Theoretical Challenges in Neutrino Physics

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2023 Fermilab Users Meeting

Outline

- Some historical context
- Neutrino-nucleus cross sections for modern experiments
- Supernova neutrinos: what physics could we get from the signal at DUNE?
- Neutrinos in the lab and in cosmology
- Pedro will discuss new BSM physics ideas

A bit of historical context

- In just two decades, we went from this:

Review of Particle Physics: R.M. Barnett *et al.* (Particle Data Group), Phys. Rev. **D54**, 1 (1996)

Massive Neutrinos and Lepton Mixing, Searches for

For excited leptons, see Compositeness Limits below.

See the Particle Listings for a Note giving details of neutrinos, masses, mixing, and the status of experimental searches.

No direct, uncontested evidence for massive neutrinos or lepton mixing has been obtained. Sample limits are:

ν oscillation: $\overline{\nu}_e \not\to \overline{\nu}_e$

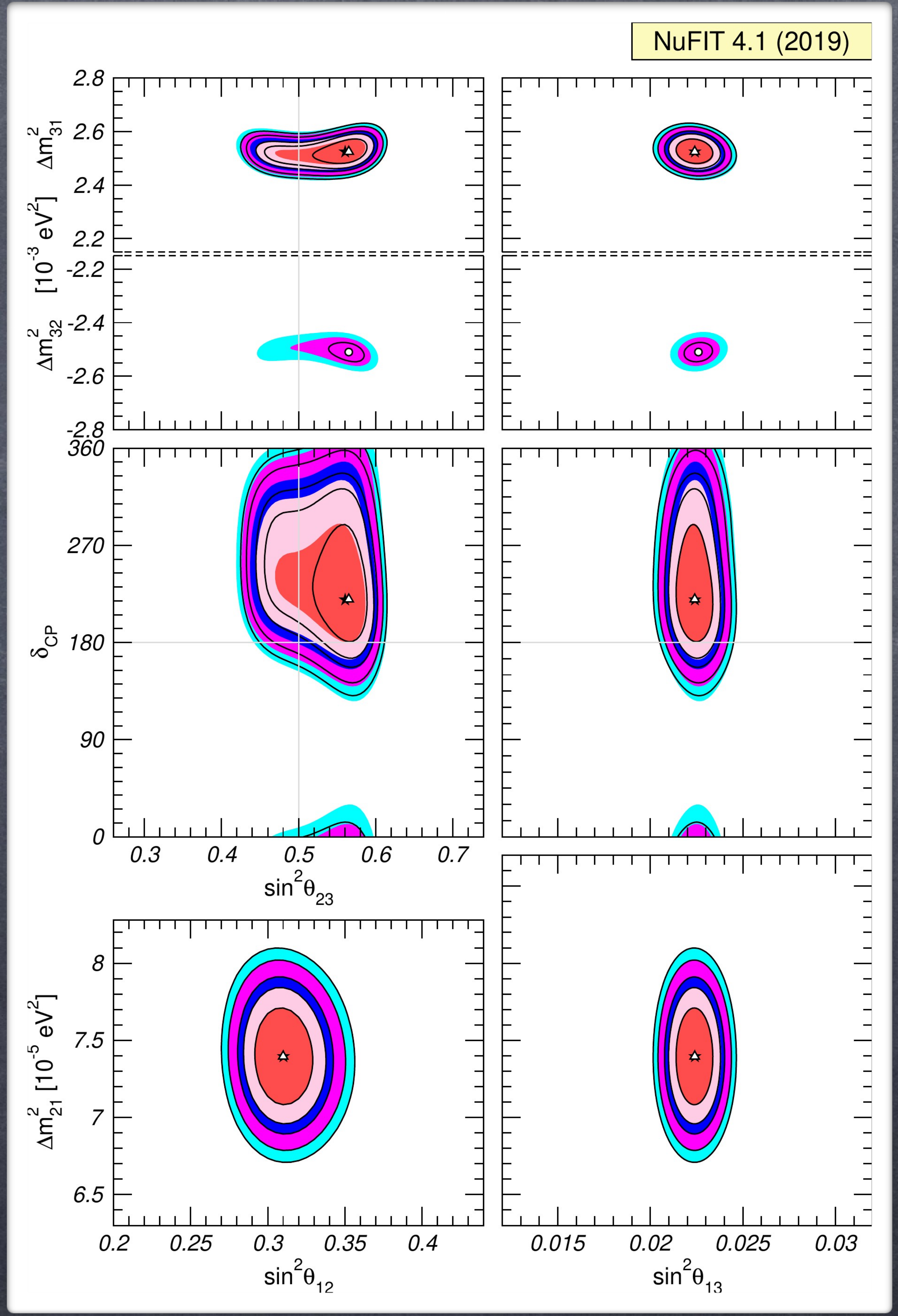
$\Delta(m^2) < 0.0075$ eV^2, CL = 90% (if $\sin^2 2\theta = 1$)
$\sin^2 2\theta < 0.02$, CL = 90% (if $\Delta(m^2)$ is large)

ν oscillation: $\nu_\mu \to \nu_e$ (θ = mixing angle)

$\Delta(m^2) < 0.09$ eV^2, CL = 90% (if $\sin^2 2\theta = 1$)
$\sin^2 2\theta < 2.5 \times 10^{-3}$, CL = 90% (if $\Delta(m^2)$ is large)

A bit of historical context

- ...to this



Ingredients of success

- Close collaboration between theory and experiment proved beneficial
  - E.g., solar neutrino predictions
  - Discovery of the MSW effect
- Synergies between fields which are traditionally separate disciplines
  - Nuclear and particle physics, astrophysics, chemistry, etc

SOLAR NEUTRINOS. I. THEORETICAL*

John N. Bahcall
California Institute of Technology, Pasadena, California
(Received 6 January 1964)

The principal energy source for main-sequence stars like the sun is believed to be the fusion, in the deep interior of the star, of four protons to form an alpha particle.[1] The fusion reactions ... star is typically less than 10^{-10} of the radius of the star. Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star and thus verify

VOLUME 12, NUMBER 11 PHYSICAL REVIEW LETTERS 16 MARCH 1964

SOLAR NEUTRINOS. II. EXPERIMENTAL*

Raymond Davis, Jr.
Chemistry Department, Brookhaven National Laboratory, Upton, New York
(Received 6 January 1964)

The prospect of observing solar neutrinos by means of the inverse beta process $^{37}Cl(\nu, e^-)^{37}Ar$ induced us to place the apparatus previously described[1] in a mine and make a preliminary search. ... 3 counts in 18 days is probably entirely due to the background activity. However, if one assumes that this rate corresponds to real events and uses the efficiencies mentioned, the upper limit of the

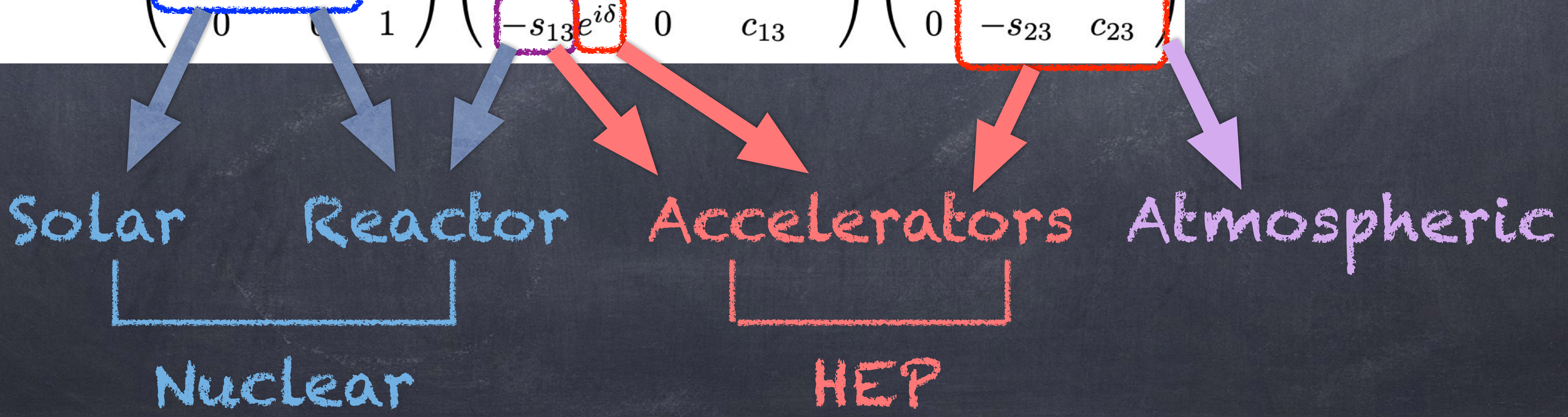
Initial Discovery Era -> Precision Era

- Initial discoveries were measuring large effects (often factor 2-3)
- Modern experiments look for O(10%) or smaller effects in search for subtle signatures of CP violation, mass hierarchy, new physics
  - -> more stringent requirements not only for experiment, but also for theory
- There are also other major developments, such as precision cosmology, improvements in lattice QCD, 3D simulations of supernova explosions, etc
  - Results of neutrino experiments should be analyzed in broad context

Misbehaving neutrinos

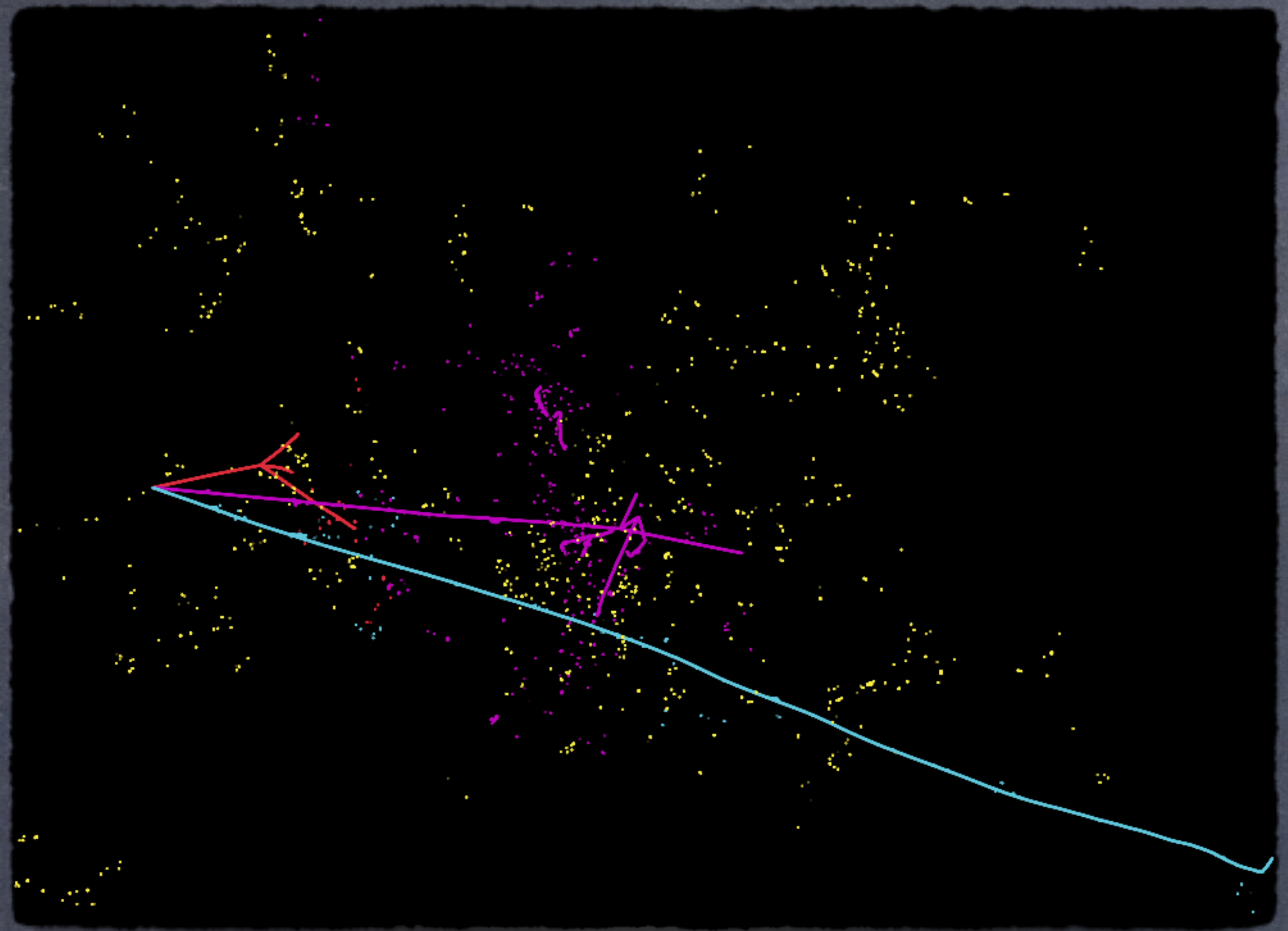
- Neutrinos are notorious for completely disrespecting our carefully crafted partitions between DOE Offices, Frontiers, etc
- Even the 3x3 neutrino mixing matrix has been split between DOE offices

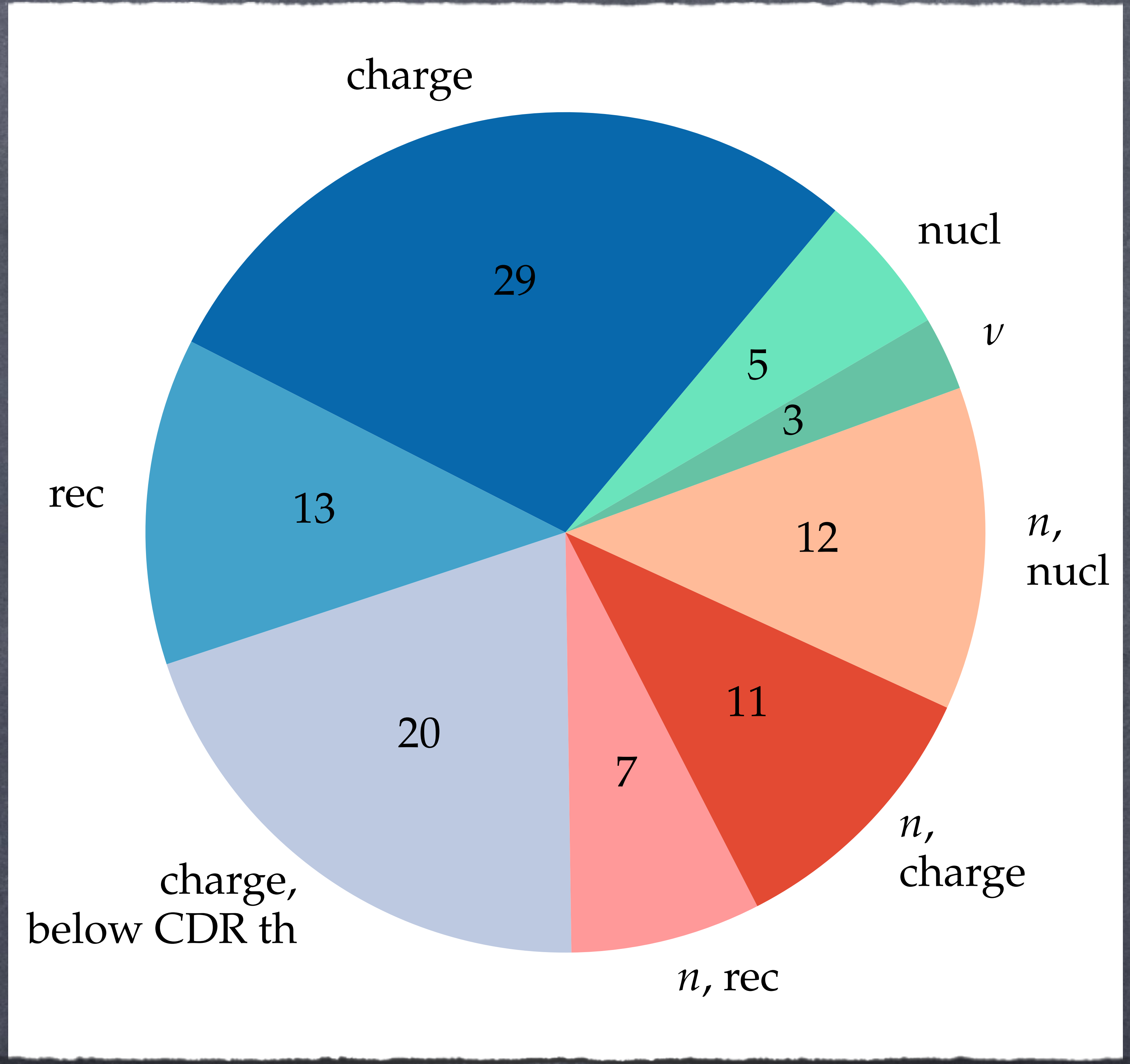
$$U_{\rm PMNS} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$



Cross sections: an urgent challenge

Let's talk about δ_{CP} (DUNE)





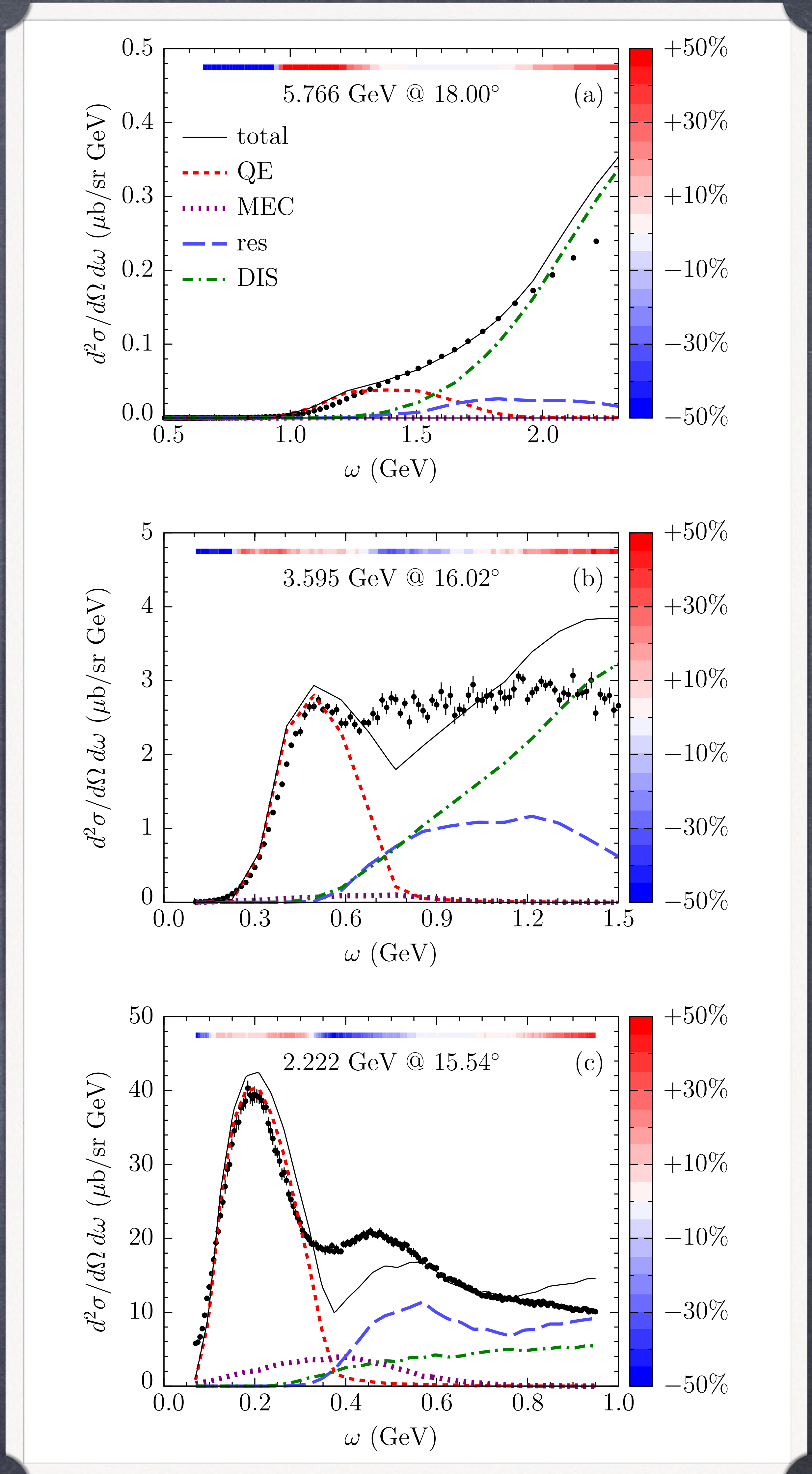
- P(E_ν) -> We need to reconstruct neutrino energy -> some of it is going to be missing in LArTPC (neutrons, mis-IDed charged particles) -> **must rely on the generators to fill in missing info!**
- Very nontrivial in the GeV regime!

Missing energy budget for 4 GeV neutrinos in LAr is complicated

see AF, S. Li,
arXiv:1811.06159,
arXiv:2007.13336

Cross sections at DUNE energies

- Below perturbative QCD
- But above the domain of traditional nuclear physics
- Modeled as a combination of quasielastic, resonant and DIS processes, with multi-nucleon effects and final-state interactions
- Has both vector and axial interactions
    - The axial part is particularly challenging
    - The vector part can be studied with electron scattering



Electron scattering comparisons are very fruitful: known kinematics allows to zoom in on specific processes

Mapping out the pattern of discrepancies

Large overlap with the kinematics of DUNE!

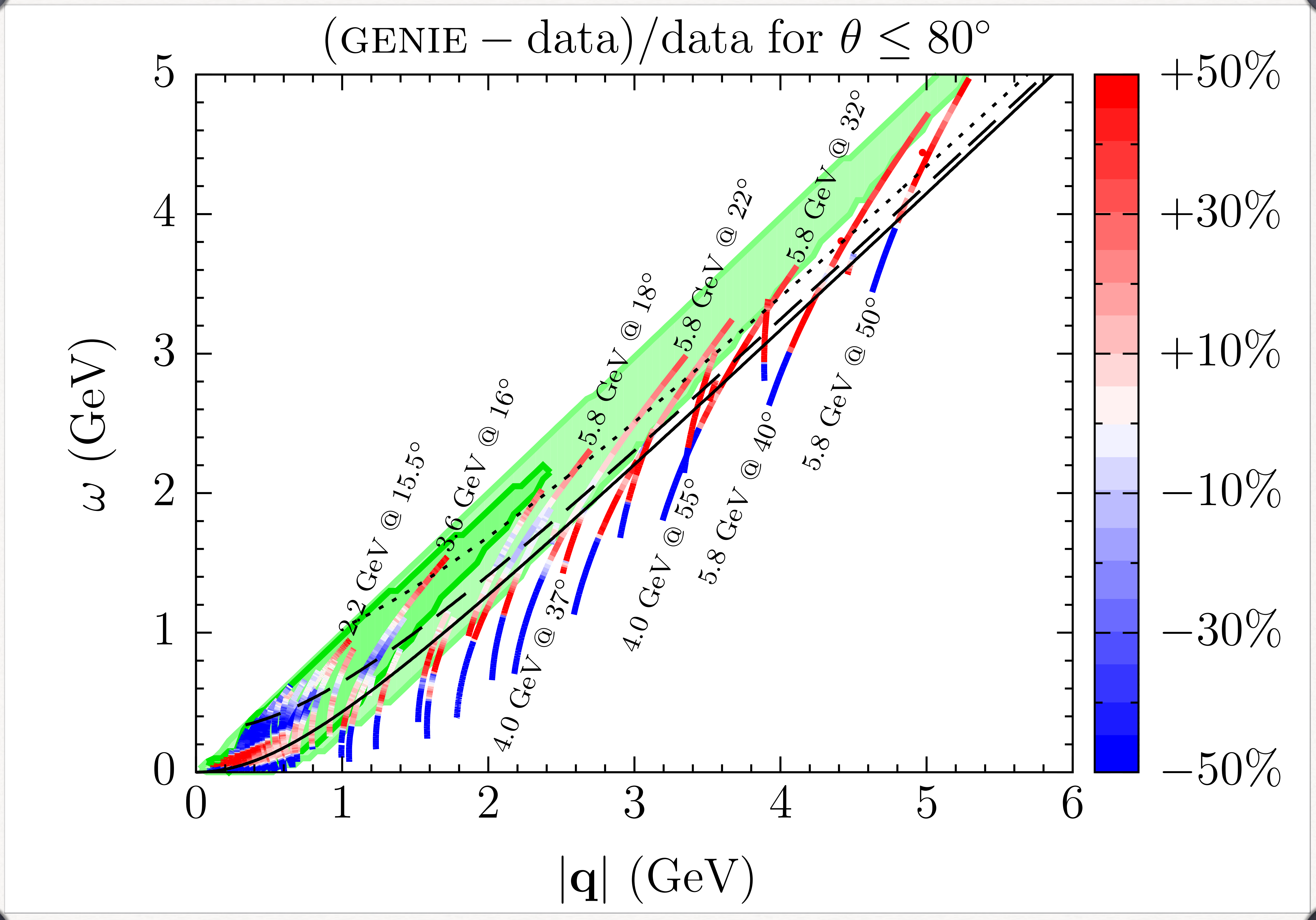
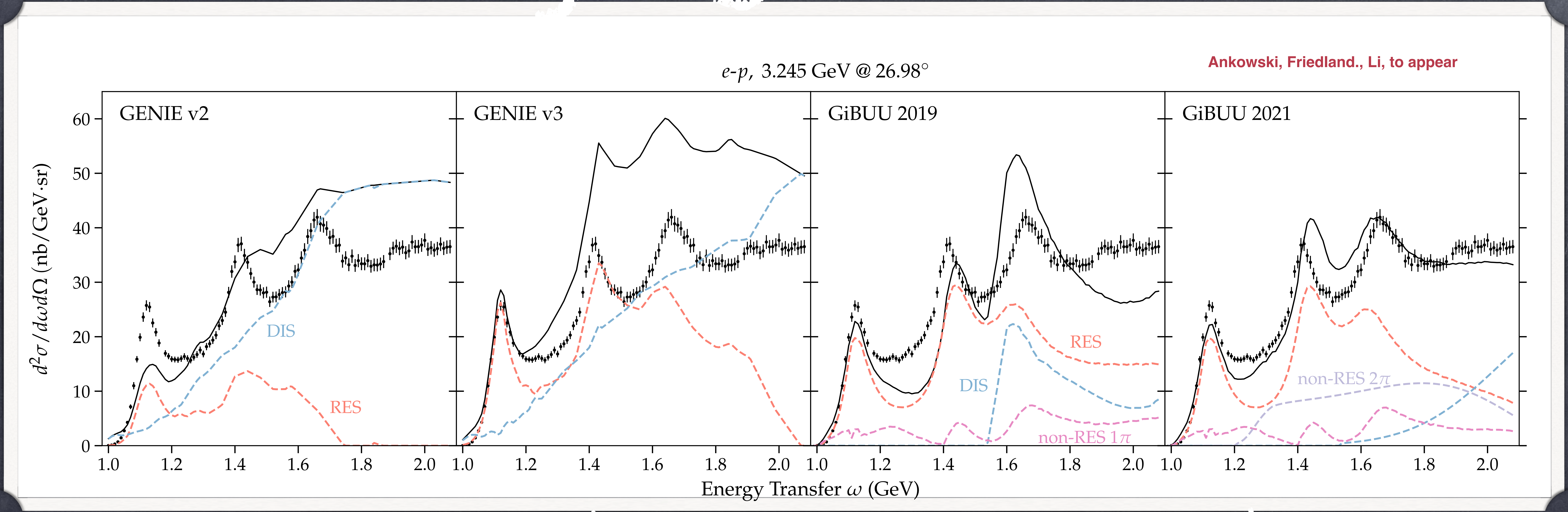


Figure: A. Ankowski, AF, Phys. Rev. D (2020)

Common challenge for today's generators



- Regimes where the models overlap several contributions, such as RES and DIS, or QE, MEC, and RES are a common challenge
- Rather than trying to address this by blind tuning, need to develop sound physics (theoretical framework).

Fundamental physics problem

Fundamental problem: theory in the strong-weak transition regime

-> quark-hadron duality

VOLUME 25, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1970

SCALING, DUALITY, AND THE BEHAVIOR OF RESONANCES IN INELASTIC ELECTRON-PROTON SCATTERING*

E. D. Bloom and F. J. Gilman
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 25 June 1970)

We propose that a substantial part of the observed behavior of inelastic electron-proton scattering is due to a nondiffractive component of virtual photon-proton scattering.

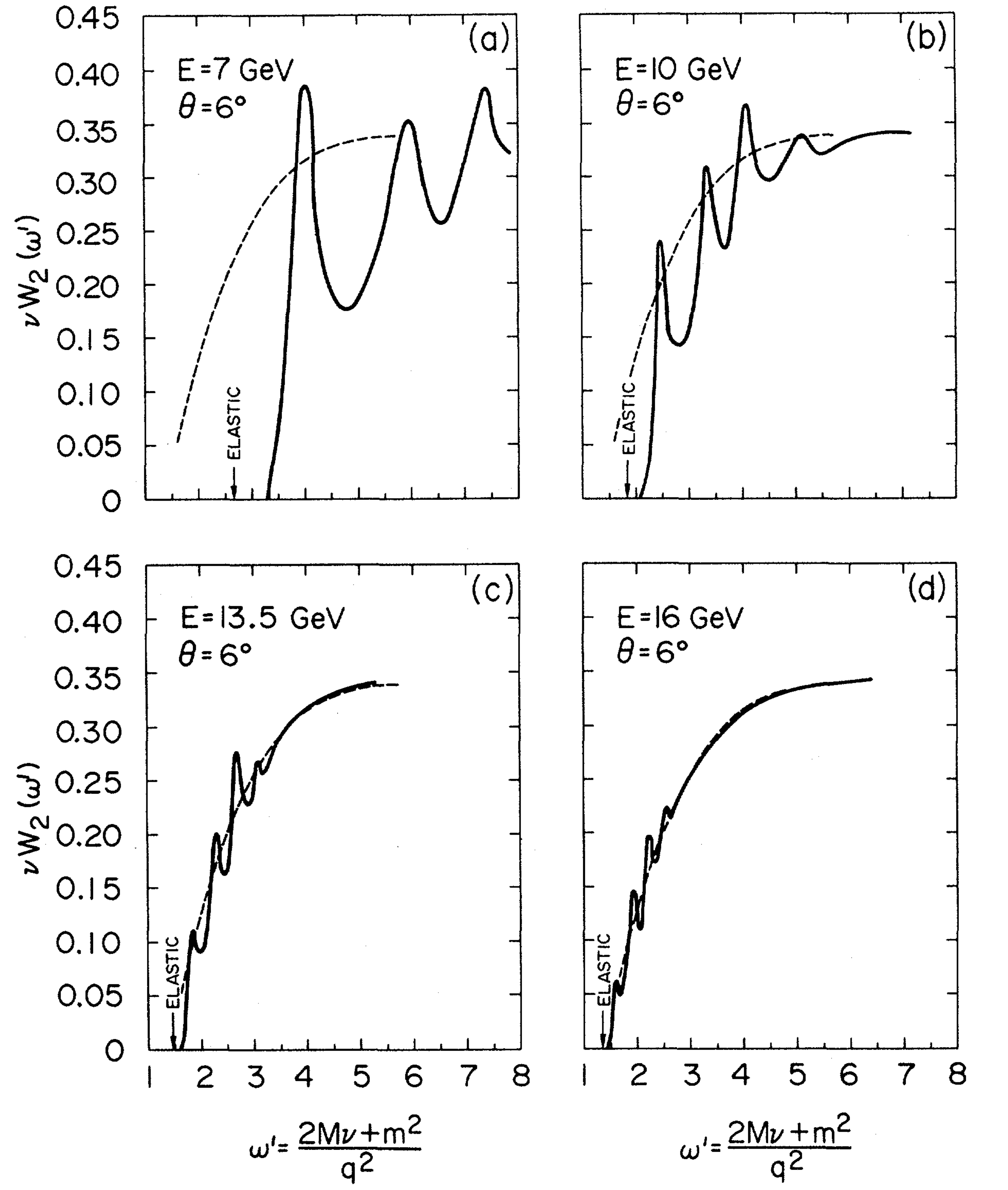


FIG. 1. The function νW_2 plotted versus $\omega' = (2M\nu + m^2)/q^2$, with $m^2 = M^2$. The solid lines are smooth curves drawn through the $\theta = 6°$ data at various incident electron energies. The dashed curve is the same in all cases and is a smooth curve through large ν and q^2 ($3 < q^2 < 7$ GeV^2, $W \geq 2$ GeV), $\theta = 10°$ data. All data are

Axial form factors & LQCD

- Lattice QCD has made tremendous progress in the last decade in modeling nucleon FF
- Excited state contamination identified and subtracted
- Although different methods are used by different groups (ETMC, NME, RQCD), the results agree, conserve PCAC, all disagree with the old dipole anzats
    - Cf. work by Hill, Paz, Meyer et al
- Tthe implications of these results for neutrino physics must be fully explored
- Need to untangle the form-factor and MEC effects

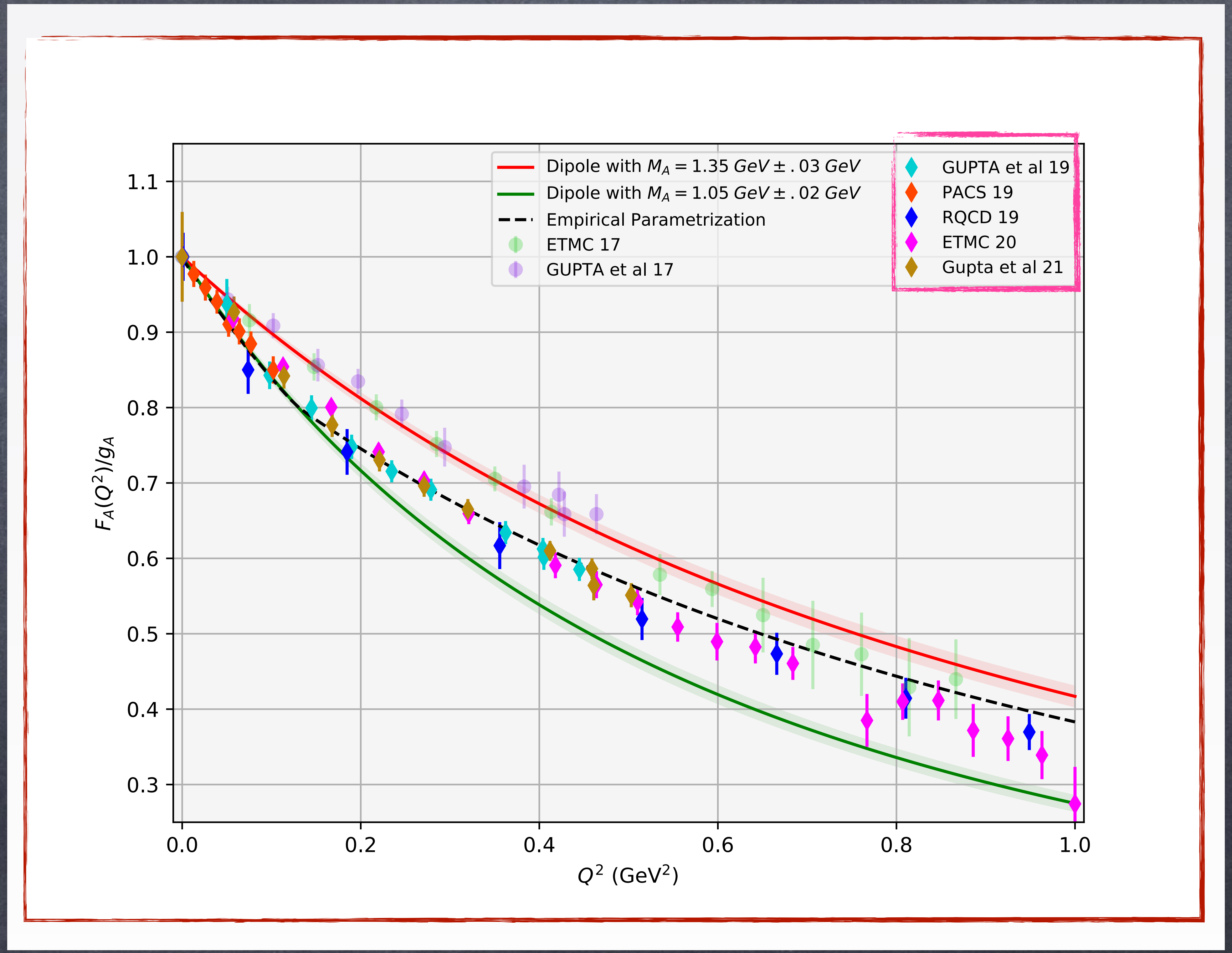


Figure credit: E. Passemar and K. Quirion (Indiana U)

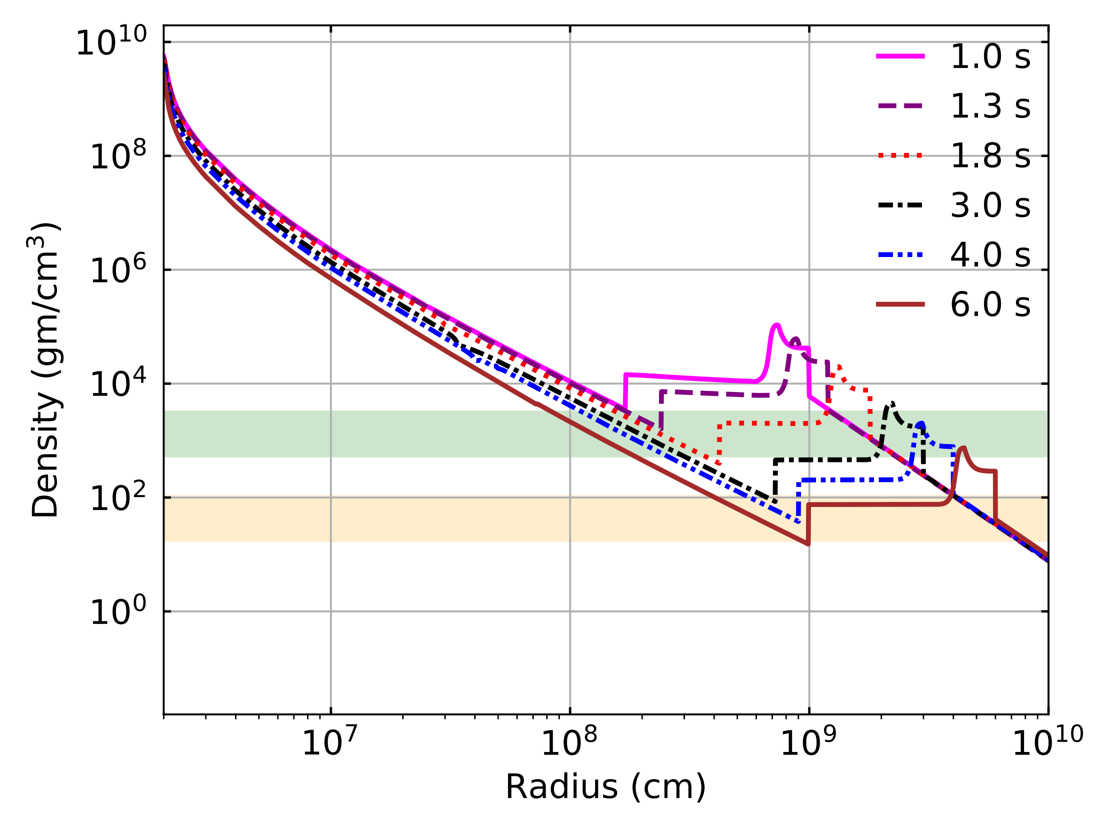
Supernova and DUNE

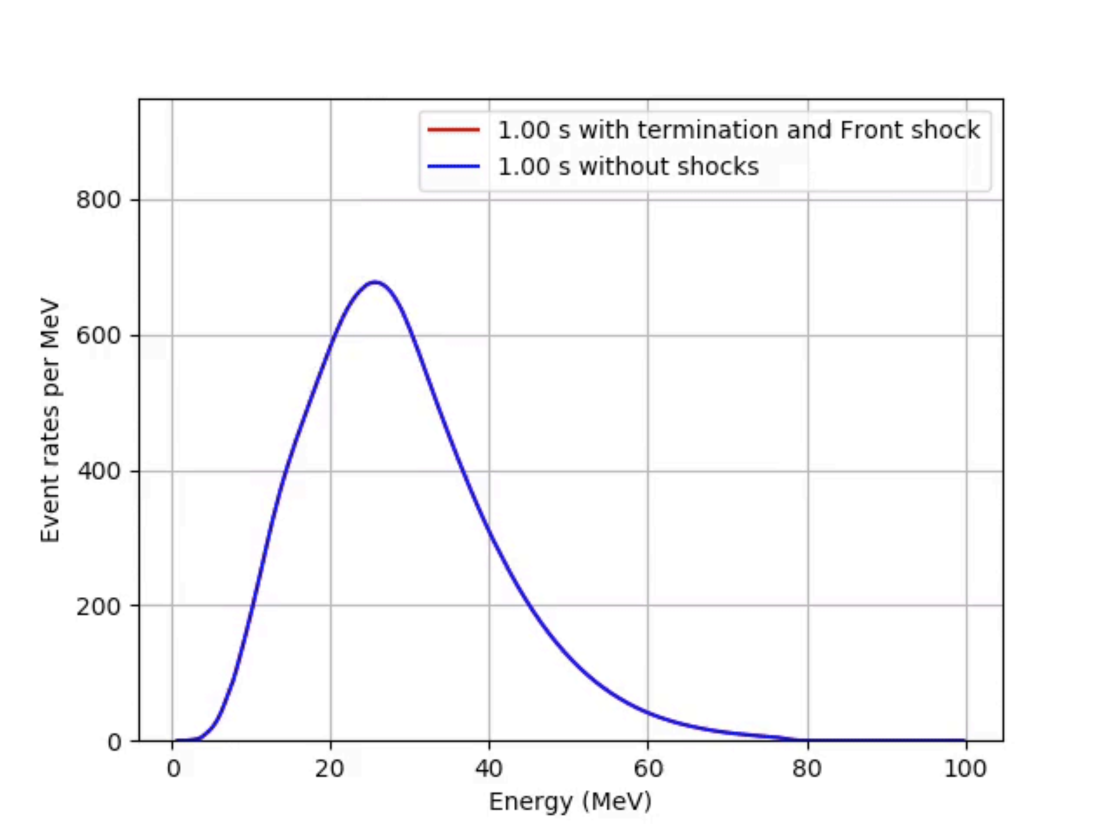
Matter profile around the core gets imprinted on the neutrino signal

- Streaming neutrinos heat the material surrounding the core -> neutrino-driven outflow

- This outflow can be smooth or with shocks. Different neutrino flavor evolution thanks to matter effect!

- The difference should be observable in DUNE

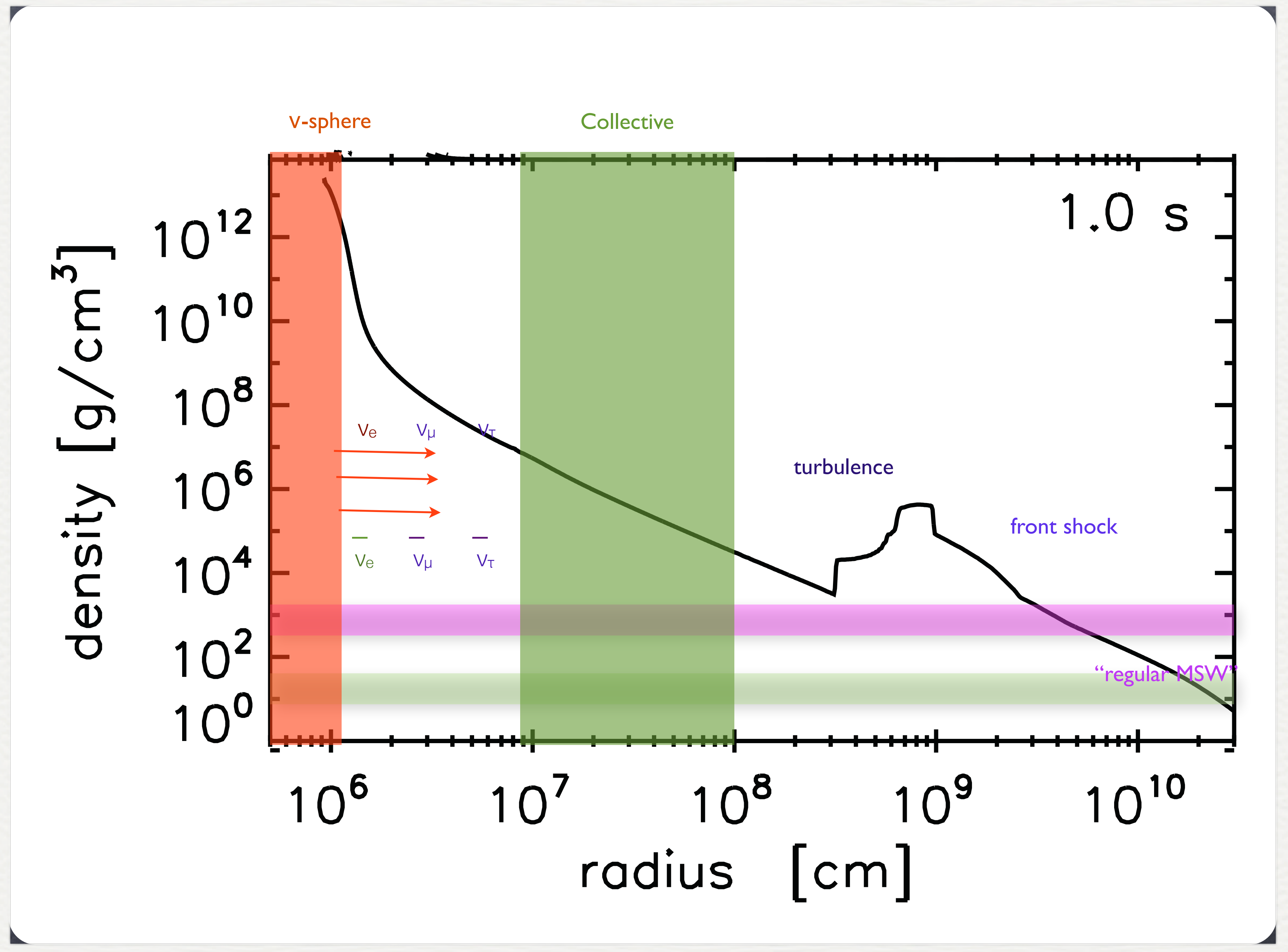




Details in: A.F., P. Mukhopadhyay, PLB (2022)

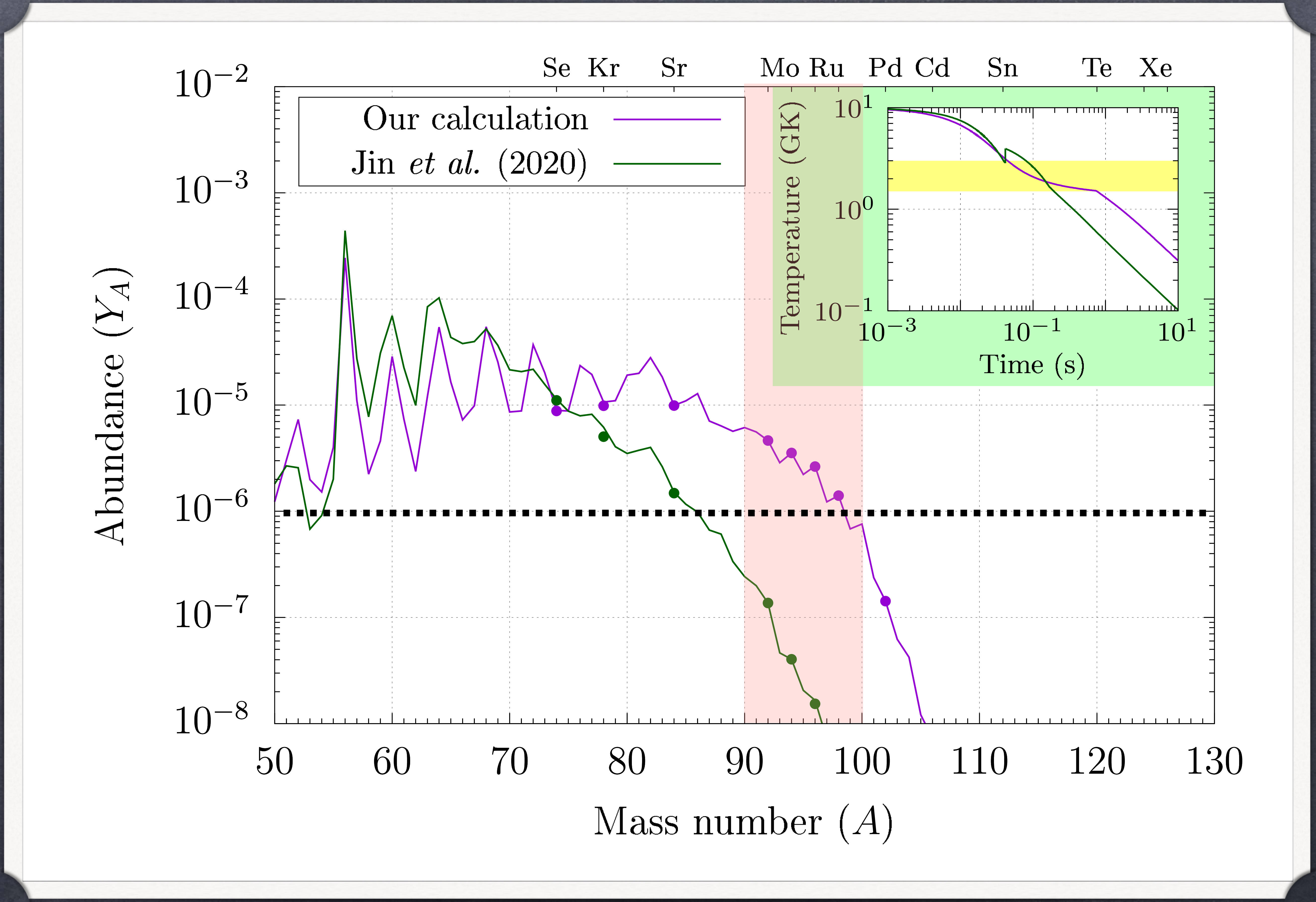
Collective neutrino oscillations

- Just above the collapsed core the number density of streaming neutrinos is ~ 10^8 moles/cm^3. Their "self-MSW" couples flavors of different neutrinos. One has to evolve neutrino ensemble as a whole. These conditions can't be reproduced in the lab
- Rich many-body quantum system, with many regimes (lots of work since 2005)
  - Connections to QIS!



DUNE as a probe of nucleosynthesis

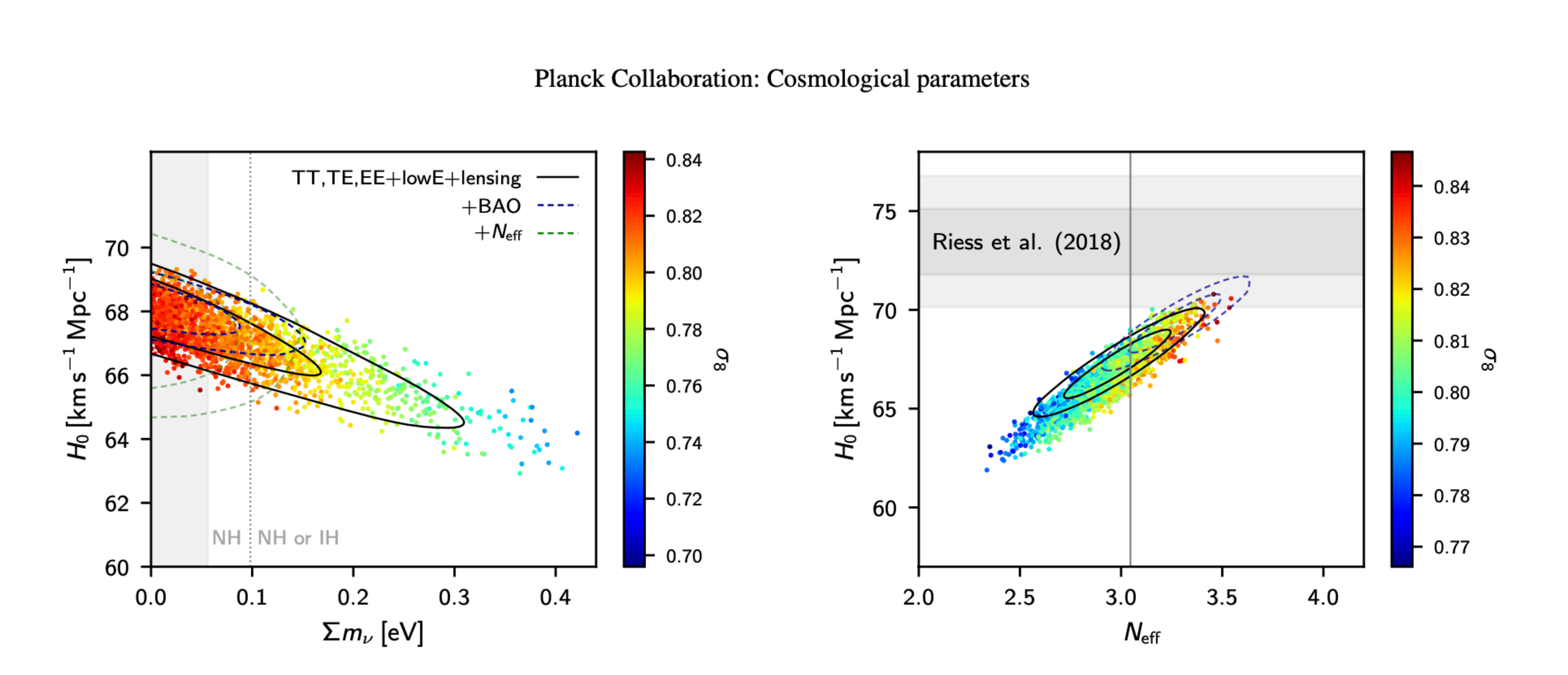
- About 1/4 of molybdenum on Earth comes in the form of two neutron-poor isotopes, 92Mo and 94Mo
  - Their origin has been a famous problem for decades
  - Neutrinos around the collapsed core could solve this mystery ("Nu-p process", Frohlich et al)
- We find that the signal at DUNE may tell us whether the conditions are optimal for this process



Short-baseline anomaly meets precision cosmology

Neutrinos and cosmology

- Modern cosmological data are very sensitive to neutrino mass and energy density in the early universe



The Hubble tension was suggested to Be a sign of sterile neutrinos

E.g. Wyman, Rudd, Vanderveld and W. Hu, PRL (2014)

Battye & Moss, PRL (2014)

This requires new physics in the neutrino sector

- What's needed is N_eff ~ 3.4, which means that the additional neutrino state is only partially populated
- A minimal sterile neutrino with the Mini-BooNE parameters would be completely thermalized in the early universe, via oscillations + collisions
- A neutrino with hidden interactions, could, however, be only partially thermalized, yielding N_eff ~ 3.2-3.4. CMB lensing + BAO limit the mass of this neutrino.
  - The full implications of such scenarios are yet to be understood
- It was suggested, e.g., that strongly self-interacting neutrinos could fit the data and help alleviate the Hubble tension (e.g., Kreisch, Cyr-Racine, Dore, 1902.00534)

We might know very soon

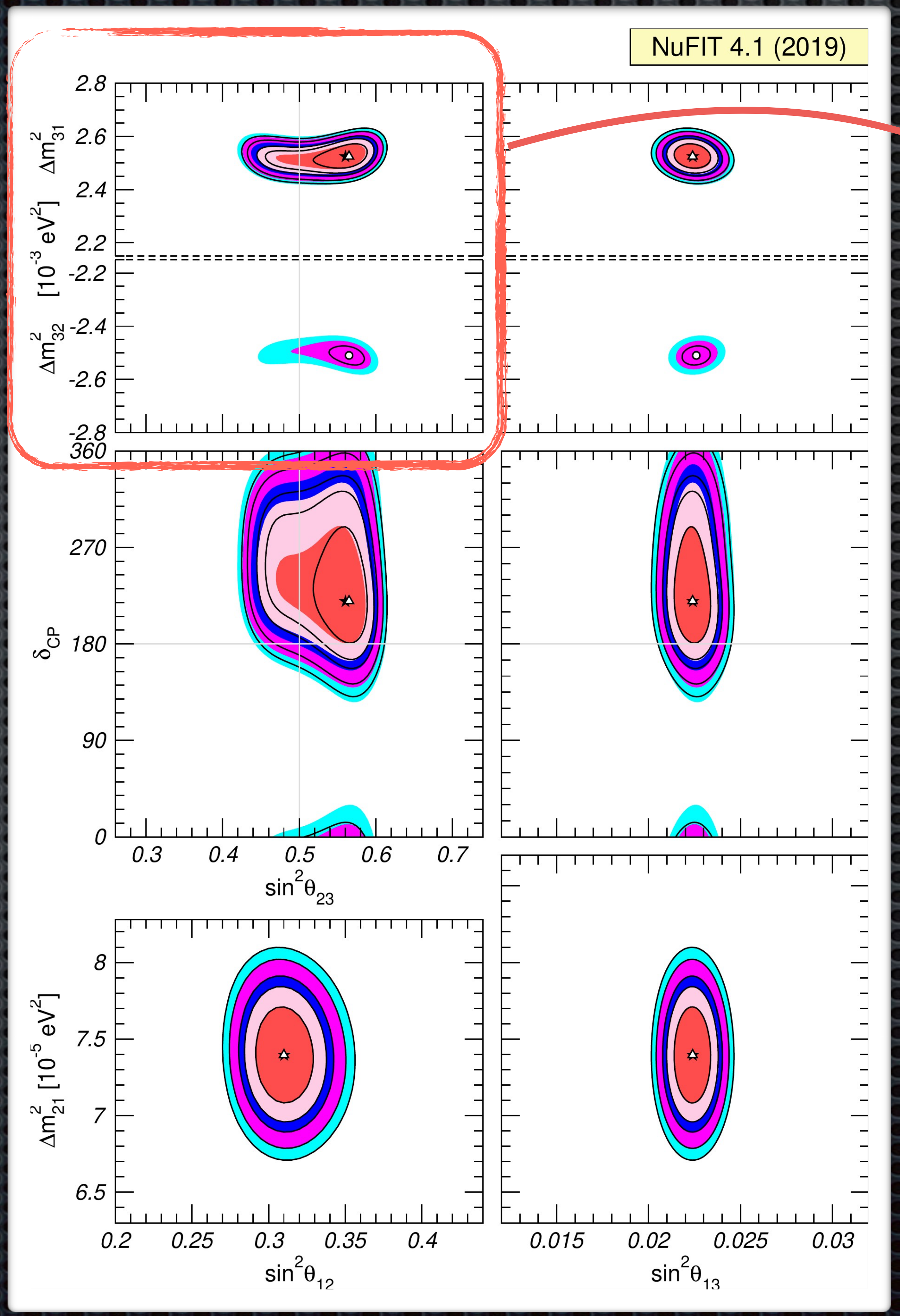
- Short-baseline program is going to give results within the next several years
- The next step in cosmology is the Simons Observatory, which is designed to have sensitivity of N_eff ~ 0.1 and should give its results on the same timescale
- An ideal situation is if the cosmology and lab results are in apparent disagreement -> new physics in the neutrino sector!

To sum up

- The neutrino program at Fermilab SNB+NOvA+DUNE+... brings a lot of exciting and rich physics together:
  - Lattice QCD, hadronic physics, nuclear physics, SN explosion astrophysics, collective oscillations and QIS connections, BSM physics, nuclear EOS, nucleosynthesis, CMB and LSS cosmology ...
- Close collaboration between theory and experiment has proven very fruitful in neutrino physics before. It looks to be even more essential going forward

Backup

Does this really matter for oscillation measurements?



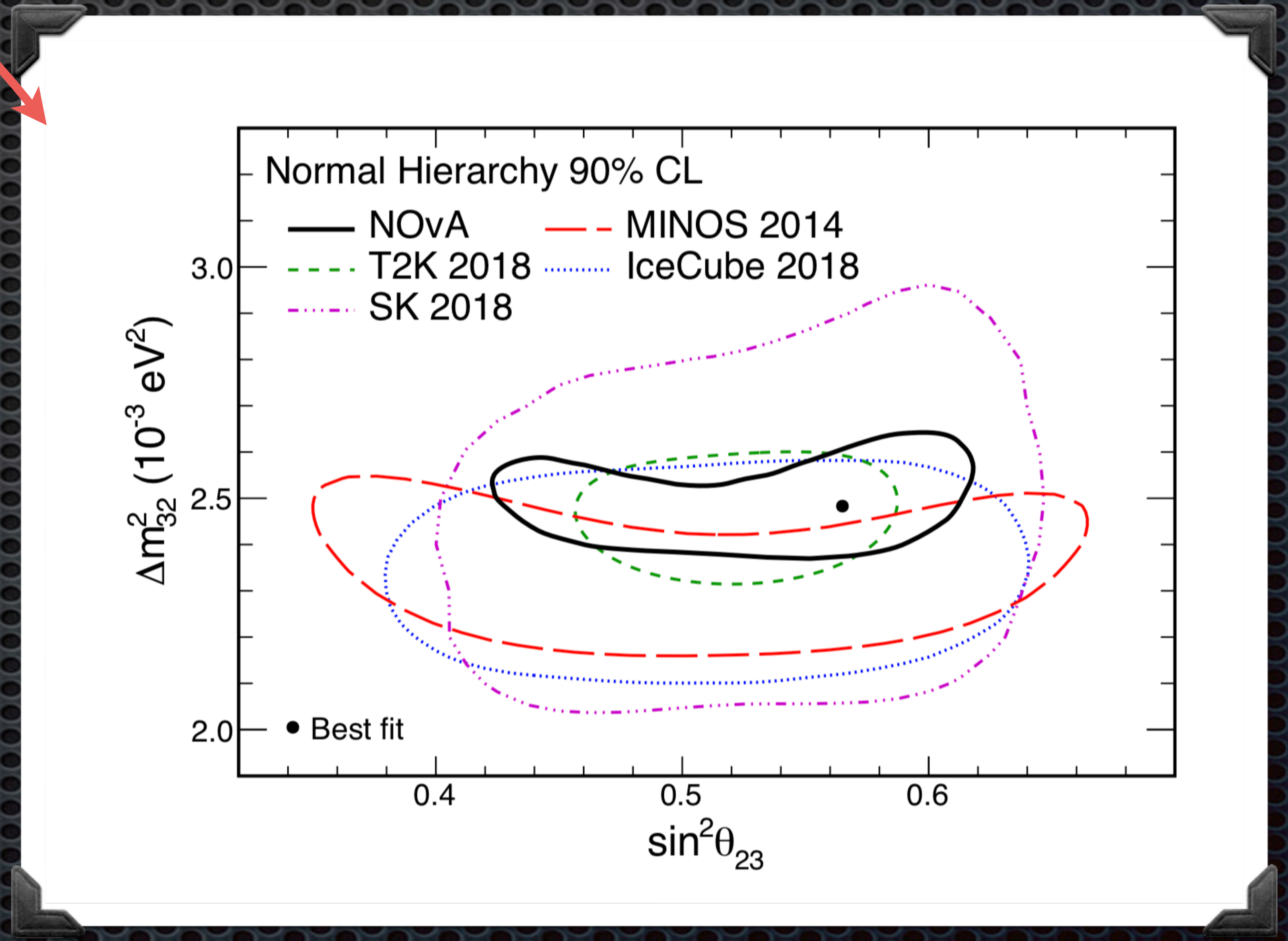
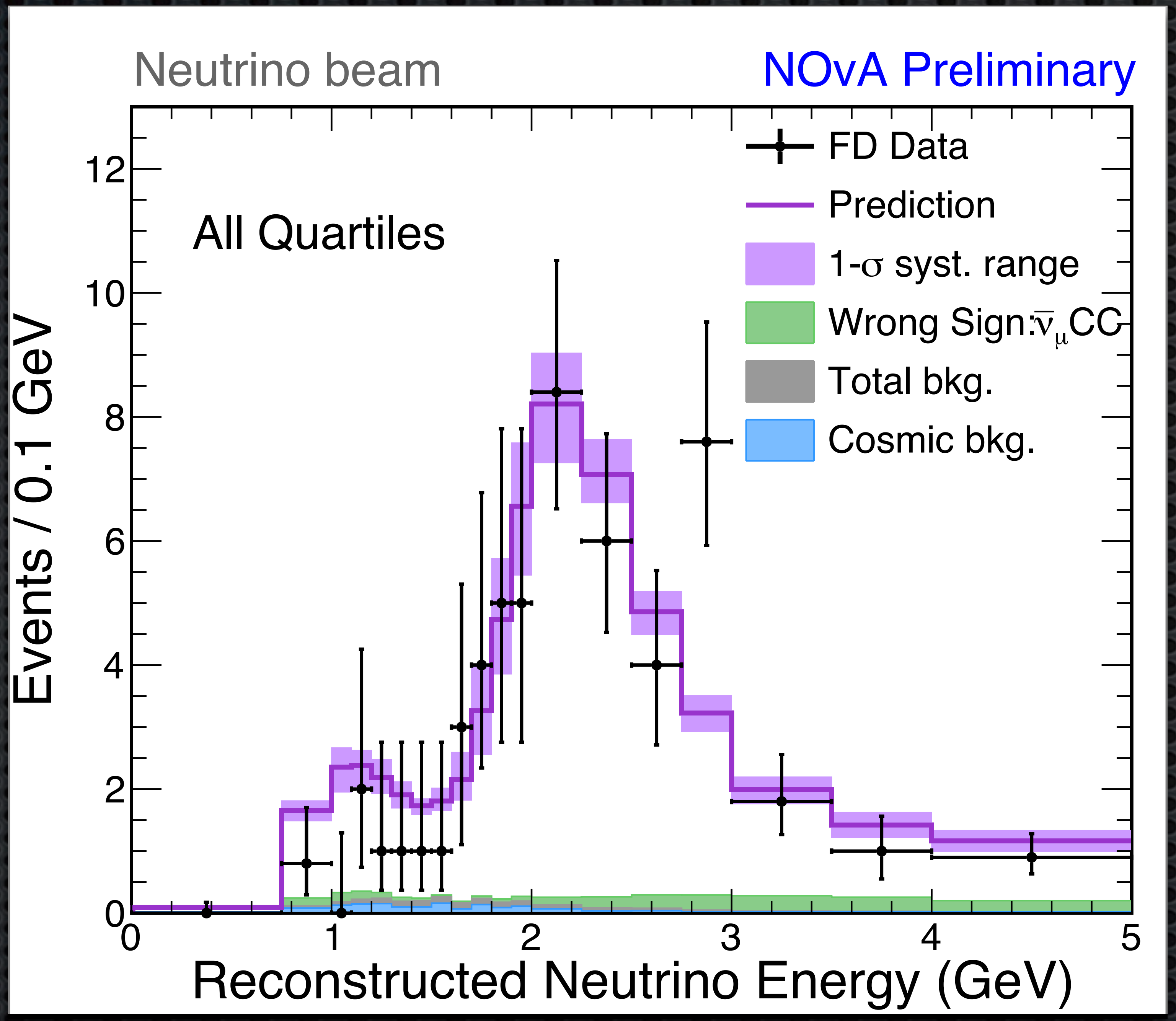
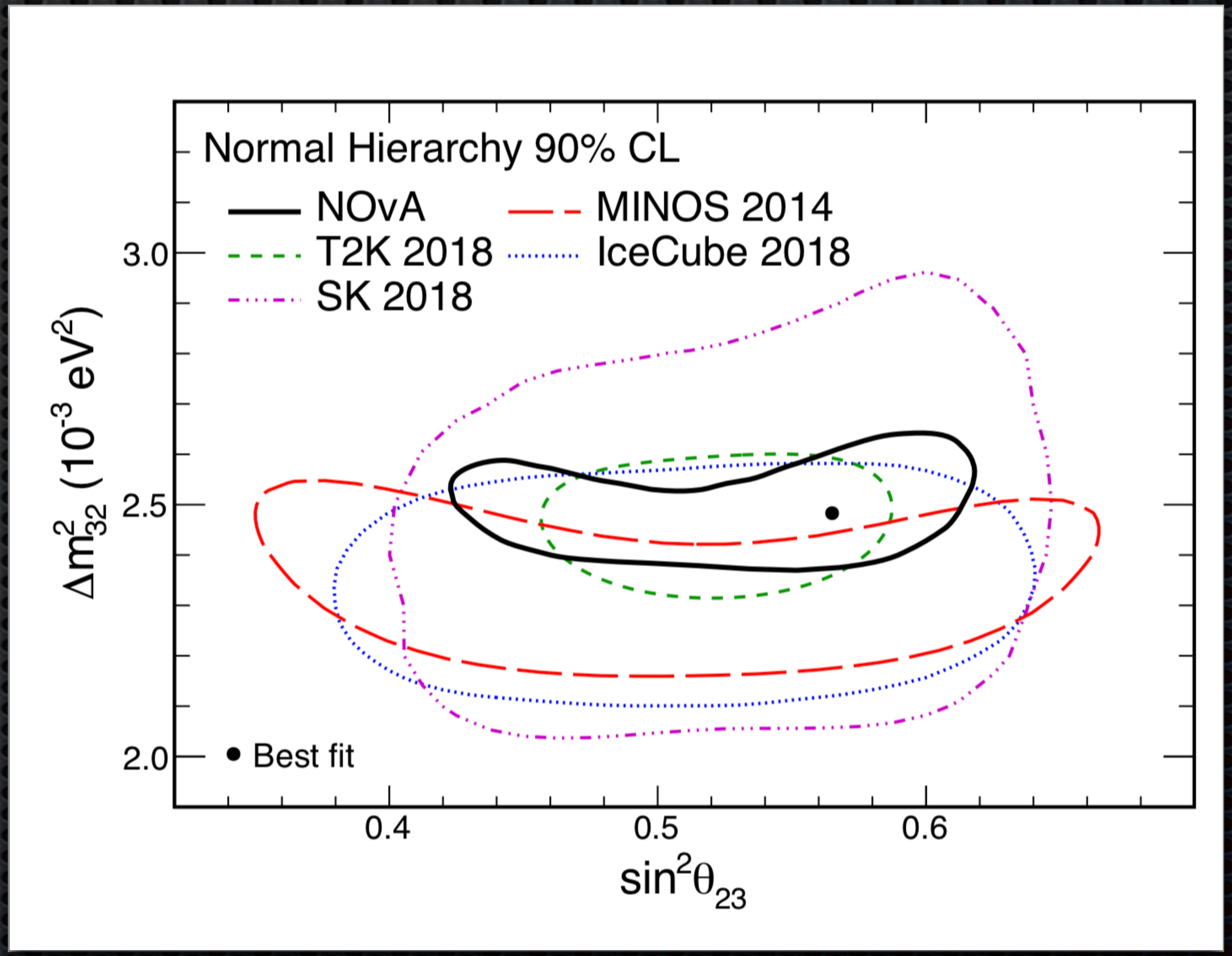


Figure from NOvA, arXiv:1906.04907

NOvA 2019

Figure from NOvA, arXiv:1906.04907

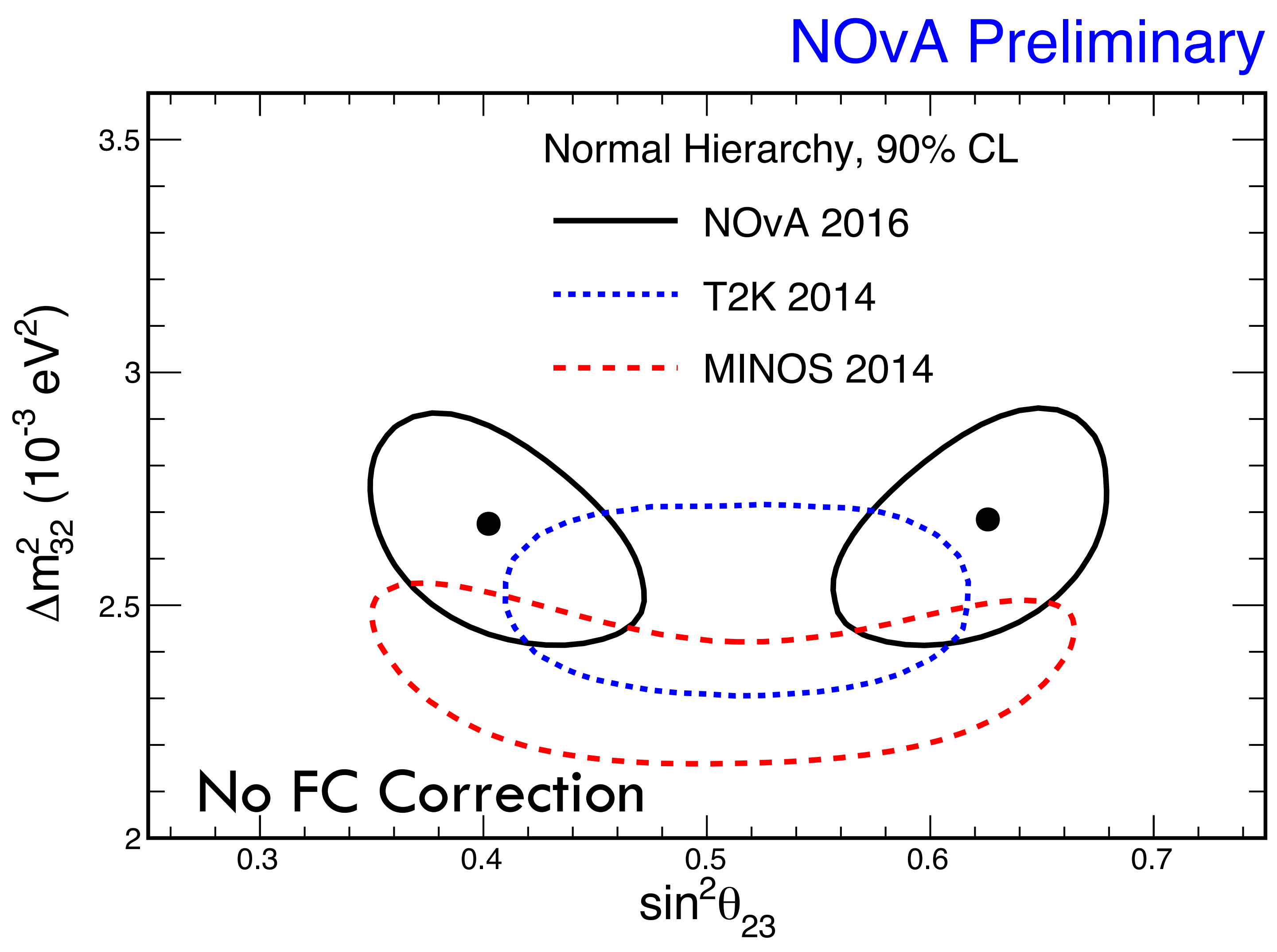


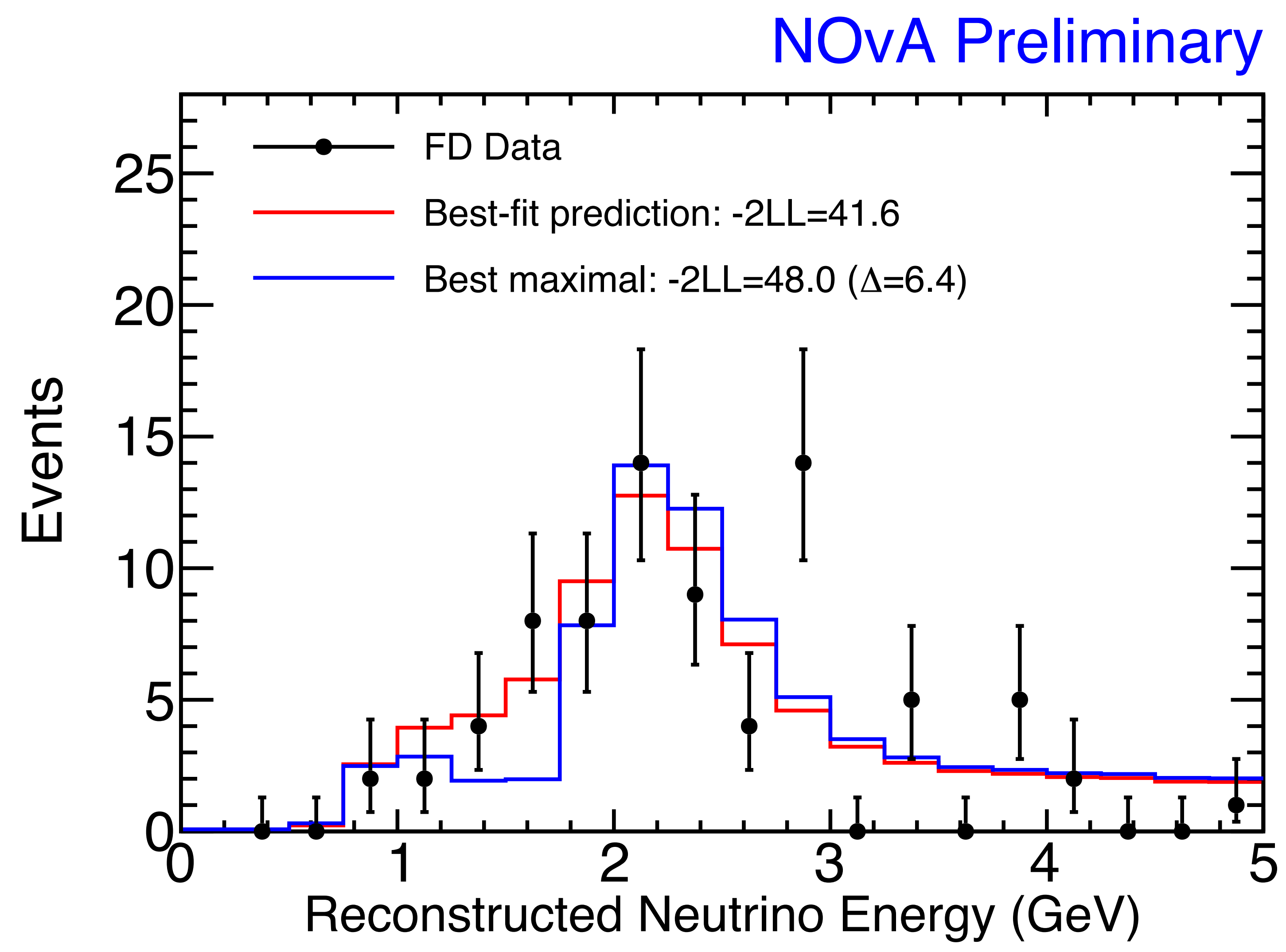


- $\theta_{23} = \pi/4$ implies maximal depletion of ν_μ at the osc. maximum

cf. NOVA 2016

- More events at the osc. maximum could be interpreted as evidence of nonmaximal mixing -> energy resolution is key!





Best Fit (in NH):

$$|\Delta m^2_{32}| = 2.67 \pm 0.12 \times 10^{-3} \mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02} (0.63^{+0.02}_{-0.03})$$

Maximal mixing excluded at 2.5σ