Bryan Ramson (he/him/his), Pedro Machado, Lisa Kaufman
September 4, 2022
Neutrino Division
Fermilab

14th Conference on the Intersections of Particle and Nuclear Physics
Neutrino Summary

The Conference at a Glance

A Broad Range of Topics and Participants in Neutrinos!

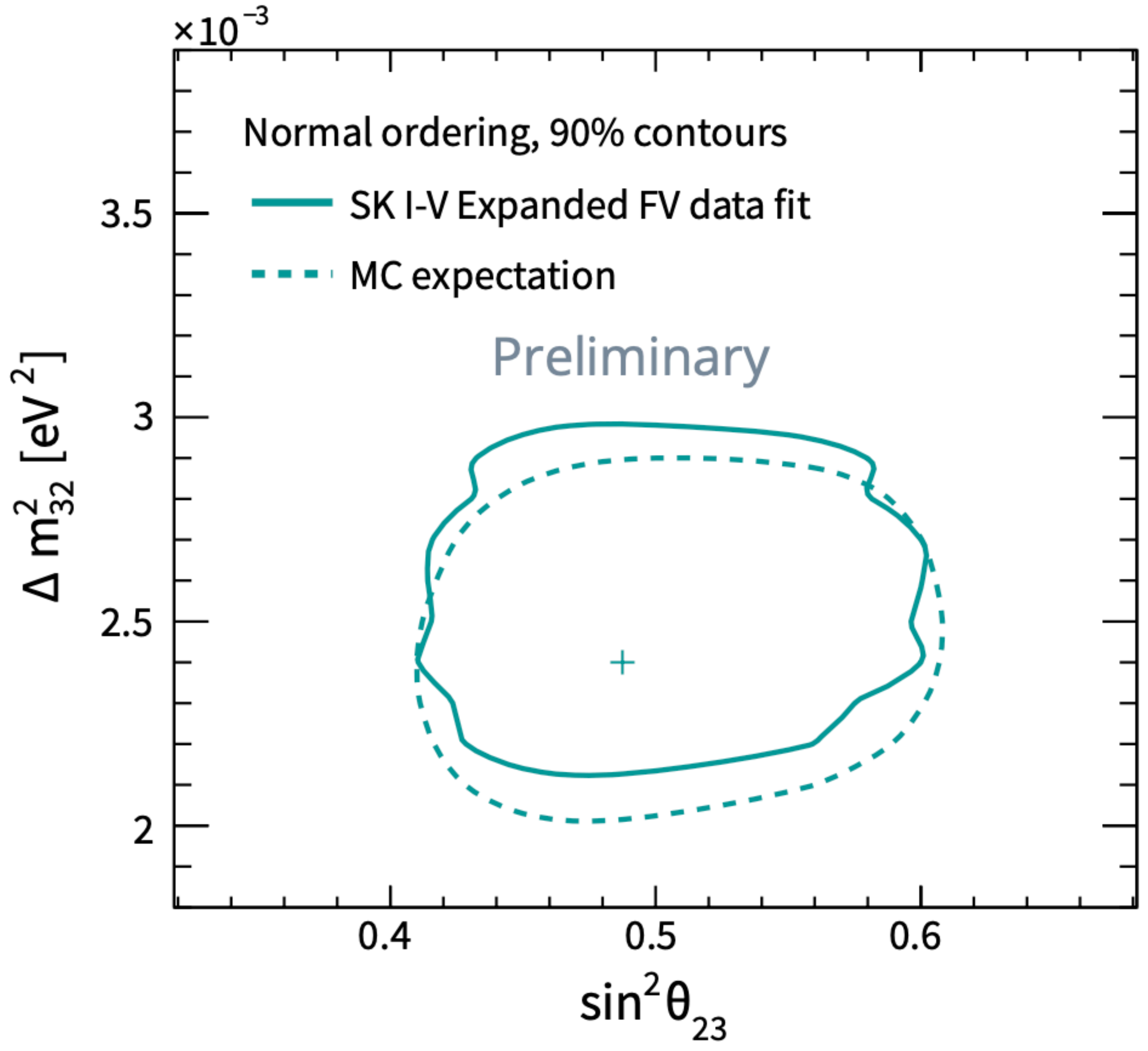
- Five overarching topics:
  - “Standard" Oscillation Physics *and Beyond!*
  - Neutrino-Nucleus *Scattering and Cross Sections*
  - Neutrino *Anomalies and Dark Matter*
  - Neutrino *Astrophysics & Cosmology*
  - Neutrino *Properties (Majorana and Mass)*
- 27 Different Speakers gave 28 unique talks:
  - 23 different institutions
  - 4 countries represented institutionally
  - 5 feminine identifying and 21 masculine identifying (as far as I know…)
  - Nationality and ethnicity/race of speakers was reasonably diverse

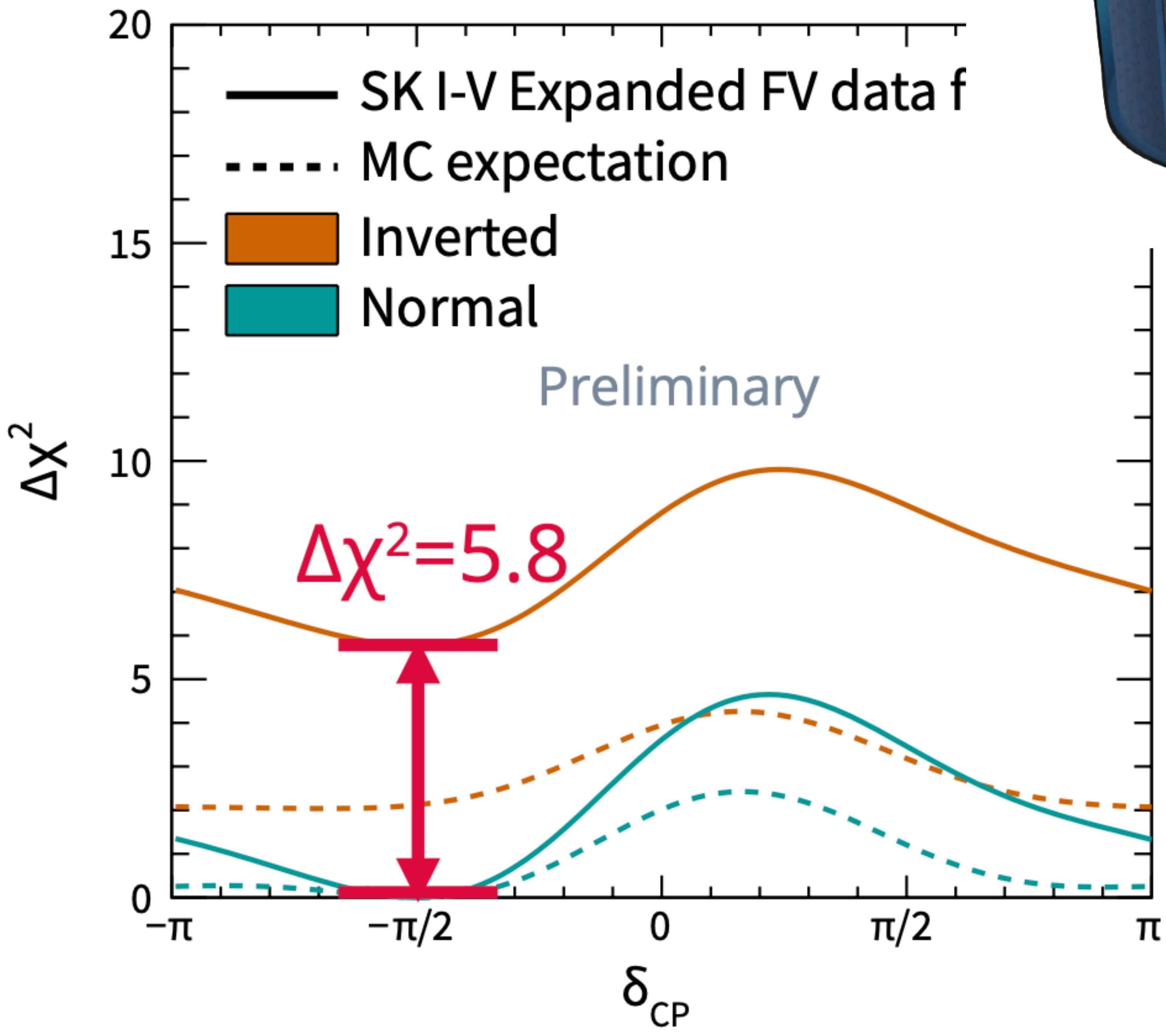
“Standard” Oscillation Physics and Beyond

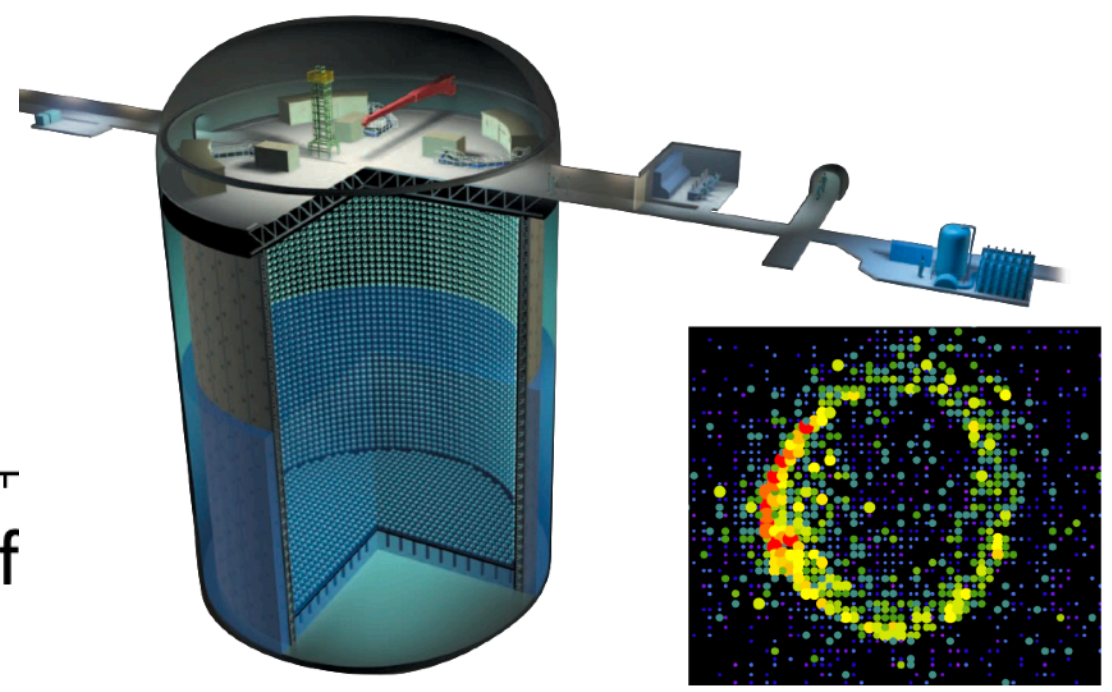
- Reports from:
  - Thomas Wester on Oscillations in Atmospheric Neutrinos from Super-Kamiokande
  - Denver Whittington on Oscillations in Accelerator Neutrinos from NOvA
  - Rupert Leitner on Reactor Neutrino Oscillations from Daya Bay
  - Tanaz Mohayai on Future Oscillations Experiments

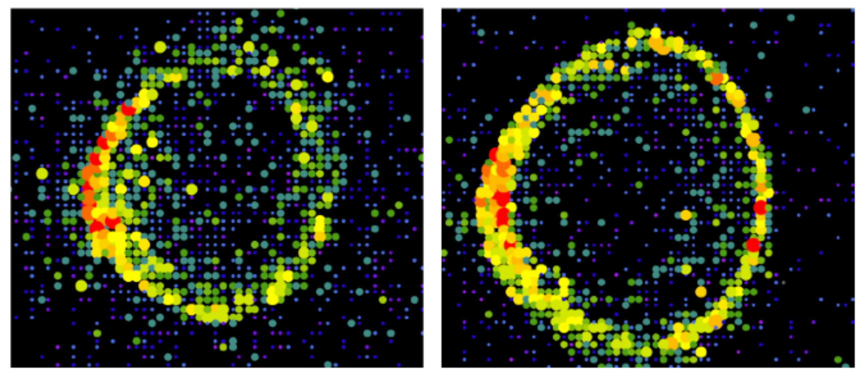
Thomas Wester on

Super-Kamiokande 2022 Results







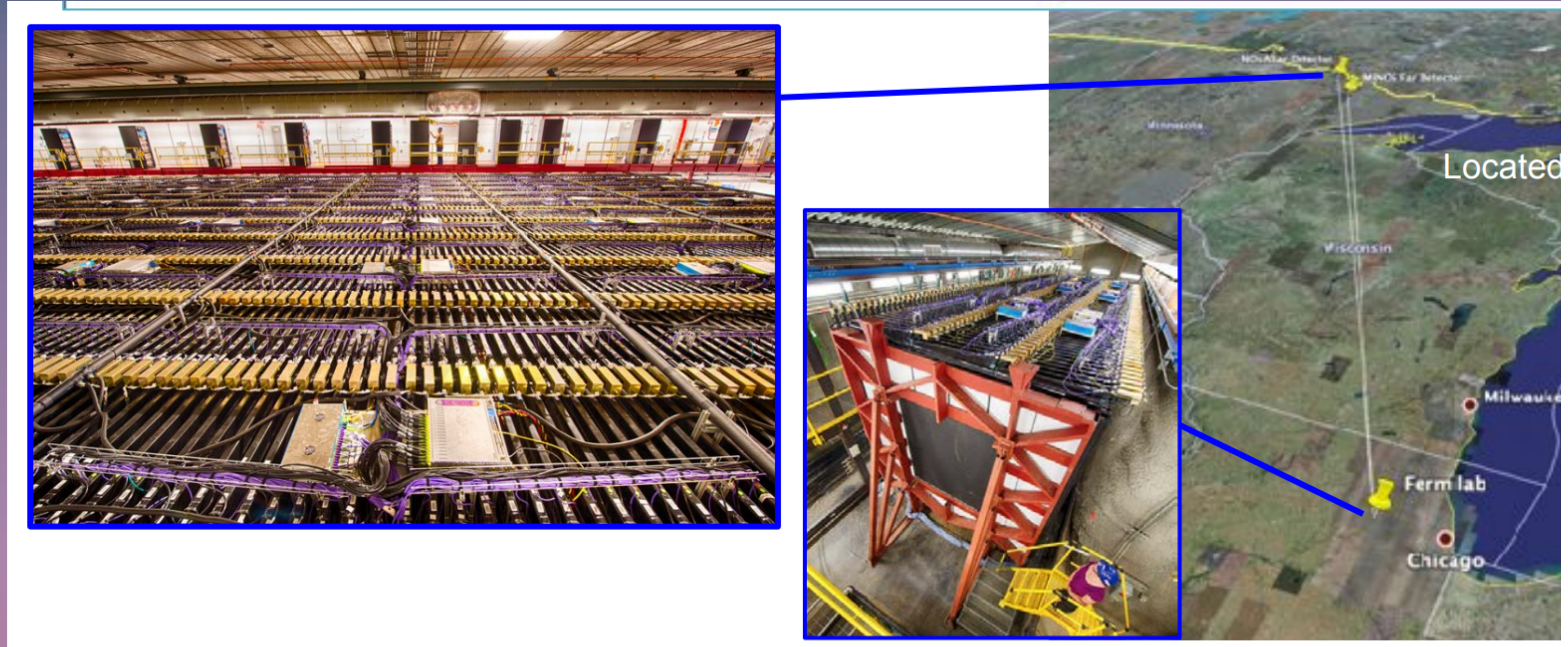


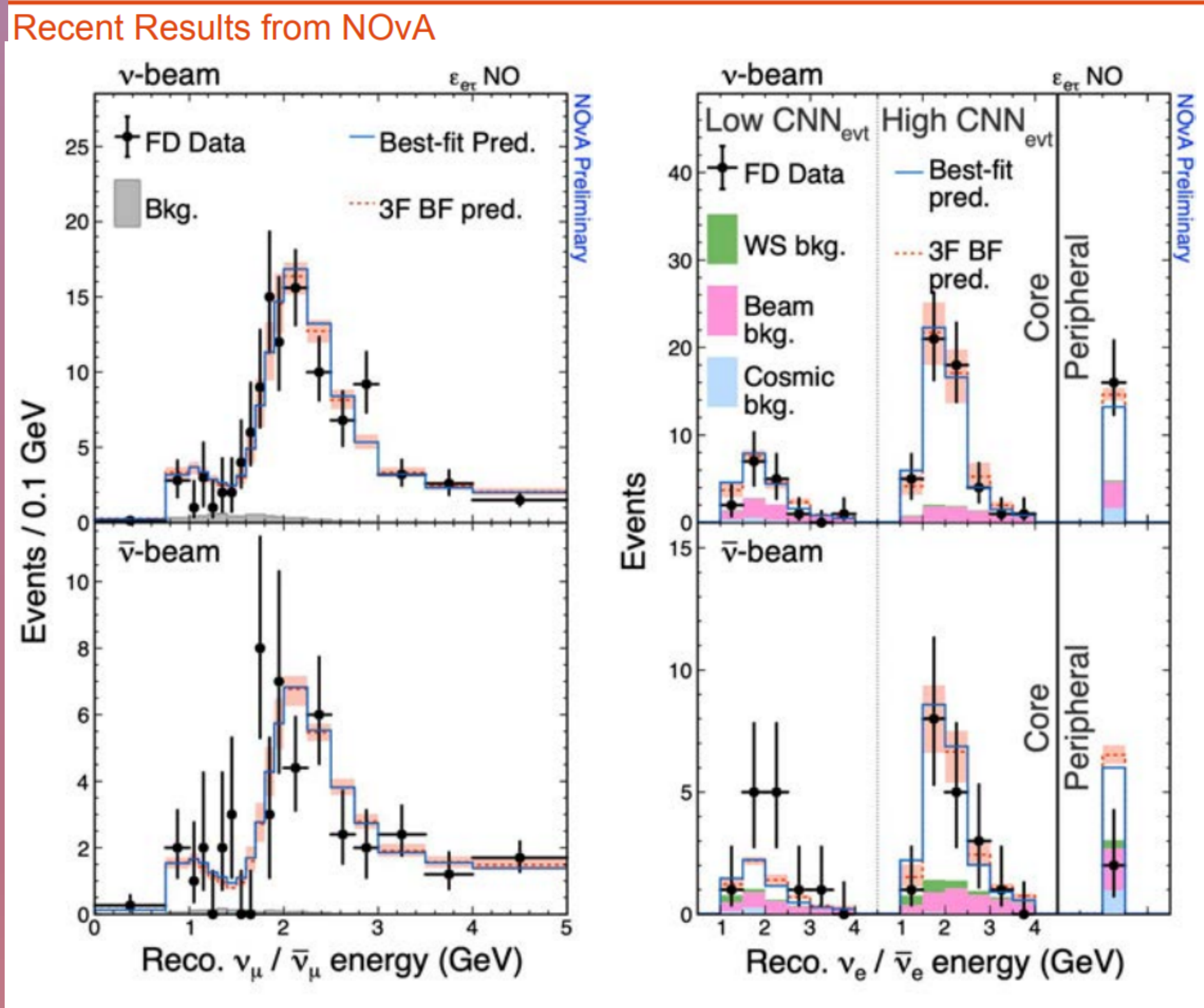
Fuzzy *e*-like ring   Sharp μ-like ring

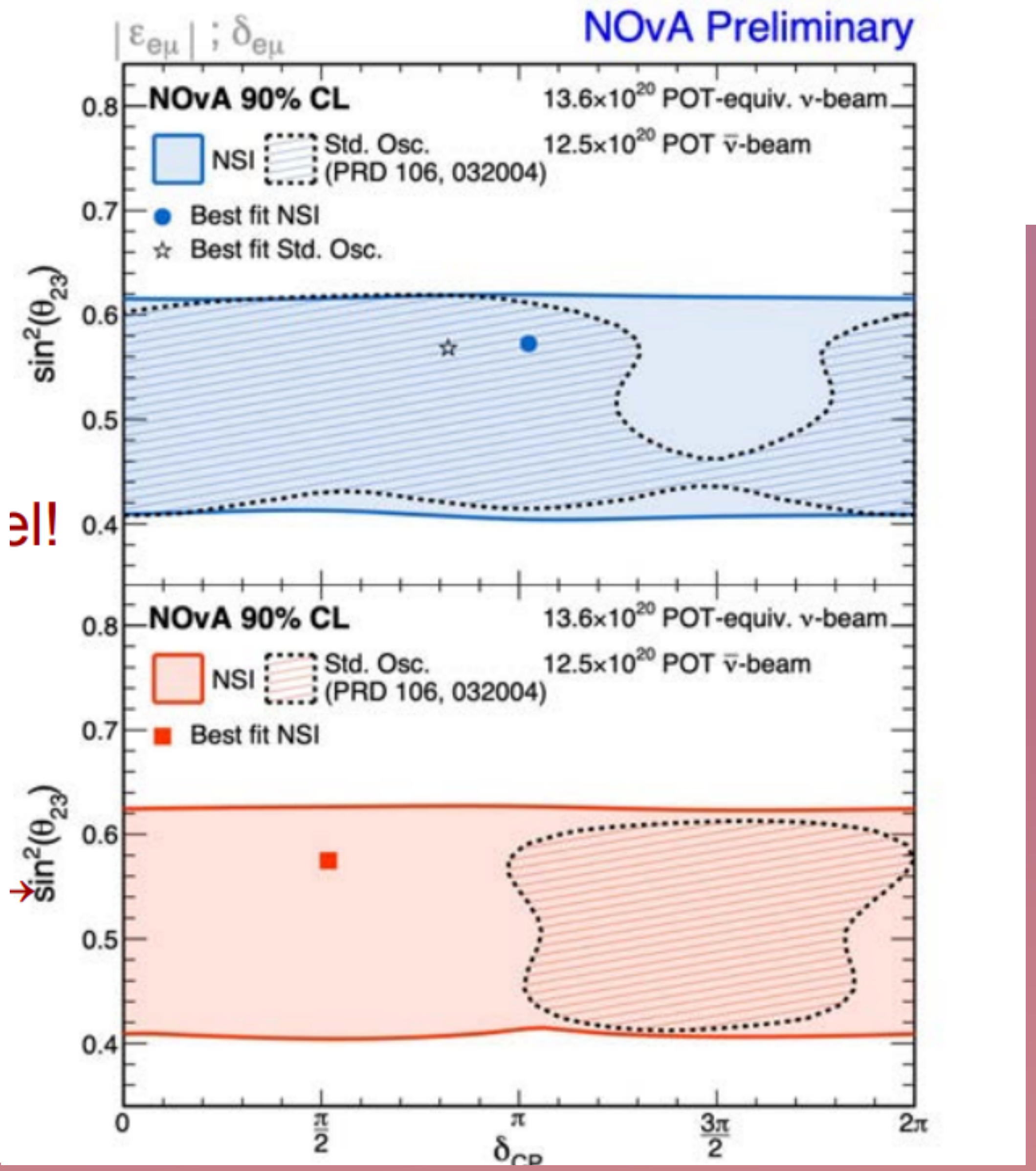
Best fits	χ^2	$\lvert\Delta m^2_{31}\rvert$ [eV²]	$\sin^2\theta_{23}$	δ_{CP}
Normal	1000.42	2.4×10^{-3}	0.49	4.71
Inverted	1006.19	2.4×10^{-3}	0.49	4.71

Identical values for θ_{23} and δ_{CP} fits slightly prefer the normal hierarchy!

Denver Whittington on Oscillations in Accelerator Neutrinos from NOvA





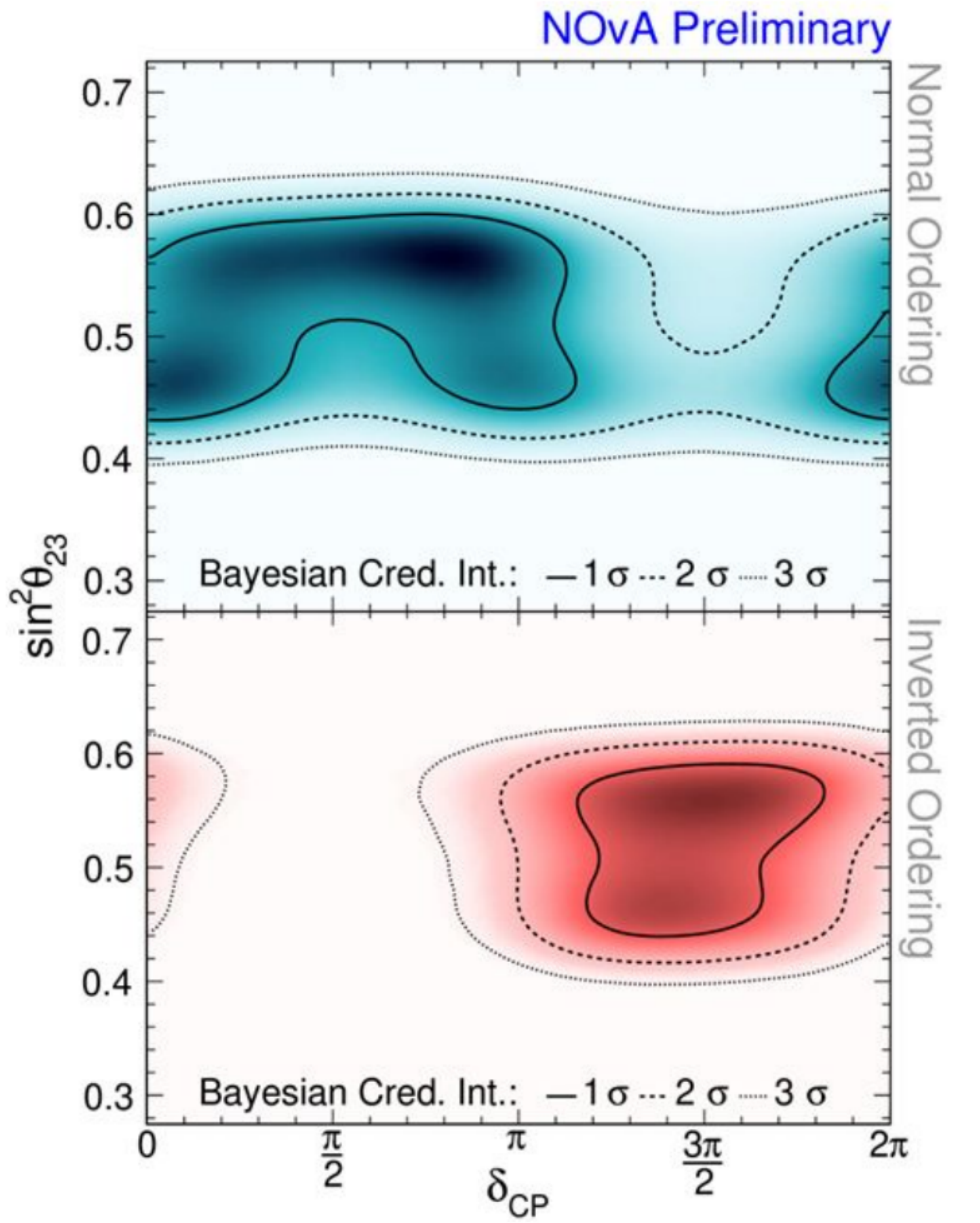


Markov Chain MC Bayesian Analysis

alternative statistical approach to previous frequentist analyses

- Allows results to be examined in new ways
- Conclusions the same as frequentist results
- Exclude (Inverted Ordering, $\delta = \pi/2$) at > 3σ

Best Fit
Normal hierarchy
$\Delta m^2_{32} = (2.41\pm0.07)\times10^{-3}$ eV^2
$\sin^2\vartheta_{23} = 0.57^{+0.04}_{-0.03}$
$\delta = 0.82\pi$ (frequentist results)

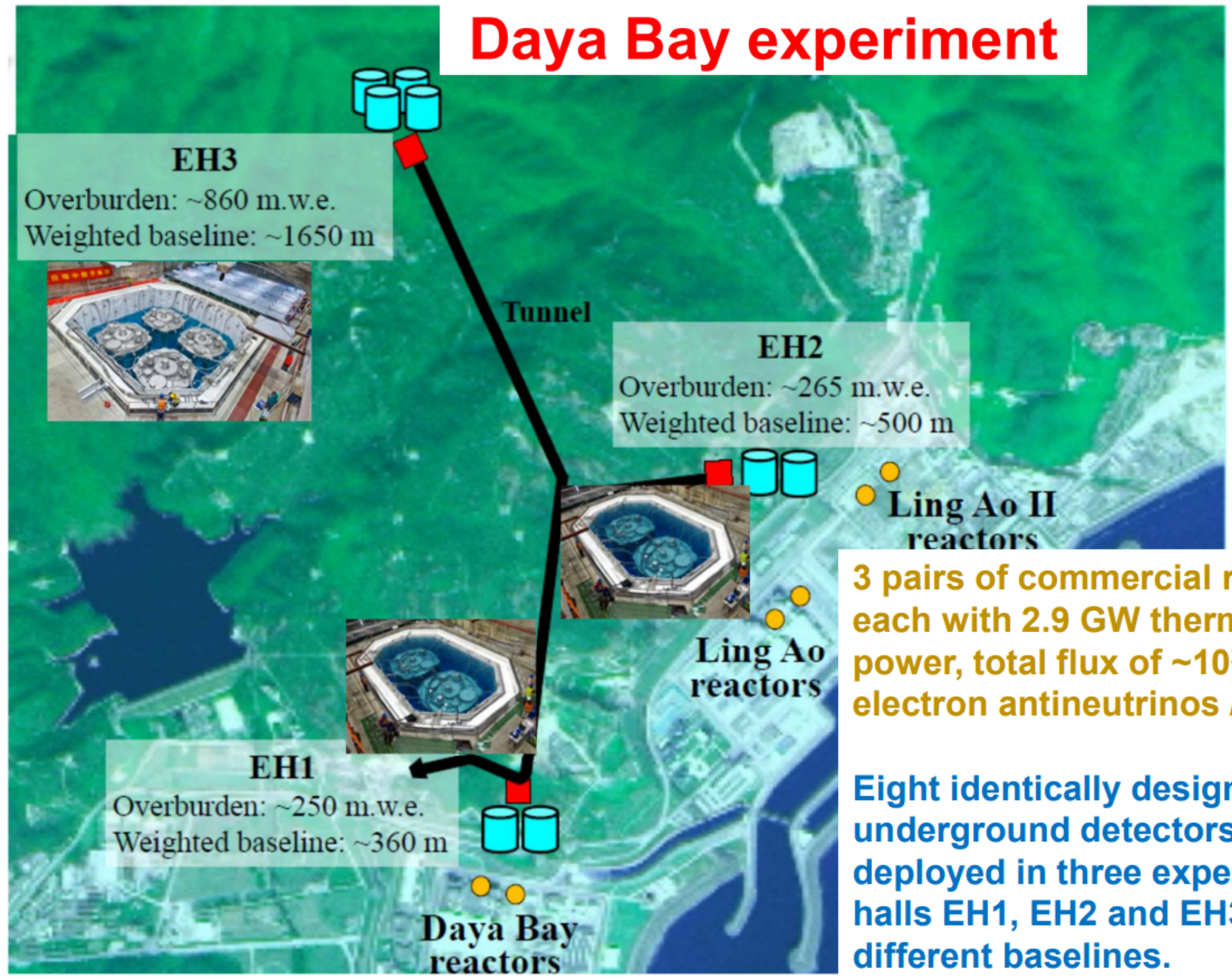


Bayesian analysis agrees with frequentist analysis!

NSI Interactions Analysis consistent with standard oscillations analysis but would lead to major reinterpretation of the initial results.

Rupert Leitner on Latest Results in Reactor Neutrinos from Daya Bay

Daya Bay experiment



3 pairs of commercial reactors, each with 2.9 GW thermal power, total flux of ~10^{21} electron antineutrinos / s

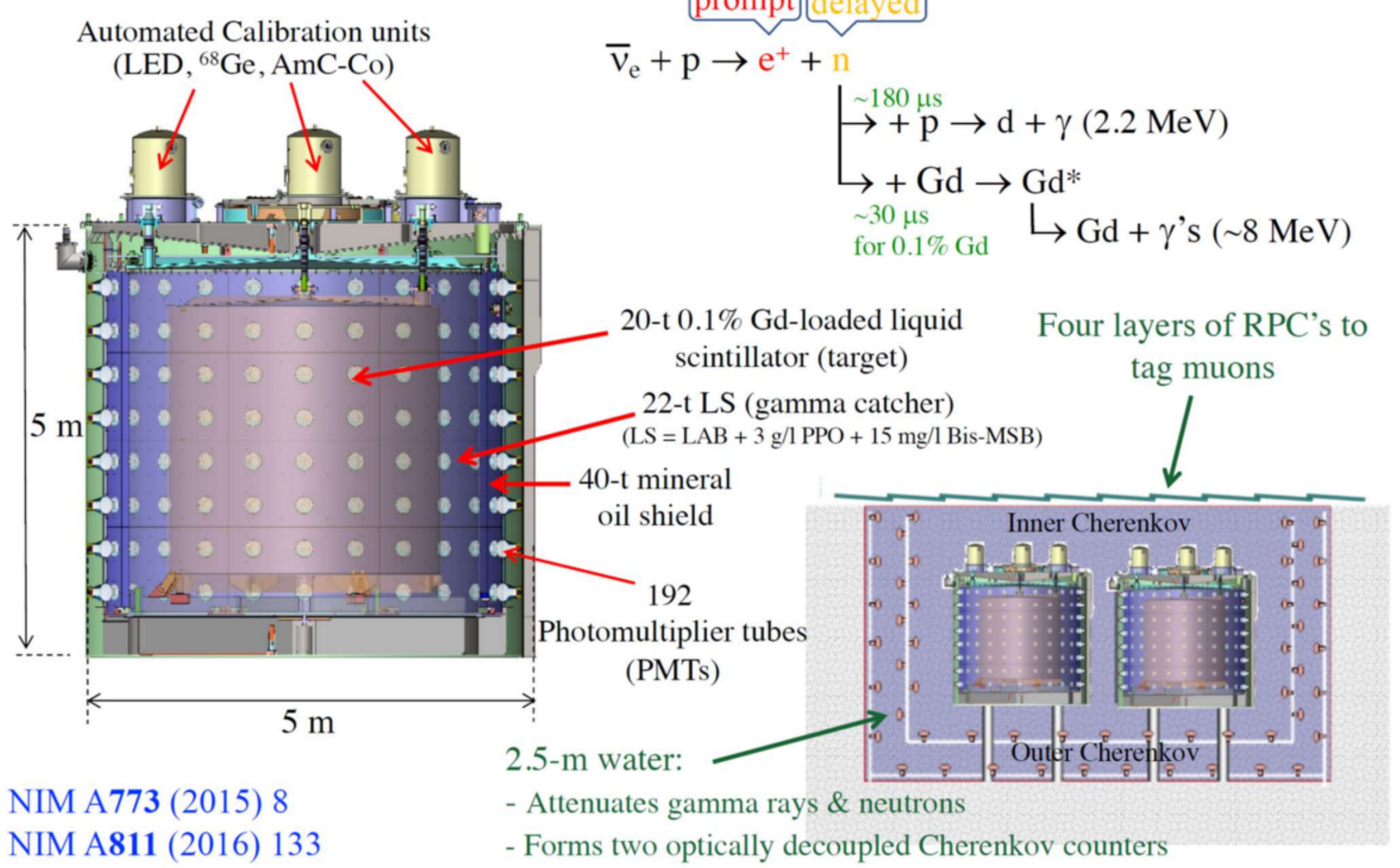
Eight identically designed underground detectors deployed in three experimental halls EH1, EH2 and EH3 at different baselines.

Detectors

- Detect inverse β-decay reaction (IBD):

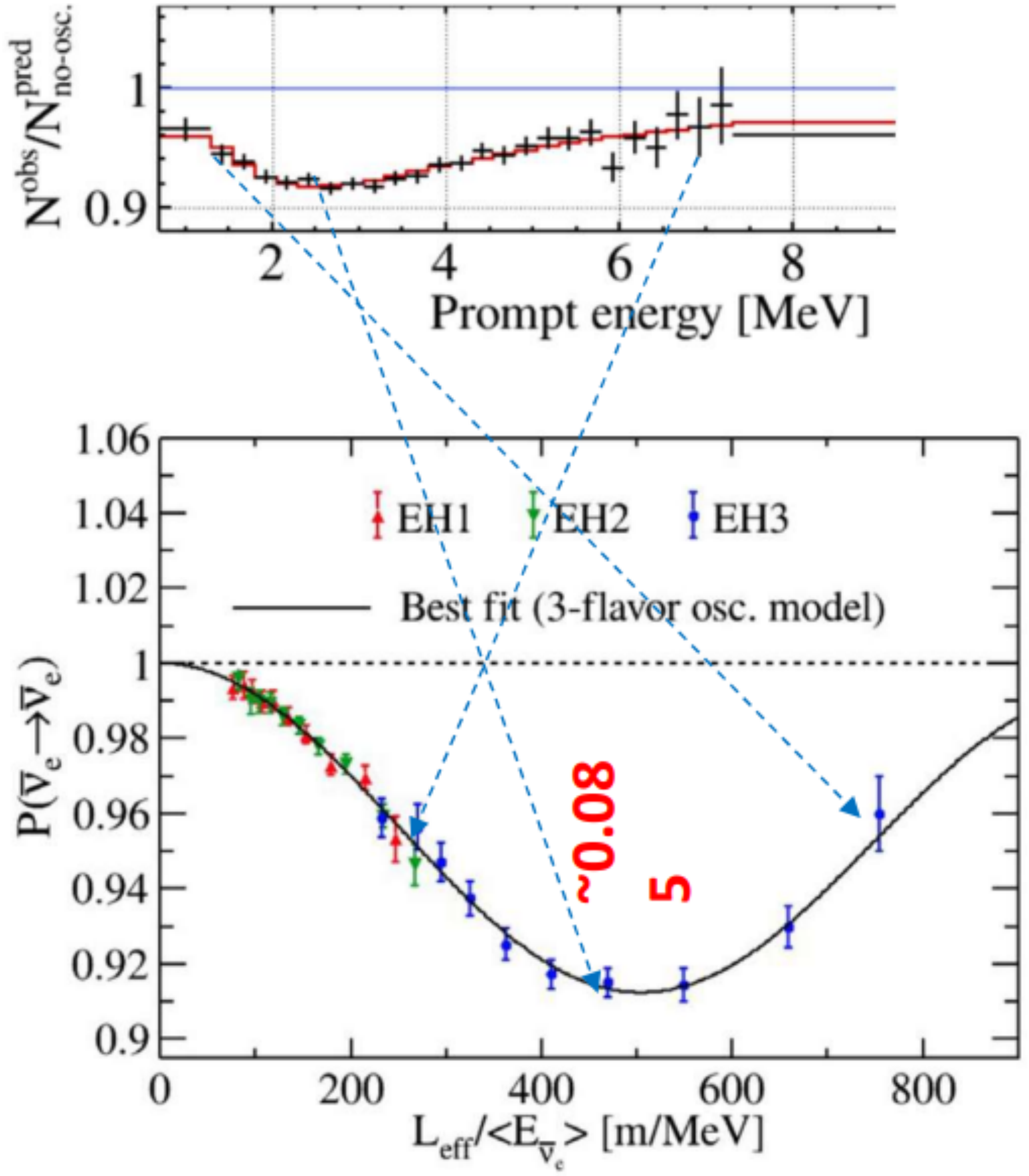
$\overline{\nu}_e + p \rightarrow e^+ + n$ (prompt: e^+, delayed: n)

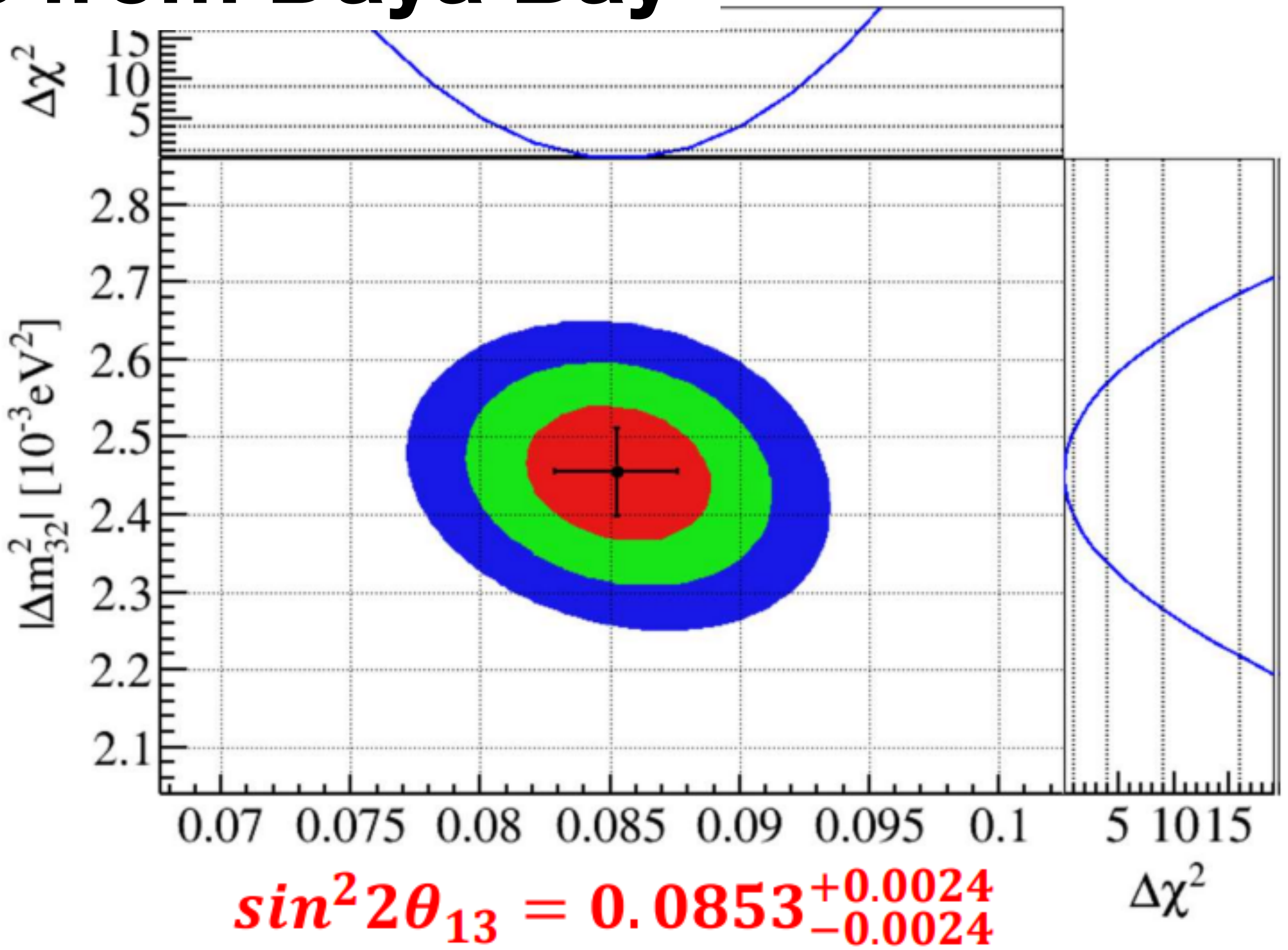
- ~180 μs: $\rightarrow + p \rightarrow d + \gamma$ (2.2 MeV)
- ~30 μs for 0.1% Gd: $\rightarrow + Gd \rightarrow Gd^*$ $\rightarrow Gd + \gamma$'s (~8 MeV)



2.5-m water:
- Attenuates gamma rays & neutrons
- Forms two optically decoupled Cherenkov counters

NIM **A773** (2015) 8
NIM **A811** (2016) 133





$$sin^2 2\theta_{13} = 0.0853^{+0.0024}_{-0.0024}$$

Normal Mass Ordering

$$\Delta m^2_{32} = +\left(2.454^{+0.057}_{-0.057}\right) \times 10^{-3}\ \text{eV}^2$$

Inverted Mass Ordering

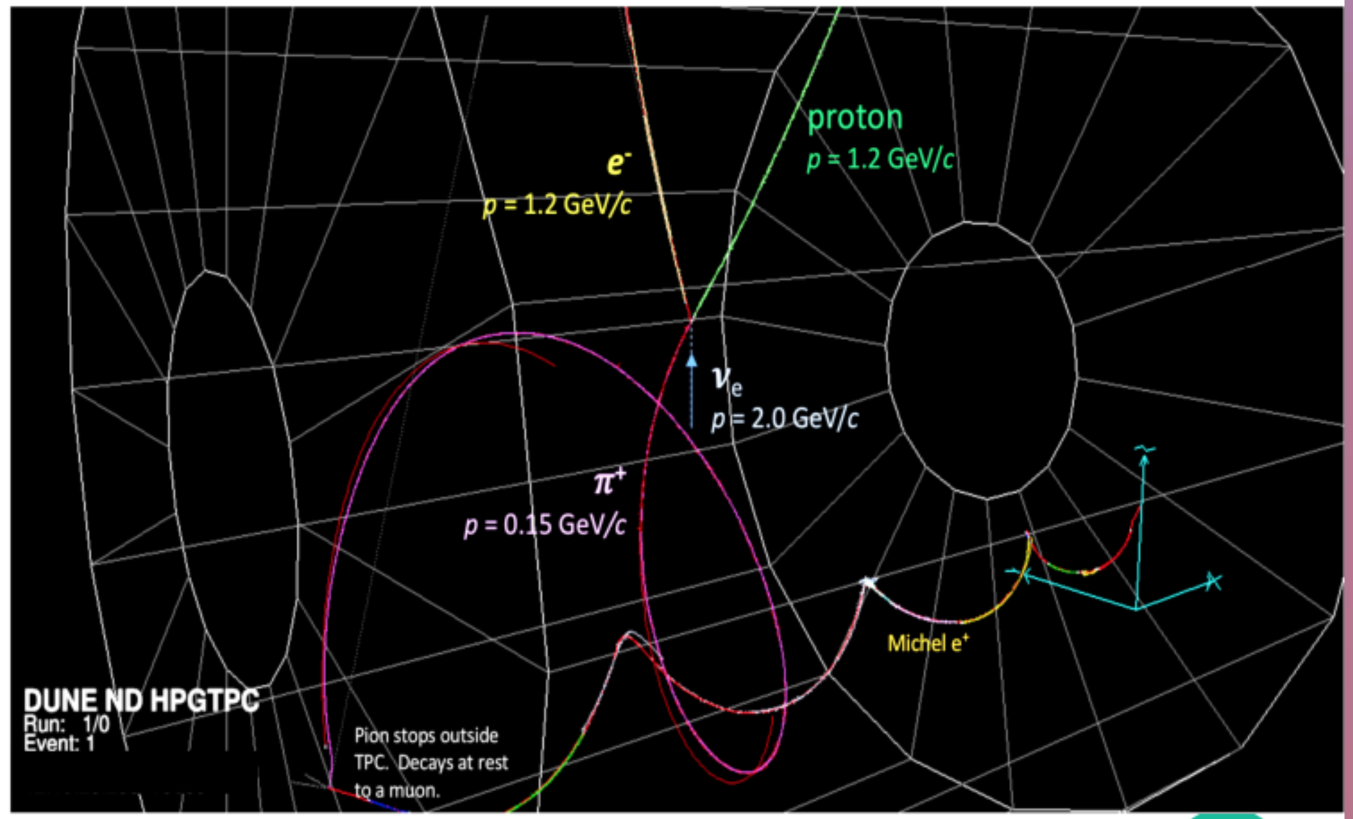
$$\Delta m^2_{32} = -\left(2.559^{+0.057}_{-0.057}\right) \times 10^{-3}\ \text{eV}^2$$

World's most precise measurements of θ_{13} and $|\Delta m^2_{32}|$ with the largest sample of reactor neutrinos to date!

Tanaz Mohayai on DUNE and T2HK/ Hyper-K as well as emerging gaseous argon TPC

- Low threshold gas TPCs for long-baseline oscillation physics (e.g. ND-GAr in DUNE & gas TPCs in ND280):
  - ★ Low density, hence low detection threshold (e.g. lower than LArTPC), leads to high sensitivity to low energy **protons** or **pions**
  - ★ **Reveals discrepancies between neutrino event generators at low energies,** getting us closer to choosing a more accurate interaction models

A detailed view of the ν-interaction vertex in ND-GAr near detector in DUNE



T. A. Mohayai

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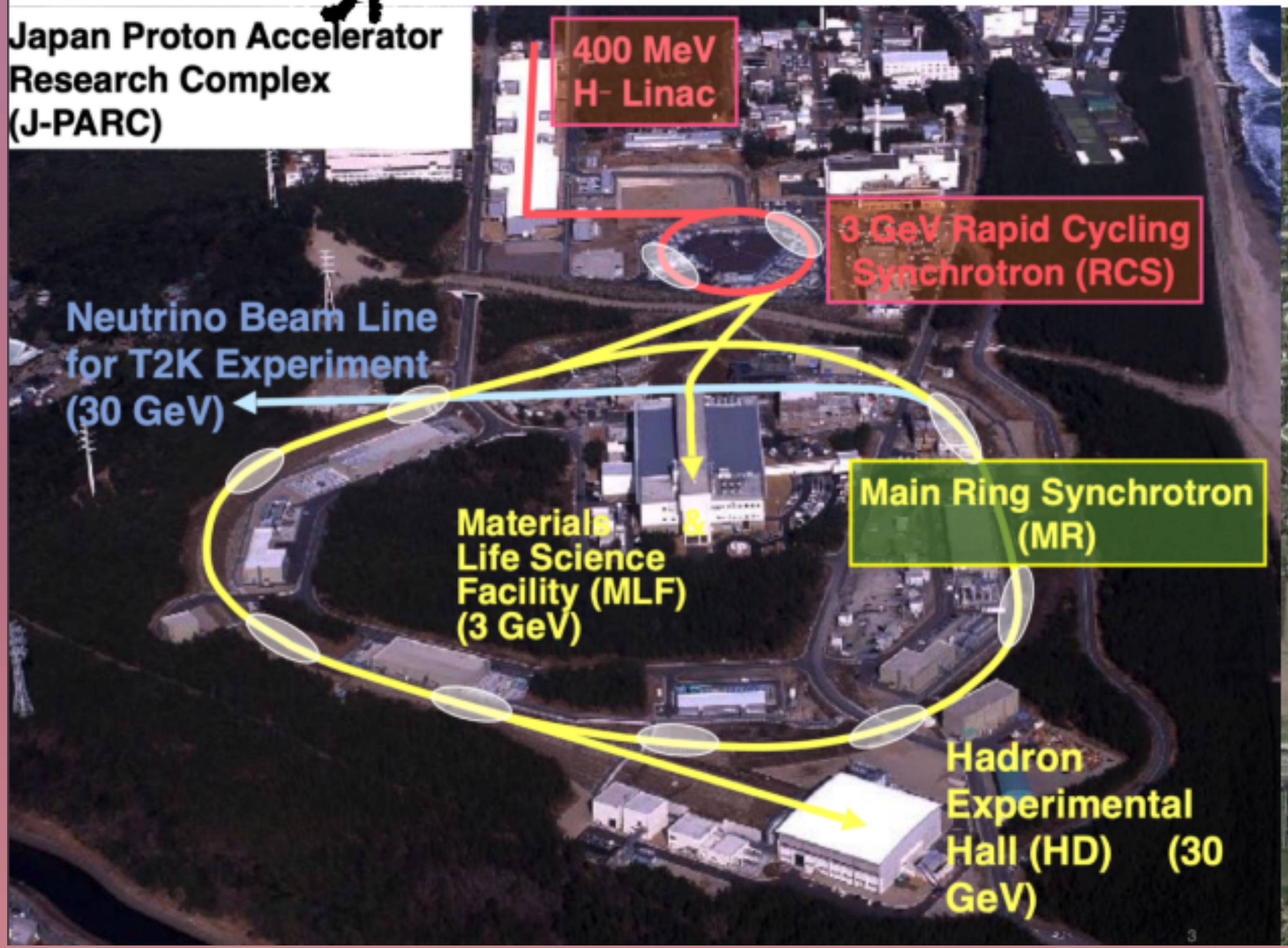
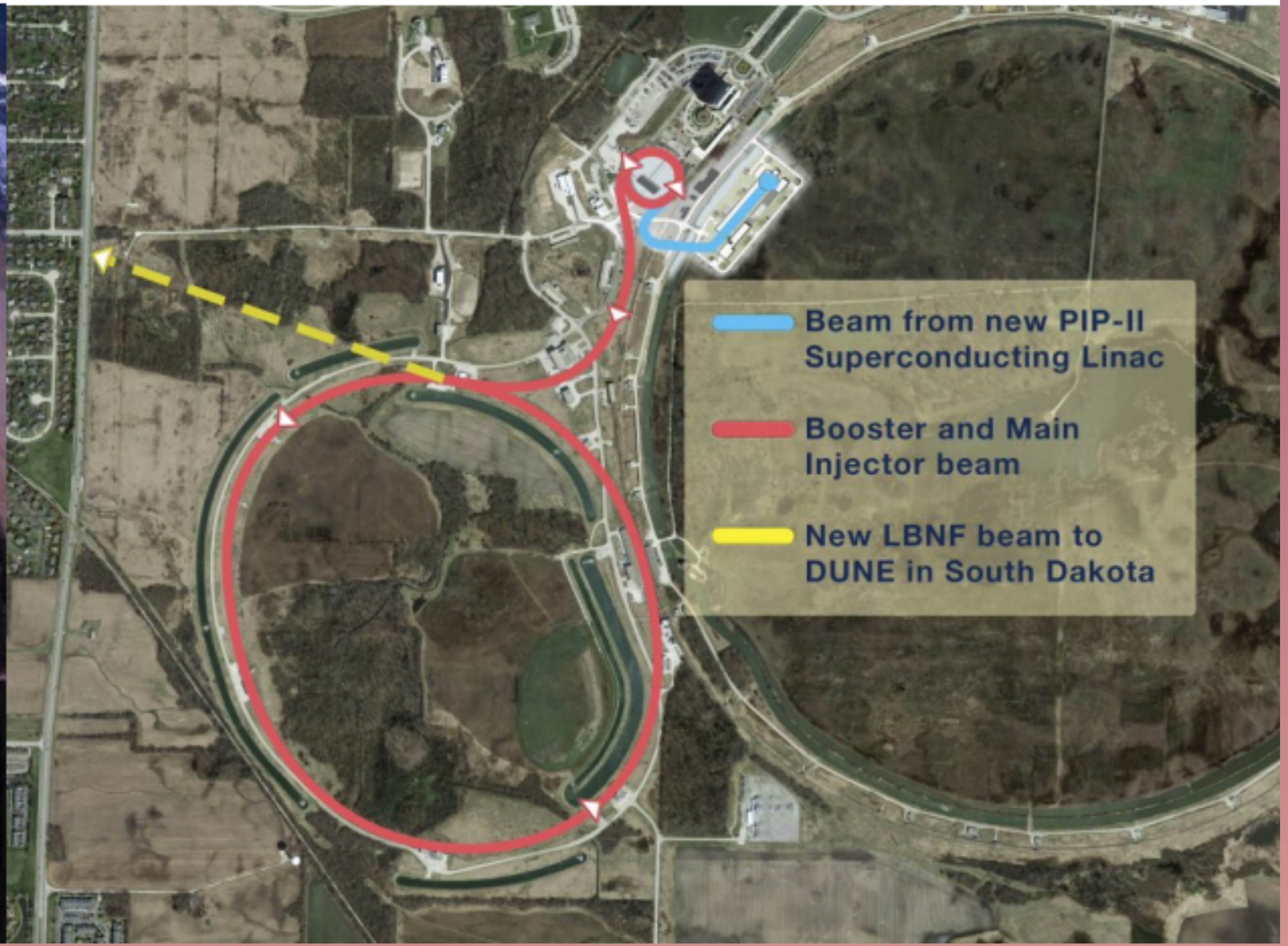
Neutrino Beams of Two Future LBL Experiments

- T2HK/HyperK neutrino beam:
  - ★ At J-PARC, **1.3 MW beam power**
  - ★ Narrow-band beam, far detector placed off the beam axis to observe neutrino flux peaked at ~600 MeV + near detectors at on and off-axis locations
- DUNE neutrino beam:
  - ★ At Fermilab, **1.2 MW beam power, upgradable to 2.4 MW**
  - ★ Wide-band beam, far detector placed on-axis to observe a broad spectrum of neutrino fluxes (0.5-5 GeV) + movable near detector for on and off-axis ν-flux measurements (DUNE-PRISM)

T2HK/HyperK Beam @ J-PARC



DUNE Beam @ Fermilab



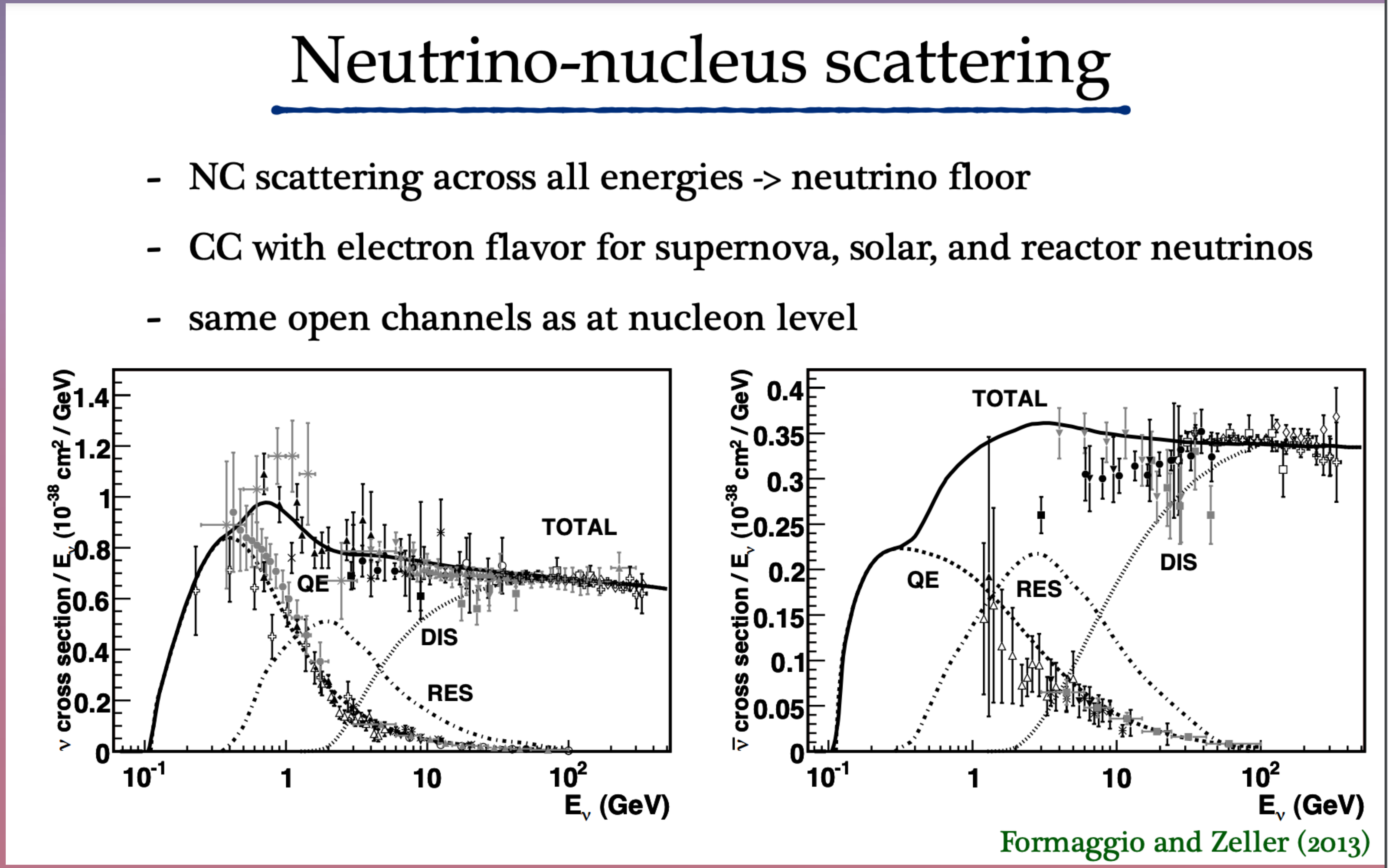
The next generation of neutrino oscillation experiments is on the horizon!

Neutrino-Nucleus Cross-Sections and Scattering

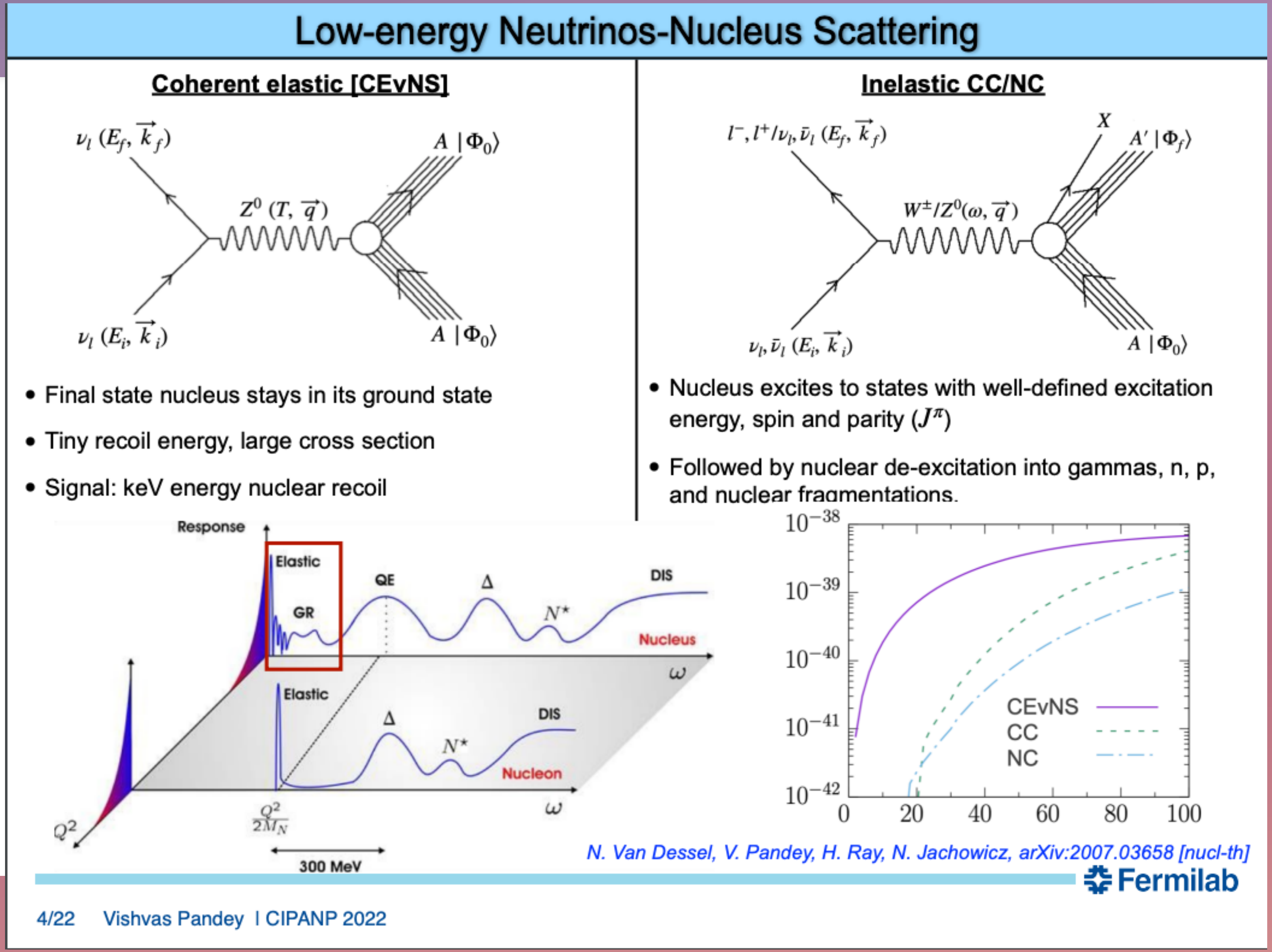
- Reports from:
  - Vishvas Pandey and Oleksandr “Sasha” Tomalak on a Introductions to Neutrino Scattering
  - Josh Barrow on $\mu/e4\nu$
  - Maria Martinez-Casales on Cross Sections in NOvA
  - Camillo Mariani on electron-Argon scattering at JLab
  - Yin Lin on Contributions from Lattice QCD
  - Alejandro Ramirez Delgado on Coherent Pion Production in MINERvA
  - Nina Coyle on Cross-Section Tuning and Effects on New Physics
  - Ishaan Vohra on Smearing in Neutrino Simulation

Introductions to Neutrino Scattering

Oleksandr “Sasha” Tomalak

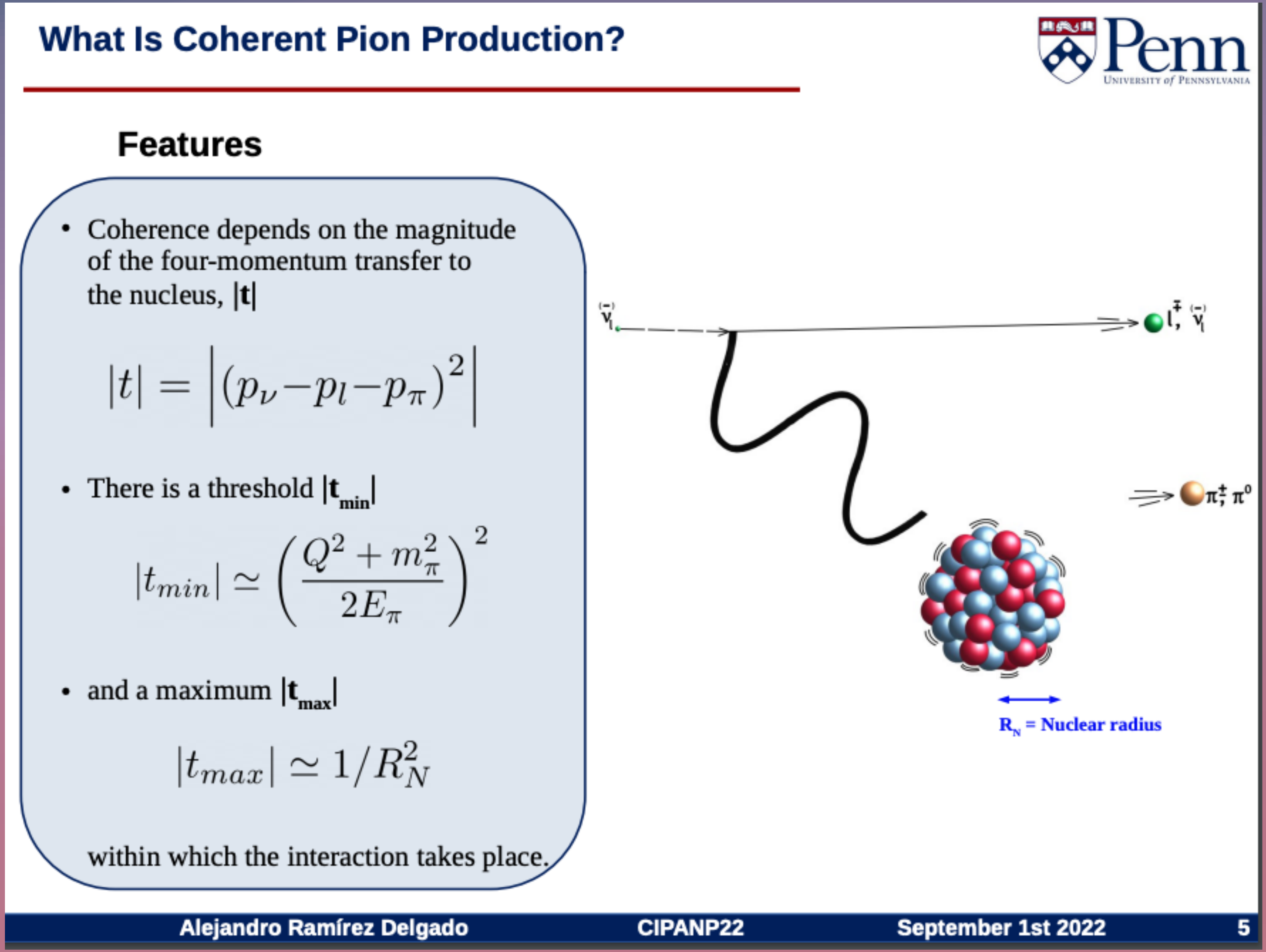


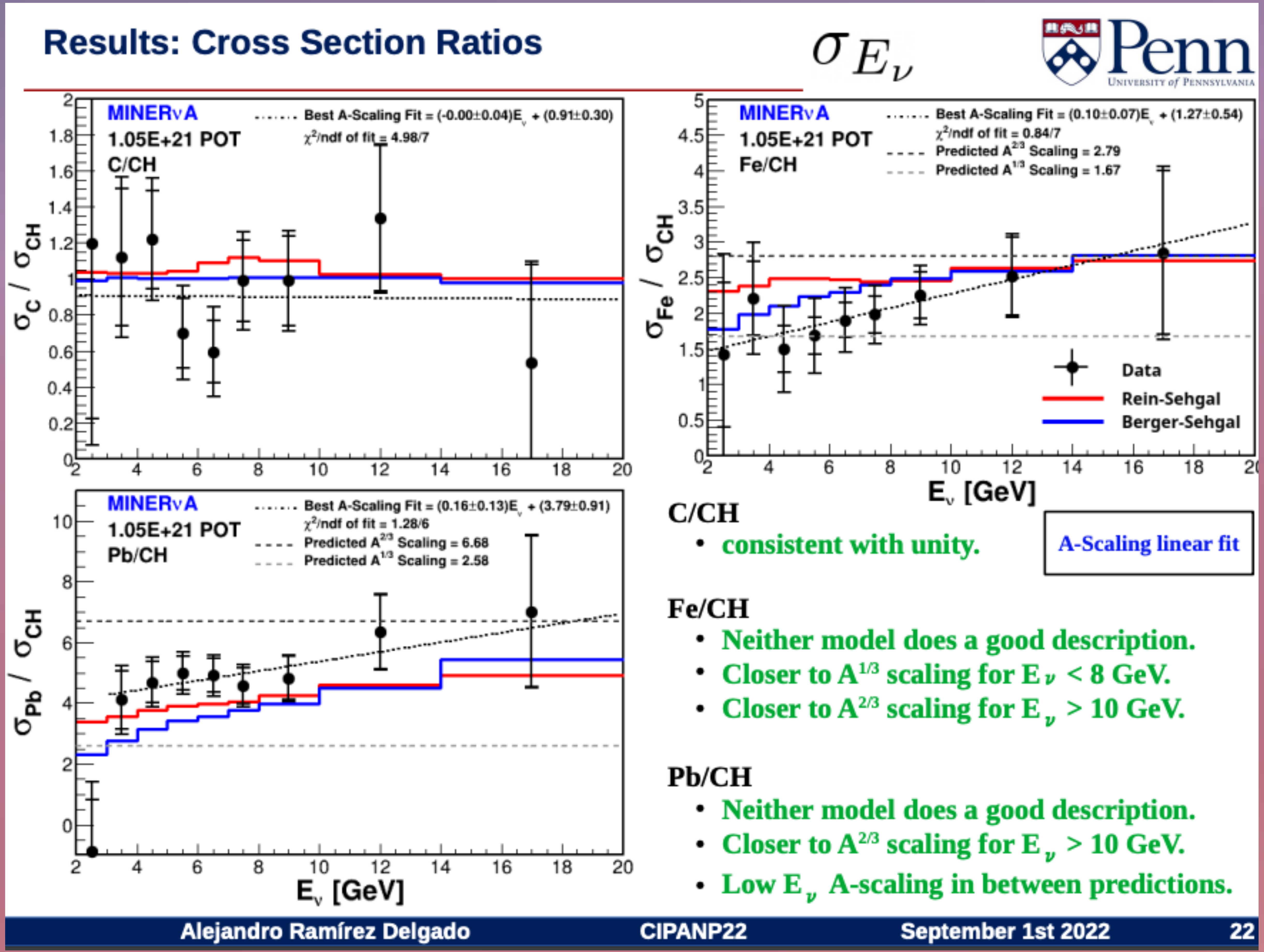
Vishvas Pandey



Overlapping descriptions of the neutrino-nucleus scattering at different nuclear recoil energies outlines the fundamental difficulty of the problem!

Alejandro Ramirez Delgado on Coherent Pion Production at MINERvA





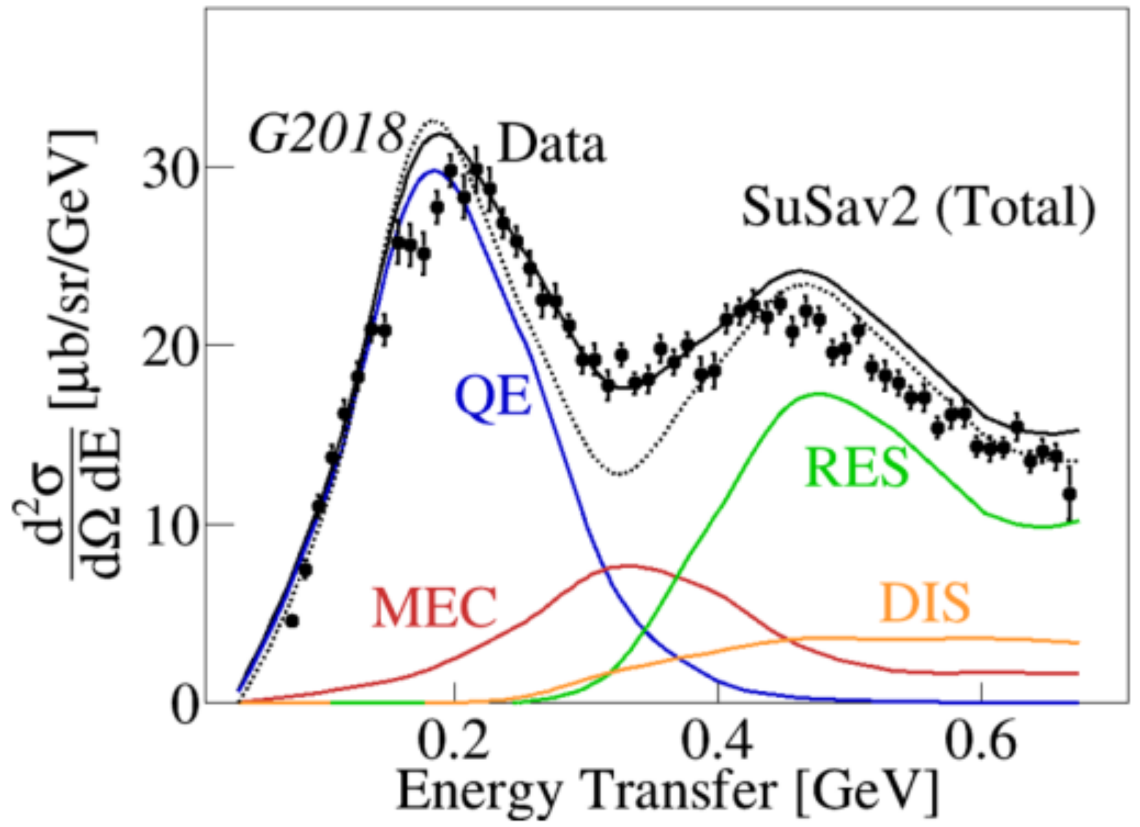
MINERvA measurements show multiple cross-sections and comparisons using a fairly well understood process, good progress in cross-section measurements and measurements of nuclear structure

Josh Barrow on $e4\nu$

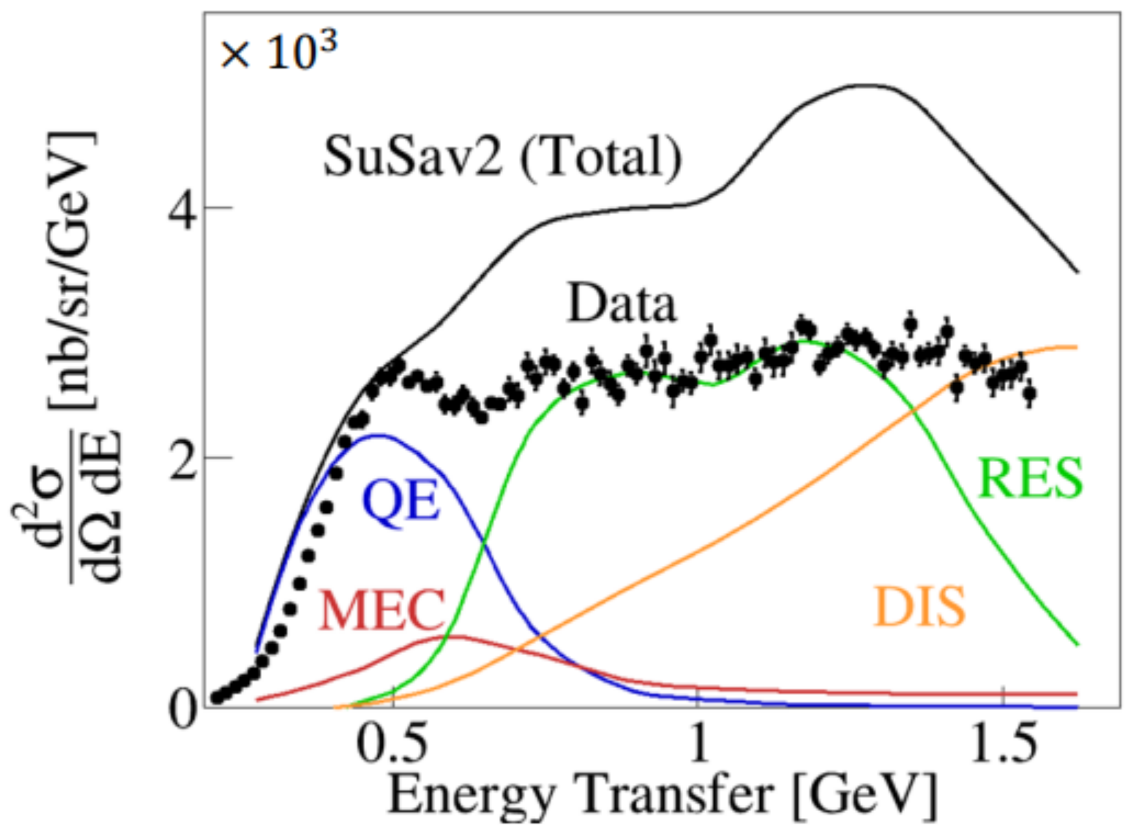
Inclusive $A(e,e')$ Data Comparisons

- Consistent $\{\nu_\ell, \ell\}$ modeling now implemented
  - Can compare to world inclusive QE electron scattering data
  - Any misconstrued behavior here won't work for νs either!
- Much work to do!
  - Must build better models, constrain any free parameters!

Fe(e,e'): 0.961 GeV at 37.5°



C(e,e'): 3.595 GeV at 16°



Phys. Rev. D 103, 113003 (2021)

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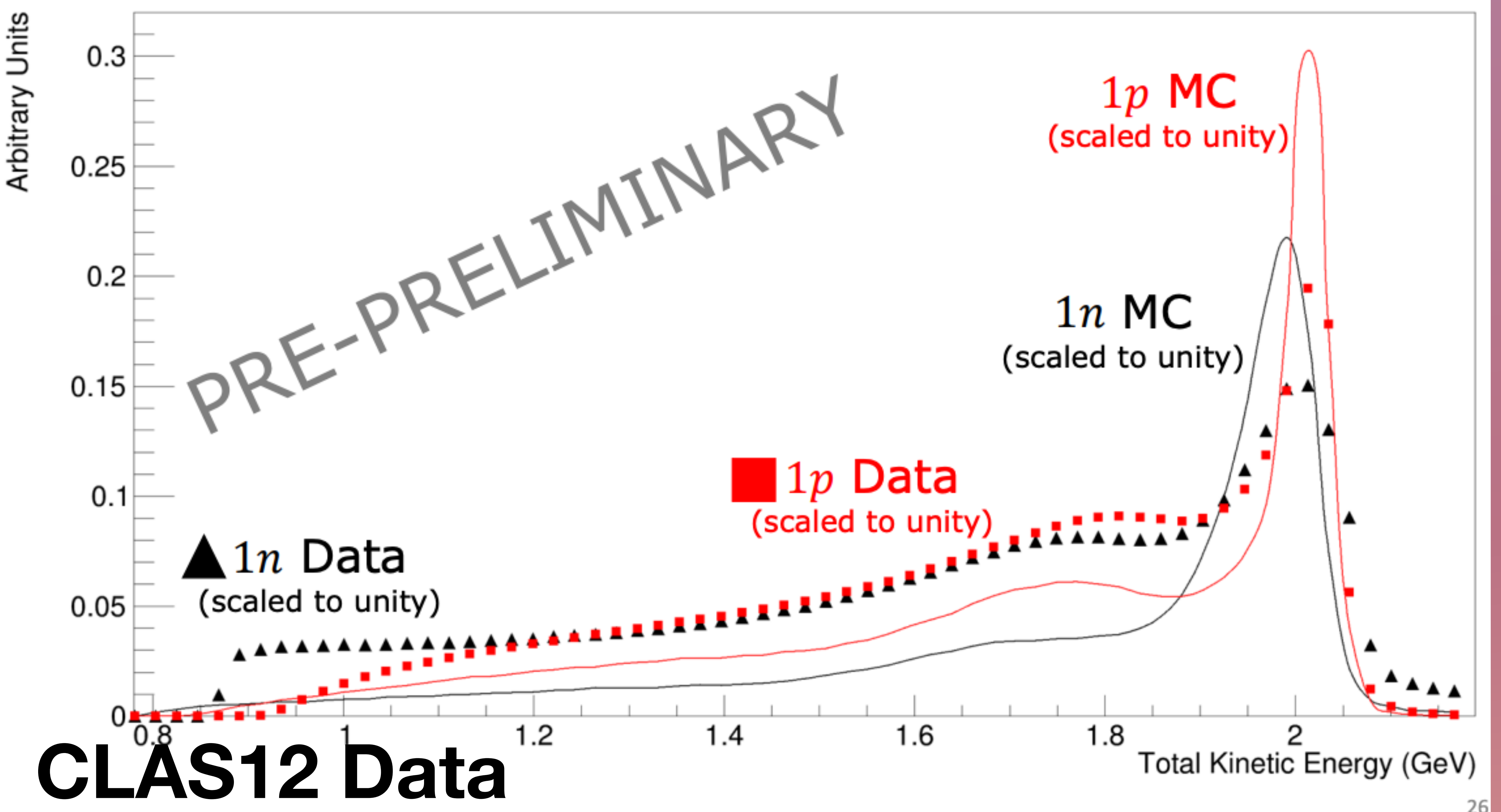
Initial Comparisons to Simulation

Showing Unphysical Differences?



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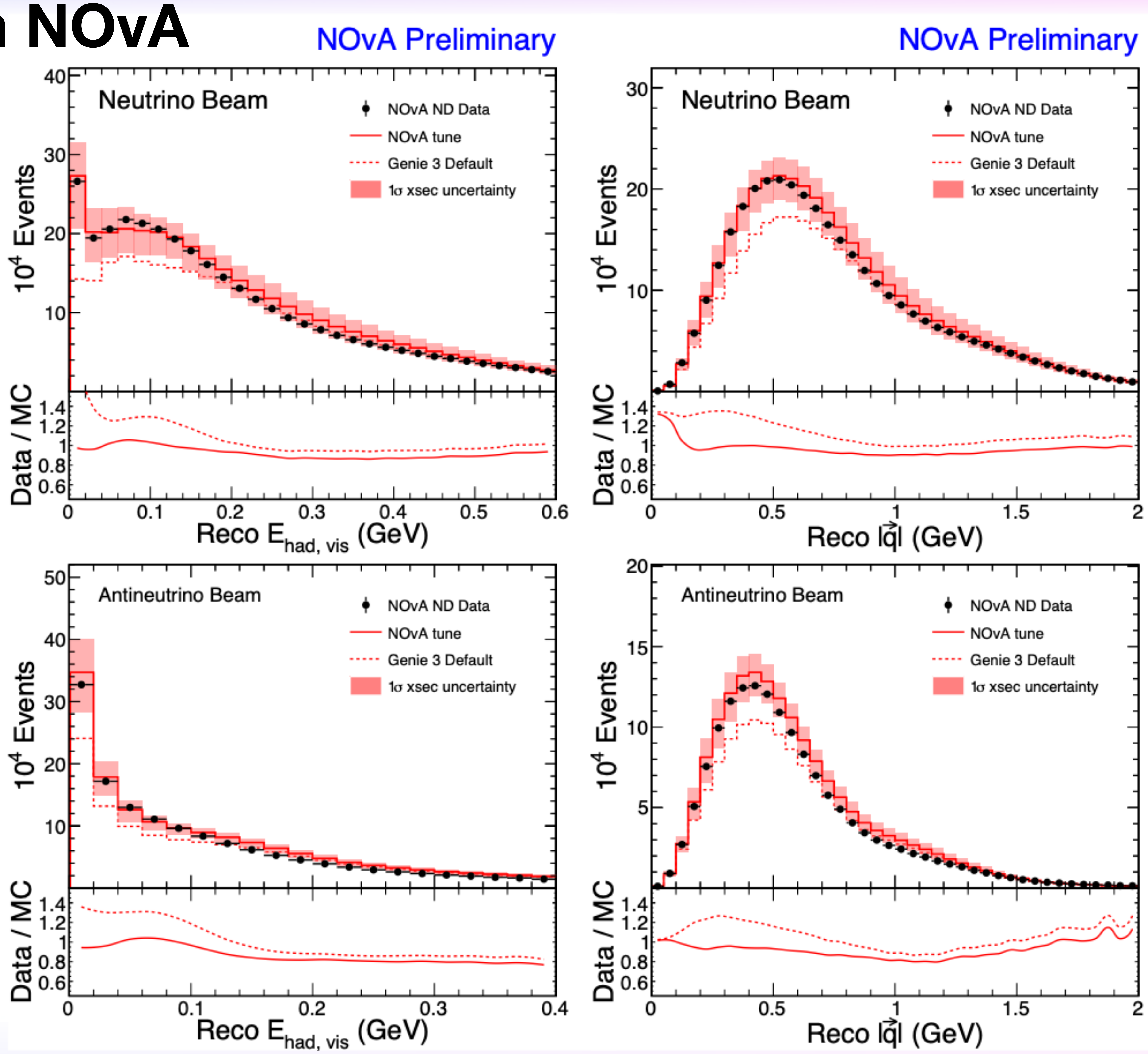
Useful but imperfect tools for inferring neutrino-nucleus scattering, shows there are a lot left to learn about nuclear and neutrino physics.

Maria Martinez-Casales on tuning in NOvA

NOvA tune and uncertainties

- Central value agreement is good after FSI and MEC adjustments.
- Cross section uncertainties include custom MEC, FSI in addition GENIE uncertainties.
- These are adequate to take into account remaining differences.



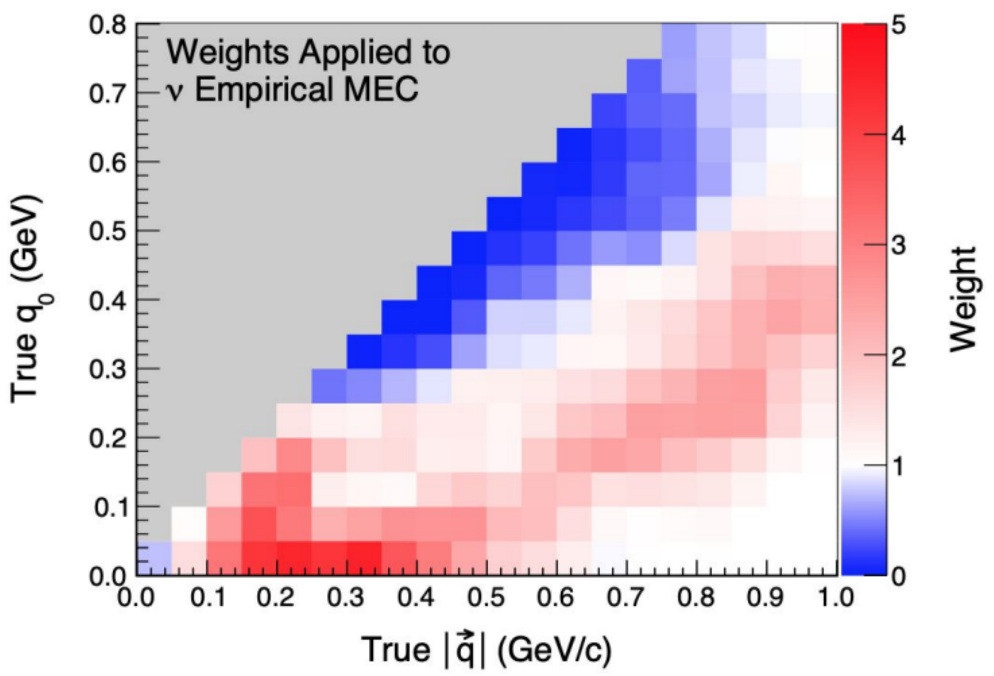
M.Martinez-Casales CIPANP 2022 19

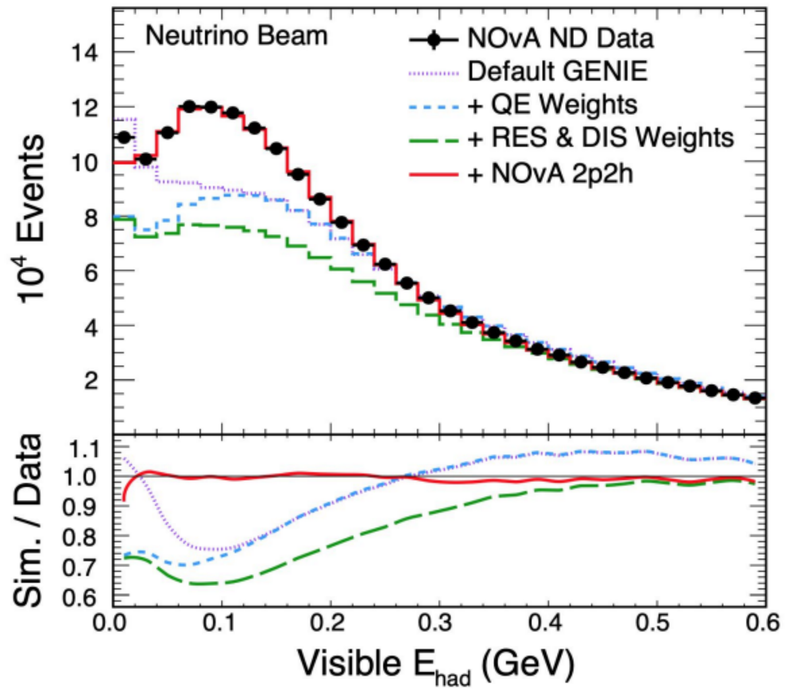
NOvA tunes its cross sections and FSI input for oscillations analyses to ND data, primarily using MEC.

Nina Coyle on Cross-Section Tuning and New Physics

Near detector tuning: NOvA

How to adjust for remaining discrepancy? Adjust the MEC contribution





NOvA collaboration, arXiv:2006.08727

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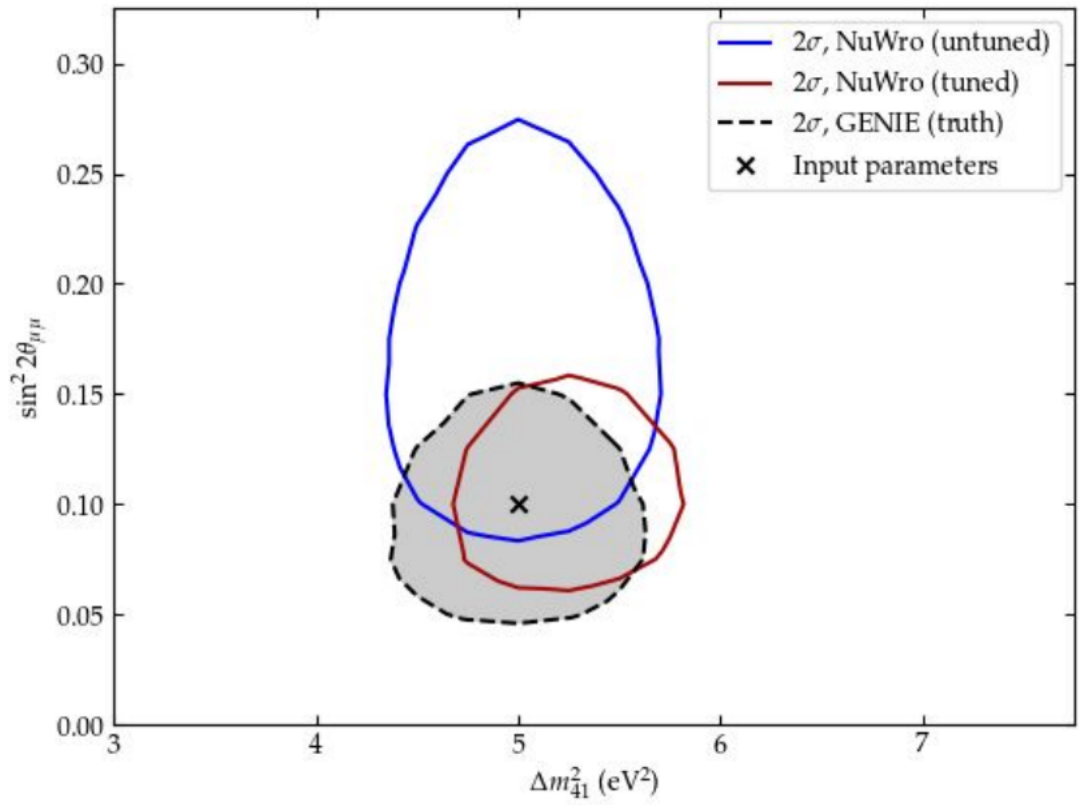
Sterile neutrino signal: direct fit

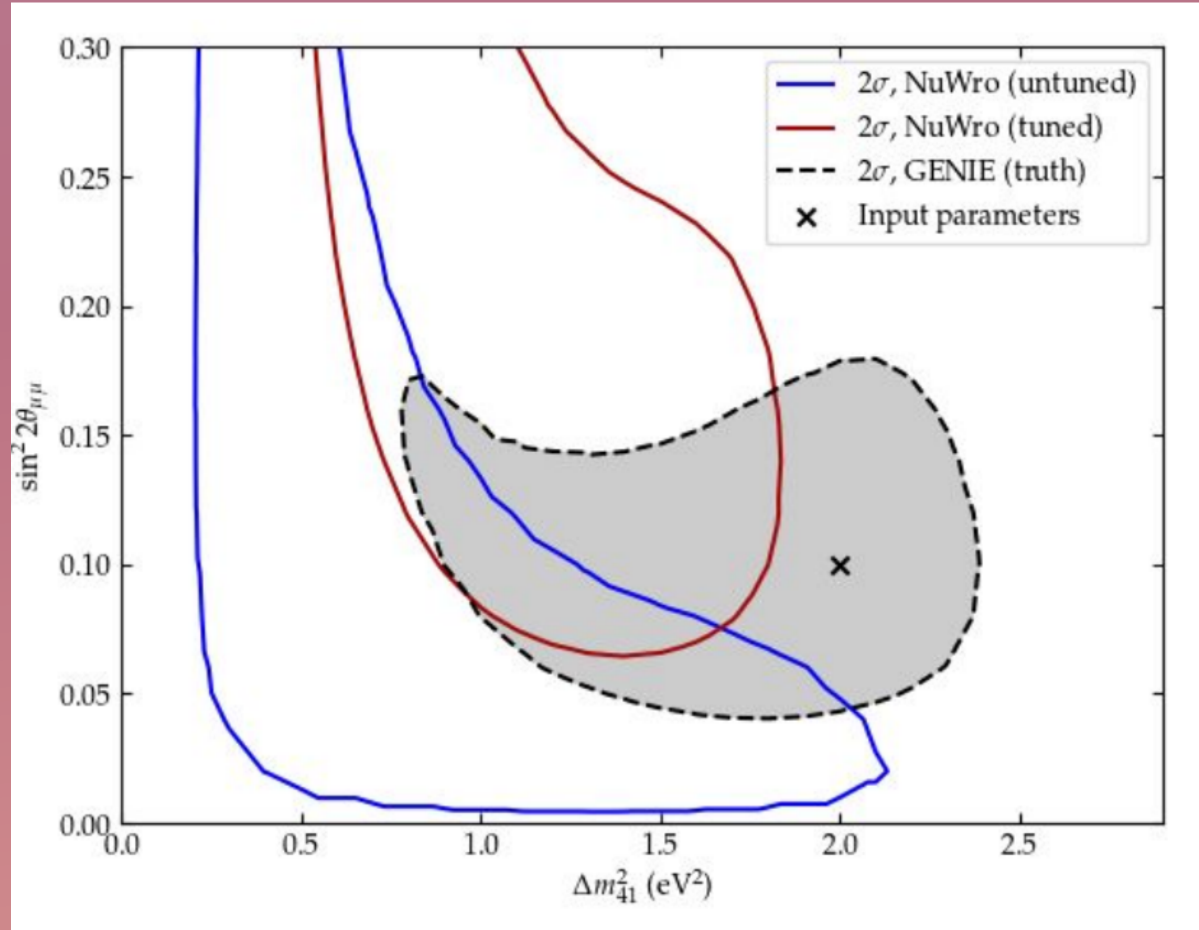
- Two different generators: GENIE for data, NuWro for simulated model
- Direct fit to FD and ND rates
- Simultaneous fit and tune



N.C., Li, Machado, in preparation

Data driven tuning (like shown in the previous NOvA talk) has consequences!

Are we making ourselves insensitive to new physics?



(e,e'p) cross section

elementary cross section

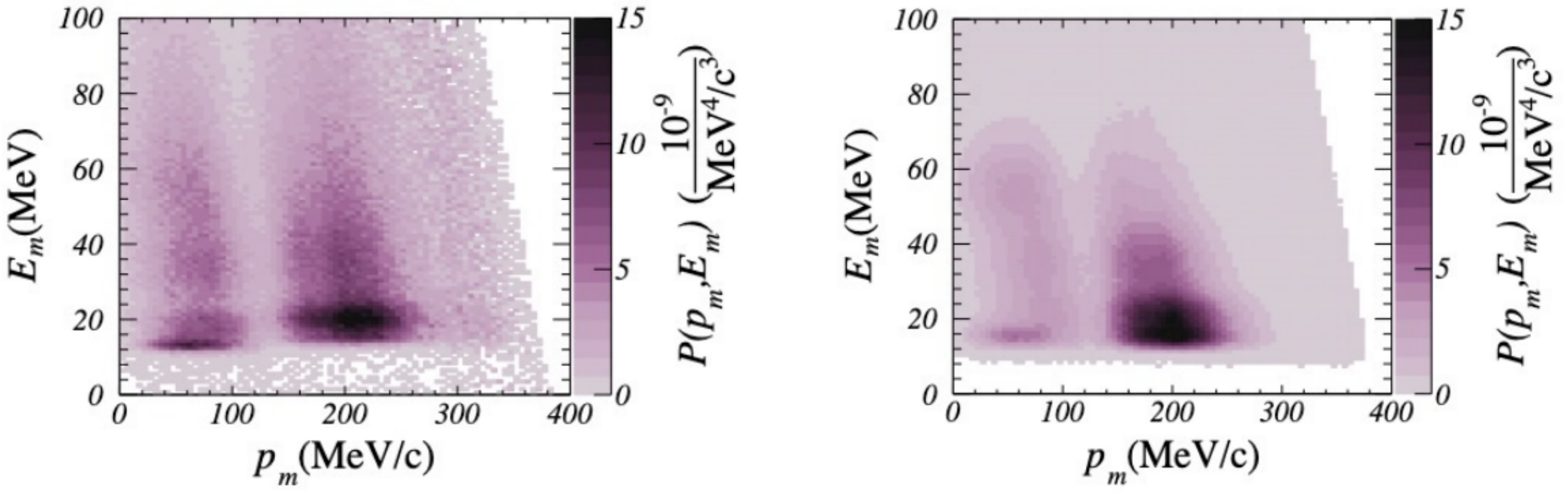
nuclear transparency

$$\frac{d^6\sigma_{IA}}{d\Omega_{e'}dE_{e'}d\Omega_{p'}dE_{p'}} \propto \sigma_{ep}\, S(p_m, E_m) T(E_{p'})$$

spectral function

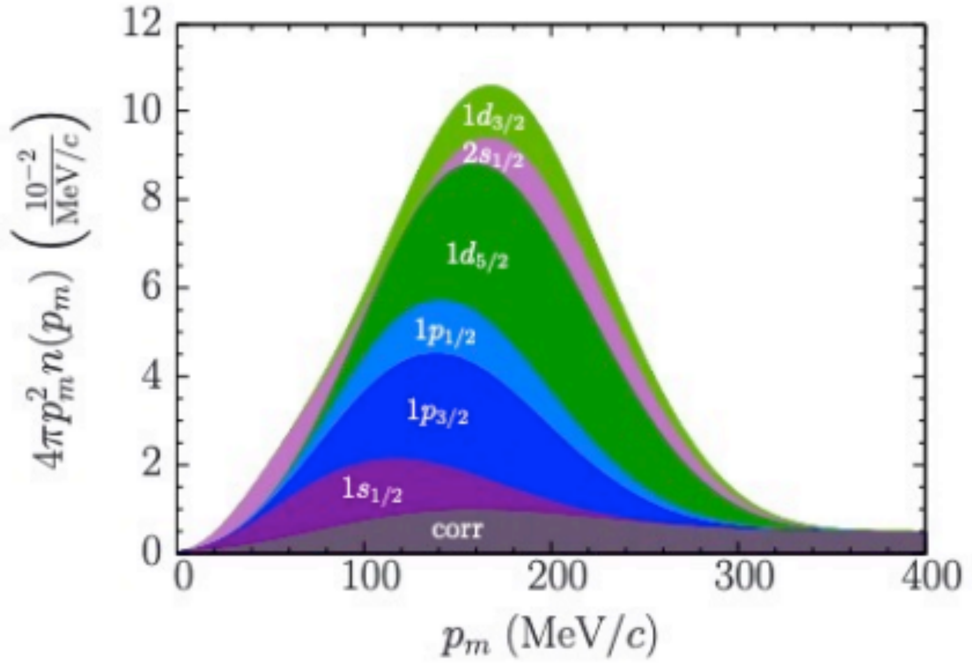
Camillo Mariani on e-scattering

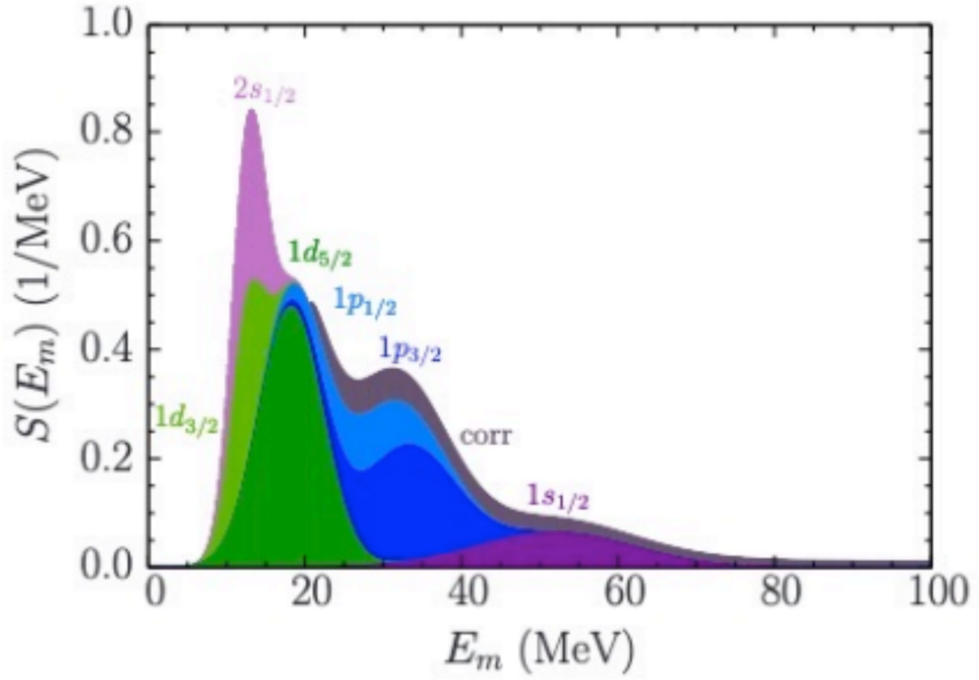
CIPANP, 2022



(a) Data (b) MC

Ar (e,e'p) – Phys. Rev. D 105, 112002, (2022)





		all priors	w/o p_m	w/o corr.
α	N_α		S_α	
$1d_{3/2}$	2	0.89 ± 0.11	1.42 ± 0.20	0.95 ± 0.11
$2s_{1/2}$	2	1.72 ± 0.15	1.22 ± 0.12	1.80 ± 0.16
$1d_{5/2}$	6	3.52 ± 0.26	3.83 ± 0.30	3.89 ± 0.30
$1p_{1/2}$	2	1.53 ± 0.21	2.01 ± 0.22	1.83 ± 0.21
$1p_{3/2}$	4	3.07 ± 0.05	2.23 ± 0.12	3.12 ± 0.05
$1s_{1/2}$	2	2.51 ± 0.05	2.05 ± 0.23	2.52 ± 0.05
corr.	0	3.77 ± 0.28	3.85 ± 0.25	excluded
$\sum_\alpha S_\alpha$		17.02 ± 0.48	16.61 ± 0.57	14.12 ± 0.42
d.o.f		206	231	232
χ^2/d.o.f.		1.9	1.4	2.0

	E_α (MeV)		σ_α (MeV)	
α	w/ priors	w/o priors	w/ priors	w/o priors
$1d_{3/2}$	12.53 ± 0.02	10.90 ± 0.12	1.9 ± 0.4	1.6 ± 0.4
$2s_{1/2}$	12.92 ± 0.02	12.57 ± 0.38	3.8 ± 0.8	3.0 ± 1.8
$1d_{5/2}$	18.23 ± 0.02	17.77 ± 0.80	9.2 ± 0.9	9.6 ± 1.3
$1p_{1/2}$	28.8 ± 0.7	28.7 ± 0.7	12.1 ± 1.0	12.0 ± 3.6
$1p_{3/2}$	33.0 ± 0.3	33.0 ± 0.3	9.3 ± 0.5	9.3 ± 0.5
$1s_{1/2}$	53.4 ± 1.1	53.4 ± 1.0	28.3 ± 2.2	28.1 ± 2.3
corr.	24.1 ± 2.7	24.1 ± 1.7	—	—

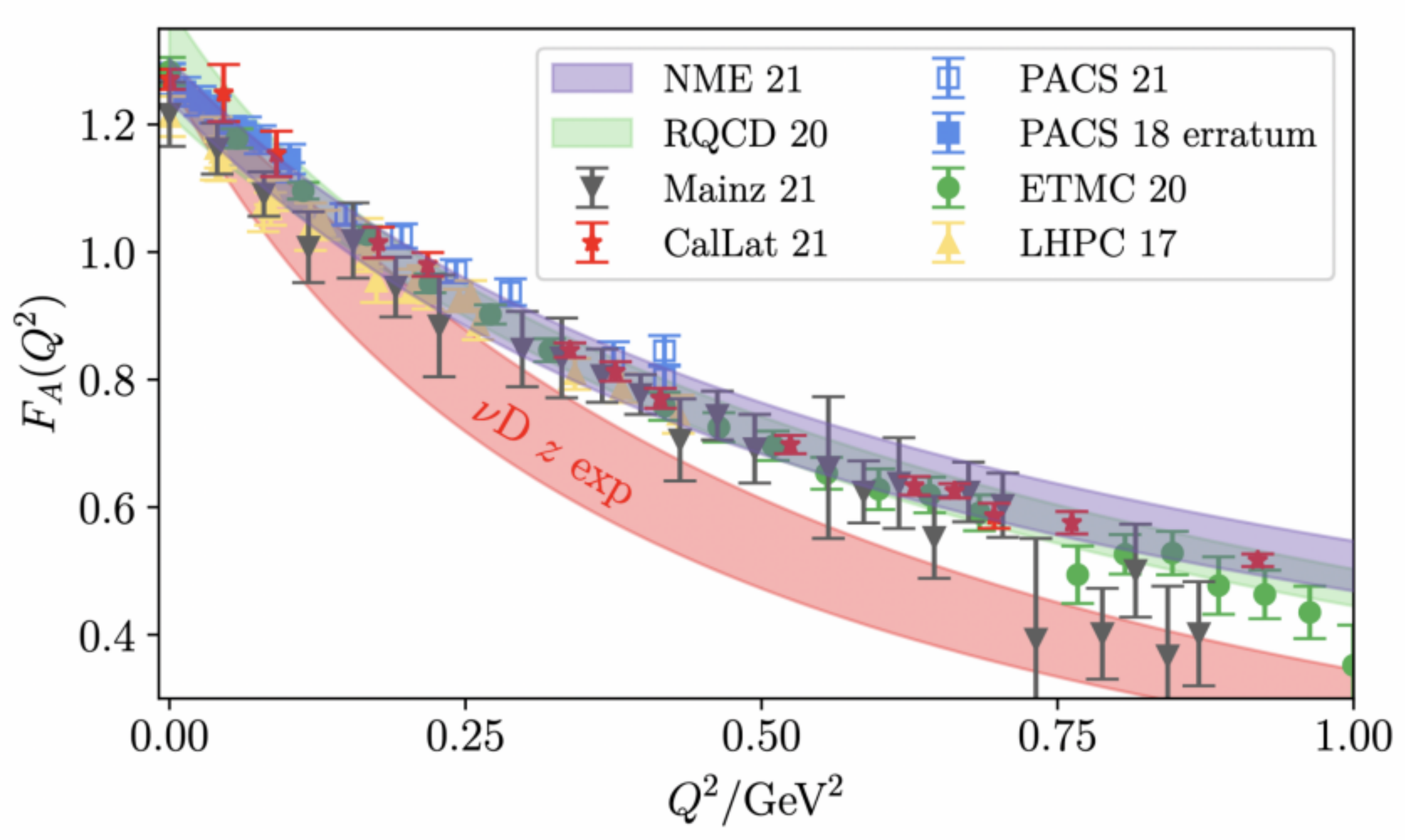
CIPANP, 2022 24

Argon proton cross-sections and spectral response measured using CLAS data! Crucial for future Argon scattering experiments

Summary

Yin Lin on Contributions from Lattice QCD

- Lattice QCD results on the nucleon axial form factors are converging
  ⟶ higher values at large Q^2
- Fully controlled systematics in the near future (new experiments?)
- Exploratory calculations of other processes (resonance transition form factors, hadronic tensors, and pdfs)



Lattice QCD now regularly provides testable predictions for neutrino nucleus scattering! Fascinating continued period of sustained growth!

What Is NuSmear?

- Energy smearing and angular smearing via parameterized model-based presets.
- Fast, generic, geometry-independent.
- Contribution package built onto the GENIE Monte Carlo event generator.
- Simulates energy and angular smearing between all flavors of neutrinos and nuclear targets within the MeV to PeV energy scales.

NuSmear

- Link to NuSmear GitHub pull request: https://github.com/GENIE-MC/Generator/pull/222

Ishaan Vohra on NuSmear, a tool for smearing GENIE simulation

Program is up on GitHub, and ready to be implemented in simulations

Energy Smearing - Complete MC Comparison

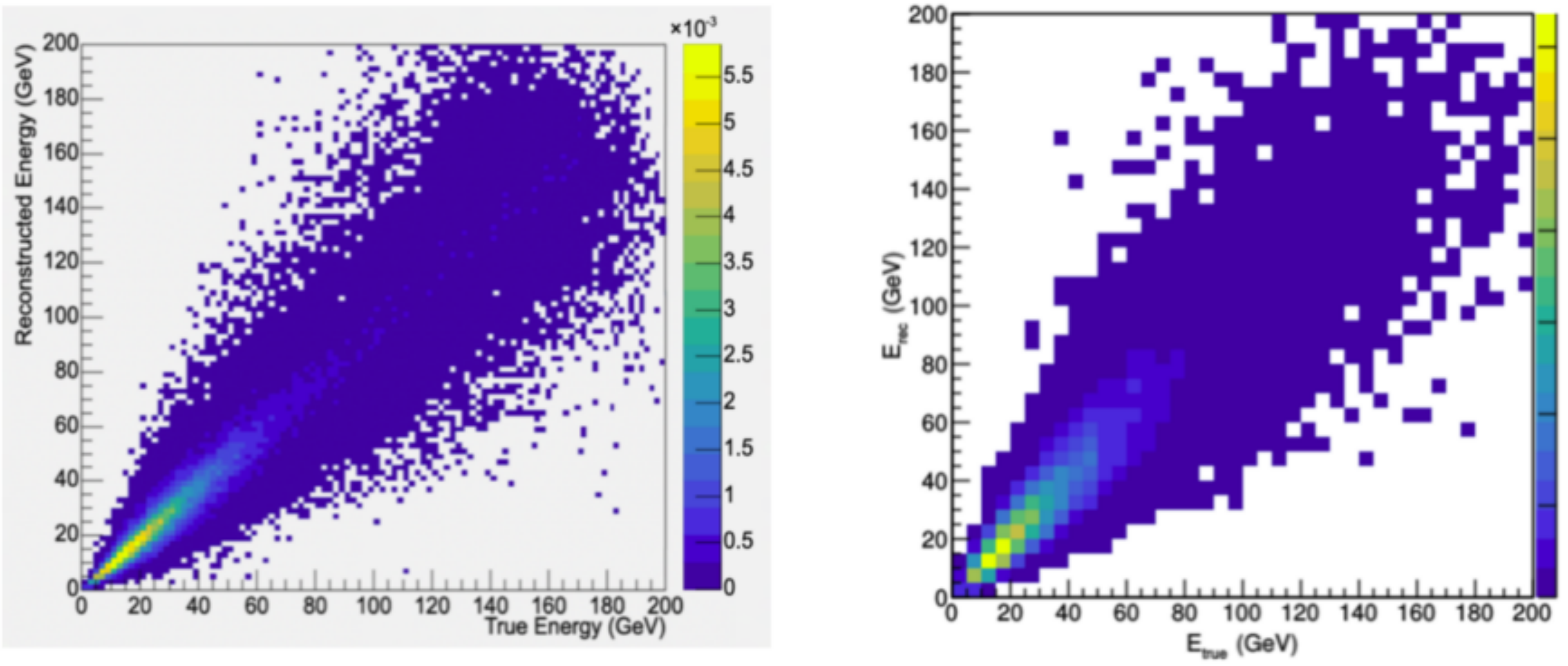
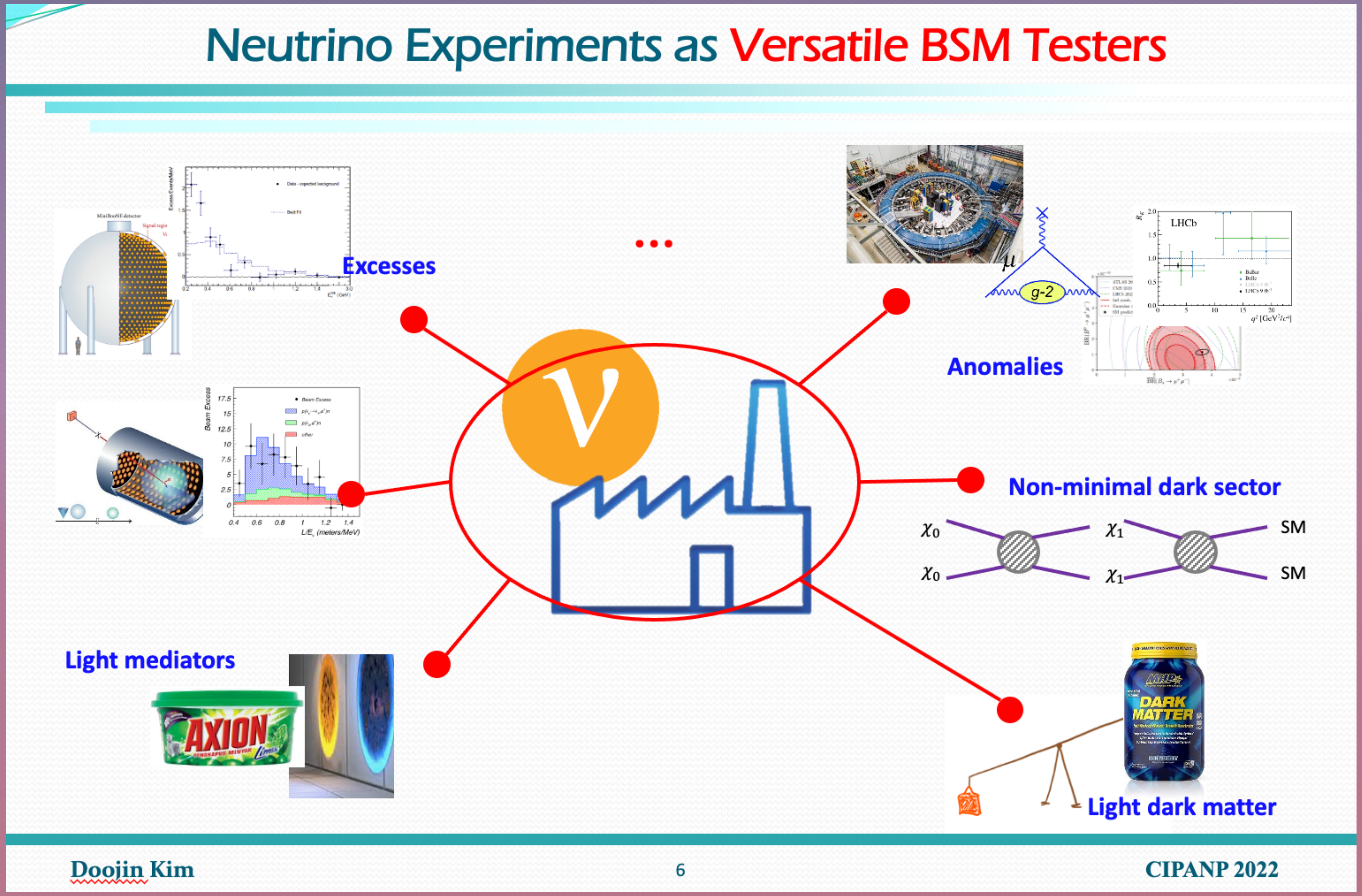


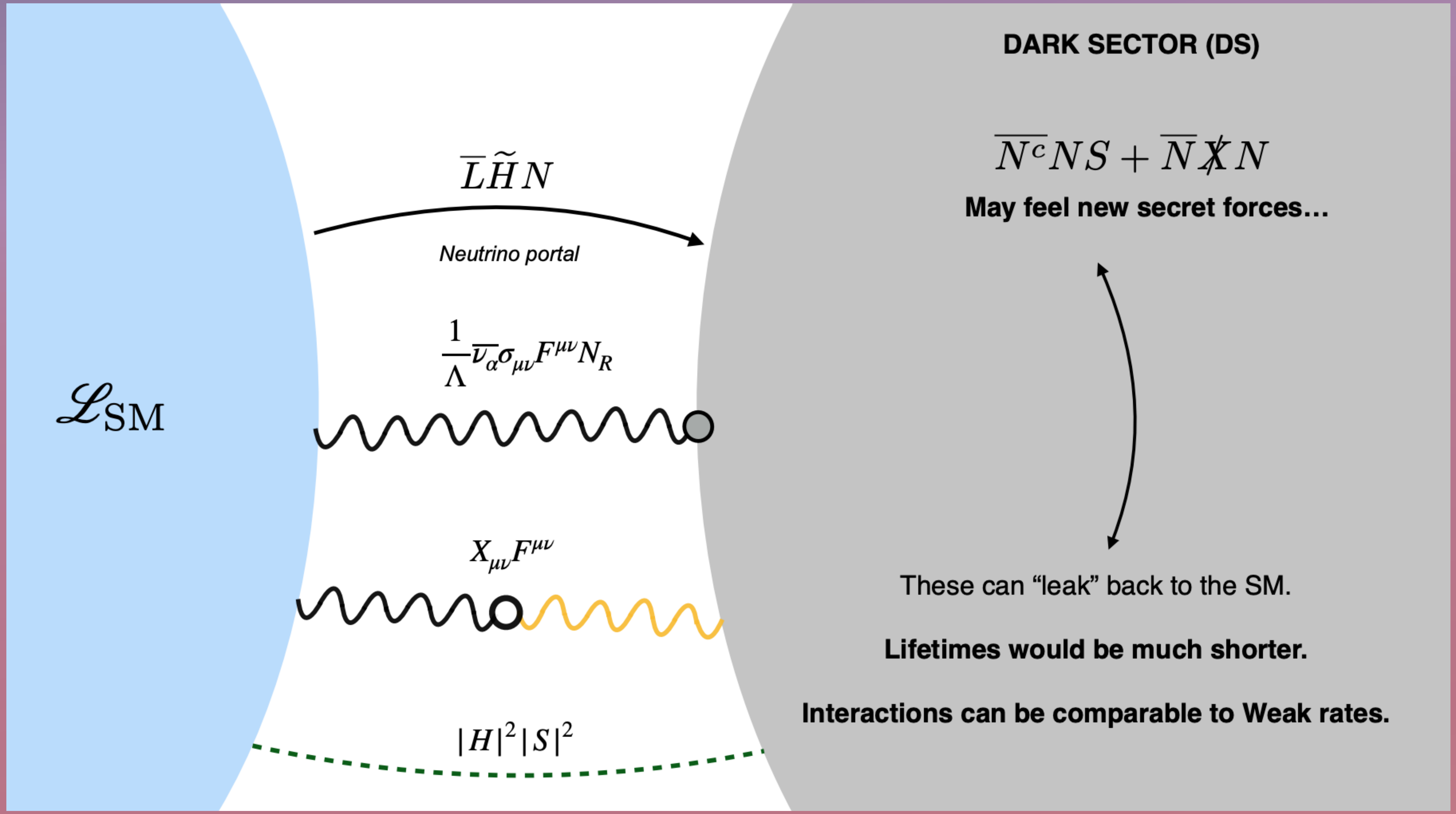
Figure 5: NuSmear Default (left) compared to complete Monte Carlo simulation (right) electron neutrino charged-current (CC) energy smearing matrices for the OPERA detector in the CNGS beam.

Neutrino Anomalies

- Reports from:
  - Doojin Kim and Matheus Hostert on Neutrinos as Windows into Dark Sectors and BSM Physics
  - Josh Barrow on Results from MicroBooNE
  - Joseph Zennamo on the status of the Fermilab SBN Program
  - Tulasi Subedi on Reactor Neutrino Experiments
  - Stephan Friedrich on the Status of the BeEST Experiment

Doojin Kim and Mateus Hostert on Neutrinos for Dark Matter and BSM Physics

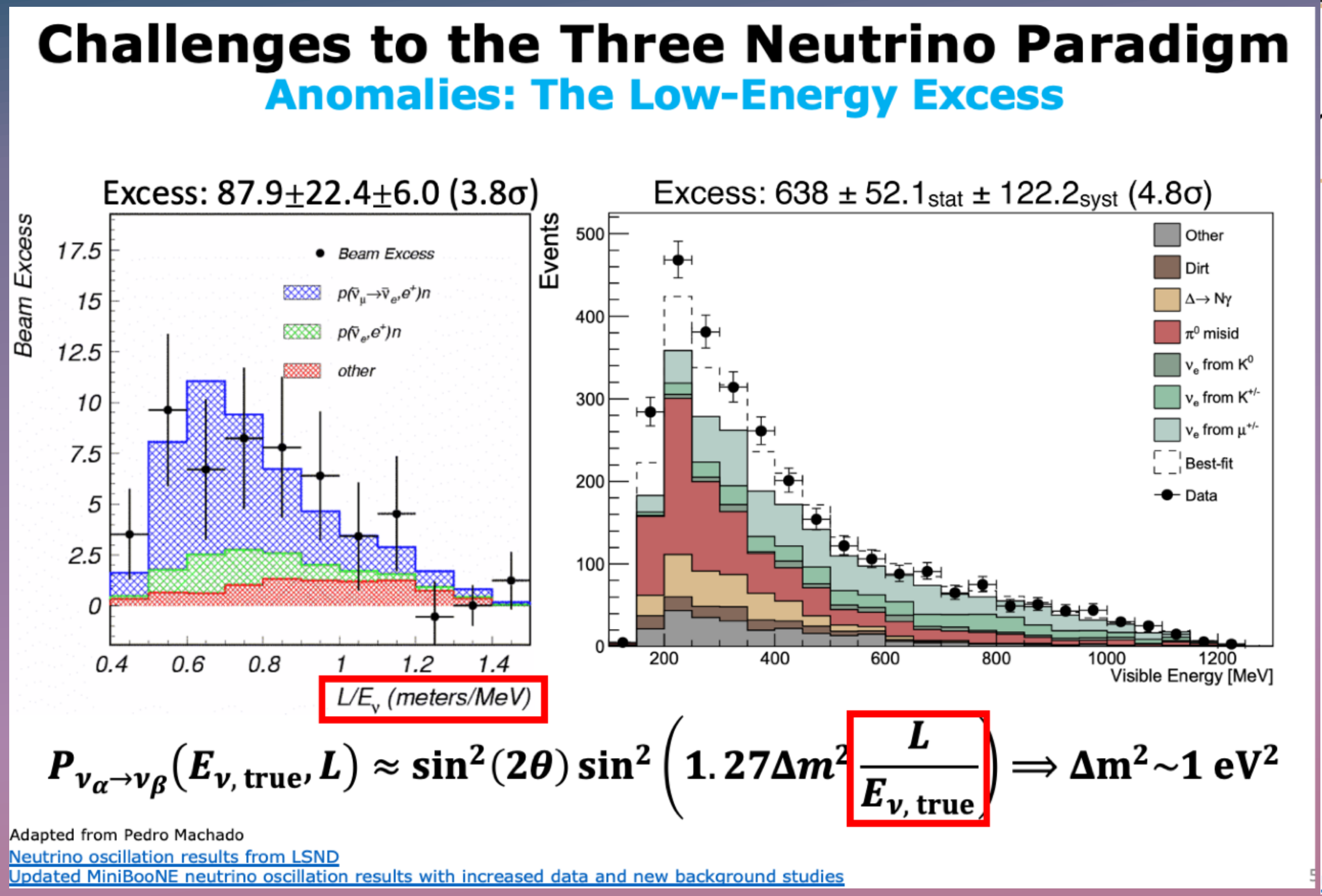


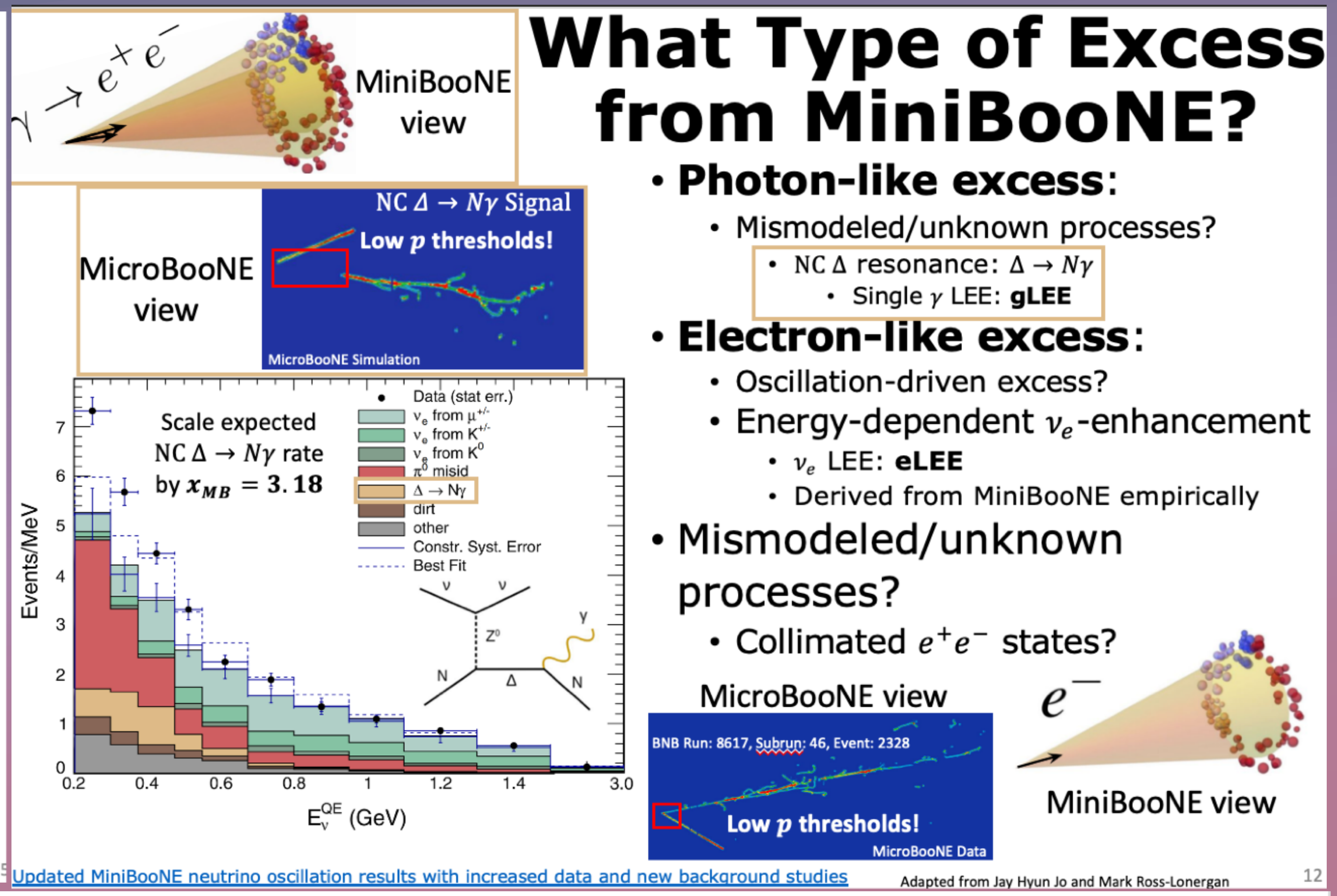


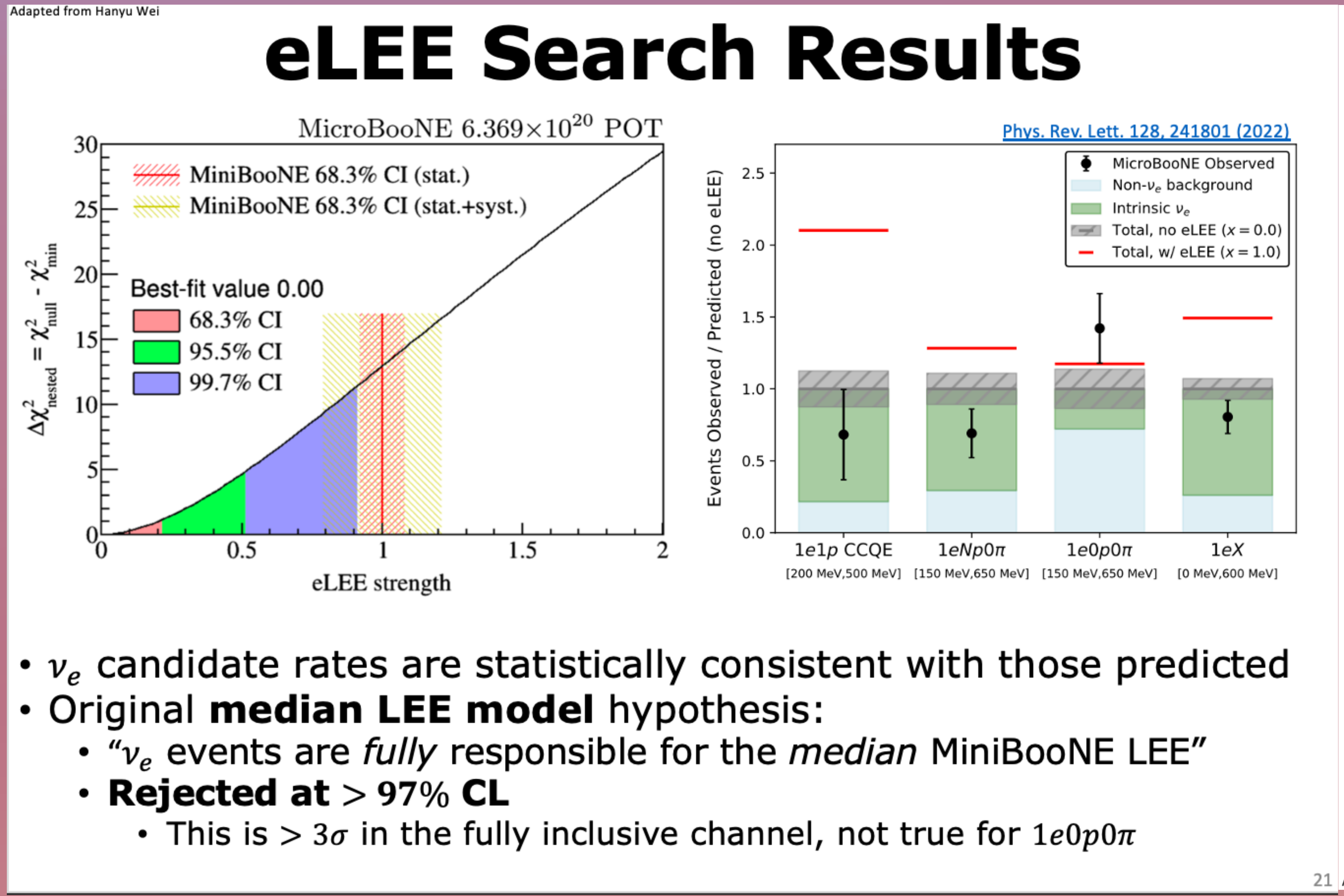
Doojin Kim **Mateus Hostert**

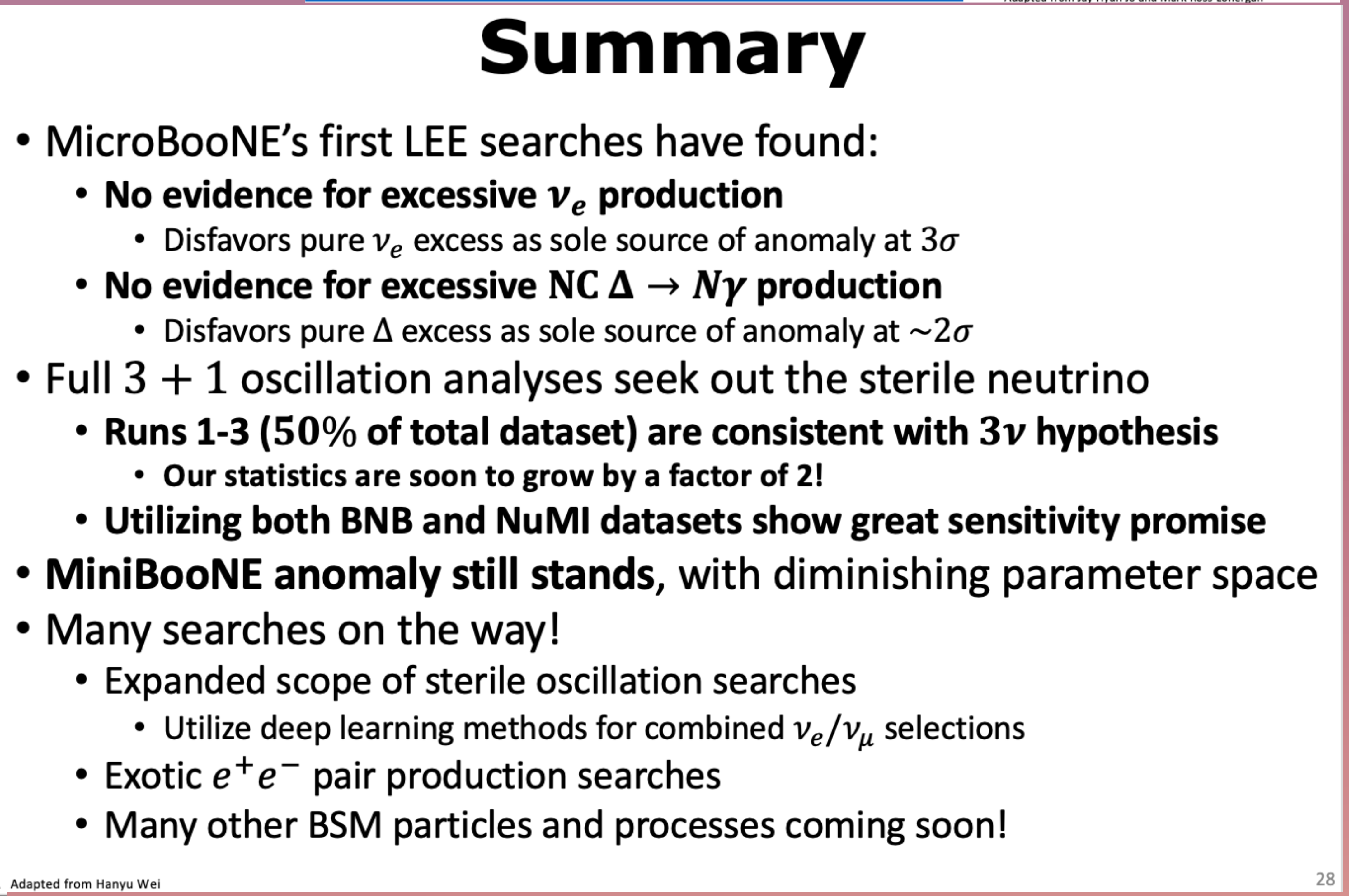
How can anomalies and sterile neutrinos serve as openings for BSM physics, Dark Matter or otherwise?

Josh Barrow on recent results from MicroBooNE on the LEE

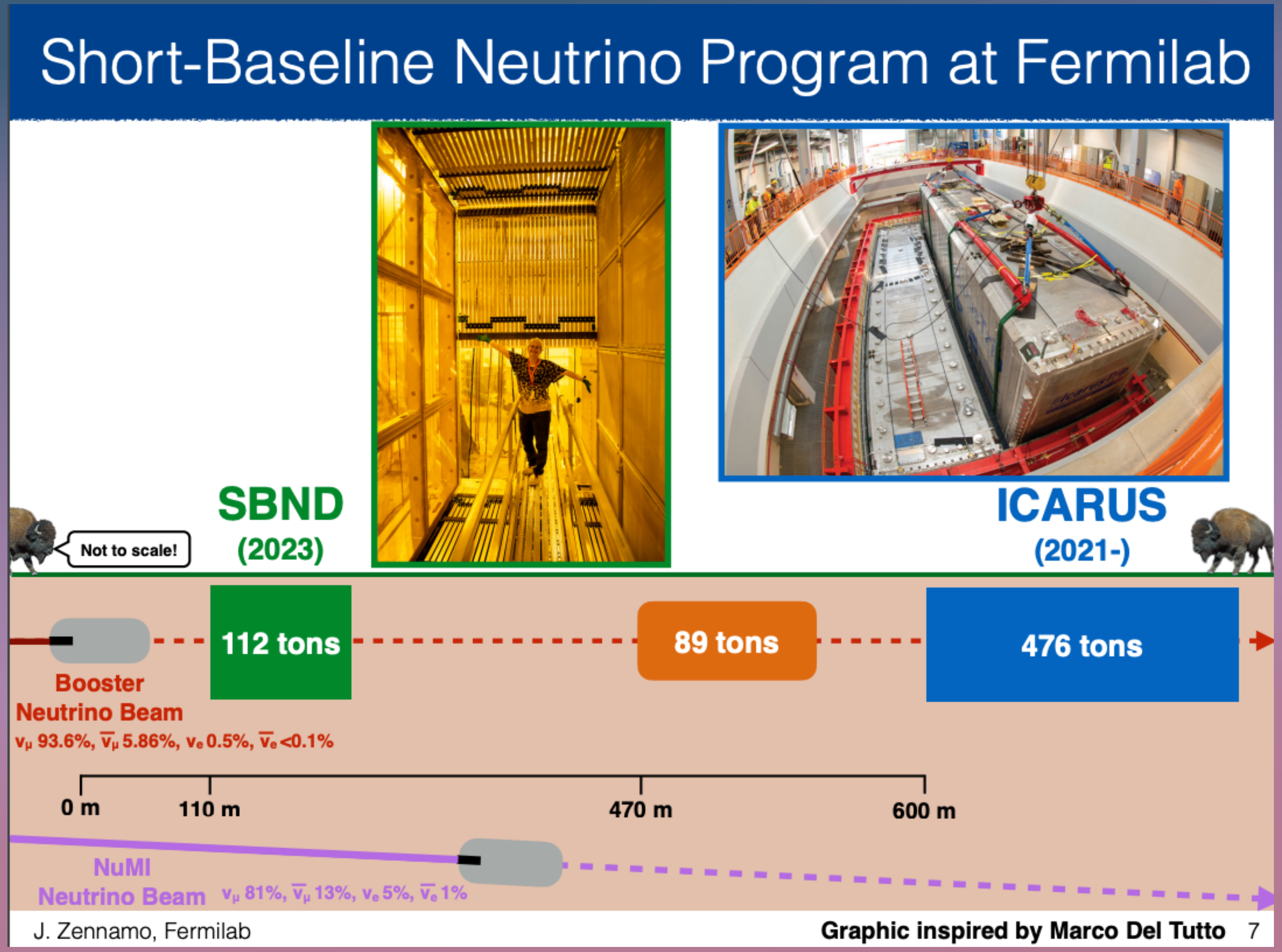








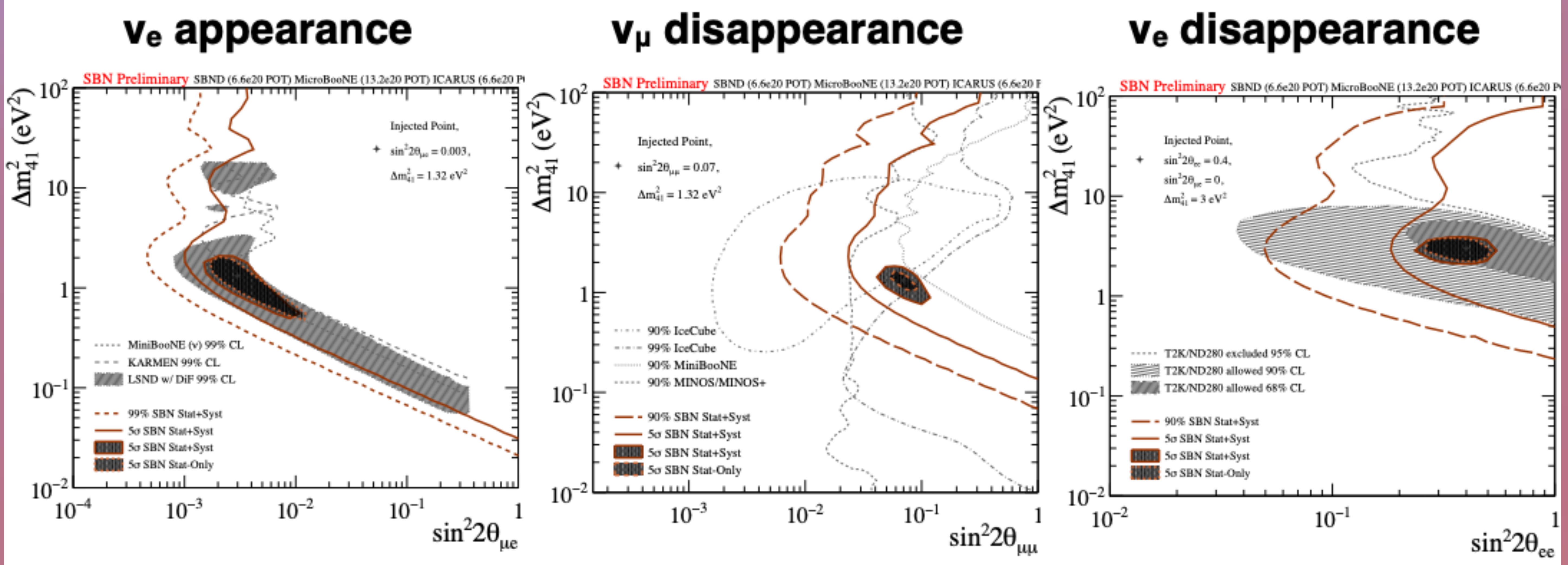
Parameter space shrinking for your favorite explanation of the excess



Joseph Zennamo updating us on the SBN program

Searches for Sterile Neutrinos

Searches for sterile neutrinos with the SBN Program will definitively cover the LSND allowed region and stringently test the global allowed regions in three channels!



J. Zennamo, Fermilab 17

Conclusions

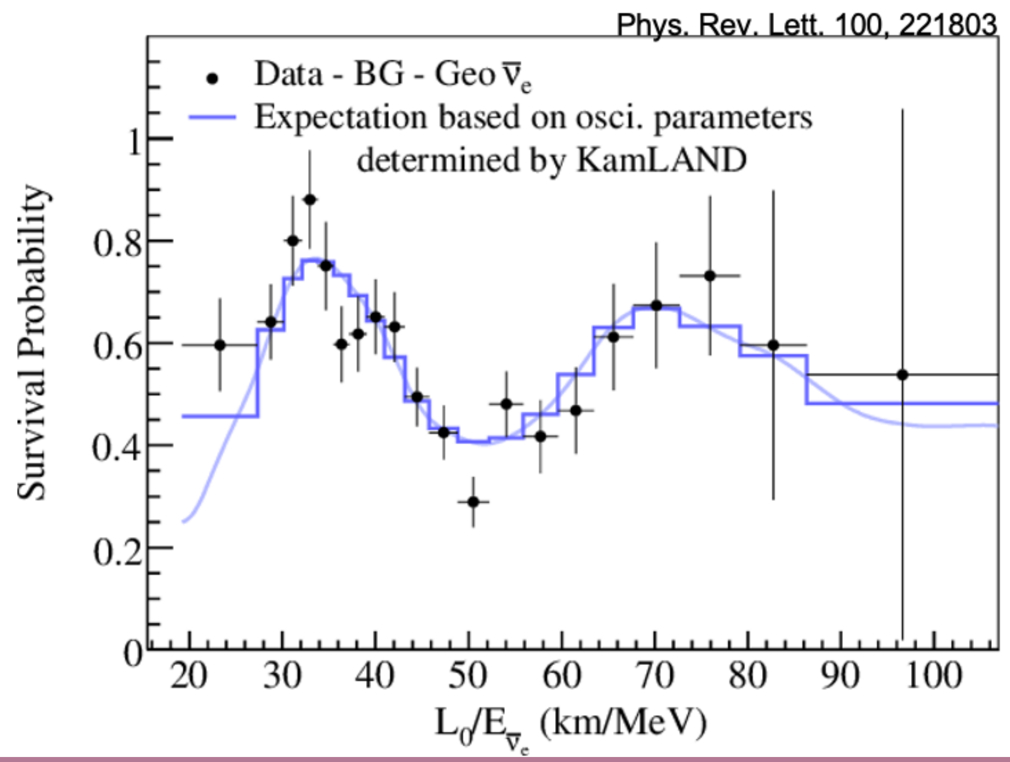
- SBND is finishing detector assembly, and ICARUS has started its physics running
- Stay tuned as the SBN Program launches itself toward an exciting physics program!
  - Including world-leading ν-Ar cross section measurements, definitive searches for eV-scale sterile neutrino oscillations, and other BSM physics

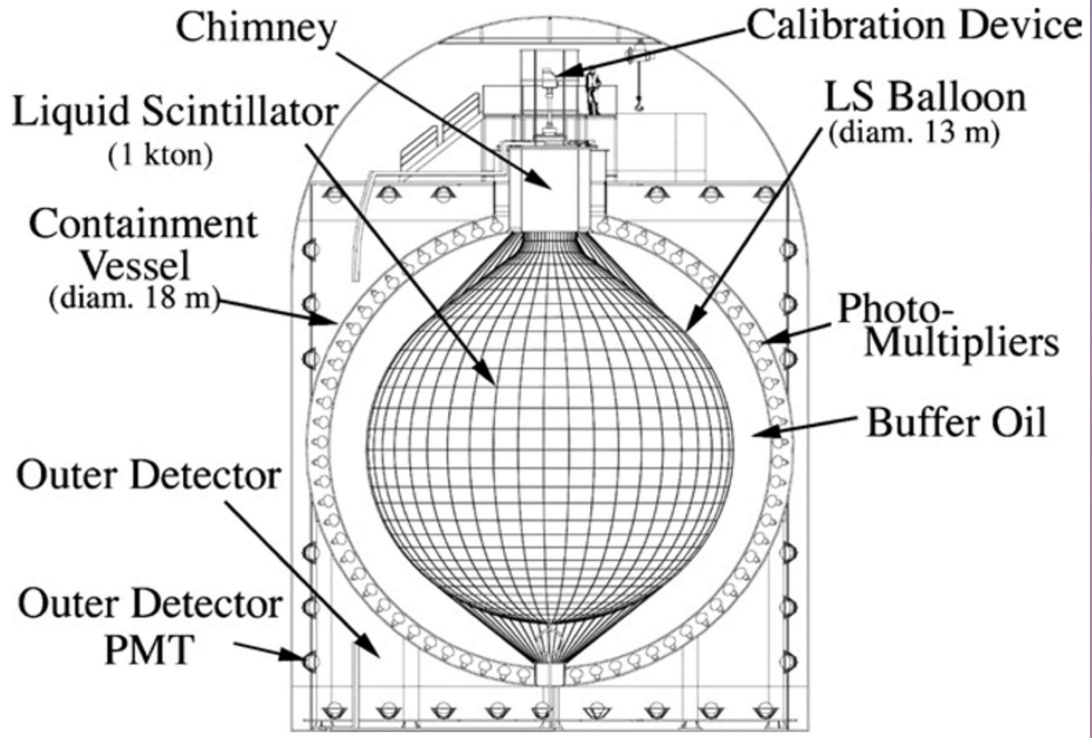
The program suggests a definitive answer for the existence of sterile neutrinos

Neutrino Oscillations

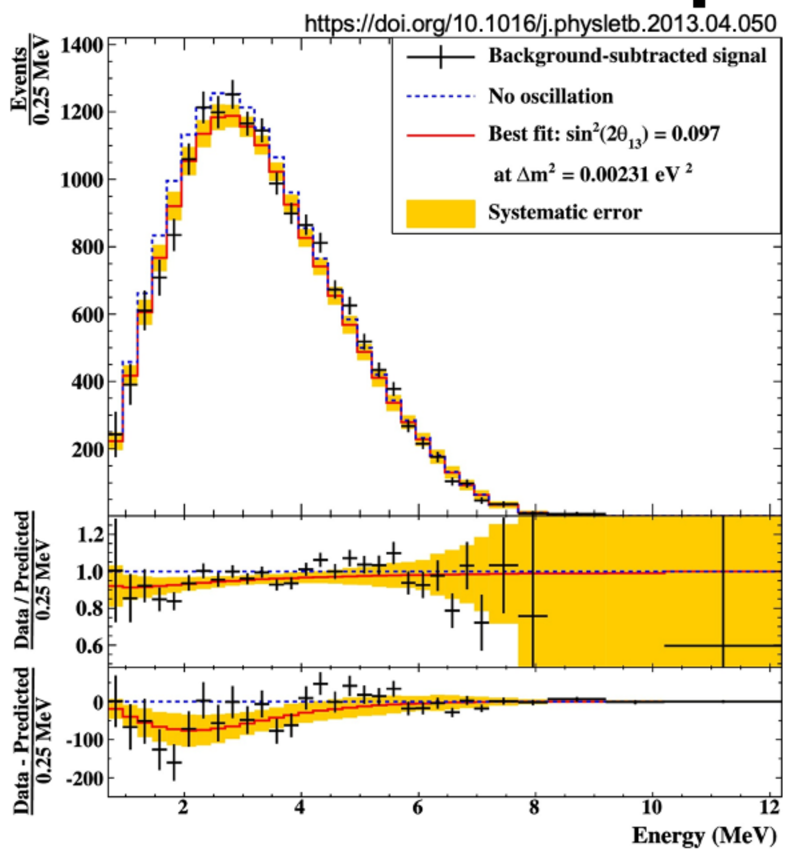
The KamLAND experiment measured Δm_{21}^2 from reactor neutrino oscillations

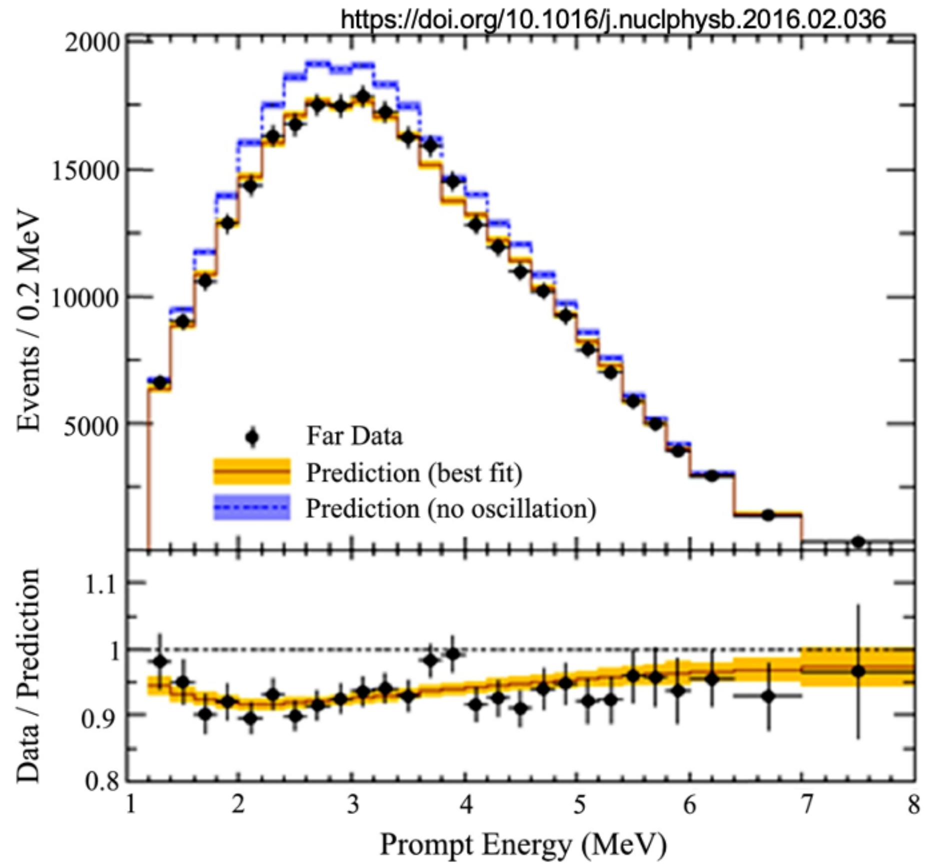
Phys. Rev. Lett. 100, 221803





Double Chooz and RENO verified the parameter values





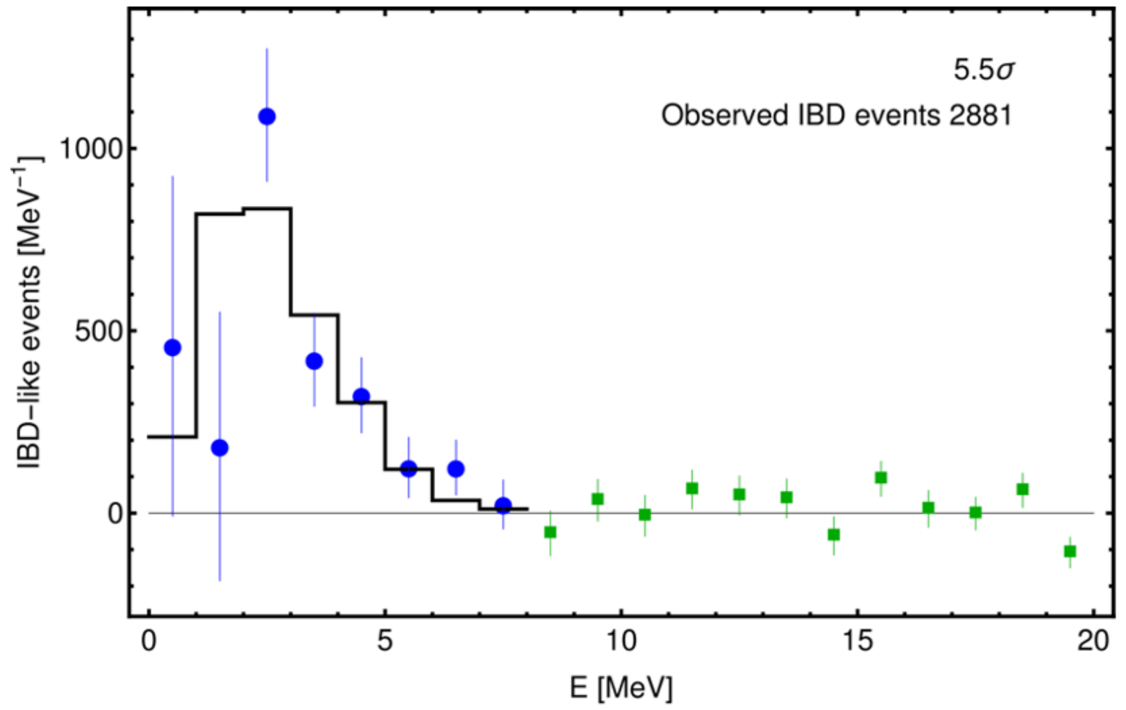
Double-Chooz

Independent of the absolute reactor flux and spectrum

RENO

MiniCHANDLER Deployment

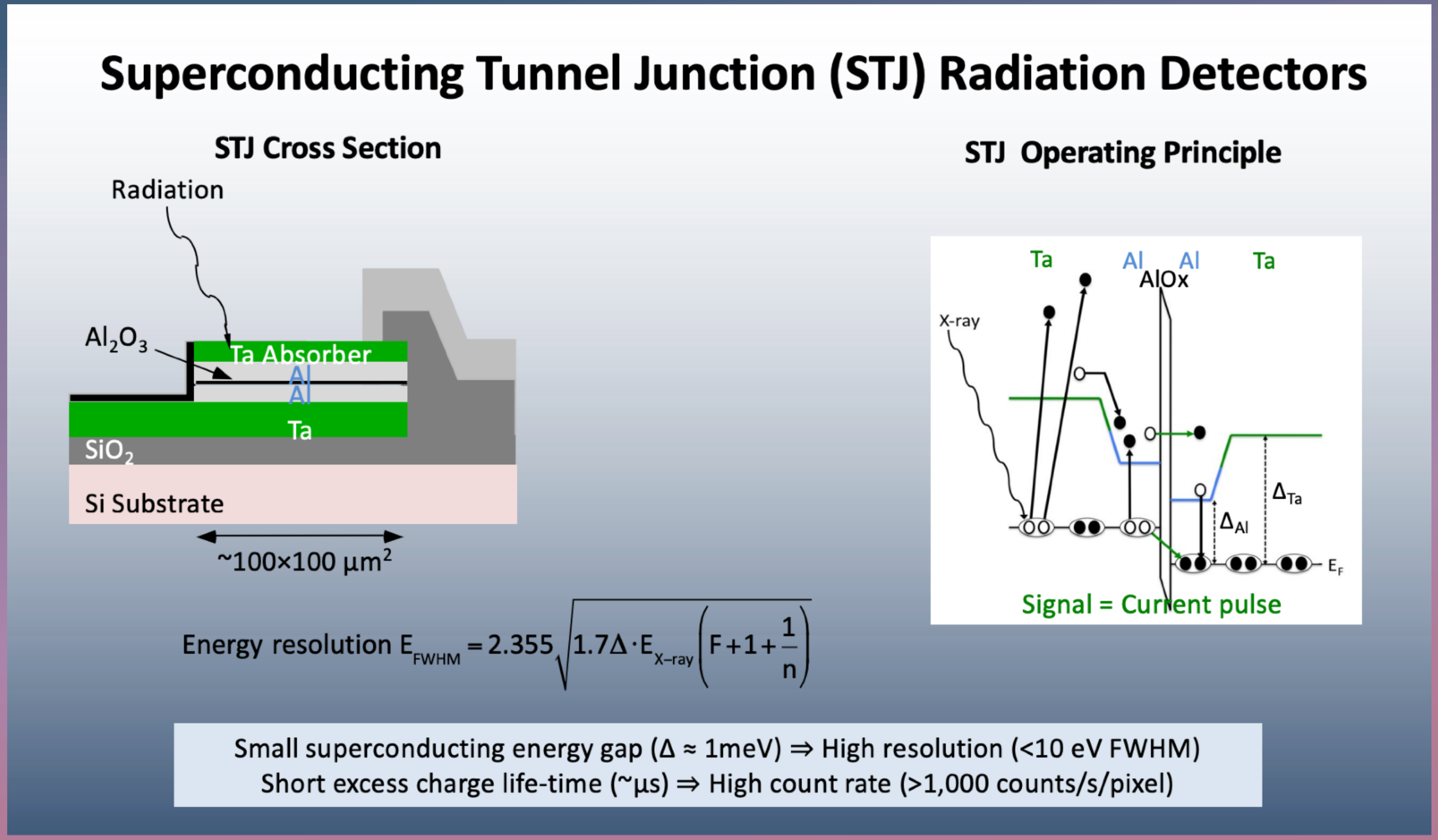
Deployed at North-Anna Nuclear Power Plant

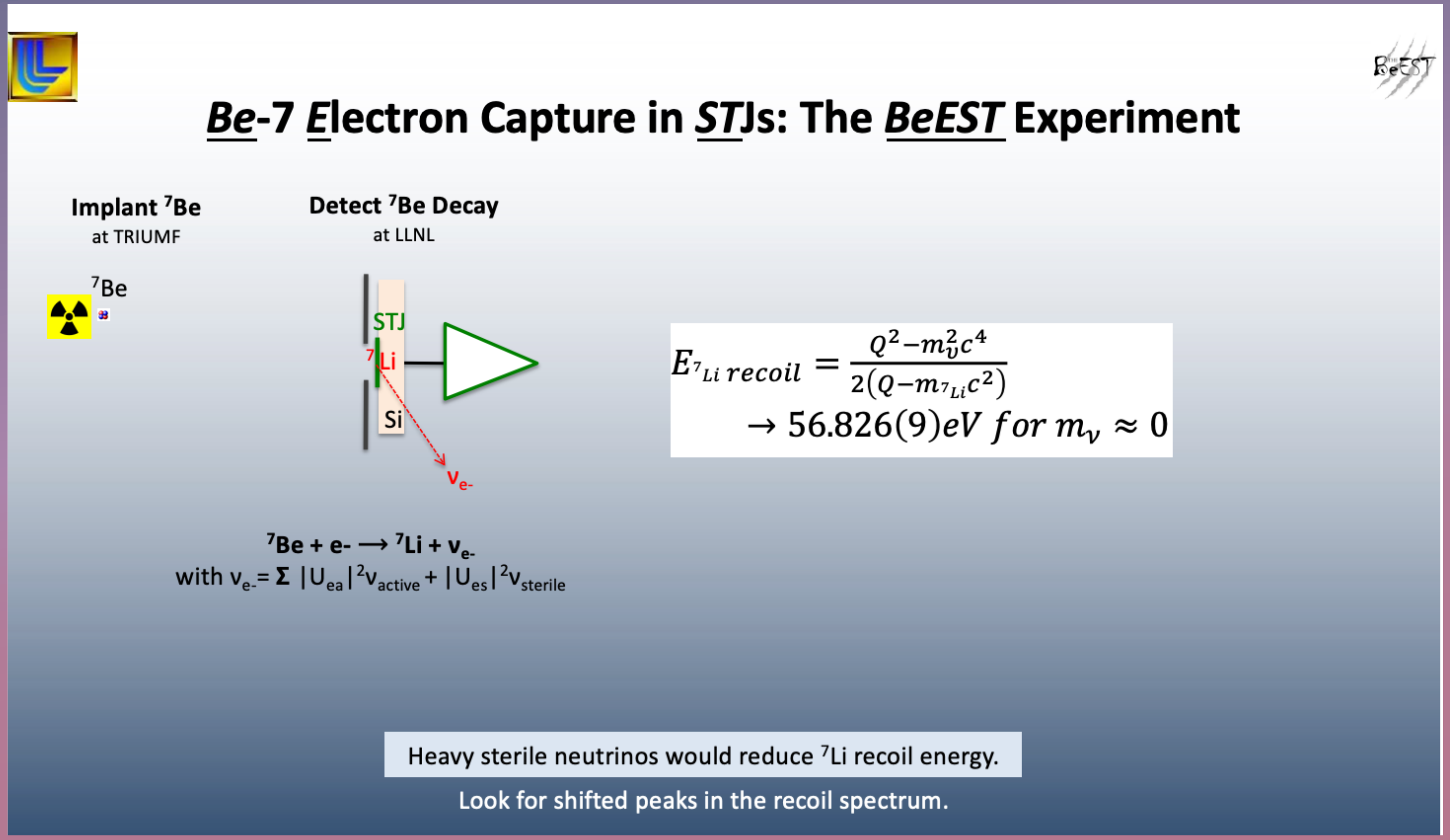


Detected antineutrinos with minimal shielding in a mobile platform at surface level environment

Tulasi Subedi gave an excellent introduction to Reactor Neutrino Experiments.

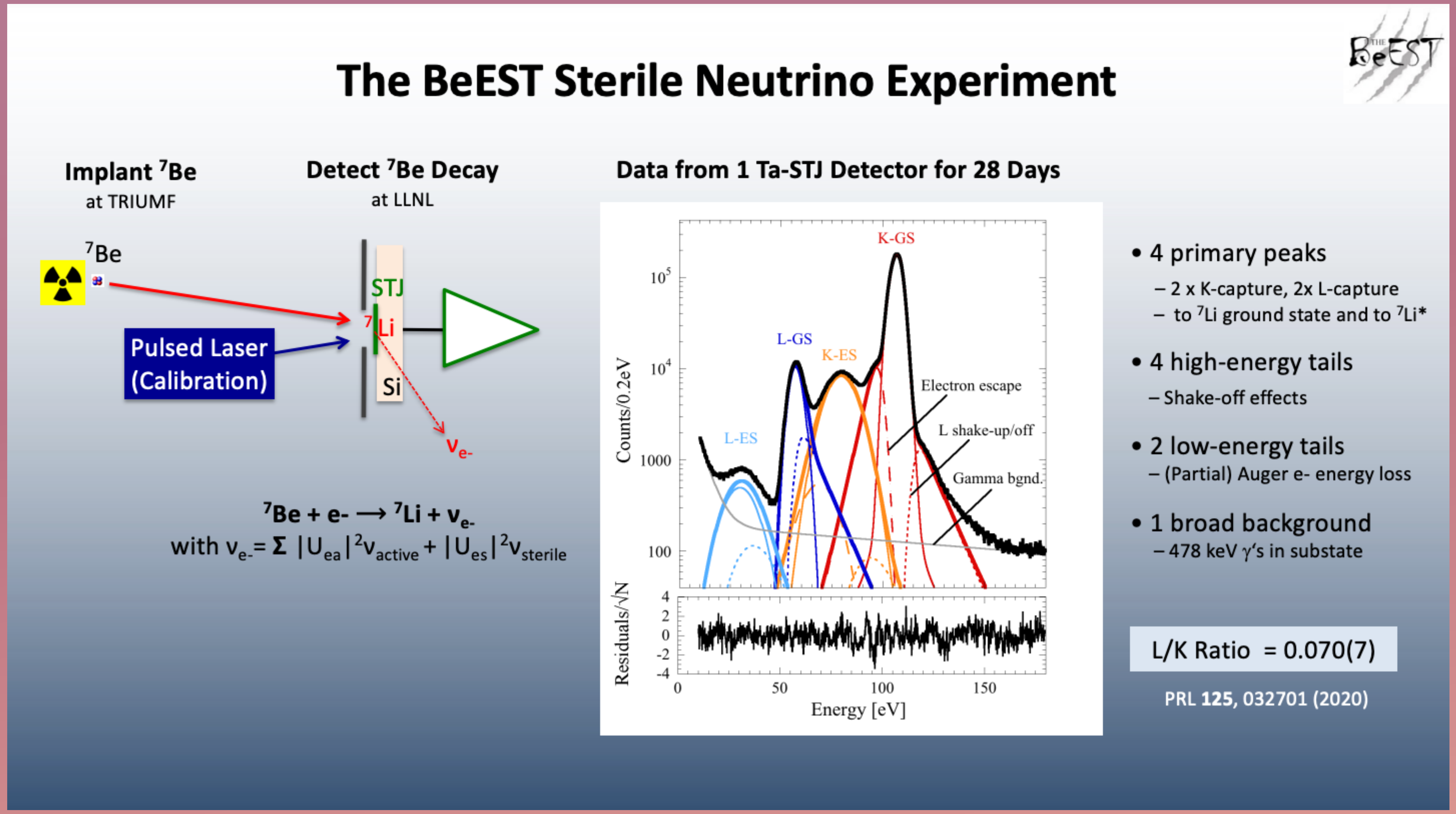
Thorough overview of important contributors, Daya Bay and JUNO not shown





Stephan Friedrich walked us through the physics of BeEST

BeEST is a complementary and novel way of observing sterile neutrinos and dark matter.



Neutrino Astrophysics & Cosmology

- Reports from:
  - Ali Keirandish with a Theory Perspective on Neutrino Astrophysics
  - Amol Patwardhan on Neutrinos in Supernovae
  - Pooja Siwach on Oscillations in Supernova Simulations
  - Evan Grohs on Cosmological Neutrinos

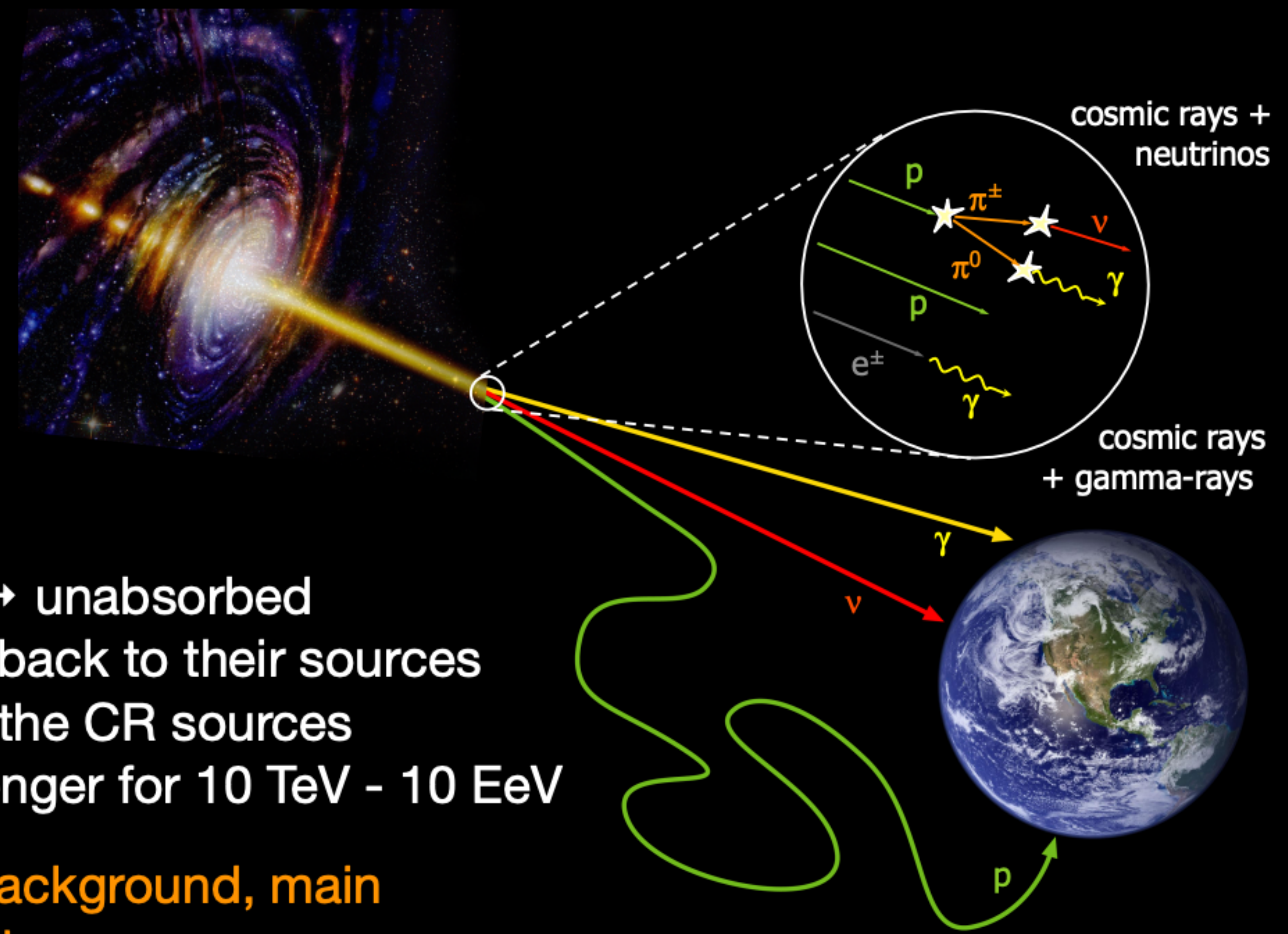
Ali Keirandish with a Theory Perspective on Neutrino Astrophysics

High energy neutrino flux used to understand the universe and neutrinos!

Neutrino Astrophysics

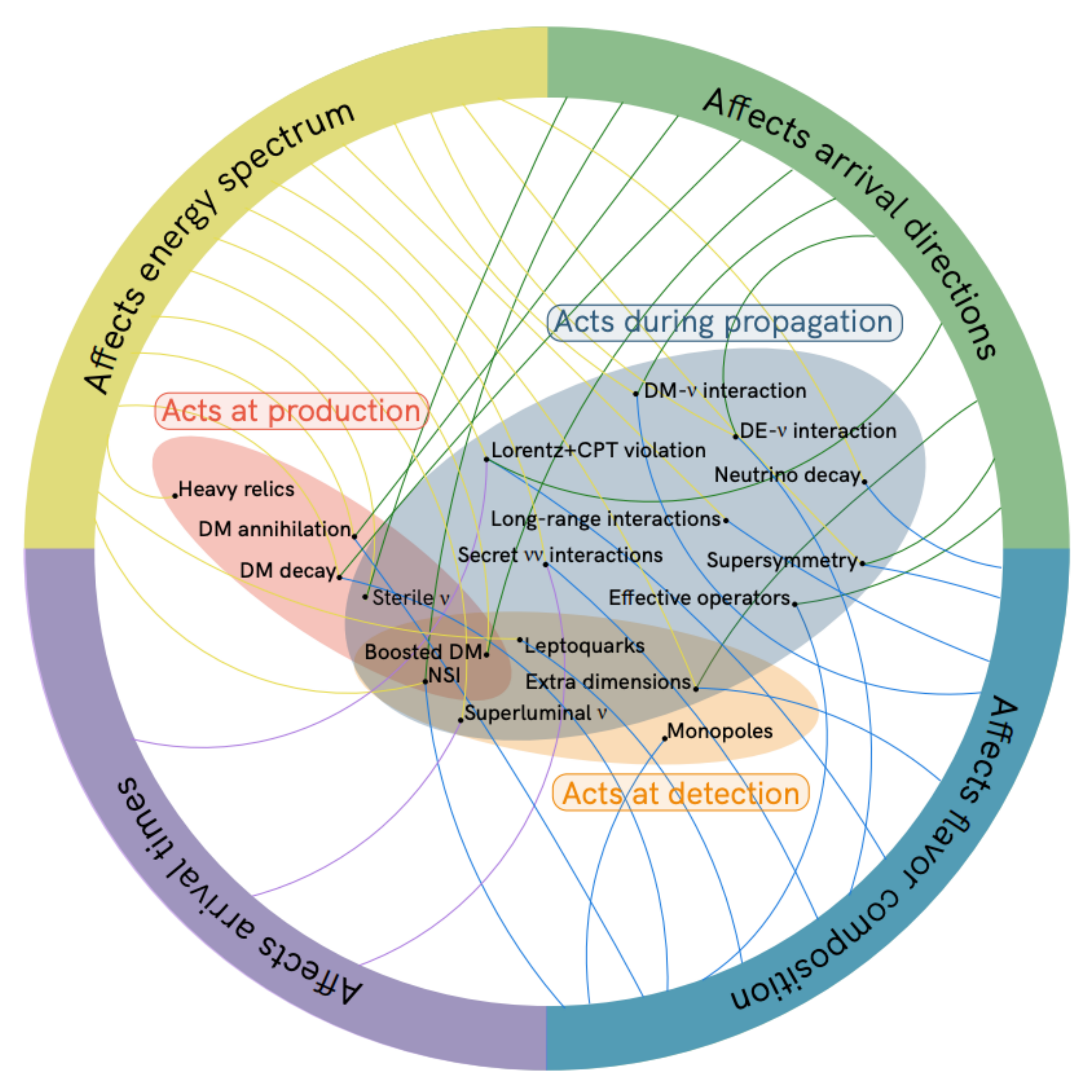
- Soon after discovery it was realized neutrinos are ideal cosmic messengers.

Accelerated CRs interact with gas or radiation in the beam dump and produce charged and neutral pions.



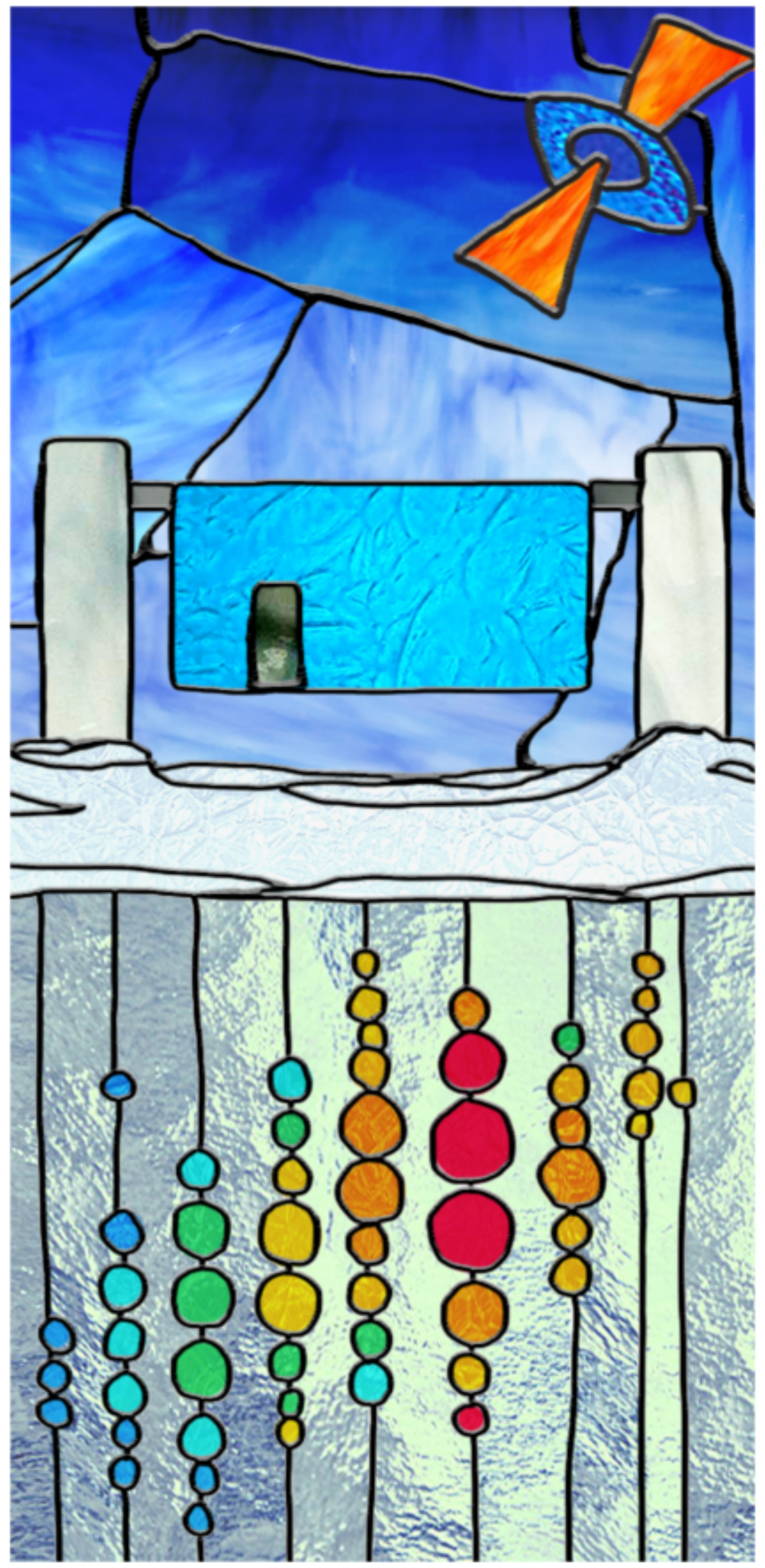
- Neutrinos:
  - ✓ Hardly interact → unabsorbed
  - ✓ Neutral → point back to their sources
  - ✓ Smoking gun of the CR sources
  - ✓ Exclusive messenger for 10 TeV - 10 EeV

Low statistics and large background, main challenges for neutrino astronomy.



Outlook

- After a decade of observation, signs of anisotropy are emerging in IceCube data.
  - Early indications points to active galactic nuclei as primary source of high-energy cosmic neutrinos.
- Identification of the origin of HE cosmic neutrinos will bring insight into the working of cosmic accelerators.
- The HE neutrino beam provided by cosmic accelerators offers unique opportunities to study neutrinos.
- Cosmic neutrinos provide complementary tests of physics beyond the Standard Model in the neutrino sector.



Core-collapse supernovae and neutrinos

- Neutrinos depositing $\sim 1\%$ of their energy behind the stalled shock front could revive the shock and explode the star
- ν-induced heating in the aftermath of explosion drives baryonic matter outflows from the surface of the nascent neutron star
- Charged-current weak processes govern the energy deposition and n/p ratio, a crucial input for nucleosynthesis

$$\nu_e + n \longleftrightarrow p + e^-$$
$$\bar{\nu}_e + p \longleftrightarrow n + e^+$$

- Flavor asymmetric processes: thorough understanding of neutrino flavor evolution therefore required

Neutrino flavor equilibration and the νp-process

Amol Patwardhan

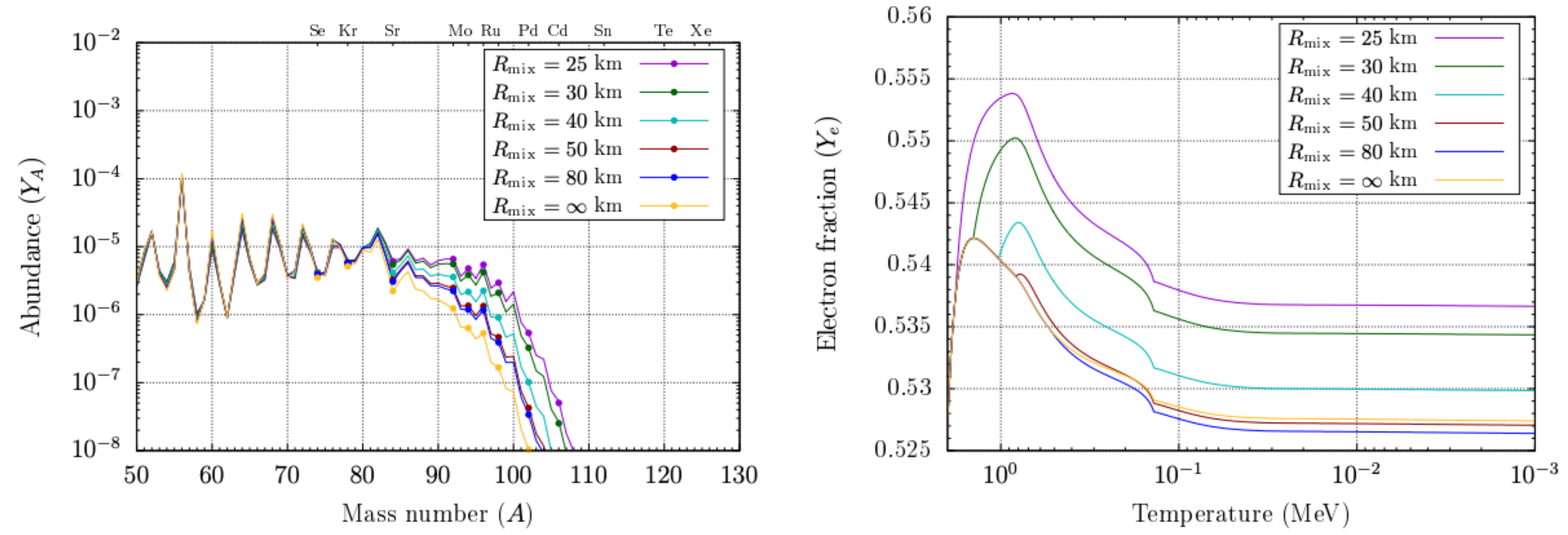
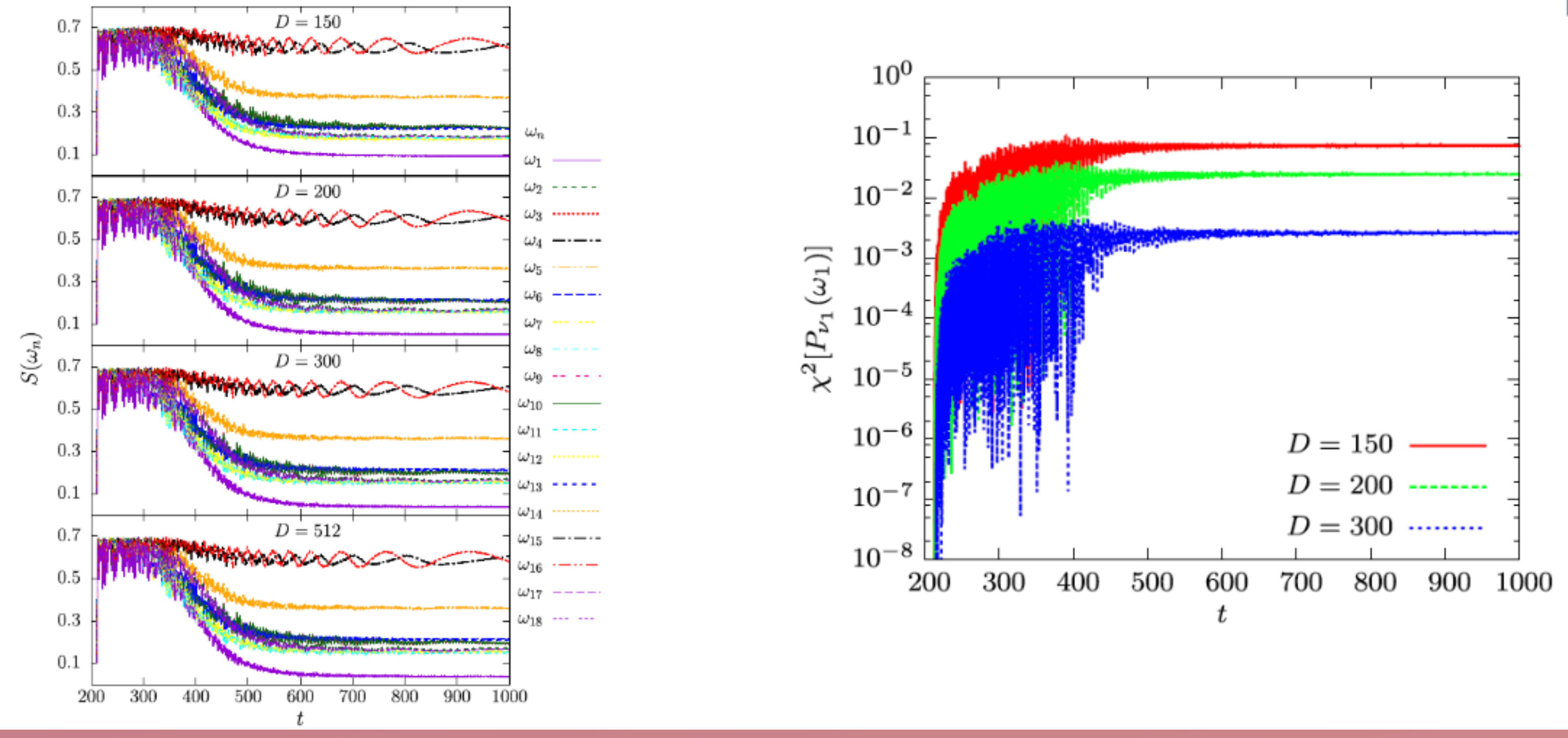


Figure: Nucleosynthesis calculations with different flavor equilibration radii $R_{\rm mix}$. **Left:** Abundance vs Mass number. **Right:** Electron fraction vs Temperature.

[AVP, A. Friedland, P. Mukhopadhyay, and S. Xin, *in preparation*]

In our model, we study these different regimes by varying the radius $R_{\rm mix}$. Flavor equilibration is found to universally improve the νp-process efficacy, more so if it occurs closer to PNS.

Results



Pooja Siwach

Amol Patwardhanon on Neutrinos in Supernovae

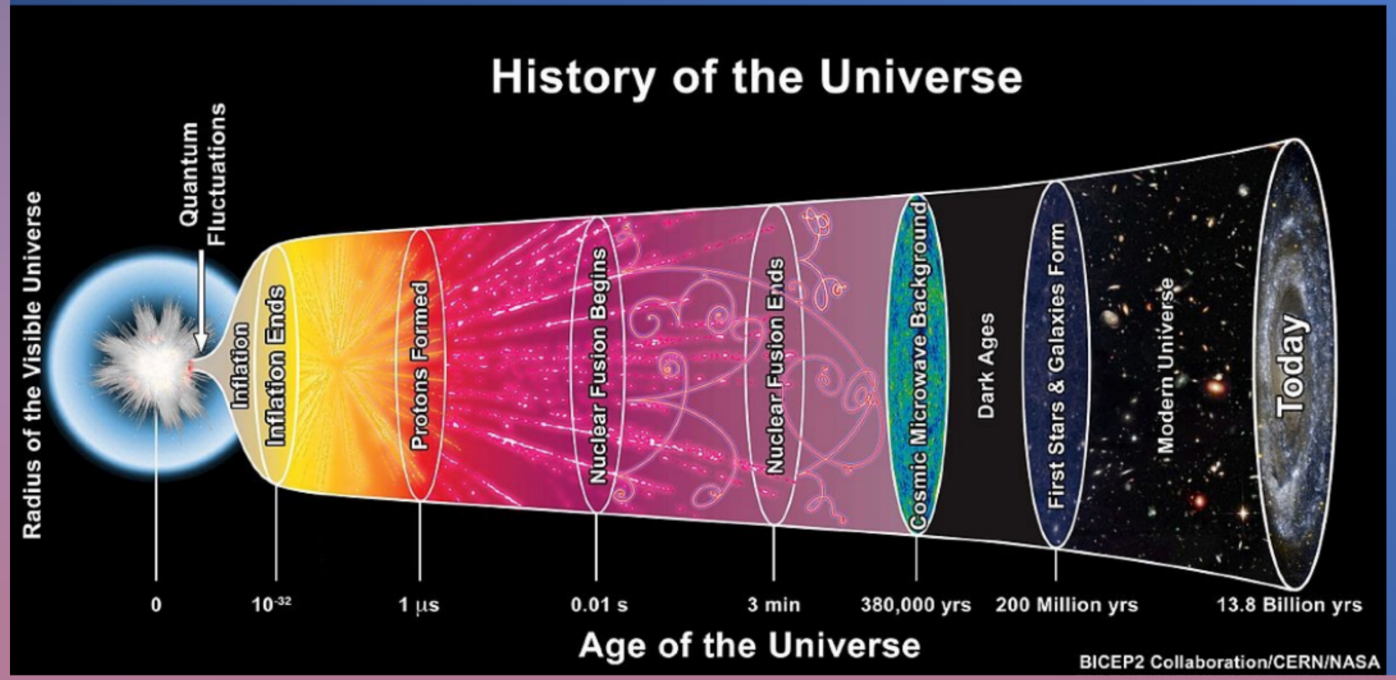
Considerable progress in understanding neutrino flavor interactions with nucleosynthesis!

Evan Grohs on Cosmological Neutrinos

Cosmology: Overview of ΛCDM

Universe begins from a "singularity" – hot Big Bang
→Near Homogeneous, Isotropic spacetime geometry
→Close to Thermal and Chemical Equilibrium
→Subsequent Expansion and Cooling

$$H \equiv \frac{1}{a}\frac{da}{dt} = \sqrt{\frac{8\pi}{3m_{\rm pl}^2}\rho}$$



Various epochs:

1. Planck epoch ~ 10^{-44} s
2. Grand Unification ~ 10^{-38} s
3. Inflation ~ 10^{-32} s?
4. Electroweak breaking ~ 10^{-11} s
5. Quark-Hadron transition ~ 10^{-5} s
6. BBN ~ 1 s – 3 mins.
7. Atomic Recomb. ~ 10^5 yrs
8. Structure ~ 100 Myr
9. Reionization ~ 500 Myr
10. Galaxies, stars, planets ~ 1 Gyr

3

Summary

1. Solid evidence for the existence of neutrinos in hot big bang cosmology
   a. CMB and BAO show $N_{\rm eff}$ not equal to zero
   b. BBN shows neutrinos have ~thermal spectra
2. Future probes will show even more sensitivity to neutrino energy spectra
3. Generalized entropy formalism can capture out-of-equilibrium neutrino distributions
4. Abundance predictions require:
   a. Neutrino spectra
   b. Radiation energy density of the universe
   c. Phasing between time and photon temperature

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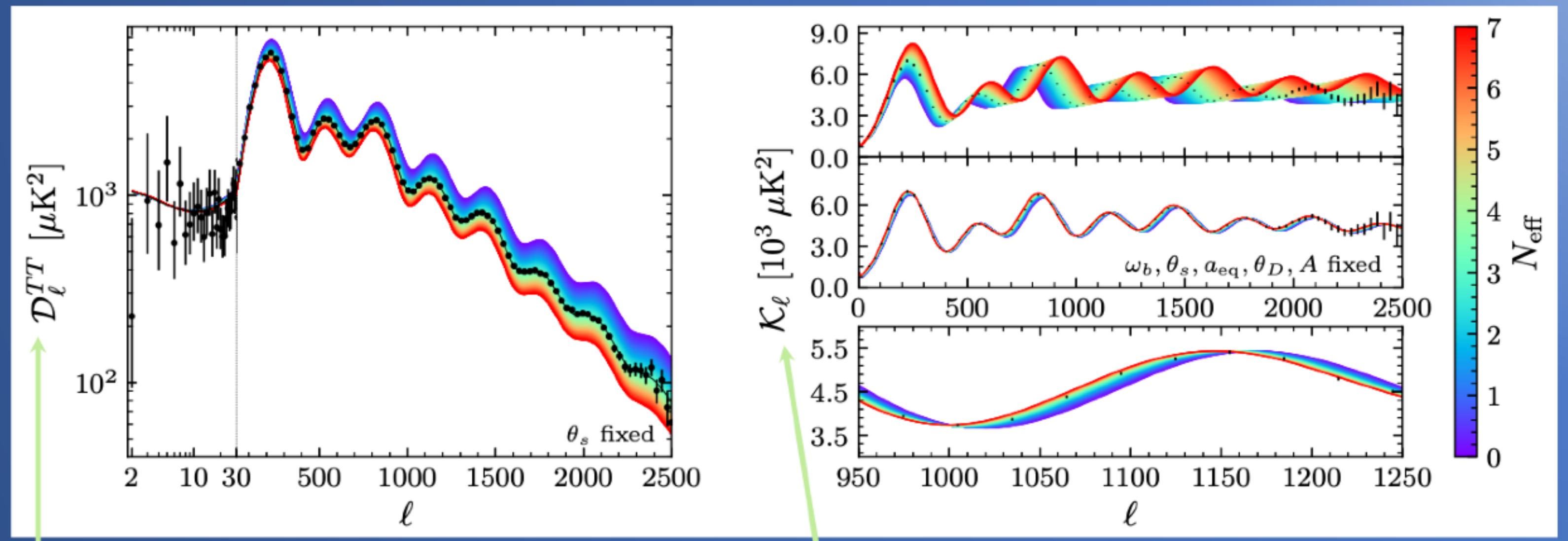
Effects of Radiation on CMB

Black points are Planck 2018 data values



Temperature Power Spectrum

Non-photon radiation

Non-damped Temperature Power Spectrum

Free-streaming radiation

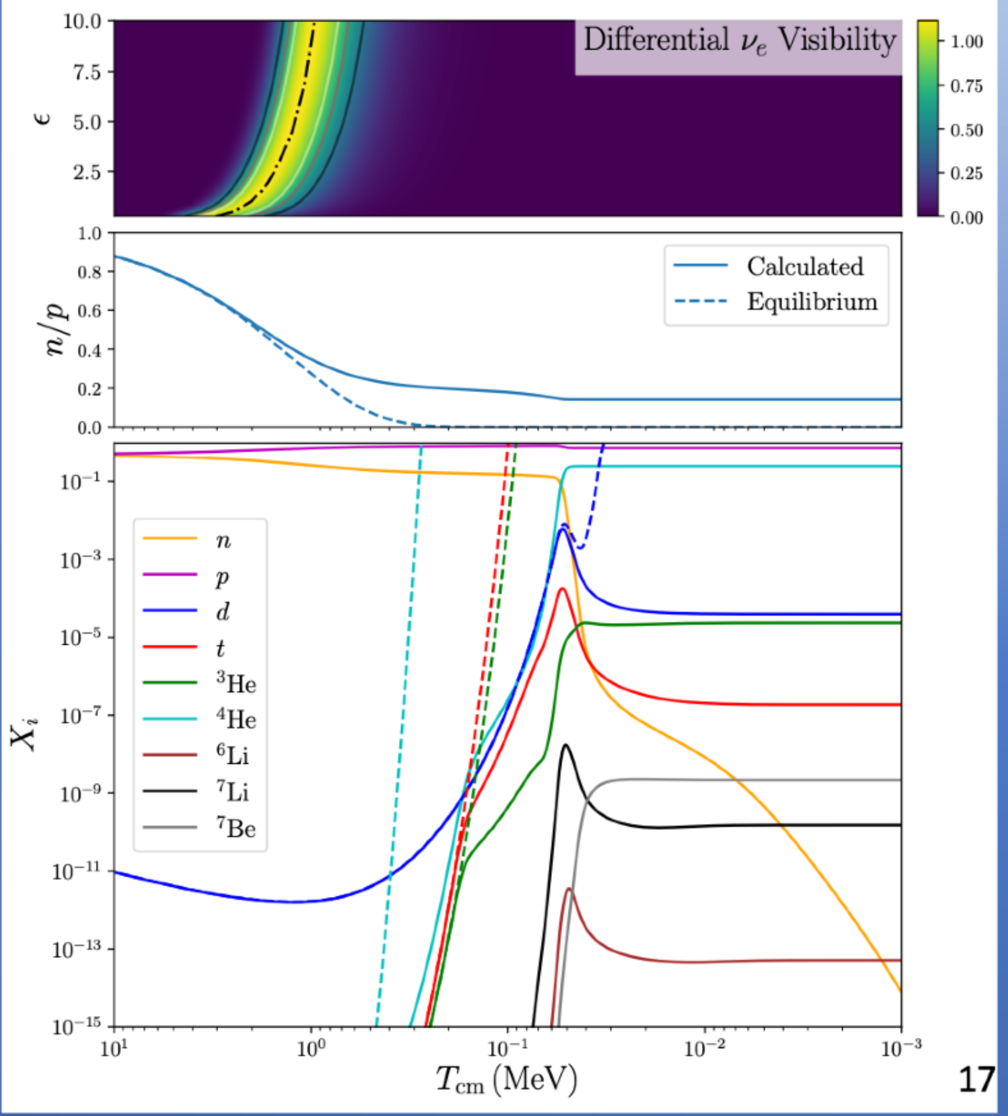
Planck 2018: $N_{\rm eff} = 2.92^{+0.18}_{-0.19}\ (1\sigma)$

7

Neutrino physics occurring during BBN

Coincident epochs during BBN:
Weak Decoupling (Diff. Vis.)
Weak Freeze-Out (n/p)
Nuclear Freeze-Out (X_i)

Dashed lines: weak equilibrium or NSE



Bond+ (In Prep.)

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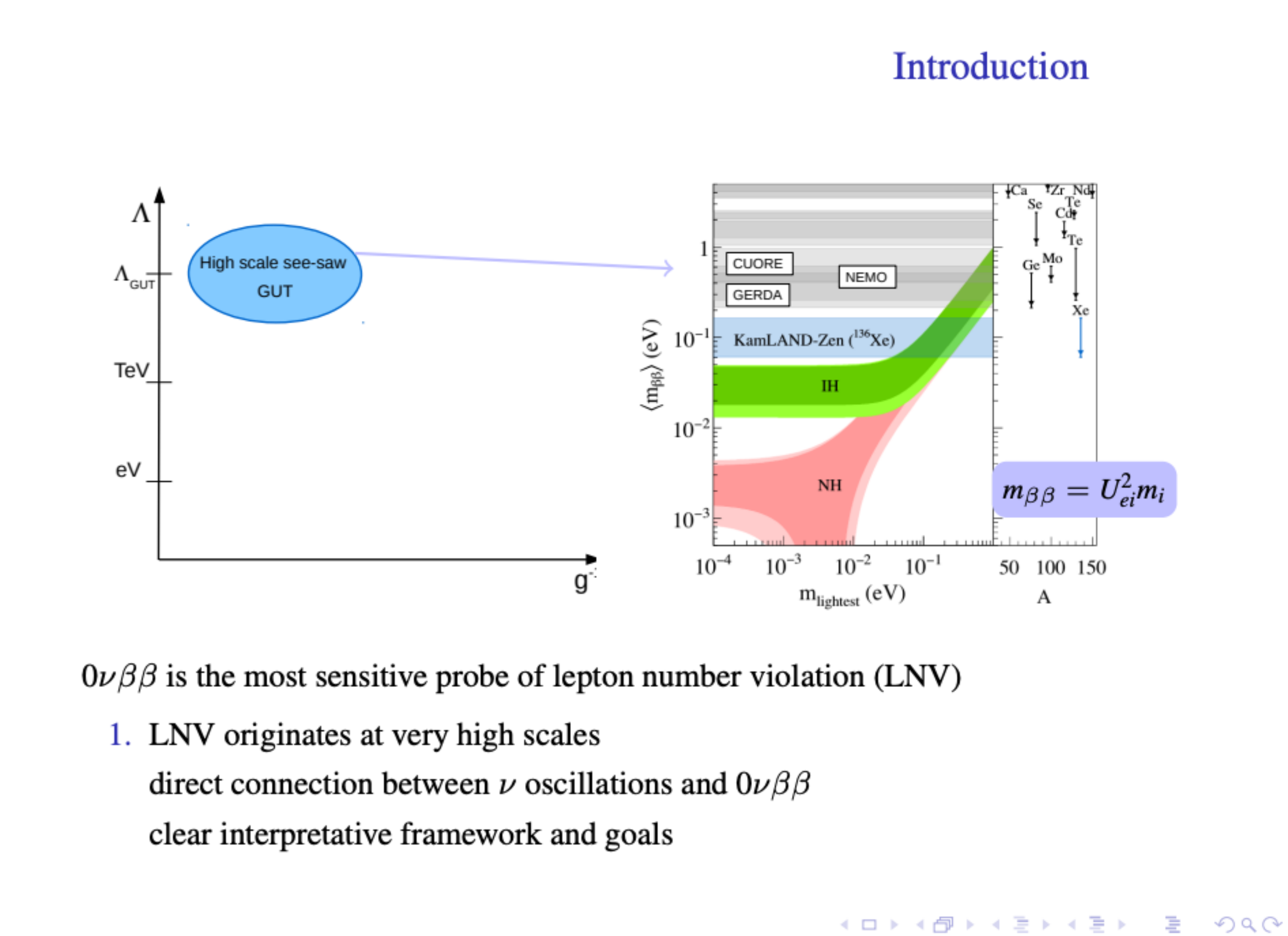
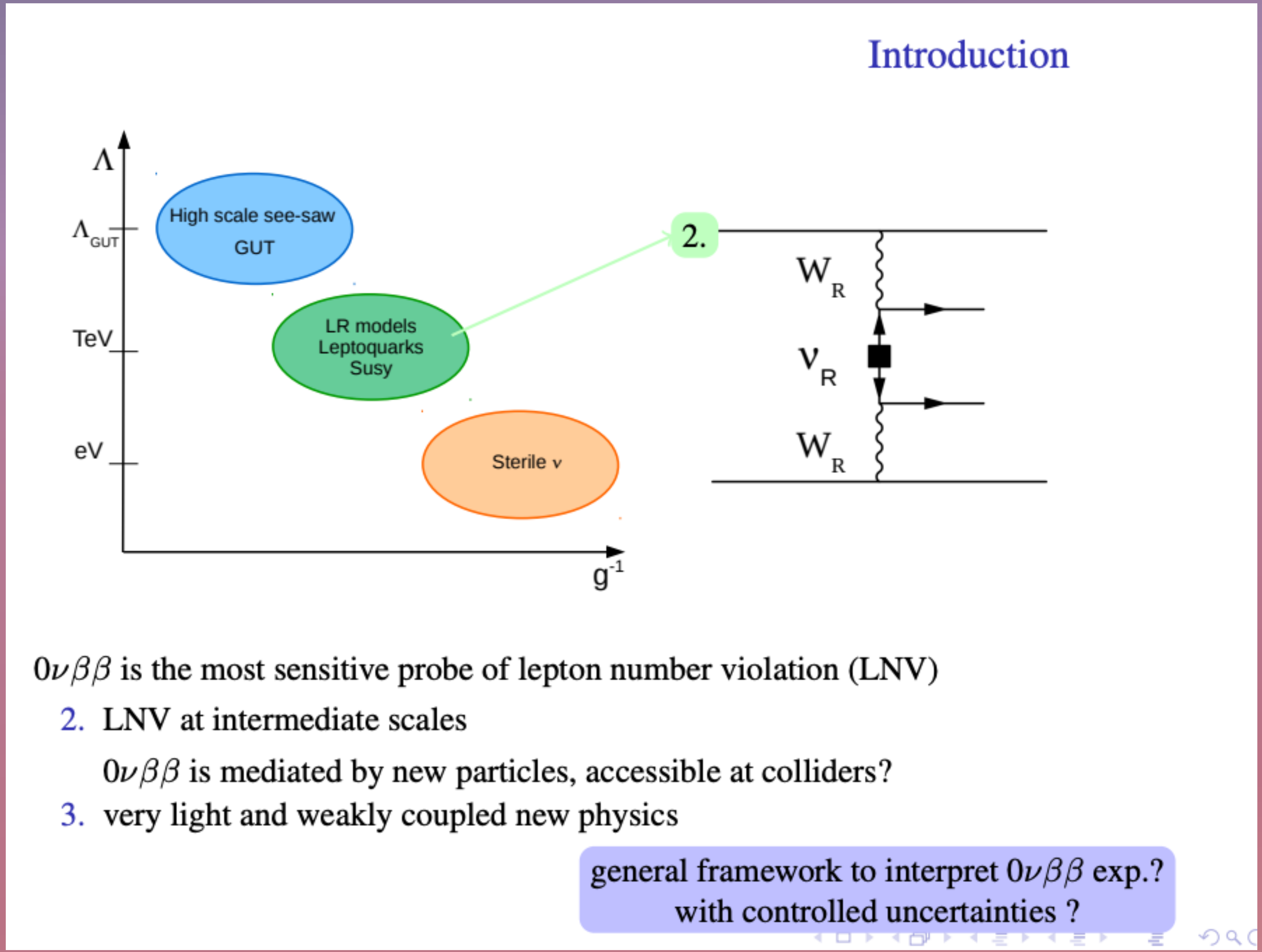
Effective neutrino flavor extracted from the CMB, Big Bang Nucleosynthesis

Neutrino Properties

- Reports from:
  - Emanuele Mereghetti on the theory behind Neutrinoless Double Beta Decay
  - Ann-Kathrin Schuetz on Results from KATRIN, Project 8, and Neutrino Mass
  - Laxman Paudel and CJ Barton on the Majorana Demonstrator and LEGEND-1000

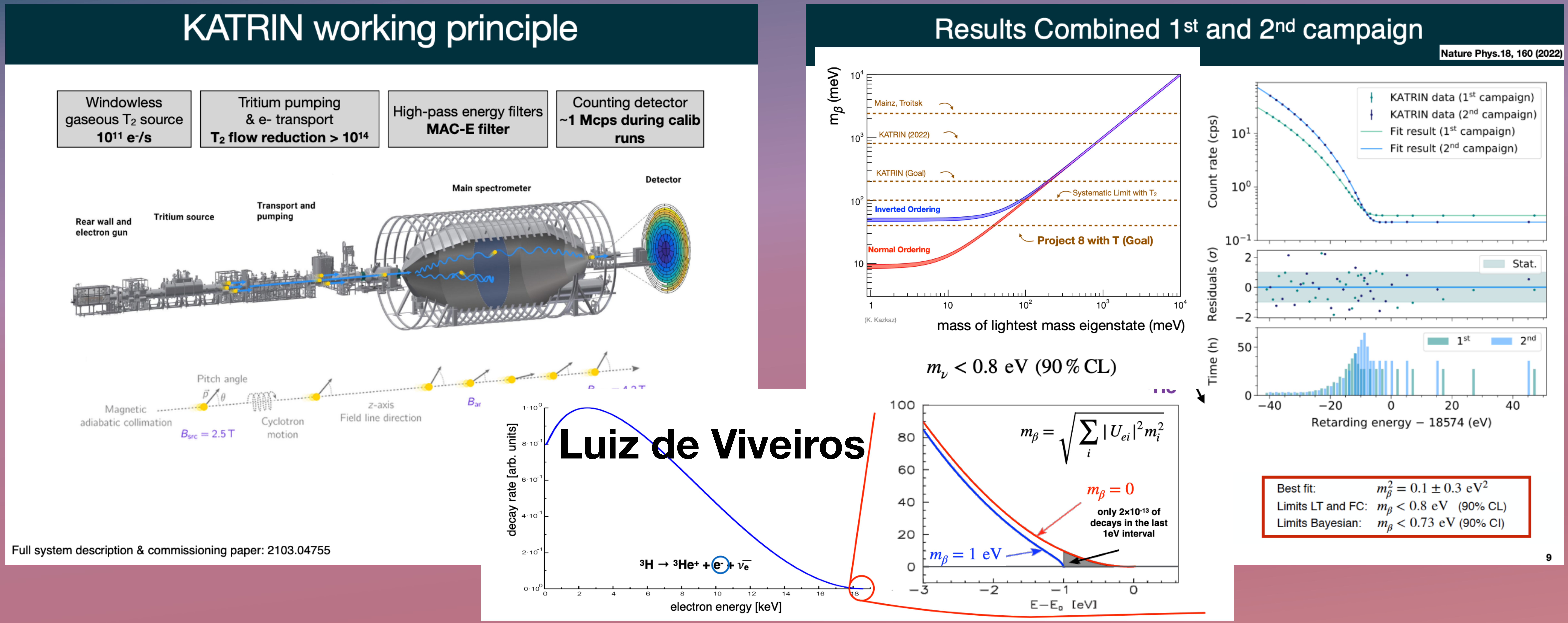
Emanuele Mereghetti on the theory behind Neutrinoless Double Beta Decay





Fantastic introduction to putting $0\nu\beta\beta$ decay in perspective!

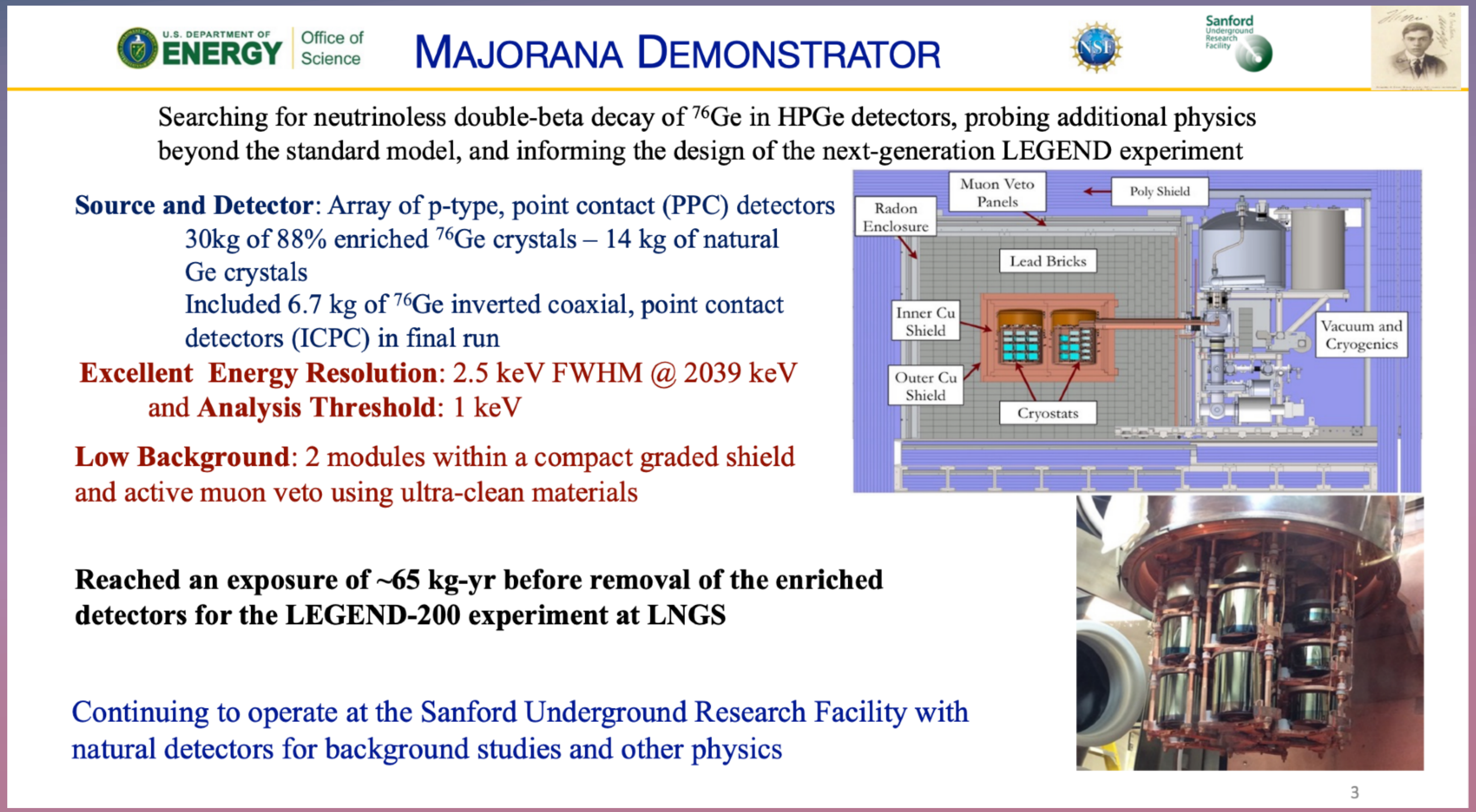
Ann-Kathrin Schuetz and Luiz de Viveiros on KATRIN, Project 8, and Neutrino Mass

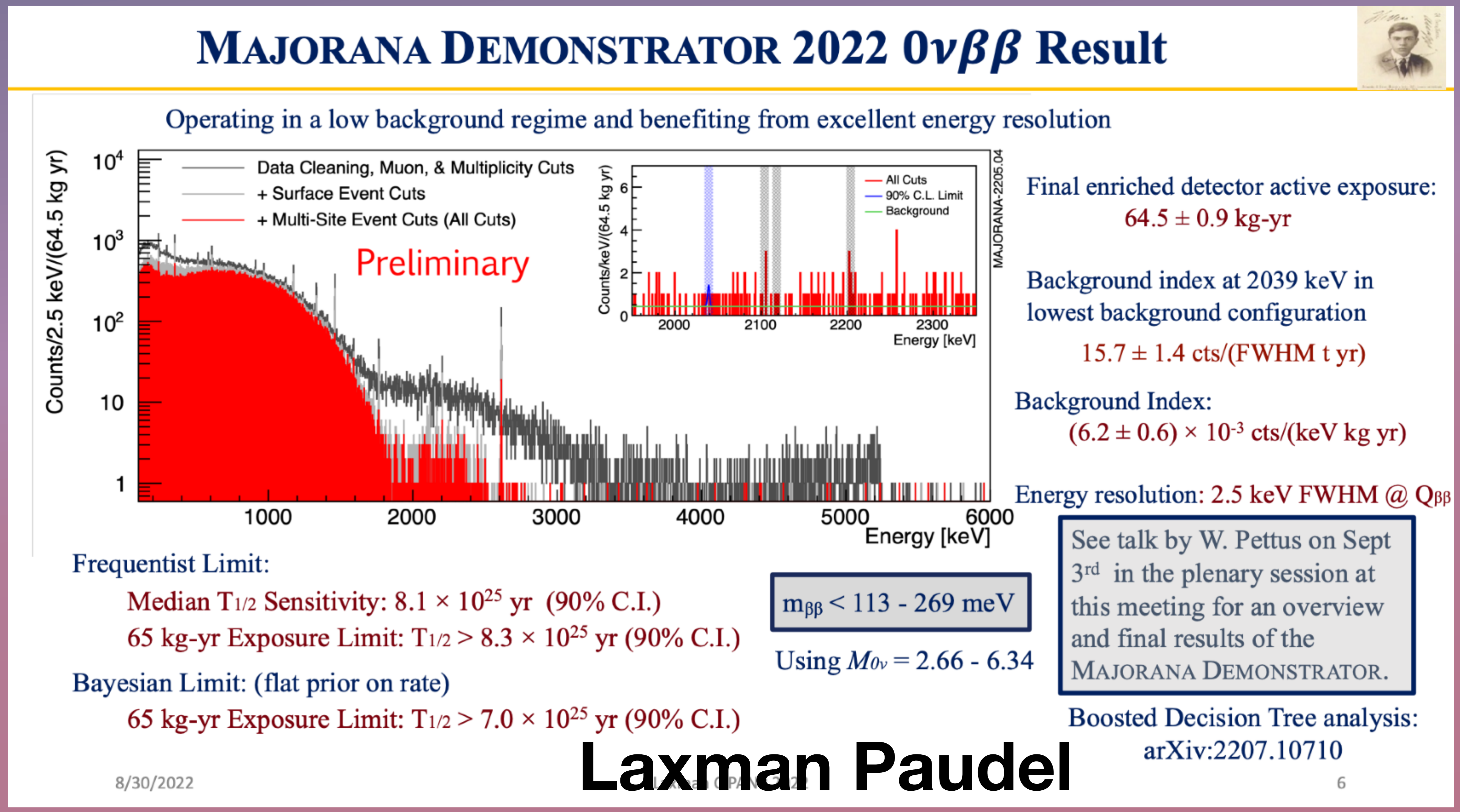


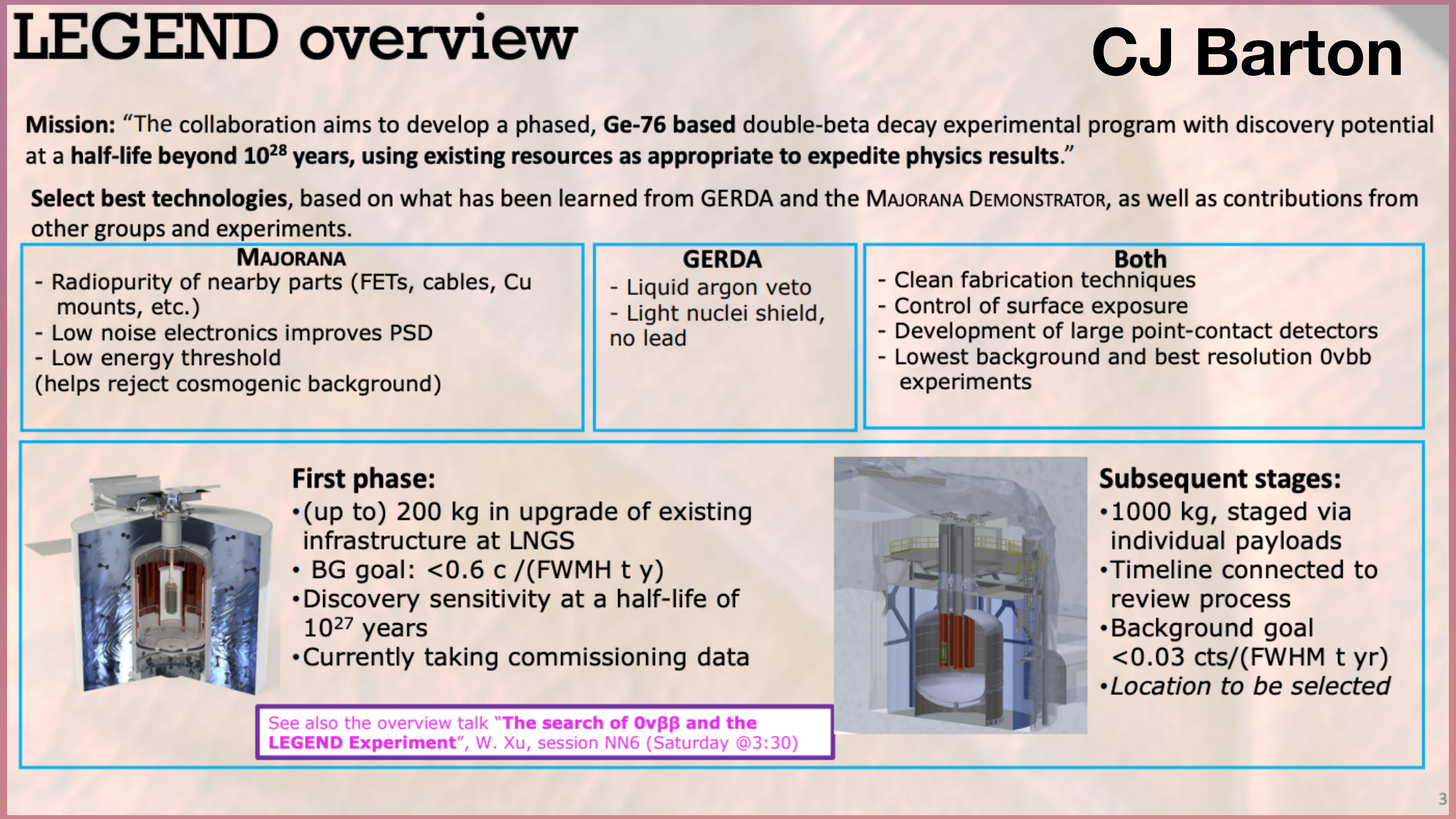
Detectors act as high pass filters, rejecting low energy electrons and allowing precise understanding of the spectral shape close to the endpoint.

New results on model independent direct measurement of neutrino mass using beta decay electrons from tritium. First demonstration of super high precision Project 8.

Laxman Paudel and CJ Barton on Germanium based $0\nu\beta\beta$ detectors







Majorana Demonstrator Showed efficacy of Ge-based detectors!

LEGEND commissioning of 20% scale phase, combines best of Majorana Demonstrator with GERDA.

Thanks for Coming!