The Deep Underground Neutrino Experiment

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on behalf of the DUNE collaboration

Workshop for Neutrino Programs with Facilities in Japan
August 5, 2015

Outline

- **Status of DUNE/LBNF**
    - Beam
    - Near Detector
    - Far Detector
    - Prototypes
    - Timeline
- **Physics prospects**
    - Long-baseline neutrino oscillation
    - Underground physics
        - Proton decay
        - Atmospheric neutrinos
        - Supernova neutrinos

P5 Recommendation, 2014

Recommendation 13: Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text. LBNF is the highest-priority large project in its timeframe.

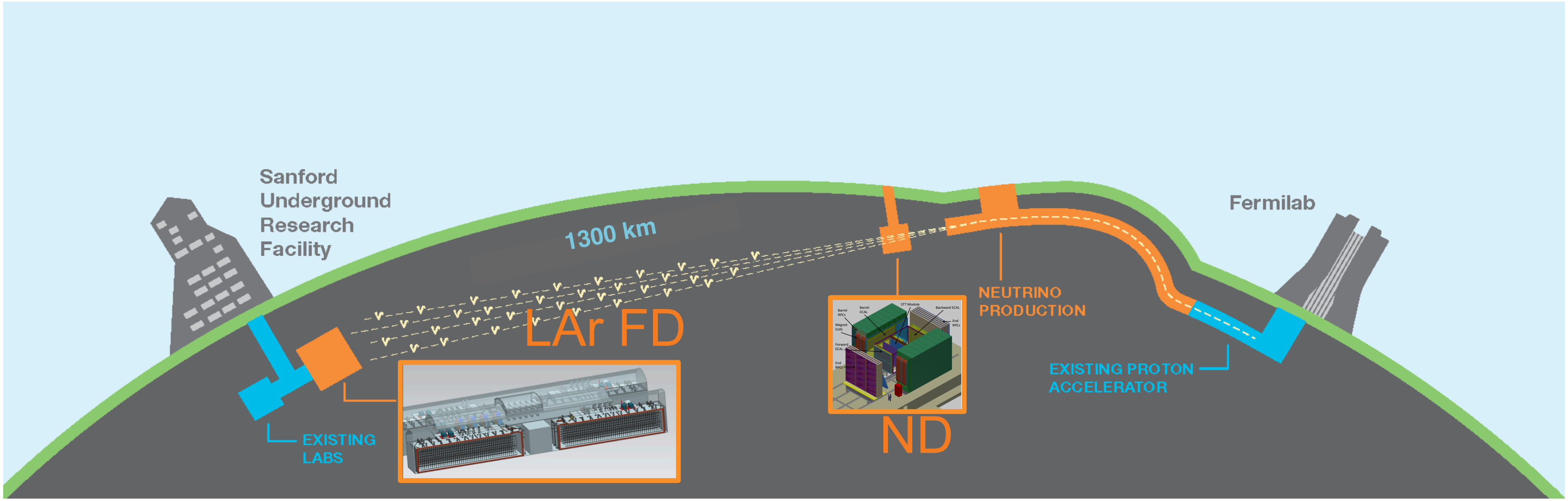
The minimum requirements to proceed are the identified capability to reach an exposure of at least 120 kt*MW*yr by the 2035 timeframe, the far detector situated underground with cavern space for expansion to at least 40 kt LAr fiducial volume, and 1.2 MW beam power upgradable to multi-megawatt power. The experiment should have the demonstrated capability to search for supernova (SN) bursts and for proton decay, providing a significant improvement in discovery sensitivity over current searches for the proton lifetime.

- international
- 40 kt LAr
- underground

Deep Underground Neutrino Experiment

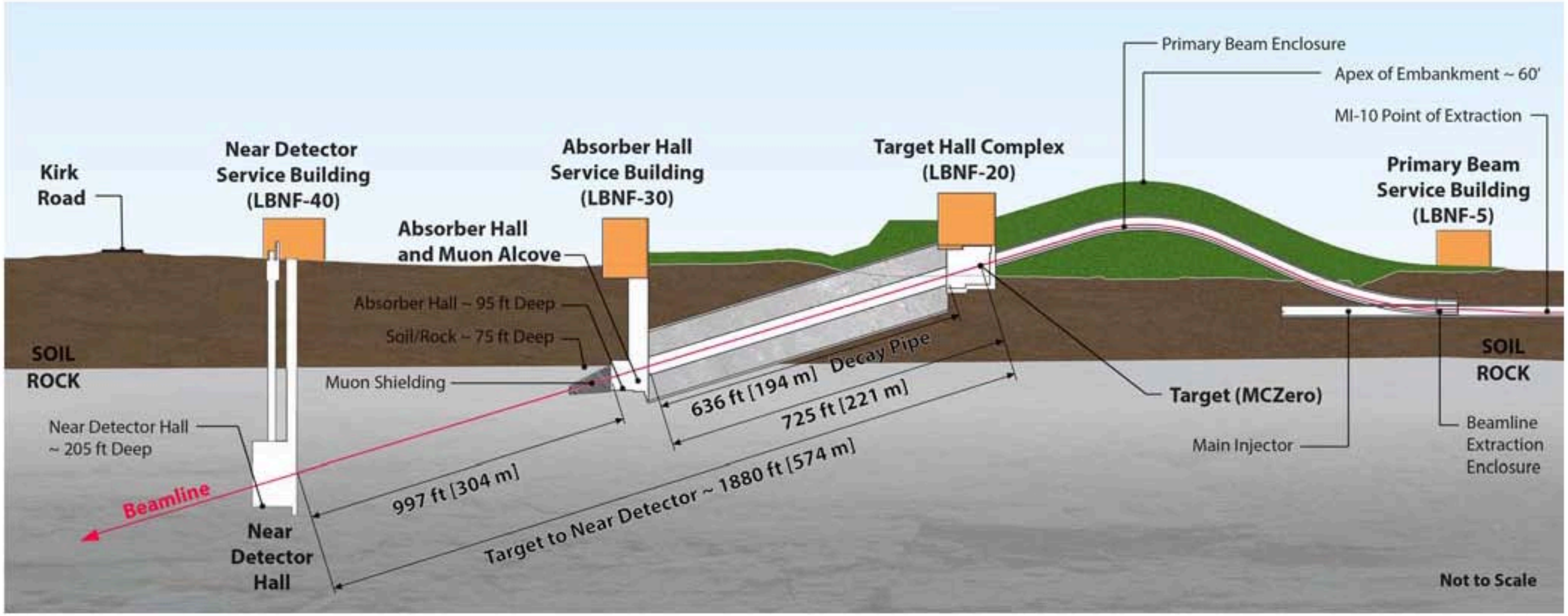
- Collaboration officially formed April 2015; evolving rapidly (LBNE+LBNO+others)
- Spokespeople: André Rubbia and Mark Thomson
- International governance based on CERN experiment model
- Currently: 776 collaborators, 144 institutes, 26 countries
- Enabled by LBNF (Long-Baseline Neutrino Facility) which comprises beam, conventional facilities, cryogenics

DUNE experiment overview



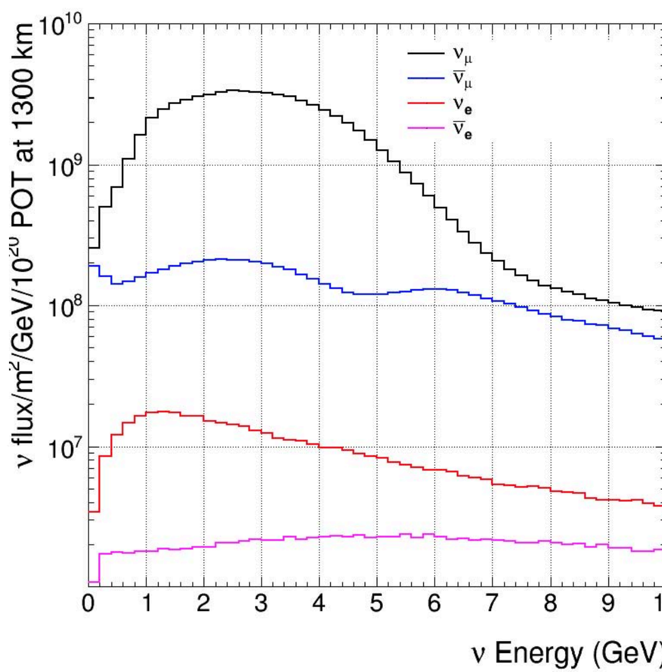
- **1.2 MW wide-band neutrino beam** from FNAL, upgradeable to 2.4 MW
- Highly-capable **near detector**
- LAr **40-kton fiducial** mass far detector @ Sanford Underground Research Facility in SD
  - **1300 km baseline**
  - 4850 ft (**2300 mwe**) depth
  - Four 10 kt modules, installation starting 2021

LBNF/DUNE beam from Fermilab



Parameter	Value	
Energy	60 GeV	120 GeV
Protons per cycle	7.5×10^{13}	7.5×10^{13}
Spill duration	1.0×10^{-5} sec	1.0×10^{-5} sec
Protons on target per year	1.9×10^{21}	1.1×10^{21}
Beam/batch (84 bunches)	12.5×10^{12} nominal; (8×10^{11} commissioning)	
Cycle time	0.7 sec	1.2 sec
Beam Power	1.03 MW	1.2 MW

- Proton Improvement Plan (PIP-II) @ FNAL will provide **>1 GW protons at time of DUNE start**
- LBNF beam optimization work underway



DUNE Near Detector

Highly capable near detector for **precision measurement of ν fluxes** required for long-baseline oscillation physics
Also: rich program of ν interaction physics

Magnetic spectrometer

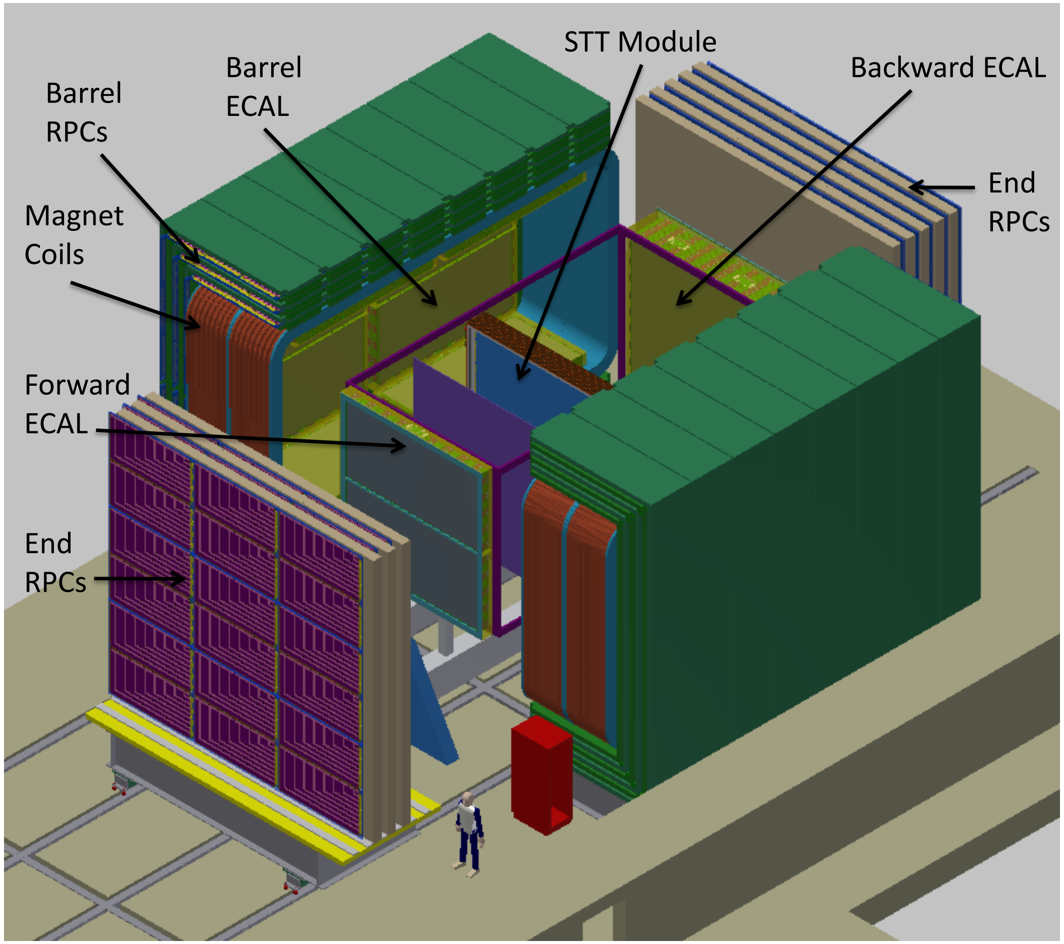
- 0.4 T field
- Straw-tube tracker
- Lead-scint ECAL

Multiple integrated nuclear targets

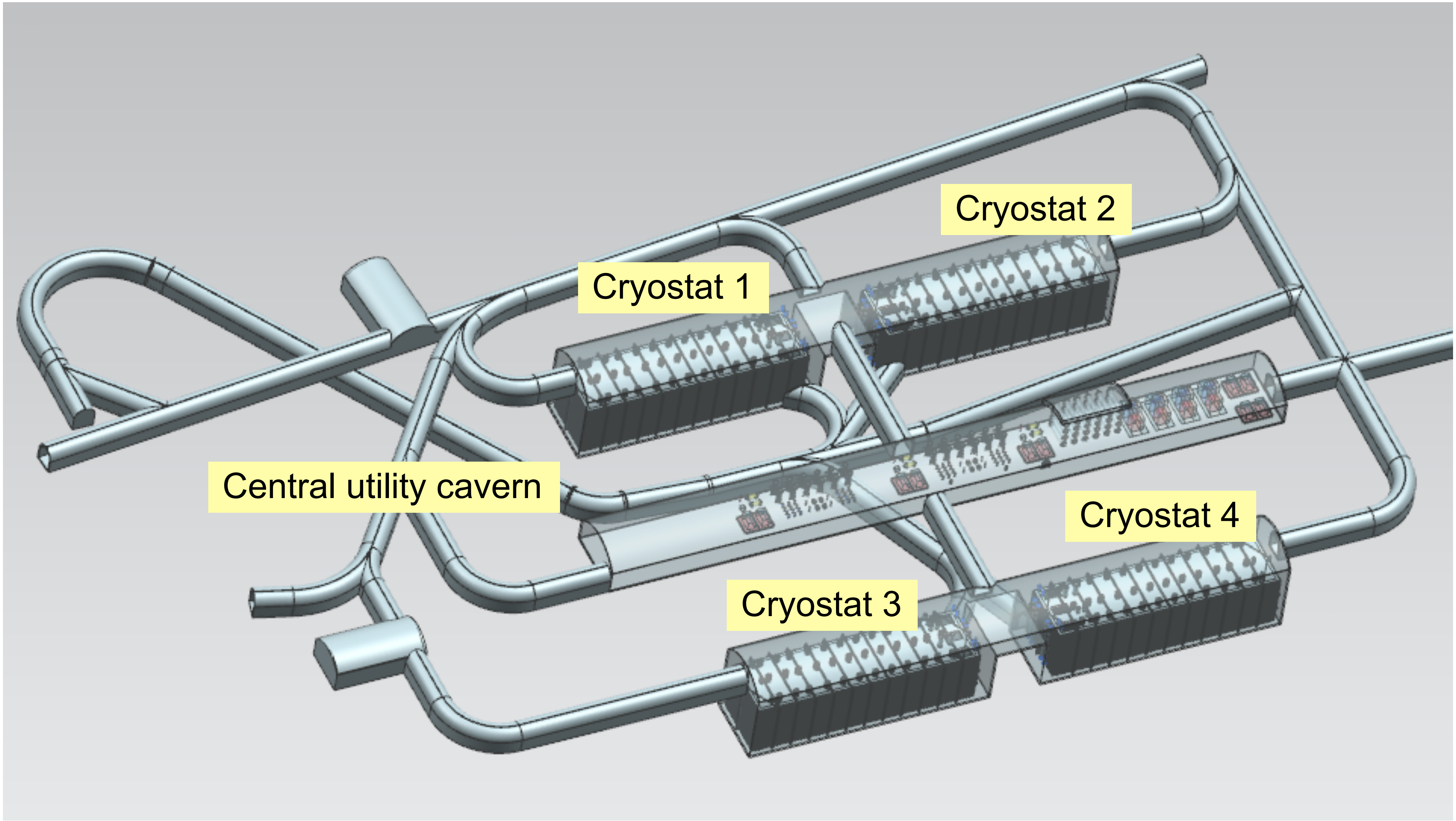
- **Ar**, C_nH_{2n}, Ca, C, Fe, ..
- Require 10x unosc FD rate from Ar targets

RPC-based muon tracker

Reference design



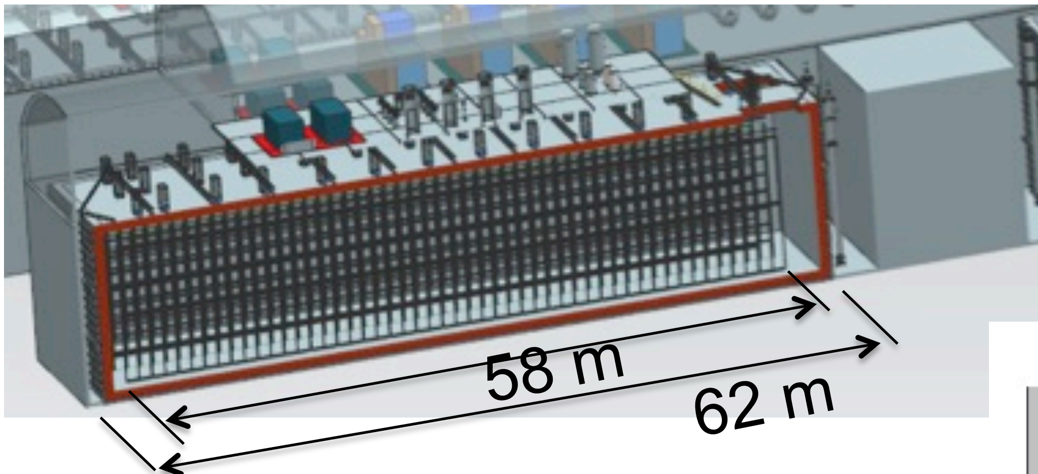
LBNF far detector facilities for DUNE



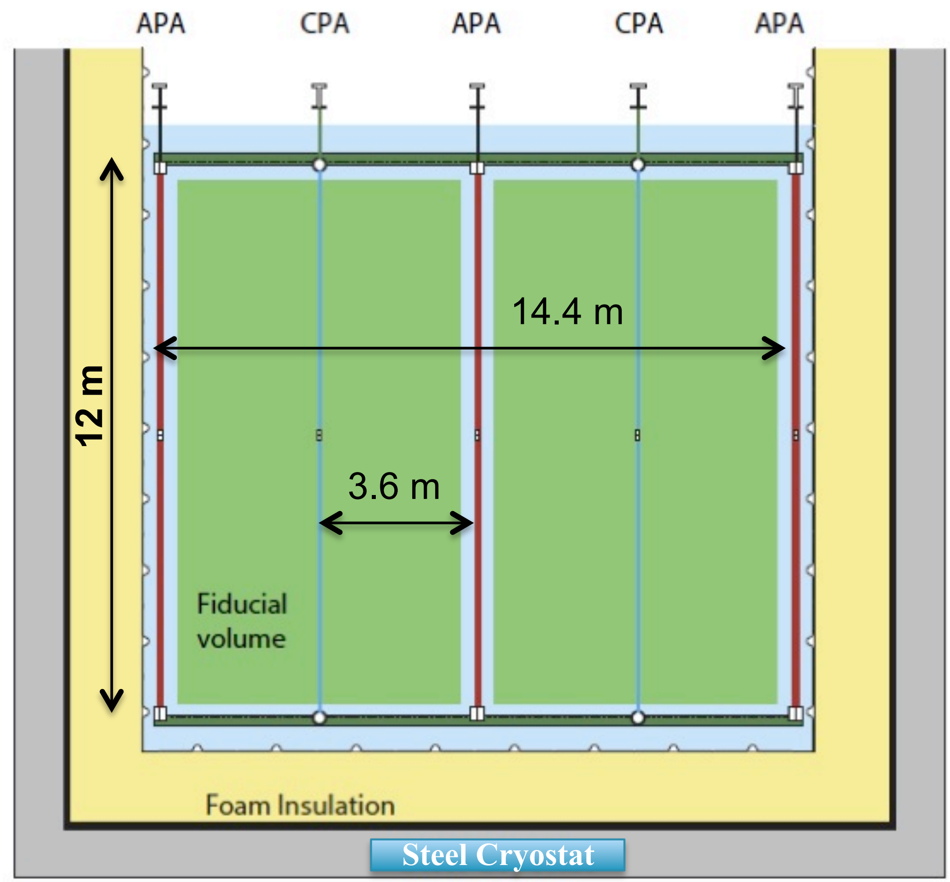
Cryostats: (CERN-FNAL design team) 17.1 kt LAr each
Free-standing steel-supported **membrane cryostats**

Central utility cavern: cryogenics support equipment

Nominal DUNE far detector technology



Reference design
(for first module):
horizontal-drift **single-phase time-projection chamber**



17.1-kt total, 13.8-kt active,
11.6-kt fiducial mass

3 Anode Plane Assemblies (APA) w/ cold electronics

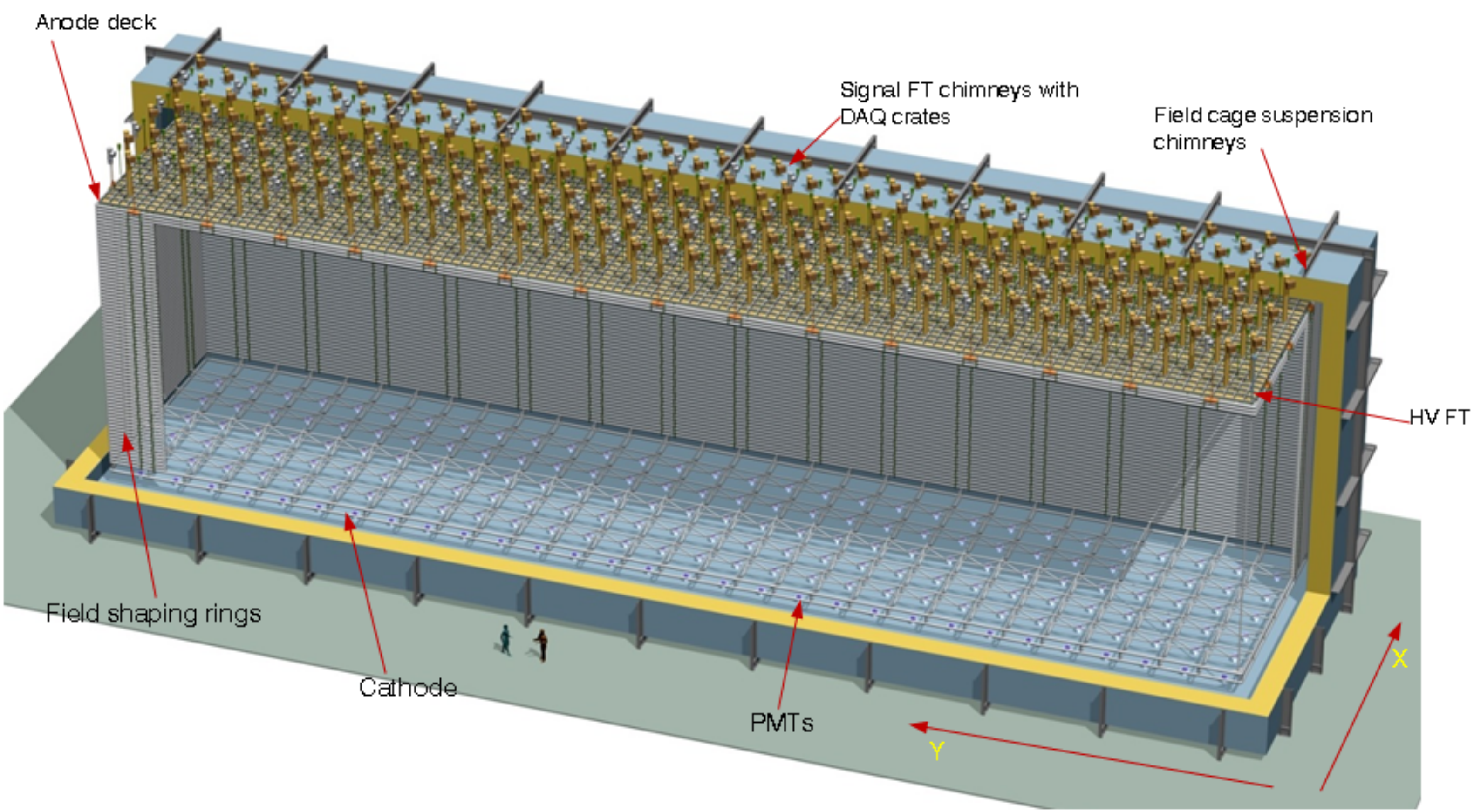
Cathode planes (CPA) at 180 kV
3.6 m max drift length

Photon detectors for fast event timing (non-beam physics)

Alternative DUNE far detector technology

Dual-phase TPC is alternative design:
vertical drift w/ multiplication and readout at liquid-gas interface
Significant R&D by LBNO collaboration

Could be implemented for module(s) 2-4

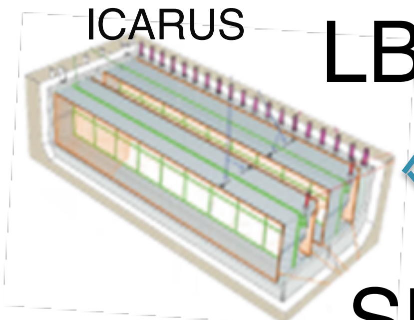


Development and prototyping of LArTPCs

CERN neutrino platform + FNAL prototyping
+ experience from FNAL SBN program

Single phase

ICARUS



LBL

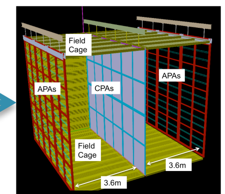
35-t prototype

2015

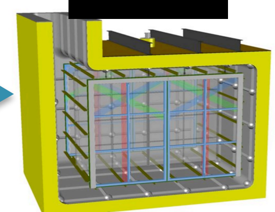
MicroBooNE

SBL

DUNE SP PT @ CERN

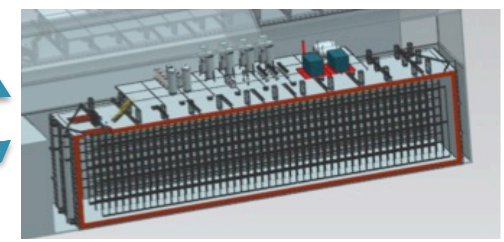


2018



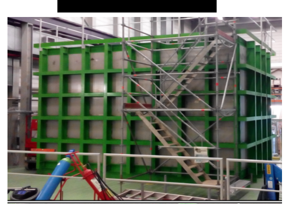
SBND

DUNE Reference Design



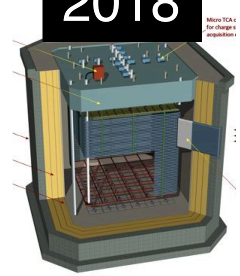
Dual phase

2016



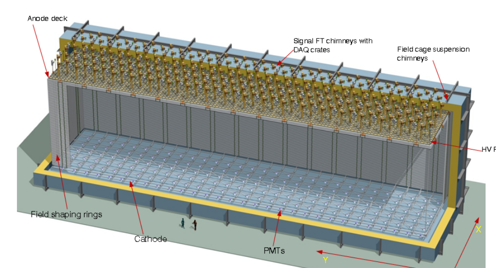
WA105: 1x1x3 m^3

2018



WA105

DUNE Alternative Design



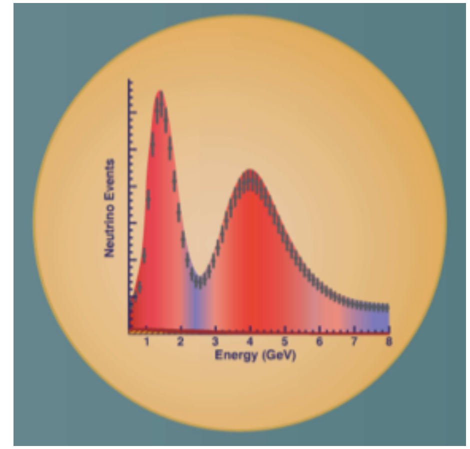
DUNE Timeline

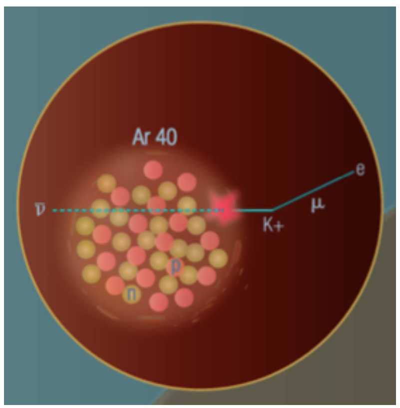
- July 2015 "CD-1 Refresh" review (conceptual design review).
- Dec. 2015 CD-3a Conventional Facilities Far Site. Needed to authorize far site conventional facilities work including underground excavation and outfitting.
- 2017 Ongoing shaft renovation at SURF complete.
- **2017 Start of far site conventional facilities construction**
- 2018 Testing of "full-scale" far detector elements at CERN.
- 2019 Technical Design review.
- 2021 Ready for start of installation of the first far detector module.
- **2024 start of physics data-taking** with one detector module Additional far detector modules every ~2 years.
- 2026 Beam available.
- 2026 Near detector available.
- 2028 DUNE construction finished.

DUNE Primary Physics Program

Long-baseline ν oscillations

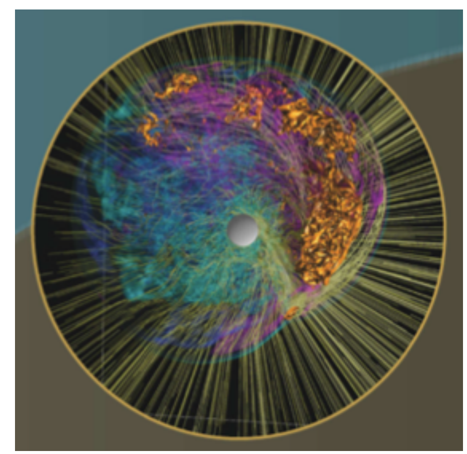
leptonic CP violation
mass hierarchy
θ_{23} octant, precision parameters
test of 3-flavor paradigm





Nucleon decay

particular sensitivity
to SUSY-predicted modes
e.g., $p \rightarrow K^+\overline{\nu}$



Supernova burst neutrinos

neutrino physics & astrophysics,
e.g., MH, black hole formation

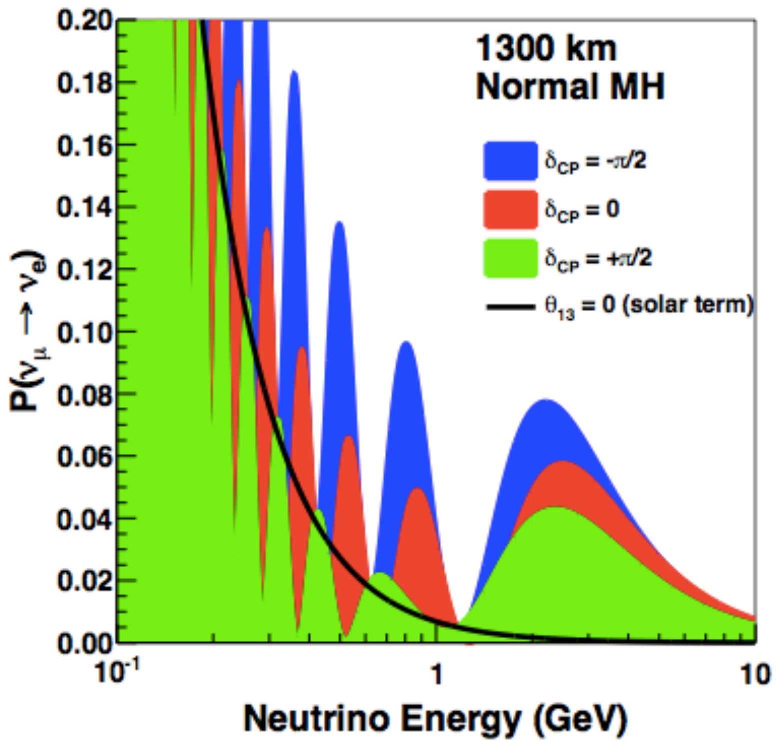
+ numerous secondary goals
(atmnus, other astro nus, ND physics...)

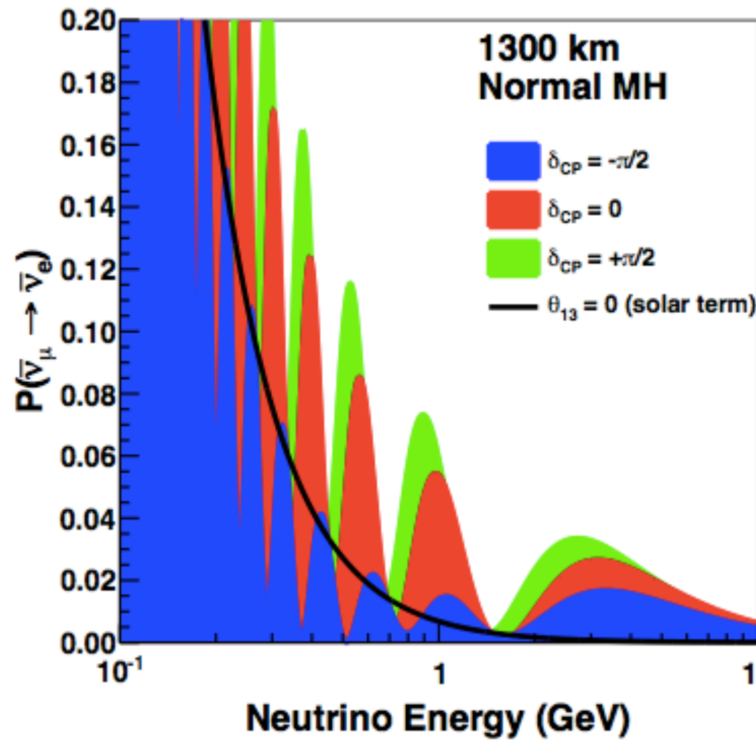
Long-baseline neutrino oscillations

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$
$$+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{CP})$$
$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,$$

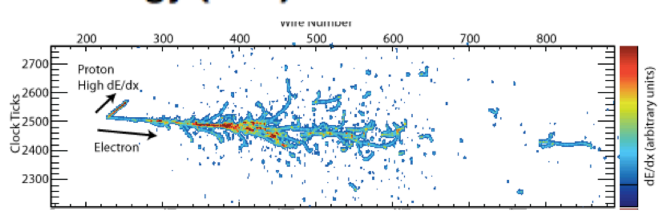
$$\Delta_{ij} = \Delta m_{ij}^2 L/4E_\nu,\ a = G_F N_e/\sqrt{2}$$

Antinus: change sign of a, δ



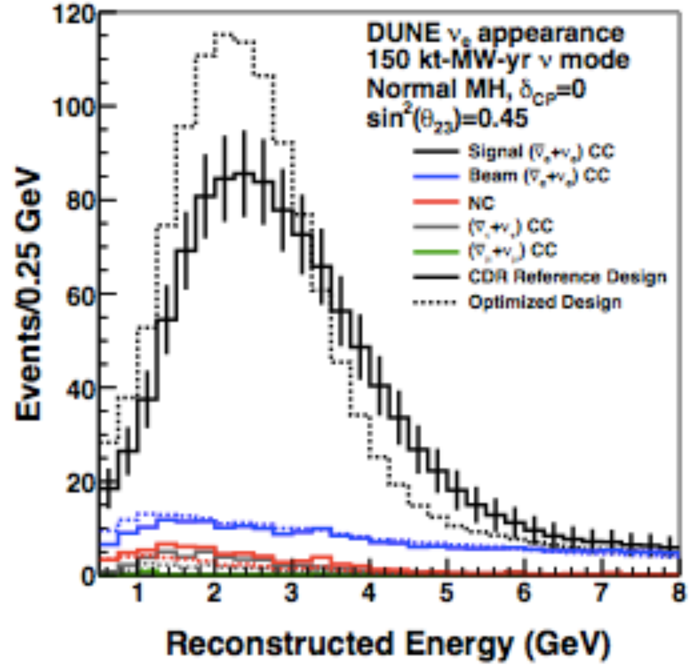


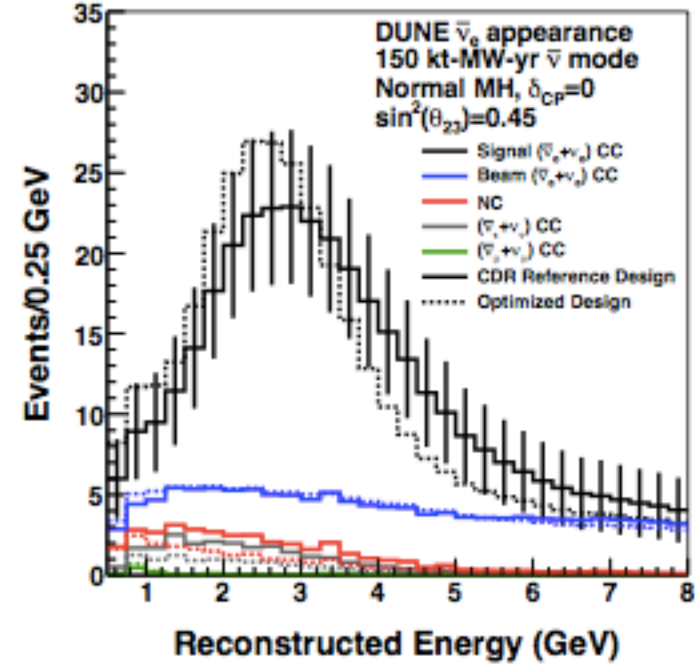
Thanks,
Nature,
for large θ_{13}!



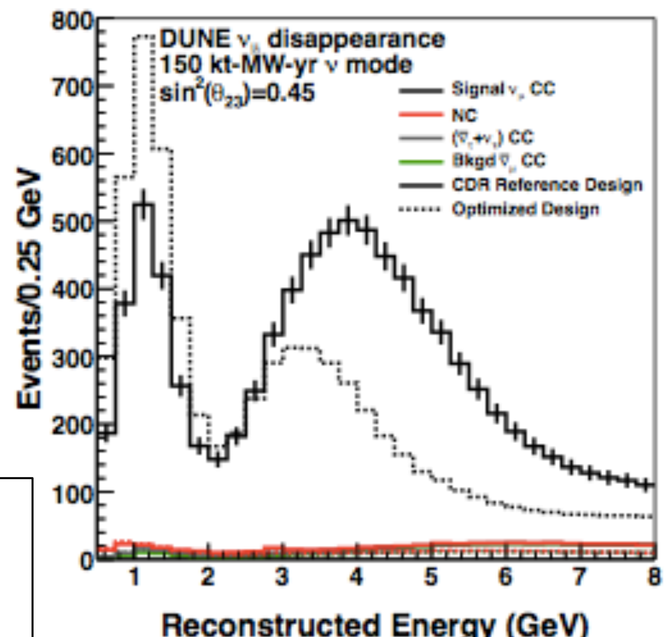
look for ~few GeV em showers in LArTPC

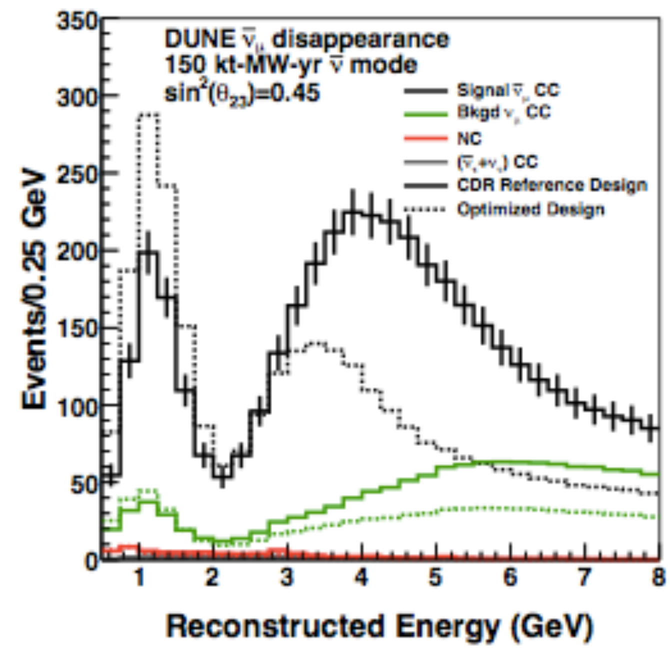
Electron (anti) neutrino appearance





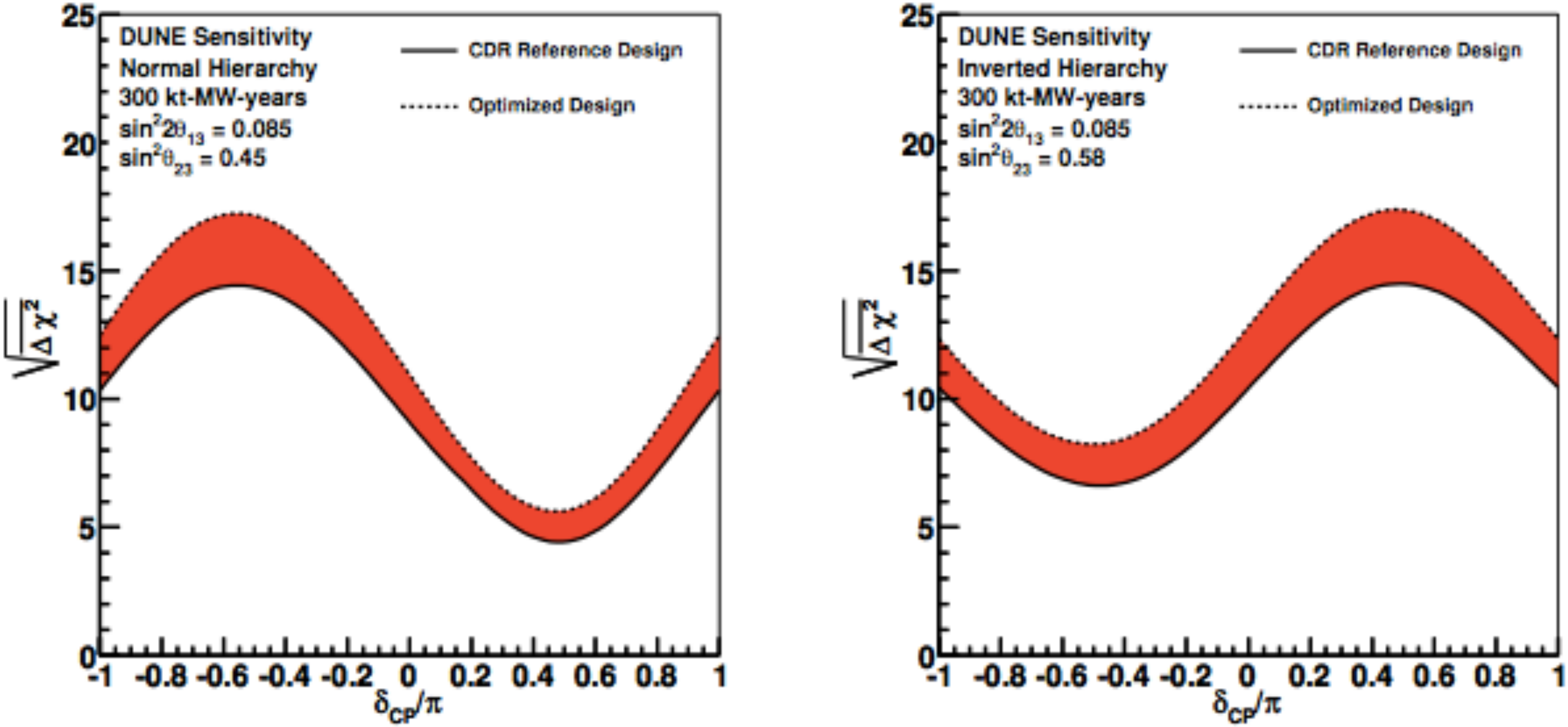
Muon (anti)neutrino disappearance



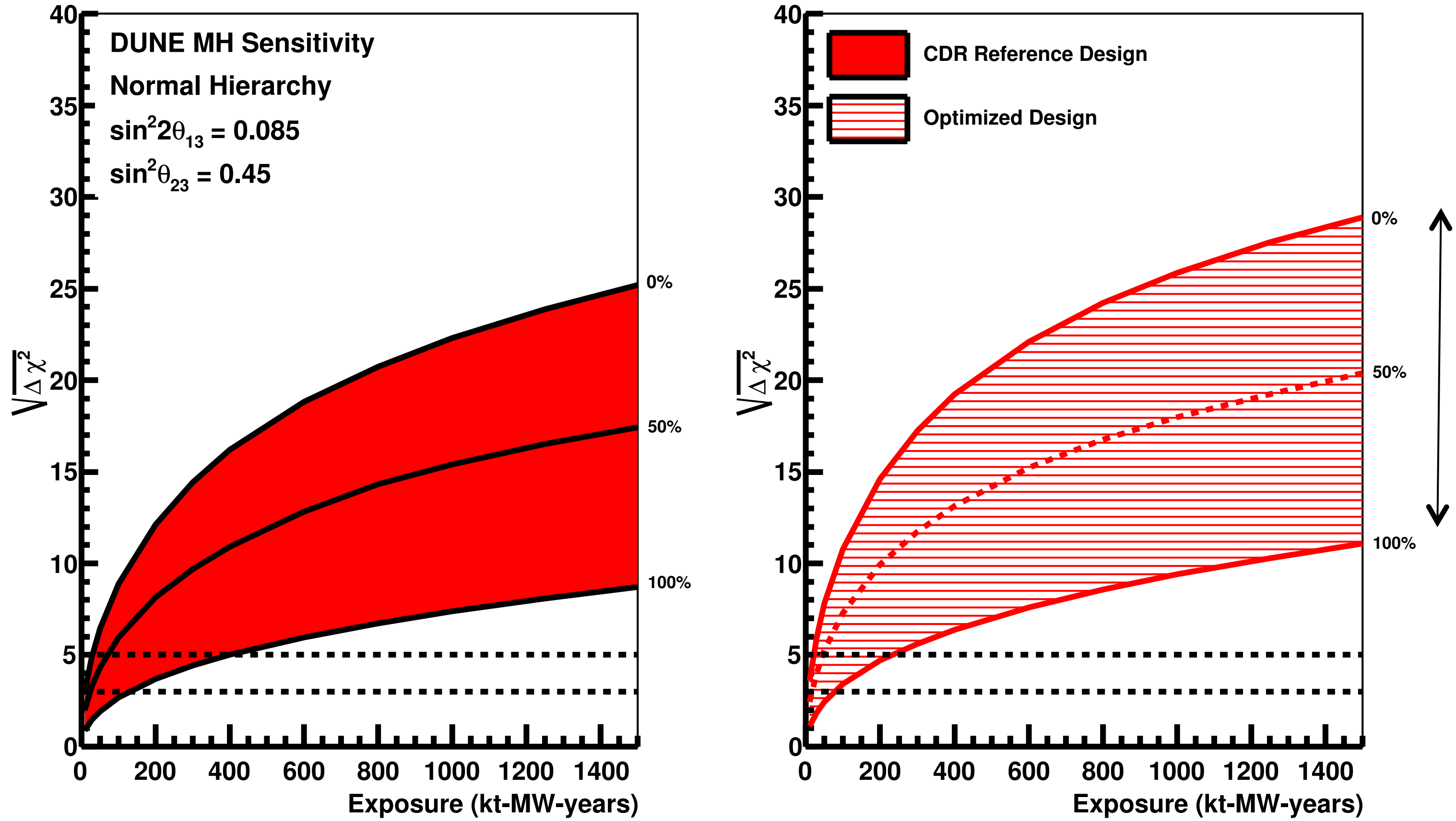


Nominal exposure:
300 kt-MW-yr:
~7 yrs of data
(3.5 nu, 3.5 antinu) w/40 kt,
1.07-MW 80-GeV beam

DUNE mass hierarchy sensitivity



DUNE mass hierarchy sensitivity vs exposure

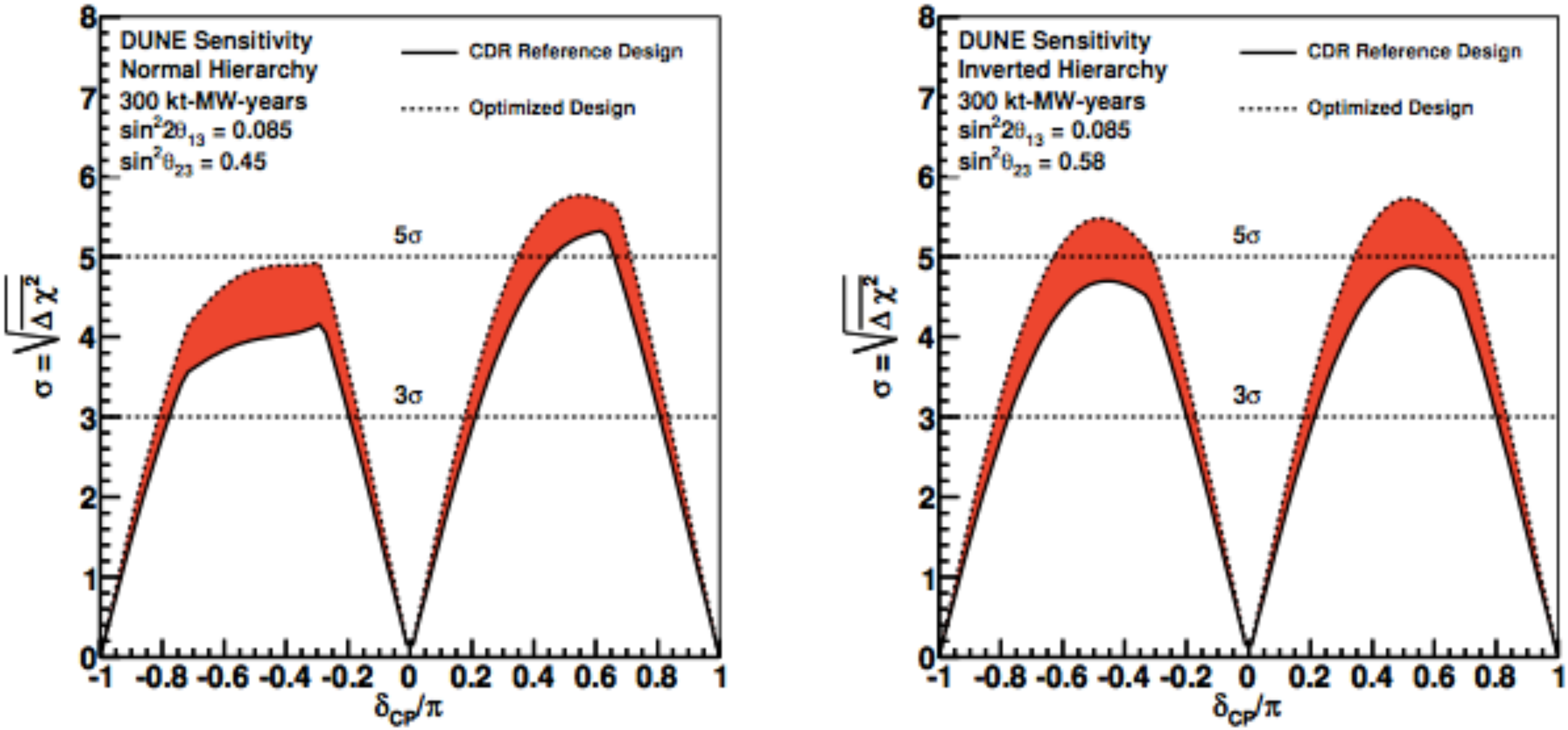


fraction of CP values for which MH can be determined at given minimum significance

(very similar for IH case)

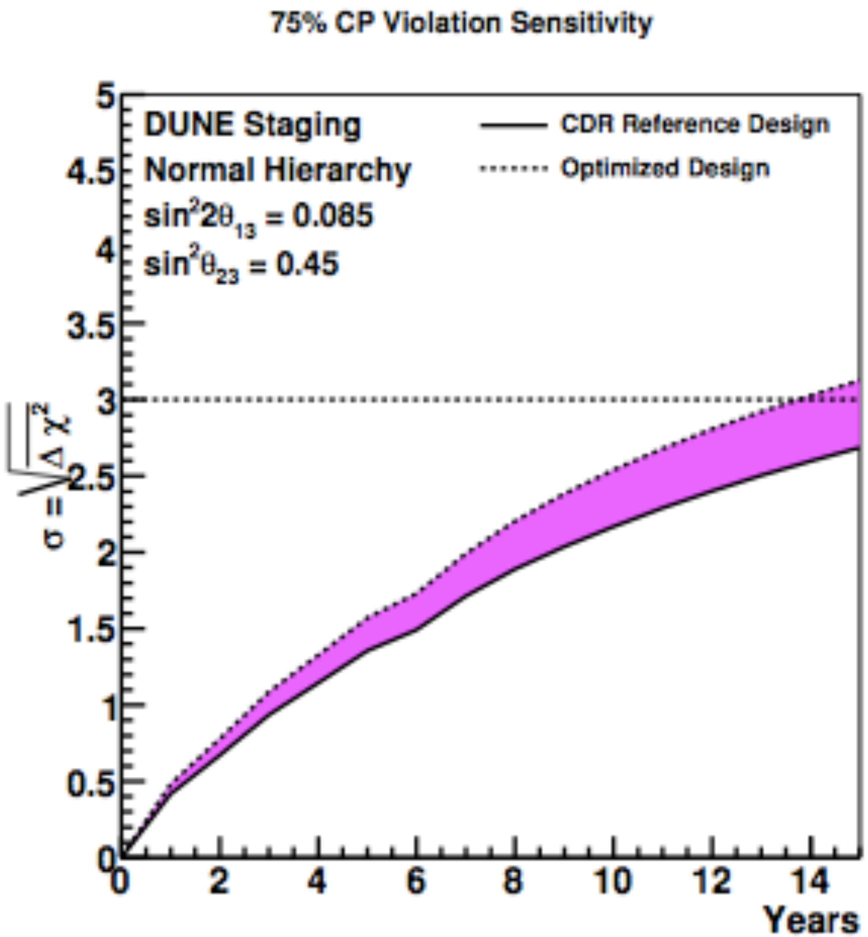
- definitive MH determination
- can get there faster with optimized beam
  (work underway)

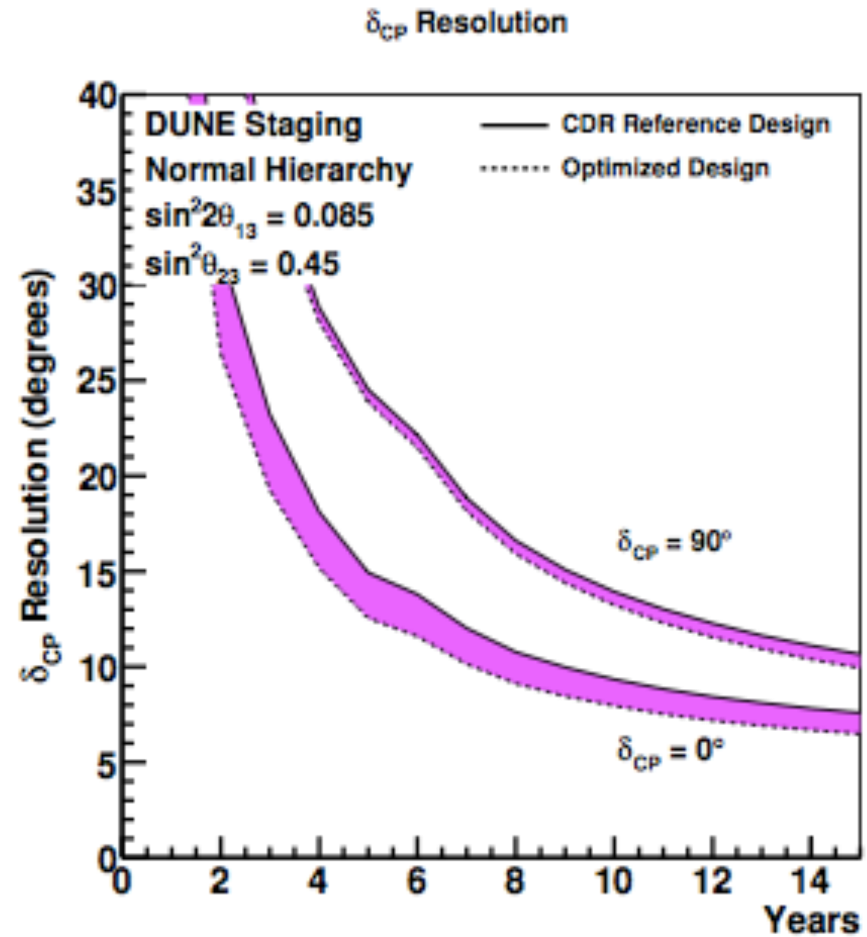
DUNE CP violation sensitivity



- optimized beam helps here too

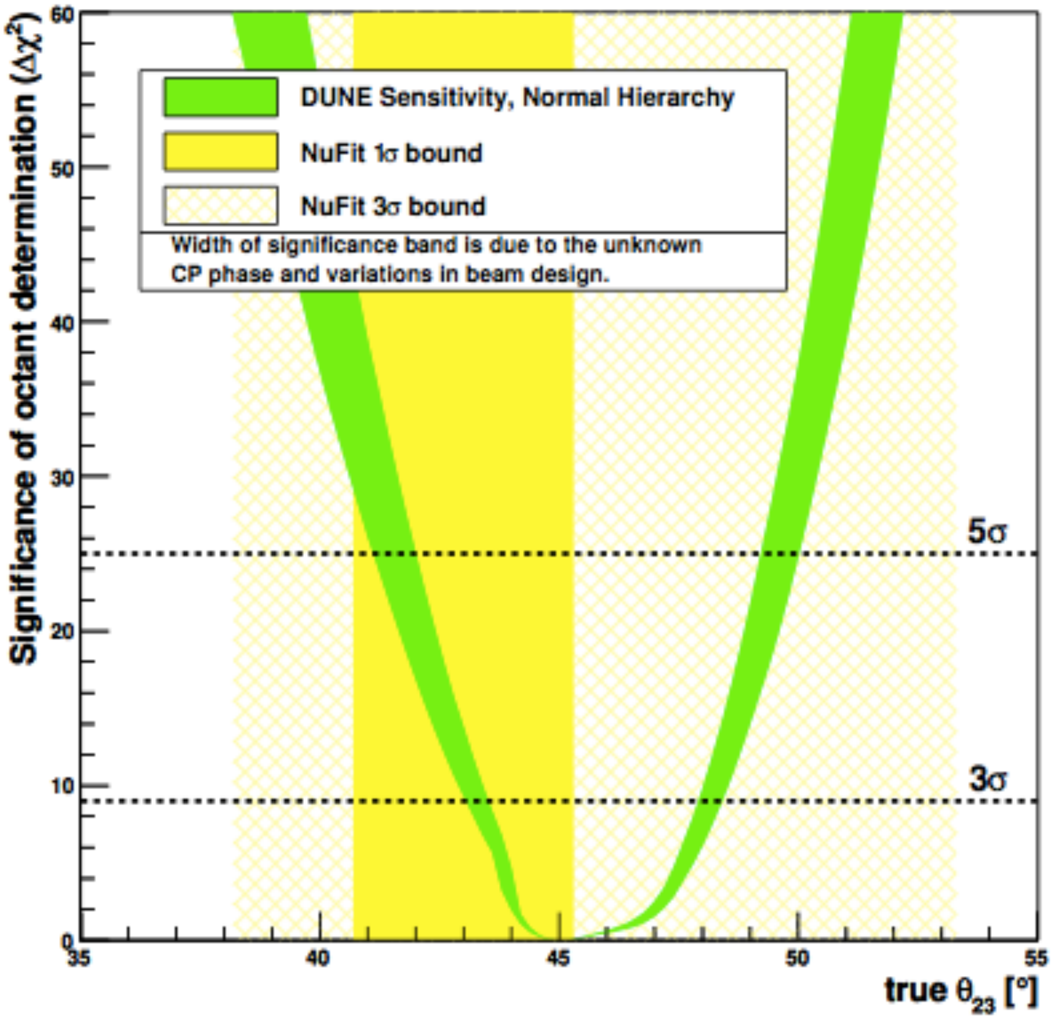
DUNE CP violation sensitivity vs exposure



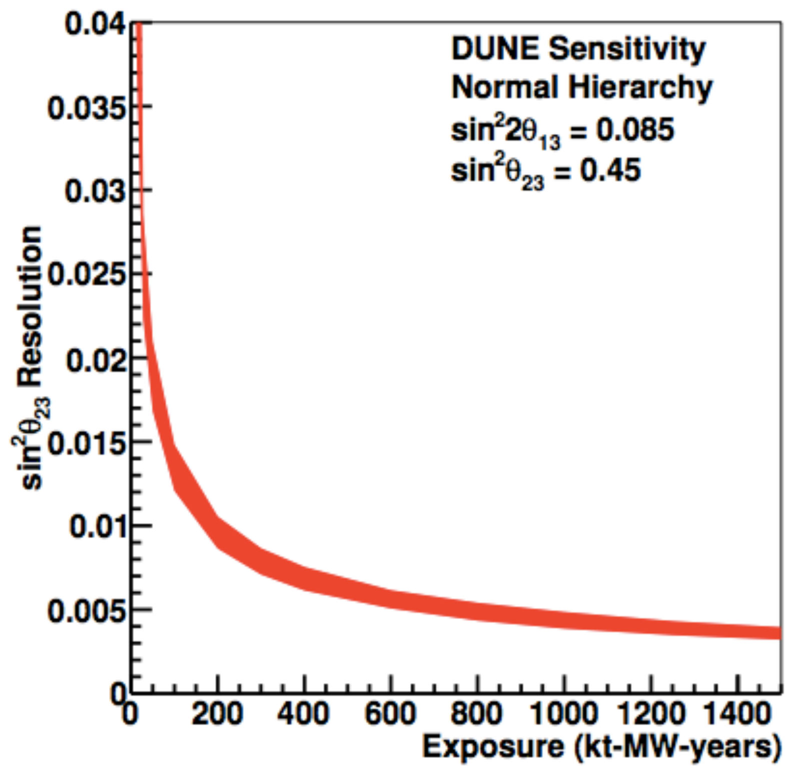


Assumes staging and 2-MW beam after 6 years

DUNE octant sensitivity



Does ν_3 have more μ or τ?



Exposure: same as
for 3σ CP measurement for 75% of values

DUNE physics milestones

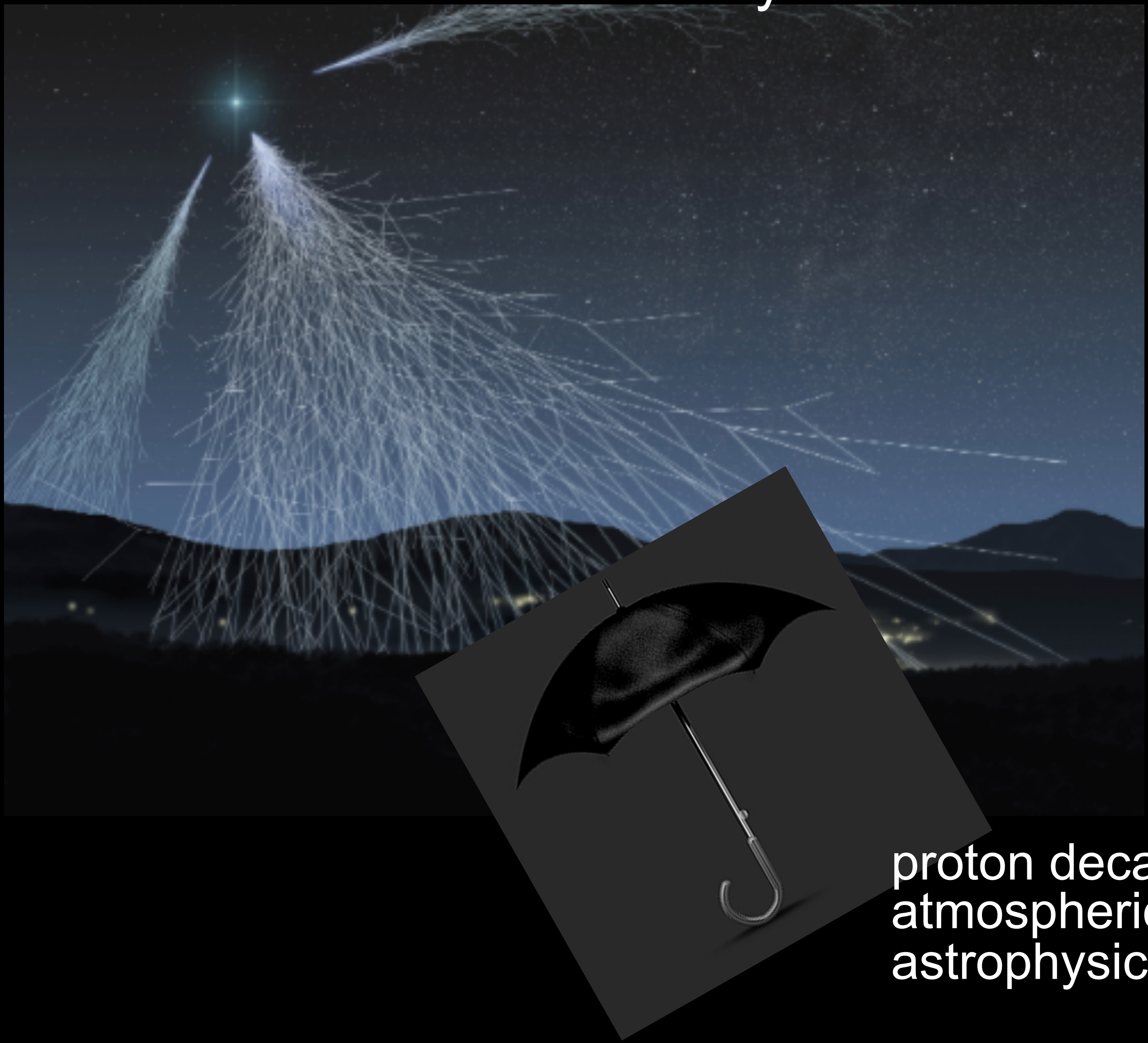
Best case MH: 5σ w/ 20-30 kt-MW-yr

Best case CPV (+π/2): 3σ w/ 60-70 kt-MW-yr

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

“Underground” Physics

enabled
by overburden



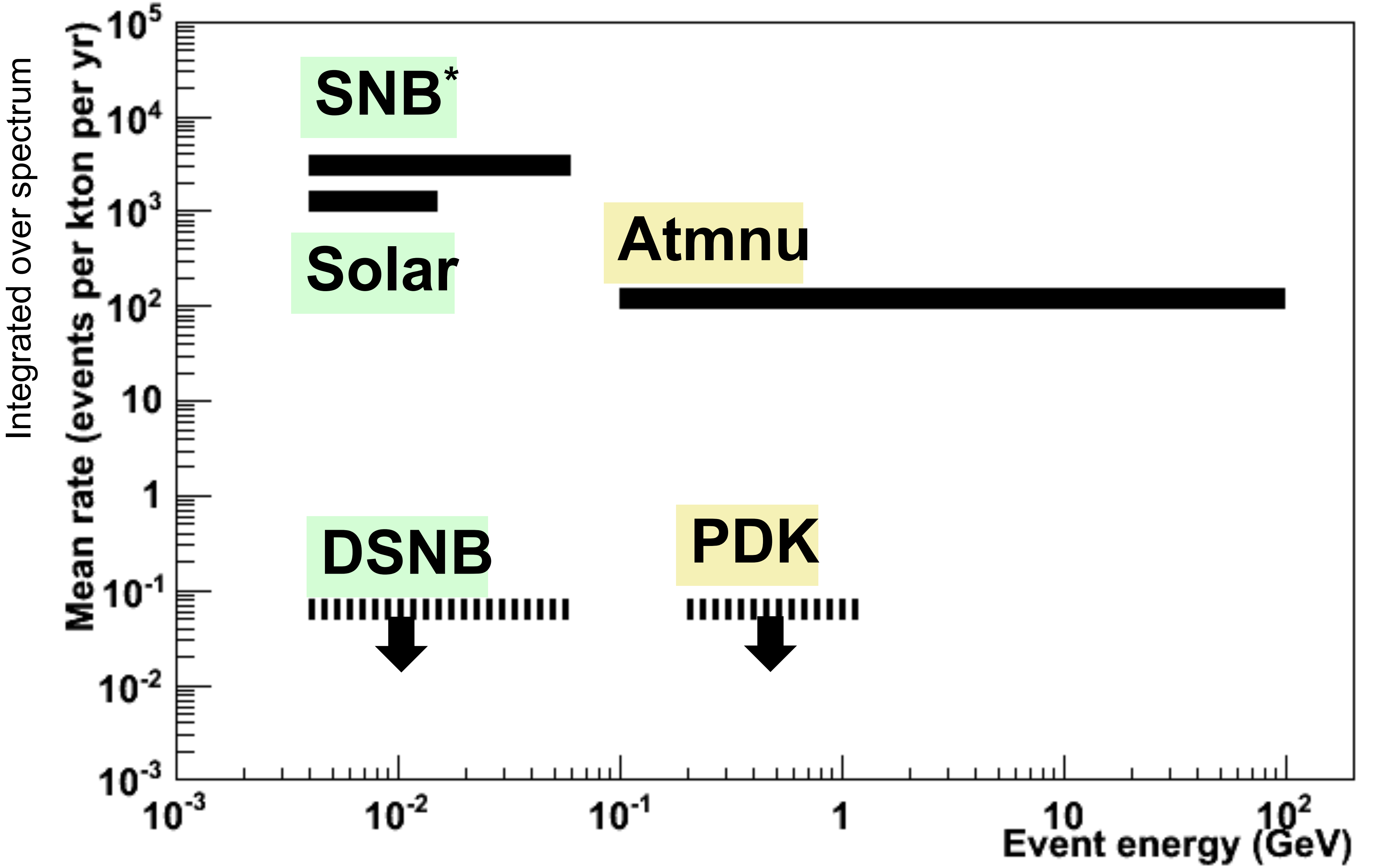
proton decay,
atmospheric ν’s,
astrophysical ν’s,...

Signal energies and expected rates in LAr

Signal	Energy range	Expected Signal Rate per kton of LAr (yr^{-1} $kton^{-1}$)
Proton decay	~ GeV	< 0.06
Atmospheric neutrinos	0.1-100 GeV	~120
Supernova burst neutrinos	few-50 MeV	~100 @ 10 kpc **over ~30 secs**
Solar neutrinos	few-15 MeV	1300
Supernova relic neutrinos (DSNB)	20-50 MeV	< 0.06

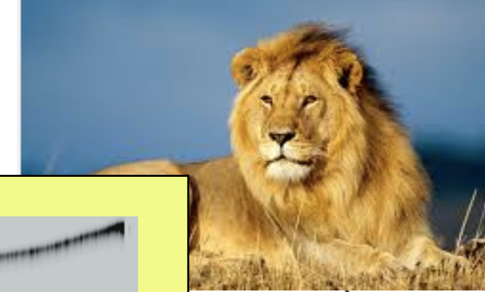
No handy beam trigger, so vulnerable to background, and require attention to triggering

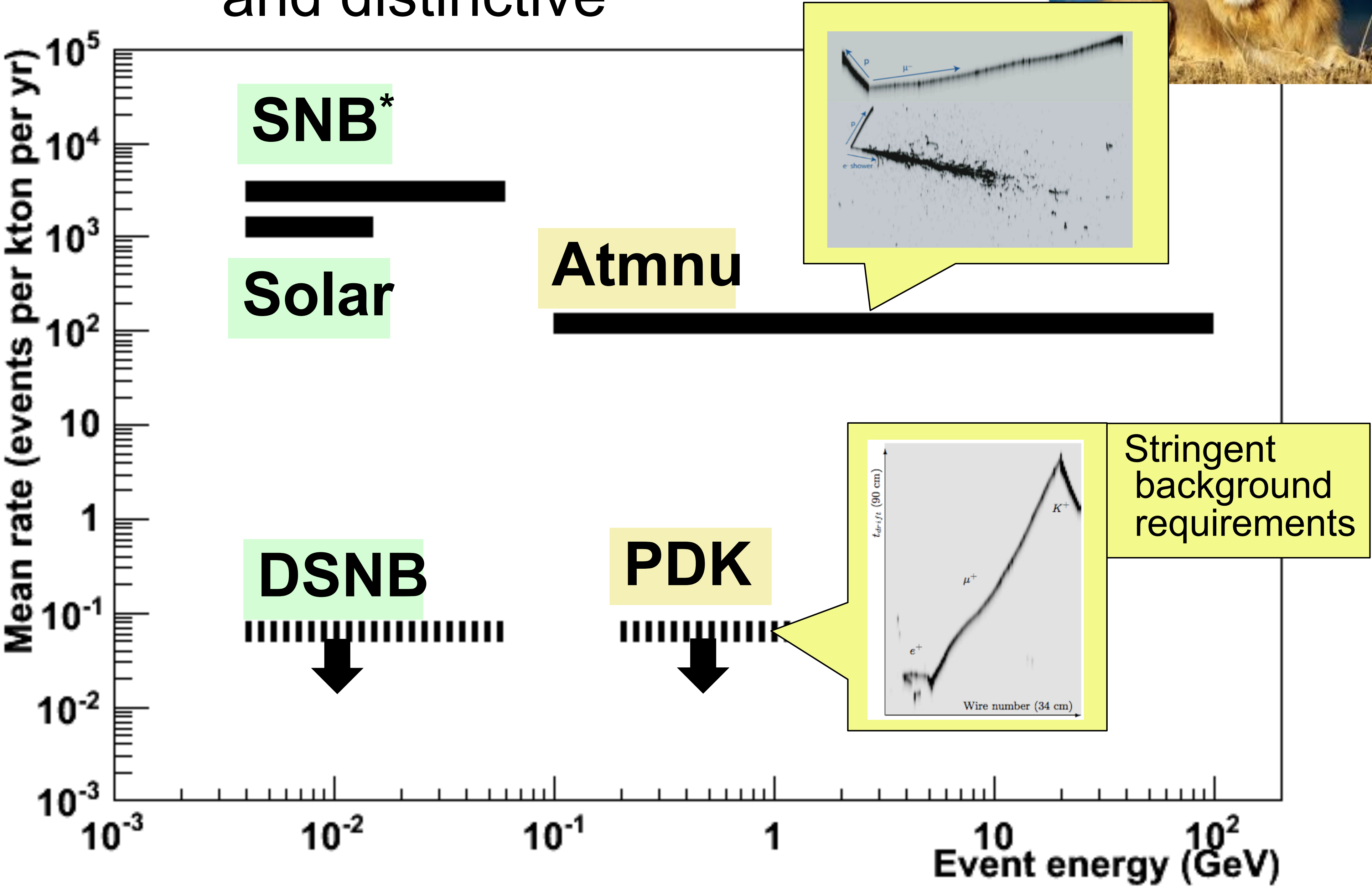
Mean rate vs event energy



* @1 kpc, 30 seconds (not steady-state rate)

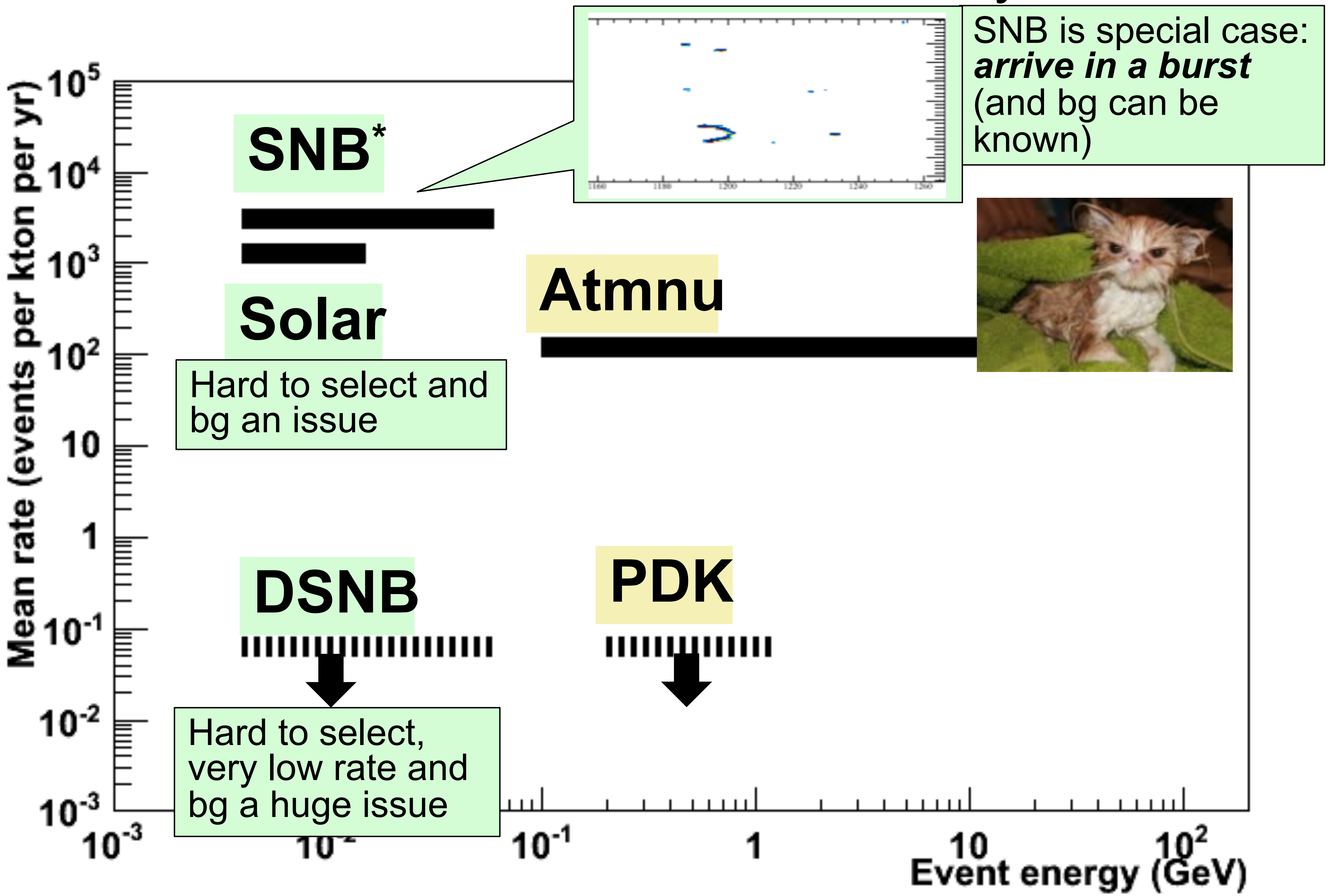
GeV-scale events: handsome and distinctive





* @1 kpc, 30 seconds (not steady-state rate)

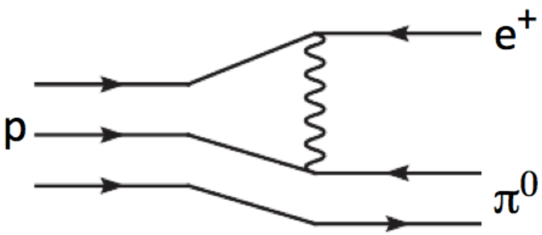
Few tens of MeV-scale events: “crummy little stubs’



* @1 kpc, 30 seconds (not steady-state rate)

Baryon Number Violation

$p \rightarrow e^+ \pi^0$

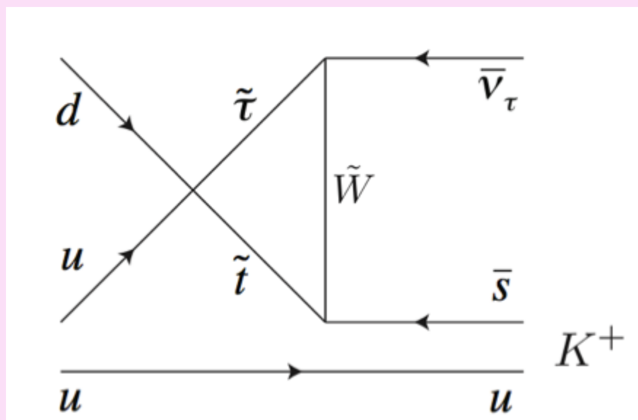


Best limit from SK (1.3 x 10^{34} yr, 206 kt-yr); water has high-efficiency, clean signal; LAr should be even cleaner but can't compete easily w/ no. of (free) protons in water (still would see fully-reconstructed events)

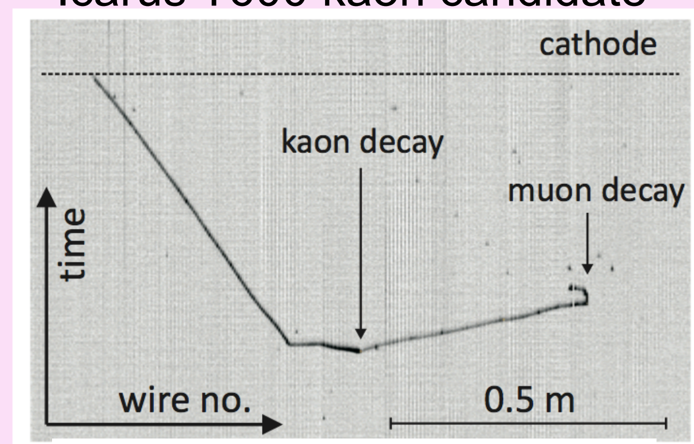
The strength of LAr:

$p \rightarrow K^+ \bar{\nu}$

SUSY
-motivated



Icarus T600 kaon candidate



$K \rightarrow \mu\nu_\mu \quad \mu \rightarrow e\nu_e\nu_\mu$

...and other modes with low efficiency in water
➔ **high quality reconstruction & lack of Cherenkov threshold enable high efficiency & purity**

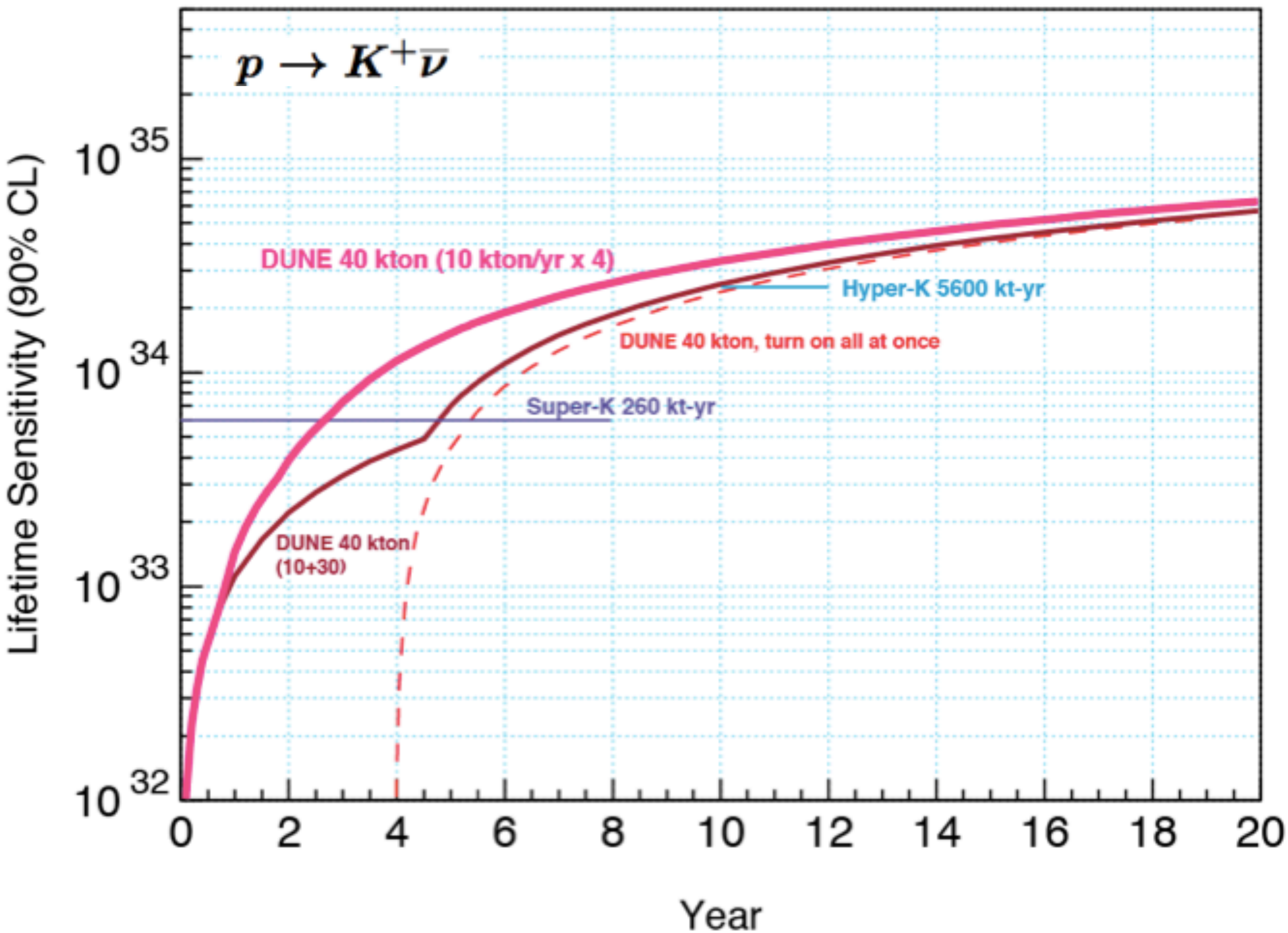
Efficiency & background (events per Mton-year) in water & argon:

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	

*Dominant bg: sneaky charge-exchanging cosmogenic K^0

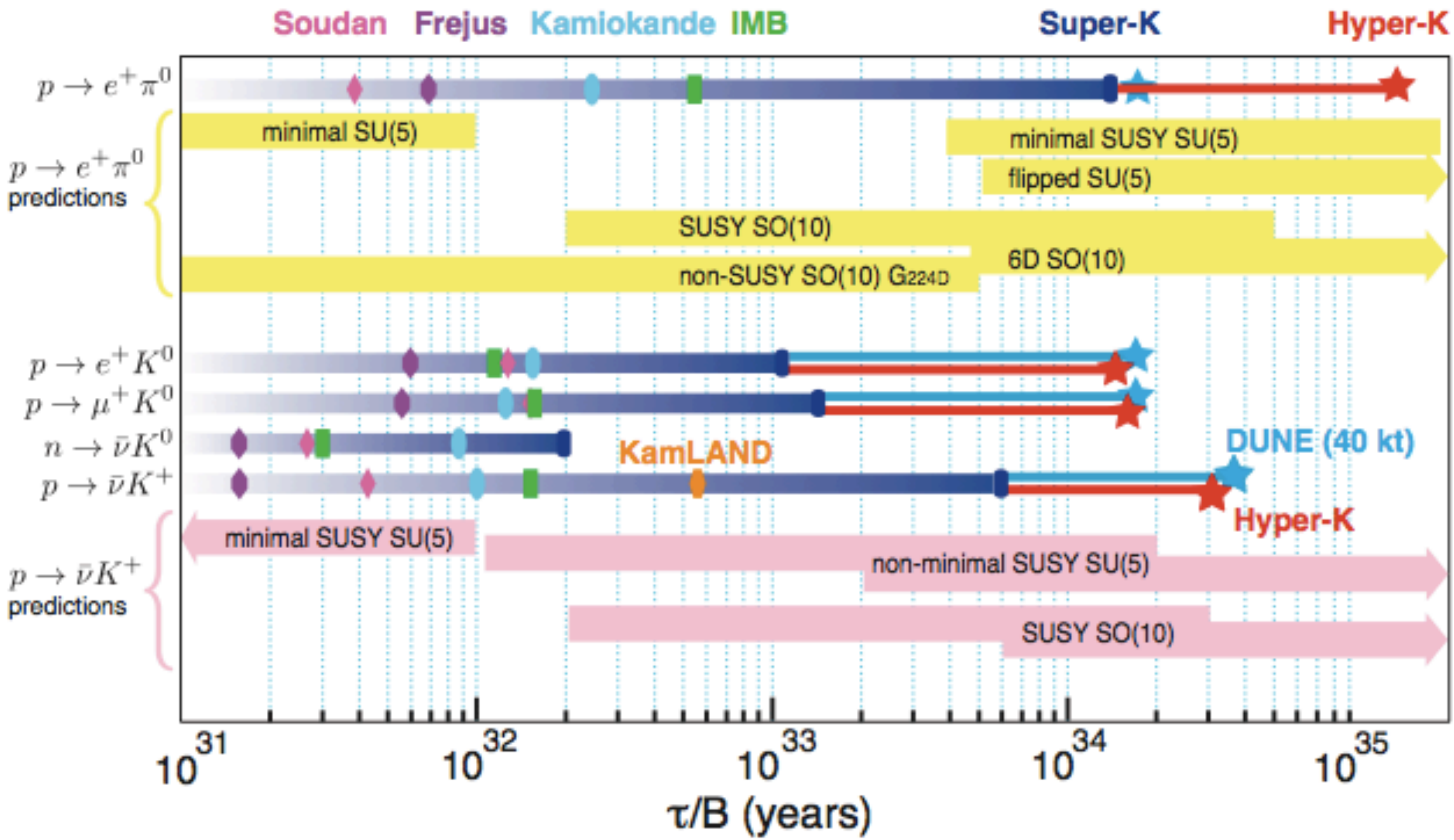
High efficiency and low bg in LAr for these modes

DUNE Lifetime Sensitivity



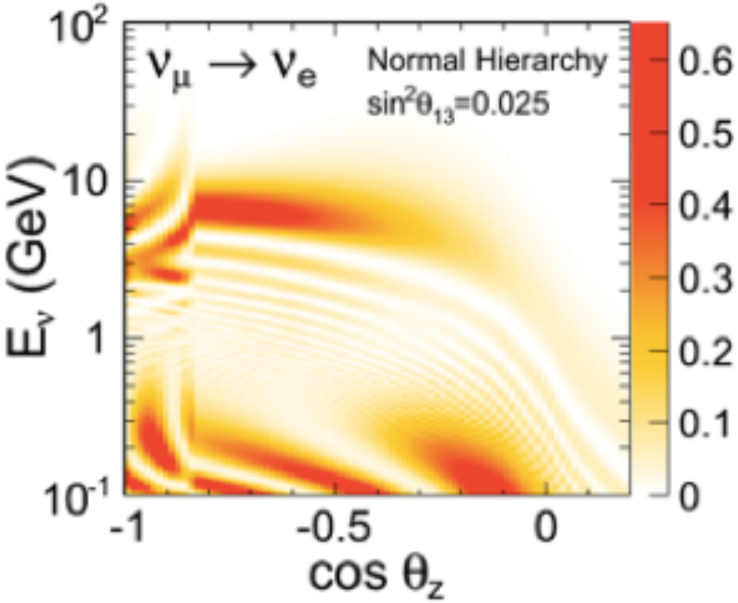
97% efficiency, 1 ev/(Mt-yr bg)

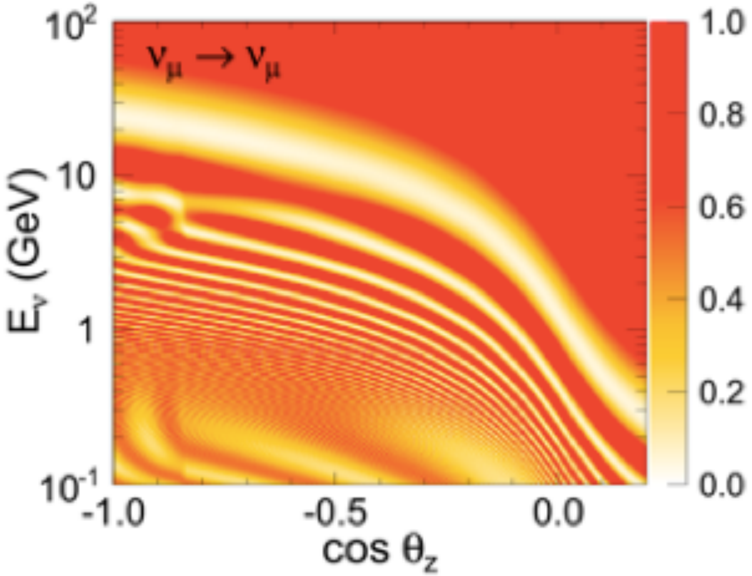
Anticipated limits wrt theory predictions



DUNE 10 yr run

Atmospheric Neutrinos





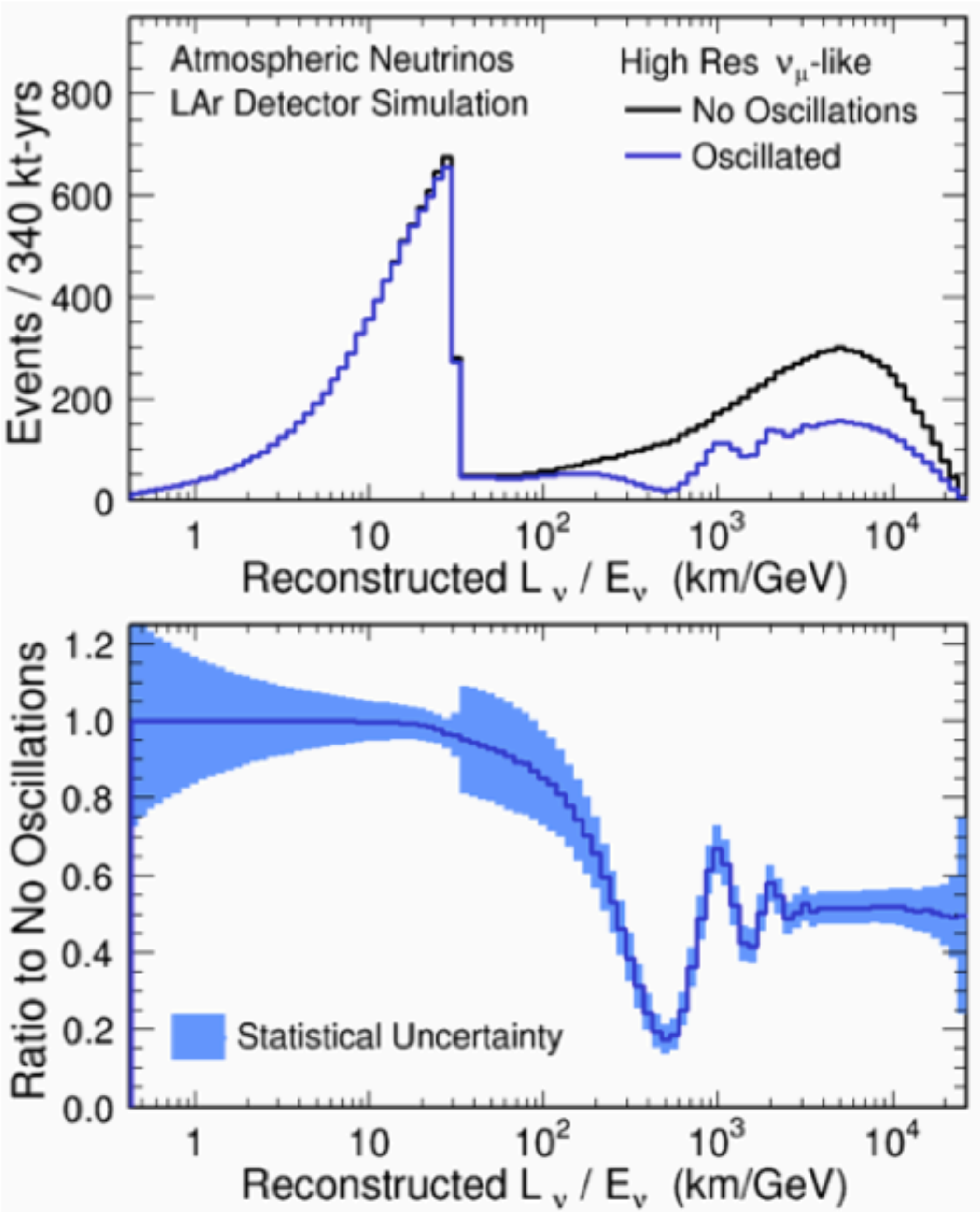
Wide range of angles and energies, sampling matter with both neutrinos and antineutrinos

Sample	Event Rate
fully contained electron-like sample	14,053
fully contained muon-like sample	20,853
partially contained muon-like sample	6,871

in 350 kt-yr

Again, advantage of LArTPC is *precision reconstruction*

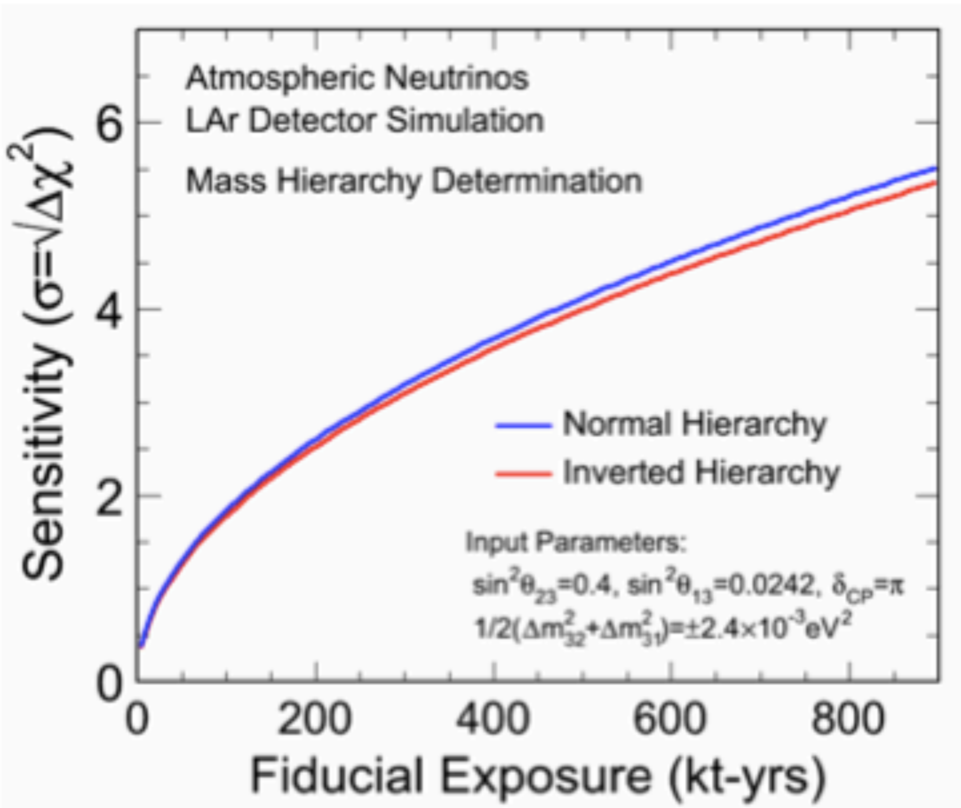
Advantage of LArTPC is *precision reconstruction*

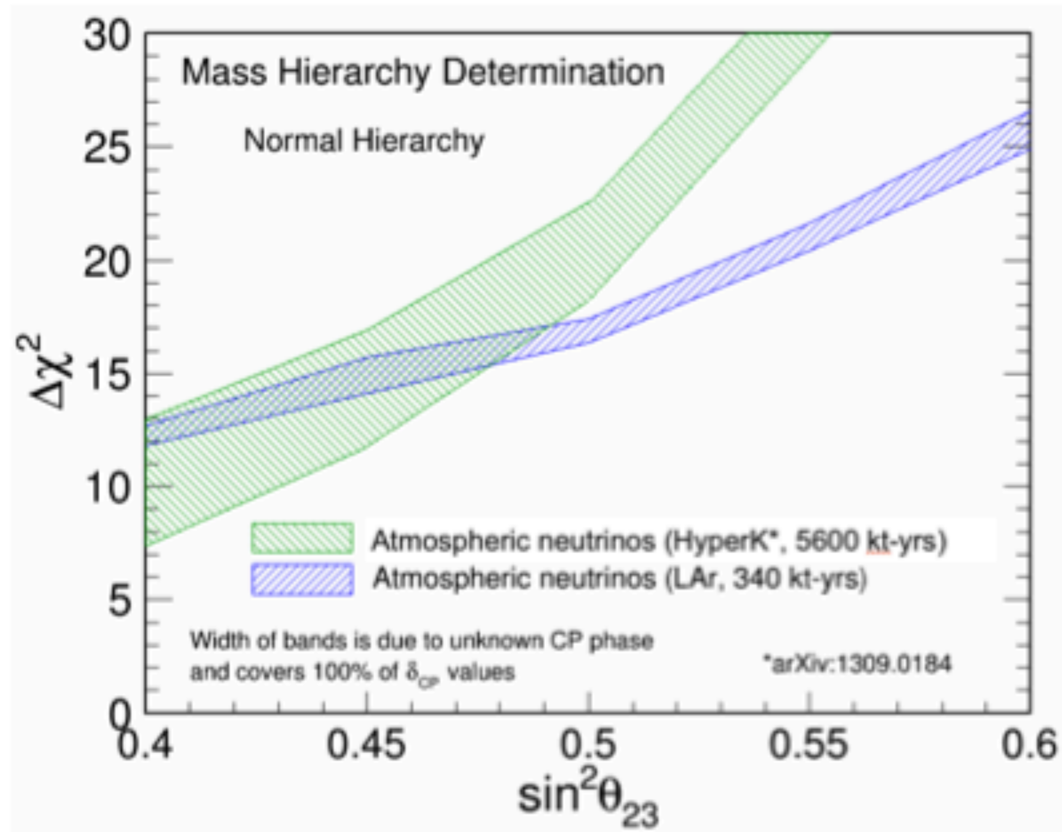


- better L and E (especially L, from angular resolution)
- potential **nu vs nubar** separation w/o B field (e.g., proton tag, μdk tag)

350 kt-yr, selected sample of high-resolution events

Mass hierarchy sensitivity with atmospheric neutrinos





- improves with nu vs nubar tagging
- unlike for beam, MH ~independent of CP δ
- also: octant, CP info; complementary to beam osc

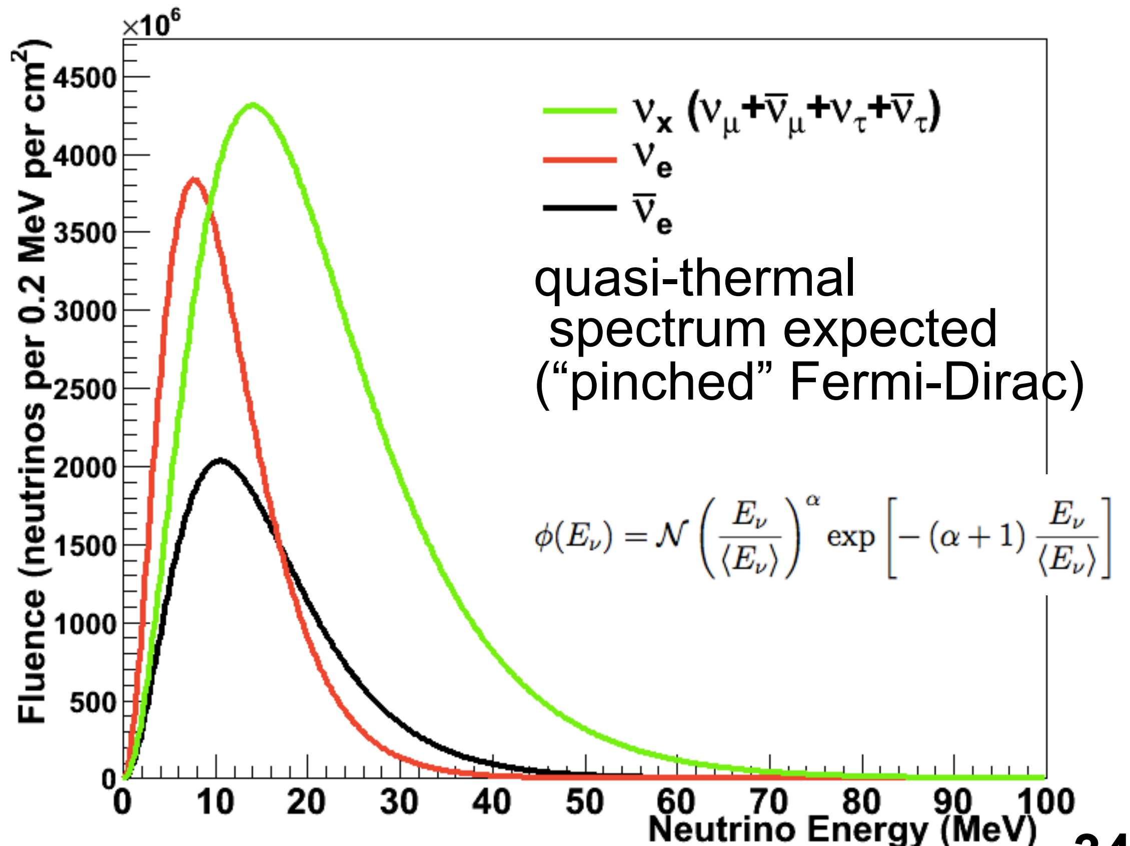
Neutrinos from core collapse

When a star's core collapses, ~99% of the gravitational binding energy of the proto-nstar goes into ν's of ***all flavors*** with **~tens-of-MeV energies**

(Energy *can* escape via ν's)

Mostly ν-$\bar{\nu}$ pairs from proto-nstar cooling

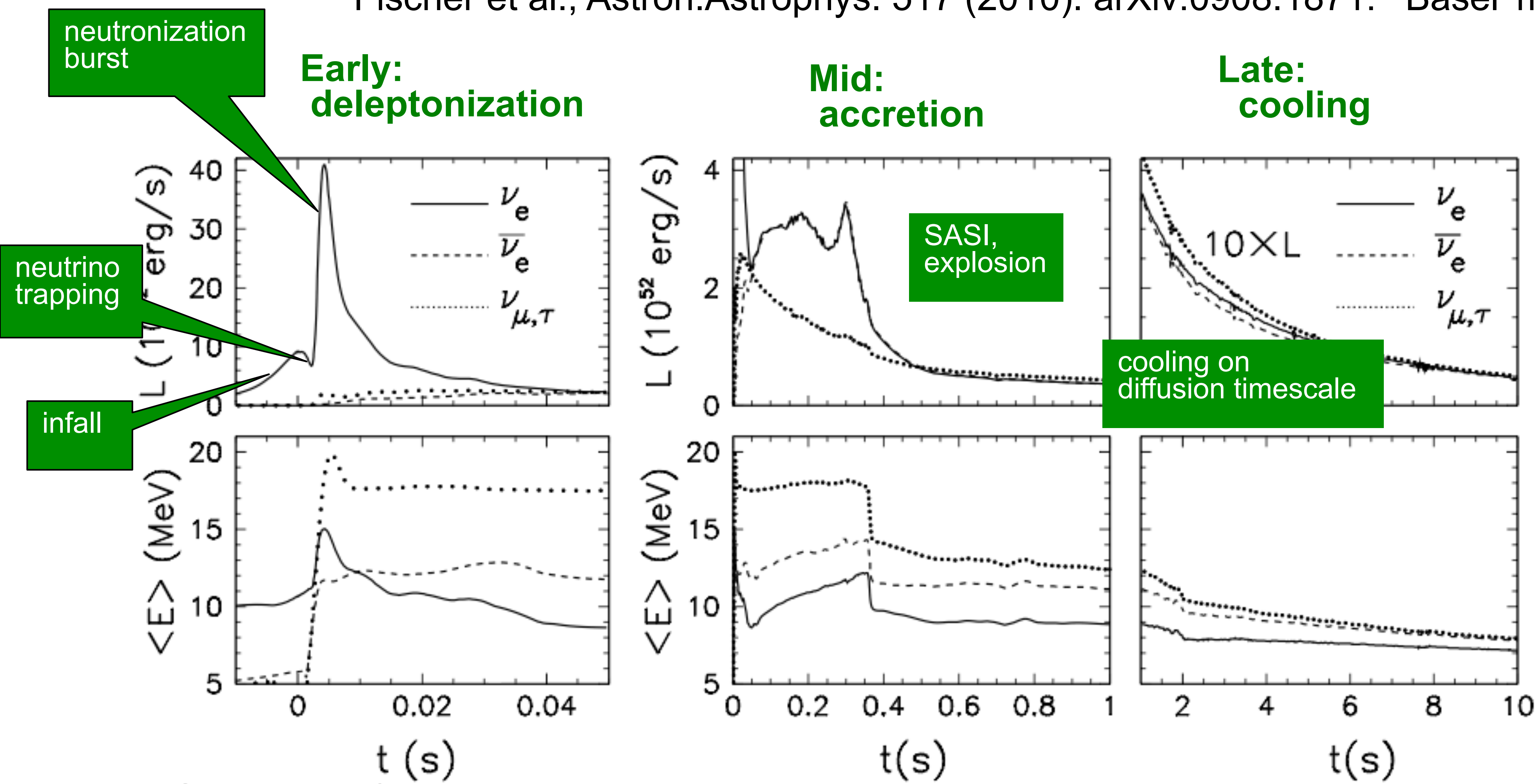
Timescale: ***prompt*** after core collapse, overall **Δt~10's of seconds**



Expected neutrino luminosity and average energy vs time

Vast information in the *flavor-energy-time profile*

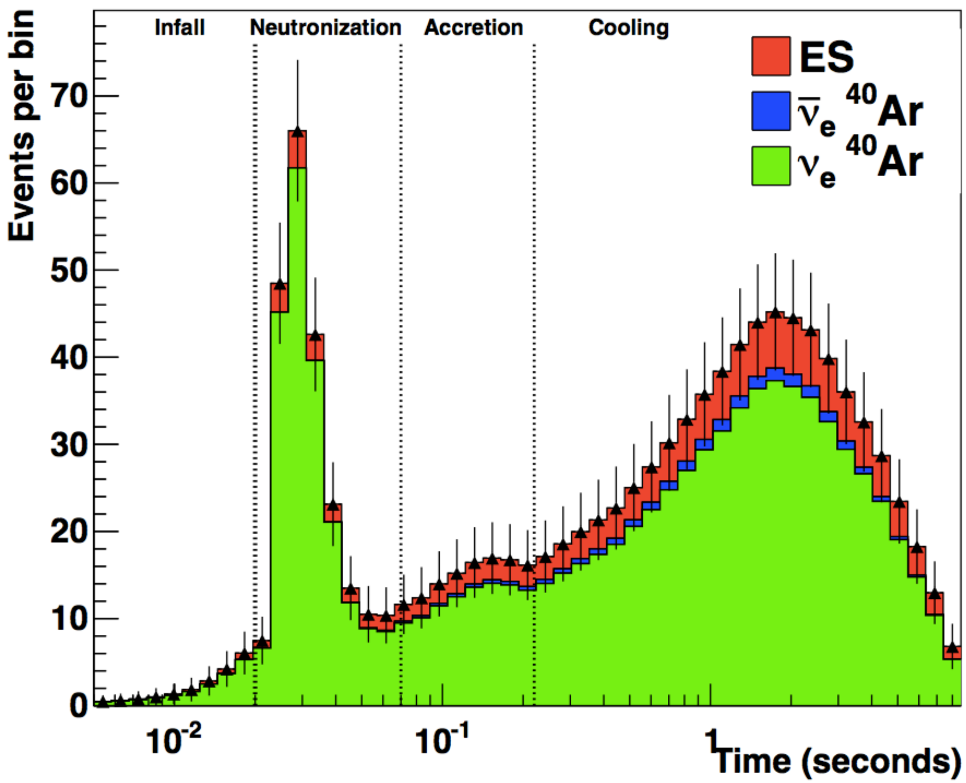
Fischer et al., Astron.Astrophys. 517 (2010). arXiv:0908.1871: ‘Basel’ model



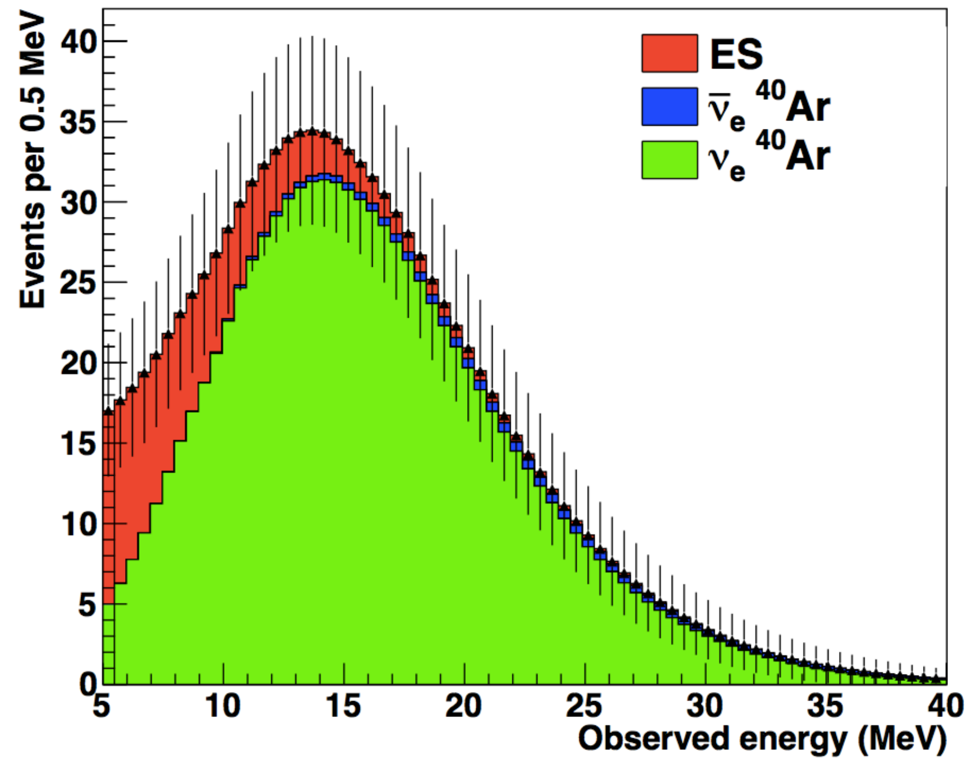
Generic feature:
(may or may not be robust)

$$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$$

Flavor composition as a function of time



Energy spectra integrated over time



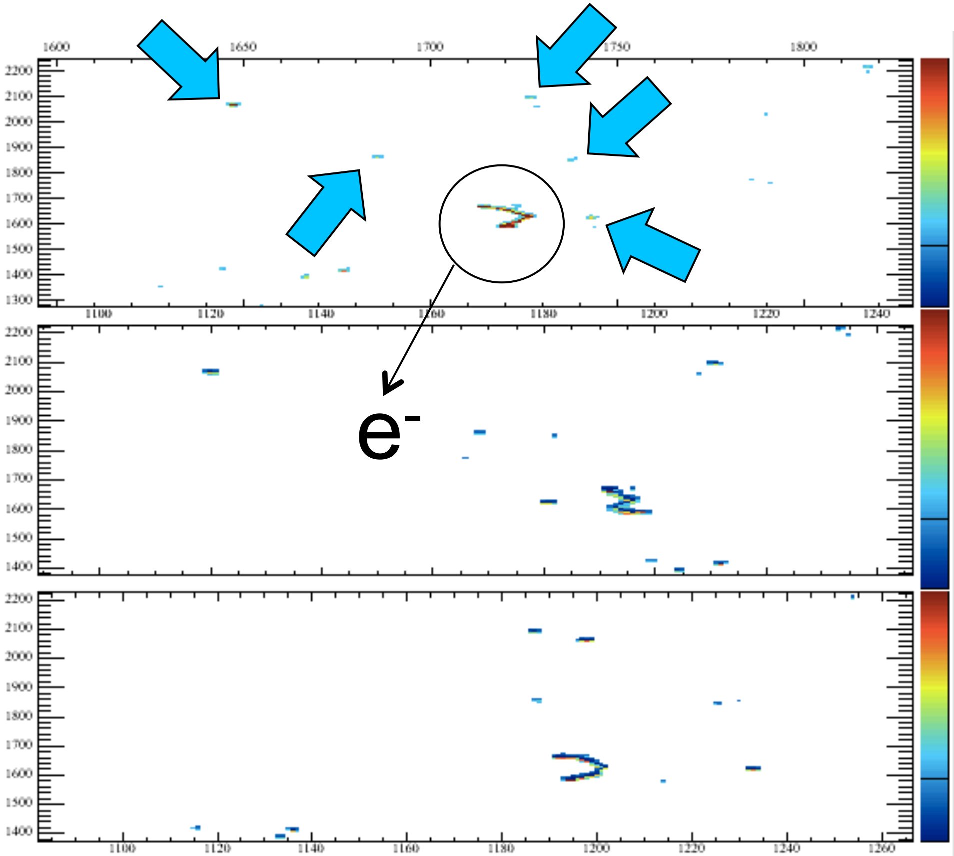
For 40 kton @ 10 kpc, Garching model

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

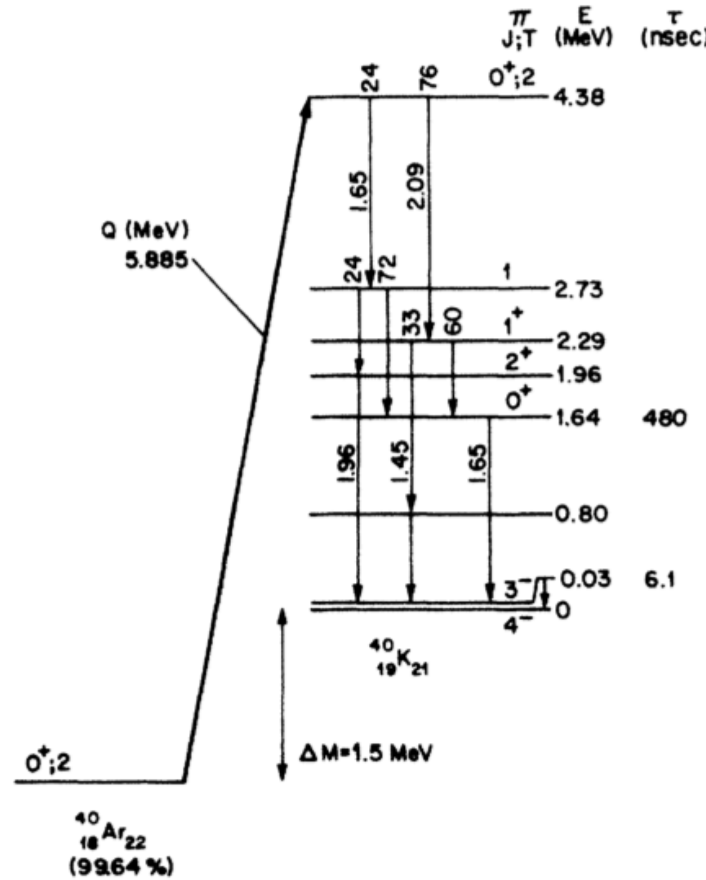
There is significant model variation

Can we tag ν_e CC interactions in argon using nuclear deexcitation γ's?

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



MicroBooNE geometry (LArSoft)

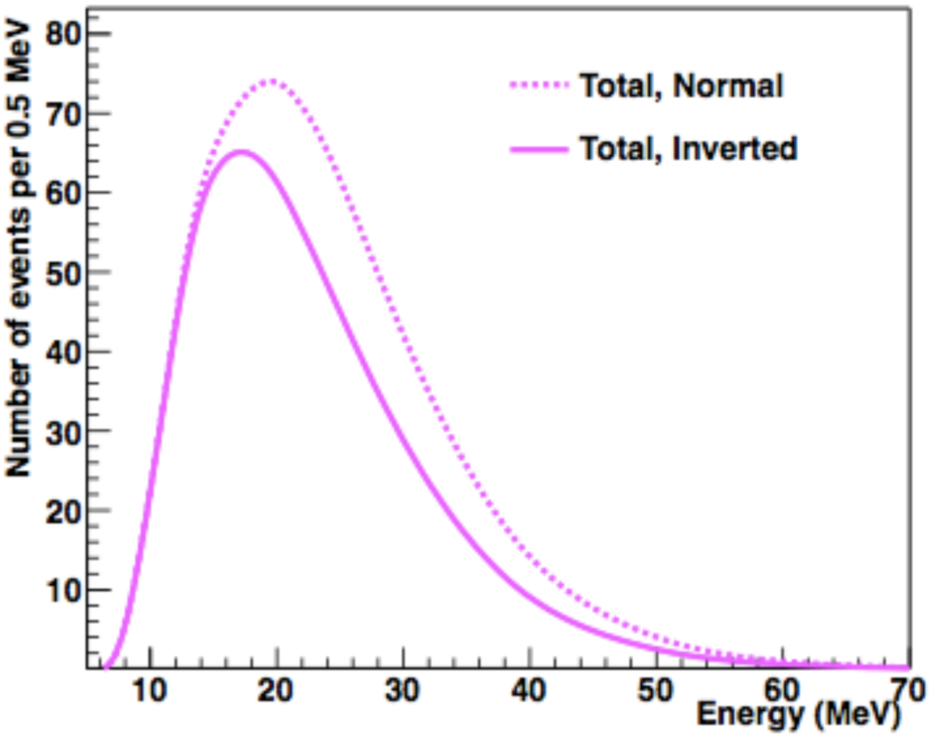


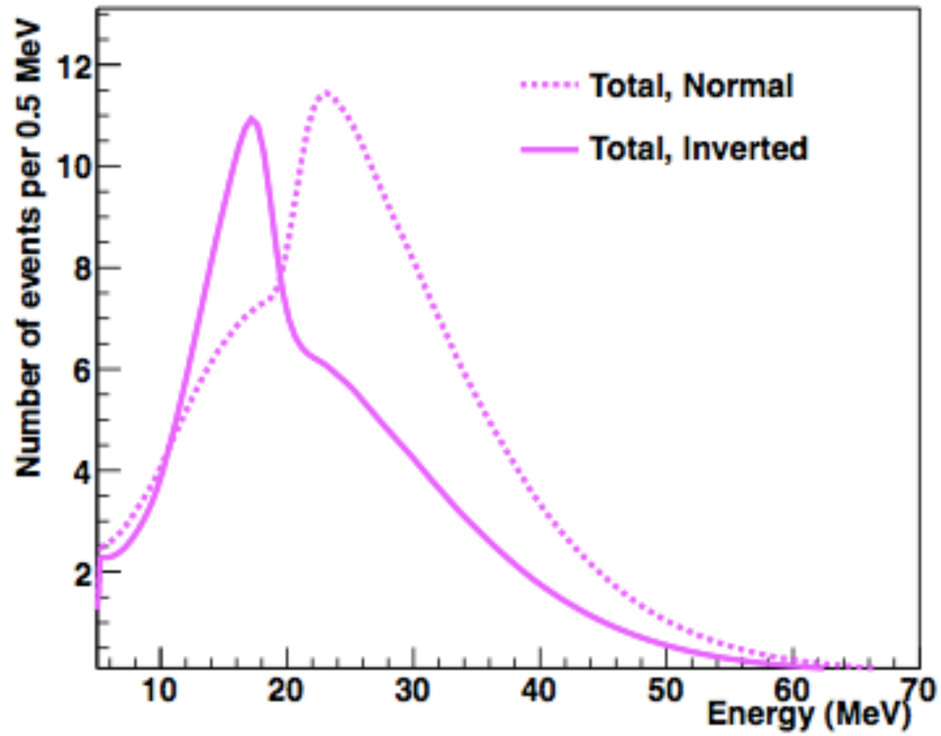
20 MeV ν_e , 14.1 MeV e^-, simple model based on R. Raghavan, PRD 34 (1986) 2088
Improved modeling based on ^{40}Ti (^{40}K mirror) β decay measurements possible
Direct measurements (and theory) needed!

Work underway to understand efficiencies

Water | Argon

1-s time slice from Duan model; 100-kt water/ 34-kt LAr (caveat: an illustrative anecdote)





mostly $\bar{\nu}_e$ | **mostly** ν_e

Different features in different flavors→ ***highly complementary***

Overall Summary

DUNE collaboration has formed and will operate as an international HEP collaboration

- Parameters: **high-power beam FNAL to SD, four 10-kton LAr TPCs** (staged)
  - first module will be single-phase, alternative dual-phase design possible for subsequent
- Timeline:
  - Far site construction to start 2017
  - Start physics data-taking w/1st module in 2024
  - Beam and ND in 2026
  - Construction finish in 2028
- Physics reach:
  - **excellent long-baseline sensitivity:** MH, CPV, octant,...
  - ***unique* capabilities for underground physics**: supernova burst, proton decay, atmnus,...; **highly complementary** to water (& scint)

Extras/backups

Electron (anti) neutrino appearance

	CDR Reference Design	Optimized Design
ν mode (150 kt · MW · year)		
ν_e Signal NH (IH)	861 (495)	945 (521)
$\bar{\nu}_e$ Signal NH (IH)	13 (26)	10 (22)
Total Signal NH (IH)	874 (521)	955 (543)
Beam $\nu_e + \bar{\nu}_e$ CC Bkgd	159	204
NC Bkgd	22	17
$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd	42	19
$\nu_\mu + \bar{\nu}_\mu$ CC Bkgd	3	3
Total Bkgd	226	243
$\bar{\nu}$ mode (150 kt · MW · year)		
ν_e Signal NH (IH)	61 (37)	47 (28)
$\bar{\nu}_e$ Signal NH (IH)	167 (378)	168 (436)
Total Signal NH (IH)	228 (415)	215 (464)
Beam $\nu_e + \bar{\nu}_e$ CC Bkgd	89	105
NC Bkgd	12	9
$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd	23	11
$\nu_\mu + \bar{\nu}_\mu$ CC Bkgd	2	2
Total Bkgd	126	127

Muon (anti)neutrino disappearance

	CDR Reference Design	Optimized Design
ν mode (150 kt · MW · year)		
ν_μ Signal	10842	7929
$\bar{\nu}_\mu$ CC Bkgd	958	511
NC Bkgd	88	76
$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd	63	29
$\bar{\nu}$ mode (150 kt · MW · year)		
$\bar{\nu}_\mu$ Signal	3754	2639
ν_μ CC Bkgd	2598	1525
NC Bkgd	50	41
$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd	39	18

Sources of backgrounds for the Kaon channels

Background Source	Mitigation Strategy
Internal cosmic ray spallation	Energy threshold
External cosmogenic K^+ production	Depth, fiducialization
External cosmogenic K^0 production +internal charge-exchange to K^+	Cuts on other secondaries
Atmospheric ν $\Delta S = 0$ processes	Cut on associated strange baryon
Atmospheric ν $\Delta S = 1$ processes	Cabibbo-suppressed, lepton ID
Atmospheric ν with π mis-ID	dE/dx discrimination, 236 MeV muon track
Reconstruction pathologies	dE/dx profiles vs track length

- Year 1: 10 kt far detector mass, 1.07-MW 80-GeV proton beam with 1.47×10^{21} protons-on-target per year beam, and no ND

- Year 2: Addition of the second 10-kt far detector module, for a total far detector mass of 20 kt

- Year 3: Addition of the third 10-kt far detector module, for a total far detector mass of 30 kt; and first constraints from the preliminary ND data analysis

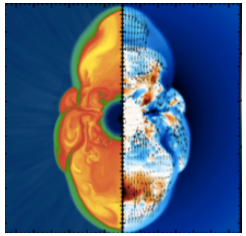
- Year 4: Addition of the fourth 10-kt far detector module, for a total far detector mass of 40 kt

- Year 5: Inclusion of constraints from a full ND data analysis

- Year 7: Upgrade of beam power to 2.14 MW for a 80-GeV proton beam

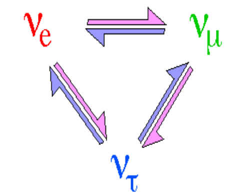
What can we learn from the next neutrino burst?

CORE COLLAPSE PHYSICS



explosion mechanism
proto nstar cooling,
quark matter
black hole formation
accretion, SASI
nucleosynthesis
....

input from neutrino experiments



from flavor, energy, time structure of burst

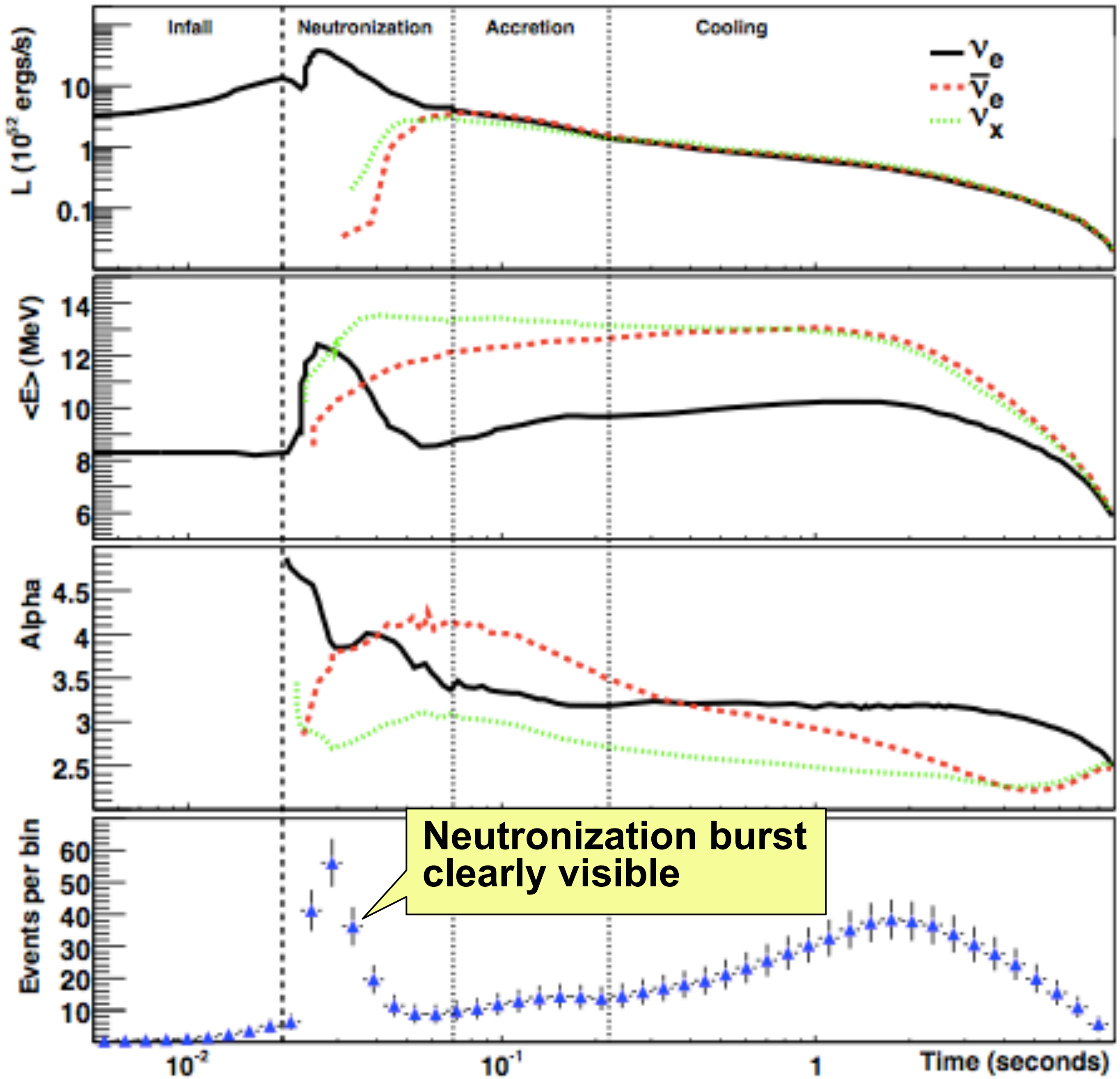
input from photon (GW) observations

NEUTRINO and OTHER PARTICLE PHYSICS

ν absolute mass (not competitive)
ν mixing from spectra:
flavor conversion in SN/Earth,
collective effects
➔ **mass hierarchy**
other ν properties: sterile ν's,
magnetic moment,...
axions, extra dimensions,
LIV, FCNC, ...

+ EARLY ALERT

Example of supernova burst signal in 34 kton of LAr



luminosity

average
ν energy

pinching
(large α ➔
suppressed tails)

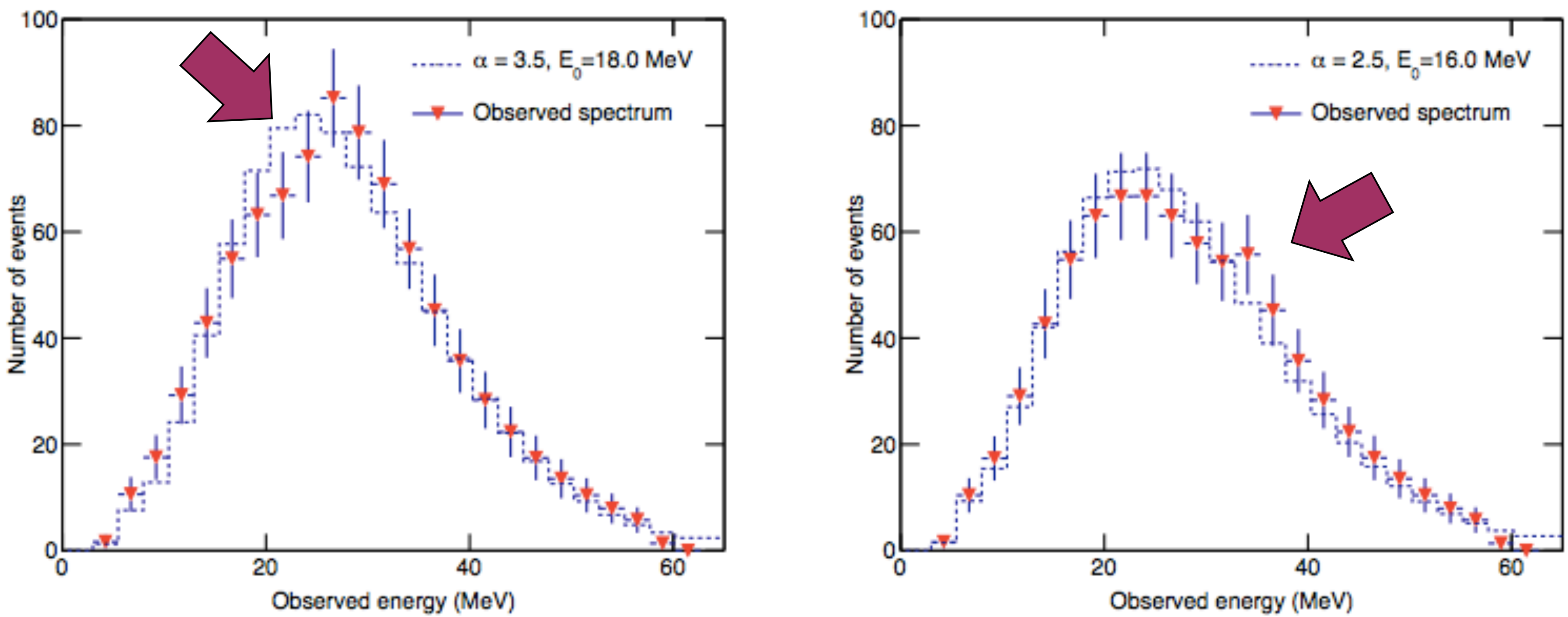
See the ν_e
light curve!

Flux from Huedepohl et al., PRL 104 (2010) 251101 ("Garching") @ 10 kpc;
assuming Bueno et al. resolution

Another anecdote:

A. Friedland, H. Duan, JJ Cherry, KS

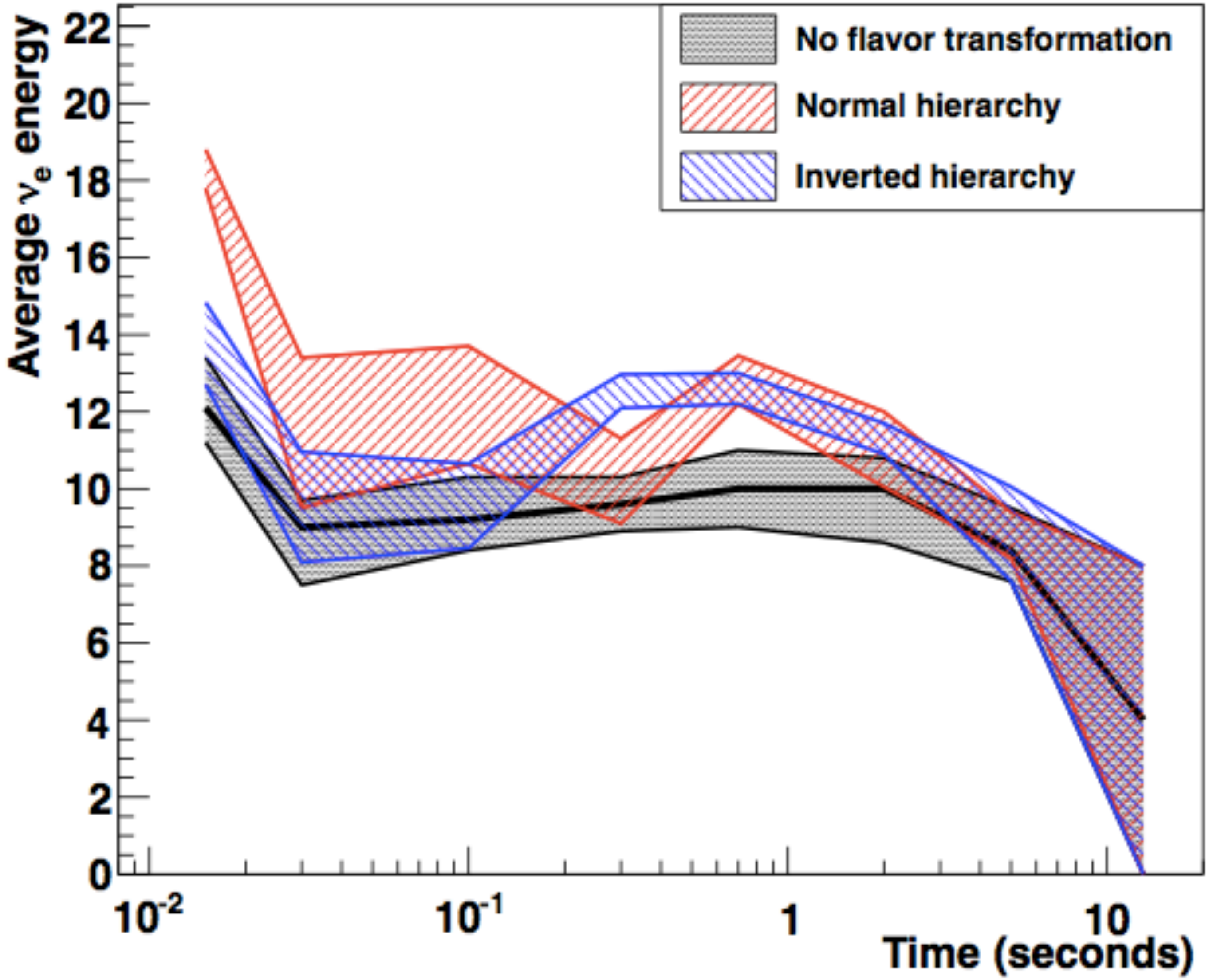
1-sec integrated spectra in 34-kton LAr, few sec apart for 10-kpc SN, NMH



MH-dependent "non-thermal" features clearly visible as shock sweeps through the supernova

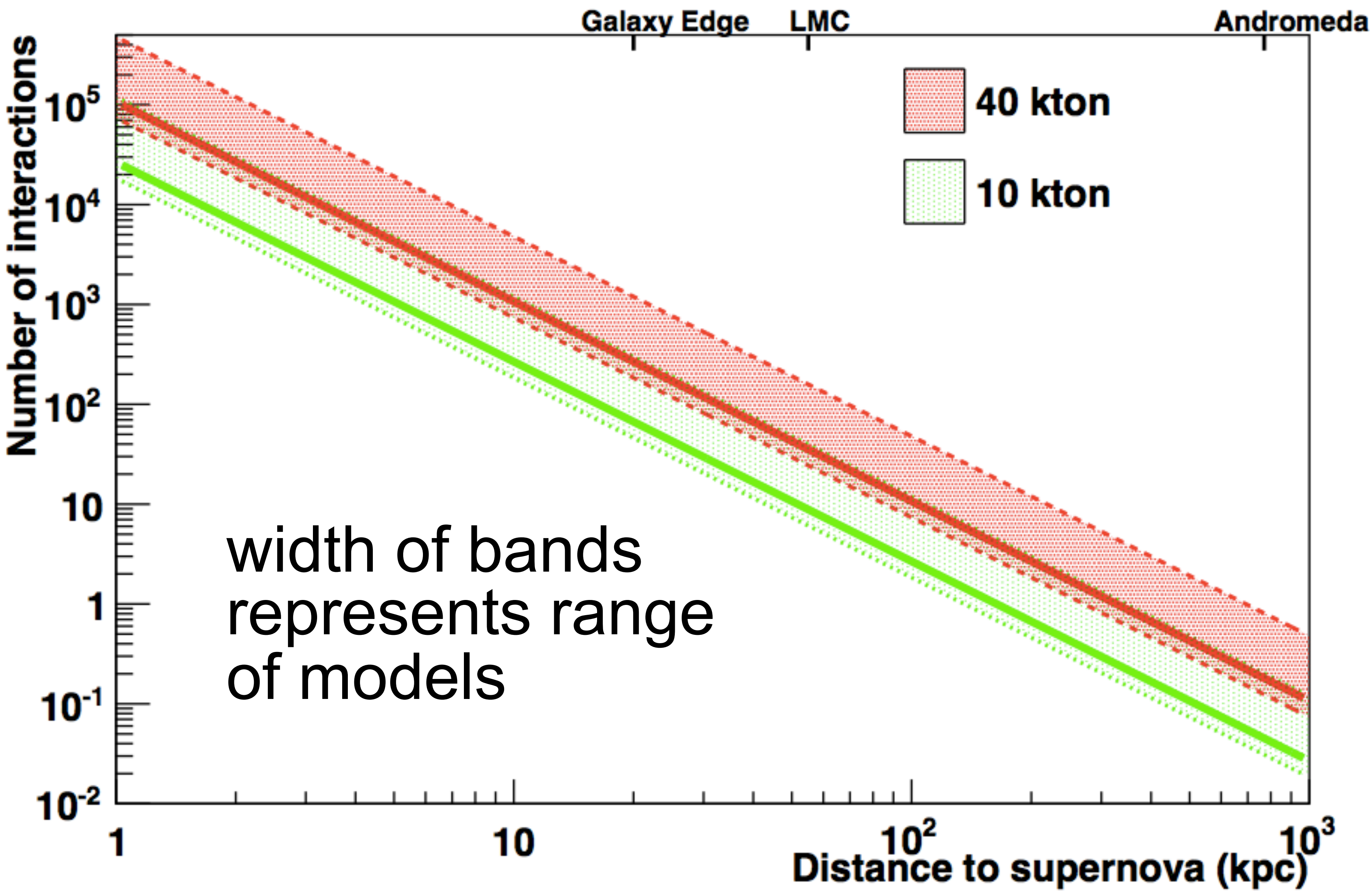
And another:

A. Friedland, H. Duan, JJ Cherry, KS

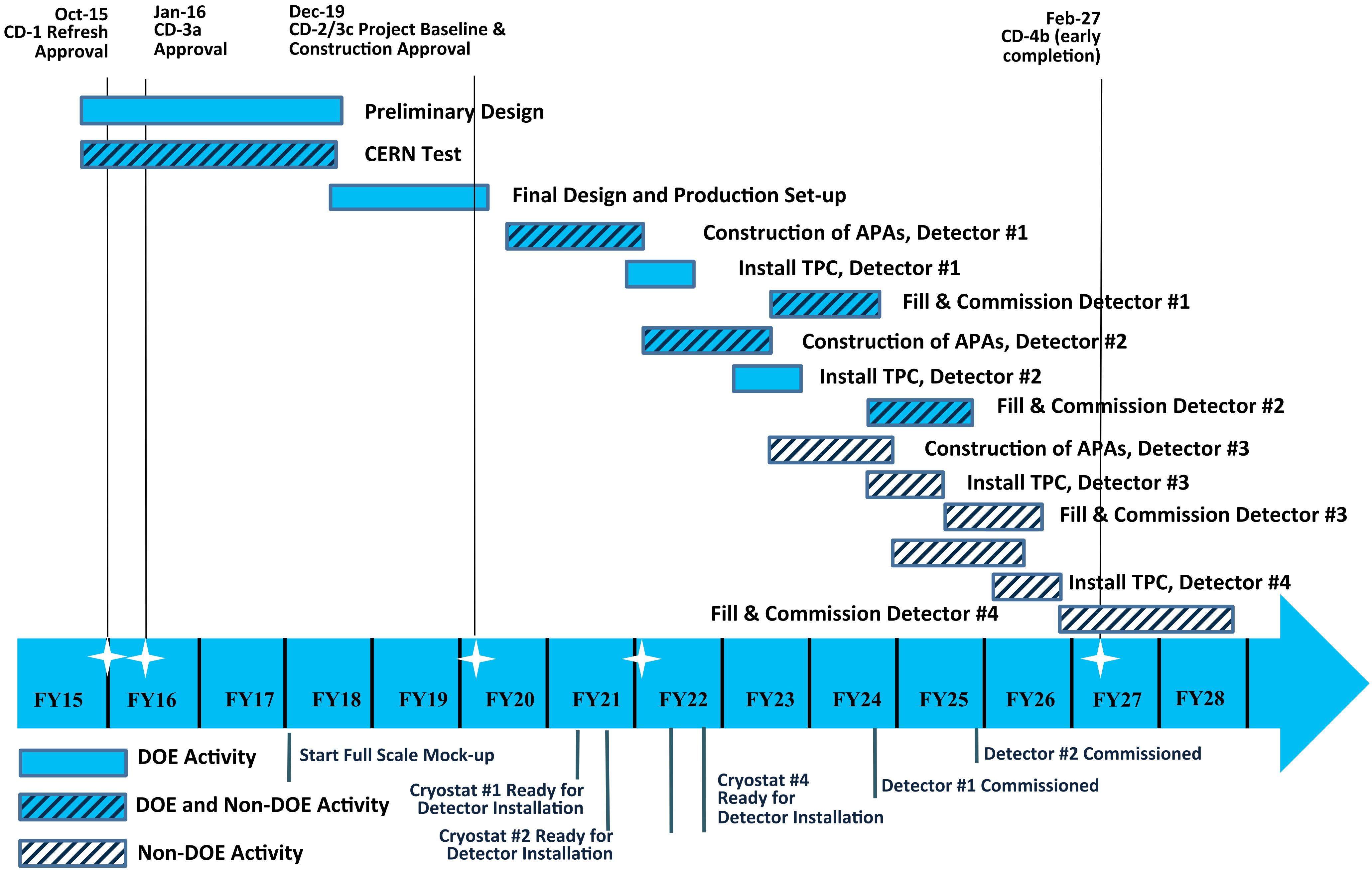


Average ν_e energy from fit to “pinched thermal”,
34-kton LAr @ 10 kpc, including collective oscillations ➔
clearly, there’s information in the spectral evolution

Events in LAr vs distance



Resource Loaded Schedule



Indicative Far Detector Decision Dates