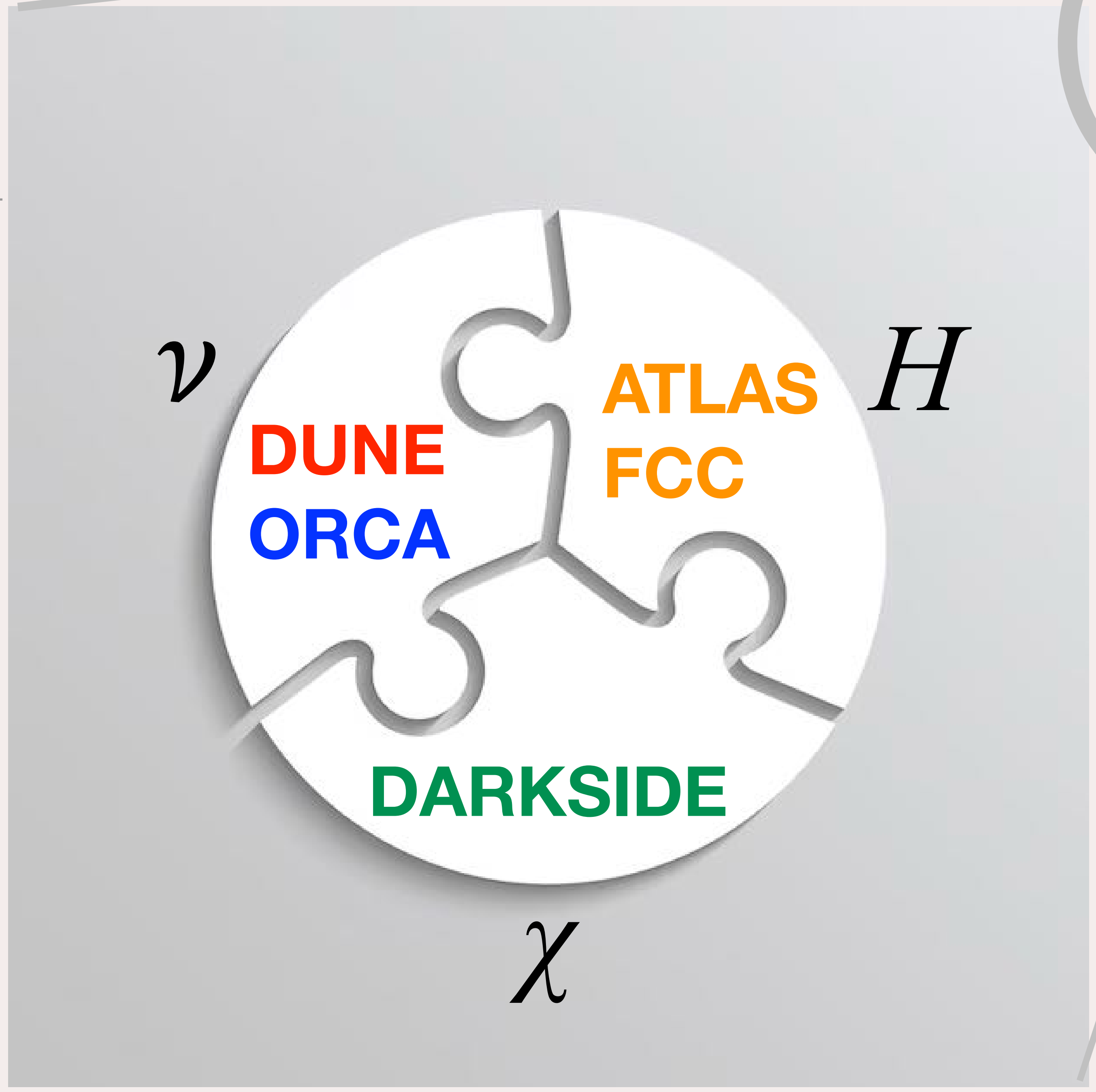
The APC Particles team

Giovanni Marchiori for (and with input from)
the Particles team

APC Biennale, 4/6/2026



The Particles team

- ***DarkSide***
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  - Timothée Hessel
  - Janna Machts
  - Evangelia Nikoloudaki
- ***DUNE***
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  - Claire Dalmazzone
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  - Dario Pullia
  - Sabrina Sacerdoti
  - Alessandra Tonazzo
- ***KM3NeT/ORCA***
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- **ATLAS/FCC**
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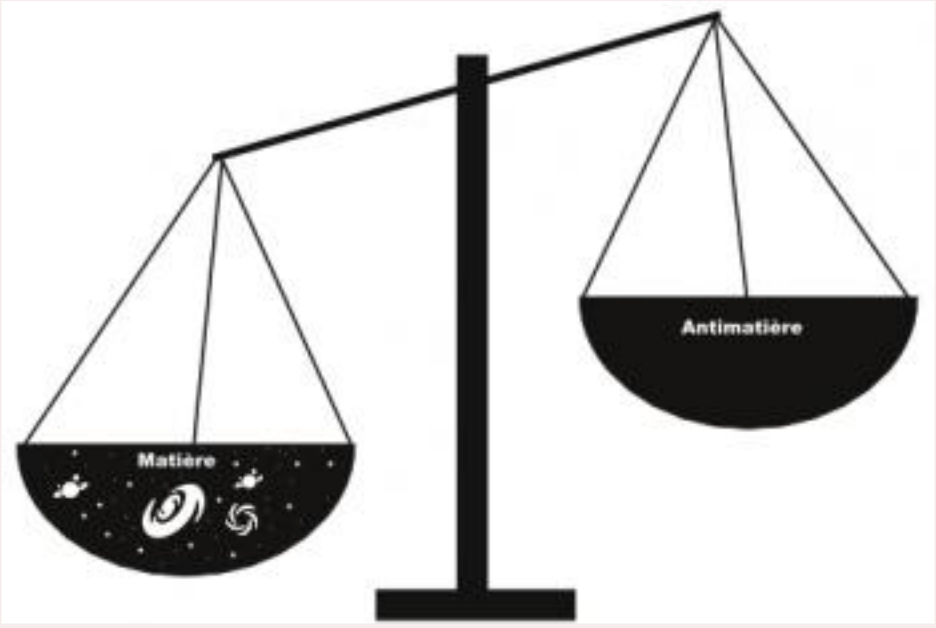
  - Dian Yu

(Very) big scientific questions of particle physics

- ***What is matter in the Universe made of?***

- ***What is the origin of particles' masses and why elementary particles' masses are so different?***

- ***Where does the observed matter/antimatter asymmetry come from?***



- **And more …** (e.g. electroweak symmetry breaking, …)

Big scientific questions of particle physics

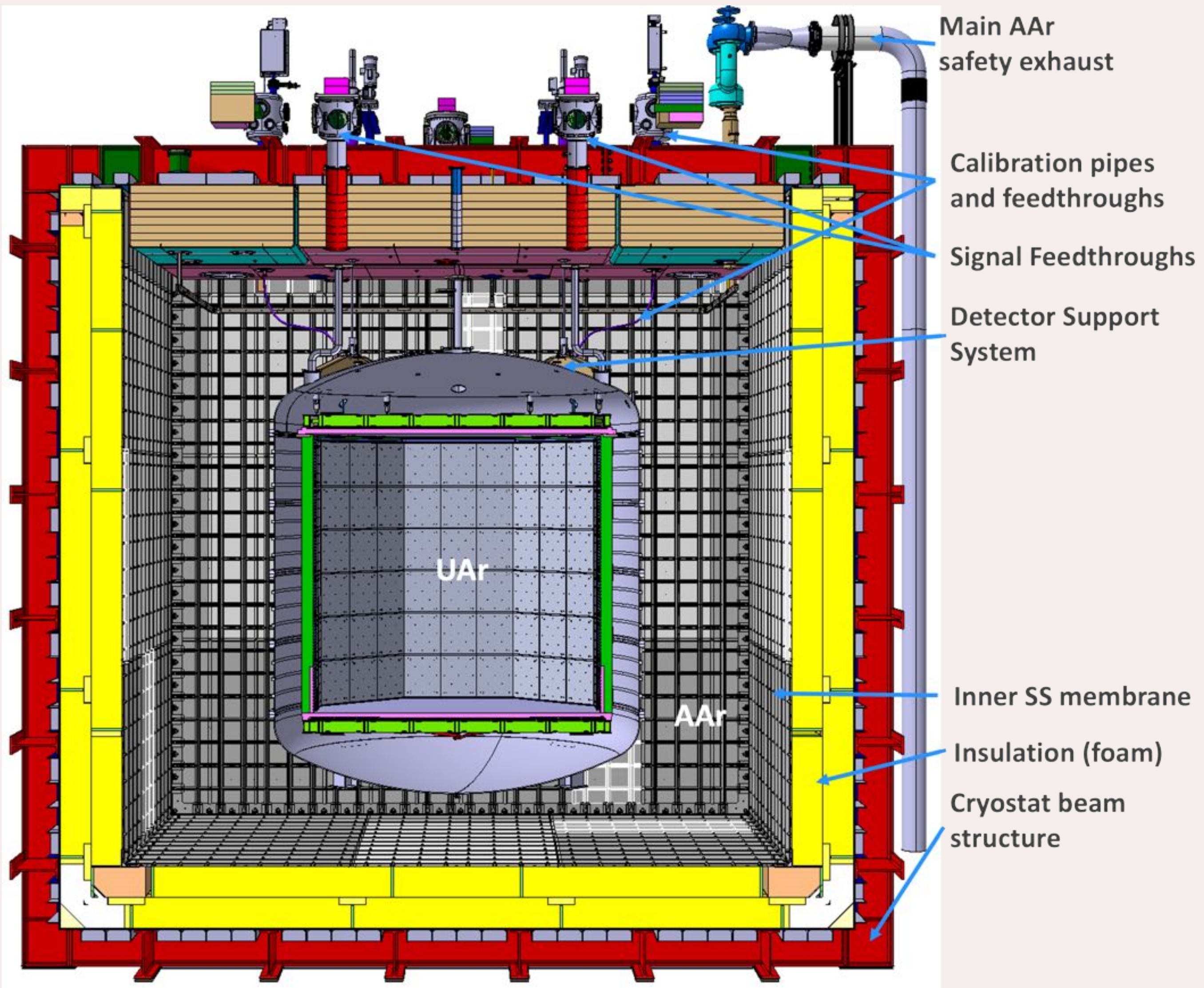
- ***What is matter in the Universe made of?***
- ***What is the origin of particles' masses?***
- ***Why elementary particles' masses are so different?***
- ***Where does the observed matter/antimatter asymmetry come from?***
- and more …

- **Dark matter:** ~25% of total matter/energy in Universe and >80% of total matter, essentially unknown yet
  - *What is it? How does it interact with ordinary matter? What are its mass and interaction cross sections with ordinary matter?*
- **Higgs boson:** could explain origin of particle masses, EW symmetry breaking, and several other open questions. Discovered in 2012, plenty of open questions
  - *Why so light? Is it elementary or composite? What is its potential (related to electroweak symmetry breaking)? Is there more than one type of Higgs bosons? Do its interactions violate CP? Does it couple to dark matter?*
- **Neutrinos:** lightest particles in the SM, interact very feebly with other particles, very challenging to observe, some properties still not known/understood
  - *What is the absolute value of their masses and their mass ordering? Why are their masses so small/unnatural? Are neutrinos Dirac or Majorana particles? Do their interactions violate CP? Are there more than the known 3 types of neutrinos?*

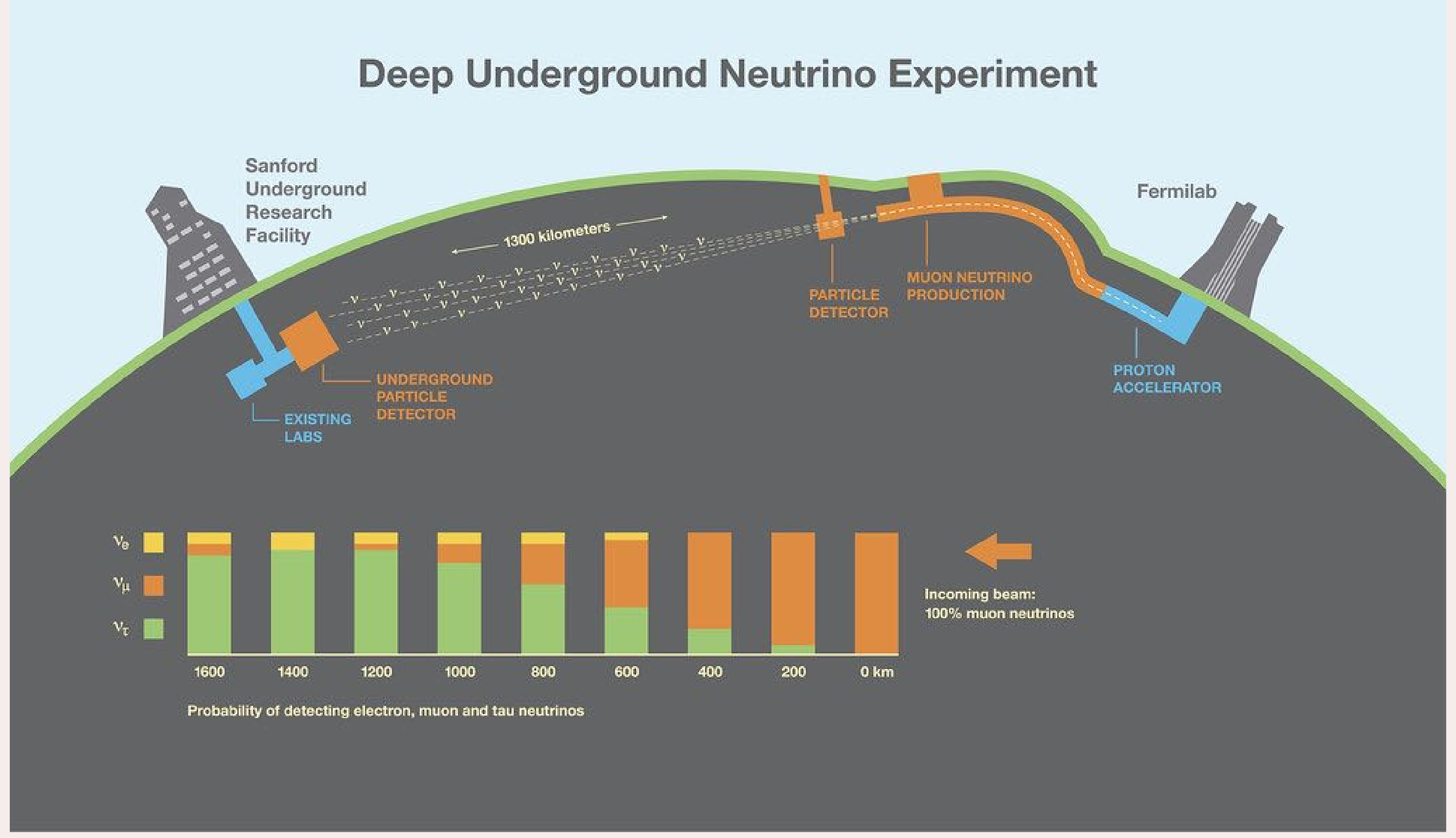
How do we tackle these questions with our projects?

- **Dark matter → DarkSide-20k**
  - Dual-phase LAr TPC underground, search for signals (energy from recoil) from dark matter scattering on Ar
- **Neutrinos**
  - **→ DUNE**
    - Underground LAr TPCs to detect neutrinos from powerful/far accelerator (and from atmosphere)
  - **→ KM3NeT/ORCA**
    - Array of optical sensors under the sea to detect neutrinos from cosmic rays interactions with the atmosphere or from cosmological sources
- **Higgs → ATLAS@LHC, FCC**
  - Big multi-purpose detectors at existing/future colliders (p-p, e-e) at CERN, abundant and controlled production of Higgs (and more)

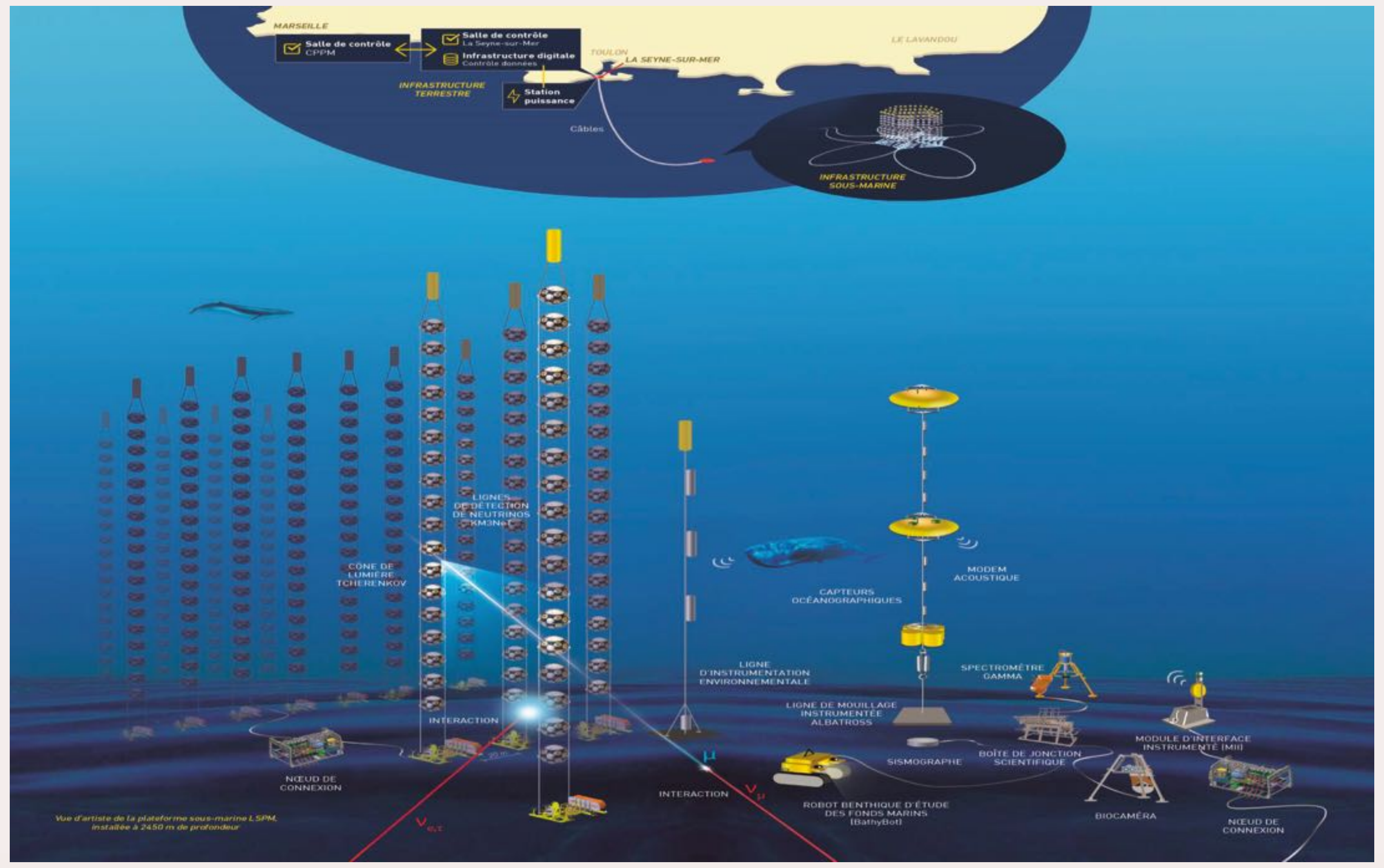
DarkSide-20k



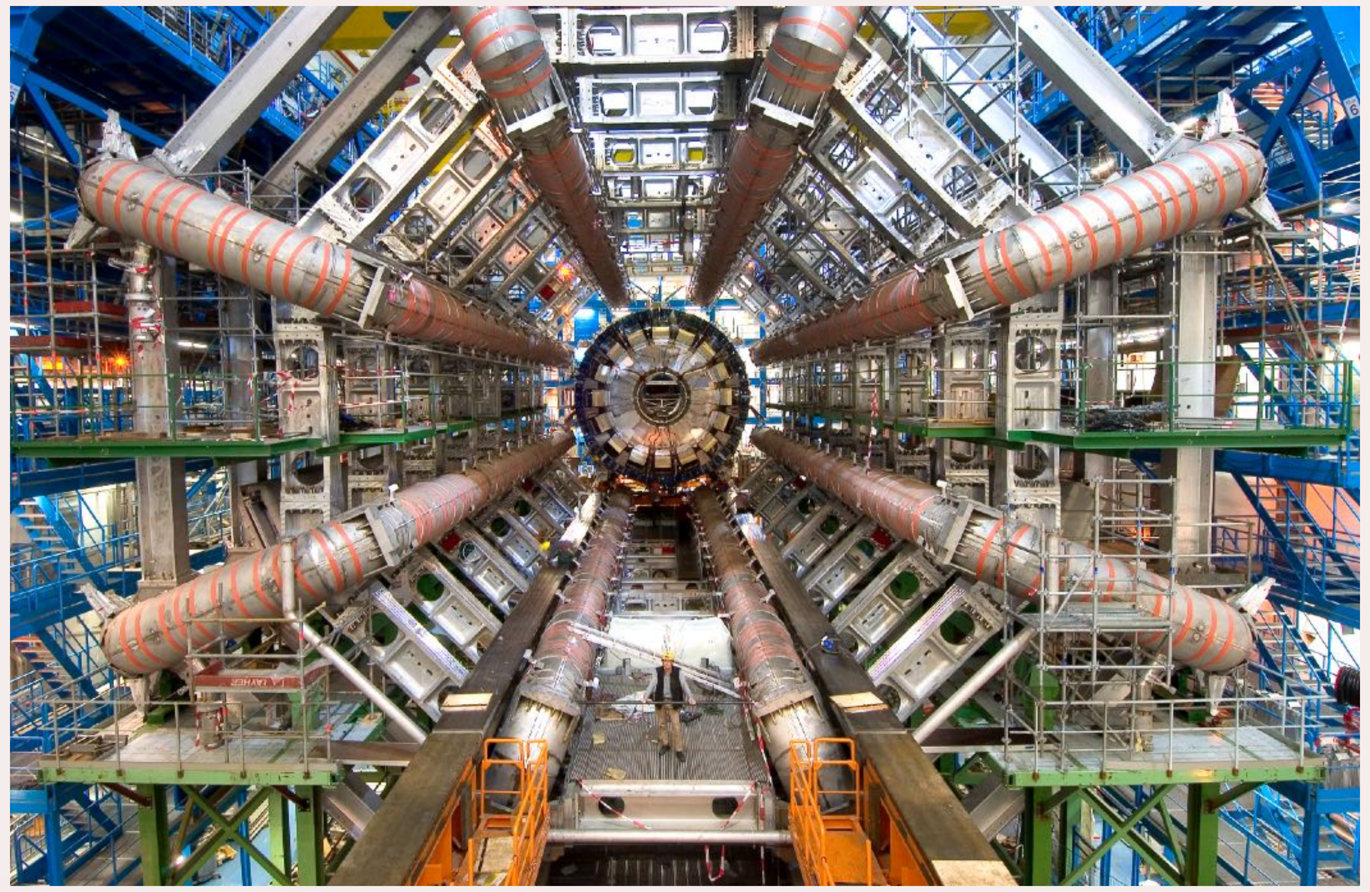
DUNE



ORCA



ATLAS



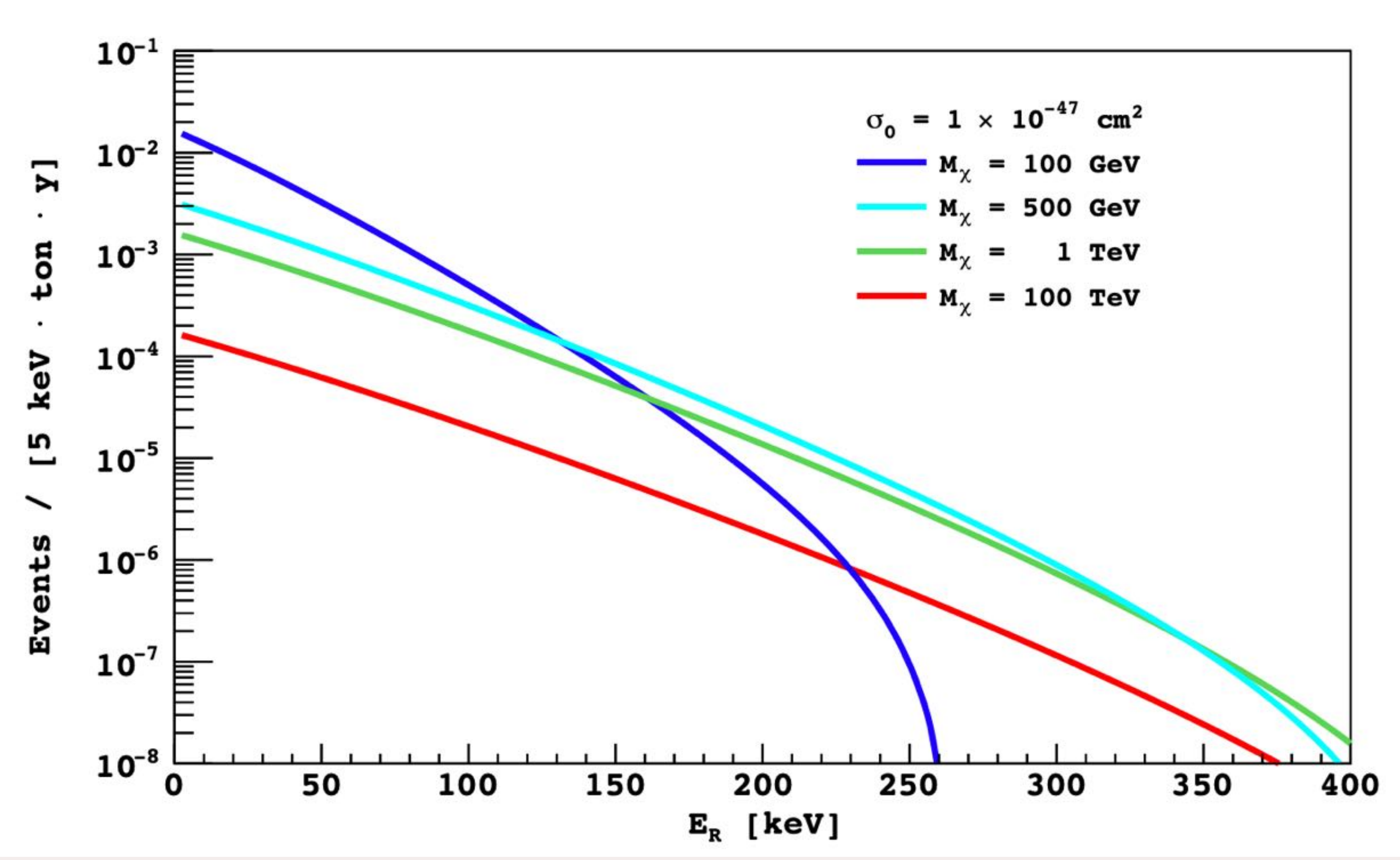
Timeline of the projects

Project	2026	2027	2028	2029	2030	2031
DARKSIDE-20k	Construction			Data taking		
ProtoDUNE-VD	Data taking					
DUNE	FD-VD, -HD Construction and filling				FD-VD data taking with atmospheric neutrinos (2032: FD-HD, ND and accelerator also ready)	
ORCA	Construction Commissioning and data taking					Data taking
ATLAS	Data taking (~500/fb)	Upgrades for HL-LHC			Commissioning / Data taking (HL-LHC target: 3000/fb)	
FCC	R&D, TDR preparation, collaboration building, funding consolidation, project approval (go/no-go: 2028; project start in late 40's)					

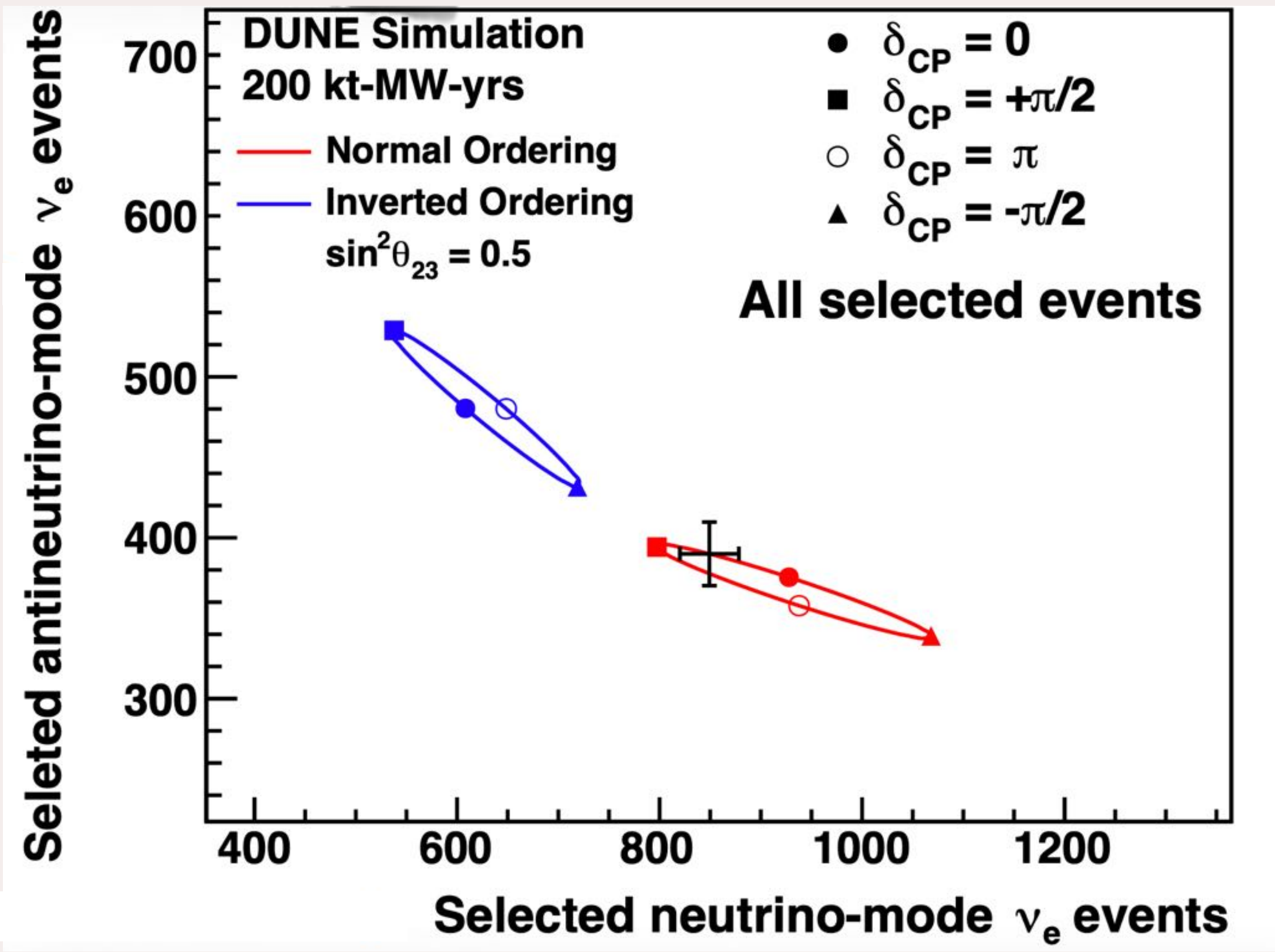
Scientific goals: what do we aim to measure?

- **DarkSide**
  - Observe yield and spectrum of recoil energy from DM particles scattering off Ar
    → **deduce mass, cross-section of DM**
- **DUNE**
  - Measure asymmetry in rate of $\nu_\mu \to \nu_e$ and anti-$\nu_\mu \to$anti-ν_e (differentially vs E_ν) → **determine CP violation in neutrino sector**; **detailed study of neutrino properties** (mass ordering, ν_τ appearance, ..)
- **ORCA**
  - Measure rate of (ν_μ+anti-ν_μ) vs (ν_e+anti-ν_e)
    → **determine neutrino mass ordering** (+ ν_τ appearance, search for sterile ν, ..)
- **Higgs → ATLAS@LHC, FCC**
  - Reconstruct single- and di-Higgs boson events
    → **measure precisely Higgs boson properties** (mass, couplings, self-coupling, CP violation, …)

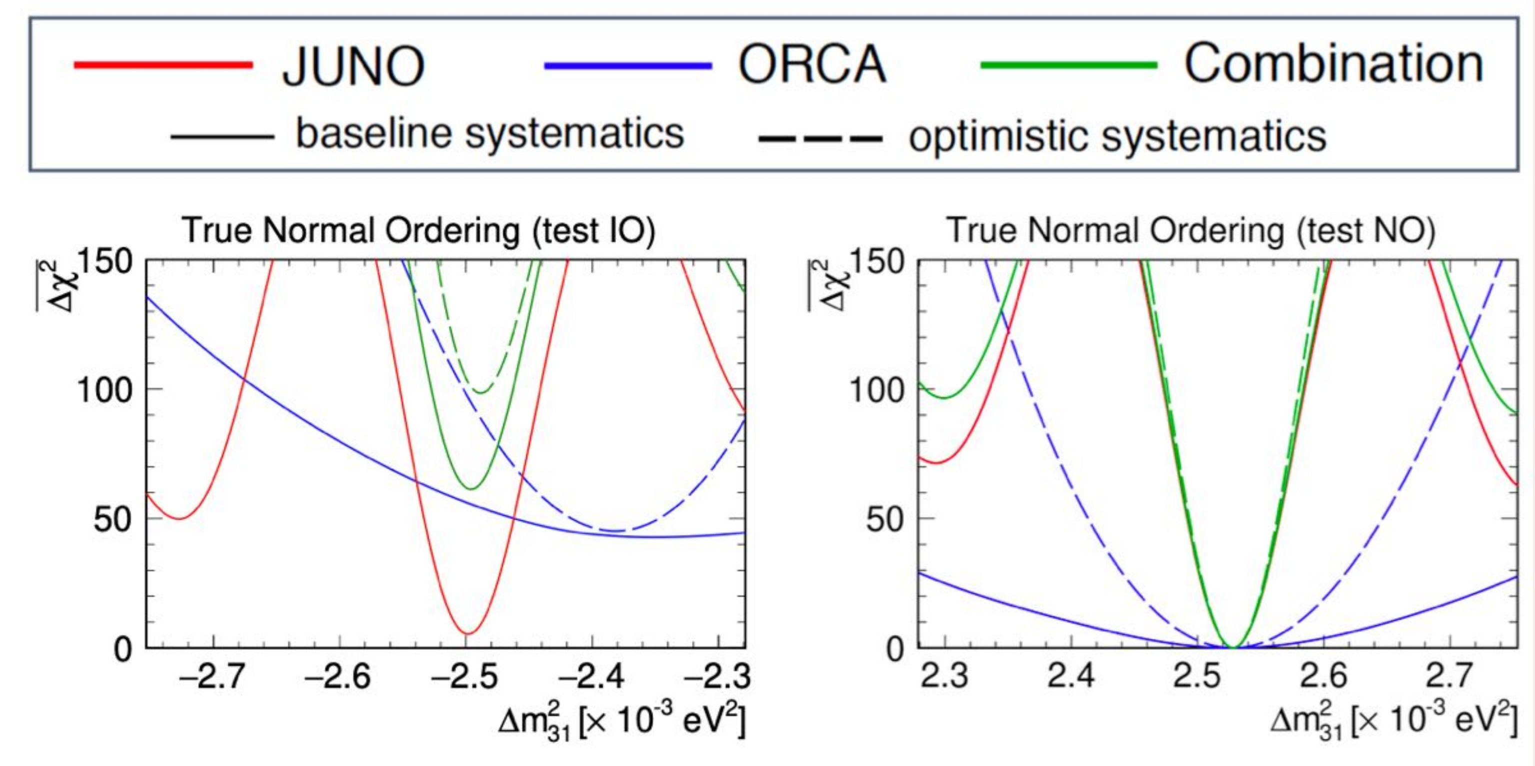
DarkSide-20k



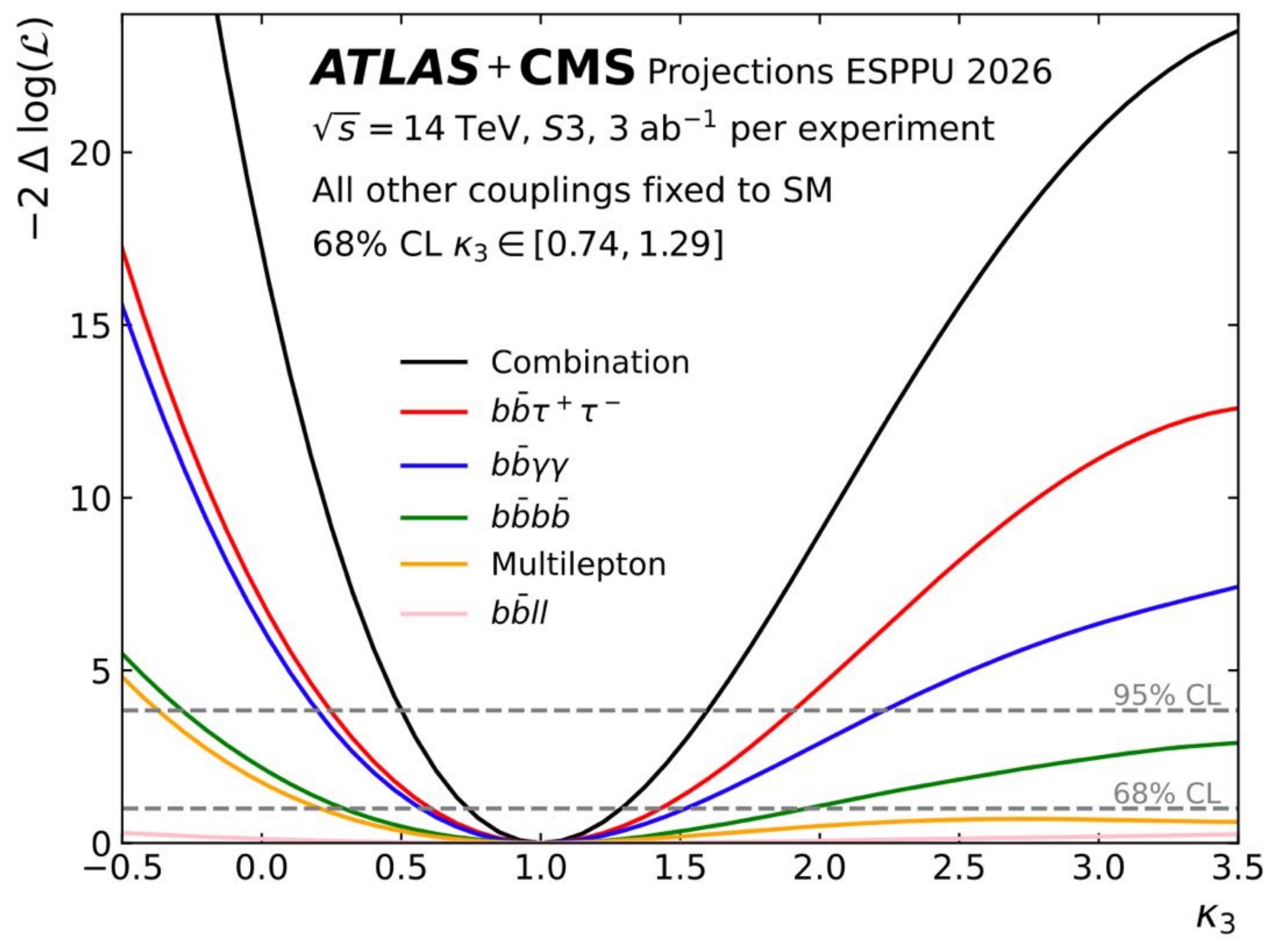
DUNE



ORCA



ATLAS (/FCC)

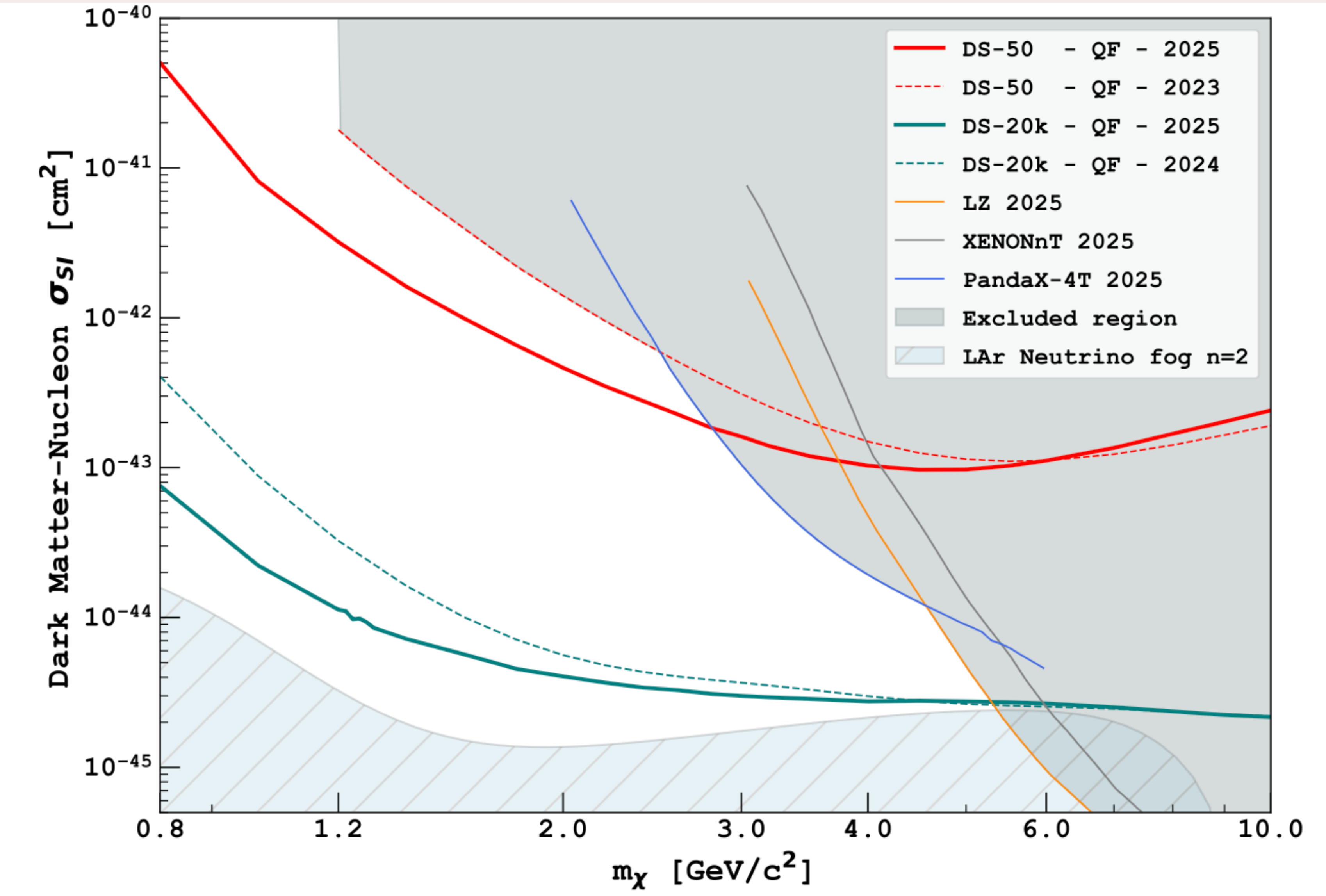


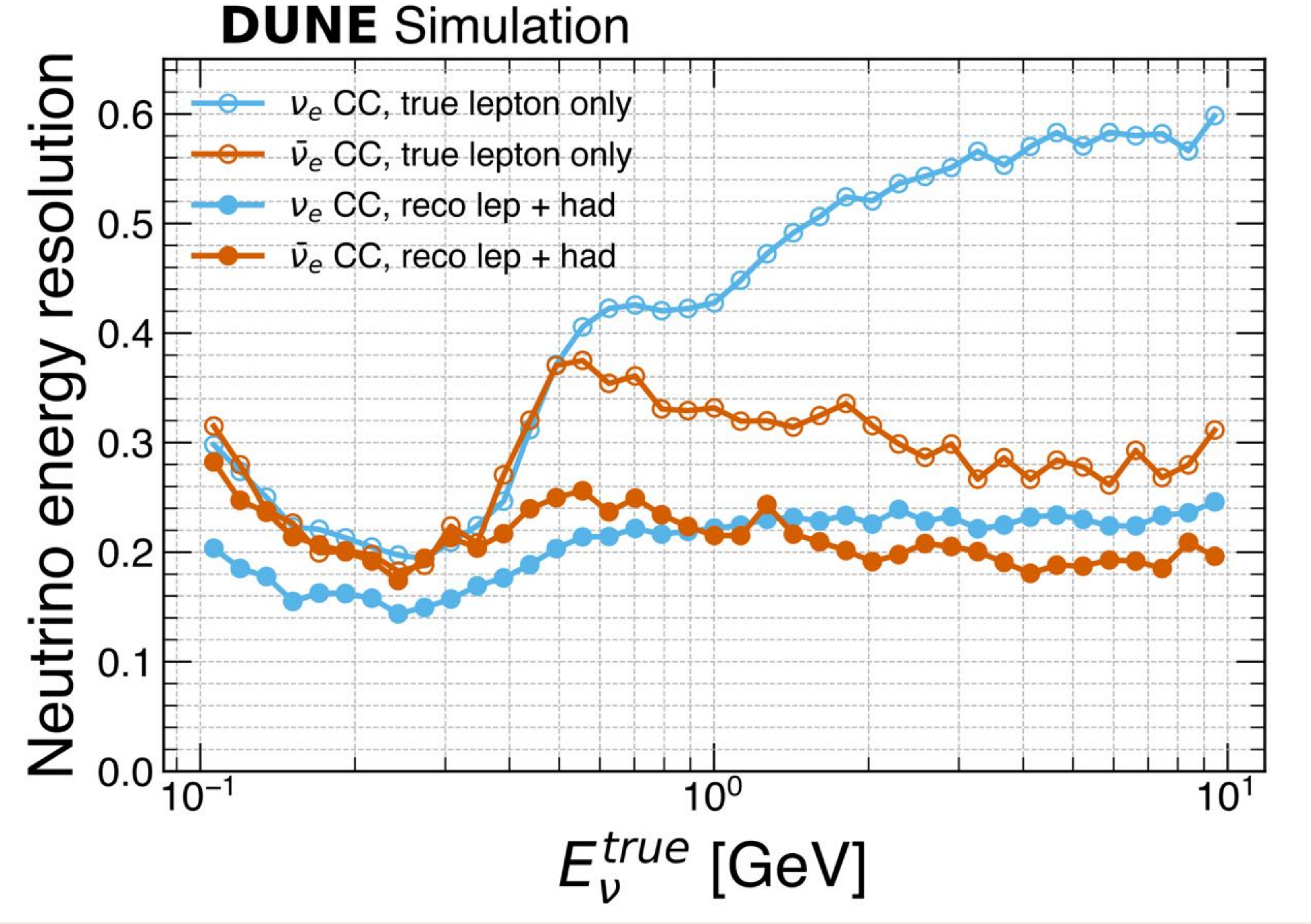
Ongoing activities: how major activities in the group support our goals

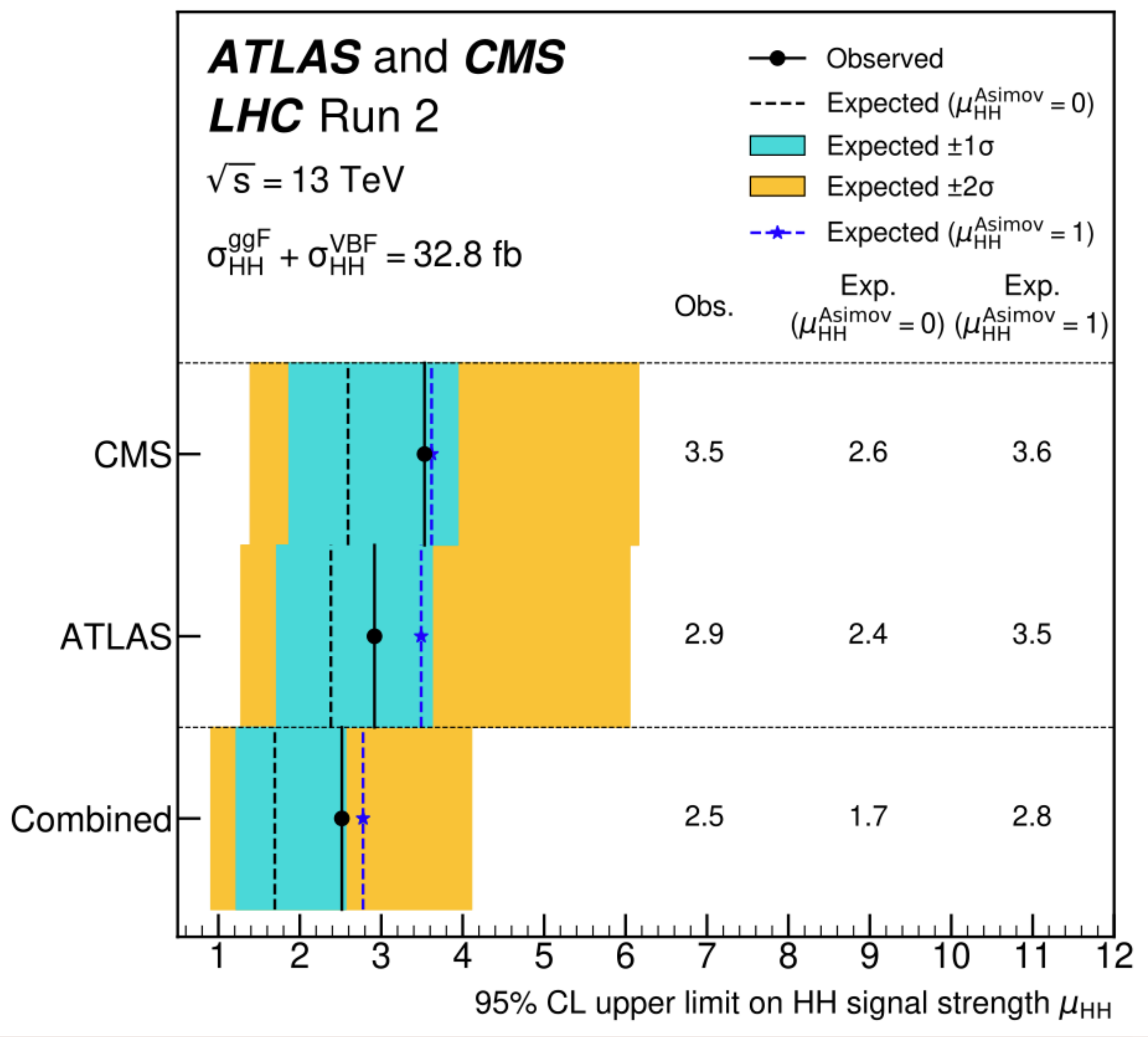
- **DarkSide**
  - **Detector**: coordination and development of DarkSide offline tools, of Event Data Model and of online data-processing
  - **Analysis**: leading efforts in physics analysis: low-mass DM searches, LAr ionisation response calibration, SN ν sensitivity studies
- **DUNE**
  - **Detector**: procurement/QC for transmission and reception from photon-detection system for FD2 (event timestamp & location in detector), developed by APC technicians and engineers
  - **Analysis**: leading role in atmospheric neutrino analysis, with emphasis on topics applicable also to beam analyses (analysis SW infrastructure; event reconstruction: vertex, energy, angle, ν/anti-ν separation; detector systematic uncertainties)
- **ORCA**
  - **Detector**: data quality and monitoring tools, to speed-up availability of data for timely analysis
  - **Analysis**: developments in analysis software (analysis improvements, joint fits with other experiments); studies of flux systematic uncertainties
- **ATLAS/FCC**
  - **ATLAS**: analysis of Run-2 and Run-3 data to search for HH production and constrain Higgs self-coupling in multiple final states
  - **FCC**: leading/coordination role in Higgs sensitivity studies, detector R&D (simulation/reconstruction), international collaboration building

(3) selected recent results related to the goals

- **Dark matter: improved LAr ionization-response model and low-mass DM sensitivity (arXiv 2511.13629)**
  - Measurement with dedicated setup (ReD in Catania) allows discriminating amont ionisation response models, leading to improved sensitivity wrt previous expectations and results
- **Neutrinos: first paper on atmospheric neutrino reconstruction with DUNE FD-HD (arXiv:2601.05697)**
  - Comprehensive review based on full simulation, achieving performance similar to those for beam neutrinos
- **Higgs: full Run2 analyses of ATLAS data performed and combined with CMS (arXiv:2602.23991)**
  - Tightest constraints on HH production and Higgs self-coupling λ ($-0.71 < \lambda/\lambda_{SM} < 6.1$)







Synergies in the lab

- **Strong synergies between neutrino groups in particles team and more broadly with KM3NeT (AHE)**
  - Strong focus on atmospheric neutrinos in both DUNE and KM3NeT groups
  - Shared expertise
  - Shared codes: some code developed for KM3NeT adapted to DUNE & viceversa (MaCh3 software for joint fits)
  - Combined ORCA+ARCA analysis for improved core-collapse supernova neutrino searches (paper)
- **Synergy with gravitation group**:
  - combined ANTARES/ORCA/Ligo+Virgo+Kagra analysis to search for coincidences between neutrinos (ORCA+ARCA) and gravitational waves, for events which could be below the thresholds of individual detectors (from compact binary coalescences)
- ***Potential synergy with AHE*** for use of LAr technology for MeV-γ astronomy on satellite (see e.g. here and here)
- ***Potential for further synergies*** w/ e.g. **cosmology** (constraints neutrino masses), **theory** (neutrinos, precision calculations for FCC), **gravitation** (joint interpretation of LISA and FCC data for constraints on electroweak symmetry breaking)

Scientific and technical opportunities on the long term

- **General remark: all these projects have a long timescale and are already projected into the future**
- **DarkSide**
  - Construction, commissioning and first physics data with DS-20k
  - Beyond: strong connection with DRD2 (noble liquid detector R&D and future rare-event searches)
- **DUNE**
  - Phase-II: FD modules 3&4 → new detectors, new R&D
  - Possibly new experiments relevant to DUNE/neutrino program at large (e.g. nuSCOPE@CERN, SBND@Fermilab)
- **KM3NeT**
  - Establish firm collaboration with other partners (IceCube, JUNO) for mass ordering
  - R&D colored DOM: coat PMTs of digital optical modules with spectrally selective filters to determine water optical properties in multiple wavelengths and improve calibration/reconstruction (break some degeneracies)
- **ATLAS/FCC**
  - FCC the clear scientific opportunity on the long term; technically: R&D on FCC e.g. on LAr calorimetry or CMOS sensors for low-mass trackers

Key challenges (scientific, technical, organisation)

- **[organisation] Common thread: person power**
  - Limited means to hire post-docs (and PhDs to a lesser extent)
  - Small size of some projects (very few staff members) despite major leadership responsibilities
- **[technical] Availability of technical expertise/technical resources at the lab**
  - Can narrow significantly the scope of or limit the amount of projects we can commit to e.g. on DUNE FDs (overall reduction/loss of technical expertise available) but also, on the longer term, on e.g. FCC or other side-projects
- **[scientific]**
  - **ORCA**: major bottlenecks in data processing need to be addressed to make data usable much sooner and deliver physics results in a timely manner
  - **DarkSide, DUNE, ATLAS @HL-LHC**: complete HW installation and SW preparation on time (no delay) and commission the detectors timely to reach the target performance
  - **FCC**: next 2 years crucial to convince the population of the host states, establish funding profile, and optimise detector designs towards prototypes by ~2030. More challenges ahead on the longer term!

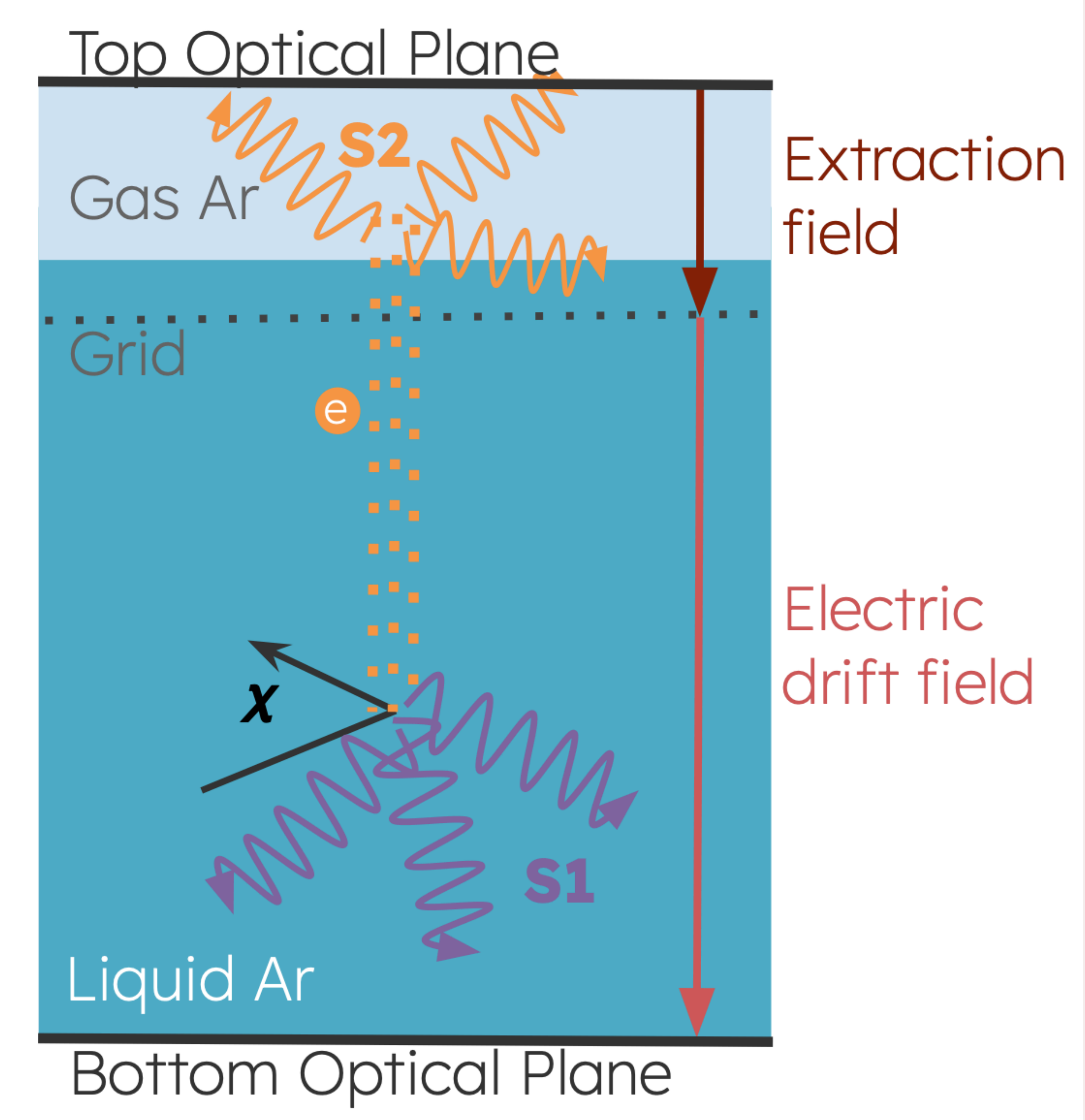
Priorities for the next 5 years (2026-2031)

- **DarkSide**
  - Detector: Deployment of the full offline chain for large-scale operations, commissioning
  - Analysis: first dark matter measurements with early data
- **ORCA**
  - Perform neutrino mass measurement in timely manner; establish joint interpretations with other experiments
- **DUNE**
  - Detector: PDS for FD Vertical Drift module: installation, commissioning, data taking; R&D on cryogenic ASIC for photon-detection readout effort for FD3
  - Analysis: prepare and lead analysis of first DUNE data
- **ATLAS/FCC**
  - ATLAS: full ATLAS Run3 analysis → possible evidence of HH production ; preparation of HL-LHC data-taking (simulation, reconstruction, analysis)
  - FCC: finalise full event reconstruction, optimise detector design, prototype tests, and project approval

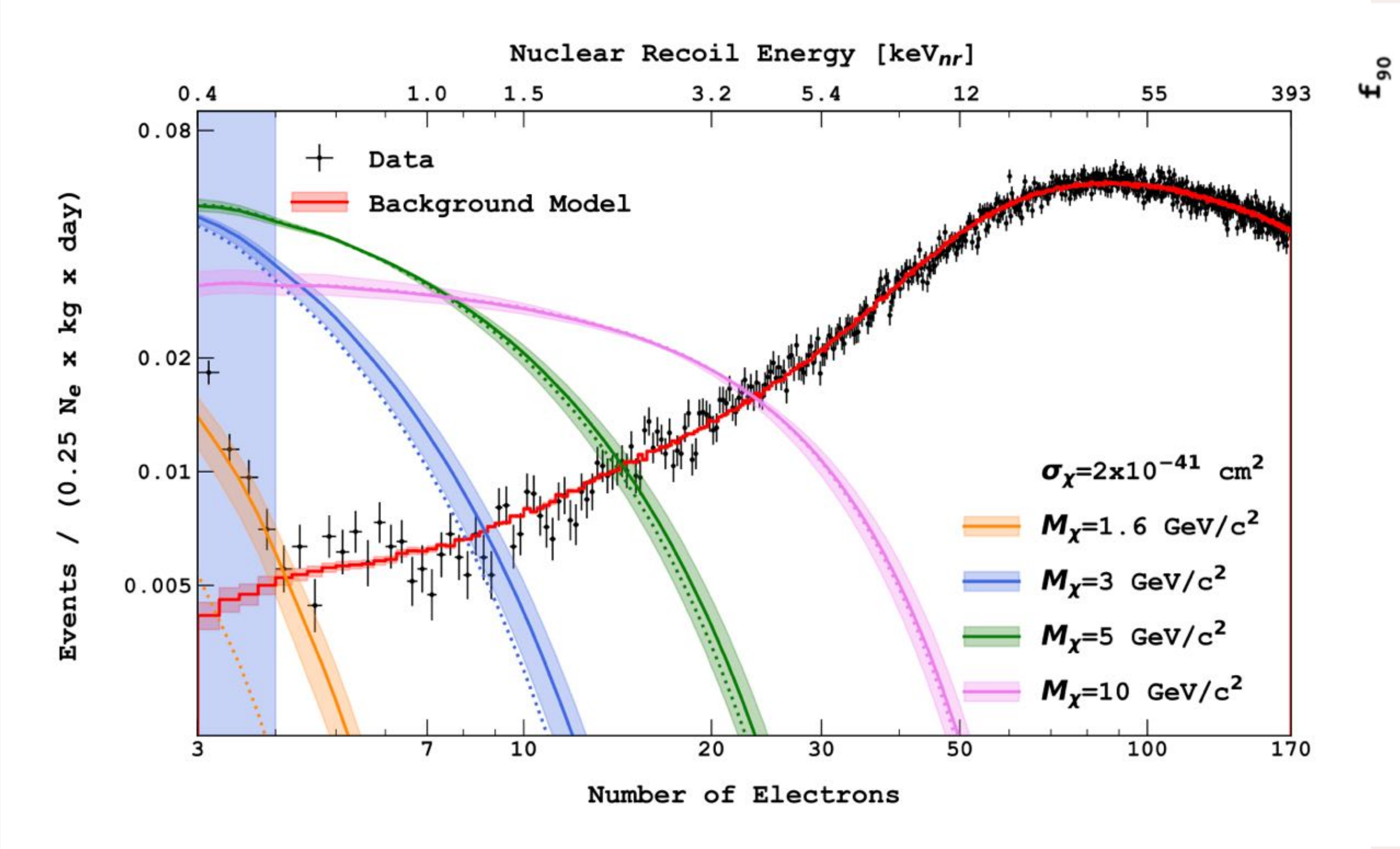
Merci!

DarkSide

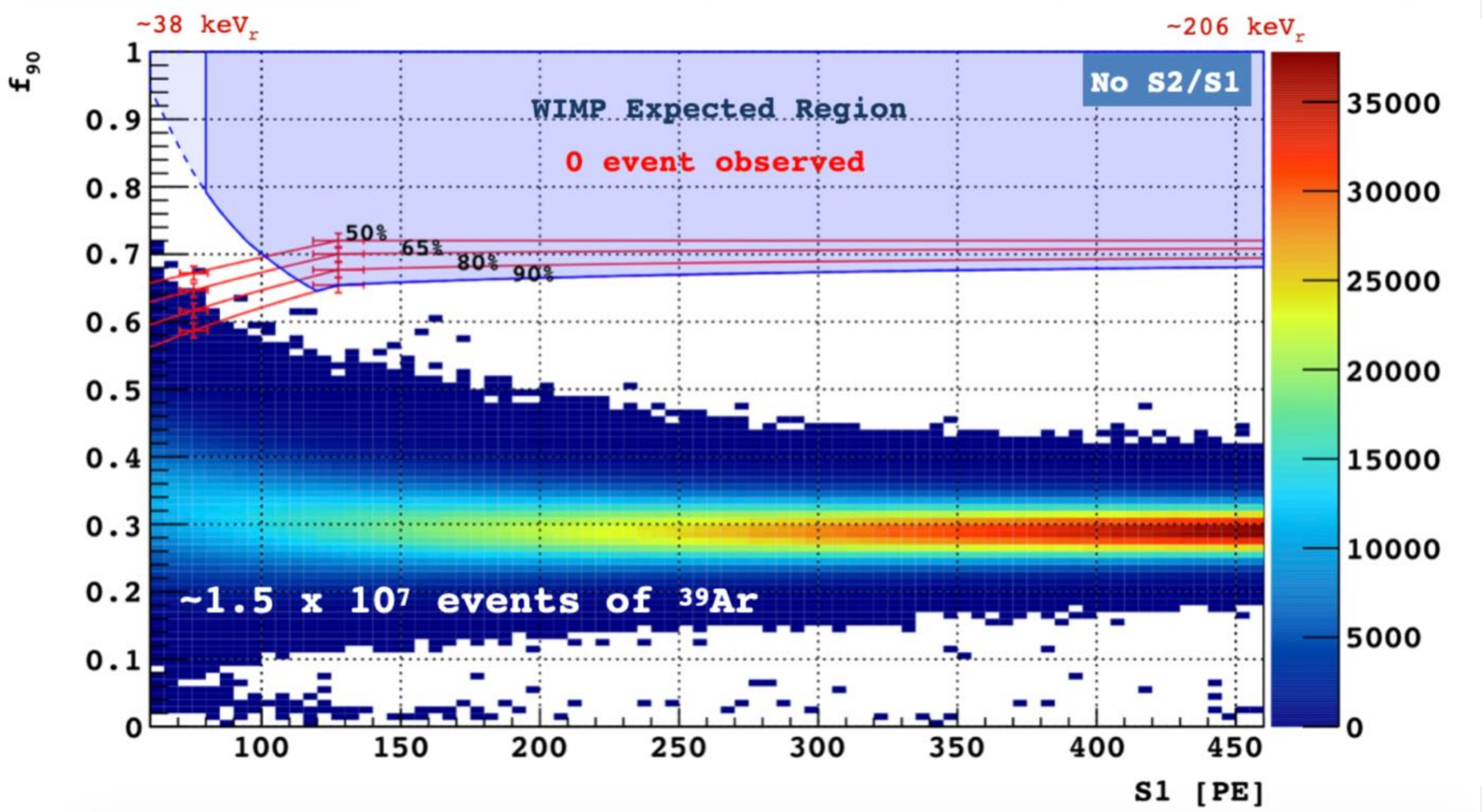
- Eur.Phys.J.Plus 133 (2018) 131
- Dual-phase LAr TPC: liquid at bottom + small “pocket” of gas at top, with top/bottom optical planes
- Signals from
  - Scintillation light (S1) - prompt, different decay time for nuclear vs electron recoil (different states created) => pulse shape discrimination (PSD) for bkg suppression
  - Electroluminescence light (S2) - delayed, photons produced by ionisation electrons once they reach the gas and are accelerated by the electric field inside it
- Searches for
  - “Vanilla” WIMPs (0.1-100 TeV): via WIMP-nucleon scattering, use both S1 and S2, and PSD to remove ~all background. Recoil energy spectrum => mass, yield => x-section
  - Low-mass DM (~1-10 GeV): use only S2 (eff.~16% for S1..), 100% efficient down to 1-electron, but some bkg (currently) from spurious electrons → threshold >=3–4 e-
  - SN neutrinos: via coherent elastic neutrino-nucleus scattering (JCAP 03 (2021) 043)



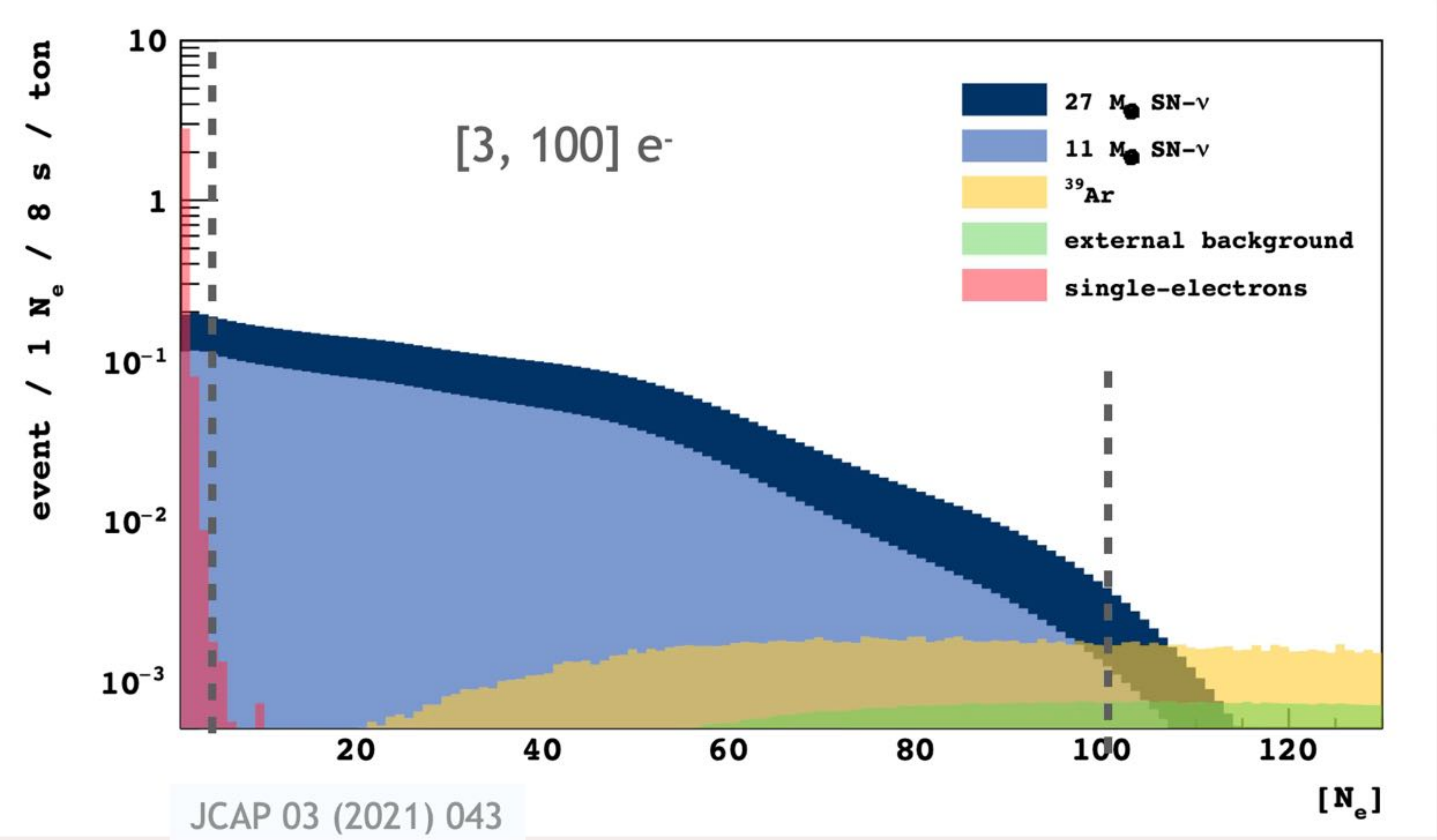
DarkSide



Light DM



0.1-10 TeV WIMPs

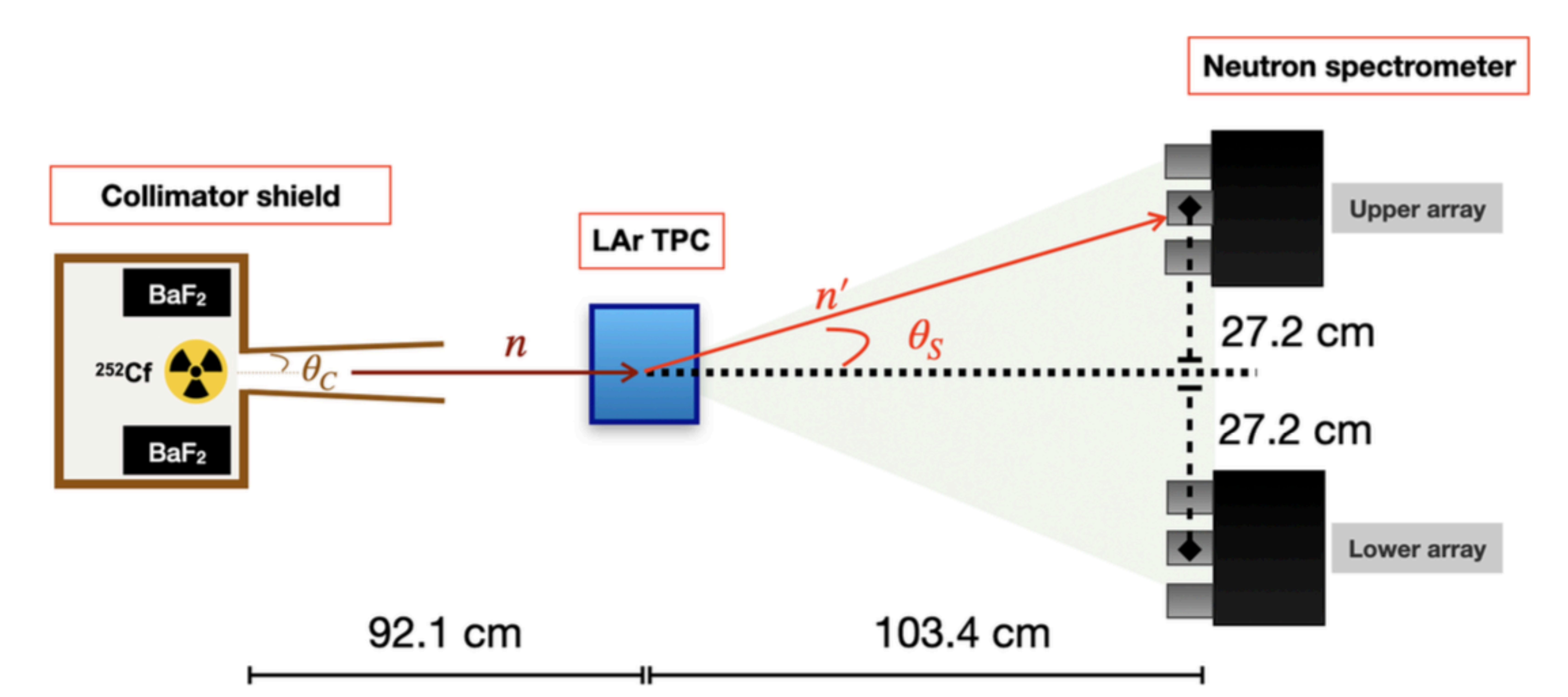


SN neutrinos

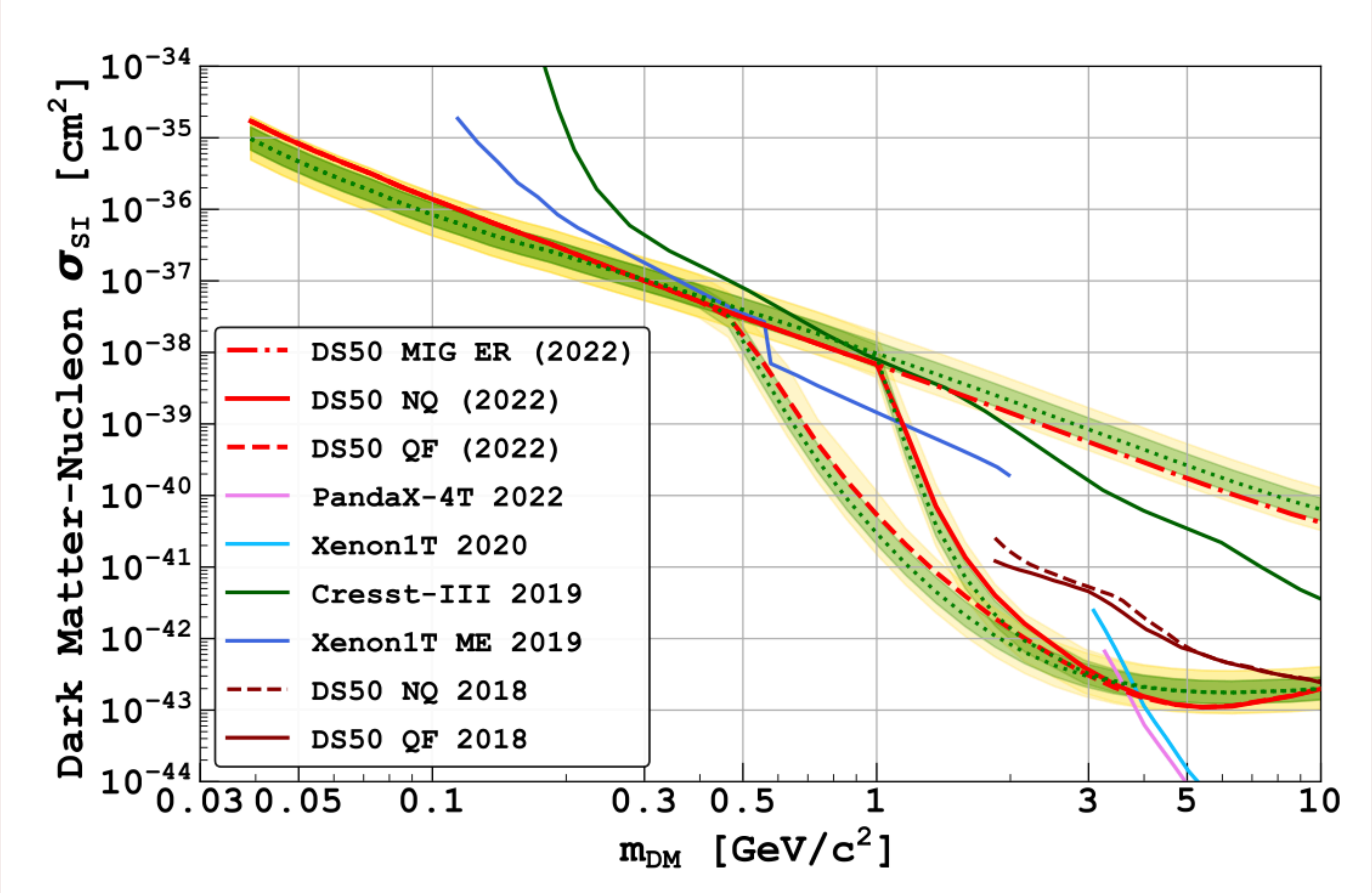
(detect all flavours from core collapse supernova via CEvNS)

Small dual-phase LAr TPC (5x5x6 cm^3)
$\mathcal{O}$(2 MeV) neutrons from spontaneous ^{252}Cf fission, tagged from γ with BaF_2 scintillator.

Eur. Phys. J. C (2026) 86:220

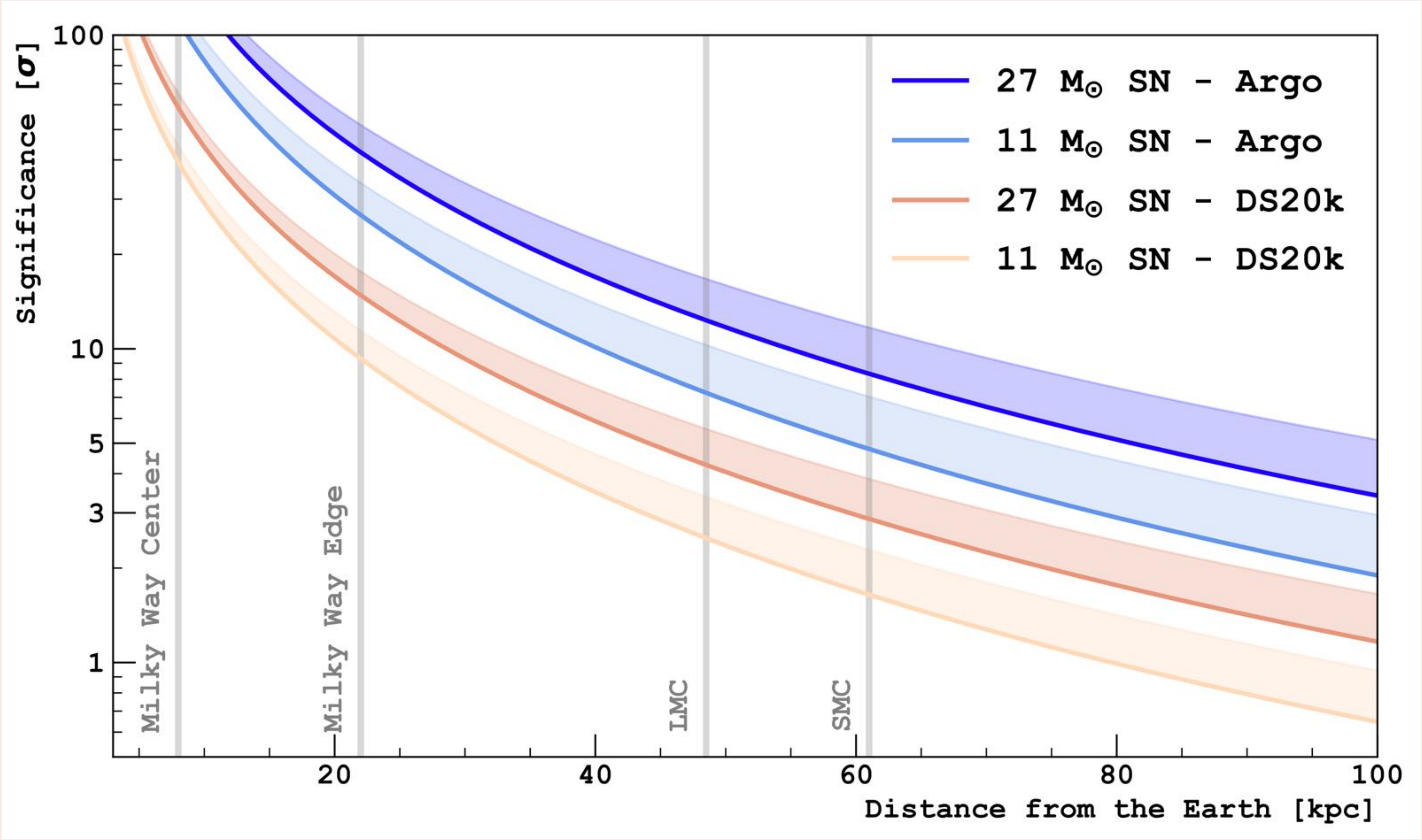


DarkSide - more (older) results



PRL130 (2023) 10, 101001: Search for low-mass DM-nucleon interactions via Migdal effect with DS-50

- only ionisation signal
- consider enhancement of ionisation by Migdal effect (atomic effects leading to emission of electrons with fraction of nuclear recoil)



JCAP 03 (2021) 043: core-collapse supernova neutrino sensitivity via coherent elastic neutrino-nucleus scattering

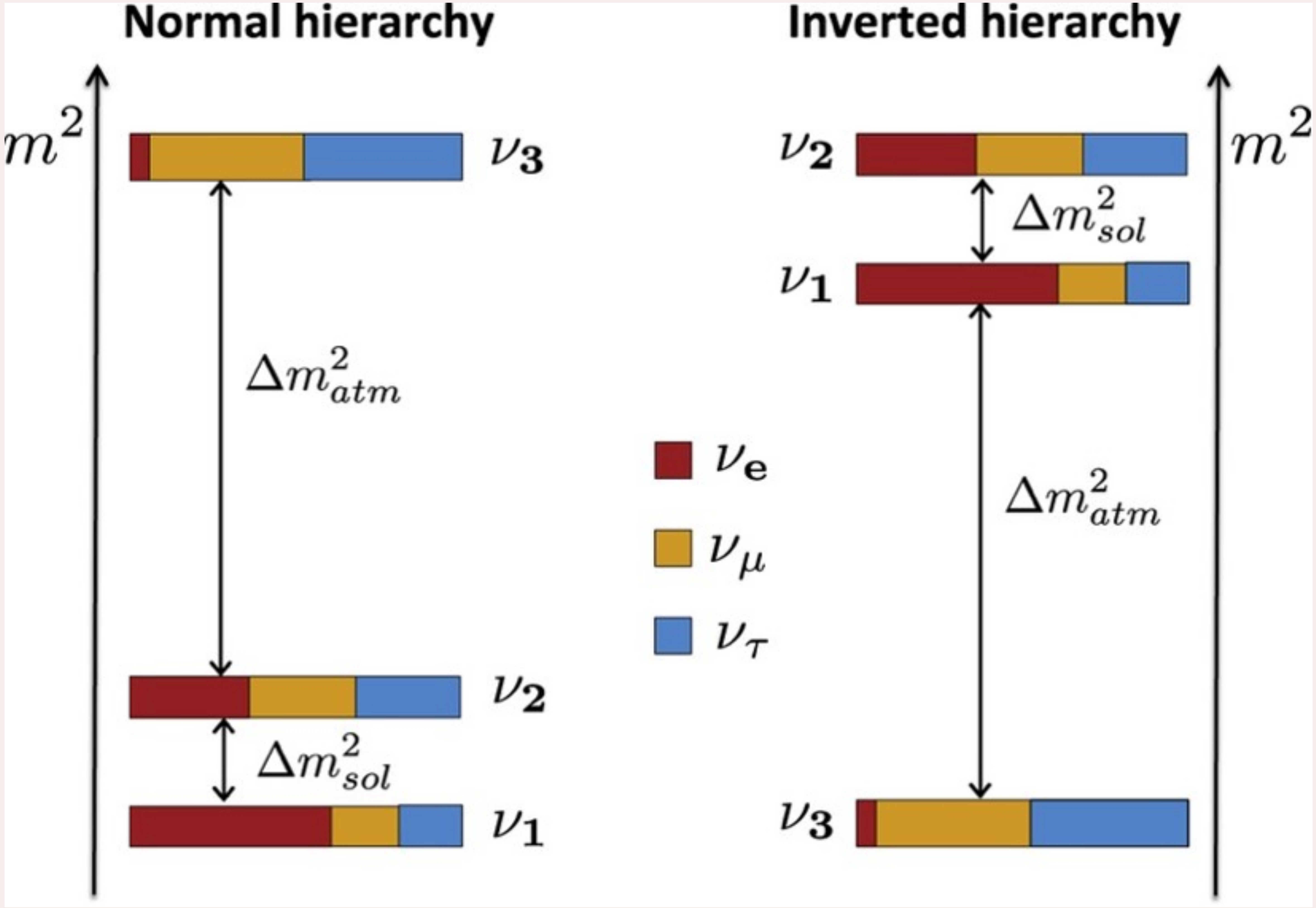
* low energy threshold -> potential to discover supernova bursts throughout our galaxy assuming a 11-M⊙ progenitor star

Neutrino mass ordering (MO)

- $|\Delta m_{12}|$~0.009 eV
- $|\Delta m_{13}|$~0.05 eV

- NO: sum(m_ν) >~ 0.06 eV
- IO: sum(m_ν) >~ 0.11 eV

- Cosmology constrains sum(m_ν) from above



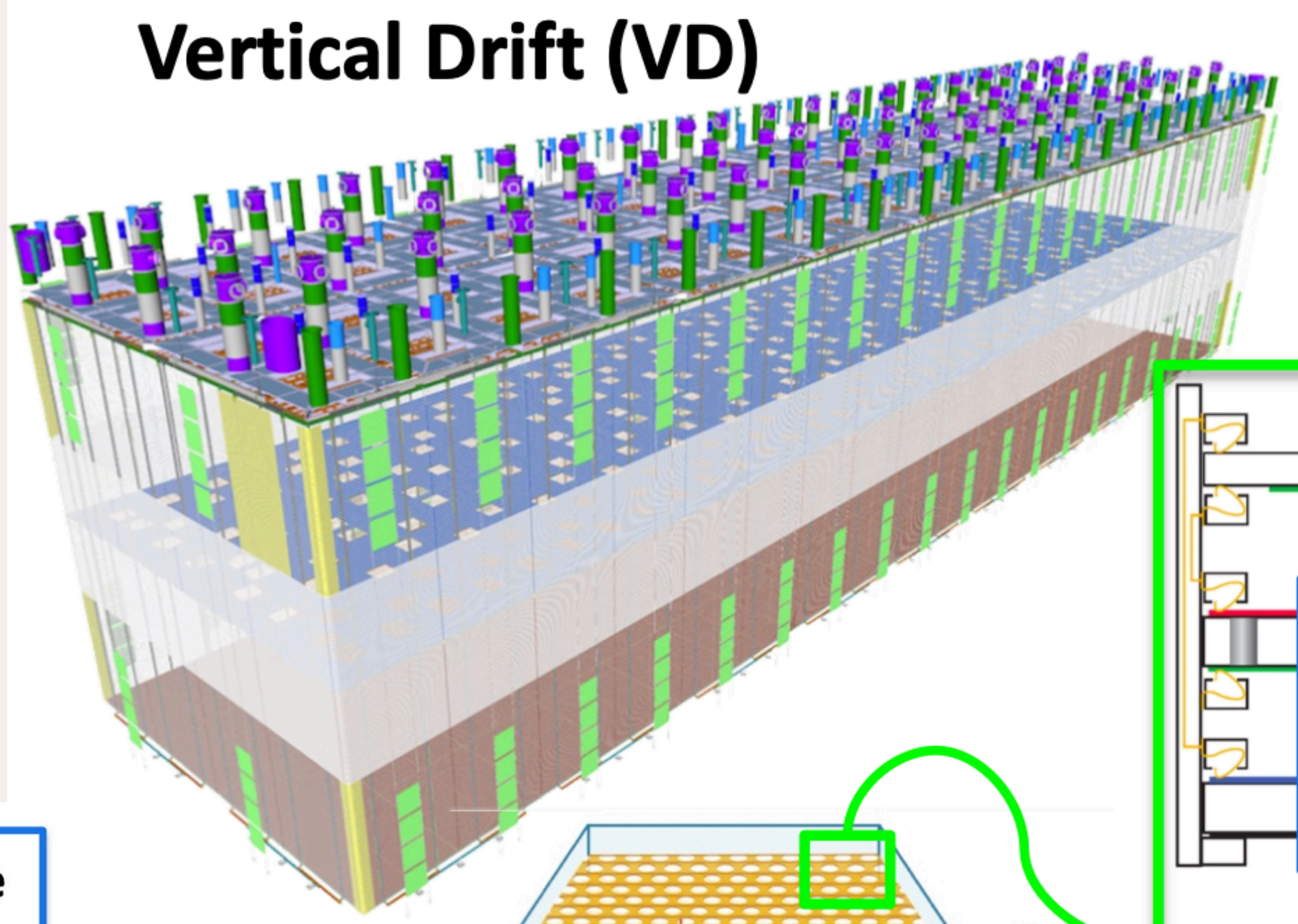
DUNE

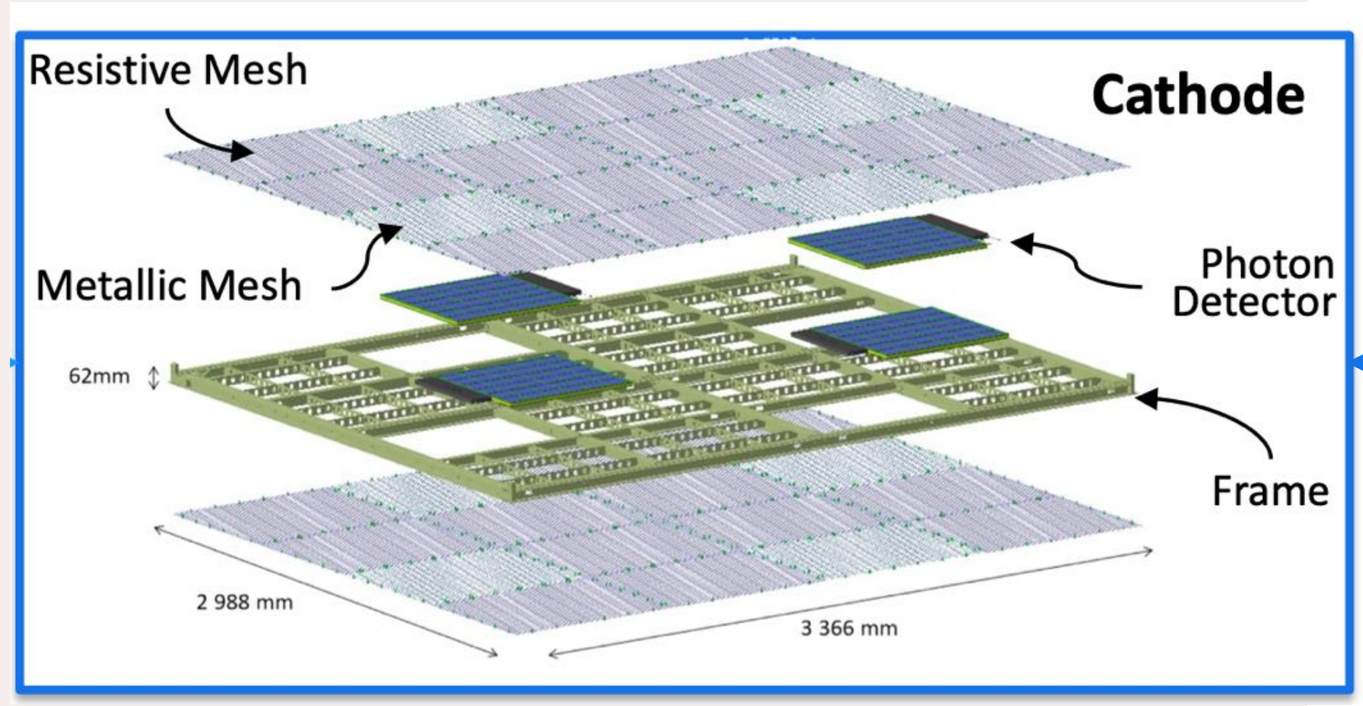
- Experiment:
  - World's most powerful wide-band neutrino beam from Fermilab, long baseline (1300 km)
  - Characterised by Near Detector (ND) system (→ control systematic uncertainties)
  - Far Detector (FD): 4 LAr TPCs each holding 14 tons of LAr.
- Staged approach for construction
  - phase-I: 2026 start installation (2 FDs) / 2030 start physics (atm, FD-VD) / 2032 beam (1.2 MW) + ND + FD-HD
  - phase-II: 2 more FDs; multi-MW beam; more capable ND
- Signals
  - Oscillating neutrinos from beam: E_ν ~0.5–6 GeV
    - >3σ CPV in 3.5 years in best scenario (δ_{CP}=90°)
    - Oscillation parameters and PMNS unitarity: can measure θ_{13}, θ_{23}, Δm^2_{13} via ν_μ disappearance, ν_e appearance (θ_{13} from long-baseline and reactor experiments only equivalent if unitarity is assumed)
  - Solar ν: measure mixing parameters and ^8B flux w/ low-energy events (5 MeV thr. for recoiling e^- from $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$ and $\nu_x + e^- \rightarrow \nu_x + e^-$)
  - Atmospheric neutrinos: first data (2030–2032), crucial for commissioning and physics studies, can provide complementary information on δ_{CP} (sub-GeV upgoing ν) and on mass ordering (few-GeV upgoing ν)
  - SN neutrinos→ 5 degree pointing resolution depending on SNB location
  - BSM: sterile neutrinos (can measure ν_τ appearance and test $P(\nu_\mu \rightarrow \nu_e)+P(\nu_\mu \rightarrow \nu_\mu)+P(\nu_\mu \rightarrow \nu_\tau)=1$); proton decay

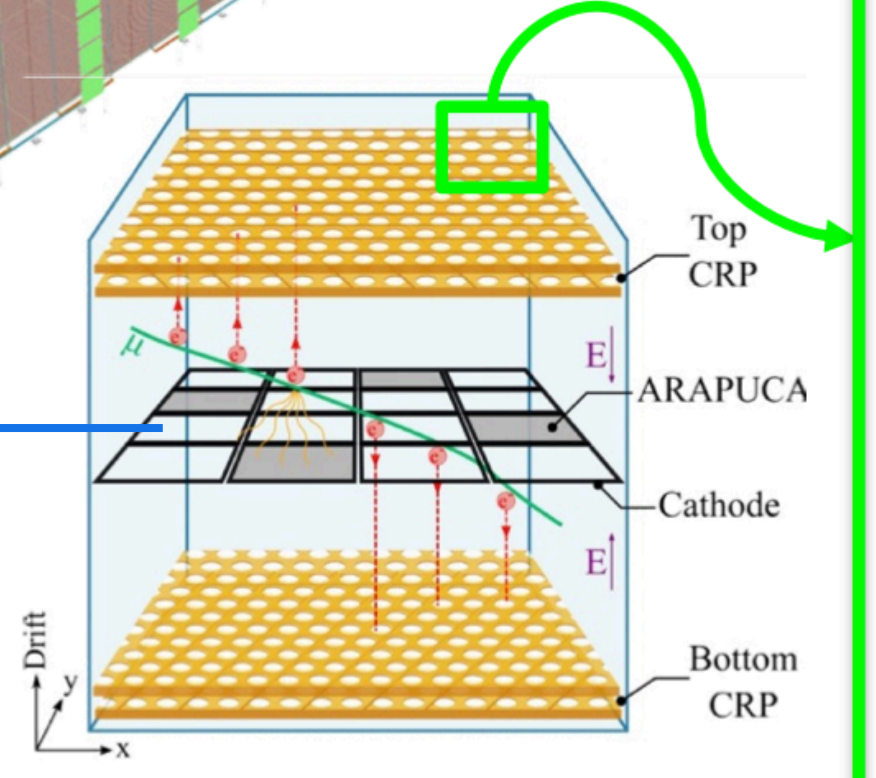
DUNE

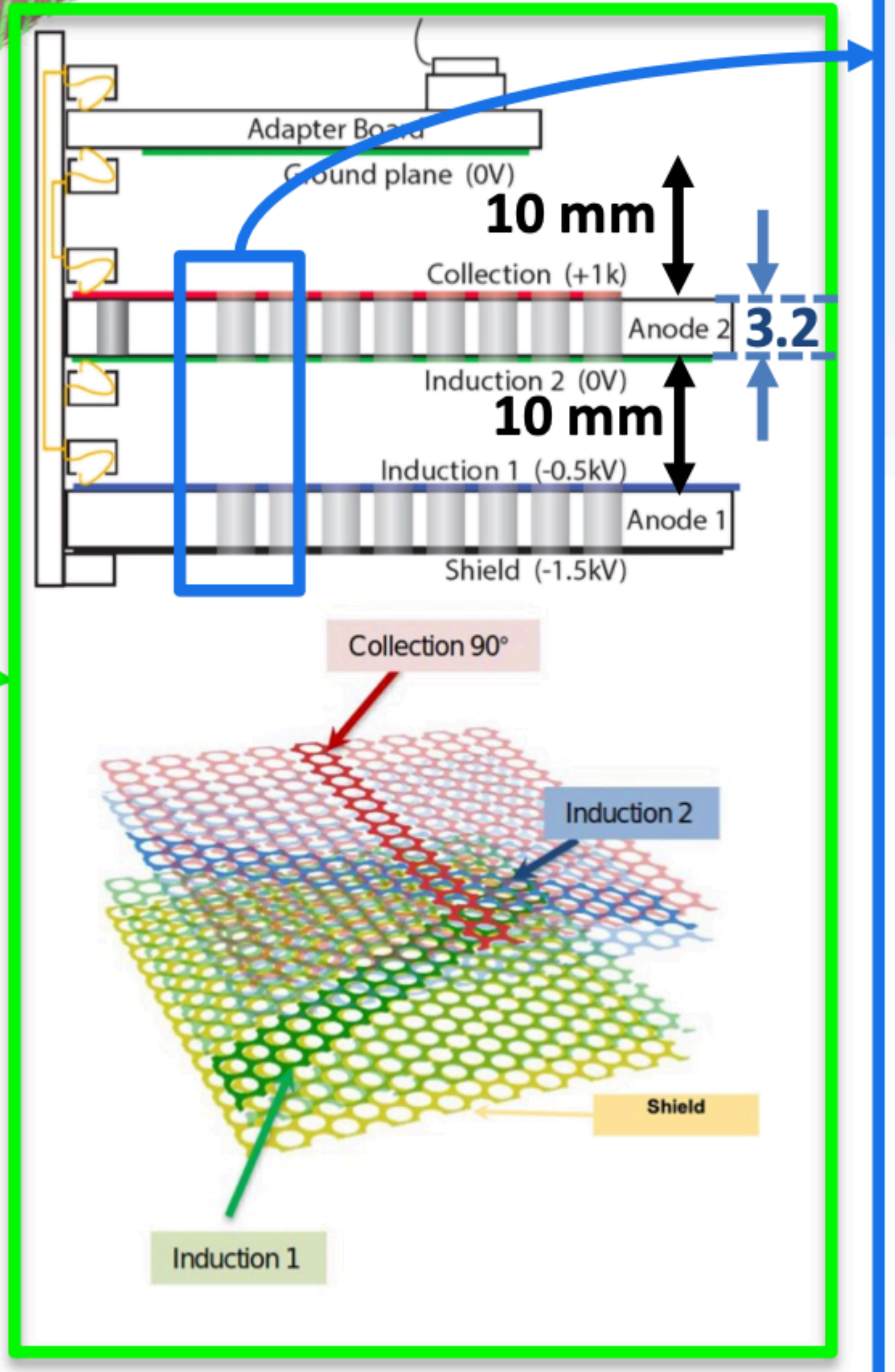
- Status of main experiment
  - Cavern excavated (2024)
  - South cavern preparation for detector completed Feb 2026
  - VD cryostat erection starts Aug 2026 (material already in the US)
  - First far detector (VD) ready by ~2030 (built by 2029, filled by 2030)
  - HD: built by 2030, filled by 2032
- CERN neutrino platform
  - Coldbox TPC: cathode + PDS, ~0.3 m drift
  - ProtoDUNE NP02: 1/40 vertical slice of DUNE, 2x3.4m vertical drift
  - Installation mockup: mechanical model 1:1 for training
  - Tests of ProtoDUNE-VS in 2025–2026 with cosmic rays, beam, laser => noise, purity, lifetime, HV, reconstruction …

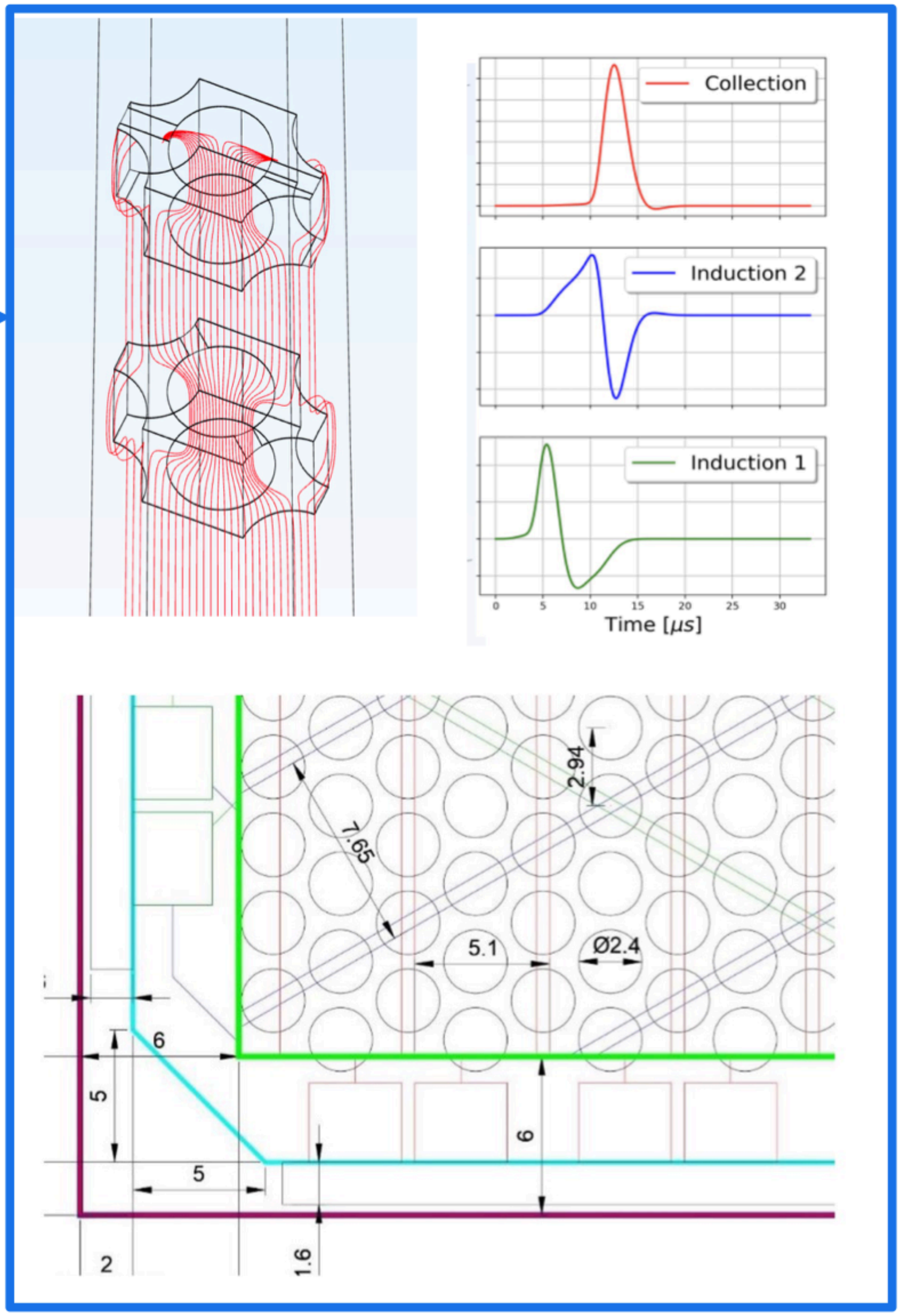
DUNE - Vertical Drift (VD)





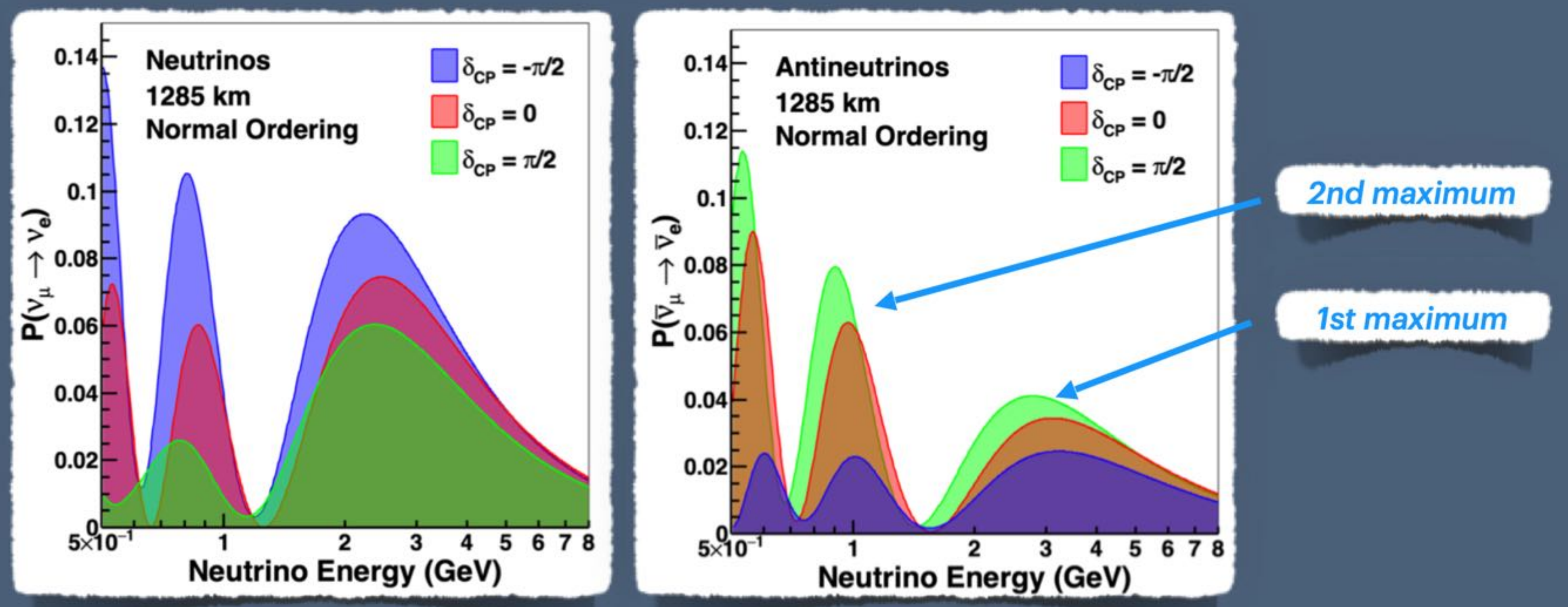




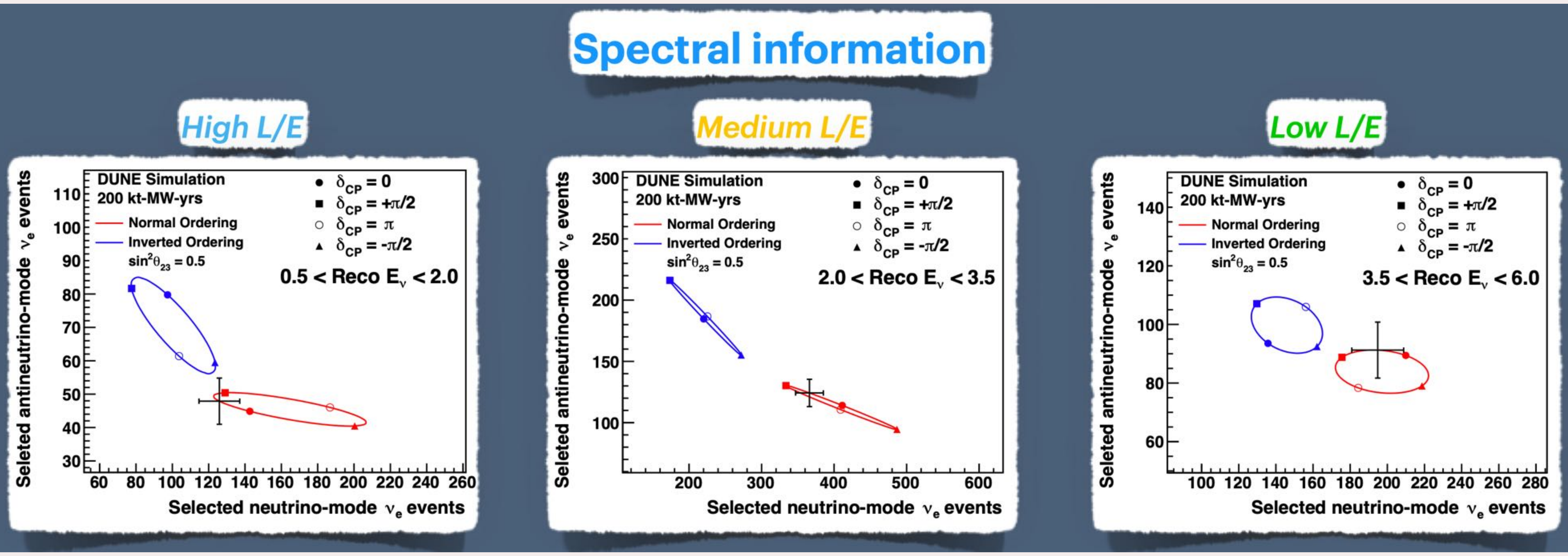


- Drift length ~ 640 cm
  - HV on cathode ~ 300 kV
- Charge readout plane (CRP) technology
- Photon detectors integrated in cathode plane and membrane walls
- **~ 14.7 kt of Instrumented Volume in LAr**

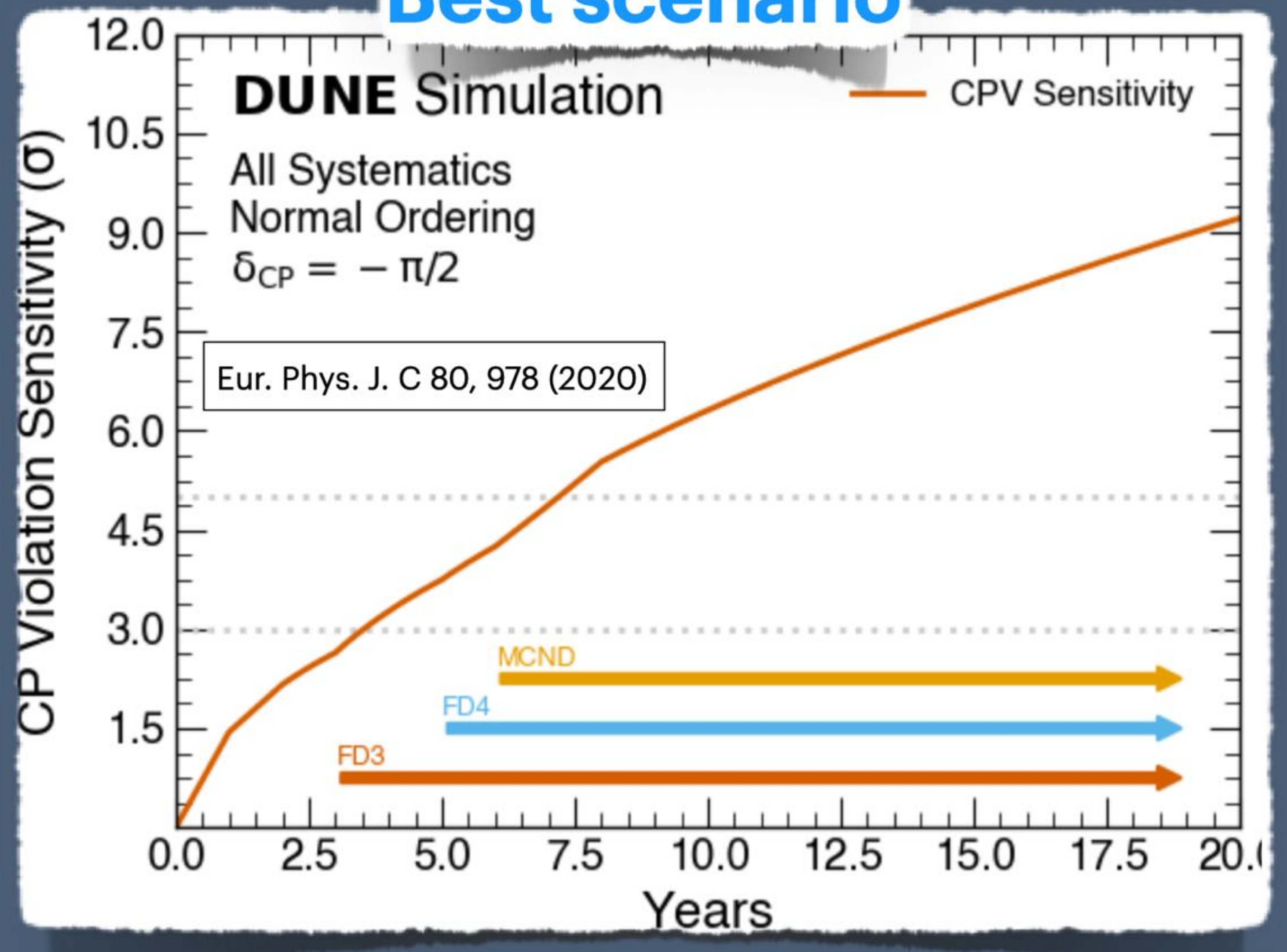
DUNE



- Wide band beam and long baselines ***break the degeneracy between δ_{CP} and matter effects***.

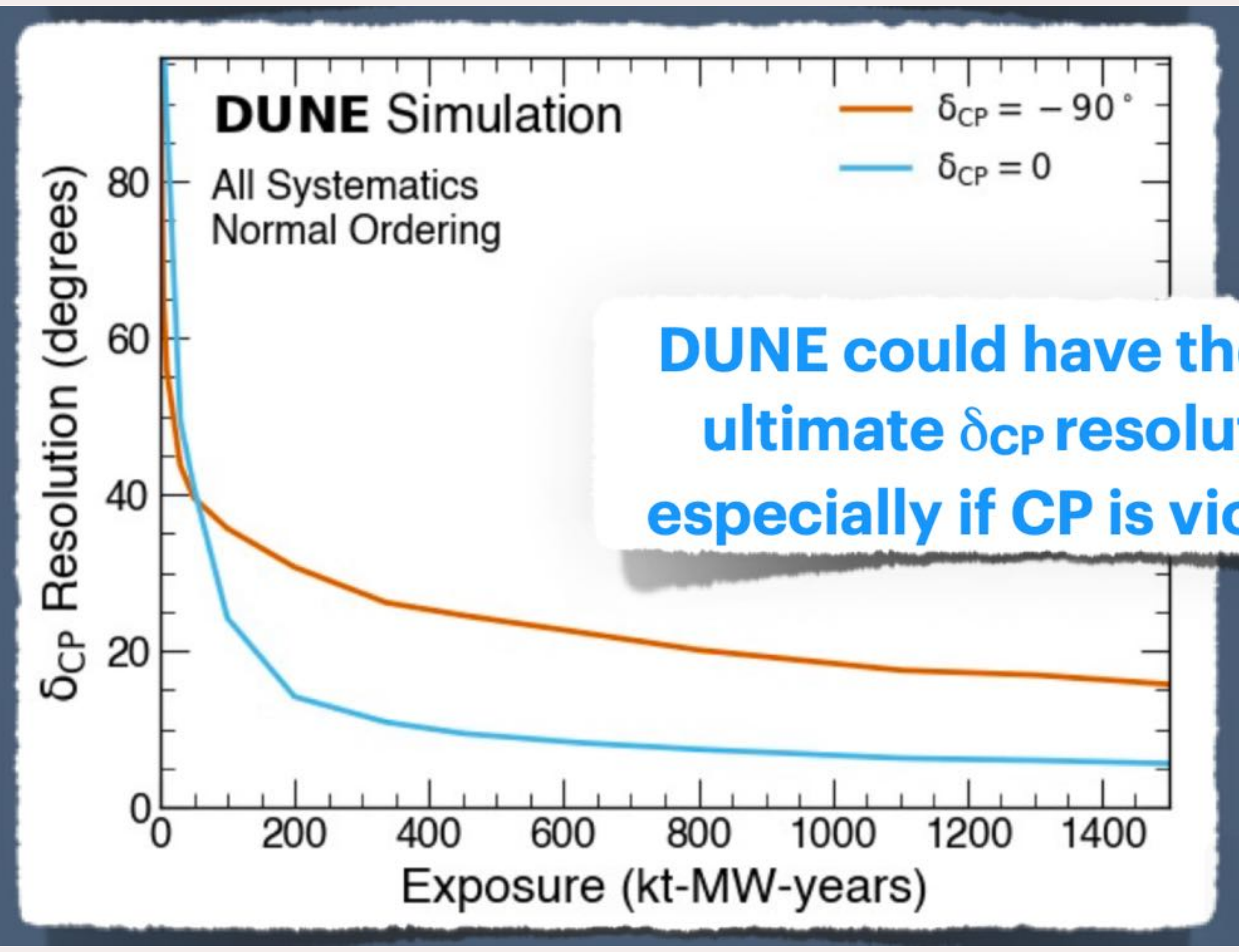


Best scenario



DUNE could have >3 σ CPV sensitivity in 3.5 years

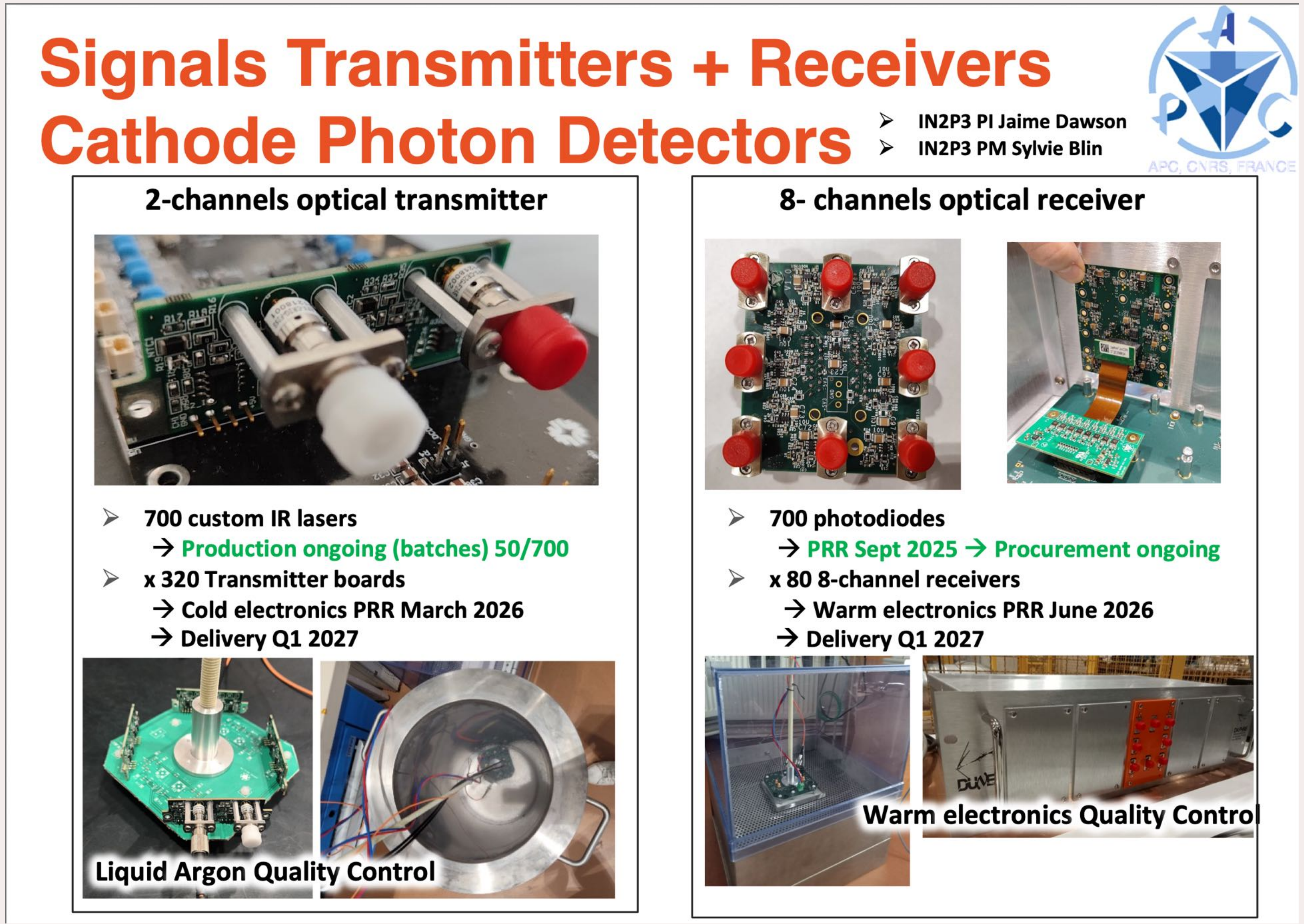
Comparable results between DUNE and HK



DUNE could have the best ultimate δ_{CP} resolution, especially if CP is violated.

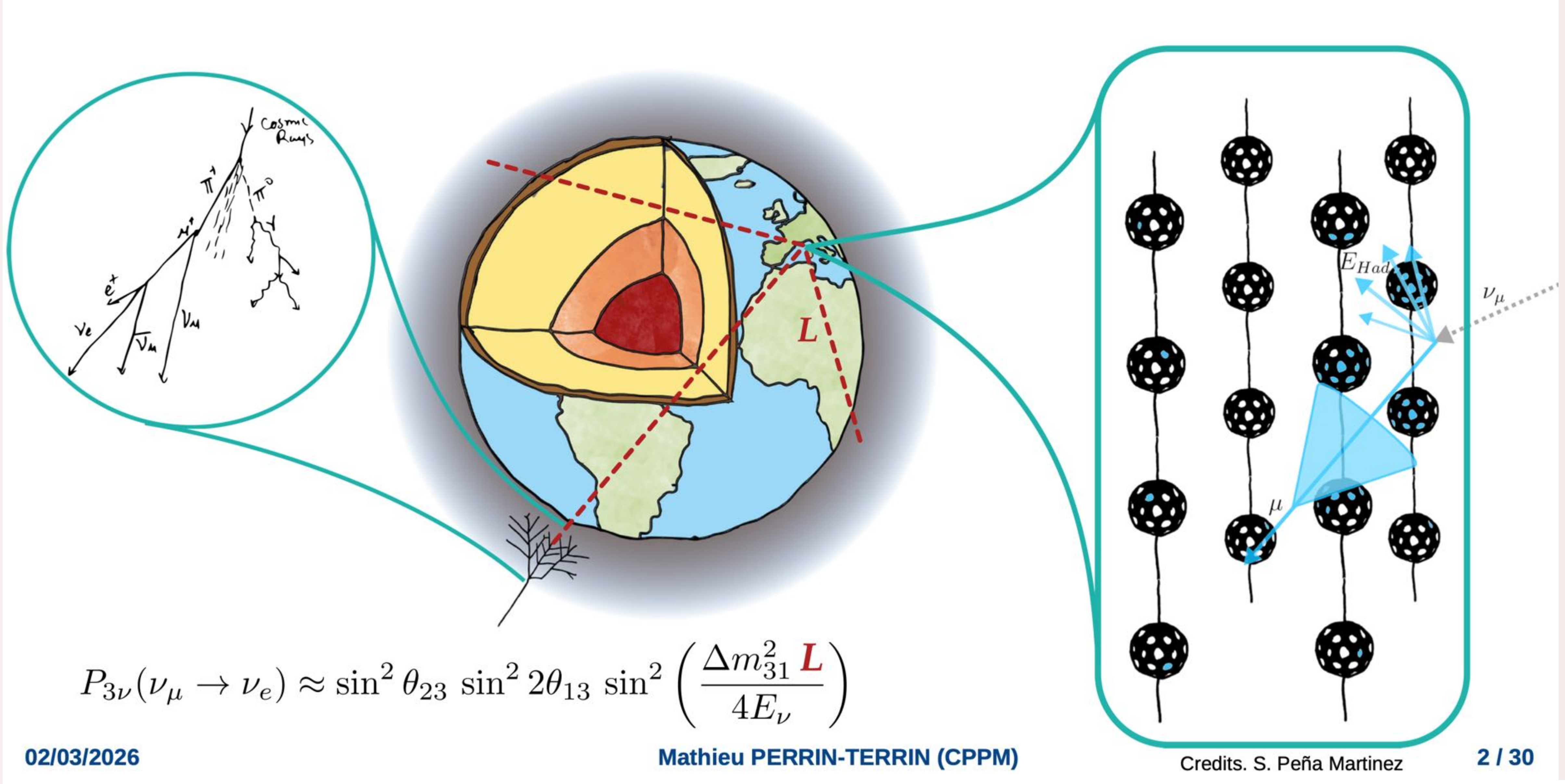
DUNE @ APC

- Atmospheric, sterile and supernova neutrinos, and systematic studies @ DUNE
  - First paper on atmospheric neutrino reconstruction (arXiv:2601.05697) / new framework for far detector systematics; development of SW framework for oscillation analysis (MaCh3) and analysis data format (CAF)
- Neutrino events, reconstruction, PDS-related analysis @ CERN prototypes (ProtoDUNE, ColdBox)
  - First observation of neutrino candidates in ProtoDUNE
- Test / Procurement / QC of optical signal transmitters (lasers) / receivers (photodiodes) for cathode photon detectors for FD-VD



- References:
  - https://indico.in2p3.fr/event/37437/contributions/163491/attachments/99954/154654/DUNE_CSIN2P3v8BK.pdf
  - https://indico.in2p3.fr/event/37437/contributions/165623/attachments/99956/154658/DUNE_CSIN2P3_final.pdf

KM3NeT/ORCA



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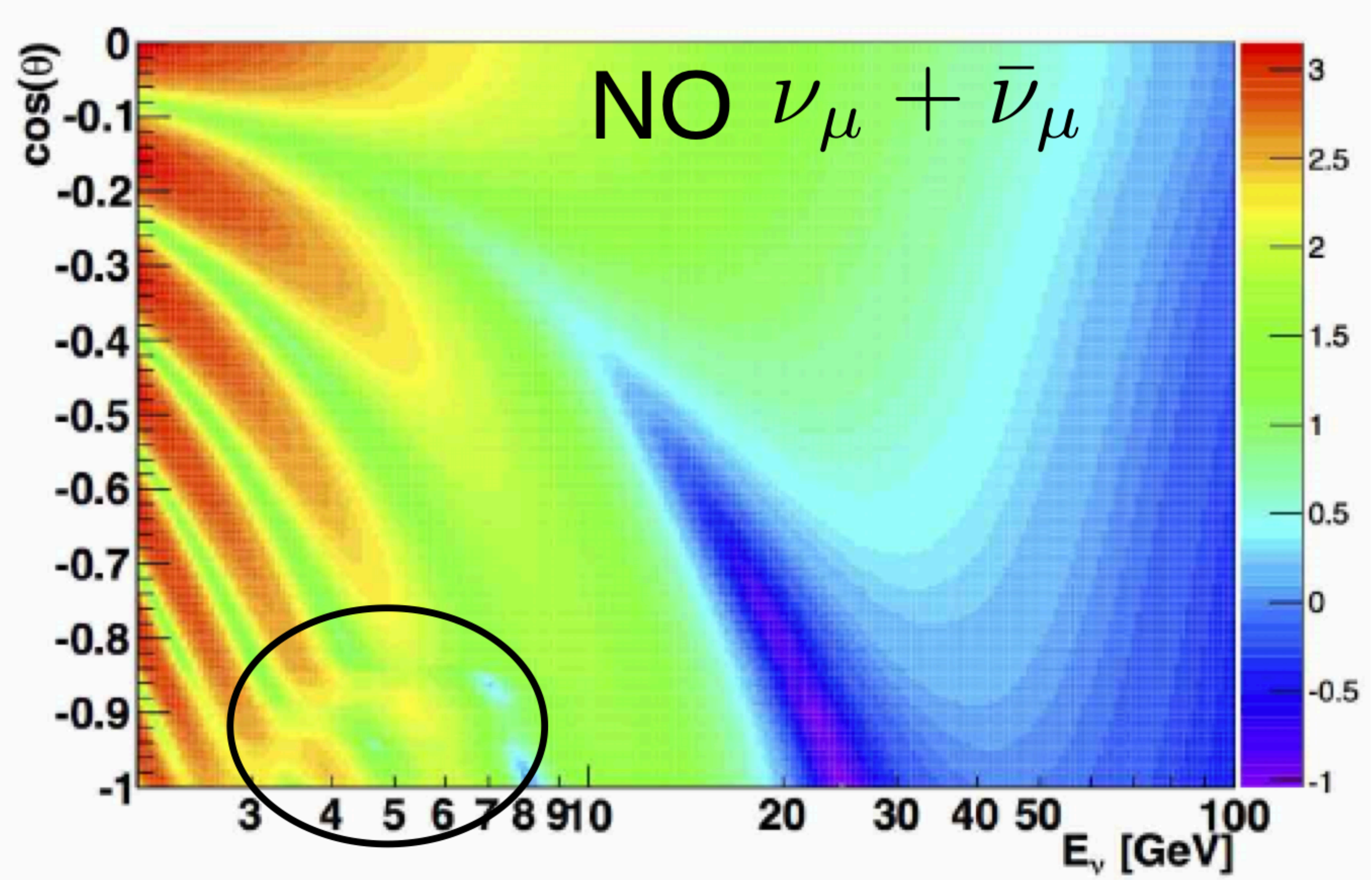
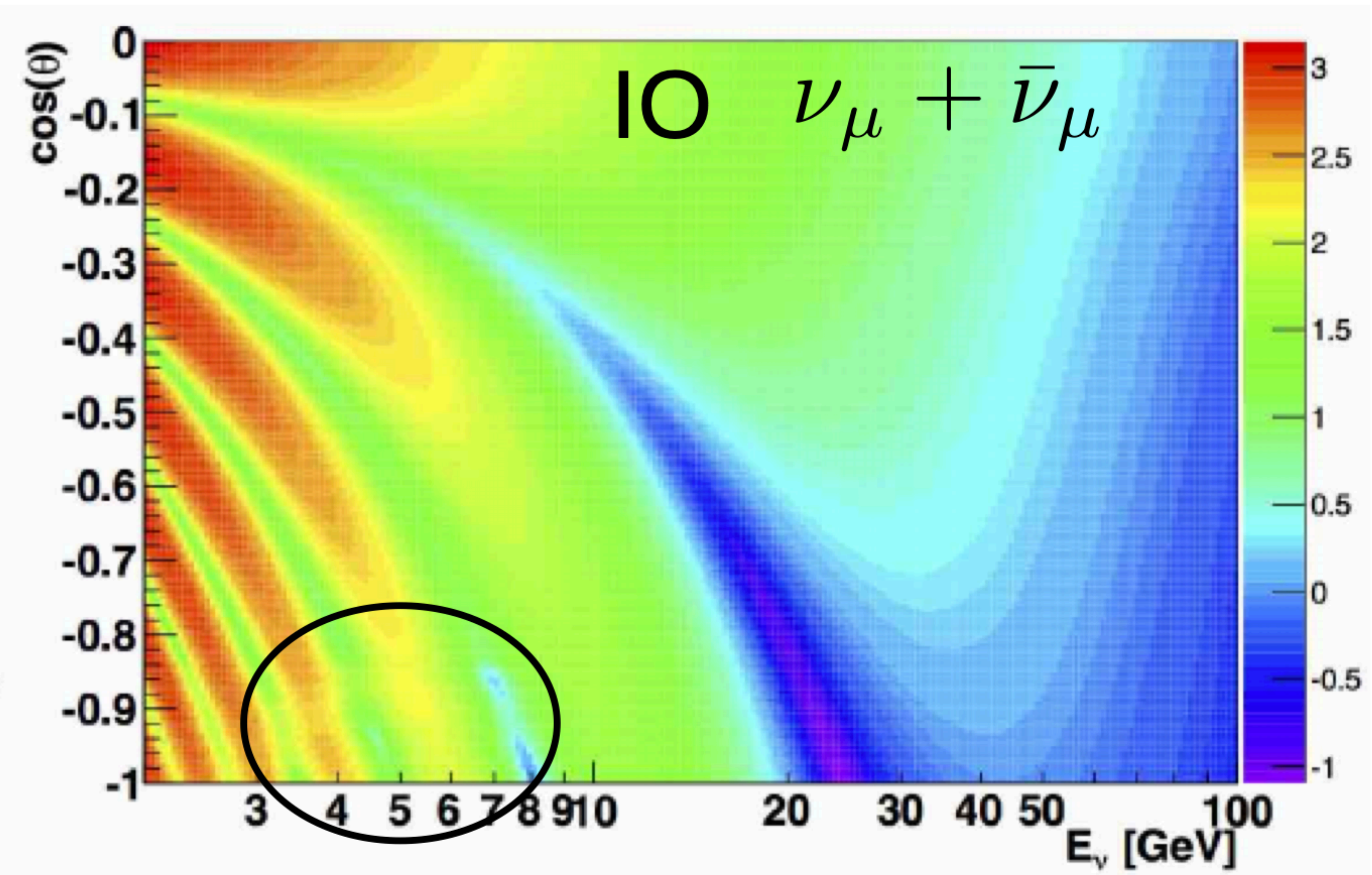
- **Matter** along the neutrino propagation makes the oscillation propability sensitive to NMO

$$P^m_{3\nu}(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} 2\sin^2\theta^m_{13}\sin^2\left(\frac{\Delta^m m^2 L}{4E_\nu}\right)$$

$$\sin^2(2\theta^m_{13}) \equiv \frac{(\Delta m^2_{31}\sin 2\theta_{13})^2}{(\Delta m^2_{31}\cos 2\theta_{13} \mp 2E_\nu V_{CC})^2 + (\Delta m^2_{31}\sin 2\theta_{13})^2}$$

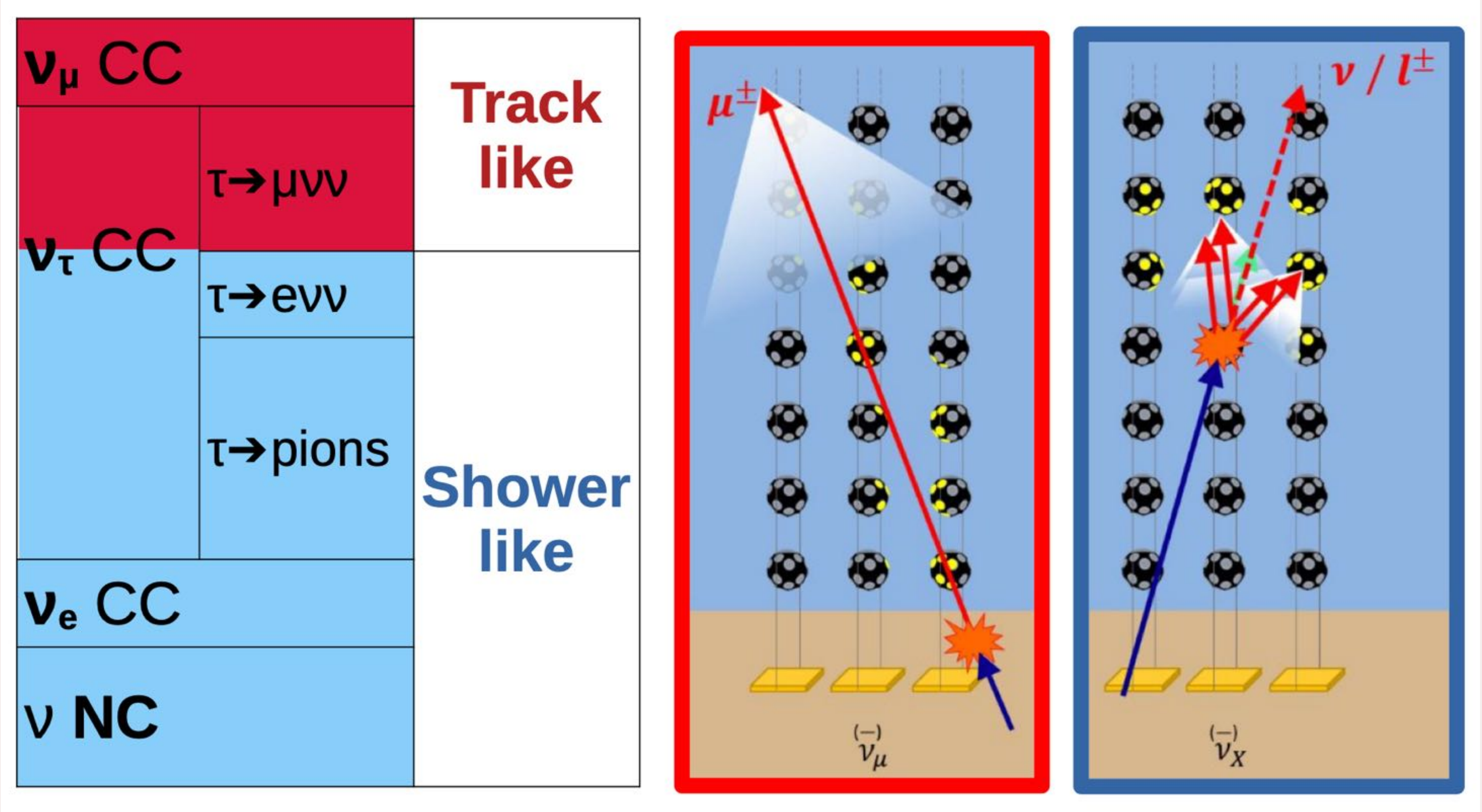
Degeneracy between NMO and chirality is broken by cross-section (and flux) difference between neutrinos and anti-neutrinos





KM3NeT/ORCA

- ORCA @ Toulon: 9m vertical x 20m horizontal spacing, targeting ν with E~1-100 GeV.
- 108 detector units (lines) - 1944 optical modules - 60264 PMTs
- 38 lines installed, +5 in October 2026, finish construction ~2030.
- Results presented so far with 6-11 lines, finalising analysis of ORCA18 for summer 2026, and preparing that of ORC24 for end-of-the-year
- Topology of events identifies flavour
  - ν_μ: elongated/narrow patterns of Cherenkov light from μ
  - ν_e, νX: shower from e- or hadrons, more compact, ~spherical burst
- Some degeneracy NMO⟷Δm^2_{31} => can boost sensitivity including Δm^2_{31} by e.g. JUNO
- Prospects by 2030:
  - NMO 2-4σ ORCA alone, 3.5-5σ ORCA+JUNO
  - θ_{23} 4-7% precision
  - ν_τ x-section 5% relative precision



APC: design, construction and qualification of ORCA Calibration Unit

Laboratoire	ETP (S/T)	Technical responsibilities	Scientific responsibilities	Management responsibilities
APC	5.9/3.8	Mechanics WG convener RAMS Manager System Engineer Calibration Base QA/QC Manager	Astronomy WG convener Oscillation WG convener (former)	ANTARES Spokesperson KM3NeT IB Chair EDI Committee Chair Technical Project Manager (former)

KM3NeT/ORCA

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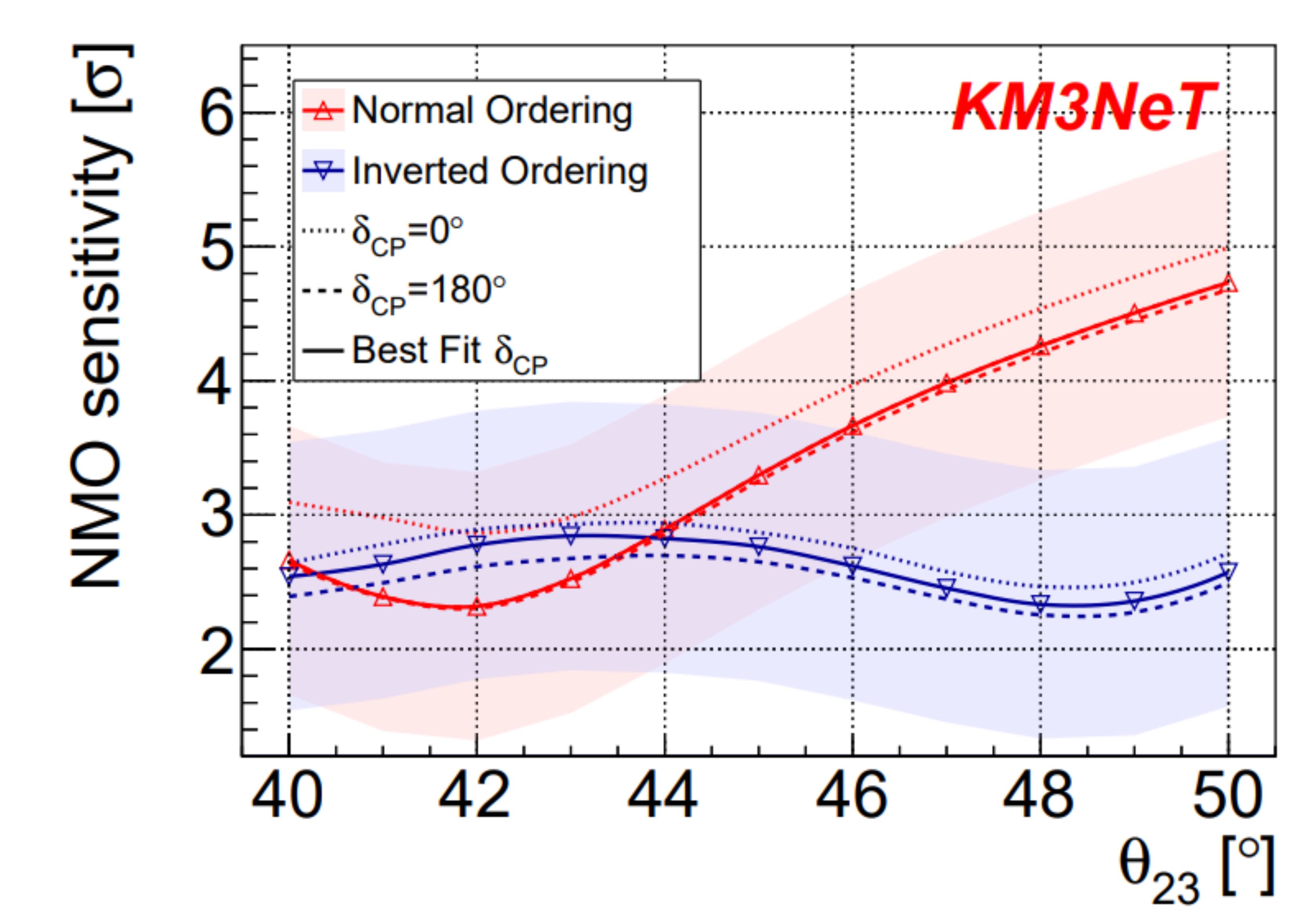
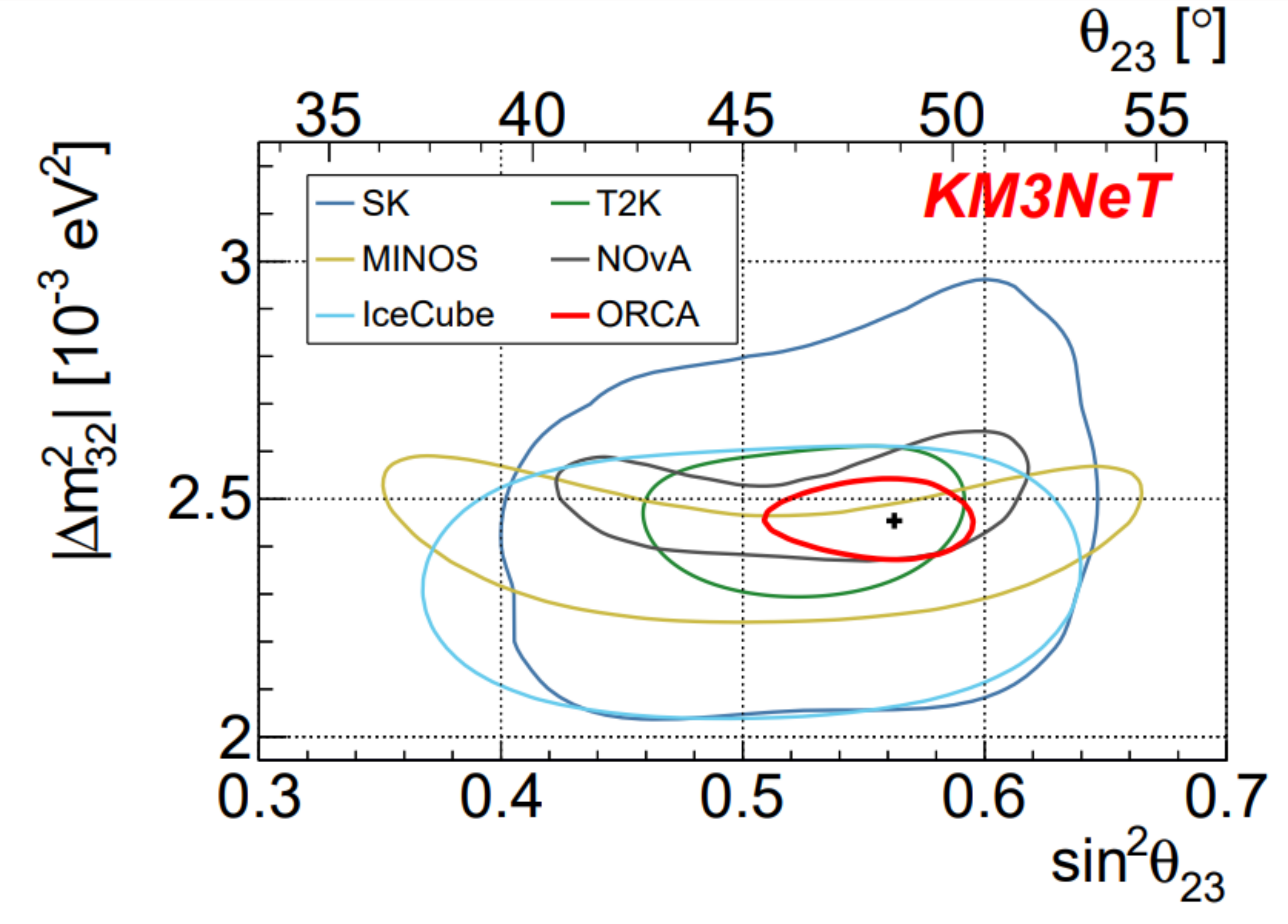
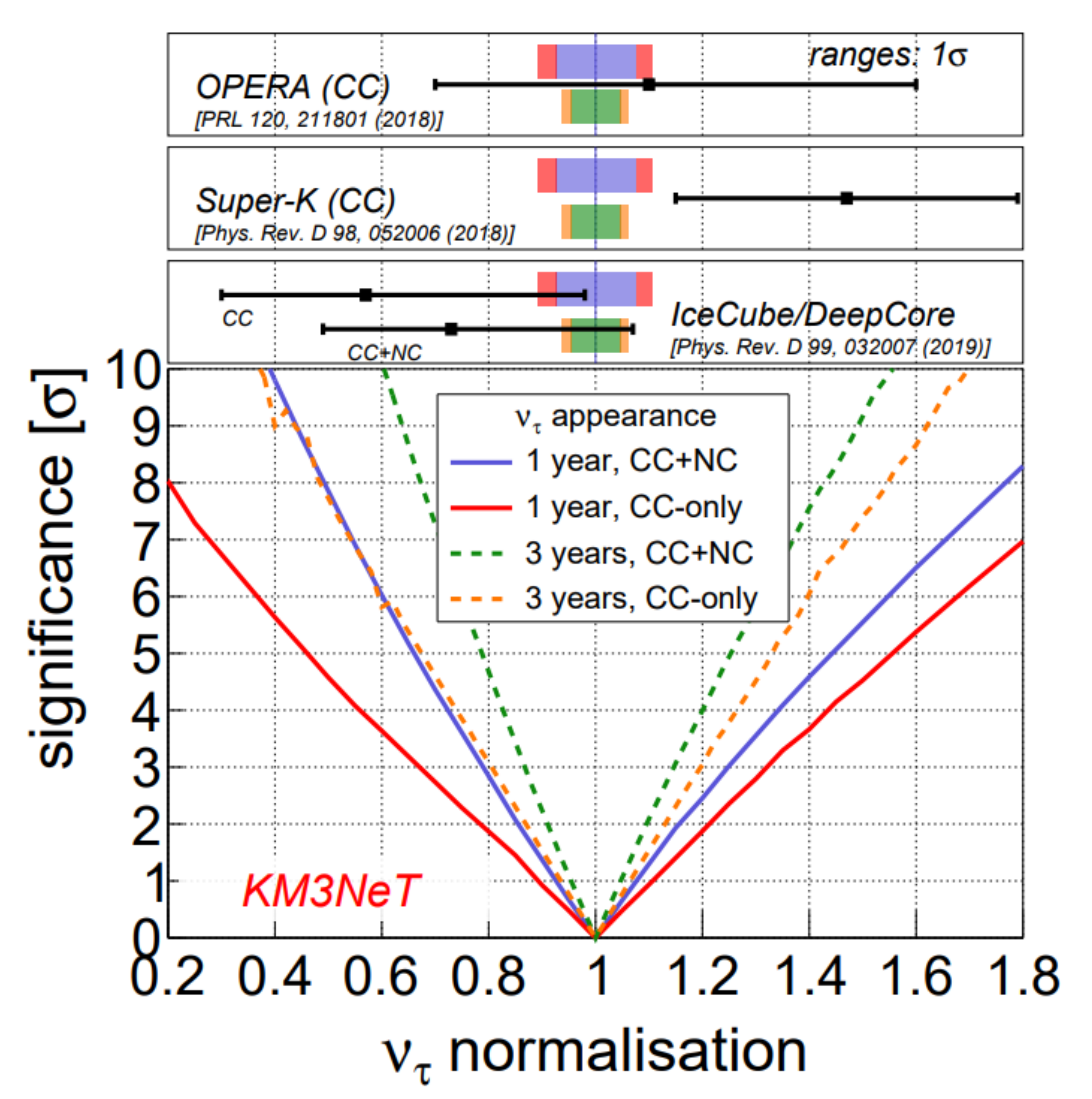


mass ordering



Atm. ν oscillation parameters



Probe unitarity of PMNS matrix by observing ν_τ appearance

The importance of combining with other experiments

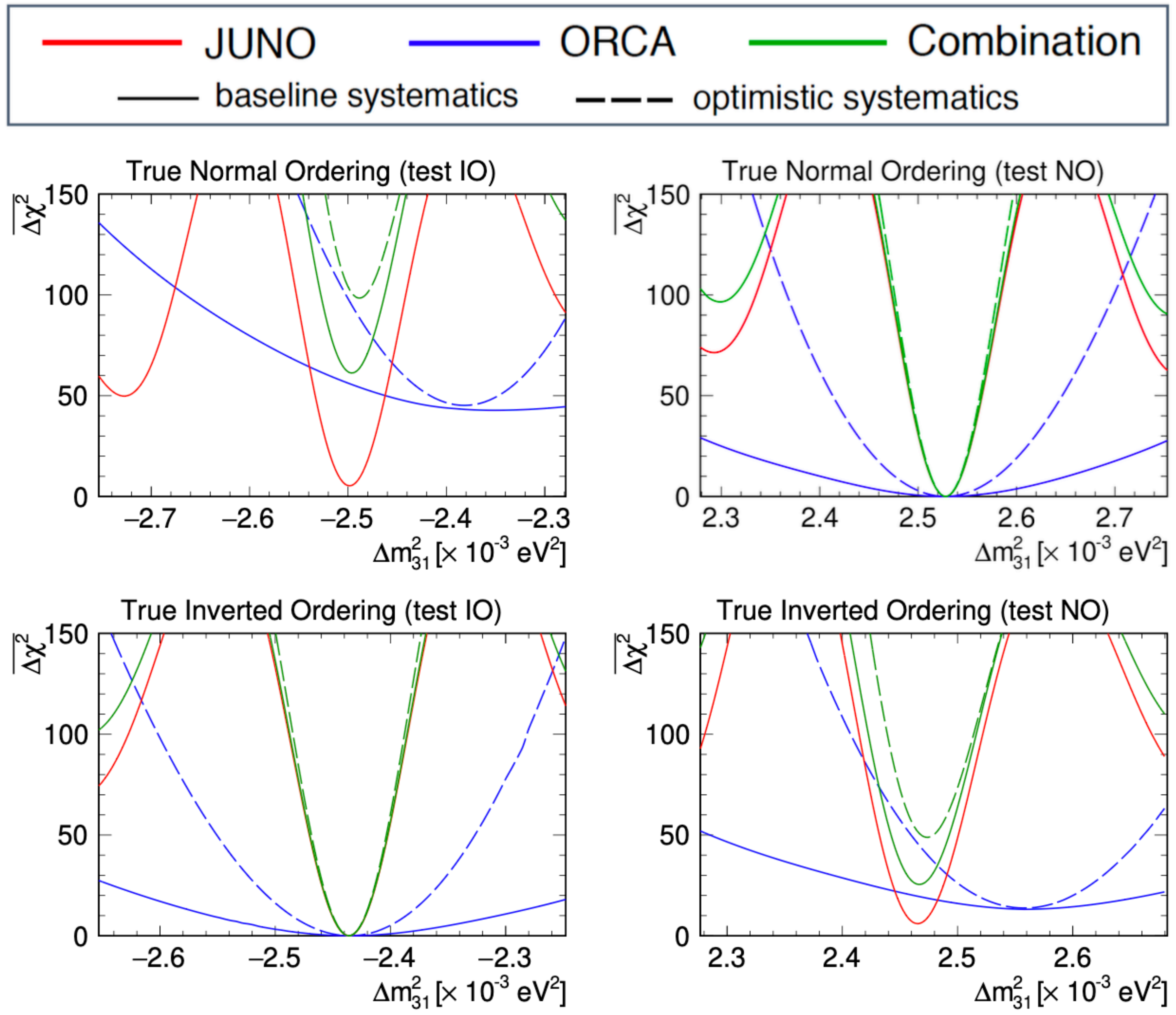
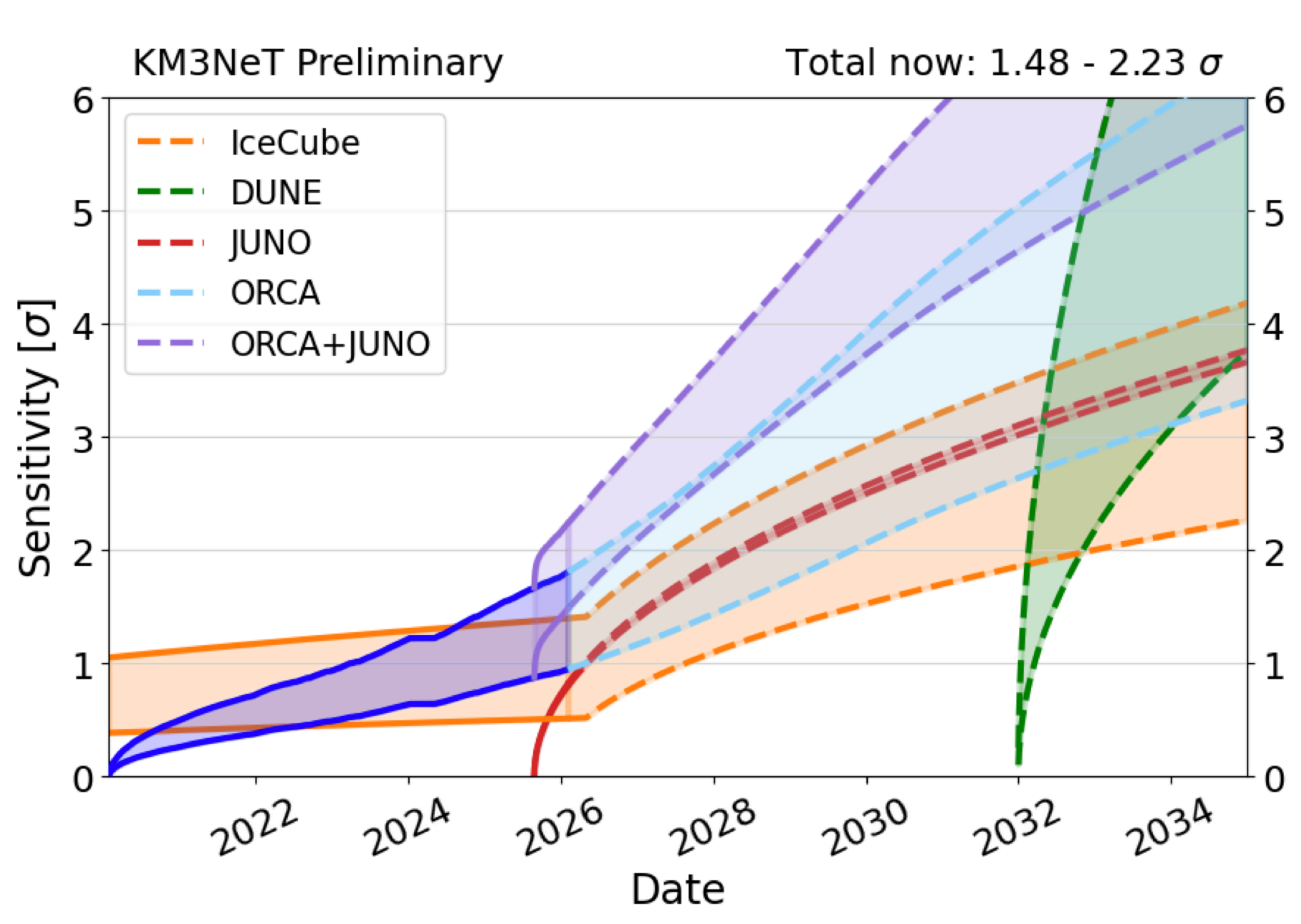
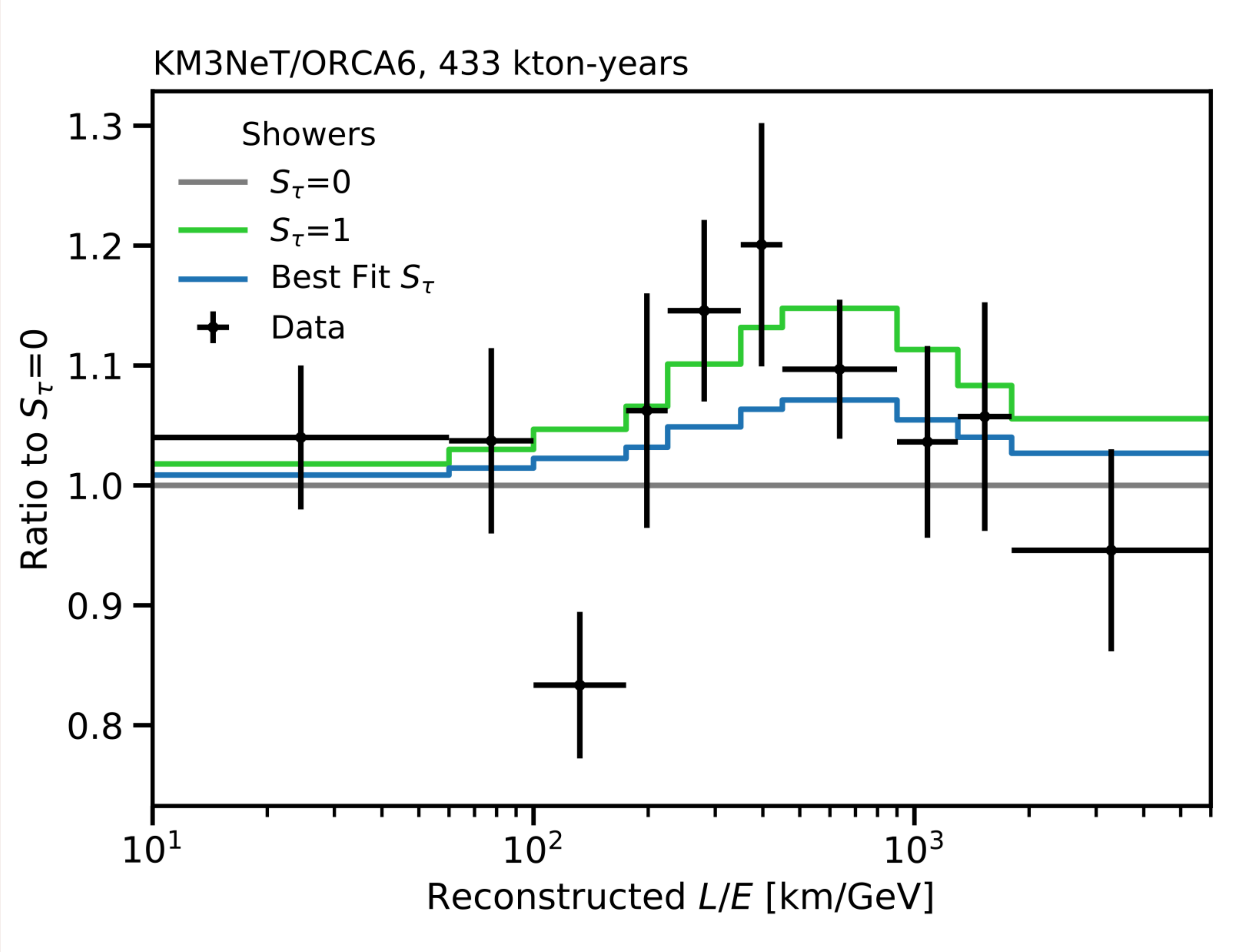


Figure 4. $\overline{\Delta\chi^2}$ profile for only JUNO (red), only ORCA (blue), and the combination of JUNO and ORCA (green) as a function of test values of Δm^2_{31} for 6 years of data taking assuming baseline (solid) or optimistic (dashed) systematics.

True NMO	JUNO, 8 cores	ORCA	Simple Sum	Combination
NO	2.3σ	6.5σ	6.9σ	7.8σ
IO	2.4σ	3.6σ	4.3σ	5.1σ

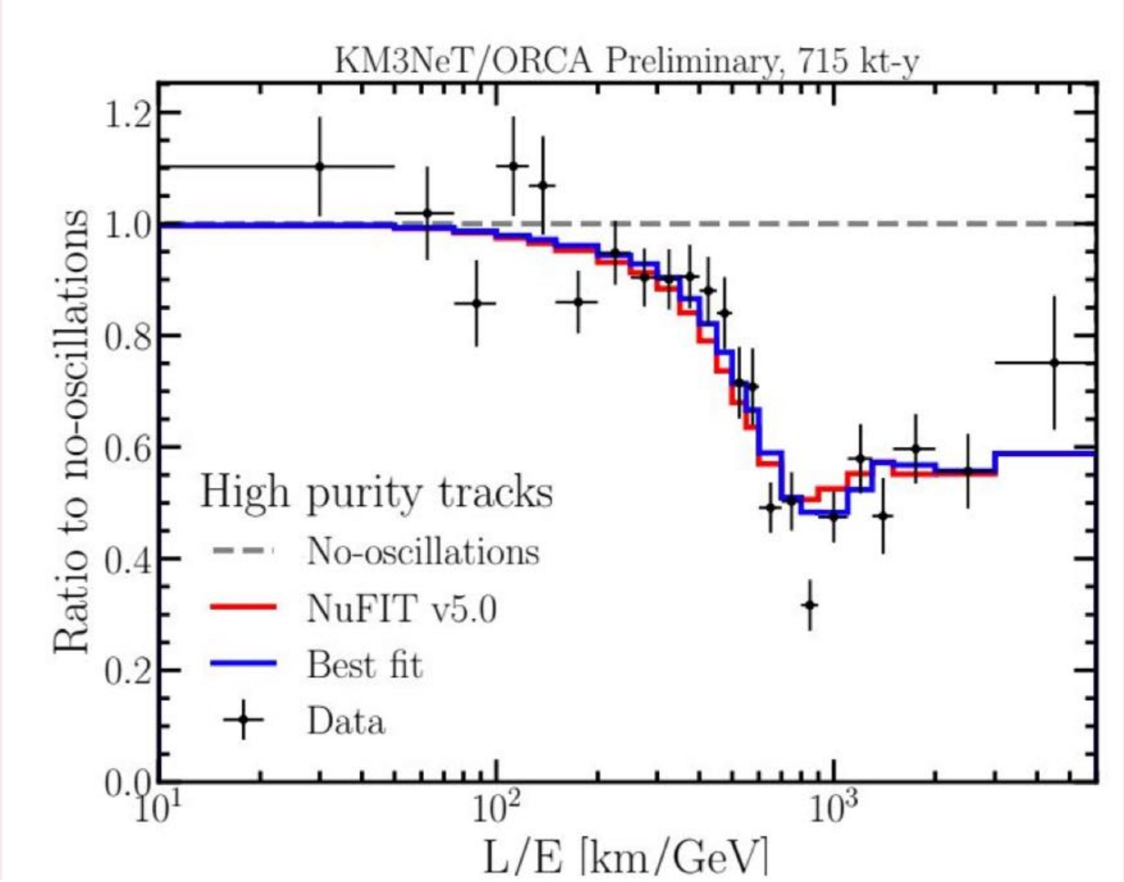


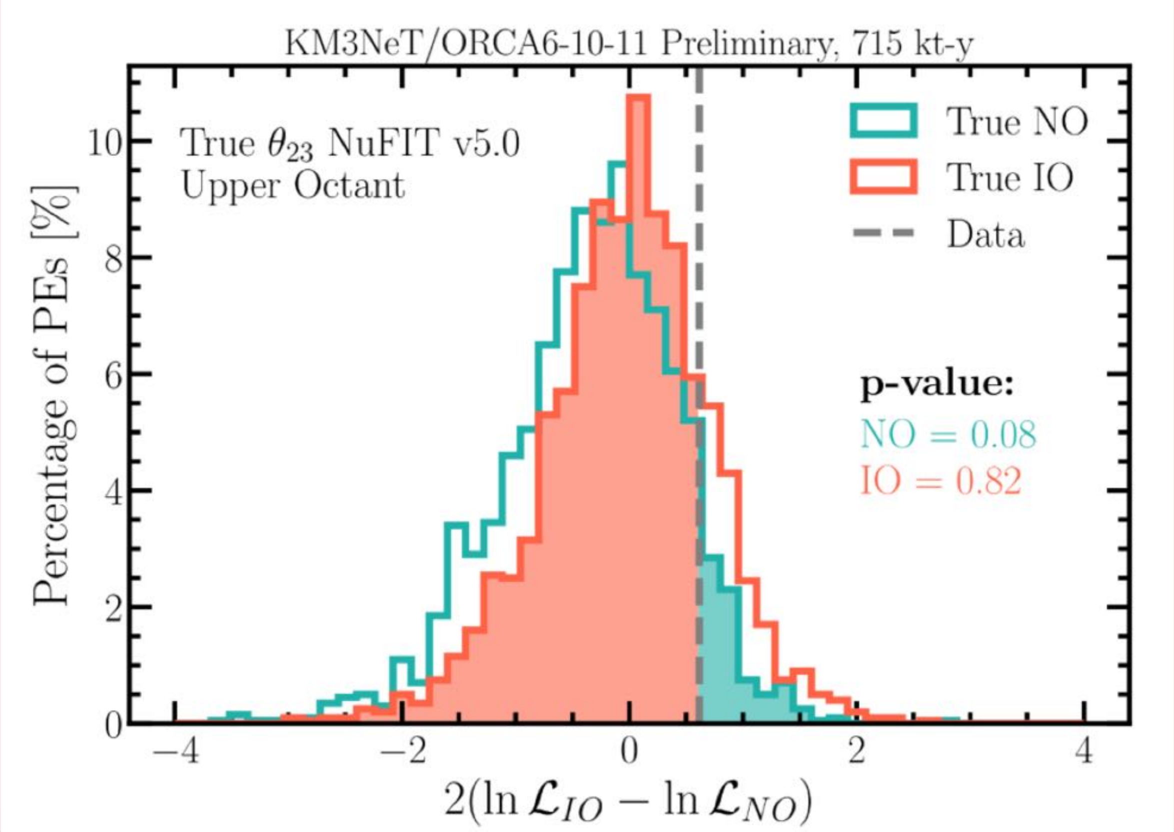
Study of tau neutrinos and non-unitary neutrino mixing with the first six detection units of KM3NeT/ORCA (JHEP 07 (2025) 213)

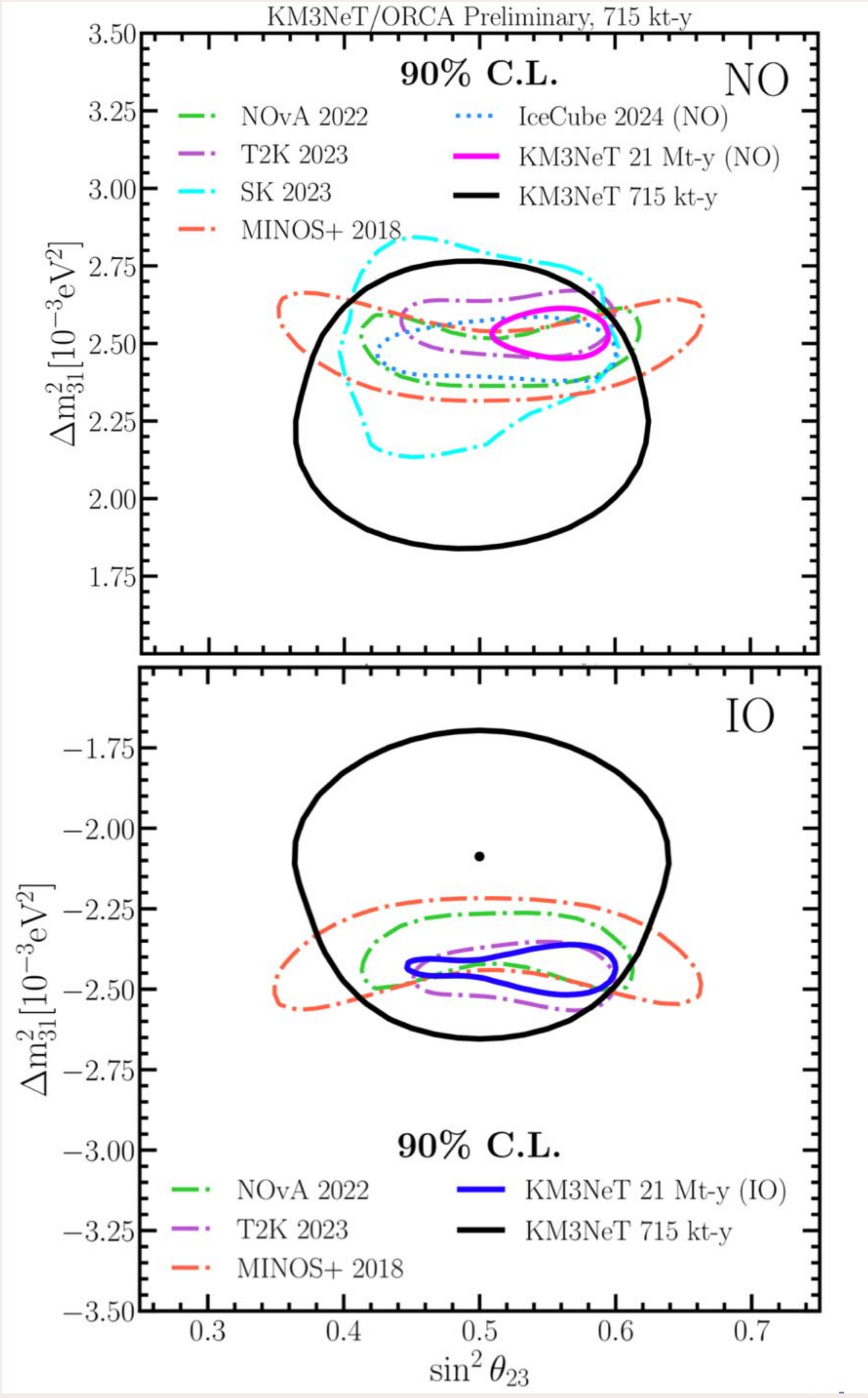


Updated results on oscillation measurements (Neutrino 2024) [https://doi.org/10.5281/zenodo.13234815] -> stay tuned for newer results very soon!

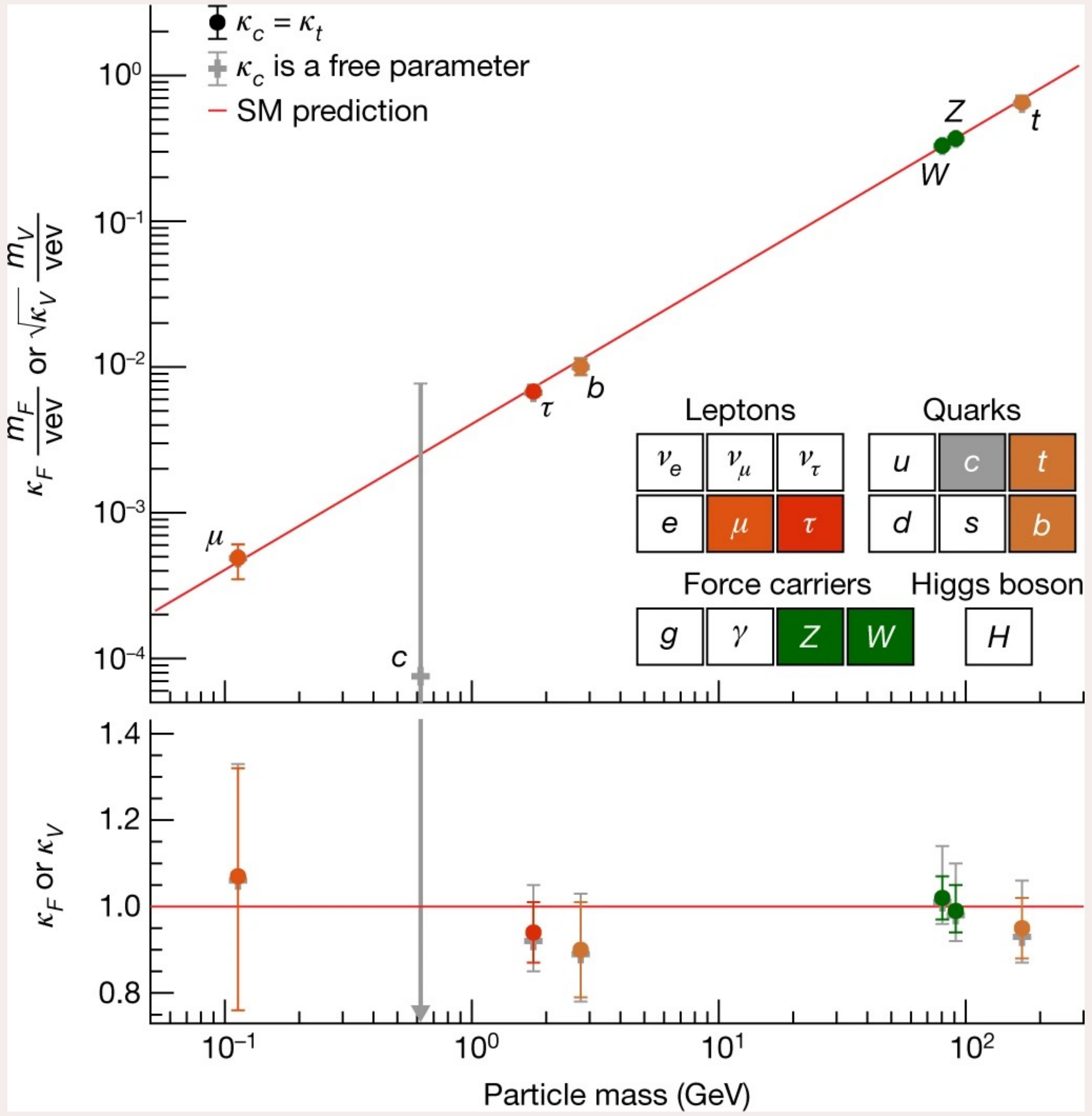
* clear oscillation pattern
* contours getting competitive
* sensitivity to MO remains limited



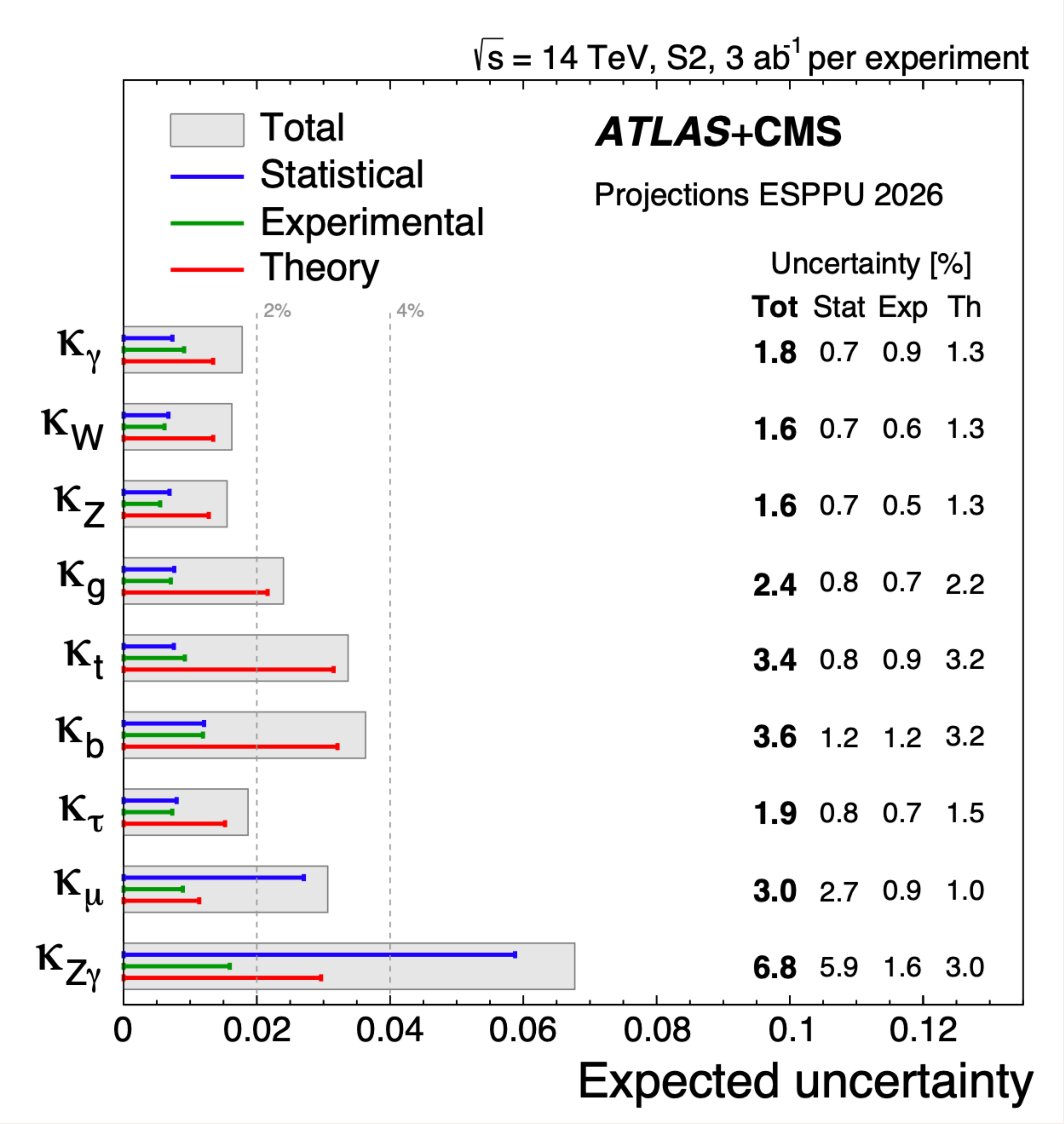




ATLAS (2022)



ATLAS+CMS (HL-LHC ~2042)



7.2σ HH significance

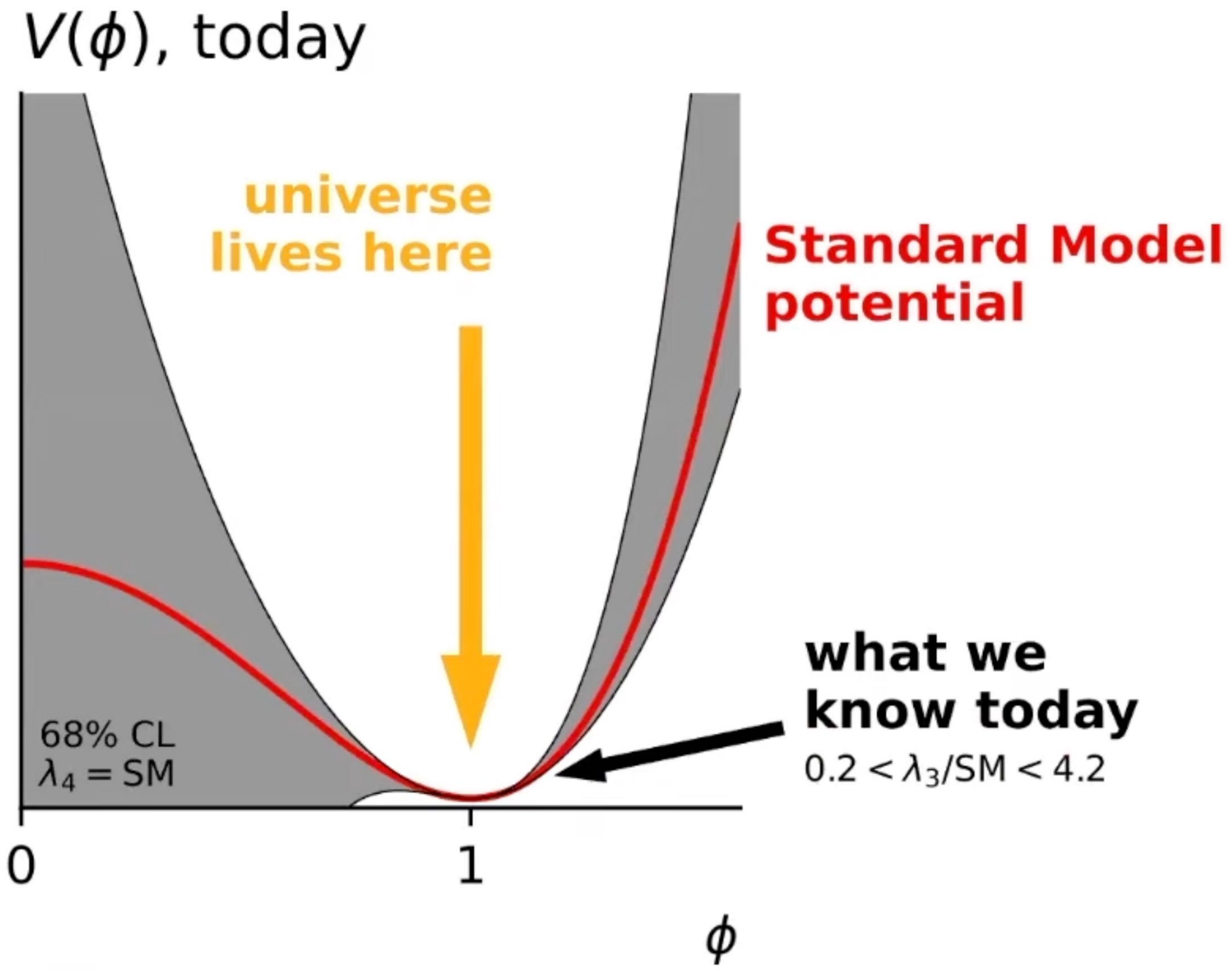
30% uncertainty on λ

FCC-ee (>2050)

$\sqrt{s}$	240 GeV		365 GeV	
channel	**ZH**	**WW → H**	**ZH**	**WW → H**
ZH → any	±0.31		±0.52	
γH → any	±150			
H → bb	±0.21	±1.9	±0.38	±0.66
H → cc	±1.6	±19	±2.9	±3.4
H → ss	±120	±990	±350	±280
H → gg	±0.80	±5.5	±2.1	±2.6
$H \to \tau\tau$	±0.58		±1.2	±5.6 (*)
$H \to \mu\mu$	±11		±25	
H → WW*	±0.80		±1.8 (*)	±2.1 (*)
H → ZZ*	±2.5		±8.3 (*)	±4.6 (*)
$H \to \gamma\gamma$	±3.6		±13	±15
$H \to Z\gamma$	±11.8		±22	±23
$H \to \nu\nu\nu\nu$	±25		±77	
H → inv.	$< 5.5 \times 10^{-4}$		$< 1.6 \times 10^{-3}$	
H → dd	$< 1.2 \times 10^{-3}$			
H → uu	$< 1.2 \times 10^{-3}$			
H → bs	$< 3.1 \times 10^{-4}$			
H → bu	$< 2.2 \times 10^{-4}$			
H → sd	$< 2.0 \times 10^{-4}$			
H → cu	$< 6.5 \times 10^{-4}$			

Mass at ~4 MeV,
Width to ~%

Higgs potential



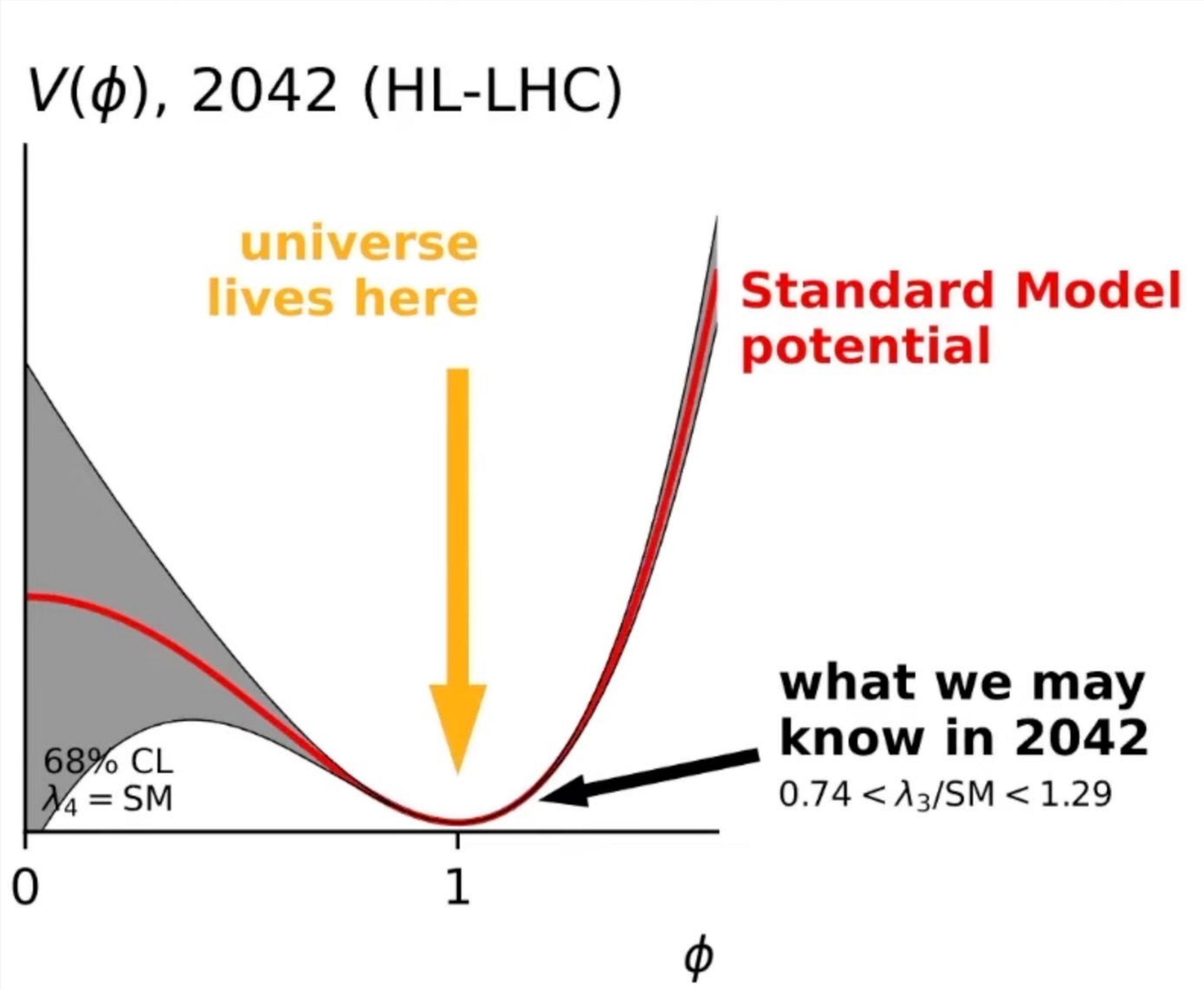
L'étude de H→HH sonde une propriété mathématique spécifique de la forme du potentiel:

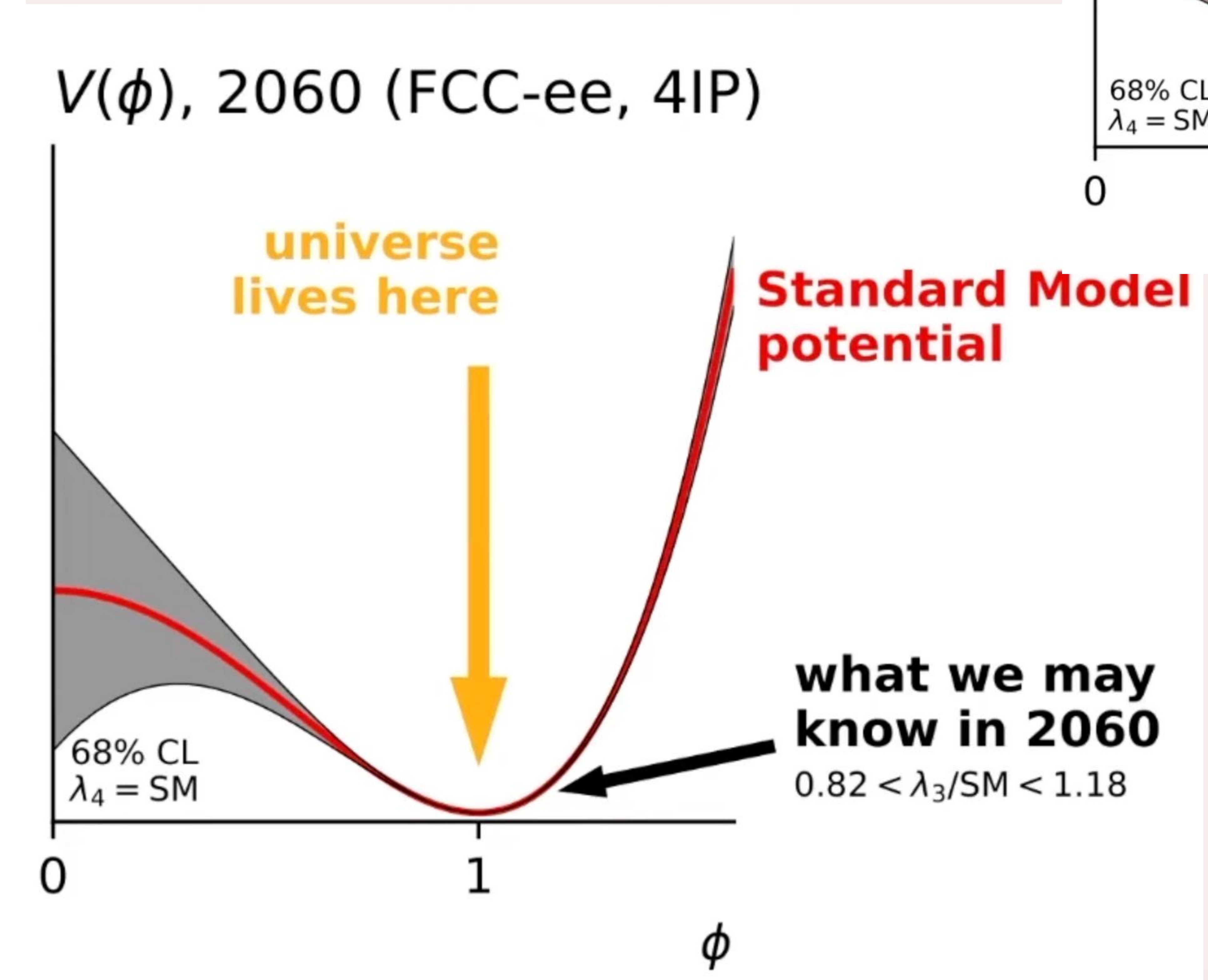
sa troisème dérivée (λ_3), c.à.d. son asymétrie au minimum

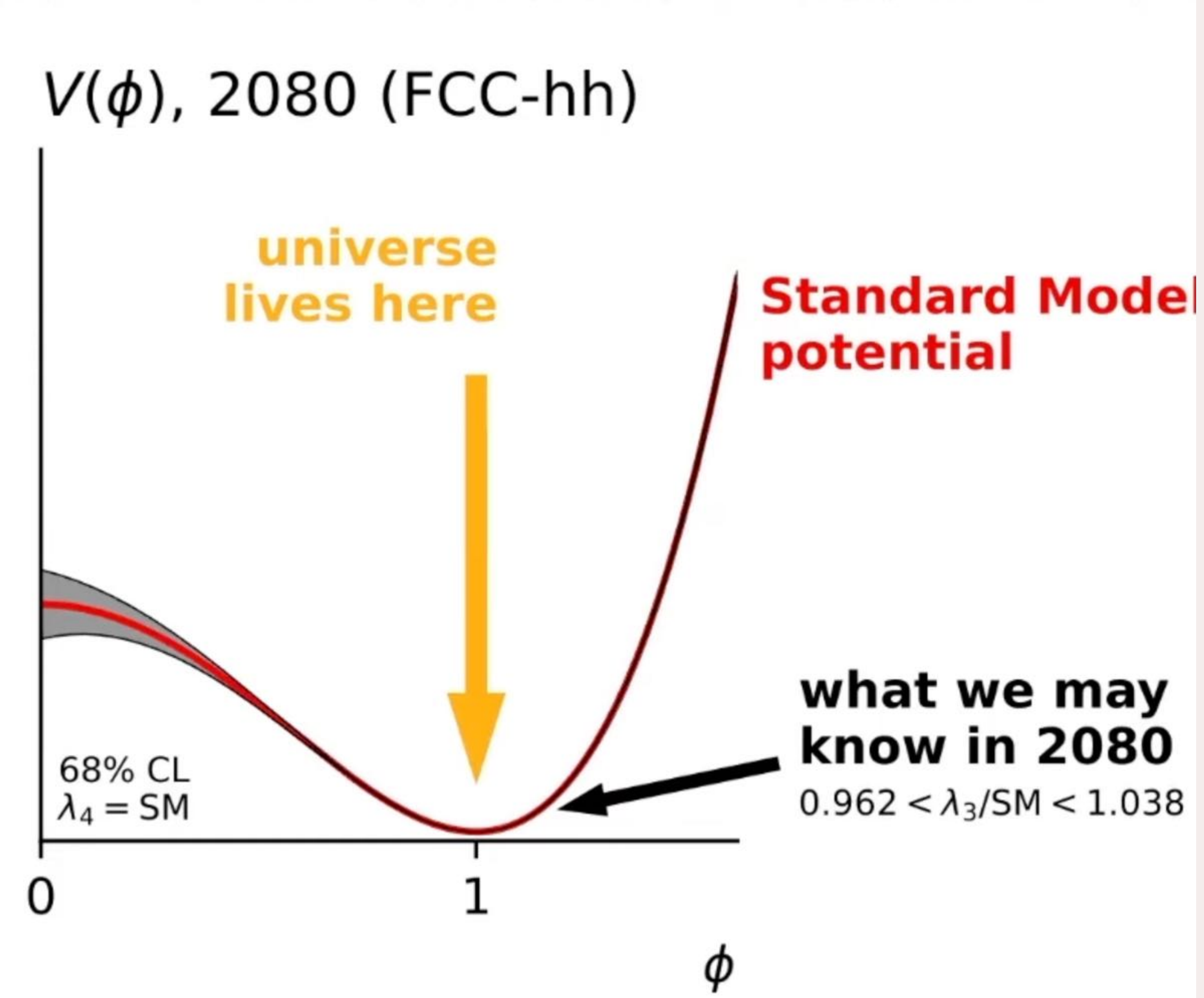
[la reconstruction du graphique suppose des dérivées ≥ 4 comme dans le MS]

G. Salam

Higgs potential







Silicon sensors for collider experiments

ATLAS: expertise in measuring and modelling radiation damage effects in silicon sensors at hadronic colliders
Convenorship of ATLAS dedicated group
FCC/DRD3: working on understanding potential performance of trackers at future colliders

Measurement and simulation of ATLAS silicon pixels performance as a function of the accumulated radiation damage

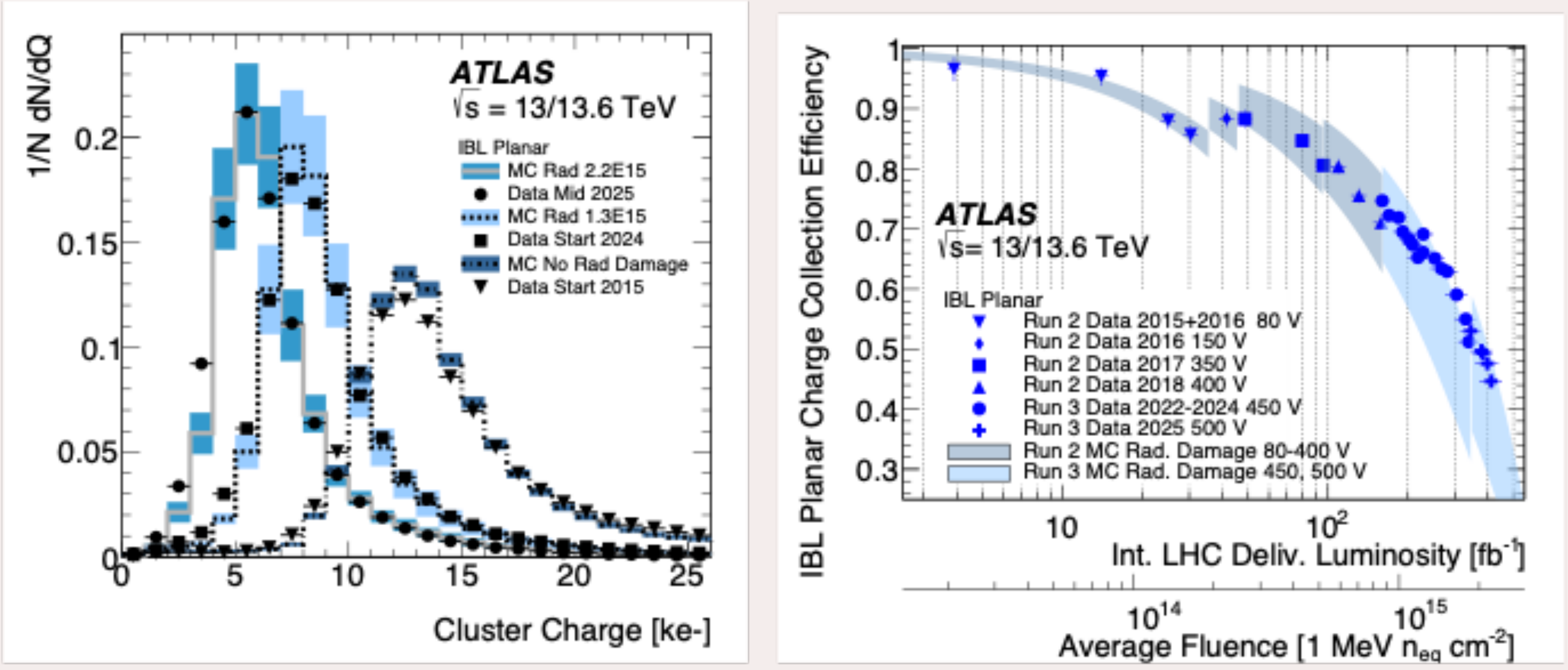
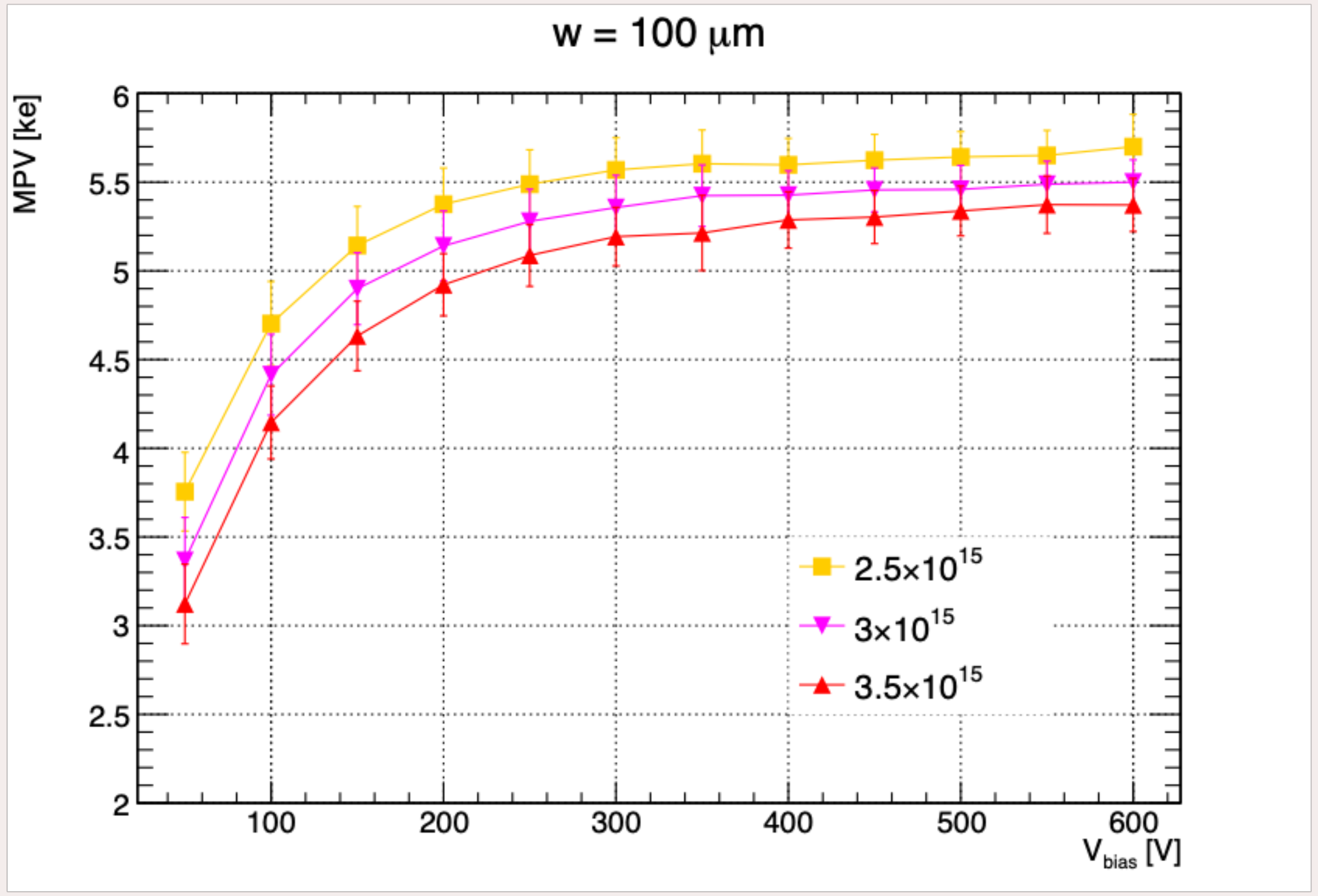


Figure 2: Charge collection in IBL and radiation damage: (Left) Distribution of cluster charges in IBL planar sensors from data taken at the start of the 2015 (filled triangles) and 2024 (filled squares) and mid-2025 (filled circles) compared with the predictions from radiation damage simulation corresponding to the estimated average fluence. The shaded regions give the range of the uncertainties in simulation. (Right) Charge collection efficiency as a function of the integrated delivered luminosity and average fluence for IBL planar sensors for data and the ATLAS radiation damage simulation from the beginning of Run 2. The points represent the data and the bands the simulation predictions with their uncertainties. Predictions for the evolution until the end of Run 3 are also given.

https://arxiv.org/abs/2605.05030v1

Simulation of expected performance of ATLAS pixels during the high luminosity phase



https://doi.org/10.1016/j.nima.2025.171000