CAPTAIN BNB
Measuring SN Neutrino XS in Liquid Argon off-axis in the BNB

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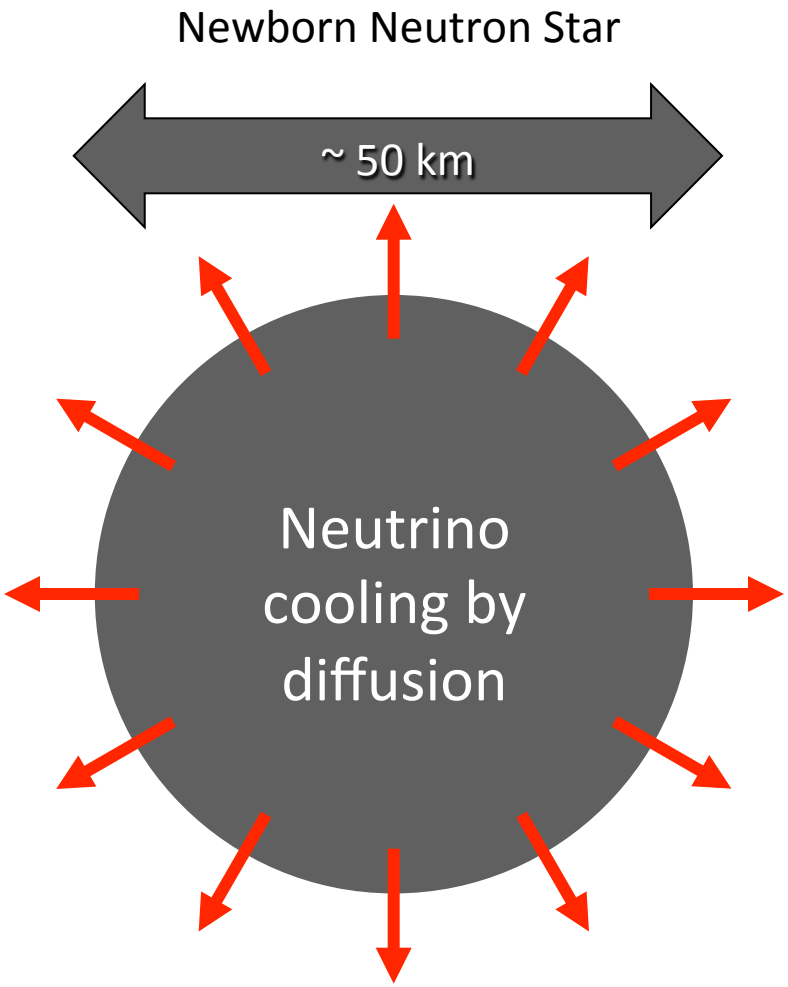
(on behalf of the CAPTAIN collaboration)

Fermilab PAC
FNAL, January 16, 2015

Introduction

- Run the CAPTAIN detector near MI-12 of the BNB
- Measure the neutrino Ar XS (mainly ν_e) to about 10% for neutrino energies of O(10) MeV:
  - never been measured before
  - large theoretical errors
  - direct relevance to the interpretation of SN data
- Test the ability of detecting SNe with LAr detectors (triggering, timing)
- Potentially influence the ELBNF design (e.g., photodetection devices)

Physics Motivation: Stellar Collapse & SN Explosion



Gravitational binding energy

$E_b \approx 3 \times 10^{53}$ erg $\approx$ 17% $M_{SUN}\, c^2$

This shows up as:

99% Neutrinos

1% Kinetic energy of explosion

(1% of this into cosmic rays)

0.01% Photons, outshine host galaxy

Neutrino luminosity:

$L_\nu \approx 3 \times 10^{53}$ erg / 3 sec

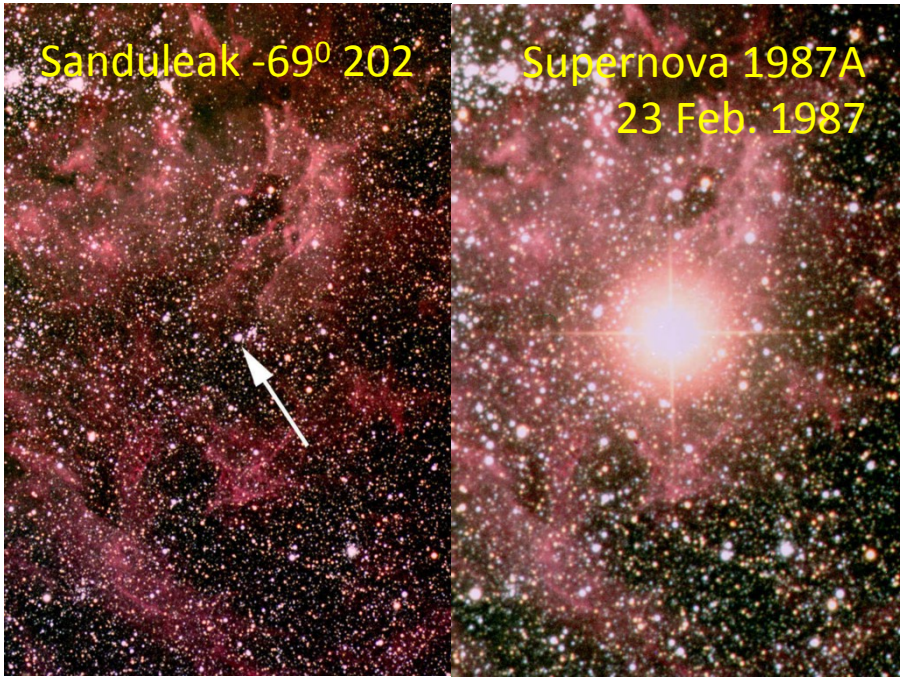
$\approx 3 \times 10^{19}\, L_{SUN}$

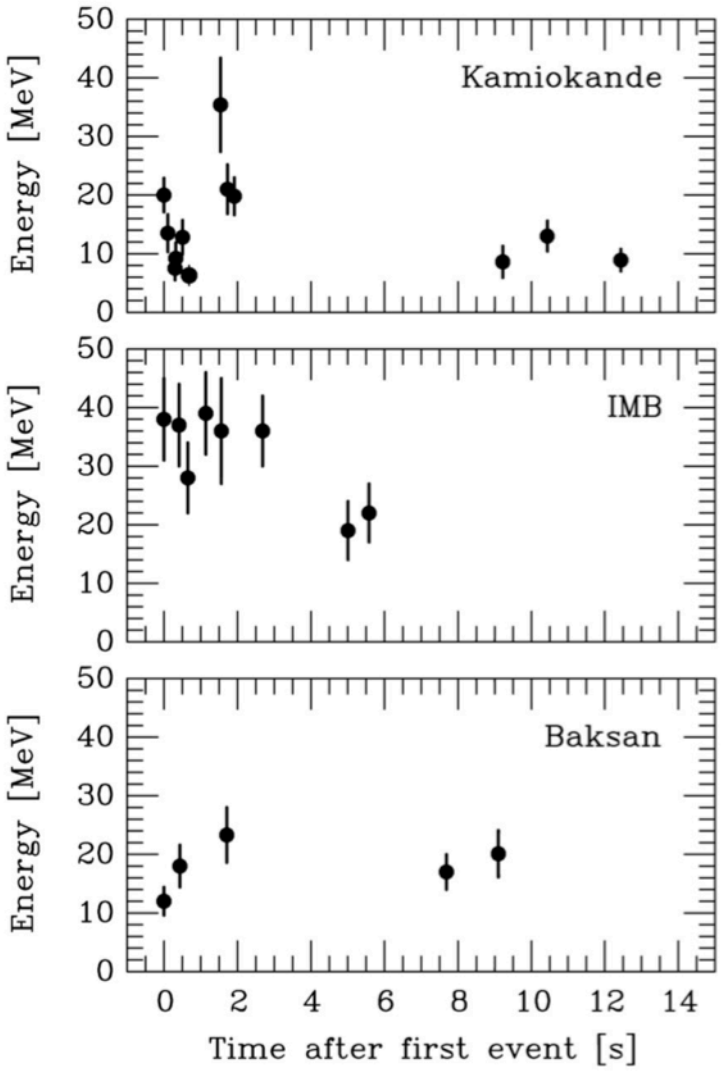
While it lasts, outshines the entire visible universe

Physics from the 1987A Supernova (LMC; 51 kpc)

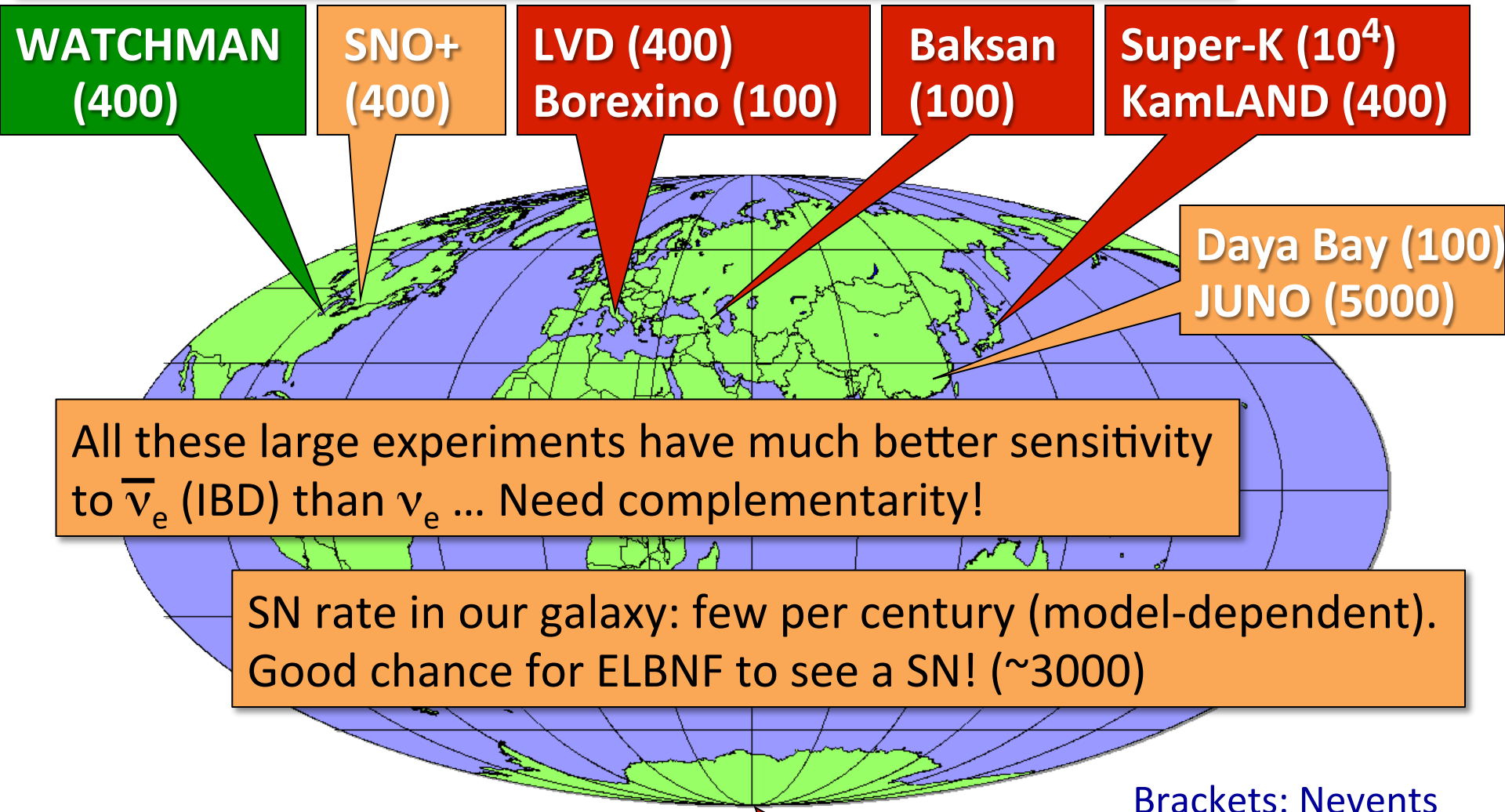
SN-1987A: average of **1 citation every 10 days for last 26 years** – only 20 (26) events total!

- Most precise straightforward test of weak equivalence
- Direct neutrino TOF with 10^5 LY baseline
- Limits on neutrino decay over 10^5 years





Large Underground Detectors for SN Neutrinos



All these large experiments have much better sensitivity to $\overline{\nu}_e$ (IBD) than ν_e … Need complementarity!

SN rate in our galaxy: few per century (model-dependent). Good chance for ELBNF to see a SN! (~3000)

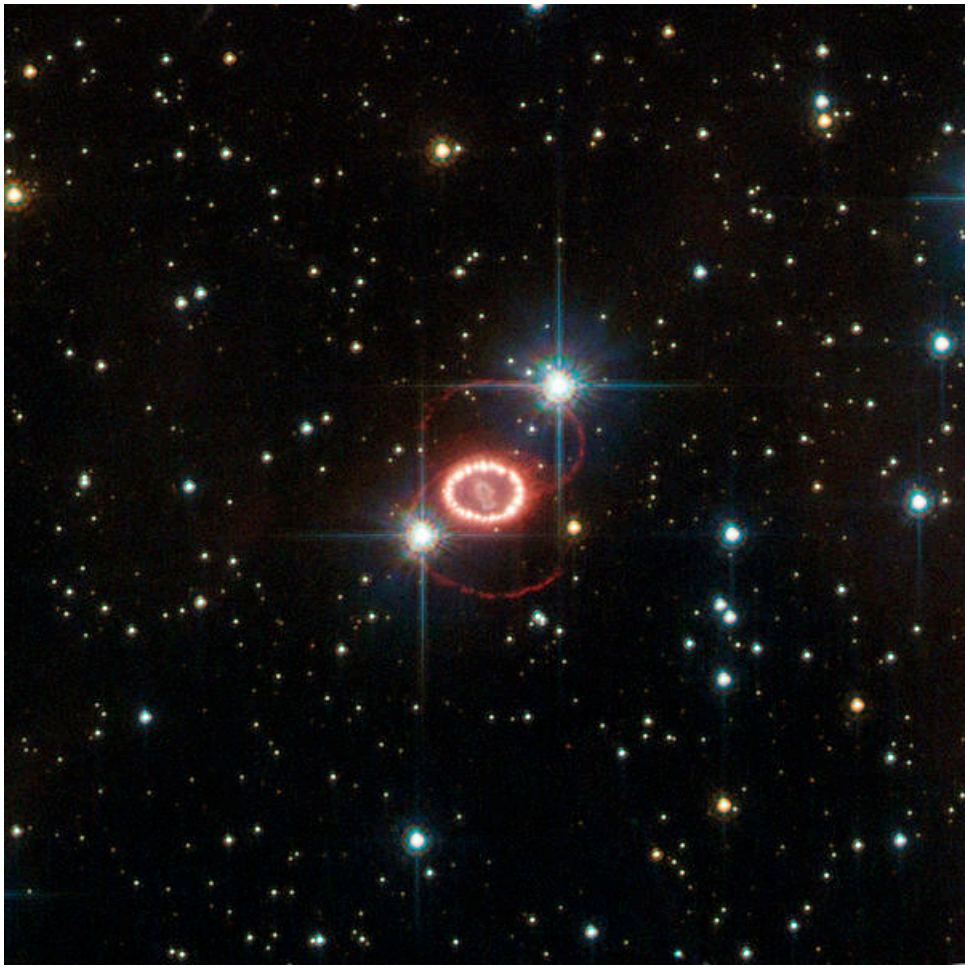
Brackets: Nevents for a "fiducial SN" at distance 10 kpc

Do We Really Know How to Detect a SN with a LAr TPC?

- Cross sections?
  - never been measured
  - large theoretical errors (at least 15%)
- Triggering?
- Timing?

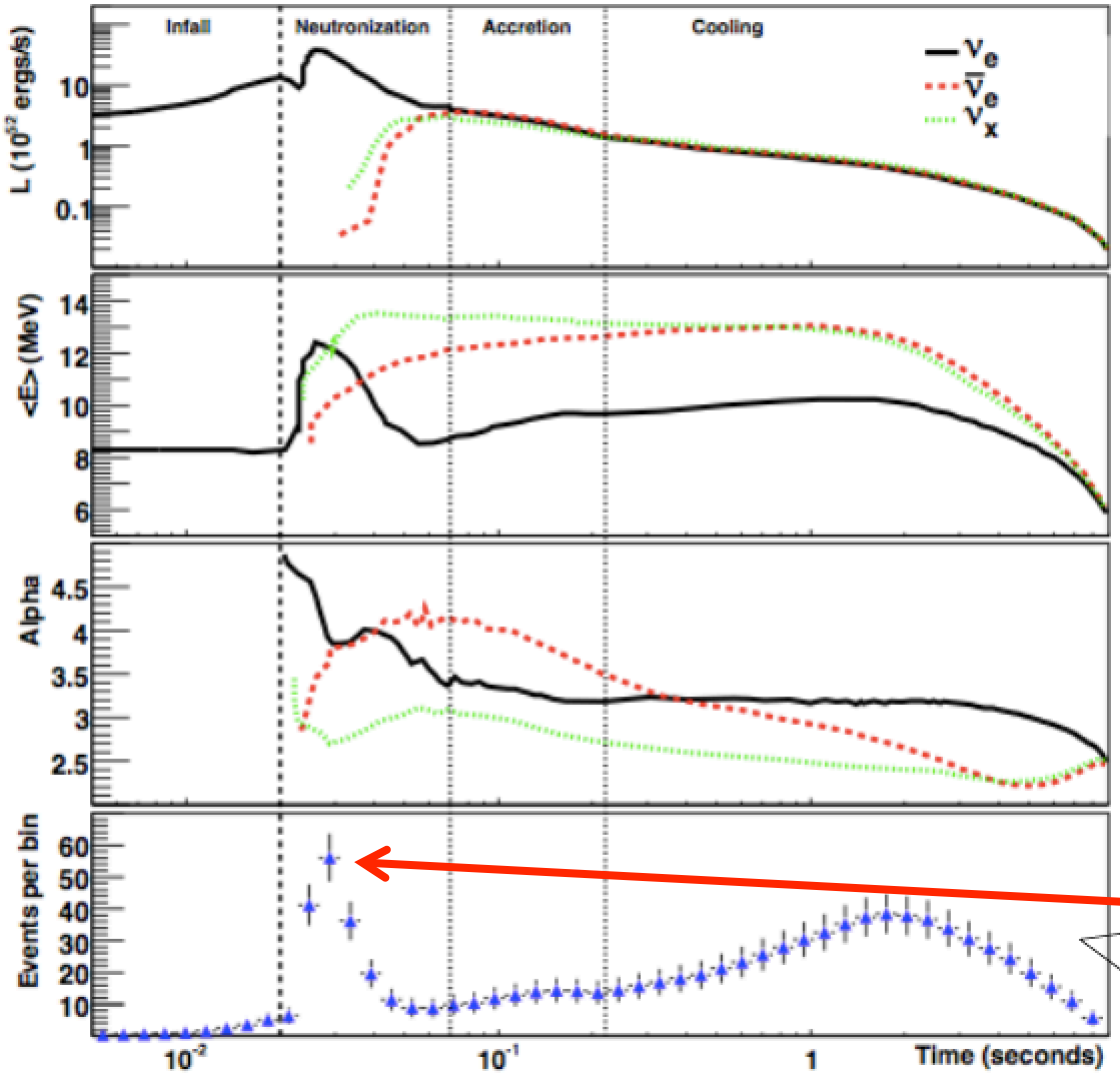
P5 recommendation:

"The (ELBNF) experiment should have the demonstrated capability to search for SN bursts…"



Detection of the SN Neutronization Burst: ν_e Sensitivity!

$$p + e^- \rightarrow n + \nu_e$$



Burst is only 20 ms long and is essentially all ν_e

Mean energy of events is low, 10−12 MeV

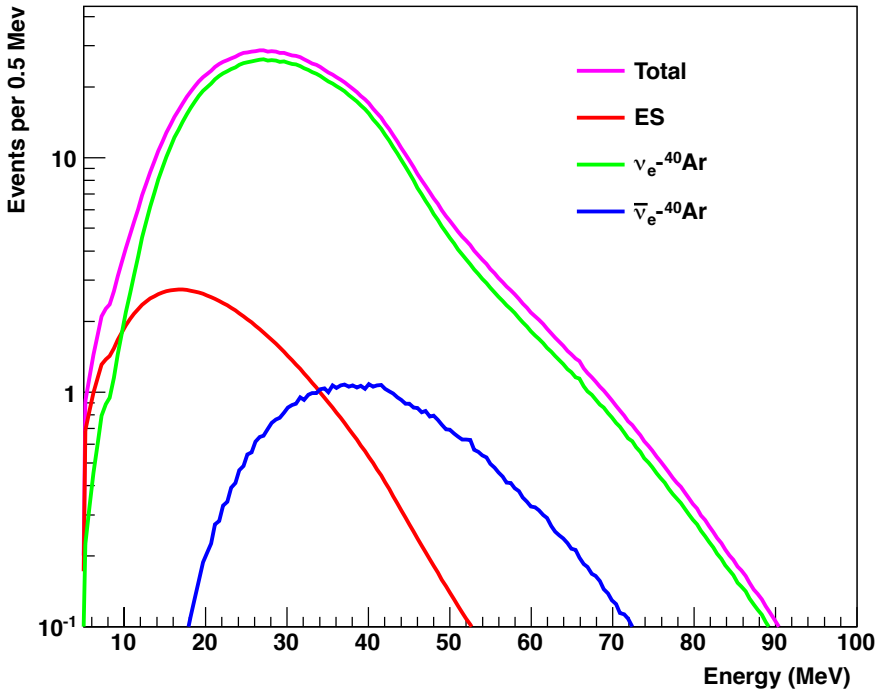
IMB/Kamiokande detected higher energy cooling neutrinos, not neutrinos from the neutronization process

Potential for ν_e detection in liquid argon by ELBNF

10 kpc SN Event Rates

K. Scholberg: arXiv 1205.6003 astro-ph
GKVM model: arXiv 0902.0317 hep-ph
(Gava, Kneller, Volpe, McLaughlin)

17 kton LAr detector



Rates in nominal 34 kton ELBNF detector:

$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$ (CC) 2848

$\bar{\nu}_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^*$ (CC) 134

$\nu_x + {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^*$ (NC) 200 (A. Hayes)

$\nu_x + e^- \rightarrow \nu_x + e^-$ (ES) 178

Critical items for supernova physics with a LAr TPC:

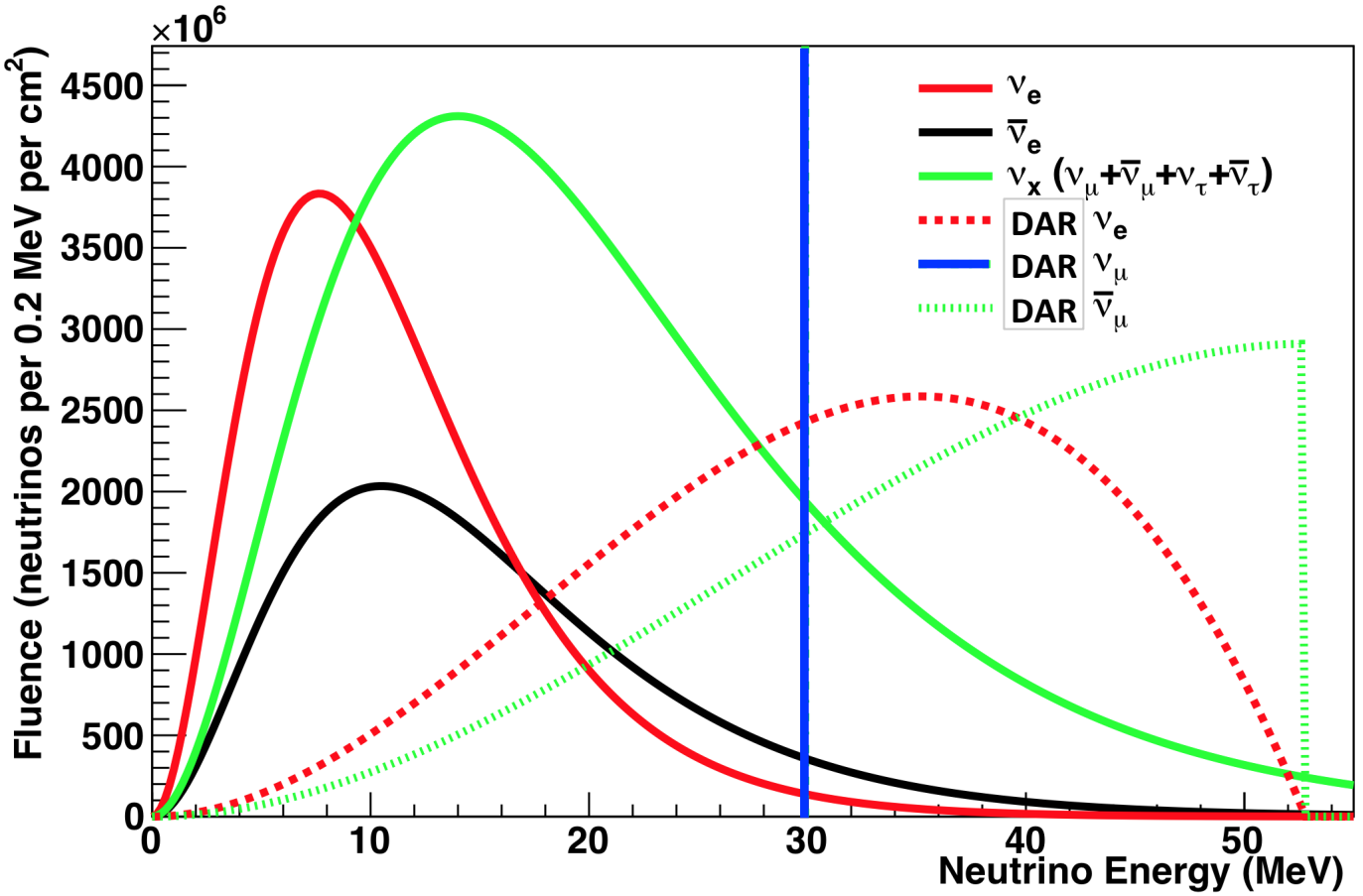
- Accurate measurements of the CC and NC cross-sections
- Ability to clearly tag excited states ^{40}K* and ^{40}Ar* using de-excitation γ's
- Ability to reject backgrounds such as neutron spallation
- Adequate energy resolution in a LAr TPC
- Reasonable event timing

O(10 MeV) Neutrino Source: Stopped Pion Facilities

DAR flux: very well understood (analytic): $\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\downarrow$

$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$



BNB @ FNAL

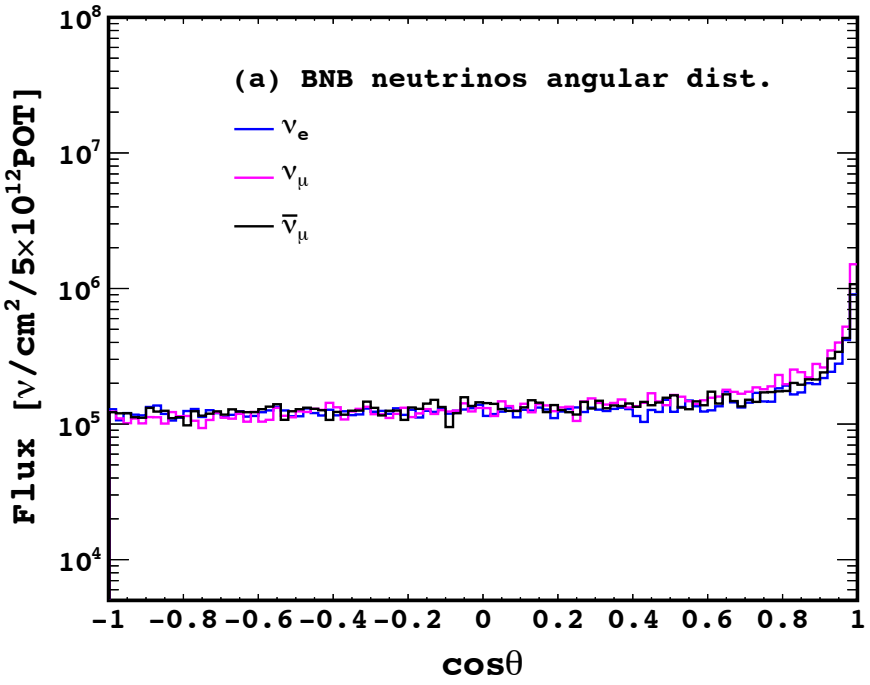
Fermilab:

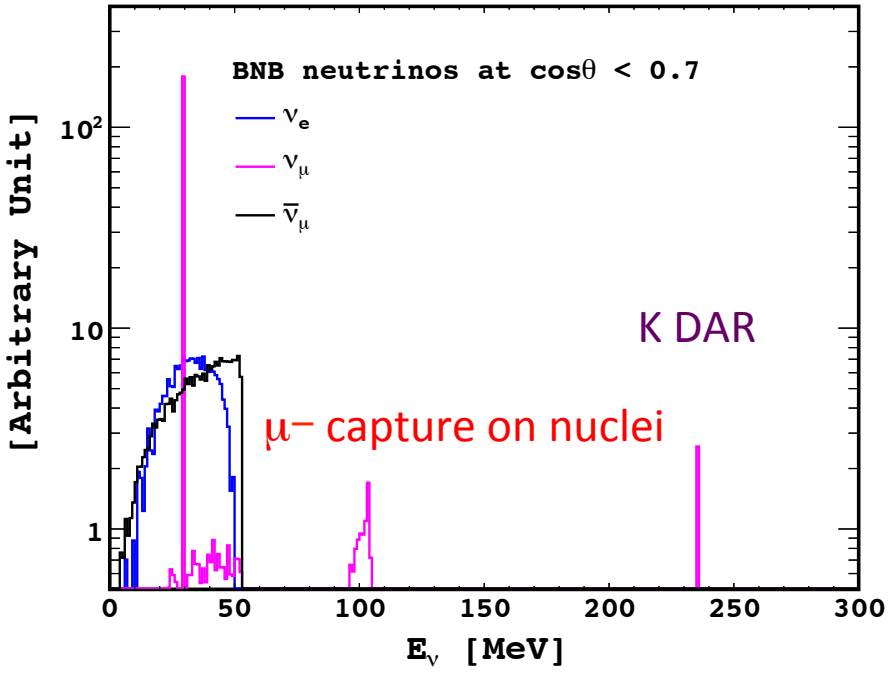
- The only national laboratory in US dedicated to the particle physics
- Strong support on neutrino physics programs

Neutrino Flux around MI-12

S. Brice calculation for CENNS 20 m from MB target using modified MB G4 code

Phys. Rev. D89 (2014) 072004 (arXiv 1311.5958 physics.ins-det)



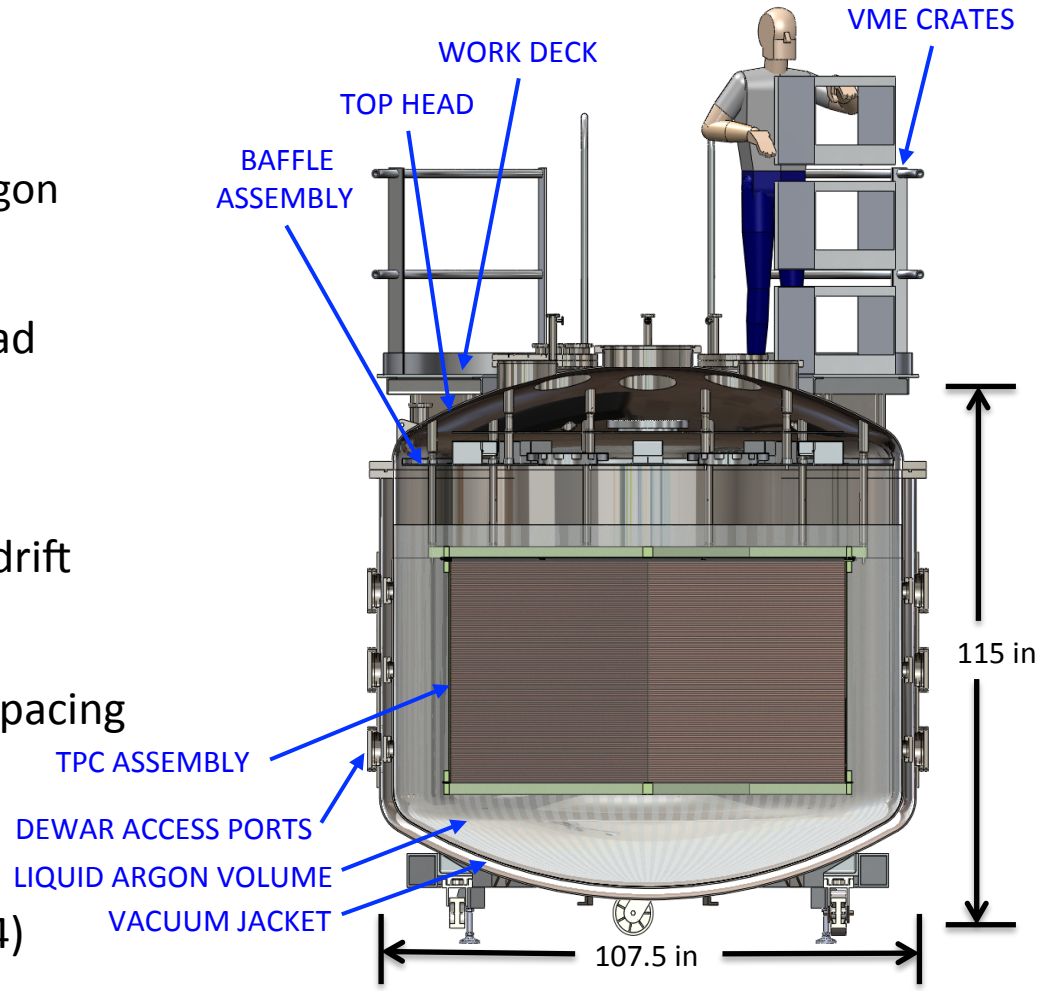


For 5e+12 ppp at 5 Hz: neutrino flux is Φ = 5 x 10^5 ν/cm^2/s/flavour

The CAPTAIN Detector

Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrinos (LANL LDRD)

- Liquid argon TPC detector:
  - Portable and evacuable cryostat
  - 7700 L, 5-ton instrumented liquid argon
  - All cryogenic and instrumentation connections made through top head
  - Transportable purification system
- TPC:
  - Hexagonal prism, vertical upward drift ($E = 500$ V/cm, $v_d = 1.6$ mm/μs)
  - 2001 channels (667/plane) 3 mm spacing
- Laser calibration system (Nd-YAG)
- Photon detection system
  - Hamamatsu R8520 (24) & 11065 (4)
- μBooNE cold electronics



CAPTAIN Status & Schedule

At EDEN Cryogenics

Arrived at LANL (08/2014)

- Electronics: done
- TPC: in progress
- Expected commissioning: during FY16
- Neutron data at WNR neutron beam:
  - test response to neutrons
  - test SN detection through NC

$$\nu_x + {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^*(NC)$$

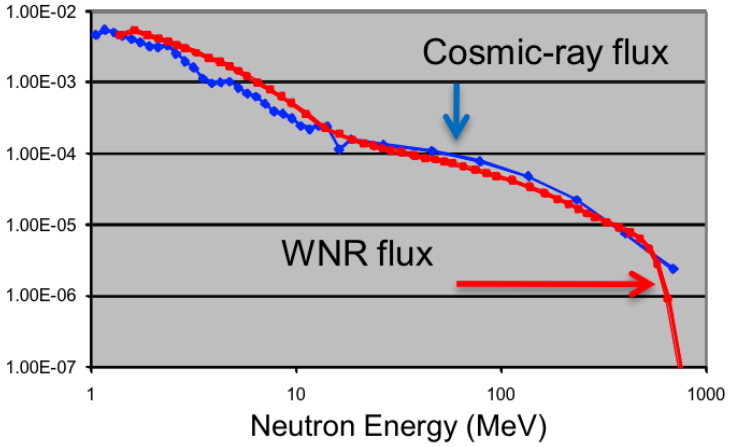
$$n + {}^{40}Ar \rightarrow n + {}^{40}Ar^*$$

- Ready to be deployed at FNAL: end of FY16 (runs in BNB & NuMI)

MiniCAPTAIN

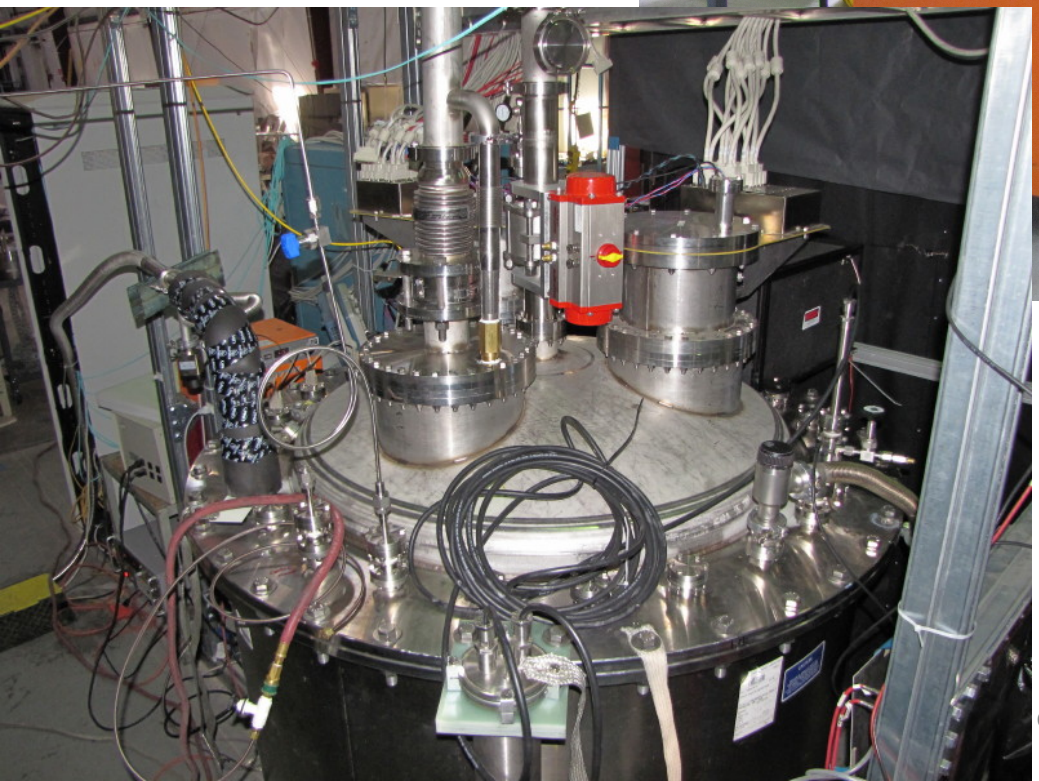
- Smaller version (1,700 l cryostat from UCLA)
- Apothem: 50 cm (vs 100 cm)
- Drift length: 32 cm (vs 100 cm)
- Number of channels: 337 per plane (vs 667)
- Instrumented volume: 1/3 tons (vs 5 tons)

- Commissioning underway …
- Will be moved to WNR to take neutron data in 10/15



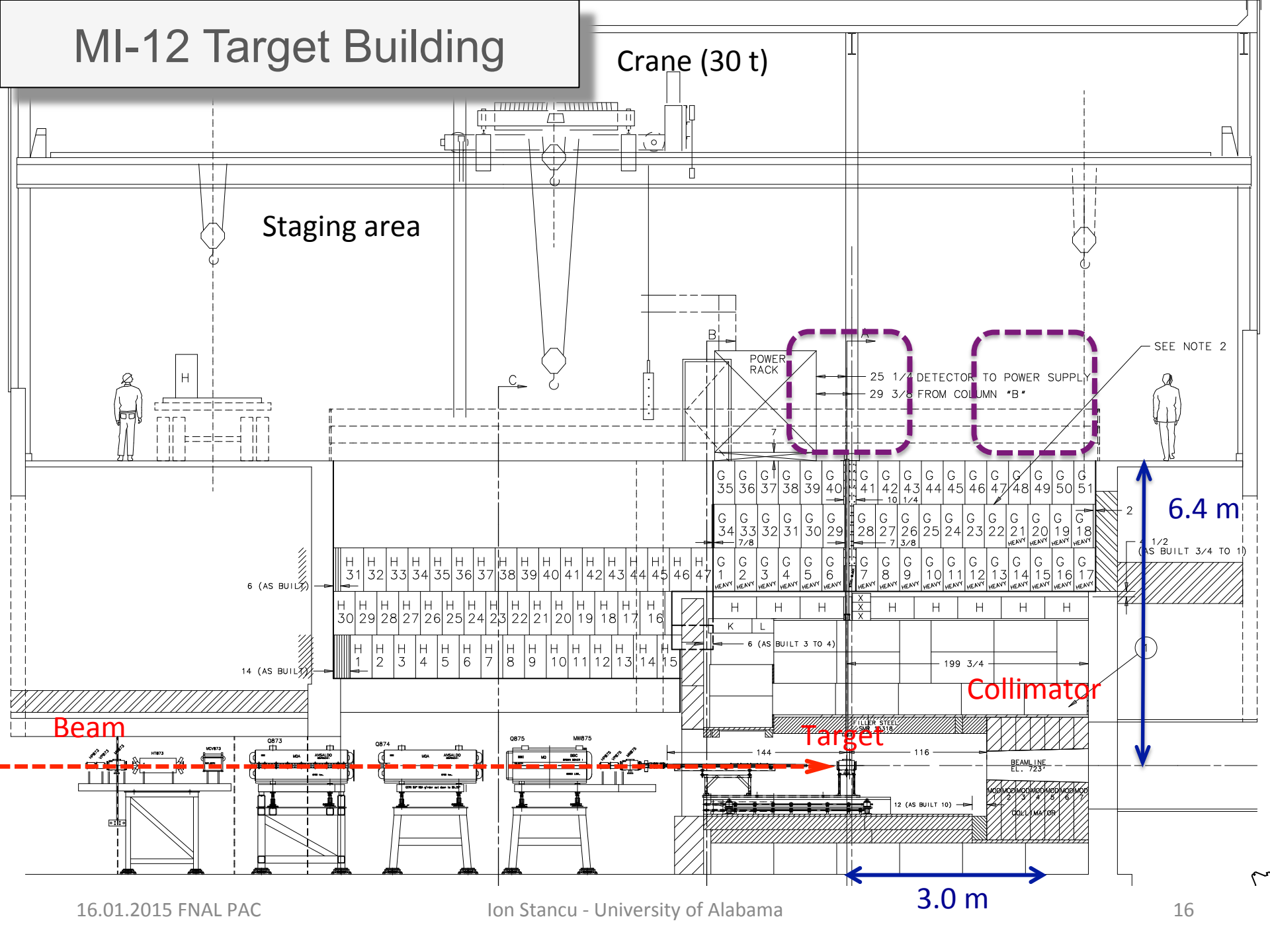
MiniCAPTAIN

… being prepared for
LN cold electronics
systems test



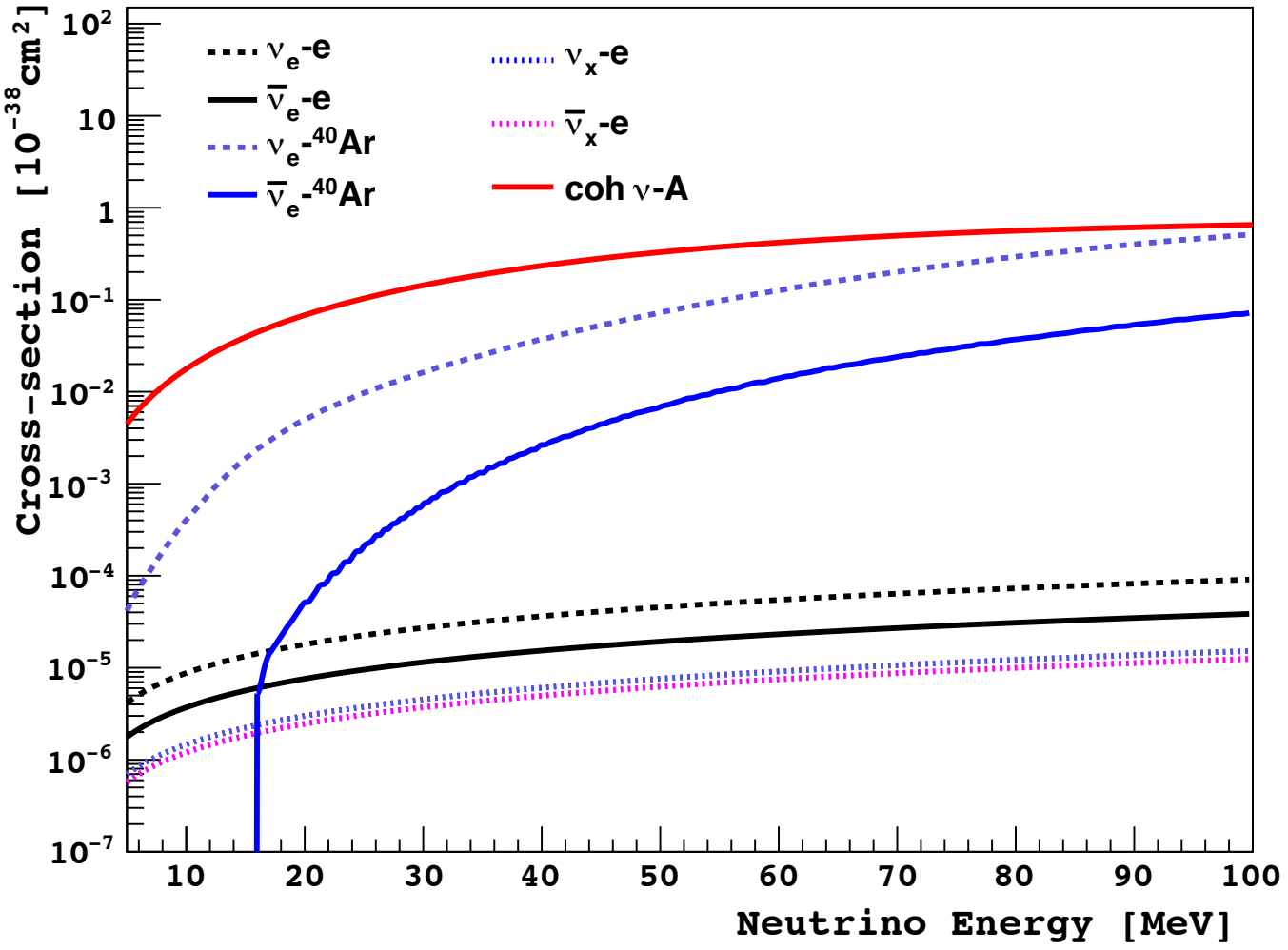
… being prepared for
LAr engineering runs

MI-12 Target Building

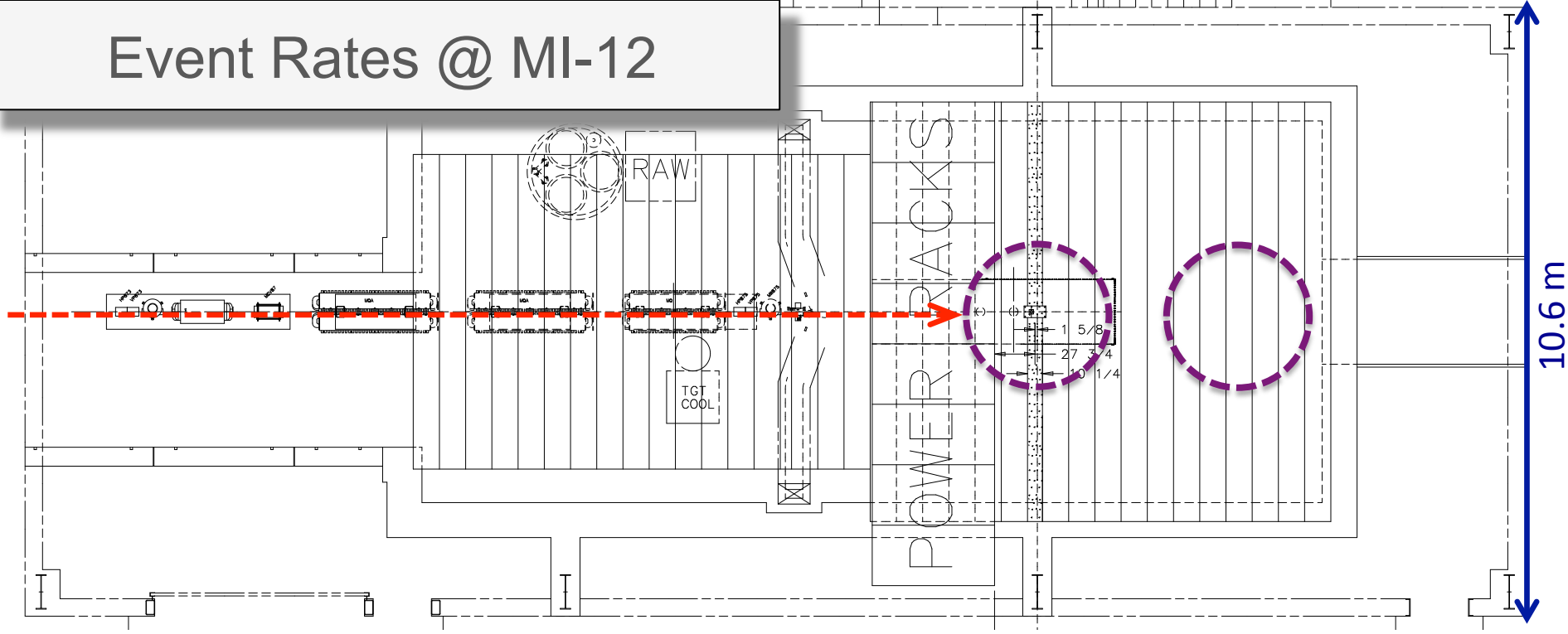


LAr Cross-sections (RPA)

CC ν_e ^{40}Ar flux-averaged cross section $\sigma \approx 10^{-40}$ cm^2

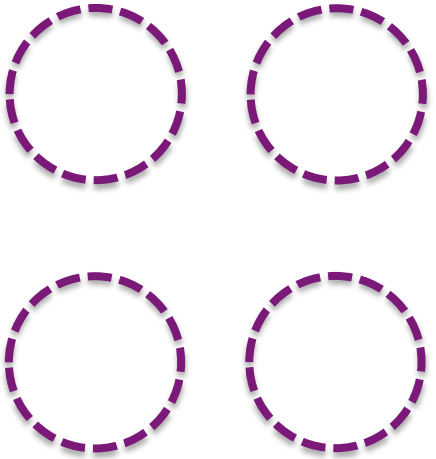


Event Rates @ MI-12



Alignment w. target & collimator

x (m)	d (m)	Nevt (CC)	Nevt (CC)
0	8.4	354	375
7.3	11.1	217	229
11.3	14.1	145	152

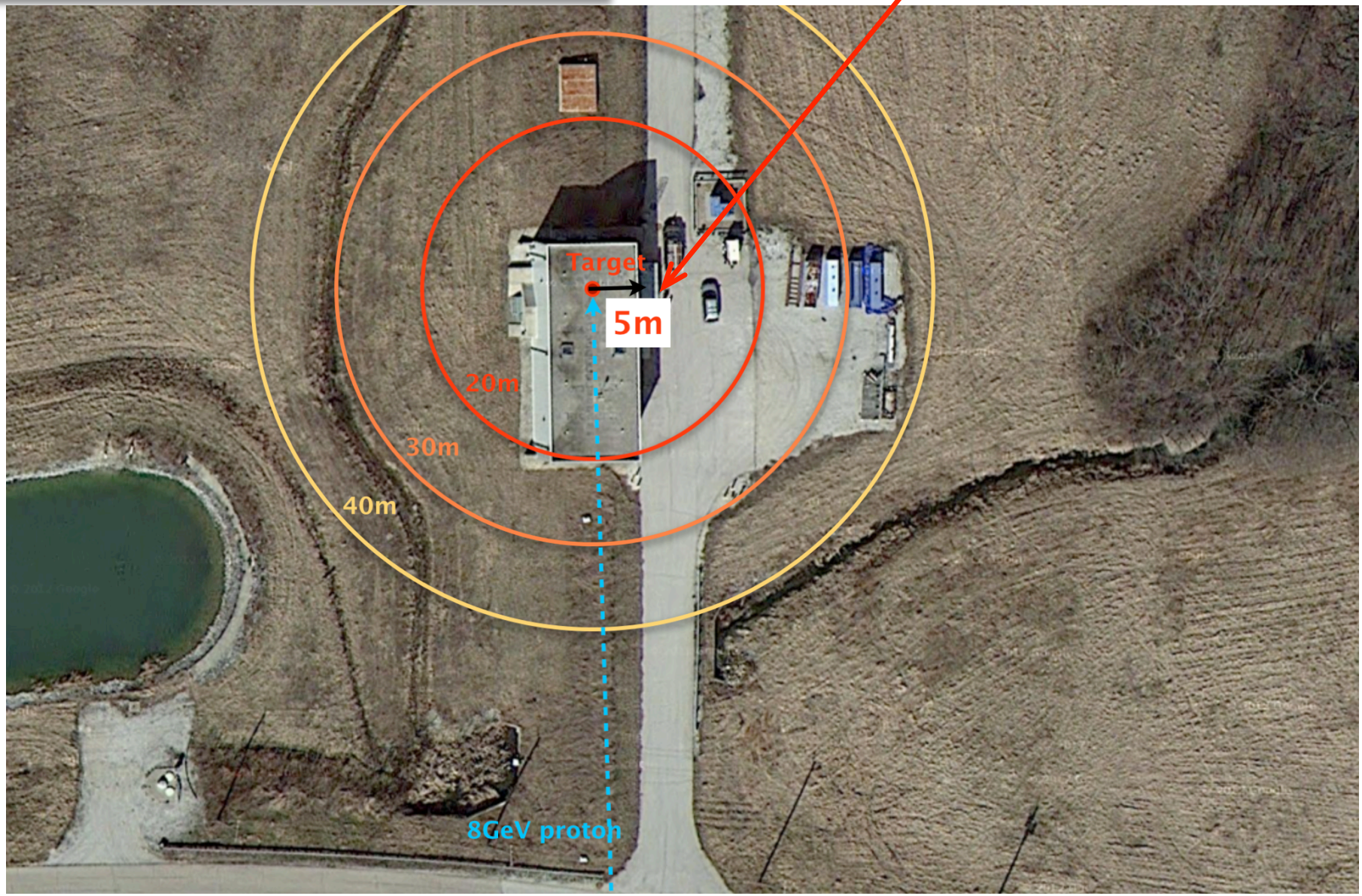


Rates: 2e20 POT (1 yr) & 100% efficiency

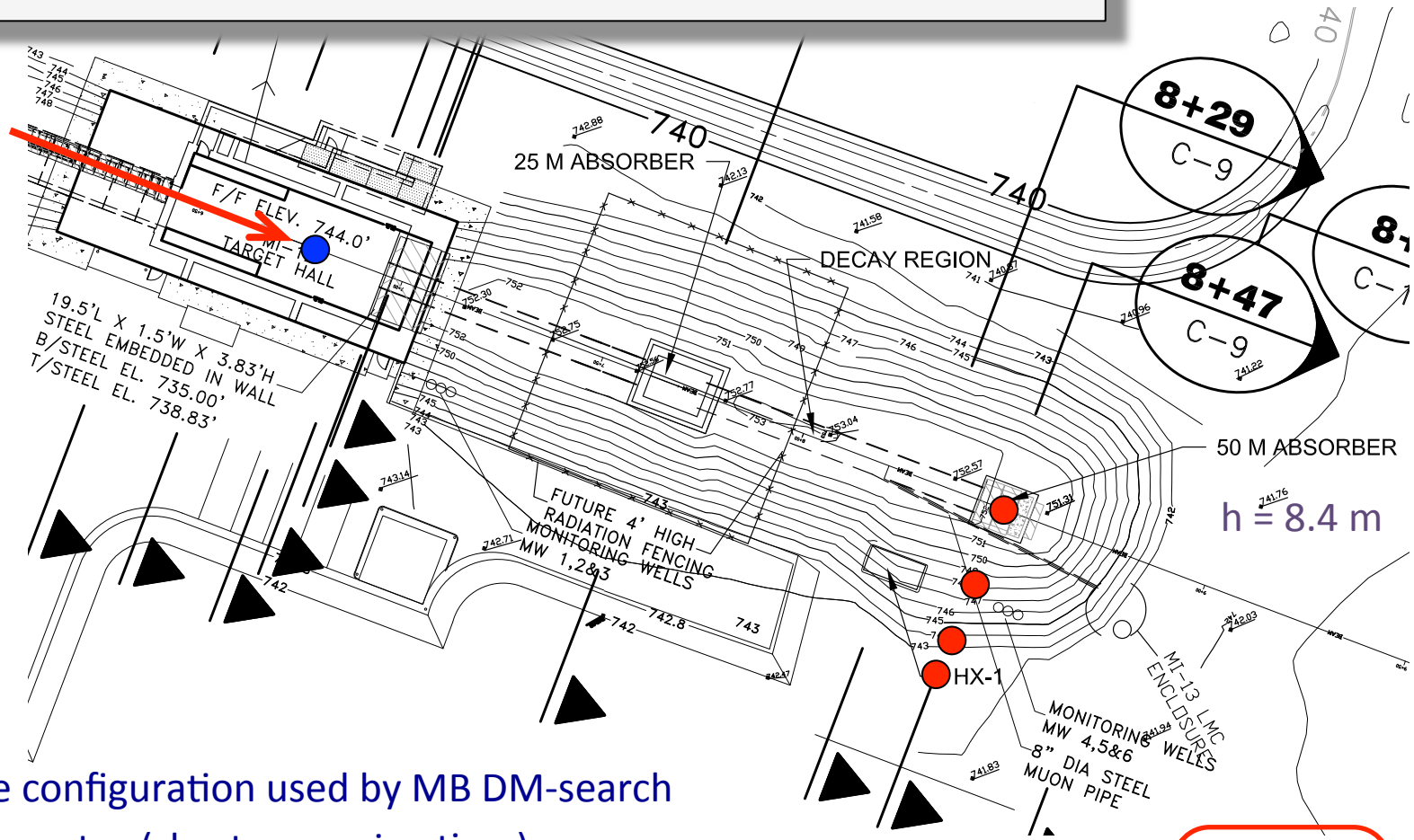
ν_μ (NC): +14%, $\overline{\nu}_\mu$ (NC): +31%

Space around MI-12

AC unit (could be moved … $$$)



Event Rates @ MI-12 in Off-Target Mode



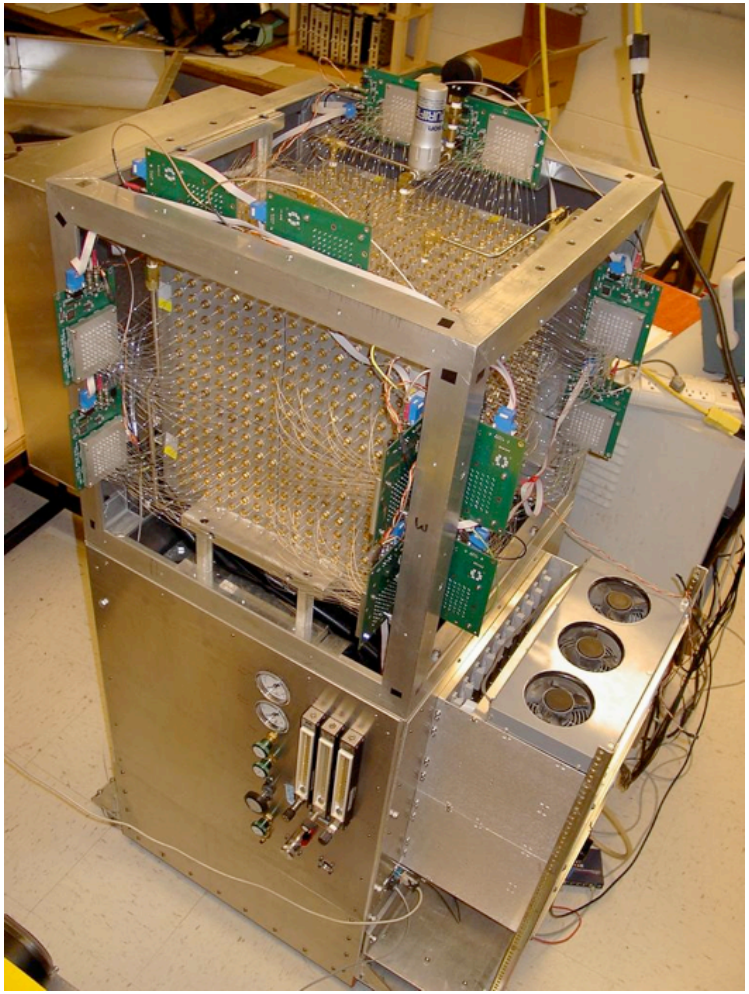
- Same configuration used by MB DM-search
- Higher rates (shorter running time)
- Potentially lower backgrounds
- Direct impact on μBooNE
- To be considered; in particular if others prefer running in this mode…

$N_1 = 743$
$N_2 = 376$
$N_3 = 250$
$N_4 = 189$

Neutron Backgrounds @ MI-12

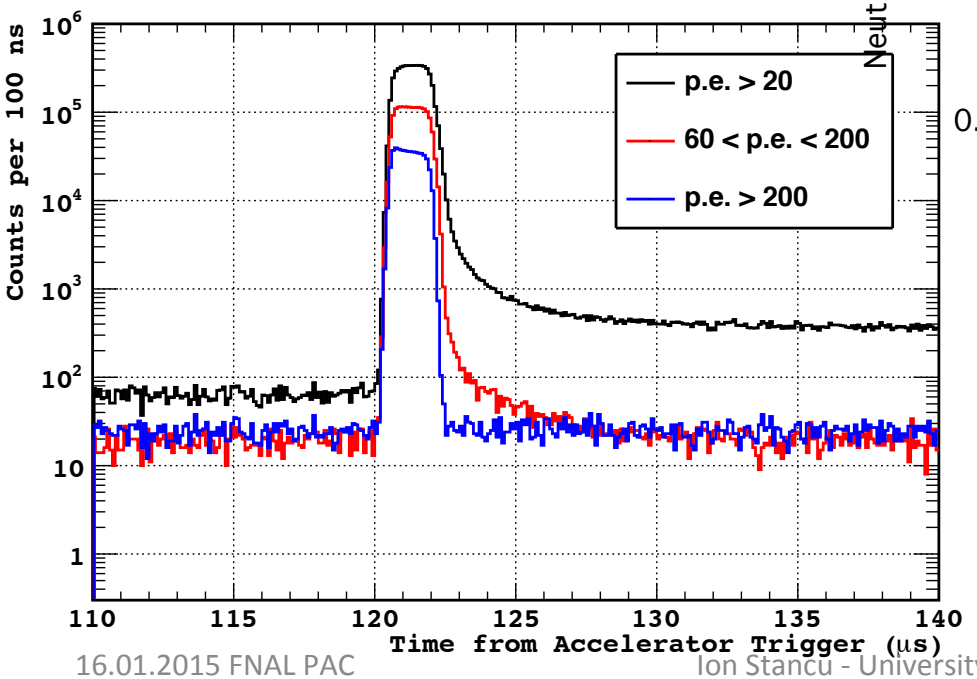
* CENNS

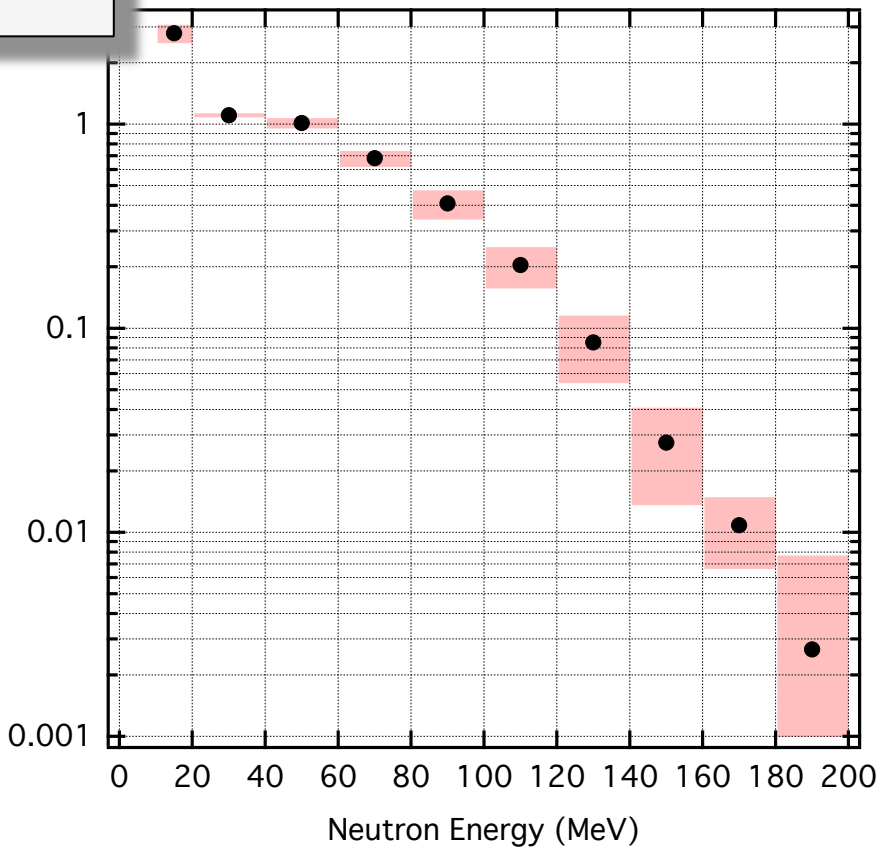
- SciBath detector (Indiana University)
  R. Tayloe & R. Cooper (FNAL IF fellow)
- 82 l volume of mineral oil based liquid scintillator.
- 768 wavelength shifting fibers readout to IU-built digitizers ($80 / channel includes multi-anode PMTs). Each direction: 16x16 array (2.5 cm spacing).
- Flux @ 20 m from target, 180^0 wrt beam
- Operated March – April 2012*:
  4.9×10^{19} POT (3.5×10^{19} POT for analysis)



Neutron Backgrounds @ MI-12

- E_n unfolded from PEs using fit and MC response function
- 6.3 ± 0.7 pulse^{-1} m^{-2} $E_n > 10$ MeV
- 2.4 ± 0.3 pulse^{-1} m^{-2} $E_n > 40$ MeV
  (blue histogram below)





- Several n events/pulse in CAPTAIN
- Need shielding at MI-12!
- Simulations: 3 m concrete yields O(10^{-4}-10^{-3}) neutron events/pulse

Neutron Backgrounds @ MI-12

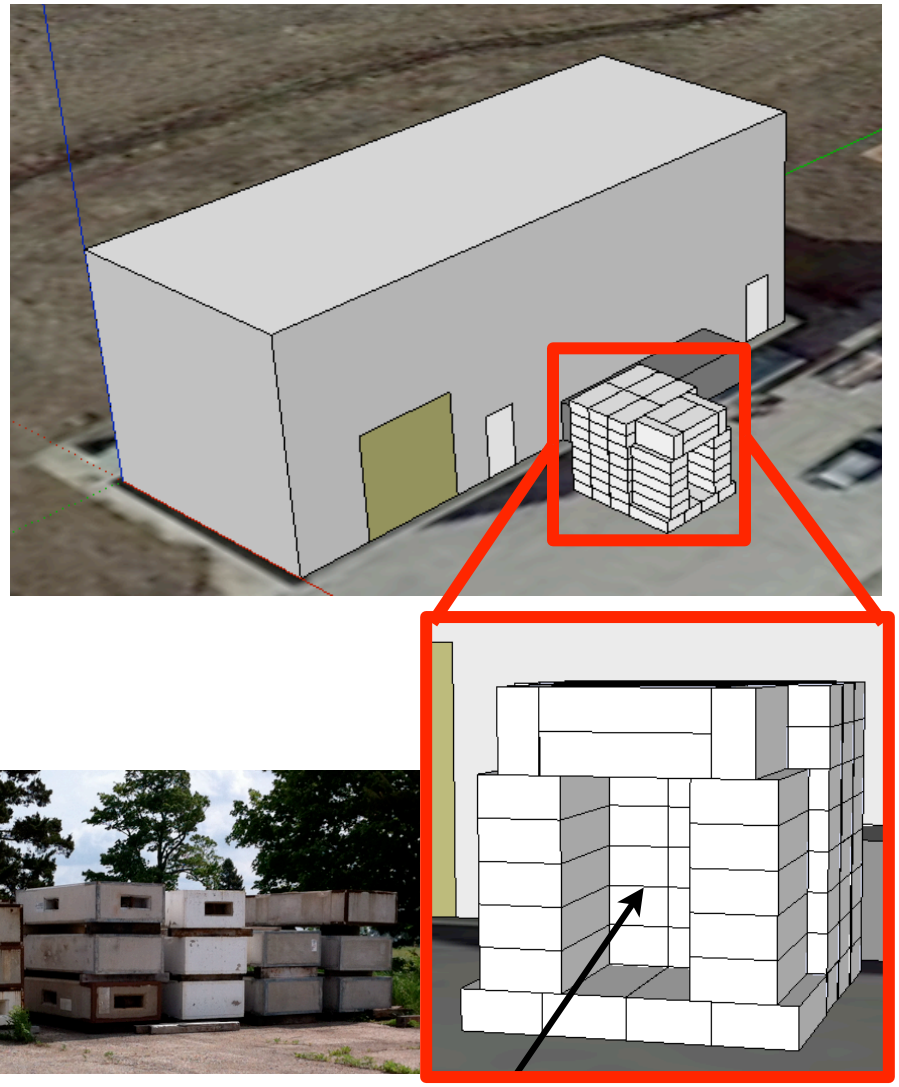
- New round of neutron background measurements is planned

- SciBath is being prepared:
  - fixing/upgrading electronics
  - new scintillator, etc.

- Start: ~ April 2015

- Duration: ~ 3 months (10^4 neutrons)

- Configuration:
  - next to MI-12
  - 3 m shielding
  - 1 m shielding, top (?)
  - 5 kg array of EJ-301 LS (sensitivity: 0.5-20 MeV)



Running Scenarios

- Scenario A: BNB first, then MINERνA
- Scenario B: MINERνA first, then BNB

Discussed in detail in L. Whitehead's talk (next)

Conclusions

- CAPTAIN intends to measure DAR ν XS on LAr at BNB
  Direct relevance to ELBNF SN detection – see P5
  (currently: only experiment which can do it)

- Running time for O(10%) measurement:
  - 4e+20 POT in standard configuration
  - 2e+20 POT in beam off-target configuration

- Running order (BNB/MINERνA): TBD

- While completing, commissioning & running CAPTAIN detectors, developing/tuning MC & developing analysis tools (e/n), we need FNAL to:
  - support for n-bkgd measurements (SciBath)
  - support for engineering studies at/around MI-12

Thank you

CAPTAIN Collaboration

University of Alabama
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Los Alamos National Laboratory
G. Garvey, E. Guardincerri, T. Haines, D.M. Lee, Q. Liu, W.C. Louis, **C. Mauger**, G. Mills, J. Ramsey, K. Rielage, G. Sinnis, W. Sondheim, C. Taylor, R. Van de Water

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University of Houston
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New Mexico State University
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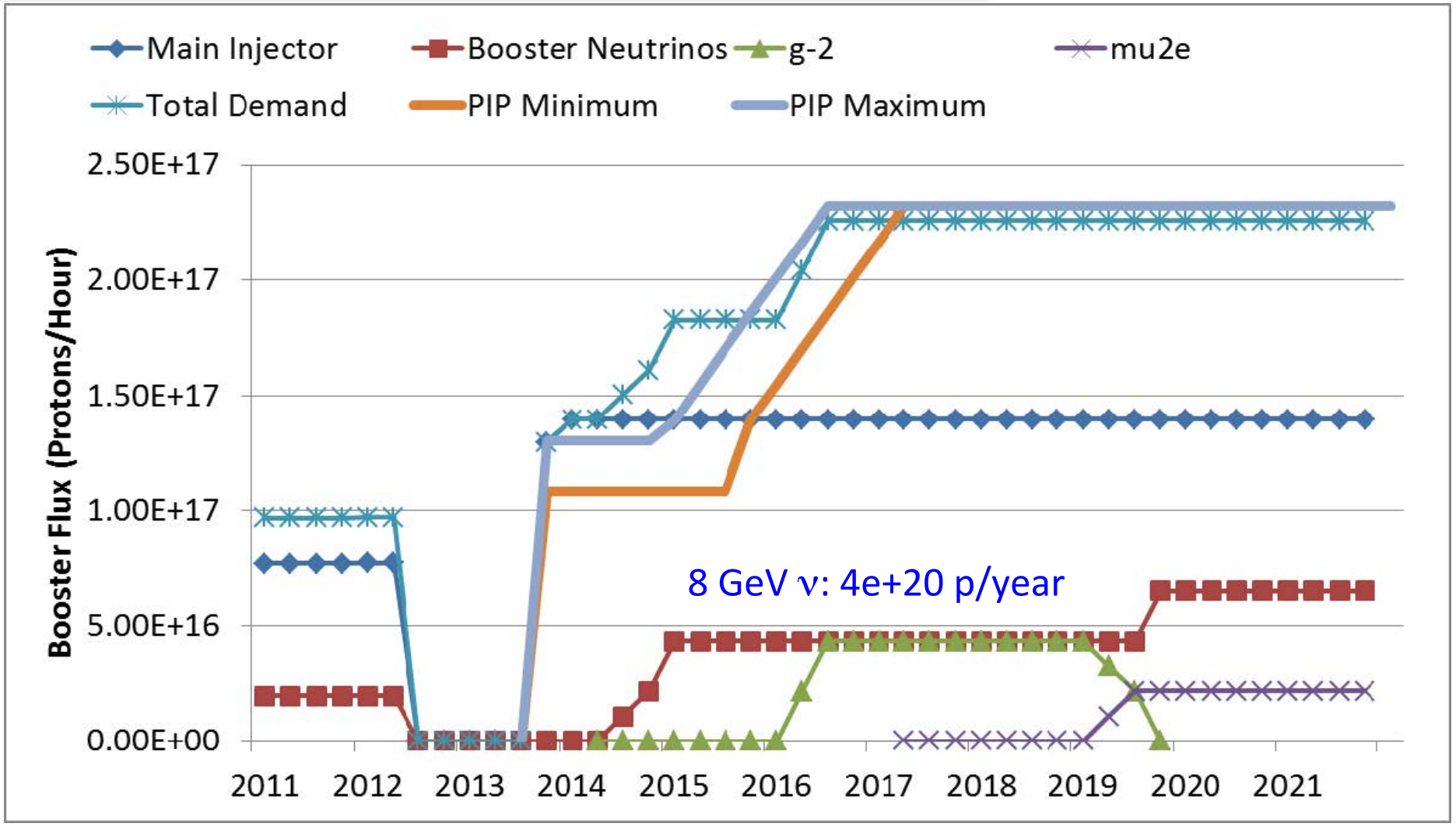
University of Hawii, Honolulu
J. Maricic, M. Rosen, Y. Sun

Stony Brook University
C. McGrew, C. Yanagisawa

University of Minnesota
J. Bian, M. Marshak

Proton Improvement Plan Projection



Paul Derwent, Fermilab S&T Review, Nov. 5-7, 2013

Power & Data Rates

Power needs:

30 kW cryogenics (480 V 3 phase)

2 kW electronics

available at MI-12.

Data volume:

Drift time = 625 μs

TPC: integration time: 1800 μs, sampling: 2 MHz, bits: 12, channels: 2001

total = 4.3 MB/trigger (0.7 compression)

PMT: integration time: 1800 μs, sampling: 200 MHz, bits: 12, channels: 24

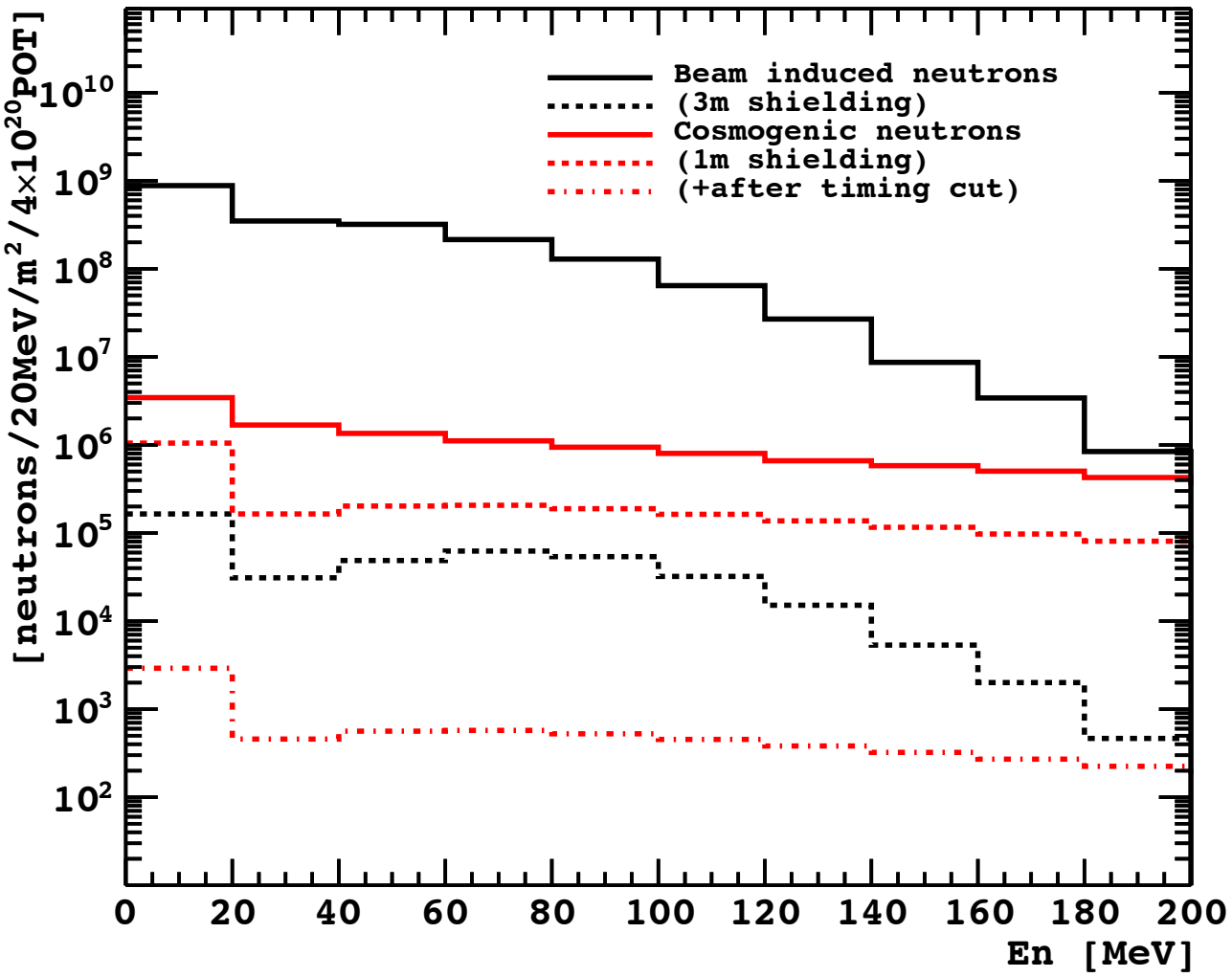
total = 3.9 MB/trigger (0.7 compression)

Event size = 8.2 MB/trigger, 0.82 MB/trigger after zero suppression

Data size = 33 TB for 2e20 POT (not including beam-off & calibrations)

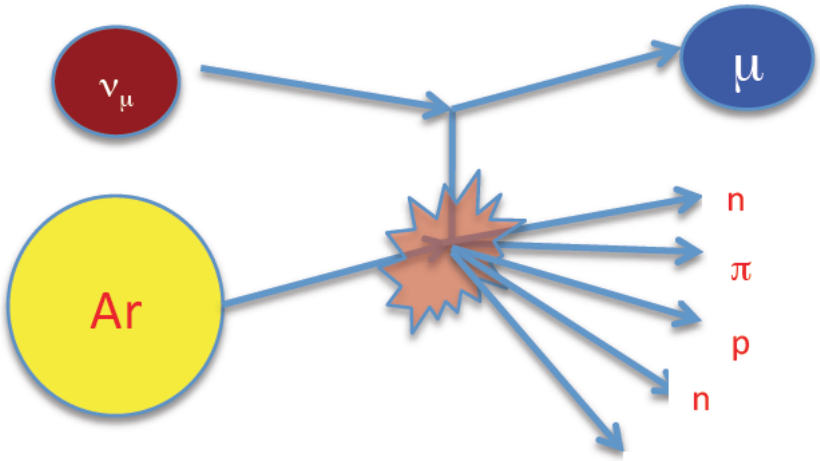
Neutron Rates & Shielding

Distance = 10 m from target

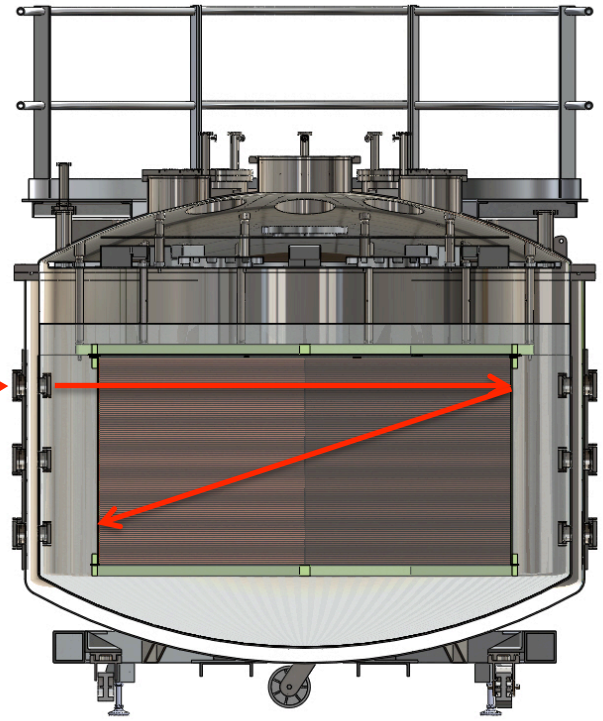


Neutron Runs @ WNR

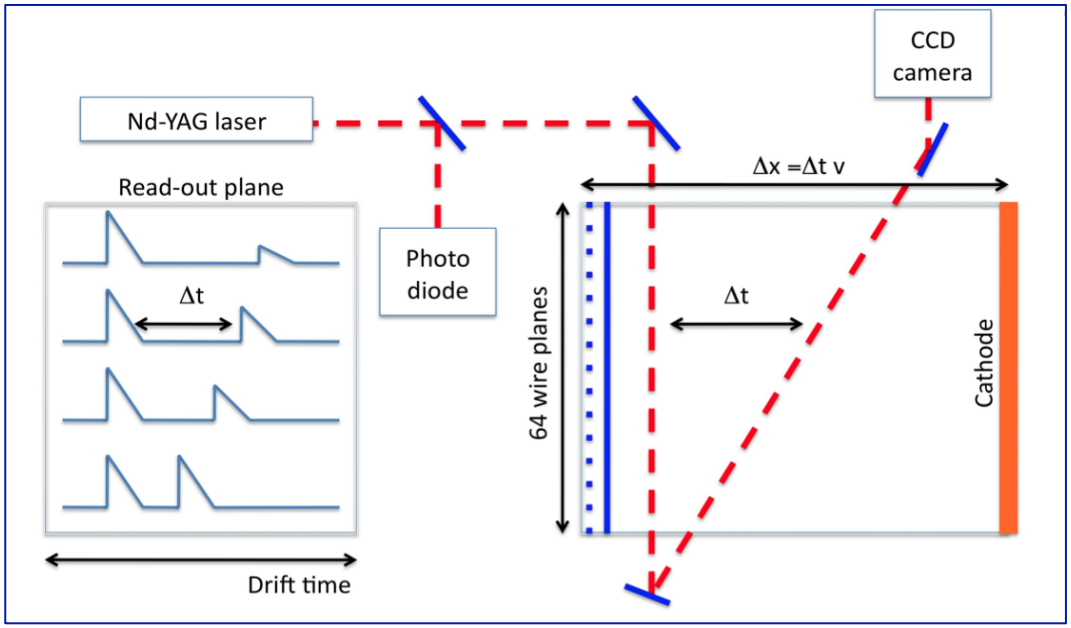
- Characterize neutron interactions to understand energy carried by neutrons in neutrino interactions with argon
- Measure response of LAr TPC to neutrons
  - multi-particle events in high-energy regime
  - characterize reconstruction efficiency of these events
- Measure "cosmogenic" production of radioactive isotopes
  - validate simulations of spallation
  - background for neutrino interactions
- Want neutron beam with cosmic-ray energy spectrum
- Ability to know neutron energy on an event-by-event basis



Laser Calibration System



Nd-YAG frequency quadrupled Quantel Brilliant-b laser: 4.66 eV
LAr ionization potential: 13.78 eV (3 photons)



4 optical ports:
- 2 @ 15cm from anode
- 2 @ 15 cm from cathode

Recombination in LAr: only a fraction of the ionization charge survives after t_{drift}:

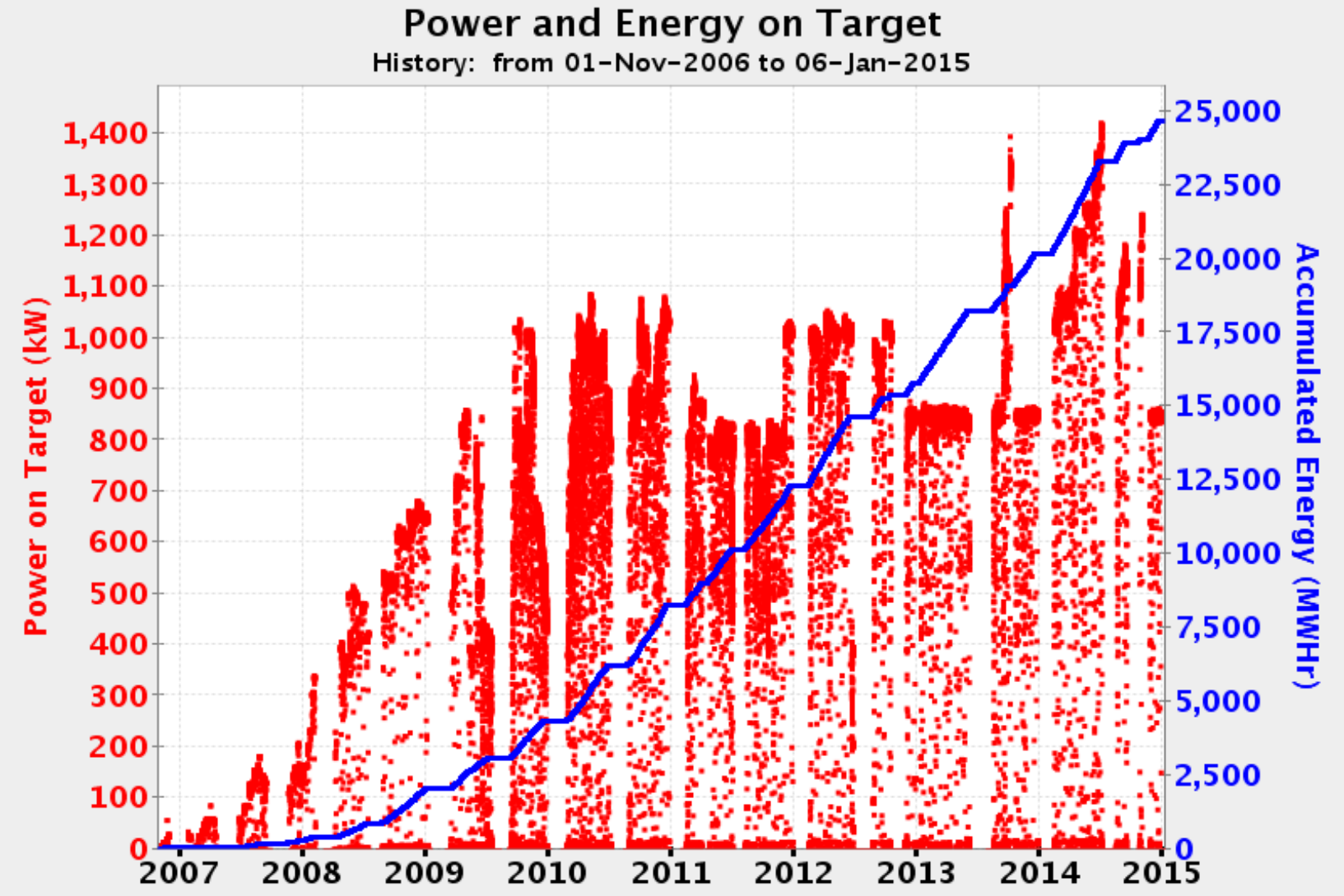
$$Q_{meas} = Q_{dep}\,\mathrm{Re}^{-t_{drift}/\tau}$$

SNS @ ORNL

1.3 GeV protons on Hg target (60 Hz, 695 ns) 1.4 MW:
Neutrino production: 2.8e+22 per year (each flavour)

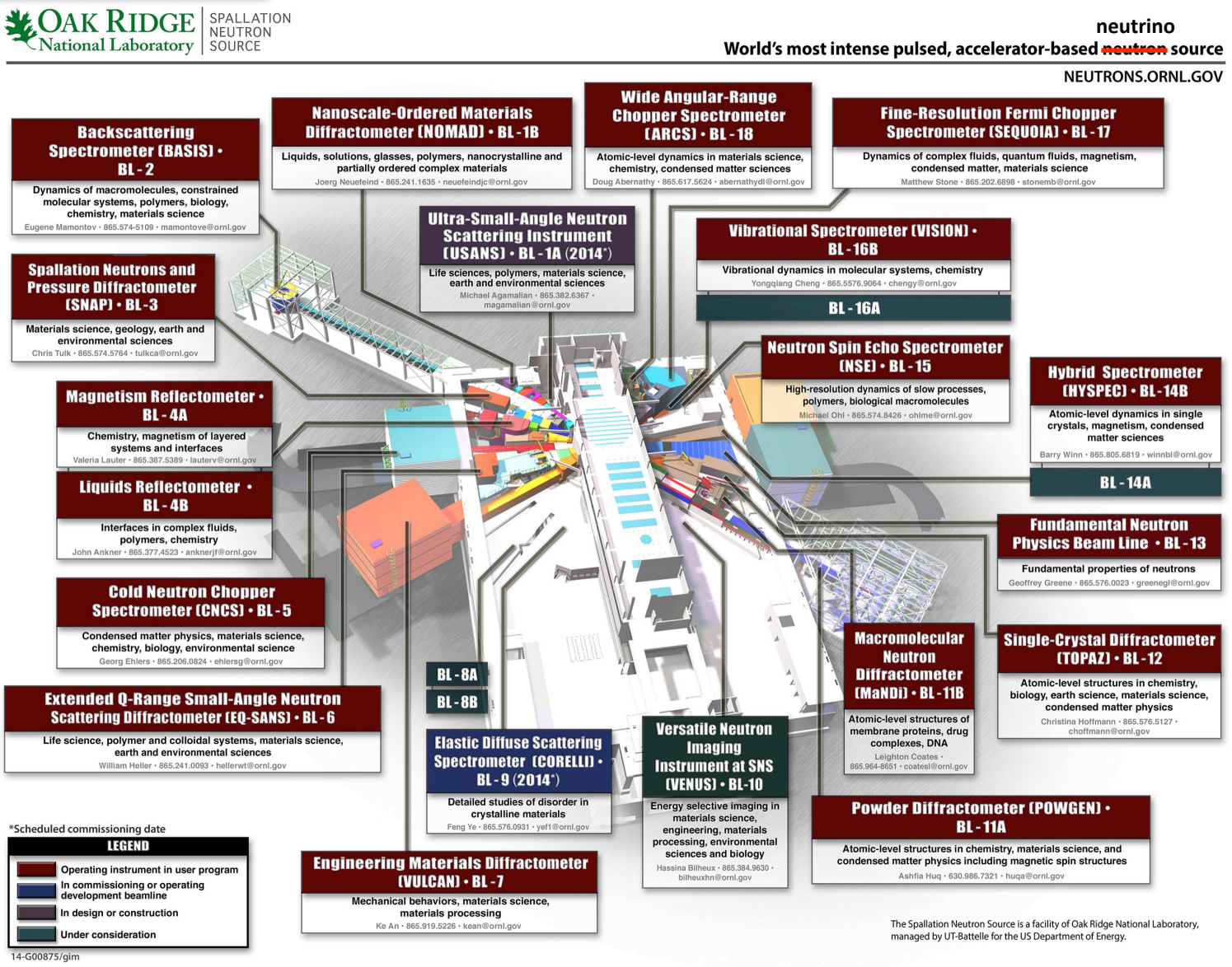
SNS @ ORNL

SNS has been running quite smoothly…



SNS @ ORNL

SNS experimental hall is a very busy place…



SNS @ ORNL

- Previous proposed neutrino experiments at SNS have failed!
- Variety of reasons; in general difficult to mount an HEP/NP experiment at a BES facility!

  NuSNS @ 20 m (XS): $\Phi = 3.5 \times 10^7\ \nu/cm^2/s/flavour$

  OscSNS @ 60 m (oscillations): $\Phi = 3.9 \times 10^6\ \nu/cm^2/s/flavour$

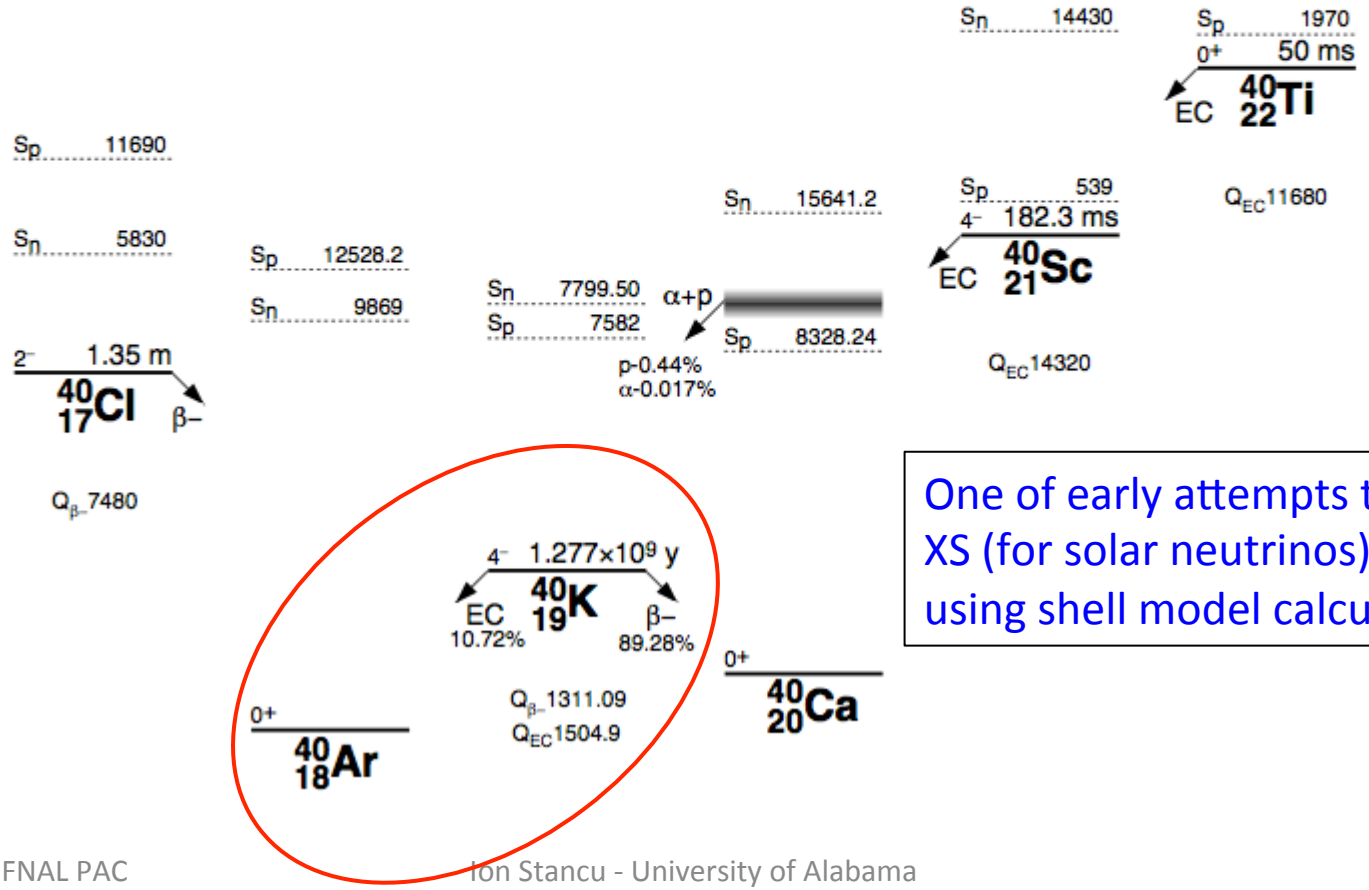
  CLEAR (coherent scattering) efforts on-going…

- Might not be ideal for measurements on a time scale which might affect the design of ELBNF in light of SN burst detection…
- Need alternative source(s) of DAR neutrinos…

Backup

$\nu_e + {}^{40}Ar \rightarrow {}^{40}K_{GS} + e^-$ has a low threshold, but rarely occurs due to $0^+ \rightarrow 4^-$ (3^{rd} forbidden) transition. Most all of the XS is into excited states of ^{40}K.

^{40}Ar is Z=18 (2 proton holes) and N=22 (2 neutron partial shell). Shell model calculations difficult and uncertain.

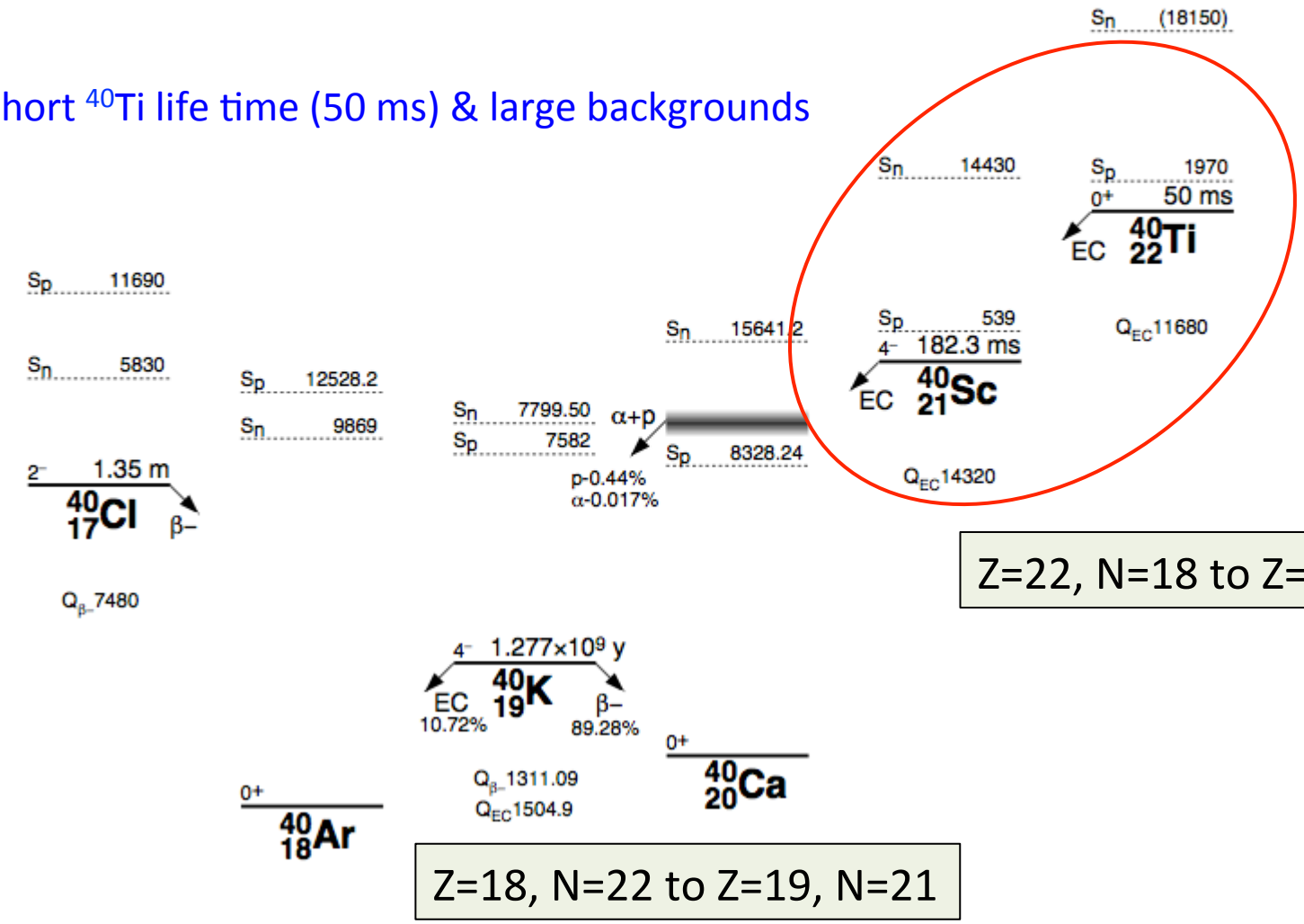


One of early attempts to calculate XS (for solar neutrinos): E.Ormand using shell model calculation.

Can One Measure the Strengths?

A=40
NP A521, 1(1990)

Short ^{40}Ti life time (50 ms) & large backgrounds

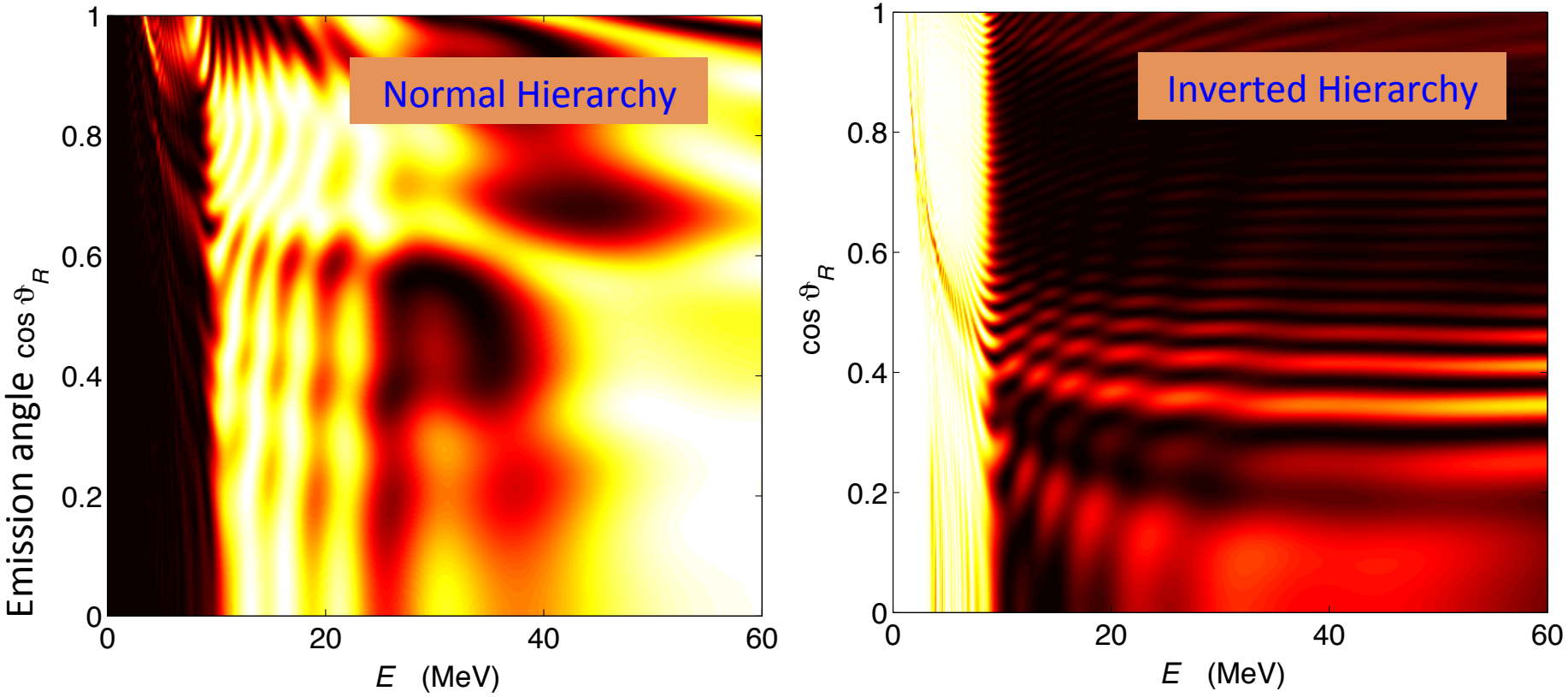


Z=22, N=18 to Z=21, N=19

Z=18, N=22 to Z=19, N=21

Backup

Neutrino survival probability



H. Duan, G. M. Fuller, and Y. Qian, Ann. Rev. Nucl. Part. Sci. 60 (2010) 569
arXiv:1001.2799 hep-ph

mCAPTAIN Drawings