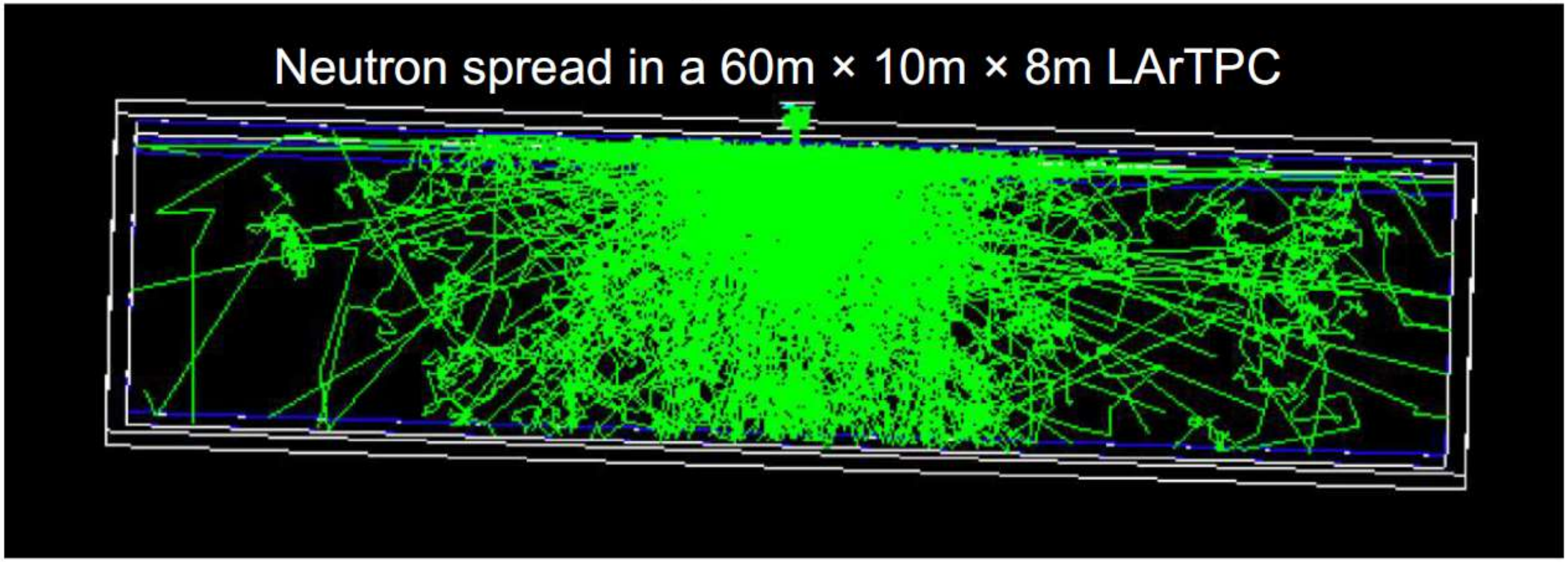
36-Ar, 0.3336%
λ = 16 cm @ 57 keV

38-Ar, 0.0634%
λ = 47 cm @ 57 keV



Well-placed neutron source…

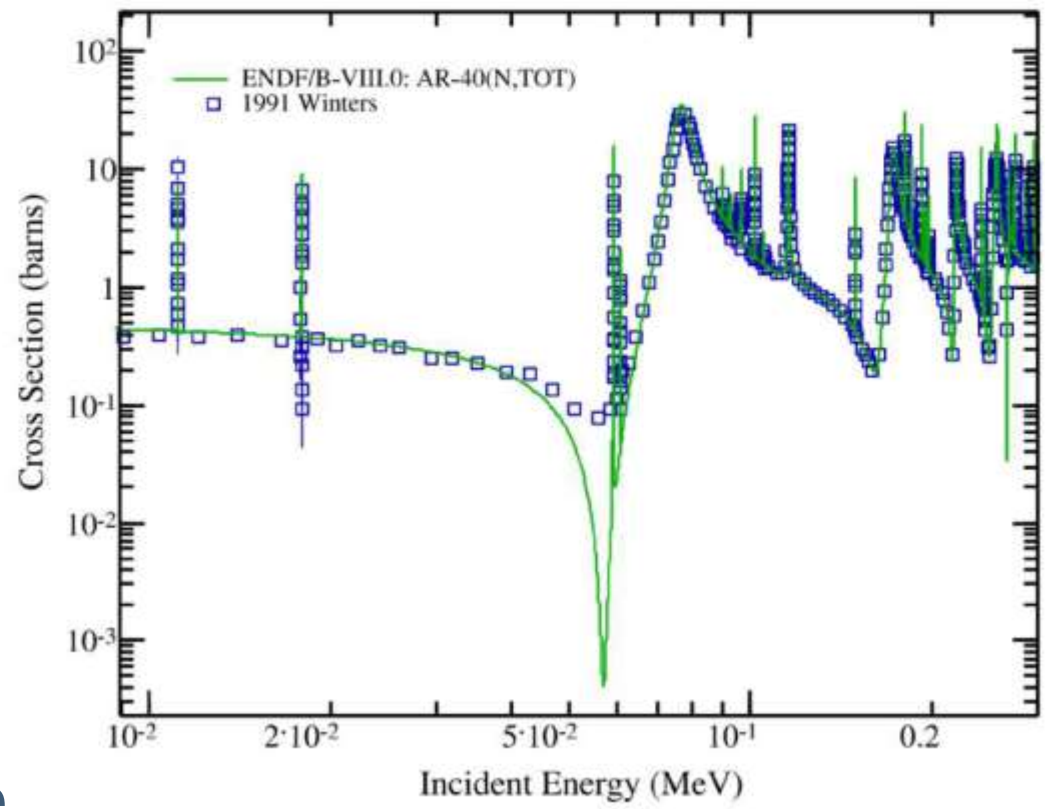
According to GEANT4…



…but is this correct??

Experimental data

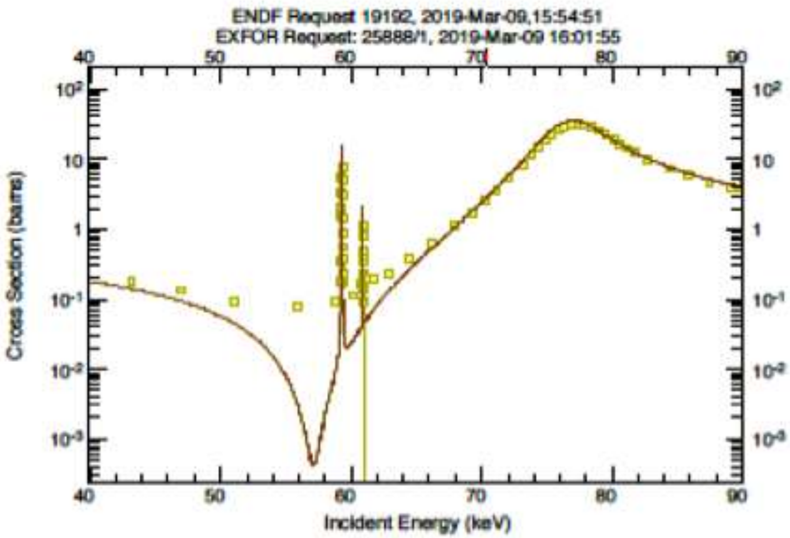
- At 57 keV, the theory predicts that there is a “deep” anti-resonance dip
- Previous measurement (Winters ‘91) doesn’t agree with the theory (a factor 100 difference)
- The sensitivity of previous measurement is limited
- Measurement needs to be done with high precision

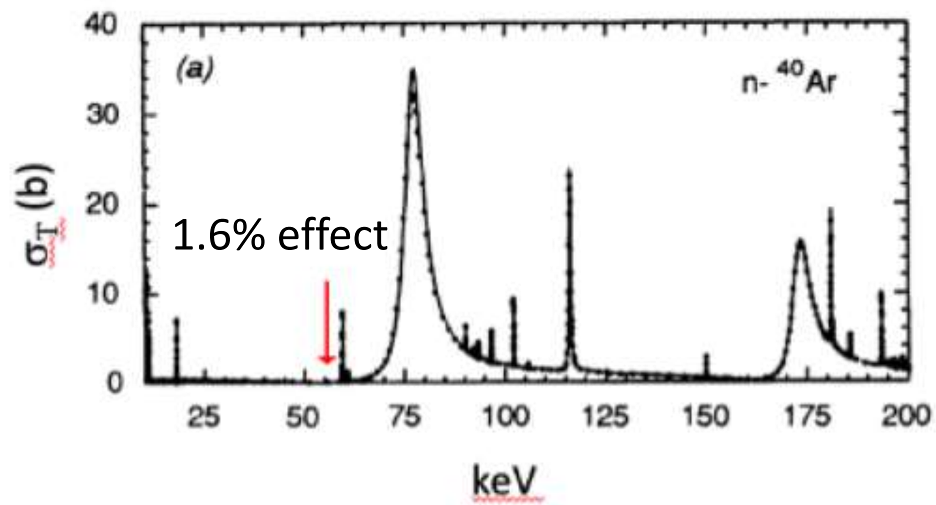


“Data”: λ = 60 cm @ 57 keV

ENDF/B-VIII.0: λ = 2 km @ 57 keV

Measurement precision



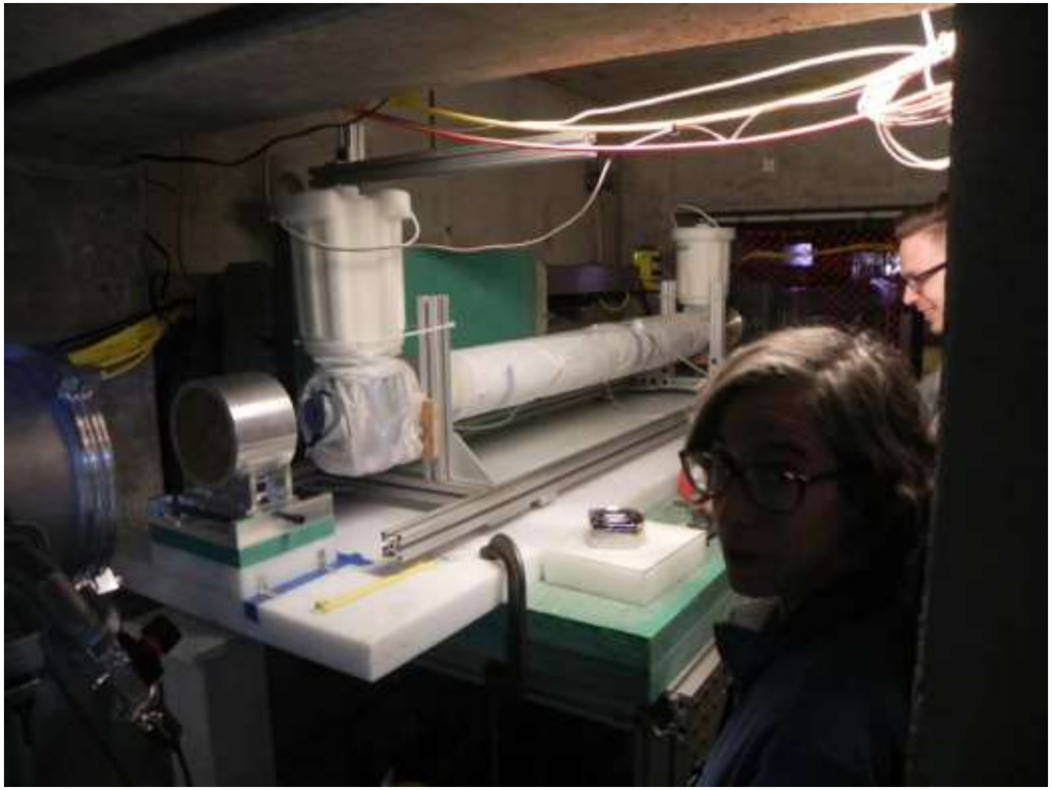


R.R. Winters, R.F. Carlton, C.H. Johnson, N.W. Hill, and M.R. Lacerna, Phys. Rev. C 43 492 (1991)

ARTIE

Argon Resonant Transport Interaction Experiment

Measurement of 57 keV neutron anti-resonance in ^{40}Ar at LANSCE (Los Alamos Neutron Science Center).



ARTIE

Argon Resonant Transport Interaction Experiment

October 8-20 beam run at LANL

- Beam off: understand constant-in-time backgrounds
- Beam on, shutter closed: understand the beam-related backgrounds (gammas, skyshine neutron)
- Liquid argon filled, beam on: sample-in neutron transmission counting
- Gaseous argon filled, beam on : sample-out neutron transmission counting
- Aluminium filter in, beam on: understand the background from scattering in the beam pipe
- Carbon target, beam on: reference material measurement

Result expected before the end of the year

Courtesy: Jing-Bo Wan/Bob Svoboda

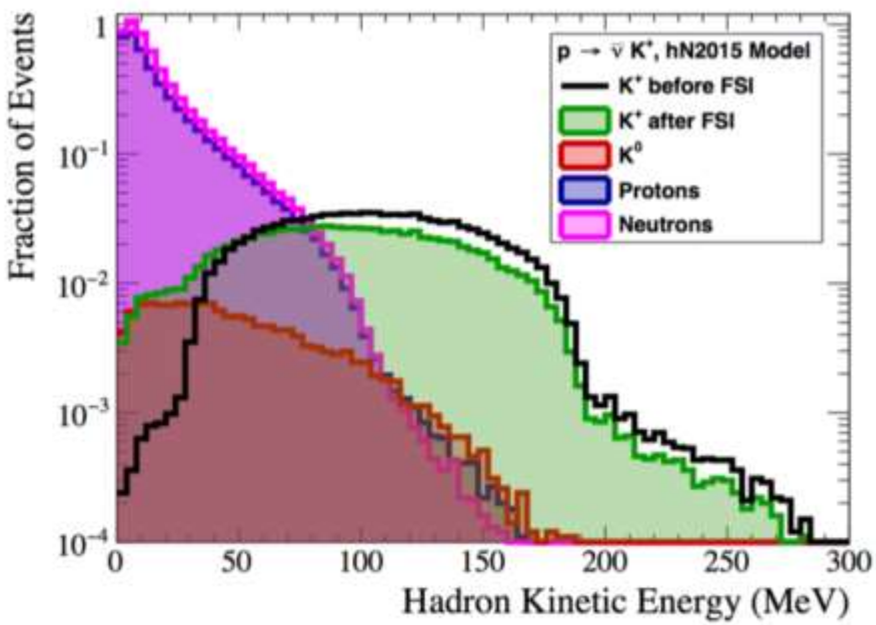
Summary

- DUNE is an exciting neutrino experiment that will provide loads of interesting physics in the next decade
- For low-energy physics, such as supernova and solar neutrinos, neutrons are an important background
- Care is being taken in the design and development of the DUNE detector module to minimise the neutron backgrounds
- Neutron interactions in Ar need to be understood in detail: we are improving our understanding

Backup slides

Nucleon decay

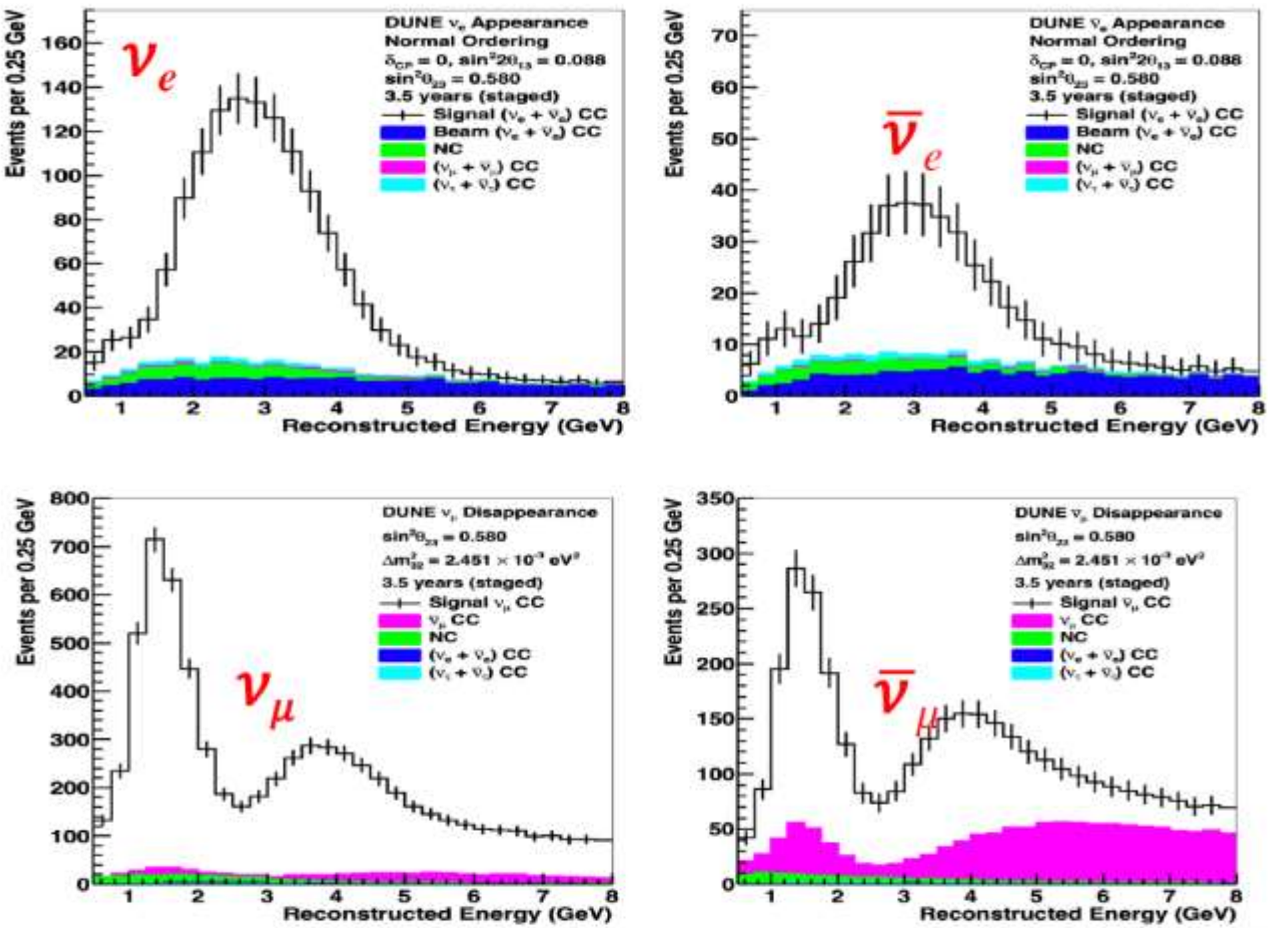
Neutrons also come in the FSI for nucleon decay



- Effects of FSI on K^+ are being updated for the TDR
- GENIE hN2015 intranuclear hadron transport model shown on the left has updated
- About 94% of the FS K^+ are above the expected threshold of 30 MeV

Courtesy: Bob Svoboda

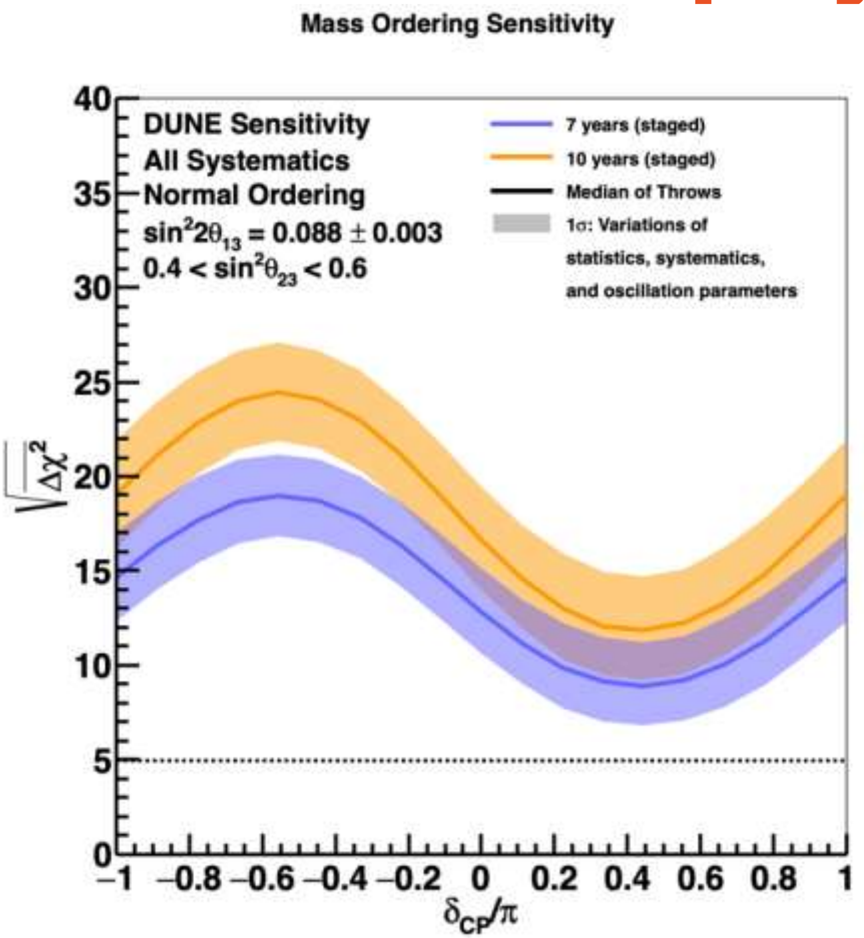
Oscillation physics

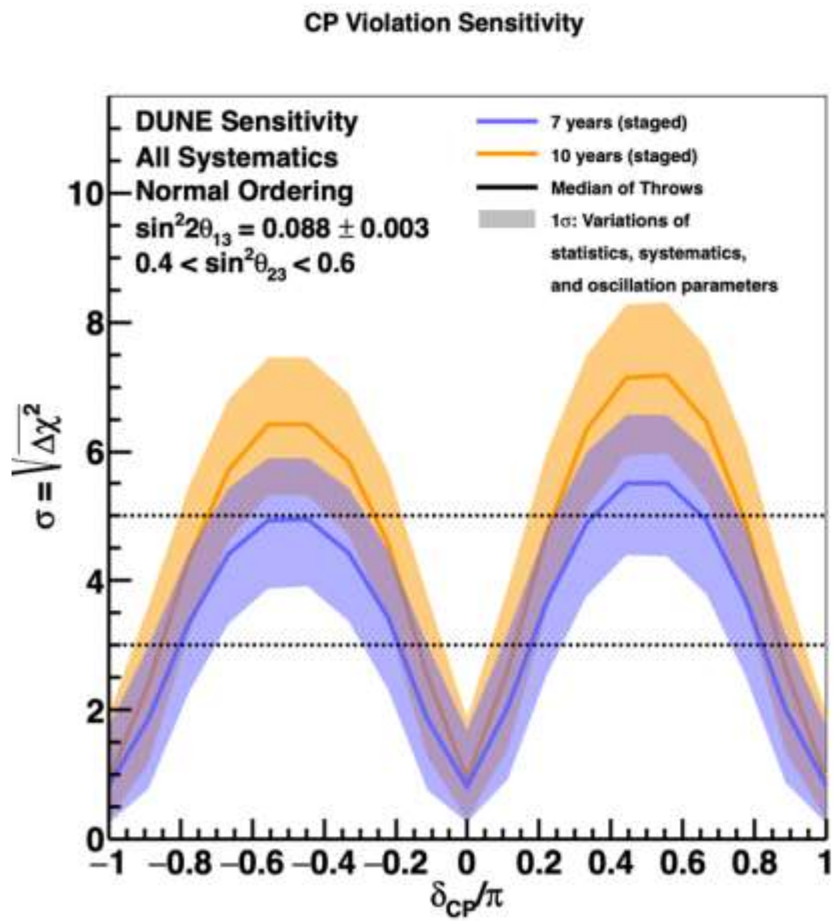


Appearance

Disappearance

Oscillation physics

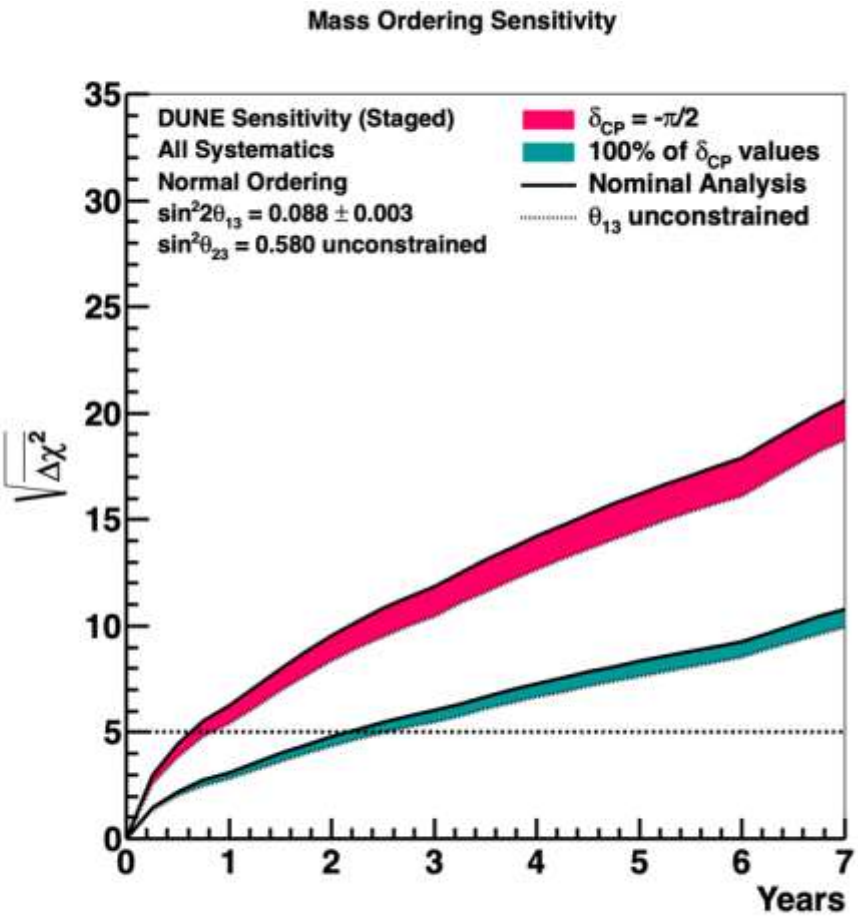


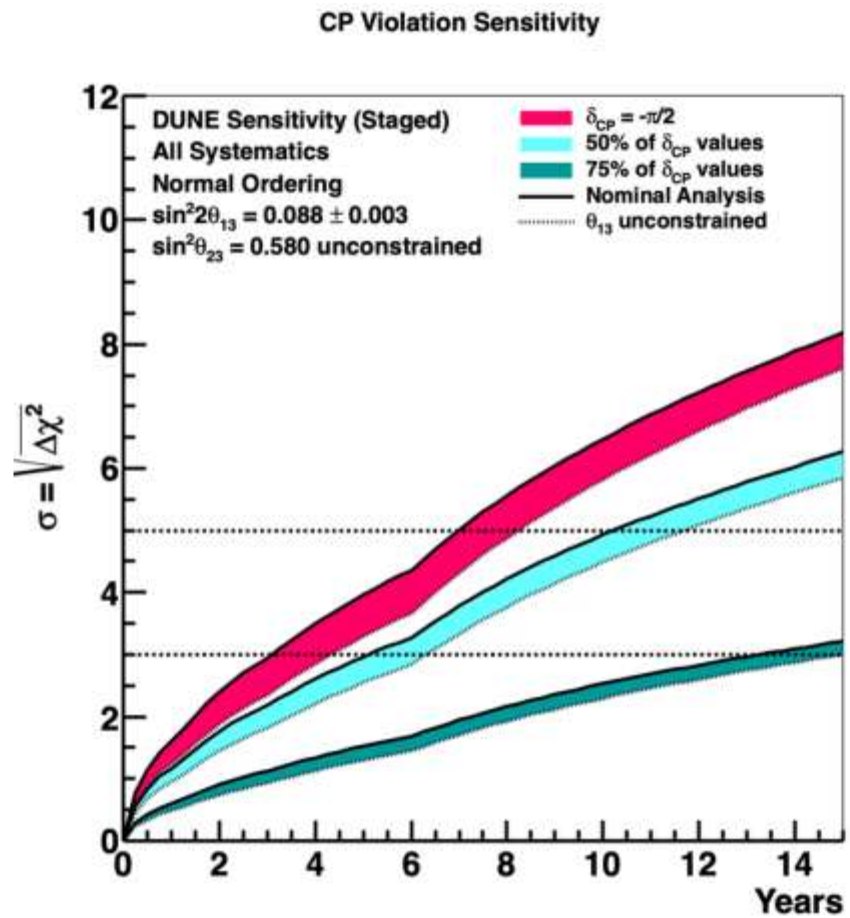


>5 σ mass ordering determination for all δ_{CP} values

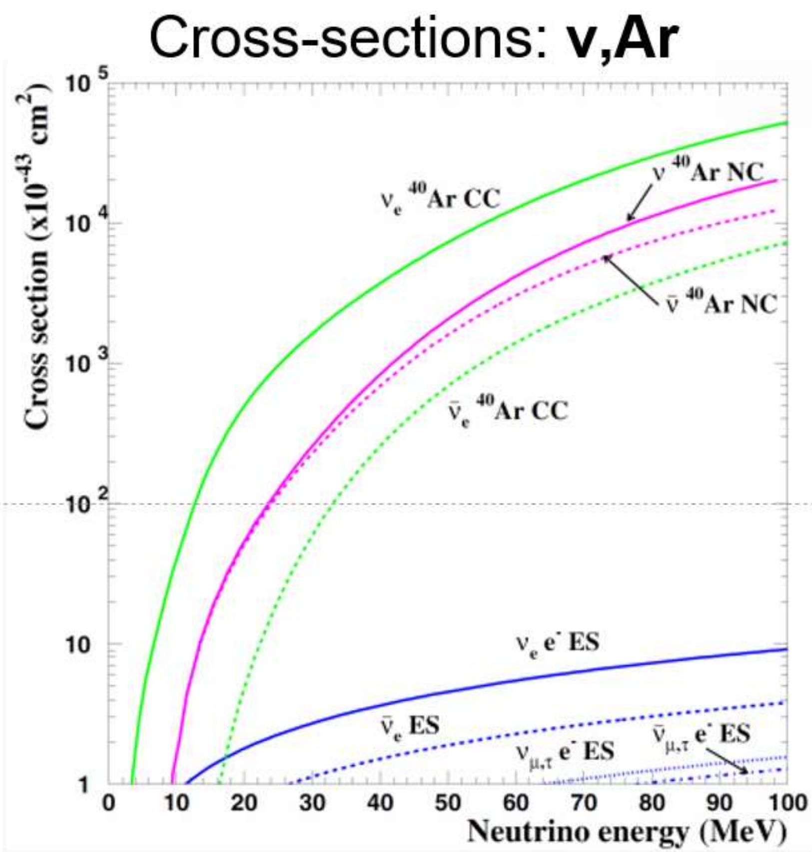
>5 σ CPV discovery over a wide range of δ_{CP} values

Oscillation physics





Neutrino cross sections on Ar



- Elastic scattering (ES) on electrons

$$\nu + e^- \rightarrow \nu + e^-$$

- Charged-current (CC) interactions on Ar

$$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$$ $E\nu_e > 4.0$ MeV

$$\bar{\nu}_e + {}^{40}Ar \rightarrow {}^{40}Cl^* + e^+$$ $E\bar{\nu}_e > 7.48$ MeV

- Neutral current (NC) interactions on Ar

$$\nu + {}^{40}Ar \rightarrow \nu + {}^{40}Ar^*$$ $E\nu > 1.46$ MeV