SAC Neutrino Working group summary

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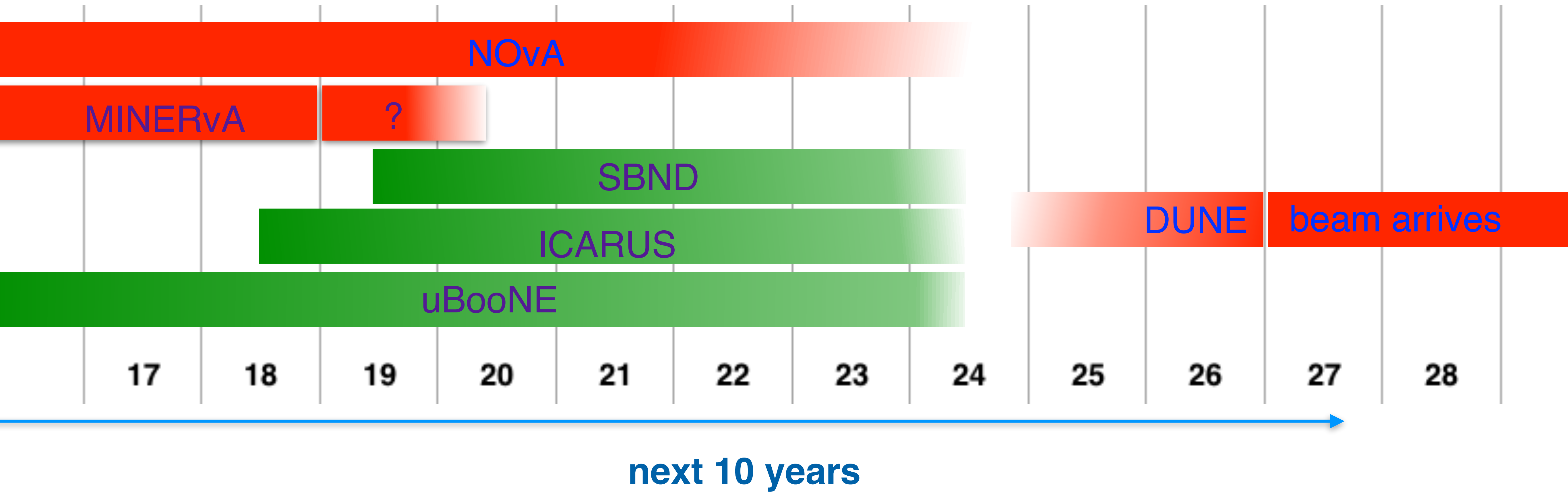
Neutrino Working Group Summary, Scientists Retreat

The current Fermilab neutrino program

- Two running beams, NuMI neutrino beam and Booster neutrino beam, running both long-baseline and short-baseline experiments

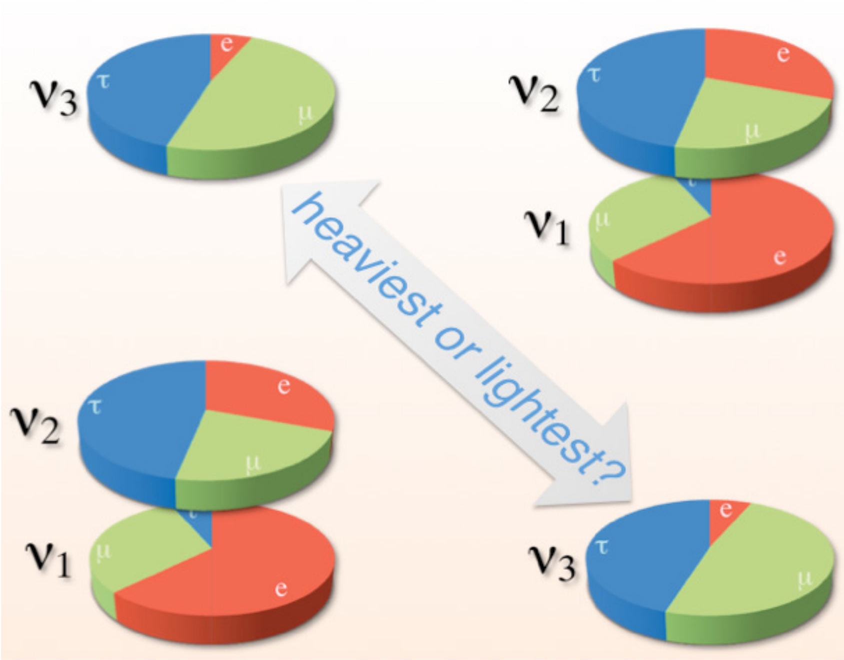


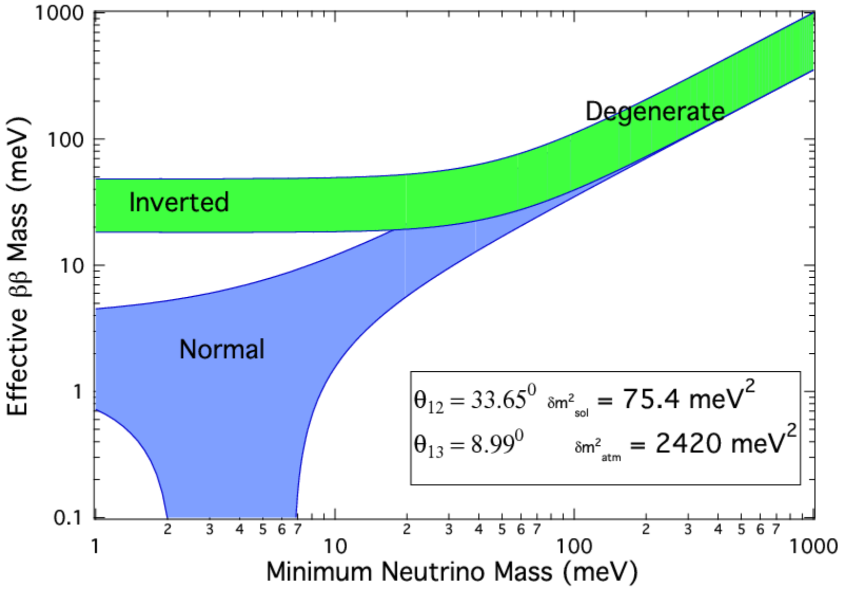
- This charge asks both the immediate 10 years, and then next 10 years
- The lab has broad program for the next 10 years and DUNE will run for the following ~10 years

The questions of the current program:Long-Baseline Program

Addressing 1 of P5 science drivers "Pursue the physics associated with neutrino mass"

- The mass hierarchy: Which of the neutrino states is lightest and which is heaviest
  - Does the mass spectrum of the neutrinos match the other known leptons?
  - Has important implications for neutrino-less double beta decay experiments
- Measuring atmospheric mixing angle, θ_{23}: Is there any symmetry/pattern of the mixing?
  - Is the ν_3 state 'Maximal mixing'? i.e does it have equal amount of ν_μ and ν_τ, ($\theta_{23} = 45$). If not what is the the Octant? i.e does it have more ν_μ or ν_τ (i.e is $\theta_{23} > 45$ or $\theta_{23} < 45$).
- Is there CP violation in the neutrino sector. If so what is the phase?
- Testing the 3-neutrino paradigm and unitarity
  - Is the 3x3 PNMS mixing matrix the whole story, are there additional neutrinos or other 'Non-standard' interactions



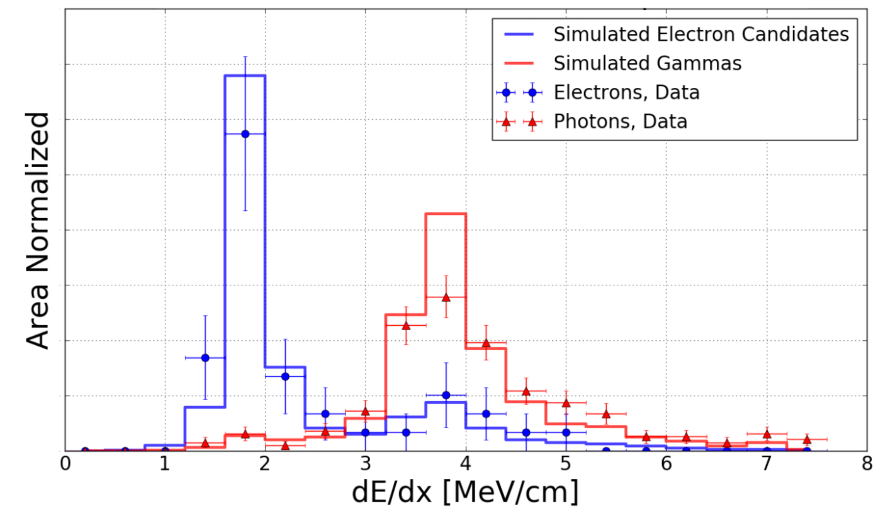


The questions of the current neutrino program

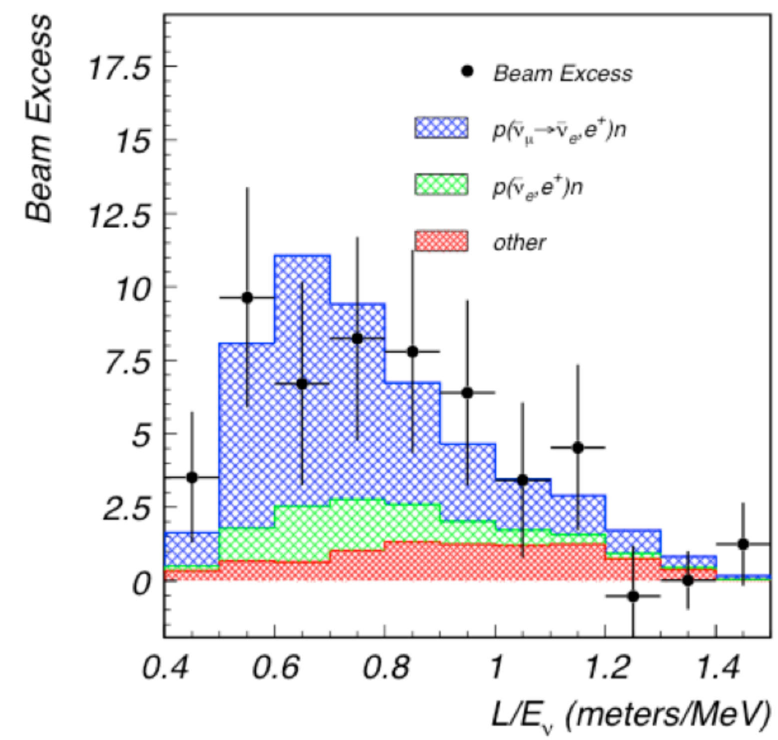
Current Short-BaseLine Program:

- What is the nature of the low energy excess seen by MiniBooNE? Is it electron or photon like?
- Is there a light sterile neutrino?
  - Measure both ν_e appearance and ν_μ disappearance
- Cross Section measurements, understanding the role of the nucleus in what neutrino oscillation experiments actually measure
- LArTPC R&D and measurements needed for DUNE

ArgoNeut e-γ seperation



LSND ν_e excess



Caveat: The sensitivity achievable to these questions, for both long and short-baseline, depends on what the true parameters are.

What will we learn from NOvA?

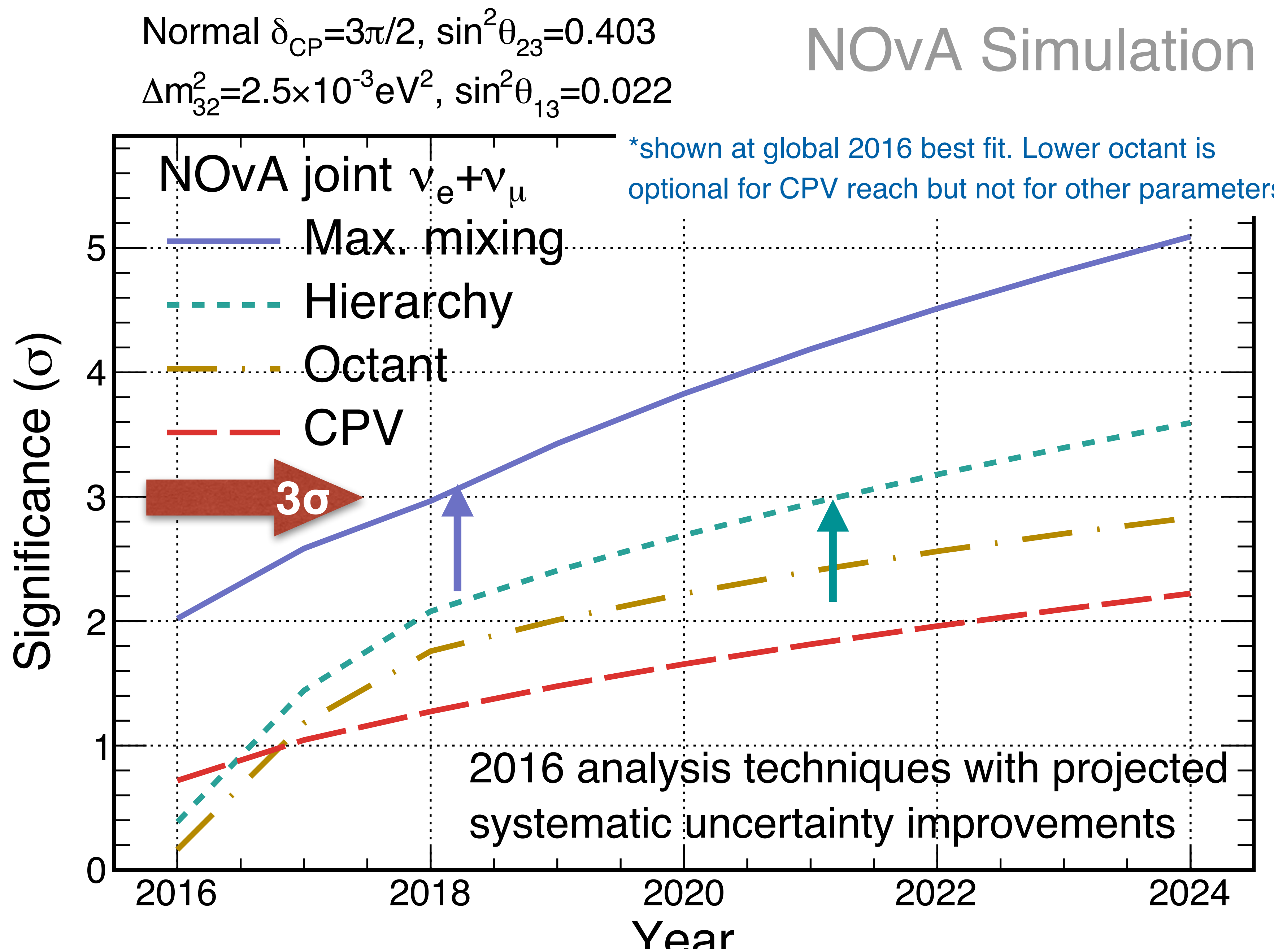
What can we learn from NOvA: current 700kW program

2018: 3σ on the max. mixing

2021: 3σ on the mass hierarchy
competition can have 3σ Mass Hierarchy reach in 2023 (ORCA), or 2022-2025 (JUNO)

2019: 2σ on the octant

2022: 2σ on CPV
T2K has proposed an extended run to get 3σ sigma evidence for CPV by 2024 and 2σ by 2021



NOvA close to T2K CP sensitivity until 2020, when T2K pulls ahead based on planned upgrades

Nominal NOvA running until 2021 but no technical conflict for running until ~2024

Extending NOvA's physics reach

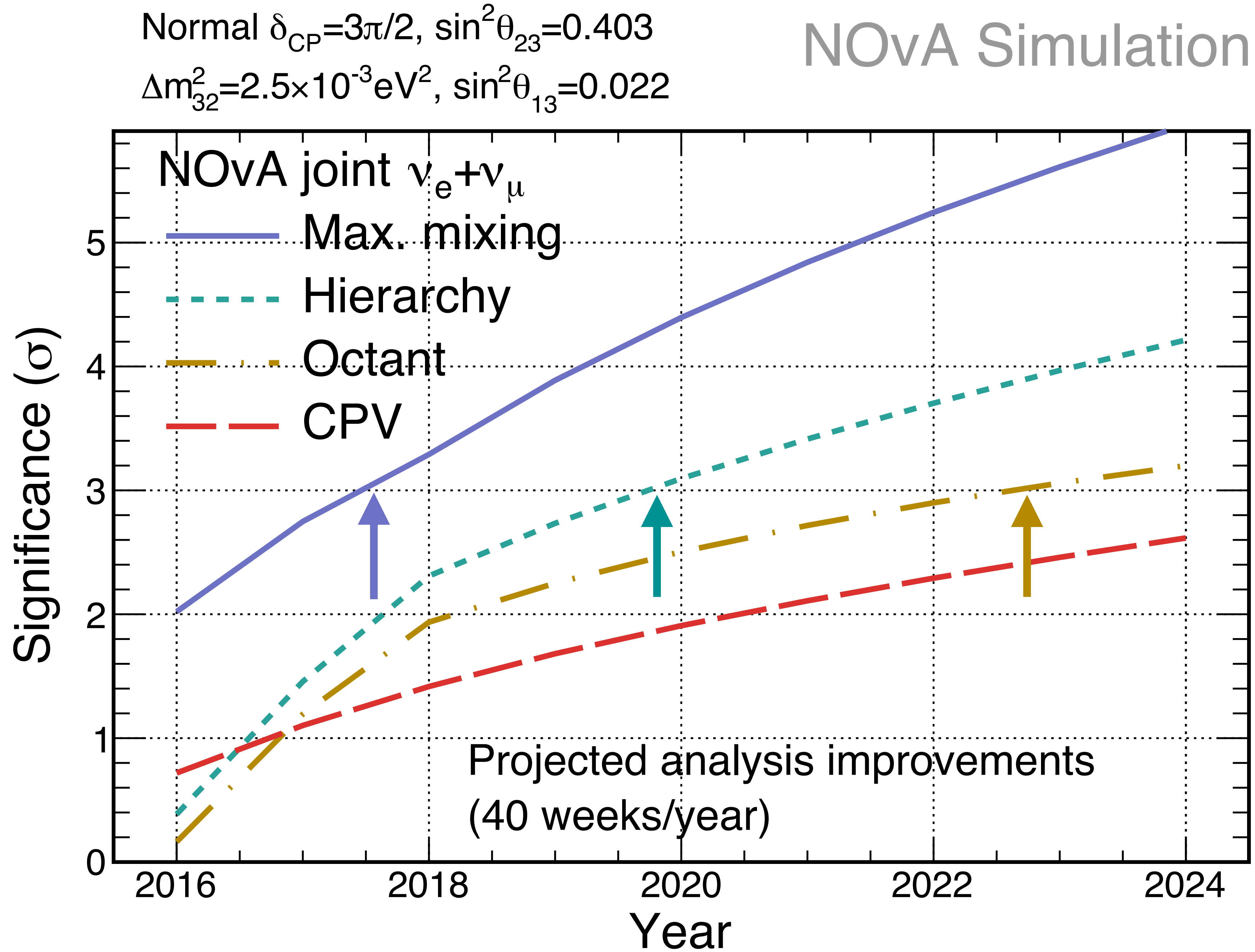
What we could learn from NOvA: current 700kW program with analysis improvements

2017: 3σ on the max. mixing
forward by 1 yr over nominal

2020: 3σ on the mass hierarchy
forward by 1 yr over nominal

2022: 3σ on the octant
now possible

2020: 2σ CPV
forward by ~2 yr over nominal



NOvA can remain competitive with T2K and beat ORCA/JUNO to the mass hierarchy, but upgrades are required.

Plus likely (25%) analysis improvements

What we could learn from NOvA: Extended Reach

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2022: 3σ on the octant
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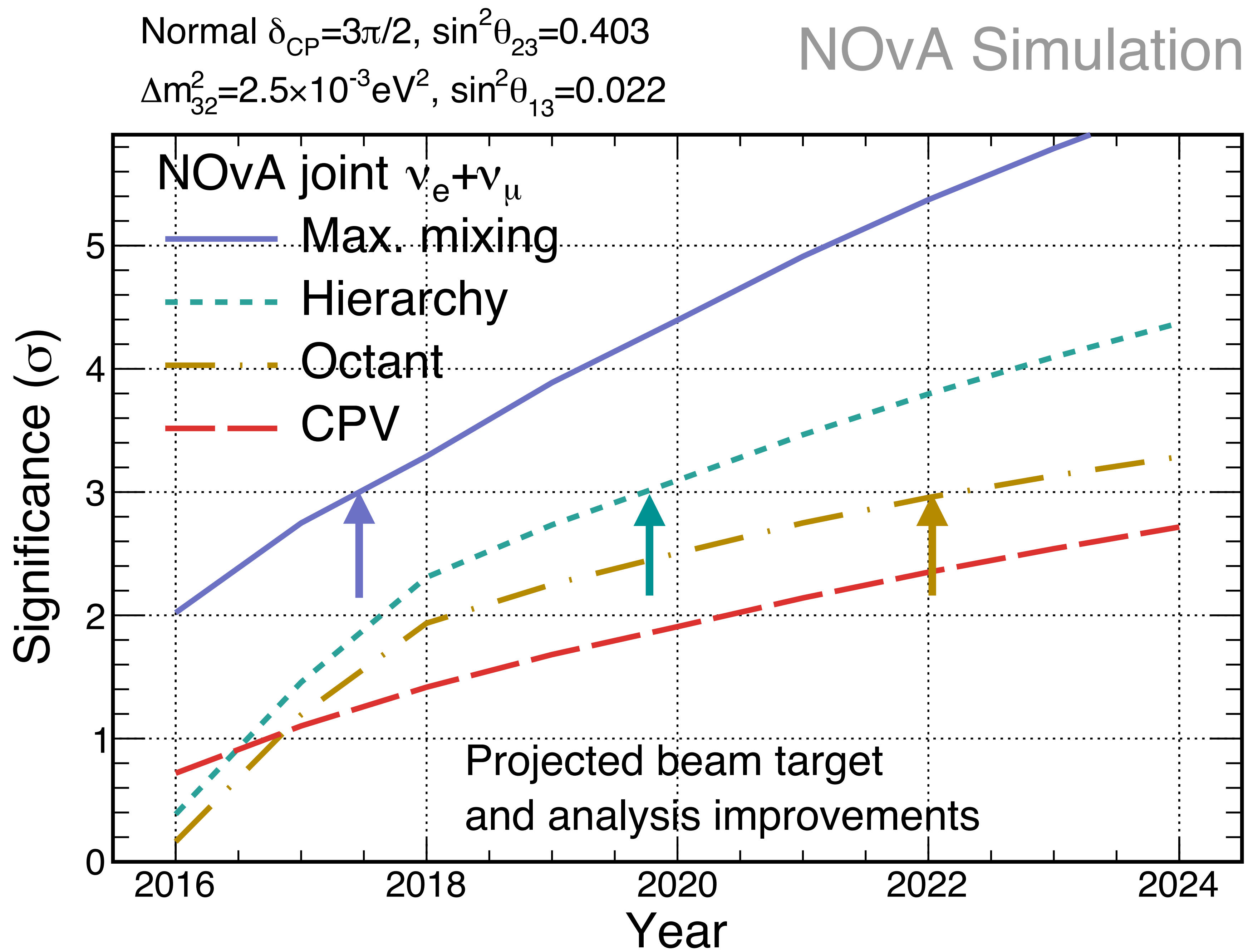

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New target design which extends into horn 1

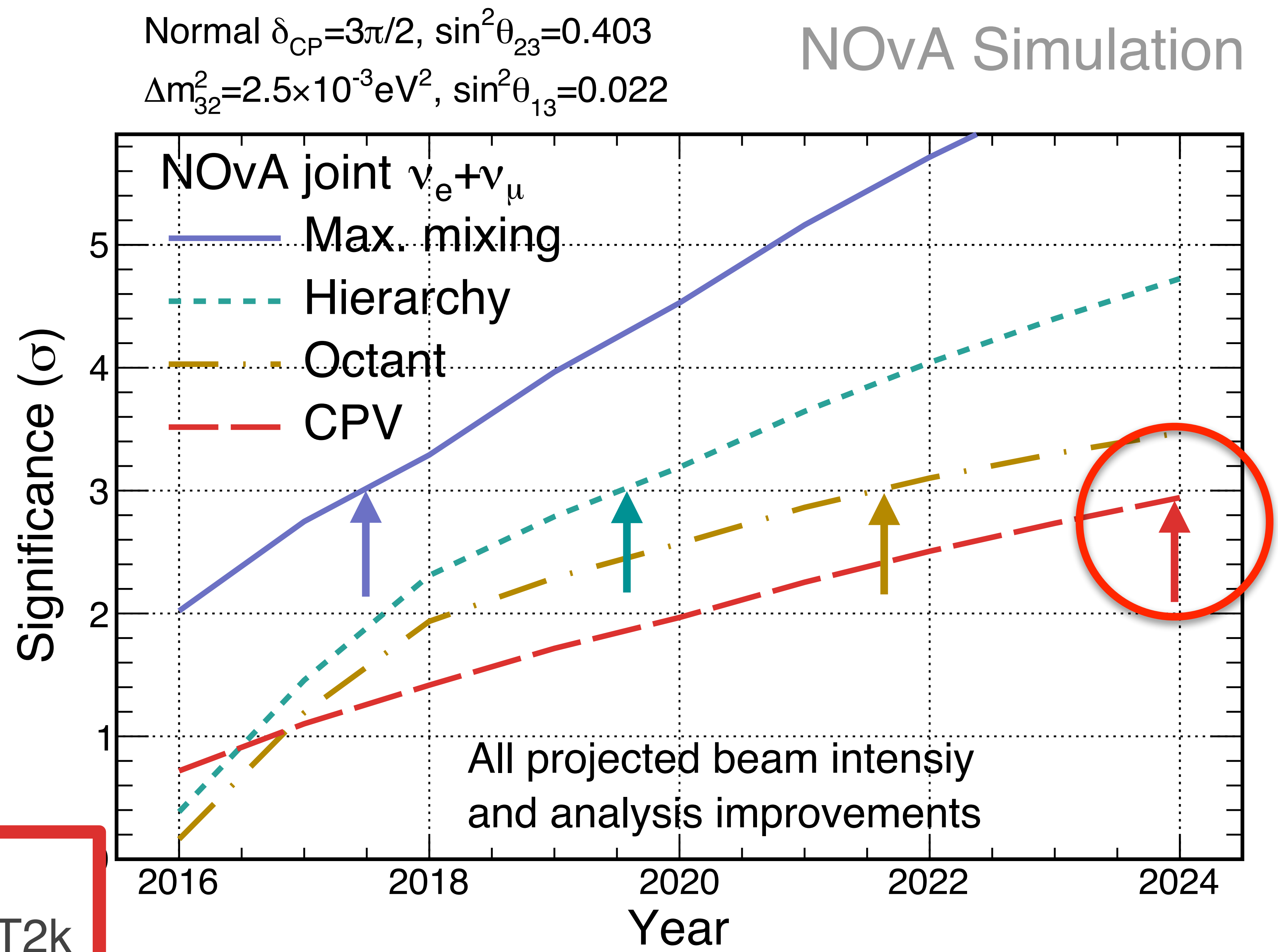
What we could learn from NOvA: Extended Reach

2017: 3σ on the max. mixing
forward by 1 yr over nominal

2019: 3σ on the mass hierarchy
forward by 2 yrs over nominal

2022: 3σ on the octant
possible now in 5 yrs

2024: 3σ CPV
can remain competitive with T2k



NOvA can remain competitive with T2K and beat ORCA/JUNO to the mass hierarchy, but upgrades are required.

Enable 3σ on octant and CPV and gain 1 yr on max. mixing and 3yrs on mass hierarchy

PIP1+, NuMI power ramp from 700kW to 900kW

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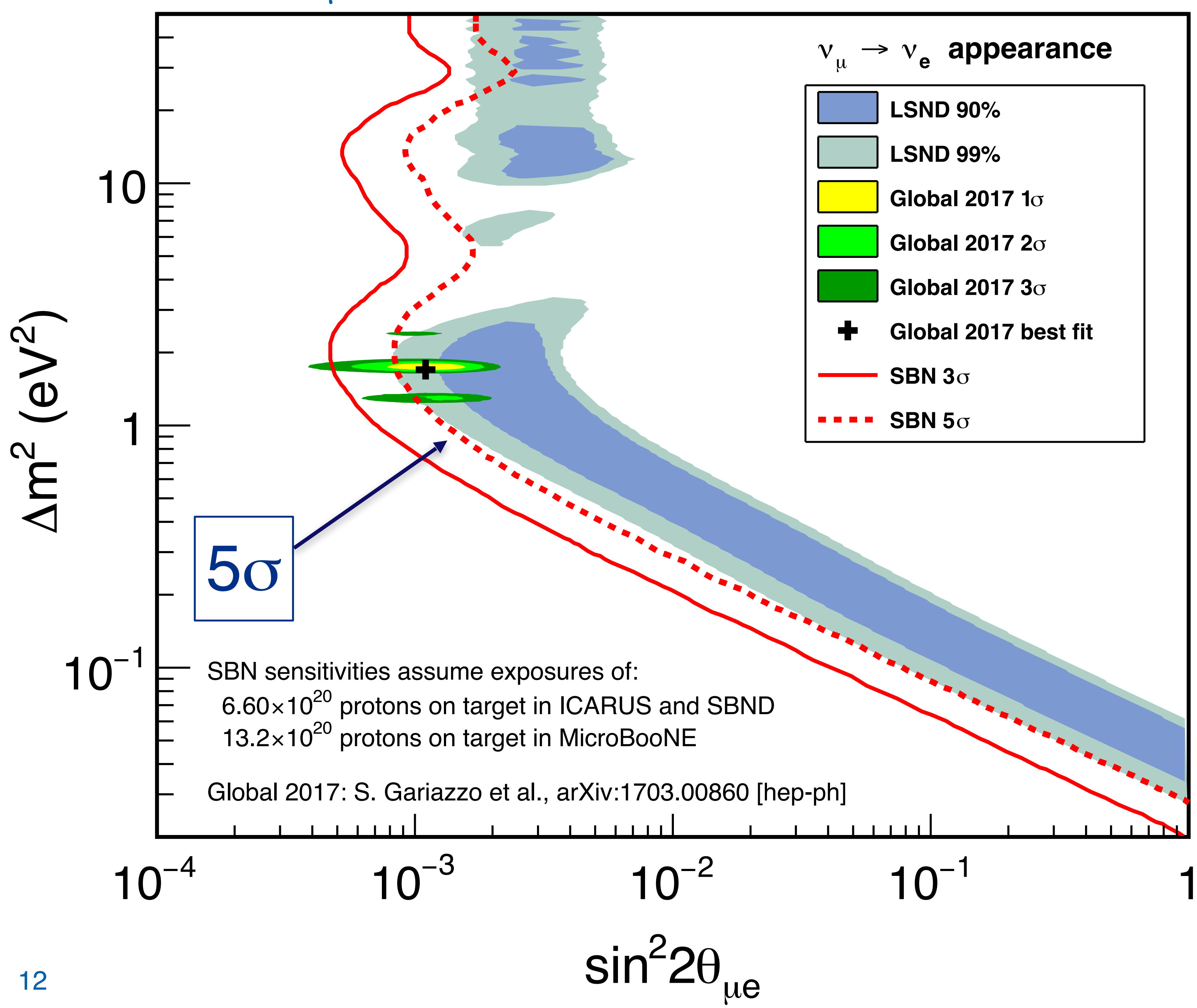
What we will learn from SBN?

What we will learn from SBN: Light Sterile neutrinos

Planning initial 3 SBN year run with MicroBooNE currently running, with ICURAS and SBND running on in next few years

SBN $\nu_\mu \rightarrow \nu_e$ Oscillation Sensitivity



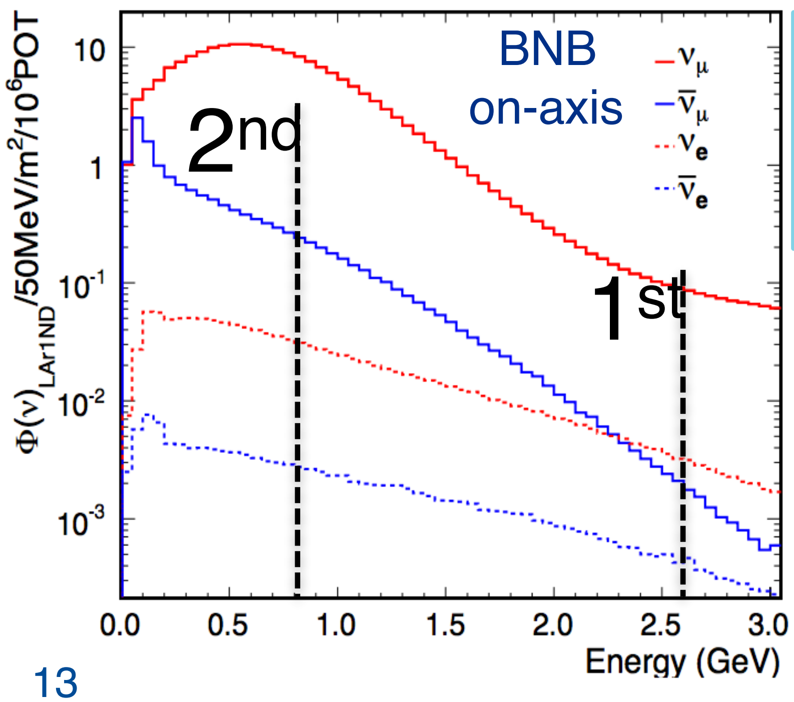
~2021: 5σ coverage of LSND allowed region

Outcomes depend on conclusiveness of ν_s search

What if SBN sees a signal?

- Keep SBN running to measure this signal?
- Build new detector in DUNE or Booster neutrinos lines to measure this signal?
- DUNE sensitivities will be significantly changed if there are additional neutrinos

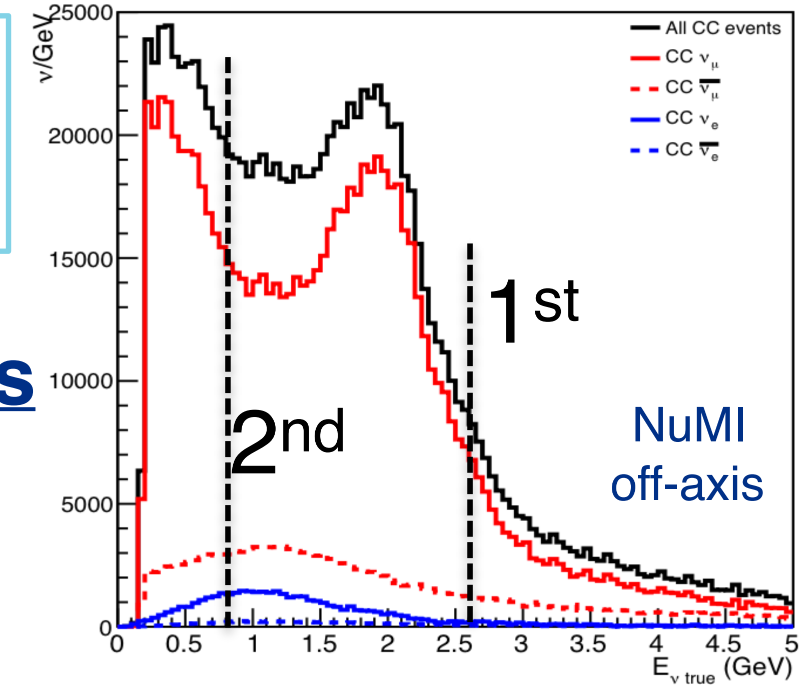
What we will learn from SBL: Neutrino Cross sections & LAr



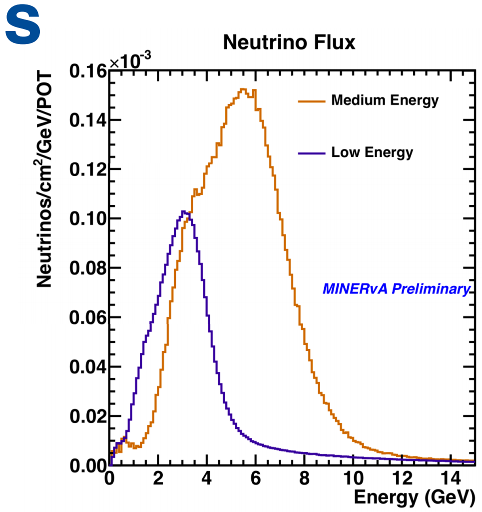
SBND: **1.5M** ν_μ CC/yr, **12k** ν_e CC/yr
+ low rate channels - e.g. coherent (10^4), strange prod (10^3), neutrino-electron (10^2)

Neutrino Interaction Physics

ICARUS: **10^5** NuMI off-axis evts/yr many at the DUNE 1st osc. max



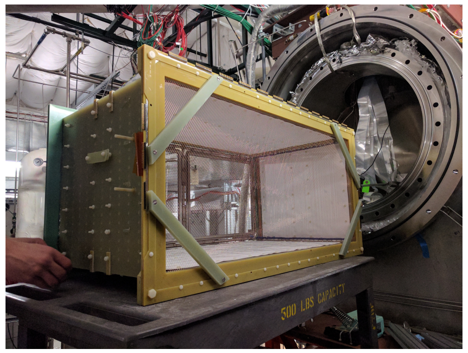
Minerva – Physics Goals



- Completing last Low-Energy Cross Section Measurements
  - Quasi-Elastic studies: double-diff, improved reco
  - ratios: Pb/CH, Fe/CH
- Current Medium-Energy Beam
  - Accumulated 3x exposure of LE neutrino mode dataset
  - Expect similar anti-neutrino exposure through FY18
  - Will be able to probe nuclear effect for several channels - Deep Inelastic Scattering

LArIAT – "the little cryostat that could"

- Run III has begun
  - Successful utilization of FTBF
- - R&D on detector parameters
  - TPC wire spacing
  - Light collection devices
  - Mesh cathode

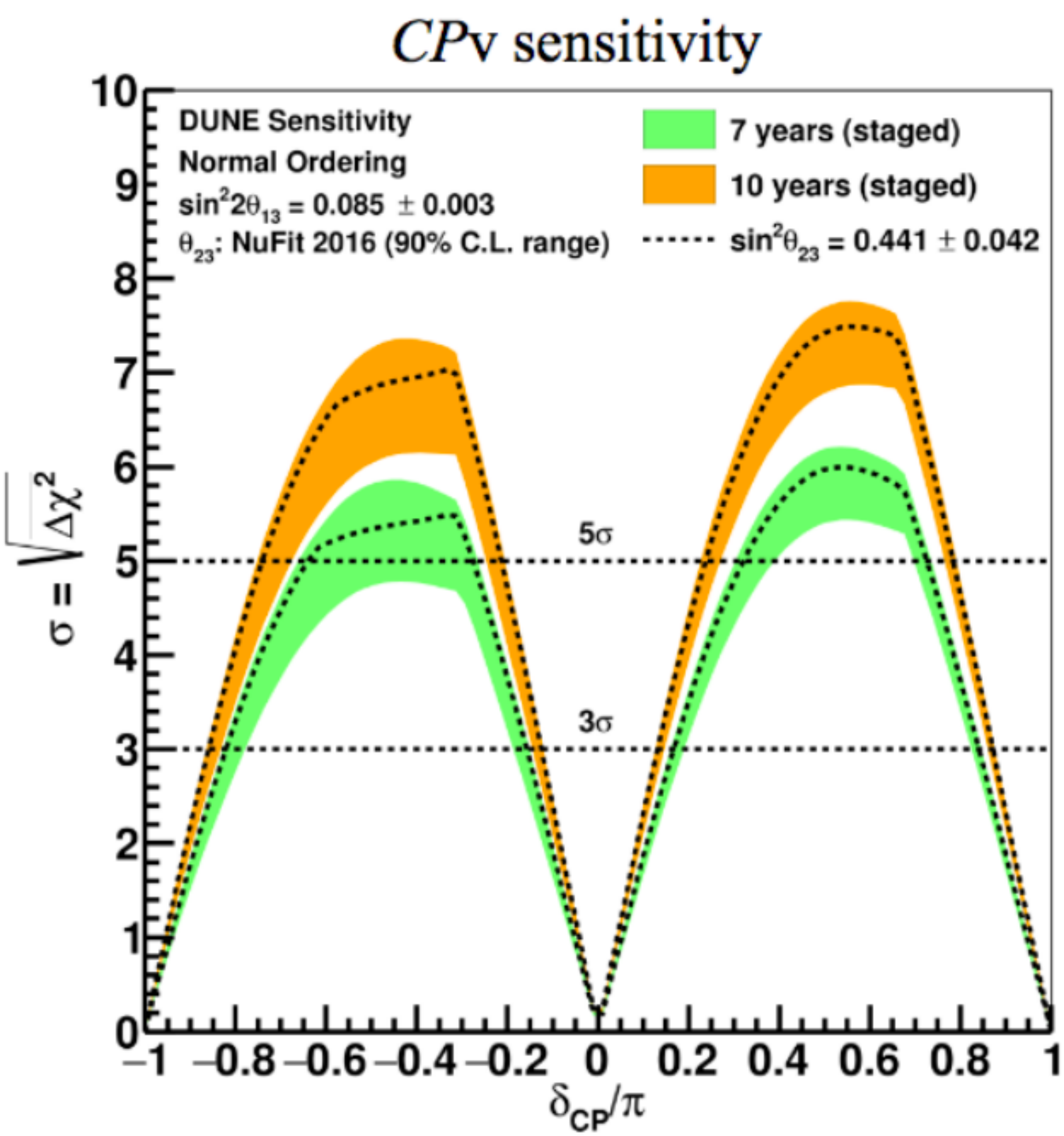


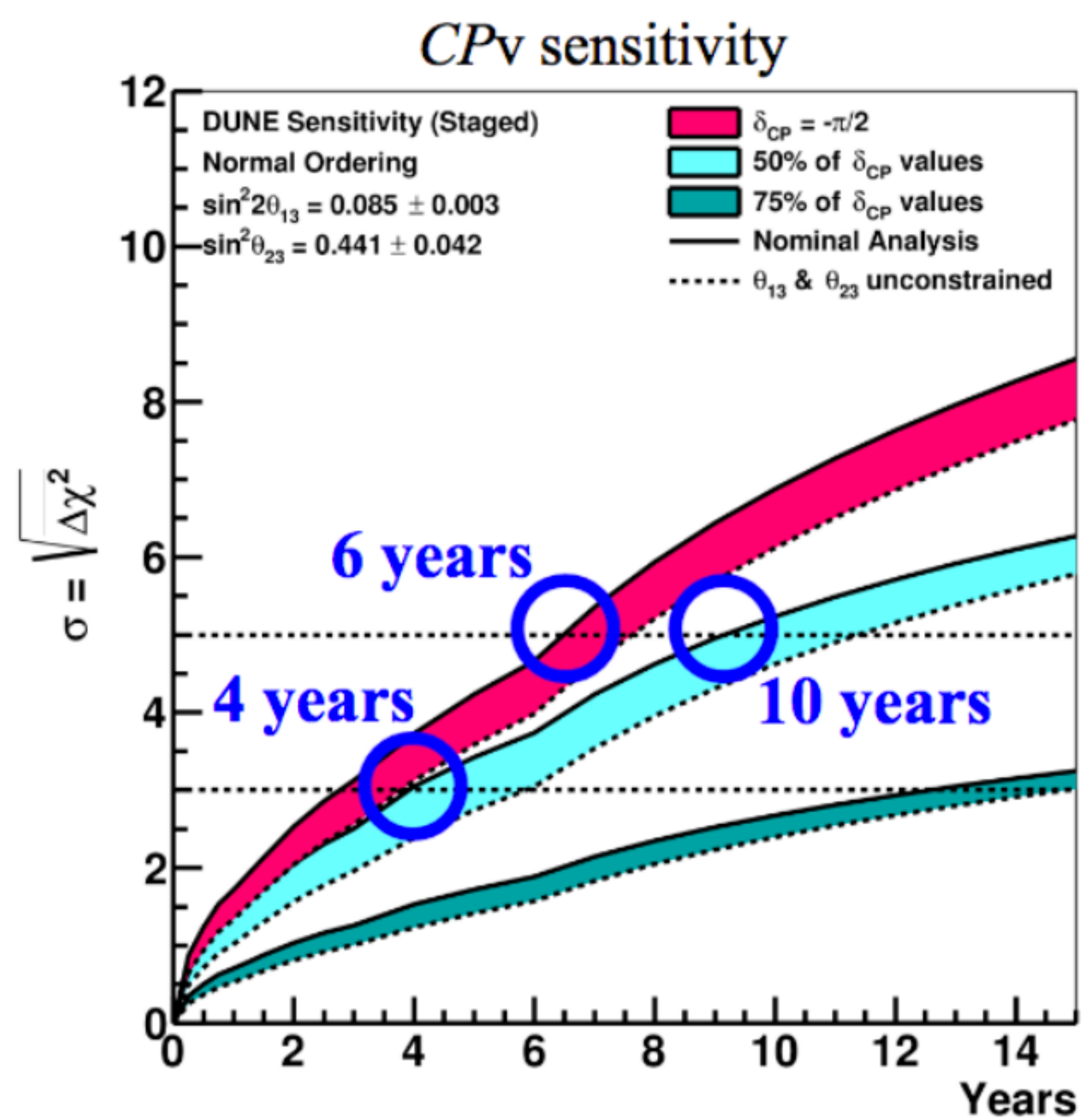
- Particle identification efficiency and separation
- Determine reconstruction eff and calorimetric resolution
- publications are on the way

What we will learn from DUNE?

What we will learn from DUNE: CP Violation

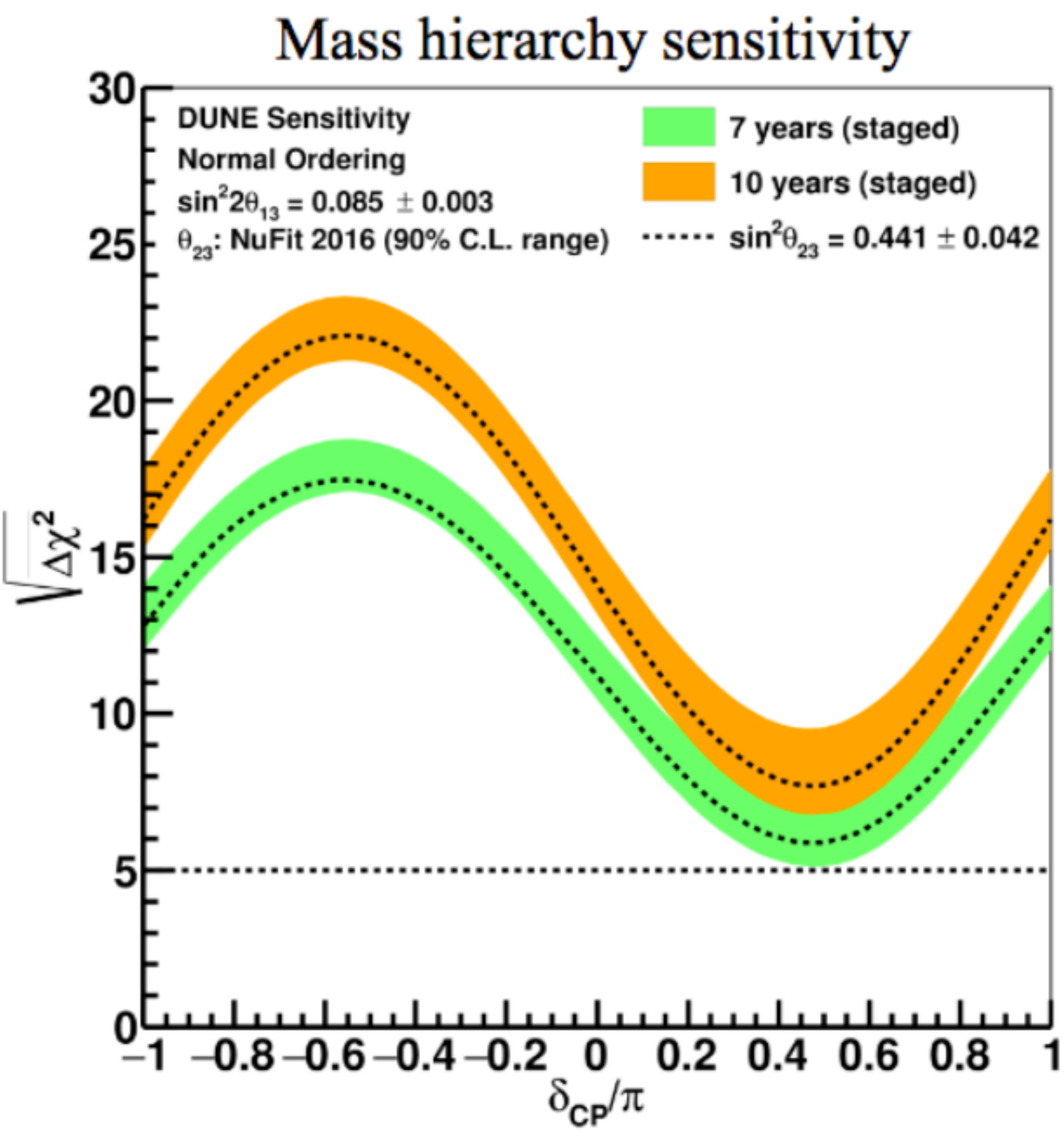
- 5σ at favorable δ within 7 years.
- 65% coverage at 3σ on similar timescale

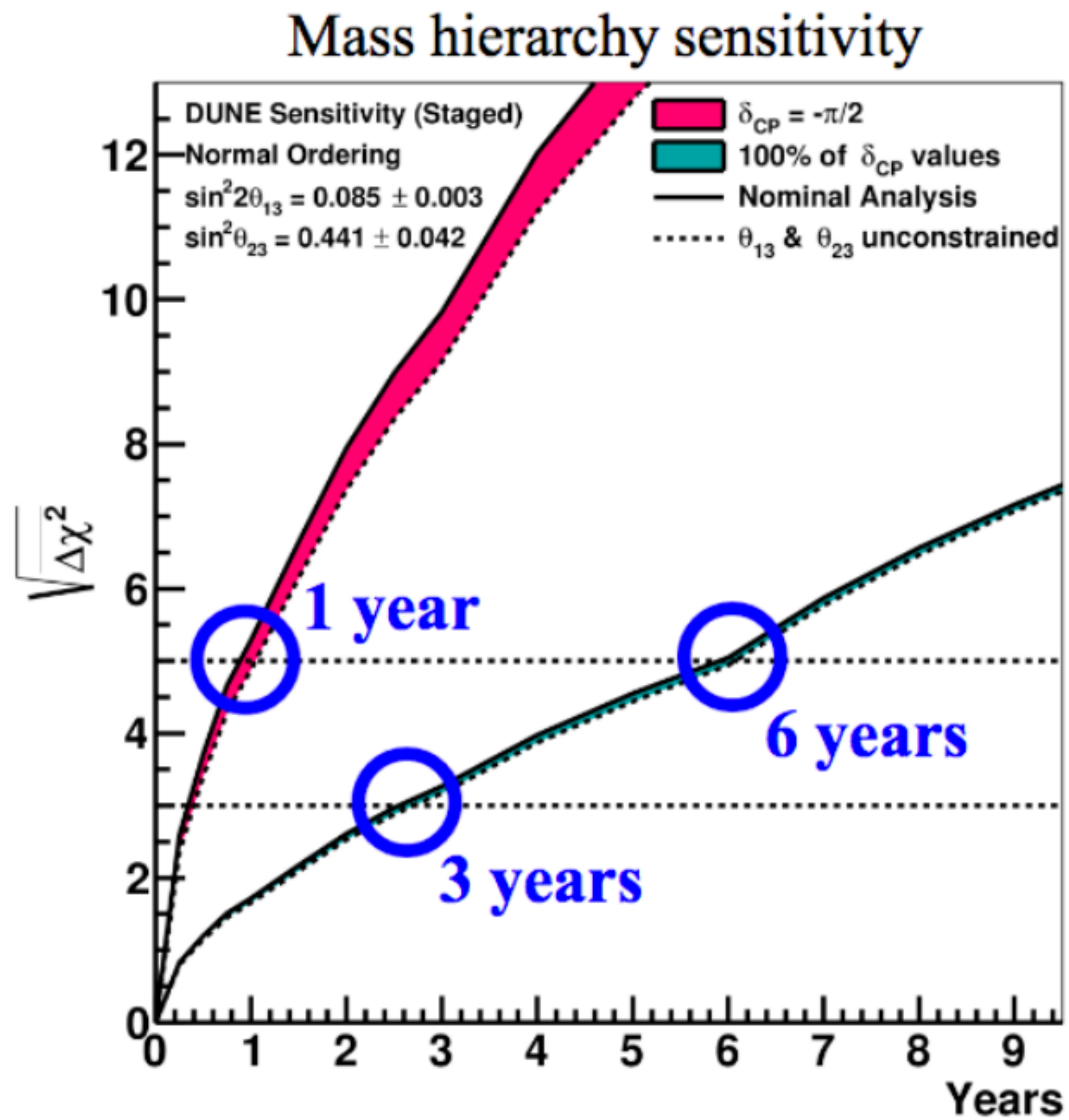




What we will learn from DUNE: Mass Hierarchy

- 5σ results as soon as 1 year if parameters are favorable.
- Complete coverage by year 6 independent of δ.





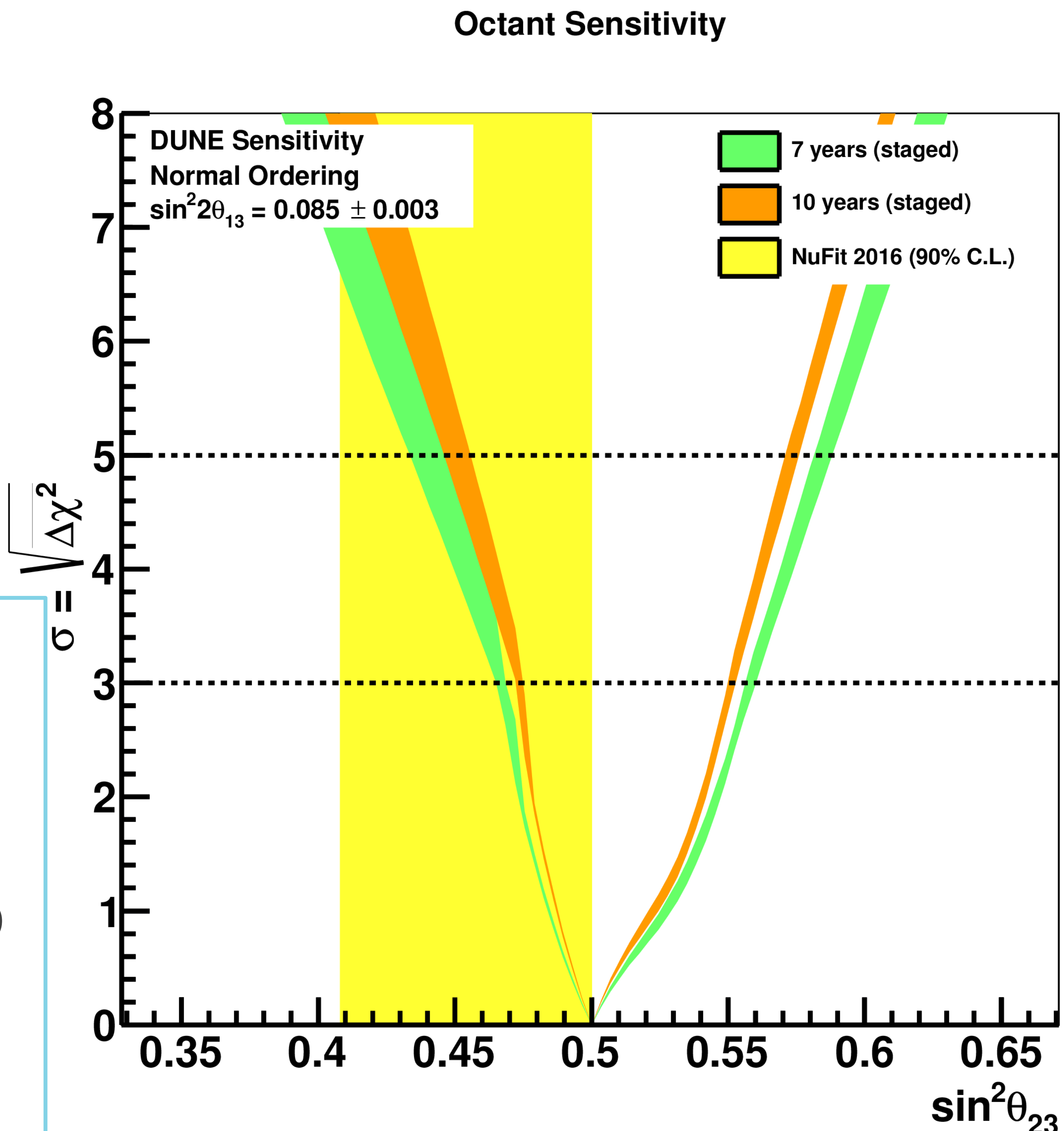
What we will learn from DUNE: Octant Determination

- For $\sin^2\theta_{23} < 0.43$ or $\sin^2\theta_{23} > 0.59$, can determine the octant to 5σ within 7 years.
- As approach $\sin^2\theta_{23} = 0.5$ value becomes harder to measure

Details of staging assumptions:

- Yr 0 (2026): 20-kt FD with 1.07 MW (80-GeV) beam and initial ND constraints
- Yr 1 (2027): 30-kt FD
- Yr 3 (2029): 40-kt FD and improved ND constraints
- Yr 6 (2032): upgrade to 2.14 MW (80-GeV) beam (technically limited schedule)

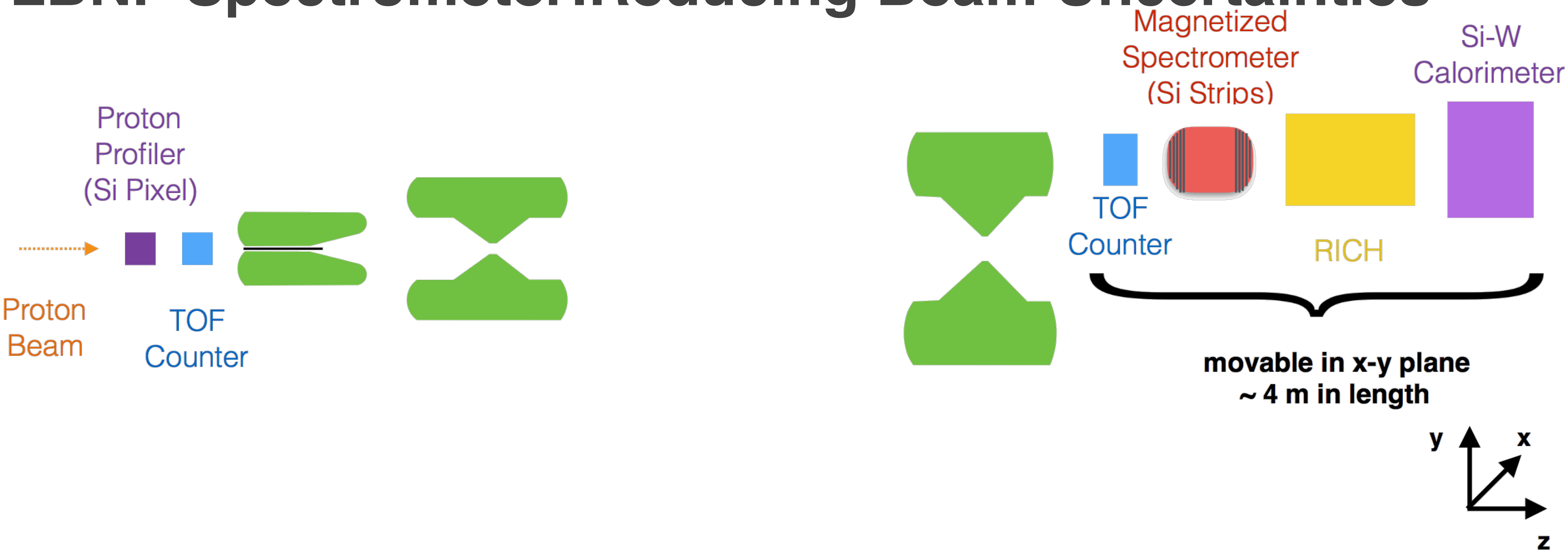
Exposure (kt-MW-years)	Exposure (Years)
171	5
300	7
556	10
984	15



What we will learn from DUNE:Broader program

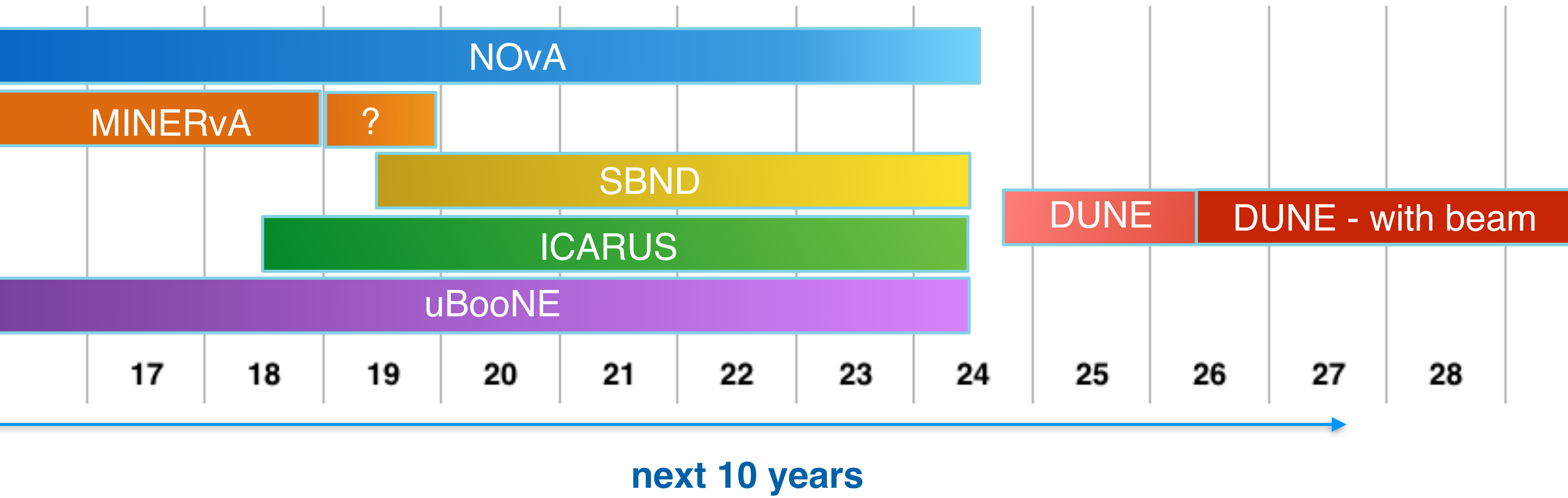
- Beyond just measuring angles, DUNE can to address the theory of flavor.
  - Making sufficiently precise measurements of the angles, octant, and hierarchy via multiple channels can provide guidance on the underlying symmetries
  - Take advantage of long-baseline, high energy to look for ν_τ appearance, possibly using a different beam tune.
- Measure Supernova neutrinos
  - DUNE at 10 kpc: ~3000 ν_e events over 10 seconds, potential for diffuse supernova discovery and ~20% rate measurement
- Look for Nucleon decay
  - A general prediction of grand unified theories,
  - LArTPC technology good for complex p-decay modes with final-state kaons, as favored by SUSY GUTs. Improve existing limits by one order of magnitude with 40 kton detector after 20 years.
- Also, light sterile neutrinos, non-standard interactions, dark matter
- Large sample in Near Detector for exploring ν-nucleus scattering: final state interactions, nuclear structure, MEC/2p2h channels, etc.

Proposal
LBNF Spectrometer:Reducing Beam Uncertainties



- DUNE will require unprecedented control of systematic uncertainties for a neutrino oscillation experiment.
- One large uncertainty arises from the neutrino flux.
- Proposal to build a spectrometer in the Fermilab test beam facility to measure the actual focused flux to high precision.
  - Requires a replica LBNF setup, made up of spare target, horns.
- Could take advantage of an upgraded test beam facility.

Looking forward next the 10 years and beyond



- The lab program for the next 10 years is quite set and DUNE will run for the following ~10 years
- Not shown, R&D work for DUNE and beam complex improvements, Spectrometer
- Cannot run NuMI and LBNF beam line at the same time, some components will be recycled for the LBNF beam

Looking beyond the current program

- What is the best use of the Booster neutrino beam and detectors after SBN?
  - Running anti-neutrino beam
  - In case of discovery: More precision sterile neutrino measurements using same or upgraded facilities
  - Precision cross section measurements
    - Higher momentum transfer measurements on argon are currently lacking
  - Other uses of beam and detectors, i.e looking for dark matter with beam dump running, etc.

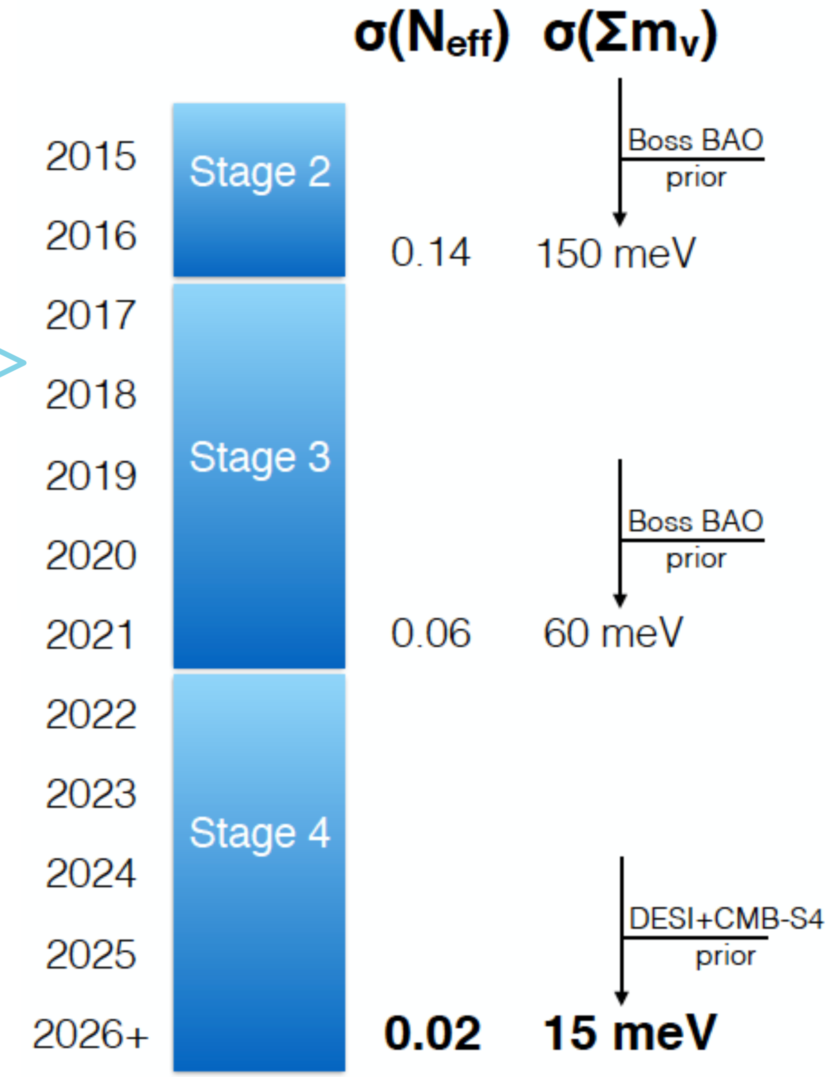
- Where do we want to go after DUNE?
  - Depends on if questions DUNE set out to answer have been answered,
  - SBN ruling out sterile neutrinos will make it clearer how likely that will be

- What will be the unanswered questions at the end of DUNE?
  - Assuming no sterile neutrinos or other non-standard interactions we **will know** the **Mass Hierarchy,** likely know the **CP phase, and $\sin^2\theta_{23}$** if far enough away from maximal. We will have a better, if not complete understanding of unitarity of PMNS matrix
  - From DUNE we will still not know; if neutrinos are Majorana or Dirac; the masses of the three neutrino states

Working with others: Cosmic Frontier

Future (~10 years) experiments (CMB-S4, DESI, LSST), expect factor of several improvements in cosmological constraints

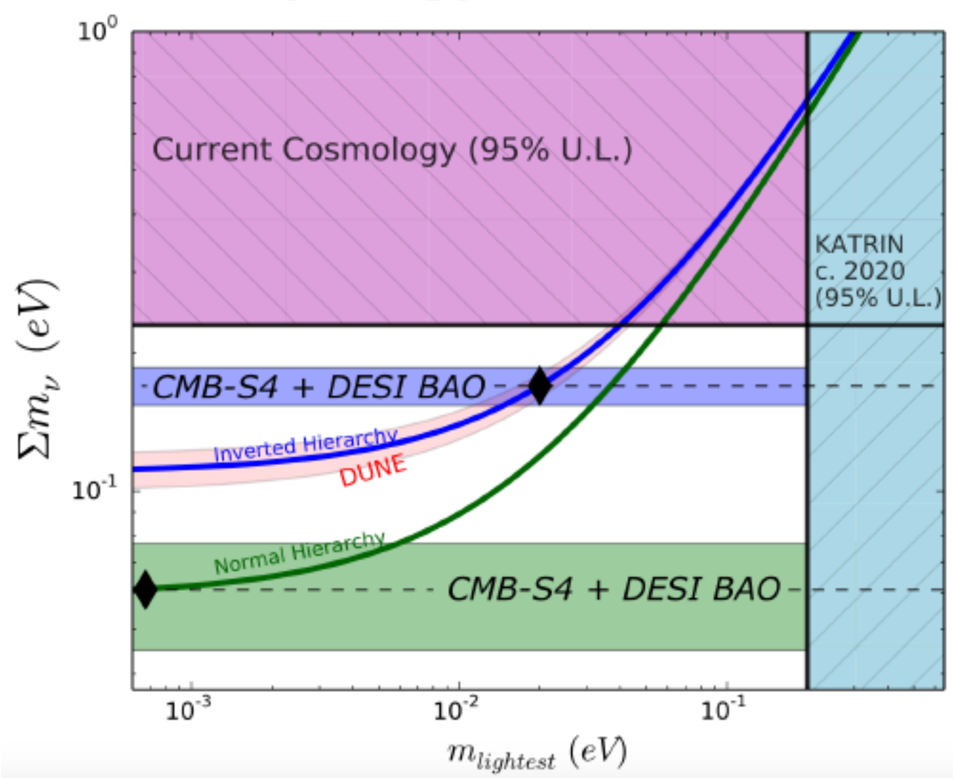
- Sum of the neutrino masses (Σm_ν)
- Relativistic energy density: Typically re-defined as the effective number of relativistic species (Neff)



For normal neutrino mass ordering, with an example case marked as diamond on the lower curve, CMB-S4 would detect the lowest Σm_ν at >3σ.

Also shown is the sensitivity DUNE as the pink shaded band, which should be sensitive to the neutrino hierarchy.

Synergy with DUNE



Scenario	$m_{\beta\beta}$	m_β	$\sum m_\nu$	$\Delta N_{\rm eff}$	Conclusion
Normal hierarchy	$< 2\sigma$	$< 2\sigma$	60 meV	0	Normal neutrino physics; no evidence for BSM
Dirac Neutrinos	$< 2\sigma$	$< 2\sigma$	350 meV	0	Neutrino is a Dirac particle
Sterile Neutrino	$< 2\sigma$	$< 2\sigma$	350 meV	> 0	Detection of sterile neutrino consistent with short-baseline

Compare measurement of Majorcan mass via NLDBD with kinematic endpoint, with the cosmogenic mass measurement and CMB N_{eff}

Working with others: Theory

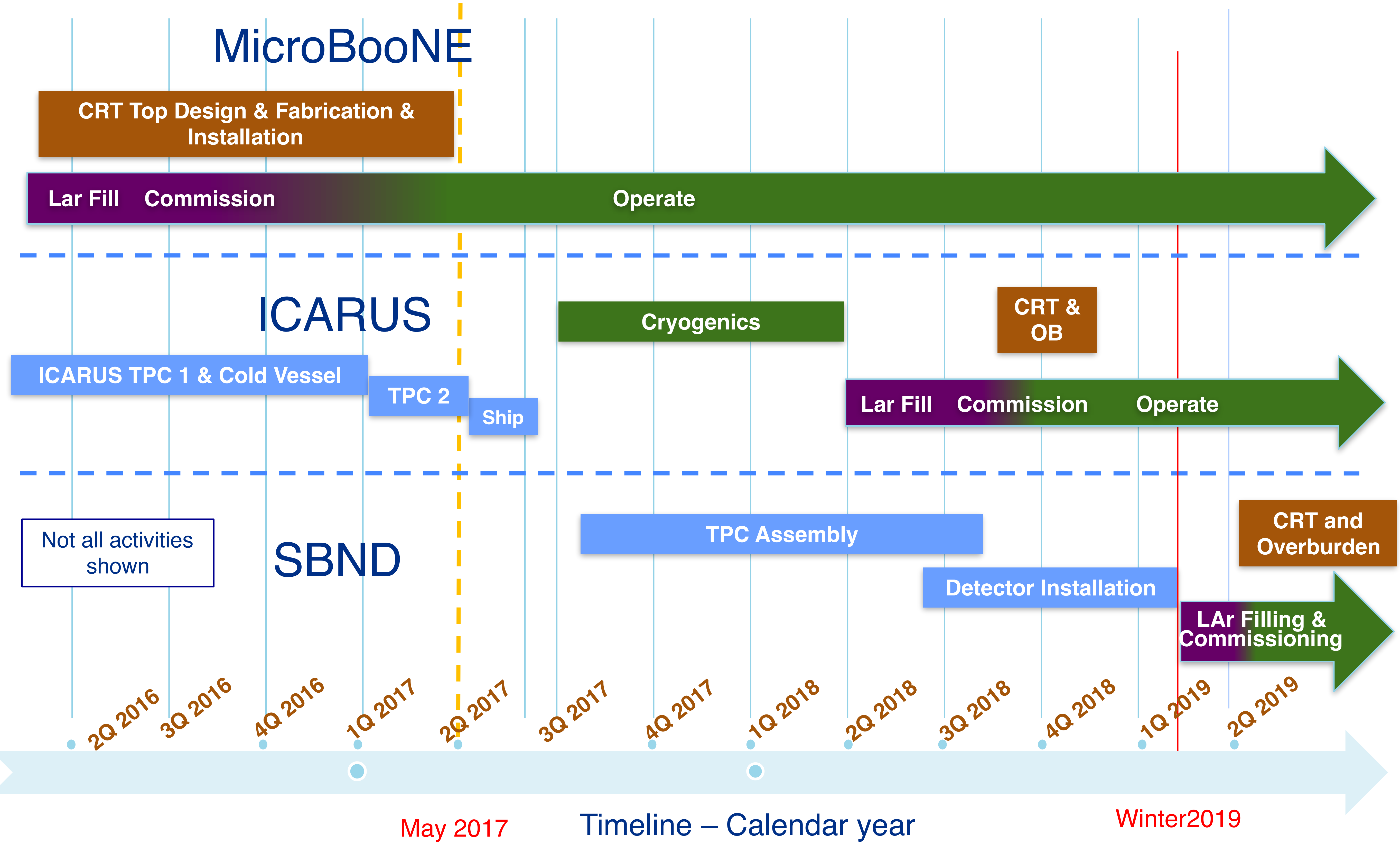
- What are the most important questions to our theory colleagues?
  - Is the 3x3 PMNS mixing matrix the whole story, are there additional neutrinos or other 'Non-standard' interactions?
  - Determining the octant is important for model building. Is there a symmetry there or not?
  - For values of θ_{23} close to maximal DUNE may not measure octant
  - Important to test the three flavor paradigm

- DUNE will require unprecedented control of systematic uncertainties for a neutrino oscillation experiment.
  - Important to exploit HEP expertise for QCD and neutrino interactions: radiative corrections, lattice QCD, propagation of uncertainties in near/far detectors and impact on oscillation analyses
  - Also important to engage with the nuclear community: parameterize and constrain nuclear effects

- Need support structure to feedback cross section measurements into generators
  - Infrastructure for this coming into place

Backup

Short Baseline Neutrino Timeline (Dec 2016)



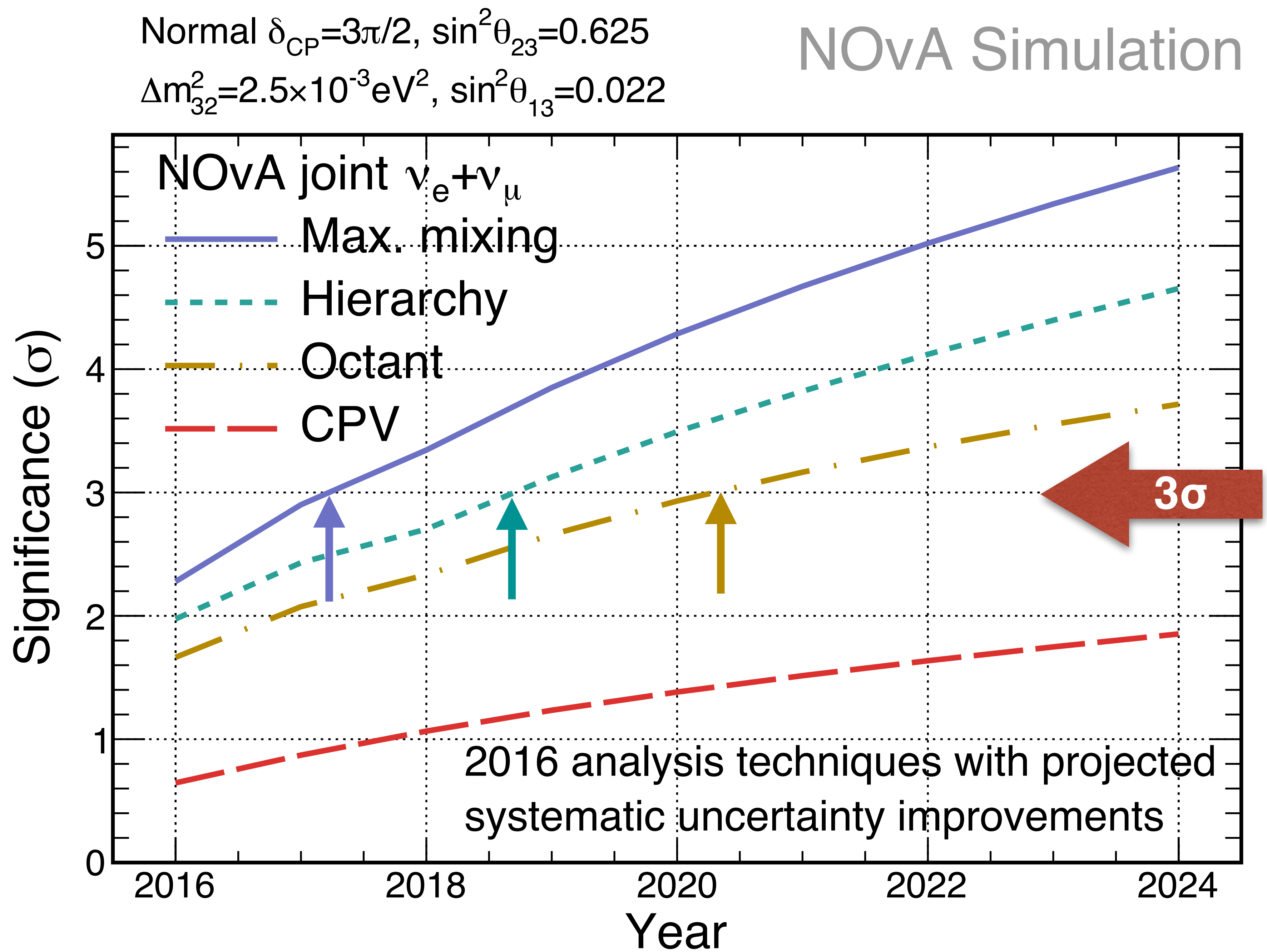
What can we learn from NOvA: current 700kW program

2017: 3σ on the max. mixing

2019: 3σ on the mass hierarchy
ORCA, JUNO both under construction, expect 3σ Mass Hierarchy reach in 2022

2020: 3σ on the octant
T2K close to NOvA δCP sensitivity until 2020, then pulls ahead due to beam & analysis upgrades

2018: 1σ CPV, never 2σ



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What we could learn from NOvA: Extended Reach

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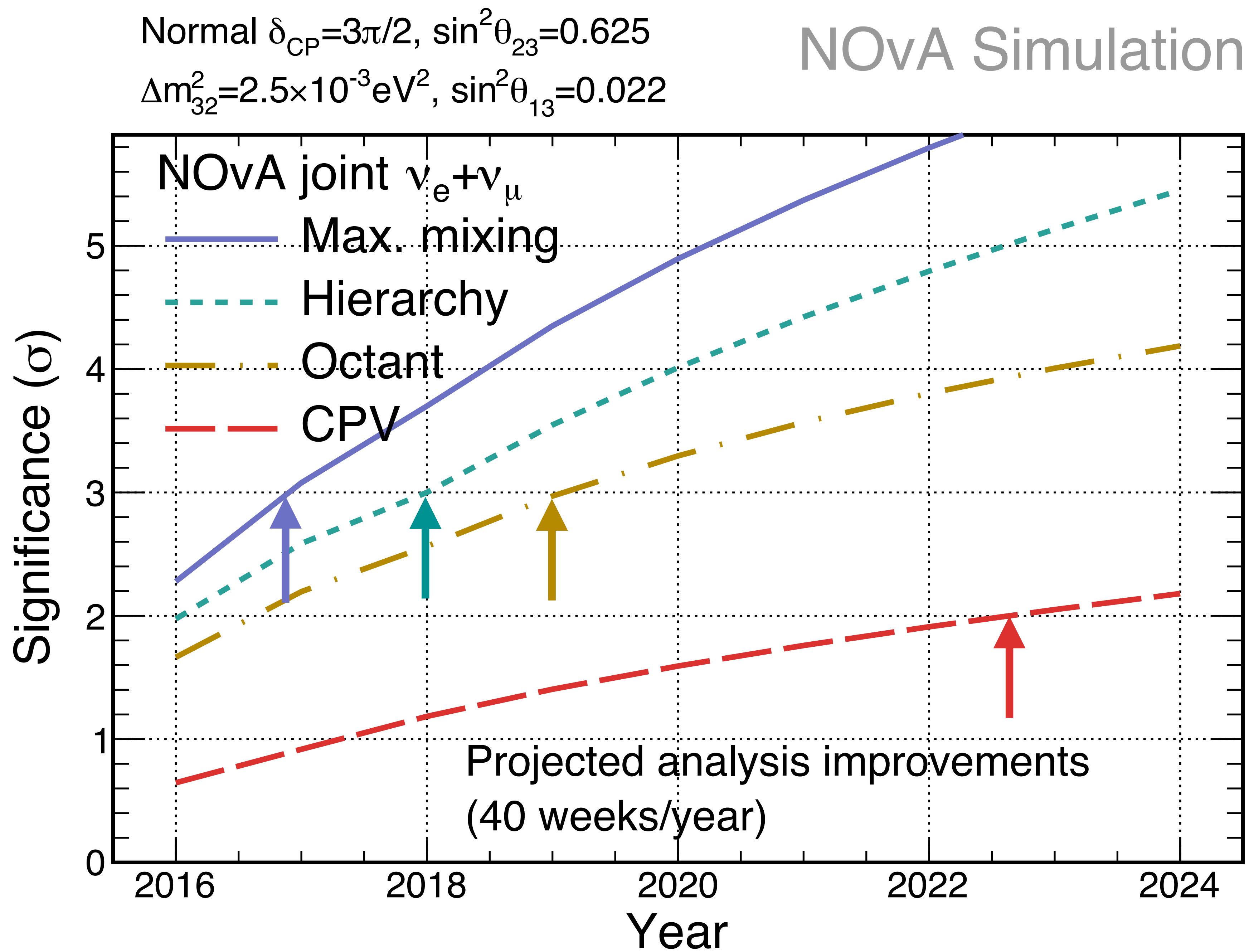
2019: 3σ on the octant

2022: 2σ CPV
T2K 3σ CPV sensitivity with 20×10^{21} by 2026. Requires analysis and hardware upgrades

Plus likely (20%) analysis improvements



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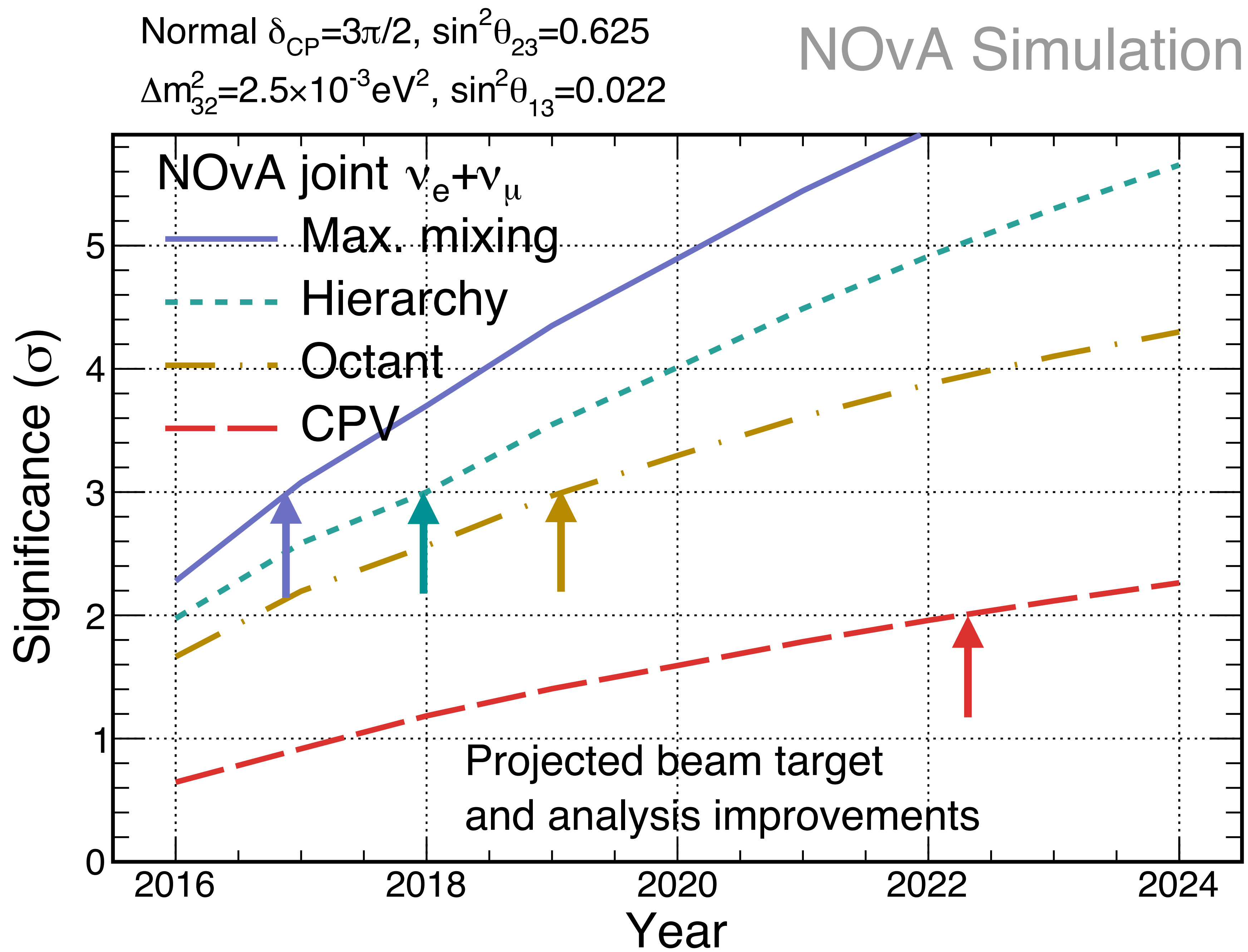

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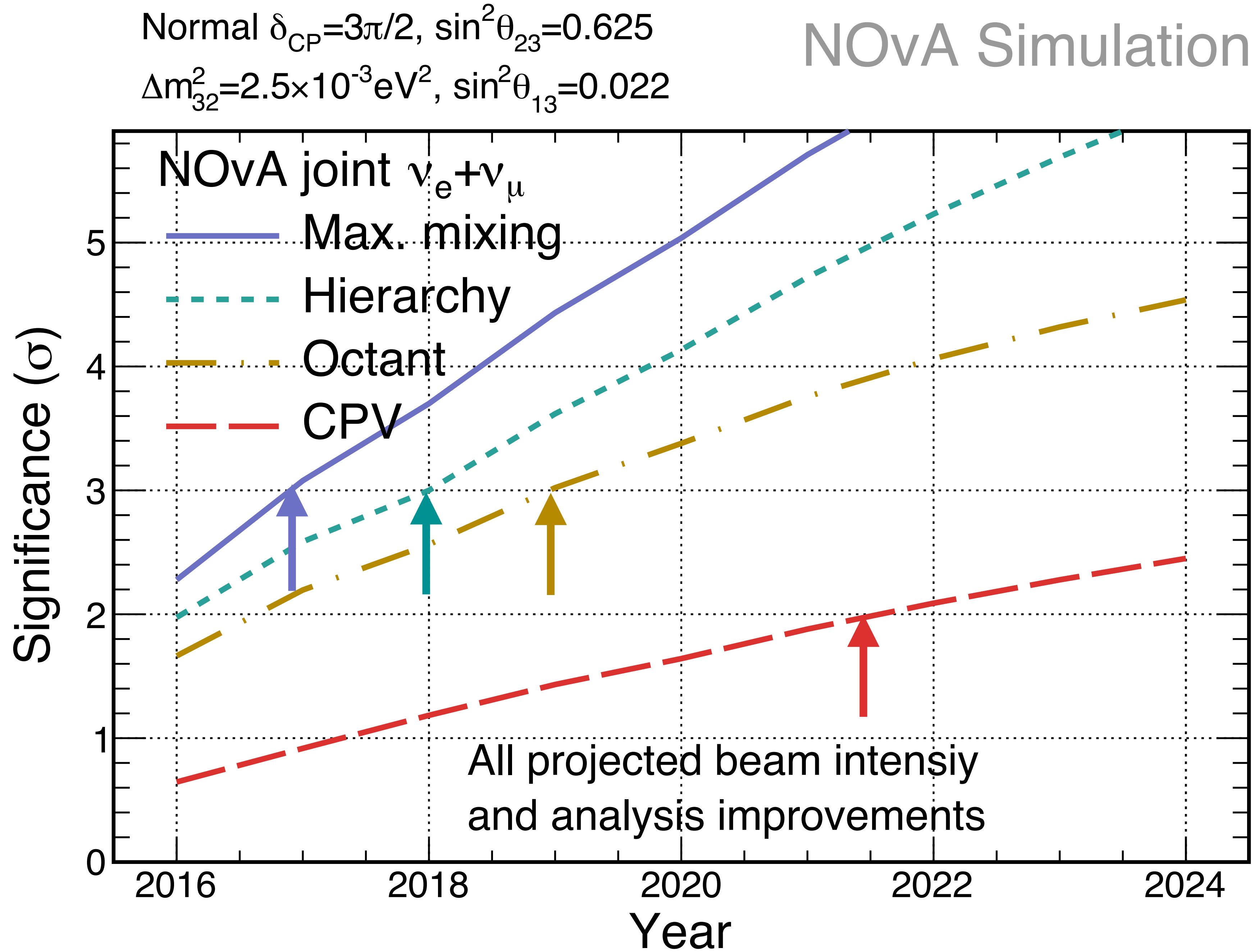

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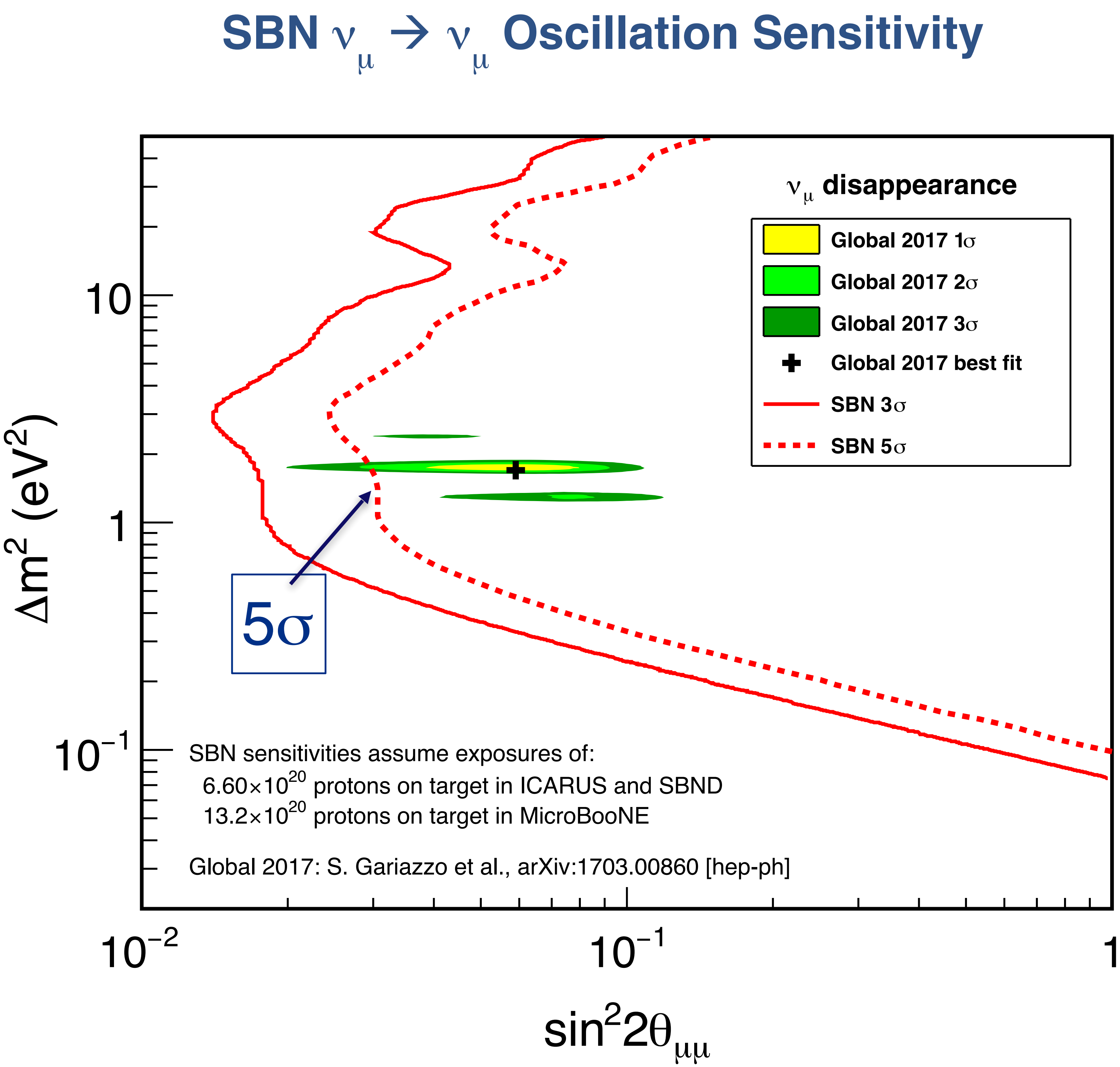
PIP1+, NuMI power ramp from 700kW to 900kW

What we will learn from SBN

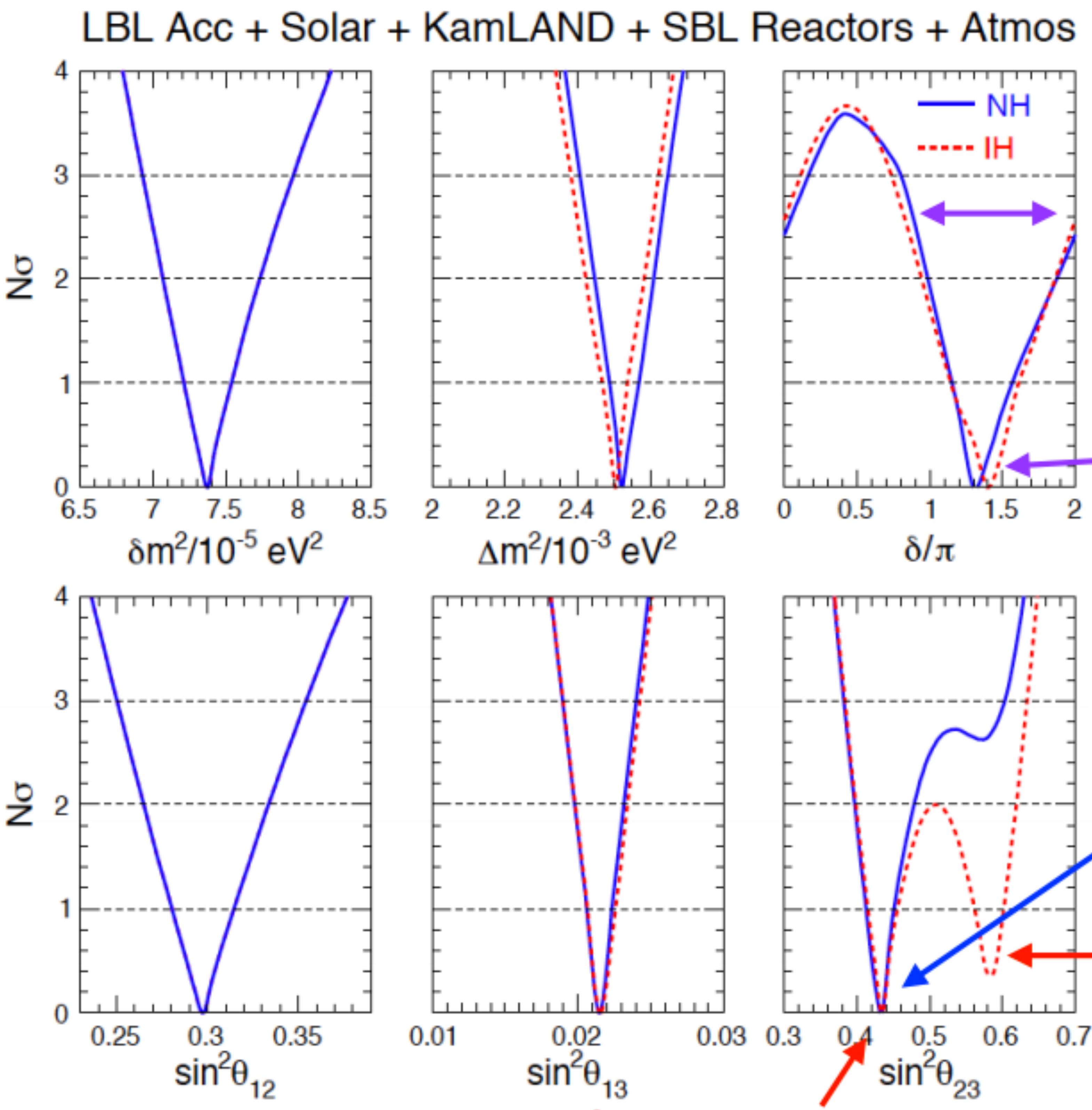
~2021: 5σ coverage of LSND allowed region



Two outcomes either sees evidence for ν_s or not

What if SBN sees a signal?

- Keep SBN running to measure this signal?
- Build new detector in DUNE or Booster neutrinos lines to measure this signal?
- DUNE sensitivities will be significantly changed if there are additional neutrinos



Still a wide range of possibilities open

Interesting trend to see large-as-possible CP violation

Preference for non-maximal mixing driven by NOvA's recent results

Preference for normal hierarchy and lower octant

Upper octant and inverted hierarchy is a viable solution

$\Delta\chi^2$=3.7 above normal hierarchy (suppressed in plot)

Post Neutrino2016 "global picture"

Francesco Capozzi (Lisi et al.) reporting at NOW2016