SN-DETECTION IN LAR-TPC AND THE QUEST FOR (ν-AR) CROSS SECTIONS

Oct. 23, 2012
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SN-neutrinos often advocated:

- as probes for (still unknown) ν-properties (e.g. mass hierarchy dilemma)
- as (more appropriately, personal opinion) **astrophysical probes** (e.g. SN core-collapse mechanisms)

In other words from SN-ν detection at Earth,
there are chances to learn on neutrinos,
but the primary output remains SN astrophysics.

In any case,
neither topics can be adequately investigated
if **ν-Cross Section in the SN-ν energy range** is not sufficiently well established.

For LArTPC detectors, the most relevant reaction XSect (CC ABS. react. : ν-$^{40}Ar_{18}$) in the 10-100 MeV ν-energy range was never experimentally measured (so far).

Organization of the Talk

SN-ν flux at Earth:

* ν-emission from Type-II Core Collapse SN
* effects of ν-oscillation (in the large θ_{13} era)

[no attempt for an in-depth analysis: just basic outputs]

the role of Cross Section:

** ν-$^{40}Ar_{18}$ XSect in the 10-100 MeV ν-energy range (Theory)

** SN-ν event rate in LAr (e.g.MicroBooNE detector)

** SN-ν event signature in LAr (TPC).

Perspectives for direct measurements of

*** νSnS: ν at the Spallation n-Source -

*** direct XSect measurements with LArTPC's

Ref's:

(*) *Neutrinos as Astrophysical Probes*, F. Cavanna, ML Costantini, O.Palamara, F.Vissani, *Surveys in HEP 19 (2004), 35* & astro-ph/0311256

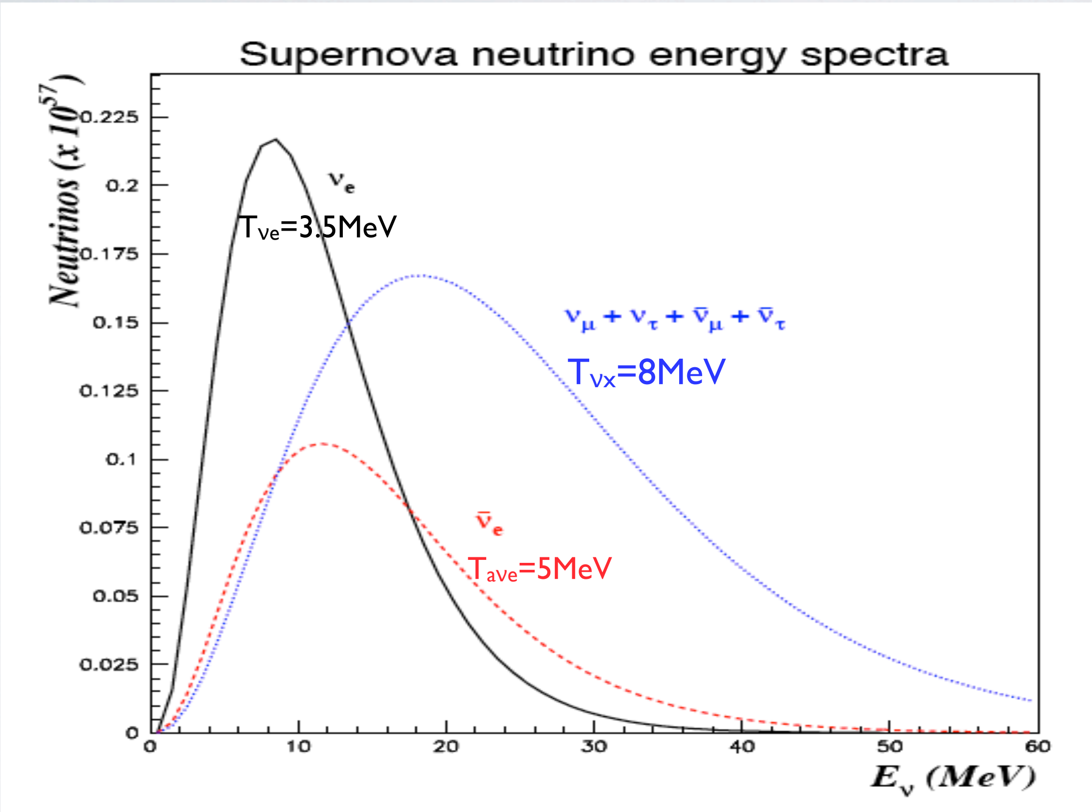
(*) *Oscillation effects on SN ν-rates and spectra and detection of the shock breakout in a LarTPC*, I. Gil-Botella, A. Rubbia, hep-ph/0307244

(**) *Neutrino–nucleus reactions and nuclear structure*, **E Kolbe, K Langanke, G Martınez-Pinedo and P Vogel**, J. Phys. G: Nucl. Part. Phys. **29** (2003) 2569

(**) *ν_e-^{40}Ar Absorption Cross Section for SN neutrino*, **M. Sajjad, AK Singh,** Phys. Lett. B591 (2004), 69.

(***) *Opportunities for Neutrino Physics at the Spallation Neutron Source: A White Paper* - K. Scholberg et al. (to be published)

SN ν-emission



<u>Energy Spectrum:</u>
black-body
of F-D type,
dependance on
Temperature and
"SN-Pinching Factor, η"

ν_e	$T = 3.5$ MeV	$\Rightarrow$	$< E >= 11$ MeV
$\bar{\nu}_e$	$T = 5.0$ MeV	$\Rightarrow$	$< E >= 16$ MeV
$\nu_{\mu,\tau}$	$T = 8.0$ MeV	$\Rightarrow$	$< E >= 25$ MeV
$\bar{\nu}_{\mu,\tau}$	$T = 8.0$ MeV	$\Rightarrow$	$< E >= 25$ MeV

$$\langle E_{\nu_e} \rangle = 10\text{–}12\,\text{MeV}, \quad \langle E_{\bar{\nu}_e} \rangle = 11\text{–}17\,\text{MeV}, \quad \langle E_{\nu_x} \rangle = 15\text{–}25\,\text{MeV}$$

Range of variation from models/parameters

EFFECTS OF OSCILLATIONS
(AFTER DISCOVERY OF THE LARGE θ_{13} VALUE)

- Flavor oscillation and matter enhanced conversion mechanism
  → $\boldsymbol{P_{ee}}$ (ν_e survival probability)

- *Recent big achievement*: exp. measurement of θ_{13} large value (8°).
  this determines: $\boldsymbol{P_{ee} = 0}$

- The (oscillated) ν_e spectra is affected:
  $\mathbf{F_{\nu e}} = P_{ee} \cdot F^0_{\nu e} + (1 - P_{ee}) \cdot F^0_{\nu x} \cong \mathbf{F^0_{\nu x}}$ i.e. ***total conversion*** $\nu_{\mu/\tau} \to \nu_e$

- ν_e En. spectra at the detector is harder (as $\nu_{\mu,\tau}$ emission spectra are harder): this is a great advantage for Ar based detectors (due to ~quadratic increase with E_ν of the main ν-Ar reaction Xsect)

SN-ν Cross Section on Ar

in the [10-100] MeV ν-energy range

1) *NC+CC* **E**lastic **S**cattering (on e⁻):

$$\nu + e \rightarrow \nu' + e'$$

- xsect linear increase with E_{ν}.
- e.g. @ E_{ν} =20 MeV ↔ $\sigma_{ES} = Z_{Ar} \times 2 \cdot 10^{-43}$ cm

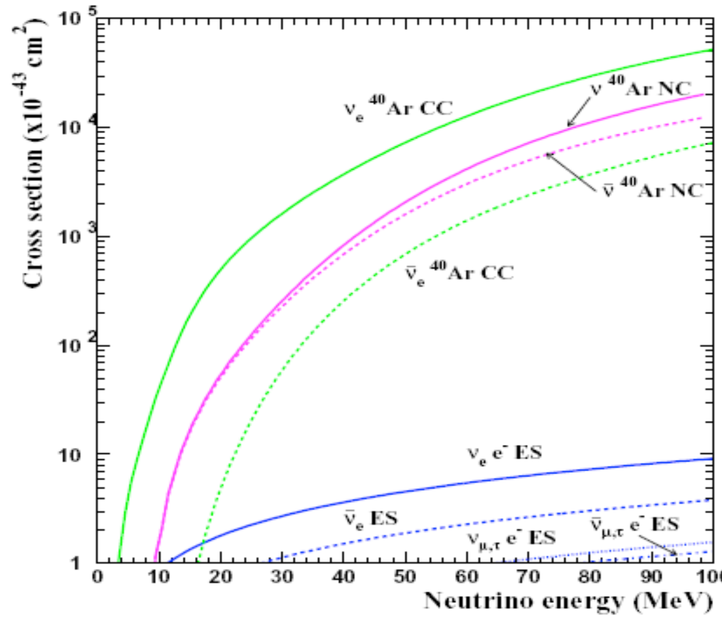


Figure 3: Neutrino cross sections relevant to the supernovae detection with a li
Argon TPC detector.

Kolbe, Langanke, Martinez-Pinedo

2)[a] *CC* ν_e **ABS**orption (on Ar):

$$\nu_e + Ar \rightarrow K^* + e^-$$

- xsect ~quadratic increase with E_{ν}.
- e.g @ E_{ν} =20 MeV ↔ $\sigma_{abs} = 6 \cdot 10^{-41}$ cm^2

2)[b] *CC* anti-ν_e **ABS**orption (on Ar): $(\bar{\nu}_e + Ar \rightarrow Cl^* + e^+)$

depressed by ***high Q-value*** wrt *CC* **ABS** for ν_e. *It will be not considered here.*

3) *NC* **N**uclear **E**xcitation (on Ar) $\nu + Ar \rightarrow \nu' + Ar^*$

difficult for detection (but maybe not impossible). *It will be not considered here.*

SN-ν ABS Cross Section on Ar

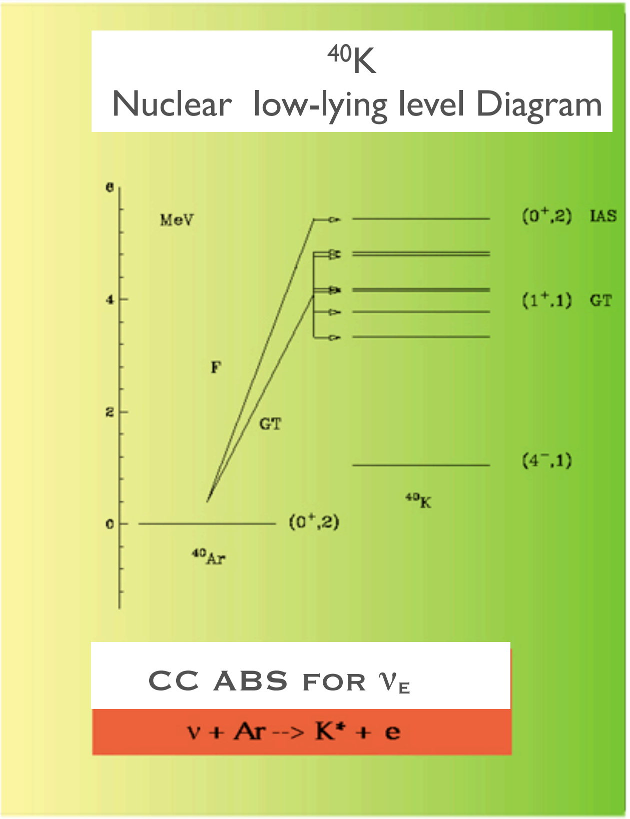
in the [10-100] MeV ν-energy range

THEORETICAL CALCULATIONS

Suzuki-san Talk (this session)

$$\nu_e + Ar \rightarrow K^* + e^-$$

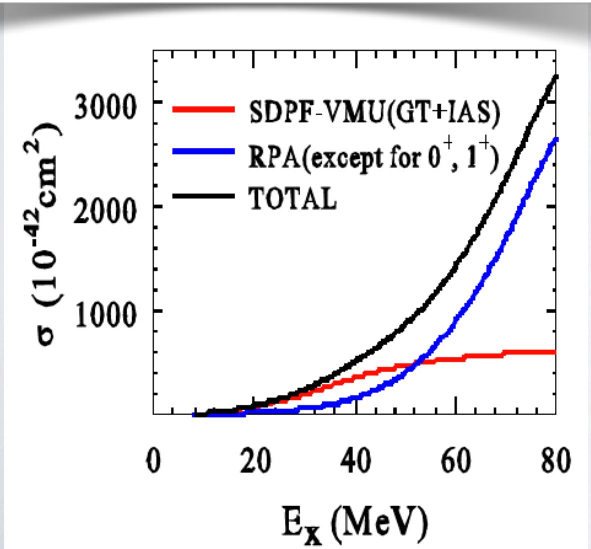
- *first proposed in 1986* [Ragahvan] and [Bahcall et al.]:
  Shell-Model calculations(Super-allowed) F Transition
- Shell-Model calculations [Ormand et al.] GT Transitions added (1996)
- Shell-Model calculations [M. Bhattacharya et al.] more GT transitions (1998)
- Random Phase Approximation (RPA) [Langanke et al.] forbidden transitions (up to J=6) (2003)
- Local Density Approximation (LDA) [Singh et al.] (2004)
- Hybrid Model: Shell-Model (F+GT) + Random Phase Approx. [T. Suzuki] (2011)

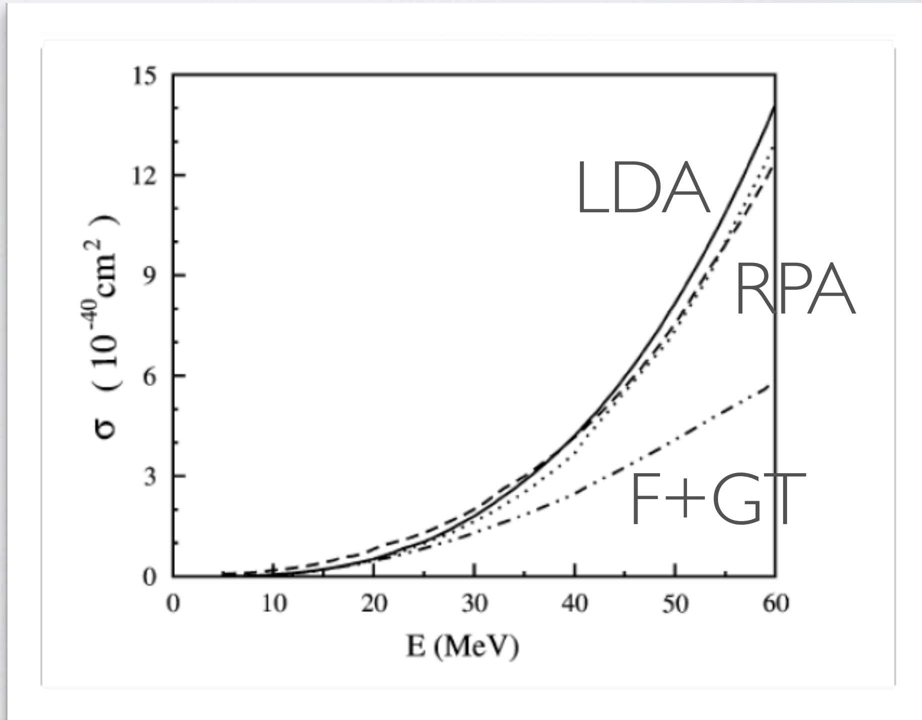


Allowed transitions ($\Delta J = 0, \pm 1$ $\pi_f = \pi_i$) dominate up to Eν~15 MeV(shell model calculations)

F : Fermi (SuperAllowed)
GT: Gamow-Teller (Allowed)

Forbidden transitions become relevant at higher energies -the SN en. range - (RPA calculations to describe the collective excitation of the nucleus, ^{40}K levels $J \leq 6$)





EVENT RATE IN AR

(e.g. with the MicroBooNE Detector)

- Event Rates are simply calculated as:

  Fluence (N_ν/cm^2 **at distance D,** including oscillations) ⊗ **N. of T**argets ⊗ **Cross Sect.**

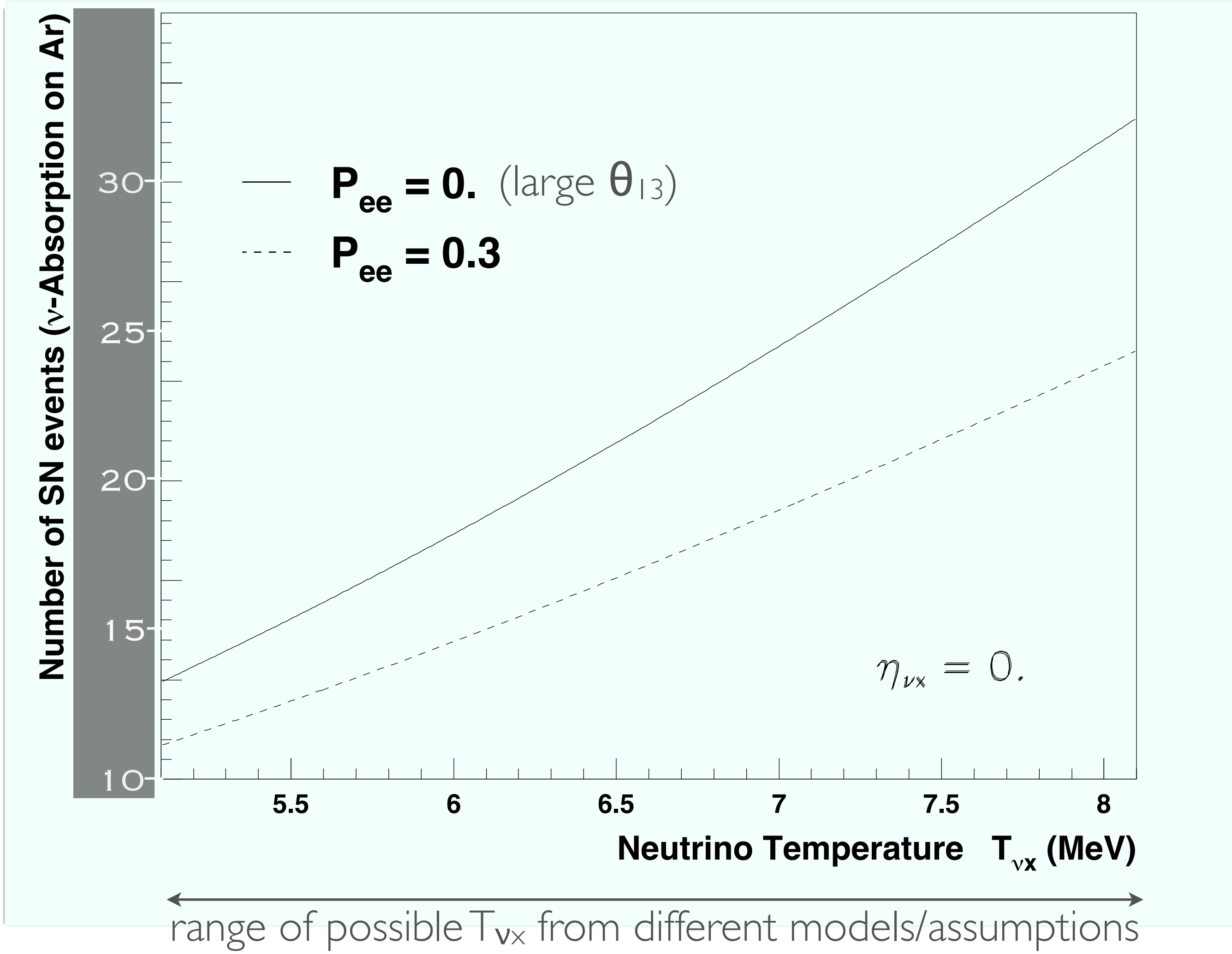
  with: $F_{\nu e}=F_{\nu x}$ (P_{ee}=0 from $\theta_{13}=8^0$, D=10 kpc), $N_T=1.5\times10^{30}$ *[MicroBooNE]*, σ_{ABS} *[Langanke et al.]*

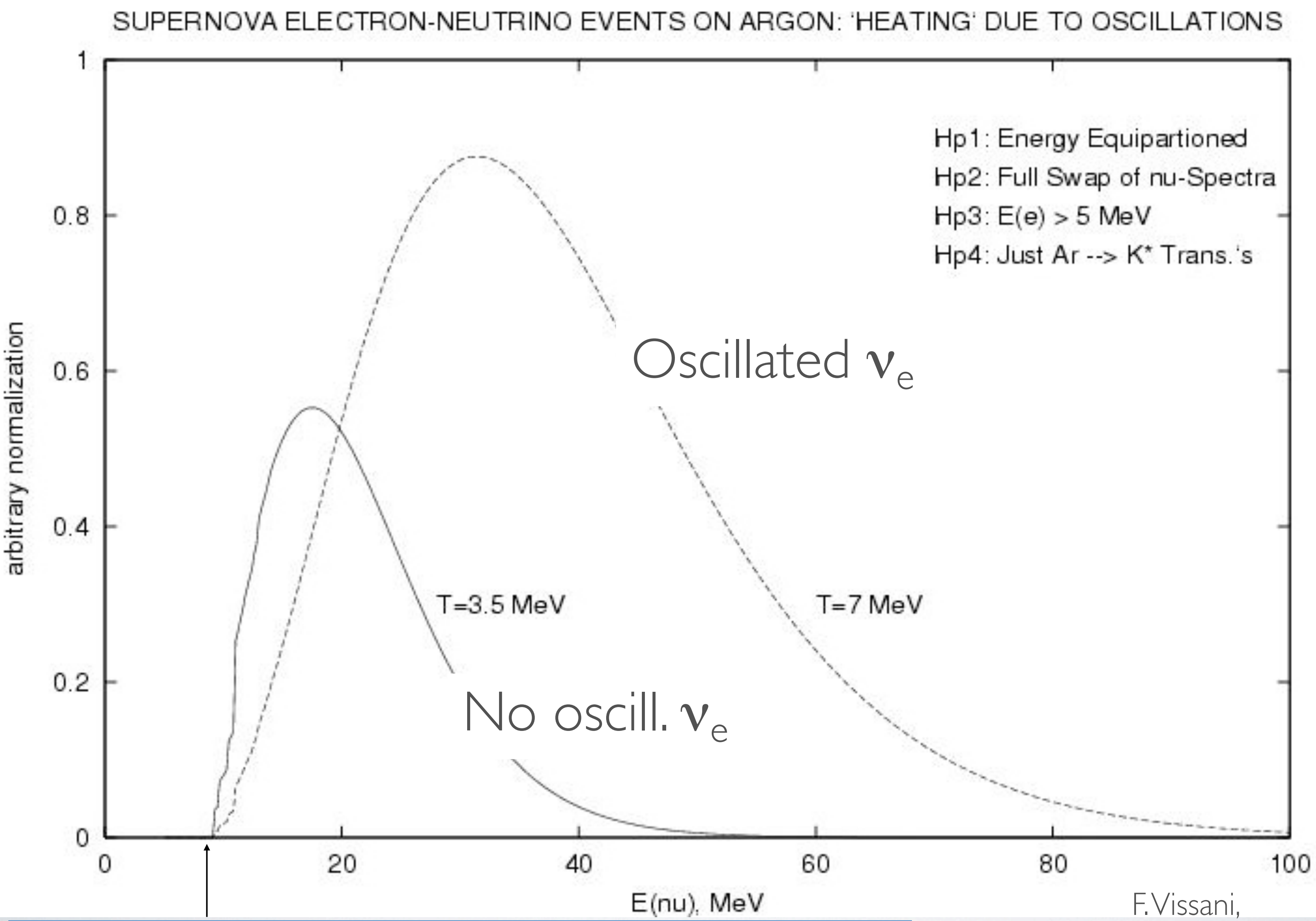
- Other Inputs (reference SN parameters):

  $\varepsilon_B=3\times10^{53}$ erg, flux equipartition, Pinching Factor η=0, ν-Temperature $T_{\nu x}$ in [5.1÷ 8] MeV.

GALACTIC SN: EVENT RATE IN MICROBOONE

Commissioning: early 2014 (FNAL)

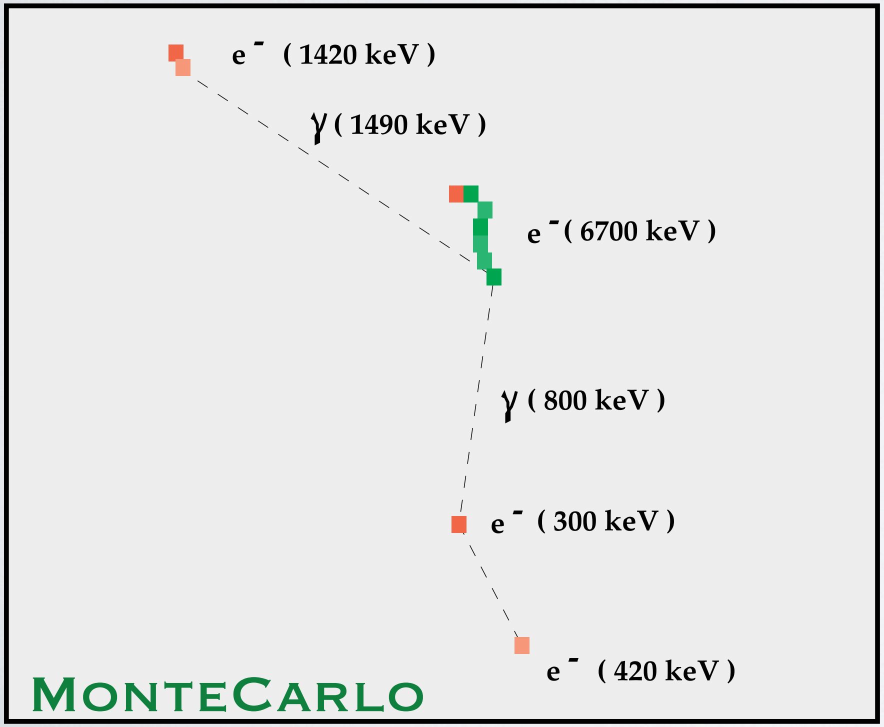




SPECTRA INCLUDE E_e^{THR} = 5 MEV AND ABS Q VALUE

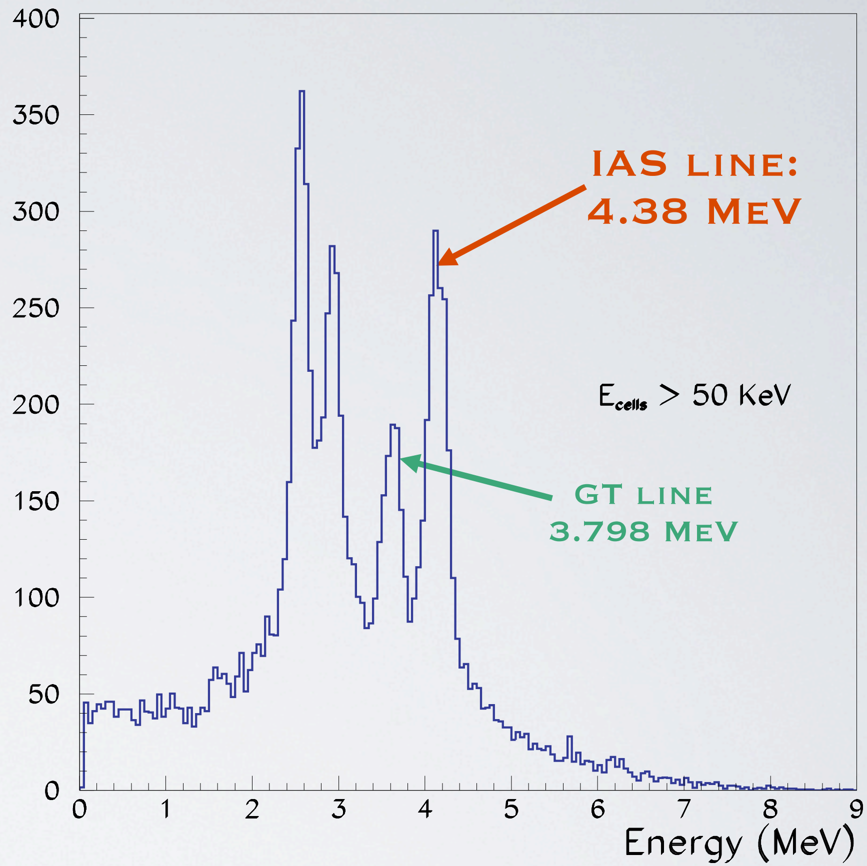
F. Vissani,
F. Cavanna, O. Palamara (2001)

The SN-ν Event Signature in LArTPC



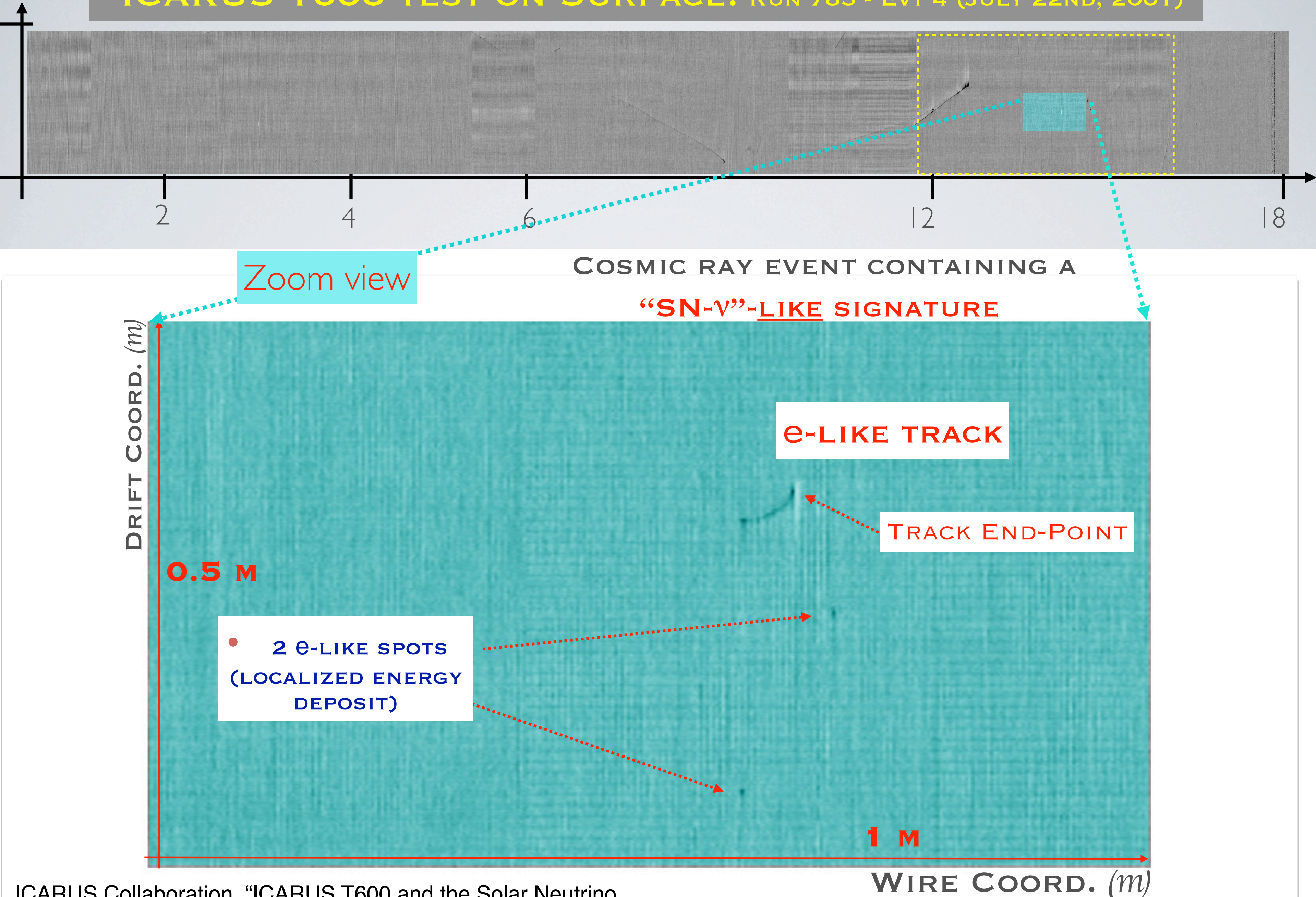
MONTECARLO SIMULATION

^{40}K DE-EXCITATION PHOTON SPECTRUM



AN ACCURATE CALIBRATION OF THE DETECTOR ENERGY RESPONSE IS FUNDAMENTAL

ICARUS T600 test on Surface: Run 785 - Evt 4 (July 22nd, 2001)



ICARUS Collaboration, "ICARUS T600 and the Solar Neutrino experiment." Proc. NOVE workshop - pp. 91-104 (2001).

Converting an observed neutrino flux into a luminosity requires knowledge of the neutrino-nucleus cross sections for the detector material.

For any nearby supernova, astronomical observations will yield distances measured to 10% or better.

This same level of accuracy for the neutrino-nucleus cross sections is required **to prevent the neutrino-nucleus uncertainty dominating the uncertainty in the supernova's luminosity.**

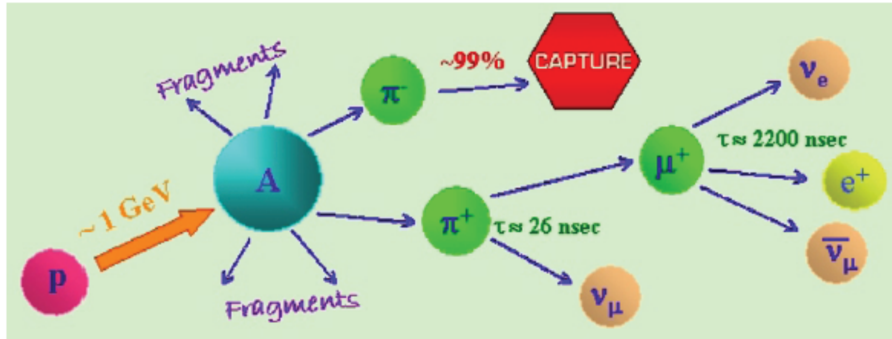
(Liquid) Argon detector is the preferred Technology Choice for the large-mass future ν Experiments

the most relevant XSect's for LArTPC detectors, [CC react. : $^{40}Ar(\nu_e,e^-)^{40}K^*$ - in the 10-100 MeV ν-energy] range, **has never been experimentally measured !!**

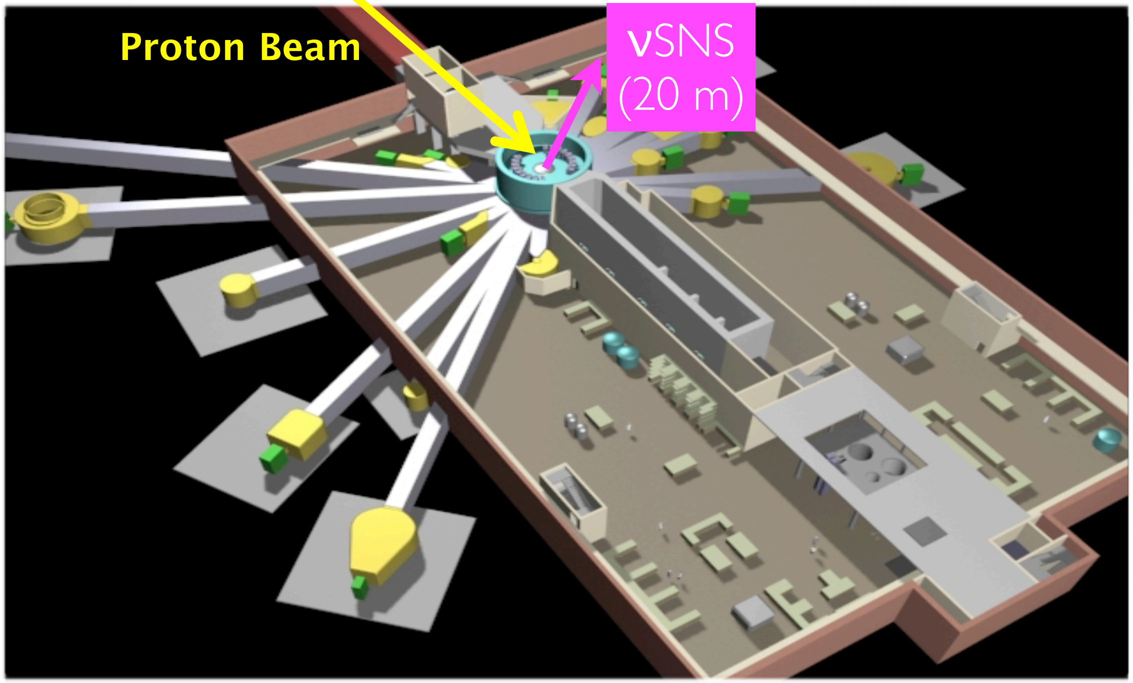
... any chance to do it?? ⇨

Oak Ridge National Laboratory
Neutron Sciences
Spallation Neutron Source • High Flux Isotope Reactor

➲ NuSNS: Neutrino at the SNS



$\pi^+/p \simeq 0.13$ ⇨ π^+ DAR into ν's



Proton beam energy – 1.0 →- 1.4 GeV

Intensity - 9.6 · 10^{15} protons/sec

Pulse duration - 380ns(FWHM)

Repetition rate - 60Hz

Total power – 1.0 → 3 MW

Liquid Mercury target

Secondary π: $\langle P_\pi \rangle$ = 200 MeV/c

$\langle$range$\rangle$ = 5 cm

Number of each flavor of neutrinos produced at SNS:

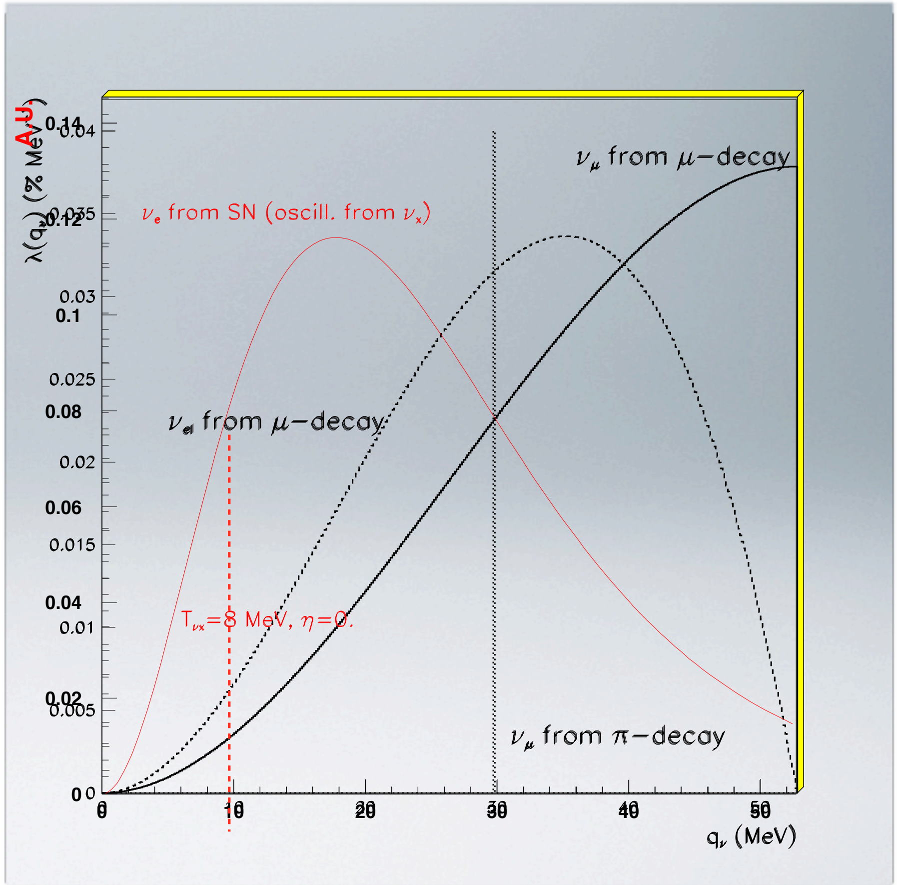
2×10^{22} year^{-1} (1 yr = 200 d)

⇨ Neutrino Flux: ≃ 2.6×10^{7}/s/cm^{2} @ 20 m

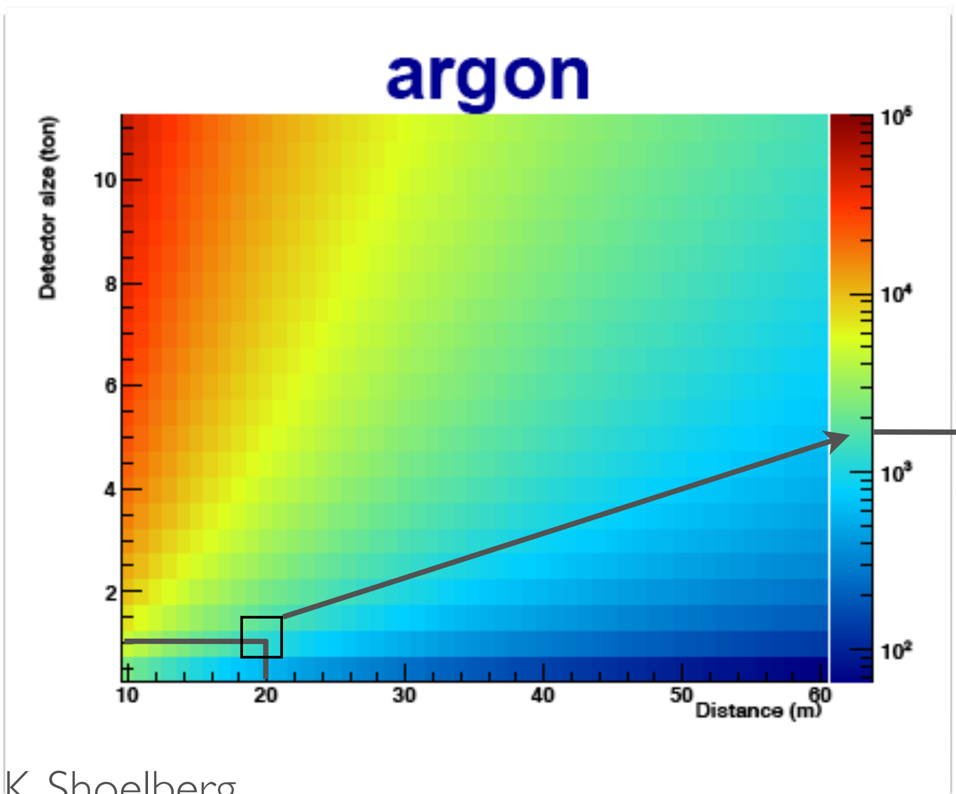
ν_e spectra from μ^+ DAR and
ν_e spectra from SN (ν_x oscill.)
beautifully overlap

ν-SNS:

Ideal ν-source for XSect measurements, of interest for LAr(TPC) experiments



EXPECTED RATES FOR LAR DETECTORS



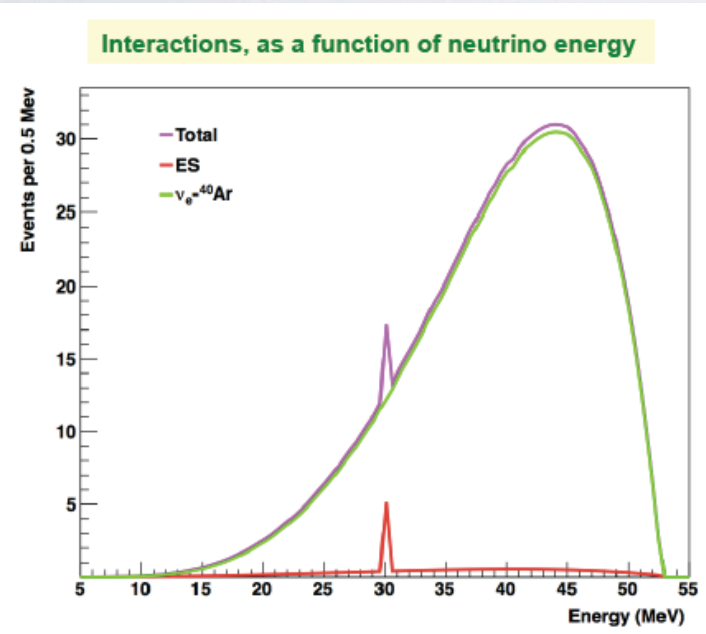
- With the nominal νSNS Fluence $F_{\nu e} \simeq 5 \times 10^{14}\ \nu/cm^2$ at D=20m,
  Fluence ⊗ **N. of** **T**argets ⊗ **XSect =**

→ $N_{evt} \cong$ **1800** per ton of LAr per yr

- A **1×1×2** m^3 (~3t) LArTPC looks adequate, considering that for LArTPCs ε_{Det} close to **1** and $V_{Fid} \approx V_{Act}$.

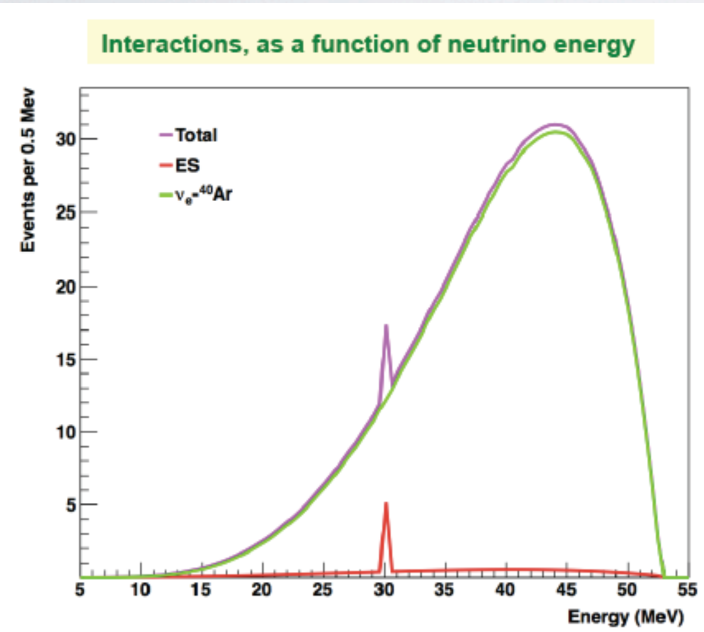
ArgoNeuT Detector

- n background assumed to be small.
- C.R. background and trigger to be understood/evaluated (*)
  (LArTPC is "slow" - e.g. 600 μs for 1 m drift).
- ***in ArgoNeuT***
  (!! an existing detector): ***350 evt/yr***



Recoil spectra of electrons produced by ABS reaction of ν from μ^+ DAR

- n background assumed to be small.
- C.R. background and trigger to be understood/evaluated (*) (LArTPC is "slow" - e.g. 600 μs for 1 m drift).
- ***in ArgoNeuT (!! an existing detector)*: *350 evt/yr***



Recoil spectra of electrons produced by ABS reaction of ν from μ^+ DAR

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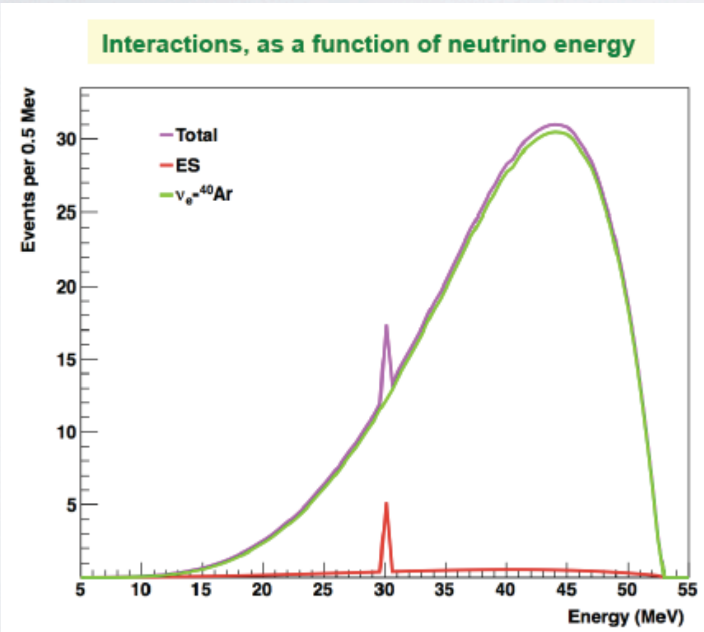
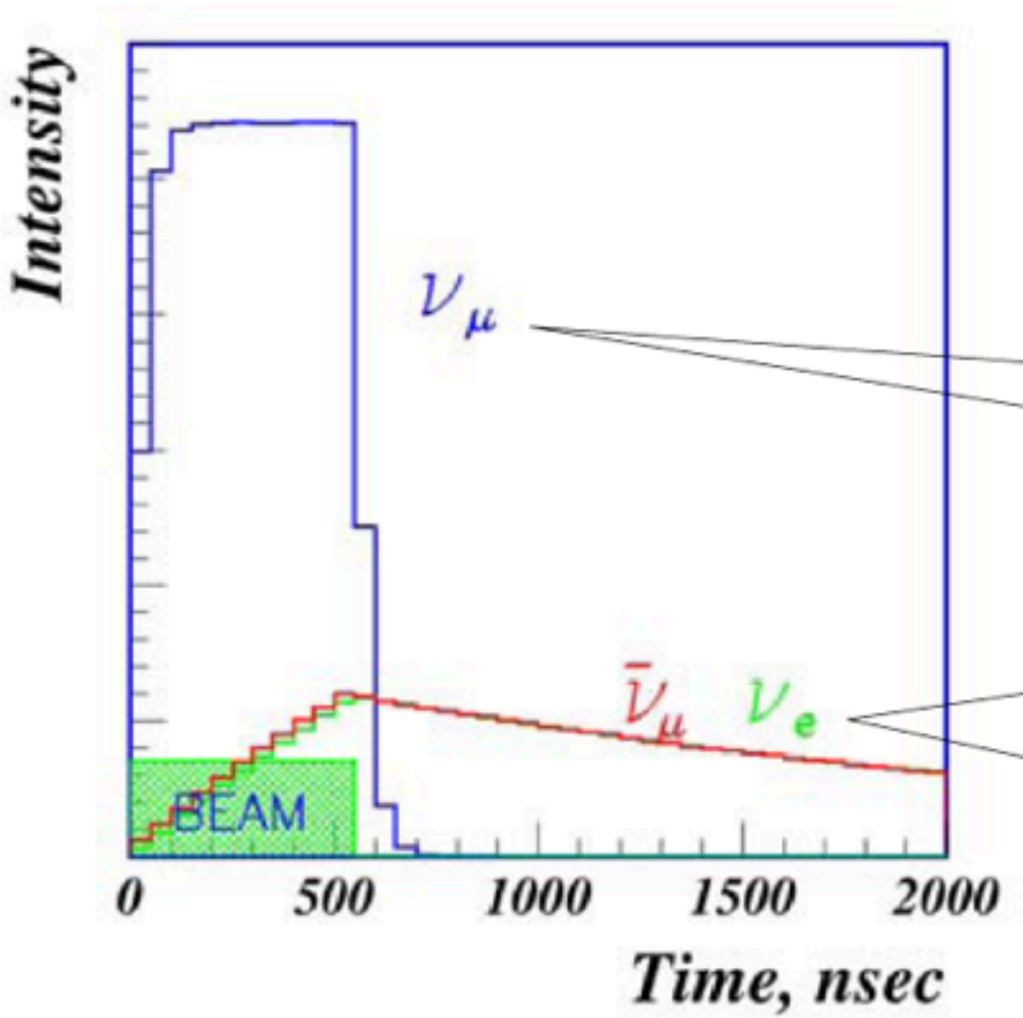


Recoil spectra of electrons produced by ABS reaction of ν from μ^+ DAR

(*) Time structure of the source



60 Hz *pulsed* source

in time with beam

delayed on μ decay timescale (2.2 μs)

Background rejection factor ~few x 10^{-4}

CONCLUSION

Let's do this measurement ...

.... before it happens again !

Talk based on:

Opportunities for Neutrino Physics at the Spallation Neutron Source: A White Paper

paper in preparation (K, Scholberg et al.)

Abstract

The Spallation Neutron Source (SNS) at Oak Ridge National Laboratory, Tennessee, provides an intense flux of neutrinos in the few tens-of-MeV range, with a sharply-pulsed timing structure that is beneficial for background rejection.

In this document, the product of a workshop at the SNS in May 2012, we describe this free, high-quality stopped-pion neutrino source and outline various physics that could be done using it.

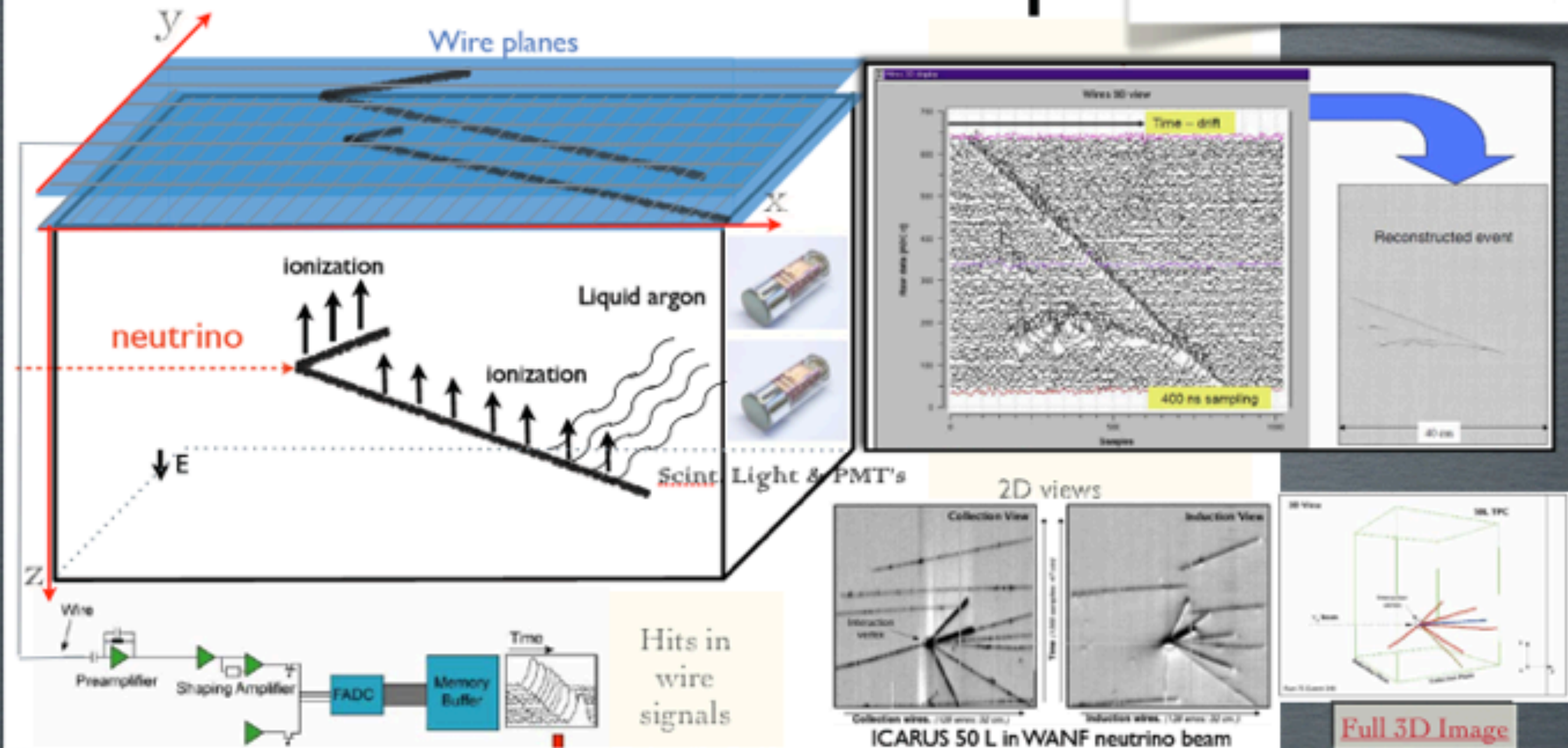
We describe without prioritization some specific experimental configurations that could address these physics topics.

- **supernova-related studies**
- **coherent NC scattering**
- **neutrino oscillation** (session this afternoon)

BACKUP SLIDES

The LArTPC concept

FOR ν PHYSICS



(Neutrino) interactions inside the LAr-TPC produce charged particles ⇒ Ionization Charge & *VUV Scintillation Light*

- Prompt Scintillation Light is detected (after VUV-Vis w.l. down-conversion) by array of PMTs.
    * Scintillation light collected by PMTs is used for Triggering.
- Free Ionization electrons tracks in EF drift towards anode planes of wires (signal read-out by low-noise charge amplifiers and fast ADCs).
    * Track segments induce hits on corresponding wires: the wire coordinate in the wire plane provide hit position.
    * Multiple (≥ 2) non-destructive wire-planes can be utilized ➡ (x,y) coordinates.
    * Timing of pulse (T_0 of event from prompt Scint.Light in PMTs ⊕ drift velocity v_d in LAr) determines the hit drift coordinate ➡ (z)

        ⇒ Multiple 2D views (x,z), (y,z) ⇒ Full 3D Image reconstruction.

    * Collection of the ionization charge on wires of the last plane (hit amplitude) measures the deposited energy

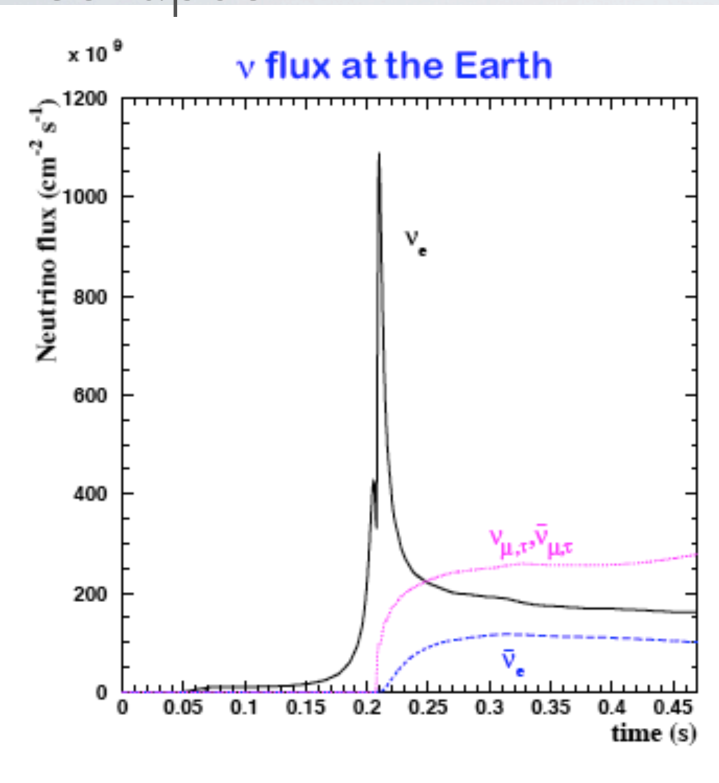
        ➡ Calorimetric Information and Ptcl.Identification

Cooling

shock breakout

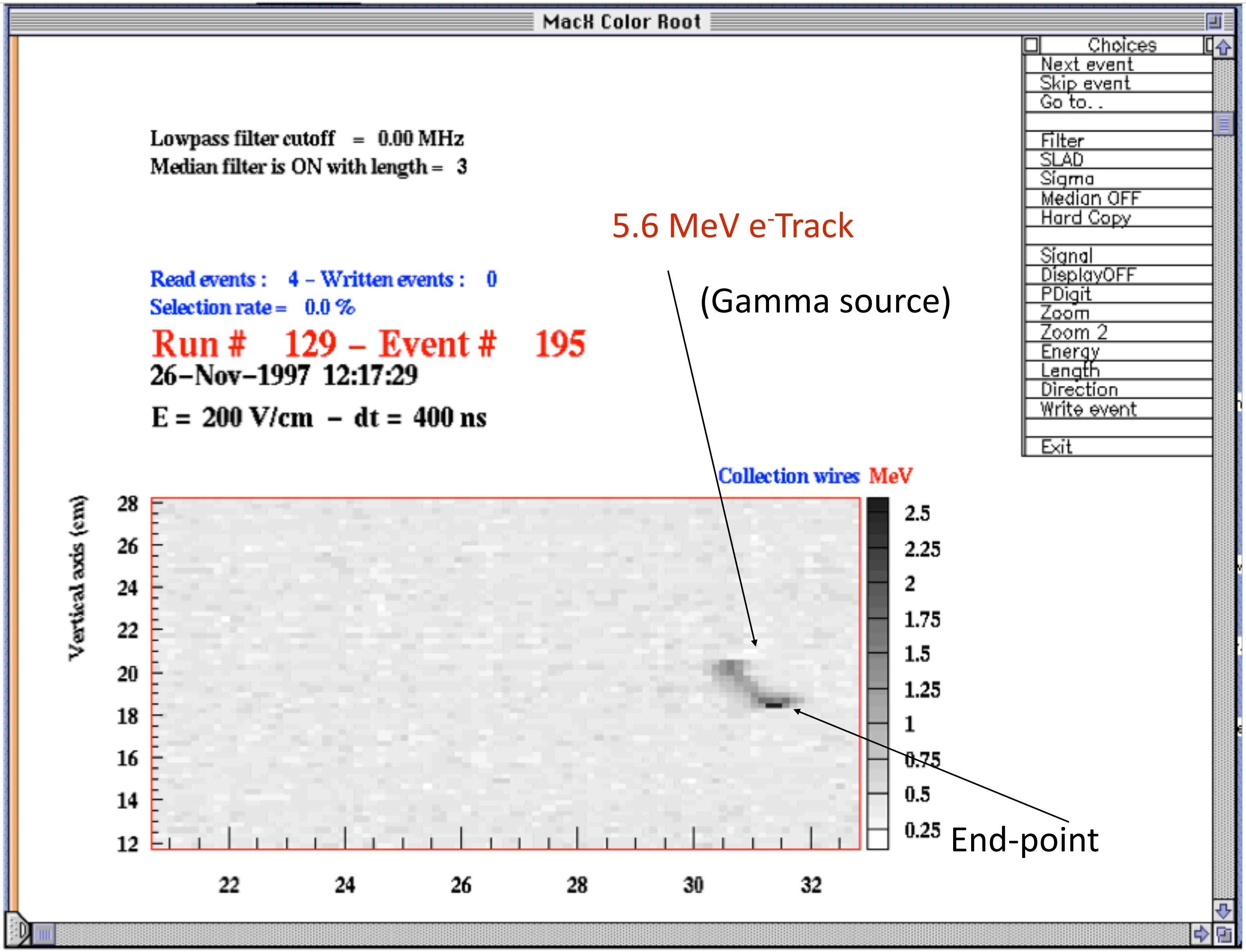
collapse

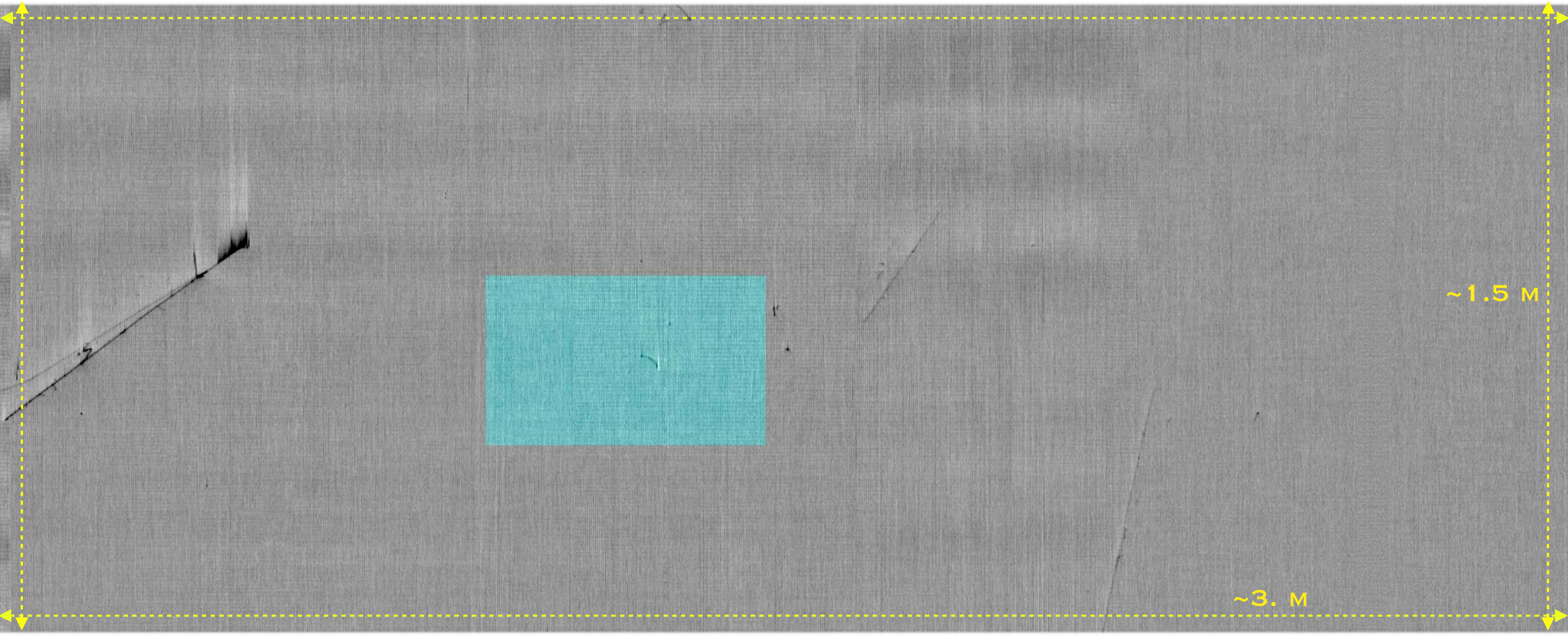
TIME SPECTRA:



Collapse Phase	Dynamics	ν Process	Duration	Energetics
"Infall" (early neutronization) of inner core $\sim 0.6 M_\odot$	Iron Core Collapse $\gamma + Fe \to 13\,^4He + 4n$ $^4He \to 2n + 2p$	ν_e-emission $e^- + p \to n + \nu_e$ ν_e-trapping $\nu_e + A \to \nu_e + A$ $\nu_e + n \to p + e^-$	~ 100 ms $\Delta t_{inf} \lesssim 25$ ms	$\delta_{inf} \leq 1\%\ \mathcal{E}_B$
"Flash" (prompt neutronization) of (part of) outer core $\sim 0.4 M_\odot$	Bounce. Wave shock $\gamma + Fe \to 13\,^4He + 4n$	ν_e-burst $e^- + p \to n + \nu_e$ at ν_e-sphere	$[t \equiv t_0]$ $\Delta t_{fl} \lesssim 10$ ms	$\delta_{fl} \sim 1\%\ \mathcal{E}_B$
"Accretion" Mantle neutronization $\sim 0.5 M_\odot$ Delayed shock revival	Stall of wave shock $\gamma \to e^+ e^-$ Proto n-star formation SN explosion	$\bar{\nu}_e$-emission $e^+ + n \to p + \bar{\nu}_e$ ν_l-emission $e^+ e^- \to \nu_l \bar{\nu}_l$ ν-heating $\nu_e + n \rightleftharpoons p + e^-$ $\bar{\nu}_e + p \rightleftharpoons n + e^+$	$\Delta t_{accr} \lesssim 500$ ms	$\delta_{accr} \approx 10\ \%\ \mathcal{E}_B$
"Cooling" residual neutronization	Mantle contraction $\gamma \to e^+ e^-$	ν_l-emission $e^+ e^- \to \nu_l \bar{\nu}_l$ at ν_l-sphere	$\Delta t_{cool} \approx 10$ s	$\delta_{cool} \approx 90\ \%\ \mathcal{E}_B$
n-star $M_{ns} \sim 1.4 M_\odot$ $R_{ns} \simeq 18$ km $\rho \simeq 3 \times 10^{14}$ g/cm^3	Steady state	ν-'fading' $n\ n \to n\ p\ e^- \bar{\nu}_e$ $n\ p\ e^- \to n\ n\ \nu_e$		few % $\mathcal{E}_B$

Real Event recorded with 50lt ICARUS Prototype





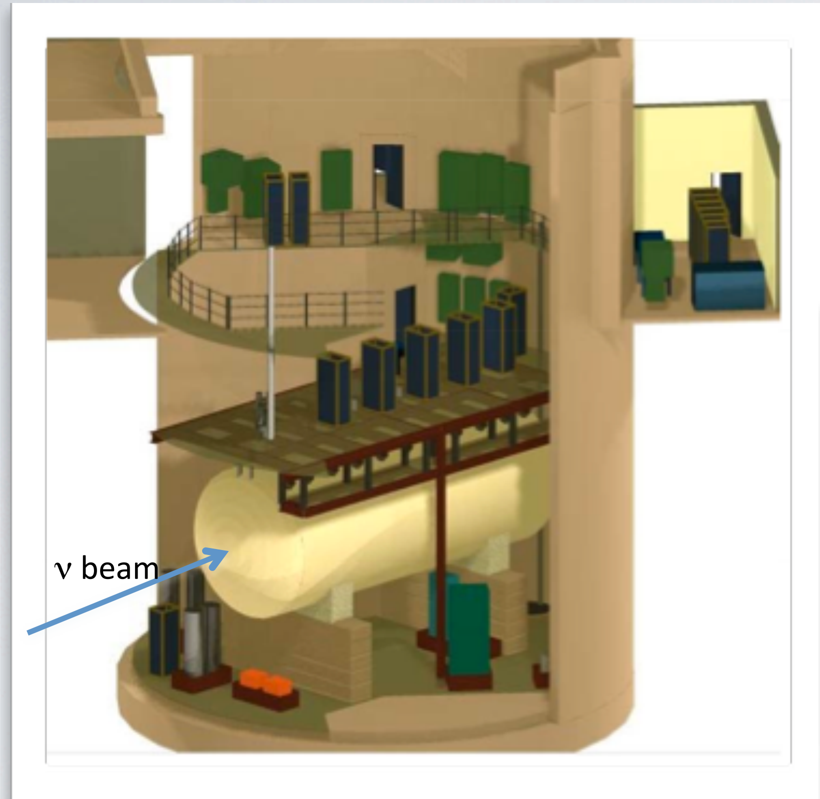
ICARUS T600 test on Surface: Run 785 - Evt 4 (July 22nd, 2001)

During the drift-time (1 ms) needed for LArTPC event recording, several (about 10 on avg.) crossing muons (c.r.) are also recorded.

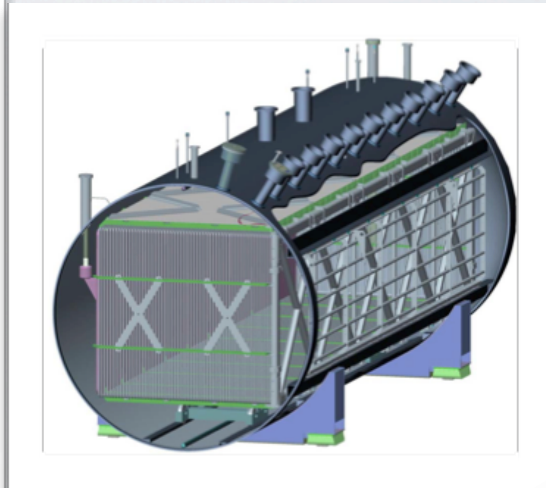
In the portion of the TPC shown here, few (3-4) X-ing tracks are visible, as projected on a 2D view (in real 3D view, these are much more apart).

The chance of overlap with the "signal event" is extremely low: even in these cases signal can be extracted by topological cuts (thanks to the very high granularity of the LArTPC).

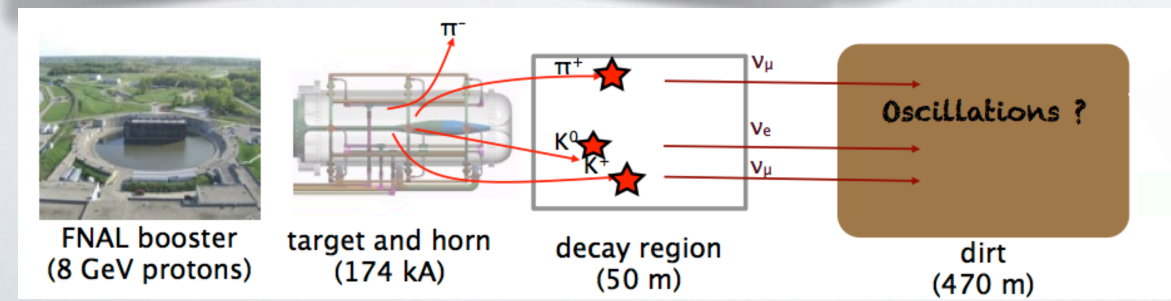
MicroBooNE: a new LArTPC at FNAL (under construction)

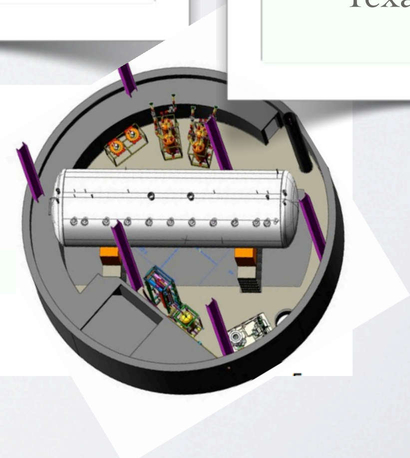


- 170 tons total liquid argon
- 86 tons active volume (60t fiducial)
- TPC dimensions: 2.5m x 2.3m x 10.4m
- 30 PMTs



Collaboration:
Bern, BNL, Columbia, FNAL, KSU, LosAlamos, MIT, MSU, Princeton, StMarys, Syracuse, Cincinnati, Texas, Yale*





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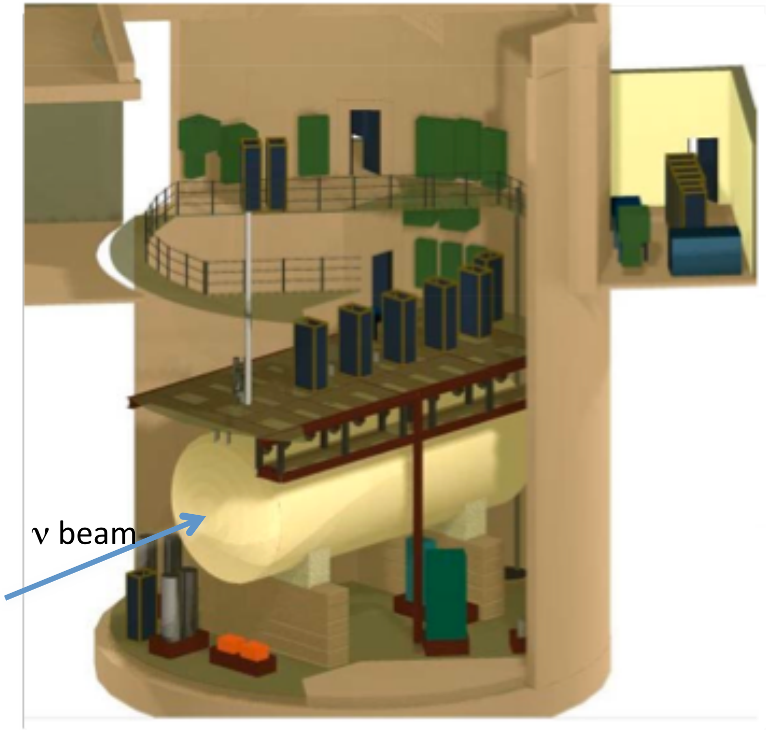

microboone

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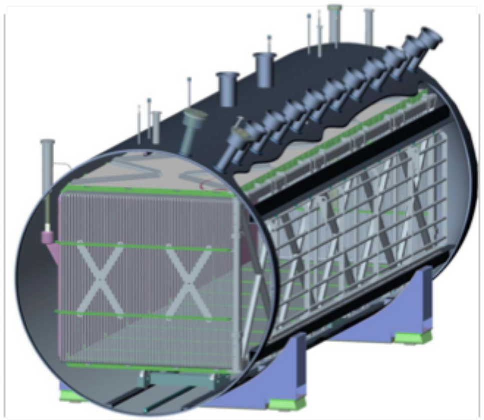

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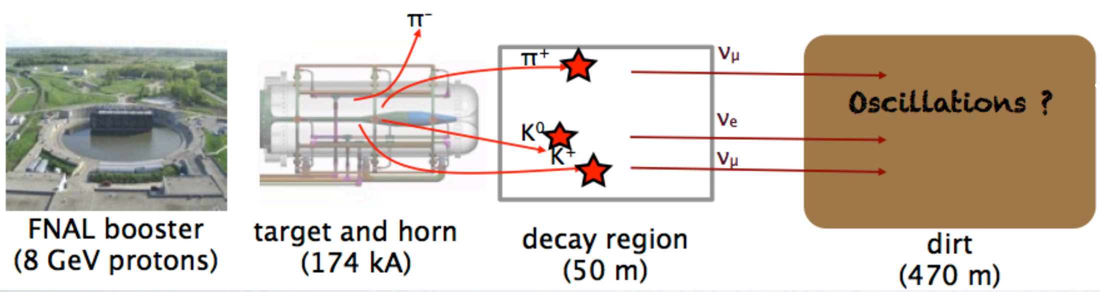

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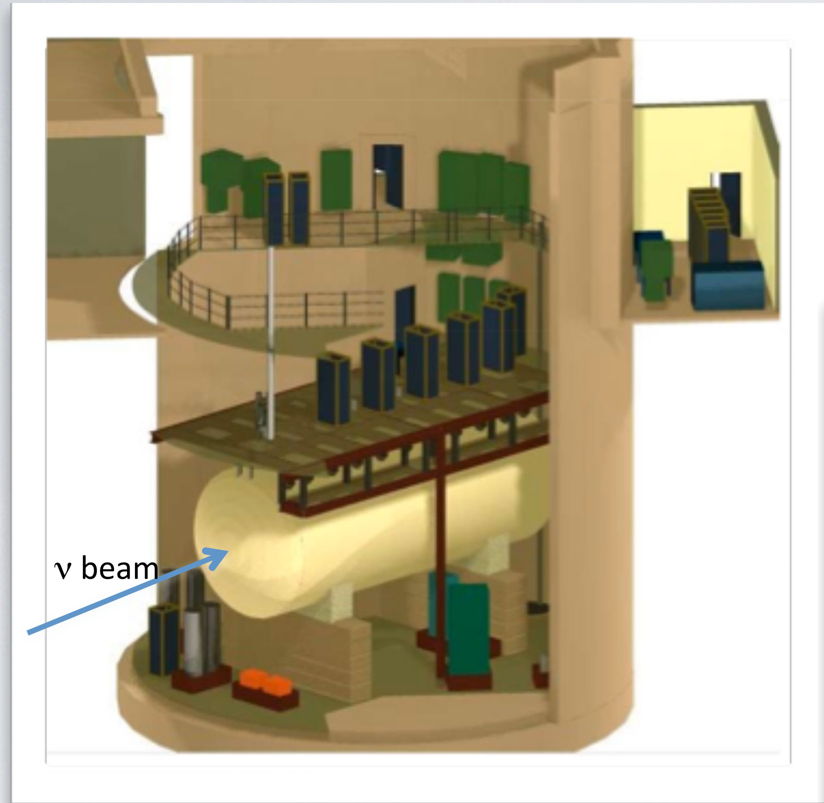

Commissioning: early 2014

microboone

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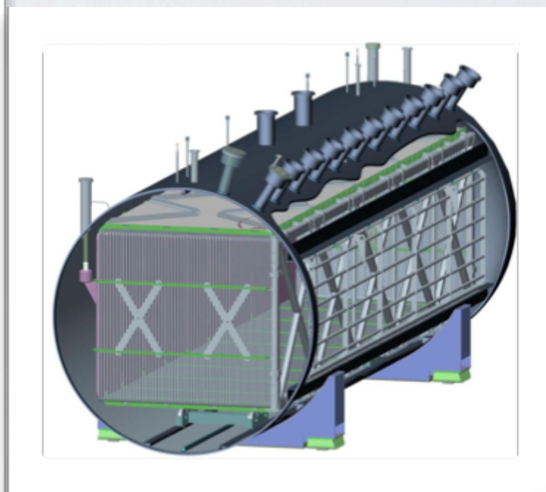
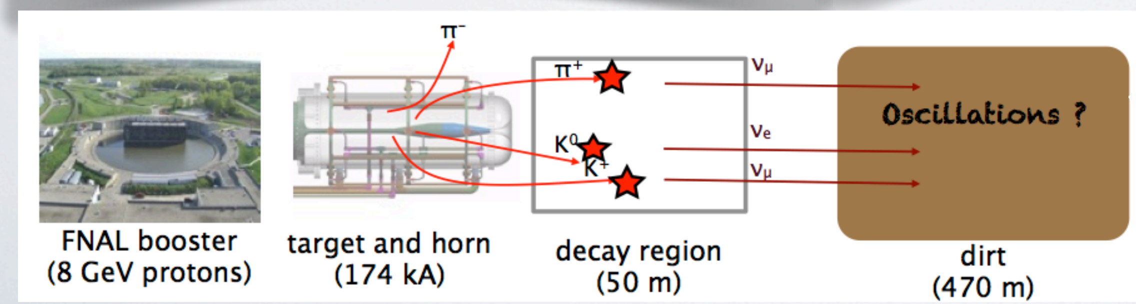


Collaboration:
Bern, BNL, Columbia, FNAL, KSU, LosAlamos, MIT, MSU, Princeton, StMarys, Syracuse, Cincinnati, Texas, Yale*



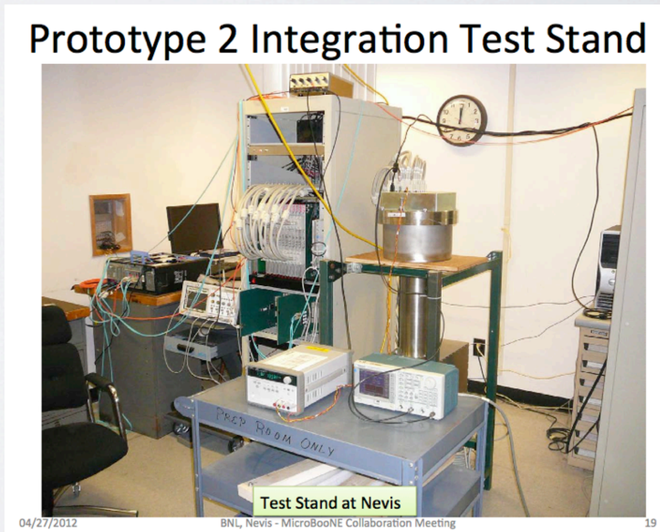
MICROBOONE:
THE SN TRIGGER AND DAQ

- Temporary record (buffer) "all" data from TPC, over a given extension of Time (e.g. 30' - 1h). The temporary storage is a very large !
(10 crates × 50 GB/s/crate × $3 \cdot 10^3$ s = 1500 TB)

- A "trigger" is received from an external "SuperNova Watch" (e.g via SNEWS)

- Extract permanent record of the Time Interval (≈ 10 s) that might contain SN neutrino Interactions.

A hw logic and I/O has been implemented in the MicroBooNE electronics design, a prototype has been made: this is currently being tested



Baseline Network Diagram