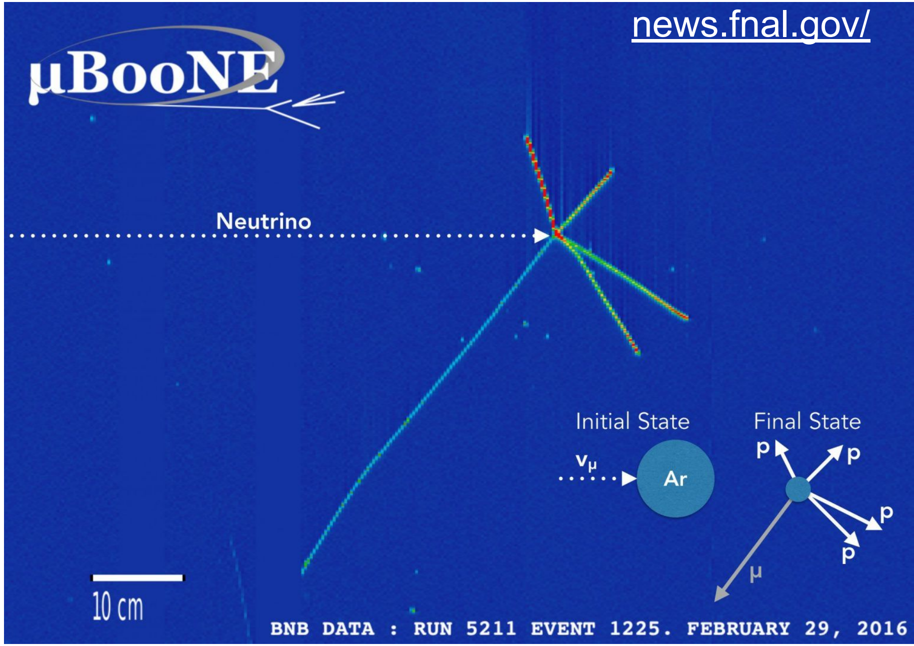
Neutrino interactions: *what, why, and how*



Kendall Mahn
Michigan State University

Snowmass colloquium series,

April 27th 2022

Support from U.S. Department of Energy, award DE-SC0015903

Office of Science
U.S. Department of Energy

Outline

What are neutrino interactions?

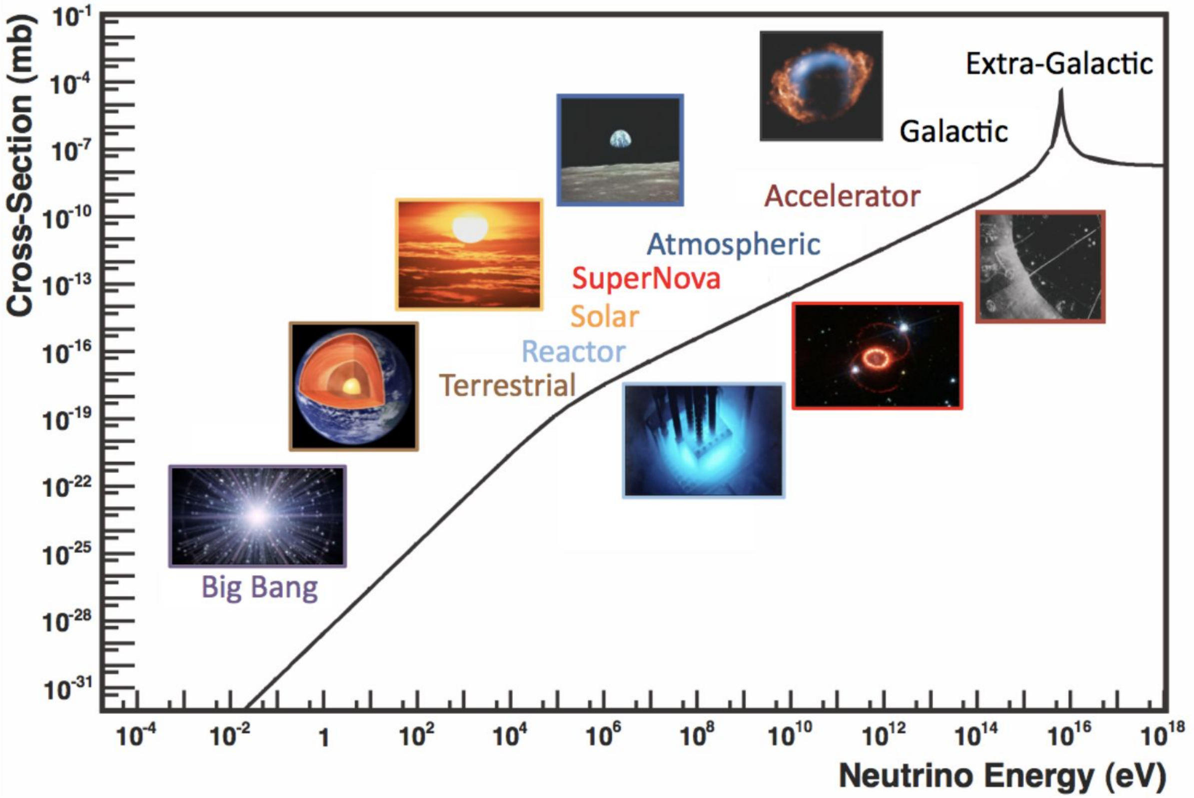
Why is an understanding of neutrino interactions essential to current and future physics programs?

What are the plans to improve our understanding of neutrino interactions?

Neutrino interactions are important to a broad variety of physics programs, and multiple efforts are underway to fully map out the open questions

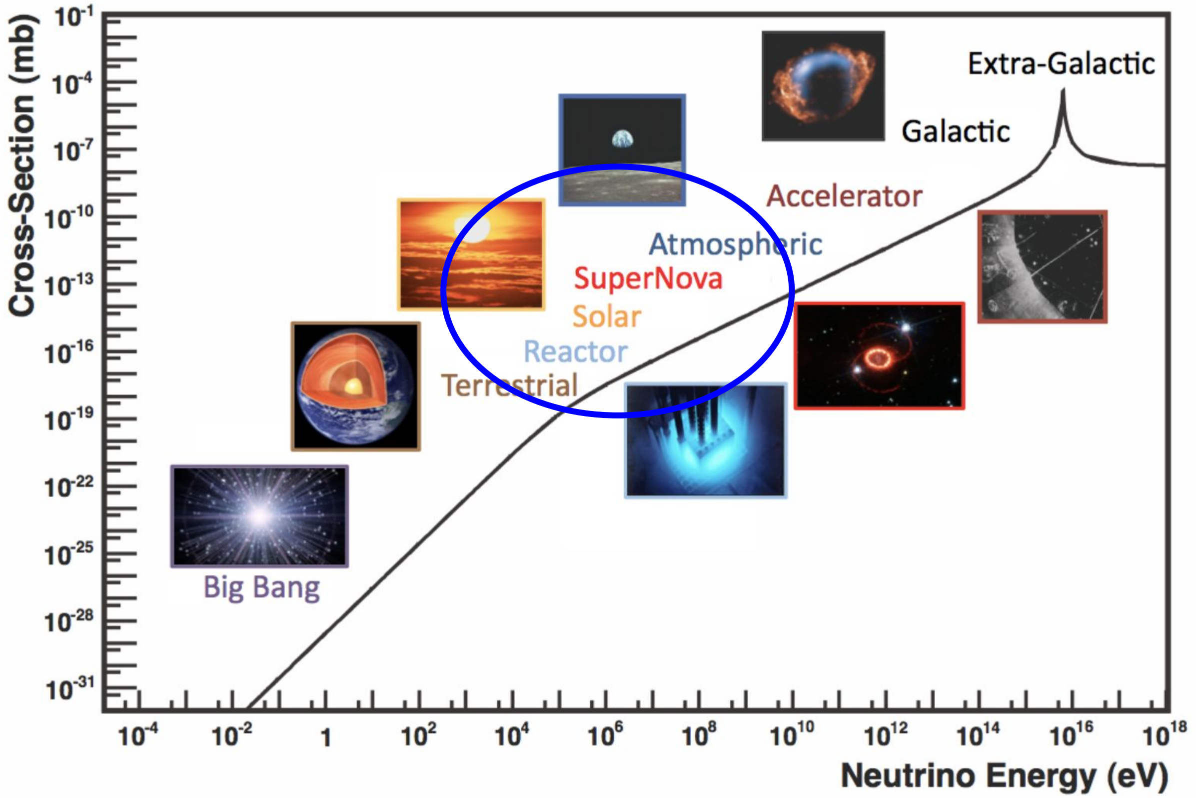
The scale of neutrino interactions

Rev. Mod. Phys. 84, 1307 (2012)



The scale of neutrino interactions: low energy, ~0-100 MeV

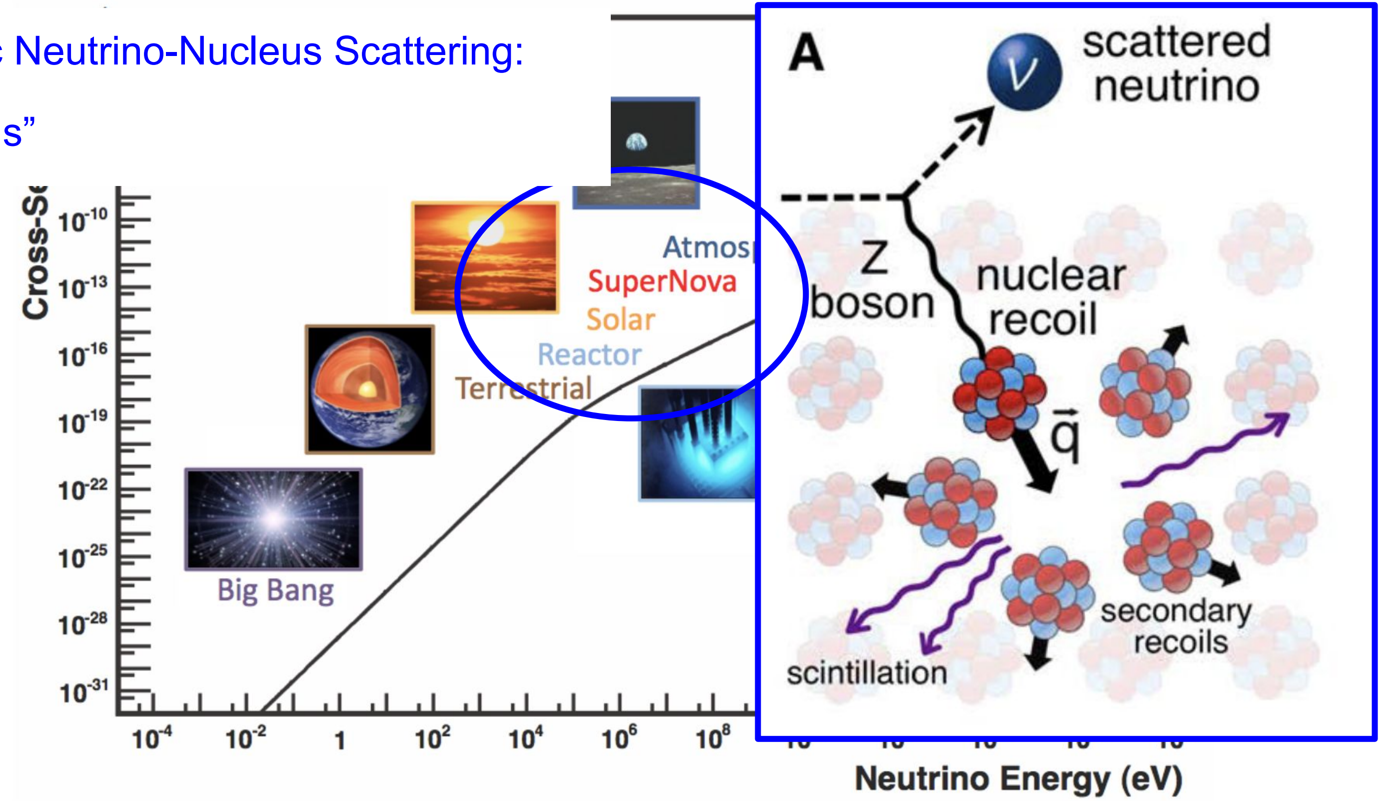
Rev. Mod. Phys. 84, 1307 (2012)



The scale of neutrino interactions: low energy, ~1-100 MeV

Coherent Elastic Neutrino-Nucleus Scattering:

CEvNS - “Sevens”



Science, Vol 357, 6356, pp. 1123-1126

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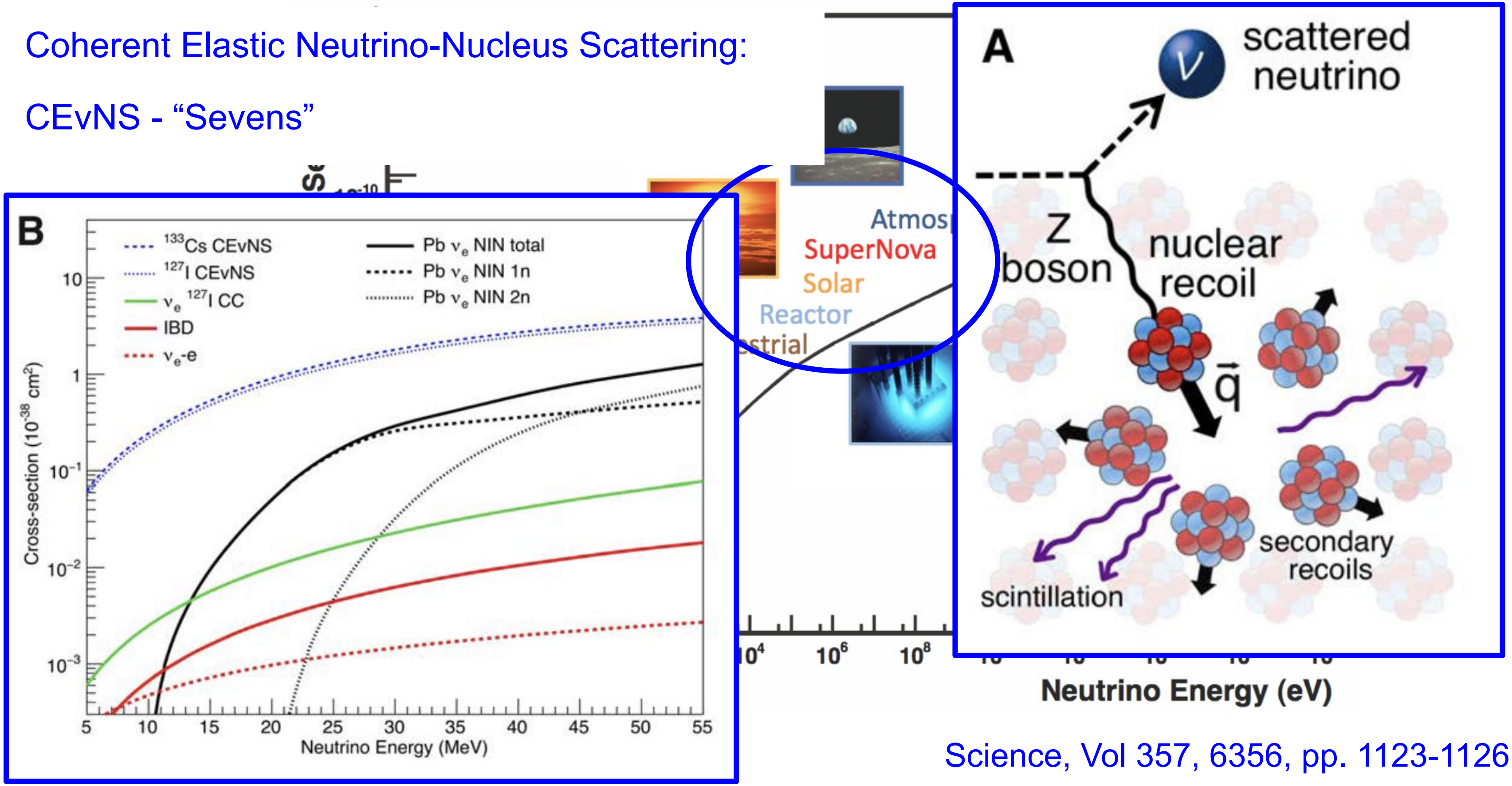
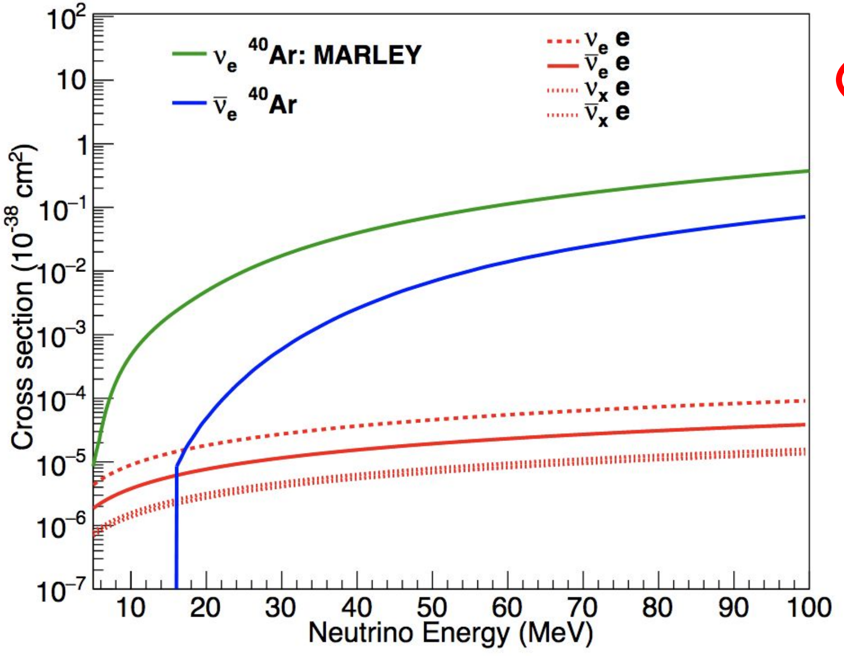


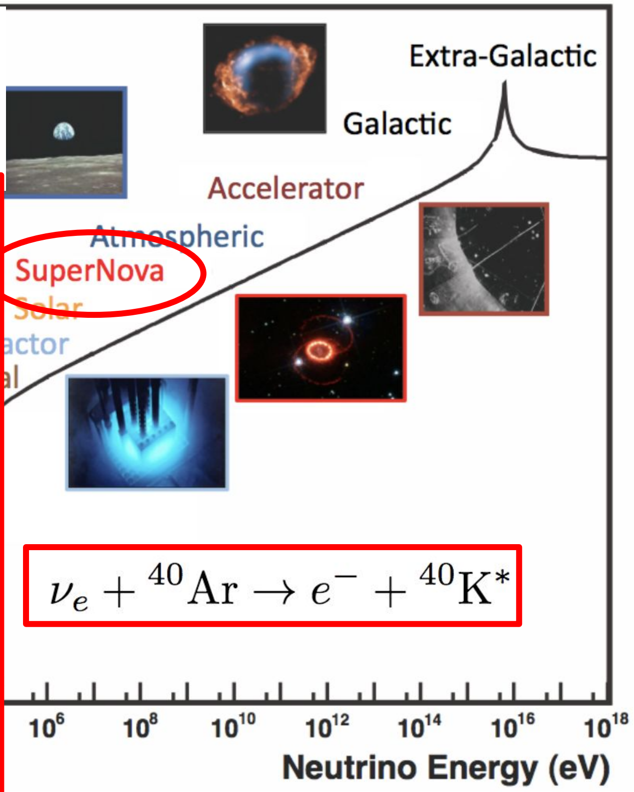
Science, Vol 357, 6356, pp. 1123-1126

The scale of neutrino interactions: low energy, ~1-100 MeV

Charged current (CC) scattering cross section for Super Nova Burst (SNB)

Example from DUNE - [arxiv 2008.06647](https://arxiv.org/abs/2008.06647)

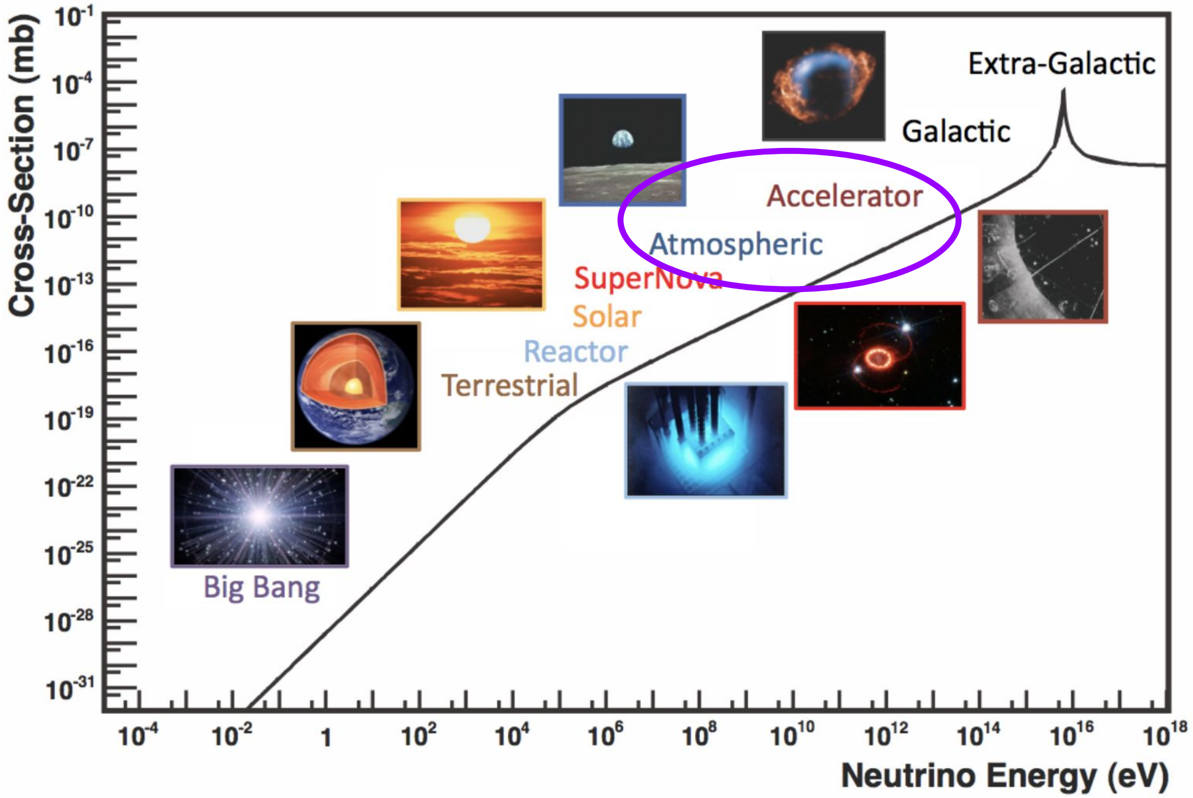




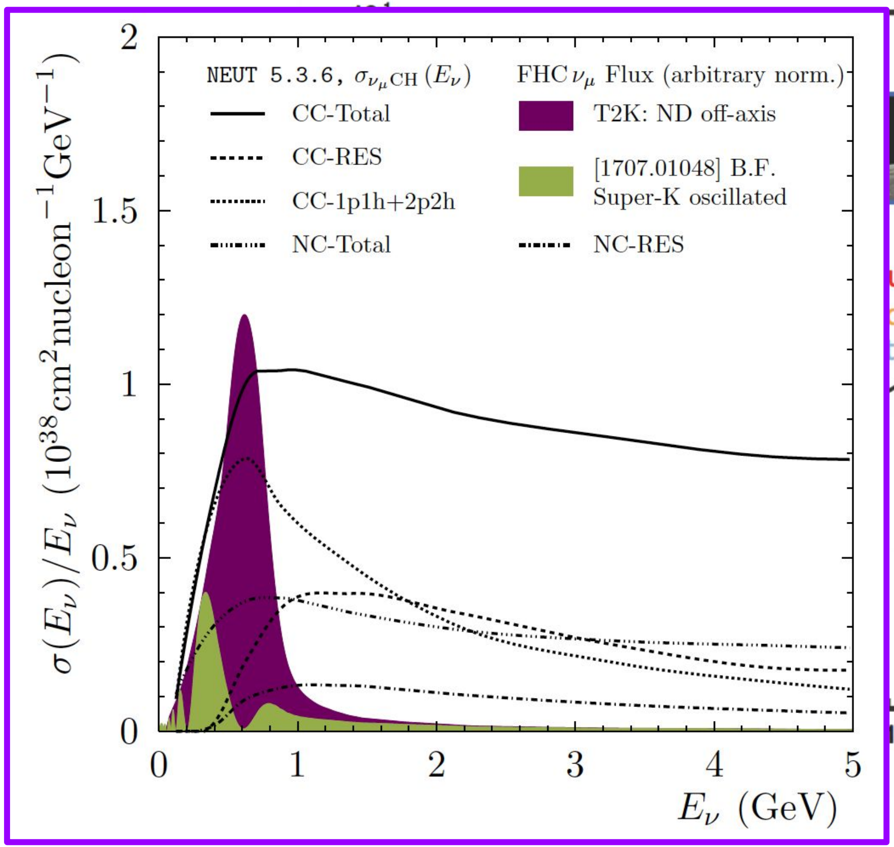
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

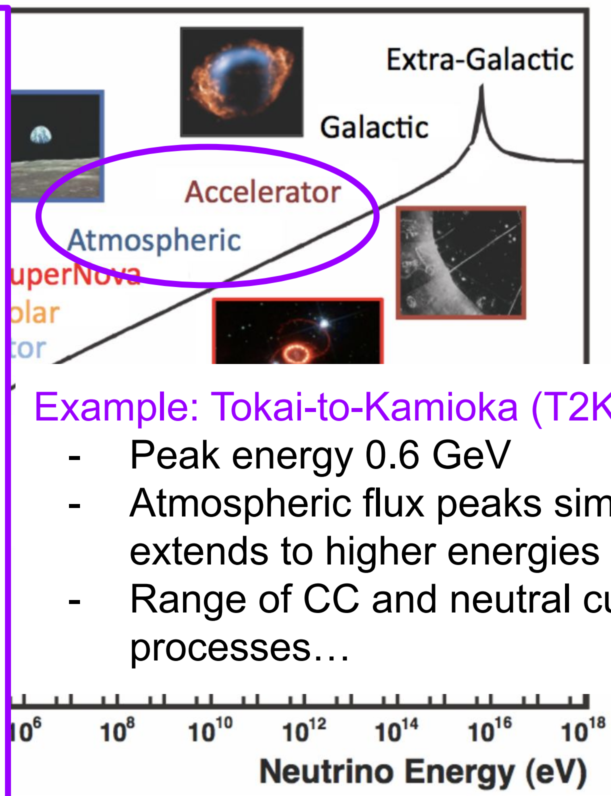
The scale of neutrino interactions: intermediate, ~0.1-20 GeV

[Rev. Mod. Phys. 84, 1307 (2012)]



The scale of neutrino interactions: intermediate, ~0.1-20 GeV



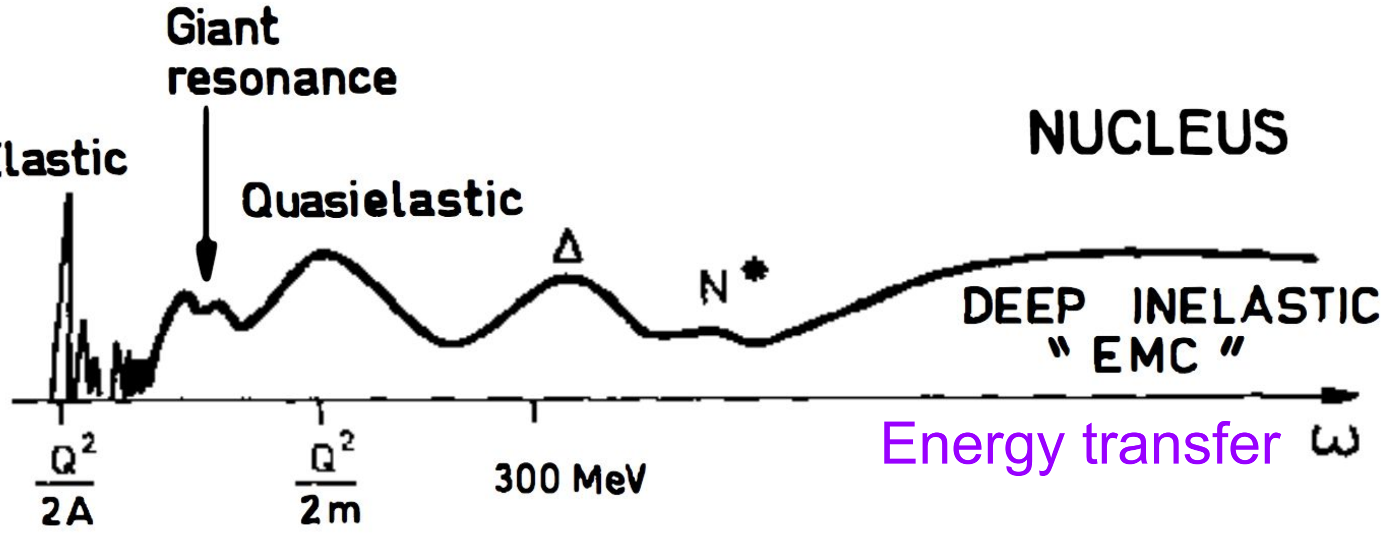


Example: Tokai-to-Kamioka (T2K) experiment

- Peak energy 0.6 GeV
- Atmospheric flux peaks similarly, and extends to higher energies
- Range of CC and neutral current (NC) processes…

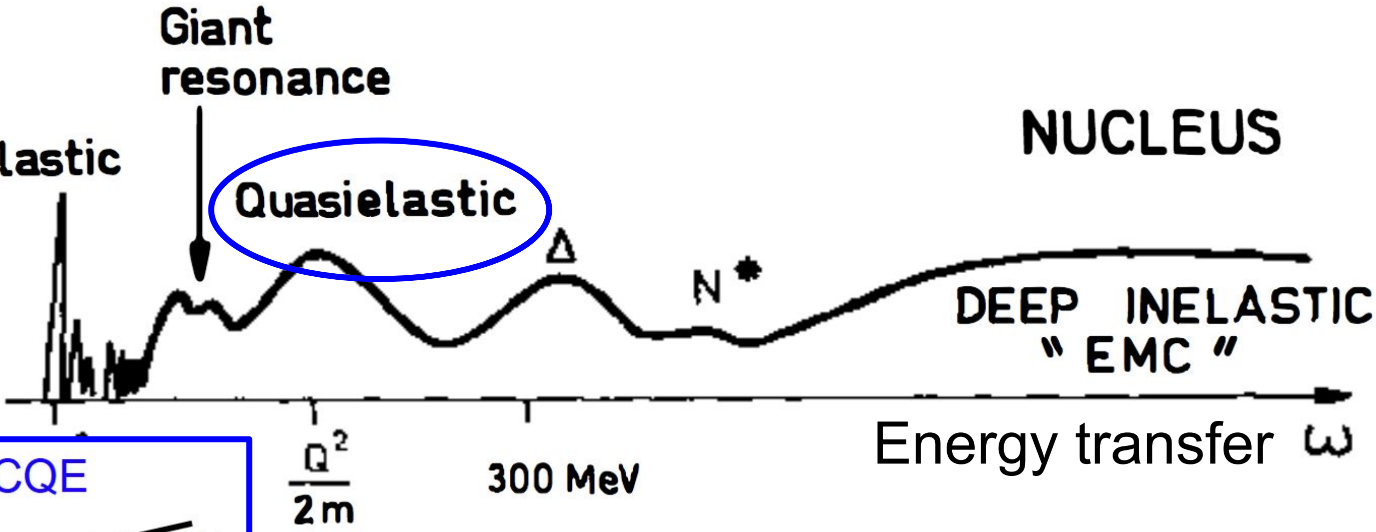
The scale of neutrino interactions: intermediate, ~0.1-20 GeV

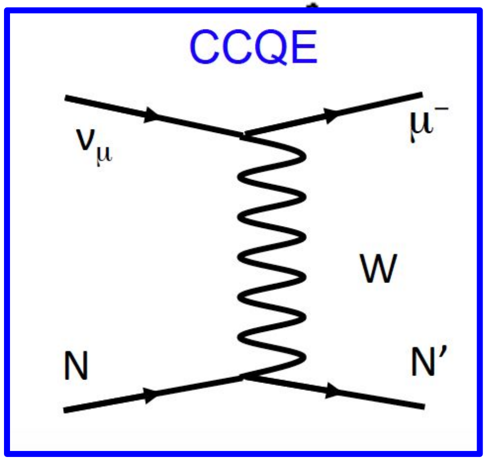
[Ann. Rev. Nucl. Part.Sci.1987.37: 133-76]



The scale of neutrino interactions: intermediate, ~0.1-20 GeV

[Ann. Rev. Nucl. Part.Sci.1987.37: 133-76]



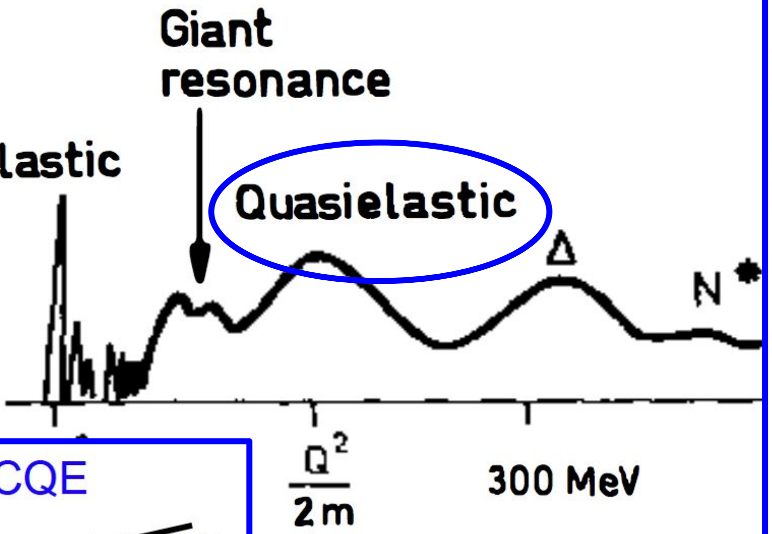


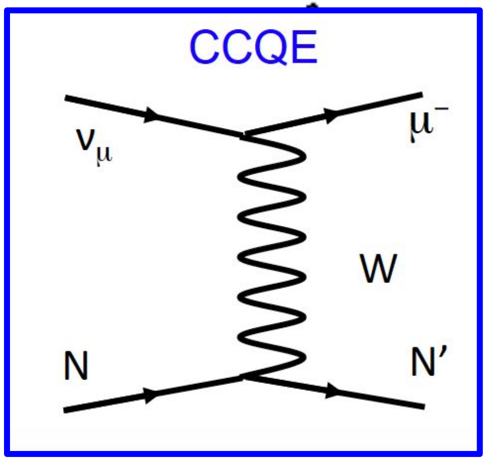
Charged current quasielastic scattering

Observables:
- lepton in final state, charge determines neutrino (-) or antineutrino (+)
- Outgoing proton (neutron)

The scale of neutrino interactions: intermediate, ~0.1-20 GeV

Ann. Rev. Nucl. Part.Sci.1987.37: 133-76

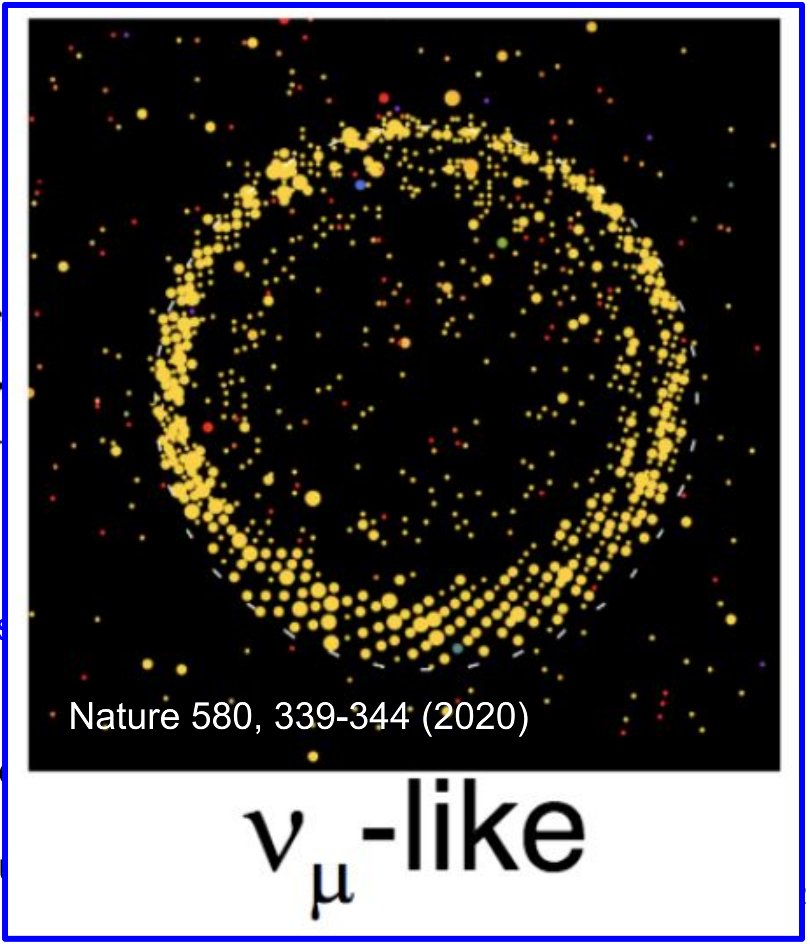




Charged current quasielas

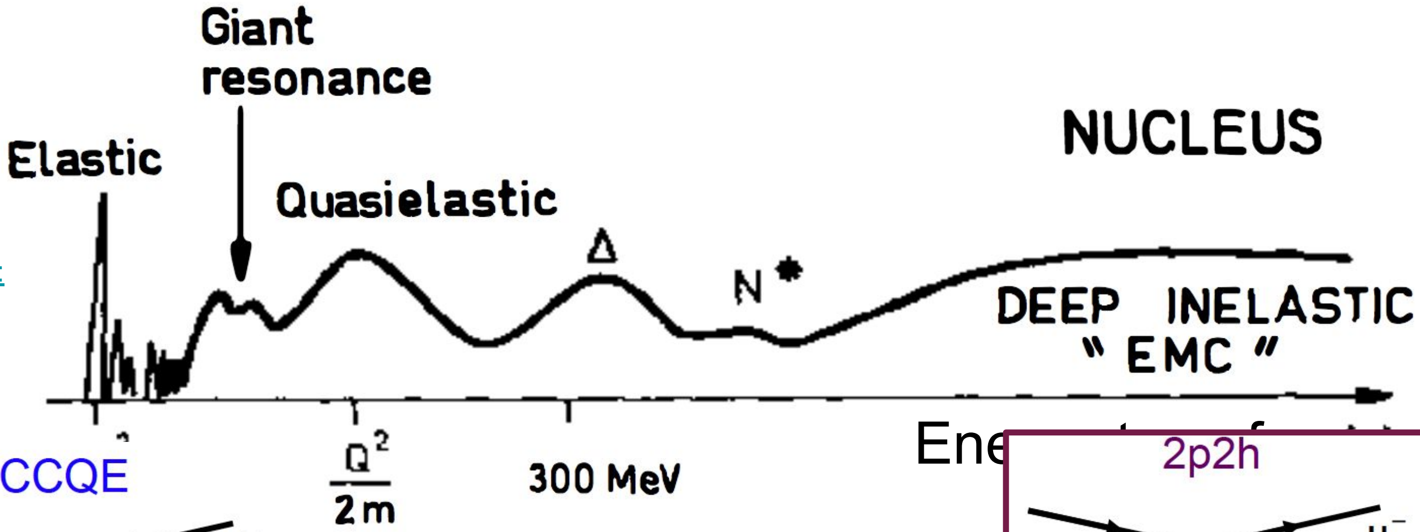
Observables:

- lepton in final state,
  antineutrino (+)
- Outgoing proton (ne

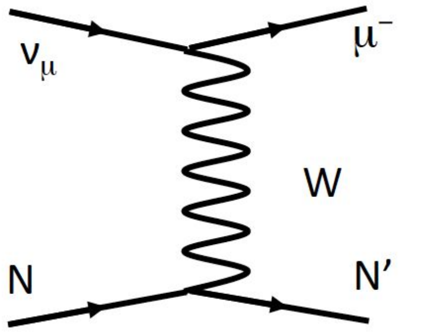


The scale of neutrino interactions: intermediate, ~0.1-20 GeV

Ann. Rev. Nucl. Part.Sci.1987.37: 133-76



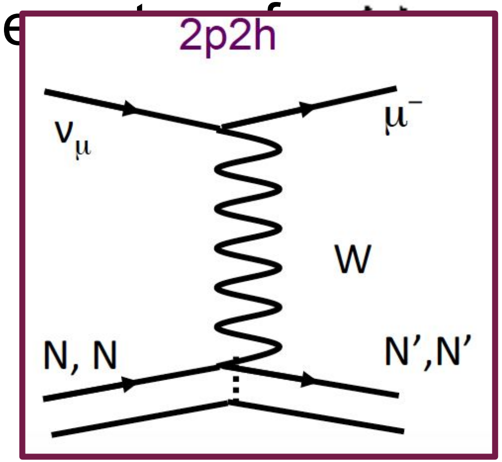
CCQE



Multinucleon scattering

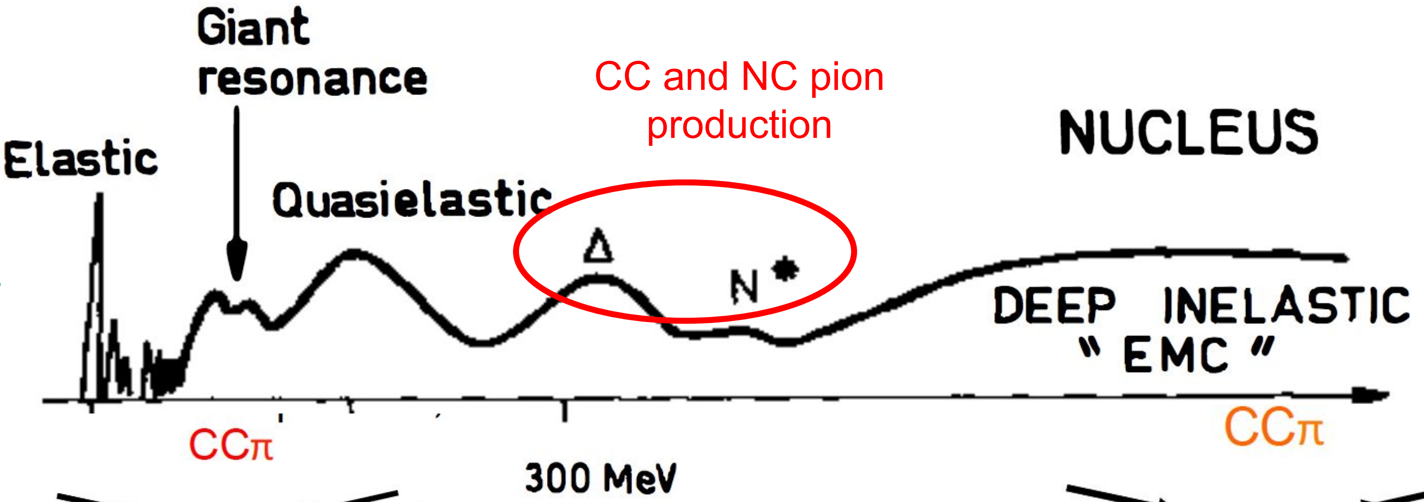
Similar observables:

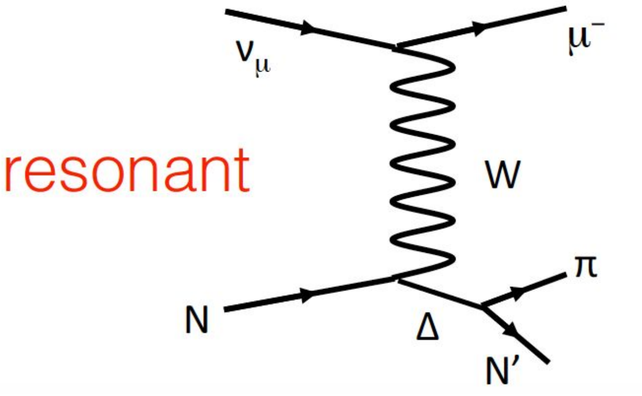
- lepton in final state
- Outgoing protons (neutrons)

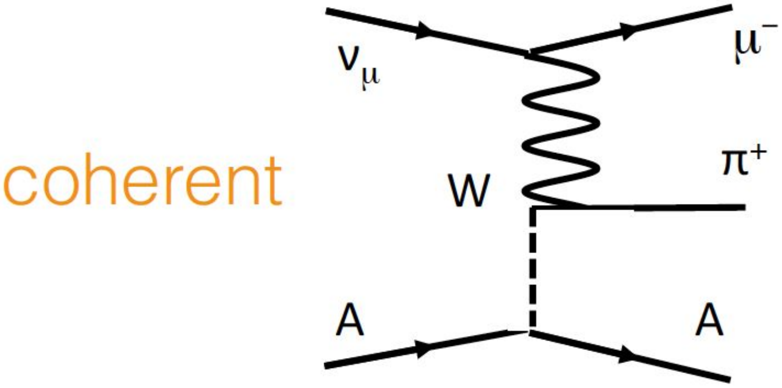


The scale of neutrino interactions: intermediate, ~0.1-20 GeV

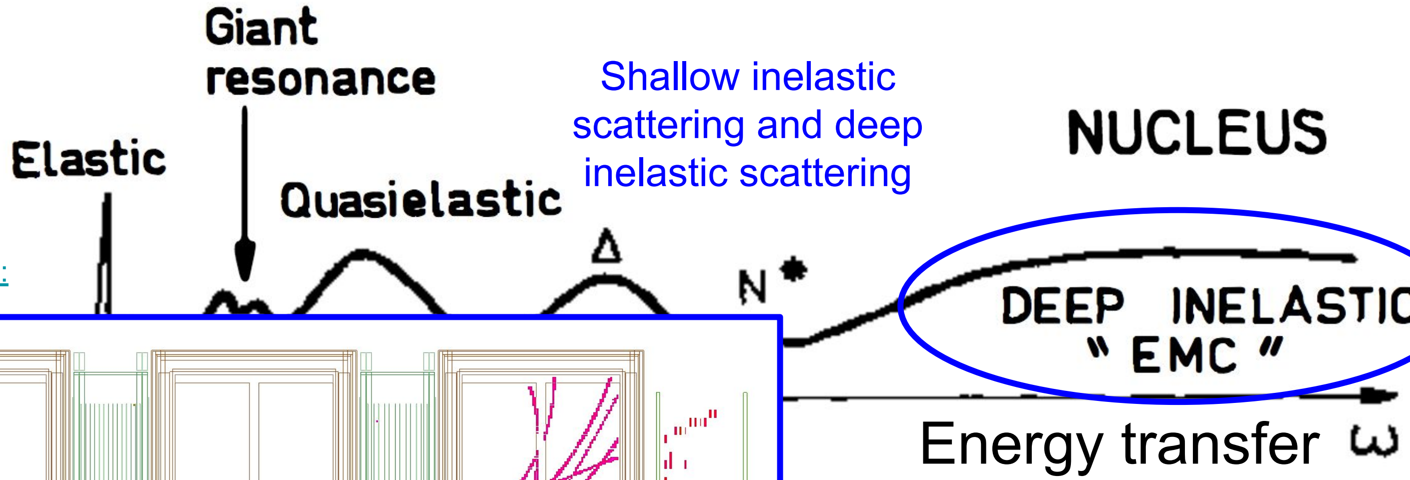
[Ann. Rev. Nucl. Part.Sci.1987.37: 133-76]





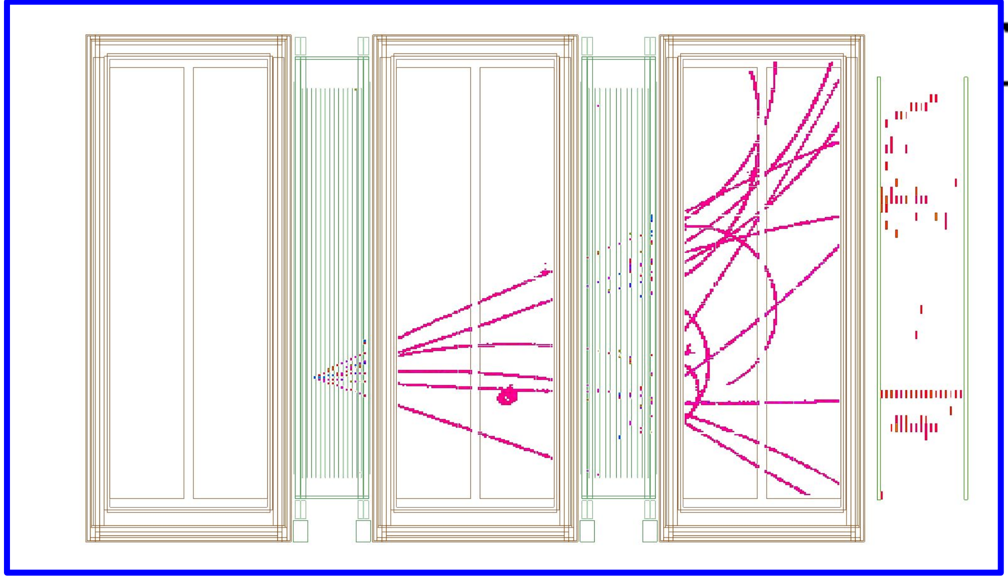


The scale of neutrino interactions: intermediate, ~0.1-20 GeV



Shallow inelastic scattering and deep inelastic scattering

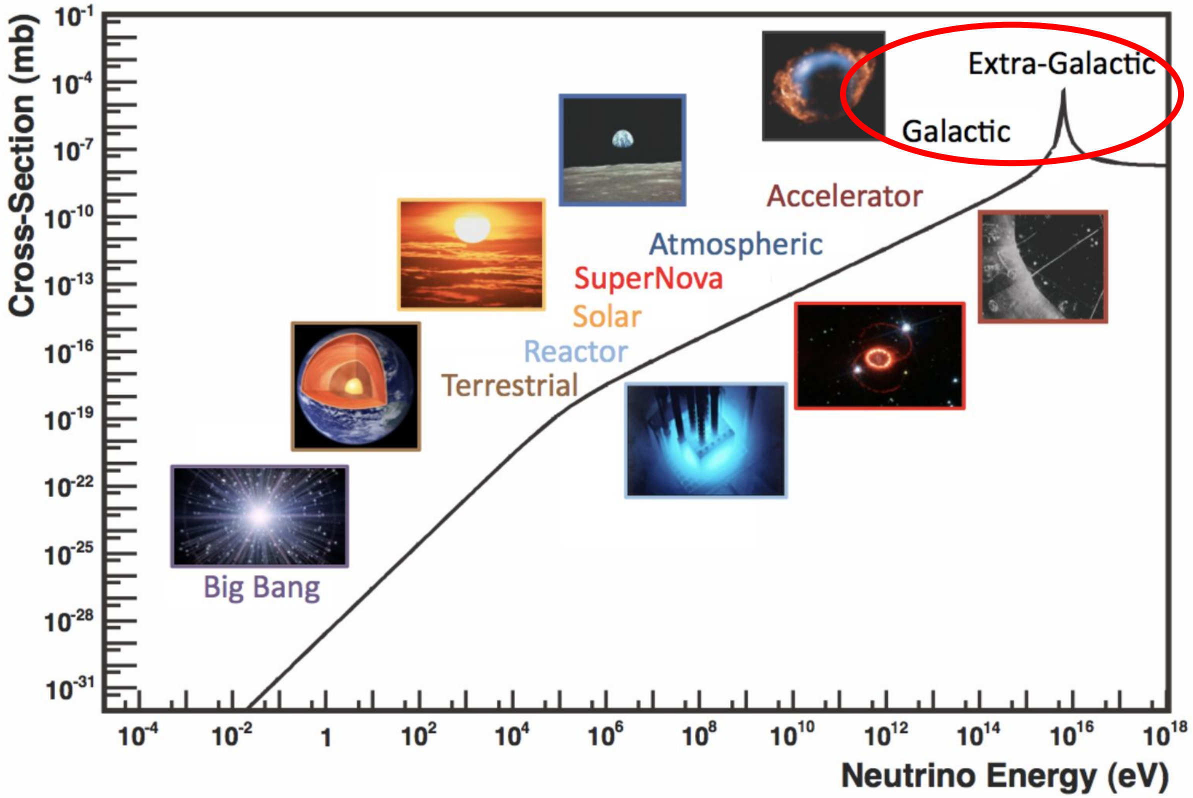
Ann. Rev. Nucl. Part.Sci.1987.37: 133-76



Example of a multiparticle shower, T2K ND280 detector

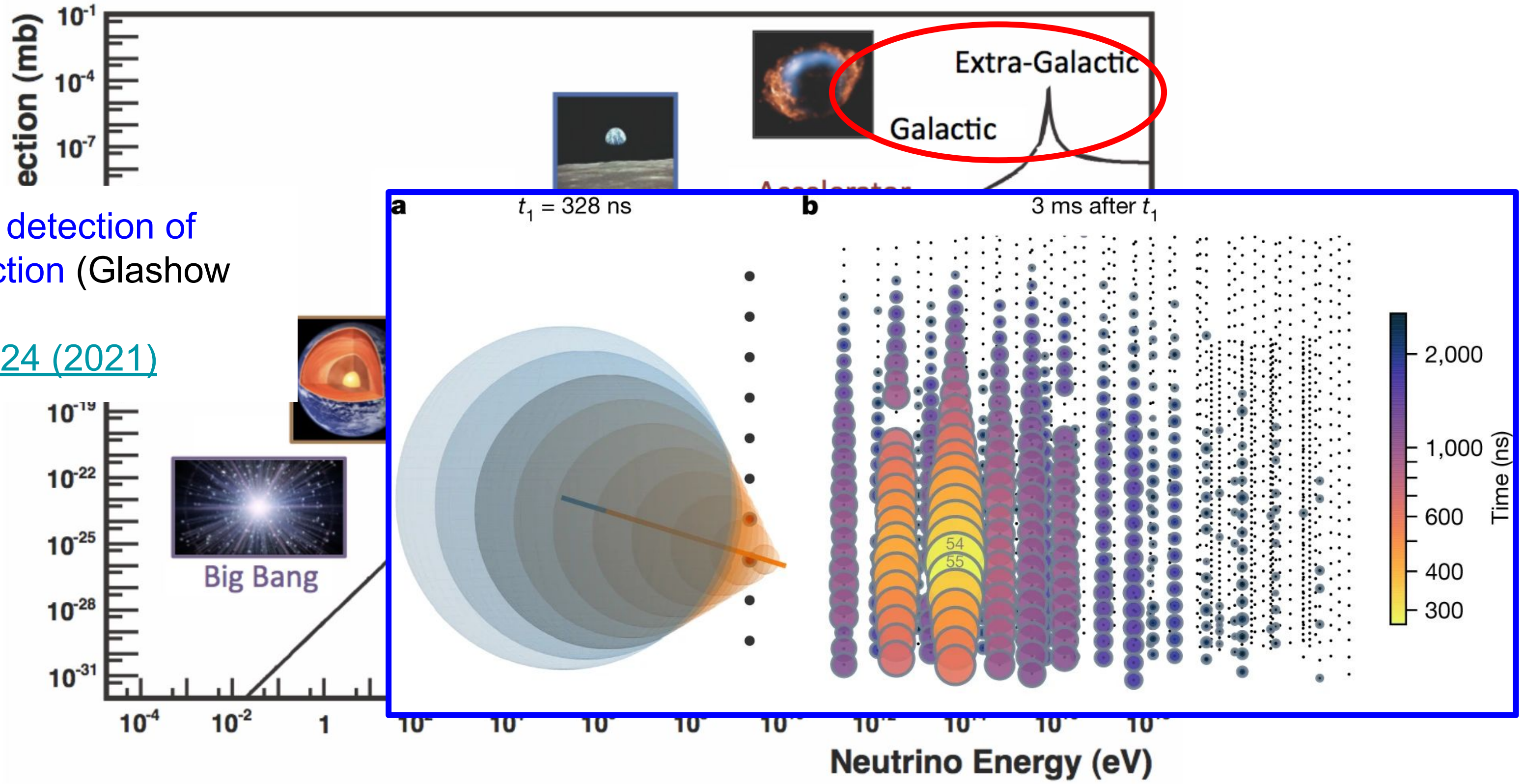
The scale of neutrino interactions: high energy,~20 GeV-1EeV

[Rev. Mod. Phys. 84, 1307 (2012)]



The scale of neutrino interactions: high energy,~20 GeV-1EeV

Example: IceCube detection of resonant W production (Glashow resonance, 6 PeV)
[Nature 591, 220–224 (2021)]



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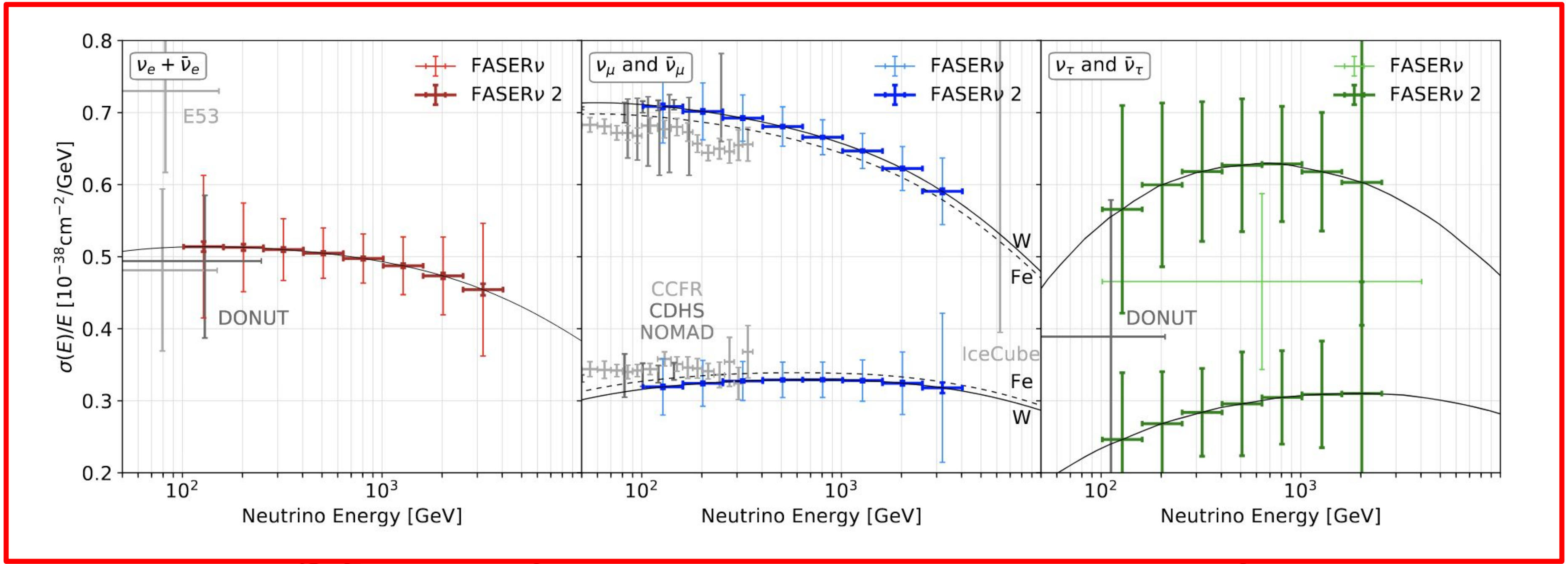

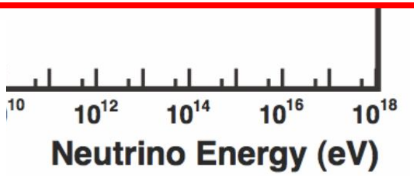

Example: Forward Physics Facility cross section measurements at LHC measurements of deep inelastic scattering (DIS)

- White Paper (WP): arxiv 2109.10905.pdf

Why are neutrino interactions important?

Energy regime

low energy, ~0-100 MeV

- CEvNS
- SNB
- Solar neutrinos

Interesting physics

BSM: sterile neutrinos, light dark matter, NSI, precision tests of SM

Astrophysics: supernova bursts, solar models

Tests of neutrino mixing model

Why are neutrino interactions important?

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Tests of neutrino mixing model

<u>Needed information about neutrino interactions</u>
- Example: CEvNS: neutron form factors
- Example: semi inclusive predictions of SNB xsec

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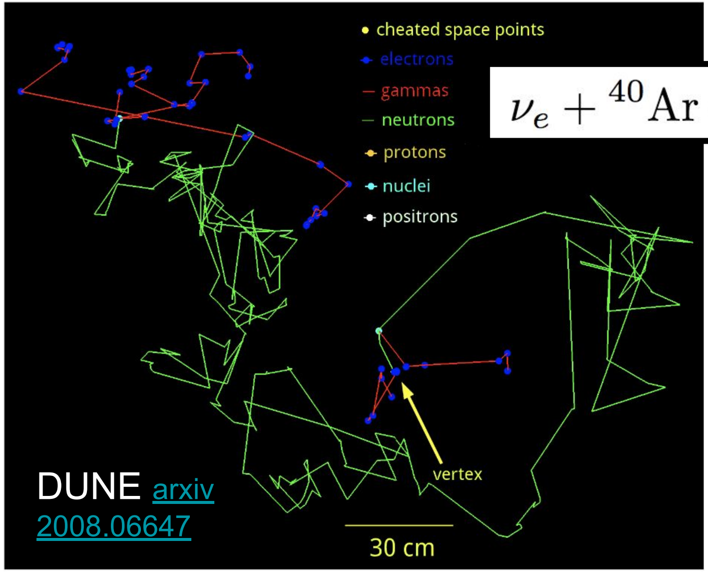

DUNE arxiv 2008.06647

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

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Tests of neutrino mixing model

Needed information about neutrino interactions

- Example: CEvNS: neutron form factors
- **Example: semi inclusive predictions of SNB xsec**

Quantification by DUNE: E. Conley, Nu@ORNL workshop

Why are neutrino interactions important?

Energy regime

intermediate energy, ~0.1-20 GeV

- Accelerator neutrinos
- Atmospheric neutrinos

Interesting physics

BSM: sterile neutrinos, light dark matter, NSI, precision tests of SM

Three flavor oscillation: θ_{23} octant, mass hierarchy, CP violation. Tests of neutrino mixing model

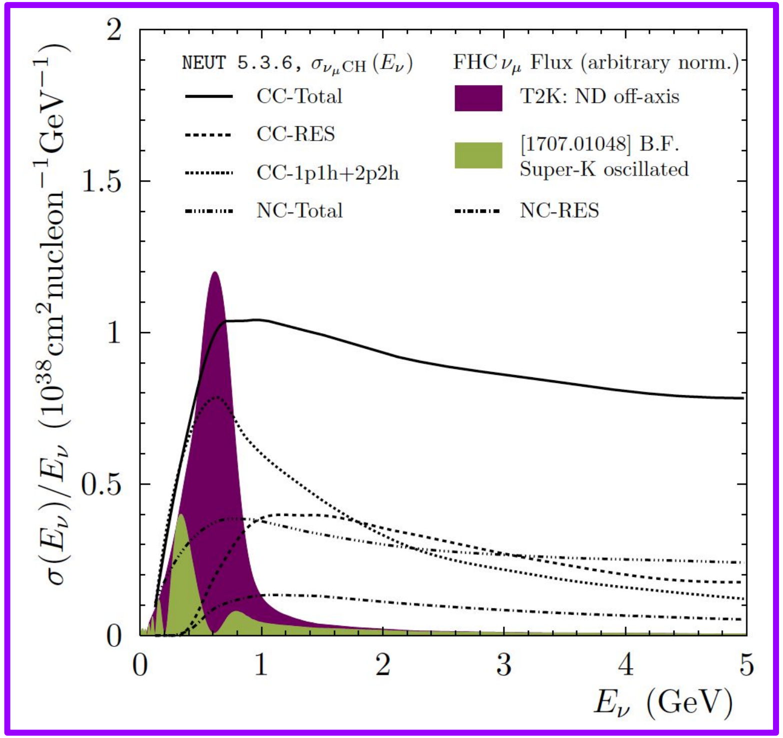
More BSM: proton decay

Example: Oscillation physics

Event rate depends on:

- Flux
- Cross section
- Oscillation probability
- Efficiency
- Relationship between true and reconstructed observables

Need predictions for neutrinos, antineutrinos and all flavors (disappearance, appearance channels)



$$N_{FD}^{\alpha\rightarrow\beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

And the event rates depend on the cross section/interaction model

Cross section (true kinematics)

Efficiency (true kinematics)

Relationship between true and reconstructed kinematics)

$$N_{FD}^{\alpha\to\beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

Role of “near detector” in oscillation experiments

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$$N_{ND}^{\alpha} E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\alpha^i(E_{true}) \times \epsilon_\alpha(E_{true}) \times R_i(E_{true}; E_{reco})$$

Near detector information provides stability monitoring, improved event rate prediction and reduces shared systematic uncertainty on the flux, interaction and/or detector model

Role of “near detector” in oscillation experiments

$$N_{FD}^{\alpha\to\beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

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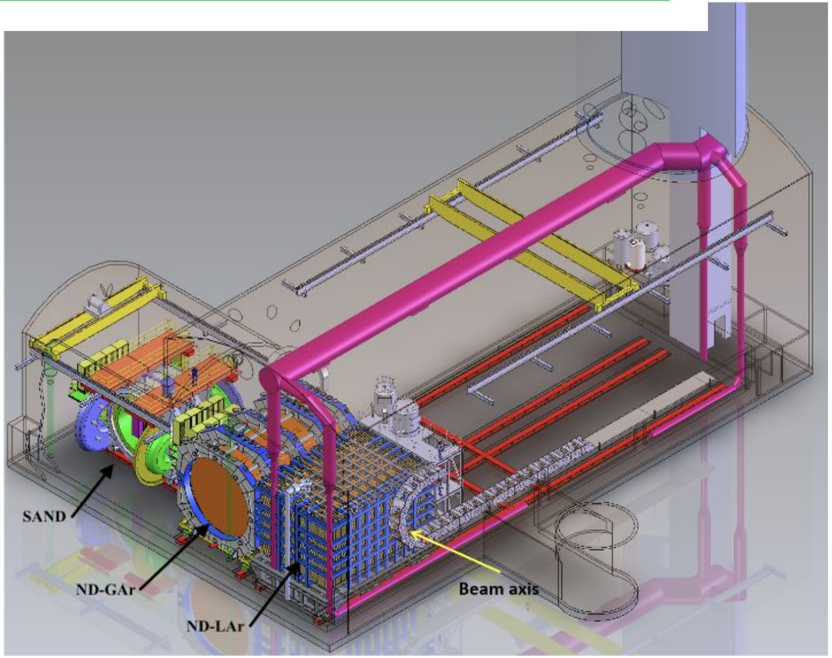
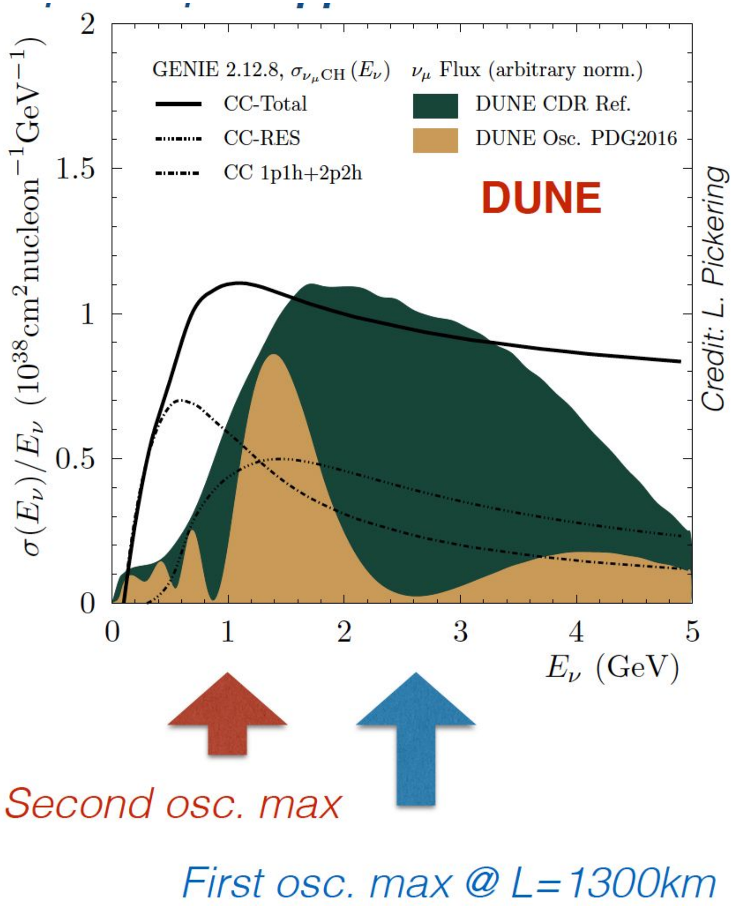
Example: DUNE Near Detector (ND complex) - arxiv 2103.13910

- Liquid Argon (ND-LAr)
- Gaseous detector (ND-GAr)
- And beam monitoring (SAND)

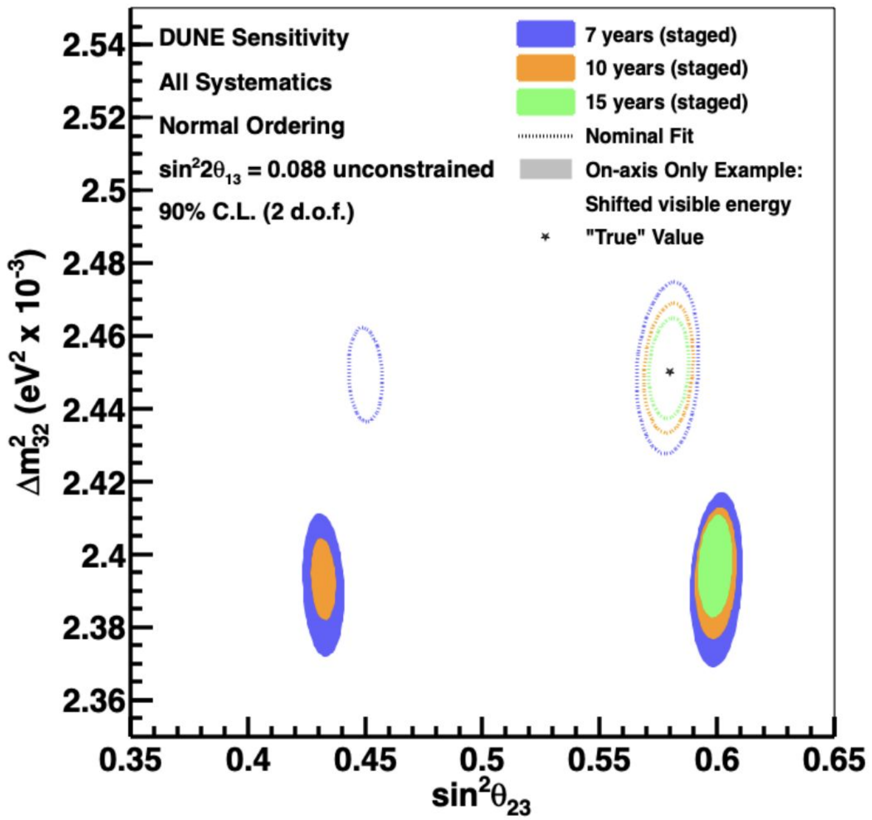


Why neutrino interactions matter - DUNE example

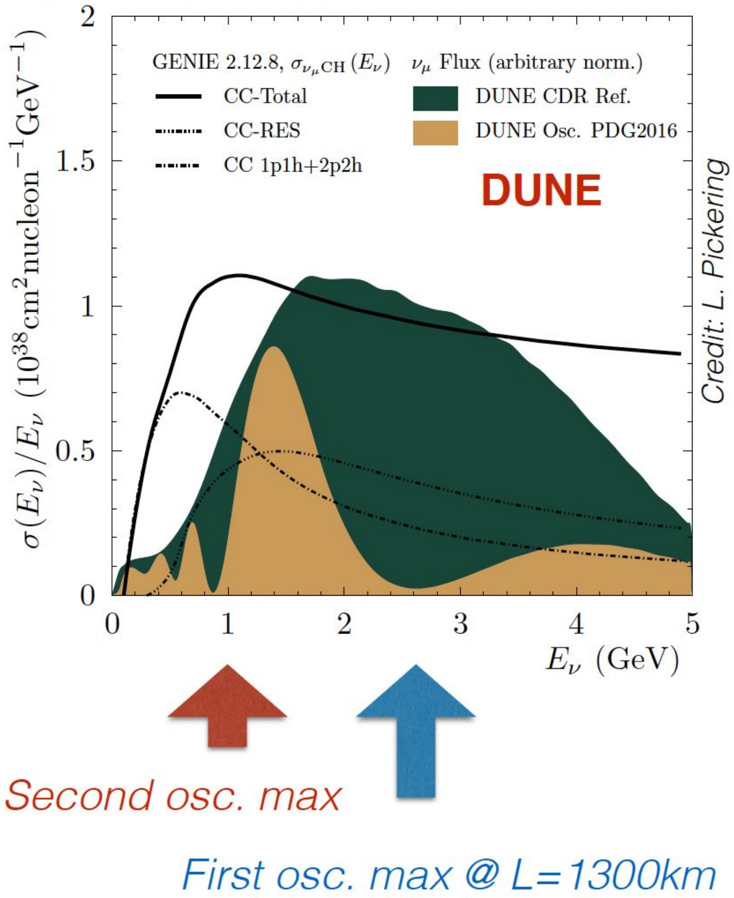


Why neutrino interactions matter - DUNE example

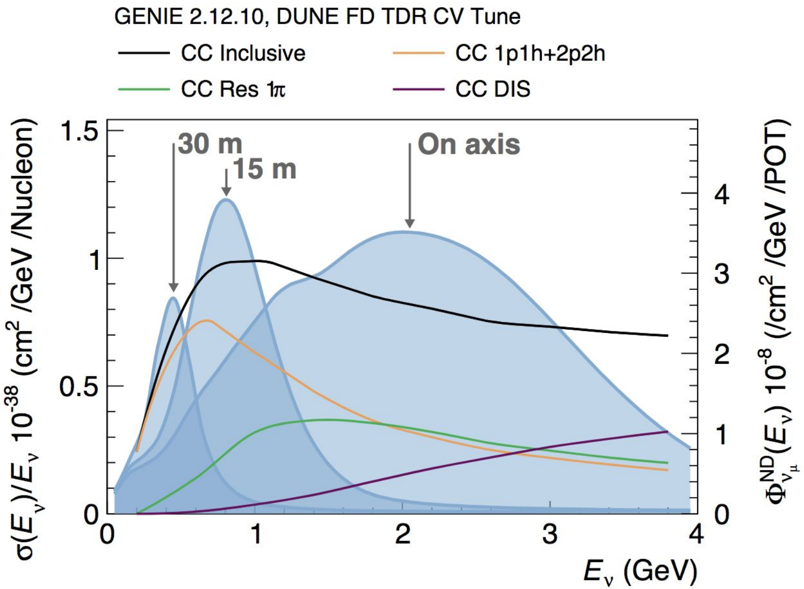
DUNE Physics TDR arxiv. 2002.03005

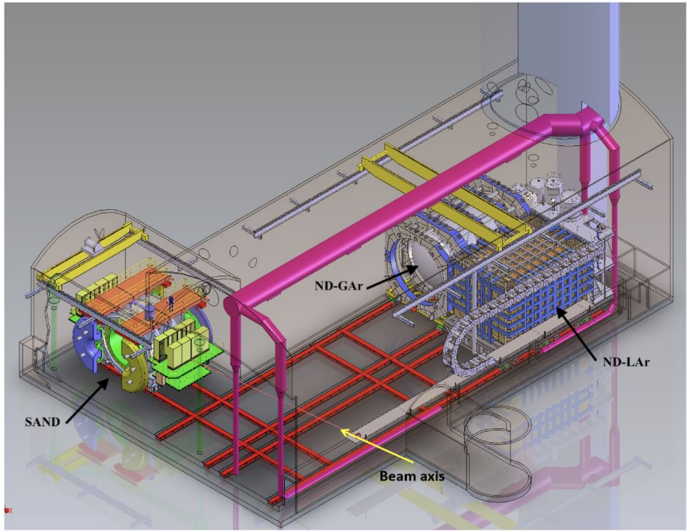


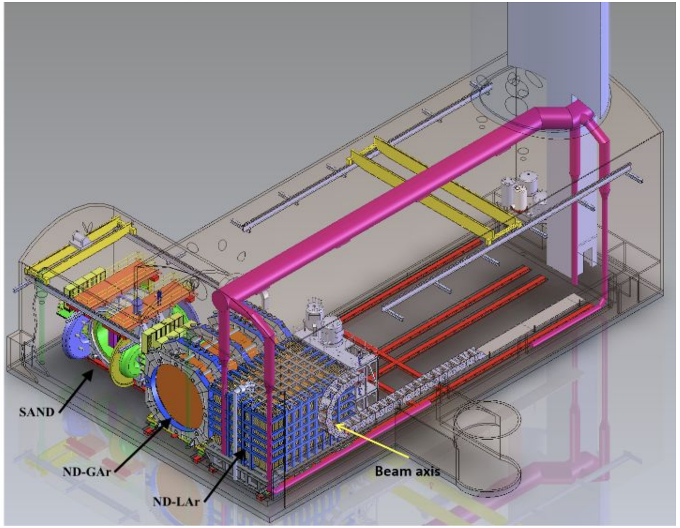
Possibility of bias in key oscillation parameters



New approach: PRISM

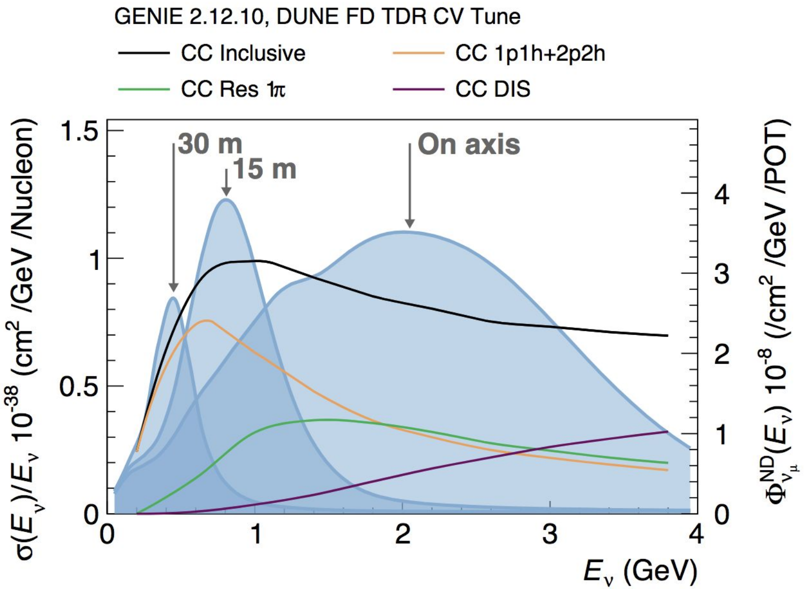


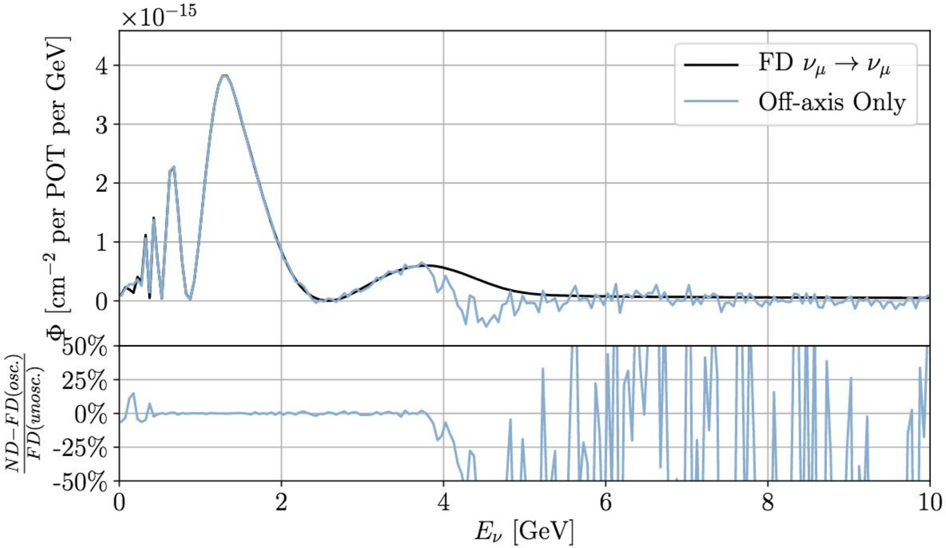




Place detectors at different positions relative to beam to measure different energy spectra arxiv 2103.13910

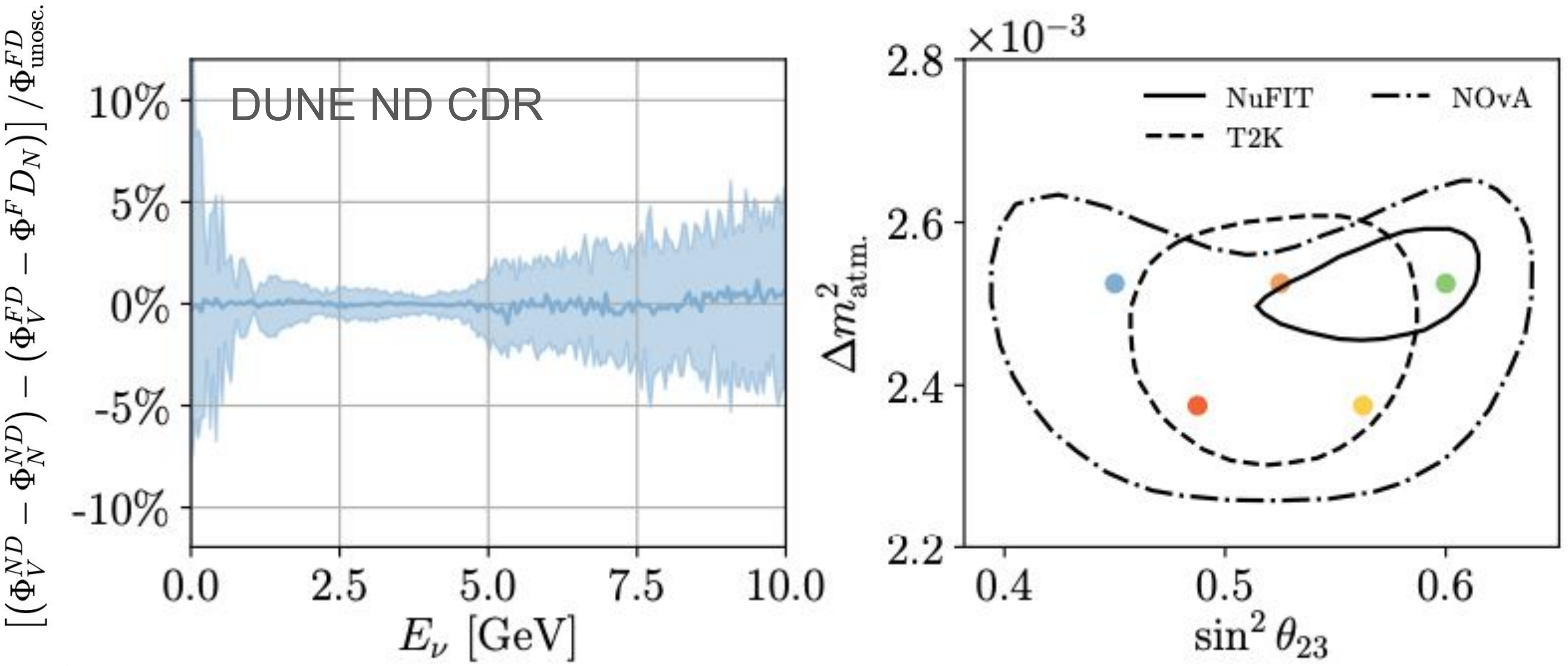
New approach: PRISM





Combine spectra for an oscillation-matched flux

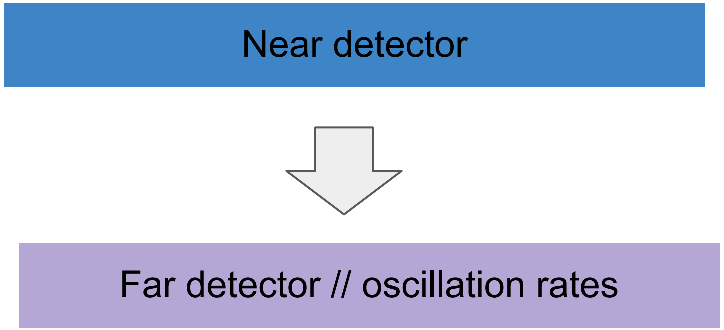
PRISM provides robustness against mismodelling



Allows for novel nuclear physics studies

Other DUNE detectors (ND-GAr, SAND) also have unique measurement opportunities

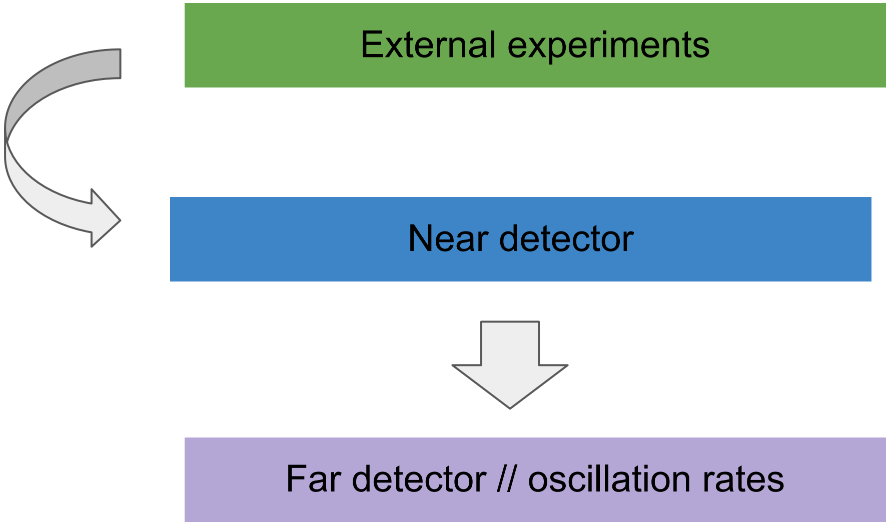
Current plans of oscillation experiments



Current and future ND are designed to meet the needs of the experiment

- NOvA ND, T2K ND (new upgrade - arxiv 1901.03750)
- DUNE ND, Hyper-Kamiokande ND

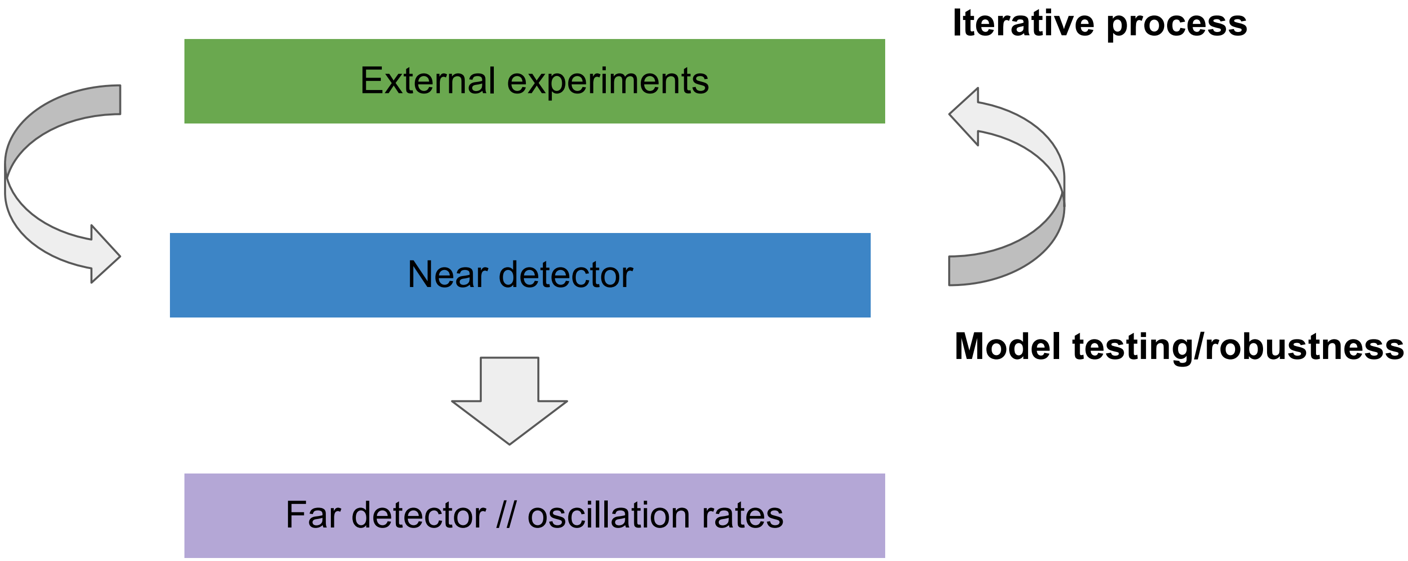
The role of external experiments



External experiments are important; determine parameterization, uncertainties.

- Electron scattering
- Pion scattering
- Neutrino H/D data
- Neutrino nucleus scattering

Time is key to understand open questions



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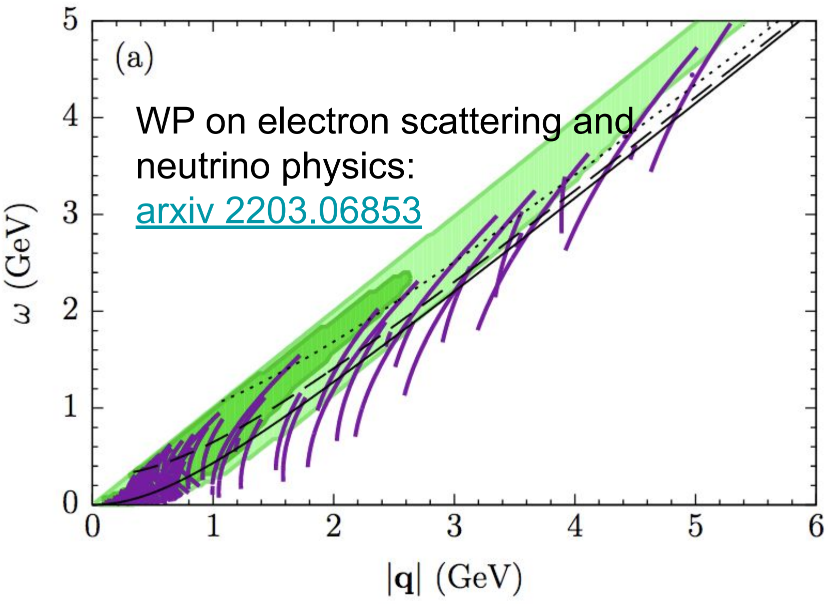
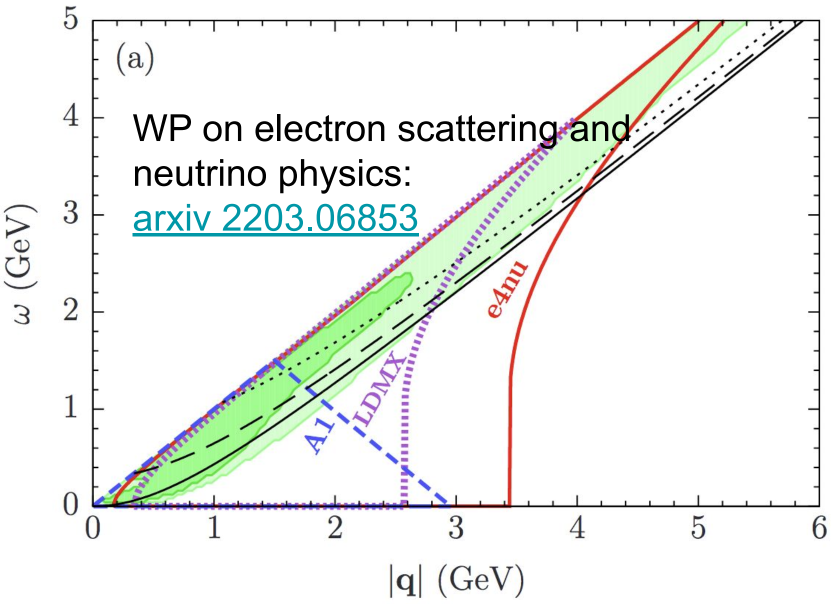
External experiments: electron scattering



WP on electron scattering and neutrino physics:
[arxiv 2203.06853](https://arxiv.org/abs/2203.06853)

Inclusive measurements do not cover all the needed phase space for future experiments, like DUNE

External experiments: electron scattering



WP on electron scattering and neutrino physics: [arxiv 2203.06853](https://arxiv.org/abs/2203.06853)

Collaborations	Kinematics	Targets	Scattering
E12-14-012 (JLab) (Data collected: 2017)	$E_e = 2.222$ GeV $15.5° \leq \theta_e \leq 21.5°$ $-50.0° \leq \theta_p \leq -39.0°$	Ar, Ti Al, C	(e, e') e, p in the final state
e4nu/CLAS (JLab) (Data collected: 1999, 2022)	$E_e = 1, 2, 4, 6$ GeV $\theta_e > 5°$	H, D, He, C, Ar, ^{40}Ca, ^{48}Ca, Fe, Sn	(e, e') e, p, n, π, γ in the final state
LDMX (SLAC) (Planned)	$E_e = 4.0, 8.0$ GeV $\theta_e < 40°$	W, Ti, Al	(e, e') e, p, n, π, γ in the final state
A1 (MAMI) (Data collected: 2020) (More data planned)	50 MeV $\lesssim E_e \leq 1.5$ GeV $7° \leq \theta_e \leq 160°$	H, D, He C, O, Al Ca, Ar, Xe	(e, e') 2 additional charged particles
A1 (eALBA) (Planned)	$E_e = 500$ MeV - few GeV	C, CH Be, Ca	(e, e')

Semi inclusive, exclusive electron scattering measurements constrain vector piece of cross section

- Measurements critical where ND constraints are not applicable (e.g. BSM)
- High multiplicity final state characterization, range of targets (nuclear effects)

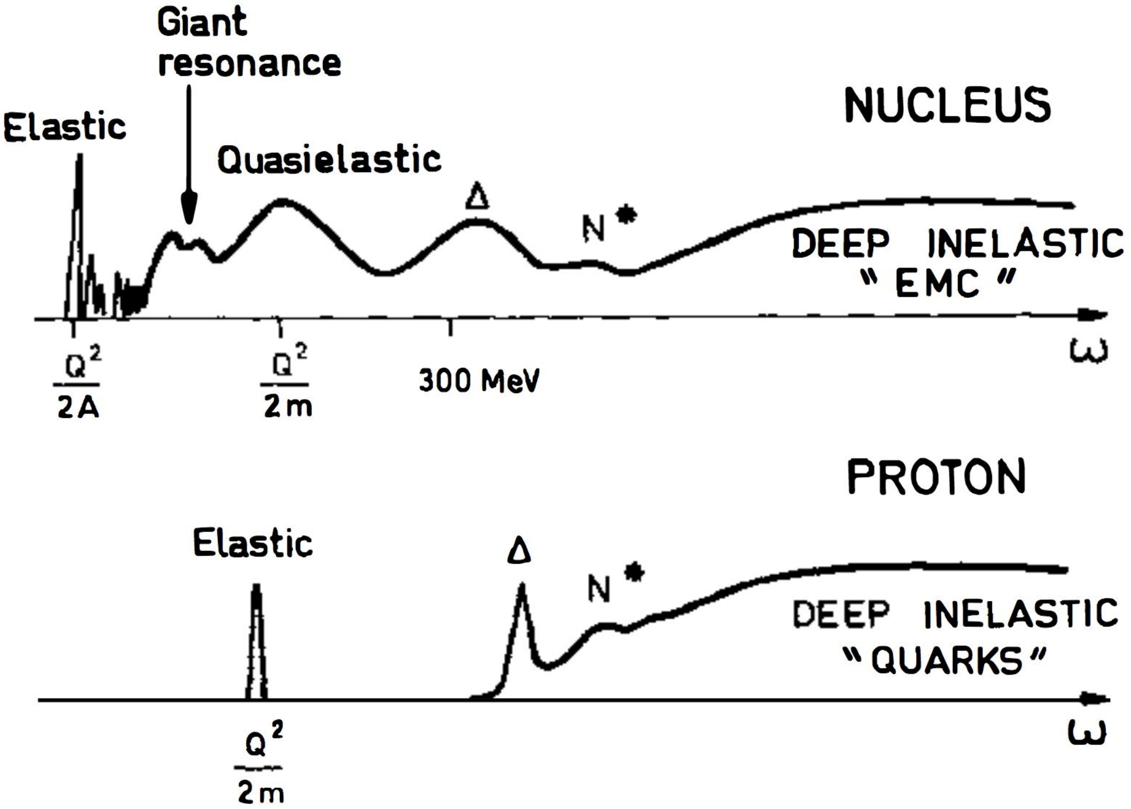
Exciting new experimental programs focused on this problem; complementary to ND

External experiments: neutrino scattering on H/D

Resolve current discrepancies in nuclear data with improved, complementary H, D measurements

WP on opportunities for new measurements - [arxiv 2203.11298]

- Using DUNE ND (GAr, SAND)
- New bubble chamber based experiments at FNAL - [arxiv 2203.11319]



External experiments: neutrinos on nuclei

Short baseline Neutrino Program:
MicroBooNE, SBND, ICARUS

sbn.fnal.gov/

ANNIE

annie.fnal.gov/

NuSTORM

MINERvA
minerva.fnal.gov/

NINJA

Recent: Phys. Rev. D 102, 072006

External experiments:

Short baseline Neutrino Program:
MicroBooNE, SBND, ICARUS

sbn.fnal.gov/

ANNIE

annie.fnal.gov/

NuSTORM

MINERvA
minerva.fnal.gov/

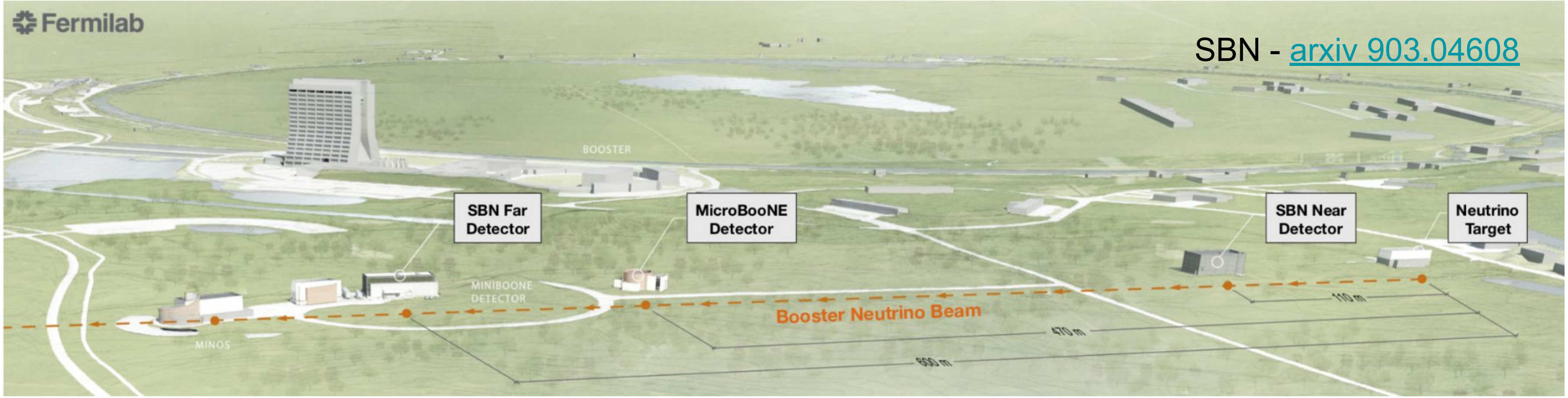
Parting gifts of data preservation, ultimate measurements

NINJA

Recent: Phys. Rev. D 102, 072006

External experiments: Short Baseline Neutrino Program

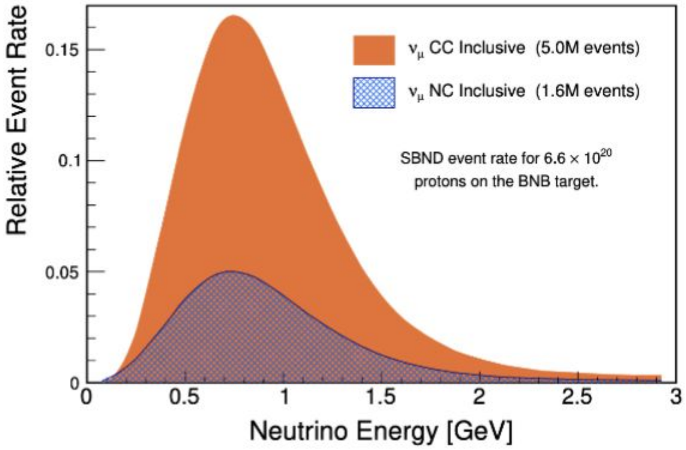
SBN - [arxiv 903.04608]

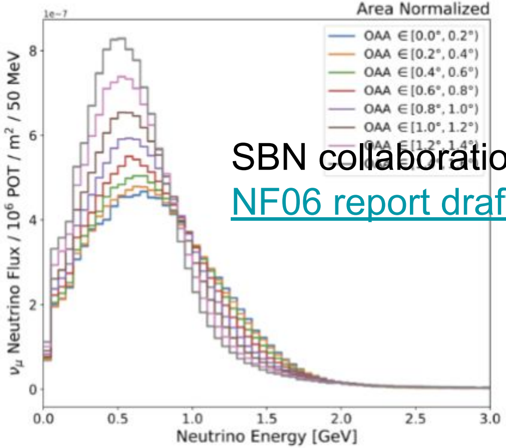


MicroBooNE: first high-statistics measurements of neutrino interactions on Ar

SBND: compare slices in detector for a PRISM-like effect

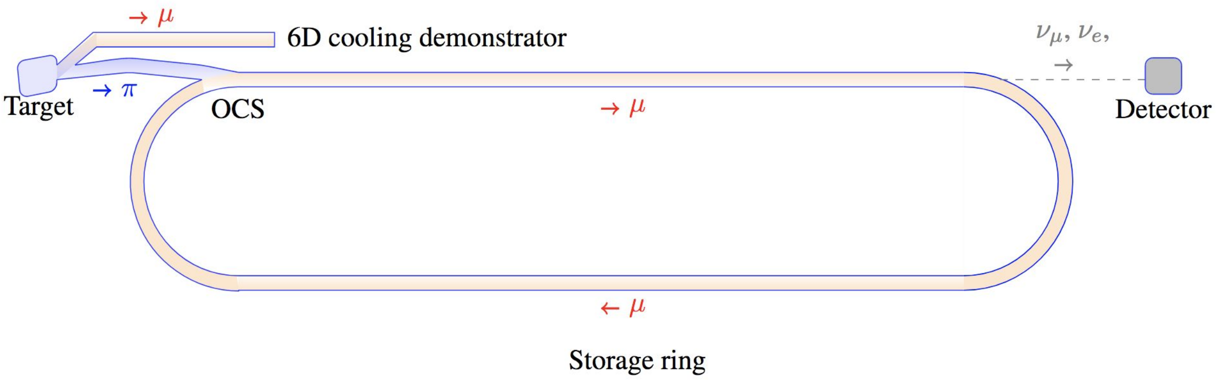
ICARUS: Extra feature: enhanced ν_e cross section capability from NuMI beam

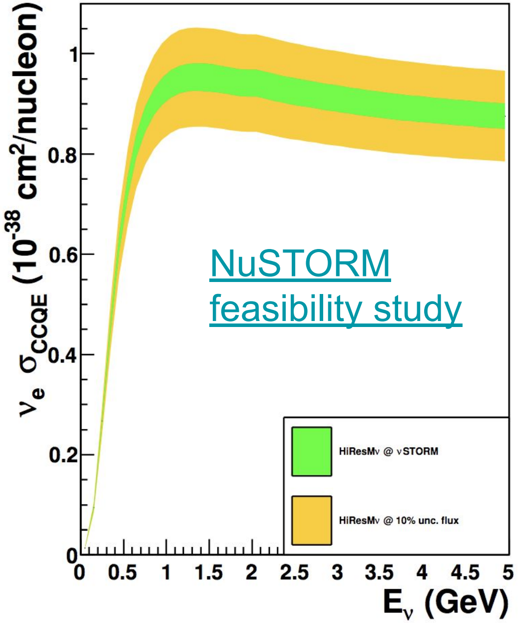




SBN collaboration, [NF06 report draft]

External experiments: Neutrinos from Stored muons (nuSTORM)





[NuSTORM feasibility study]

Muon decay based beam, provides 1% level flux uncertainties

Precision ν_e / ν_μ (and antineutrino) cross section measurements

CPV measurements depend on electron neutrino-antineutrino asymmetry

WP: [arxiv 2203.07545]

Let's not forget low energy!

Experiment	Source	Target	Time
COHERENT	πDAR	Na, Ar, Ge, CsI,	2014 -
Coherent CAPTAIN Mills	πDAR	Ar	
JSNS^2	πDAR		
ESS	πDAR		
CHILLAX	Reactor	Ar	
CONNIE	Reactor	Si	
CONUS	Reactor	Ge	
MINER	Reactor	Ge, Si	
NEON	Reactor	Na	
NUCLEUS	Reactor		
NUXE	Reactor	Xe	
PALEOCCENE	Paleo		
Ricochet	Reactor	Ge, Zn	
RED-100	Reactor	Xe	
NuGen	Reactor		
SBC	Reactor	Ar	
TEXONO	Reactor	Ge	
NEWSG	Reactor	H, He, C, Ne	

Multiple measurements underway or planned for CEvNS - arxiv 2203.07361

Complementary interplay with Parity Violating Electron Scattering - arxiv 2203.06853

- Determination of form factor from PVES can be used (with theory) to improve predictions and reach of CEvNS programs

Summary

A robust understanding of neutrino interactions is important to answer many of the open questions we face today:

BSM: sterile neutrinos, light dark matter, NSI, precision tests of SM

Astrophysics: supernova bursts, solar models

Three flavor oscillation: θ_{23} octant, mass hierarchy, CP violation.
Tests of neutrino mixing model

More BSM: proton decay

Summary

A robust understanding of neutrino interactions is important to answer many of the open questions we face today

There are multiple efforts planned or underway, to inform theory and simulation:

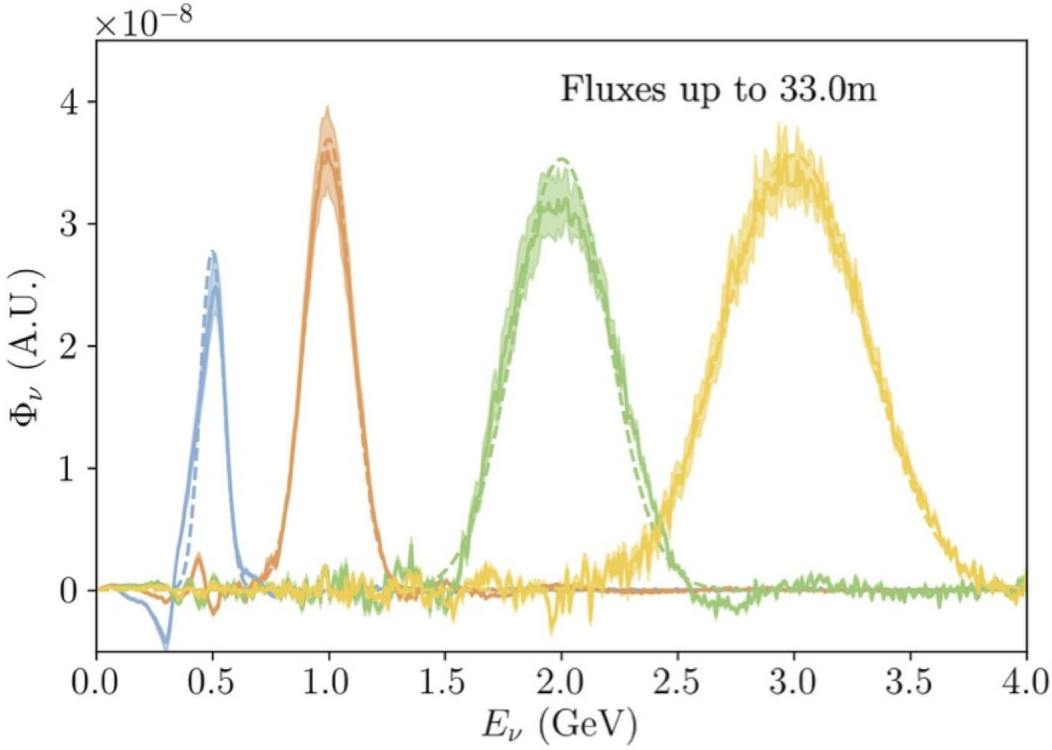
- Measurements from the current near detector program (T2K, NOvA), short baseline program (SBN), and external measurements (MINERvA, ANNIE, NINJA, nuSTORM, and more)
- Future experiments, like DUNE, have incorporated neutrino interaction measurements into their (near detector) design
- External measurements, including electron scattering and H/D targets, are complementary to information at near detectors
- For low energy, CEvNS measurements in combination with PVES, will provide a new channel for physics

Backup

Another view of the necessity of precision modelling

From: DUNE ND CDR:

https://arxiv.org/pdf/2103.13910.pdf



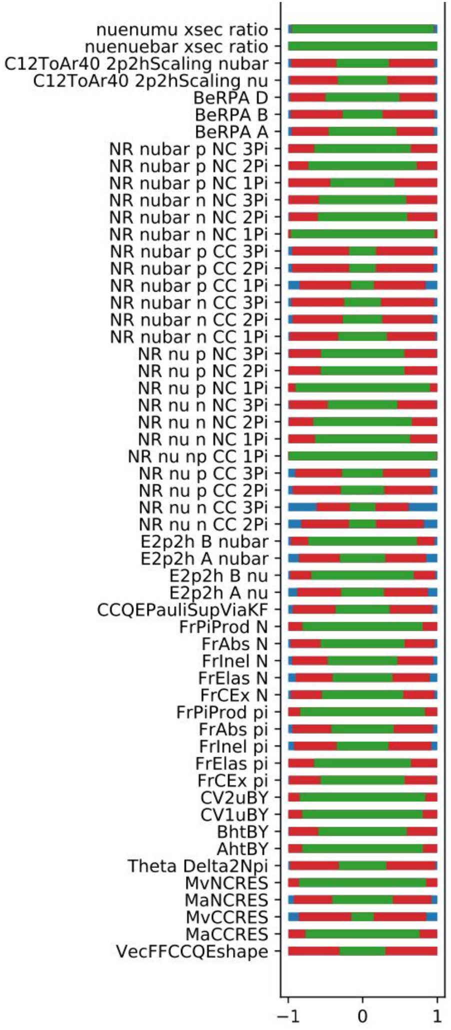
What we learn at the ND: parameter constraints

From: DUNE Physics TDR, Fig 5.34

https://arxiv.org/pdf/2002.03005.pdf

What's not obvious here:

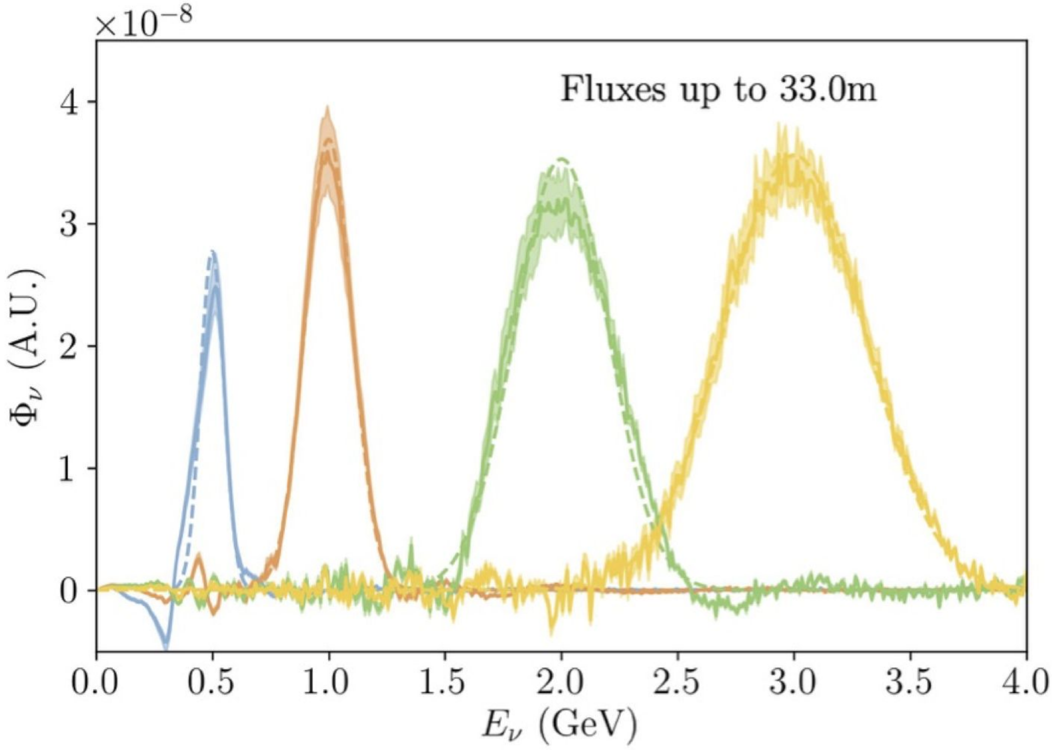
- Important measurements needed by THEORY from electron scattering
- How the model development needs go with time (iterative process takes time, this is at the end)
- What if the model is wrong? (PRISM, electron scattering)



Example: DUNE near detector complex

From: DUNE ND CDR:

https://arxiv.org/pdf/2103.13910.pdf



Why is electron scattering a key component of the current and future program?

From: Electron scattering white paper https://arxiv.org/abs/2203.06853 - *credit of many here!*

To have a robust model requires multiple tests of the model

- *Elec scattering is highly complementary to the ND program, and enhances ND physics reach in a novel way;*
- *Resonance region expected to be very important - major discrepancies and need for electron measurements for theory*

We know next to nothing in transition region, which is also where the power of PRISM decreases

- *need H/D measurements and need to build a basic and complete model of multiplicity and final state composition; atm nu physics may also really need this region*

Both of these problems need TIME and DATA to confront

- *mature state of T2K/NOvA combined with electron scattering program is exciting*