The Deep Underground Neutrino Experiment

with an emphasis on astrophysics

Fermilab

SURF

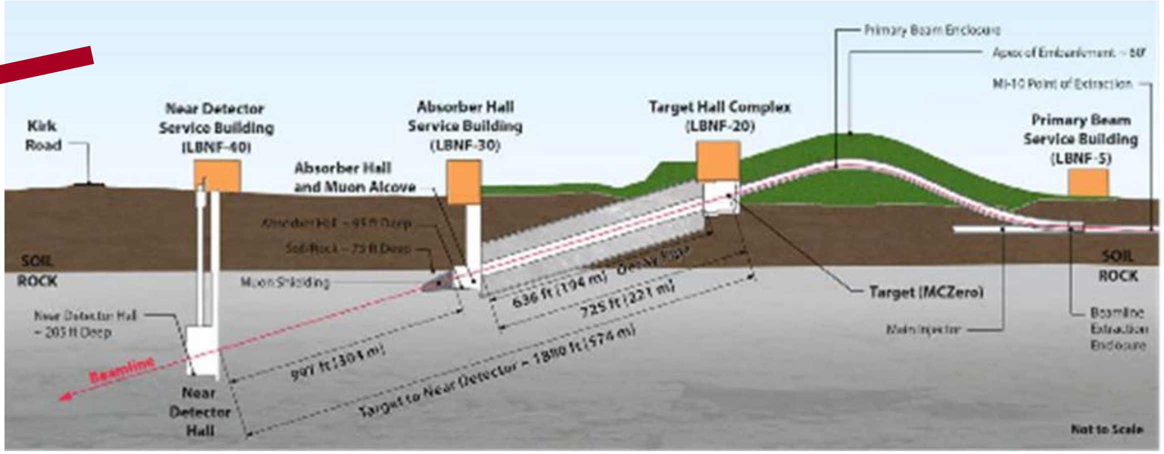
Outline

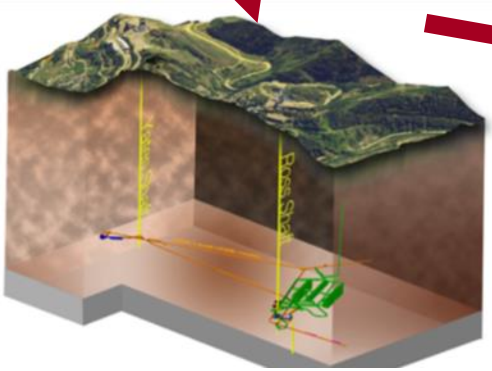
I. Status of DUNE
   – Design
   – Collaboration
   – Schedule, including ProtoDUNE

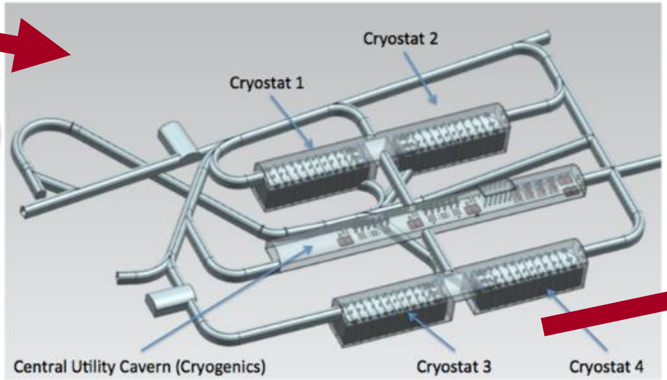
II. Physics of DUNE
   – Beam and atmospheric neutrinos
   – Supernova neutrinos
   – Nucleon decay
   – Other

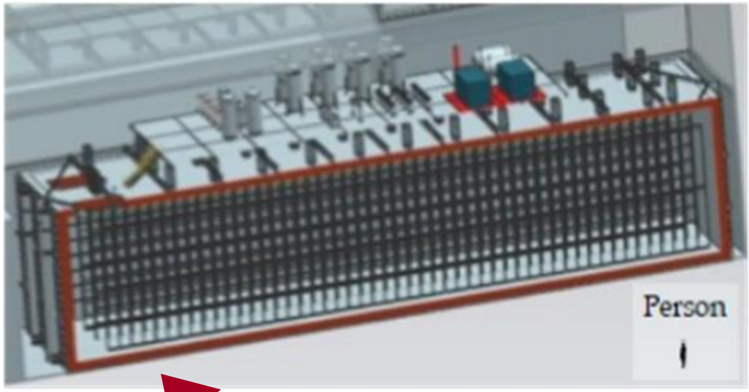
Overview

Anatomy of DUNE



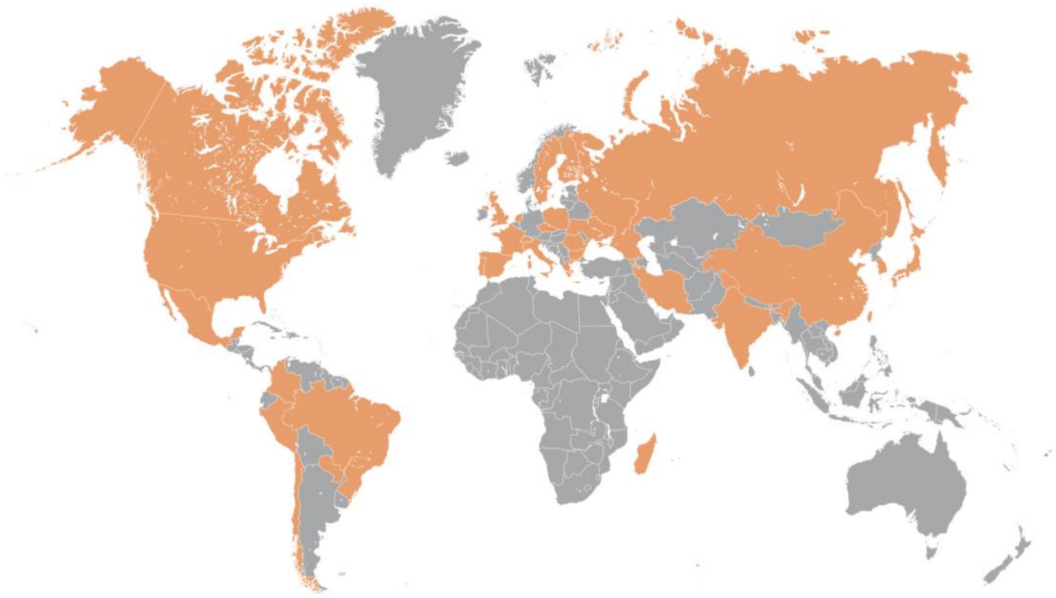






15m x 15 m x 65 m

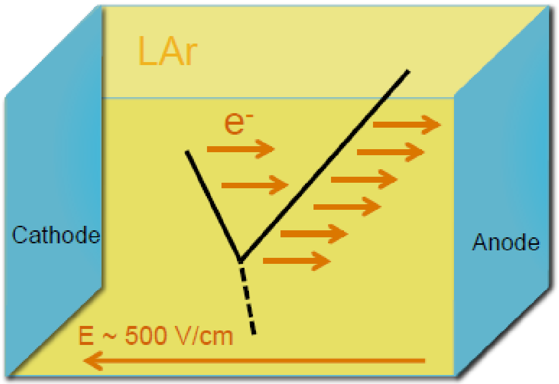
The growing collaboration

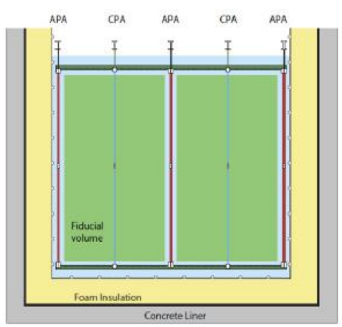


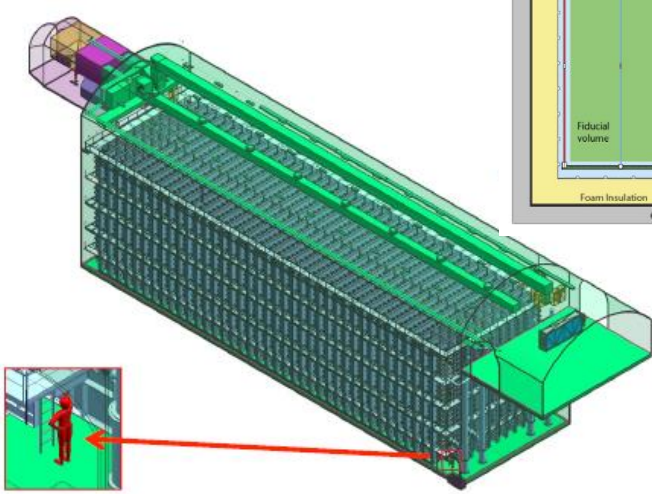
As of January 2019

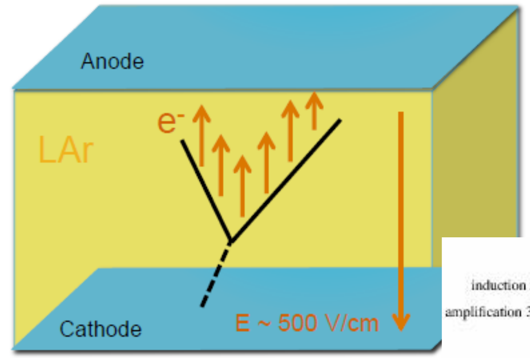
- 1202 collaborators from 183 institutions in 31 countries
- 648 faculty/scientist, 201 PDs, 119 engineers, 234 PhD students

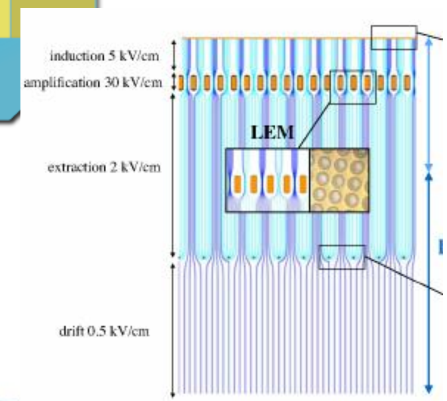
Single Phase---------------Dual Phase

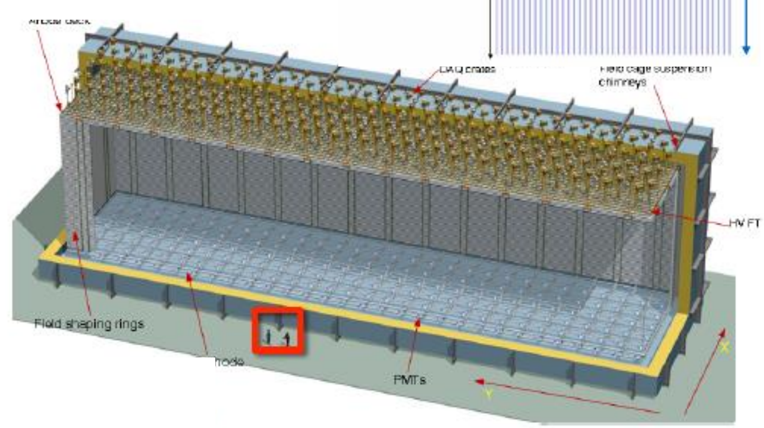












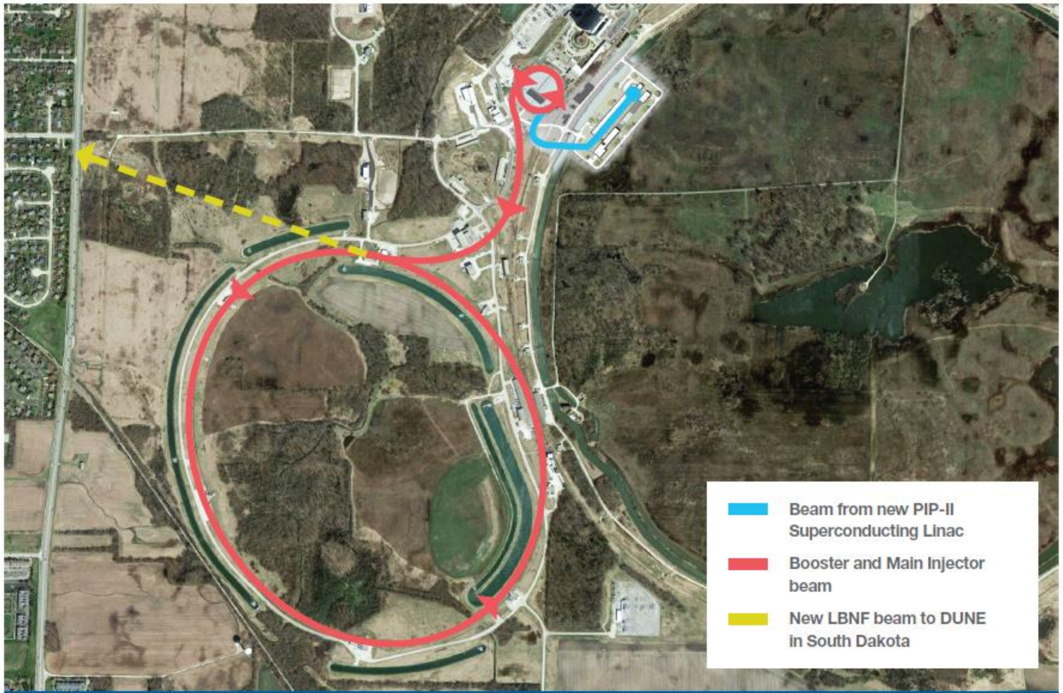
Strategy

- The DUNE Collaboration is pursuing and prototyping two LAr TPC technologies, SP &DP
- The collaboration is planning for the 1^{st} 10 kT module to be SP & 2^{nd} DP (2+1+1 model with 3^{rd} module SP and 4^{th} ‘module of opportunity’)
- Sequencing (SP-DP-SP vs. SP-SP-DP) will depend on ProtoDUNE results & resources

PIP II

- ☆Proton Improvement Plan Phase 2 using superconducting cryomodules
- ☆Groundbreaking Ceremony

 15 March 2019



The PIP-II project will supply powerful neutrino beams for the LBNF/DUNE experiment.

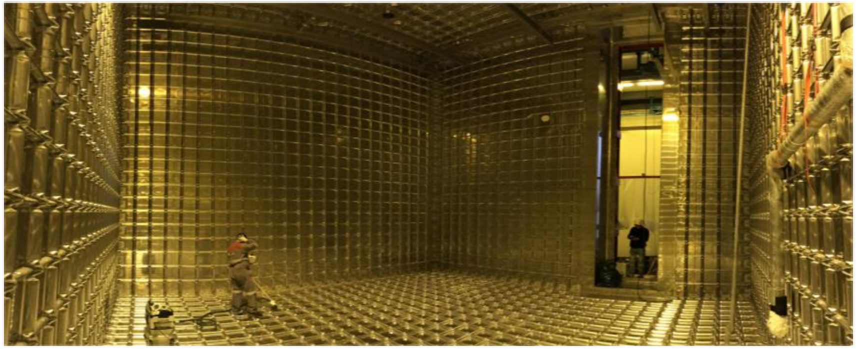
DUNE Schedule

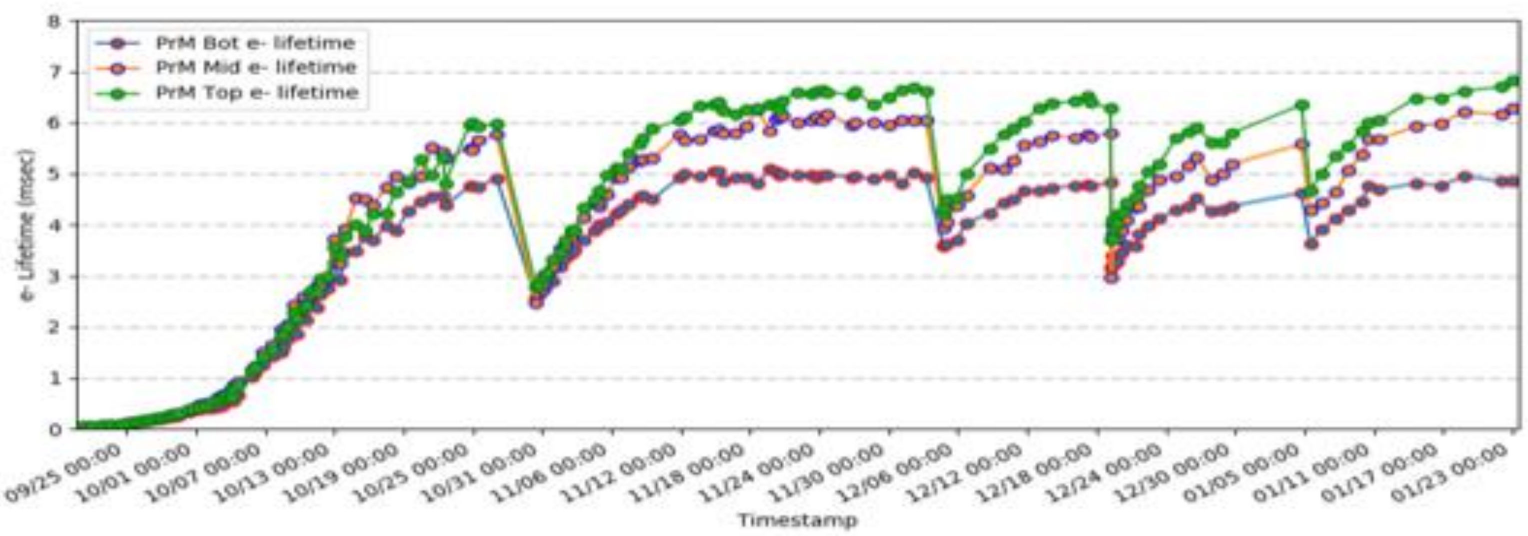
- Physics TDR will be available soon
- Detector 1 ready to start installation August 2024
- Detector 1 ready for cool down August 2025
- Detector 1 ready for physics late summer 2026
- Detector 2 ready to start installation August 2025
- Detector 2 ready for cool down August 2026
- Detector 2 ready for physics late summer 2027

ProtoDUNE

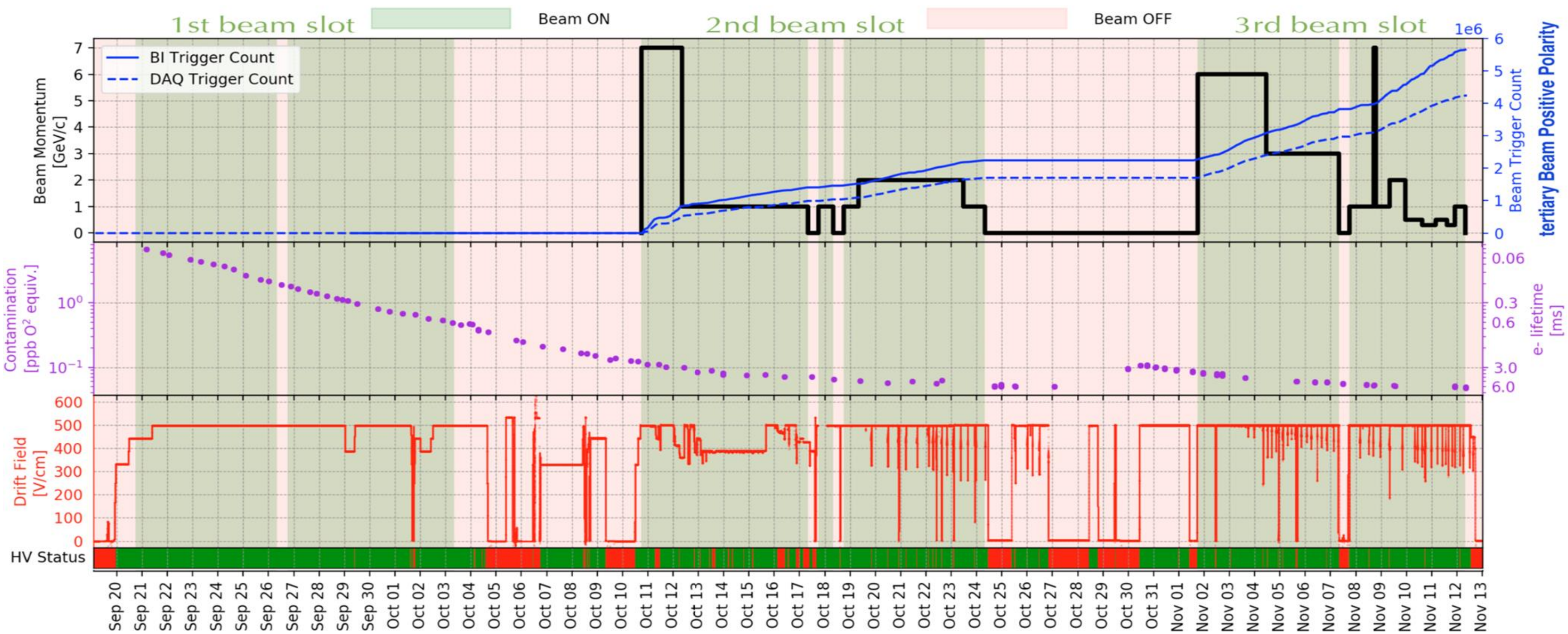
Purity

- Drops in purity due to stop of the liquid argon recirculation (sometime planned and sometime not)





CERN Beam
ProtoDUNE running



Events / future CERN plan

✓ 2018 ProtoDUNE-SP run

Beam Data Accumulation

Particle content is based on the expected rates from the Geant simulation of the beamline

Momentum (GeV/c)	Total Triggers Recorded (K)	Total Triggers Expected (K)	Expected Pi trig. (K)	Expected Proton Trig. (K)	Expected Electron Trig. (K)	Expected Kaon Trig. (K)
0.3	269	242	0	0	242	0
0.5	340	299	1.5	1.5	296	0
1	1089	1064	382	420	262	0
2	728	639	333	128	173	5
3	568	519	284	107	113	15
6	702	689	394	70	197	28
7	477	472	299	51	98	24
All momenta	4173	3924	1693.5	777.5	1381	72

✓ Use cosmics through Oct 2020 for SP & DP

✓ Upgrade SP Oct 2020- Sep 2021

✓ more beam Apr-May 2022

Supernova neutrinos

DEEP UNDERGROUND NEUTRINO EXPERIMENT

ν Signals in Liquid Ar

A LAr detector is primarily sensitive to ***neutrinos***, as opposed to water/scintillator sensitivity to antineutrinos

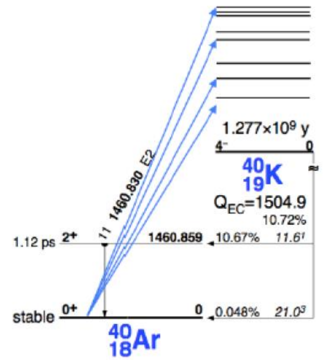
- Elastic scattering (ES) on electrons

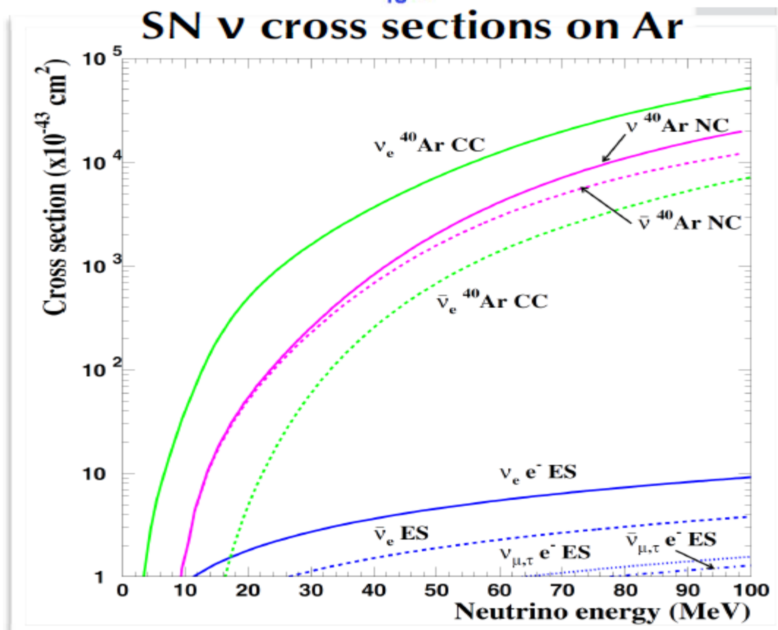
$$\boxed{\nu + e^- \rightarrow \nu + e^-}$$

- Charged-current (CC) interactions on Ar

$$\boxed{\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-} \quad E\nu_e > 1.5\ \text{MeV}$$

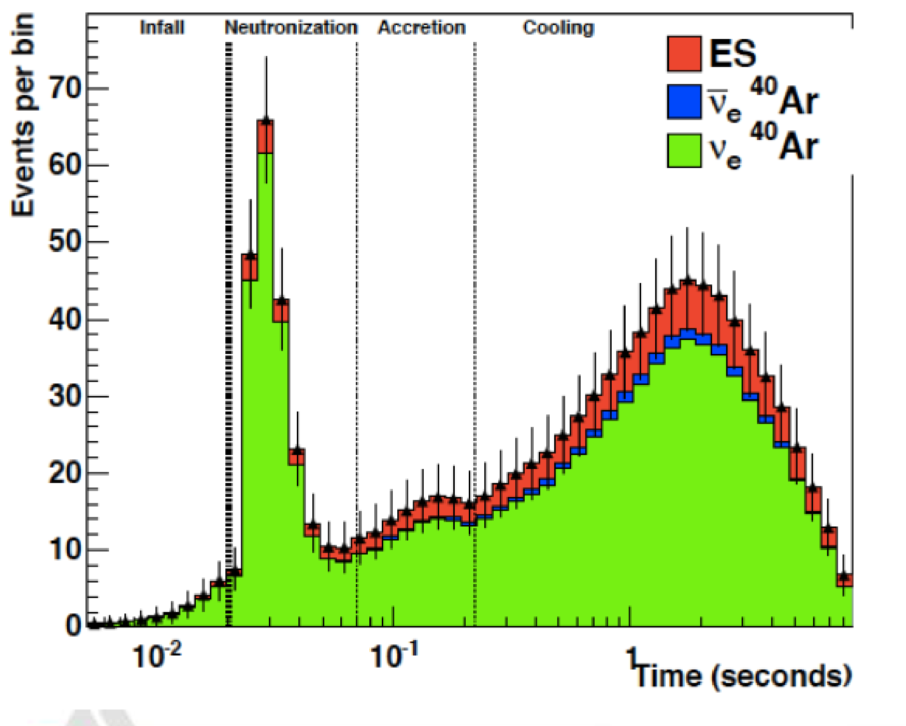
$$\boxed{\bar{\nu}_e + {}^{40}Ar \rightarrow {}^{40}Cl^* + e^+} \quad E\bar{\nu}_e > 7.48\ \text{MeV}$$

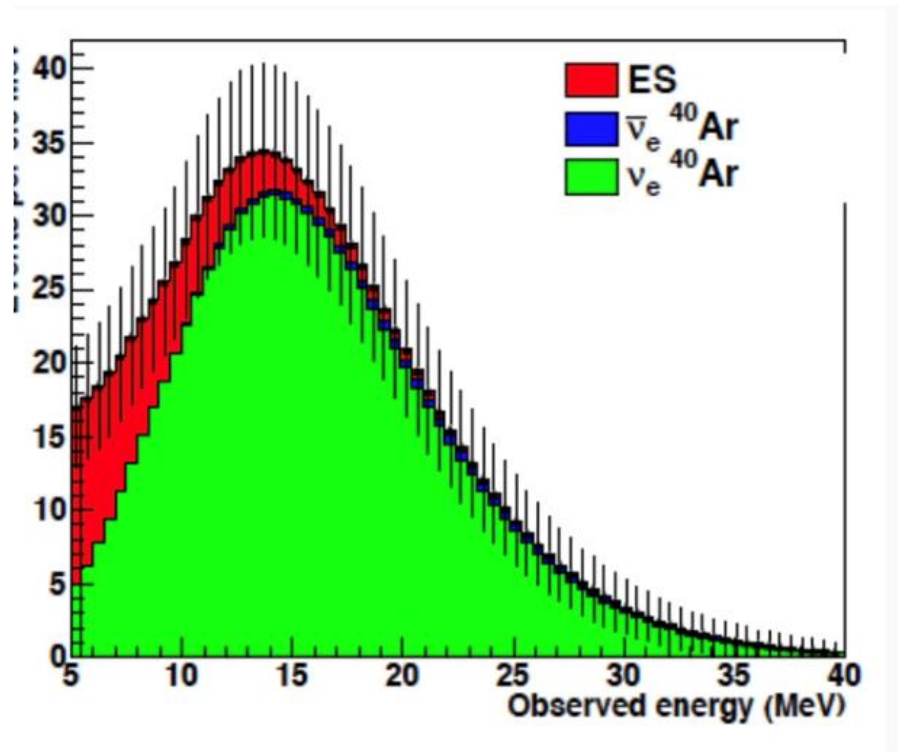




ν distributions (t, E_ν) **before** oscillations

Garching Model



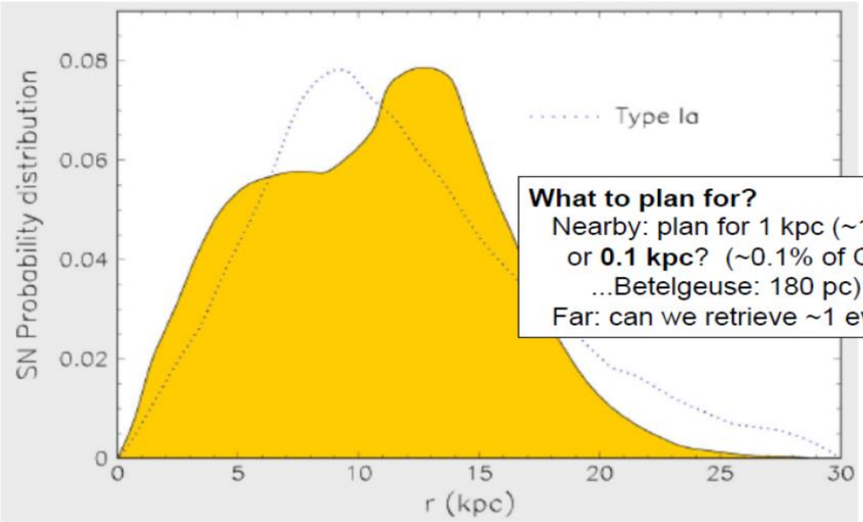


Rates and distance

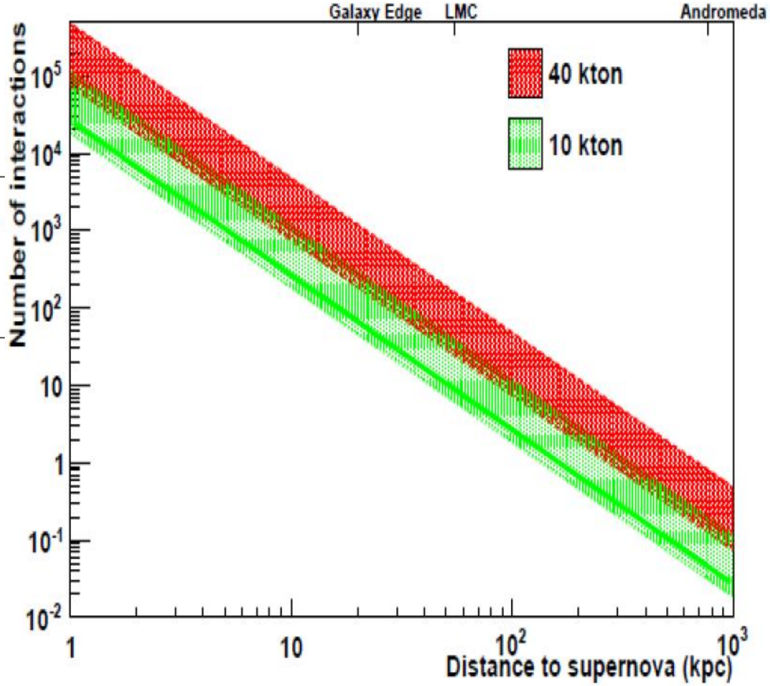
- Rate versus distance

Typical distance from us: ~10-15 kpc

(10 kpc is "standard distance")



What to plan for?
Nearby: plan for 1 kpc (~1% of CCSN)?
or **0.1 kpc**? (~0.1% of CCSN?
...Betelgeuse: 180 pc)
Far: can we retrieve ~1 event??



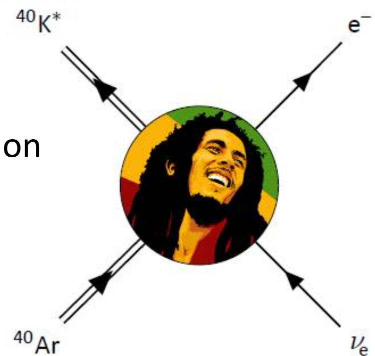
At 10 kpc:

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

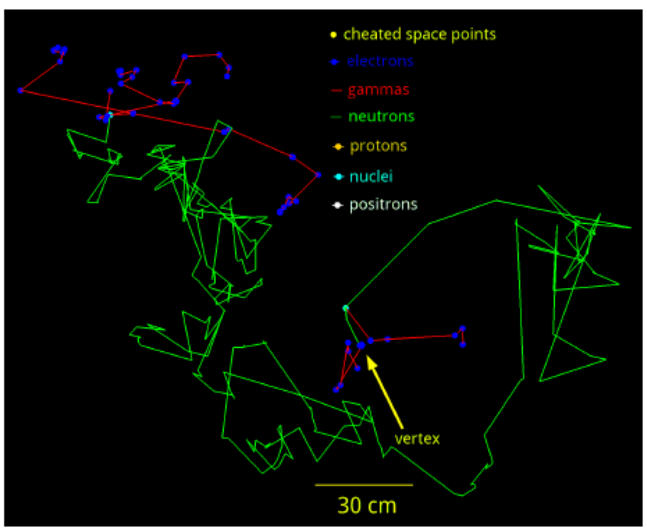
SIMULATIONS
MARLEY & SNOGLOBES

MARLEY

Model of Argon Reaction
Low Energy Yields



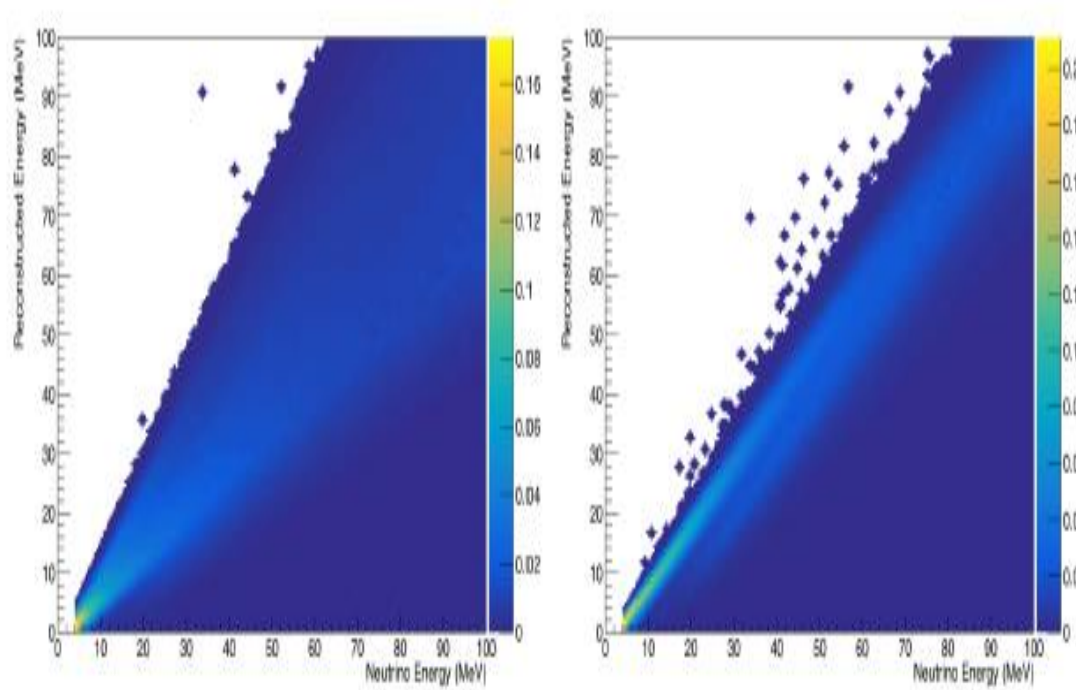
http://www.marleygen.org/



SNOwGLoBES

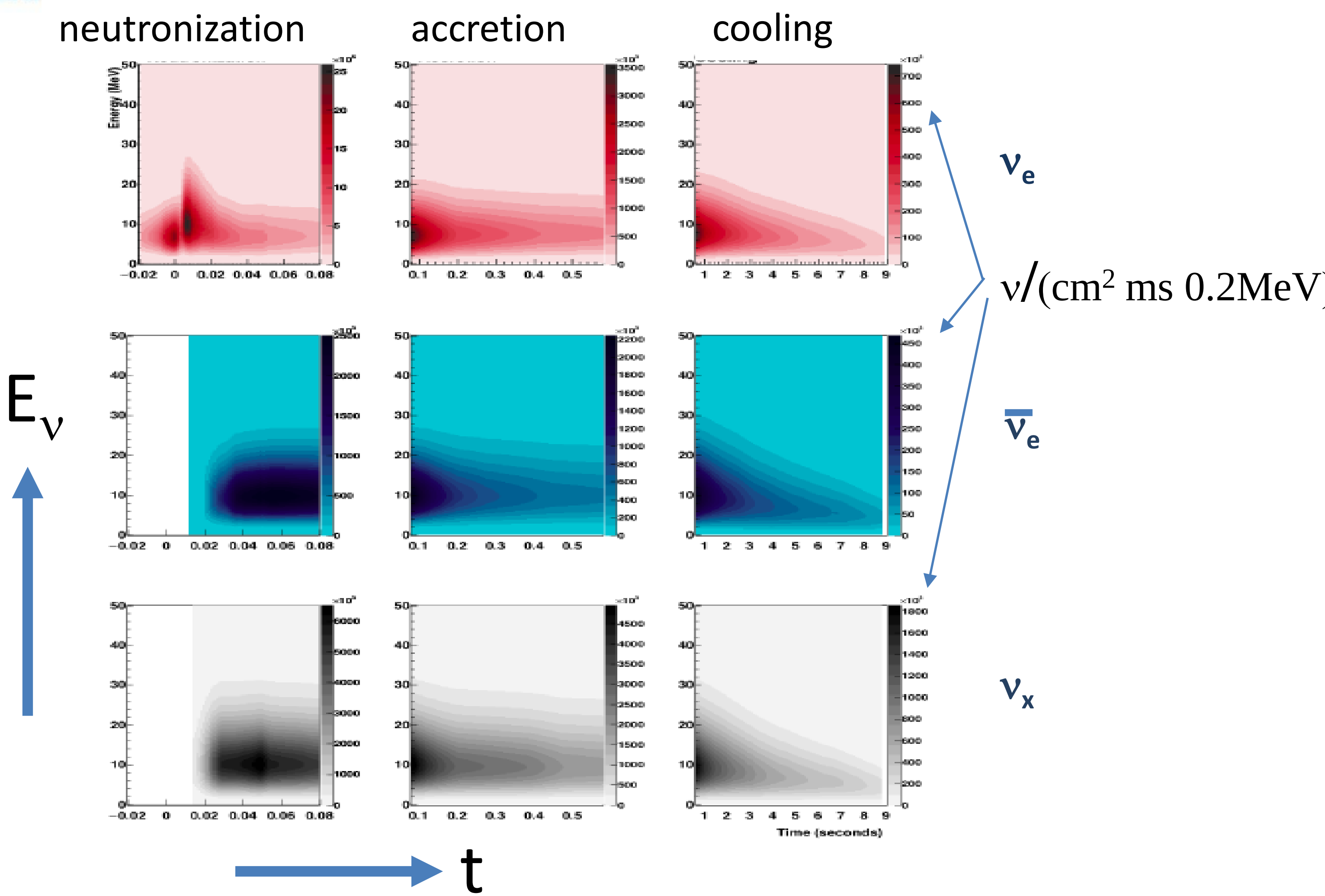
A fast event rate computation tool for long-baseline experiments

http://webhome.phy.duke.edu/~schol/snowglobes/



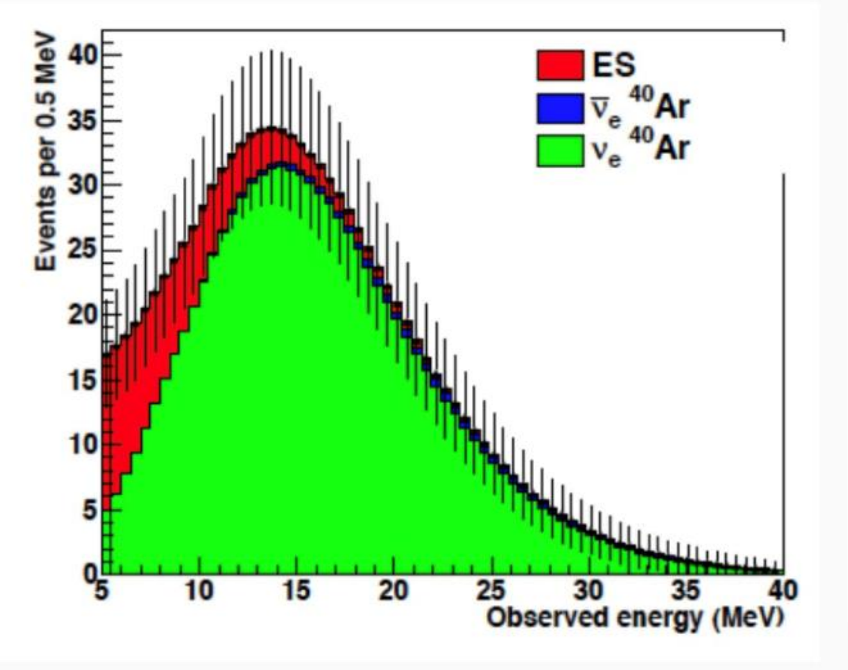
Energy smearing without/with drift correction

Time details

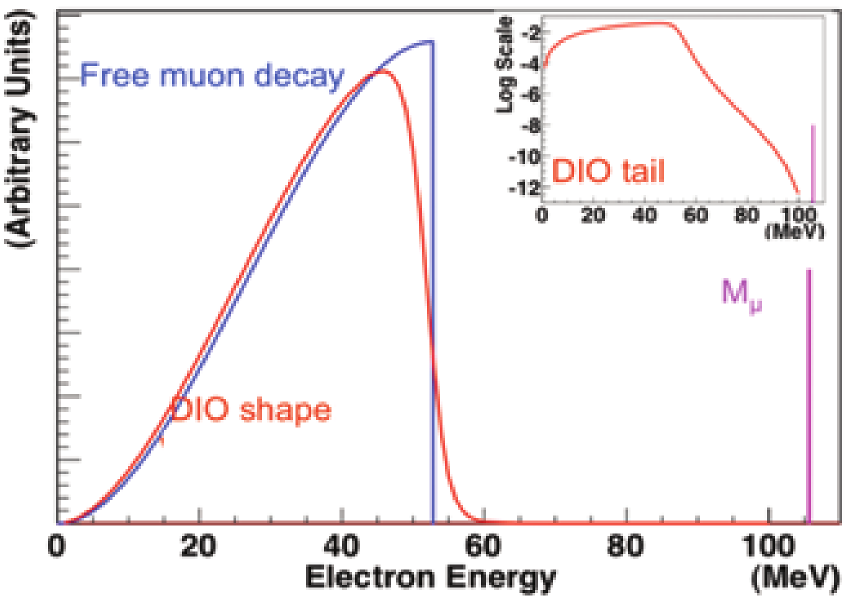


Michels from stopping μ appropriate for calibration

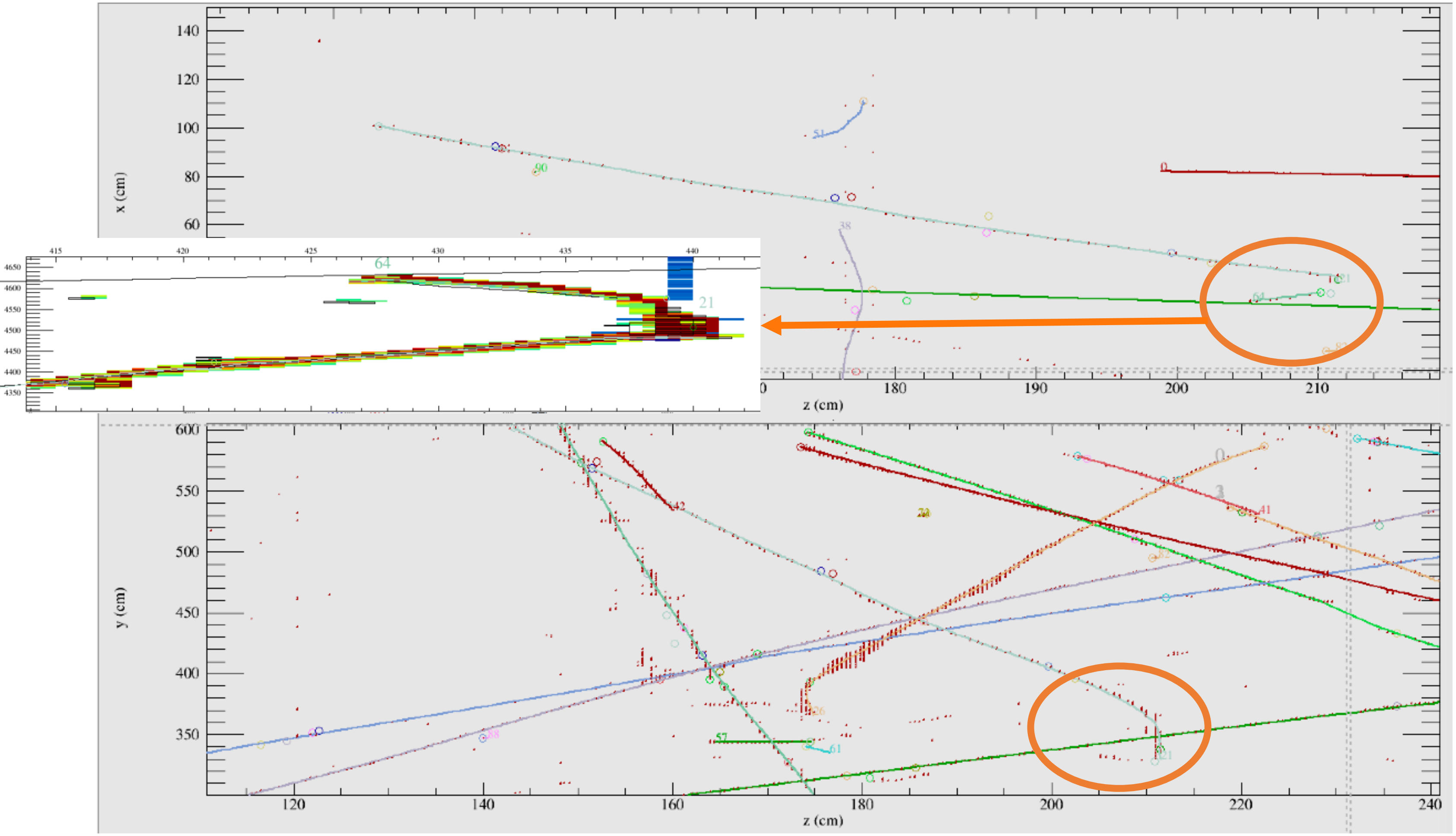
Supernova spectrum in DUNE



Michel Electron Spectrum



Stopping μ in ProtoDUNE



Trigger challenge

- SN triggering is a challenge for a slow LArTPC
  - Sampling at 1.15 TB/s for 10 kT single phase
  - 100 s of uninterrupted data if SN happens
  - Don't want to miss any galactic SN
- Very rough rates:
  - 1 SN@LMC makes 50 events in 40 kT
  - 13 events in 10 kT
  - Spread over ~10 s
  - 13 events/10 s ≅ 1 Bq
  - For Background 4×10^{-8} Bq
    - 1 fake per month

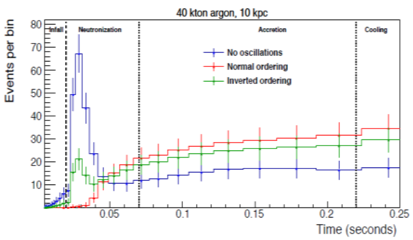
Background contributions

Signal	Type	Rate [Bq]	Reduction needed	Energy [MeV]
Argon 39	Beta	3×10^{7}	7×10^{14}	< 1
Argon 42	Multiple	2×10^{3}	6×10^{10}	3
Rock/Cement Uranium 238	Neutrons	1×10^{2}	3×10^{9}	0-10
Polonium on Photodetector	Alpha	70	2×10^{9}	5
Radon 222 decay chain	Alpha	1×10^{6}	3×10^{13}	5
Other		3×10^{6}	8×10^{13}	≈ 1
SN Signal	Electron	1Hz	1	5-25

- Need a fast & efficient trigger algorithm

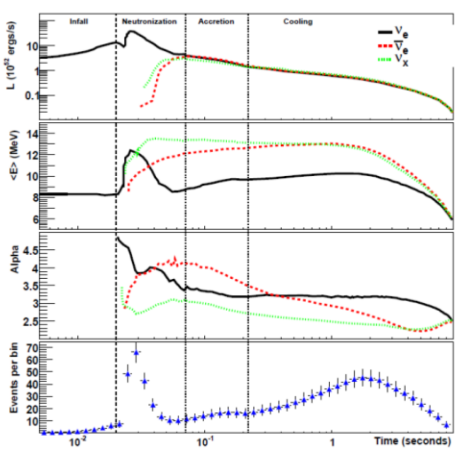
Parameter	single-phase	dual-phase
TPC unit	APA	CRO crate
Unit multiplicity	150	240
Channels per unit	2560 (800 collection)	640 (all collection)
ADC sampling	2 MHz	2.5 MHz
ADC resolution	12 bit	12 bit

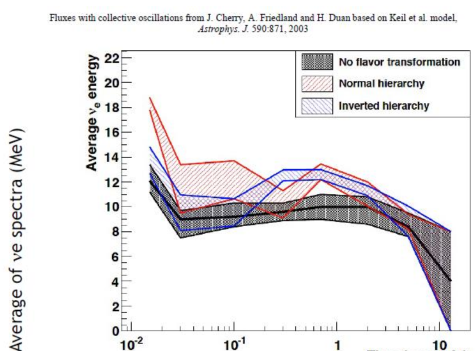
Interpretation challenges

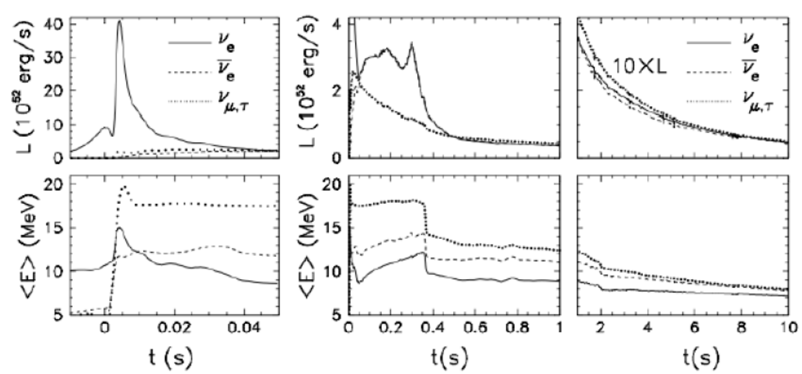


We can predict an E_ν spectrum from a model, but how well can we point to a model based on a measured spectrum?

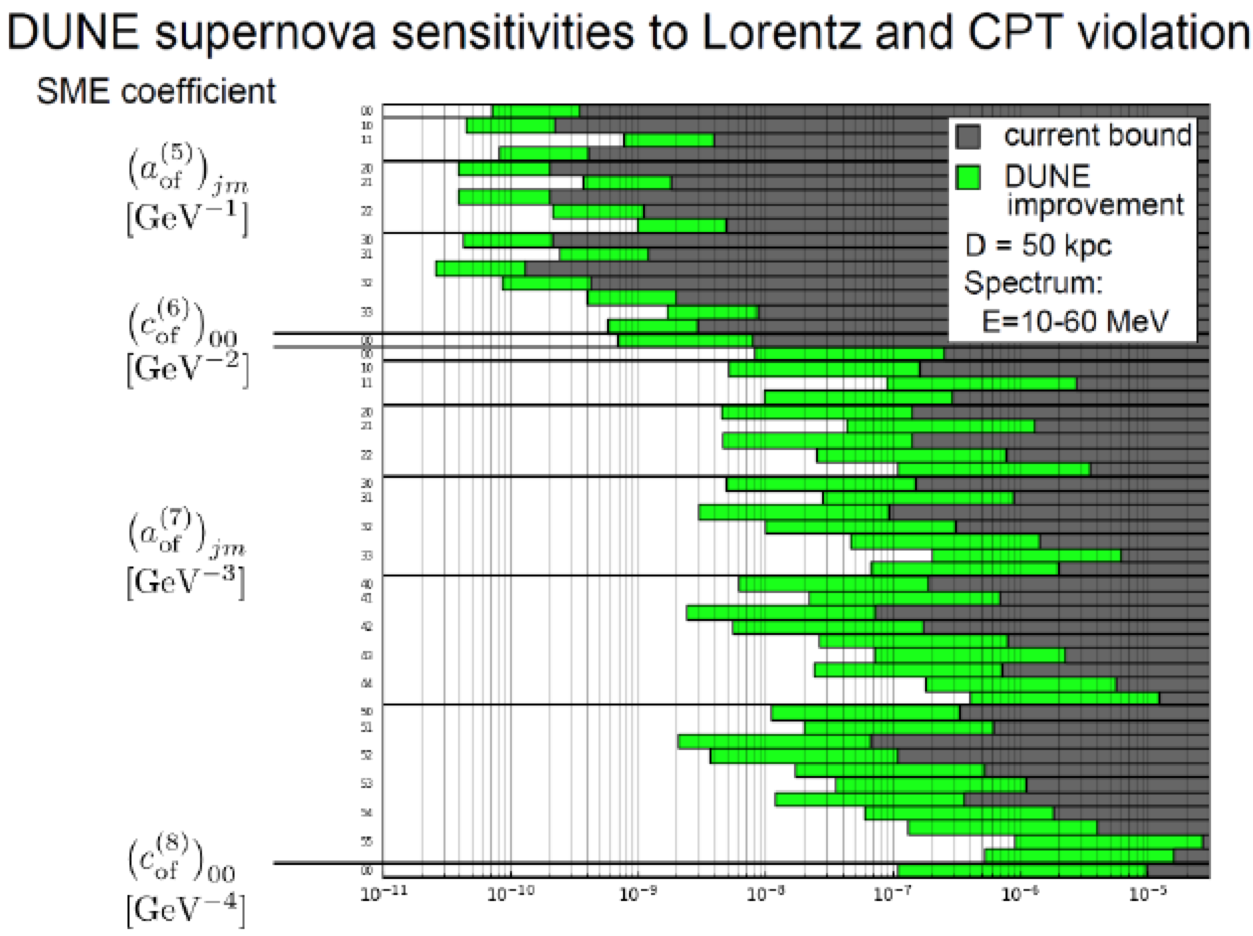
We need theorists to be perfect!





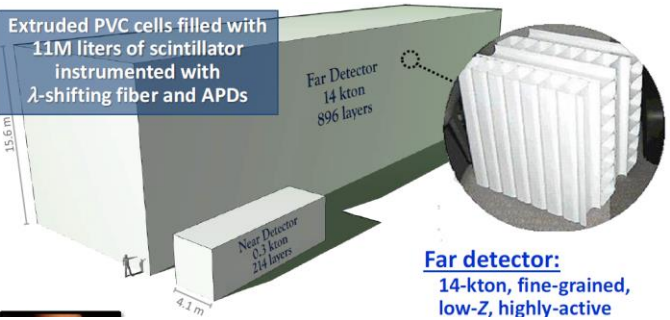


Tests using DUNE SN ν of Lorentz/CPT violation



Slide from Kostolecky

SN ν's in NOvA



- Reconstructed e^+ from 10kpc in 1 s:

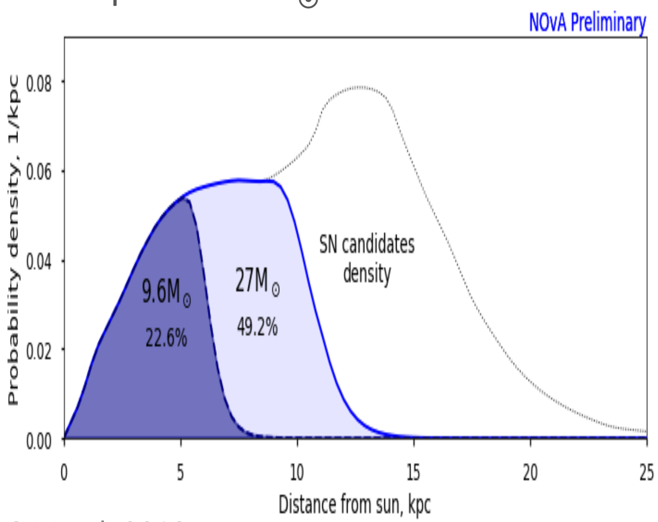
  299 for 27 $M_\odot$

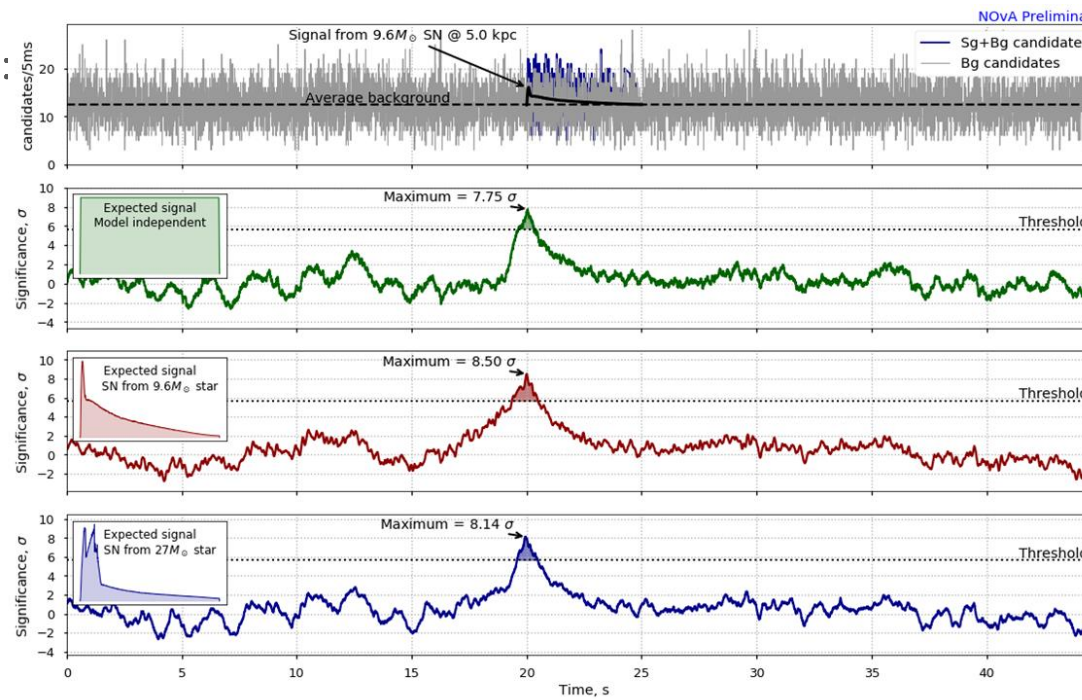
  87 for 9.6 $M_\odot$

SN distance NOvA can detect with ε = 50%:

6.23 kpc for 9.6 $M_\odot$

10.58 kpc for 27 $M_\odot$



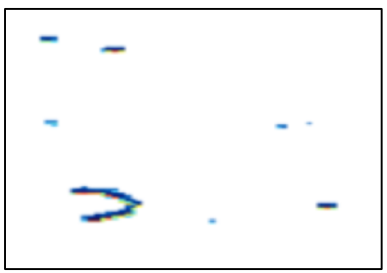


Solar neutrinos

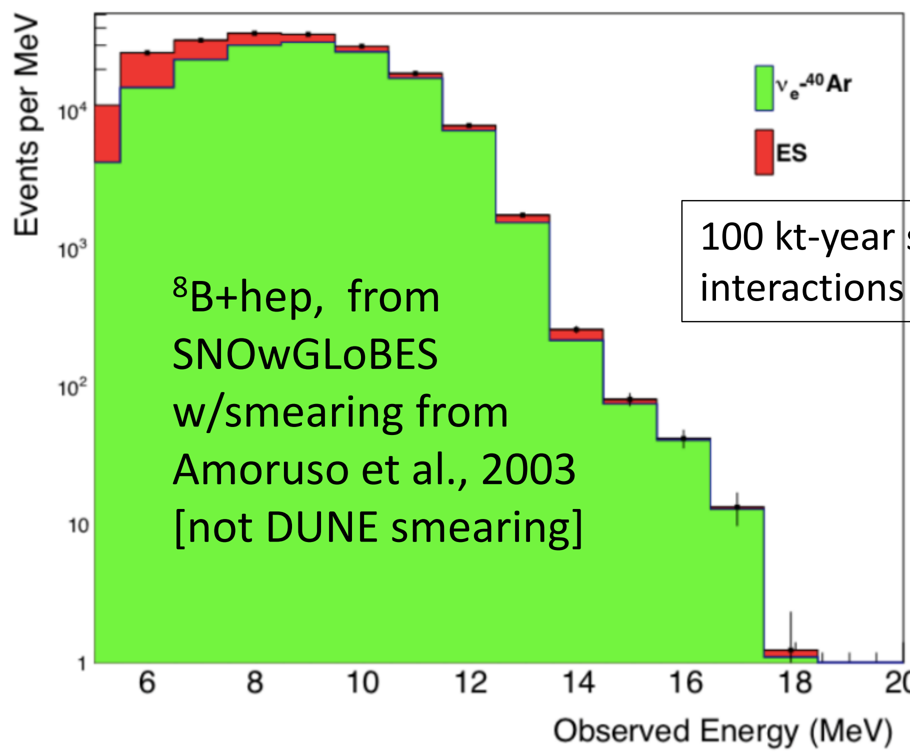
Solar ν's in DUNE

The key advantage of DUNE:
event-by-event energy reconstruction,
rather than ν-e recoil spectrum

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



Solar signal without background



^{8}B+hep, from SNOwGLoBES w/smearing from Amoruso et al., 2003 [not DUNE smearing]

100 kt-year solar ν interactions

- theoretical studies: A. Ioannisian et al., Phys.Rev. D96 (2017) no.3, 036005
- newer paper-- arXiv:1808.08232

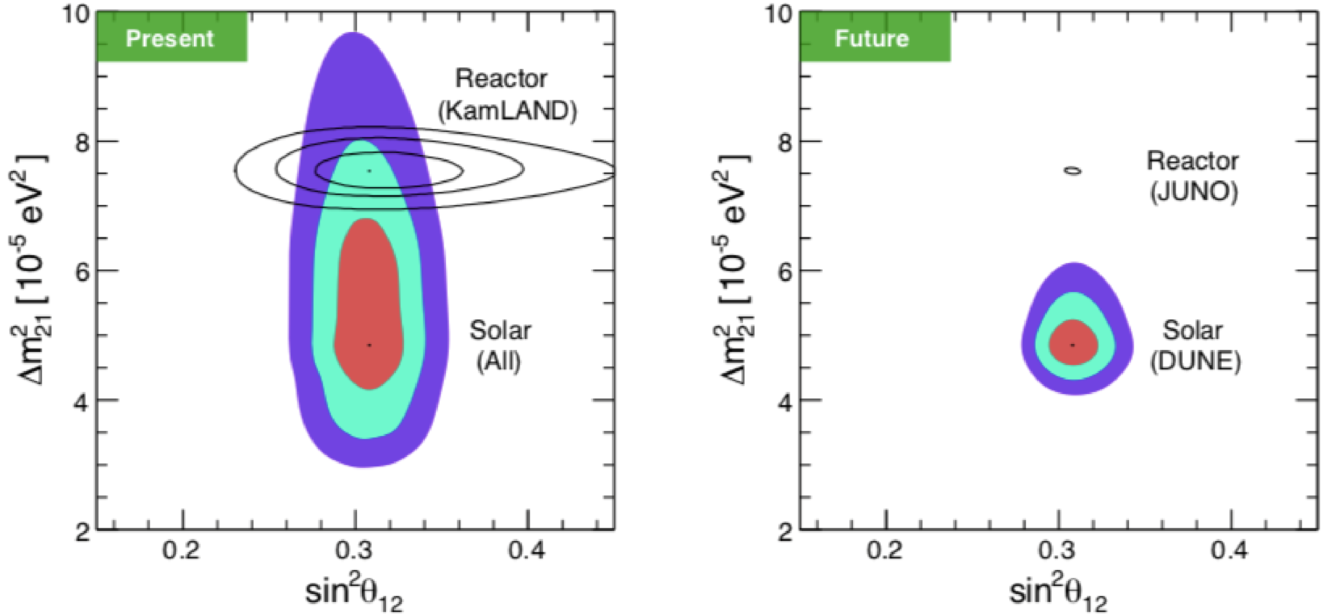
DUNE as the Next-Generation Solar Neutrino Experiment

Francesco Capozzi,[1,2,3] Shirley Weishi Li,[1,2,4] Guanying Zhu,[1,2] and John F. Beacom[1,2,5]
[1] *Center for Cosmology and AstroParticle Physics (CCAPP), Ohio State University, Columbus, OH 43210*
[2] *Department of Physics, Ohio State University, Columbus, OH 43210*
[3] *Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), 80805 München, Germany*
[4] *SLAC National Accelerator Laboratory, Menlo Park, CA, 94025*
[5] *Department of Astronomy, Ohio State University, Columbus, OH 43210*
(Dated: 24 August, 2018)

Slide from K. Scholberg

A Δm^2_{21} sensitivity estimate

Capozzi et al. paper presents intriguing sensitivity:



BUT: makes very optimistic assumptions:

(7% energy resolution, 25% angular resolution, modest bg, no systematics, ...these may not be achieved*)

- Triggering studies still needed (different issues than SNB)
- Overall realistic sensitivity for solar νs still under study

From K. Scholberg

*~20% energy resolution more likely, e.g., μBooNE 1704.02927

Nucleon decay

NDK sensitivity 400 kT-y

$p \rightarrow \nu K^+$

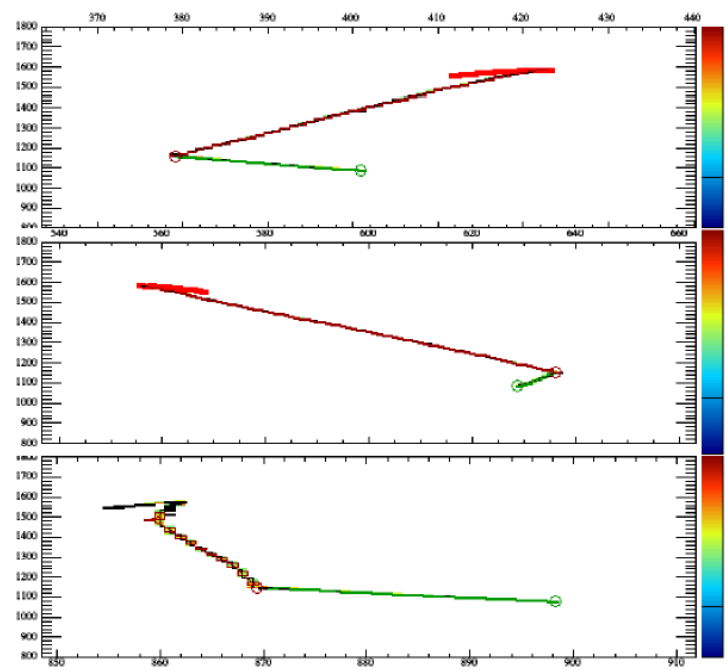
- Comparable to Super-K

$n \rightarrow e^- K^+$

- Improve by ~100

91 modes in 2014 RPP

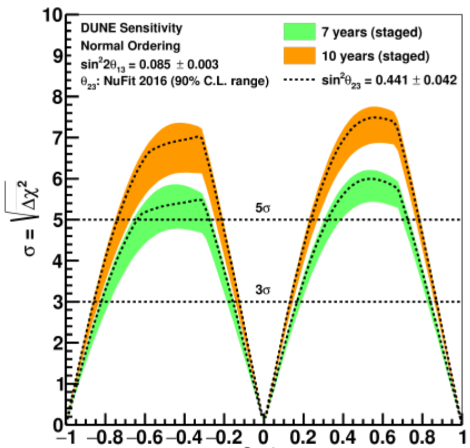
(Super-K had reported best limit for only 14, but probably could do better in most modes. DUNE could compete in ~ 20.)



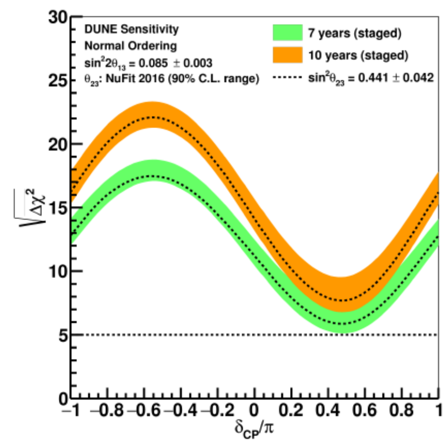
Beam neutrinos

CP, Order, θ_{23} sensitivity

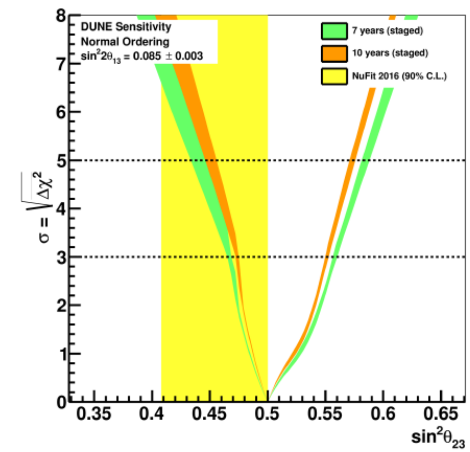
CP Violation

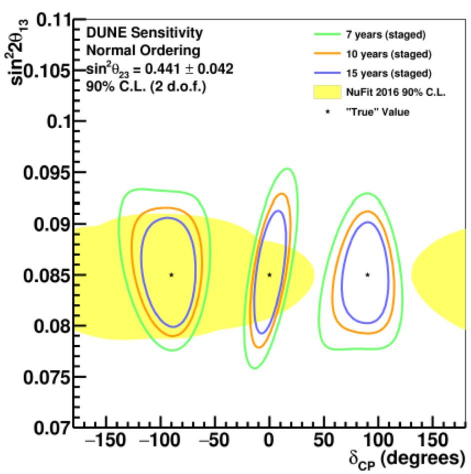


Mass Ordering

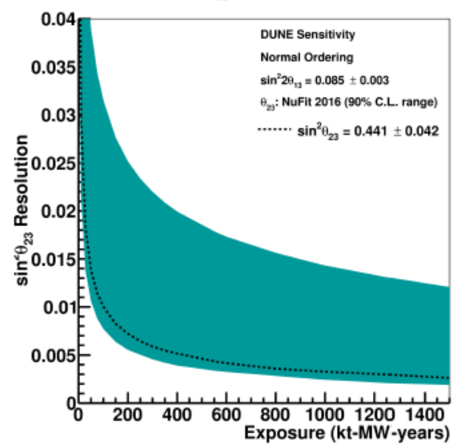


Octant



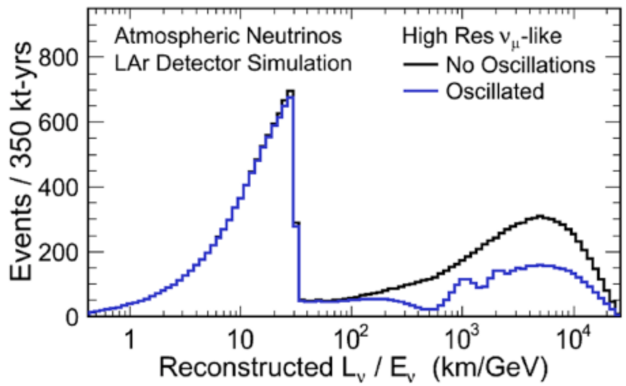


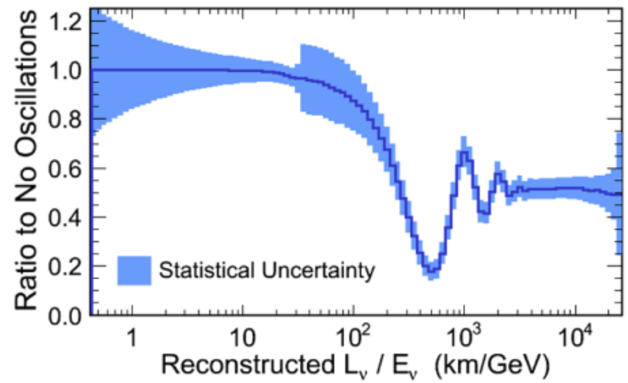
$\sin^2\theta_{23}$ Resolution



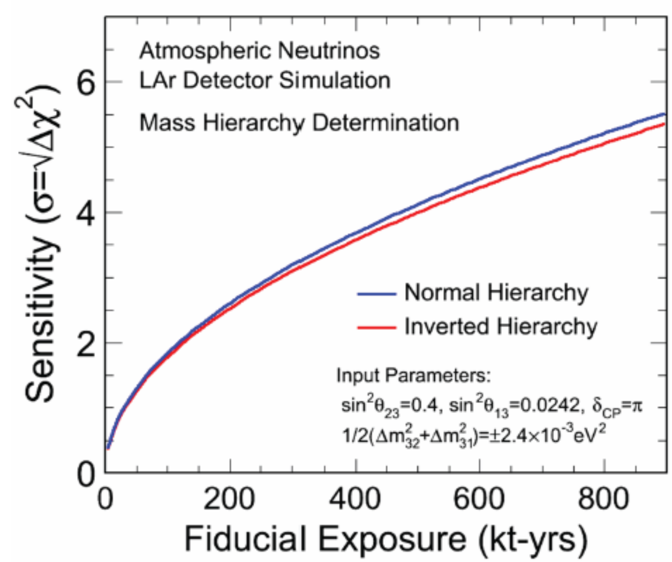
Atmospheric neutrinos

3ν oscillations with Atmospheric ν's





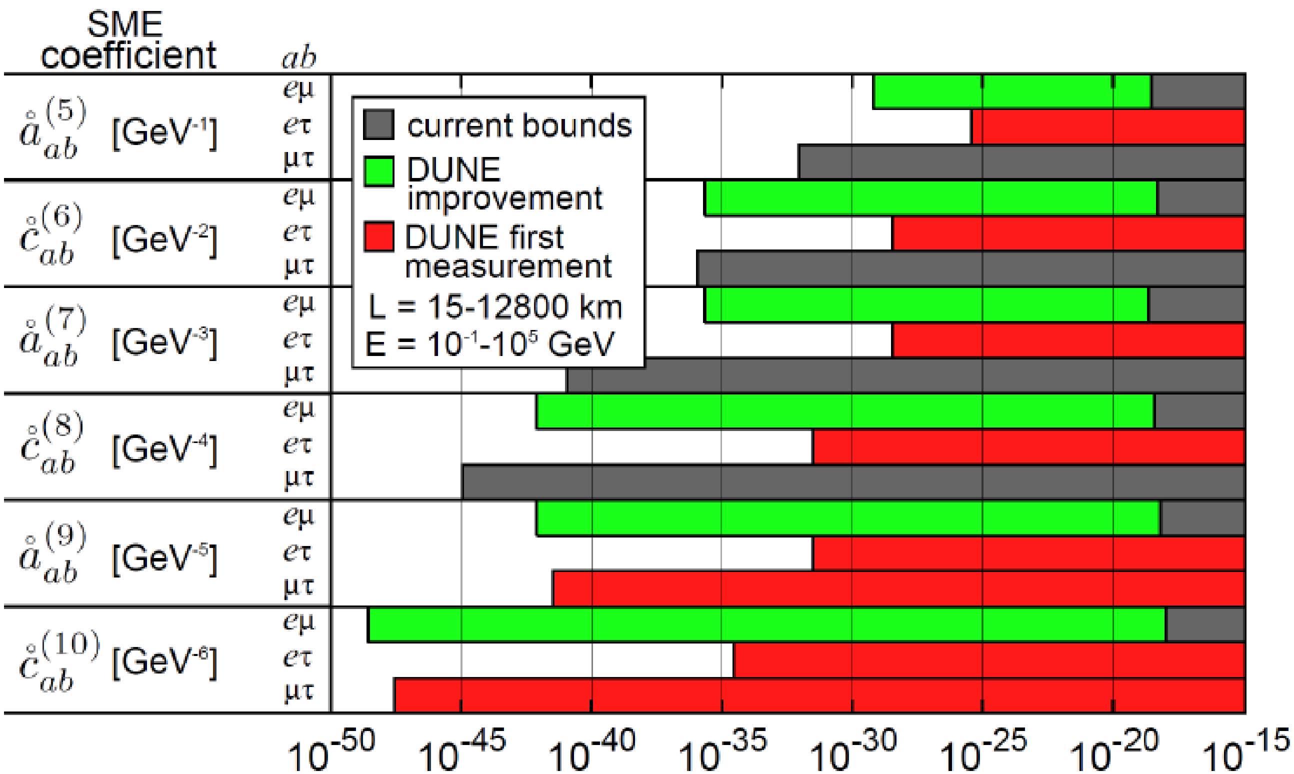
Sample	Event rate per year
fully contained electron-like	1.6×10^3
fully contained muon-like	2.4×10^3
partly contained muon-like	7.9×10^2



Lorentz & CPT violation

using Standard Model Extension (SME)

DUNE atmospheric sensitivities to Lorentz and CPT Violation



Sensitivity from Kostolecky, no simulation

Other

Additional topics

- Relic Supernova neutrinos
- GUT monopoles
- Light Dark Matter
- Boosted Dark Matter
- Neutrinos from DM annihilation in the sun
- Solar neutrinos
- CPT and Lorentz Violation
- Sterile Neutrino searches
- Coincidences with GRB, gravitational waves

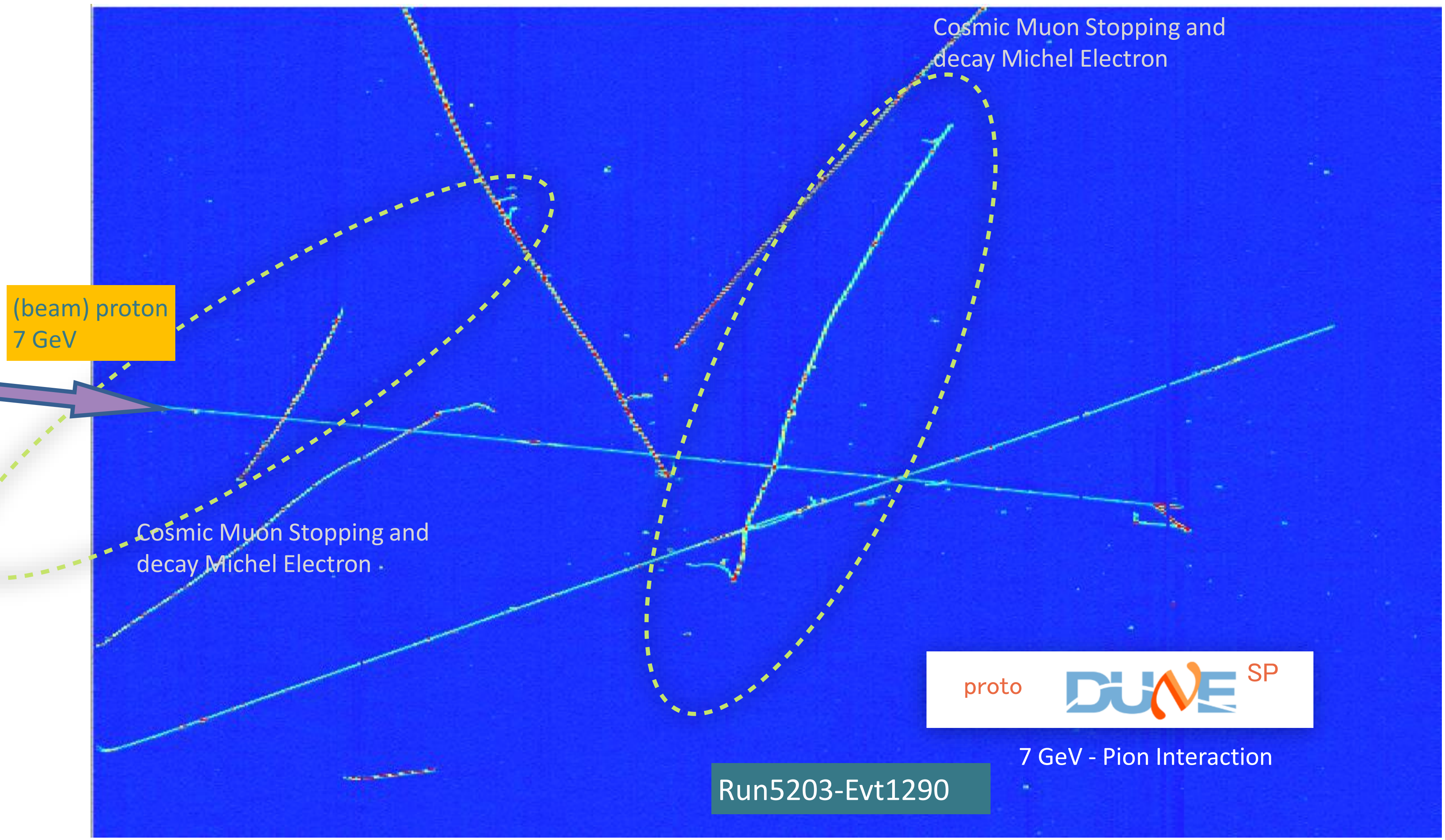
Thank you!

Backup

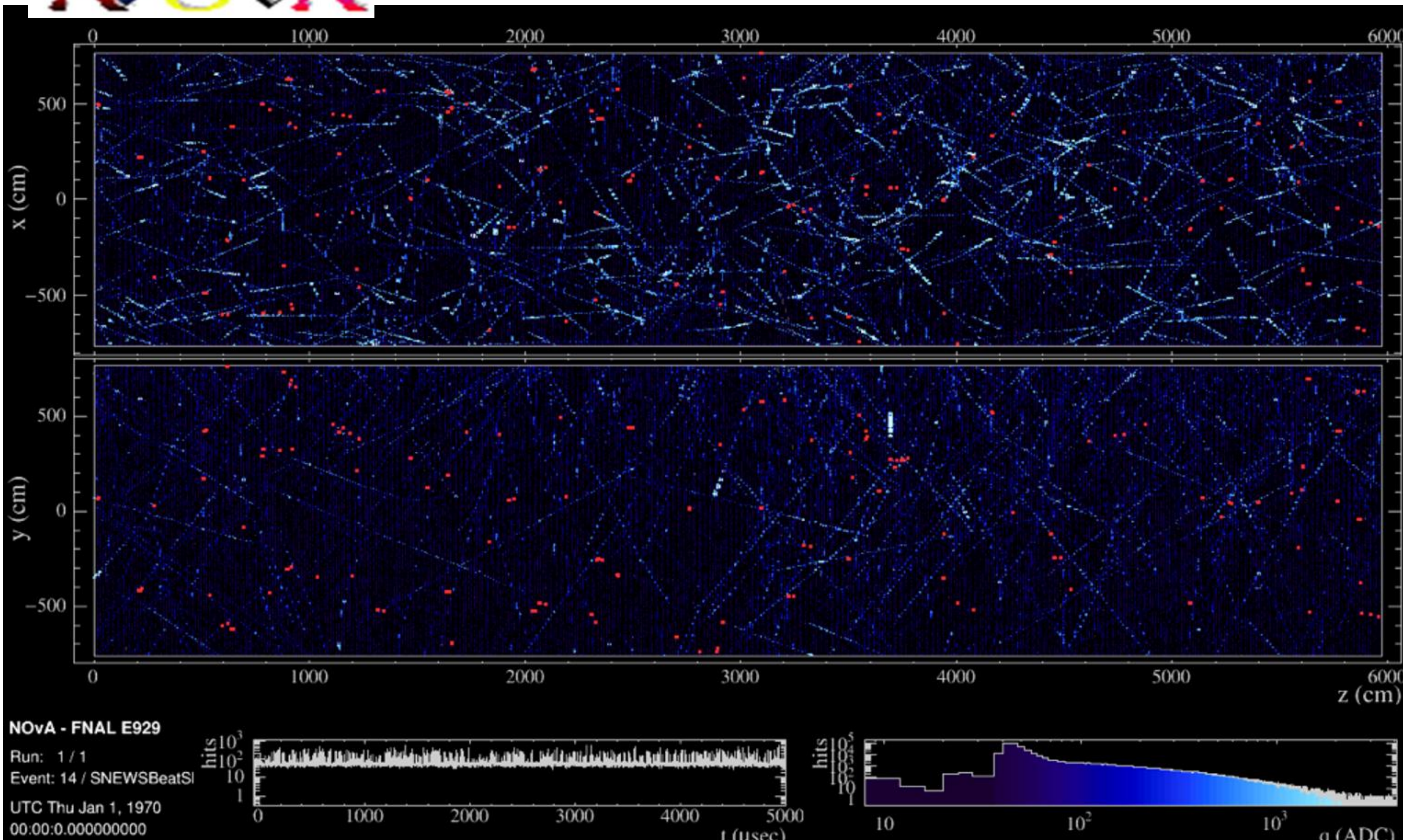
SN direction

- Some promising work is taking place on reconstructing the direction from νe elastics.

ProtoDUNE event



SN signal (red) on background (blue) in NOvA FarDet



SN signal versus distance for NOvA

The resulting detection ε for 3 signal shapes vs. t.