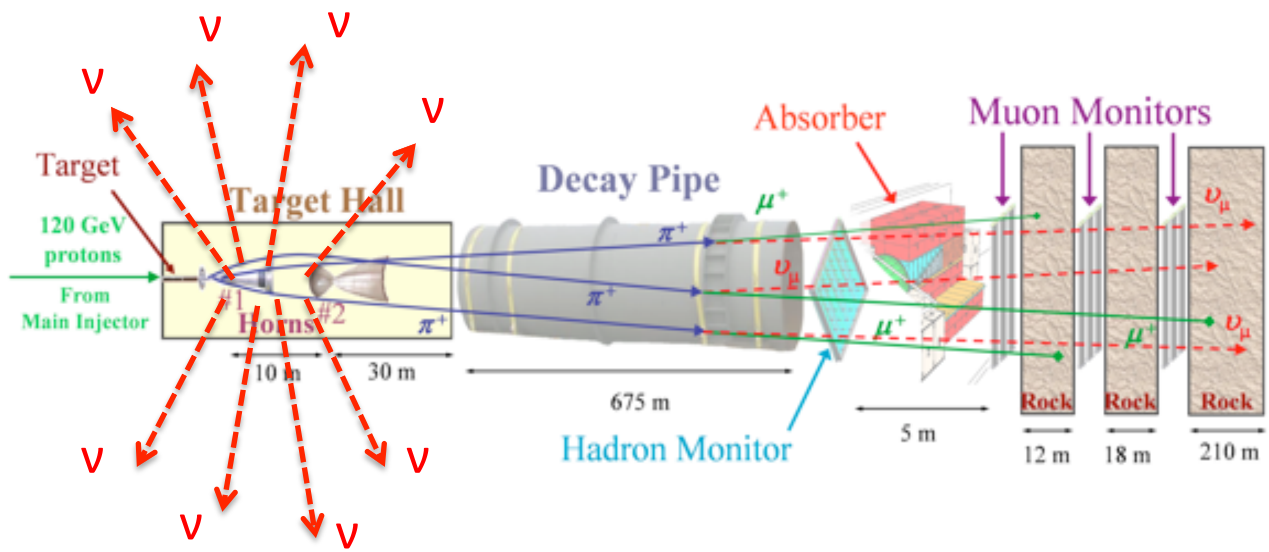


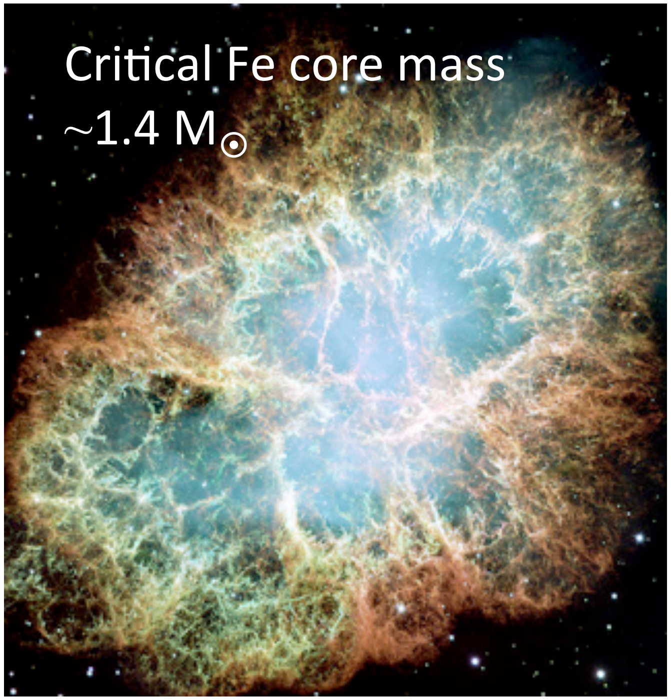
Opportunities with Decay-at-rest Neutrinos at Decay-in-flight Neutrino Beams

Christopher Grant

Boston University

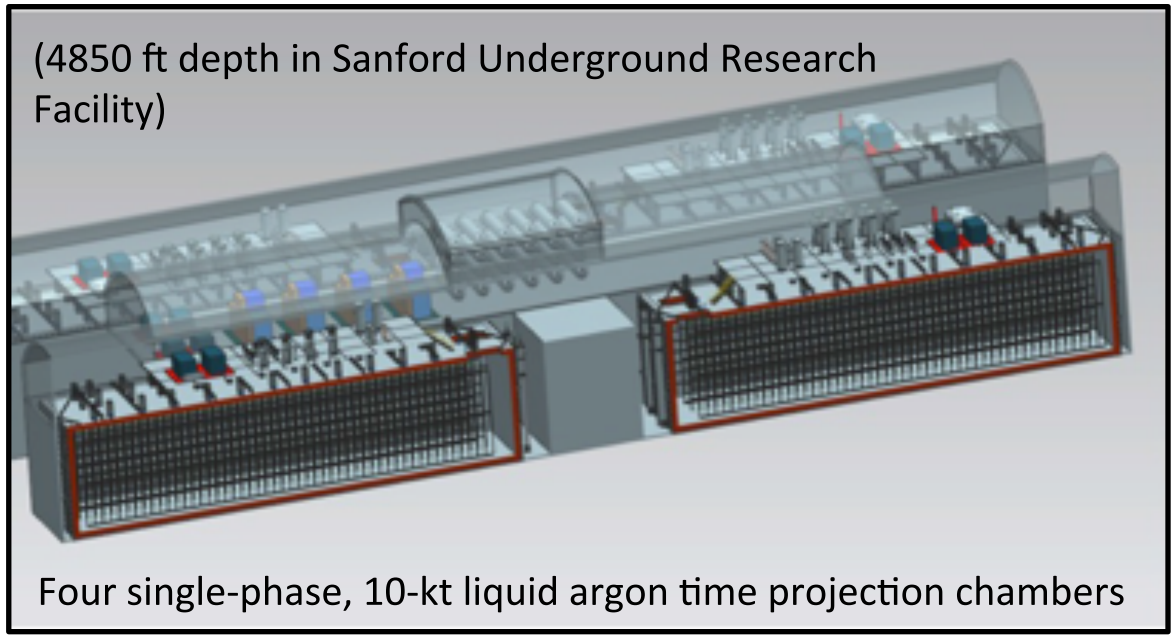
ICHEP 2016 – Chicago, IL

Supernova physics with liquid argon detectors



For core-collapse supernovae (SN), about 99% of the gravitational binding energy is emitted in the form of neutrinos – on the order of 10^{58} neutrinos!

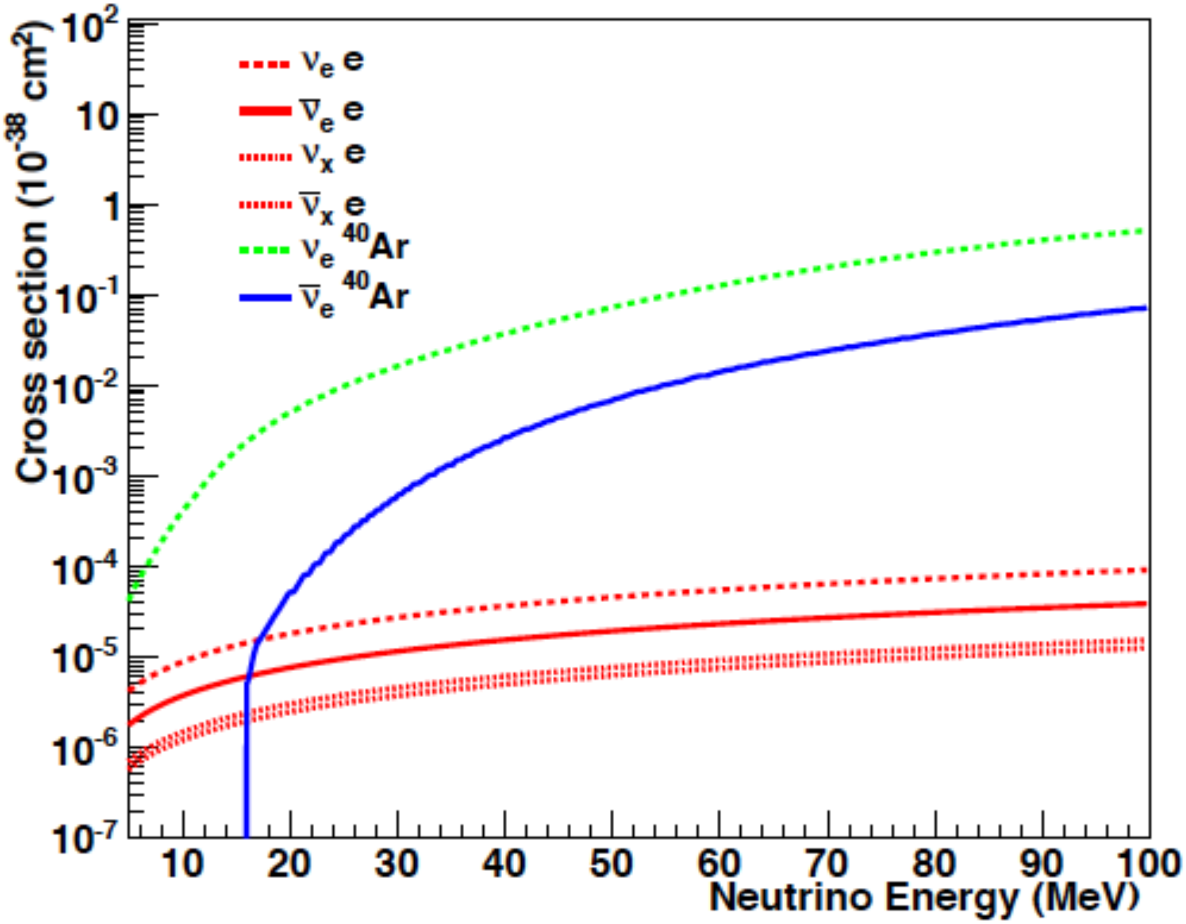
Deep Underground Neutrino Experiment (DUNE)



Neutronization ($p + e^{-} \rightarrow n + \nu_e$) burst at early times (< 20 ms) is primarily electron flavor

Expected SN event rates in DUNE

LBNE SciDoc: arXiv:1307.7335v3



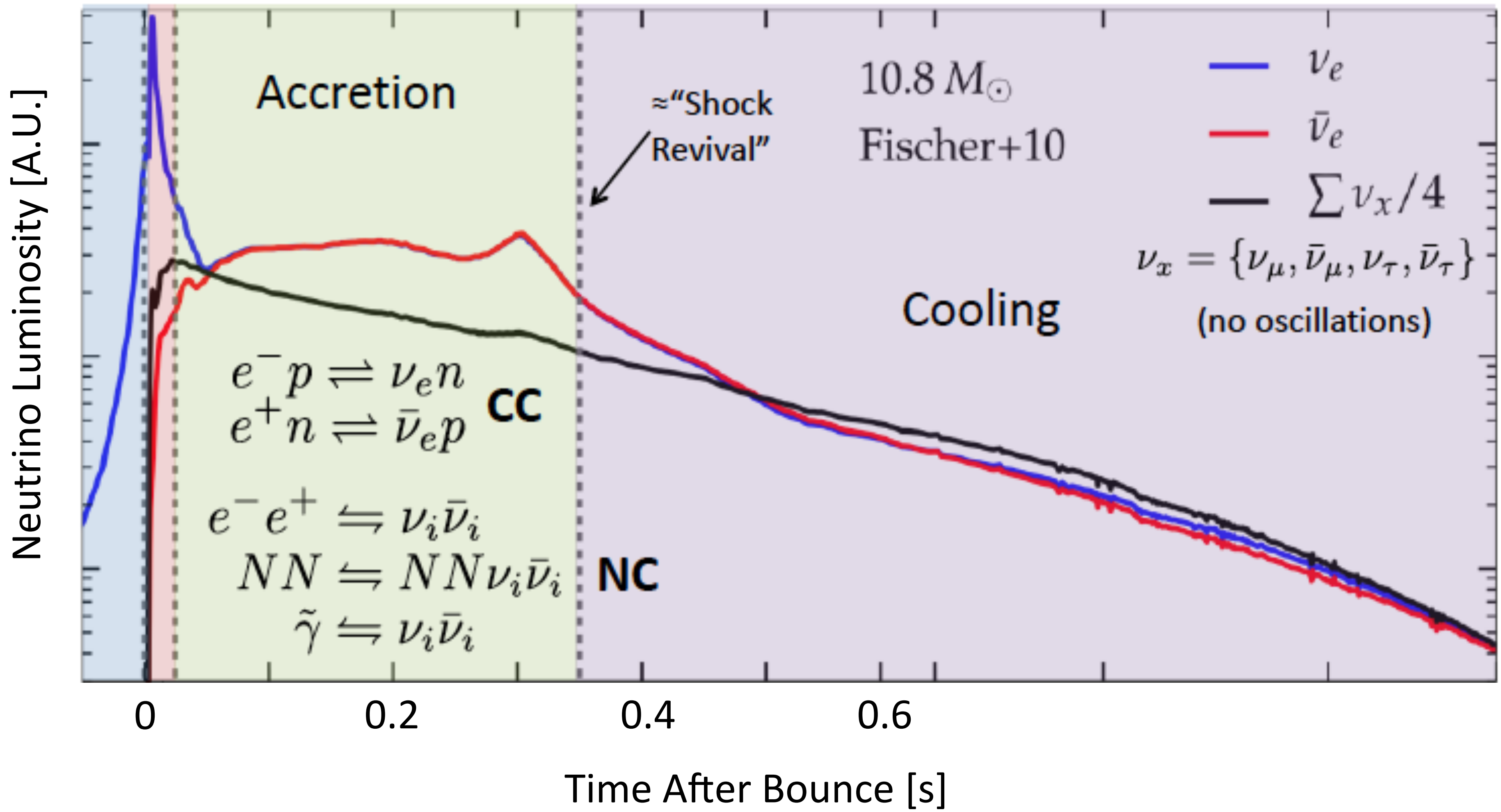
More than 2000 CC events from a 10 kpc core-collapse SN burst:

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

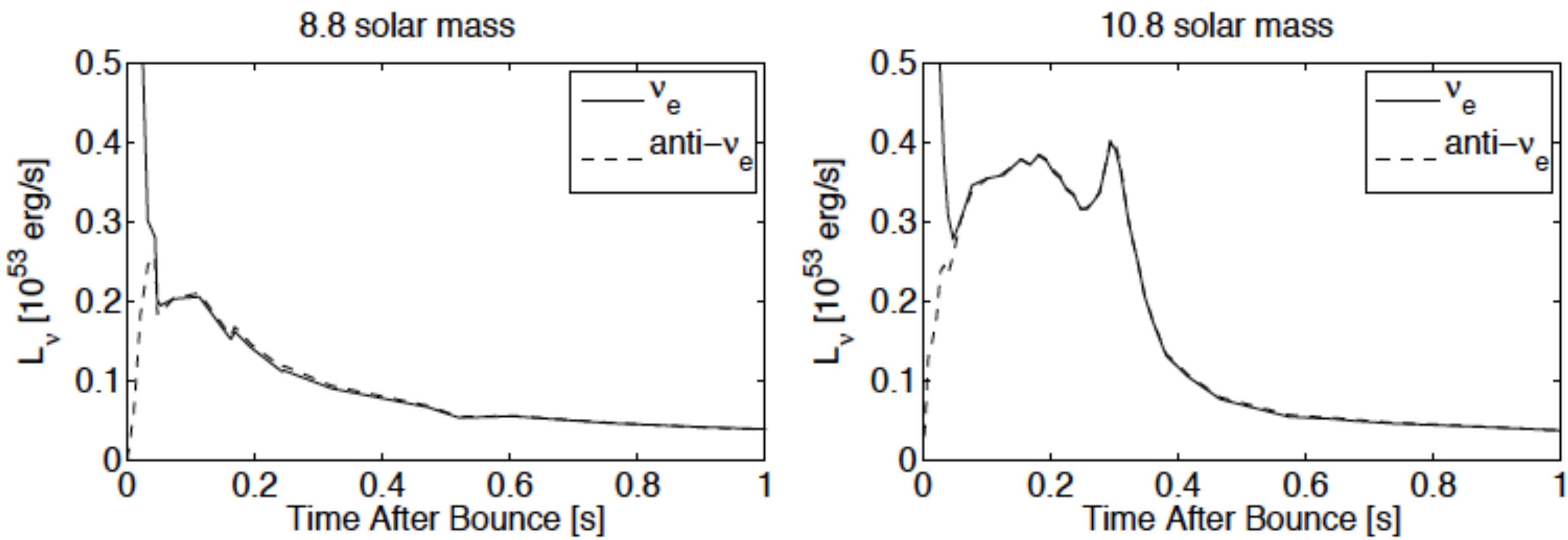
Evolution of neutrino "light curves"

Neutronization burst only appears in electron neutrinos

B. Messer (ORNL)



Evolution of burst depends on progenitor star

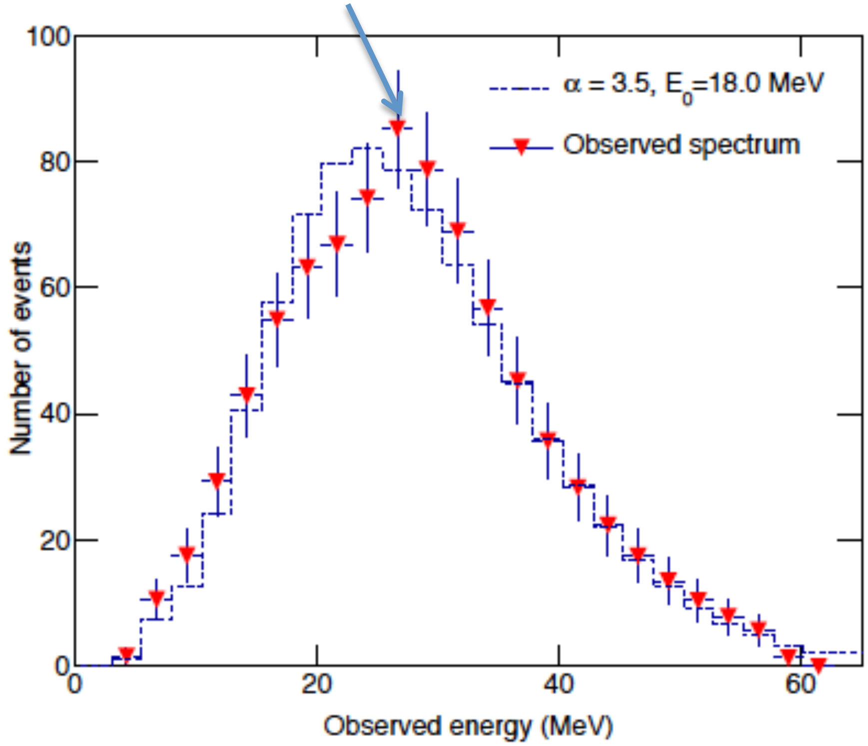


T. Fischer, et al., arXiv:0908.1871

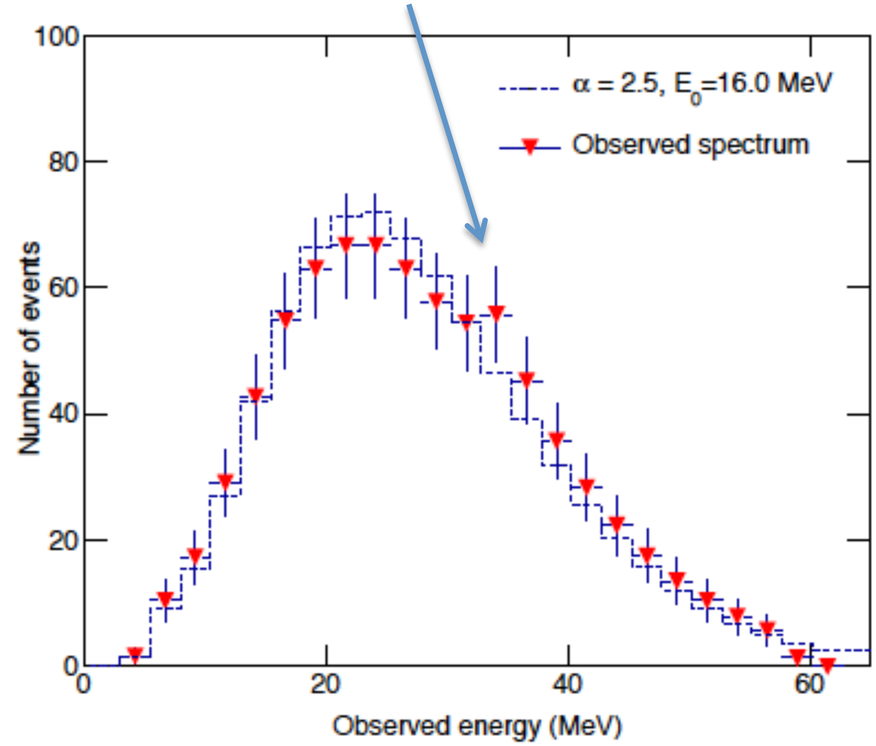
As Alex Friedland (SLAC) tells us, "Neutronization burst, accretion, cooling phases can all be seen in neutrinos. All stages are extremely important!!!"

Shock wave tracking in real time

First snap shot, 1 s integration



Second snap shot, 1 s integration

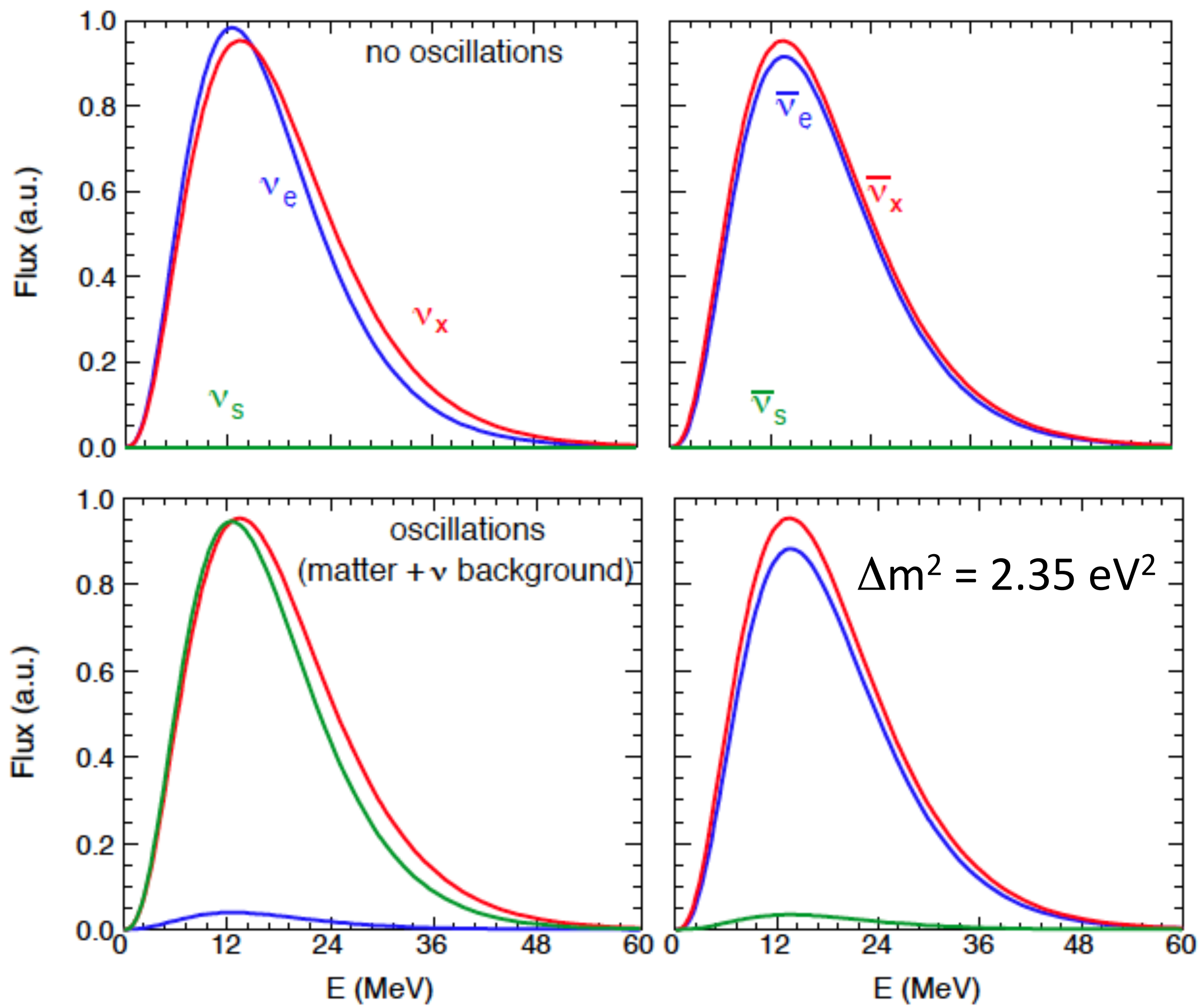


LBNE SciDoc: arXiv:1307.7335v3

This signature of oscillations depends on neutrino mass hierarchy and the presence of neutrino-neutrino interactions (collective oscillations).

More exotic suprises

Predictions of sterile oscillations: arXiv:1110.2104v3



Neutrinos experience almost complete conversion into sterile flavors. Anti-neutrinos don't have an MSW resonance in an adiabatic conversion region.

0.5 seconds after core bounce at r=1000 km from proto-neutron star

Expect the unexpected!

Collective oscillations, shock waves, sterile oscillations, dark photons, dark matter, axions…

Many of these surprises reveal themselves in the electron neutrino energy distribution – need resolution at least 10% or better, and need to understand energy reconstruction systematics.

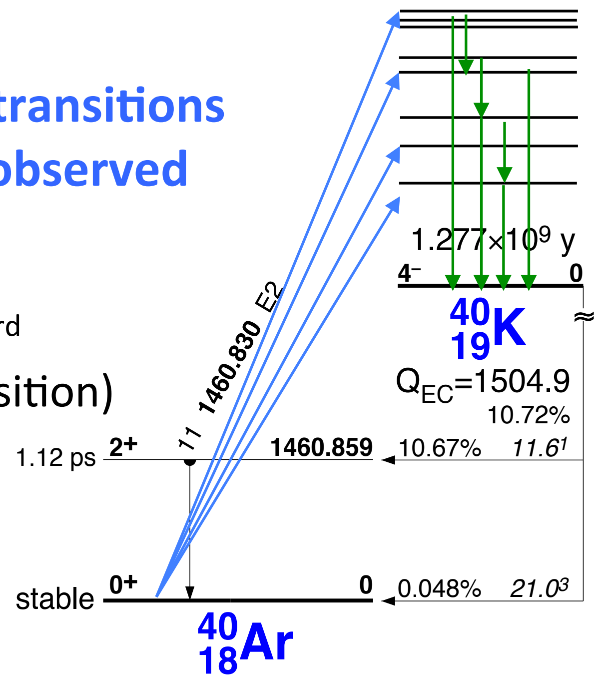
Supernova neutrino detection in liquid argon

Charged-current absorption:

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

At least 25 transitions have been observed indirectly

(g.s. to g.s. is 3rd forbidden transition)



Transition levels are determined by observing de-excitations (γ's and nucleons)

Reconstructing true neutrino energy:

Q is determined from de-excitation gammas and nucleons

Outgoing e^- Energy

Energy donated to transition

Recoil Energy of Nucleus (negligible)

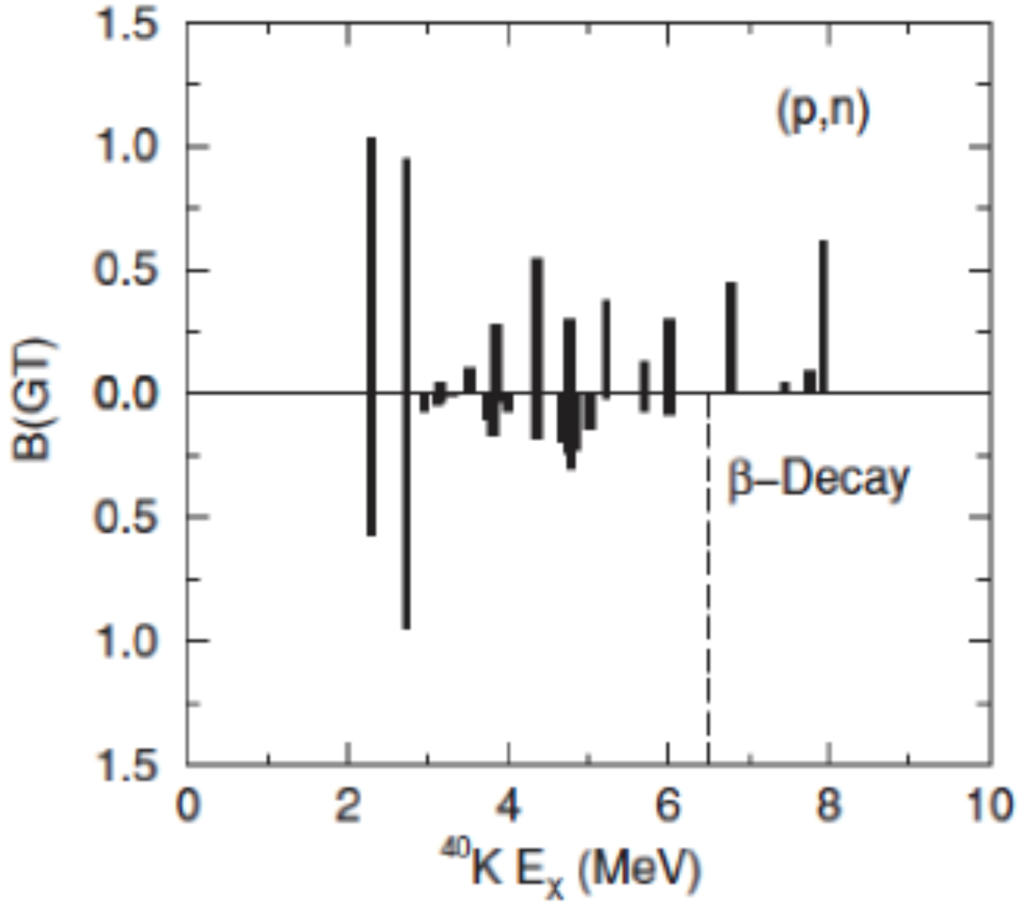
$$E_\nu = E_e + Q + K_{\text{recoil}}$$

Uncertainties in the cross-section:

Need to measure the transition intensities

$$\sigma(E_\nu) = \frac{G_F^2 \cos^2(\theta_{ud})}{\pi \hbar^4 c^3} \sum_i p_i W_i F(Z, W_i)[B_i(GT) + B_i(F)]$$

World's GT data for ^{40}K* excitation



(p,n) forward scattering on ^{40}Ar

M. Bhattacharya, et al. PRC 80, 055501 (2009)

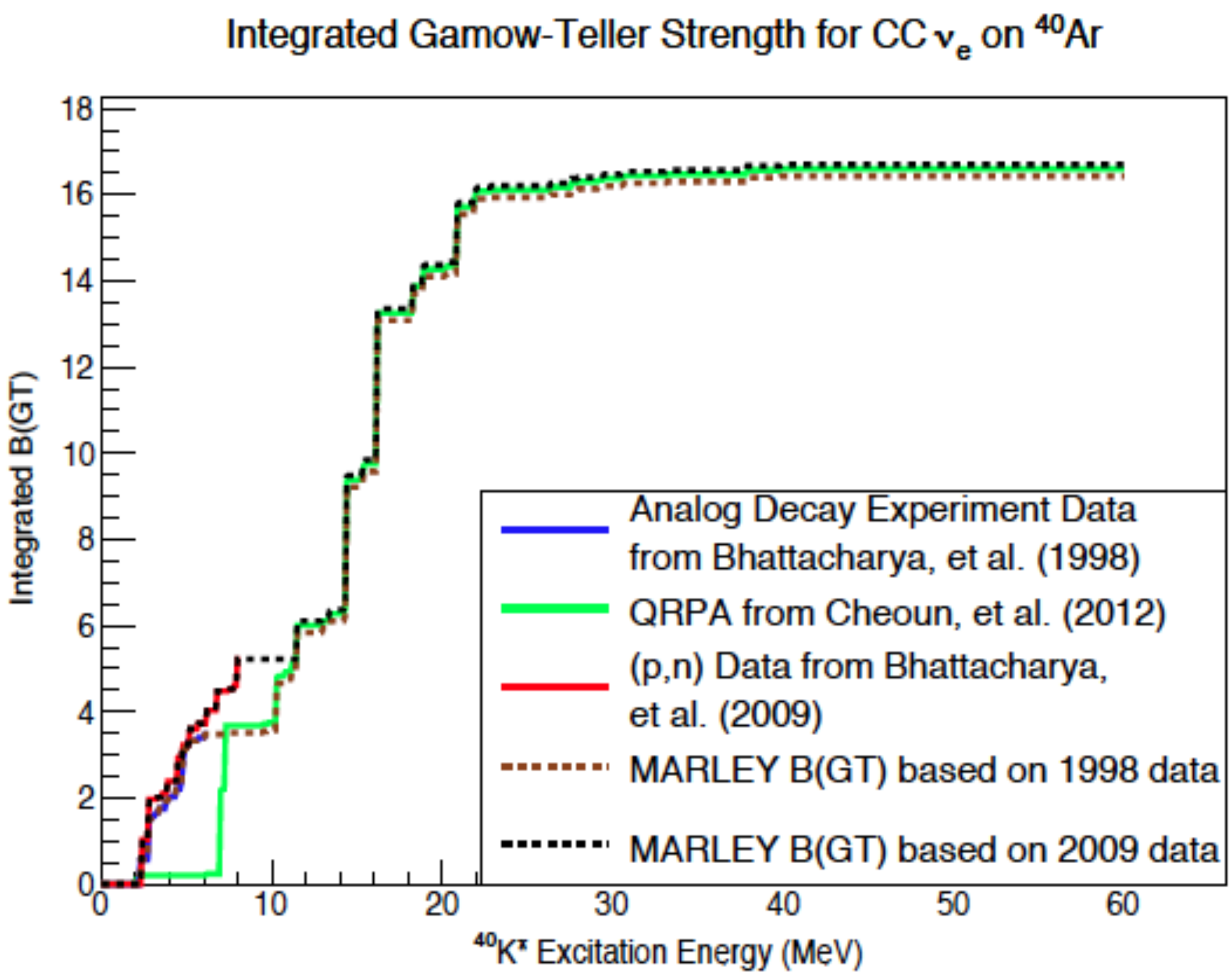
Analog decay of ^{40}Ti to ^{40}Sc
(isospin mirror nucleus)

M. Bhattacharya, et al. PRC 58, 6 (1998)

Tabulated strengths incorporated into a semi-unified model

MARLEY: Model of Argon Reaction Low Energy Yields

Steven Gardiner, Chris Grant, Emilija Pantic, Bob Svoboda



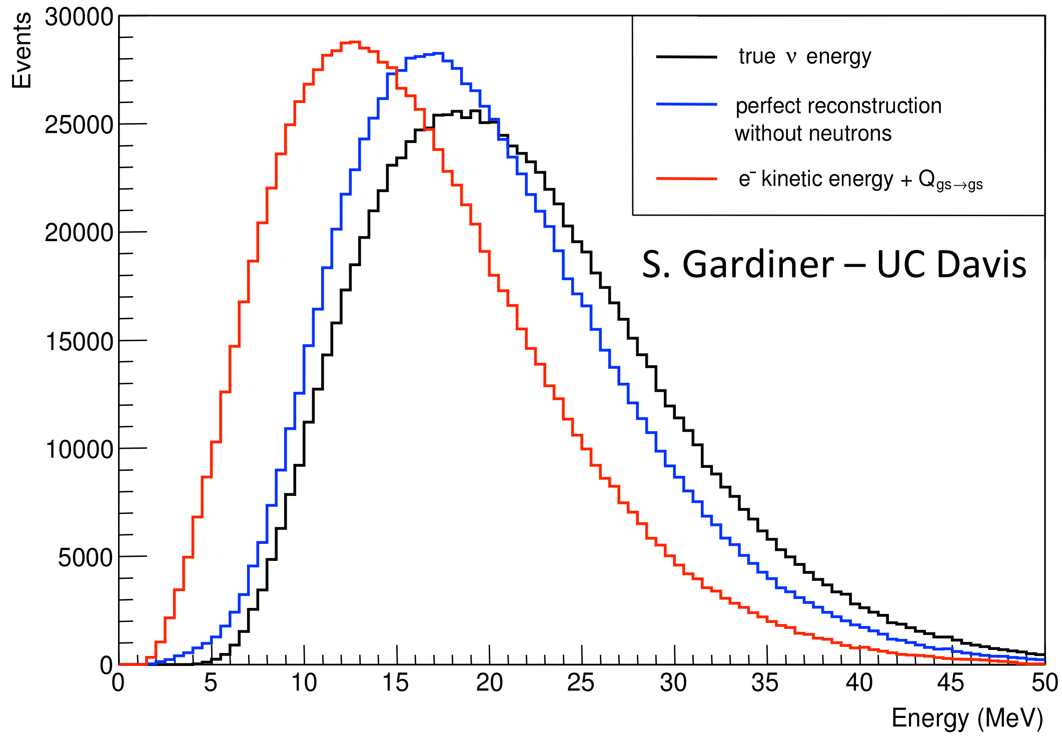
- Experimental data is interpolated (naively) to a QRPA calculation for levels above 8 MeV
- Gamma de-excitation for about half the levels are evaluated using TALYS
- Nucleon emission is modeled according to Hauser-Feshbach

Where does the energy go in MARLEY?

$^{40}K^*$ de-excitations:

γs only = 82.5%
single n + γs = 15.9%
single p + γs = 1.4%
other = 0.2%

Fermi-Dirac spectrum (T = 3.5 MeV)



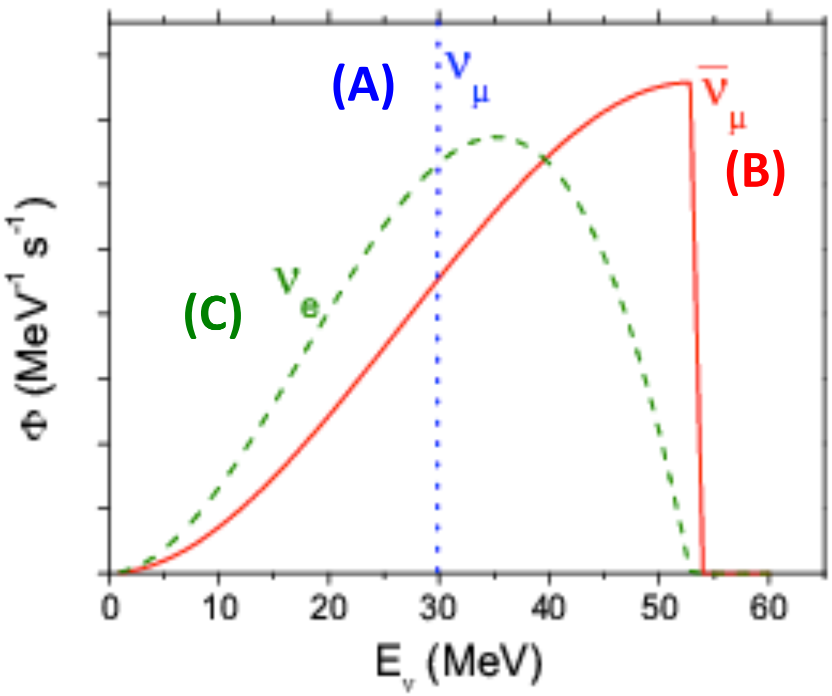
True ν spectrum
Electron only + Q (g.s. -> g.s.)
Perfect reco. but missing all neutrons

Details of neutrino interactions < 100 MeV largely unknown!

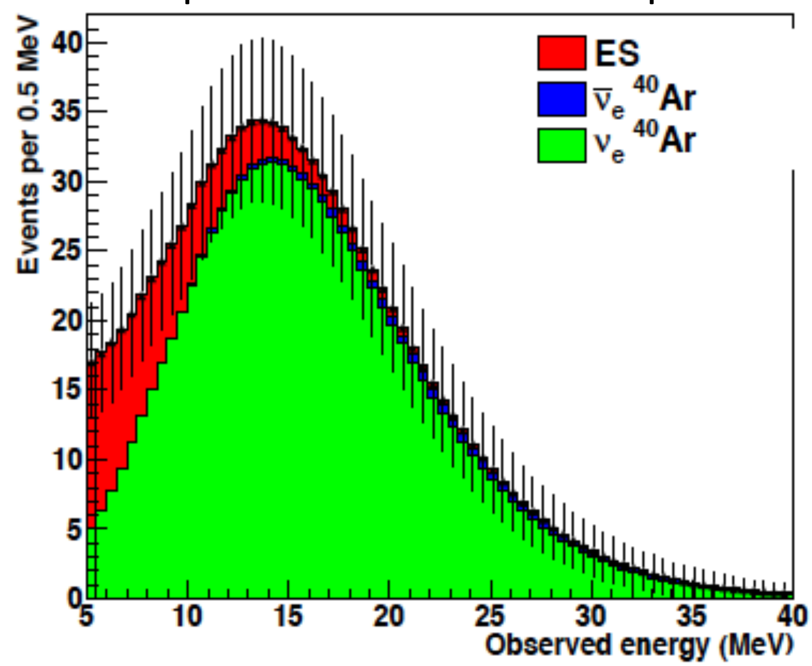
How do we solve the problem of knowing what to expect in DUNE?

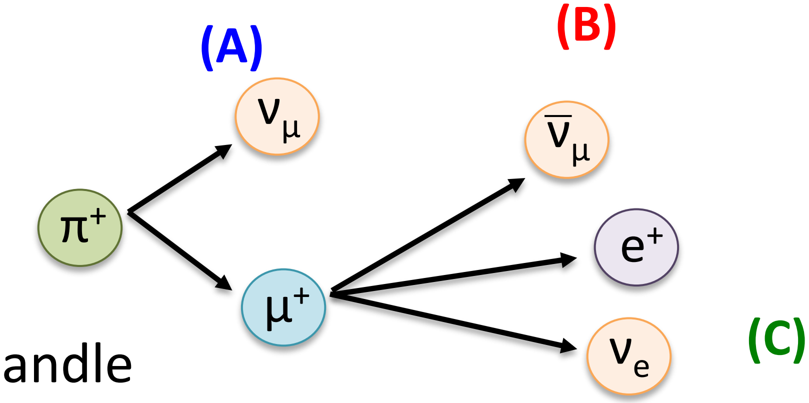
Pion and muon decay-at-rest spectra

Traditionally done by shooting a beam of ~1 GeV protons onto a target and create lots of stopped pions:



Example DUNE detected SN spectrum





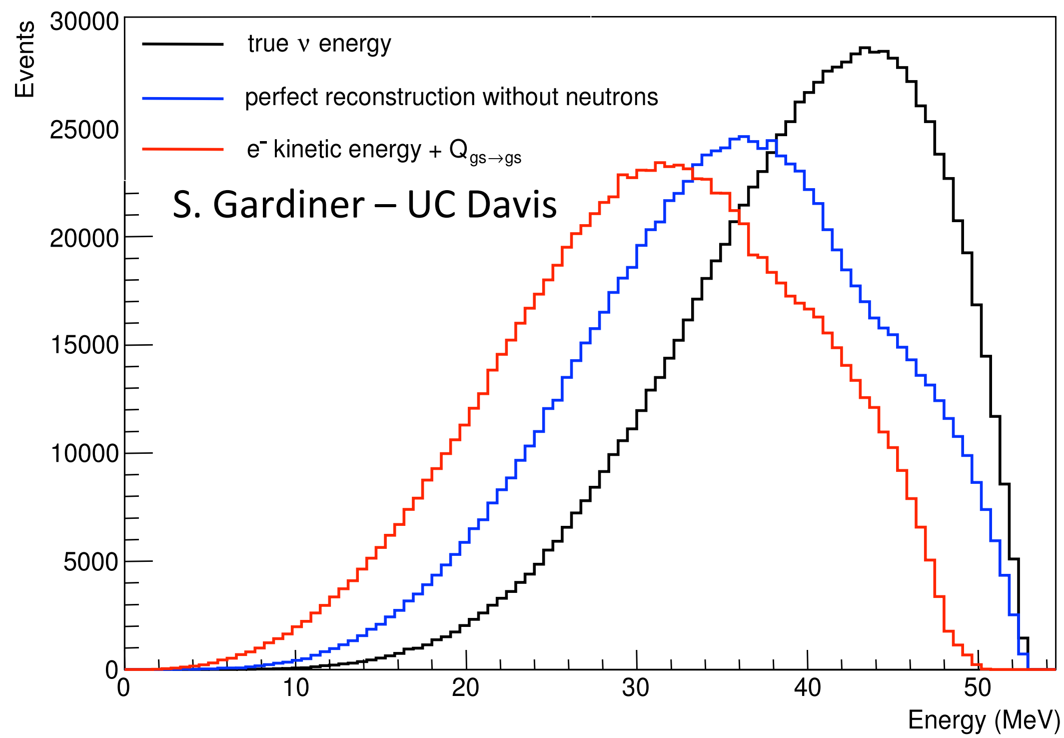
The Michel spectrum is a great standard candle for low-energy neutrino studies (SN neutrinos and coherent scattering).

Again, where does the energy go in MARLEY?

$^{40}K^*$ de-excitations:

γs only = 58.0%
single n + γs = 36.3%
single p + γs = 4.6%
other = 1.1%

Muon decay-at-rest ν_e spectrum



True ν spectrum
Electron only + Q (g.s. -> g.s.)
Perfect reco. but missing all neutrons

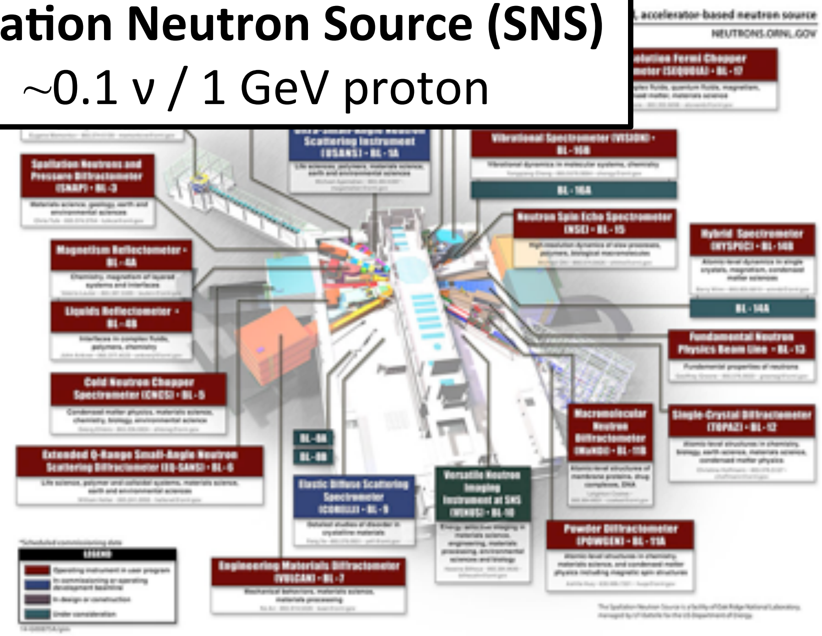
Need to measure and characterize this spectrum – go back and tune MARLEY modeling of these events for DUNE

Modern beam-stop facilities

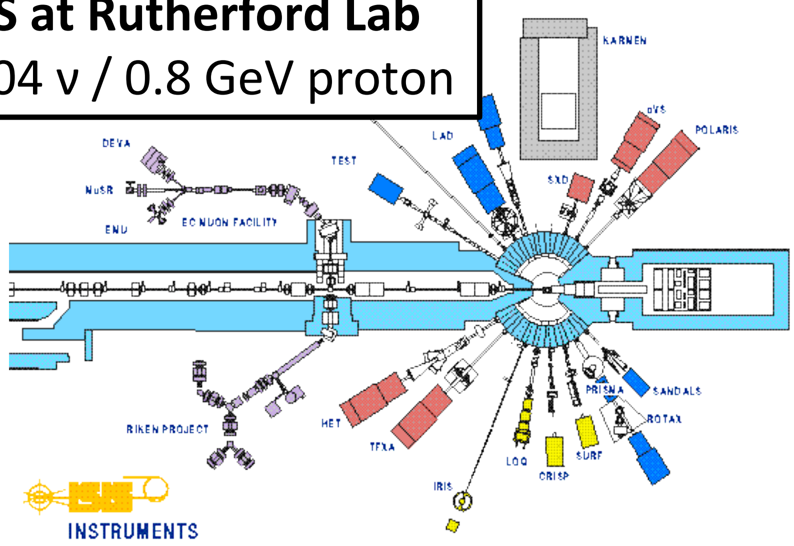
There are several beam stop facilities currently available around the world.

Beam powers are 160 kW – 1.4 MW

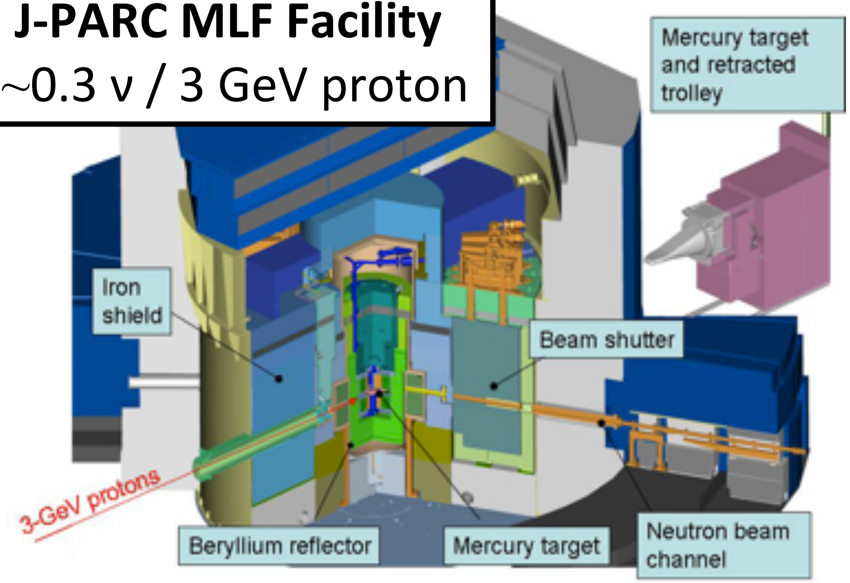
Spallation Neutron Source (SNS)
~0.1 ν / 1 GeV proton



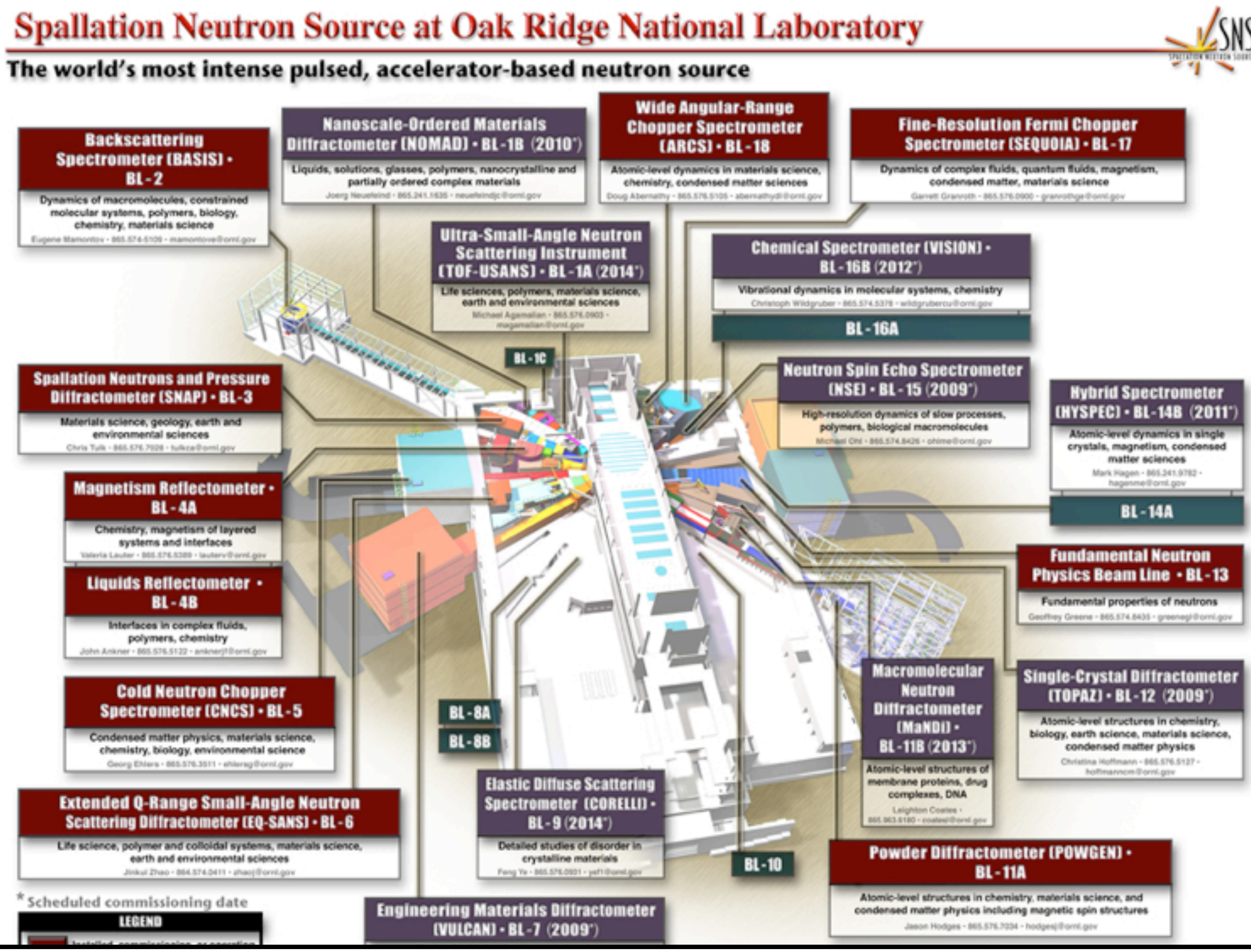
ISIS at Rutherford Lab
~0.04 ν / 0.8 GeV proton



J-PARC MLF Facility
~0.3 ν / 3 GeV proton



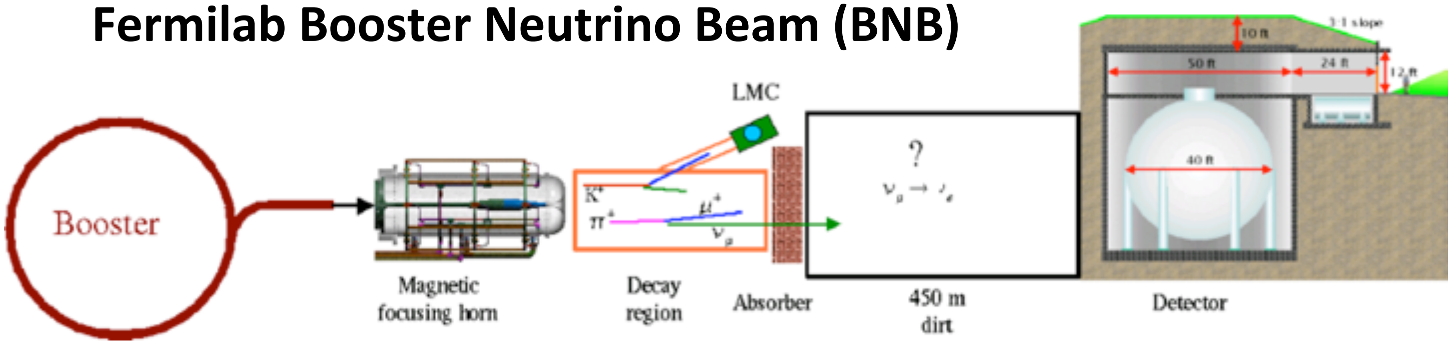
Modern beam-stop facilities



The real estate near the source is taken up by other experiments. Closest proximity for a multi-ton detector ~ 35 - 40 meters away from source.

Decay-in-flight facilities

Fermilab Booster Neutrino Beam (BNB)

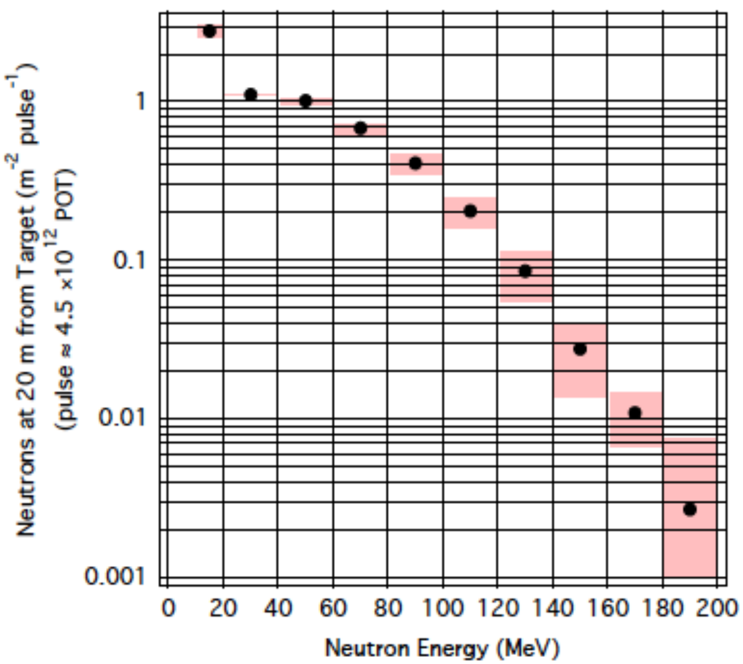


8 GeV protons onto beryllium target
Typically running at 16 kW beam power (max 32 kW)

Decay-at-rest neutrinos from pions and kaons stopping in the shielding material.

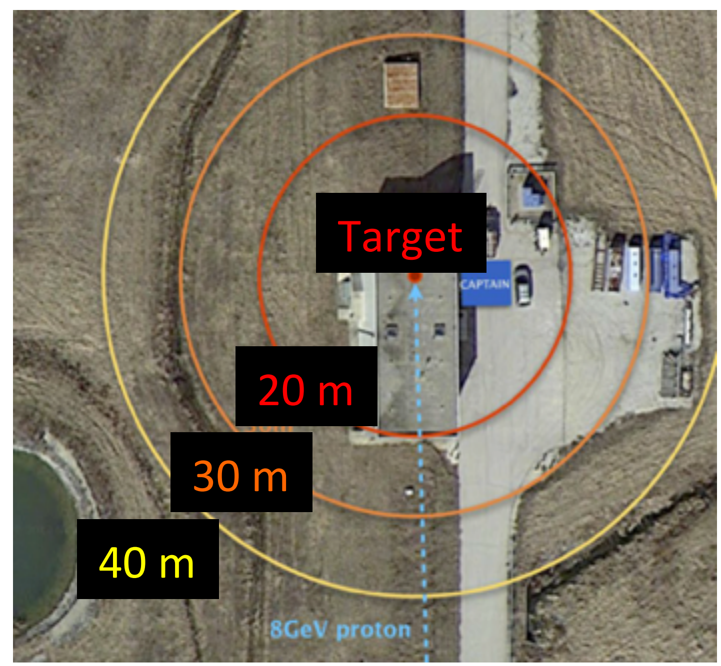
Need to be very close for high flux – beam backgrounds become a problem.

SciBath Detected Neutrons at BNB



SciBath @ 20 m from BNB target measures a flux of:

~2.4 n/pulse/m²
(E_n > 40 MeV)



But there's more…

Opportunities With Decay-At-Rest Neutrinos From Decay-In-Flight Neutrino Beams

Christopher Grant*
Physics Department, University of California, Davis, Davis, CA 95616, USA

Bryce Littlejohn†
Physics Department, Illinois Institute of Technology, Chicago, IL 60616, USA

(Dated: November 6, 2015)

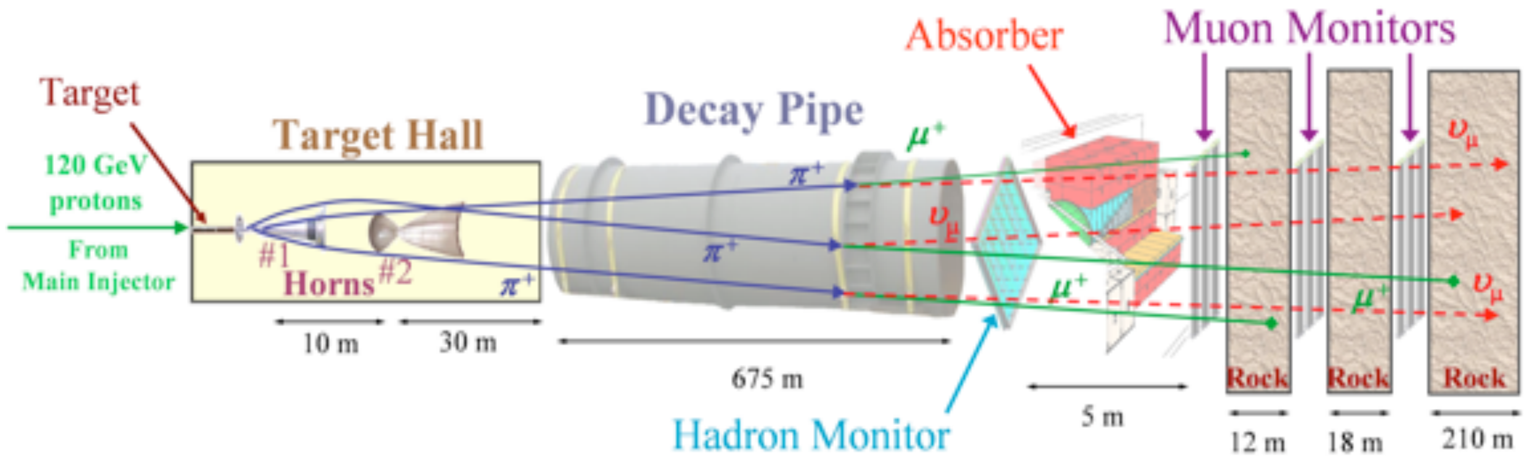
Neutrino beam facilities, like spallation neutron facilities, produce copious quantities of neutrinos from the decay at rest of mesons and muons. The viability of decay-in-flight neutrino beams as sites for decay-at-rest neutrino studies has been investigated by calculating expected low-energy neutrino fluxes from the existing Fermilab NuMI beam facility. Decay-at-rest neutrino production in NuMI is found to be roughly equivalent per megawatt to that of spallation facilities, and is concentrated in the facility's target hall and beam stop regions. Interaction rates in 5 and 60 ton liquid argon detectors at a variety of existing and hypothetical locations along the beamline are found to be comparable to the largest existing decay-at-rest datasets for some channels. The physics implications and experimental challenges of such a measurement are discussed, along with prospects for measurements at targeted facilities along a future Fermilab long-baseline neutrino beam.

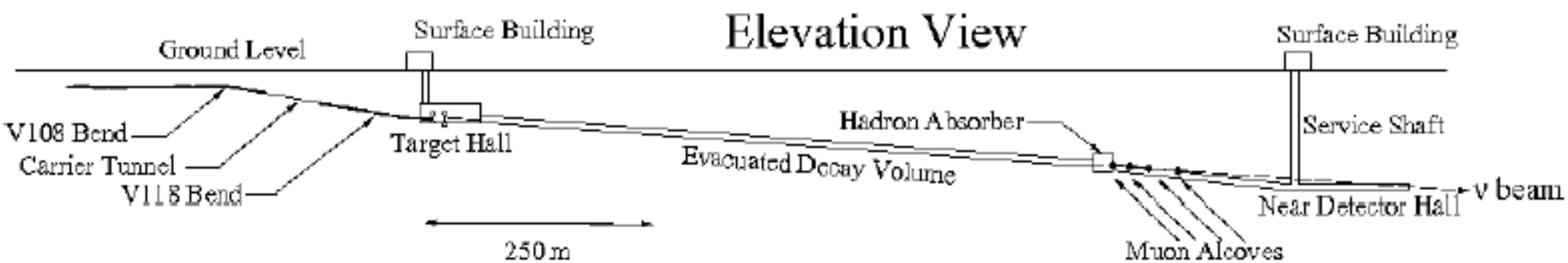
C. Grant and B. Littlejohn, arXiv:1510.08431

Submitted to Physical Review

NuMI beamline

120 GeV protons on carbon target
Upgrade to 700 kW expected in at the end of 2016





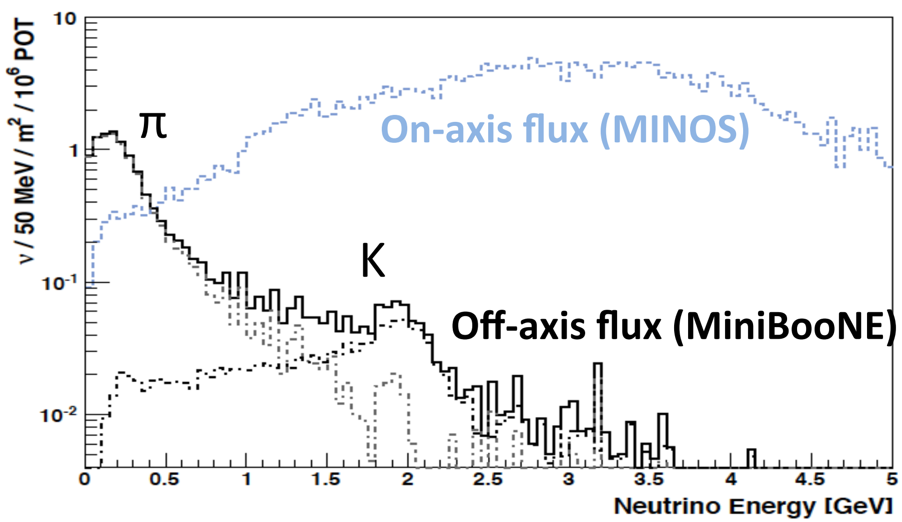
Target is at ~40 m depth

Absorber is at ~80 m depth

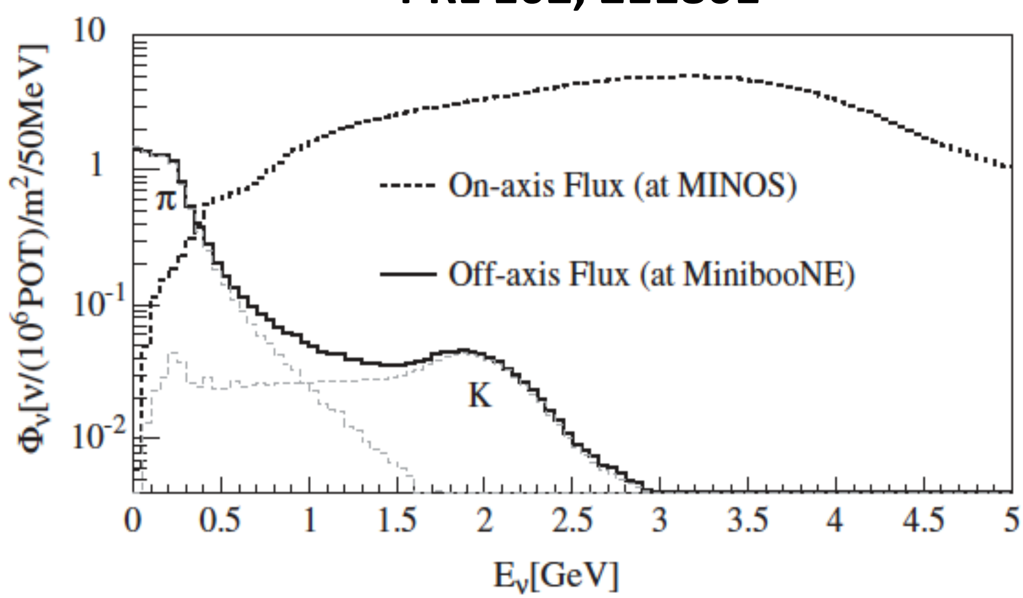
NuMI beamline simulation debugging and sanity checks

- NUMI-X collaboration maintains the NuMI beam simulation code.
- Simulation is optimized to calculate decay-in-flight neutrinos (obviously).
- Some tweaking of the code is necessary to get decay-at-rest neutrinos – ask me offline for details if you're interested.
  (Ex: throw away particles with ***p*** in the upstream direction, lepton number was never conserved during muon decay, etc…)

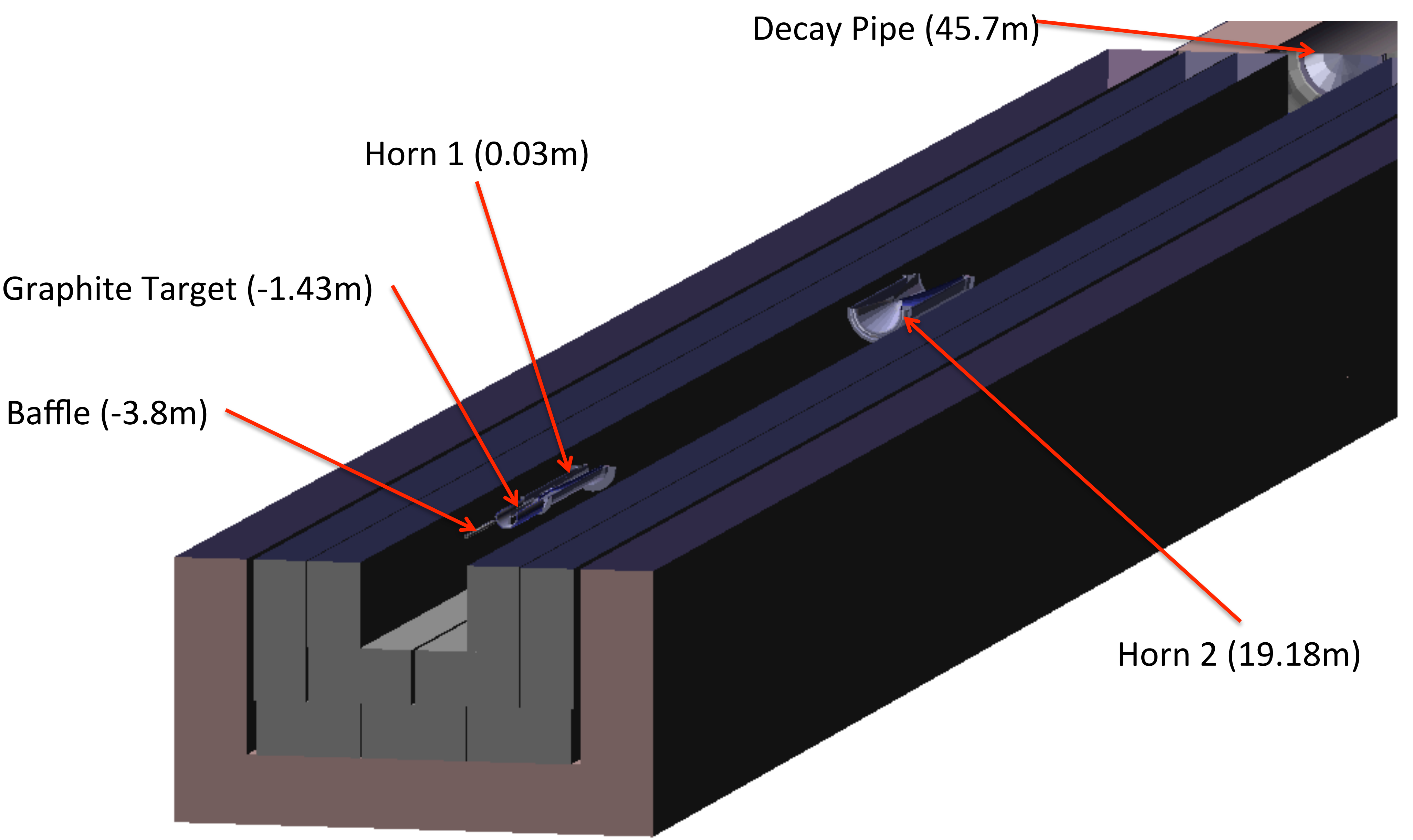
C. Grant (Decay-in-flight cross-check)



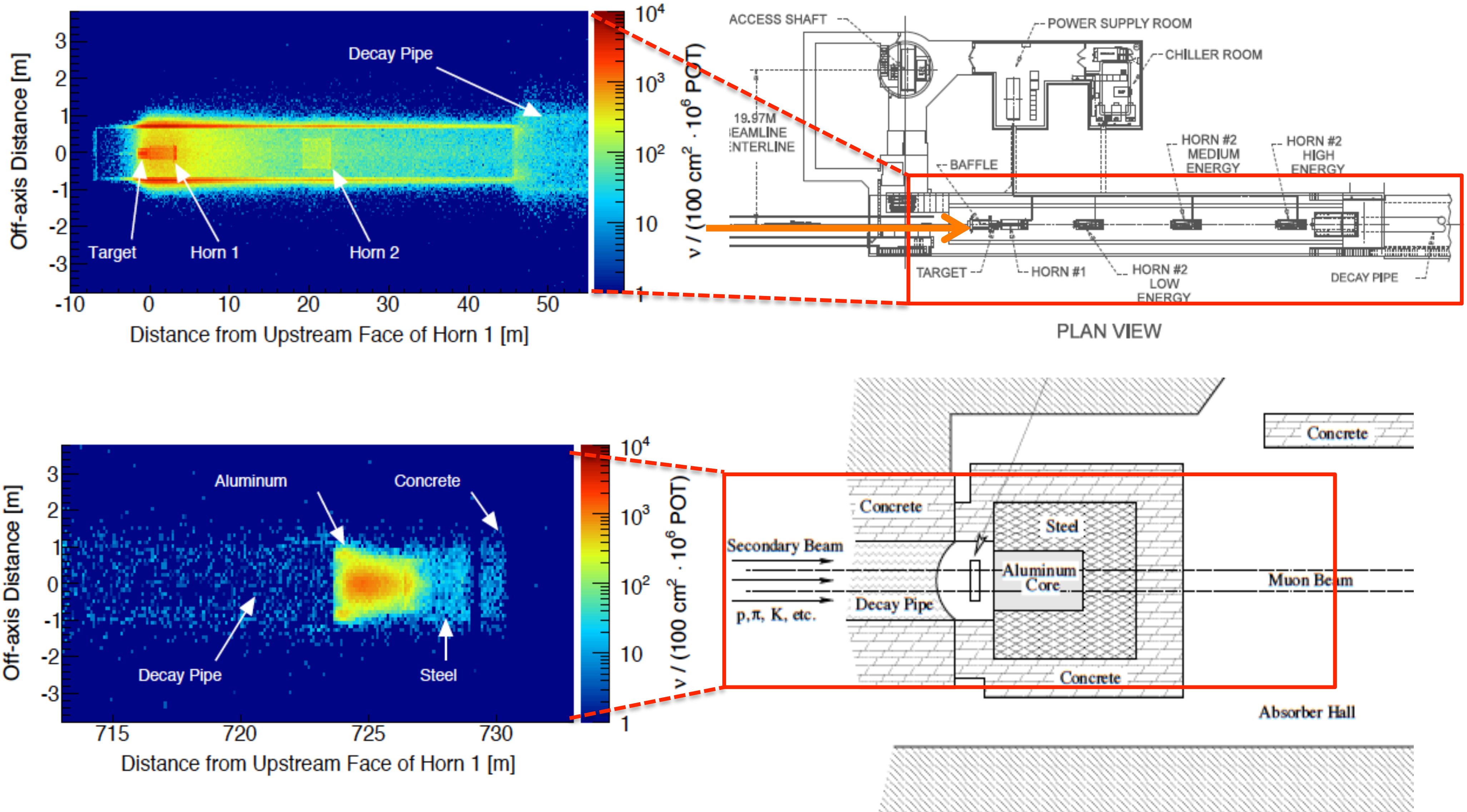
PRL 102, 211801



Detailed look at the NuMI target in GEANT4

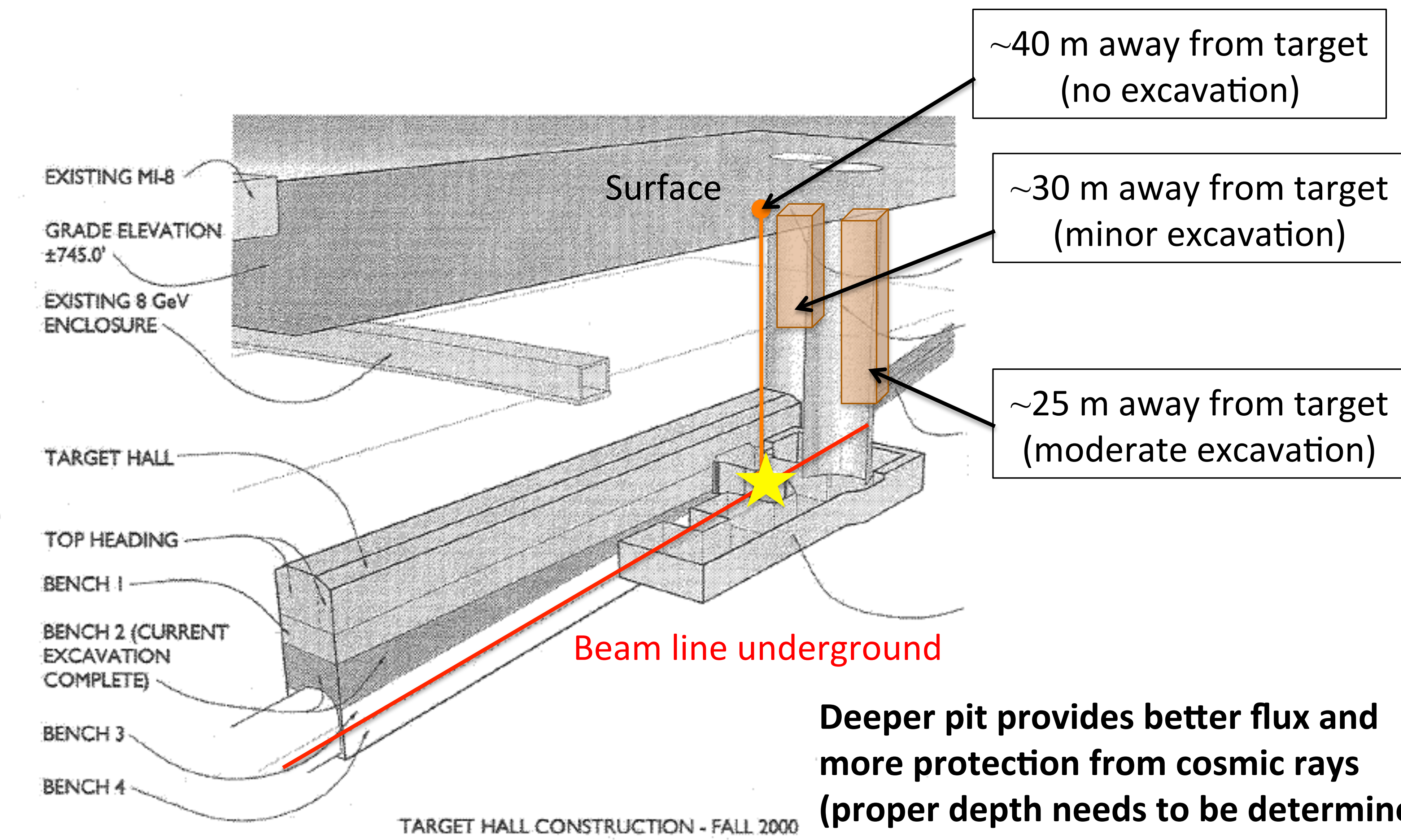


Decay-at-rest neutrino production along the beam line



C. Grant and B. Littlejohn, arXiv:1510.08431 ***41 stopped ν per 120 GeV proton on target!***

Potential detector positions near the NuMI target

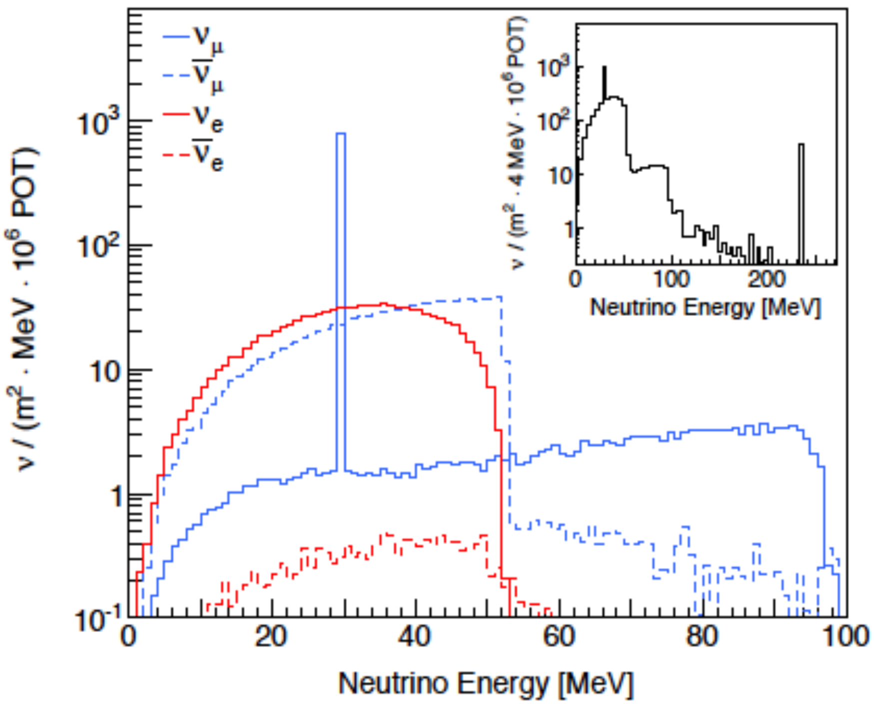


Deeper pit provides better flux and more protection from cosmic rays (proper depth needs to be determine)

Potential detector positions near the NuMI target

NuMI flux comparison with other facilities

C. Grant and B. Littlejohn, arXiv:1510.08431



- NuMI provides an order of magnitude increase in flux over the BNB.
- Flux is almost comparable to SNS at the same distance (factor 2 less)
- When choosing a facility, details of the experiment and distance from source matter!

Facility:	NuMI	BNB	SNS
Source:	120 GeV and 700 kW	8 GeV and 32 kW	1 GeV and 1.4 MW
Total flux below 53 MeV:	**5.4 x 10^6 ν/cm^2/s @ 25 m**	**3.2 x 10^5 ν/cm^2/s @ 25 m**	**~1.3 x 10^7 ν/cm^2/s @ 25 m**

NuMI CC ν_e interaction rate comparison with other facilities

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

CC ν_e rates were calculated using the flux between 0 - 53 MeV:

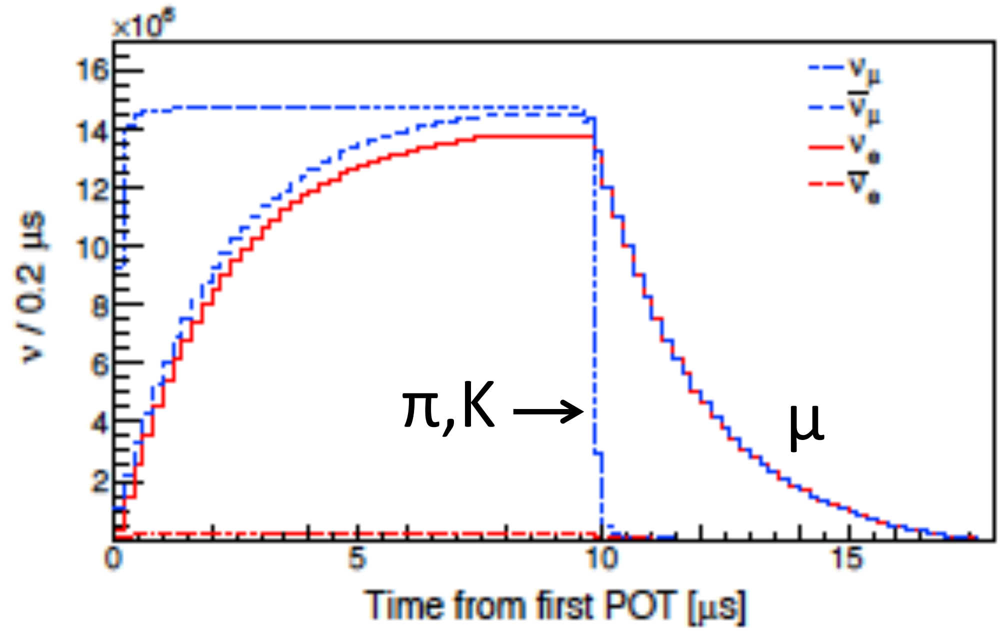
- *No detection efficiencies, threshold effects, etc… were assumed*
- Need to also consider gammas and neutrons escaping the de-excitation of the Argon nucleus

Facility:	NuMI	BNB	SNS
Source:	120 GeV and 700 kW	8 GeV and 32 kW	1 GeV and 1.4 MW
Total rate in 5 tons of Argon:	~1,100 events / year @ 25 meters	~350 / year @ 12 m	~1000 / year @ 35 m

Decay-at-Rest Backgrounds

Detailed studies of the backgrounds are not yet available, but can be categorized as:

- **Cosmic-induced:**
  How much overburden is needed?
- **Beam-induced:**
  Prompt neutrons coming from the protons on target could be reduced with time-cut of ~10 μs after the spill.
- **Neutrino-induced:**
  Neutrinos interact with material in between detector and target to produce background. Again, a time cut would help.



Only 15% of DAR signal left after 10μs

Summary and Conclusions

Nuclear physics details of SN neutrino-Argon interactions remains largely unknown – we need measurements

- **How close can one get to decay-at-rest sources like SNS, BNB, and NuMI?**
  - Space and infrastructure need to be addressed.
    Ex: it appears that ton-scale detectors need to be at least ~35 meters away from SNS

- **DUNE/LBNF beam (similar to NuMI) will be constructed in the near future**
  - Beam power is designed to operate up to 2.4 MW
  - More than a factor of 3 increase in DAR flux over NuMI

Summary and Conclusions

- **First chance to demonstrate low-energy neutrino detection in liquid argon**
- **1,100 CC ν_e interactions / year in 5 tons of liquid argon positioned 25 meters from NuMI target. Several 10^3 interactions / year if placed near the future LBNF neutrino beam**
- **Determine the effect on energy reconstruction of missing neutrons and gammas**
- **Tune MARLEY event generator on real data – use to predict what will be observed in DUNE**

The End