

IFIC summer school 2019

03/07/2019



DEEP UNDERGROUND
NEUTRINO EXPERIMENT

Anselmo Cervera Villanueva
IFIC-Valencia



SURF

Fermilab

1300 km

United States

Mexico

La colaboración DUNE

175 instituciones

+



de

31 paises



Mezcla de neutrinos

autoestados débiles

ν_e

ν_μ

ν_τ

$$\nu_{\alpha L} = \sum_{k=1}^n U_{\alpha k} \nu_{kL}$$

autoestados de masa

ν_1

ν_2

ν_3

(arbitrary sizes)

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PMNS mixing matrix

Pontecorvo–Maki–Nakagawa–Sakata

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$c_{ij} = \cos \theta_{ij}$
 $s_{ij} = \sin \theta_{ij}$

atmospheric sector

connection between
solar and atmospheric

solar sector

Dirac

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Dirac **Majorana**

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autoestados de masa

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Δm_{12}^2

Δm_{23}^2

$\Delta m_{ij}^2 = m_i^2 - m_j^2$

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(arbitrary sizes)

$$\Delta m_{12}^2$$

$$7.53 \times 10^{-5} \text{ eV}^2$$

(2.4%)

$$\Delta m_{23}^2$$

$$2.45 \times 10^{-3} \text{ eV}^2$$

(2%)

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

$$46^\circ \text{ (8\%)}$$

$$\theta_{23}$$

$$8.3^\circ \text{ (5\%)}$$

$$\theta_{13}$$

$$\delta_{CP}$$

$$33^\circ \text{ (4\%)}$$

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$$\alpha_1, \alpha_2$$

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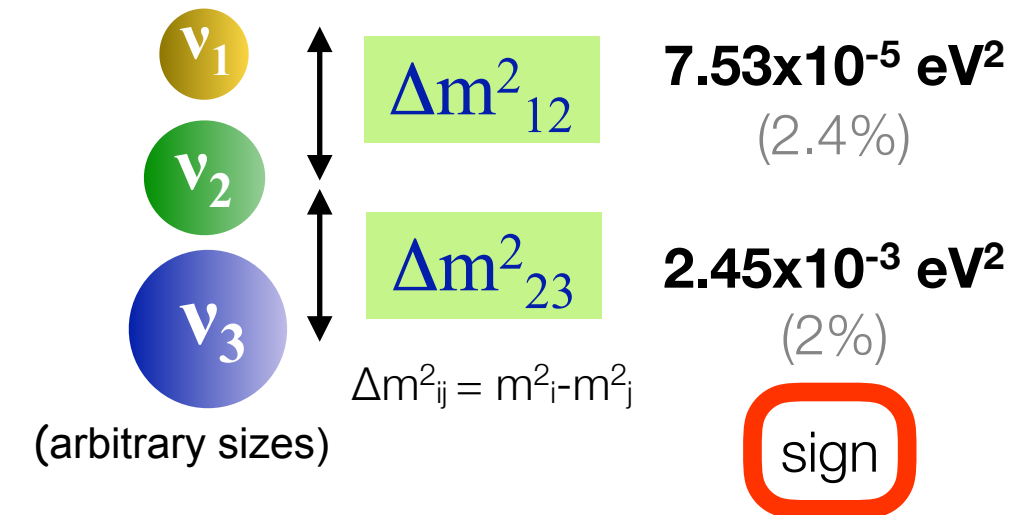
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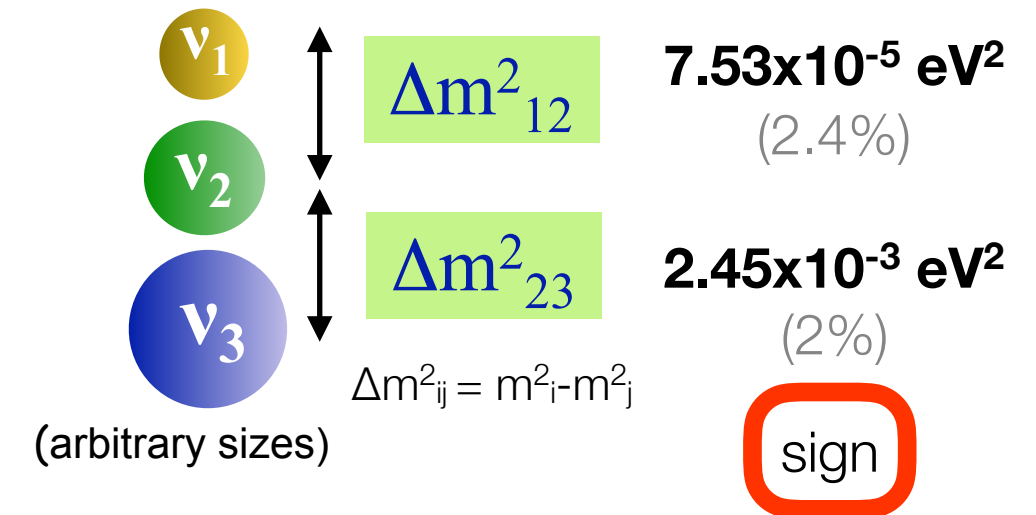
Jerarquía de masas

autoestados de masa

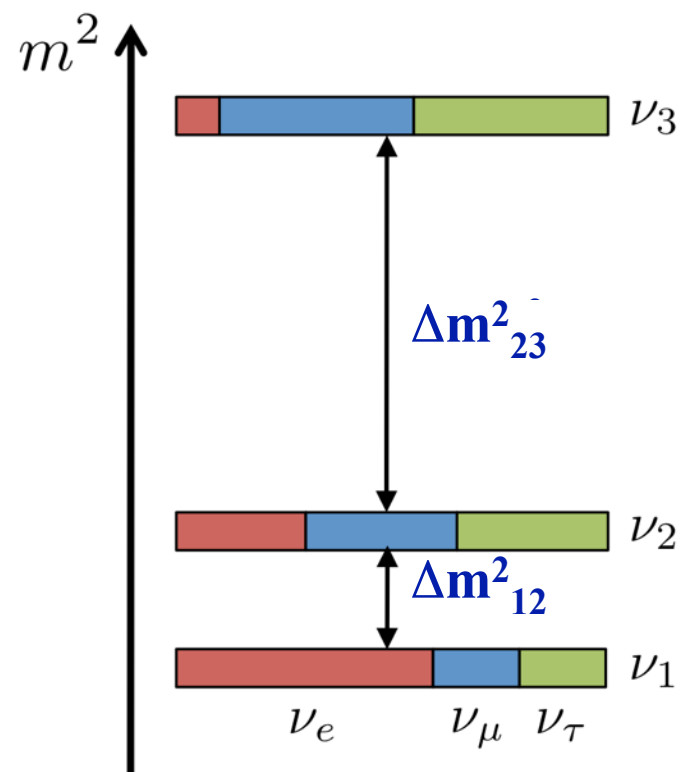


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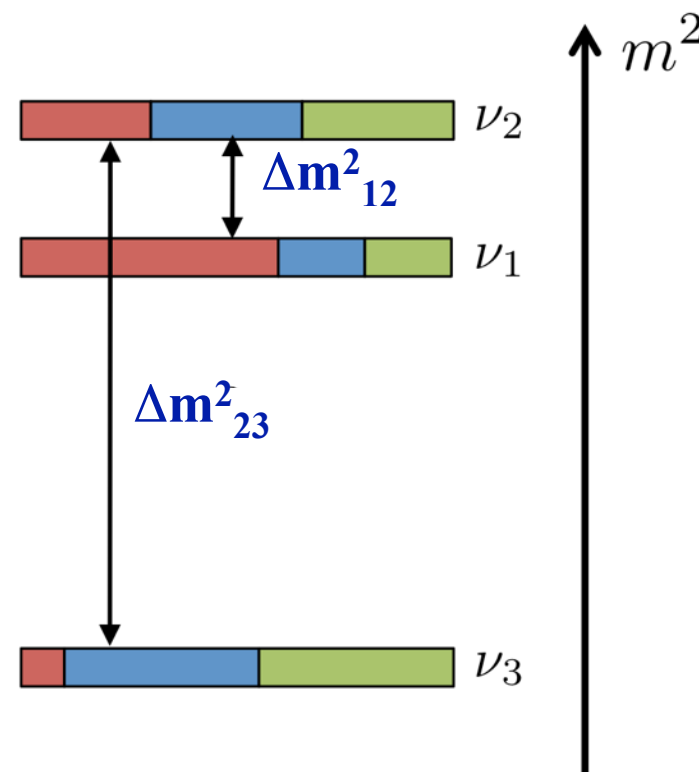
autoestados de masa



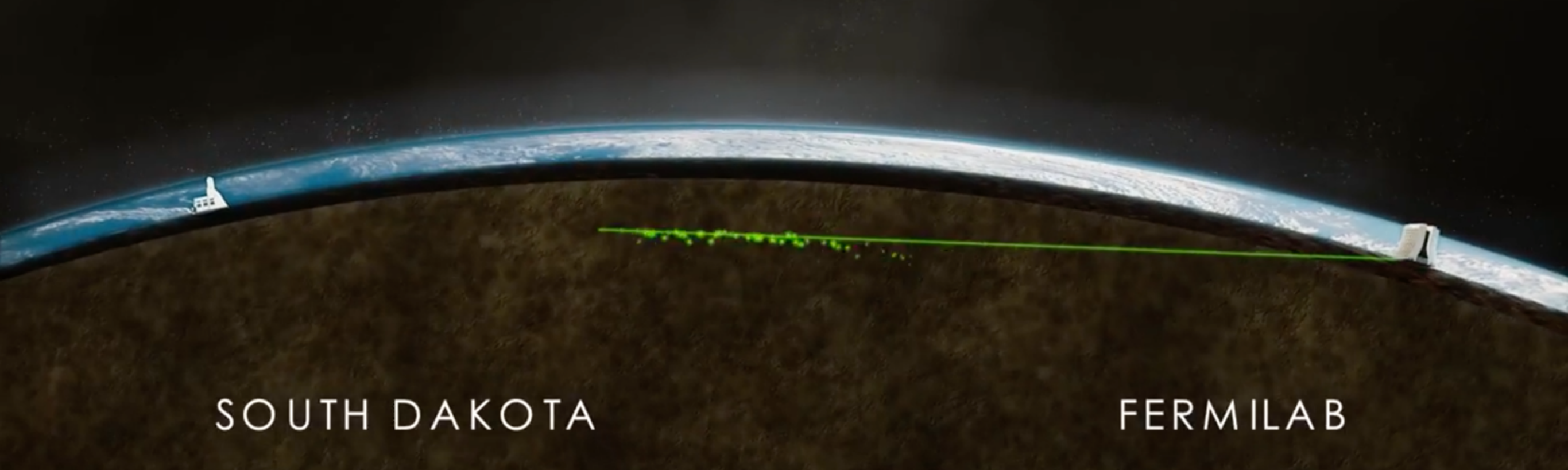
normal hierarchy (NH)



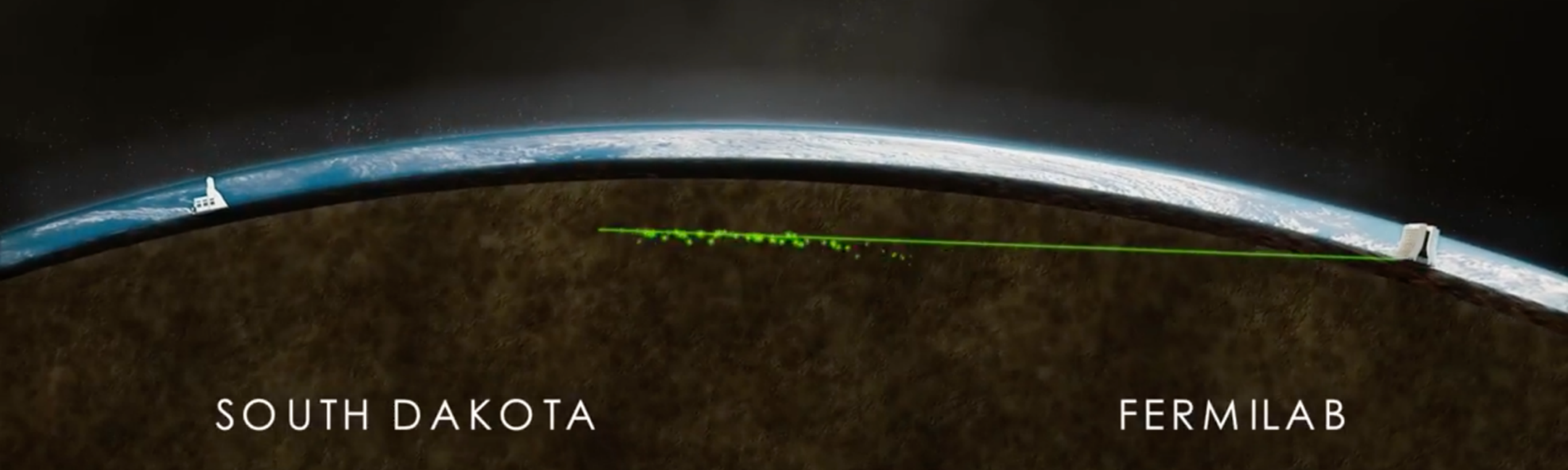
inverted hierarchy (IH)



La materia contiene electrones (no positrones)



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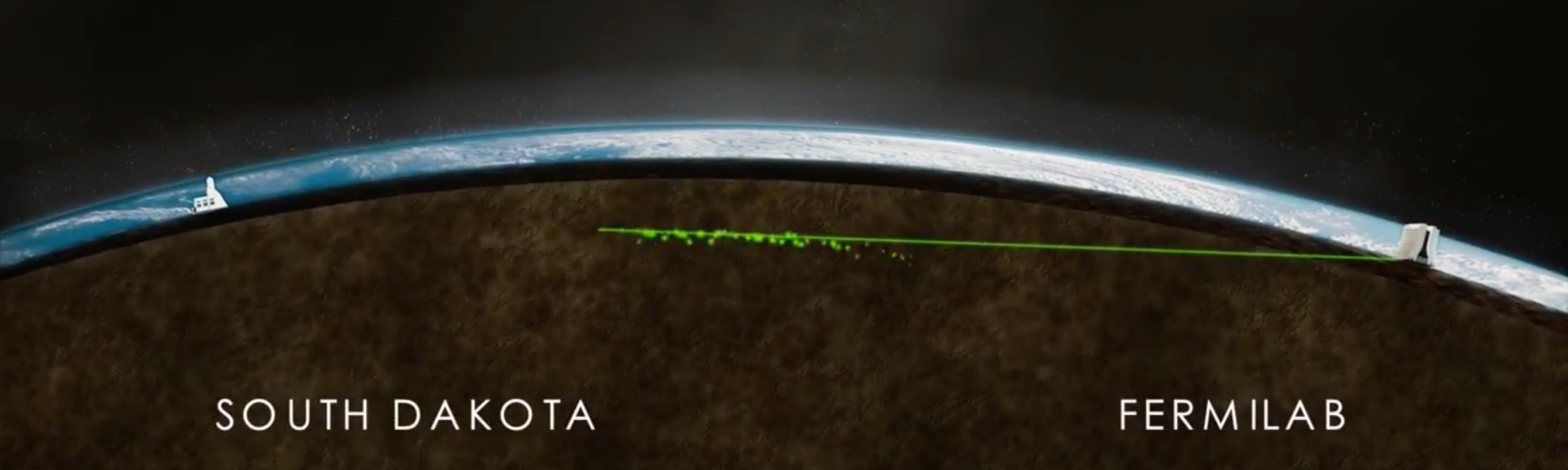


SOUTH DAKOTA

FERMILAB

La materia contiene electrones (no positrones)

**“neutrinos” electrónicos no se comportan igual que los “anti-neutrinos”
electrónicos al atravesar materia**



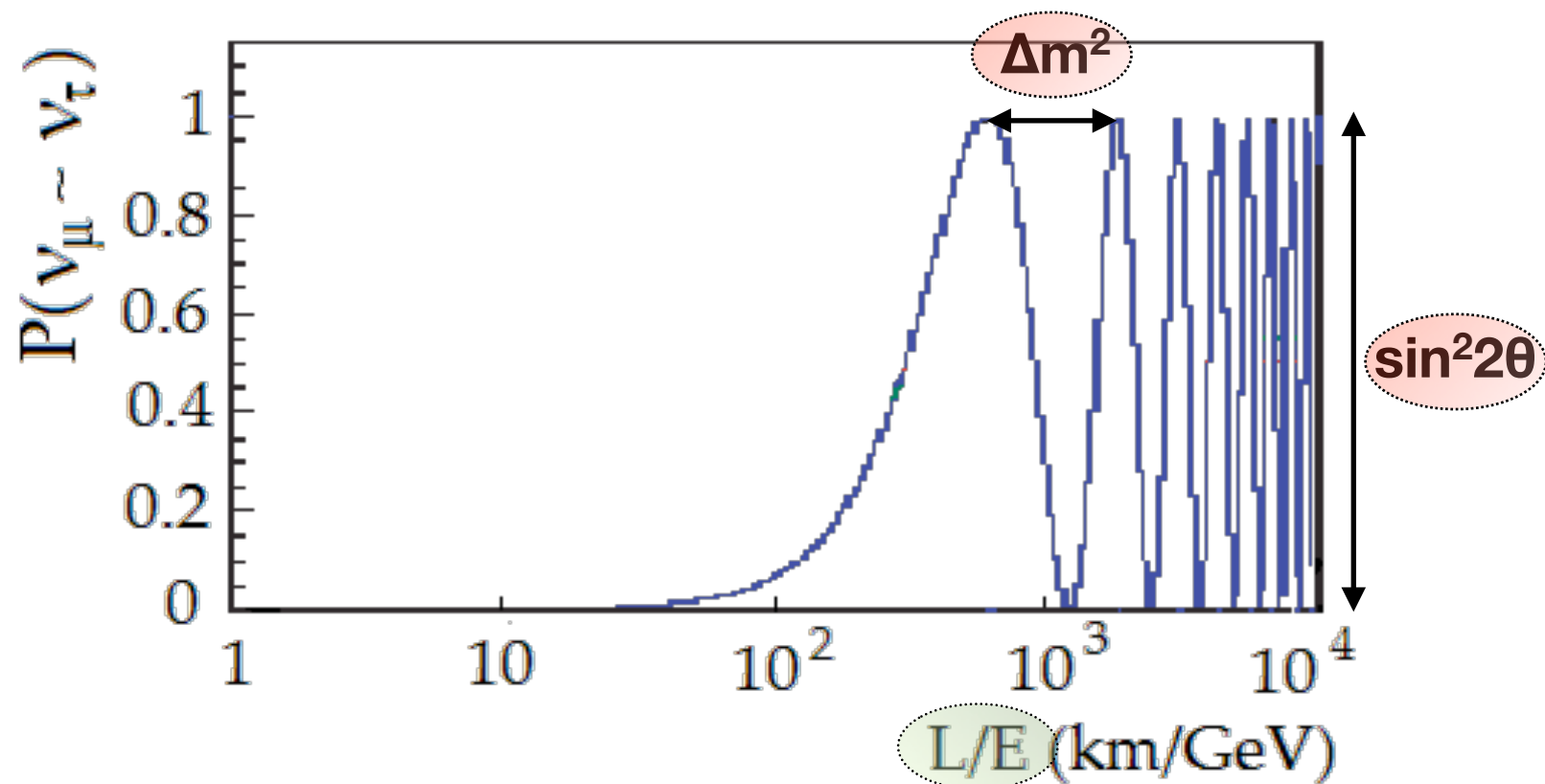
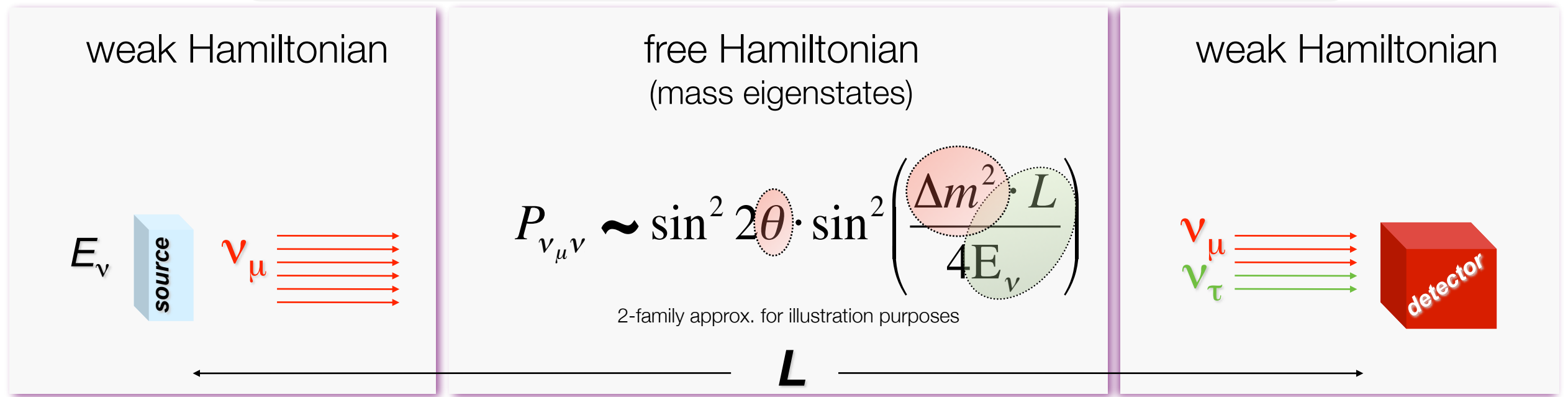
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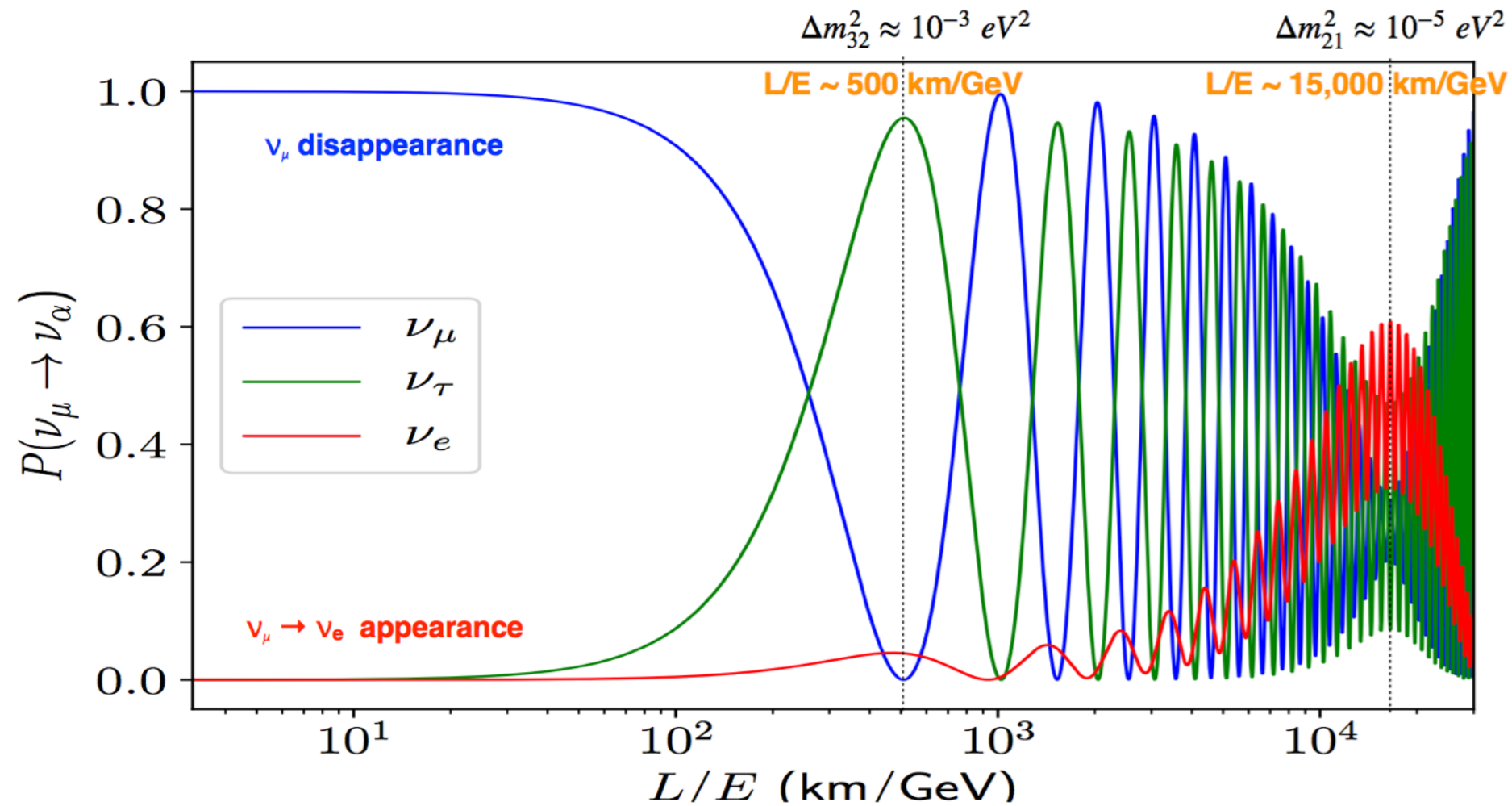
**esto produce una asimetría entre neutrinos y anti-neutrinos
cuyo signo depende de la jerarquía de masas**

Oscilaciones de neutrinos

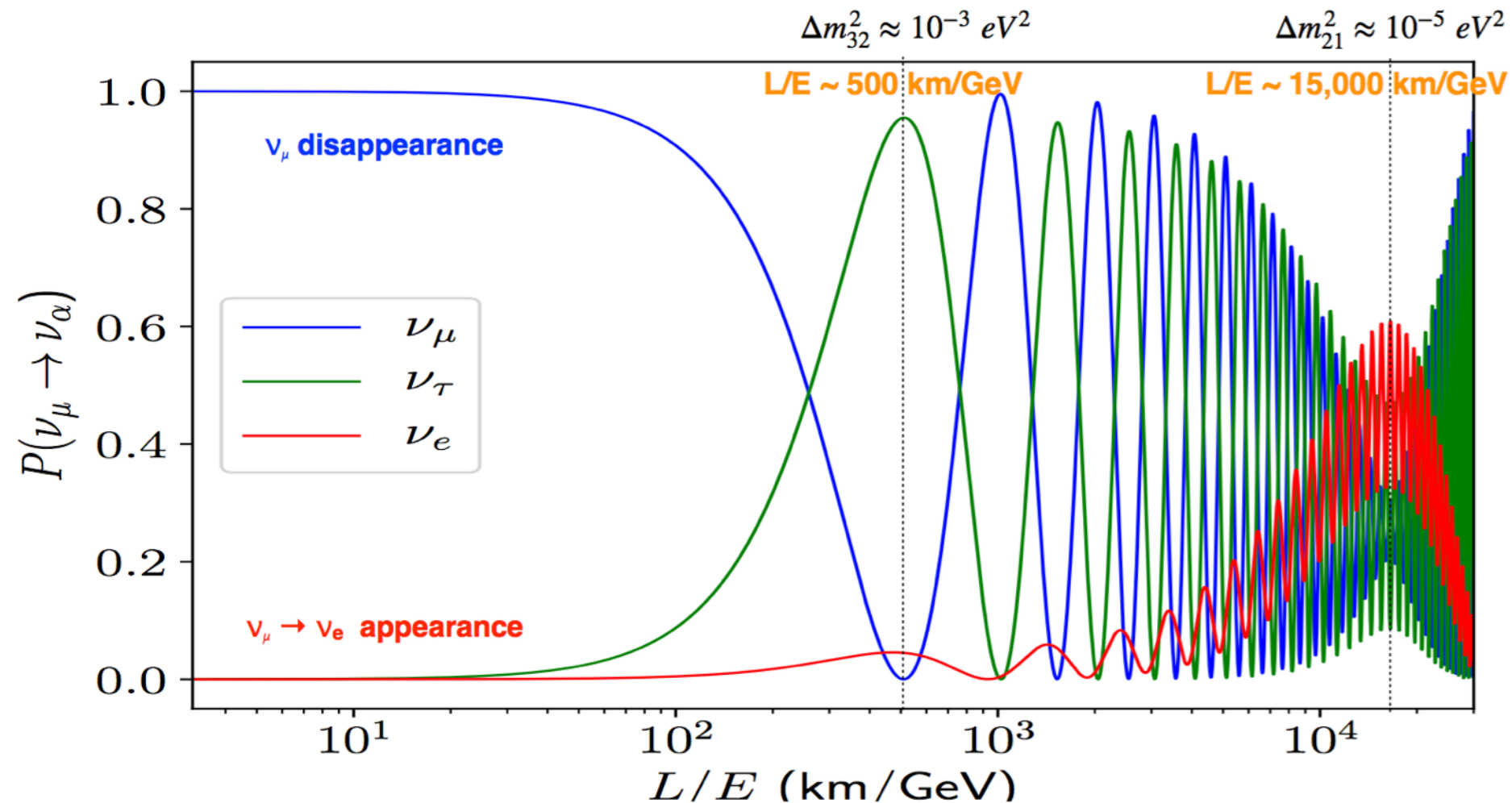
Requirements: Massive neutrinos & different masses



How L and E are chosen ?

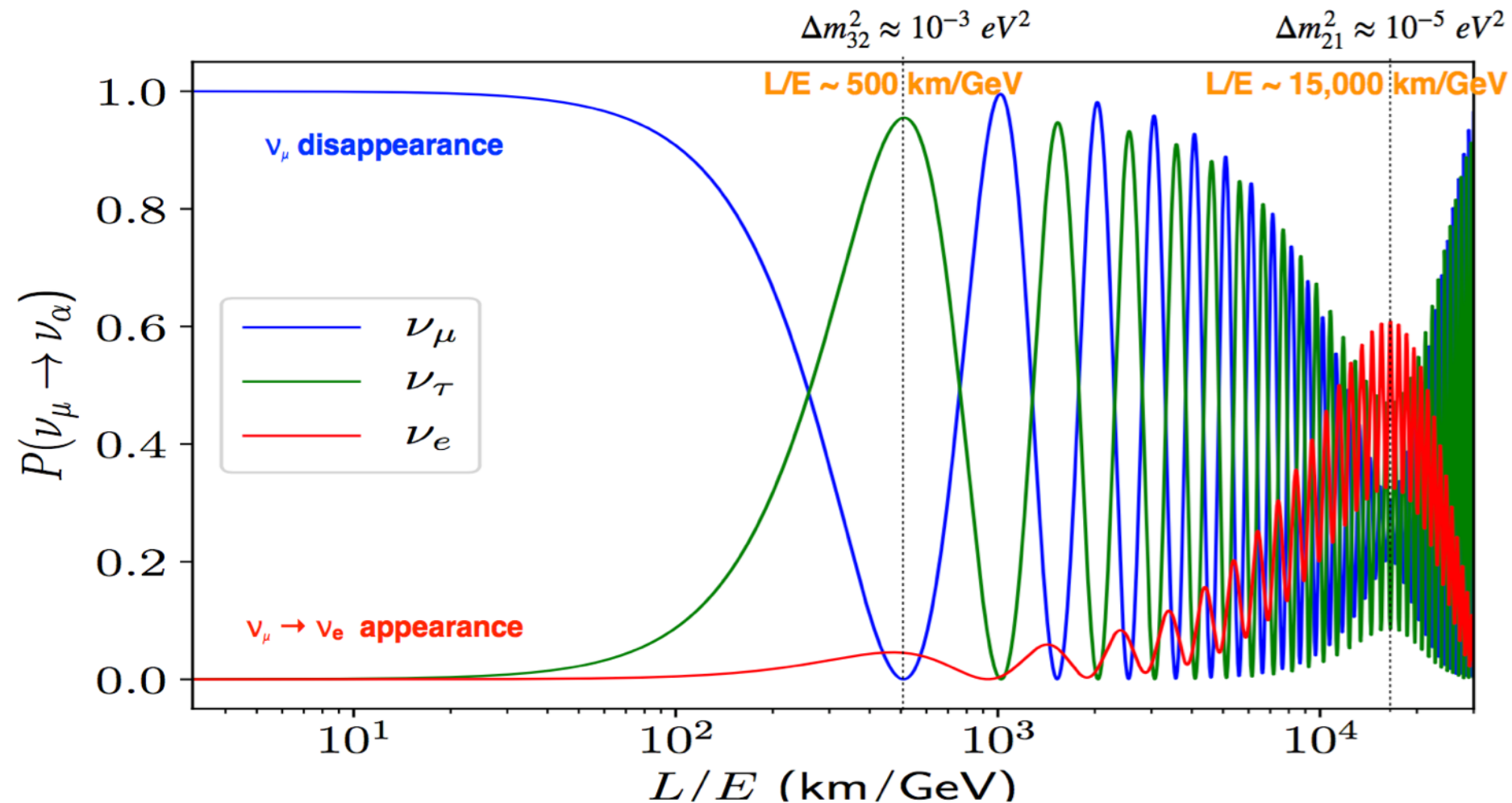


How L and E are chosen ?



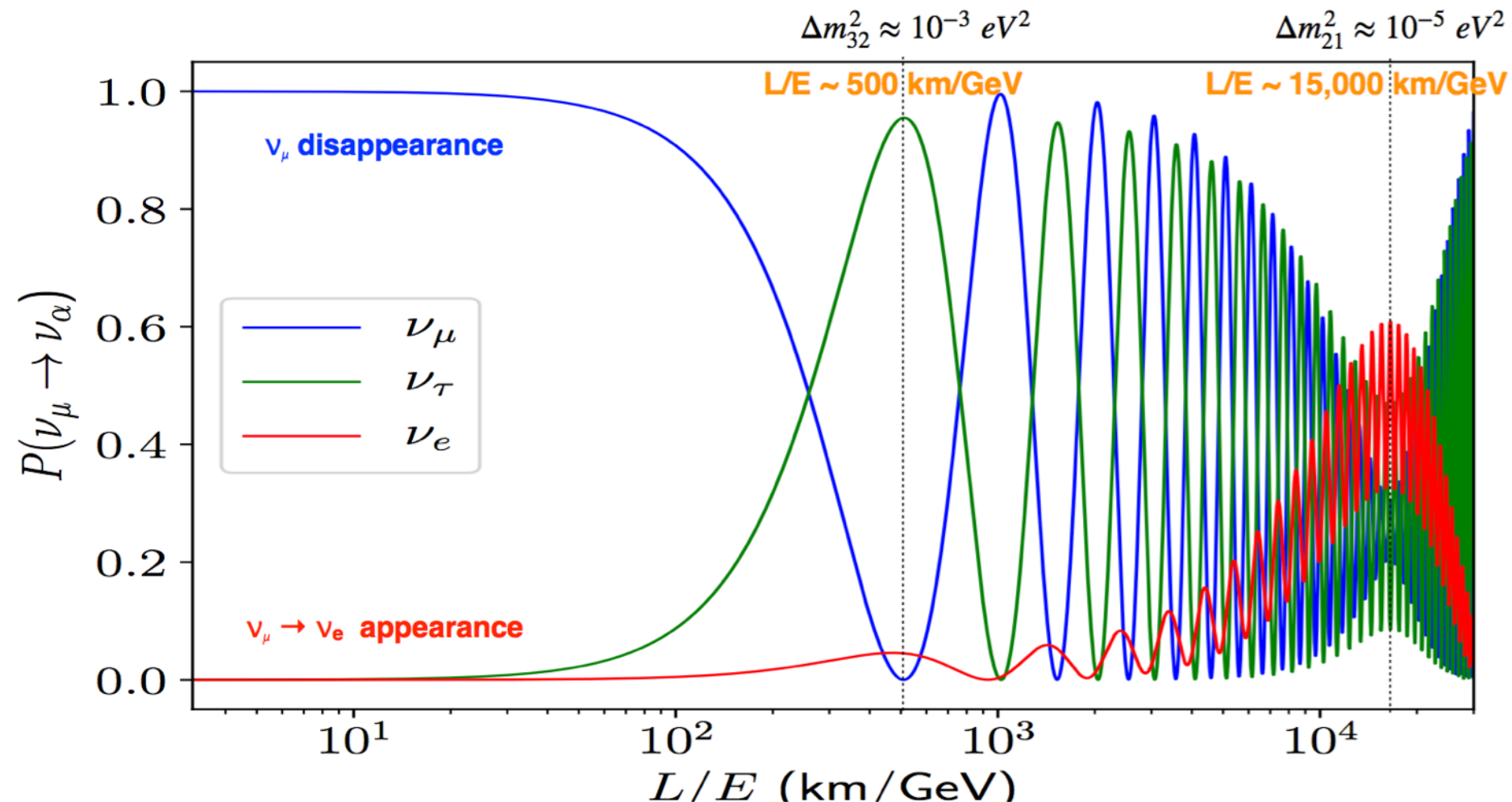
- Need long distances for the the mass hierarchy

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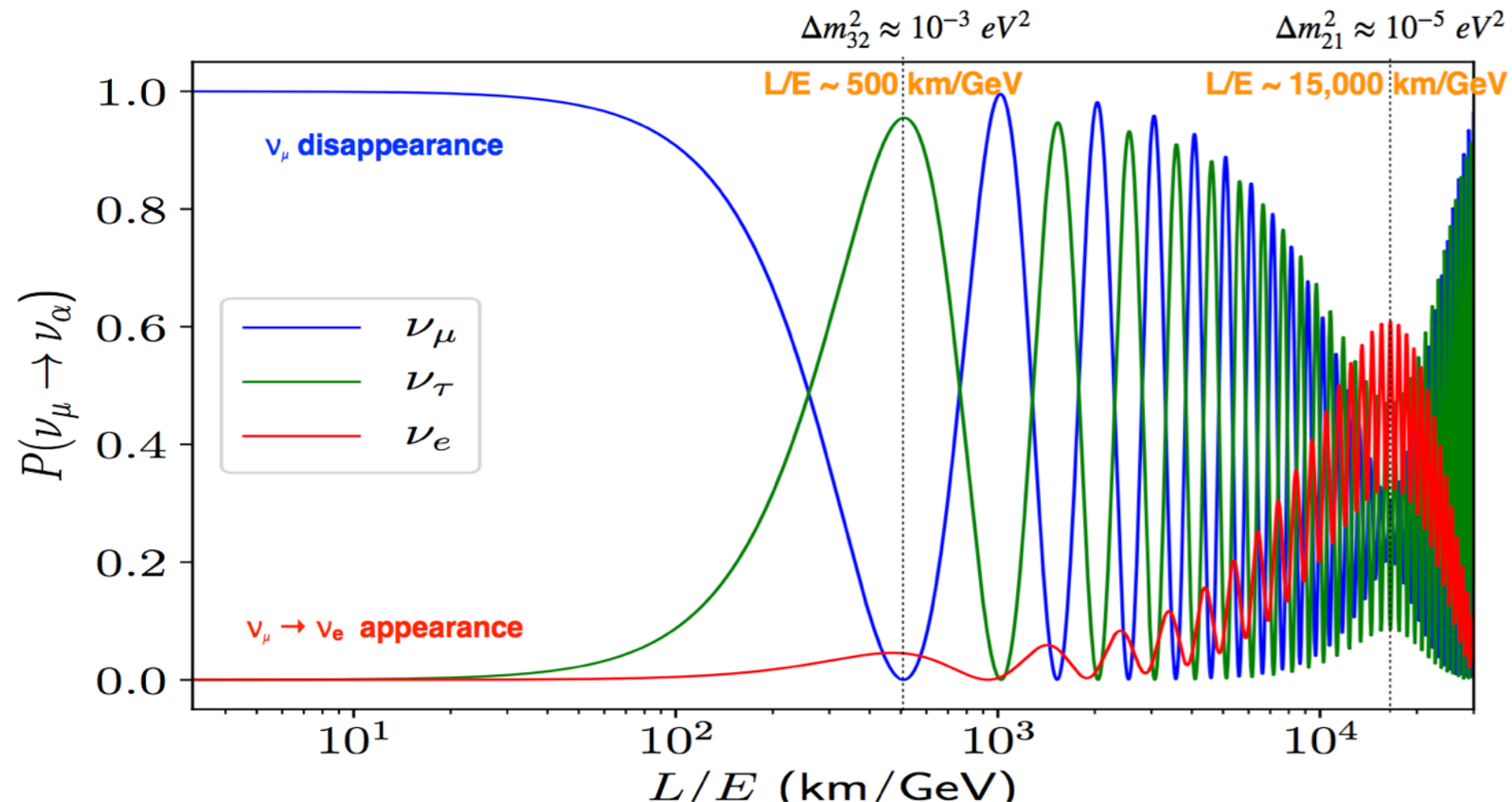
- Need long distances for the the mass hierarchy
- Need a deep underground location at appropriate distance (1300 km)

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- Once chosen a suitable location the energy of the beam should be tuned such that $L/E \sim 500$

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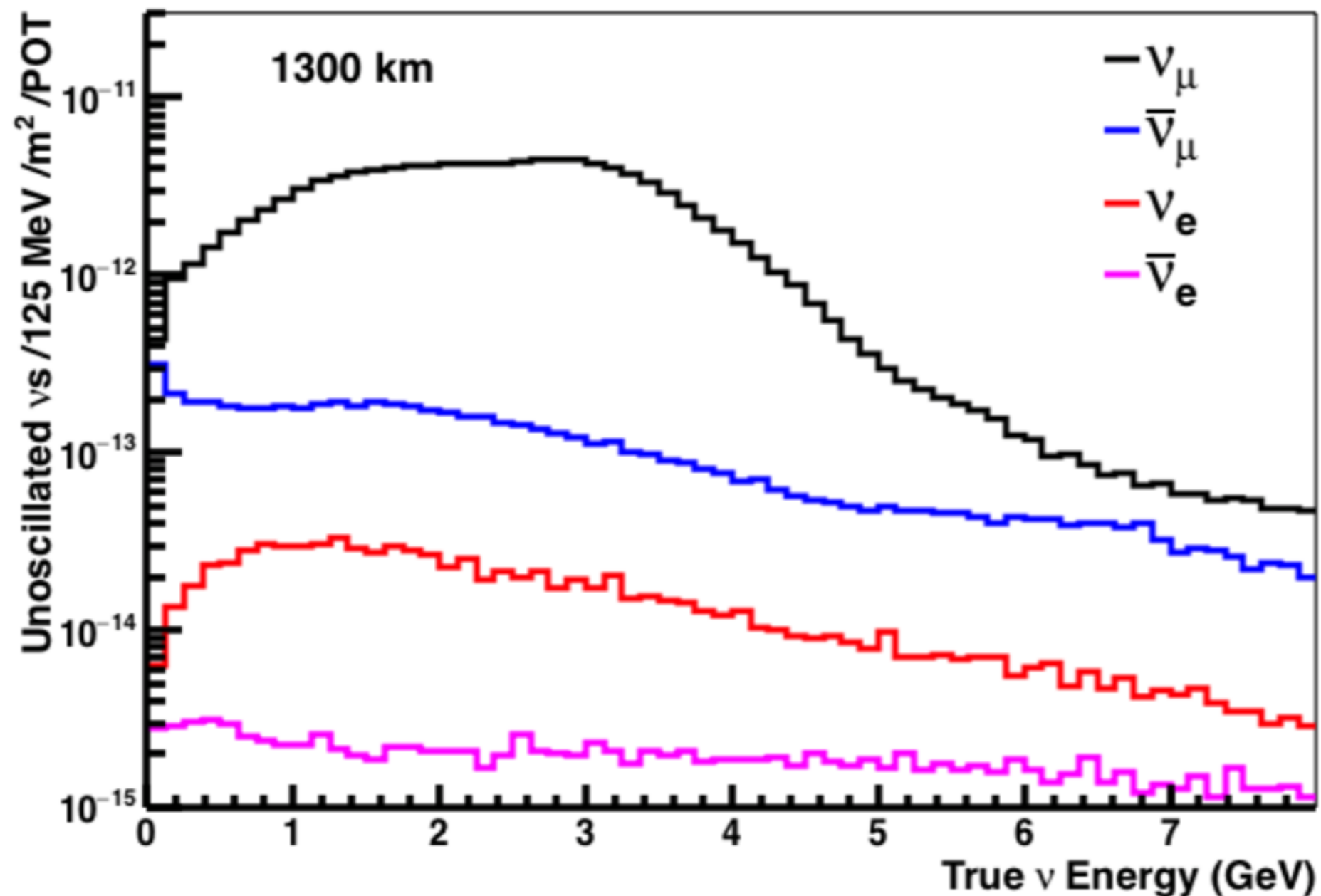


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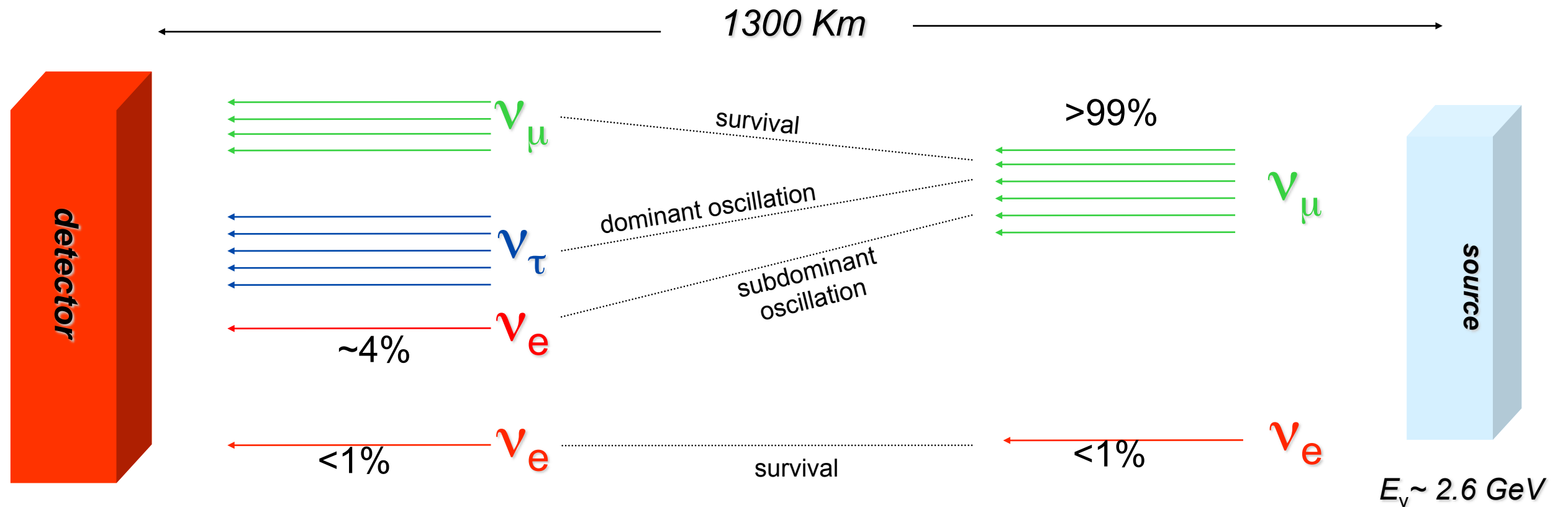
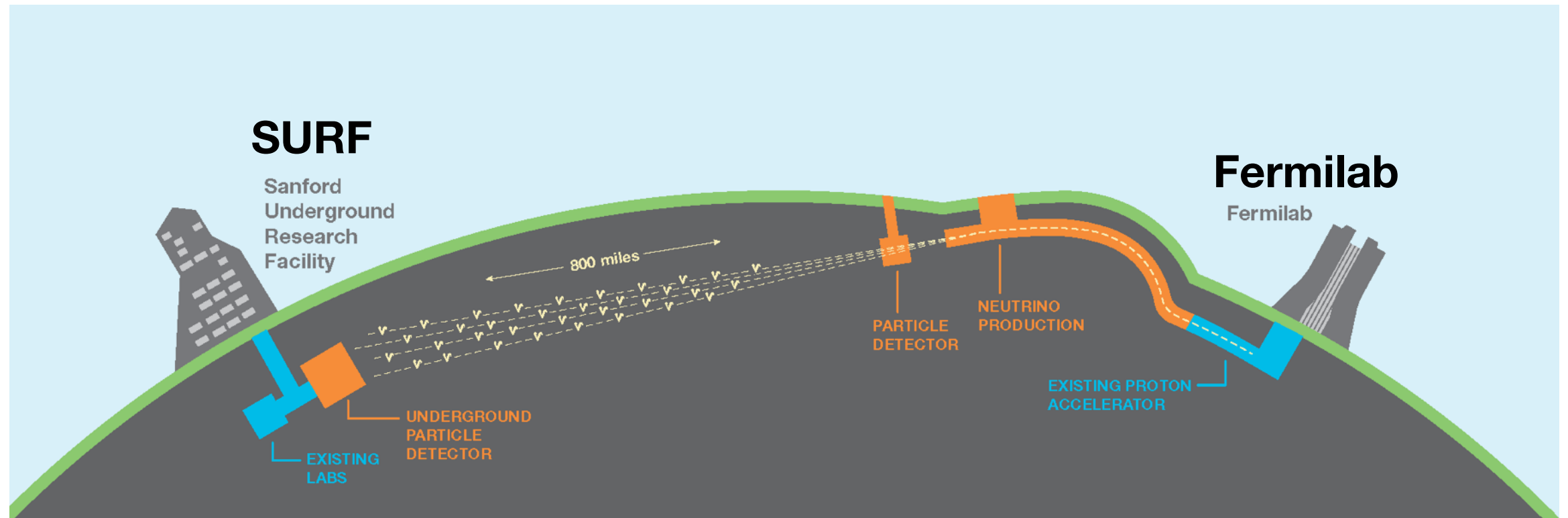
$$E = 1300 / 500 = 2.6 \text{ GeV}$$

The DUNE neutrino beam

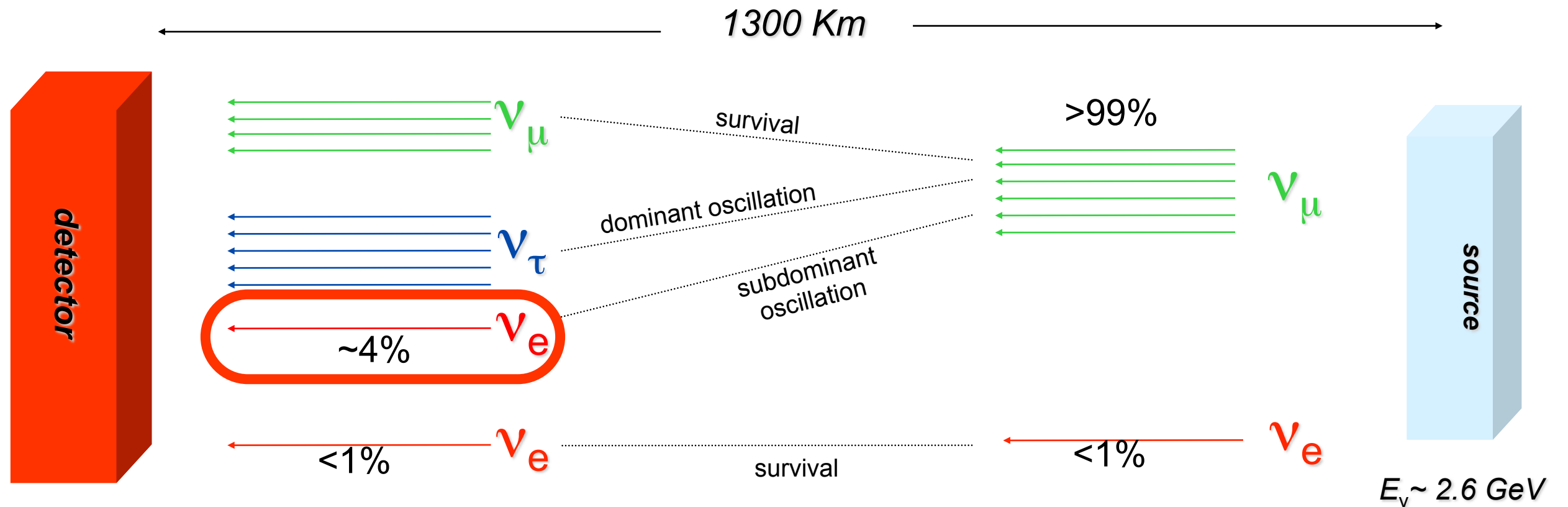
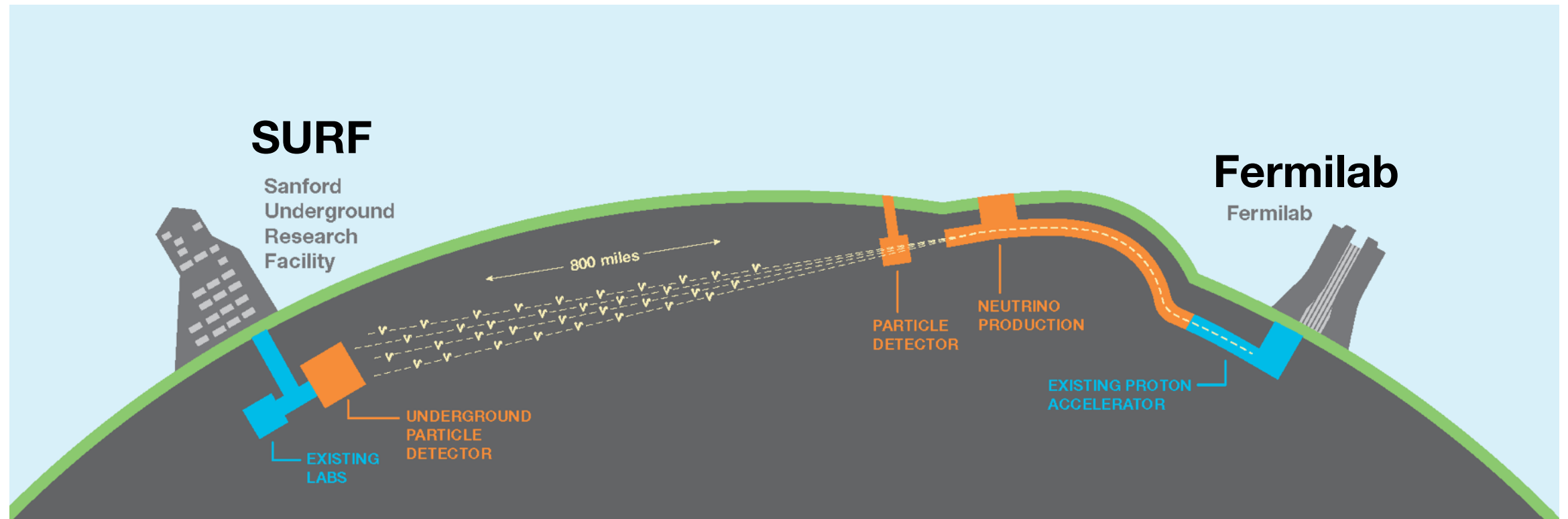
Neutrino Flux at 1300 km (CDR Optimized Beam)



Modos de oscilación en DUNE



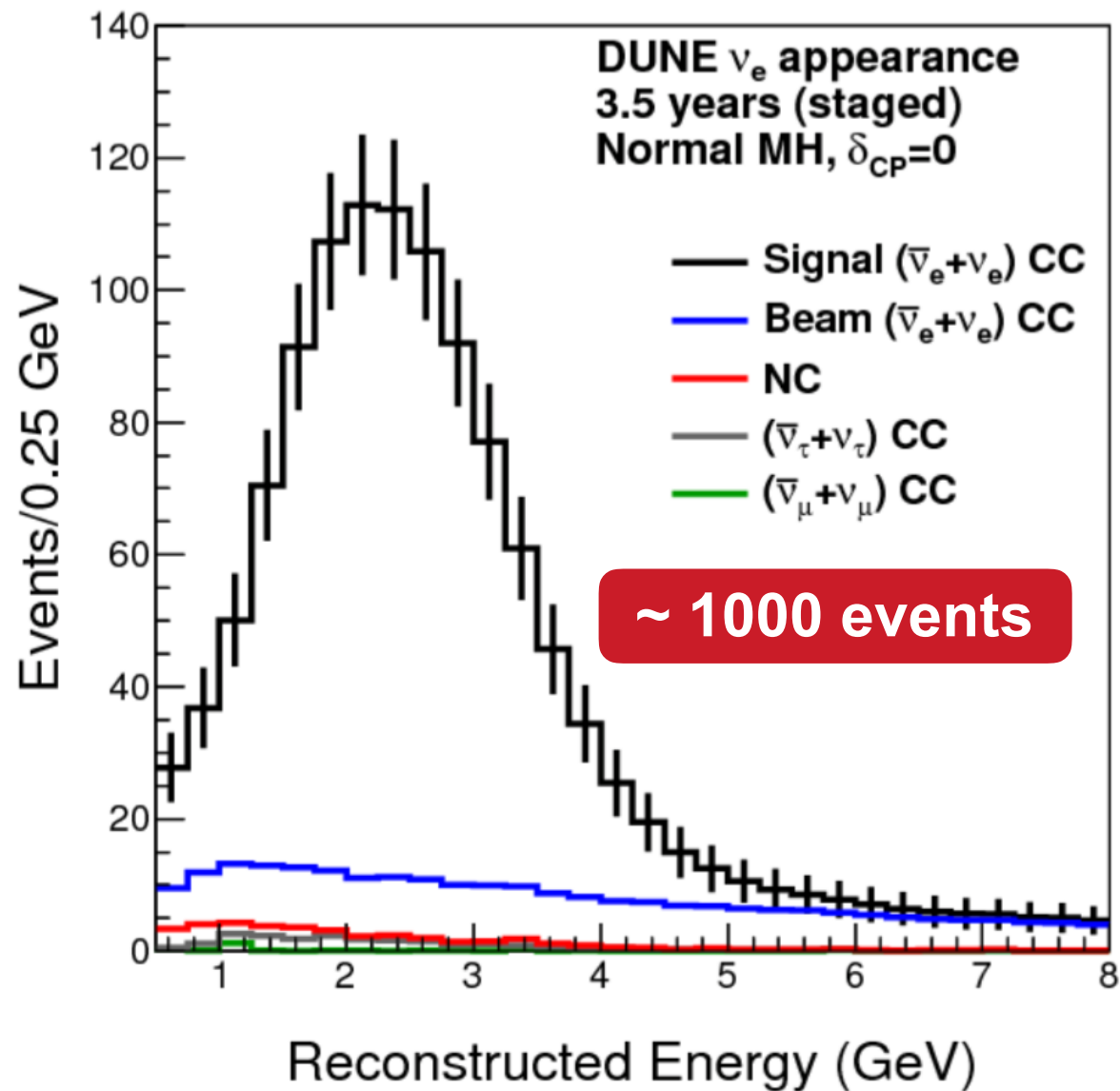
Modos de oscilación en DUNE



Beam observed events

DUNE Conceptual Design Report (CDR)
arXiv:1512.06148

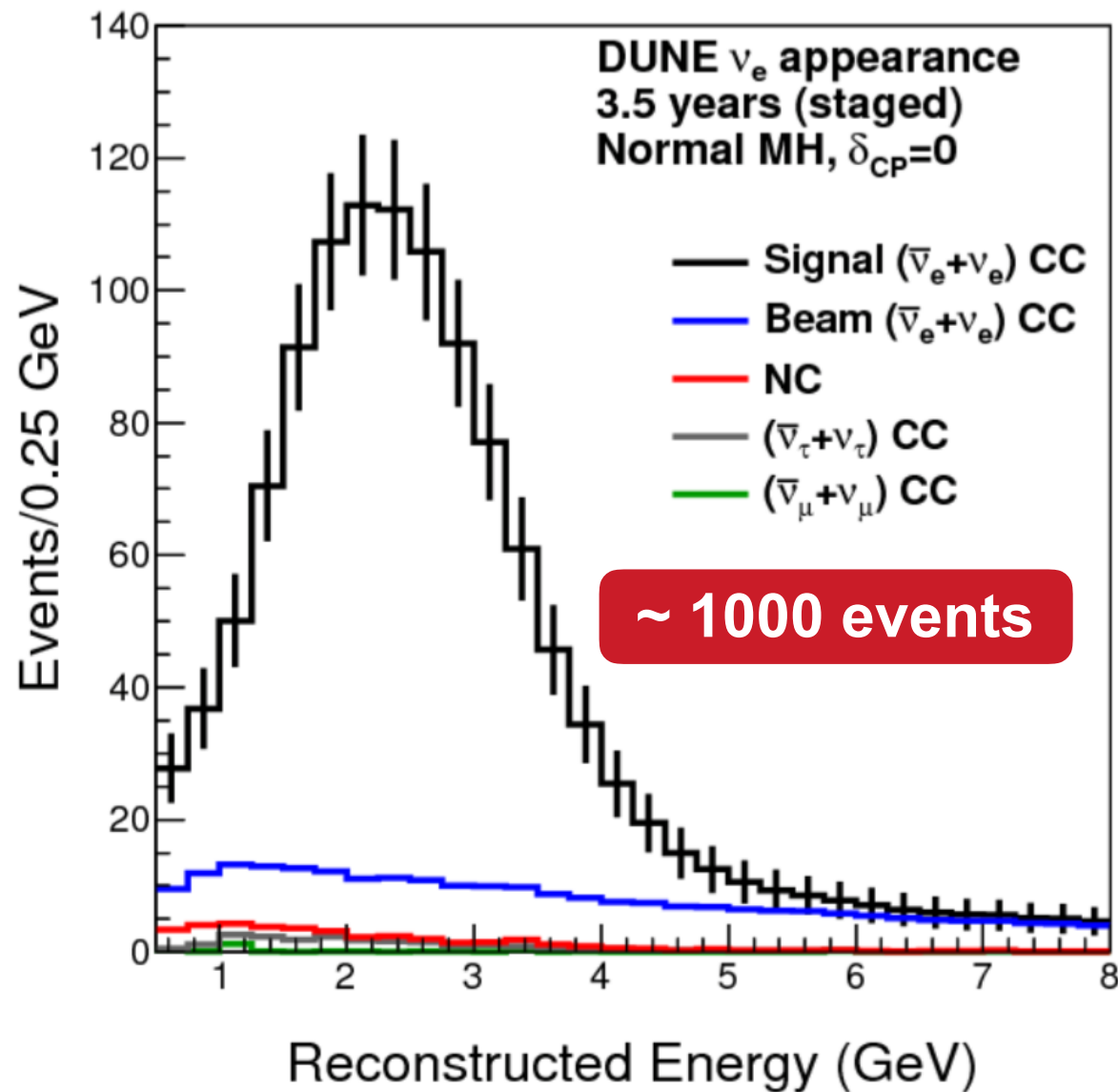
ν_e events in DUNE



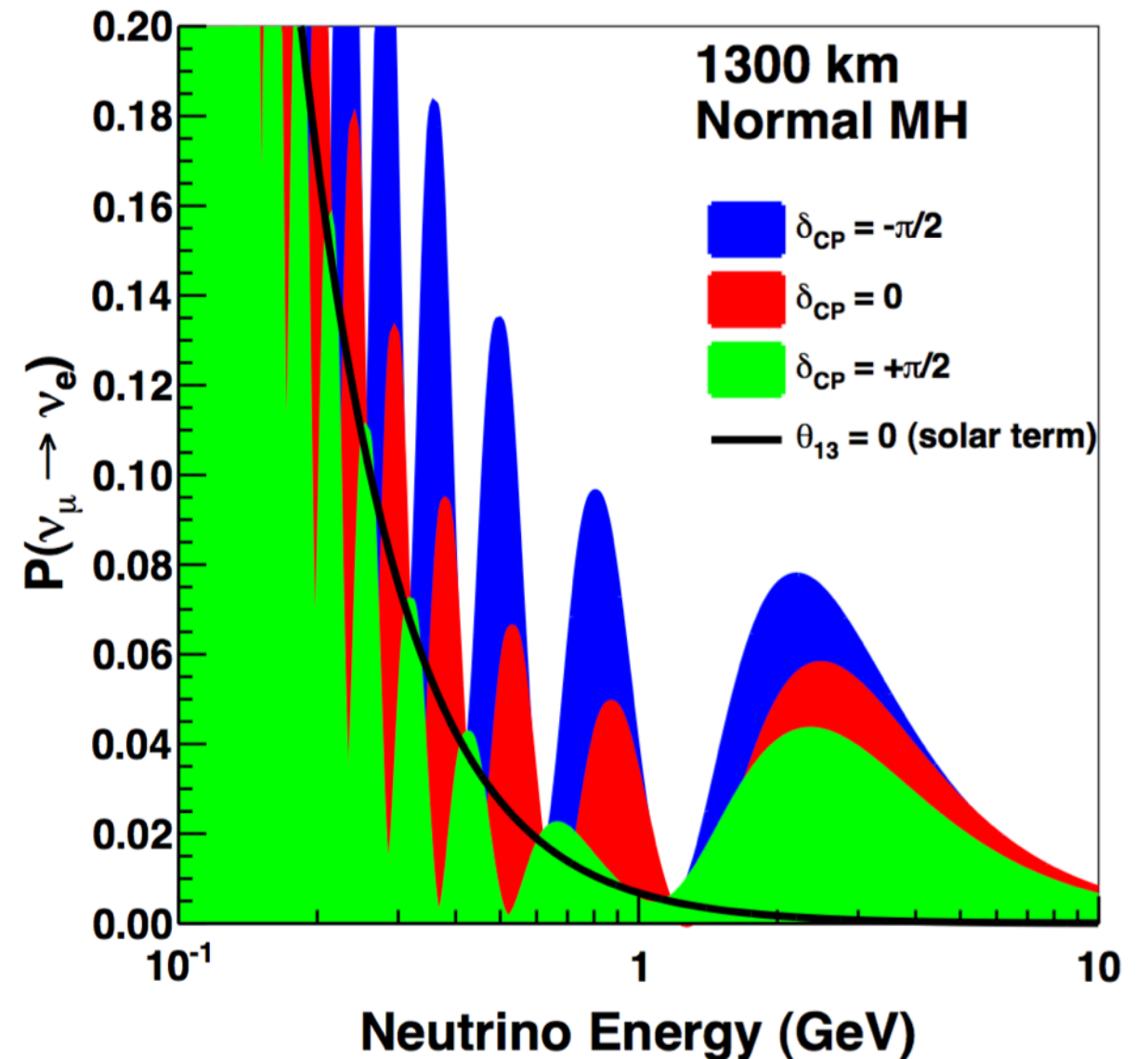
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ν_e events in DUNE



Oscillation probability for different values of δ_{CP}



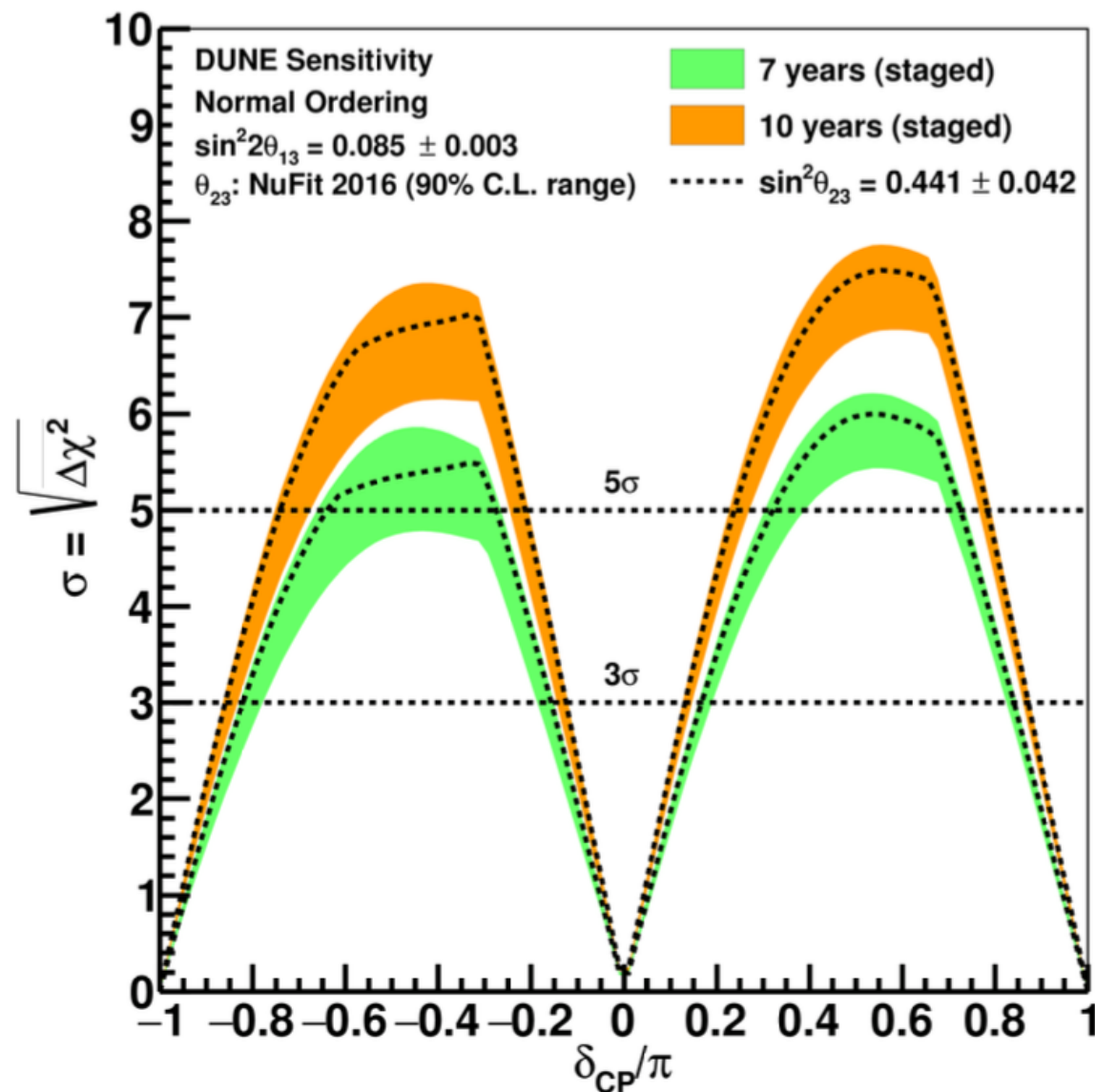
Sensibilidad

5 σ en 7 años

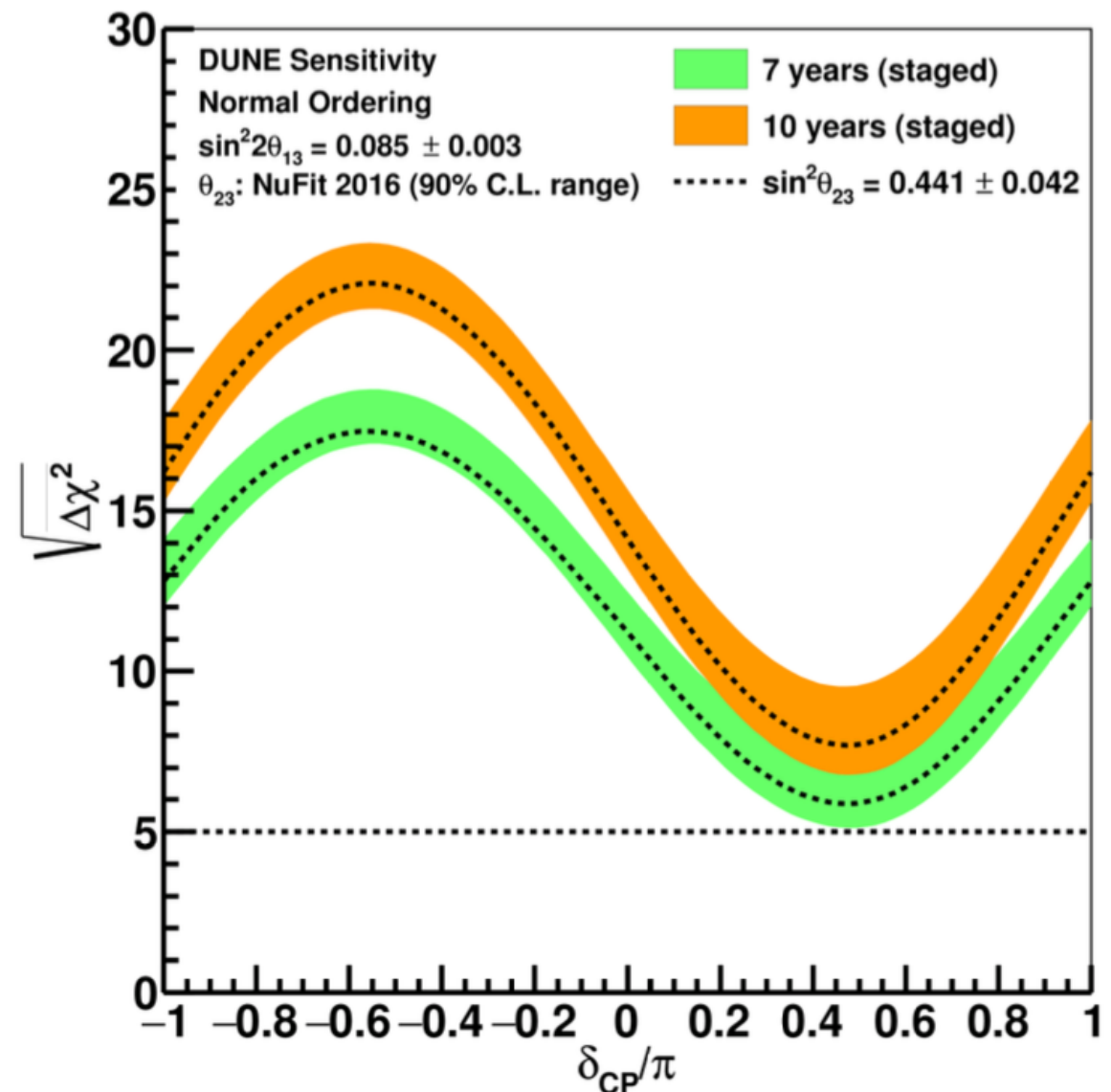
7 σ en 10 años

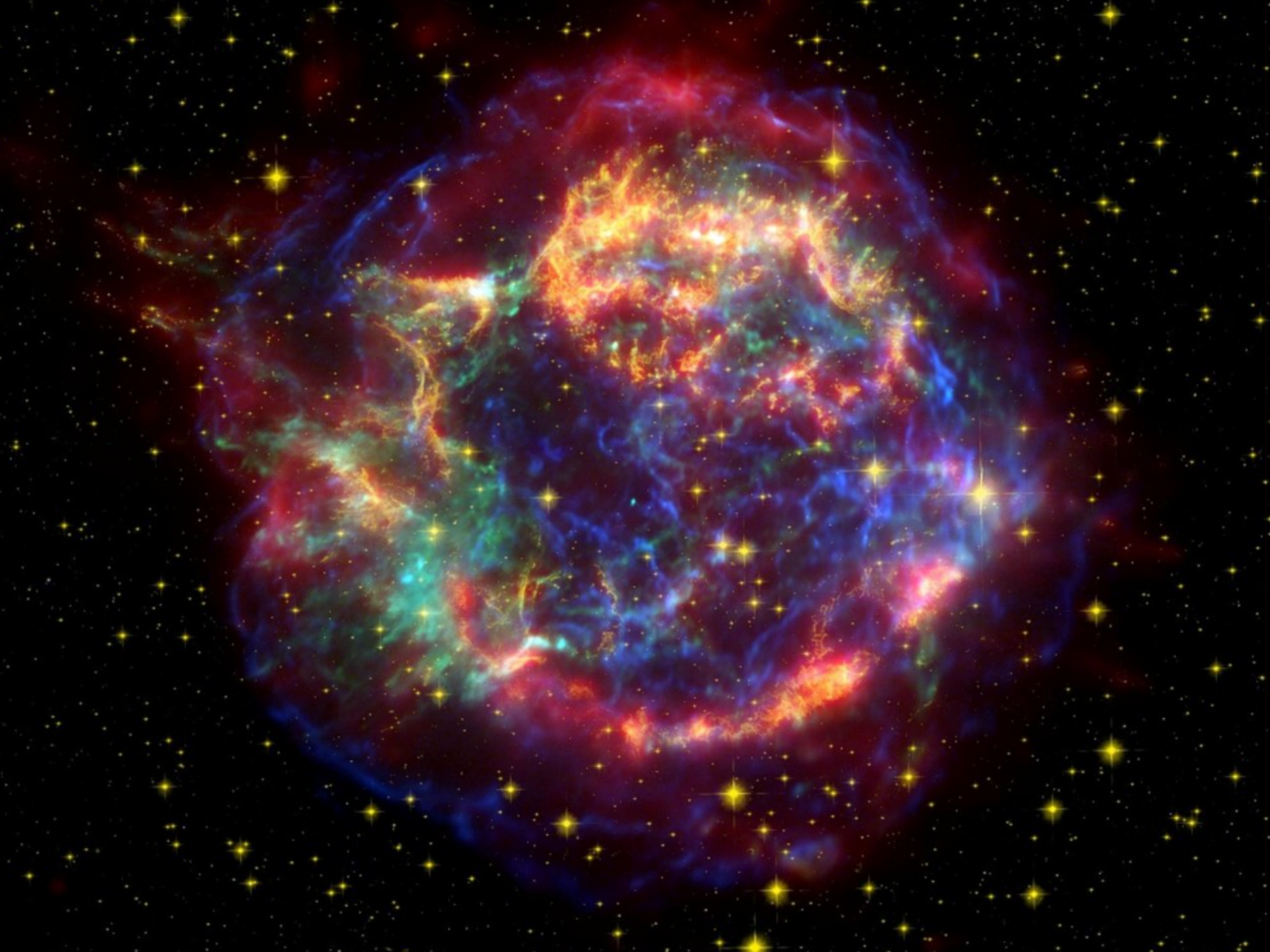
medida inequívoca

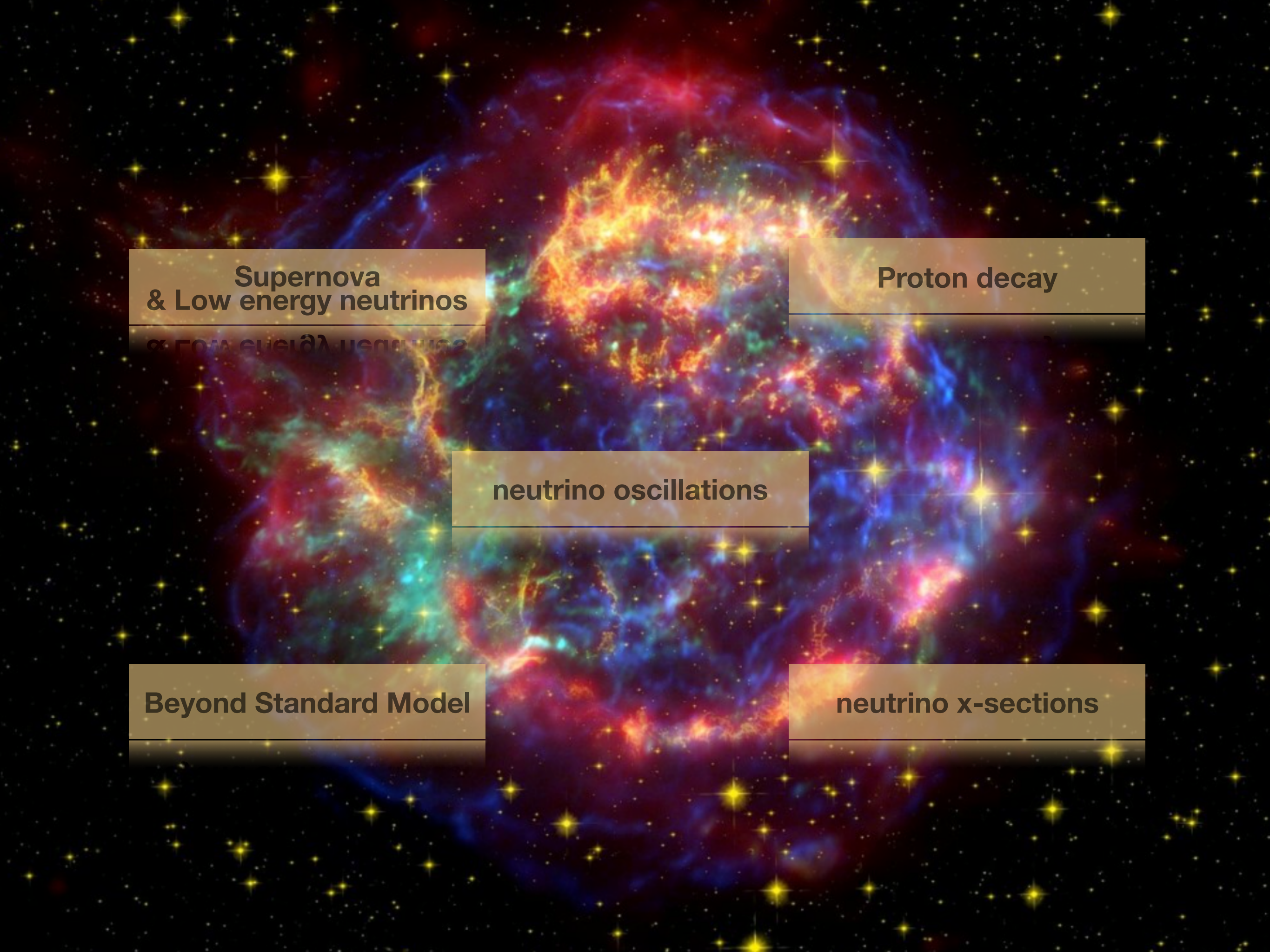
Violación de CP



Jerarquía de masas







**Supernova
& Low energy neutrinos**

Proton decay

neutrino oscillations

Beyond Standard Model

neutrino x-sections







Fine-grained, 3D images of neutrino interactions.
Particle identification based on dE/dx and range.
Close to full acceptance.

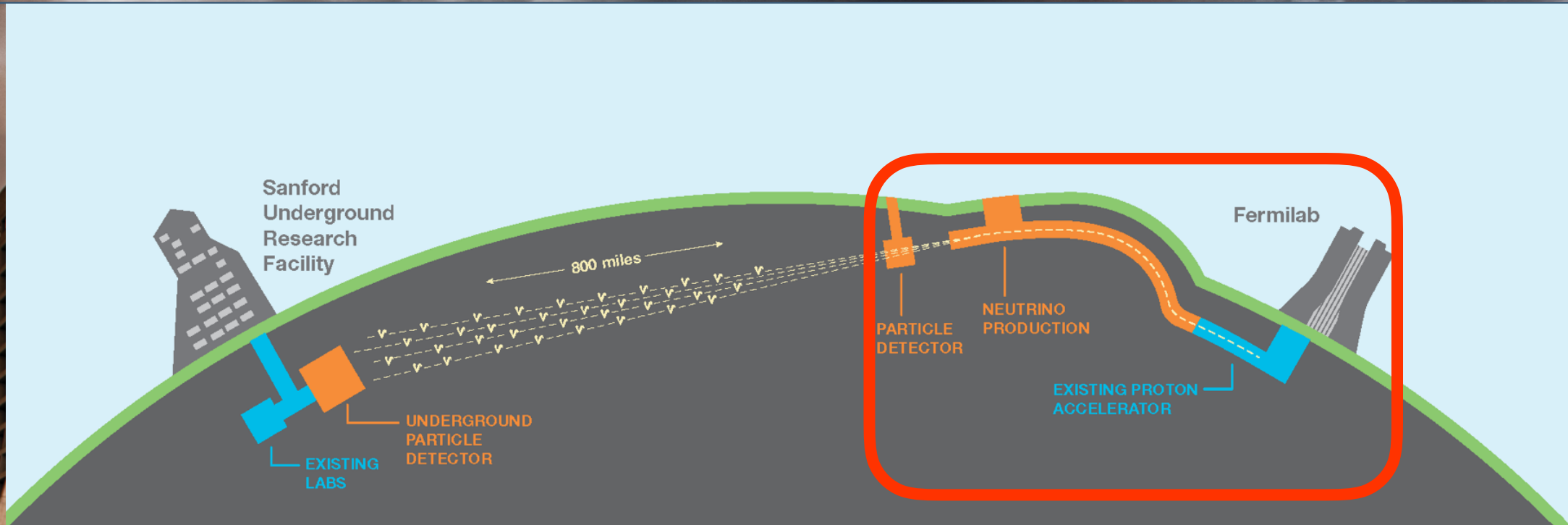
75 cm

Run 3493 Event 41075, October 23rd, 2015



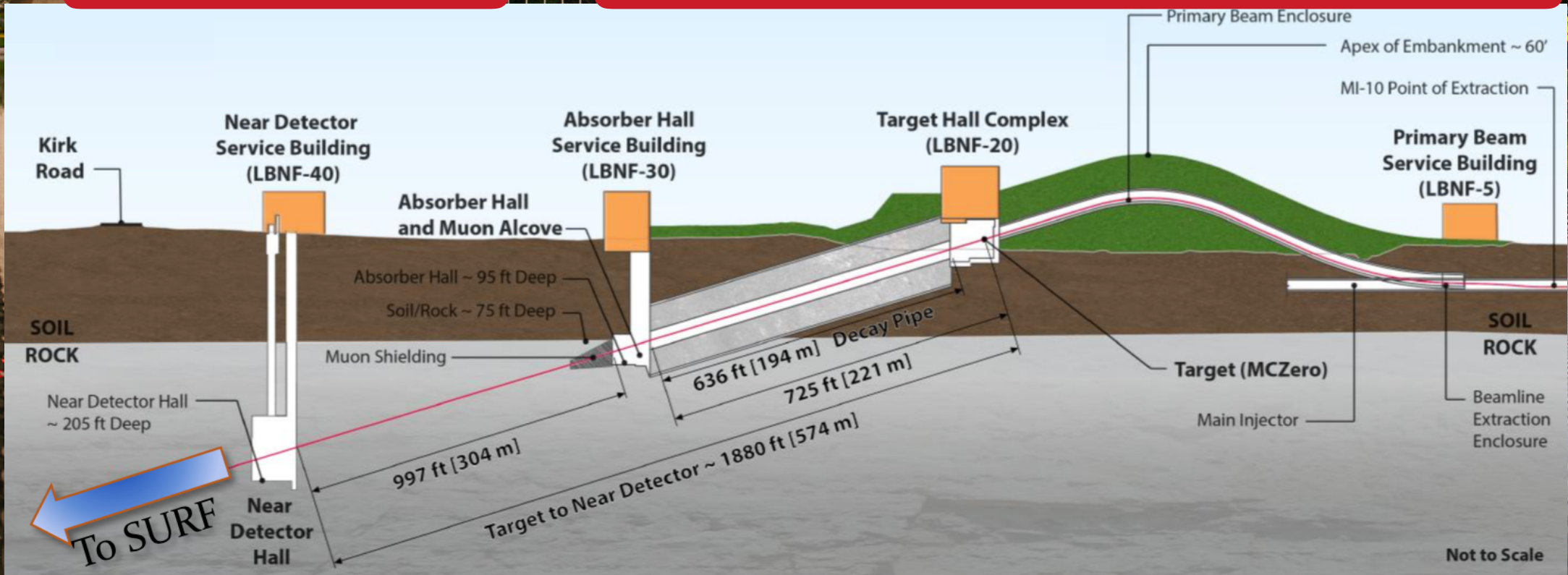
 **Fermilab**

Fermilab



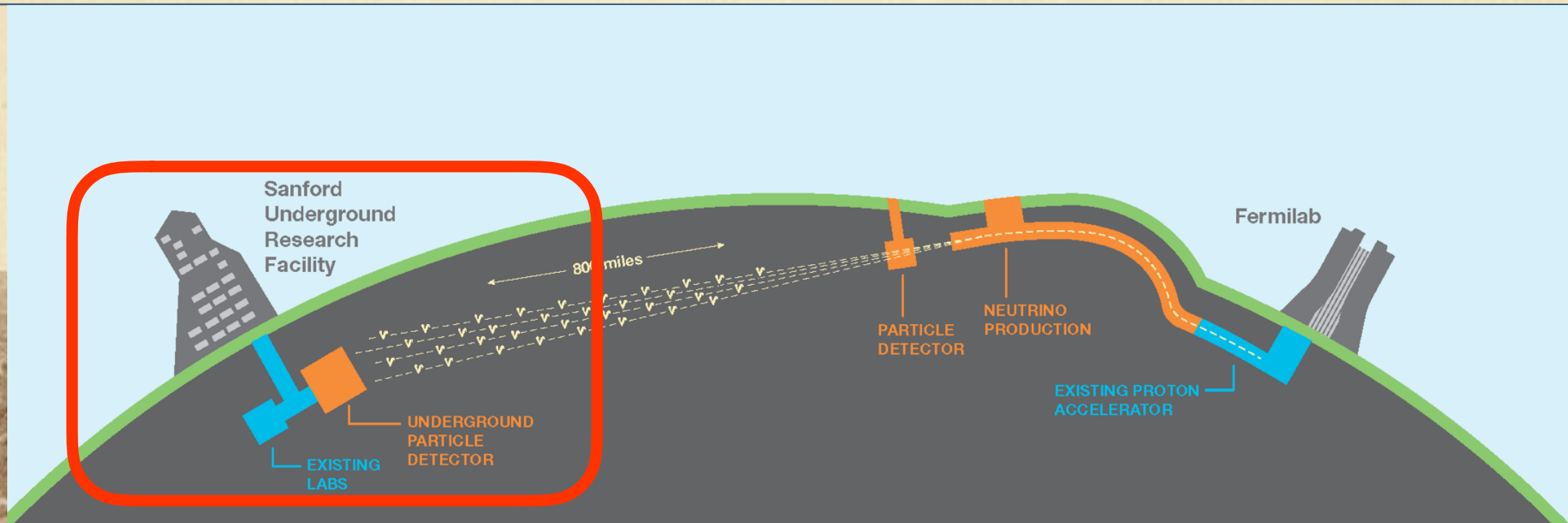
Detector cercano

LBNF Neutrino beam-line

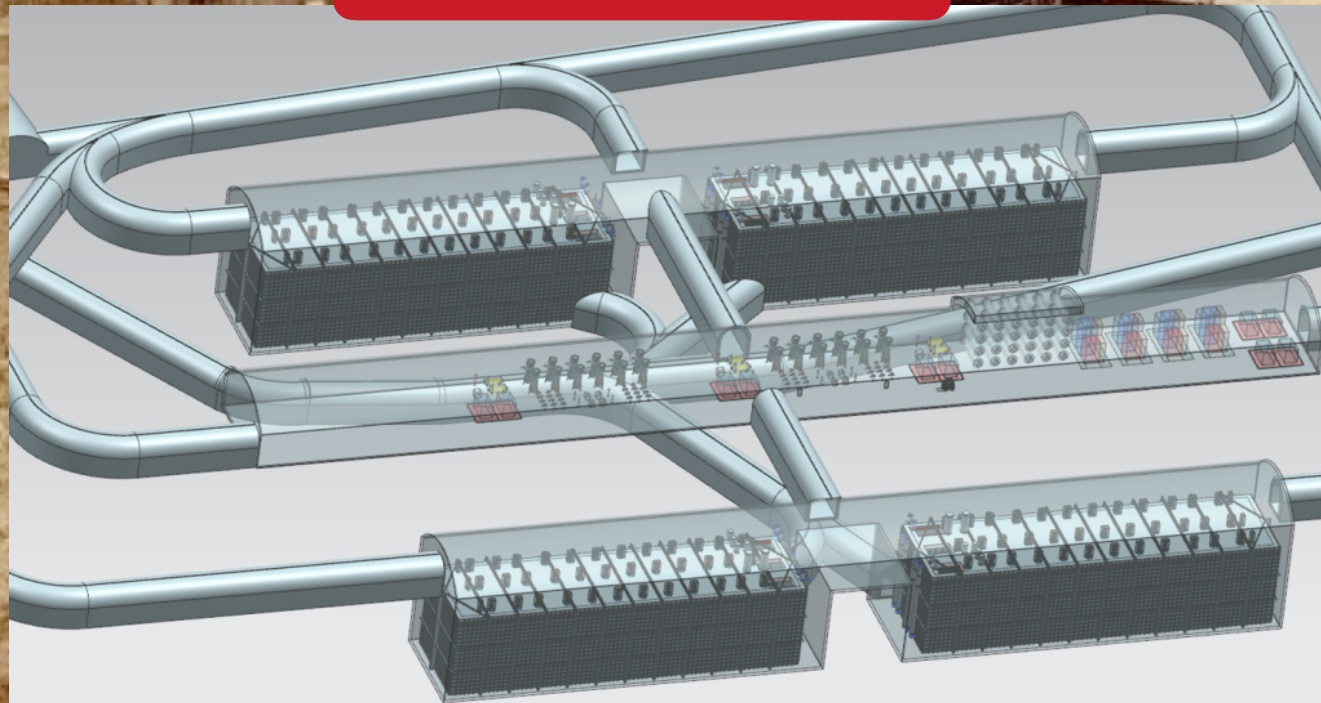


SURF

Sanford Underground Research Facility (Lead, SD)



Detector lejano

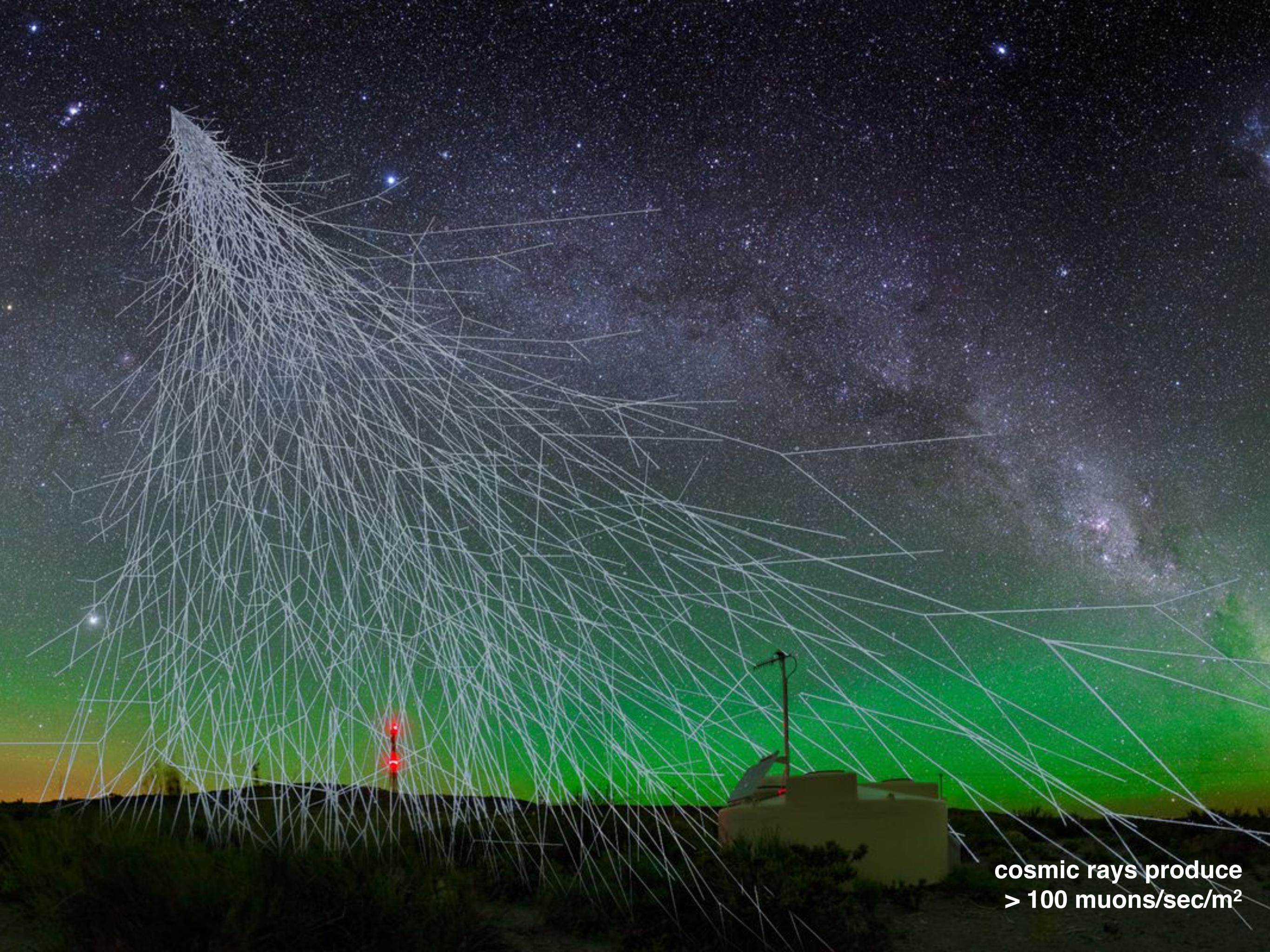


Baseline Neutrino Facility

a 1300 Km de Fermilab

The Homestake Mine in 1889





**cosmic rays produce
> 100 muons/sec/m²**

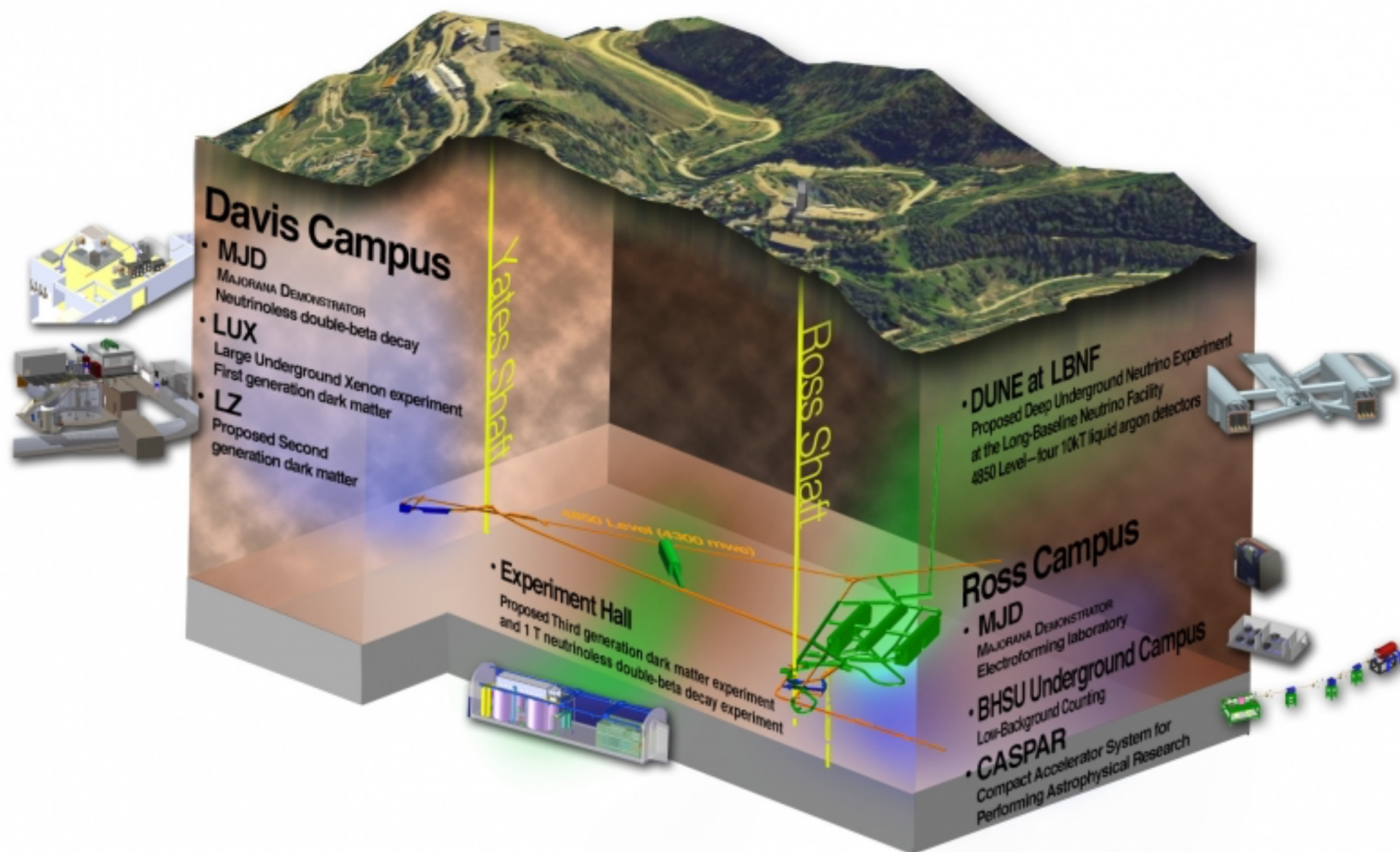


Most neutrino detectors are placed deep underground to shield them against cosmic rays

10^{-6} reduction for DUNE, 1.5 km underground

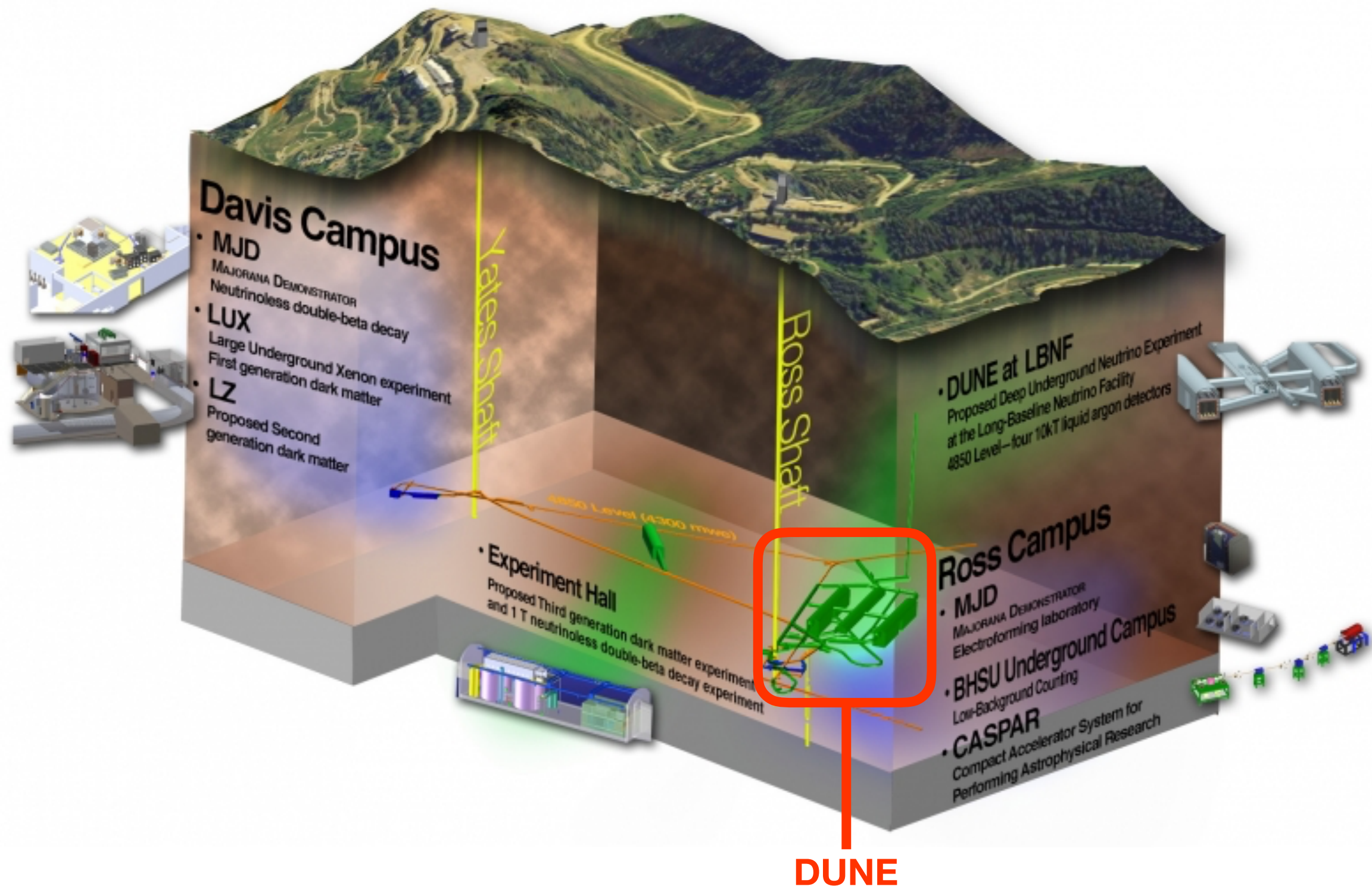
SURF Sanford Underground Research Facility (Lead, SD)

En la vieja mina de oro de Homestake 1.5 Km bajo tierra

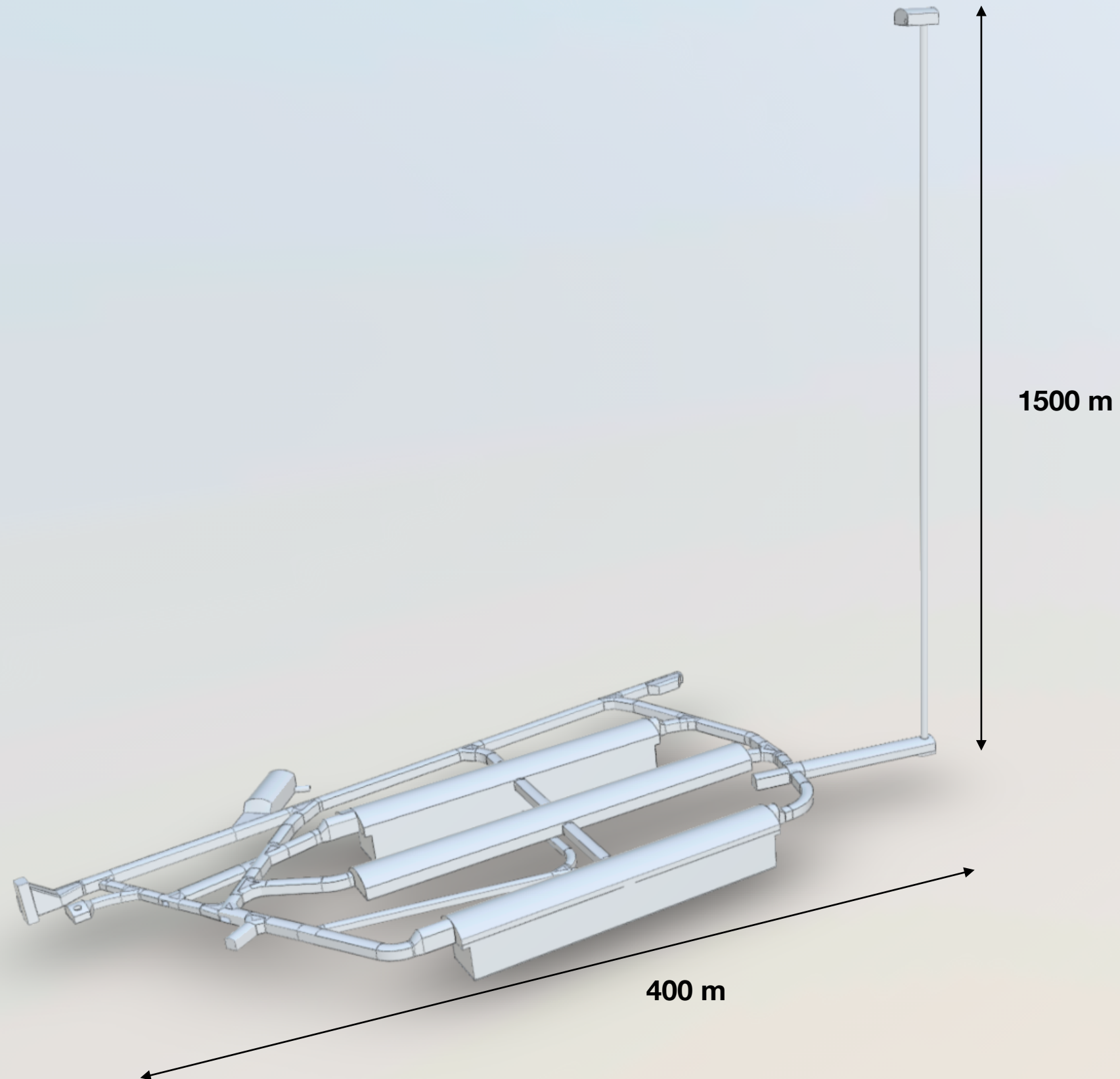


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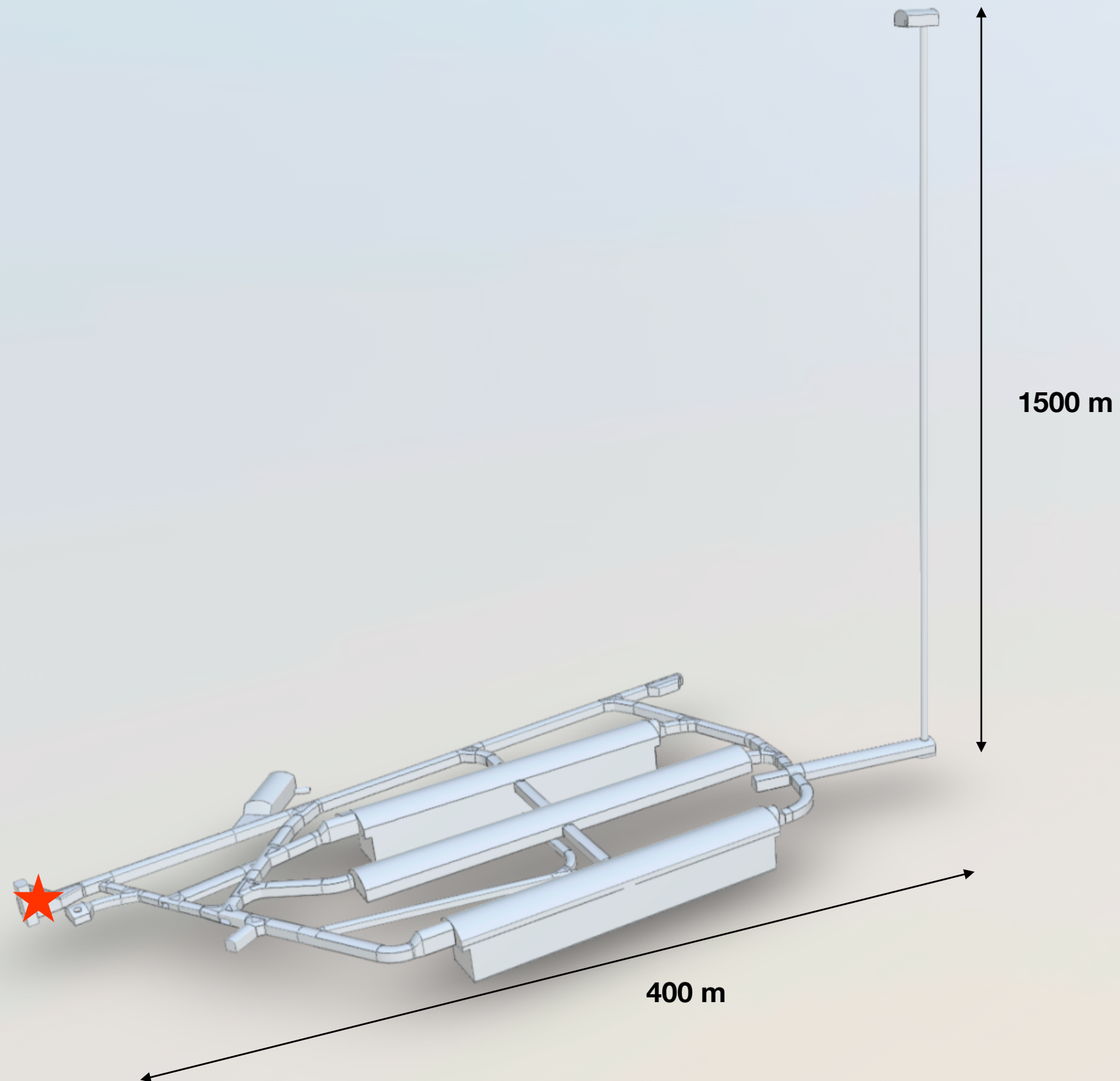
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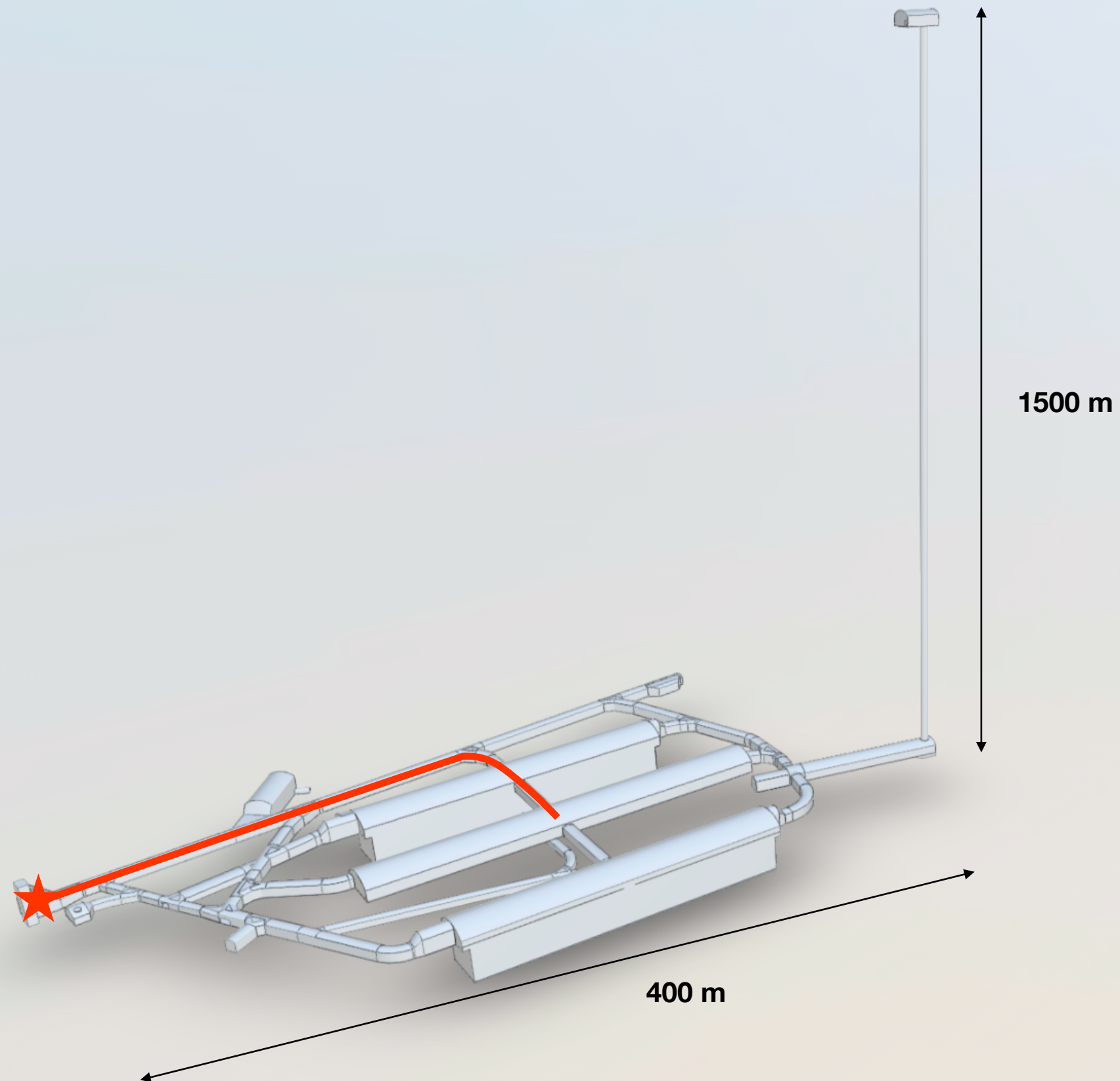
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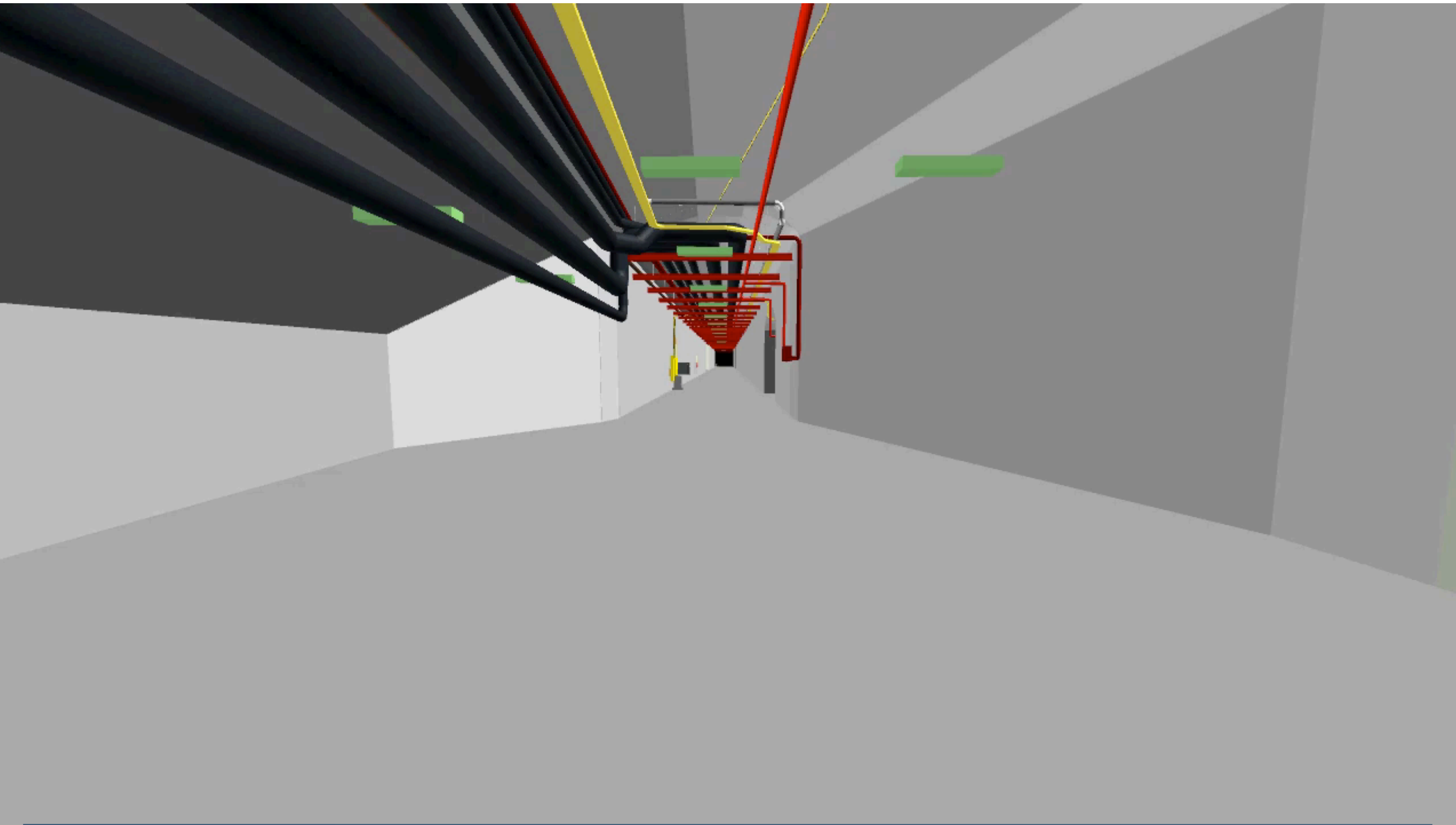
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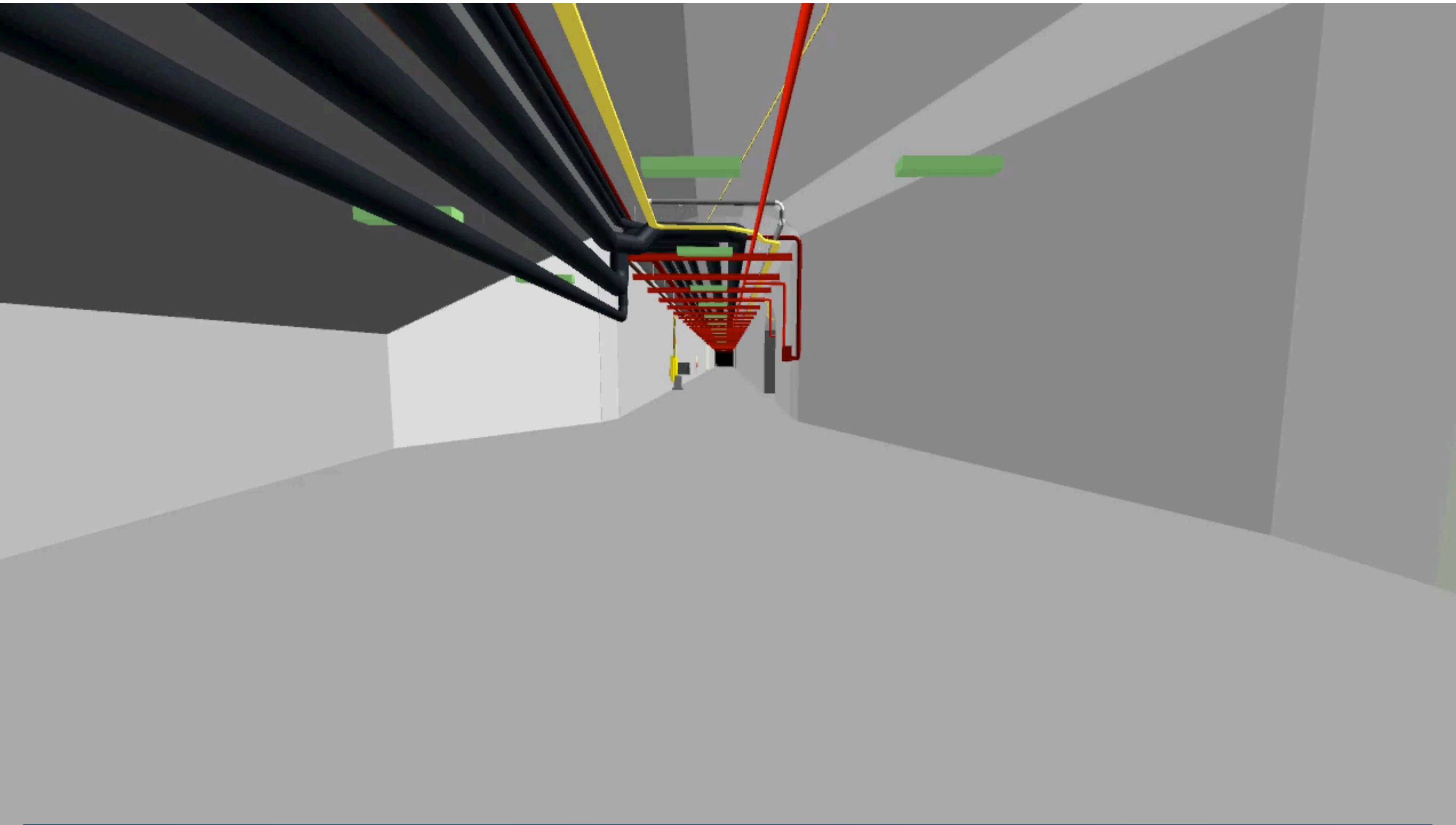
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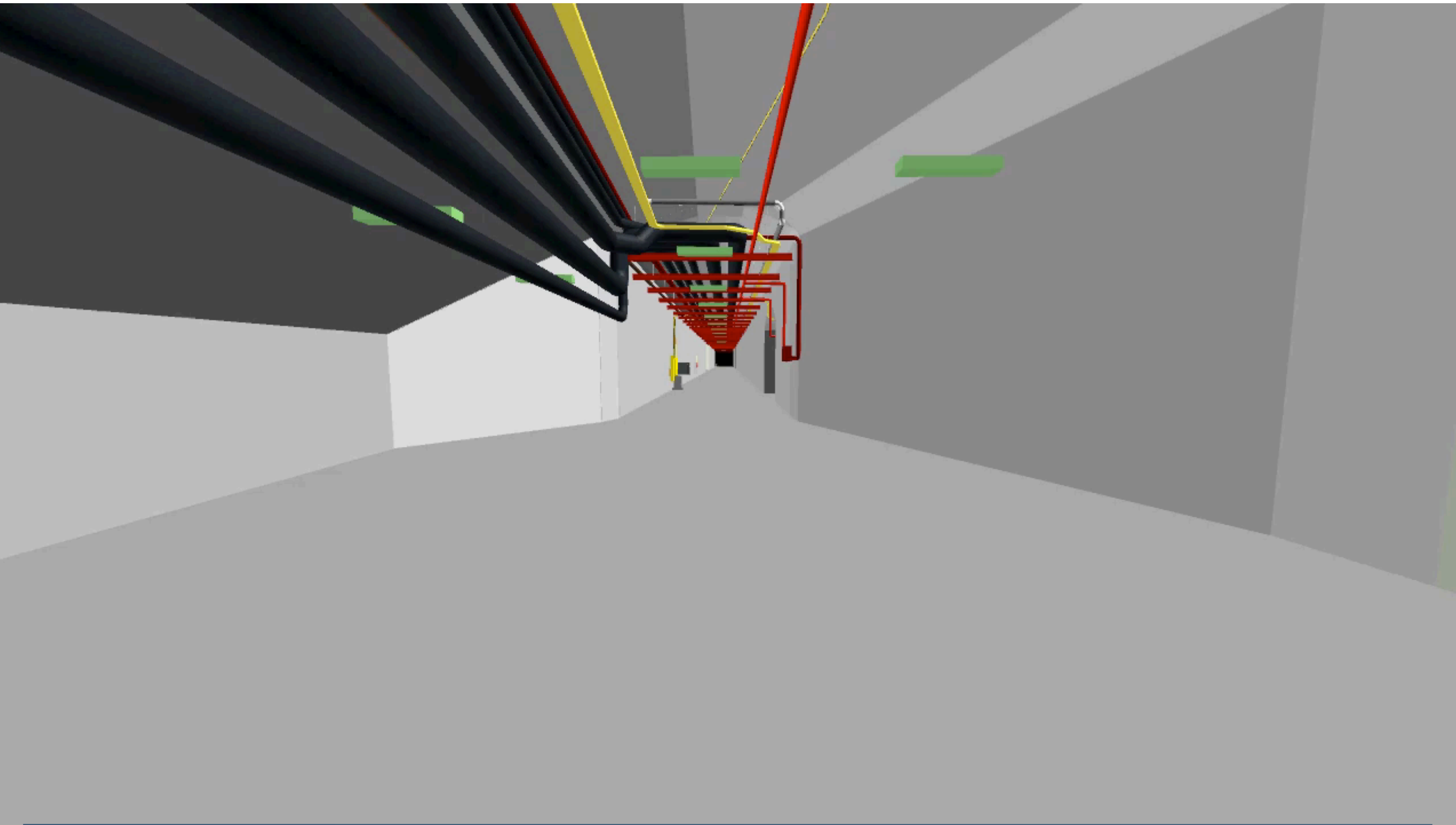
Un paseo por los tuneles



Un paseo por los tuneles

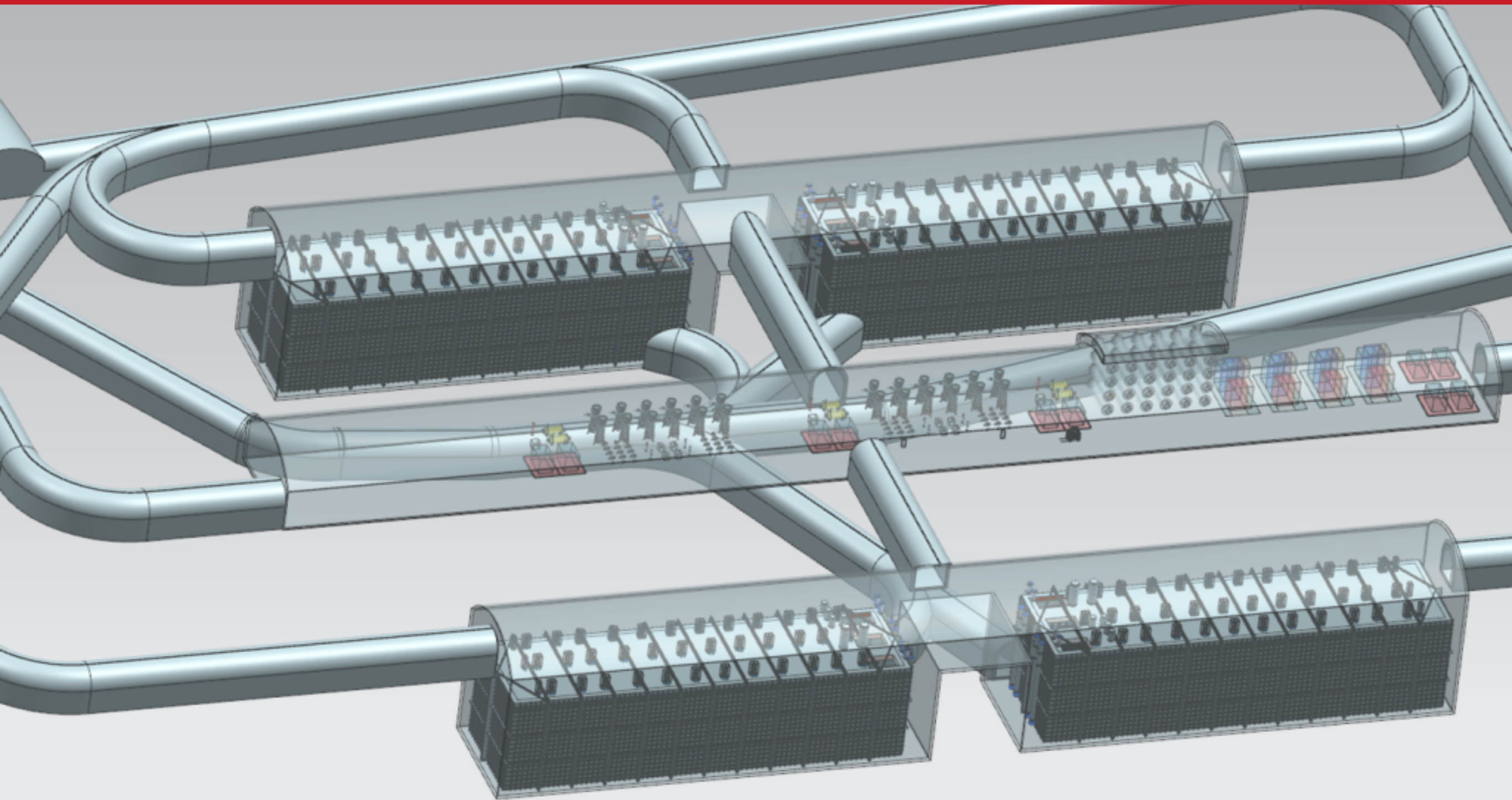


Un paseo por los tuneles



Detector lejano

**Cuatro TPCs de Argón Líquido de
10 Kton útiles (17 Kton total) cada una**



Por qué una TPC ?

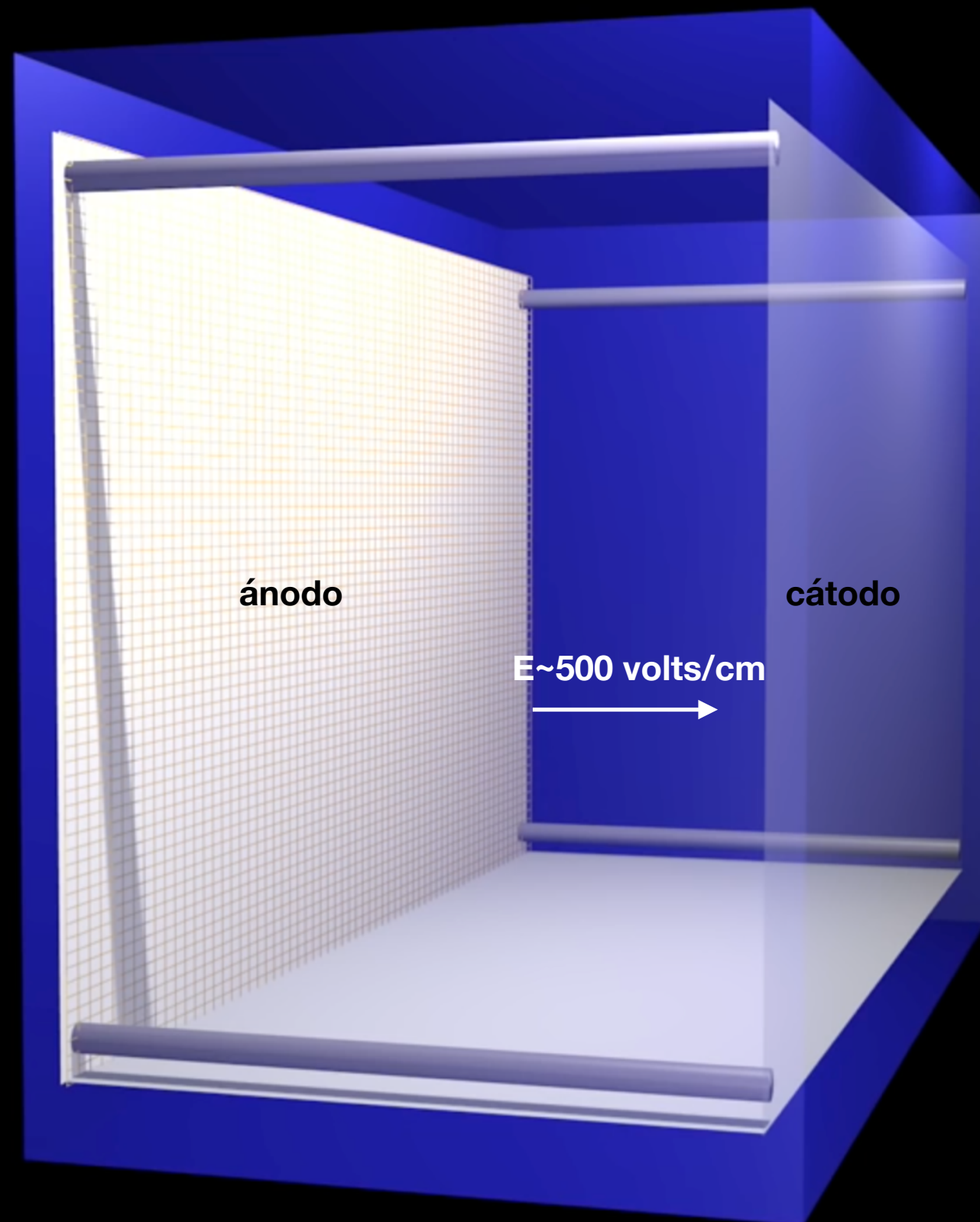
μ BooNE

Fine-grained, 3D images of neutrino interactions.
Particle identification based on dE/dx and range.
Close to full acceptance.

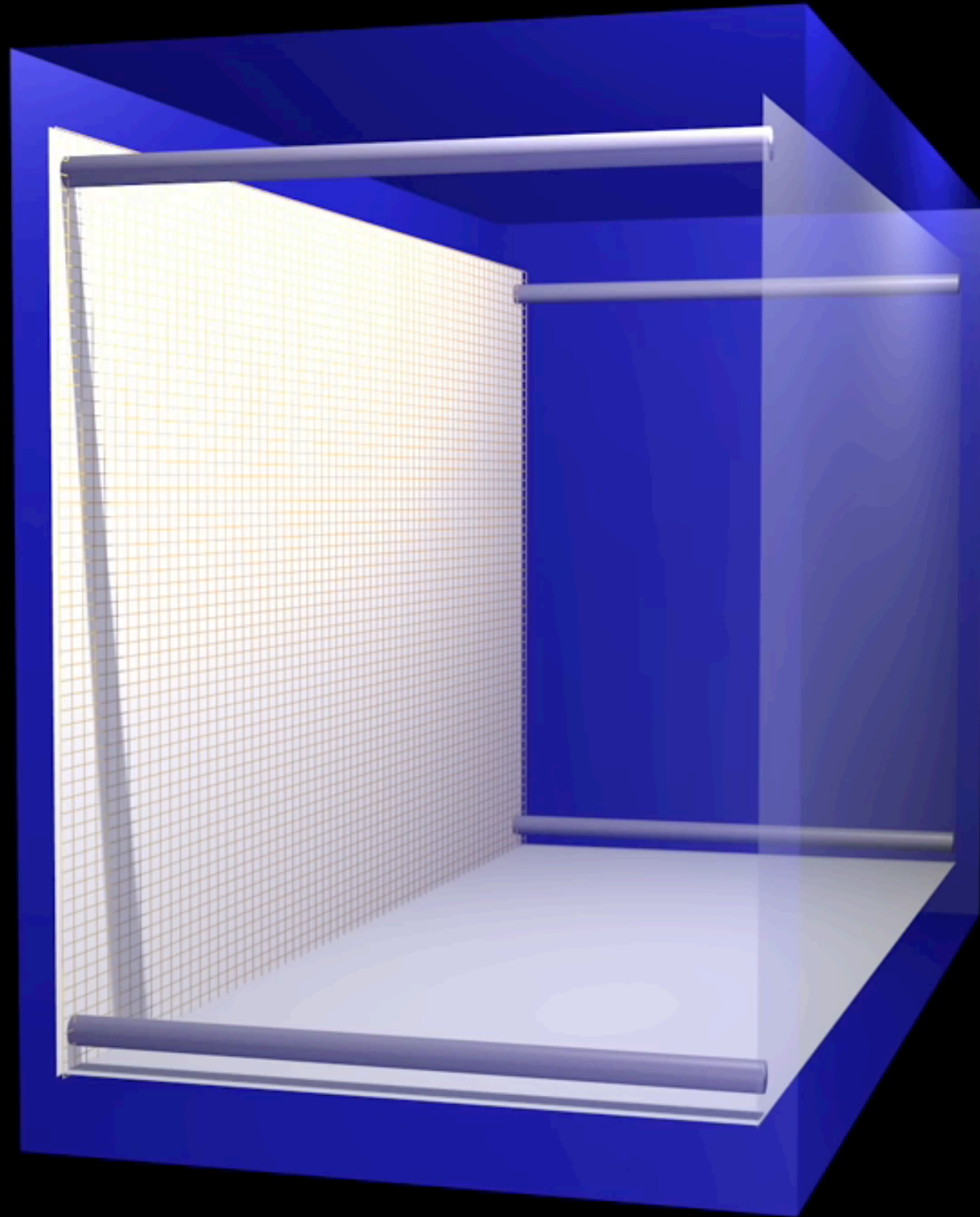
75 cm

Run 3493 Event 41075, October 23rd, 2015

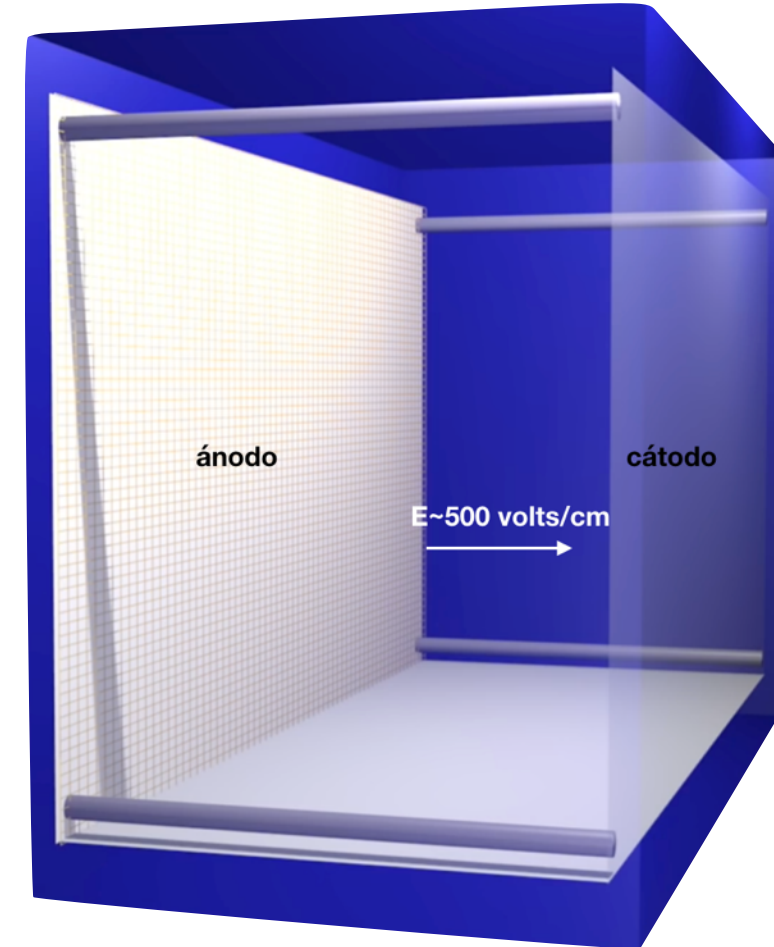
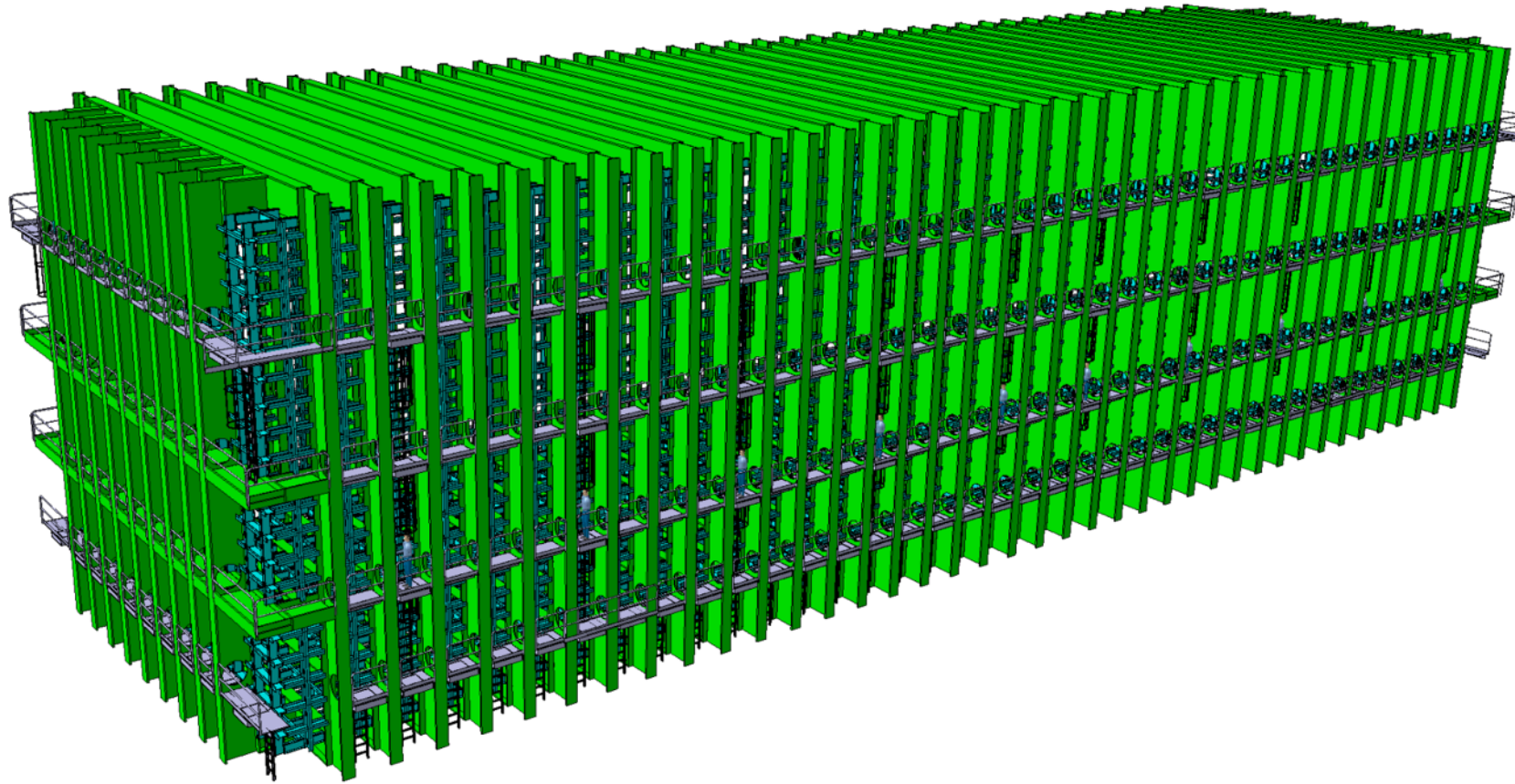
¿Como funciona ?



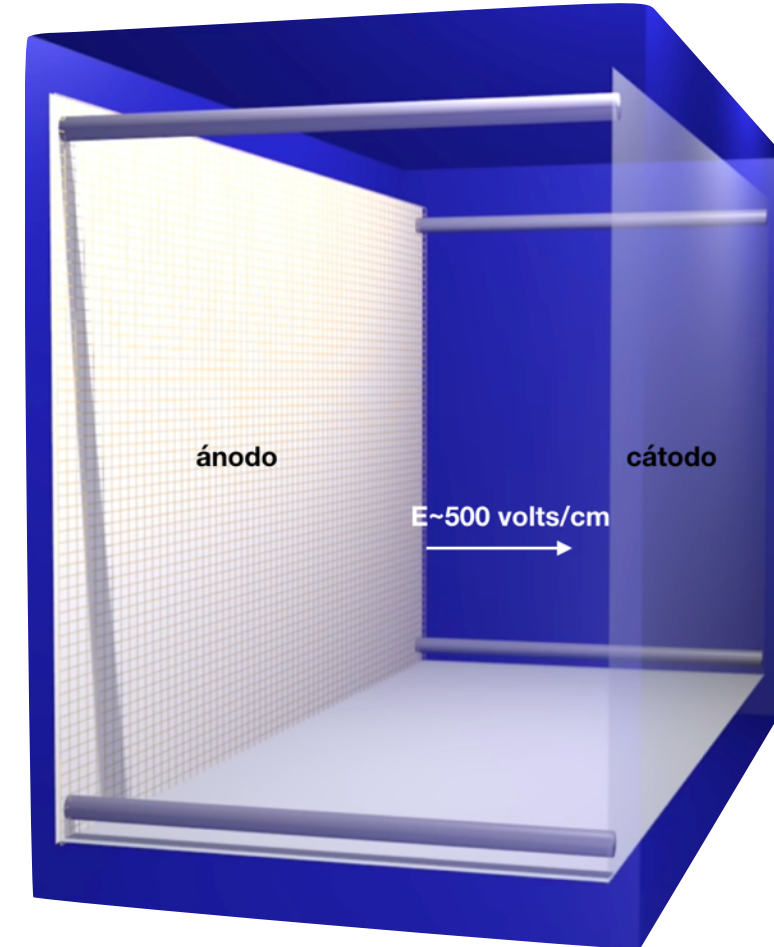
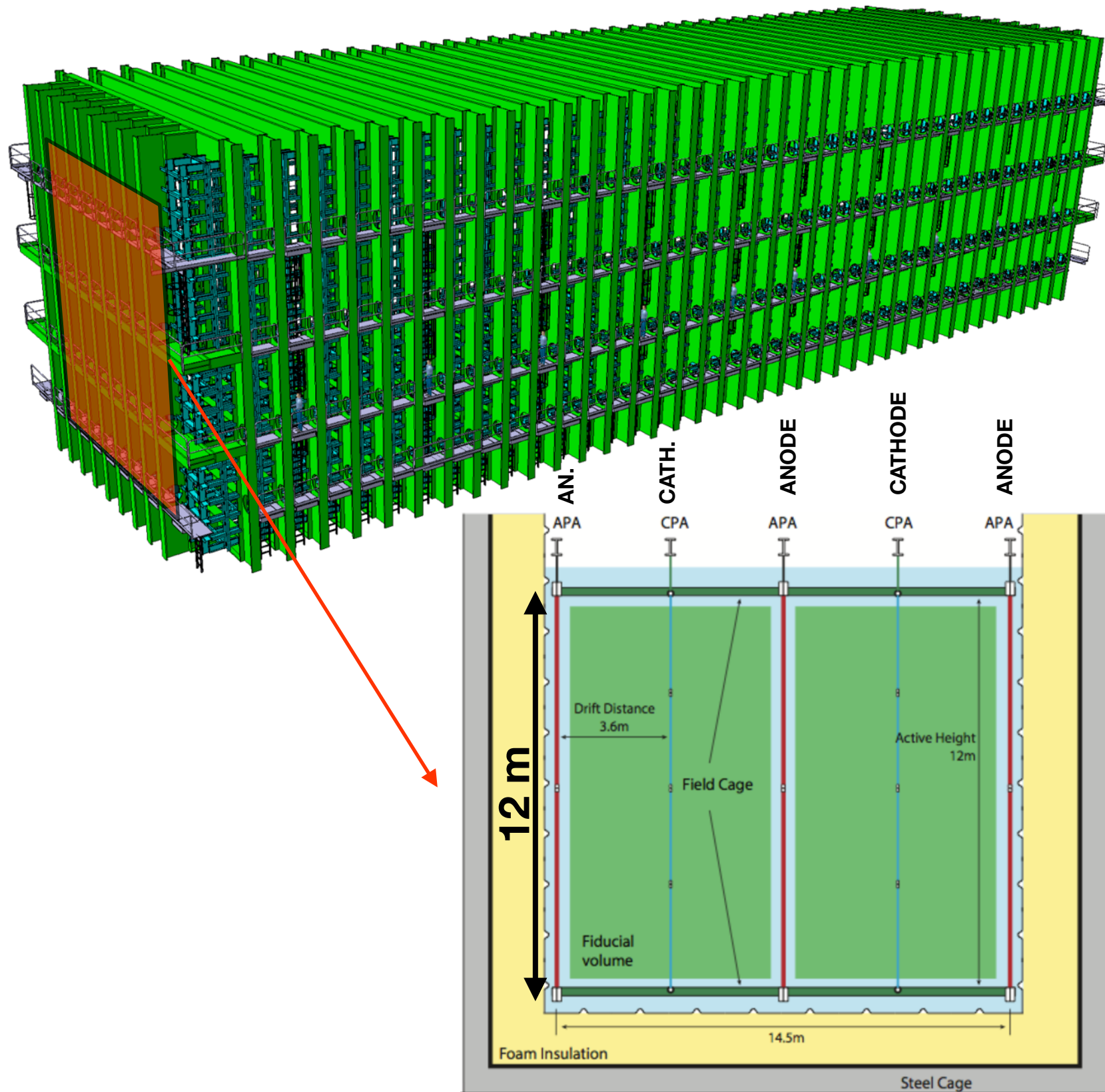
¿Como funciona ?



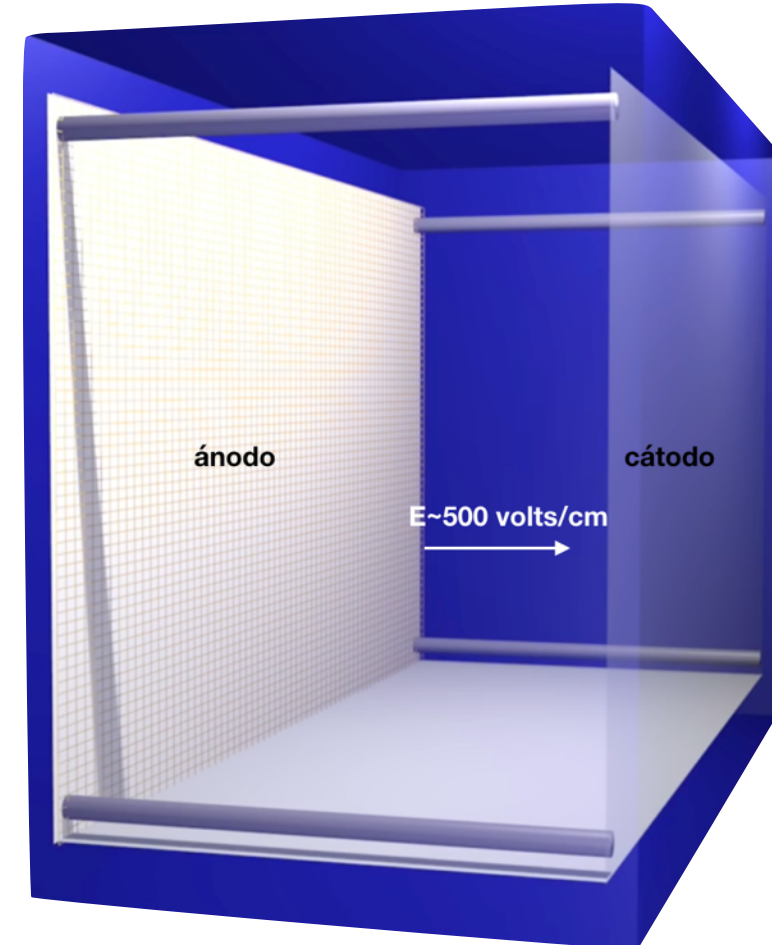
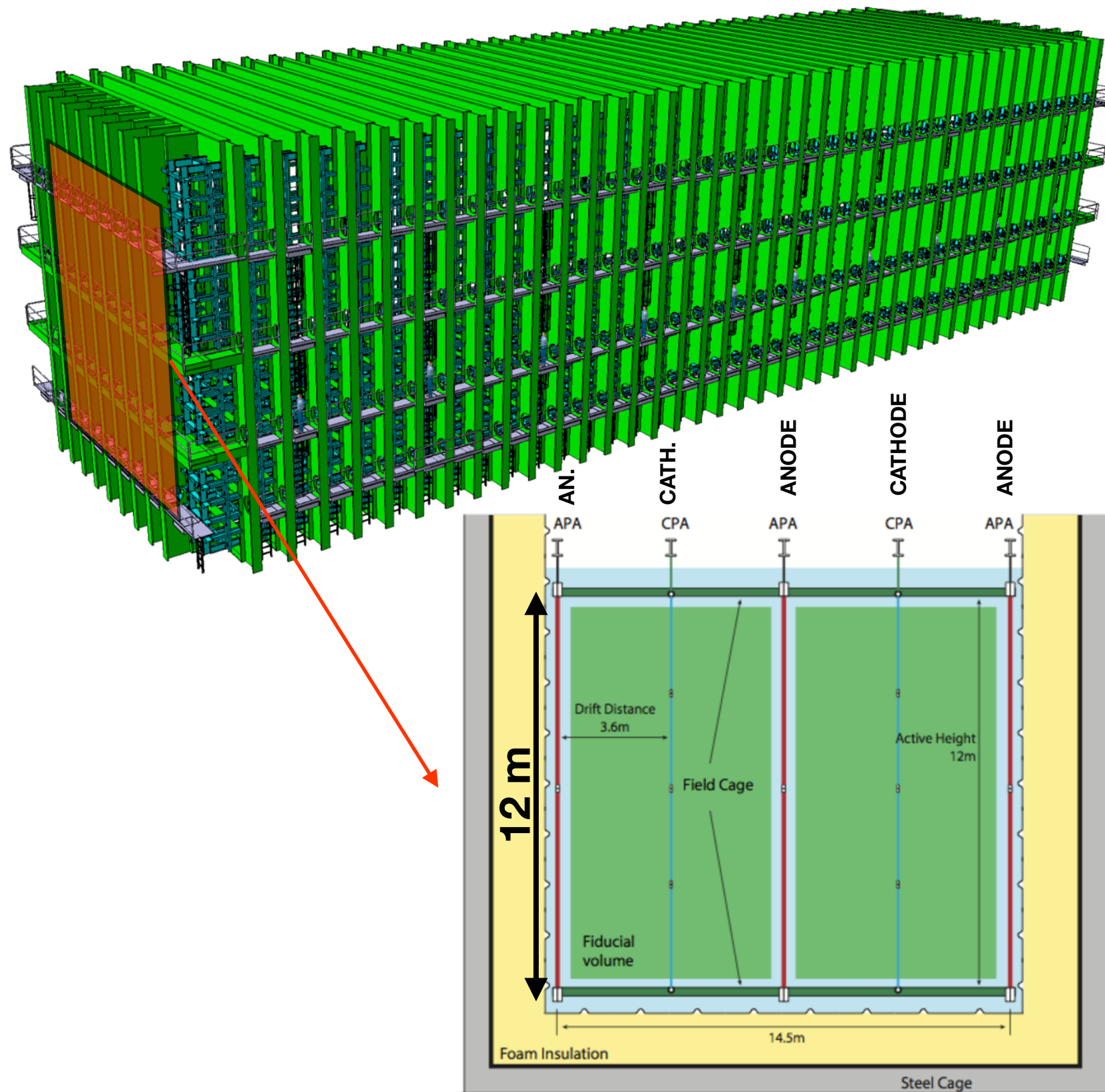
Detectores lejanos



Detectores lejanos



Detectores lejanos



180,000 volts between cathode and anode

ANODE

CATHODE

ANODE

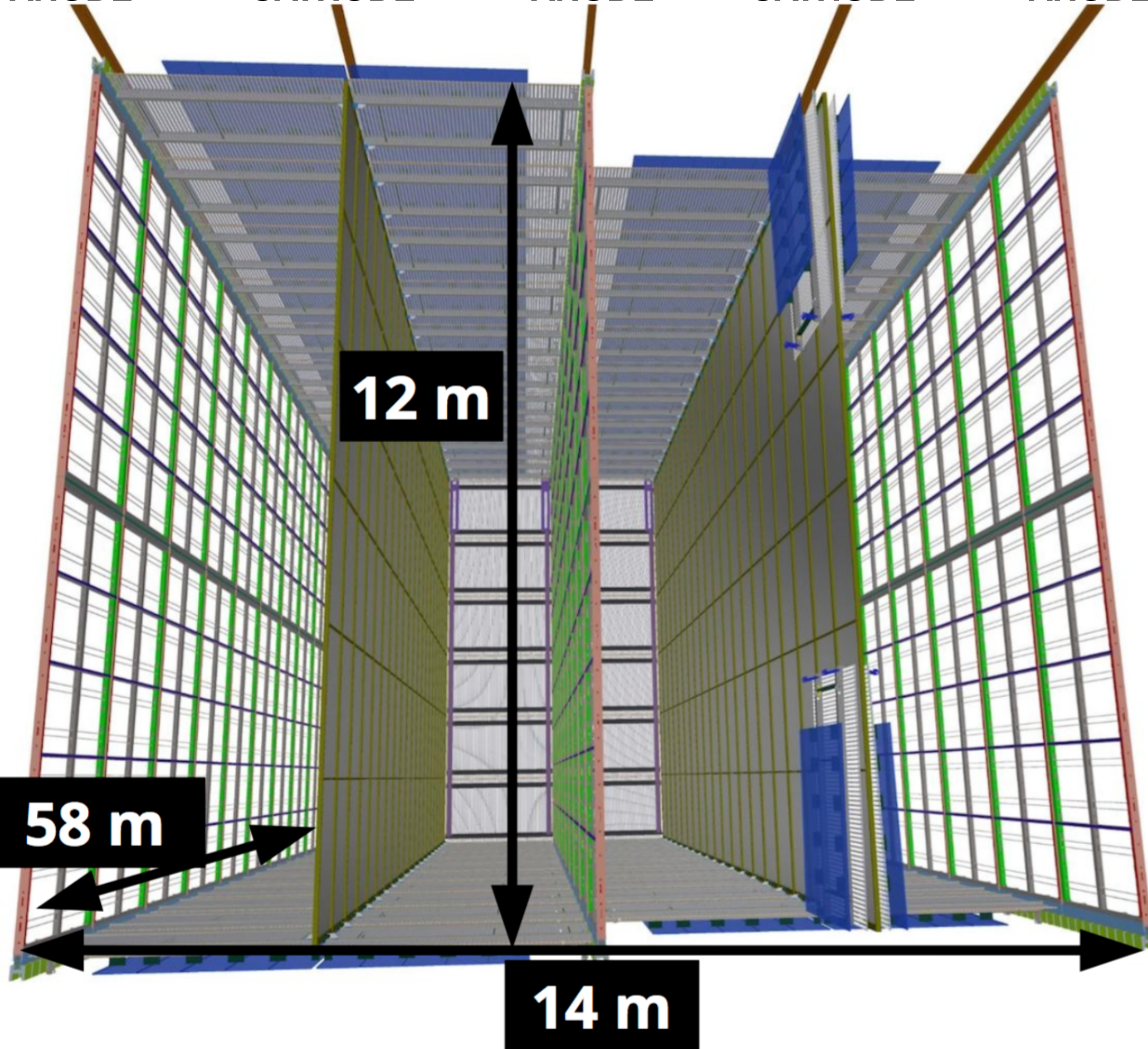
CATHODE

ANODE

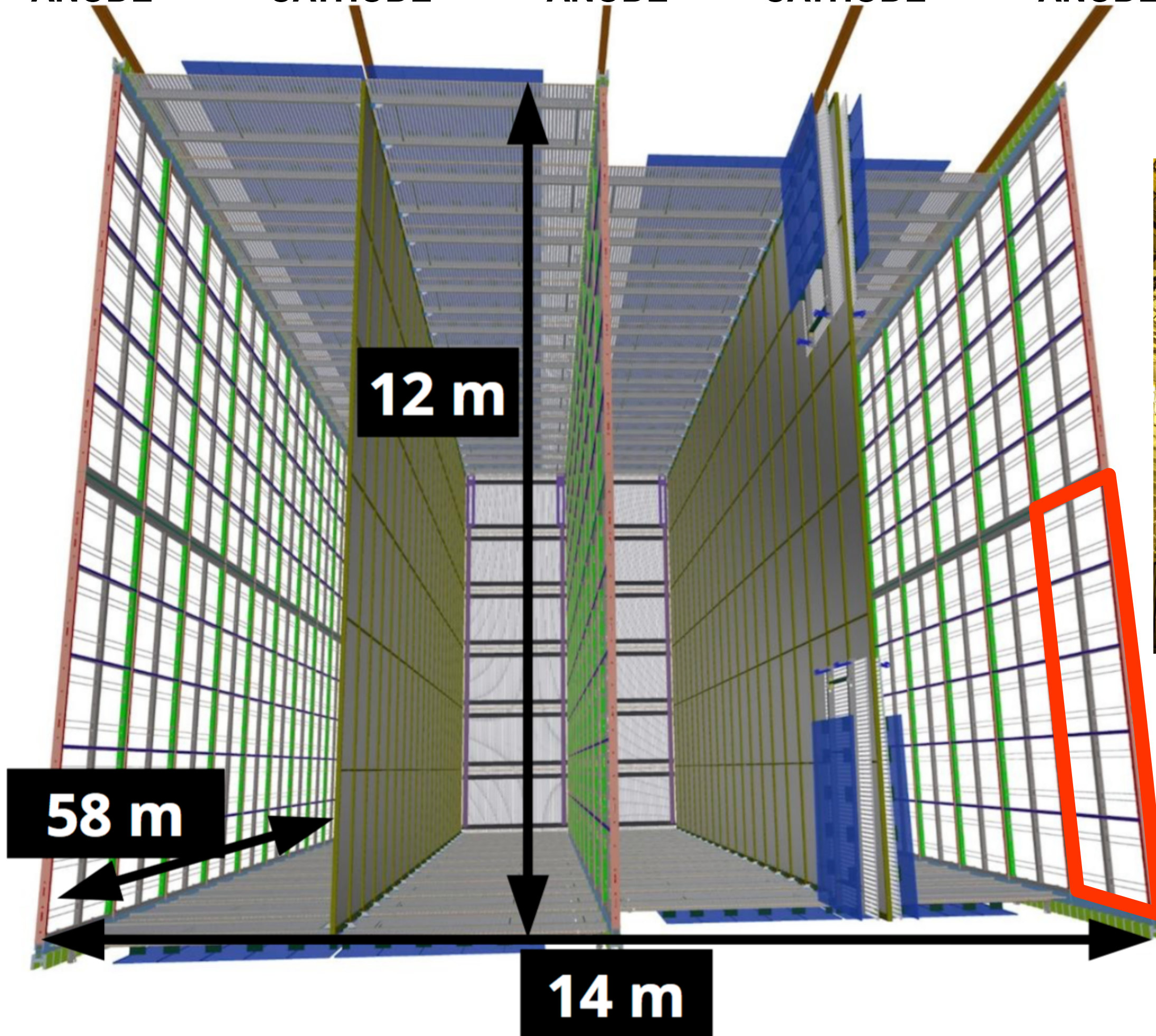
12 m

58 m

14 m



ANODE CATHODE ANODE CATHODE ANODE

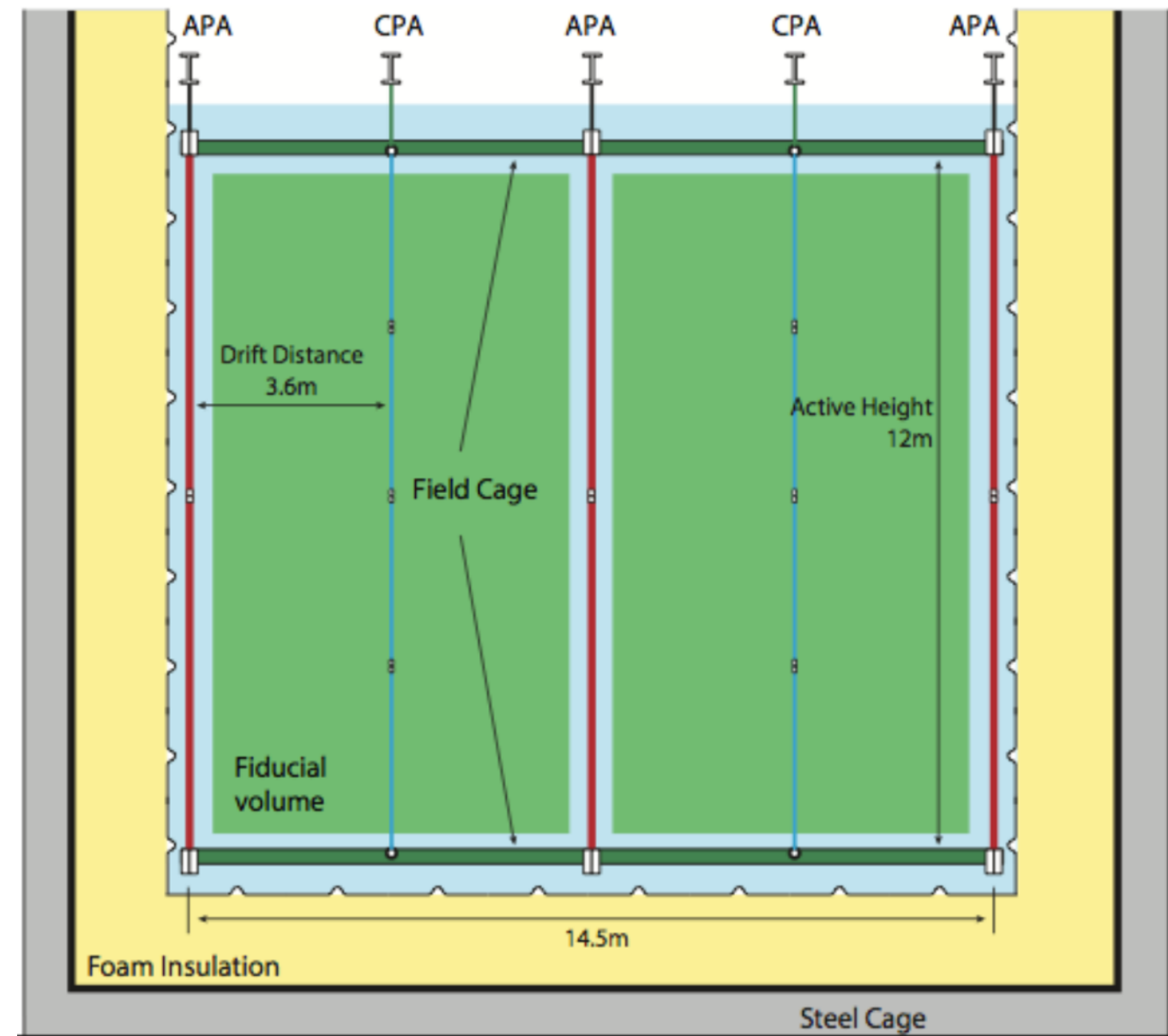


Icarus x 20

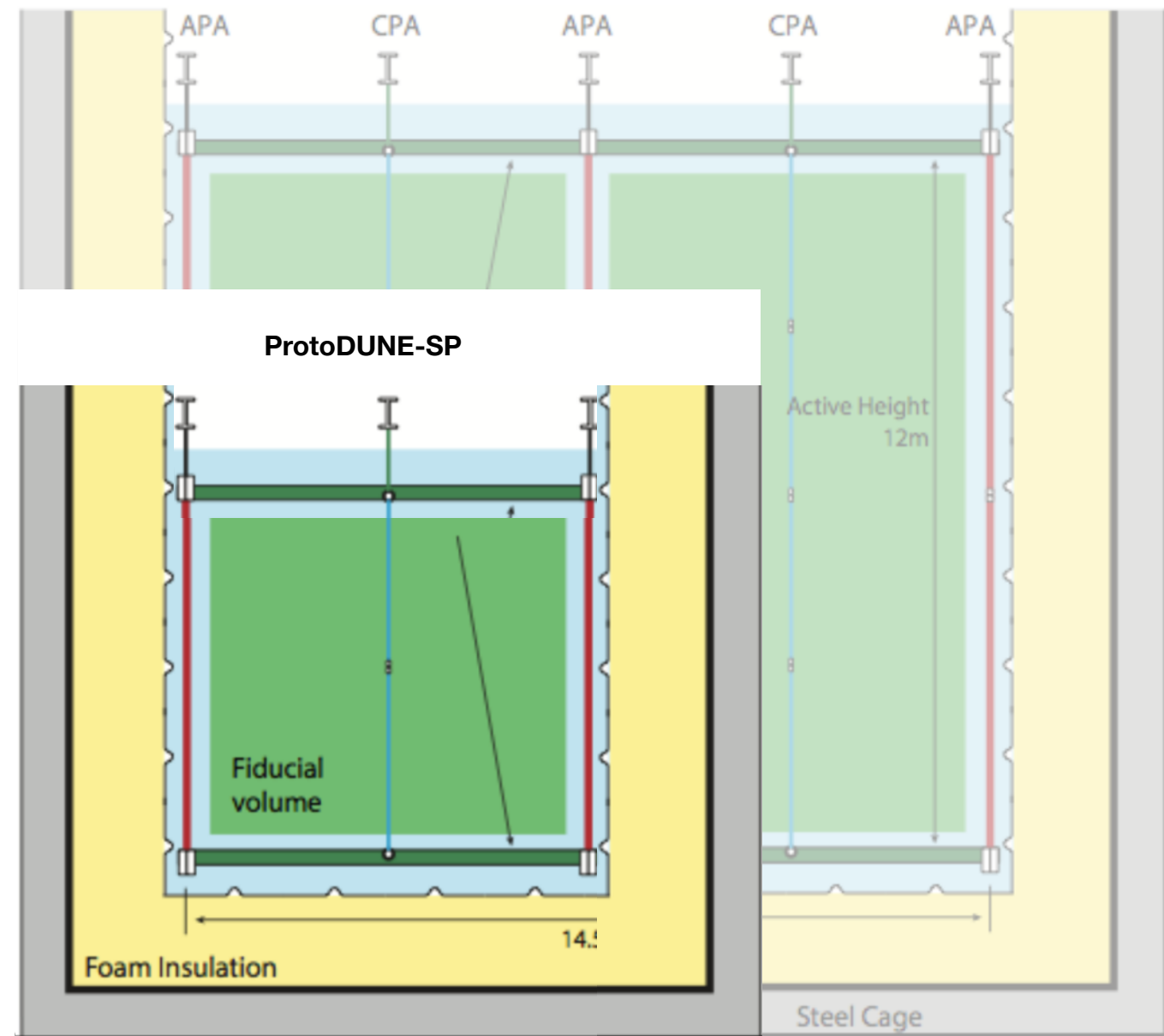
1/2 Icarus



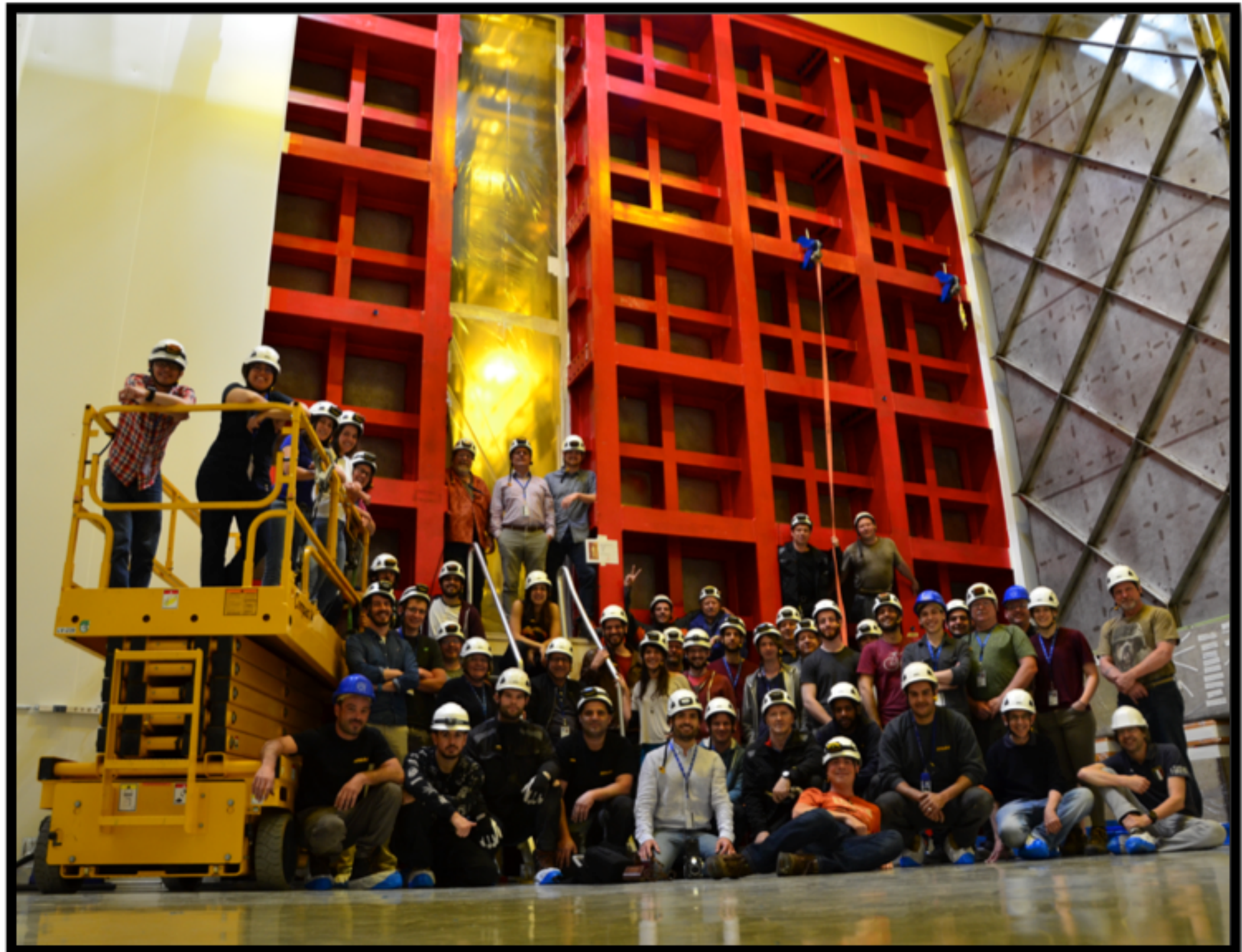
ProtoDUNE en el CERN



ProtoDUNE en el CERN



ProtoDUNE cryostats



The CERN Neutrino Platform



March 2016

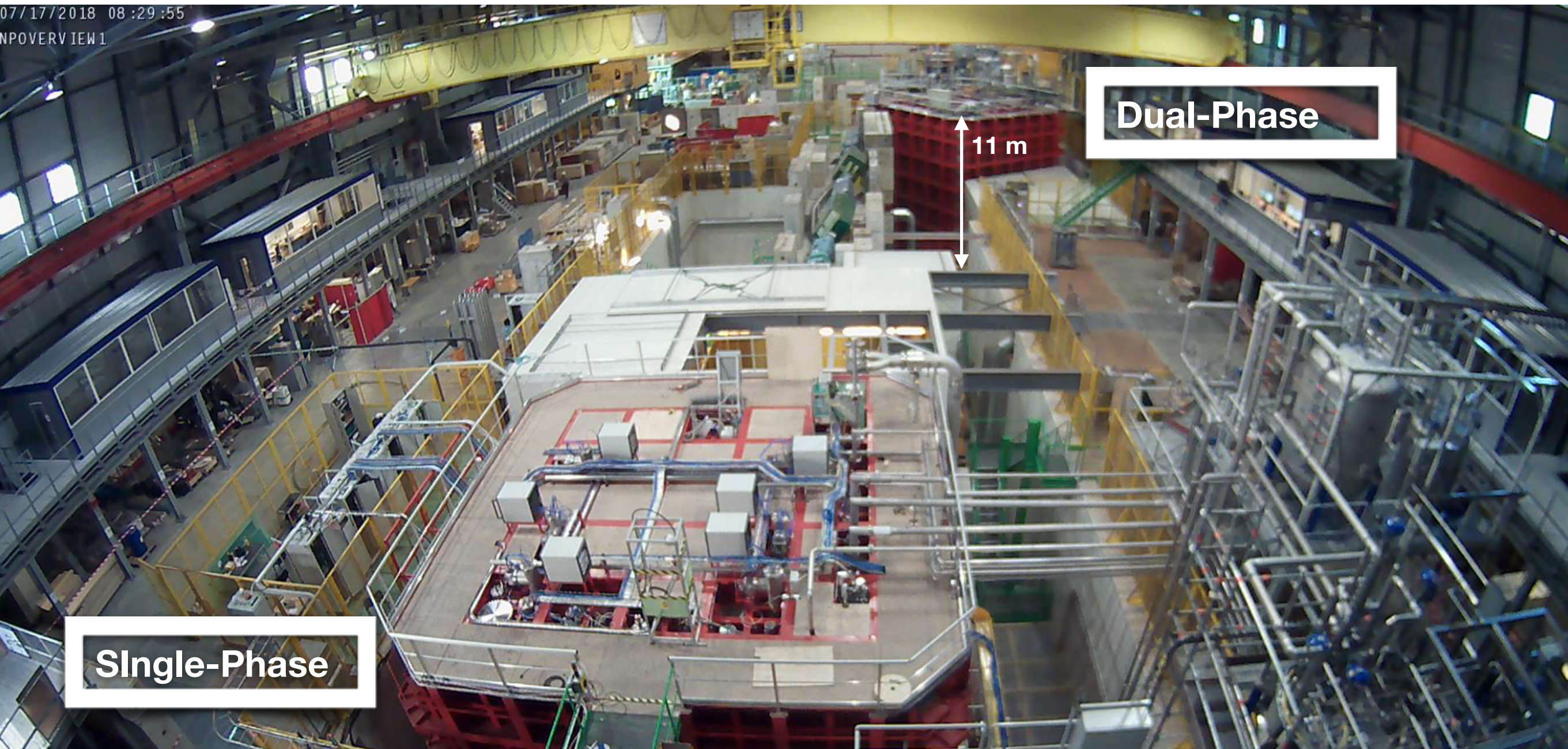


October 2016



July 2018

07/17/2018 08:29:55
NPOVERVIEW1

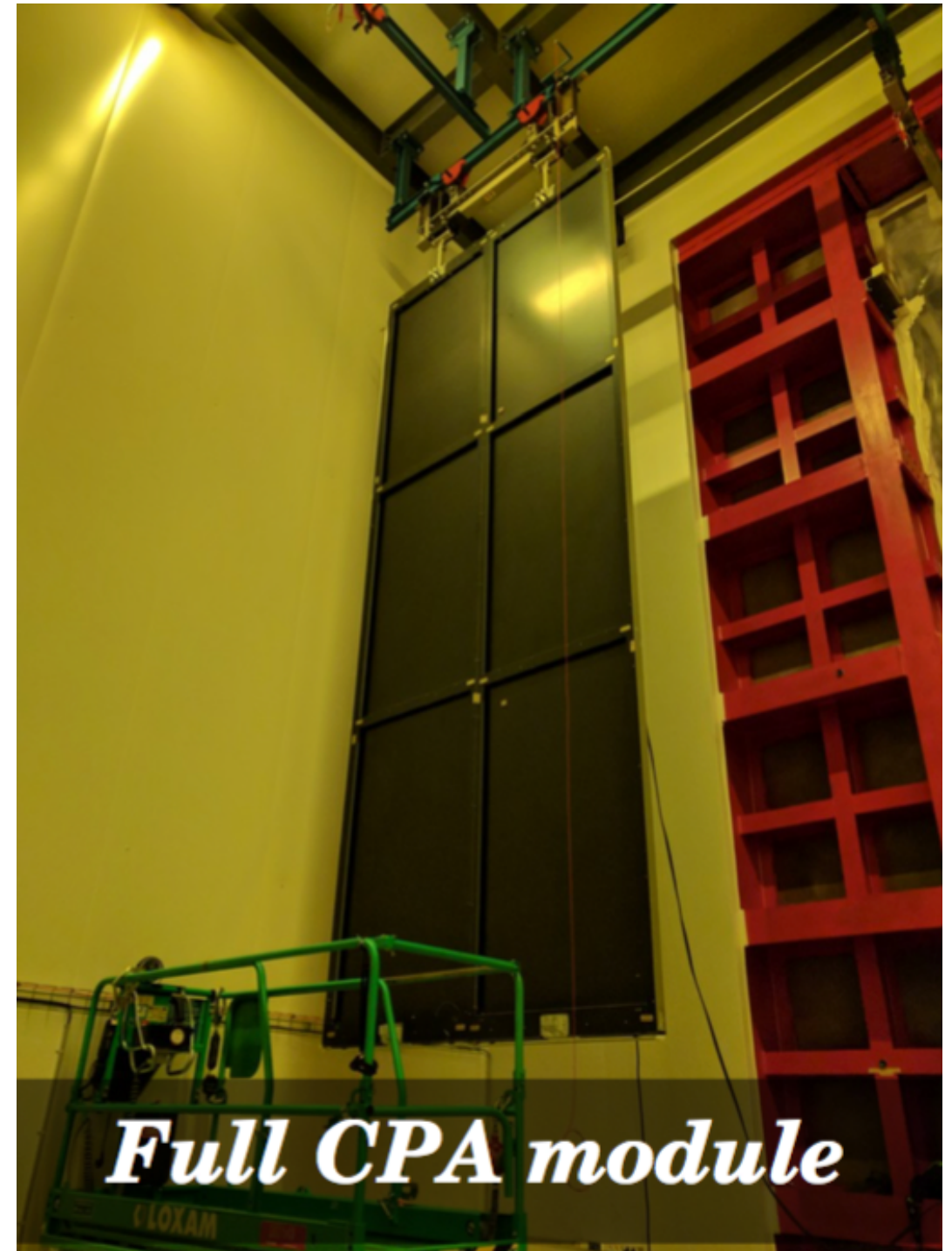


July 2018

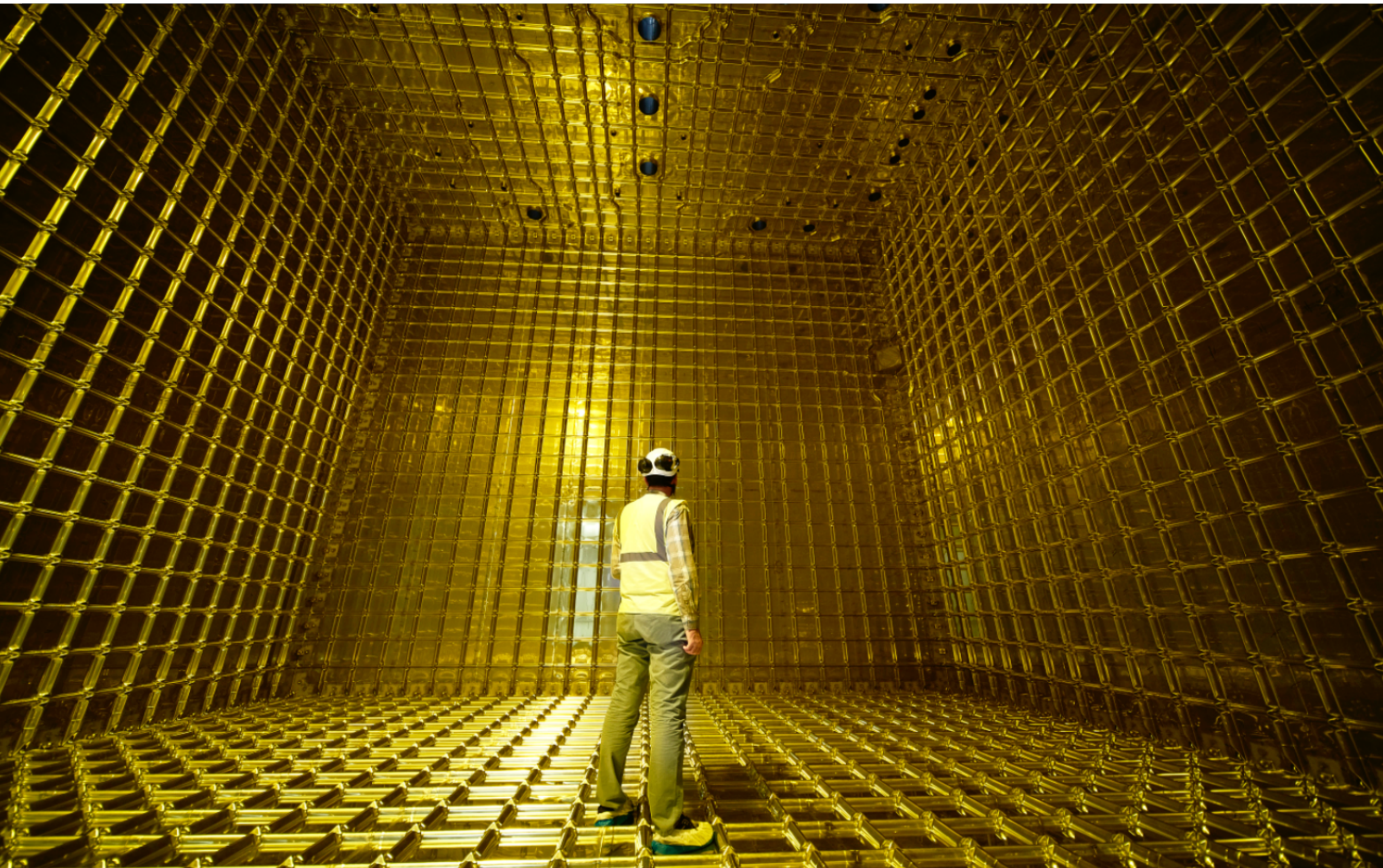


ProtoDUNE-SP

in the clean room

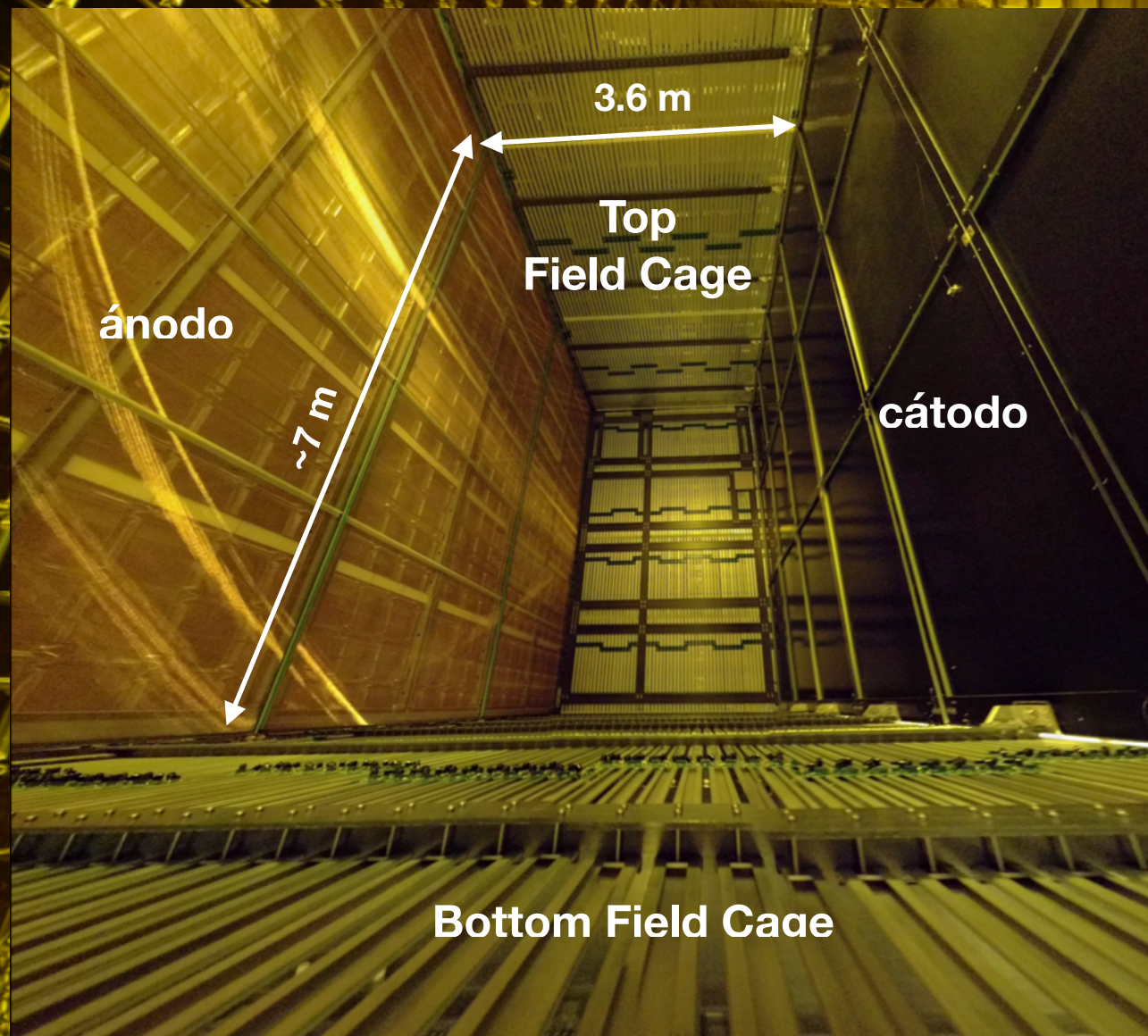


Criostato vacío



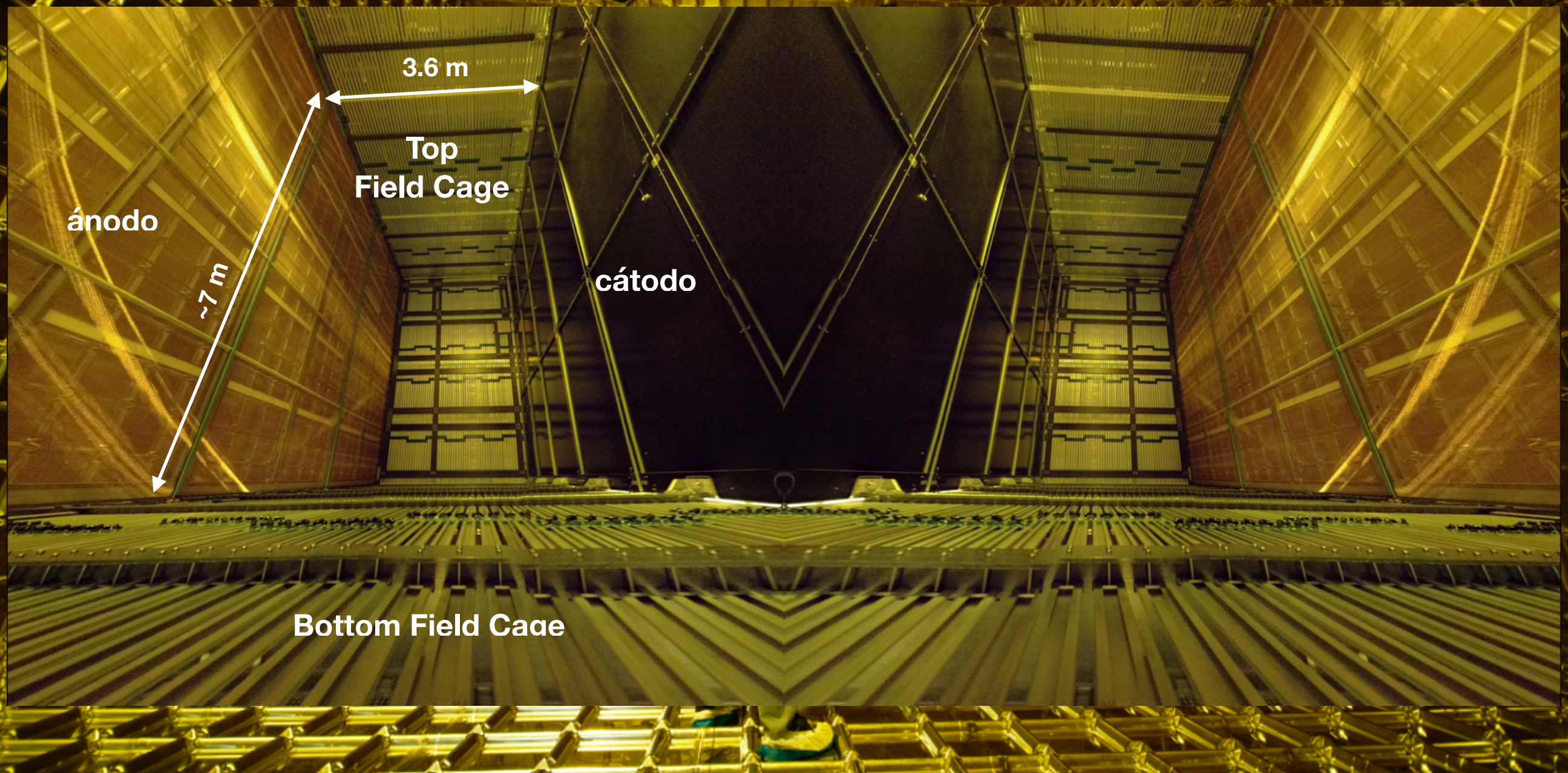
ProtoDUNE-SP

One fully instrumented drift volume



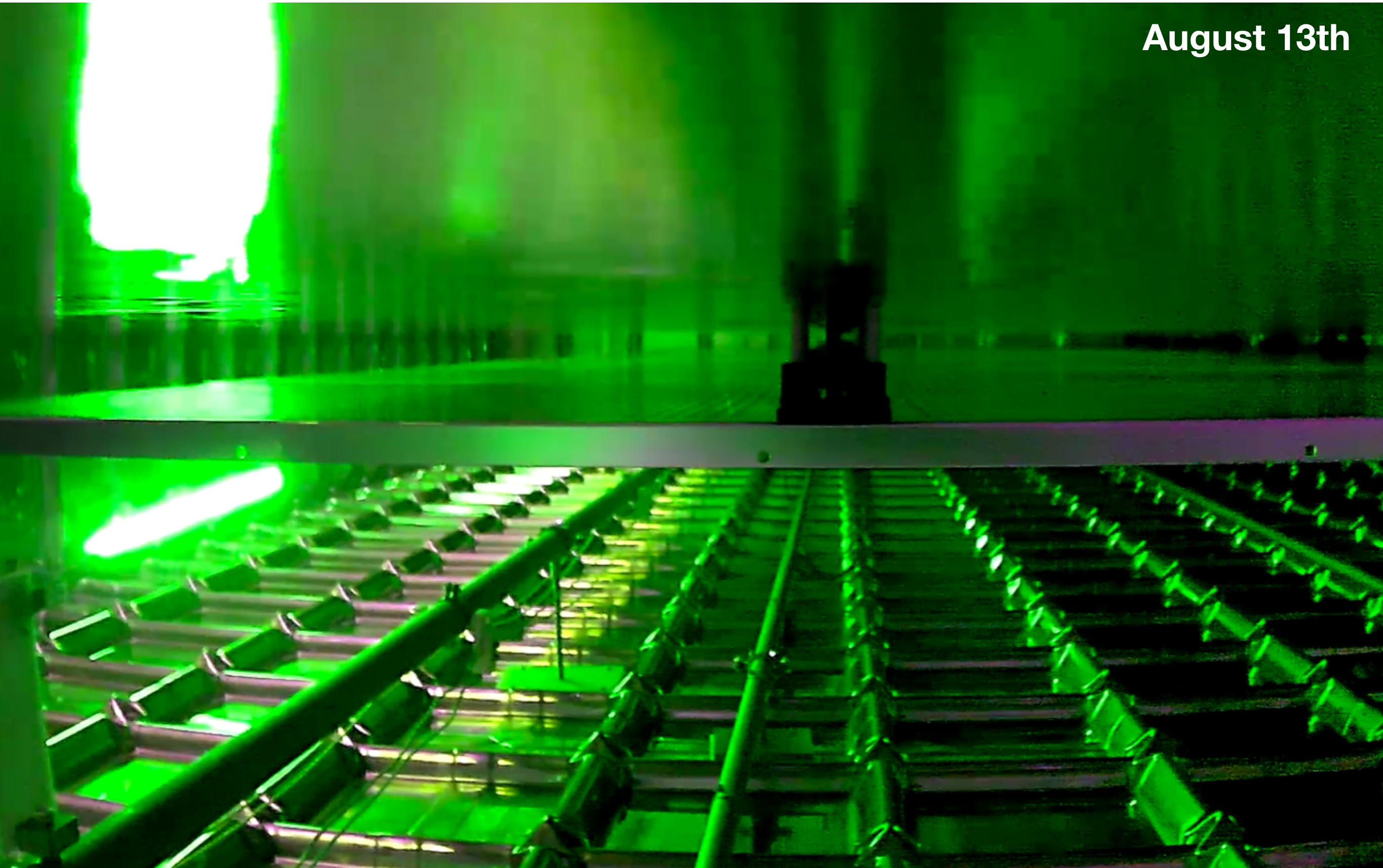
ProtoDUNE-SP

One fully instrumented drift volume



La luz amarilla se vuelve verde

August 13th



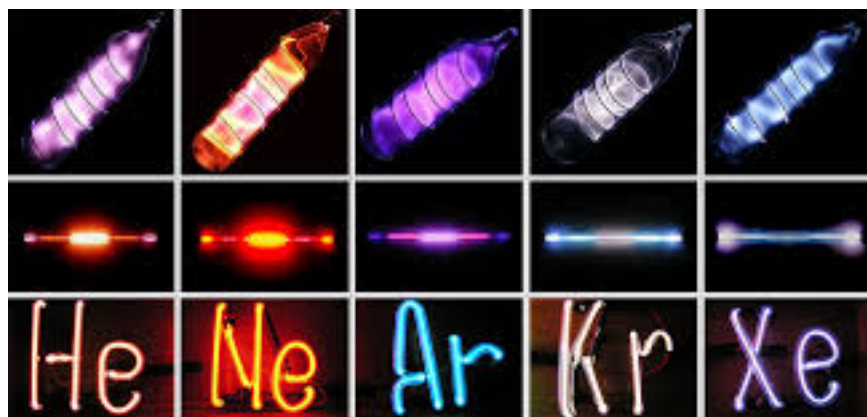
La luz amarilla se vuelve verde

August 14th



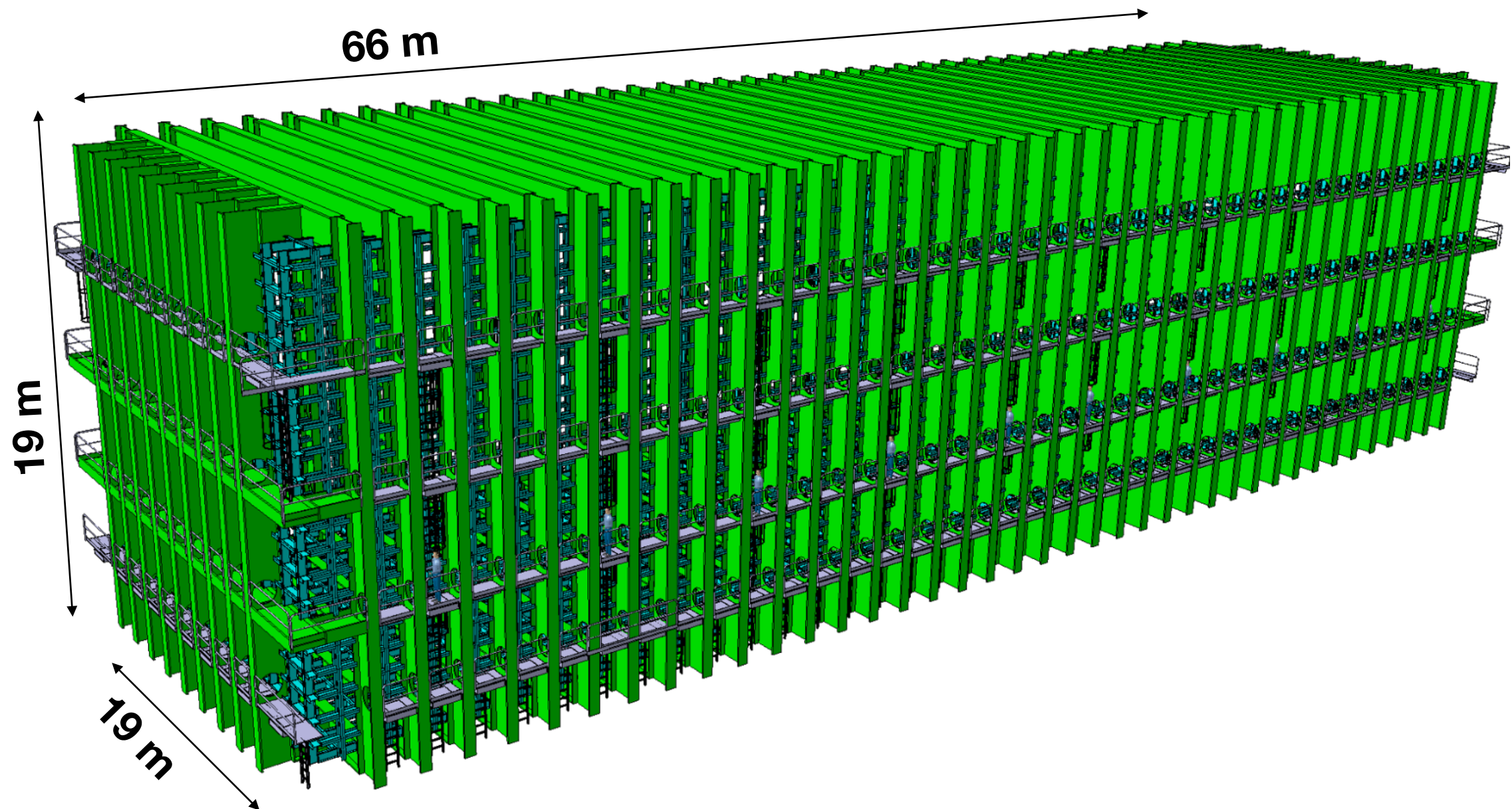
Por qué Argón Líquido ?

- **Dense:**
40% denser than water
- **Cheap:** abundant
(1 % of the atmosphere)
- **Ionizes easily:**
55,000 electrons/cm
- **Excellent scintillation:**
20,000 photons/MeV
(@ 500 V/cm)

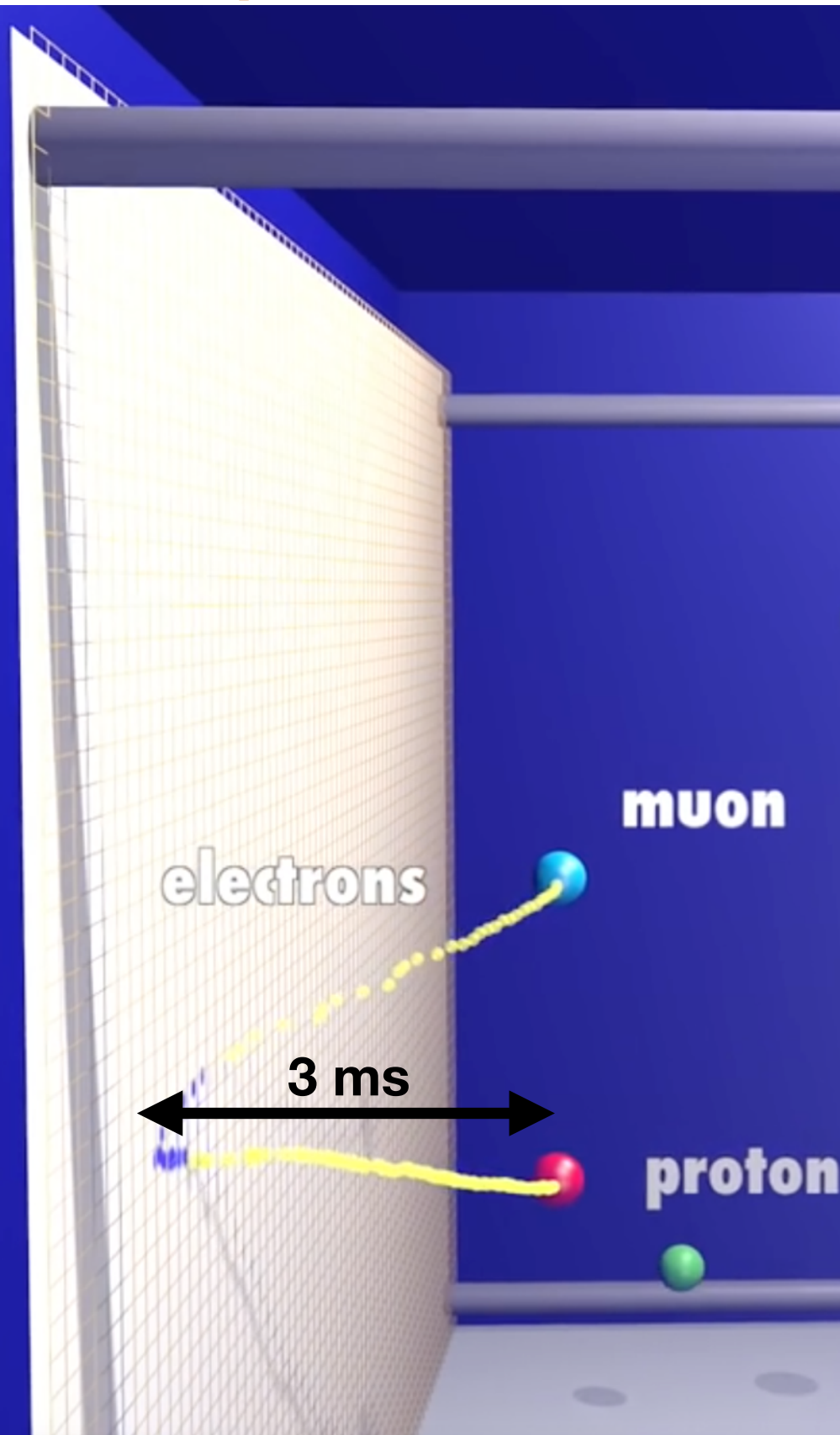


El criostato

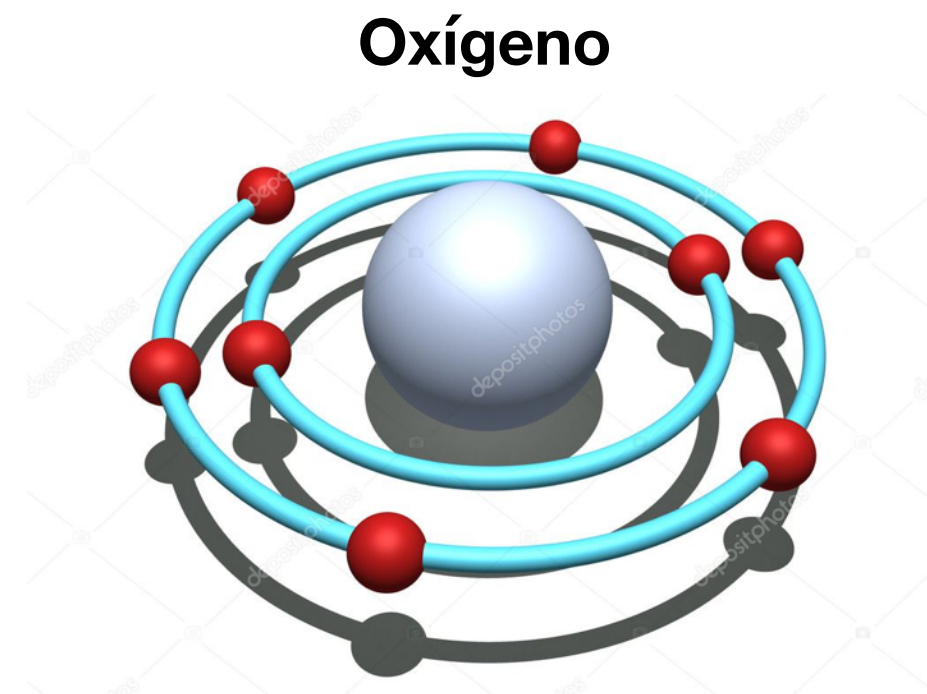
**Mantener 17 Kilotoneladas de Argón a 87 K,
con pérdidas mínimas, y con altísima pureza**



La pureza del argón

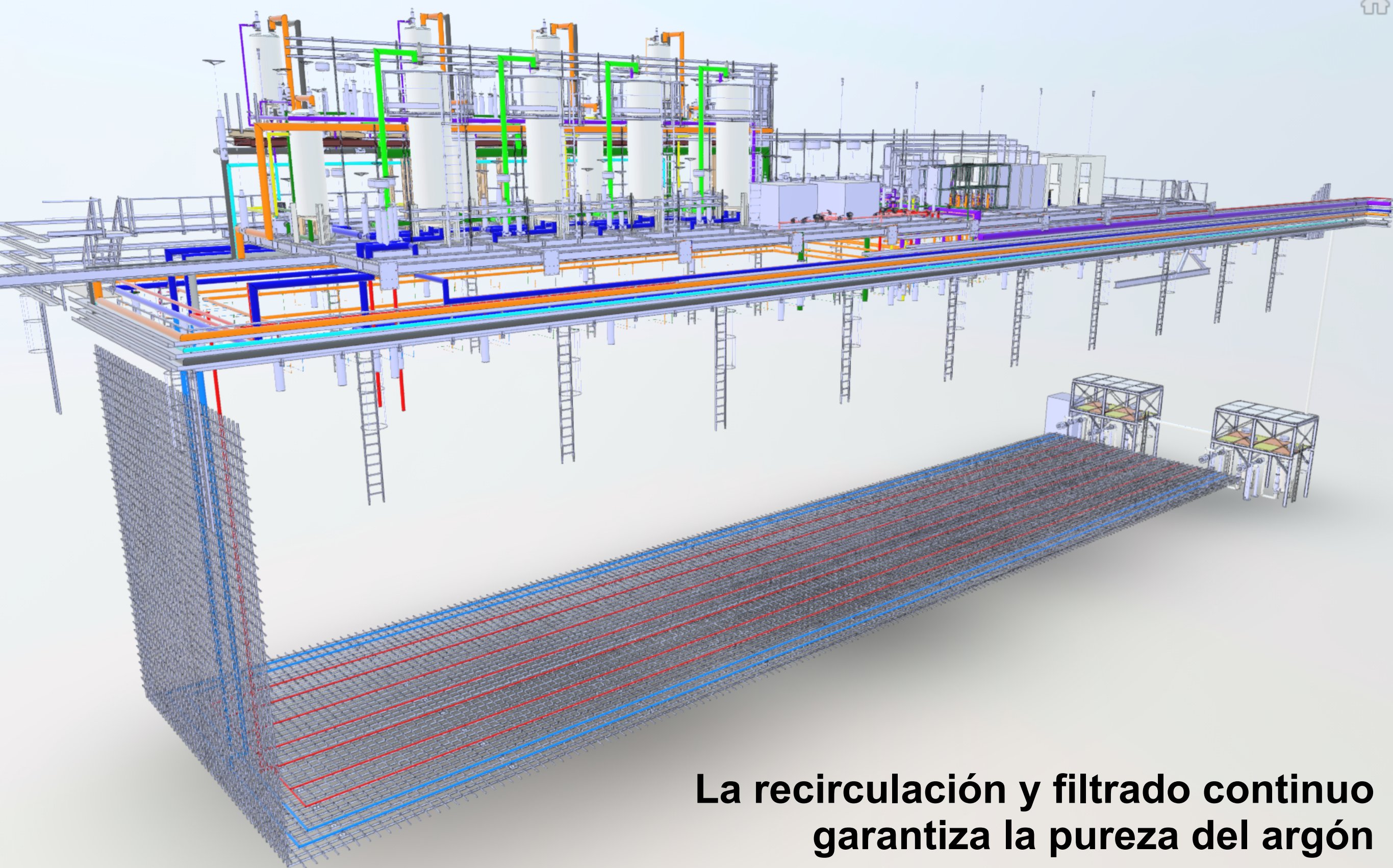


- Los electrones pueden tardar hasta 3 ms en llegar al ánodo
- Tiempo suficiente para ser capturados por impurezas electronegativas en el Argón



< 1 átomo de oxígeno por cada 10^{10} átomos de Argón

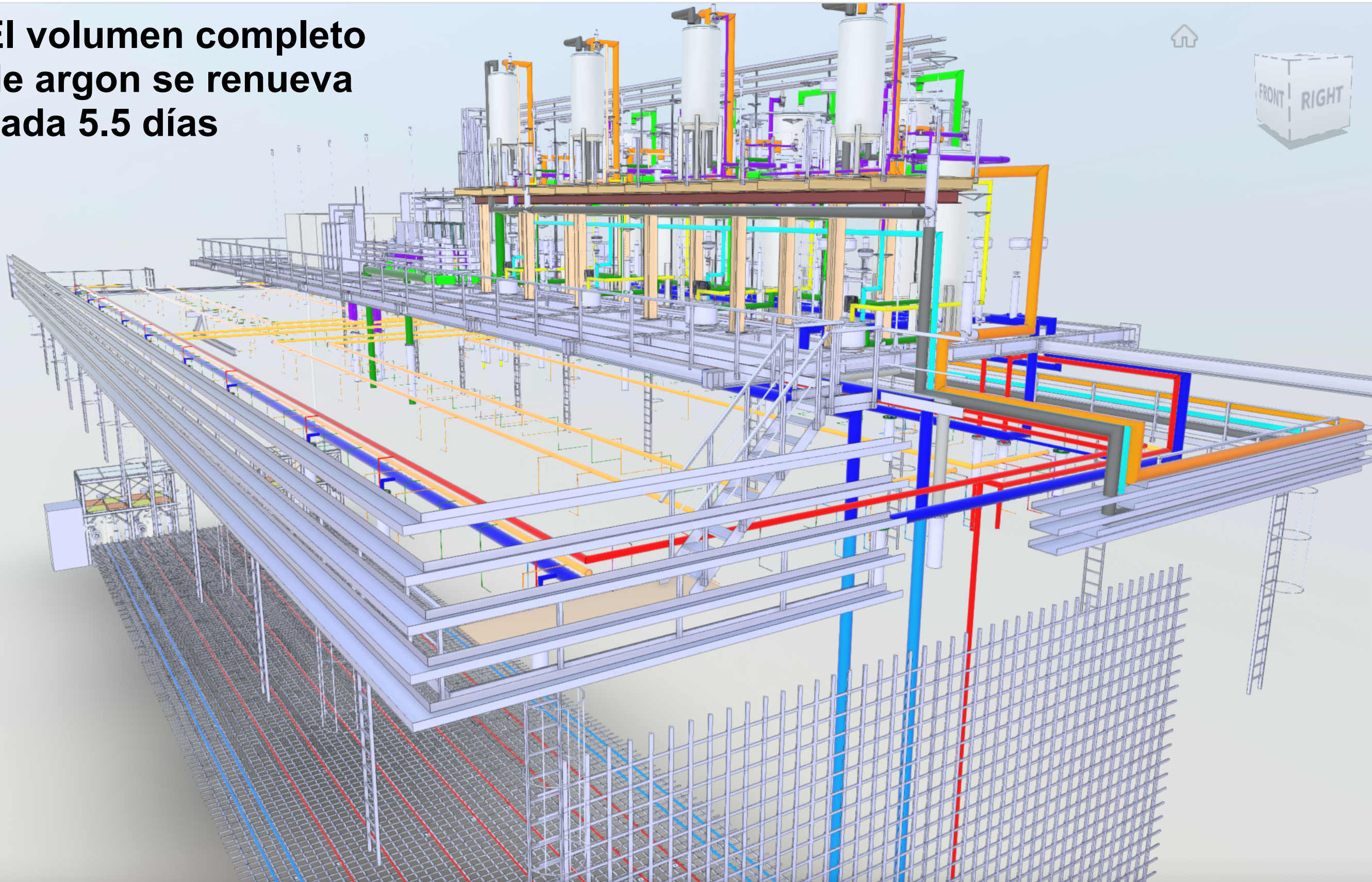
El sistema criogénico



La recirculación y filtrado continuo garantiza la pureza del argón

El sistema criogénico

**El volumen completo
de argón se renueva
cada 5.5 días**



Instrumentación criogénica

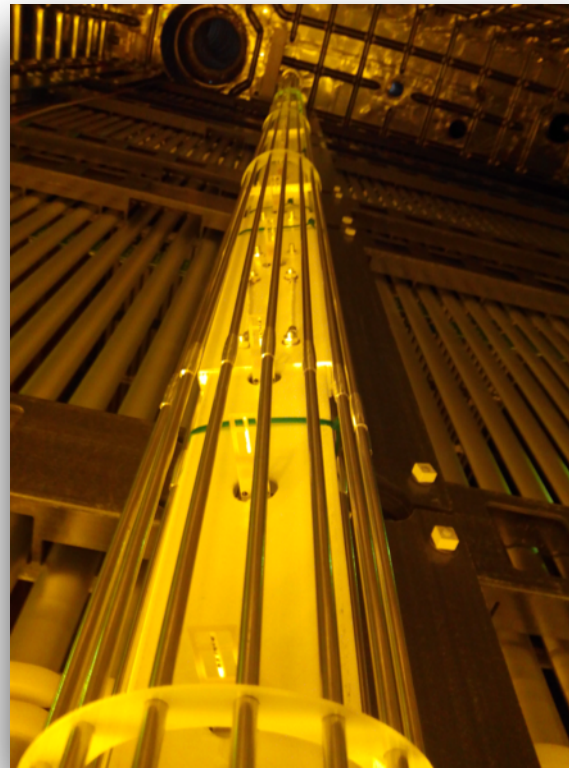
Monitores de Pureza



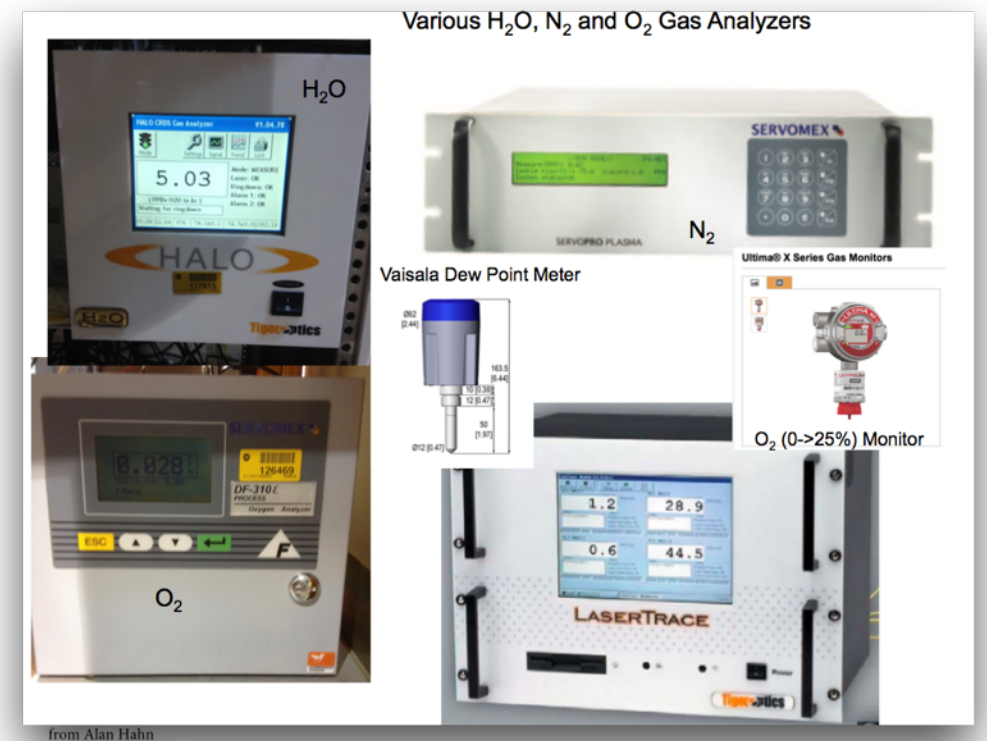
Nivel de LAr



Termómetros



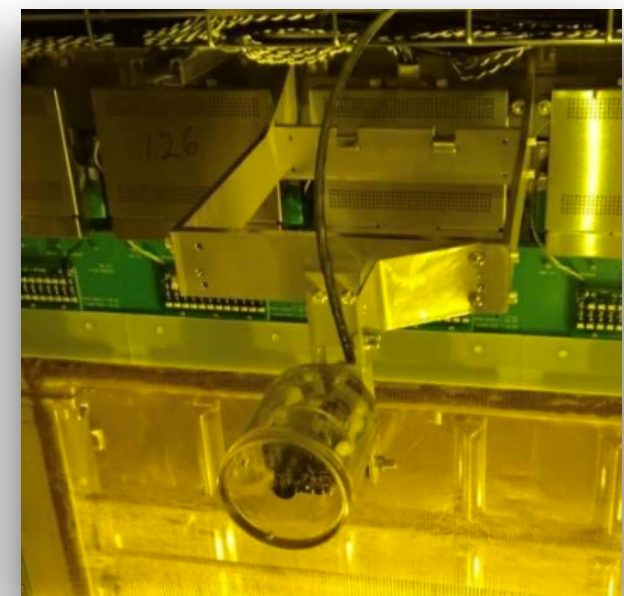
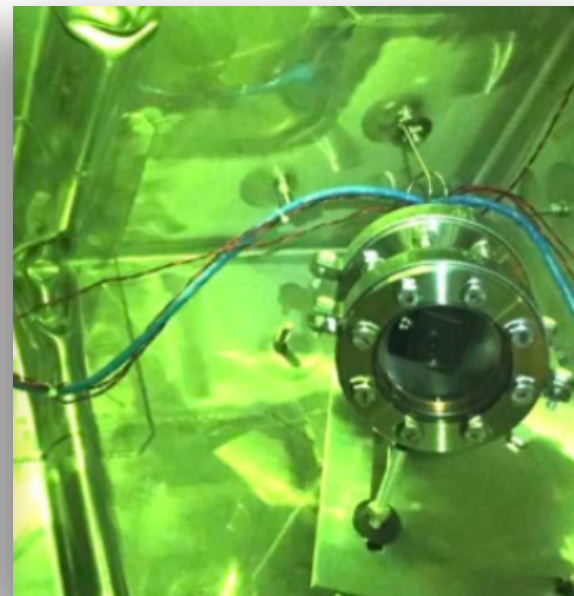
Analizadores de gas



Luces



Cámaras



El termómetro más grande y preciso del mundo para estudiar la partícula más misteriosa

Científicos del IFIC desarrollan unos criostatos para el prototipo de detector de neutrinos del CERN con destino al proyecto DUNE



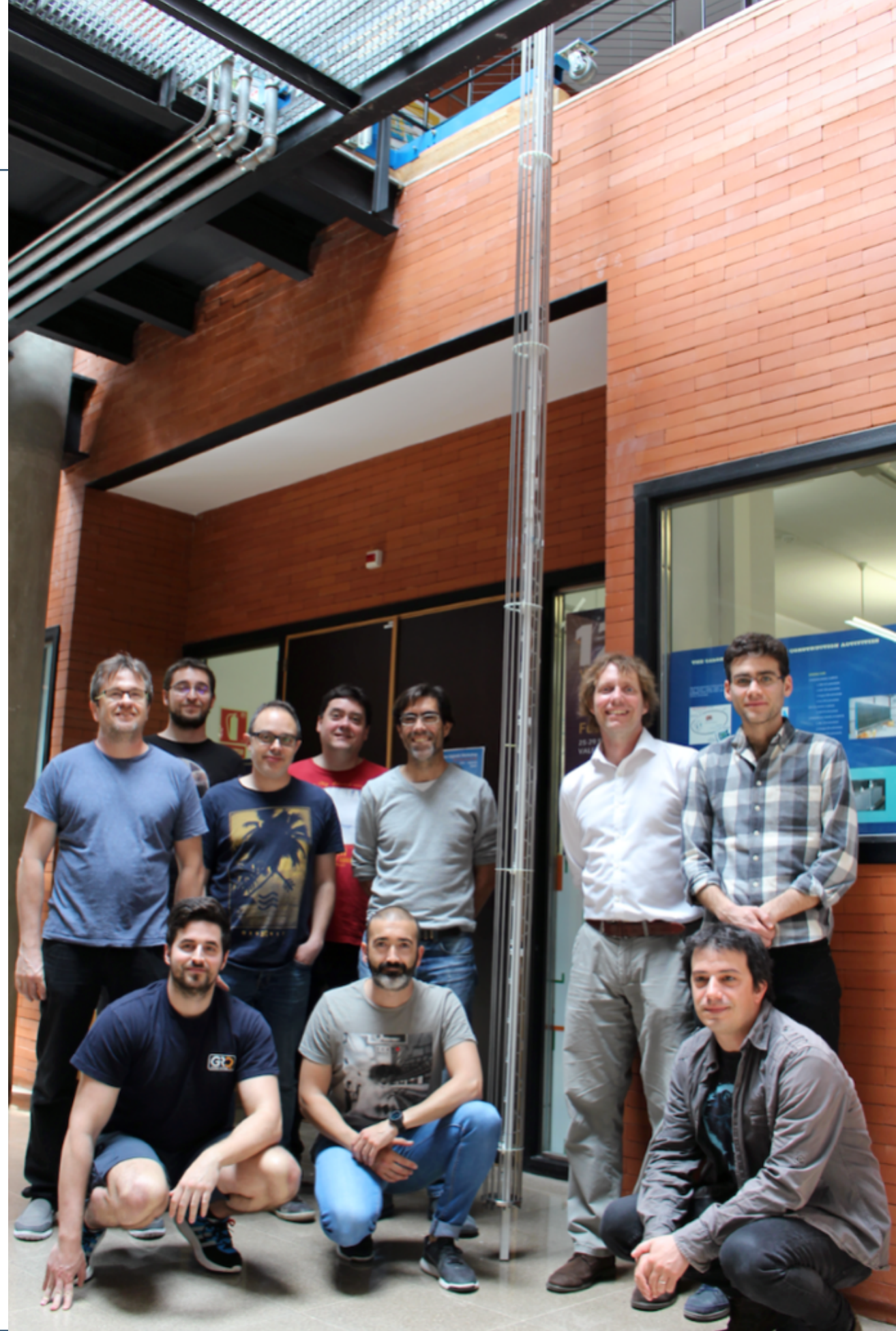
KRISTIN SULENG

12 JUL 2018 - 20:12 CEST



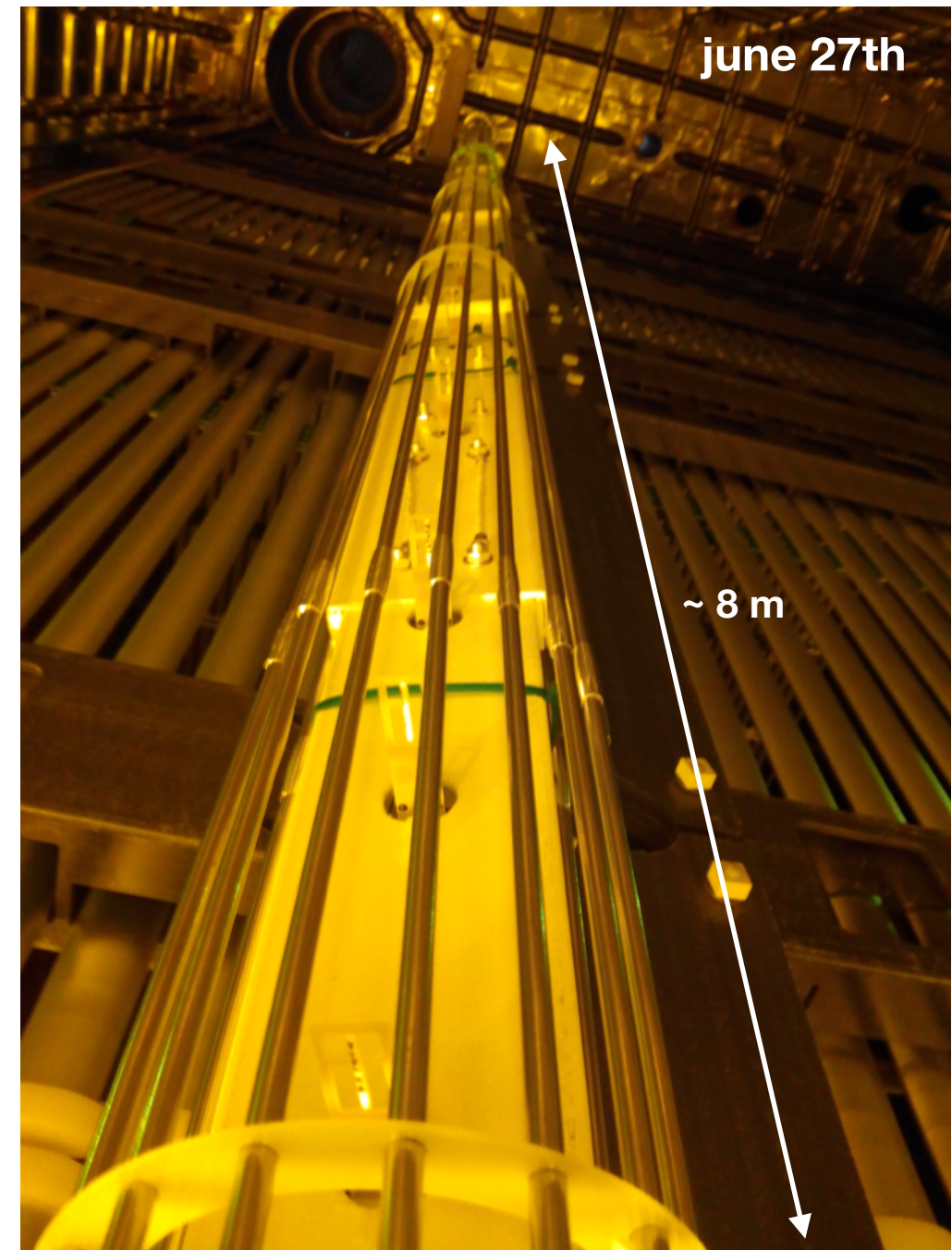
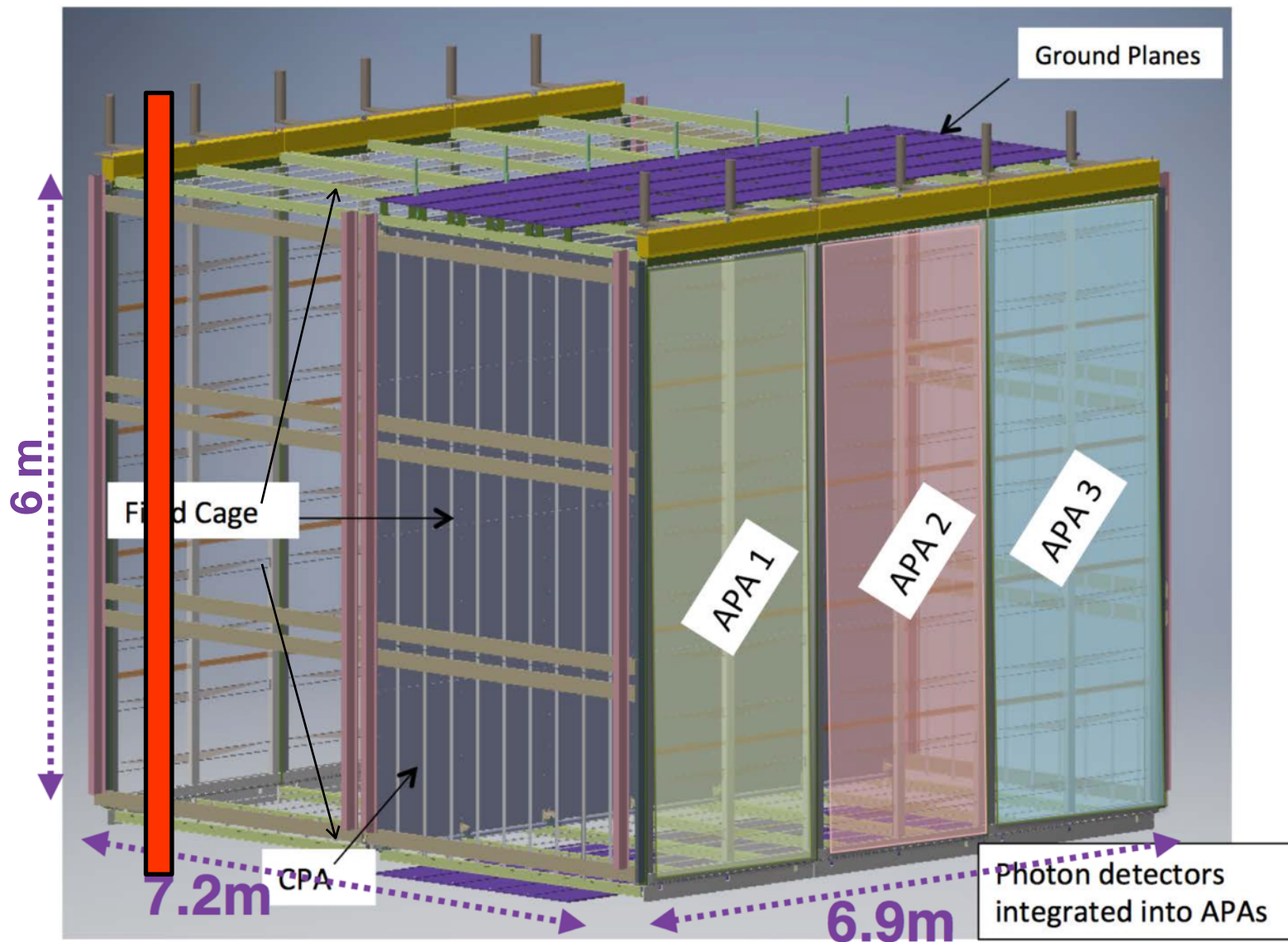
Trabajos para el desarrollo del termómetro más grande y preciso en el campo de la física de neutrinos.

- T-Gradient en el IFIC



Dentro de ProtoDUNE-SP

Situado a 20 cm de la FC en un punto de potencial 60000 voltios



Enlaces

- More pictures

<https://www.symmetrismagazine.org/article/protodune-in-pictures>

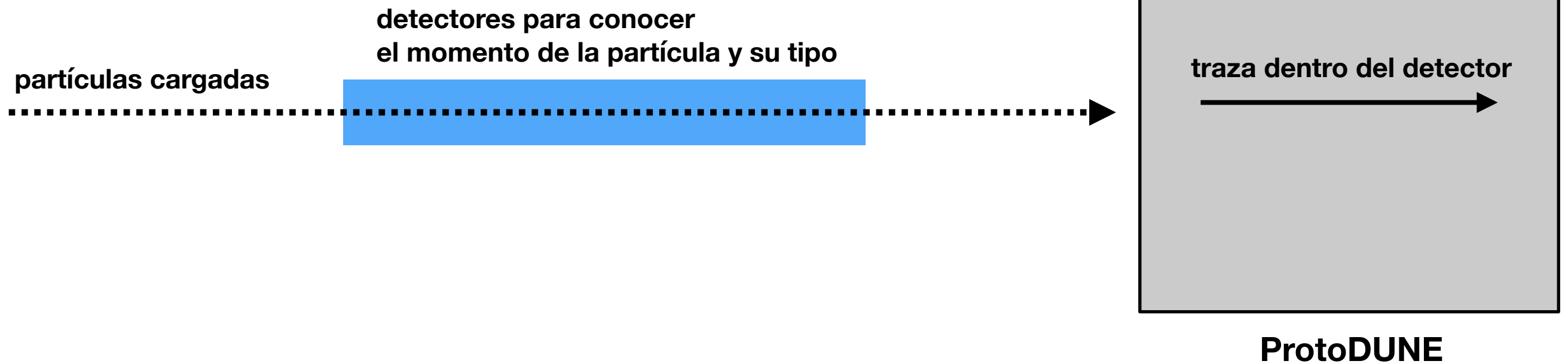
- Enlace a medidas de temperatura en tiempo real

<http://np04-slow-control.web.cern.ch/np04-slow-control/app/index.html#!/tinternal>

El test-beam

- Un test-beam es un haz controlado y muy bien conocido de partículas cargadas al que se expone un detector, normalmente un prototipo, para entender su funcionamiento
- Esto no se podría hacer con los detectores finales de DUNE pues no podemos construir un haz de partículas a 1.5 km de profundidad
- El test-beam nos sirve para entender “que ve” el detector cuando le llega un muón, un electrón, un protón, un pión, ...
- De esta forma cuando se construya DUNE y estemos tratando de distinguir electrones de muones sabremos como hacerlo y, sobre todo, sabremos cuantas veces nos estamos equivocando

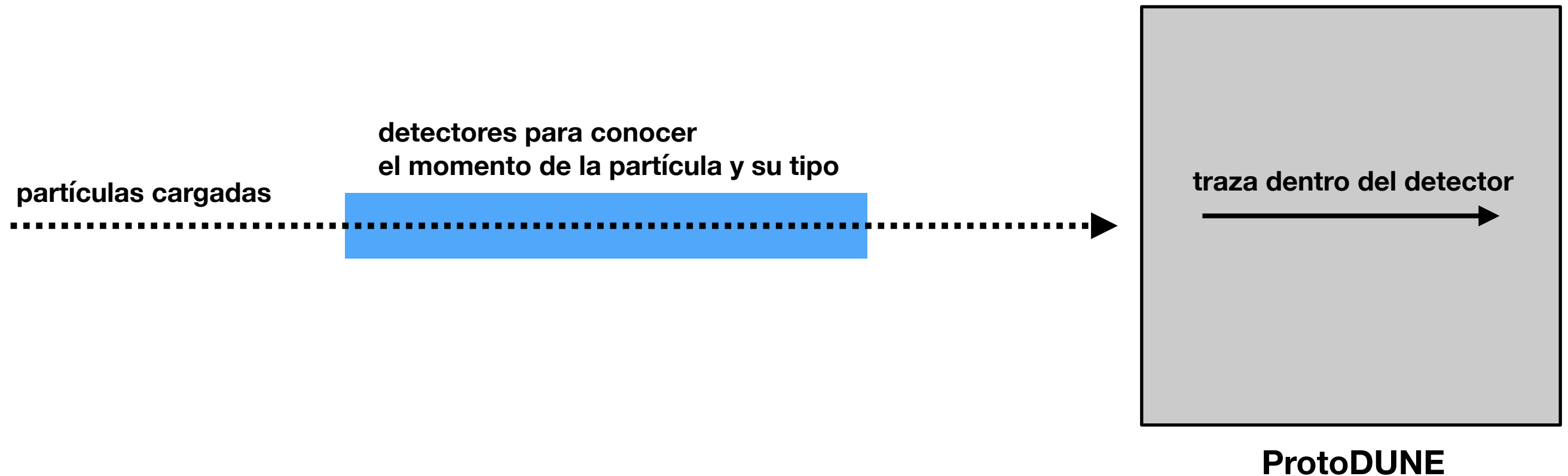
El test-beam



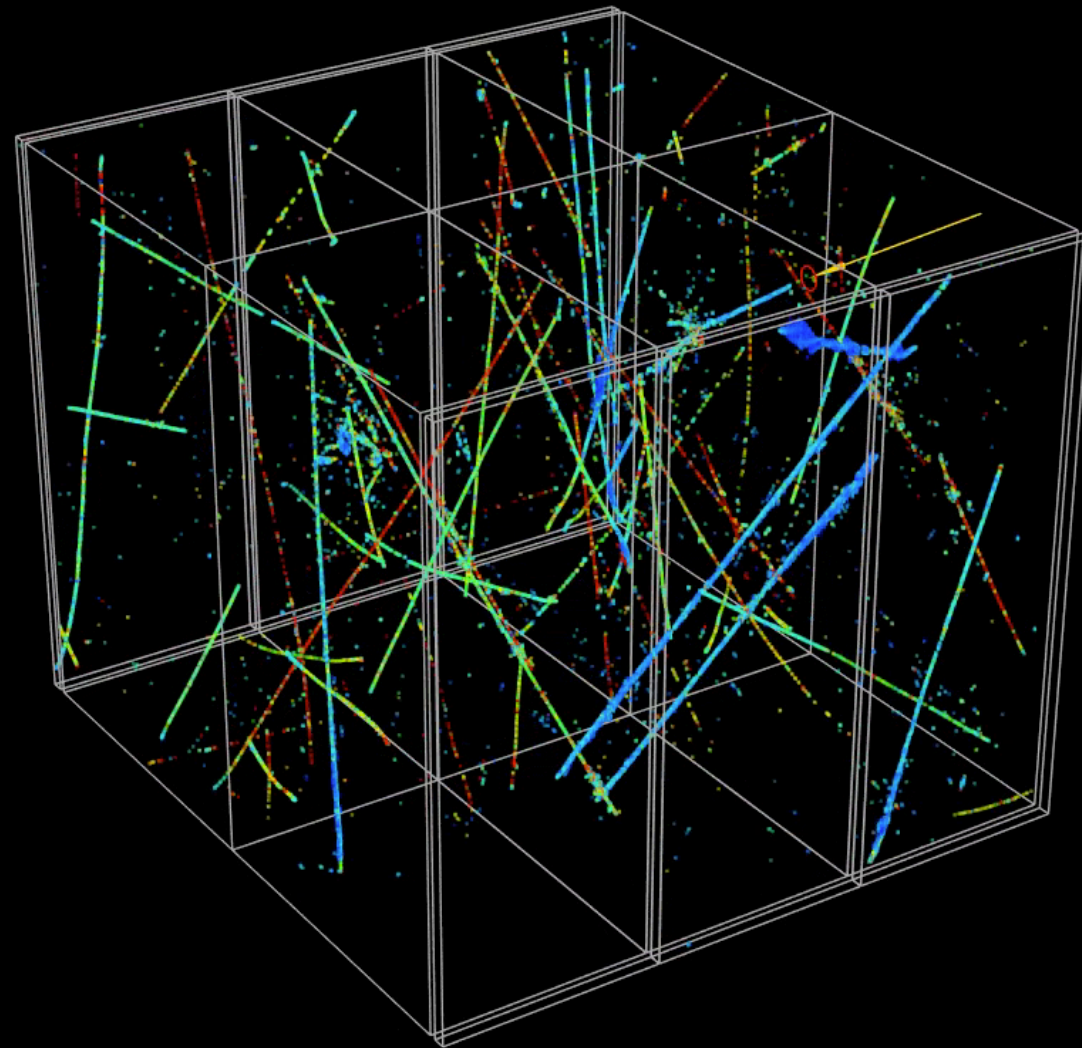
Observables Físicos

- **Posición**
- **Dirección**
- **Momento**
- **Tiempo de vuelo**
(tipo de partícula)

- **Posición**
- **Dirección**
- **Longitud**
- **Perdida de energía por**
unidad de longitud (dE/dx)

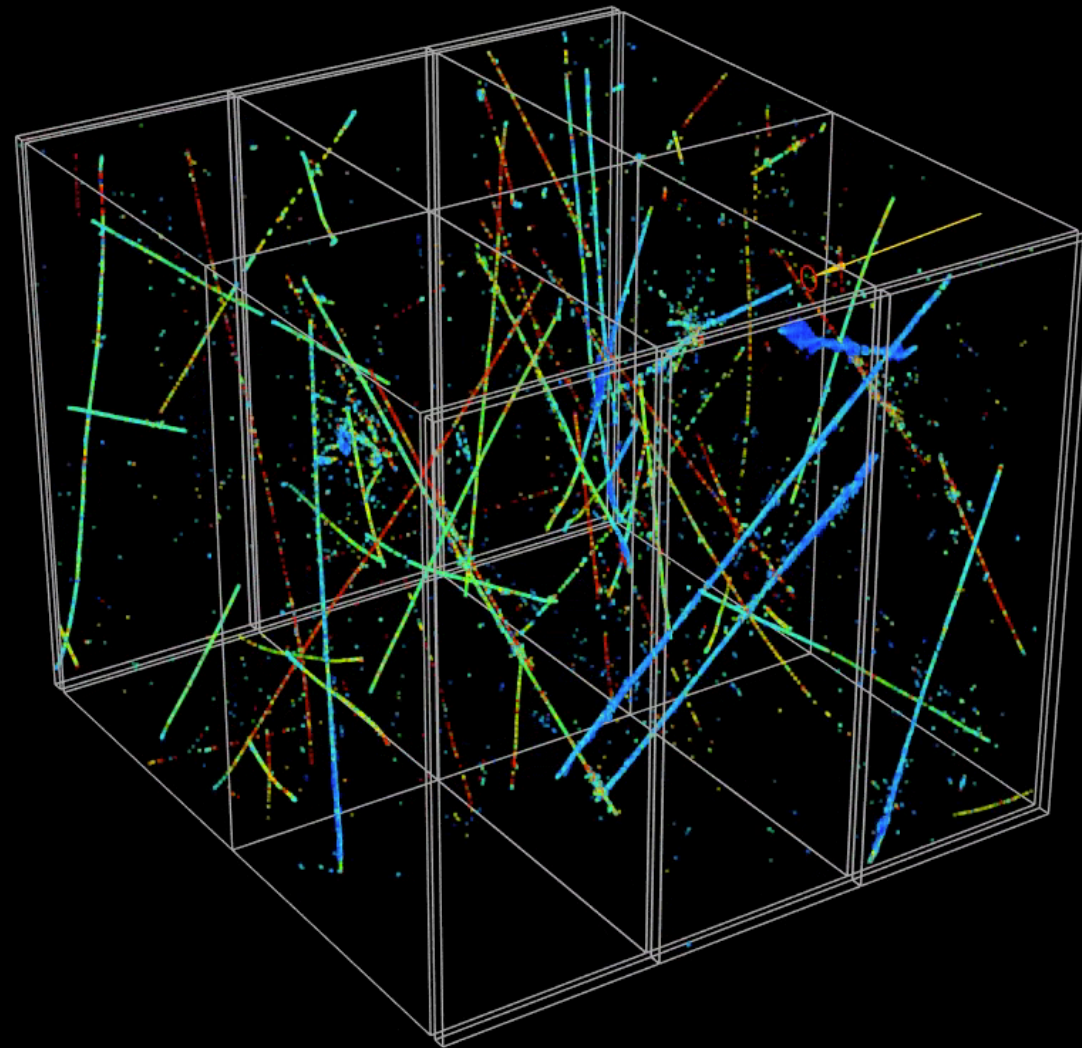


Press Esc to exit full screen



Event: 5145 - 1 - 26918
Trigger: 12 [Beam] [momentum = 7 GeV]
Wed, 10 Oct 2018 22:57:33 +0000 (GMT) + 0 nsec

Press Esc to exit full screen



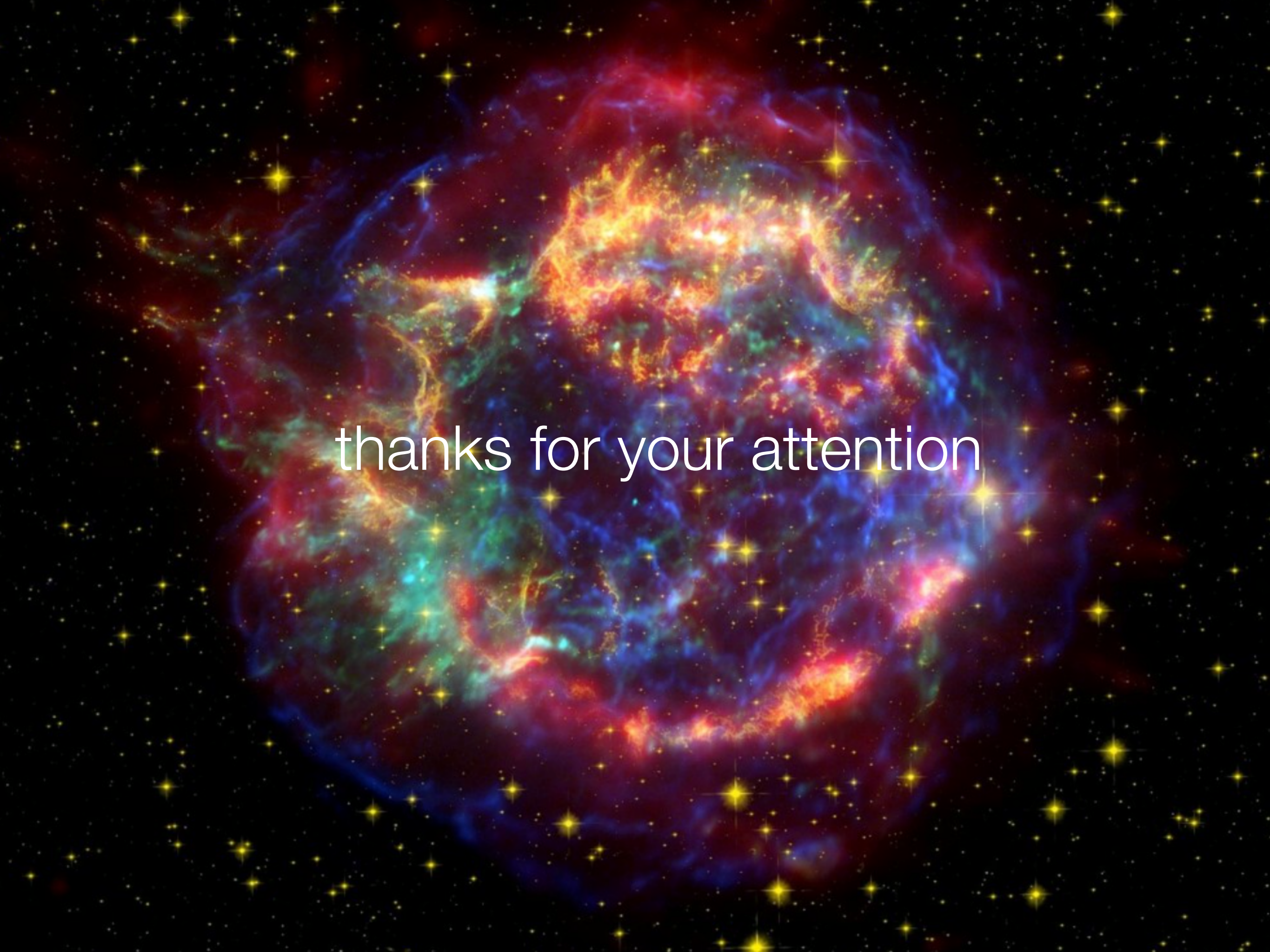
Event: 5145 - 1 - 26918
Trigger: 12 [Beam] [momentum = 7 GeV]
Wed, 10 Oct 2018 22:57:33 +0000 (GMT) + 0 nsec





Outlook

- DUNE is the result of combining international efforts (>20 years R&D on LAr) and the next accelerator mega-science project
- LBNF and DUNE making rapid progress on facility construction, detector design, and physics analysis
- Ongoing R&D program at CERN with two large scale prototypes:
 - ProtoDUNE beam data looks great !!!
- Look for DUNE Technical Design Report and ProtoDUNE results in 2019
- Expect first DUNE FD data in ~2026...



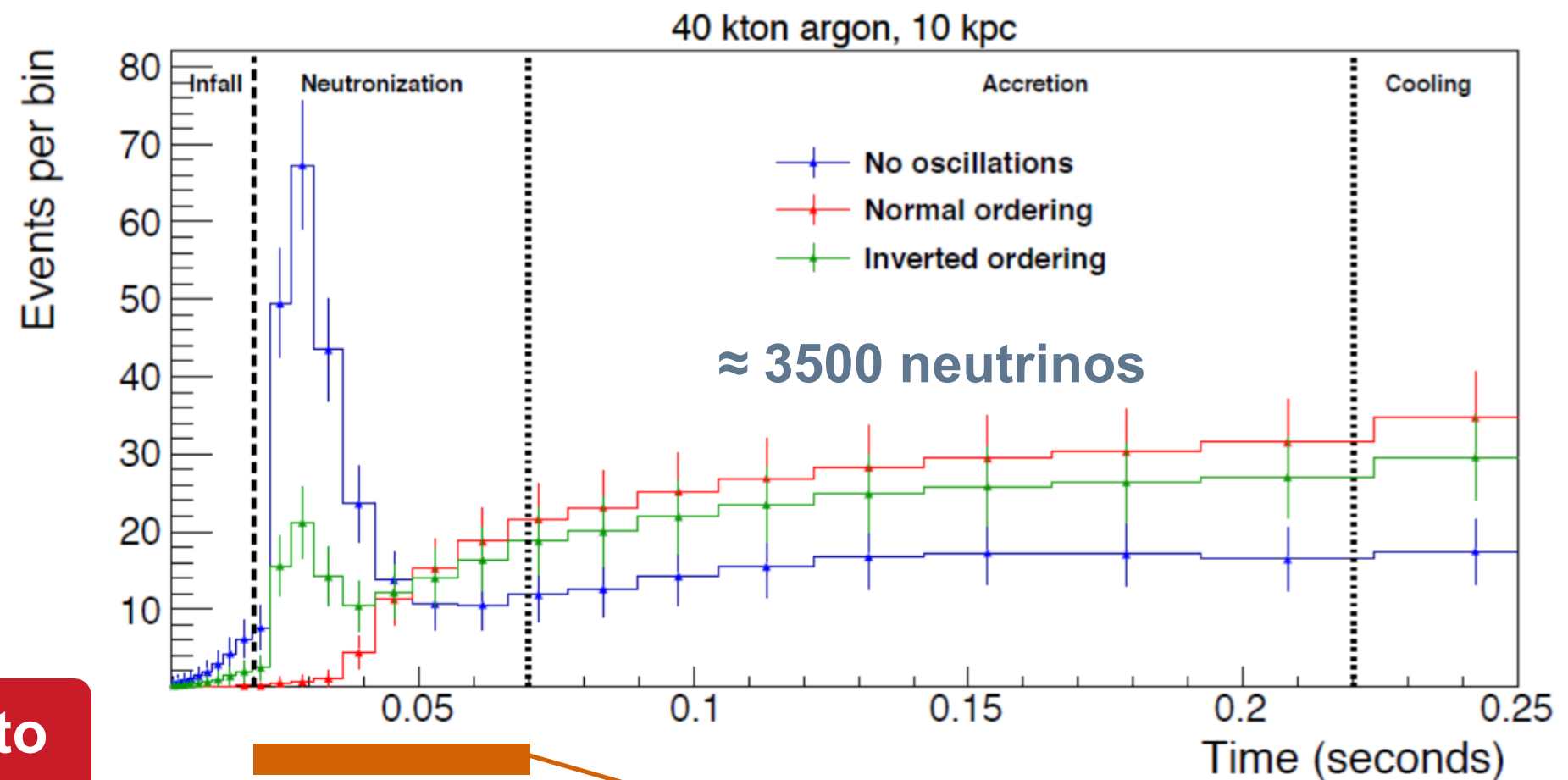
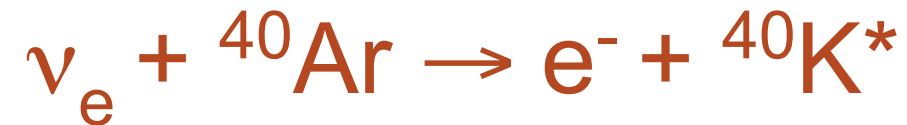
thanks for your attention

BACKUP SLIDES

SuperNova neutrinos

Expect 2-3 core-collapse supernovae in the Milky Way per century

In LArTPC, SNB signal dominated by electron neutrinos



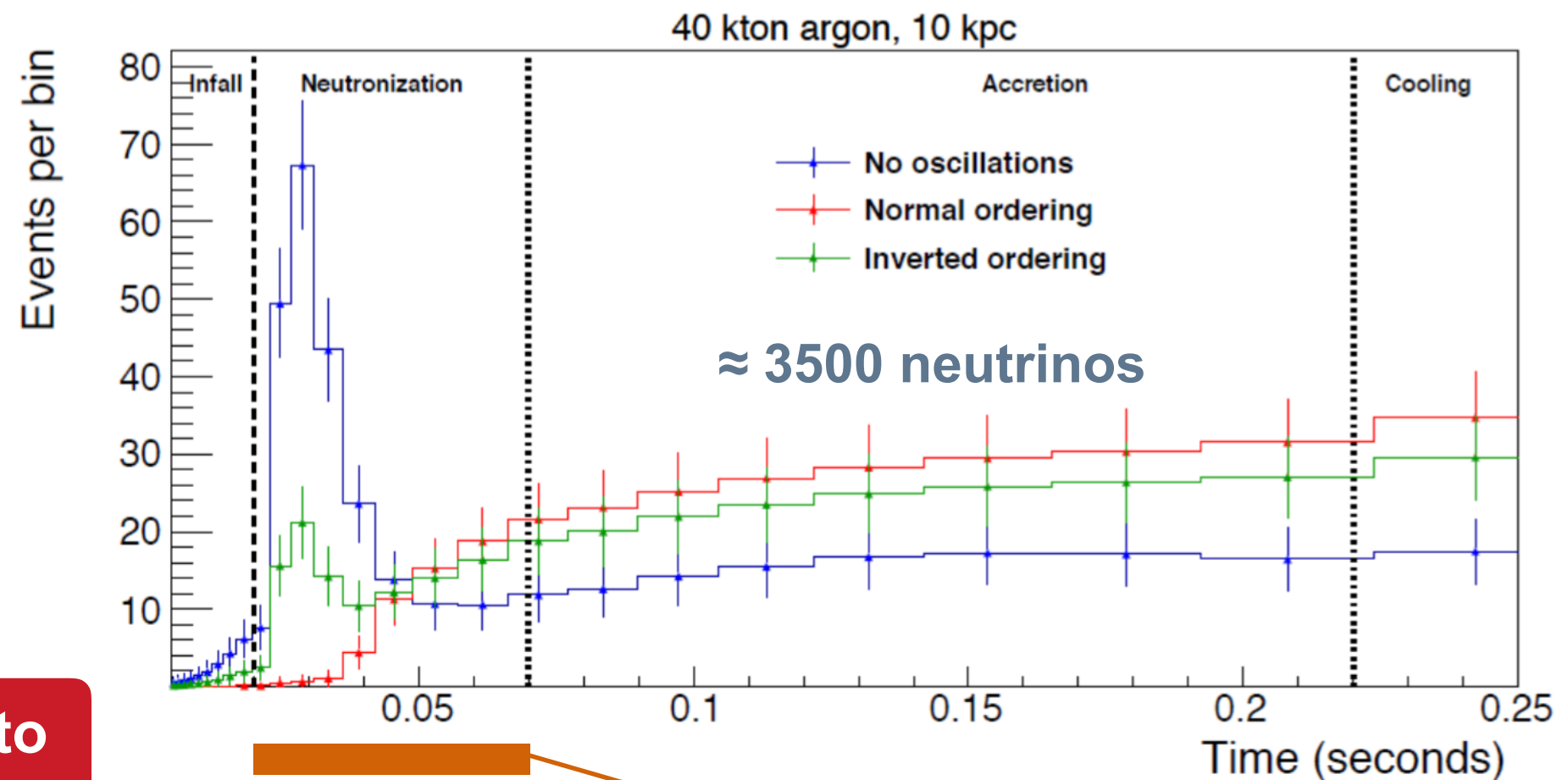
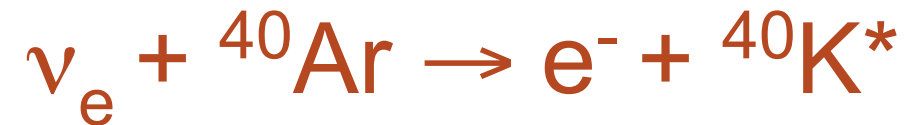
LAr uniquely sensitive to
neutronization process at
~30ms

Observation of **early time** development yields sensitivity to
neutrino mass ordering and details of SNB model.

SuperNova neutrinos

Expect 2-3 core-collapse supernovae in the Milky Way per century

In LArTPC, SNB signal dominated by electron neutrinos



LAr uniquely sensitive to neutronization process at $\sim 30\text{ms}$

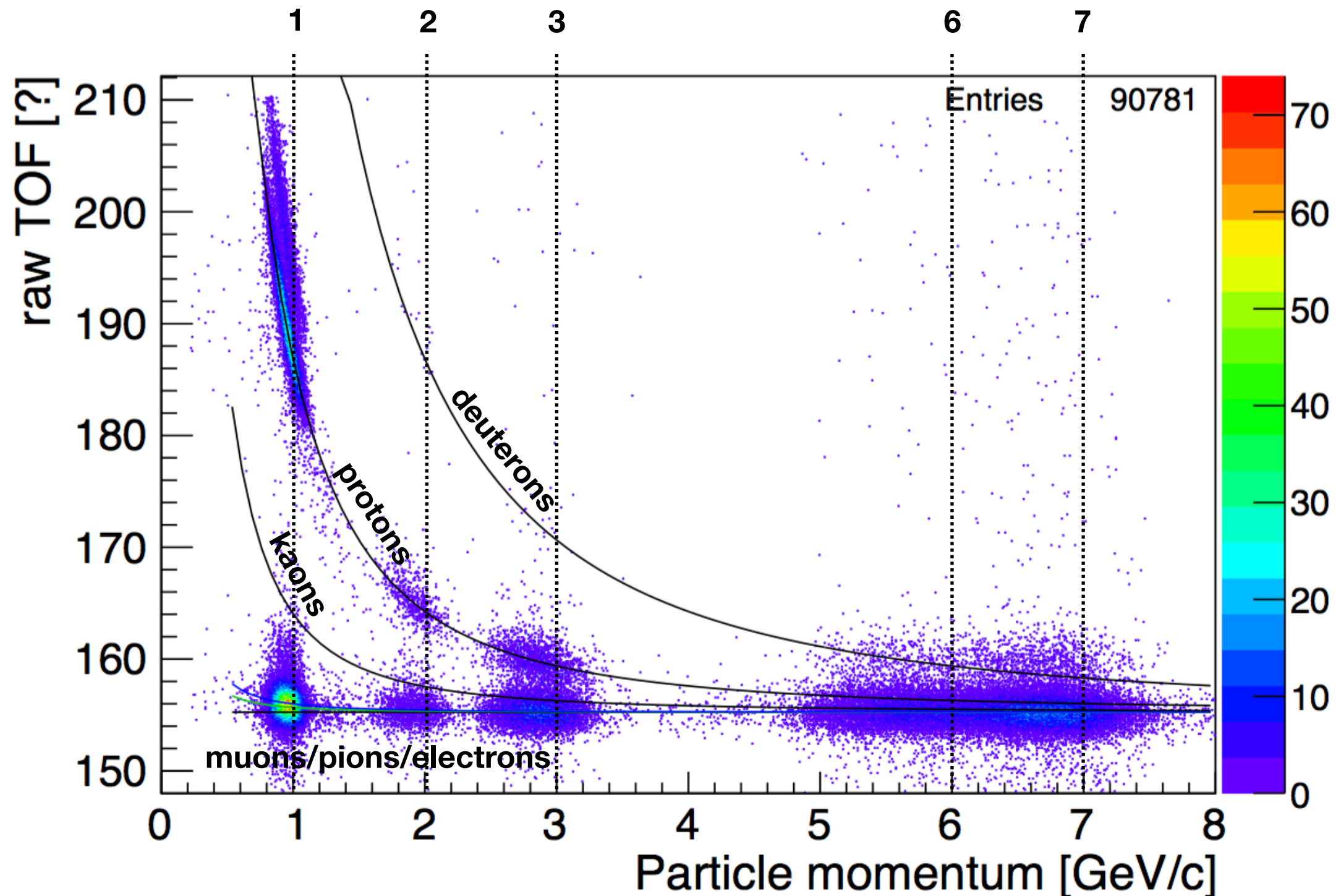
Observation of **early time** development yields sensitivity to neutrino mass ordering and details of SNB model.

Photon Detectors

- LAr is an excellent scintillating medium: 20,000 photons/MeV @ 500 V/cm, with a wavelength of 128 nm
- Wavelength shifter converts VUV light to visible light that is readout by SiPMs
- 3 photodetector designs will be tested in ProtoDUNE-SP
 - Design#1: Dip-coated light guide (MIT and Fermilab)
 - Design#2: Double-shift light guide (Indiana University)
 - Design#3: ARAPUCA (Campinas University and Fermilab)

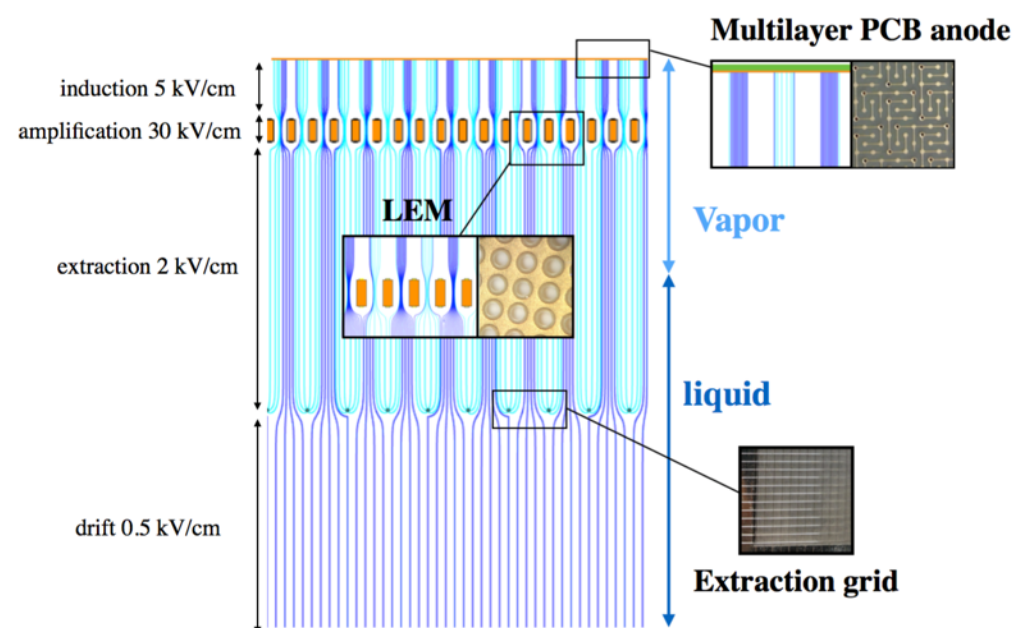
Beam detectors

Time of Flight for beam particles



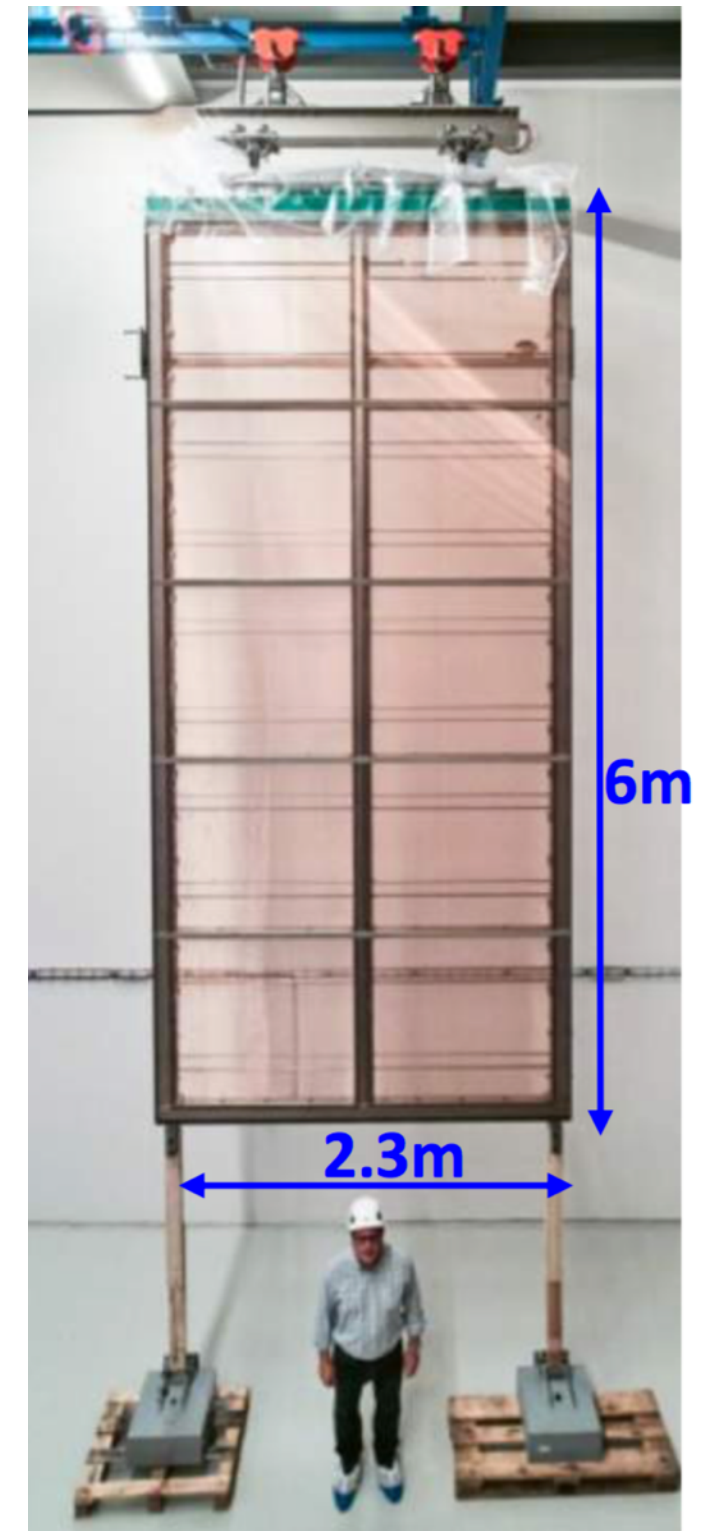
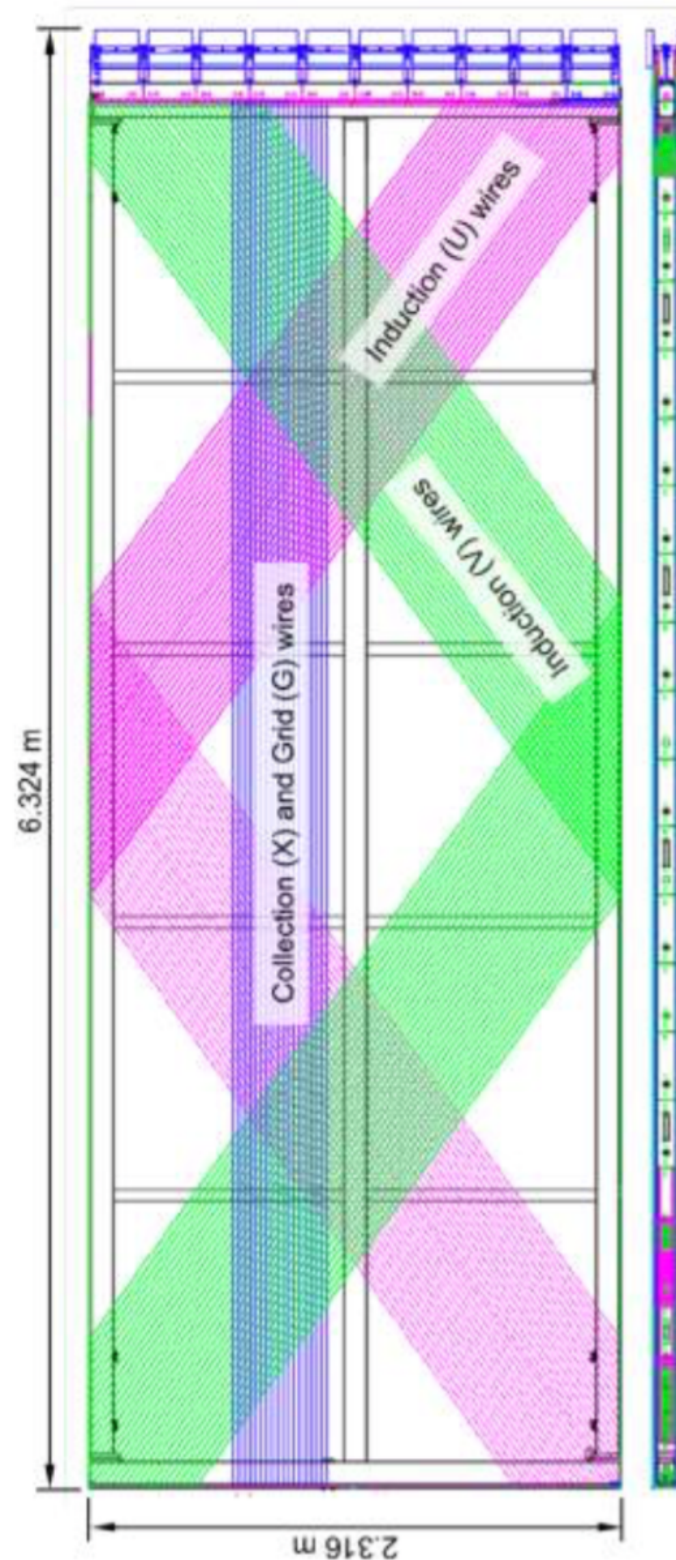
CRP: Charge Readout Plane

- Large Electron Multiplier (LEM) and anodes are mounted to CRP
- Charge is amplified in LEM and then collected by multi-layer Printed Circuit Board (PCB) anode, providing track views in two directions
- 3x3 m² LEM and readout module completed and tested in dedicated cold box, filled with gaseous N₂



APA: Anode Plane Assemblies

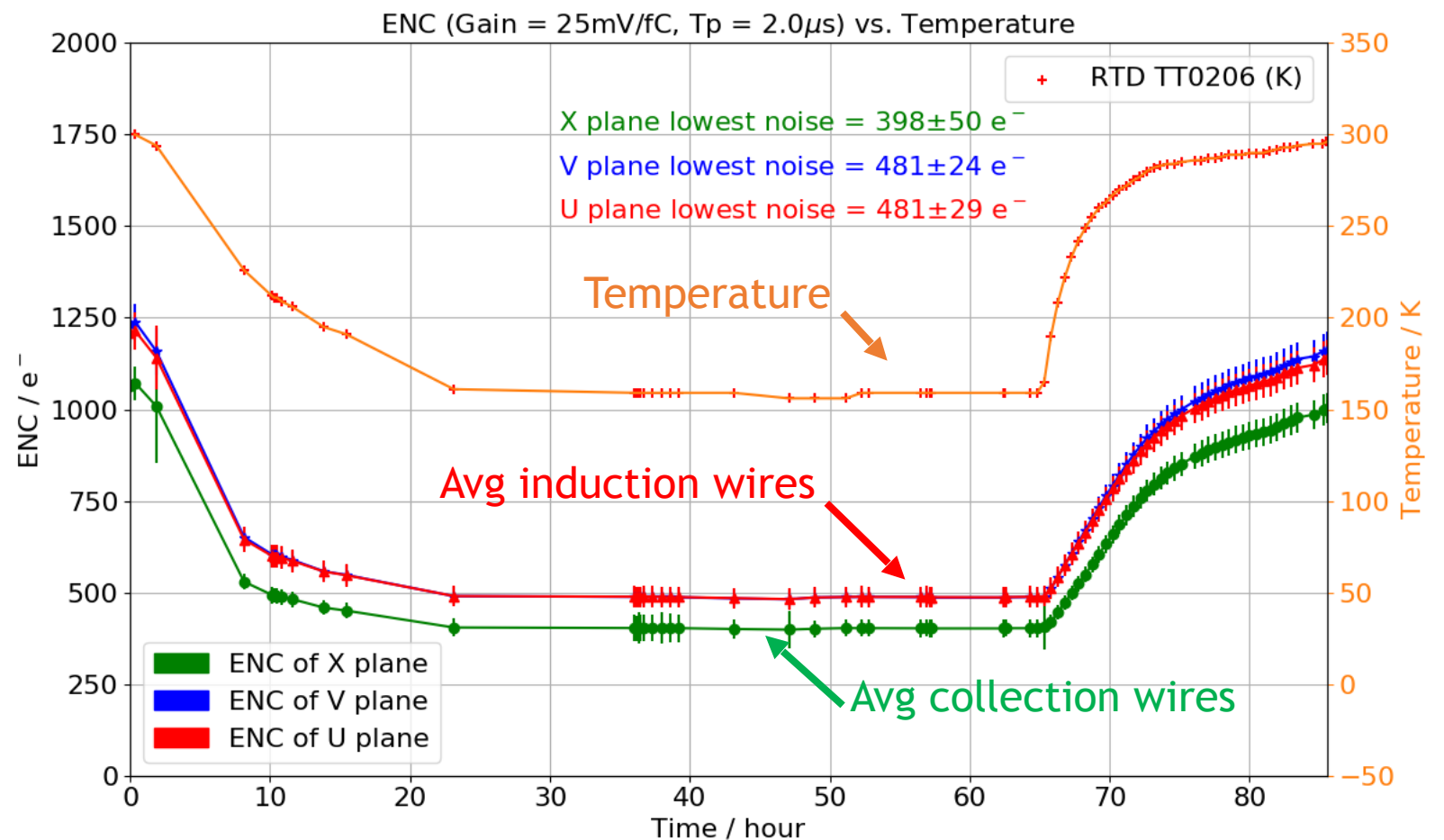
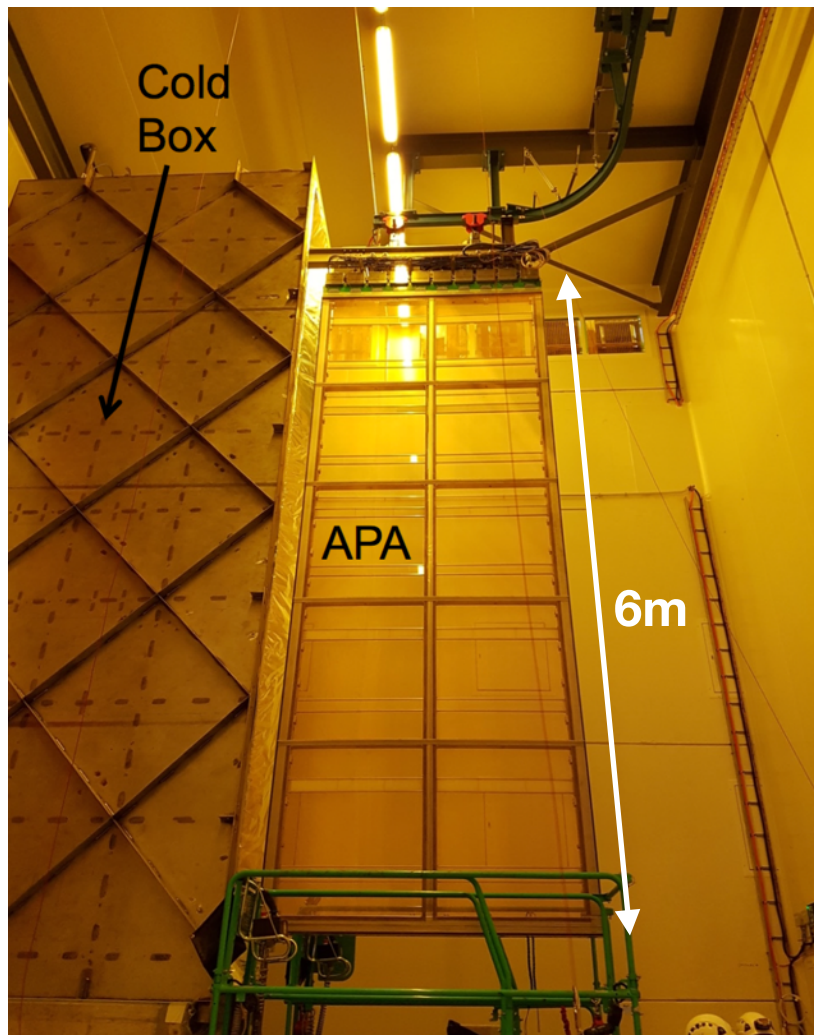
- APA: three wire planes (UVX) + one grid plane (G)
- Wrapped wire design reduces number of electronic channels and allows more active volume: all electronics are on top



Cold Electronics

Cold box is filled with nitrogen gas for testing at “cold” temperature (150 K)

ENC (Equivalent Noise Charge) is charge (in e^-) injected to detector capacitance which produces on the output side a signal with amplitude equals the output RMS noise



ProtoDUNE goals

ProtoDUNE goals

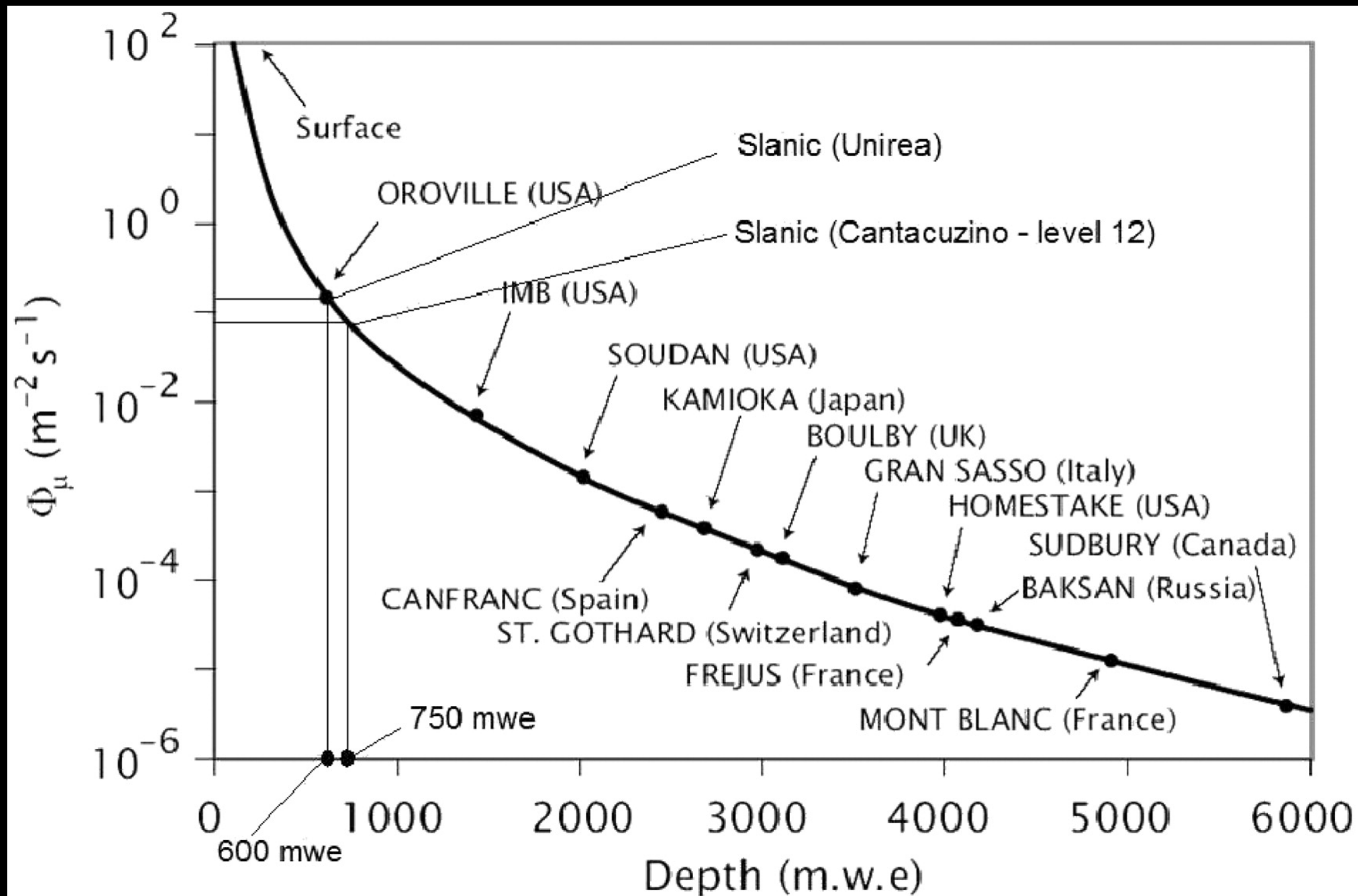
- Hardware:
 - Prototyping **production** and (underground) **installation** procedures
 - **Validating the design** from basic detector performance
 - Demonstrating **long-term** operational stability

ProtoDUNE goals

- Hardware:
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 - **Validating the design** from basic detector performance
 - Demonstrating **long-term** operational stability
- Test beam data:
 - **Detector response** understanding, calibration, dE/dx, PID, etc.
 - Perform **cross section** measurements of hadrons on Argon
 - of interest for the entire LAr community (SBN)
 - knowledge of π Ar interactions are key to control systematics for DUNE

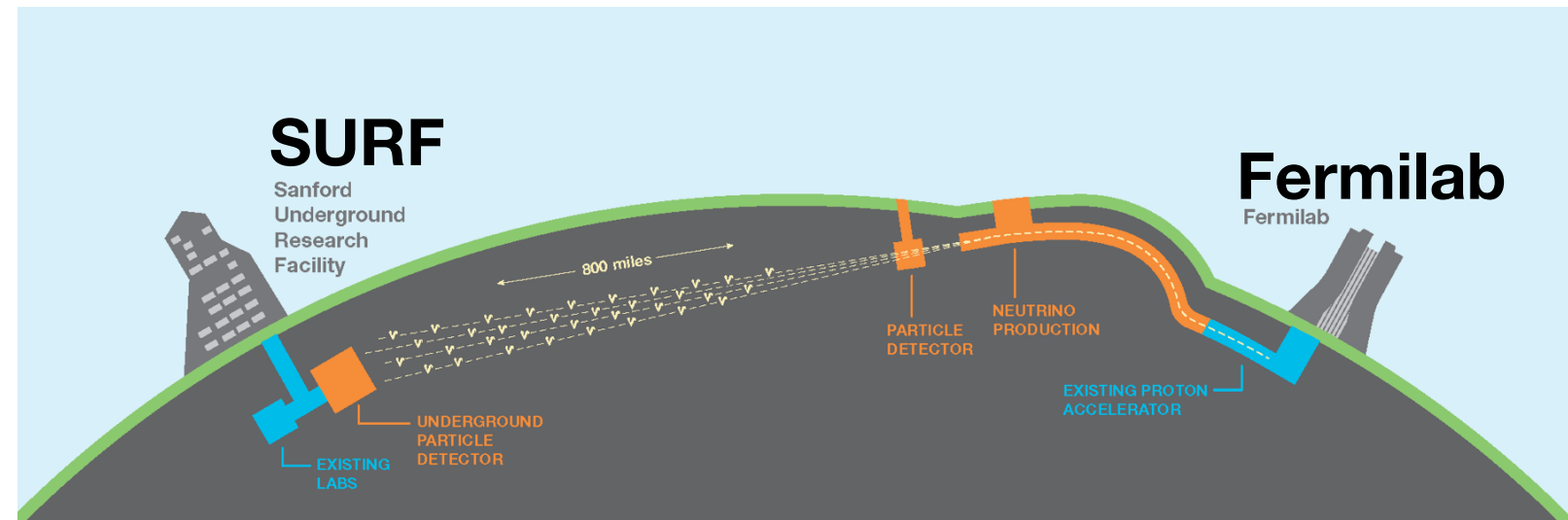
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- Cosmics data:
 - 3D map of **detector response**: space charge and E field distortions
 - **Different E-field**: dE/dx , dQ/dx , and charge recombination models
 - Identify and **reconstruct Michel e-** in order to use their energy spectrum (10 – 60 MeV) to test the calibration of the detector in the energy range interesting for Supernova ν



Deep Underground Neutrino Experiment

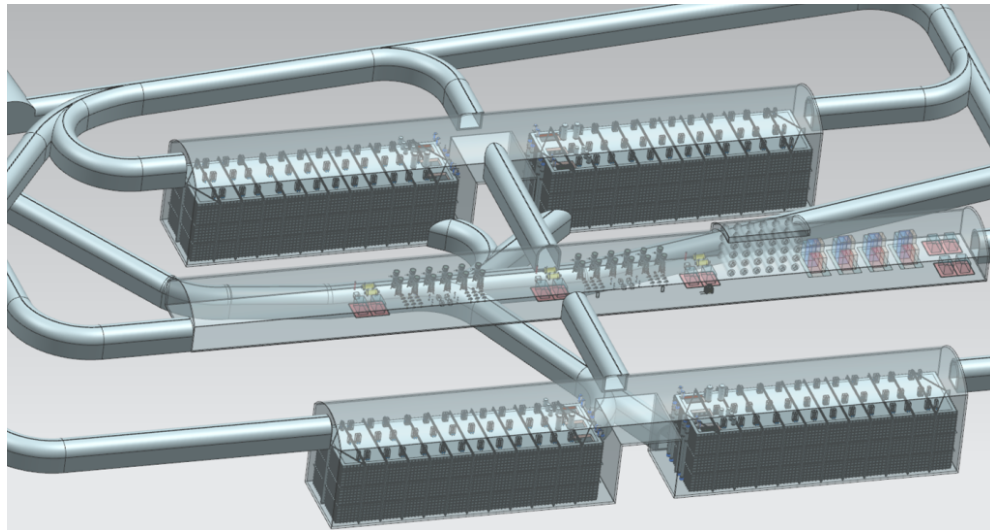
High power *wide band* muon neutrino beam from Fermilab to SURF, in South-Dakota, 1300 km away



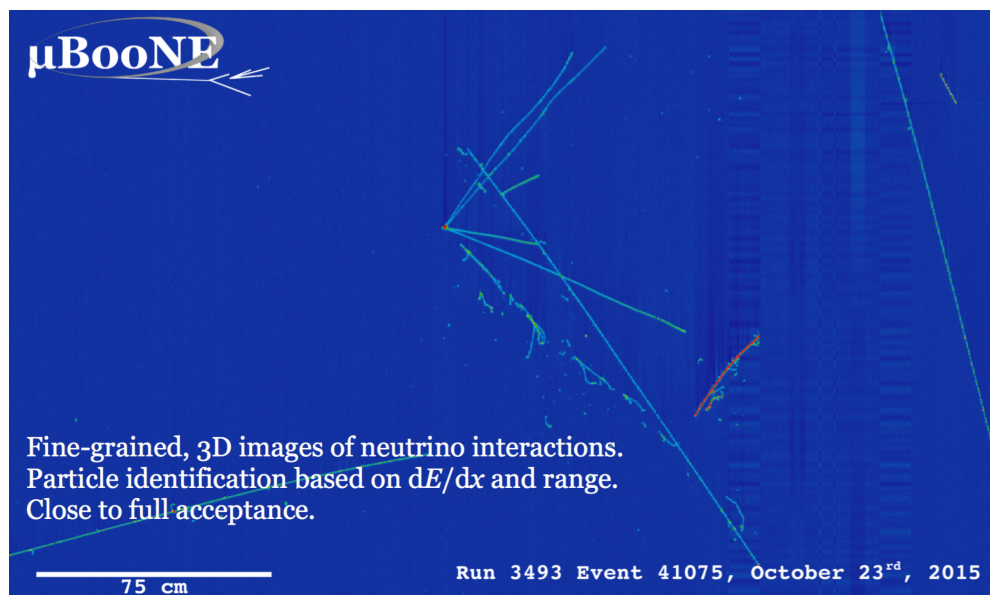
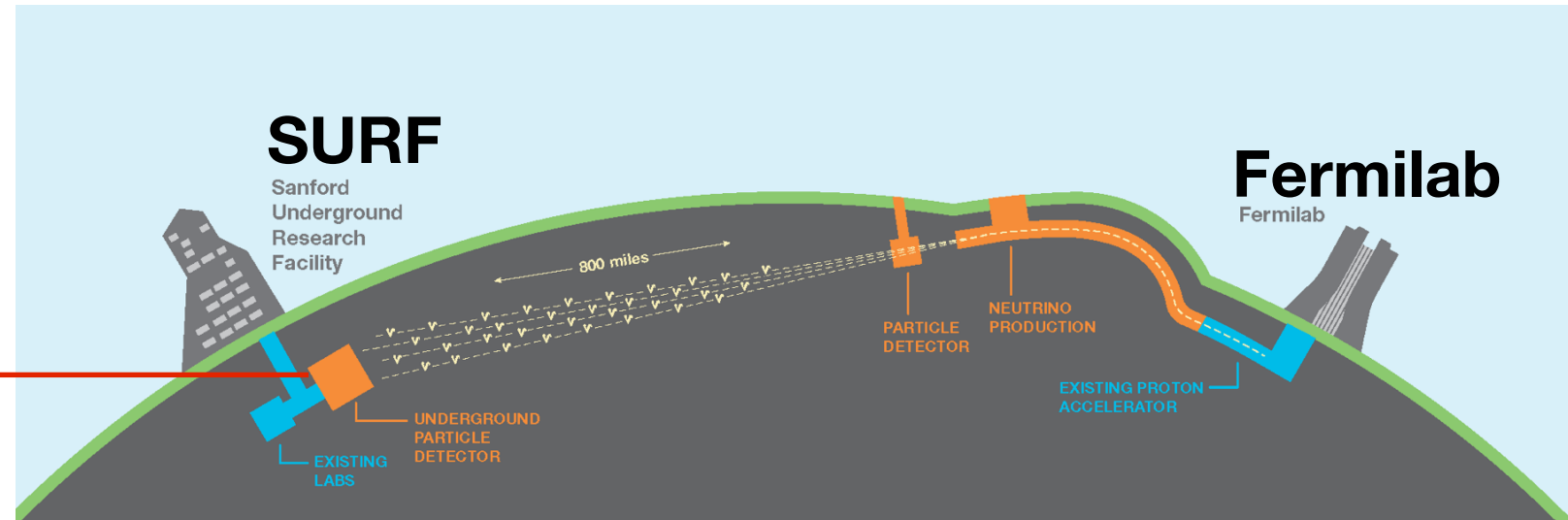
Deep Underground Neutrino Experiment

40 Kton far detector using
Liquid Argon TPC technology

Time Projection Chamber



High power *wide band* muon neutrino beam from
Fermilab to SURF, in South-Dakota, 1300 km away



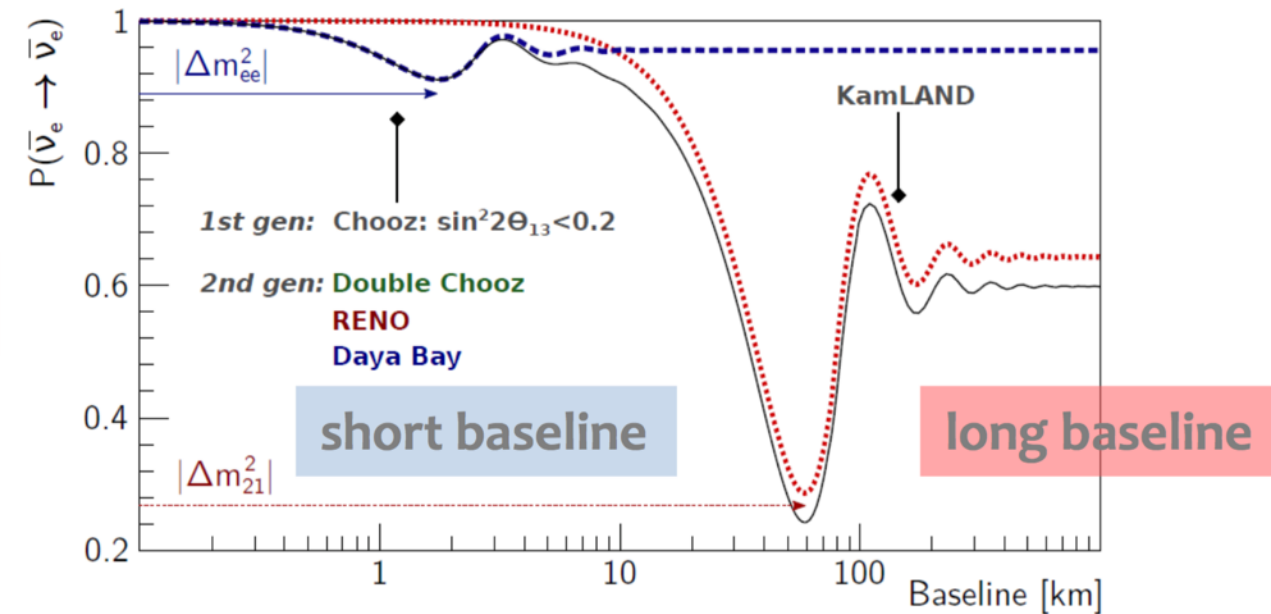
Experimental strategies

Experimental strategies

- Independent θ_{13} measurement at reactor experiments: $\bar{\nu}_e$ dissap.

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \underbrace{\sin^2 2\theta_{13} \sin^2\left(\Delta m_{ee}^2 \frac{L}{4E}\right)}_{\text{short baseline}} - \underbrace{\cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2\left(\Delta m_{21}^2 \frac{L}{4E}\right)}_{\text{long baseline}}$$

$$\sin^2\left(\Delta m_{ee}^2 \frac{L}{4E}\right) \equiv \cos^2 \theta_{12} \sin^2\left(\Delta m_{31}^2 \frac{L}{4E}\right) + \sin^2 \theta_{12} \sin^2\left(\Delta m_{32}^2 \frac{L}{4E}\right)$$

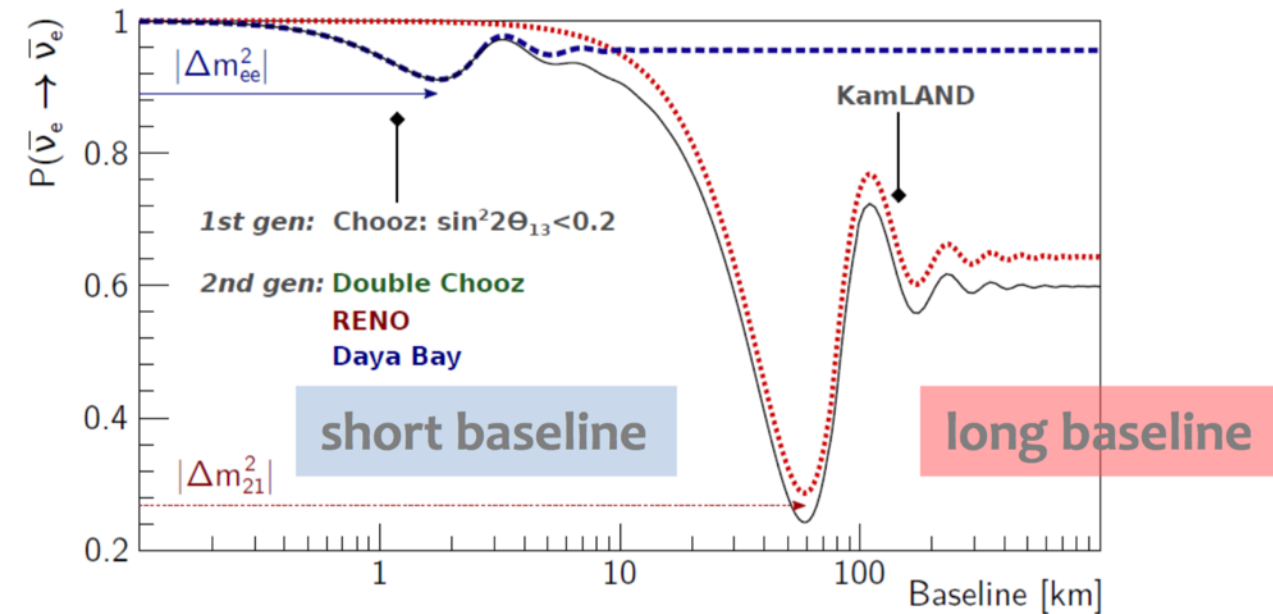


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- θ_{13} - δ_{CP} measurement at LBL experiments: $\nu_e / \bar{\nu}_e$ appearance

$$P(\nu_\mu \rightarrow \nu_e) \sim \underbrace{\sin^2 2\theta_{13}}_{\text{green}} \times \underbrace{\sin^2 \theta_{23}}_{\text{blue}} \times \underbrace{\frac{\sin^2[(1-x)\Delta]}{(1-x)^2}}_{\text{purple}} \times \sin \Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

$$+ \underbrace{-\alpha \sin \delta}_{\text{red}} \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \cos \Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

$$+ \alpha \cos \delta \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \cos \Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

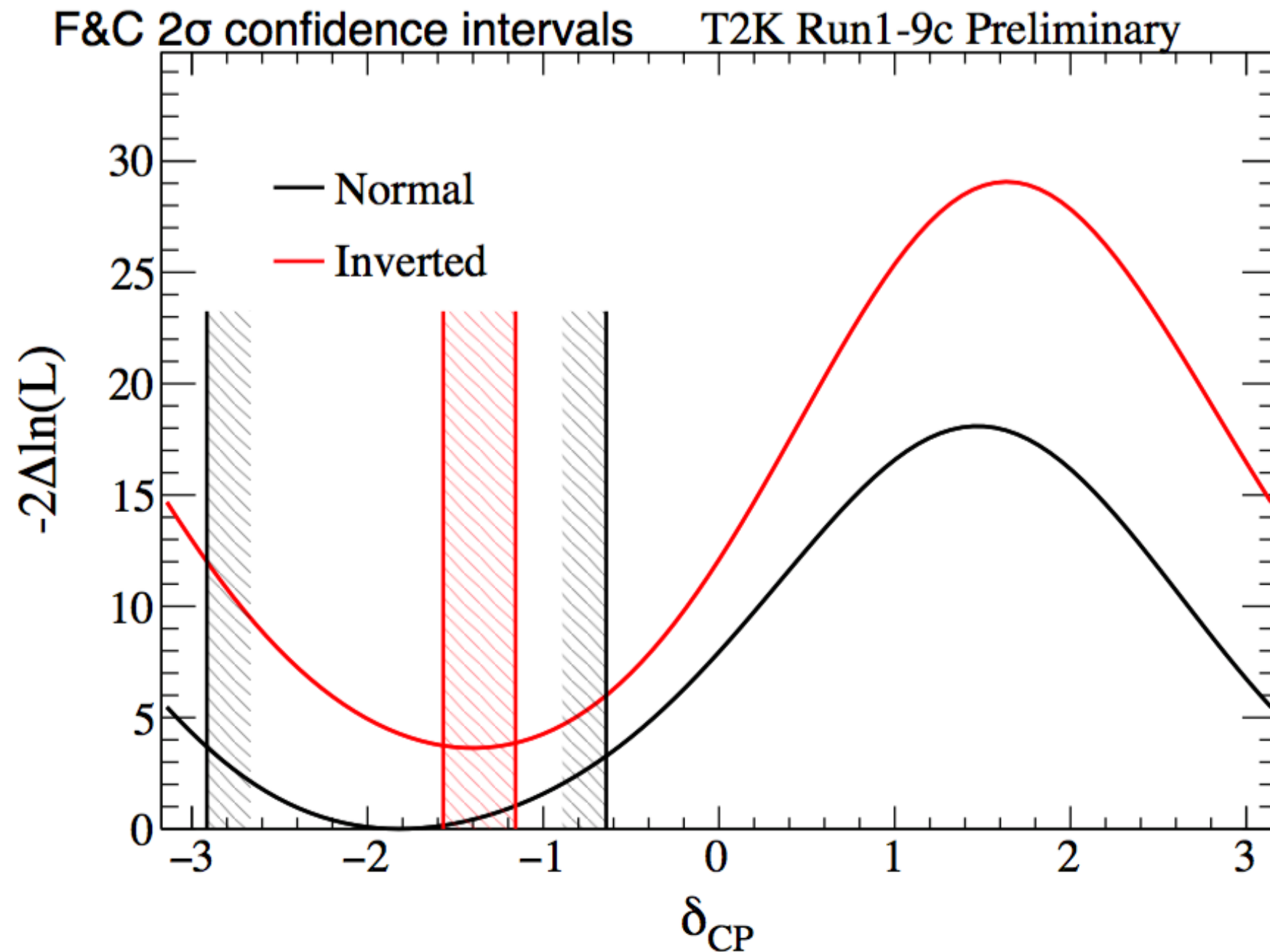
$$+ \mathcal{O}(\alpha^2)$$

$$\alpha = \left| \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \right| \sim \frac{1}{30} \quad \Delta \equiv \frac{\Delta m_{31}^2 L}{4E} \quad x \equiv \frac{2\sqrt{2}G_F N_e E}{\Delta m_{31}^2}$$

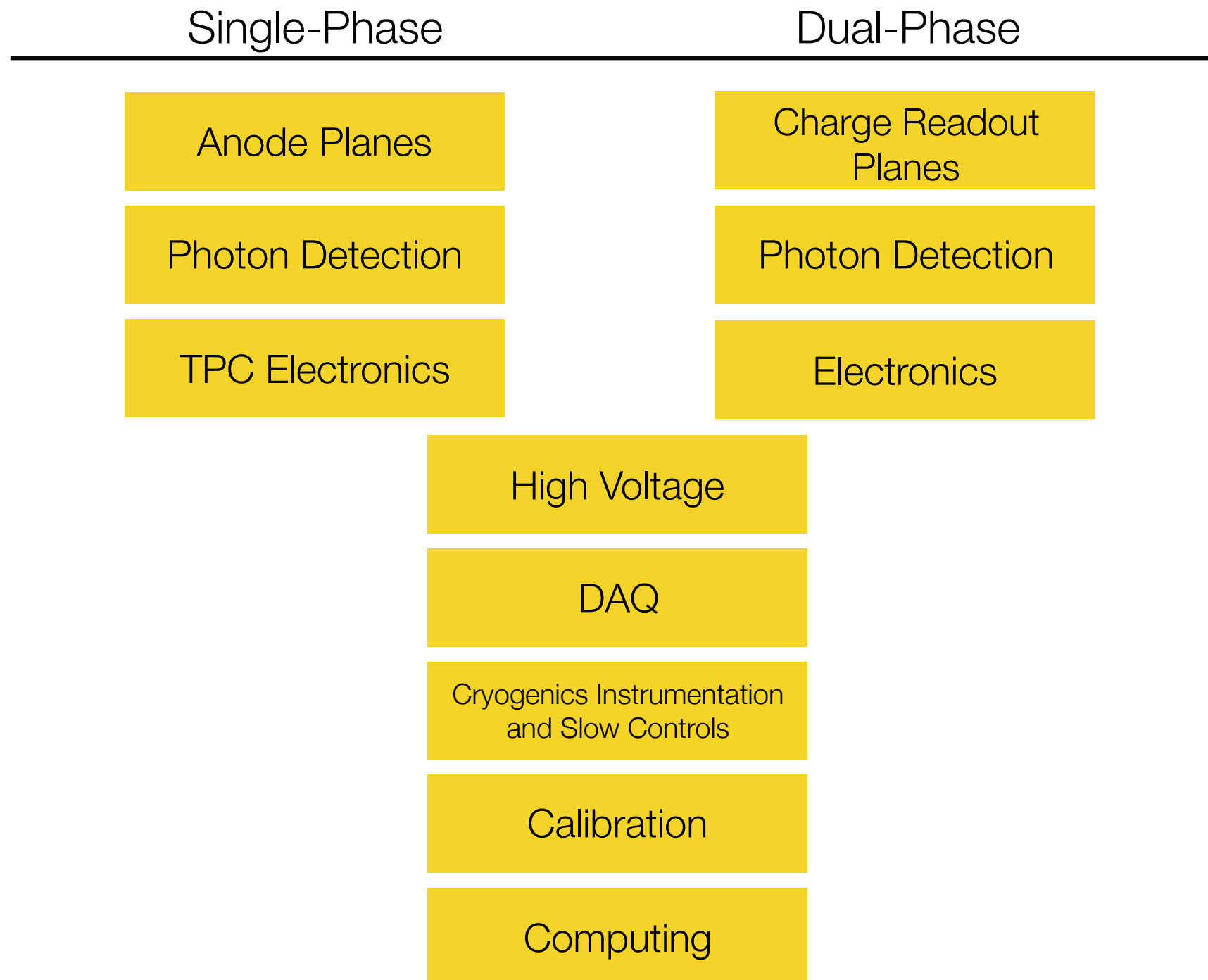
M. Freund, Phys.Rev. D64 (2001) 053003

- $\sin^2 2\theta_{13}$ dependence of leading term
- θ_{23} dependence of leading term: "octant" dependence ($\theta_{23} = /> / < 45^\circ$)
- CP odd phase δ : asymmetry of probabilities $P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ if $\sin \delta \neq 0$
- Matter effect through x : $\nu_e (\bar{\nu}_e)$ enhanced in normal (inverted) hierarchy

CP conservation excluded at 2 sigma by T2K



DUNE far detector consortia



- Sensitivities in DUNE CDR are based on **GLoBES** calculations in which the effect of systematic uncertainty is approximated using signal and background normalization uncertainties.

Spectral uncertainty not included in this treatment.

- Signal normalization uncertainties are treated as uncorrelated among the modes (ν_e , $\bar{\nu}_e$, ν_μ , $\bar{\nu}_\mu$) and represent the residual uncertainty expected after constraints from the near detector and the four-sample fit are applied.
 - $\nu_\mu = \bar{\nu}_\mu = 5\%$ Flux uncertainty after ND constraint
 - $\nu_e = \bar{\nu}_e = 2\%$ Residual uncertainty after ν_μ and $\nu/\bar{\nu}$ constraint

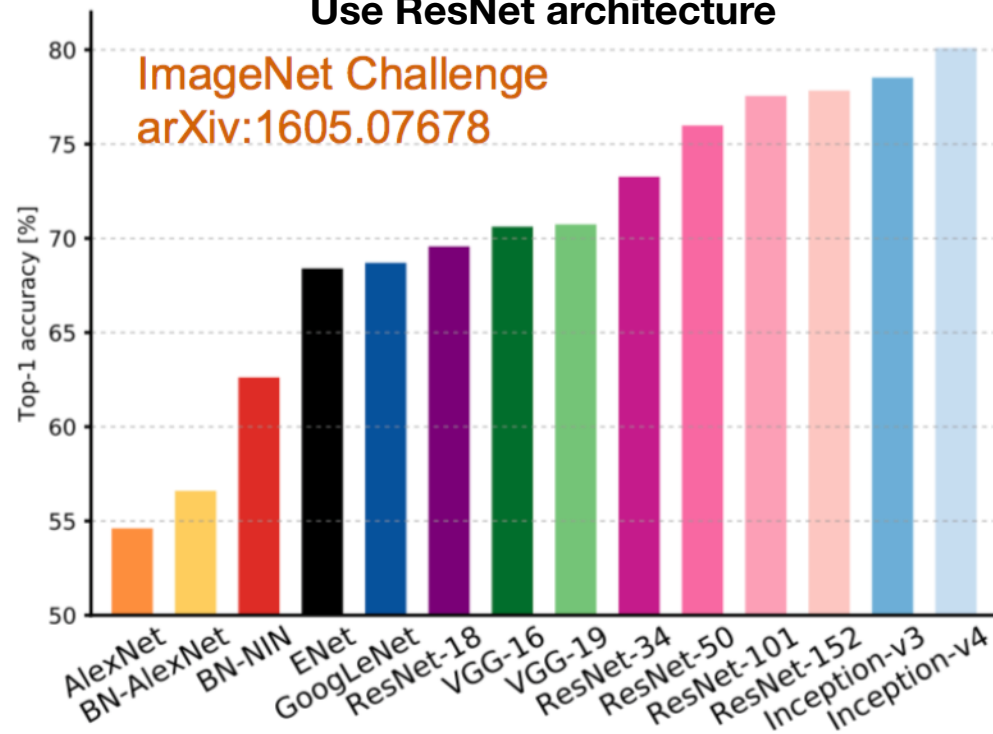
New MC Analysis (2018)

- GEANT4 beam simulation of updated beam design
- Full LArSoft Monte Carlo simulation
 - Shared framework among many LArTPC experiments
 - GENIE event generator
 - GEANT4 particle propagation
 - Detector readout simulation including realistic waveforms and white noise
- Automated signal processing and hit finding
- Automated energy reconstruction
 - Muon momentum from range (contained) or multiple Coulomb scattering (exiting)
 - Electron and hadron energy from calorimetry

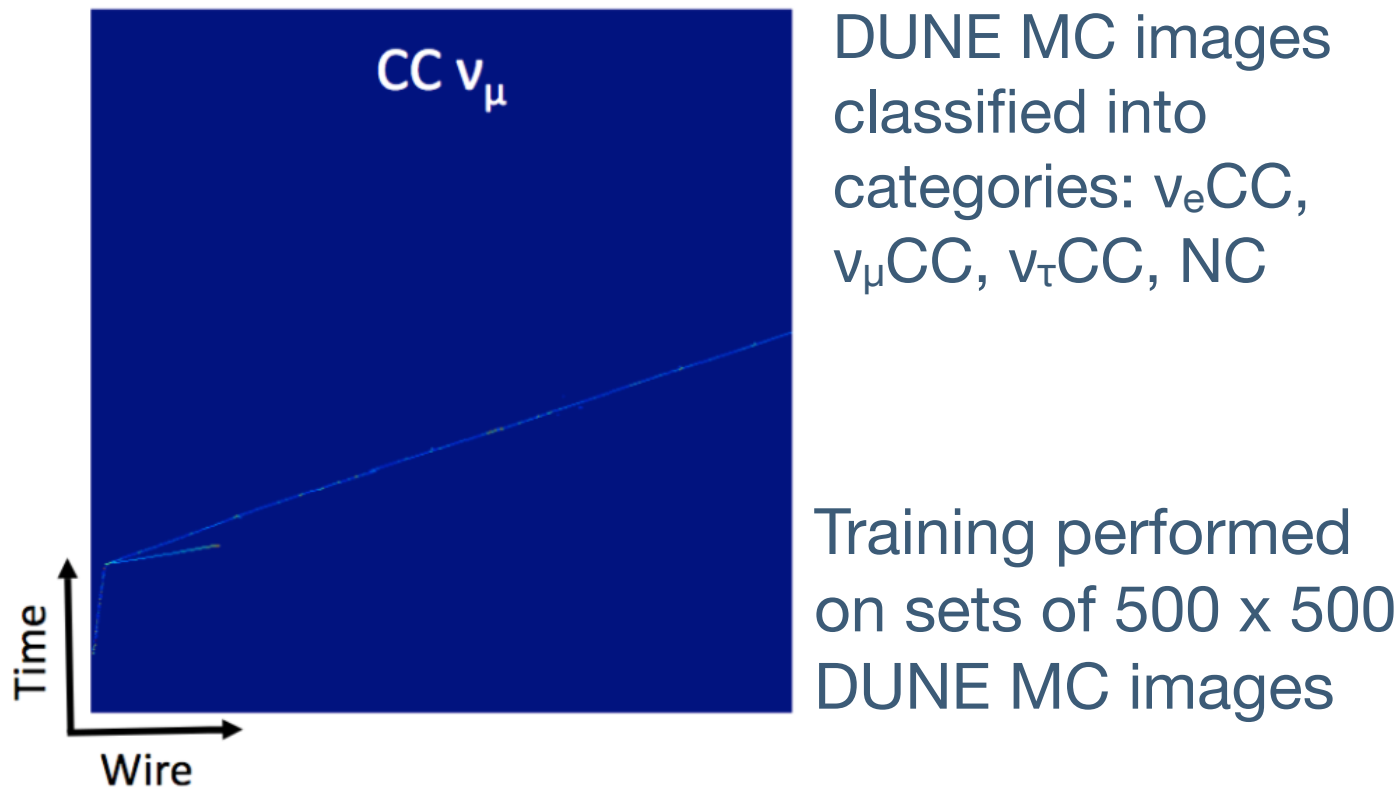
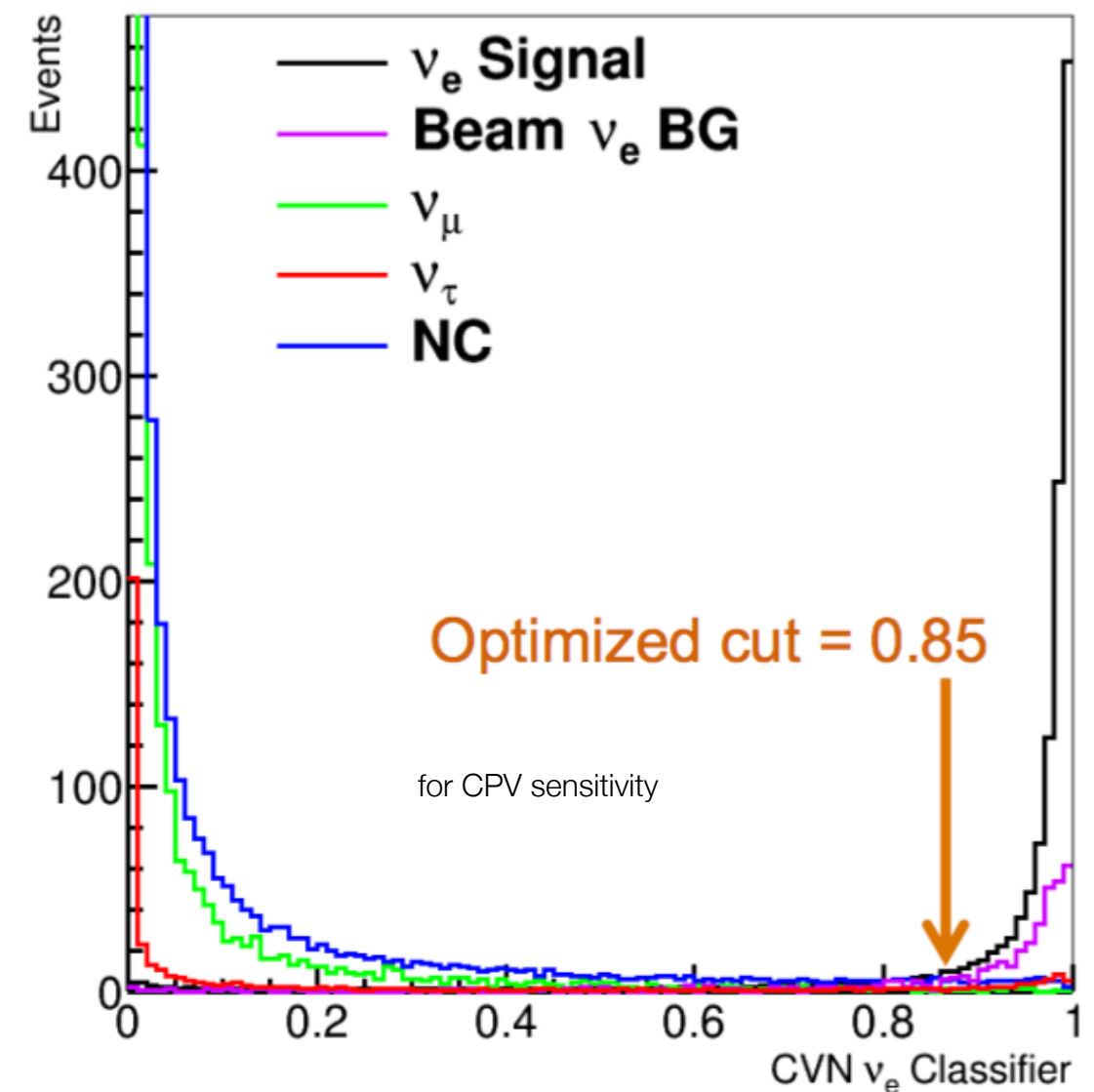
Use CVN techniques

Convolutional Visual Networks

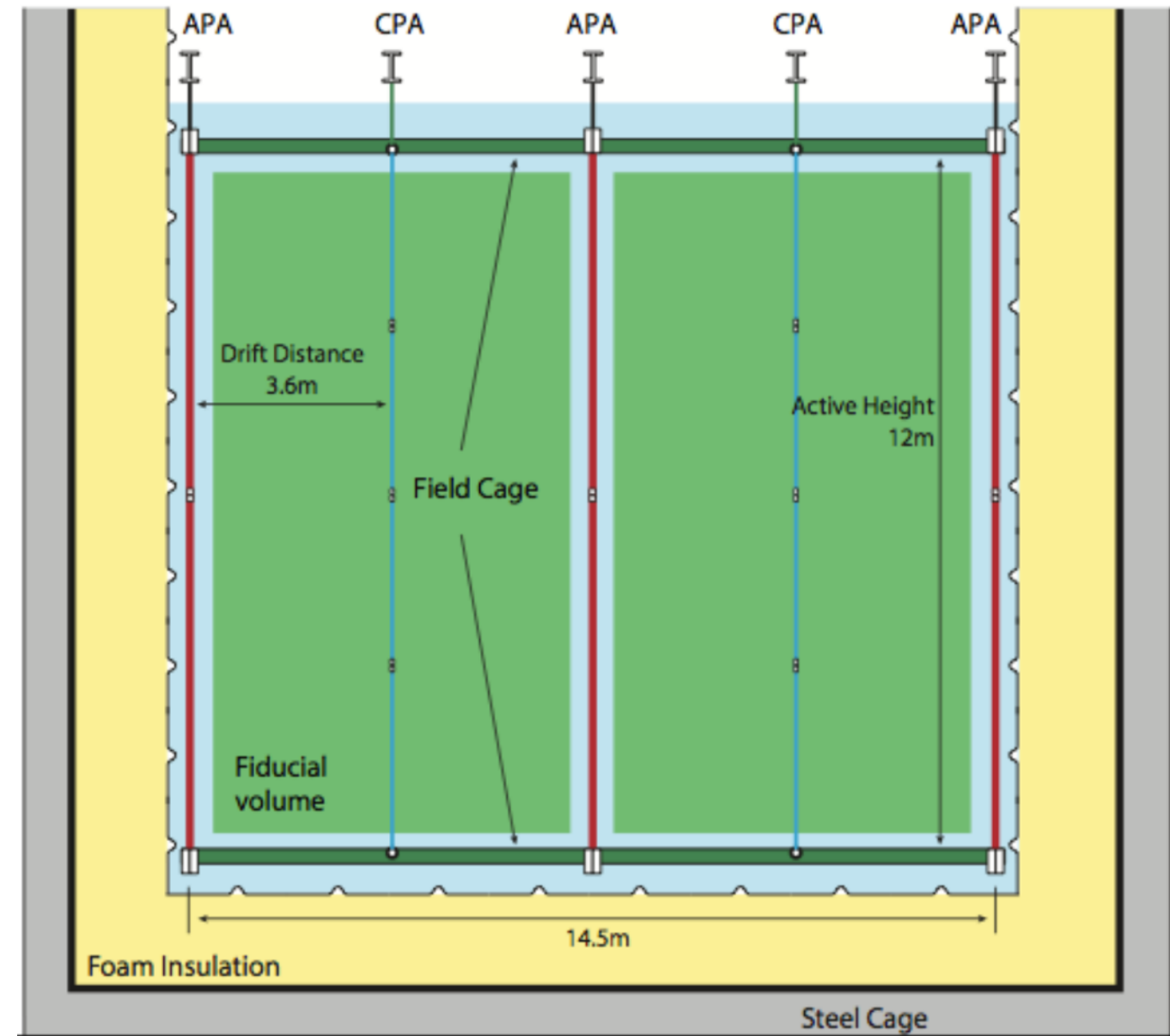
Use ResNet architecture



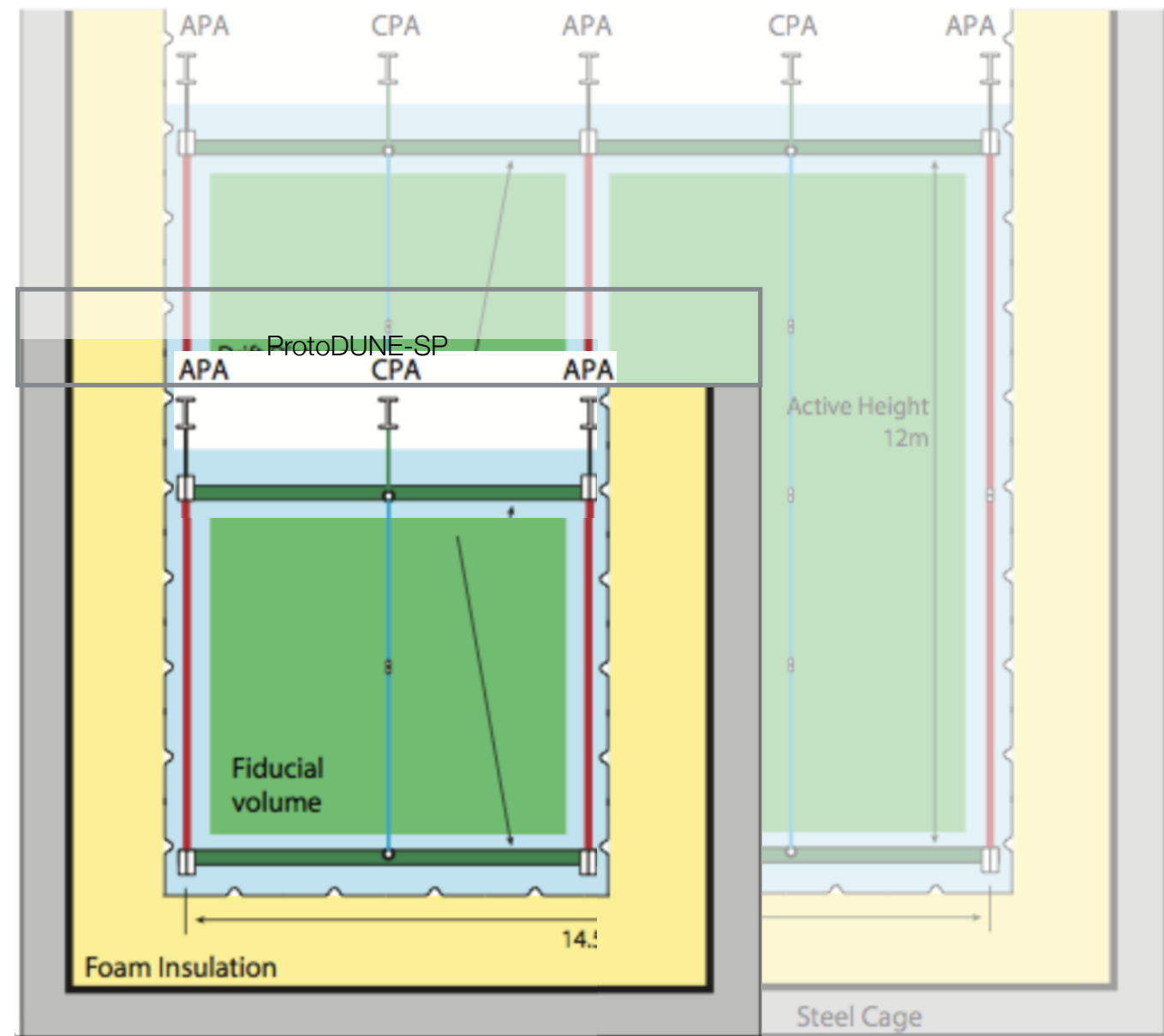
Event selection performed by applying cuts on ν_e CC-like and ν_μ CC-like CVN classifiers

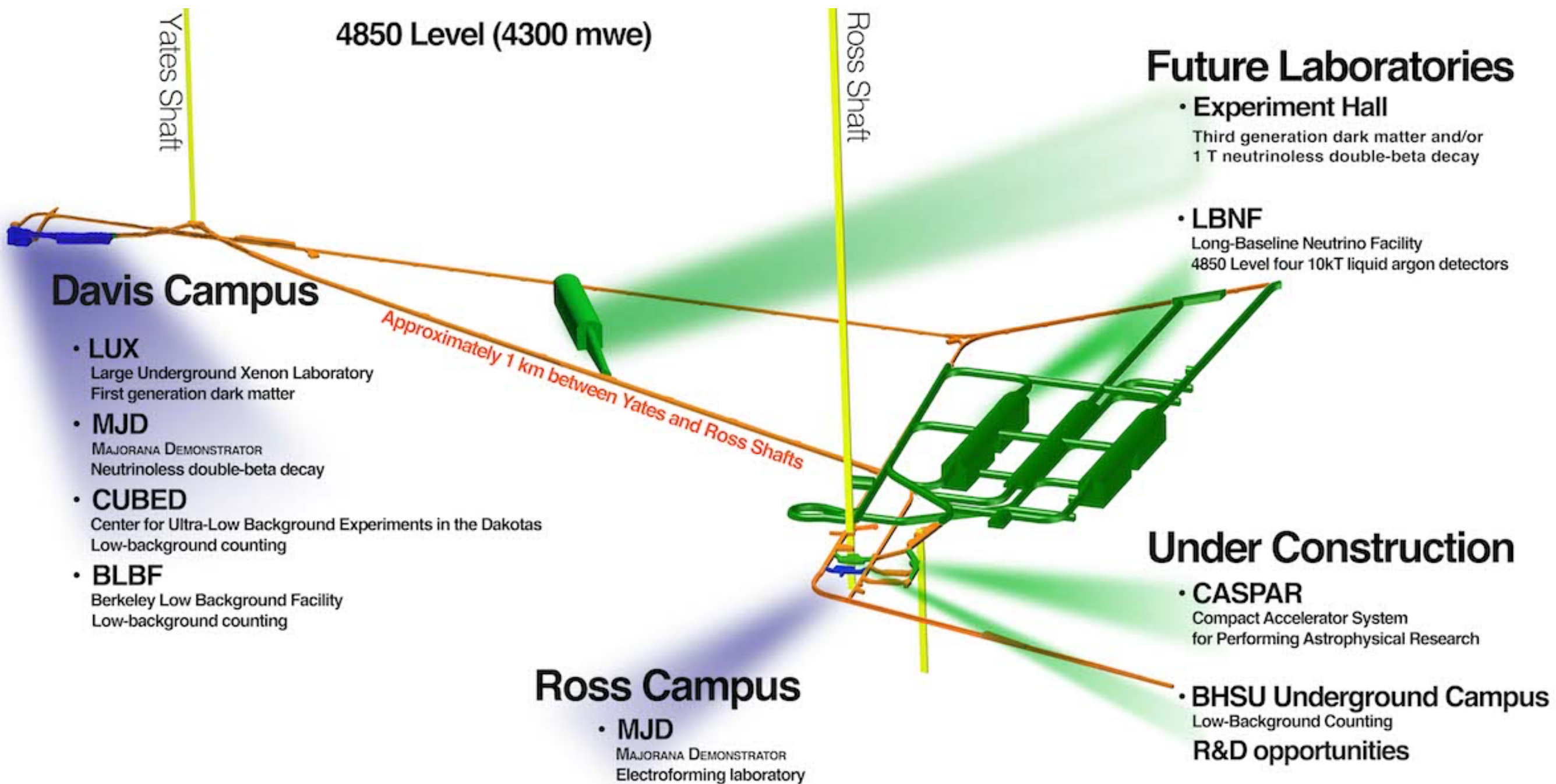


ProtoDUNE at CERN



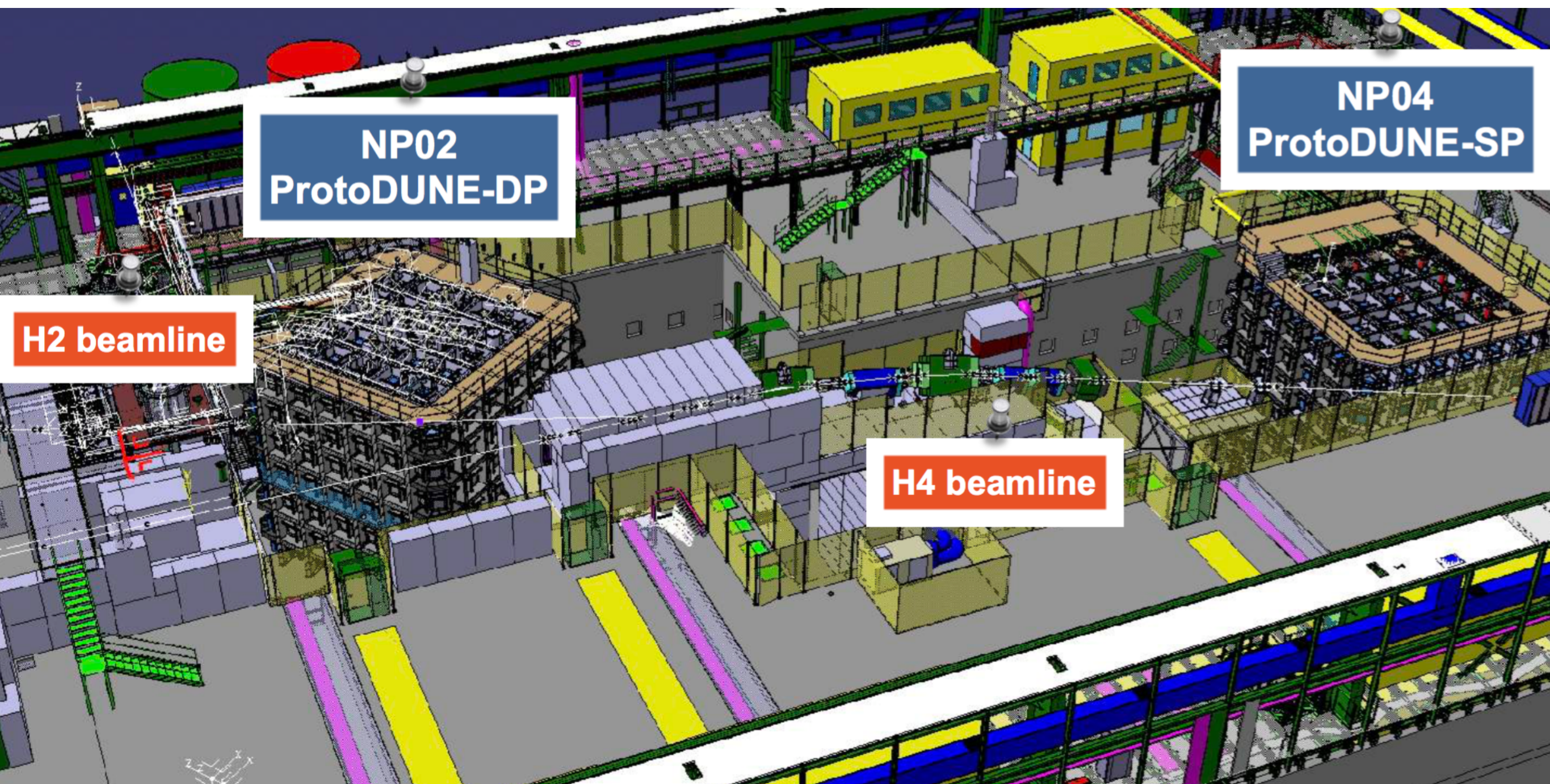
ProtoDUNE at CERN

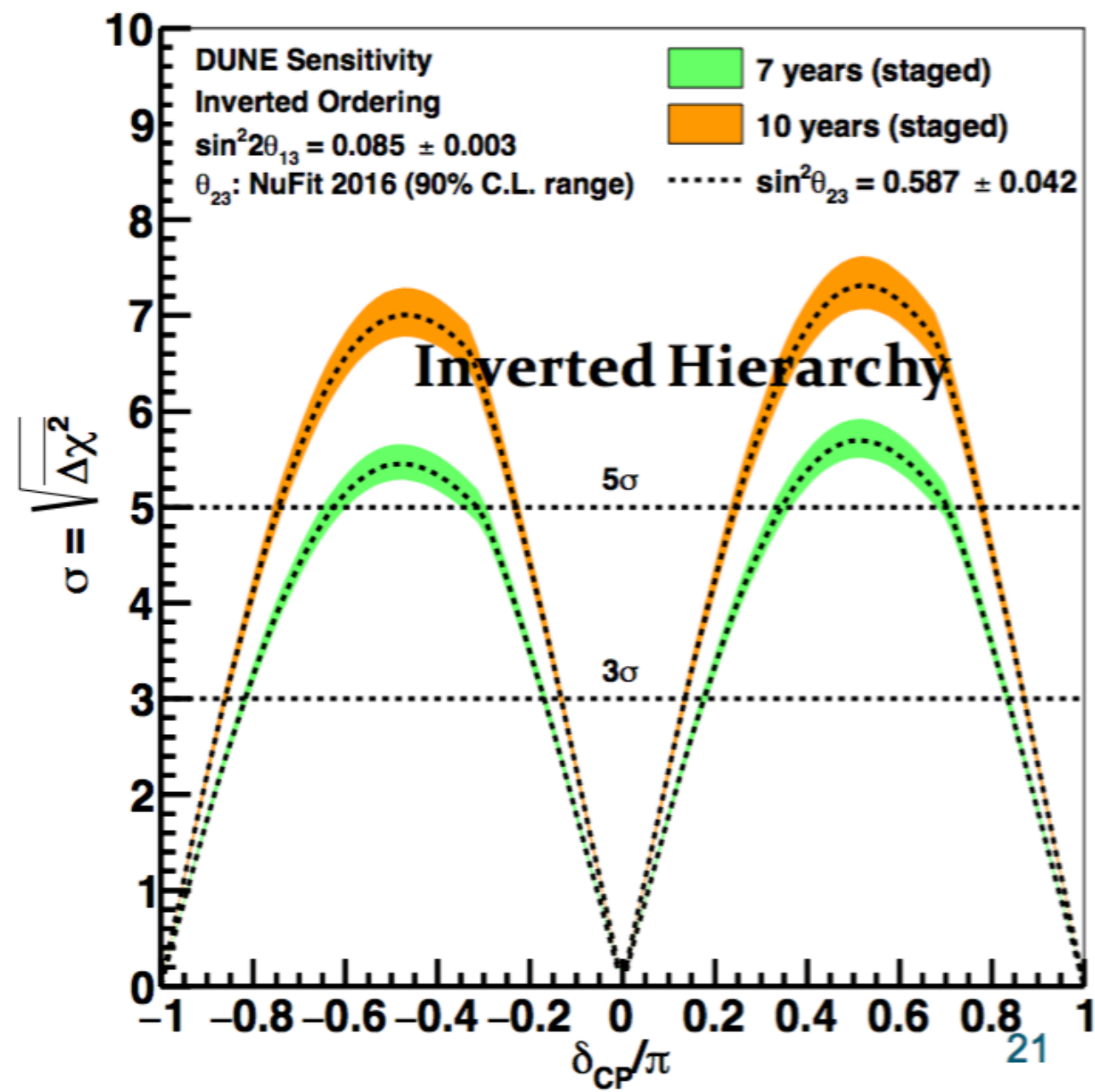
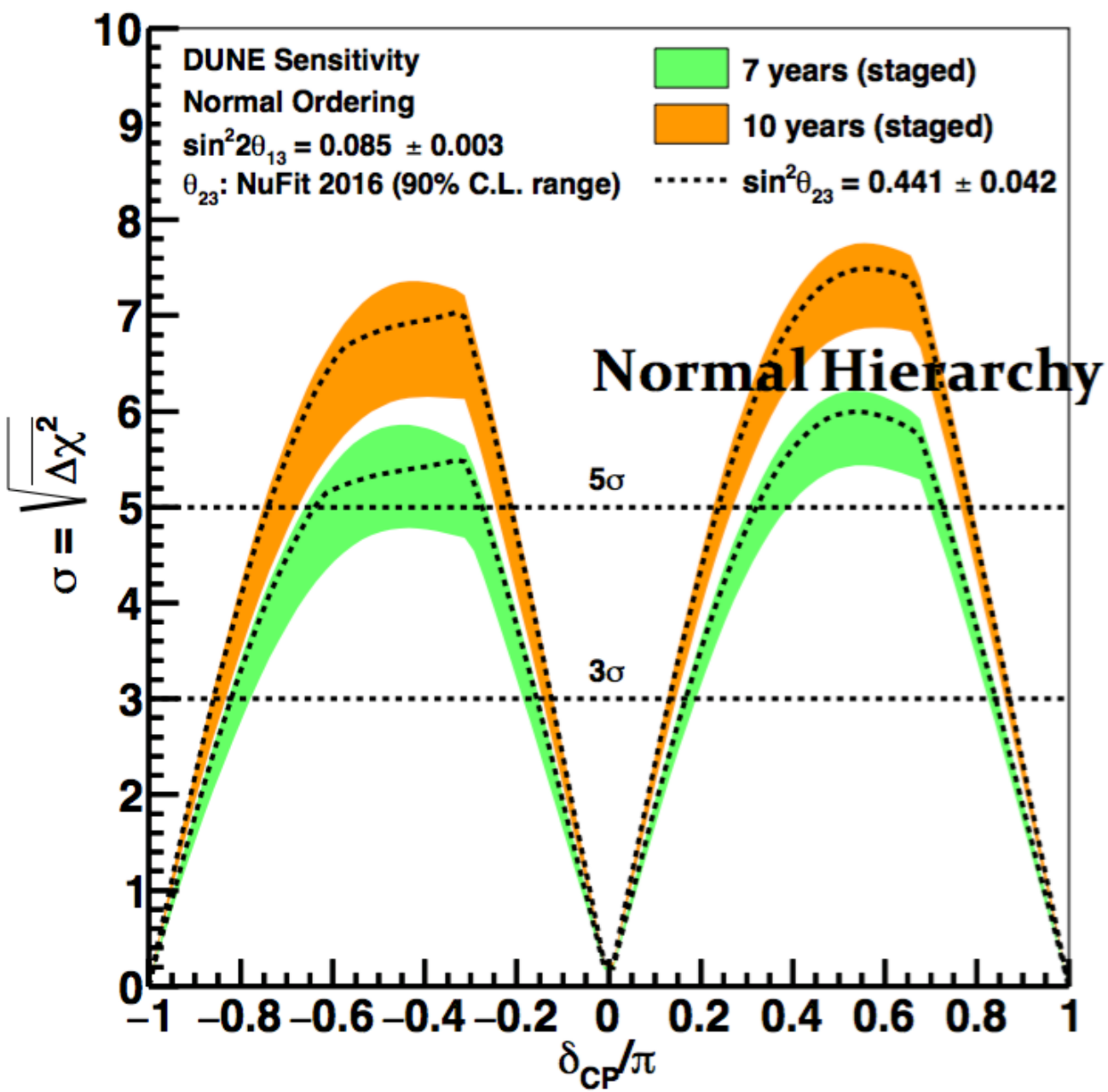




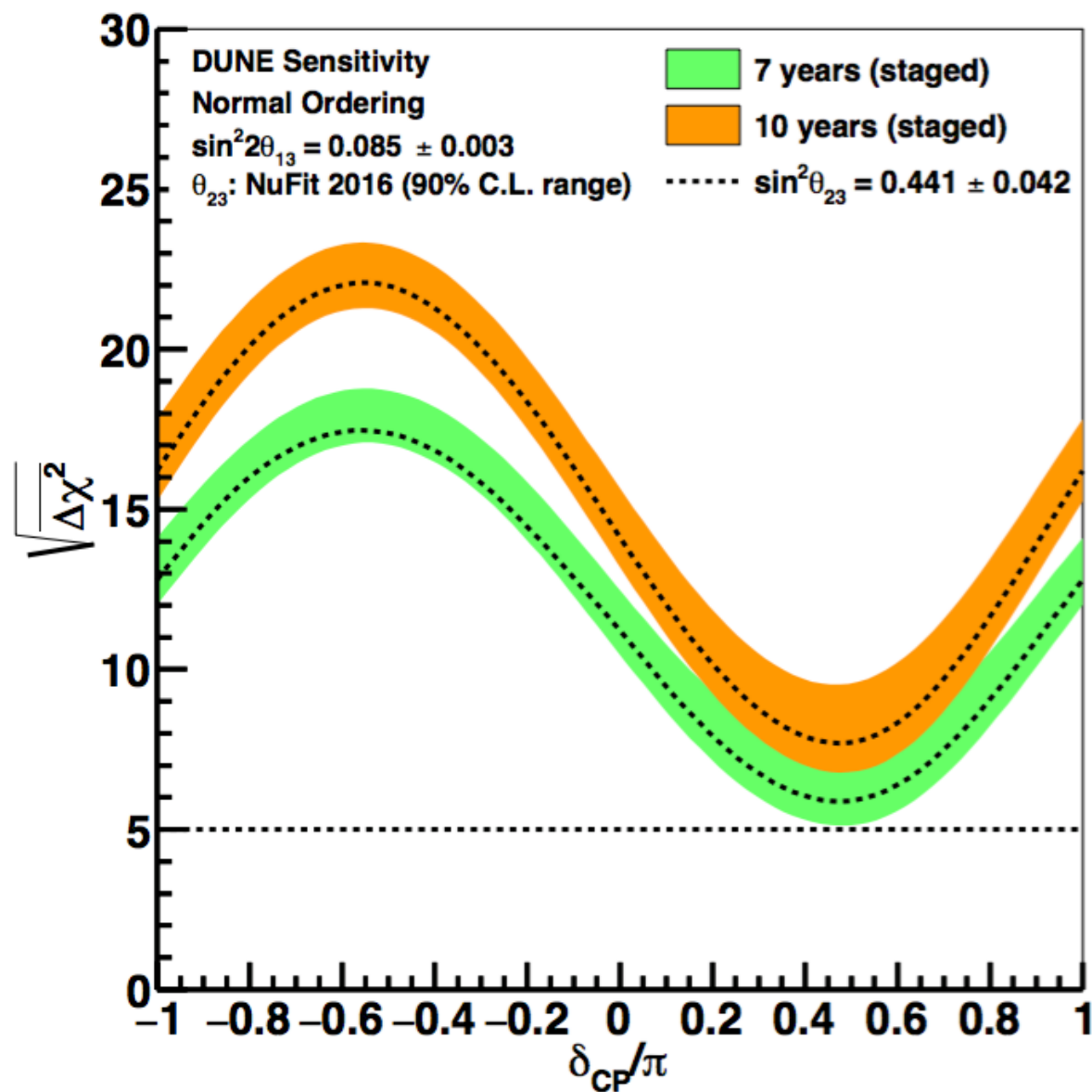


Another view

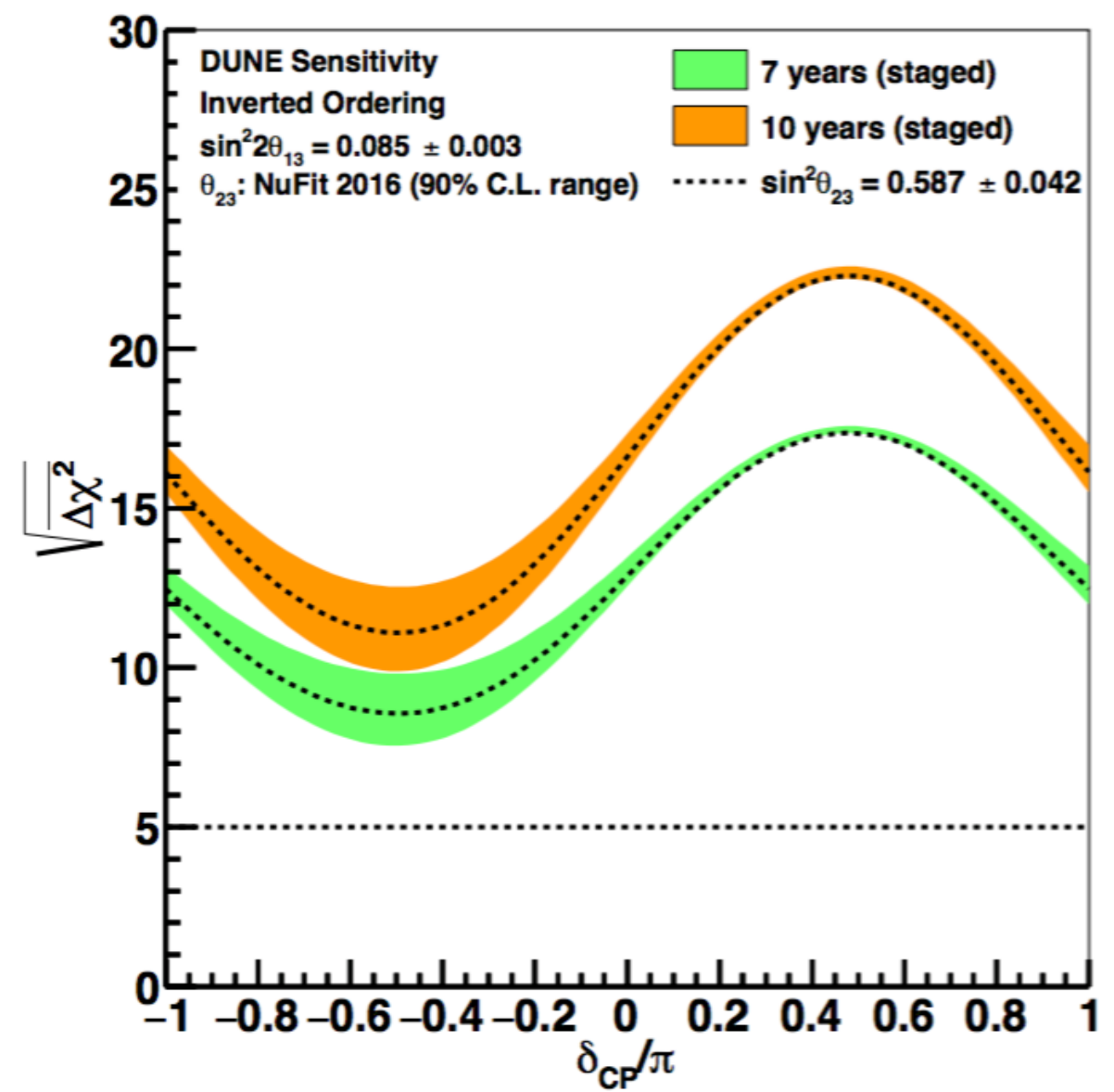




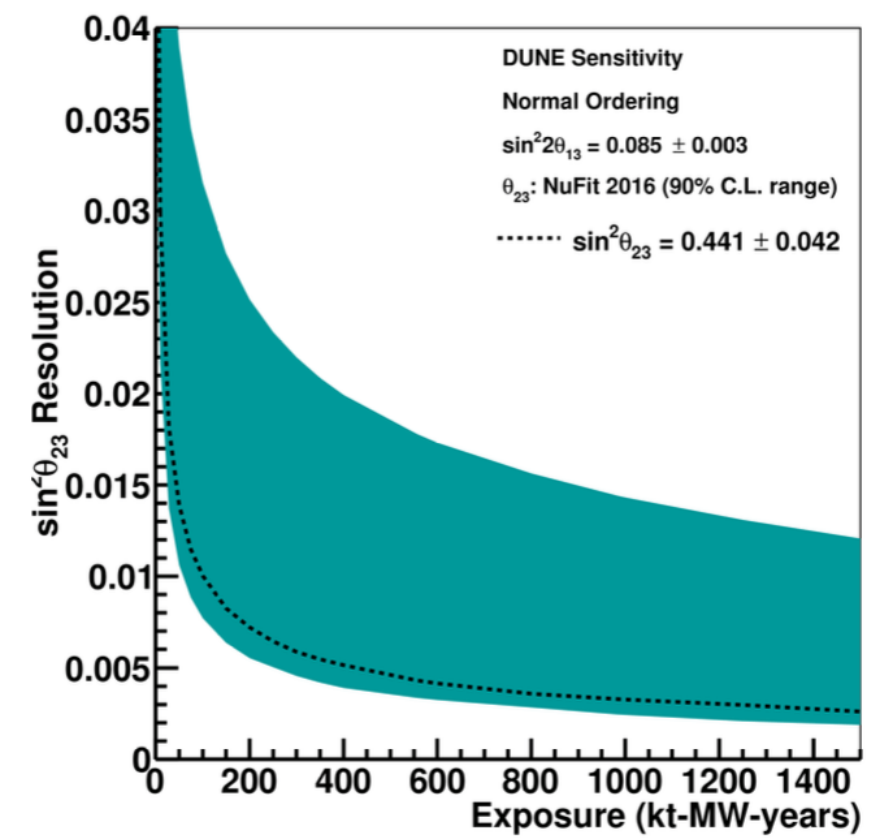
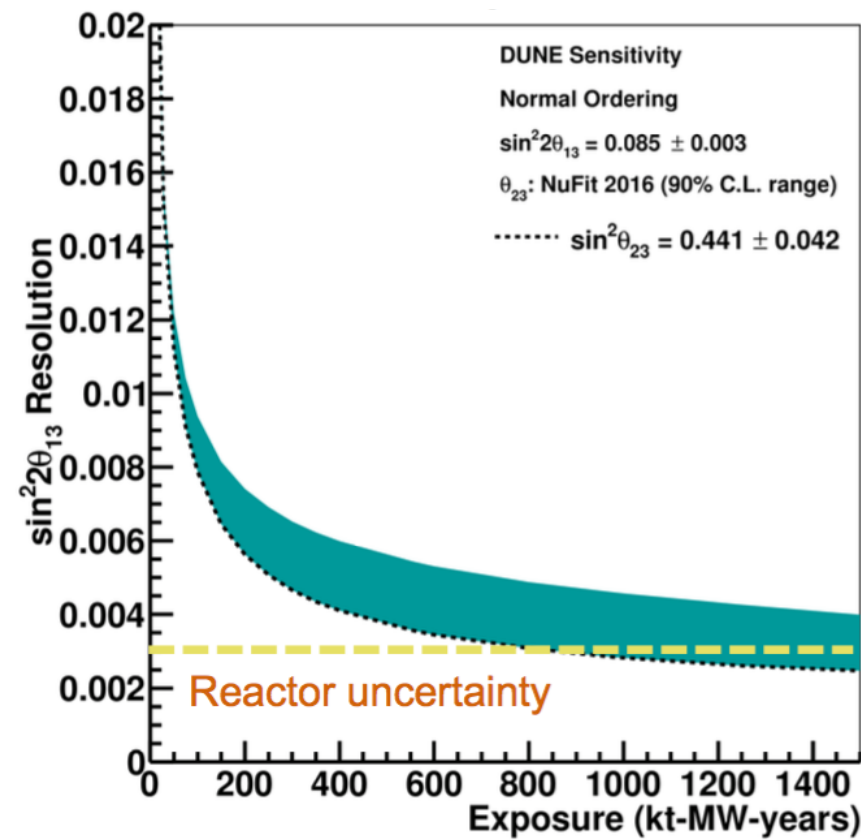
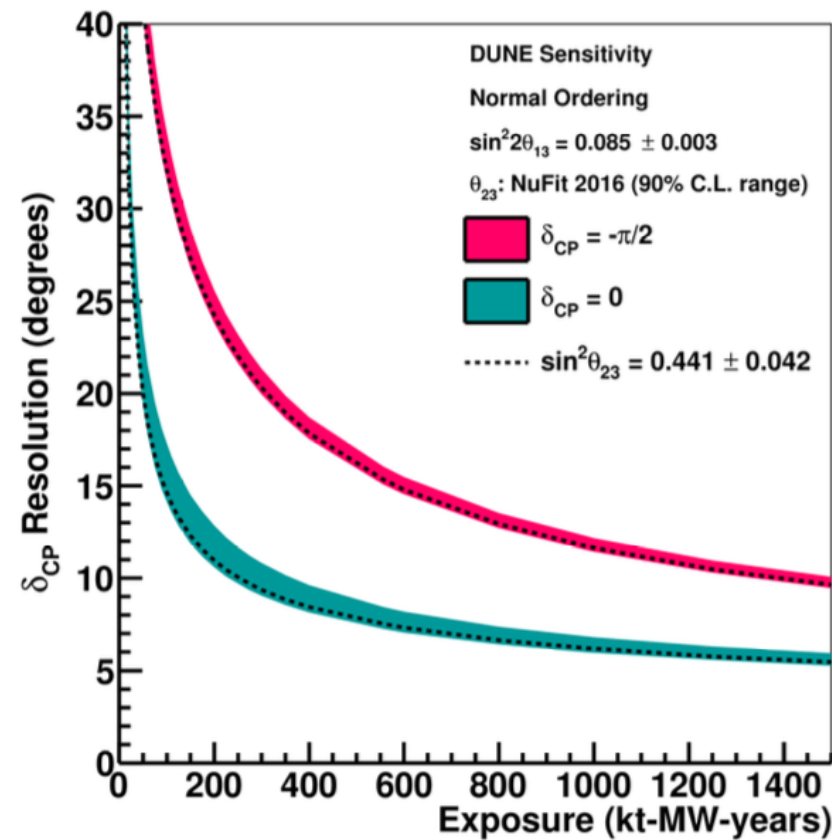
Normal ordering



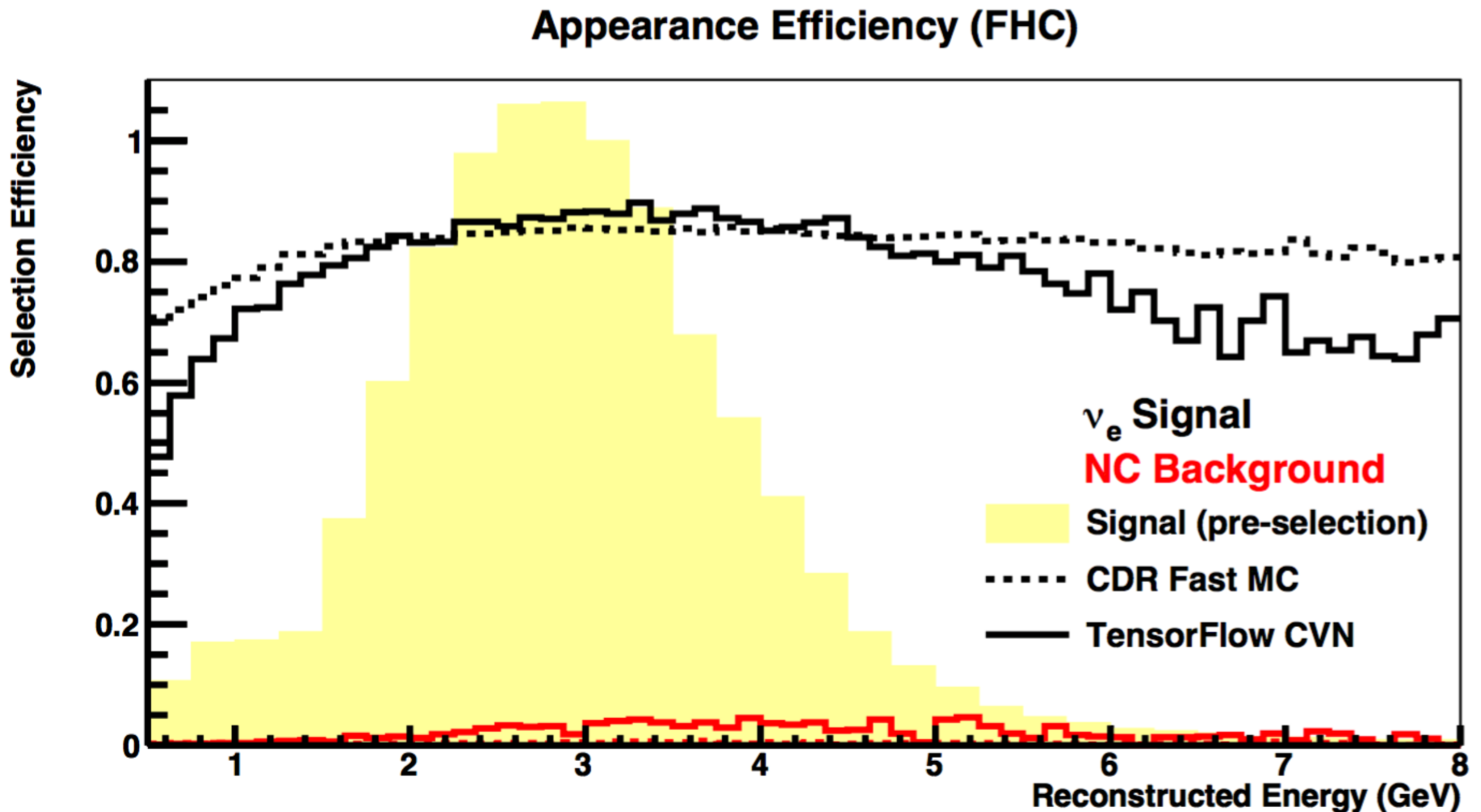
Inverted ordering



Resolution



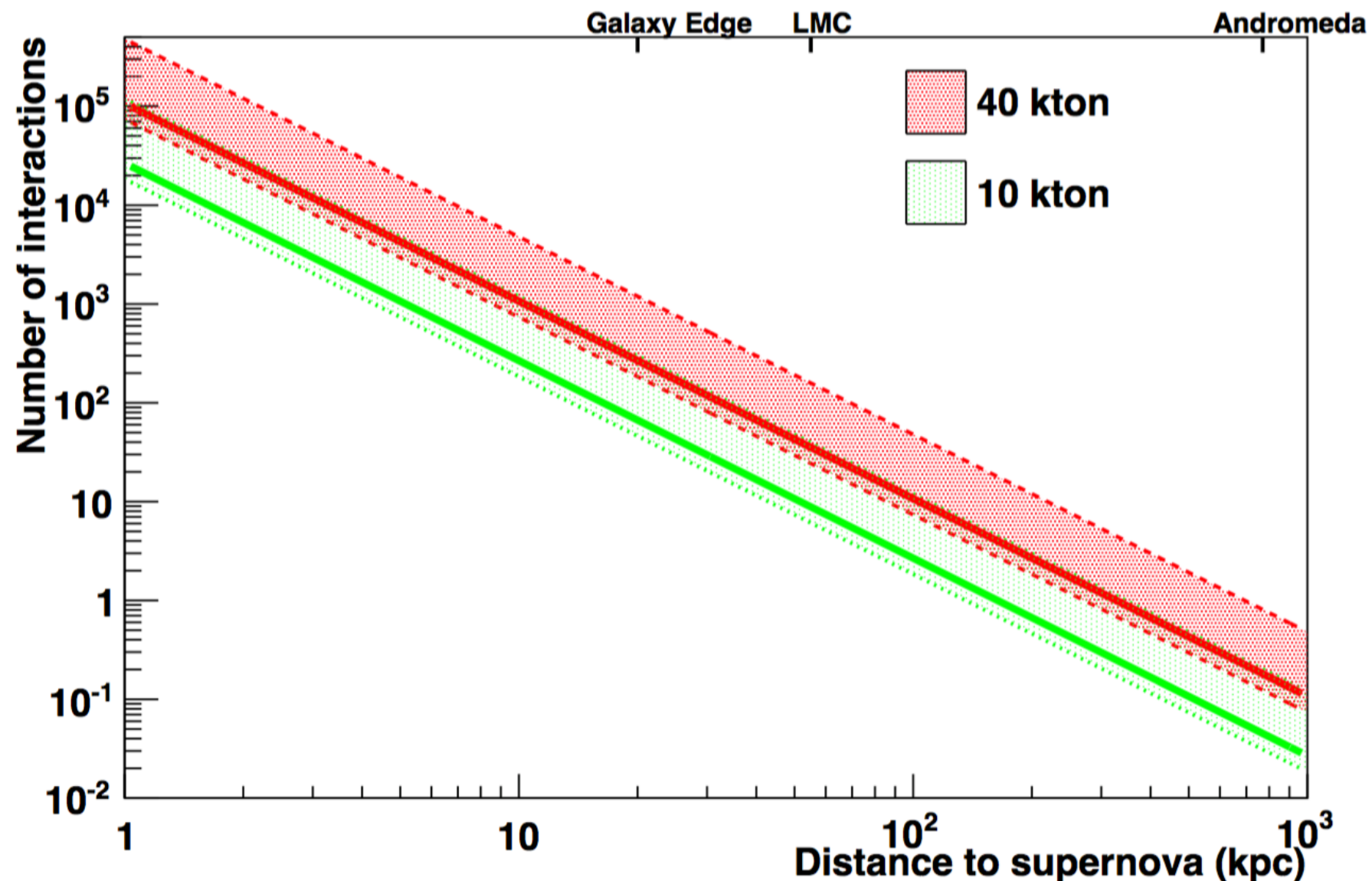
Selection efficiency



CVN ν_e event selection efficiency similar to that from CDR Fast MC

Supernova event rates

- Expected total ν signal from SNOwGLoBES). Solid lines are from Huedepohl (2010), for both 10 kt and the full 40 kt DUNE: systematic bands are from the Garching parameterization (2014) of $\langle E \rangle = 12$ MeV and $\langle E \rangle = 2$ (top) and $\langle E \rangle = 8$ MeV and $\langle E \rangle = 6$ (bottom).



SNB event rates

Table 5.1: Event rates for different supernova models in 40 kt of liquid argon for a core collapse at 10 kpc, for ν_e and $\bar{\nu}_e$ charged-current channels and elastic scattering (ES) on electrons. Event rates will simply scale by active detector mass and inverse square of supernova distance. The “Livermore” model assumes no oscillations; “GKVM” assumes collective oscillation effects. Oscillations (both standard and “collective”) will potentially have a large, model-dependent effect.

Channel	Events	Events
	“Livermore” model	“GKVM” model
$\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$	2720	3350
$\bar{\nu}_e + {}^{40}\text{Ar} \rightarrow e^+ + {}^{40}\text{Cl}^*$	230	160
$\nu_x + e^- \rightarrow \nu_x + e^-$	350	260
Total	3300	3770

Total Uncertainties Assigned to the Normalization Parameters

Based on the preceding considerations, the DUNE signal normalization uncertainty is taken to be $5\% \oplus 2\%$ in both neutrino and antineutrino mode, where 5% is the normalization uncertainty on the FD ν_μ sample and 2% is the effective uncorrelated uncertainty on the FD ν_e sample after fits to both near and far detector data and all external constraints. These signal normalization parameters are treated as 100% uncorrelated between neutrinos and antineutrinos. The normalization uncertainties on background to these samples and their respective correlations are given in Table 3.9. These assumptions for the non-oscillation systematic uncertainties are used to calculate the sensitivities presented in Section 3.2. The goal for the *total* uncertainty on the ν_e sample in DUNE is less than 4%, so the $5\% \oplus 2\%$ signal normalization uncertainty used for sensitivity calculations is appropriately conservative. Additionally, cancellation of the correlated portion of the uncertainty is expected in the four-sample fit, so the residual uncorrelated normalization uncertainty on the ν_e sample is expected to be reduced to the 1–2% level, such that the 2% residual normalization uncertainty used in the sensitivity calculations is also well-justified. Variations on these assumptions are explored in Section 3.6.3.

Table 3.9: Normalization uncertainties and correlations for background to the ν_e , $\bar{\nu}_e$, ν_μ , and $\bar{\nu}_\mu$ data samples

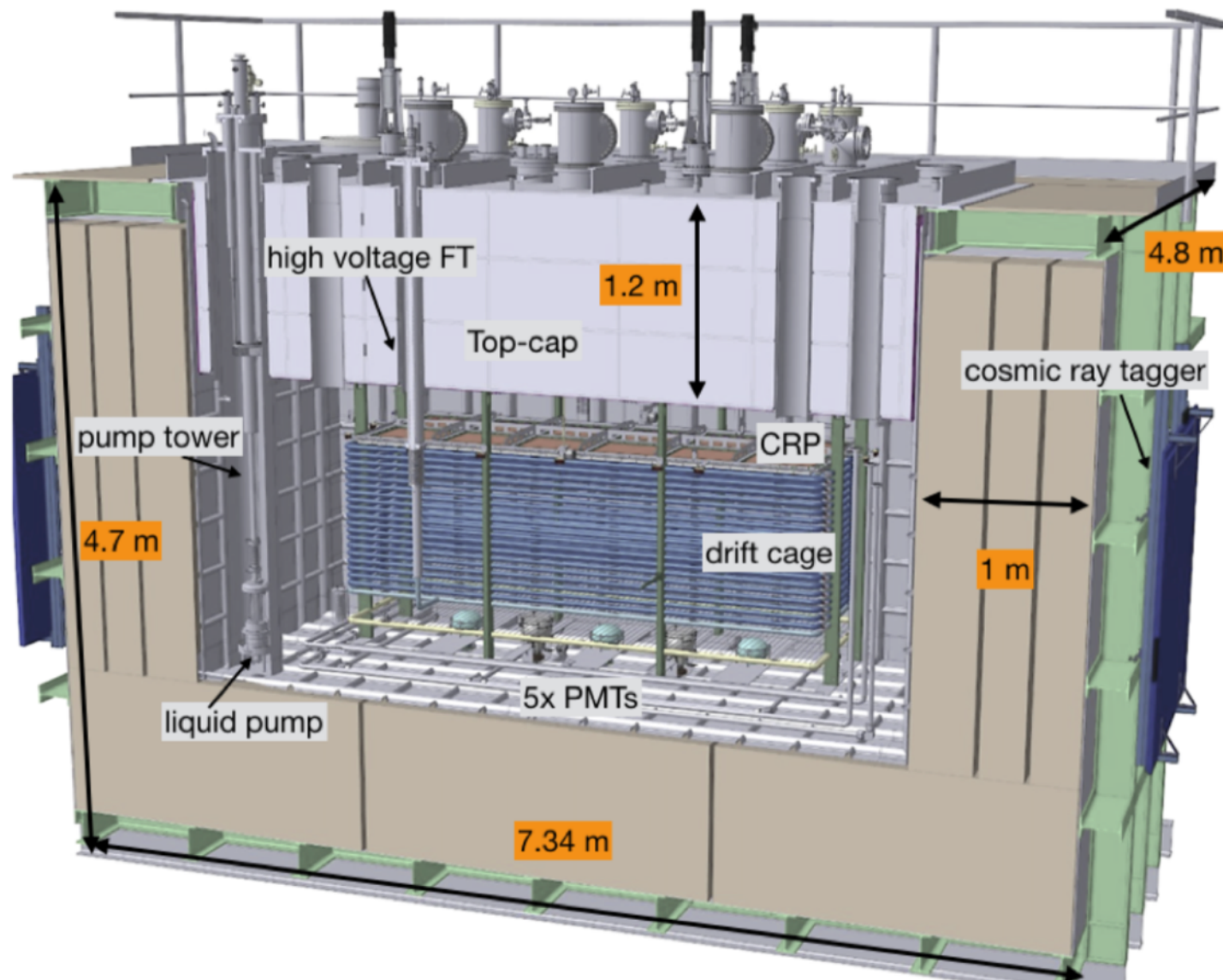
Background	Normalization Uncertainty	Correlations
For $\nu_e/\bar{\nu}_e$ appearance:		
Beam ν_e	5%	Uncorrelated in ν_e and $\bar{\nu}_e$ samples
NC	5%	Correlated in ν_e and $\bar{\nu}_e$ samples
ν_μ CC	5%	Correlated to NC
ν_τ CC	20%	Correlated in ν_e and $\bar{\nu}_e$ samples
For $\nu_\mu/\bar{\nu}_\mu$ disappearance:		
NC	5%	Uncorrelated to $\nu_e/\bar{\nu}_e$ NC background
ν_τ	20%	Correlated to $\nu_e/\bar{\nu}_e$ ν_τ background

Systematics

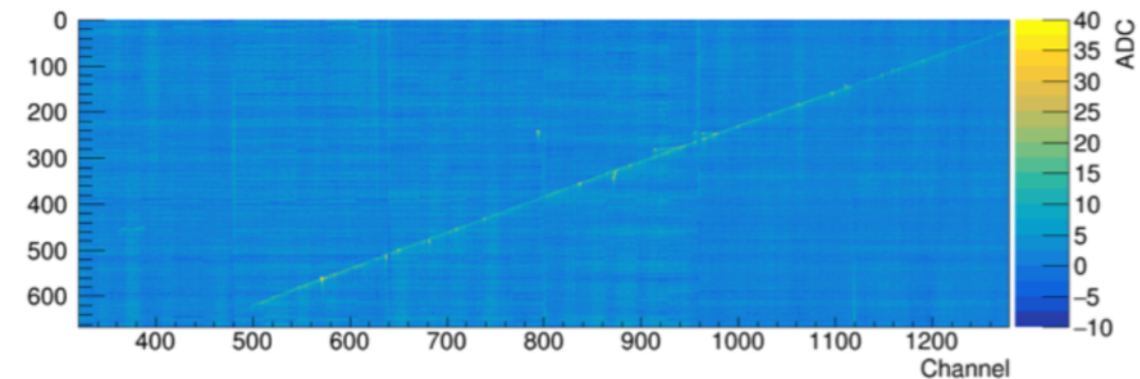
Source of Uncertainty	MINOS ν_e	T2K ν_e	DUNE ν_e	Comments
Beam Flux after N/F extrapolation	0.3%	3.2%	2%	See “Flux Uncertainties” in Section 3.6.2
Interaction Model	2.7%	5.3%	$\sim 2\%$	See “Interaction Model Uncertainties” in Section 3.6.2
Energy scale (ν_μ)	3.5%	included above	(2%)	Included in 5% ν_μ sample normalization uncertainty in DUNE 3-flavor fit.
Energy scale (ν_e)	2.7%	2.5% includes all FD effects	2%	See “ ν_e Energy-Scale Uncertainties” in Section 3.6.2
Fiducial volume	2.4%	1%	1%	Larger detectors = smaller uncertainty.
Total	5.7%	6.8%	3.6 %	
Used in DUNE Sensitivity Calculations			$5\% \oplus 2\%$ $\nu_\mu \quad \nu_e$	Residual ν_e uncertainty: 2%

3x1x1 prototype (WA105)

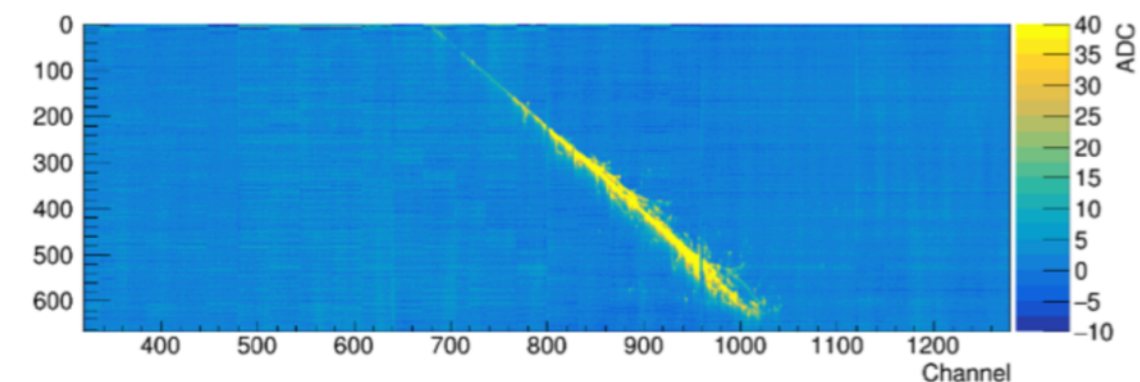
- Successful demonstration of Dual-Phase technology
- Operated at CERN between June and November 2017



Thru-going muon:



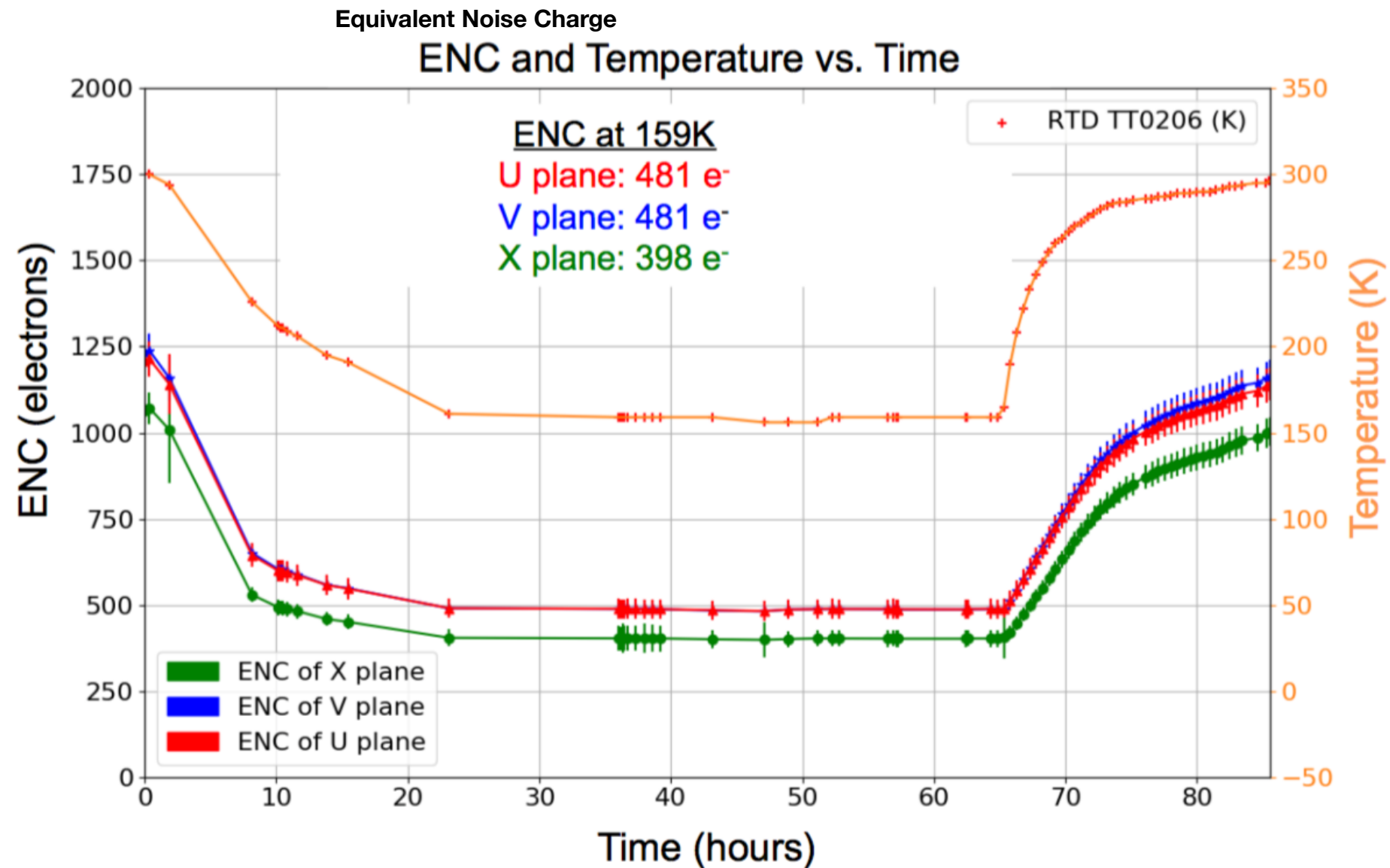
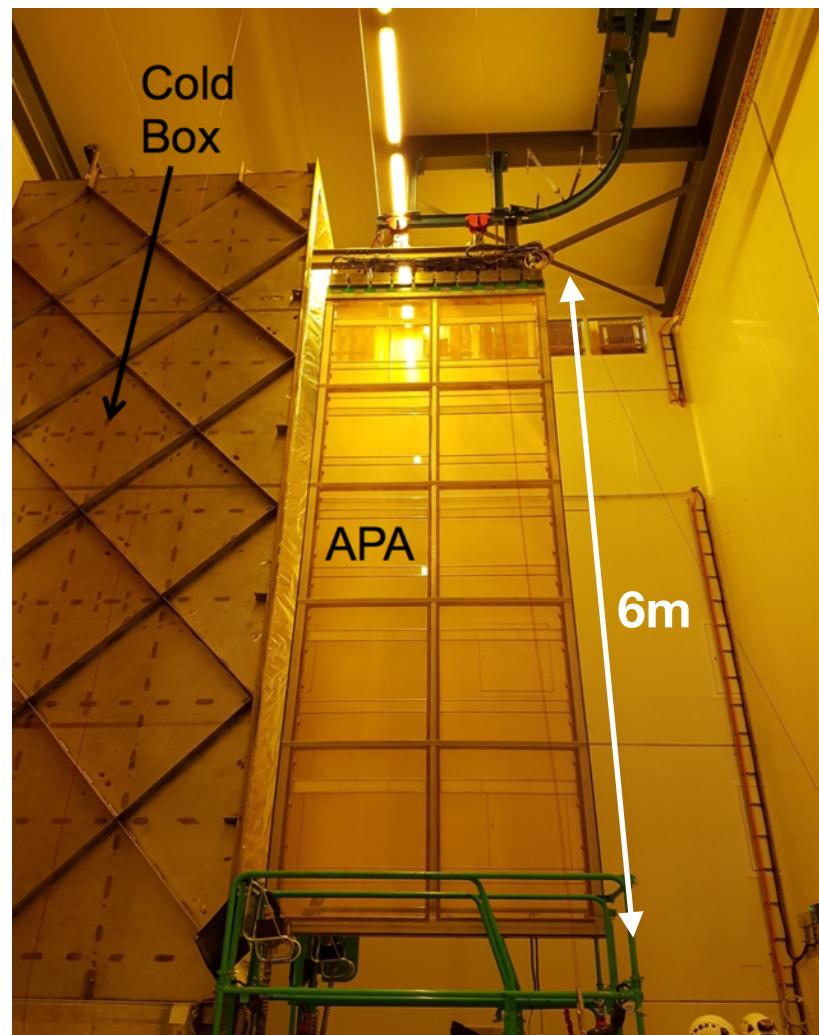
EM Shower:



ProtoDUNE cold box results

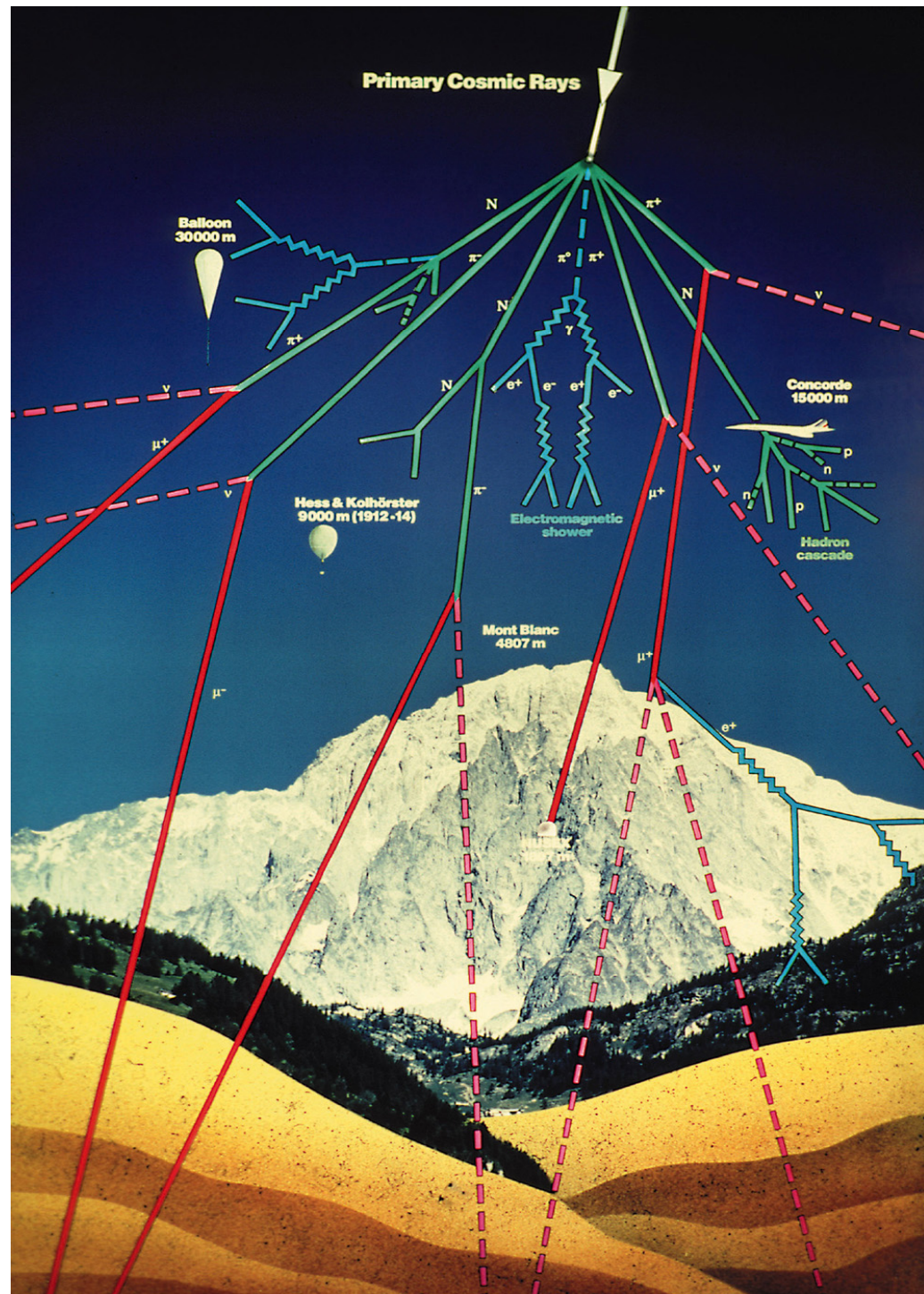
- Promising results of APA wire noise in cold box

Anode Plane Assembly

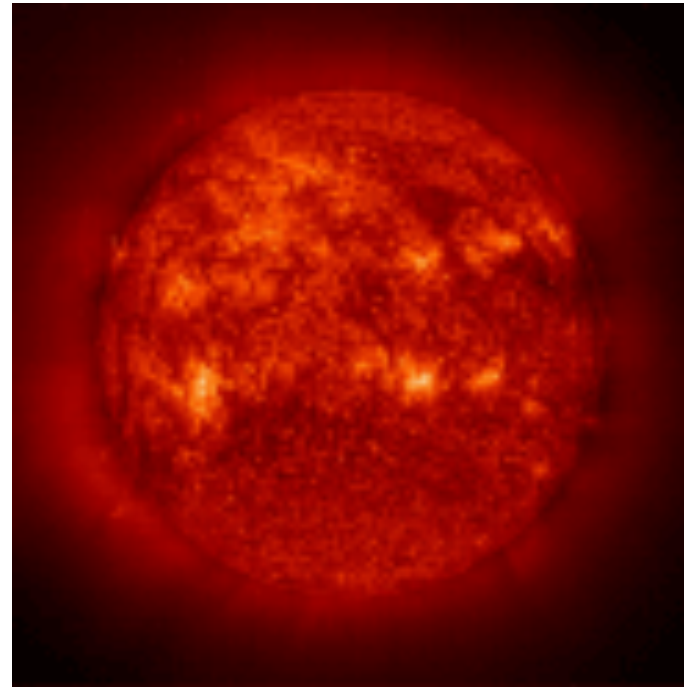


Neutrino sources

Atmosphere



Sun



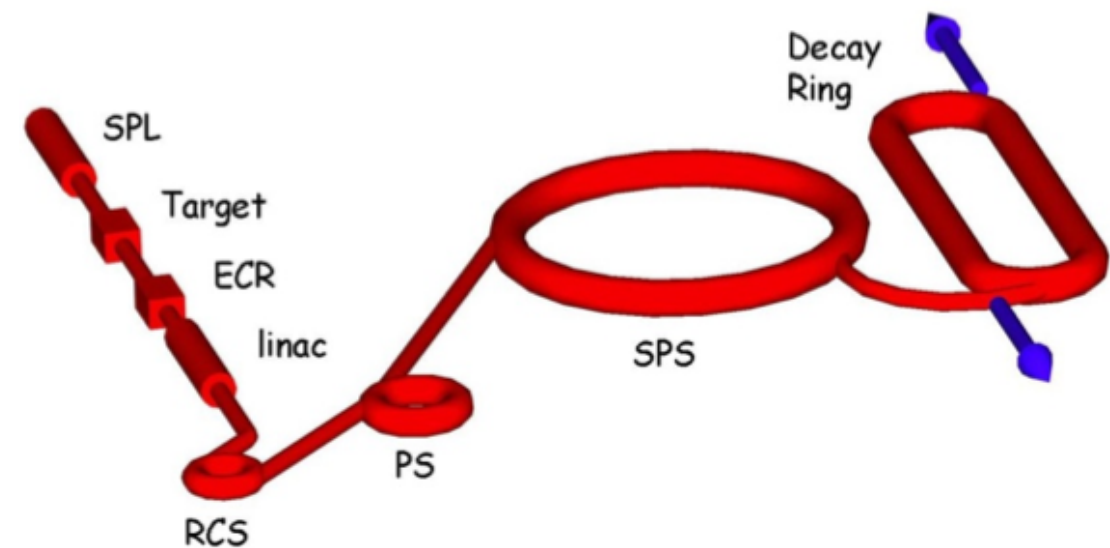
Supernovae



Reactors



Accelerators



DUNE/LBNF Staging Assumption

Year 1 (2026): 20-kt FD with 1.07 MW (80-GeV) beam and initial ND constraints

Year 2 (2027): 30-kt FD

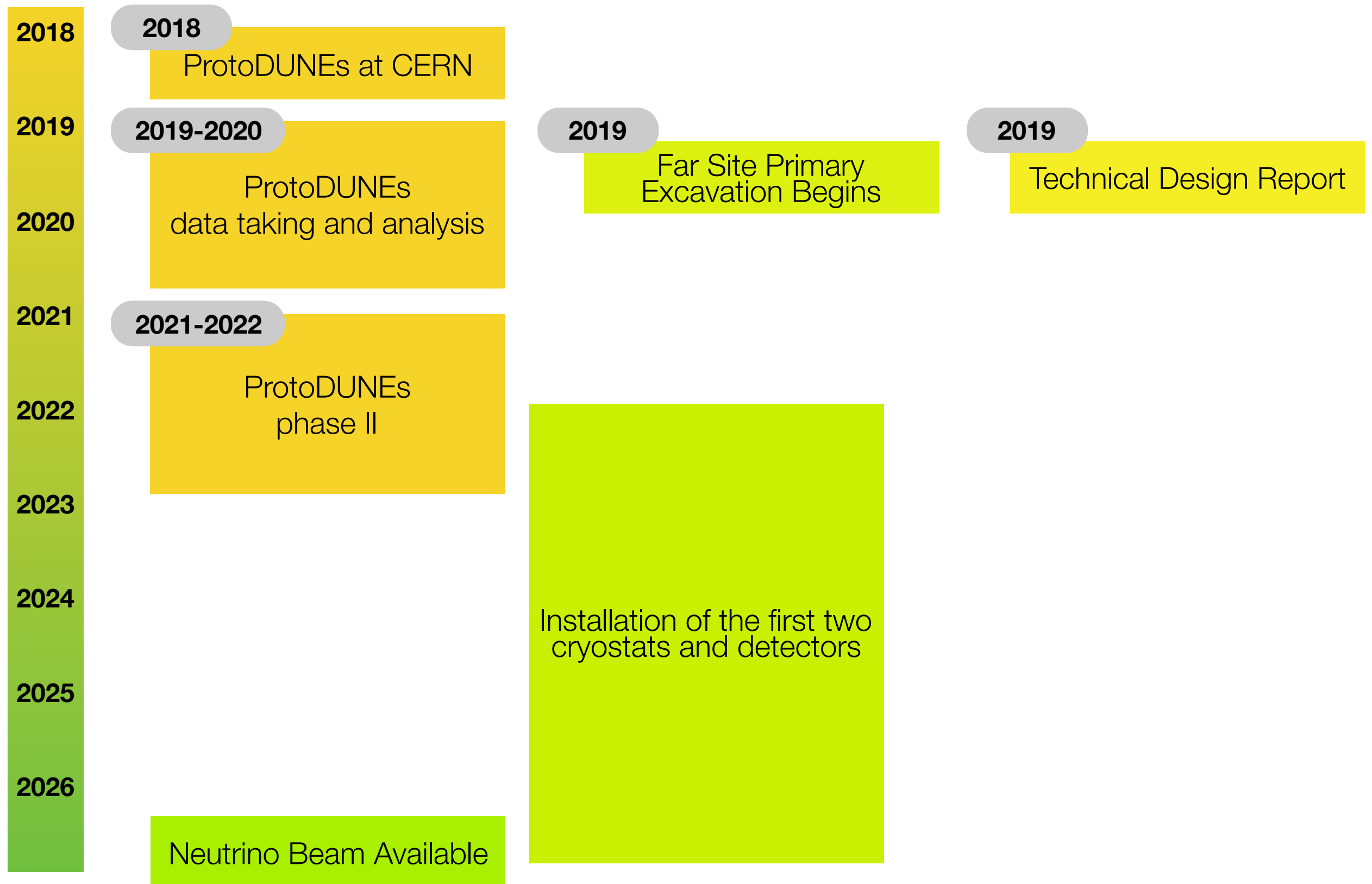
Year 4 (2029): 40-kt FD and improved ND constraints

Year 7 (2032): upgrade to 2.14 MW (80-GeV) beam

Exposure Years	Number of FD modules	Total FD target mass (kt)	LBNF beam power (MW)	Exposure (kt MW yr)
1	2	20	1.07	21
2	3	30	1.07	54
4	4	40	1.07	128
7	4	40	2.14	300
10	4	40	2.14	556

Staging scenario assumes equal ν and $\bar{\nu}$ running time

DUNE timeline



DUNE timeline

