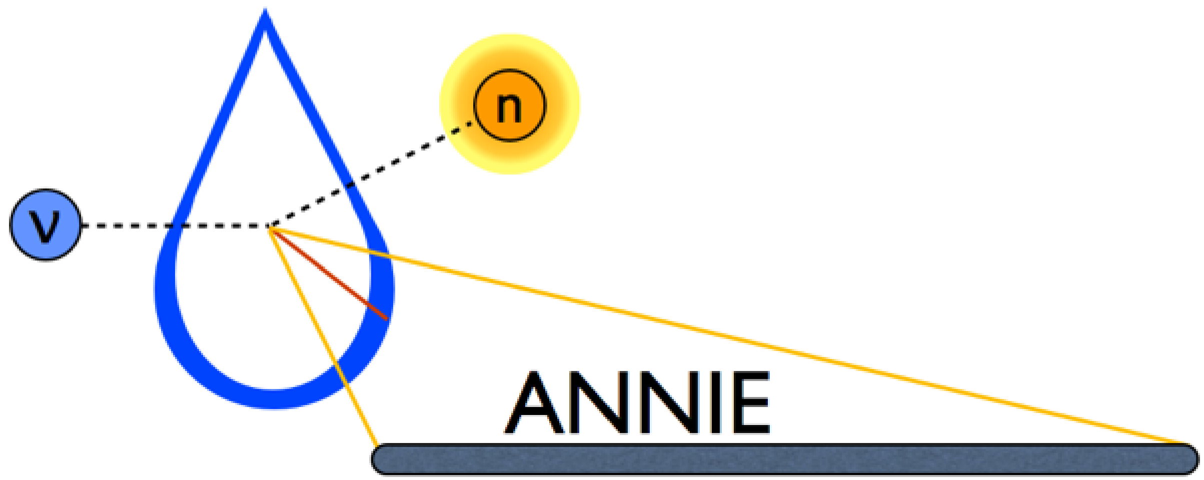
The Accelerator Neutrino-Nucleus Interaction Experiment



Matthew Malek
The University of Sheffield

University of Oxford – Particle Physics Seminar
12 May 2015

Outline

I) Motivation:

- Physics objectives
- Technical goals

II) Project overview:

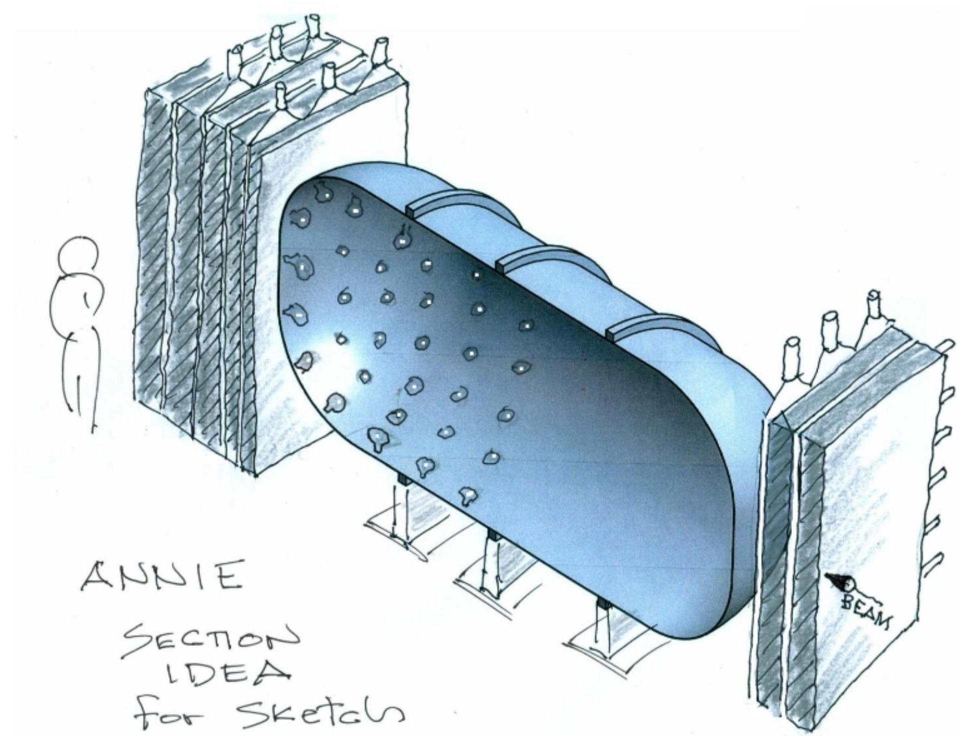
- Detector
- Beam

III) Current Status:

- Hardware
- Software & simulations

IV) Future:

- Timeline
- Application to other experiments

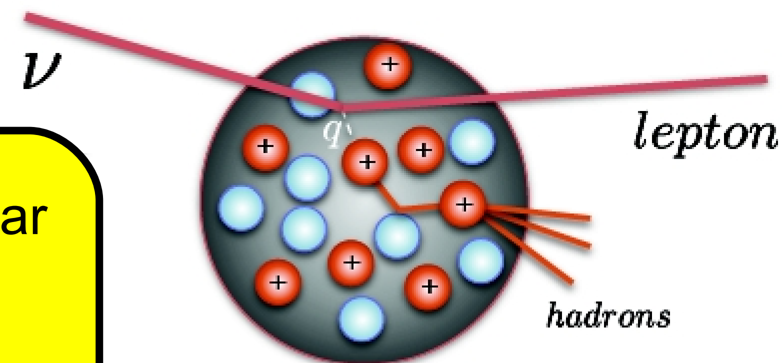


R. Northrop

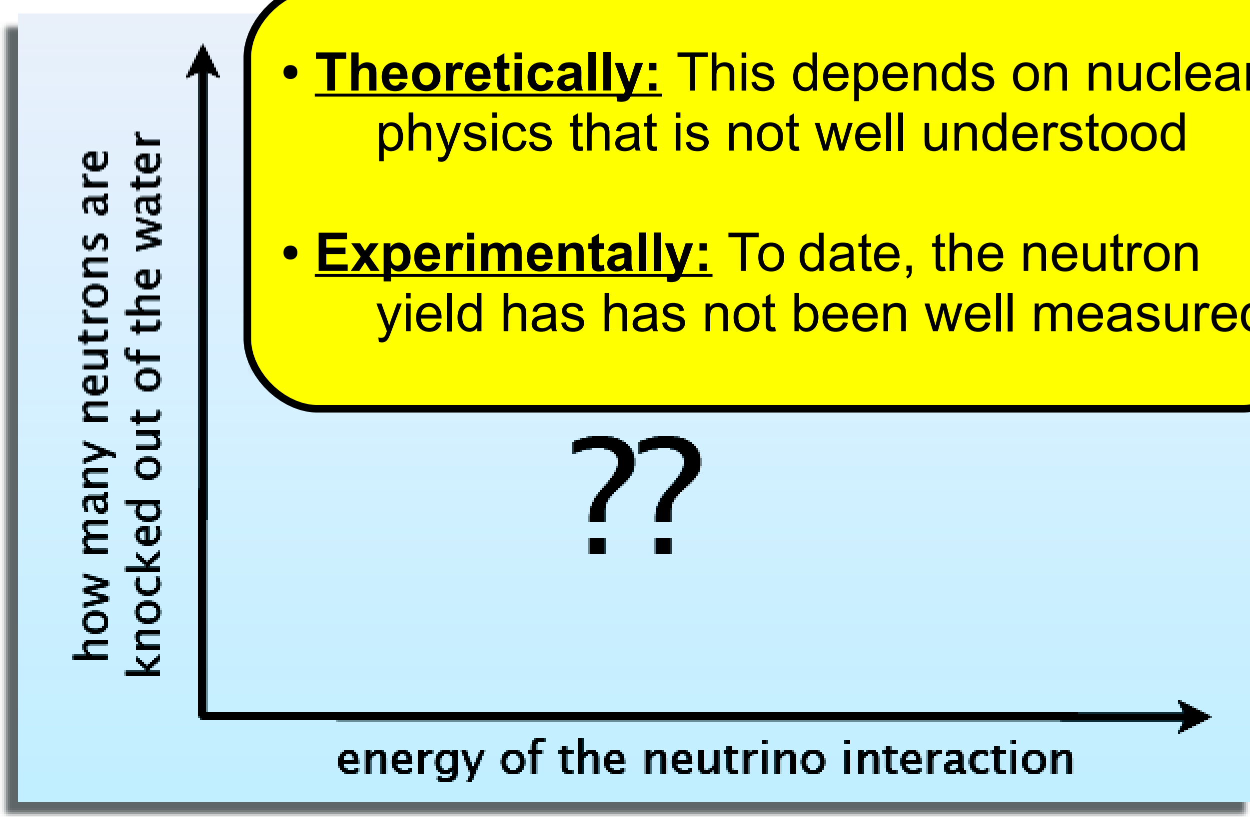
Motivation

Primary physics objective:

– A measurement of the abundance of final state neutrons ("neutron yield") from neutrino interactions in water, as a function of energy.



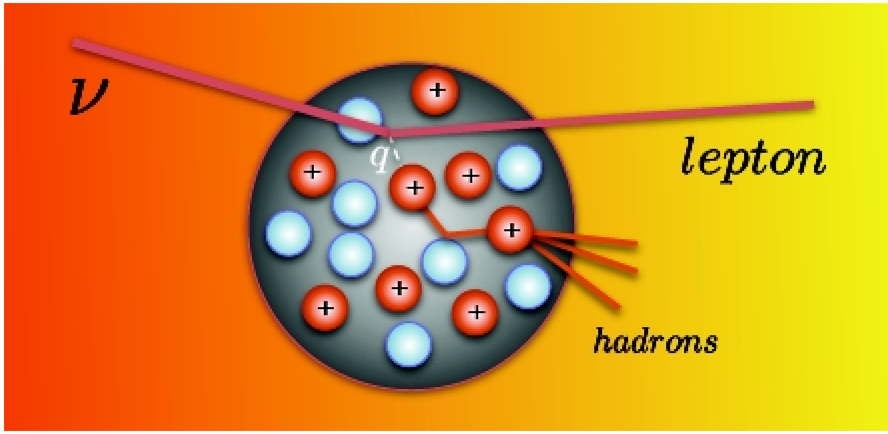
- **Theoretically:** This depends on nuclear physics that is not well understood
- **Experimentally:** To date, the neutron yield has has not been well measured



Motivation

Primary physics objective:

– A measurement of the abundance of final state neutrons ("neutron yield") from neutrino interactions in water, as a function of energy.



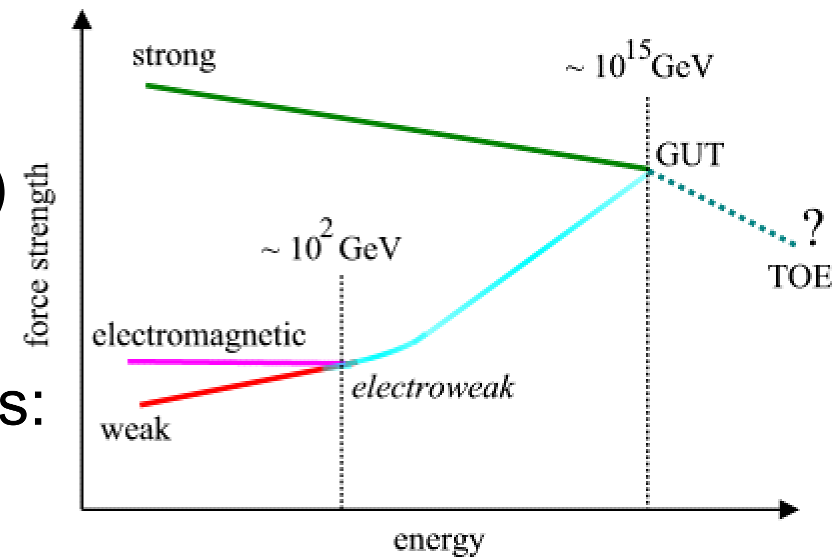
Q: Why do we want to know this?

A: Relevant to studies of:

- Proton decay measurements
- Supernova neutrino observations
- Neutrino interaction physics

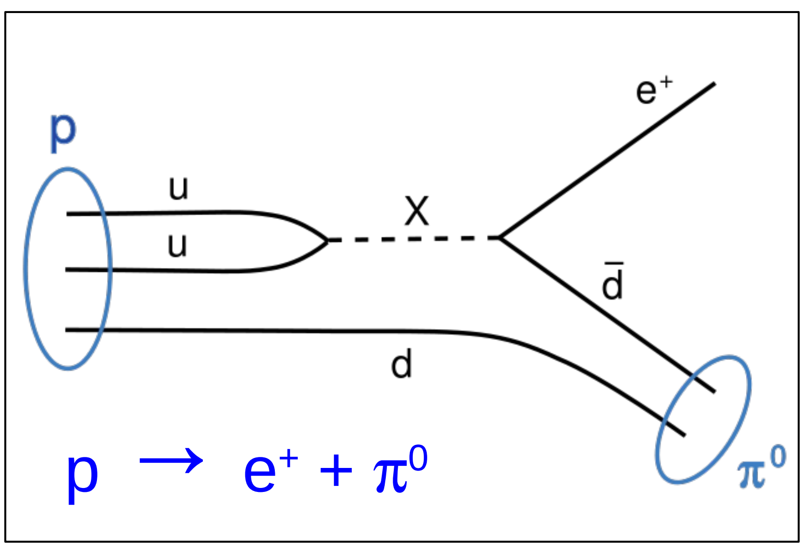
Proton Decay

Possible "grand unification" of strong & electroweak forces not directly testable due to energy scale involved ($\sim 10^{15}$ GeV)



Can test *indirectly*, searching for effects of Grand Unified Theories (GUTs) such as:

- Electric dipole moment of the neutron
- Proton decay



Proton decay has been experimentally pursued for ~35 years.

Early Grand Unified models (*e.g.*, SU(5)) predicted lifetime of $\sim 10^{29}$ years.

Current experimental limits from Super-Kamiokande are at the 10^{34} year level.

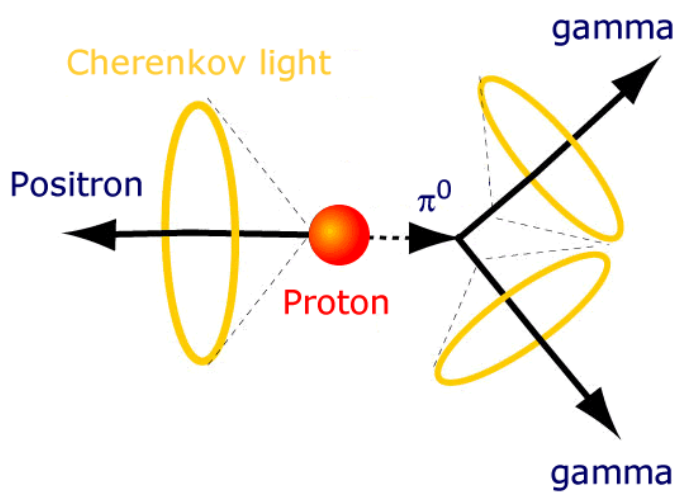
Modern GUTs predict lifetimes of $10^{35\text{-}36}$ years.

Proton Decay

In a water Cherenkov detector, a typical signal looks like:

- Three rings (all electron-like)
- Total energy close to M_p
- Unbalanced momentum close to 0.

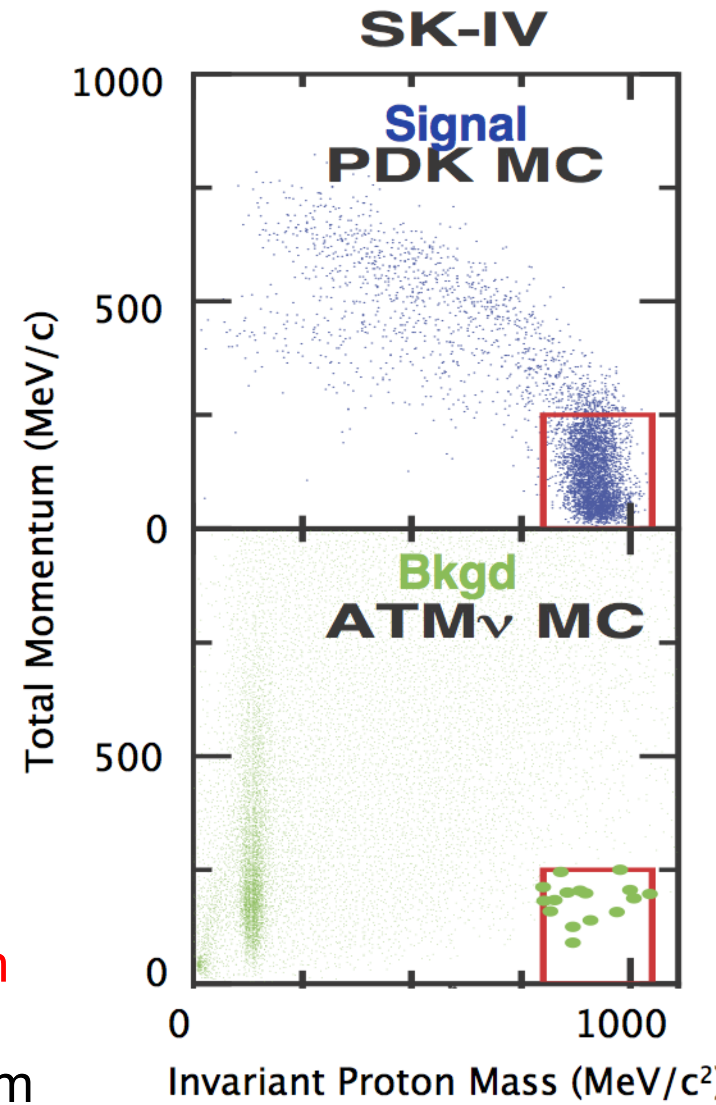
$$p \rightarrow e^{+} + \pi^{0}$$



Modern GUTs predict lifetimes of $10^{35\text{-}36}$ years.

→ Larger detectors needed to probe this region

At this scale, previously negligible backgrounds from atmospheric neutrinos start to limit sensitivity.

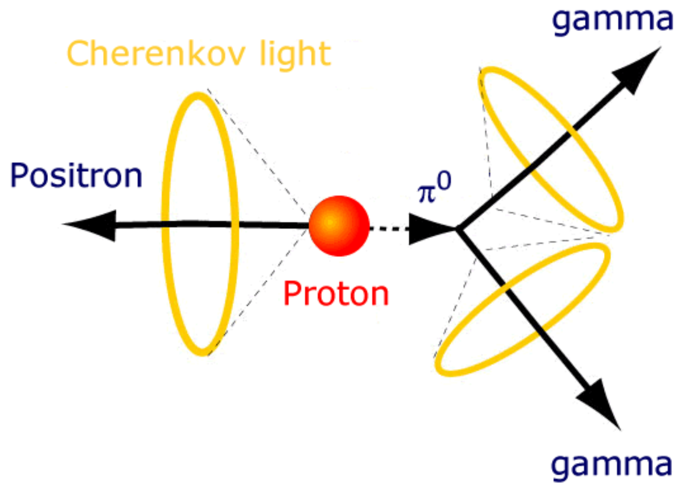


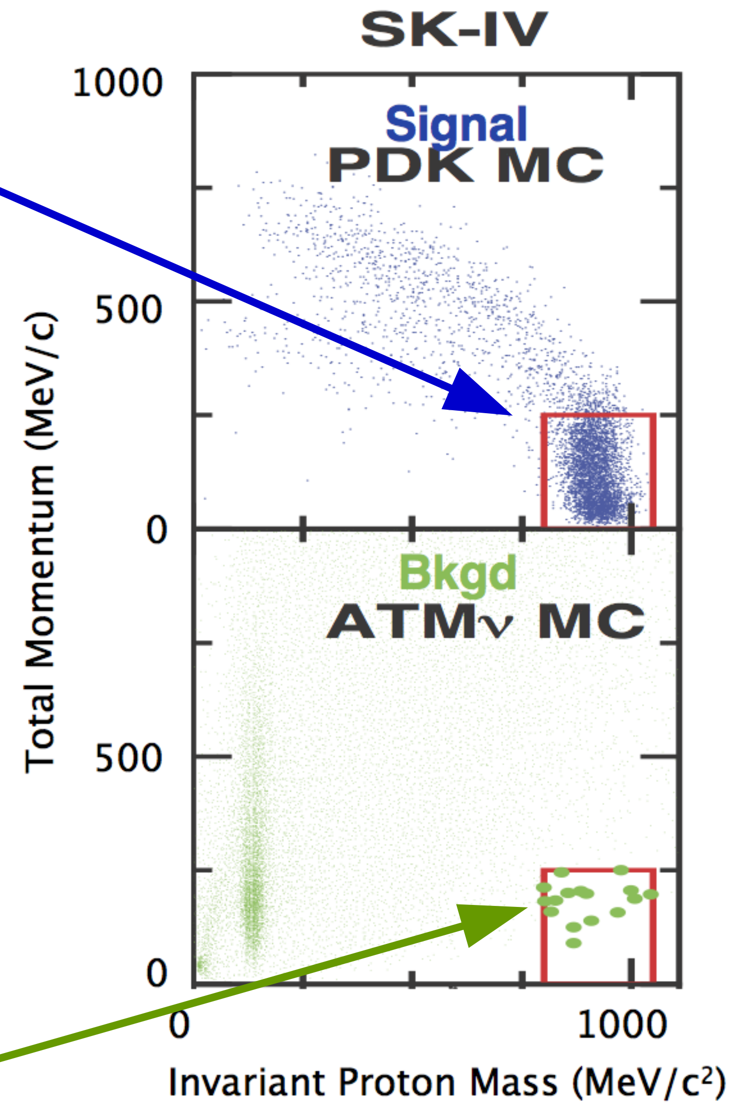
Proton Decay

Q: How can ANNIE help?

Proton decay events only rarely produce neutrons in the final state

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

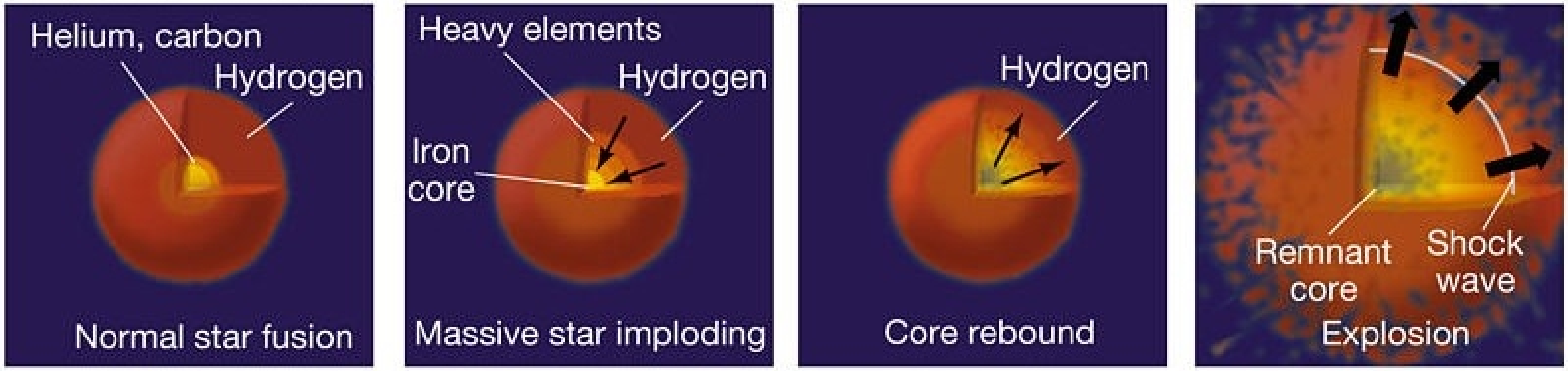




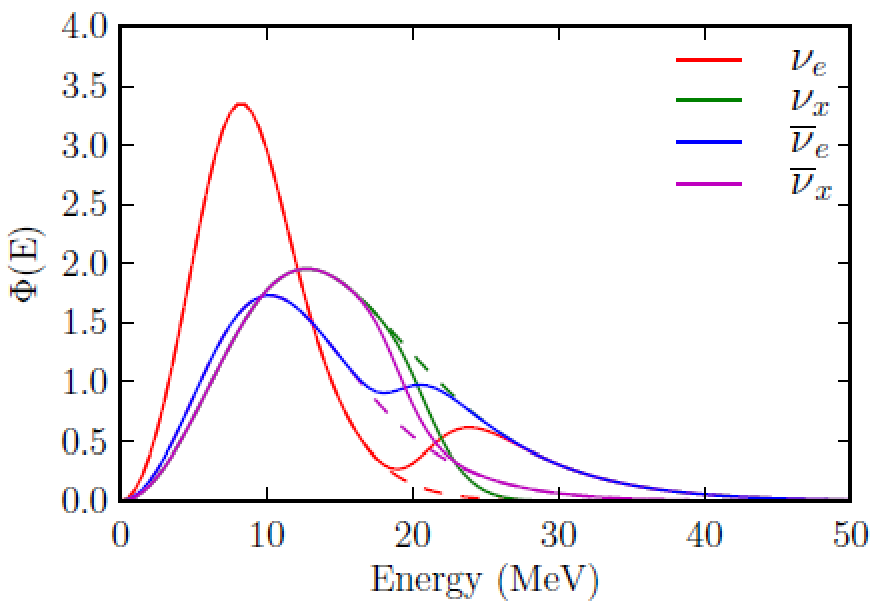
Atmospheric neutrino interactions frequently produce final state neutrons

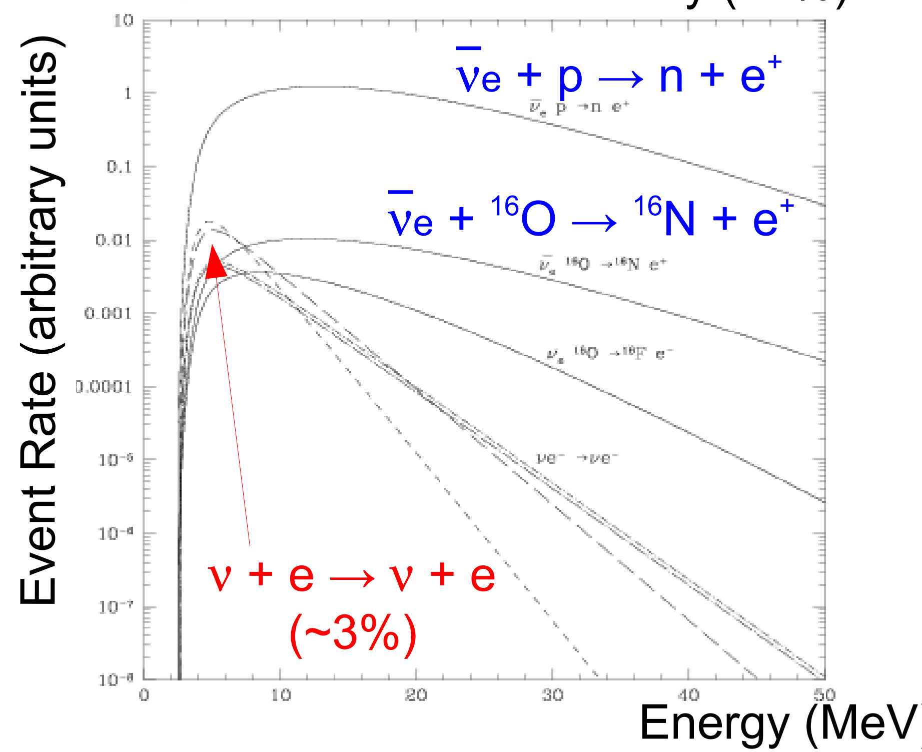
Supernova Neutrino Burst

Stars with M > 8 M☉ end as a core-collapse supernova when nuclear fuel exhausted:



All 6 ν species produced; most likely to detect in WC is $\overline{\nu}_e$ via inverse beta decay (89%):





Understanding neutron yield can help disentangle the various fluxes from a core-collapse SN burst.

Supernova Relic Neutrinos

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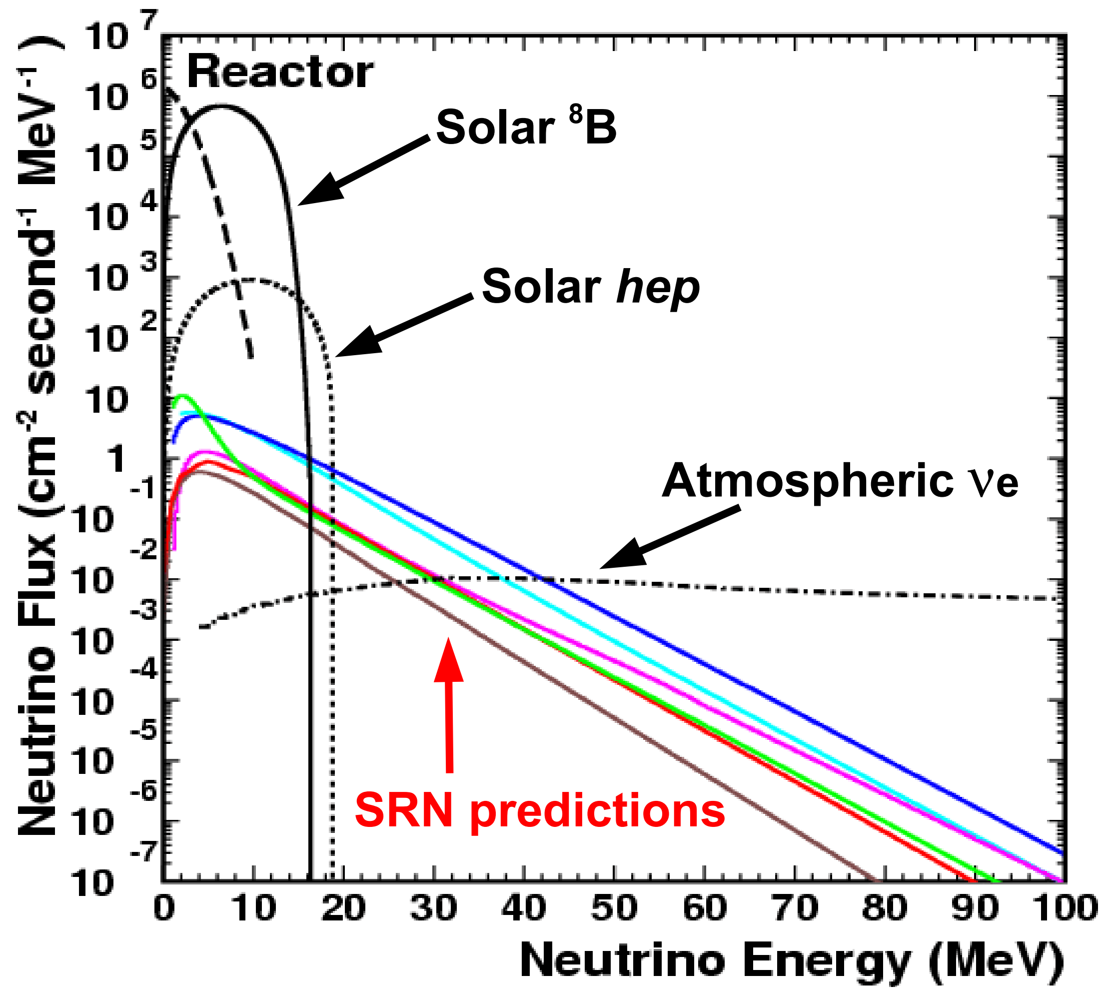
In 1987, neutrinos were detected from a SN burst in Large Magellanic Cloud (Sanduleak -69^o 292 → SN1987a)

25 neutrino events at 3 detectors (Kamiokande, IMB, Baksan)

Today, Super-Kamiokande would detect **~10,000** neutrinos from SN burst in galactic centre.

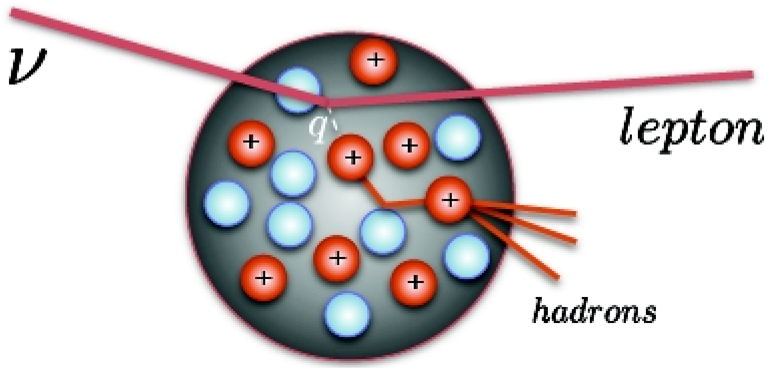
Even a SN in Andromeda would produce **1 – 2** neutrinos in SK.

Our universe is **big**, with many supernovae explosions; besides neutrinos from individual SN bursts, it should also be possible to detect a diffuse isotropic neutrino signal from **all** the core-collapse supernova ever.



Searches for these "Supernova Relic Neutrinos" (SRN) are currently background limited; understanding neutron yield could help separate the signal from various backgrounds

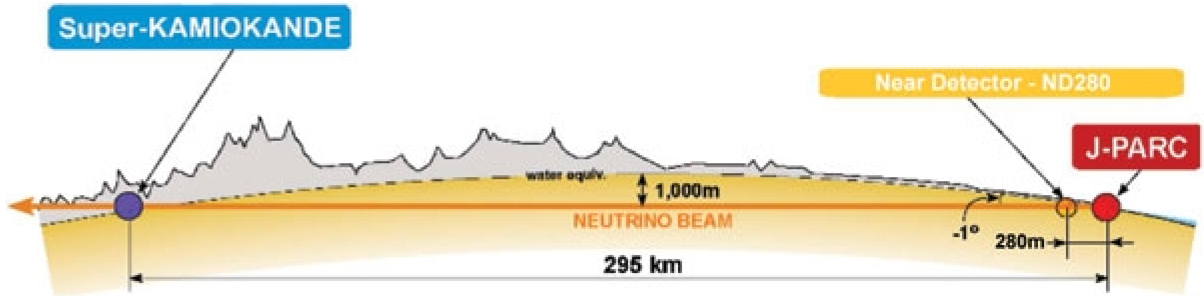
Neutrino Interactions



Studies of neutrino-nucleon interactions are also interesting in their own right! (see NuInt conference series)

ANNIE measurements can help constrain and distinguish between various interaction models.

Precision neutrino oscillation measurements:

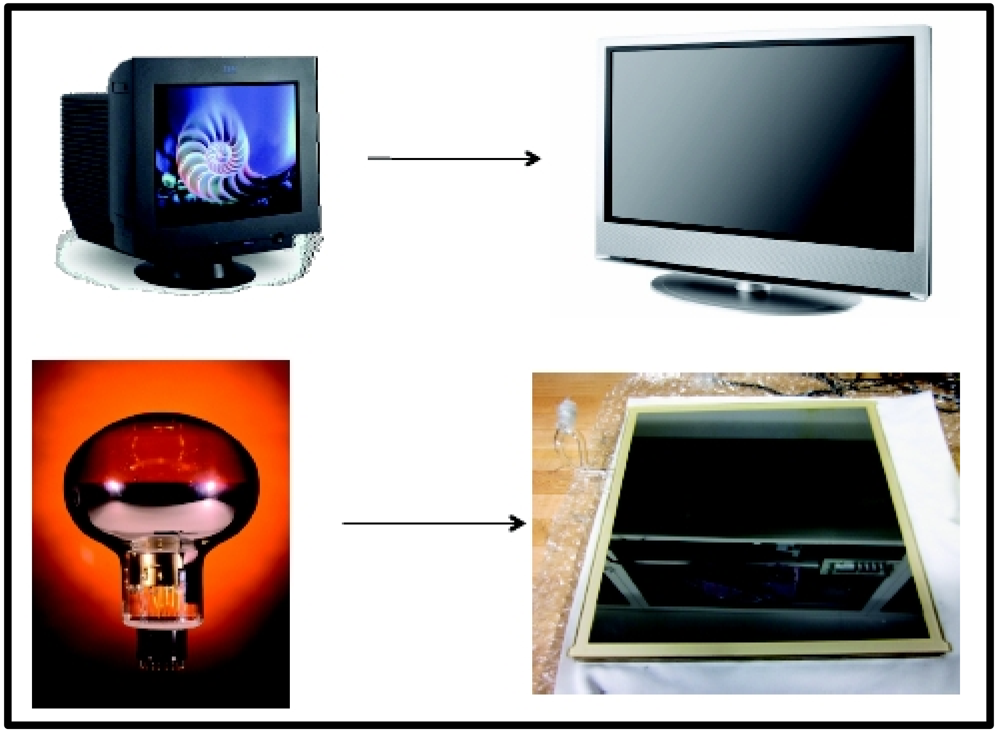


Neutrino cross-sections are a dominant systematic in long-baseline oscillation experiments, like T2K.

Reduction of this uncertainty will be necessary to conduct searches for δ_{CP}, resolve the mass hierarchy, octant degeneracy, etc.

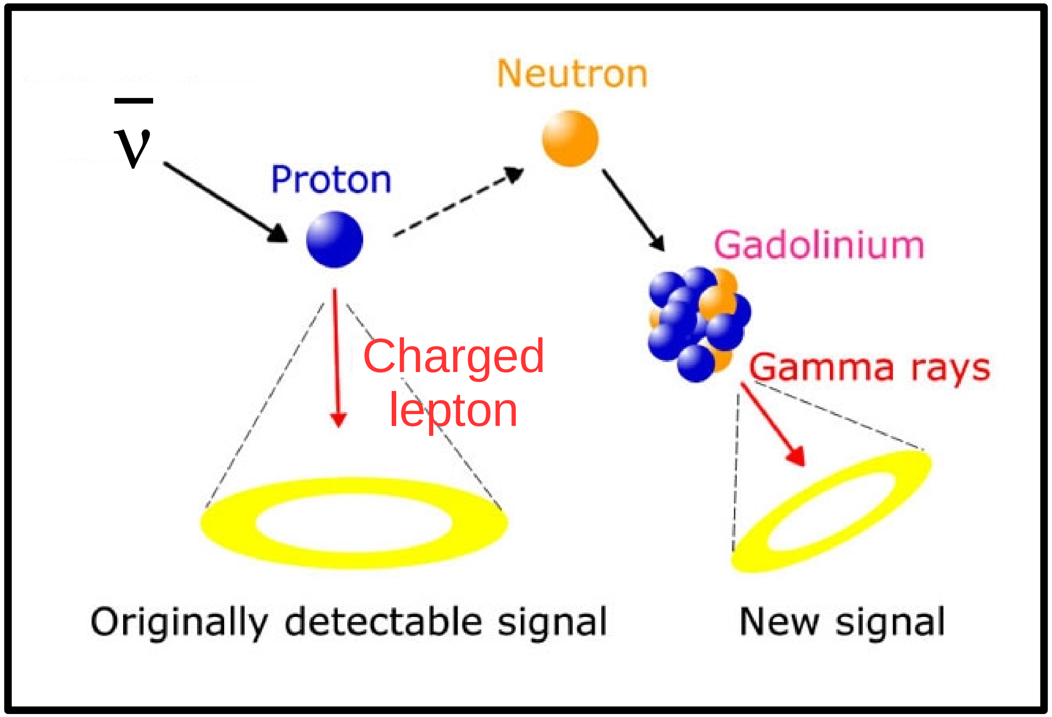
Technical Goals

ANNIE is also a test for new technologies:



First *in situ* test of Large Area Picosecond Photo-Detectors (LAPPDs) in a water Cherenkov experiment. [Left]

First use of a Gadolinum-doped WC detector in a ν beam. [Below]



Also, may possibly be first use of
WC + Magnetised MRD
for enhanced particle identification.

More on all of these later in the talk...

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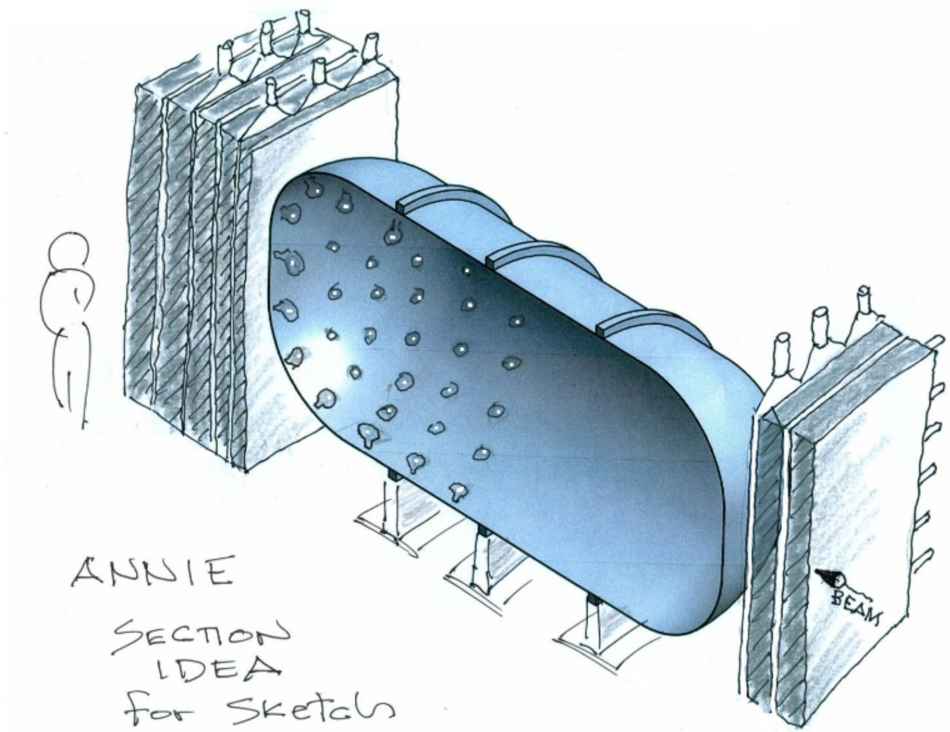

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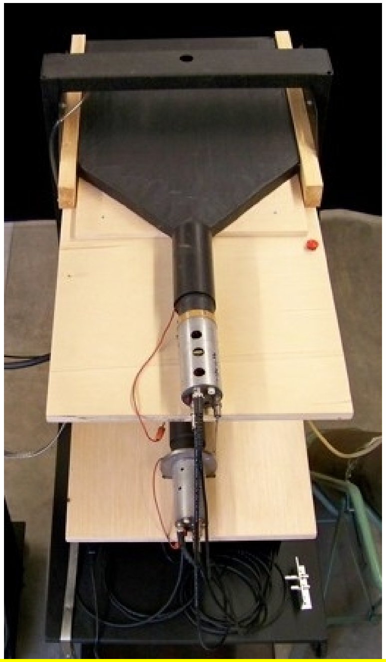
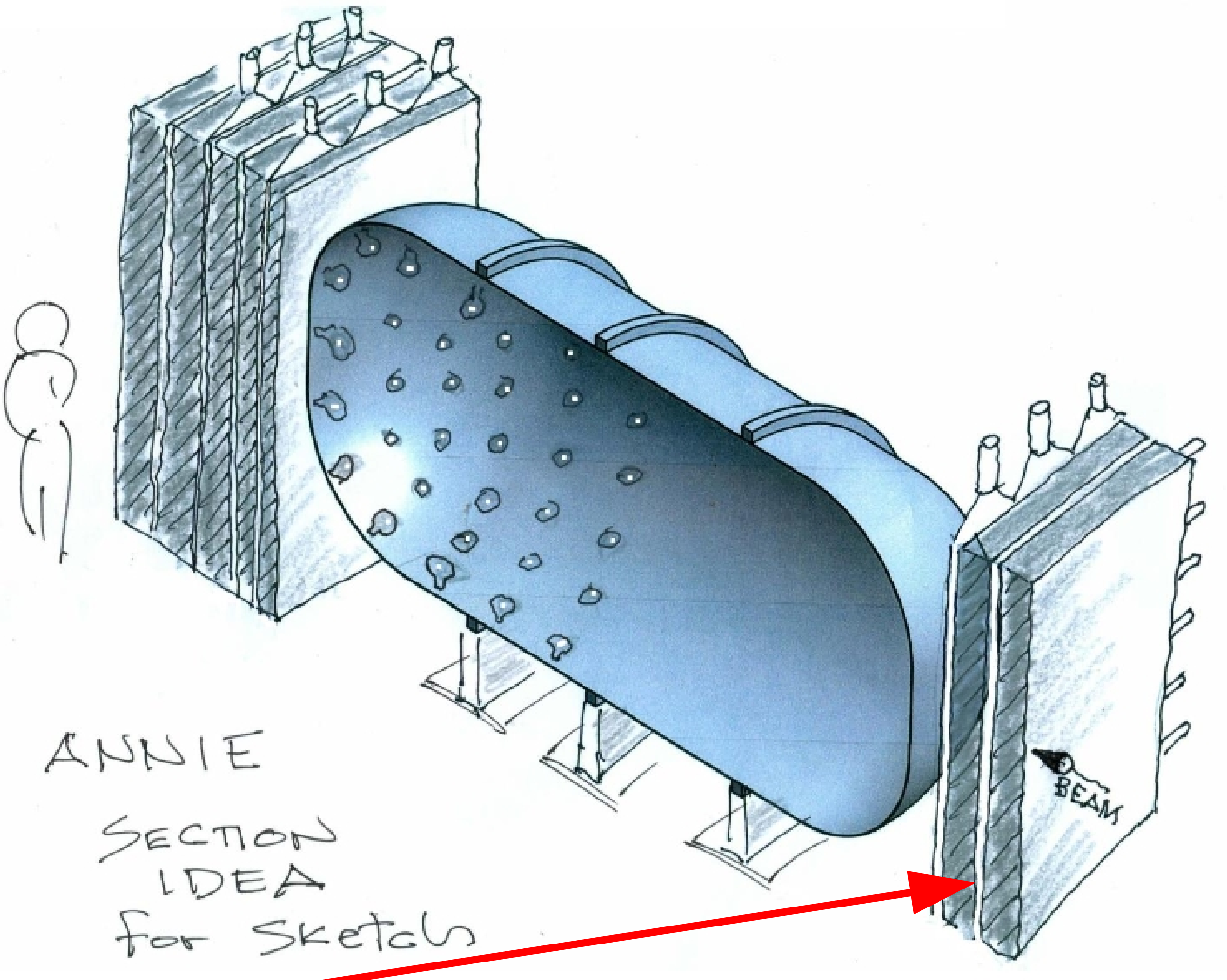
The ANNIE Detector

Major components of ANNIE:

Upstream
anti-coincidence
scintillation
detector
(μ veto)





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The ANNIE Detector

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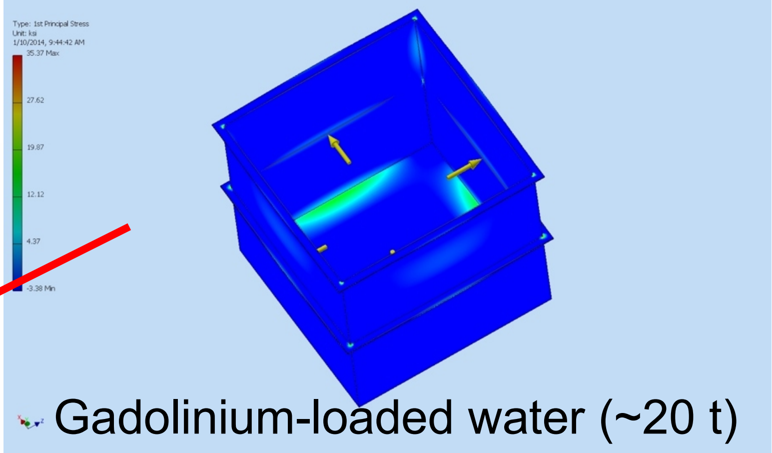
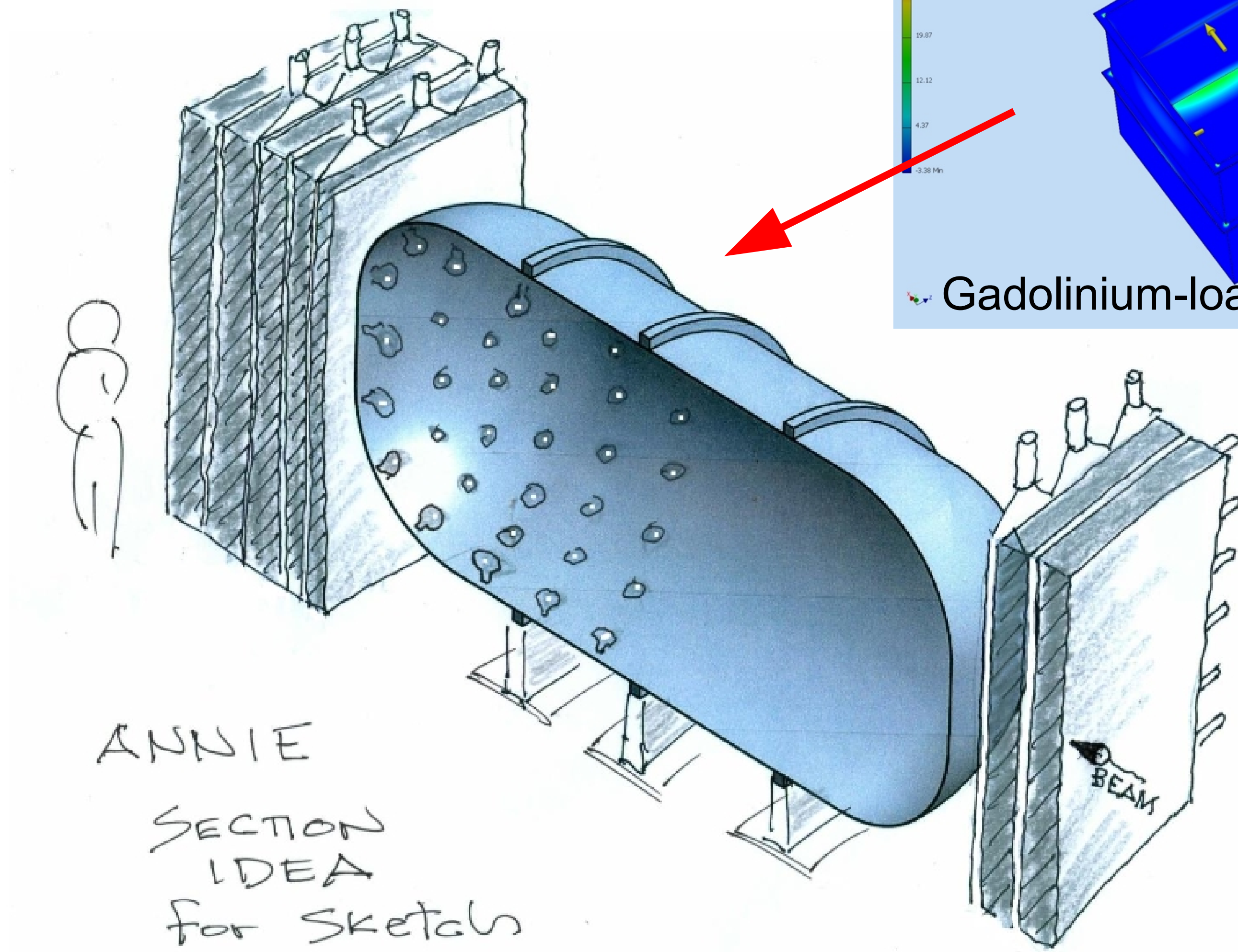
Major components of ANNIE:





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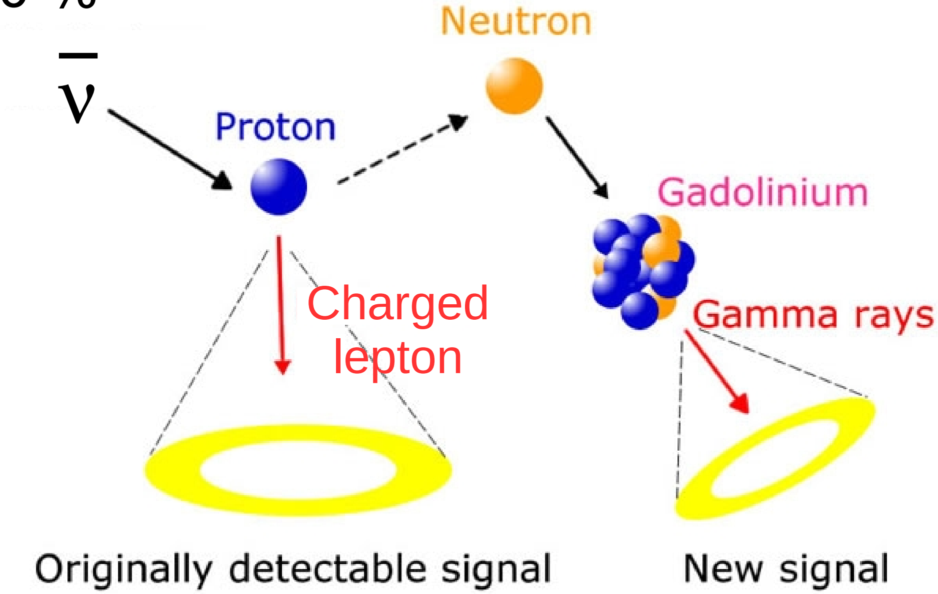
Gadolinium Doping

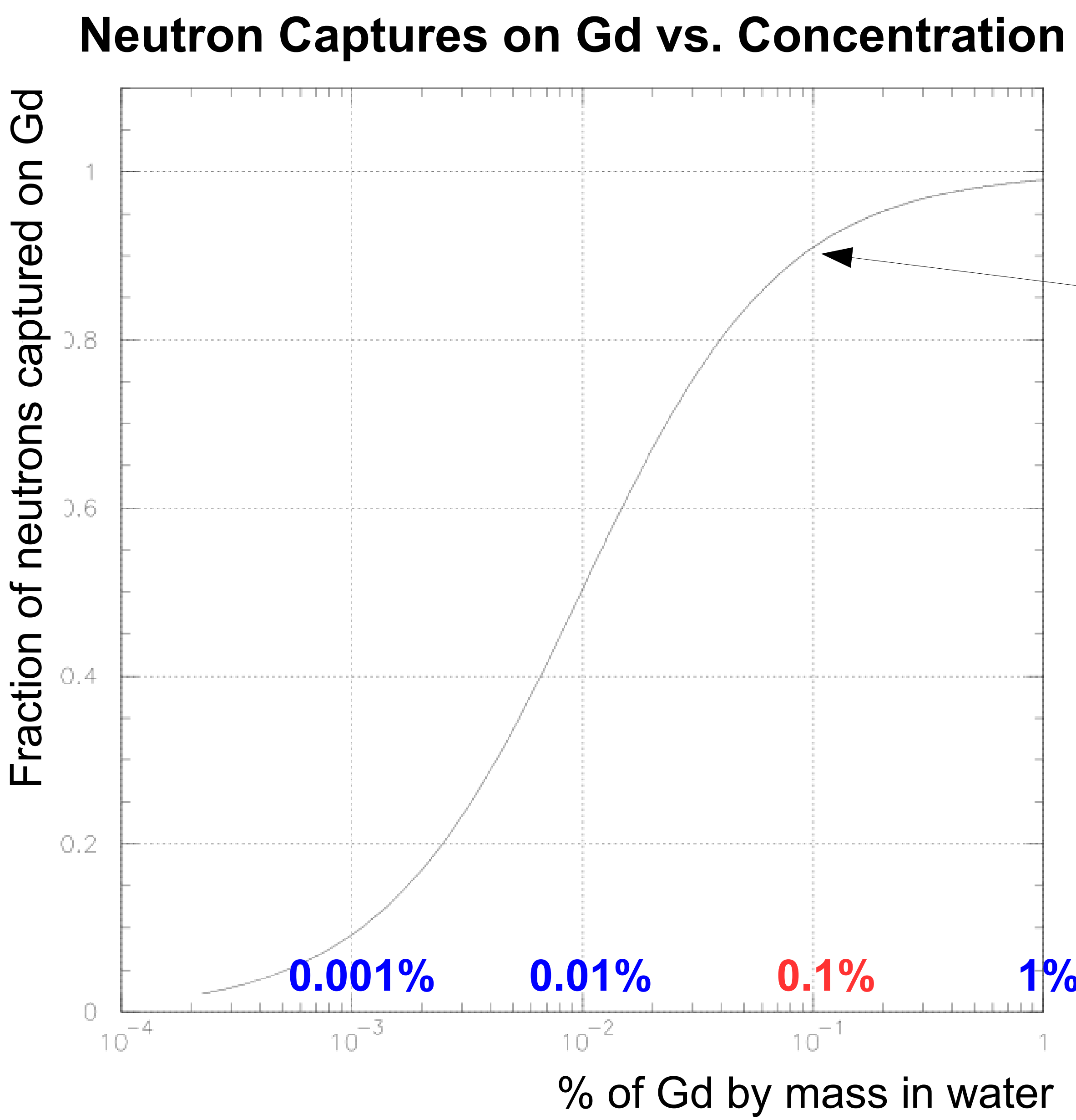
- **CCQE for ν:** $\nu + n \rightarrow l^- + p$ (p is "invisible")

  CCQE for $\bar{\nu}$: $\bar{\nu} + p \rightarrow l^+ + n$

- In ordinary water: n thermalizes, then is captured on a free proton
  - Capture time is ~200 μsec
  - 2.2 MeV gamma emitted
  - Detection efficiency @ SK is ~20 %
- When n captured on Gd:
  - Capture time ~20 μsec
  - ~8 MeV gamma cascade
  - 4 - 5 MeV visible energy
  - 100% detection efficiency



Neutron Capture w/ Gd

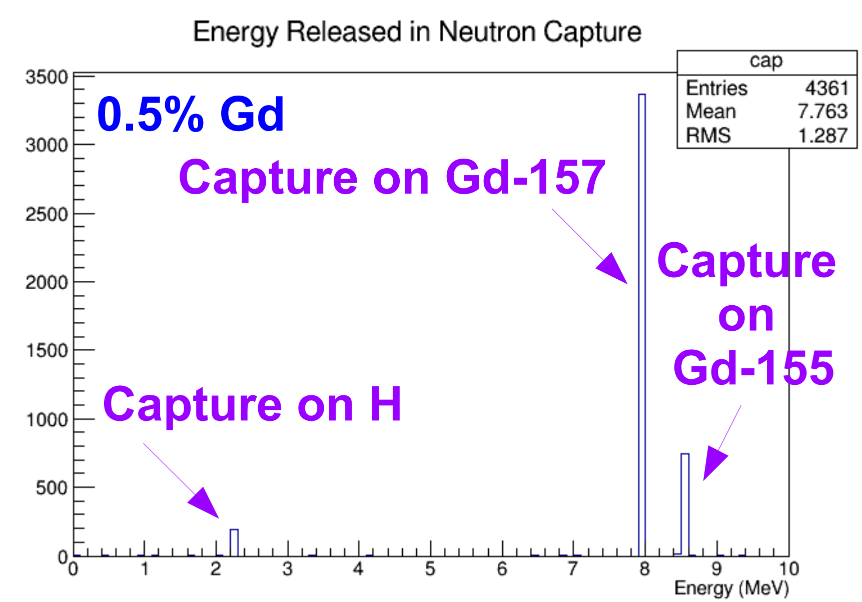


Cross-section for neutron capture is:

- ~49,000 barns for Gd
- 0.3 barns for H

0.1% Gd concentration results in ~90% of neutrons capturing on Gd

Currently, EGADS experiment is investigating feasibility of doping with gadolinium sulfate [$Gd_2(SO_4)_3$]



Physics Benefits of Gd

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- **Long-baseline neutrino experiments:**
  - "Wrong sign" neutrino discrimination
    - From T2K sensitivity studies, we know that running a mix of neutrino mode & antineutrino mode enhances δ_{CP} sensitivity
    - Antineutrino mode has greater contamination from neutrinos (~20%)
    - With Gd-doping, can separate ν from $\bar{\nu}$ to understand contamination, characterize beams, and reduce systematics

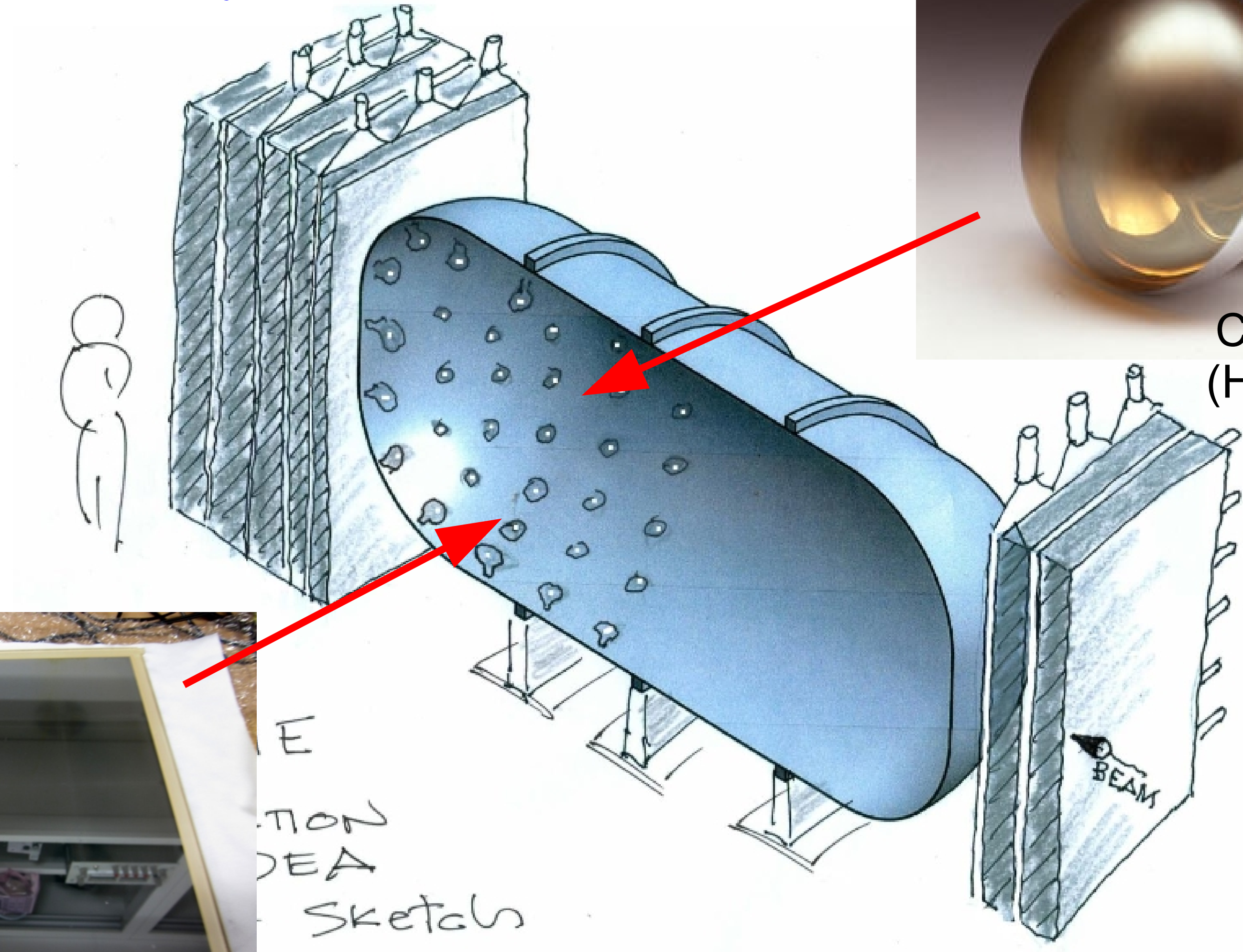
- **Neutrino interaction physics:**
  - Neutron yield can be used to separate CC quasi-elastic events from CC Meson Exchange Currents (MEC) and CC Other:
    - ν_μ CCQE: 0 neutrons
    - ν_μ CC MEC: 0.2 neutrons (average): $\nu_\mu + (n\text{-}n) \rightarrow \mu^- + p + n$
    - $\bar{\nu}_\mu$ CCQE: 1 neutron
    - $\bar{\nu}_\mu$ CC MEC: 1.8 neutrons (average): $\bar{\nu}_\mu + (p\text{-}n) \rightarrow \mu^+ + n + n$ (~80%)

      $\bar{\nu}_\mu + (p\text{-}p) \rightarrow \mu^+ + p + n$ (~10%)

The ANNIE Detector

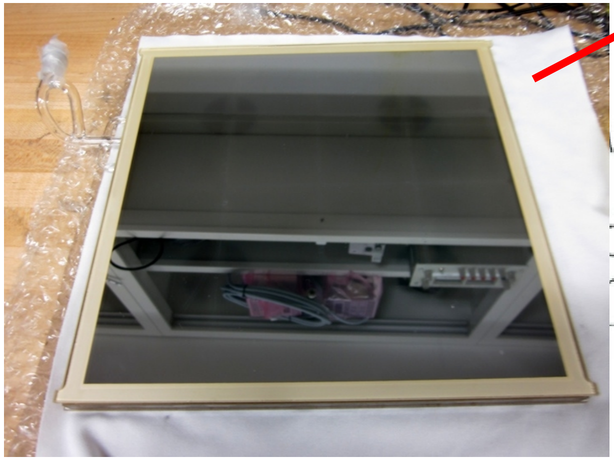
Major components of ANNIE:

Photosensors will be a hybrid of PMTs and LAPPDs



Conventional PMTs
(Hamamatsu 8 inch)
x ~100

LAPPDs
(Incom)
8 inch squares
x 10 – 20



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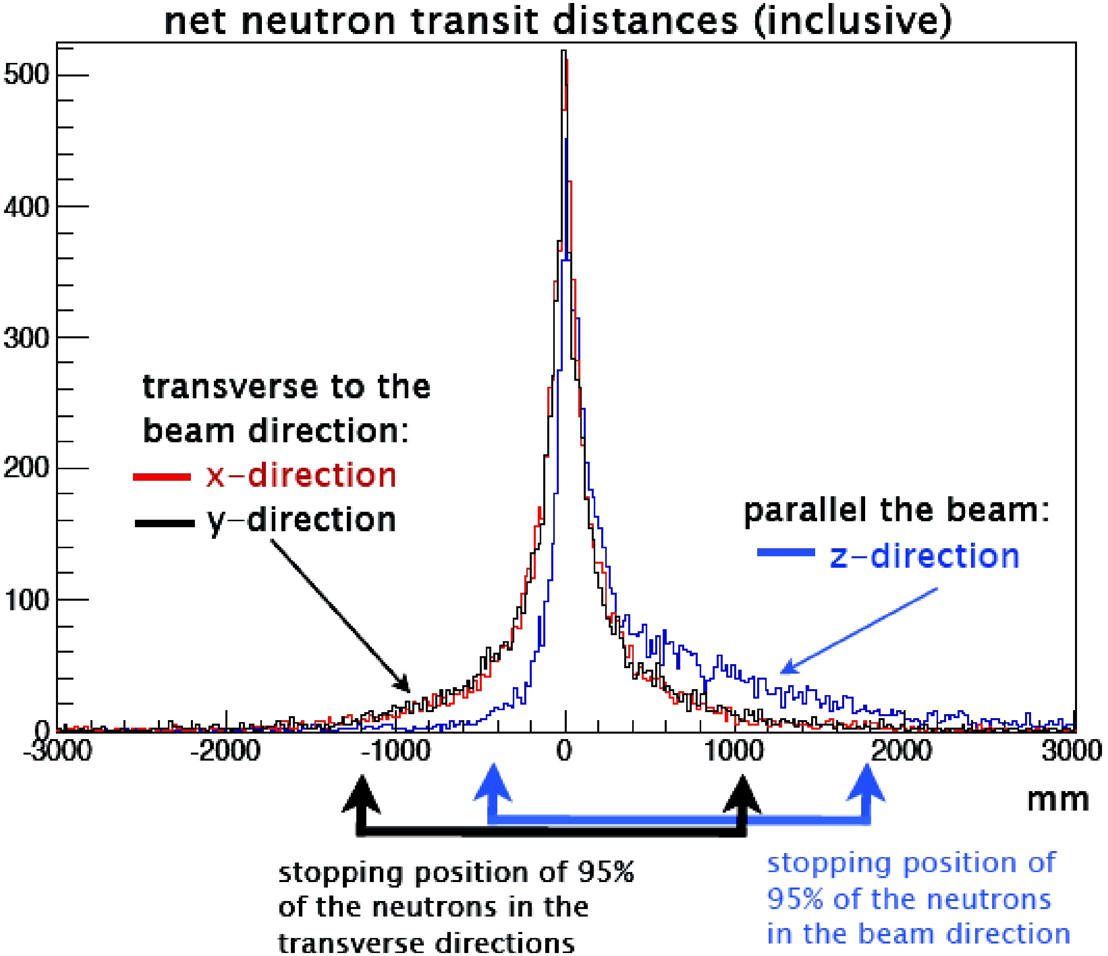
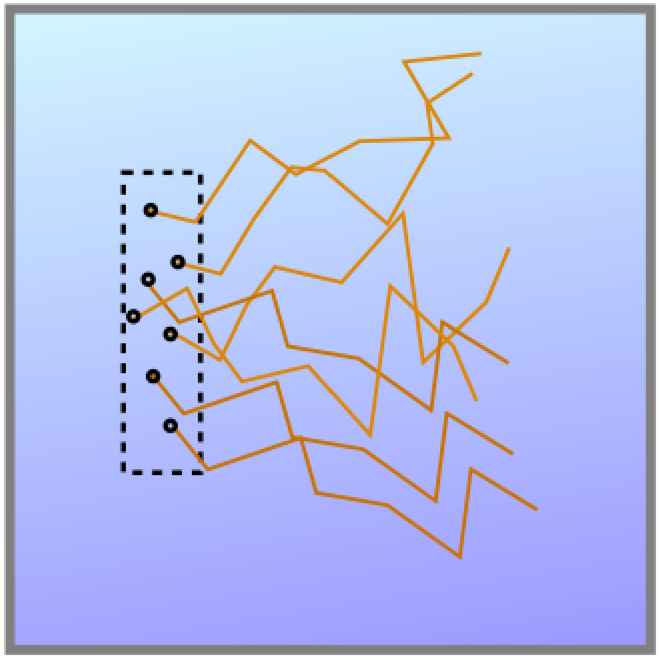
Neutron Drift

- At energies of ~1 GeV, neutrons typically drift up to 2 meters:
  - Transverse to beam, drift is symmetric
  - In longitudinal direction, drift is forward boosted



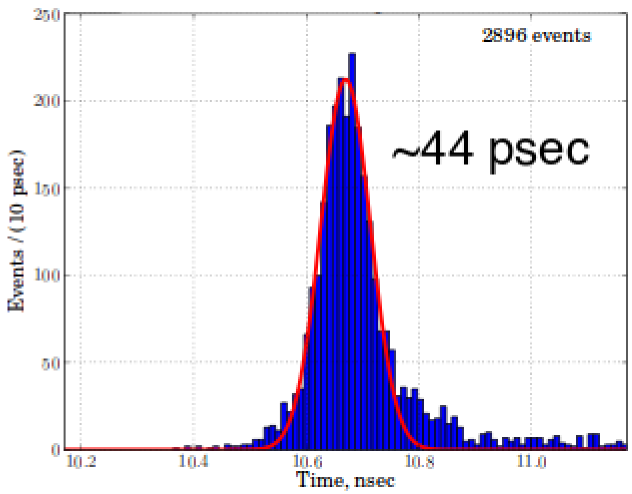
Fiducial Volume

- At energies of ~1 GeV, neutrons typically drift up to 2 meters:
  - Transverse to beam, drift is symmetric
  - In longitudinal direction, drift is forward boosted
- To get a 'clean' sample of neutrons, analysis is restricted to a small (~1 tonne) fiducial volume near the upstream and far from walls.
- To properly identify events in FV, we need vertex resolution of < 10 cm
  - This is beyond the capability of conventional PMTs!
  - Accurate timing-based reconstruction from LAPPDs necessary for this essential reco.



LAPPDs

- Large Area Picosecond Photo-Detectors (LAPPDs) are:
  - Large, flat-panel multi-channel plate (MCP) based photosensors
  - Based on new, potentially economical industrial processes
- ANNIE will be the first use of LAPPDs in water, as well as first use in a high energy physics experiment
  - Pioneering work for other HEP expts (*e.g.*, Ar-based ν & DM)
  - High spin-off potential for medical imaging, etc.
- LAPPDs offer:
  - **50 – 100 psec** timing resolution
  - **< 1 cm** spacial resolution
    - Imaging sensors, can resolve individual hits on a single module
    - May be possible to reconstruct track parameters from light on a single tile!



LAPPDs

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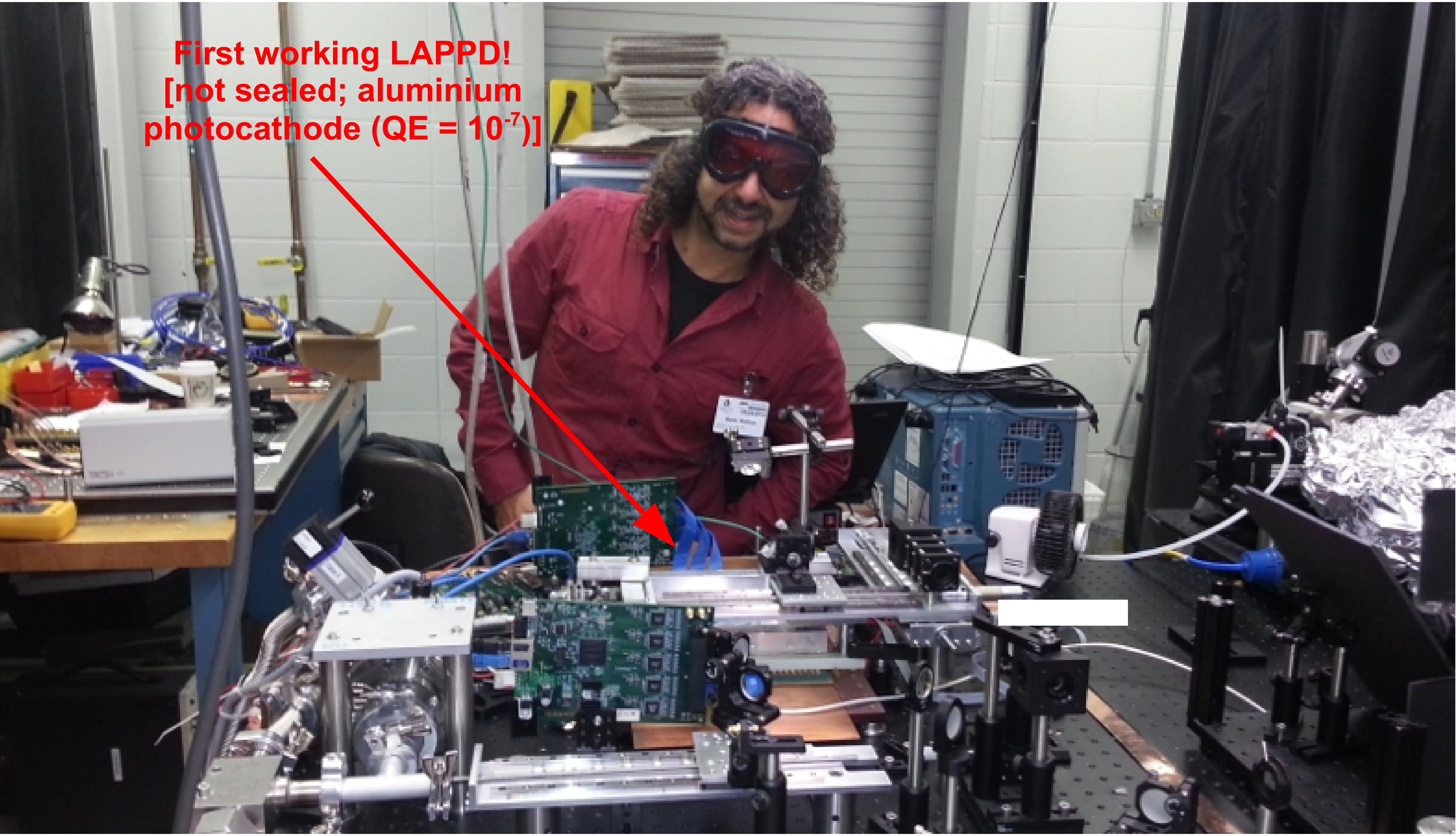
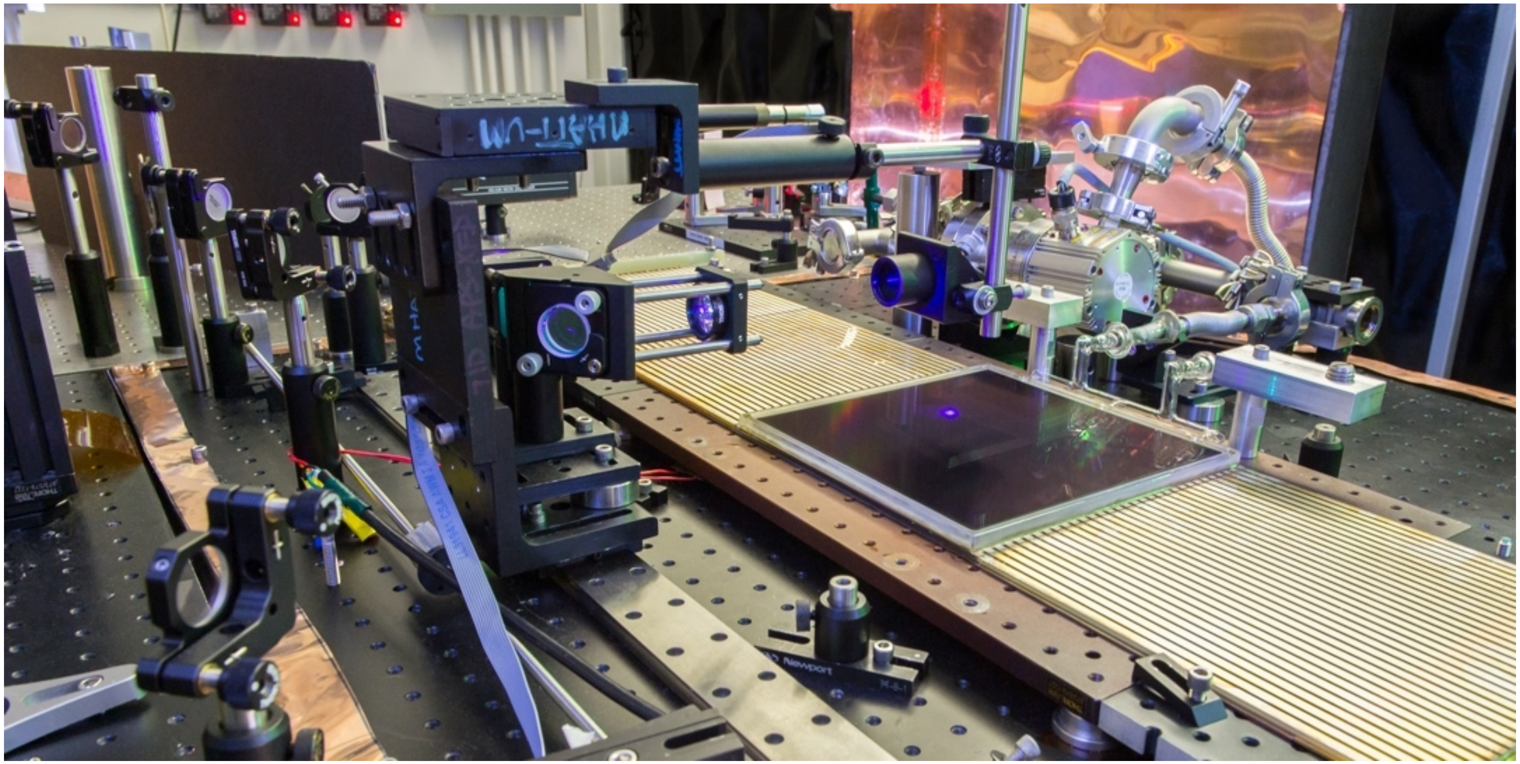


LAPPDs



- ANNIE will take advantage of *hybrid* photosensor deployment:
  - A few LAPPDs (10 – 20?) to do precise vertex reconstruction for HE events
  - A larger number (100 – 200) of PMTs will:
    - Obtain energy reconstruction for HE beam muons
    - Gather light from delayed neutron capture for neutron multiplicity studies

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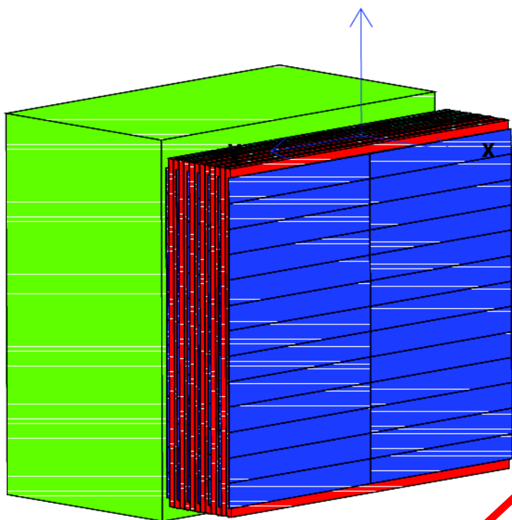
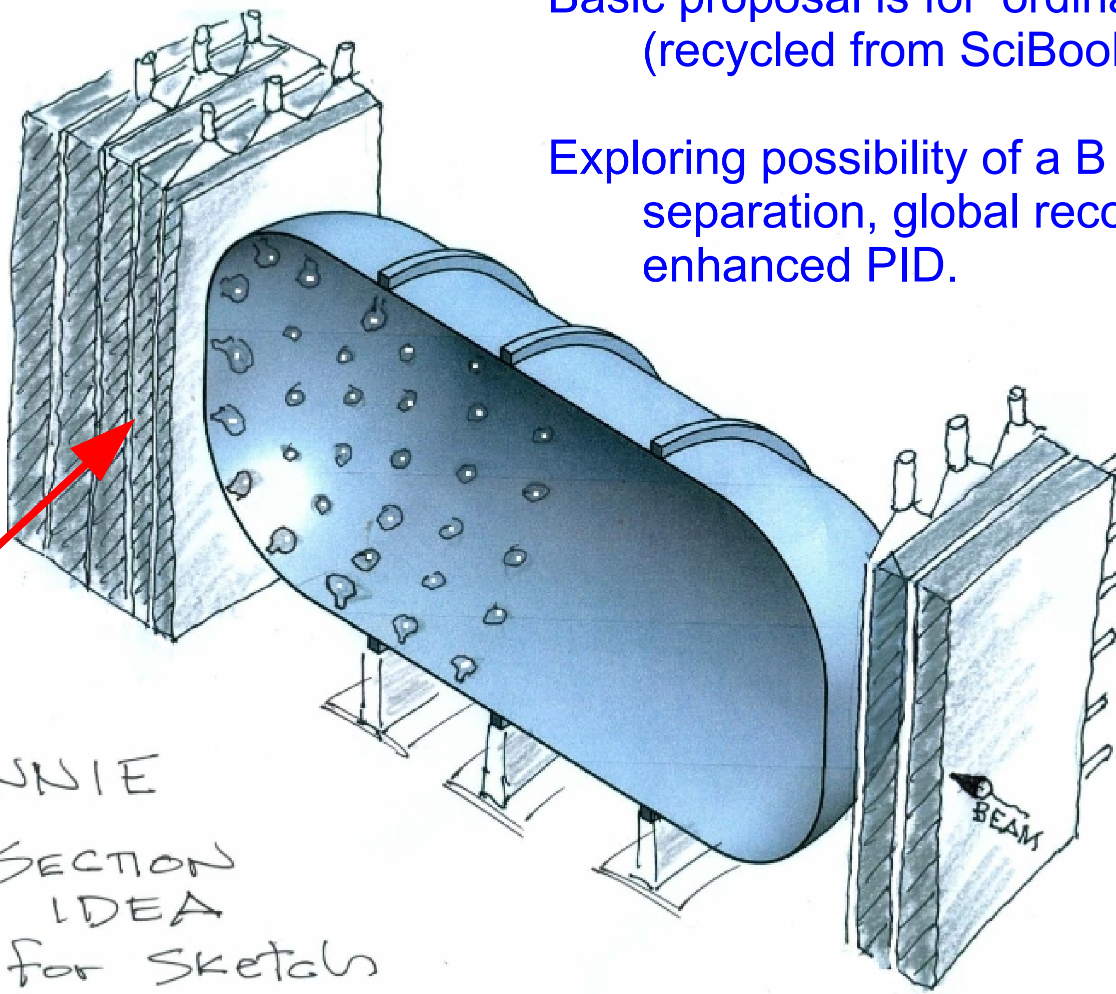
Major components of ANNIE:

Basic proposal is for 'ordinary' MRD.
(recycled from SciBooNE)

Exploring possibility of a B field for charge sign separation, global reconstruction, and enhanced PID.



Muon Range Detector (MRD)



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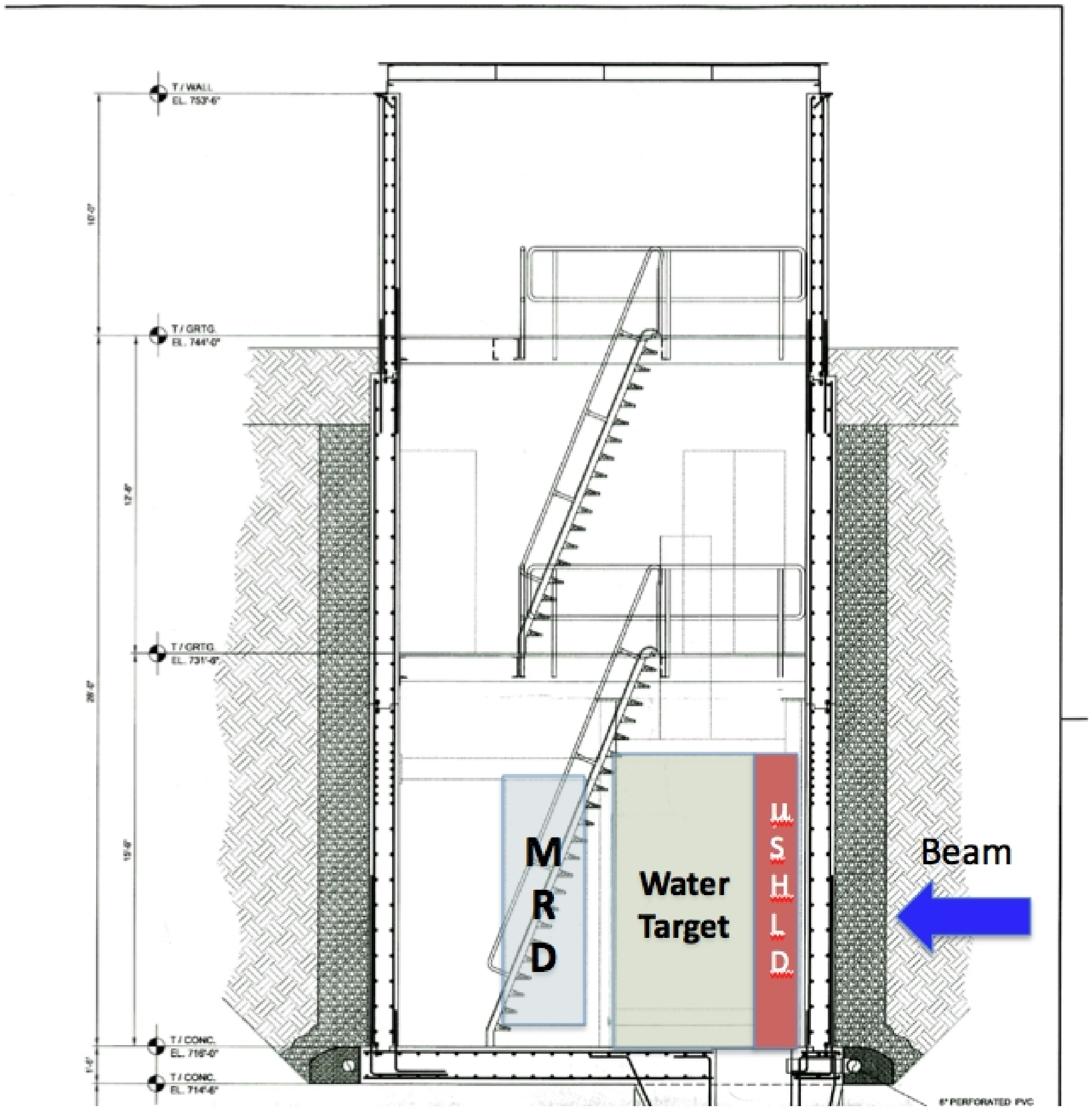
Neutrino Beam



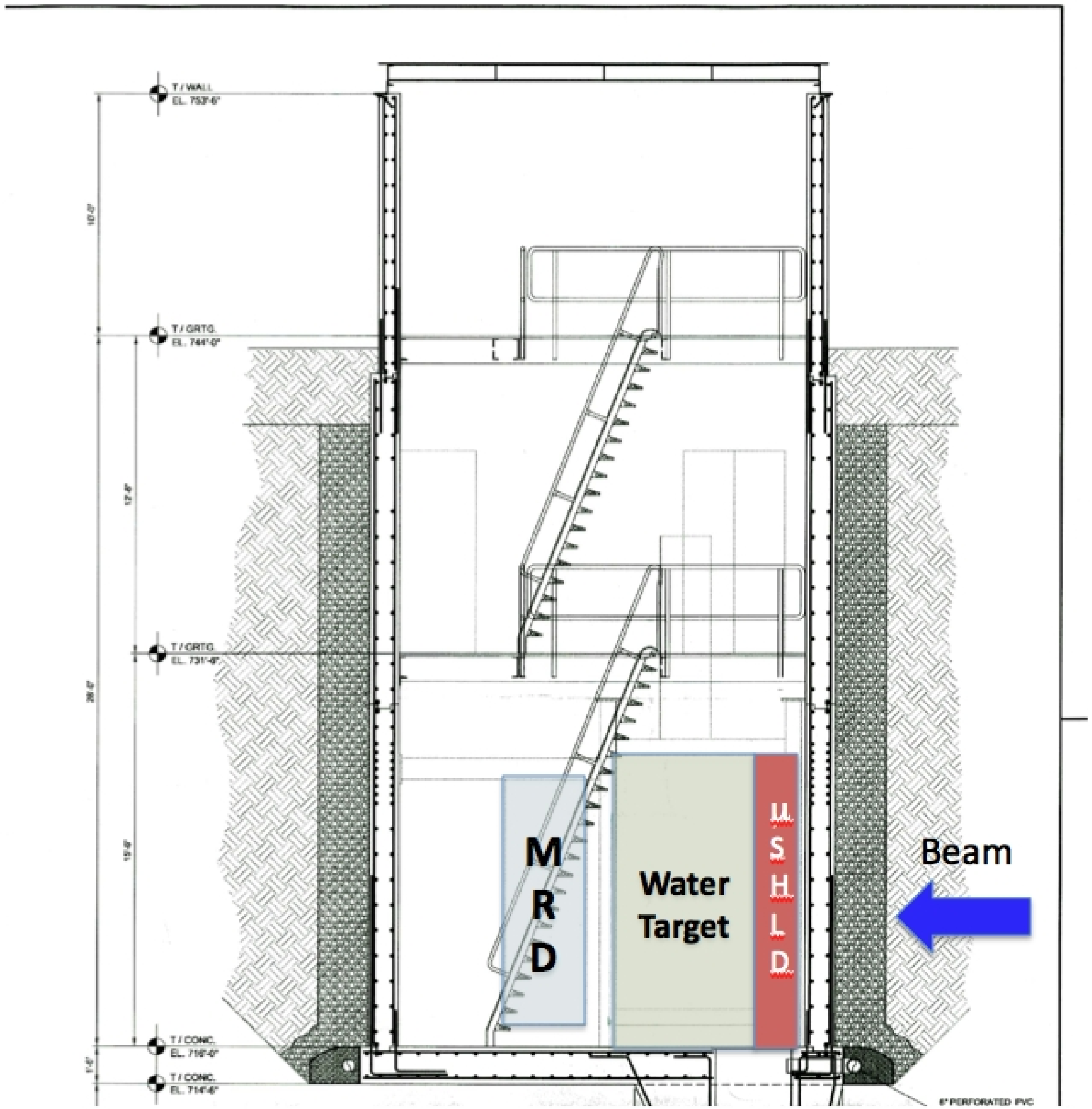
ANNIE is designed to run in the Booster Neutrino Beam (BNB) at Fermilab.

ANNIE will be situated in the former SciBooNE hall. (now 'ANNIE Hall'?)

Relevant BNB statistics at this site:

- On-axis neutrino beam
- 100 meters from target
- 4 x 10^{12} P.O.T. per pulse
- ~700 MeV peak energy
- 93% pure $\nu\mu$ (in neutrino mode)

Neutrino Beam



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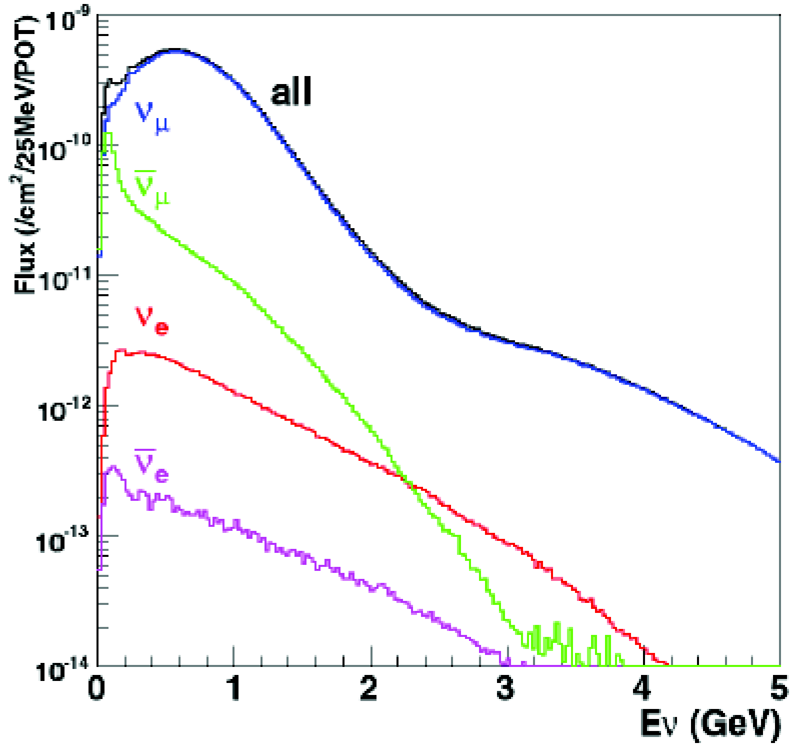
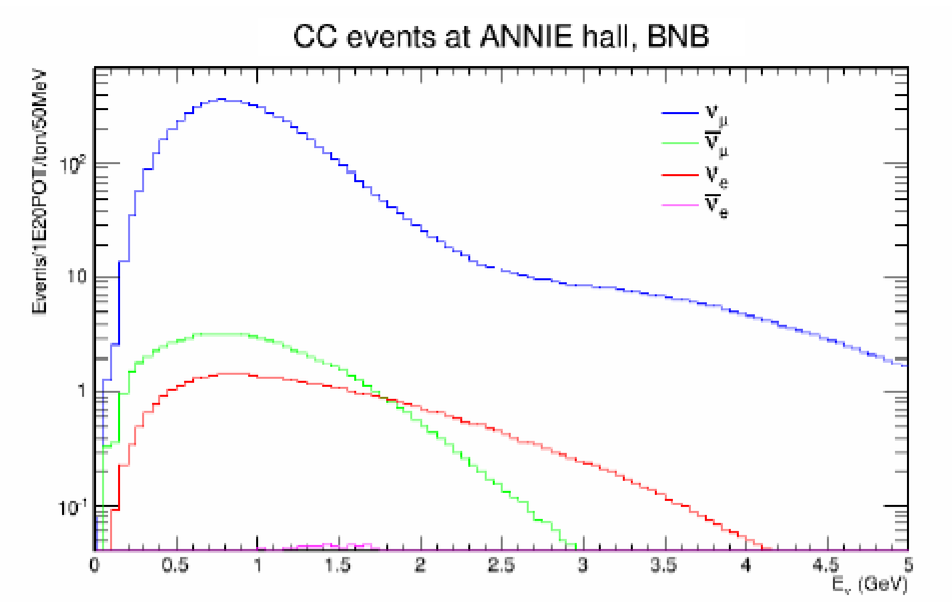
Fluxes at this site:

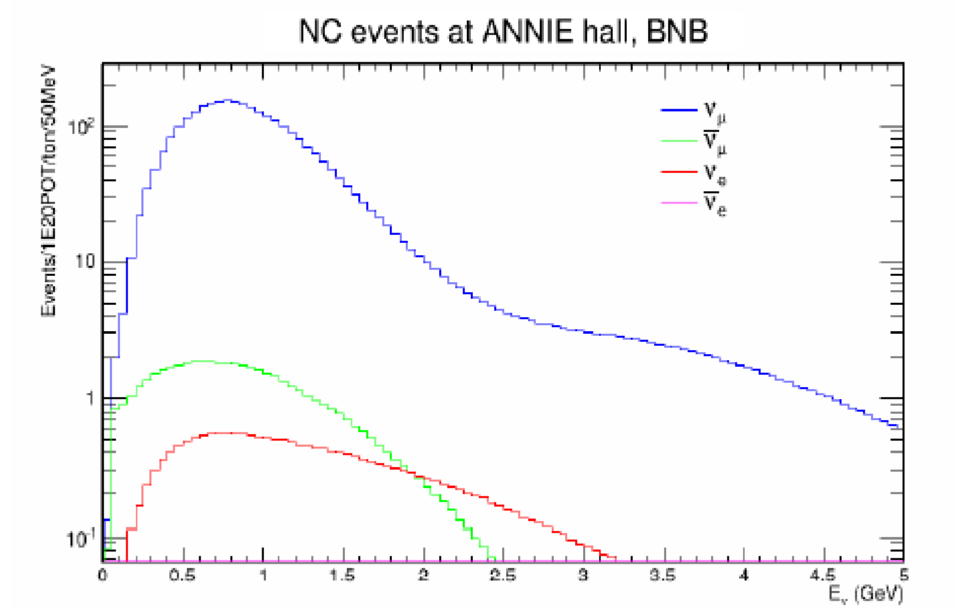


'ANNIE Hall'

Assuming ANNIE running in the BNB from SciBooNE hall, we expect the following event rates for a 10^{20} P.O.T. exposure (~1 year) in neutrino mode:



Eν (GeV)



Eν (GeV)

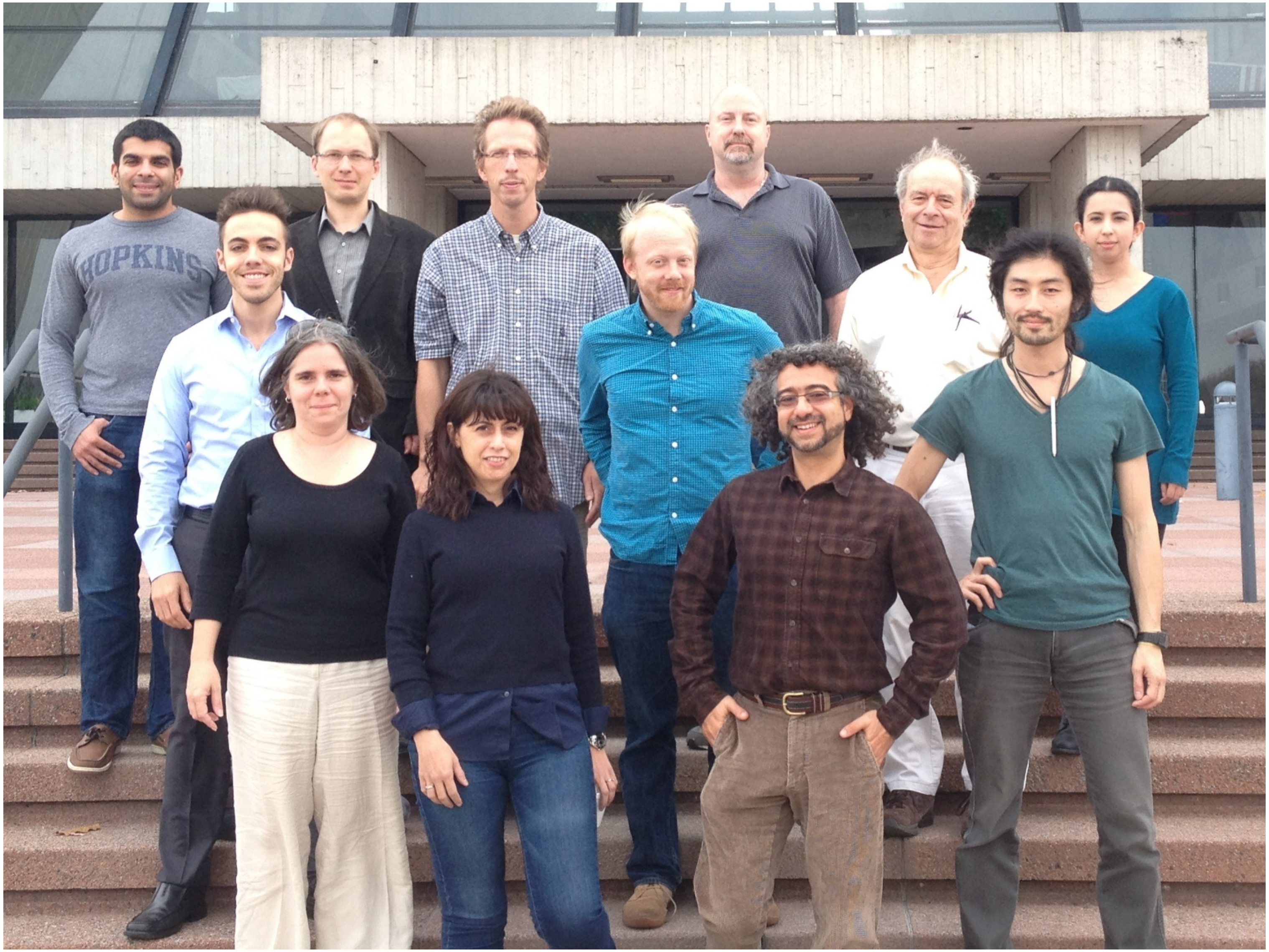
Reminder:

- On-axis neutrino beam
- 100 meters from target
- 4 x 10^{12} P.O.T. per pulse
- 600 MeV peak energy

ν-type	Total Interactions	Charged Current	Neutral Current
ν_μ	9892	6991	2900
$\bar{\nu}_\mu$	130	83	47
ν_e	71	51	20
$\bar{\nu}_e$	3.0	2.0	1.0

The ANNIE Collaboration

Picture taken at most recent collaboration meeting (Oct 2014 @ Fermilab)



33 collaborators from 16 institutions in 2 countries (USA & UK)

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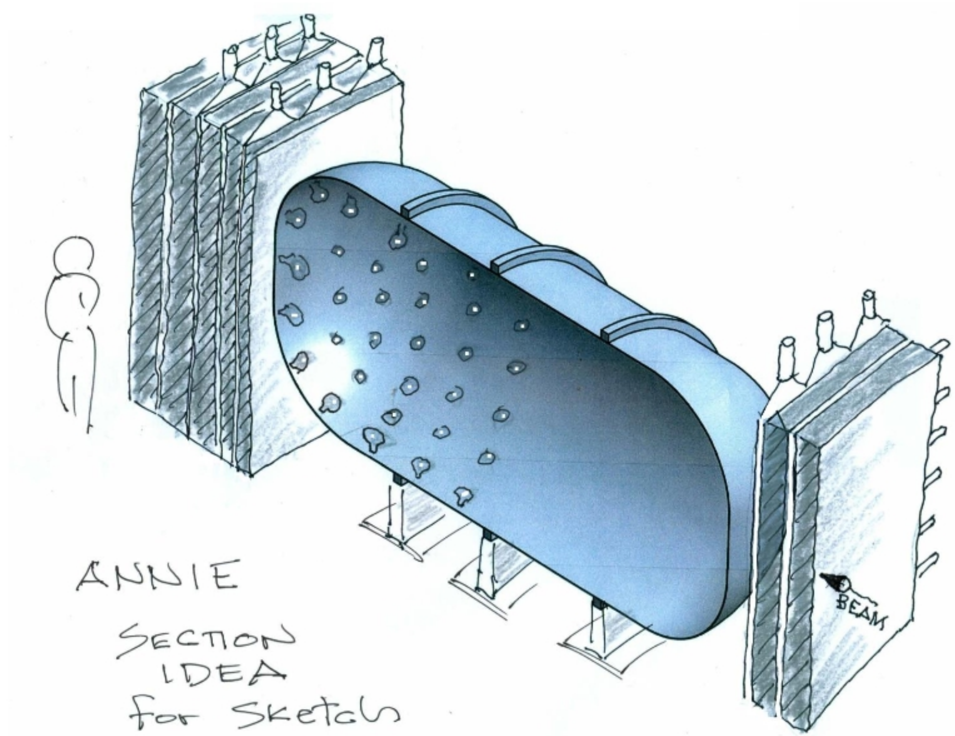

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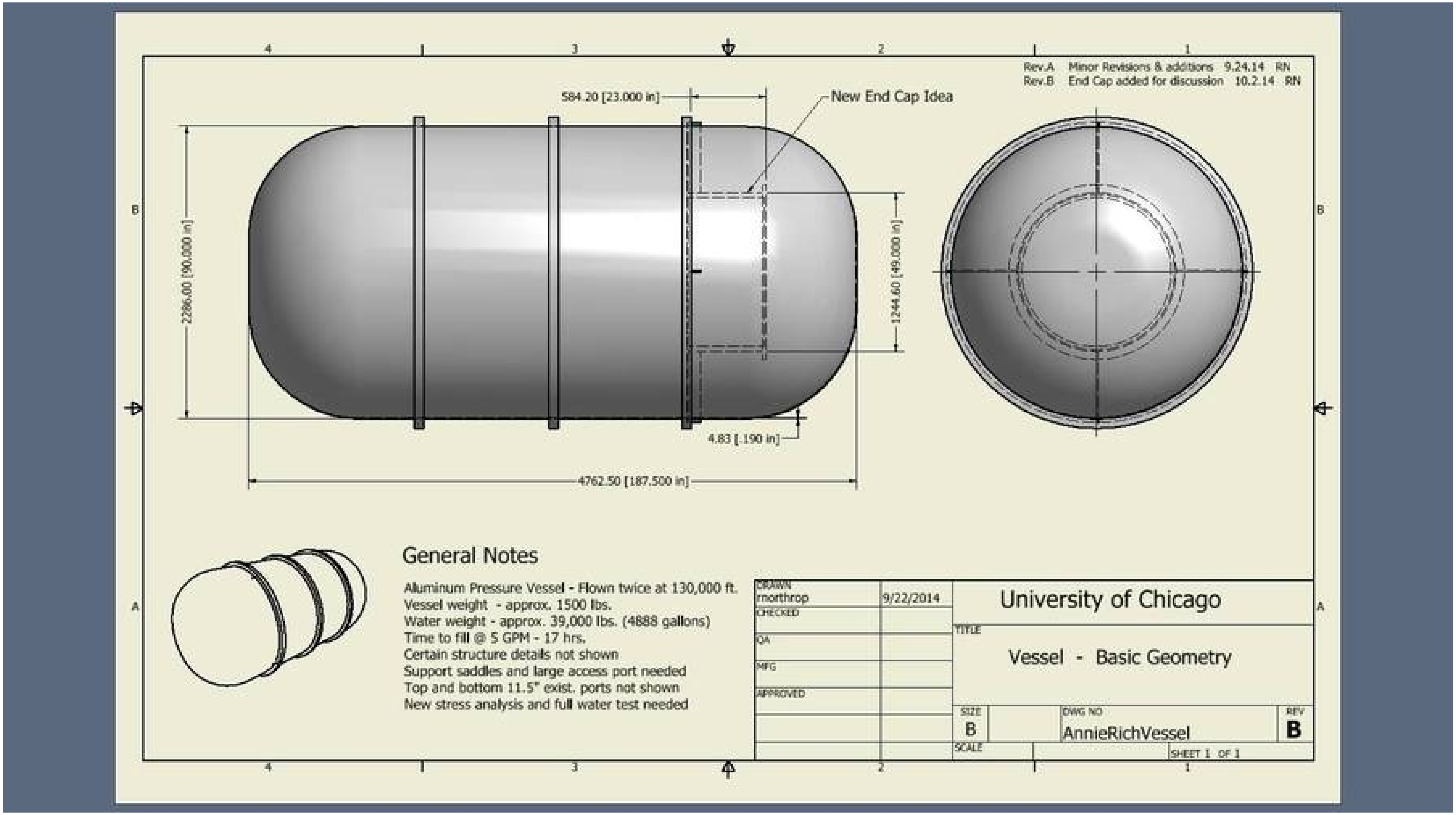
Hardware: Tank

We have access to an aluminium pressure vessel owned by the University of Chicago:

- Previously used as a balloon experiment for cosmic ray measurements
- Has flown twice at altitude of 40,000 meters



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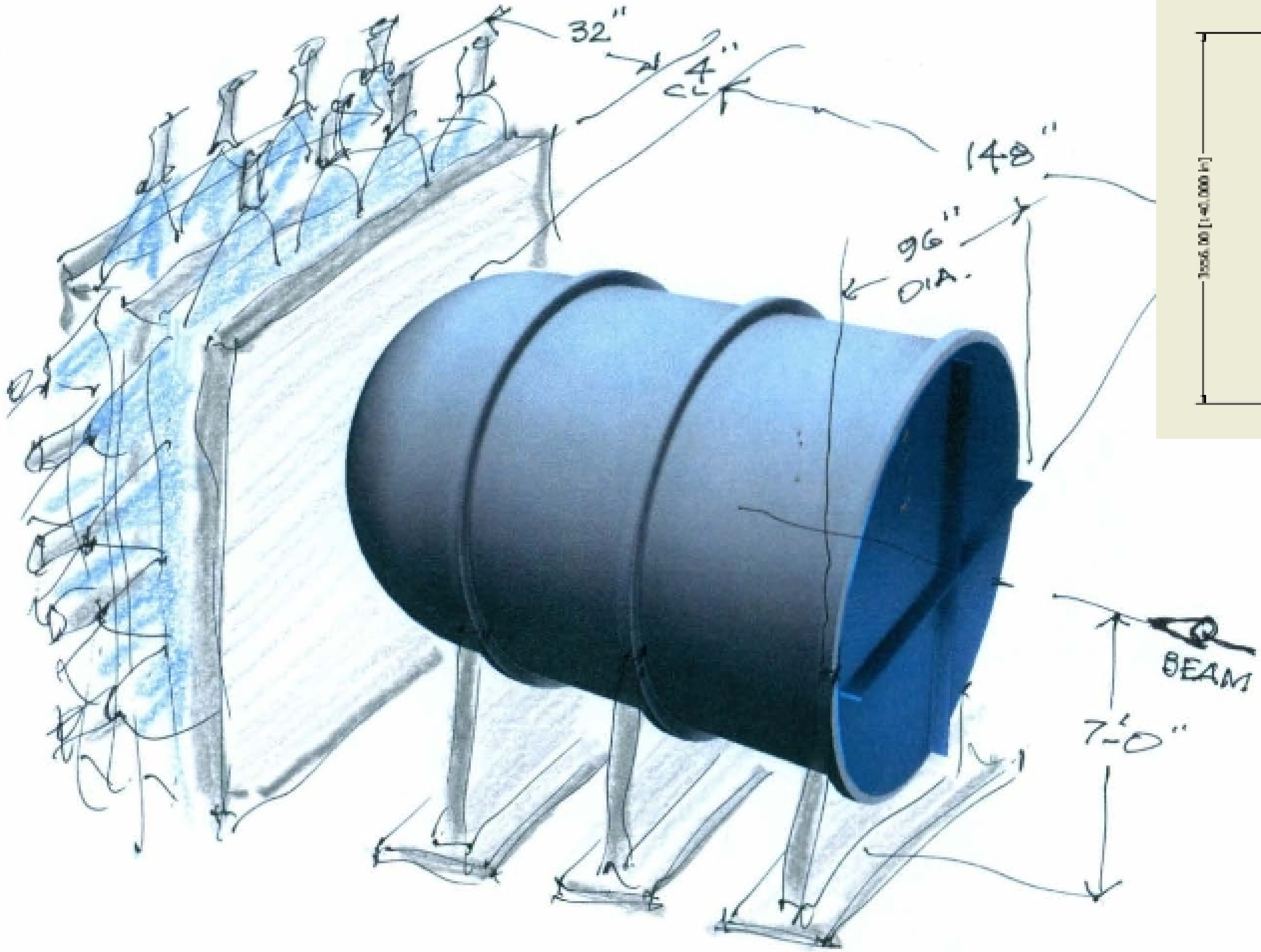
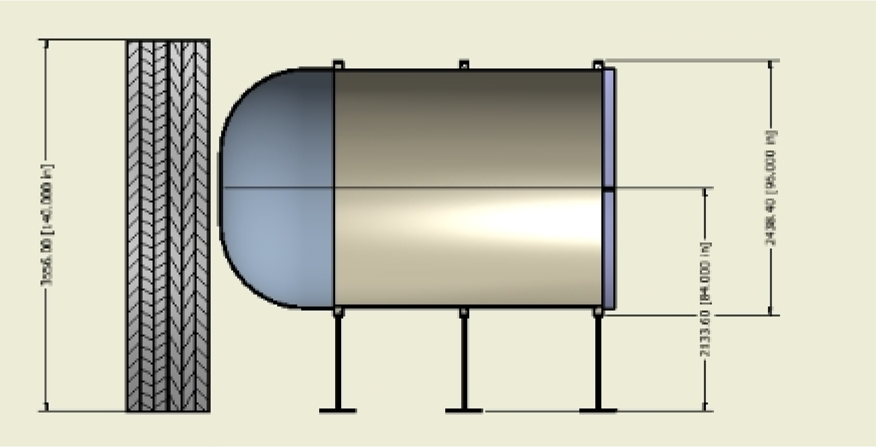
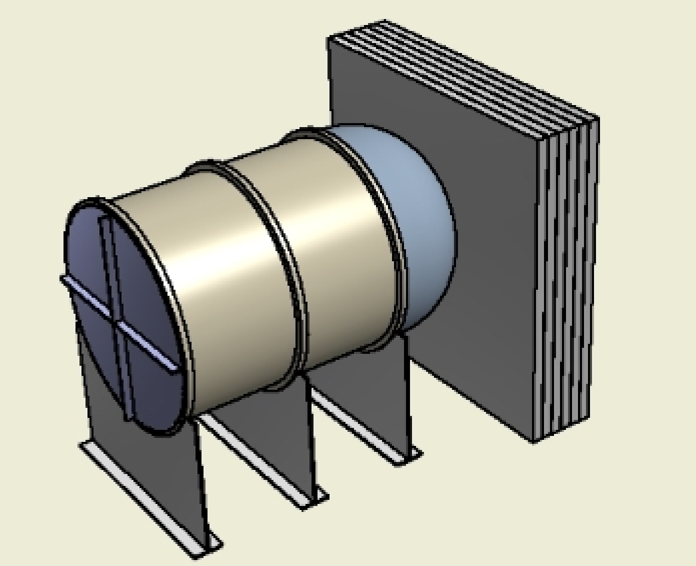
N.B. To operate Al tank with Gd-laced water, will need plastic liner for protection...

Plan is to remove one endcap, making ANNIE a 'bullet-shaped' experiment:







Alternate plan would be to purchase a custom-build stainless steel tank (~$13k) and run in upright position.

Hardware: PMTs

Will borrow PMTs from: University of California at Irvine (UCI)
WATCHBOY experiment (1 ktonne prototype for WATCHMAN)

UCI: All PMTs are Hamamatsu 8 inch.
Two types of PMTs are available:

- 63 SK-type tubes [manufactured circa 2000]
- 43 PMTs from IMB (!) [manufactured circa 1980]

UCI will also perform final PMT testing.

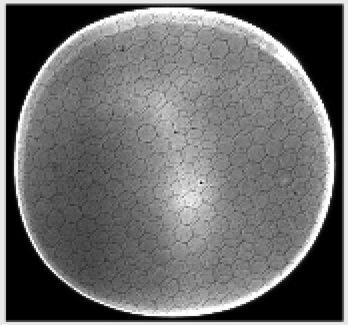
WATCHBOY:

- 58 PMTs are available (also 8”)
- Ran recently (2013 – 2014 at KURF: Kimballton Underground Research Facility)
- On loan to ANNIE, accompanied by WATCHBOY readout electronics

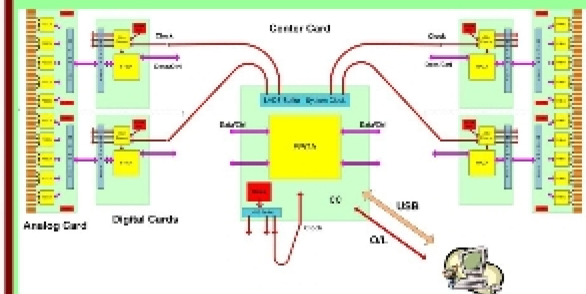
Hardware: LAPPDs

R&D still ongoing on multiple fronts:

MicroChannel Plates

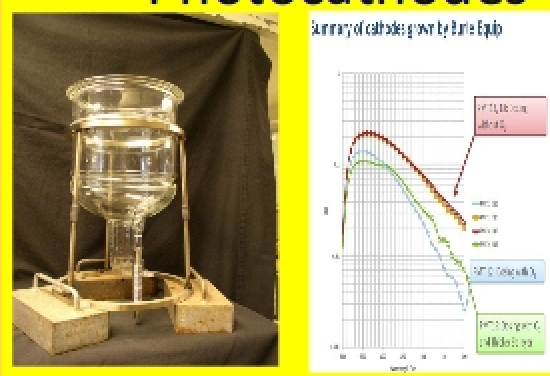


Electronics/Integration



Hermetic Packaging

Photocathodes



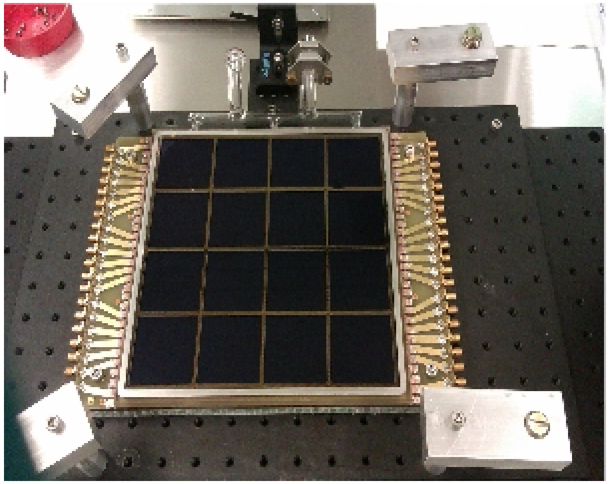
Major milestone: First sealed unit produced last Summer

Also: Argonne Nat'l Lab producing miniatures (6 cm) at rate of 1/week
Photocathodes now at 0.15 – 0.25 (much better than 10^{-7}!)
Psec4 electronics currently in use; Psec5 under development

Hardware: LAPPDs

The University Of Sheffield.

Commercialisation process has begun; Incom to produce LAPPDs as consumer product



Micro-capillary arrays by Incom Inc.

- **Material:** Ordinary glass
- **Area:** 20 cm x 20 cm (8" x 8")
- **Thickness:** 1.2 mm
- **Pore size:** 20 μm

Much more could be said on LAPPDs (*i.e.*, a dedicated talk!)
For more information, see:

- "RF Stripline Anodes for Psec Large-Area MCP-Based Photodetectors" by H.Grabas *et al*, Nucl. Instr. Meth. A71:124-131 (2013)
- "A Test Facility for Large-Area Microchannel Plate Detector Assemblies using a Pule Sub-Picosecond Laser" by B. Adams *et al*, Review of Scientific Instruments 84:061301 (2013)
- "Large Area Event Counting Detectors with High Spatial and Temporal Resolution" by O.H.W. Siegmund *et al*, JINST (2014)

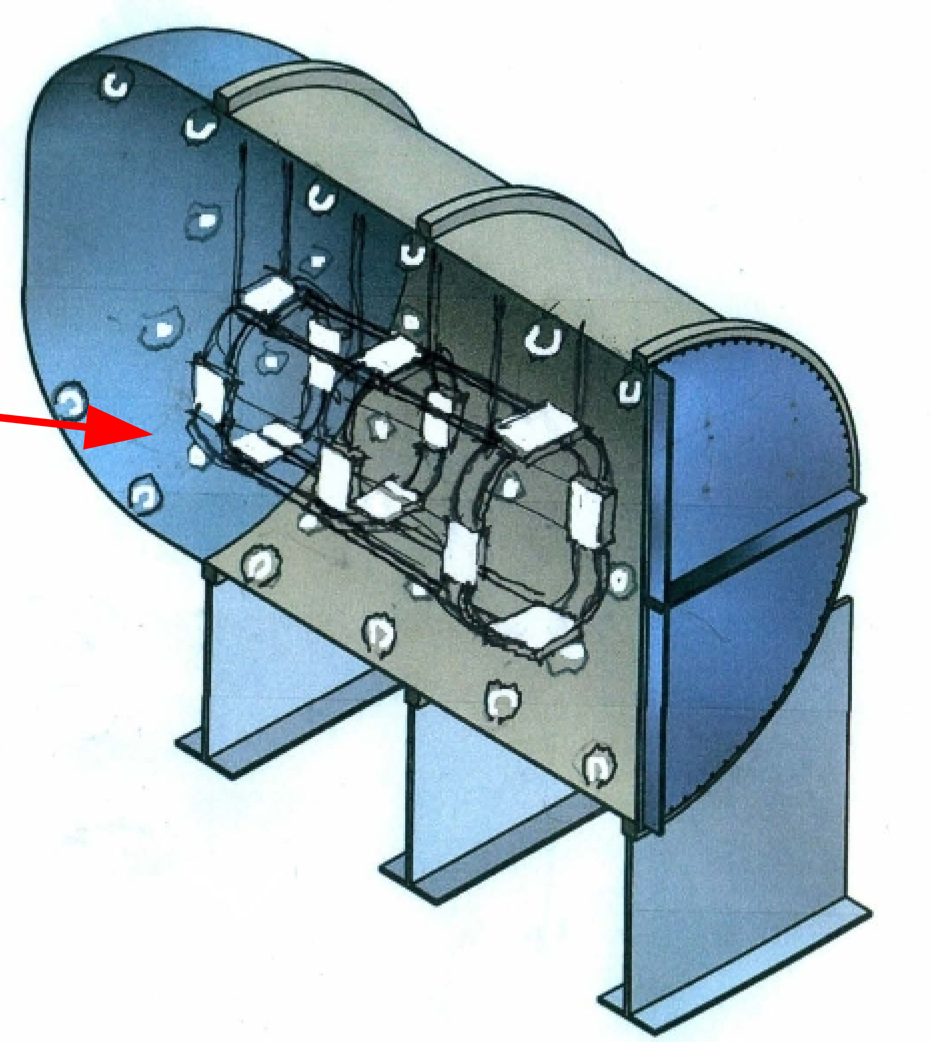
- Also: http://psec.uchicago.edu has more references... (Enjoy!)

Hardware: Mounting

Due to ongoing R&D, a **<u>very</u>** limited number of LAPPDs will be available for in near future, for ANNIE Phase I (possibly 1 ± 1?)

Studies and discussions are underway to optimise available photosensors.

One idea is to arrange limited quantity of LAPPDs on wire frame around FV, with conventional PMTs at edge of tank.



Not yet clear if this is wise!

Advantage:

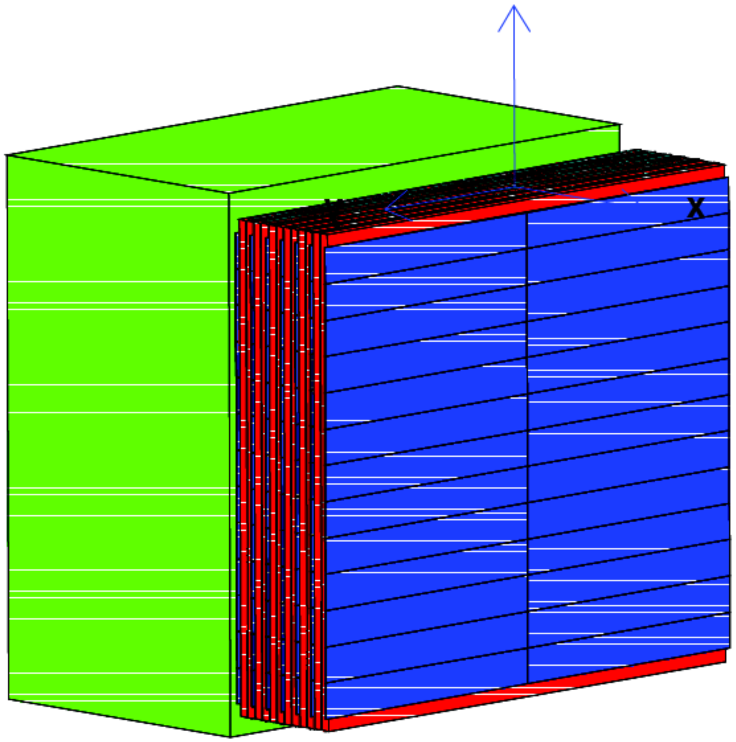
- Smaller angle and better light collection maximises LAPPD exposure

Disadvantage:

- Risk of shadowing effects from frame; difficult to model & introduces large systematics

Hardware: MRD

The University Of Sheffield.



Will 'resurrect' the SciBooNE MRD:

- Twelve 2” thick steel & scintillator sandwich
- 2” PMTs

At present:

– **Scintillator** owned by New Mexico State University

– **PMTs** owned by Rochester, Kansas State, Fermilab

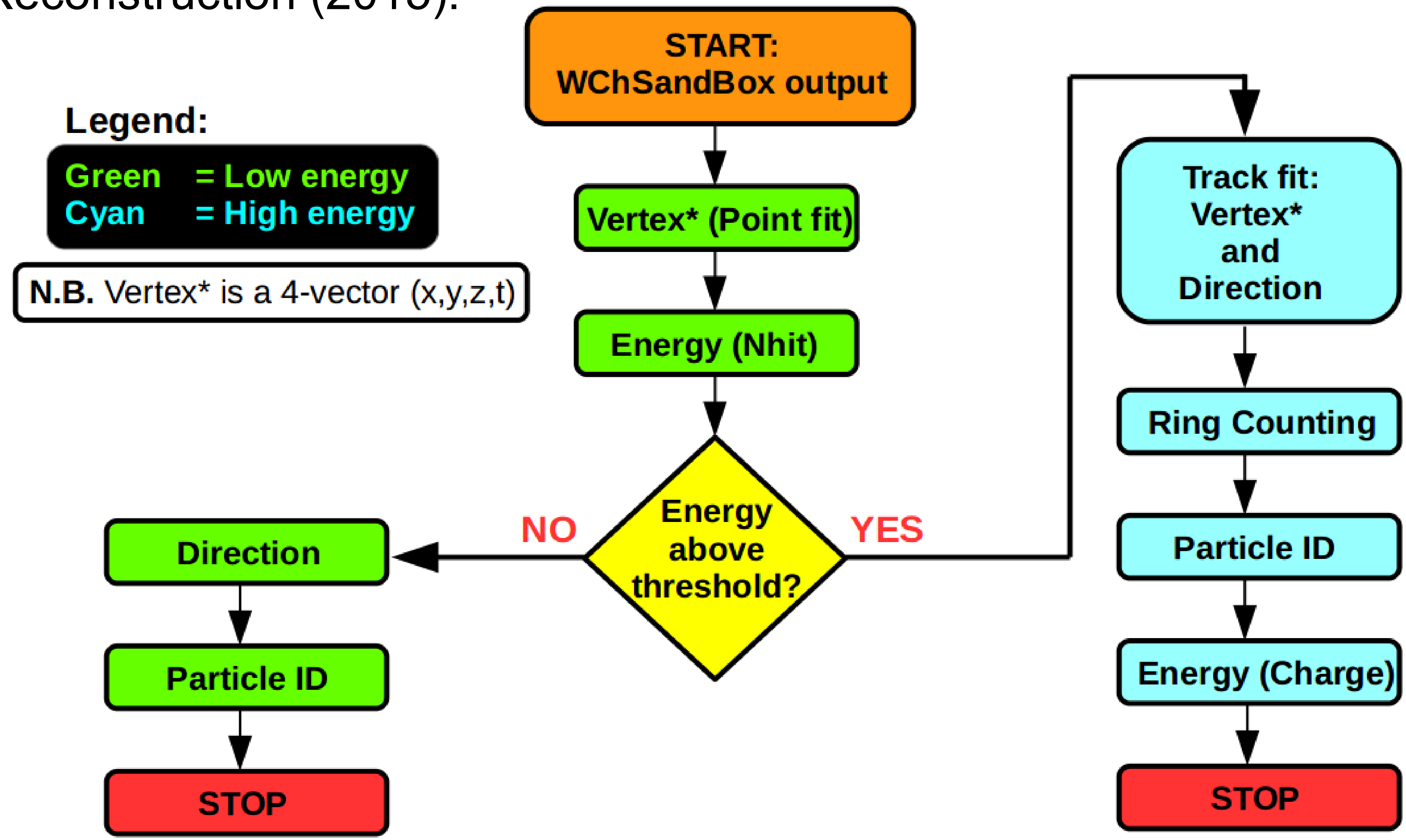
– **Steel** owned by Fermilab
- We have permission to use all of these in ANNIE (M.O.U.s are currently being prepared)

– **Electronics** have been entirely removed!
- SciBooNE MRD borrowed their electronics from Fermilab PREP. The parts are available on-site and we plan to borrow them back for ANNIE.

The proposal for ANNIE Phase I did not include a functioning MRD.
Physical access may be difficult once tank is in place, so schedule may be accelerated.

ANNIE Simulation

- Neutrino generation via NEUT & GENIE
- Detector simulation with WChSandBox: **New** fast simulation package! (2014)
- Reconstruction (2015):



Outline

The University Of Sheffield.

I) Motivation:

- Physics objectives
- Technical goals

II) Project overview:

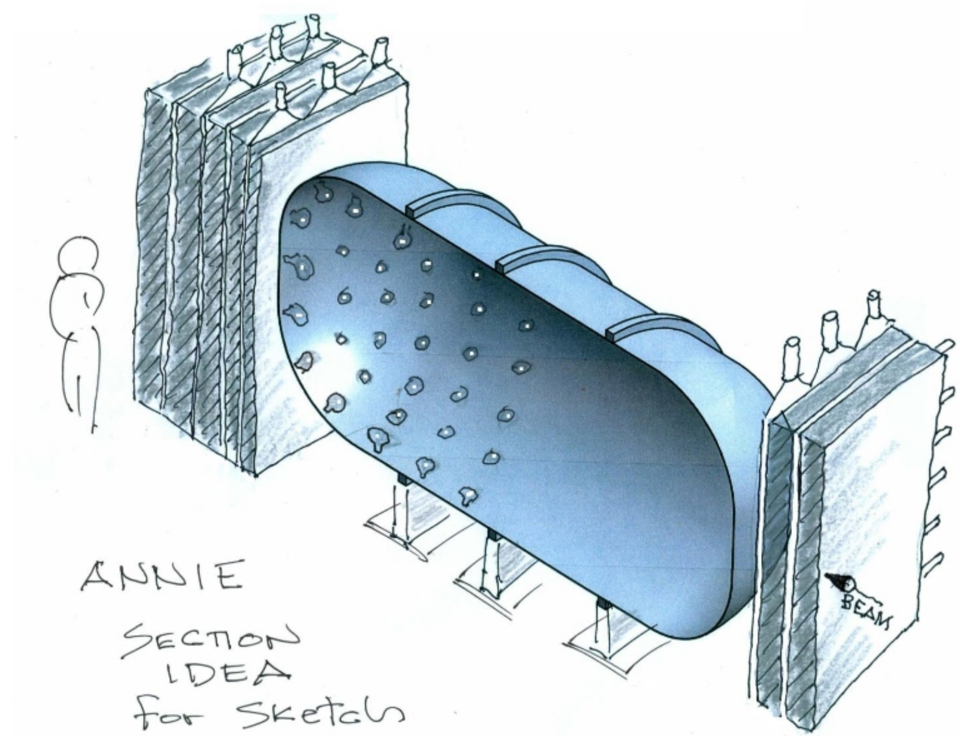
- Detector
- Beam

III) Current Status:

- Hardware
- Software & simulations

IV) Future:

- Timeline
- Application to other experiments



R. Northrop

ANNIE Phase I

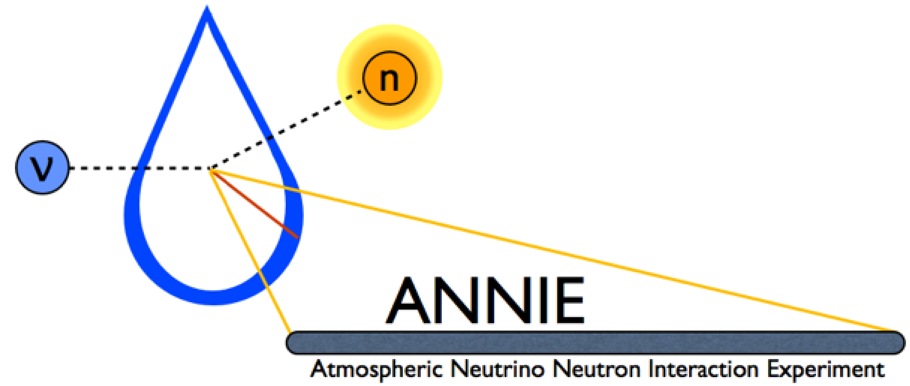
The University Of Sheffield.

First phase will have:

- ~20 tonnes of Gd-doped water
- ~60 PMTs (from WATCHBOY)

It will NOT have:

- Significant numbers of LAPPDs (or any?)
- Magnetised MRD



ANNIE Phase I proposal **approved** in February by Fermilab PAC!

→ Will run as a 'test' and not an 'experiment'

→ See: http://arxiv.org/pdf/1504.01480v1.pdf

Fermilab has a new 'Neutrino Division', which has a 'short baseline' section headed by Peter Wilson. [N.B. 'Short' ≡ 'contained on site']

Fermilab seems to view ANNIE as a welcome addition to the SBL programme, complementing the various LAr detectors in the BNB.

Phase I & Beyond

<u>Timetable:</u> Build Phase I in Summer 2015 and run from Autumn 2015

Physics goals for Phase I are neutron background measurements at various positions in ANNIE hall (dirt neutrons, 'skyshine', etc.)

→ Will likely run DCTPC in conjunction with Phase I

<u>Looking ahead:</u> ANNIE Phase II

From Autumn 2016, we hope to run for ~2 years with:

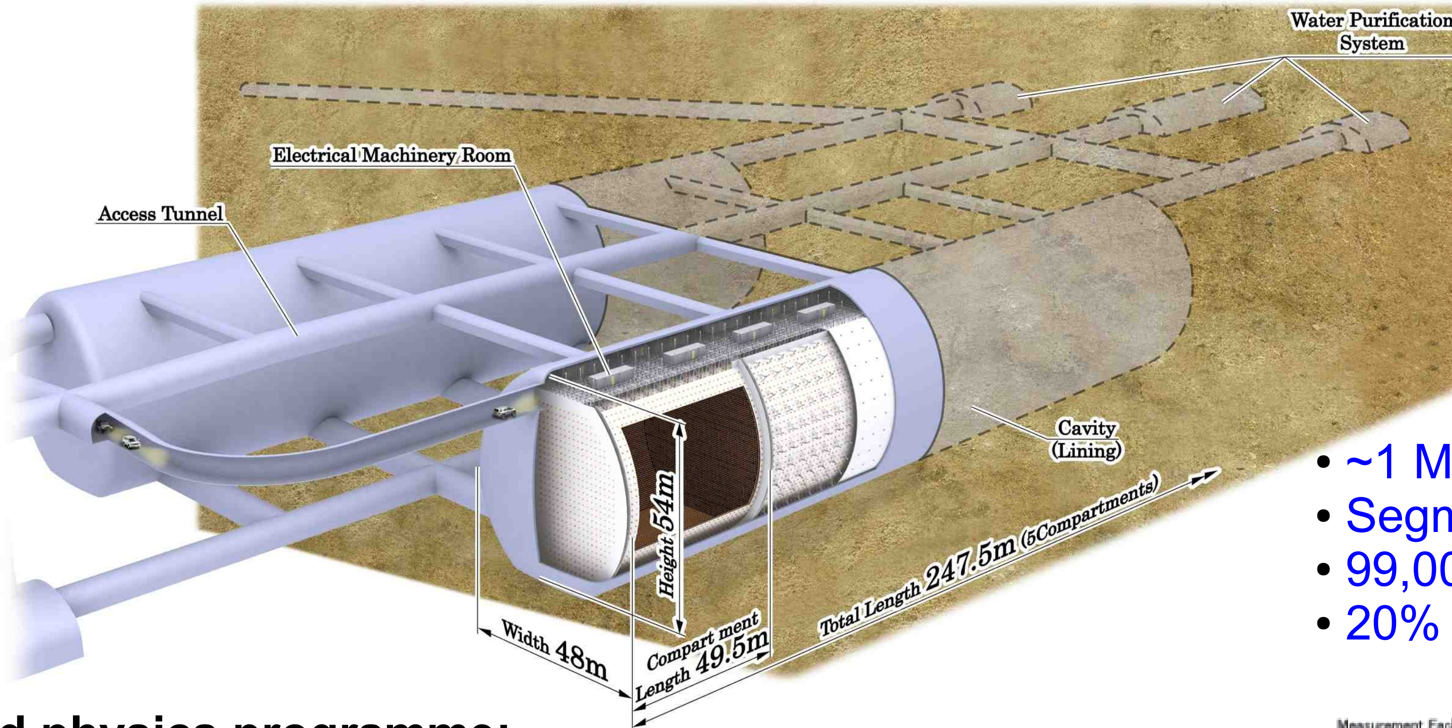
- ~20 tonnes of Gd-doped water
- ~150 PMTs
- 10 – 20 LAPPDs
- MRD (possibly magnetised)

– Physics goals include proper neutron yield measurements, and CC-inclusive measurement of ν_μ on water

– Technical goals include first running of LAPPDs in water

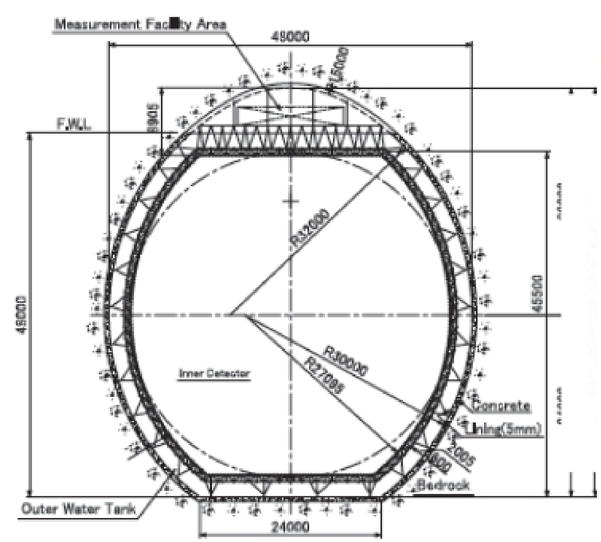
Hyper-Kamiokande

The University Of Sheffield.



- ~1 Megatonne total mass
- Segmented design
- 99,000 PMTs (20")
- 20% photo-coverage

CROSS SECTION



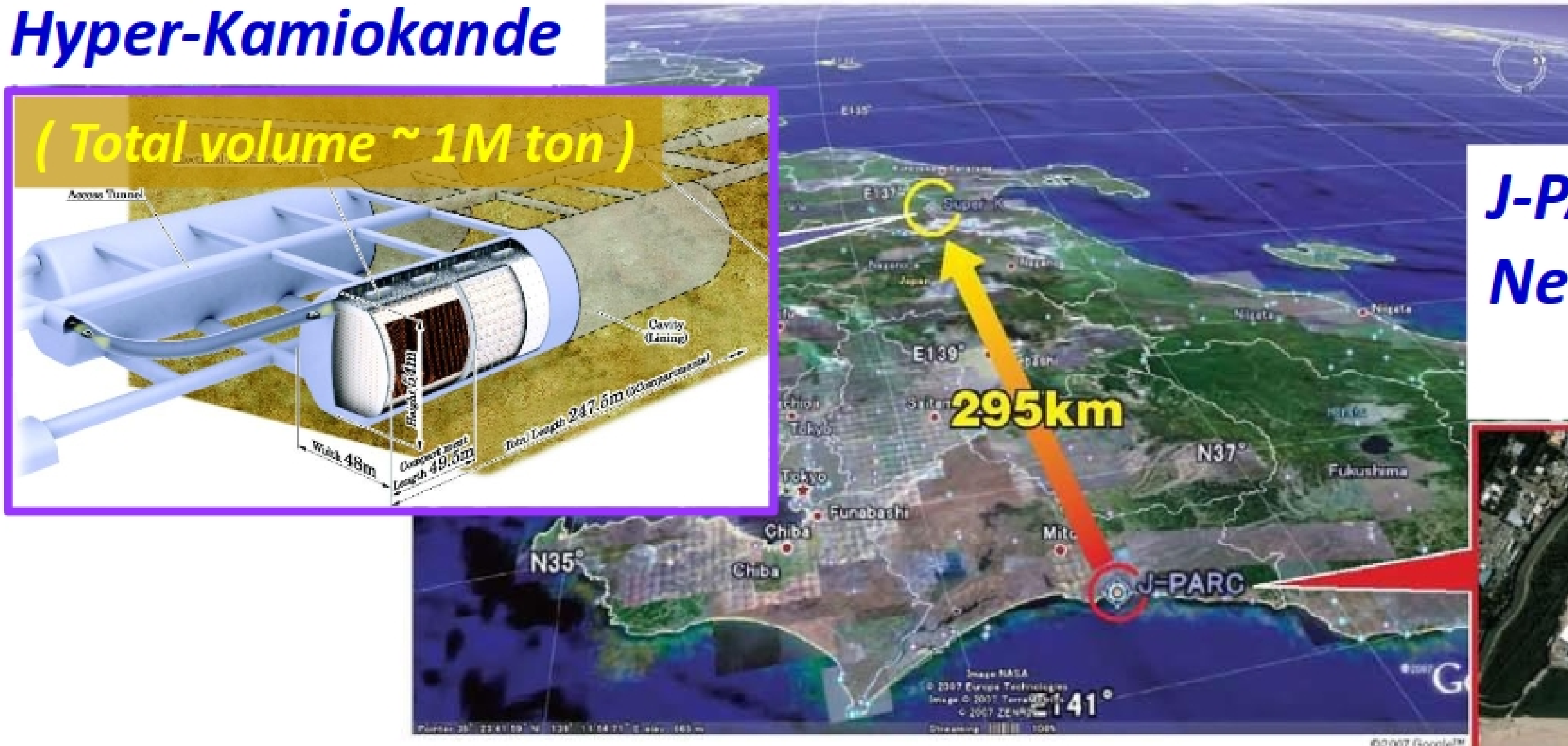
Broad physics programme:

- Neutrino oscillation:
  - **Atmospheric neutrinos** (still statistics limited!)
  - **Accelerator neutrinos** [see next slide]
  - Solar neutrinos
- **Proton decay**
- Neutrino astrophysics
  - **Supernova burst** (~250,000 events expected @ 10 kpc)
  - **Supernova relic neutrinos**
- Various other physics (indirect WIMP search, n-$\bar{n}$ osc., etc.)

Hyper-K Beam Programme

The University Of Sheffield.

Hyper-Kamiokande



J-PARC Main Ring Neutrino beamline
(KEK – JAEA)

- Expected # of events for $\sin^2 2\theta_{13} = 0.1$, $\delta = 0$ and NH

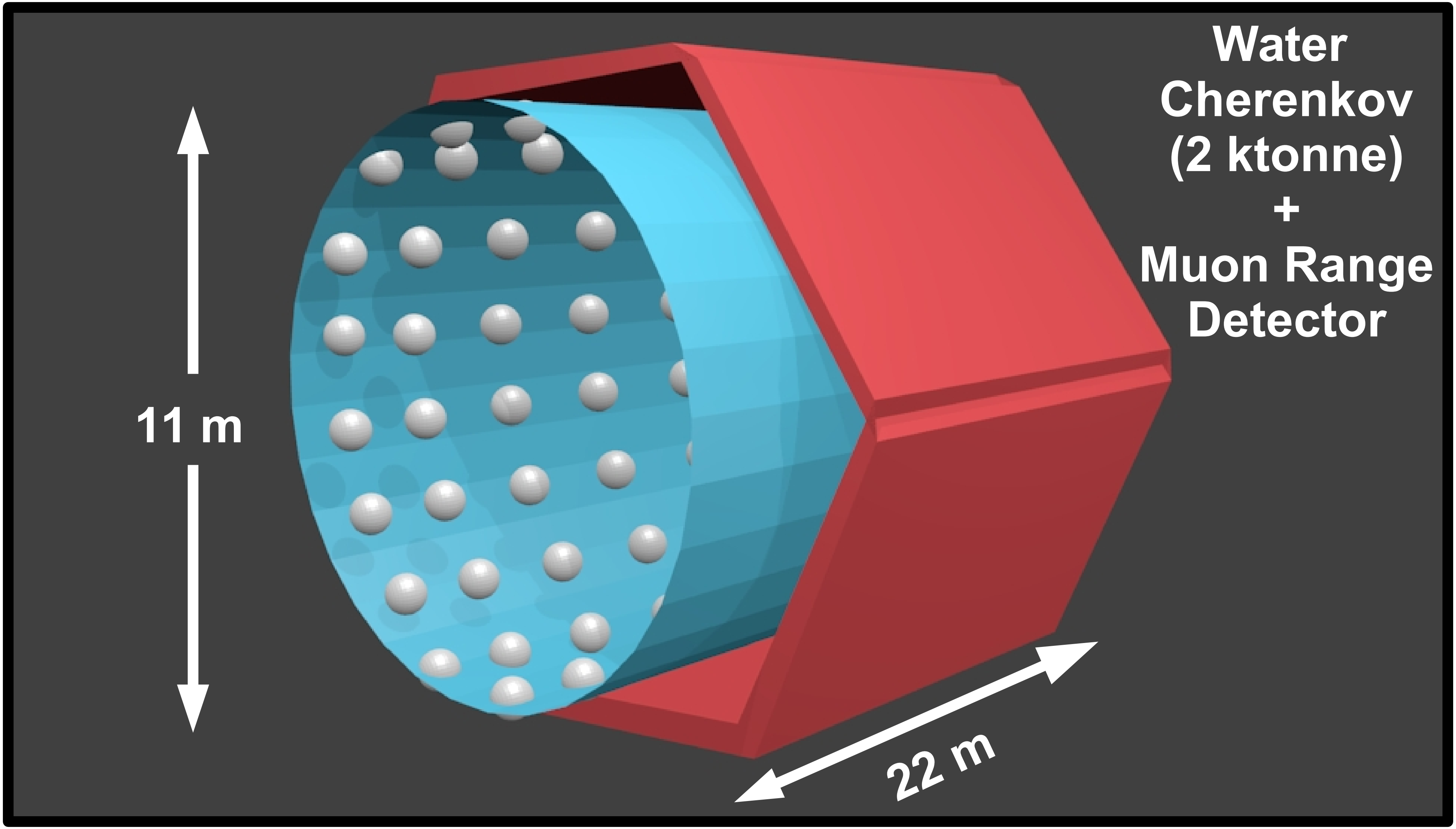
(7.5 x 10^7 MW·sec)

	Signal ($\nu\mu \rightarrow \nu e$ CC)	Wrong sign appearance	$\nu\mu/\bar{\nu}\mu$ CC	beam $\nu e/\bar{\nu}e$ contamination	NC
ν	3,016	28	11	523	172
$\bar{\nu}$	2,110	396	9	618	265

From Hayato (Neutrino 2014)

Significantly larger statistics merit better systematics:

New near detector(s)!

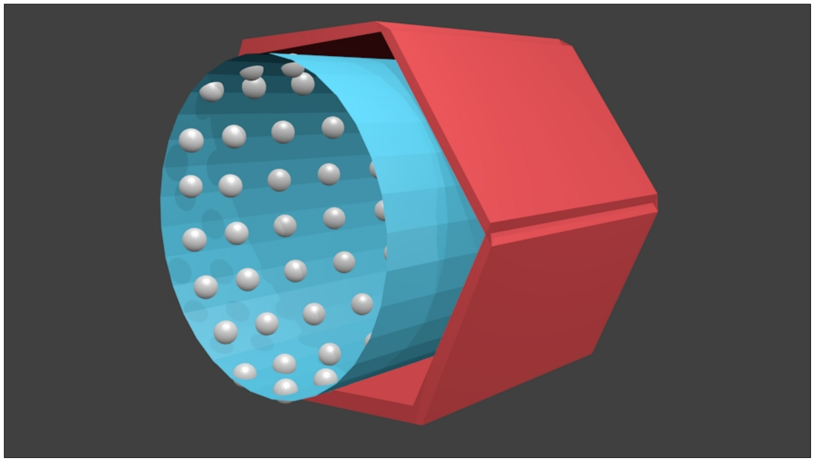


Water
Cherenkov
(2 ktonne)
+
Muon Range
Detector
11 m
22 m

TITUS Overview

The University Of Sheffield.

TITUS: The Tokai Intermediate Tank w/ Unoscillated Spectrum

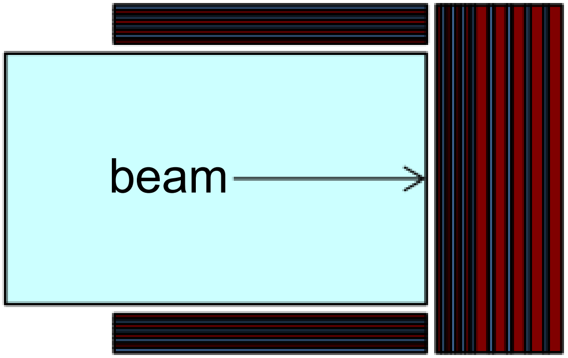


- Proposed new near detector for HK beam programme
- To be located ~2 km from J-PARC neutrino beam

- Baseline design includes:
  - ~2 ktonne water Cherenkov tank
  - 0.1% Gadolinium-doping
  - Partly enclosed by Muon Range Detector

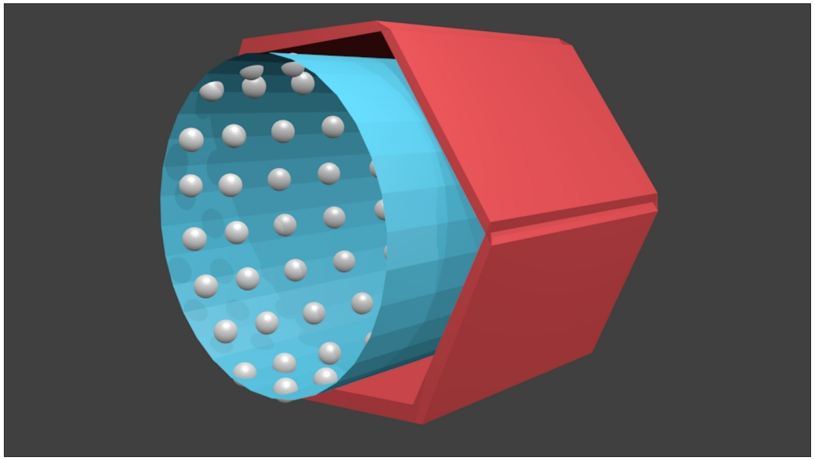
- Likely add-ons / upgrades currently being investigated include:
  - Magnetised MRD (1.5 Tesla field) for charge-sign reconstruction
  - Large Area Picosecond Photo-Detectors (LAPPDs) for high precision timing

- Future possible add-ons / upgrades include:
  - Water-based liquid scintillator
  - TPC inside an aluminium coil air core magnet (replacing MRD?)



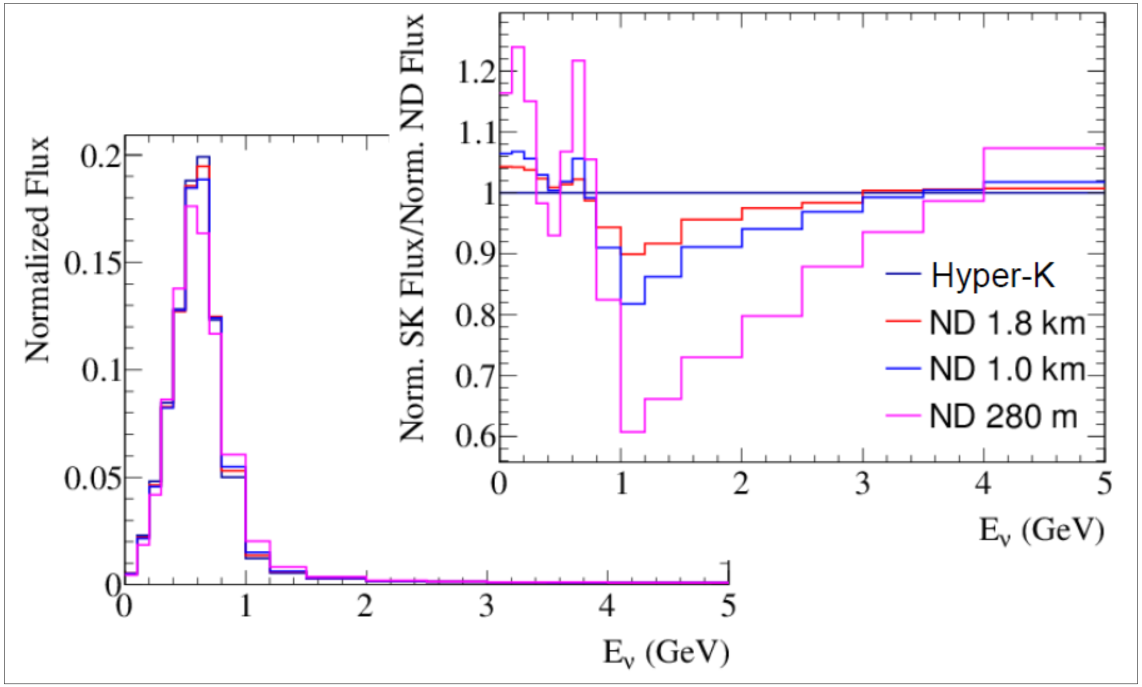
TITUS Overview

TITUS: The **T**okai **I**ntermediate **T**ank w/ **U**noscillated **S**pectrum



- Proposed new near detector for HK beam programme
- To be located ~2 km from J-PARC neutrino beam

- Baseline design includes:
  - ~2 ktonne water Cherenkov tank
  - 0.1% Gadolinium-doping
  - Partly enclosed by Muon Range Detector



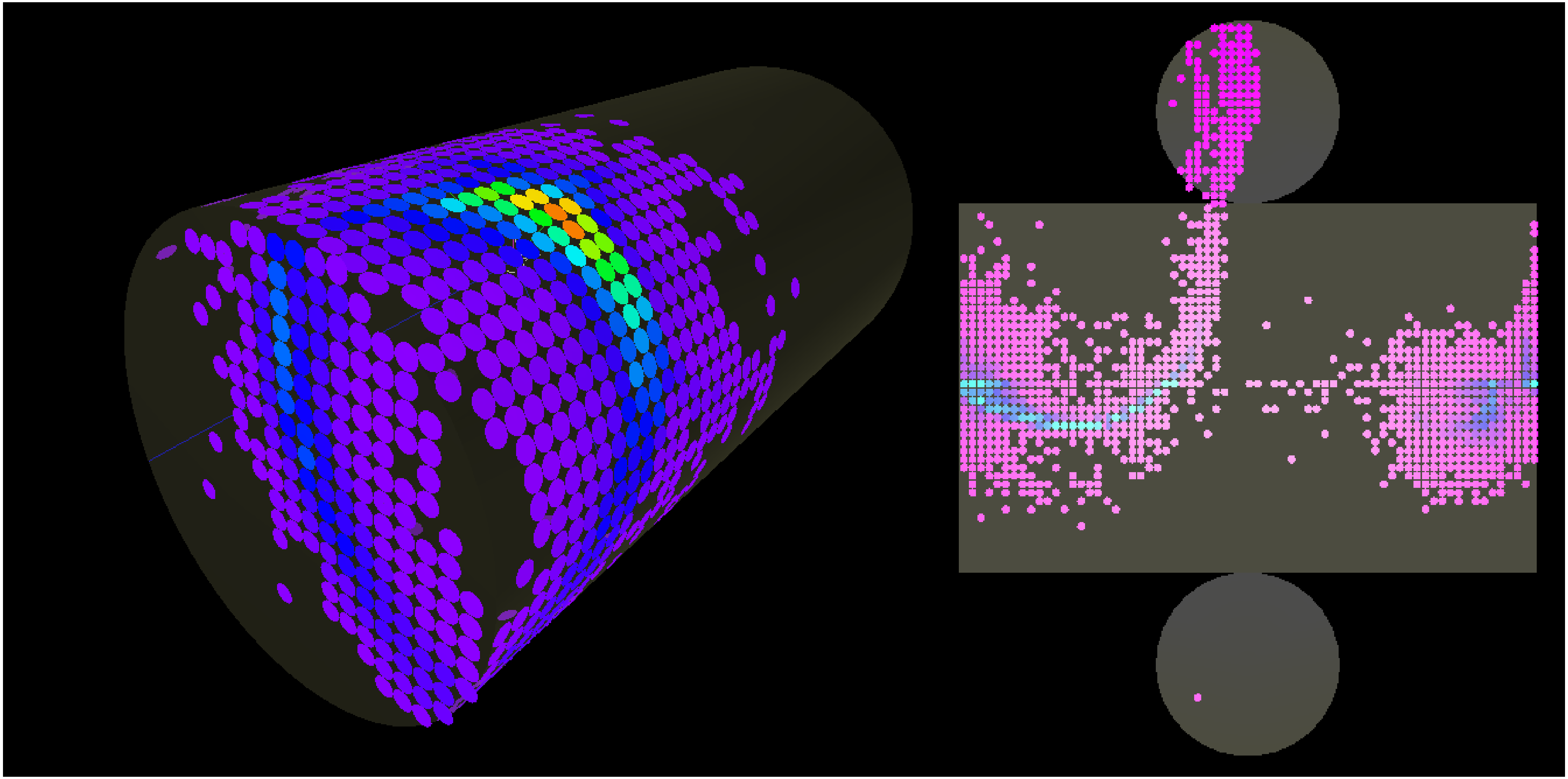
- Same target nuclei as Hyper-K
  - H_2O (and maybe Gd)

- Nearly the same target angle and ν energy spectrum

- Many systematics cancel out in Far/Near ratio

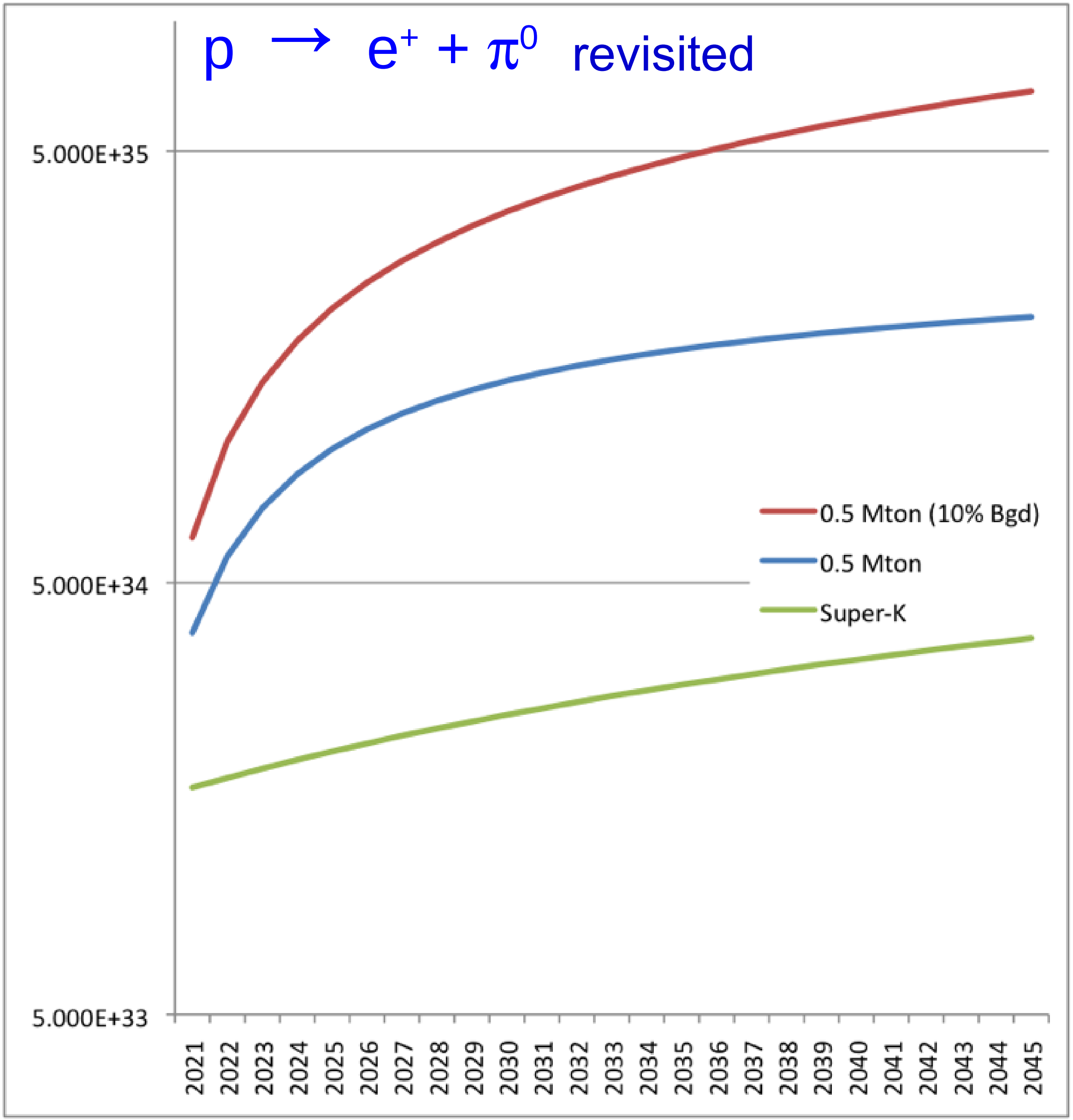
TITUS Event Display

Neutrino event simulated with WChSandBox:



CCQE (1Rμ)

Hyper-K Proton Decay



Hyper-Kamiokande (with 10% B.G.)

Hyper-Kamiokande (baseline design)

Super-Kamiokande

Conclusions

The University Of Sheffield.

- **The ANNIE experiment will measure neutrino-nucleus interactions in the energy range of atmospheric ν**
  - Primary physics goal is neutron yield as a function of neutrino energy
  - Secondary physics goal is neutrino cross-section measurements on oxygen
- **Technical goals include:**
  - First Gd-doped water Cherenkov detector to run in a neutrino beam
  - First application of LAPPDs in water and for high energy physics
  - Possible first joint use of WC + magnetised MRD
- **ANNIE Phase I is now approved!**
  - Will commence running later this year in SciBooNE hall, using Booster Neutrino Beam
  - Background neutron measurement is primary goal for Phase I
  - Phase II planned for next year, adding LAPPDs and making physics measurements
- **Application to future WC experiments (*e.g.*, Hyper-Kamiokande)**
  - Beam programme can benefit from a new near detector modelled similar to ANNIE
  - Proton decay analysis may increase sensitivity by order of magnitude

Thank you for listening!