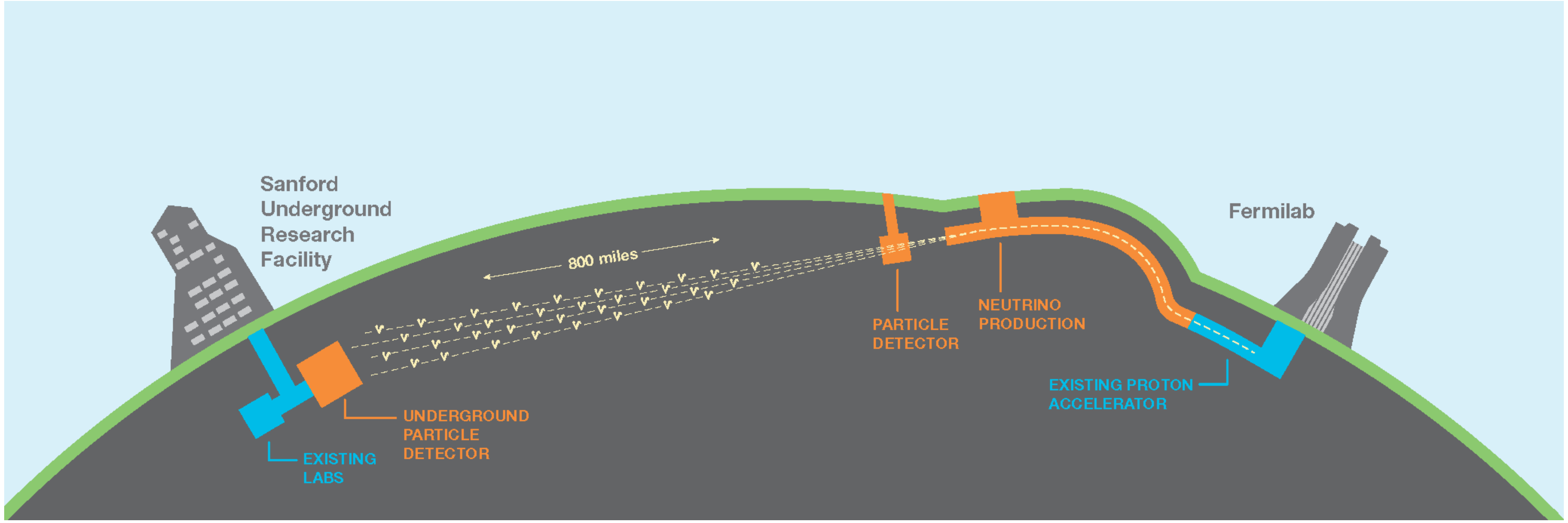


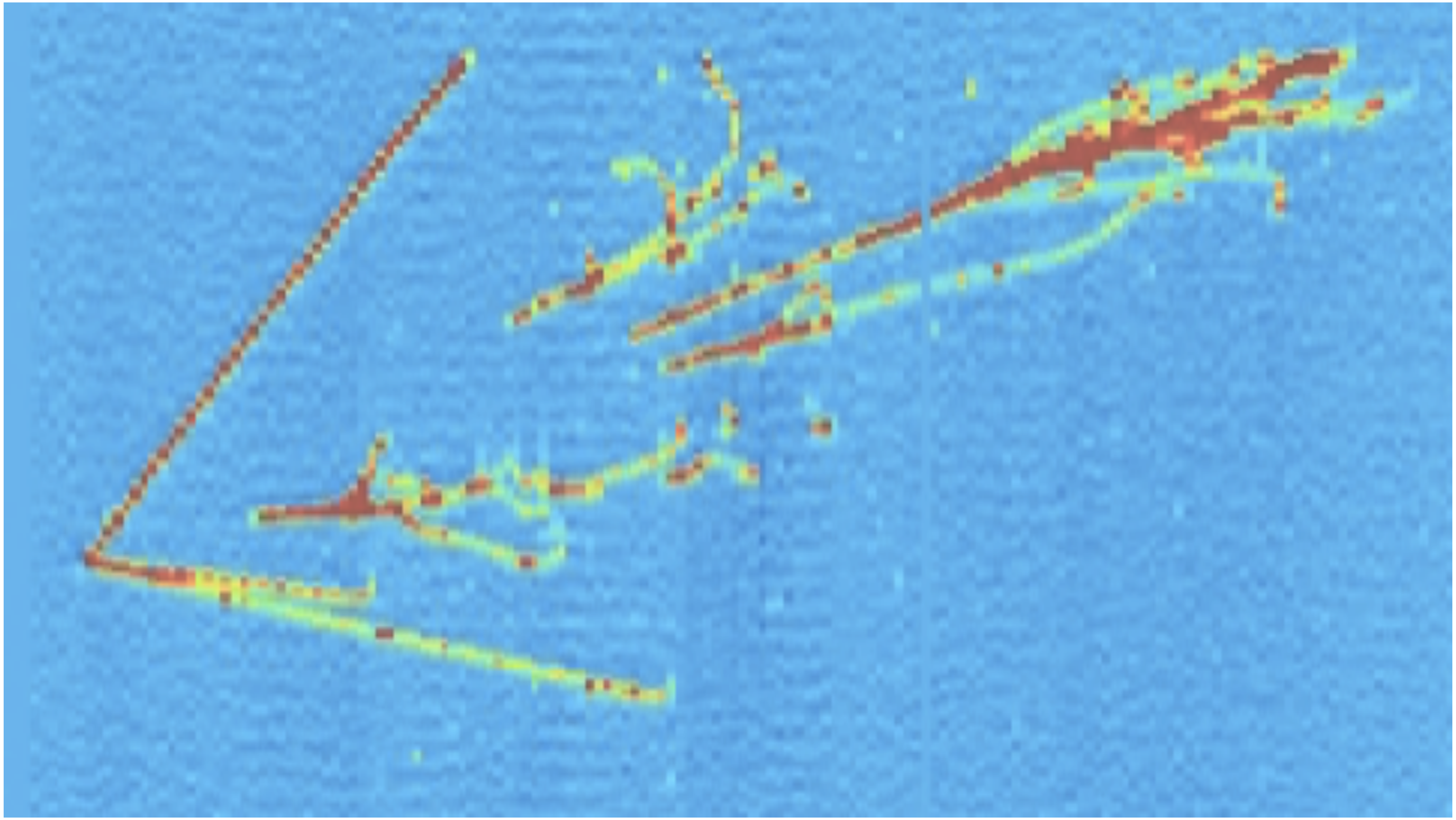
DUNE: Physics Highlights

Mark Thomson

University of Cambridge & co-spokesperson of DUNE

CERN: 7th April 2016

1: Neutrino Physics - Context



The Standard 3-Flavour Paradigm

★ **Unitary PNMS matrix ⇨ mixing described by:**

- three "Euler angles": $(\theta_{12},\ \theta_{13},\ \theta_{23})$
- and one complex phase: δ

$$U_{\mathrm{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

★ If $\delta \neq \{0, \pi\}$ then SM leptonic sector ⇨ CP violation (CPV)

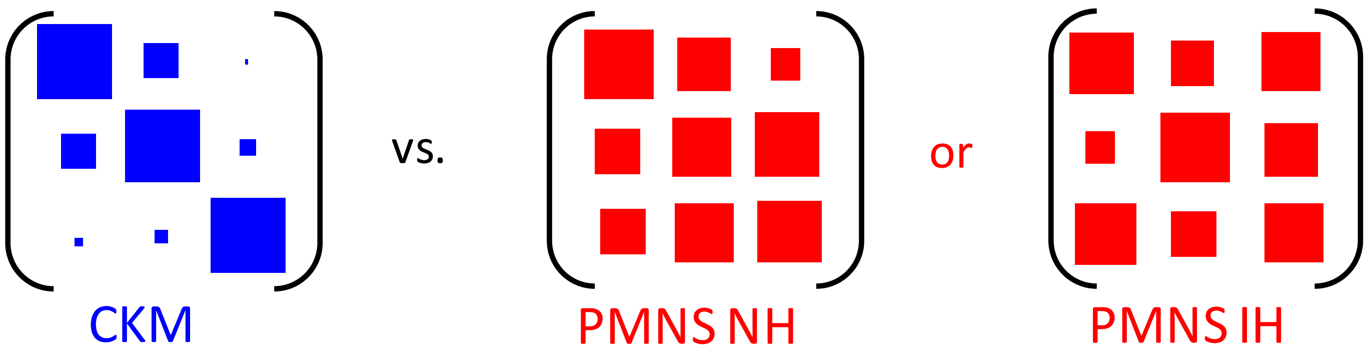
- CPV effects $\propto \sin\theta_{13}$
- **now know that θ_{13} is relatively large**

⇨ **CPV is observable with conventional ν beams**

⇨ **LBNF/DUNE**
Hyper-Kamiokande

The Known Unknowns

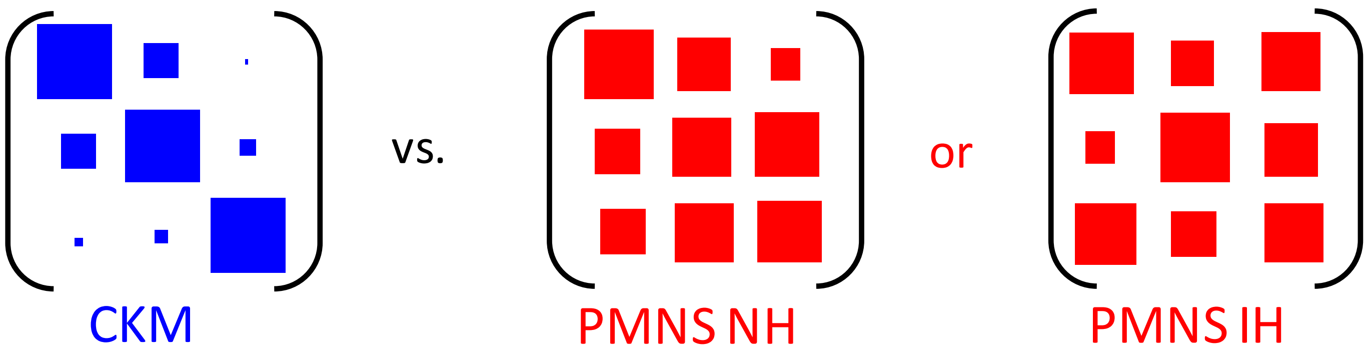
- ★ **We now know a lot about the neutrino sector**
- ★ **But still many profound questions**
  - Why are neutrino masses so small ?
    - Is there a connection to the GUT scale?
  - Are there light sterile neutrino states ?
    - No clear theoretical guidance on mass scale, M_R, …
  - What is the neutrino mass hierarchy ?
    - An important question in flavor physics, e.g. CKM vs. PNMS



  - **Is CP violated in the leptonic sector ?**
    - Are νs key to understanding the matter-antimatter asymmetry?

The Known Unknowns

- ★ We now know a lot about the neutrino sector
- ★ DUNE can address three of these questions + more
  - Why are neutrino masses so small ?
    - Is there a connection to the GUT scale?
  - Are there light sterile neutrino states ? → Breaks 3-flavor paradigm
    - No clear theoretical guidance on mass scale, M, …
  - What is the neutrino mass hierarchy ?
    - An important question in flavor physics, e.g. CKM vs. PNMS



  - Is CP violated in the leptonic sector ?
    - Are νs key to understanding the matter-antimatter asymmetry?

The Key Question (my personal bias)

Is CP violated in the neutrino sector ?

★ If $\delta \neq \{0, \pi\}$ the answer is YES

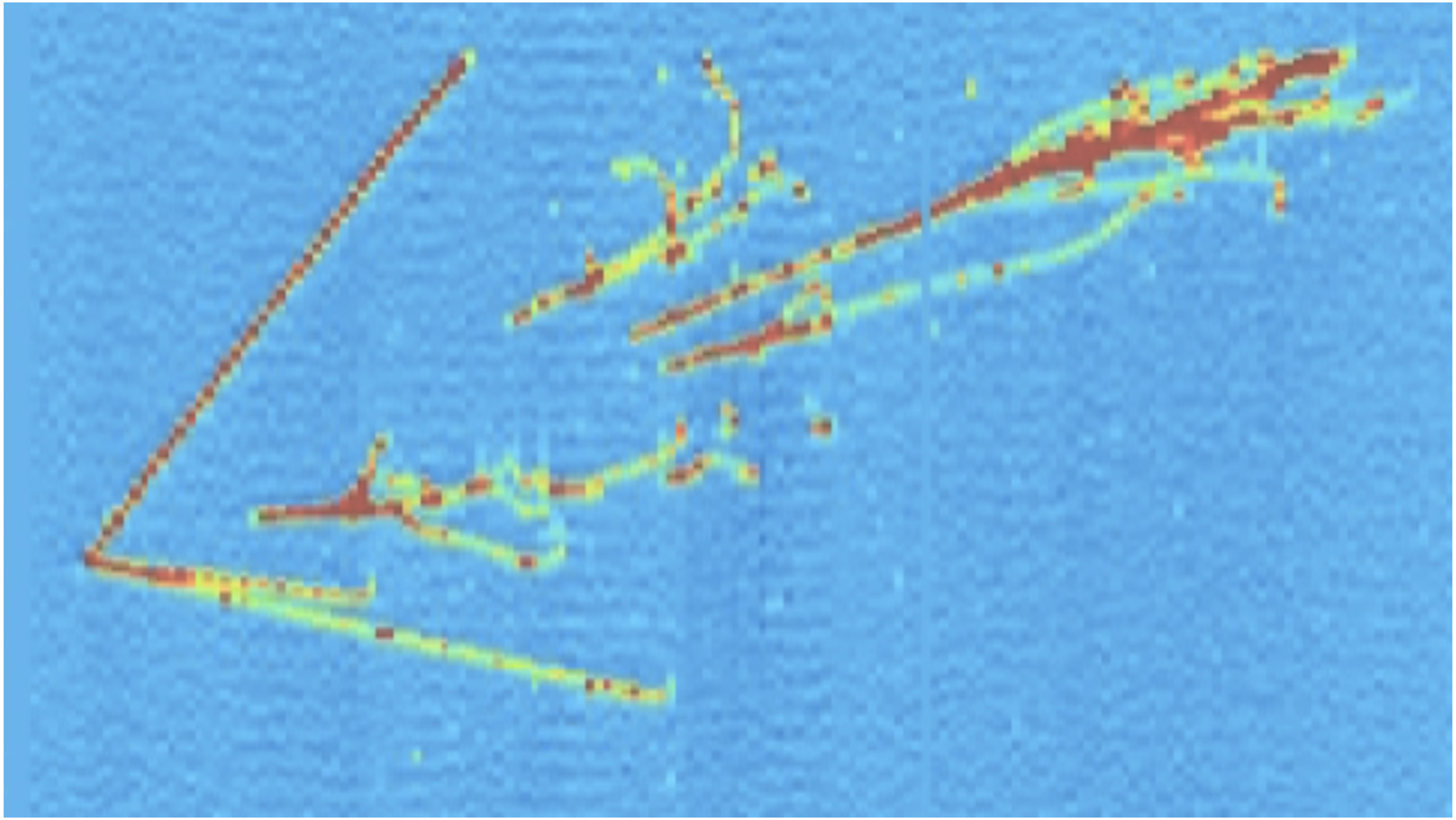
- If yes, would provide support* for the hypothesis of Leptogenesis as the mechanism for generating the matter-antimatter asymmetry in the universe

★ Strong motivation to aim for a definitive observation for CPV in the ν sector

- Ideally want "precise" measurement of CP phase

*not proof, since still need to connect low-scale ν CPV physics to the high-scale N CPV physics

2: How to Detect CPV with νs



Matter Effects

★ Even in the absence of CPV

$$P(\nu_\mu \rightarrow \nu_e) - P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e) \neq 0$$

Neutrinos travel through material that is not CP symmetric, i.e. matter not antimatter

★ Complicates the simple picture !!!!

$$P(\nu_\mu \rightarrow \nu_e) - P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e) =$$

ME $$\frac{16A}{\Delta m^2_{31}} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) c^2_{13} s^2_{13} s^2_{23} (1 - 2s^2_{13})$$

ME $$- \frac{2AL}{E} \sin\left(\frac{\Delta m^2_{31} L}{4E}\right) c^2_{13} s^2_{13} s^2_{23} (1 - 2s^2_{13})$$

CPV $$- 8 \frac{\Delta m^2_{21} L}{2E} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) \sin\delta \cdot s_{13} c^2_{13} c_{23} s_{23} c_{12} s_{12}$$

with $A = 2\sqrt{2} G_F n_e E = 7.6 \times 10^{-5} \mathrm{eV}^2 \cdot \frac{\rho}{\mathrm{g\,cm^{-3}}} \cdot \frac{E}{\mathrm{GeV}}$

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- ★ Complicates the simple picture !!!!

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) =$$ ← What we measure

ME $$\frac{16A}{\Delta m^2_{31}} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) c^2_{13} s^2_{13} s^2_{23} (1 - 2s^2_{13})$$ ← Small

ME $$- \frac{2AL}{E} \sin\left(\frac{\Delta m^2_{31} L}{4E}\right) c^2_{13} s^2_{13} s^2_{23} (1 - 2s^2_{13})$$ ← Proportional to L

CPV $$- 8\frac{\Delta m^2_{21} L}{2E} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) \sin\delta \cdot s_{13} c^2_{13} c_{23} s_{23} c_{12} s_{12}$$ ← What we want

with $A = 2\sqrt{2} G_F n_e E = 7.6 \times 10^{-5} \mathrm{eV}^2 \cdot \frac{\rho}{\mathrm{g\,cm^{-3}}} \cdot \frac{E}{\mathrm{GeV}}$

Experimental Strategy

EITHER:

- ★ Keep L small (~200 km): so that matter effects are insignificant
  - First oscillation maximum:

$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2} \Rightarrow E_\nu < 1\,\text{GeV}$$

  - Since $\sigma \propto E_\nu$ need a high flux at oscillation maximum

⇨ Off-axis beam: narrow range of neutrino energies

OR:

- ★ Make L large (>1000 km): measure the matter effects (i.e. MH)
  - First oscillation maximum:

$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2} \Rightarrow E_\nu > 2\,\text{GeV}$$

  - **Unfold CPV from Matter Effects through E dependence**

⇨ On-axis beam: wide range of neutrino energies

Experimental Strategy

EITHER:

★ Keep L small (~200 km): so that matter effects are insignificant

- First oscillation maximum:

$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2}$$

- Since ... high flux at oscillation maximum

⇨ Off-axis beam: narrow range of neutrino energies

Hyper-Kamiokande

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★ Make L large (>1000 km): measure the matter effects (i.e. MH)

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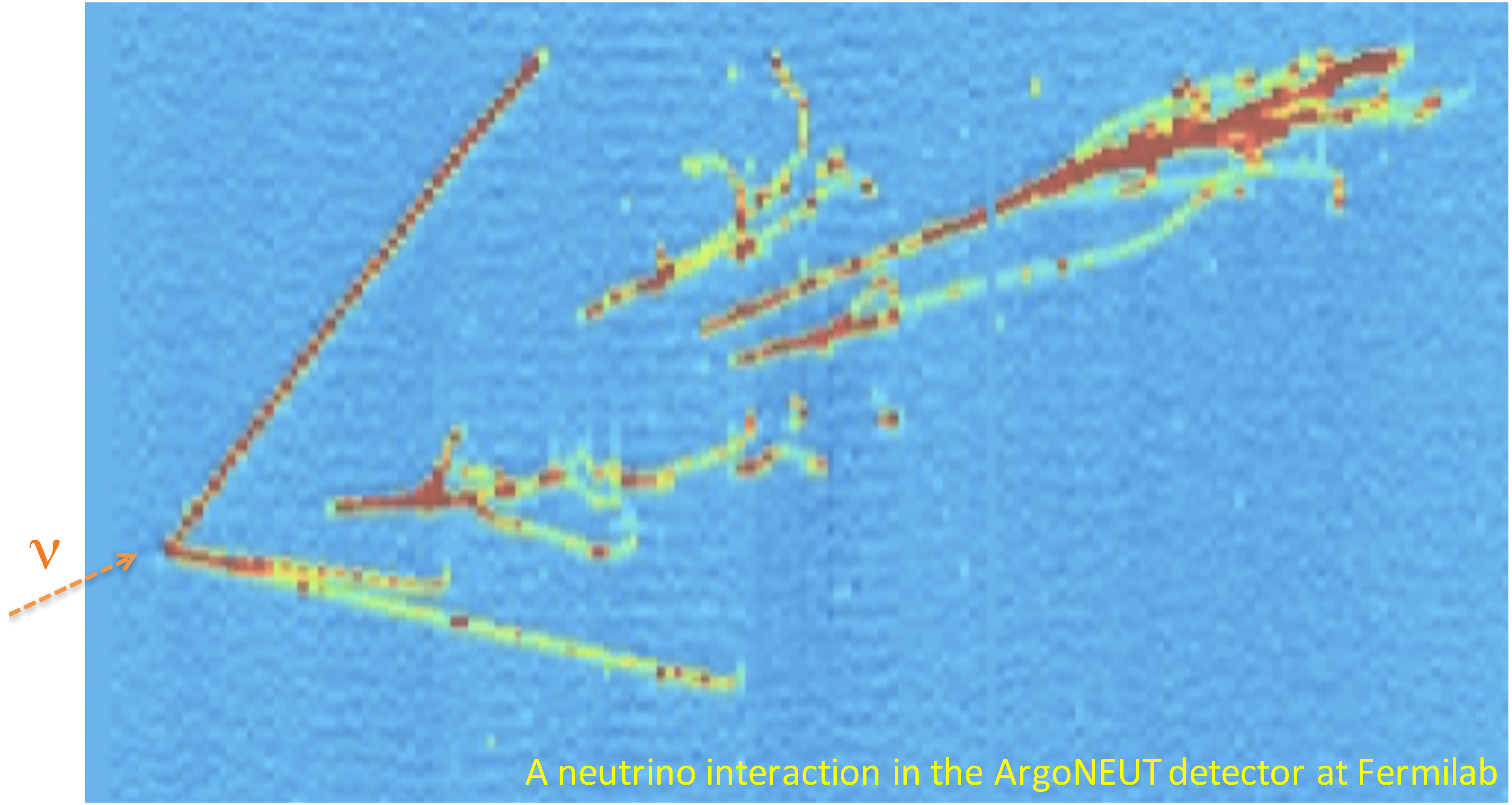
- **Unfold CPV from ... through E dependence**

⇨ On-axis beam: wide range of neutrino energies

DUNE

3. DUNE Science Strategy

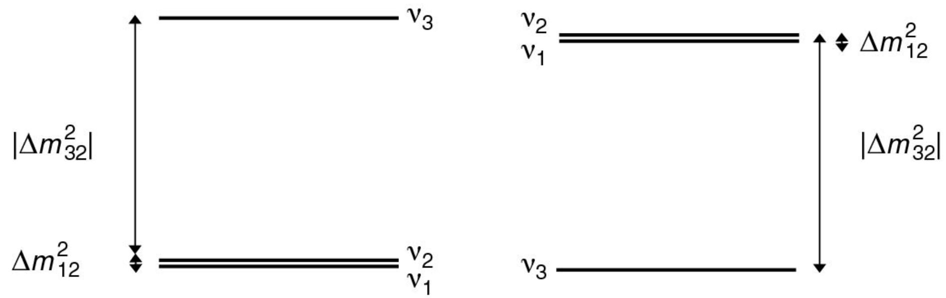
Unprecedented precision utilizing a massive Liquid Argon TPC



DUNE Primary Science Program

Focus on fundamental open questions in particle physics and astroparticle physics:

- **1) Neutrino Oscillation Physics**
  - **Discover CP Violation** in the leptonic sector
  - Mass Hierarchy
  - Precision Oscillation Physics:
    - e.g. parameter measurement, θ_{23} octant, **testing the 3-flavor paradigm**



- **2) Nucleon Decay**
  - e.g. targeting SUSY-favored modes, $p \rightarrow K^+\bar{\nu}$
- **3) Supernova burst physics & astrophysics**
  - Galactic core collapse supernova, sensitivity to ν_e

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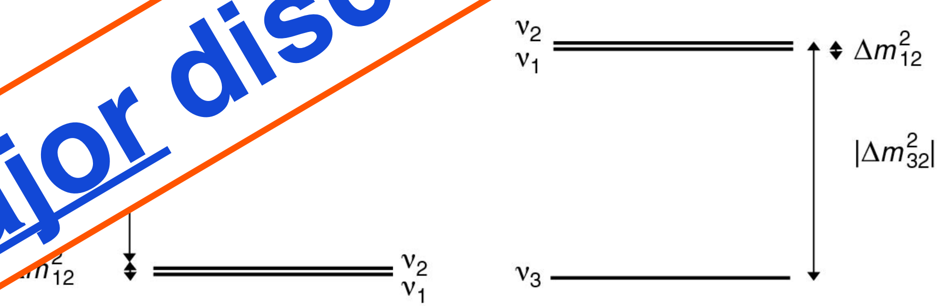


All would be major discoveries

DUNE Ancillary Science Program

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

- **Other neutrino oscillation physics with BSM sensitivity**
  - Neutrino non-standard interactions (NSIs)
  - Sterile Neutrinos at the near and far sites
  - Measurements of tau neutrino appearance

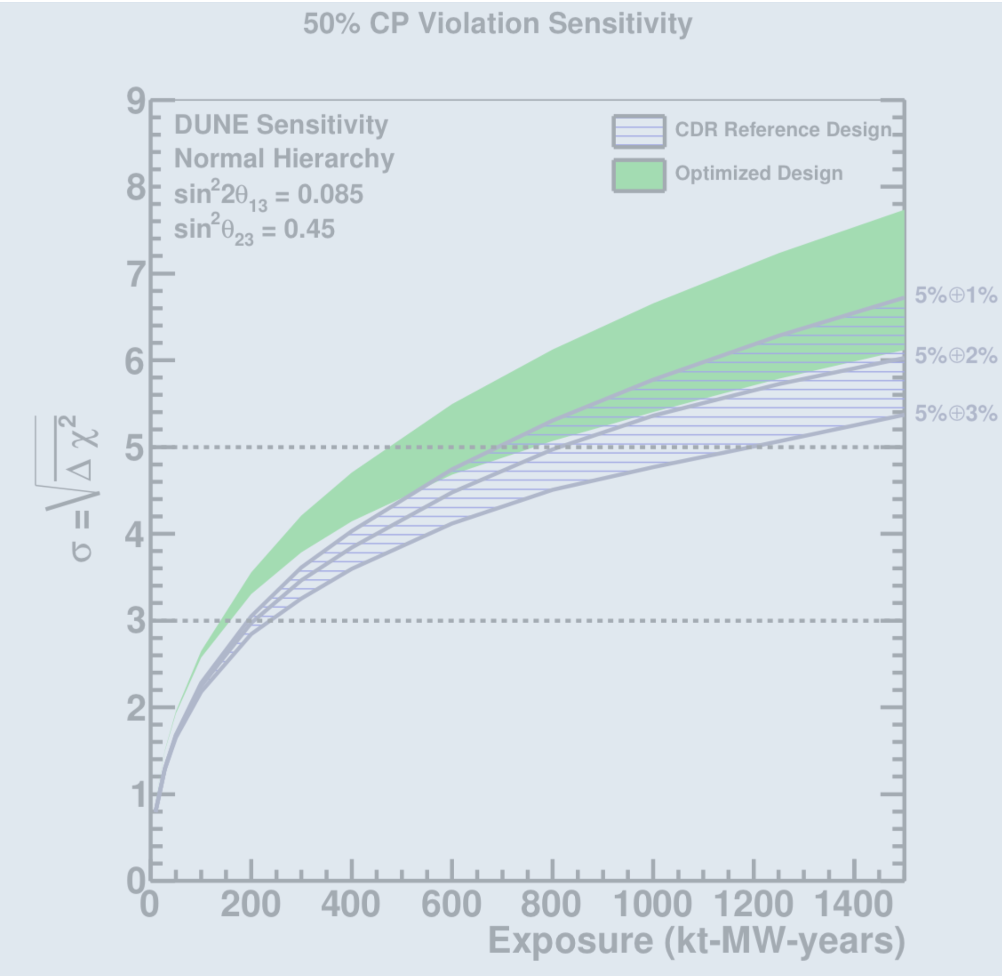
  Benefit from wide band beam

- **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 $\sin^2\theta_W$

  > 100M neutrino interactions in a few years of operation

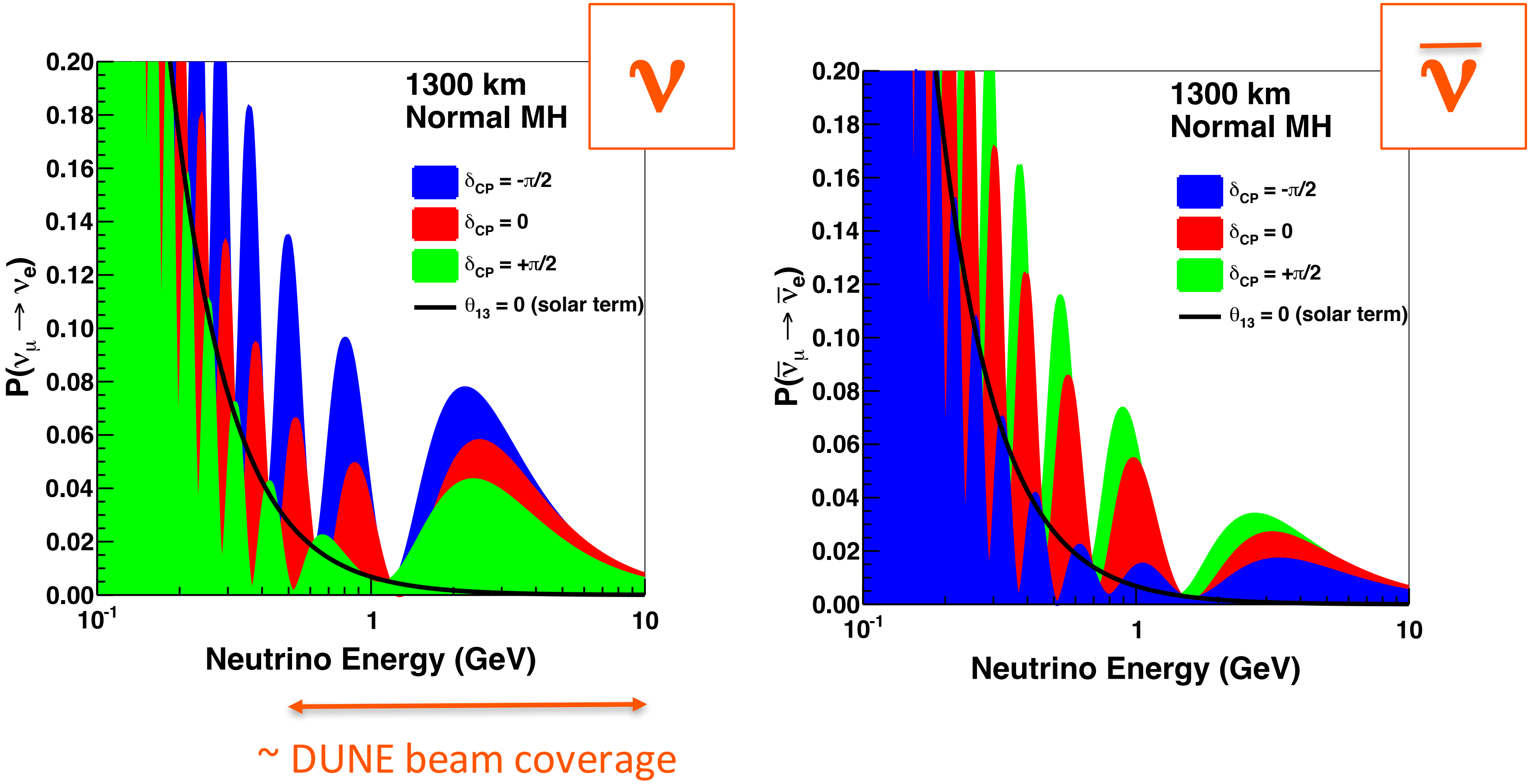
- **Search for signatures of Dark Matter**

4: DUNE Neutrino Oscillations



Neutrino Oscillations

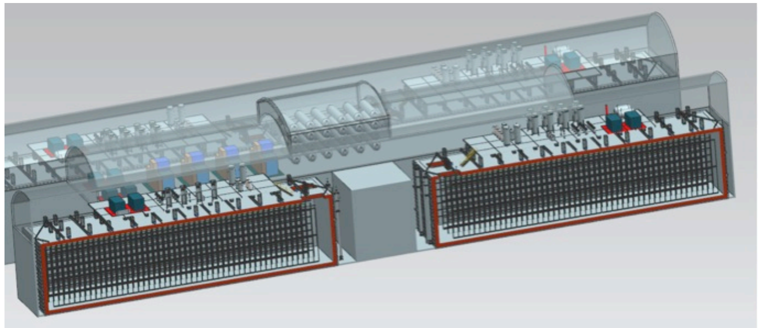
Measure neutrino spectra at 1300 km in a wide-band beam



- ★ LBNF beam covers first and second oscillation maxima
  - CP dependence varies with energy

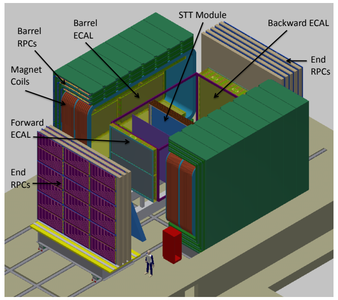
Sensitivities based on…

- **Far detector: 40-kt LAr-TPC**



For more details refer to DUNE CDR

- **Assumed systematics uncertainties including Near Detector data: Multi-purpose high-resolution detector**



For more details refer to DUNE CDR

- Beam and detector staging project plan based on expected funding profile

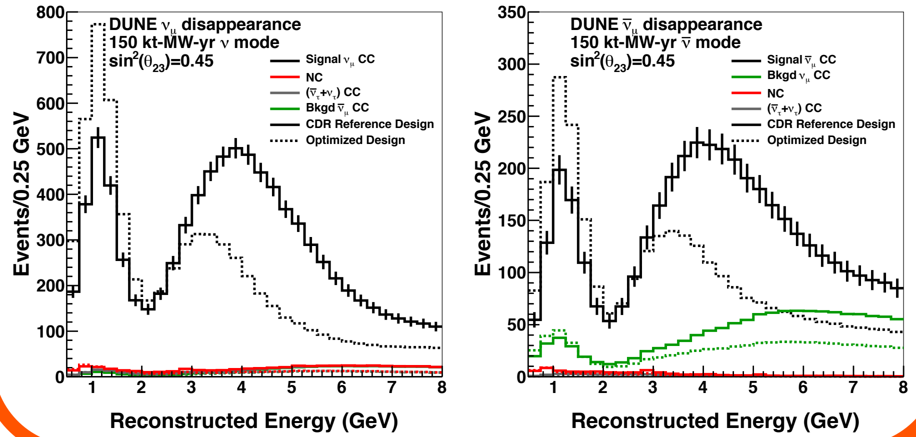
DUNE Oscillation Strategy

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

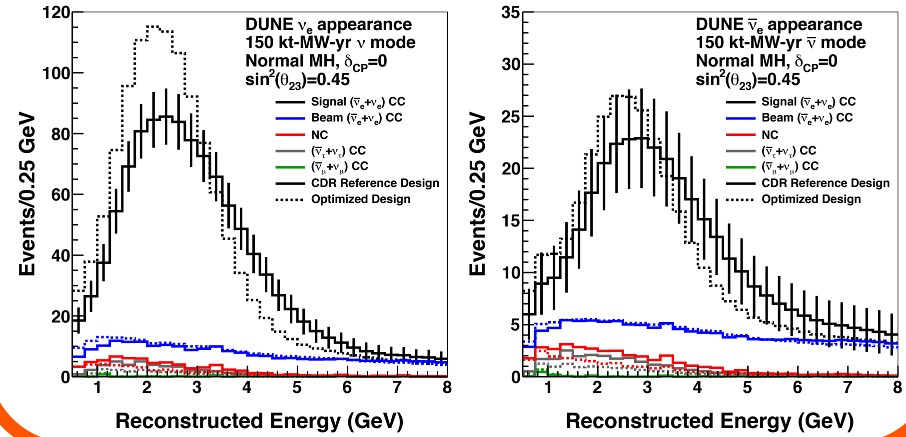
- **Determine MH and θ_{23} octant, probe CPV, test 3-flavor paradigm and search for BSM effects (e.g. NSI) in a single experiment**
  - Long baseline:
    - Matter effects are large ~ 40%
  - Wide-band beam:
    - Measure ν_e appearance and ν_μ disappearance over range of energies
    - MH & CPV effects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

E ~ few GeV

ν_μ / $\bar{\nu}_\mu$ disappearance



ν_e / $\bar{\nu}_e$ appearance

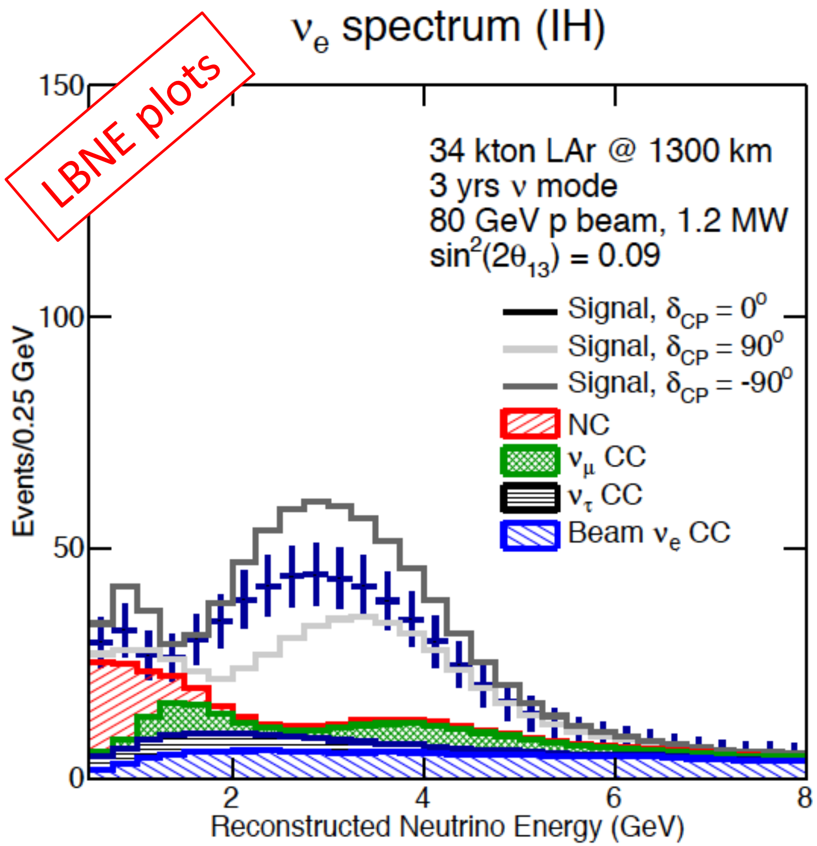


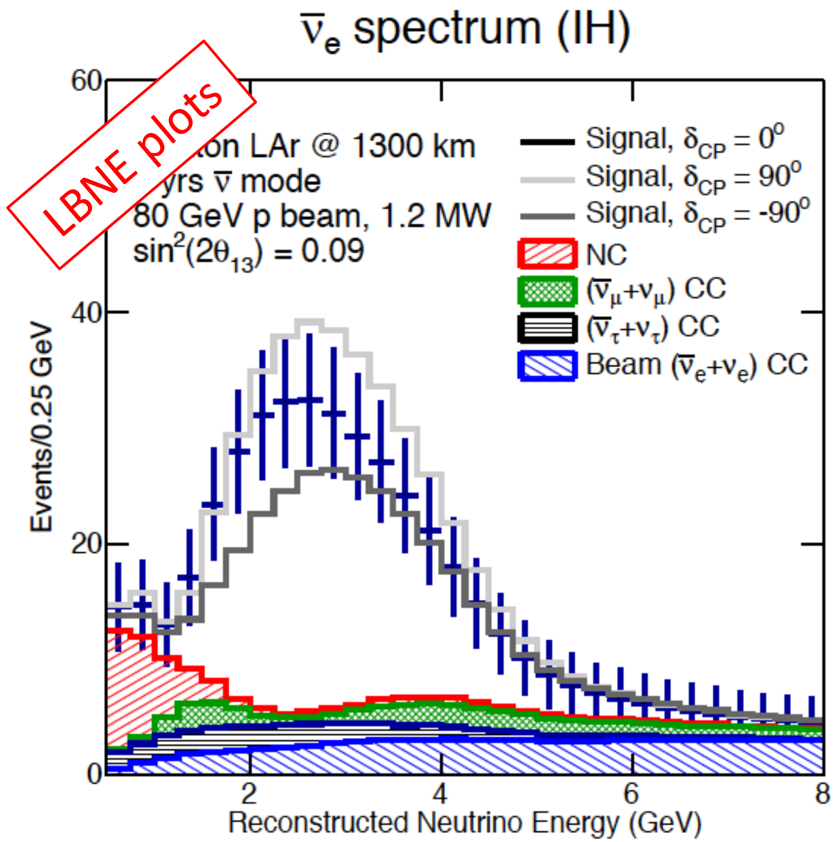
Separating MH & CPV

DUNE: **Determine MH and probe CPV in a single experiment**

Recall: $$\mathcal{A} = P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = \mathcal{A}_{CP} + \mathcal{A}_{Matter}$$

with different energy dependence





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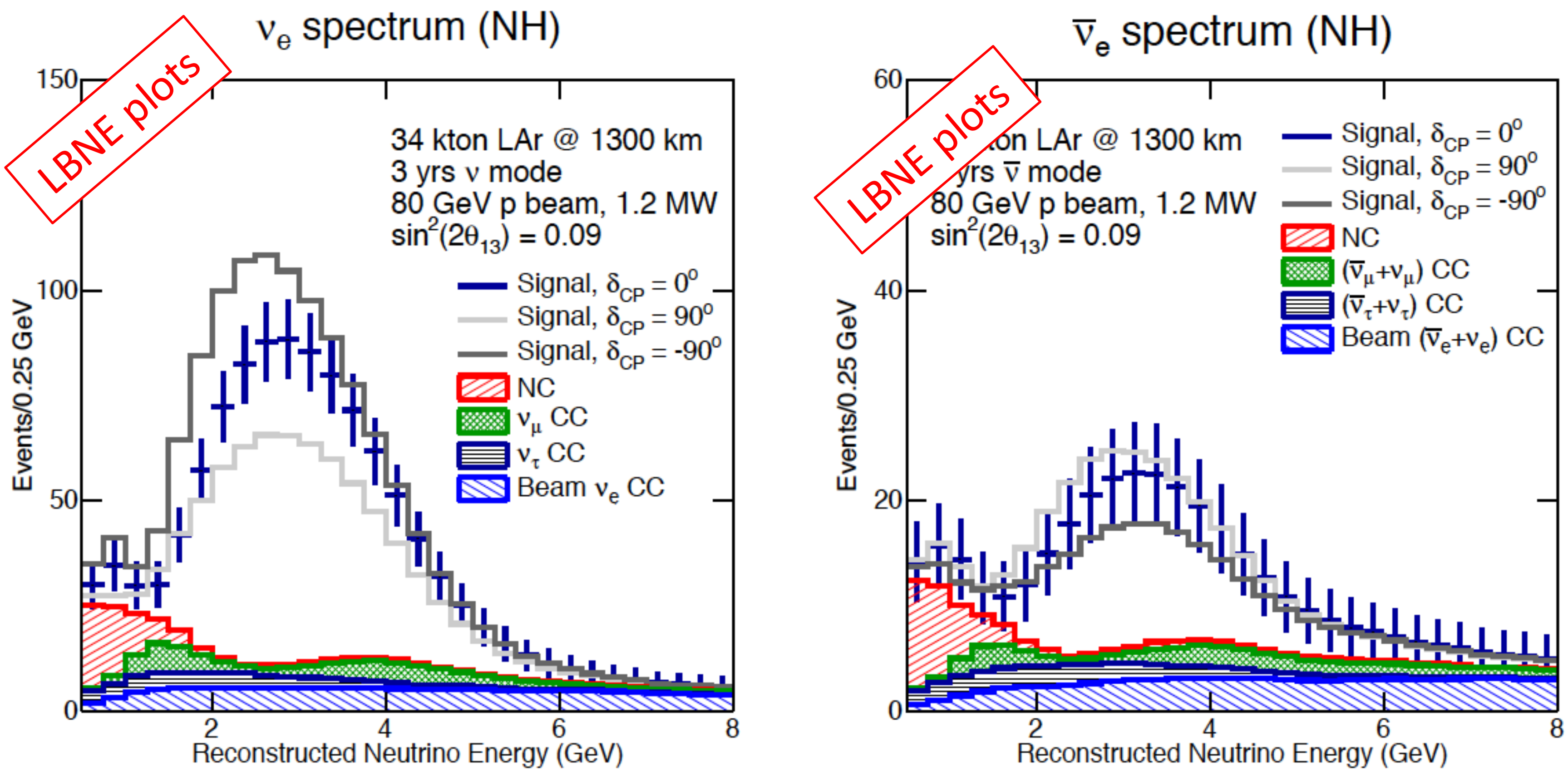
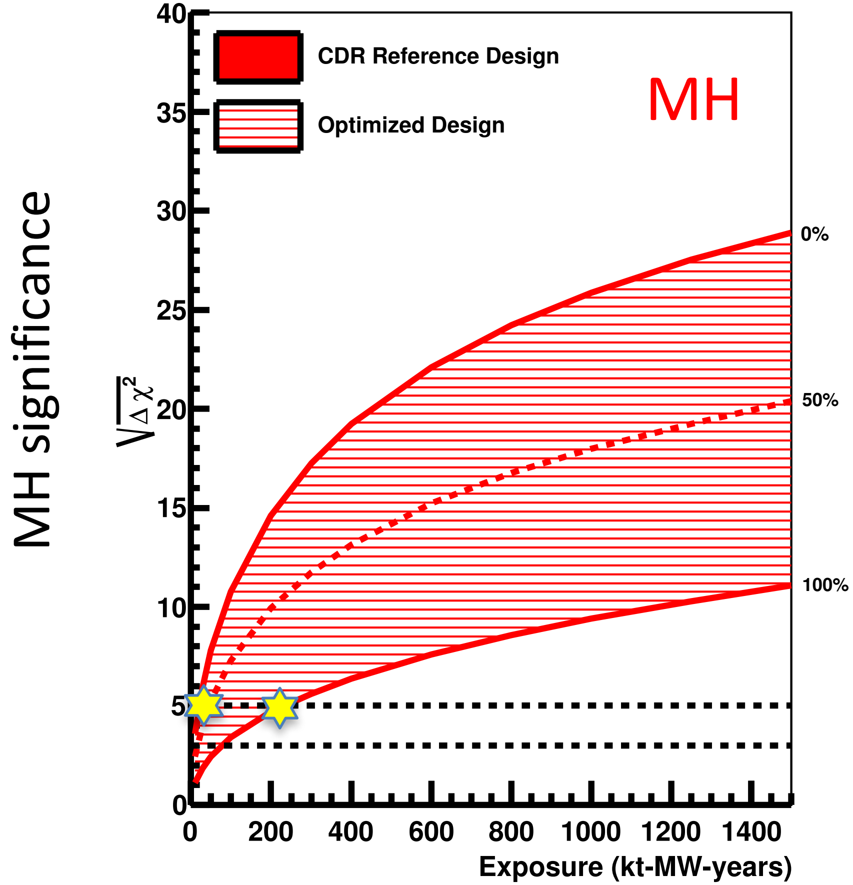


MH Sensitivity

★ Sensitivities depend on multiple factors:
- Other parameters, e.g. δ
- Details of beam spectrum, …



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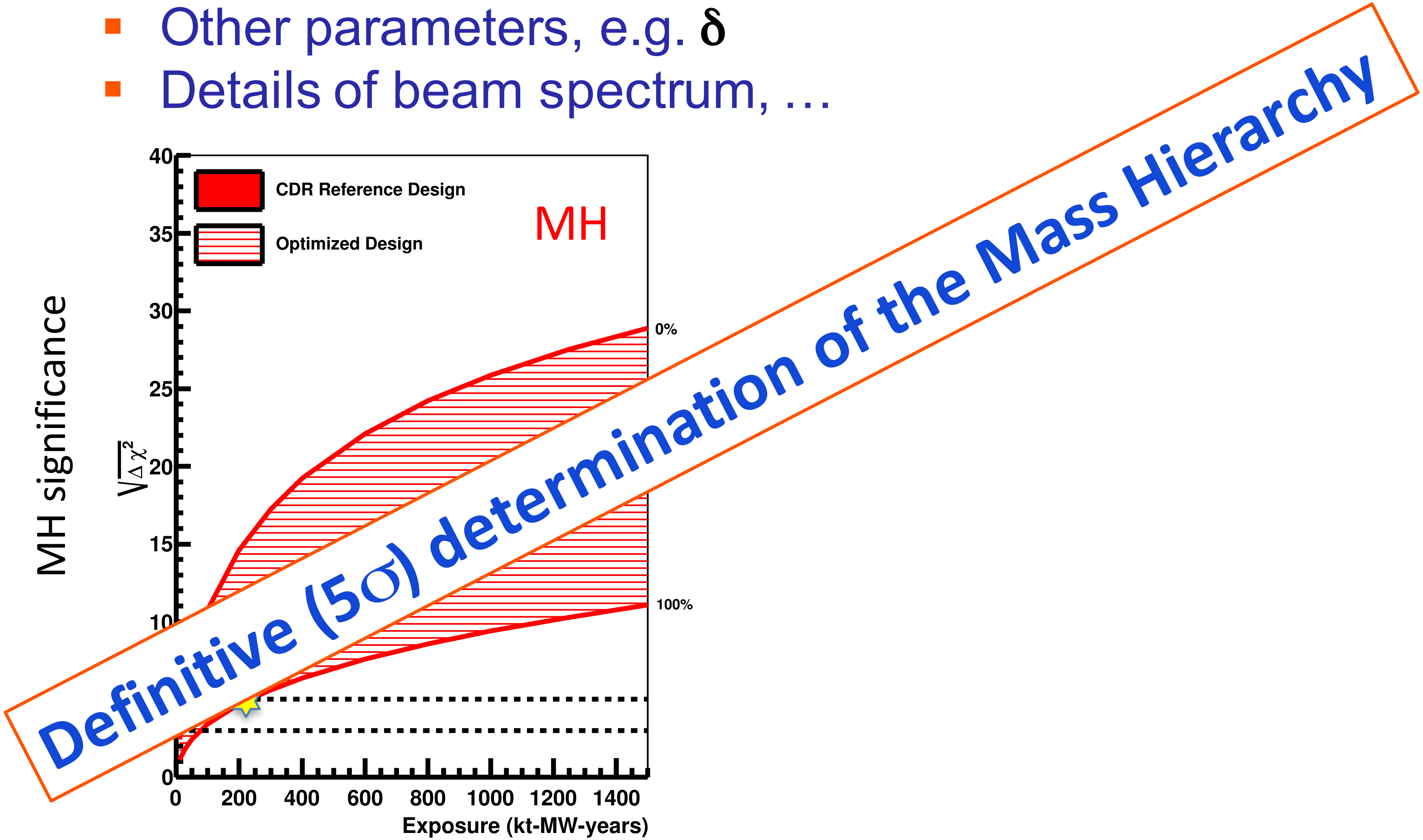

MH and CPV Sensitivities

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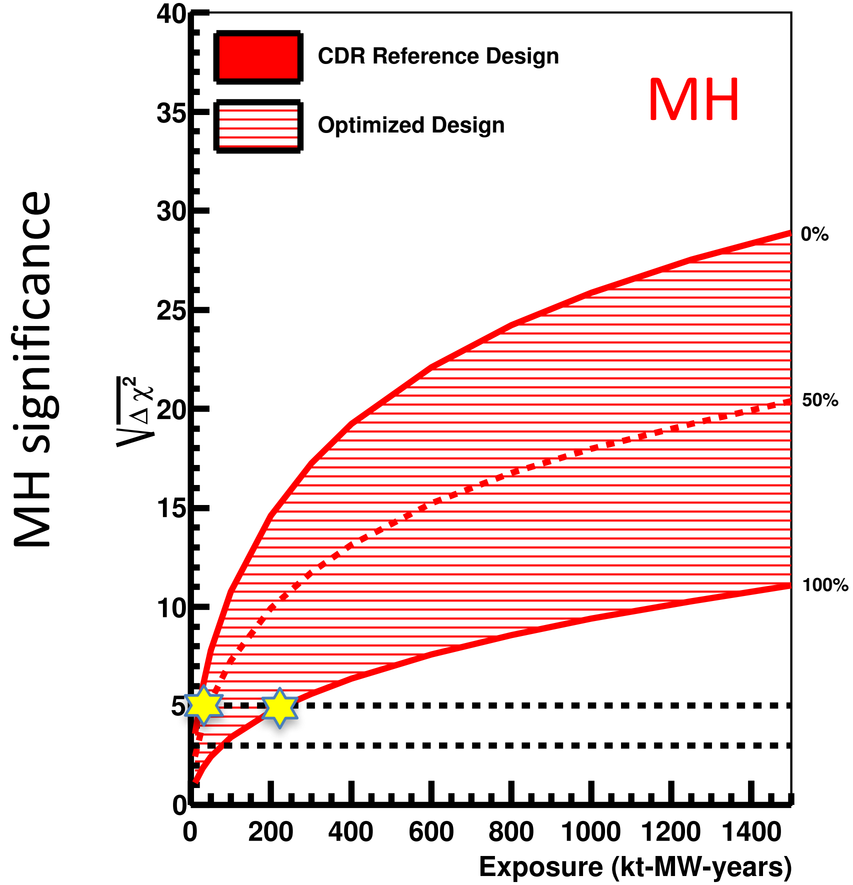

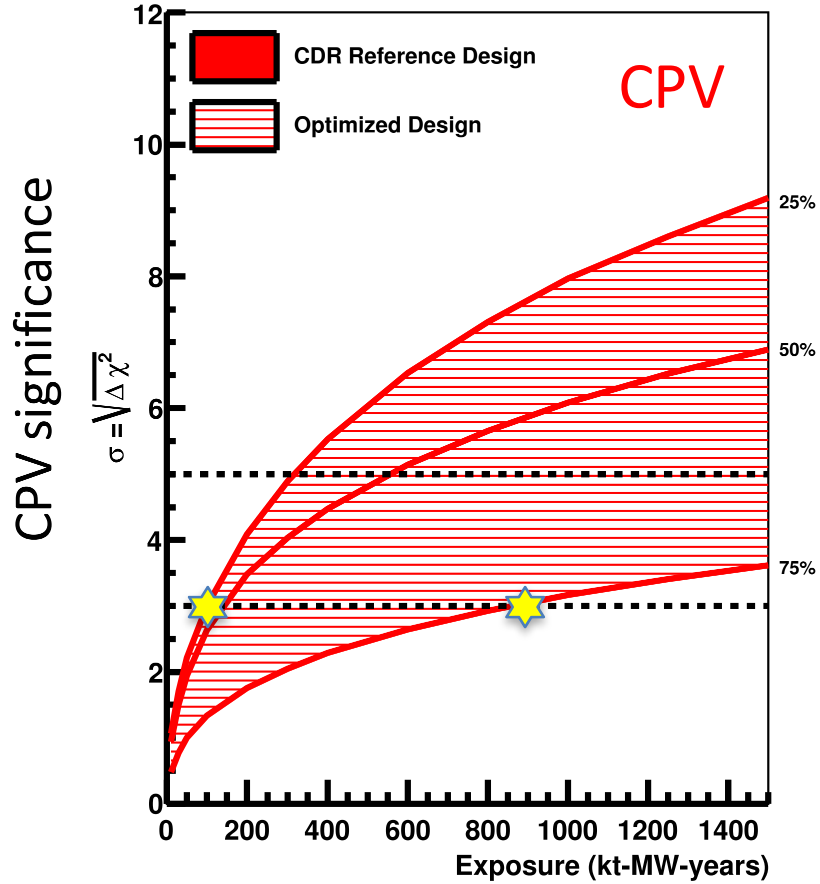

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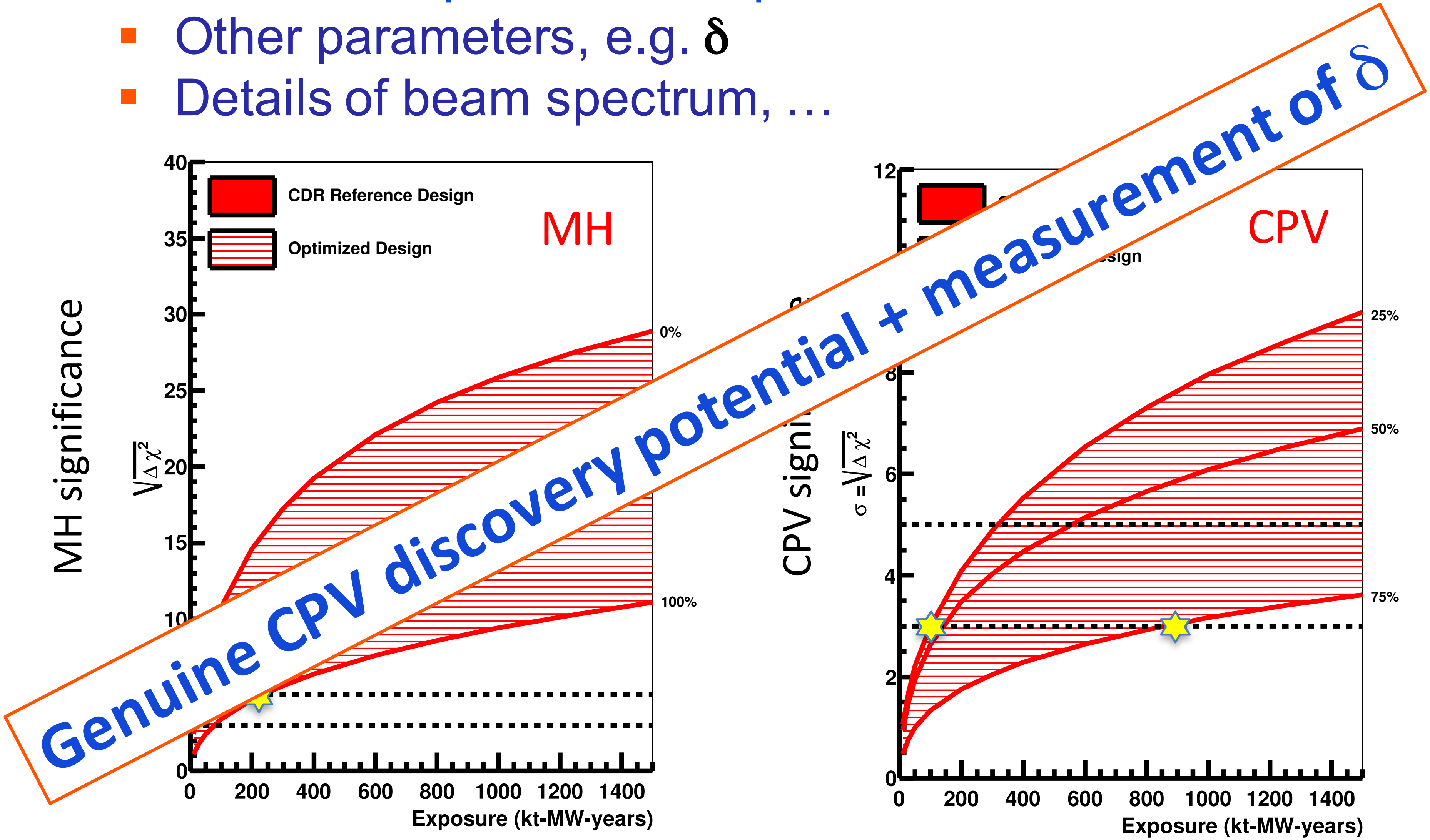
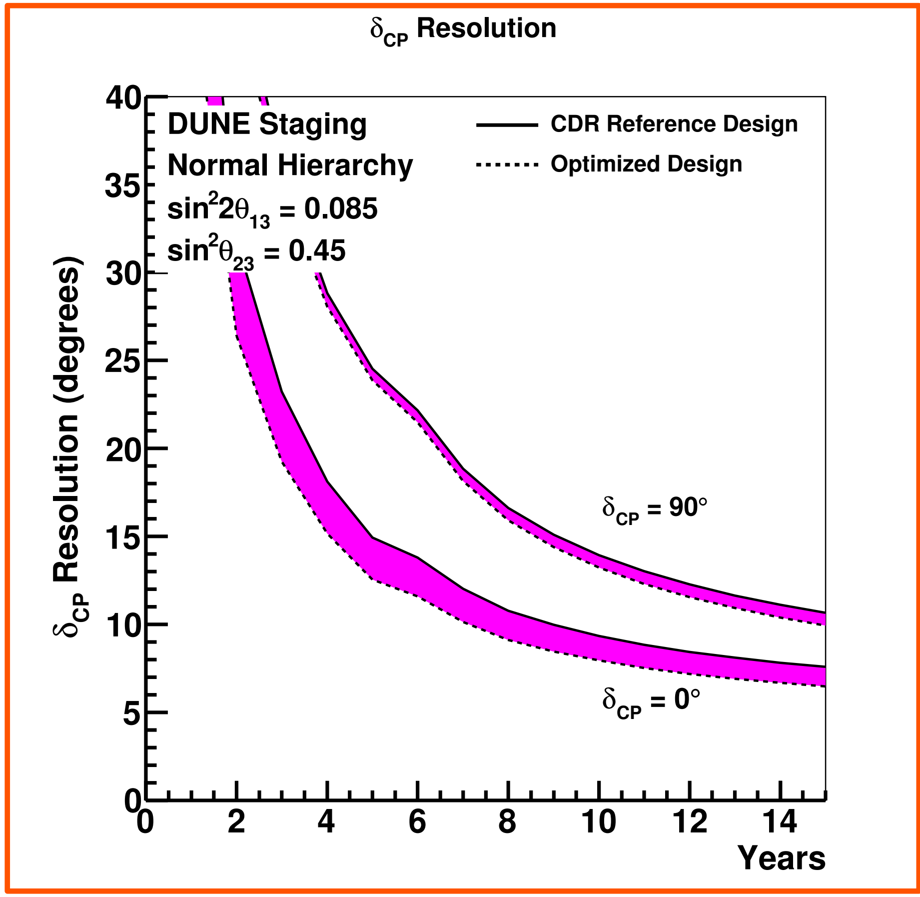


Beyond discovery: measurement of δ

- ★ CPV "coverage" is just one way of looking at sensitivity…
- ★ Can also express in terms of the uncertainty on **δ**



Start to ~approach current level of precision on quark-sector CPV phase (although takes time)

Timescales: year zero = 2026

Rapidly reach scientifically interesting sensitivities:

- e.g. in best-case scenario for Mass Hierarchy :
  - **Reach 5σ MH sensitivity with 20 kt.MW.year**

Discovery

~2 years

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

Strong evidence

~3-4 years

- e.g. in best-case scenario for CPV ($\delta_{CP} = +\pi/2$) :
  - **Reach 5σ CPV sensitivity with 210 kt.MW.year**

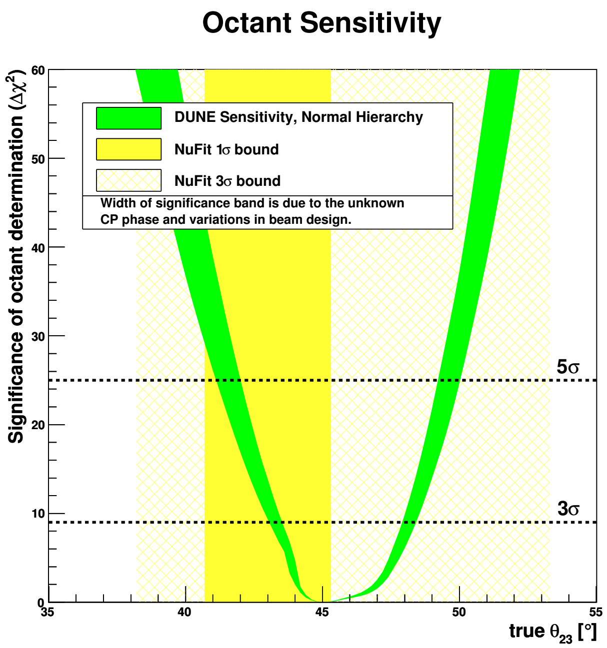
Discovery

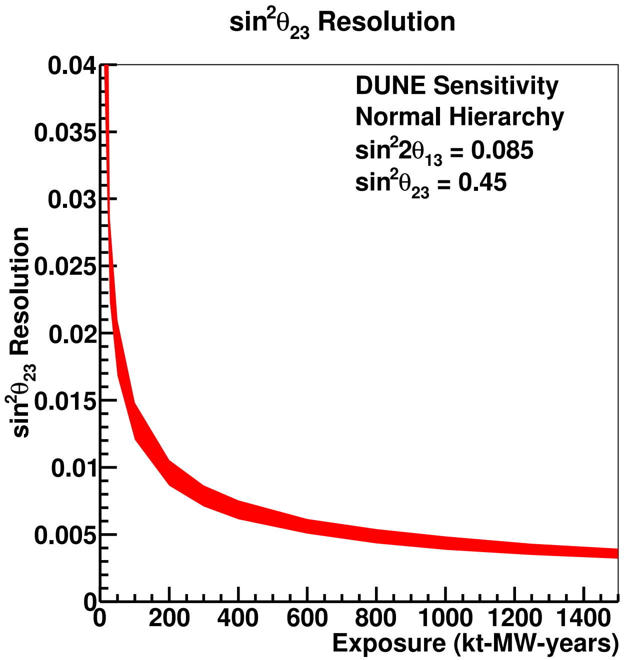
~6-7 years

★ **Genuine potential for early physics discovery**

Other oscillation measurements…

★ e.g. resolution of θ_{23} octant

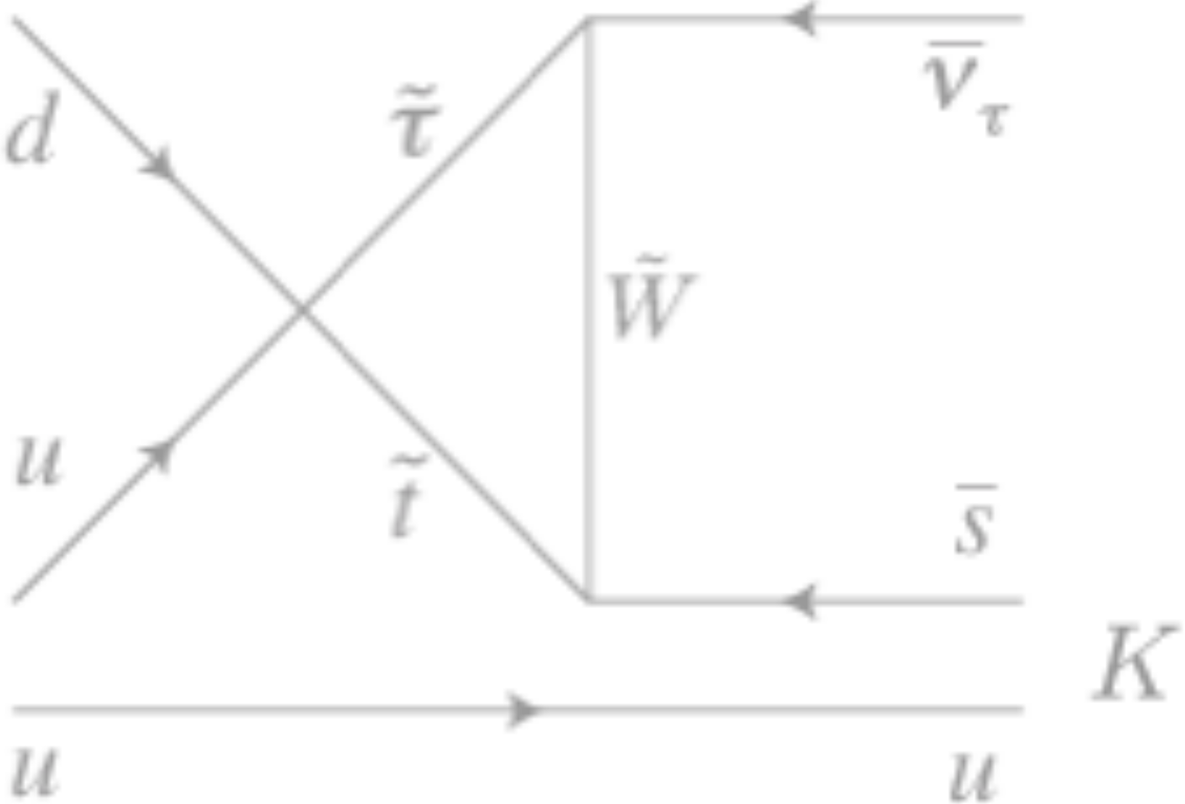




★ **NOTE:** in a wide-band beam, determine many parameters in a single experiment

➡ **+ precision test of 3-flavour paradigm**

5. Proton Decay

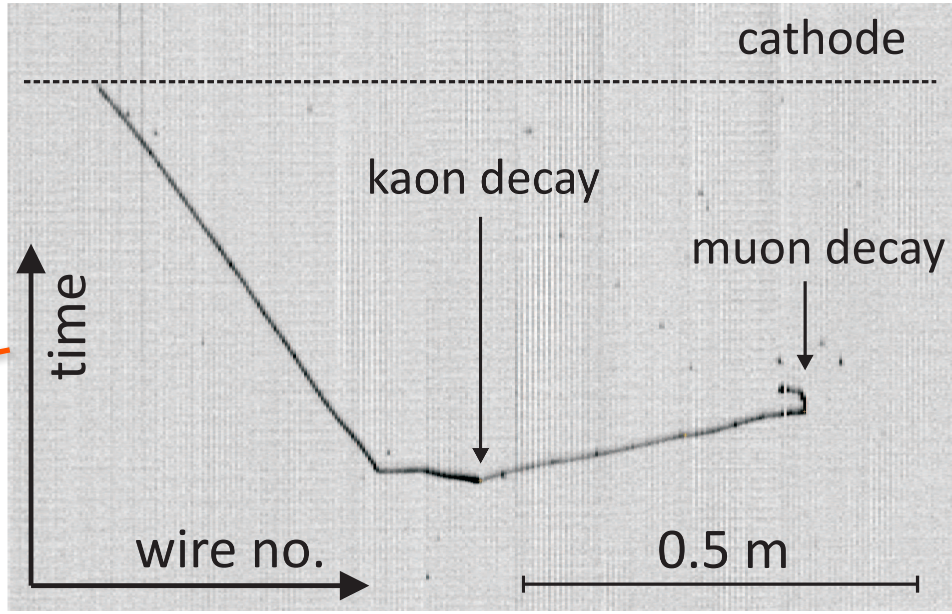


5. Proton Decay

Nucleon (proton) decay is expected in most new physics models – not yet observed

- **Image particles from a single nucleon decay in detector volume**
  - For example, look for kaons (from d*E*/d*x*) from SUSY-inspired GUT p-decay modes such as $p \rightarrow K^{+}\overline{\nu}$

E ~ O(200 MeV)



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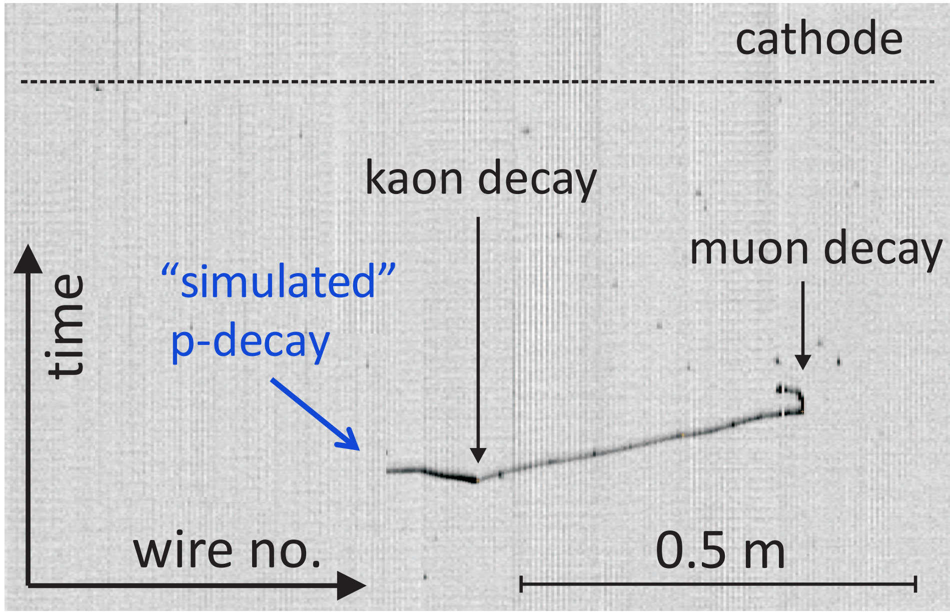
Clean signature in LAr

Remove incoming cosmic ray



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Clean signature in LAr

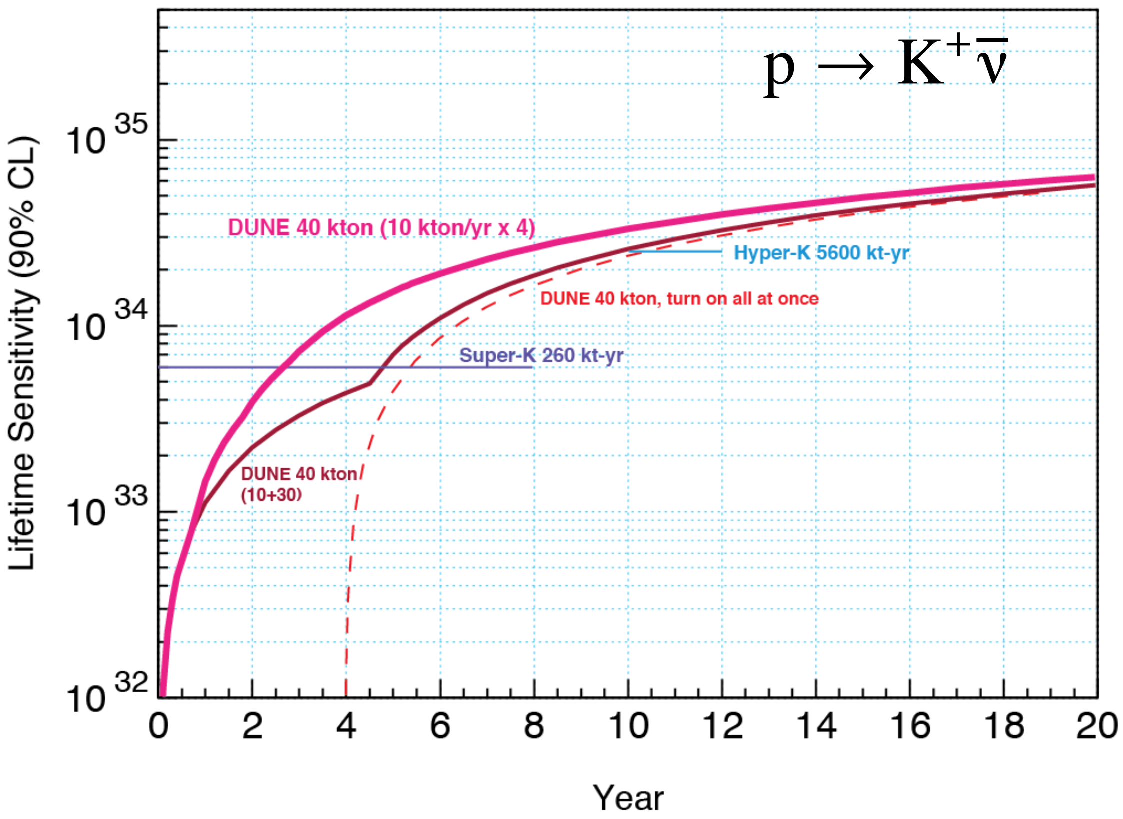
Decay Mode	Water Cherenkov		Liquid Argon TPC	
	Efficiency	Background	Efficiency	Background
$p \rightarrow K^+\overline{\nu}$	19%	4	97%	1
$p \rightarrow K^0\mu^+$	10%	8	47%	< 2
$p \rightarrow K^+\mu^-\pi^+$			97%	1
$n \rightarrow K^+e^-$	10%	3	96%	< 2
$n \rightarrow e^+\pi^-$	19%	2	44%	0.8

1 Mt.yr

Proton Decay

★ **The clean signatures for kaon modes**

➡ Highly competitive measurements with larger water Cherenkov detectors



6. Supernova νs

Supernova νs

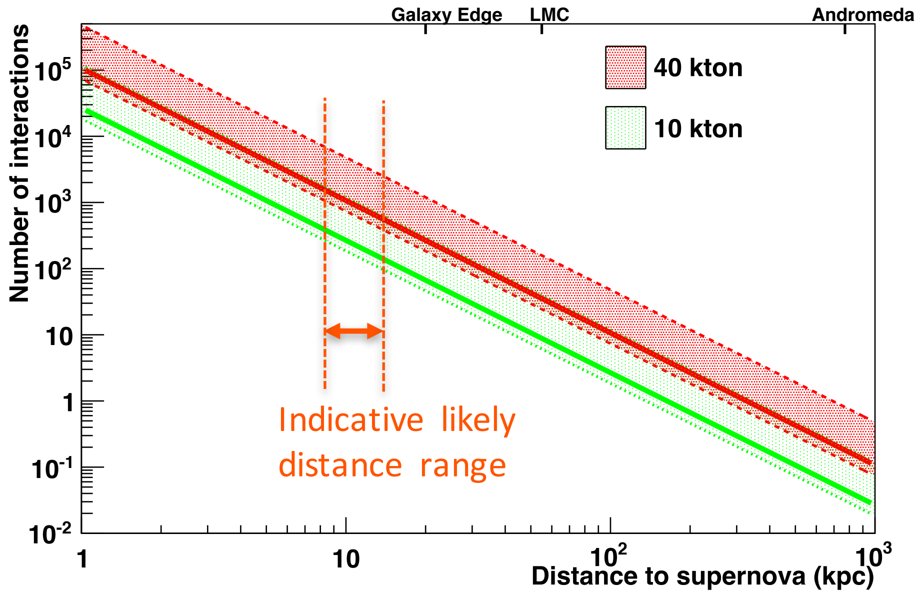
A core collapse supernova produces an incredibly intense burst of neutrinos

- Measure energies and times of neutrinos from galactic supernova bursts
  - In argon (uniquely) the largest sensitivity is to ν_e

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

→ ~3000 interactions @ 10 kpc

Channel	Events "Livermore" model
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	2720
$\overline{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	230
$\nu_x + e^- \rightarrow \nu_x + e^-$	350
Total	3300



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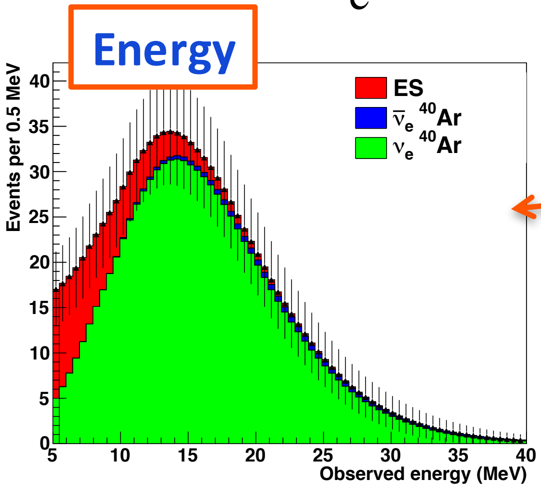
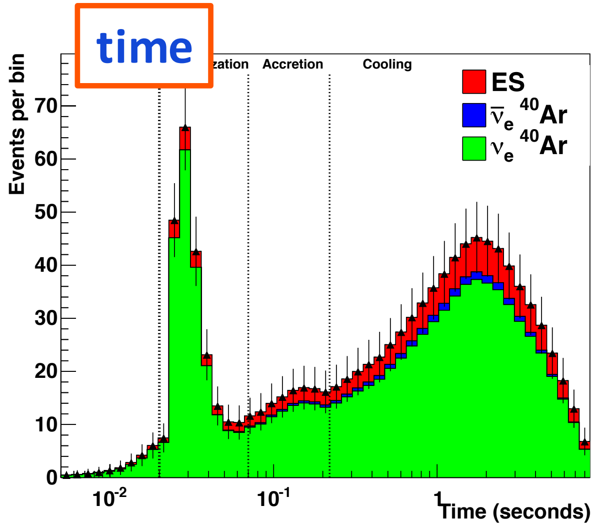


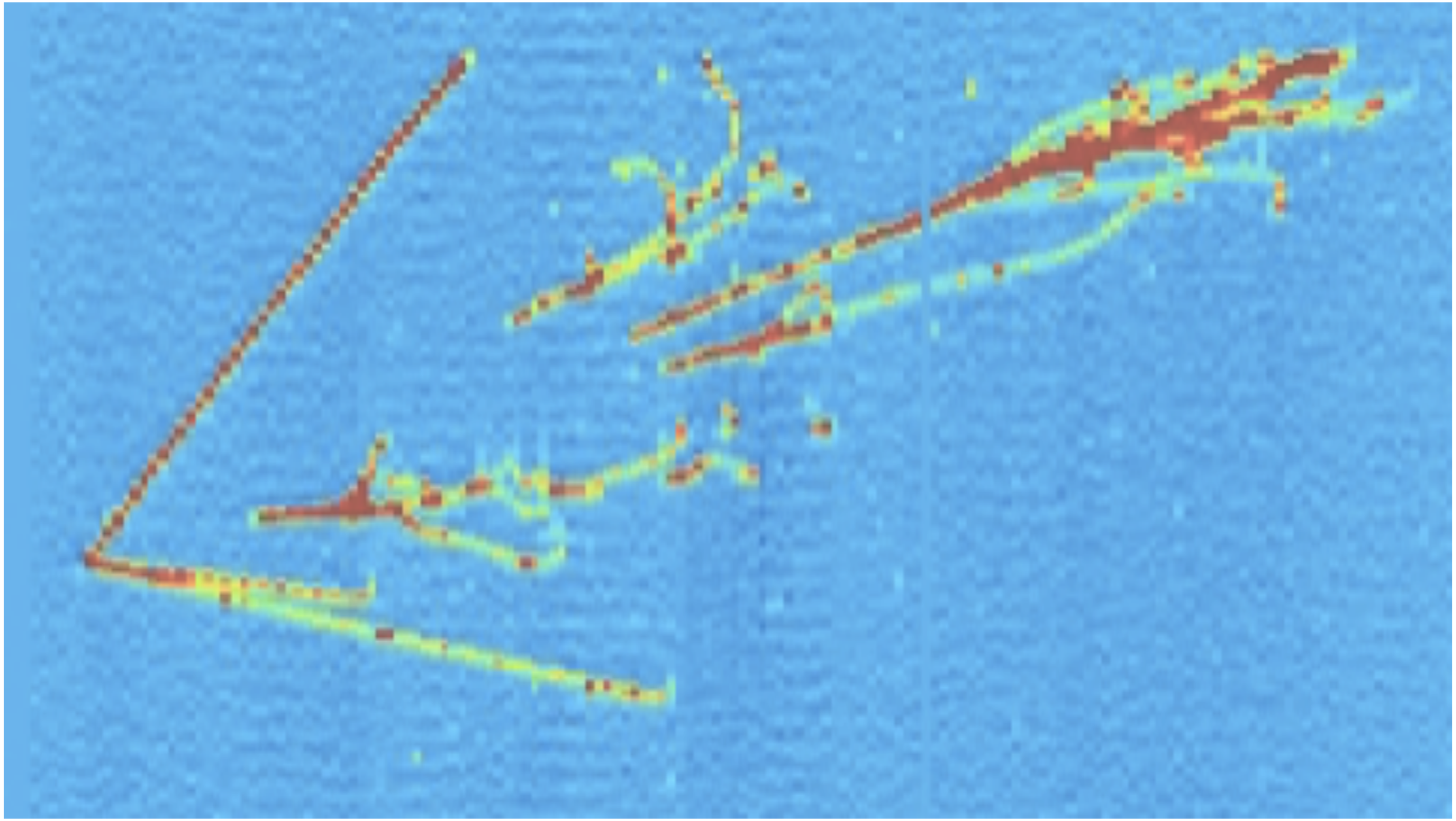
E ~ O(10 MeV)



Physics Highlights include:

- Possibility to "see" neutron star formation stage
- Even the potential to see black hole formation !

7. Scientific Opportunities



Scientific Opportunities

★ **For DUNE CDR** (July 2015)

- Neutrino Physics sensitivities based on:
  - Detailed physics simulation
  - Well-motivated single particle response
  - "fast" parametric MC

  ⇨ some assumptions probably quite conservative

★ **For DUNE TDR**

- Neutrino Physics sensitivities will be based on:
  - Full physics and detector simulation
  - Full reconstruction
  - Complete MC analysis chain
- Very significant undertaking

  ⇨ **major opportunity for additional scientific effort**
- + complete survey of DUNE science capabilities

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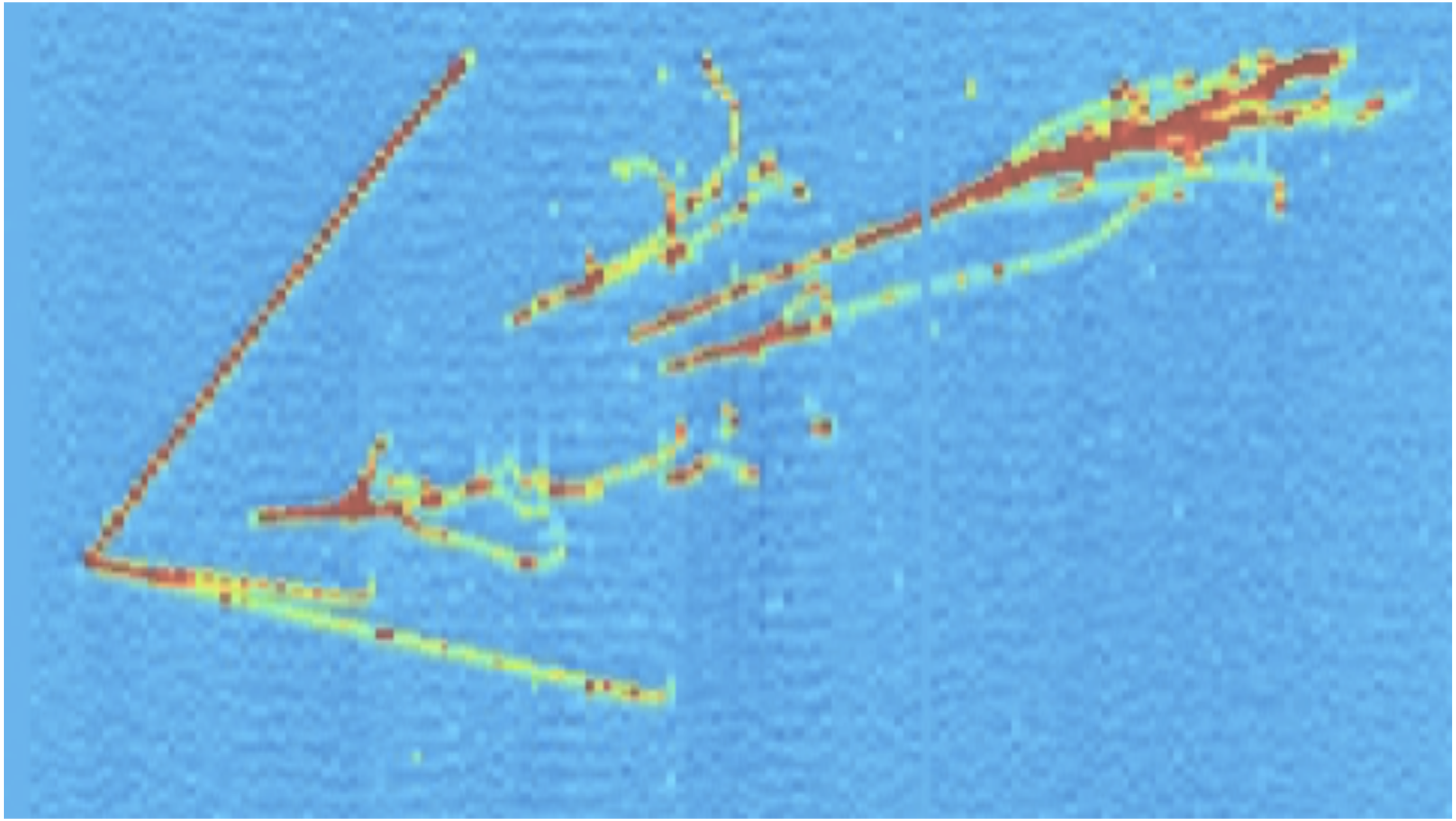
  - ⇒ **major opportunity for additional scientific effort**
- + complete survey of DUNE science capabilities

Opportunities to make major contributions to DUNE science

8. Summary

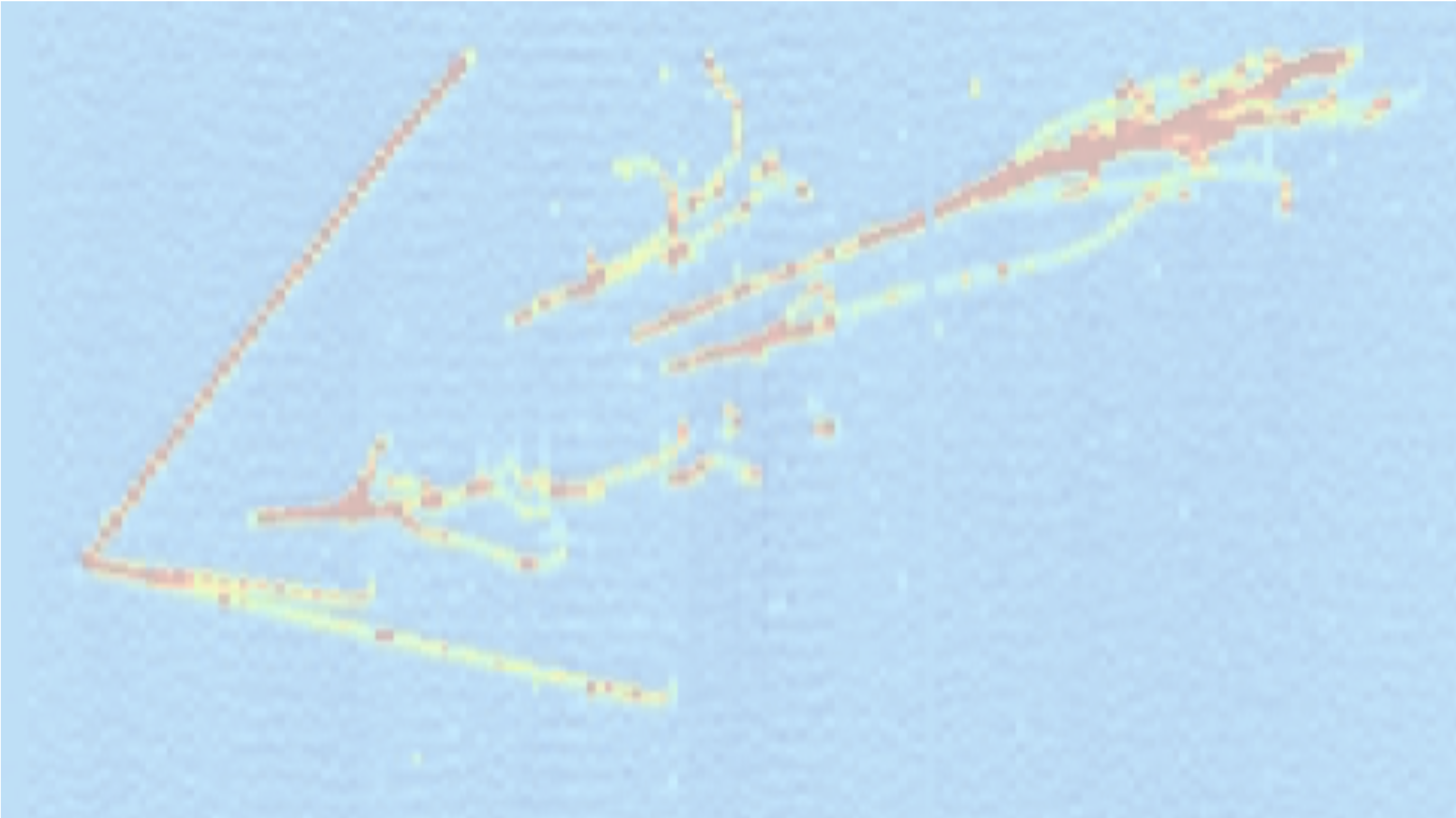


DUNE Science Summary

DUNE physics:

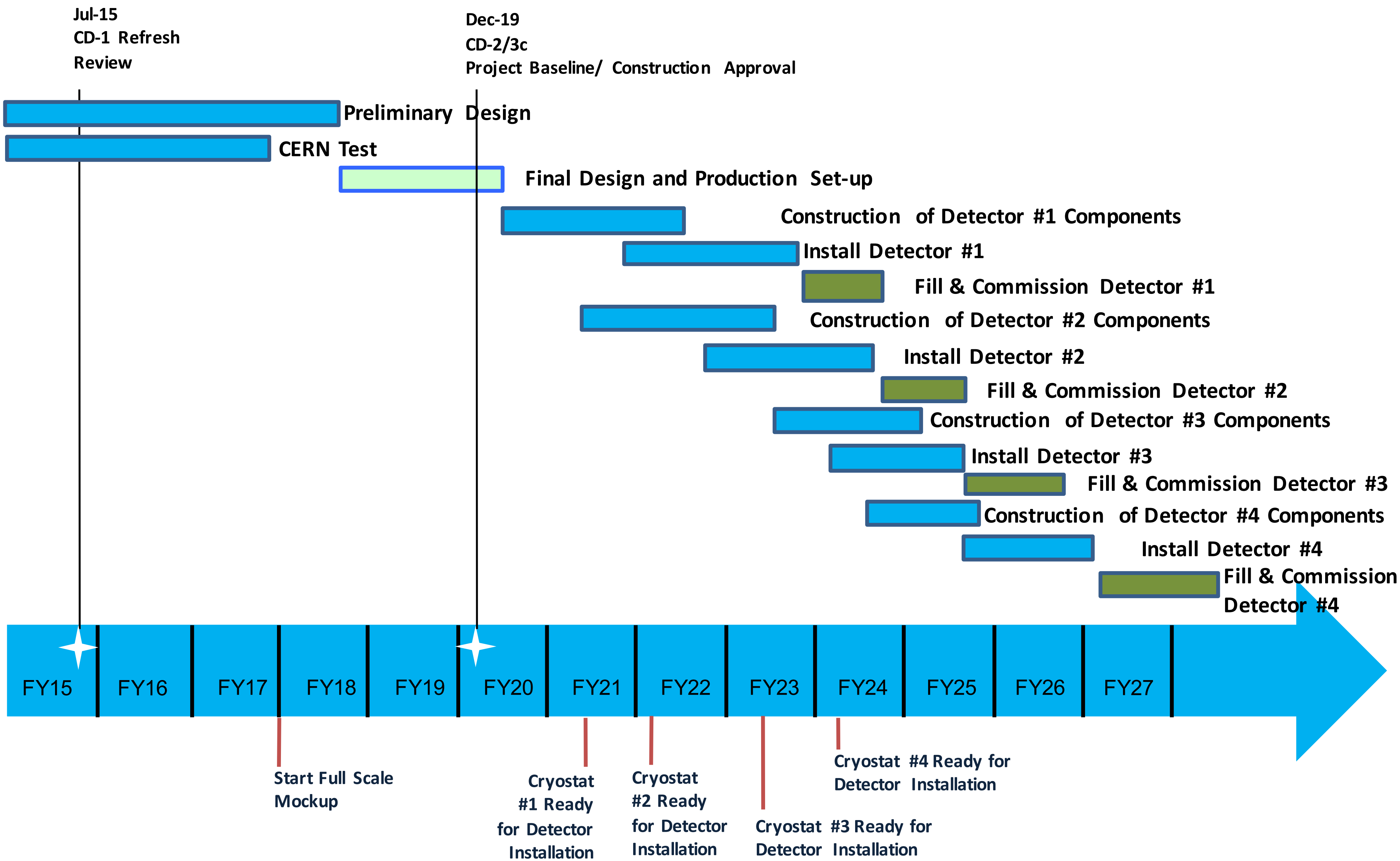
- **Game-changing program in Neutrino Physics**
  - Definitive 5σ determination of MH
  - Probe leptonic CPV
  - Precisely test 3-flavour oscillation paradigm
- **Potential for major discoveries in astroparticle physics**
  - Extend sensitivity to nucleon decay
  - Unique measurements of supernova neutrinos (if one should occur in lifetime of experiment)
- **+ much more…**

Thank you for your attention

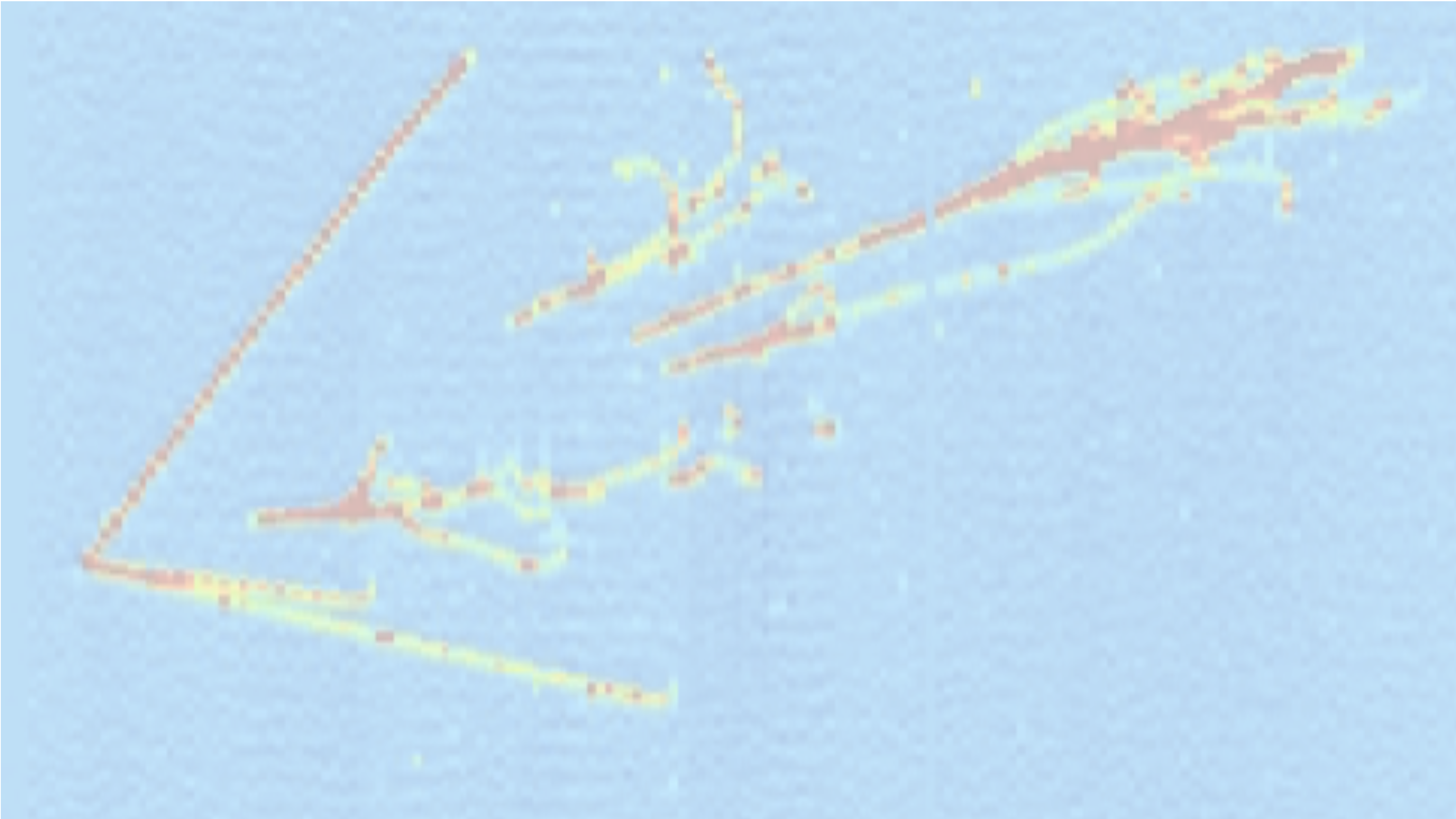


Backup Slides

Indicative schedule



Calculating Sensitivies



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

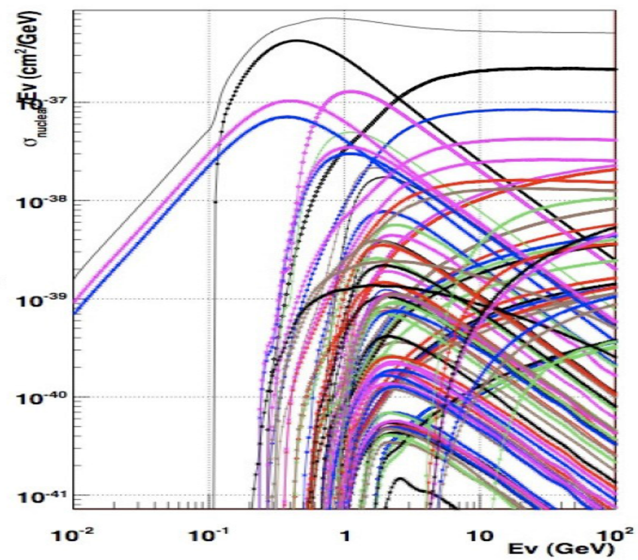
Evaluating DUNE Sensitivities I

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

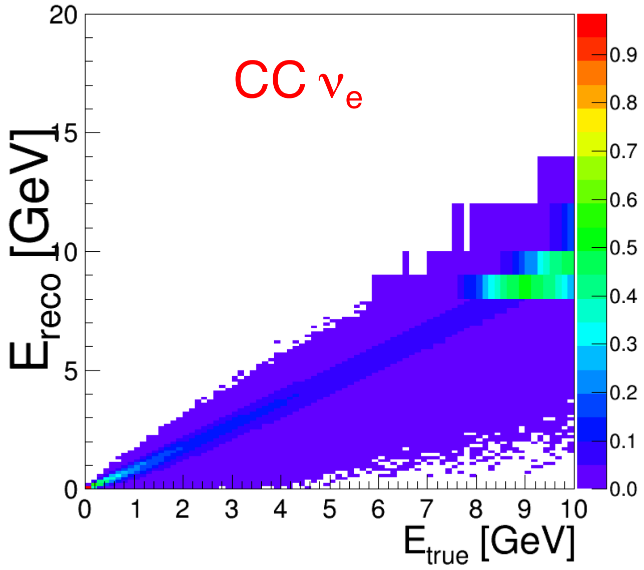
- **Assumed* Particle response/thresholds**
  - Parameterized detector response for individual final-state particles

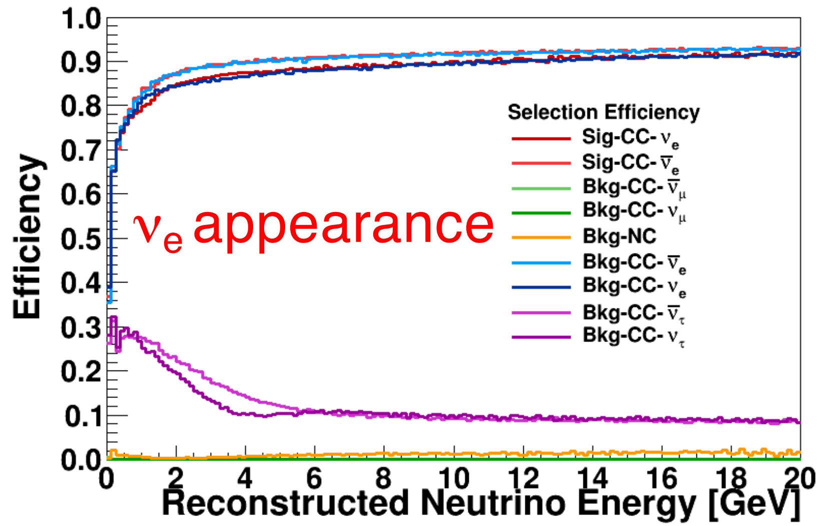
Particle Type	Threshold (KE)	Energy/momentum Resolution	Angular Resolution
$\mu^{\pm}$	30 MeV	Contained: from track length Exiting: 30 %	1^{o}
$\pi^{\pm}$	100 MeV	MIP-like: from track length Contained π-like track: 5% Showering/Exiting: 30 %	1^{o}
$e^{\pm}/\gamma$	30 MeV	$2\% \oplus 15\ \%/\sqrt{(E/GeV)}$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





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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