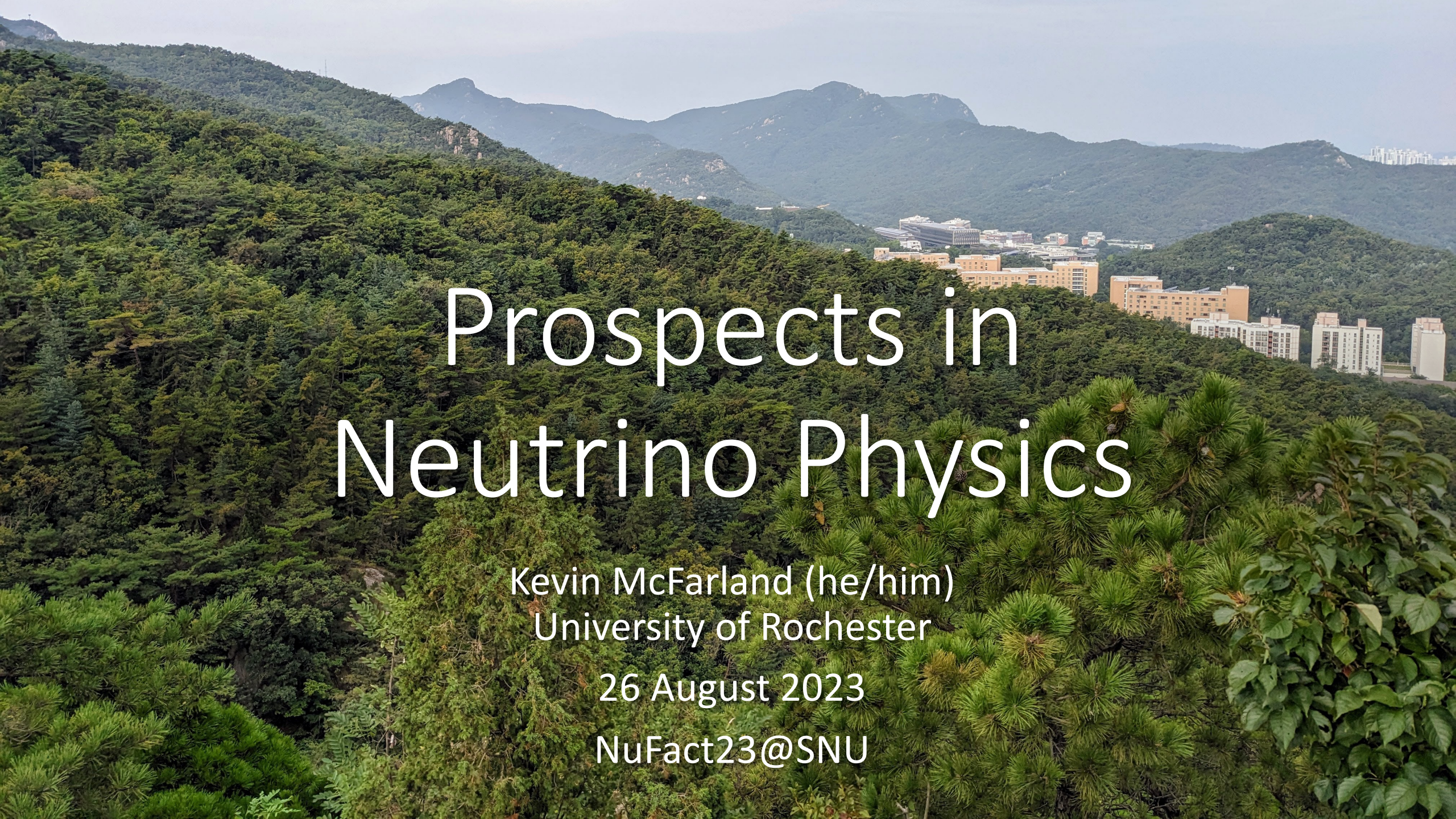

Prospects in Neutrino Physics

Kevin McFarland (he/him)
University of Rochester

26 August 2023

NuFact23@SNU

The first business of the last talk…

- We've enjoyed a wonderful and productive meeting this week at Seoul National University.
- We should thank the entire local organizing committee (at right) and especially our scientific organizers.

Johghee Yoo

Un-Ki Yang

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Prospects, not a Summary

- We've just heard wonderful summaries from our hard-working conveners. Thank you!

- Fortunately, my job today is not to summarize the summaries.
  - (I have enough of that in the other half of my job, thank you very much.)

- What is it that we should discuss under the heading of "prospect"?

Deconstruction of “Prospect”

- Prospect is word that comes from Latin
  - “Pro-” is a prefix meaning “before” or “forward”: pro-logue, pro-found, etc.
  - “Spect” is a root related to seeing or looking: spect-acle, spec-ular, etc.
- In modern English, it can mean many things:

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  - The likelihood of a future event
  - To search for something
  - An expansive view
- Which one of these should we discuss?

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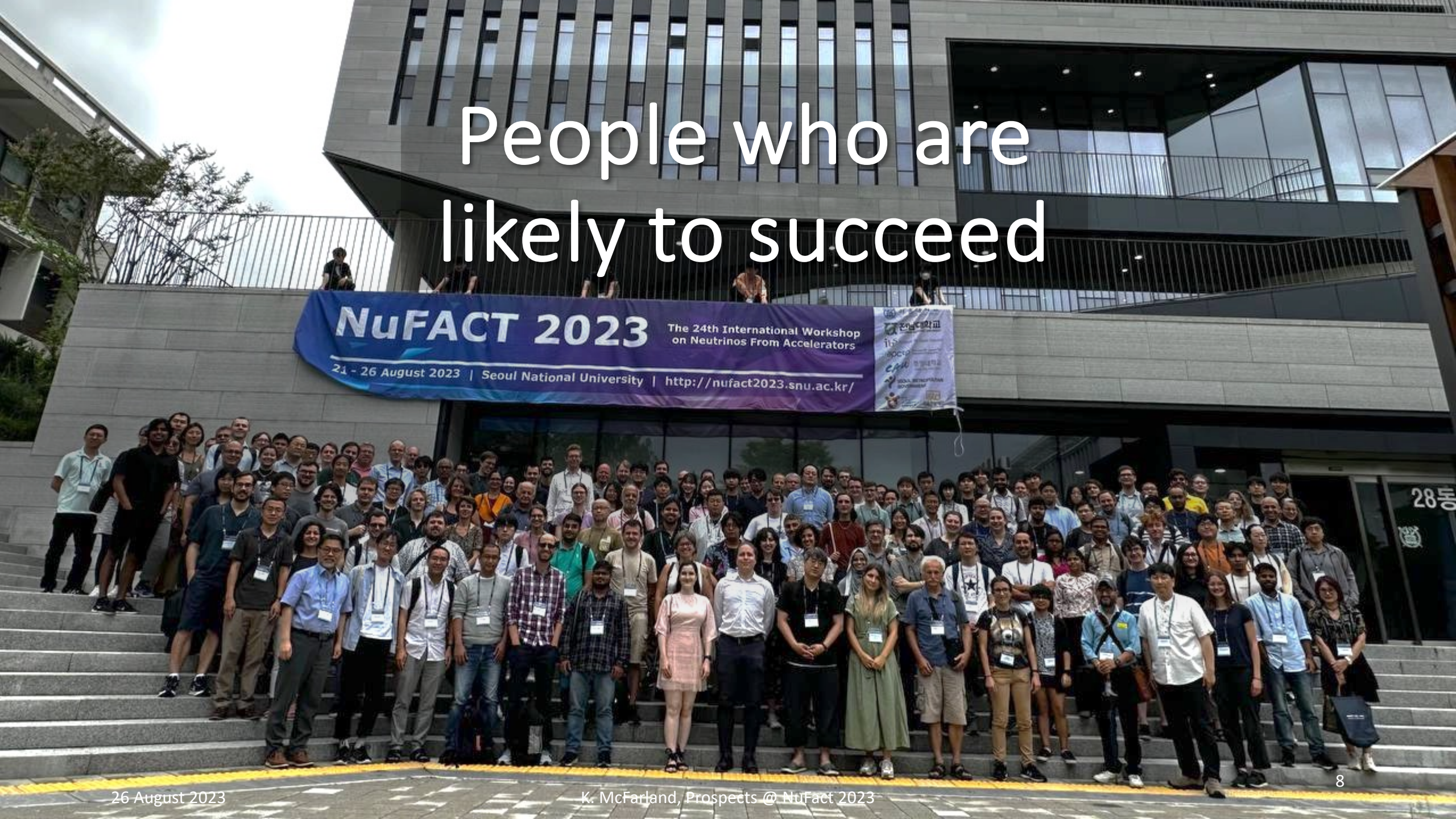
- Which one of these should we discuss?
  - Yes, please!

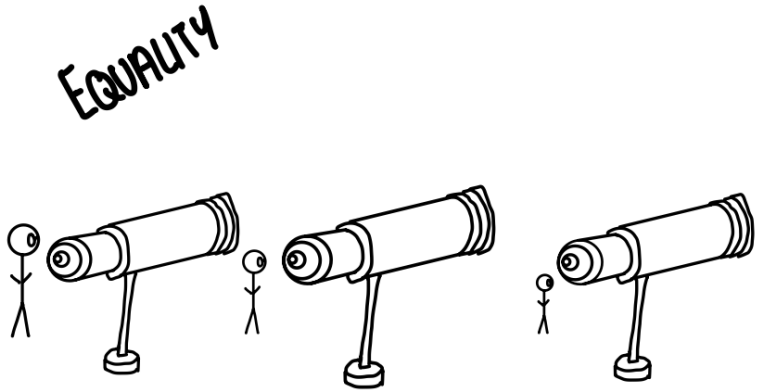
People who are likely to succeed



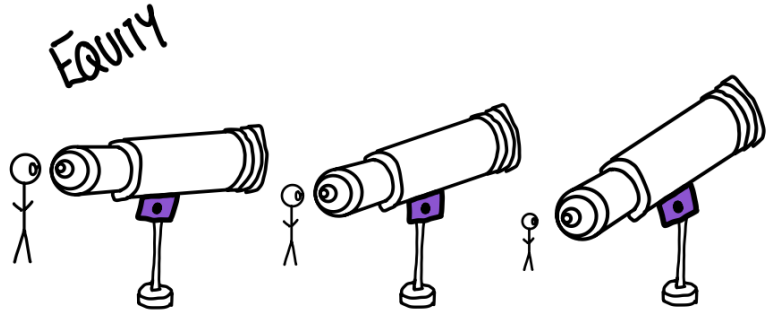
Who does neutrino (or lepton) physics?

- Eun-Joo Ahn told us about the history of invisible workers in the astronomy program at Mt. Wilson.

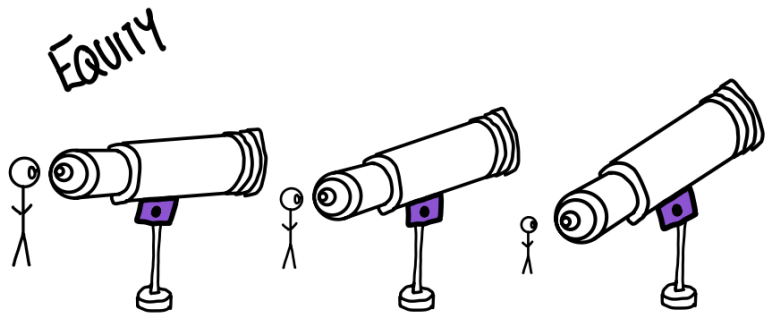
- The same decisions that rendered them invisible also limited their careers.



- Mia West told us about the benefits of efforts to include all contributors in our work.



Who does neutrino (or lepton) physics?



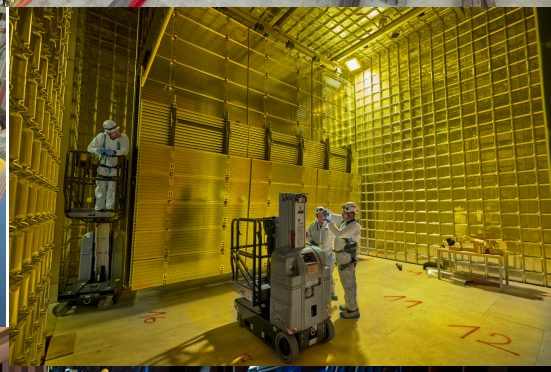
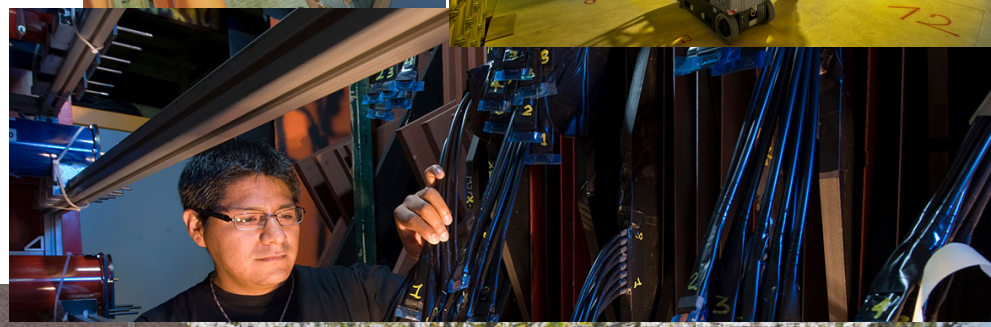
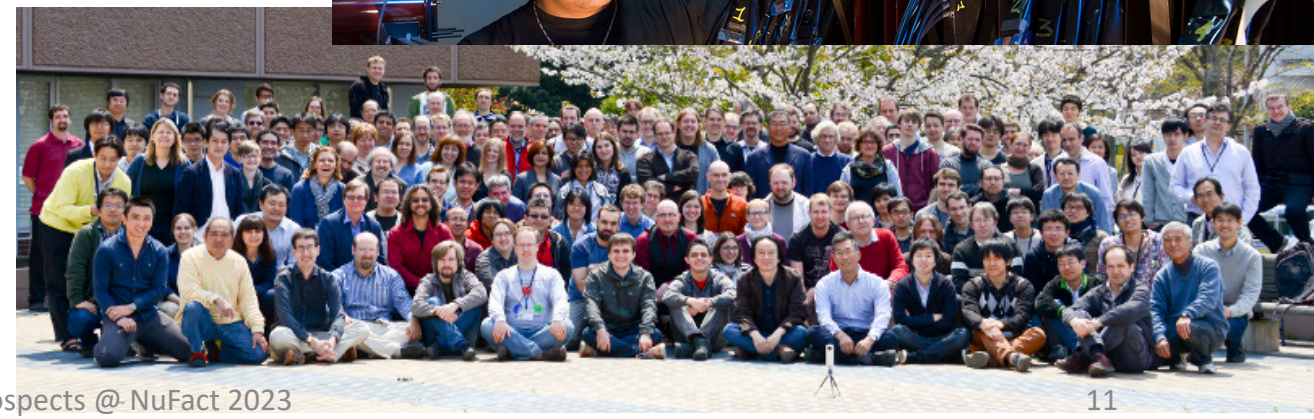
- The common thread is that ***humans*** do neutrino physics.
- We should treat each other as humans, with humanity.

- So let me introduce myself to you as a human…

Who am I, and why am I here?

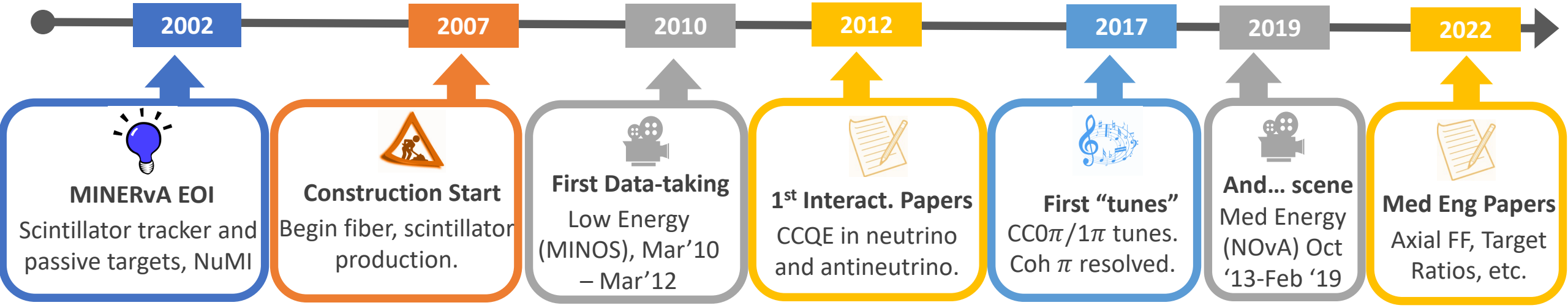
- I've been fortunate to work on neutrinos for a long time, through most of my career.
- NuTeV (1996-1998), a high energy experiment focused on measurement of NC/CC ratios in DIS as a test of the electroweak theory.
- MINERvA (2008-2019), a ~GeV neutrino interaction experiment.
- T2K (2009-), LBL oscillations at J-PARC.
- SBN-FD a.k.a. ICARUS (2021-), SBL oscillations at FNAL
- DUNE (future), LBL oscillations at FNAL.



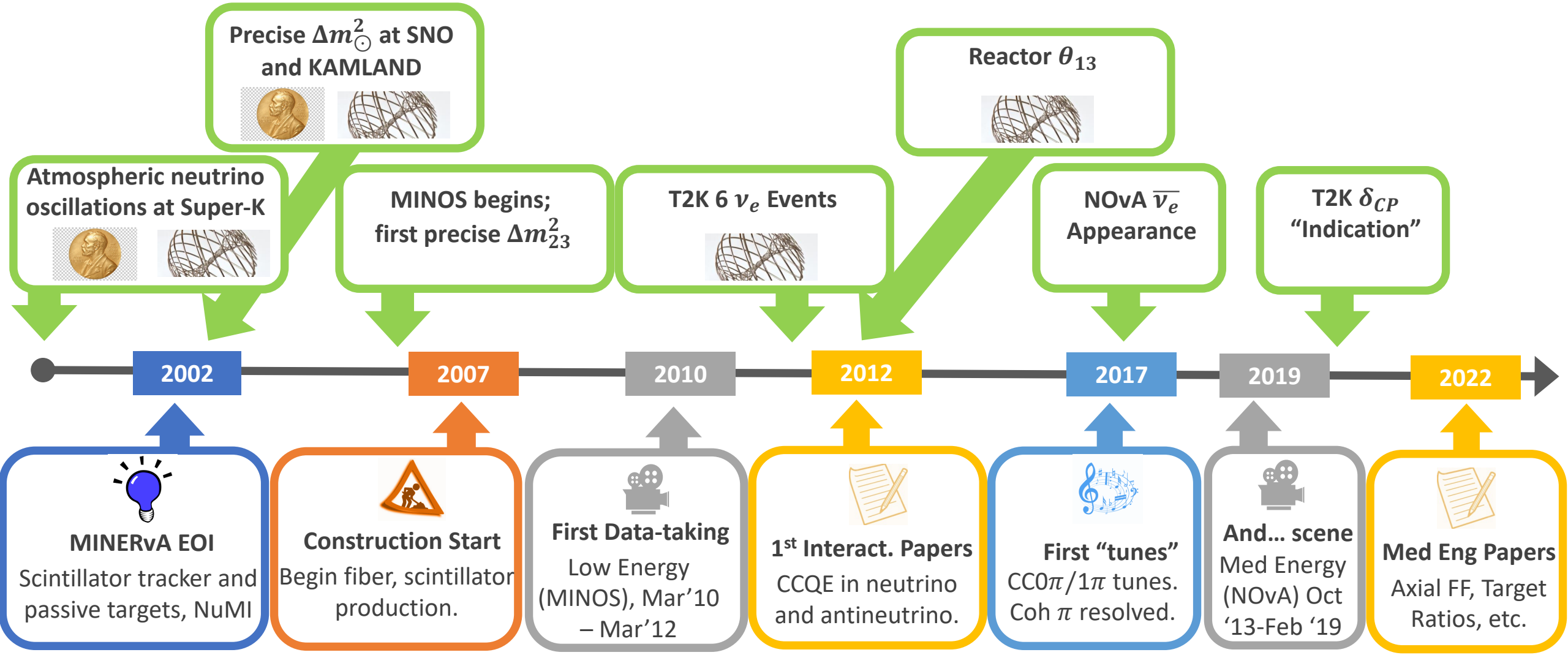




Zooming in on the History of MINERvA

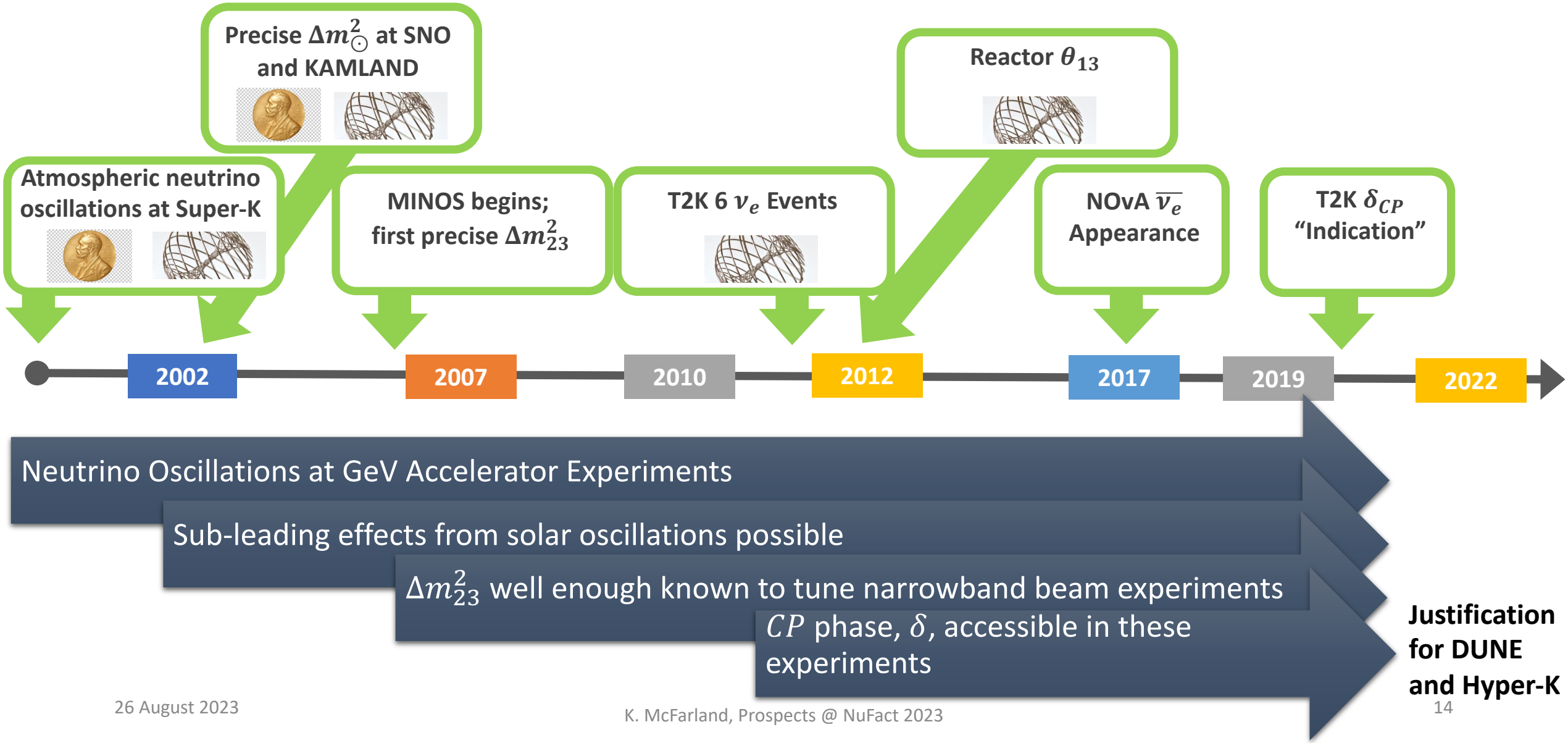
- Please indulge me for a minute while I set the history of one of my collaborations, MINERvA, in context.
- MINERvA holds a special place in my career. I wrote the "Expression of Interest" in July 2002 and served as a co-spokesperson for a long time.
- But I also have a purpose beyond myself in saying this.



History of MINERvA in Neutrinos



Implications of that History in Accelerator Neutrinos



My Personal History of MINERvA

Elizabeth McFarland-Porter

Crane School of Music (‘21), Elementary School Music Teacher.

2002

MINERvA EOI
Scintillator tracker and passive targets, NuMI

2007

Construction Start
Begin fiber, scintillator production.

2010

First Data-taking
Low Energy (MINOS), Mar’10 – Mar’12

2012

1st Interact. Papers
CCQE in neutrino and antineutrino.

2017

First “tunes”
CC0π/1π tunes. Coh π resolved.

2019

And… scene
Med Energy (NOvA) Oct ‘13-Feb ‘19

2022

Med Eng Papers
Axial FF, Target Ratios, etc.

Why did I tell you all of this?

- My personal history is just one story. But some common threads…

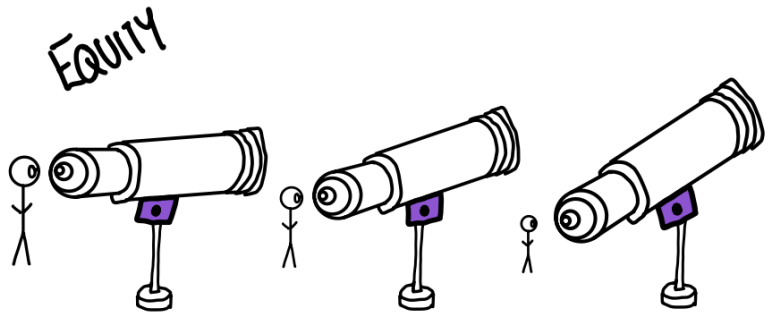
- I had support to launch MINERvA:
  - I was hired at University of Rochester to join a CDF/CMS group.
  - Nevertheless, when opportunities in neutrino physics began to catch my interest, my colleagues not only were happy for me to chase those opportunities, they helped me with their ideas and with resources from our group.
- If you are early in your career, take heart.
- If you are less early in your career, pay it forward.

Why did I tell you all of this?

- My personal history is just one story. But some common threads…

- Timelines for projects are both daunting and exhilarating.
  - Twenty years for an experiment is a long time.
  - But it's also been the sum of many short-term adventures:
    - Project management and construction.
    - Detector commissioning, calibrations, and reconstruction.
    - A dozen physics puzzles and projects, varying over the years.
- Truisms: Long time scales are often the sum of shorter parts.
  And short-term projects are often parts of a larger whole.

Who does neutrino (or lepton) physics? We do!



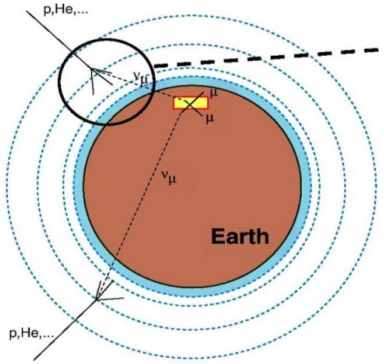
- Without the support of our colleagues, we go nowhere.
- Without *giving support* to our colleagues, we diminish our field.
- Let's resolve to keep taking the risks we need to take, both as workers and supporters, to accomplish and to enable creative and courageous work.

The Likelihood of Future Success

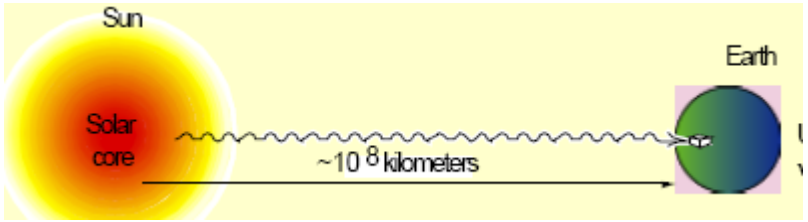
Neutrino physicists have been fortunate

"We live in the best of all possible worlds"
– Alvaro deRujula @ Neutrino 2000

- By which he meant…
  had not
  $E_{atm\ \nu}/R_{earth} < \Delta m^2_{atm} < E_{atm\ \nu}/h_{atm}$



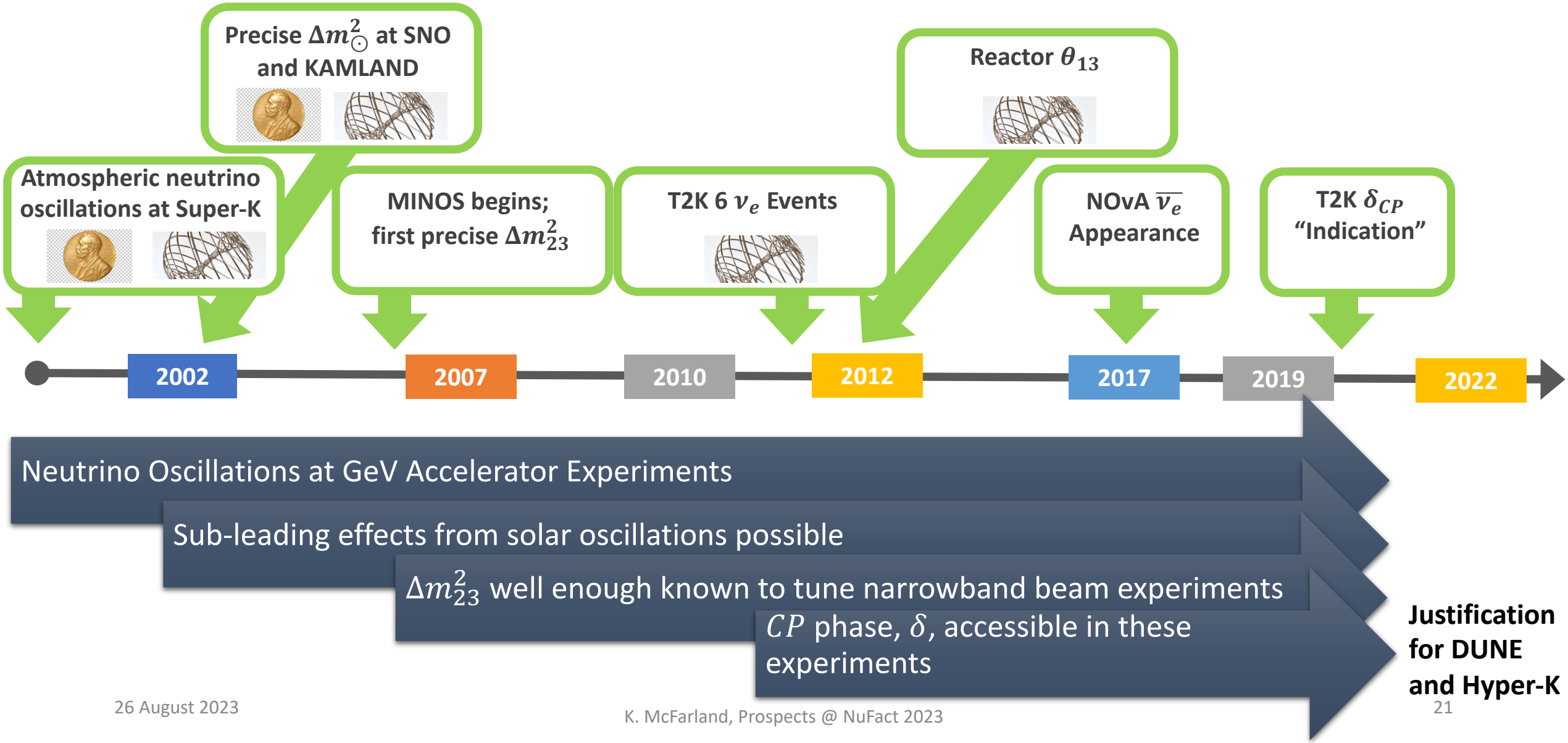
- and had not solar density profile and Δm^2_{sol} been well-matched…



- *We might not have ever discovered ν oscillations!*

Art McDonald and Takaaki Kajita, 2015 Nobel Laureates in Physics & Lucky People

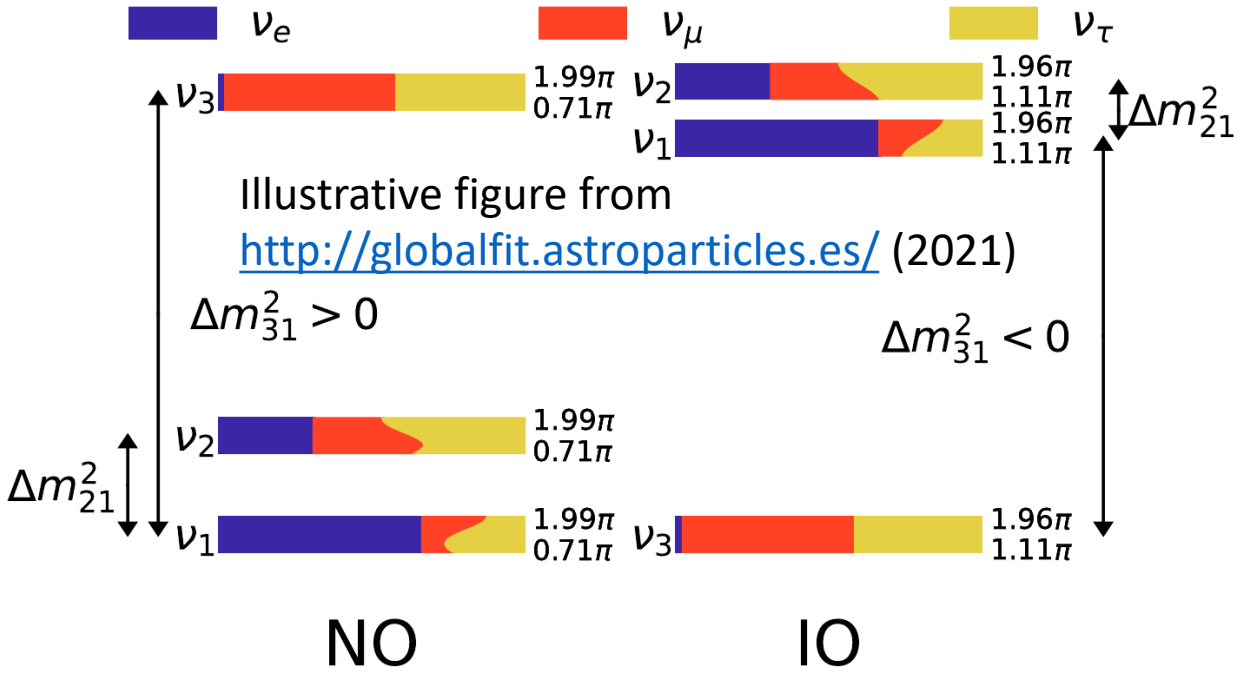
Our good fortune is not ancient history



The Result: Major Projects in Motion

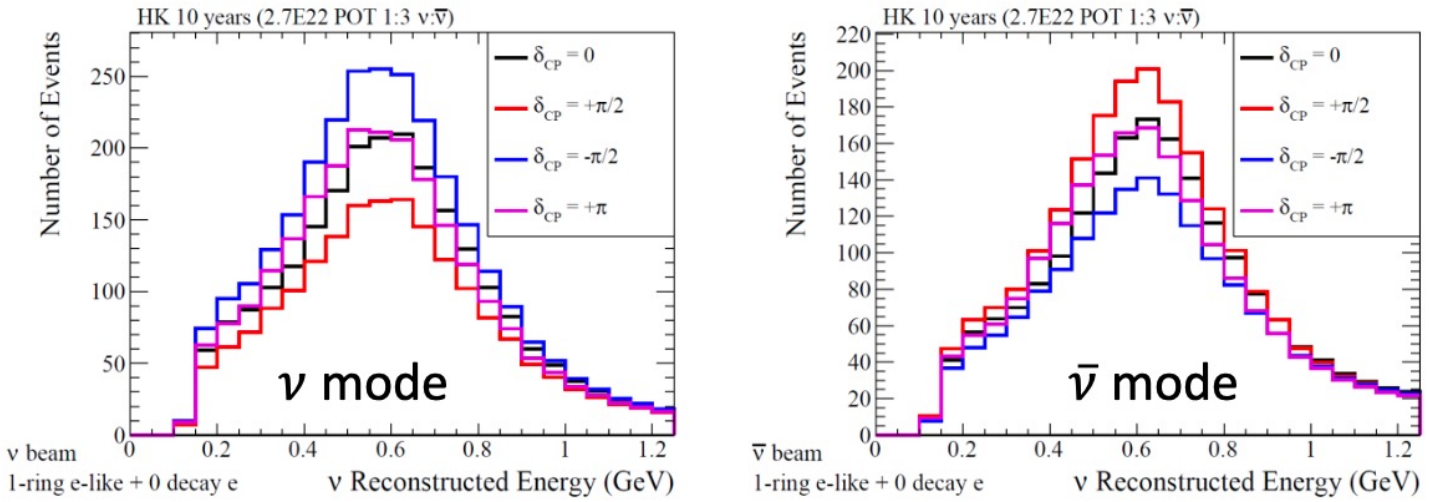
- We find ourselves in the incredibly fortunate situation of having three major long baseline projects exploring the interplay of the solar and atmospheric mass splitting.
- JUNO, Hyper-K, DUNE

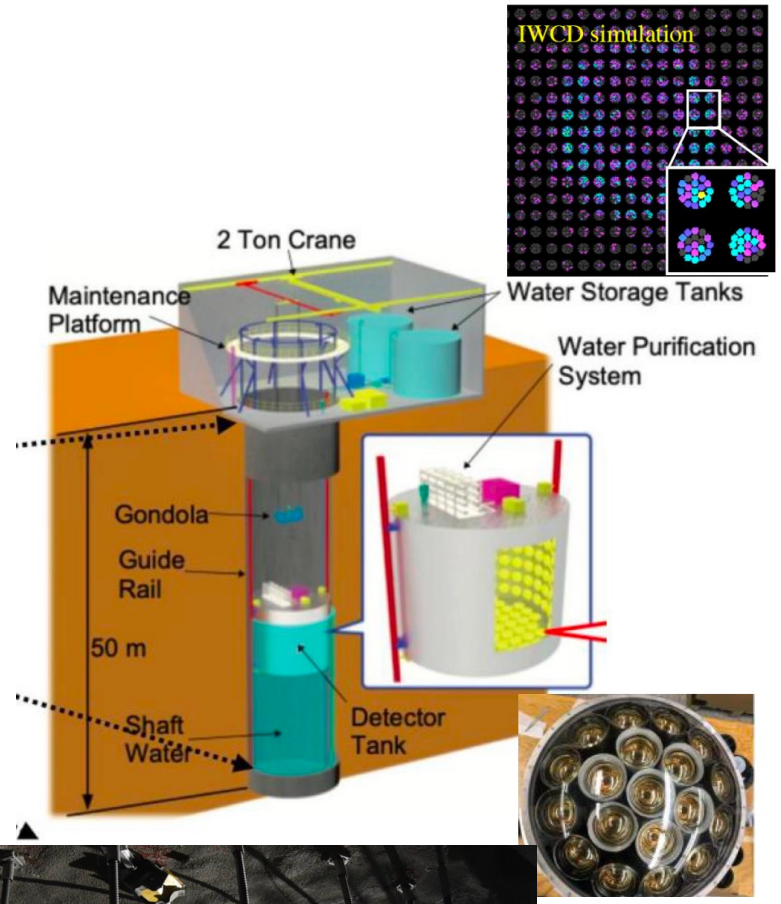
- *How lucky are we to have these three enormous efforts all on track to succeed?*



Hyper-K

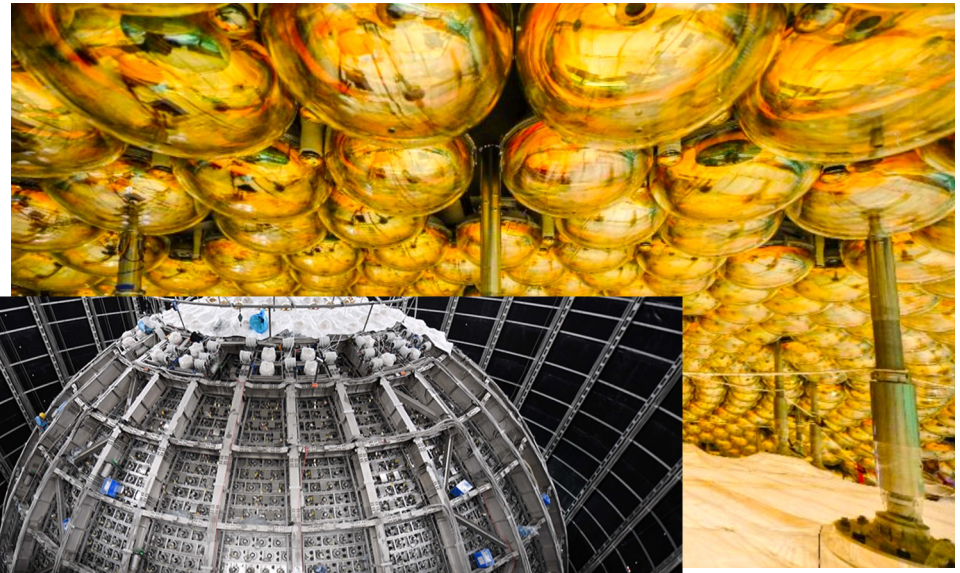
- Hyper-K is evolutionary in approach, but revolutionary in exposure, and will follow on the success of T2K (McCauley)

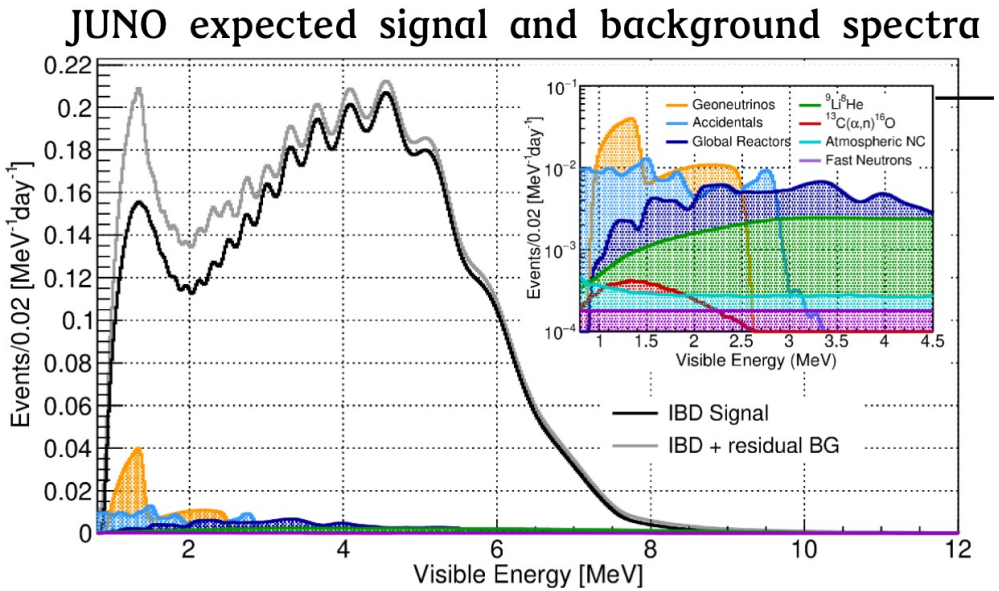


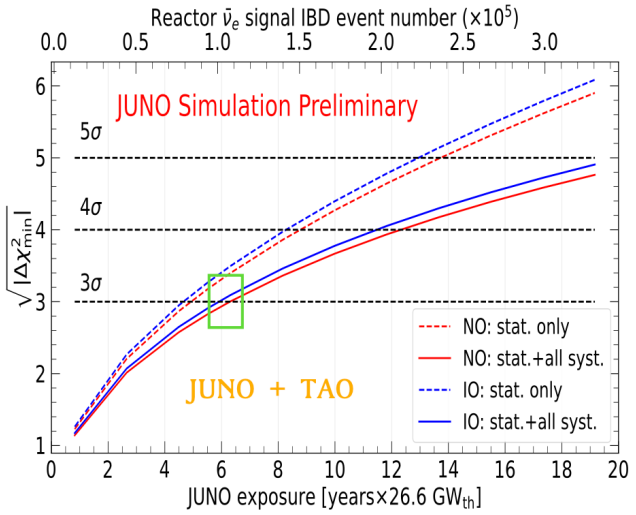


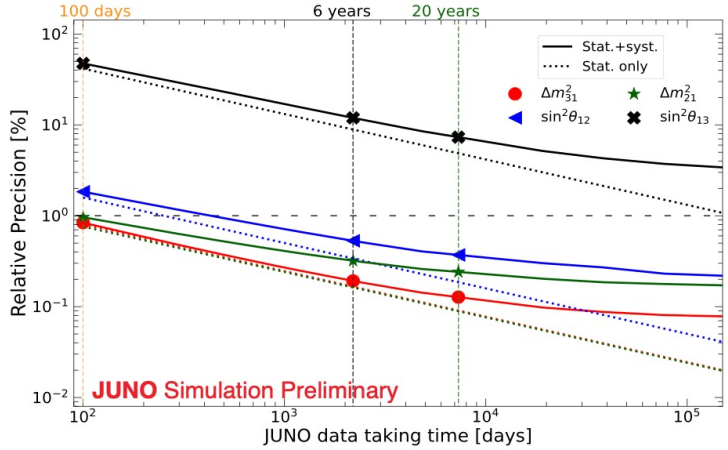
JUNO

- JUNO construction is proceeding rapidly. Very ambitious project, with capabilities well beyond mass ordering of neutrinos. (Han)



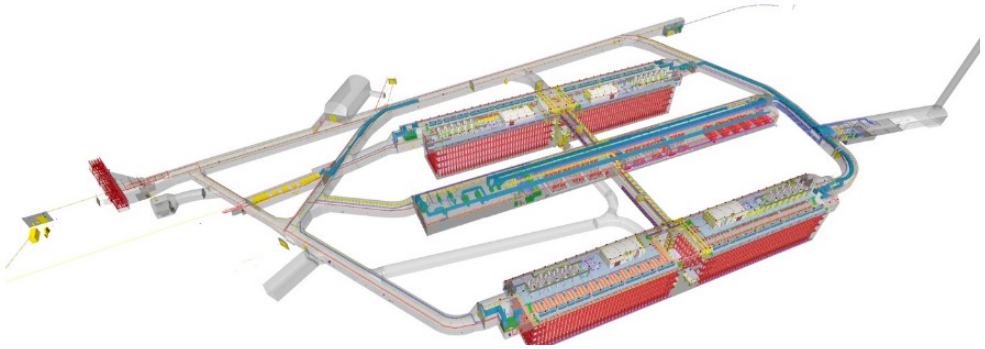


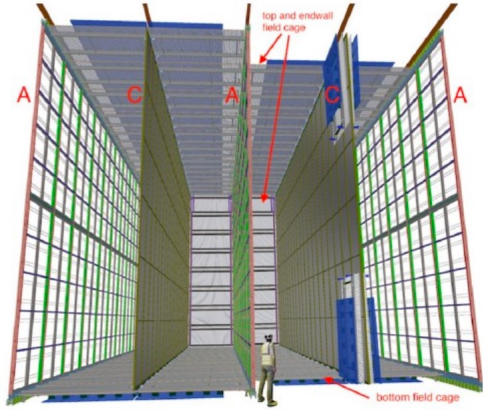


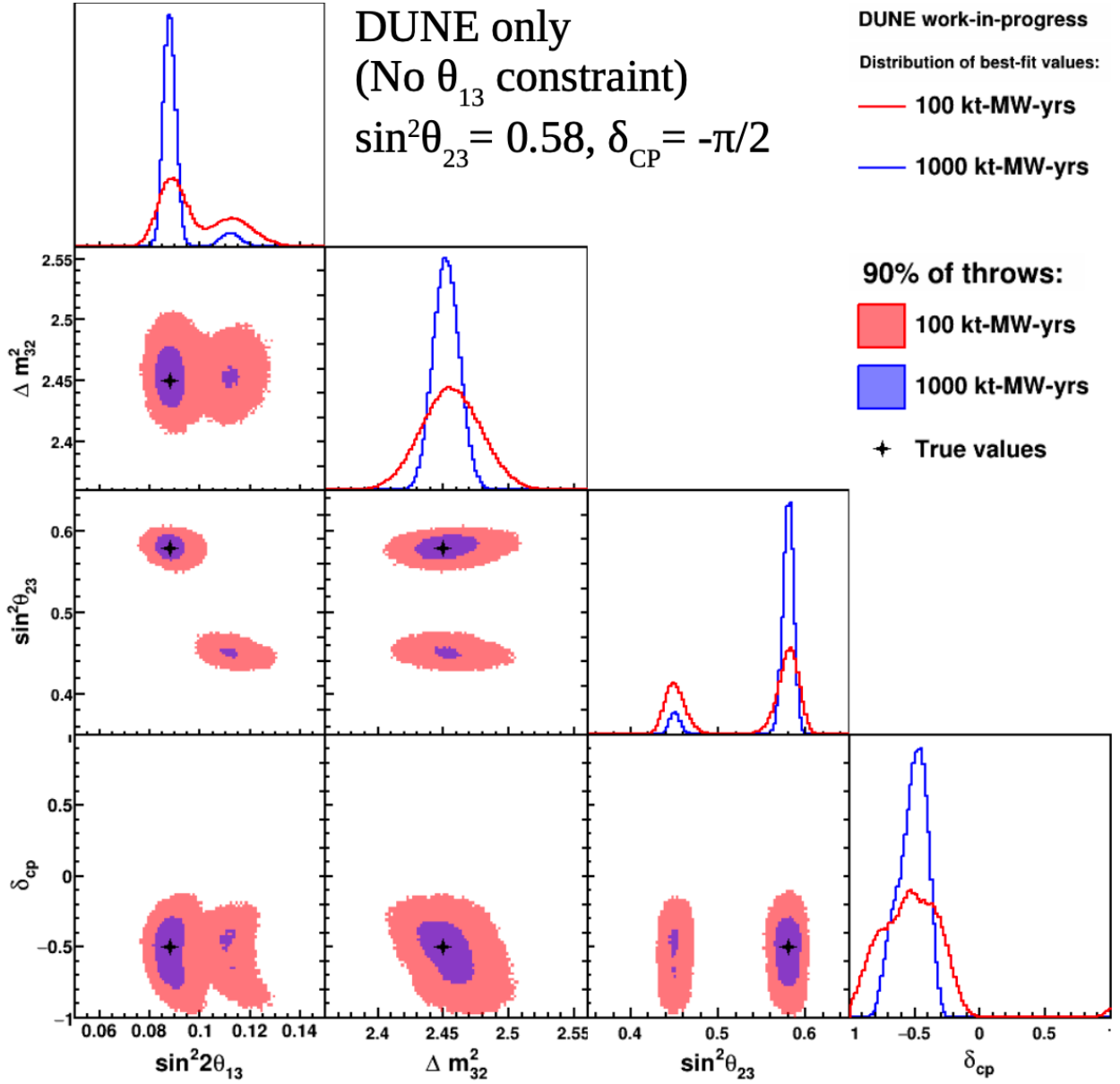


DUNE

- DUNE constrains many neutrino parameters simultaneously. (Marshall)

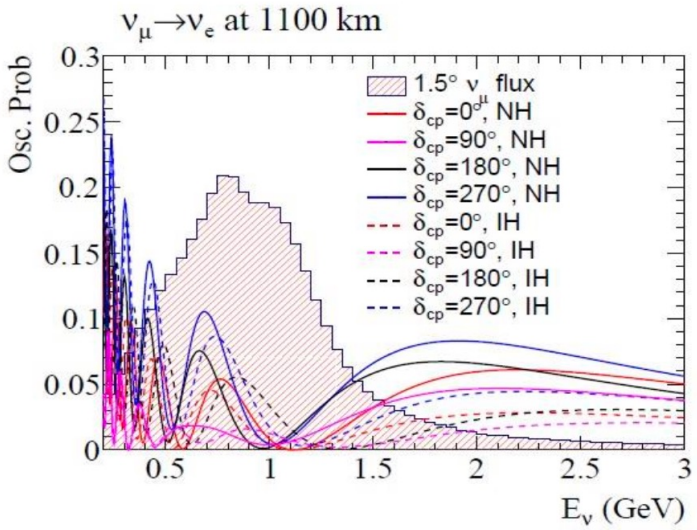


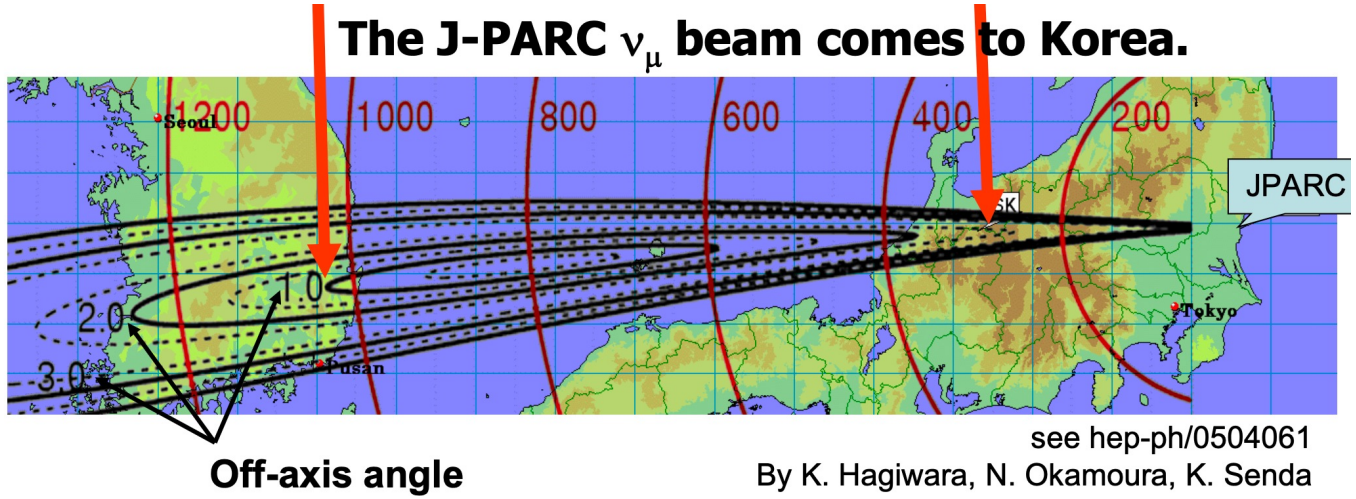




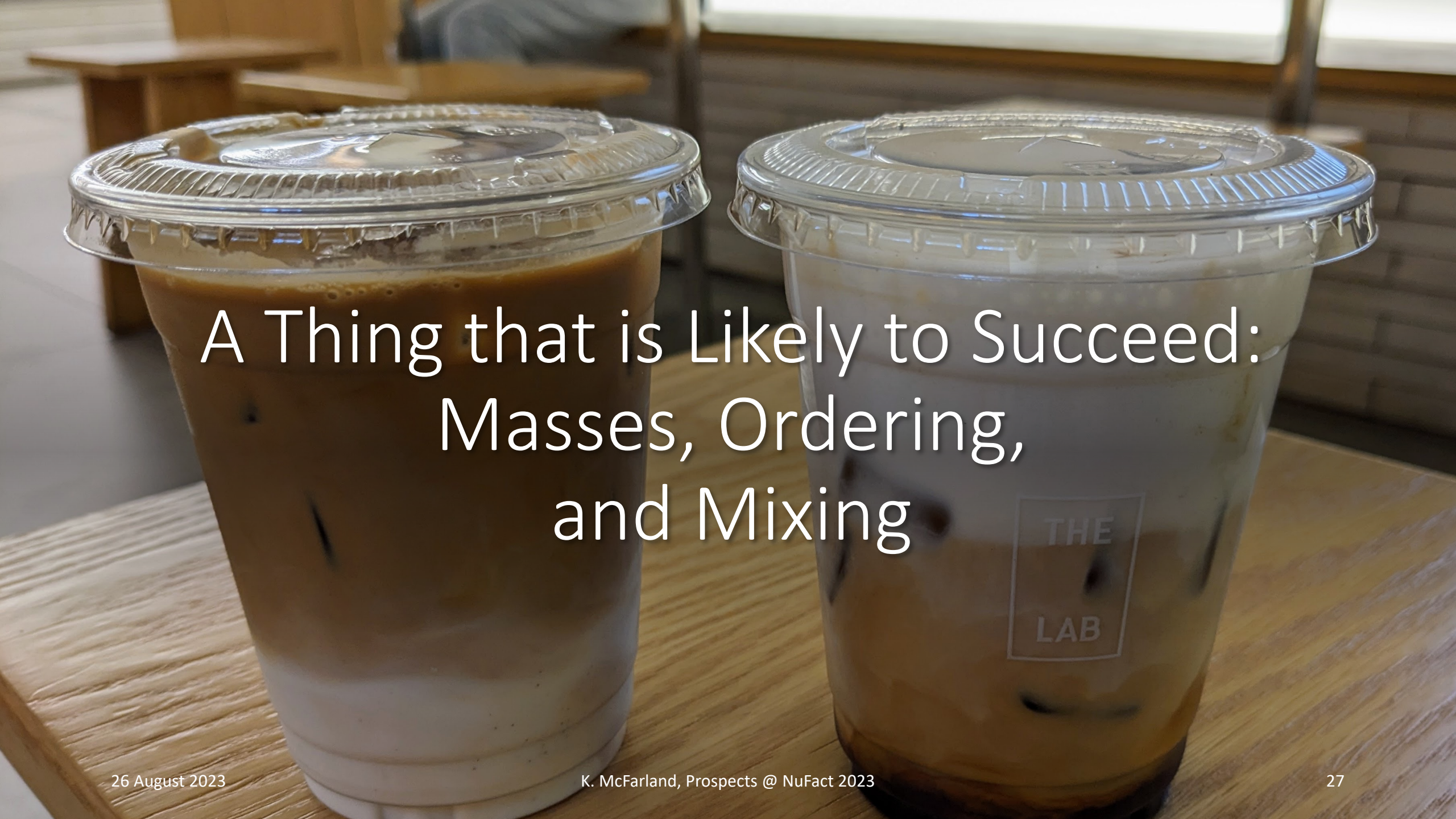
And many augmentations!

- KNO, to explore multiple oscillation maxima in T2HKK (Yu)





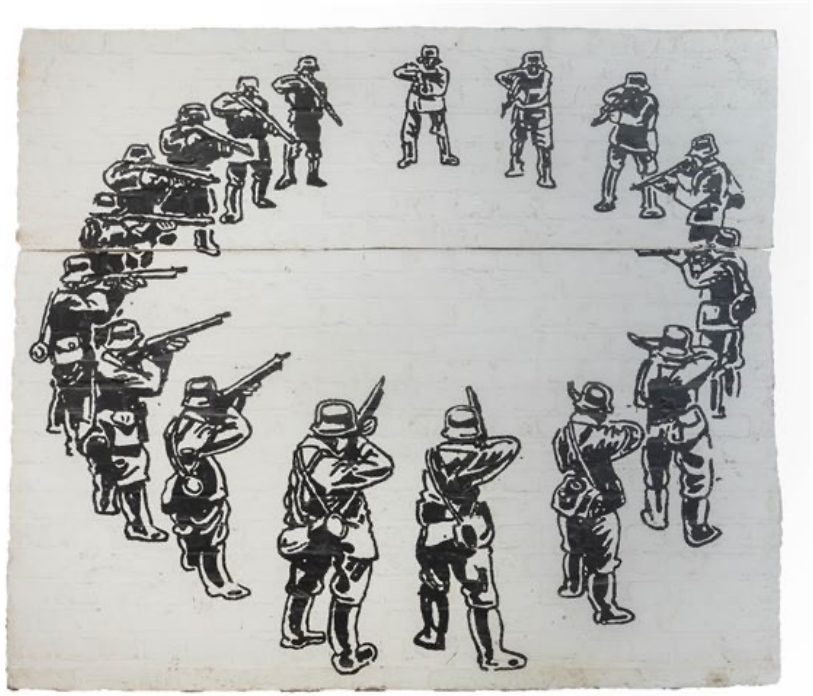
- DUNE "module of opportunity" (Bishai)
  - New technologies to augment capability for long-baseline neutrinos or neutrino astronomy to DUNE.



A Thing that is Likely to Succeed: Masses, Ordering, and Mixing

The difficulty of being lucky

- We as a community suffer a little from our success. With so many projects doing exciting science, sometimes we feel as if we are in competition with each other, instead of cooperation.
- There is an idiom in American English, originally developed in a political context, of the “circular firing squad”.



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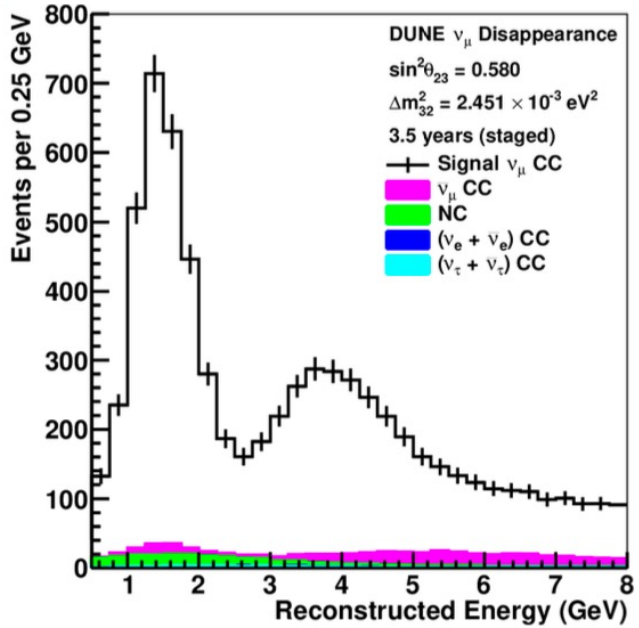
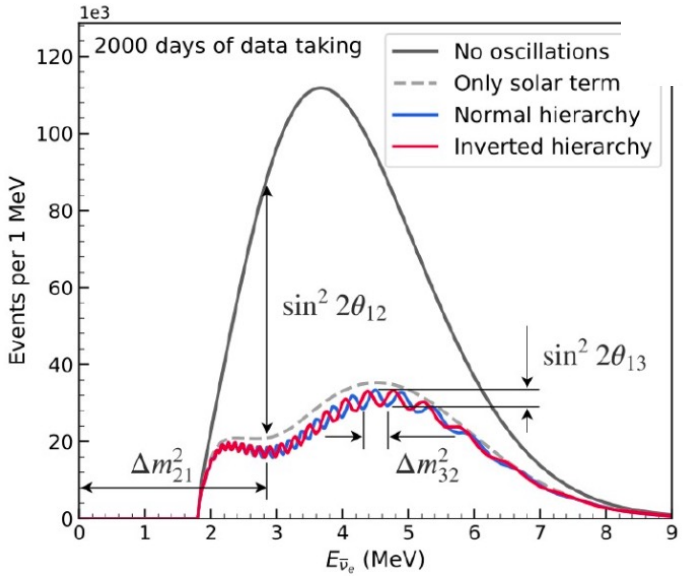
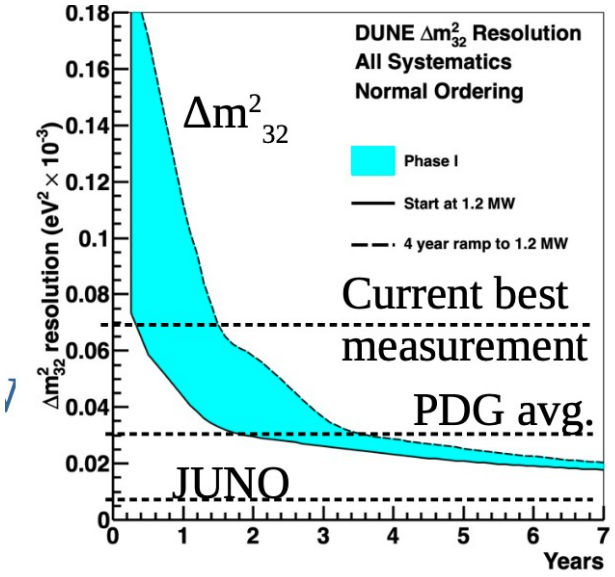
- There is an idiom in American English, originally developed in a political context, of the “circular firing squad”.
- *Let’s resolve to reconsider that feeling of competition.*

Why so many experiments?

- If the three-flavor picture is correct, we will test it to very high precision with these complementary approaches.
- If it is not, then comparisons among experiments with vastly different energies, capabilities, matter effects, etc. will light our path forward. (Marshall, Aurisano)

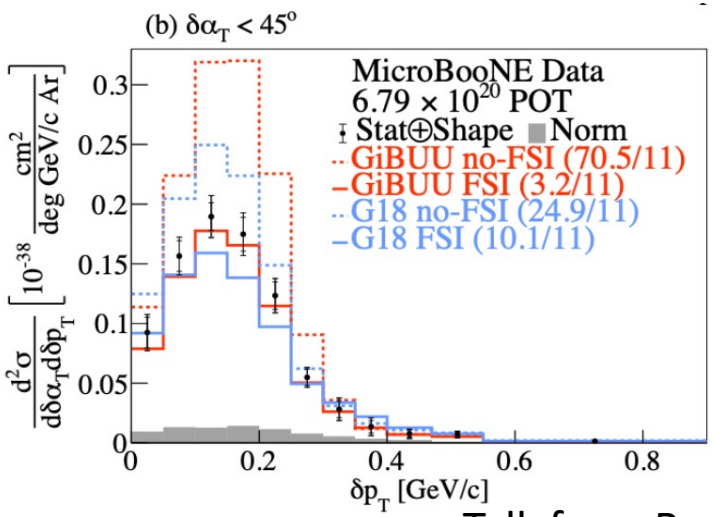


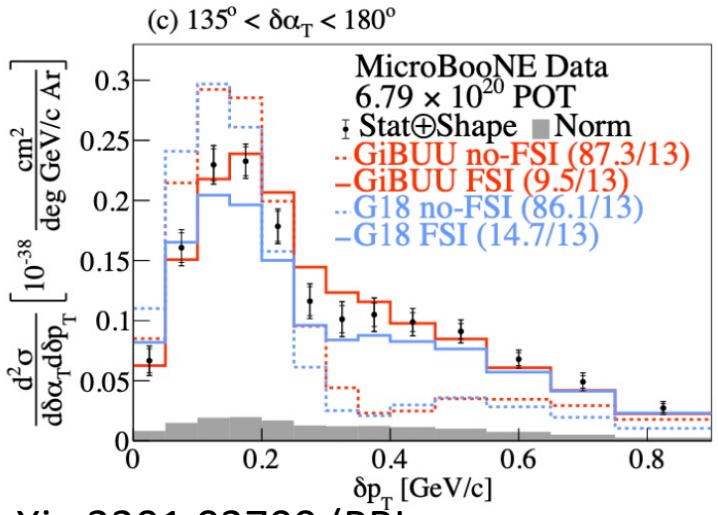




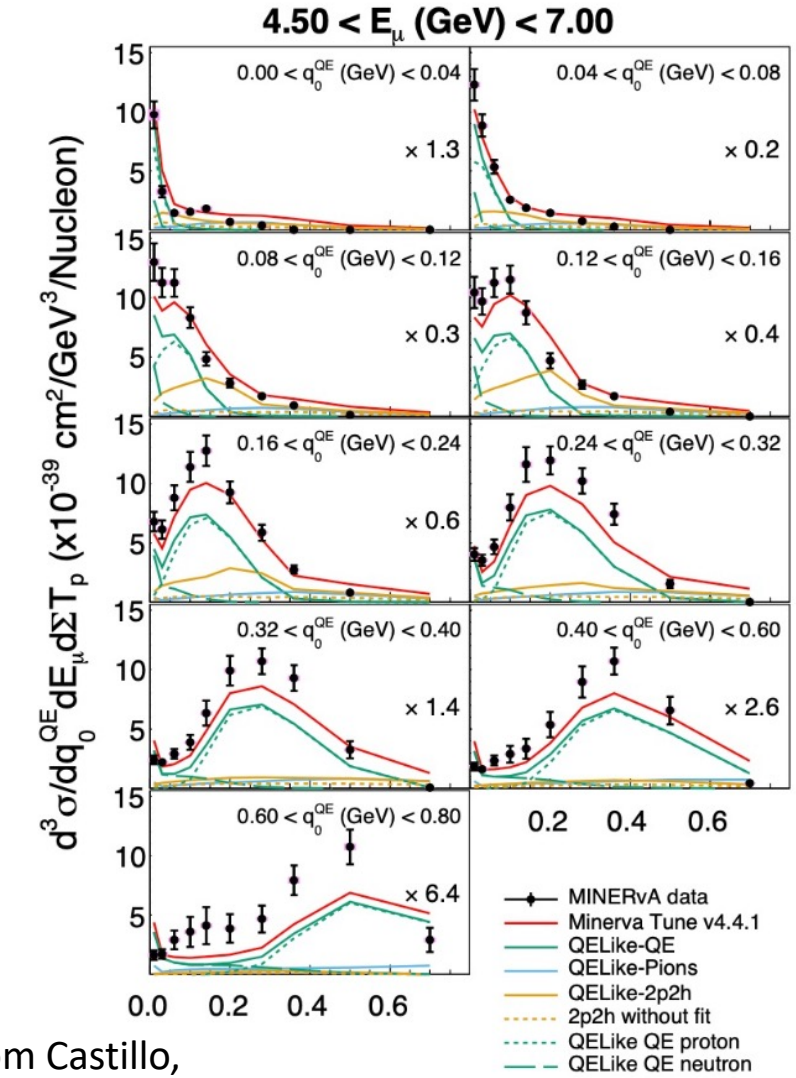
Another answer to "Why go to all this trouble to measure one number"?

- Why would we? That's NOT what we do.
- As we heard in WG2, experiments use their near detectors and other experiments share the beam to produce neutrino interaction physics.
- Rich, productive interaction with nuclear theory (Jachowicz)





Talk from Berkman, arXiv:2301.03700 (PRL_ arXiv:2301.03706 (PRD) [MicroBooNE}



Talk from Castillo, Phys.Rev.Lett. 129 (2022) 2, 021803 [MINERvA]

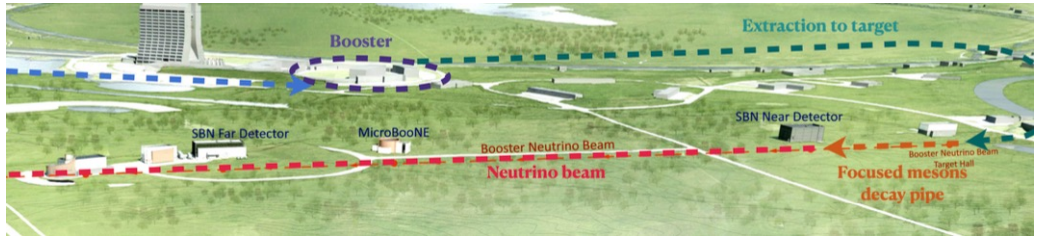
To Search for Something

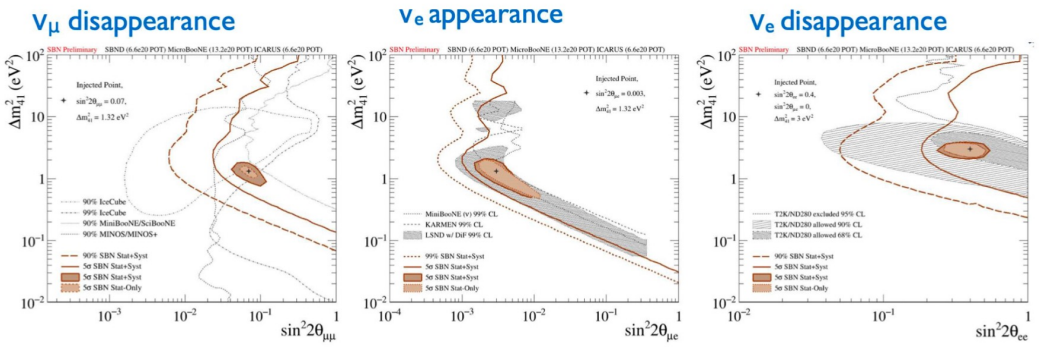
What else do we search for?

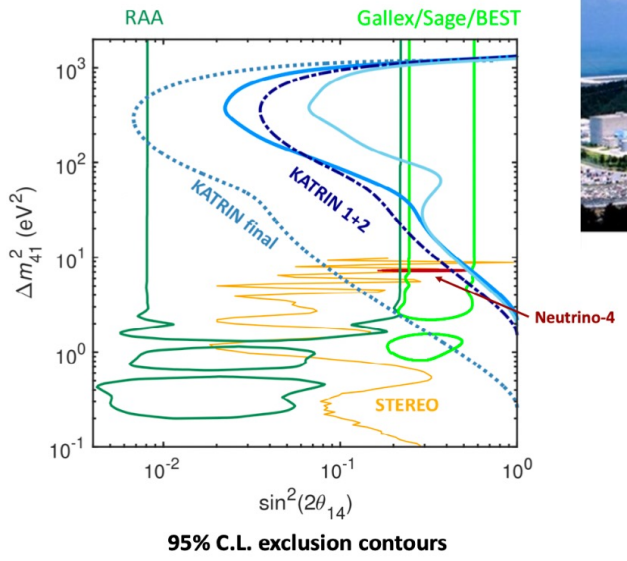
- Are there neutrinos (sterile) beyond the three that have been established in oscillation and detection experiments?
- Can we find evidence of neutrino mass in beta or double beta decay?
- Are there *neutrone* (BIG neutral states) that we can identify in high energy or high intensity experiments?
- Are their charged lepton flavor violating or non-universality phenomena that are associated with the physics of neutrino mass?

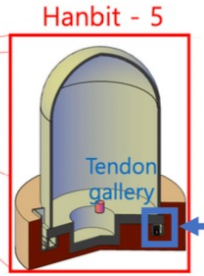
Sterile Neutrinos

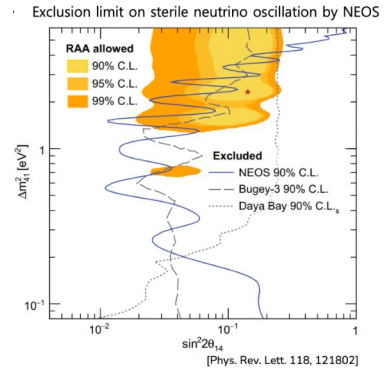
- I will not enter the debate of what current signals are or are not good indications of a heavy sterile neutrino that mixes with light neutrinos.
- A robust array of efforts with many different techniques and technologies (Choi)
  - Accelerators, reactors, sources, beta decay, etc.





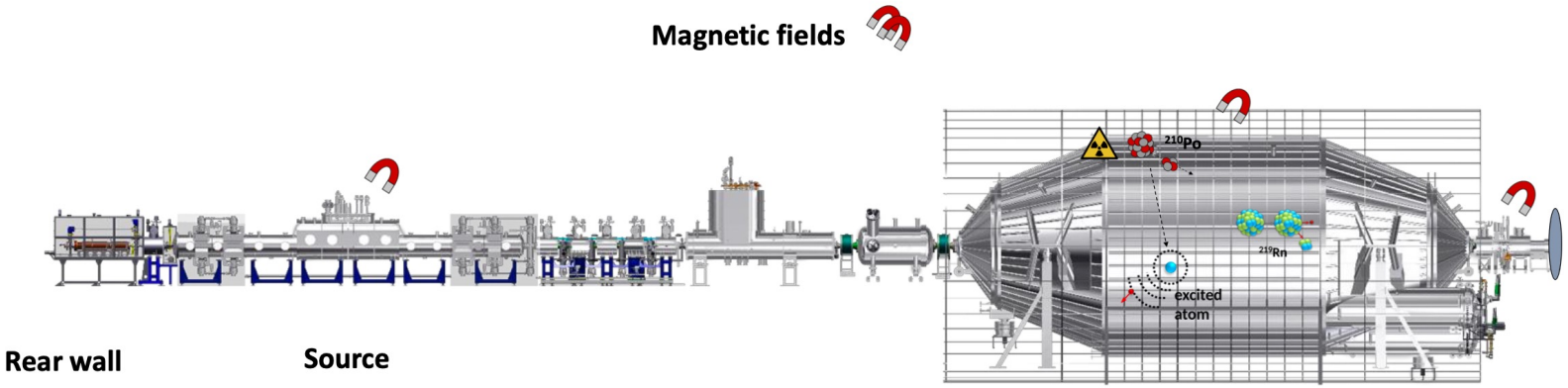


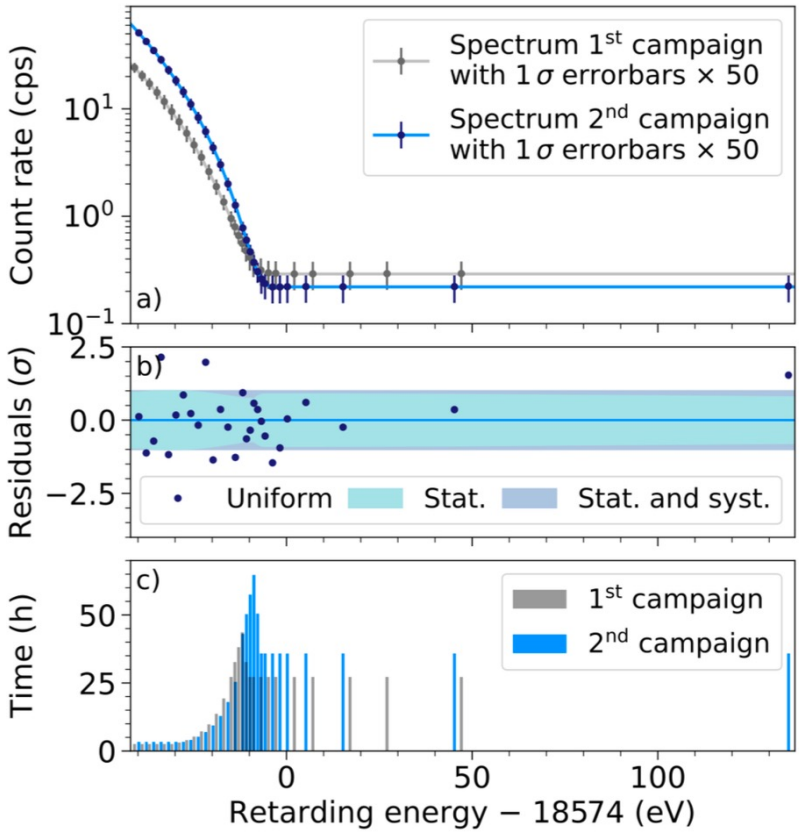




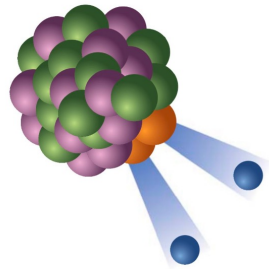
Neutrino mass through beta decay

- KATRIN currently dominates this area. (Should pay attention to new ideas though!) (Onillon)
- Systematics! Systematics! Systematics!
- Limits below 1 eV.

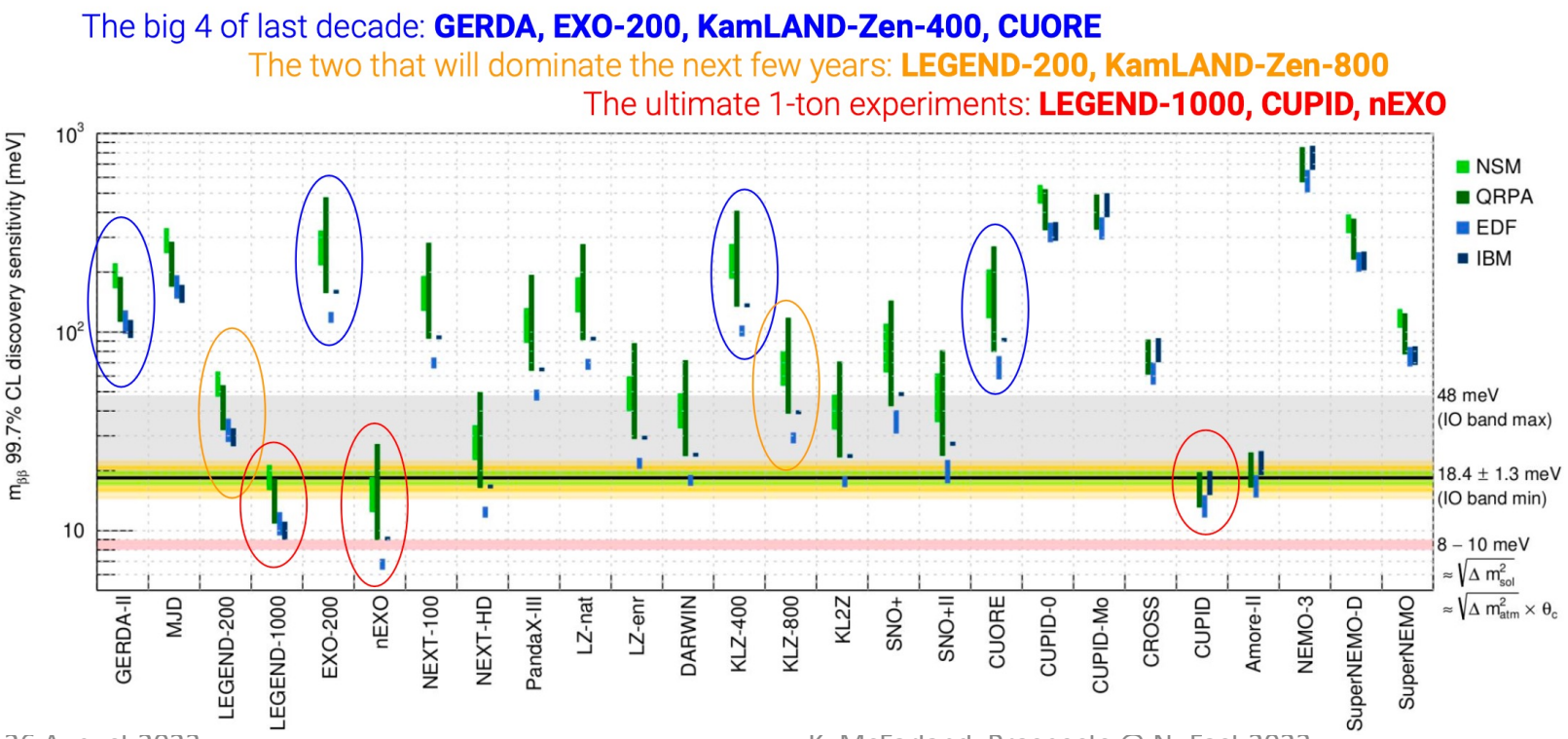


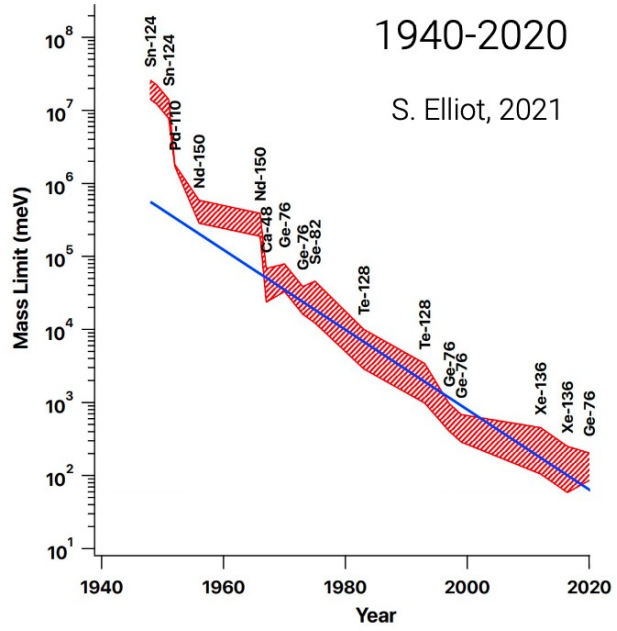


Neutrinoless Double Beta Decay



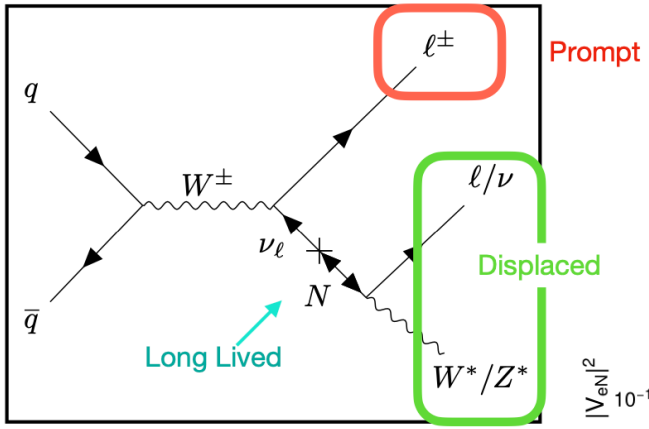
- Key probe of neutrino mass and the Majorana nature of the neutrino.
- A rich array of experiments in progress (Agostini)

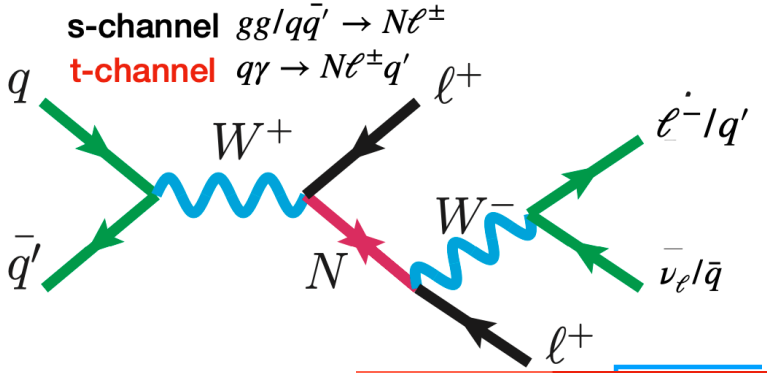


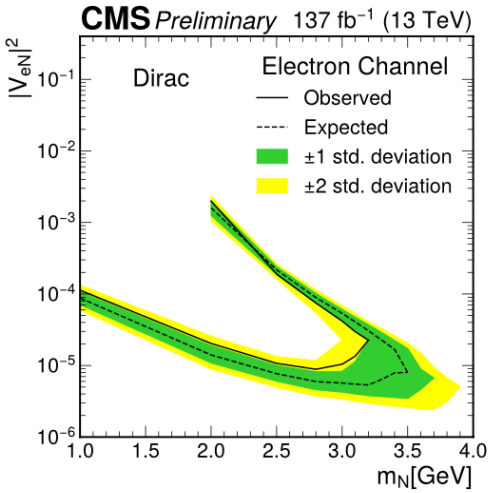


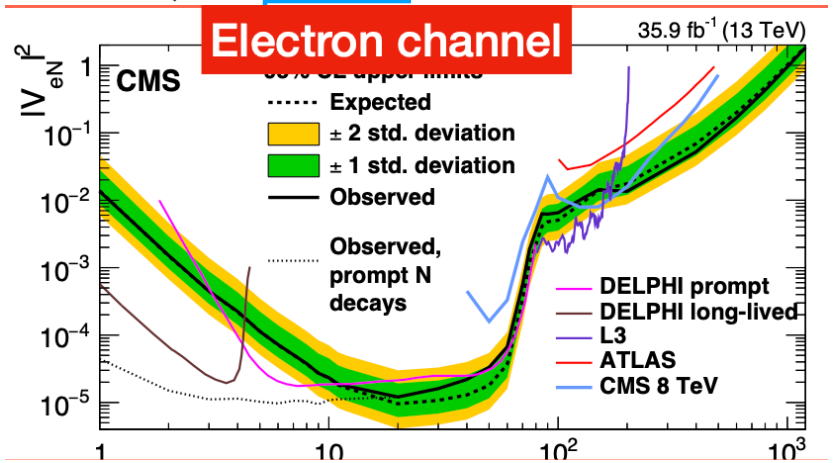
Searches for Heavy Neutrinos

- High mass states can be directly accessed at colliders; significant space for an illuminating discovery in many channels. (Ariga, Almond)



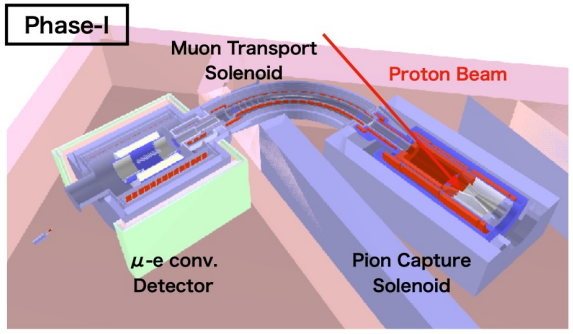


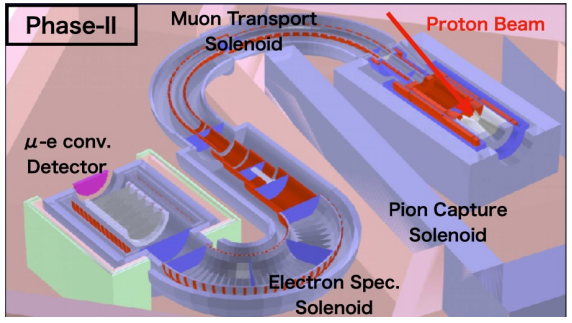




And charged lepton experiments…

- Charged lepton flavor violation or non-universality effects have the potential to explore the mechanisms behind neutrino mass. (Bigaran)
- Very active area of research with new prospects. (Sobara, Mihara)





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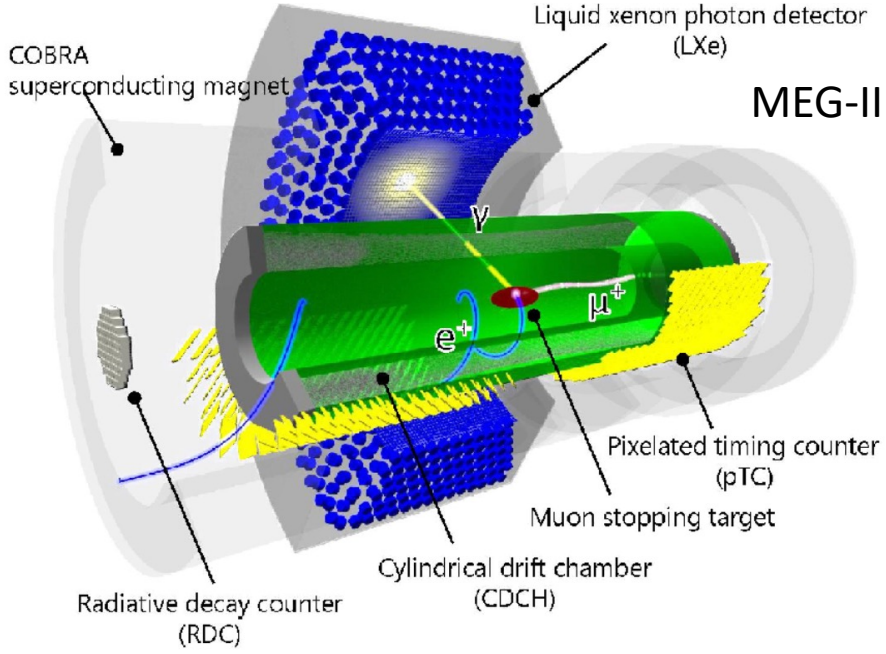
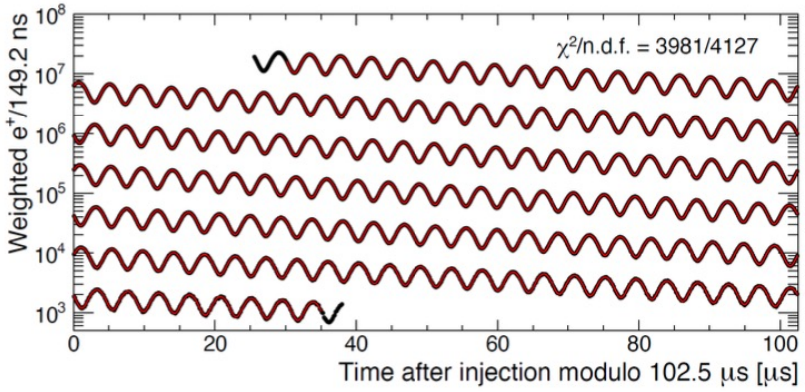
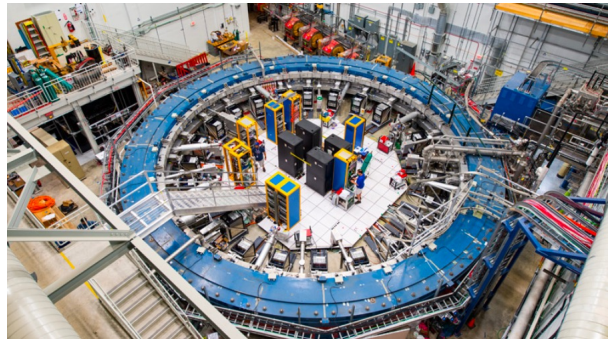


MEG-II





Muon g-2

What else do we search for?

- Are there neutrinos (sterile) beyond the three that have been established in oscillation and detection experiments?
- Can we find evidence of neutrino mass in beta or double beta decay?
- Are there *neutrone* (BIG neutral states) that we can identify in high energy or high intensity experiments?
- Are their charged lepton flavor violating or non-universality phenomena that are associated with the physics of neutrino mass?

- *These searches are an asset to our community and may be the next piece of luck that we have in our attempts to understand nature.*

Expansive Views: Neutrino Sources and Our Future

Where's My Damned NuFact?

- A lot of us have been at this business of considering a muon storage ring, with its potential for a muon collider and neutrino factory. (So long ago that a capable digital camera was <<1MP.)

photos from Kirk McDonald

What would a muon neutrino source bring us?

- Muon and electron flavor neutrinos.
- Potentially high energies, if needed.
- Precisely known flux and energy spectrum.
- Very high rates for near detectors and precision electron neutrino interaction studies.

- It’s a program that would excel at illuminating corners of our neutrino matrix that are difficult for our current experiments:
  - tau appearance
  - sterile neutrino disappearance

pErspectIVE

- We've been incredibly fortunate to be on the accelerated path of accelerator and reactor neutrino discoveries.
- That program will play out over my lifetime.
- But we should remember that we may need a muon source in our pocket for surprises in the future.

- I'll observe that we have underinvested in the copious R&D needed for this future opportunity. It's a mistake, similar to not saving money for one's retirement, that we need to rectify as a community.


Prospectus?

Our future, in one slide

- Our future is inspiring!
- We have great science opportunities that nature has opened to us by lucky choices of parameters.
- We have so many new projects and facilities – and more all the time – to work at to explore this science.
- We are ready to take risks, and we are creative.
- We have a community of excited, engaged, dedicated scientists, who deserve our support and recognition.

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"Failure is impossible" – Susan B. Anthony, 1884, Rochester, New York