NOvA & T2K:

15(ish) years of 3-flavor oscillations

what have we learned? (personal reflections)

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Preliminaries

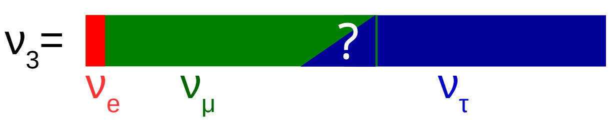
- JW: reluctant biographer?
  - Both experiments were proposed (T2K: 2001, NOvA: 2002) while I was a high-schooler, and started taking FD data (2010, 2014) while I was a PhD student working on a standalone neutrino interaction experiment
  - I haven't made much effort to interview the collaborations for historical completeness–I rely mostly on public info for stuff that predates me
  - Some of you have been members of T2K longer than I've been a physicist and can correct the record on that side, as needed :)
- My goal is to highlight **through-lines in the experiments' experience of 3-flavor oscillations** relating to cross sections, to stimulate discussion
  - What important decisions have shaped their scientific output?
  - What obstacles have been overcome?

Physics aims

Goals (as we see them today):

the "big 3" PMNS questions*

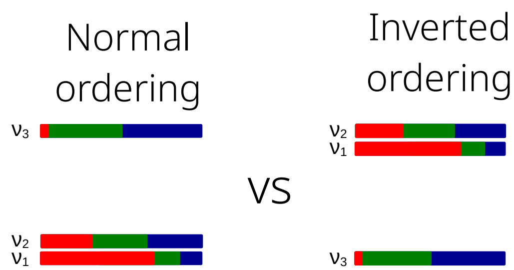
①



Is θ_{23} = 45°?

Do ν_μ/ν_τ **mix equally into** ν_3?

"the octant"



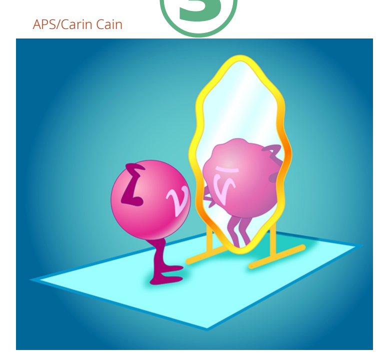
Which way are the **neutrino mass states ordered**?

②

"the ordering"

(or "hierarchy")

③



$$\Delta P_{\nu\bar{\nu}} \propto \sin\delta_{CP}$$

Do neutrinos exhibit **CP violation**?

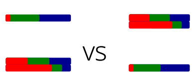
"the asymmetry" (?)

* restricting to "standard," 3-flavor PMNS oscillations.
Even in the proposals for these experiments in early 2000s, sterile νs and tests of CPT were seen as questions they might address, but I won't delve into them today.

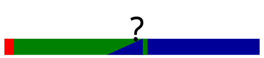
Physics aims

ν_μ disappearance

$$P_{\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu} \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\Delta m^2_{32} \frac{L}{4E}\right)$$

① 

→ Δm^2_{32}

② 

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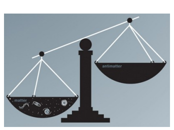
③ 
→ δ_{CP}

ν_e appearance

$$P_{\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e} \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \frac{(A-1)\Delta}{(A-1)^2}$$
$$+ 2\alpha \sin\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}$$
$$\times \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1} \sin\Delta$$
$$\times (\cos\delta_{CP} \cos\Delta \mp \sin\delta_{CP} \sin\Delta)$$

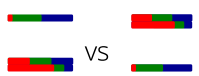
$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \qquad \Delta = \Delta m^2_{31} \frac{L}{4E} \qquad A = \mp G_f N_e \frac{L}{\sqrt{2}\Delta}$$

The observables have complex trigonometric dependence on the parameters…

Physics aims

ν_μ disappearance

$$P_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu} \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\Delta m^2_{32} \frac{1}{4} \frac{L}{E}\right)$$

① 

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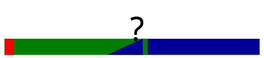
② 

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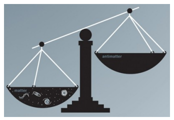
③ 
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$$\times \left(\cos\delta_{CP} \cos\Delta \mp \sin\delta_{CP} \sin\Delta\right)$$

$\sim\left(\frac{L}{E} - L\right)^2$ $\quad$ $\sim\frac{L}{E} - L$ $\quad$ $\sim\frac{L}{E}$

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \qquad \Delta = \Delta m^2_{31} \frac{1}{4} \frac{L}{E} \qquad A = \mp G_f N_e \frac{L}{\sqrt{2}\Delta}$$

… but L/E is the independent variable that matters the most

Why do it twice?

Far detectors are super expensive.
T2K's existed already before the experiment was proposed.
Q: Why do this experiment twice?

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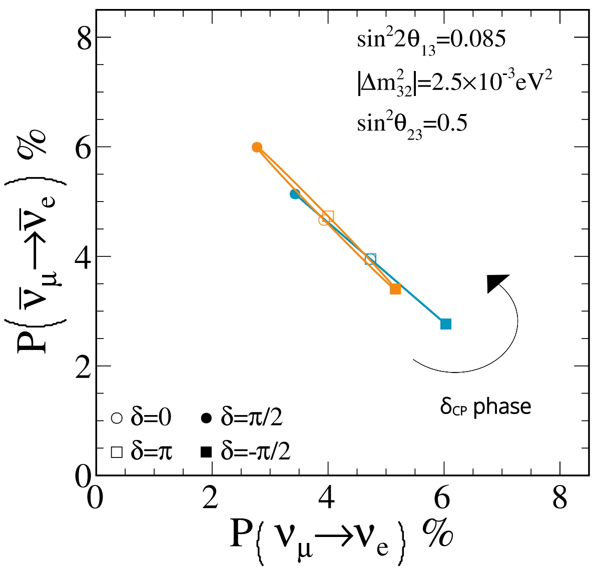
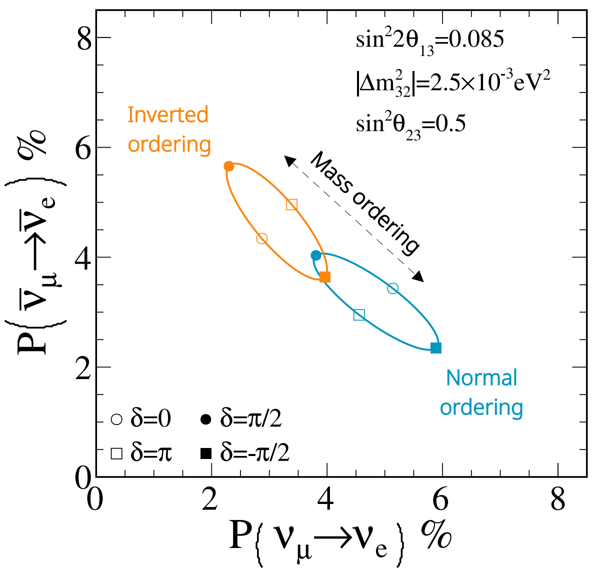
T2K: L=295 km, E=0.6 GeV



NOvA: L=810 km, E=2.0 GeV



Matter effects depend on E, not L/E

① **so mass ordering "interference" with δ_{CP} is different**

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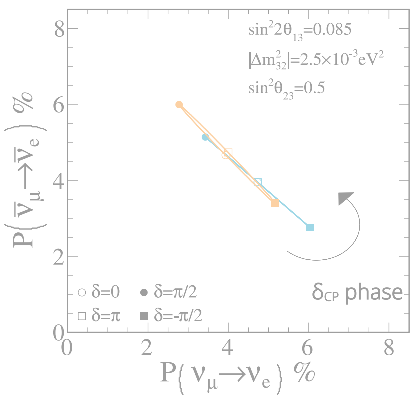

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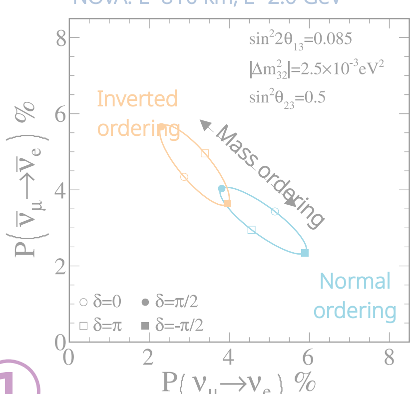

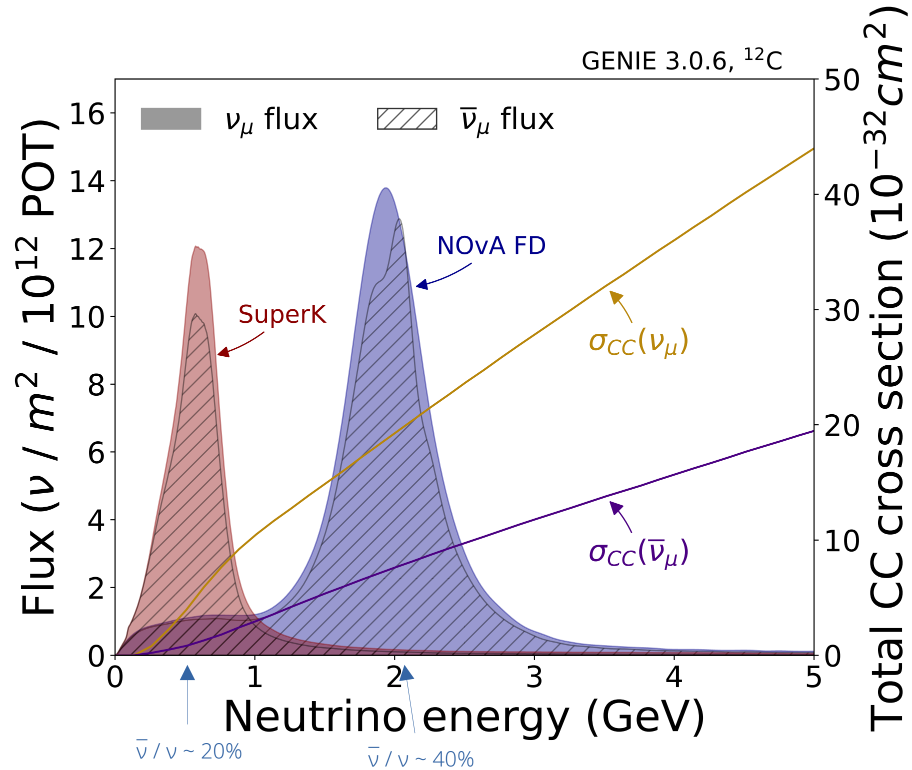

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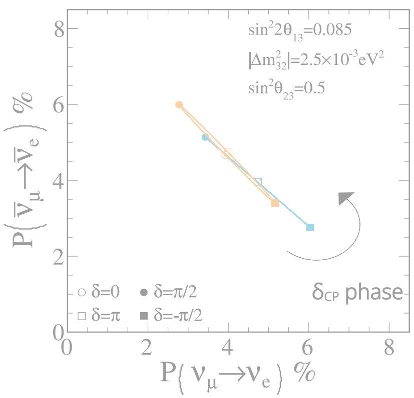

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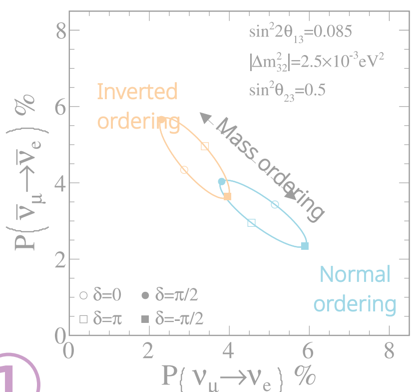

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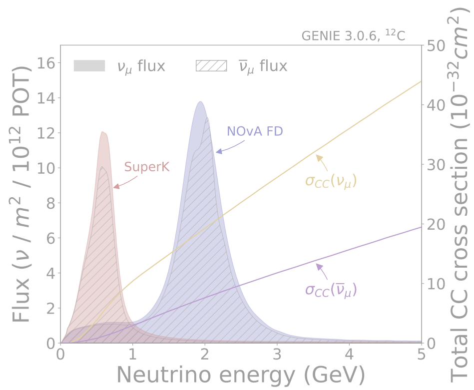

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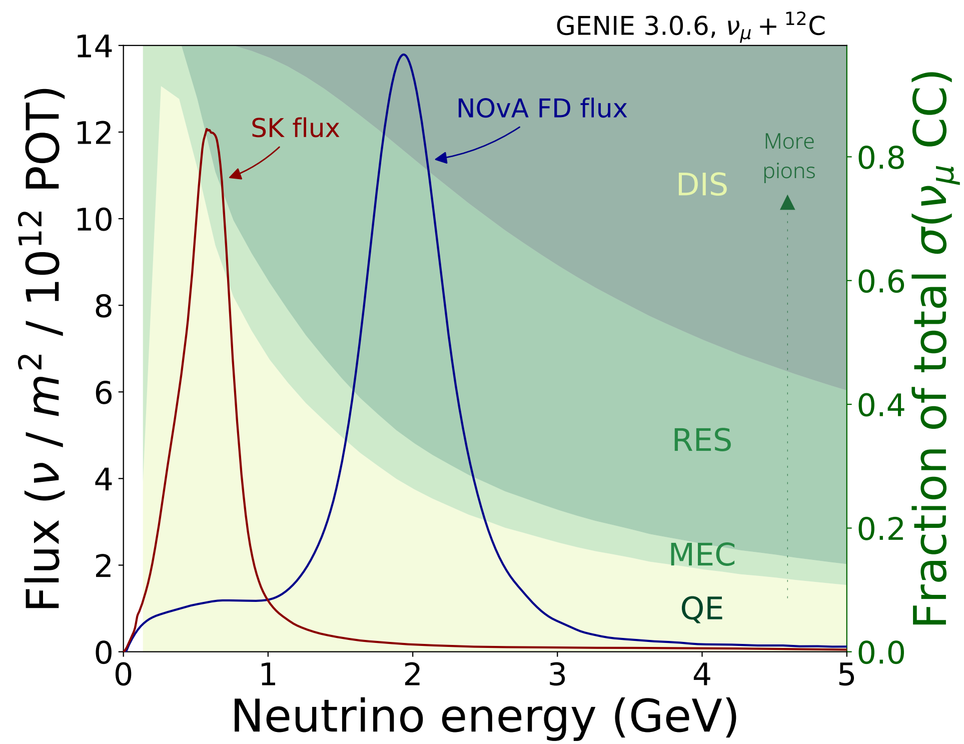
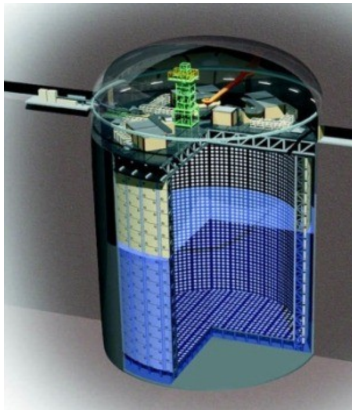


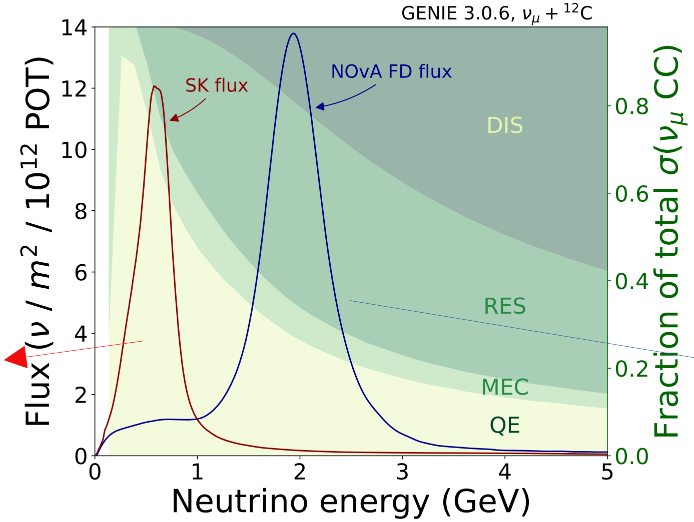
③ Different neutrino energies imply **different samples & reconstruction**

Different detectors for different challenges

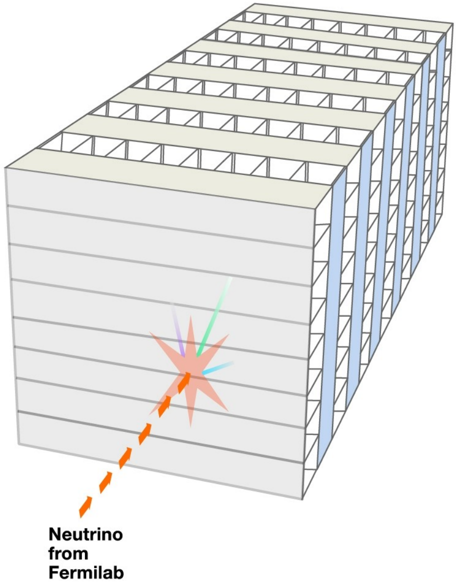
T2K



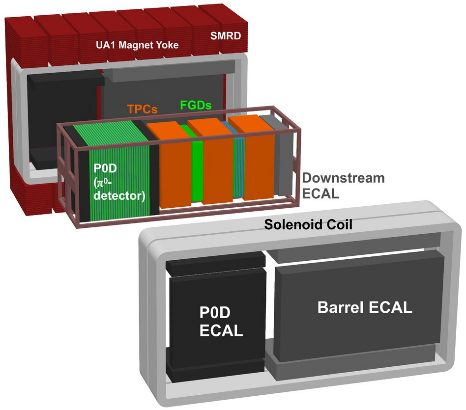
Water Cherenkov detector (mostly blind to hadrons) **well-suited to mostly-QE sample…**



NOvA



… corresponding **ND is significantly more capable**, in order to check that QE-based E_ν formula is working as model says it is

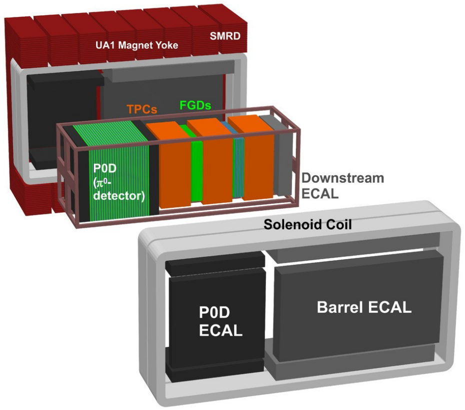


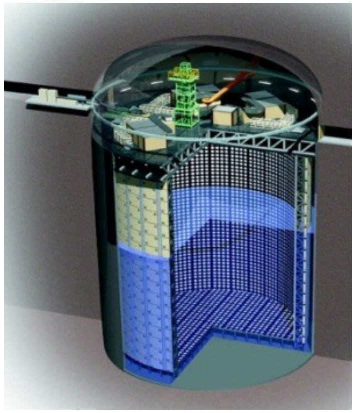
More complex topologies require up-front investment in more complex FD that has **hadron system sensitivity…**

… but **ND and FD can be made very similar**

Different challenges for different detectors

T2K





NOvA

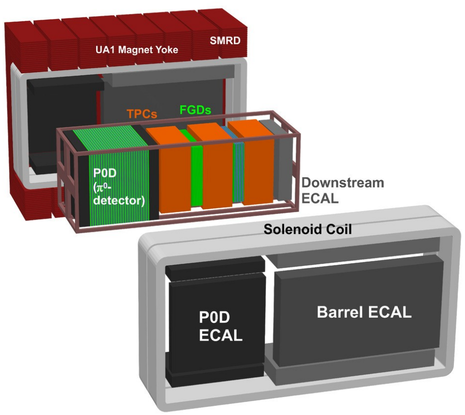
Near Det.

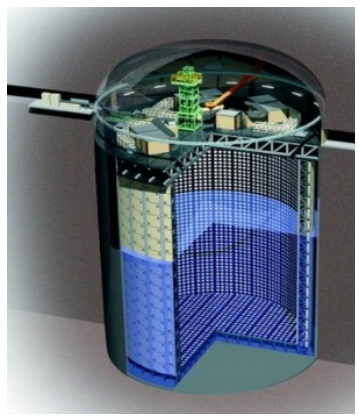
Far Det.

ND spectrum	FD spectrum	ND spectrum	FD spectrum
ν_μ(, ν_e) on CH	ν_μ, ν_e on H_2O	ν_μ(, ν_e) on CH_2	ν_μ, ν_e on CH_2
detailed hadronic system	~invisible hadronic system	detailed hadronic system	detailed hadronic system
~forward acceptance	4π acceptance	~forward acceptance	~forward (slightly larger) acceptance

Different challenges for different detectors

T2K





NOvA

Near Det.

Far Det.

ND spectrum

$\nu_\mu (, \nu_e)$ on CH

detailed hadron
system

~forward acceptan

Expect to need to mitigate cross section model weaknesses

FD spectrum

ν_μ, ν_e on H_2O

invisible hadronic system

4π acceptance

ND spectrum

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detailed hadronic system

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Look for ways to leverage data similarities

FD spectrum

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forward (slightly larger) acceptance

Philosophies of analysis

T2K

Expect to need to mitigate cross section model weaknesses

Philosophy: "model-driven"

Approach: Predict FD via comprehensive ν interaction model ("ND fit")

- incorporate best theory available
- parameterize uncertainties by surveying models, using dedicated measurements
- fit free parameters using ND data
- use fitted constraints as input to osc. param. fit with FD data

Attitude:

NOvA

Look for ways to leverage data similarities across detectors

Philosophy: "data-driven"

Approach: Predict FD by applying corrections to ND data ("extrapolation")

- prioritize degrees of freedom in models that move closer to data
- parameterize uncertainties by bracketing ND-FD potential differences
- use variation in "corrected ND" predictions from uncertainties as input to FD fit

Attitude:

Philosophies of analysis

T2K

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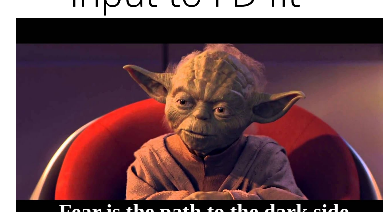
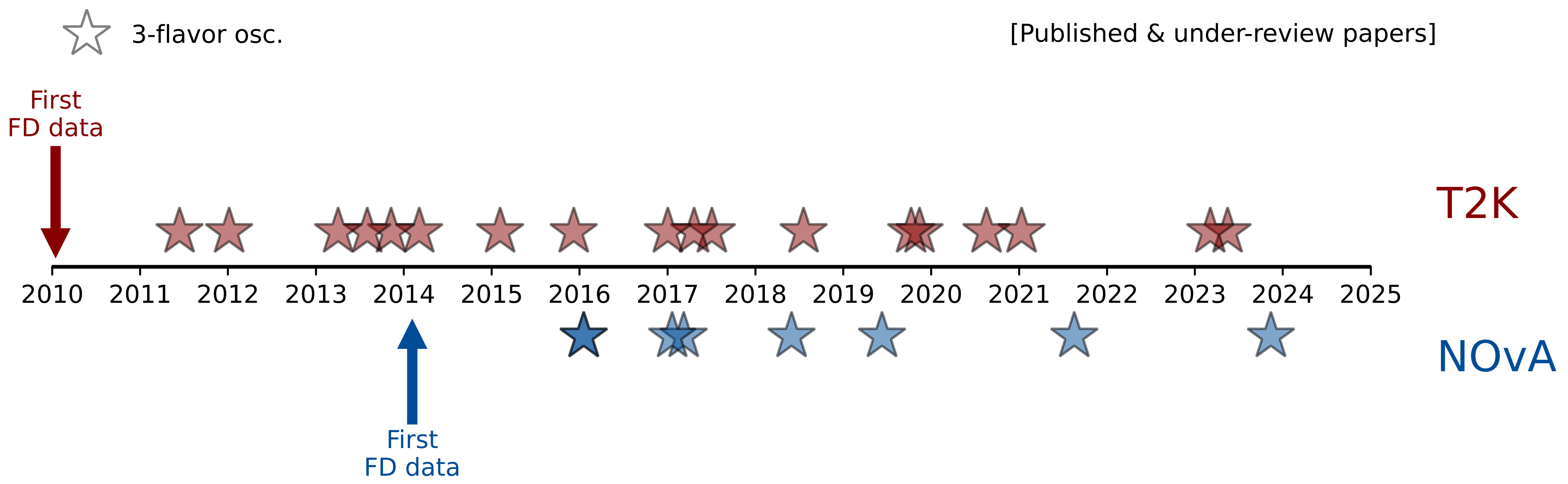


More details on “approaches” in tomorrow’s session

The paper record illustrates these philosophical differences:



Oscillation papers provide a normalization point, of sorts

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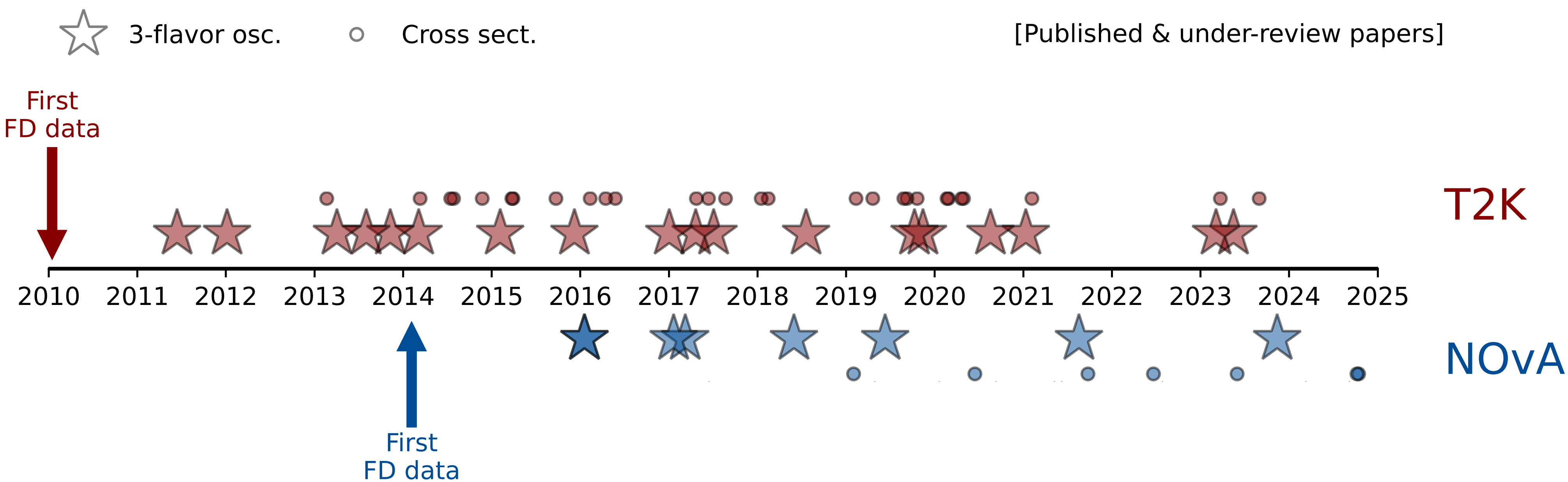

Strong cross section program from ~beginning of T2K

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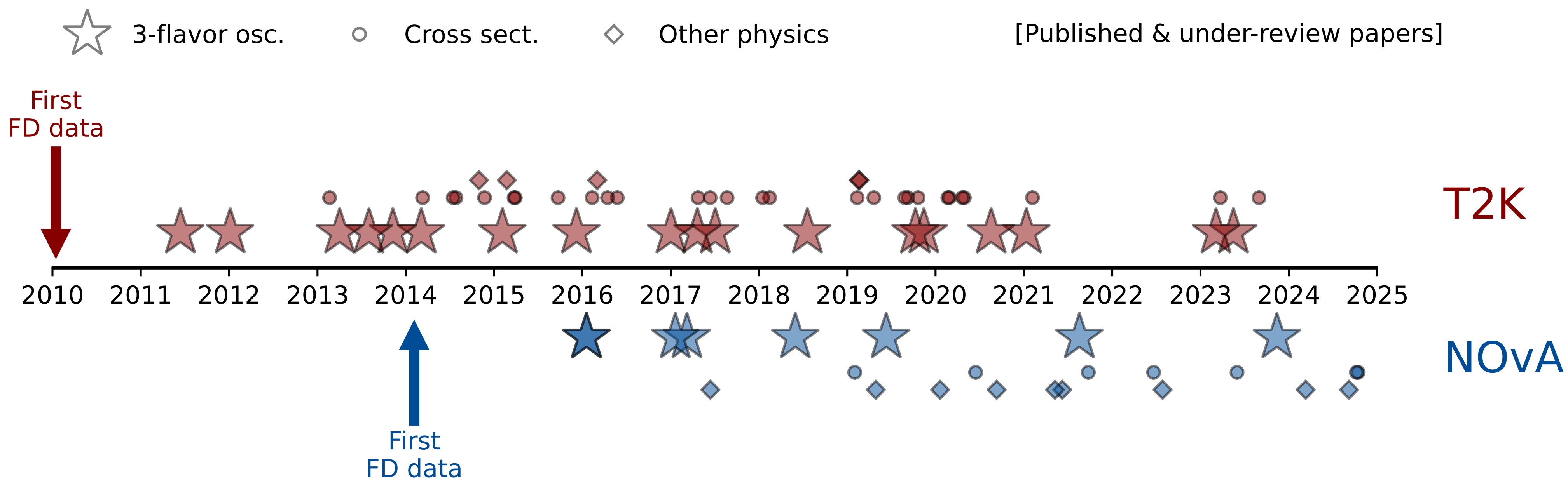

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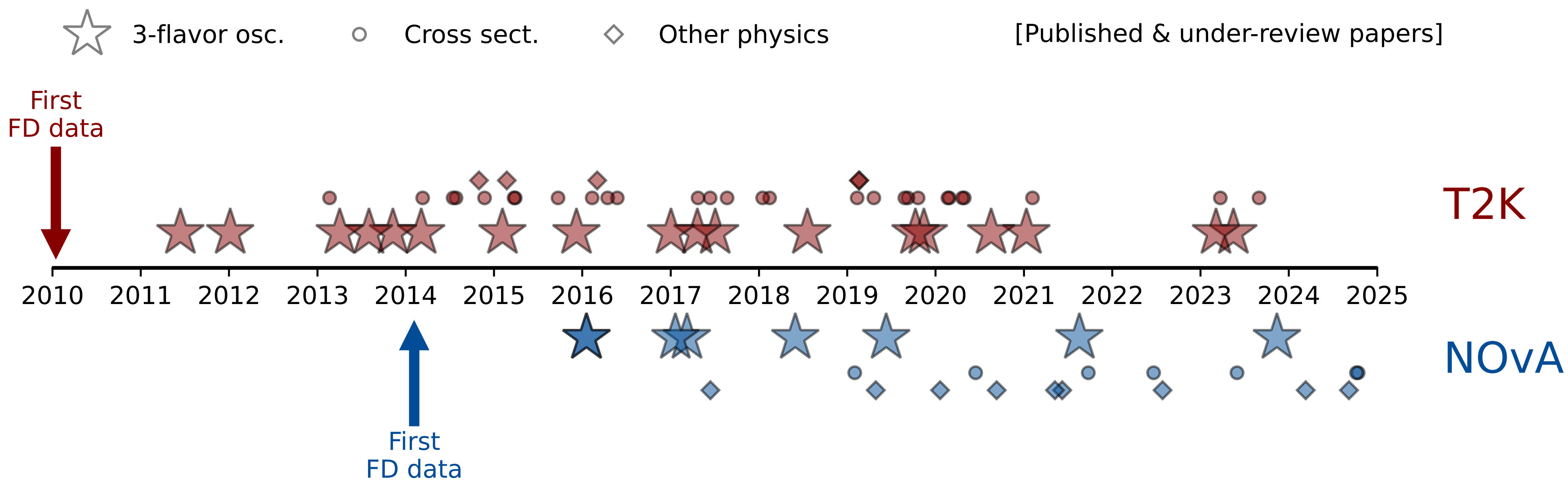

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I think the record shows *both* approaches are appropriate for their context

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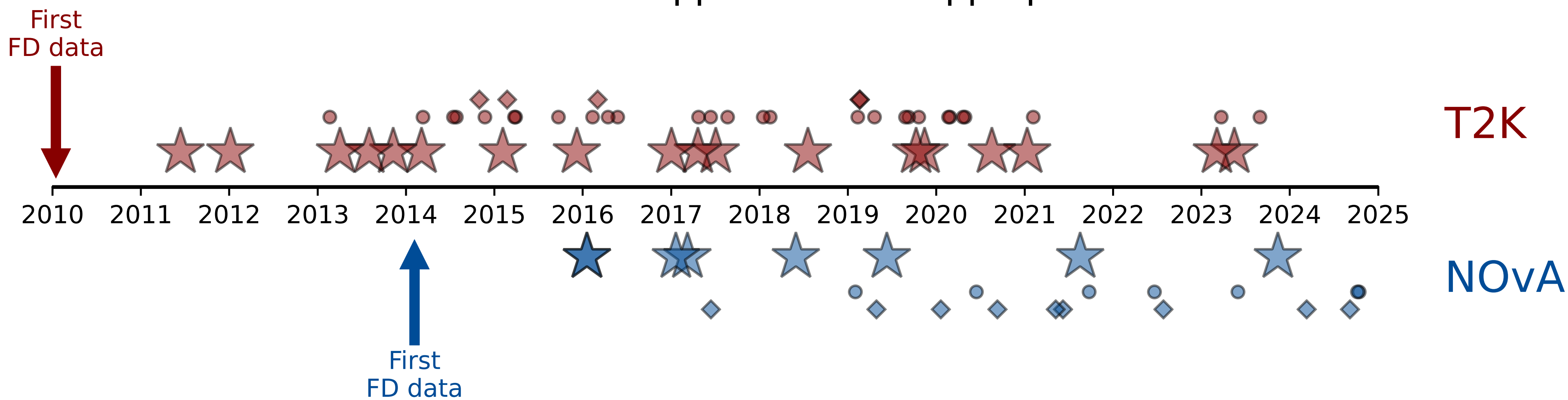

Example #1: NOvA & 2p2h

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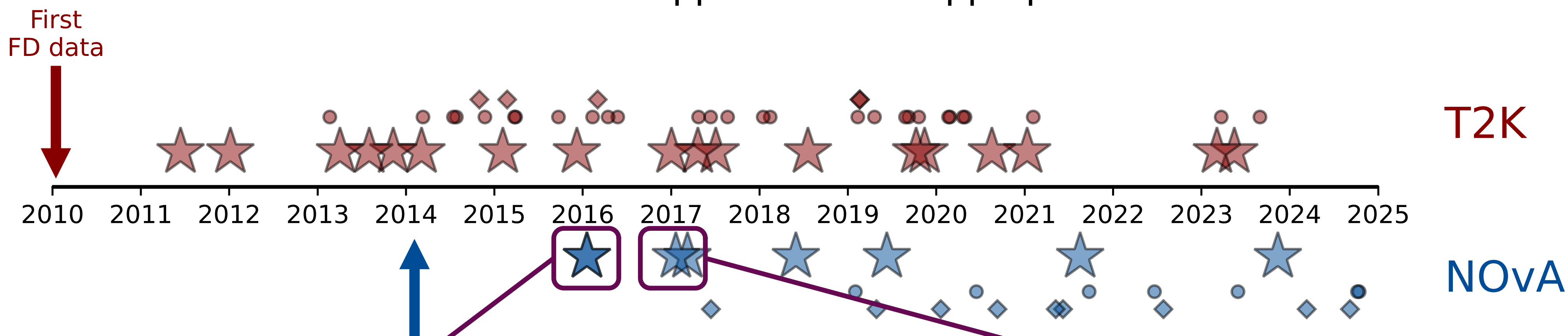

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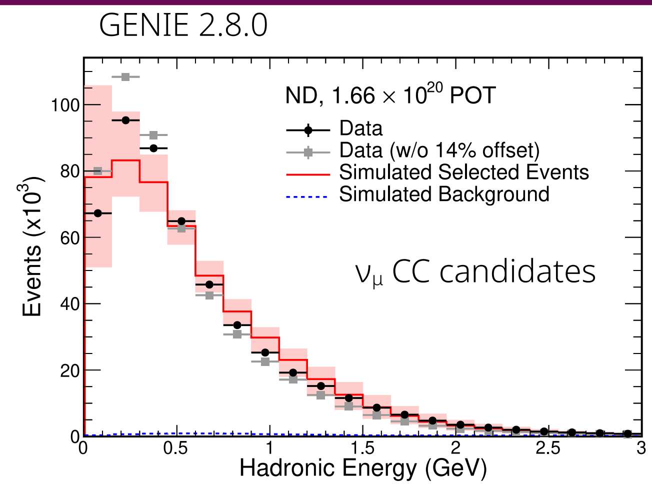
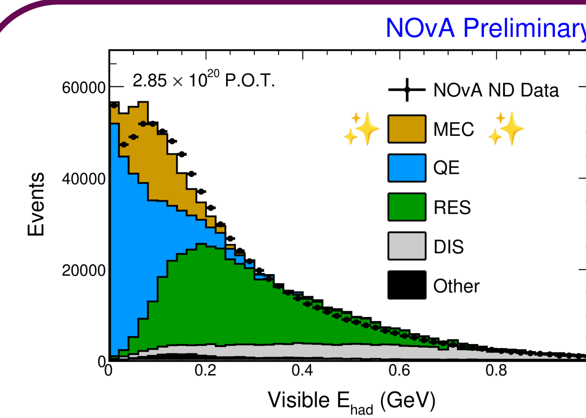
GENIE 2.8.0



Source of Uncertainty	Fractional Uncertainty $\sin^2\theta_{23}$ ($\pm$%)	Fractional Uncertainty Δm^2_{32} ($\pm$%)
Absolute Calorimetric Energy Calibration (14.9%)	4.1	2.6
⋮	⬆ ±4%	⬆ ±3%
Total Systematic Uncertainty	6.8	3.7
Statistical Uncertainty	17.0	4.5

NOvA Preliminary



Source of uncertainty	Uncertainty in $\sin^2\theta_{23} (\times 10^{-3})$	Uncertainty in Δm^2_{32} $(\times 10^{-6}$ eV$^2)$
⋮		
Cross sections and final-state interactions	+3 / -3	+12 / -15
⋮	⬆ ±0.5%	⬆
Total systematic uncertainty	+17 / -19	+50 / -47
Statistical uncertainty	+21 / -23	+93 / -99

NOvA's first analyses see big sim/data discrepancy in reco E_{had}.
Analyzed as a possible calibration issue (14% calibration error!)
since that results in the largest effect on the results

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Once convinced it's a cross section issue (lack of 2p2h),
even with generous uncertainties,
drops into the subdominant "cross section" category

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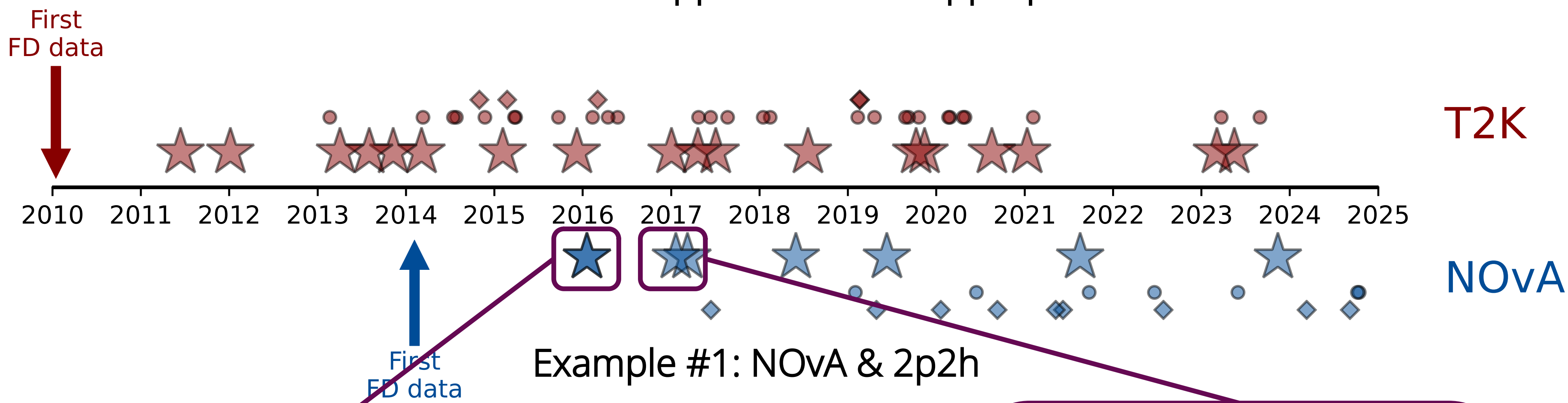

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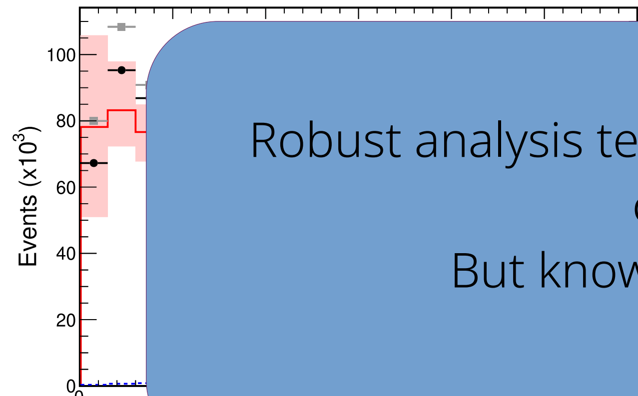

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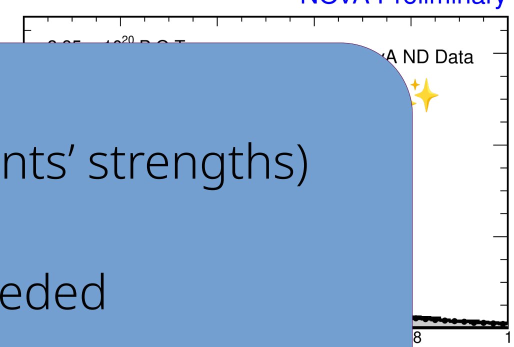

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Lesson:

Robust analysis techniques (tailored to experiments' strengths) can insulate from disasters.

But knowledge about cross sections needed for maximum sensitivity!

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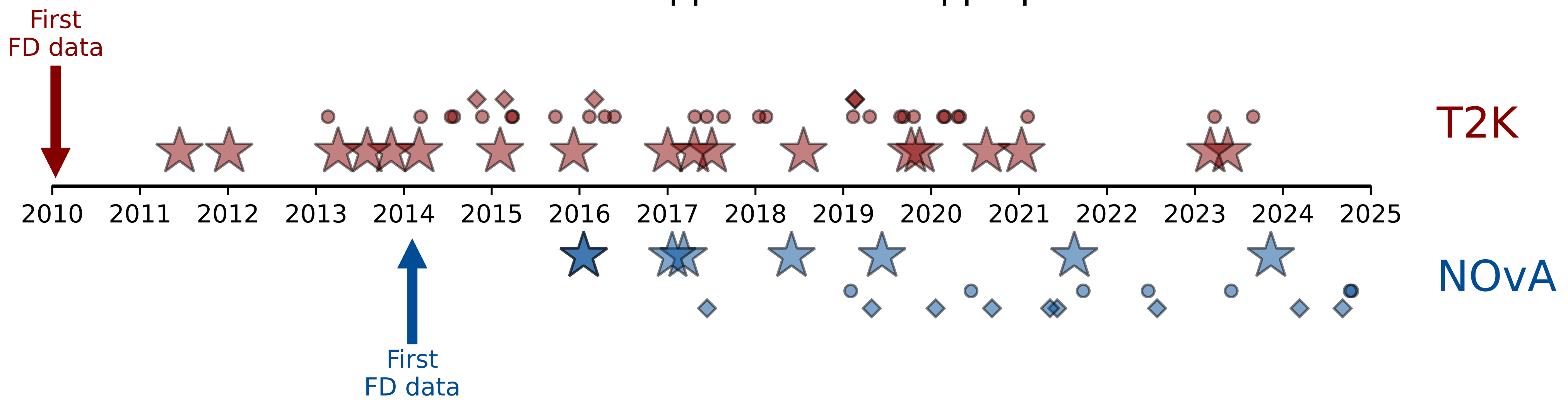

Example #2: T2K & "binding energy"

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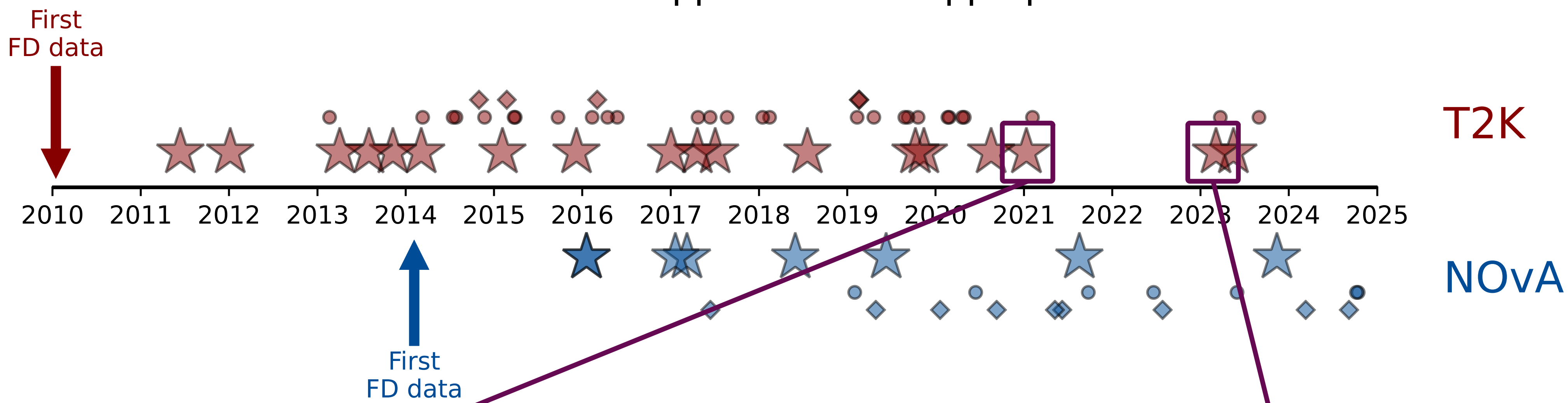

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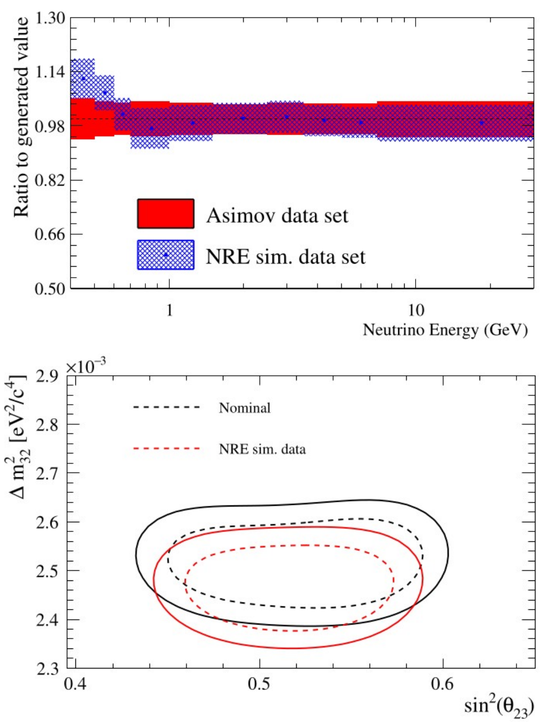


Simulated data set	Relative to	$\sin^2\theta_{23}$	Δm^2_{32}	δ_{CP}
⋮				
Nucleon removal energy	Total	5.0 %	33 %	0.1 %
	Syst.	10 %	46 %	0.6 %

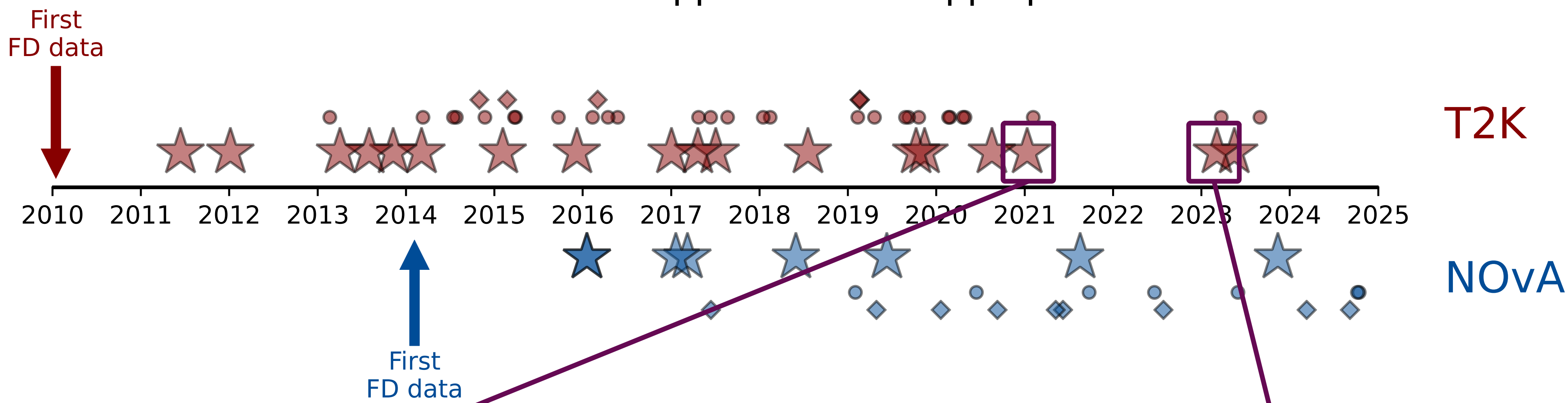
T2K finds (2021) that NEUT model of nucleon removal energy (RFG+systs) is not flexible enough to cover more realistic treatment (different E_{bind})
(potential bias in Δm^2_{32} 33% of error budget)

Addressed with fake data studies
➞ *post hoc* inflation of contours

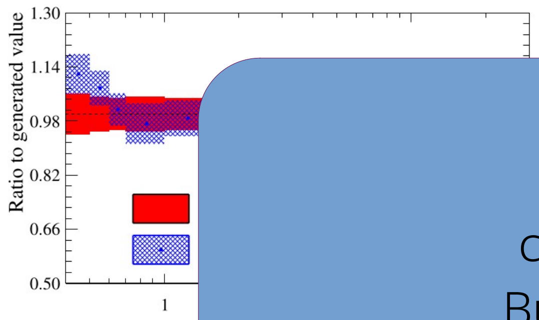
Implementation (2023) of **more sophisticated model** (SF) + more general uncertainties **reduces to minimal bias**

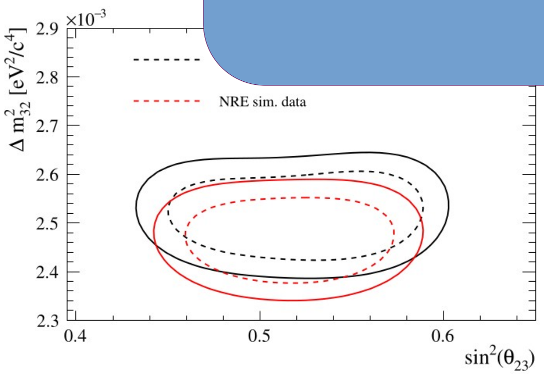
Simulated data set	Relative to	$\sin^2\theta_{23}$	Δm^2_{32}	δ_{CP}
⋮				
CCQE removal energy	Total	0.0%	4.8%	1.3%
	Syst.	0.0%	13.4%	5.2%

I think the record shows *both* approaches are appropriate for their context



Example #2: T2K & "binding energy"





Lesson:

Hard work and cross section expertise
can remediate otherwise fatal model flaws.
But need *plausible* solutions in model space!

flexible enough to cover more realistic treatment (different E_{bind})
(potential bias in Δm^2_{32} 33% of error budget)

Addressed with fake data studies
→ *post hoc* inflation of contours

3) of **more**
more general
minimal bias

Simulated data set	Relative to	$\sin^2\theta_{23}$	Δm^2_{32}	δ_{CP}
⋮				
CCQE removal energy	Total	0.0%	4.8%	1.3%
	Syst.	0.0%	13.4%	5.2%

What does progress look like?

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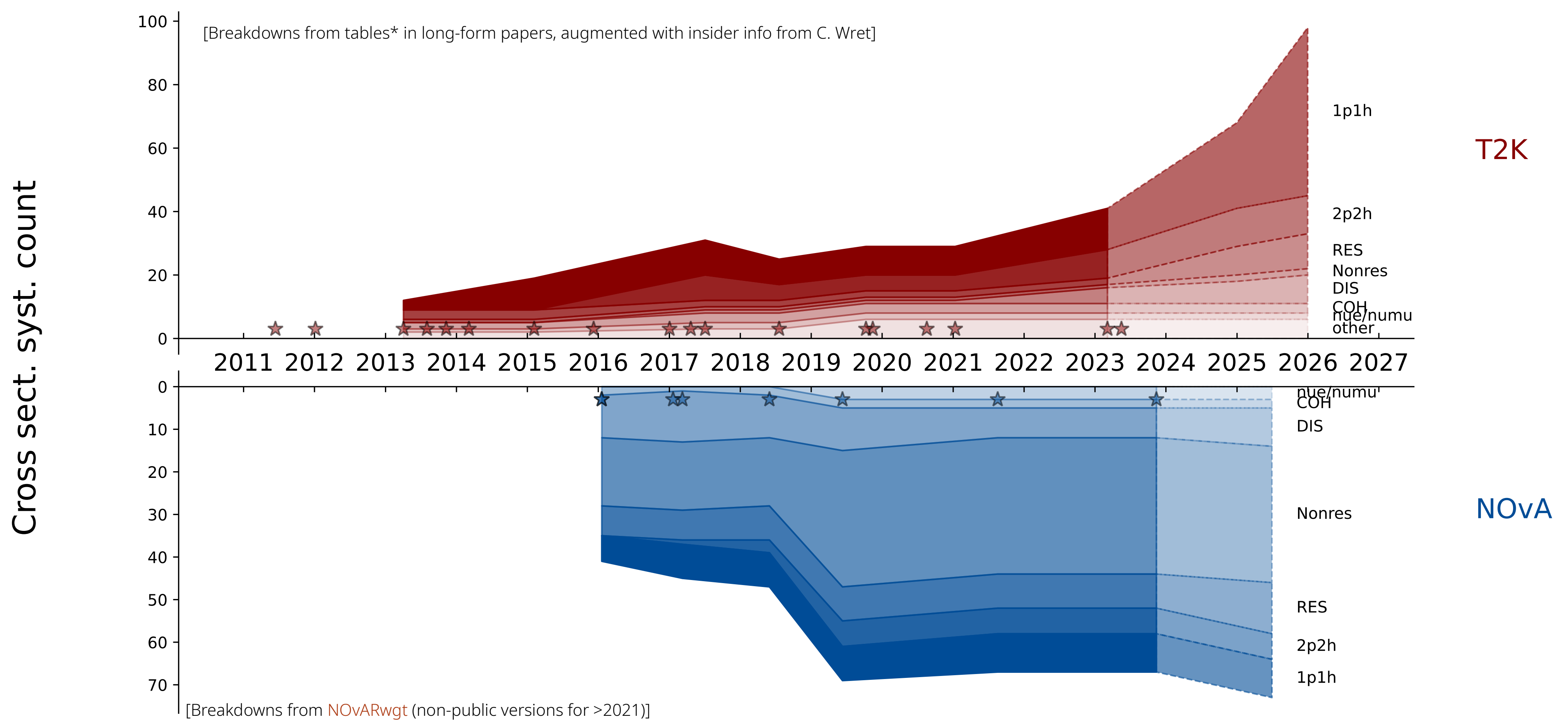

* 2013-04-03: Tabs. XII and XVI in https://doi.org/10.1103/PhysRevD.88.032002
2015-02-05: Tab. VII in https://doi.org/10.1103/PhysRevD.91.072010
2017-07-04: Tab. IX in https://doi.org/10.1103/PhysRevD.96.092006
2021-01-11: Tab. XXV in https://doi.org/10.1103/PhysRevD.103.112008
2023-03-06: Tab. 22 in https://doi.org/10.1140/epjc/s10052-023-11819-x

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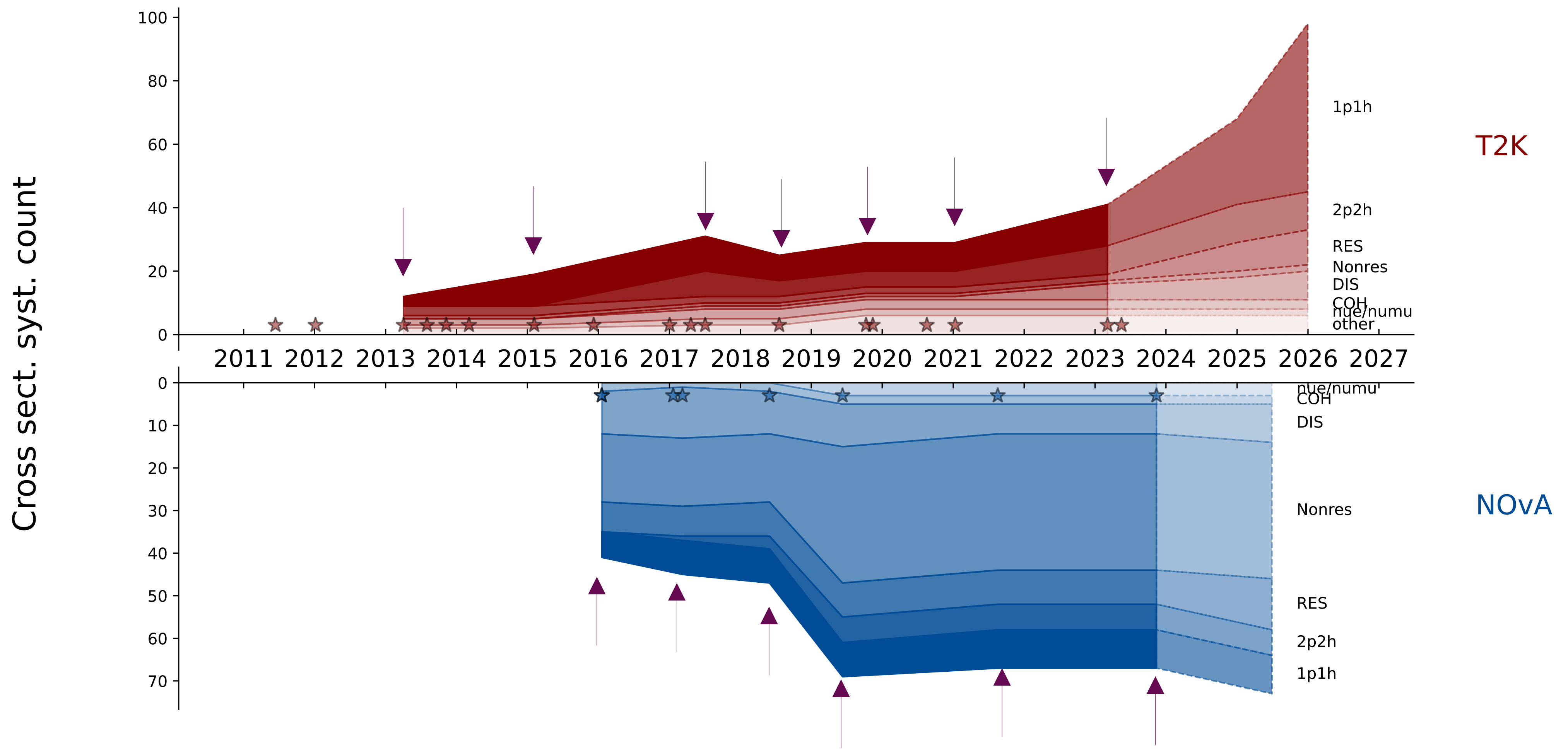
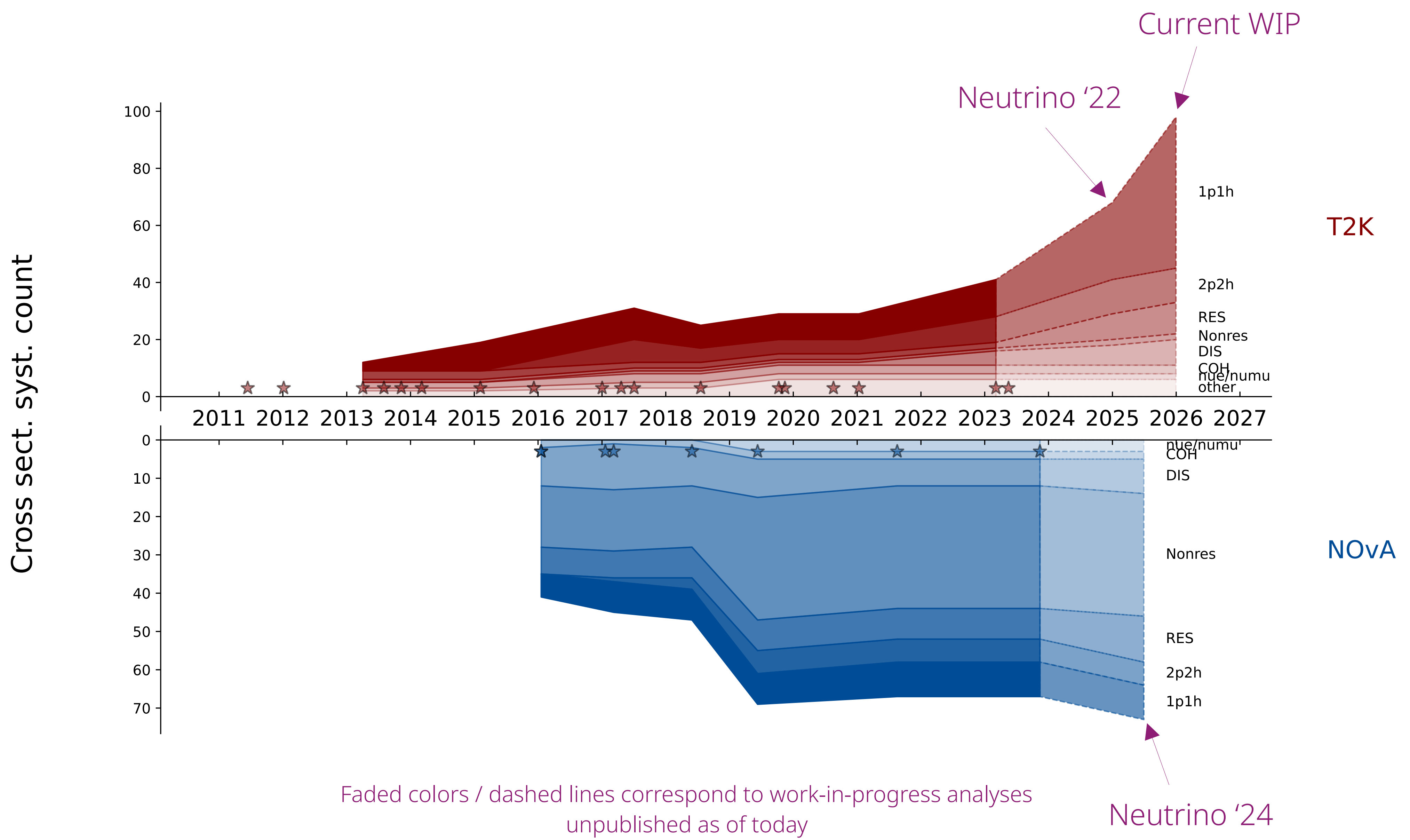


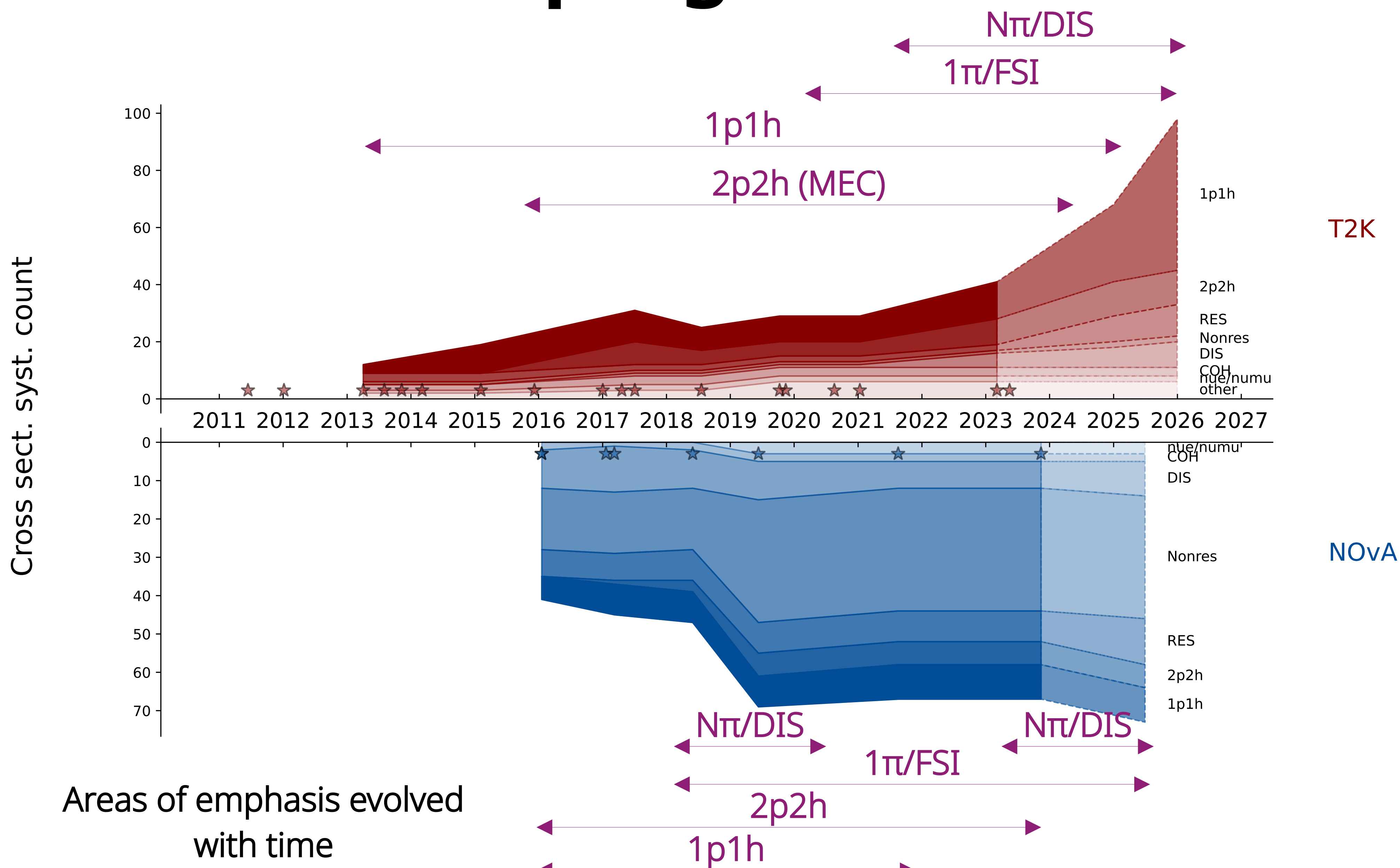
"Kinks" correspond to analyses where I was able to obtain the uncertainty composition.
(Linear extrapolation in between just to guide the eye.)

What does progress look like?



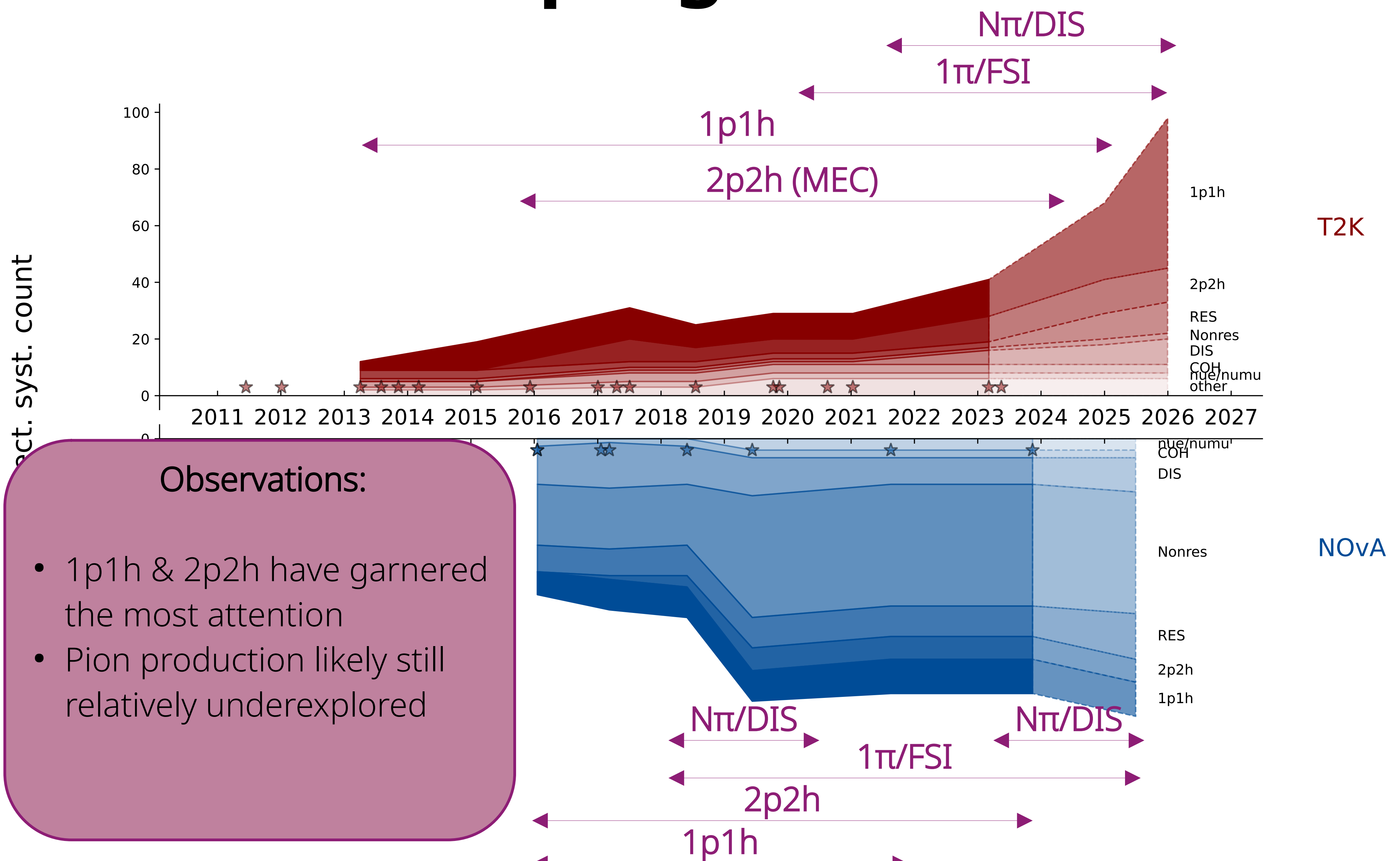
Faded colors / dashed lines correspond to work-in-progress analyses unpublished as of today

What does progress look like?



Areas of emphasis evolved with time

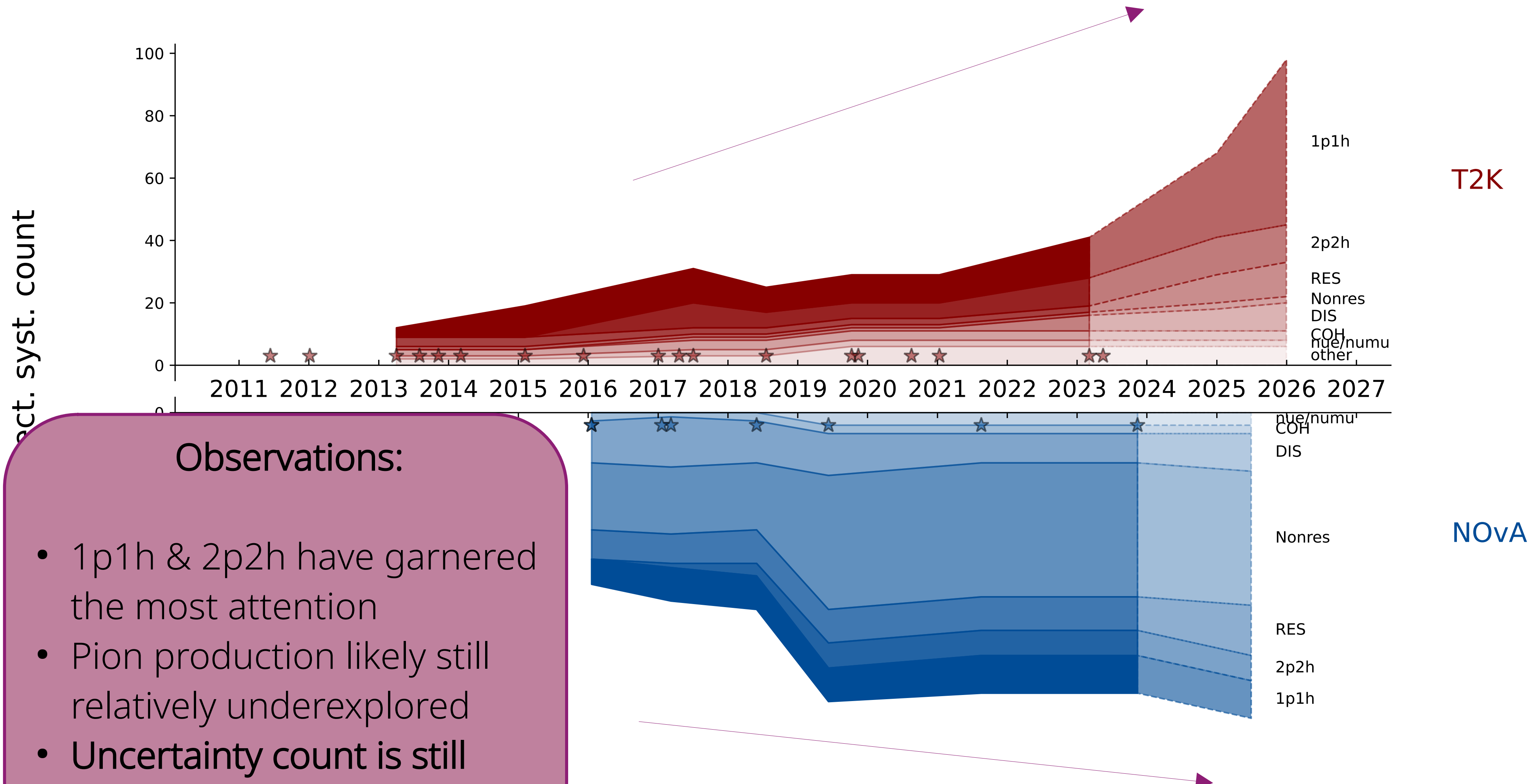
What does progress look like?



Observations:

- 1p1h & 2p2h have garnered the most attention
- Pion production likely still relatively underexplored

What does progress look like?



Observations:

- 1p1h & 2p2h have garnered the most attention
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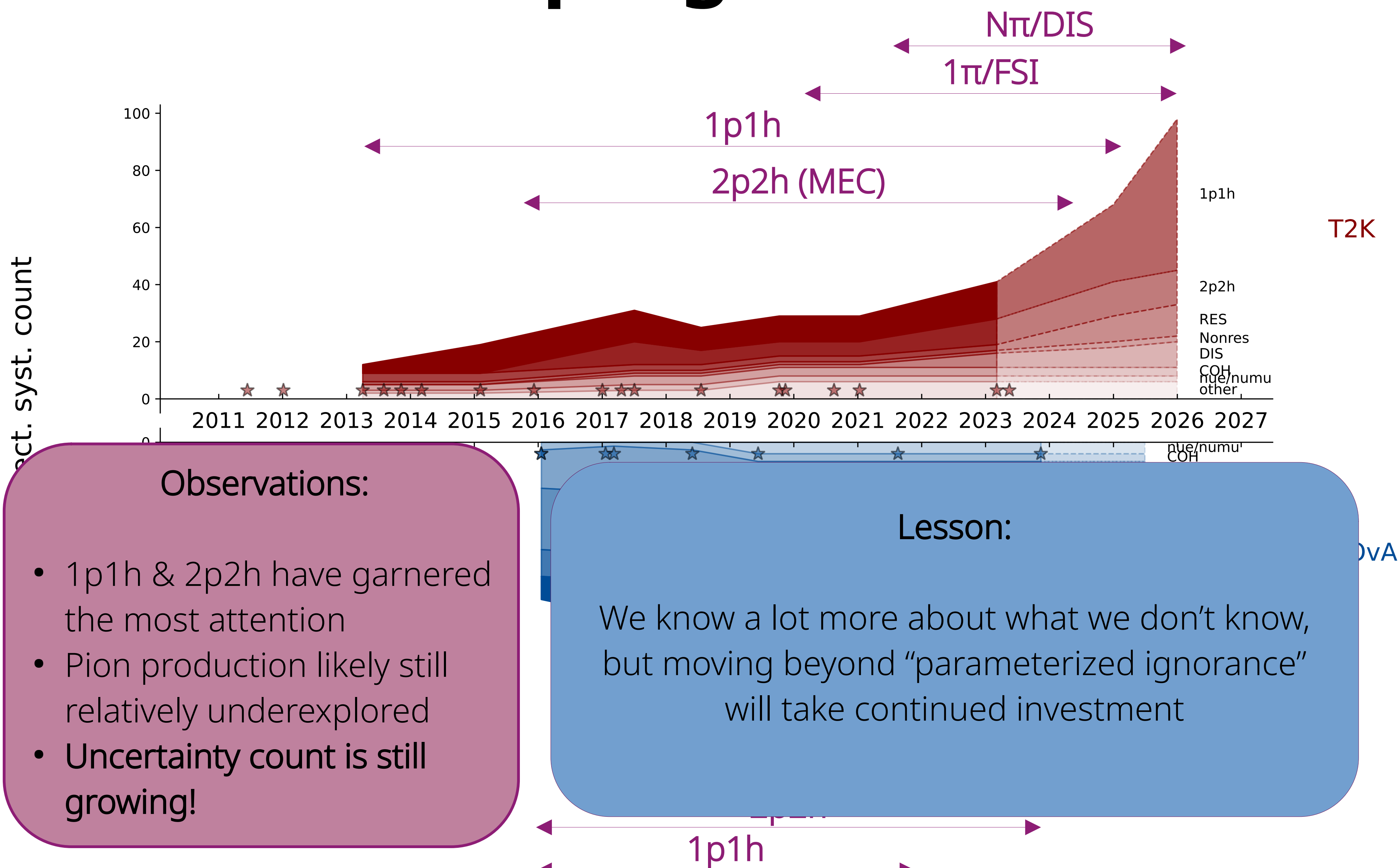
- **Uncertainty count is still growing!**

What does progress look like?



Observations:

- 1p1h & 2p2h have garnered the most attention
- Pion production likely still relatively underexplored
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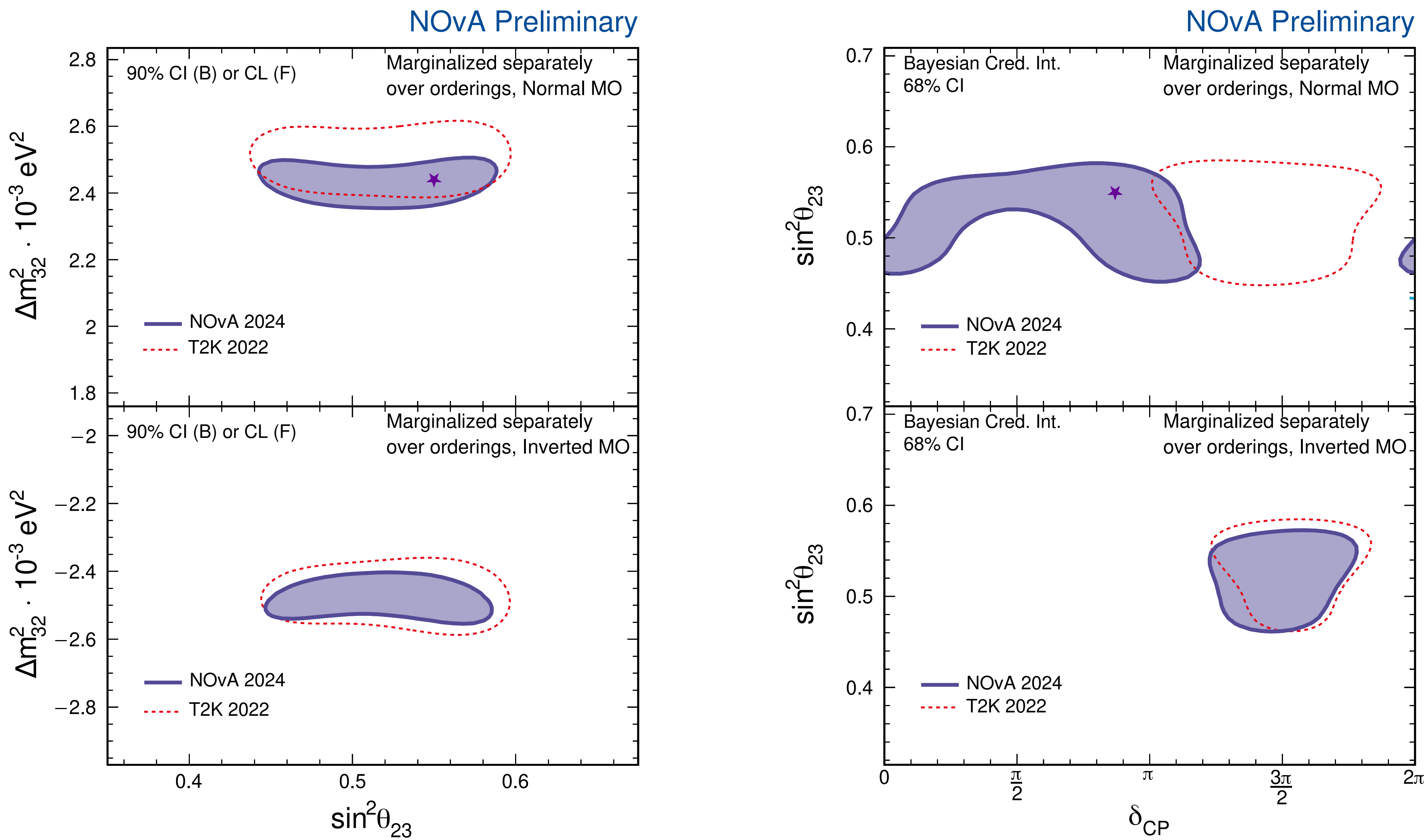
Lesson:

We know a lot more about what we don't know, but moving beyond "parameterized ignorance" will take continued investment

What's gotten us this far?

- **Heavy use of electron scattering measurements**
  - Foundation for nuclear ground state models (current generation: Ar)
  - Theory for 2p2h, newer higher-mass-than-Δ RES models originally worked out in this context
  - Workhorse testing ground for theoretical advances
- **Extensive attempts to incorporate ν scattering data (but difficult!)**
  - Still rely heavily on "archival" (= older than me) light target data (^{1}H, ^{2}H)
  - Many effects interfere in nuclei! "Second generation" observables (transv. kin. imb., etc.) disentangle some of them... sometimes
  - Need "model soup" to span full kinematic range → weaknesses can overlap, cancel, hide one another
- **Hadron scattering data**
  - Crucial for learning about reinteractions
- **Development of models!**
  - There were 0 νA 2p2h models in 2010, at least 3 now
  - Radiative corrections for ν_e CC was ~unstudied in 2010, detailed calculations for QE available now
- **Investments in generator development**

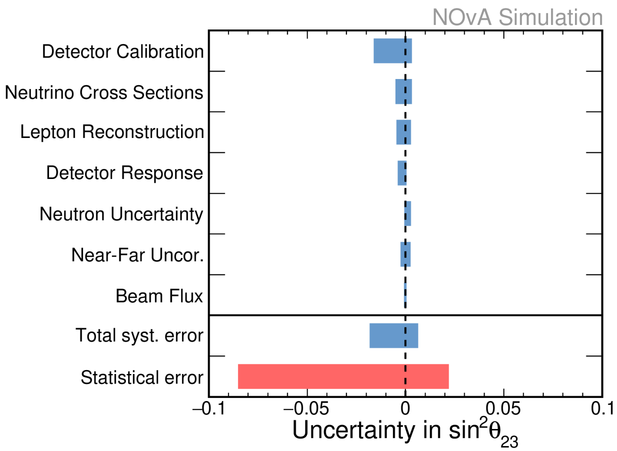
Where are we today*?

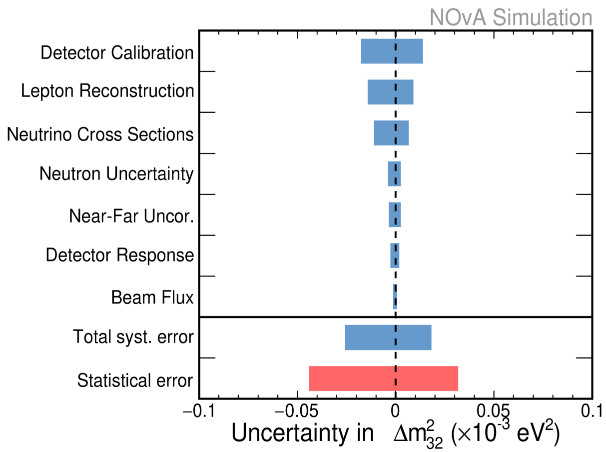


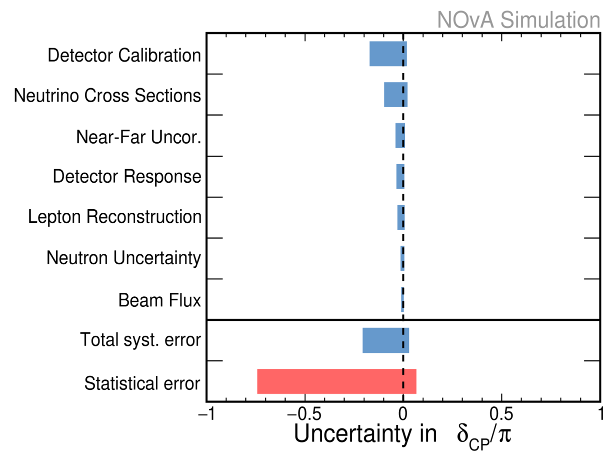
Good (if intriguing) oscillation parameter consistency

*My apologies to T2K folks: didn't have a version with both expts' NEUTRINO 2024 contours at press time, but story is ~unchanged

Where are we today*?







[EPJ C83, 782

The results are limited by statistics

[Recent T2K results do not separate stat. vs. syst. uncertainties on parameters]

Still dominated by statistical uncertainties…

Impressions (lessons?)

- Essential to be able to differentiate what are, aren't cross section issues
  - Model & data expertise are important to know what skeletons live in which closets
  - "Fake data studies" are a critical component of robustness testing

- Statistical uncertainties have covered a multitude of sins
  - Current gen experiments have benefited from hiding behind stat. uncertainties while model development happened
  - Techniques for dealing with "unknown unknowns" will be much more valuable in next-gen expts to hold space for model work while stats accumulate much faster
- We've depended a *lot* on electron scattering work paving the way for us
  - When will need for axial current start to dominate? (Will we be able to get what we need from light target ν scattering data?)
  - Can we learn anything from *muon* scattering? e.g.: arXiv:2410.12005
  - Do we need a muon storage ring to measure ν xsecs at <2%?
- Pion production uncertainties still underconstrained
  - Will DUNE be able to make do until ND-GAr?...

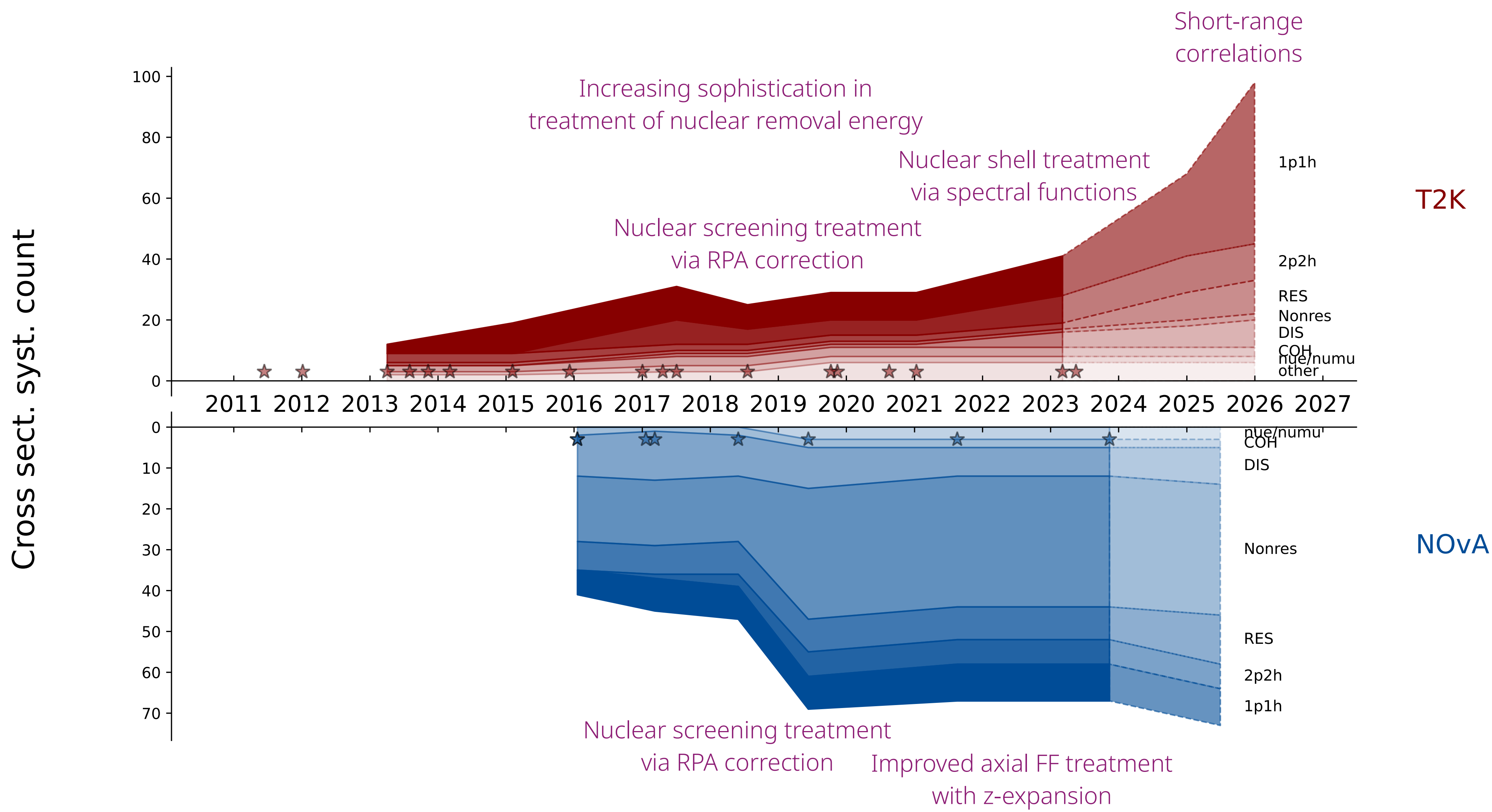
Summary

- **NOvA & T2K's 3F measurements:**
  - Take different philosophical → analysis approaches, each suited to their context
  - Have confronted significant cross section model issues over the last decade with encouraging progress
  - Are still limited by statistical uncertainties
- **Progress so far has depended on:**
  - Electron and hadron scattering
  - Light-target ν scattering
  - Heavier nucleus ν scattering

We've built a solid foundation,
but the edifice is still under construction!

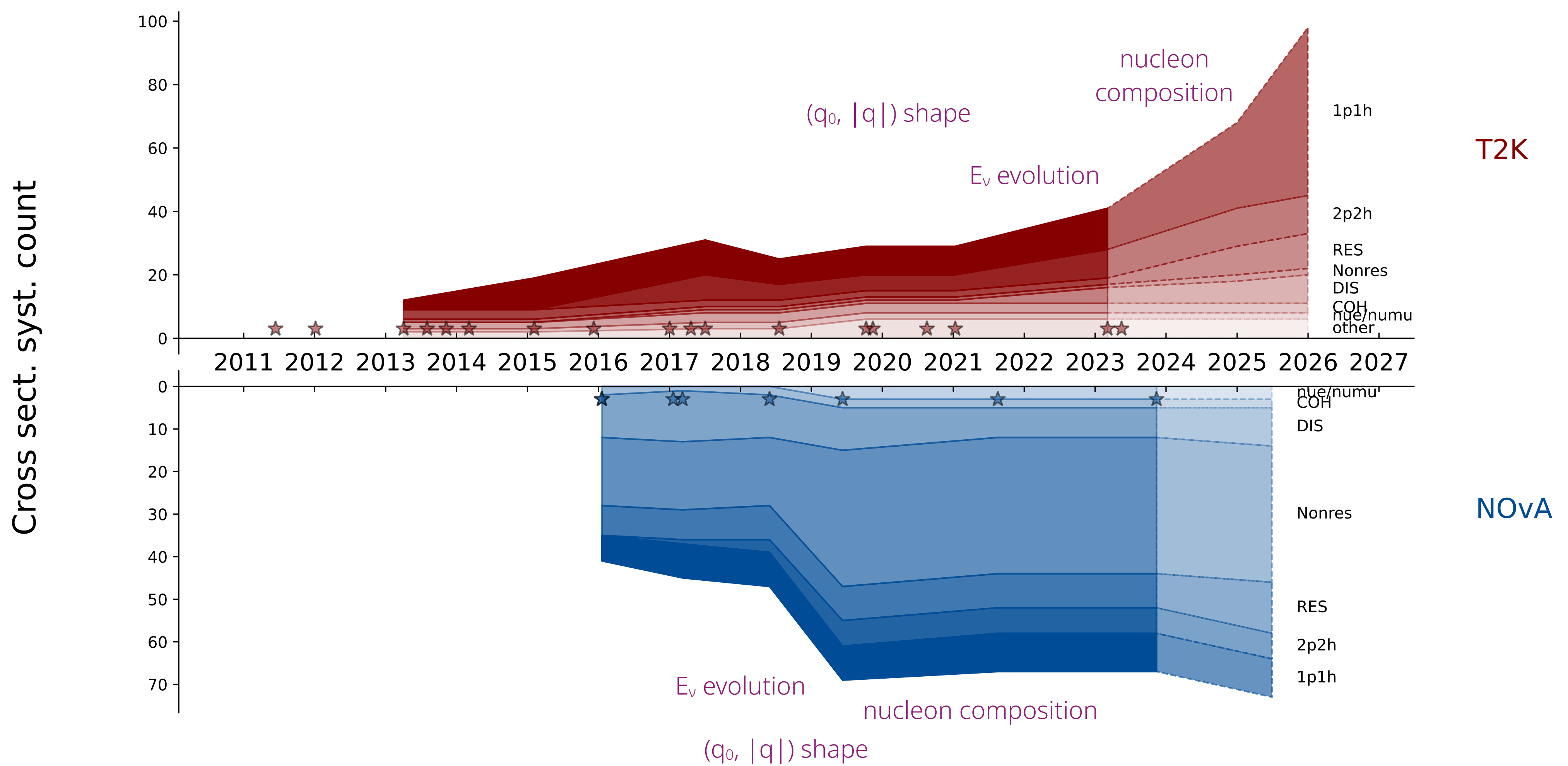
Overflow

What does progress look like?



1p1h trends: nuclear ground state, low-Q^2 dynamics, form factors

What does progress look like?



2p2h trends: nucleon identity, kinematic shape