MANCHESTER 1824
The University of Manchester

Neutrino scattering (WG 2):

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Elena Gramellini, University of Manchester
NuFact 2023, August 21st , Seoul

Neutrinos are difficult

Neutrinos are the most abundant massive particle in the universe, and one of the least understood.
They are neutral: we can't directly detect them. We can study them only if they interact, but…

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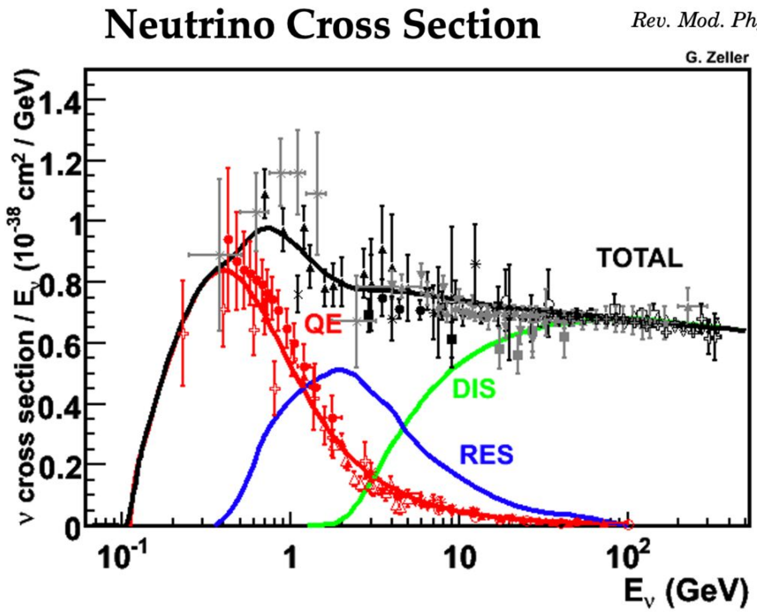
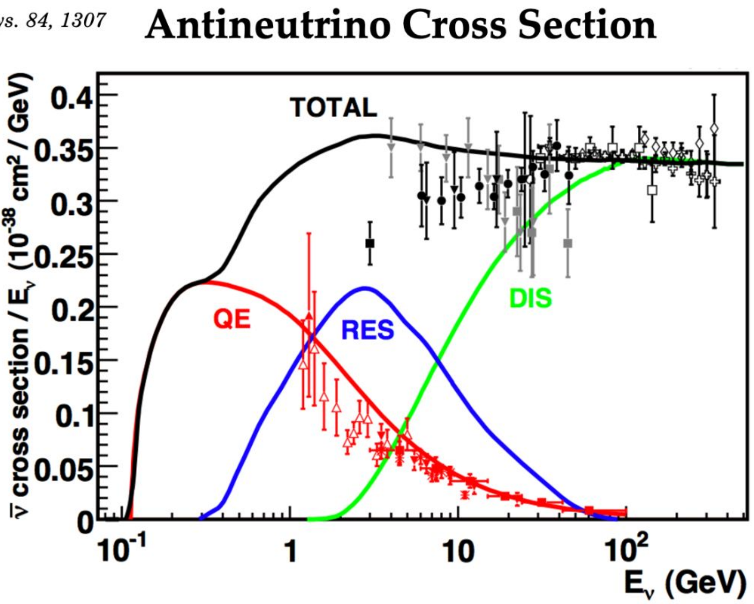


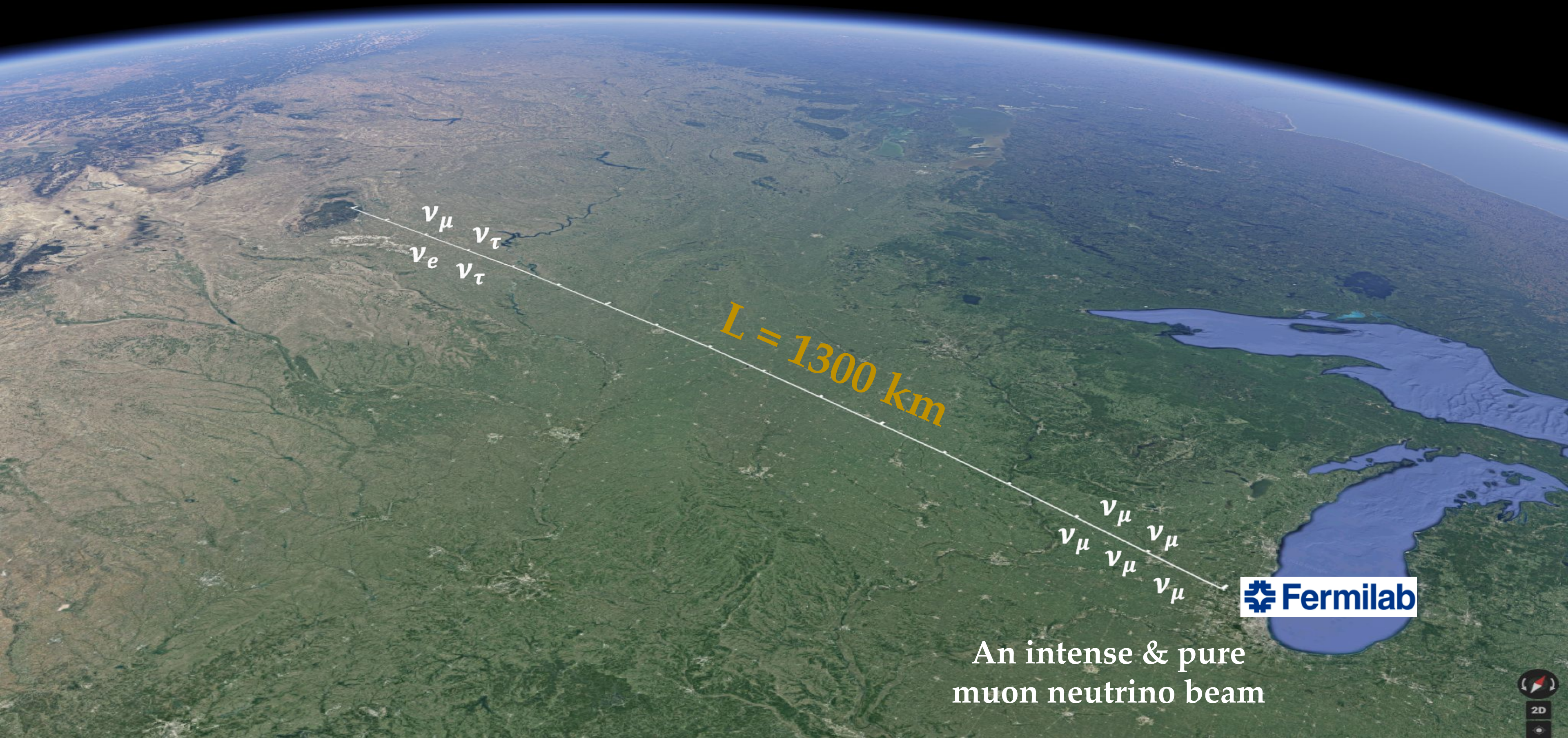
Rev. Mod. Phys. 84, 1307



Neutrinos **don't really like to interact**!

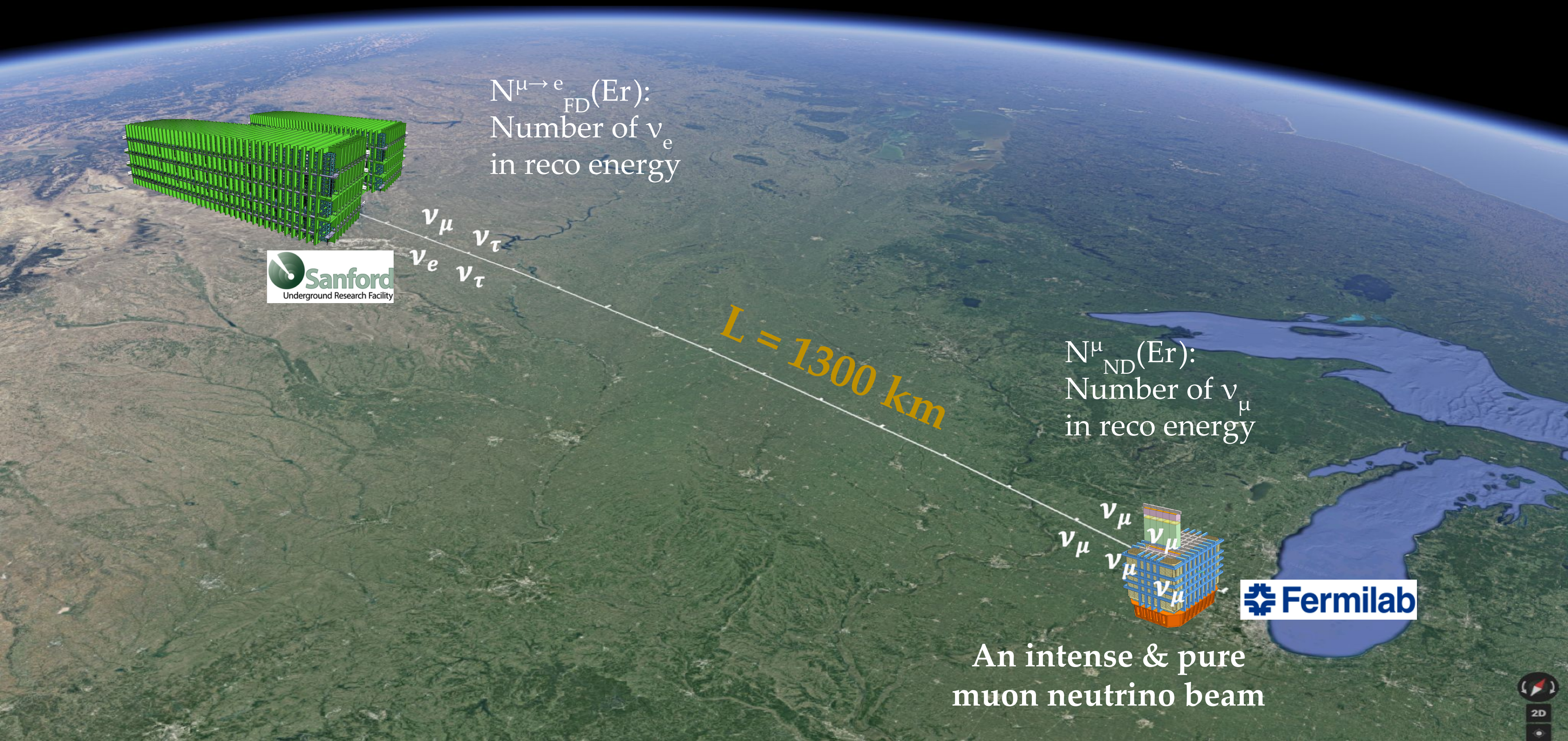
ν-oscillations experiment 101

***STEP 1**: Making a beam*



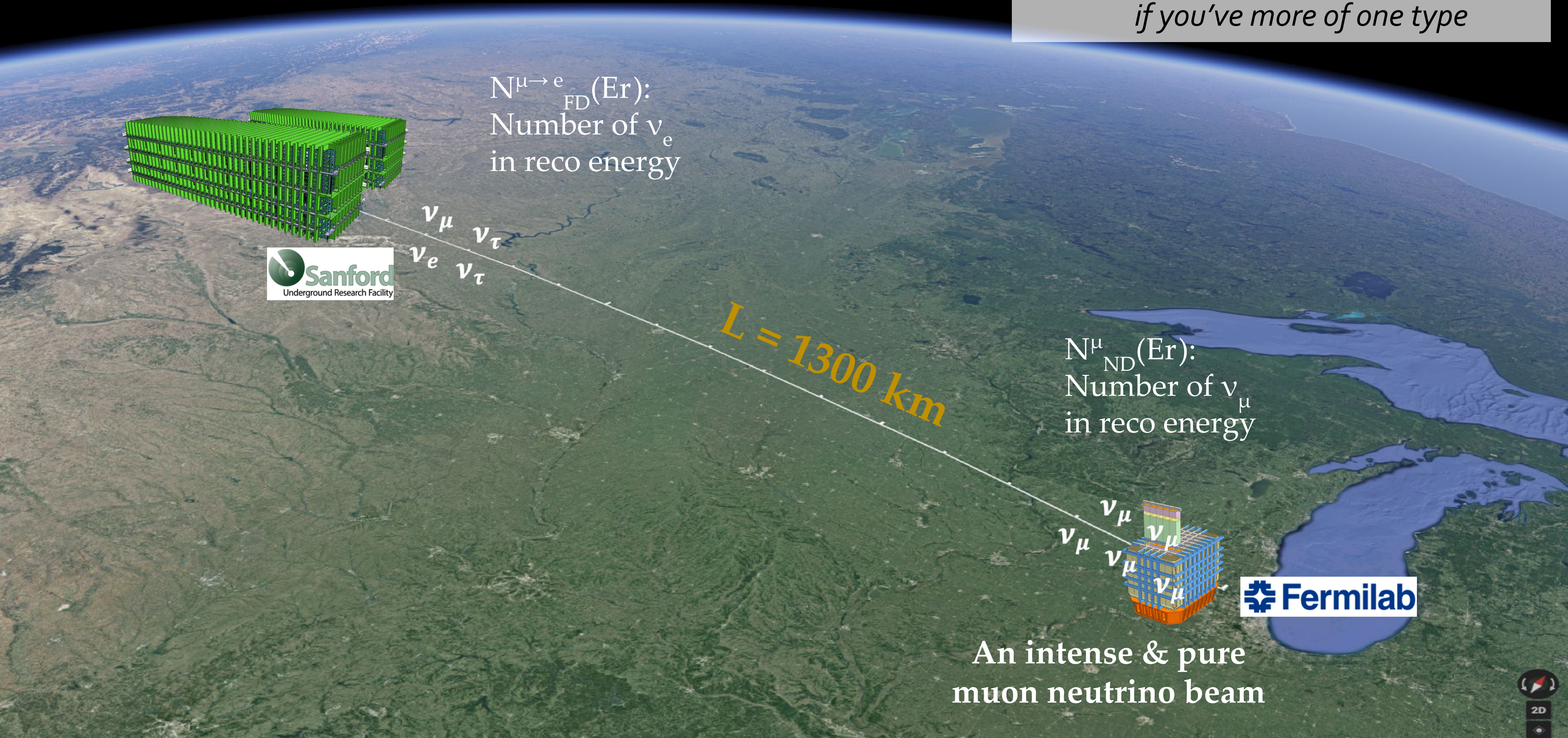
ν-oscillations experiment 101

***STEP 1**: Making a beam*
***STEP 2**: Checking twice*



ν-oscillations experiment 101

STEP 1: *Making a beam*
STEP 2: *Checking twice*
STEP 3: *Gonna find out*
if you've more of one type



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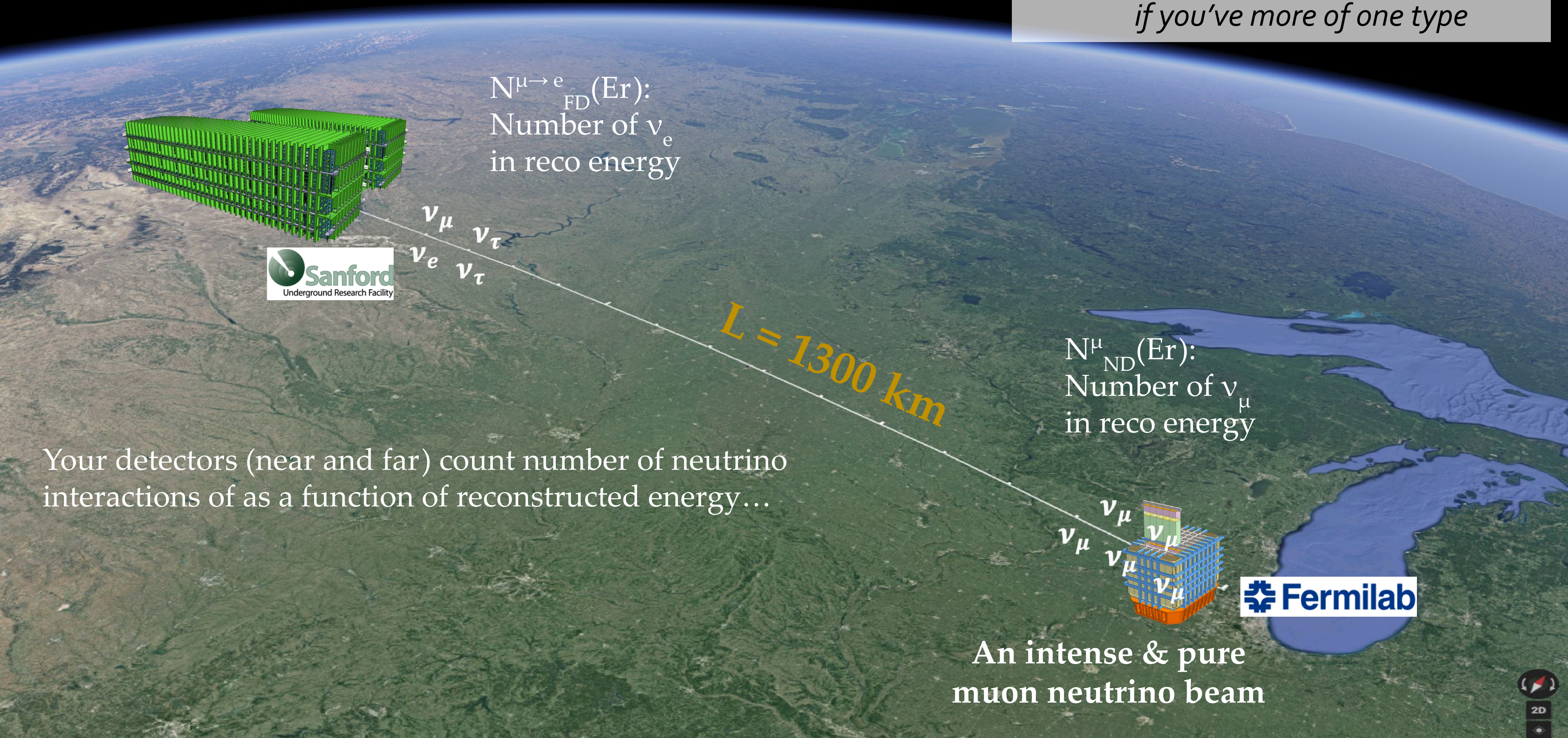

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$N^{\mu\rightarrow e}_{FD}(Er) = \int \phi^{\mu}_{FD}\,(Et)\, \mathbf{P_{\mu\rightarrow e}(Et)}\sigma_e(Et)\varepsilon_e(Et)U_{FD}(Et, Er)dEt$

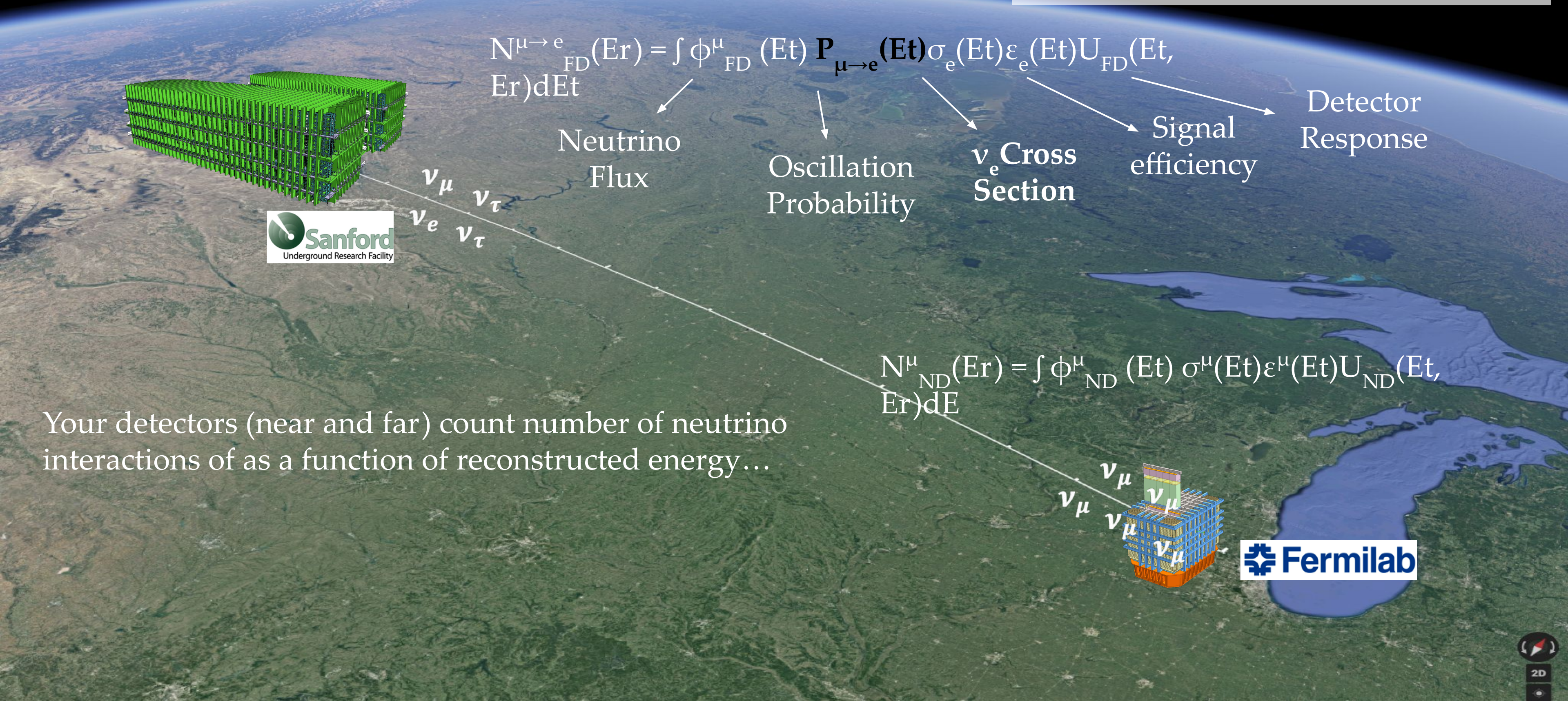
Neutrino Flux

Oscillation Probability

ν_e Cross Section

Signal efficiency

Detector Response



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Your detectors (near and far) count number of neutrino interactions of as a function of reconstructed energy…

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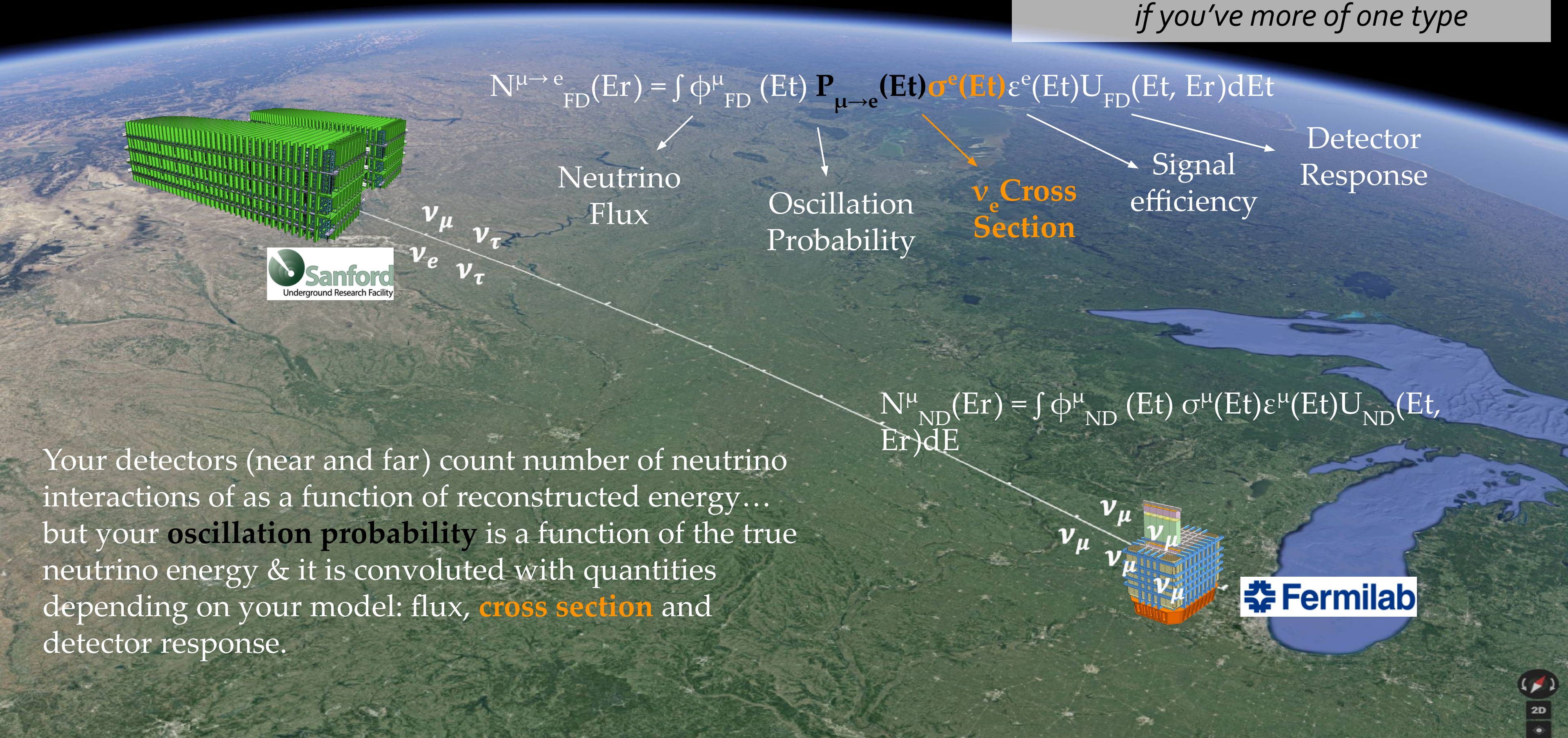
Neutrino Flux — Oscillation Probability — ν_e Cross Section — Signal efficiency — Detector Response



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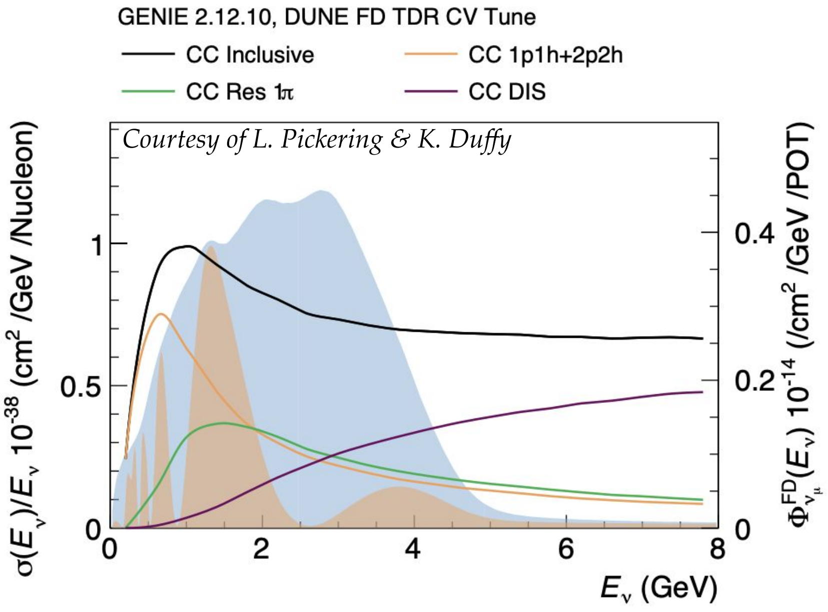
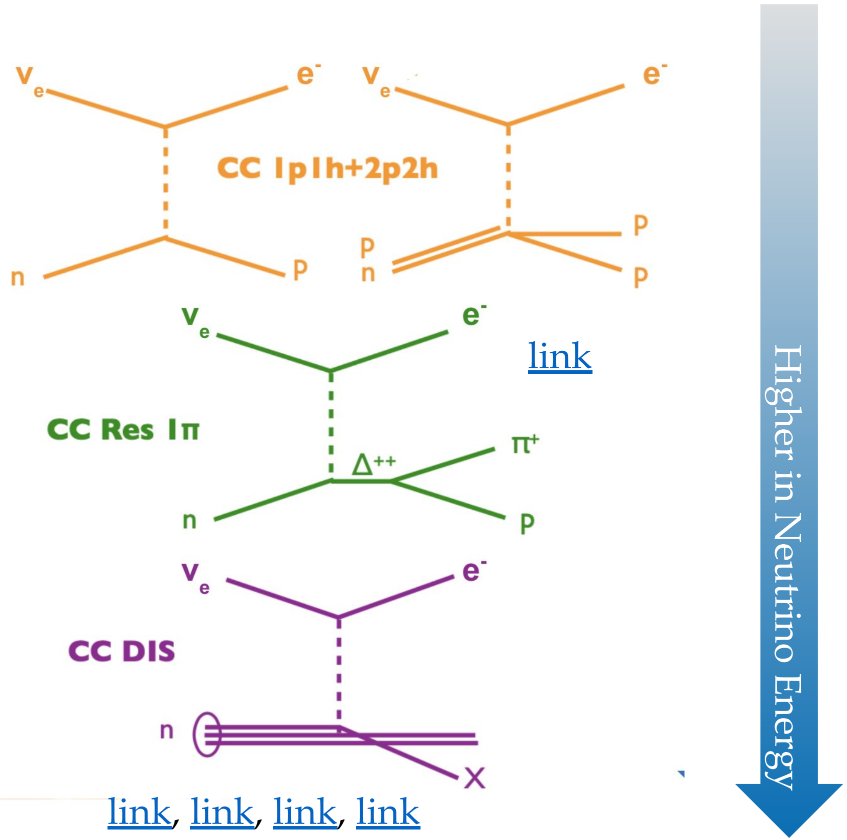
Your detectors (near and far) count number of neutrino interactions of as a function of reconstructed energy… but your **oscillation probability** is a function of the true neutrino energy & it is convoluted with quantities depending on your model: flux, **cross section** and detector response.

Why **Step 2** is hard

In broad energy beams several underlying interactions are available
→ different signatures at same energy





link, link, link, link

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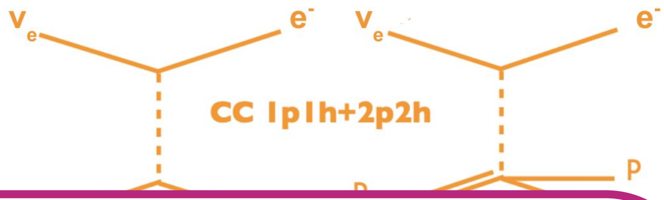
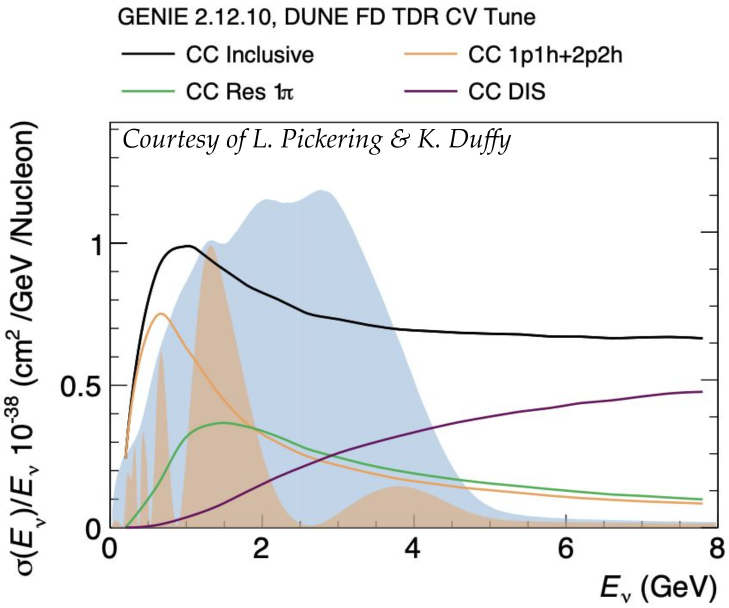




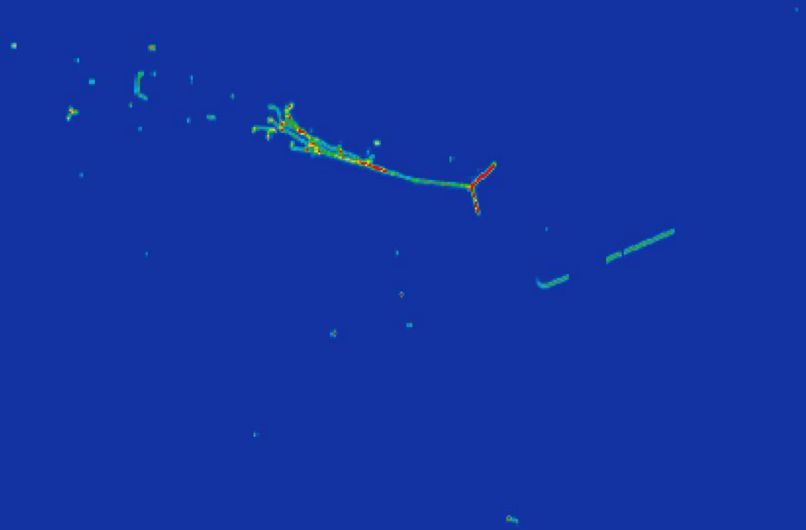
The flux and cross section models are convoluted.

The cross section will not cancel out and is crucial for extraction of the oscillation parameters.

Higher in Neutrino Energy

Why **Step 2** is hard

This is all you see in your detector:
we never see the neutrino directly!



Event display courtesy of μBooNE

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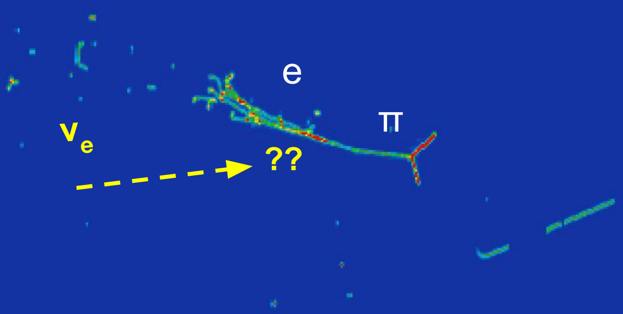

You identify the final state particles to **infer neutrino flavor:** count how many ν_e and ν_μ

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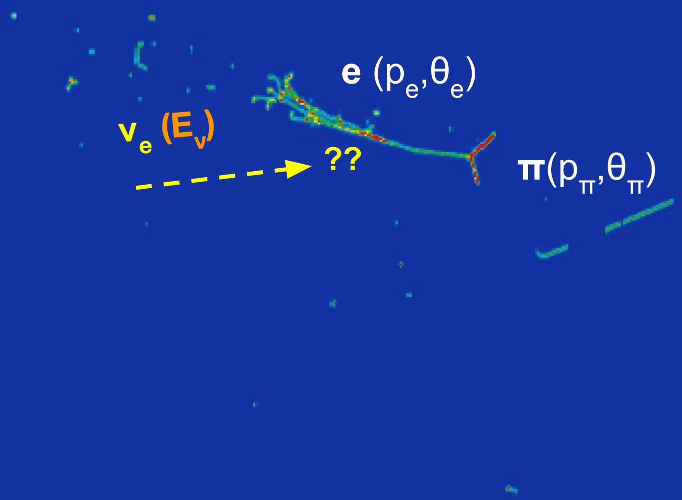

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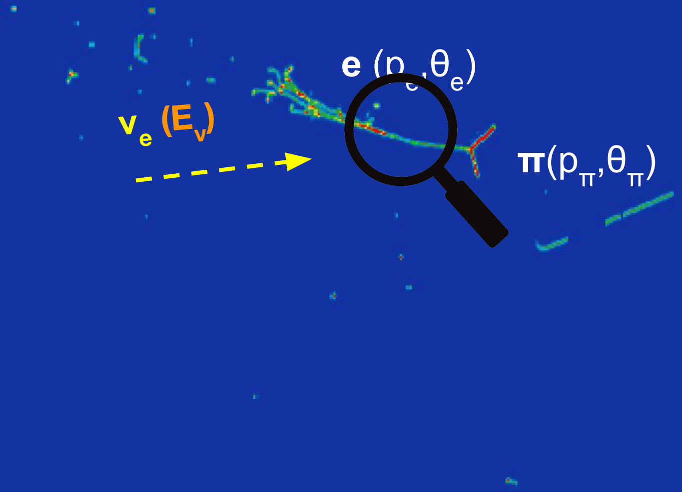
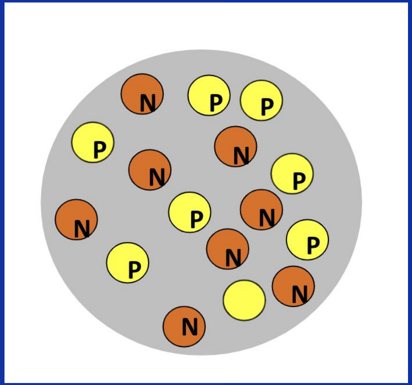


What gets in between



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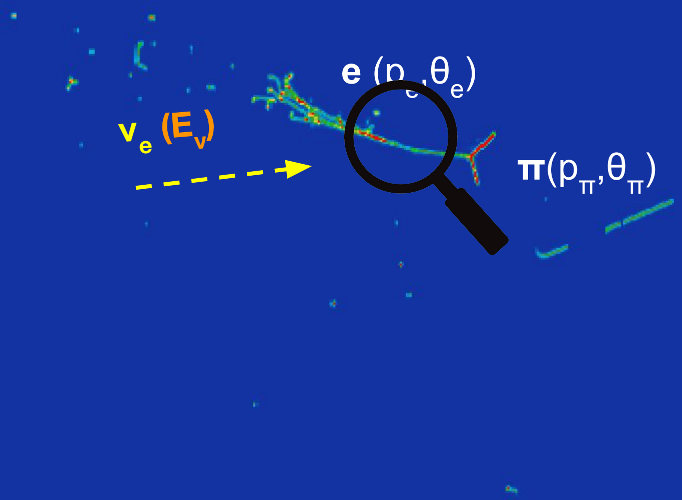

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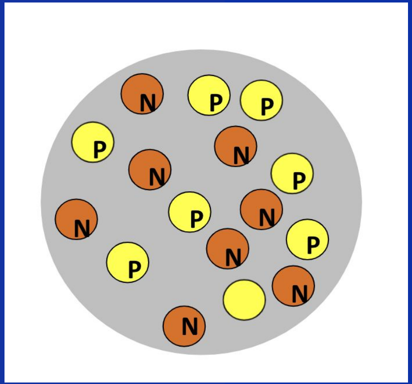

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Cross-section models relate measured particles to (un-measurable) neutrinos, need to correctly predict the ν-N interaction make-up as a function of energy

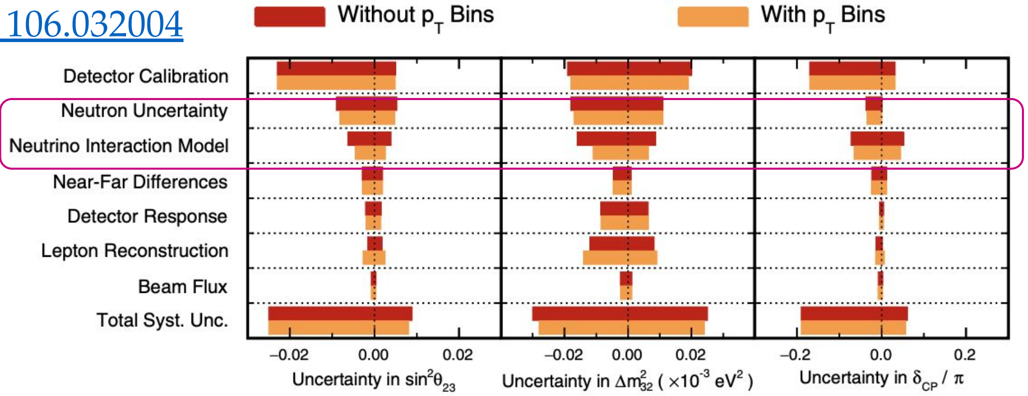
How does this feeds back into neutrino "new" physics?
CP Violation @ long baseline

Type of Uncertainty	$\nu_e/\bar{\nu}_e$ Candidate Relative Uncertainty (%)
Super-K Detector Model	1.5
Pion Final State Interaction and Rescattering Model	1.6
Neutrino Production and Interaction Model Constrained by ND280 Data	2.7
Electron Neutrino and Antineutrino Interaction Model	3.0
Nucleon Removal Energy in Interaction Model	3.7
Modeling of Neutral Current Interactions with Single γ Production	1.5
Modeling of Other Neutral Current Interactions	0.2
Total Systematic Uncertainty	6.0

T2K, Nature 2020

"uncertainty on the ν_e and $\bar{\nu}_e$ cross-sections… [is] the 2nd largest single source of systematic uncertainty in the CP asymmetry measurement."

NOνA PRD 106.032004



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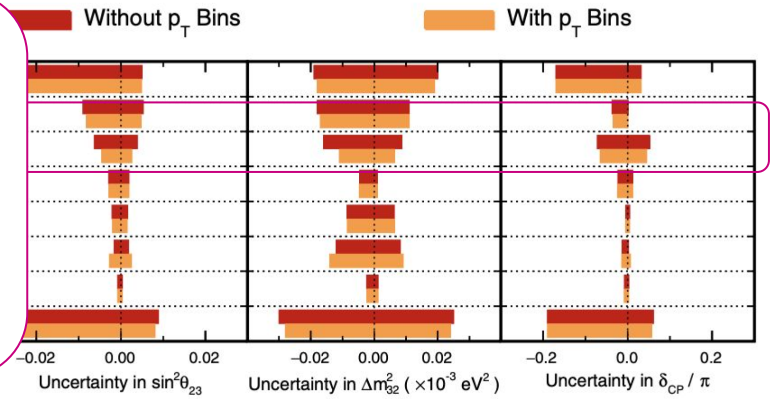
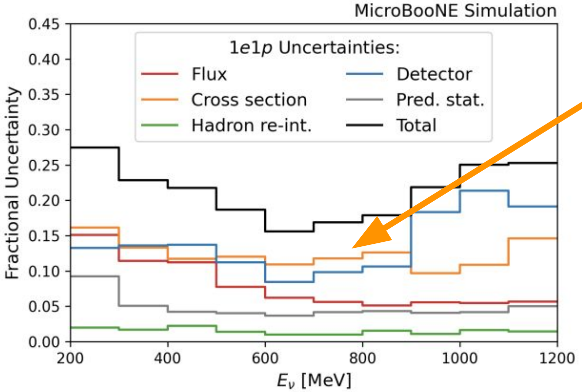
DUNE/HyperK/JUNO
CP violation uncertainty budget is extremely stringent.
We need to do better than this!

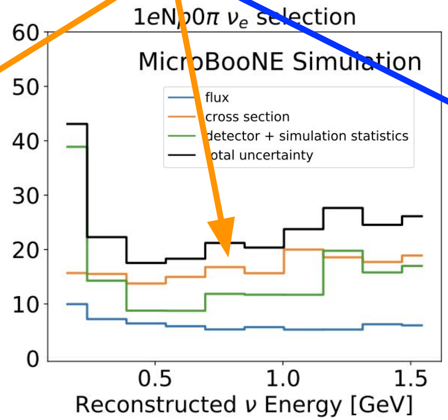


How does this feeds back into neutrino “new” physics? Anomaly hunting @ short baseline

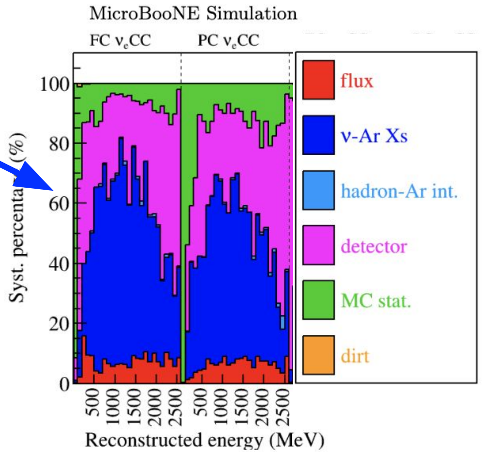
ν_e Cross Section Systematics



CC-QE like
Phys. Rev. D105, 112003 (2022)



Pionless
Phys. Rev. D105, 112004 (2022)



Inclusive
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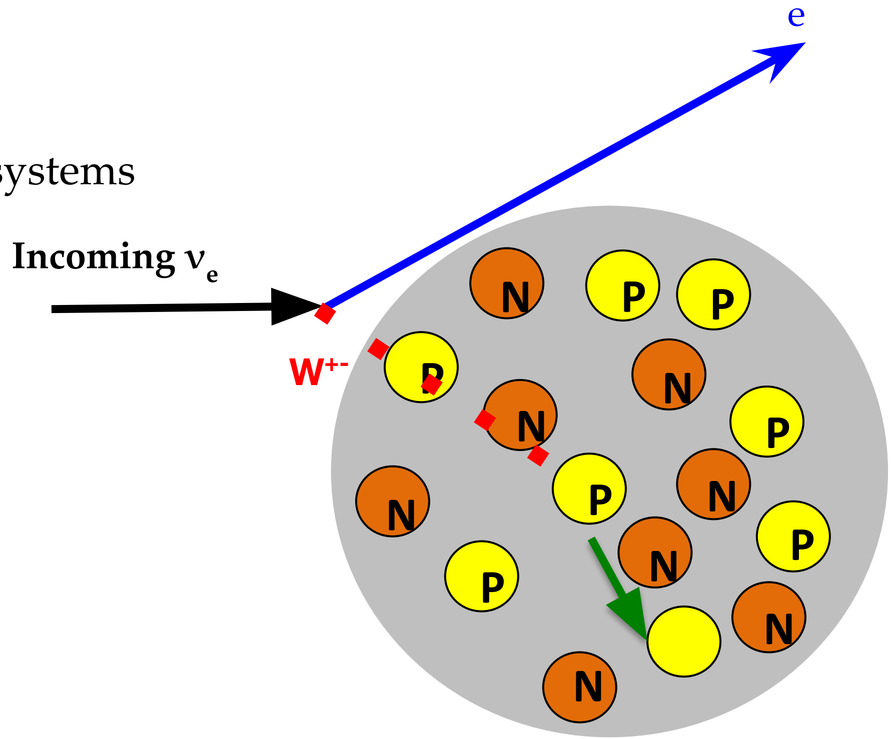
The Nucleus is a Complex System

Neutrinos do not interact in a vacuum:
they scattering off complex nuclear and atomic systems



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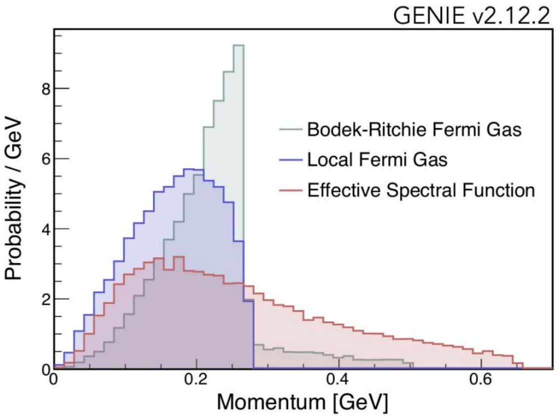
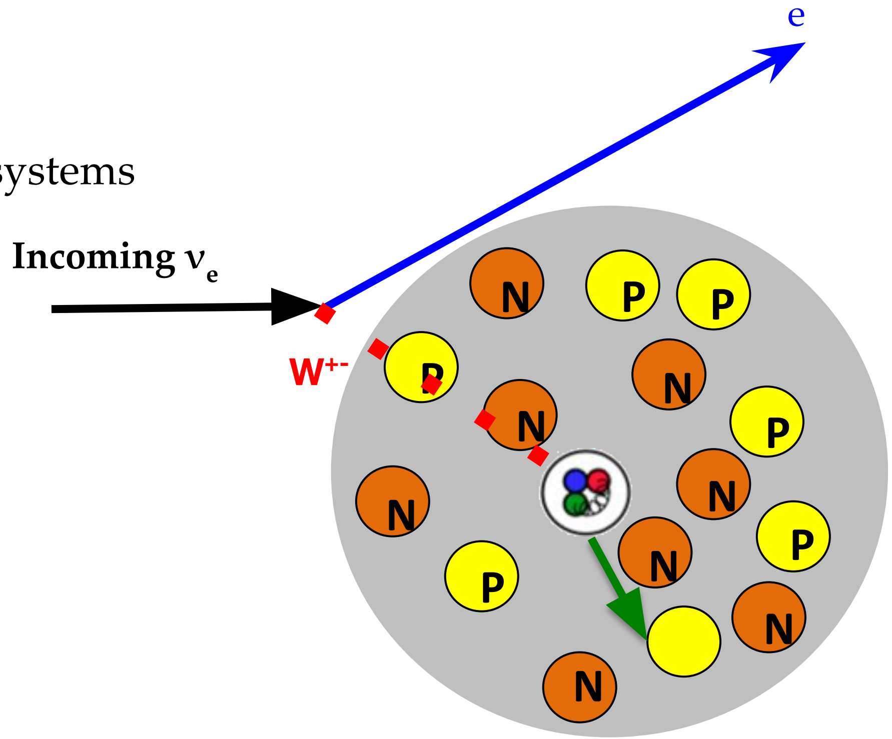
The nucleon is not at rest!
Fermi Motion must be modeled



Credit: M. Del Tutto



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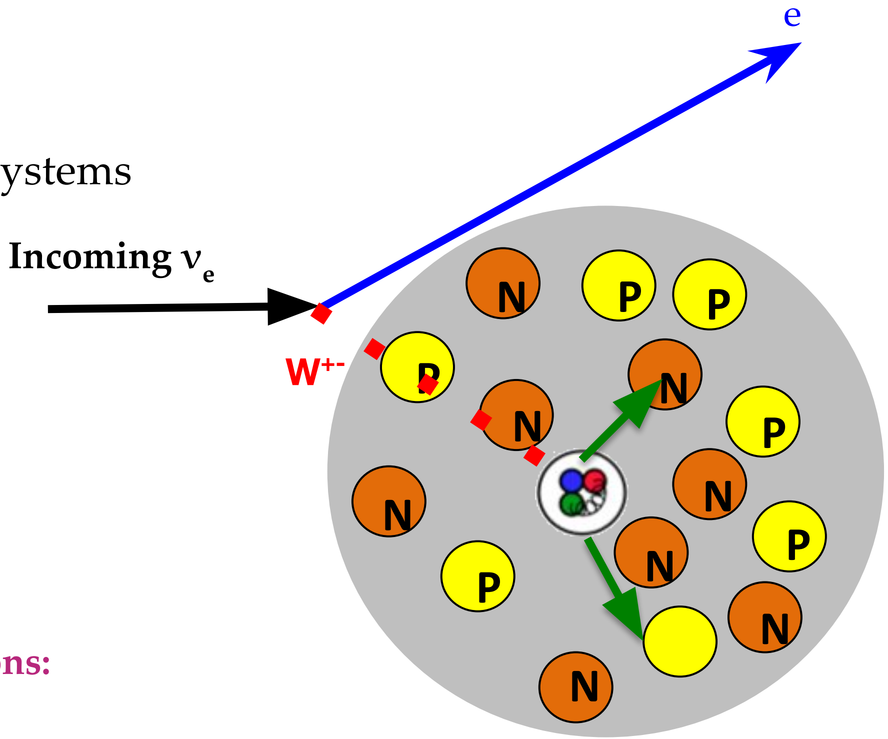

Strongly interacting nucleons

→ alteration of electroweak couplings (modeled w/RPA or more complex models link)

→ rich physics effects for forward-going charged lepton

Interactions with correlated pair of nucleons:

→ Meson Exchange Current (**MEC**)

→ Short Range Correlations

 Elena Gramellini | elena.gramellini@manchester.ac.uk

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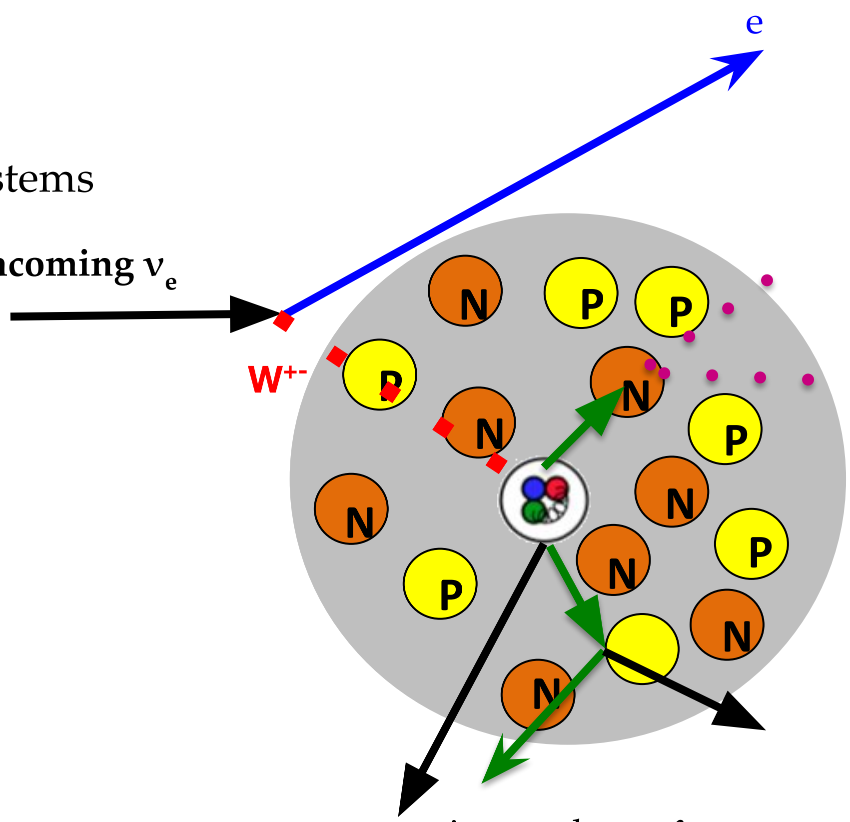
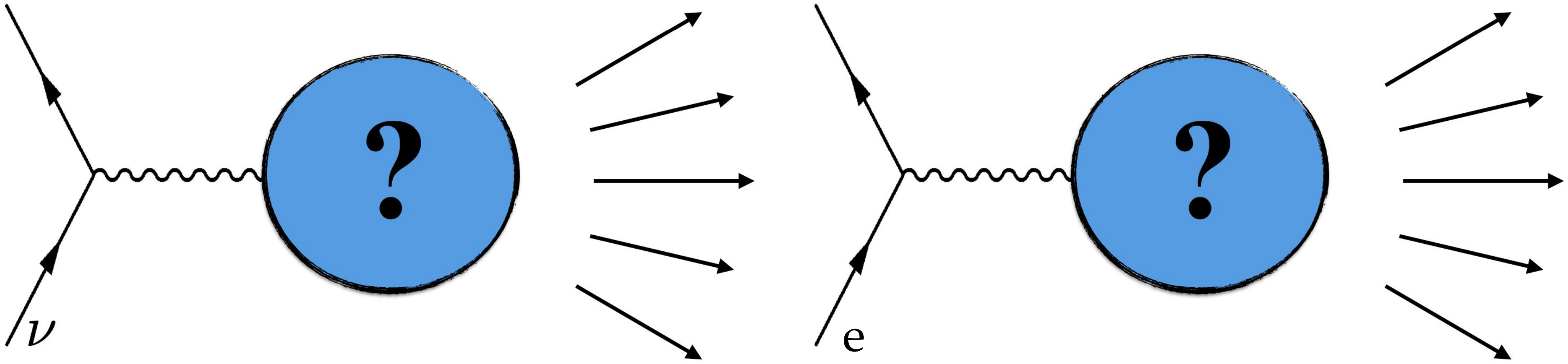


Final State Interactions
→ charged and neutral mesons & nucleons
link

2+ outgoing protons possible even for "true" CCQE events

A word on charge lepton scattering



Electron scattering experiments enormous advantage: the energy of the incoming lepton is KNOWN. Data from these experiments helps us constrain “the vector” portion of the V-A interaction common to neutrinos! Many contributions link, link,link, link

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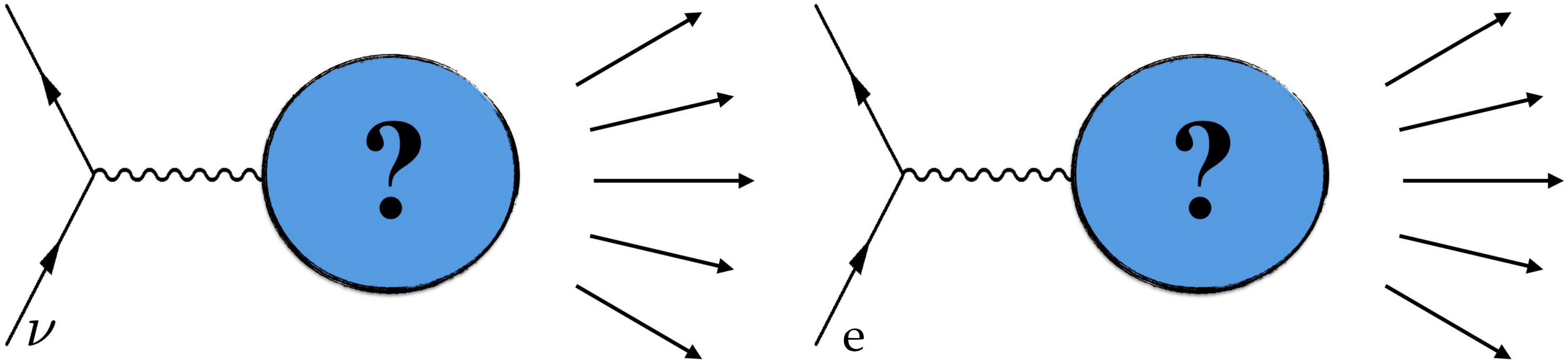
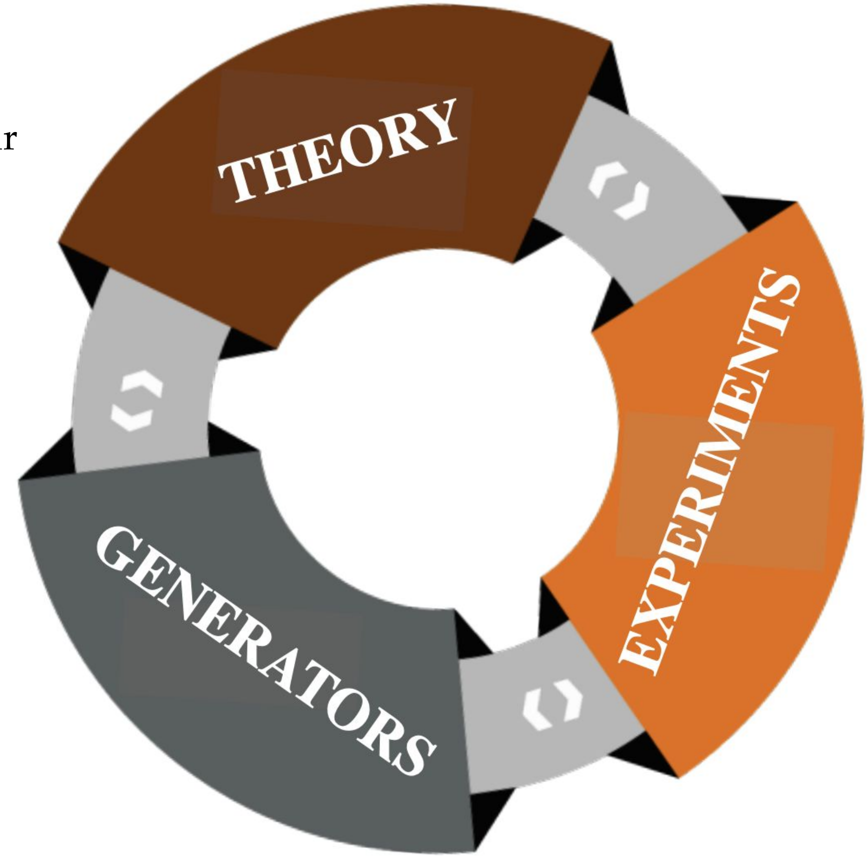


Electron scattering experiments enormous advantage: the energy of the incoming lepton is KNOWN. Data from these experiments helps us constrain "the vector" portion of the V-A interaction common to neutrinos! To probe the axial nucleon form factor we can only use neutrinos… talk on Tue!

It all plays together

Continuous improvement of our understanding neutrino interactions from the interplay between model development (theory & implementation) and cross section results.



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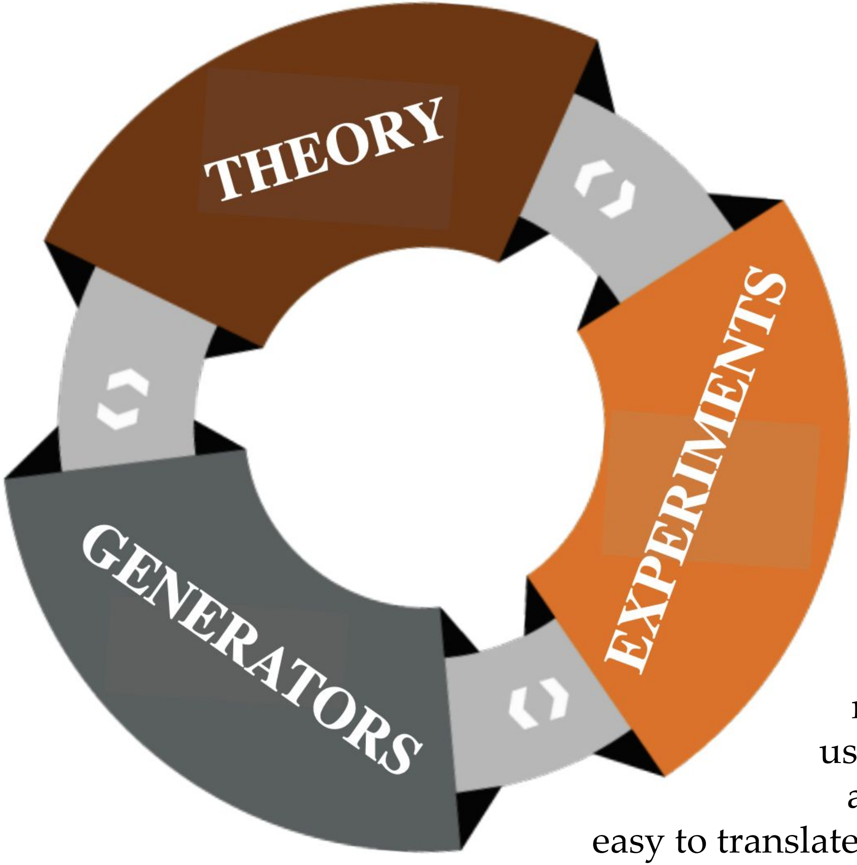
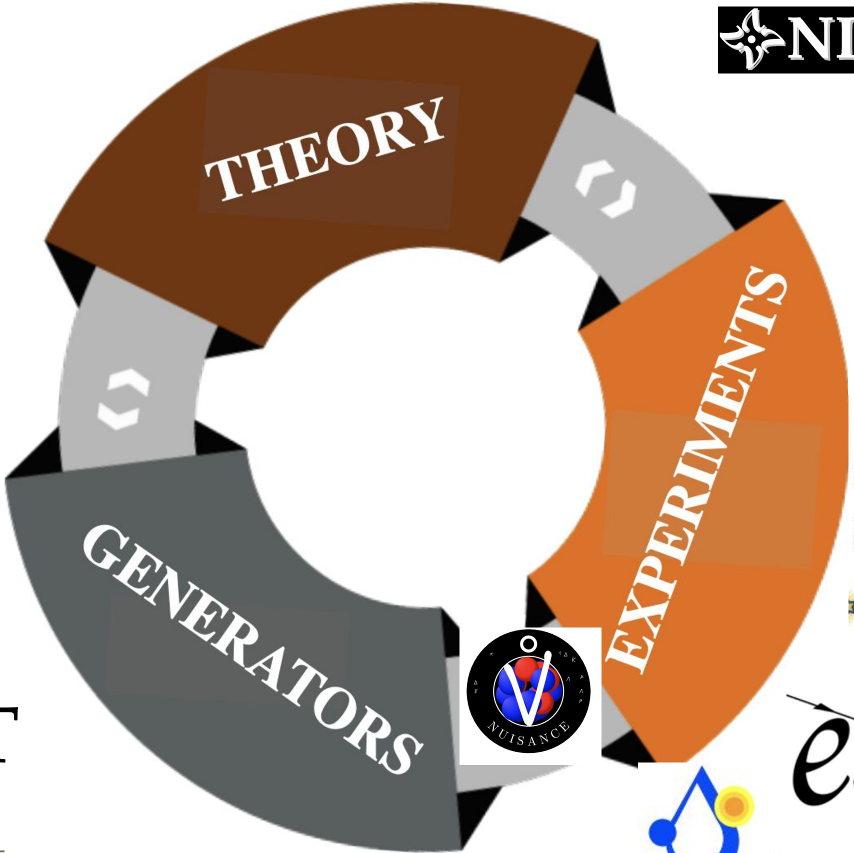


Aim to perform measurements in a form useful for model building, and produce predictions easy to translate into usable observables

It all plays together



NINJA

COHERENT SNS

ICECUBE NEUTRINO OBSERVATORY

MINERvA

LHC Scattering and Neutrino Detector at the LHC

SBN Program

NOvA

T2K

e4V

FASER

annie

NUISANCE

Genie

NuWro Wroclaw Neutrino Event Generator

NEUT

GiBUU The Giessen Boltzma

This week for WG2

Experimental efforts:
→ 14 talks

Theory inputs
→ 8 talks

Generator developments
→ 4 talks + 5 at the boundary with theory + 2 at the boundary with experiment

Joint session WG1-WG2:
Constraining Xsec systematics / Xsec tuning
→ 6 talks

This week for WG2: Schedule (please check the indico here)

	Mon	Tue	Wed	Thu	Fri	Sat
8:30-10:30		Plenary Experimental results SF from e-scattering			Generators	
11:00-13:00	YOU ARE HERE		Poster session		DIS	Closeout
14:00-16:00	Plenary XS future experiments theory and event gen	Theory			Experiment	
16:30-18:30		WG1-WG2 joint Axial form factor			Experiment	

WG2 Plenaries

This afternoon:
Cross Section for future experiments
-- Laura Munteanu

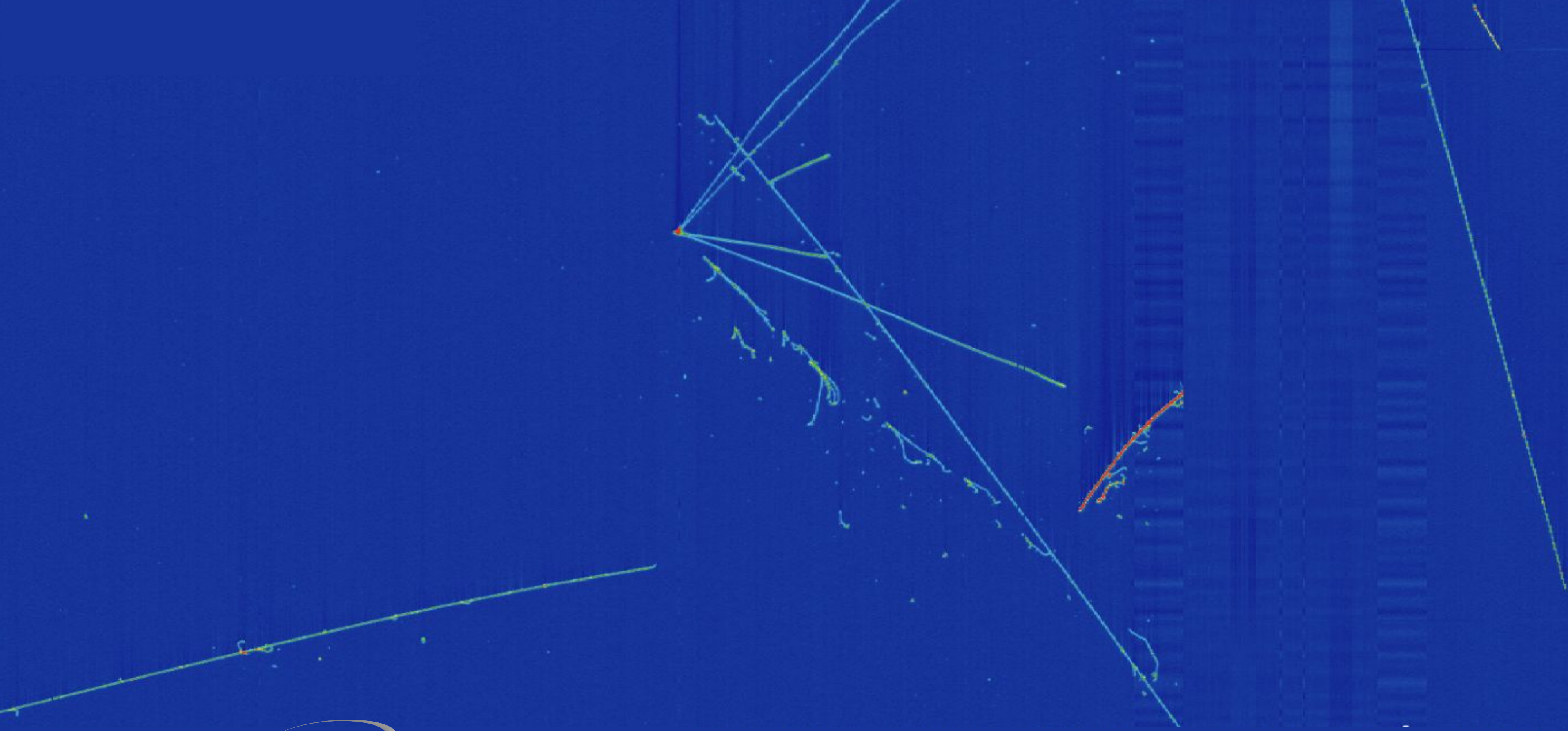
Modeling neutrino-nucleus cross section: theory and generators
-- Natalie Yvonne Jachowicz

Tomorrow Morning:
Overview of cross section experimental results: Argon-Based technologies
-- Sophie Berkman

Overview of cross section experimental results: Non Argon-Based technologies
-- Raquel Castillo

Determination of the Argon spectral function from (e,e'p) data
-- Omar Benhar

In ν interaction physics much needs to be done…



Event display courtesy of μBooNE

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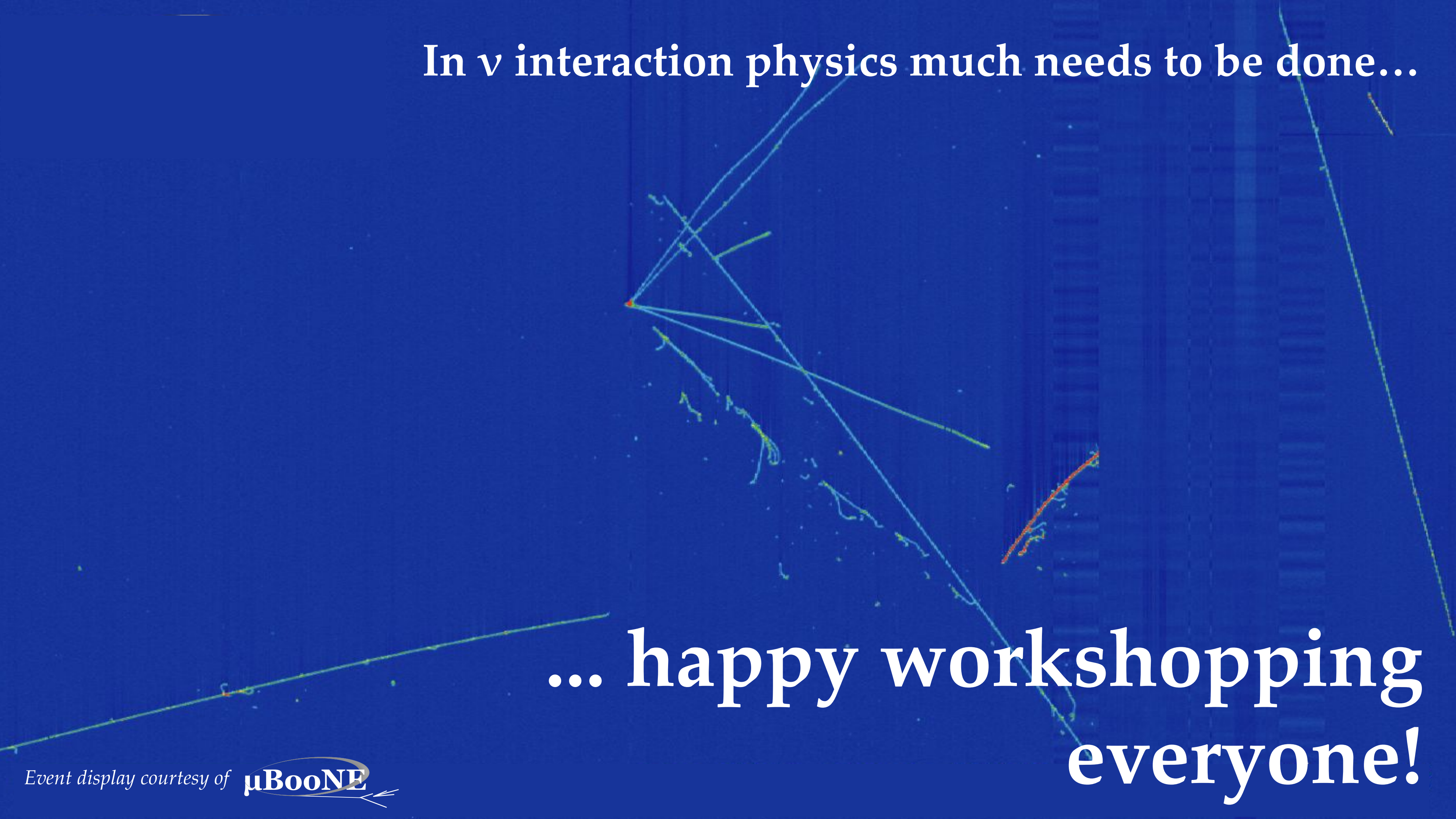
… happy workshopping everyone!



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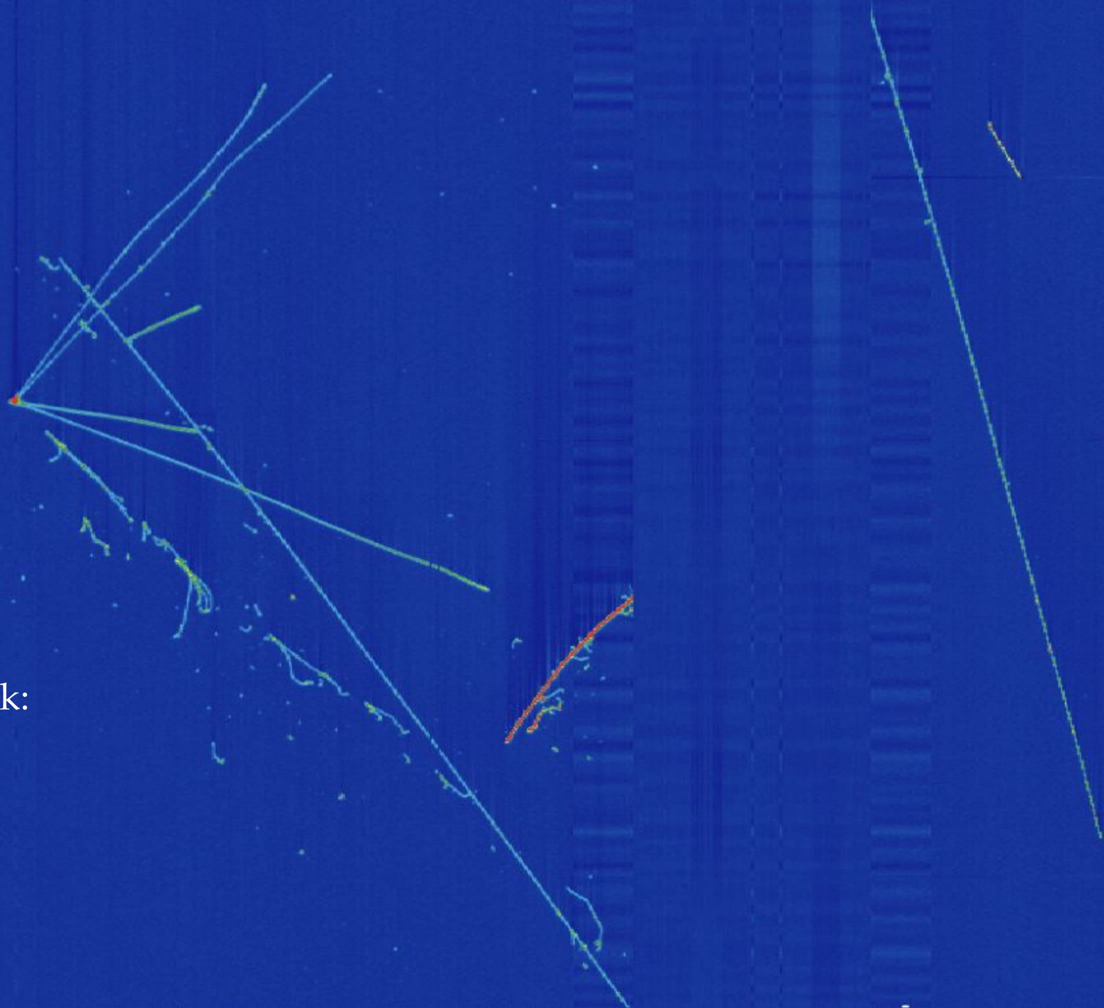
Thank you!

Special thanks for your help in preparing this talk:
Adi Ashkenazi



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