DUNE Status Report

Mark Thomson
on behalf of the DUNE Collaboration

Fermilab PAC Meeting
June 23, 2015

1: The DUNE Collaboration

Introduction: DUNE and P5

Paraphrasing P5

- **Called for the formation of LBNF:**
  - as a international collaboration bringing together the LBL community
  - ambitious scientific goals with discovery potential for:
    - Leptonic CP violation
    - Proton decay
    - Supernova burst neutrinos

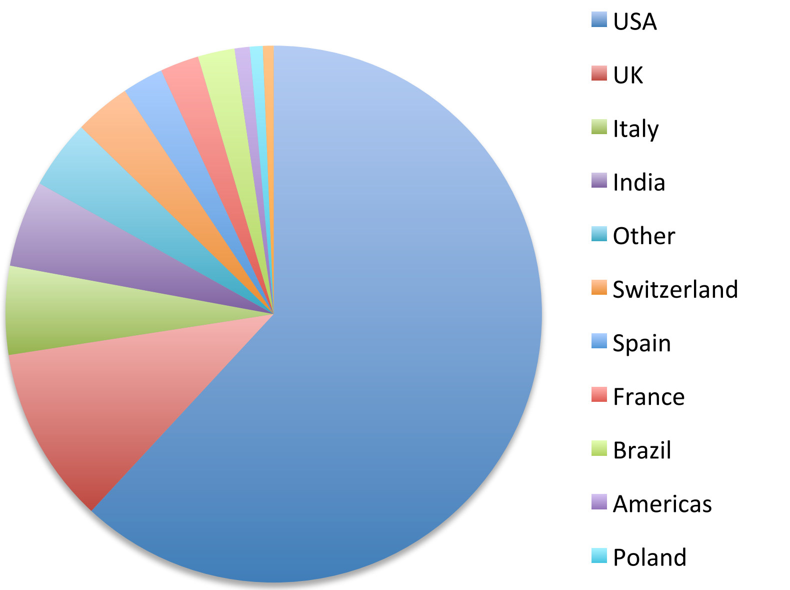
Resulted in the formation of the DUNE collaboration with strong representation from:

- LBNE
- LBNO
- Other interested institutes

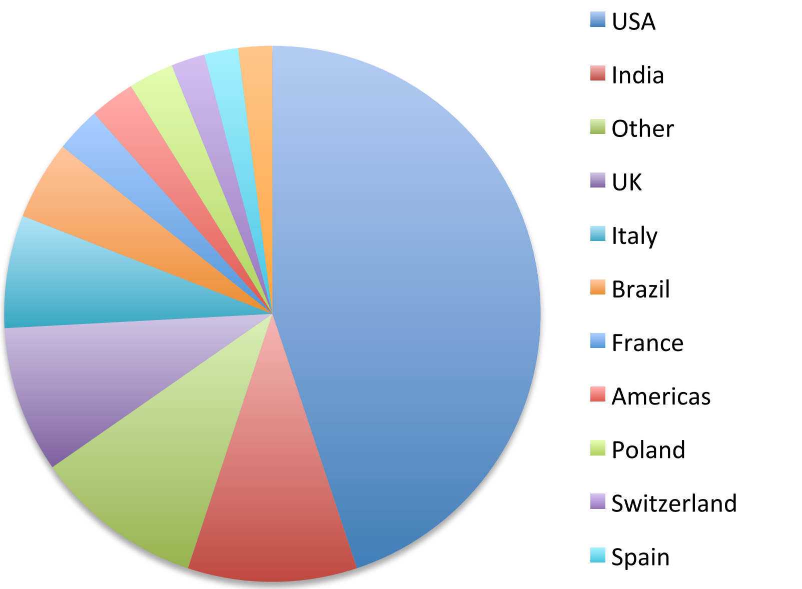
The DUNE Collaboration

As of today: from

776 Collaborators



144 Institutes



The DUNE Collaboration

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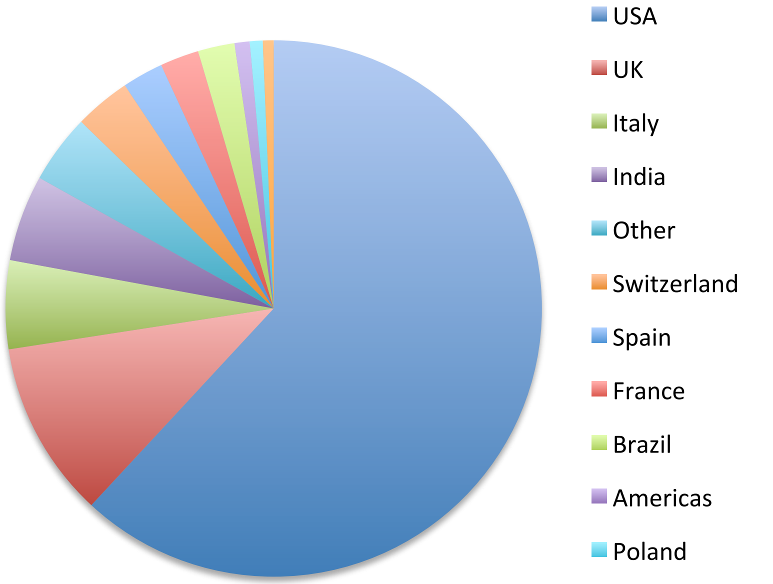


from

26 Nations

Armenia, Belgium, Brazil, Bulgaria, Canada, Colombia, Czech Republic, France, Germany, India, Iran, Italy, Japan, Madagascar, Mexico, Netherlands, Peru, Poland, Romania, Russia, Spain, Switzerland, Turkey, UK, USA, Ukraine

DUNE already has broad international support

DUNE

is a rapidly evolving scientific collaboration…

- **Collaboration rules adopted in April**
  - Now have full management structure and executive committee
  - Ten task forces were set up to prepare draft CD-1-R documents
  - Review of documents involving >75 members of the collaboration
- **First formal collaboration meeting April 16th-18th 2015**
  - Over 200 people attended in person

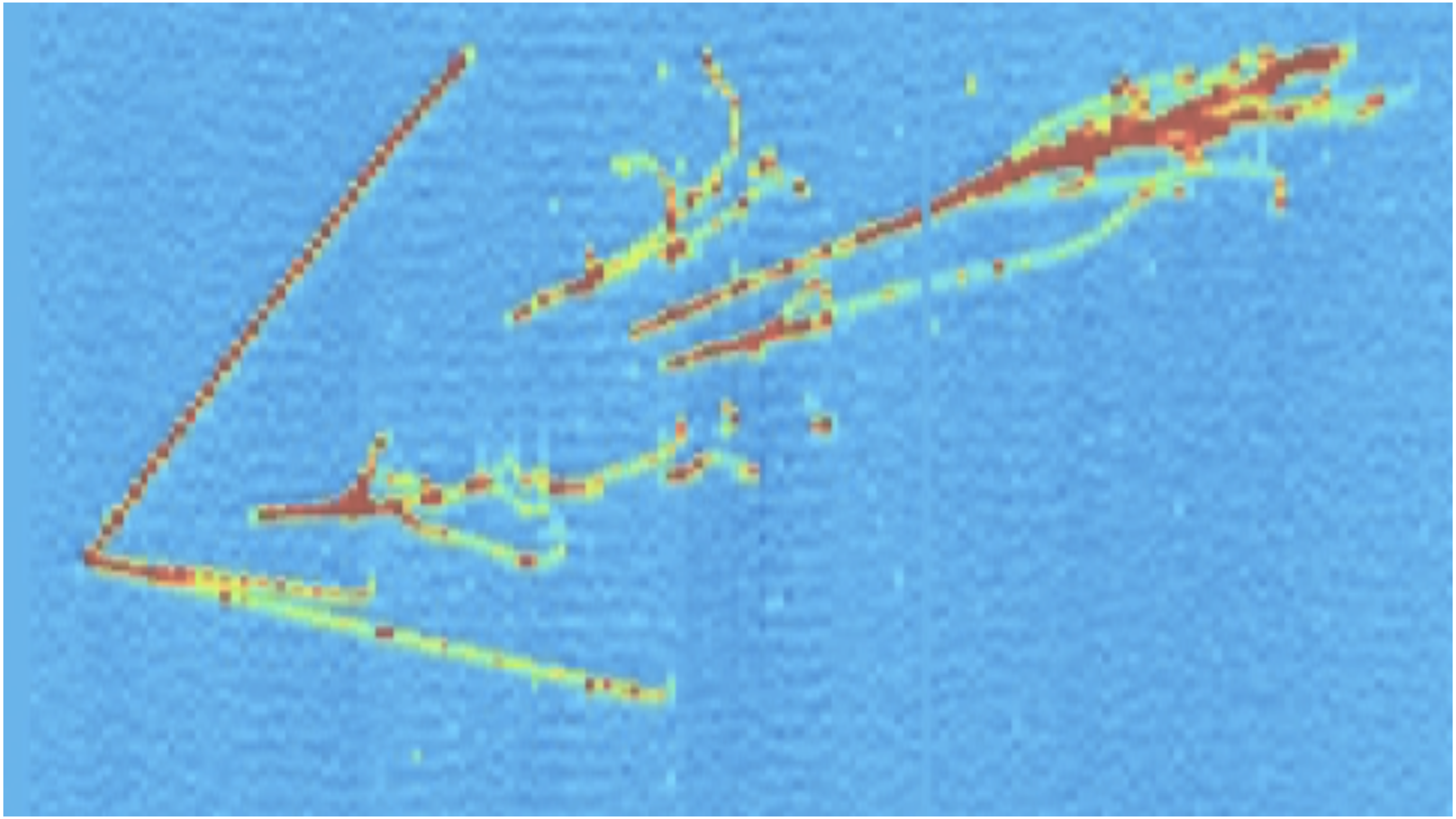
DUNE Progress

- **A lot has happened in a compressed timescale…**
  - 11 March DUNE Co-spokespersons elected ✔
  - 18 March DUNE technical coordinator named ✔
  - 24 March Task Force conveners named – charged to prepare CDR ✔
  - 31 March CD-1 Document Scope Defined ✔
  - 15 April Zeroth-order Draft of CD-1-R Documents ✔
  - 16-18 April First DUNE Collaboration Meeting ✔
  - 18 April Institute Board Rules approved ✔
  - 19 April First full LBNC Meeting ✔
  - 25 April Deadline for first CDR draft ✔
  - 4 May First DUNE Executive Committee meeting ✔
  - 15 May Scientific Priorities agreed by collaboration ✔
  - 19 May CD-1-R documents posted for Director's Review ✔
  - 2-3 June Director's Review ✔
  - ~23 June CD-1-R documents posted for CD-1-R Review
  - 14-16 July DOE CD-1-R Review

DUNE CDR

- **The DOE CD-1-Refresh review is a major milestone for DUNE**
- **It has been the main focus of the first months of the new collaboration**
  - Fortunately building on strength: LBNE, LBNO, …
- **CDR Volumes 1 – 4**
  - Volume 1 : "The LBNF and DUNE Projects"
    - Overview, strategy, organization
  - Volume 2 : "DUNE Physics"
  - Volume 3 : "The Long Baseline Neutrino Facility for DUNE"
  - Volume 4 : "The DUNE Detectors at LBNF"
- **This has been a major effort from the DUNE collaboration and everyone on LBNF**
- **The CDR is essentially "done": now actively working on the next steps** (will come back to this)

2: DUNE Science Strategy



A neutrino interaction in the ArgoNEUT detector at Fermilab

Scientific Objectives

The LBNF/DUNE scientific objectives are categorized as

- the *primary science program*, addressing the key science questions highlighted by P5
- The high-priority *ancillary science program* that is enabled by the construction of LBNF and the DUNE;
- and *additional scientific objectives*

The primary science program defines the high-level requirements for LBNF and DUNE

- The ancillary program provides further goals for the design of the near detector, required for the full scientific exploitation of LBNF/DUNE

DUNE Primary Science Program

Focus on fundamental open questions in particle physics and astro-particle physics:

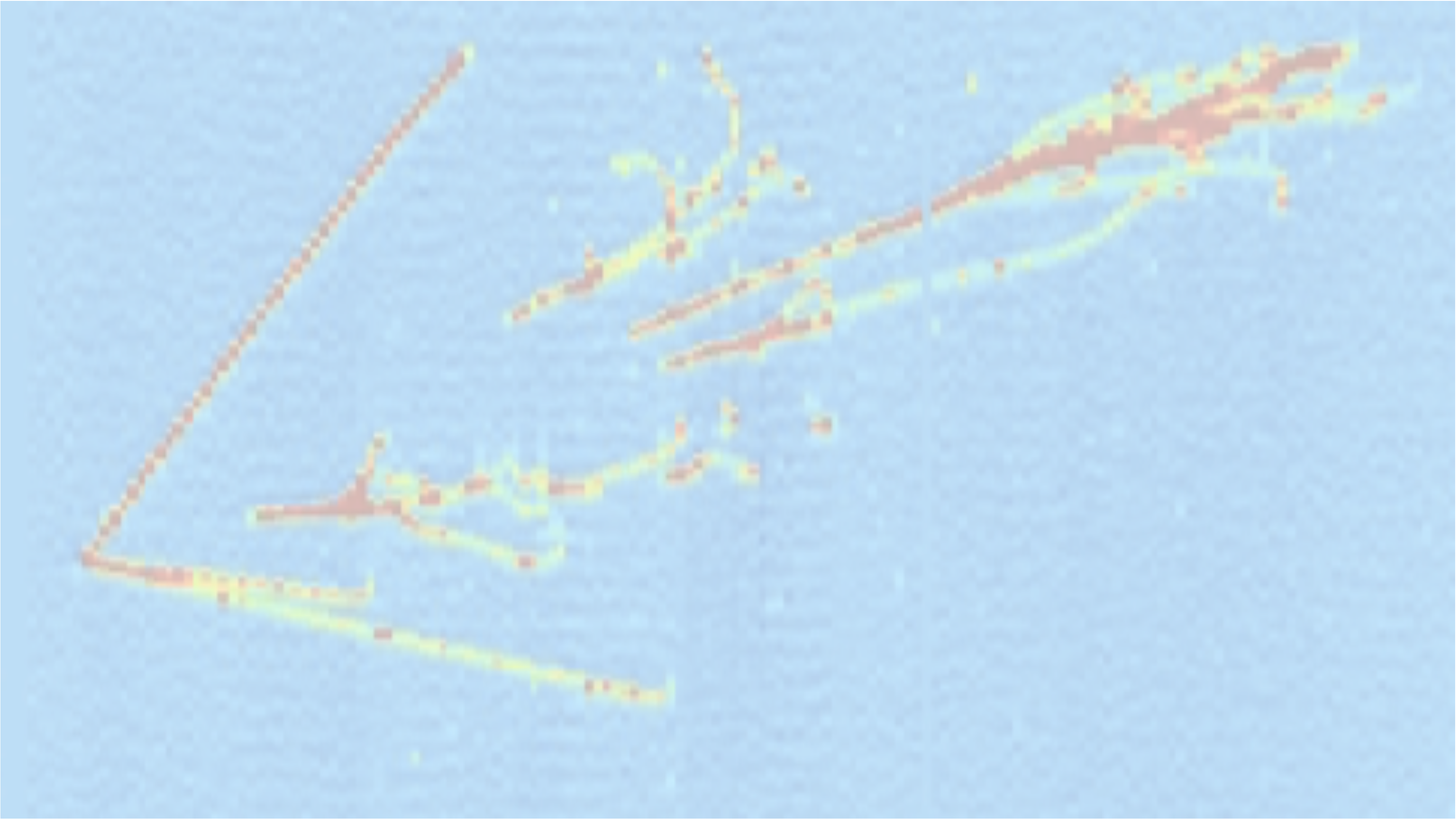
- **1) Neutrino Oscillation Physics**
  - CPV in the leptonic sector
  - Mass Hierarchy
  - Precision Oscillation Physics (θ_{23} octant, …) & testing the 3-flavor paradigm
- **2) Nucleon Decay**
  - Targeting SUSY-favored modes, e.g. $p \rightarrow K^{+}\overline{\nu}$
- **3) Supernova burst physics & astrophysics**
  - Galactic core collapse supernova, sensitivity to ν_e

DUNE Ancillary Science Program

Enabled by the intense LBNF beam and the DUNE near and far detectors

- **Other LBL oscillation physics with BSM sensitivity**
  - Neutrino non-standard interactions (NSIs)
  - Sterile Neutrinos at the near and far sites
  - Measurements of tau neutrino appearance
- **Oscillation physics with atmospheric neutrinos**
- **Neutrino Physics in the near detector**
  - Neutrino cross section measurements
  - Studies of nuclear effects, FSI etc.
  - Measurements of the structure of nucleons
  - Neutrino-based measurements of $\sin^2\theta_W$
- **Search for signatures of Dark Matter**

3. Primary Science Strategy



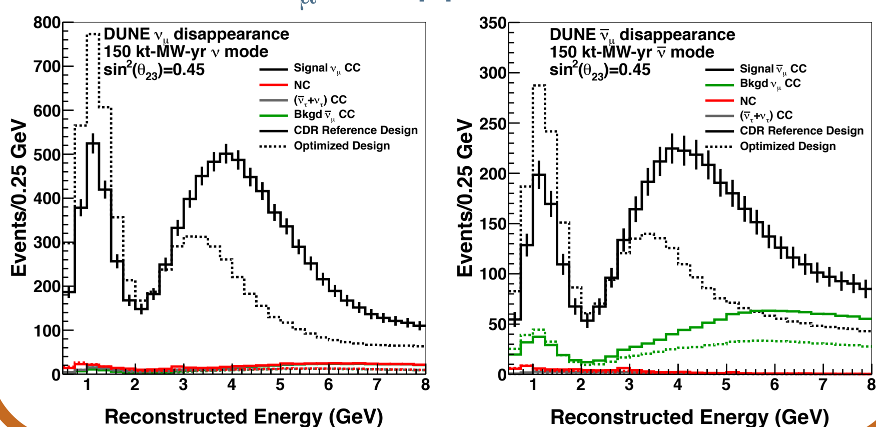
LBL Oscillation Strategy

Measure neutrino spectra at 1300 km in a wide-band beam

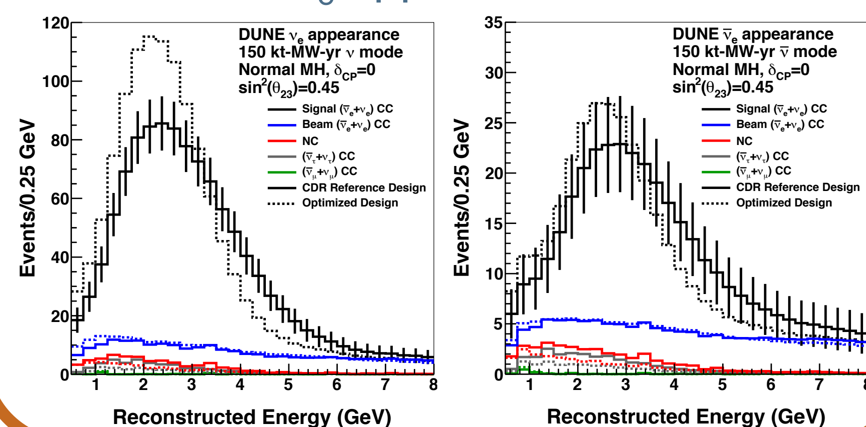
- **Determine MH and θ_{23} octant, probe CPV, test 3-flavor paradigm and search for ν NSI in a single experiment**
  - Long baseline:
    - Matter effects are large ~ 40%
  - Wide-band beam:
    - Measure ν_e appearance and ν_μ disappearance over range of energies
    - MH & CPV effects are separable

E ~ few GeV

ν_μ disappearance



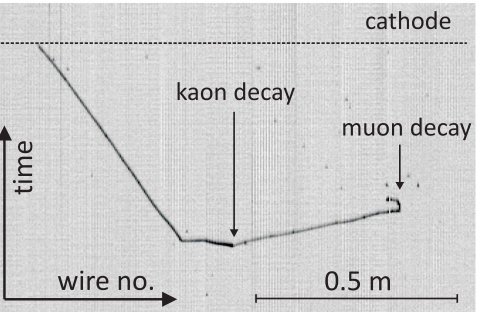
ν_e appearance



PDK & SNB

Nucleon decay

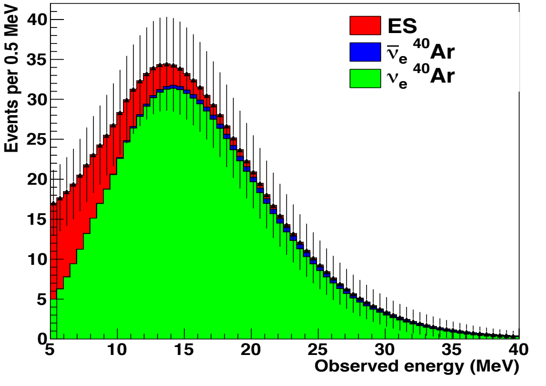
- **Image particles from nucleon decay**
  - target sensitivity to kaons (from dE/dx) from SUSY-inspired GUT p-decay modes



E ~ O(200 MeV)

SNB neutrinos

- **Trigger on and measure energy of neutrinos from galactic SNB**
  - In argon, the largest sensitivity is to ν_e
  - CC $\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$ interaction



E ~ O(10 MeV)

DUNE Design Choices

Far detector design requirements in a nutshell:

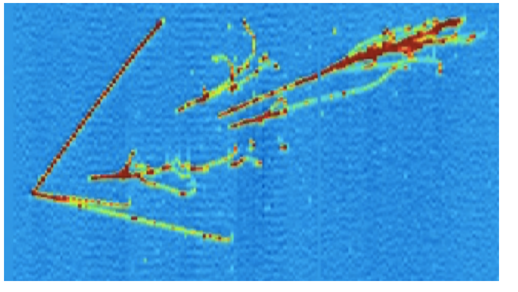
- Pattern recognition
- Energy measurement

} in energy range: few MeV – few GeV

LBNE
LBNO
→ **LAr-TPC**

LAr-TPC Far Detector technology gives:

- Exquisite imaging capability in 3D
  - ~ few mm scale
- Excellent energy measurement capability:
  - totally active calorimeter

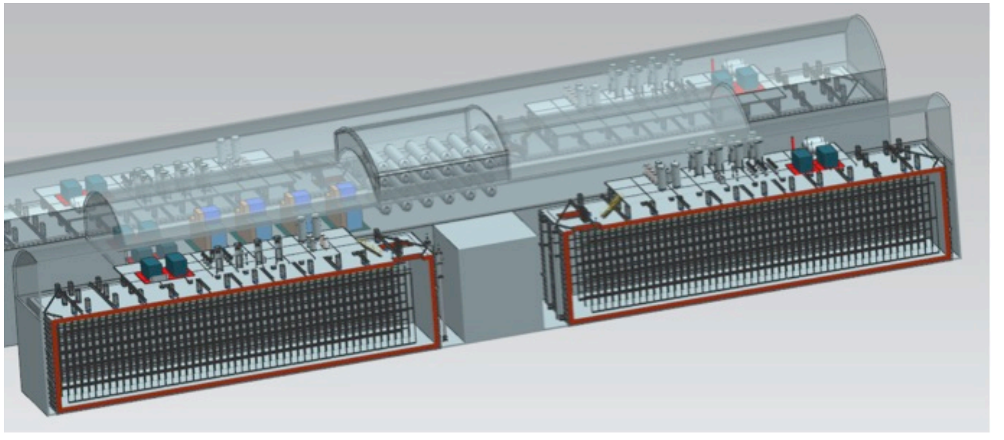


Near detector design requirements in a nutshell:

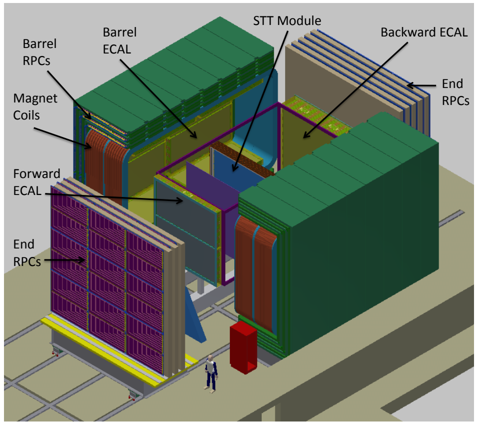
- Constrain systematic uncertainties in LBL oscillation analysis
  - Near detector must be able to constrain ν cross sections & ν flux

DUNE Reference Design =

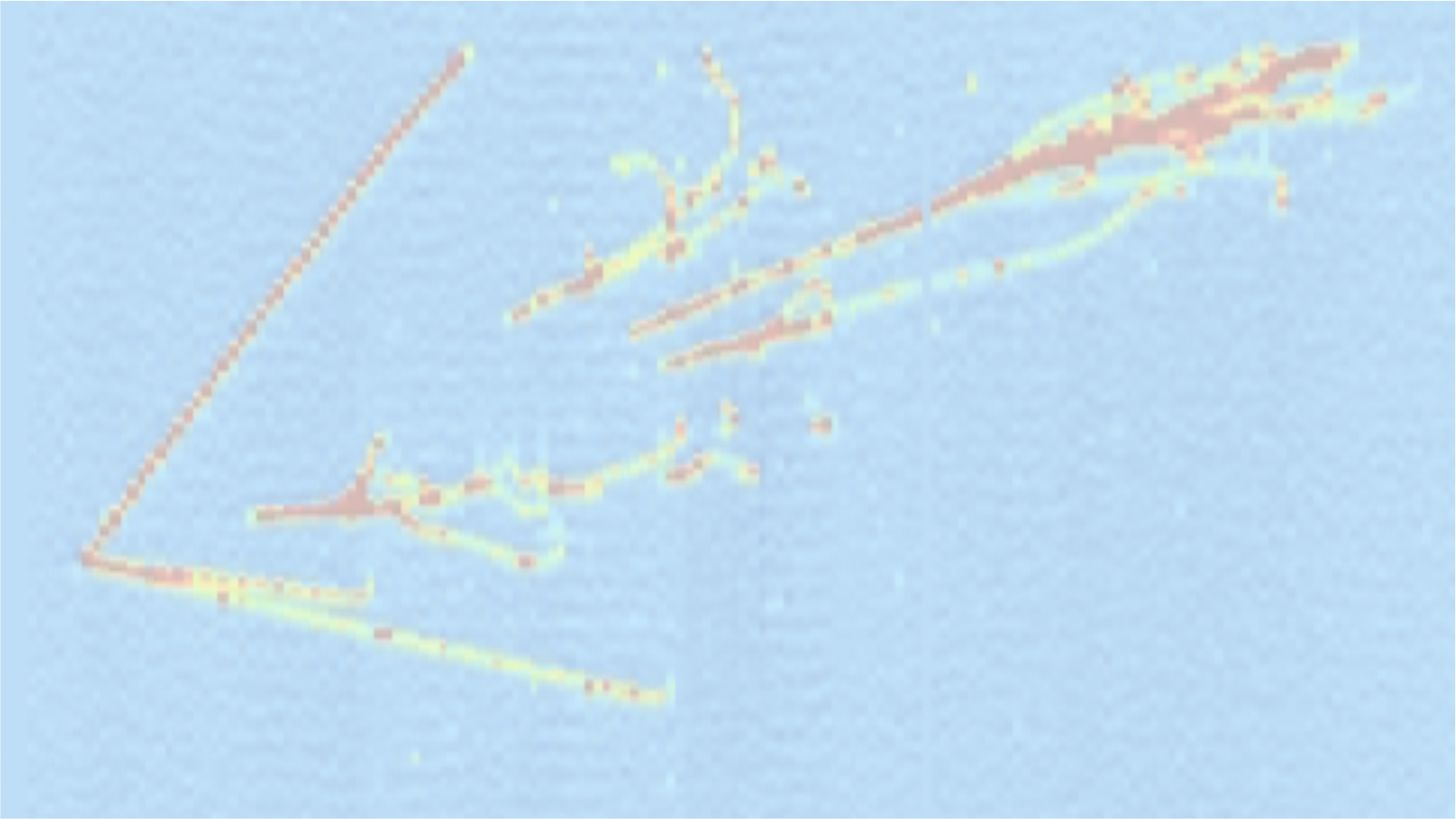
Far detector: 40-kt LArTPC



Near detector: Multi-purpose high-resolution detector



4. DUNE Physics Sensitivities



Determining Physics Sensitivities

For Conceptual Design Report

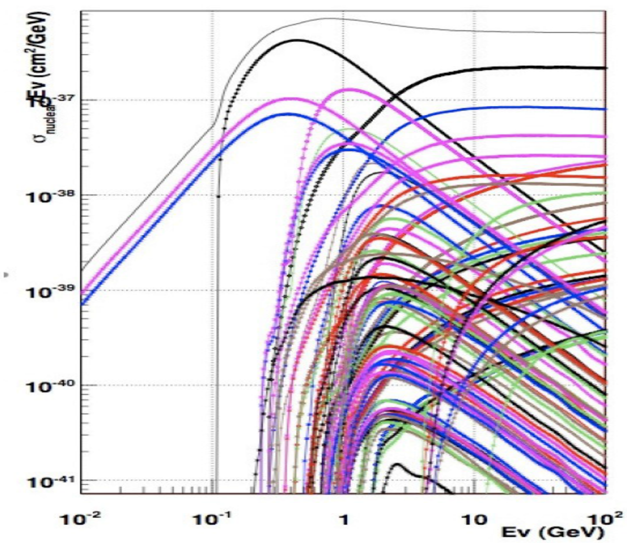
- **Full detector simulation/reconstruction not available**
  - See later in talk for plans
- **For Far Detector response**
  - Use parameterized single-particle response based on achieved/ expected performance (with ICARUS and elsewhere)
- **Systematic constraints from Near Detector + …**
  - Based on current understanding of cross section/hadro-production uncertainties
  - \+ Expected constraints from near detector
    - in part, evaluated using fast Monte Carlo

Evaluating DUNE Sensitivities I

Many inputs calculation (implemented in GLoBeS):

- **Reference Beam Flux**
  - 80 GeV protons
  - 204m x 4m He-filled decay pipe
  - 1.07 MW
  - NuMI-style two horn system
- **Optimized Beam Flux**
  - Horn system optimized for lower energies
- **Expected Detector Performance**
  - Based on previous experience (ICARUS, ArgoNEUT, …)
- **Cross sections**
  - GENIE 2.8.4
  - CC & NC
  - all (anti)neutrino flavors

Exclusive ν-nucleon cross sections



Evaluating DUNE Sensitivities II

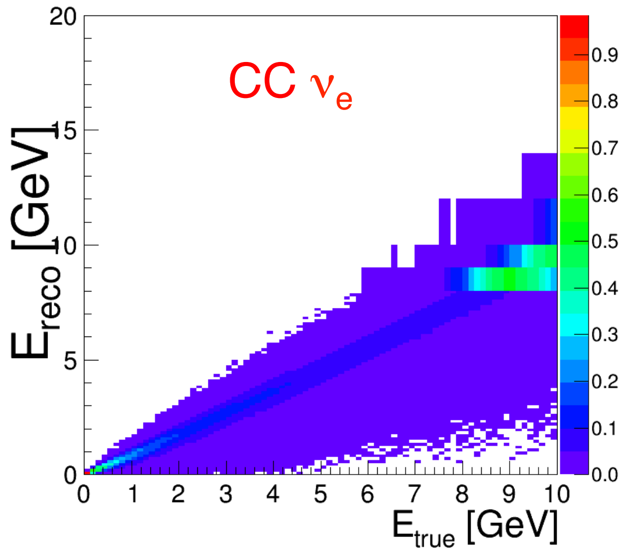
- **Assumed* Particle response/thresholds**
  - Parameterized detector response for individual final-state particles

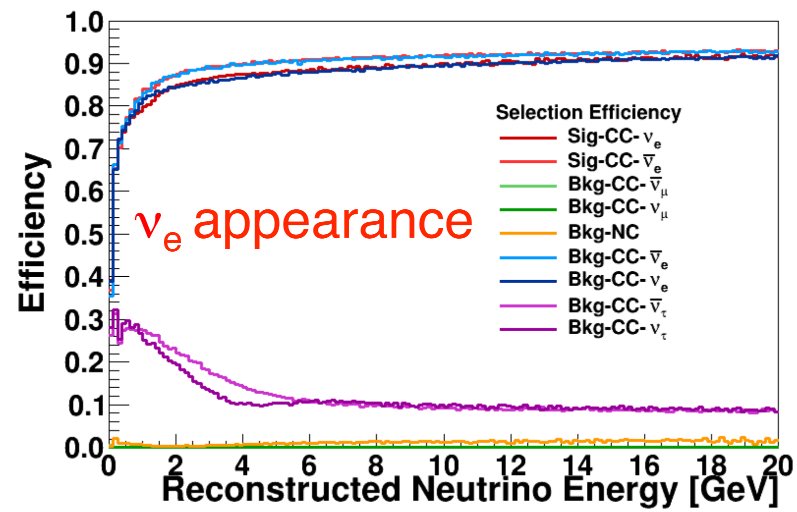
Particle Type	Threshold (KE)	Energy/momentum Resolution	Angular Resolution
$\mu^{\pm}$	30 MeV	Contained: from track length Exiting: 30 %	1^{o}
$\pi^{\pm}$	100 MeV	MIP-like: from track length Contained π-like track: 5% Showering/Exiting: 30 %	1^{o}
$e^{\pm}/\gamma$	30 MeV	$2\% \oplus 15\%/\sqrt{(E/GeV)}$	1^{o}
p	50 MeV	p < 400 MeV: 10 % p > 400 MeV: $5\% \oplus 30\%/\sqrt{(E/GeV)}$	5^{o}
n	50 MeV	$440\%/\sqrt{(E/GeV)}$	5^{o}
other	50 MeV	$5\% \oplus 30\%/\sqrt{(E/GeV)}$	5^{o}

*current assumptions to be addressed by FD Task Force

Evaluating DUNE Sensitivities III

- **Efficiencies & Energy Reconstruction**
  - Generate neutrino interactions using GENIE
  - **Fast MC** smears response at generated final-state particle level
    - "Reconstructed" neutrino energy
    - kNN-based MV technique used for ν_e "event selection", parameterized as efficiencies
  - Used as inputs to GLoBES





Evaluating DUNE Sensitivities IV

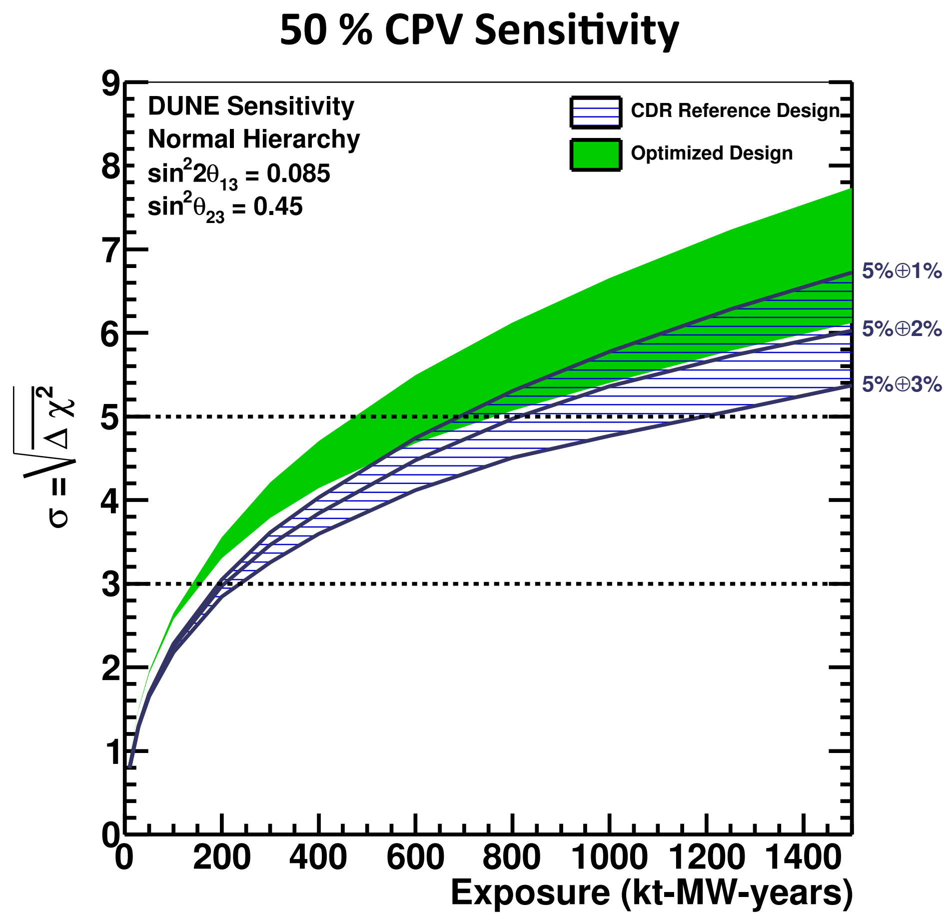
- **Systematic Uncertainties**
  - Anticipated uncertainties based on MINOS/T2K experience
  - Supported by preliminary fast simulation studies of ND

Source	MINOS ν_e	T2K ν_e	DUNE ν_e
Flux after N/F extrapolation	0.3 %	3.2 %	2 %
Interaction Model	2.7 %	5.3 %	~ 2 %
Energy Scale (ν_μ)	3.5 %	Inc. above	(2 %)
Energy Scale (ν_e)	2.7 %	2 %	2 %
Fiducial Volume	2.4 %	1 %	1 %
Total	**5.7 %**	**6.8 %**	**3.6 %**

- **DUNE goal for ν_e appearance < 4 %**
  - For sensitivities used: 5 % $\oplus$ 2 %
    - where 5 % is correlated with ν_μ & 2 % is uncorrelated ν_e only

DUNE Sensitivities

Propagate to Oscillation Sensitivities, e.g.

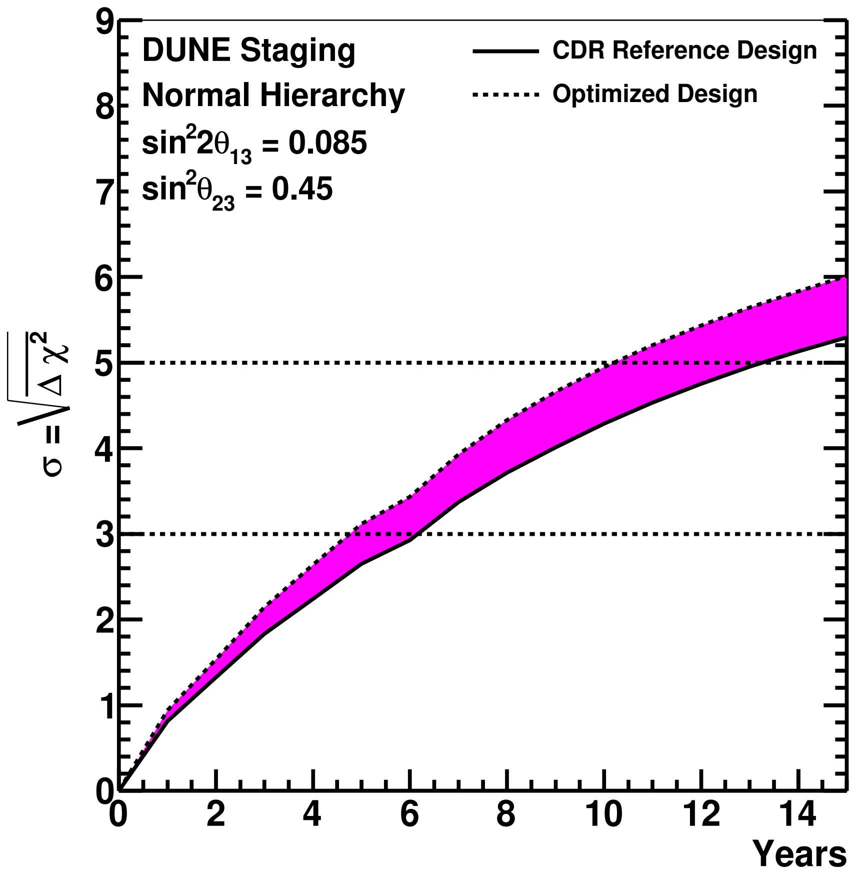


- **Comments**
  - Beam optimization is important
  - For 100–200 kt.MW.years details of systematics are not critical
  - For high exposure, controlling systematics is essential, see 1 – 3 %

DUNE Sensitivities

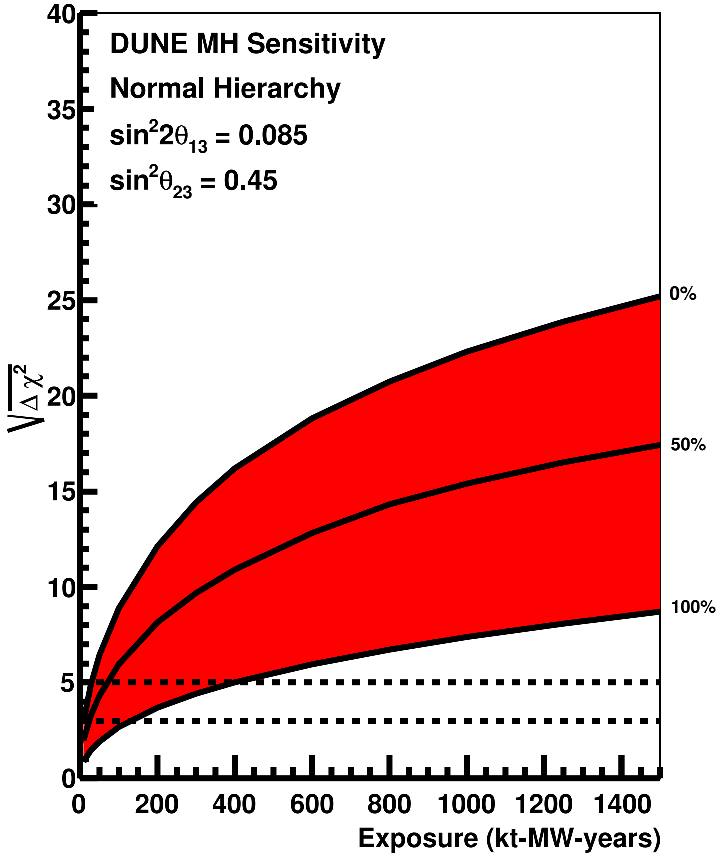
+ add in Resource Loaded Schedule (see Elaine's talk)

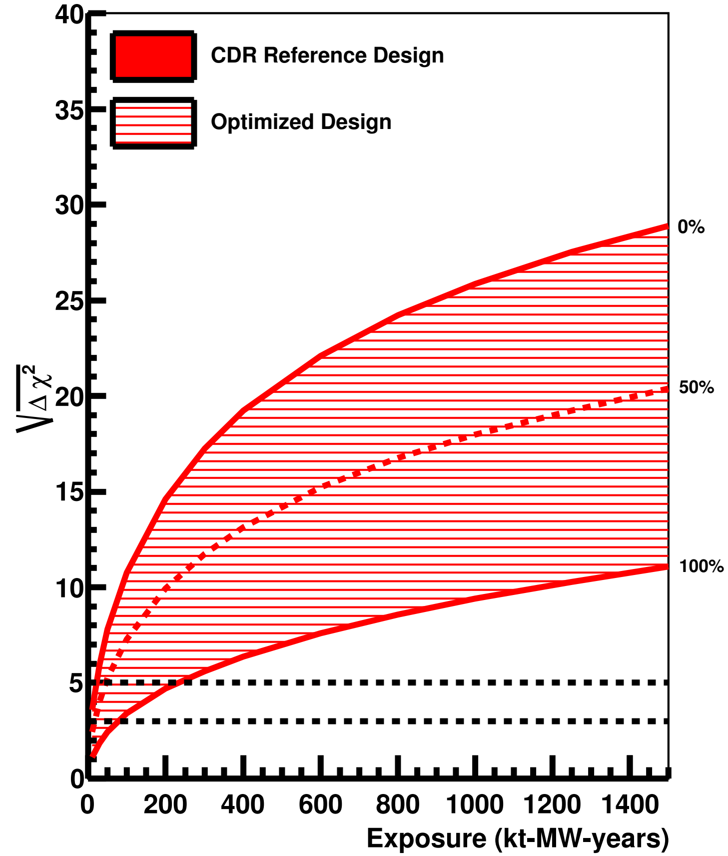
50 % CPV Sensitivity ivity



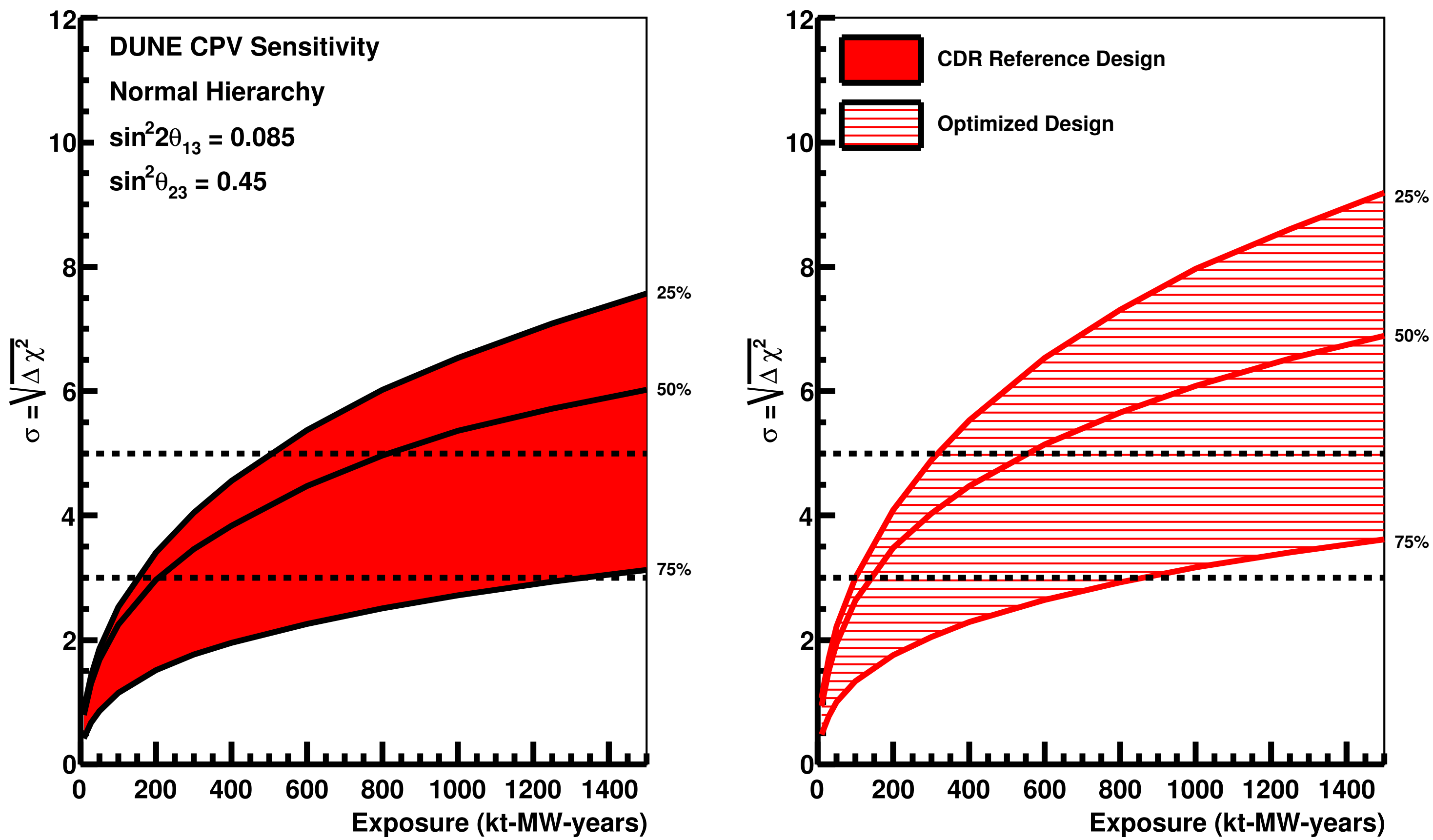
- **Comments**
  - Year zero ~2025
  - P5 "minimum to proceed" of 120 kt.MW.years comfortably met

Mass Hierarchy Sensitivity





CPV Sensitivity



Physics Milestones

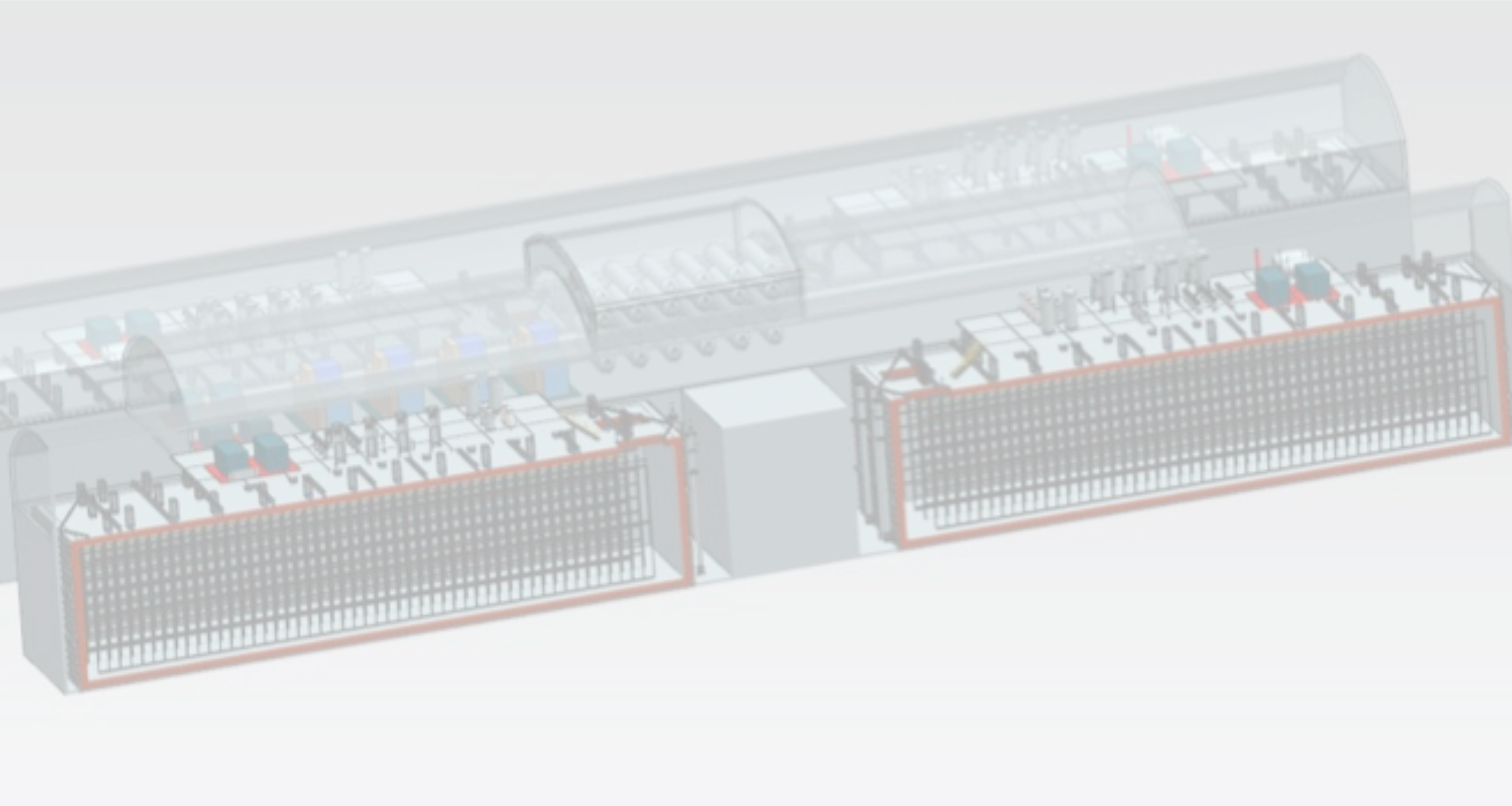
Rapidly reach scientifically interesting sensitivities:

- e.g. in best-case scenario for CPV ($\delta_{CP} = +\pi/2$) :
  - **Reach 3σ CPV sensitivity with 60 – 70 kt.MW.year**
- e.g. in best-case scenario for MH :
  - **Reach 5σ MH sensitivity with 20 – 30 kt.MW.year**

Physics milestone	Exposure kt · MW · year (reference beam)	Exposure kt · MW · year (optimized beam)
1° θ_{23} resolution ($\theta_{23} = 42^\circ$)	70	45
CPV at 3σ ($\delta_{CP} = +\pi/2$)	70	60
CPV at 3σ ($\delta_{CP} = -\pi/2$)	160	100
CPV at 5σ ($\delta_{CP} = +\pi/2$)	280	210
MH at 5σ (worst point)	400	230
10° resolution ($\delta_{CP} = 0$)	450	290
CPV at 5σ ($\delta_{CP} = -\pi/2$)	525	320
CPV at 5σ 50% of δ_{CP}	810	550
Reactor θ_{13} resolution ($\sin^2 2\theta_{13} = 0.084 \pm 0.003$)	1200	850
CPV at 3σ 75% of δ_{CP}	1320	850

★ **Genuine potential for early physics discovery**

6. The DUNE Far Detector



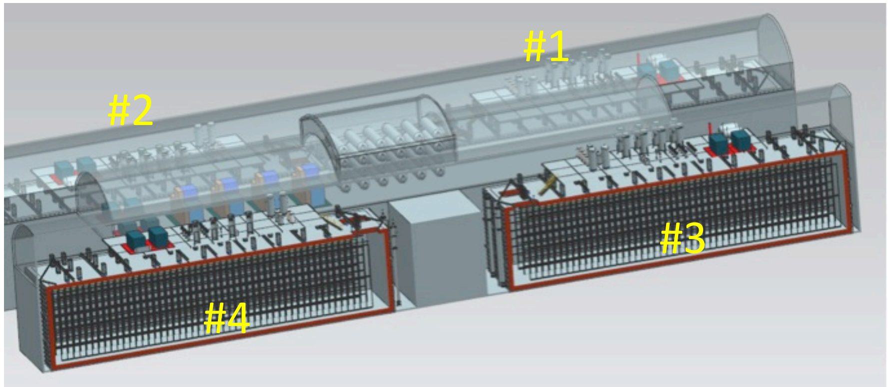
Staged Approach to 40 kt

Cavern Layout at the Sanford Underground Research Facility (SURF) discussed in detail by EFIG: more in Elaine's talk

- **Decision based on: strategic + technical input**

➡ **four caverns hosting four independent 10-kt FD modules**

- Allows for staged construction of FD
- Gives flexibility for evolution of LArTPC technology design
  - Assume four identical cryostats
  - But, assume that the four 10-kt modules will be similar but **not identical**



LAr TPC Technologies

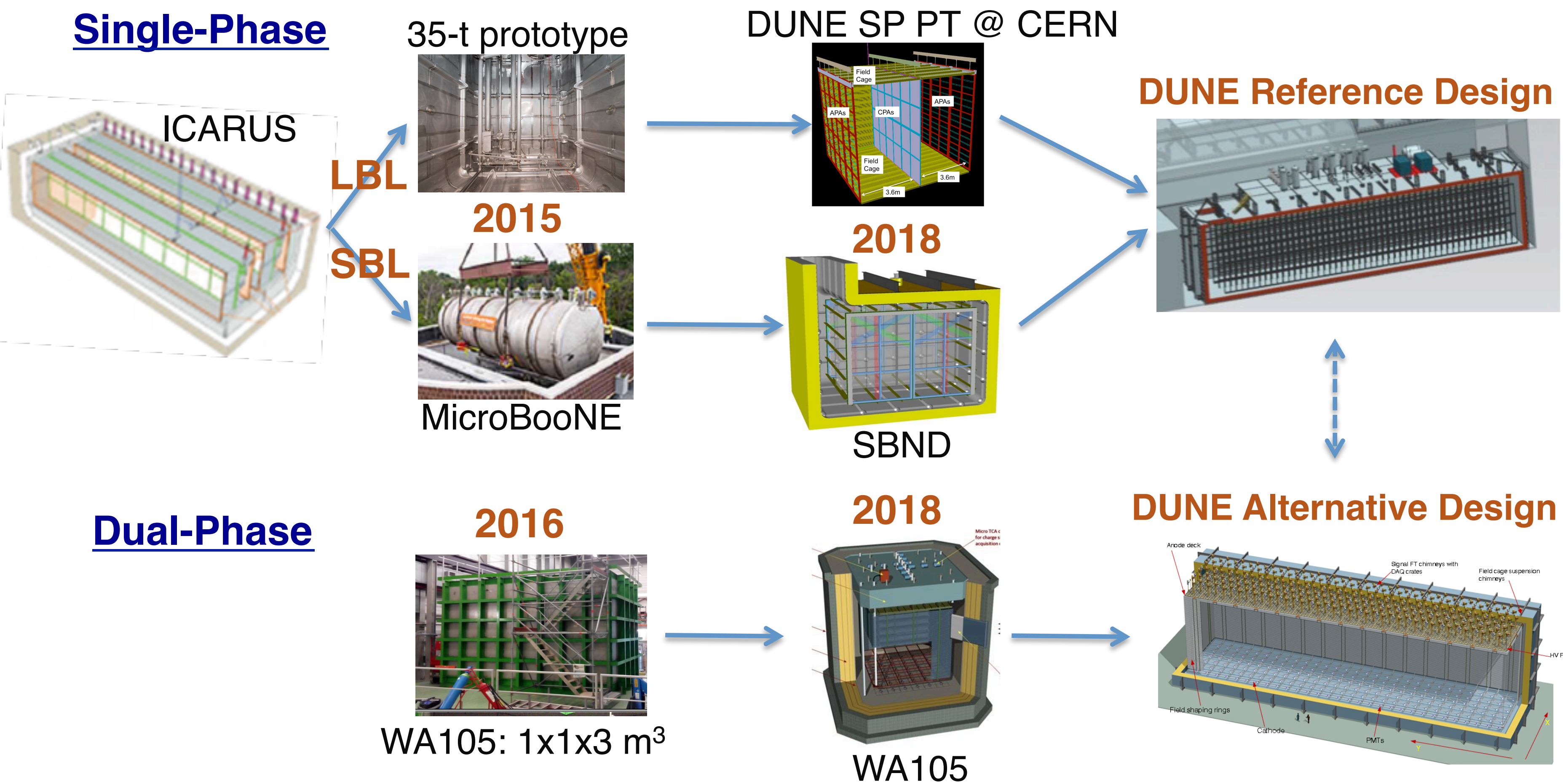
LArTPC technology has been demonstrated by ICARUS

DUNE is considering two options for readout of ionization signals:

- **Single-phase wire-plane readout**
  - Ionization signals (collection + induction) read out in liquid volume
  - As used in ICARUS, ArgoNEUT/LArIAT, MicroBooNE
  - Long-term operation/stability demonstrated by ICARUS T600
- **Dual-phase readout**
  - Ionization signals amplified and detected in gaseous argon above the liquid surface
  - Being pioneered by the WA105 collaboration
  - If demonstrated, potential advantages over single-phase approach

LArTPC Development Path

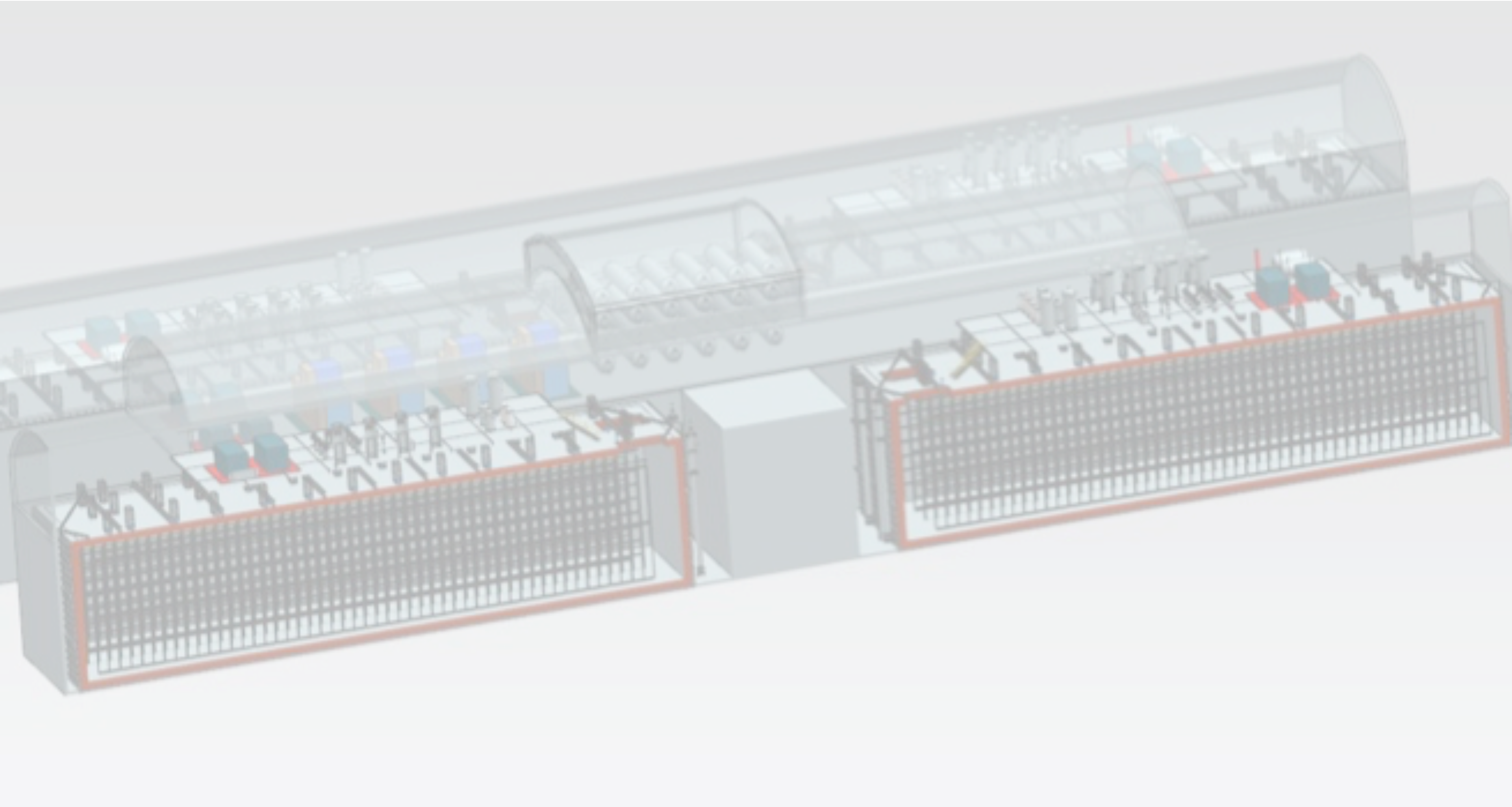
Fermilab SBN and CERN neutrino platform provide a strong **LArTPC** development and prototyping program



How this feeds into DUNE

- **35-t prototype**
  - First validation of use of wrapped APAs
- **MicroBooNE**
  - Operational experience with a large LArTPC
  - Development of simulation, reconstruction and analysis tools
  - Lessons learned…
- **SBND**
  - Tests of dune of cold analog electronics
  - Light detection system
  - Cryostat design + cold ullage
- **DUNE Single Phase Prototype at CERN**
  - "Full-scale drift cell" engineering prototype of DUNE single-phase design
  - Engineering validation and risk mitigation
- **WA105**
  - Validation of dual-phase design

7. DUNE Far Detector Strategy



Reference Design

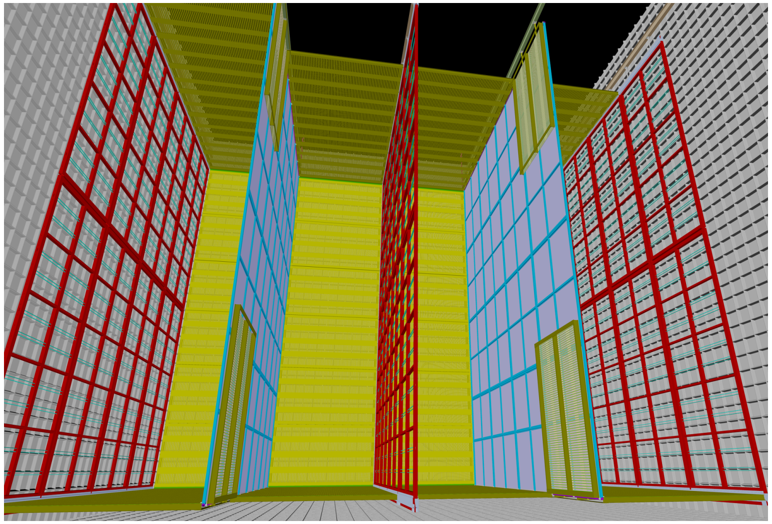
The single-phase APA/CPA LArTPC design is the reference design for the CDR

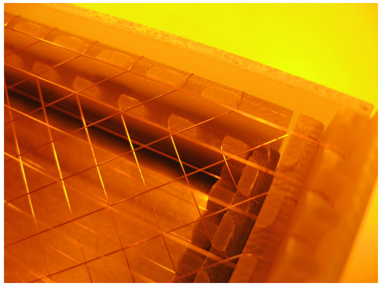
- **Design is already advanced for CDR stage**
- **Supported by strong development program at Fermilab**
  - 35-t prototype (operational in 2015)
  - Developments of single-phase technology in the Fermilab SBN program (e.g. MicroBooNE & SBND)
- **"Full-scale prototype" with the DUNE Single-Phase Prototype at the CERN Neutrino Platform**
  - Engineering prototype of DUNE reference design
    - 6 full-sized drift cells
  - Proposal presented to SPSC today
  - Aiming for operation in 2018

Reference Design – facts & figures

Modular implementation of Single-Phase TPC

- **Each 10 kt FD module:**
  - Active volume: 12m x 14m x 58m
  - 150 Anode Plane Assemblies
    - 6.3m high x 2.3m wide
  - 200 Cathode Plane Assemblies
    - 3m high x 2.3m wide
  - A:C:A:C:A arrangement
  - Cathodes at -180 kV for 3.5m drift
  - APAs have wrapped wires – read out both sides
  - Each side has one collection wire plane & two induction planes

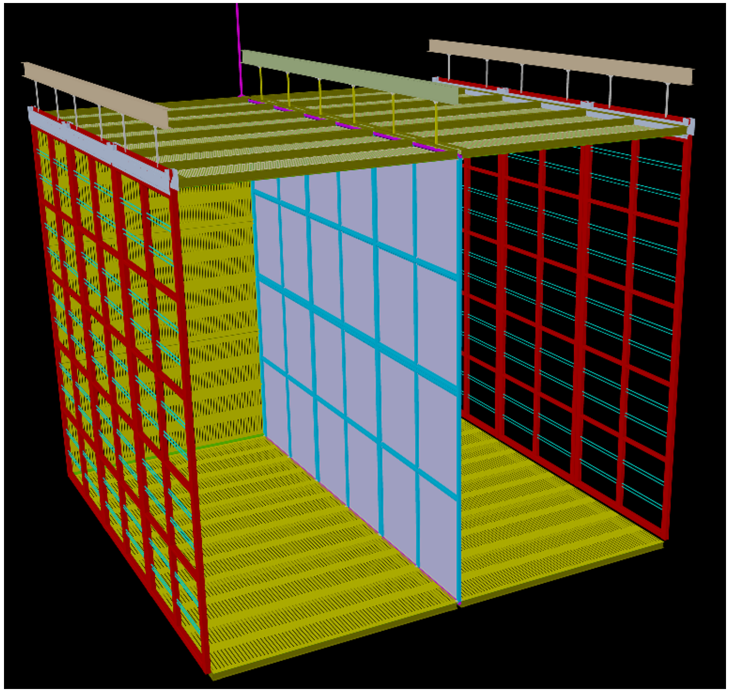




DUNE Single Phase Prototype at CERN

Engineering prototype of DUNE single-phase TPC

- **DUNE PT @ CERN ~ 2018**
  - Active volume: 6m x 7m x 7m
  - 6 Anode Plane Assemblies
    - 6.3m high x 2.3m wide
  - 6 Cathode Plane Assemblies
    - 3m high x 2.3m wide
  - A:C:A arrangement
  - Cathode at -180 kV for 3.5m drift



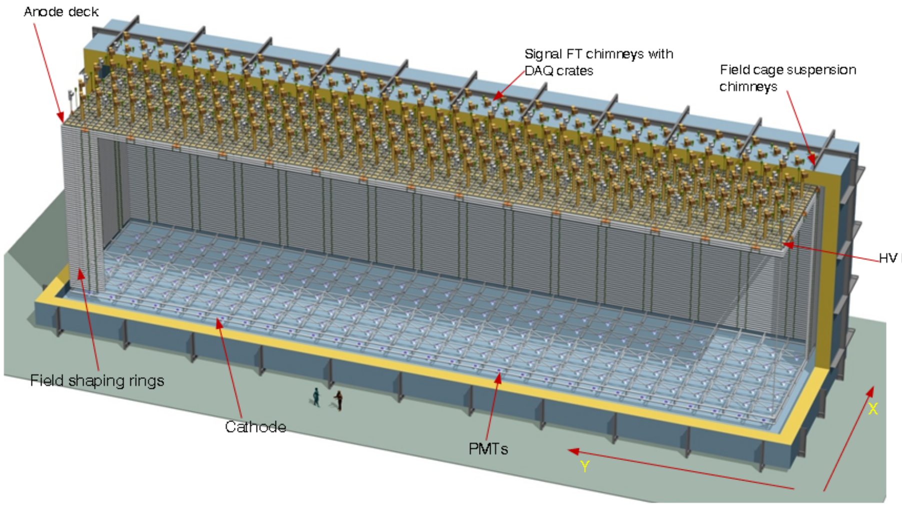
Prototyping of FD drift cell + setting up module factories

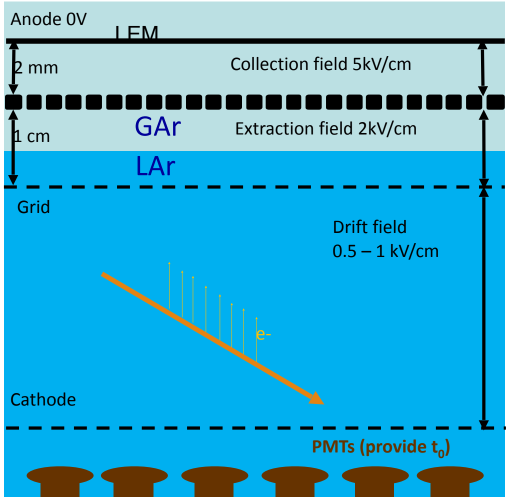
- **Science: Charged-particle test-beam campaign**

Alternative Design

DUNE collaboration recognizes the potential of the dual-phase technology

- Strongly supports the WA105 development program at the CERN neutrino platform
- A dual-phase implementation of the DUNE far detector is presented as an **alternative design** in the CDR
- If demonstrated, could form basis of second or subsequent 10-kt far detector modules

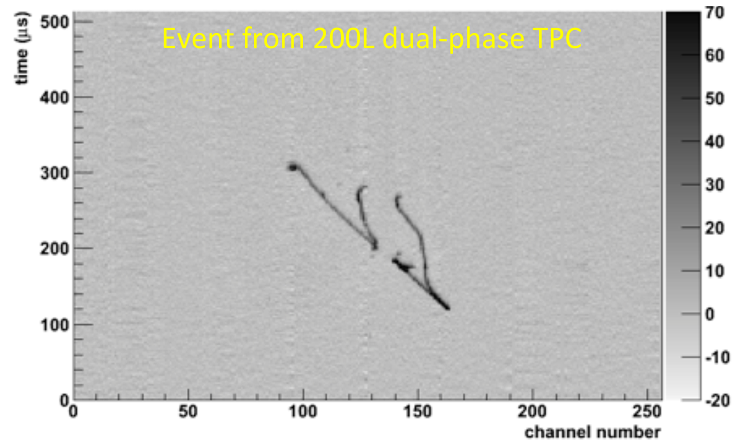




WA105: Dual-Phase Prototype at CERN

Potential advantages of dual-phase approach

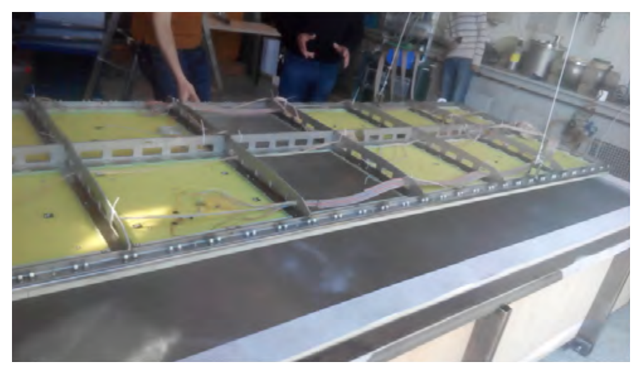
- Longer drift path with less #channels
- Finer readout pitch
- More robust S/N ratio with tunable gain
- Lower detection energy threshold
- Better pattern reconstruction of events
- Only charge collection views (no induction)



Phase 1 (prototype) : 3 x 1 x 1 m^3 operation in 2016
Phase 2 (demonstrator) : 6 x 6 x 6 m^3 test beam in 2018

- **WA105 effort is funded and is on-track**

  e.g. cryo-test of 3 x 1 x 1 m^3 readout plane (06/15)



Staging Strategy

Far Detector Implementation strategy

- **First 10-kt will be the single-phase APA/CPA design**
  - Represents lowest risk route to installation in 2021
- **Experience at CERN neutrino platform / SBN → evolution of LArTPC design**
  - Refinements of single-phase design
  - Validation of operation of dual-phase design
- **Technology choice for second 10-kt module:**
  - Based on risk, cost (including potential opportunities of additional funding sources) and physics performance
  - Review process organized by the DUNE technical board – exact process will be defined when TB is in place. Will take place in **FY2020**
  - Ultimate decision by DUNE executive committee
- **Process repeated for third & fourth 10-kt module**

8. The DUNE Near Detector

DUNE Near Detector Strategy

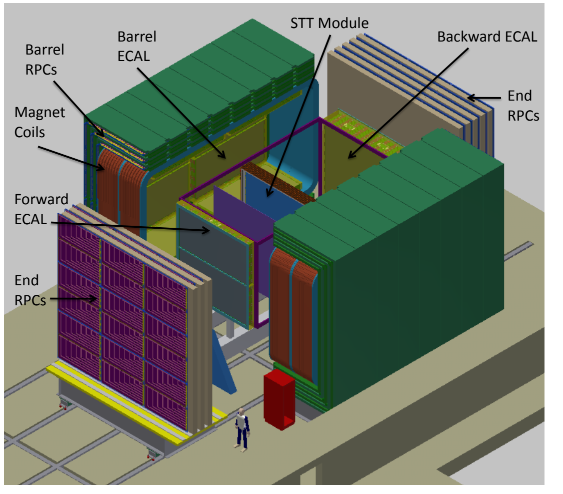
- **Guiding Principles**
  - Ability to constrain systematic uncertainties for the DUNE LBL oscillation analysis
    - ⇨ Capability to precisely measure exclusive neutrino interactions
  - Naturally results in a self-contained non-oscillation neutrino physics program
    - Exploiting the intense LBNF neutrino beam

- **International context**
  - The proposed contribution of Indian institutions to the design and construction of the DUNE near detector is a central part of the DUNE strategy for the construction of the experiment

Reference Design

The NOMAD-inspired Fine-Grained Tracker (FGT)

- **It consists of:**
  - Central straw-tube tracking system
  - Lead-scintillator sampling ECAL
  - Large-bore warm dipole magnet
  - RPC-based muon tracking systems



- **It provides:**
  - Constraints on cross sections and the neutrino flux
  - A rich self-contained non-oscillation neutrino physics program

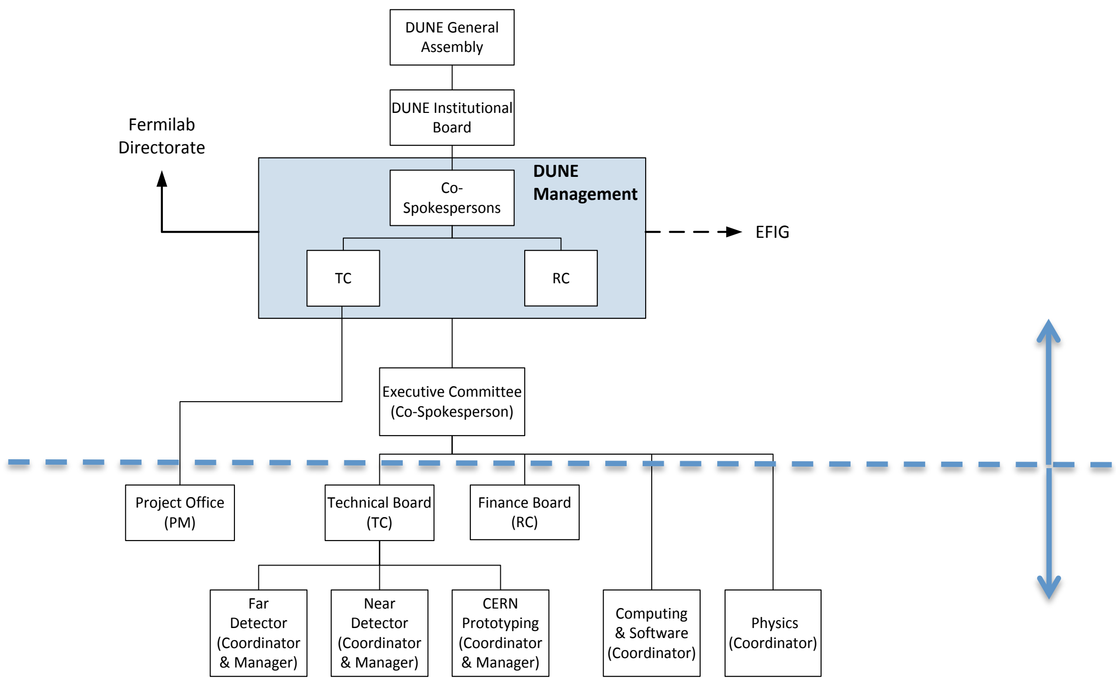
This conceptual design should meet ND requirements

- a full end-to-end (ND to FD) physics study needs to be performed
  - Tools be developed (simulation/reconstruction/fitting methodology)
- current design is not yet optimized

9. DUNE Organization: Next Steps

Collaboration Organization

- **Organization as presented in CDR Volume 1**



Organization in place for CDR

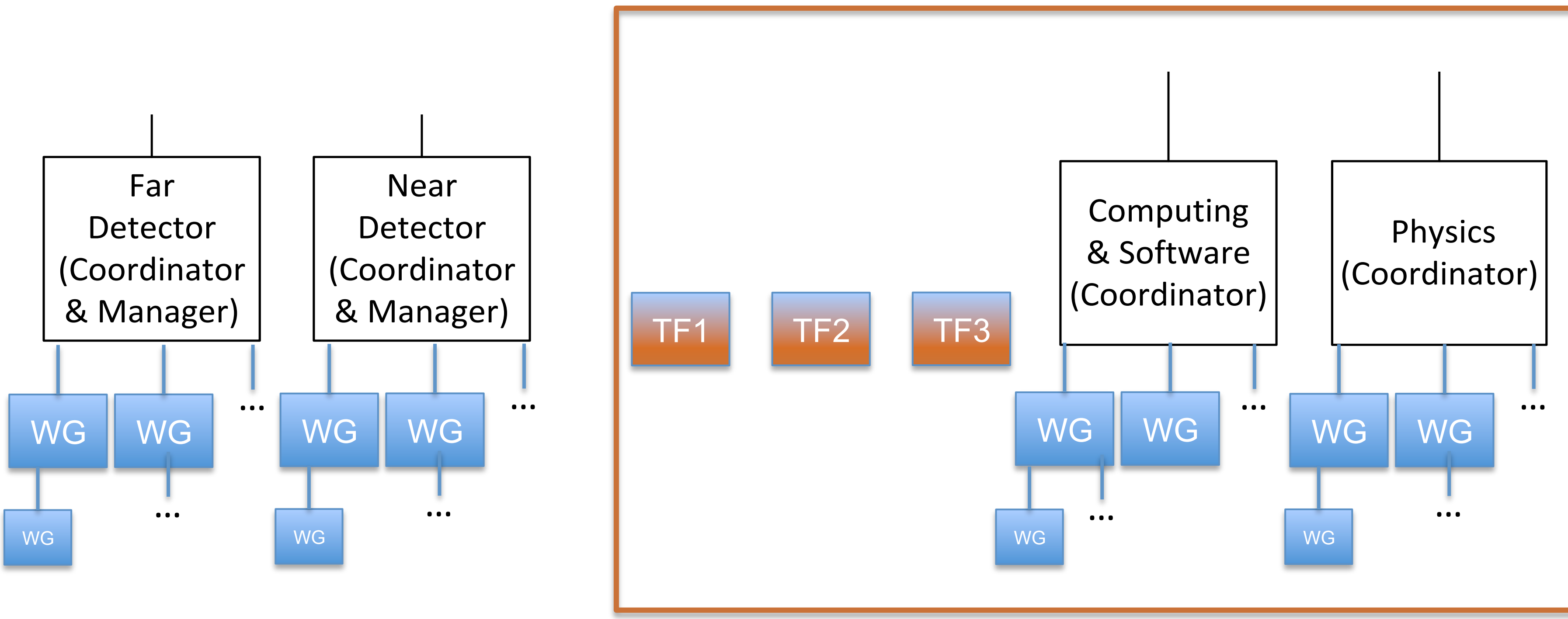
Now aim to complete “working” structures

- **Scientific Management now being implemented**
  - Presented at Friday’s DUNE Weekly Meeting
  - Plan approved at Yesterday’s DUNE Executive Committee

DUNE Scientific Structure

- **Organization of Physics & Software Computing**

  \+ focused (fixed duration) Task Forces



- **Comments:**
  - Details of the WG structure, put in place in consultation with coordinators
  - TFs draw on Science & Detector WGs to address specific issues

DUNE Task Forces

- **Proposing three new task forces**
  - Tackle time-critical questions for the collaboration
  - Differ from the working groups; they are fixed duration
  - Bring together activities that cross WG boundaries
    - E.g. Physics – Reconstruction – Far Detector
  - Tasked to deliver short reports addressing specific questions
    - But main role is ensuring that the required work is completed in a timely manner
- **Task force leadership**
  - Convenor
    - Typically a more "senior" person – who can organize the work
  - Two deputies
    - Typically younger/more junior people – with necessary detailed knowledge

Task Force 1: ND Optimization

- **Highlighted as strategically important in CDR**
- **Main goals:**
  - GEANT4 simulations of FGT and possible alternatives;
  - end-to-end simulation connecting the measurements in the ND to the far detector systematics using, for example, the VALOR framework;
  - Evaluate potential benefits of alternatives e.g. LArTPC or HPTPC augmenting reference design

This is central part to our ND strategy:

- **ND task force will deliver a report in 12 – 18 months:**

  ⇒ will inform the evolution of the ND design

Task Force 2: FD Reco/Physics

- **Needed to address key FD design questions**
- **Take account of both reference (Single-Phase) and alternate (Dual-Phase) designs**
- **Main goals:**
  - full far detector simulation and reconstruction chain;
  - produce detector optimization studies, e.g. 3mm vs 5mm wire pitch & evaluation of light readout system configurations;
  - DUNE long-baseline physics sensitivity studies using full simulation and event reconstruction;
  - develop the simulation and reconstruction for SNB and nucleon decay physics.

This is central part to our FD strategy:

- **FD task force will deliver a report in 12 – 18 months:**

will inform the evolution of the FD design

Task Force 3: Beam optimization

- **As highlighted in CDR, optimization of beam line is critical to DUNE physics reach**
- **Main goals are:**
  - further develop the physics-driven optimization of the beam line, including the target, horn configuration and decay pipe;
  - identify potential options and develop a first-order cost-benefit analysis.

Aim to close loop on beam optimization

- **Task force will deliver a report in 12 – 18 months:**

  requires strong interaction with engineers

Timeline for next steps:

- **In ~2 weeks:**
  - Physics coordinator & deputy
  - Computing coordinator & deputy
  - 3 x Task force convenor & two deputies
  - 3 x Detector coordinator & Detector manager
- **In ~4 weeks**
  - Full working group structure
- **In ~6 weeks**
  - Working group co-convenors in place
- **DUNE Collaboration Meeting September 2nd – 5th**
  - Working & Task Force Meetings

10. Particle Physics Project Prioritization Panel

P5

DUNE Reference Design & P5

P5 identified the following "minimum requirements to proceed":

- reach an exposure of 120 kt.MW.years by 2035
- Far detector underground with cavern space for expansion to 40 kt LAr (fiducial)
- 1.2 MW beam upgradable to multi-MW power
- Demonstrated capability for supernova bursts
- Demonstrated capability for proton decay, providing a significant improvement over current searches

P5 "goal" is for 3σ CPV coverage for > 75 % of δ values

DUNE Reference Design & P5

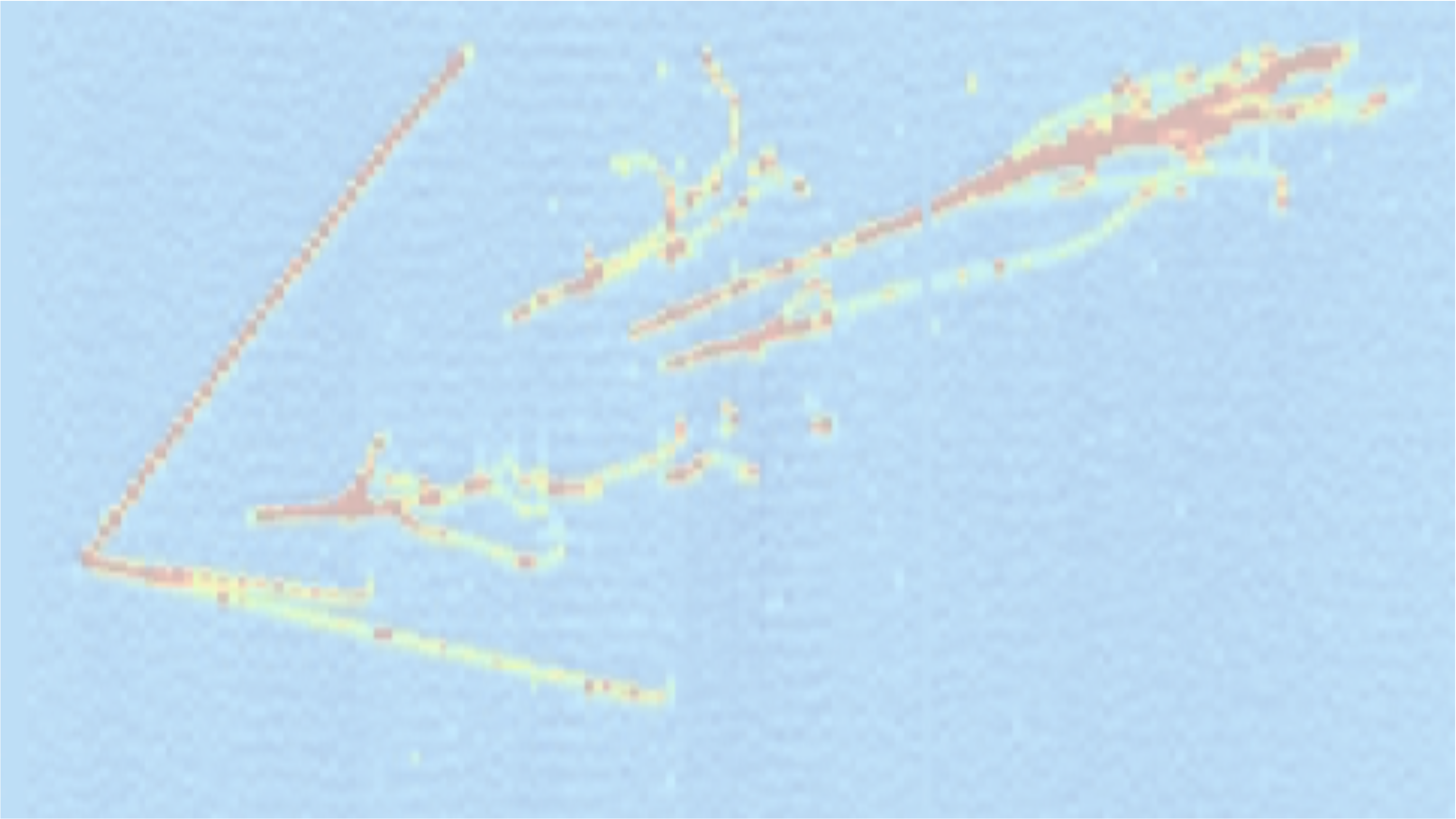
P5 identified the following "minimum requirements to proceed":

- reach an exposure of 120 kt.MW.years by 2035 ✅
- Far detector underground with cavern space for expansion to 40 kt LAr (fiducial) ✅
- 1.2 MW beam upgradable to multi-MW power ✅
- Demonstrated capability for supernova bursts ✅
- Demonstrated capability for proton decay, providing a significant improvement over current searches ✅

P5 "goal" is for 3σ CPV coverage for > 75 % of δ values ✅

CD-1-Refresh design meets the P5 goals

11. Summary



Summary

We believe we have:

i) A **clear plan** for the installation of the first 10-kt far detector module starting in **2021**
   - Based on the **demonstrated** single-phase technology

ii) A staging plan that allows for the **evolution** of LArTPC design
   - Refinements of single-phase design
   - Validation of operation of dual-phase design

iii) A clear strategy for evolution of near detector design

iv) A clear plan for implementation of the full DUNE collaboration structure

Summary

We believe we have:

i) A **clear plan** for the installation of the first 10-kt far detector module starting in **2021**
  - Based on the **demonstrated** single-phase technology

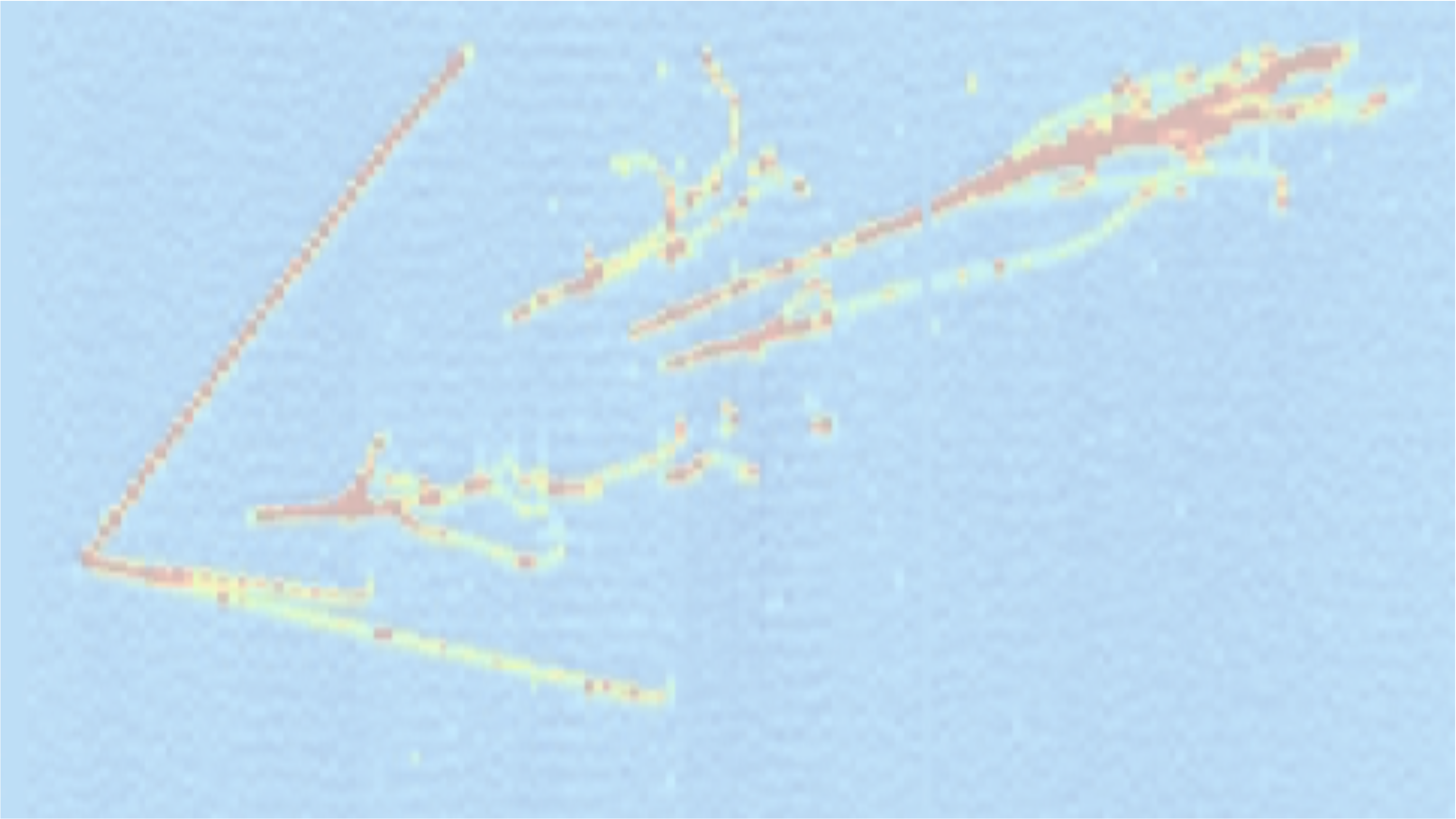
ii) A staging plan that allows for the **evolution** of LArTPC design
  - Refinements of single-phase design
  - Validation of operation of dual-phase design

iii) A strategy for evolution of near detector design

iv) A process for the implementation of the full DUNE collaboration structure

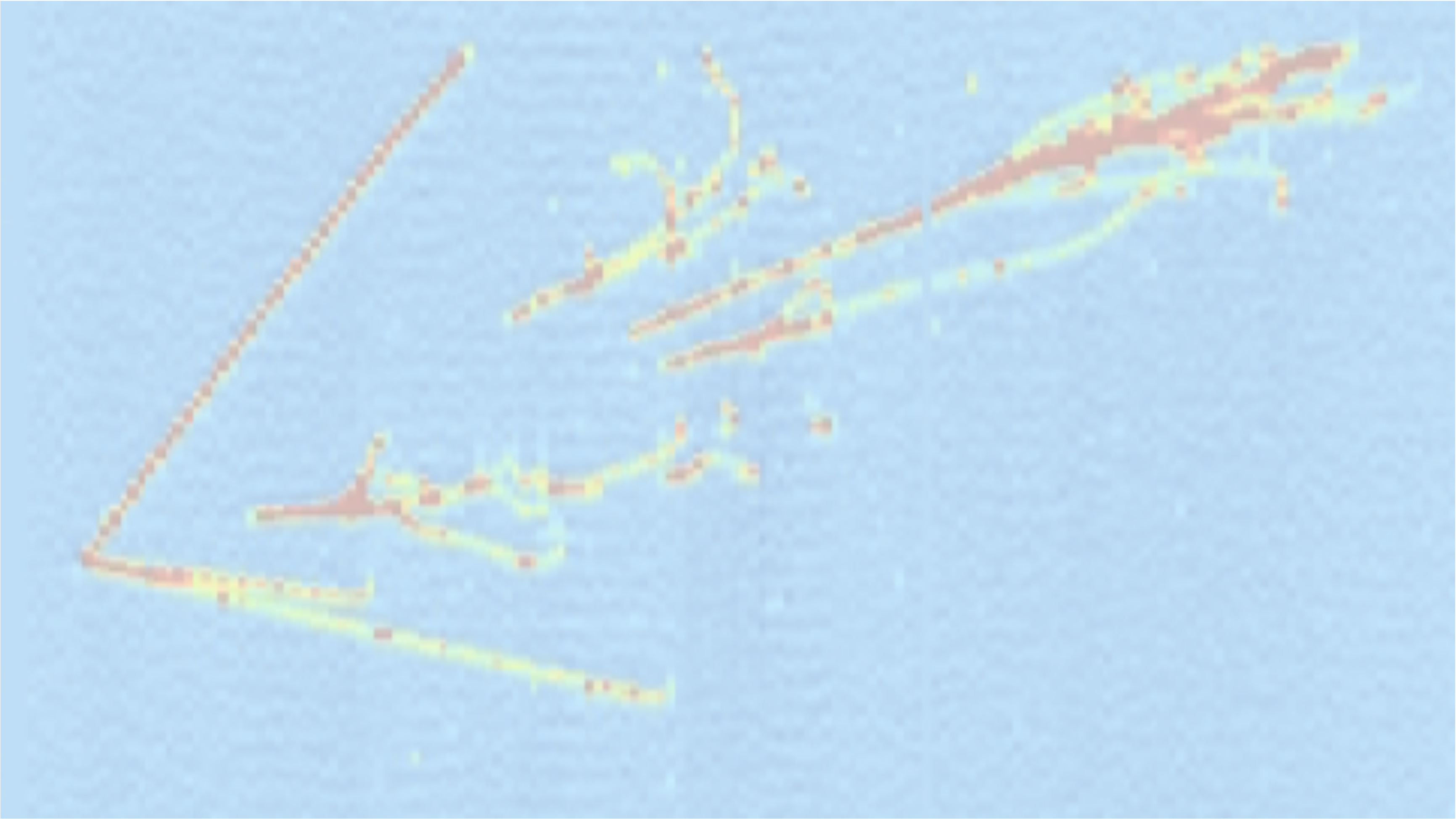
⇒ **A well-defined plan for implementing the DUNE detectors, which will deliver the P5 physics goals in a timely manner**

Thank you for your attention



Backup Slides

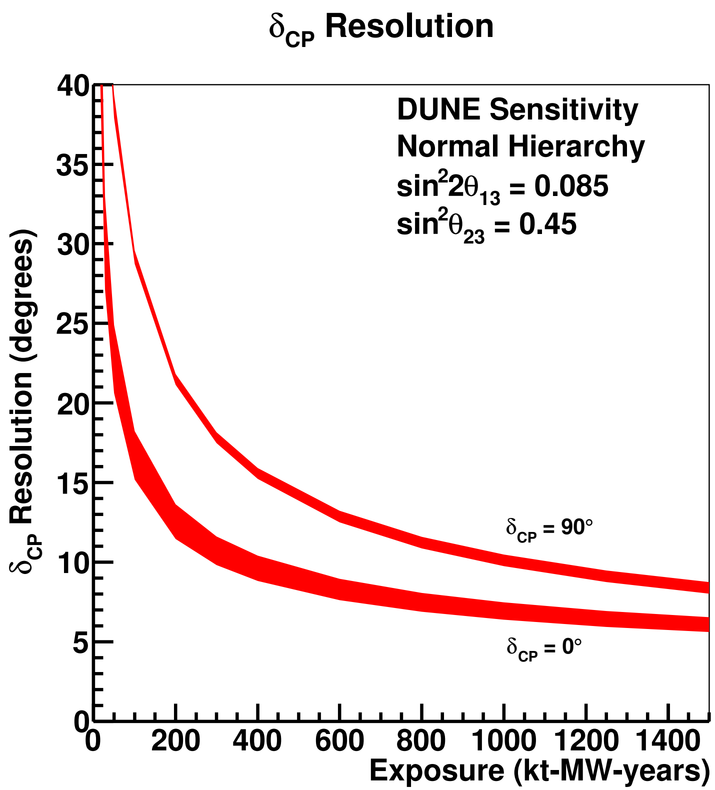
Science

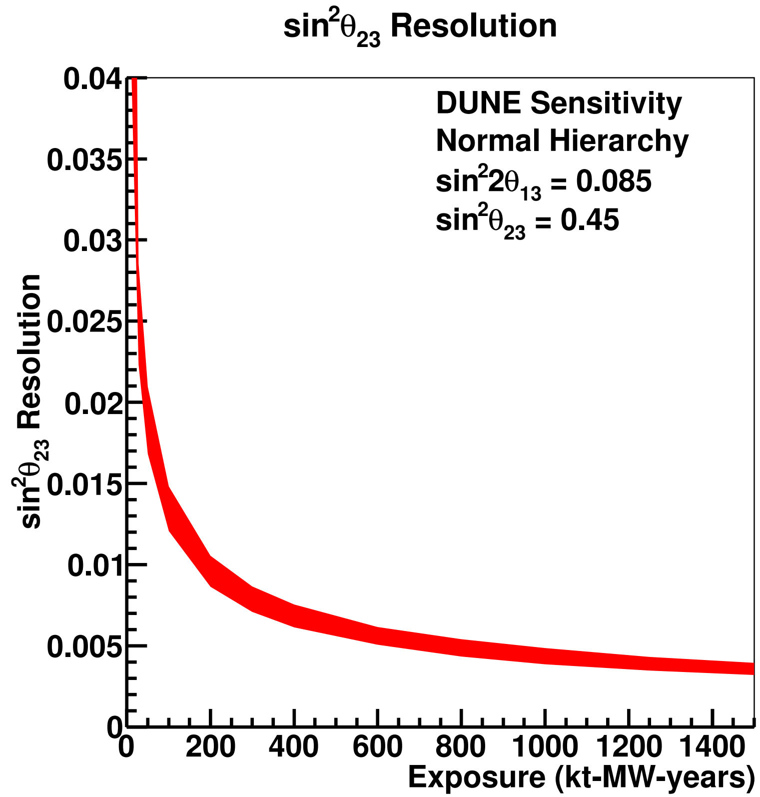


Parameter Resolutions

δ_{CP} & θ_{23}

- As a function of exposure

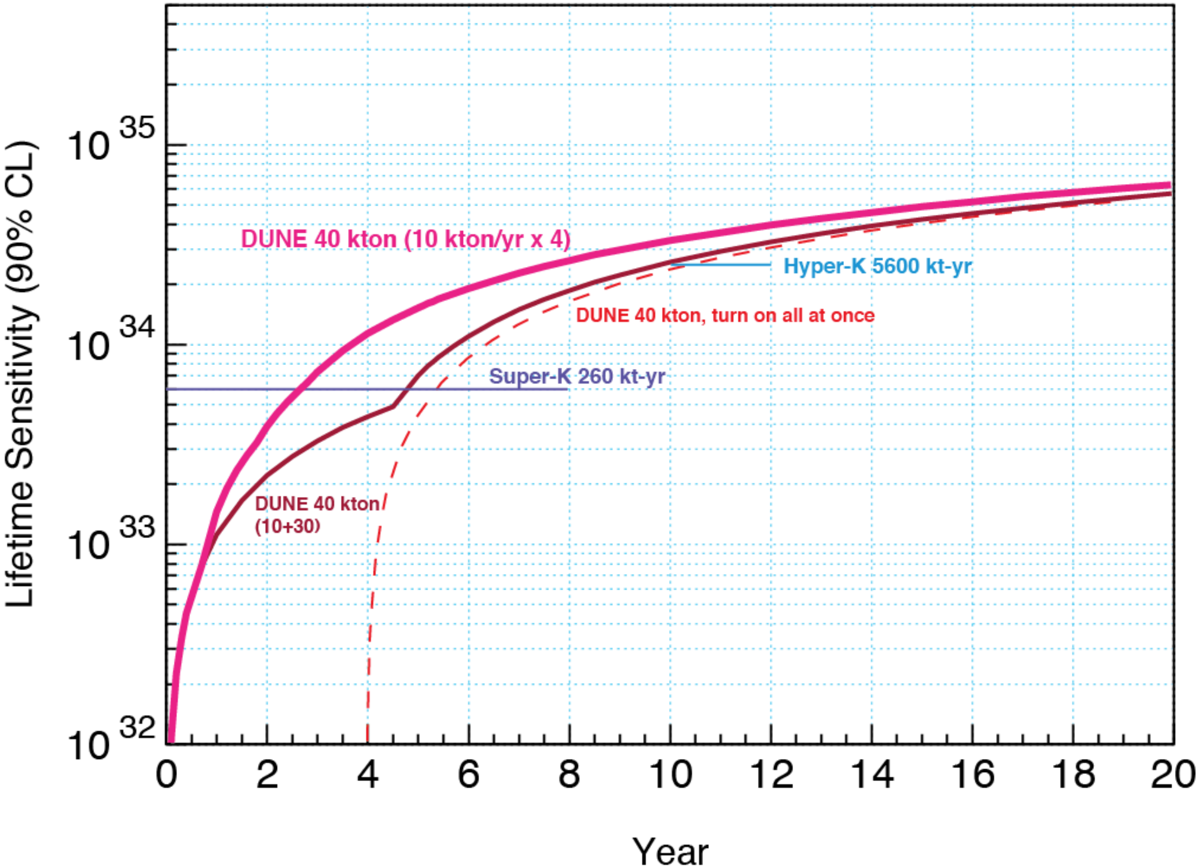




PDK

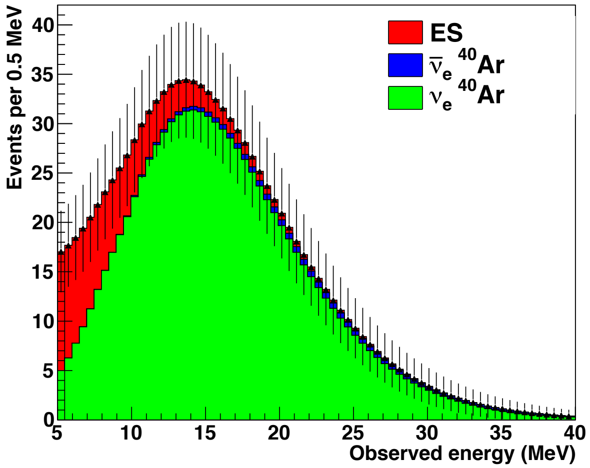
$p \rightarrow K \nu$

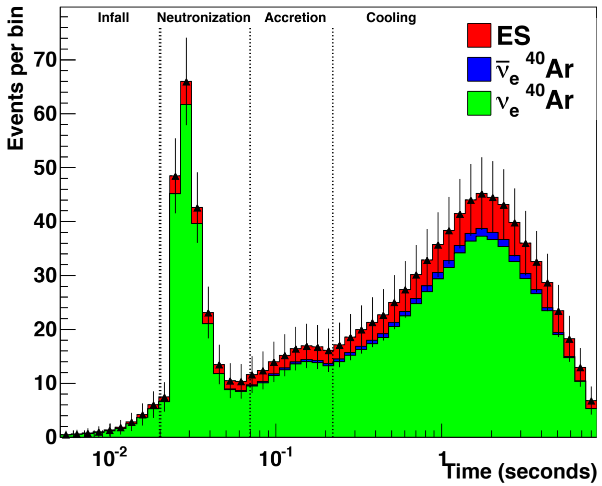
- DUNE for various staging assumptions



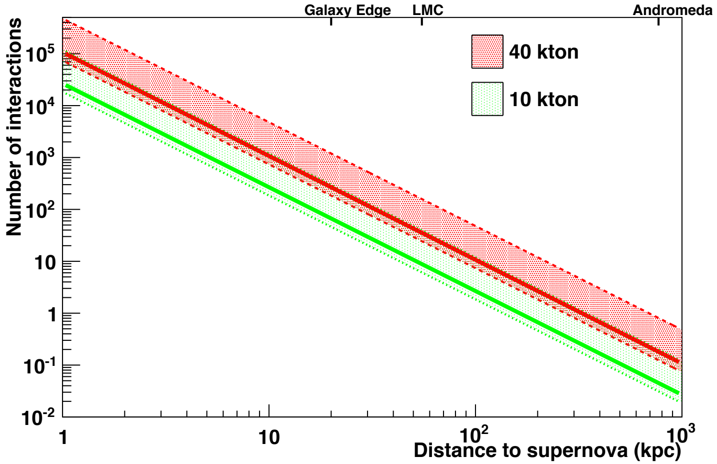
SNB

- Energy and timing sensitive to particle & astrophysics

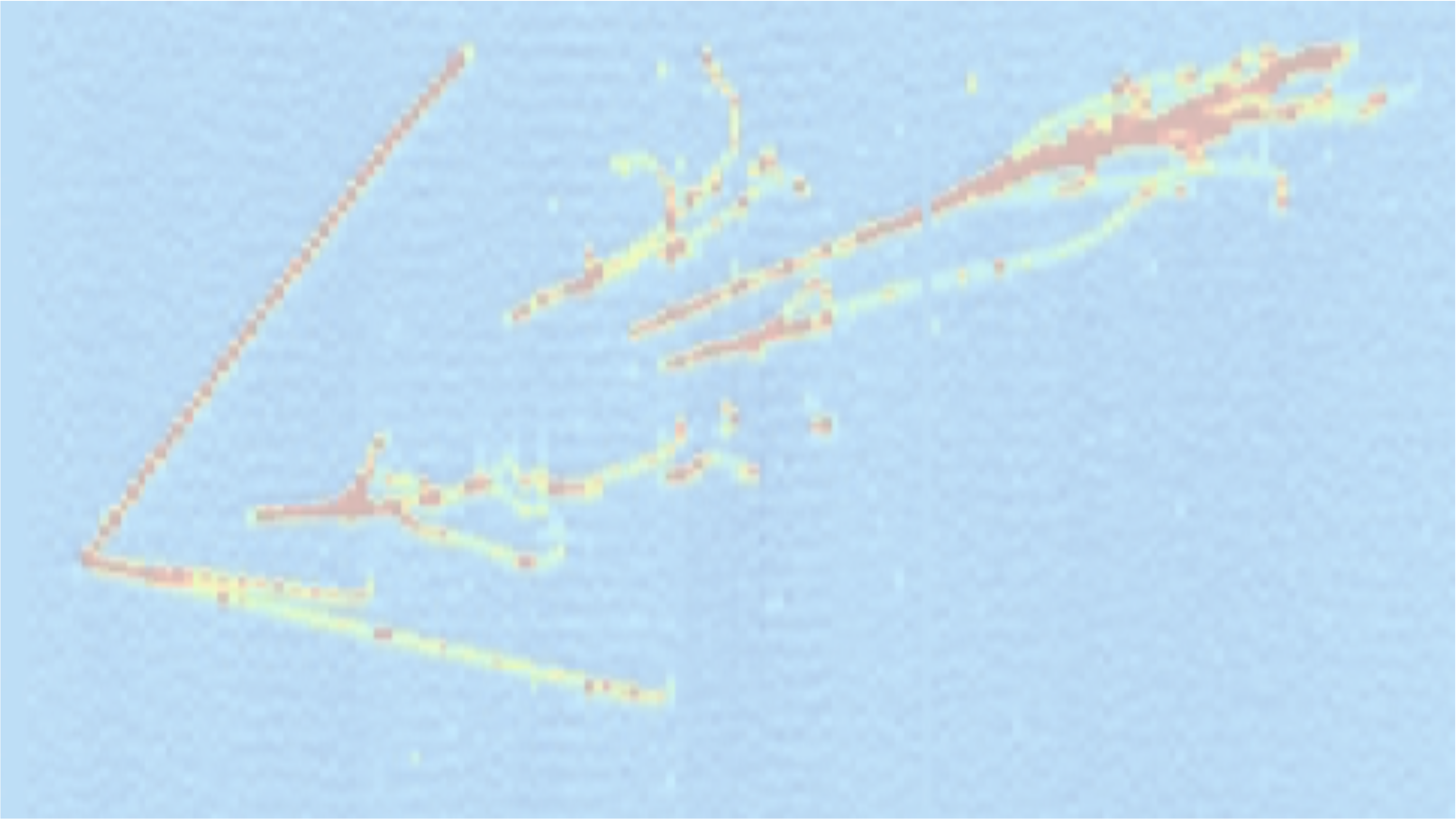




- Event Rates:

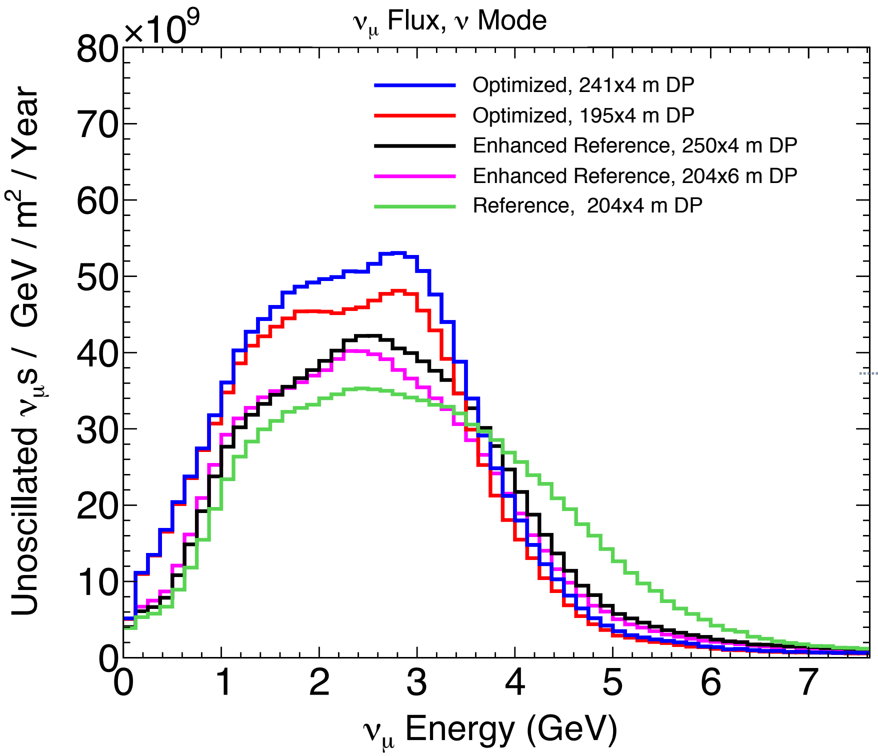


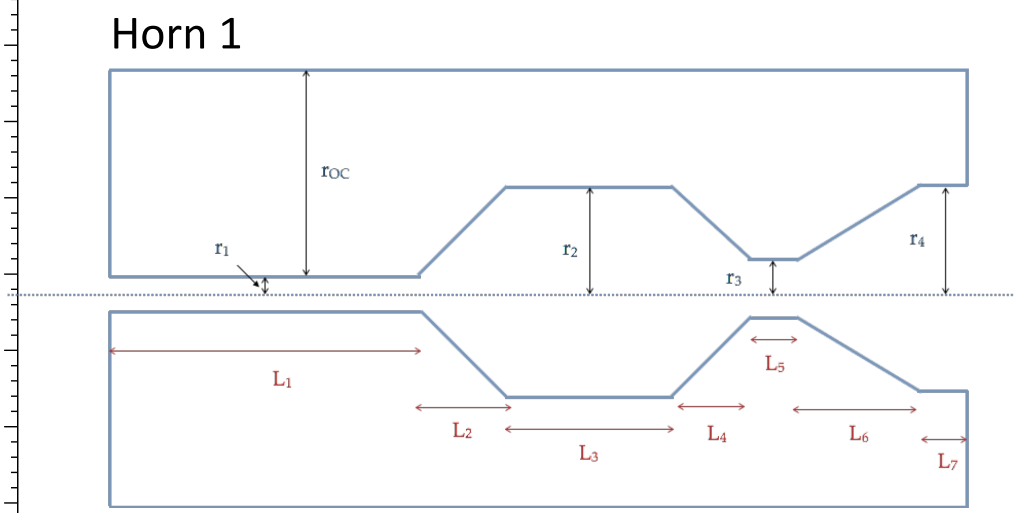
Beam Optimization



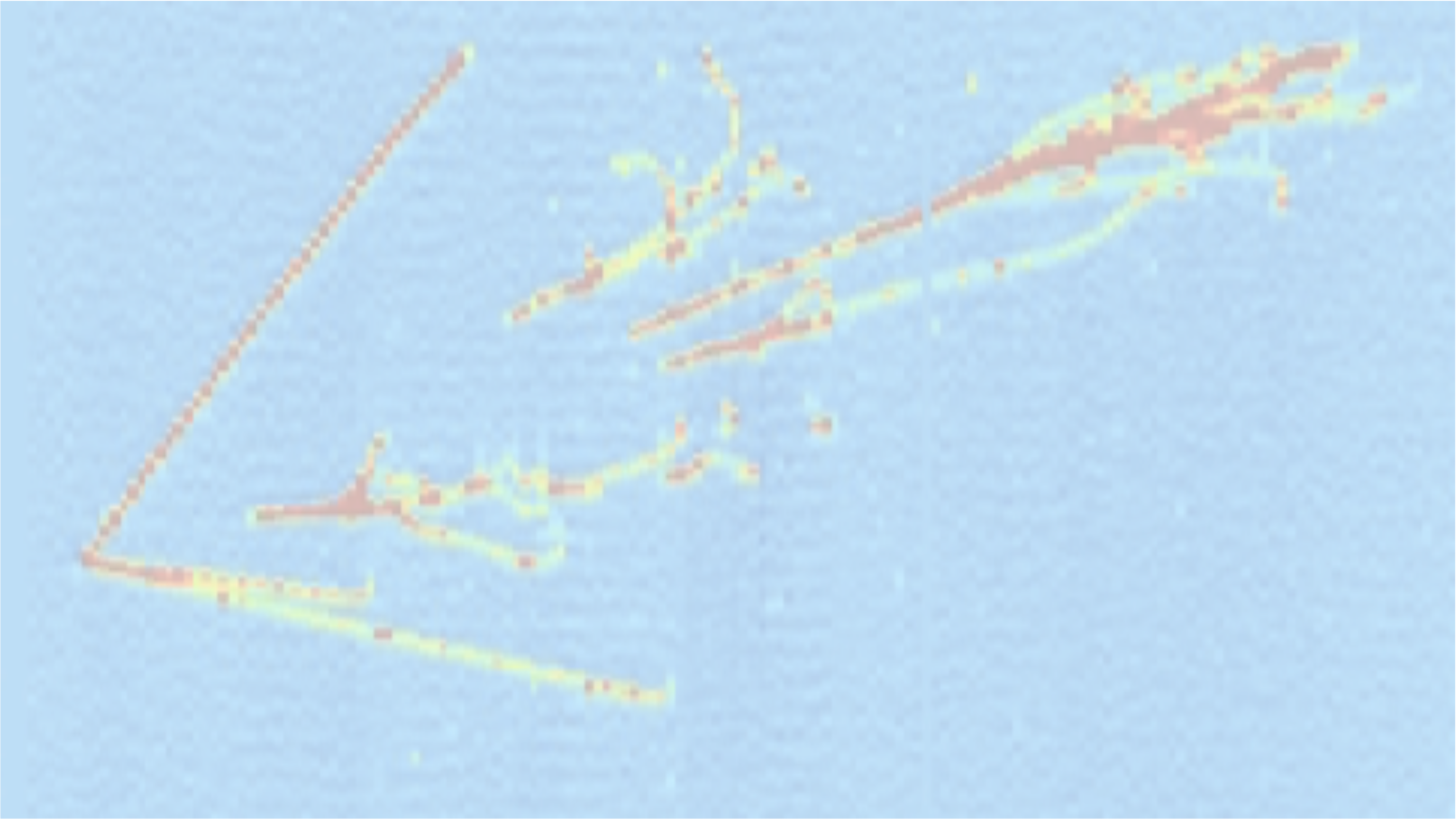
Beam Optimization

Following LBNO approach, genetic algorithm used to optimize horn design – increase neutrino flux at lower energies





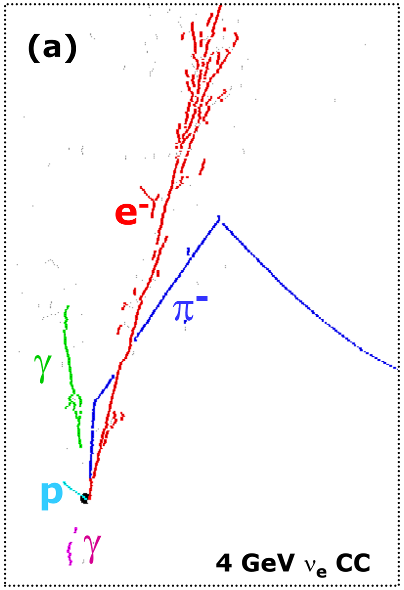
Reconstruction

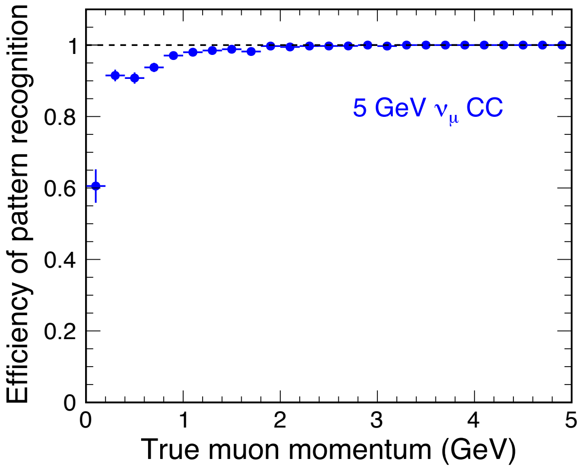


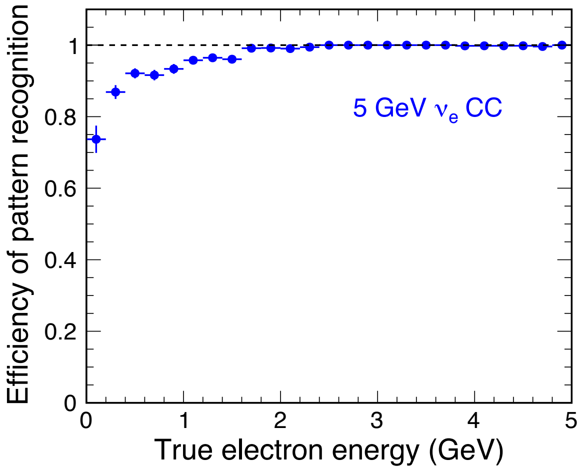
LAr-TPC Reconstruction

Real progress in last year – driven by 35-t & MicroBooNE

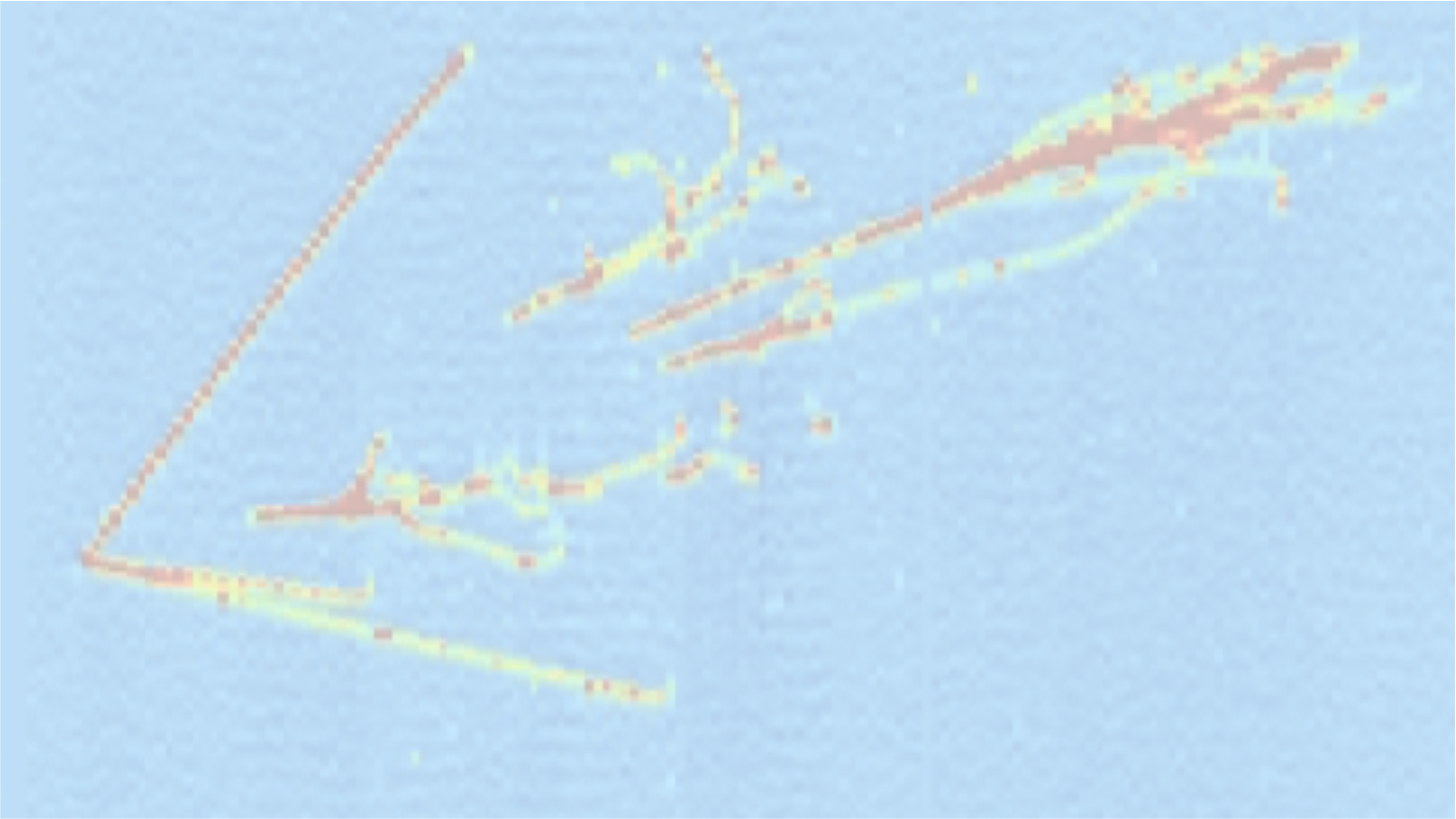
- Full DUNE simulation/reconstruction now in reach







Detector Requirements



Requirements

DUNE and LBNF requirements are:

- **Determined by the primary science goals of the collaboration**
  - LBNF: Baseline, Conventional Facilities & Beam
  - Far Detector: for oscillation physics, proton decay, and SNB neutrinos
  - Near Detector: to constrain LBL systematics
- **Informed by the ancillary science program**
  - Near Detector: to provide a rich self-contained neutrino physics program (largely follows from primary requirements)

Requirements: Methodology

Detailed flow-down of requirements from the:

- DUNE Scientific Objectives → Scientific Requirements → Science/Engineering requirements → Engineering specification

e.g.

Glo-obj-2	Precision measurements of oscillations in the $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance channel	Precision measurements in both Near and Far detectors which are necessary to determine the parameters that govern $\nu_\mu \to \nu_e$ appearance, and similarly, $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance	These will allow accurate measurements of the third mixing angle θ_{13}, and simultaneous measurement of the CP violating phase δ, and the mass-hierarchy (sign of Δm^2_{32}).

→

Glo-Sci-3	requirement	Identification of Electron Neutrino and Anti-neutrino Events	Far detector shall be capable of identifying electron neutrino and anti-neutrino charged current beam events in sufficient numbers within the fiducial volume of the detector. The neutrino flavor of the event will be identified by clearly identifying the primary final state charged electron.

→

LArFD-L2-se-66	requirement	EM showers	High energy EM showers [>100MeV] shall be identified by their topology.
LArFD-L2-se-67	requirement	e-gamma Separation	Electron and photon induced showers shall be separated using ionization density at the start of the shower.

→ Key Detector Performance Requirements

Flow-down available in document 10873
http://lbne2-docdb.fnal.gov:8080/cgi-bin/DocumentDatabase/

e.g. Far Detector Performance Reqs.

Physics objectives set goals for key detector performance requirements, e.g.

Requirement	Physics Driver(s)
Electron/Photon separation	LBL Oscillations
Tracking: Distinguish MIP deposits from noise	LBL Oscillations, NDK & SNB
Continuous data collection	NDK & SNB
Particle Identification/Energy Reconstruction	LBL Oscillations, NDK & SNB
Energy Threshold	SNB
Electron Energy Resolution	LBL Oscillations & SNB
Hadronic Energy Resolution	LBL Oscillations & NDK
…	

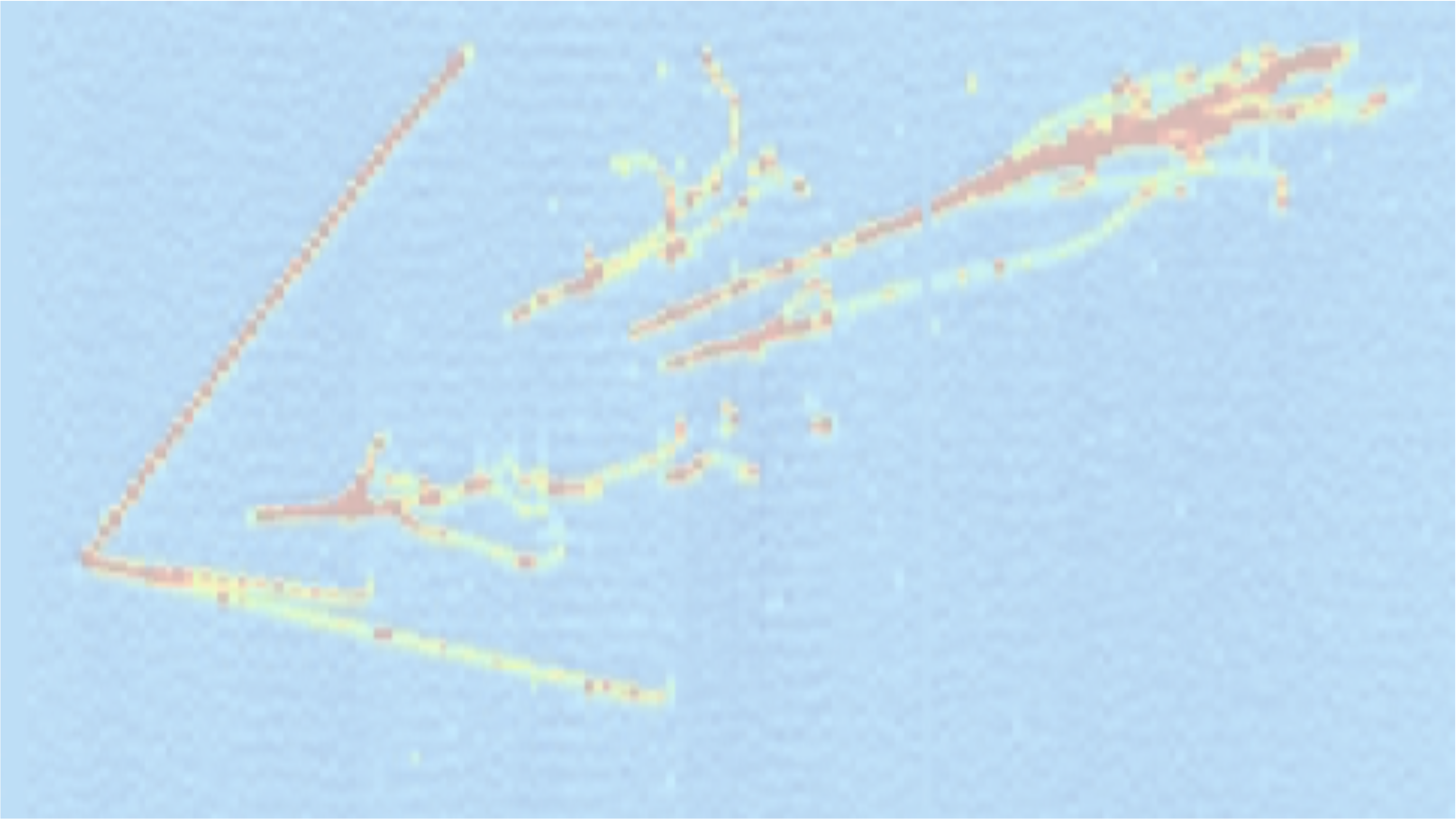
Physics Driver(s)

⇨ **Detector parameters chosen to meet performance requirements**

Requirements

- **DUNE Independent Technical Reviews: Charge question 1:**
  - "Is the design technically adequate? Is the design likely to meet the technical requirements? Are the physics requirements clearly stated and documented? Have these requirements been translated into technical performance requirements and specifications?"
- **Far Detector:**
  - "The design should meet the technical requirements as stated" ✅
  - "However, a tight connection between the goals and the technical design is not yet fully in place. Some scope increase may be needed as the simulation, the R&D on alternatives, and the prototype data advance."
- **Near Detector:**
  - "The design is likely to meet technical requirements and physics specifications of the DUNE experiment." ✅
  - "The connection between high level physics requirements of the DUNE experiment and technical specifications of each specific detector could be improved."

Detector Requirements

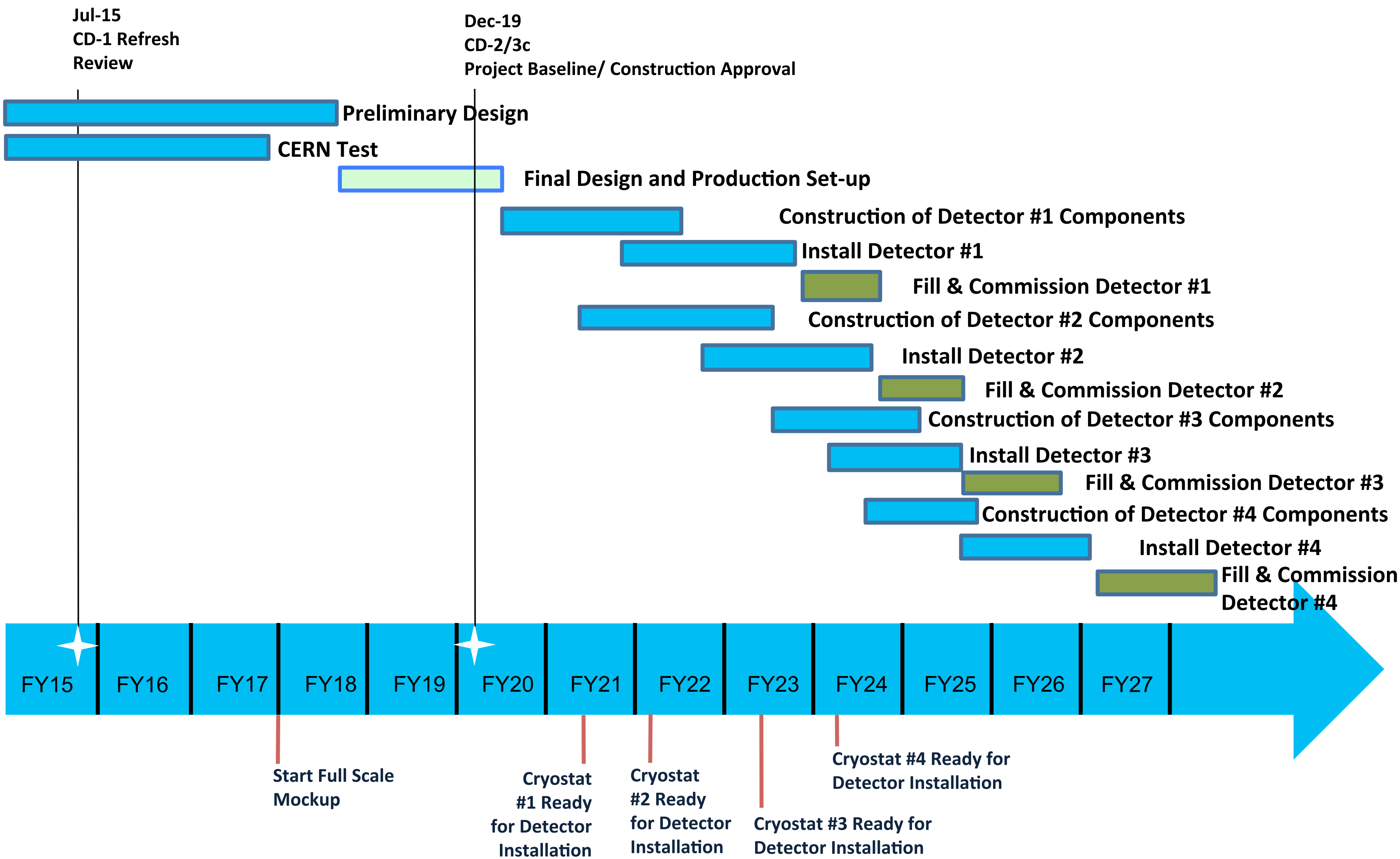


FD Technology Decisions

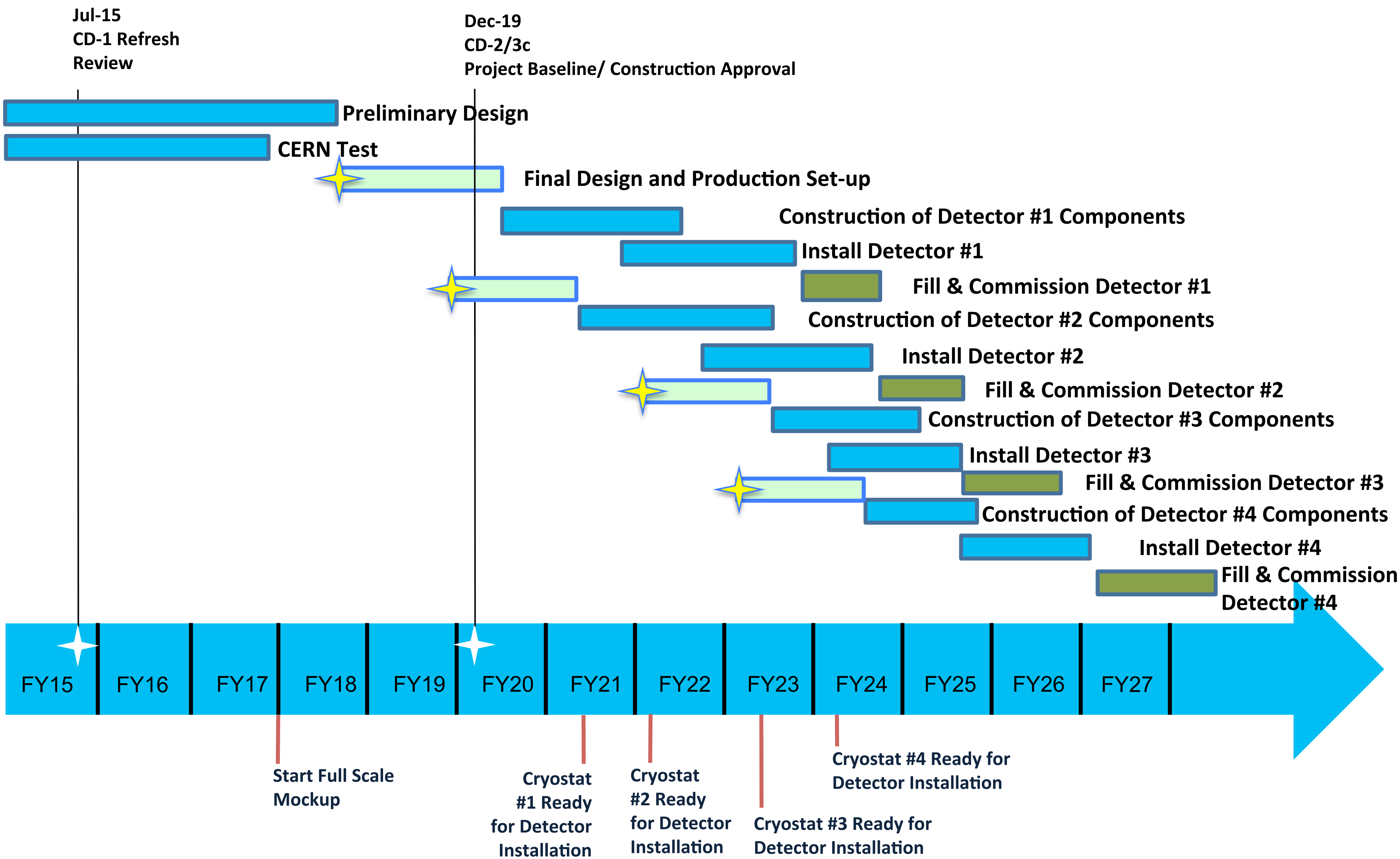
Context: Prototypes at CERN

- DUNE Single-Phase Prototype (proposal to SPSC today)
  - Pioneered by ICARUS; LArIAT/MicroBooNE/SBND to demonstrate performance
  - DUNE SP-PT is a full-scale engineering prototype of APA/CPA design
  - Essential physics calibration measurements with charged-particle beams
- Dual-phase WA105 (approved in 2013)
  - 3L and 200L prototypes operated at CERN
  - 1x1x3 m^3 is a technology demonstrator
  - 6x6x6 m^3 is a large-scale prototype
    - scale up the technology
  - Essential physics calibration measurements with charged-particle beams

Indicative schedule



Indicative schedule



FD Technology Decision Criteria

Far Detector Technology Decision Criteria

- Based on (for both single and dual phase)
  - Cost (incremental)
  - Risk (technical and schedule)
  - Physics performance
    - Intend to compare using common reconstruction software etc.
  - Funding opportunities
- For dual-phase technology next steps are:
  - Scaling up to 1x1x3 m^3 and the 6x6x6 m^3
  - Demonstrate long-term stability
- Need to accumulate sufficient beam data to make direct comparison between single- and double-phase designs

FD Technology Decision Timeline

Far Detector Technology Timeline

- **DOE scope is for 50 % of two 10-kt FD modules**
  - Remaining 50% from international partners
  - Gives scope for **two** single-phase detectors
  - Timescale for CD-2 is 2019/2020 sets timescale for baseline design
  - Matches the decision time for second 10-kt module
- **Currently, the funding for other two 10-kt FD modules 100 % from non-DOE sources**
  - Opportunity for to attract new international partners with desire to contribute to enhanced designs, e.g. dual phase
  - Flexibility is required: will take 3 – 4 years for international agreements
- **Given schedule – first 10-kt will be single phase (see CDR)**
- **Second and subsequent 10-kt modules:**
  - Details will depend on timescale of demonstration and performance of alternative technologies
  - CERN neutrino platform critical here